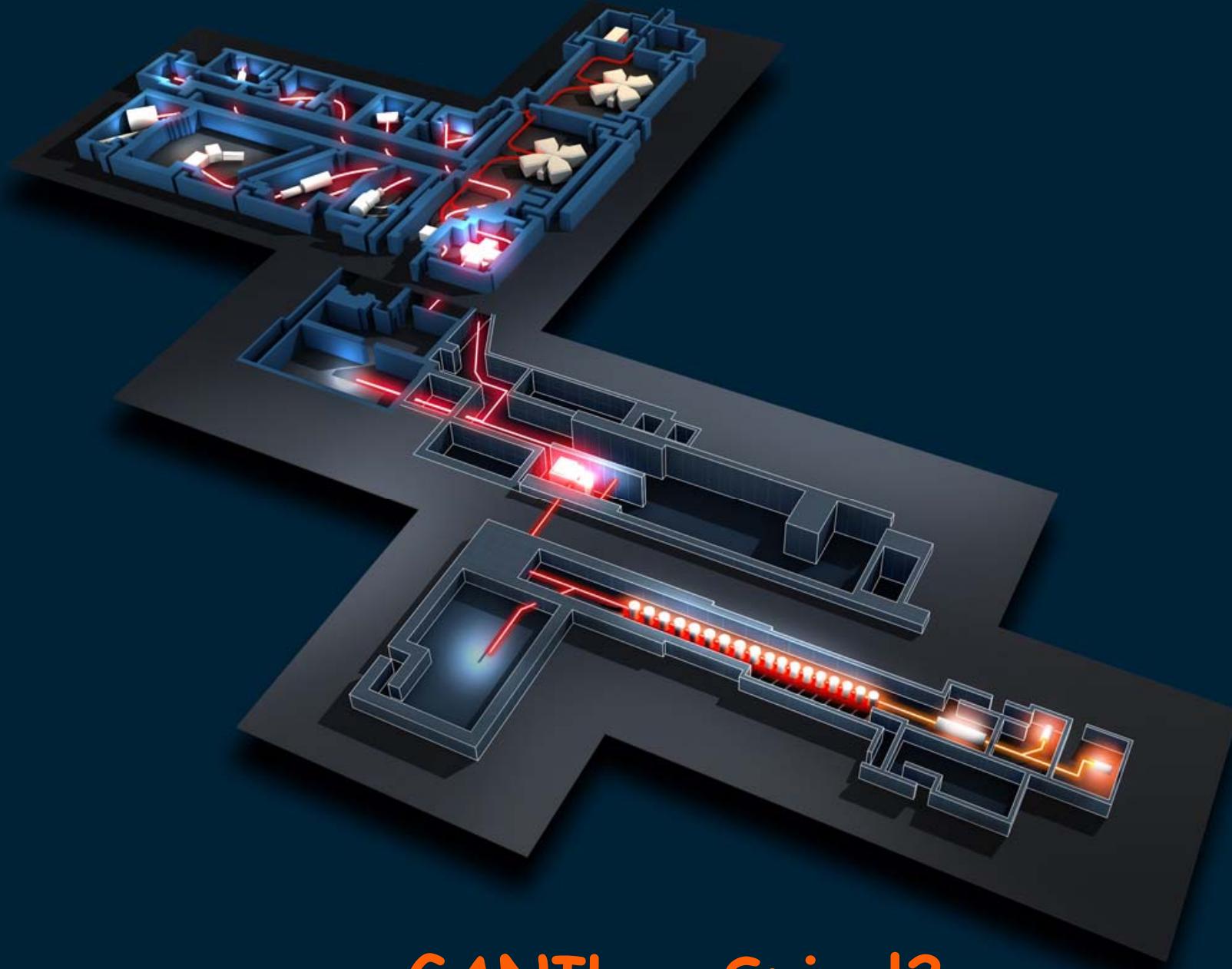


GANIL - Spiral2





GANIL - Spiral2

Play 









Image © 2005 EarthSat

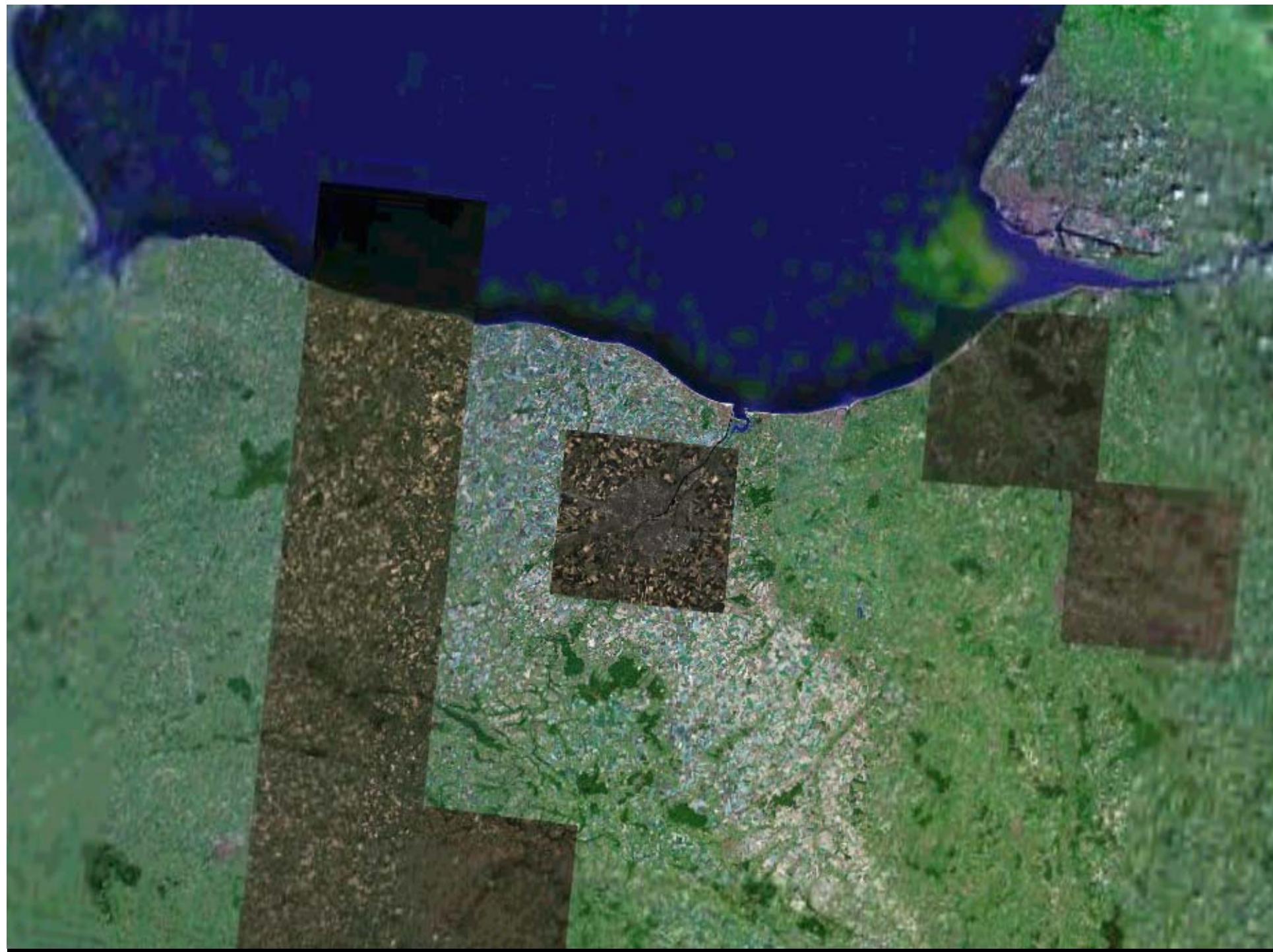


























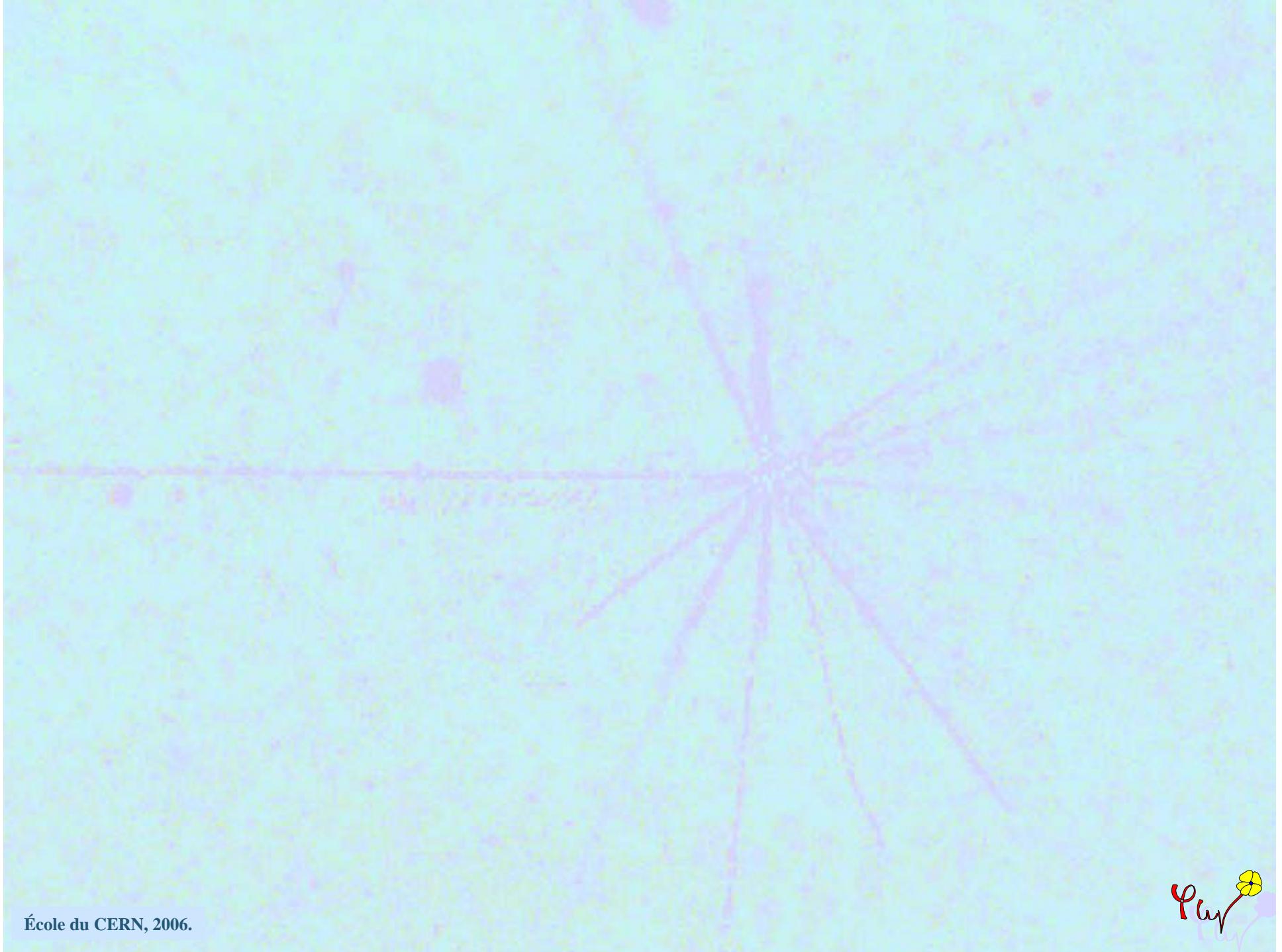


Nuclear Physics

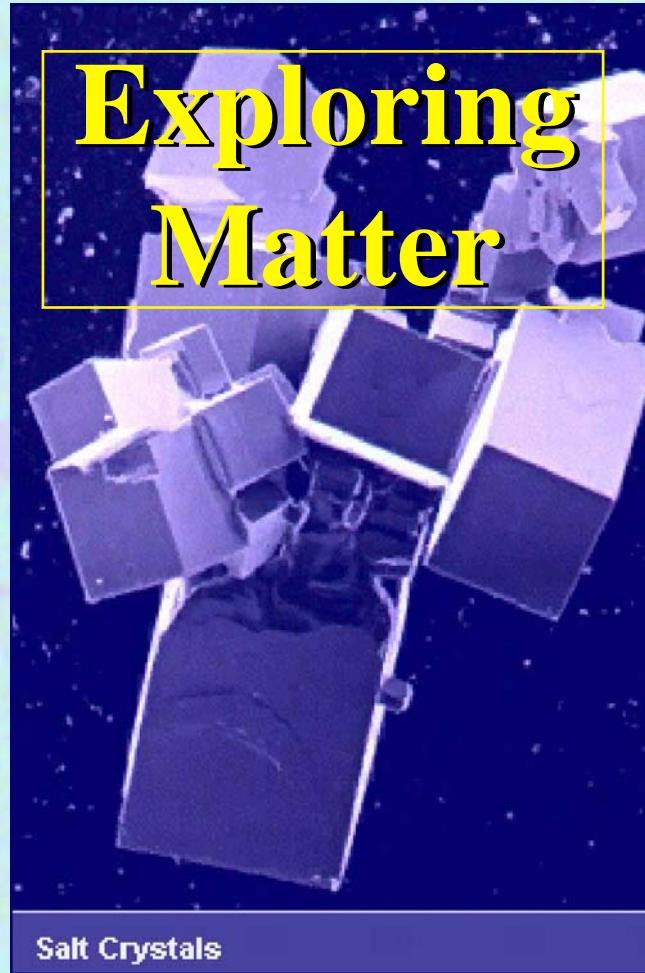
an Introduction

**Philippe CHOMAZ
GANIL-CAEN**

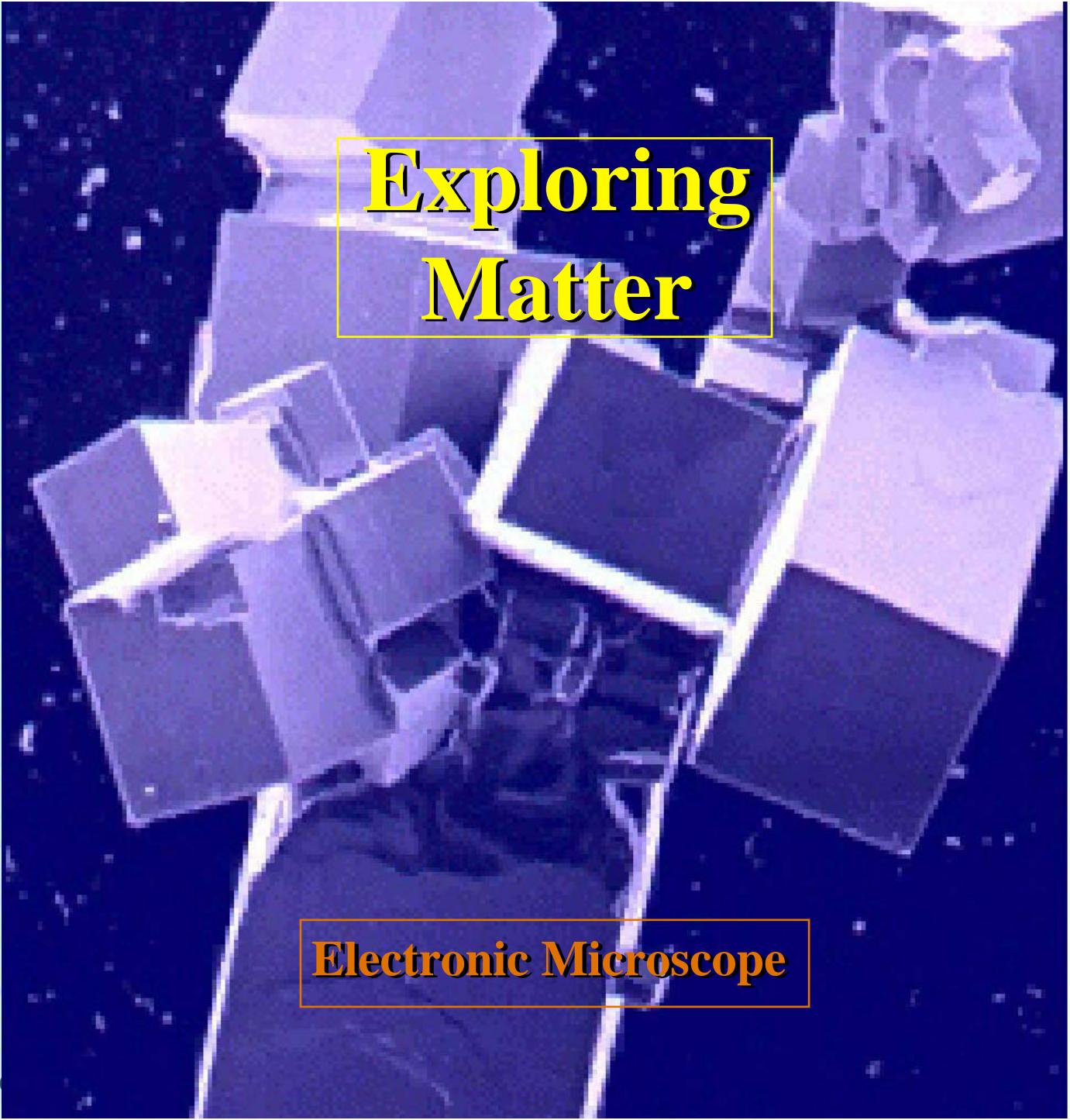




École du CERN, 2006.



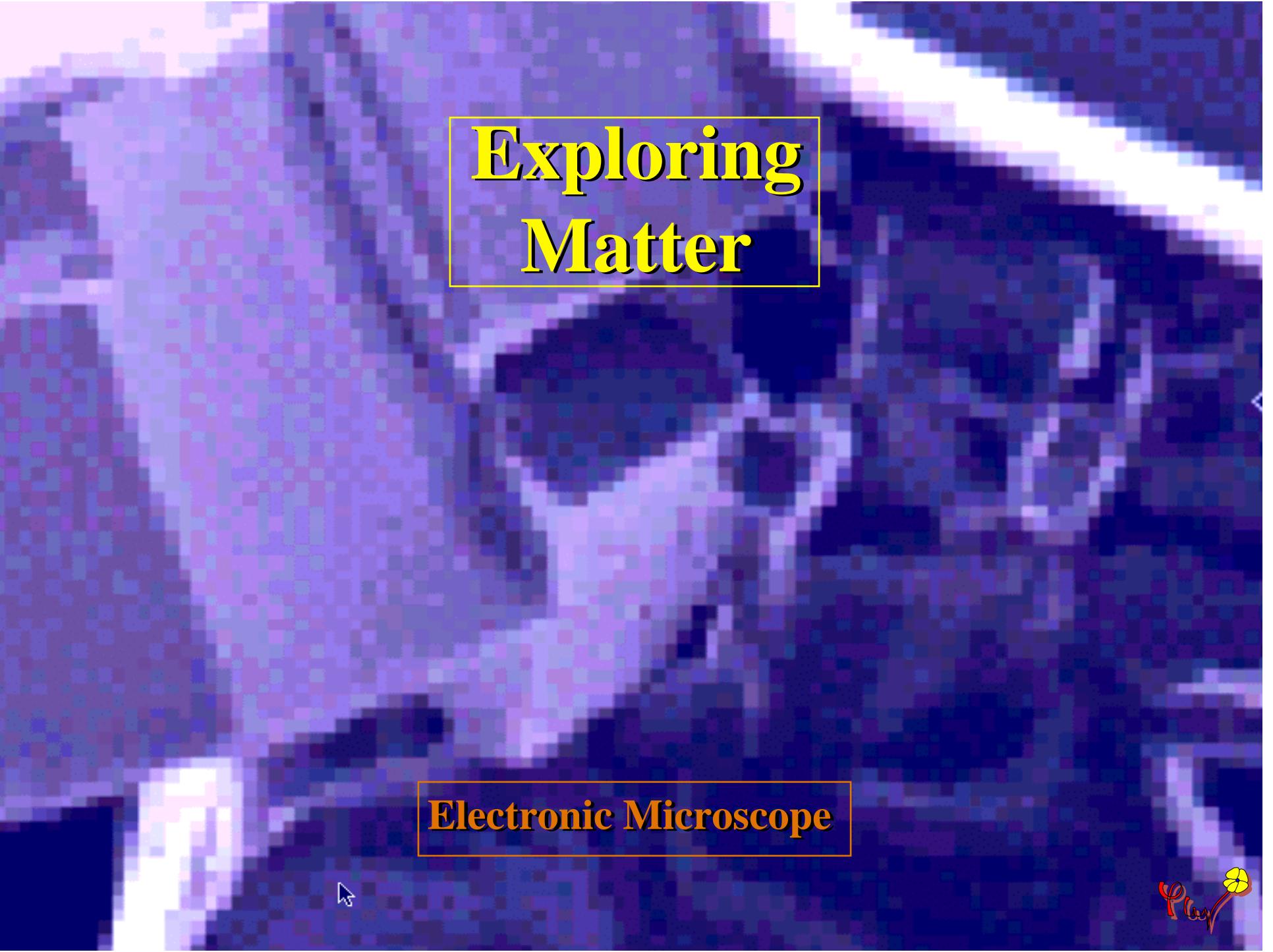
Electronic Microscope



Exploring Matter

Electronic Microscope





Exploring Matter

Electronic Microscope



Exploring Matter

Matter is made of atoms...

Atomic Force Microscope

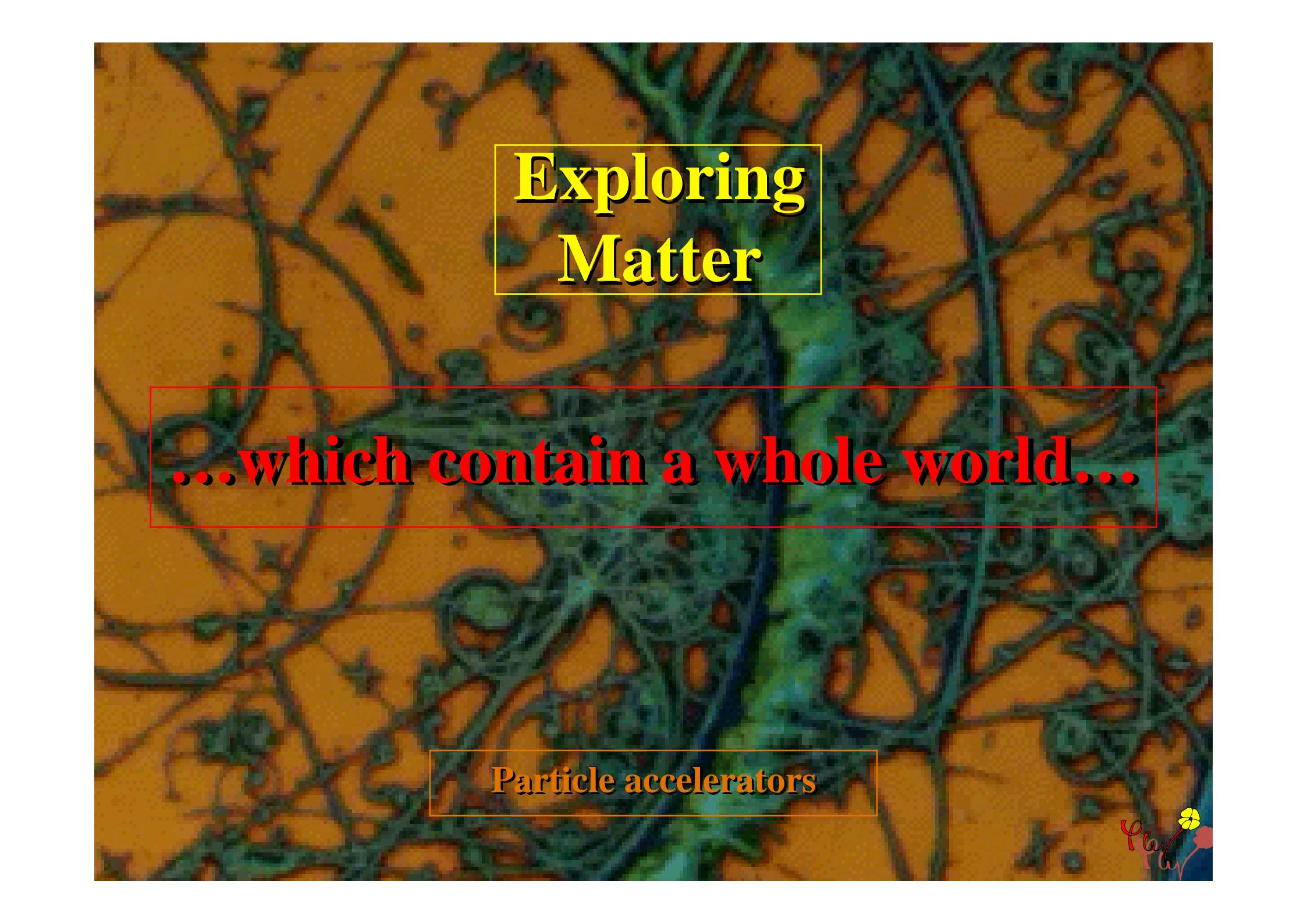


Exploring Matter

Matter is made of atoms...

Atomic Force Microscope



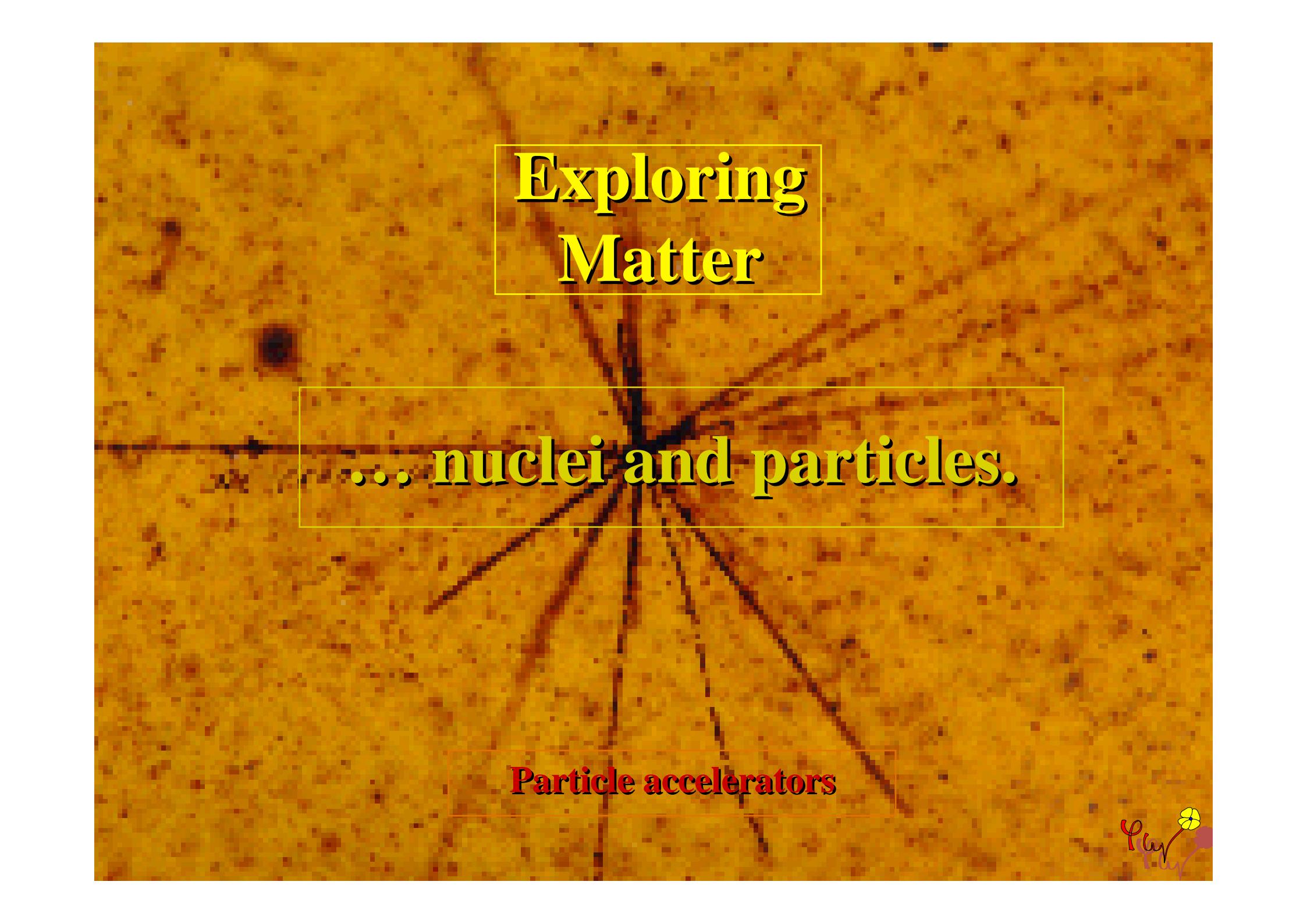


Exploring Matter

...which contain a whole world...

Particle accelerators



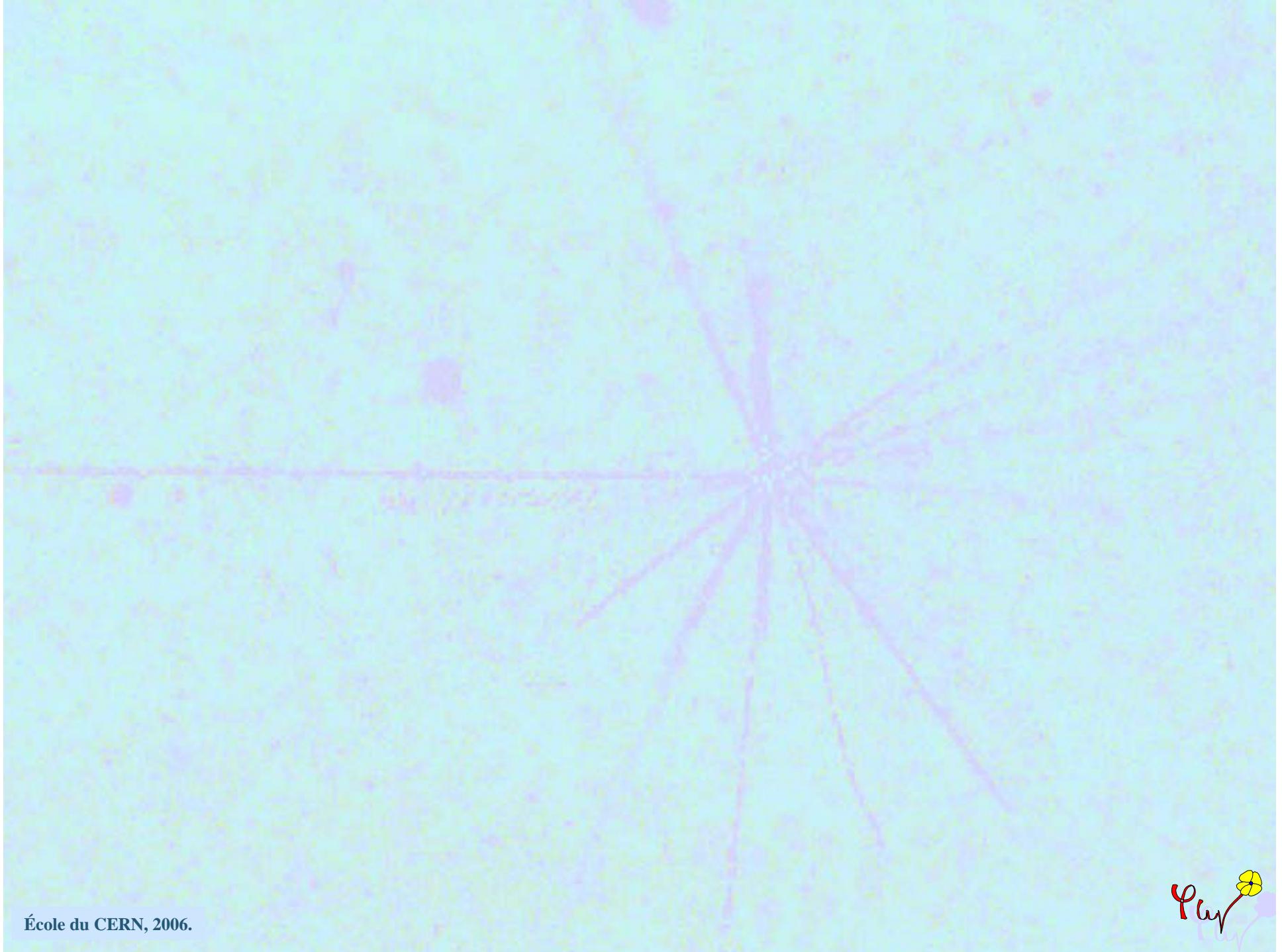


Exploring Matter

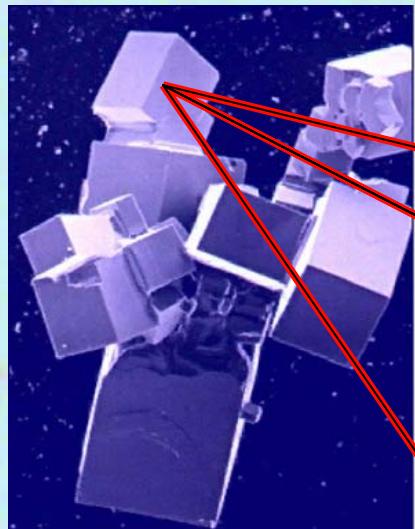
... nuclei and particles.

Particle accelerators

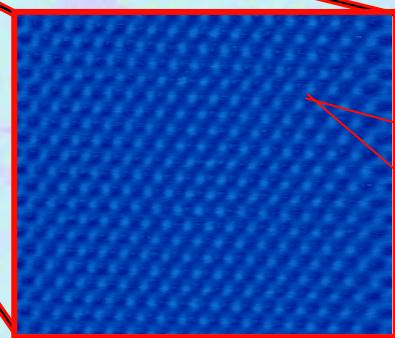




École du CERN, 2006.



Salt cristal



Atoms

Electrons

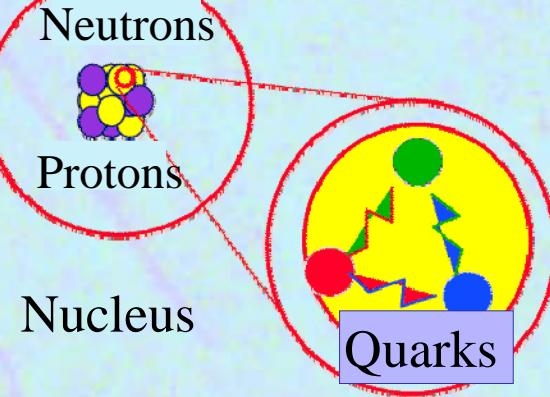


Neutrons



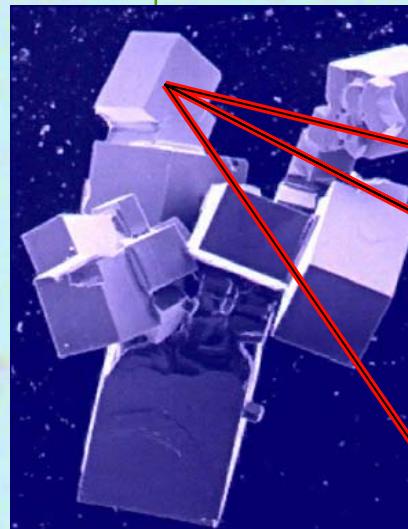
Protons

Nucleus

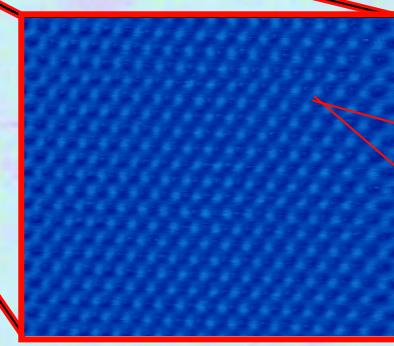


Quarks

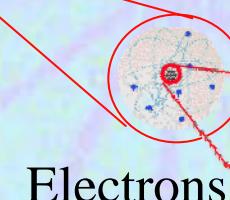
Steps toward the elementary structure of matter



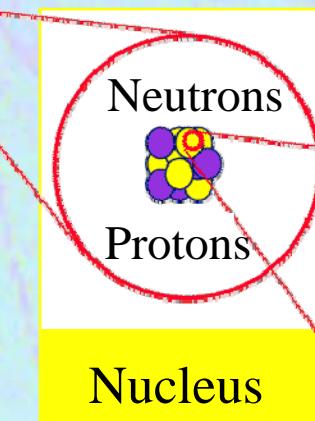
Salt cristal



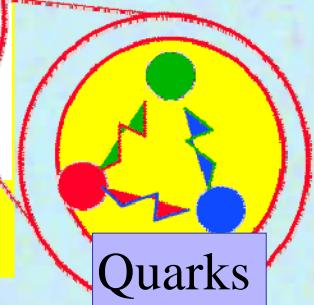
Atoms



Electrons

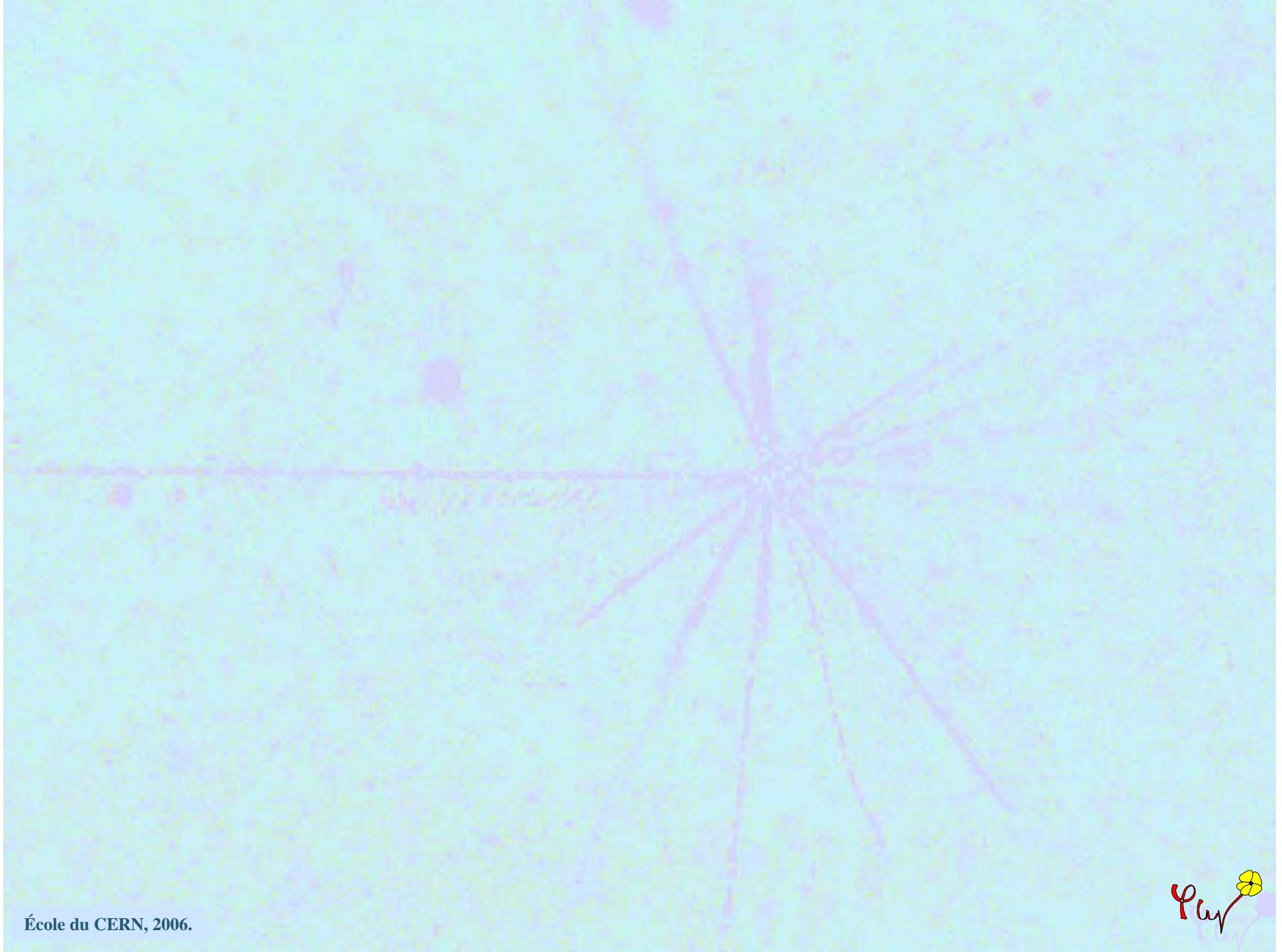


Nucleus



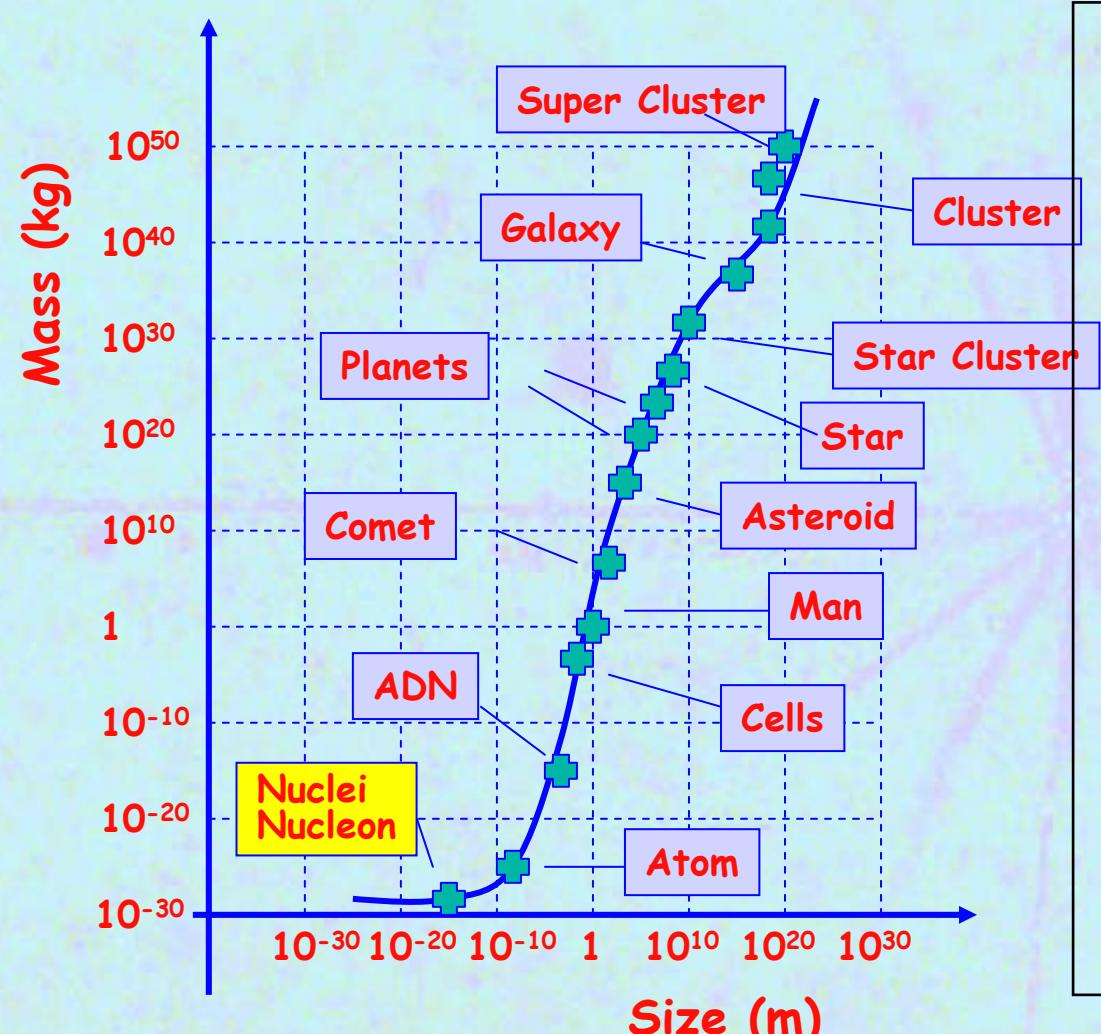
Quarks

Nucleons and nuclei:



École du CERN, 2006.

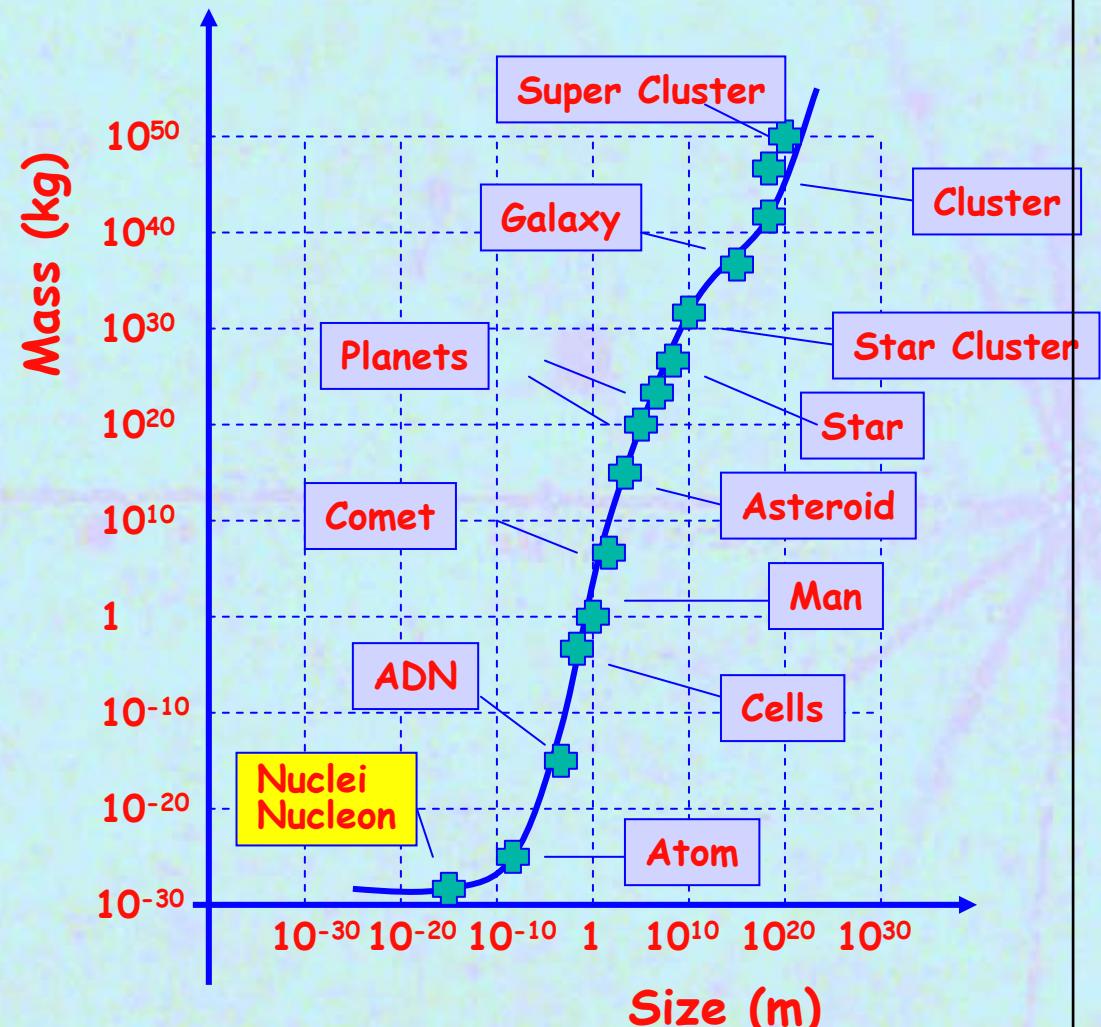
A multi-scale Universe



Nucleons
and
nuclei
the first
steps in
the hierarchy
of complex
systems



A multi-scale Universe

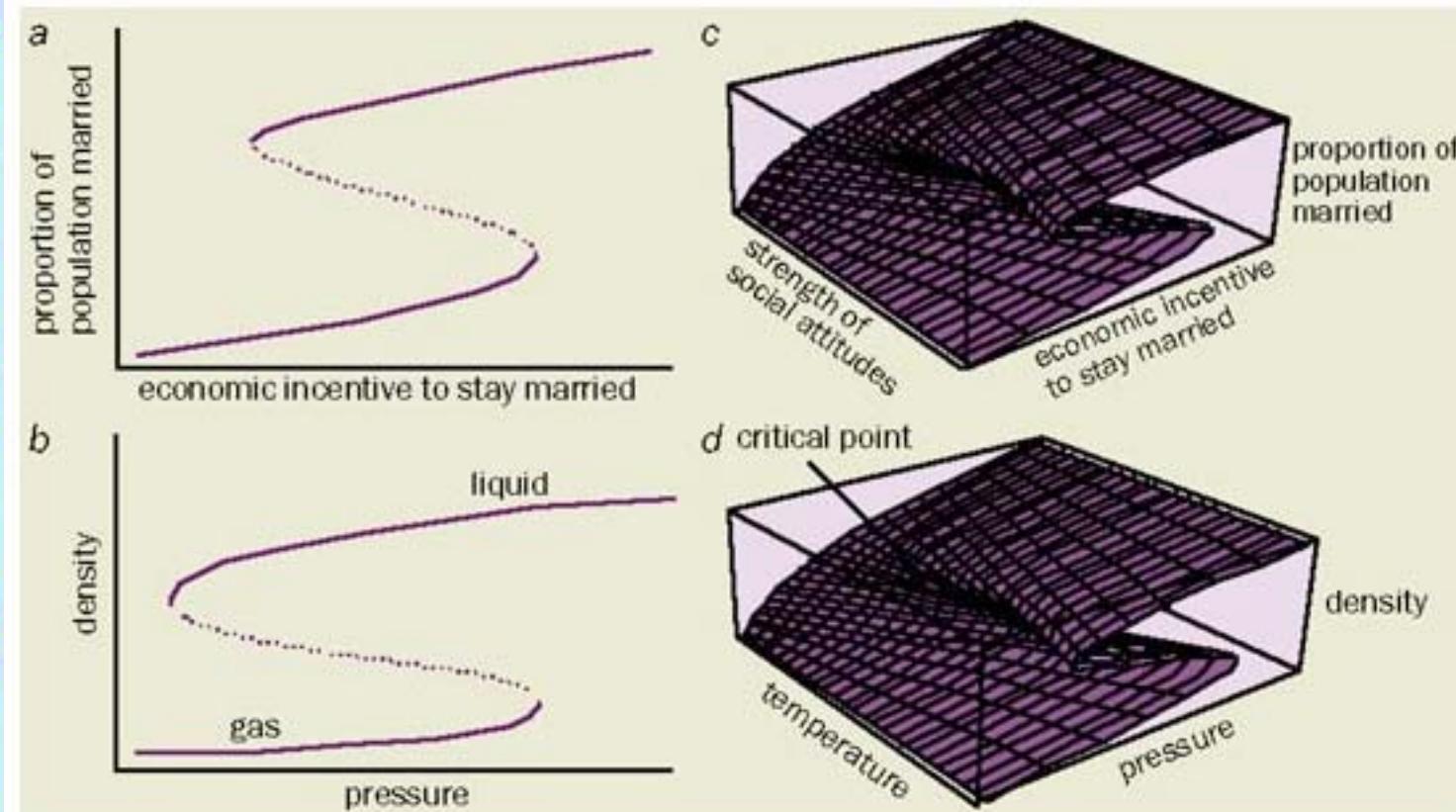


Fundamental Questions:

- ✓ Relevant degree of freedom
- ✓ Effective interaction
- ✓ Complex structure
- ✓ Connection with elementary level

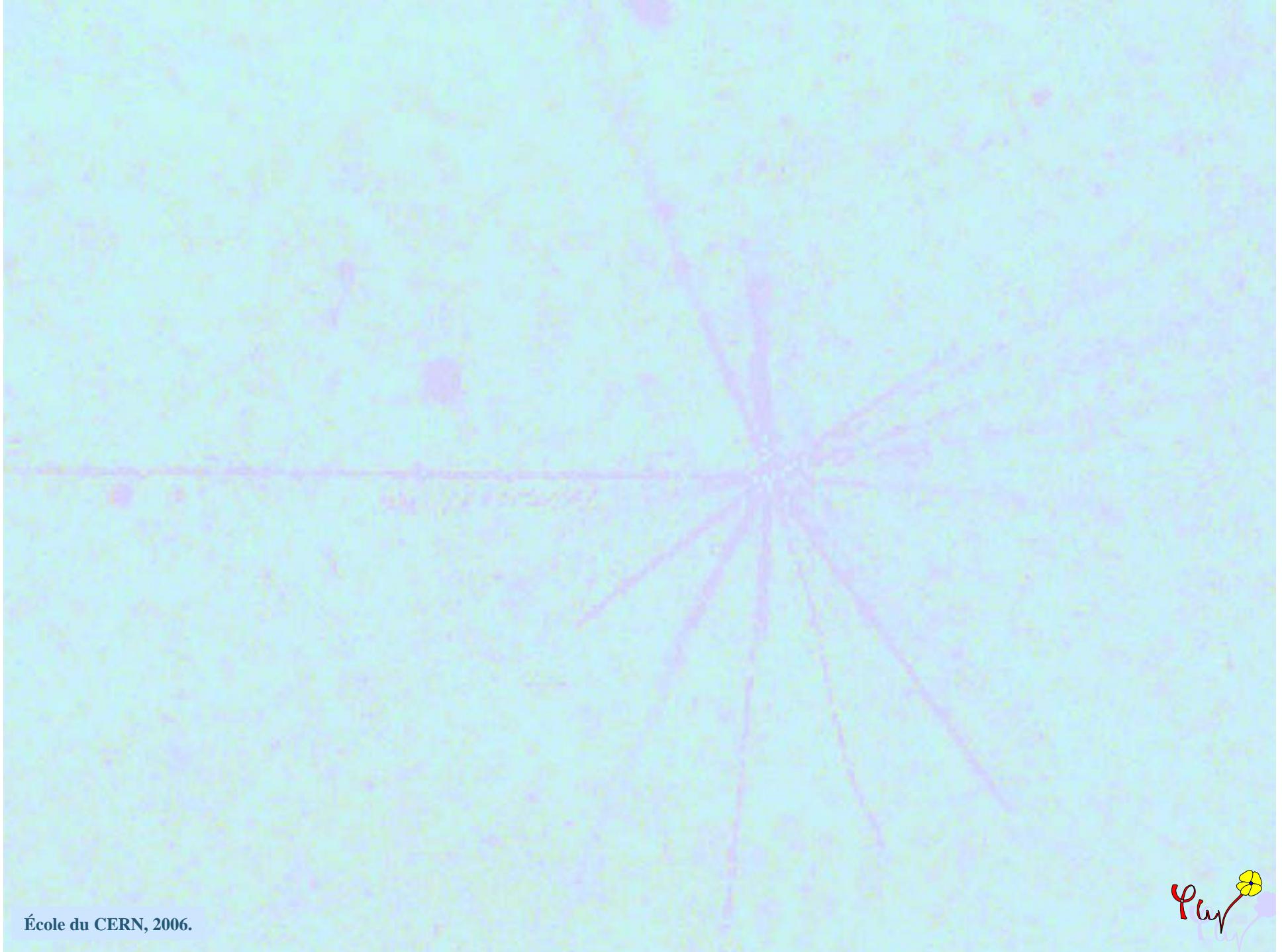


nental
ons:
at degree
dom
e
ction
X
re
tion with
tary level



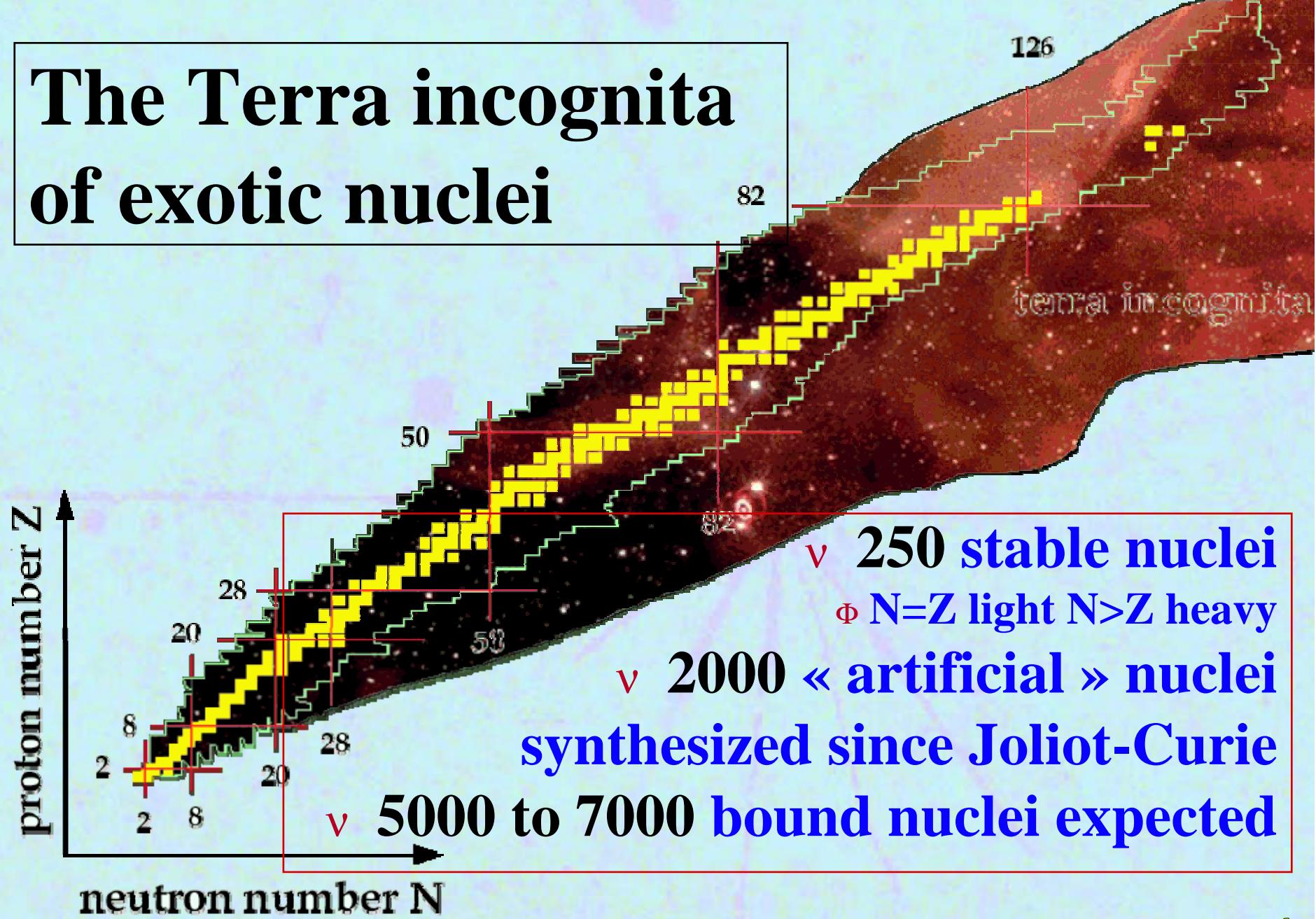
How marriage depends on social attitudes and economic incentives. (a) There may be two stable states that contain different proportions of married people for the same set of conditions (solid lines). In fact, these two branches are linked by a continuous curve (dotted line). However, beyond the turning points of the upper and lower solid curves, the states represented by the dotted curve are unstable. (b) This looped curve is exactly what emerges from van der Waals' theory of the liquid-gas phase transition. (c) A 3D graph shows the dependence of marriage on both social and economic factors. The loop in the curve appears only if the strength of social attitudes is strong enough. This plot is also familiar from van der Waals' theory, in which the inception of the kink in the surface marks the liquid-gas critical point (d). If "strength of social attitudes" is replaced by temperature, "economic incentives" by pressure, and "proportion of married population" by density, we have the phase space of a fluid.



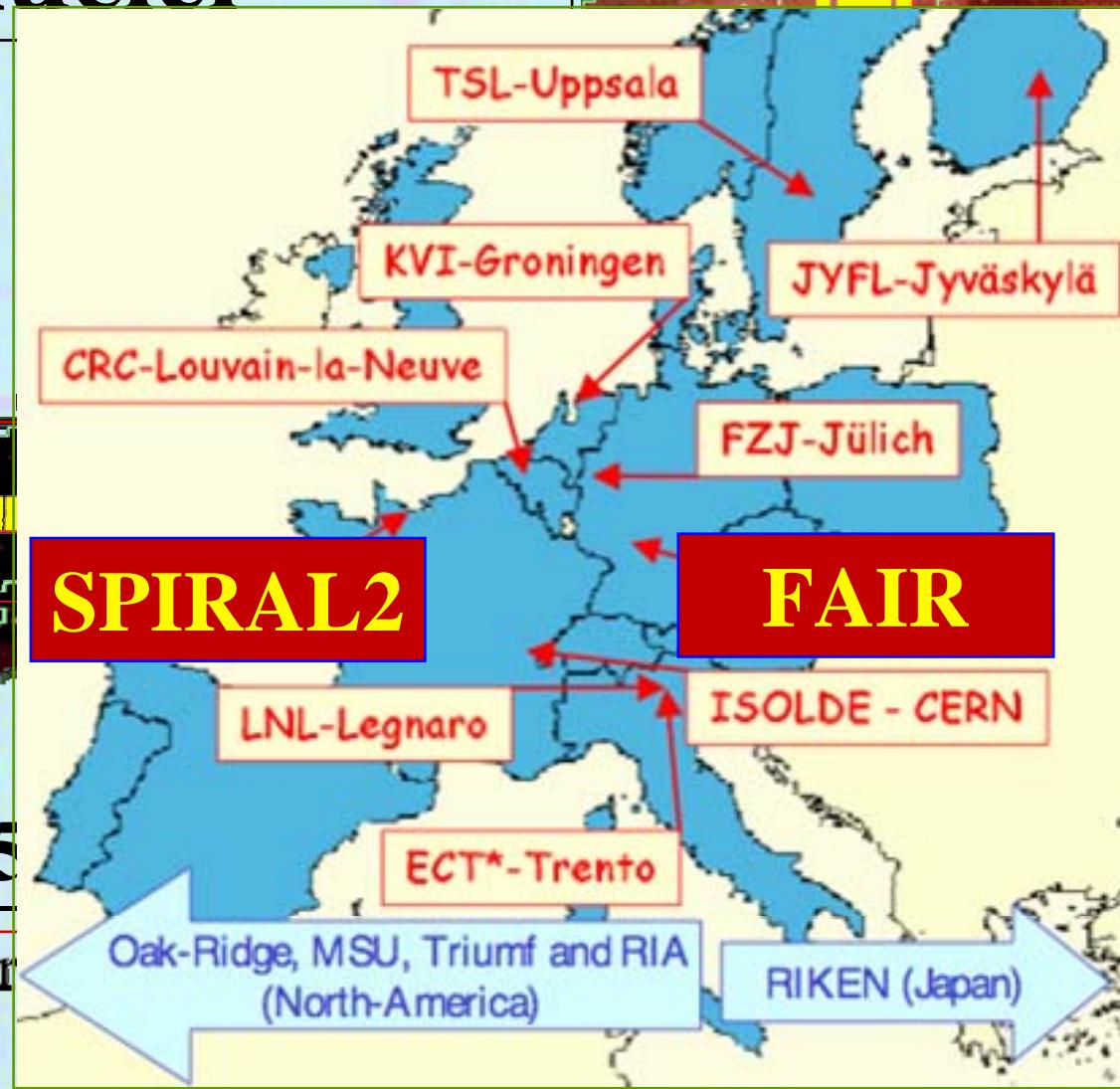
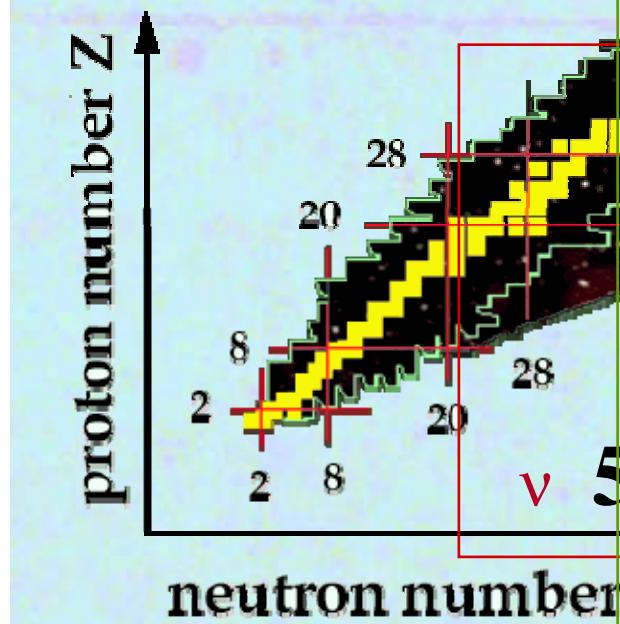


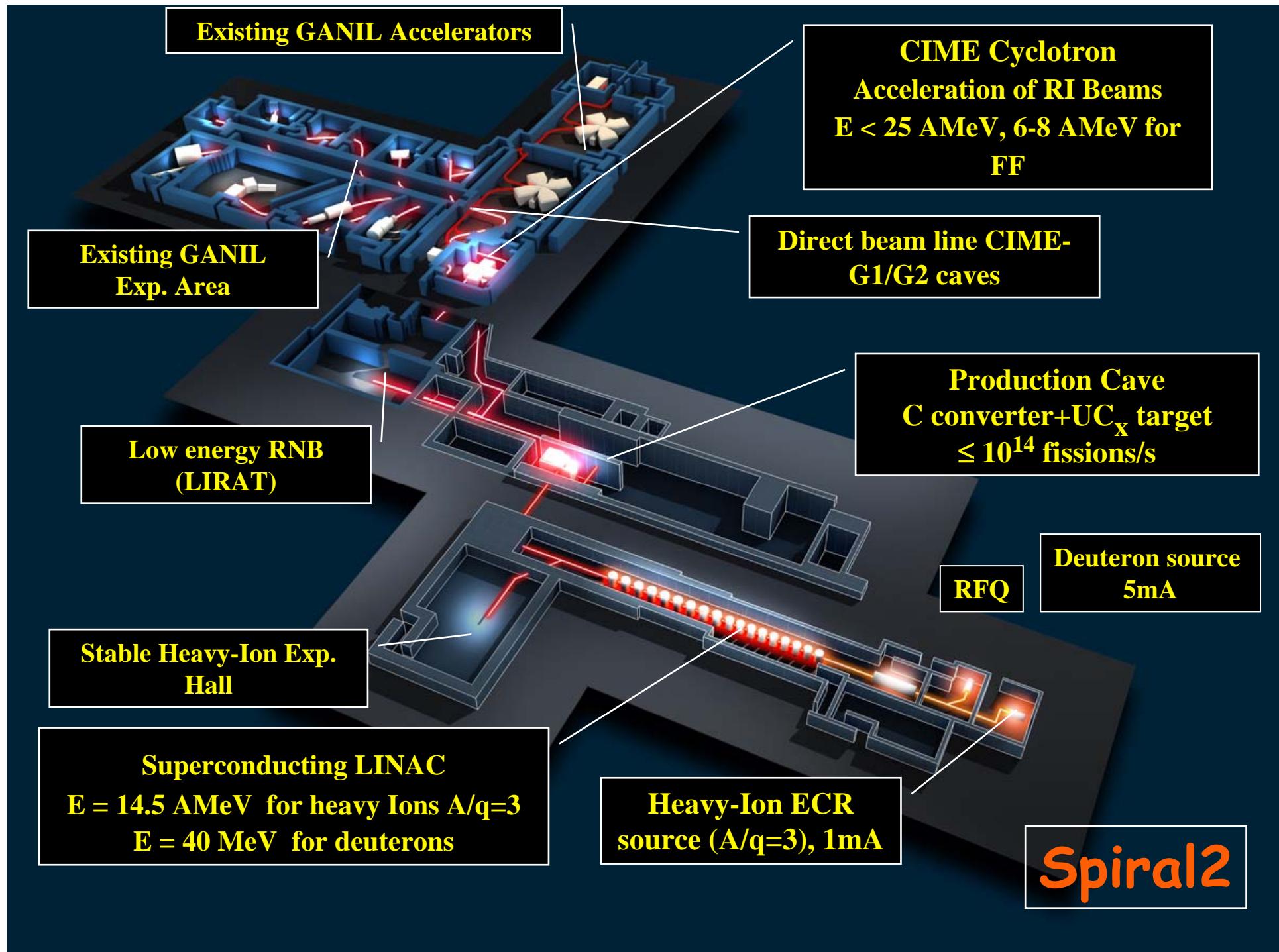
École du CERN, 2006.

The Terra incognita of exotic nuclei

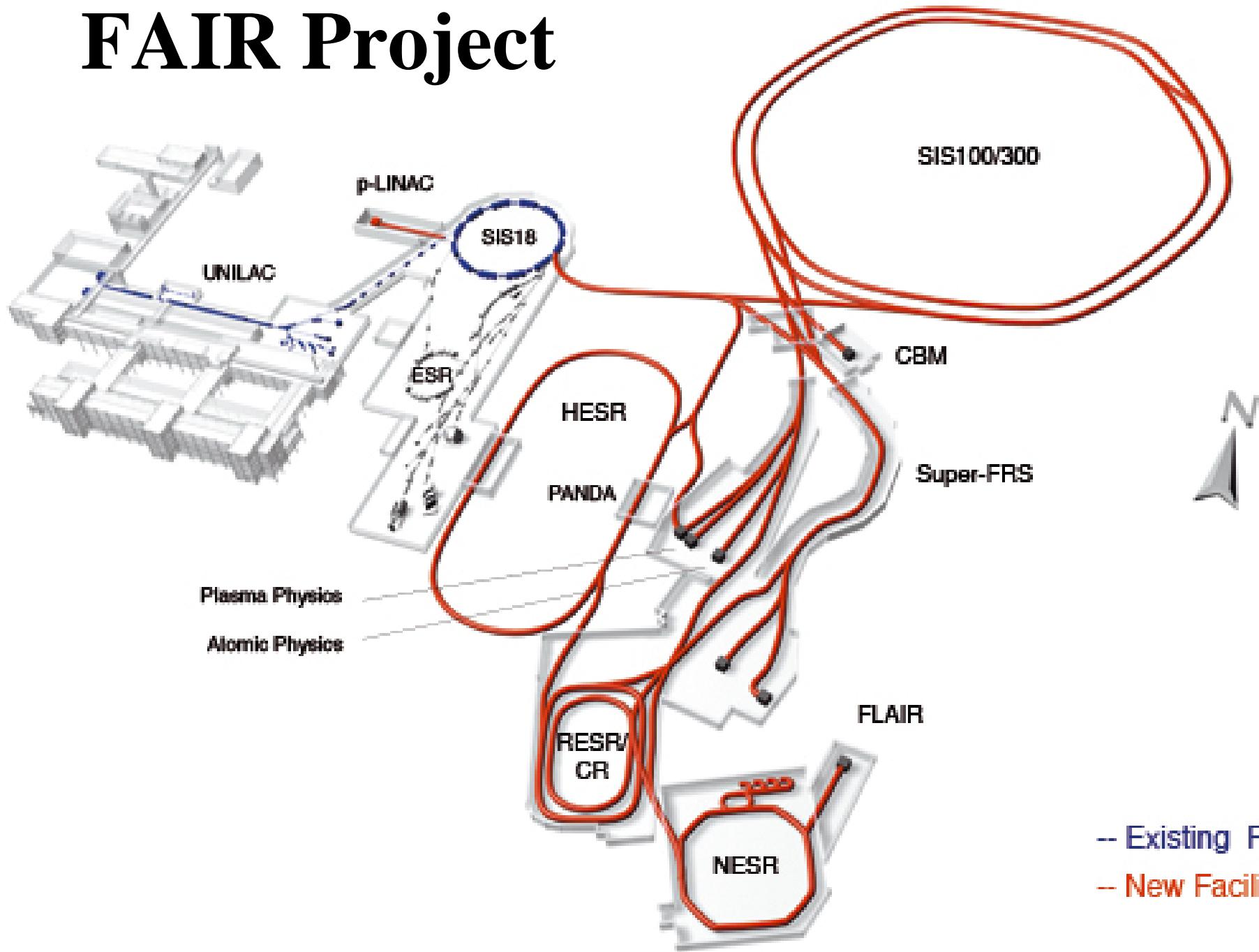


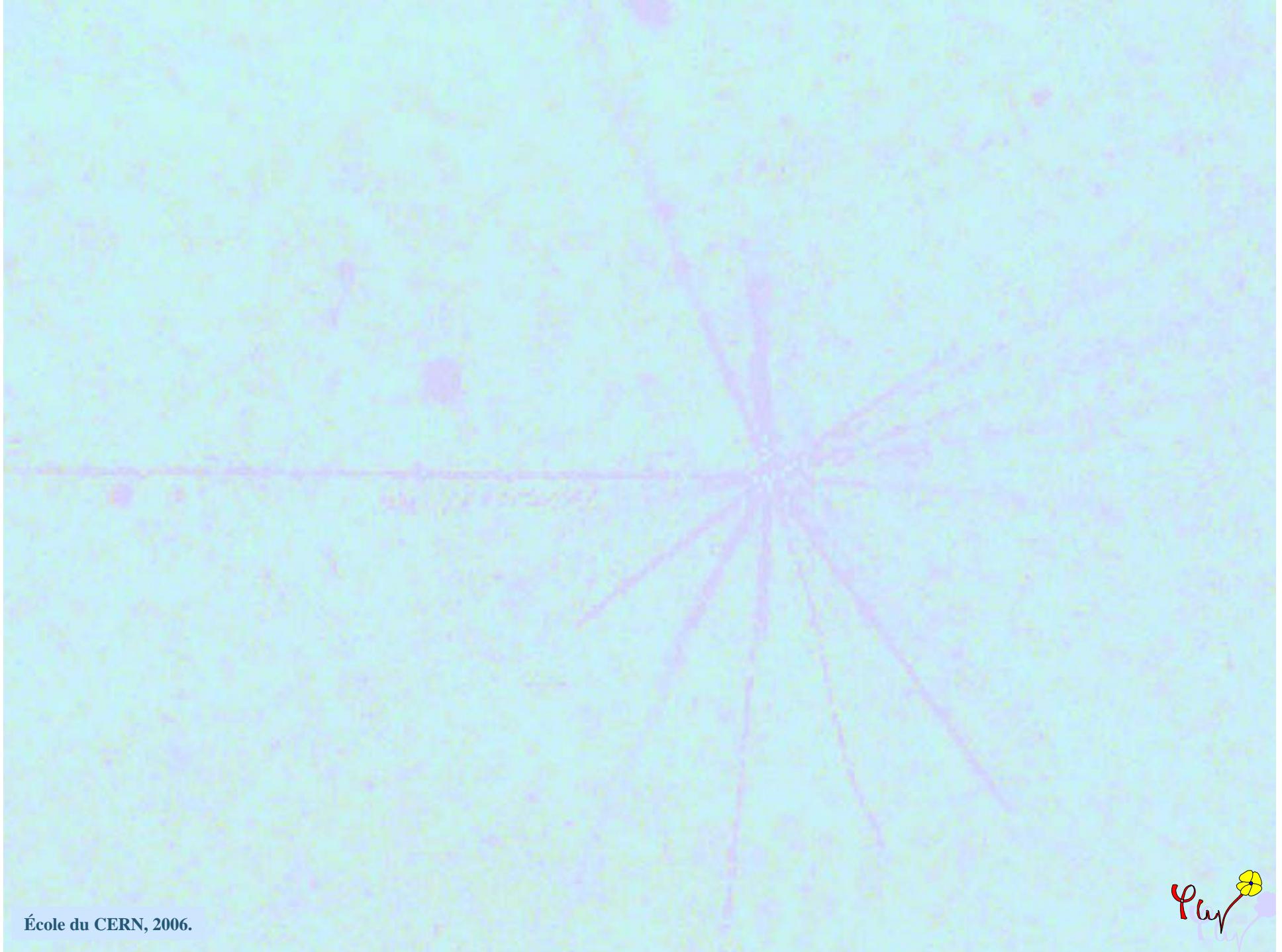
The Terra incognita of exotic nuclei





FAIR Project

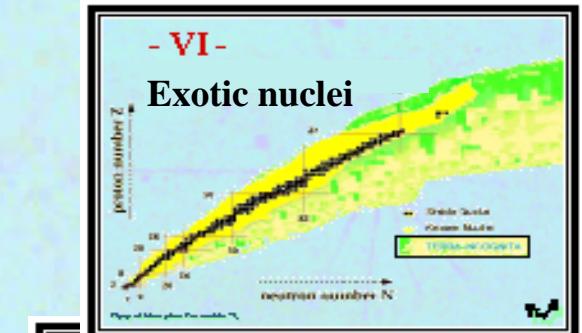
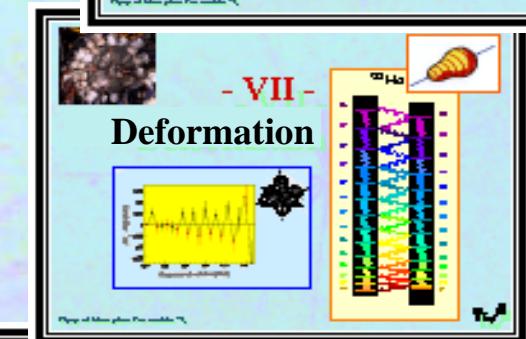
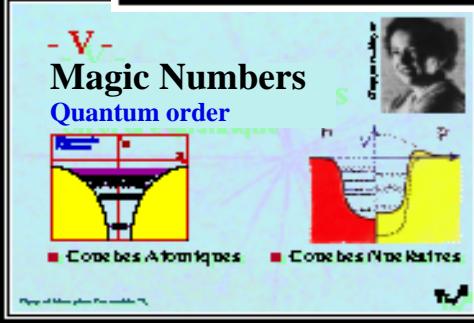
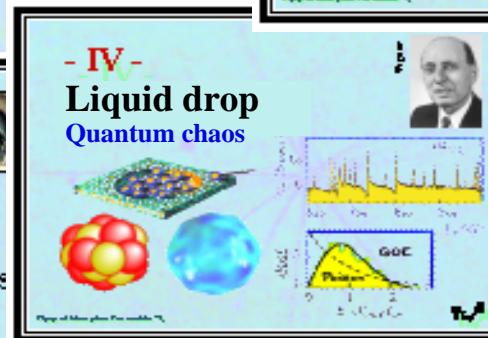
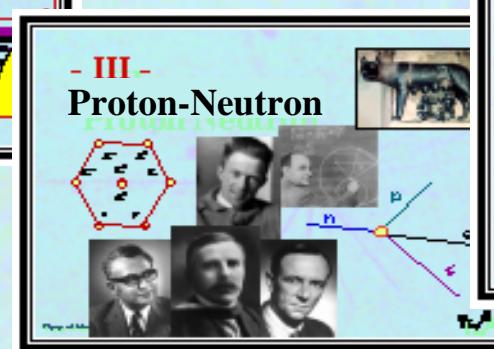
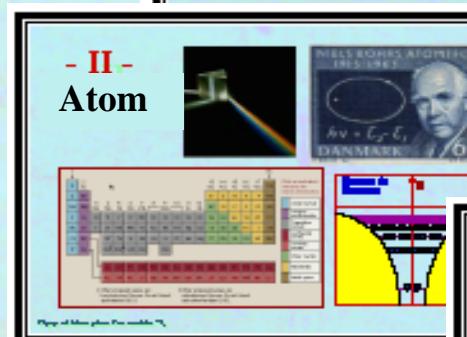
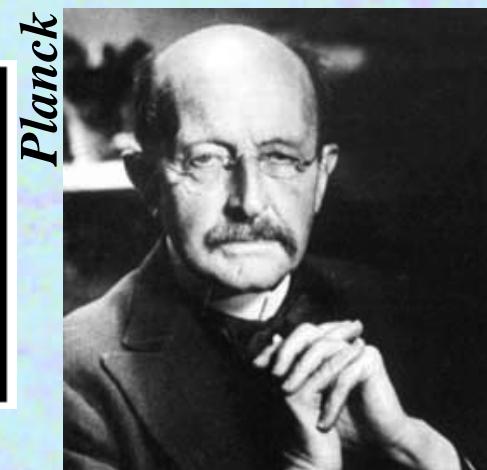
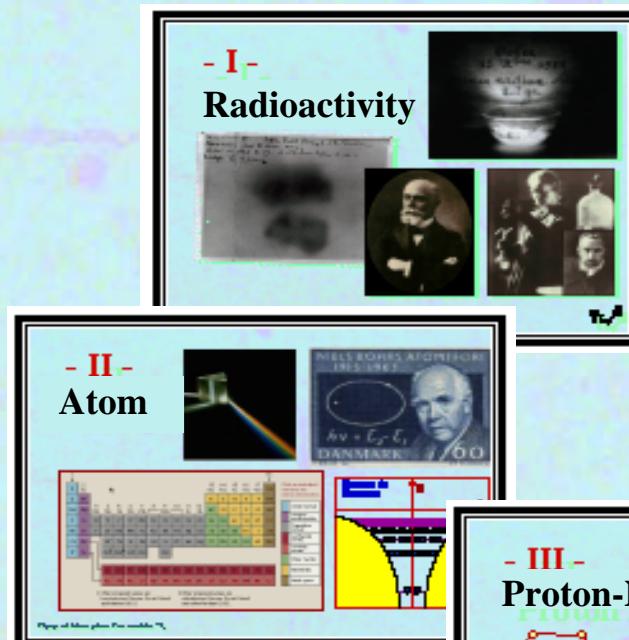


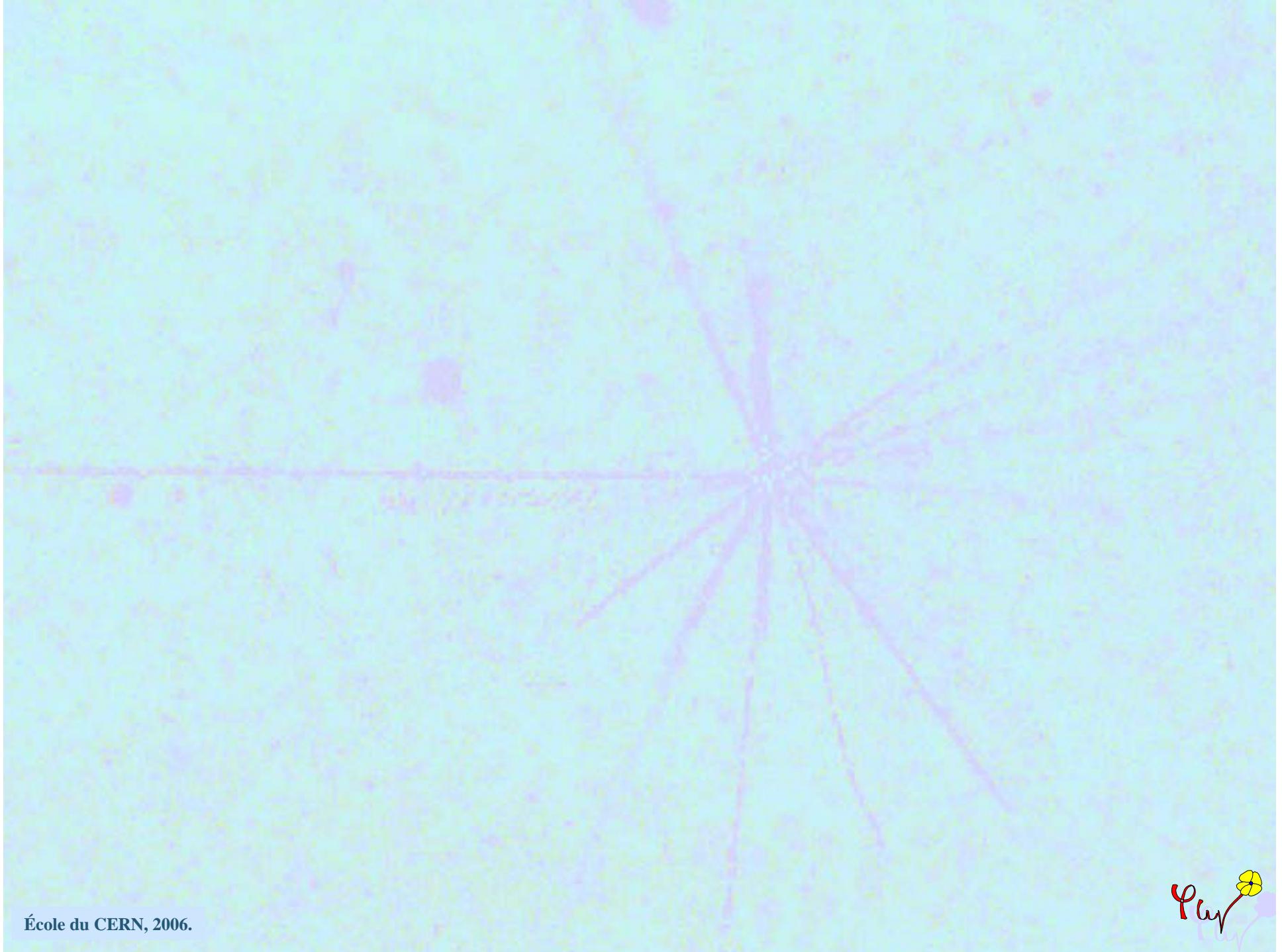


École du CERN, 2006.

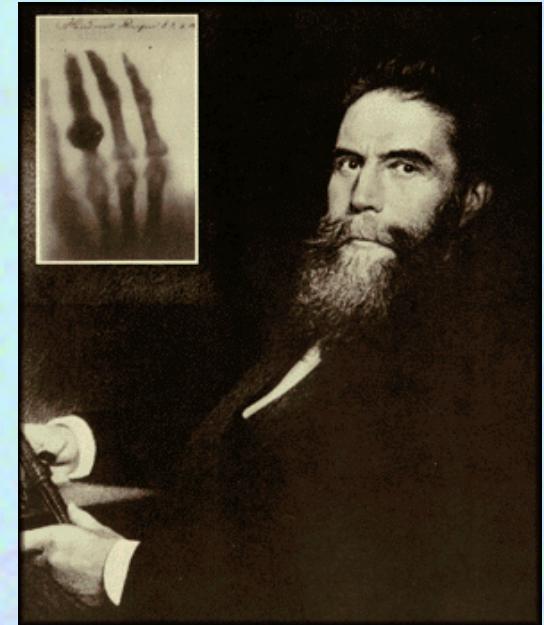
Atomic Nuclei

Complex quantum systems





École du CERN, 2006.



*1895 Røntgen
Discovery of X rays*

- I -

Radioactivity

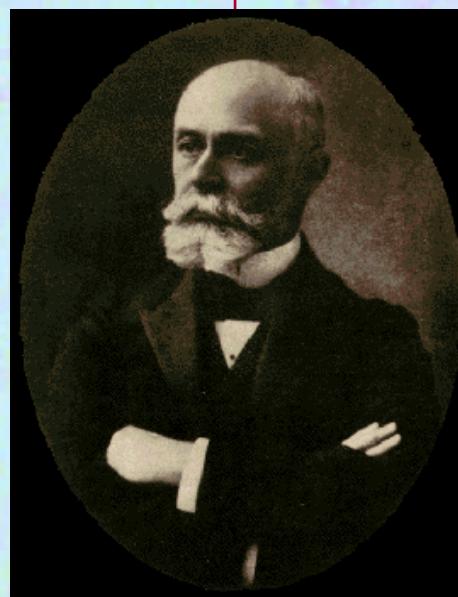


- I -

Radioactivity



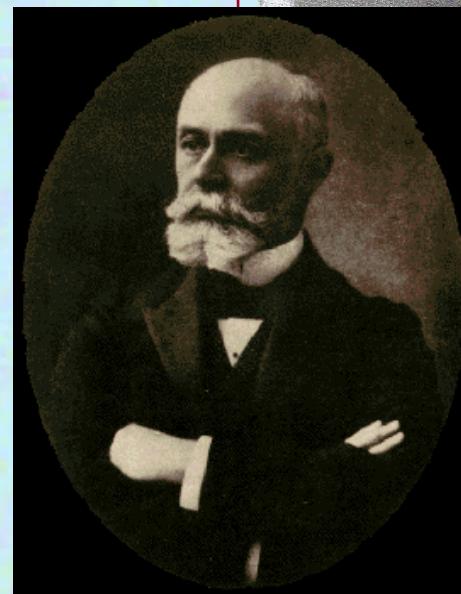
1896: Becquerel



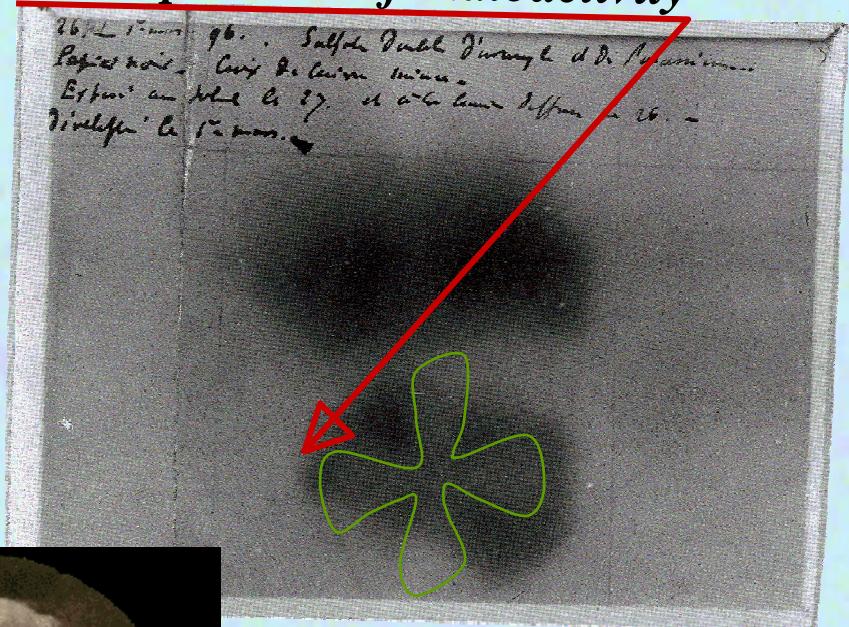
- I -

Radioactivity

v 1896: Becquerel



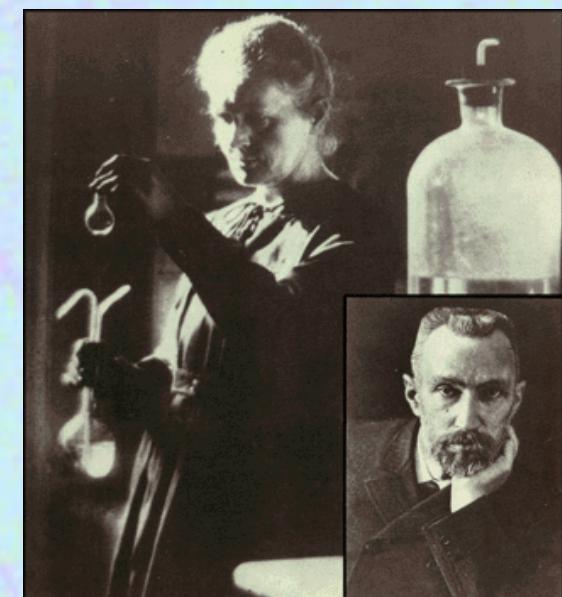
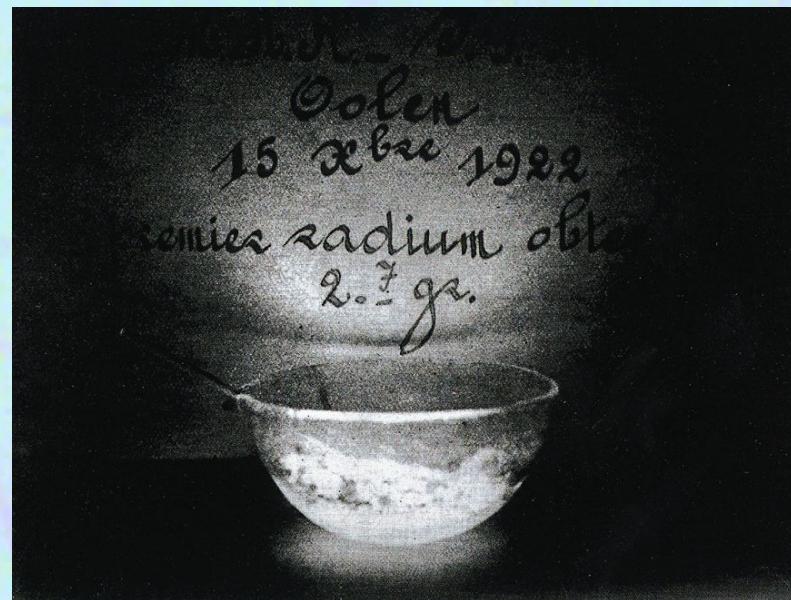
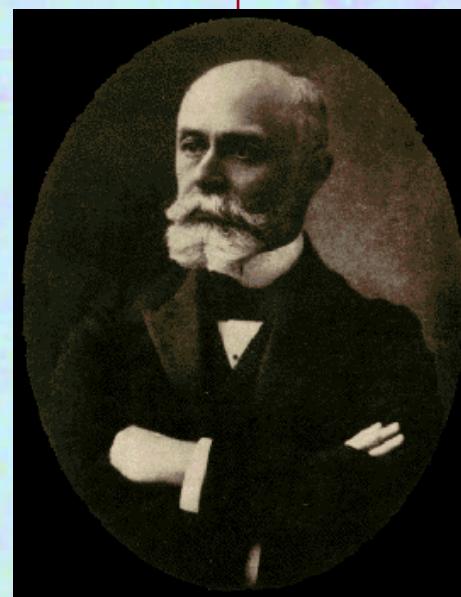
First “picture” of radioactivity



- I -

Radioactivity

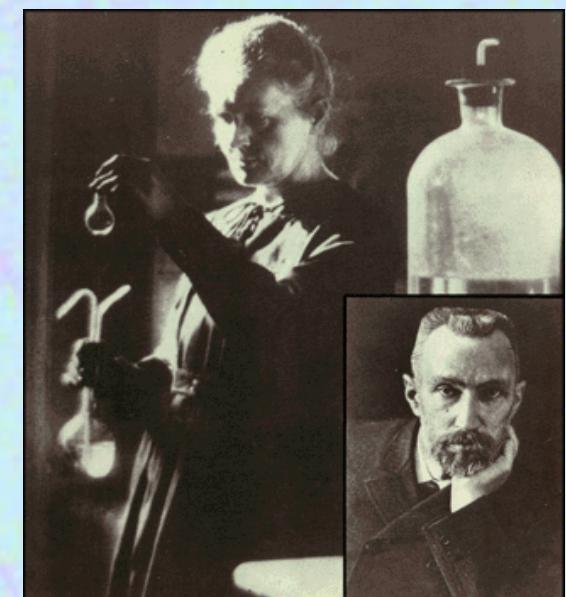
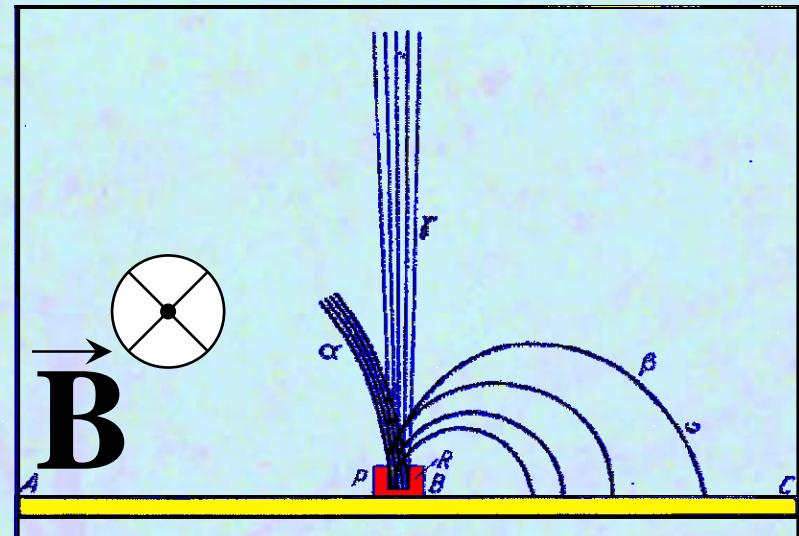
- ✓ 1896: Becquerel
- ✓ 1898: Curie



- I -

Radioactivity

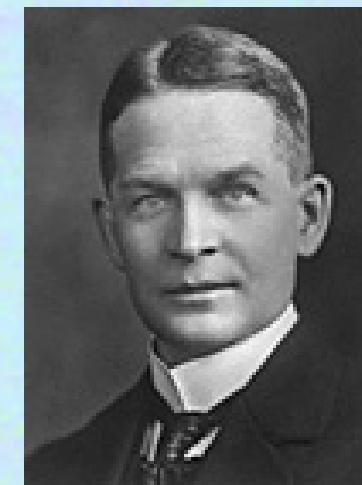
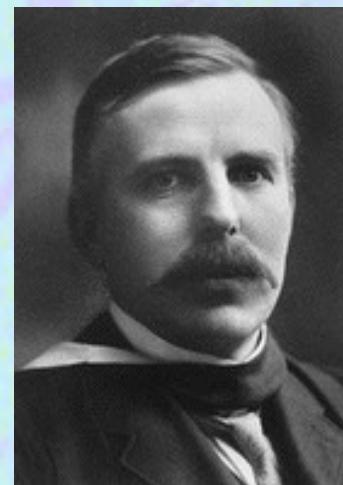
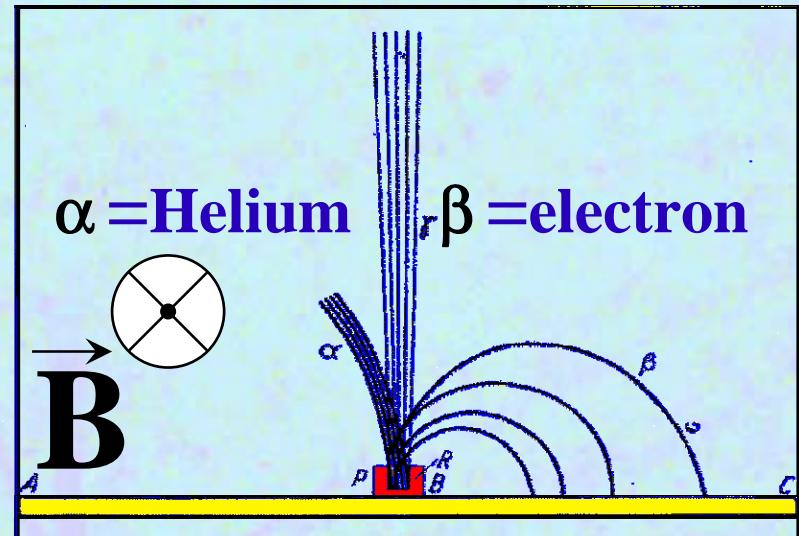
- ✓ 1896: Becquerel
- ✓ 1898: Curie
- ✓ 3 types: α , β , γ



- I -

Radioactivity

- ✓ 1896: Becquerel
- ✓ 1898: Curie
- ✓ 3 types: α , β , γ
- ✓ Transmutation 1901:



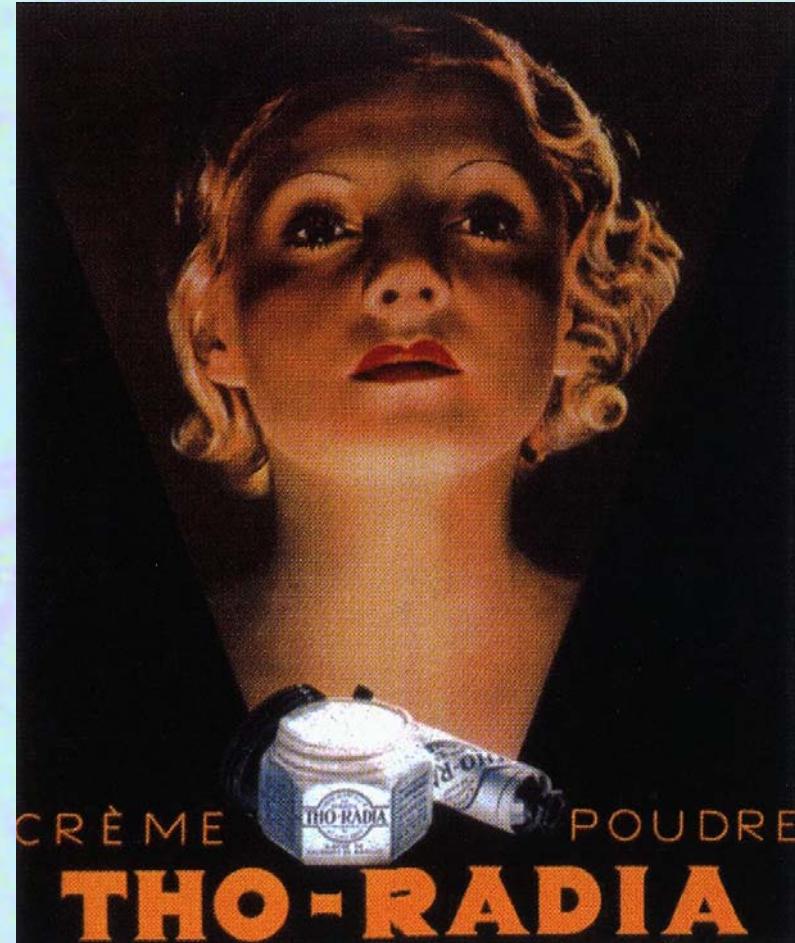
Rutherford et Soddy



- I -

Radioactivity Mystery

- ✓ Finite life time
but always young
- ✓ Transmutation

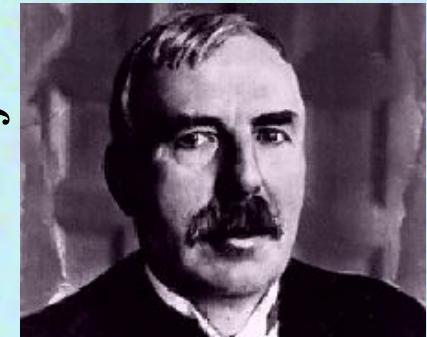


- I -

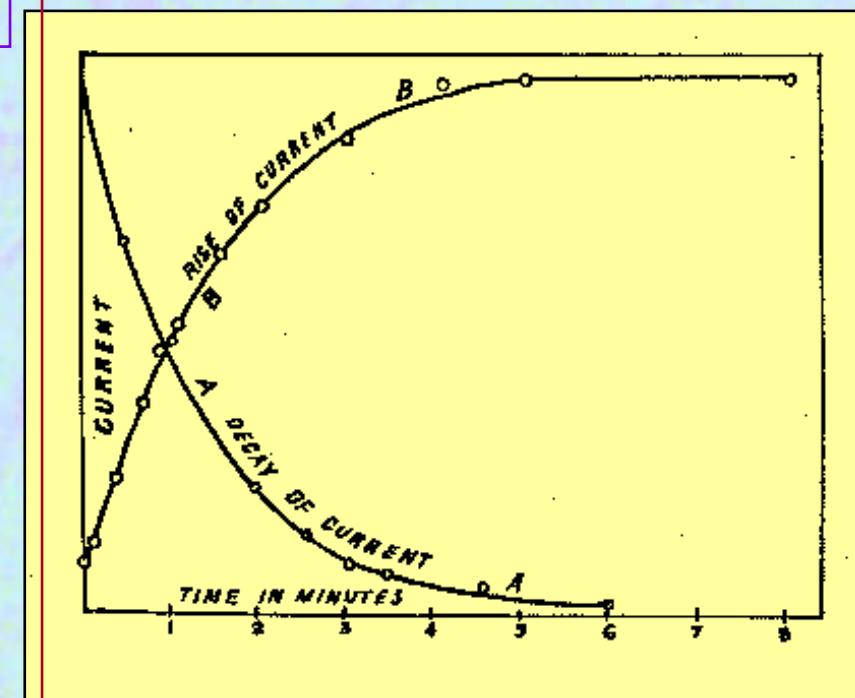
Radioactivity Mystery

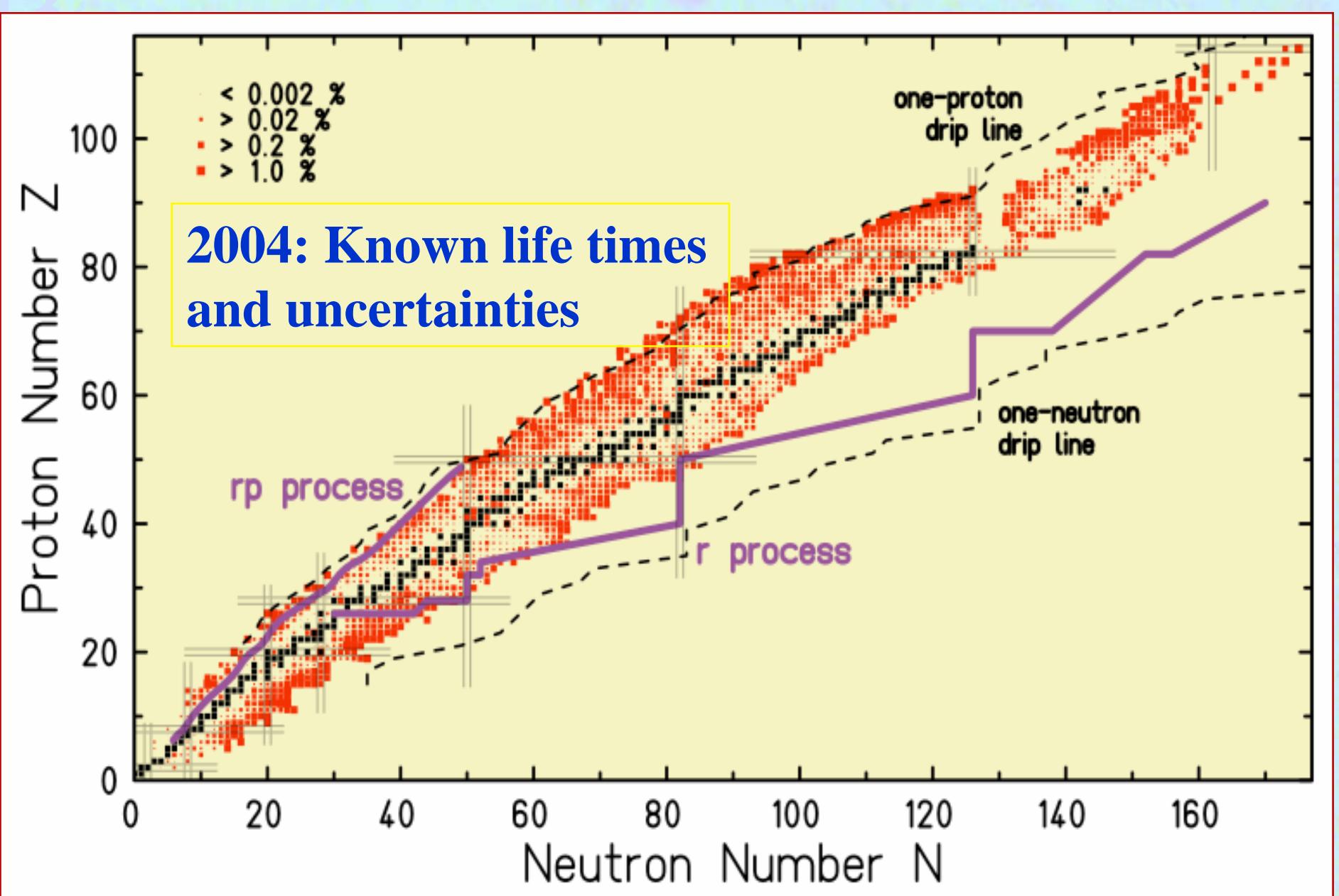
- ✓ Exponential decay
- $dN/dt = -N/T_{\text{life}}$
- ✓ Finite life time
but always young
- ✓ Transmutation

Rutherford



1902: First measure of decay laws





- I -

Radioactivity

Mystery solved

- ✓ Exponential decay
- ✓ $dN/dt = -N/T_{\text{life}}$
- ✓ Finite life time
but always young
- ✓ Transmutation



Gamov

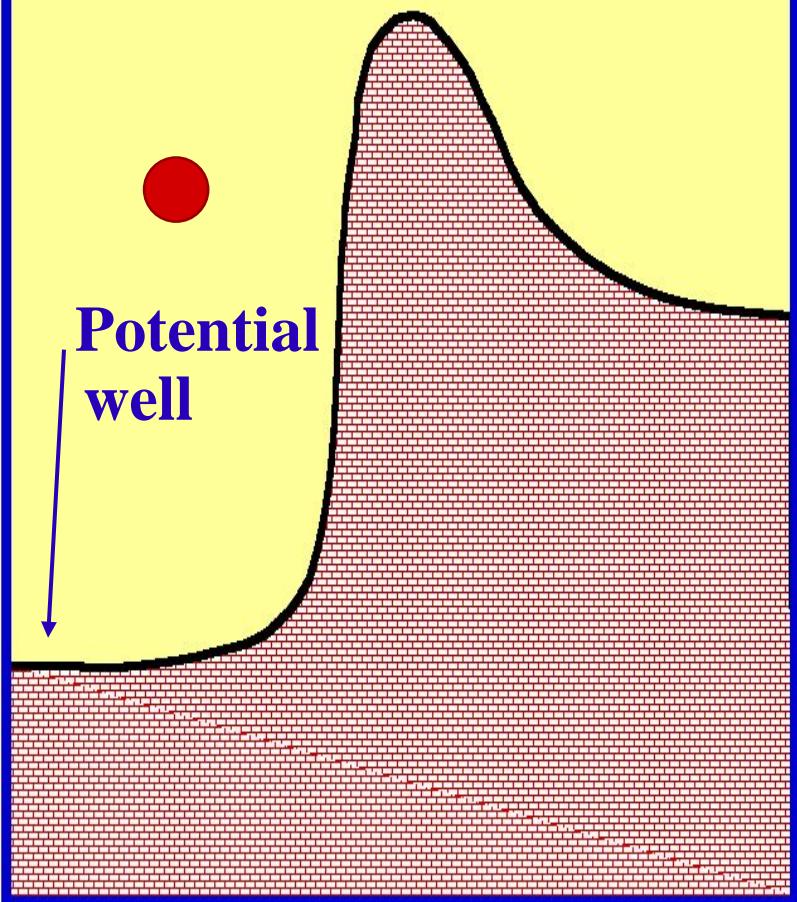
- I -

Radioactivity

Quantum property

- ✓ Exponential decay
- $dN/dt = -N/T_{\text{life}}$
- ✓ Finite life time
but always young
- ✓ Transmutation

α particle in a nucleus



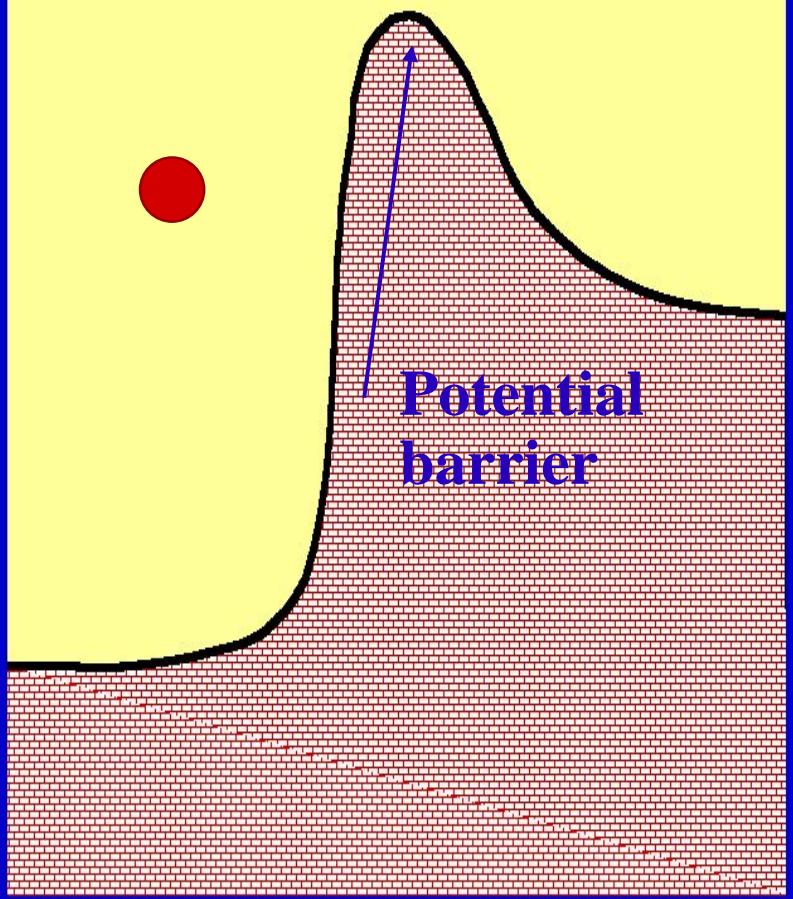
- I -

Radioactivity

Quantum property

- ✓ Exponential decay
- $dN/dt = -N/T_{\text{life}}$
- ✓ Finite life time
but always young
- ✓ Transmutation

α particle in a nucleus

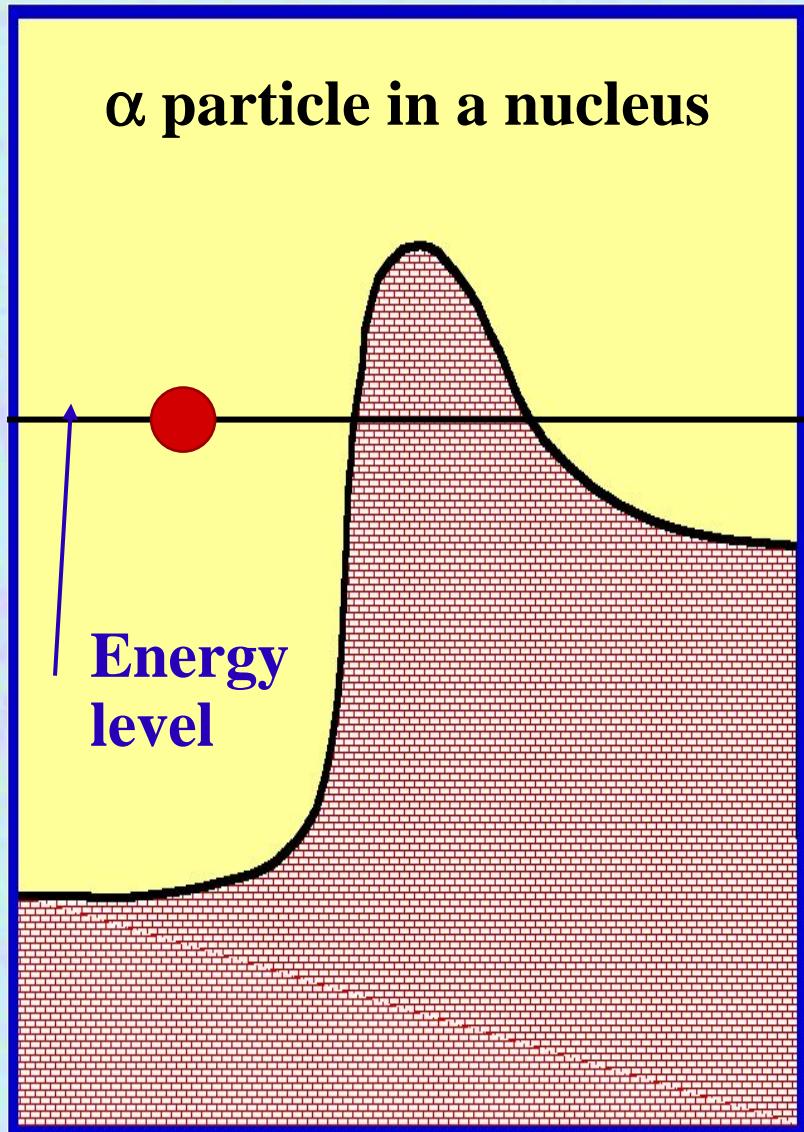


- I -

Radioactivity

Quantum property

- ✓ Exponential decay
- $dN/dt = -N/T_{\text{life}}$
- ✓ Finite life time
but always young
- ✓ Transmutation

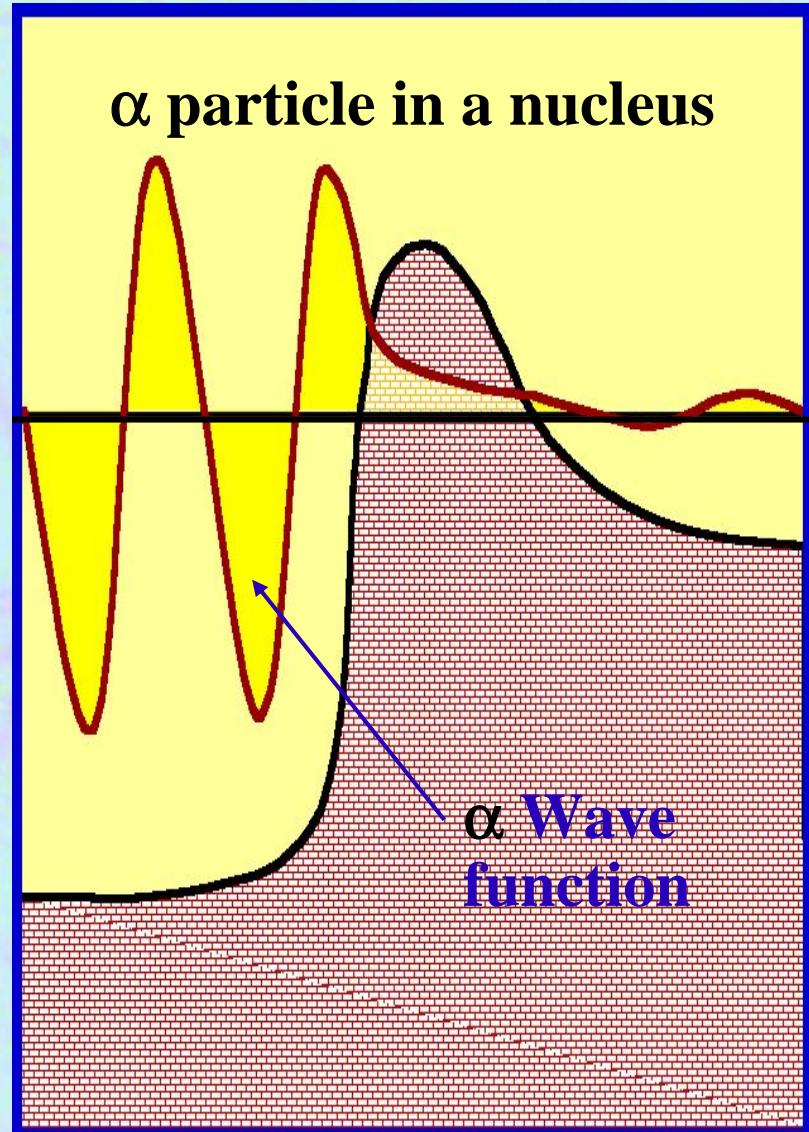


- I -

Radioactivity

Quantum property

- ✓ Exponential decay
- $dN/dt = -N/T_{\text{life}}$
- ✓ Finite life time
but always young
- ✓ Transmutation

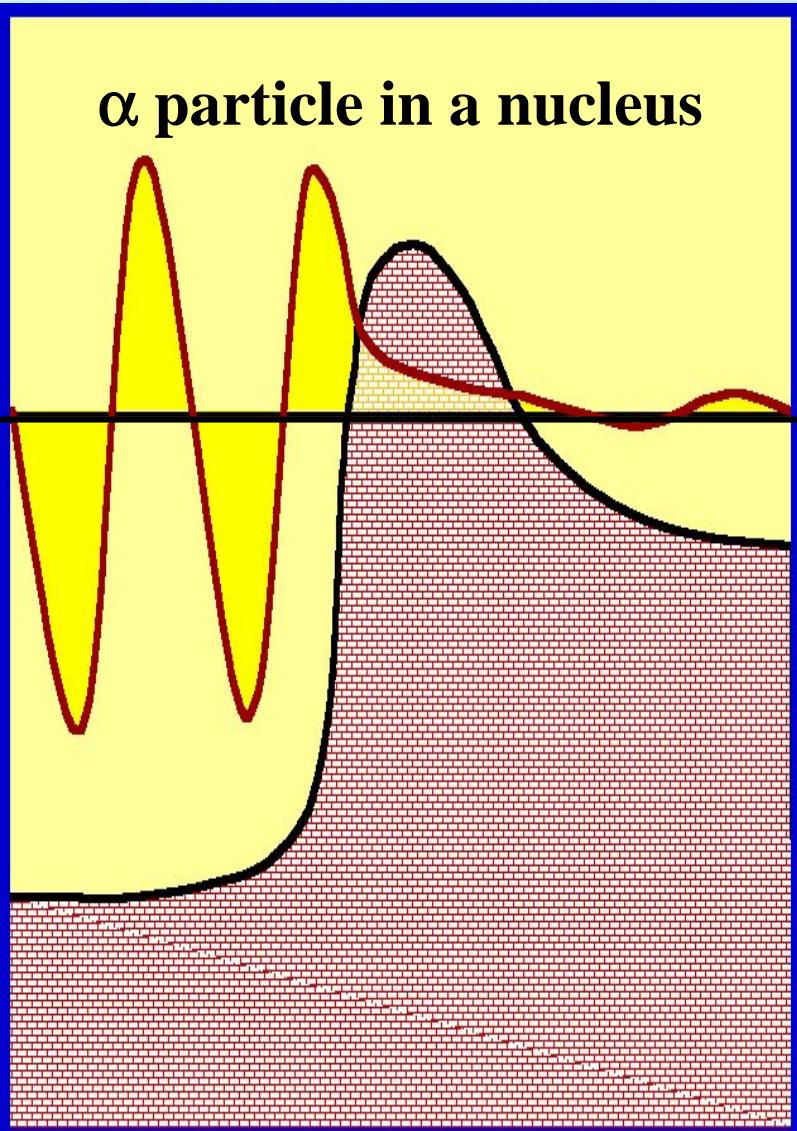


- I -

Radioactivity

Quantum property

- ✓ Exponential decay
- $dN/dt = -N/T_{\text{life}}$
- ✓ Finite life time
but always young
- ✓ Transmutation

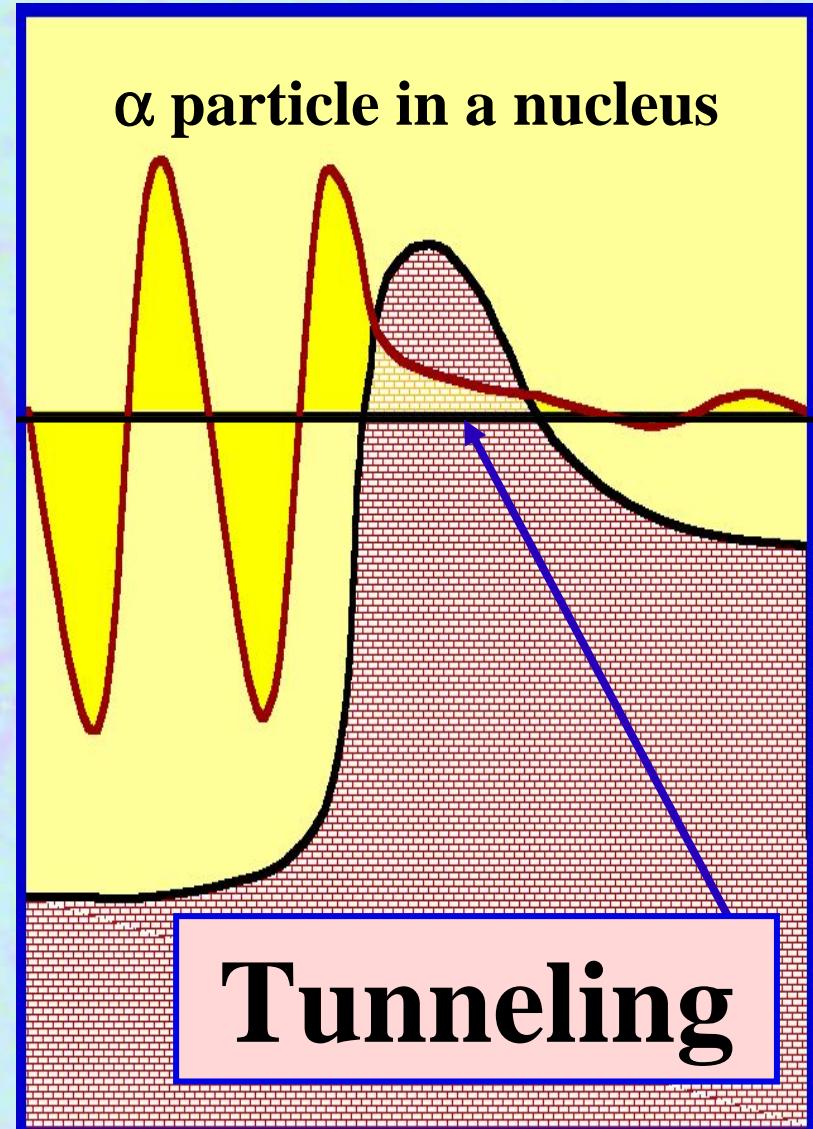


- I -

Radioactivity

Quantum property

- ✓ Exponential decay
- $dN/dt = -N/T_{\text{life}}$
- ✓ Finite life time
but always young
- ✓ Transmutation



- I -

Radioactivity



- I -

Radioactivity

Still a mystery

- ✓ Radioactivity of nuclei
- ✓ Fission
- ✓ $2p$ or ${}^2\text{He}$



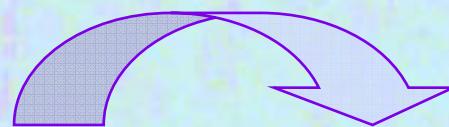
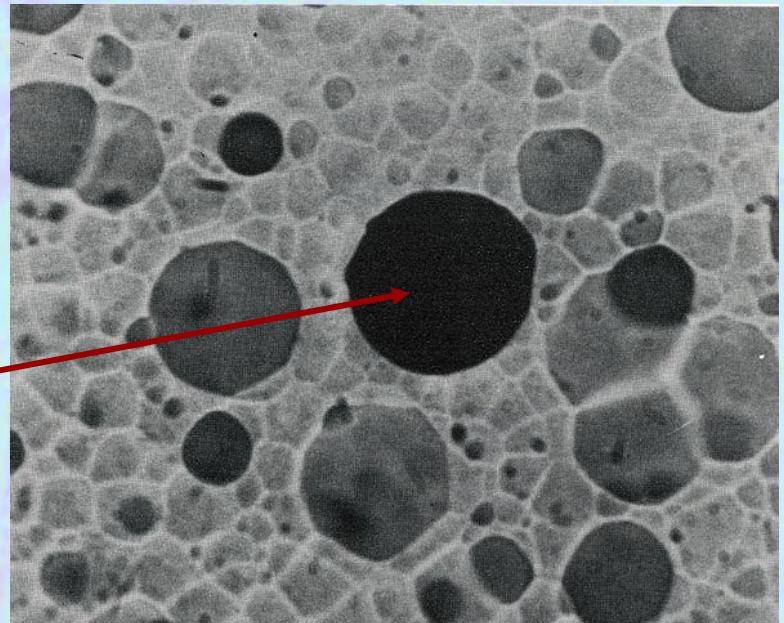
- I -

Radioactivity

Still a mystery

✓ Radioactivity of nuclei

^{14}C trace
one ^{14}C
for
 $10^{6-8} \alpha$



- I -

Radioactivity

Still a mystery

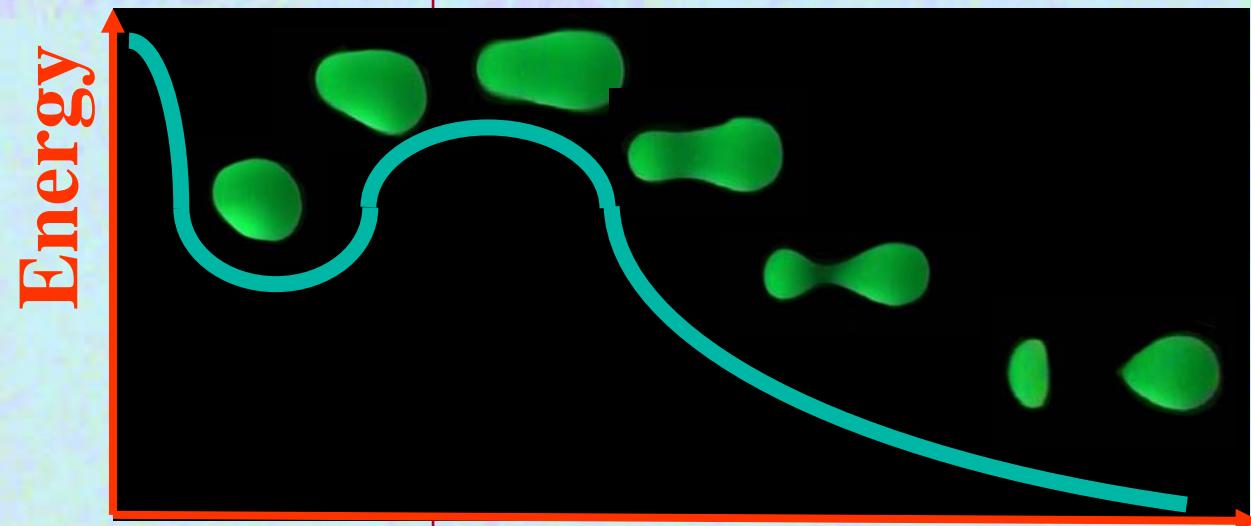
Joliot-Curie



Meitner



- ✓ Radioactivity of nuclei
- ✓ Fission



Deformation



- I -

Radioactivity

Still a mystery

- ✓ Radioactivity of nuclei
- ✓ Fission

Fermi



QuickTime™ et un décompresseur
GIF sont requis pour visualiser
cette image.

- I -

Radioactivity

Still a mystery

- ✓ Radioactivity of nuclei
- ✓ Fission

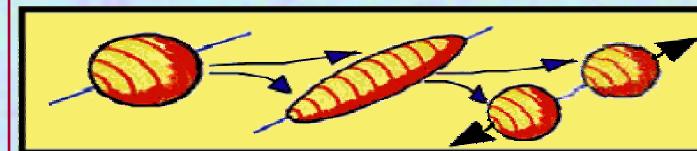


- I -

Radioactivity

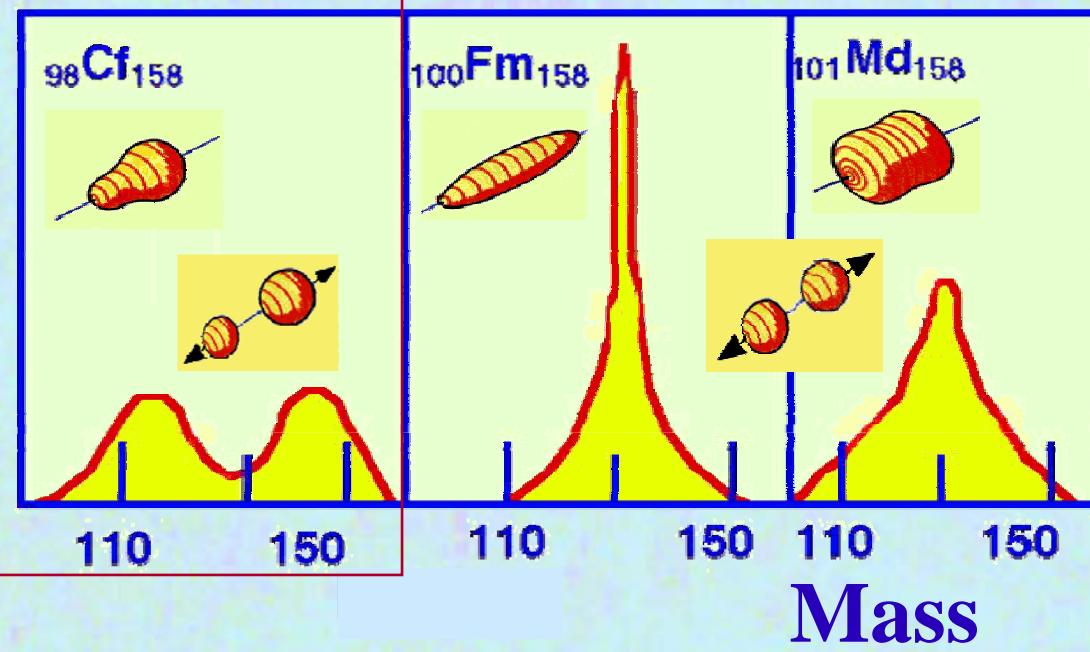
Still a mystery

✓ Radioactivity of nuclei



✓ Fission

✓ Shapes and
Symmetry
breaking



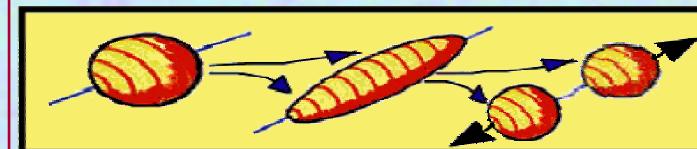
Fragment yield

- I -

Radioactivity

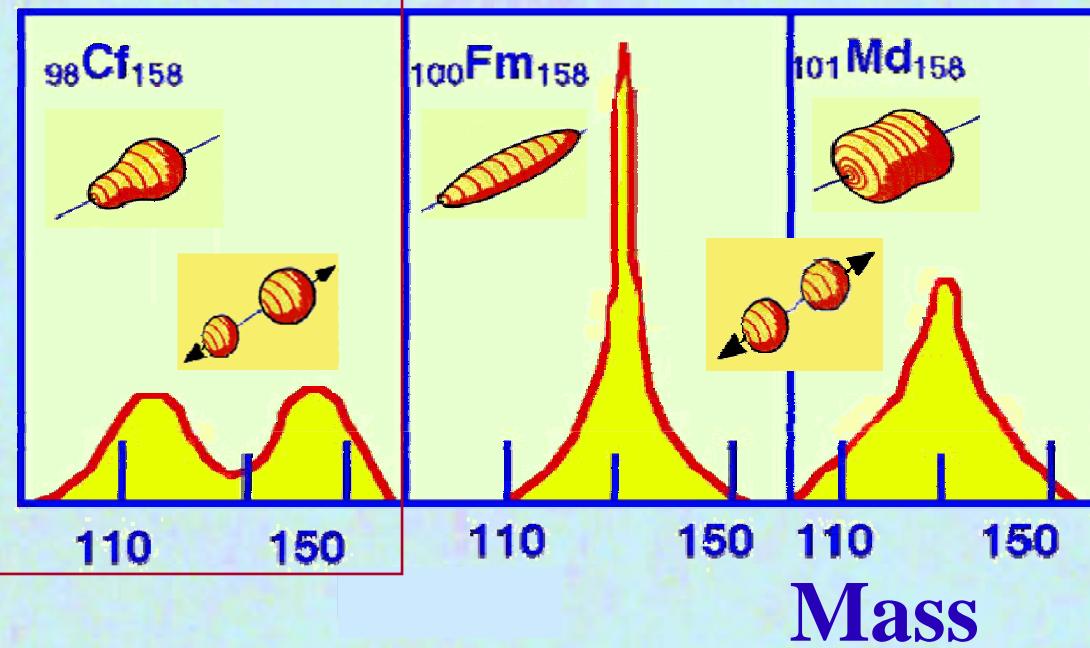
Still a mystery

✓ Radioactivity of nuclei



✓ Fission

✓ Shapes and
Symmetry
breaking



Fragment yield

- I -

Radioactivity

Still a mystery

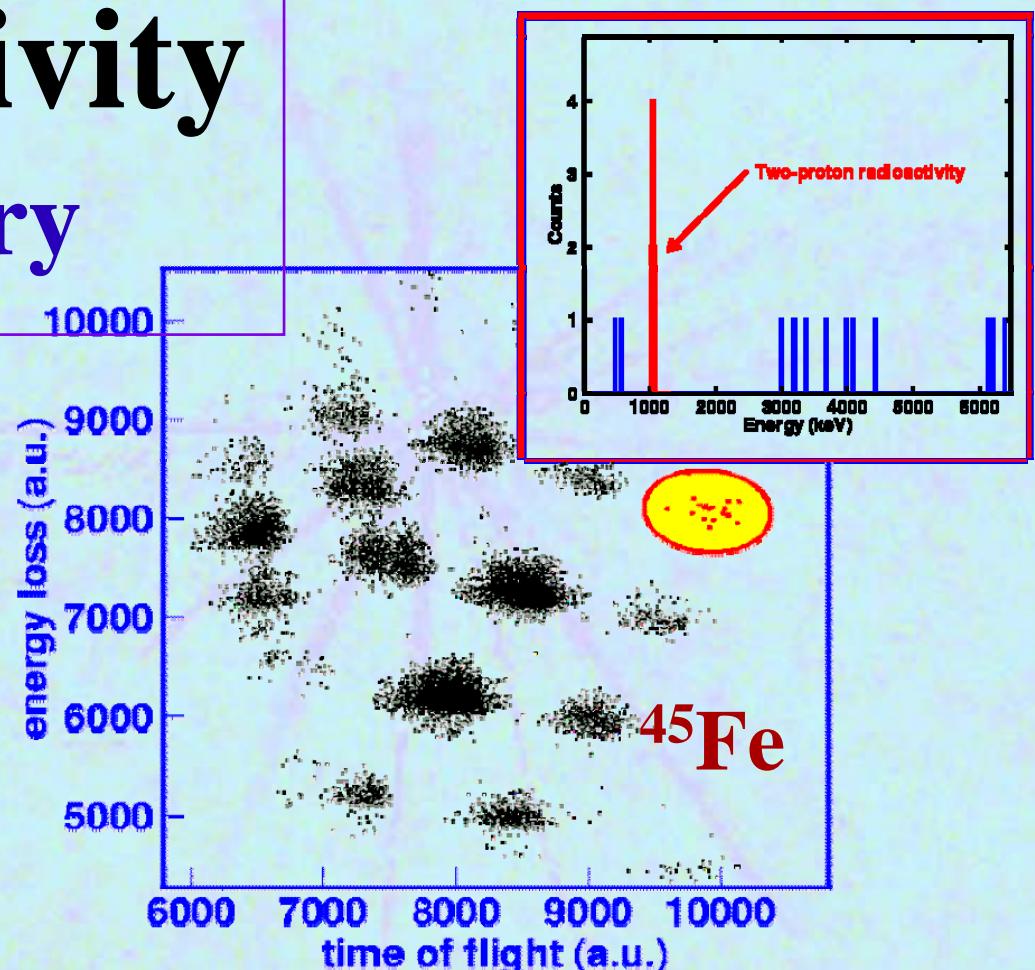
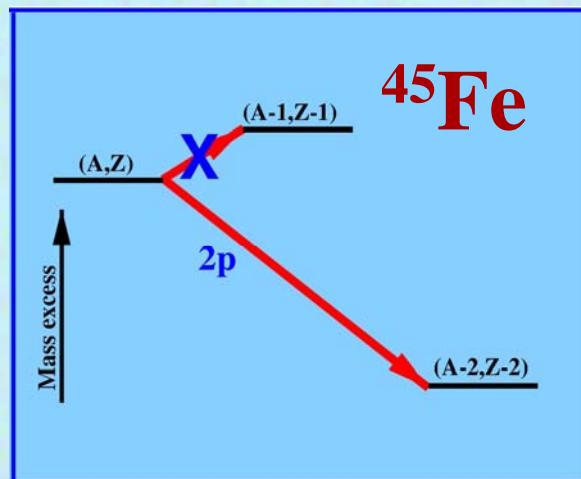


- I -

Radioactivity

Still a mystery

✓ 2p radioactivity



Blank et al, 2003

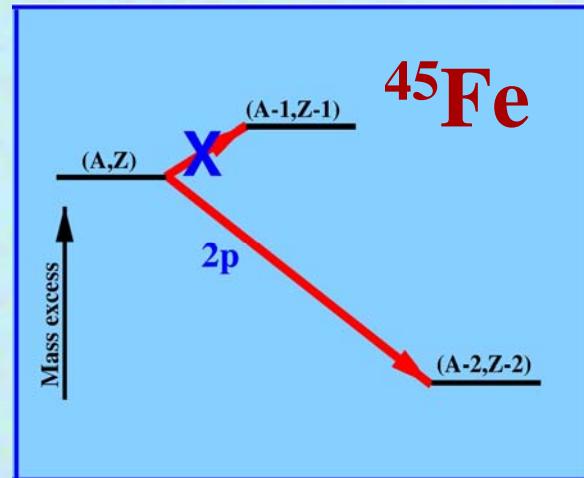


- I -

Radioactivity

Still a mystery

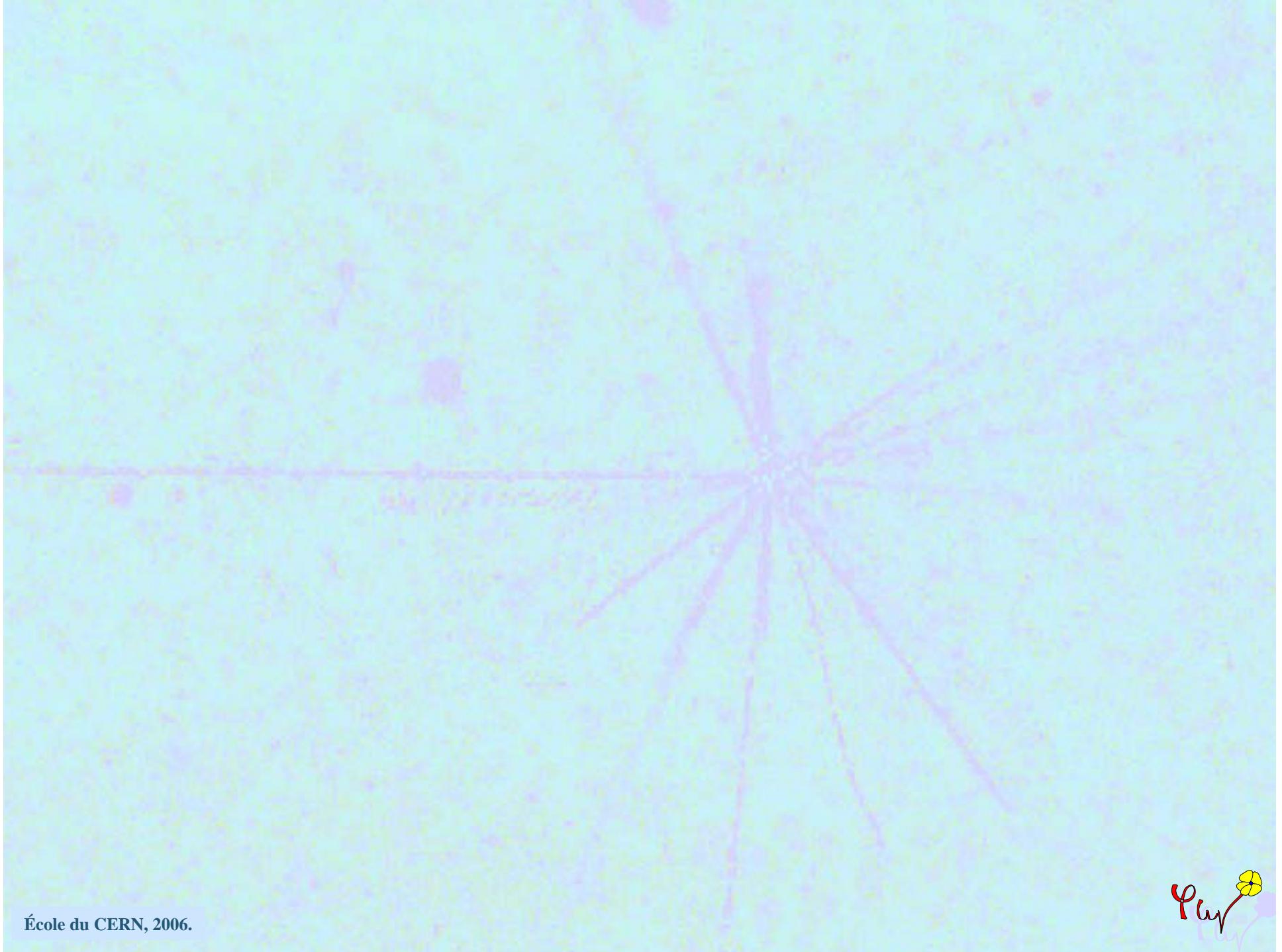
✓ 2p radioactivity



- ✓ Sequential decay
- ✓ Tunneling of complex system ^2He ?
- ✓ Correlations in ^{45}Fe ?

Blank et al, 2003

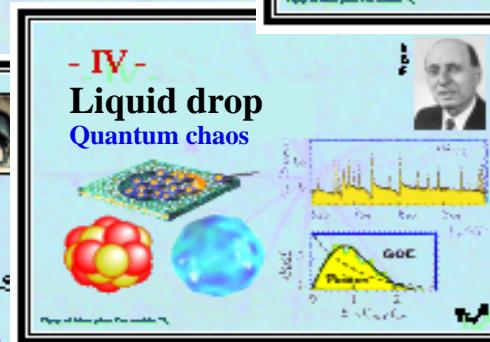
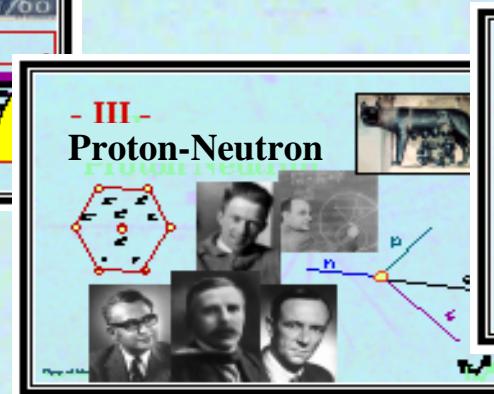
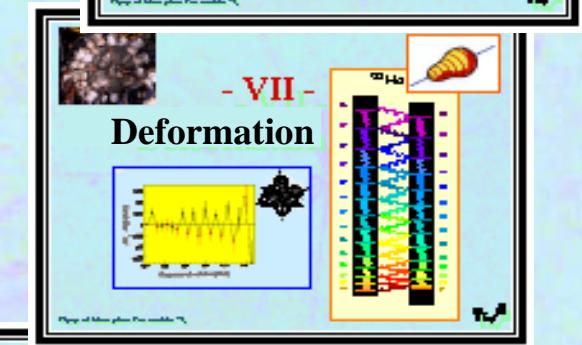
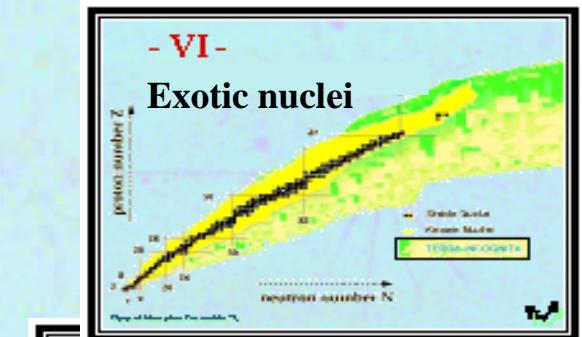
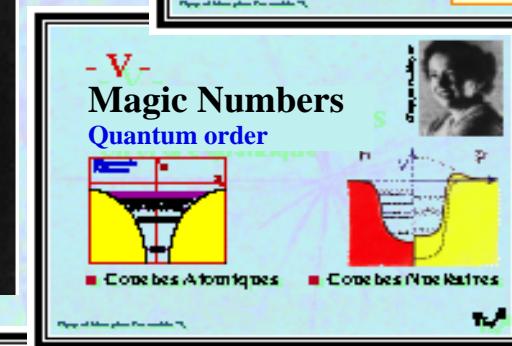
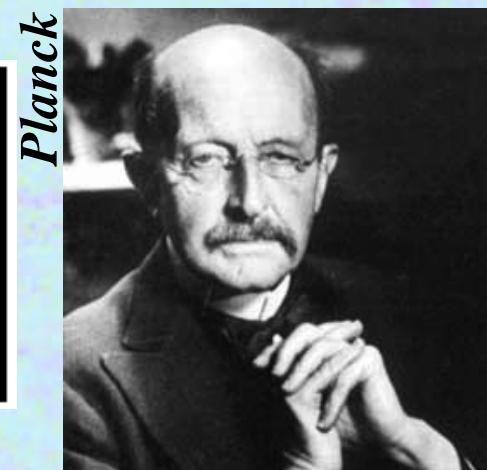
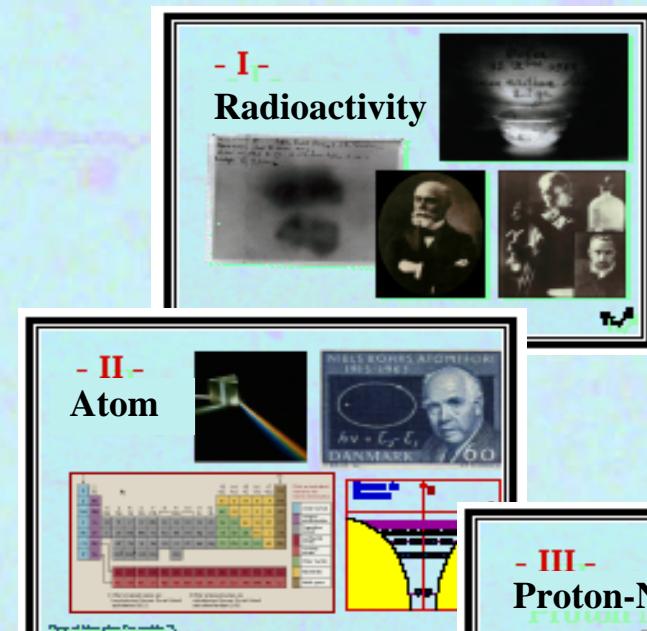


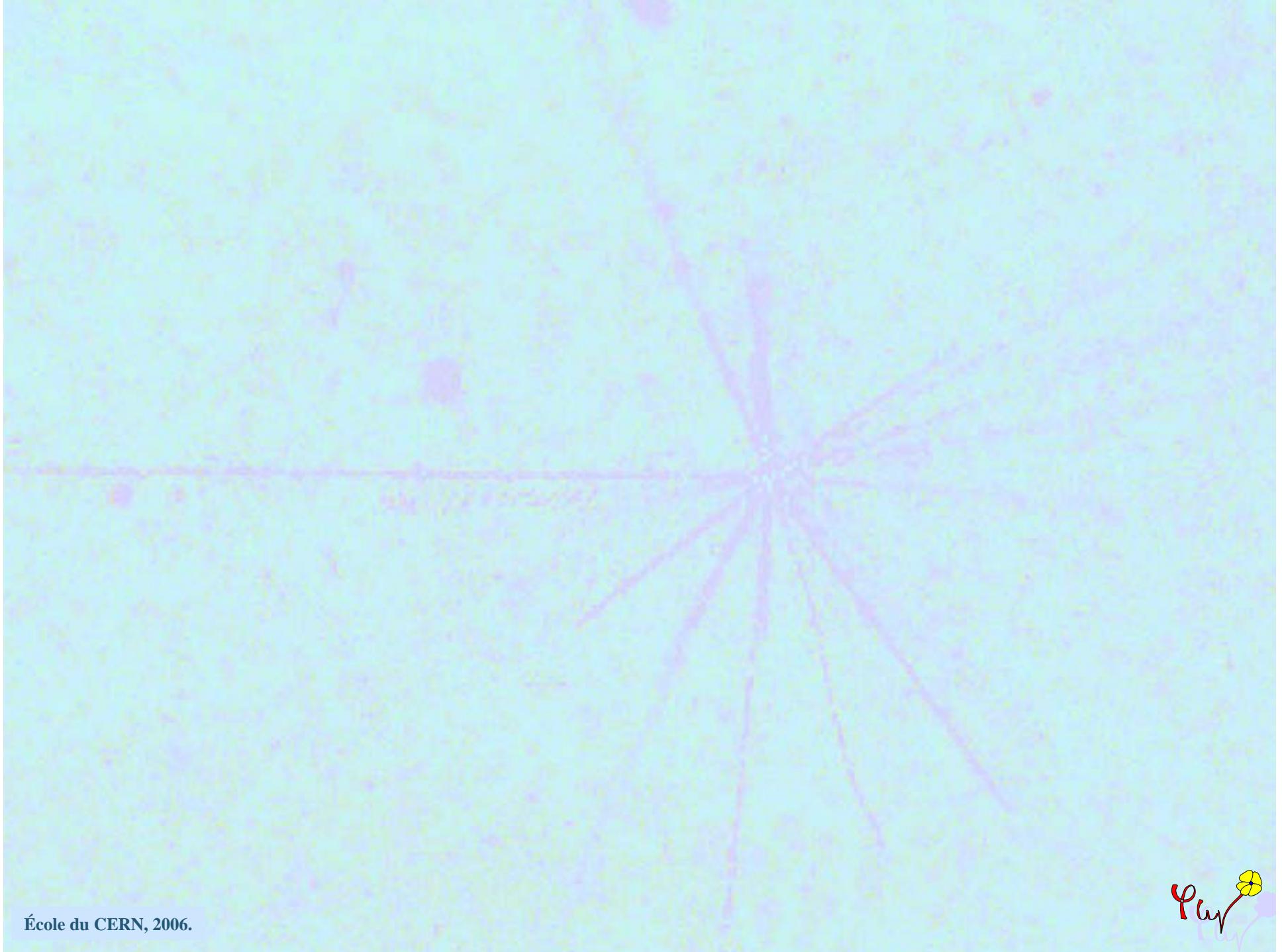


École du CERN, 2006.

Atomic Nuclei

Complex quantum systems





École du CERN, 2006.

- II -

- II -

Exploring atom

Exploration

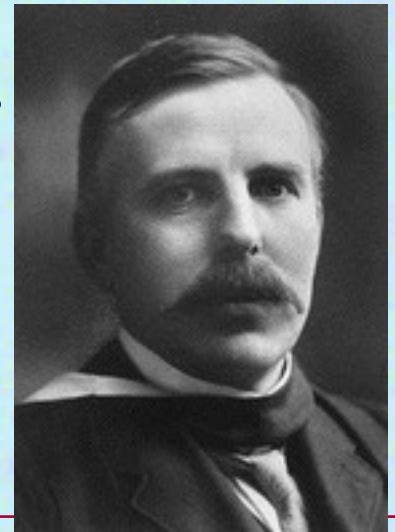


- II -

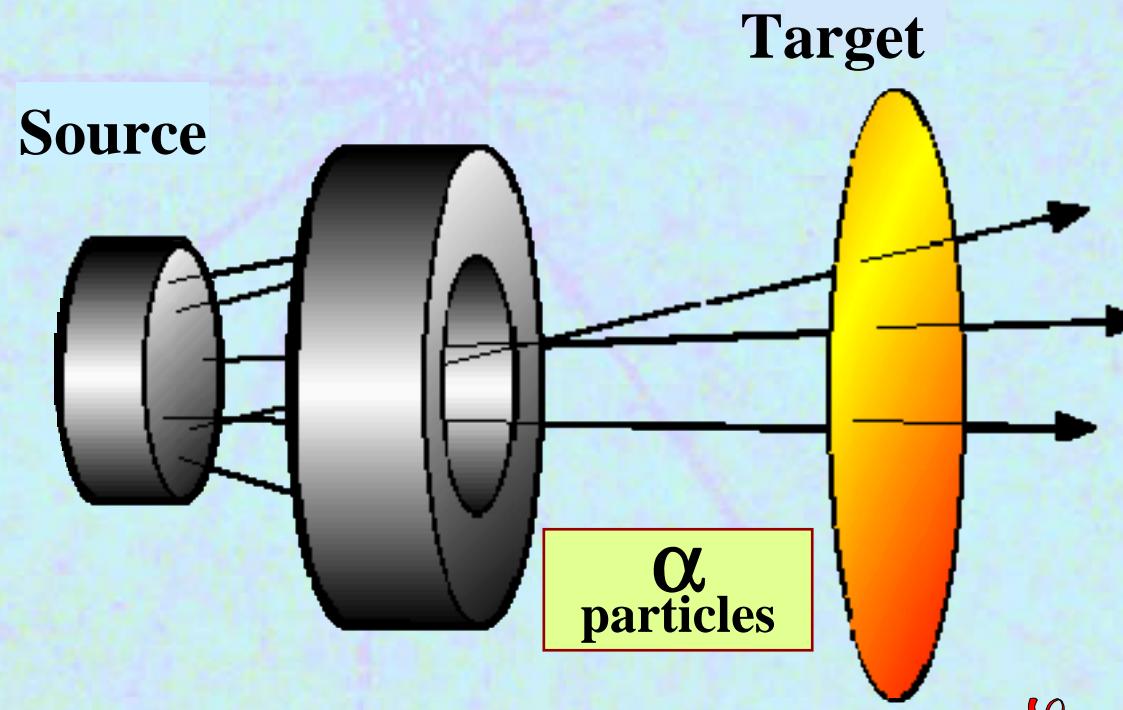
- III -

Exploring atom

Rutherford



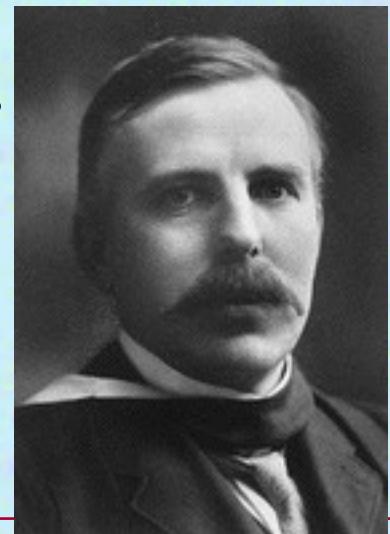
v 1911



- II -

Exploring atom

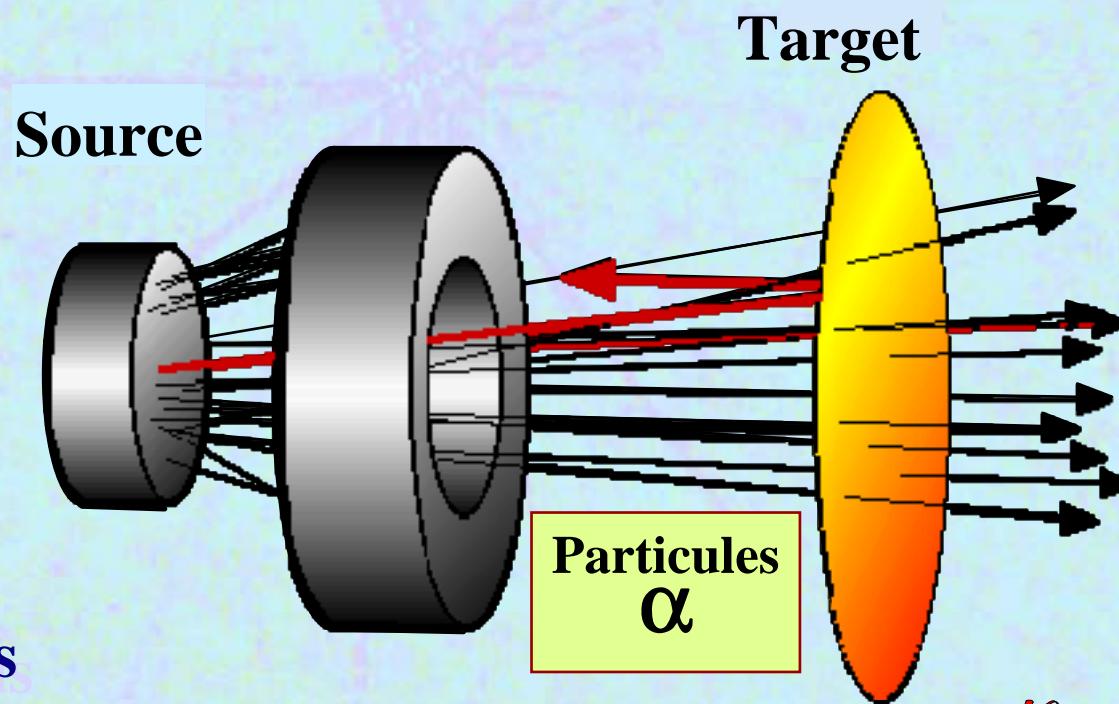
Rutherford



v 1911

Atoms are almost
empty

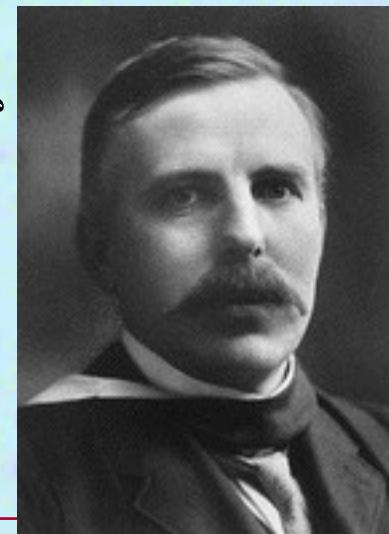
Except a hard
scattering center:
The atomic nucleus



- II -

Exploring atom

Rutherford

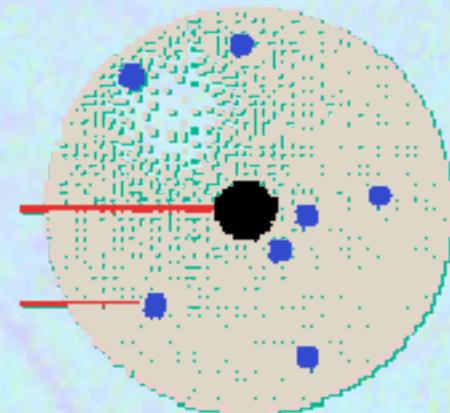


v Atomic Models

Atoms are almost empty

Except a hard scattering center:
The atomic nucleus

Nucleus
few fm
electron



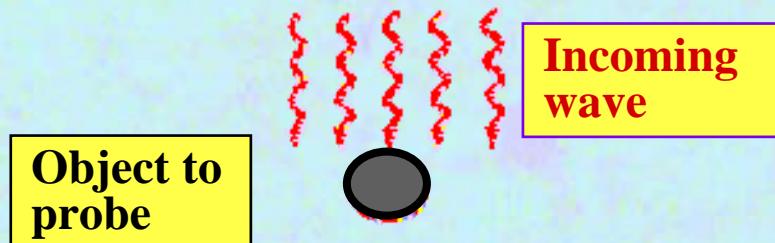
v Modern measures

Φ Scattering of particles



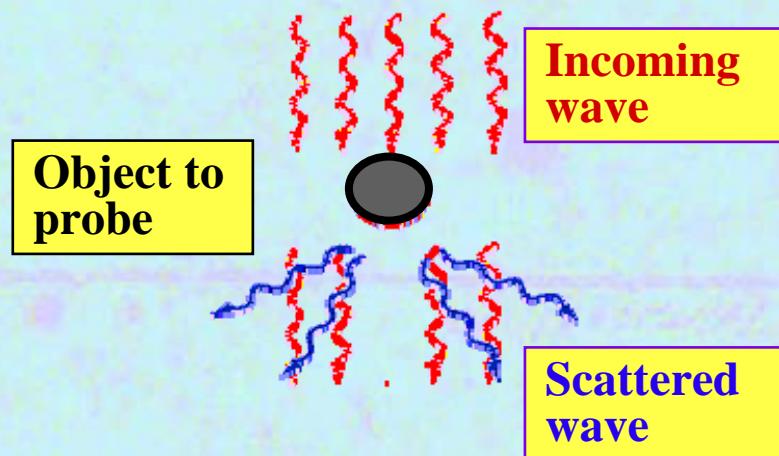
v Modern measures

Φ Scattering of particles



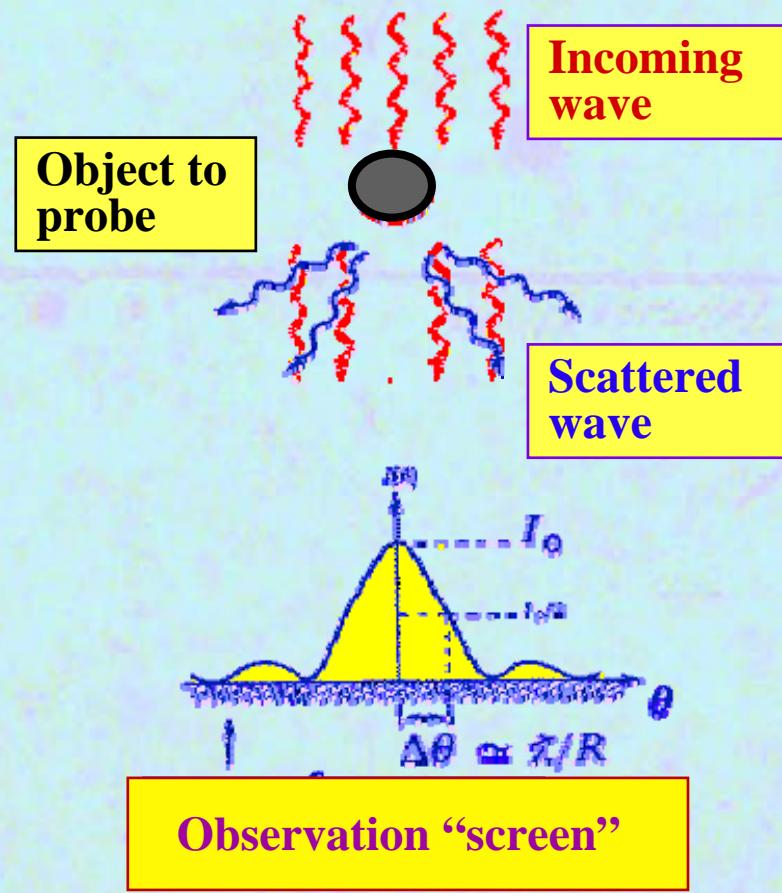
v Modern measures

Φ Scattering of particles



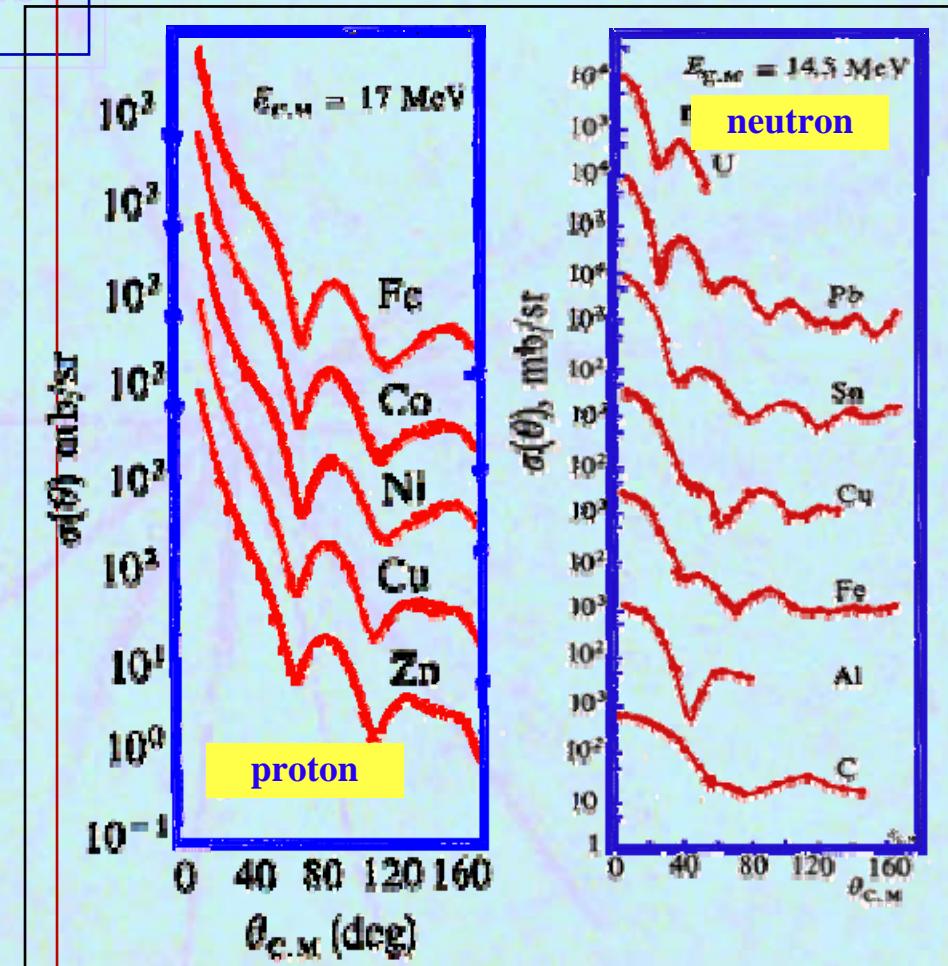
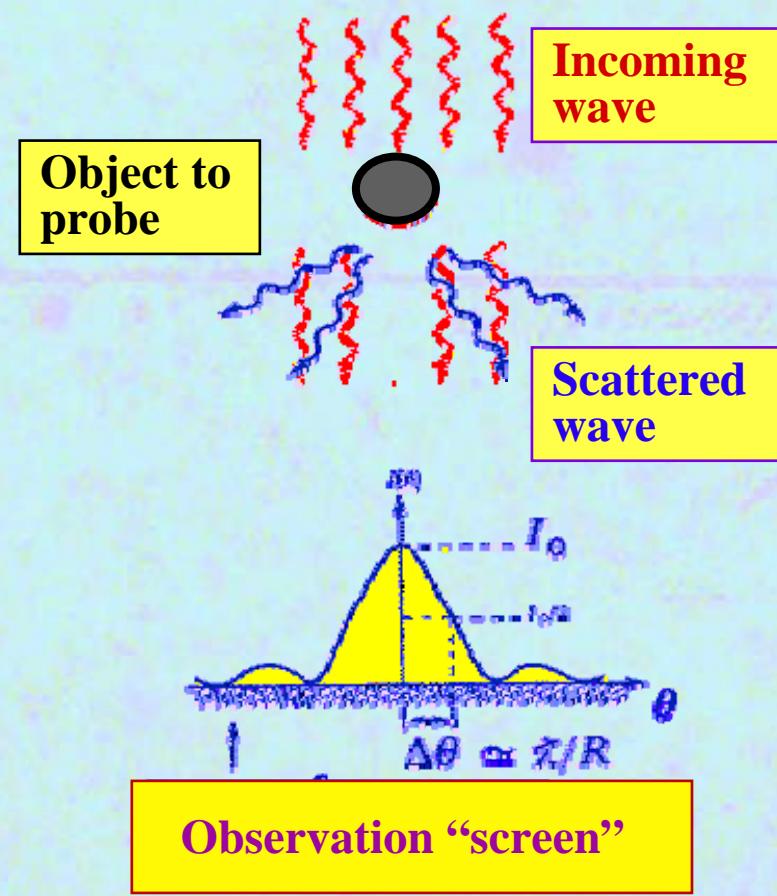
v Modern measures

Φ Scattering of particles



v Modern measures

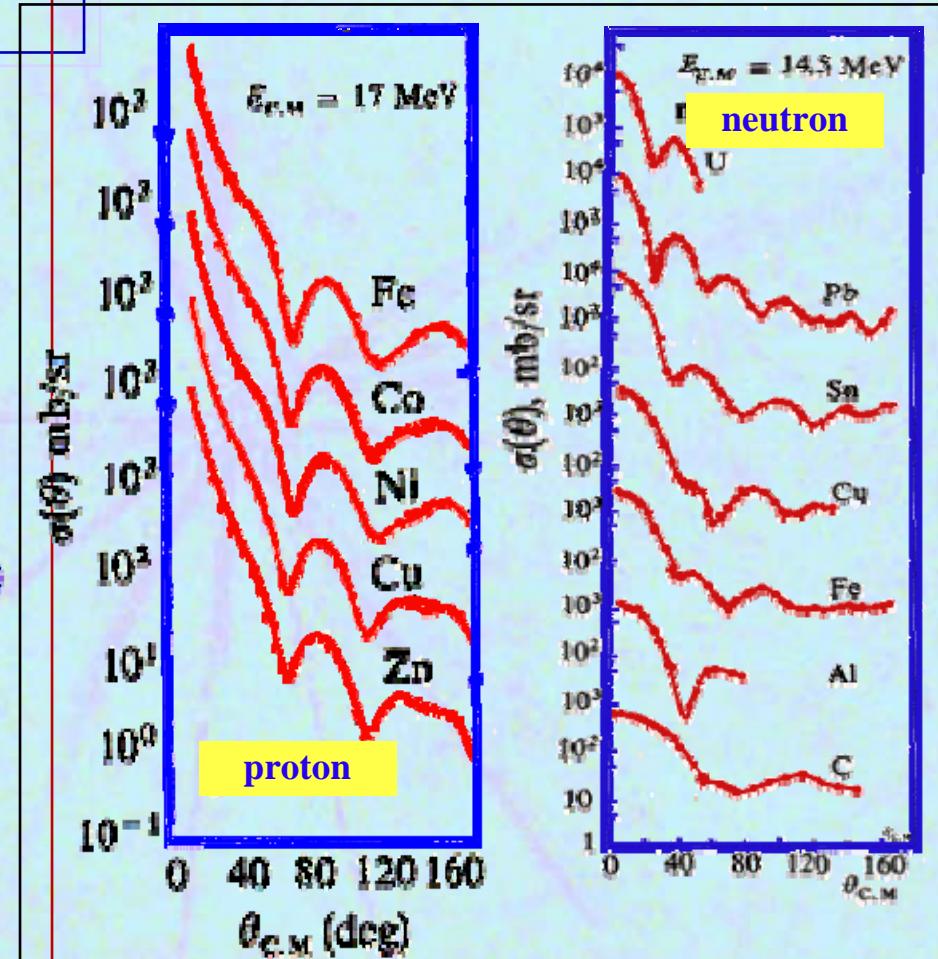
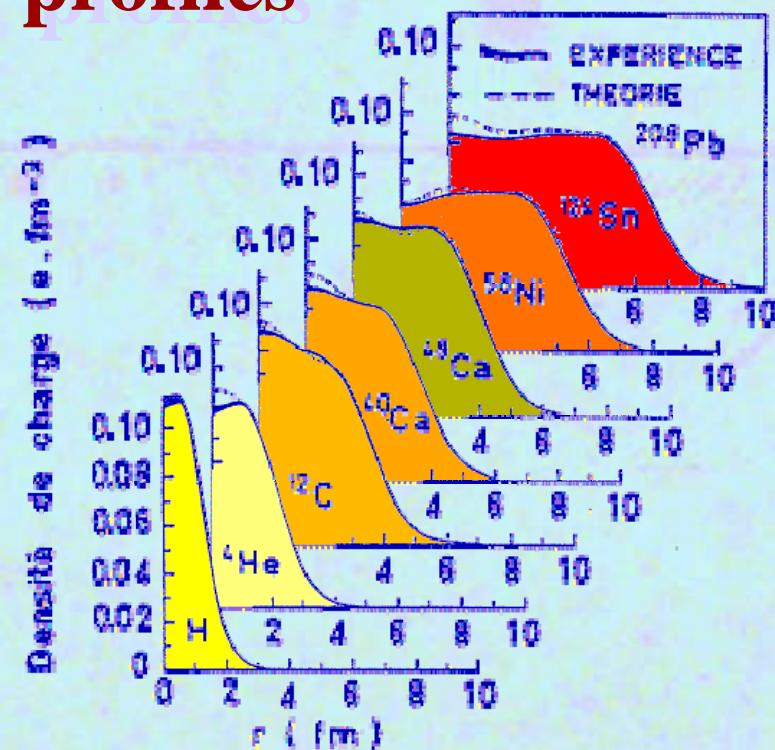
Φ Scattering of particles



v Modern measures

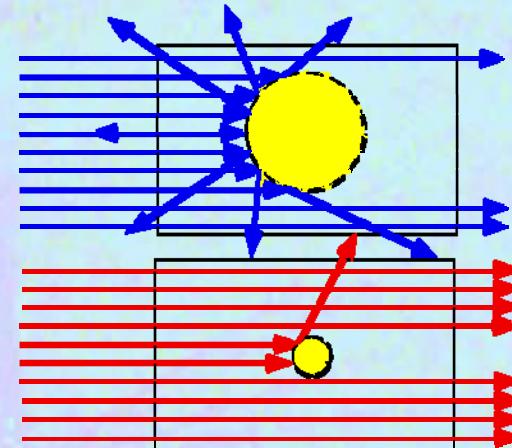
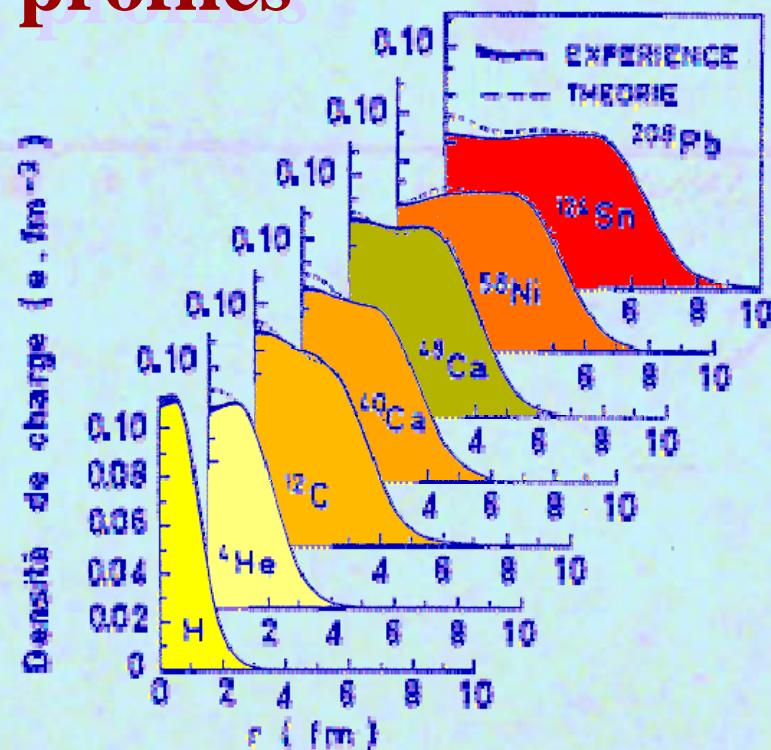
Φ Scattering of particles

v Nuclei density profiles



v Modern measures
 Φ Scattering of particles

v Nuclei density profiles

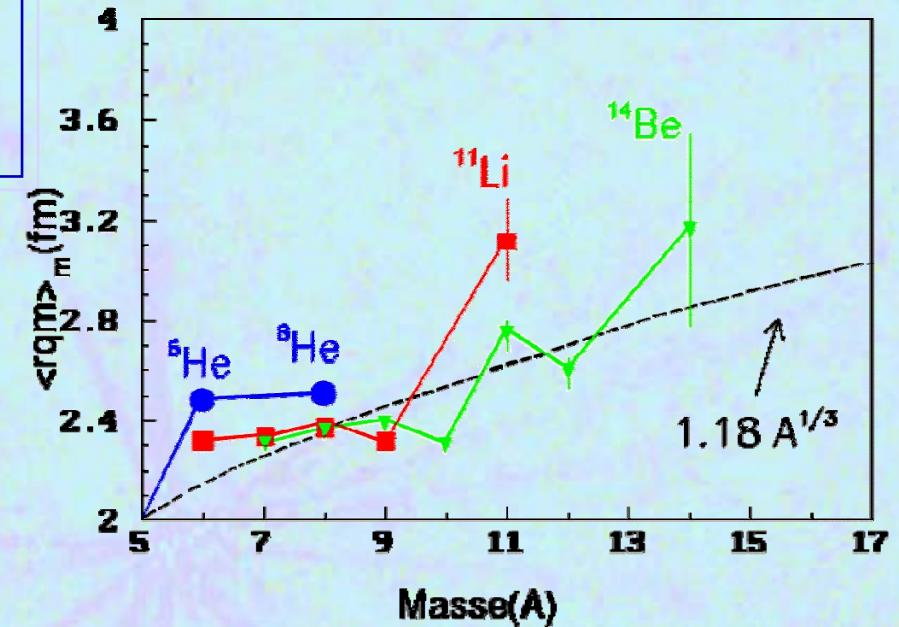
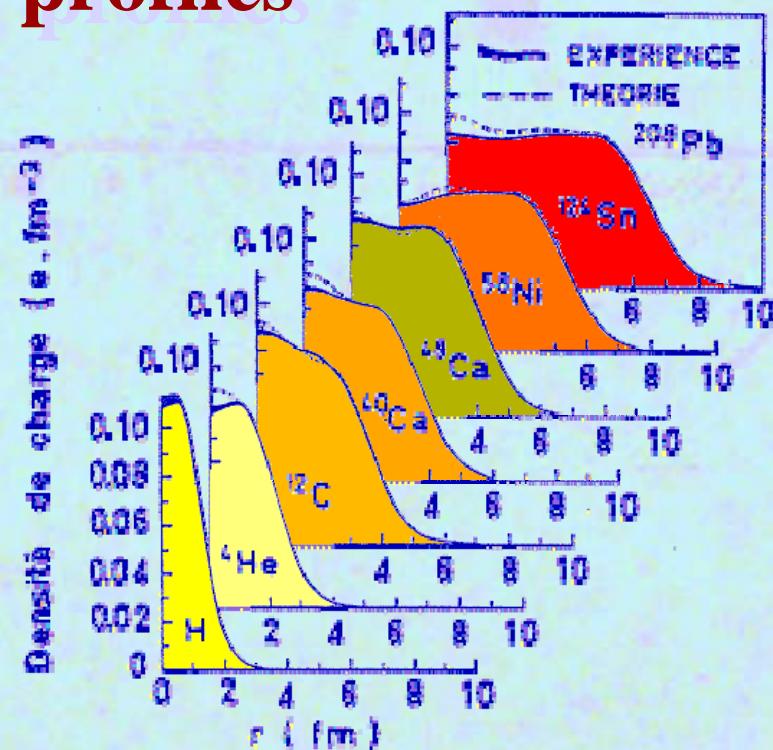


Rutherford experiment

v Measure of reaction cross-section: $\sigma = \pi \langle R^2 \rangle$

v Modern measures
 Φ Scattering of particles

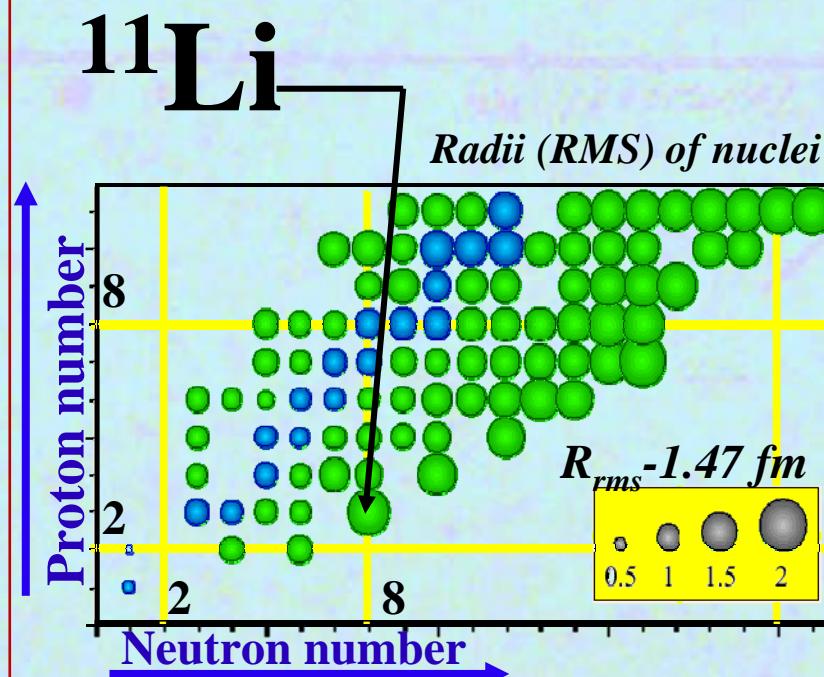
v Nuclei density profiles



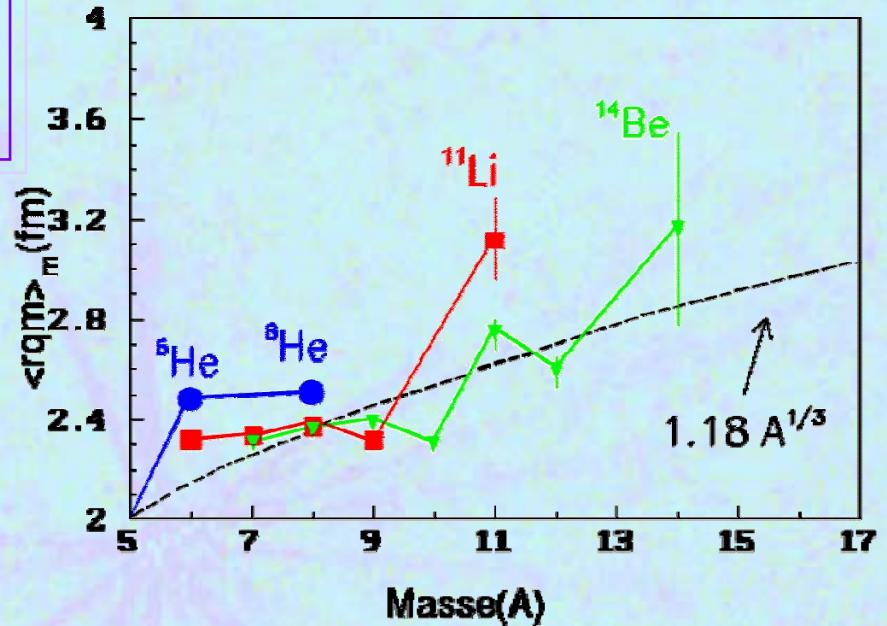
v Measure of reaction cross-section: $\sigma = \pi \langle R^2 \rangle$
 v Drip line nuclei anomalously large



Discovery of halo nuclei



École du CERN, 2006.



Measure of reaction cross-section: $\sigma = \pi \langle R^2 \rangle$

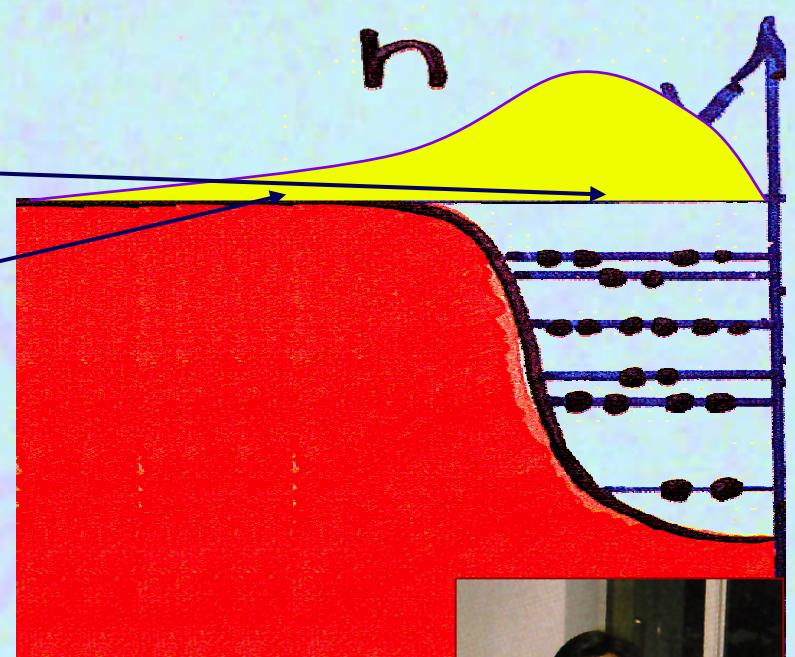
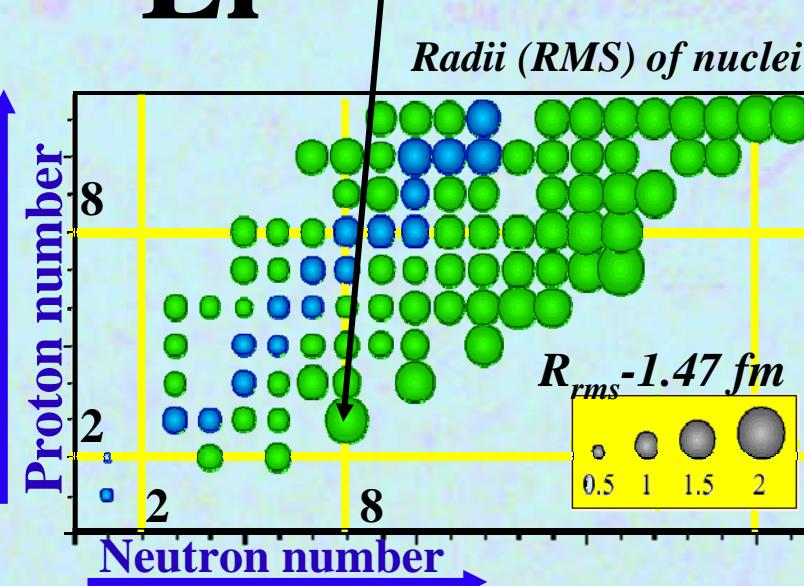
Drip line nuclei anomalously large



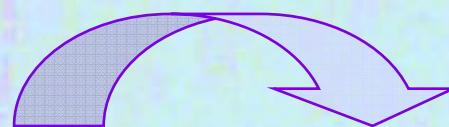
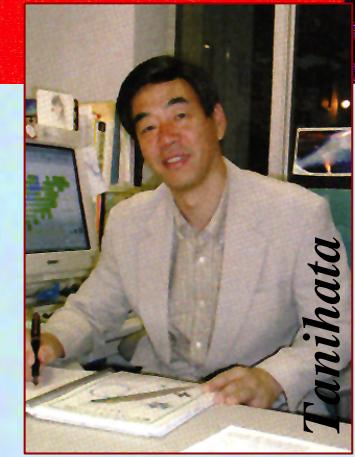
Discovery of halo nuclei

- Weakly bound n
- Tunnel effect

^{11}Li



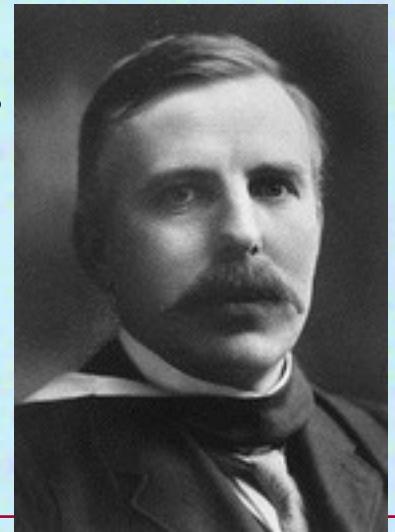
Halo nuclei



- II -

Exploring atom

Rutherford

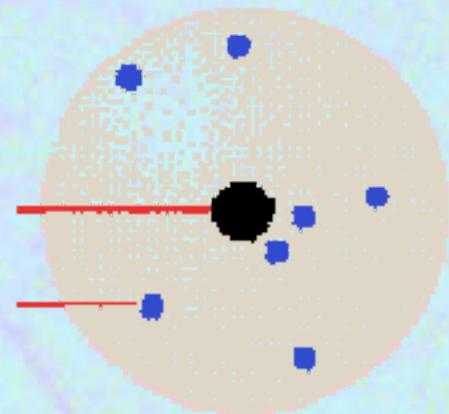


v Atomic Models

Atoms are almost empty

Except a hard scattering center:
The atomic nucleus

Nucleus
electron



Play

- II -

Exploring atom Quantum object

v Atomic Models

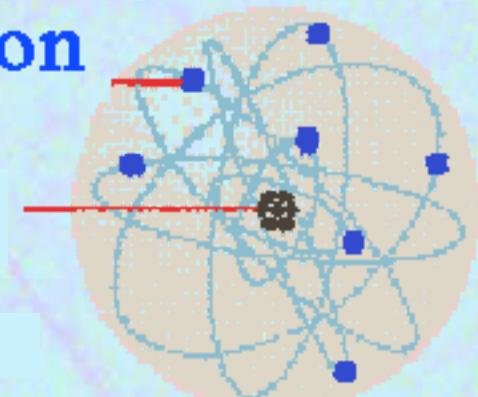
Atoms are almost empty

Except a hard scattering center:
The atomic nucleus

électron

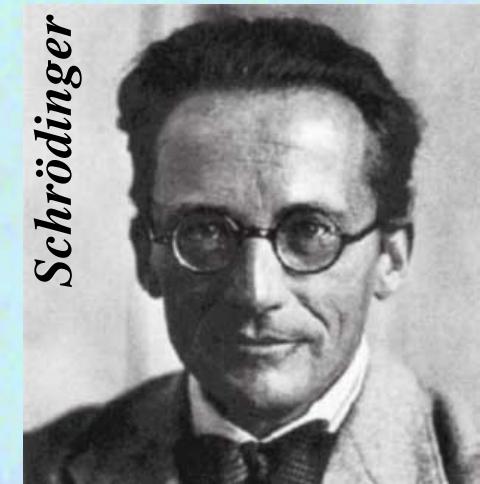
Nucleus

orbit



- II -

Exploring atom Quantum object

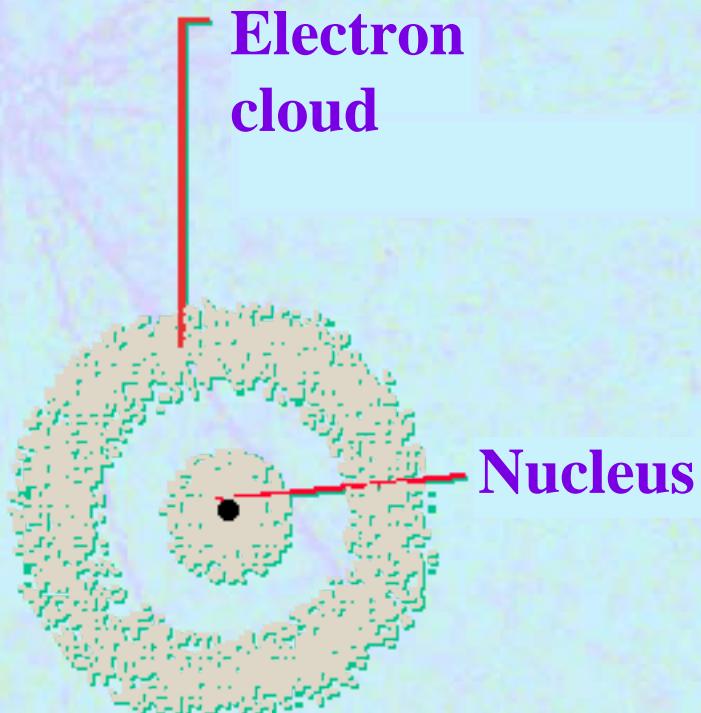


Schrödinger

v Atomic Models

Atoms are almost empty

Except a hard scattering center:
The atomic nucleus



Play

- II -

Exploring atom Quantum object

v

Electron
cloud

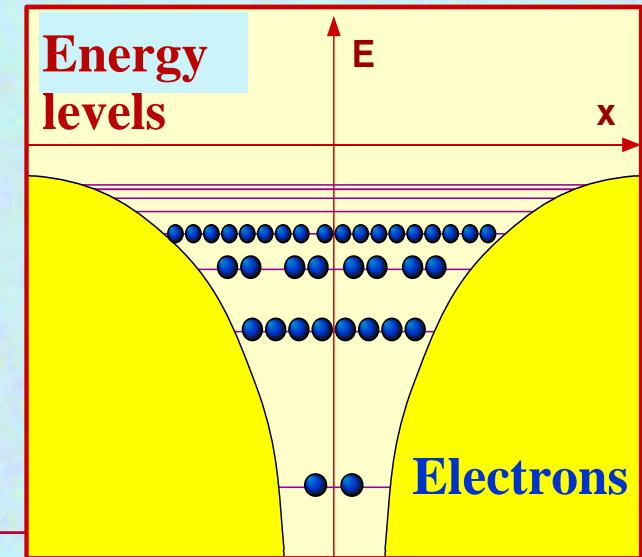
Nucleus

Play

- II -

Exploring atom Quantum object

- v Electrons on energy levels orbiting around a tiny heavy center: the nucleus

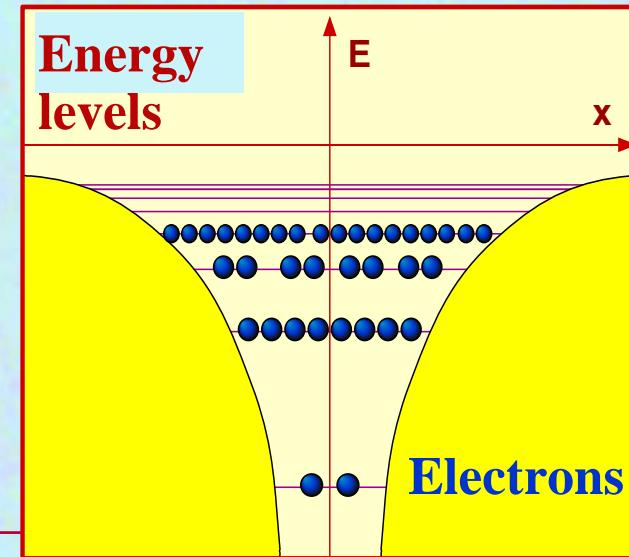


Electron
cloud

Nucleus

- II -

Exploring atom Quantum object



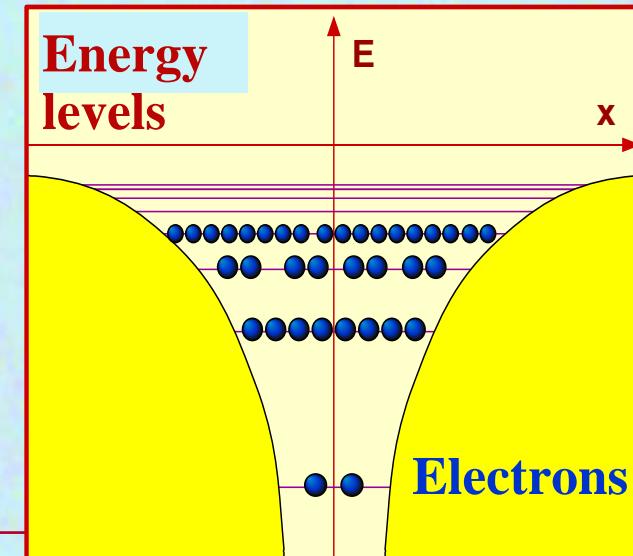
v Electrons on energy levels orbiting around a tiny heavy center: the nucleus



Decomposition of the light

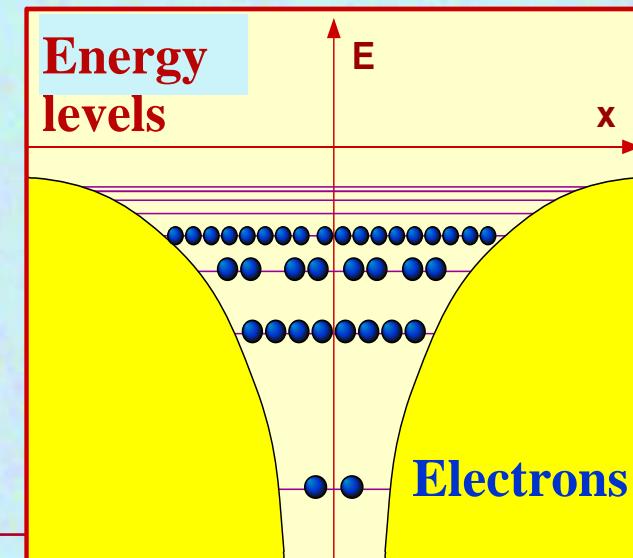
- II -

Exploring atom Quantum object

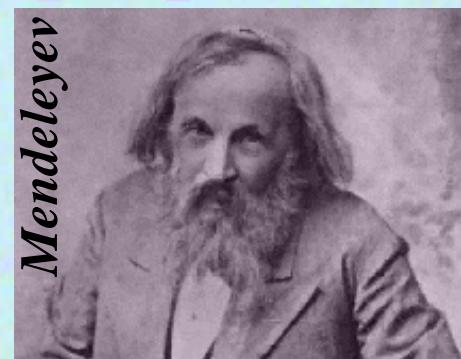


- II -

Exploring atom Quantum object



v Periodic properties



Mendeleev

Click on individual elements for atomic information.

1	1a		2	2a																18	0							
H			Li	Be															He									
Na	Mg	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	VIIa											
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	B	C	N	O	F	Ne											
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	Al	Si	P	S	Cl	Ar											
Cs	Ba		Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Ga	Ge	As	Se	Br	Kr											
Fr	Ra		Unq [†]	Unp [§]	Unh	Uns					Une	In	Sn	Sb	Te	I	Xe											
												Tl	Pb	Bi	Po	At	Rn											
												La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu		
												AC	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr		

[†] Other proposed names are kurchatovium (former Soviet Union) and hahnium (U.S.).

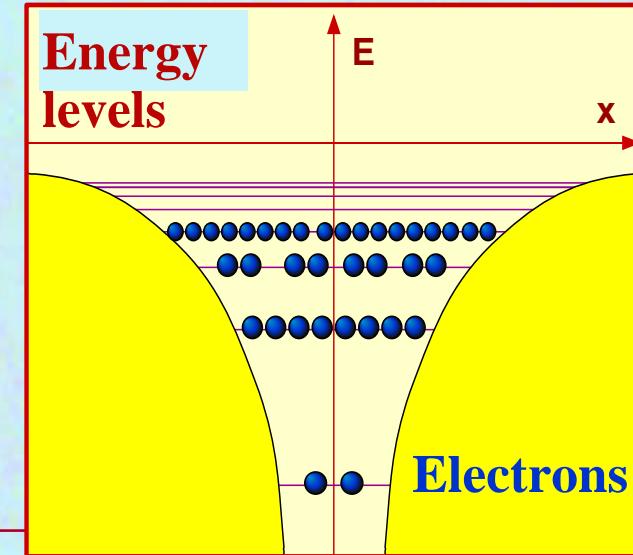
[§] Other proposed names are nielsbohrium (former Soviet Union) and rutherfordium (U.S.).



- II -

Exploring atom Quantum object

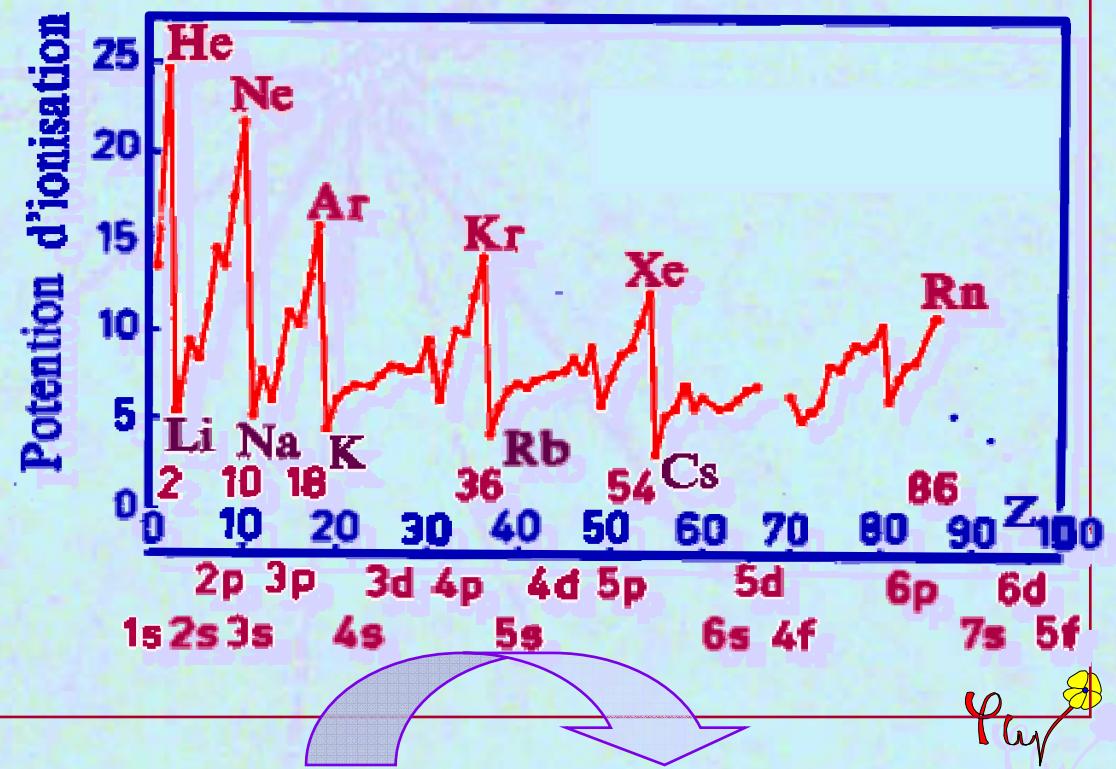
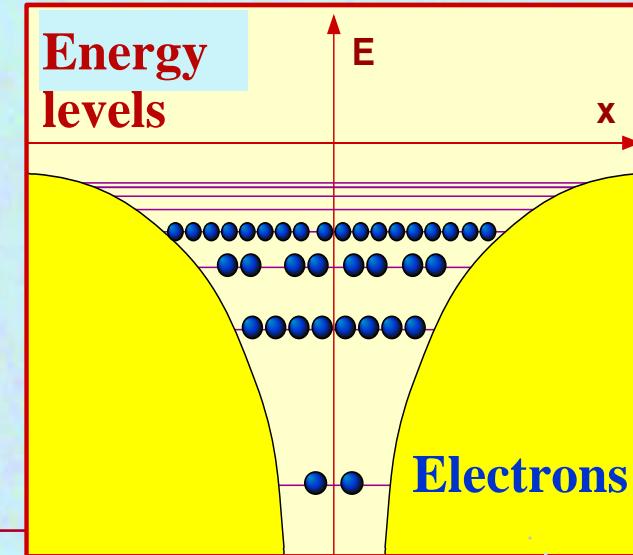
v Periodic
properties



- II -

Exploring atom Quantum object

- ✓ Periodic properties
- ✓ Magic numbers
2, 10, 18,
36, 54, 86



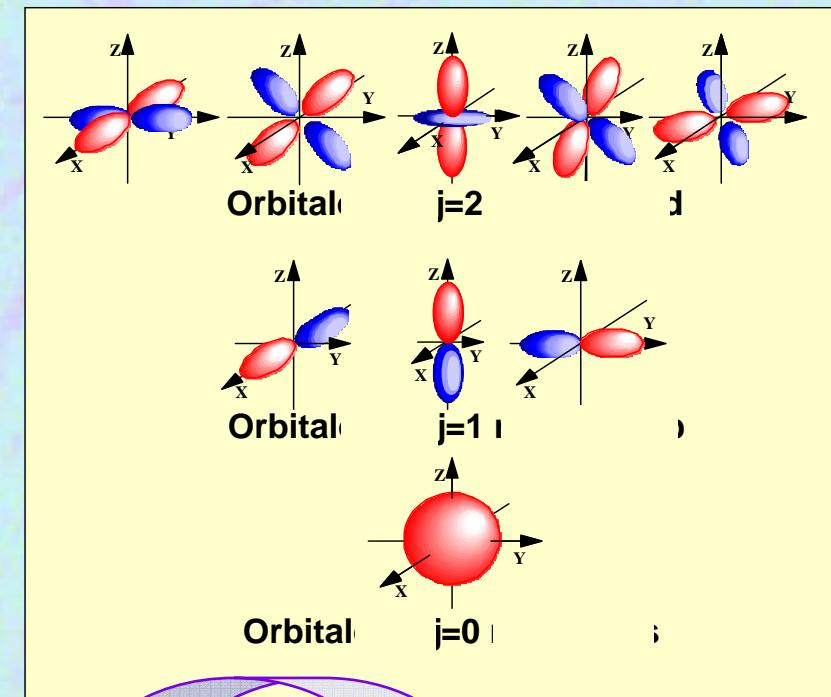
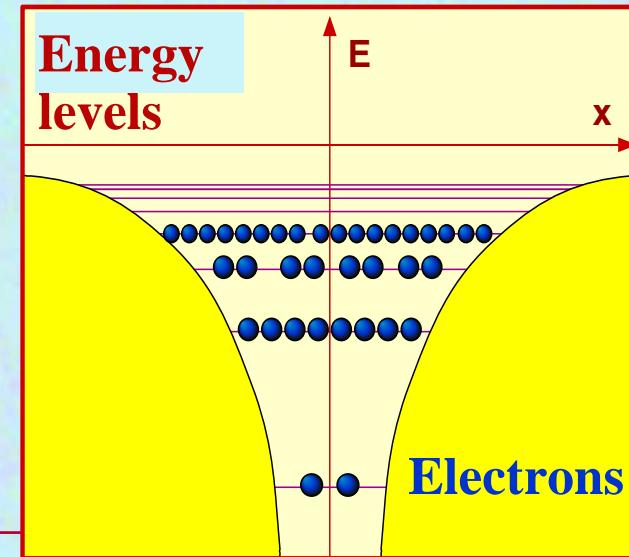
- II -

Exploring atom Quantum object

- ✓ Orbitals and shapes
- ✓ Symmetry,
quantum numbers
and degeneracy

$$[\hat{H}, \hat{Q}] = 0$$

$$\hat{Q}|\varphi\rangle = q|\varphi\rangle; \hat{H}|\varphi\rangle = E_q|\varphi\rangle$$



Definition of symmetry

- A hamiltonian H has **symmetry** G (is invariant under G) if

$$\forall g \in G : [H, g] = 0$$

- The transformations g are assumed to form a Lie algebra.

Consequences of symmetry

- **Degeneracy:**

$$H|\Gamma\rangle = E|\Gamma\rangle \Rightarrow Hg|\Gamma\rangle = Eg|\Gamma\rangle$$

- **State labelling:**

$$H|\Gamma\gamma\rangle = E(\Gamma)|\Gamma\gamma\rangle$$

- Action of transformations g :

$$g|\Gamma\gamma\rangle = \sum_{\gamma'} a_{\gamma\gamma'}^{\Gamma}(g)|\Gamma\gamma'\rangle$$

- The a -matrices constitute a **representation** of the elements g of G .

Definition of a Lie algebra

- A Lie group contains an infinite number of elements that depend on a set of **continuous variables**.
- The corresponding Lie algebra is obtained from (a finite number of) **infinitesimal operators**, called **generators**.
- An algebraic structure over the generators is defined through **commutation relations** in terms of **structure constants**:

$$[g_i, g_j] \equiv g_i \circ g_j - g_j \circ g_i = \sum_k c_{ij}^k g_k$$

- Structure constants are **antisymmetric** in i and j .

- Generators satisfy the **Jacobi identity**:

$$[g_i, [g_j, g_k]] + [g_j, [g_k, g_i]] + [g_k, [g_i, g_j]] = 0$$



Definition of symmetry

Definition of a Lie algebra

Transformation Operators Eigenstates Symmetry

Degeneracy Transitions

elements g of G.

École du CERN, 2006.

$$|\varphi\rangle \rightarrow \hat{U}(\theta)|\varphi\rangle$$

$$\theta \vec{u}$$

$$\hat{U}(\delta\theta) = 1 + i\delta\theta \hat{Q}$$

$$\vec{\hat{L}} \Rightarrow \hat{L}^2$$

$$\hat{Q}|\varphi_q\rangle = q|\varphi_q\rangle$$

$$\hat{L}_z|l,m\rangle = m|l,m\rangle$$

$$[\hat{H}, \hat{Q}] = 0$$

$$\hat{L}^2|l,m\rangle = l(l+1)|l,m\rangle$$

$$\hat{H}|\varphi_q\rangle = E_q|\varphi_q\rangle$$

$$H|l,m\rangle = E_l|l,m\rangle$$

$$E_q = E_{q'} \text{ if } \hat{U}|\varphi_q\rangle = |\varphi_{q'}\rangle$$

$$\langle \varphi_{q'} | \hat{Q}' | \varphi_q \rangle$$

$$\hat{L}_{x/y}|l,m\rangle \Rightarrow |l,m\pm 1\rangle$$



Definition of symmetry

- A hamiltonian H has **symmetry** G (is invariant under G) if

$$\forall g \in G : [H, g] = 0$$

- The transformations g are assumed to form a Lie algebra.

Consequences of symmetry

- **Degeneracy:**

$$H|\Gamma\rangle = E|\Gamma\rangle \Rightarrow Hg|\Gamma\rangle = Eg|\Gamma\rangle$$

- **State labelling:**

$$H|\Gamma\gamma\rangle = E(\Gamma)|\Gamma\gamma\rangle$$

- Action of transformations g :

$$g|\Gamma\gamma\rangle = \sum_{\gamma'} a_{\gamma\gamma'}^{\Gamma}(g)|\Gamma\gamma'\rangle$$

- The a -matrices constitute a **representation** of the elements g of G .

Definition of a Lie algebra

- A Lie group contains an infinite number of elements that depend on a set of **continuous variables**.
- The corresponding Lie algebra is obtained from (a finite number of) **infinitesimal operators**, called **generators**.
- An algebraic structure over the generators is defined through **commutation relations** in terms of **structure constants**:

$$[g_i, g_j] \equiv g_i \circ g_j - g_j \circ g_i = \sum_k c_{ij}^k g_k$$

- Structure constants are **antisymmetric** in i and j .

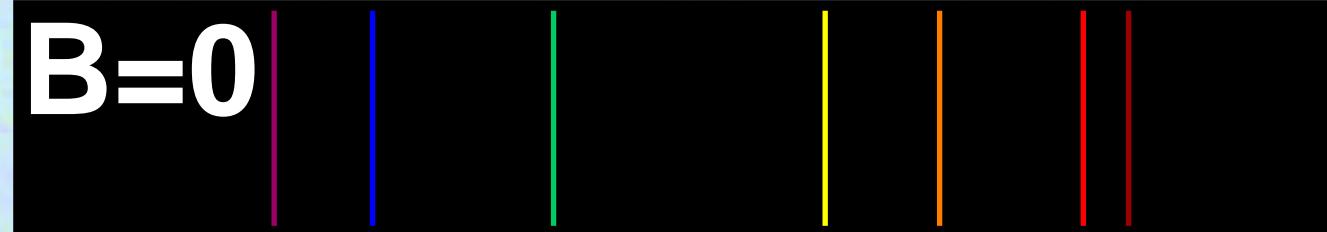
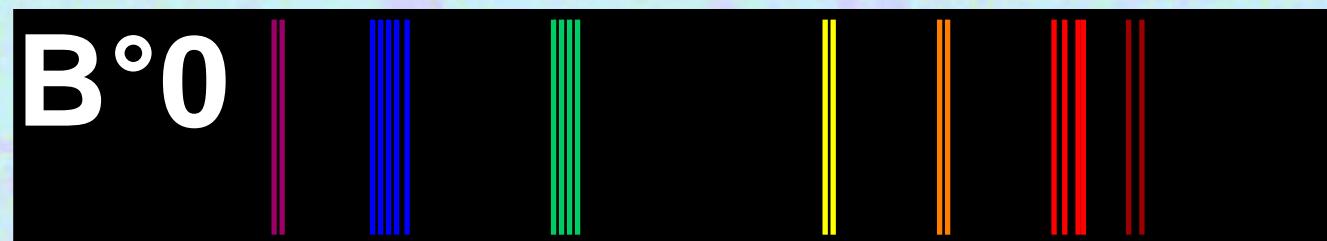
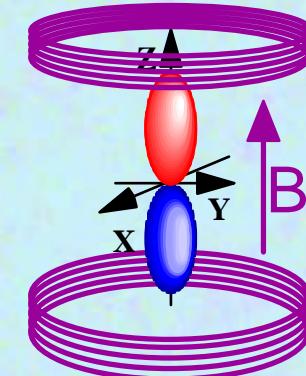
- Generators satisfy the **Jacobi identity**:

$$[g_i, [g_j, g_k]] + [g_j, [g_k, g_i]] + [g_k, [g_i, g_j]] = 0$$



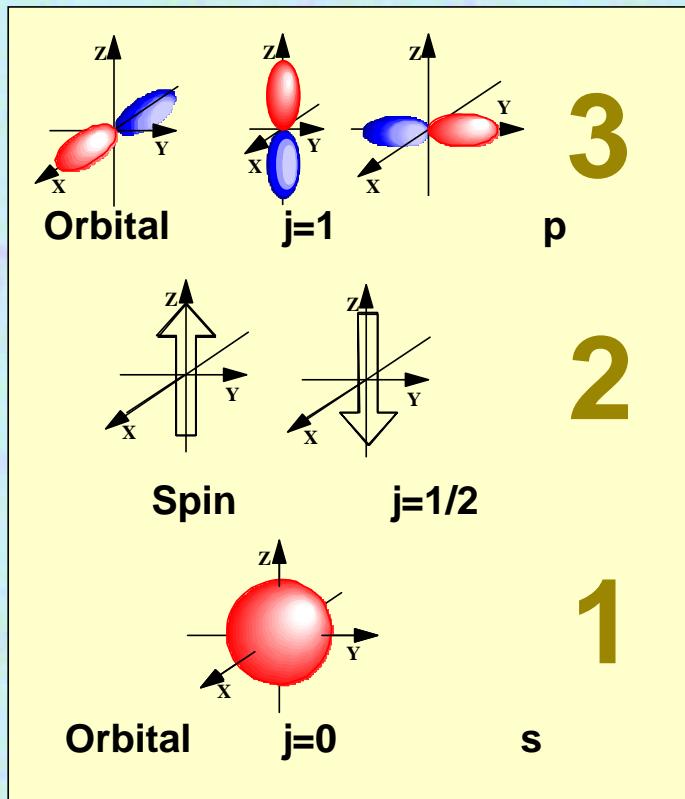
Symmetry breaking

✓ Breaking degeneracy



Spin 1/2

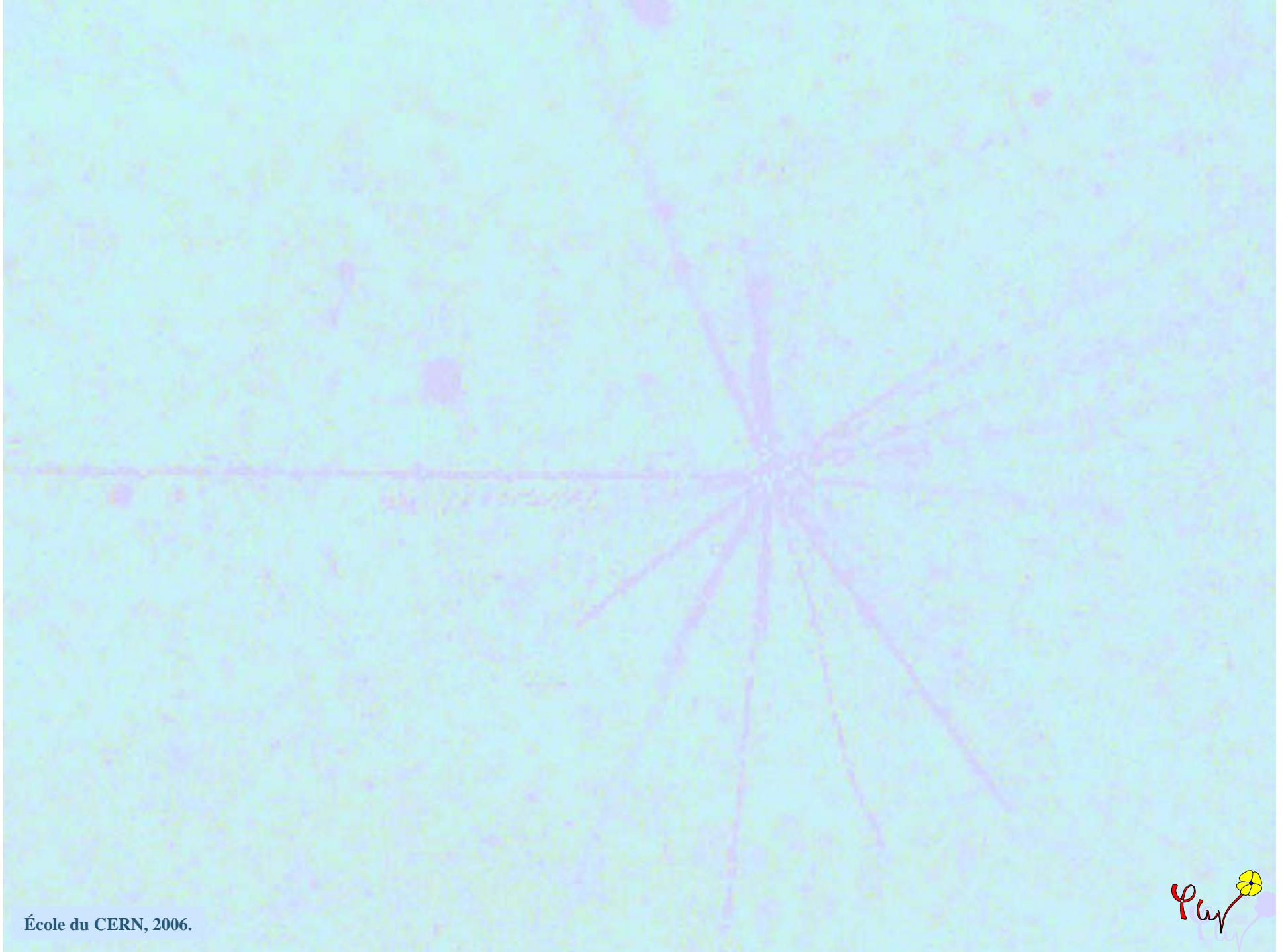
Internal symmetry



“Those doublets and their anomalous Zeeman effects, are manifestations of an intrinsic electron ambivalence (Zweideutigkeit)”

Pauli 1925

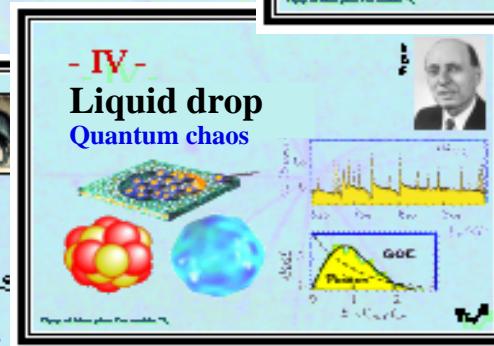
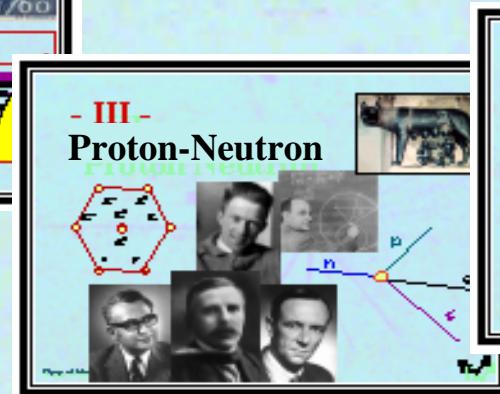
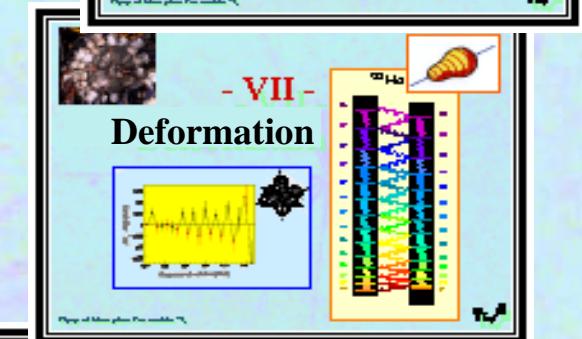
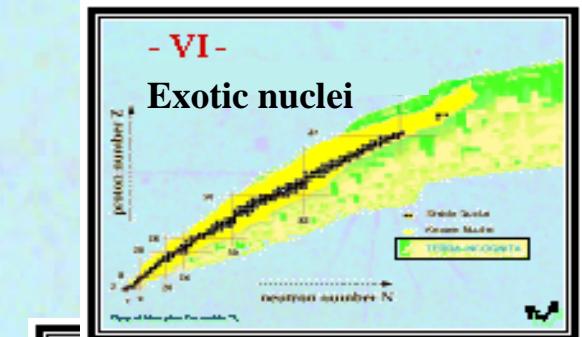
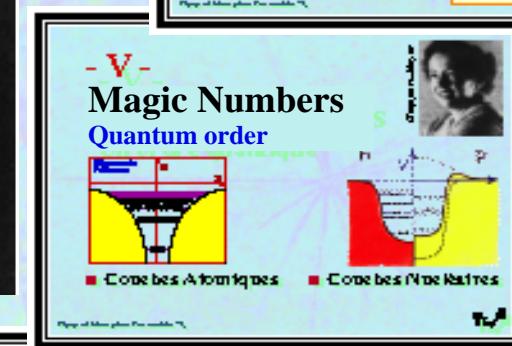
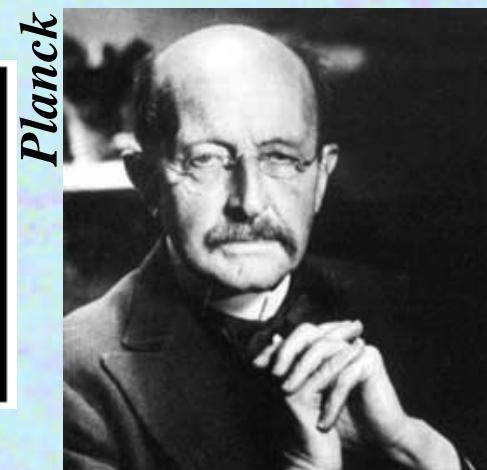
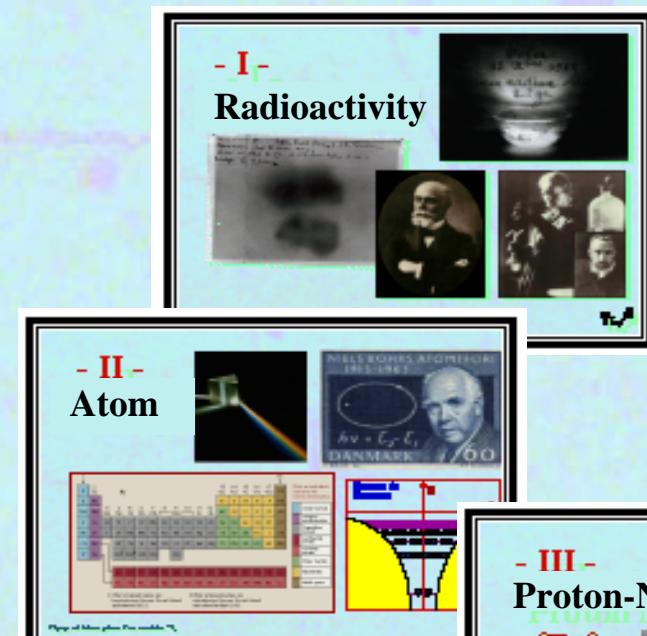
Zweideutigkeit => spin

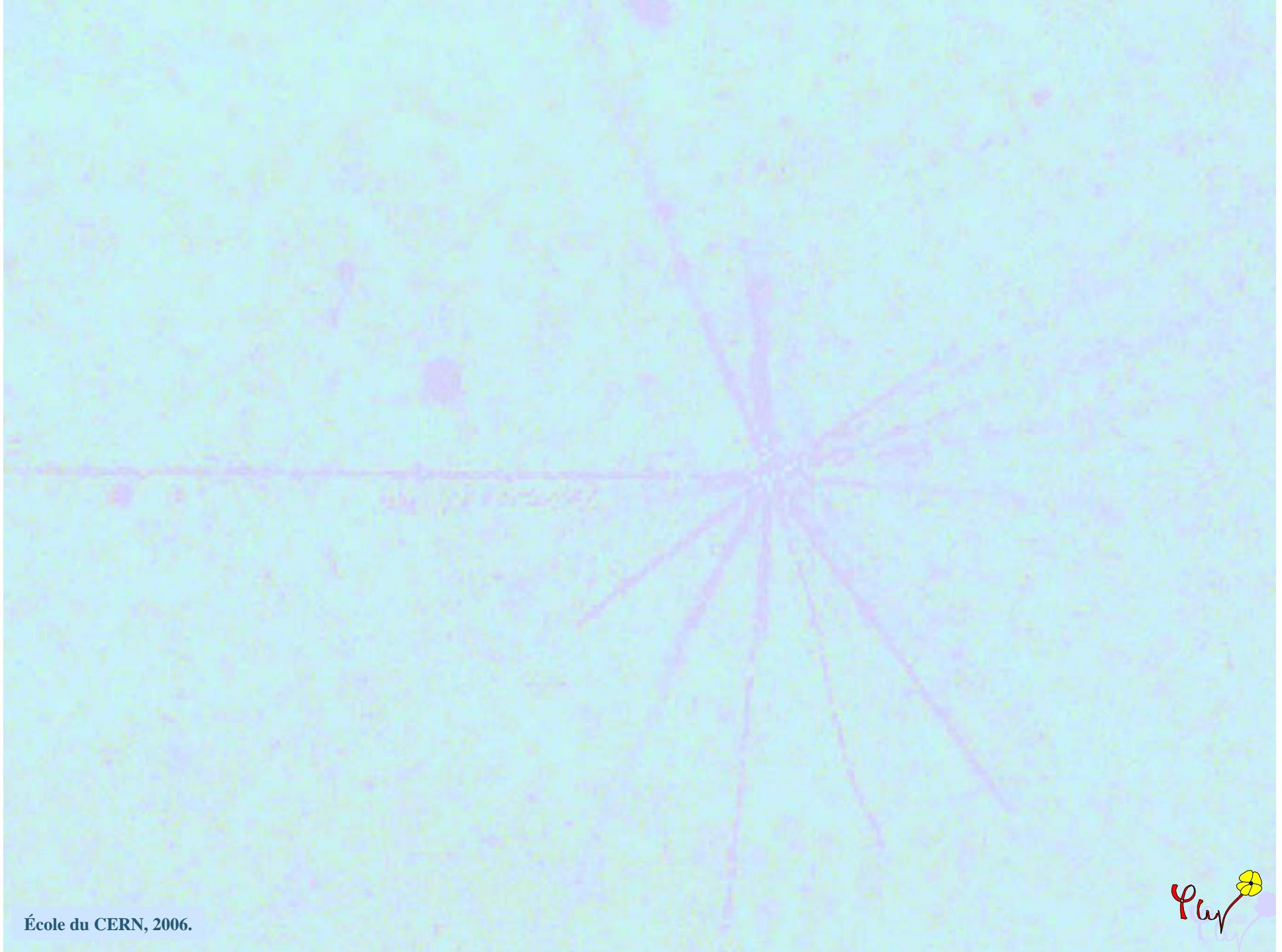


École du CERN, 2006.

Atomic Nuclei

Complex quantum systems





École du CERN, 2006.

- V -

Magic Numbers

Quantum order



- V -

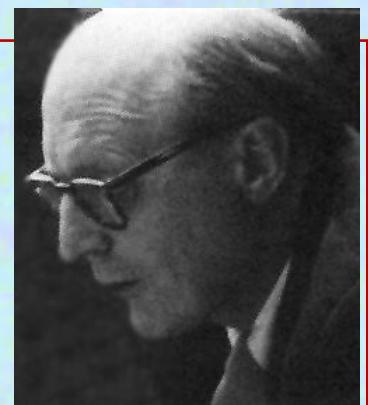
Magic Numbers

v Striking regularities

Goeppert-Mayer



Jensen



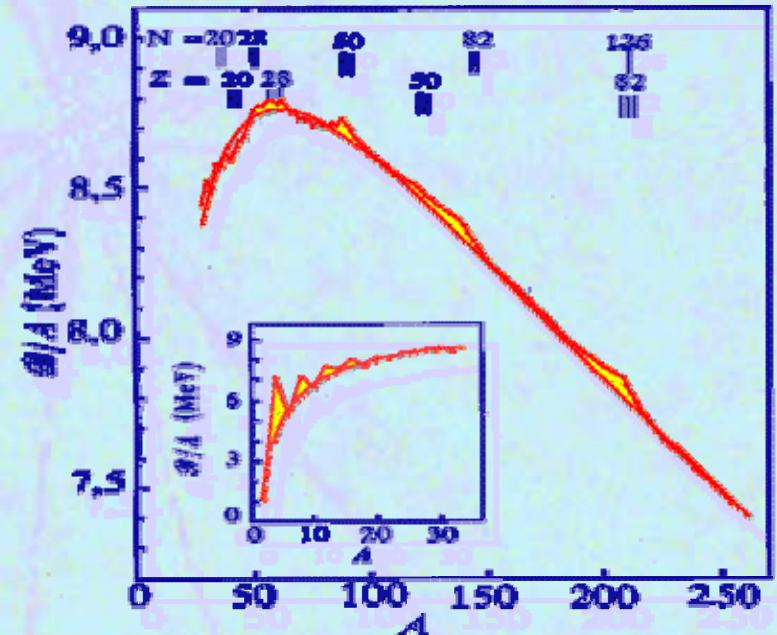
- V -

Magic Numbers

Goeppert-Mayer



v Striking regularities



- V -

Magic Numbers

Goeppert-Mayer

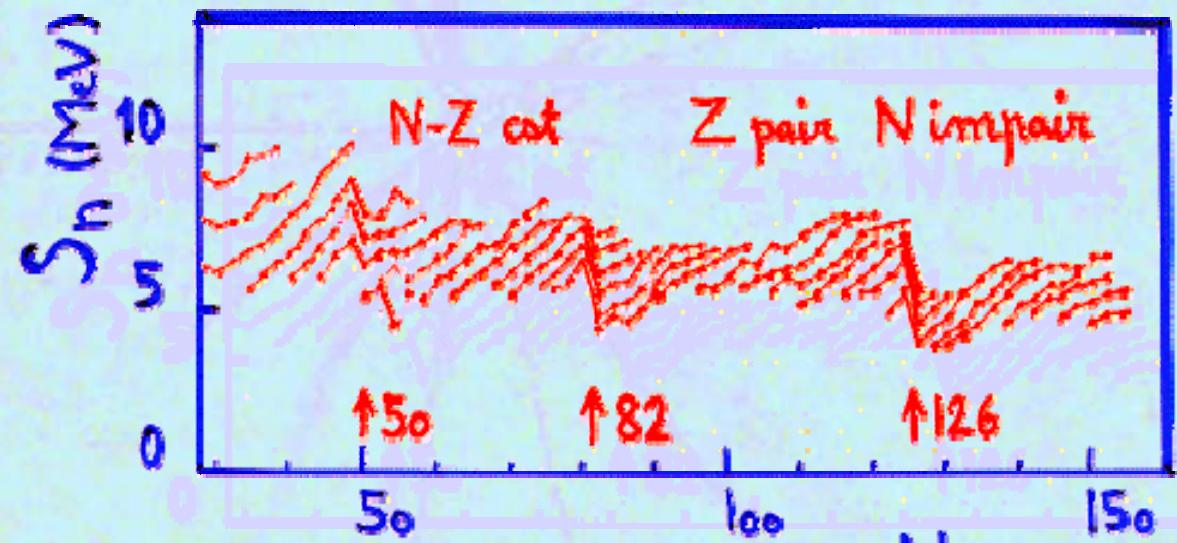


v Striking regularities

- V -

Magic Numbers

Goeppert-Mayer

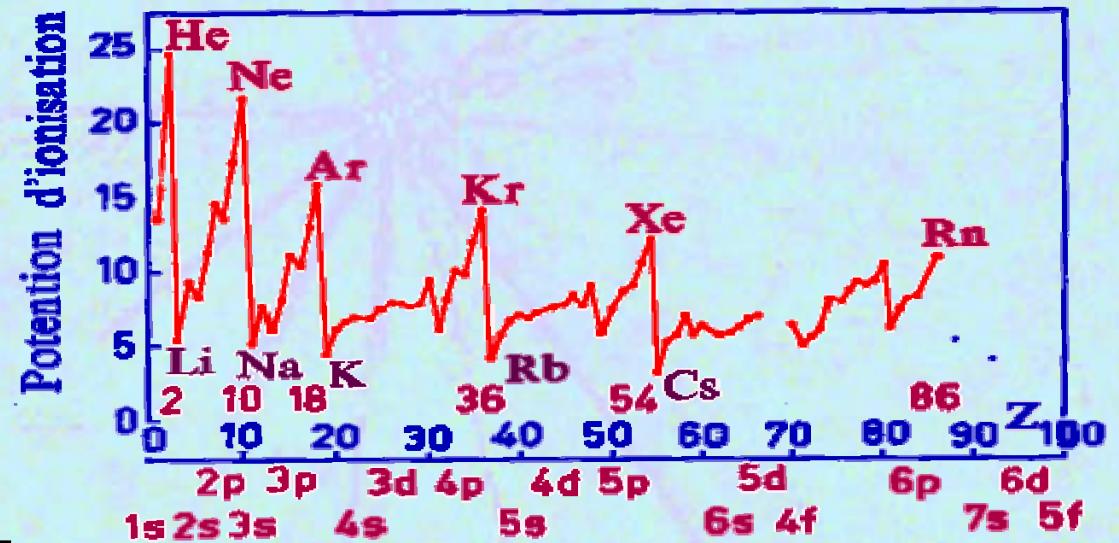


v Striking regularities

- V -

Magic Numbers

Goeppert-Mayer



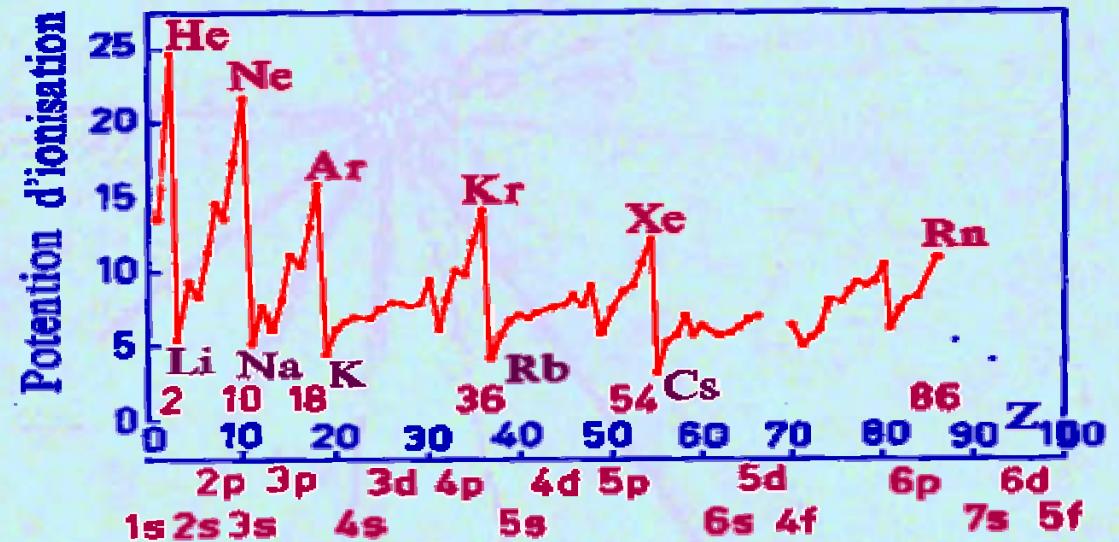
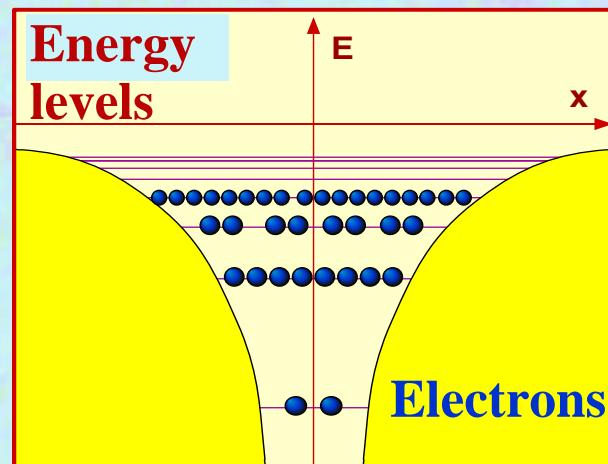
v Cf Atomic shells

- V -

Magic Numbers

Quantum order

Goeppert-Mayer

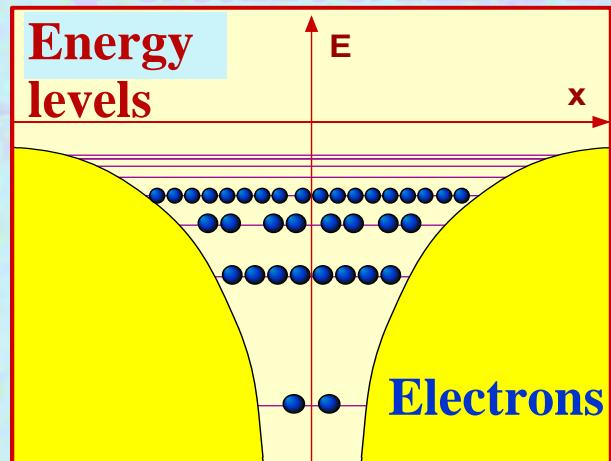


v Atomic shells

- V -

Magic Numbers

Quantum order



v Atomic shells

Goeppert-Mayer

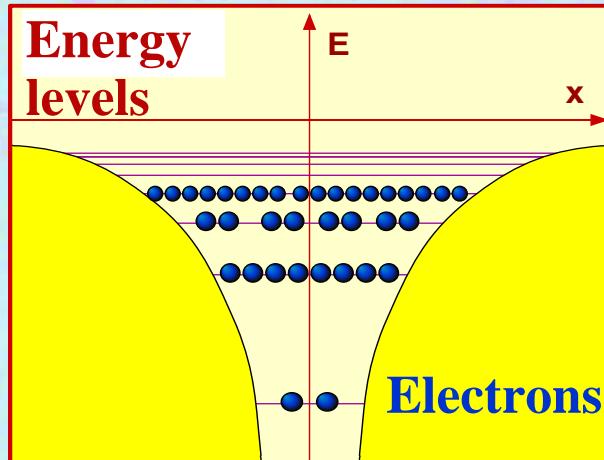


13

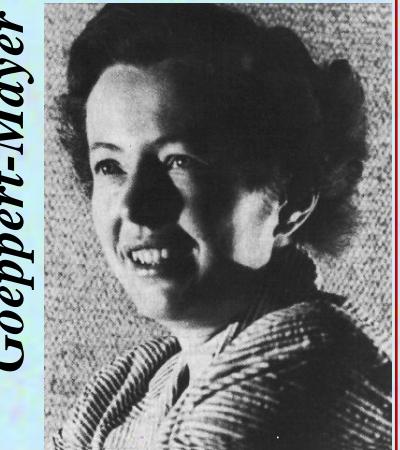
- V -

Magic Numbers

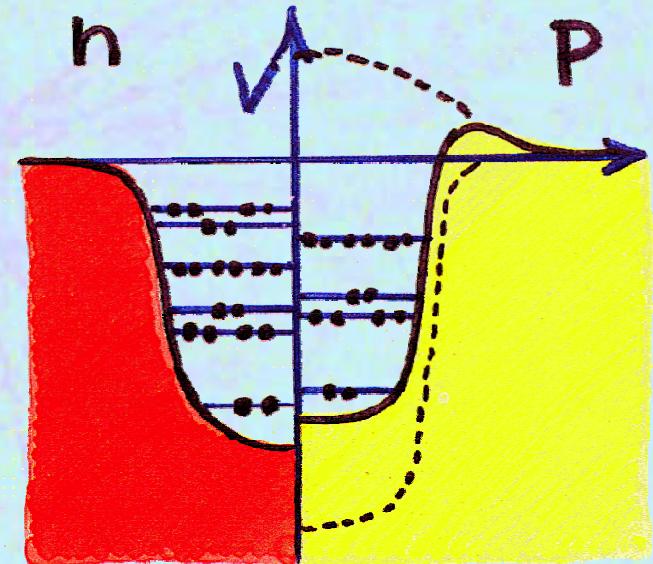
Quantum order



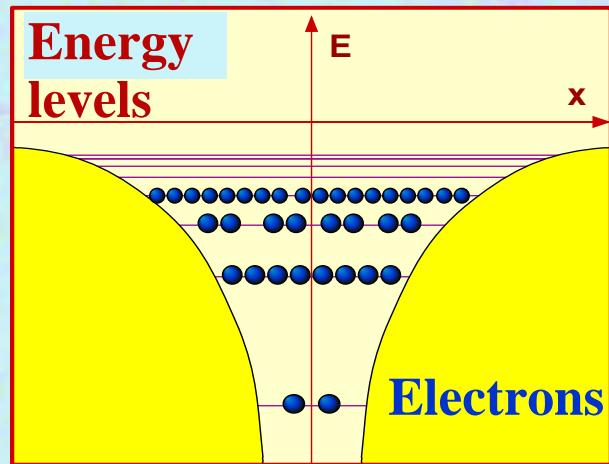
v Atomic shells



Goepert-Mayer

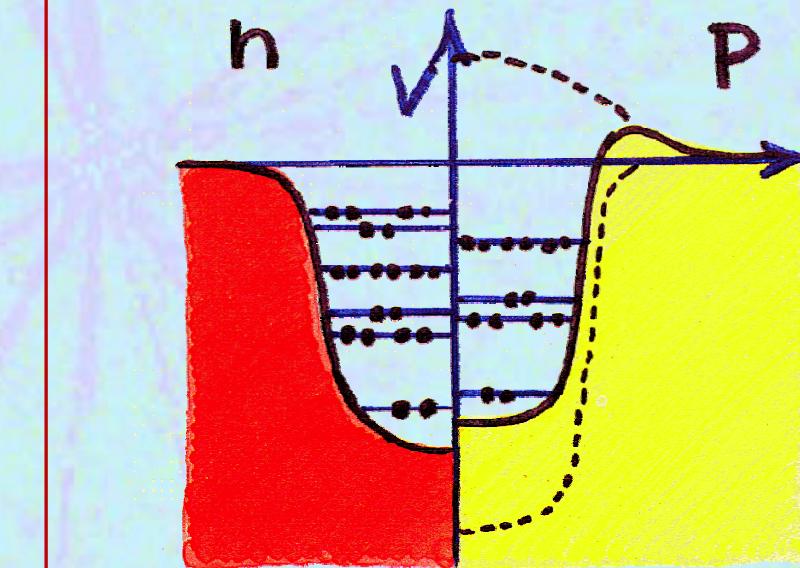


v Nuclear shells



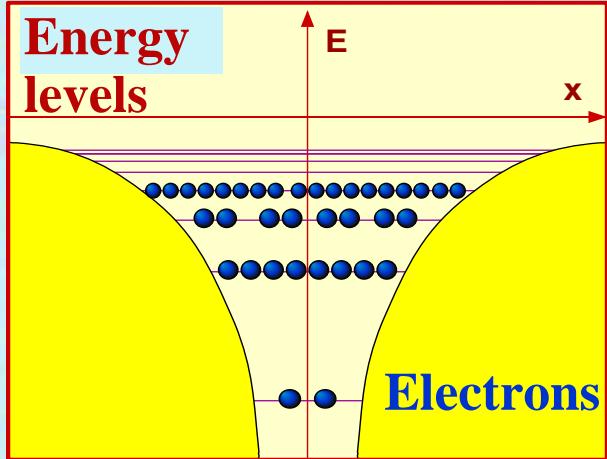
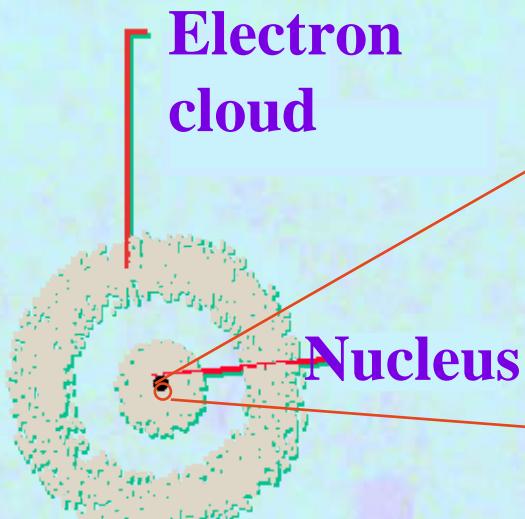
✓ **Atomic shells**

École du CERN, 2006.

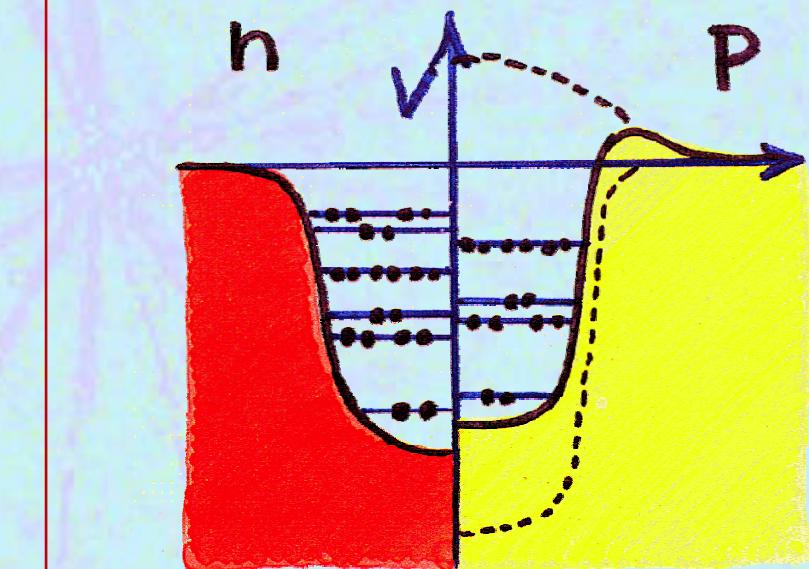
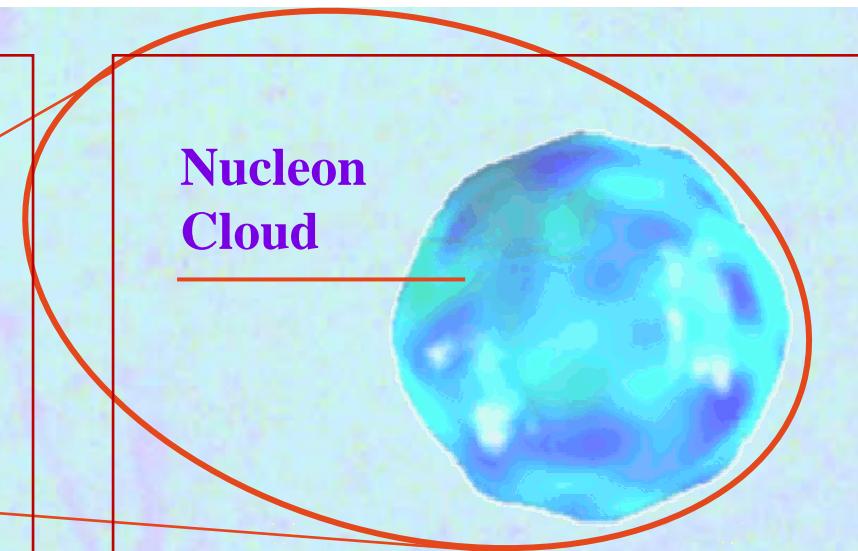


✓ **Nuclear shells**

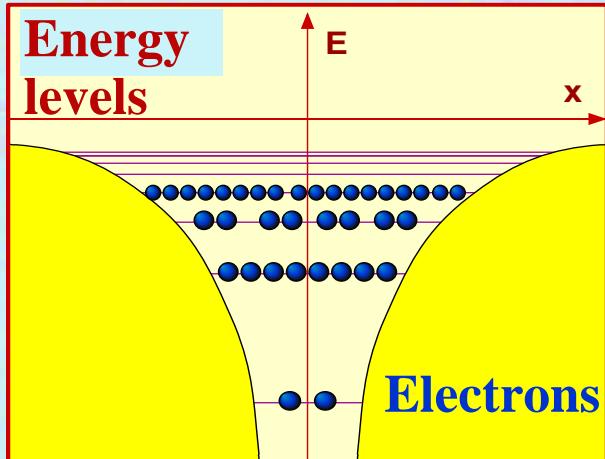
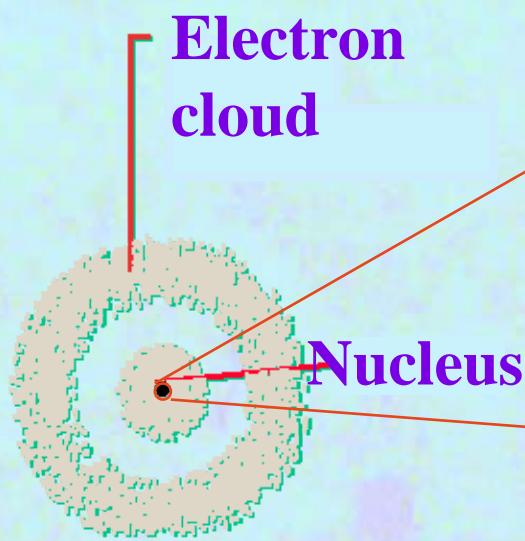
Play



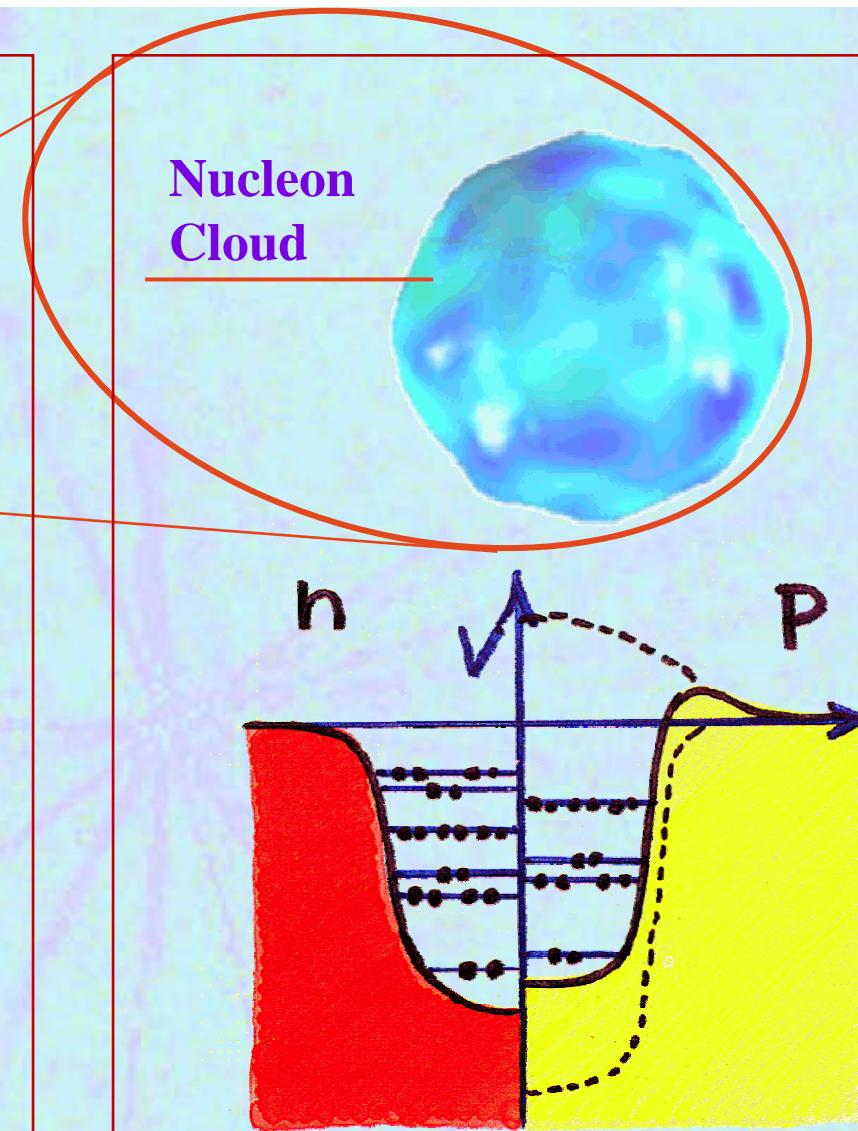
✓ **Atomic shells**



✓ **Nuclear shells**

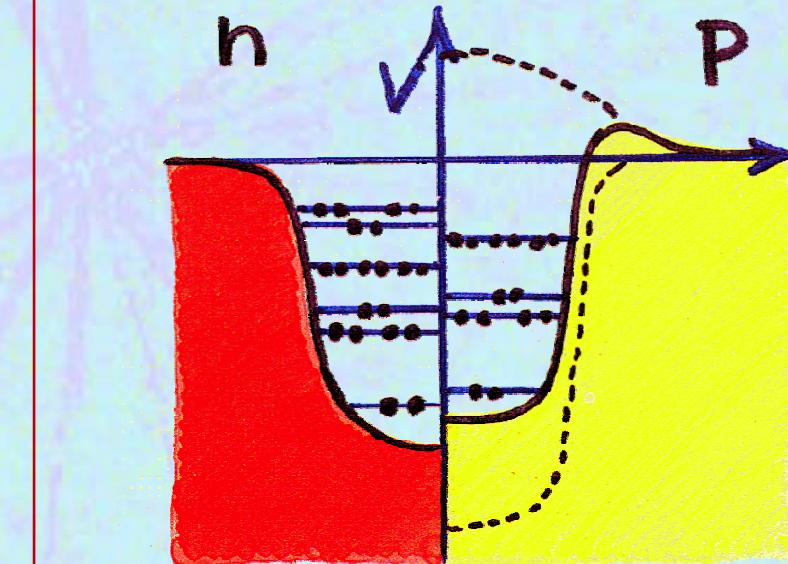
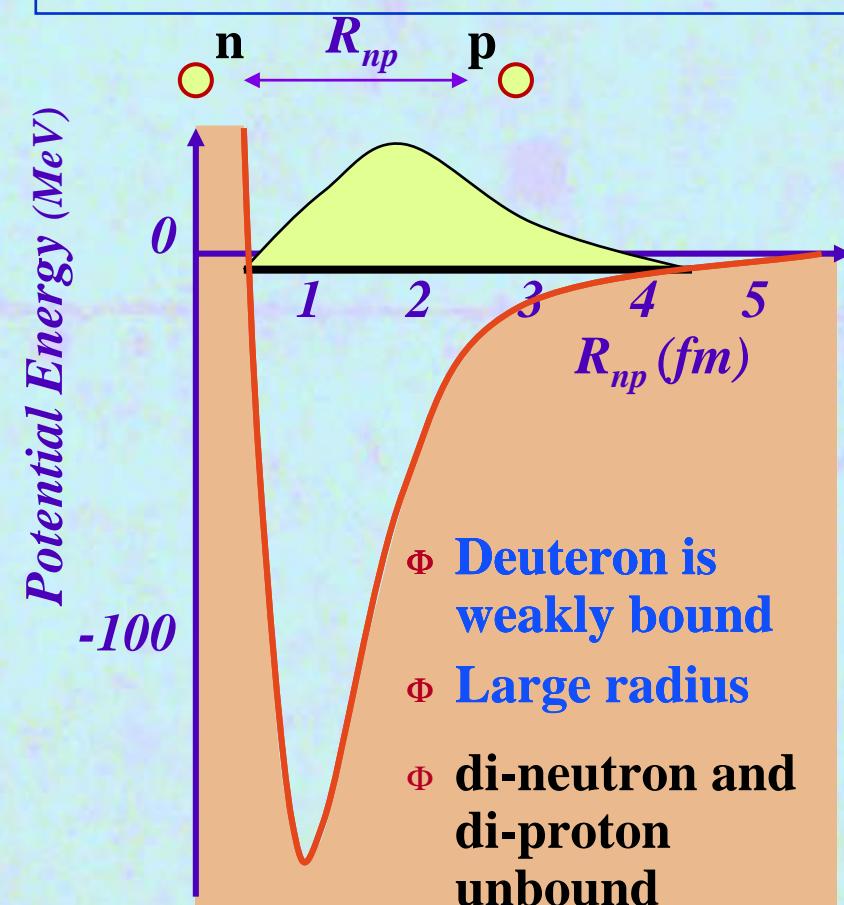


v Electrons organized by the atomic nucleus



v Nucleons are self-organized in nuclei

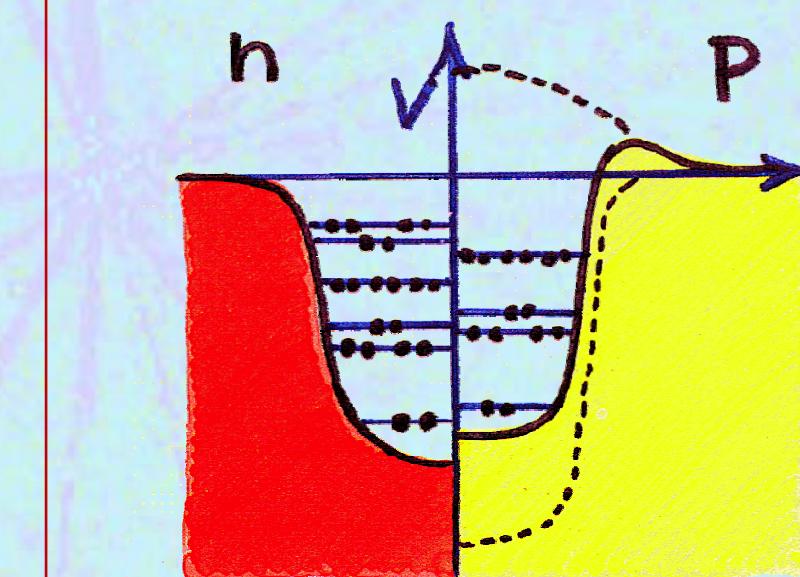
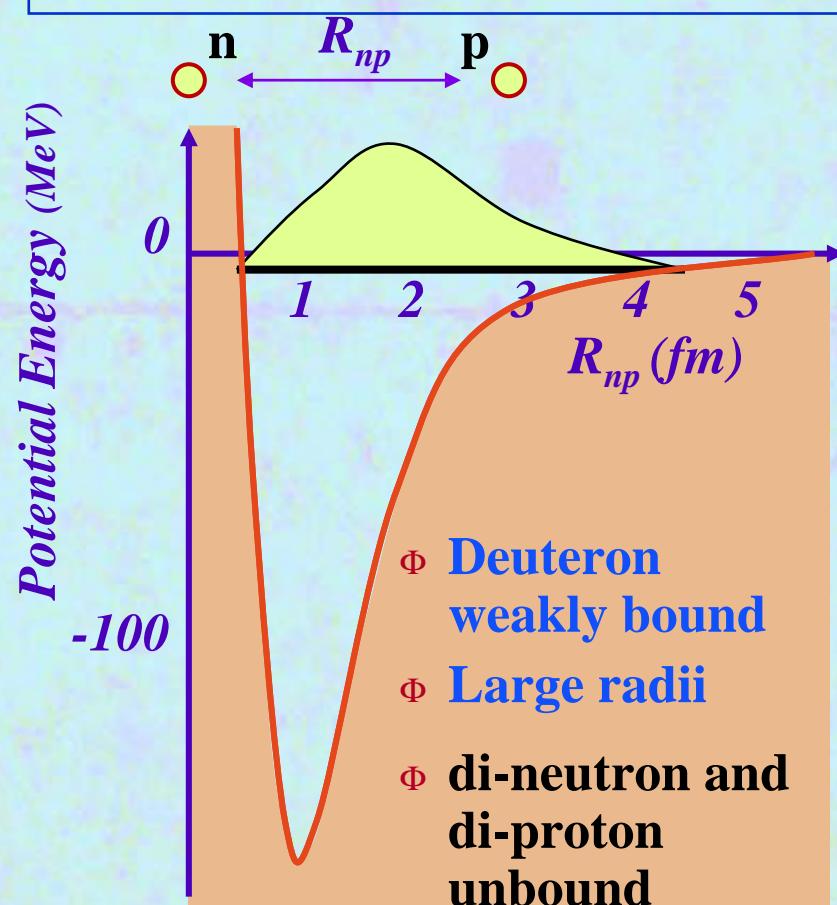
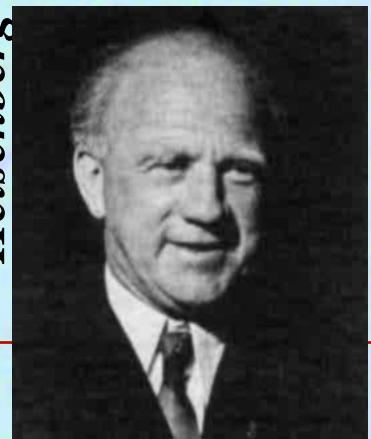
▼ To understand, let us look at the nucleon-nucleon interaction:



▼ Nucleons are self-organized in nuclei

Uncertainty principle: $\Delta x \Delta p \geq \hbar$
 imposes delocalized nucleons
 occupying all the nucleus

Heisenberg

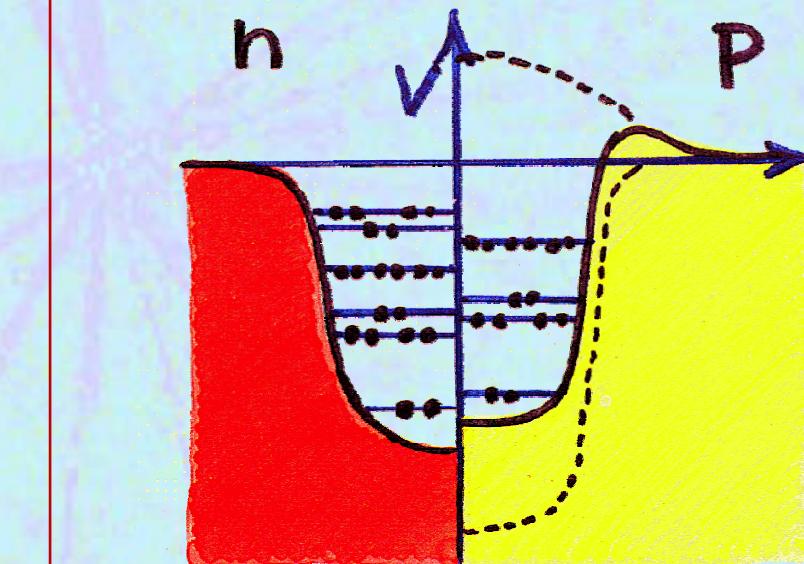


Nucleons are self-organized in nuclei

v Measuring waves
Φ Scattering of particles



v Many confirmations

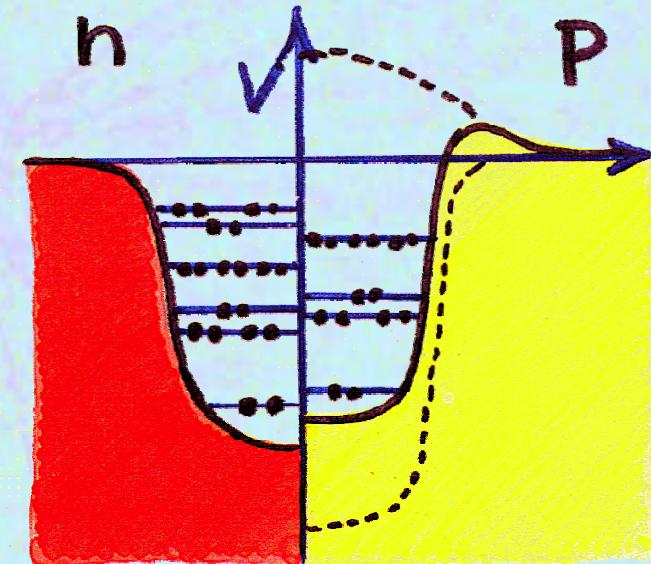


v Nucleons are self-organized in nuclei

v Measuring waves Φ Scattering of particles

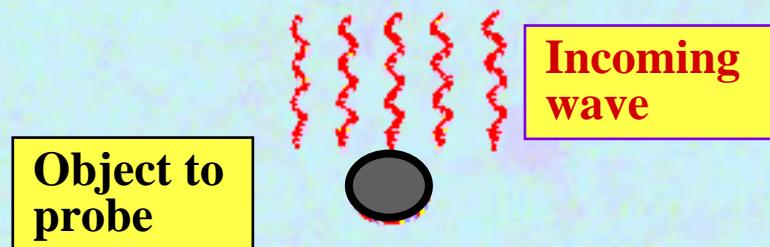


v Many confirmations

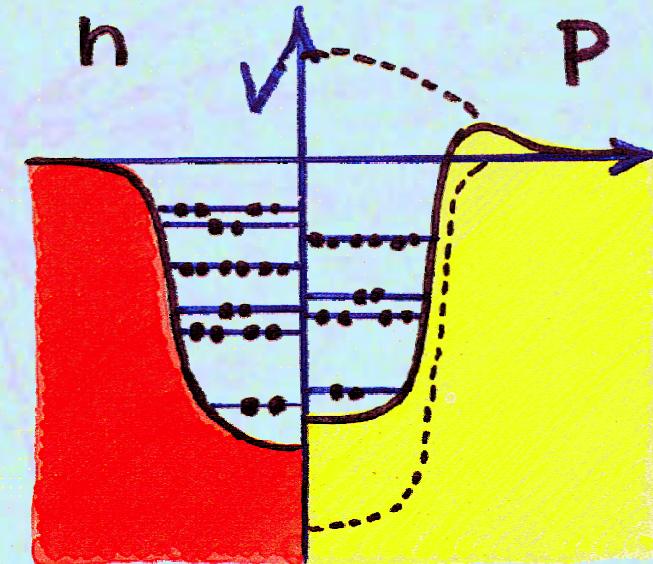


v Nucleons are self-organized in nuclei

v Measuring waves Φ Scattering of particles



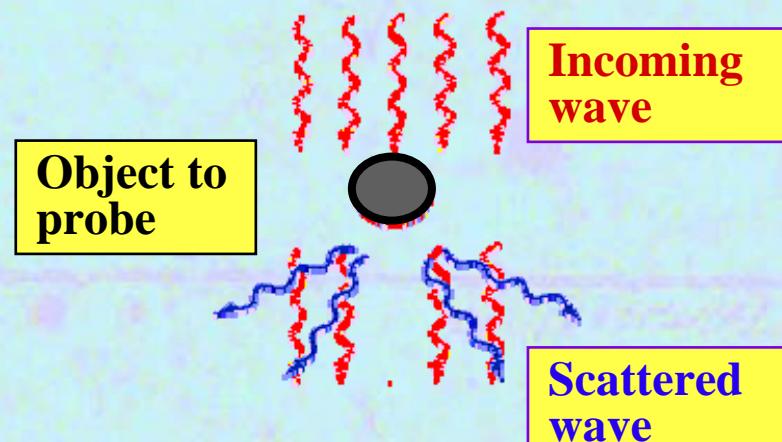
v Many confirmations



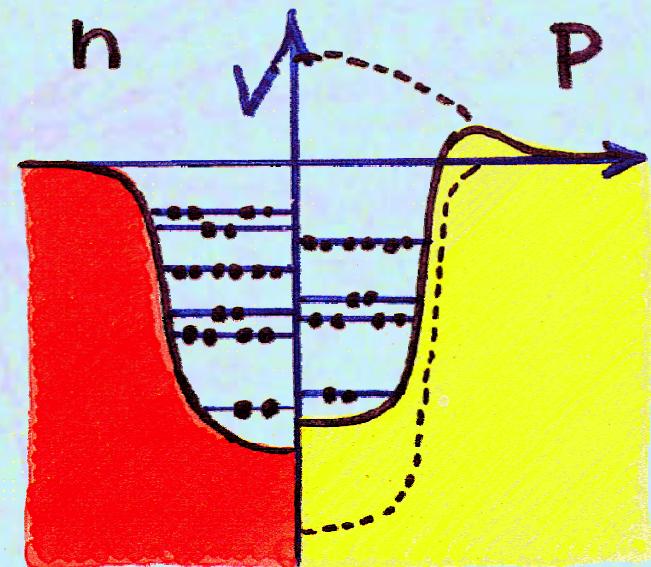
v Nucleons are self-organized in nuclei

Play

v Measuring waves Φ Scattering of particles

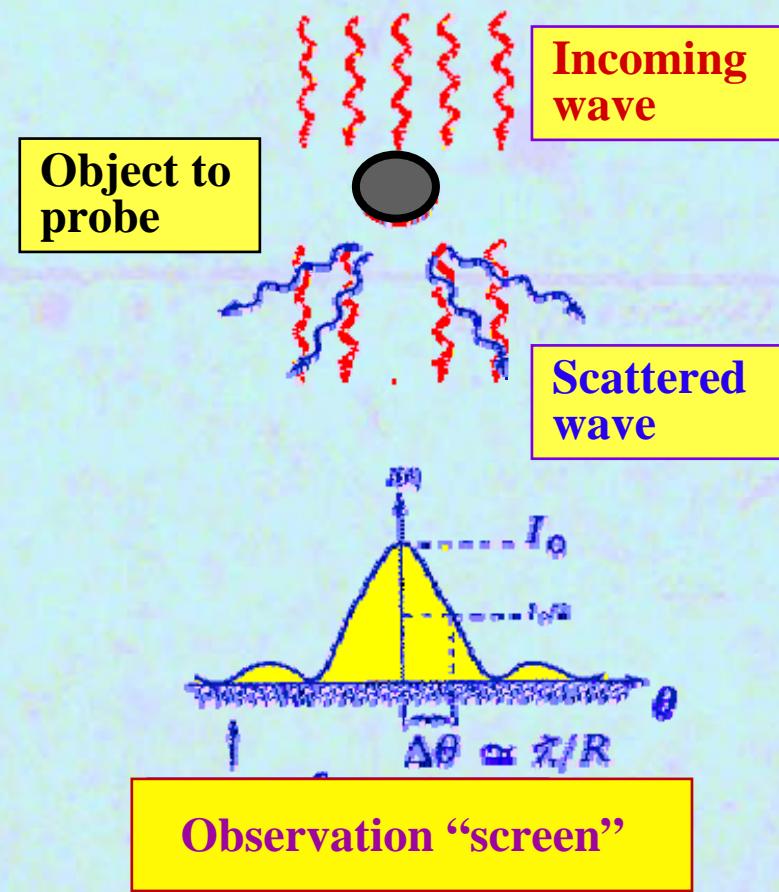


v Many confirmations

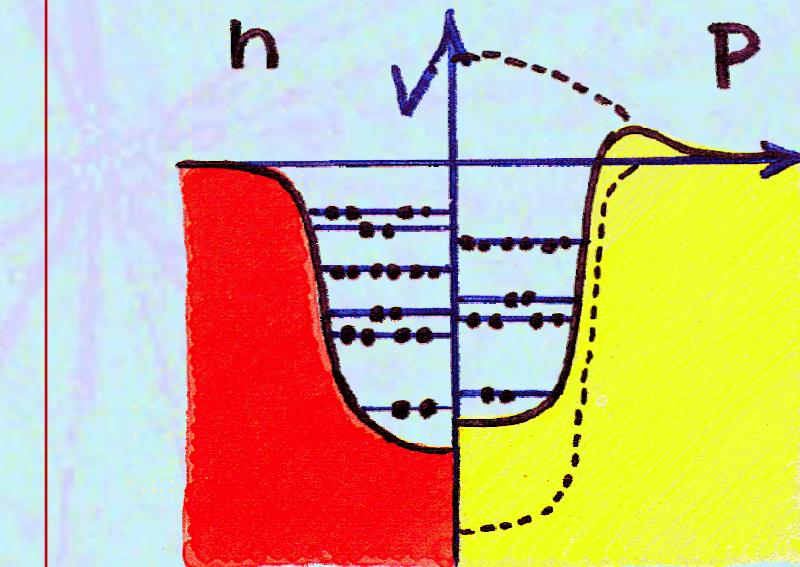


v Nucleons are self-organized in nuclei

v Measuring waves Φ Scattering of particles



v Many confirmations

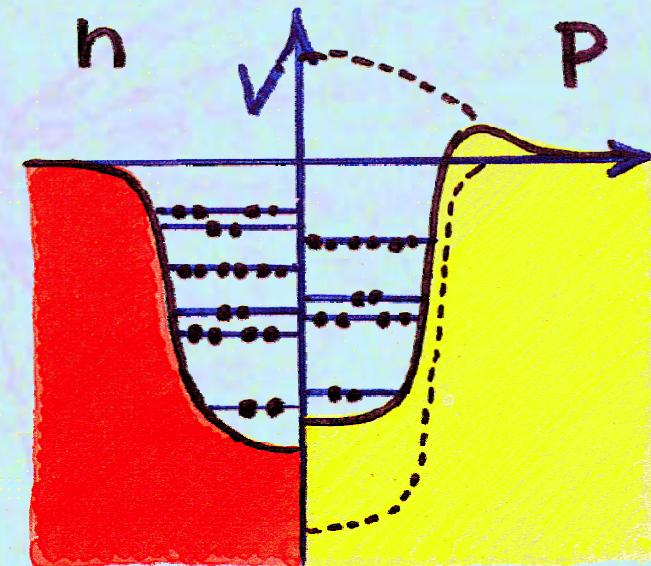


v Nucleons are self-organized in nuclei

v Measuring waves
Φ Scattering of particles



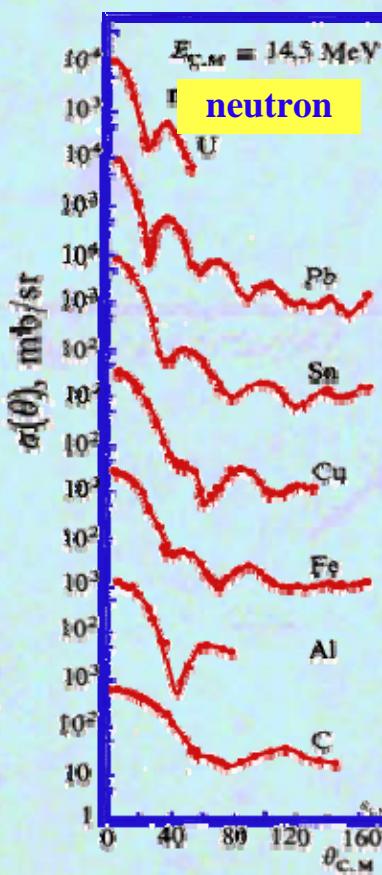
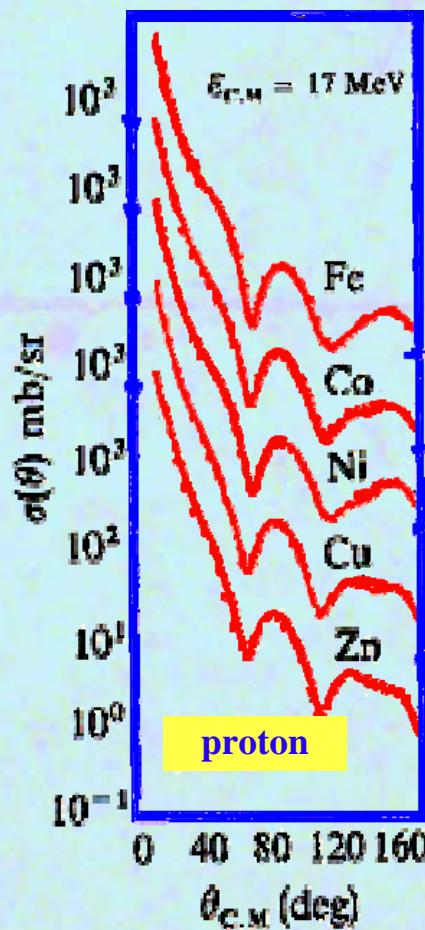
v Many confirmations



v Nucleons are self-organized in nuclei

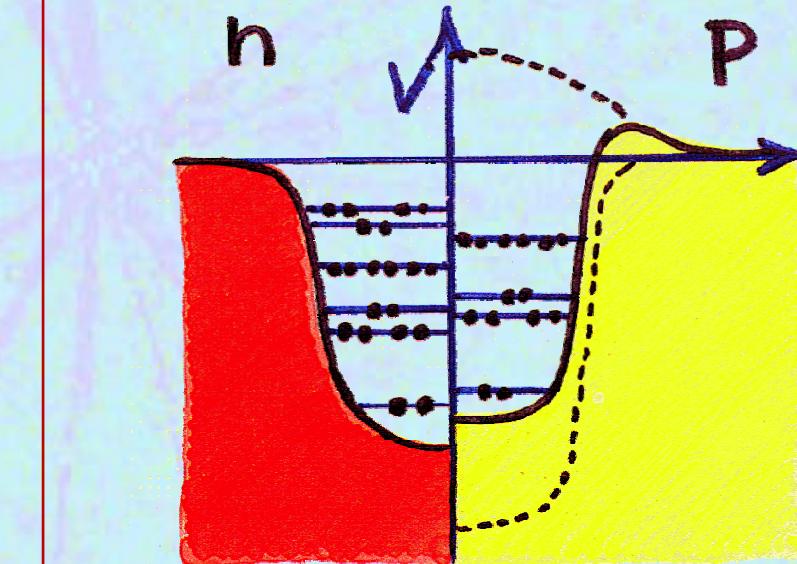
v Measuring waves

Φ Scattering of particles



École du CERN, 2006.

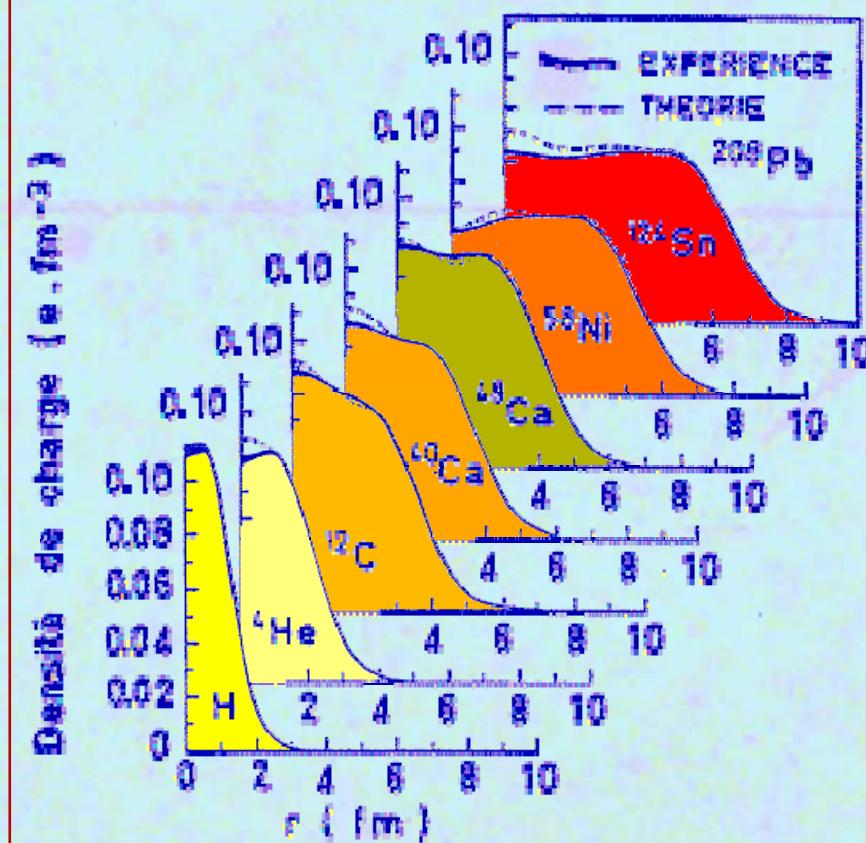
v Many confirmations



v Nucleons are self-organized in nuclei

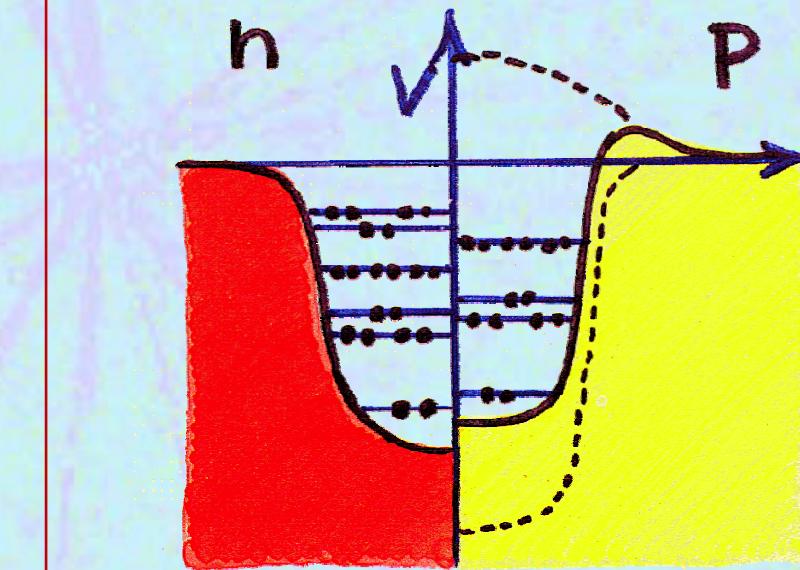
Play

v Measuring waves Φ Scattering of particles



École du CERN, 2006.

v Many confirmations

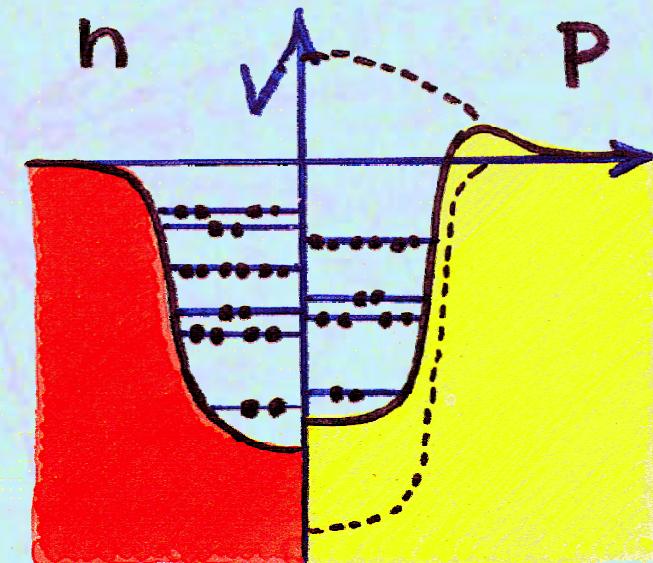


v Nucleons are self-organized in nuclei

Play

v Measuring waves
Φ Scattering of particles

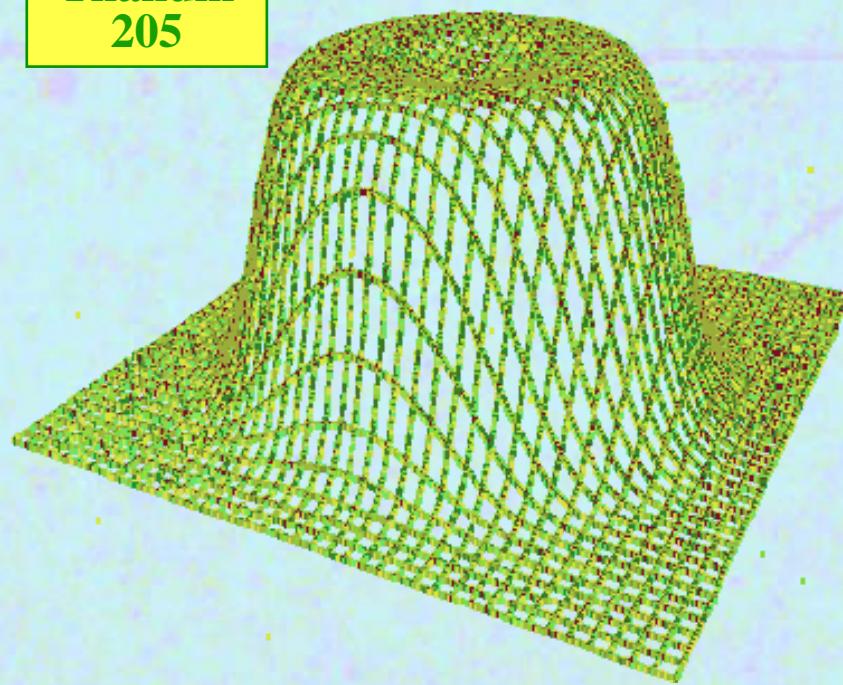
v Many confirmations



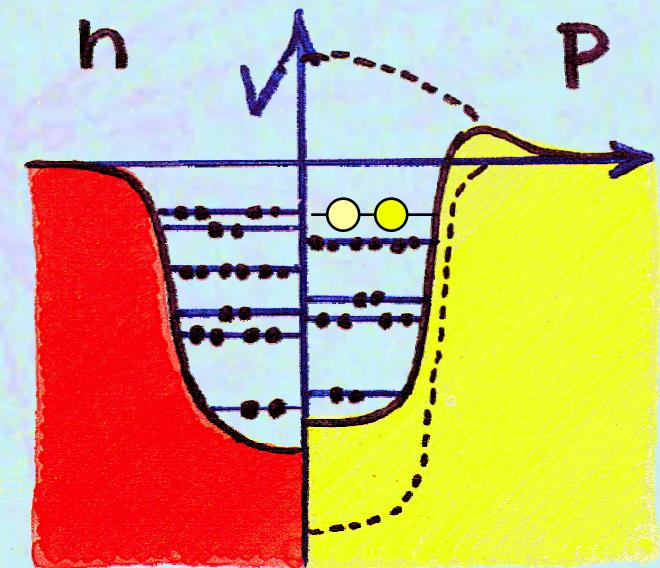
v Nucleons are self-organized in nuclei

✓ Measuring waves
Φ Scattering of particles

Thalium
205

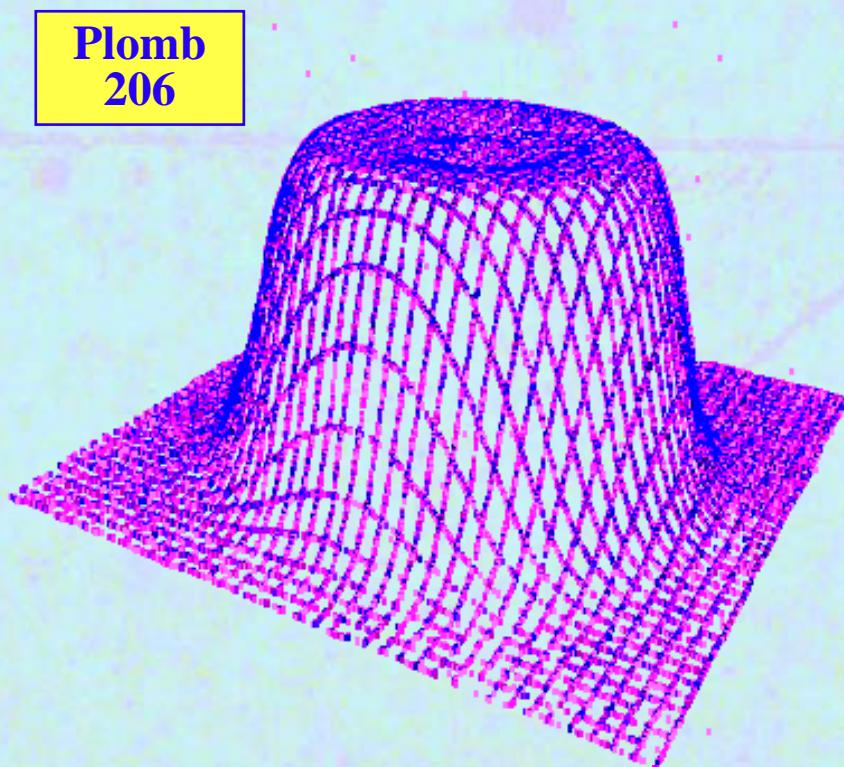


✓ Many confirmations

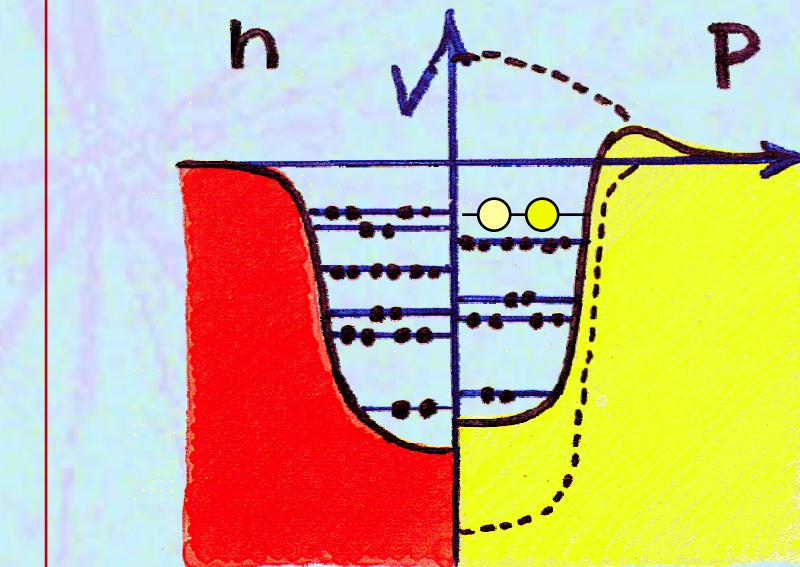


✓ Nucleons are self-organized in nuclei

✓ Measuring waves
Φ Scattering of particles



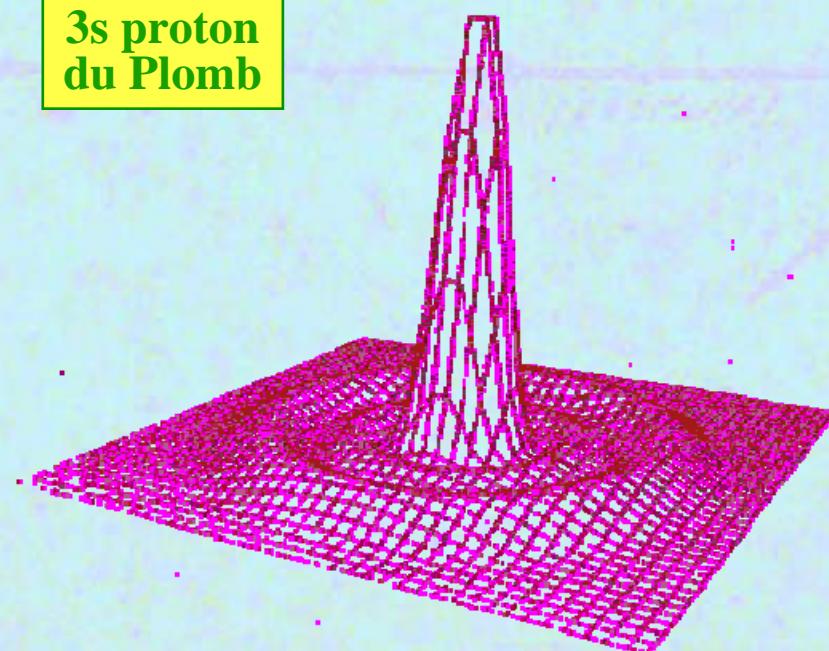
✓ Many confirmations



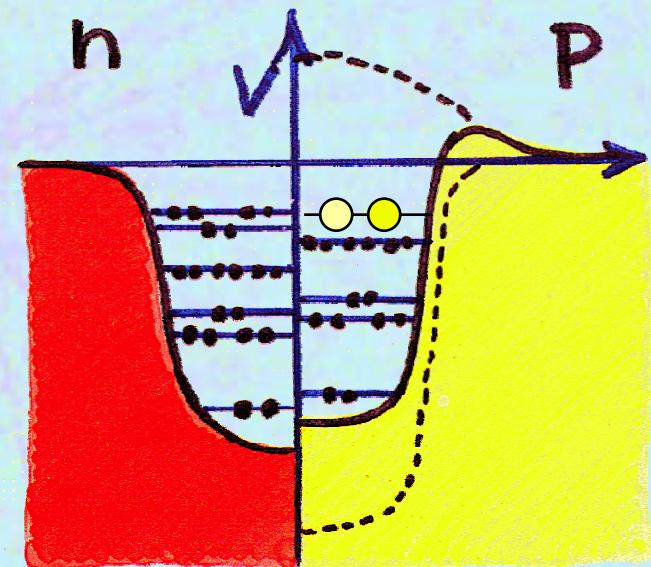
✓ Nucleons are self-organized in nuclei

✓ Measuring waves
Φ Scattering of particles

Orbitale
3s proton
du Plomb



✓ Many confirmations



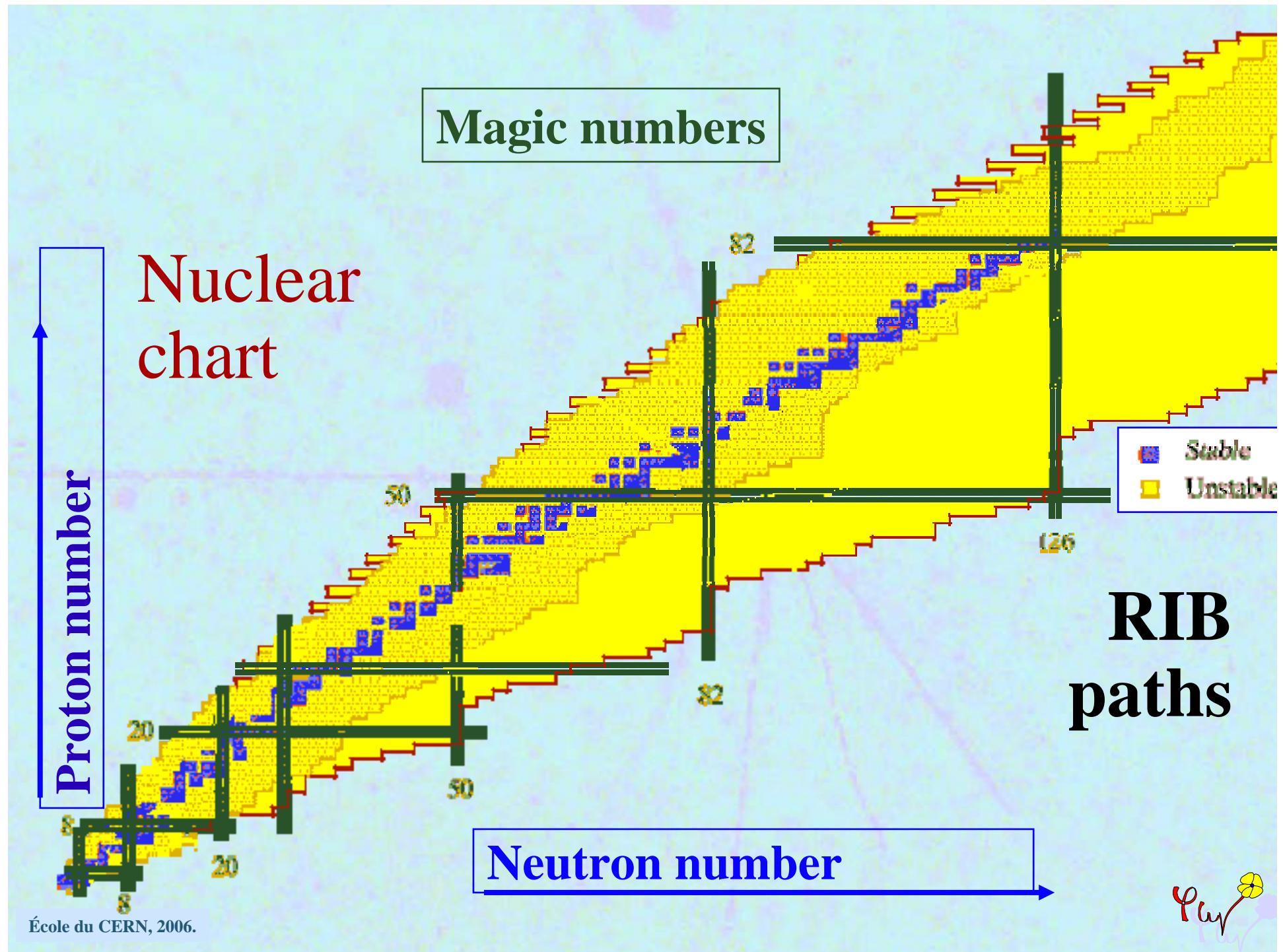
✓ Nucleons are self-organized in nuclei

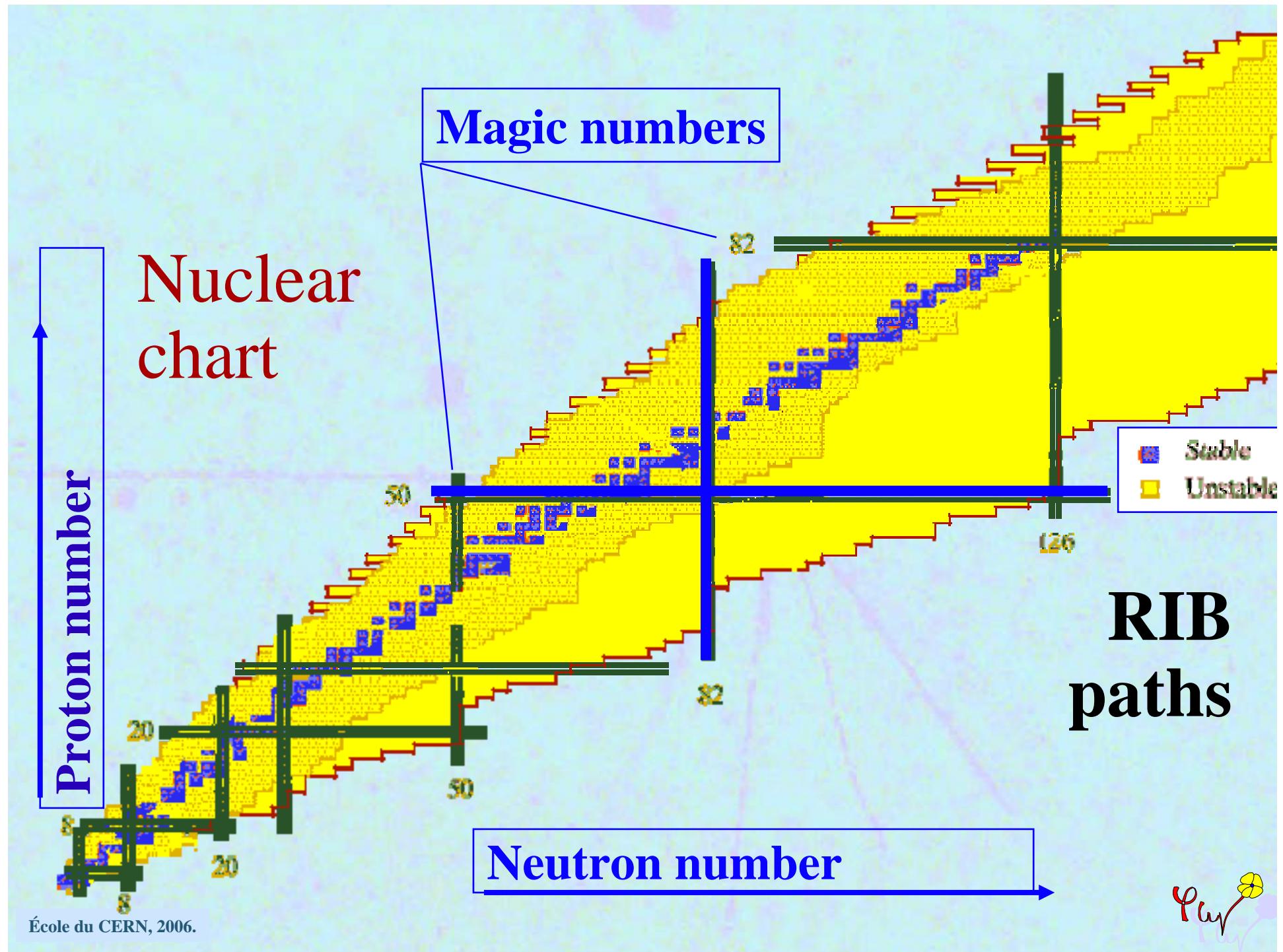
Proton number

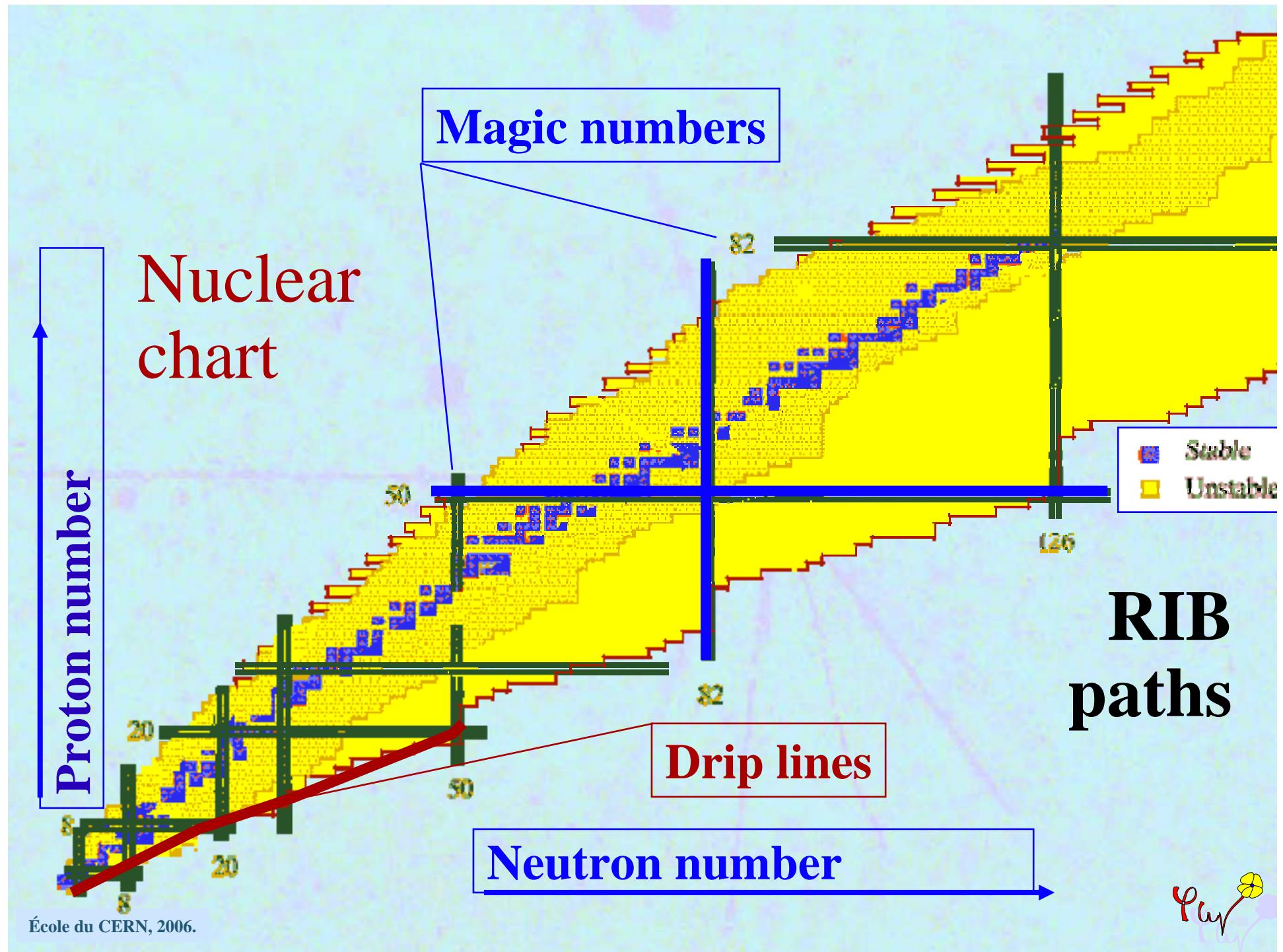
Nuclear chart

Neutron number









21

Nuclear chart

Proton number

$N=Z$

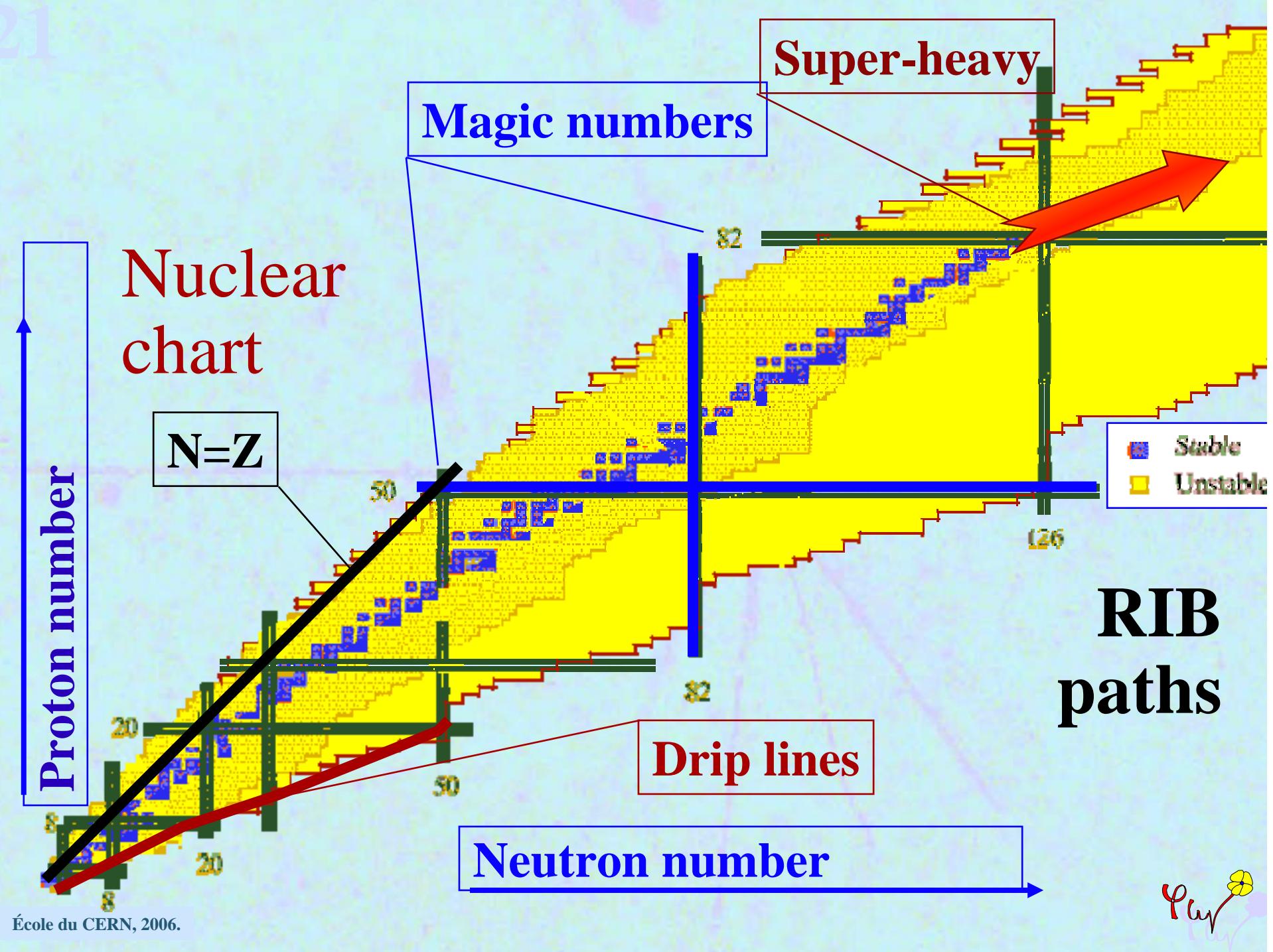
Magic numbers

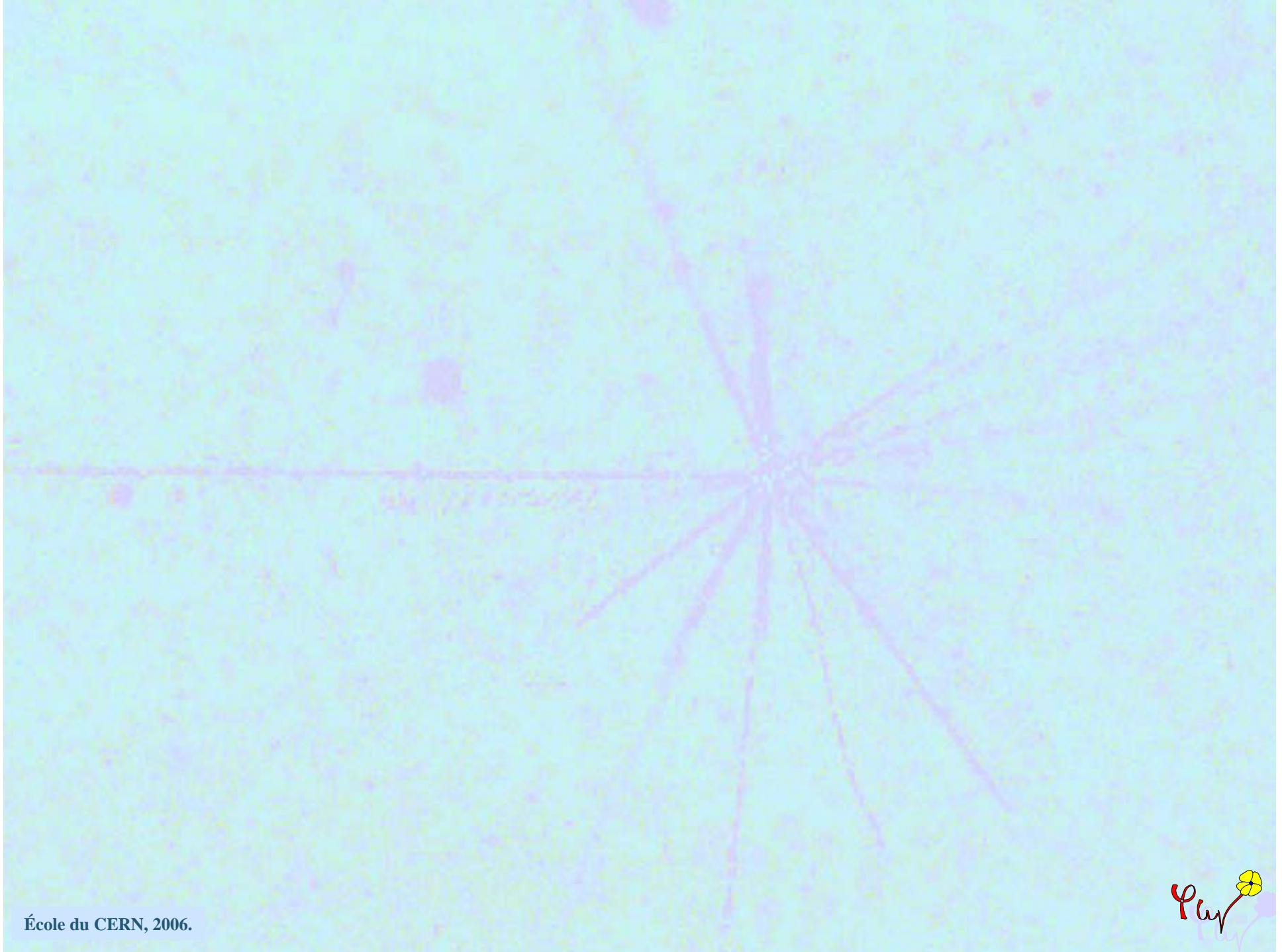
Super-heavy

Drip lines

Neutron number

RIB paths



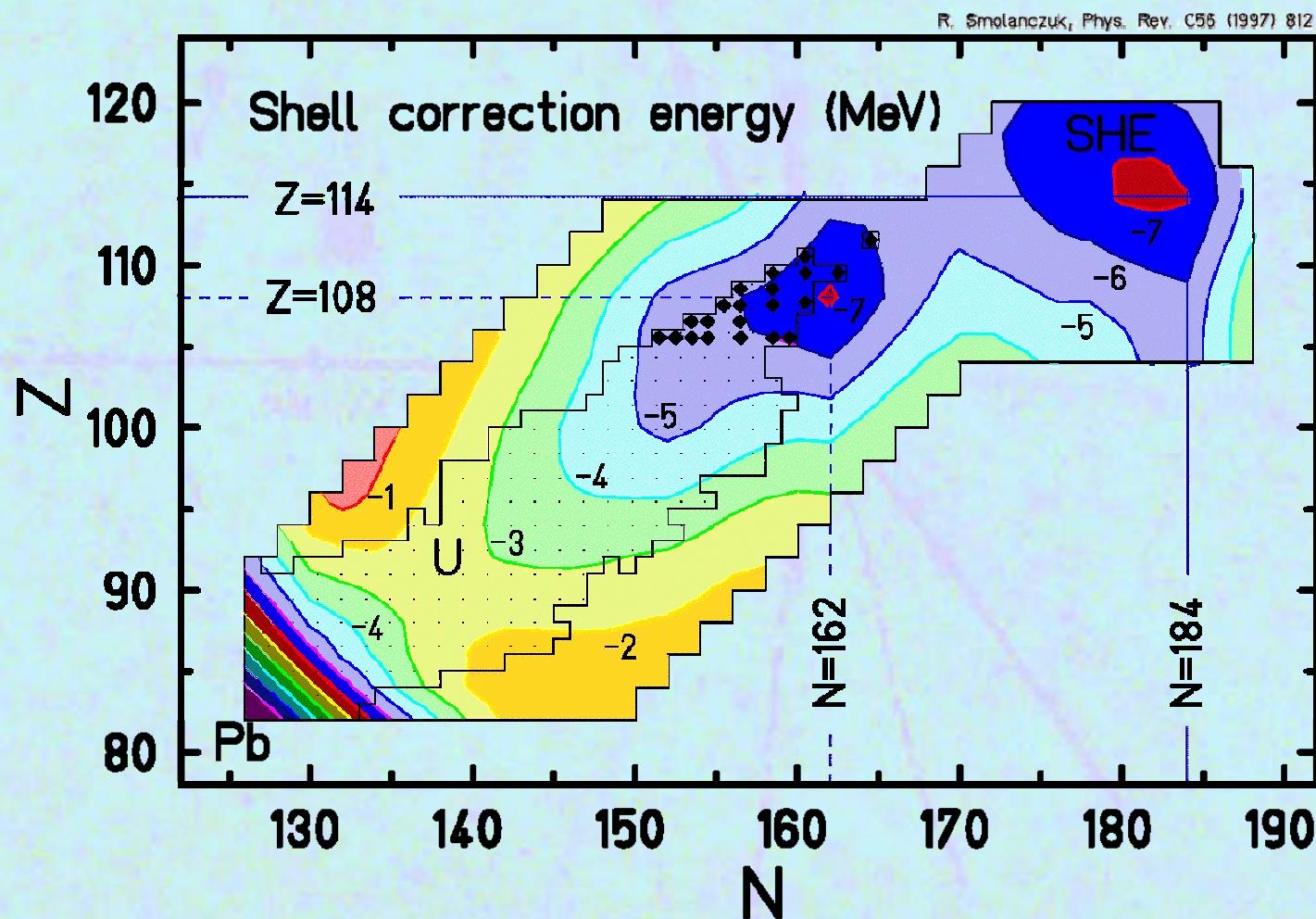


École du CERN, 2006.

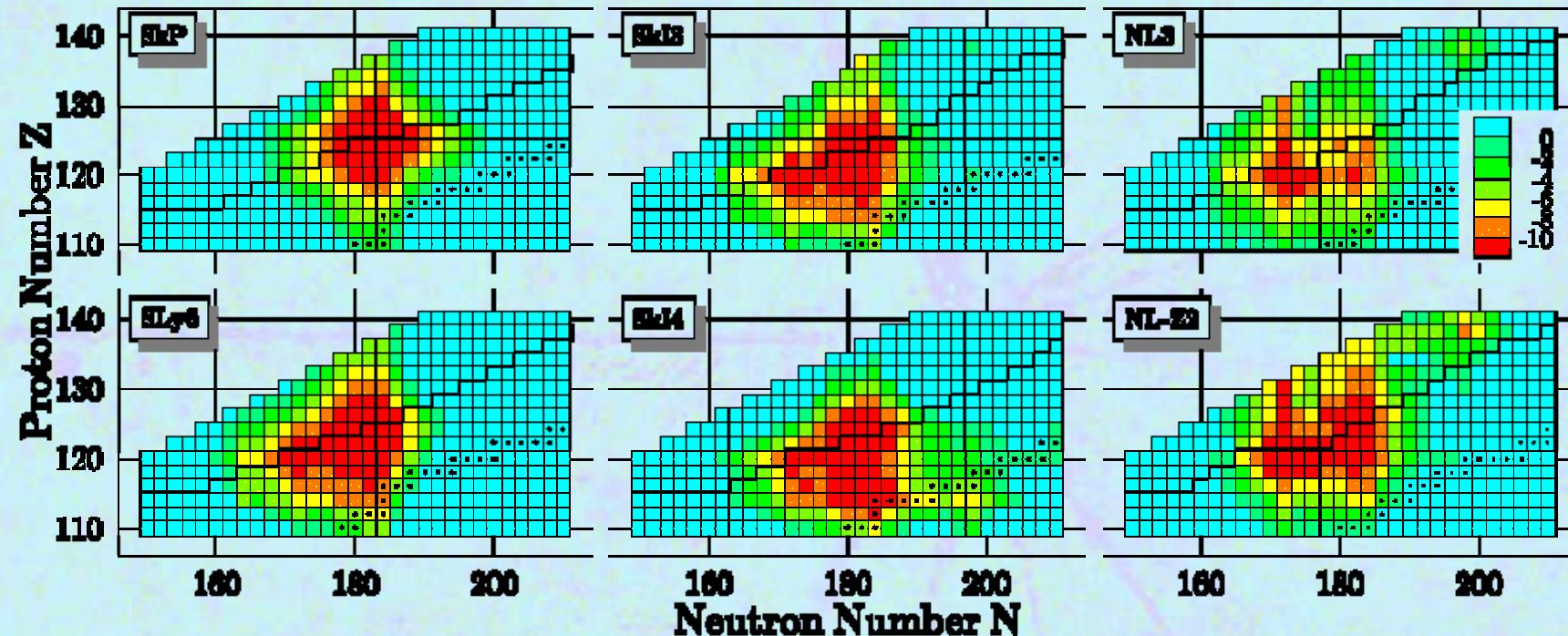
Nuclear shell: Super-heavy



Nuclear shell: Super-heavy



Nuclear shell: Super-heavy



✓ 114, 120, 126 ? Theories disagree on superheavy magic number.

1 H	2 Be	3 Li	4 Mg	5 Na	6 K	7 Rb	8 Cs	9 Fr	10 Ra	11 Ac ⁺	12 Th	13 Pa	14 U	15 Np	16 Pu	17 Am	18 Cm	19 Bk	20 Cf	21 Es	22 Fm	23 Md	24 No	25 Lr	26 Ho	27 Dy	28 Tb	29 Eu	30 Gd	31 Tb	32 Dy	33 Ho	34 Er	35 Tm	36 Yb	37 Lu	38 He	39 Ne	40 Ar	41 Cl	42 S	43 P	44 As	45 Se	46 Br	47 Kr	48 Xe	49 I	50 Te	51 Sb	52 Sn	53 In	54 Ge	55 Ga	56 As	57 Se	58 Br	59 Kr	60 I	61 Te	62 Po	63 At	64 Rn	65 Po	66 At	67 Rn	68 Fr	69 Ra	70 Ac ⁺	71 Th	72 Pa	73 U	74 Np	75 Pu	76 Am	77 Cm	78 Bk	79 Cf	80 Es	81 Fm	82 Md	83 No	84 Lr	85 Ho	86 Dy	87 Tb	88 Eu	89 Gd	90 Bk	91 Cf	92 Es	93 Fm	94 Md	95 No	96 Lr	97 Ce	98 Pr	99 Nd	100 Pm	101 Sm	102 Eu	103 Gd	104 Bh	105 Hs	106 Mt	107 110	108 111	109 112	110 114	111 116	112 116
--------	---------	---------	---------	---------	--------	---------	---------	---------	----------	-----------------------	----------	----------	---------	----------	----------	----------	----------	----------	----------	----------	----------	----------	----------	----------	----------	----------	----------	----------	----------	----------	----------	----------	----------	----------	----------	----------	----------	----------	----------	----------	---------	---------	----------	----------	----------	----------	----------	---------	----------	----------	----------	----------	----------	----------	----------	----------	----------	----------	---------	----------	----------	----------	----------	----------	----------	----------	----------	----------	-----------------------	----------	----------	---------	----------	----------	----------	----------	----------	----------	----------	----------	----------	----------	----------	----------	----------	----------	----------	----------	----------	----------	----------	----------	----------	----------	----------	----------	----------	----------	-----------	-----------	-----------	-----------	-----------	-----------	-----------	------------	------------	------------	------------	------------	------------

Super-heavy New Elements

+Actinides

Transactinides = Superheavy Elements

* Lanthanides

Ce 58	Pr 59	Nd 60	Pm 61	Sm 62	Eu 63	Gd 64	Tb 65	Dy 66	Ho 67	Er 68	Tm 69	Yb 70	Lu 71
----------	----------	----------	----------	----------	----------	----------	----------	----------	----------	----------	----------	----------	----------

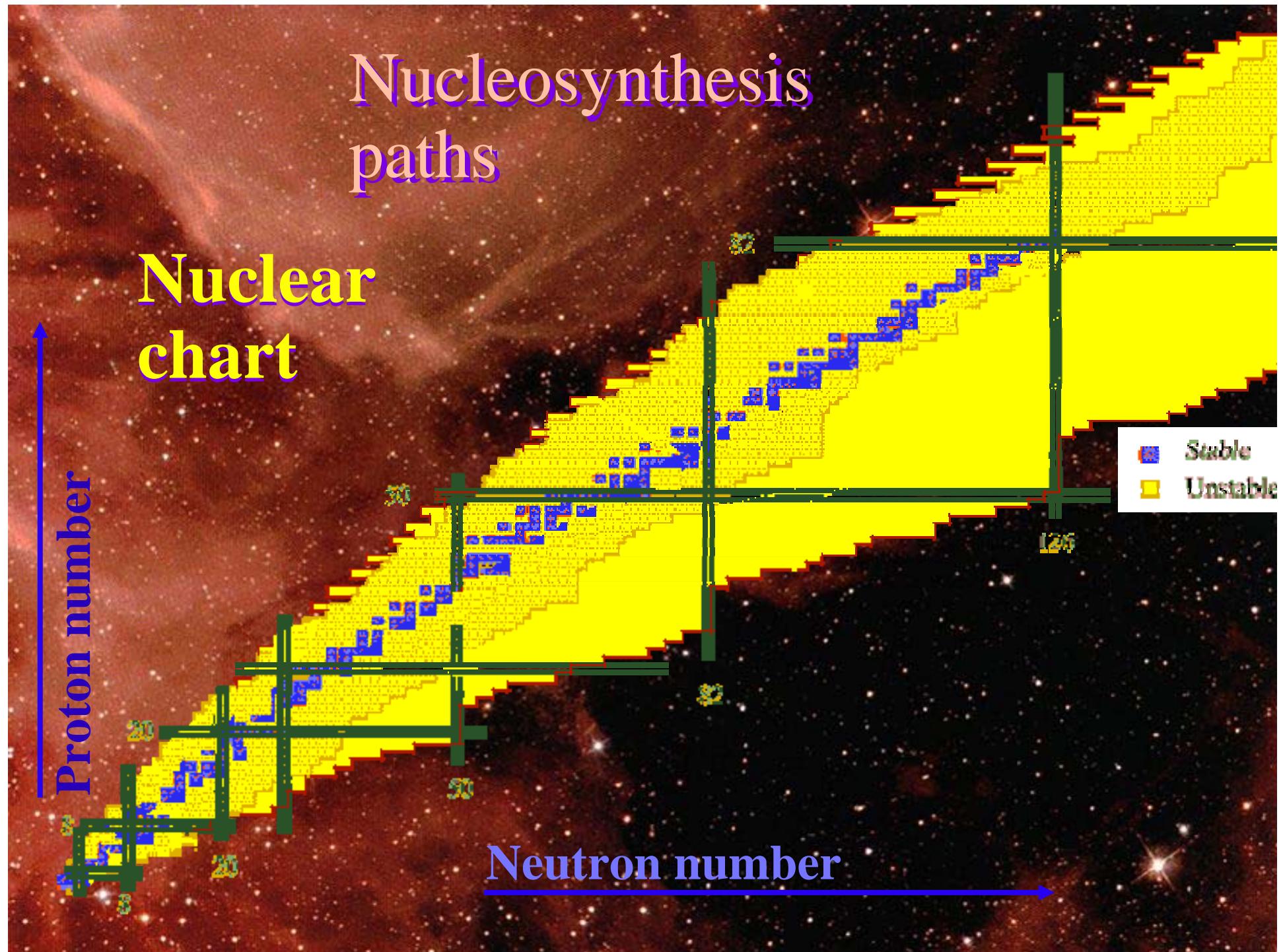


Super-heavy New Elements

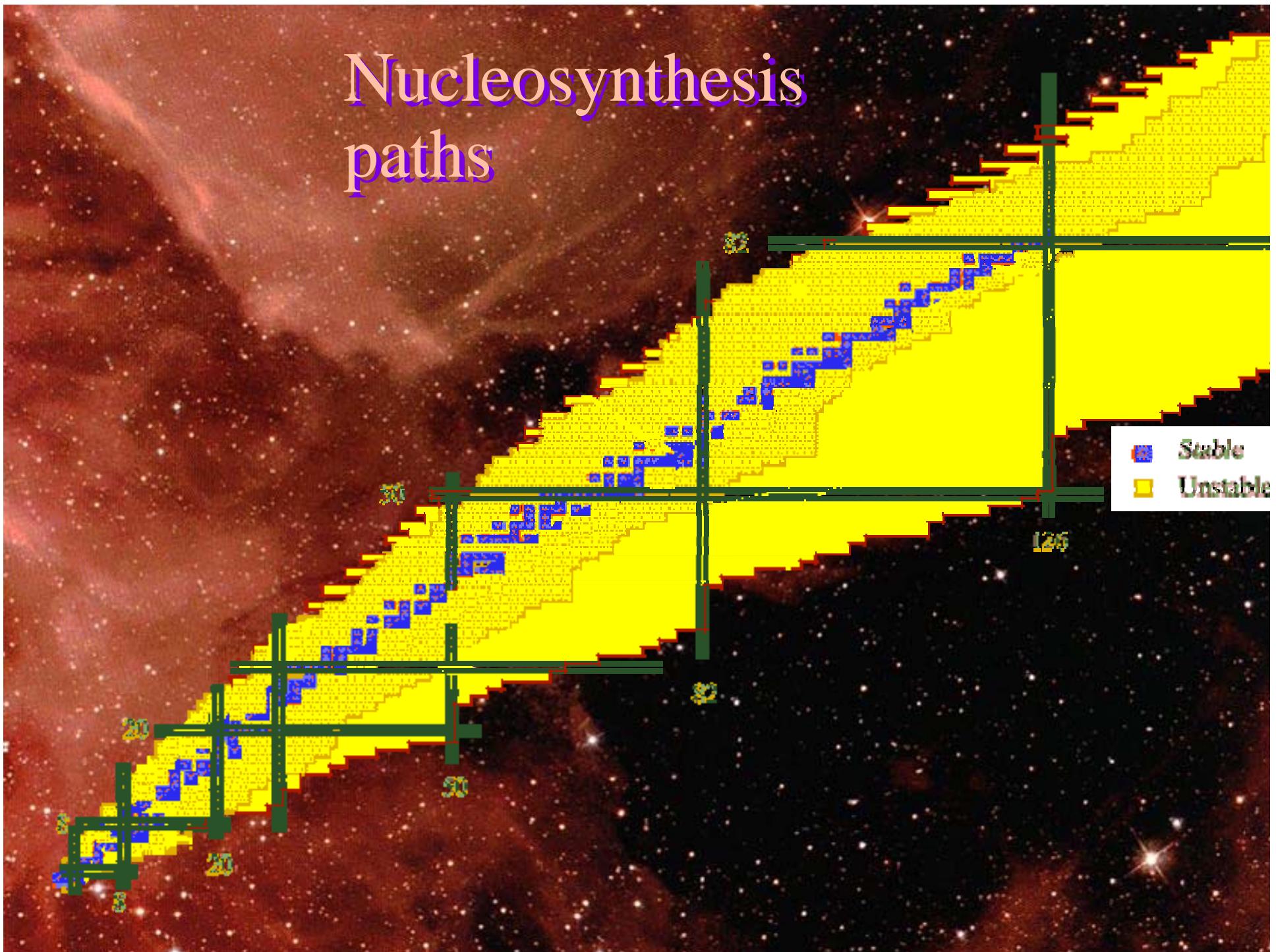
Super-heavy New Elements

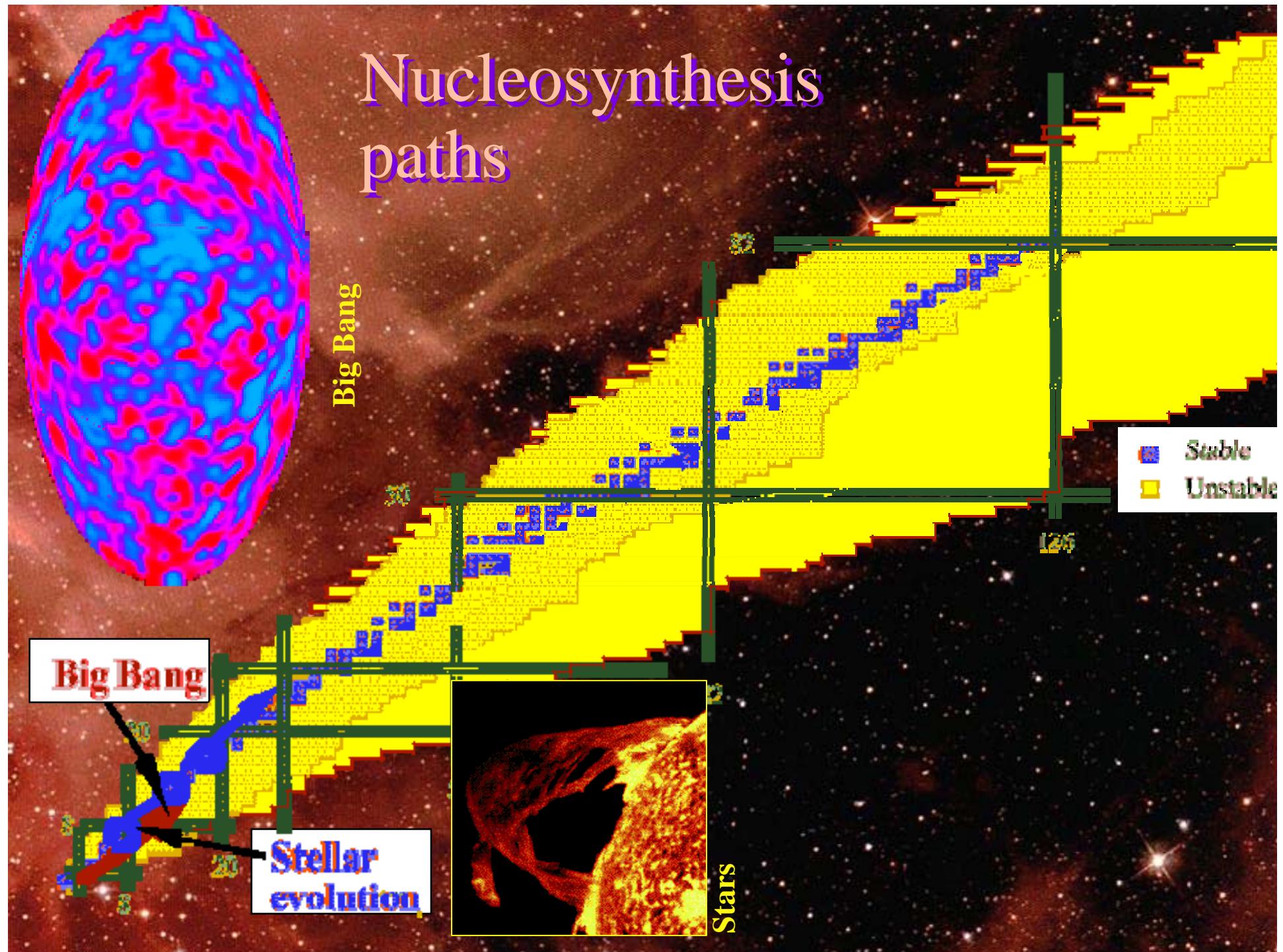
H	He																
Li	Be																
Na	Mg																
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	La*	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Ac ⁺	Rf	Db	Sg	Bh	Hs	Mt	110	111	112	114	116				
Transactinides = Superheavy Elements																	
* Lanthanides	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu			

École du CERN, 2006

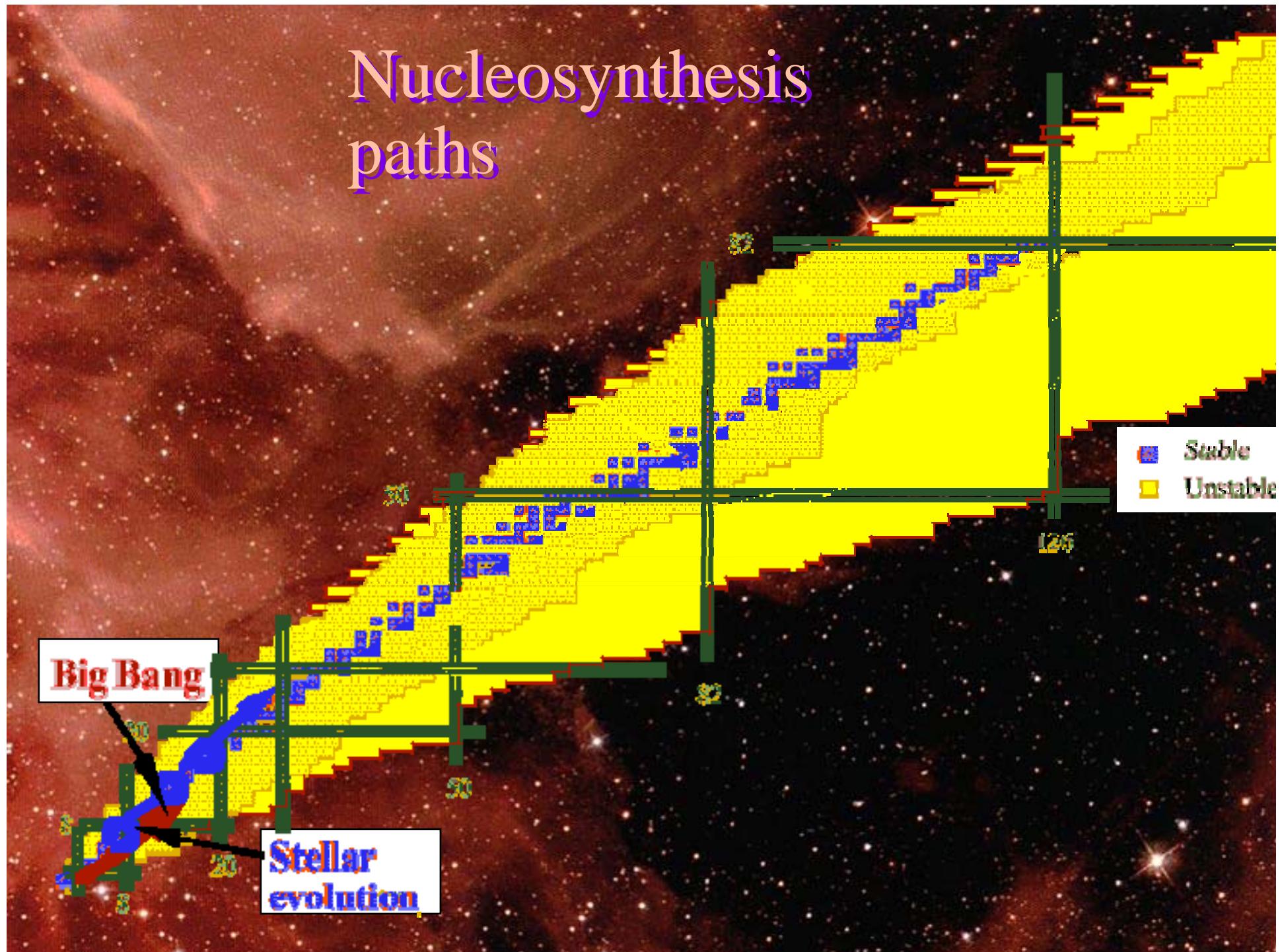


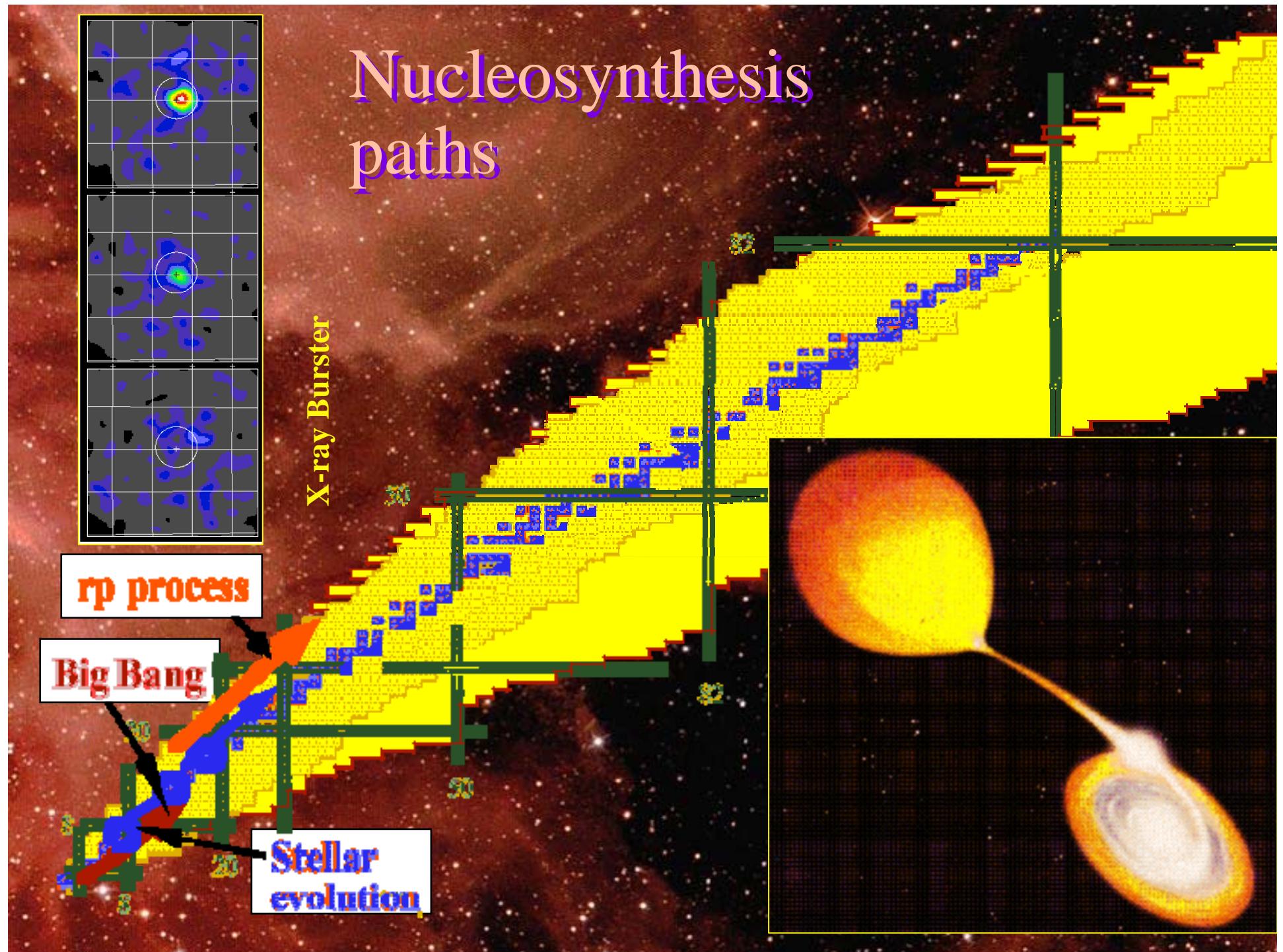
Nucleosynthesis paths



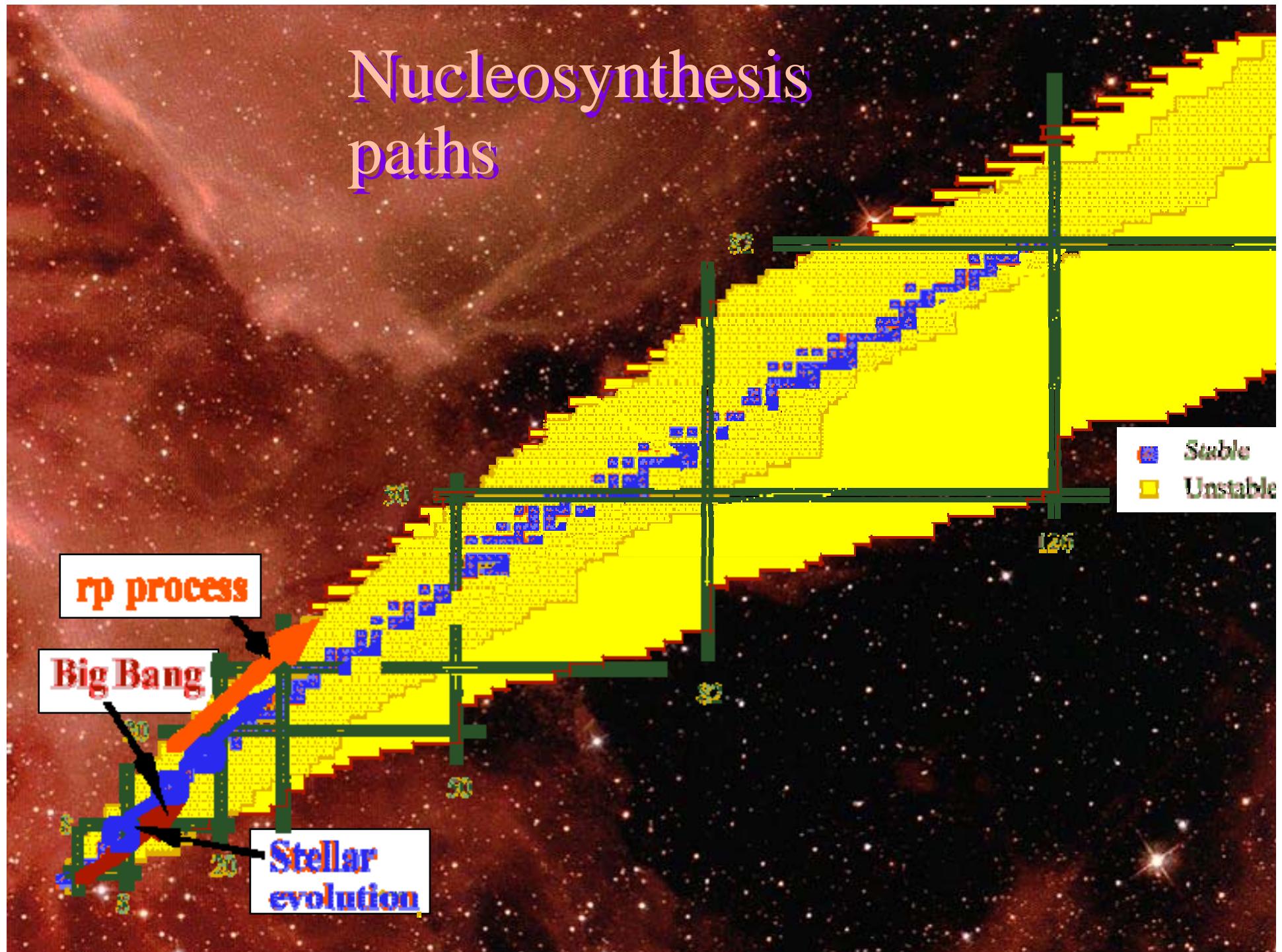


Nucleosynthesis paths

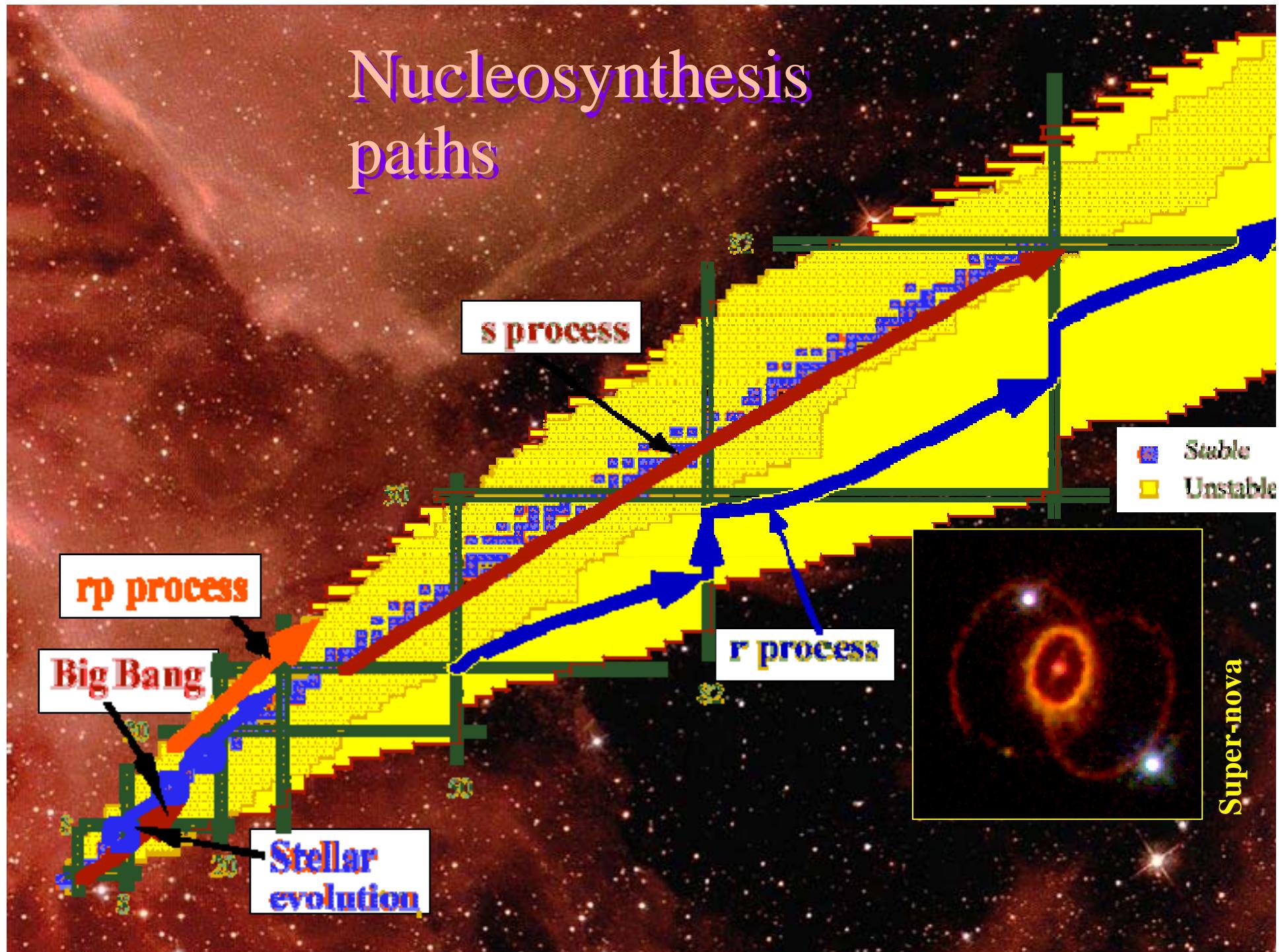




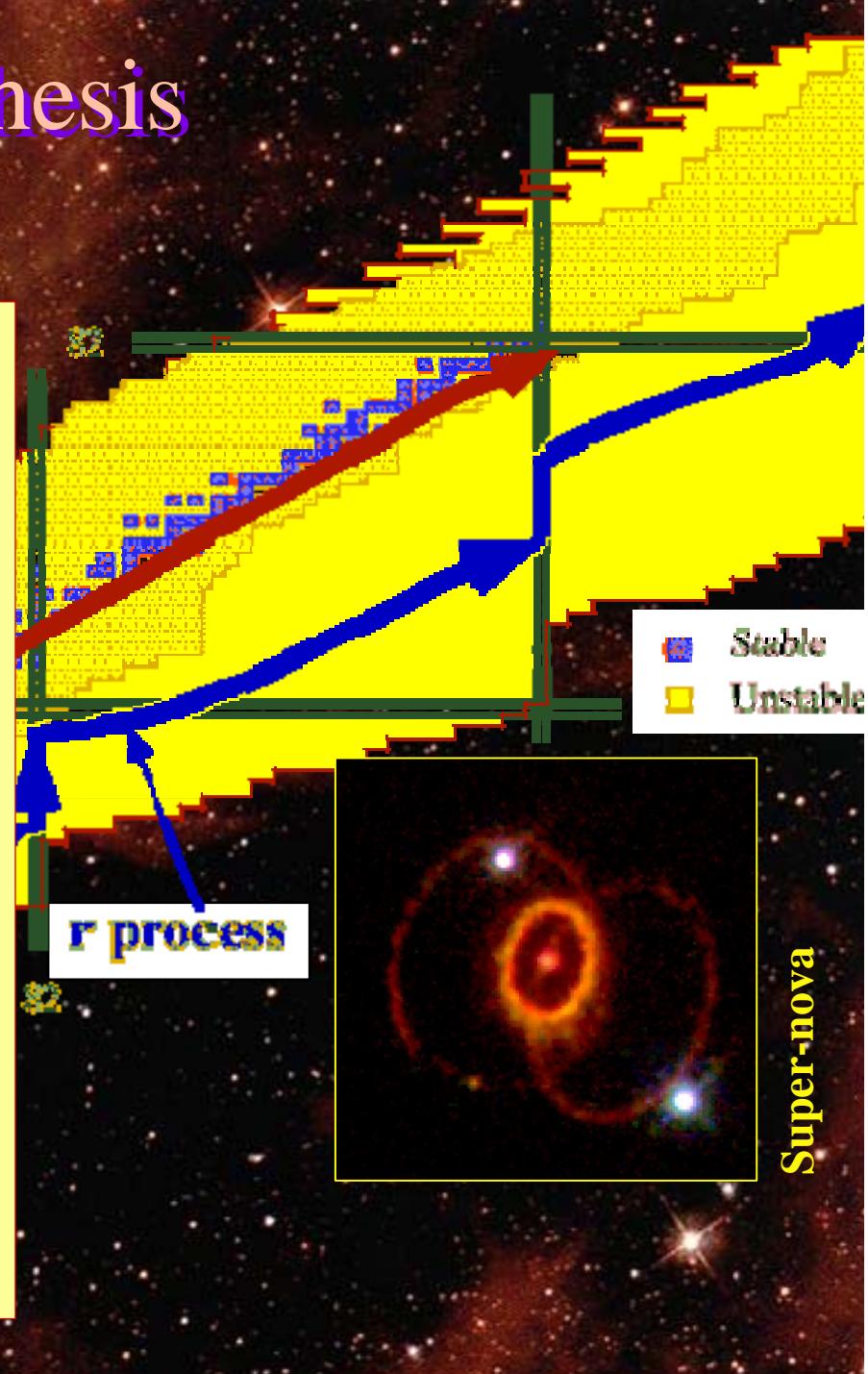
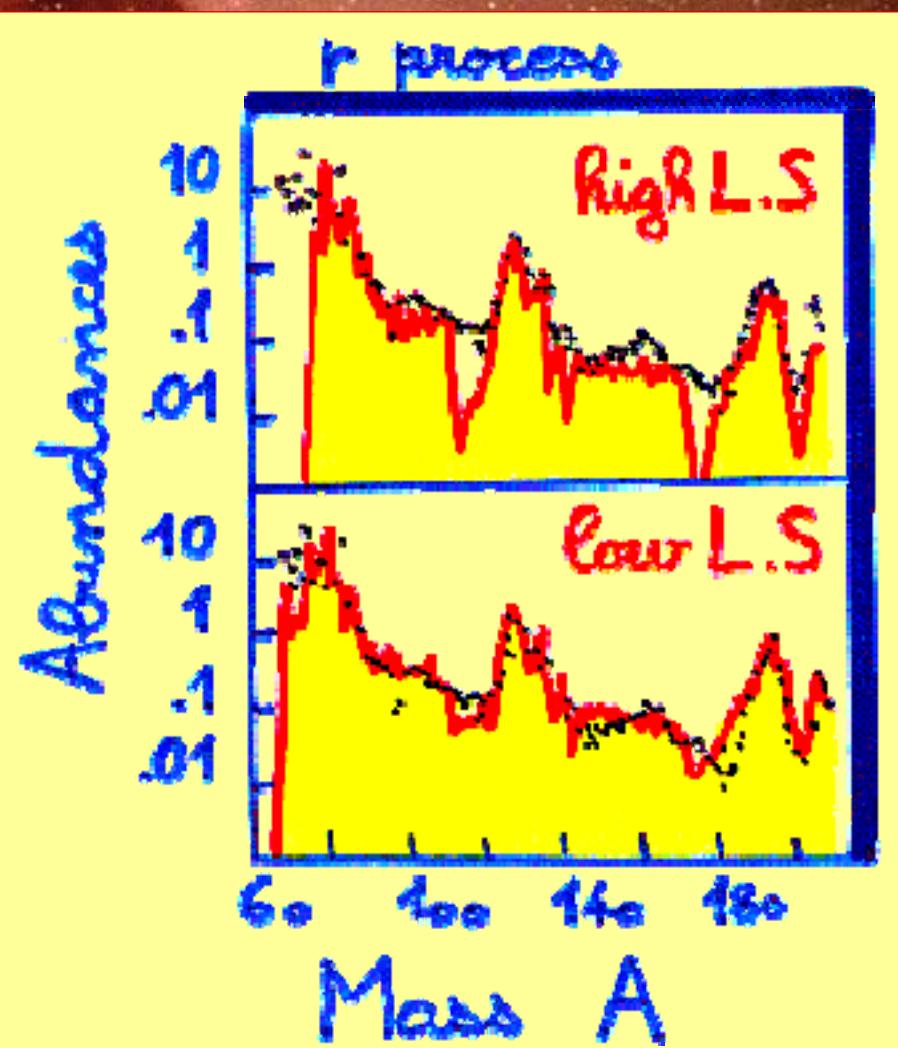
Nucleosynthesis paths



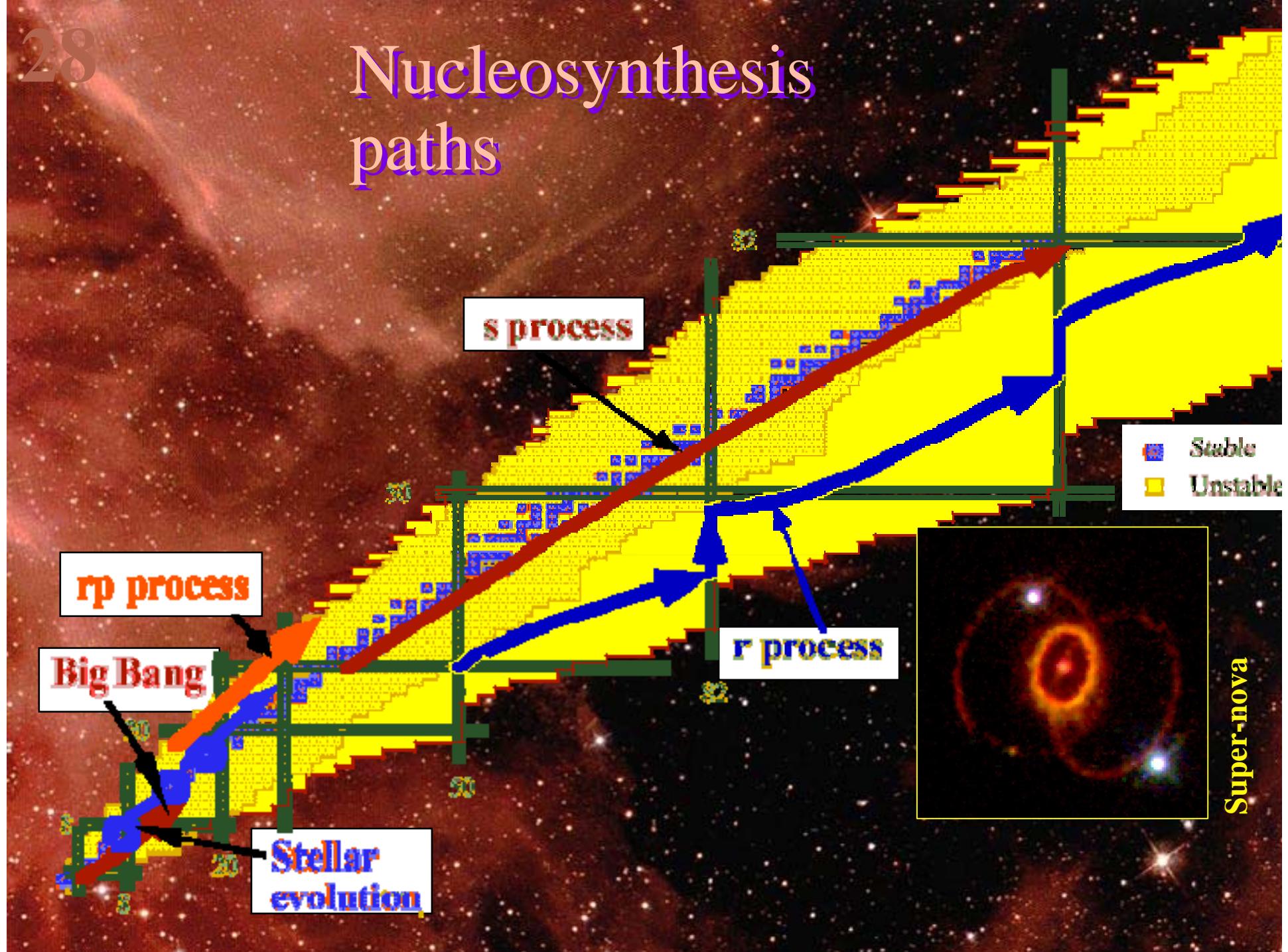
Nucleosynthesis paths

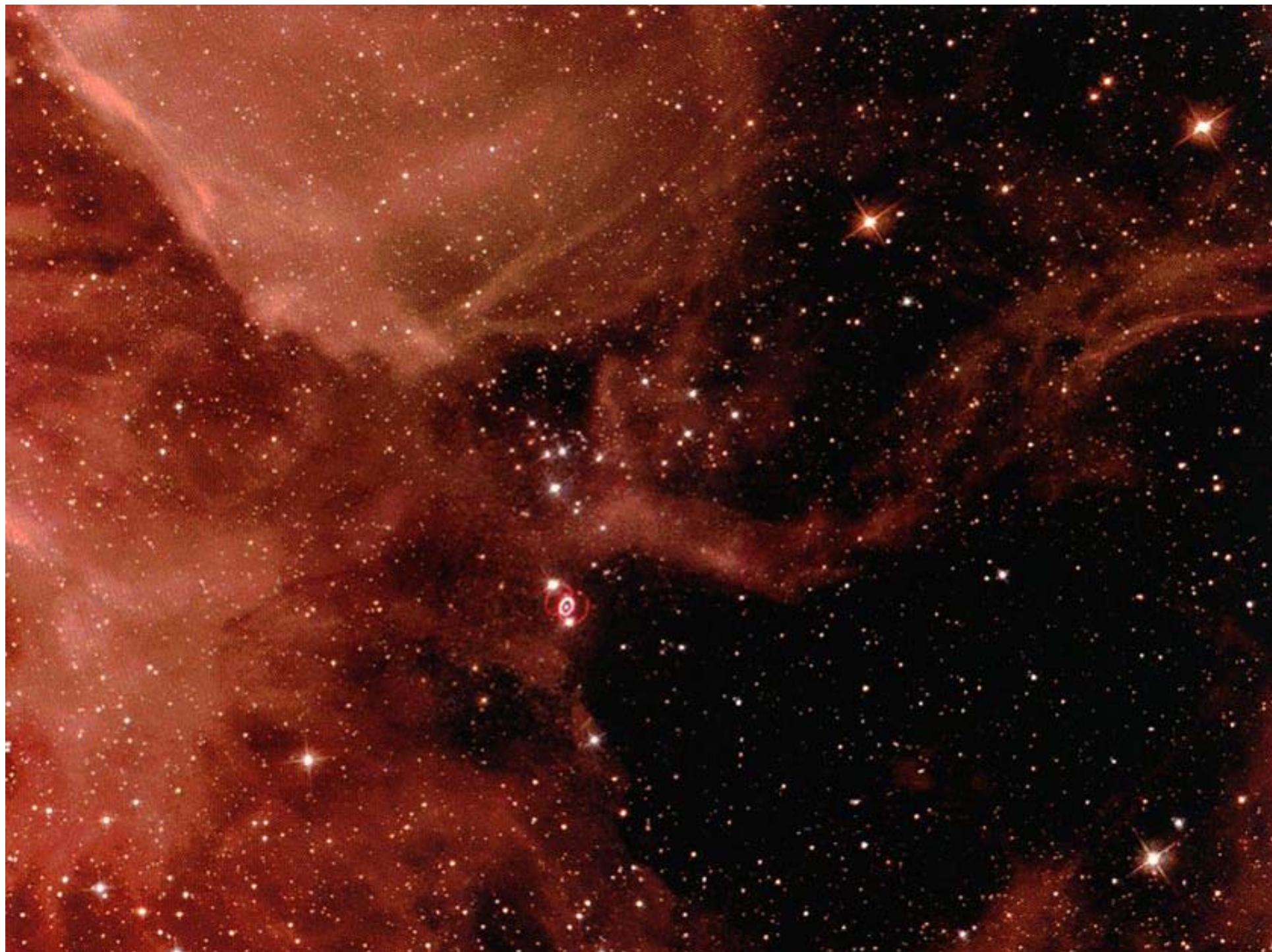


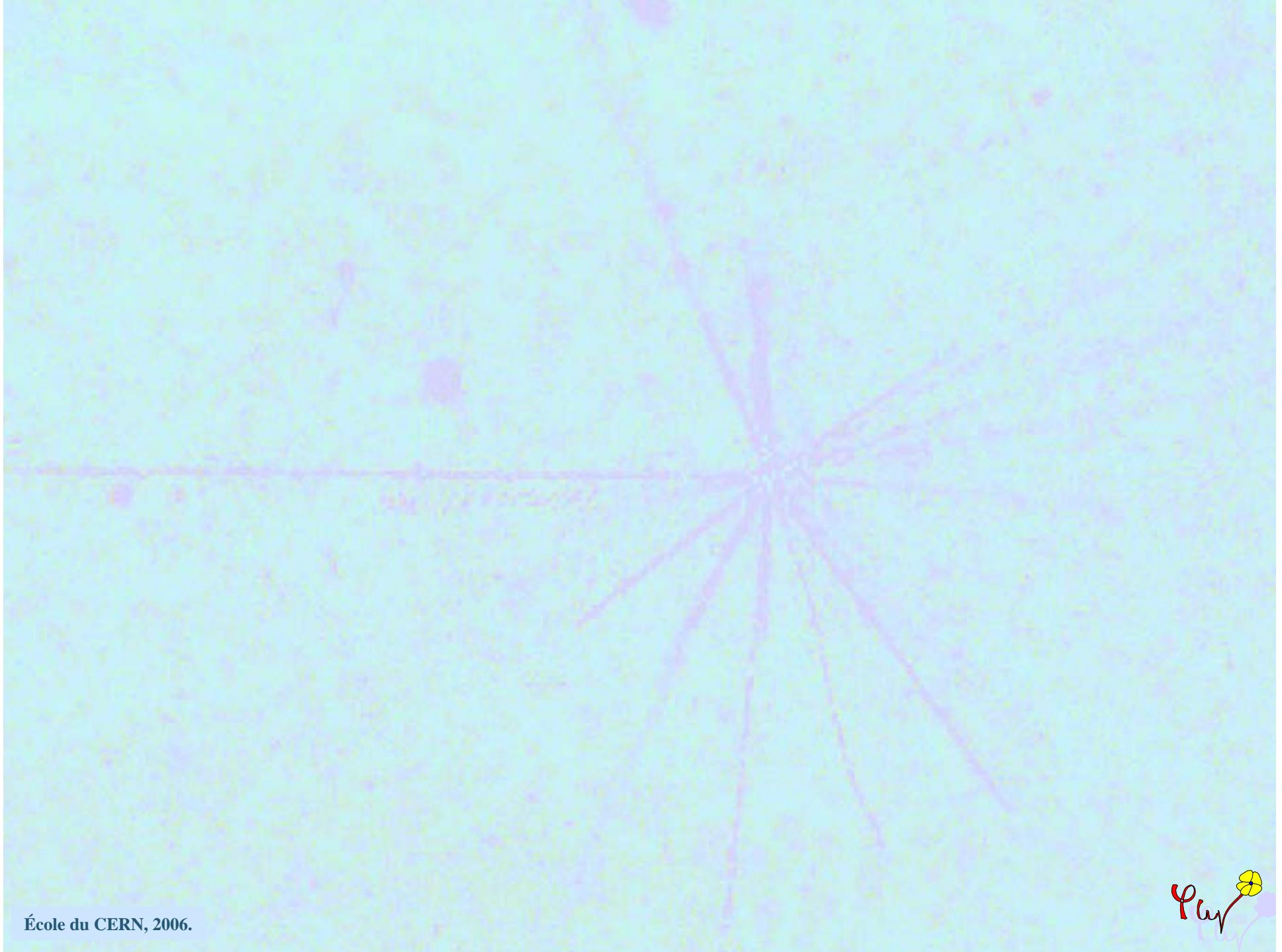
Nucleosynthesis paths



Nucleosynthesis paths





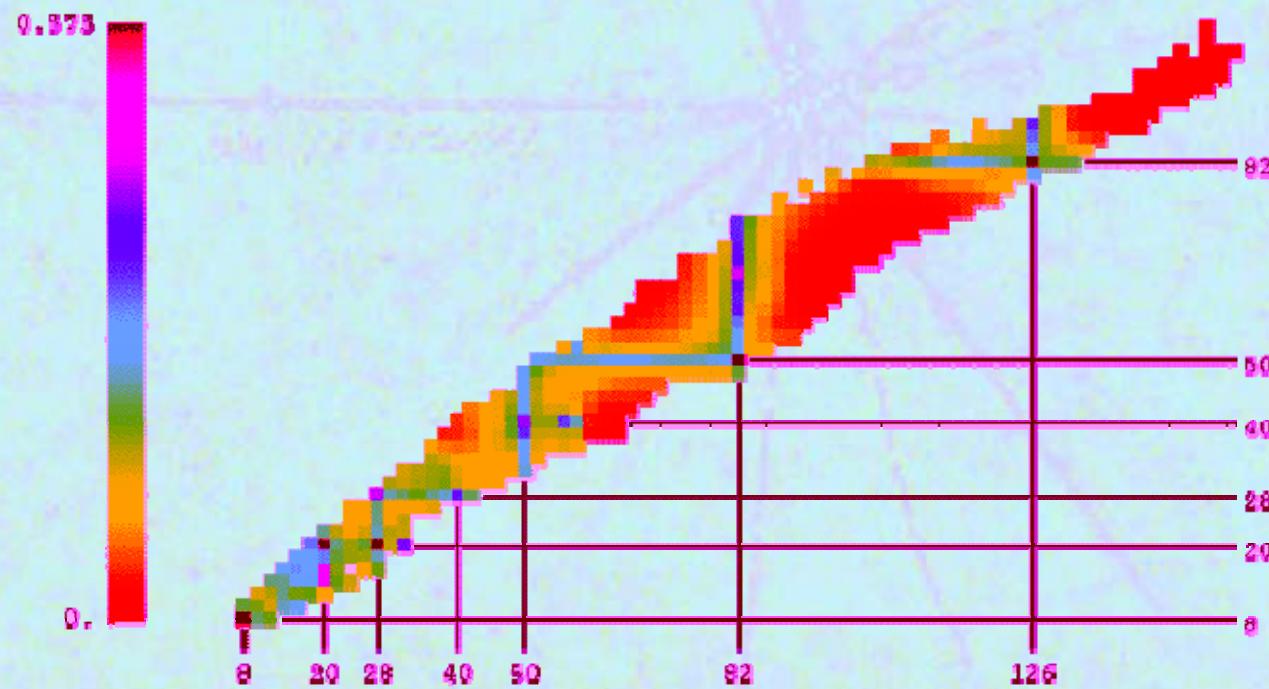


École du CERN, 2006.

Nuclear shells: systematics

Shell structure from $E_x(2_1)$

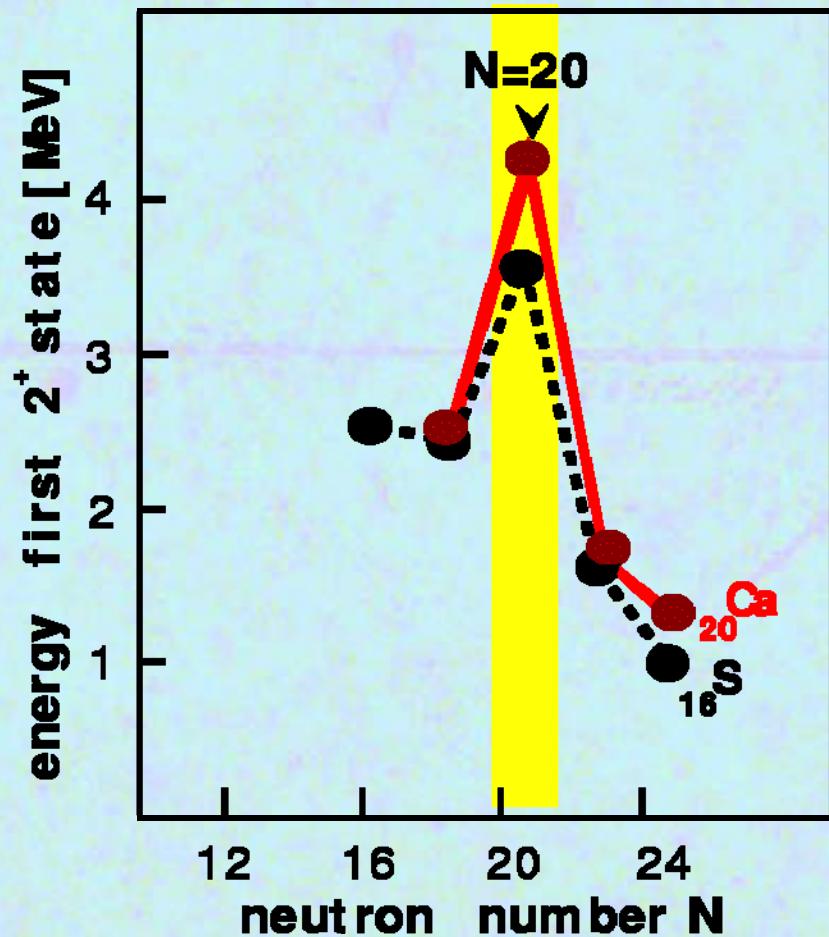
- High $E_x(2_1)$ indicates stable shell structure:



IAEA Workshop on NSDD, Trieste, November 2008



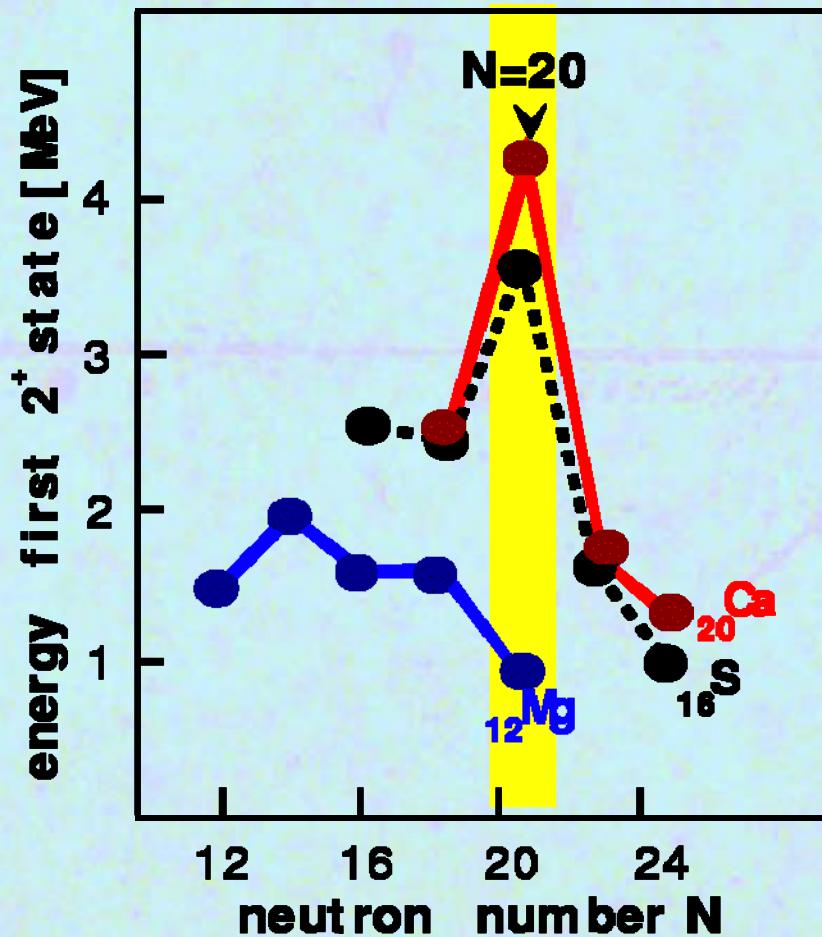
Nuclear shells:



✓ High E_{2^+} and shell closure
Φ Ex: $N=20$?

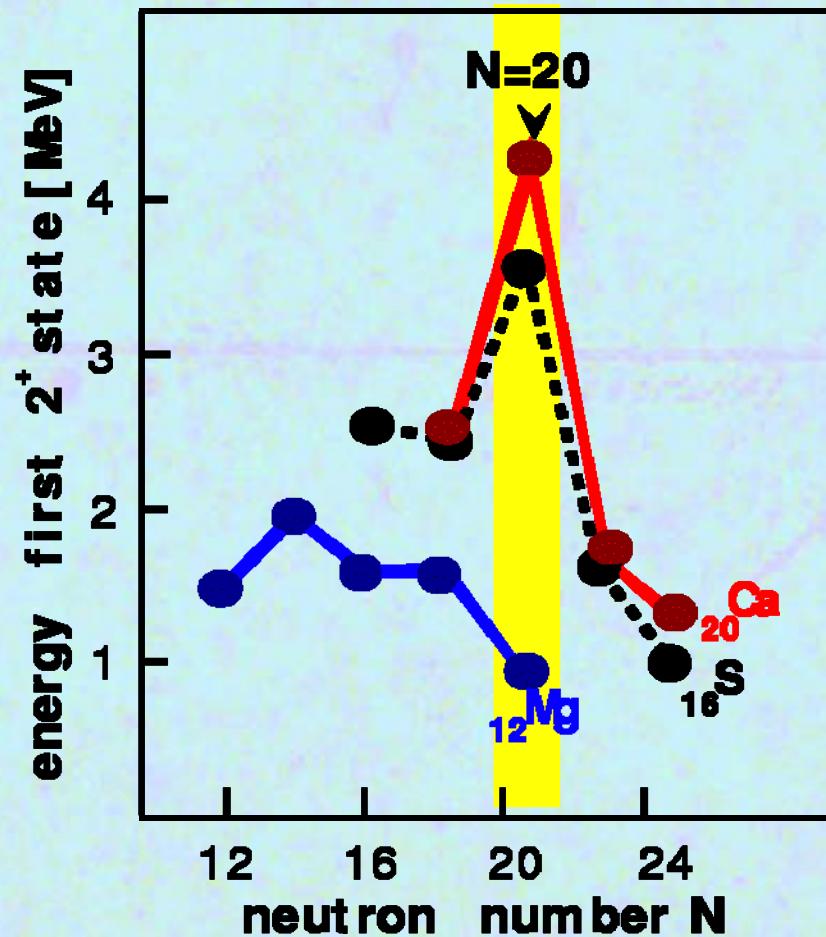


Nuclear shells: neutron rich



- ✓ High E_{2^+} and shell closure
 - Φ Ex: $N=20$?
- ✓ Magic number disappears far from stability

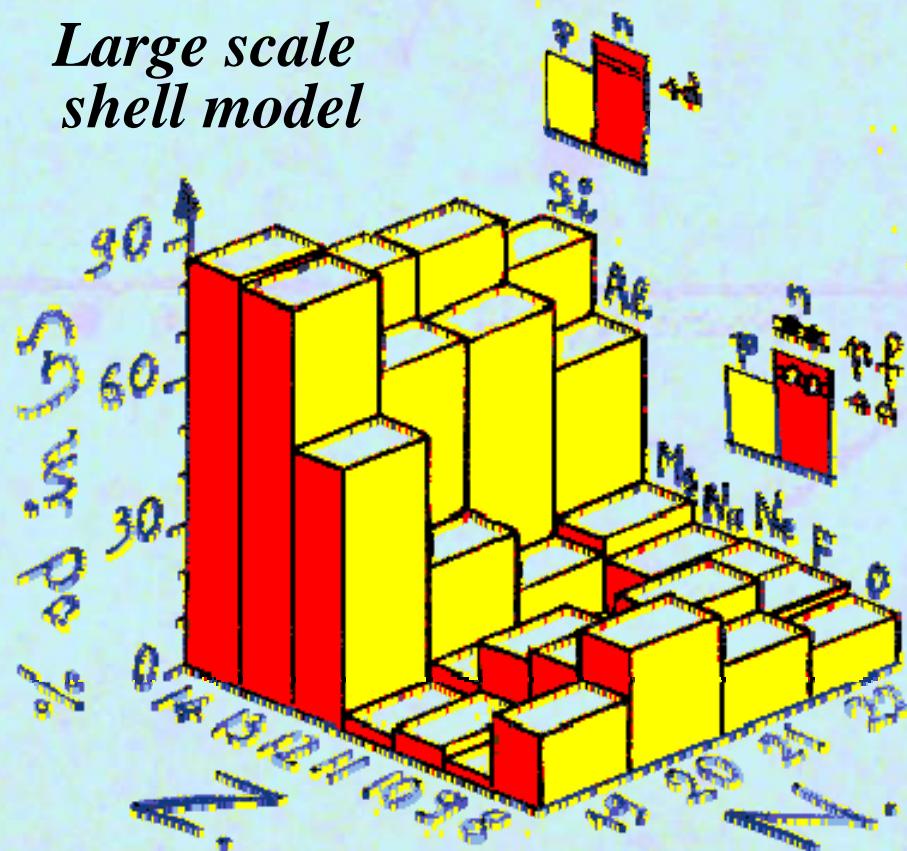
Nuclear shells: neutron rich



- ✓ High E_{2+} and shell closure
 - Φ Ex: $N=20$?
- ✓ Magic number disappears far from stability

Nuclear shells: neutron rich

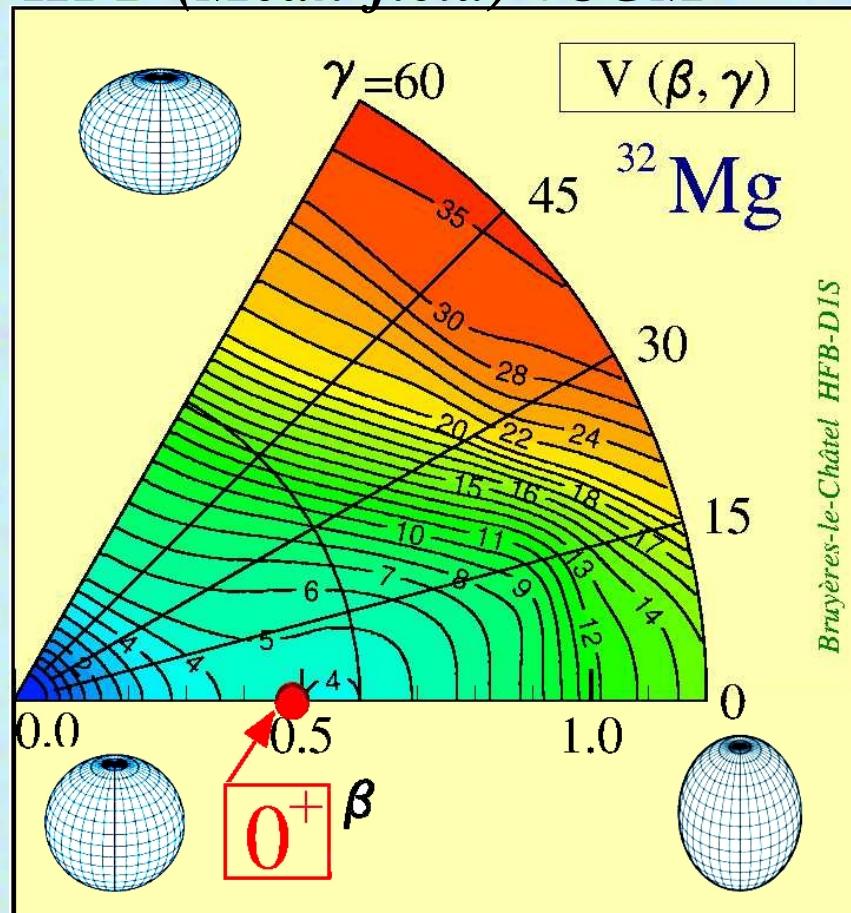
Large scale shell model



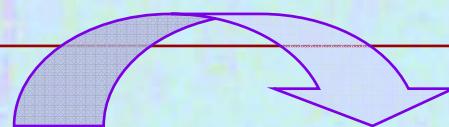
- v High E_{2+} and shell closure
 - Φ Ex: N=20?
 - v Magic number disappears far from stability
 - v Configuration mixing

Nuclear shells: neutron rich

HFB (Mean-field) +CGM

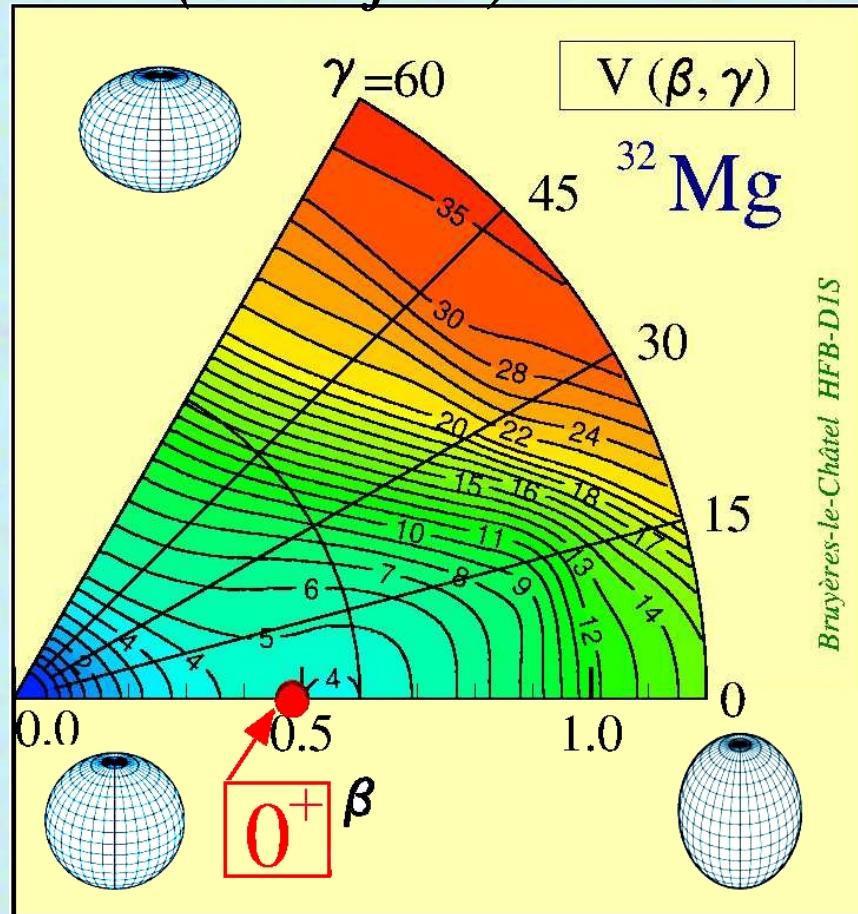


- ✓ What about the lighter shells?
Φ Ex: N=20?
- ✓ Magic number disappears far from stability
- ✓ Island of deformation



Nuclear deformation

HFB (Mean-field) +CGM

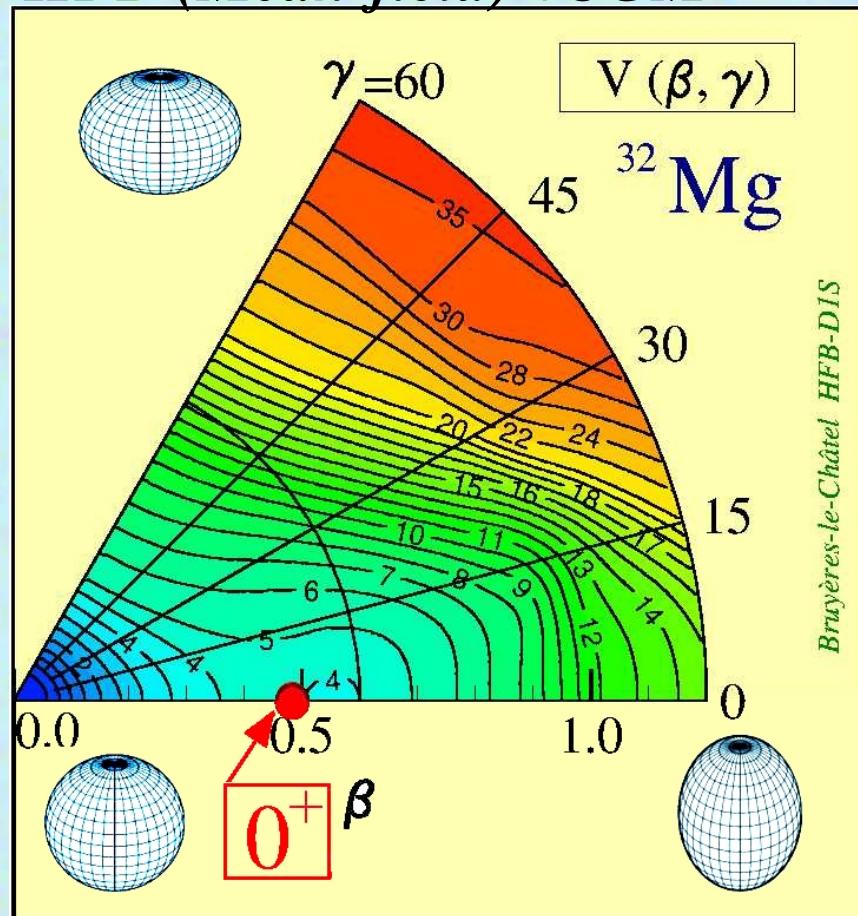


▼ Island of deformation



Nuclear deformation

HFB (Mean-field) +CGM

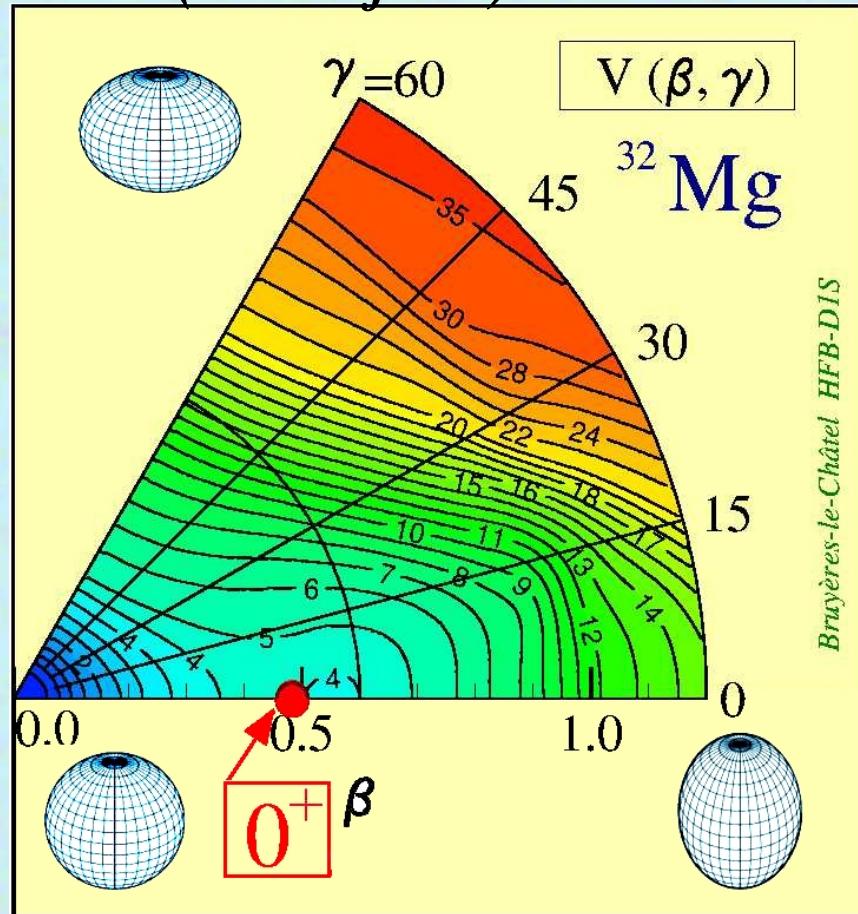


▼ Island of deformation

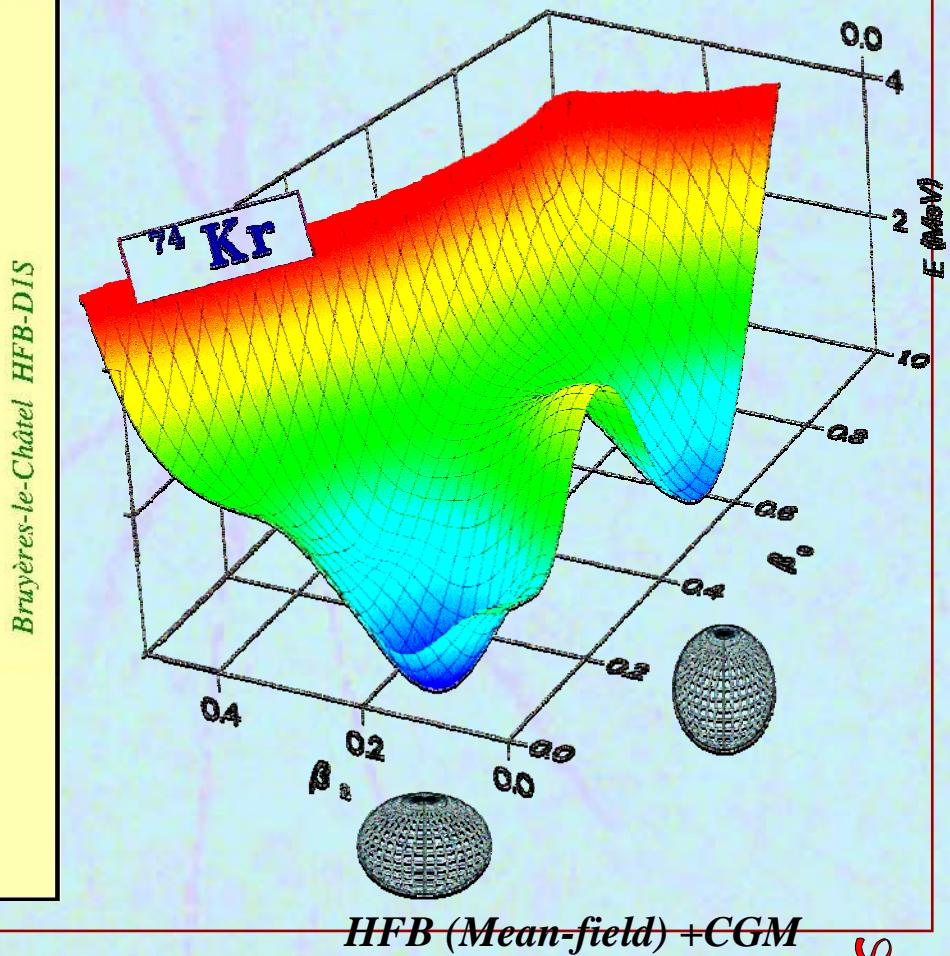
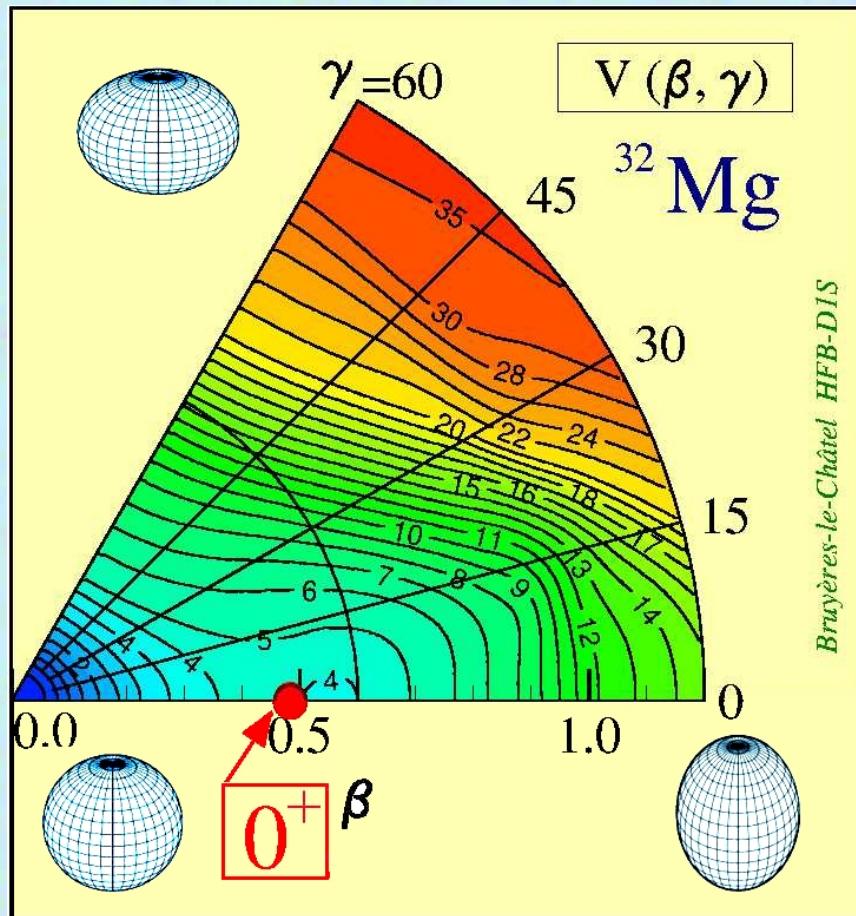


Nuclear deformation

HFB (Mean-field) +CGM

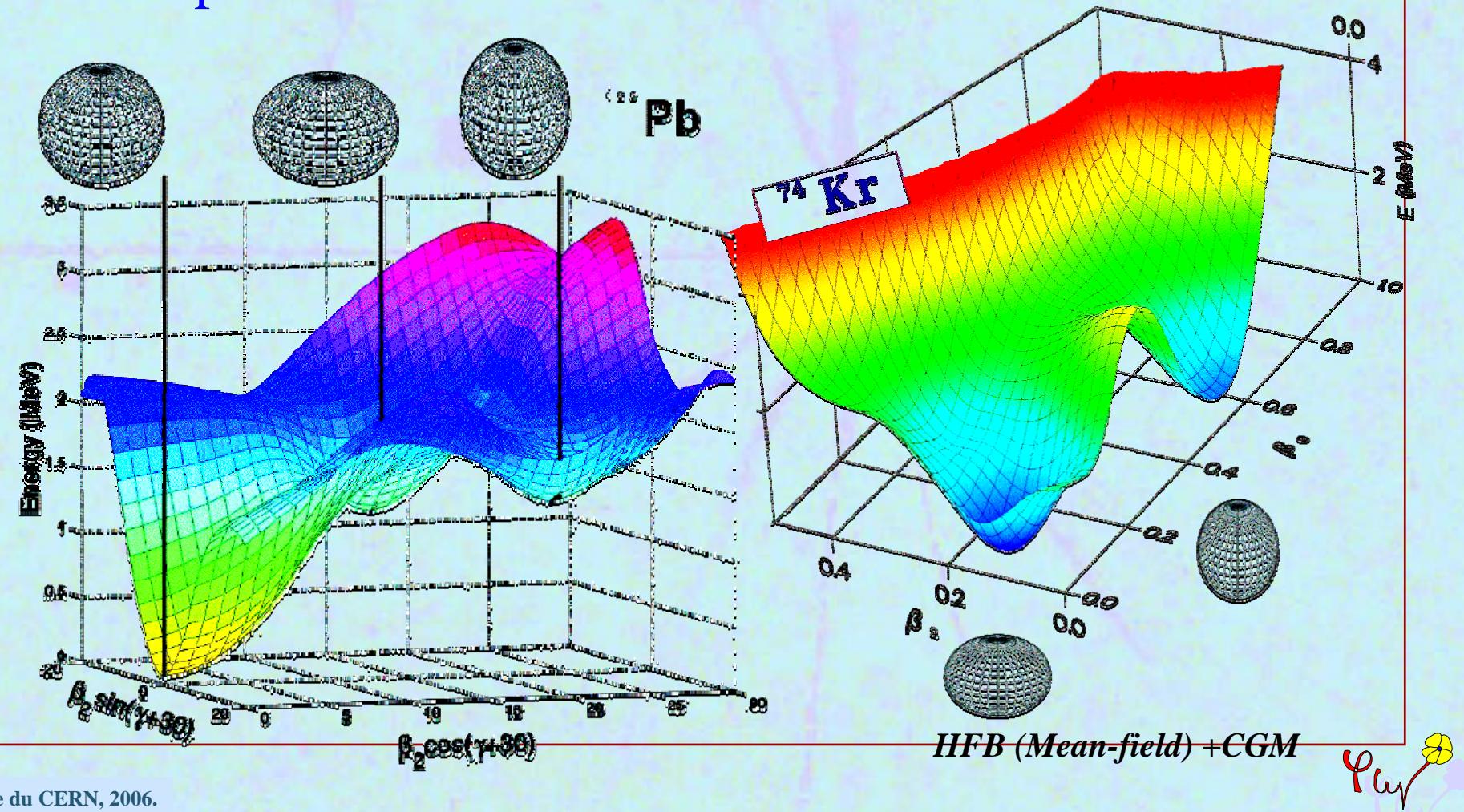


Nuclear deformation

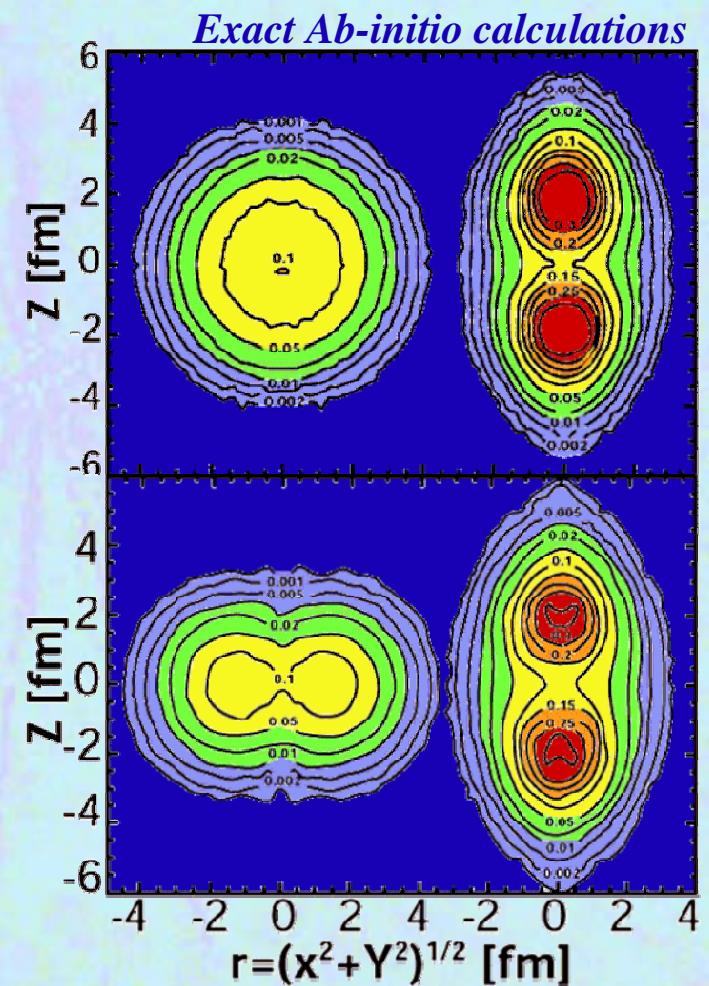
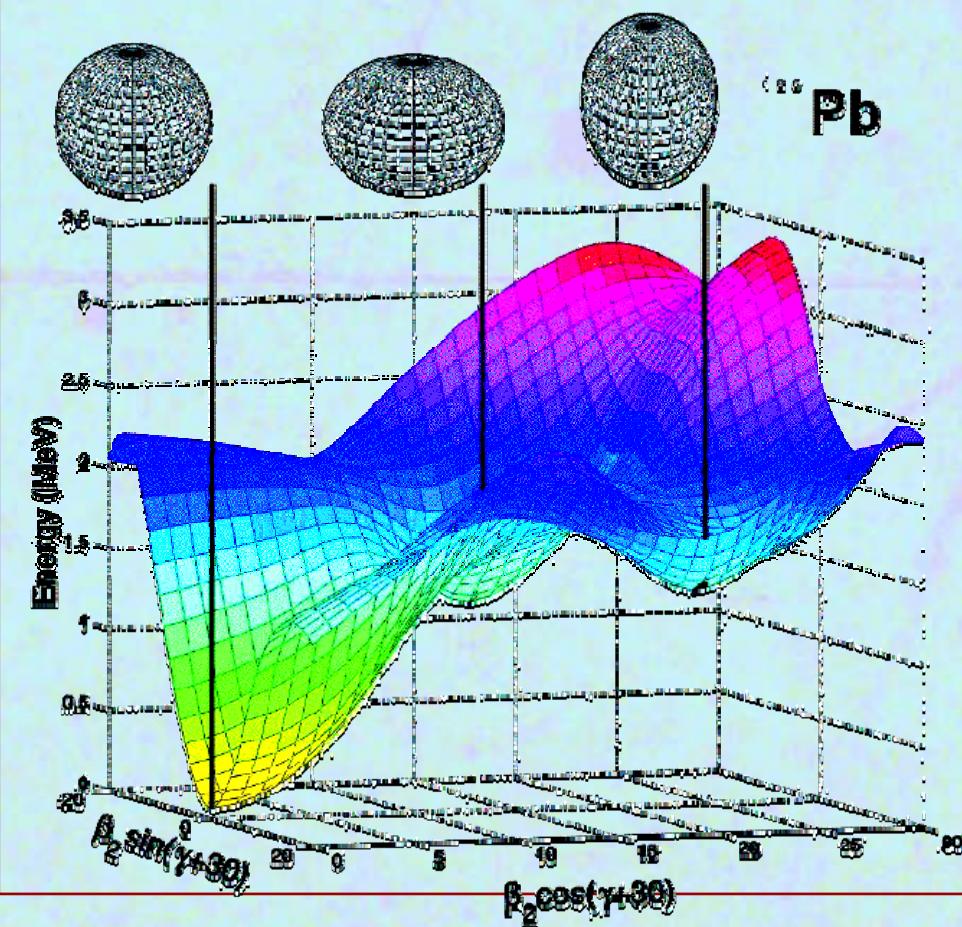


Nuclear deformation

▼ Shape coexistence and isomers



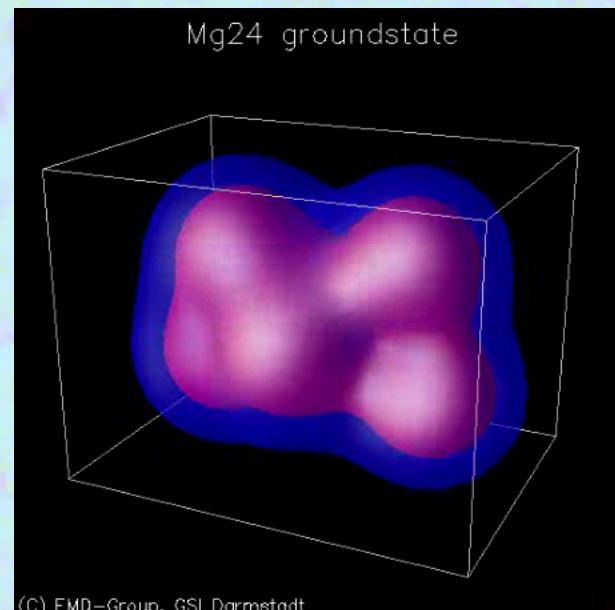
Nuclear deformation



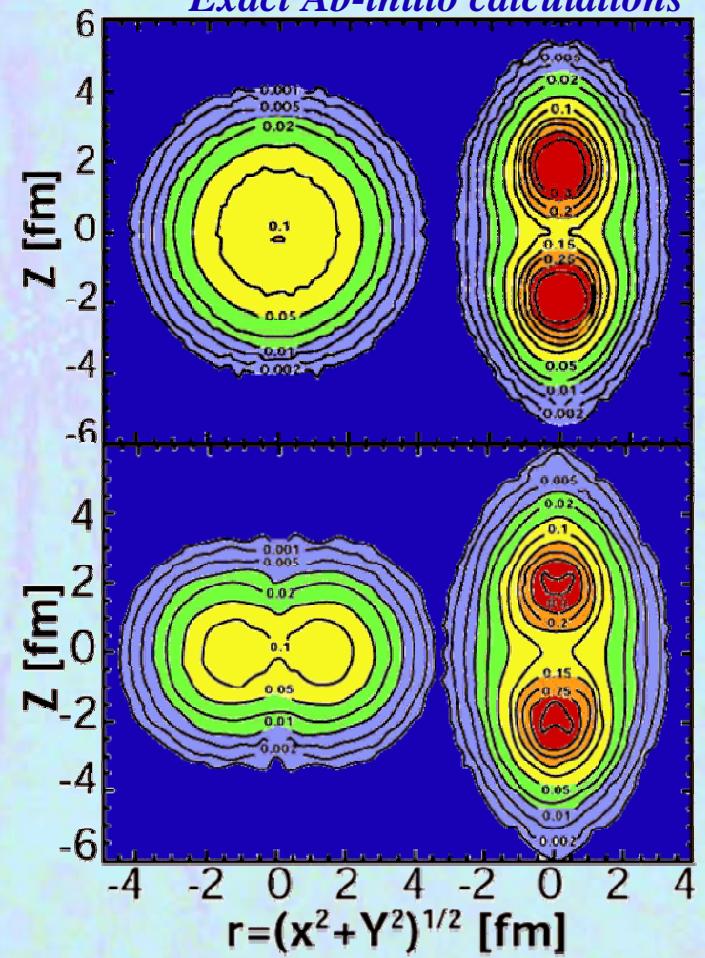
Deformation

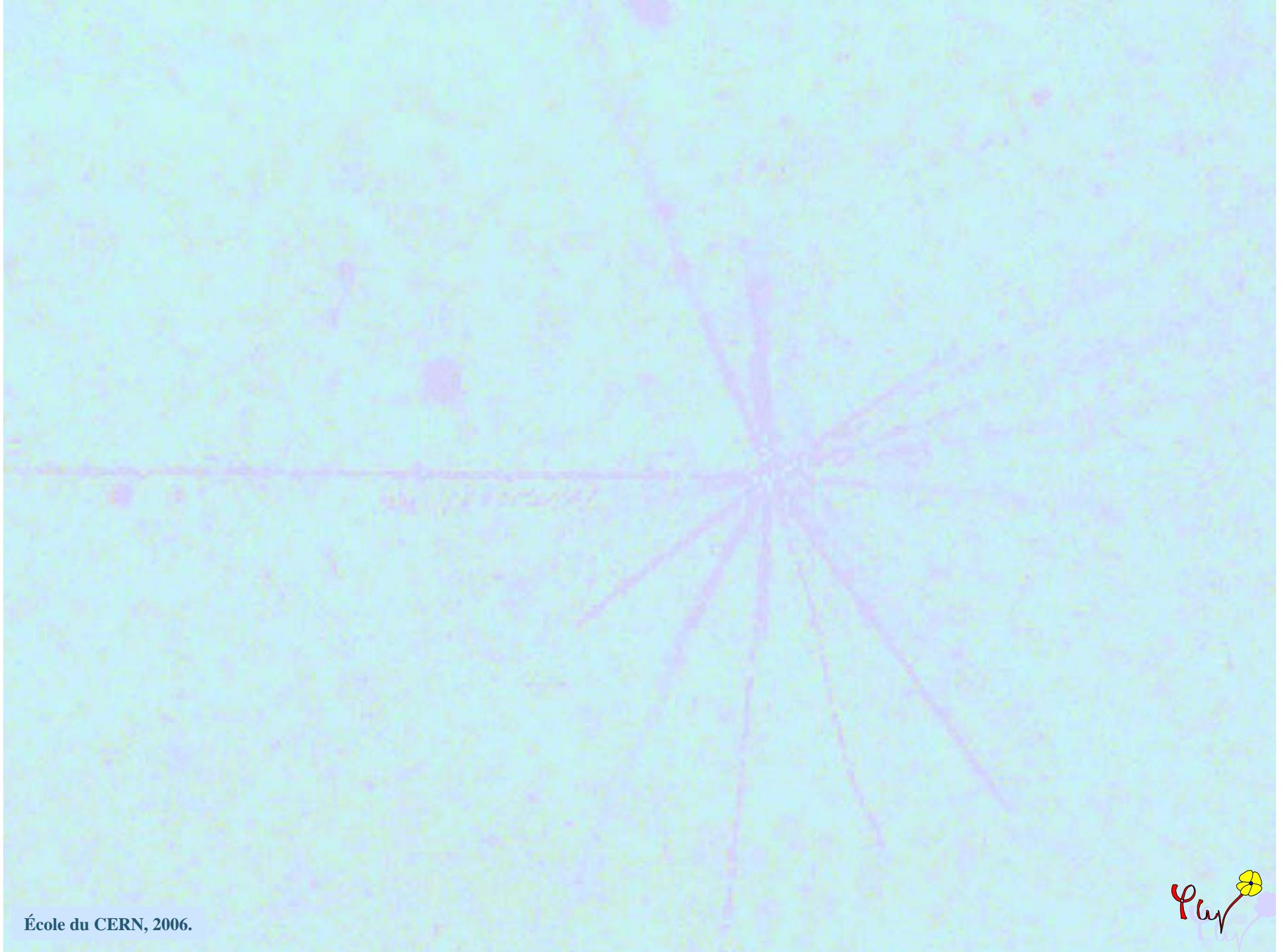
Dramatic
effect in
small system

Quantum molecular approach



Exact Ab-initio calculations

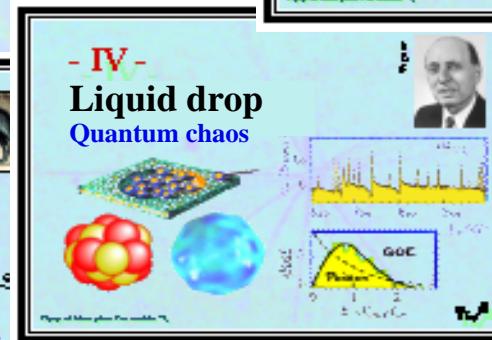
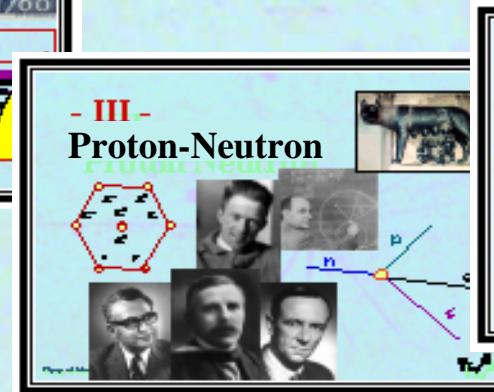
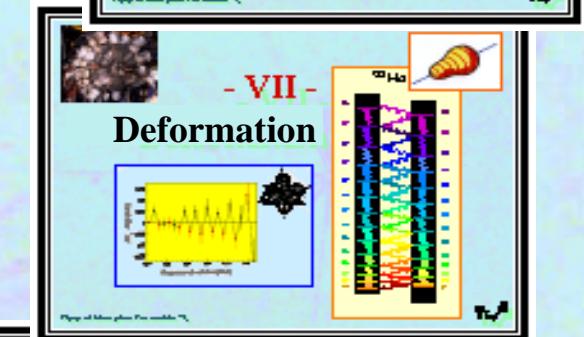
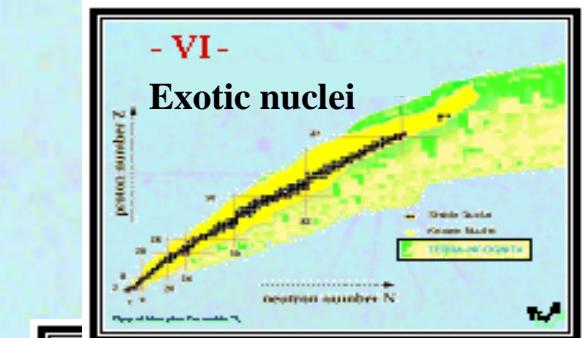
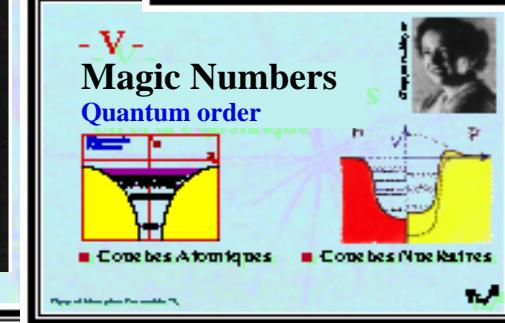
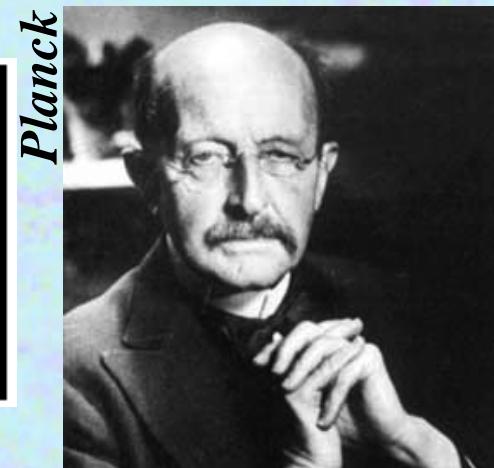
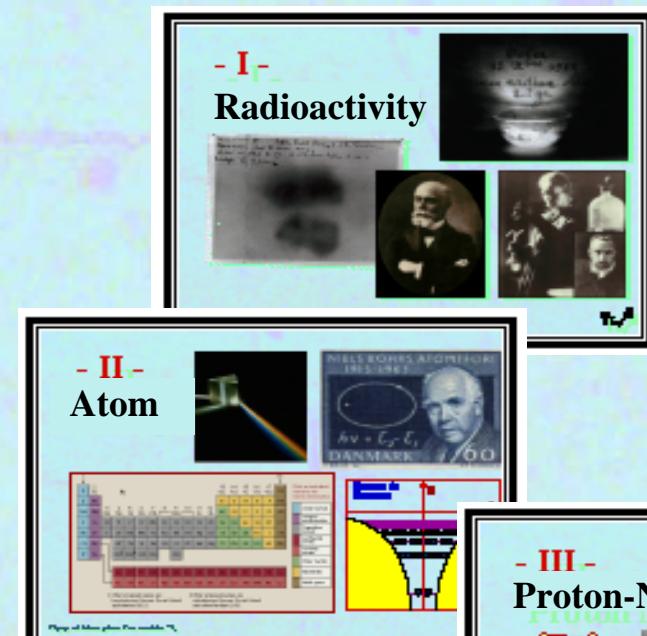


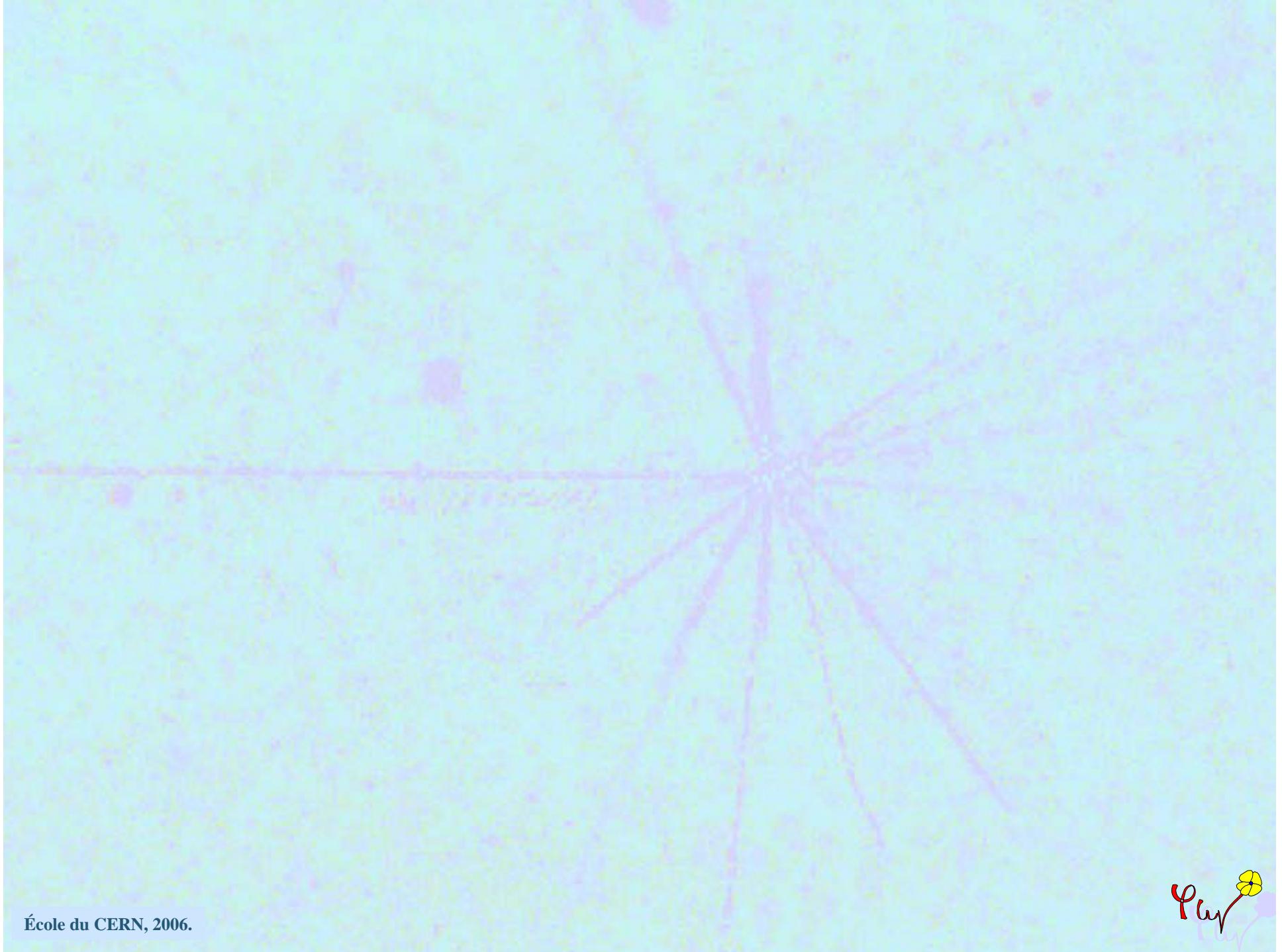


École du CERN, 2006.

Atomic Nuclei

Complex quantum systems





École du CERN, 2006.

- VI -

Exotic Nuclei

New Quantum structures



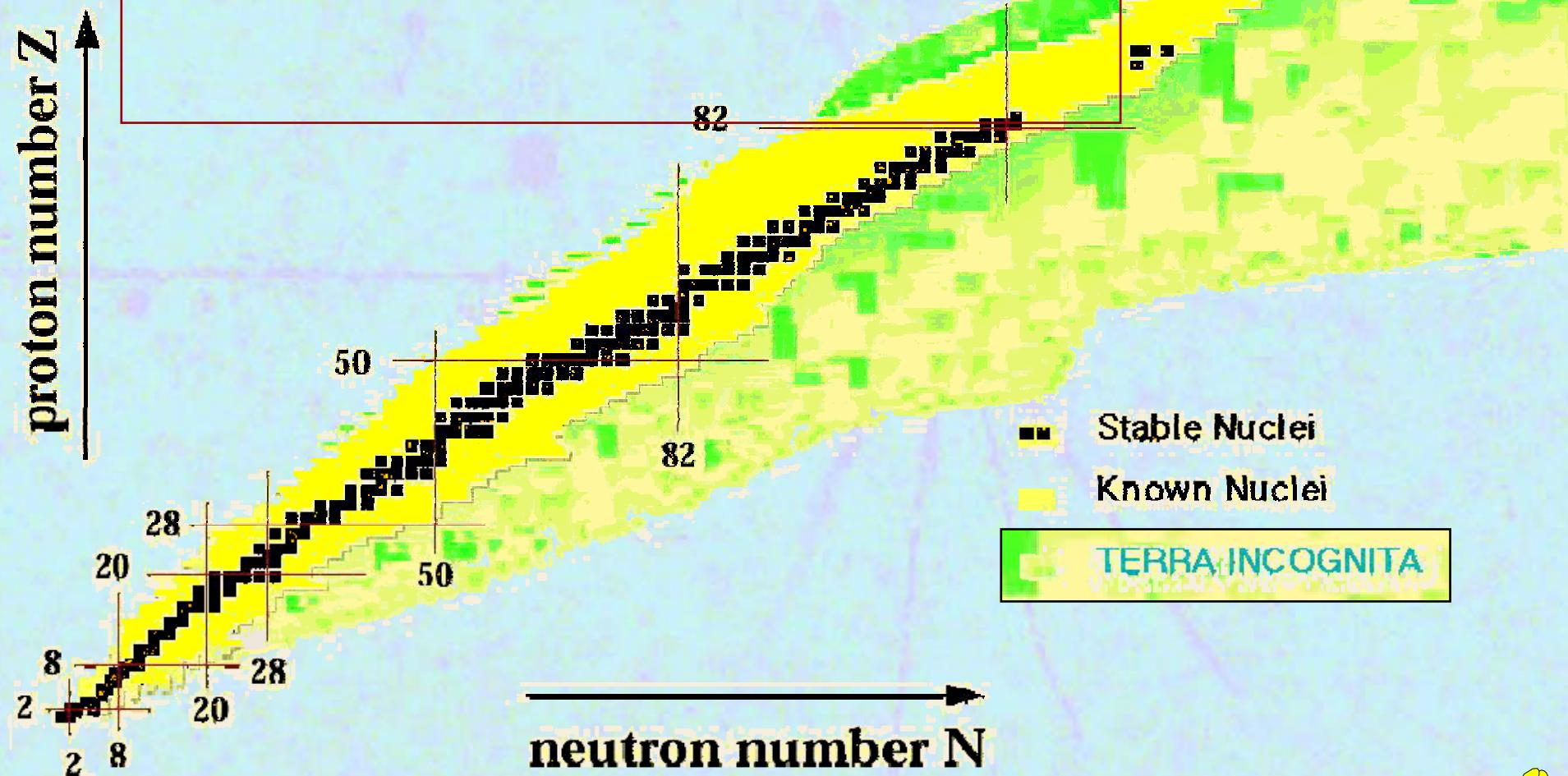
- VI -

Exotic Nuclei



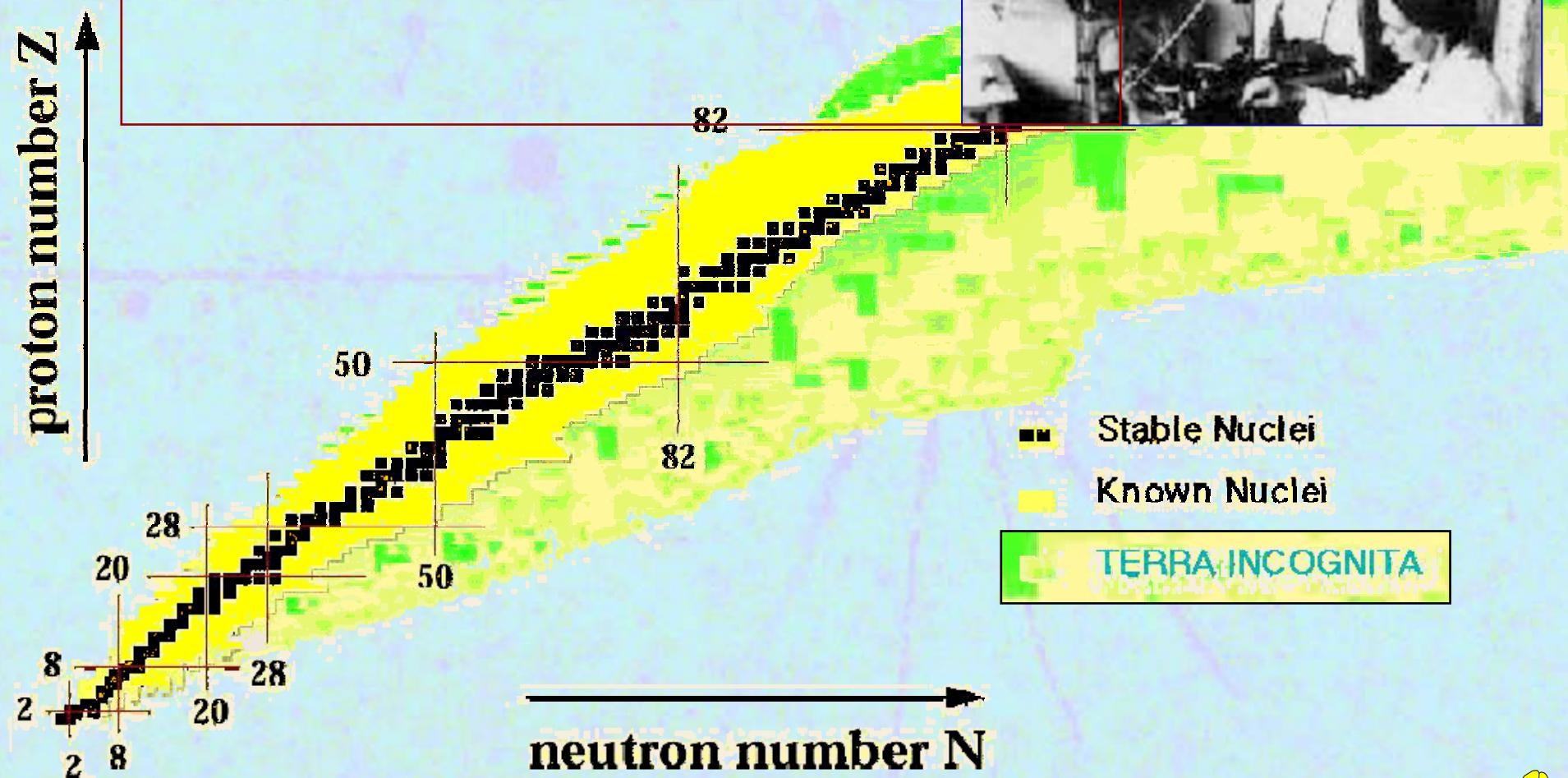
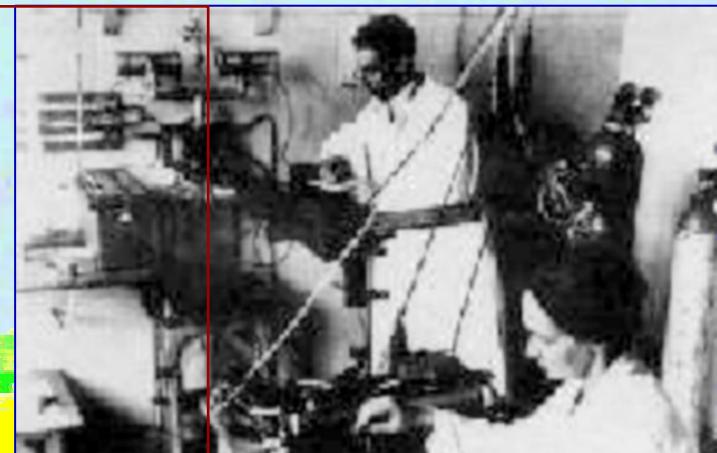
- VI -

Exotic Nuclei



- VI - Exotic Nuclei

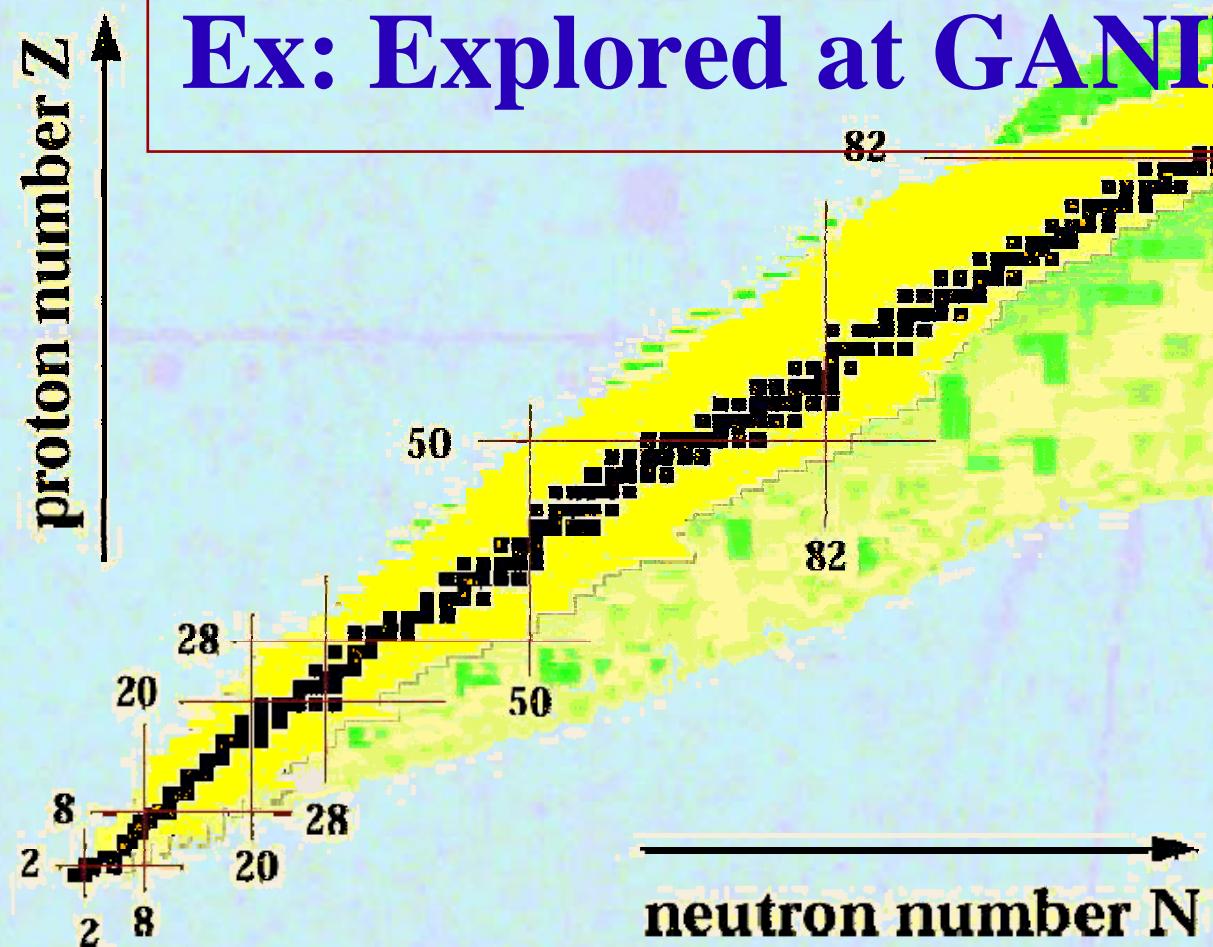
Joliot-Curie



- VI -

Exotic Nuclei

Ex: Explored at GANIL

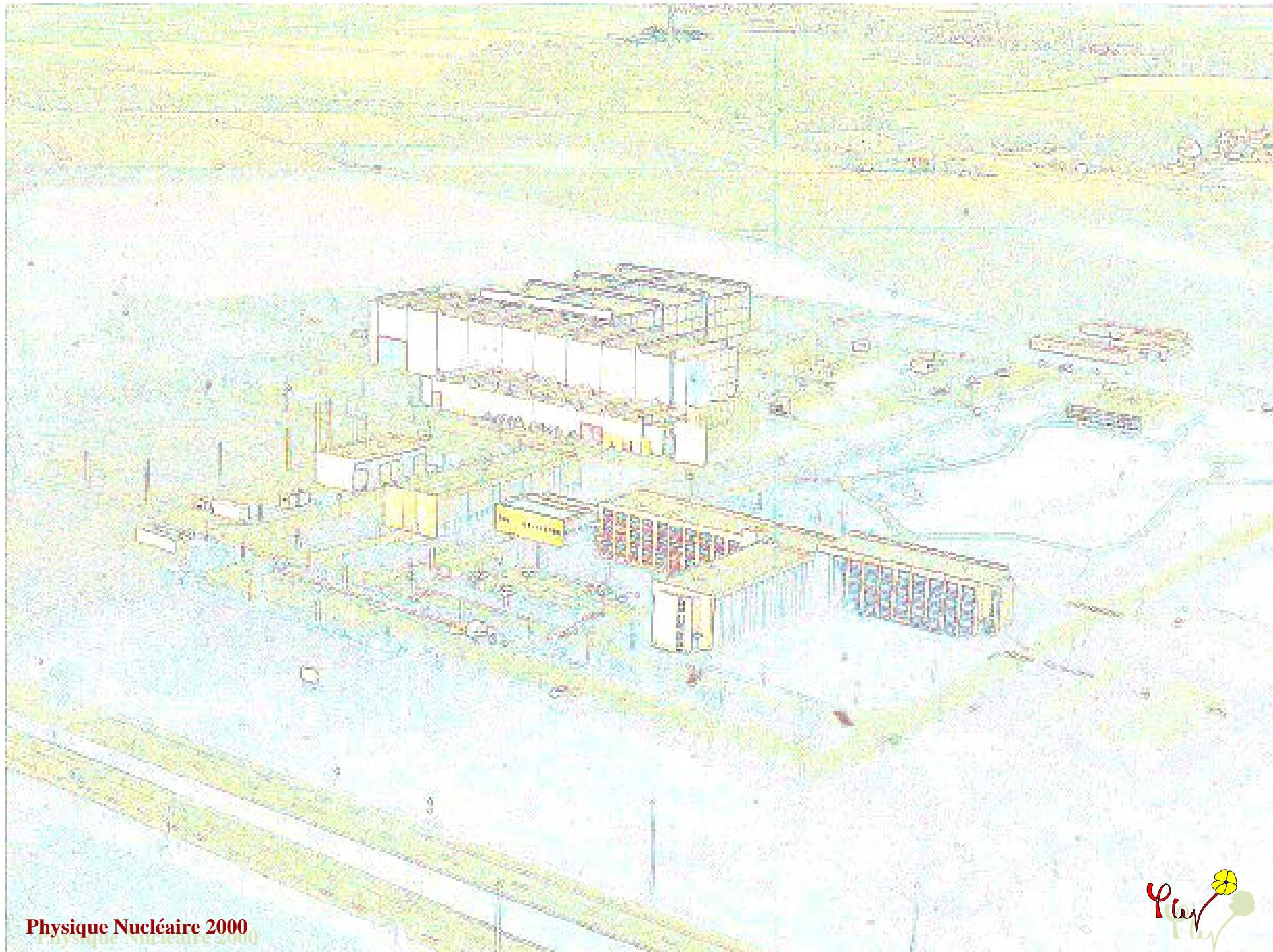




- VI -

Exotic Nuclei

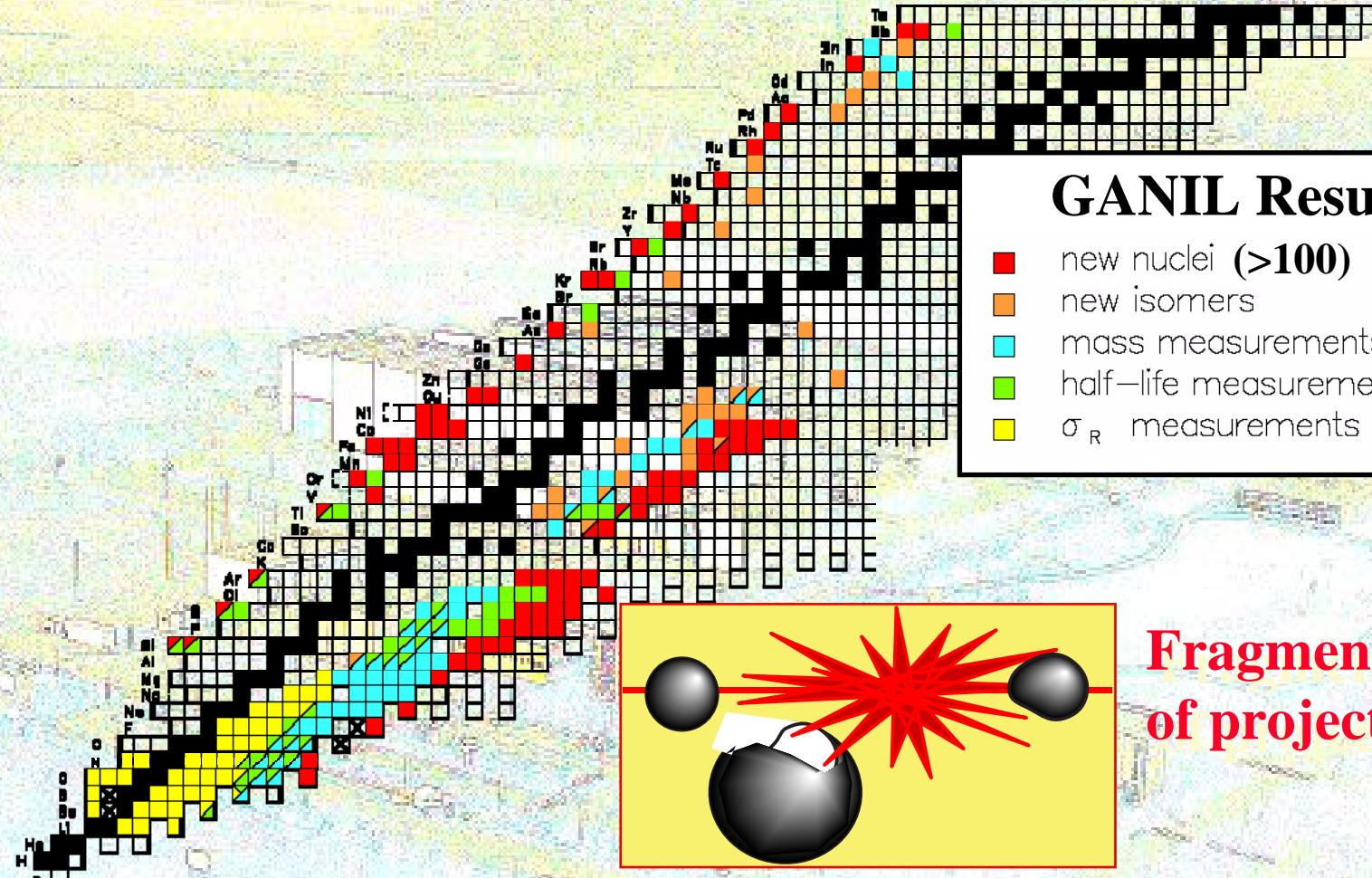
Ex: Explored at GANIL



Protons number

Neutrons number

Neutrons number

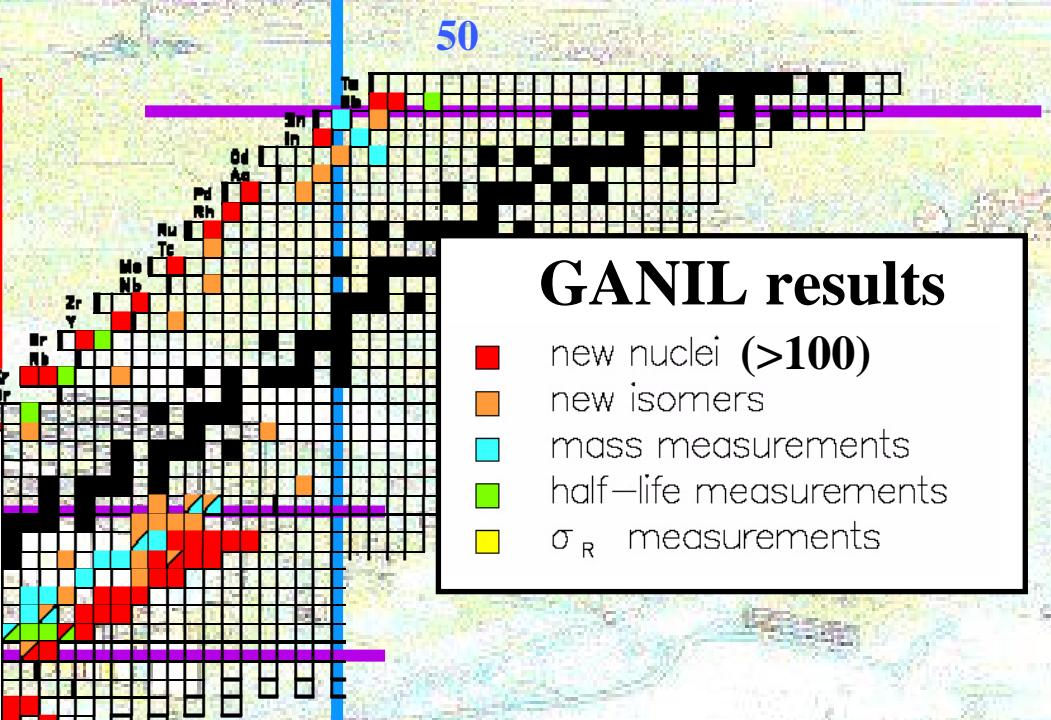
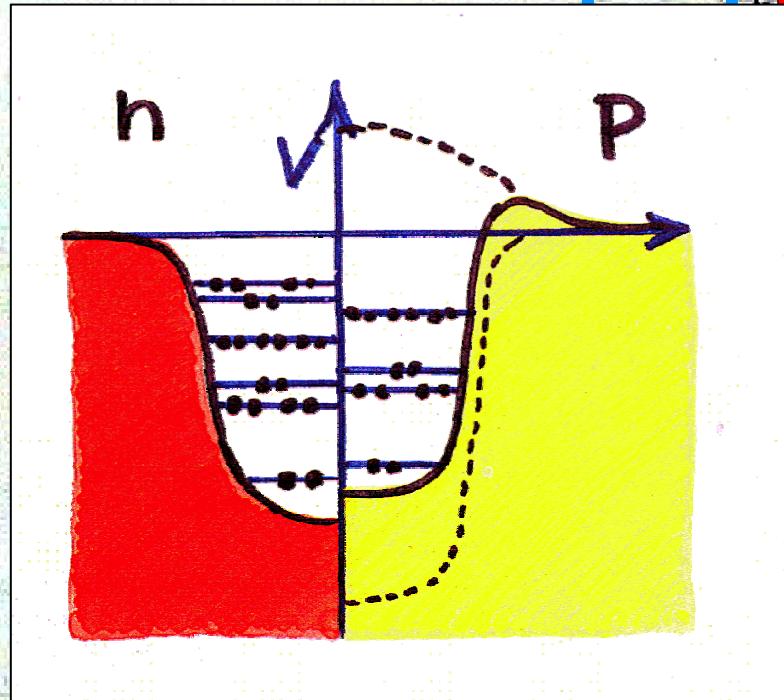


Fragmentation
of projectiles

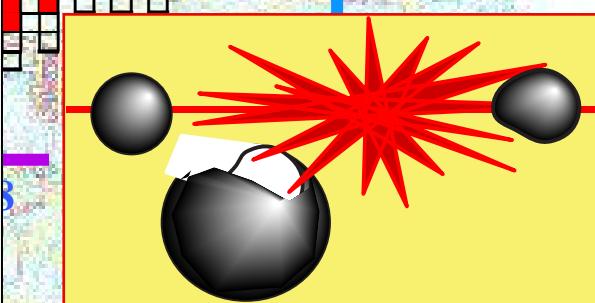
Exotic
Nuclei



Magic Numbers



GANIL results



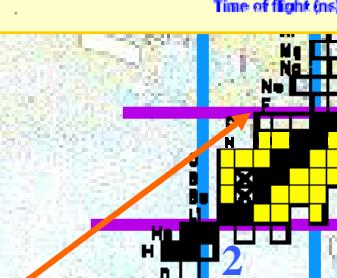
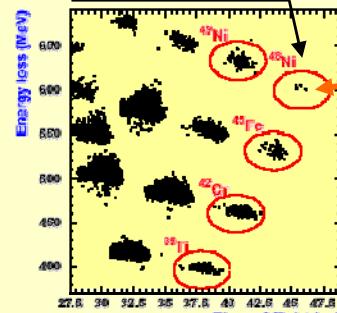
Fragmentation
of projectile

Exotic Nuclei

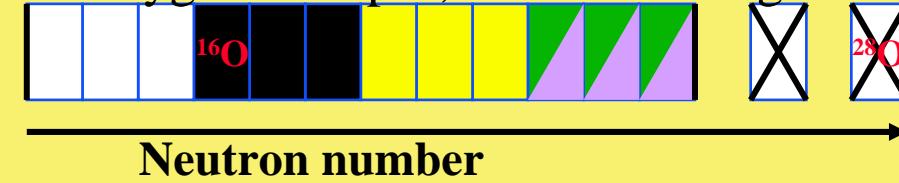


Magic Numbers

Nickel 48



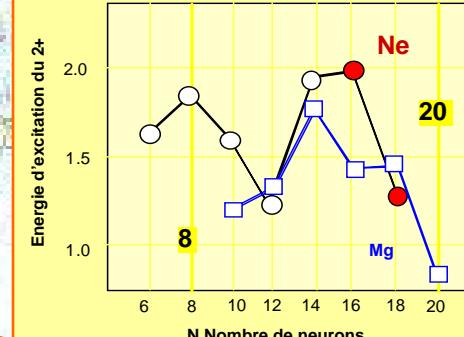
Oxygen Isotopes, ^{28}O is missing



50

^{100}Sn

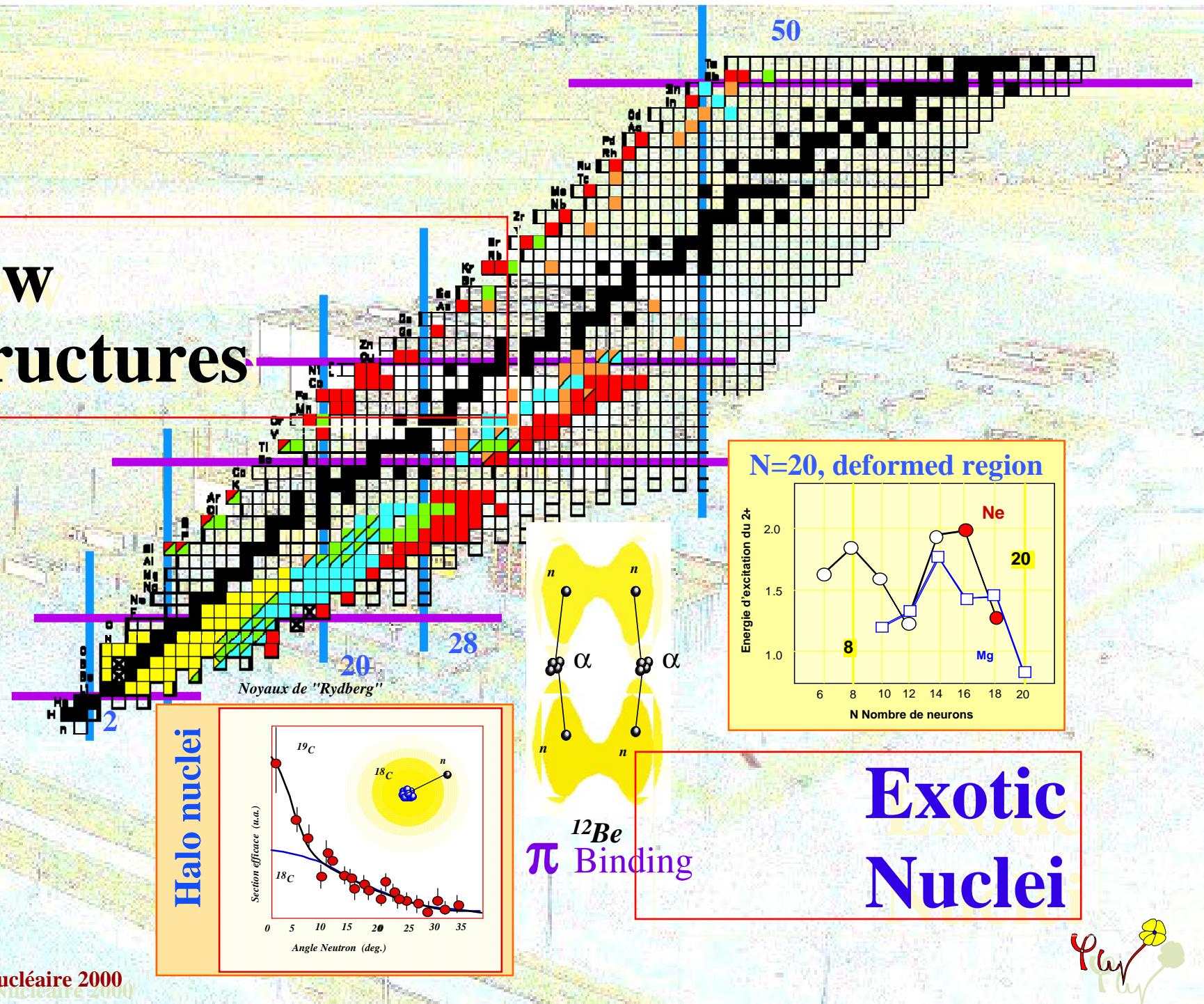
$N=20$ deformed region

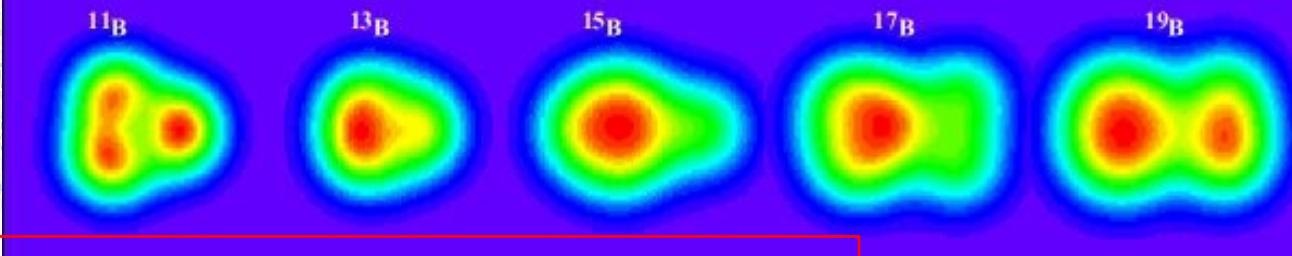


Exotic Nuclei



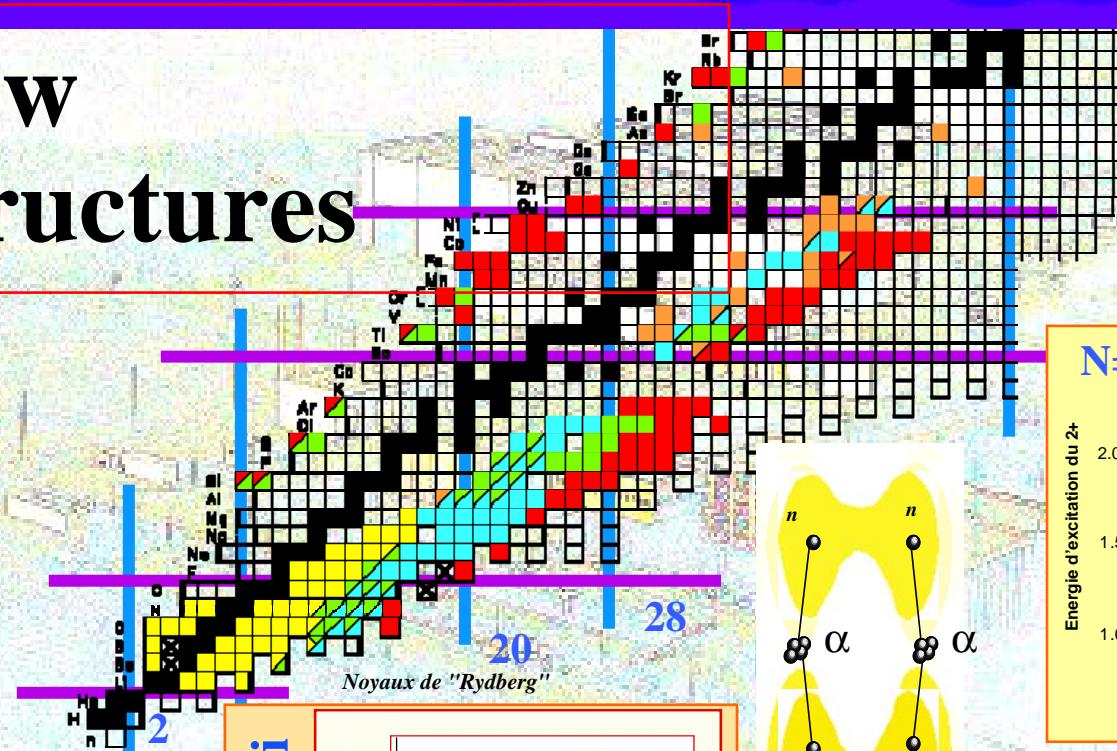
New Structures



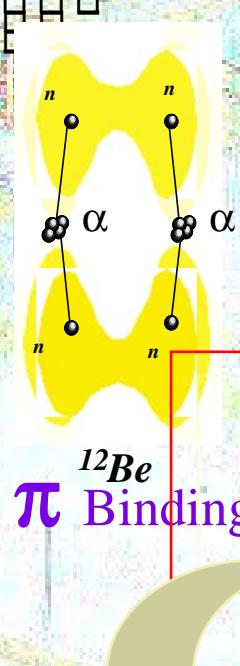
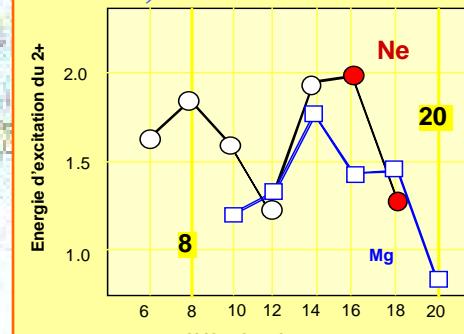


QuickTime™ et un décompresseur sont requis pour visualiser cette image.

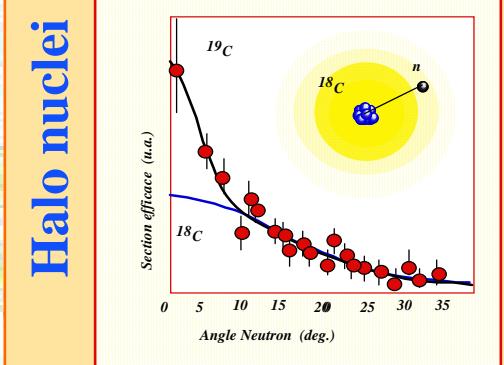
New Structures



N=20, deformed nuclei



π^{+} ^{12}Be Binding

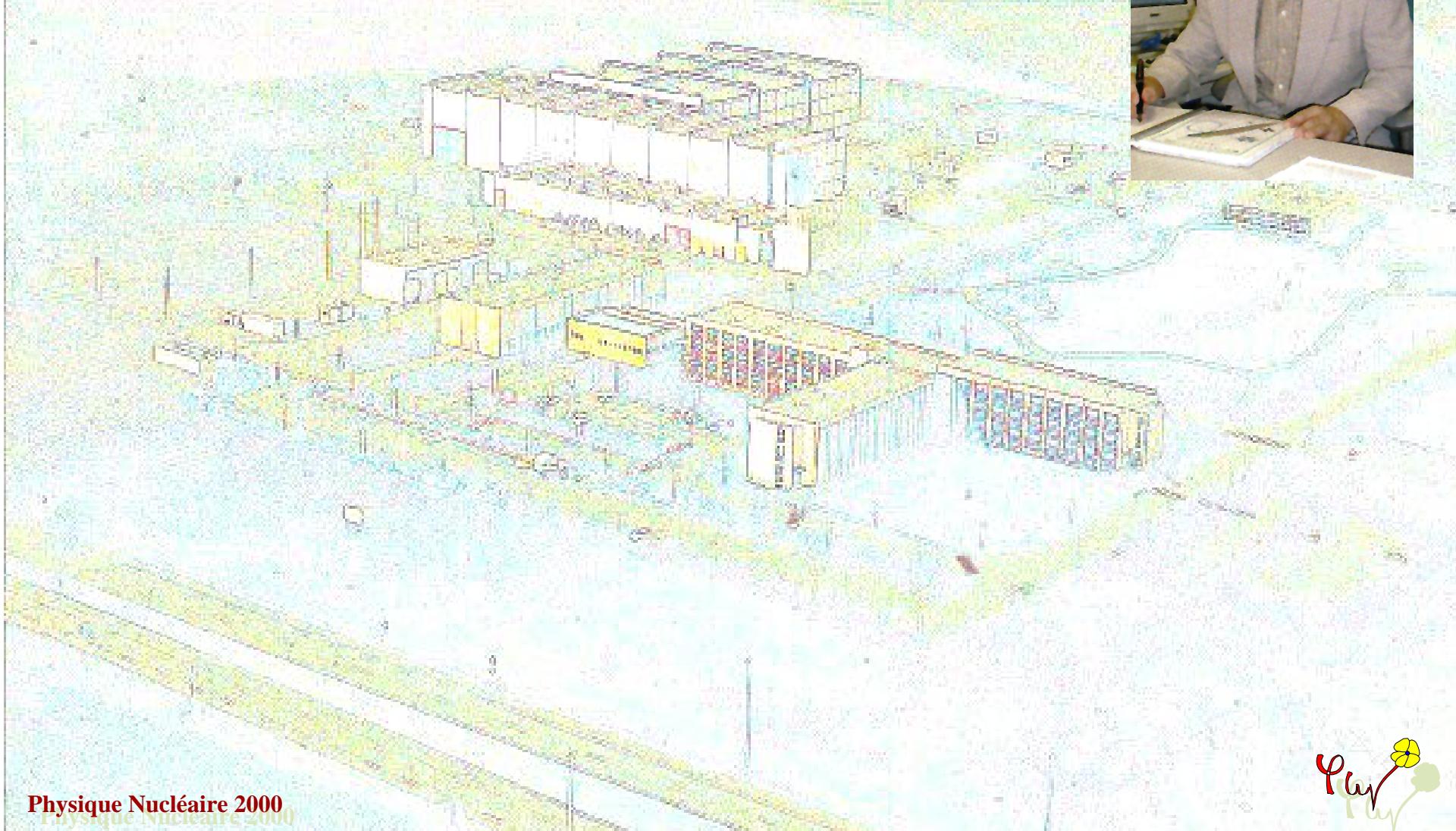


Exotic Nuclei



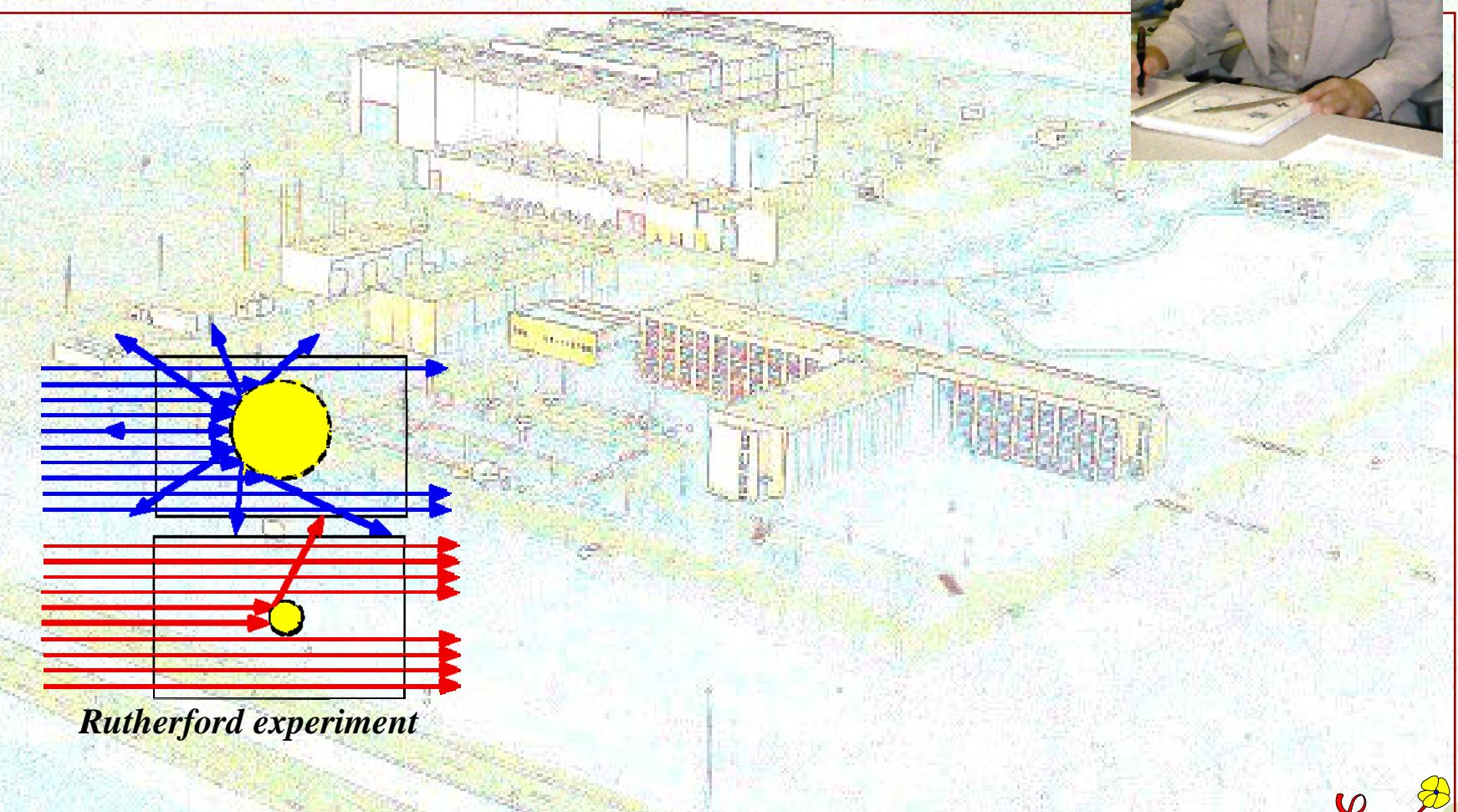
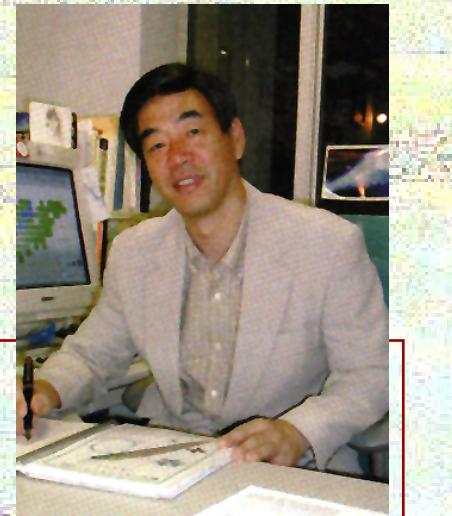
Halo nuclei

Tanikawa
Tanihata



Halo nuclei

Tanihata

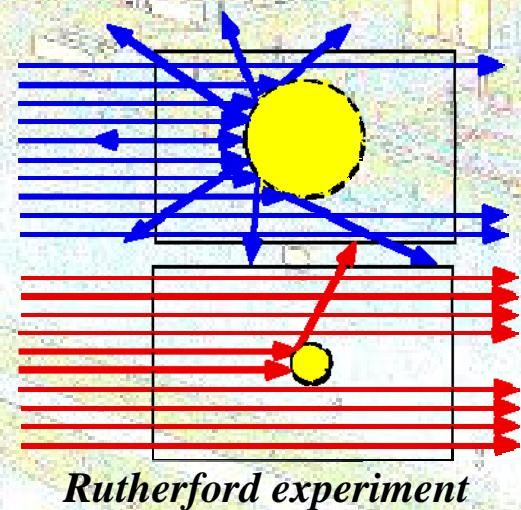


Halo nuclei

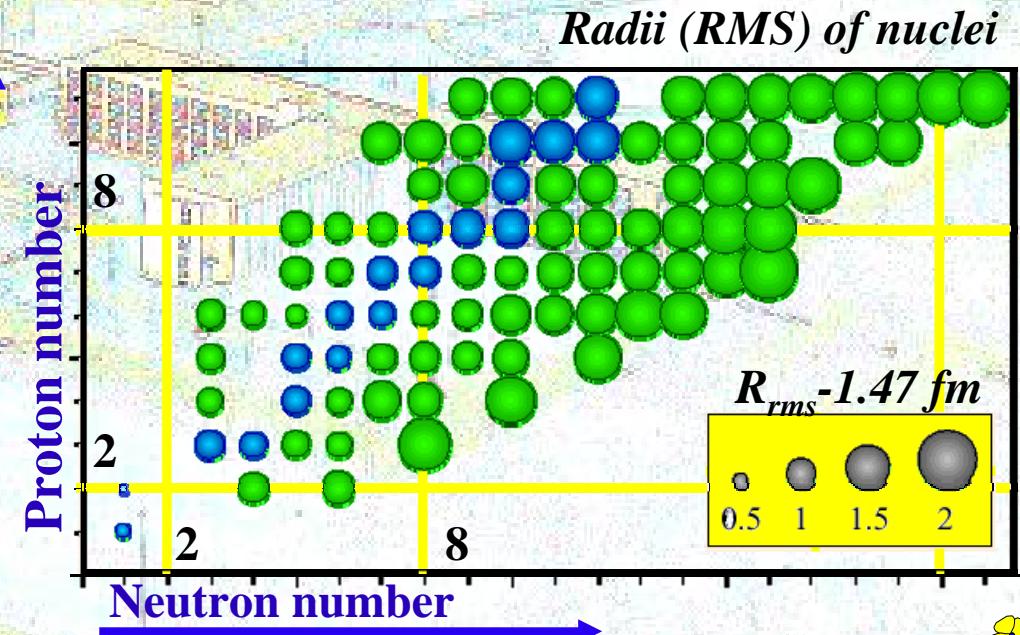
Tanihata



Abnormal size of
neutron rich nuclei



Rutherford experiment

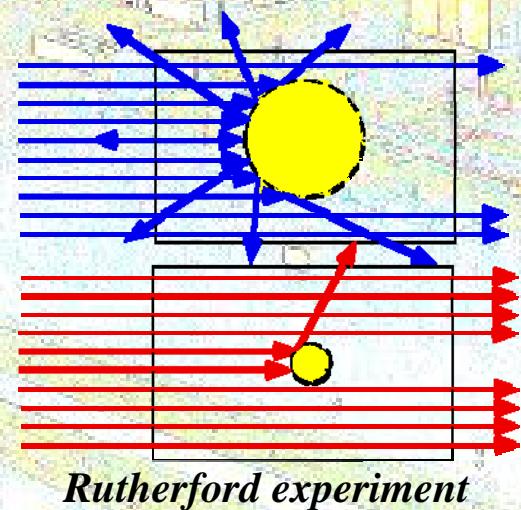


Halo nuclei

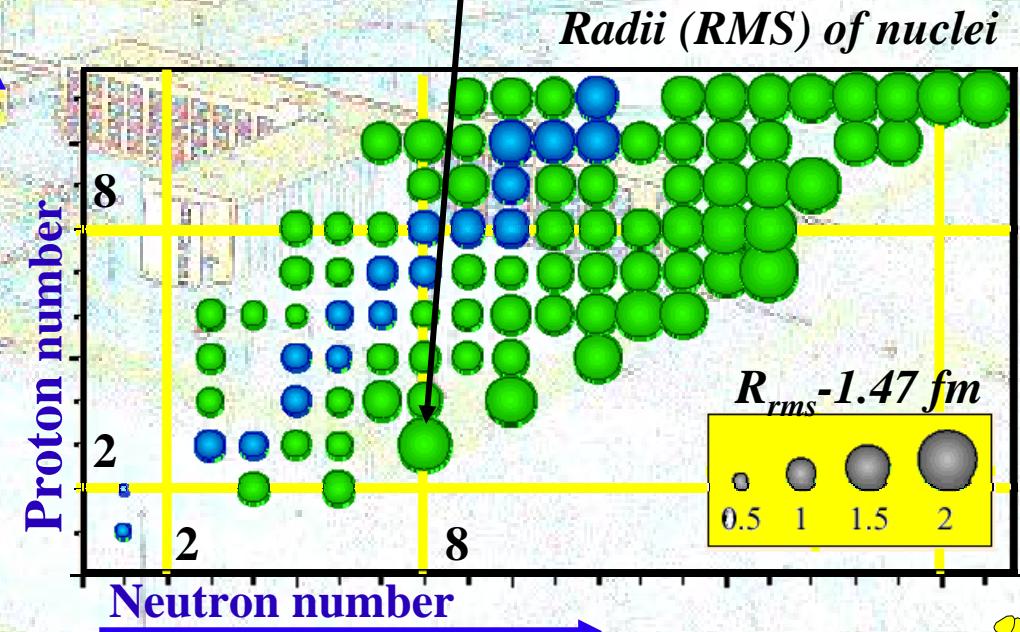
Tanihata



● Abnormal size of ^{11}Li neutron rich nuclei

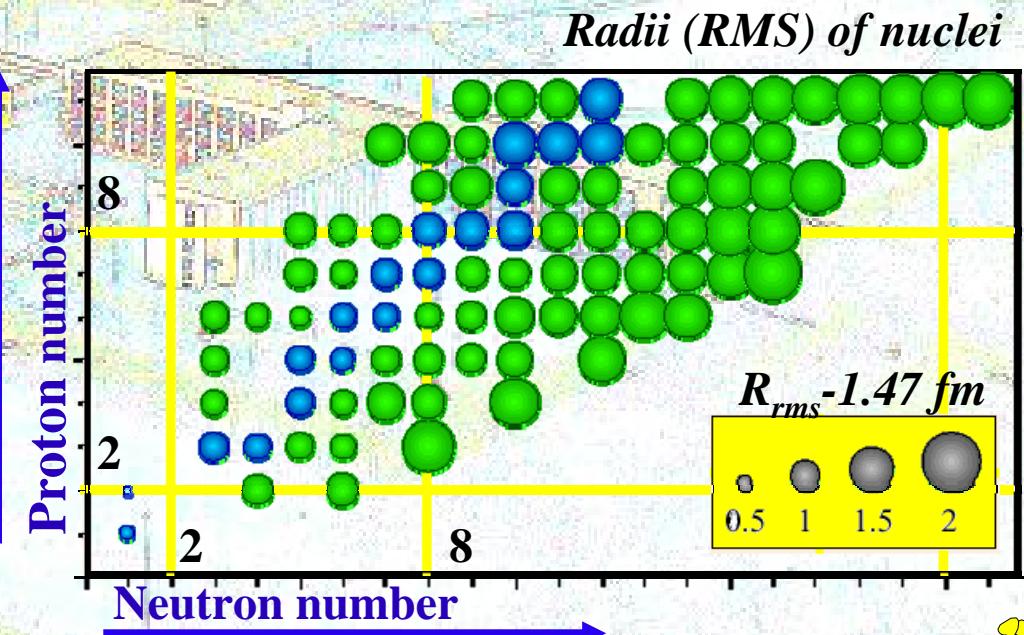


Rutherford experiment



Halo nuclei

- Abnormal size of neutron rich nuclei

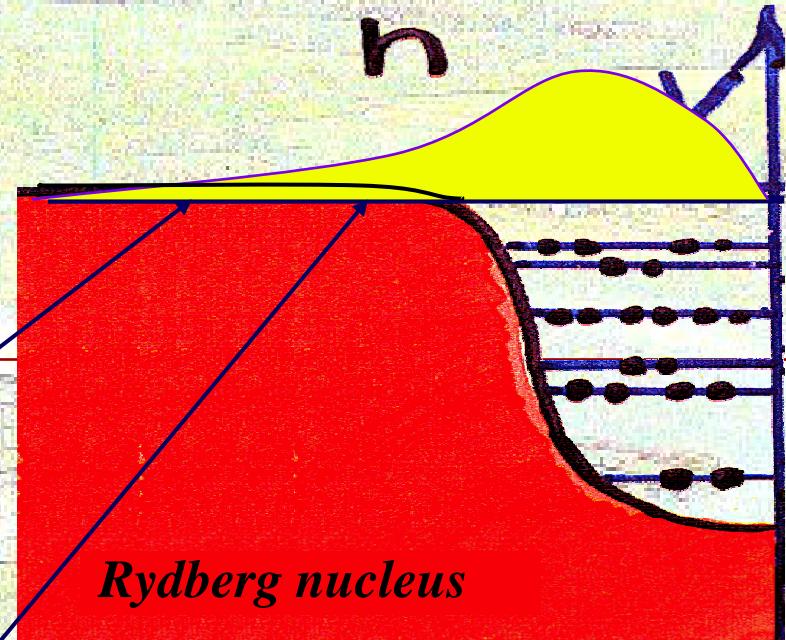


Halo nuclei

- Abnormal size of neutron rich nuclei

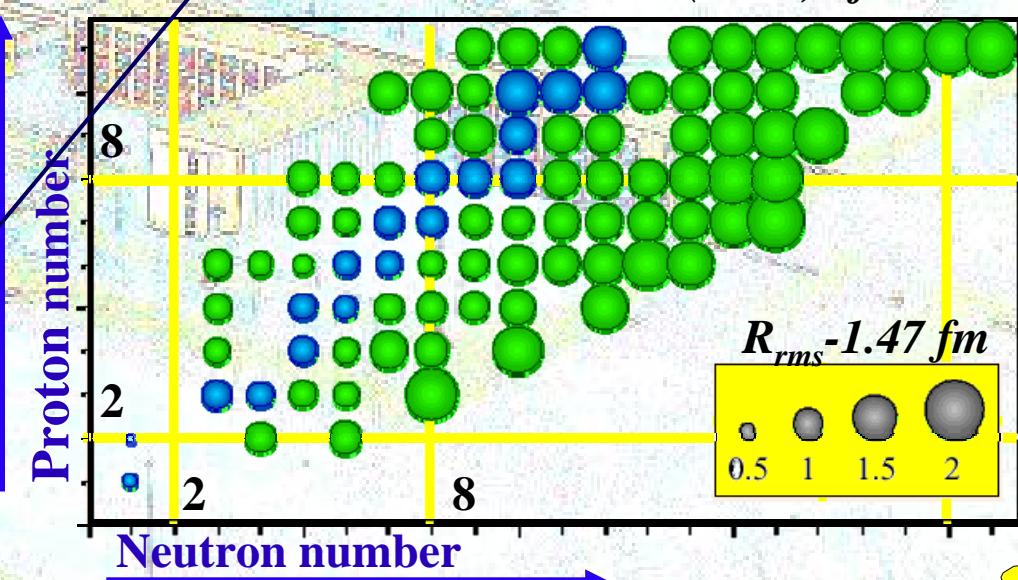
- Weakly bound

- Tunnel effect



Rydberg nucleus

Radii (RMS) of nuclei

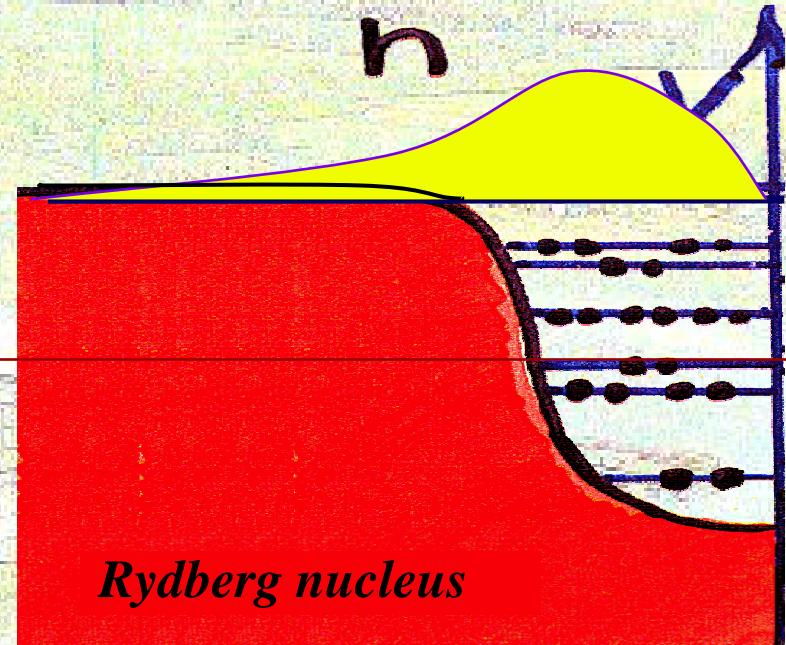


Halo nuclei

- Abnormal size of neutron rich nuclei

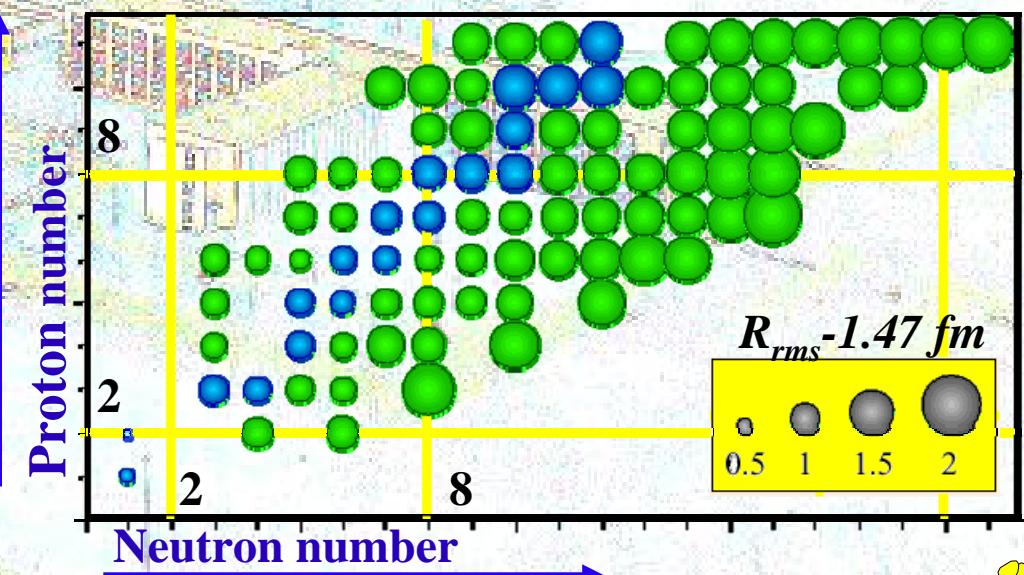
- Weakly bound

- Tunnel effect
THE HALO



Rydberg nucleus

Radii (RMS) of nuclei

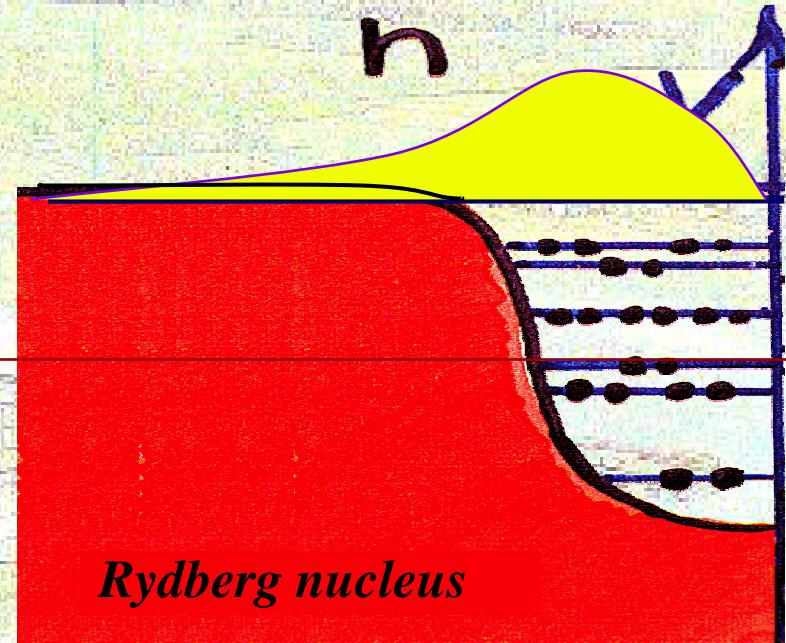


Halo nuclei

- Abnormal size of neutron rich nuclei

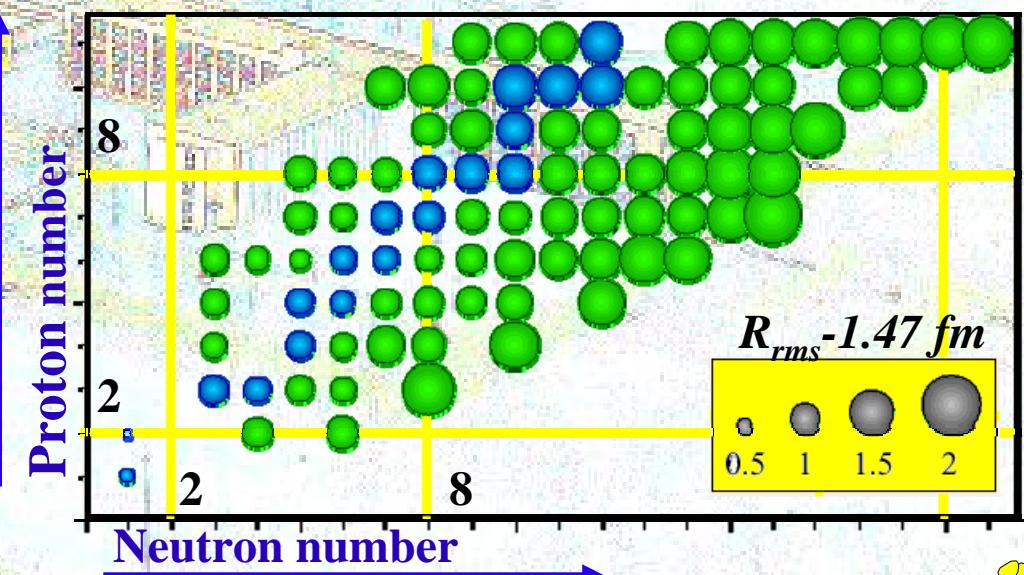
- Weakly bound

- Tunnel effect
THE HALO



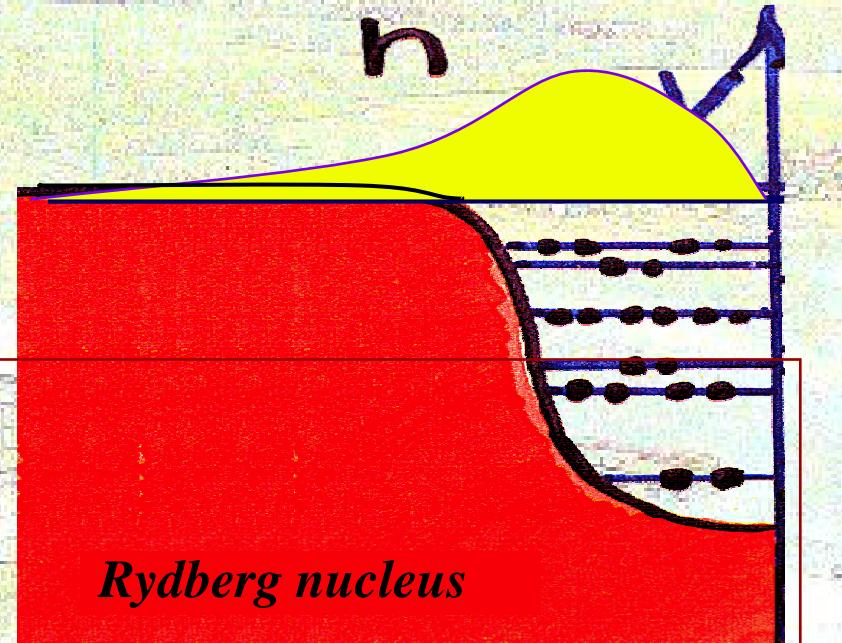
Rydberg nucleus

Radii (RMS) of nuclei



Halo nuclei

- Confirmed by nuclear reaction



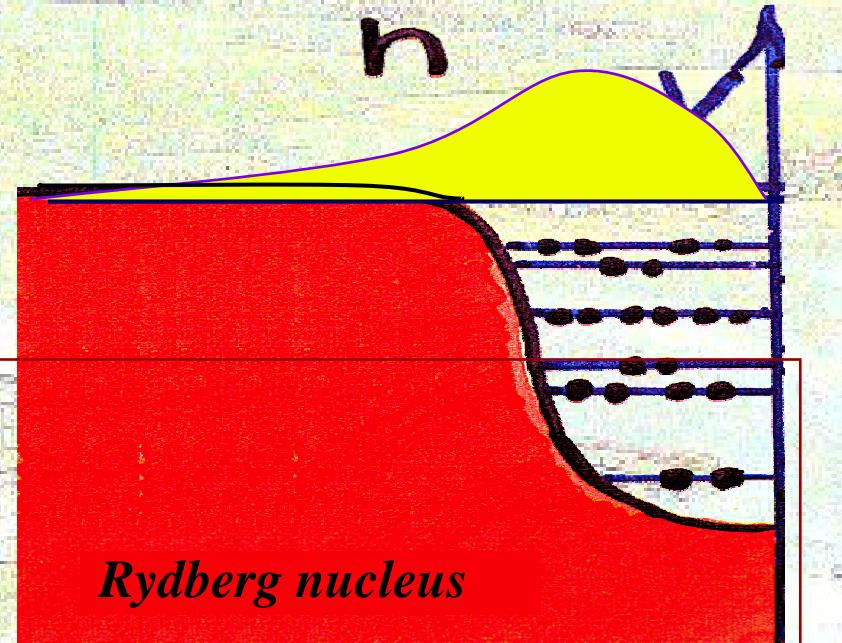
Rydberg nucleus



Halo nuclei

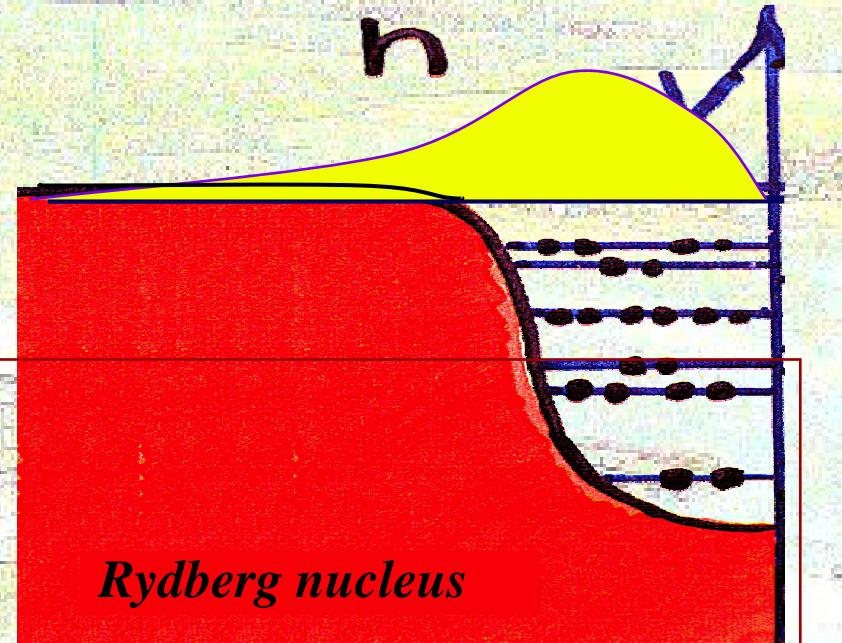
- Confirmed by nuclear reaction

Halo nucleus
bombarding
a target nucleus

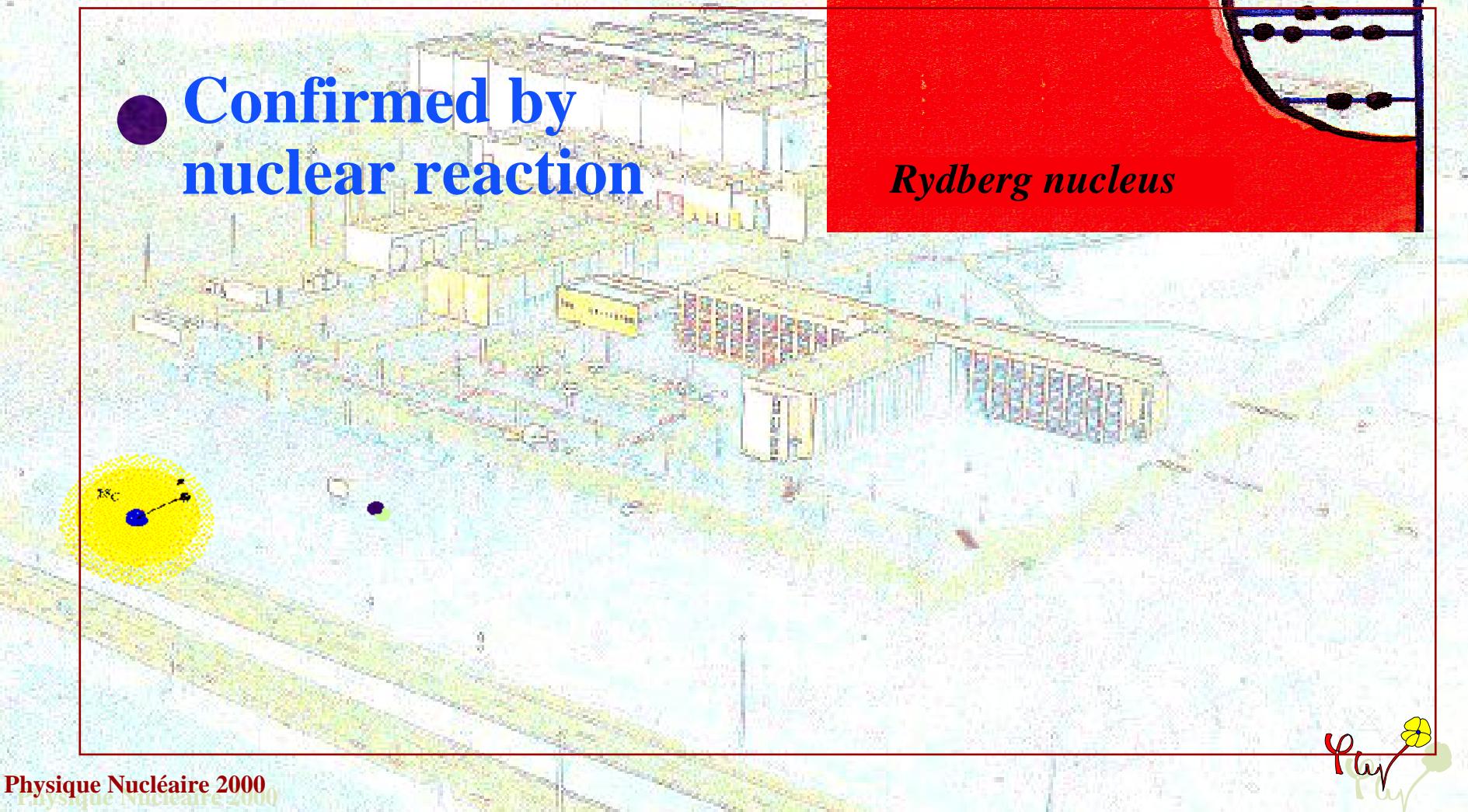


Halo nuclei

- Confirmed by nuclear reaction

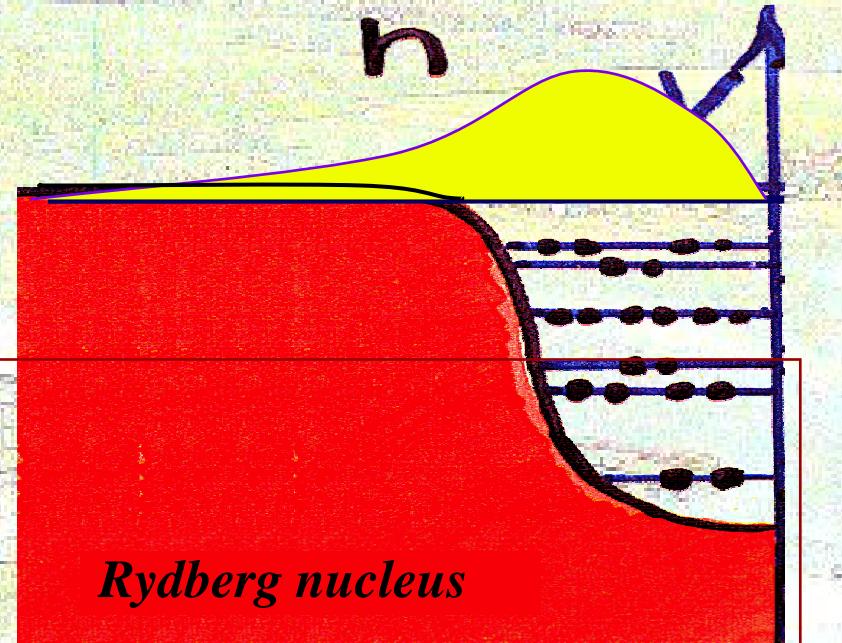


Rydberg nucleus

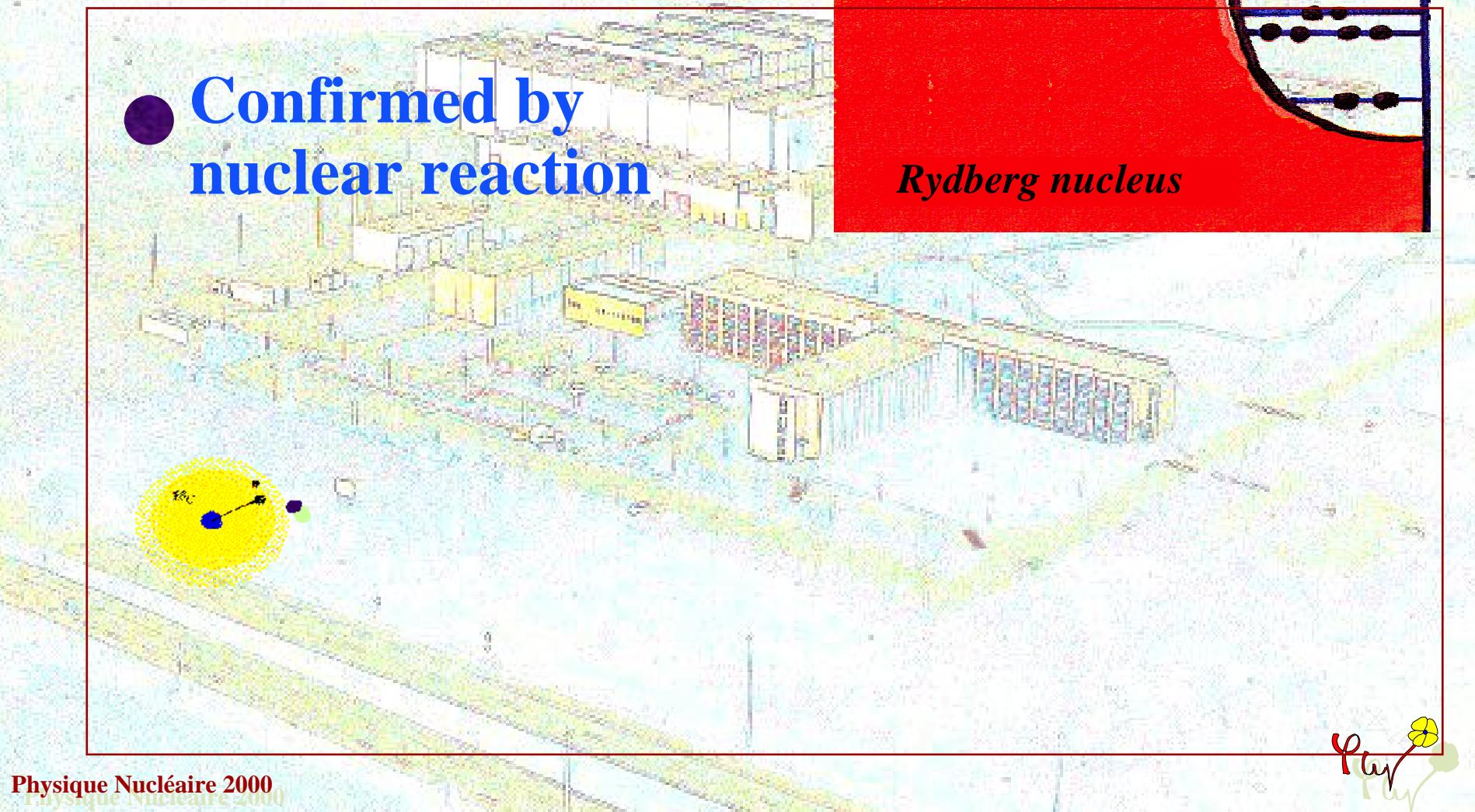


Halo nuclei

- Confirmed by nuclear reaction

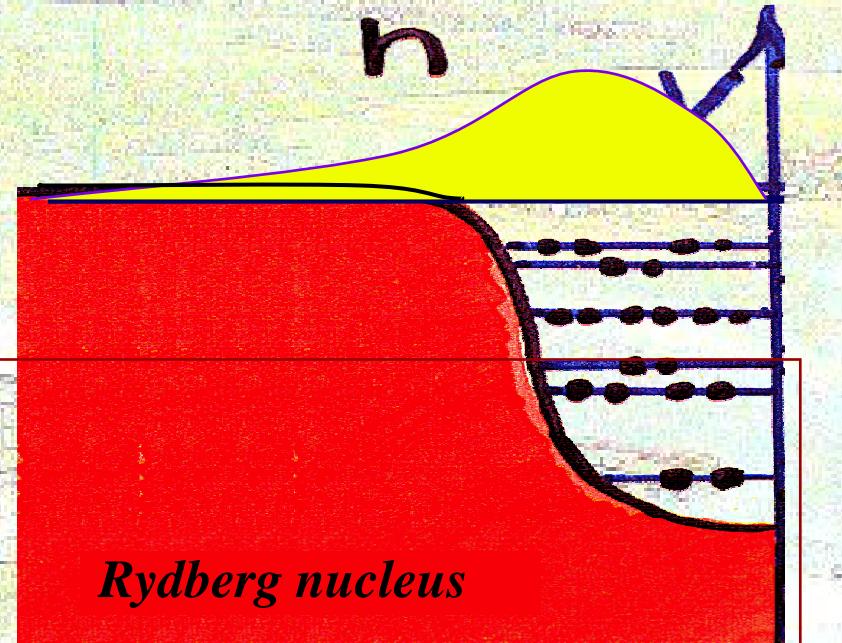


Rydberg nucleus



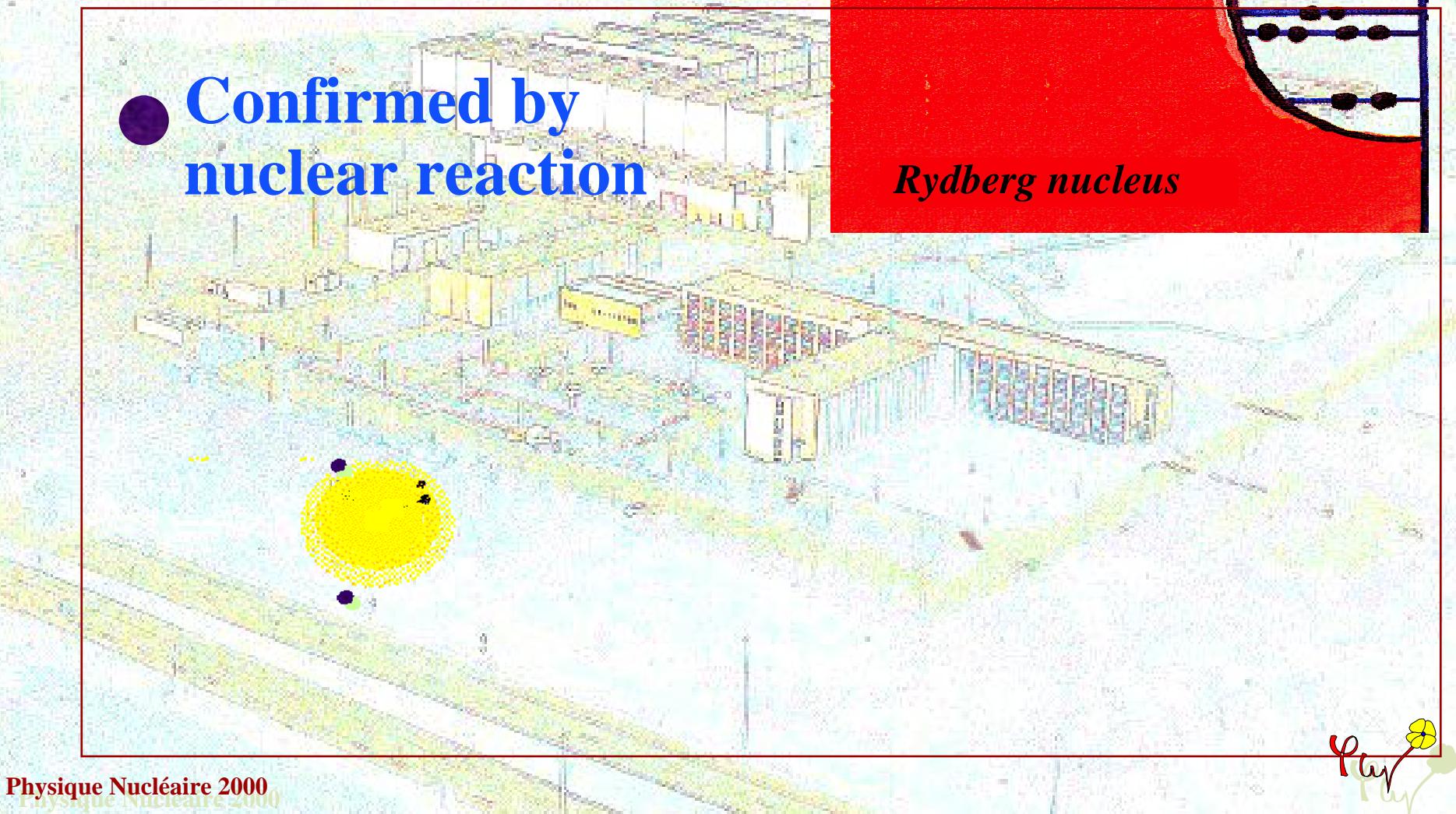
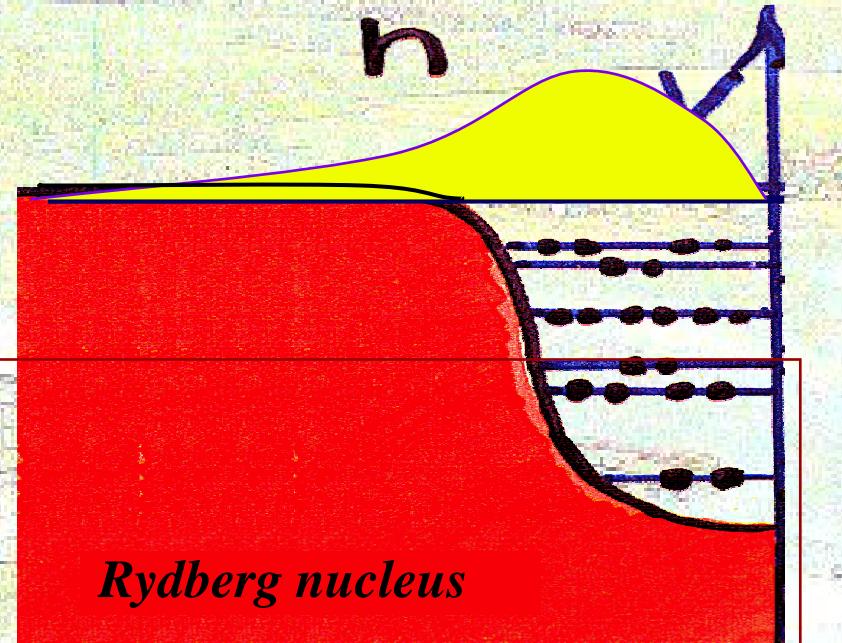
Halo nuclei

- Confirmed by nuclear reaction



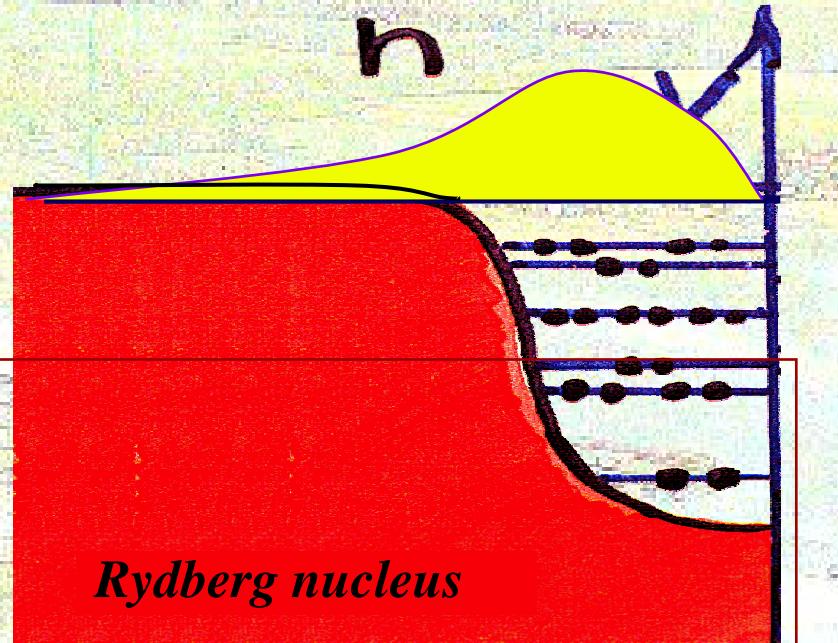
Halo nuclei

- Confirmed by nuclear reaction



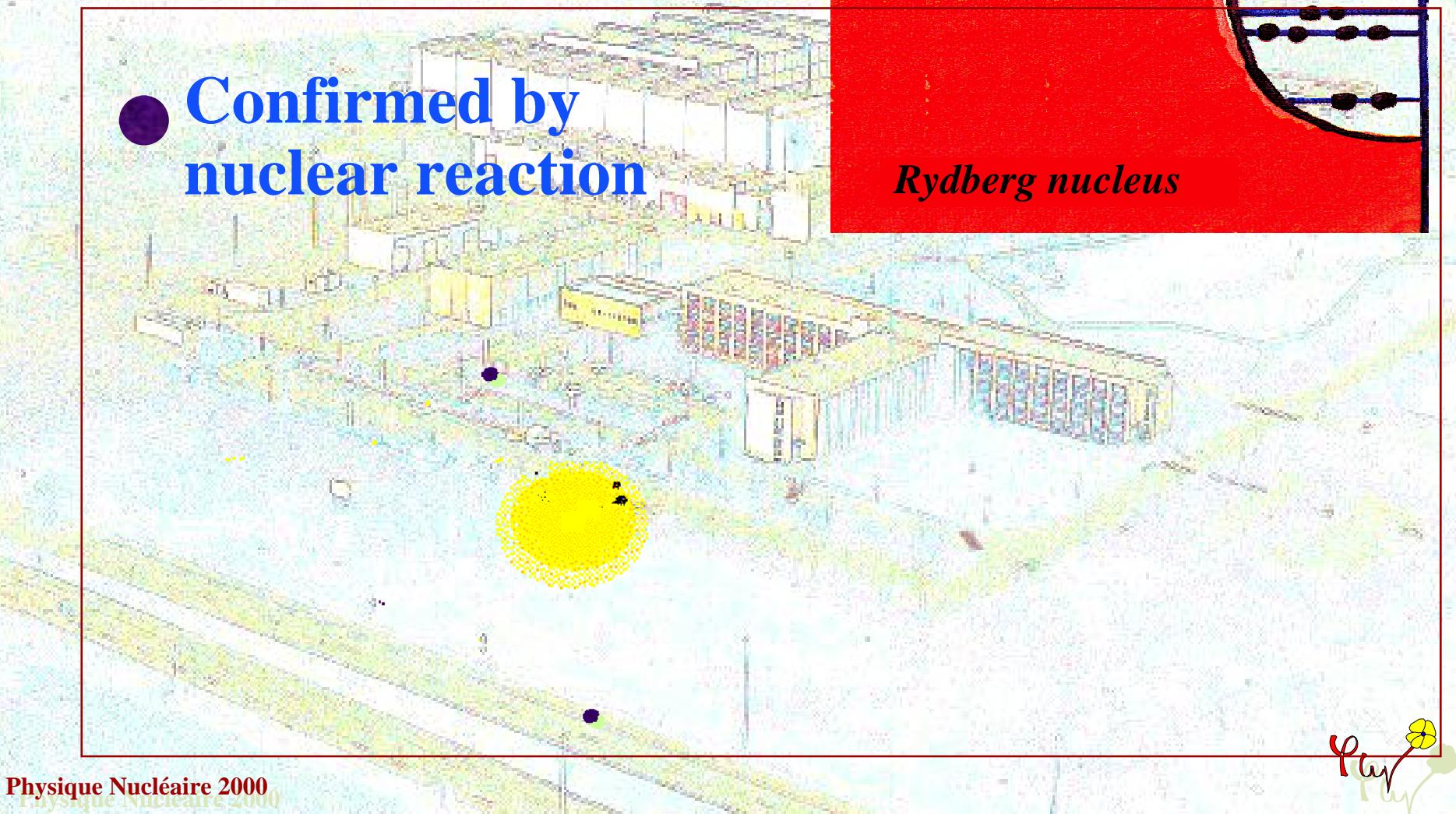
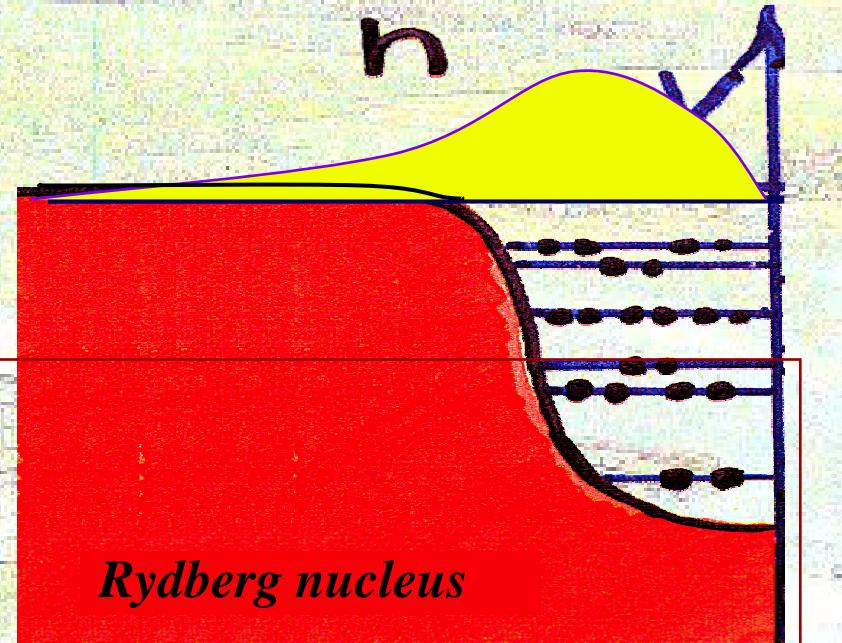
Halo nuclei

- Confirmed by nuclear reaction



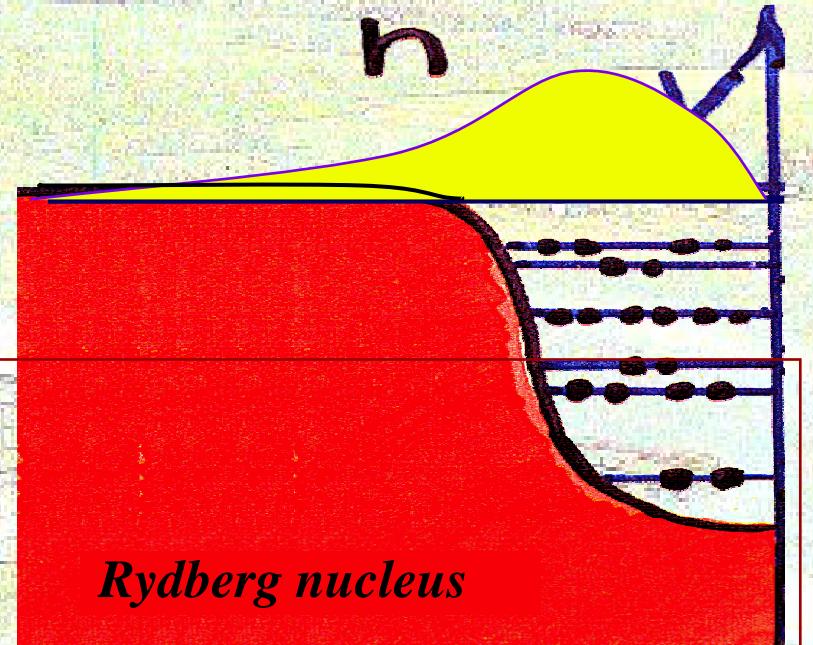
Halo nuclei

- Confirmed by nuclear reaction

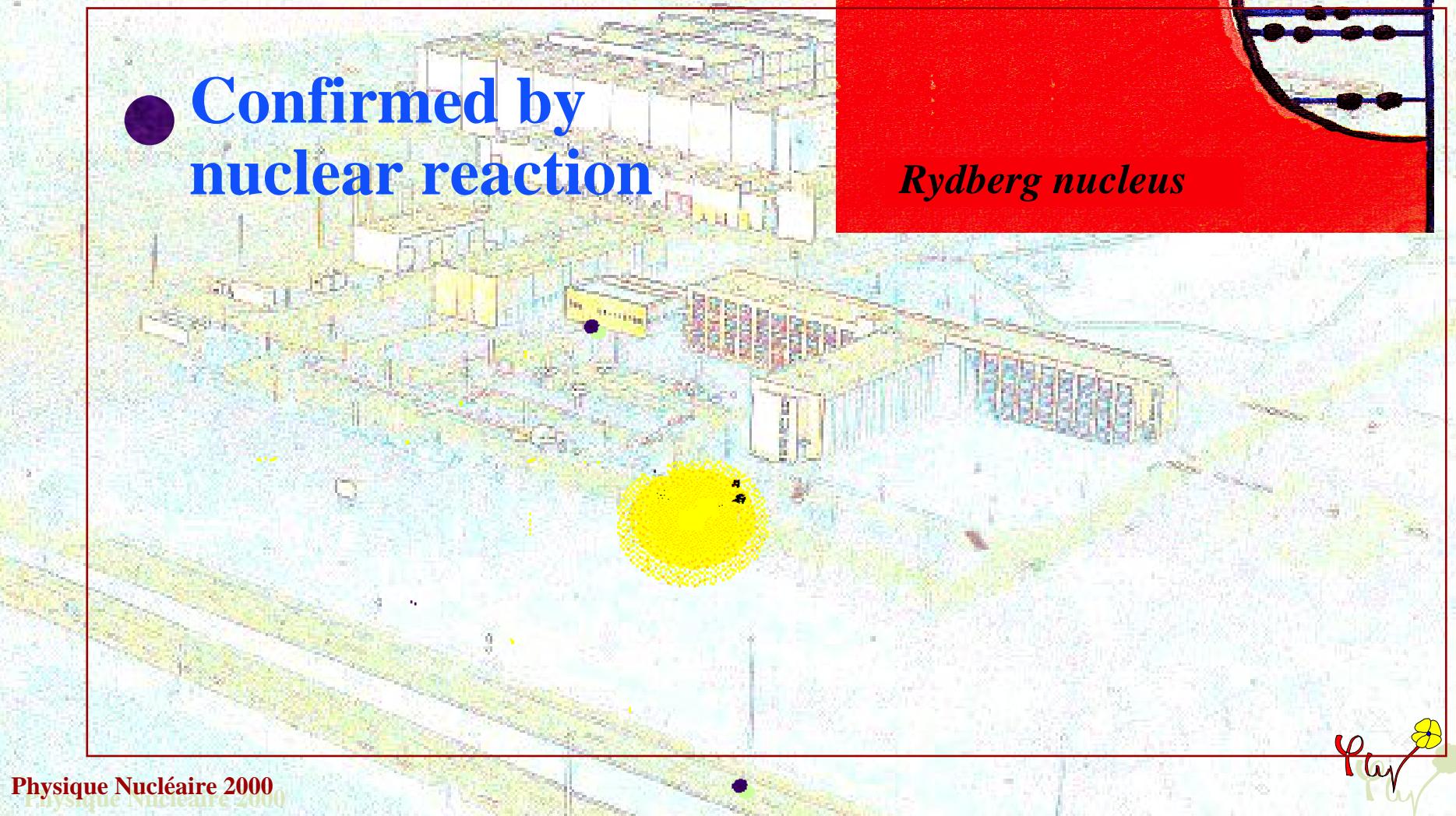


Halo nuclei

- Confirmed by nuclear reaction

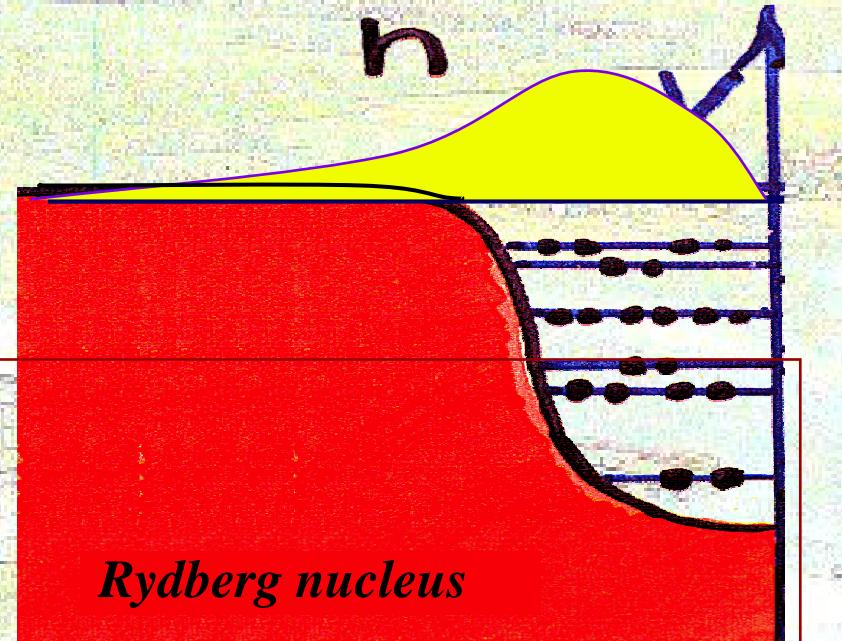


Rydberg nucleus



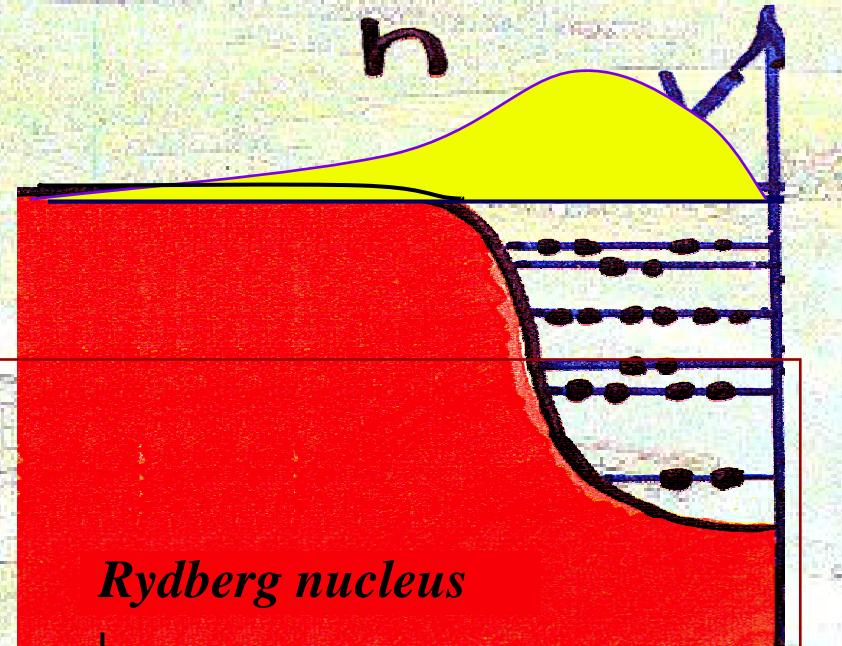
Halo nuclei

- Confirmed by nuclear reaction

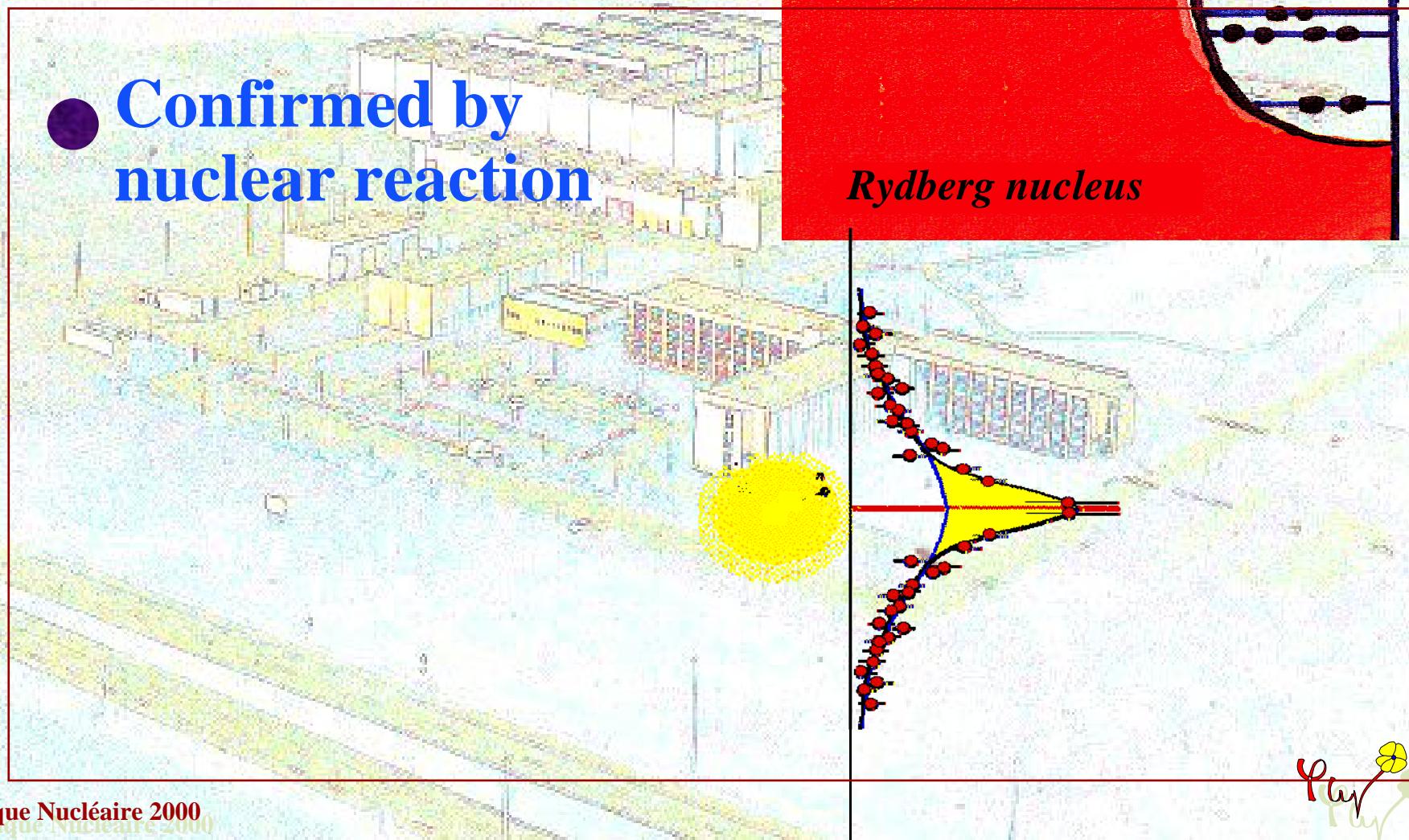


Halo nuclei

- Confirmed by nuclear reaction



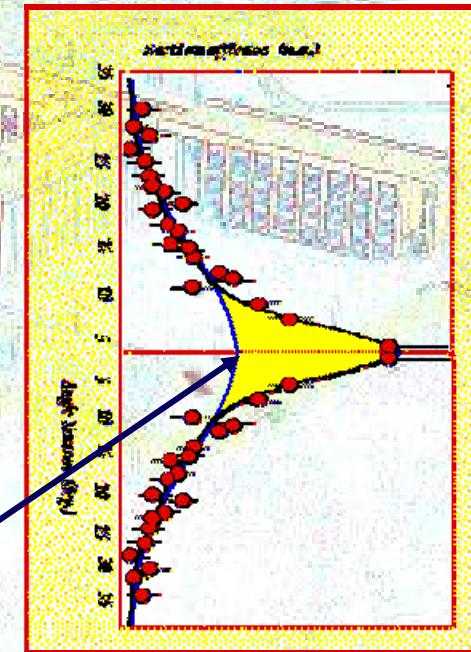
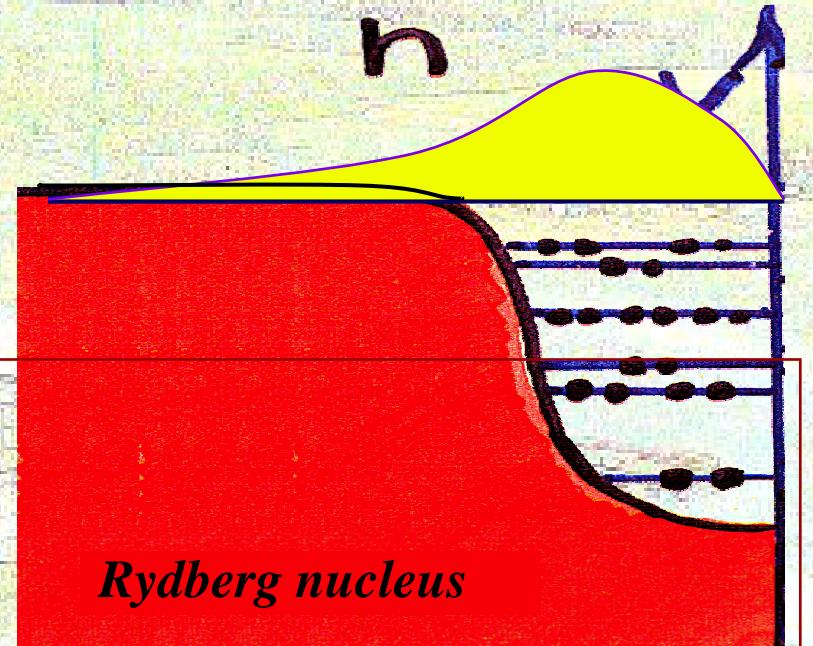
Rydberg nucleus



Halo nuclei

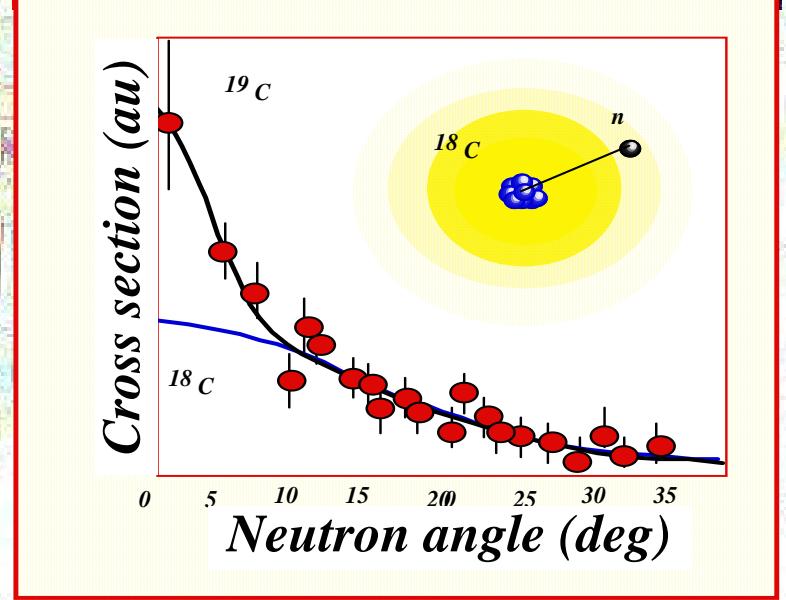
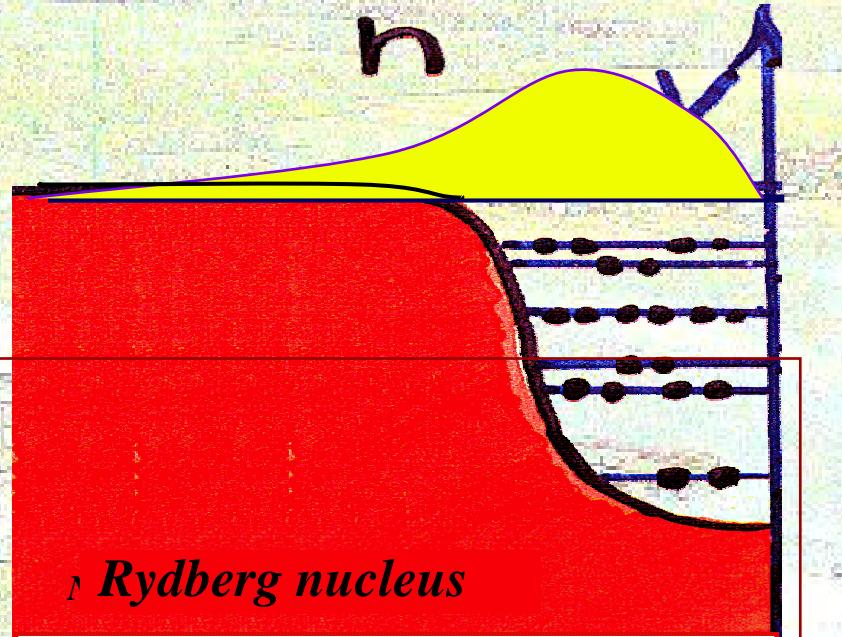
- Confirmed by nuclear reaction

- Direct measure of the wave function in p

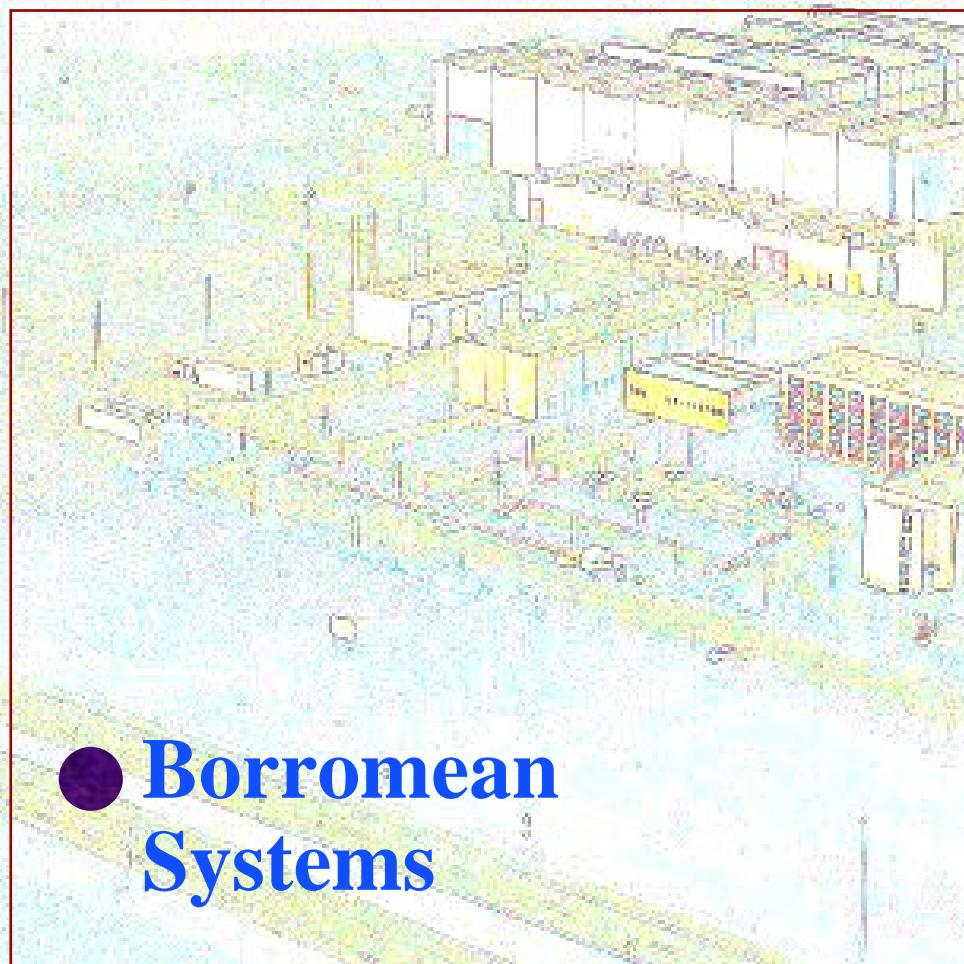


Halo nuclei

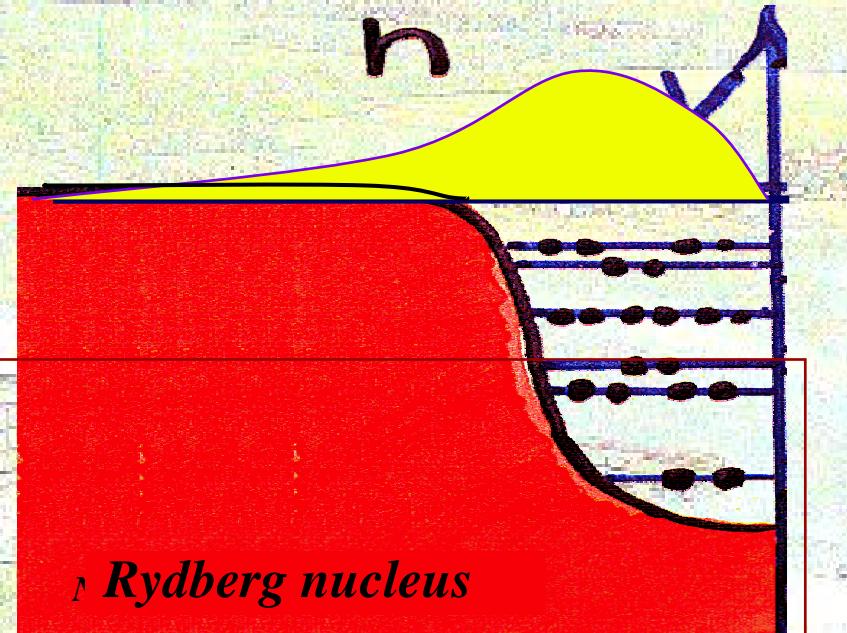
- Confirmed by nuclear reaction
- Uncertainty principle,
 $\Delta x \Delta p \geq \hbar$: Δp small =>
 Δx big => a Halo
- Direct measure of the wave function in p



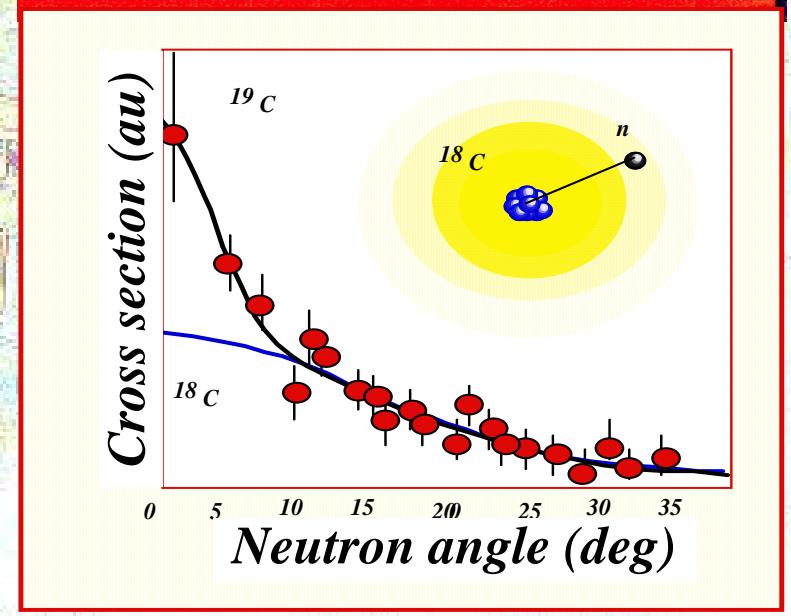
Halo nuclei



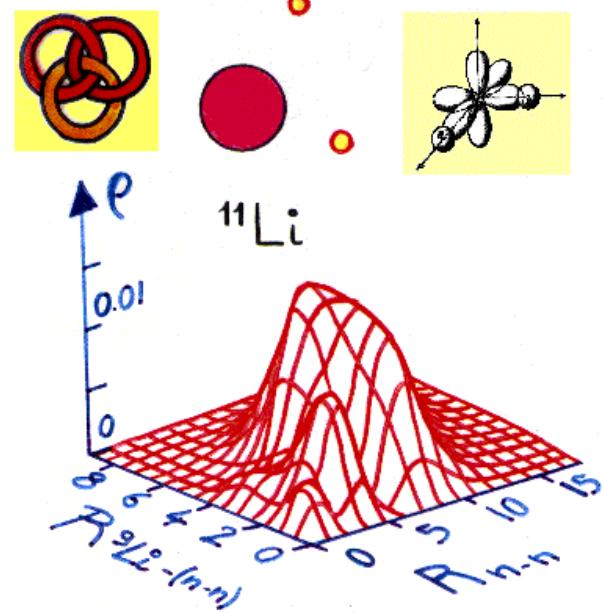
● **Borromean
Systems**



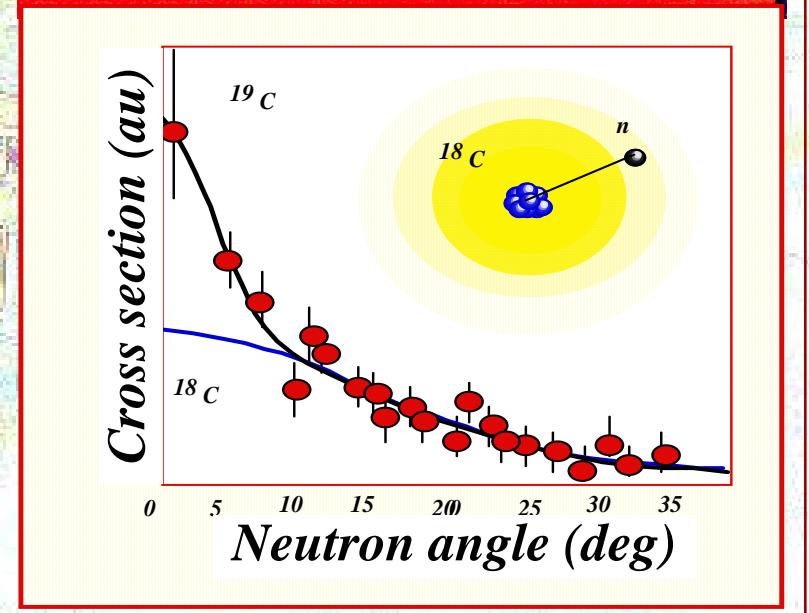
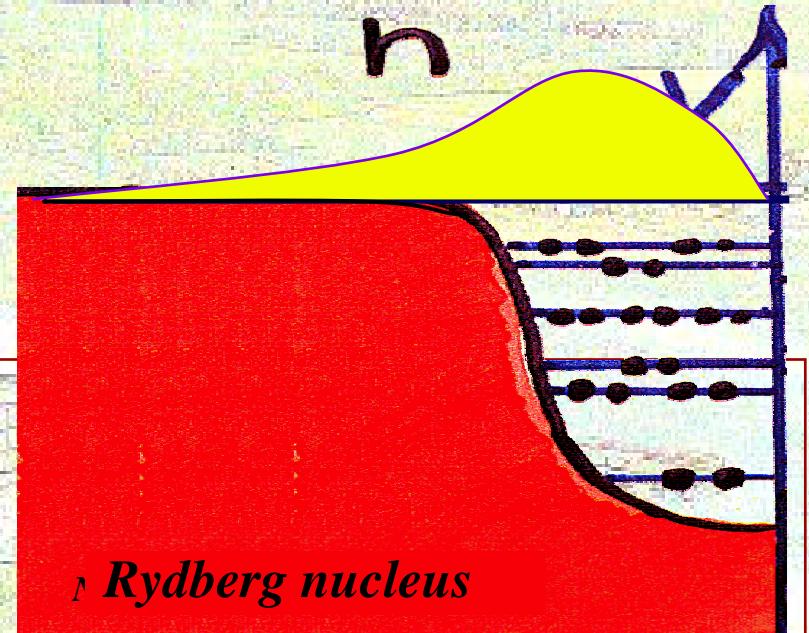
▀ *Rydberg nucleus*



Halo nuclei

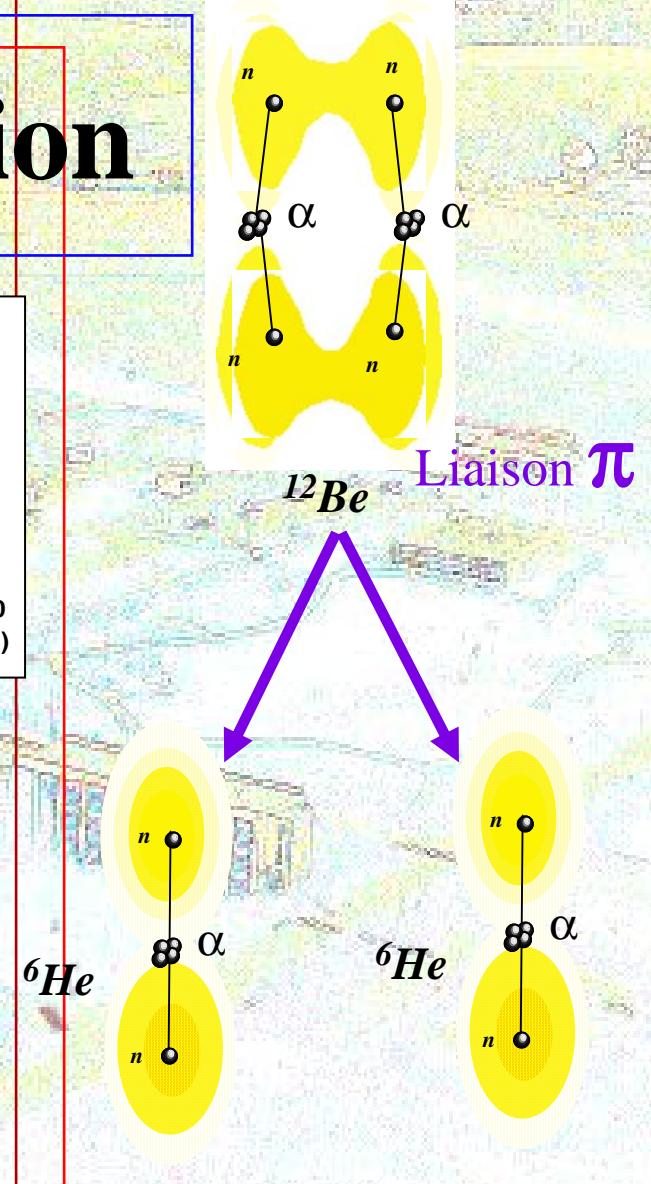
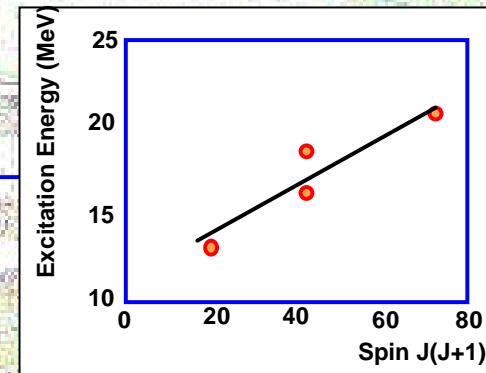
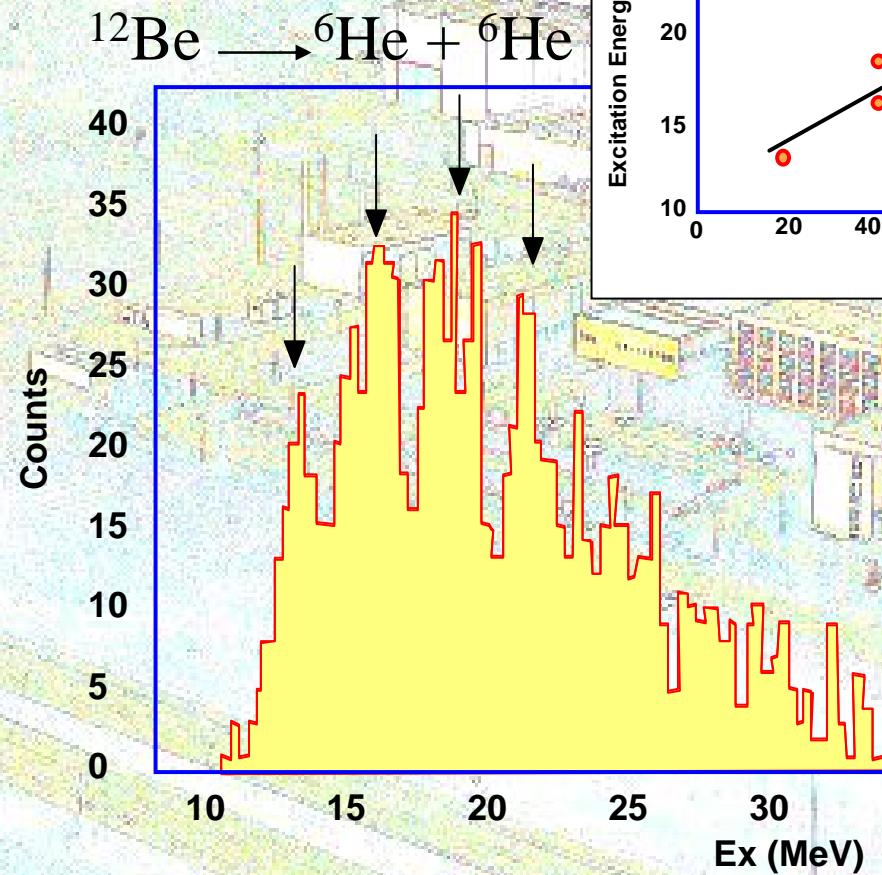


● Borromean
Systems



Nuclear Polymerization

ν Reactions

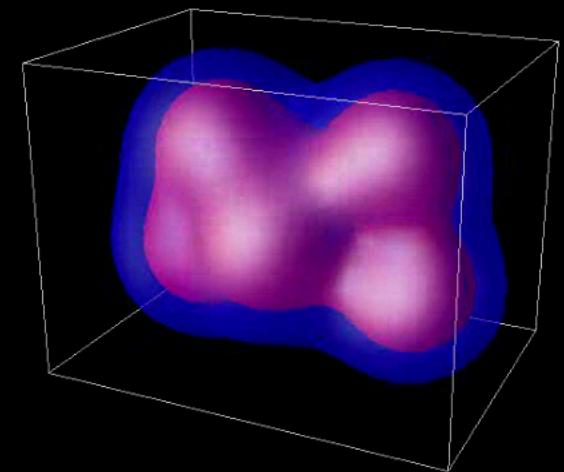


Deformation

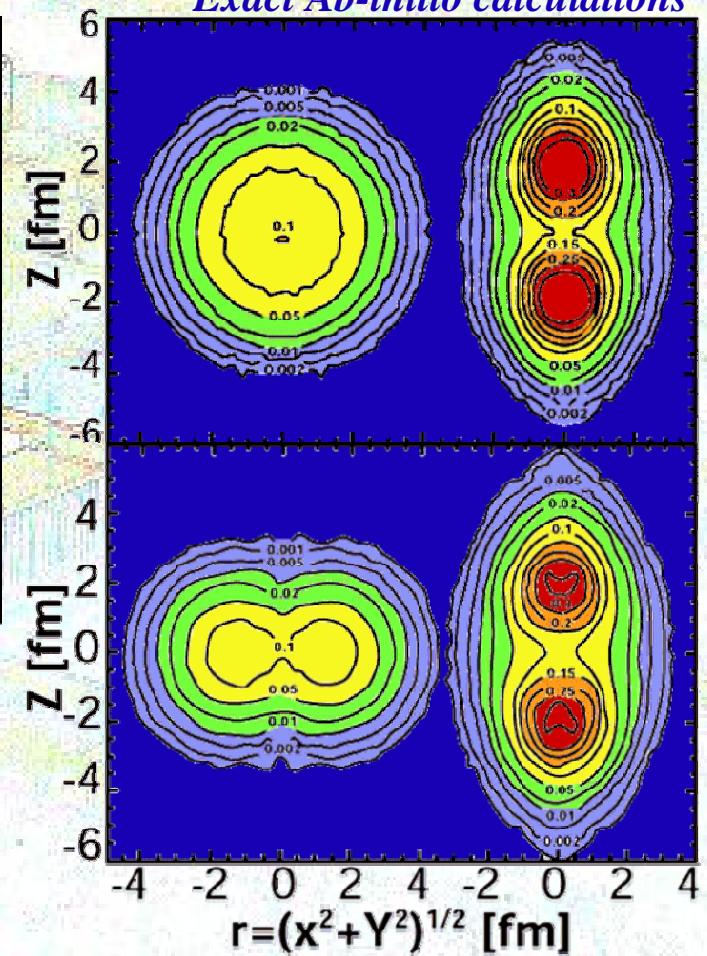
Clusters and
alpha in
small system

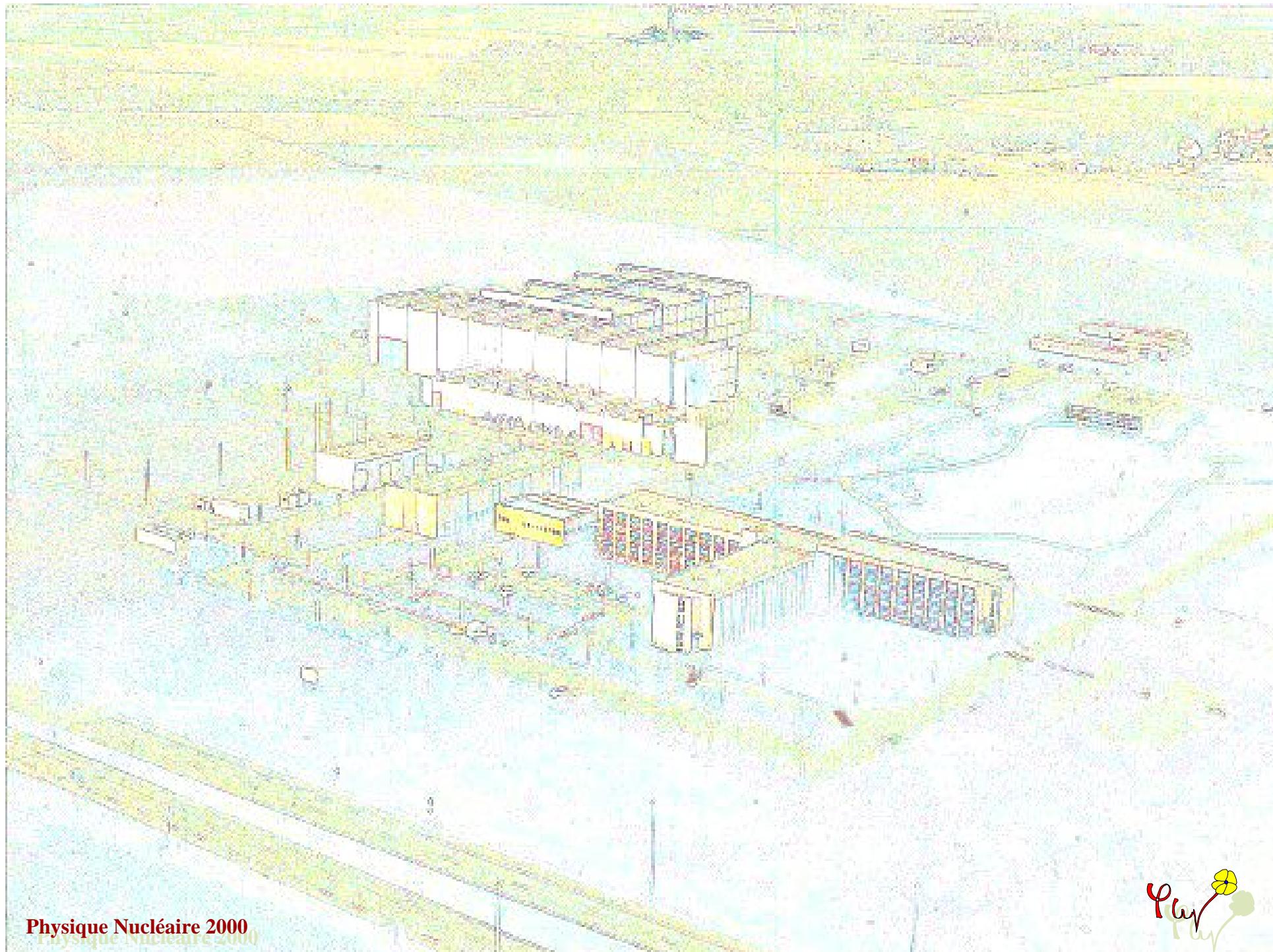
Quantum molecular approach

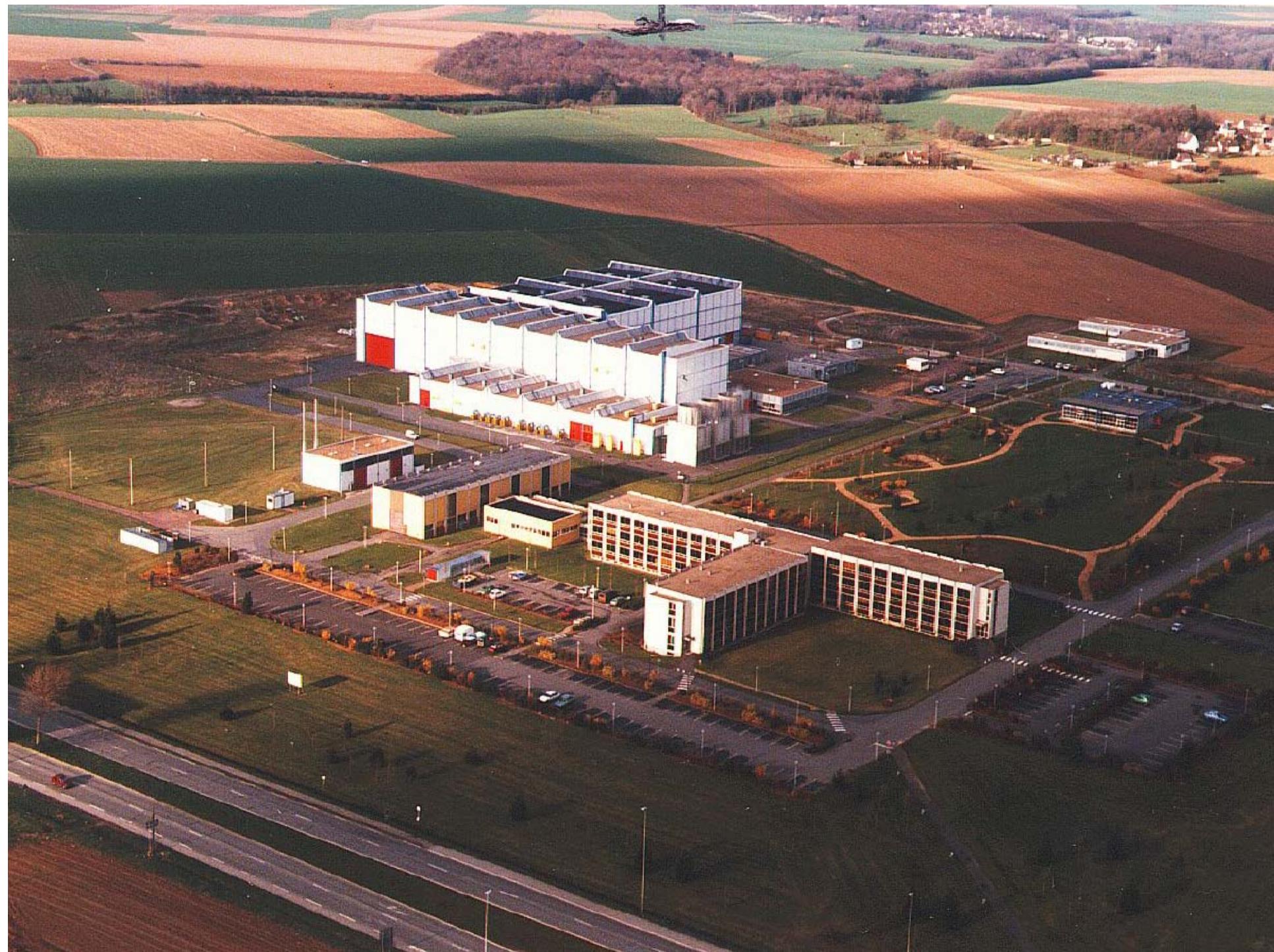
Mg24 groundstate

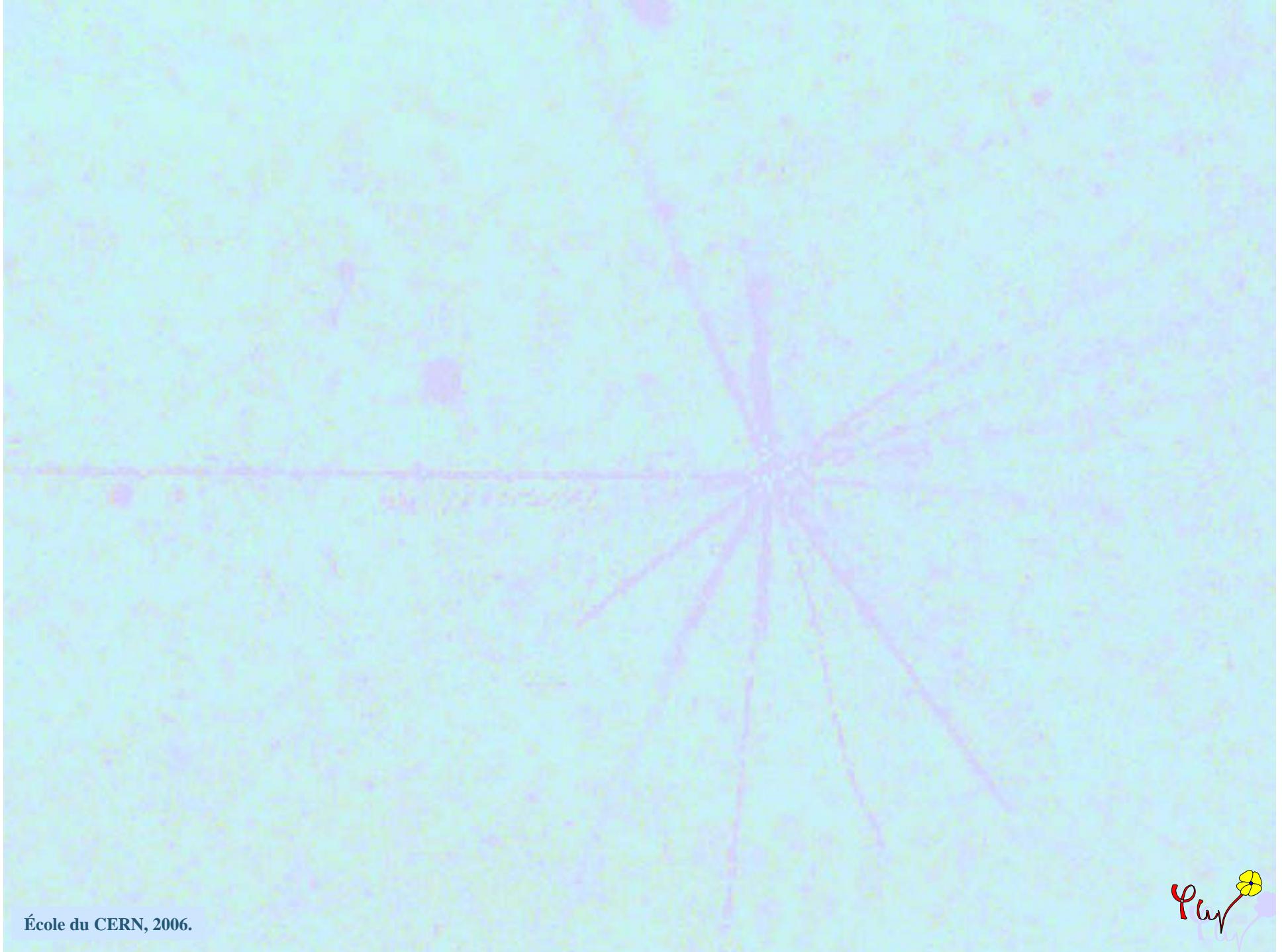


Exact Ab-initio calculations





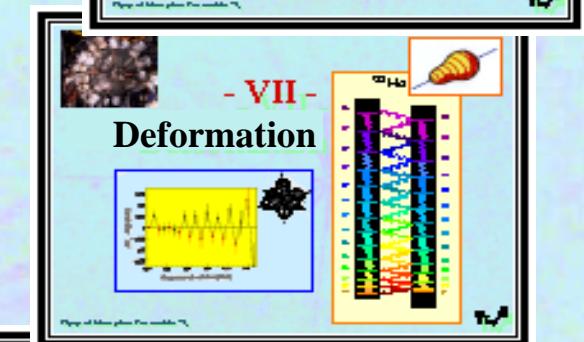
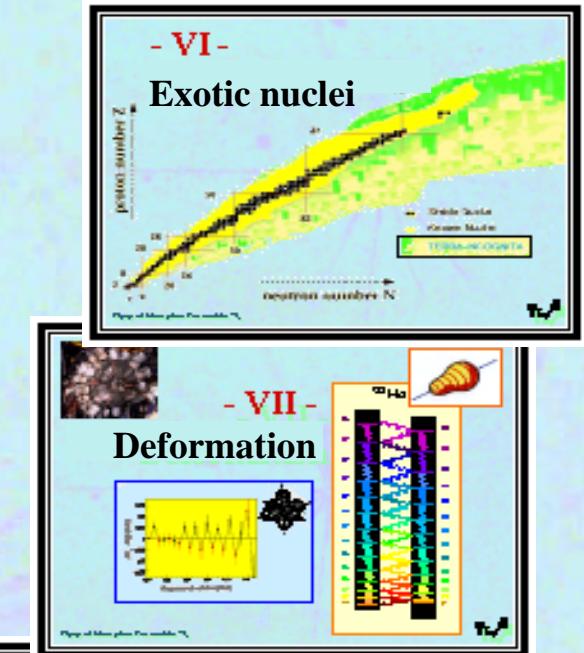
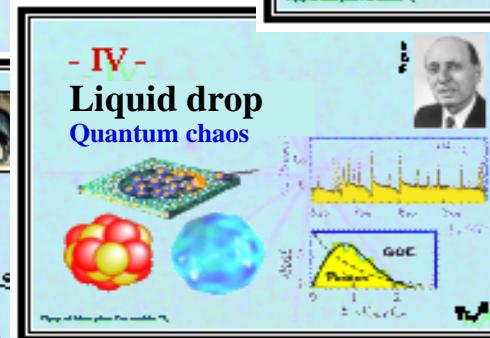
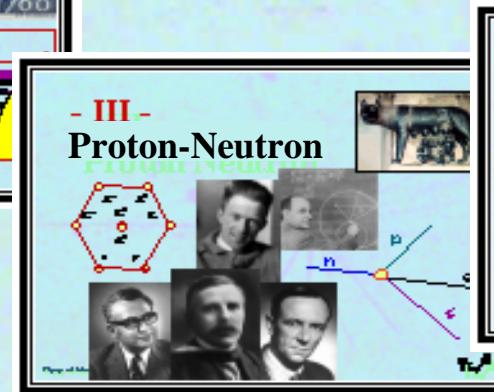
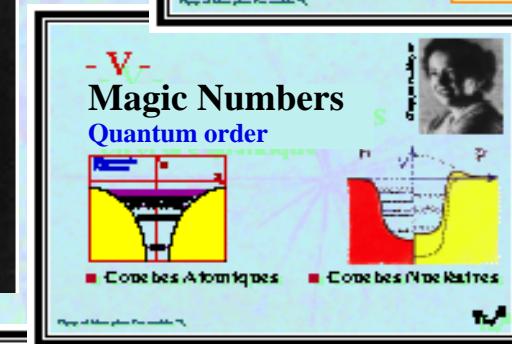
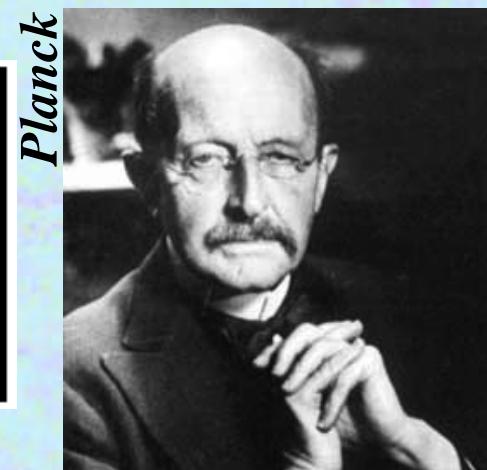
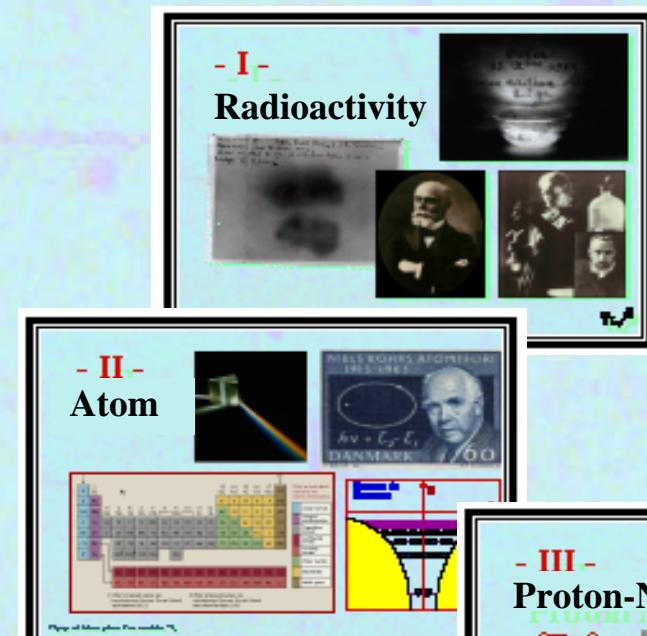




École du CERN, 2006.

Atomic Nuclei

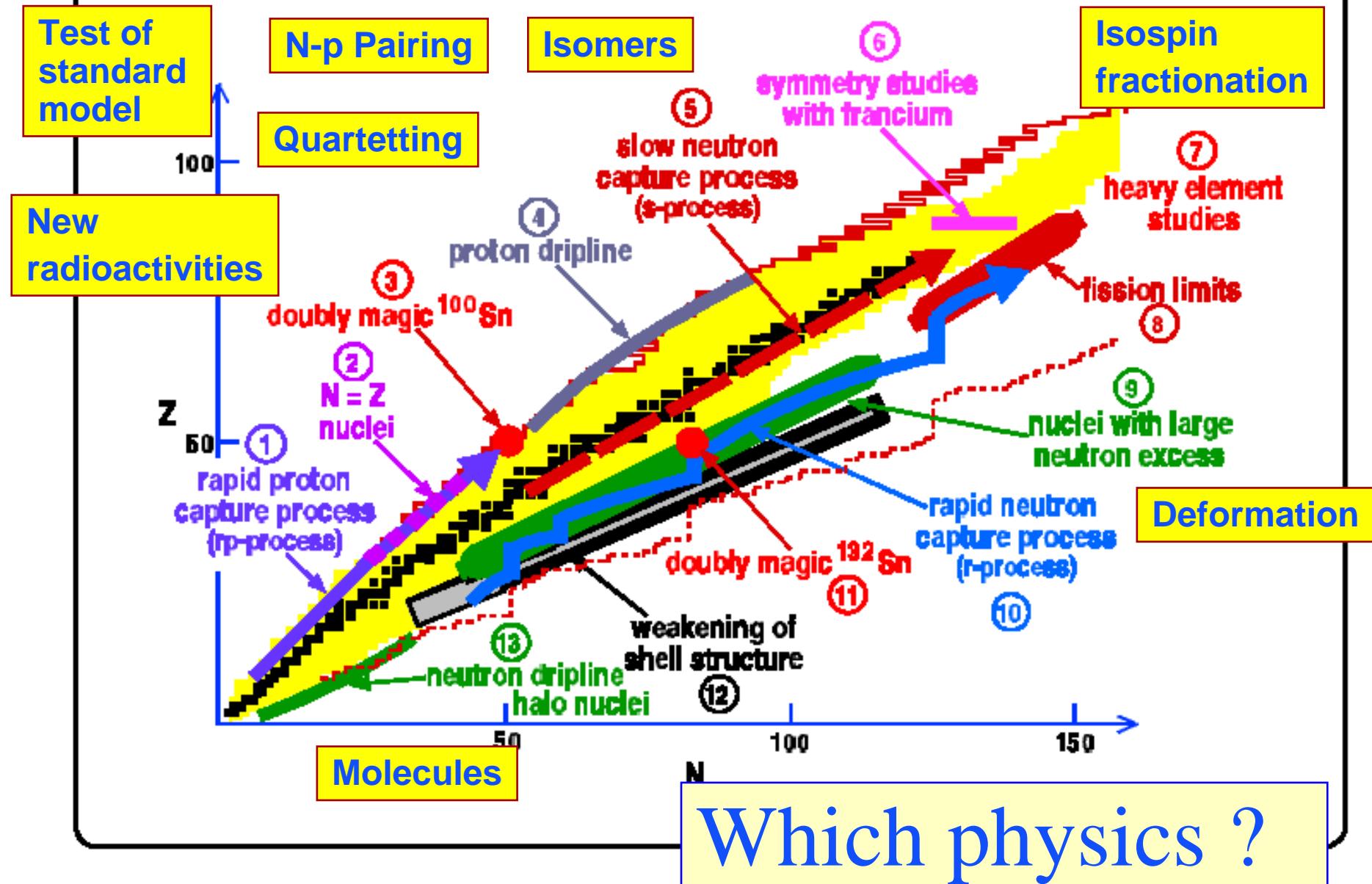
Complex quantum systems

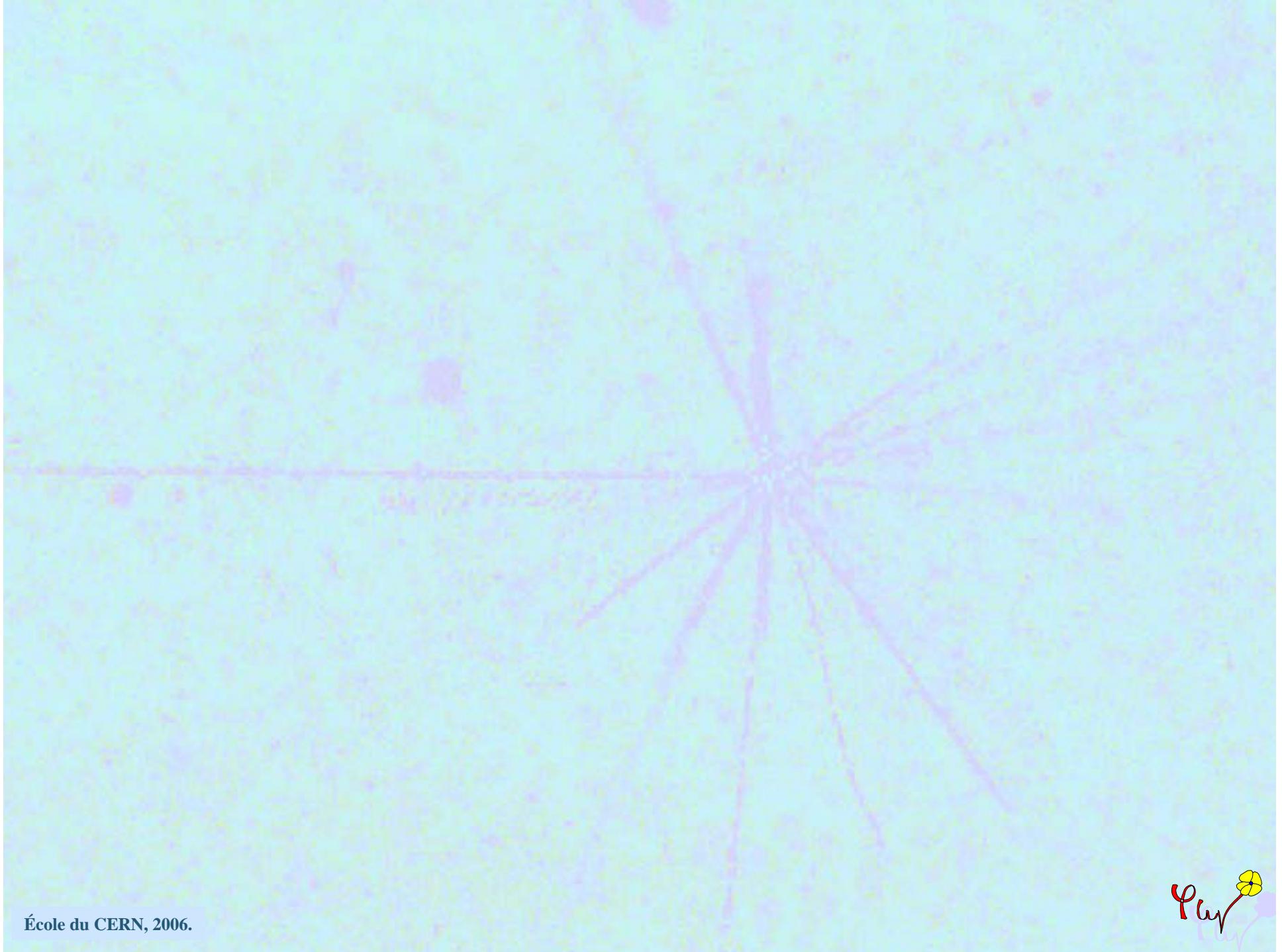


Play

RIA PRESENTATION TO NSAC

Isospin EOS

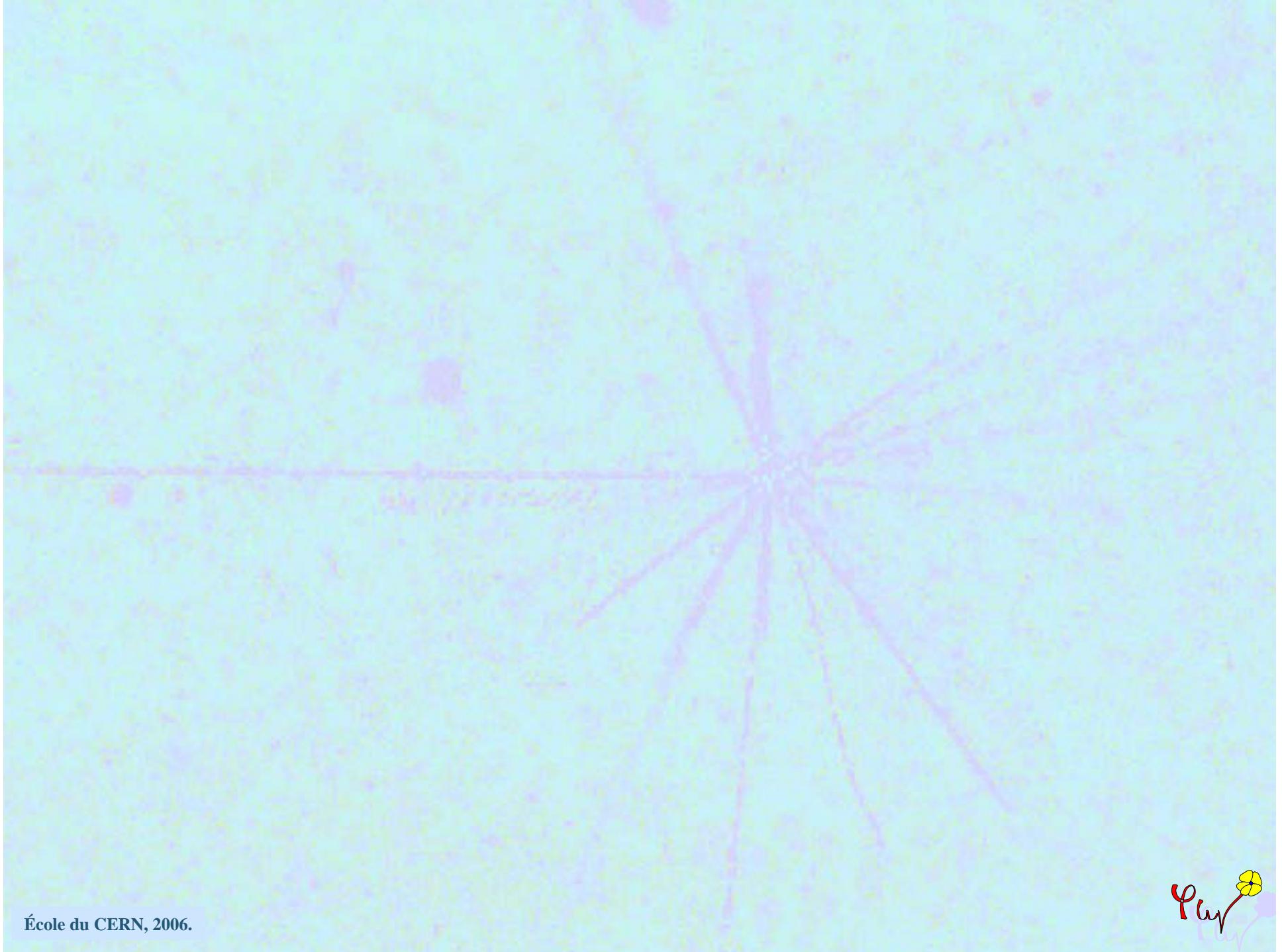




École du CERN, 2006.

- VIII -
Fin





École du CERN, 2006.

- III -

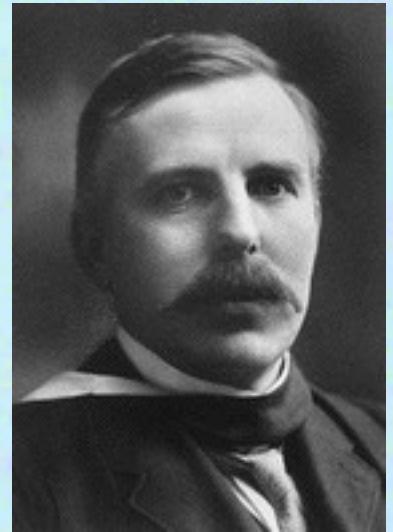
Proton Neutron Novel Quantum Symmetry



- III -

Proton Neutron

Rutherford

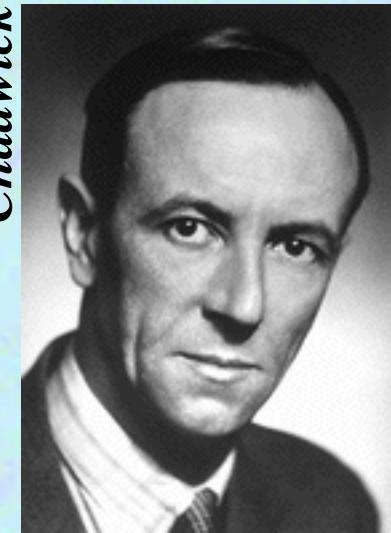


✓ 1919: H nuclei in nuclei => protons

- III -

Proton Neutron

Chadwick



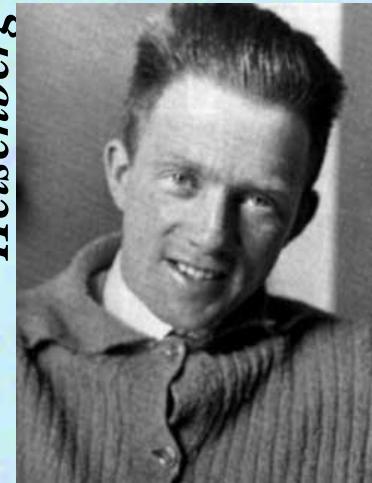
- ✓ **1919:** Protons
- ✓ **1932:** Discovery of neutrons

- III -

Proton Neutron

Novel symmetry

Heisenberg



- ✓ 1919: Protons
- ✓ 1932: Neutrons
- ✓ 1932: Twin particles ($m_n \approx m_p$)
 - Φ Proton : nucleon with the isotopic spin +1/2
 - Φ Neutron : nucleon of isospin -1/2

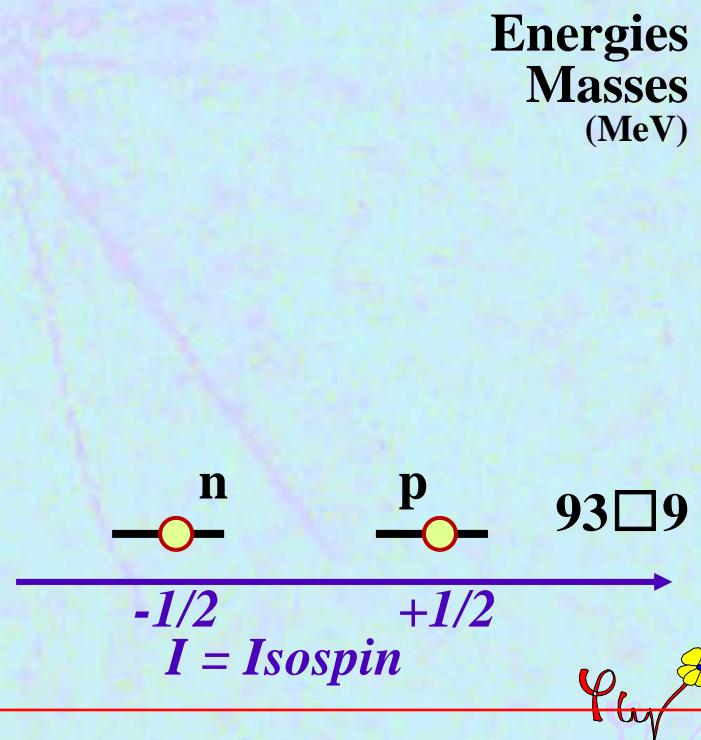


- III -

Proton Neutron Novel symmetry



- Φ New quantum number
- Φ Proton \leftrightarrow neutron



- III -

Proton Neutron Novel symmetry



✓ Symmetric nuclei

Φ Mirror nuclei: $N \leftrightarrow Z$

Φ Proton \leftrightarrow neutron

$-1/2$ $+1/2$
 $I = Isospin$



- III -

Proton Neutron Novel symmetry



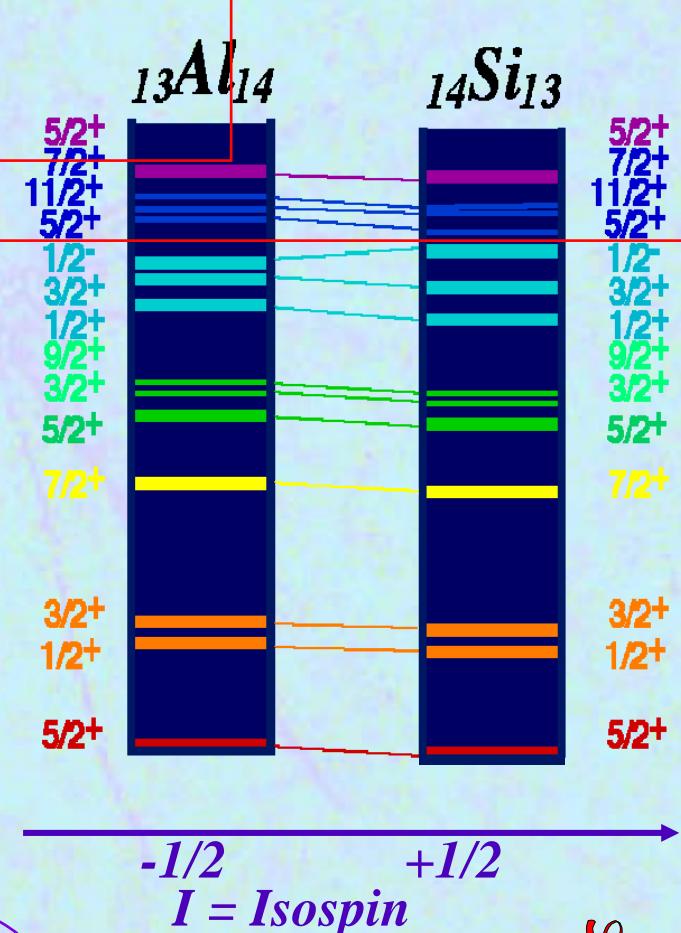
v Symmetric nuclei

Φ Mirror nuclei, $N \leftrightarrow Z$

Φ Isospin multiplets,

Φ A tool for structure
studies

Φ Proton \leftrightarrow neutron



- III -

Proton Neutron Novel symmetry

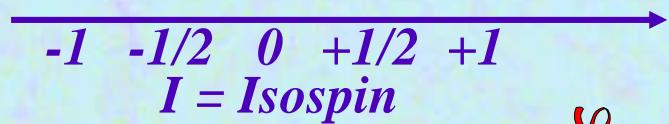


✓ Symmetric nuclei

- Φ Mirror nuclei
- Φ Isospin multiplets,

Φ A tool for structure
studies

Φ Proton \leftrightarrow neutron



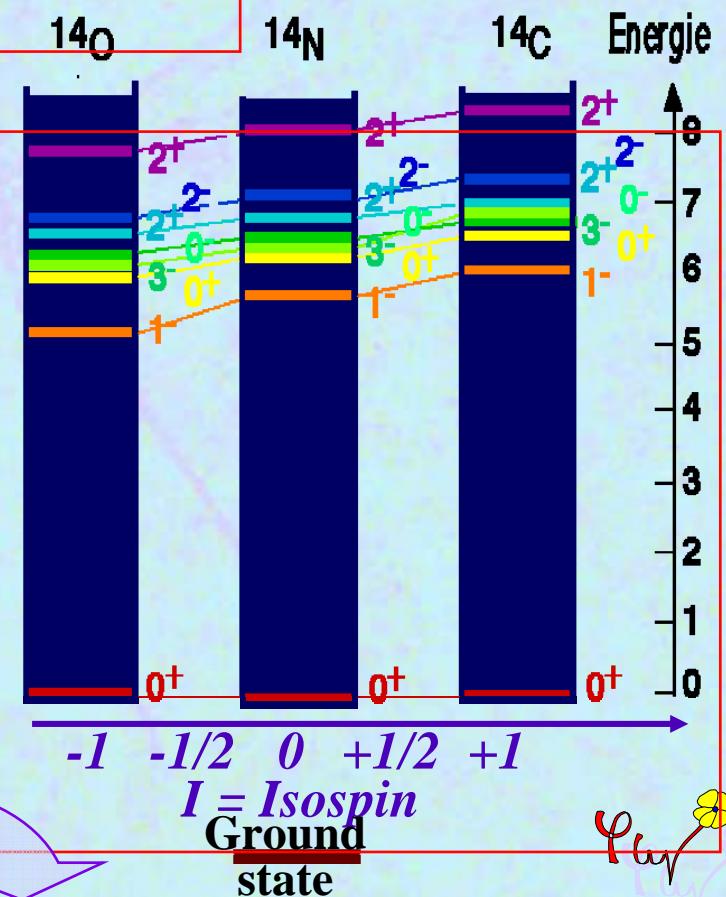
- III -

Proton Neutron Novel symmetry



v Symmetric nuclei

- Φ Mirror nuclei
- Φ Isospin multiplets,
triplets, quadruplets, ...
- Φ A tool for structure
studies
- Φ Proton \leftrightarrow neutron



- III -

Proton Neutron Novel symmetry

Φ Proton \leftrightarrow neutron

$-1 \quad -1/2 \quad 0 \quad +1/2 \quad +1$
 $I = Isospin$



- III -

Proton Neutron Novel symmetry

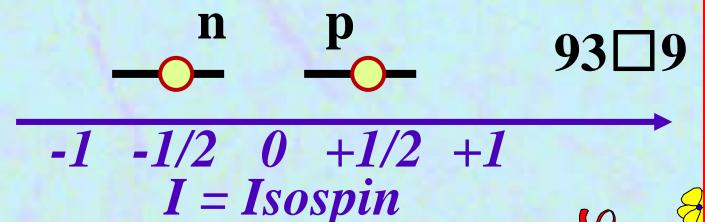


v Many particles

Φ Proton \leftrightarrow neutron

$J^\pi = 1/2^+$

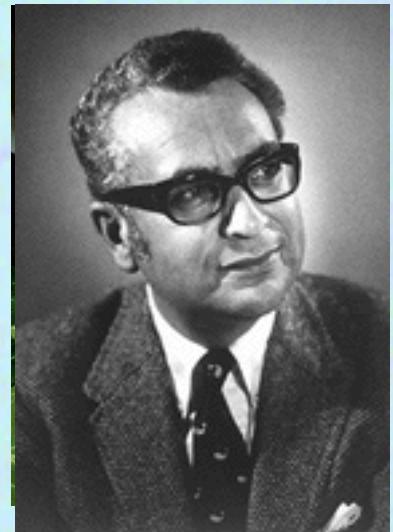
Masses
(MeV)



- III -

Proton Neutron Novel symmetry

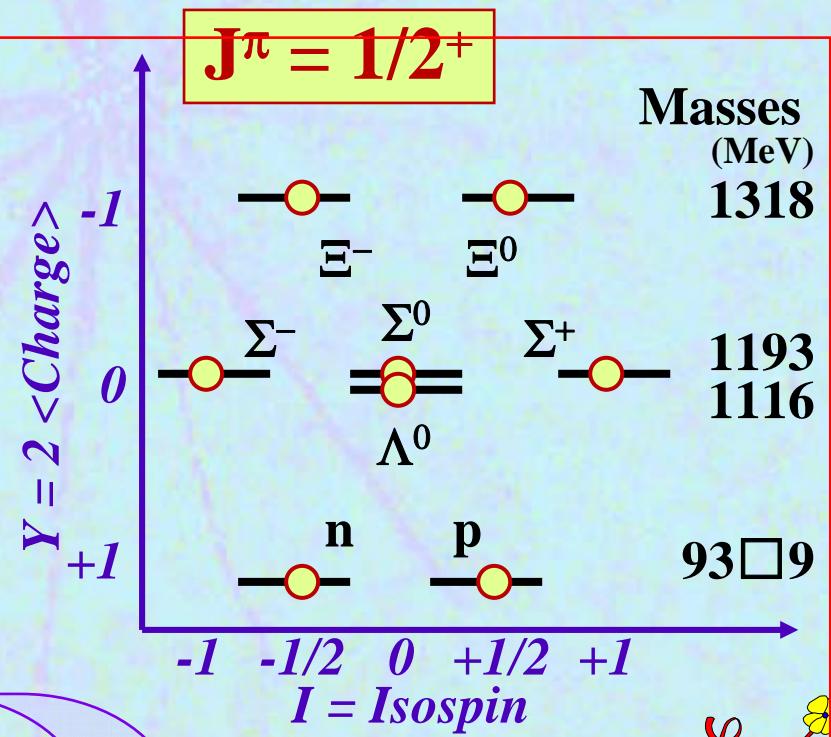
Gell Man



v Many particles

Φ Many twins

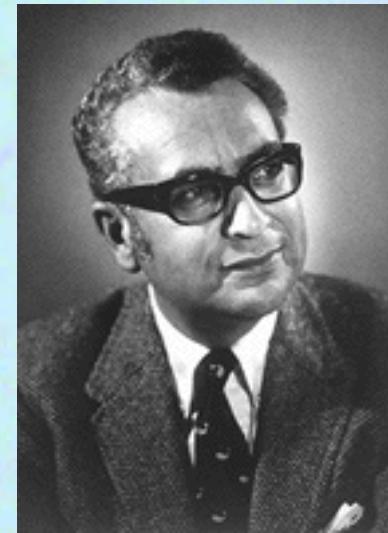
Φ Novel quantum number:
The hypercharge : Y



- III -

Proton Neutron Novel symmetry

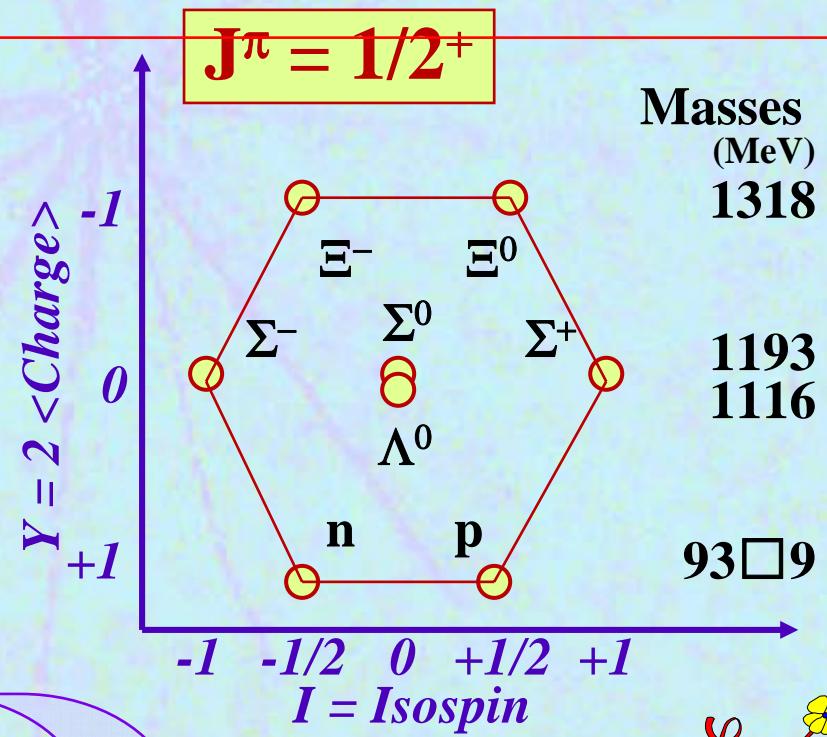
Gell Man



✓ Many particles

Φ Many twins

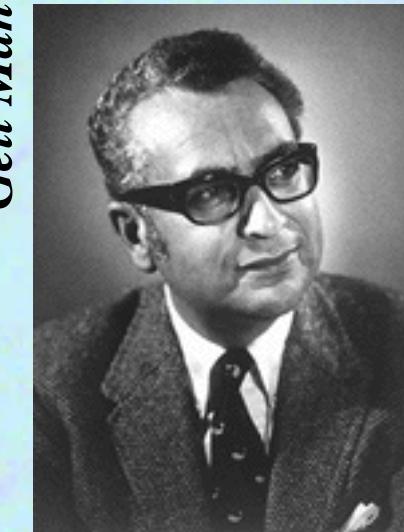
Φ Novel quantum number:
The hypercharge : Y



- III -

Proton Neutron

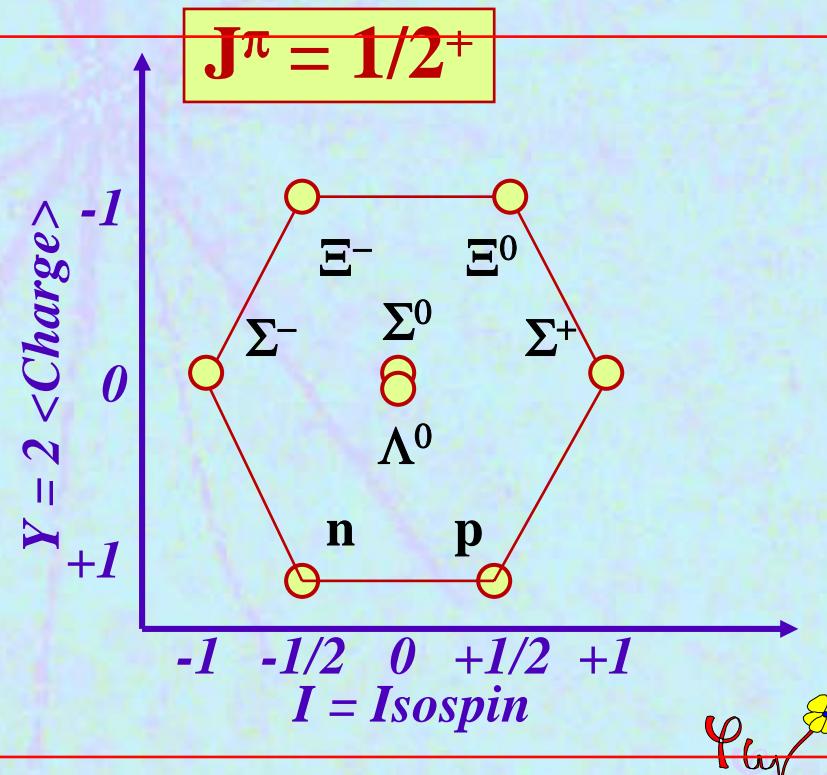
Novel symmetry



Gell Man

- ✓ Many particles
 - Φ Many twins
 - Φ Novel quantum number:
The hypercharge : Y

- ✓ 3 Quarks in baryons

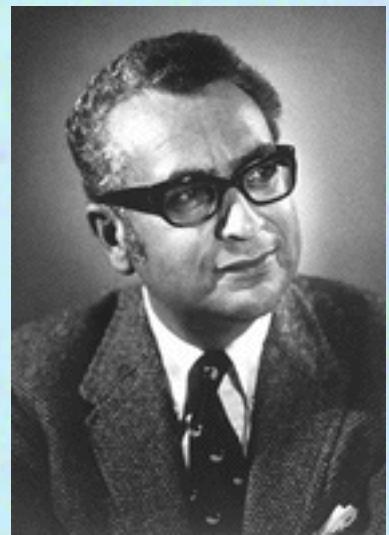


- III -

Proton Neutron

Novel symmetry

Gell Man

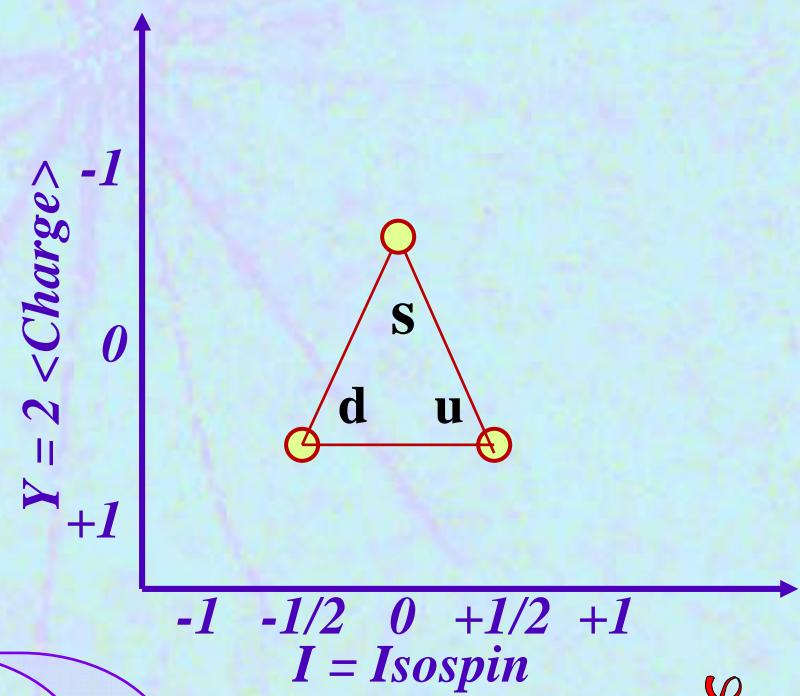


✓ Many particles

Φ Many twins

Φ Novel quantum number:
The hypercharge : Y

✓ 3 Quarks in baryons



- III -

Proton Neutron Novel symmetry

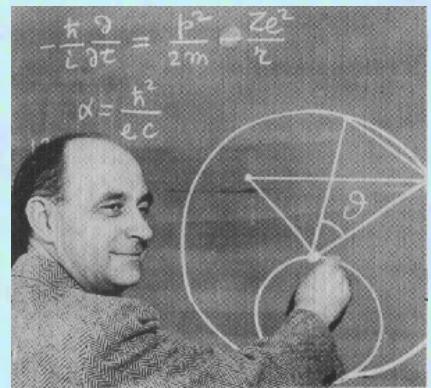
- ✓ 3 Quarks in baryons
- Φ Today 6 flavors and 3 colors (QCD)



- III -

Proton Neutron Novel symmetry

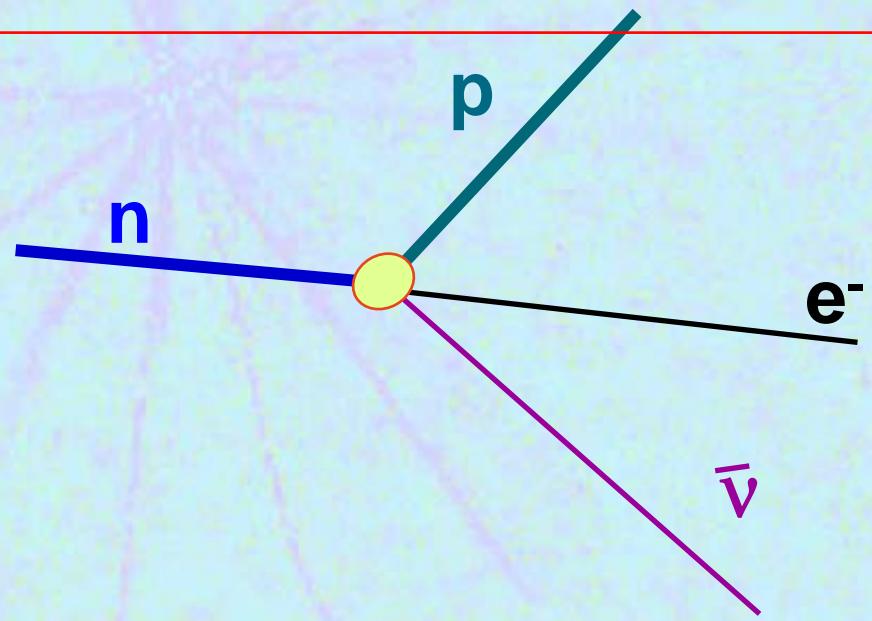
Fermi



✓ β Radioactivity

✓ 3 Quarks in baryons

Φ Today 6 flavors and 3 colors (QCD)



- III -

Proton Neutron Novel symmetry

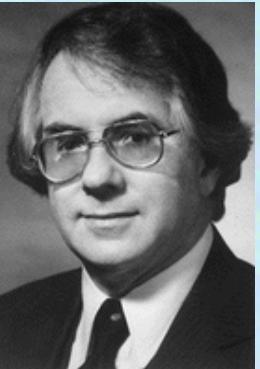
Weinberg



Salam



Glashow



✓ β Radioactivity

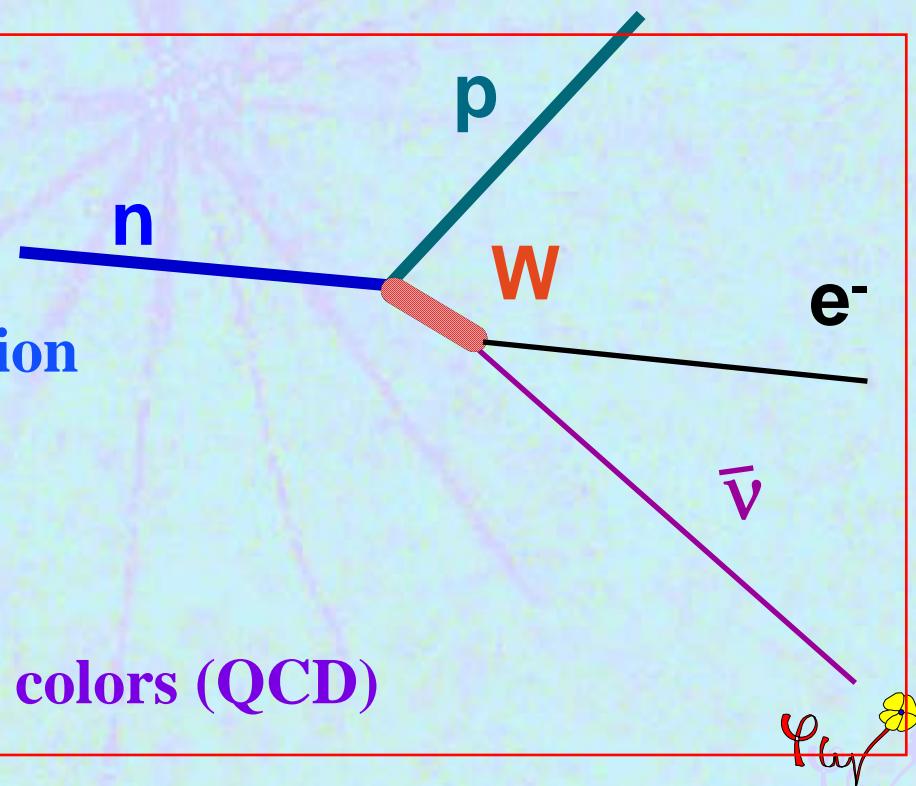
Φ Isospin (weak)

Φ Electro-weak unification

Φ Gauge Theory

✓ 3 Quarks in baryons

Φ Today 6 flavors and 3 colors (QCD)



- III -

Proton Neutron Novel symmetry

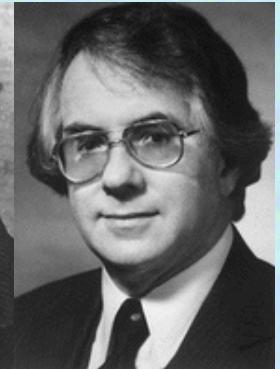
Weinberg



Salam



Glashow



✓ **β Radioactivity**

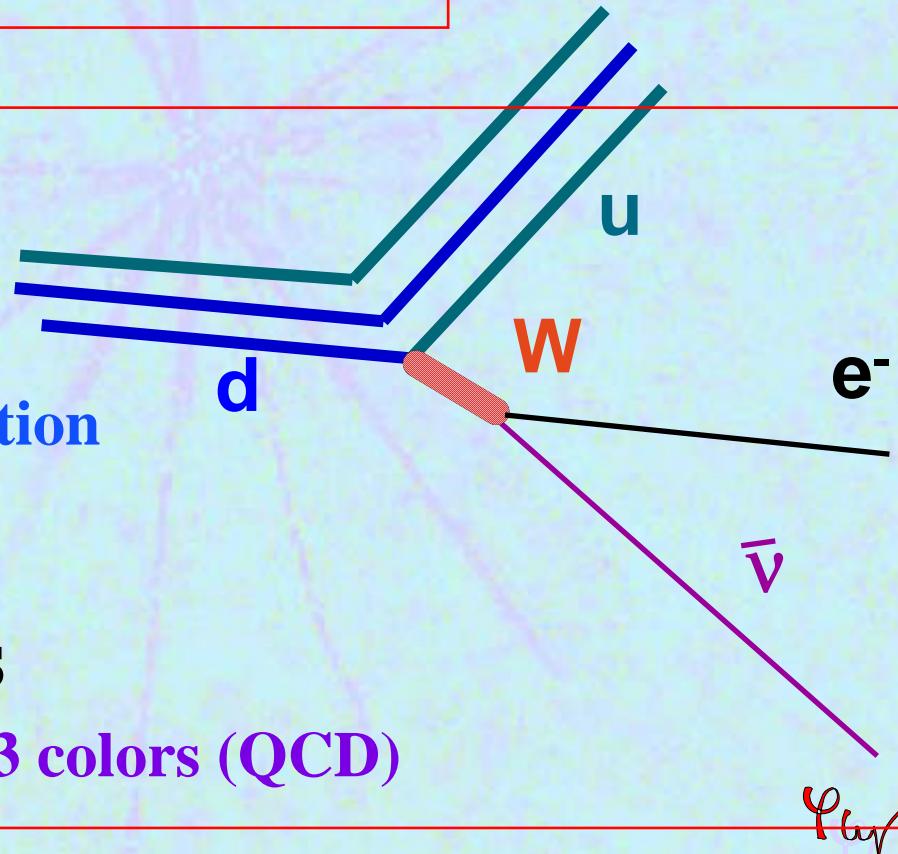
Φ Isospin (weak)

Φ Electro-weak unification

Φ Gauge Theory

✓ **3 Quarks in baryons**

Φ Today 6 flavors and 3 colors (QCD)



- III -

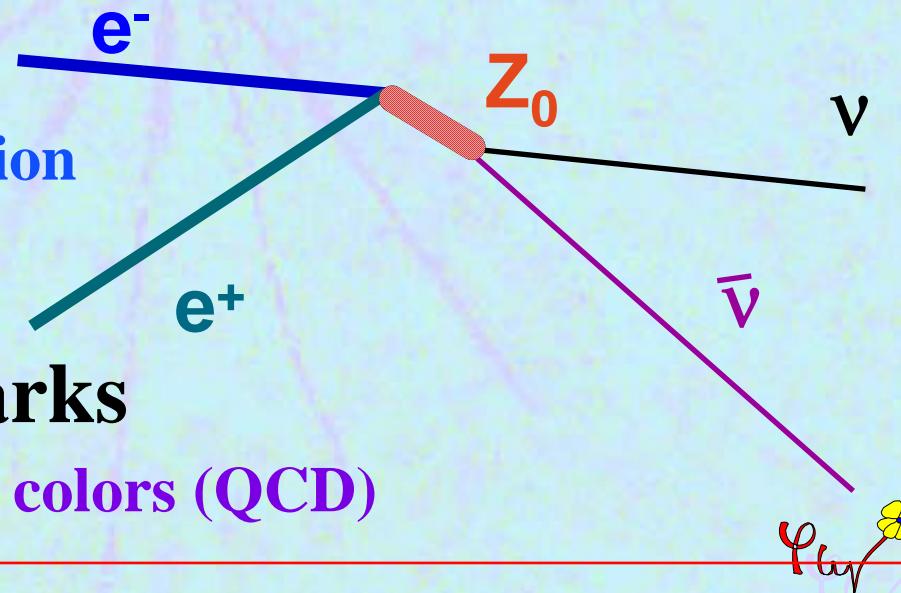
Proton Neutron Novel symmetry

CERN



Weak Interaction

- Φ Isospin (weak)
- Φ Electro-weak unification
- Φ Gauge theory



Structure with 3 Quarks

- Φ Today 6 flavors and 3 colors (QCD)

Quarks and gluons in Nuclei

v **Nuclei: Laboratories for elementary properties**

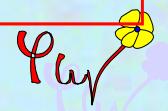
Φβ radioactivity and weak interaction (neutrinos)

Φβ radioactivity and CKM matrix

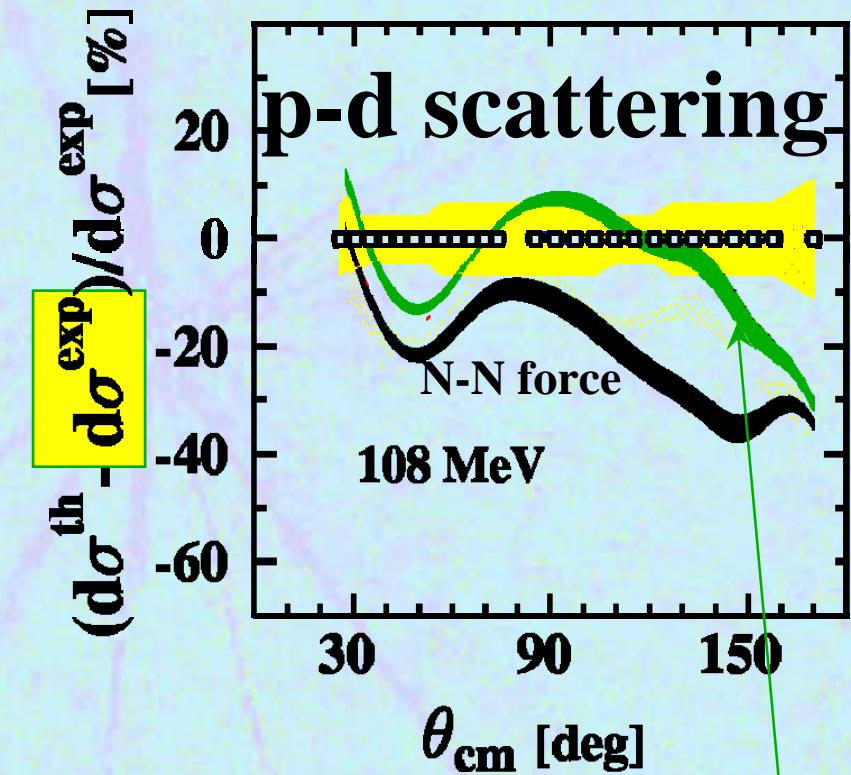
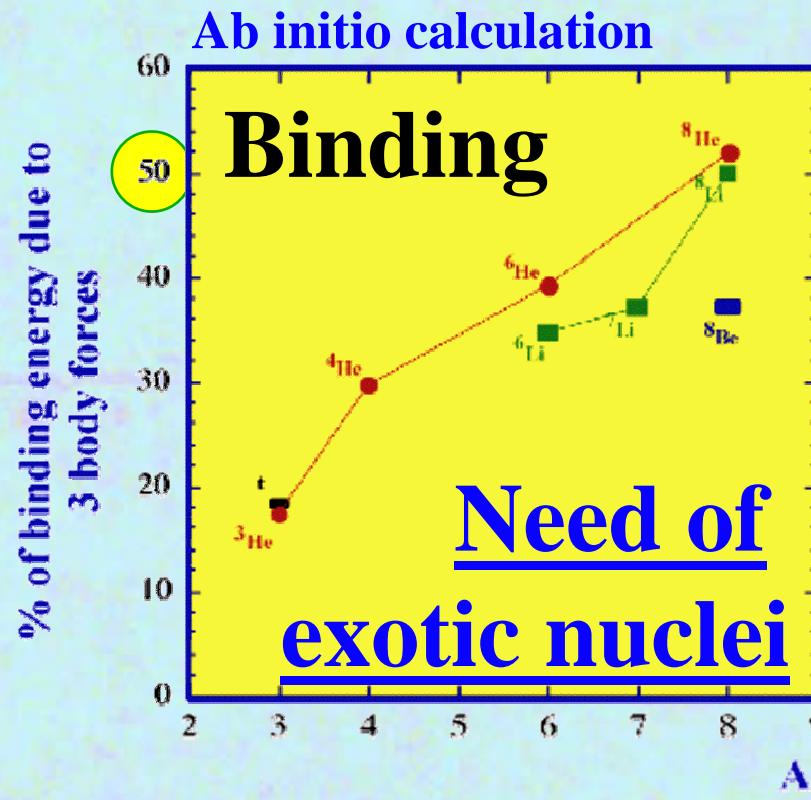
⇒ Nuclear structure should be under control

Quarks and gluons in Nuclei

- ✓ **Nuclei: Laboratories for elementary properties**
 - Φ β radioactivity and weak interaction (neutrinos)
 - Φ β radioactivity and CKM matrix
 - ⇒ Nuclear structure should be under control
- ✓ **QCD for nuclei far to be possible** (non-perturbative)
 - Φ Decoupling of the various scales => nucleons
 - Φ Effective interaction for nucleon (measured ?)
 - ⇒ Coming from QCD constraints (chiral symmetry)

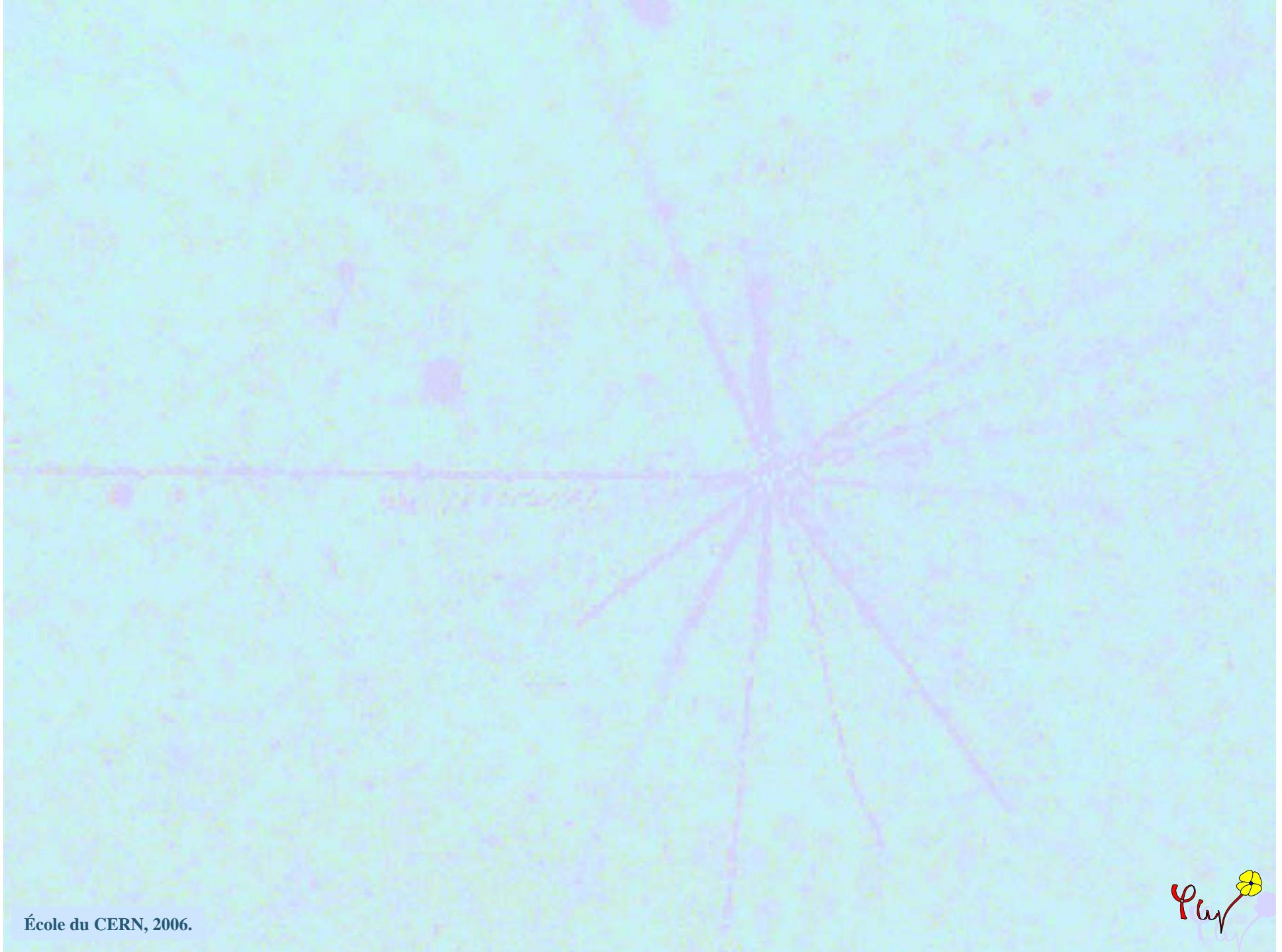


N-N forces not enough=>3-body



=> Coming from QCD constraints (chiral symmetry)

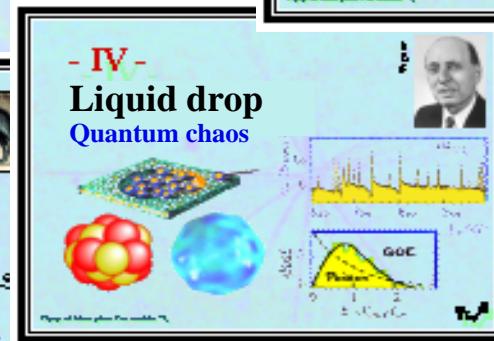
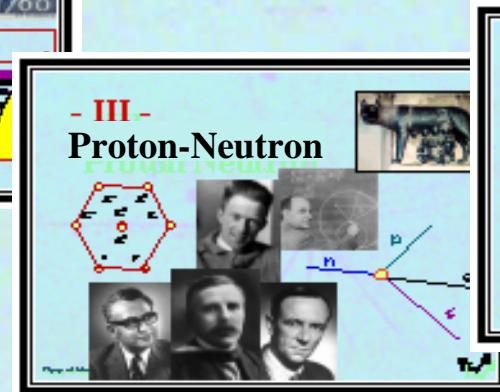
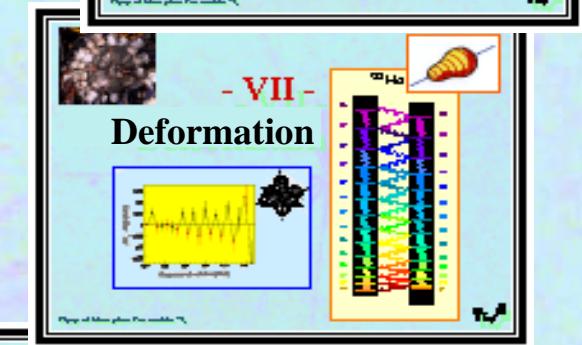
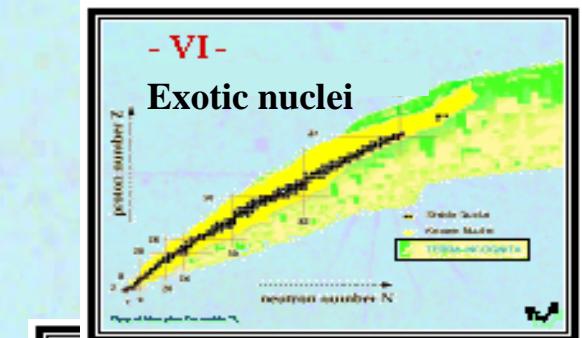
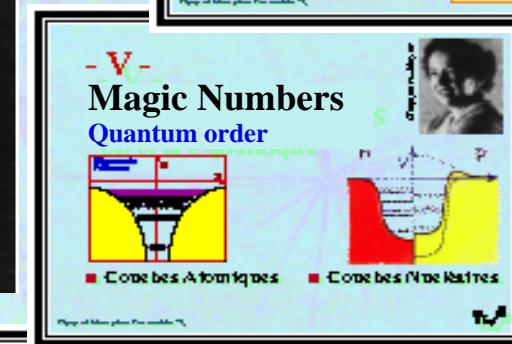
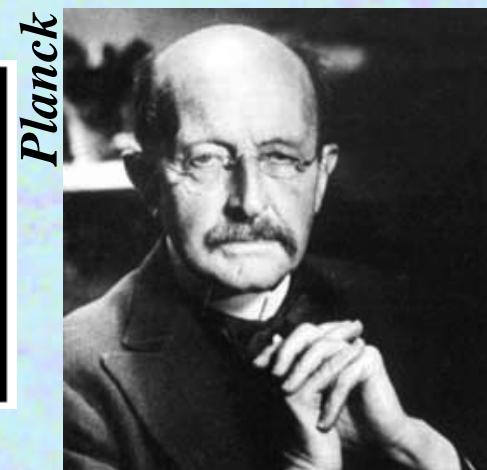
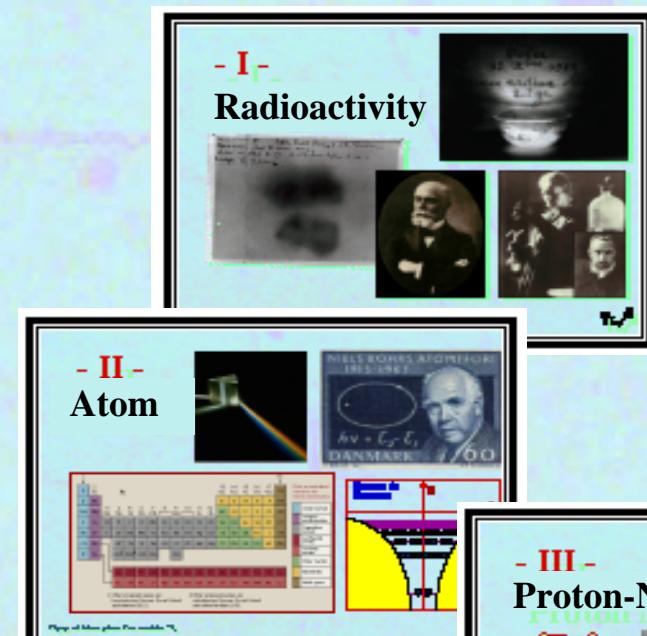


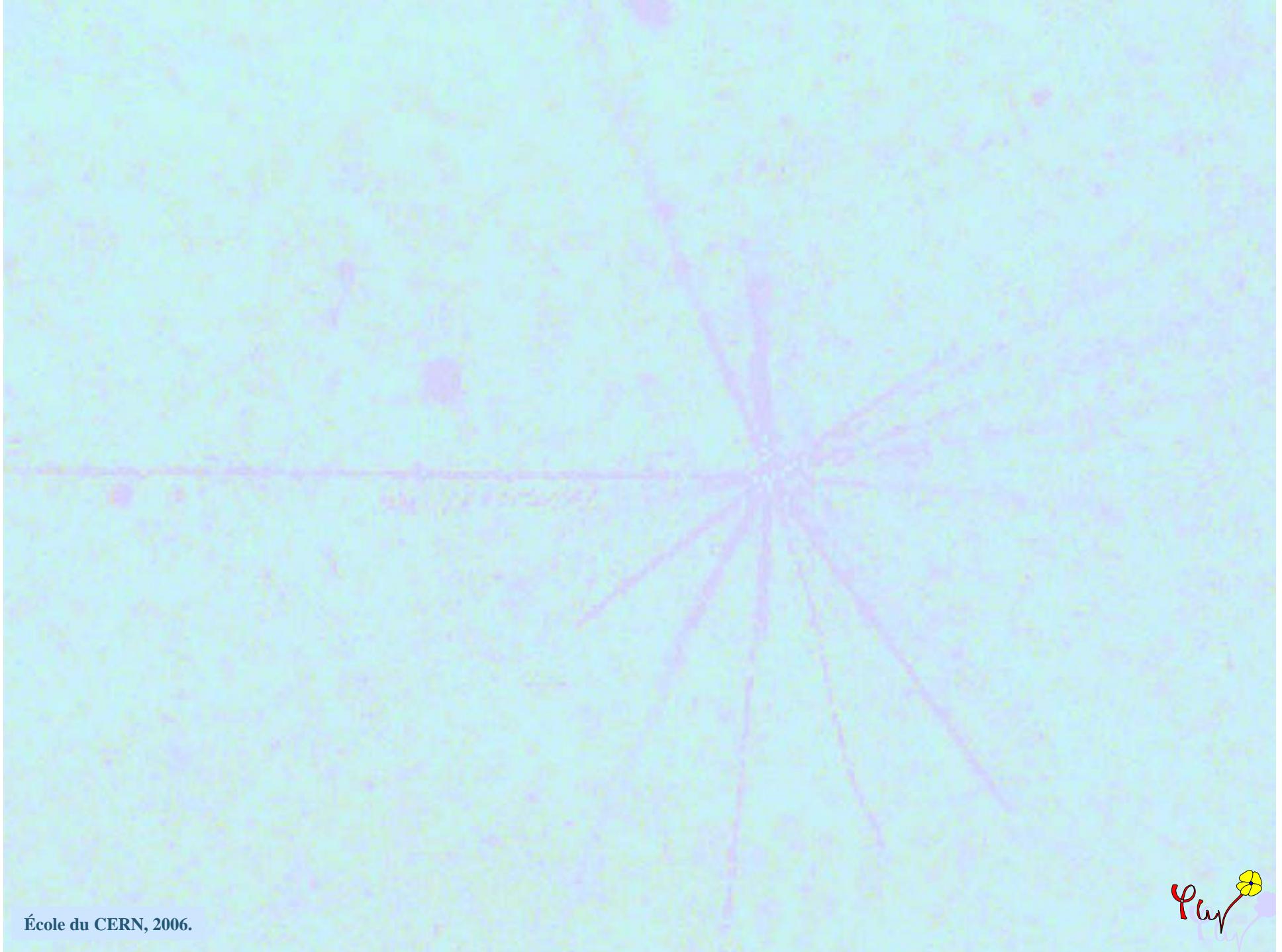


École du CERN, 2006.

Atomic Nuclei

Complex quantum systems





École du CERN, 2006.

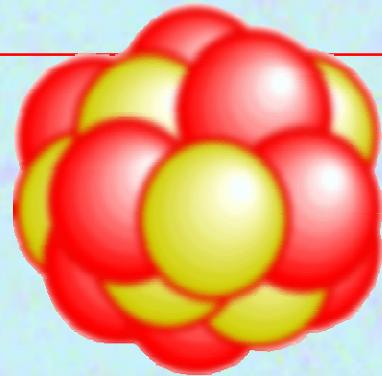
- IV -

Liquid Drop Quantum Chaos



- IV -

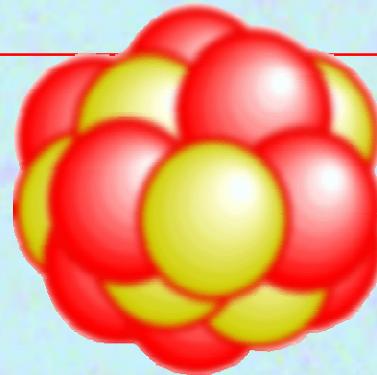
Liquid Drop



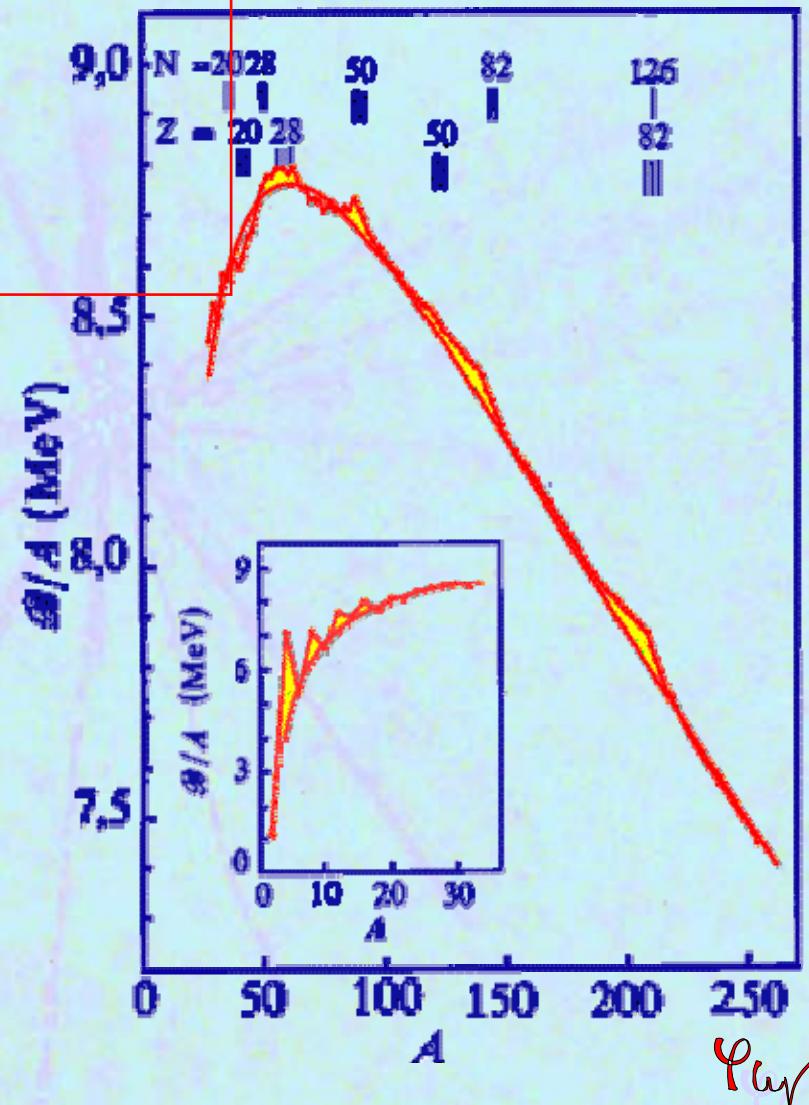
v Binding
 Φ Energy

- IV -

Liquid Drop

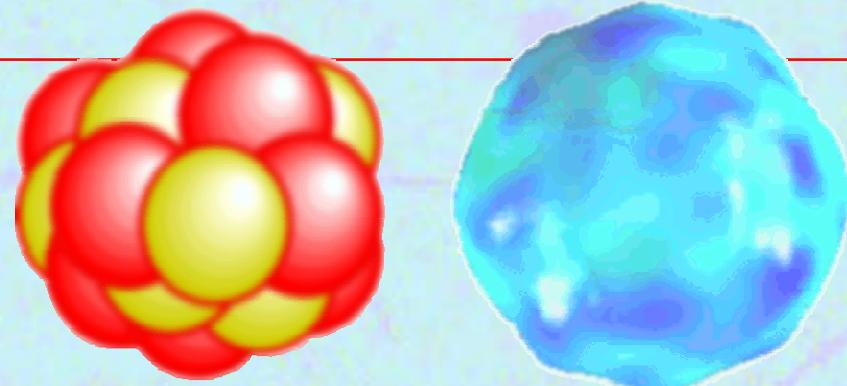


v Binding
 Φ Energy



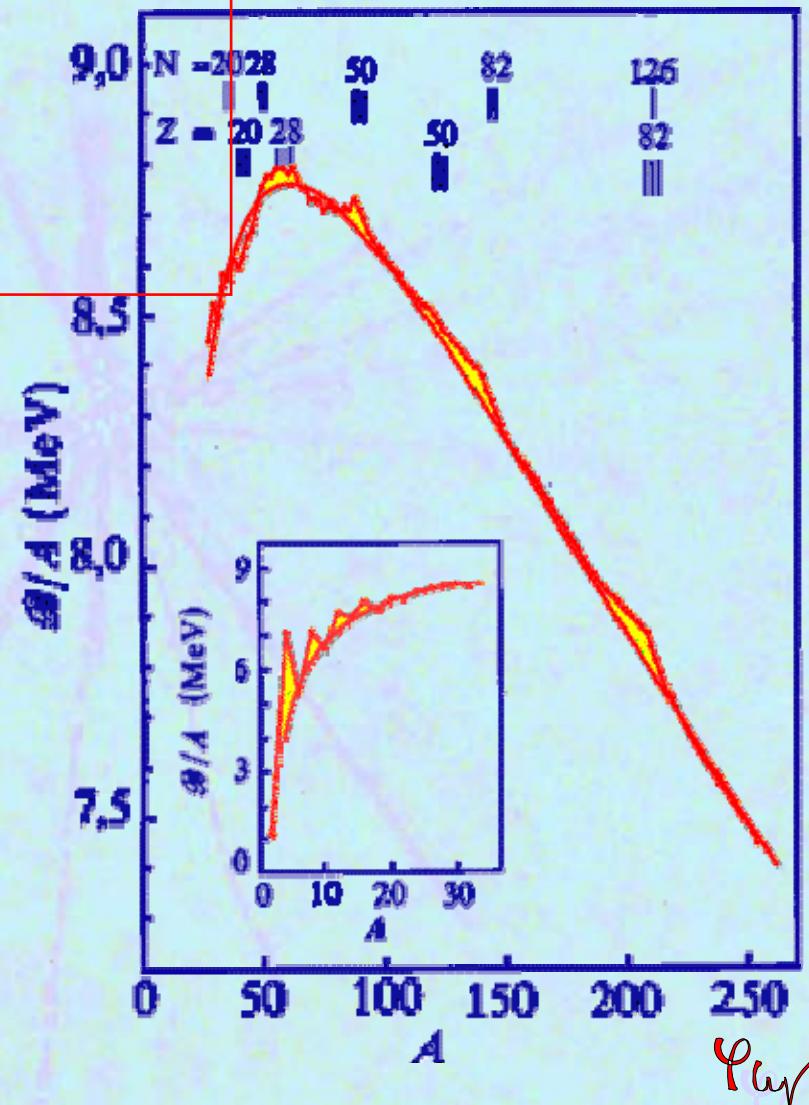
- IV -

Liquid Drop



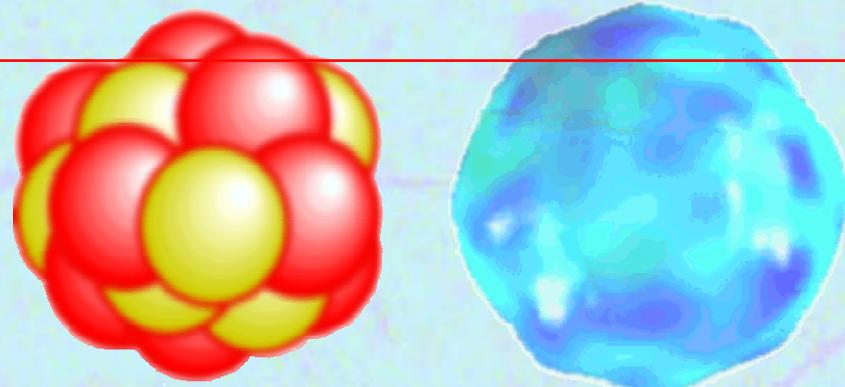
v Bond like a drop

Φ Energy proportional to
the number of particles



- IV -

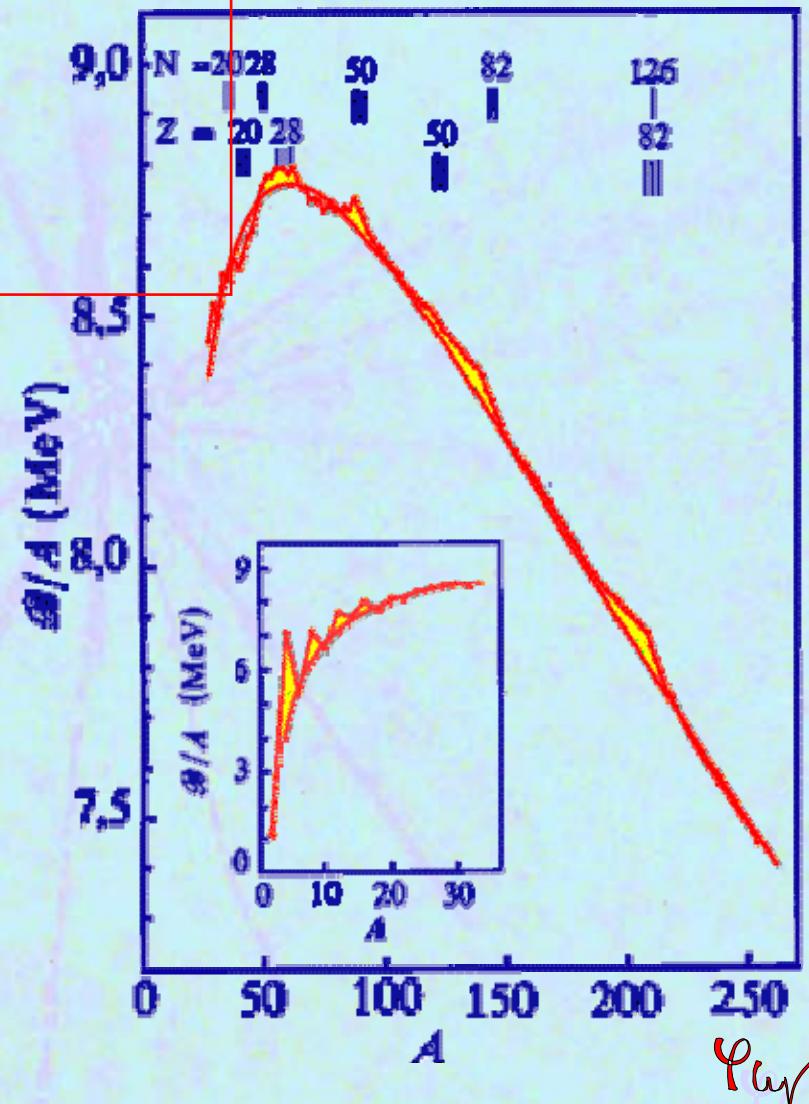
Liquid Drop



v Bond like a drop

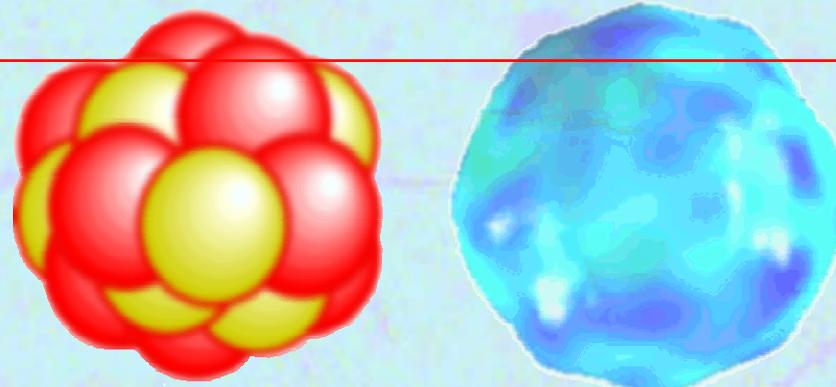
Φ Energy proportional to
the number of particles
 $E/A = -16 \text{ MeV}$

Φ Strong force short
range



- IV -

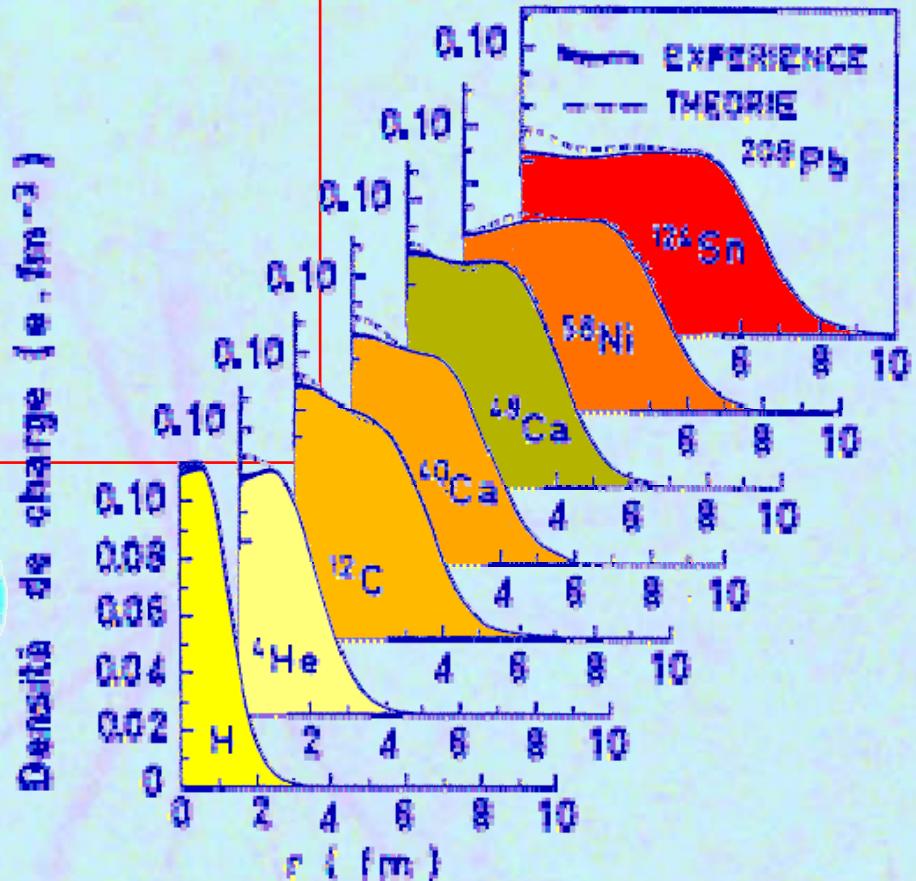
Liquid Drop



v Bond like a drop

Φ Energy proportional to
the number of particles
 $E/A = -16 \text{ MeV}$

Φ Strong force short
range



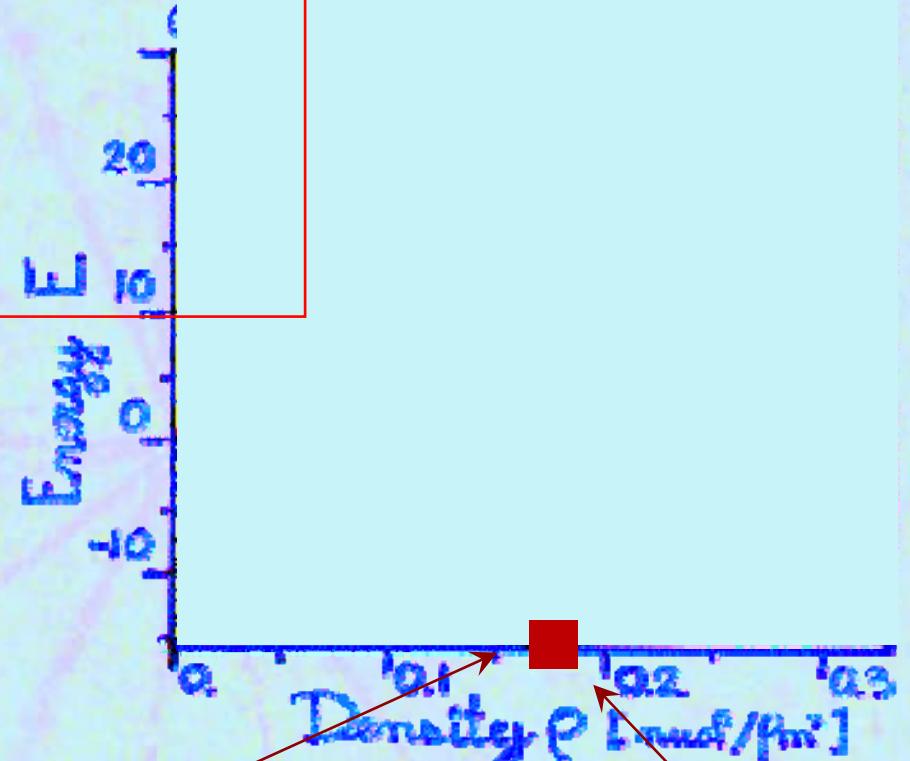
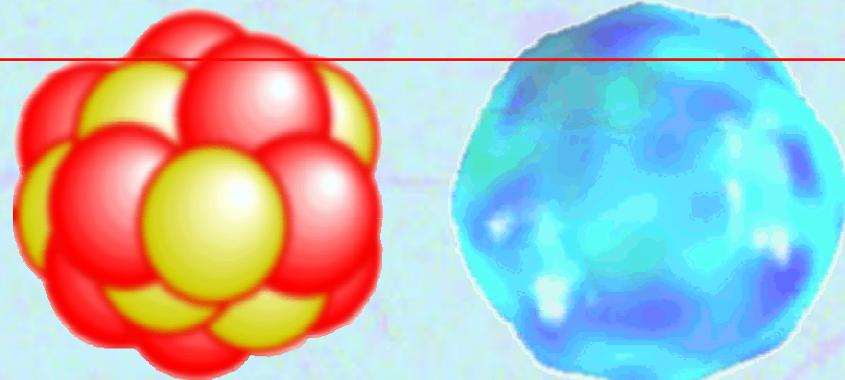
v Drop density profile

Φ Central density
 $\rho = 0.17 \text{ nucleon/fm}^3$



- IV -

Liquid Drop



v Bond like a drop

- Φ Energy proportional to the number of particles
 $E/A = -16 \text{ MeV}$

- Φ Strong force short range

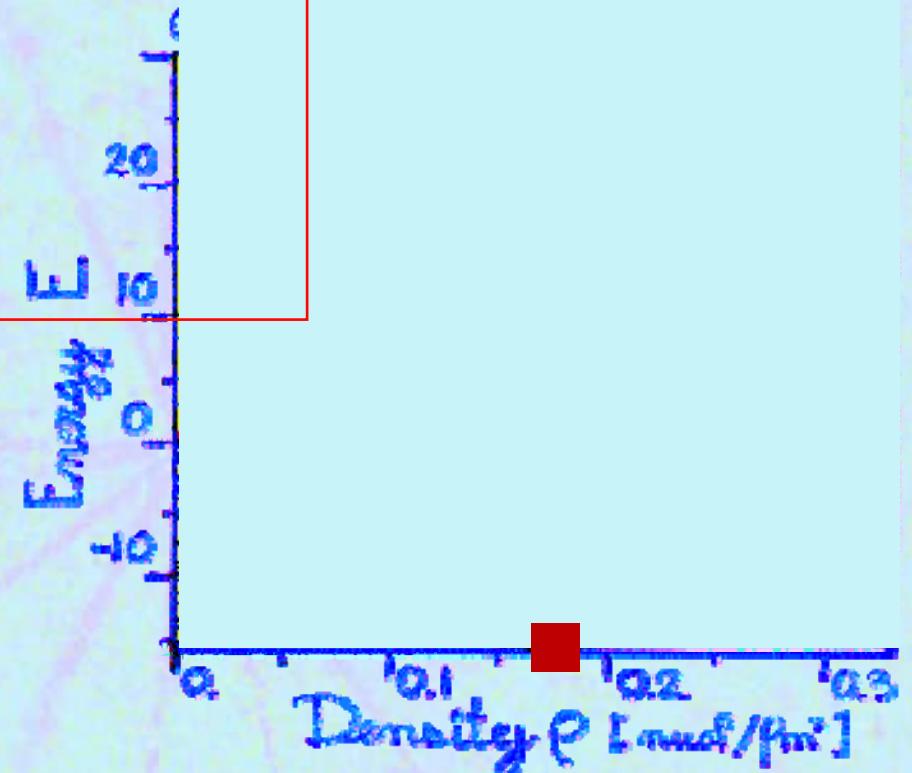
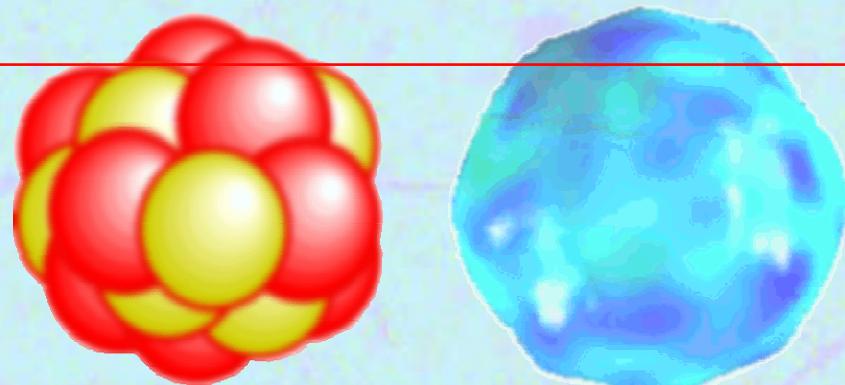
v Drop density profile

- Φ Central density
 $\rho = 0.17 \text{ nucleon/fm}^3$

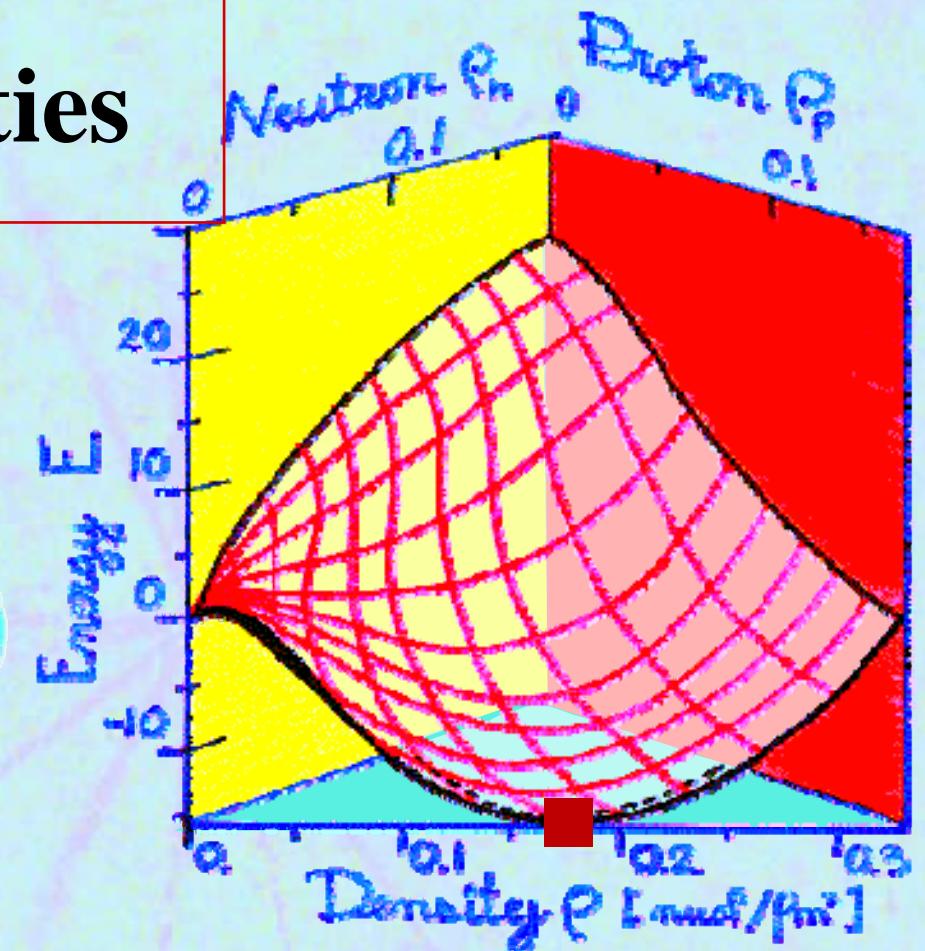
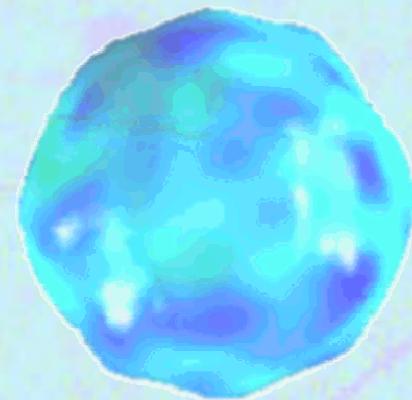
φ_{ω}

- IV -

Liquid Drop

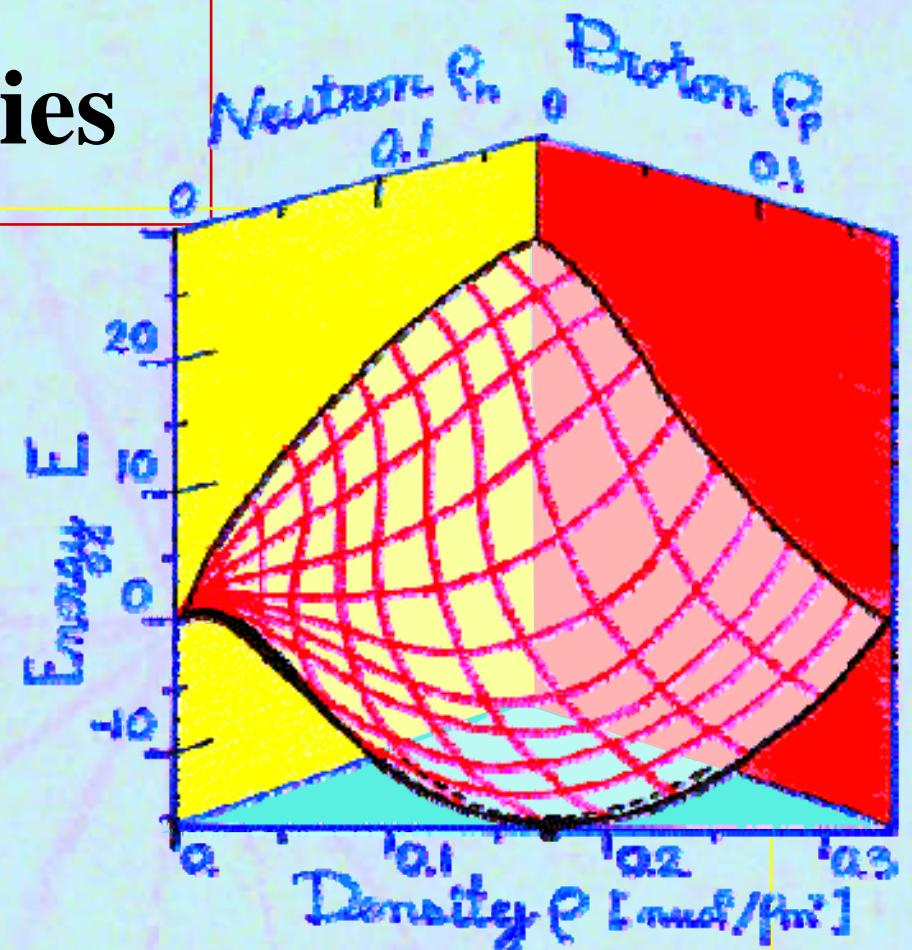
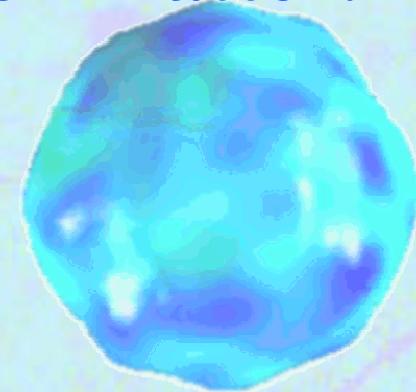


Mechanical properties



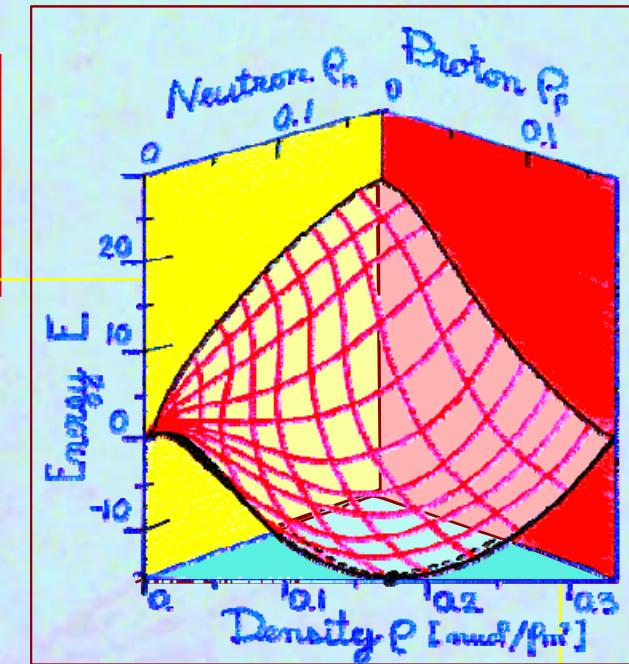
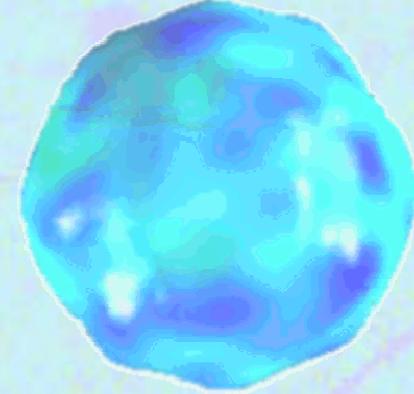
Mechanical properties

- ✓ Still badly known for neutron matter.



Mechanical properties

- ✓ Still badly known for neutron matter.

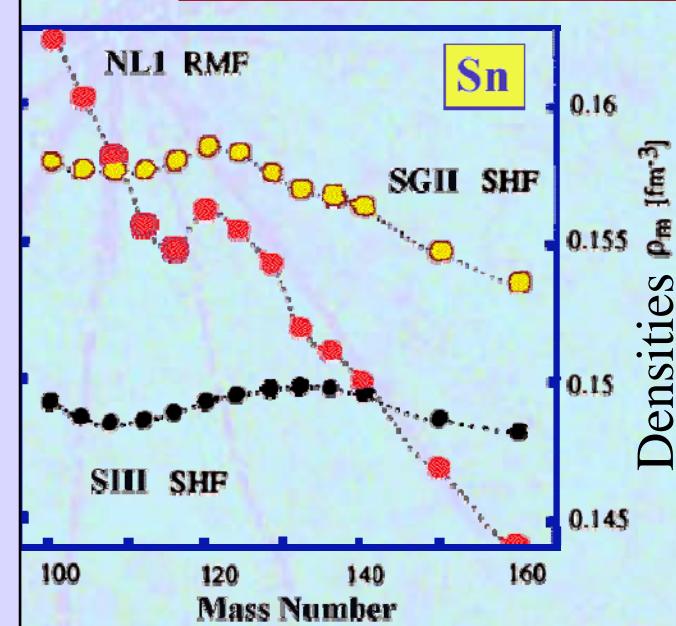
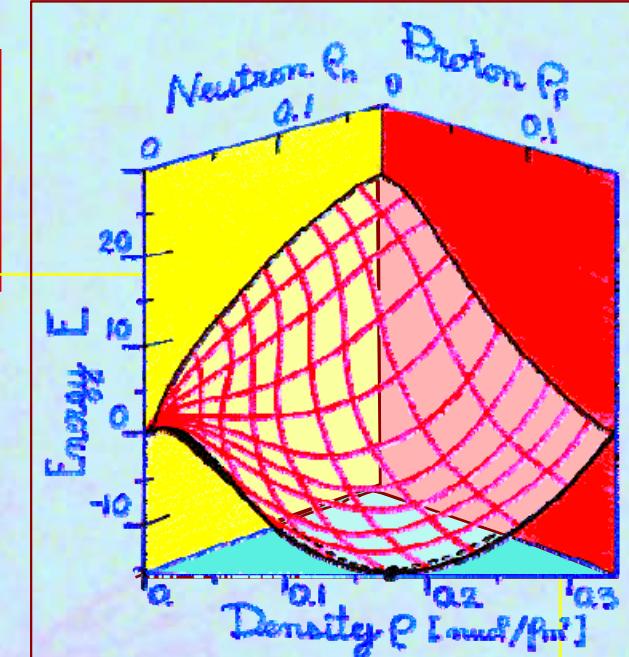


Mechanical properties

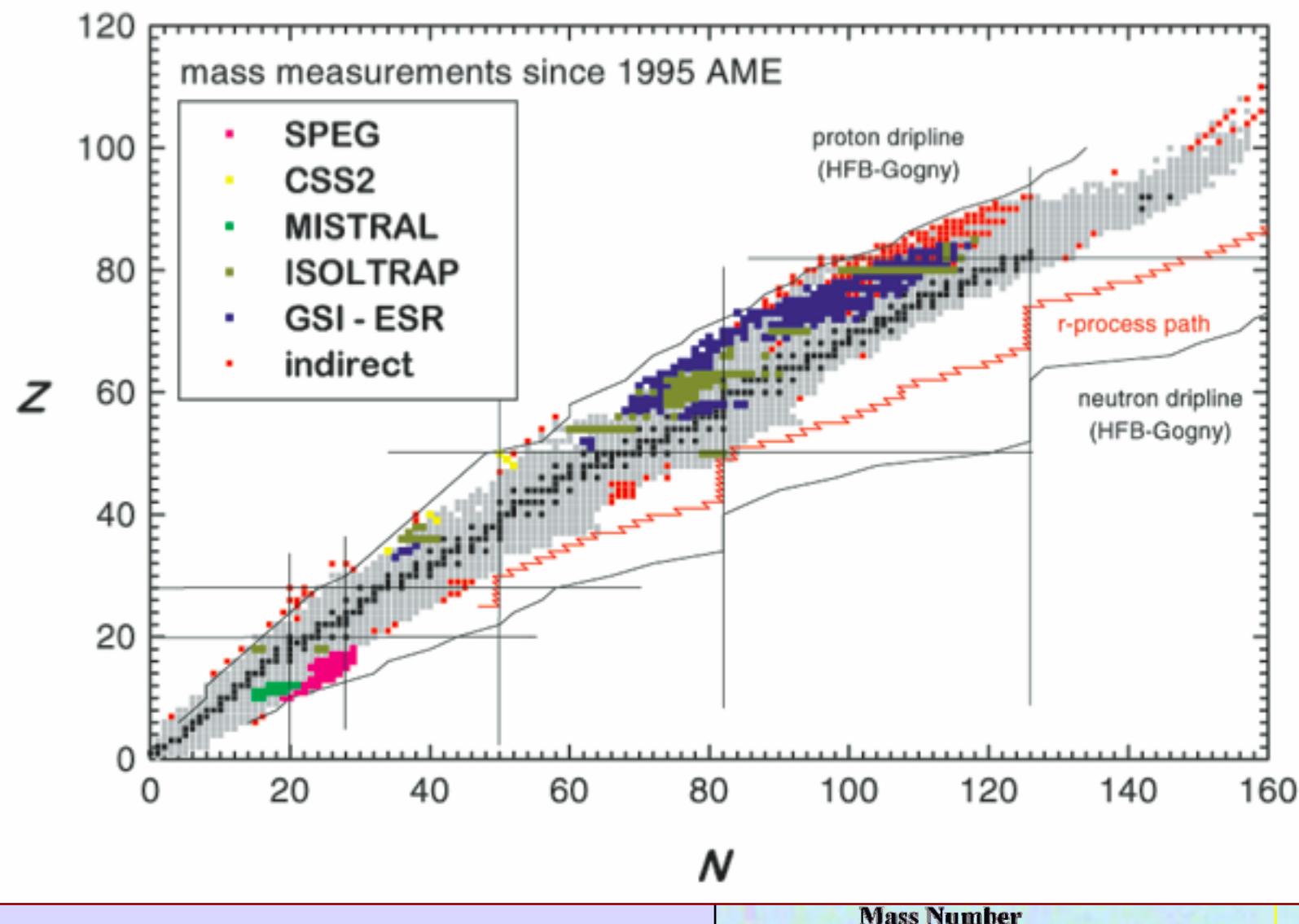
✓ Still badly known
for neutron matter.

✓ Isospin dependence:
Radii, densities
Masses and energies

✓ Compressibility:
Breathing mode,
reactions and flow



Neutron Q_n
proton Q_p



N
Separation energy $S(2n)$ (MeV)

Two-neutron separation energies

$Z=36$ Zr

- Duflo-Zuker
- ETFSI
- ETFSI-Q
- FRDM
- FRLDM

100 105 110 115 120

Mass number

N

Separation energy $S(2n)$ (MeV)

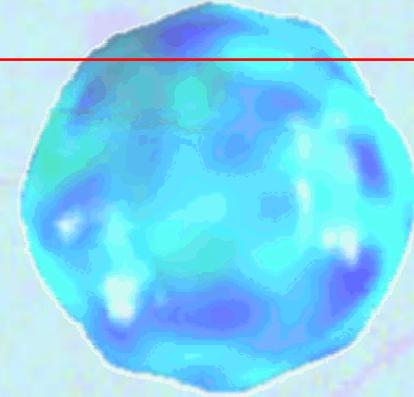
Two-neutron separation energies $Z=36$

- Duflo-Zuker
- ETFSI
- ETFSI-Q
- FRDM
- FRLDM

Mass number

- IV -

Liquid Drop

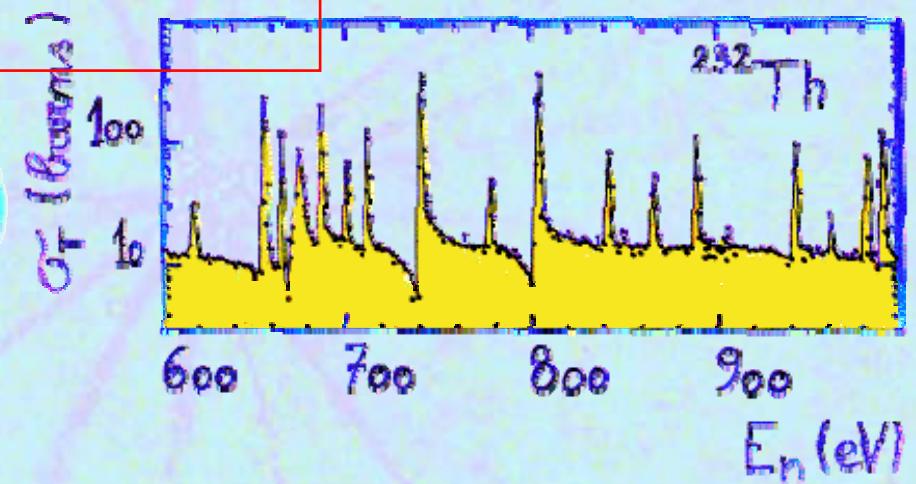
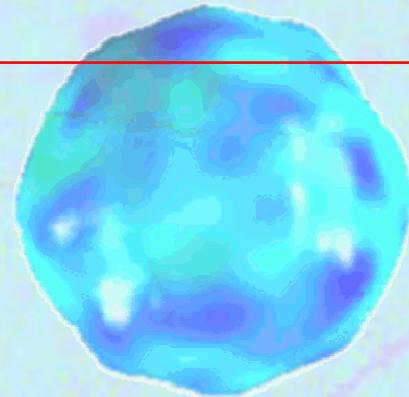


V

Φ Neutron absorption

- IV -

Liquid Drop



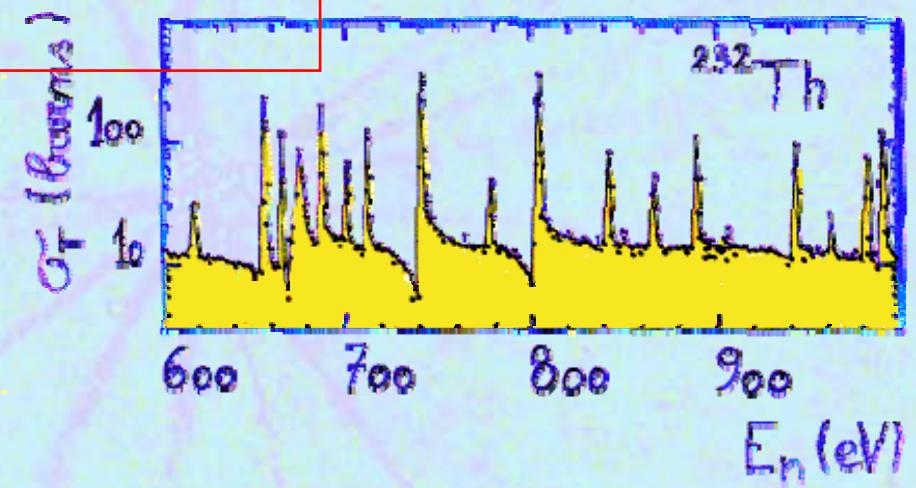
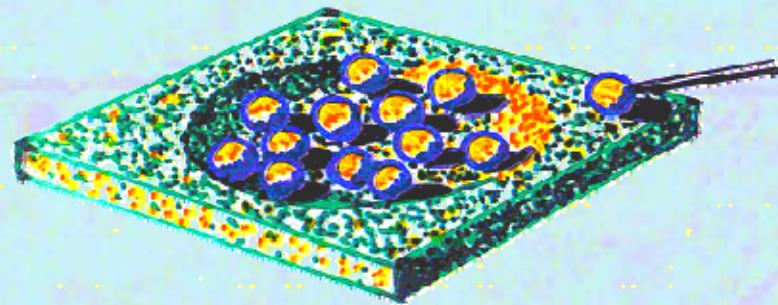
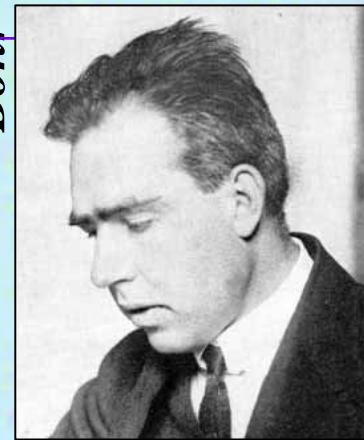
v React like a liquid

- Φ Neutron absorption
- Φ State in disorder

- IV -

Liquid Drop

Bohr



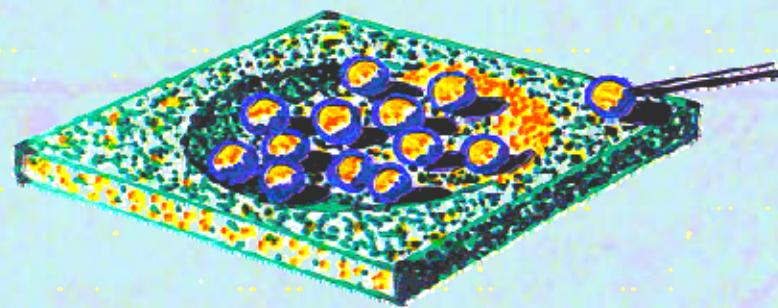
v React like a liquid

- Φ Neutron absorption
- Φ State in disorder

- IV -

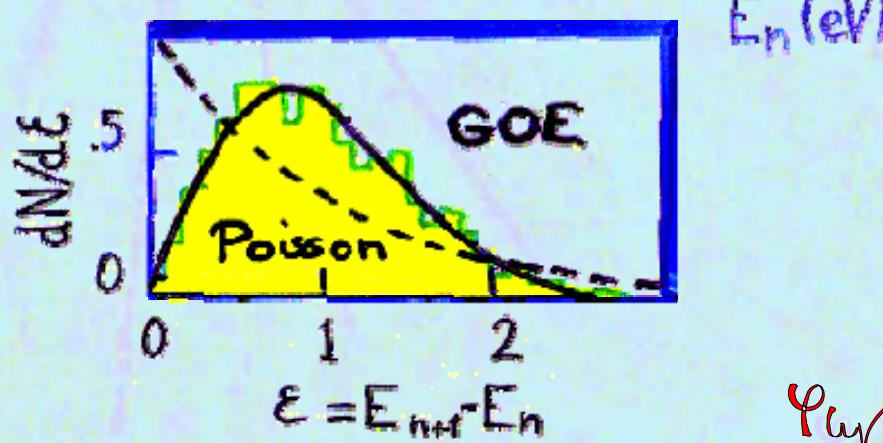
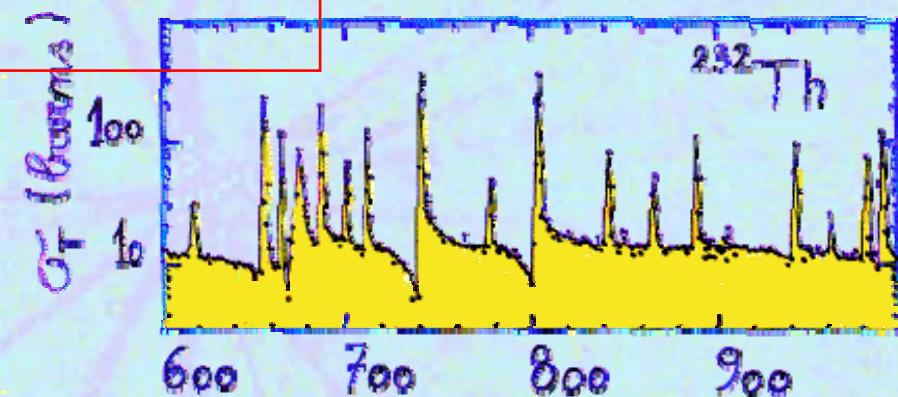
Liquid Drop

Wigner



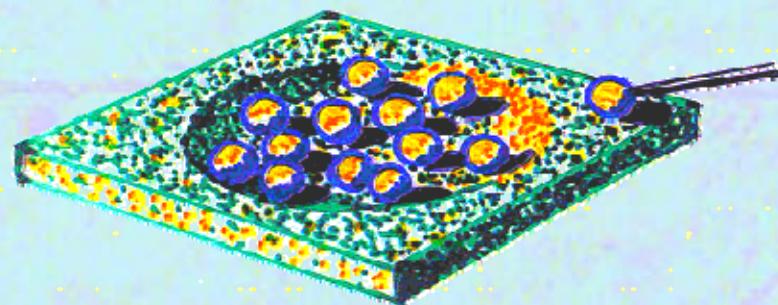
v React like a liquid

- Φ Neutron absorption
- Φ State in disorder



- IV -

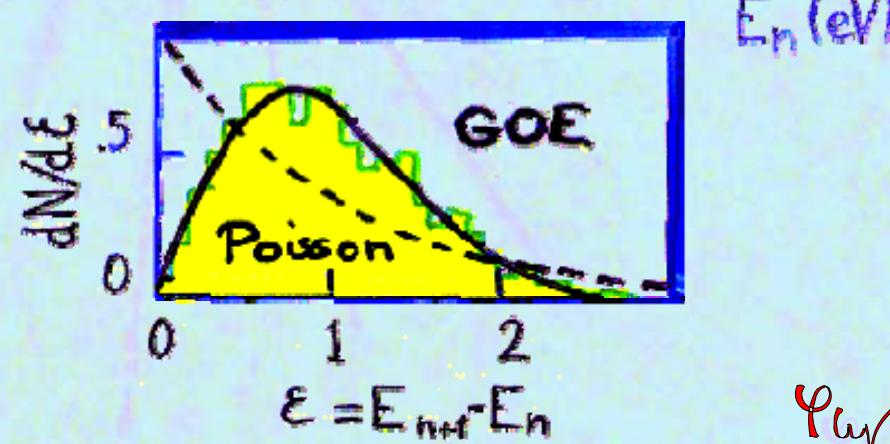
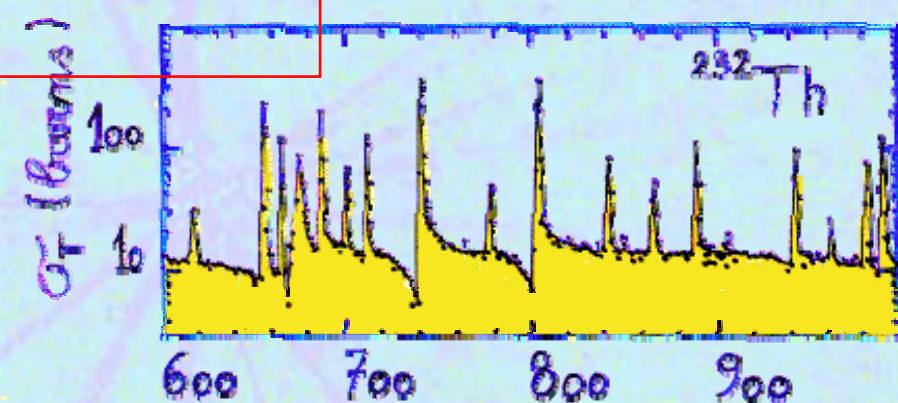
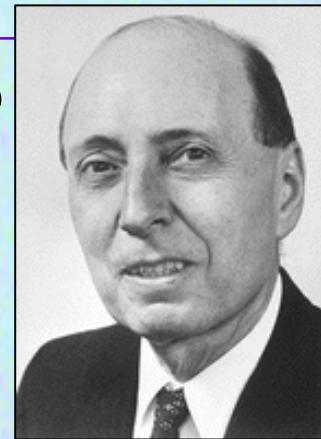
Liquid Drop Quantum Chaos



v React like a liquid

- Φ Neutron absorption
- Φ State in disorder

Wigner



- IV -

Liquid Drop Quantum Chaos

- v Thermodynamics
- v Liquid-gas phase transition

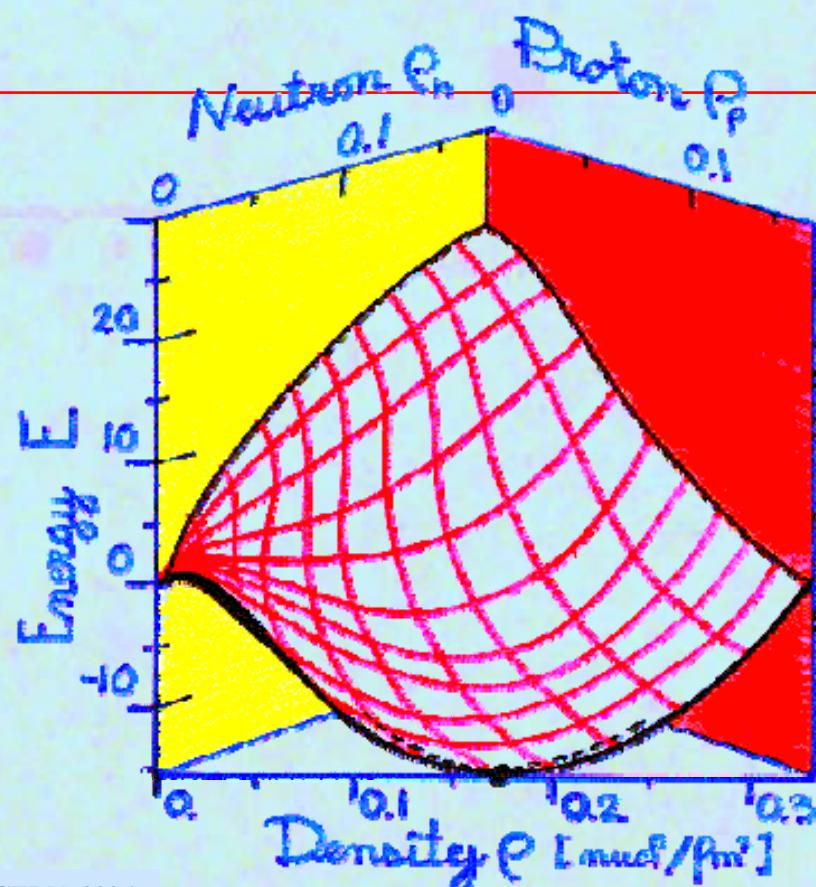
- v React like a liquid
 - Φ Neutron absorption
 - Φ State in disorder



- IV -

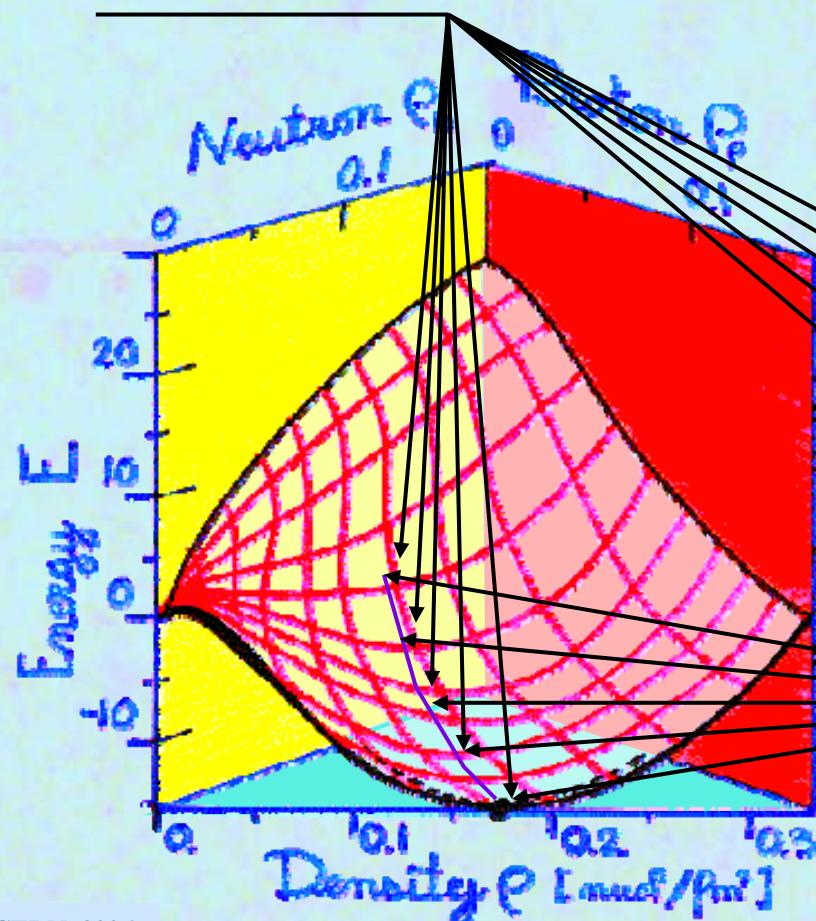
Liquid Drop

- ✓ Thermodynamics
- ✓ Liquid-gas phase transition

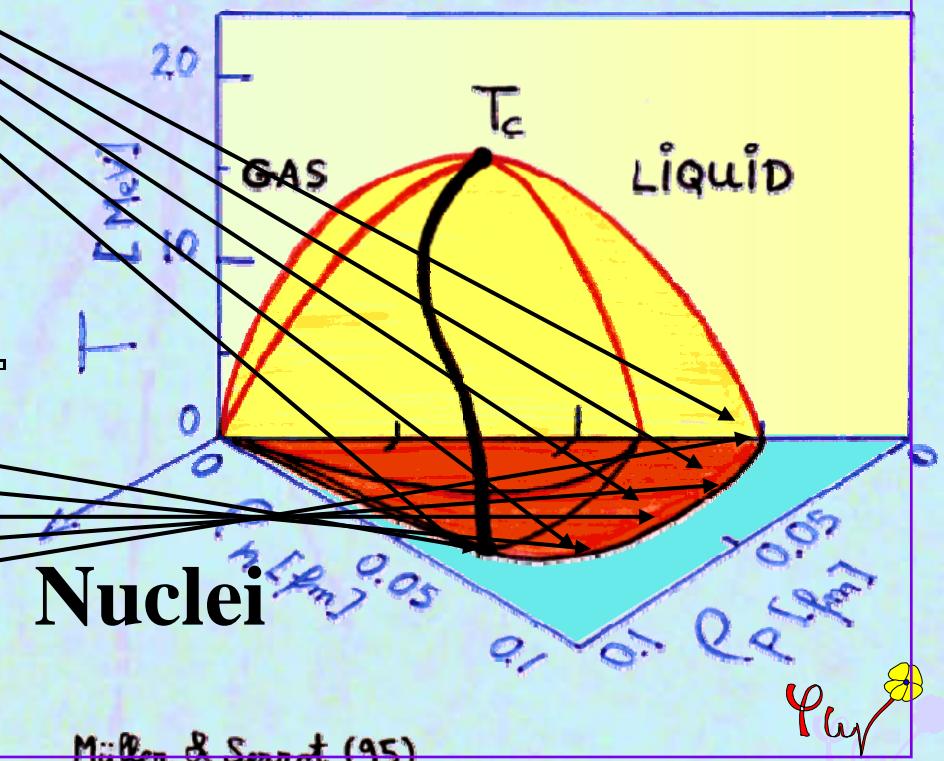


v Thermodynamics
v Liquid-gas phase transition

● Saturation



● Equation of states



Nuclei

Fragmentation of nuclei

Heavy ion collisions



$t = 0$

Fragmentation of nuclei

Heavy ion collisions

$t = 1.16$

s

Fragmentation of nuclei

Heavy ion collisions



$t = 2 \frac{zz}{16}$

s

Fragmentation of nuclei

Heavy ion collisions

$t = 3 \frac{22}{16}$

s

Fragmentation of nuclei

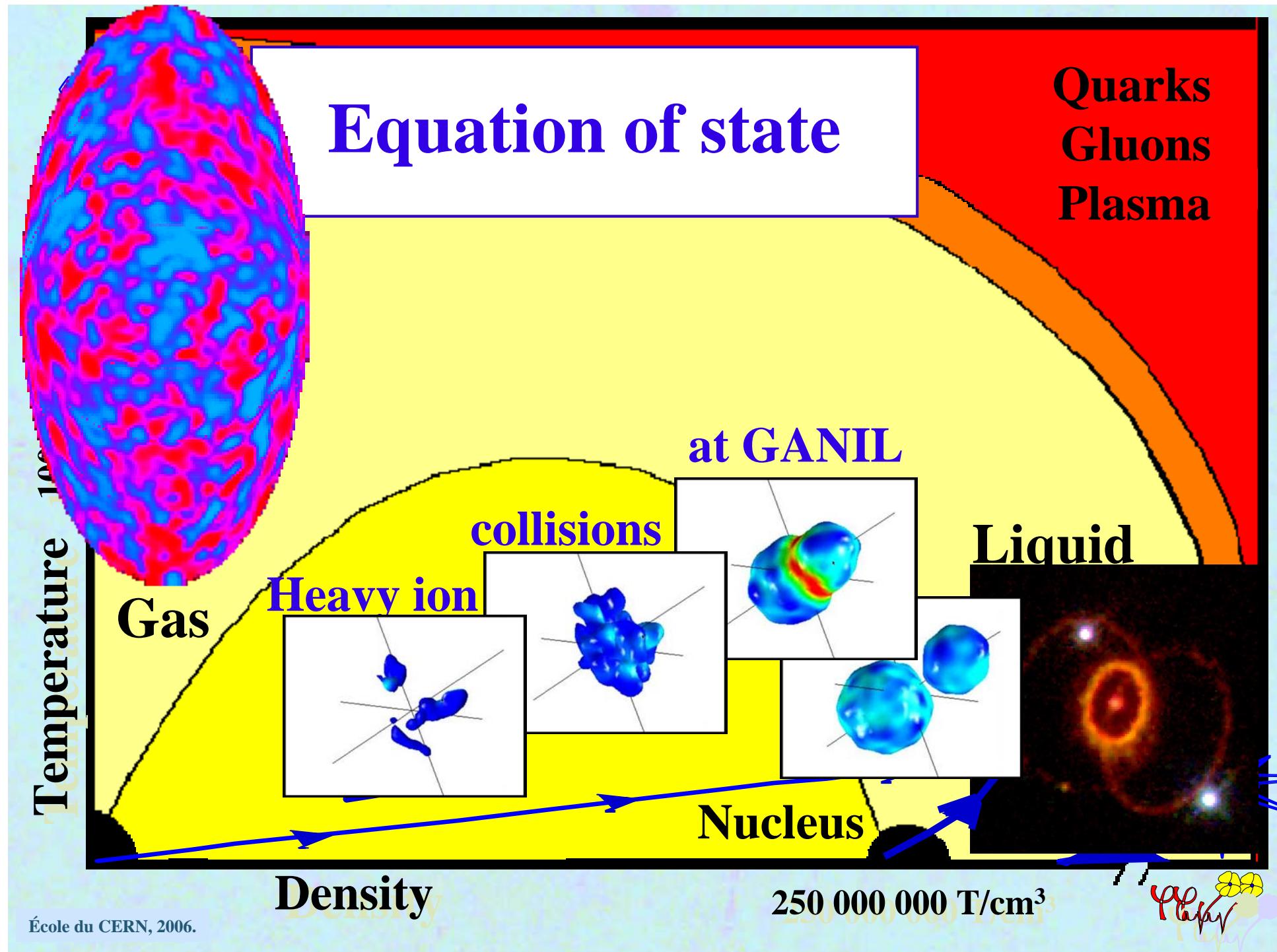
Heavy ion collisions

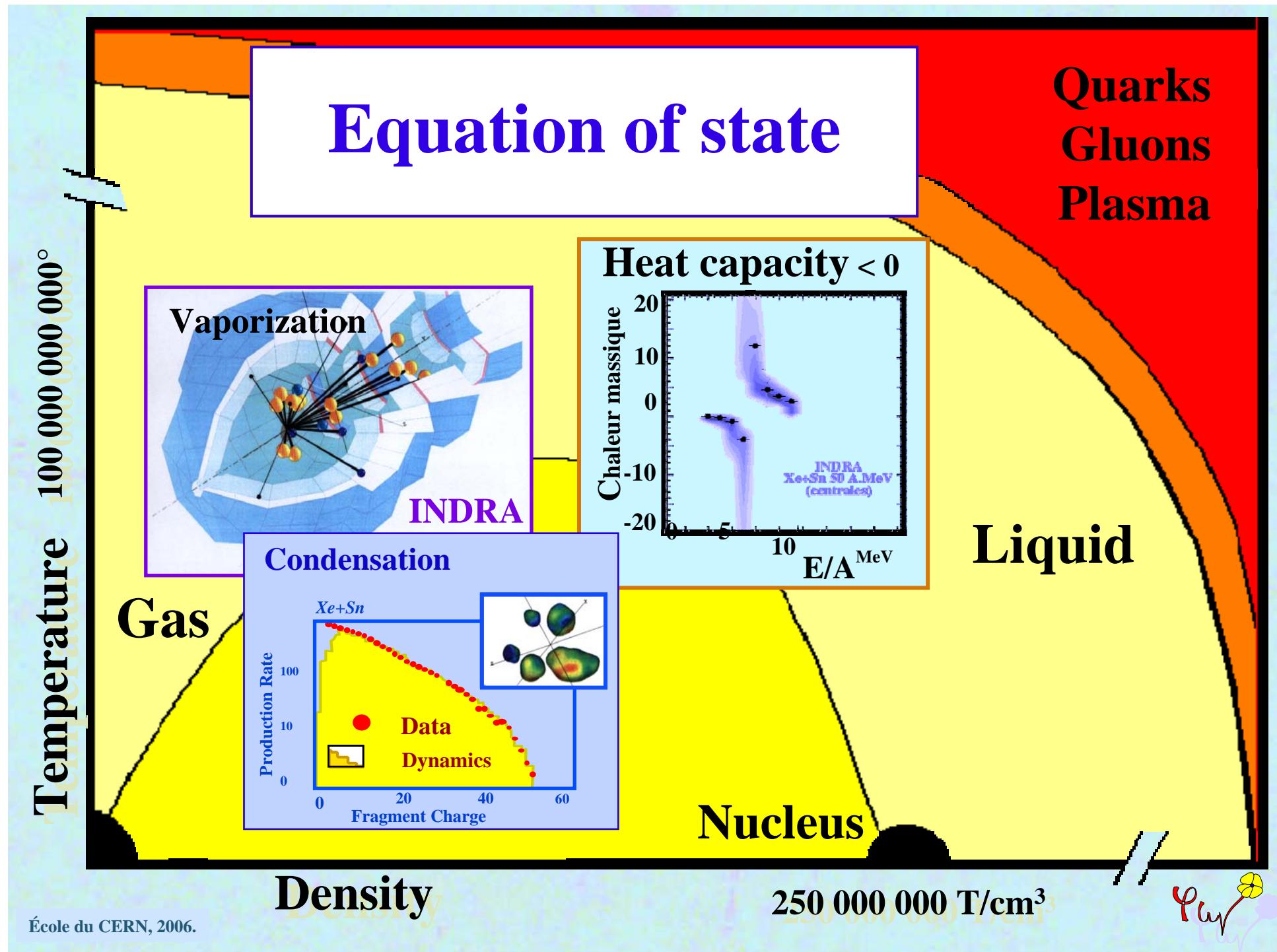
Fragmentation of nuclei

Heavy ion collisions

Fragmentation of nuclei

Caen
INDRA
Multidetector

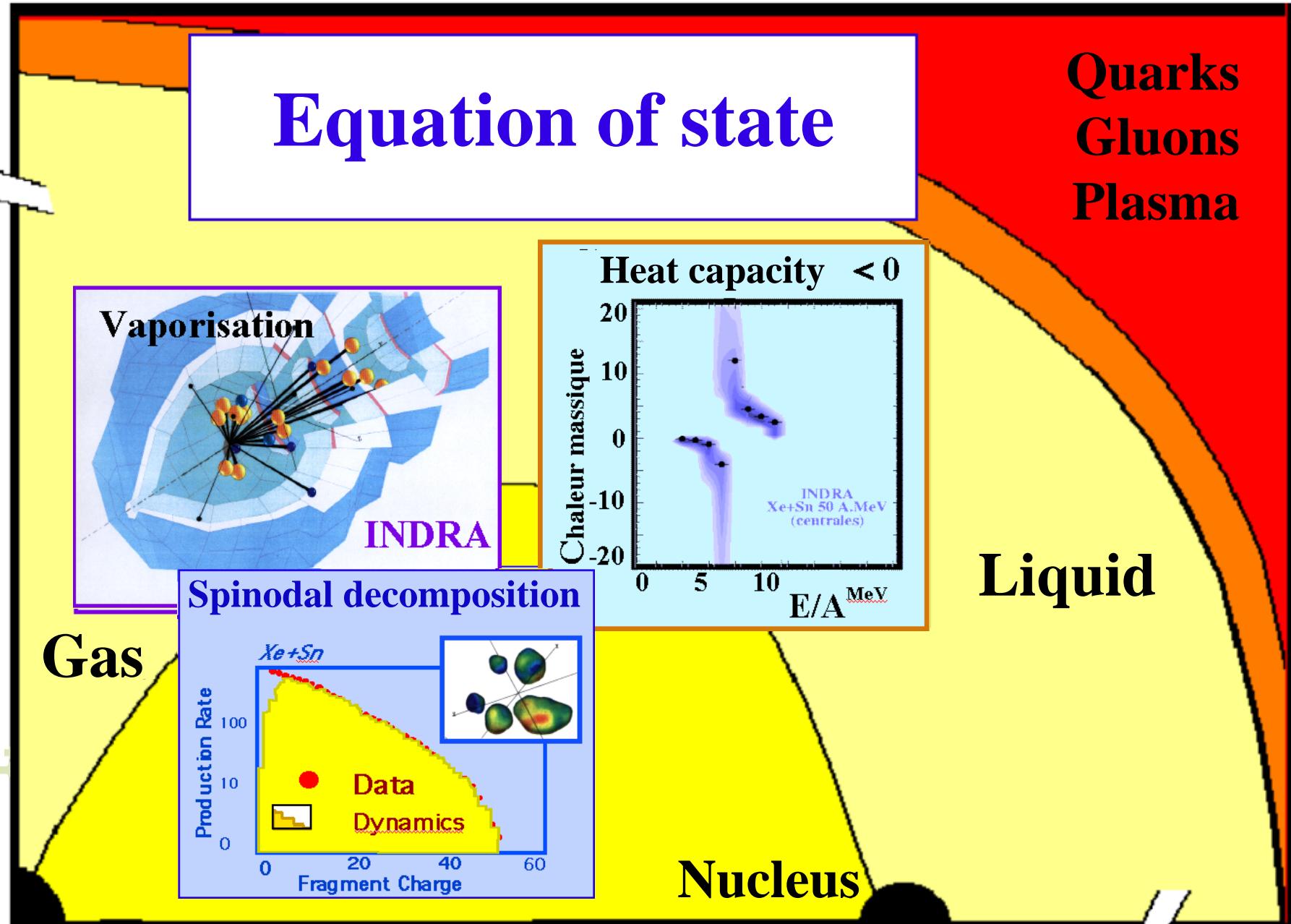




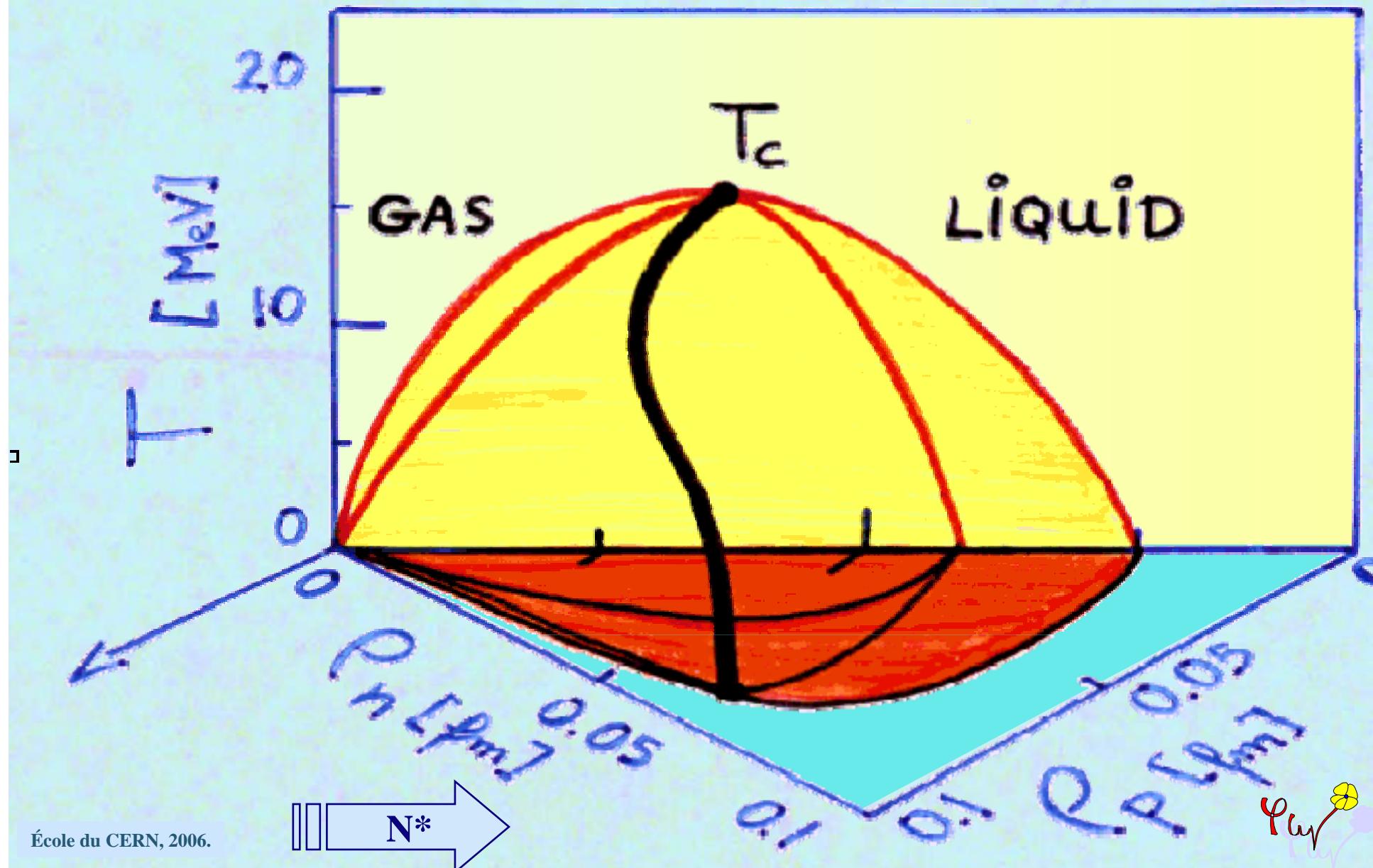
Equation of state

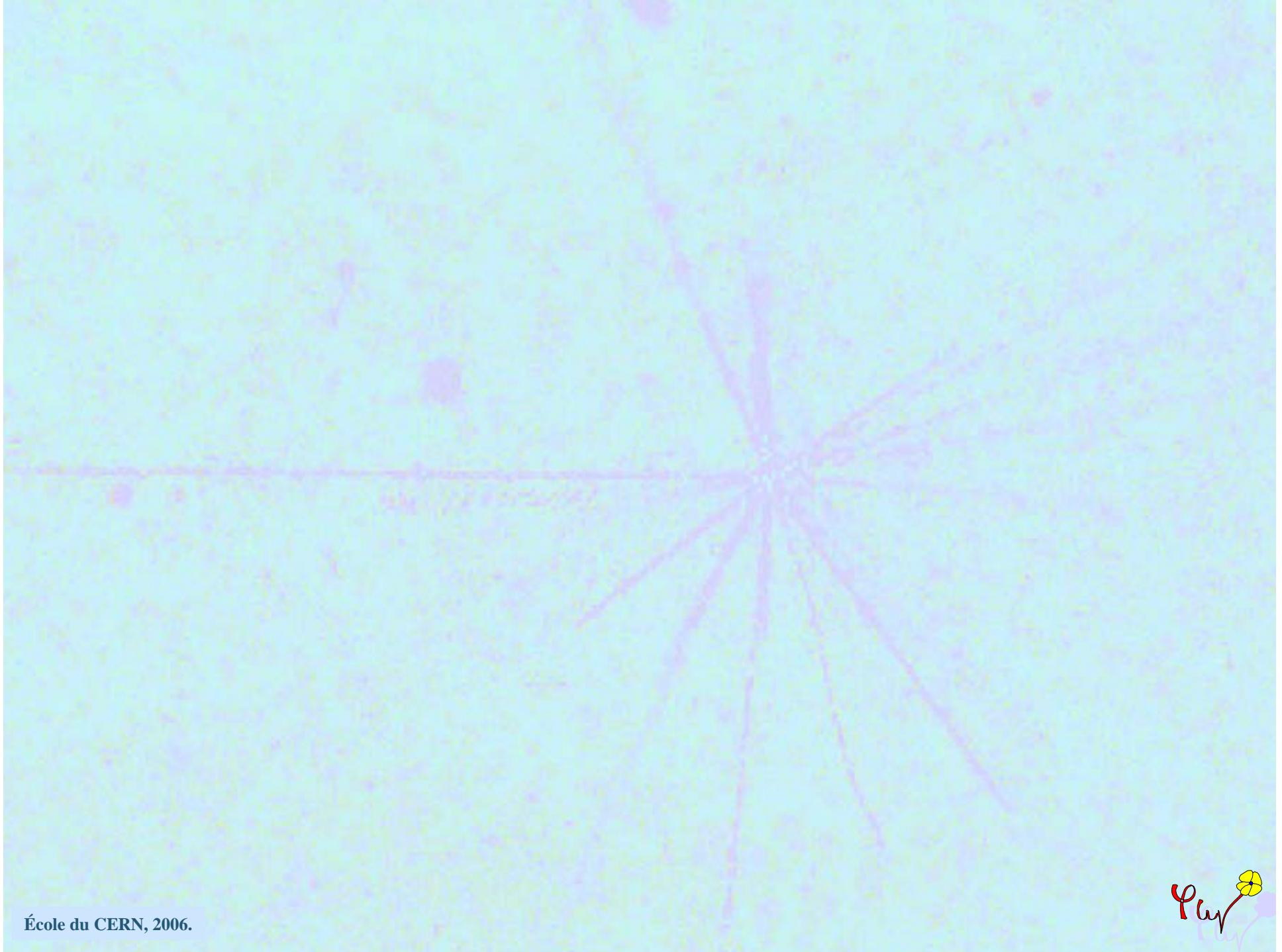
Quarks
Gluons
Plasma

Temperature $100\,000\,000\,000^\circ$



Isospin dependence of EOS?

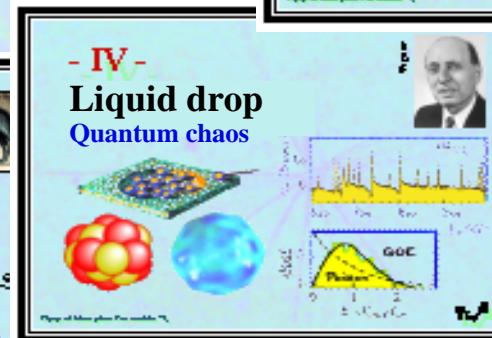
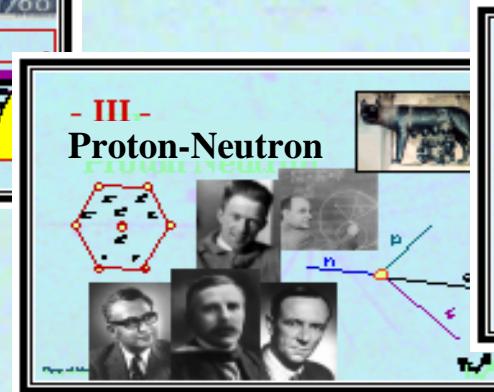
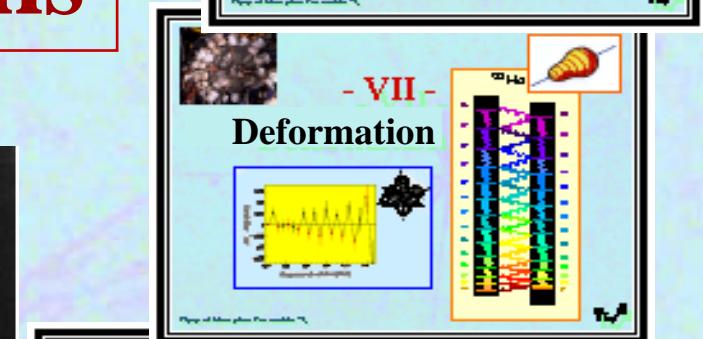
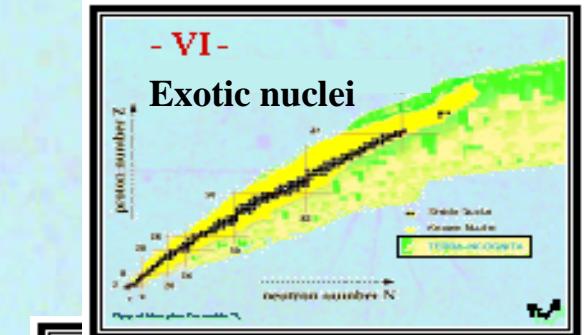
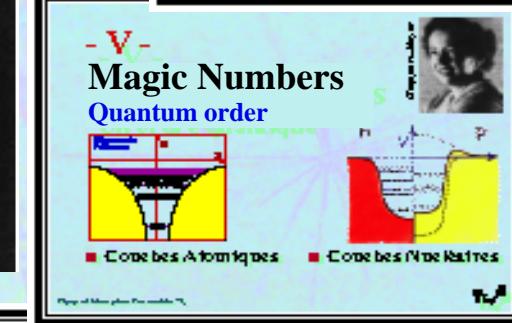
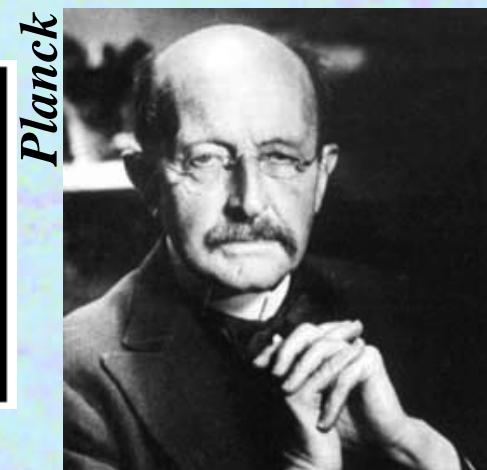
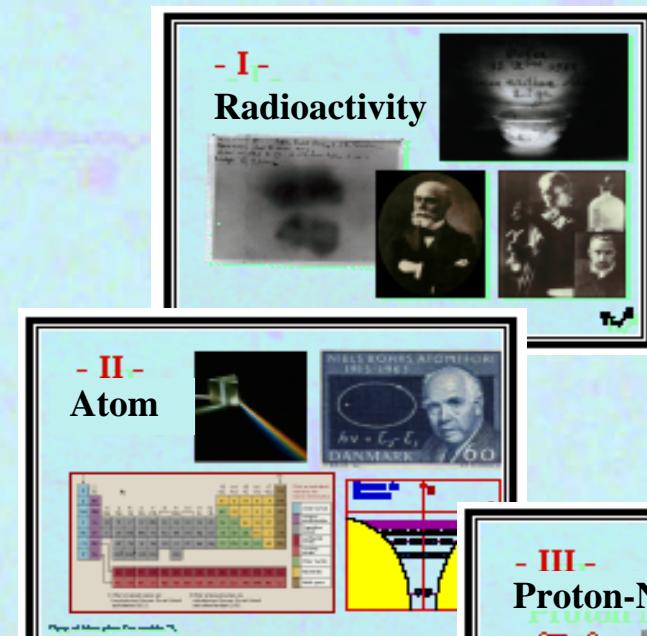


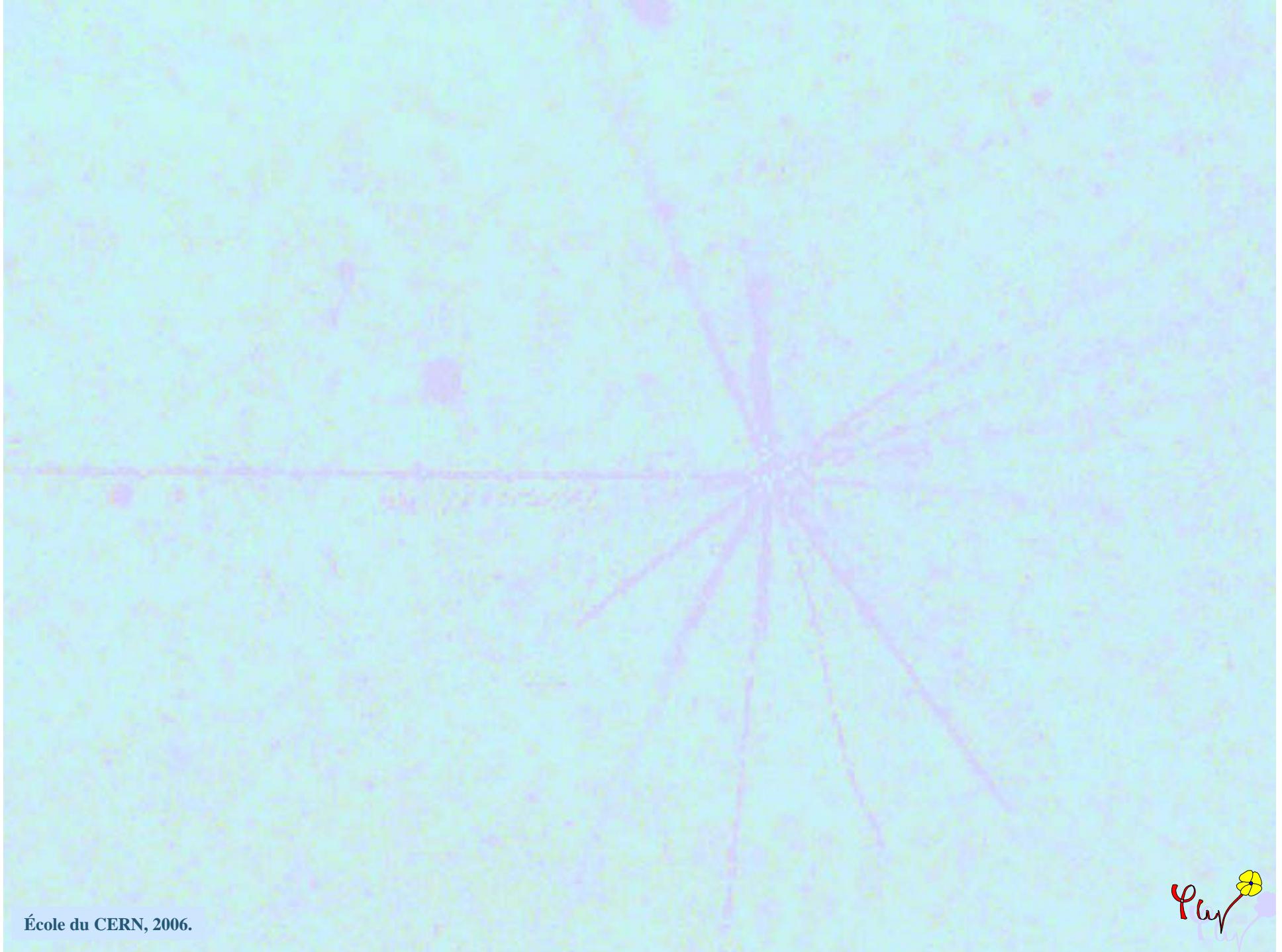


École du CERN, 2006.

Atomic Nuclei

Complex quantum systems





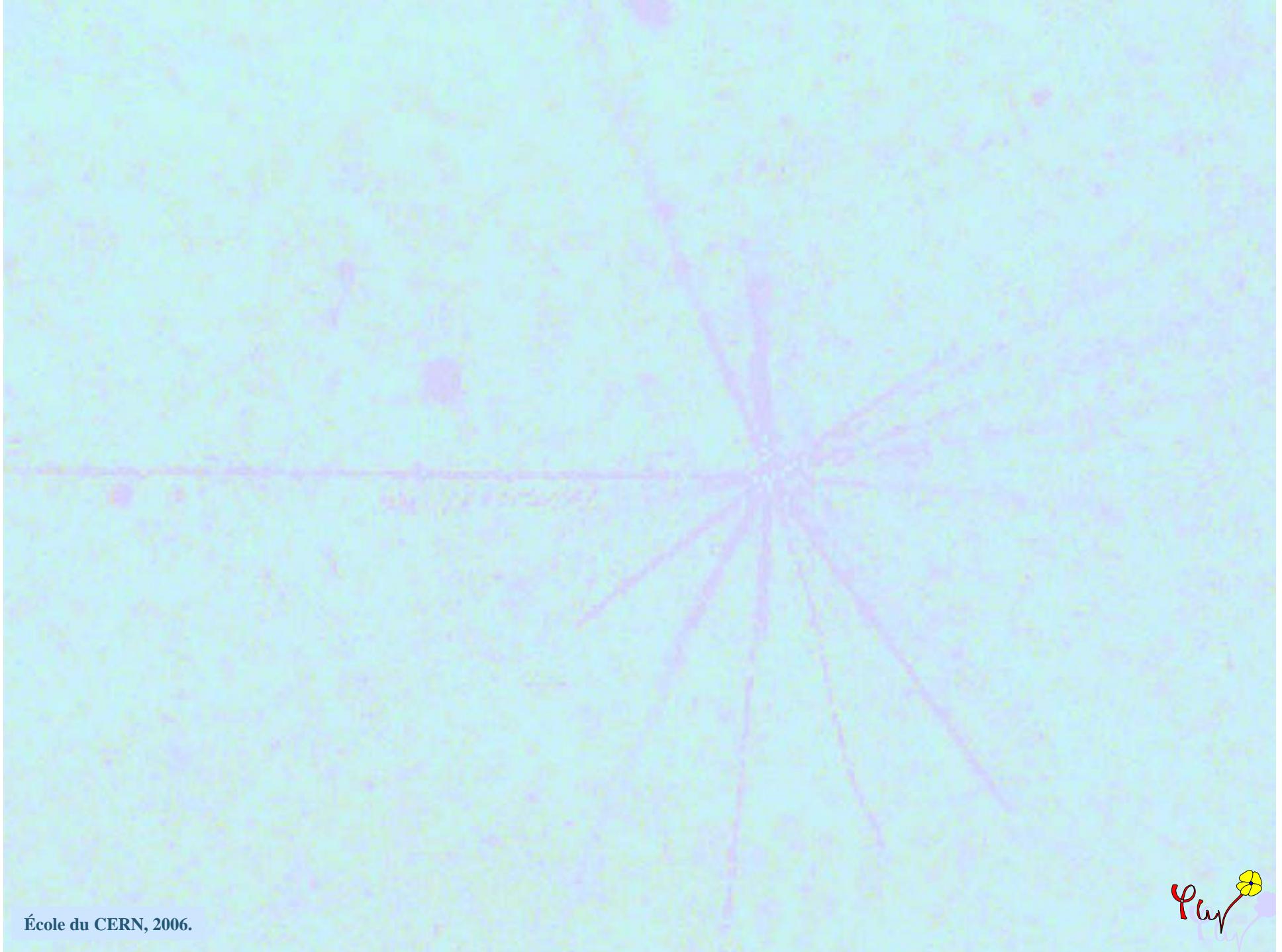
École du CERN, 2006.

- VII -

Spontaneous deformation

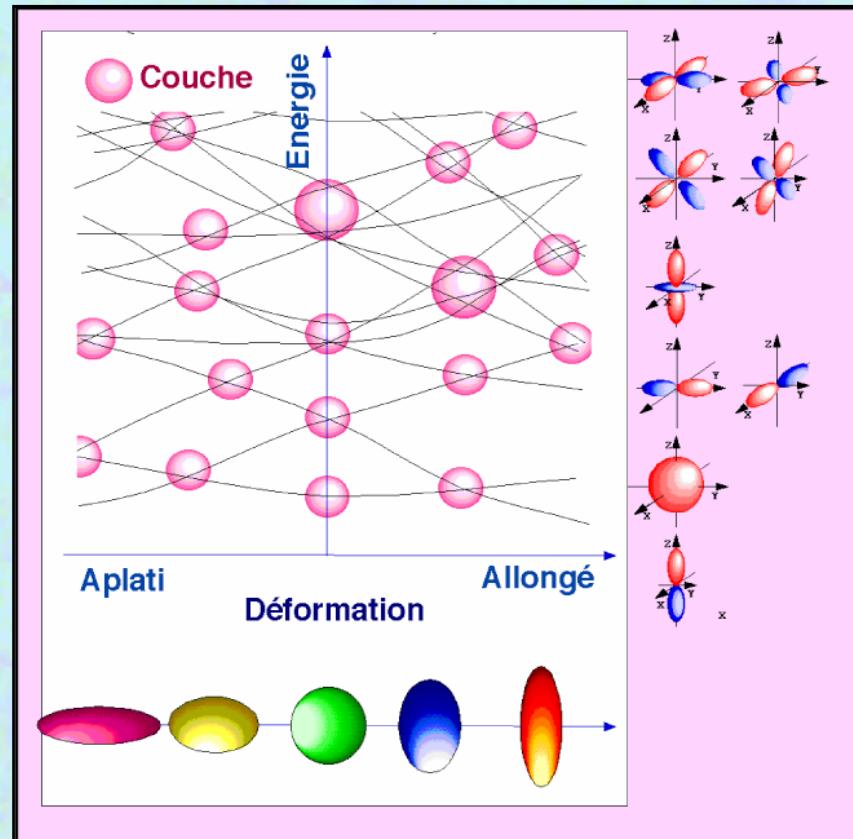
Quantum top



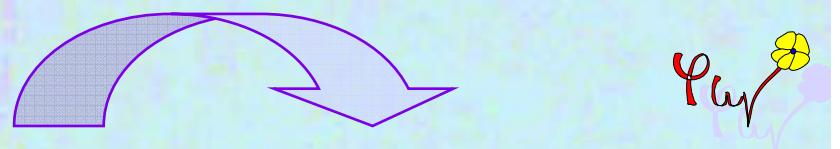


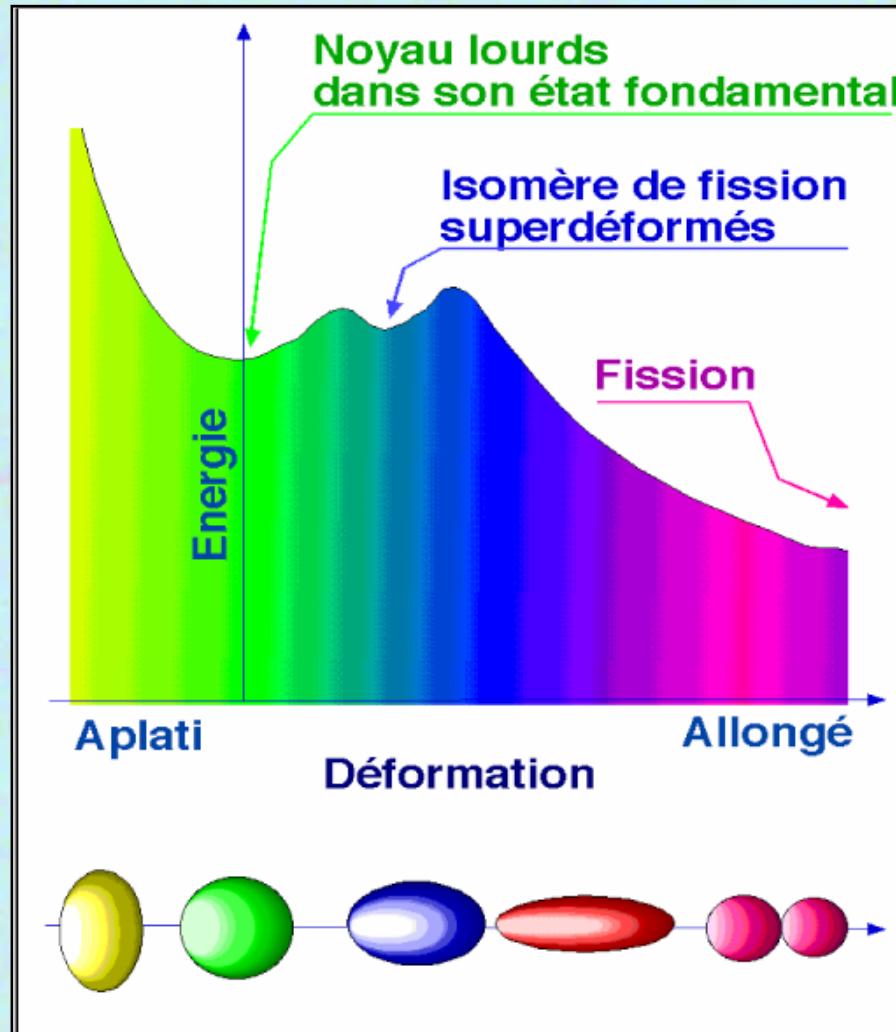
École du CERN, 2006.

The nucleus is auto-organized



- v Orbitals have shapes and deform the nucleus
- v This deformation favors specific orbitals

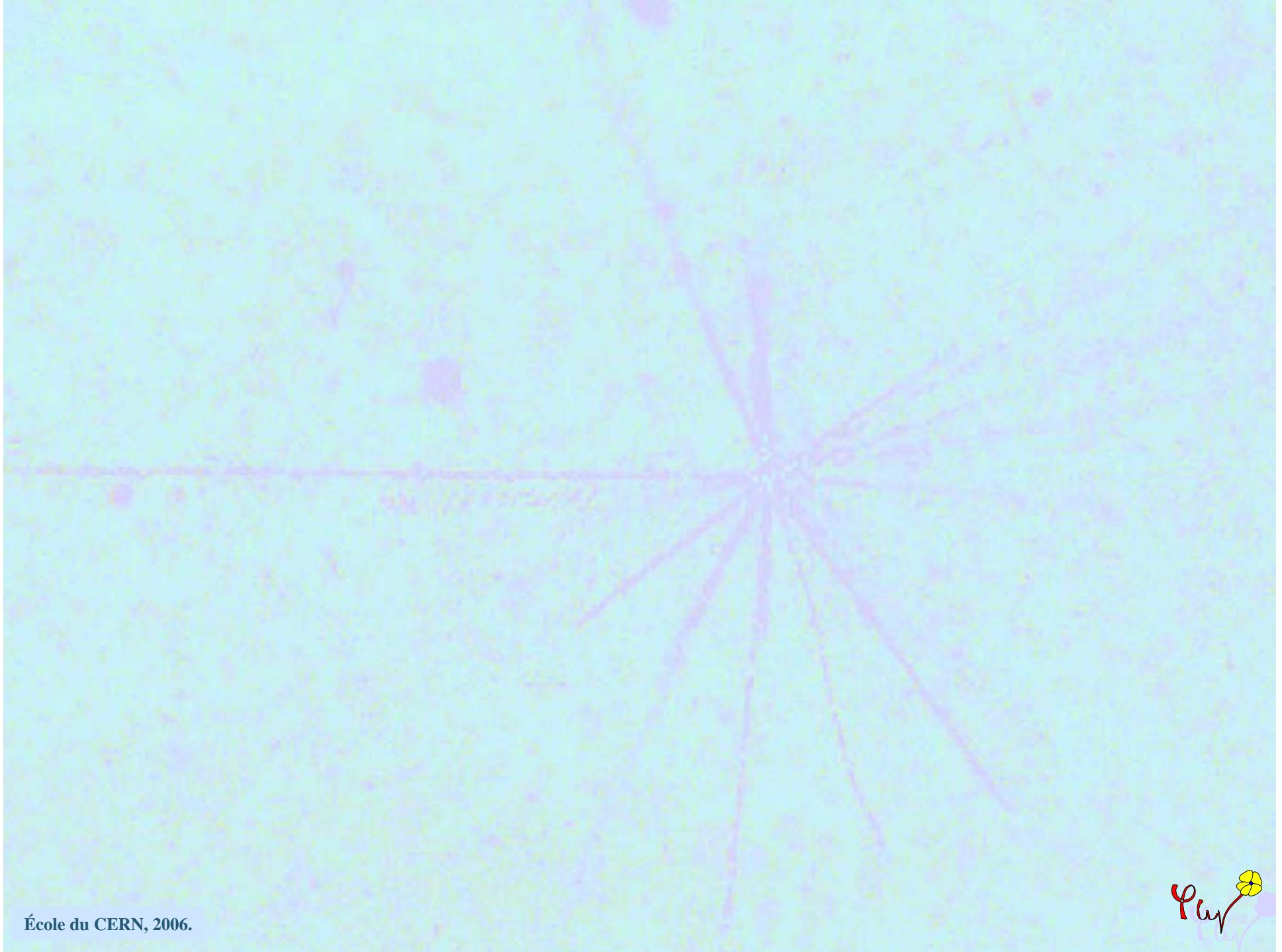




Deformed until breaking : Fission

- ✓ Spontaneous symmetry breaking
- ✓ Superdeformed nuclei



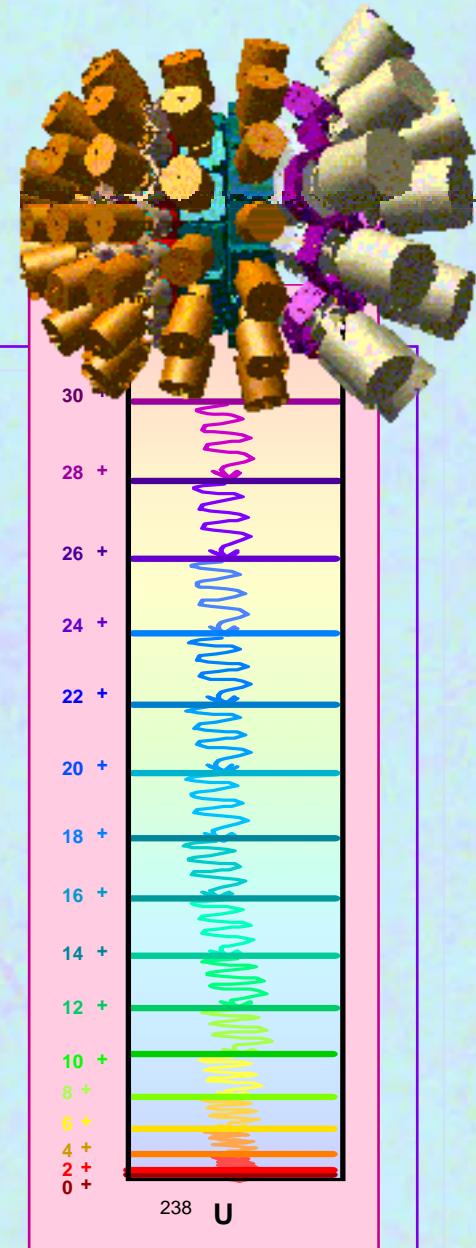
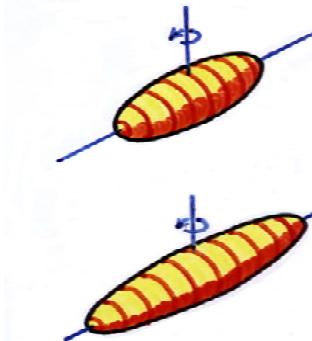
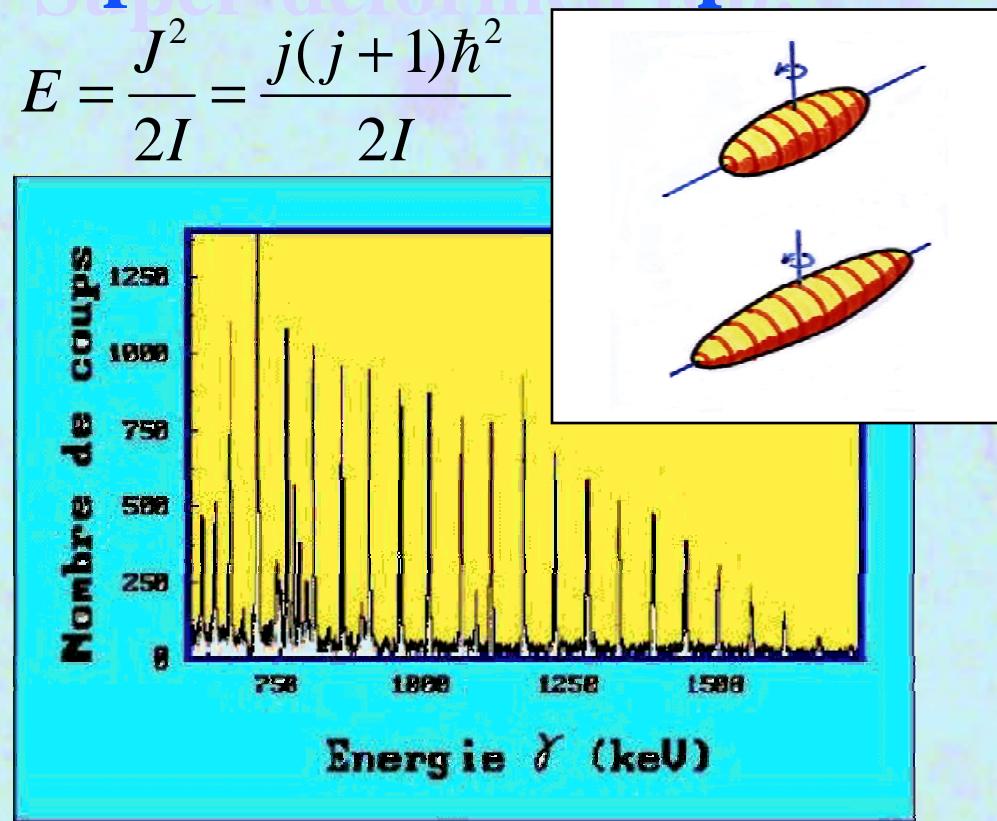


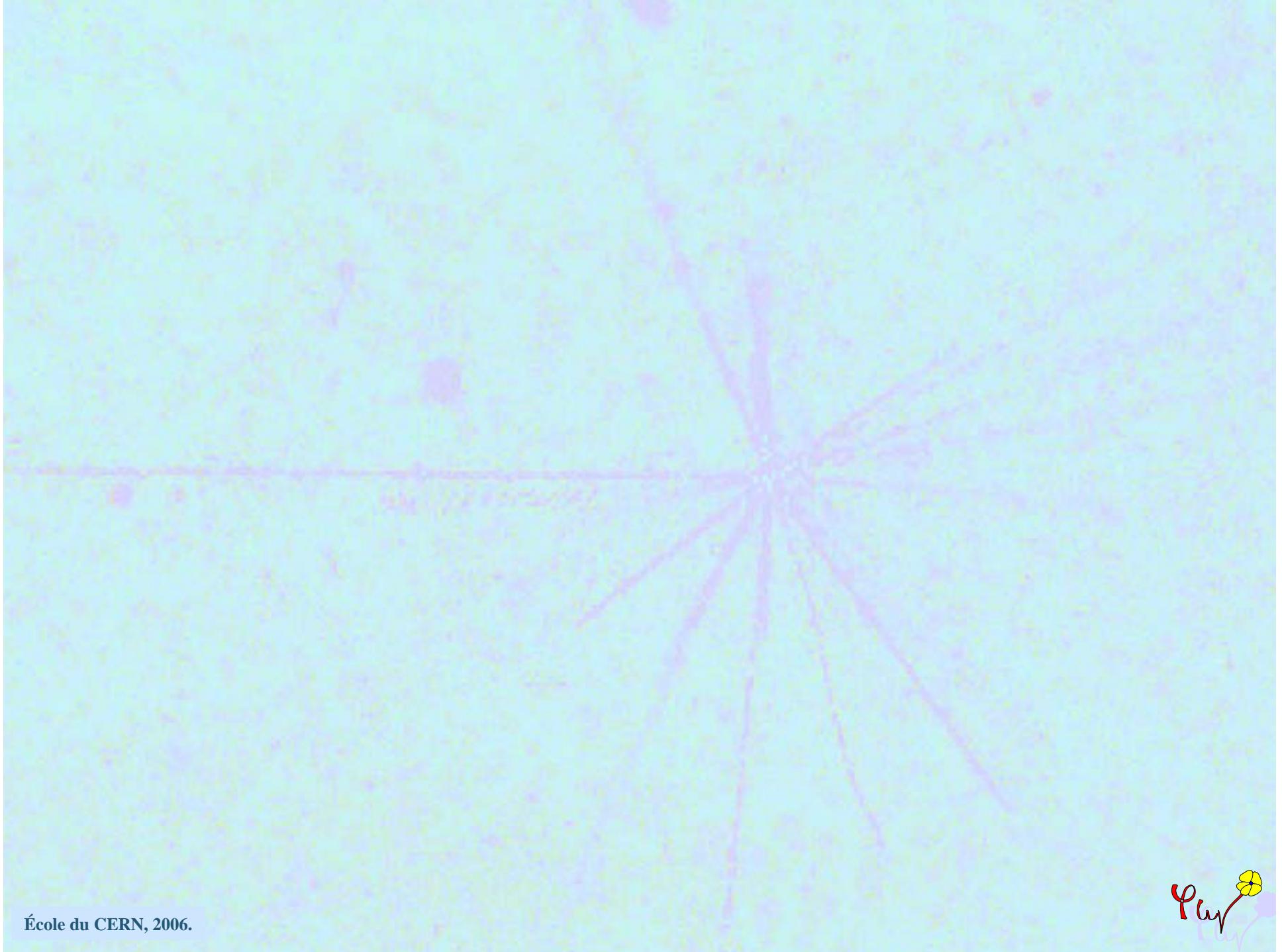
École du CERN, 2006.

Quantum order

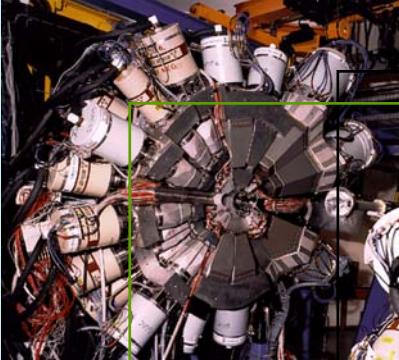
✓ Super-deformed top:

$$E = \frac{J^2}{2I} = \frac{j(j+1)\hbar^2}{2I}$$





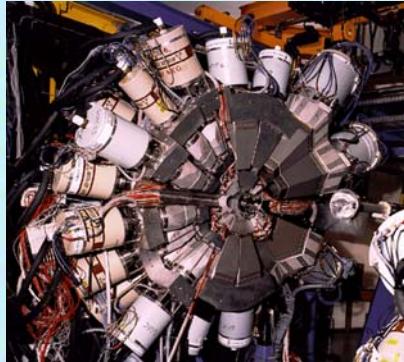
École du CERN, 2006.



Symmetry Breaking

Eurogam

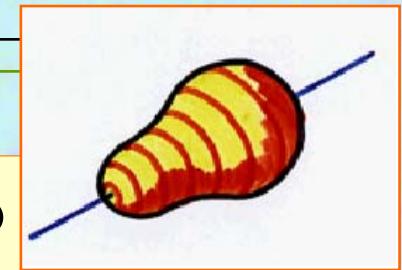
v More complex
shapes



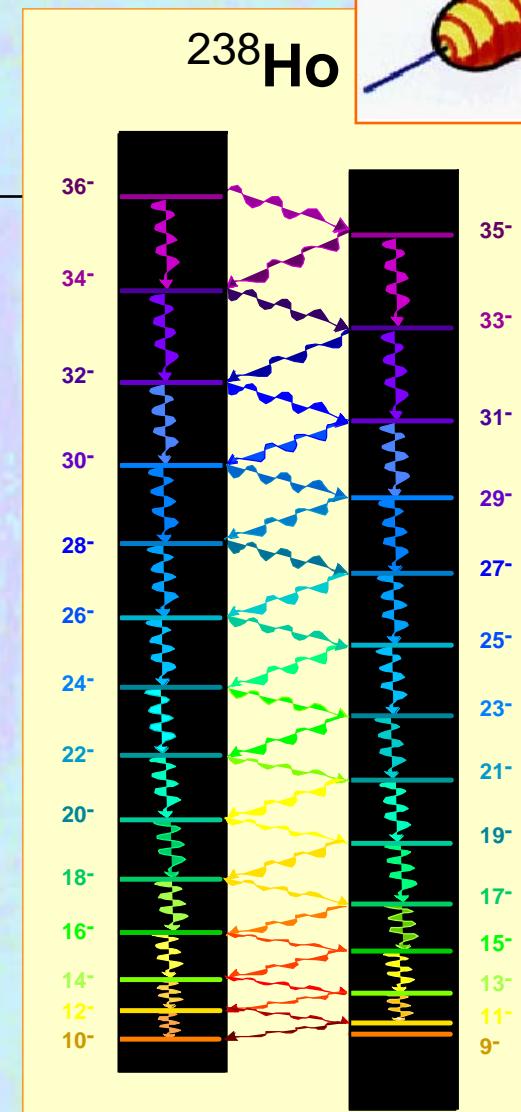
Symmetry Breaking

Eurogam

v More complex
shapes

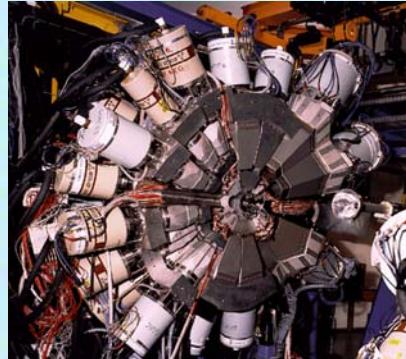


^{238}Ho



Brisure de la symétrie droite gauche

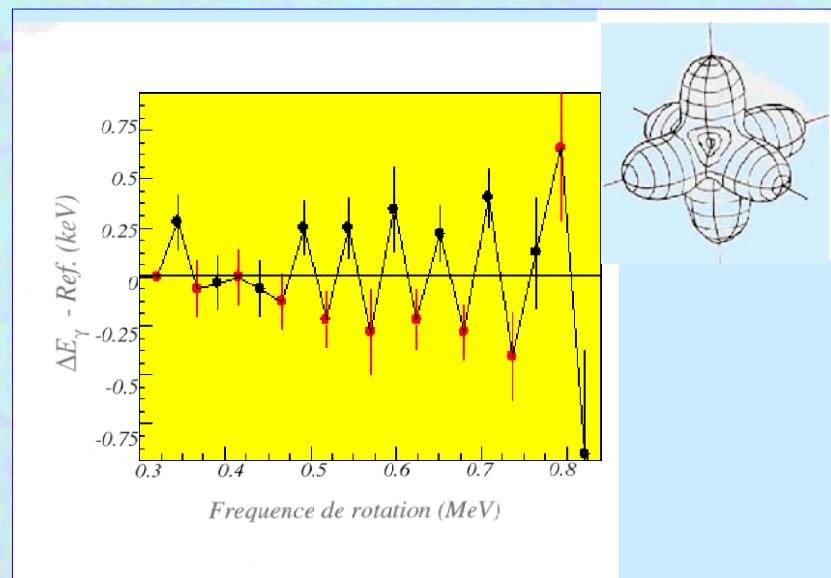
Qay



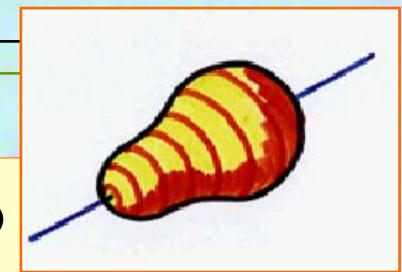
Symmetry Breaking

Eurogam

v More complex
shapes

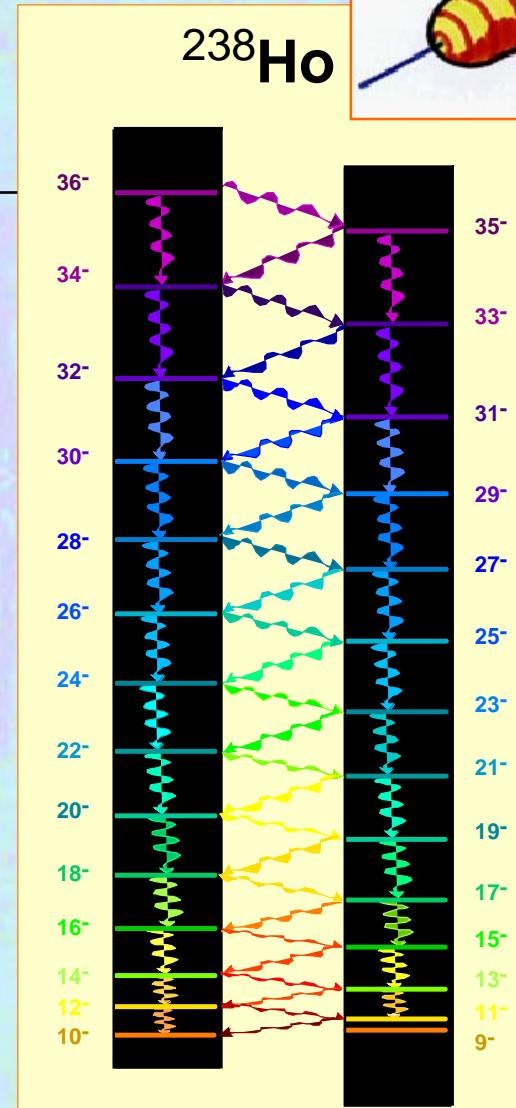


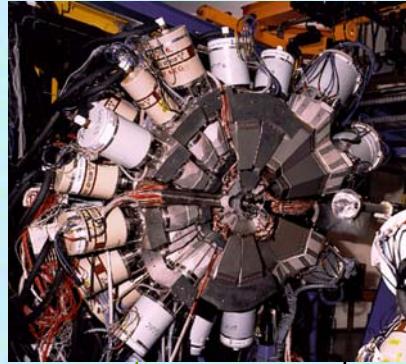
C4 shape



^{238}Ho

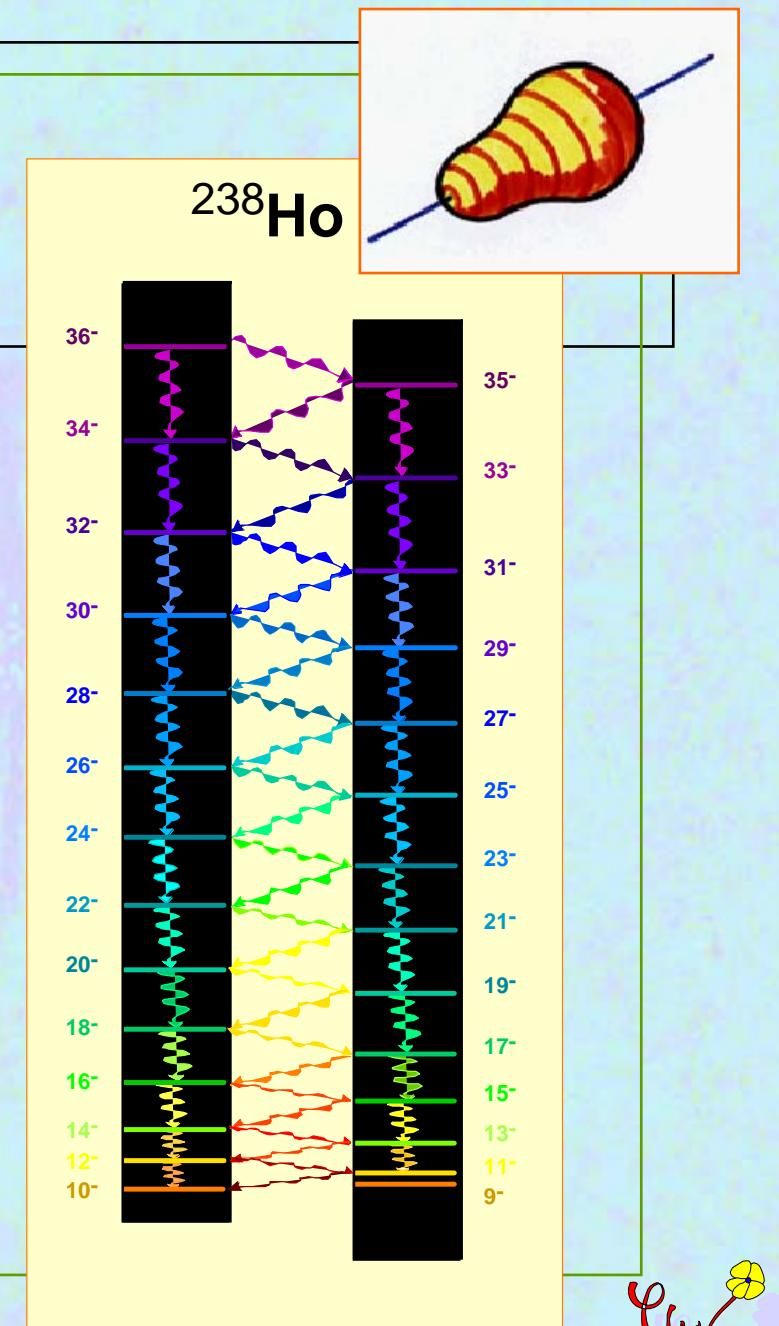
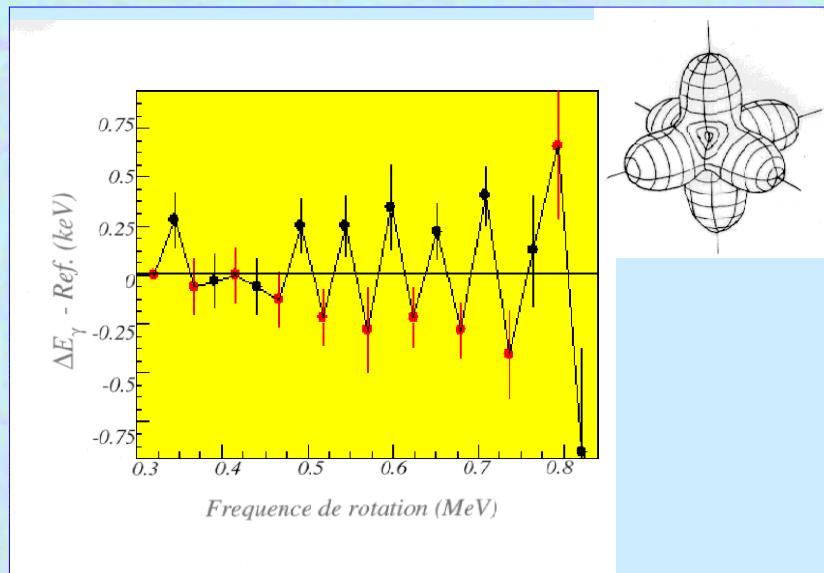
Breaking of the left-right symmetry

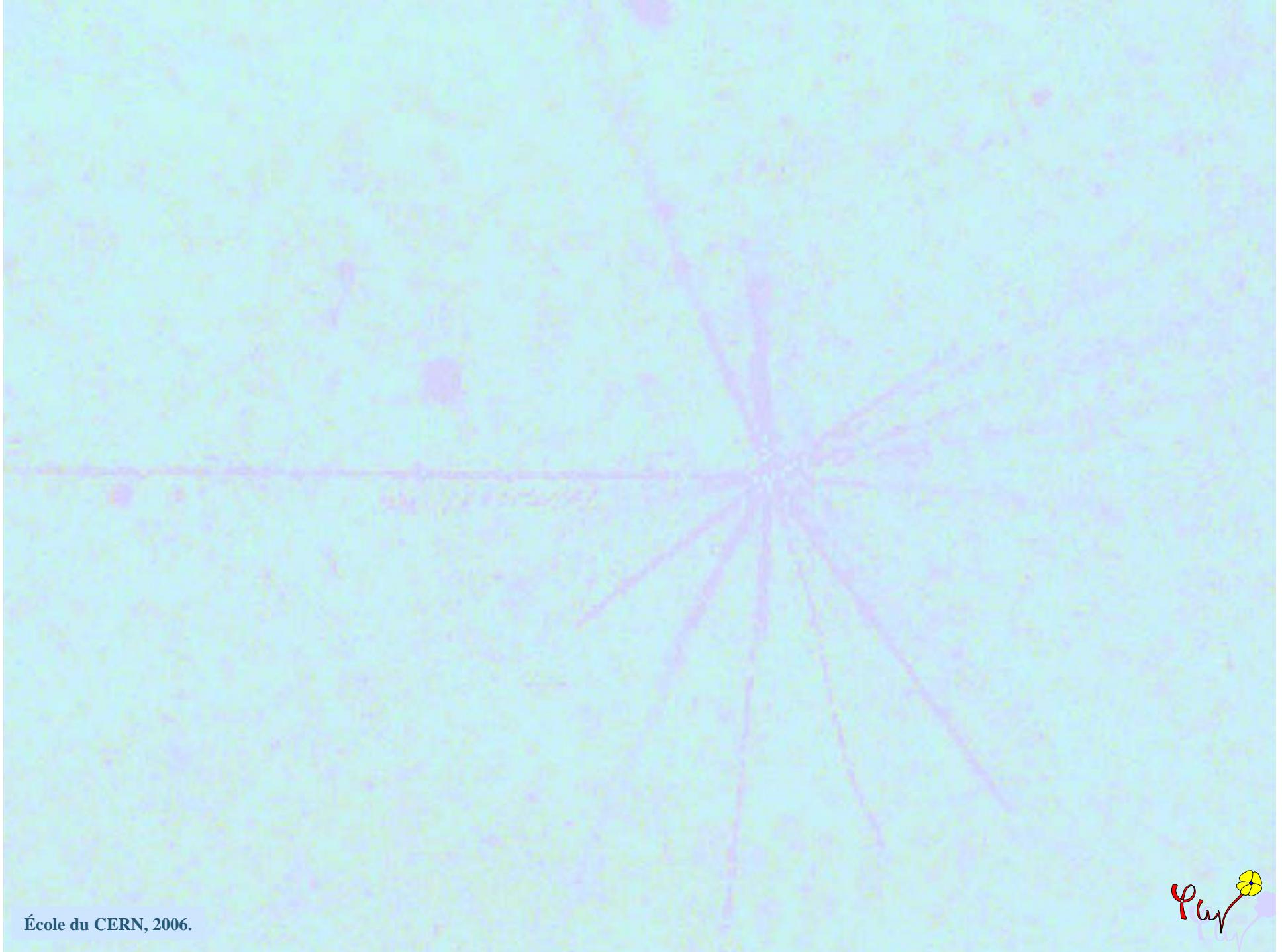




Symmetry Breaking

✓ Spectra signals
symmetries.

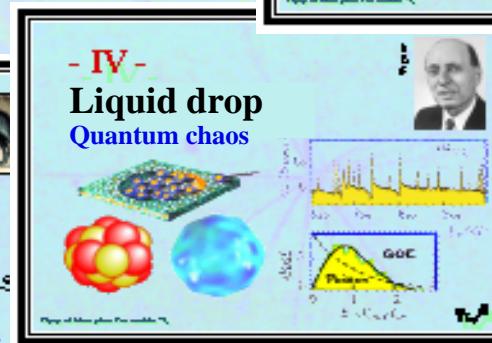
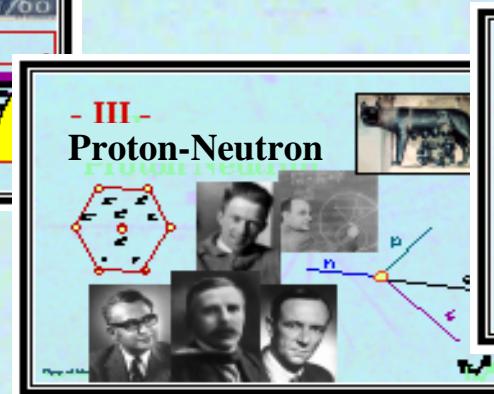
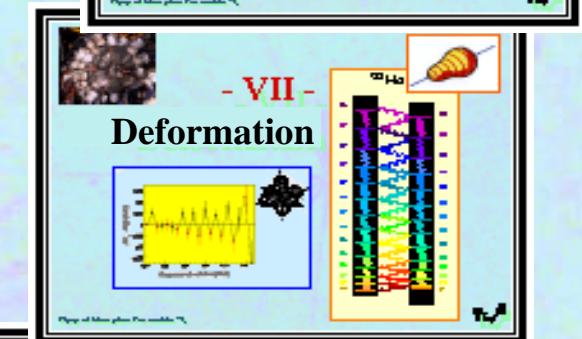
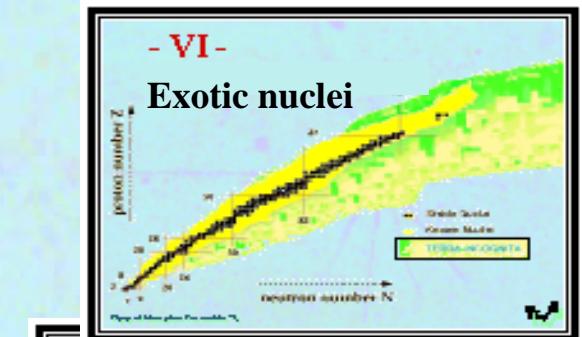
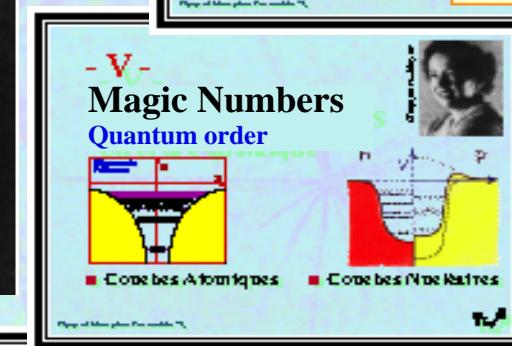
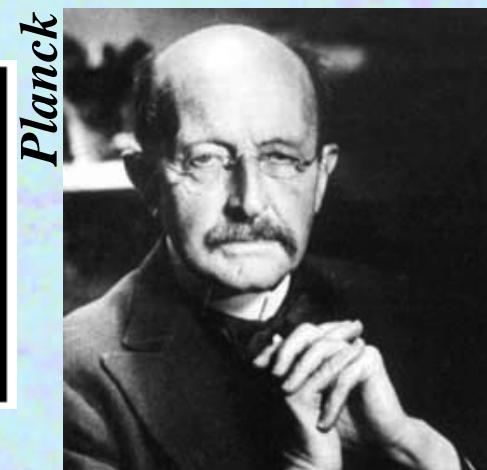
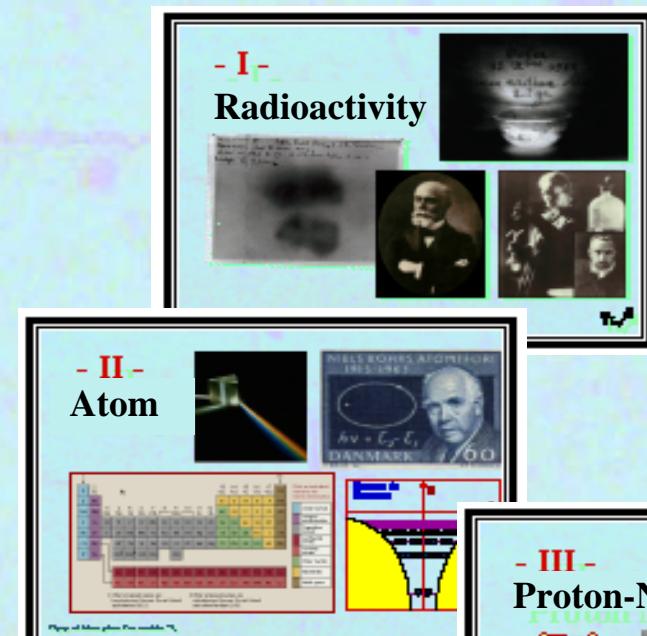


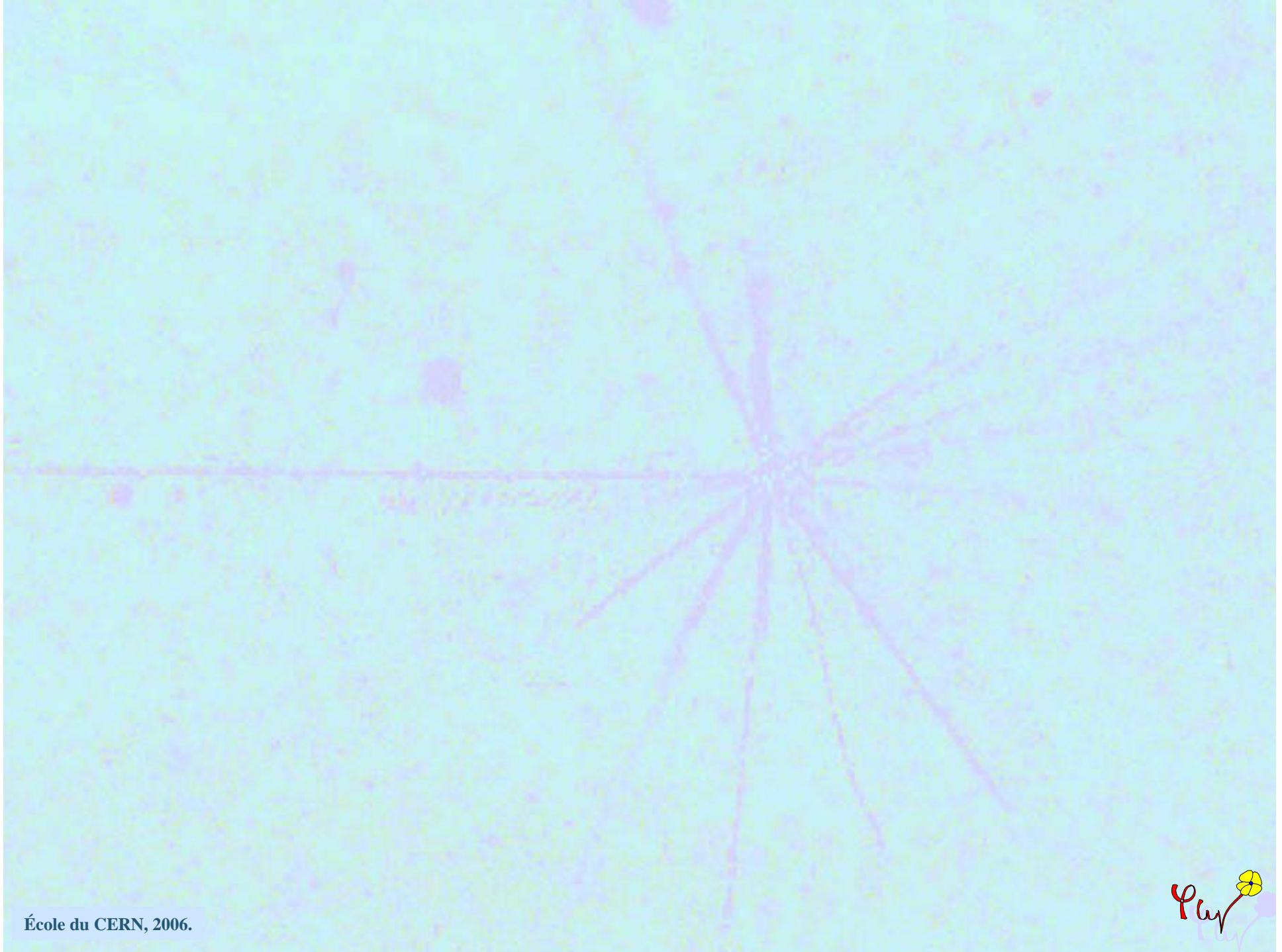


École du CERN, 2006.

Atomic Nuclei

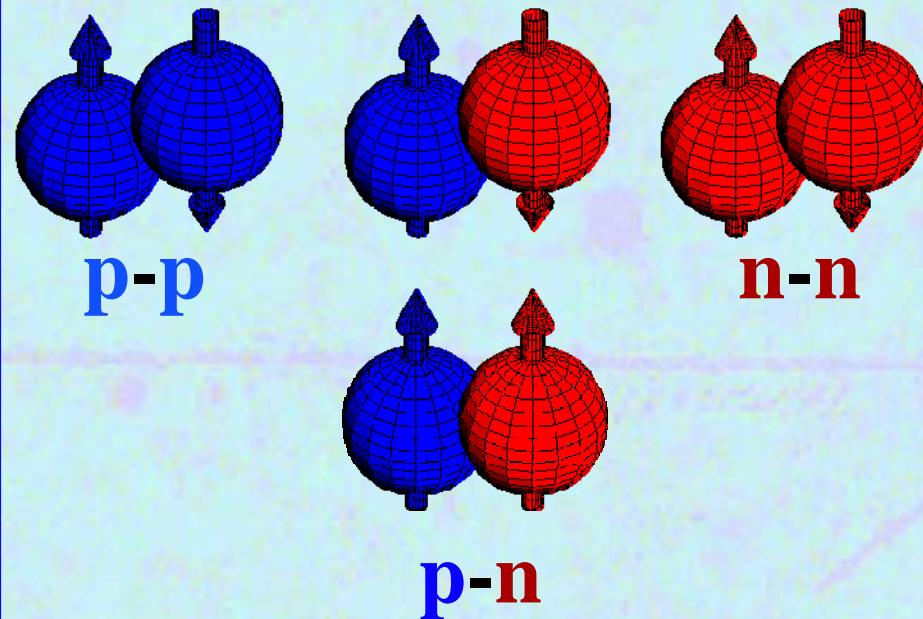
Complex quantum systems





École du CERN, 2006.

Bosons (pairs, quartets) in Nuclei



✓ Normal superfluidity

Φ Opposite spins

✓ New superfluidity

N=Z nuclei

Φ Parallel spins

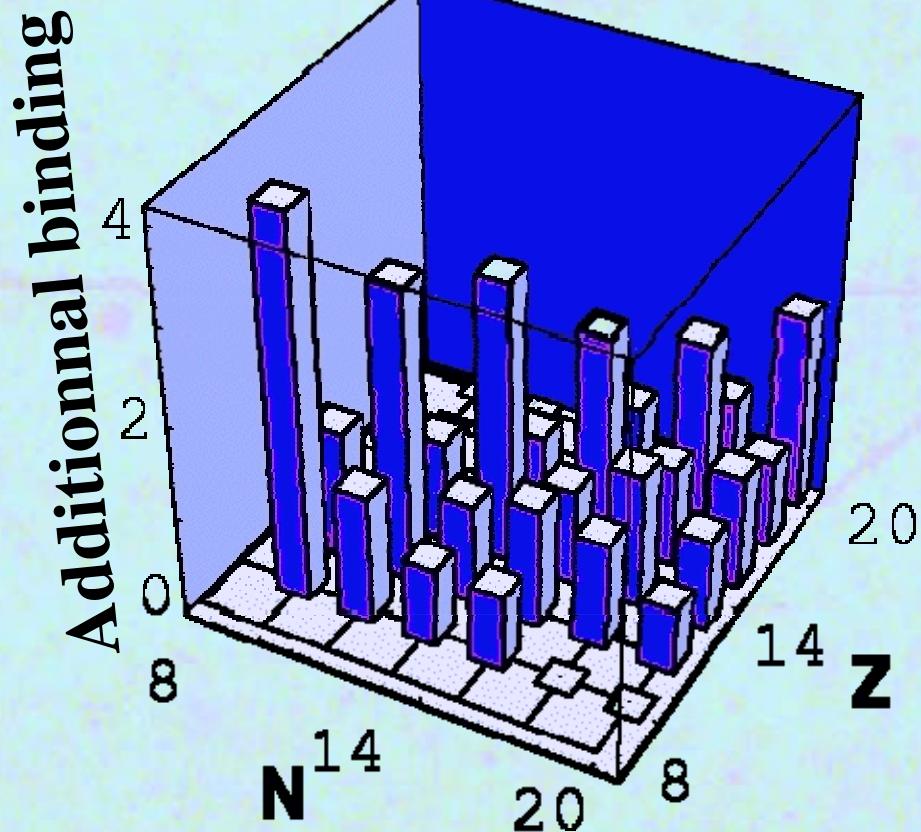
Φ T=0 (n-p) pairs

Φ Additionnal binding

N=Z Nuclei

Bosons (pairs, quartets) in Nuclei

sd shell



v Normal superfluidity

Φ Opposite spins

v New superfluidity

$N=Z$ nuclei

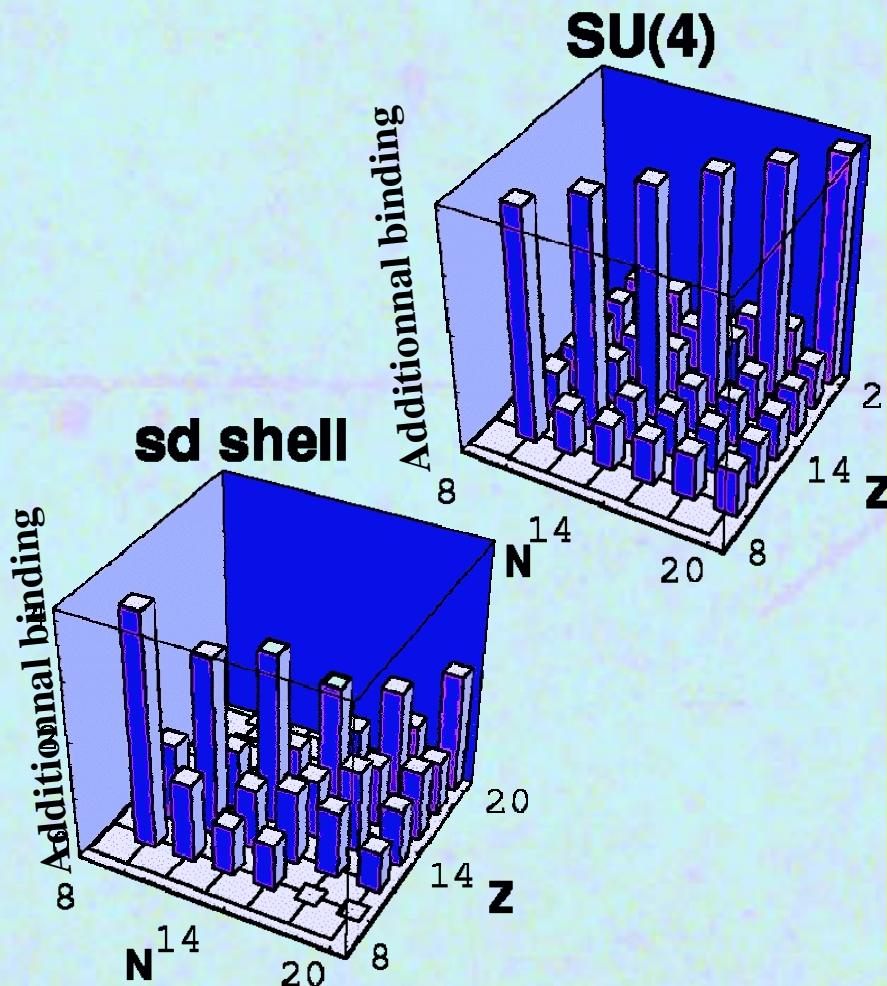
Φ Parallel spins

Φ $T=0$ (n-p) pairs

Φ Additional binding
 $N=Z$ Nuclei



Bosons (pairs, quartets) in Nuclei



Quartet condensate?

- Φ Spin-isospin (α)
- Φ Pseudo-spin (new)

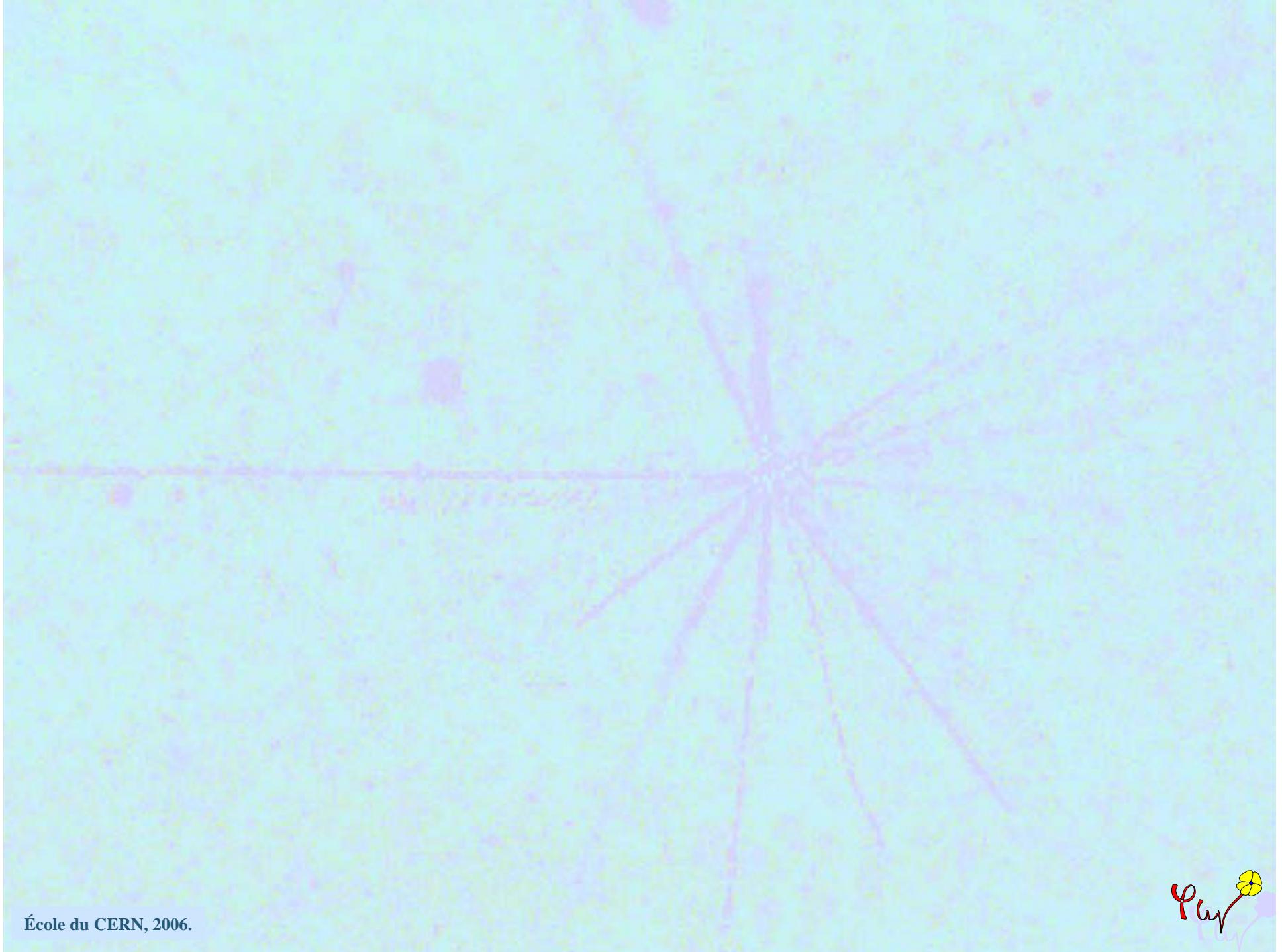
New superfluidity

$N=Z$ nuclei

- Φ Parallel spins
- Φ $T=0$ (n-p) pairs
- Φ Additional binding

$N=Z$ Nuclei

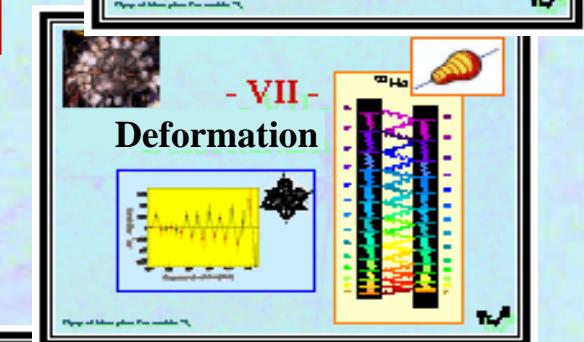
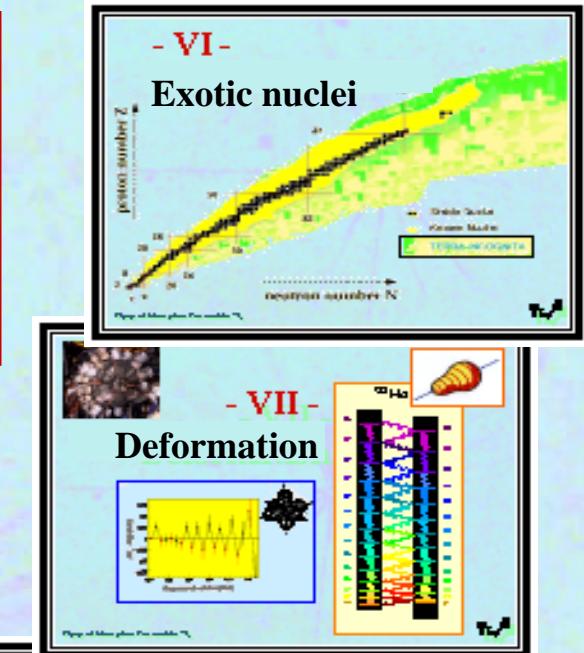
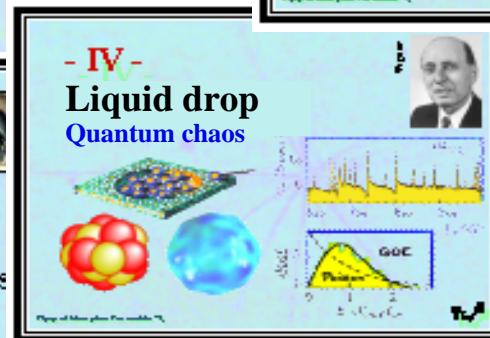
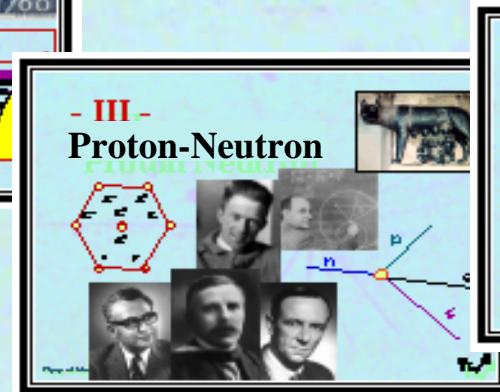
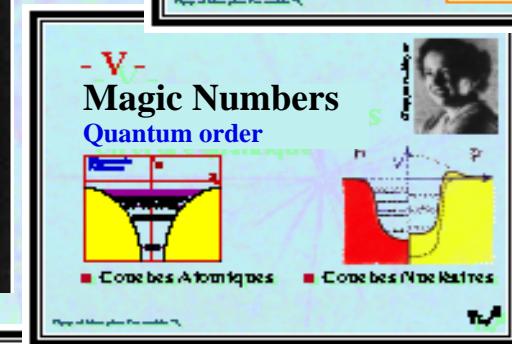
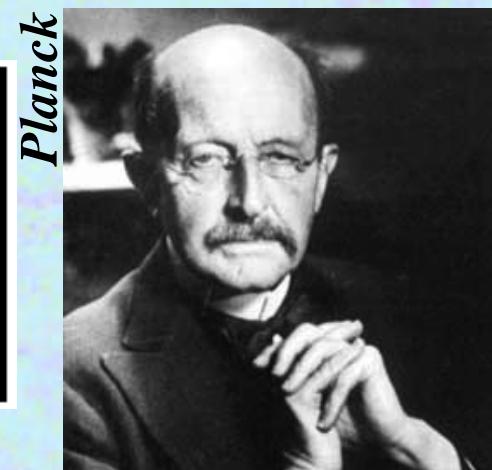
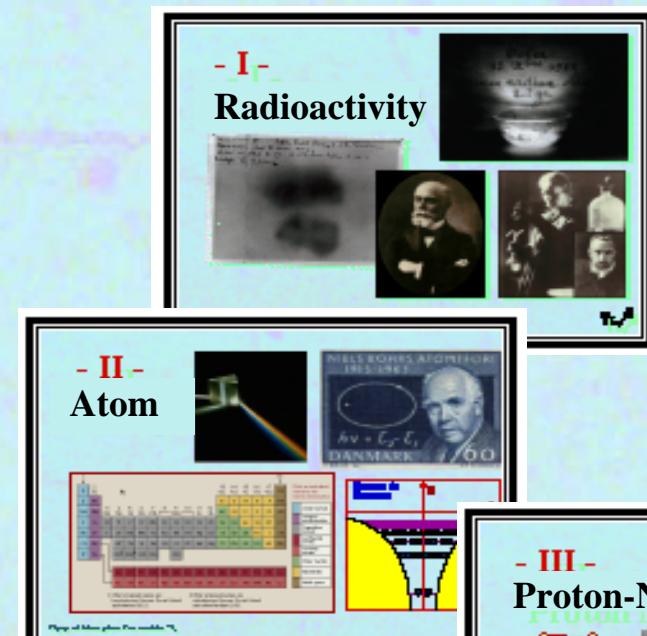




École du CERN, 2006.

Atomic Nuclei

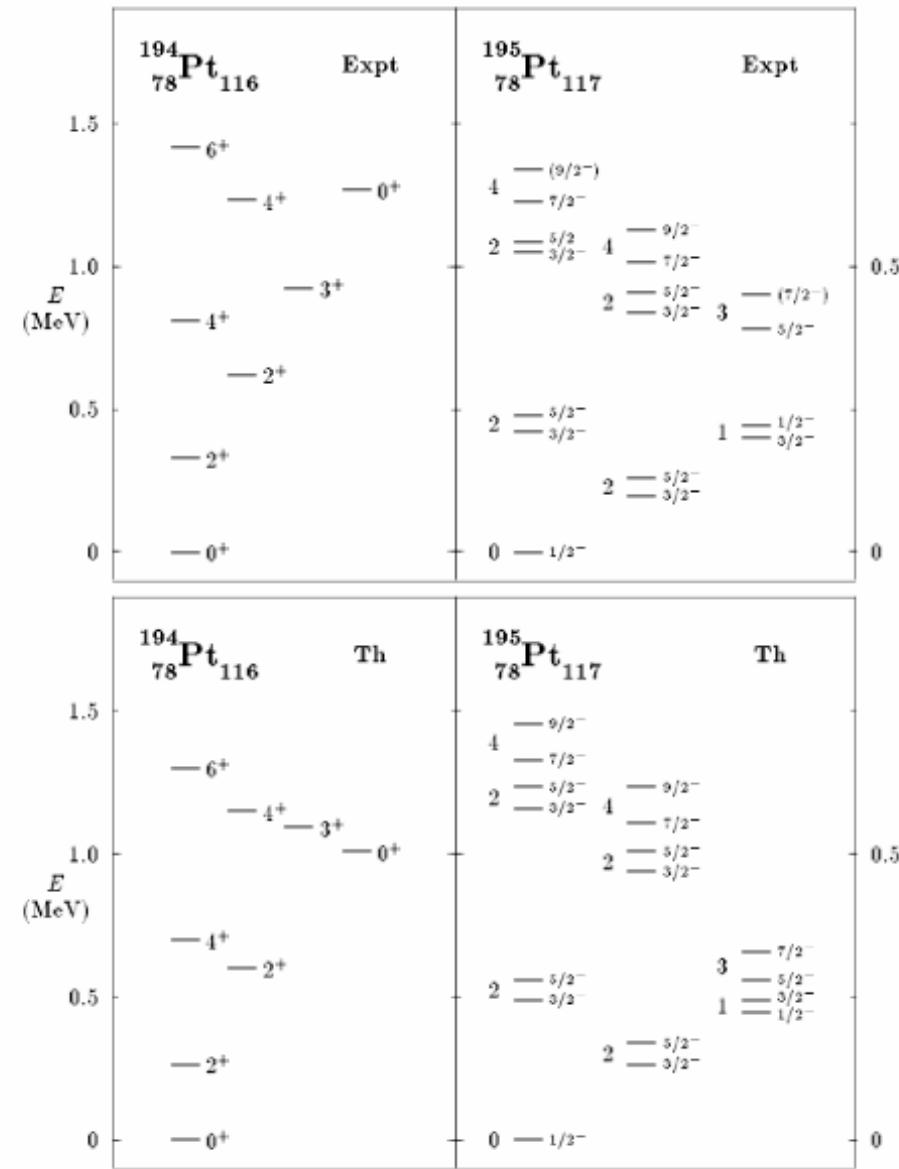
Complex quantum systems



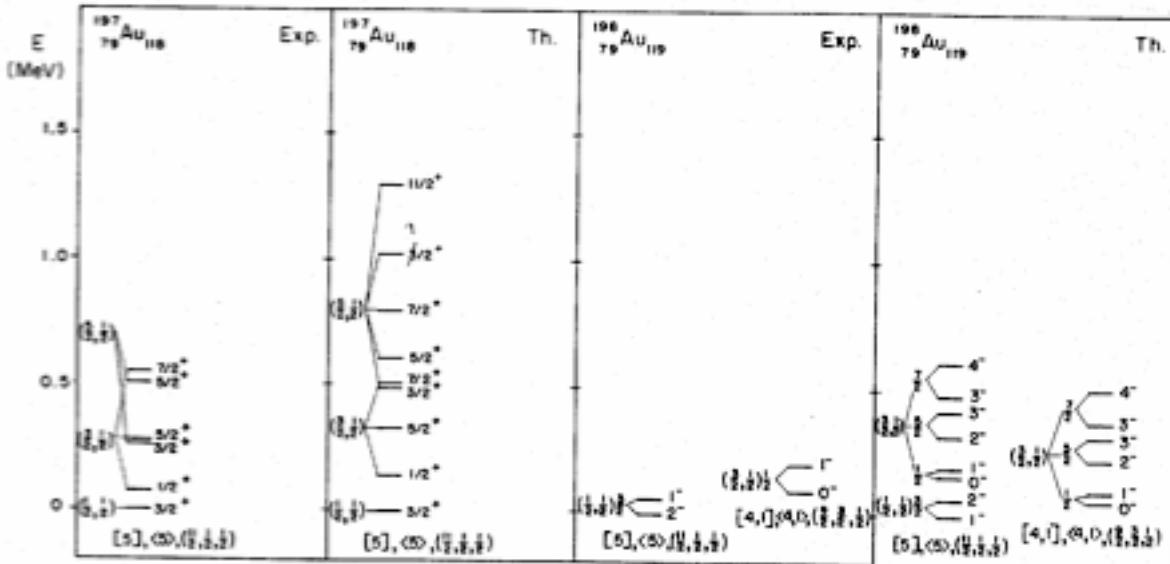
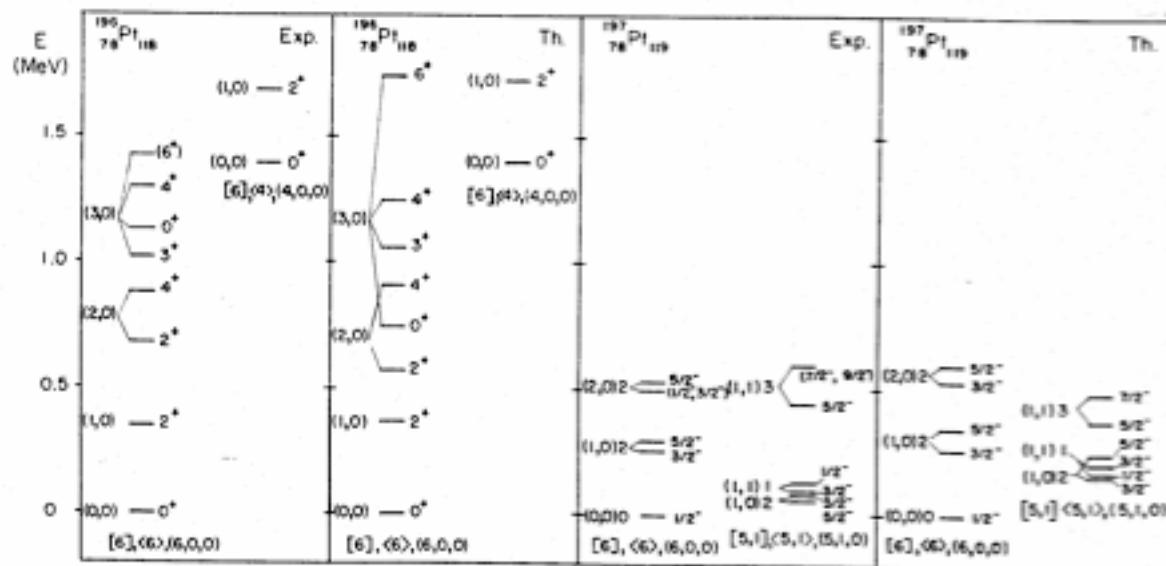
Play

Super-symmetry

- Example: The ^{194}Pt - ^{195}Pt doublet.



• Example: The ^{196}Pt - ^{197}Pt - ^{197}Au - ^{198}Au quartet.



Ψ_ω

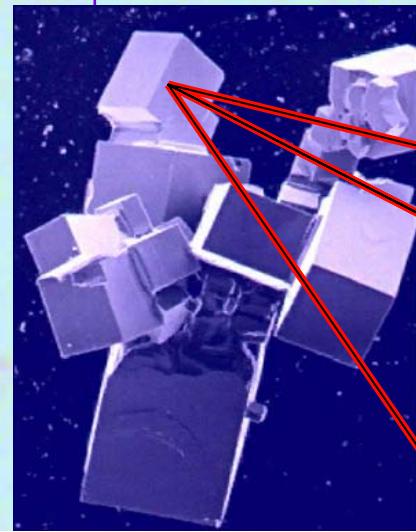
Play

Nuclear Physics an Introduction

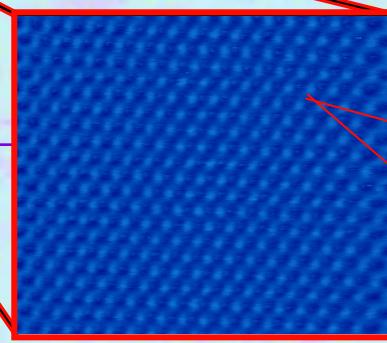
Philippe CHOMAZ
GANIL-CAEN



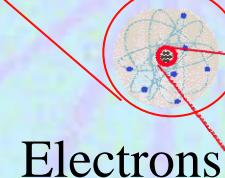
Nucleons and nuclei: steps toward the elementary structure of matter



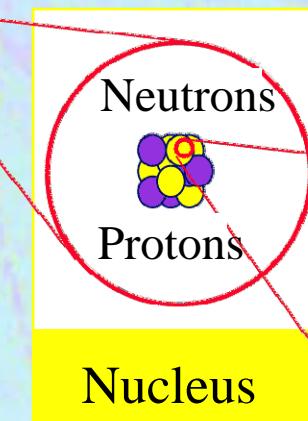
Salt cristal



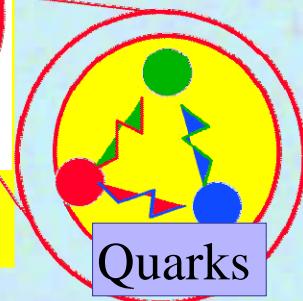
Atoms



Electrons

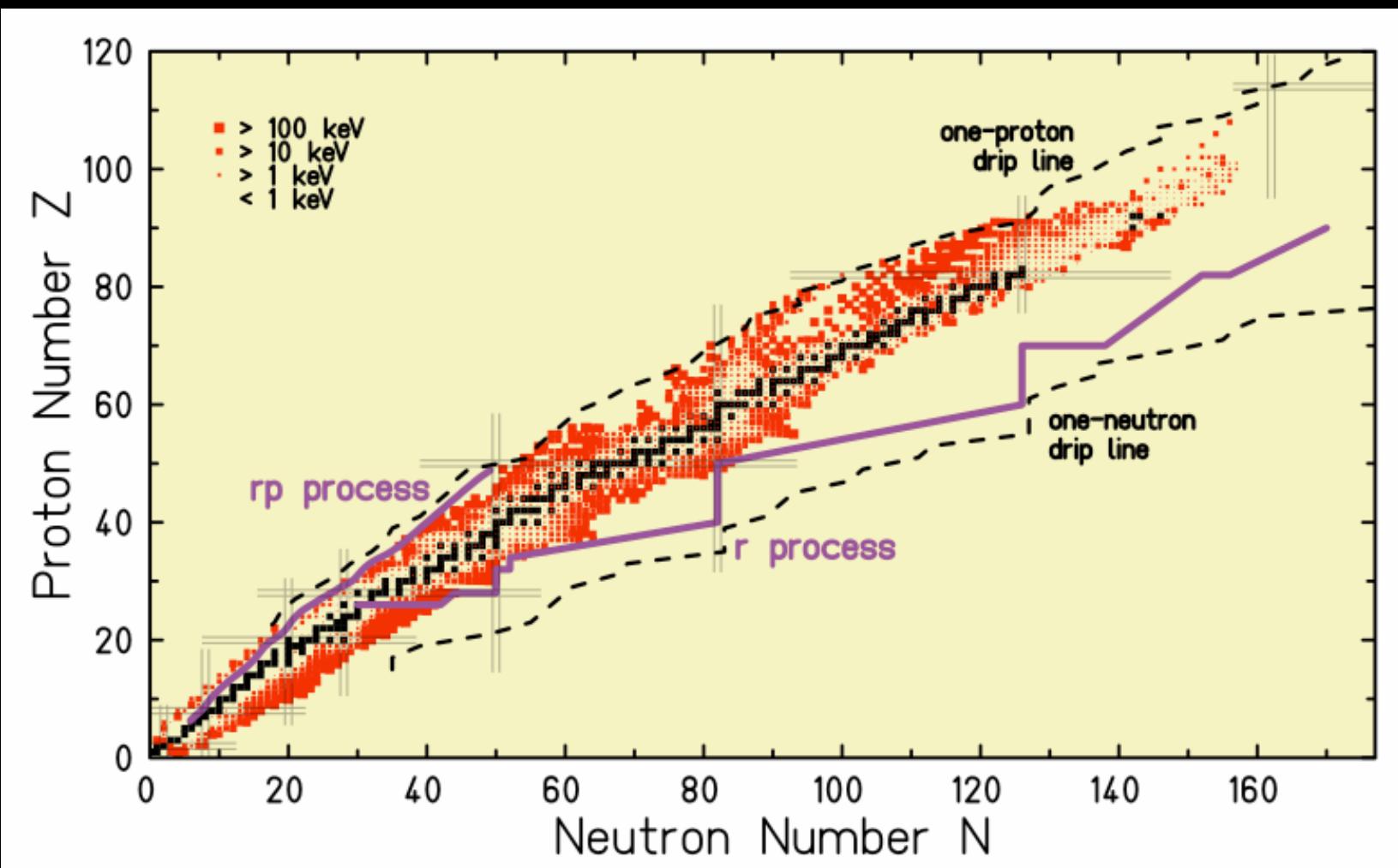


Nucleus



Quarks





Definition of symmetry

- A hamiltonian H has **symmetry** G (is invariant under G) if

$$\forall g \in G : [H, g] = 0$$

- The transformations g are assumed to form a Lie algebra.

Consequences of symmetry

- **Degeneracy:**

$$H|\Gamma\rangle = E|\Gamma\rangle \Rightarrow Hg|\Gamma\rangle = Eg|\Gamma\rangle$$

- **State labelling:**

$$H|\Gamma\gamma\rangle = E(\Gamma)|\Gamma\gamma\rangle$$

- **Action of transformations g :**

$$g|\Gamma\gamma\rangle = \sum_{\gamma'} a_{\gamma\gamma'}^{\Gamma}(g)|\Gamma\gamma'\rangle$$

- The a -matrices constitute a **representation** of the elements g of G .



Definition of a group

- A set of elements G and a multiplication operation.
- Axioms:

- Closure

$$g \in G \wedge g' \in G \Rightarrow g \circ g' \in G$$

- Associativity

$$g \circ (g' \circ g'') = (g \circ g') \circ g''$$

- Existence of an identity element e

$$e \circ g = g \circ e = g$$

- Existence of unique inverse for every element g

$$g \circ g^{-1} = g^{-1} \circ g = e$$

- Commutativity is not required.



Definition of a Lie algebra

- A Lie group contains an infinite number of elements that depend on a set of **continuous** variables.
- The corresponding Lie algebra is obtained from (a finite number of) **infinitesimal** operators, called **generators**.
- An algebraic structure over the generators is defined through **commutation relations** in terms of **structure constants**:

$$[g_i, g_j] \equiv g_i \circ g_j - g_j \circ g_i = \sum_k c_{ij}^k g_k$$

- Structure constants are **antisymmetric** in i and j.
- Generators satisfy the **Jacobi identity**:

$$[g_i, [g_j, g_k]] + [g_j, [g_k, g_i]] + [g_k, [g_i, g_j]] = 0$$



Casimir operators

- An operator that commutes with all generators of G is called a **Casimir operator** and denoted as (n is the order of the operator in the generators)

$$C_n[G]$$

- Thus:

$$H = \sum_n \kappa_n C_n[G] \Rightarrow H \text{ has symmetry } G$$

- Example: Rotations in three dimensions, $SO(3)$.

- Second-order Casimir operator of $SO(3)$:

$$C_2[SO(3)] = j_x^2 + j_y^2 + j_z^2 \equiv j^2$$

- $SO(3)$ symmetry:

$$H = j^2 \Rightarrow H \text{ has } SO(3) \text{ symmetry}$$

- Degeneracy and state labelling:

$$C_2[SO(3)] jm_j \rangle = j(j+1) | jm_j \rangle$$

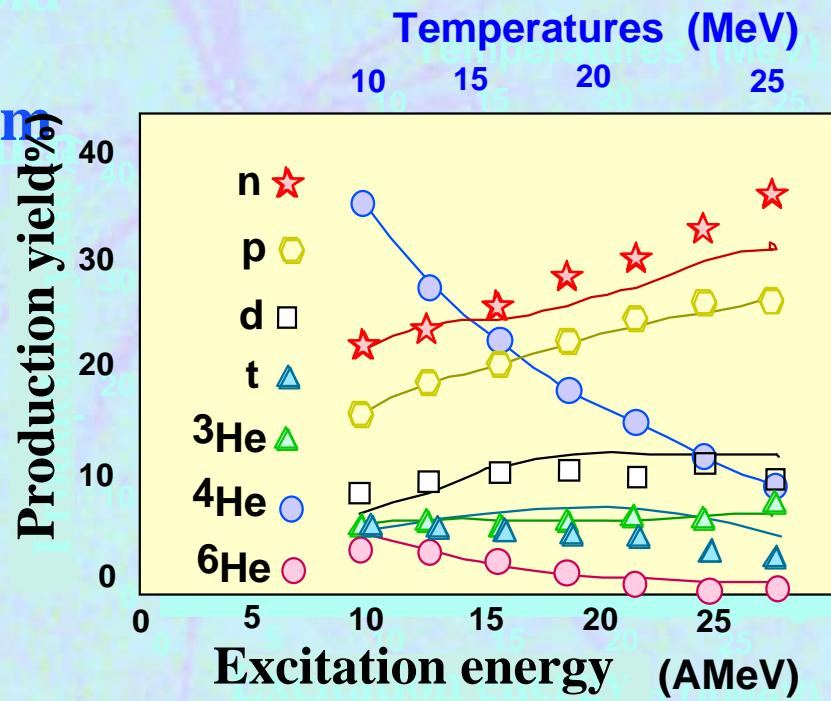
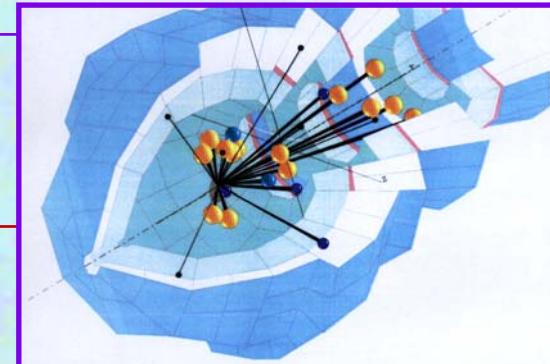


Vaporization

✓ Determination of vaporization threshold

✓ Real gas at equilibrium

✓ $T > 100\ 000\ 000\ 000^\circ$.



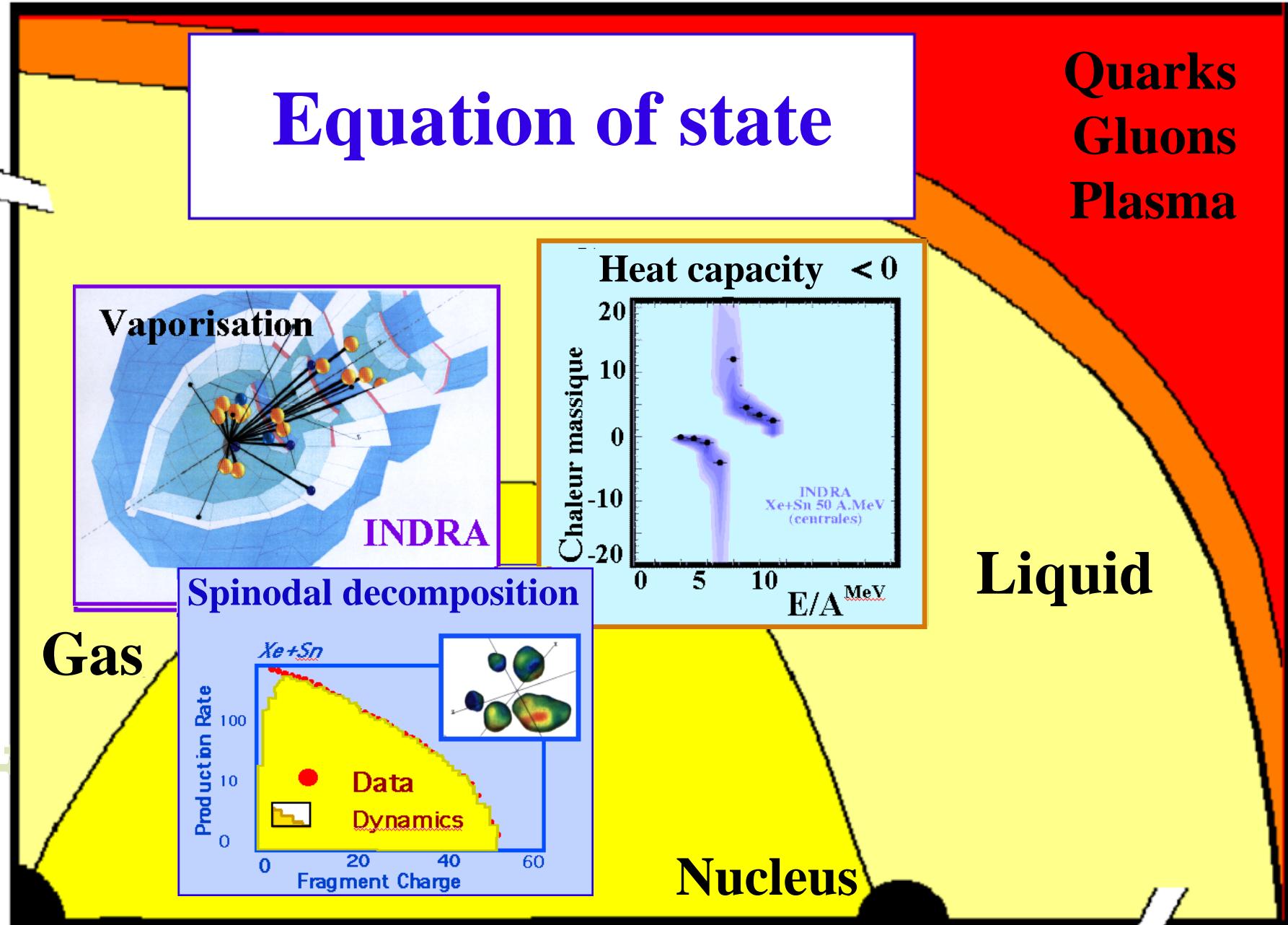
Gulminelli and INDRA collaboration



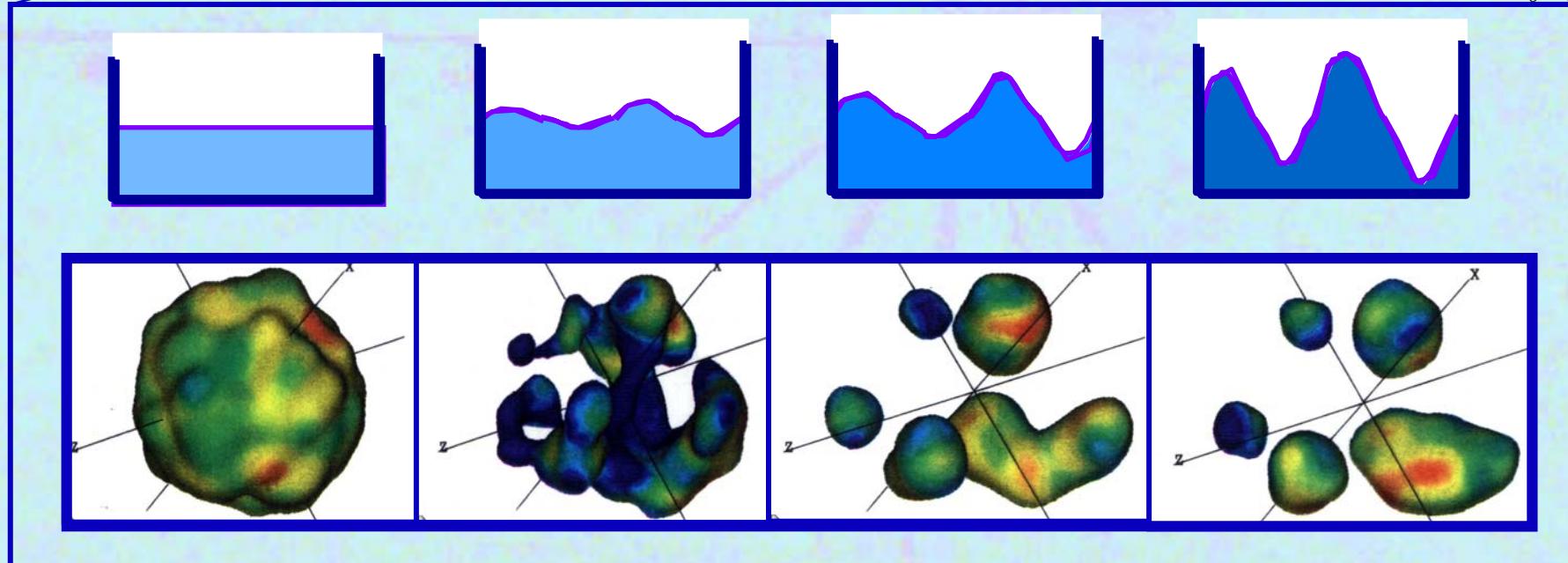
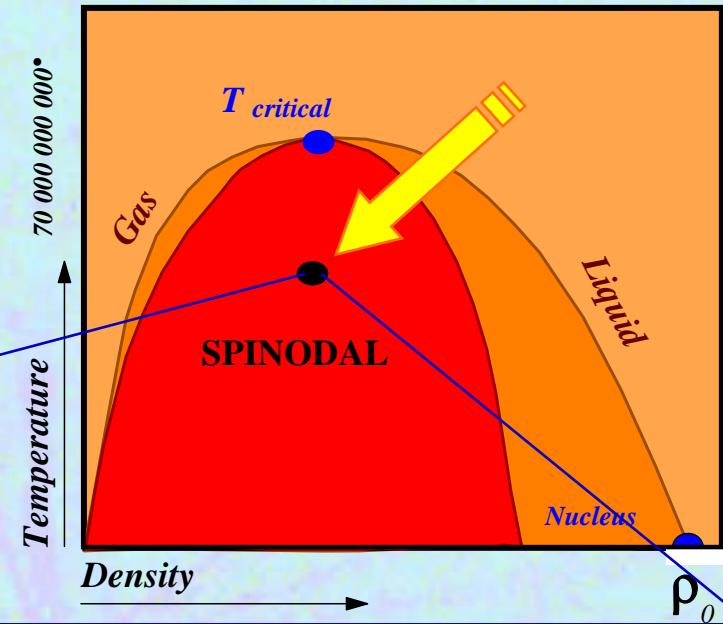
Equation of state

Quarks
Gluons
Plasma

Temperature $100\,000\,000\,000^\circ$



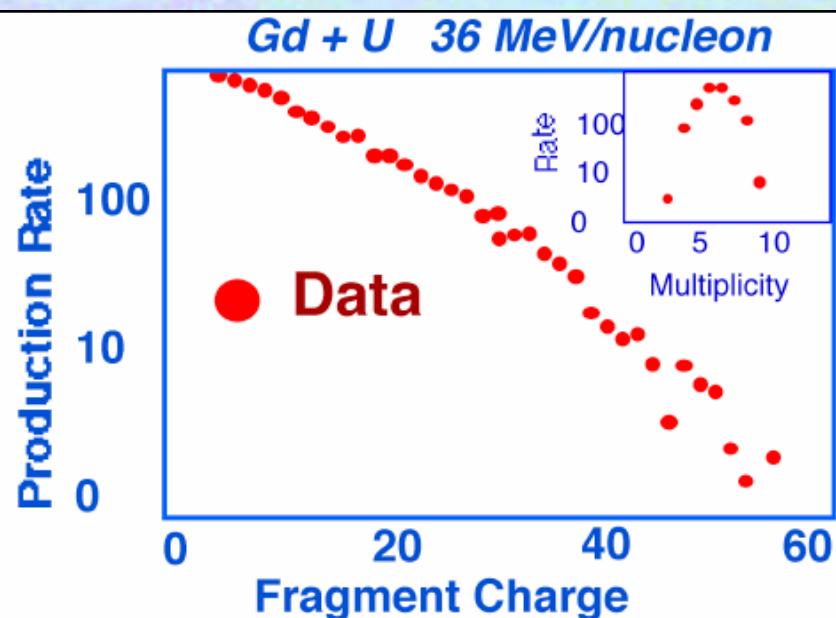
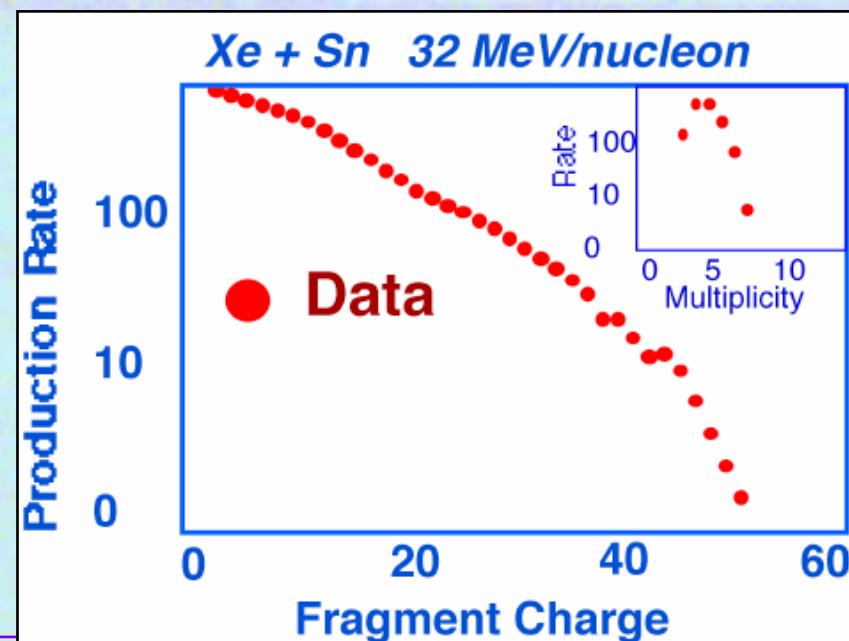
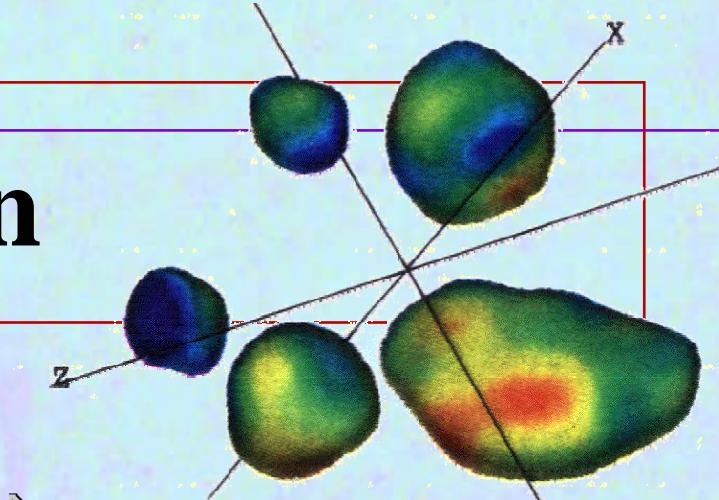
Condensation after a rapid Expansion



Multifragmentation

v Volume effect

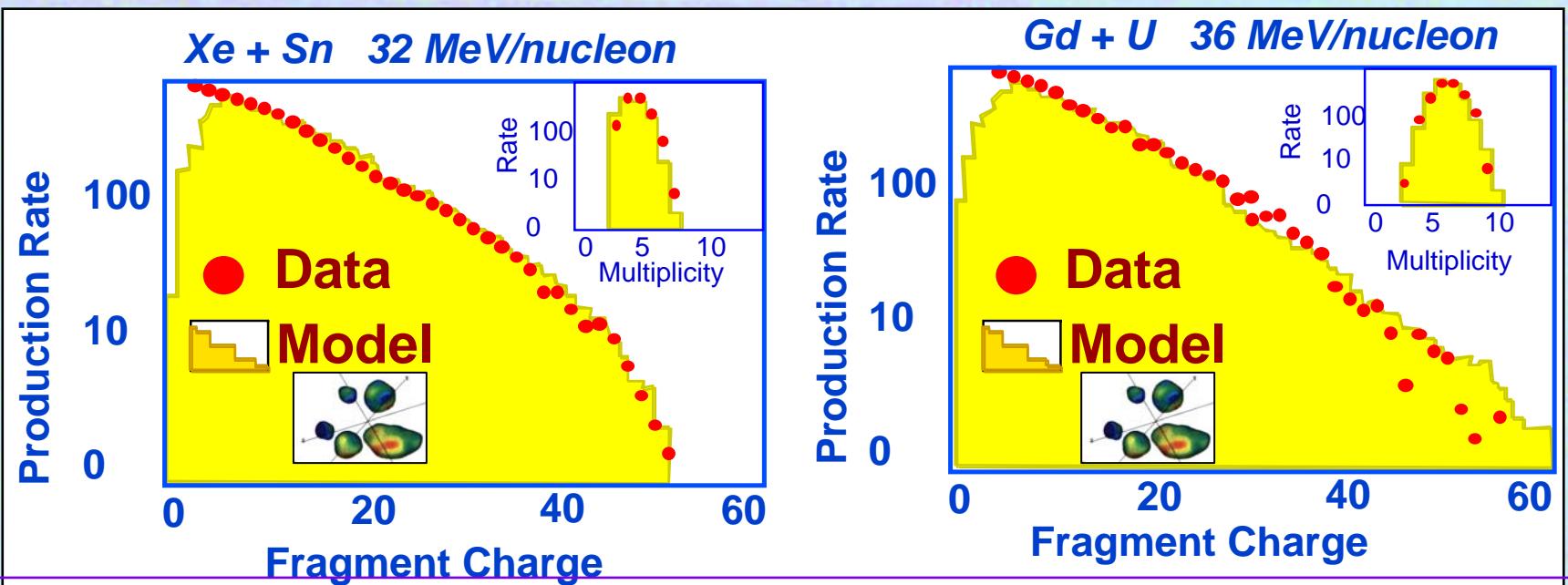
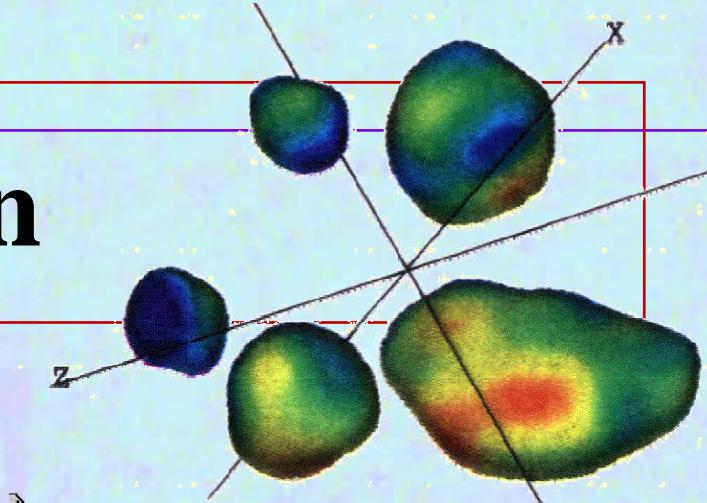
Dynamics of a phase transition



Multifragmentation

v Volume effect

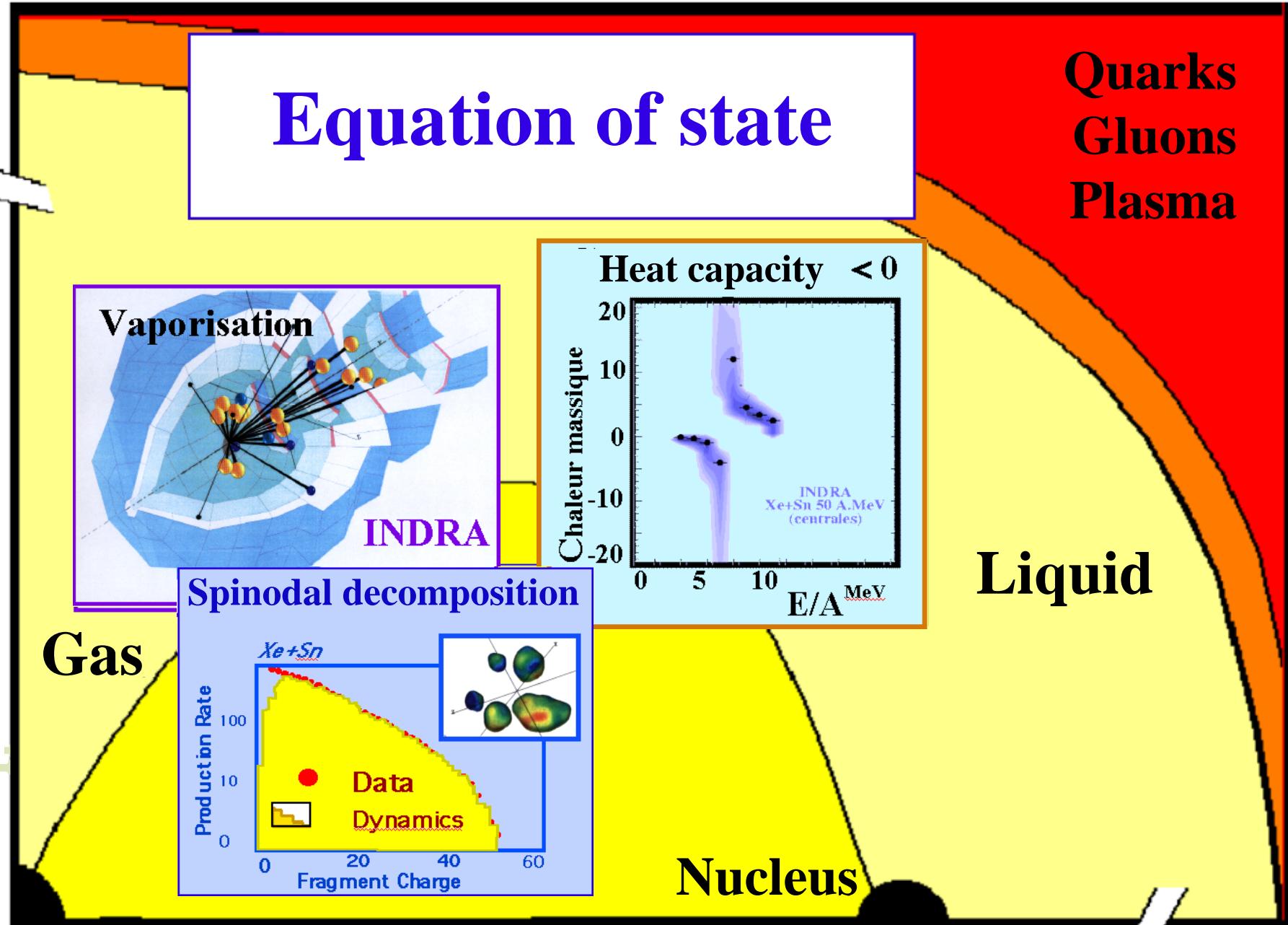
Dynamics of a phase transition



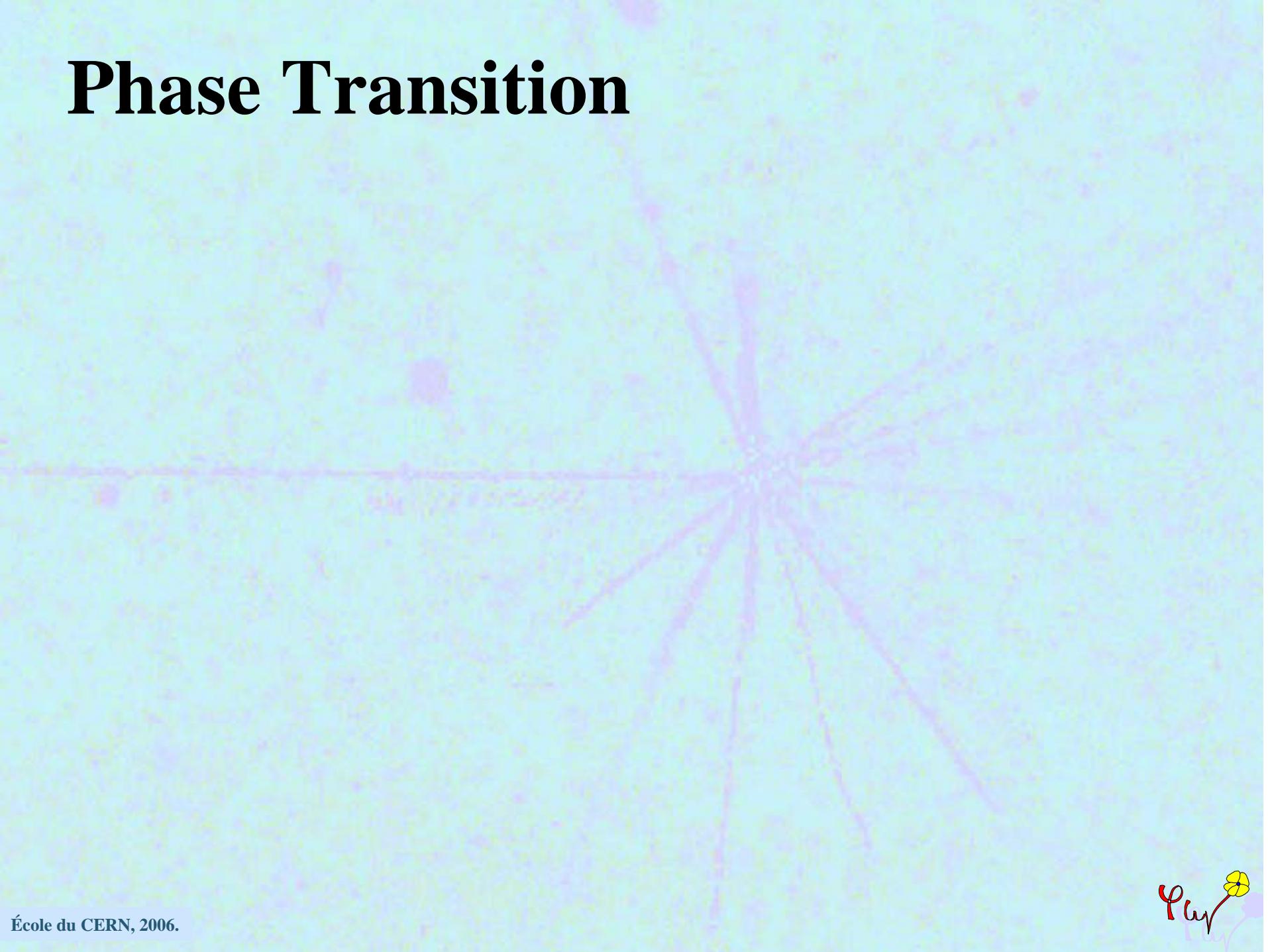
Equation of state

Quarks
Gluons
Plasma

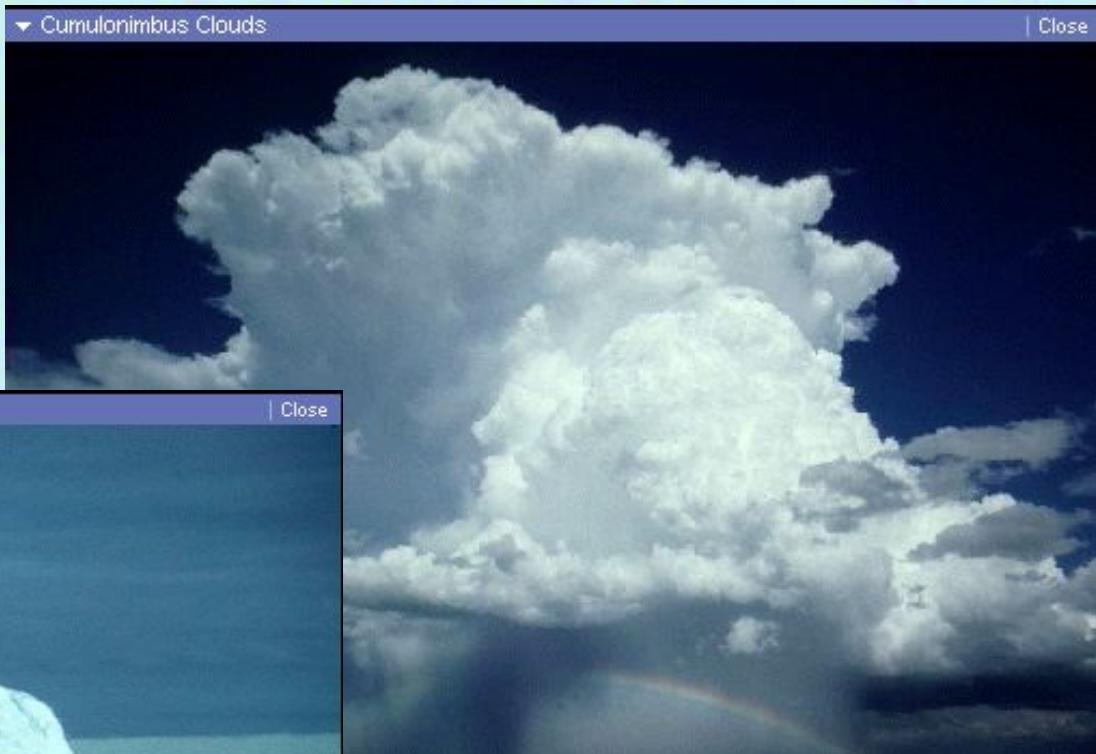
Temperature $100\,000\,000\,000^\circ$



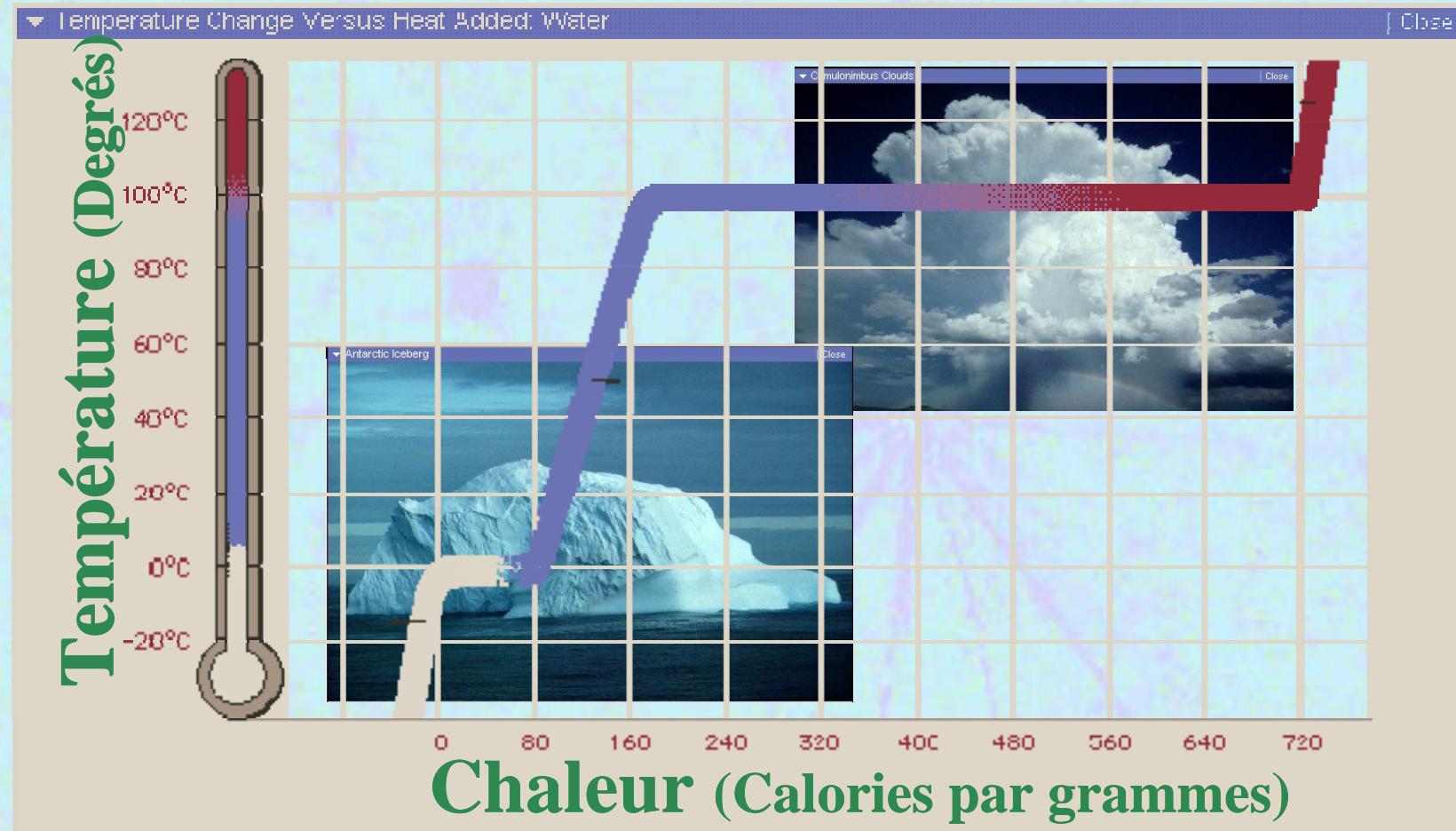
Phase Transition



Phase Transition

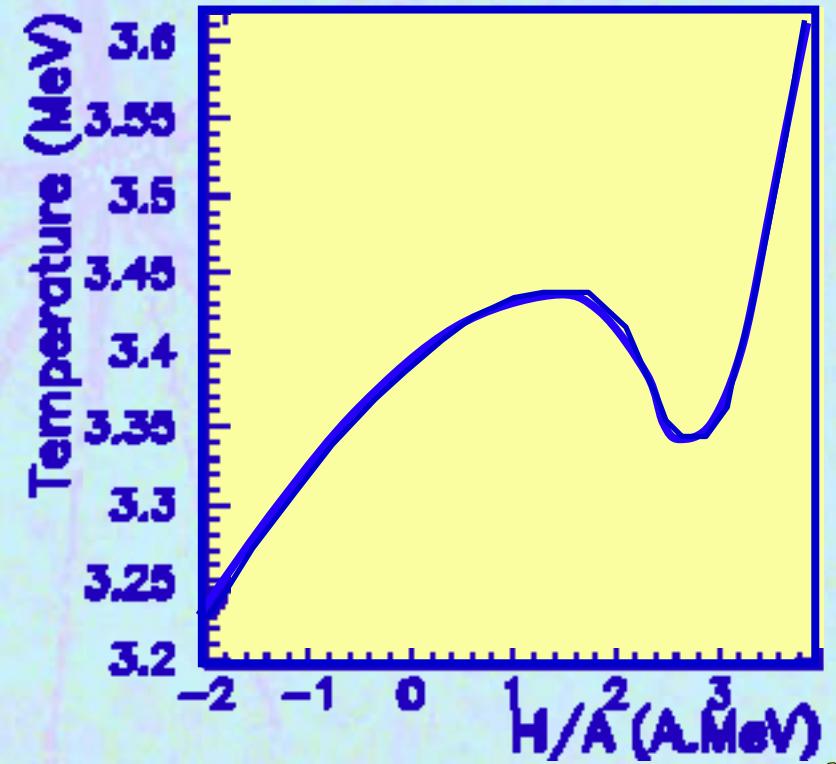
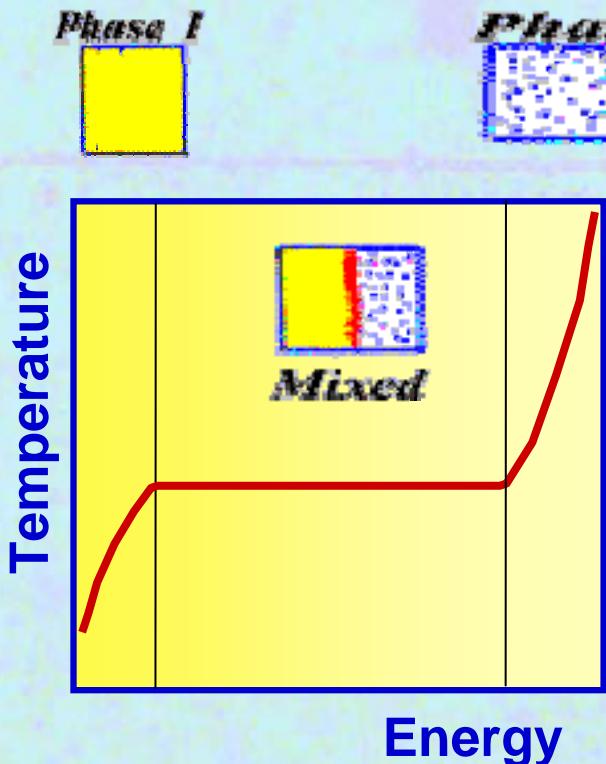
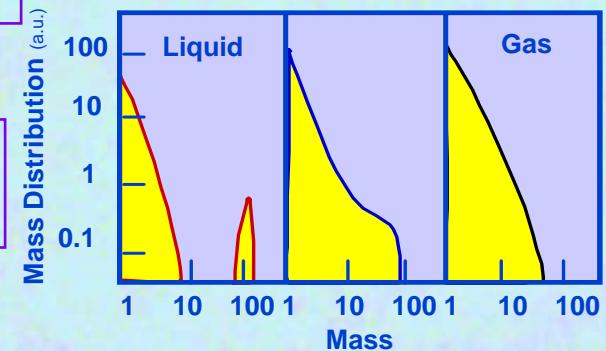


Phase Transition

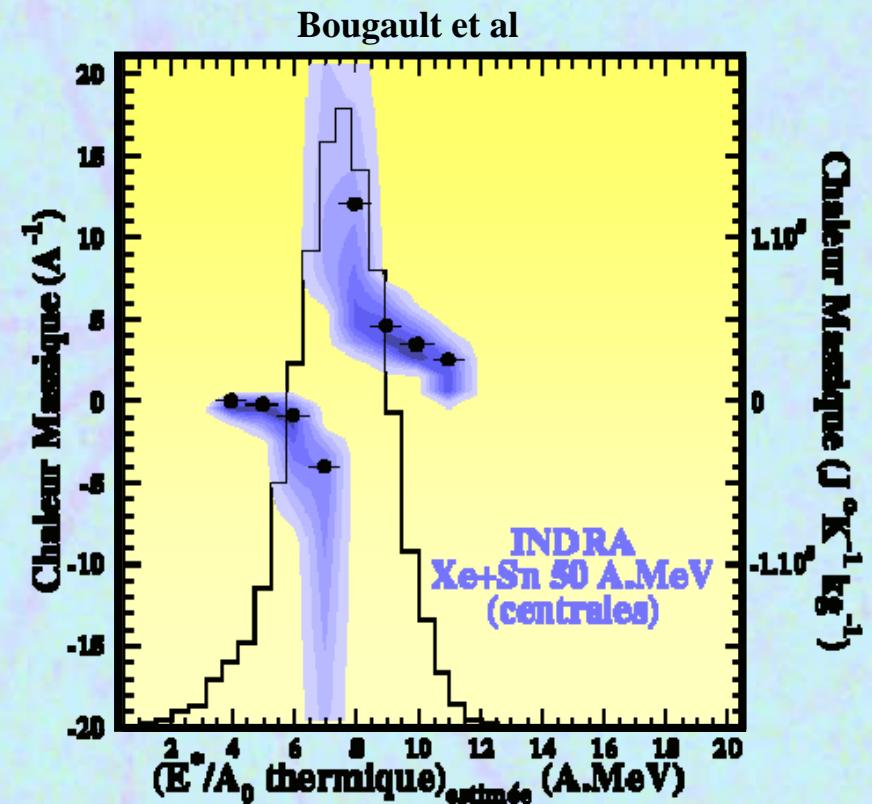
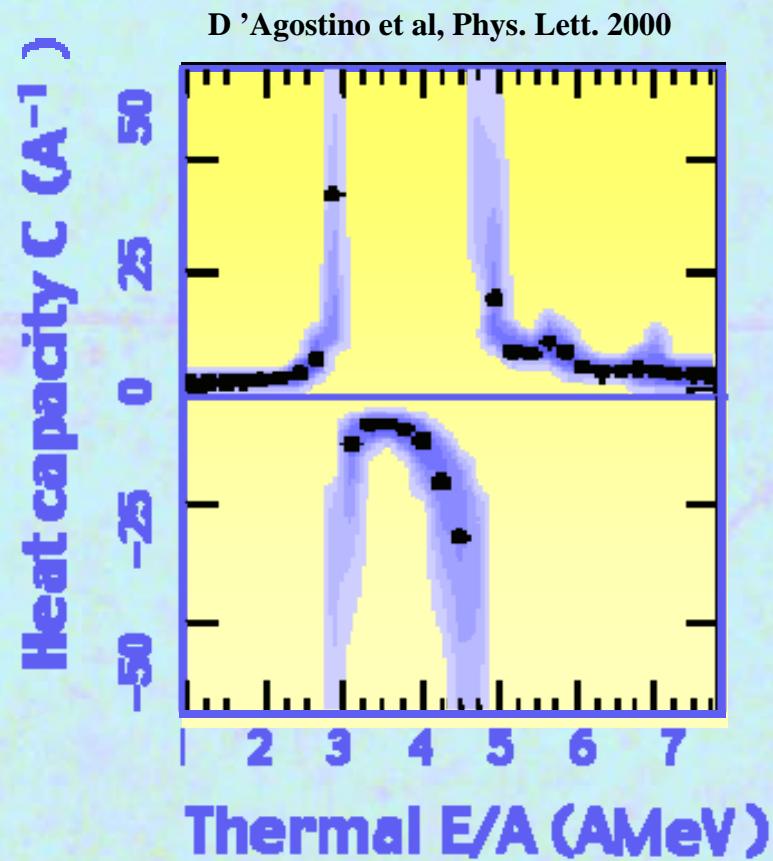


Phase Transition

In small systems



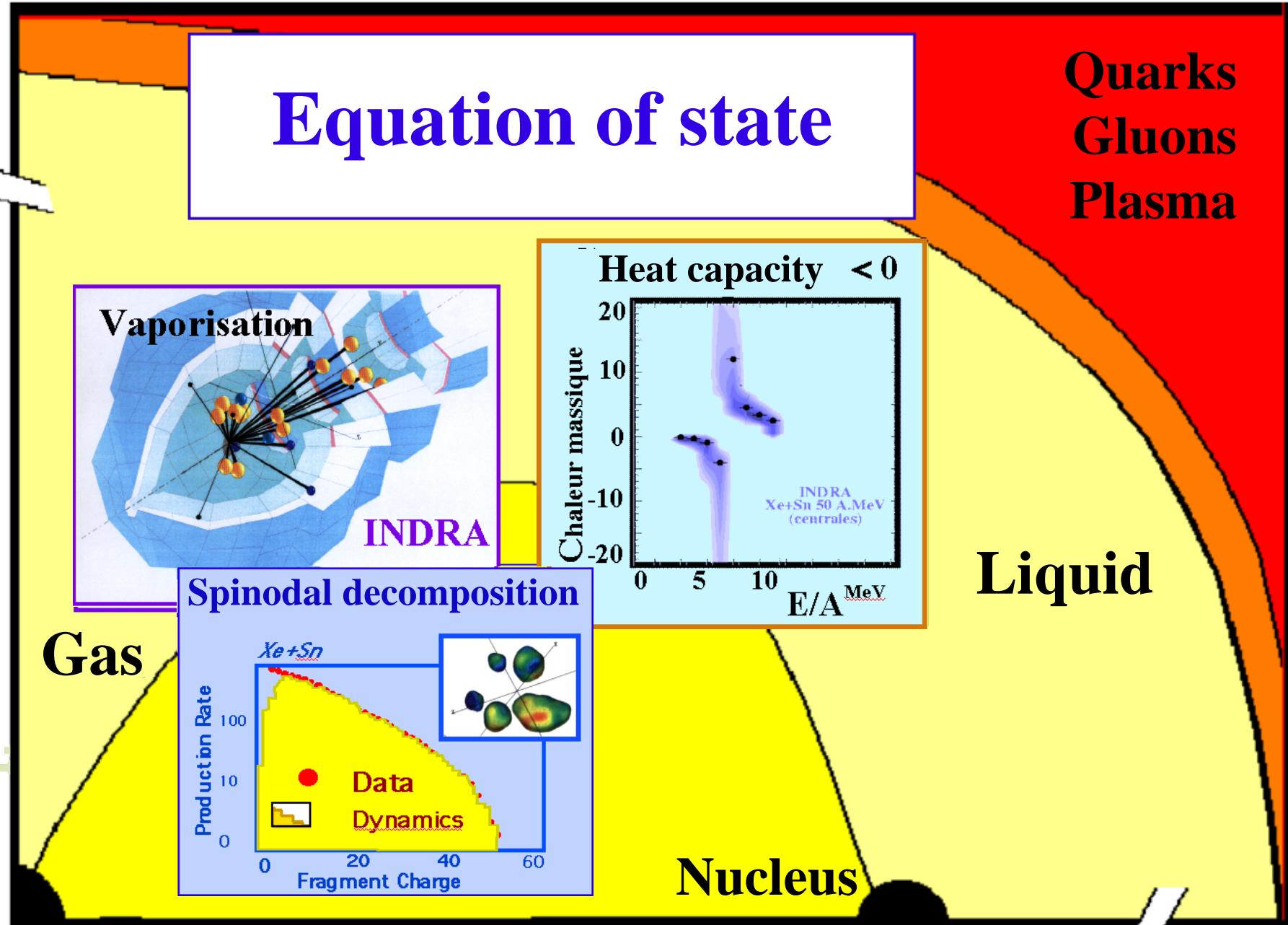
First Observations



Equation of state

Quarks
Gluons
Plasma

Temperature $100\,000\,000\,000^\circ$

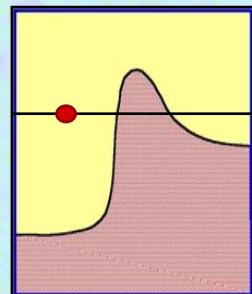


- I -

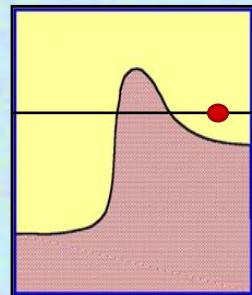
Radioactivity Quantum property

- ✓ Exponential decay
- ✓ $dN/dt = -N/T_{\text{life}}$
- ✓ Finite life time
but always young
- ✓ Transmutation

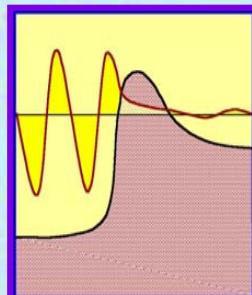
« In »
Or
« Out »



« In »
And
« Out »



Schrödinger Cat



- I -

Radioactivity

Quantum property

- ✓ Exponential decay
- $dN/dt = -N/T_{\text{life}}$
- ✓ Finite life time
but always young
- ✓ Transmutation



Schrödinger cat

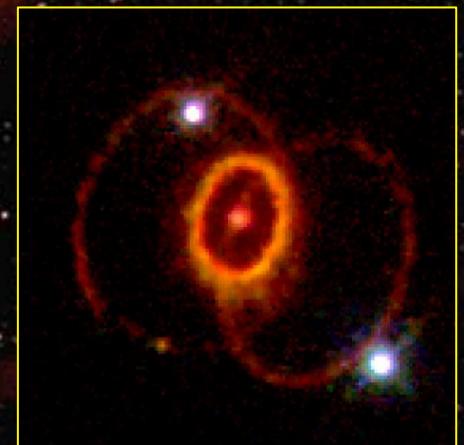




École du CERN, 2006.

Play

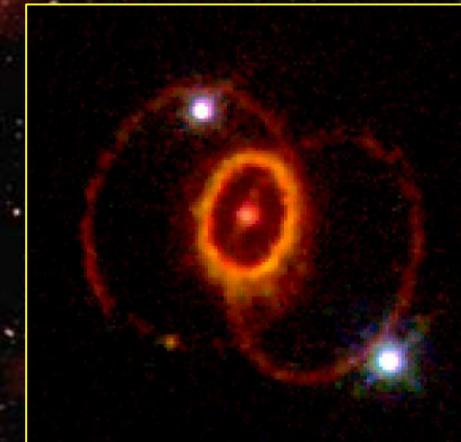
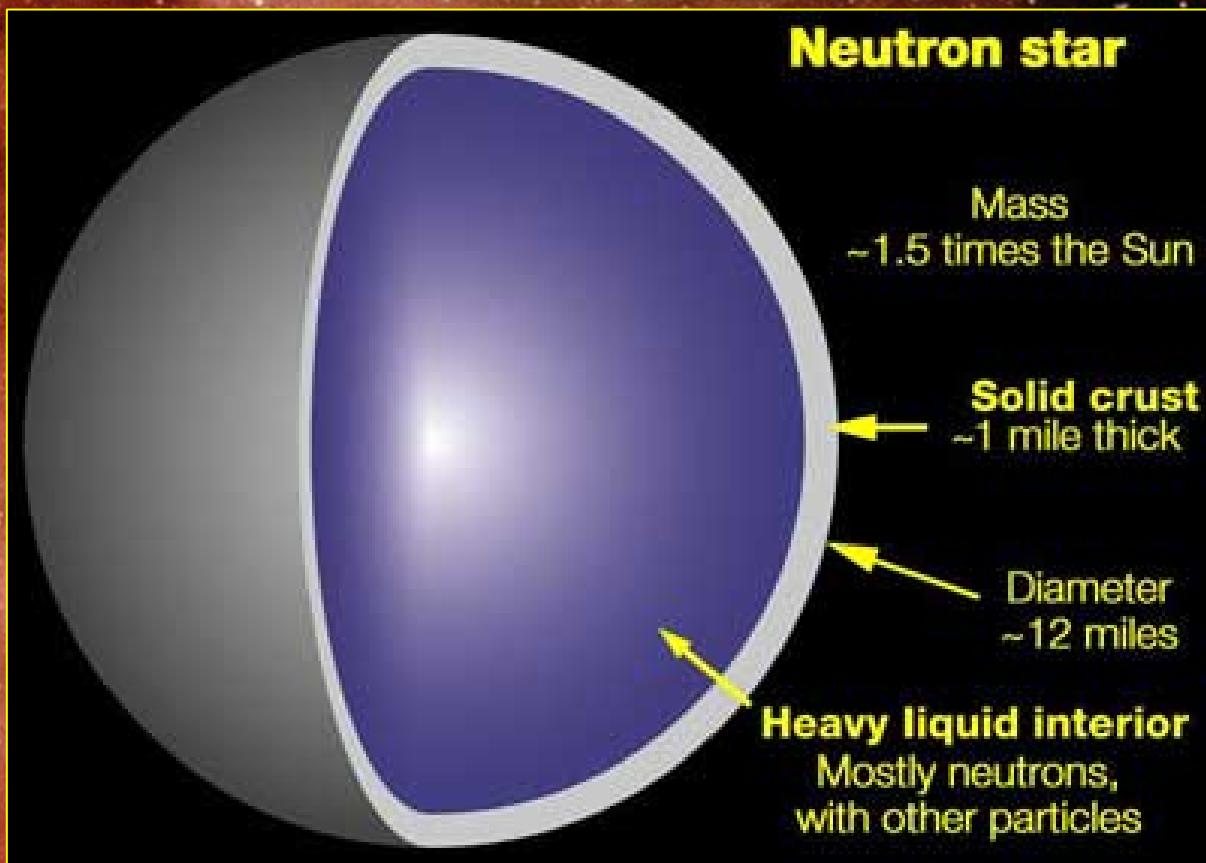
Neutron stars



Super-nova

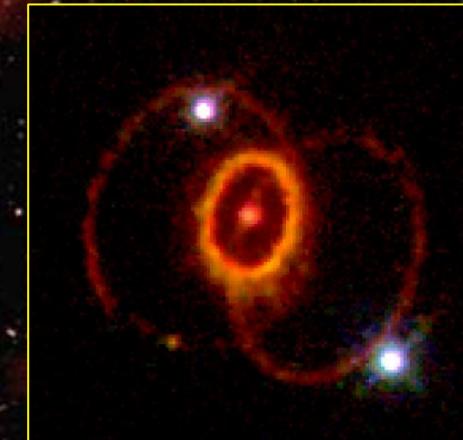
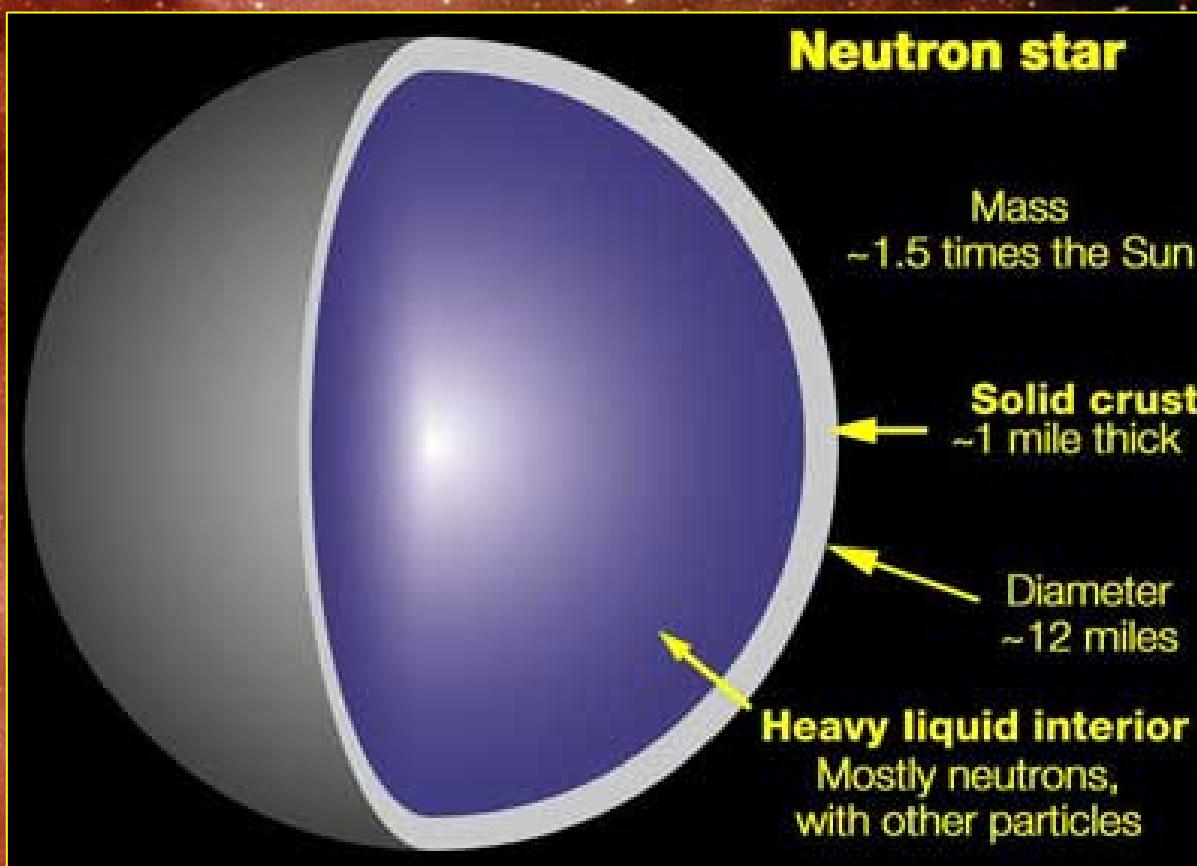
Dense exotic matter in the cosmos

Supernovae and Neutron stars

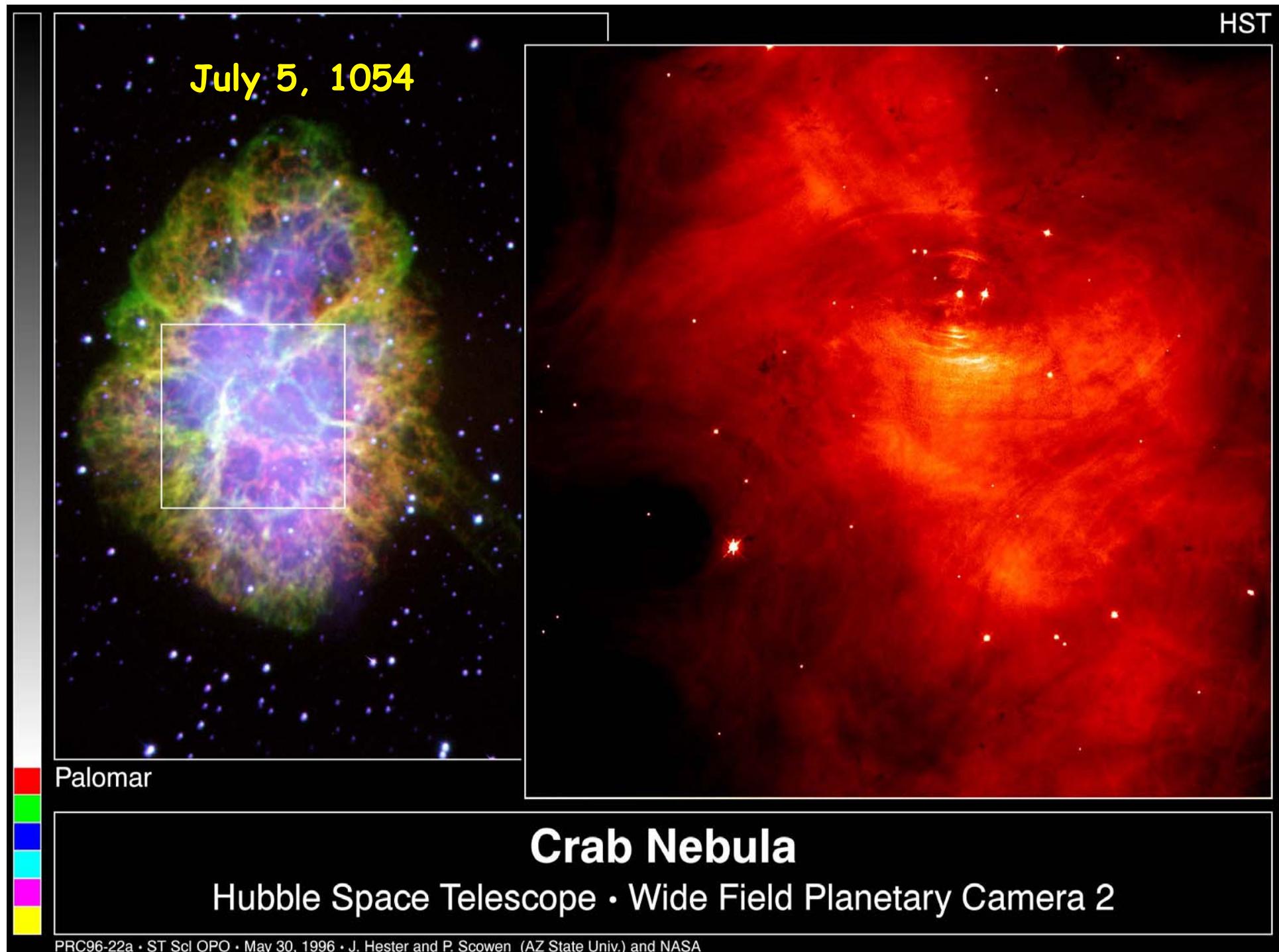


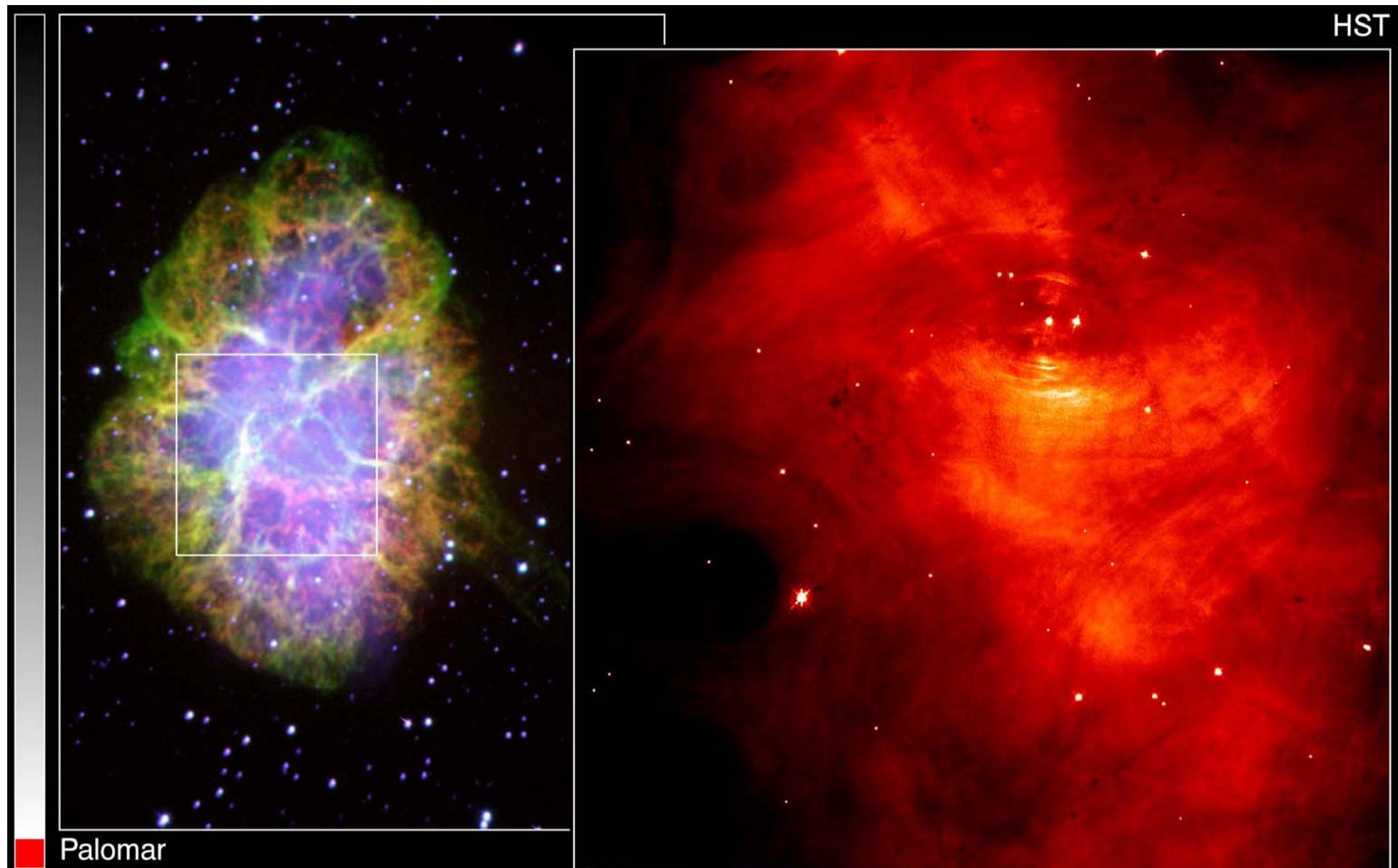
Super-nova

Matière exotique dans le Cosmos Supernovae et Etoiles à Neutron



Super-nova





HST

Crab Nebula

Hubble Space Telescope • Wide Field Planetary Camera 2

PRC96-22a • ST Scl OPO • May 30, 1996 • J. Hester and P. Scowen (AZ State Univ.) and NASA

