Quark Gluon Plasma Physics

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- Lecture I: Dense Matter and the Quark-Gluon Plasma
- Lecture II: Statistical Hadron Production
- Lecture III: Heavy Quarks and Jets as Probes of the QGP

Lectures assembled in collaboration with Peter Braun-Munzinger

Lecture I:
Dense Matter and the Quark Gluon Plasma

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Outline:

- **Introduction, historical remarks**
- **Early universe**
- **Critical temperature and density**
- **The phases of strongly interacting matter**
- **Results from lattice QCD**
- **Making strongly interacting matter in nuclear collisions**
- **Survey of experiments**

Historical Remarks

- Pomeranchuk 1951: finite hadron size → critical density n_c.
  Dokl. Akad. Nauk. SSSR 78 (1951) 889.

- Hagedorn 1965: mass spectrum of hadronic states $\rho(m) \propto m^{\alpha} \exp{(m/B)}$
  → critical temperature $T_c = B$. Nuovo Cim. Suppl. 3 (1965) 147.

- QCD 1973: asymptotic freedom Nobelprize 2004
  D.J. Gross, F. Wilczek, Phys. Rev. Lett. 30 (1973)1343
  H.D. Politzer, Phys. Rev. Lett. 30 (1973) 1346.

- asymptotic QCD and deconfined quarks and gluons:
  N. Cabibbo, G. Parisi, Phys. Lett. B59 (1975) 67.
  J.C. Collins, M.J. Perry, Phys. Rev. Lett. 34 (1975) 1353.

- first perturbative corrections to ideal gas: Baym, Chin 1976, Shuryak 1978

- since 1980 new phase was called Quark-Gluon Plasma (QGP): excitations are quark/gluon quasiparticles plus collective plasmon modes
  (similar to QED plasma)

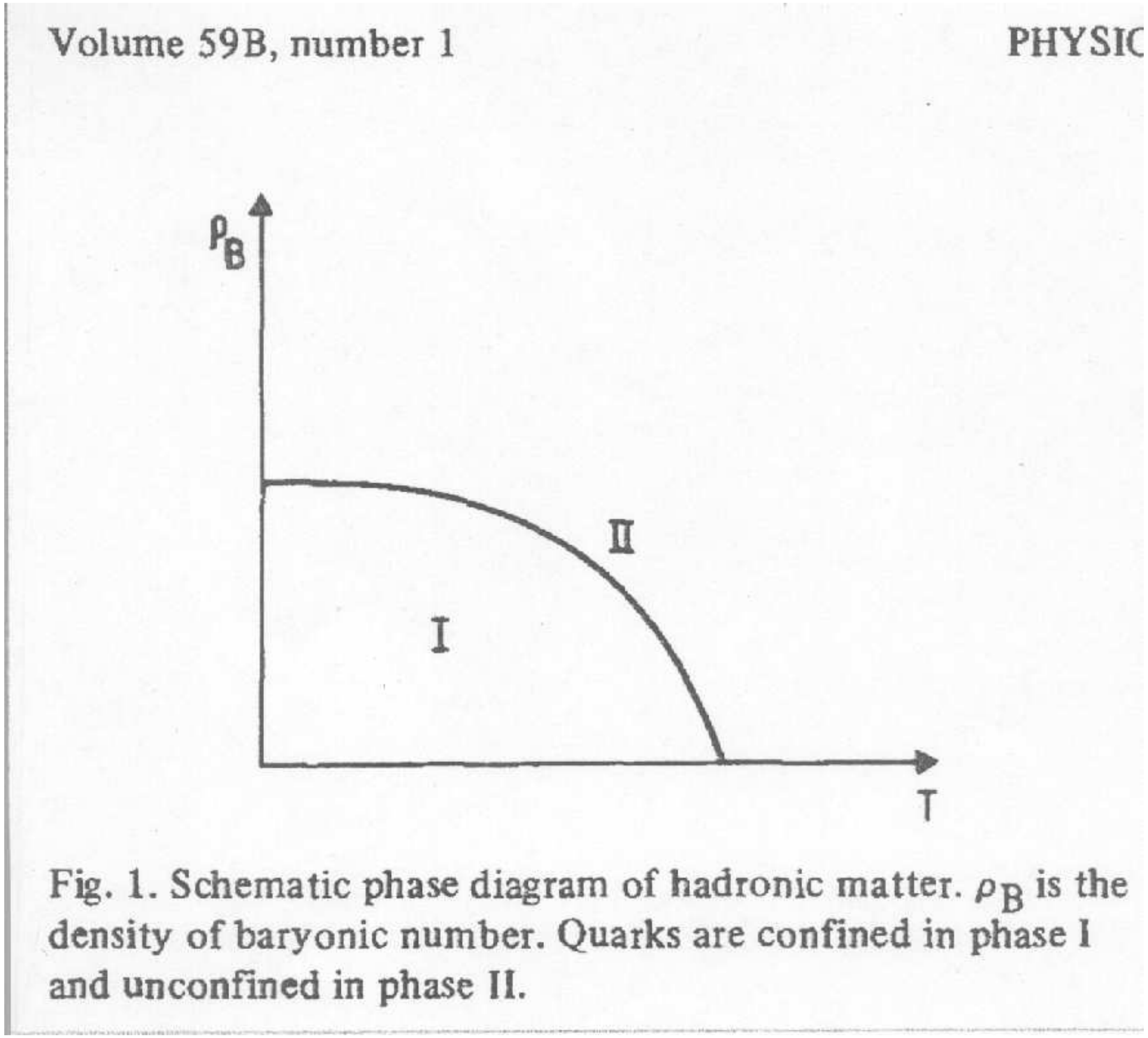
First Phase Diagram

Cabibbo/Parisi PL(1975)

more refined:

G. Baym 1983, see also

Nucl.Phys. A698 (2002)xxiii



Volume 59B, number 1

PHYSIC

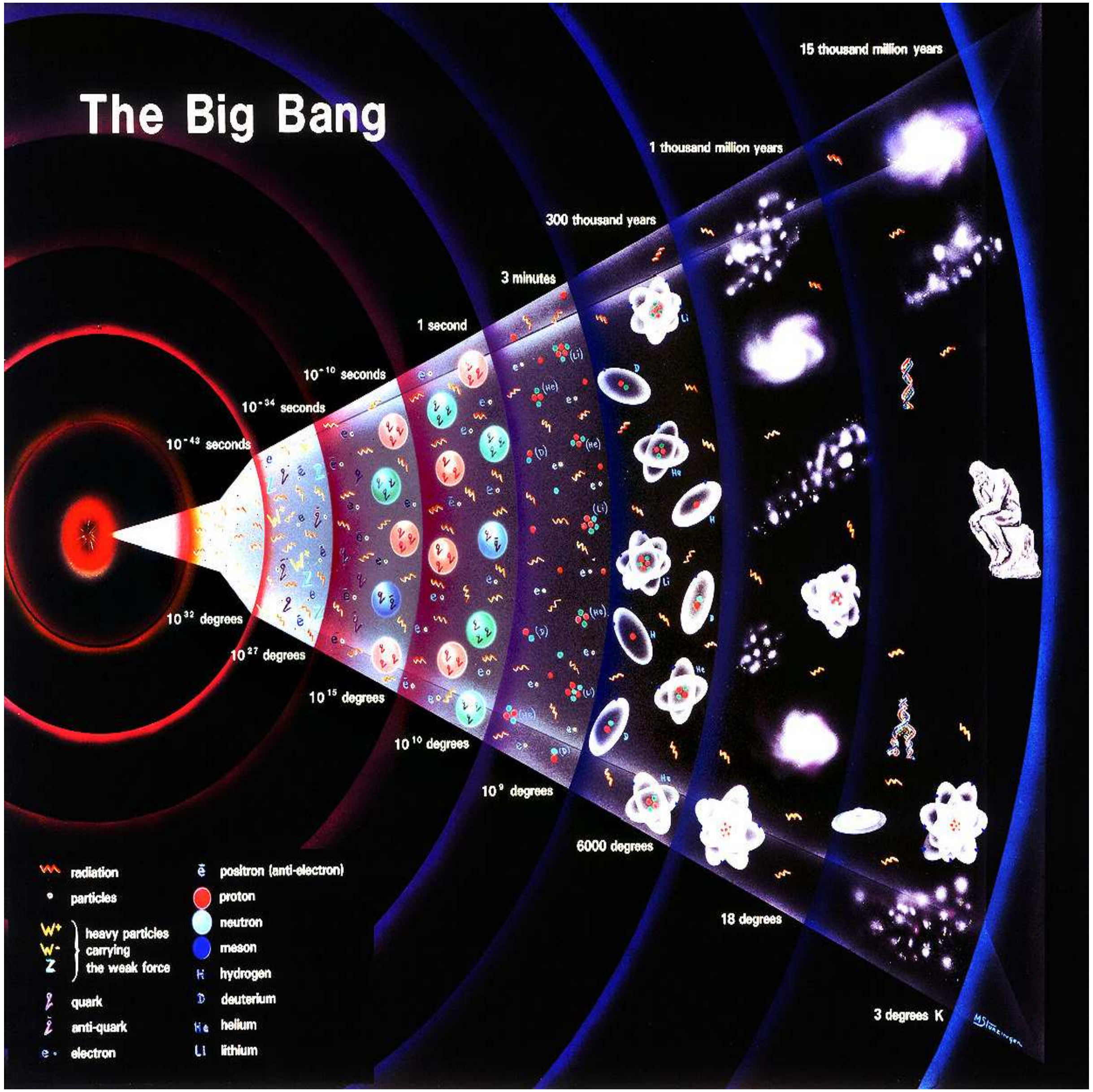
Fig. 1. Schematic phase diagram of hadronic matter. ρ_B is the density of baryonic number. Quarks are confined in phase I and unconfined in phase II.

Evolution of the Universe

from the big bang to galaxies

10^{-5} s after big bang:
phase transition from quarks
and gluons to hadronic matter

temperature at phase transition:
$\mathbf{T} \approx 2 \cdot 10^{12}\mathbf{K} = \mathbf{200\ MeV}$



Simple Estimates of critical conditions

1. deconfinement at high temperature (a la Polyakov 1978):

$T = 0$

energy of color string $E_{q\bar{q}}(r) = \sigma\ r$

with string tension $\sigma \approx 1$ GeV/fm

$T > 0$

free energy of string

$$\begin{aligned} F_{q\bar{q}}(L) &= E_{q\bar{q}}(L) - T\,S(L) \\ &= \sigma\,L - T\ln N(L) \\ &= (\sigma - T/a\ \ln 5)L \\ &= \sigma_{eff}(T)\ L \end{aligned}$$

with number of string configurations: $N(L) = 5^{L/a}$

and typical stepsize a = string thickness ≈ 0.3 fm

critical temperature when $\sigma_{eff}(T)=0$

$$\rightarrow T_c = \frac{1\mathrm{GeV}\ 0.3\mathrm{fm}}{\mathrm{fm}\ \ln 5} = 185\ \mathrm{MeV}$$

2. at high baryon density:

- **normal nuclear matter:**

  baryon density $\rho_0 = \frac{\mathrm{A}}{4\pi/3\mathrm{R}^3} = \frac{1}{4\pi/3\mathrm{r}_0^3} \approx \mathbf{0.16\ /fm^3}$

  with r_0 **= 1.15 fm**

- **if nuclei are compressed, eventually nucleons start to overlap**

  nucleon charge radius r_n **= 0.8 fm**

  $\rightarrow \rho_\mathrm{c} = \frac{1}{4\pi/3\mathrm{r}_\mathrm{n}^3} \approx \mathbf{0.47/fm^3 = 3}\ \rho_0$

- **more stringent:**

  pressure of quark-gluon bubble has to sustain

  vacuum pressure

  at T=0 with bag constant B = 0.2 GeV/fm^3

  $\rightarrow \mu \geq$ **0.42 GeV**

  critical net quark density $\mathrm{n_q} - \mathrm{n_{\bar{q}}} \geq$ **1.9/fm**^{3}

  $\rightarrow \rho_\mathrm{c} = 1/3(\mathrm{n_q} - \mathrm{n_{\bar{q}}}) \geq 0.64 = 4\rho_0$

Hagedorn's Limiting Temperature

all thermodynamical quantities diverge at T_{limit}

(R. Hagedorn, Suppl. Nuovo Cim. 3 (1965) 147)

assume $\rho_m \propto (m_0^2 + m^2)^{(-5/4)} \exp{(m/b)}$

take energy density of hadron gas, $\epsilon(\mathrm{T})$

$\epsilon(\mathrm{T}) = \Sigma_{\mathrm{m}_\pi}^{\mathrm{M}} \epsilon(\mathrm{m_i}, \mathrm{T}) + \int_{\mathrm{M}}^{\infty} \epsilon(\mathrm{m}, \mathrm{T})\rho(\mathrm{m})$,

but for large masses $m > M$, $\epsilon(m, \mathrm{T}) \propto \exp{(-\mathrm{m}/\mathrm{T})}$

→ **integral diverges if T > b**

Hagedorn’s Limiting Temperature

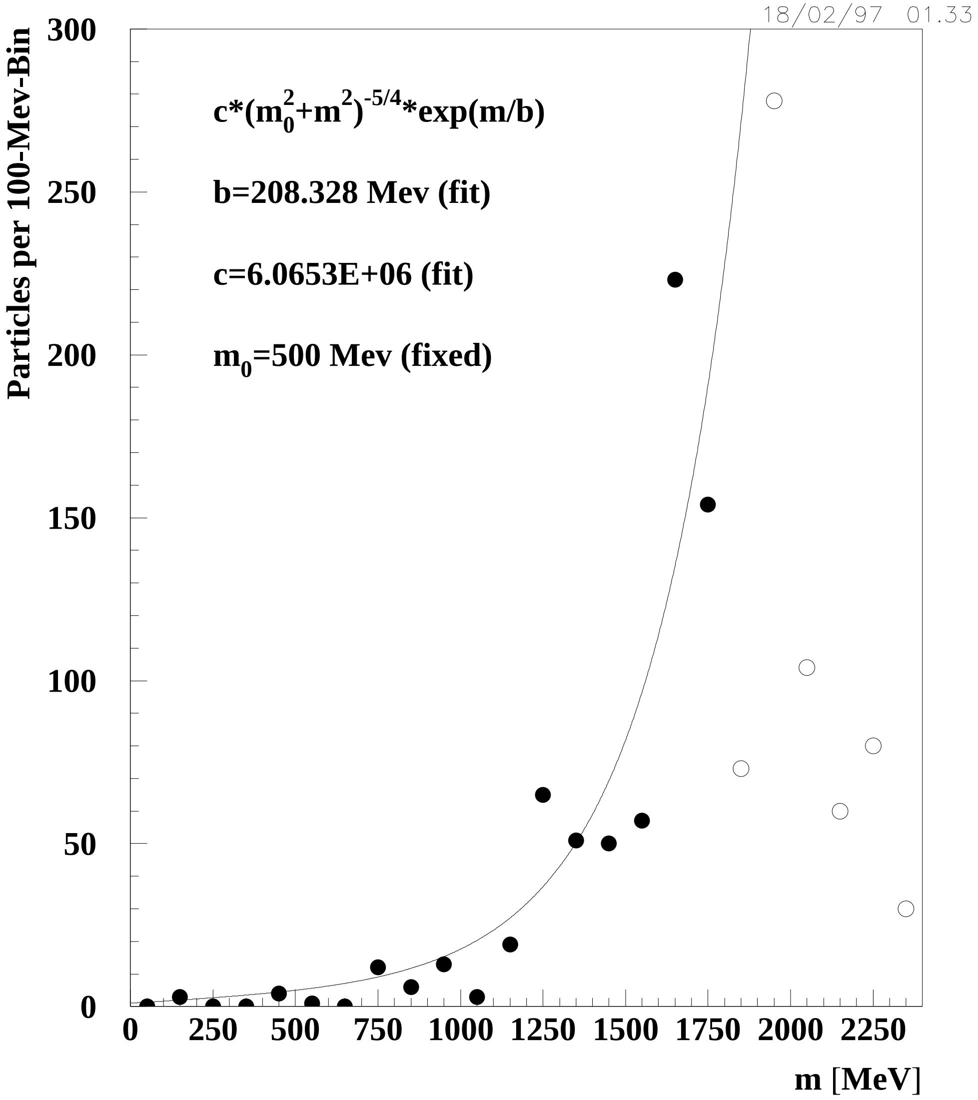
hadronic mass spectrum as of 1997

fit with

Hagedorn mass formula

$$\rho_m \propto (m_0^2 + m^2)^{(-5/4)} \exp{(m/b)}$$

b = T$_{limit}$ = 200 ± 30 **MeV**



Simple Construction of Phase Transition

Basis: MIT bag model with bag constant B

B is energy density of QCD vacuum (see above)

energy density of quark-gluon matter: $\epsilon = \epsilon_{thermal} + \mathbf{B}$

pressure: $\mathbf{P = 1/3\ (}\epsilon\ \mathbf{-\ 4\ B)}$

with $\epsilon_{thermal} \propto n_{thermal}^{4/3}$ **and** $\mathbf{P = n}^2 \partial(\epsilon/n)/\partial n$

note: at T = 0, P = -B!

energy density (pressure) of hadron gas:

sum up energy density (pressure) due to each particle

Gibbs criterion for phase transition:

$\mathbf{P}_{had} = \mathbf{P}_{QGP}$ **and** $\mu_{had} = \mu_{QGP}$

Constructing the Phase Boundary

compute P as above and

look for the crossing points

first order phase transition

by construction

B = 250 MeV/fm^3

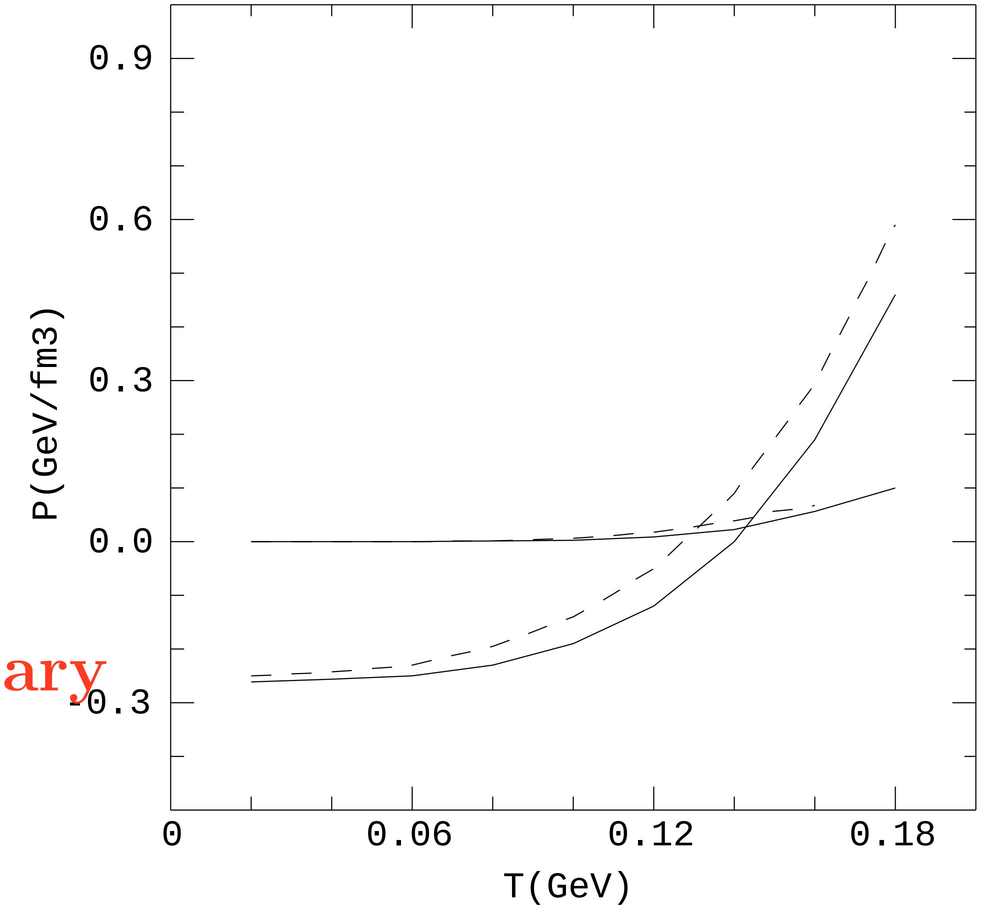
from lattice QCD

determination of the phase boundary

in the T $- \mu$ plane

solid lines: μ =170 MeV

dashed lines: μ = 540 MeV

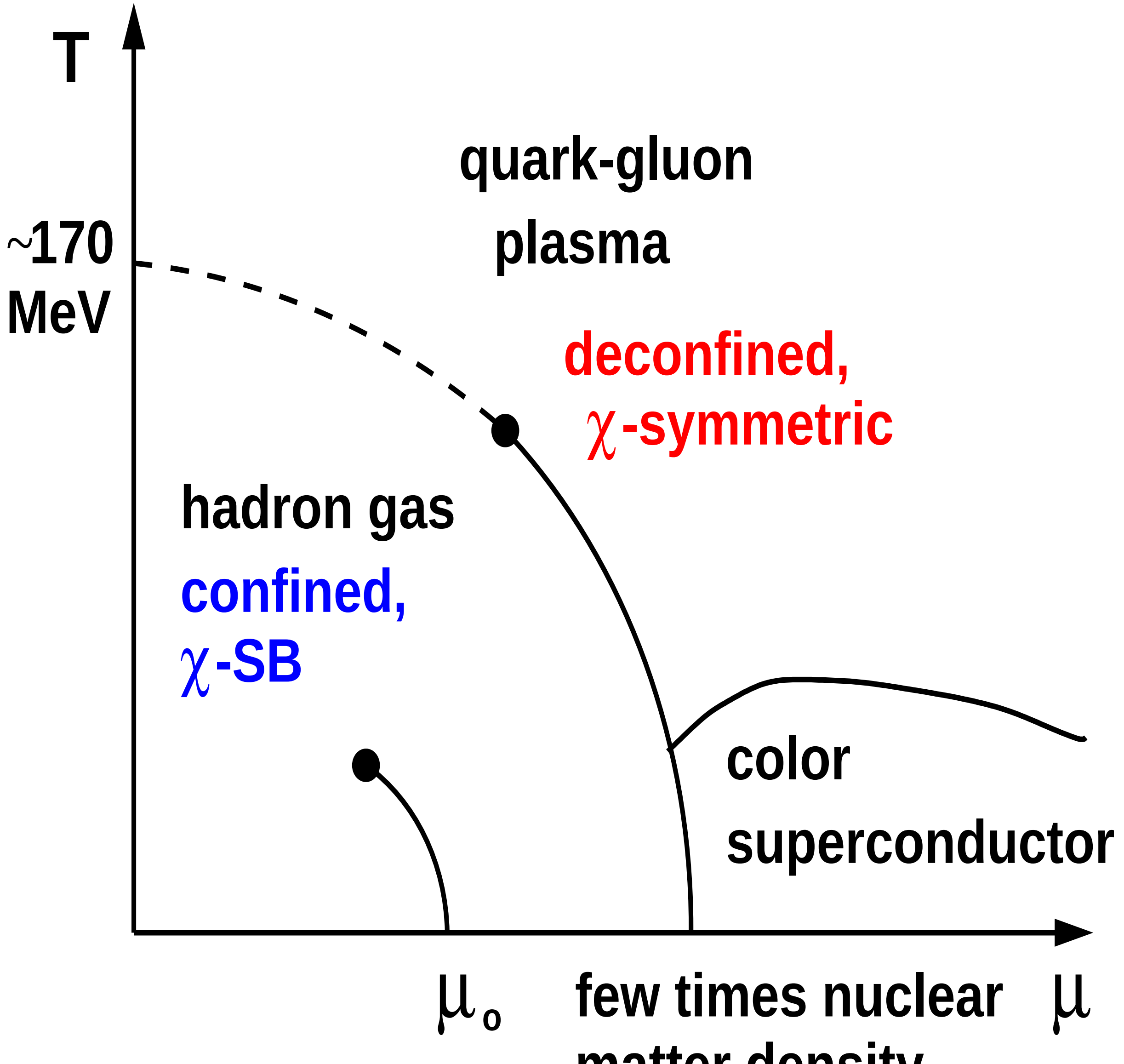


Phase Diagram (modern)

from nuclear to quark matter

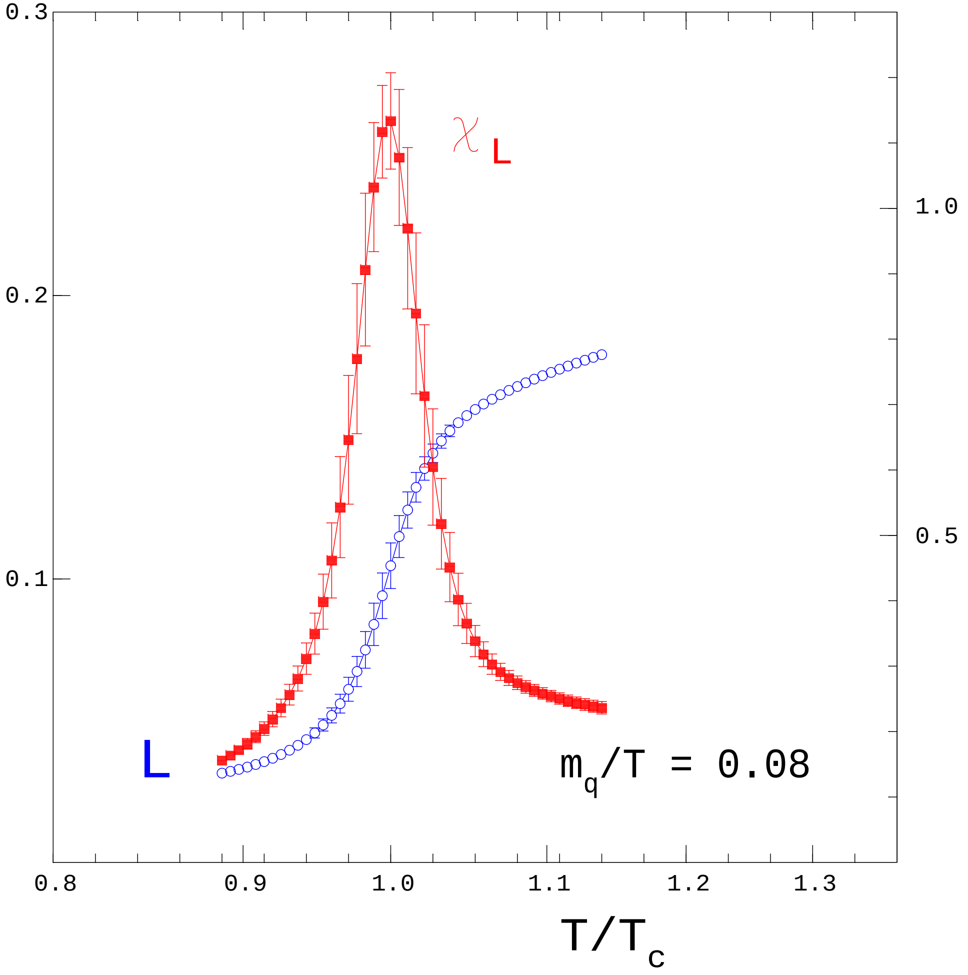
at low temperatures:
color is confined
and
chiral symmetry is broken

temperature at
phase transition:
T≈ 170 MeV for $\mu = 0$

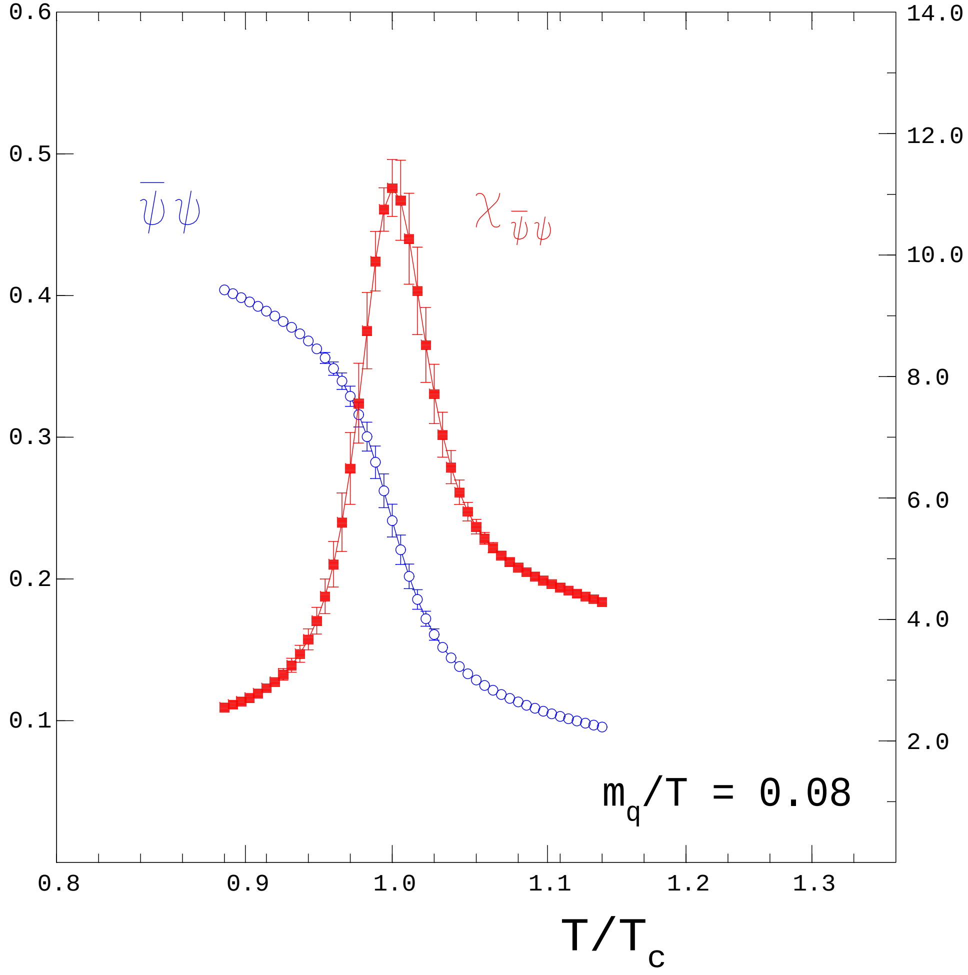


Results from “Lattice QCD”

Polyakov loop - deconfinement



quark condensate - chiral sym. restoration



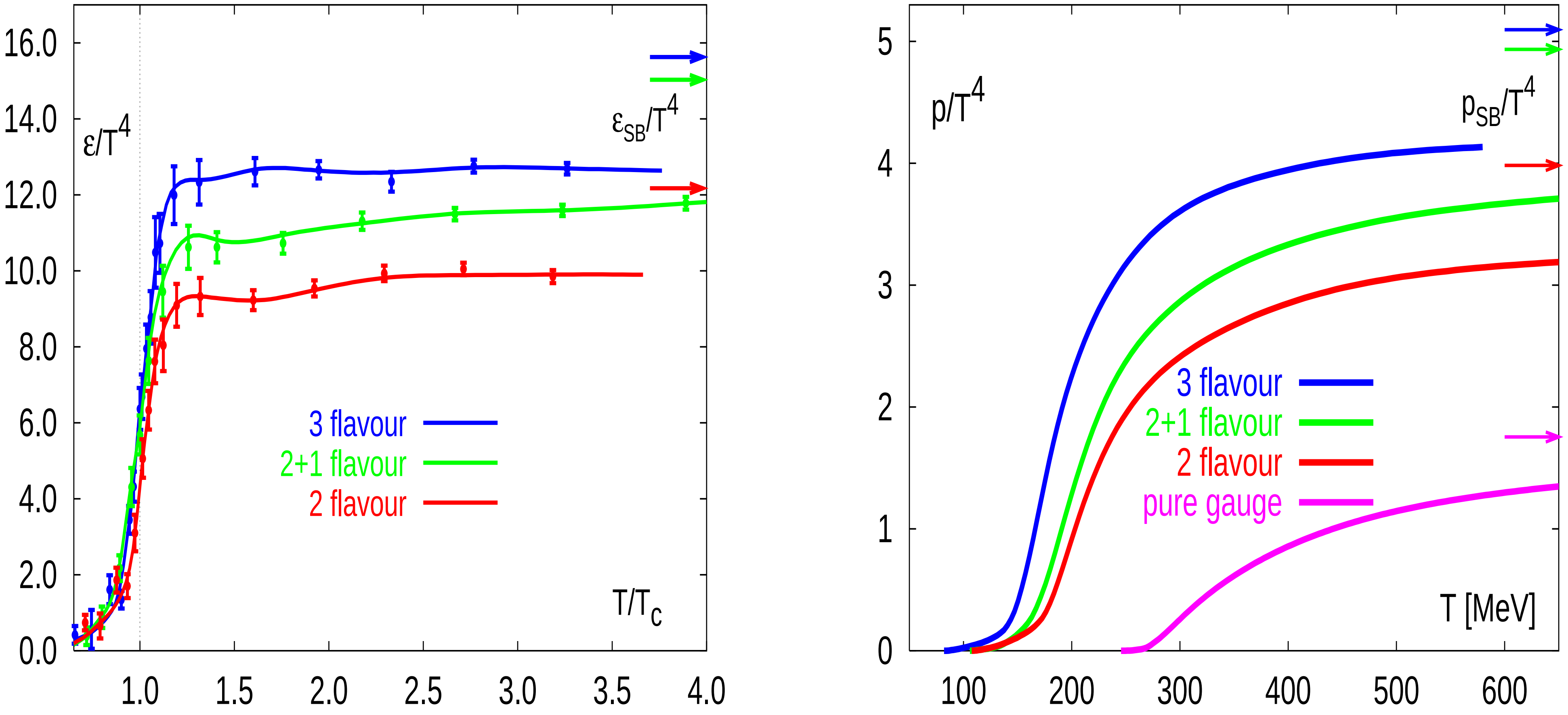
Suceptibilities χ: measure of fluctuations

F. Karsch, E. Laermann, hep-lat/0305025

Results from "Lattice QCD"

energy density

pressure



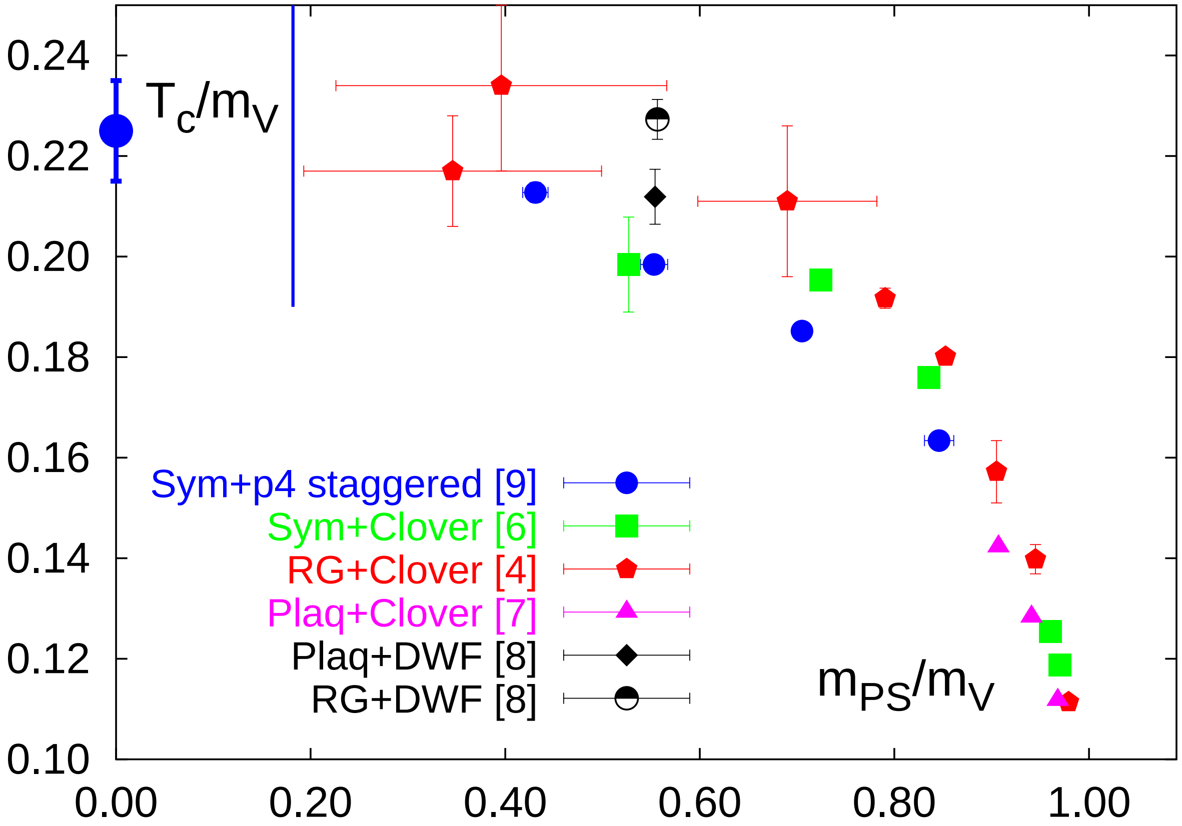
$\epsilon_c = \mathbf{0.7\ GeV/fm^3}$

F. Karsch et al. Bielefeld group, Phys. Lett. B478(2000)447 and Nucl. Phys. A698(2002)199c

$16^3\times$ 4 lattice, $m_{ql}/T=0.4$, $m_{qh}/T=1$

Critical Temperature from “Lattice QCD”

F. Karsch, Nucl. Phys. A698(2002)199c and E. Laermann, Proc. Hirschegg 2002

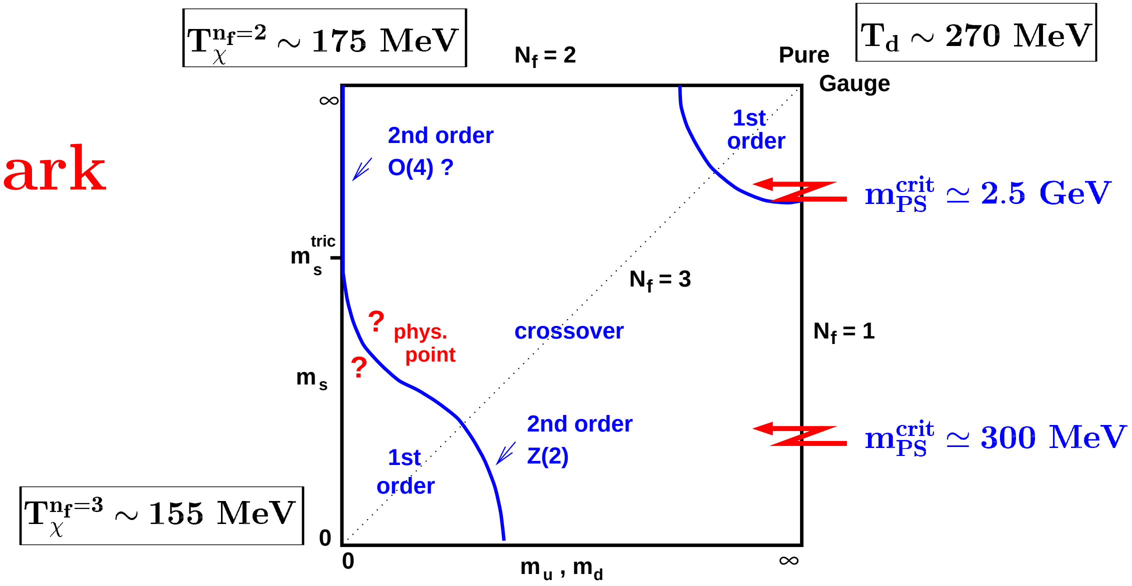


fix temperature scale with m_ρ → $\mathbf{T}_c = 173 \pm 8$ **MeV**

Order of the Phase Transition

key role of strange quark

3-flavour phase diagram


$T_\chi^{n_f=2} \sim 175$ MeV

$T_d \sim 270$ MeV

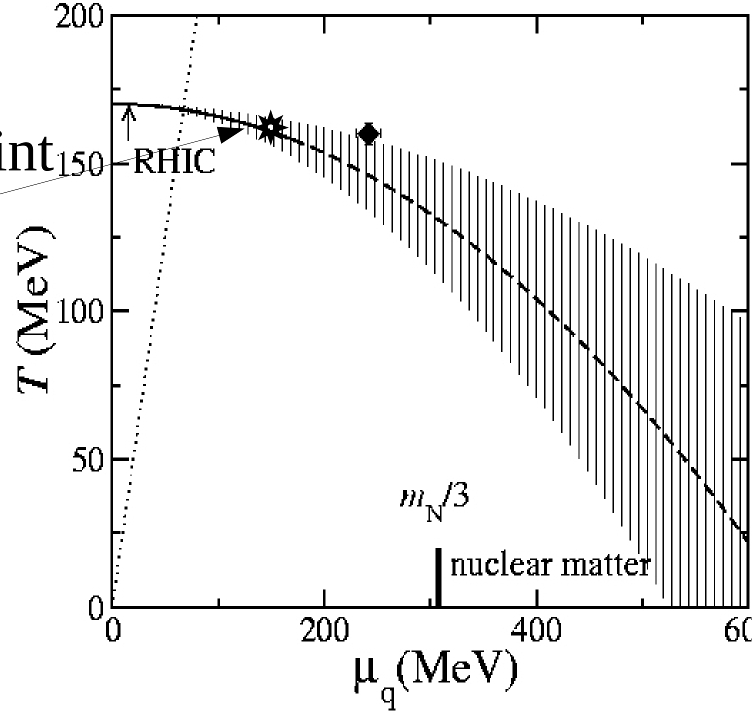
$T_\chi^{n_f=3} \sim 155$ MeV

$m_{PS}^{crit} \simeq 2.5$ GeV

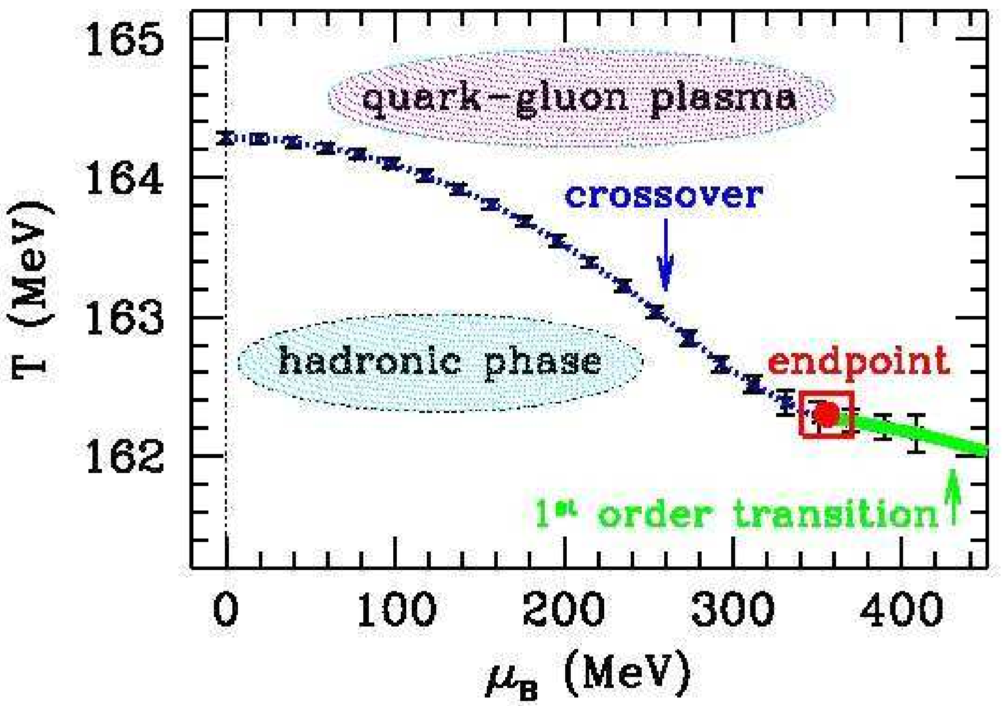
$m_{PS}^{crit} \simeq 300$ MeV

Phase boundary from lattice QCD at finite baryon density

New endpoint



S. Ejiri et al, hep-lat/0312006



Z. Fodor, S. Katz, JHEP0404, (2004) 050

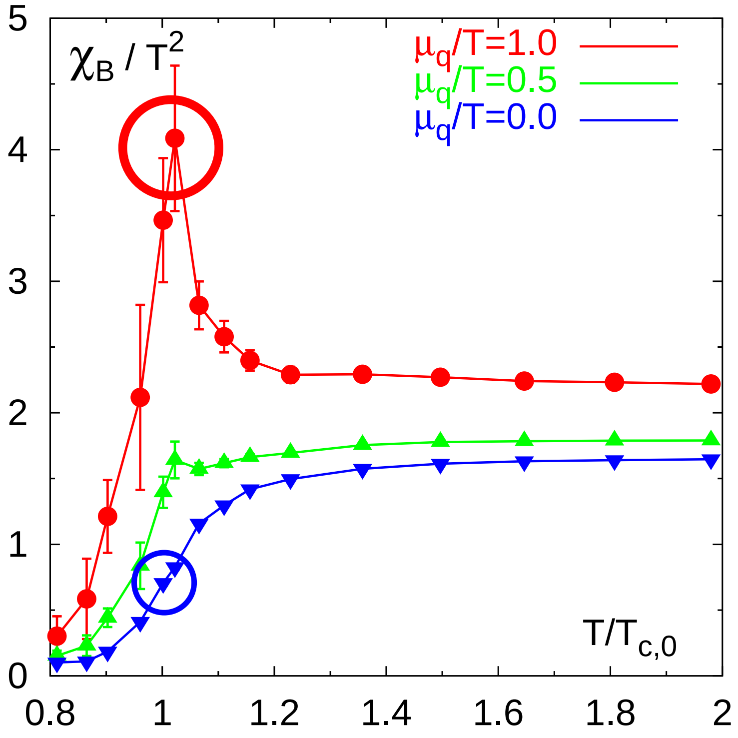
Note: $3\,\mu_q = \mu_B$

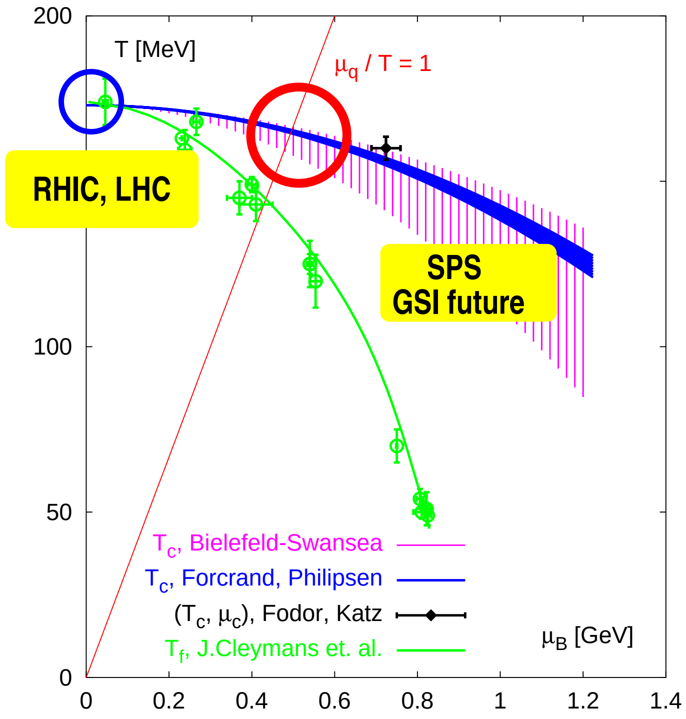
critical end point not (yet) well determined theoretically

Fluctuations of the baryon number density ($\mu > 0$)

$$\frac{\chi_B}{T^2} = \left(\frac{\mathbf{d}^2}{\mathbf{d}(\mu/T)^2} \frac{p}{T^4} \right)_{T\ \mathrm{fixed}}$$

baryon number density fluctuations:
(Bielefeld-Swansea, in preparation)

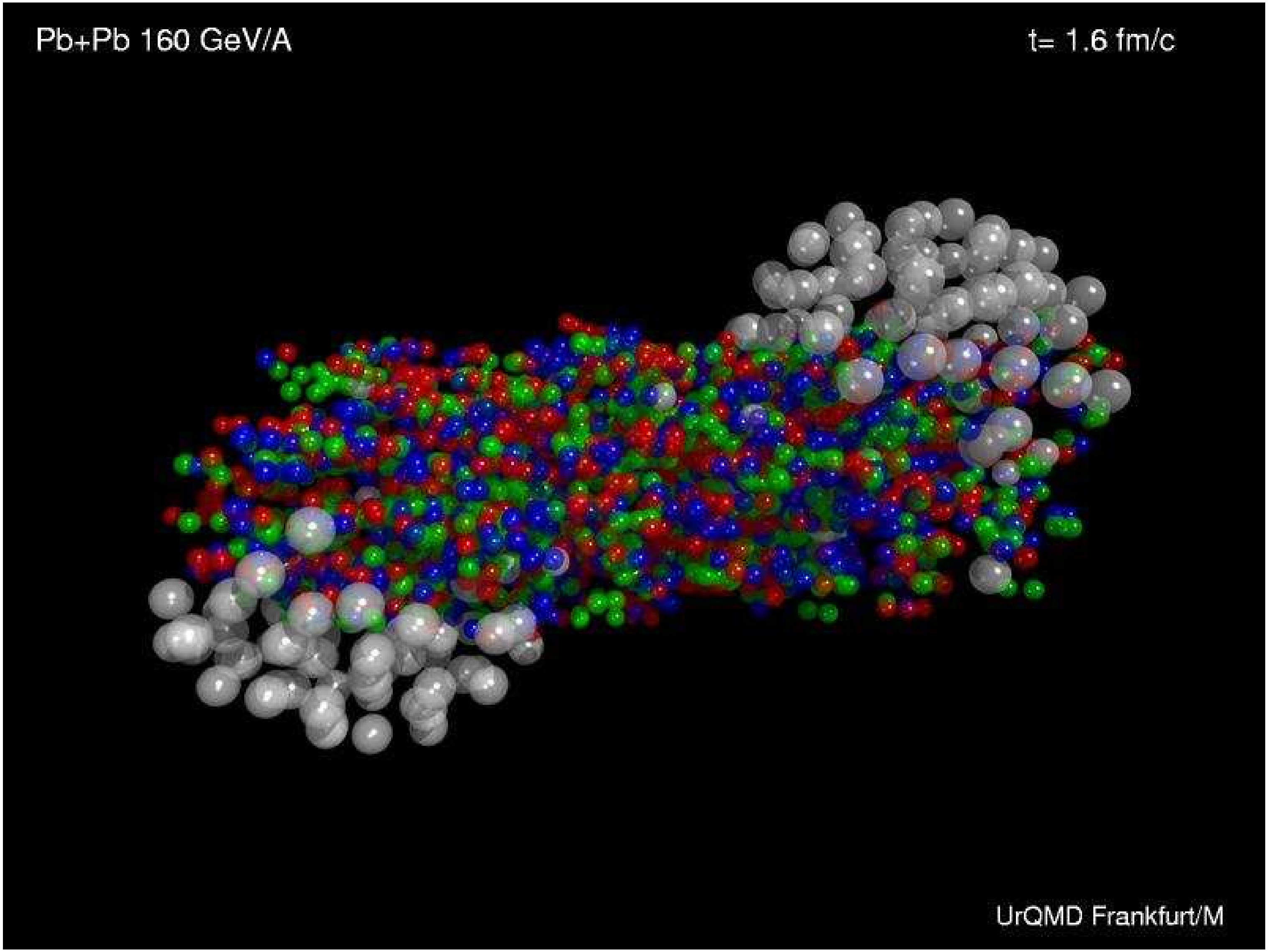




Snapshot of a Pb – Pb Collision

SPS Energy

semi-central collision



white: hadrons colored: quarks and gluons

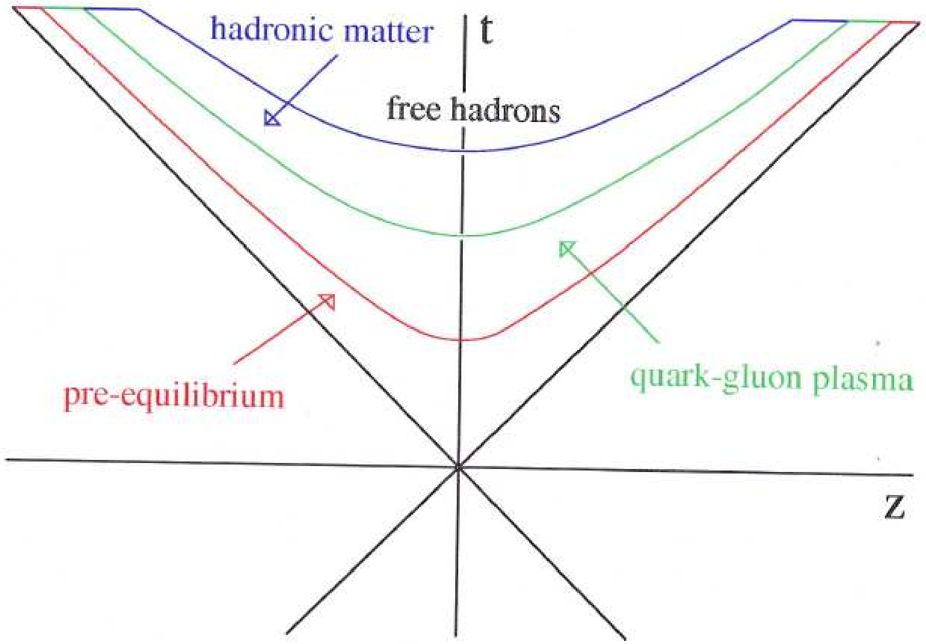
Space Time Development

1st stage: liberation of quarks and gluons

2nd stage: equilibration of quarks and gluons
→ formation of QGP

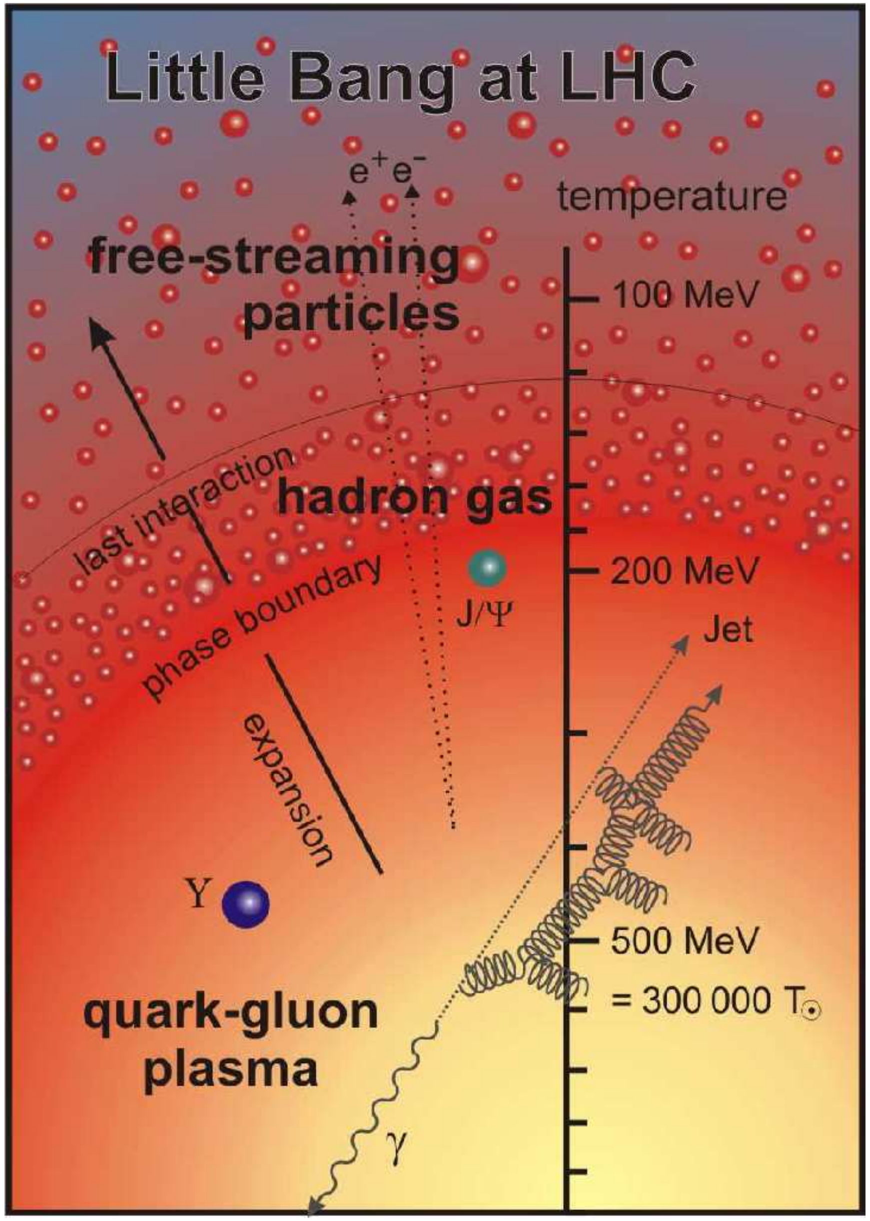
3rd stage: hadronization

4th stage: freeze-out



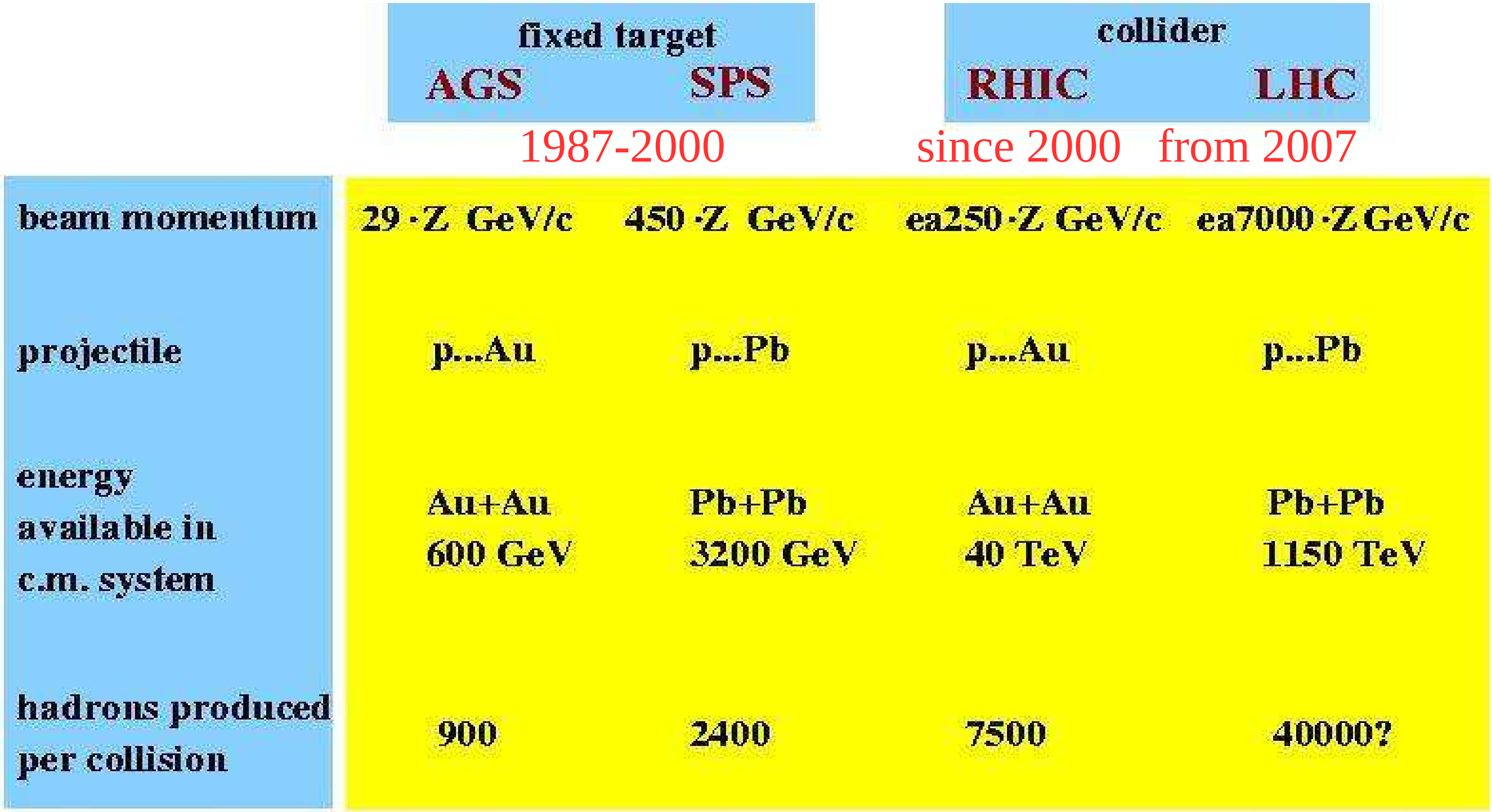
Evolution of the Fireball

signals of hot phase:
penetrating probes
jets, γ, lepton pairs



information on
phase boundary:
yields of produced hadrons

Accelerators where ultra-relativistic nuclei collide



	fixed target		collider	
	AGS	SPS	RHIC	LHC
	1987-2000		since 2000	from 2007
beam momentum	29 ·Z GeV/c	450 ·Z GeV/c	ea250 ·Z GeV/c	ea7000 ·Z GeV/c
projectile	p...Au	p...Pb	p...Au	p...Pb
energy available in c.m. system	Au+Au 600 GeV	Pb+Pb 3200 GeV	Au+Au 40 TeV	Pb+Pb 1150 TeV
hadrons produced per collision	900	2400	7500	40000?

Accelerators and Experiments for Nuclear Collisions

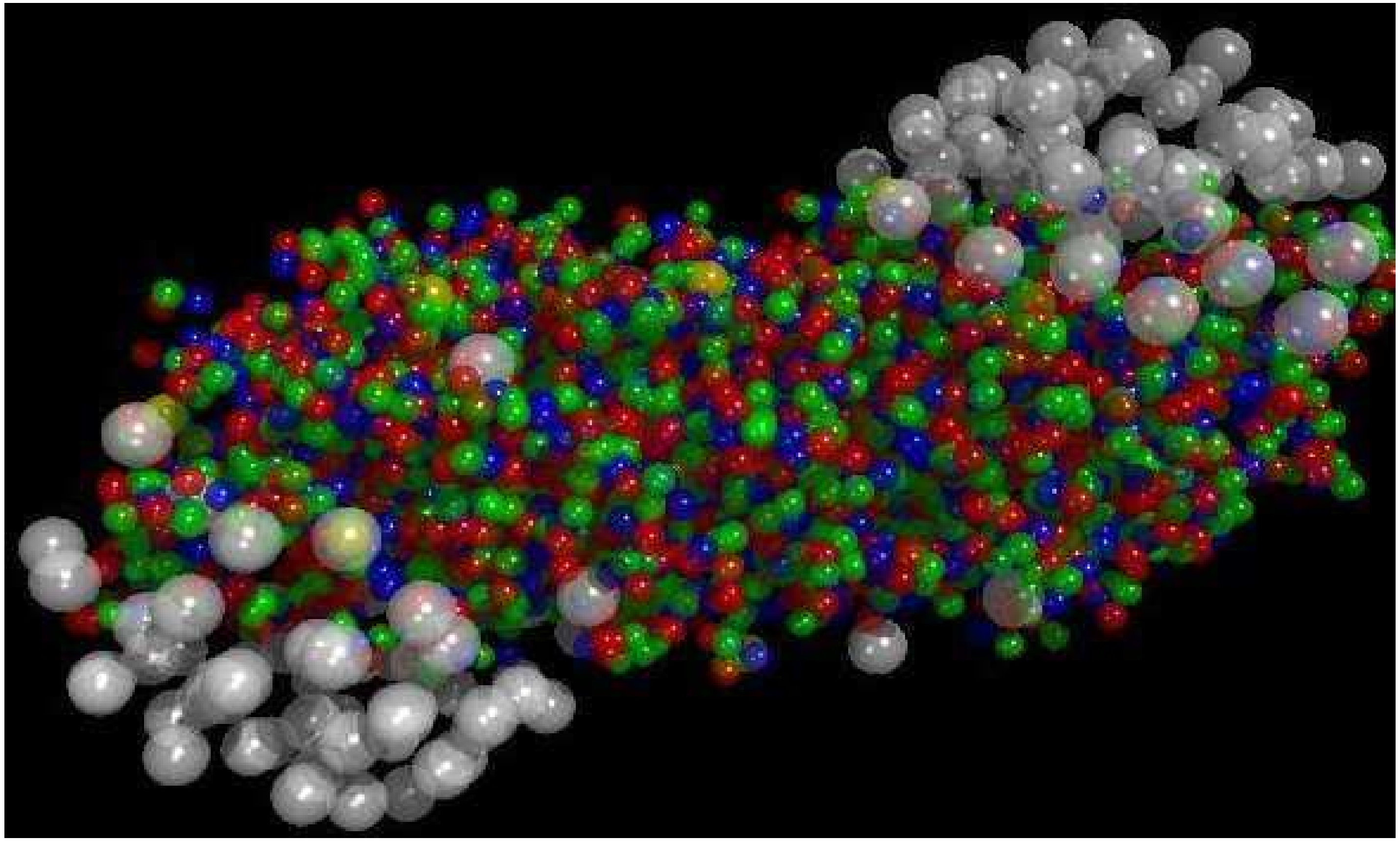
- **BNL-AGS (1986 - 2002): $\sqrt{s} = 5.5$ GeV, Au + Au collisions**
  5 large experiments: E802/866/917, E810, E814/877, E864, E895.

- **CERN-SPS (1986 - 2004): $\sqrt{s} = 17$ GeV, Pb + Pb collisions**
  7 large experiments: WA80/98, NA35/49, NA38/50/60, NA44 NA45/CERES, WA97/NA57, NA52.

- **BNL-RHIC (from 2000): $\sqrt{s} = 200$ GeV, Au + Au collisions**
  4 large experiments: BRAHMS, PHENIX, PHOBOS, STAR.

- **CERN-LHC (from 2007): $\sqrt{s} = 5.5$ TeV, Pb + Pb collisions**
  3 large experiments: ATLAS, ALICE, CMS

Press Release Feb. 2000: New State of Matter created at CERN

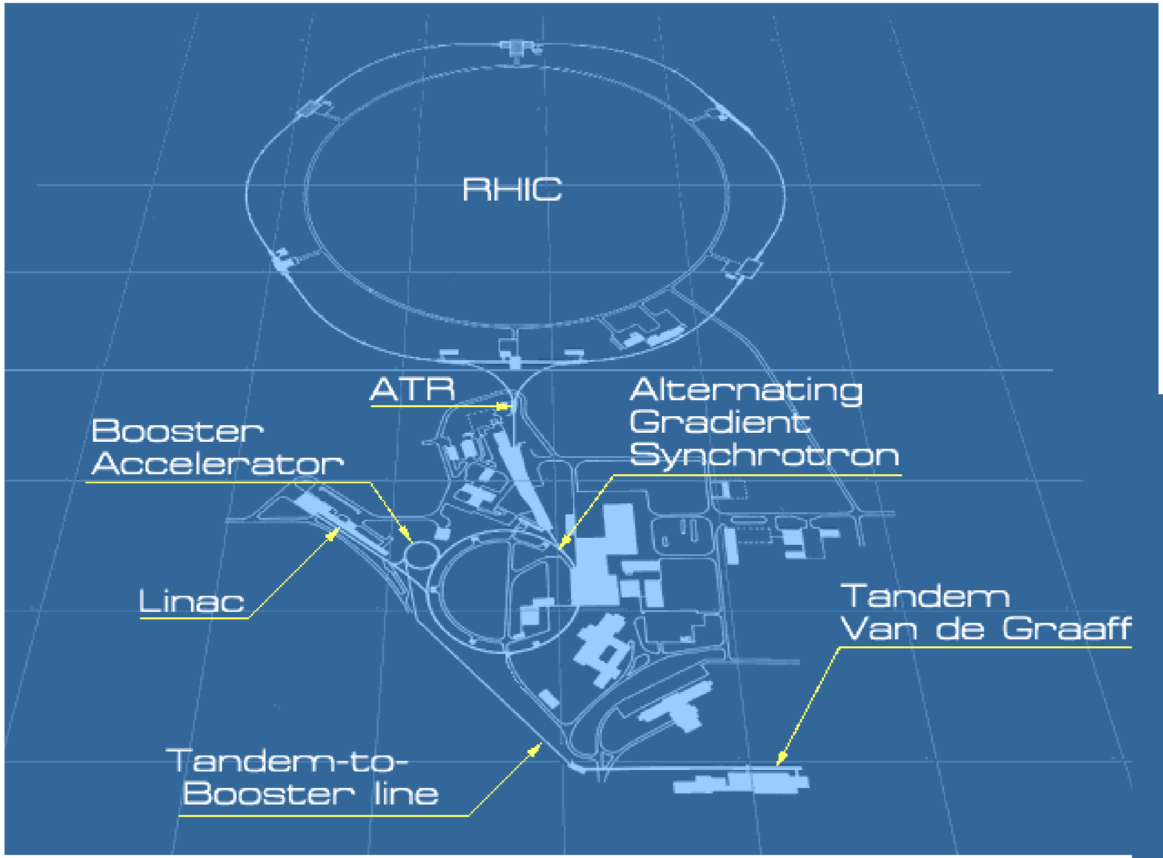


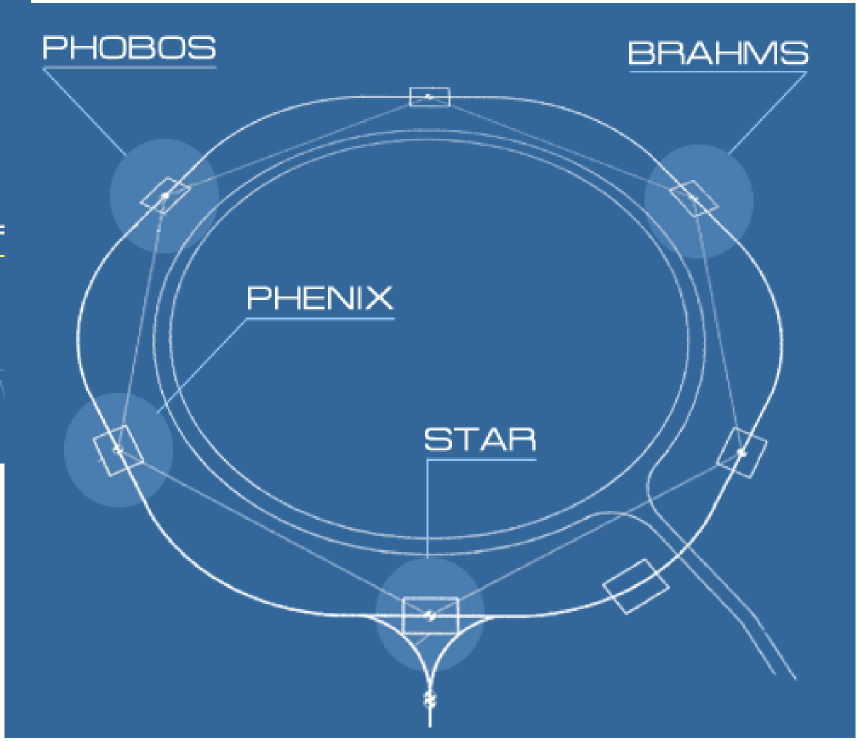
At a special seminar on 10 February, spokespersons from the experiments on CERN* 's Heavy Ion programme presented compelling evidence for the existence of a new state of matter in which quarks, instead of being bound up into more complex particles such as protons and neutrons, are liberated to roam freely.

nothing know yet about properties of new state

RHIC starts from here

heavy ion collider RHIC – dedicated machine





RHIC press release after analysis of first 3 years

BROOKHAVEN
NATIONAL LABORATORY

Contact: Karen McNulty Walsh, (631) 344-8350 or Mona S. Rowe, (631) 344-5056

RHIC Scientists Serve Up "Perfect" Liquid

New state of matter more remarkable than predicted -- raising many new questions

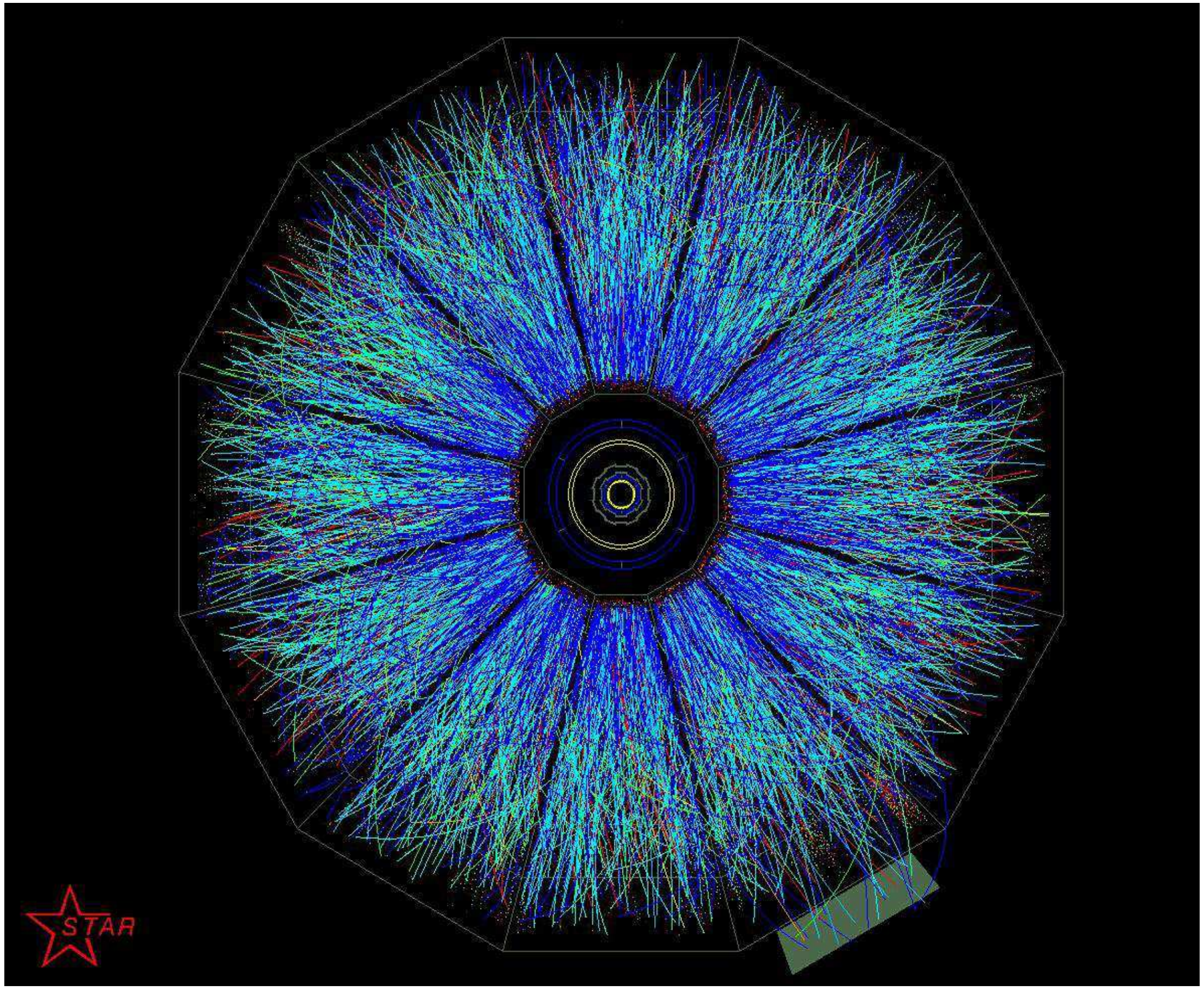
April 18, 2005

TAMPA, FL -- The four detector groups conducting research at the Relativistic Heavy Ion Collider (RHIC) -- a giant atom "smasher" located at the U.S. Department of Energy's Brookhaven National Laboratory -- say they've created a new state of hot, dense matter out of the quarks and gluons that are the basic particles of atomic nuclei, but it is a state quite different and even more remarkable than had been predicted. In peer-reviewed papers summarizing the first three years of RHIC findings, the scientists say that instead of behaving like a gas of free quarks and gluons, as was expected, the matter created in RHIC's heavy ion collisions appears to be more like a liquid.

STAR event display

in central AuAu collsions
at RHIC √s = 200 GeV
about 7500 hadrons
produced

about three times as
much as at CERN SPS



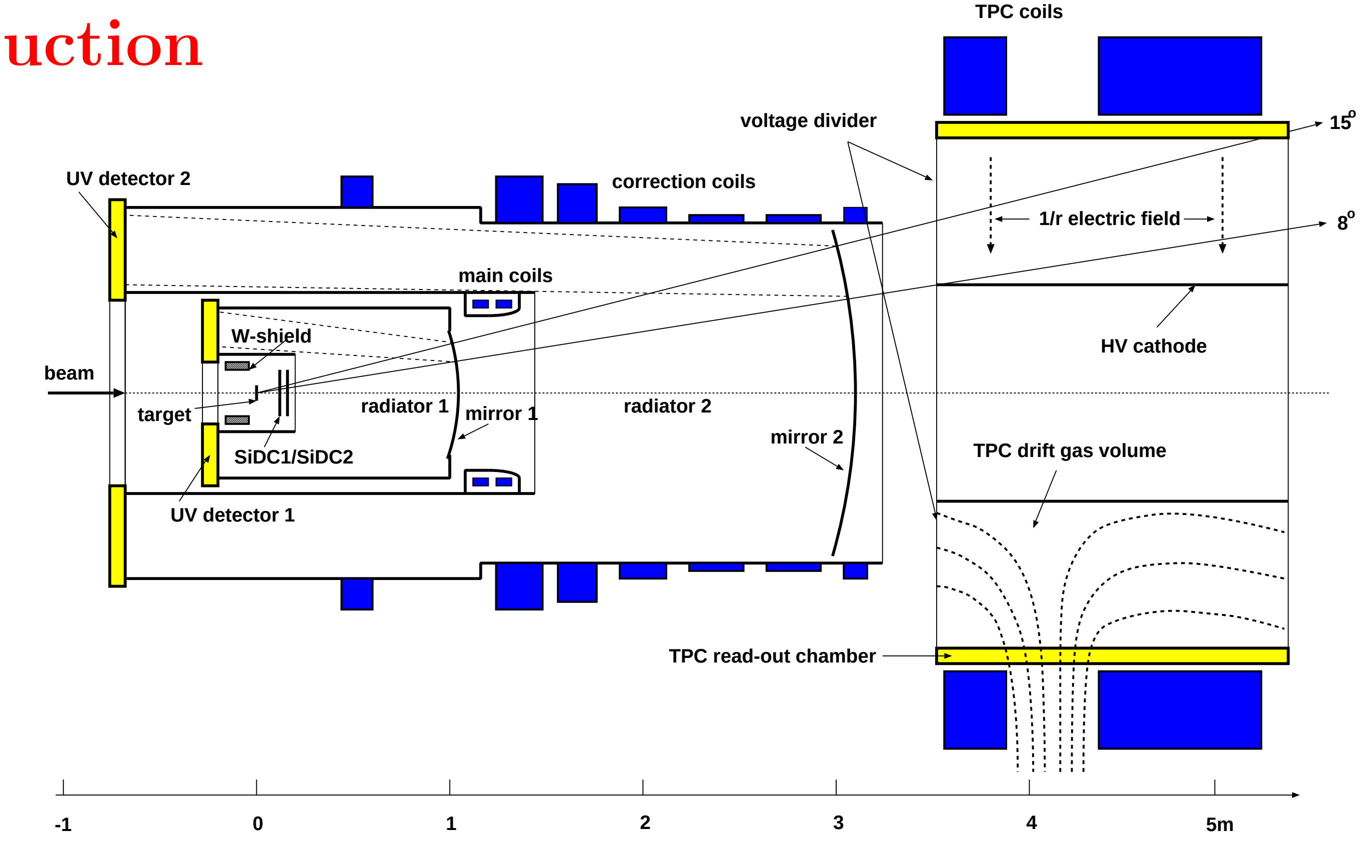
Experimental Challenge of High Energy Heavy Ion Experiments

- **Very high multiplicities demanded new developments**

1. **Time Projection Chambers (TPC)**
   developed to unprecedented performance
2. **Silicon Pixel (and Drift) Detectors**
   with large area and very fine granularity
3. **Electron Identification**
   in high hadron density environment (RICH and TRD development)

NA45/CERES Experiment at CERN SPS

Study of e^+e^- Production

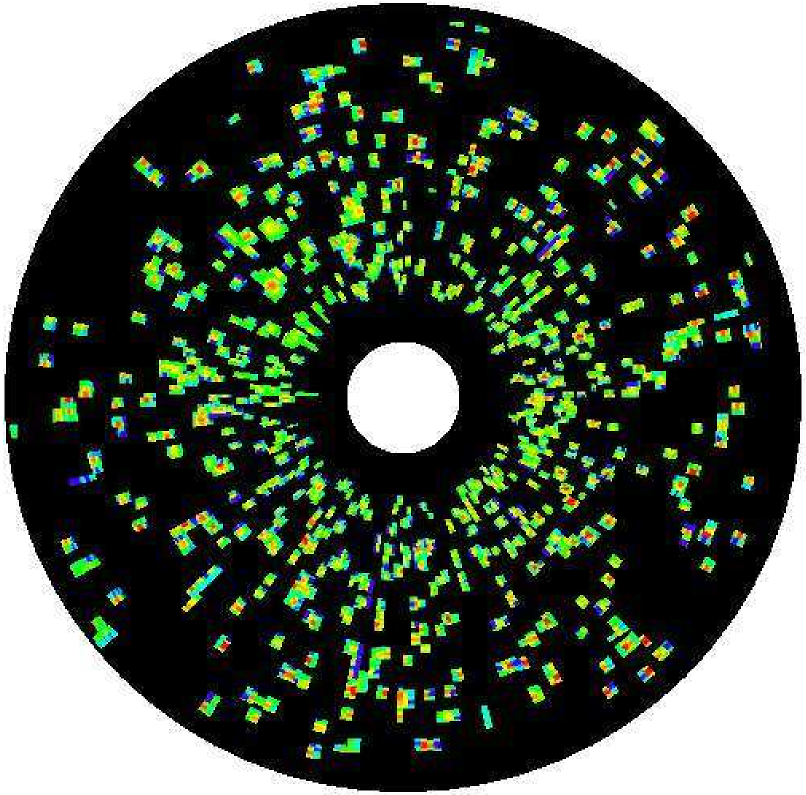


Since 1999:

also hadronic observables

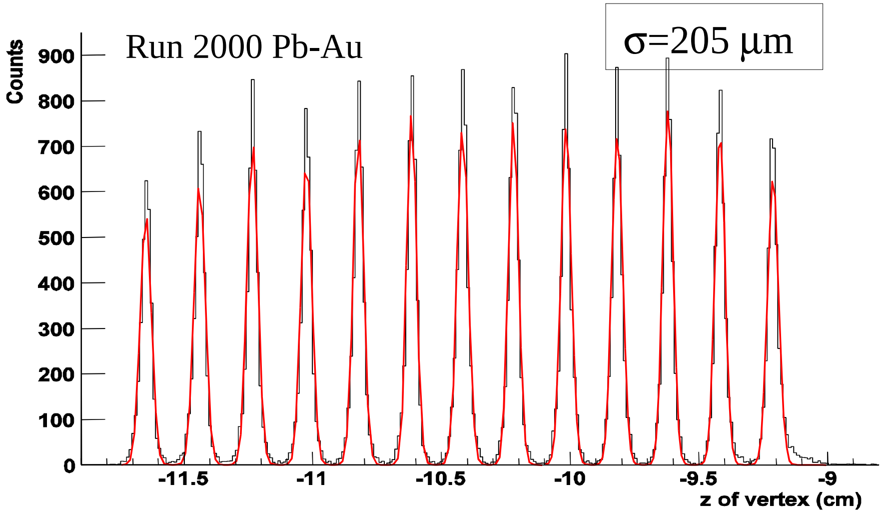
all novel detectors: 2 Si Drift detectors, 2 RICHes, large radial TPC

CERES Silicon Drift Detectors



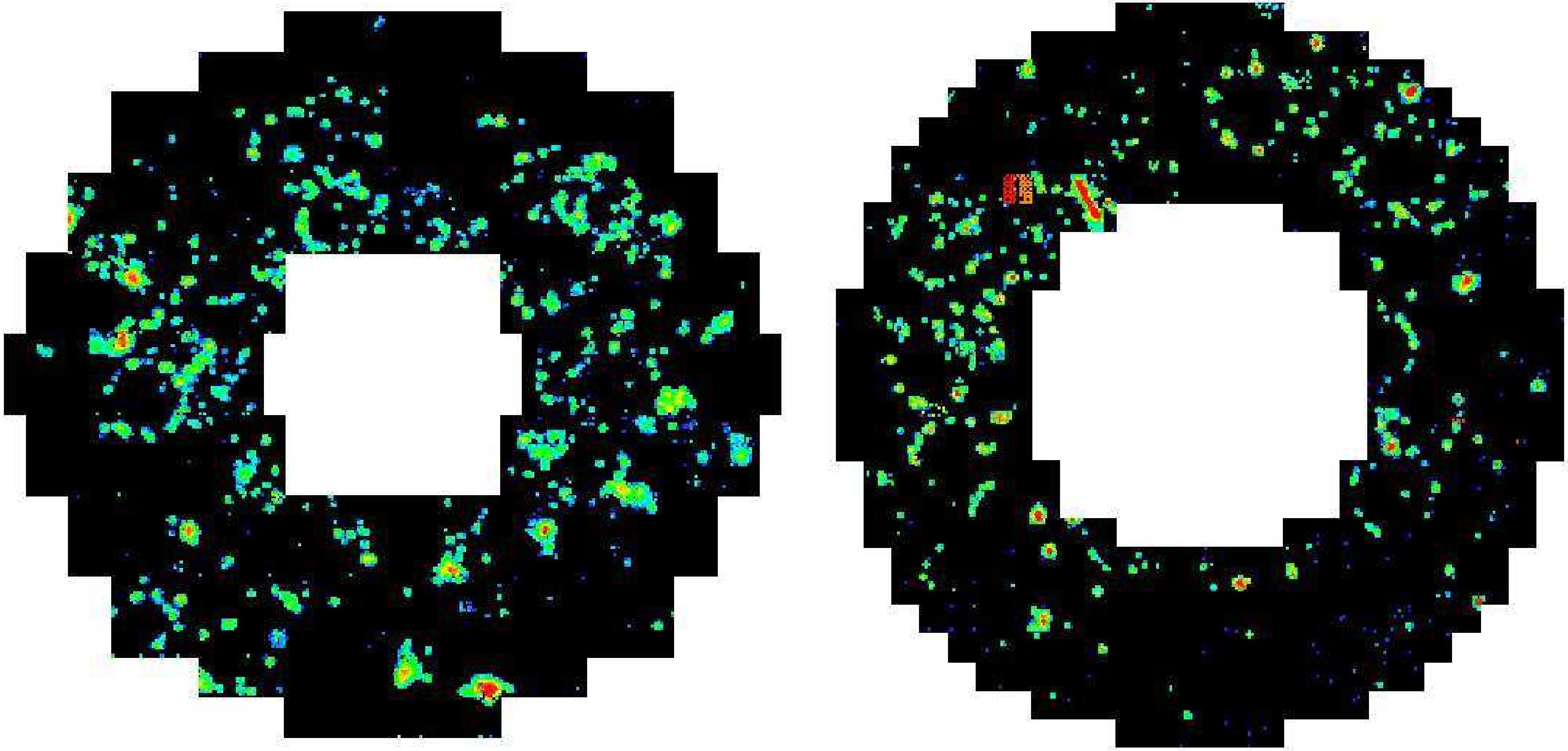
two 4” Silicon wafers

- charged particle tracking
- vertex reconstruction



combination of 2 or more:
form telescopes

CERES Ring Imaging Cherenkov Counters RICH1/2

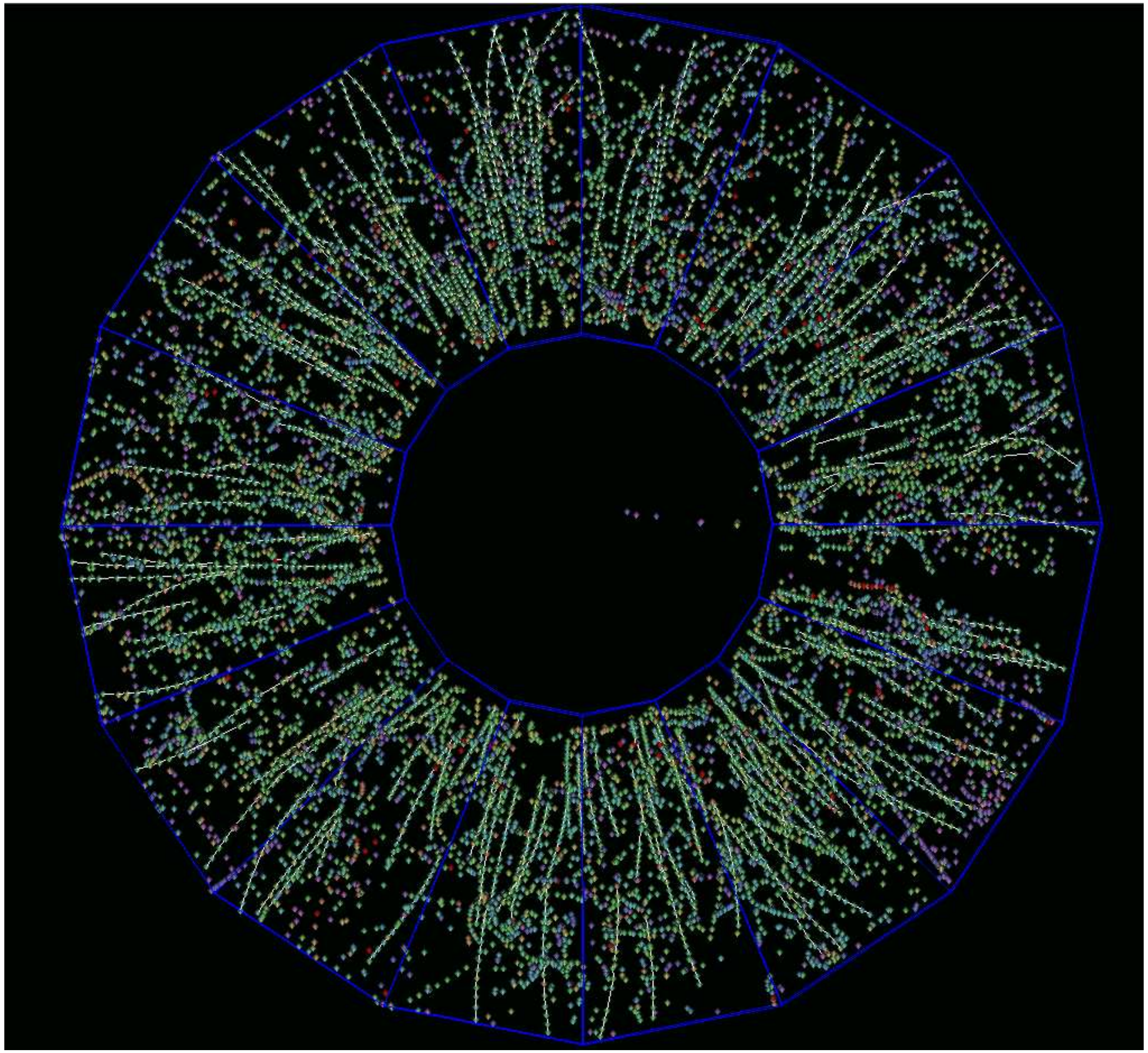


electron identification via ring signature
about 10 photons per electron ring

CERES Event Display

charged particle tracking
with TPC
10 m^3, $4{\cdot}10^6$ pixels

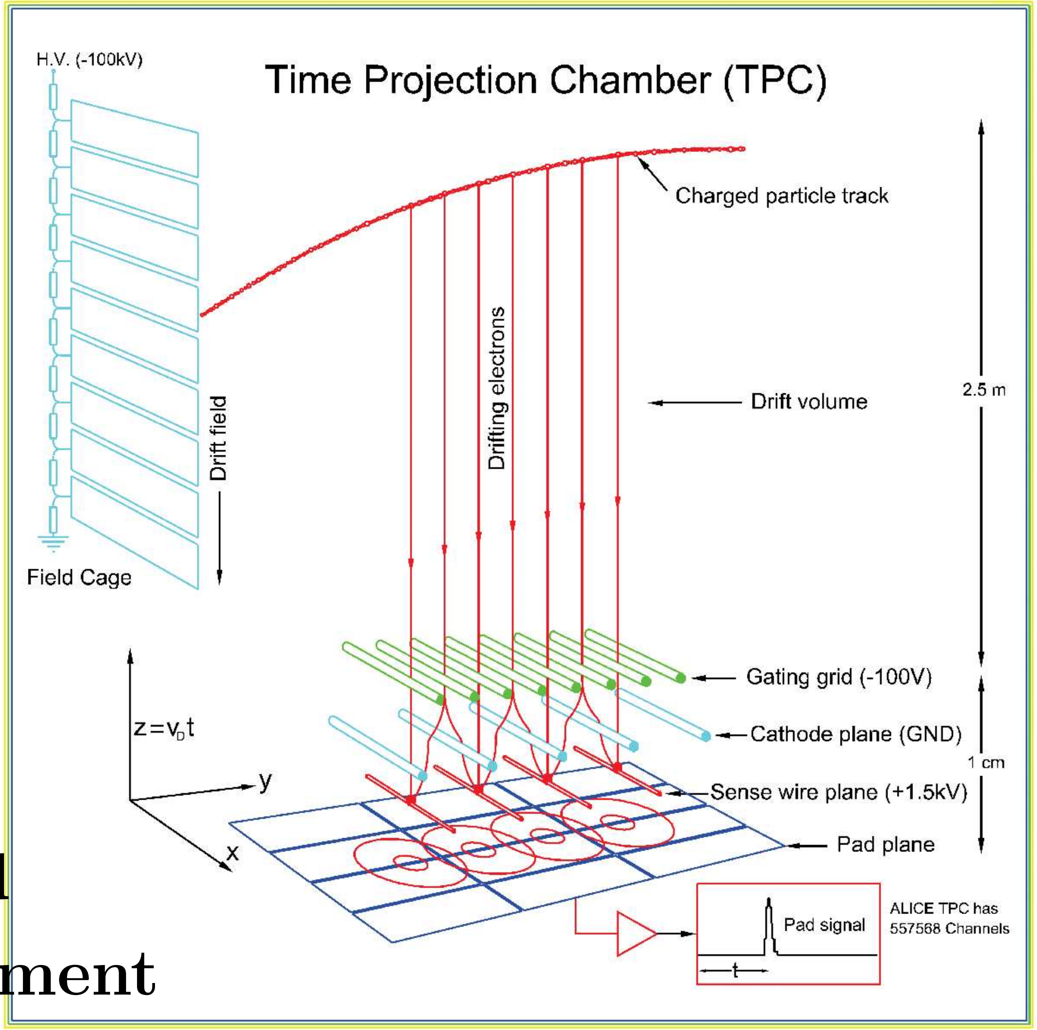
up to 400 charged particles



Time Projection Chamber (TPC) Principle

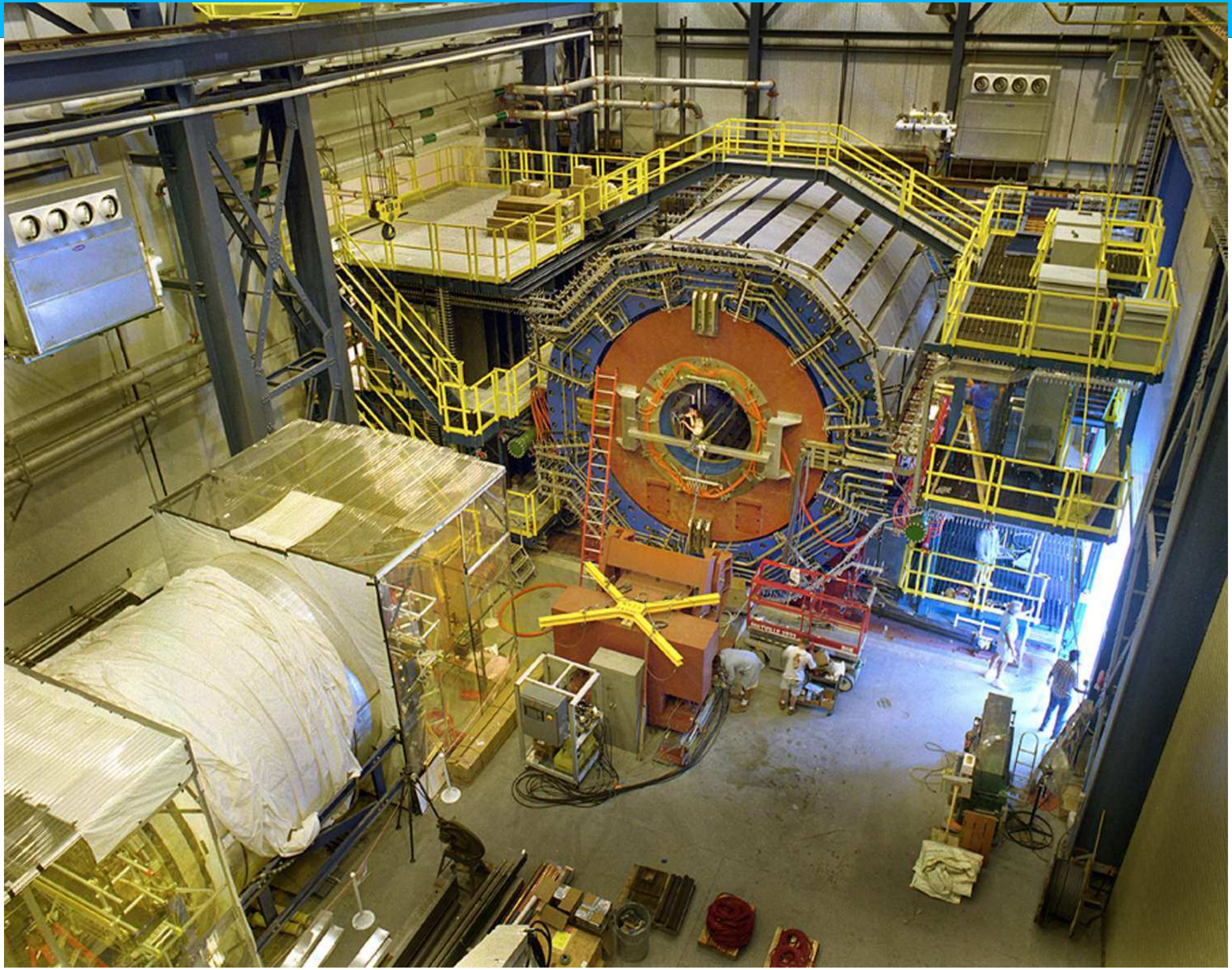
3-dimensional tracking

large volumes possible
90 m^3 and
$3{\cdot}10^8$ read out pixels
for ALICE TPC



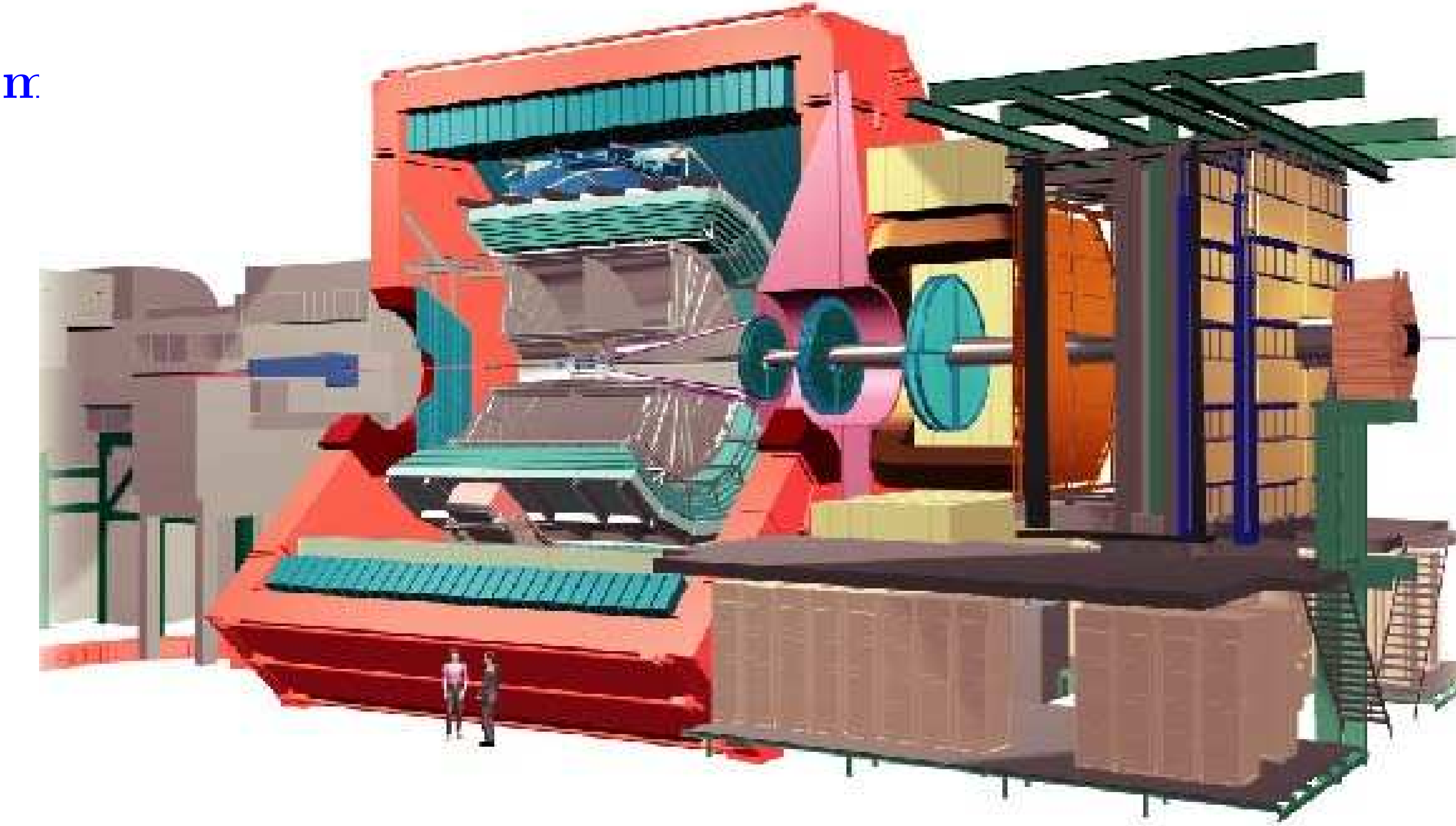
information from drift time and
2-dimensional position measurement

STAR Experiment at RHIC



The ALICE Experiment at LHC

running from
2007



central barrel: ITS, TPC, TRD, TOF +
forward muon detector

The ALICE TPC field cage