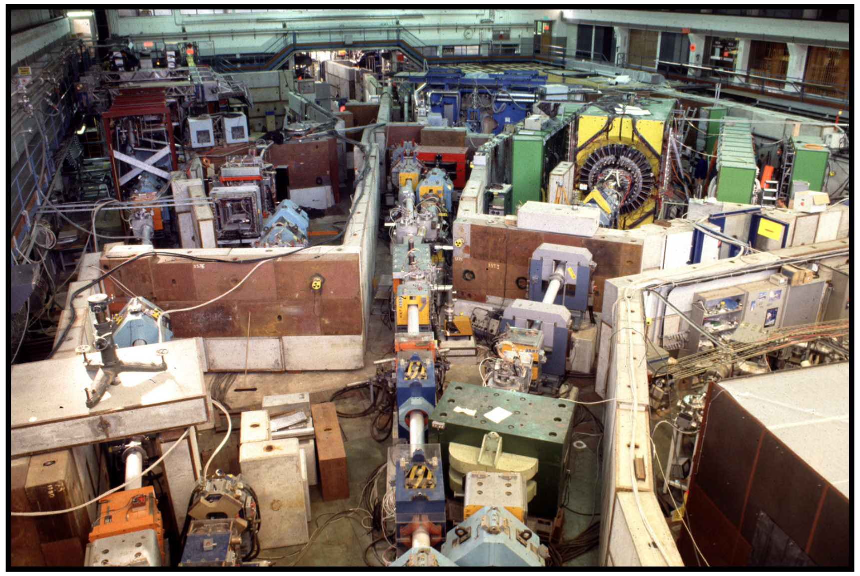
ANTIMATTER IN THE LAB

Chloé Malbrunot
CERN


CERN Summer student lecture 2019

Content

LECTURE # 1 (This lecture)
- What is antimatter?
- Some historical reminders
- Discrete symmetries
- Primordial antimatter search

LECTURE # 2 (This lecture)
- Antiprotons at low energies : cooling and trapping
- Experiments at the AD : exotic atoms made of antimatter
- Antihydrogen : a tool to study matter-antimatter asymmetry
- Everyday's application of antimatter

Production of antimatter

The case of antiprotons

$$p + p \rightarrow \boxed{\bar{p} + p} + p + p$$

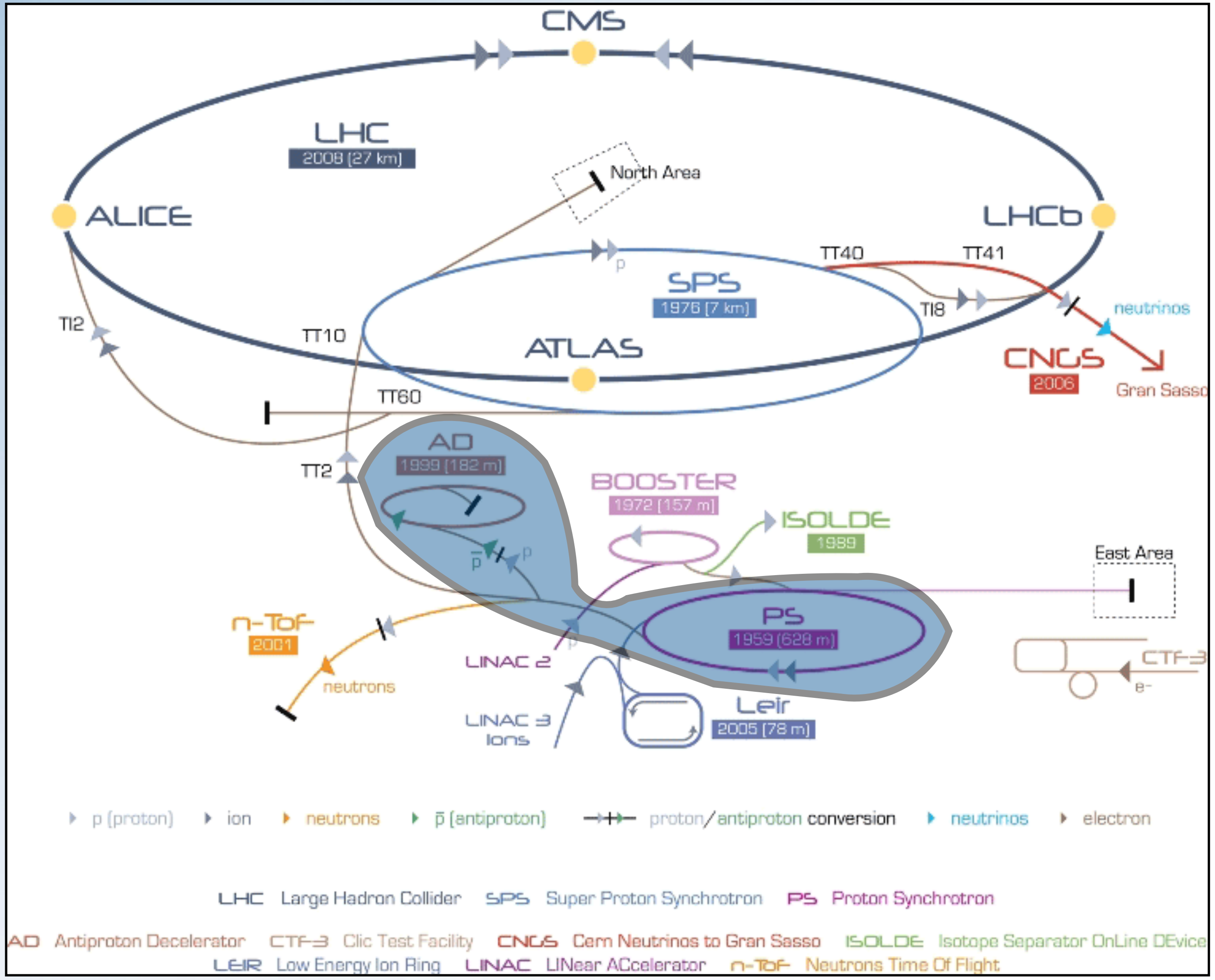
$$\boxed{\sqrt{s} = \sqrt{2m_p^2 + 2E_p m_p}}$$

Pair production : Threshold energy at 5.6 GeV

Bevatron was right at threshold when producing the first antiprotons !

Need higher proton energies to produce more antiprotons

Antiproton Cooling



Production at 26 GeV/c

Maximum production at 3.7 GeV/c
(~ collection momentum)
Sharp fall-off around the peak

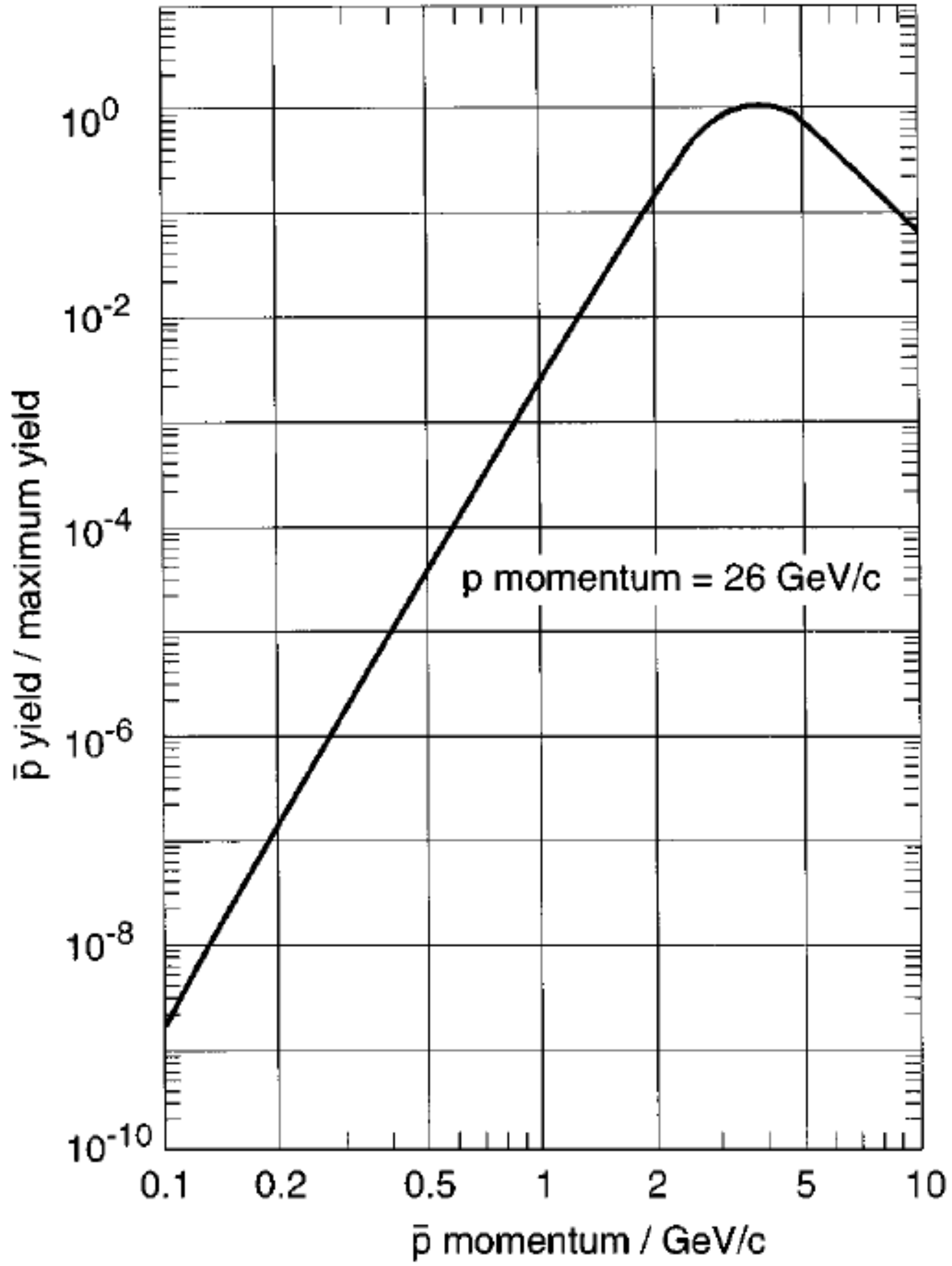


FIG. 1. Normalized antiproton yield (antiprotons per proton) at 26 GeV/c proton-beam momentum. The normalization is chosen so that the yield is one at the maximum.

Antiprotons at lower energies

Antiprotons at lower energies

Antiproton Cooling

Cooling : reduce phase space and increase phase-space density

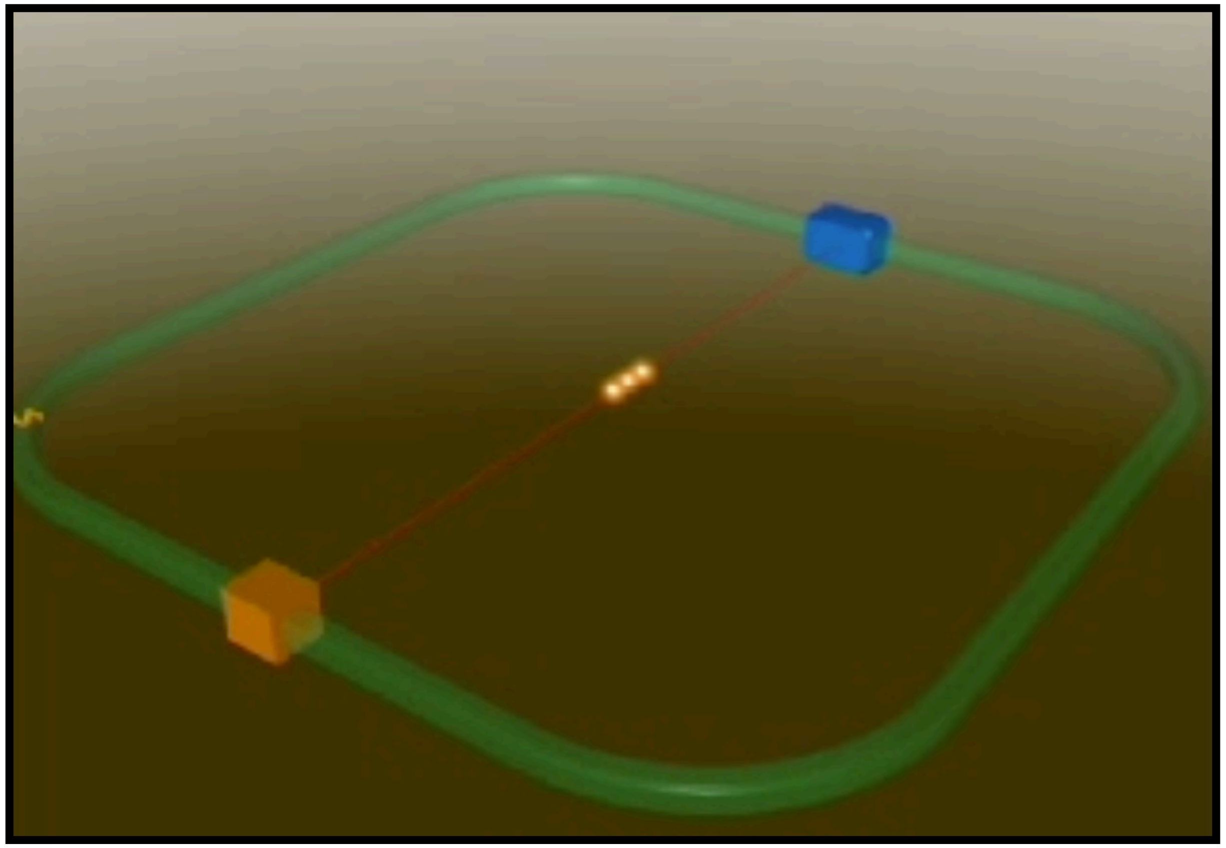
$$D = \frac{N}{\sqrt{E_h E_v L \frac{\Delta p}{p}}}$$

E_h, E_v: horizontal, vertical emittances
L: longitudinal spread
N: number of particles
$\Delta p/p$: momentum spread

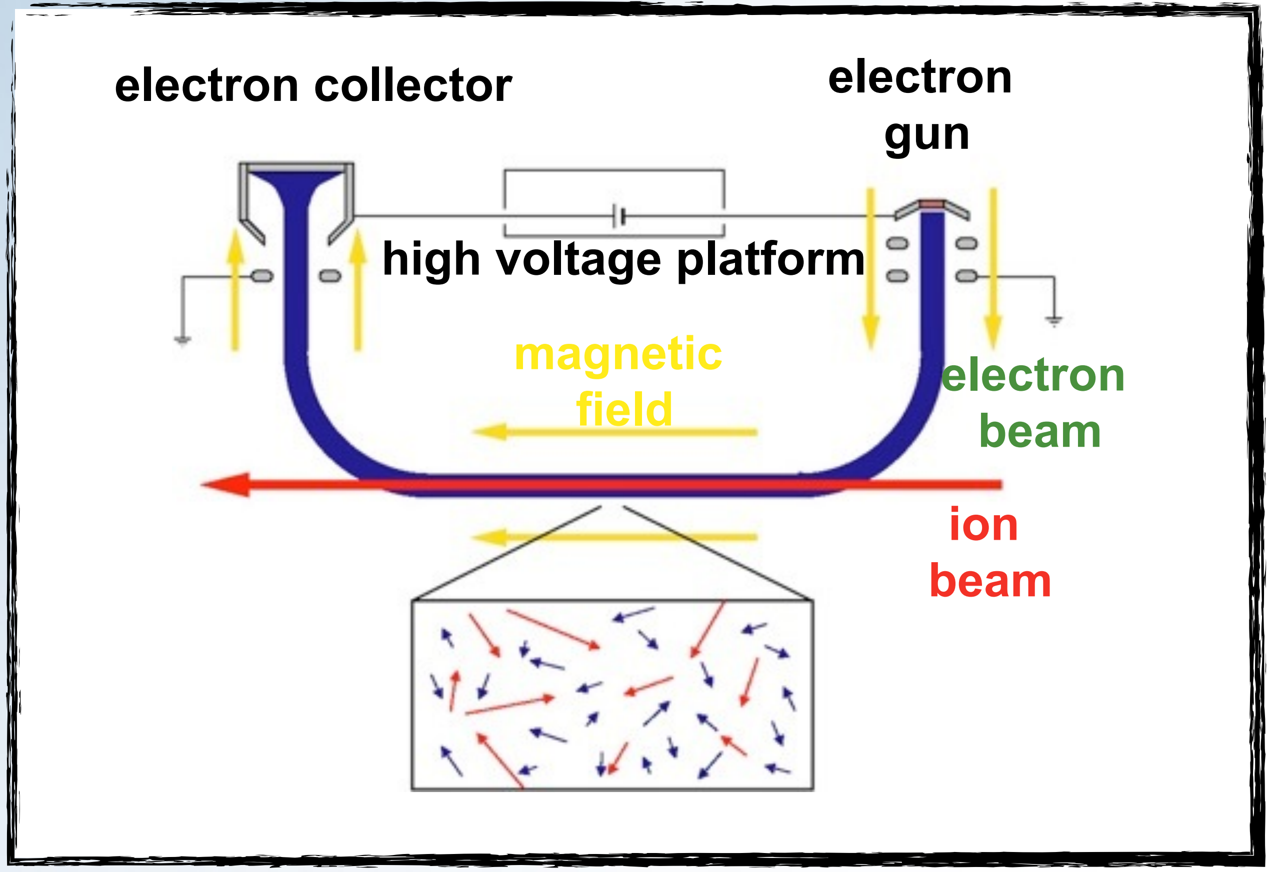
Cooling methods :

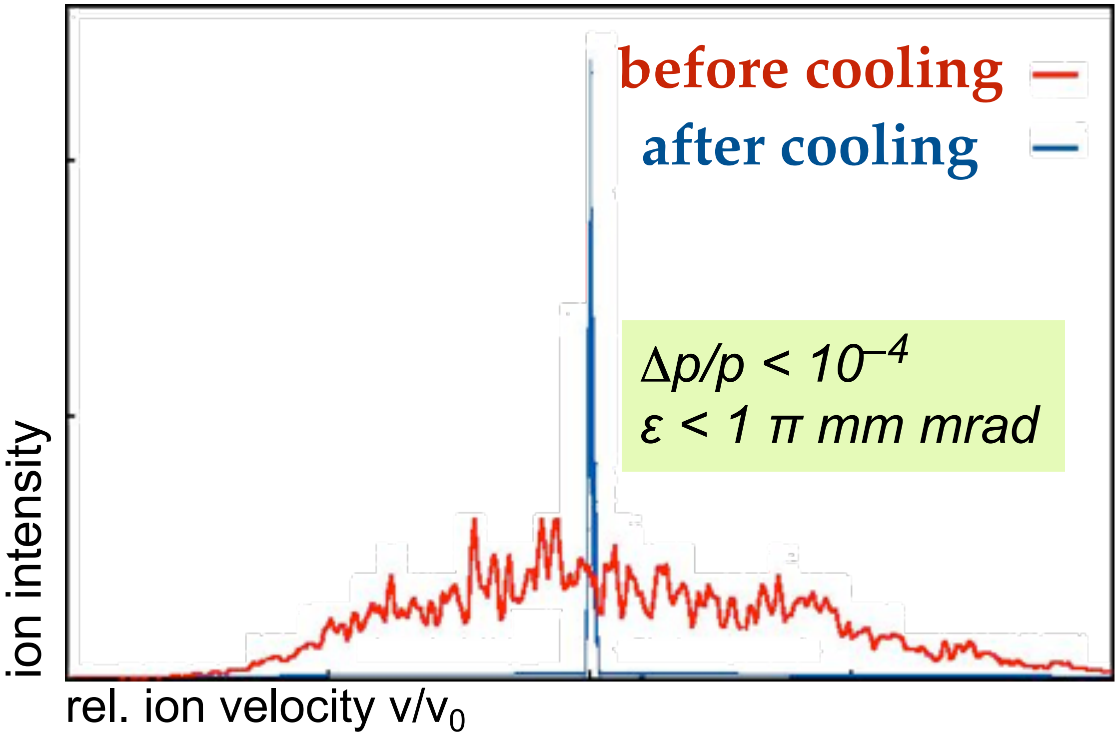
- Stochastic cooling

- Electron cooling



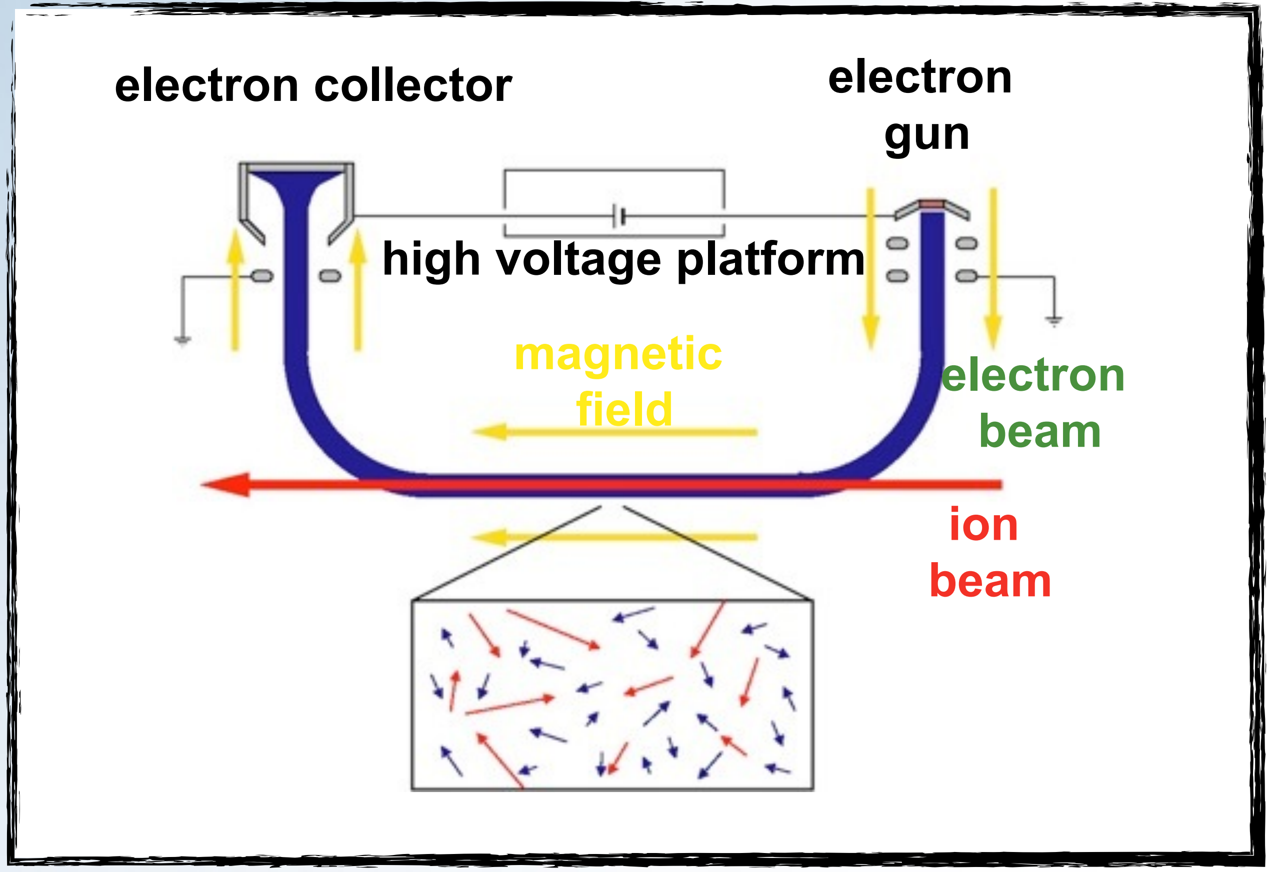
Electron cooling

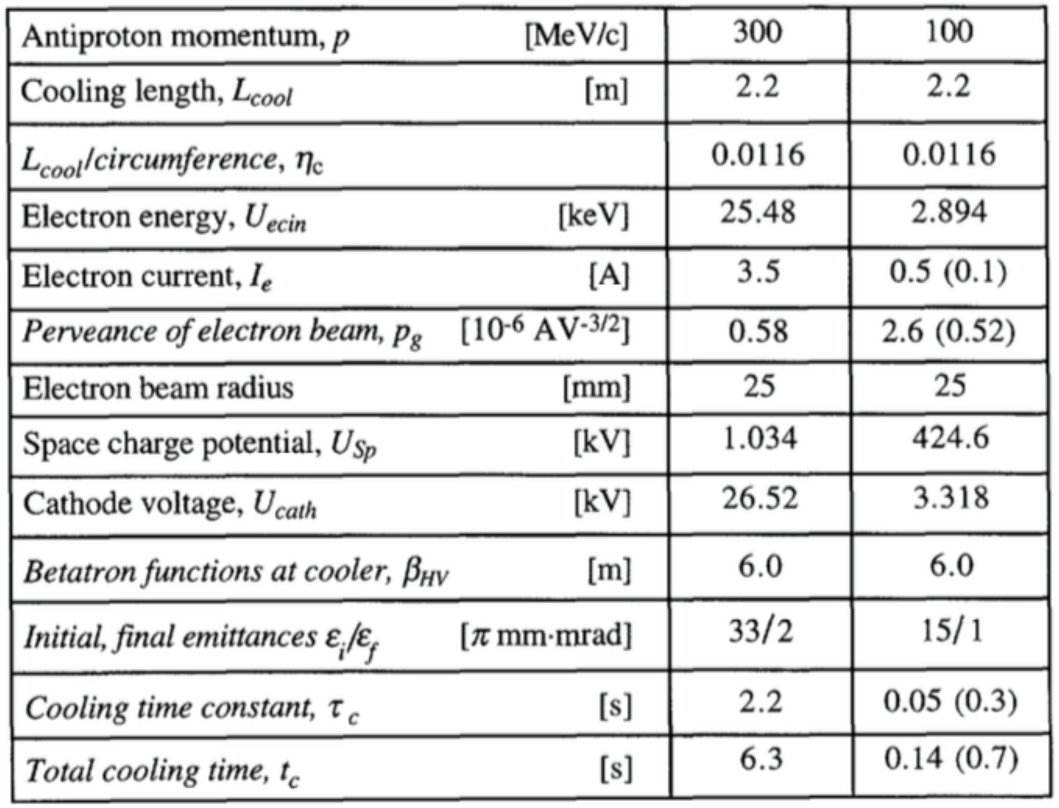




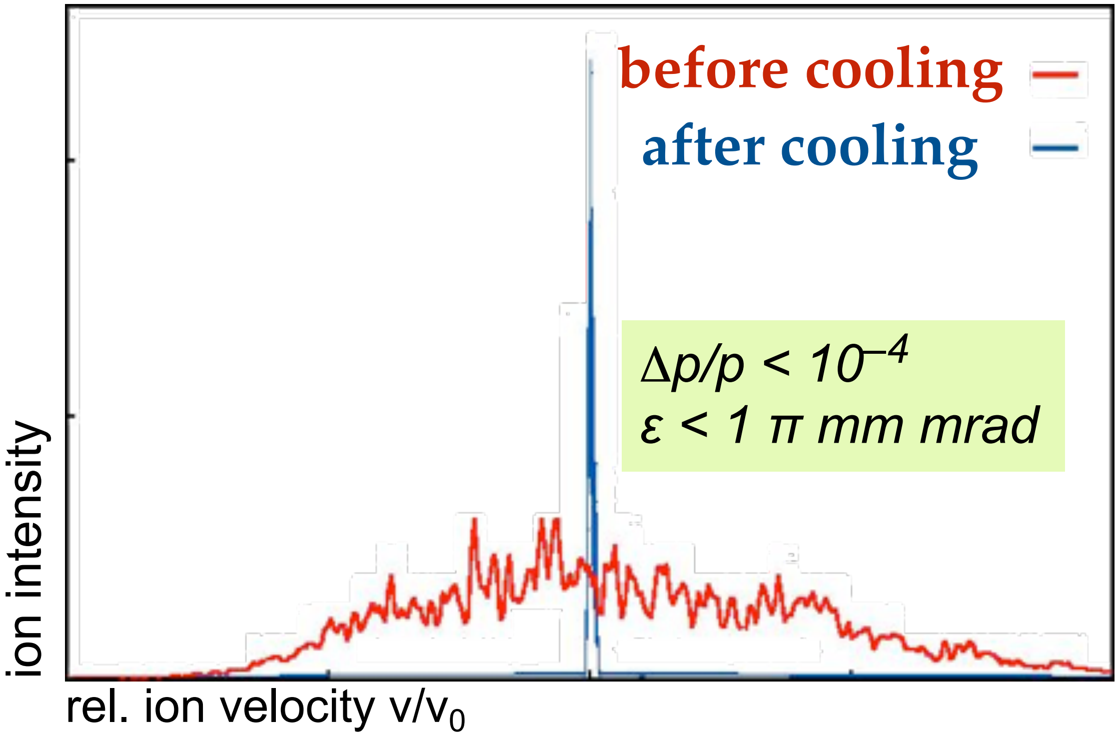
$\Delta p/p < 10^{-4}$
$\varepsilon < 1\ \pi$ mm mrad

Electron cooling





Antiproton momentum, p [MeV/c]	300	100
Cooling length, L_{cool} [m]	2.2	2.2
L_{cool}/*circumference*, η_c	0.0116	0.0116
Electron energy, U_{ecin} [keV]	25.48	2.894
Electron current, I_e [A]	3.5	0.5 (0.1)
Perveance of electron beam, p_g [10^{-6} AV$^{-3/2}$]	0.58	2.6 (0.52)
Electron beam radius [mm]	25	25
Space charge potential, U_{Sp} [kV]	1.034	424.6
Cathode voltage, U_{cath} [kV]	26.52	3.318
Betatron functions at cooler, β_{HV} [m]	6.0	6.0
Initial, final emittances $\varepsilon_i/\varepsilon_f$ [π mm·mrad]	33/2	15/1
Cooling time constant, τ_c [s]	2.2	0.05 (0.3)
Total cooling time, t_c [s]	6.3	0.14 (0.7)



$\Delta p/p < 10^{-4}$
$\varepsilon < 1\ \pi$ mm mrad

Stochastic cooling

Measure beam center by pick-ups
Correction signal to opposite kicker

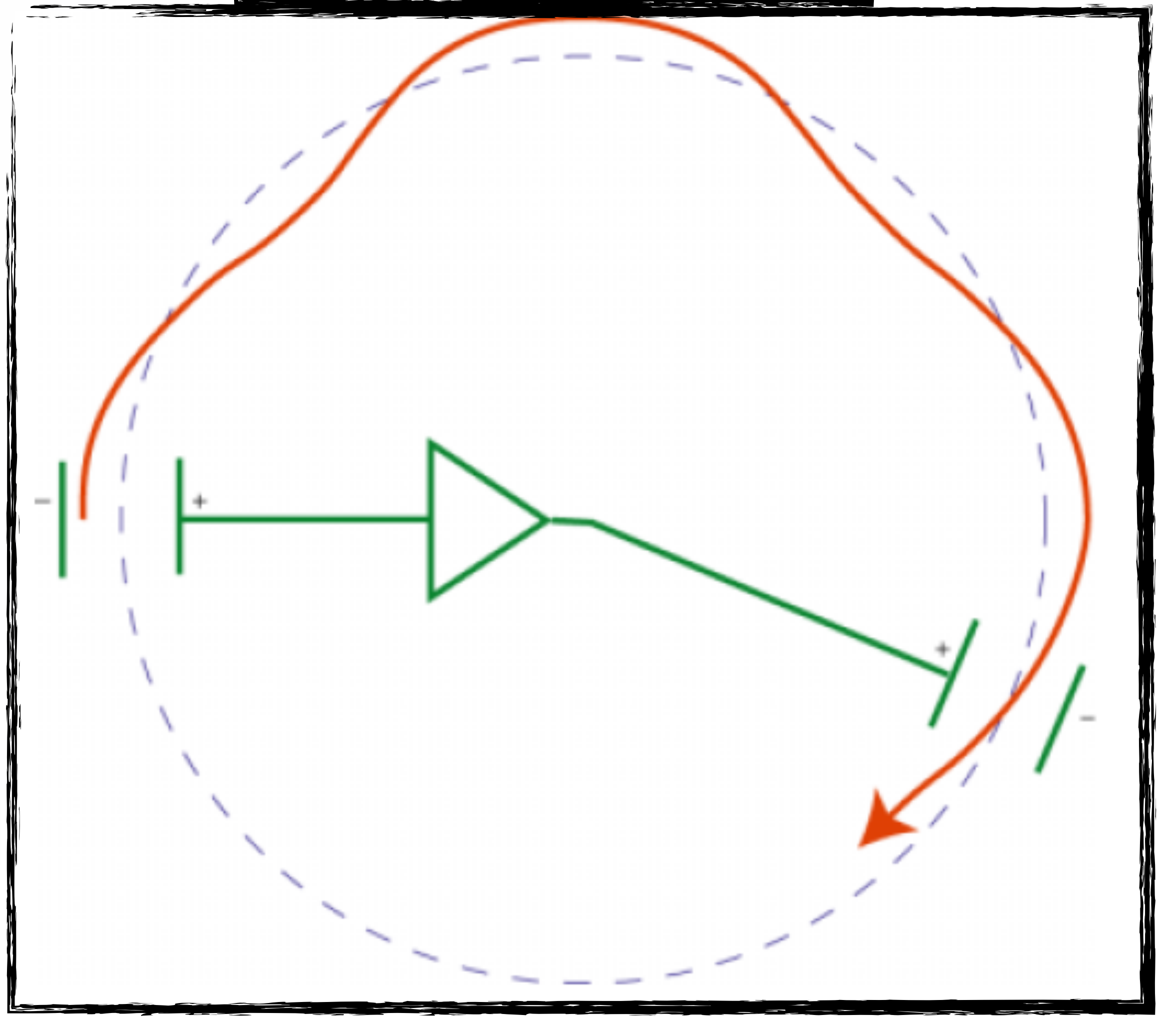
Pioneered at CERN for discovery W,Z bosons

Nobel Prize S. van der Meer

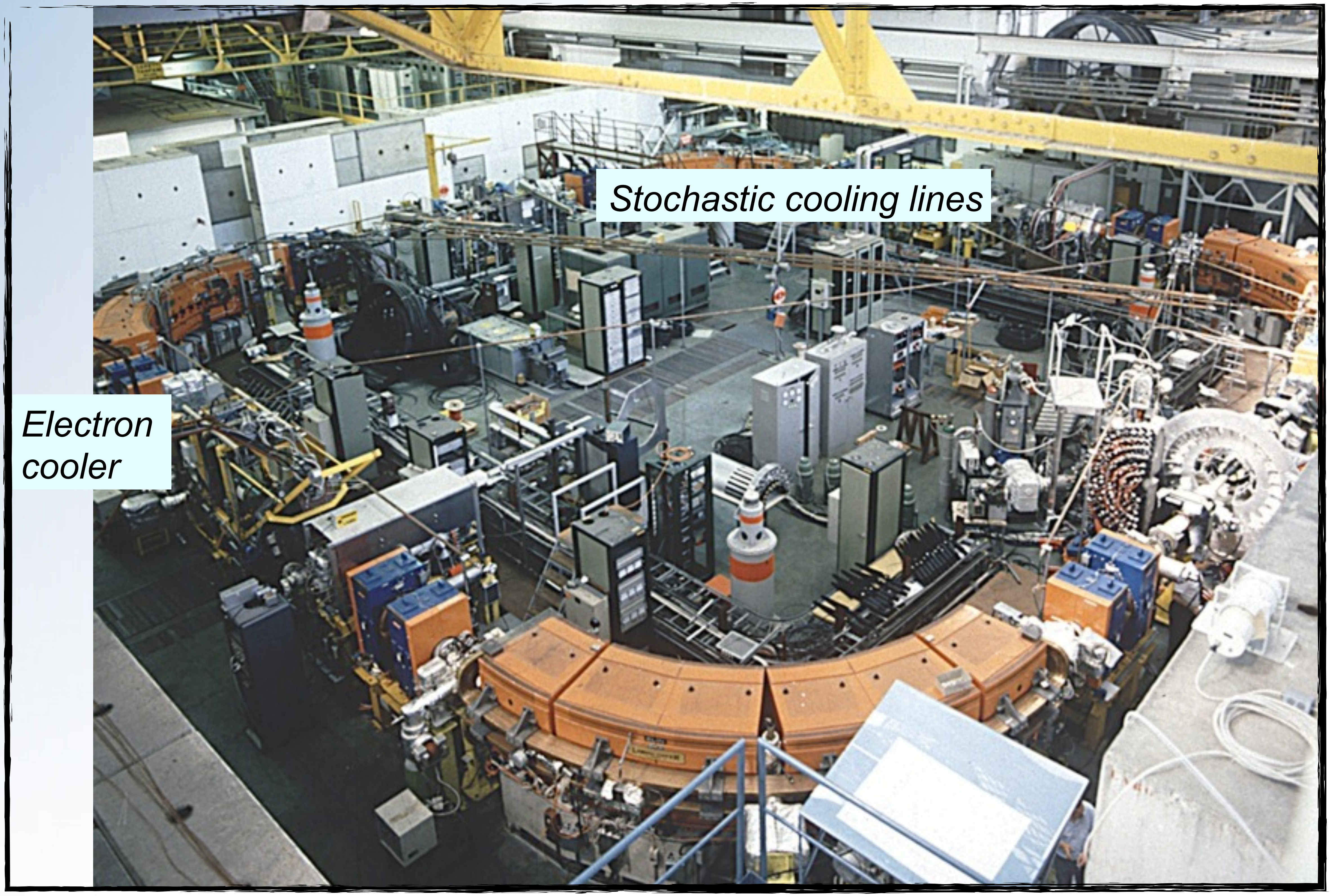
Cooling power decreases with decreasing energy

Cooling time ~ number of particles

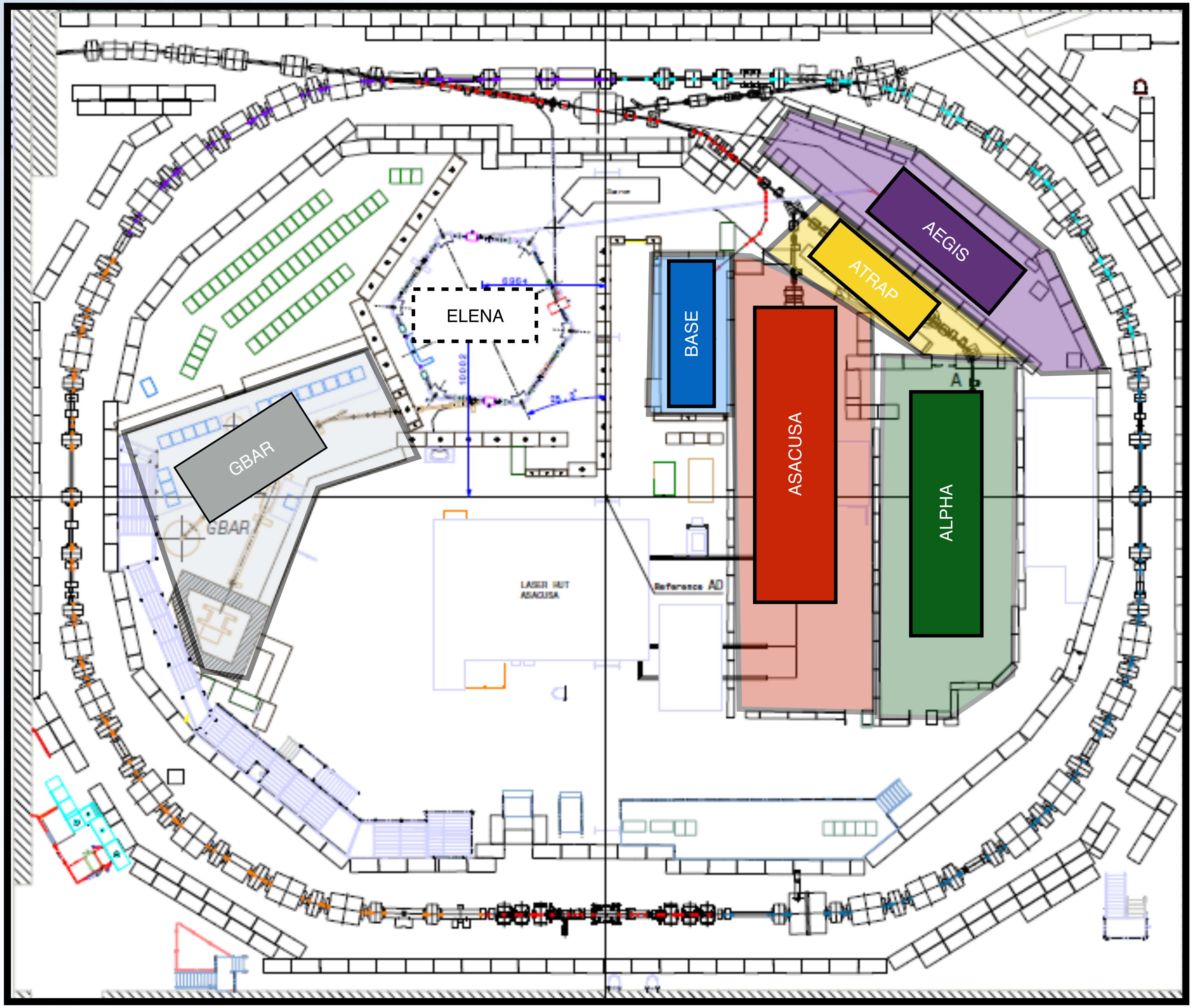
$$\Delta p/p \sim 0.07\%$$
$$\epsilon = 3 - 4\ \pi\text{mm.mrad}$$



LEAR



The AD Facility



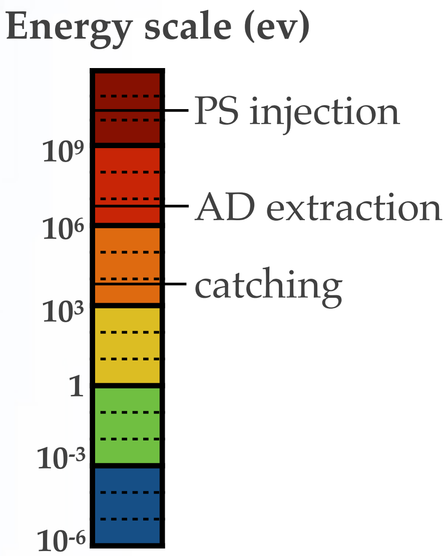
The AD complex

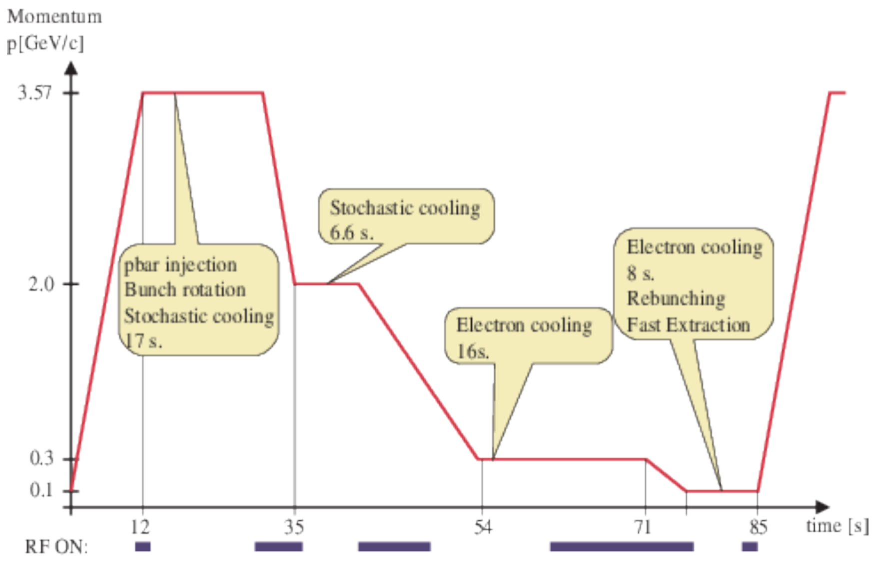
AD

PS : 26 GeV/c proton on target

3x10^7 $\bar{p}$ at 5.3 MeV (100 MeV/c) ~120s cycle

$\bar{p}$ caught in Penning traps: 99.9% are lost





The AD complex

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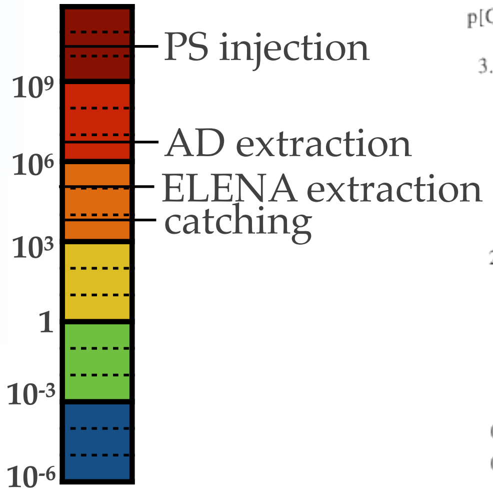
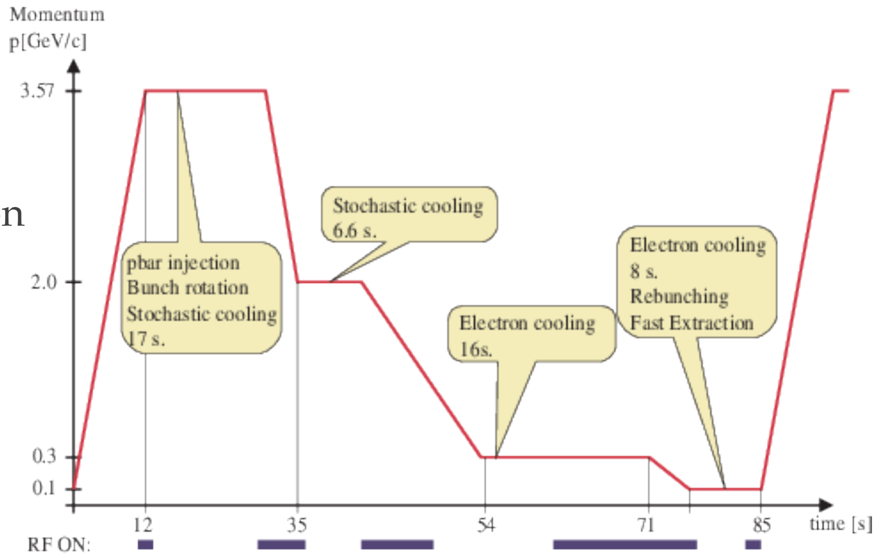
Energy scale (ev)





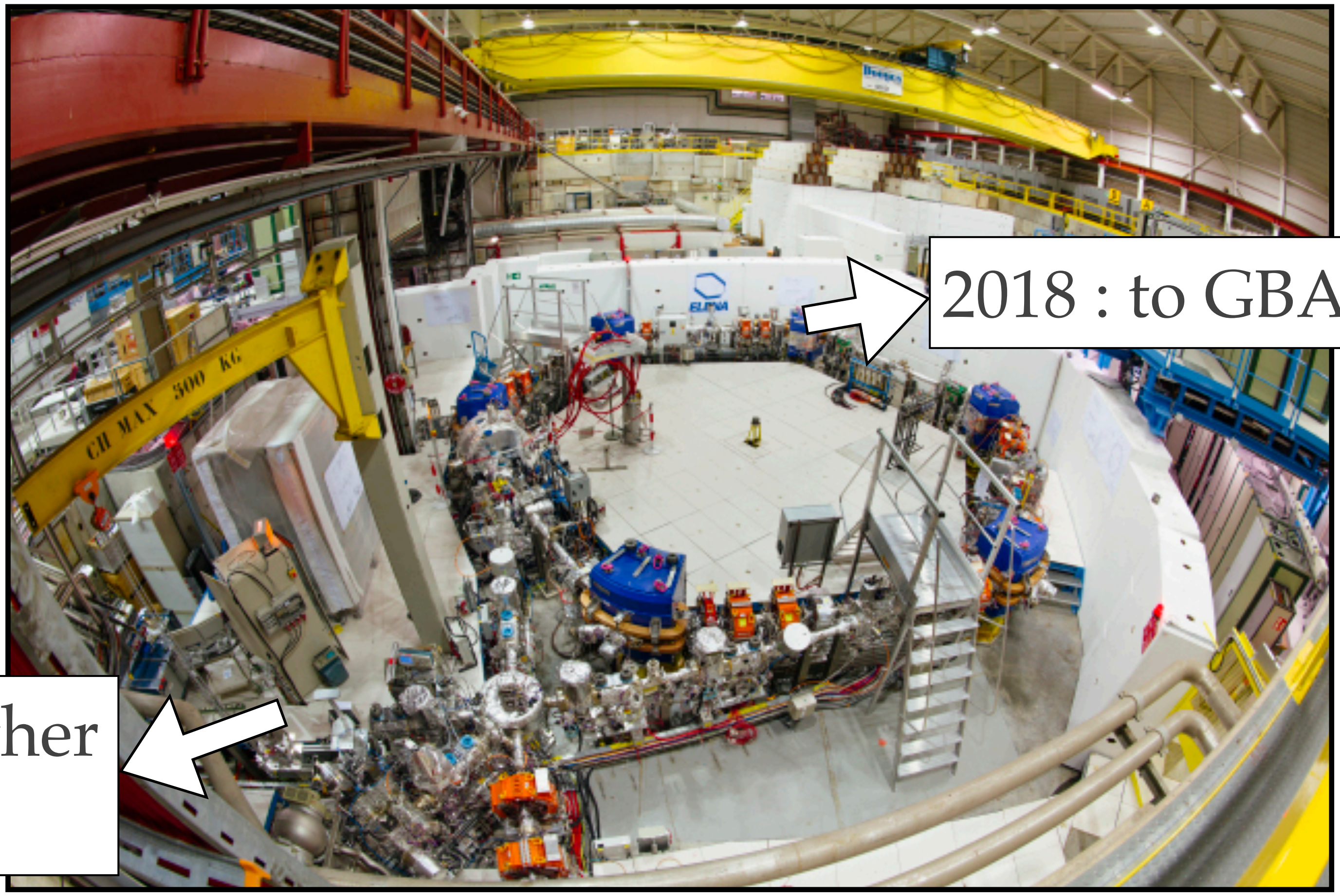
ELENA

p̄ at 100 keV at improved beam emittance

all experiments gain a factor 10-100 in trapping efficiency

"simultaneous" delivery to almost all experiments

additional experimental zone



2018 : to GBAR

2021: to all other experiments

The AD complex

AD

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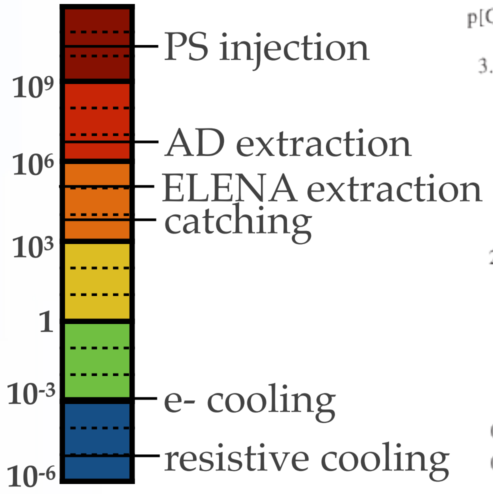

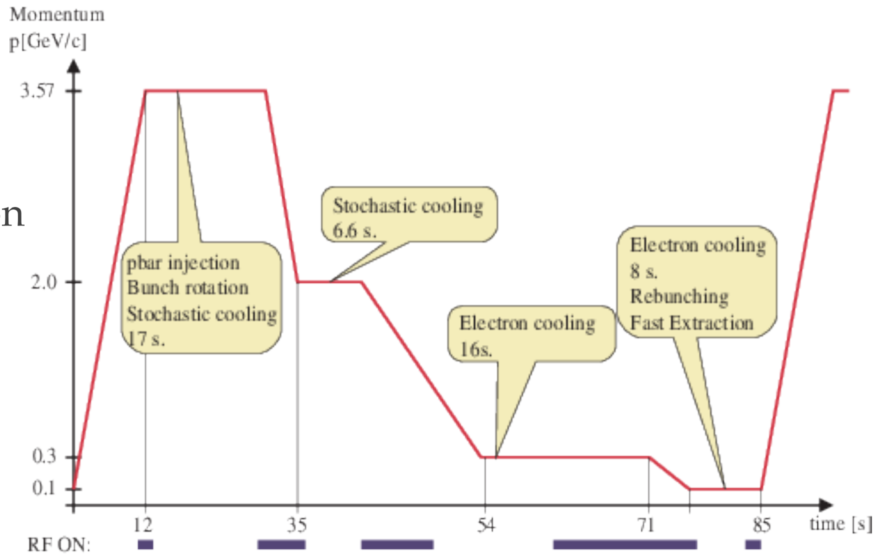

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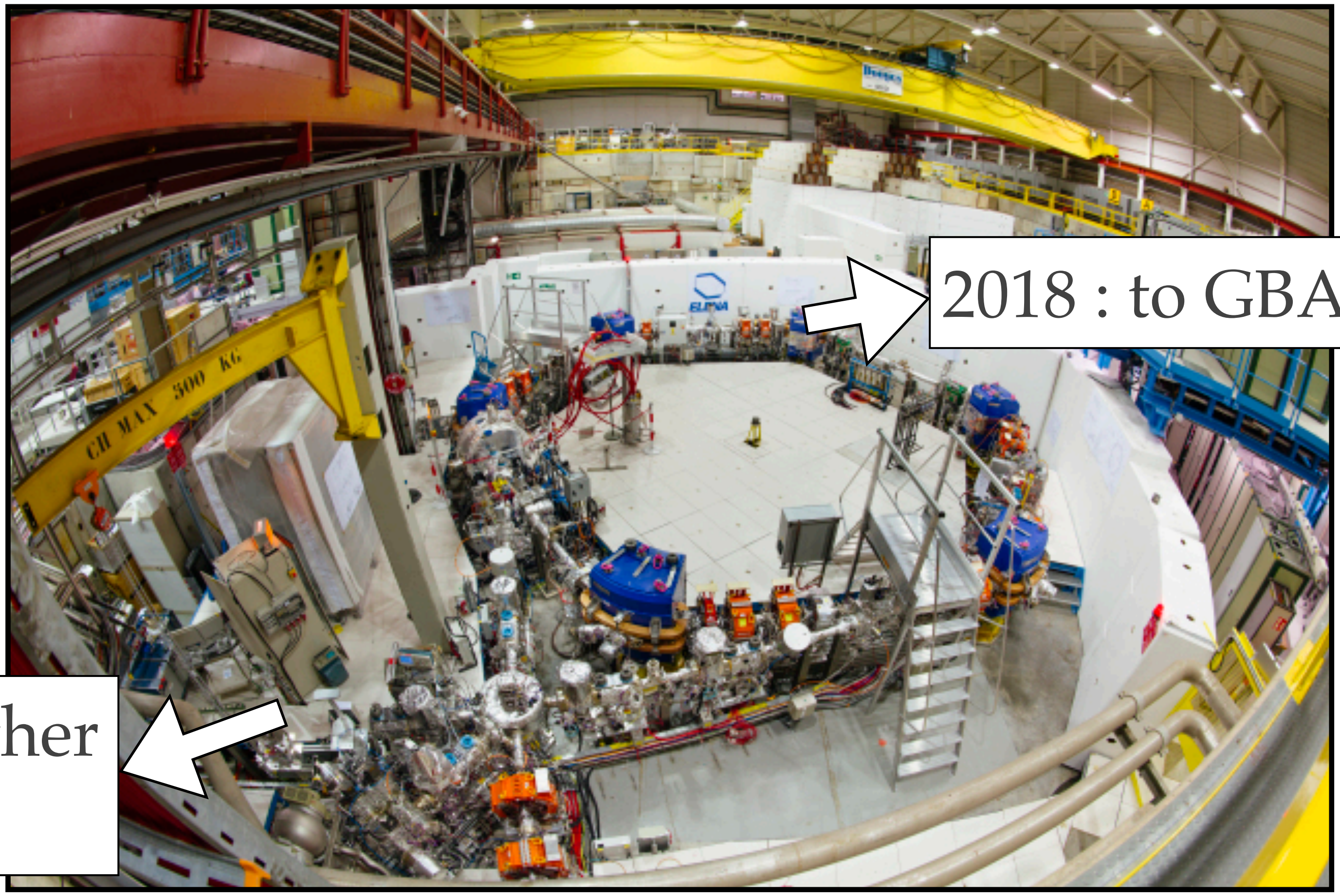
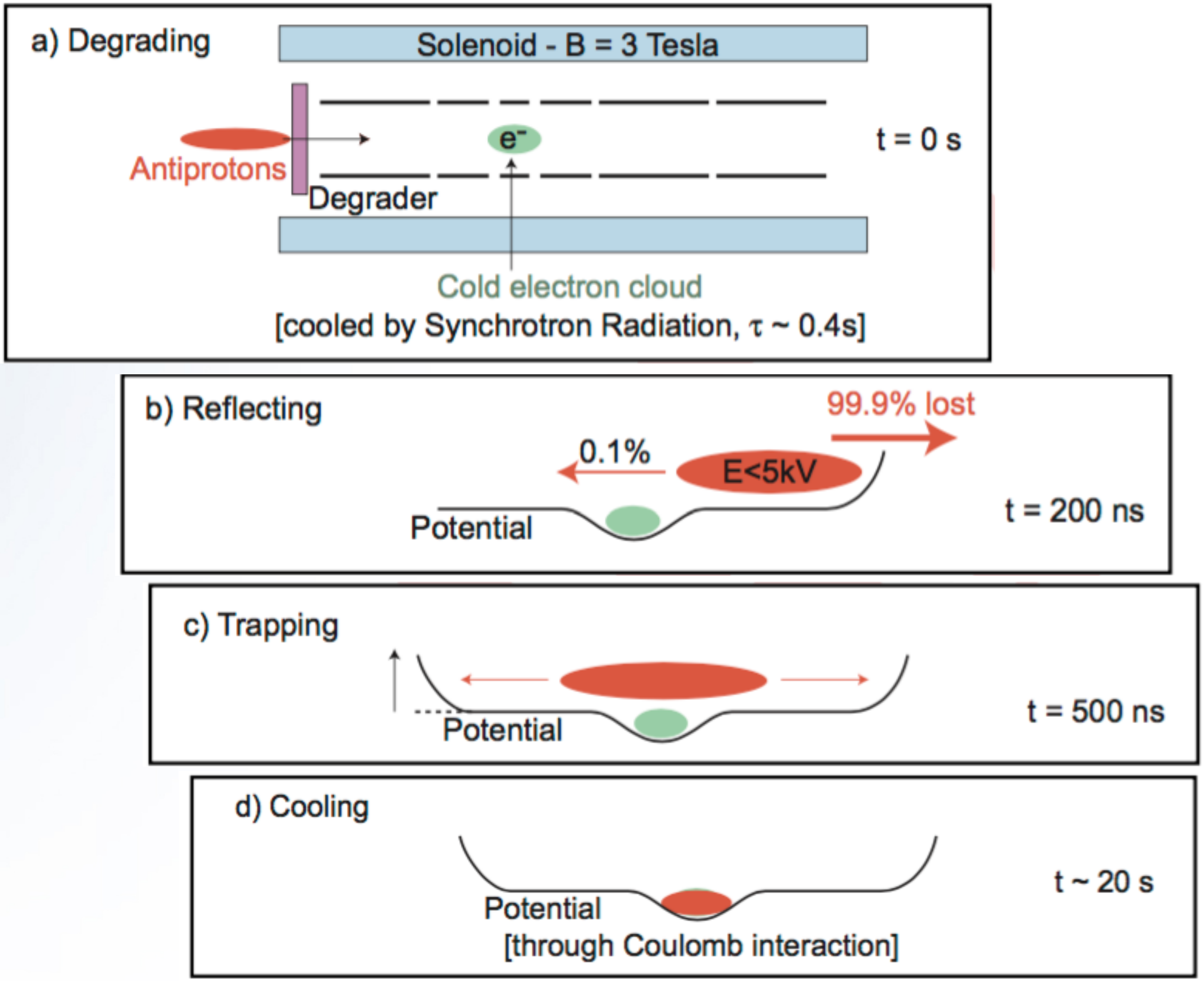


2018 : to GBAR

2021: to all other experiments

Penning traps

Long trapping times require
good vacuum!



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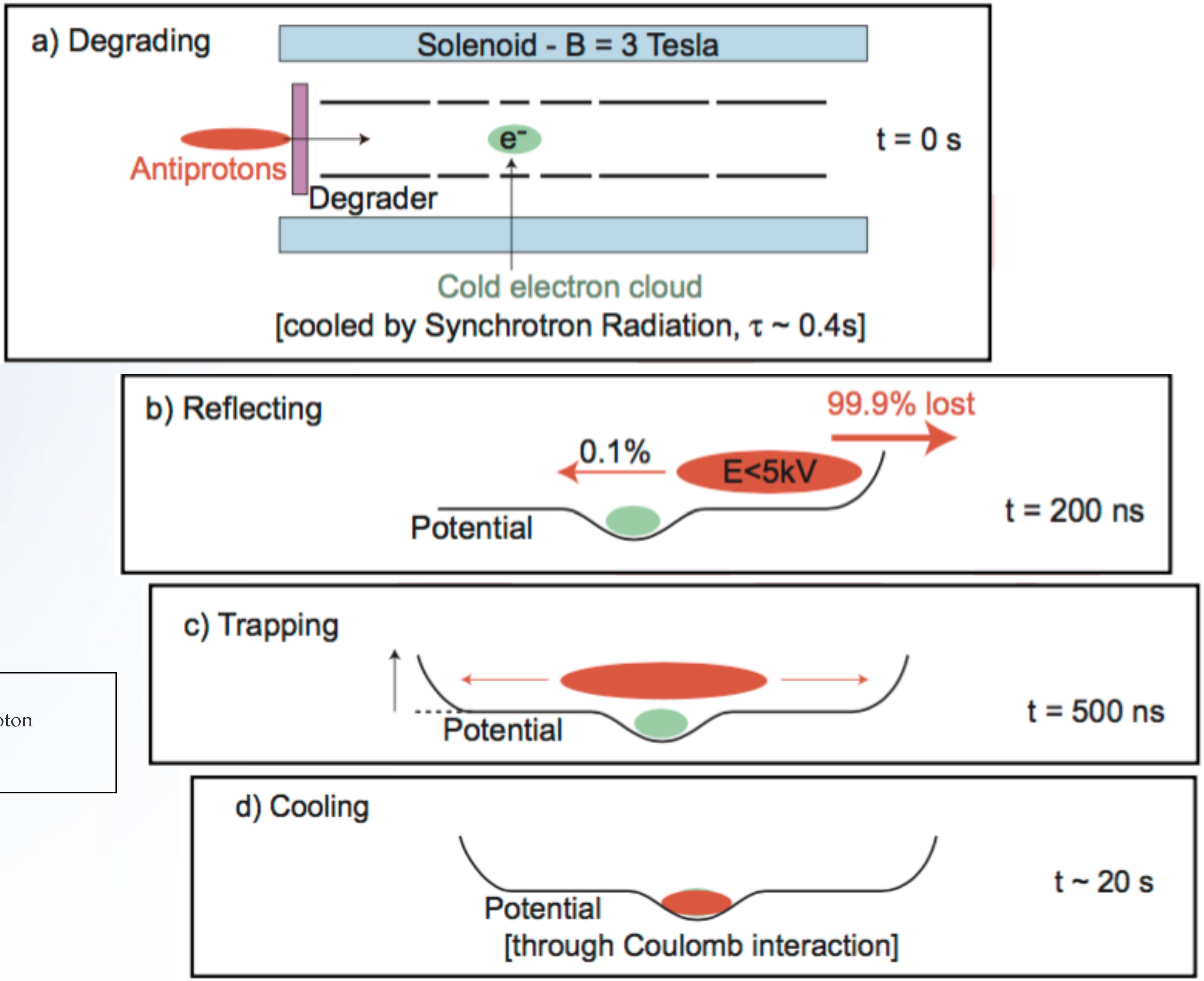
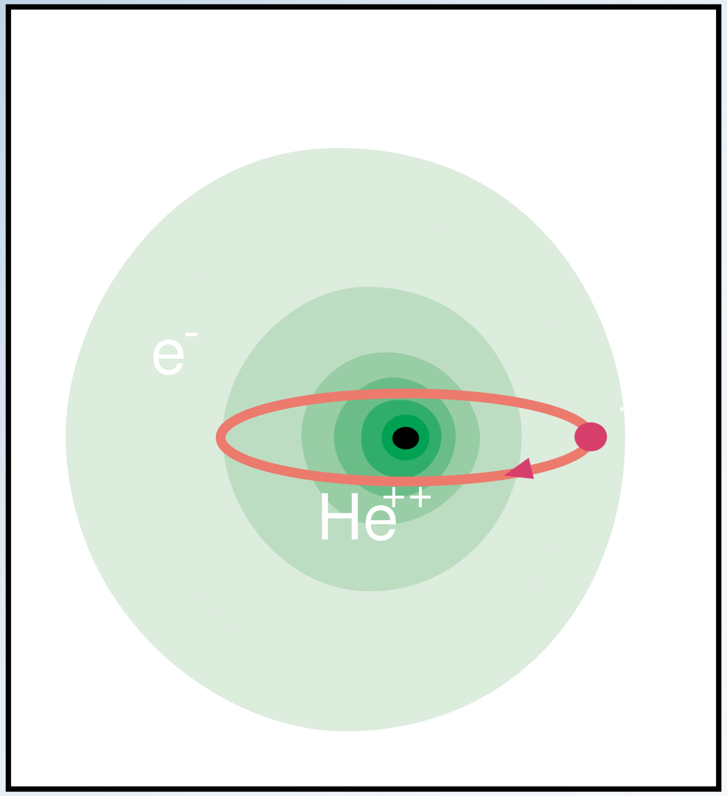


BASE : **P < 2. 10⁻¹⁸ mbar**

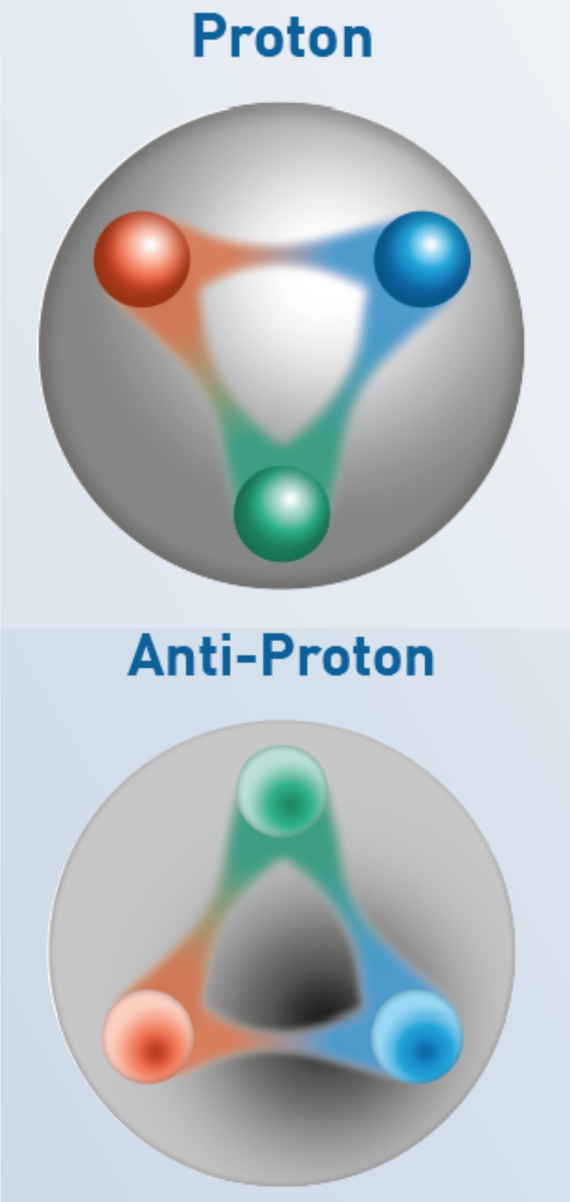
$\tau(\bar{p})$ > 10.2 years (68% confidence level)

Stefan Sellner et al.
"Improved limit on the directly measured antiproton lifetime"
New Journal of Physics, 19, (2017)

AD experiments



ASACUSA



BASE

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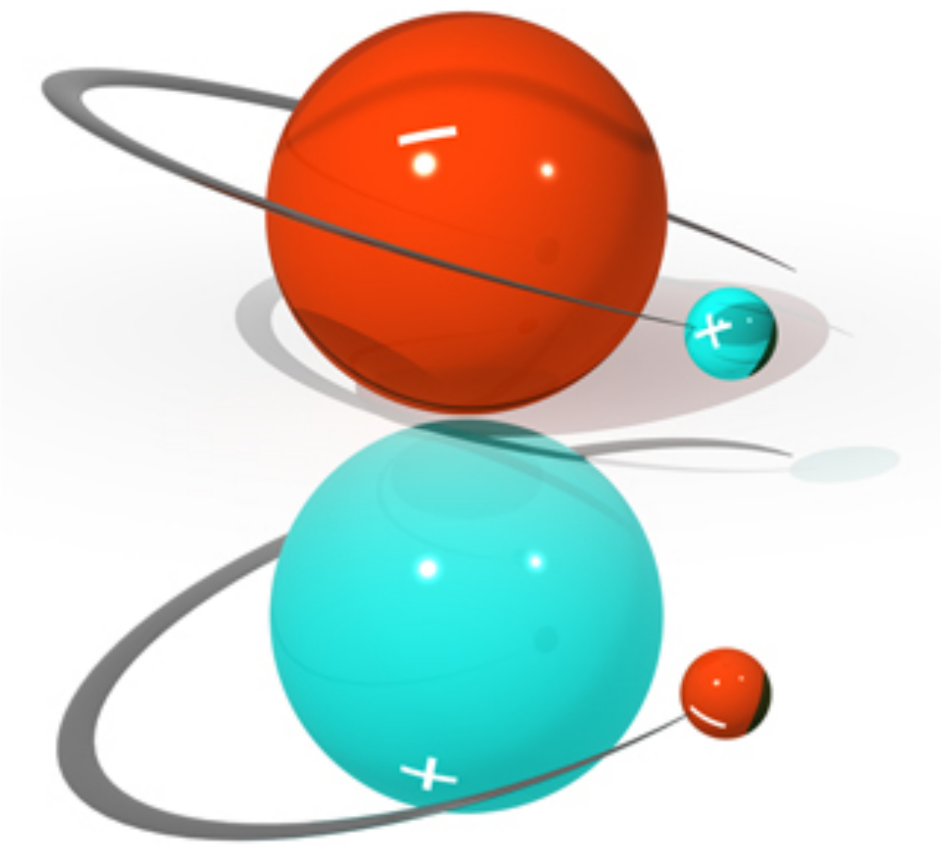
ATRAP



ALPHA

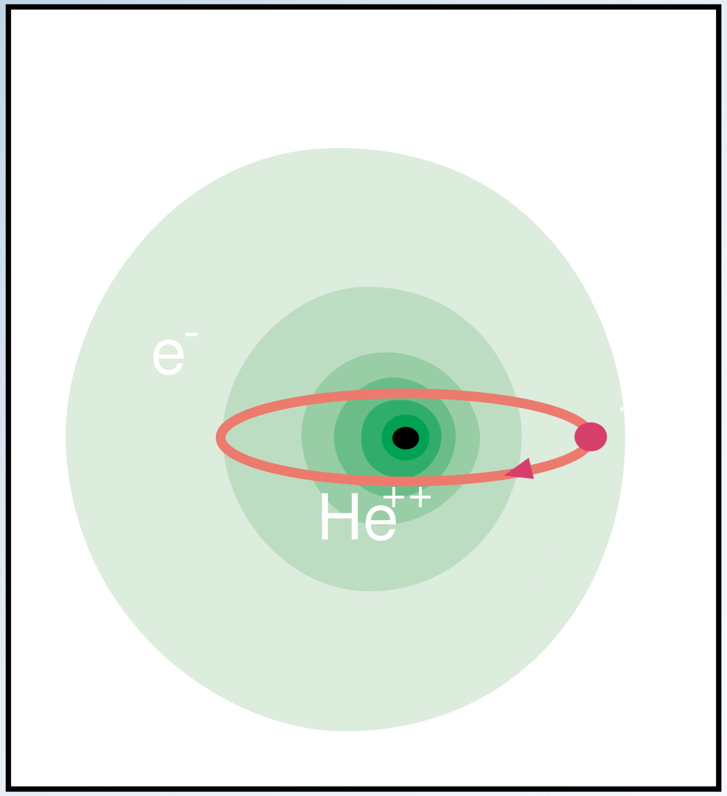
ATRAP

ASACUSA

AEGIS

GBAR

AD experiments



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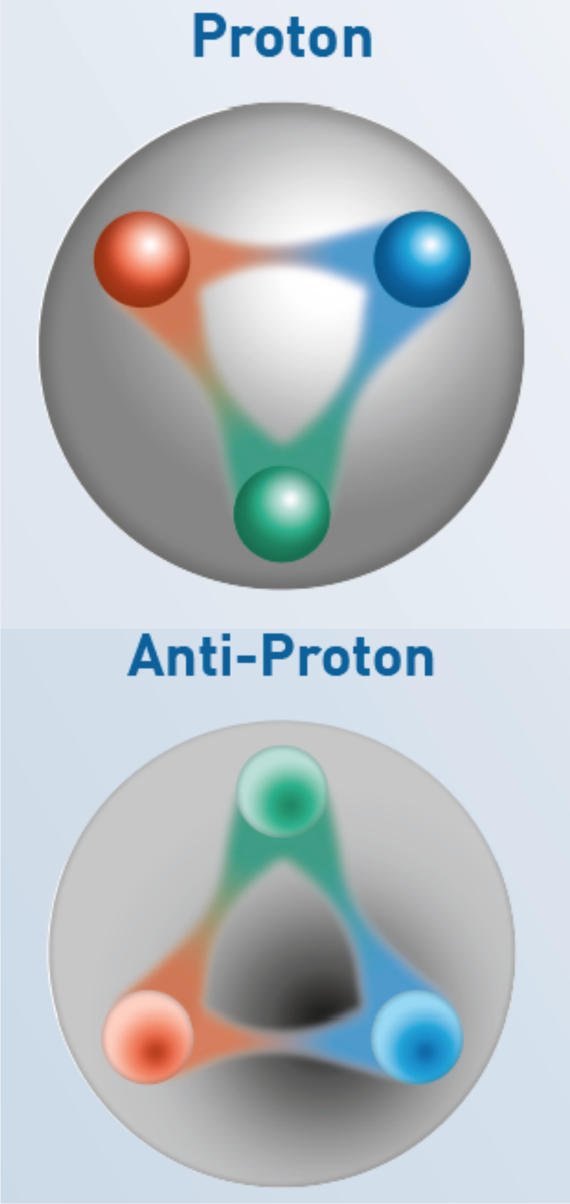

BASE

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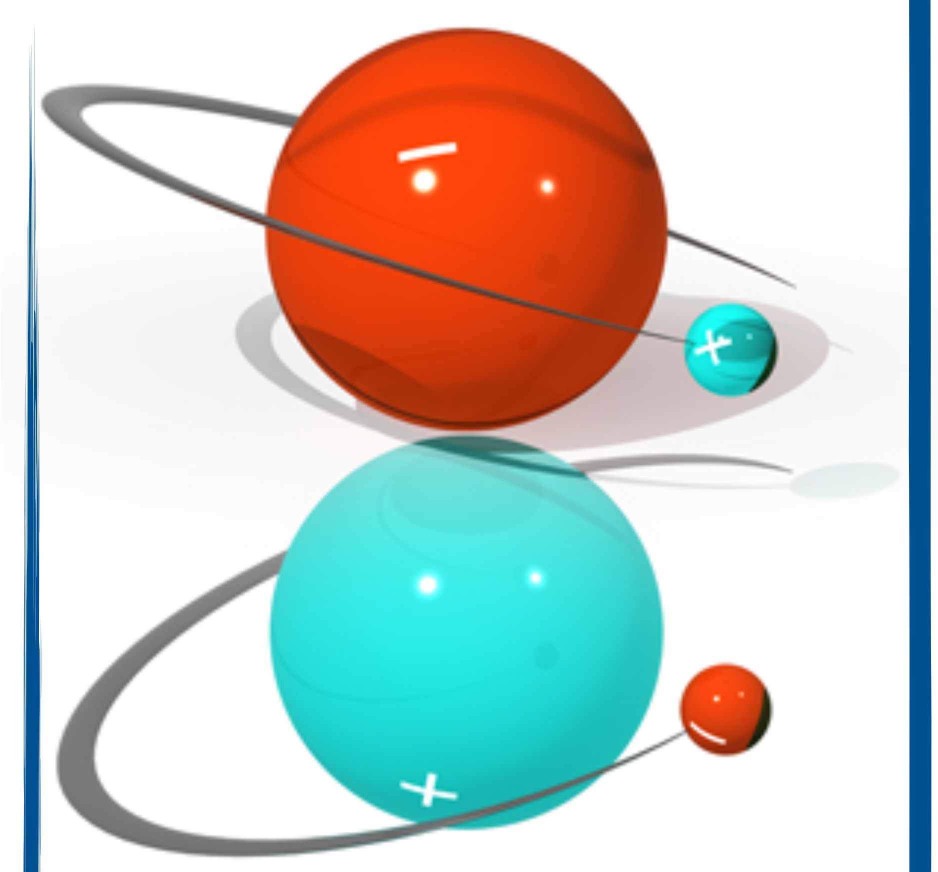

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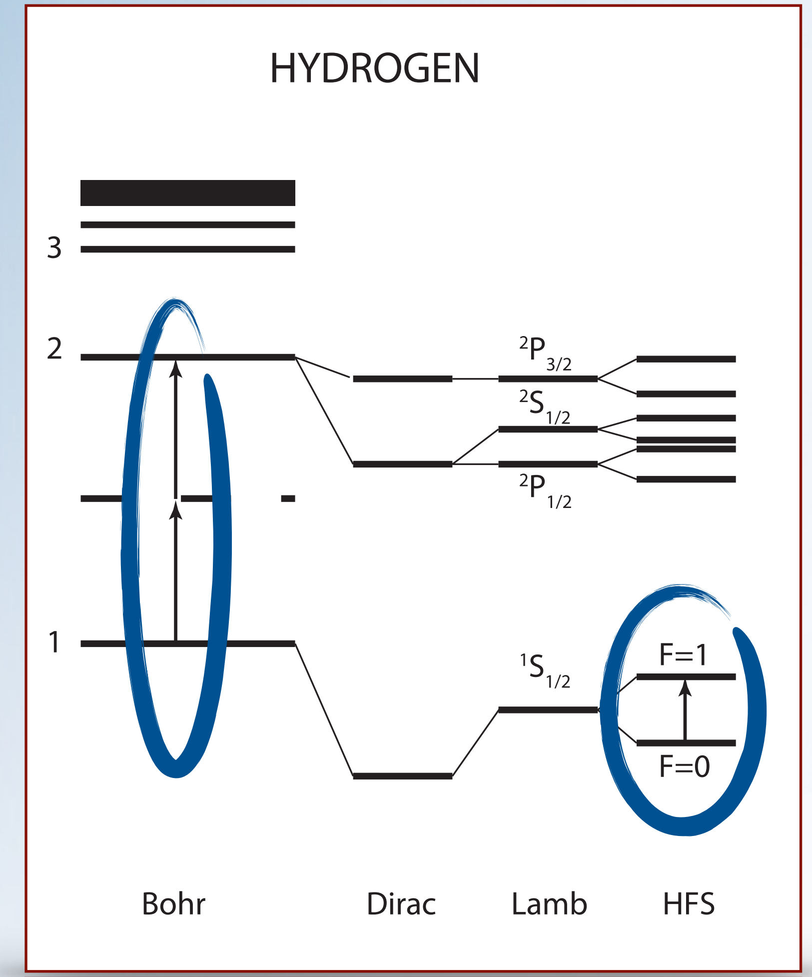
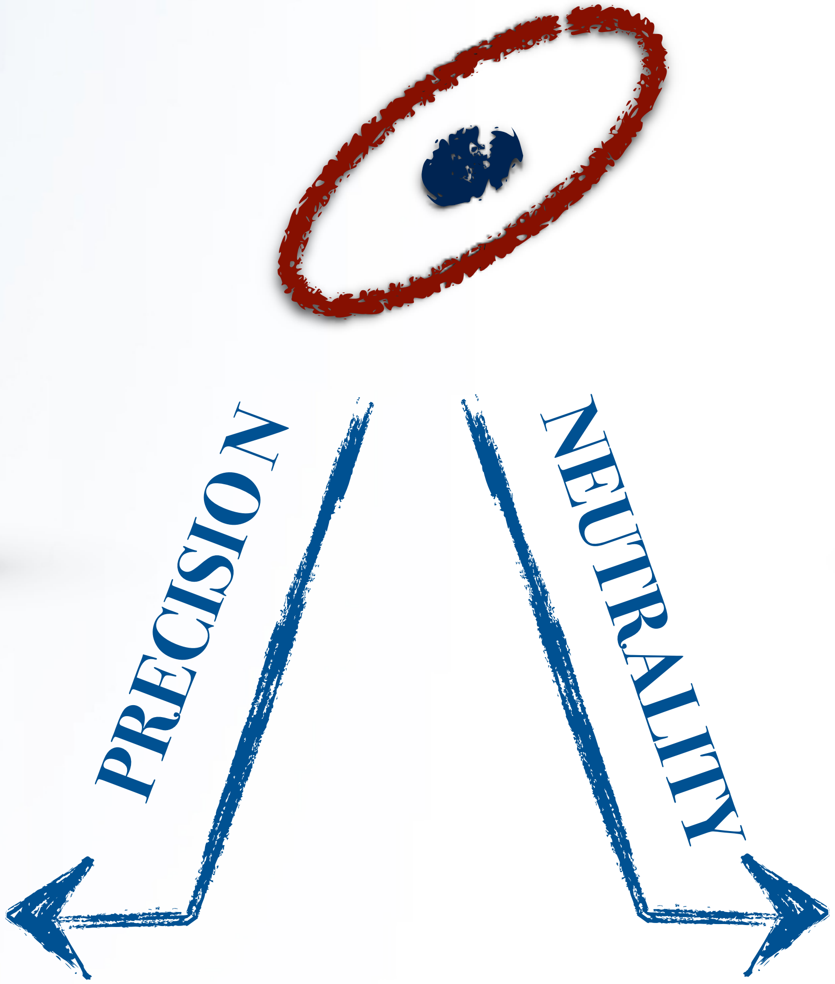
Antihydrogen experiments





PRECISION

NEUTRALITY

ASACUSA

ALPHA

ATRAP

AEGIS

GBAR

ALPHA-G

How to make antihydrogen

How to make antihydrogen

$\bar{p}$

e^+

$$\boxed{\bar{p} + e^+ \rightarrow \bar{H} + \gamma}$$

$$\boxed{\bar{p} + e^+ + e^+ \rightarrow \bar{H} + e^+}$$

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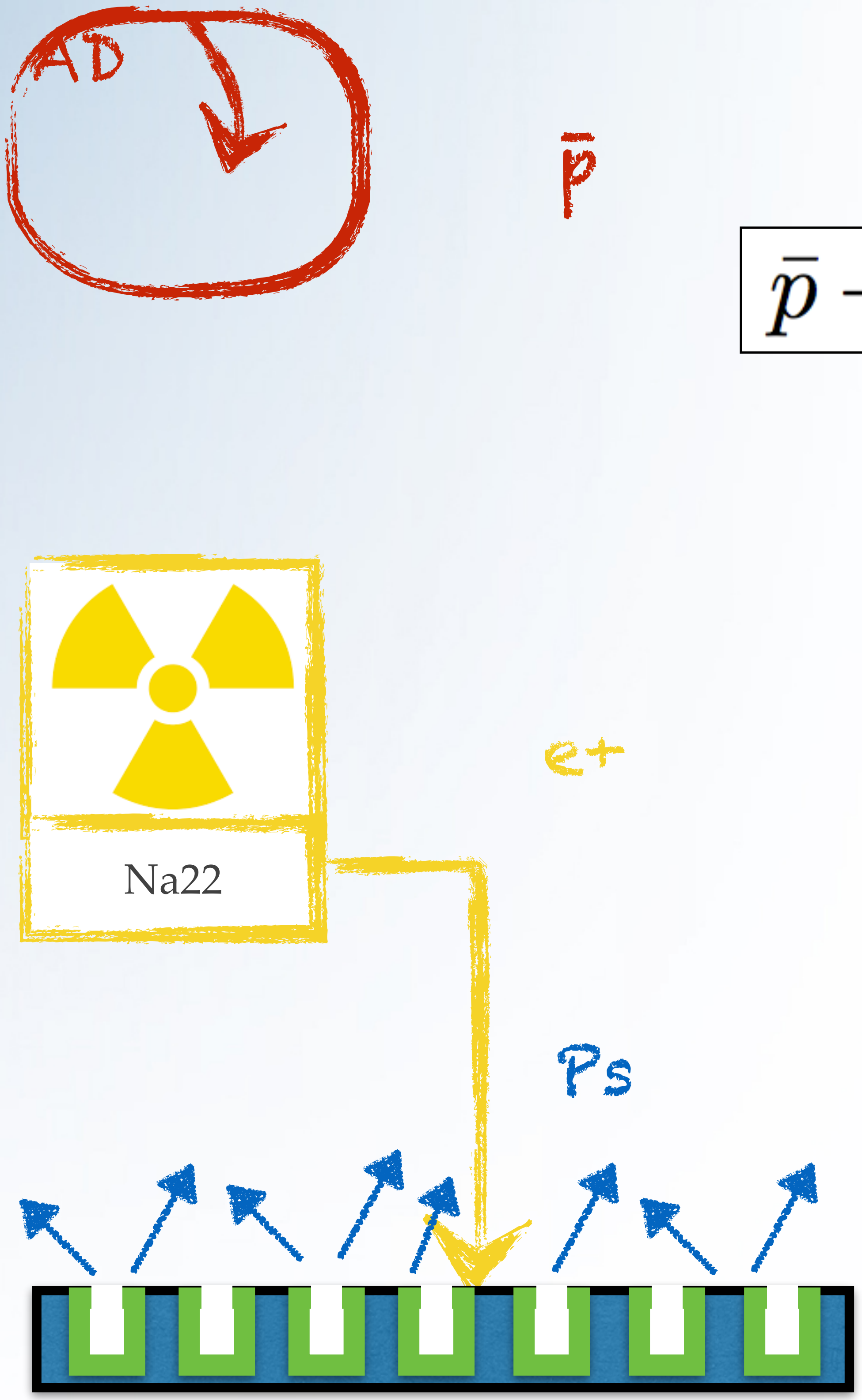
How to make antihydrogen



$$\boxed{\bar{p} + e^+ \rightarrow \bar{H} + \gamma}$$

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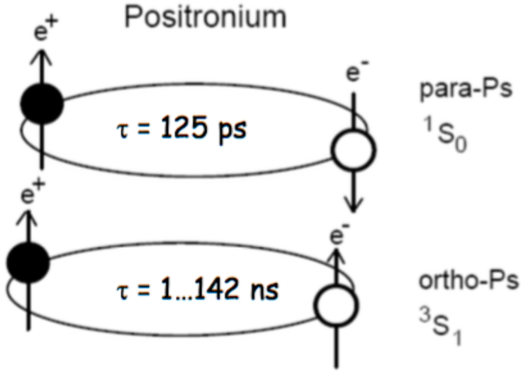
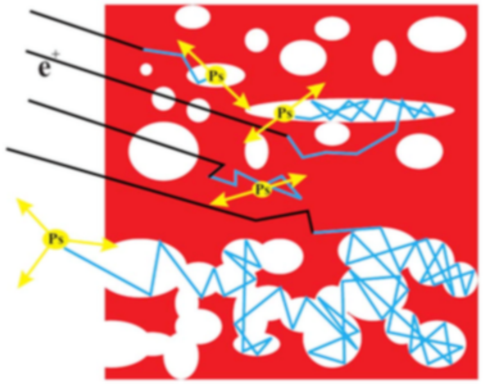
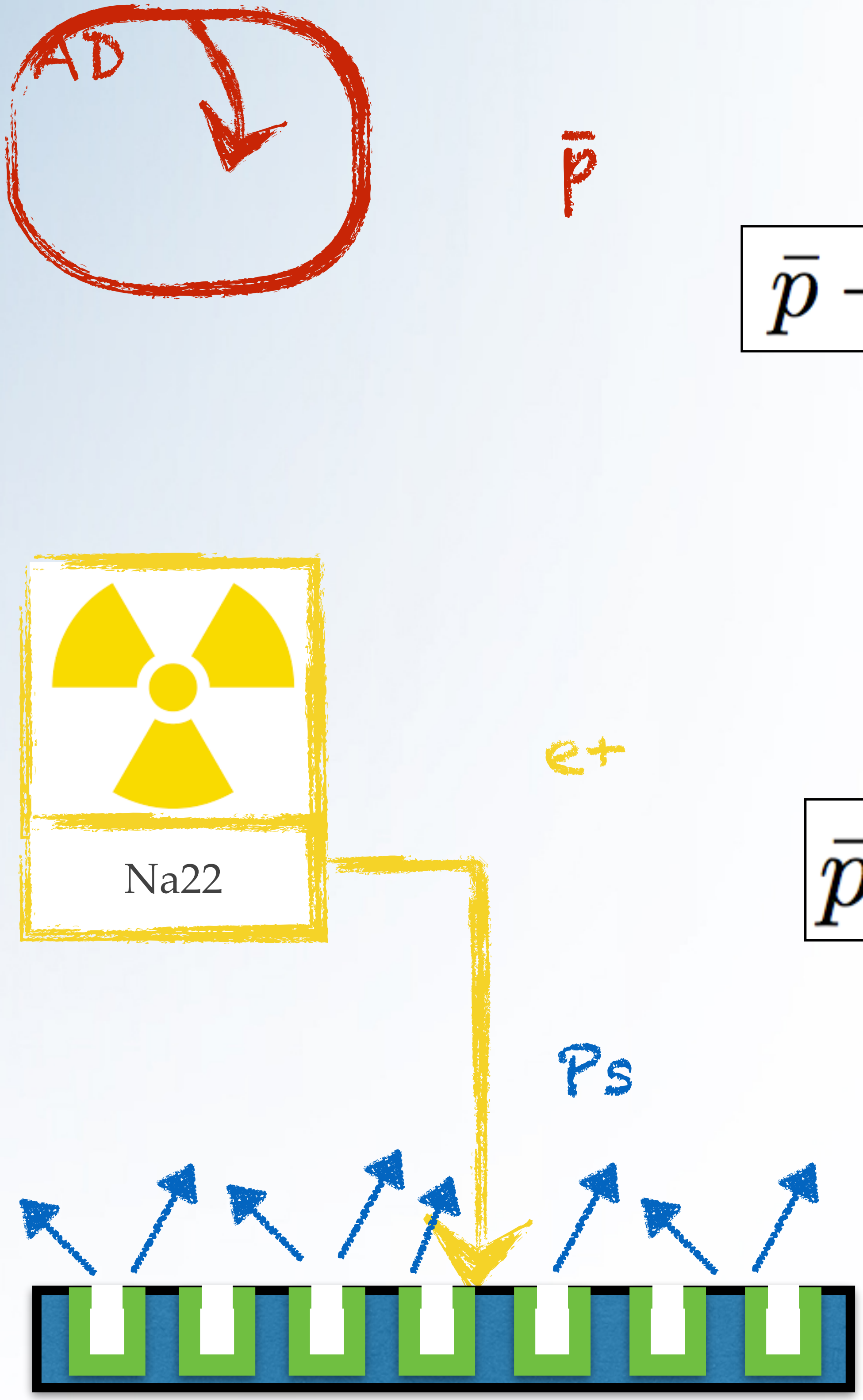




How to make antihydrogen



$$\boxed{\bar{p} + e^{+} \rightarrow \bar{H} + \gamma}$$

$$\boxed{\bar{p} + e^{+} + e^{+} \rightarrow \bar{H} + e^{+}}$$

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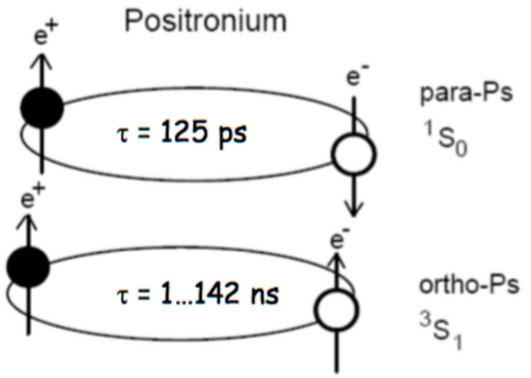

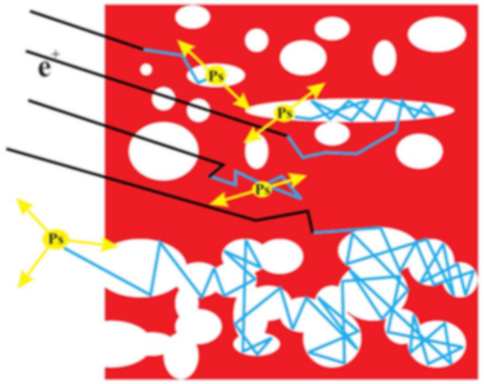

$$\boxed{\bar{p} + Ps^{\star} \rightarrow \bar{H}^{\star} + e^{-}}$$

AEGIS

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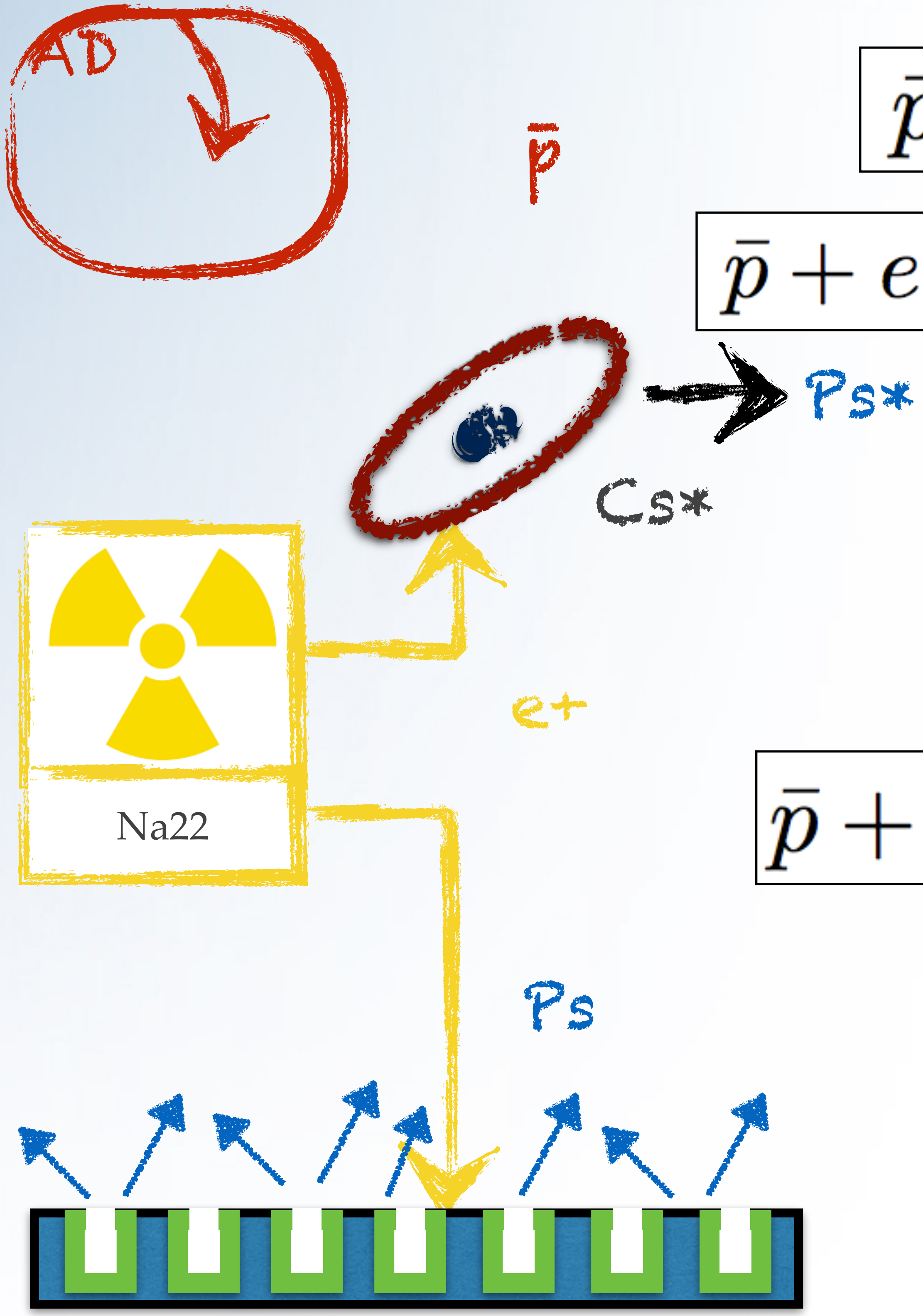
How to make antihydrogen



$$\boxed{\bar{p} + e^+ \rightarrow \bar{H} + \gamma}$$

ASACUSA

ALPHA

$$\boxed{\bar{p} + e^+ + e^+ \rightarrow \bar{H} + e^+}$$

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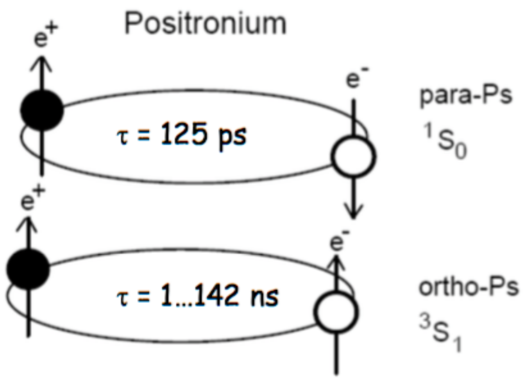

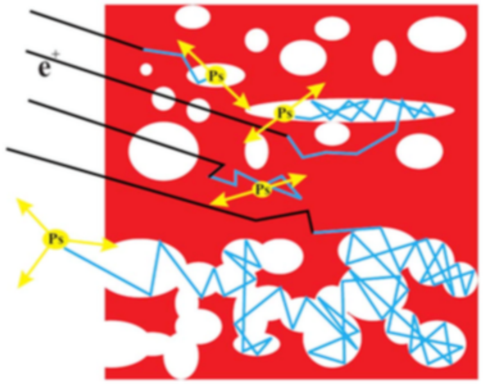

$$\boxed{\bar{p} + Ps^\star \rightarrow \bar{H}^\star + e^-}$$

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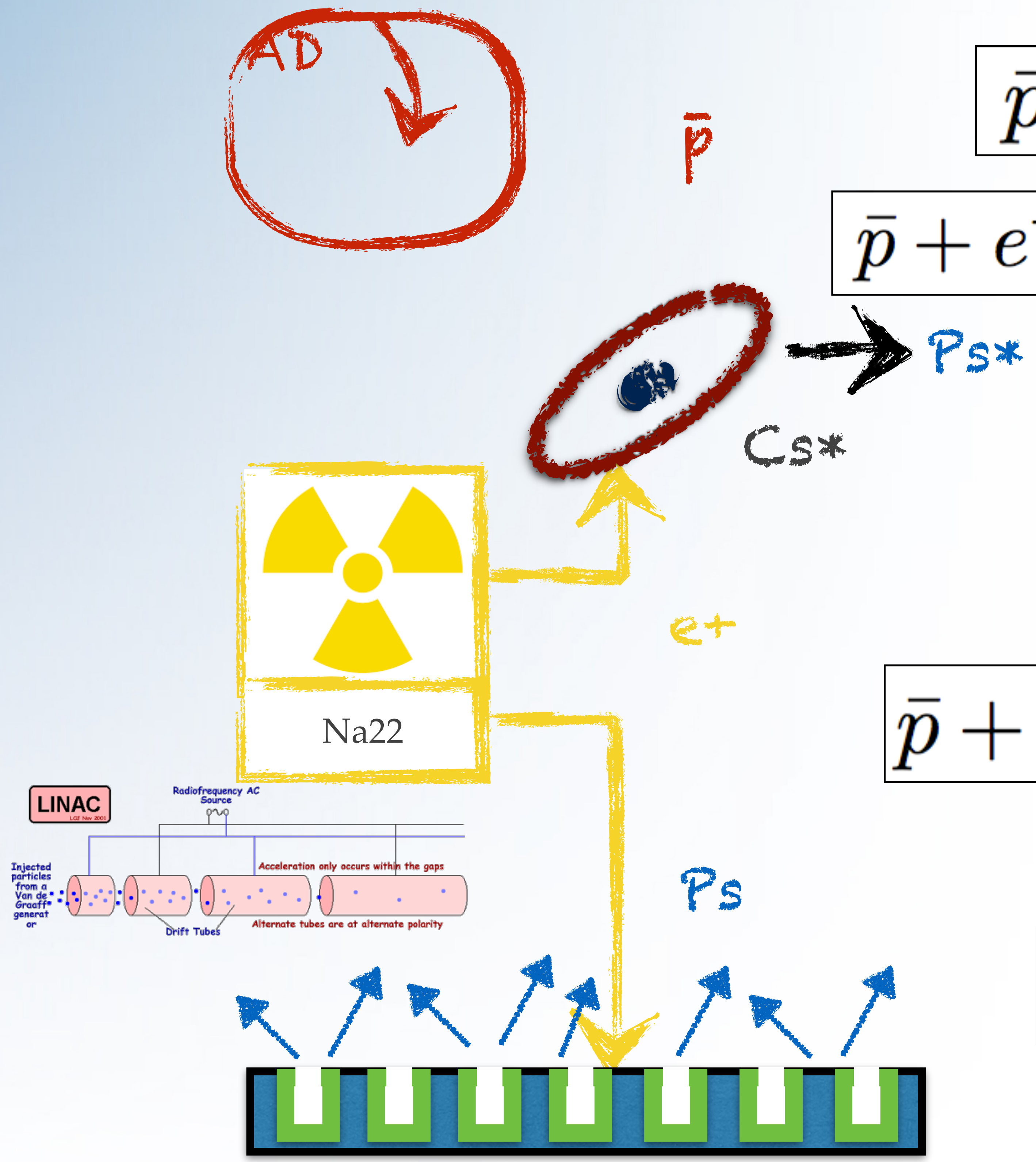
How to make antihydrogen



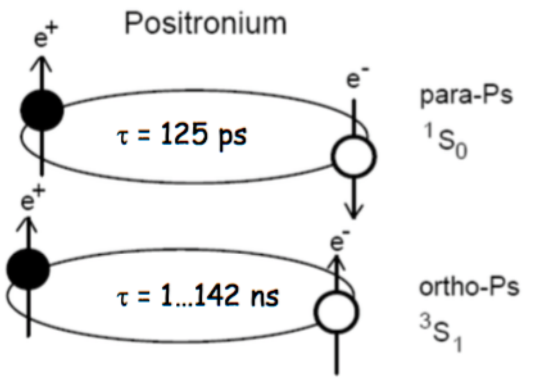
$$\bar{p} + e^{+} \rightarrow \bar{H} + \gamma$$

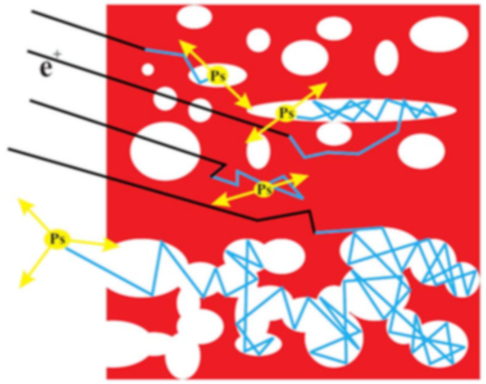
$$\bar{p} + e^{+} + e^{+} \rightarrow \bar{H} + e^{+}$$

ASACUSA

ALPHA

ATRAP





$$\bar{p} + Ps^{\star} \rightarrow \bar{H}^{\star} + e^{-}$$

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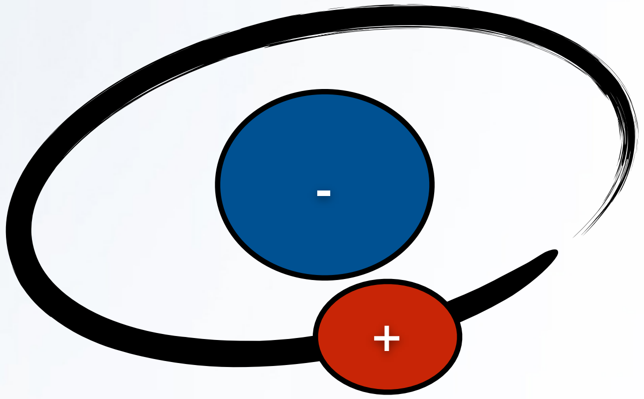
Antihydrogen ION !

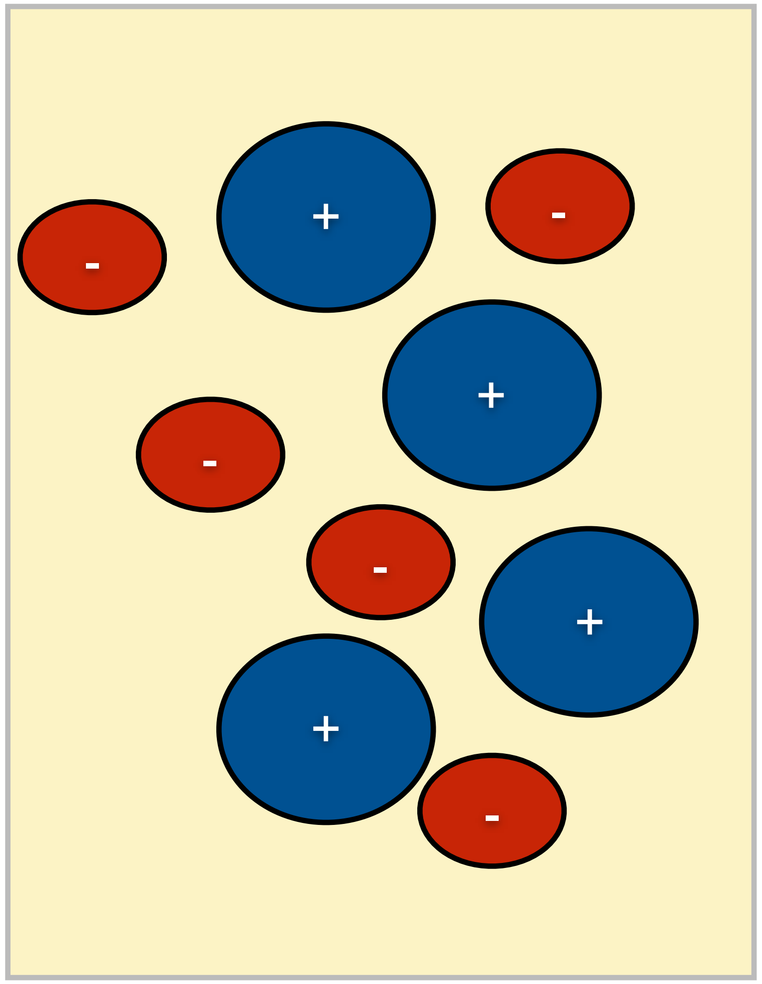
$$\bar{p} + Ps \rightarrow \bar{H} + e^{-}$$

$$\bar{H} + Ps \rightarrow \bar{H}^{+} + e^{-}$$

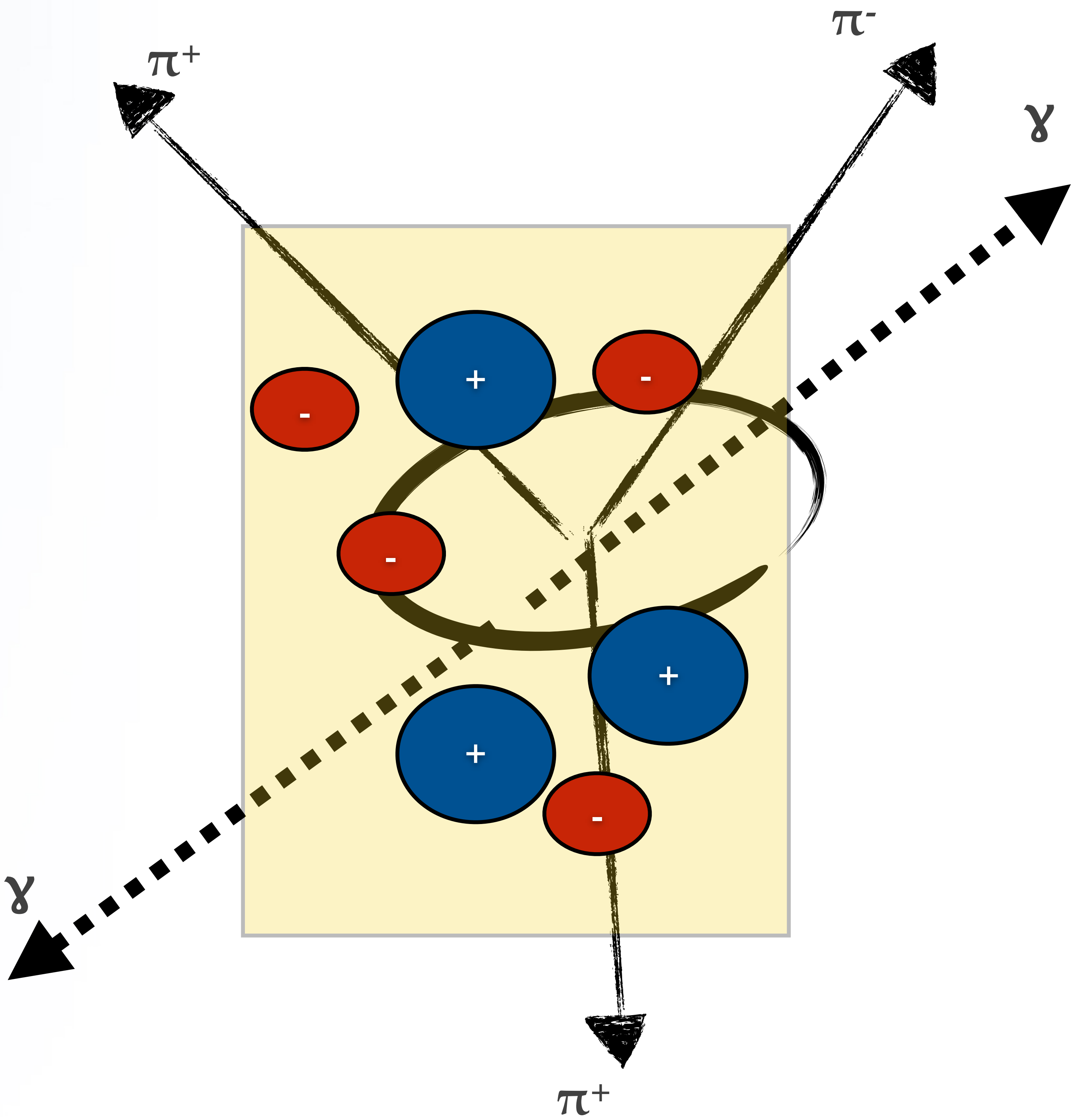
GBAR

Antiprotons at lower energies

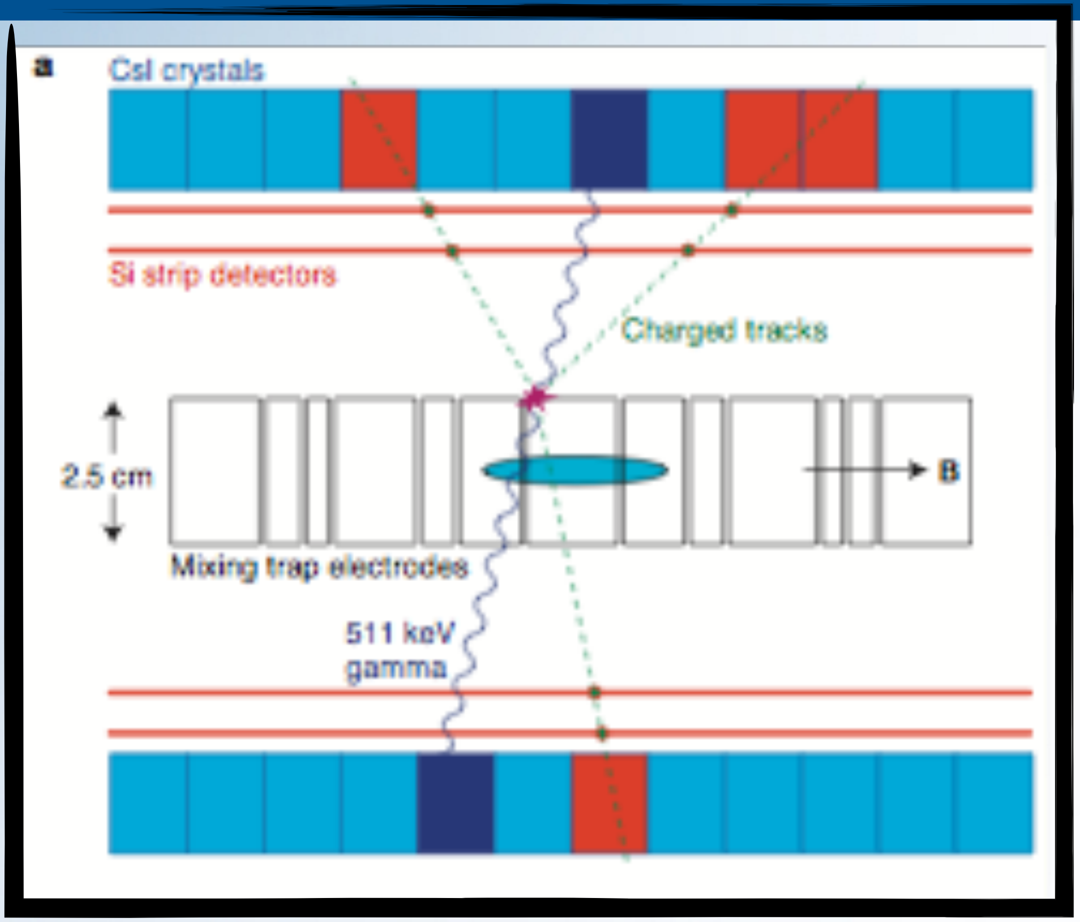




Antiprotons at lower energies



Antiprotons at lower energies



Production and detection of cold antihydrogen atoms

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C. Carraro[*], C. L. Cesar[¶], M. Charlton[#], M. J. T. Collier[#], M. Doser[‡],
V. Filippini[☆], K. S. Fine[‡], A. Fontana[☆**], M. C. Fujiwara[††],
R. Funakoshi[††], P. Genova[☆**], J. S. Hangst[‖], R. S. Hayano[††]
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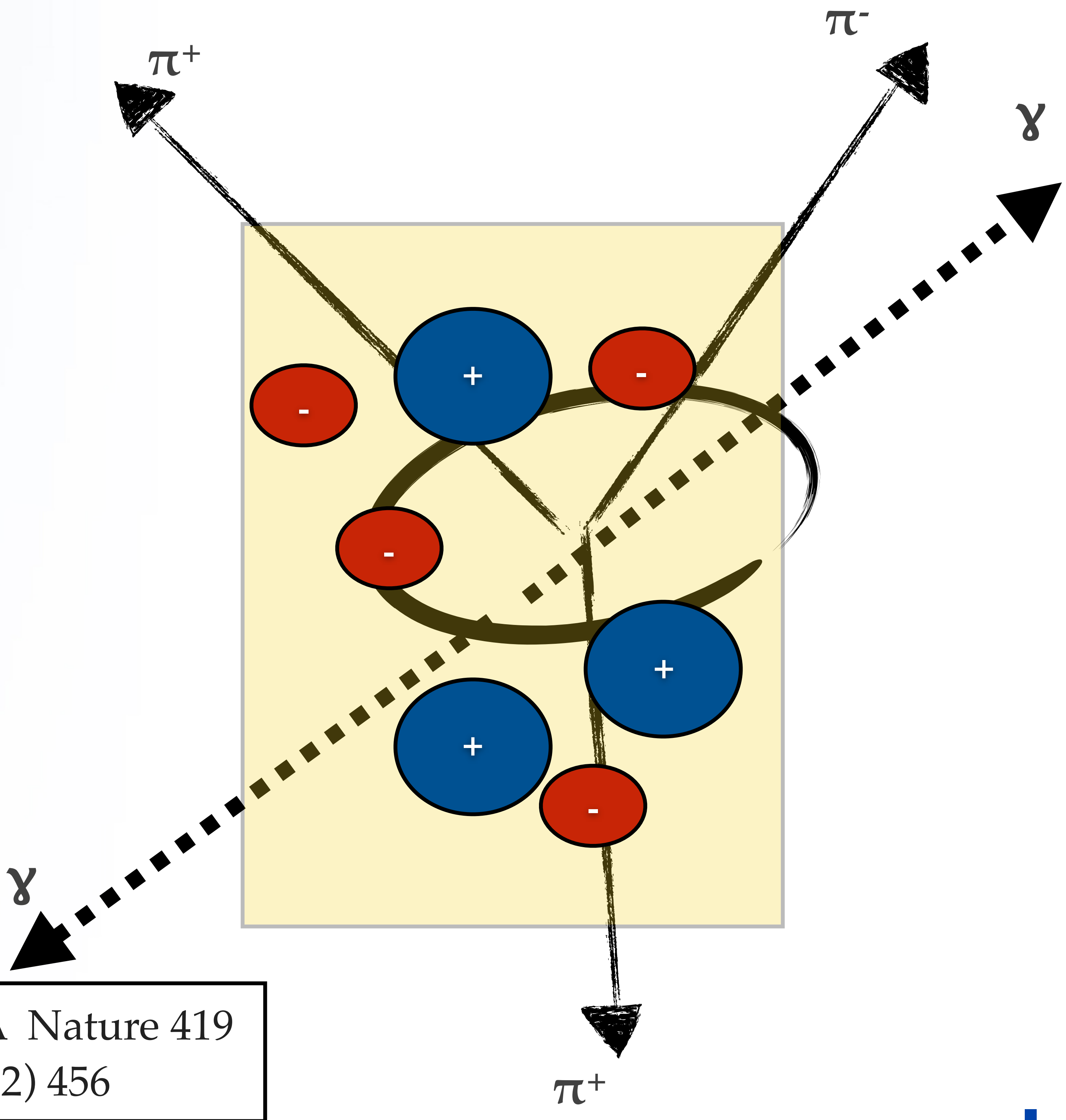
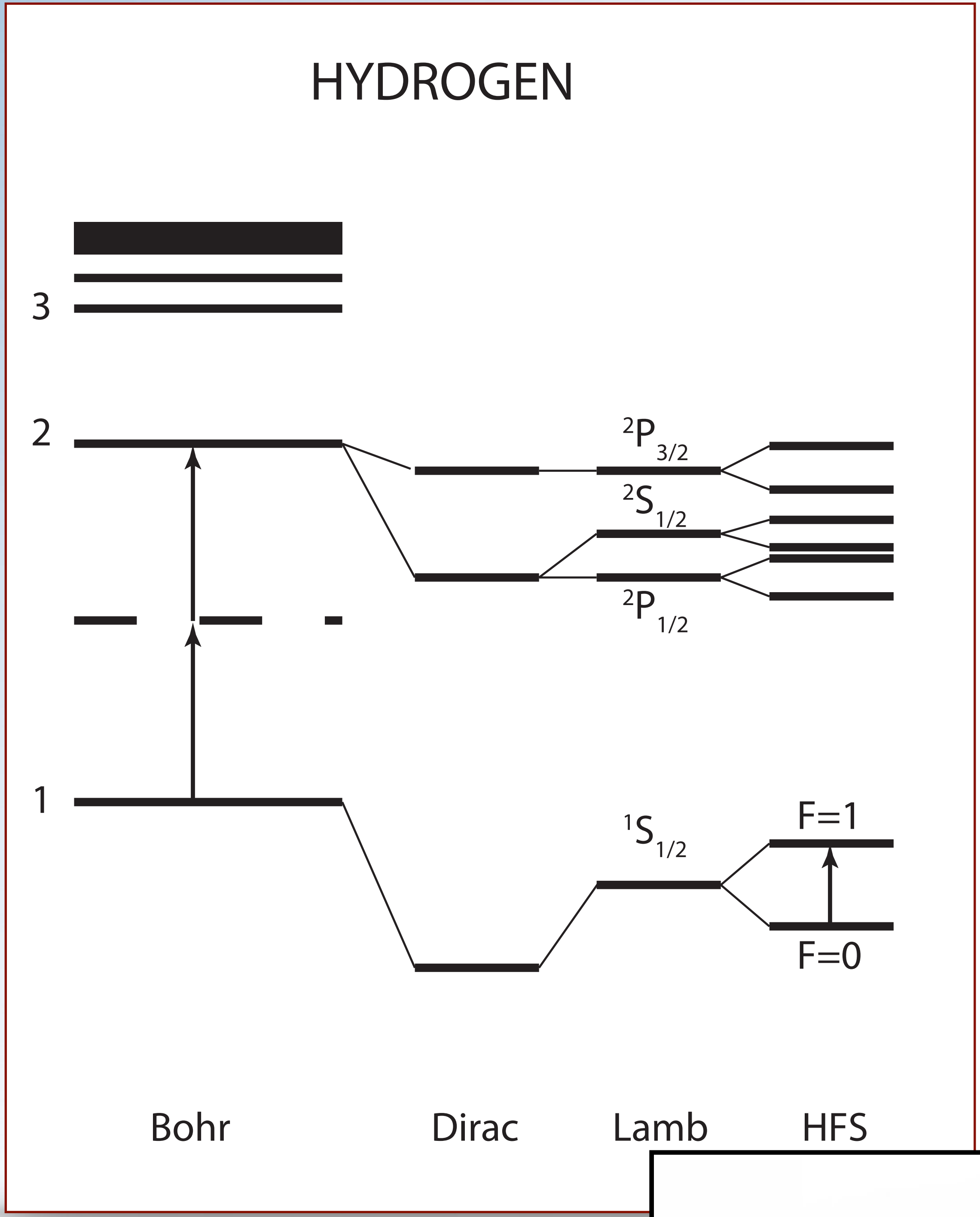
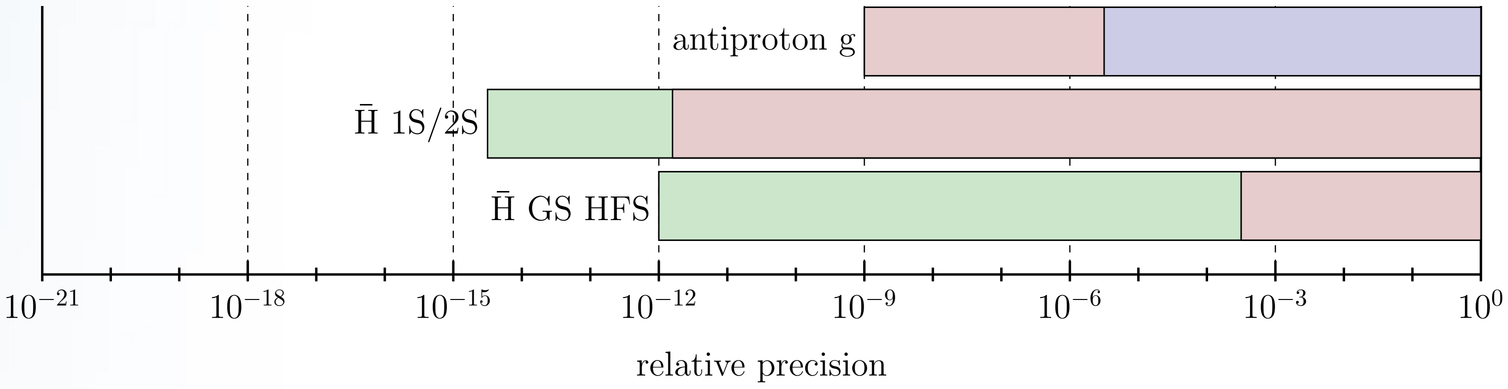
D. Lindelöf[†], E. Lodi Rizzini[§☆], M. Macrì[*], N. Madsen[†], G. Manuzio[*‡‡],
M. Marchesotti[☆], P. Montagna[☆**], H. Pruys[†], C. Regenfus[†], P. Riedler[‡],
J. Rochet[†#], A. Rotondi[☆**], G. Rouleau[‡#], G. Testera[*], A. Variola[*],
T. L. Watson[#] & D. P. van der Werf[#]



ATHENA Nature 419 (2002) 456

Spectroscopy of $\bar{\mathrm{H}}$





Precision reached on Hydrogen

Recent measurements with $\bar{\mathrm{H}}$ and $\bar{\mathrm{p}}$

$$\nu_F = \frac{16}{3}\left(\frac{M_p}{M_p + m_e}\right)^3 \frac{m_e}{M_p}\frac{\mu_p}{\mu_N}\alpha^2 c R_y$$

$$\Delta\nu(\mathrm{Zemach}) = \nu_{\mathrm{F}} \frac{2Z\alpha m_{\mathrm{e}}}{\pi^2} \int \frac{d^3p}{p^4}\left[\frac{G_E(p^2)G_M(p^2)}{1+\kappa} - 1\right]$$

Hyperfine splitting

21cm line

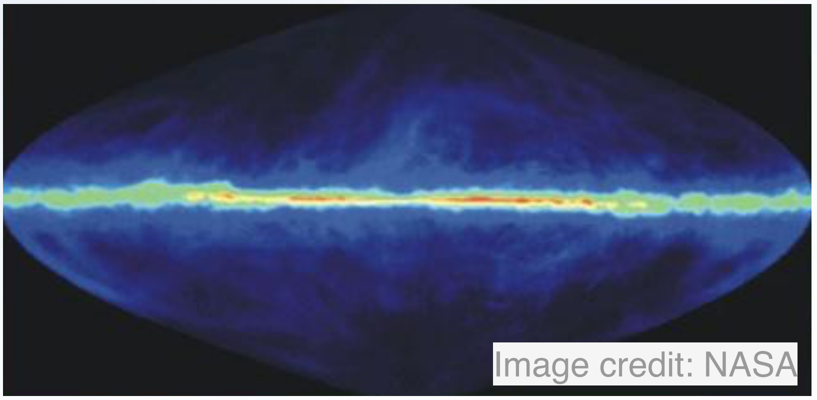


Image credit: NASA

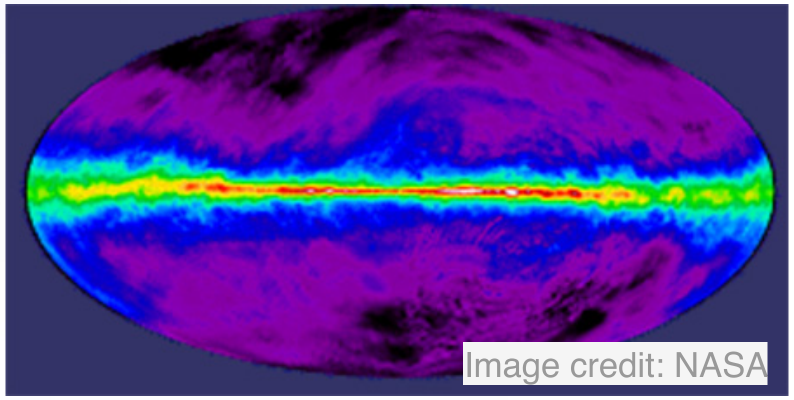
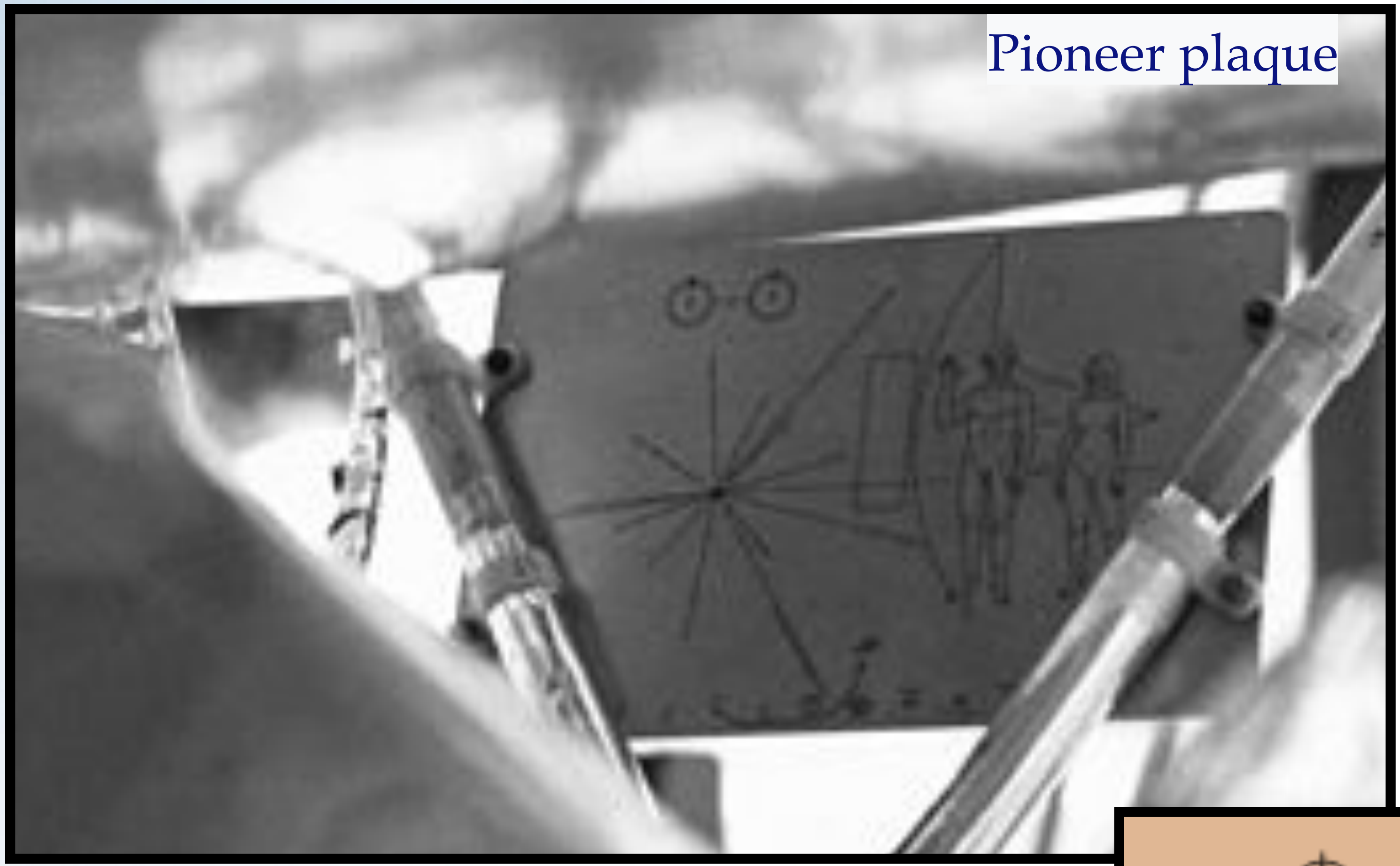
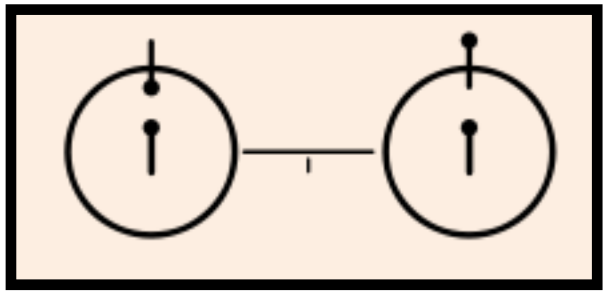


Image credit: NASA

Hyperfine splitting



Pioneer plaque



21cm line

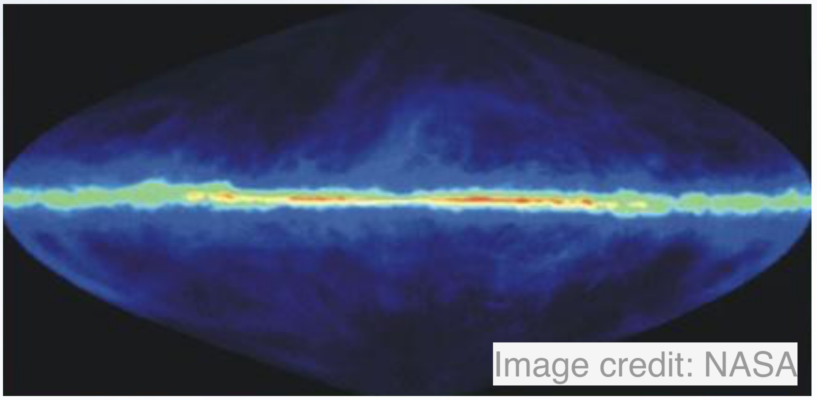


Image credit: NASA

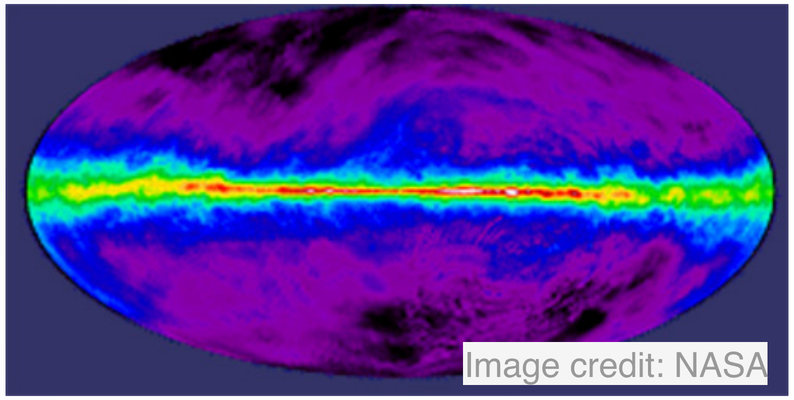
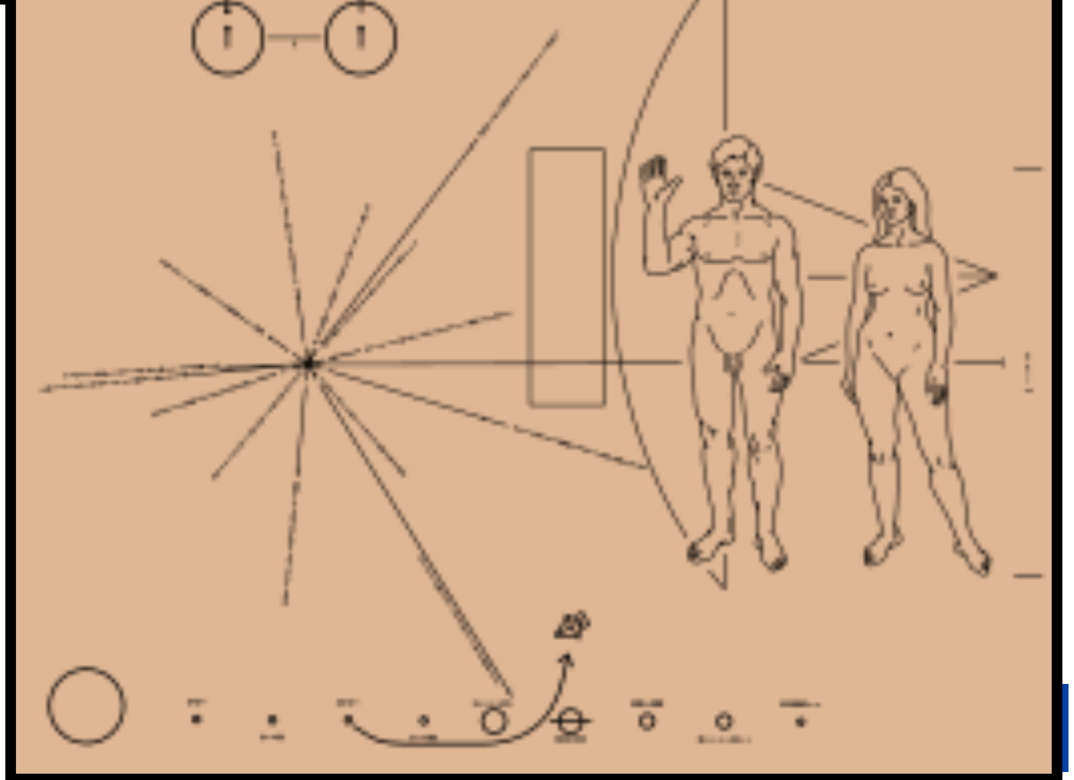
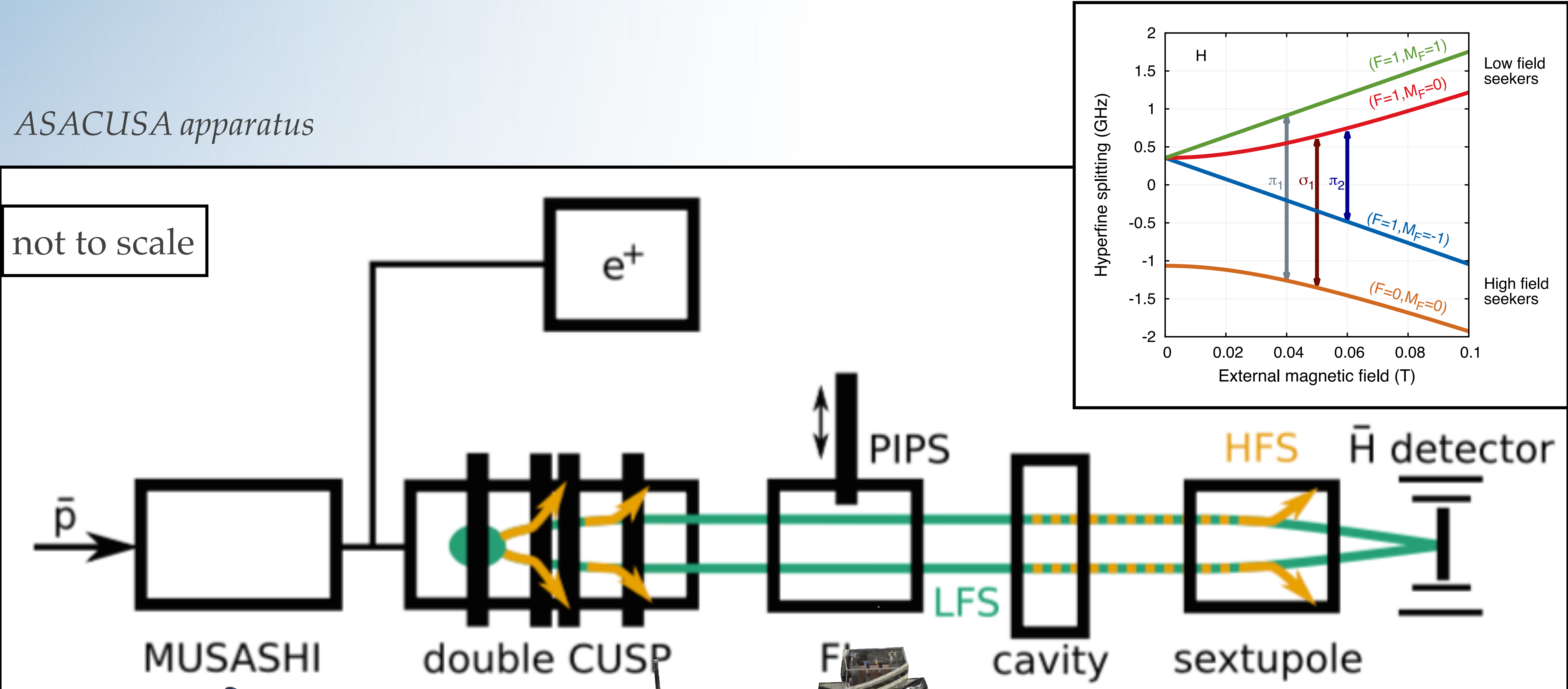


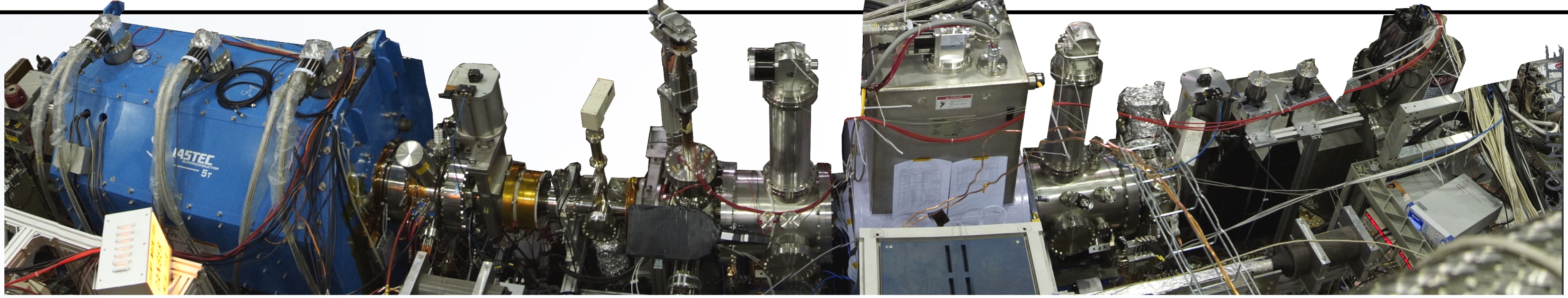
Image credit: NASA

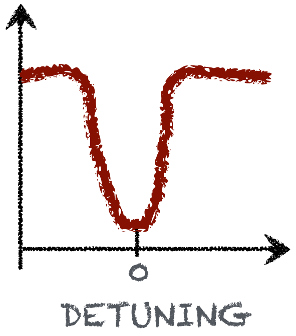


EXPERIMENTAL CONCEPTS

ASACUSA apparatus



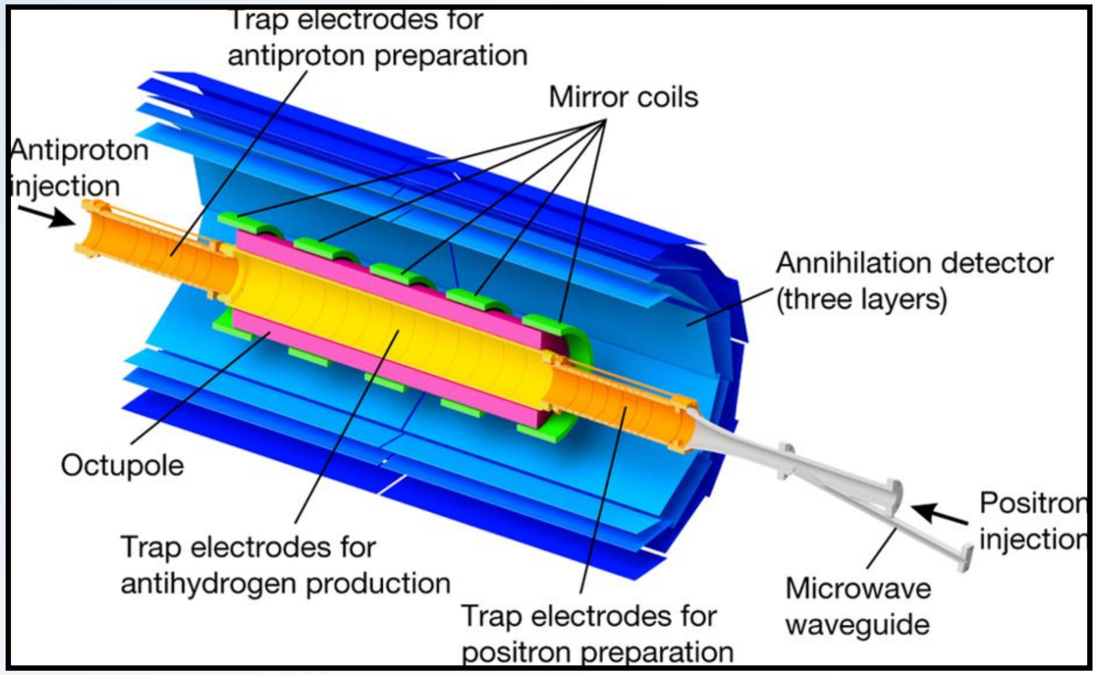




EXPERIMENTAL CONCEPTS

TRAP

ALPHA-2 apparatus

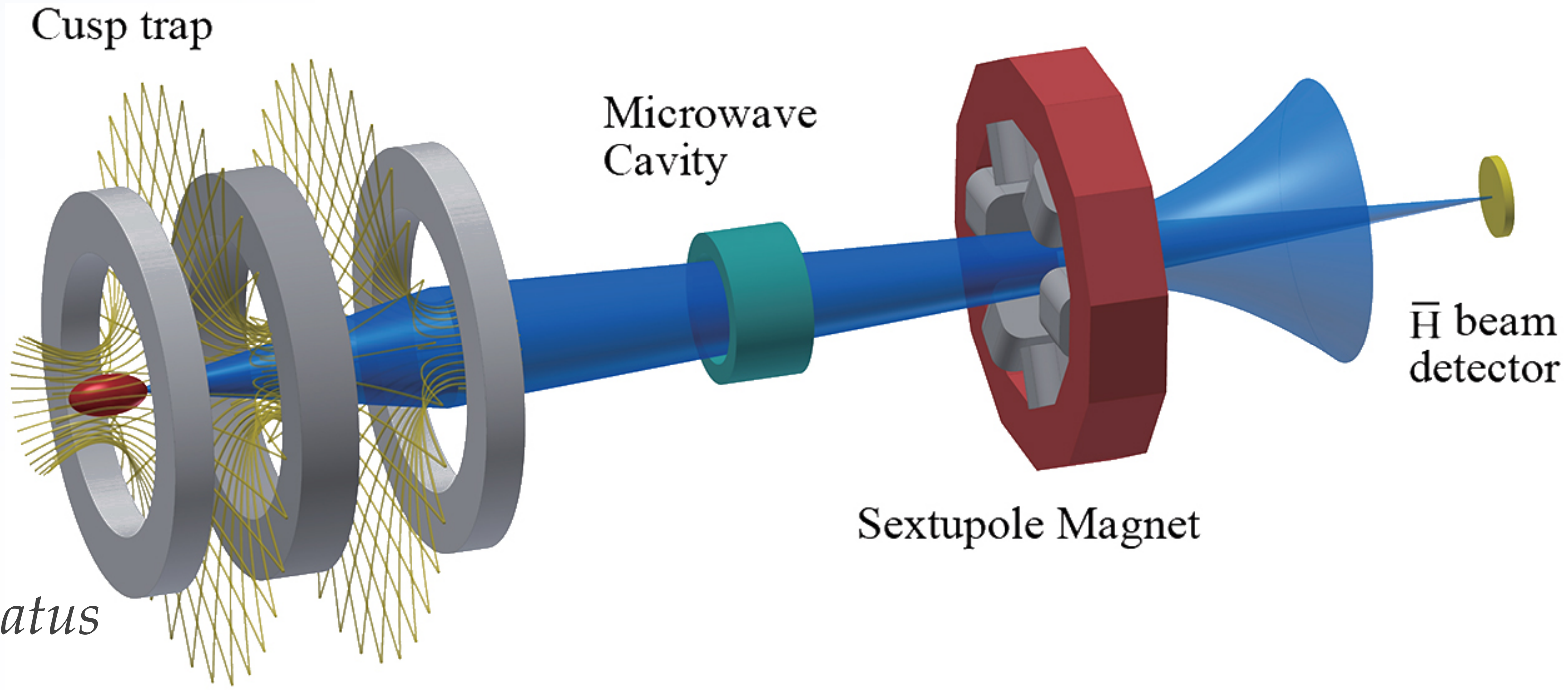


$$kT = \mu(B - B_0)$$

$$\frac{\mu_B}{k} = 0.6\,\mathrm{K.T}^{-1}$$

BEAM

Vs.

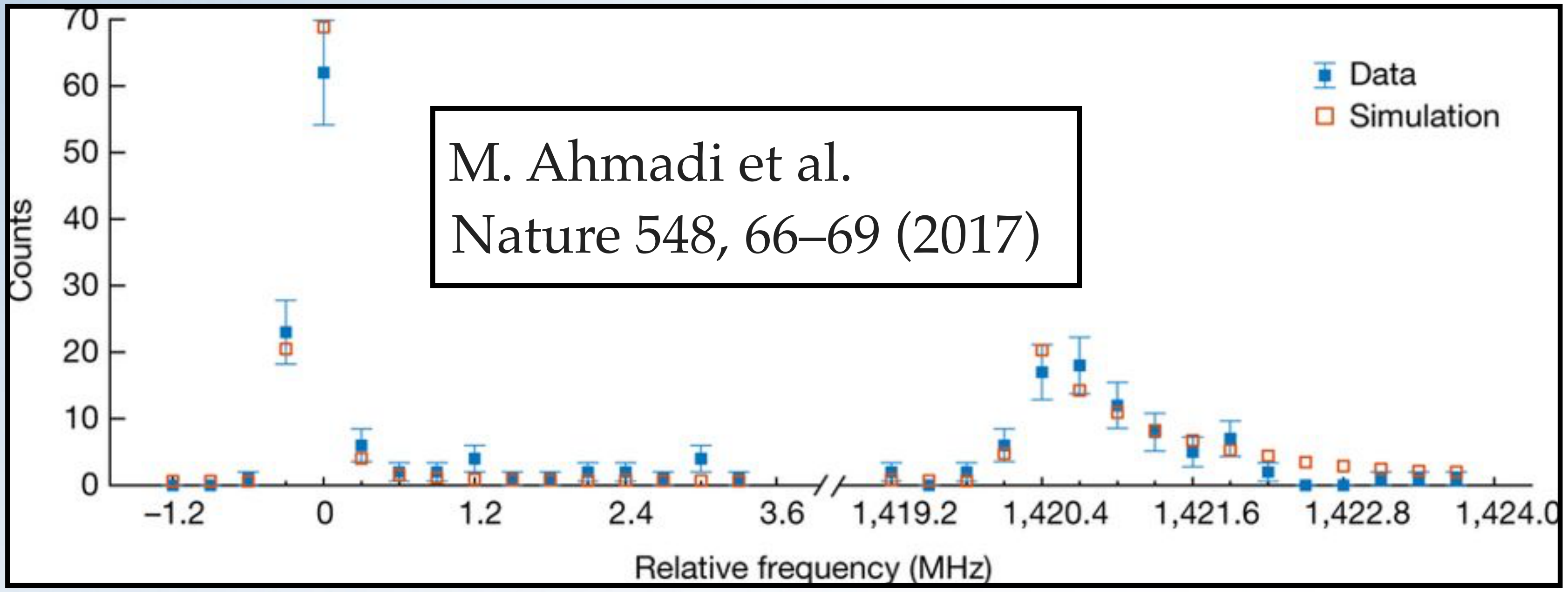


ASACUSA apparatus

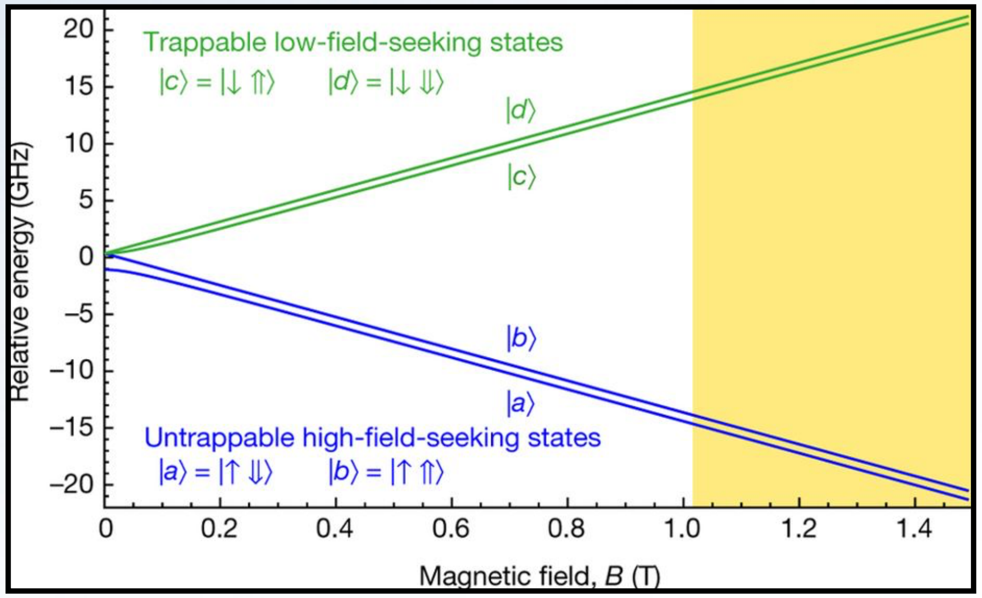
STATUS OF GS-HFS OF $\bar{H}$/H

In a TRAP:

Precision of ~ 500 kHz



M. Ahmadi et al.
Nature 548, 66–69 (2017)



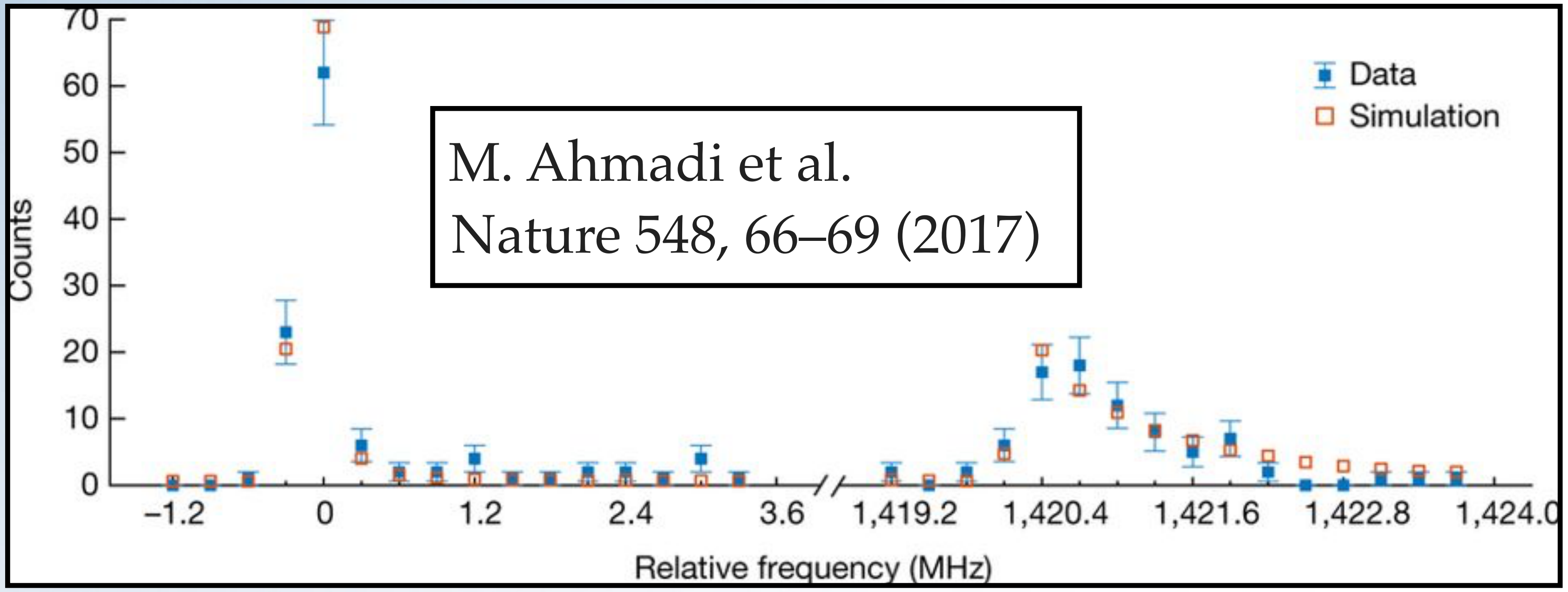
STATUS OF GS-HFS OF $\bar{H}$/H

In a TRAP:

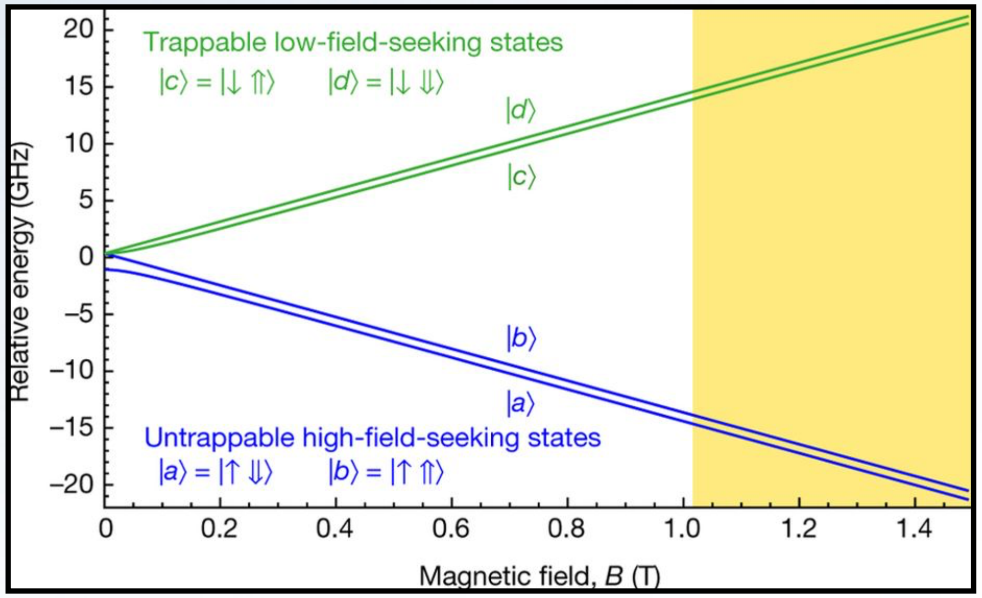
Precision of ~ 500 kHz

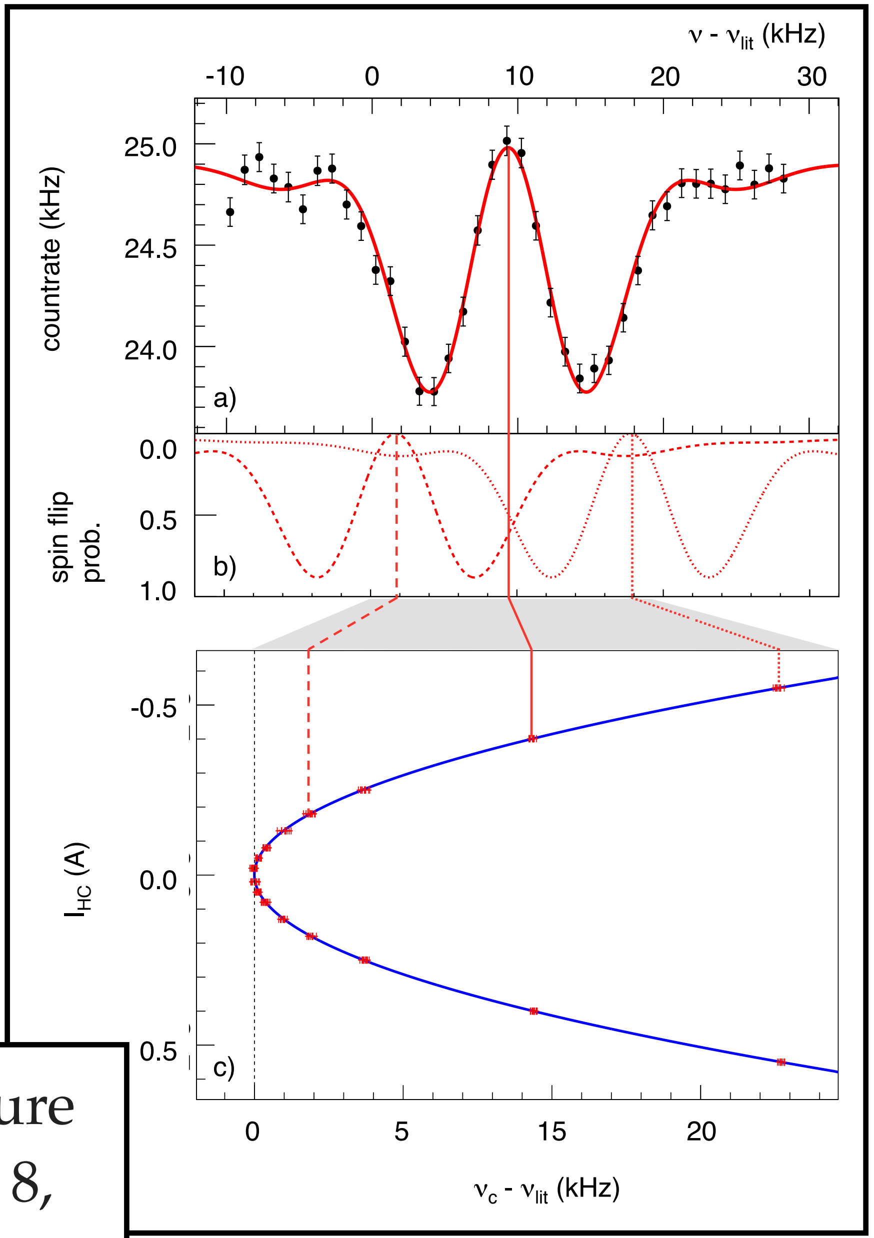
In a BEAM:

Precision of ~3Hz on HYDROGEN



M. Ahmadi et al.
Nature 548, 66–69 (2017)



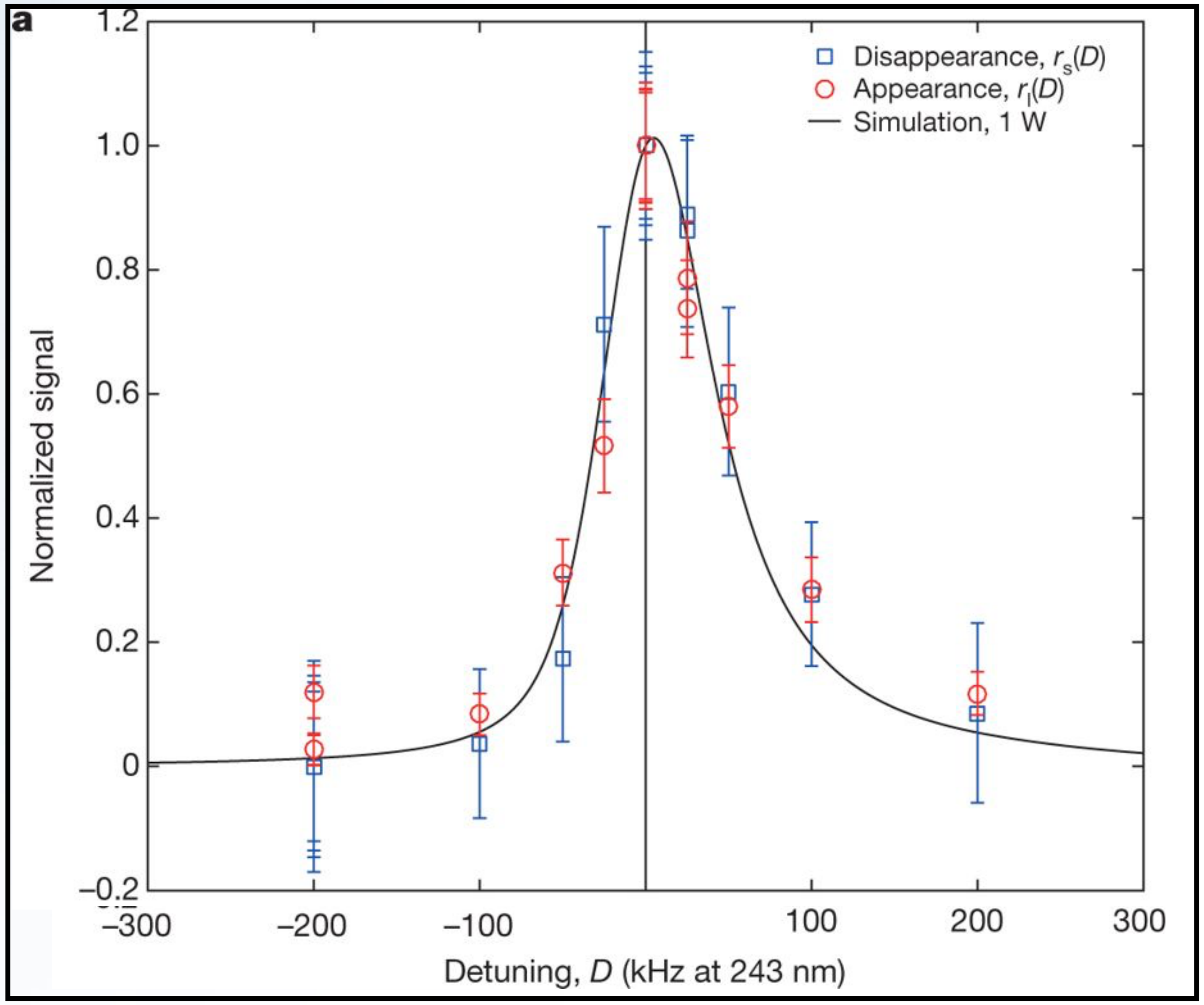


M. Diermaier et al. Nature Communications 8, 15749 (2017)

STATUS OF 1S-2S OF $\bar{H}$

In a TRAP:

Relative precision obtained : 2 × 10^{-12} (~ 5 kHz)



M. Ahmadi et al., Nature 557 71–75 (2018)

FUTURE GOALS

Comparison to H in the same apparatus

Constraints for further precision

- More $\bar{H}$

- Control the QS (for beam)

- Colder $\bar{H}$:

  - Laser cooling (sympathetic cooling of particles/ions) Be^+, La^-,C_2^- …

  - Lyman-alpha cooling of $\bar{H}$

FUTURE GOALS

Comparison to H in the same apparatus

<u>Constraints for further precision</u>

- More $\bar{H}$

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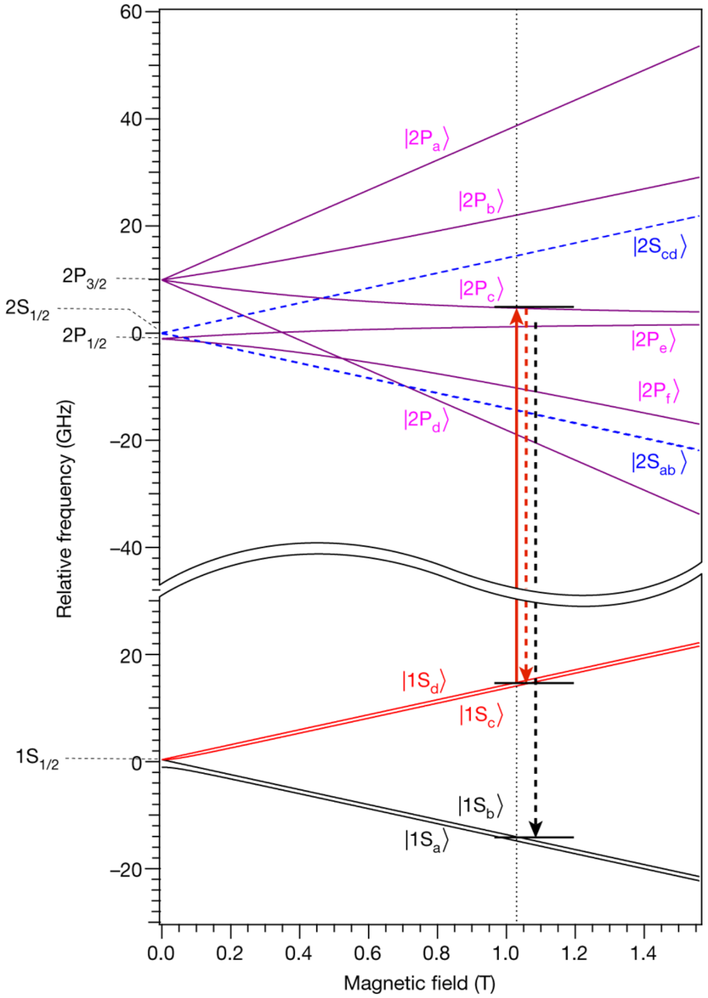
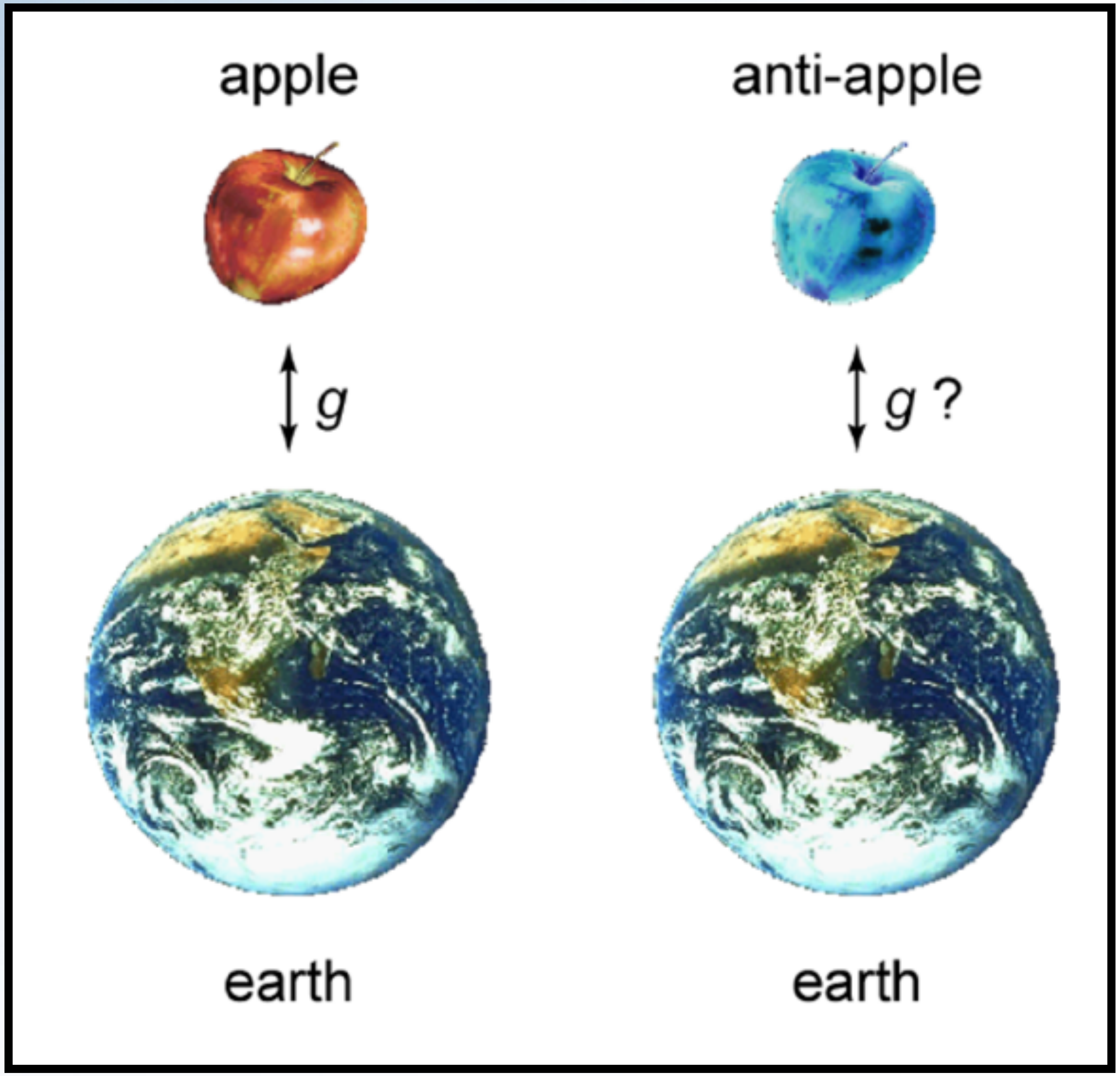
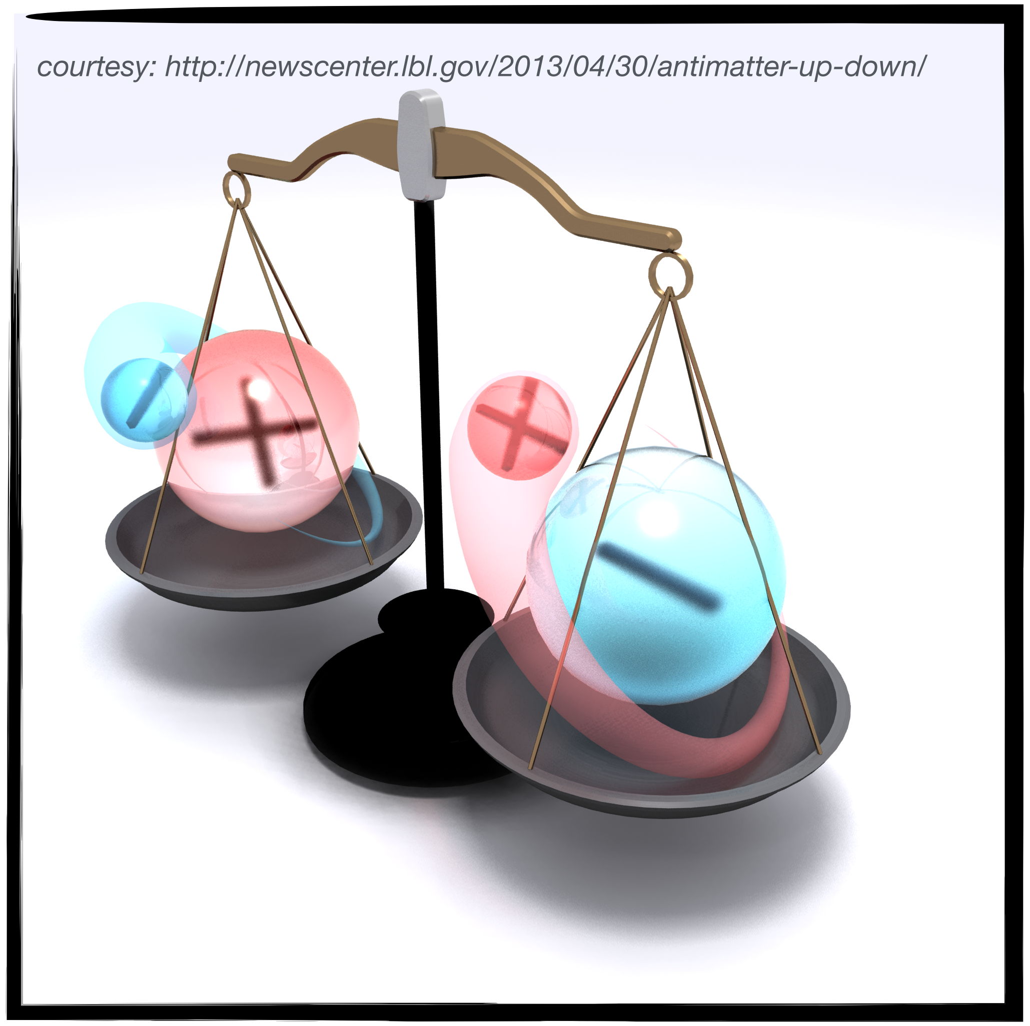


Observation of the 1S–2P Lyman-α transition in antihydrogen
M. Ahmadi et al., Nature 561, 211-215 (2018)

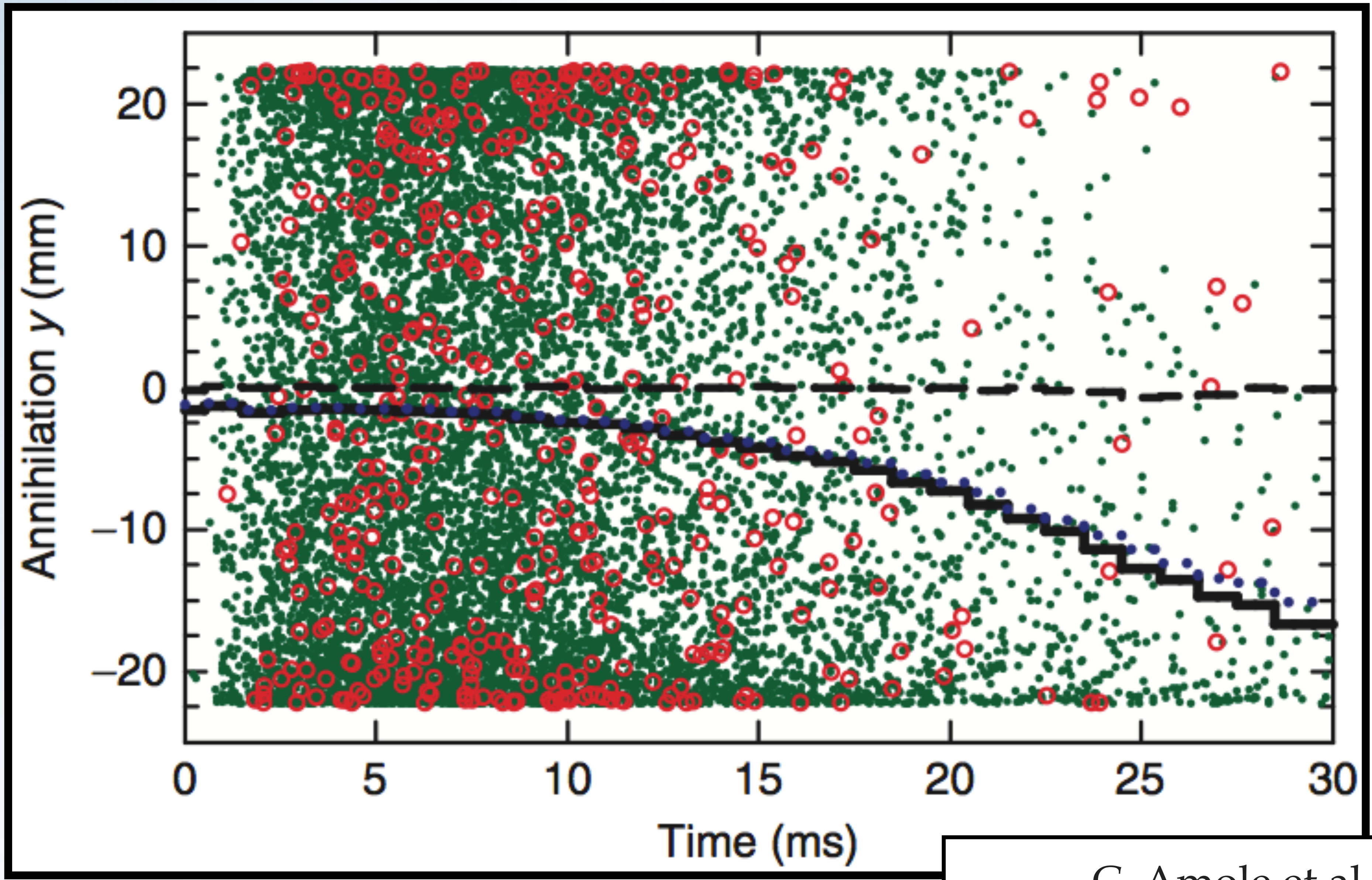
ON THE GRAVITY SIDE




courtesy: http://newscenter.lbl.gov/2013/04/30/antimatter-up-down/

$$\bar{m}_g \overset{?}{=} \bar{m}_i$$

STATUS OF THE FIELD



C. Amole et al. Nature Communications 4, 1785 (2013)

-65 < g/ḡ < 110

Green dots---simulated annihilations

Red circles---434 Observed annihilations

Vertical position of annihilation vertex during release of trapping field

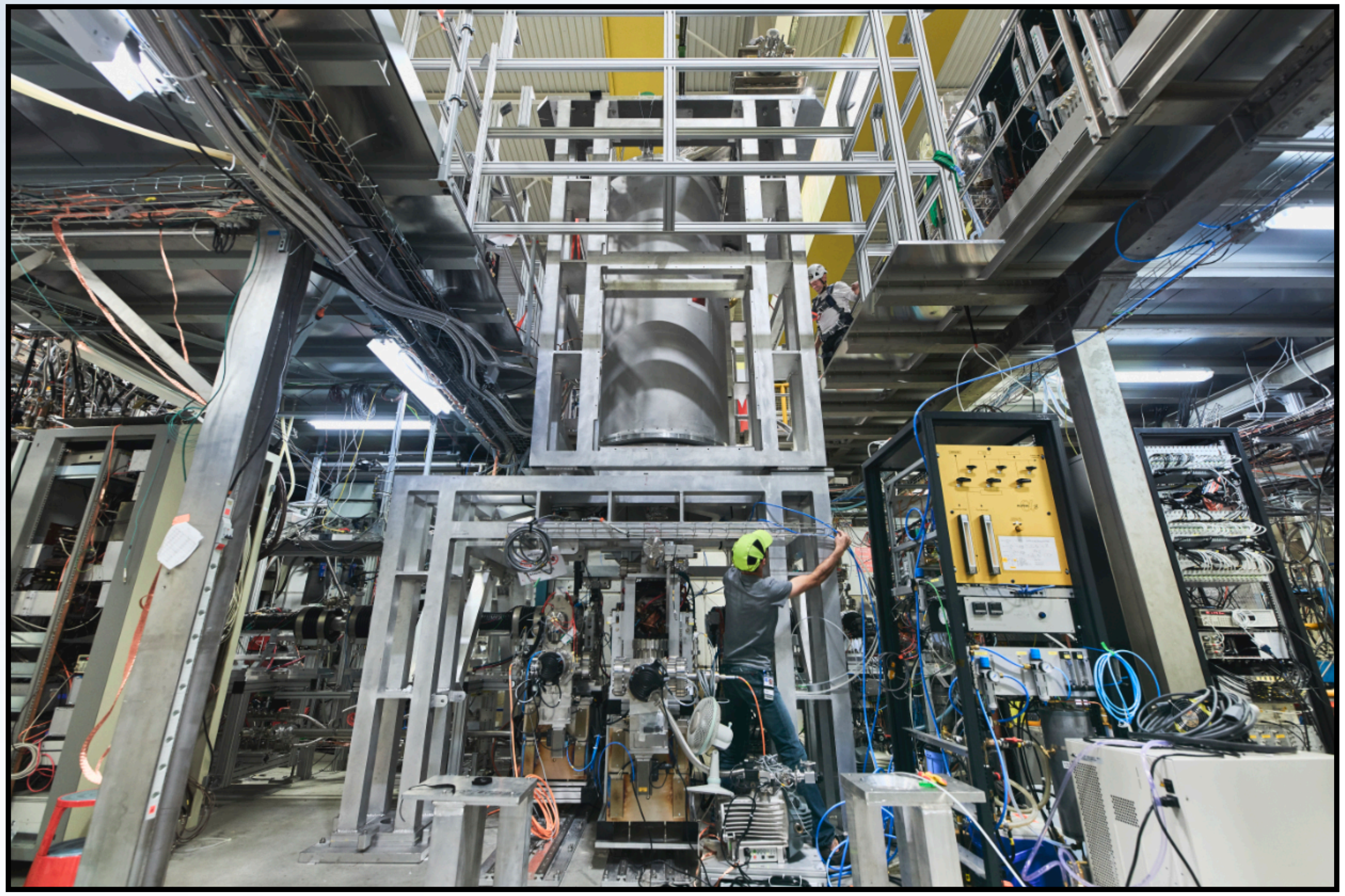
RECENT GRAVITY HIGHLIGHTS

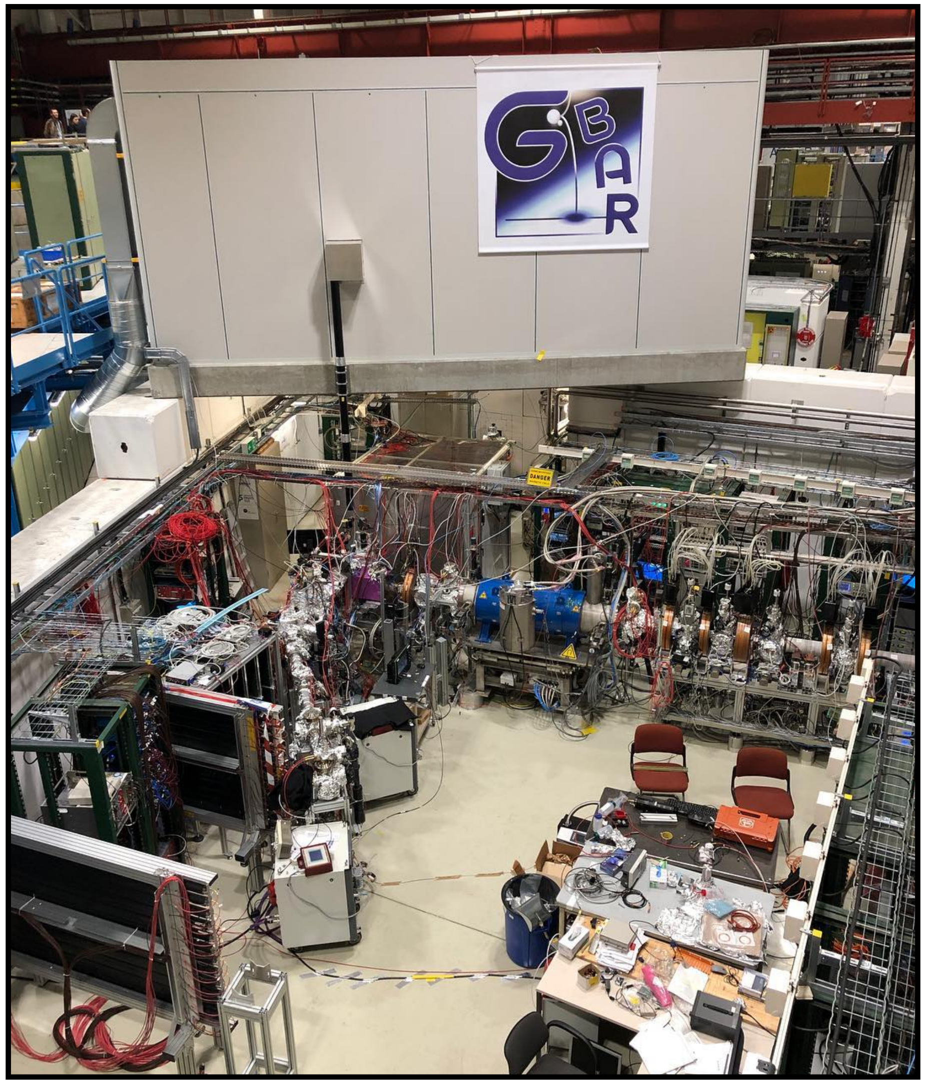
New antimatter gravity experiments begin at CERN

The ALPHA-g and GBAR experiments have received their first beams of antiprotons

2 NOVEMBER, 2018 | By Ana Lopes

GBAR & ALPHA-g getting their first beam





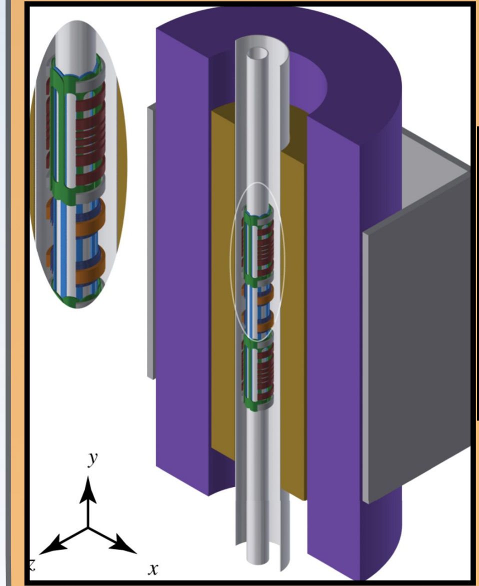
FUTURE GRAVITY GOALS

Plurality of approaches

VERTICAL TRAP

- increase up/down sensitivity (up to 1.3m trapping range)
- much improved field control

<u>Sign measurement</u> planned soon
1% targeted $\bar{H}$ cooling to ~20 mK and advanced magnetometry



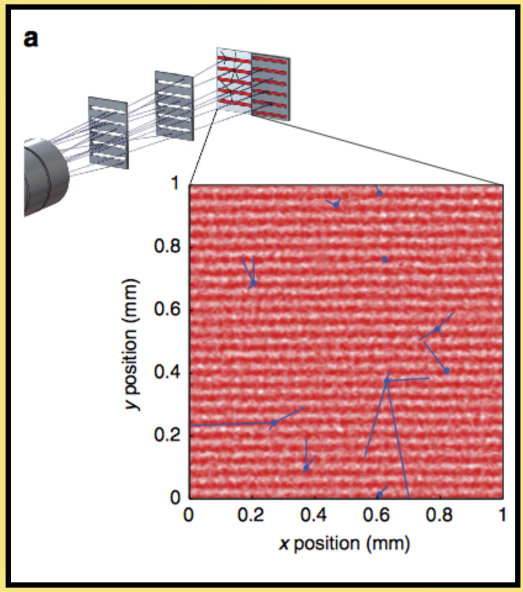
W. A. Bertsche
Phil. Trans. R. Soc. A 2018 376 20170265;
DOI: 10.1098/rsta.2017.0265. (2018)

ALPHA-G

$\bar{H}$ BEAM

- Sensitivity to ~10 µm deflection needed
- cold antiproton translates in cold $\bar{H}$ thanks to CE mechanism

<u>Sign measurement</u> targeted



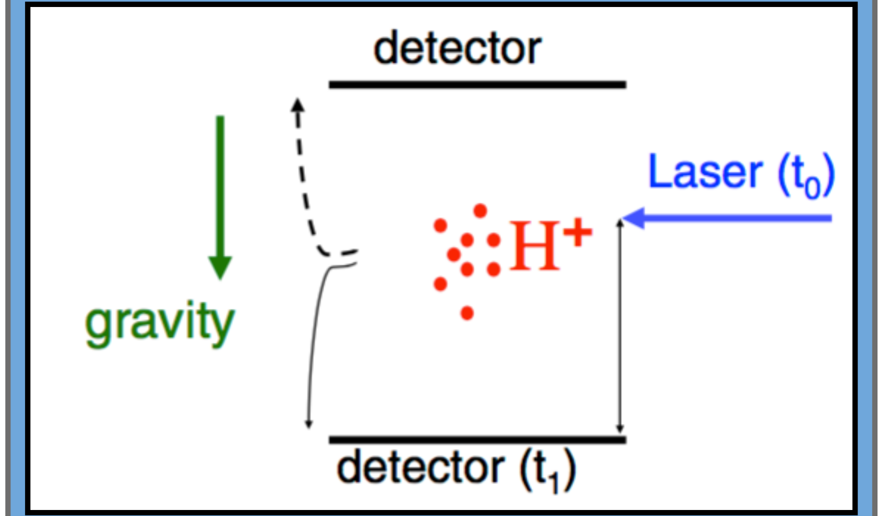
S. Aghion et al.
Nature Communications
5 (2014) 4538

AEGIS

$\bar{H}^+$ BEAM

- Cooling below 1 m/s : Sympathetic cooling of $\bar{H}^+$
- opens new horizons

<u>1% measurement</u> targeted

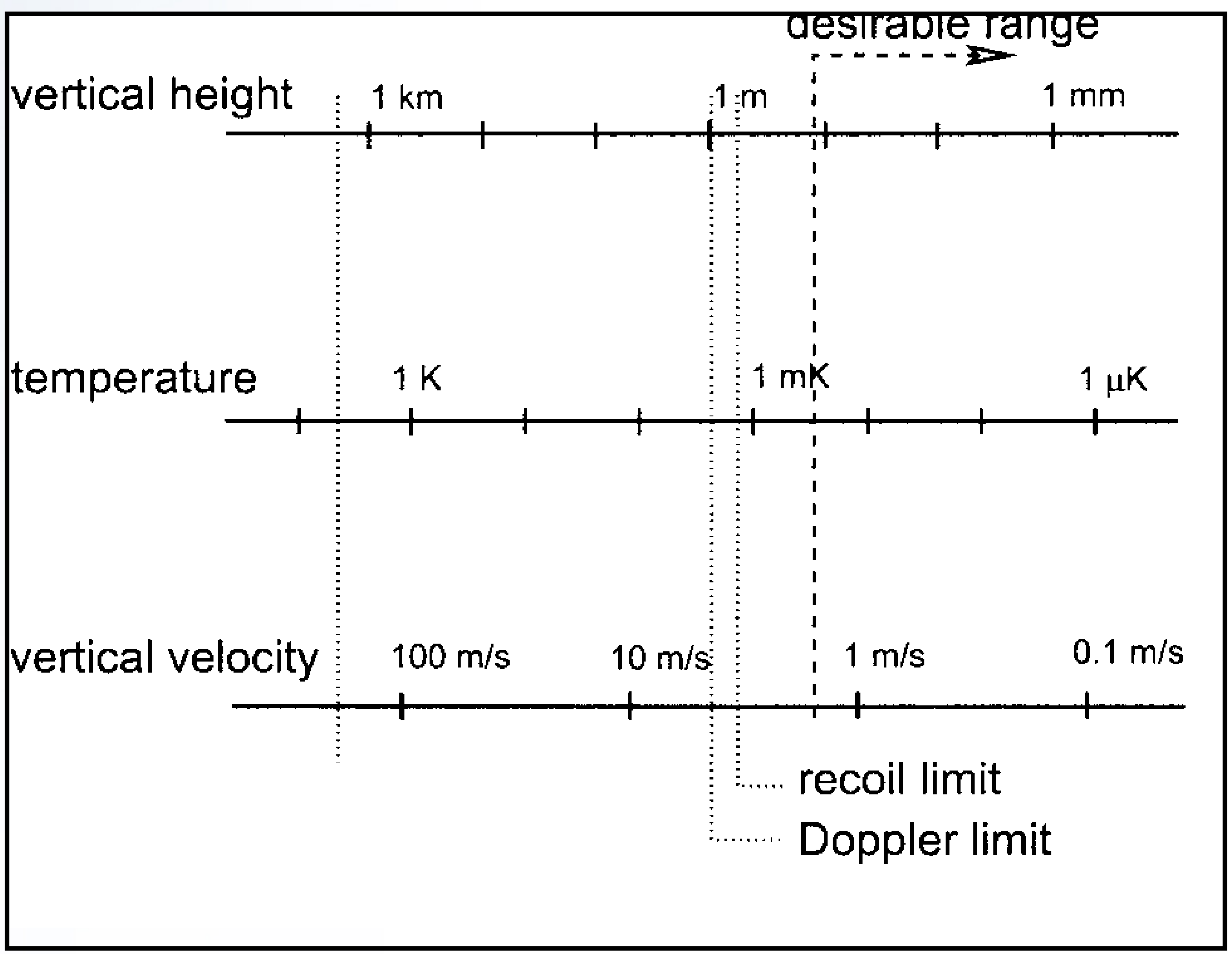


e.g.: The GBAR antimatter gravity experiment
P. Pérez et al., Hyperfine Interactions 233, 21-27 (2015)

GBAR

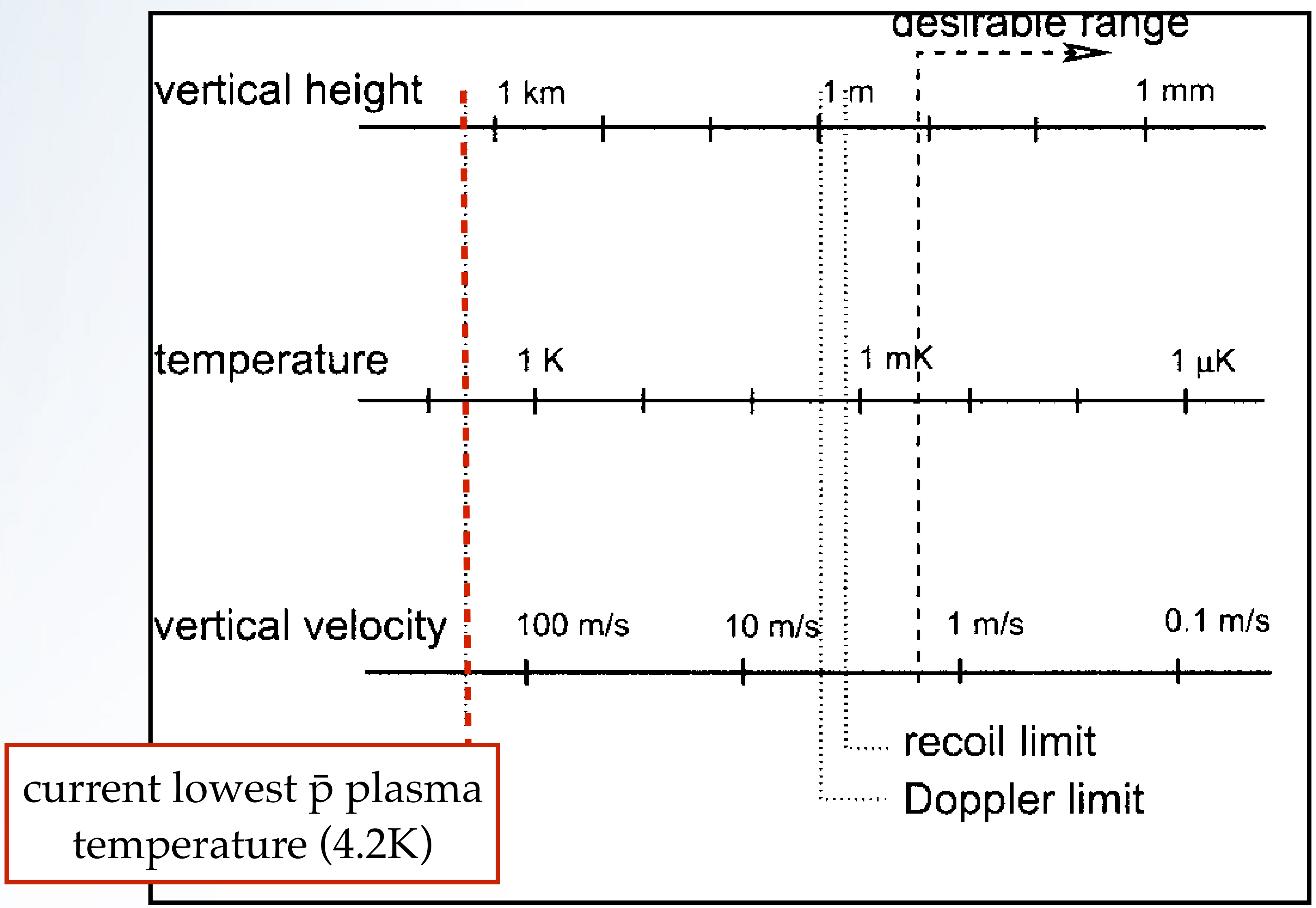
FUTURE GOALS

Some numbers to set the scale



FUTURE GOALS

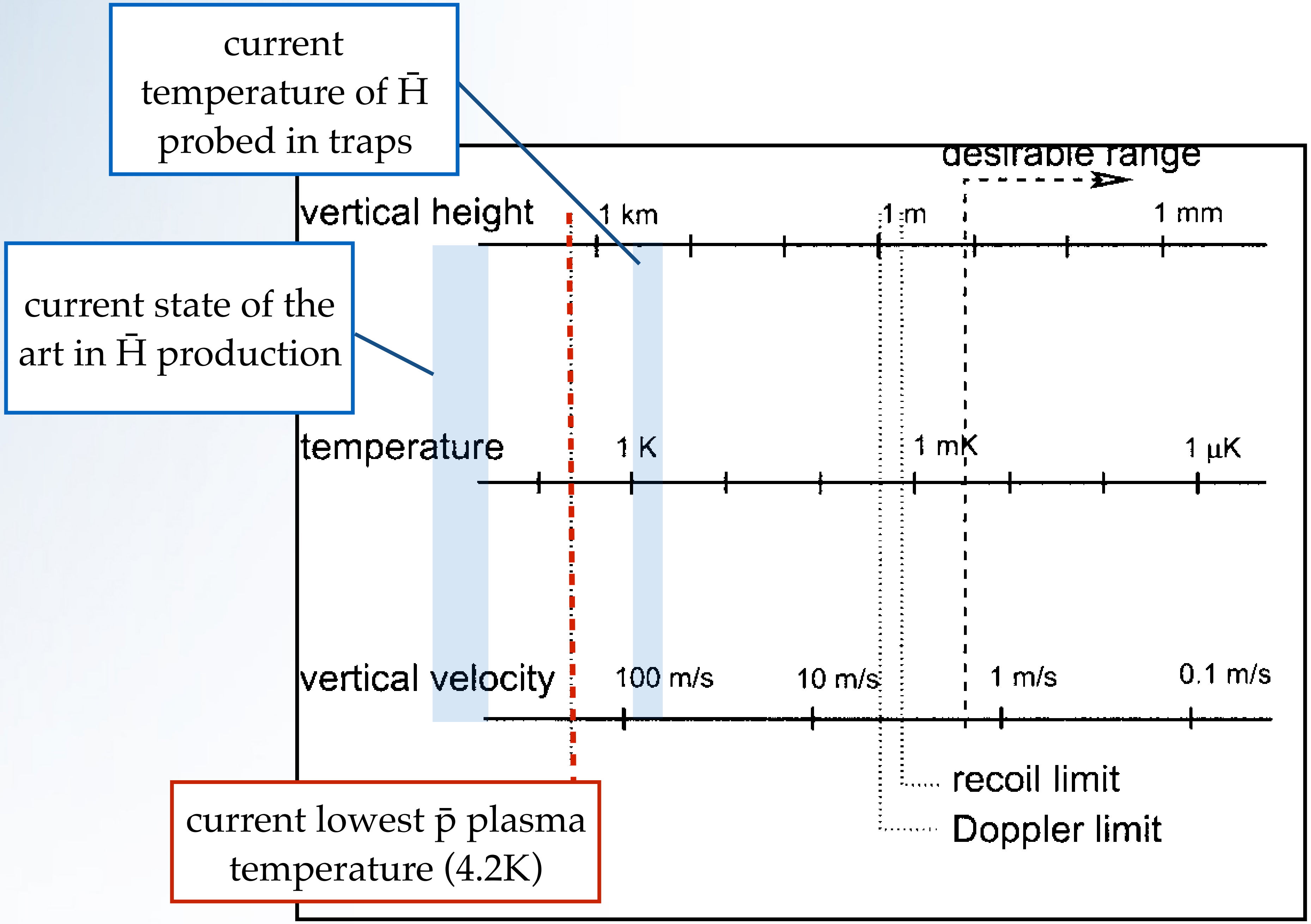
Some numbers to set the scale



current lowest $\bar{p}$ plasma temperature (4.2K)

FUTURE GOALS

Some numbers to set the scale



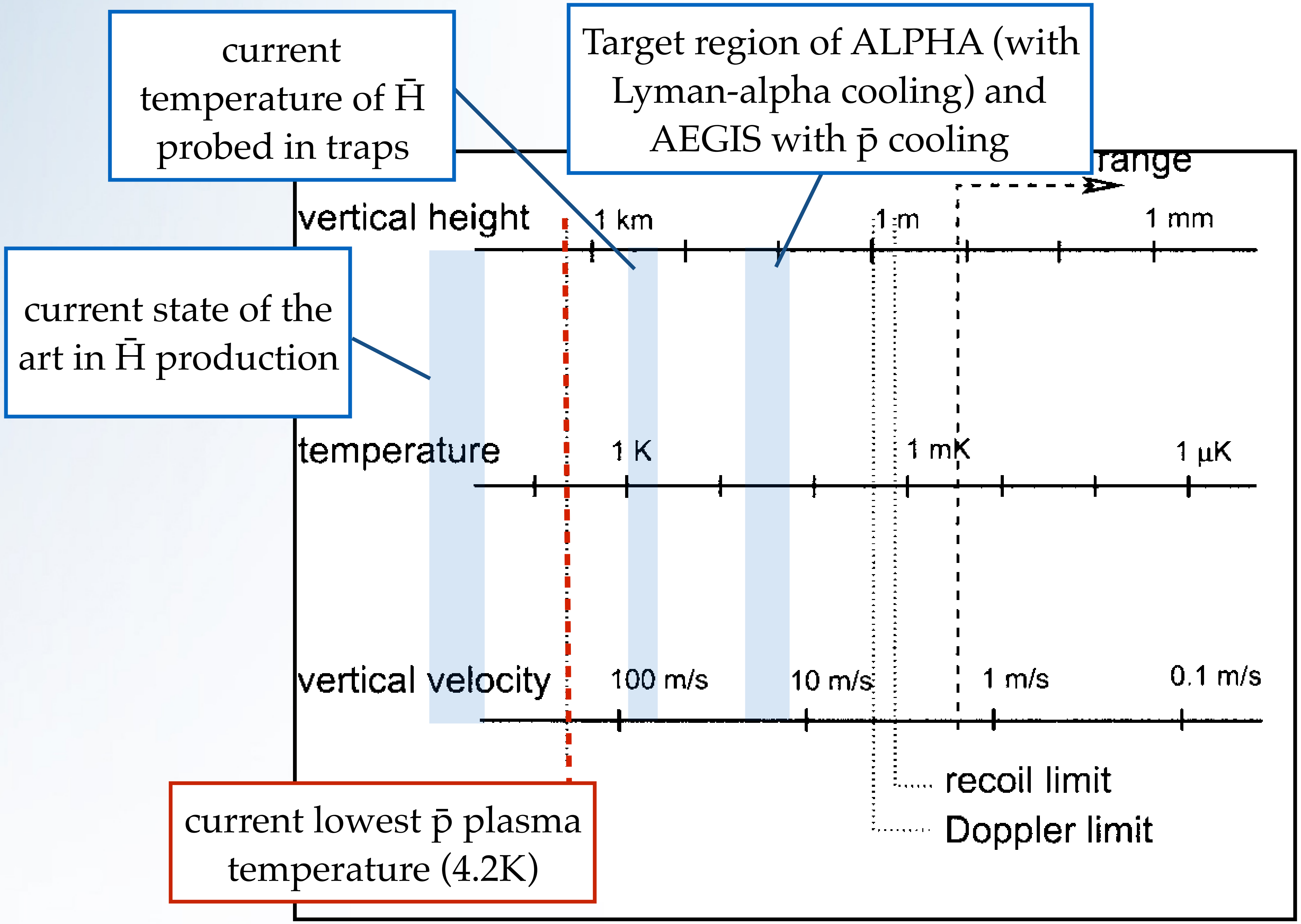
current temperature of $\bar{\mathrm{H}}$ probed in traps

current state of the art in $\bar{\mathrm{H}}$ production

current lowest $\bar{p}$ plasma temperature (4.2K)

FUTURE GOALS

Some numbers to set the scale



current temperature of $\bar{H}$ probed in traps

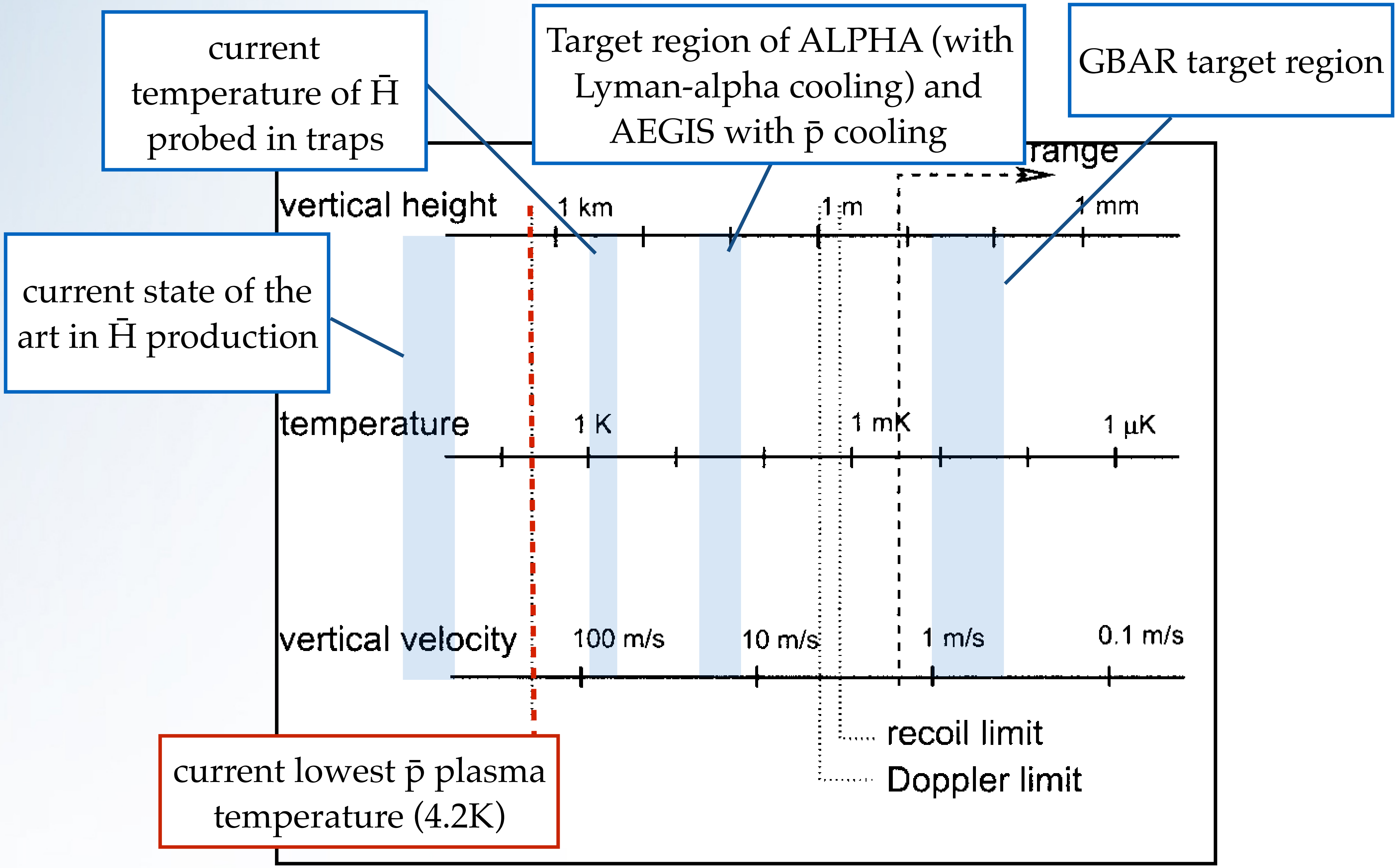
Target region of ALPHA (with Lyman-alpha cooling) and AEGIS with $\bar{p}$ cooling

current state of the art in $\bar{H}$ production

current lowest $\bar{p}$ plasma temperature (4.2K)

FUTURE GOALS

Some numbers to set the scale



current temperature of $\bar{H}$ probed in traps

Target region of ALPHA (with Lyman-alpha cooling) and AEGIS with $\bar{p}$ cooling

GBAR target region

current state of the art in $\bar{H}$ production

current lowest $\bar{p}$ plasma temperature (4.2K)

ANTIPROTON EXPERIMENTS

Inject antiprotons along magnetic field axis

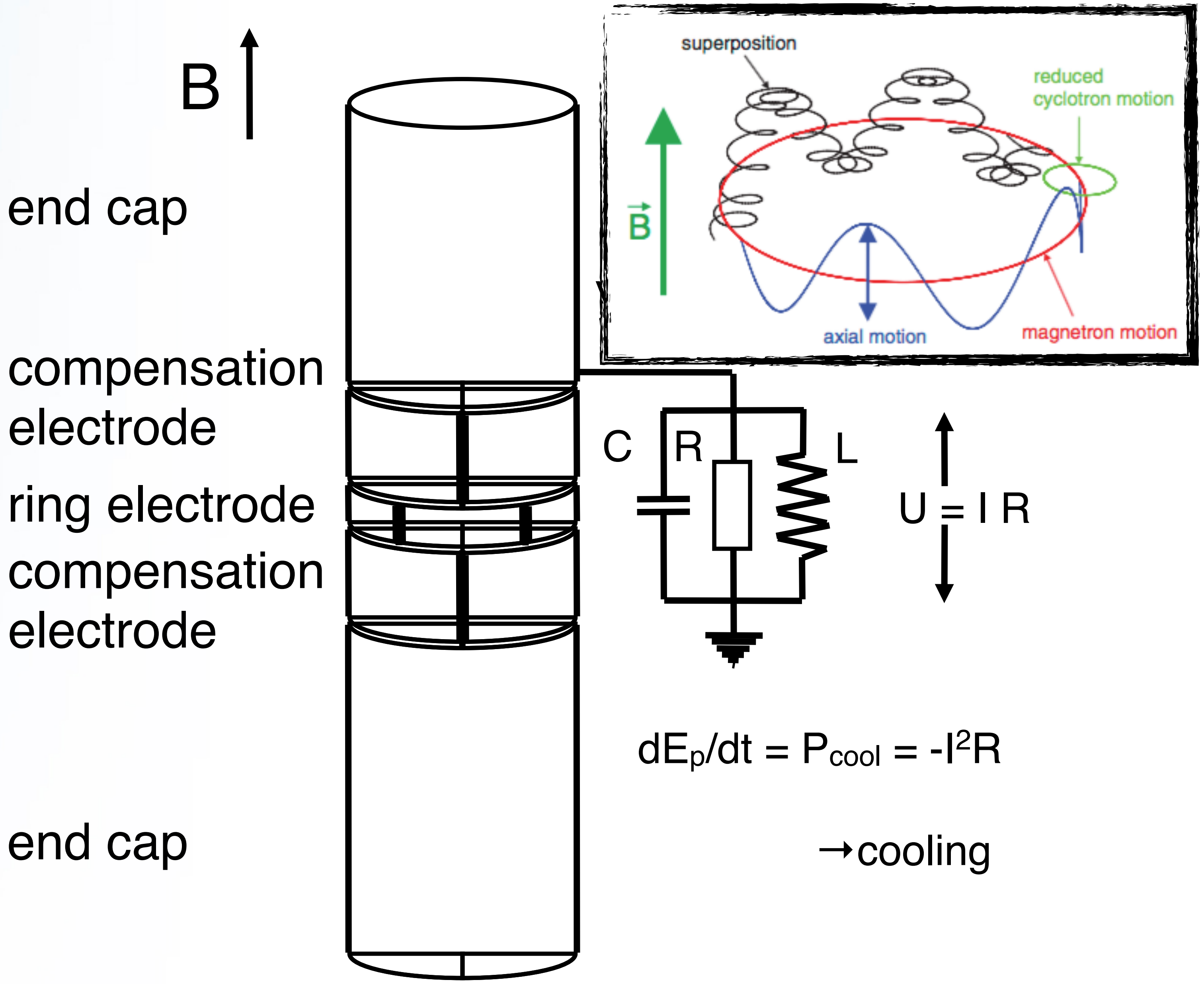
Energy ~ few keV

Precisions measurement : only 1 p̄

Detect image current in resonance circuit due to charge movement in the Penning trap

Detection by cryogenic resonance circuit (low noise)

$$\nu_c^2 = \nu_-^2 + \nu_z^2 + \nu_+^2$$



B

end cap

compensation electrode

ring electrode

compensation electrode

end cap

U = I R

$dE_p/dt = P_{cool} = -I^2R$

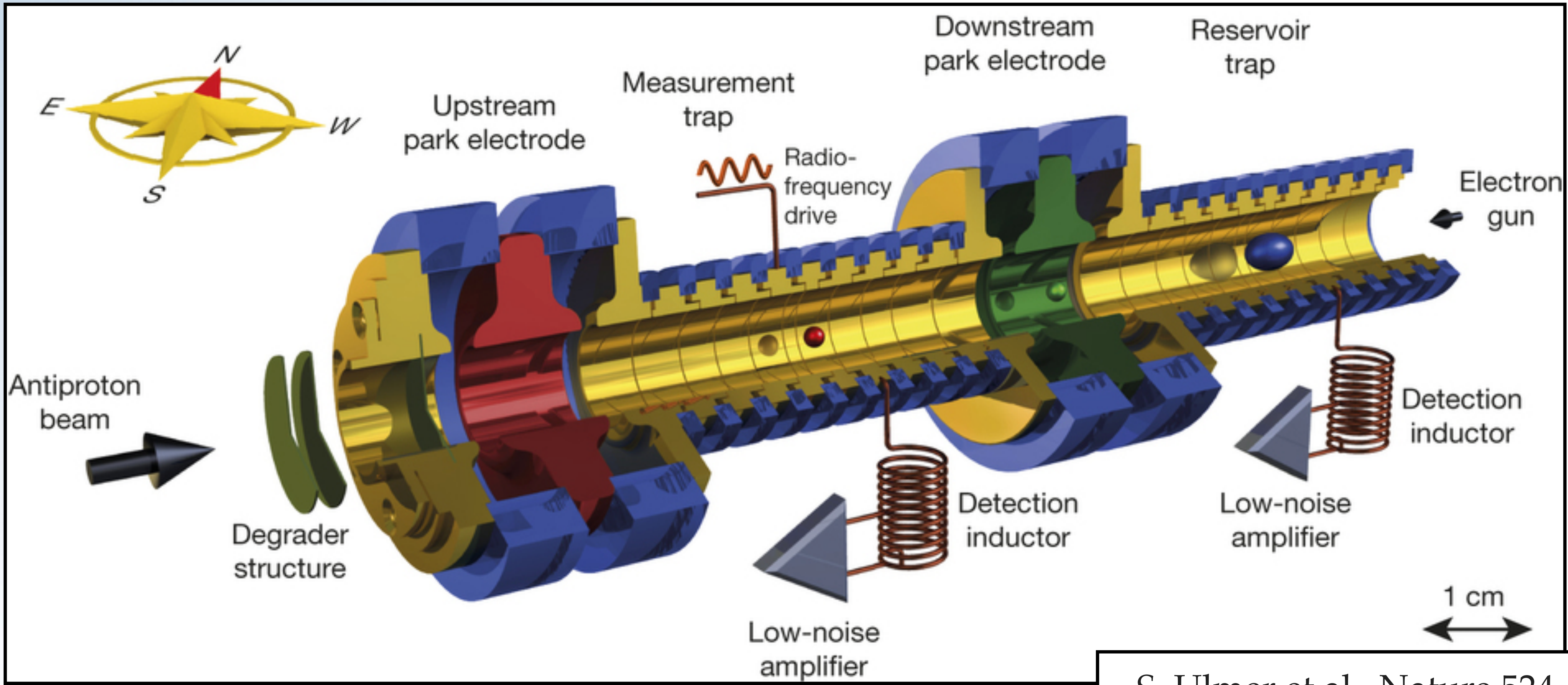
→cooling

G. Gabrielse, W. Quint (LEAR)

ANTIPROTON EXPERIMENTS

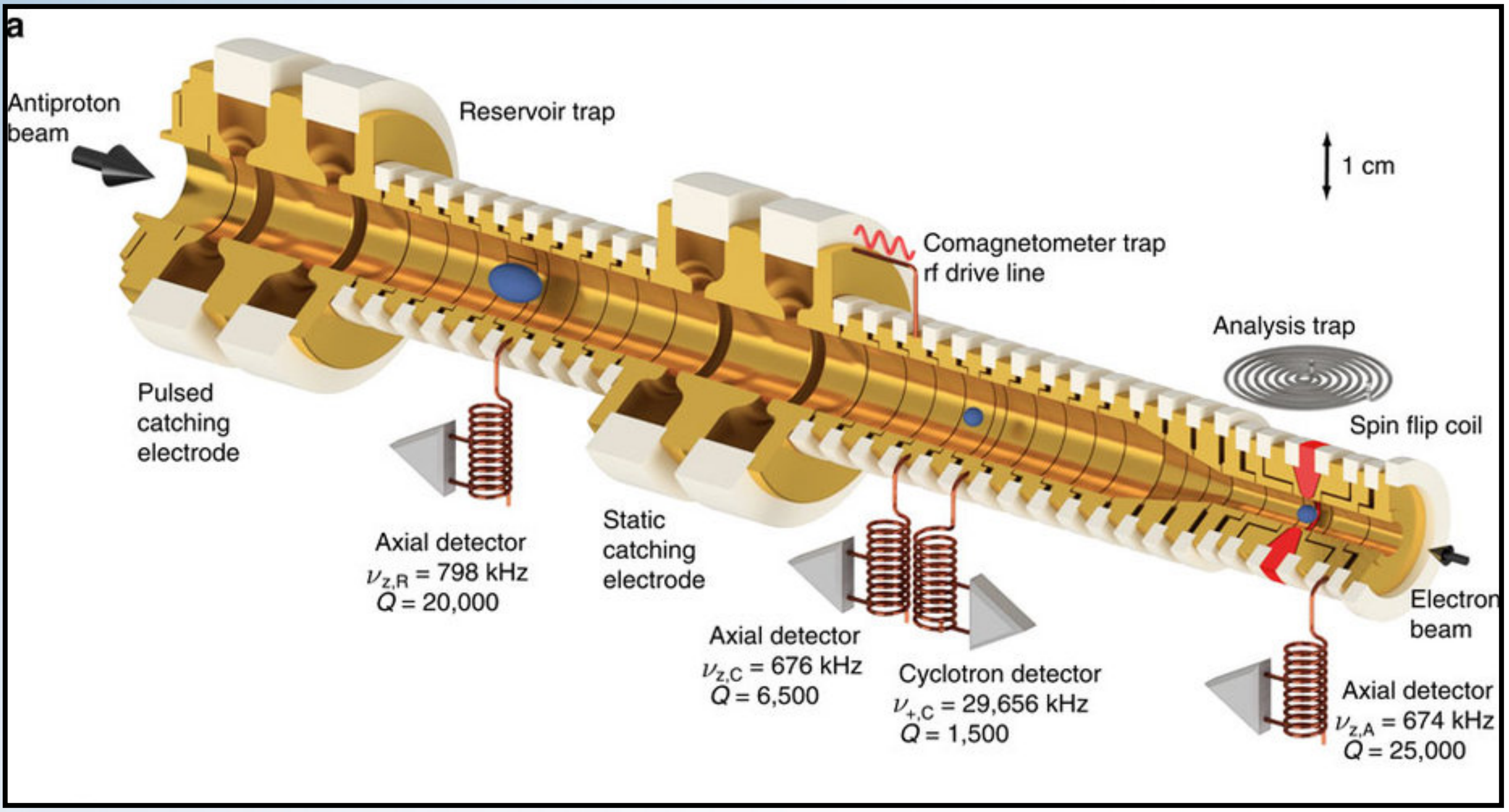
$$\nu_c = \frac{1}{2\pi}\frac{Q_{\bar{p}}}{M_{\bar{p}}}B$$

$$\boxed{\frac{(\frac{Q}{M})_{\bar{p}}}{(\frac{Q}{M})_p} - 1 = 1(69) \times 10^{-12}}$$



S. Ulmer et al., Nature 524, 196–199 (2015)

ANTIPROTON EXPERIMENTS



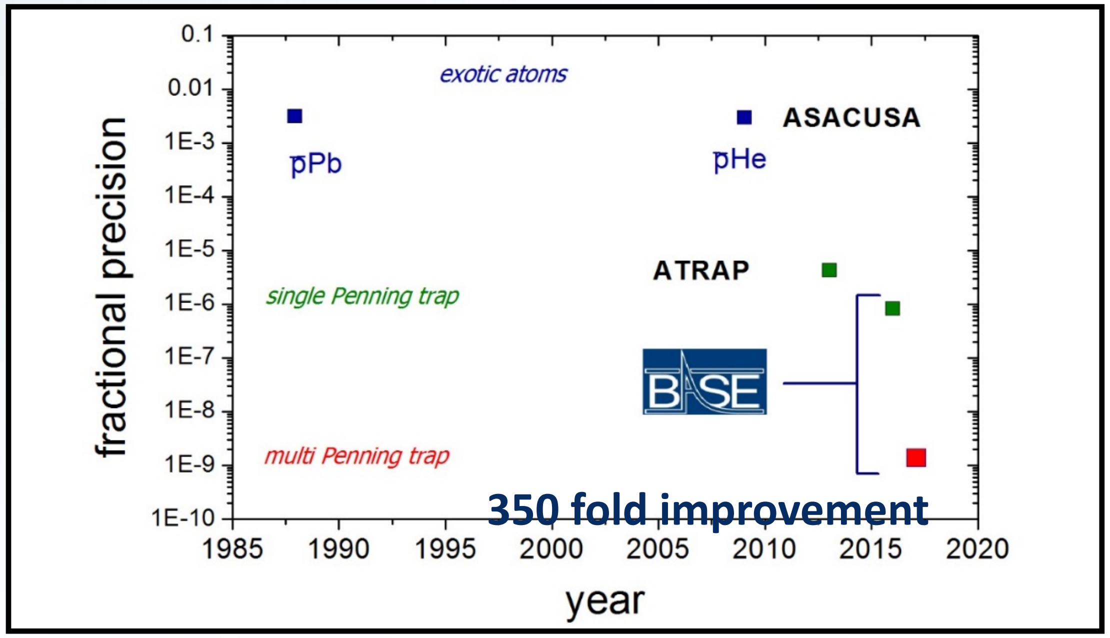
$$\frac{g_{p,\bar{p}}}{2} = \frac{\nu_L}{\nu_c} = \frac{\mu_{p,\bar{p}}}{\mu_N}$$

$$\frac{g_p}{2} = 2.792\,847\,344\,62\,(82)$$

G. Schneider et al., Science 358, 1081 (2017)

$$\frac{g_{\bar{p}}}{2} = 2.792\,847\,344\,1\,(42)$$

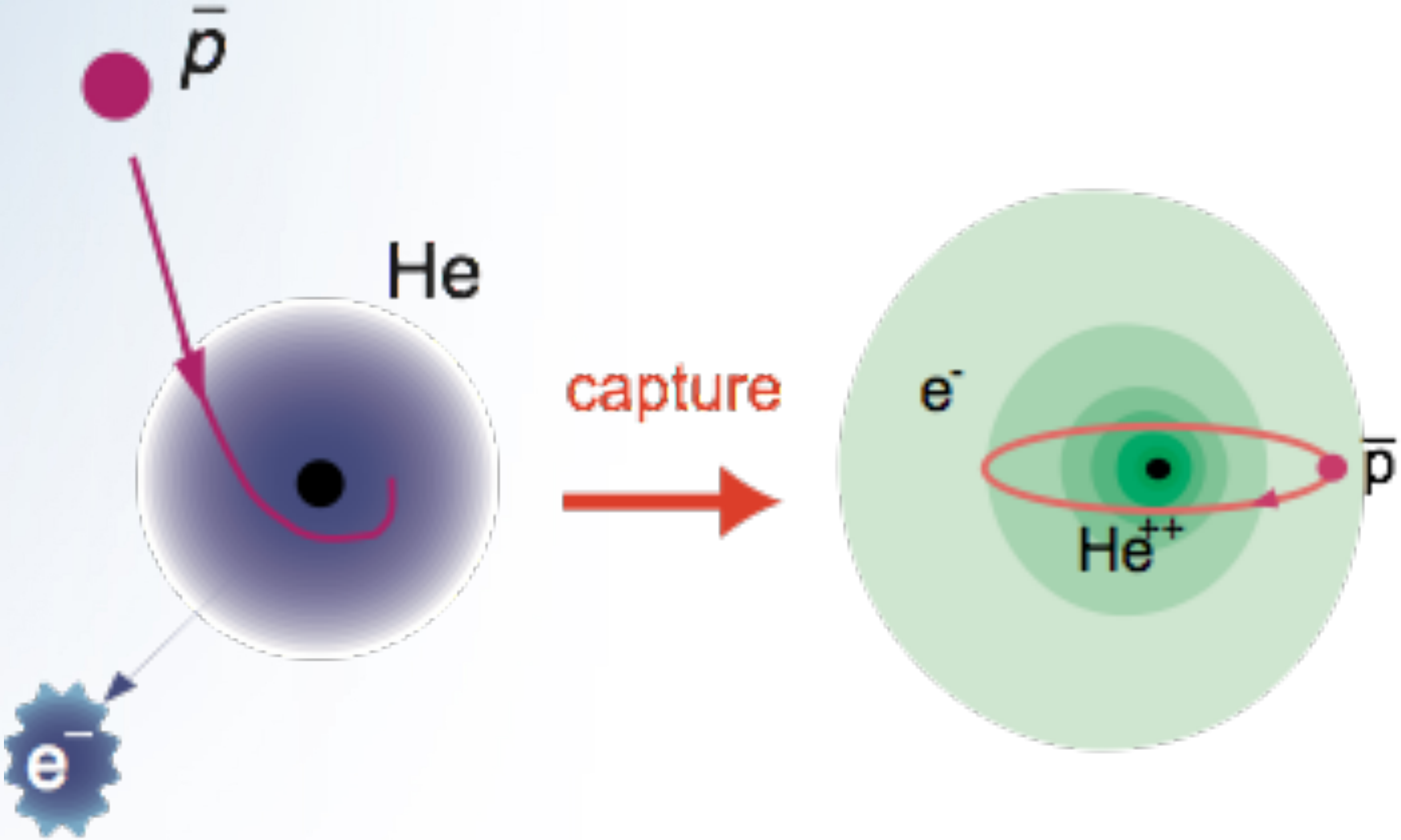
C. Smorra et al., Nature 550, 371 (2017)



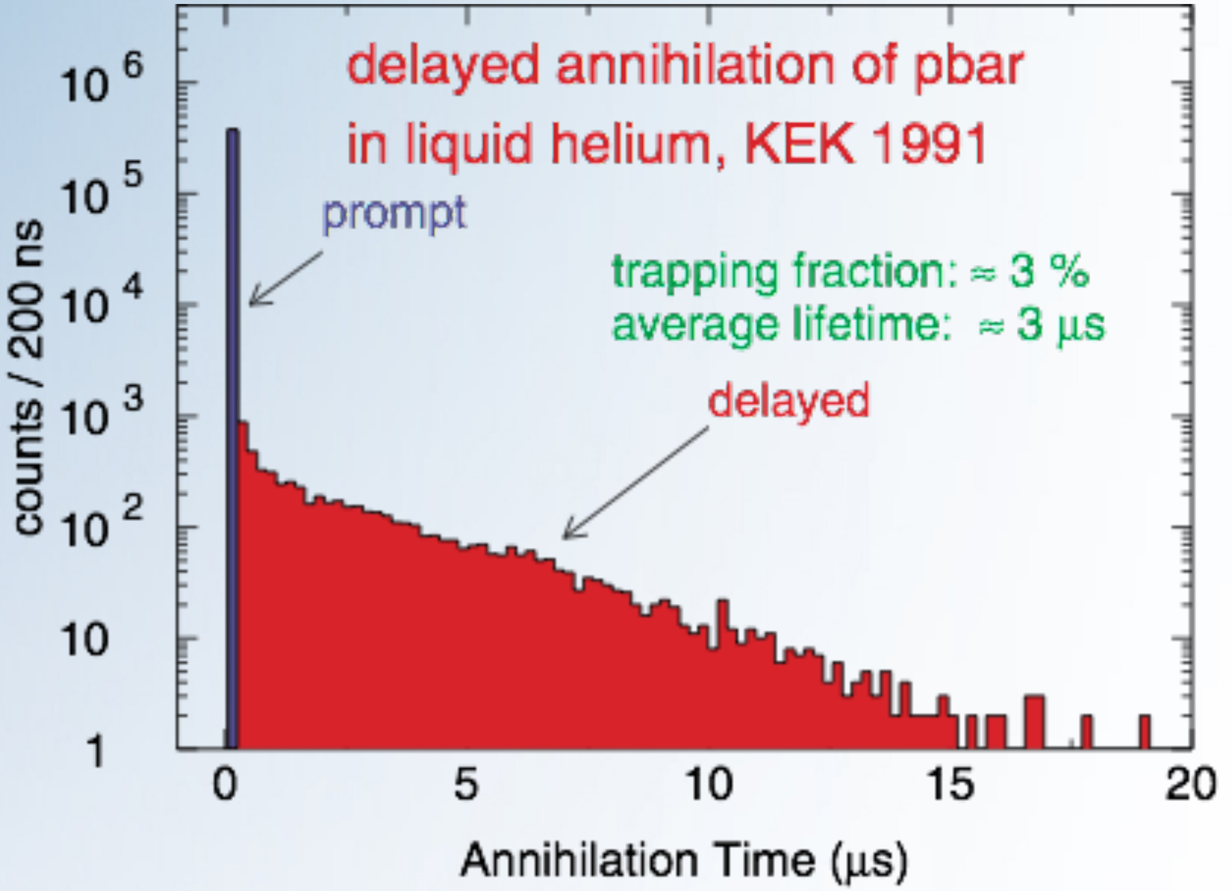
Previous work by the ATRAP collaboration Di Saccia et al. Phys. Rev. Lett. 110, 130801 (2013)

first measurement more precise for antimatter than for matter

ANTIPROTONIC HELIUM



ANTIPROTONIC HELIUM

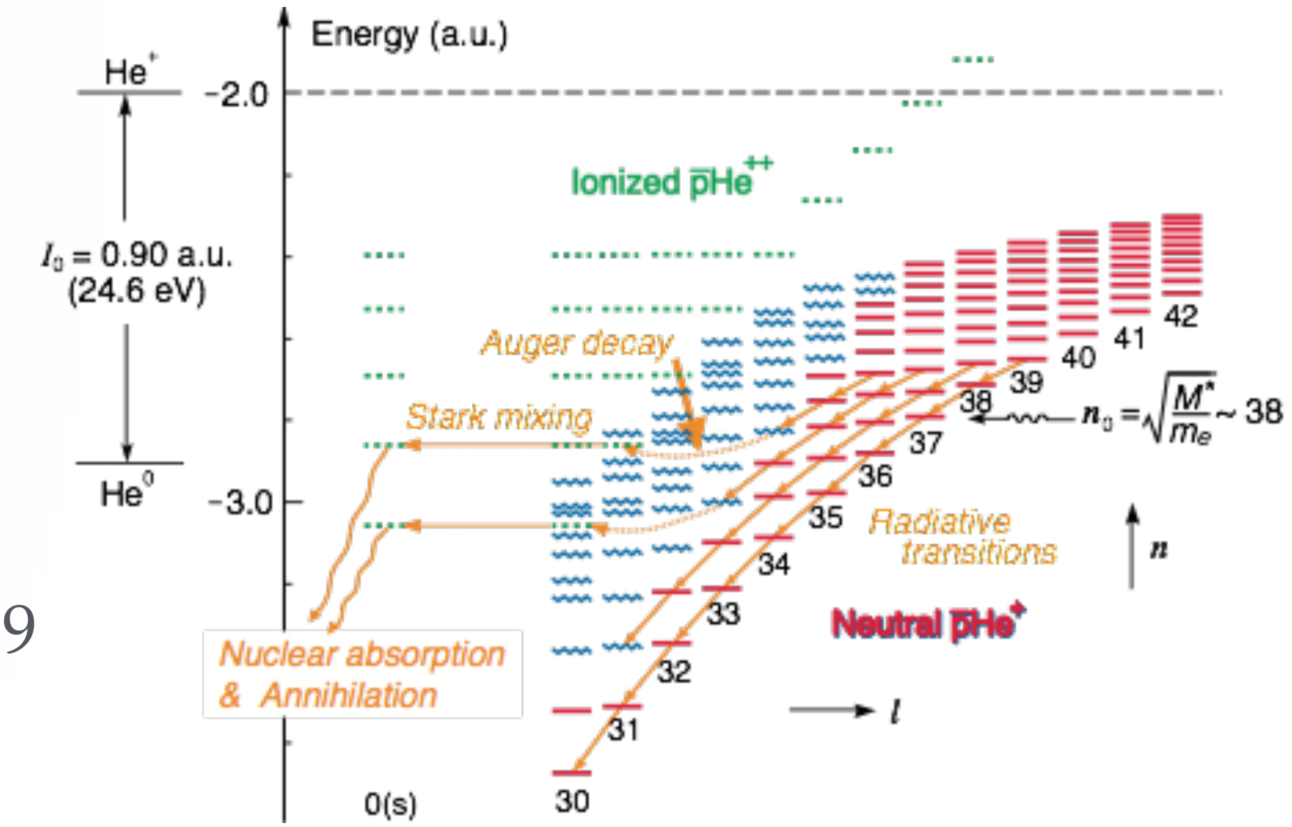


Three-body system $He^{++}e^{-}\bar{p}$,
$\bar{p}$ in highly excited, near circular states (n,l) ~ (38,37)

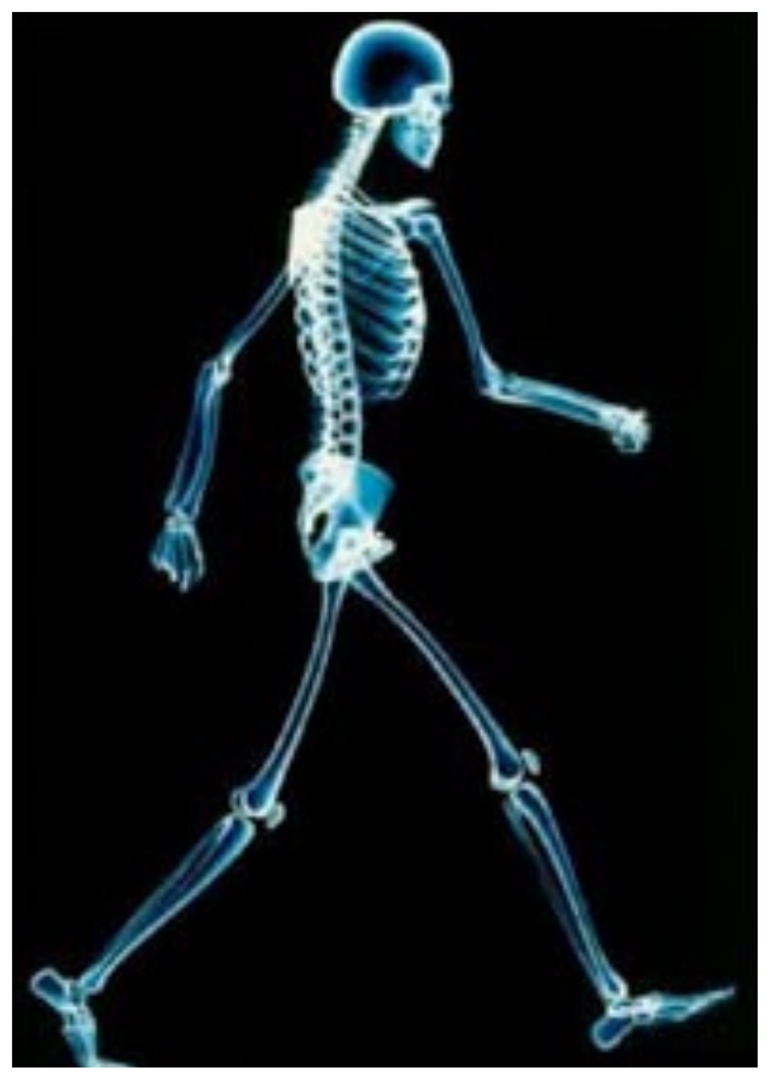
Comparison to 3-body QED calculations that use proton mass, magnetic moment

laser and microwave spectroscopy

CPT test
antiproton properties
mass,charge: $7\text{x}10^{-10}$ 2011
magnetic moment: $2.9\text{x}10^{-3}$ 2009



"DAILY "APPLICATIONS



Your body produces antimatter:

The body of an 80 kg individual produces 180 positrons per hour! These come mostly from the disintegration of potassium-40, a natural isotope which is absorbed by drinking water, eating and breathing.

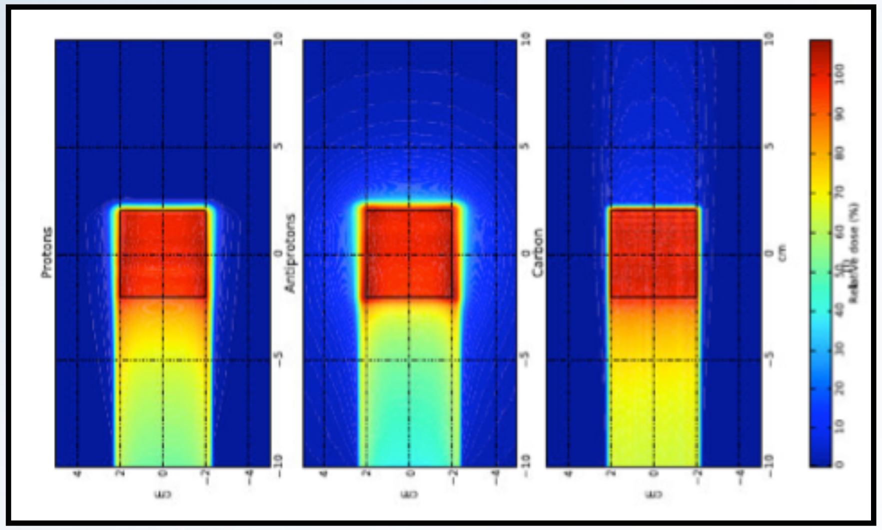
10 e+/s !

“DAILY ”APPLICATIONS

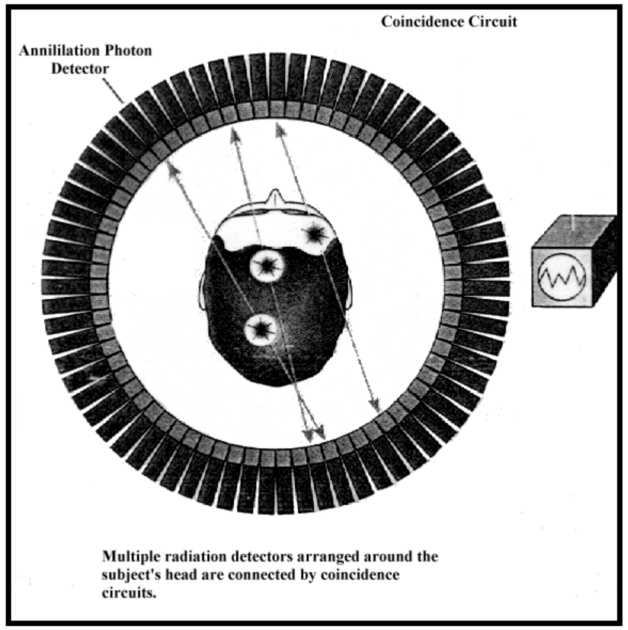
Antiprotons in accelerators!

Antiprotons for nuclear studies (PUMA)

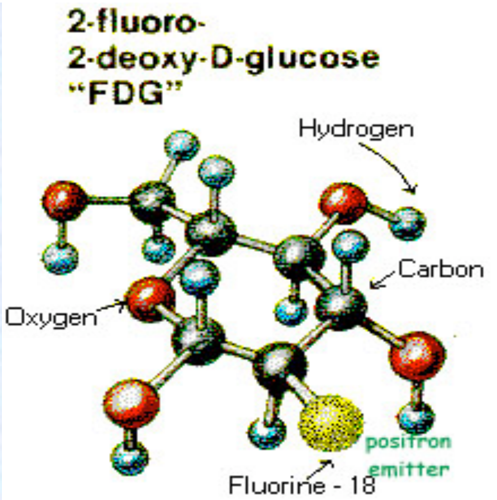
Antiproton Therapy (under study)



Medical imaging : PET



Multiple radiation detectors arranged around the subject's head are connected by coincidence circuits.



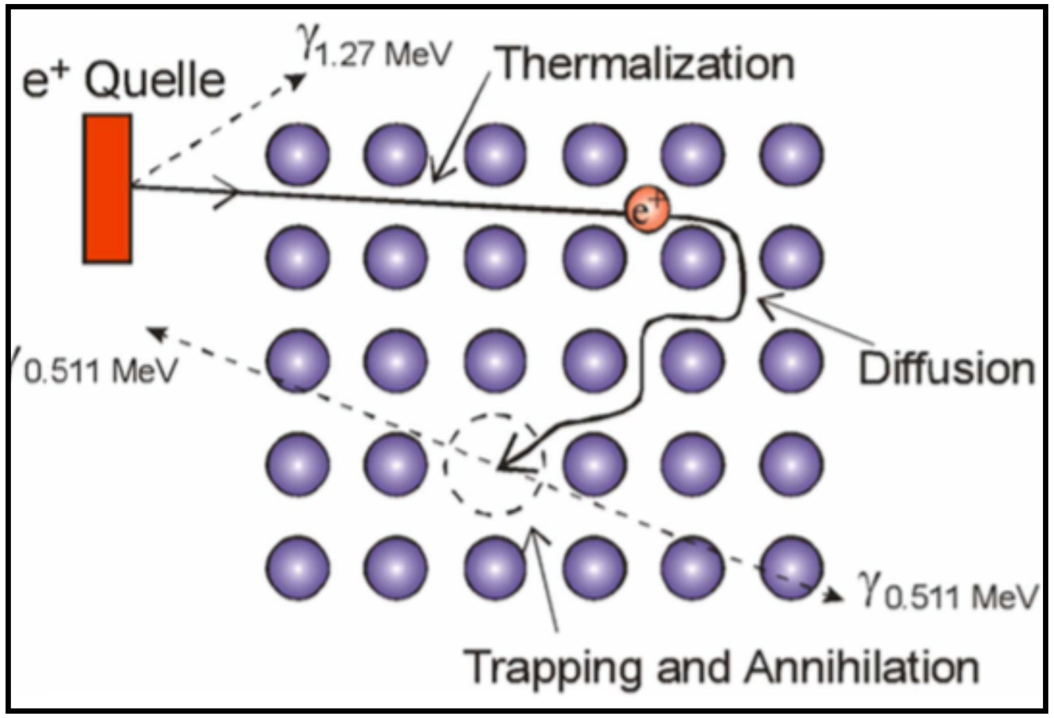
e+ emitting isotope (C-11, N-13, O-15)

(Lifetimes ~ few to 100 minutes)

Material Science

positron lifetime spectroscopy : positron wave-function can be localized in the attractive potential of a defect

Check material structure, defects etc



“DAILY ”APPLICATIONS

A fuel?

Most powerful fuel you can imagine.

1g would be enough to drive a car around the earth for 1000 times or bring the space shuttle into orbit
BUT ….

“DAILY” APPLICATIONS

1g of antimatter contains 90 TJ (~21kT of TNT)
1g of $\bar{p}$ ~ $6x10^{23}$

CERN produces $3x10^{7}$ $\bar{p}$/cycle ~ 10^{15} $\bar{p}$/yr

“DAILY” APPLICATIONS

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Almost a billion years needed to produce 1g (not saying trapping them all!)

“DAILY” APPLICATIONS

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1g of $\bar{p} \sim 6 \times 10^{23}$

CERN produces 3×10^{7} $\bar{p}$/cycle ~ 10^{15} $\bar{p}$/yr

Almost a billion years needed to produce 1g (not saying trapping them all!)

Energy efficiency is about 10^{-9}

We need ~9×10^{22} J

Electricity discount price @ CERN 1kWh =3.6×10^{6} J =0.1€

“DAILY” APPLICATIONS

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2 000 000 000 000 000 €

“DAILY” APPLICATIONS

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Electricity discount price @ CERN 1kWh =3.6 10^{6} J =0.1€

2 000 000 000 000 000 €

a year of p̄ trapped and annihilating would illuminate a light bulb for 5s

Enjoy your Summer Studentship!

AD PHYSICS PROGRAMME :
TESTING FUNDAMENTAL SYMMETRIES & CORNERSTONE OF SM

TEST BODIES : EXOTIC ANTIMATTER ATOMS & ANTIPROTONS

>20 YEARS OF UNIQUE RESEARCH WITH ANTIHYDROGEN

ENTERING PRECISION AREA WITH ANTIHYDROGEN

MANY OTHER IDEAS : CHARGE NEUTRALITY, PROTONIUM SPECTROSCOPY, PORTABLE PBAR TRAP …

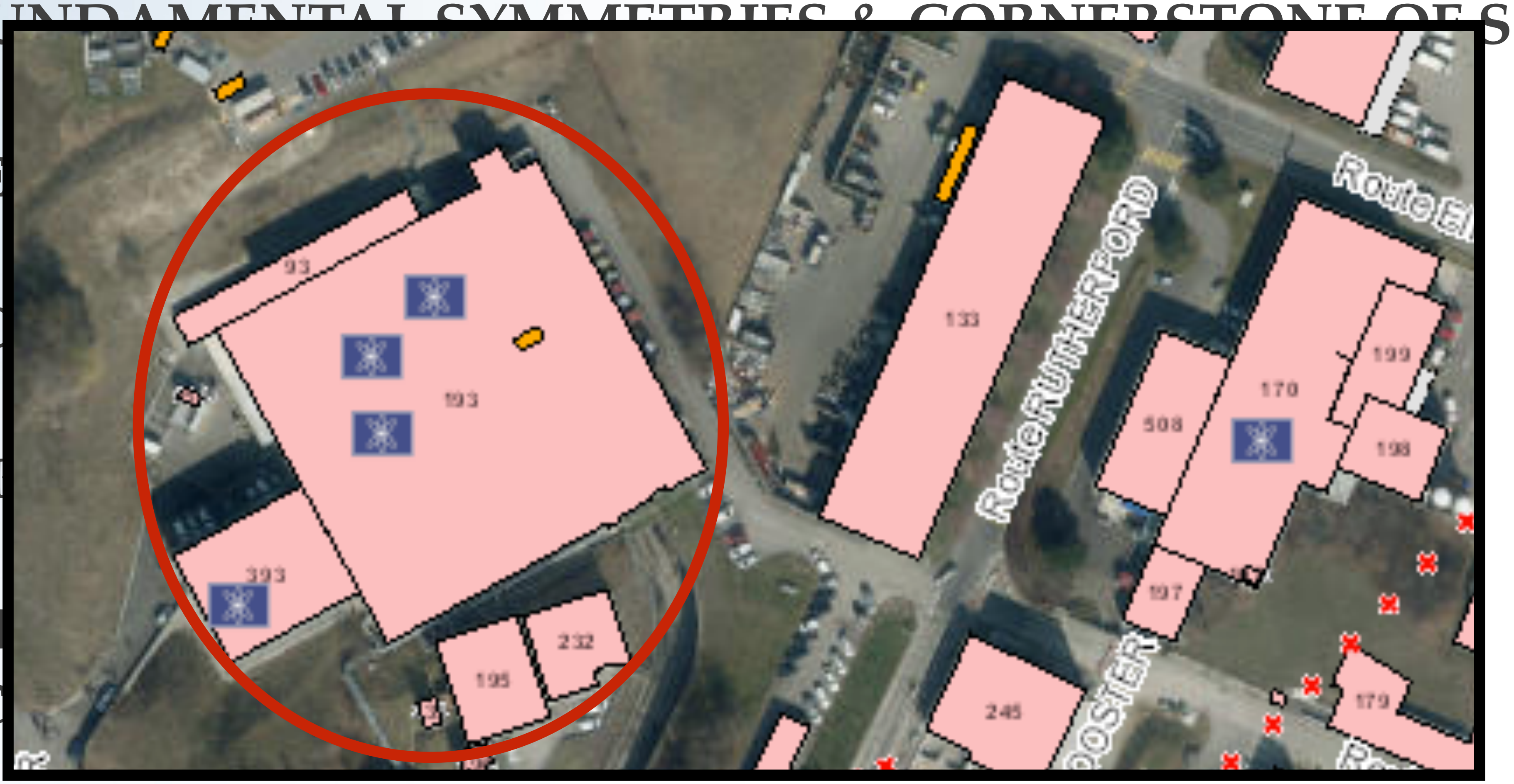
ANTIMATTER AS MEDICAL AND SCIENTIFIC TOOLS

OTHER APPLICATIONS OF ANTIMATTER?

Enjoy your Summer Studentship!

AD PHYSICS PROGRAMME :

TESTING FUNDAMENTAL SYMMETRIES & CORNERSTONE OF SM



TEST BODIE

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ANTIMATTER AS MEDICAL AND SCIENTIFIC TOOLS

OTHER APPLICATIONS OF ANTIMATTER?