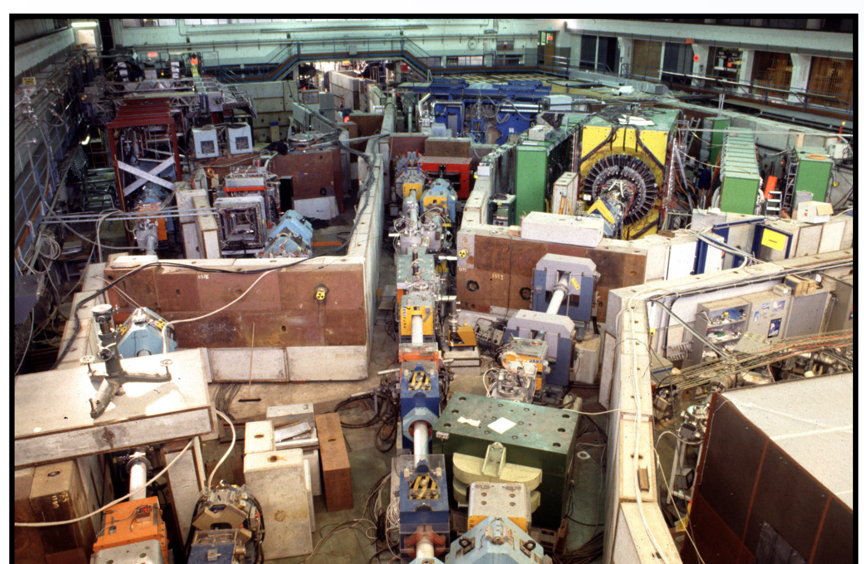
ANTIMATTER IN THE LAB

Chloé Malbrunot
CERN



CERN Summer student lecture 2018

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

<u>**The case of antiprotons**</u>

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

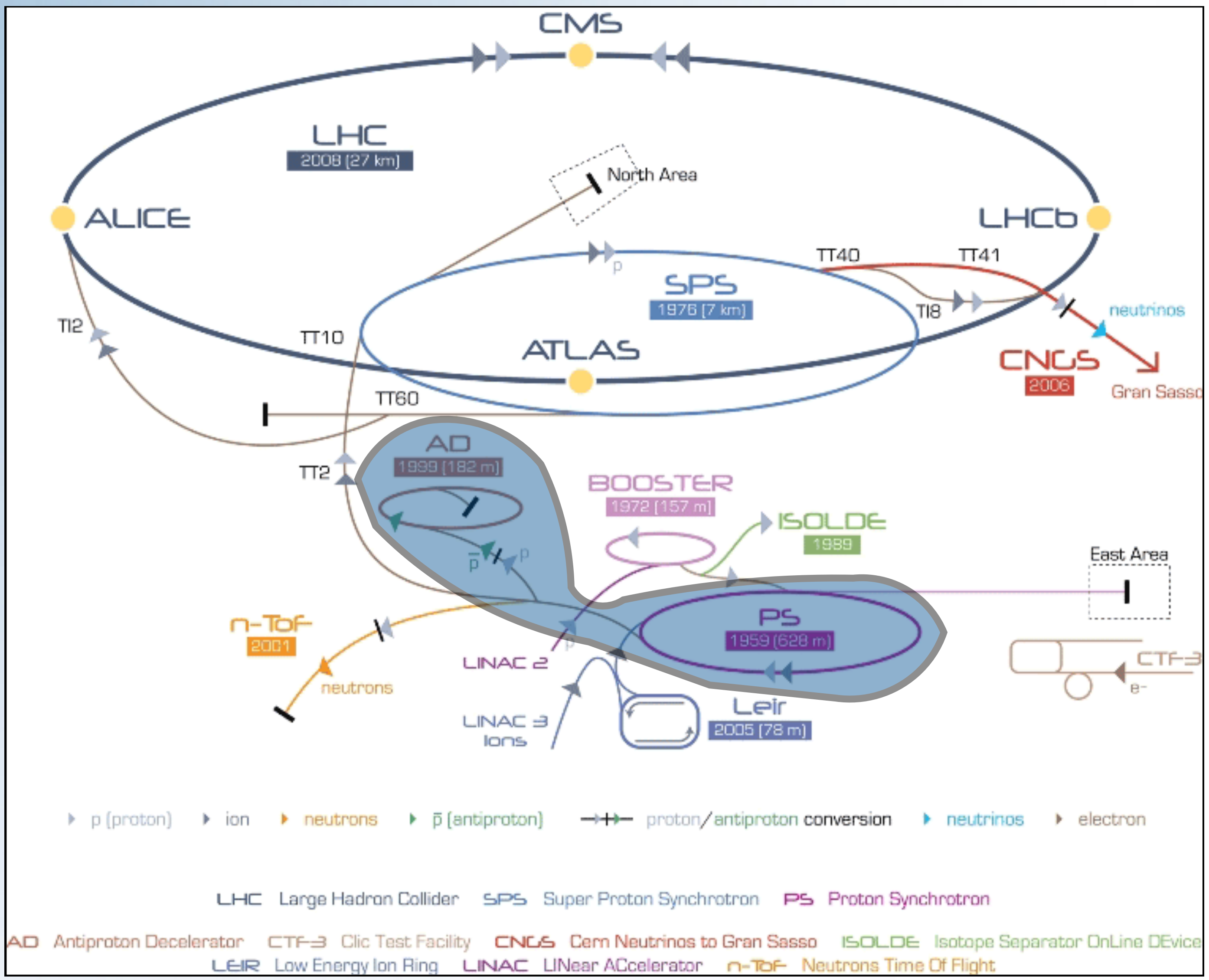
$$\boxed{\sqrt{s} = \sqrt{2m_p^2 + 2E_p m_p}}$$

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



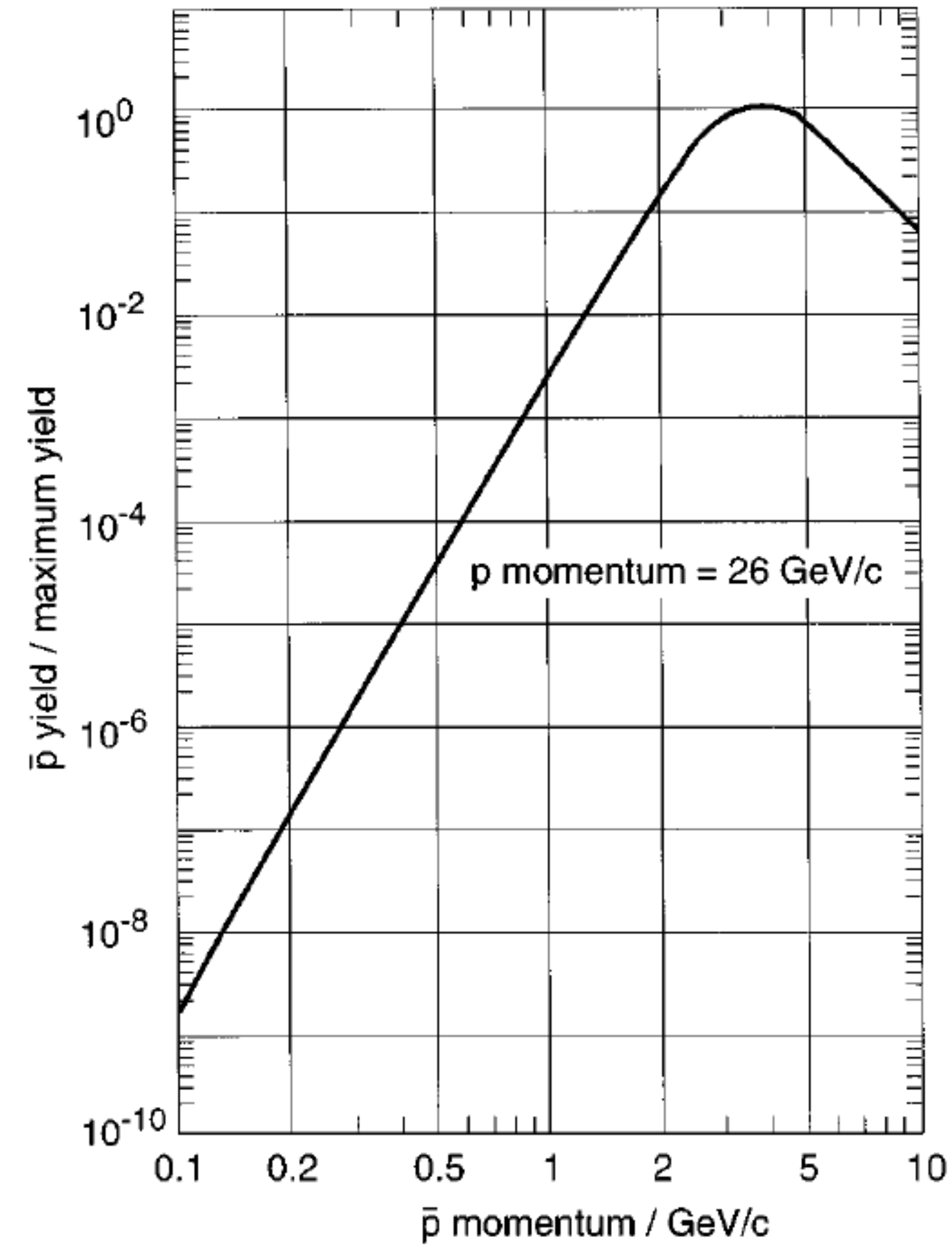
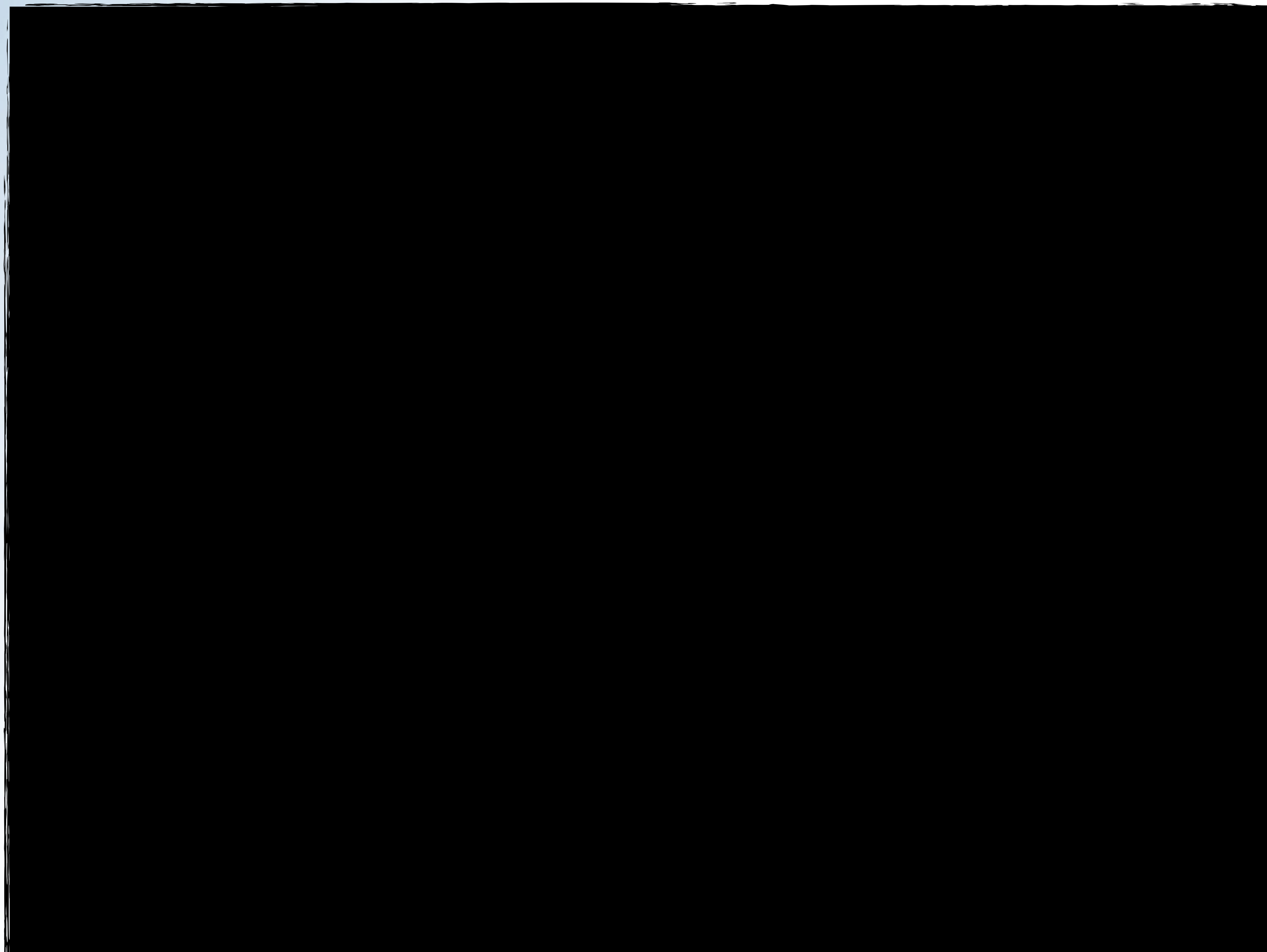


FIG. 1. Normalized antiproton yield (antiprotons per proton) at 26 GeV/c proton-beam momentum. The normalization is chosen so that the yield is one at the maximum.

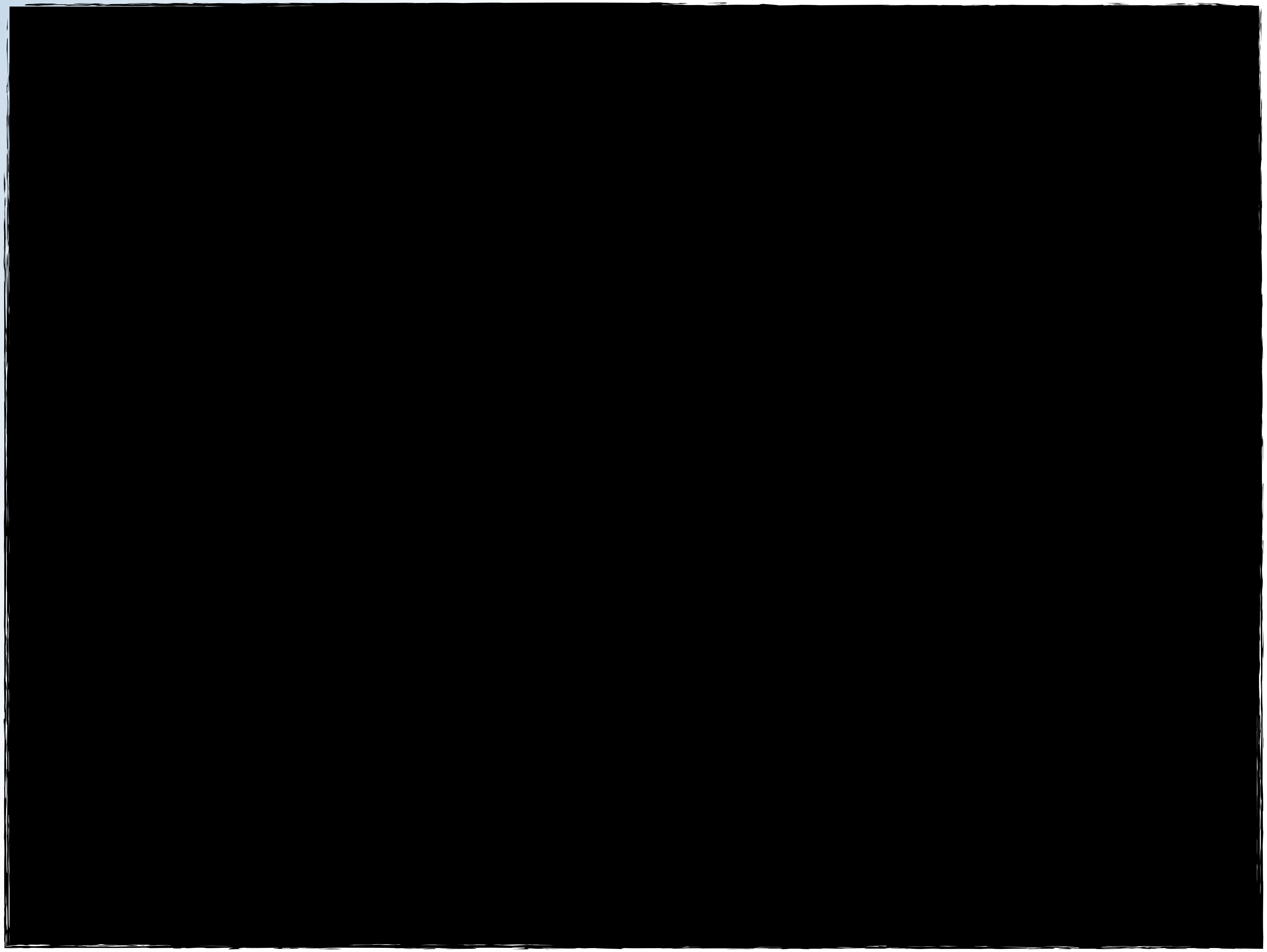
Production at 26 GeV/c

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

Antiprotons at lower energies



Antiprotons at lower energies



Antiproton Cooling

Cooling : reduce phase space and increase phase-space density

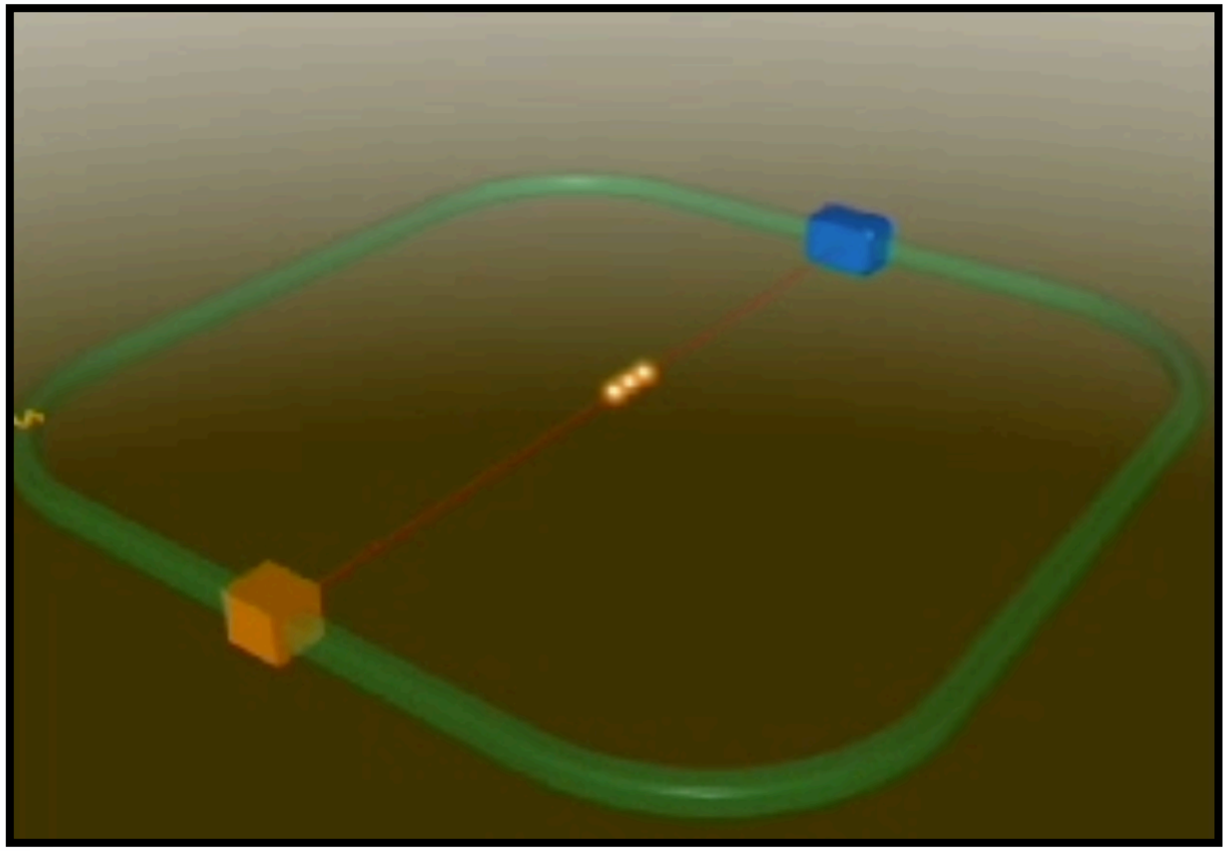
$$D = \frac{N}{\sqrt{E_h E_v} L \frac{\Delta p}{p}}$$

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

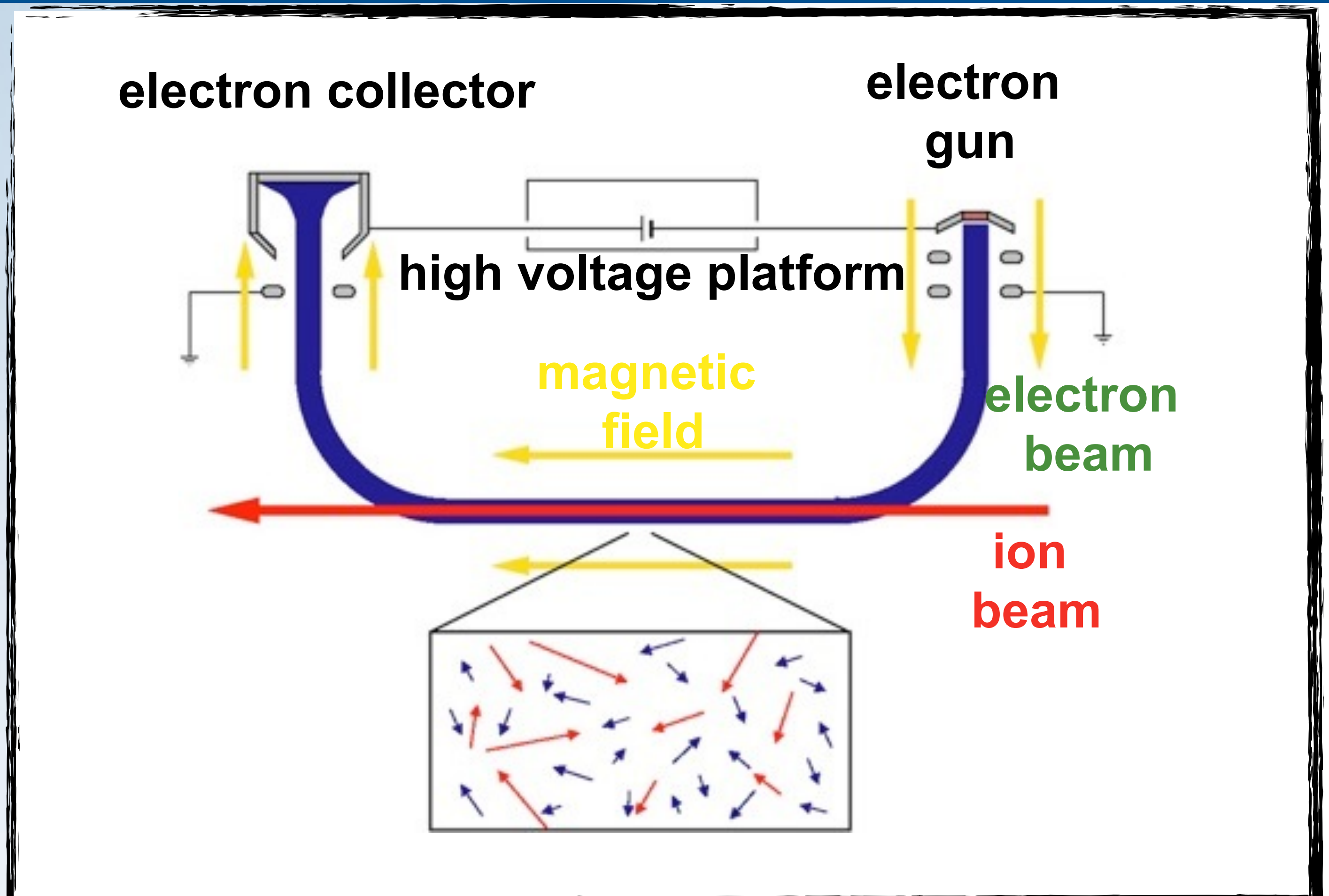
Cooling methods :

- Stochastic cooling

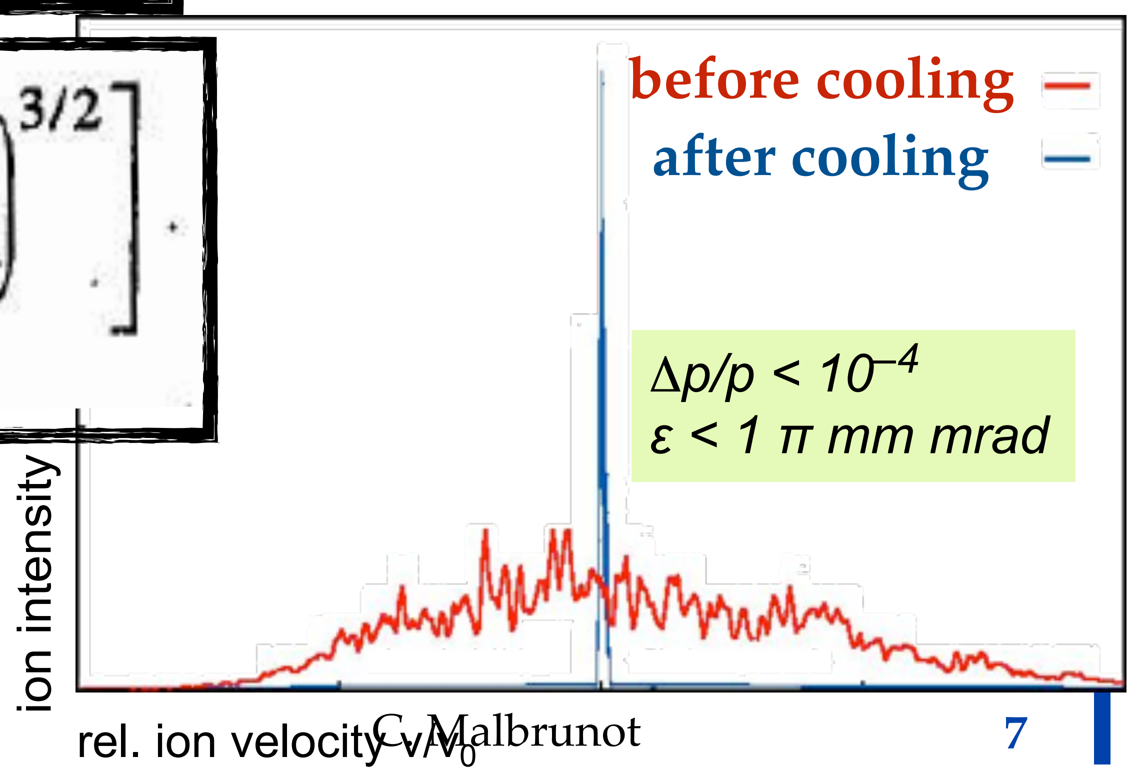
- Electron cooling



Electron cooling



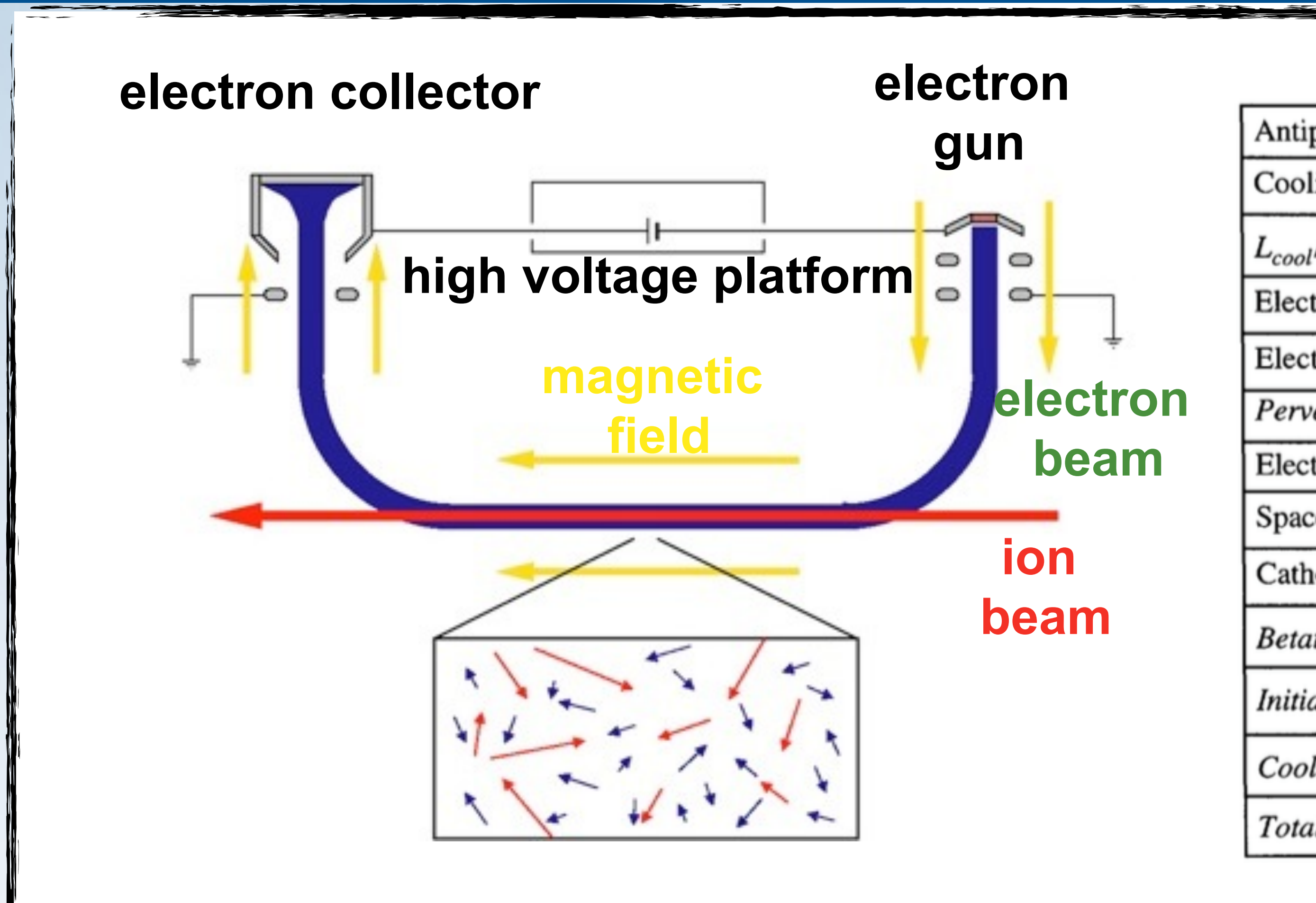
$$\tau_e = \frac{C}{L_e} \frac{F_1 \gamma_0^2}{r_e r_i n_e c \ln\Lambda} \left[\left(\frac{k_B T_{be}}{m_e c^2} \right)^{3/2} + \left(\frac{k_B T_{bi}}{m_i c^2} \right)^{3/2} \right].$$



Le/C: fraction of circ. covered by electrons

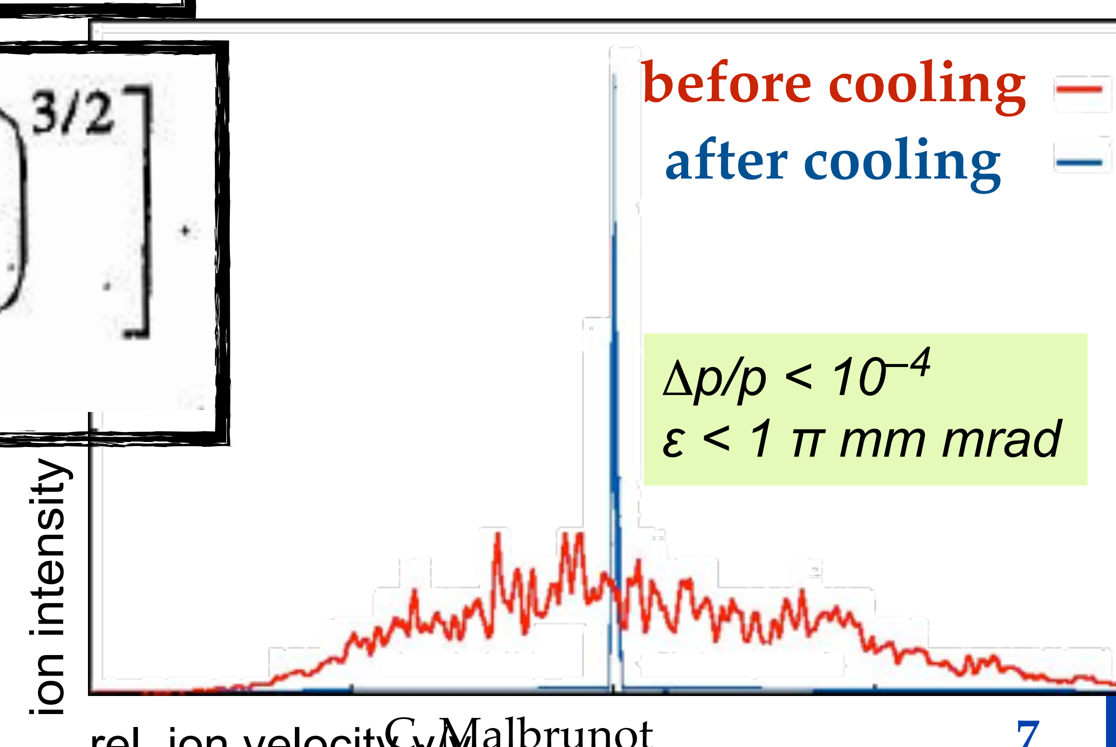
R: classical radii, F~ 0.3

Electron cooling



		300	100
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)

$$\tau_e = \frac{C}{L_e}\frac{F_1\gamma_0^2}{r_e r_i n_e c \ln\Lambda}\left[\left(\frac{k_B T_{be}}{m_e c^2}\right)^{3/2} + \left(\frac{k_B T_{bi}}{m_i c^2}\right)^{3/2}\right].$$



Le/C: fraction of circ. covered by electrons
R: classical radii, F~ 0.3

Stochastic cooling

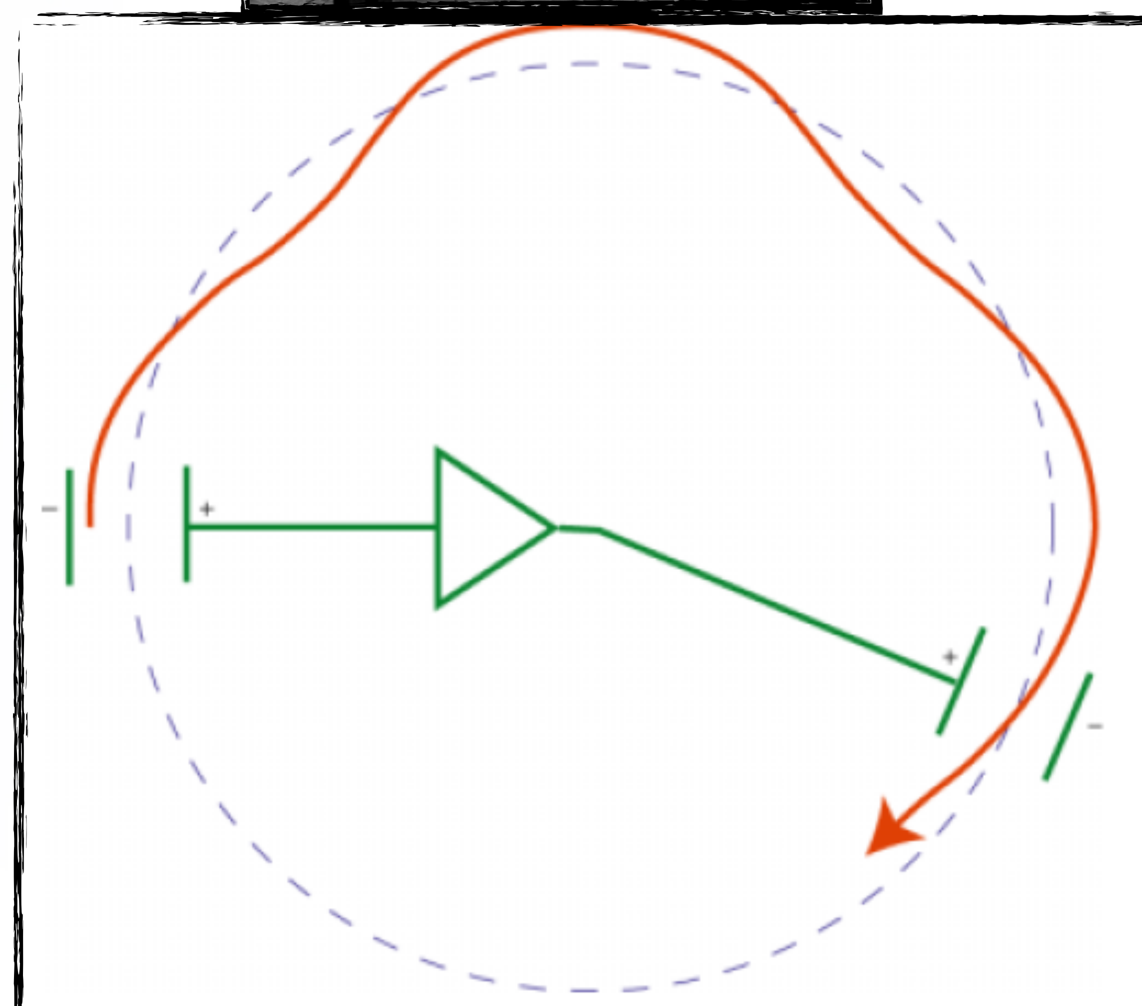
Measure beam center by pick-ups
Correction signal to opposite kicker

Pioneered at CERN for discovery W,Z bosons

Nobel Prize S. van der Meer

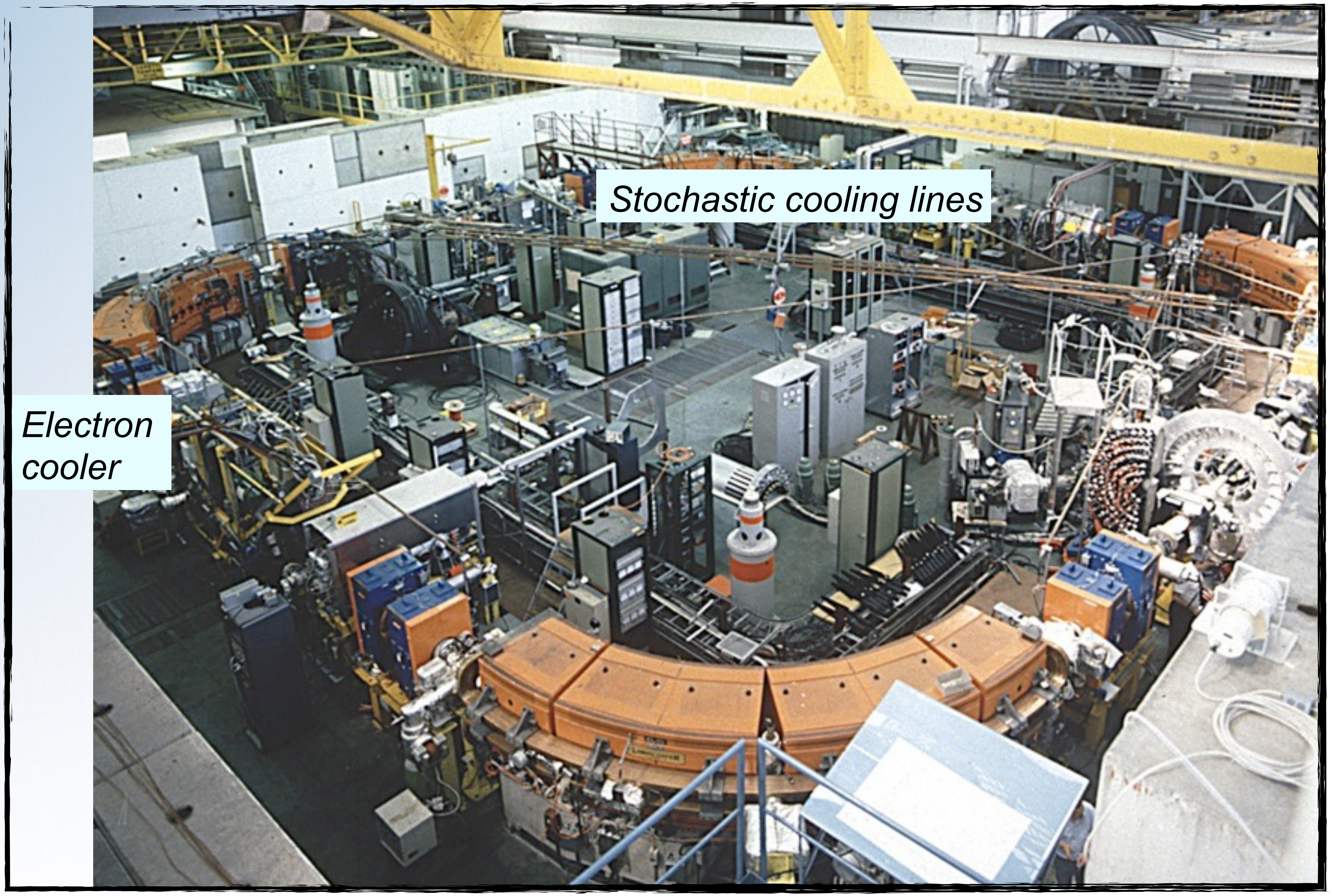
Cooling power decreases with decreasing energy

Cooling time ~ number of particles

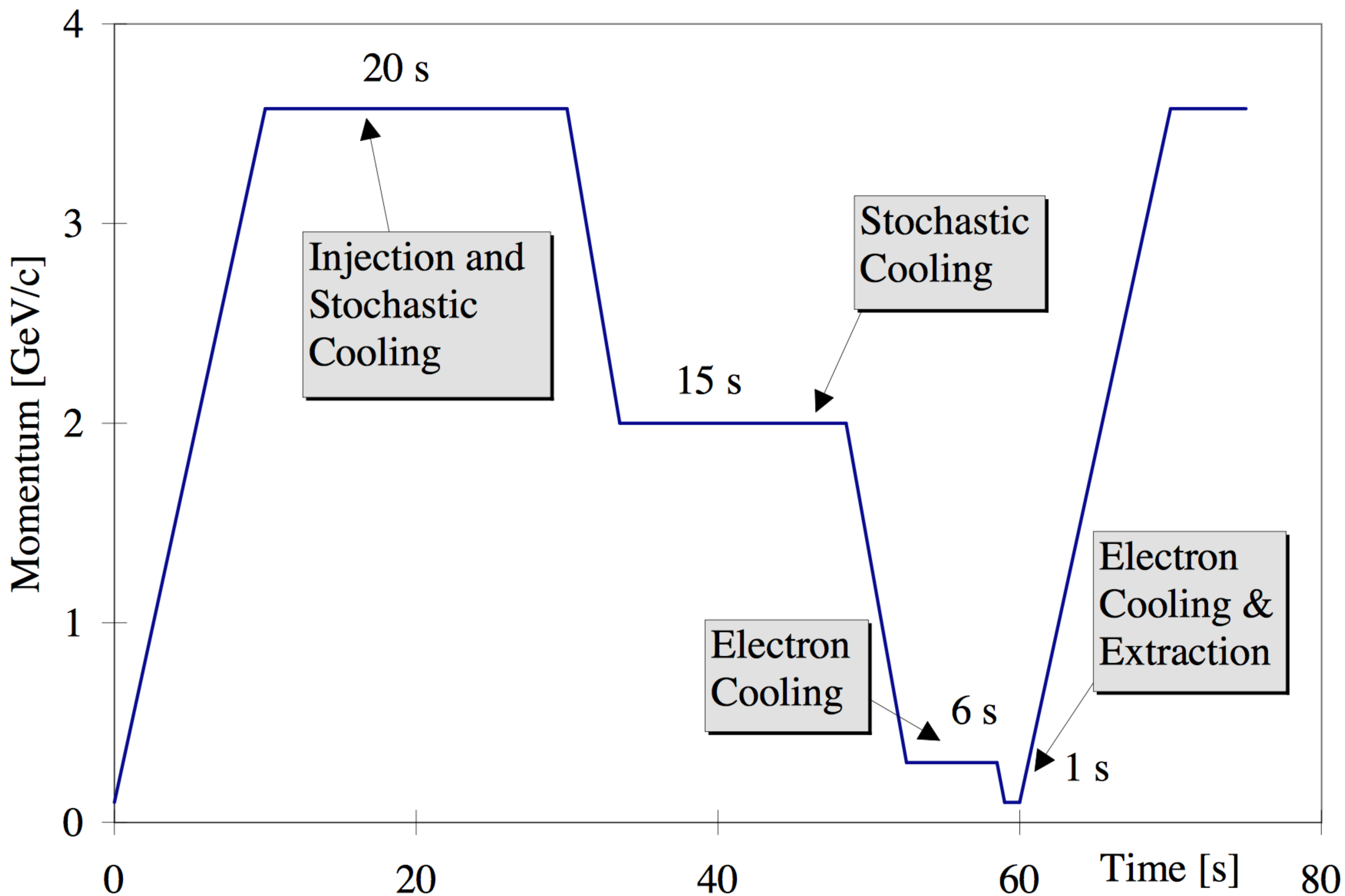


$$\Delta p/p \sim 0.07\%$$
$$\epsilon = 3 - 4\ \pi \mathrm{mm.mrad}$$

LEAR



The Antiproton Decelerator



The AD Facility

All-in-one machine:

Antiproton capture

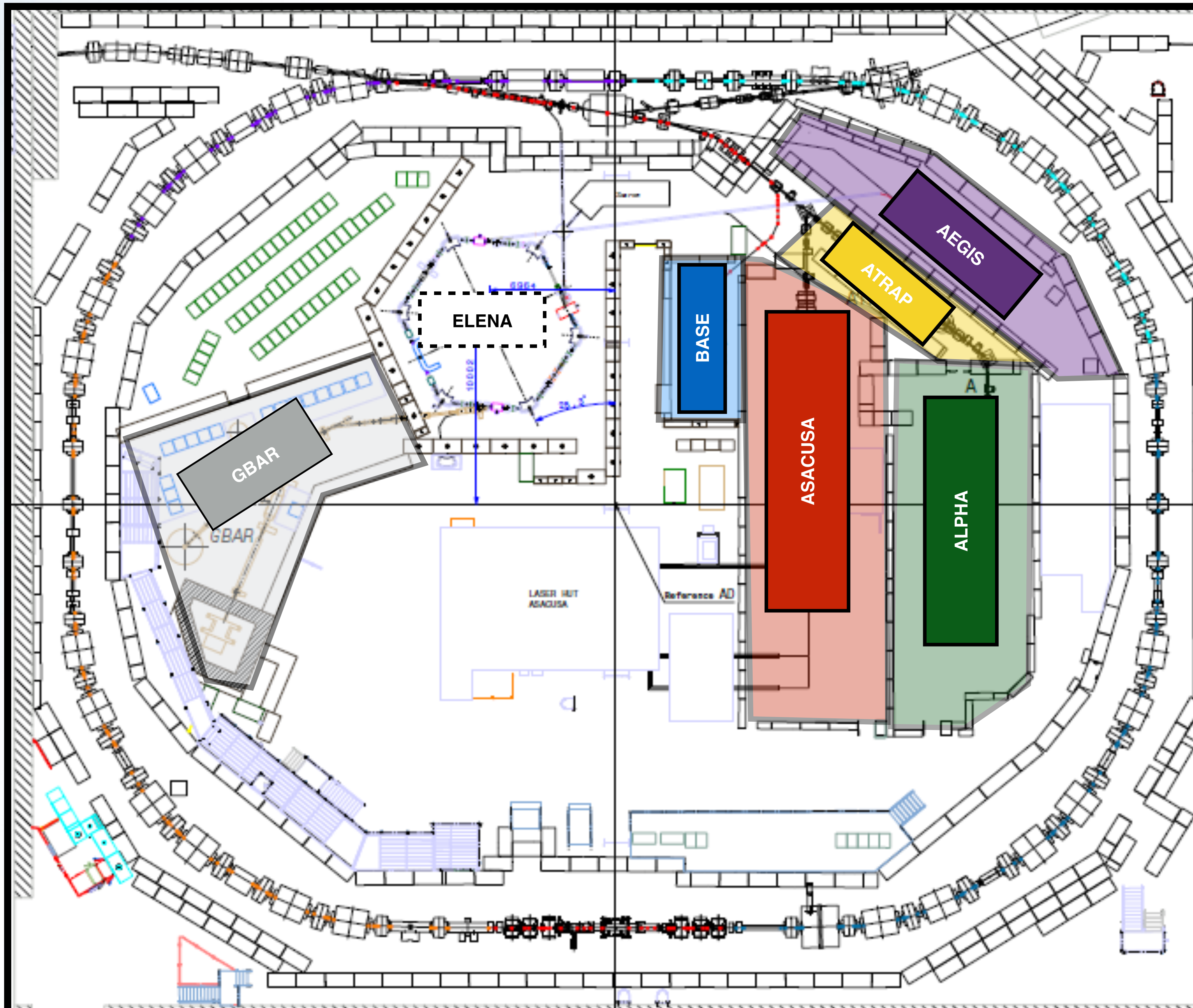
deceleration & cooling

100 MeV/c (5.3 MeV)

Pulsed extraction

2-4 x 10^7 antiprotons per pulse of 100 ns length

1 pulse / 85–120 seconds



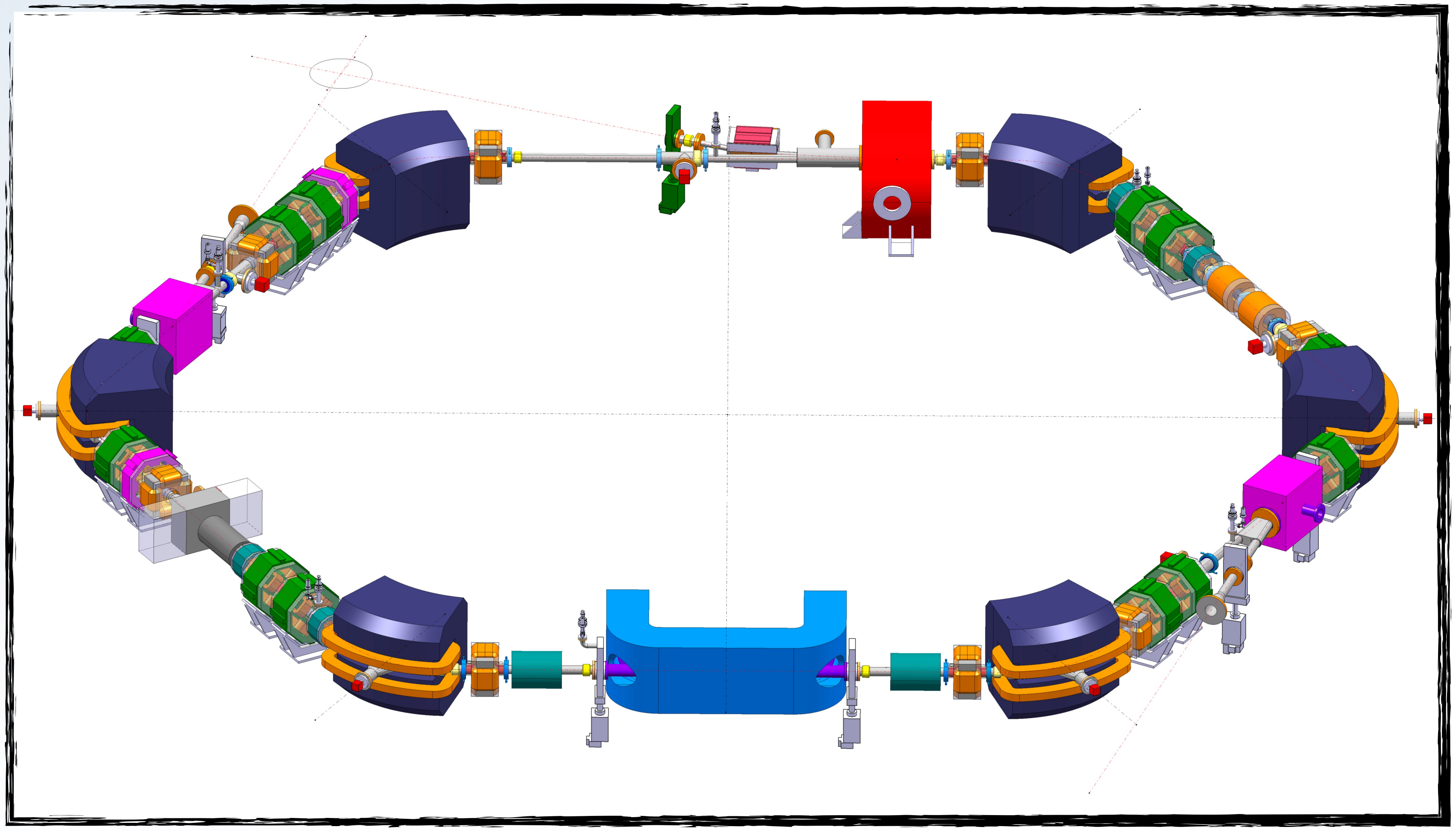
ELENA

Decelerator after the AD : 5.3 MeV -> 100 keV

In commissioning.

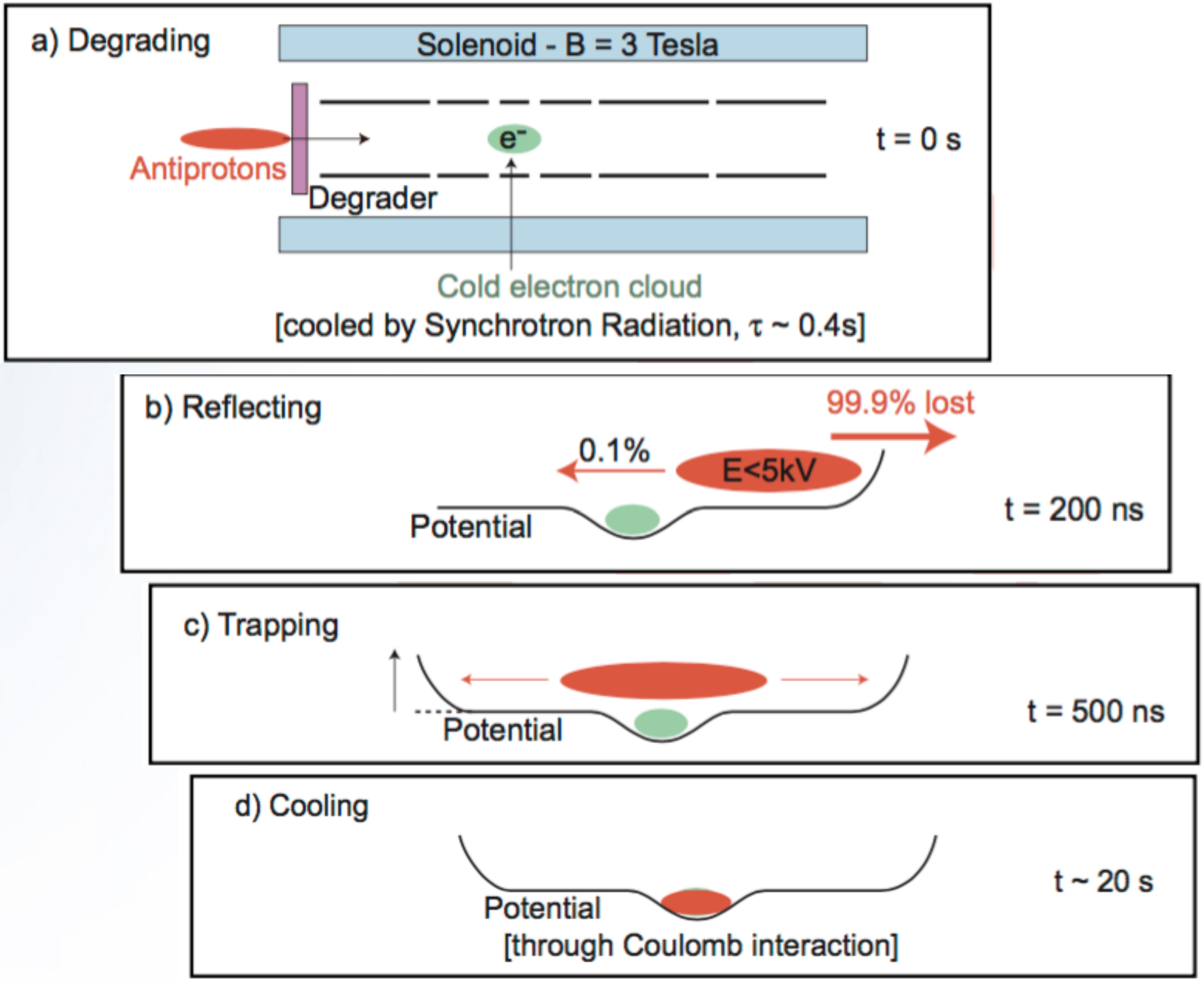
Delivery of $\bar{p}$ to all AD experiments planned for 2021

Can be seen at the AD!



Penning traps

Long trapping times require good vacuum!



Penning traps

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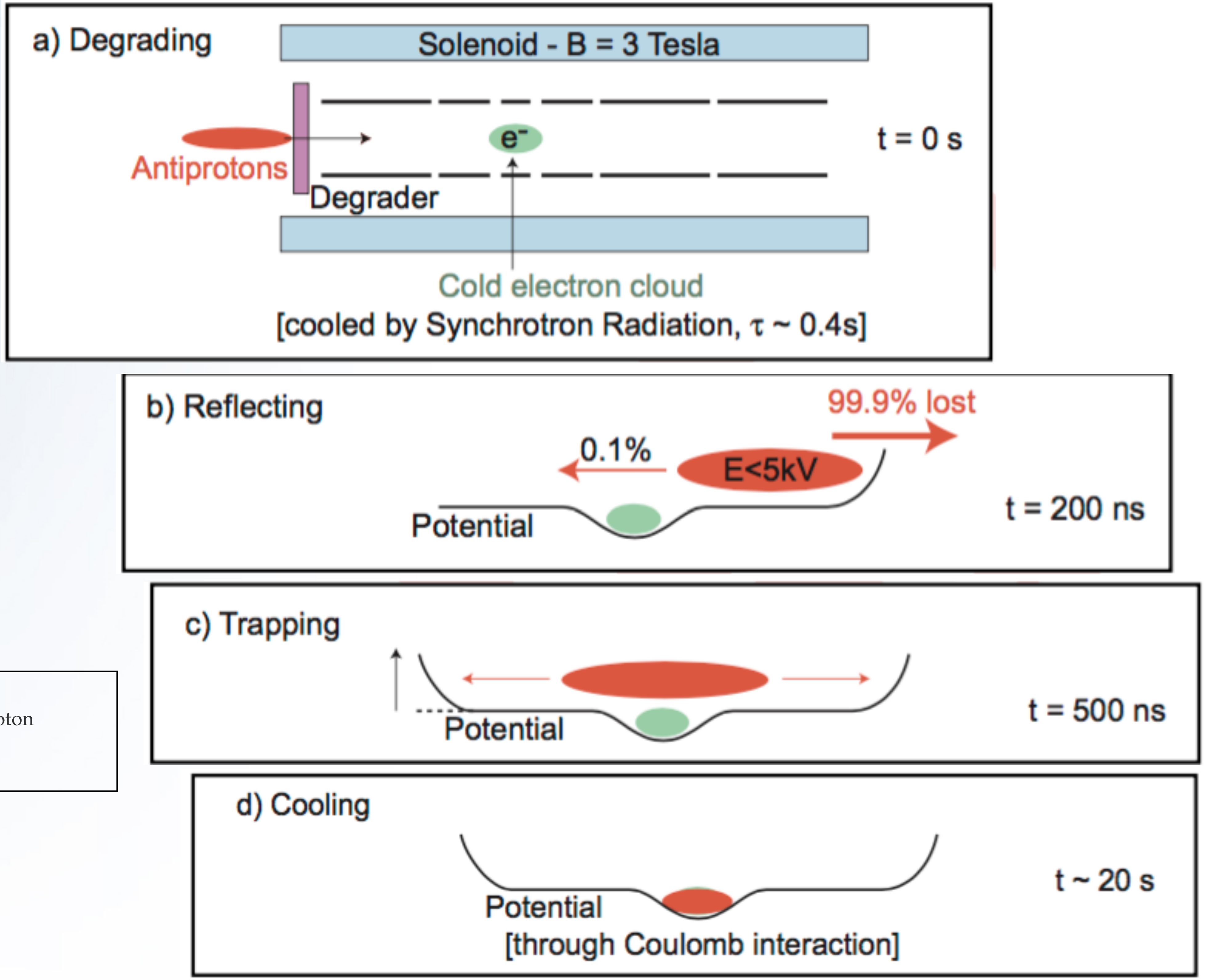
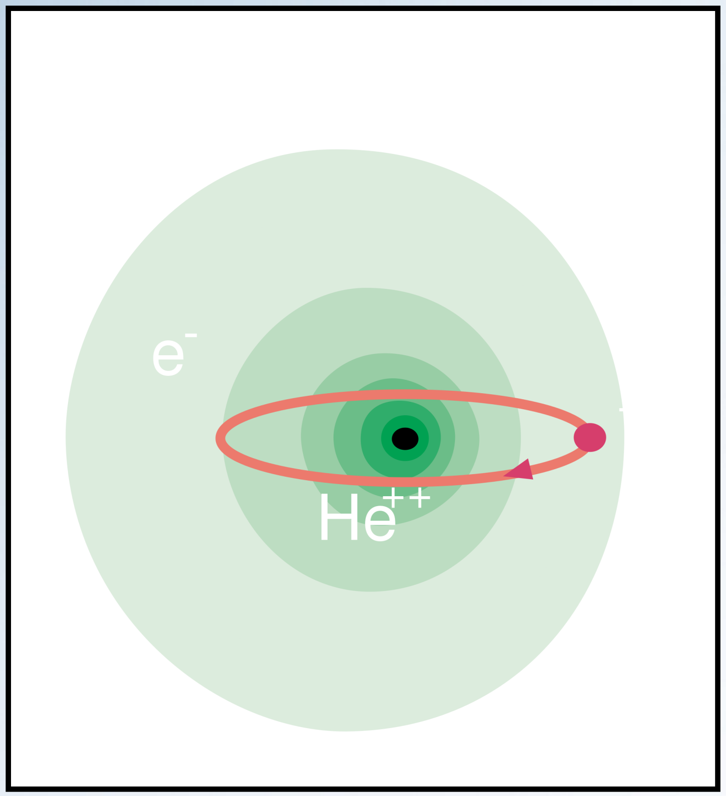


BASE : **P < 2. 10^{-18} mbar**

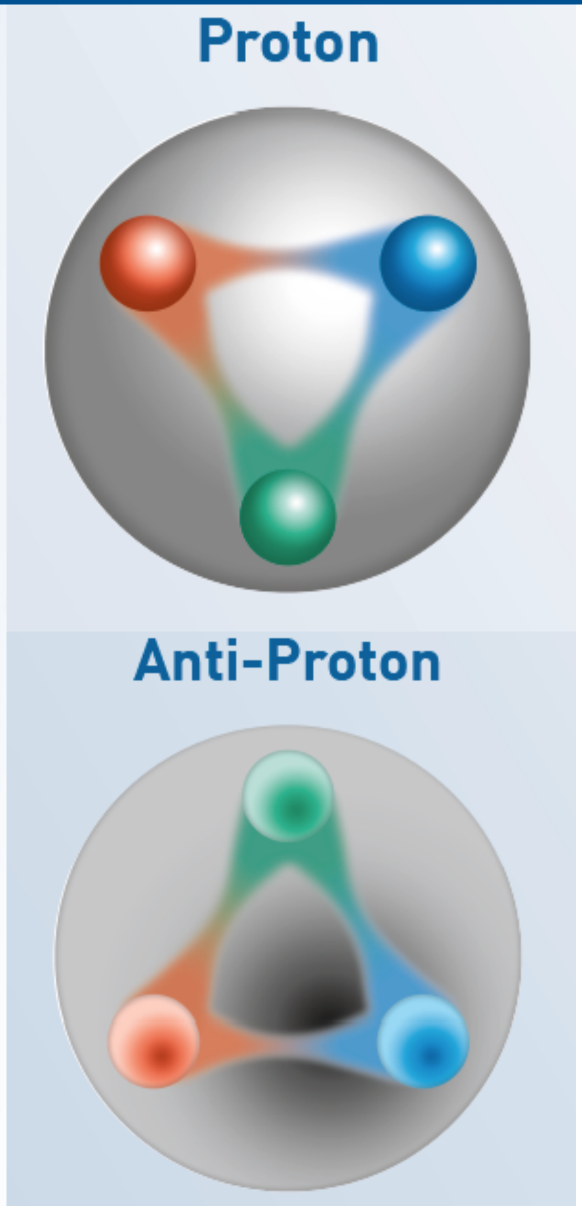
$\tau(\bar{p})$ **> 10.2 years** (68% confidence level)

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

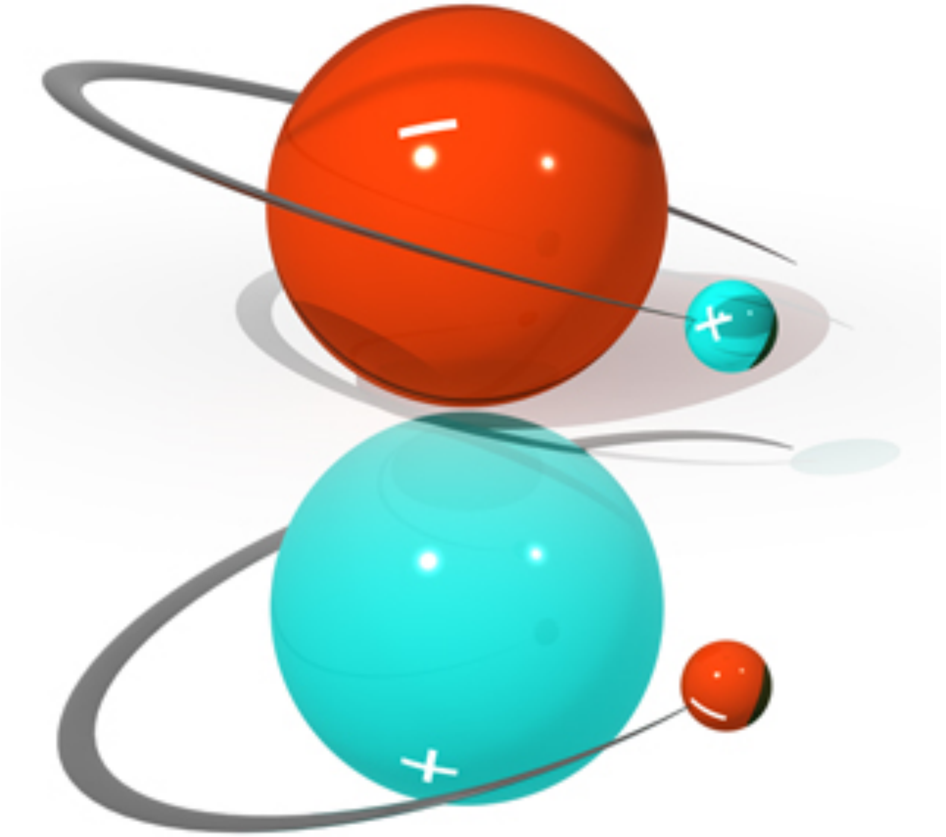
AD EXPERIMENTS



ASACUSA



BASE
ASACUSA
ATRAP



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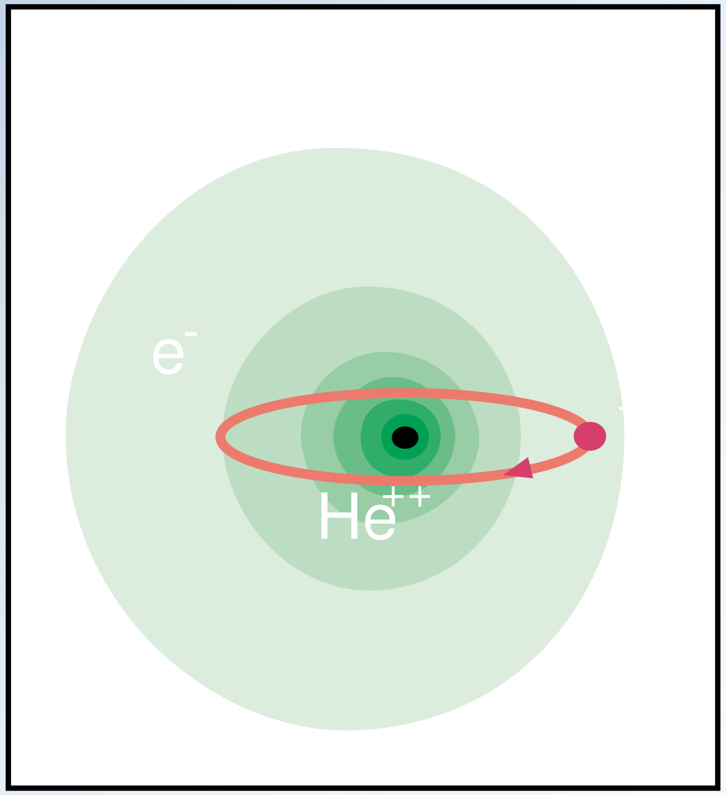
ATRAP
ASACUSA
AEGIS
GBAR

AD EXPERIMENTS



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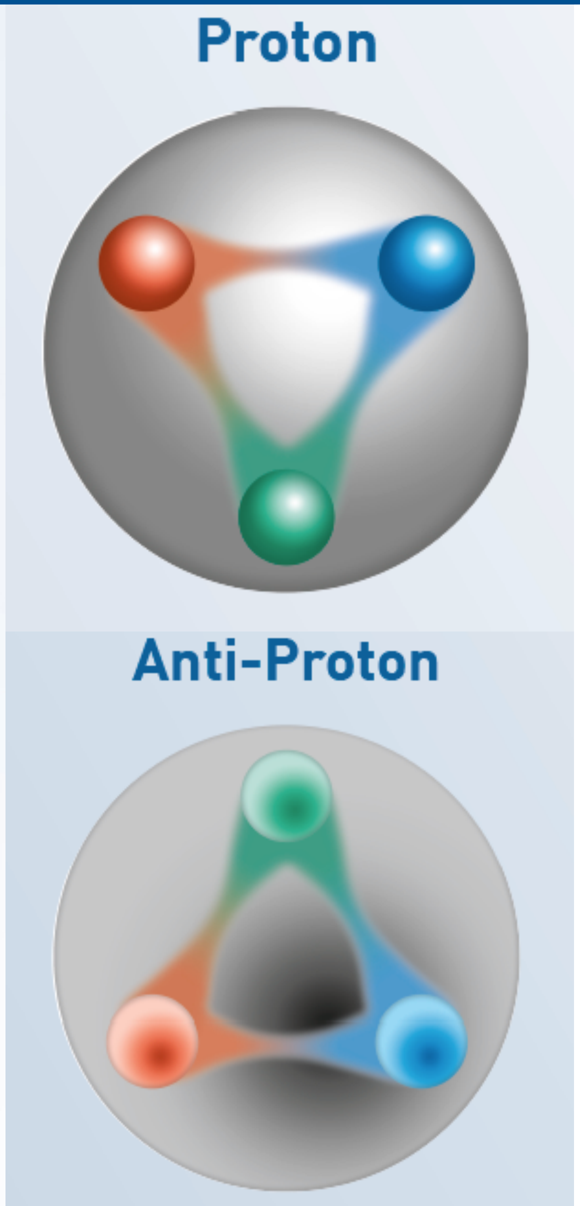

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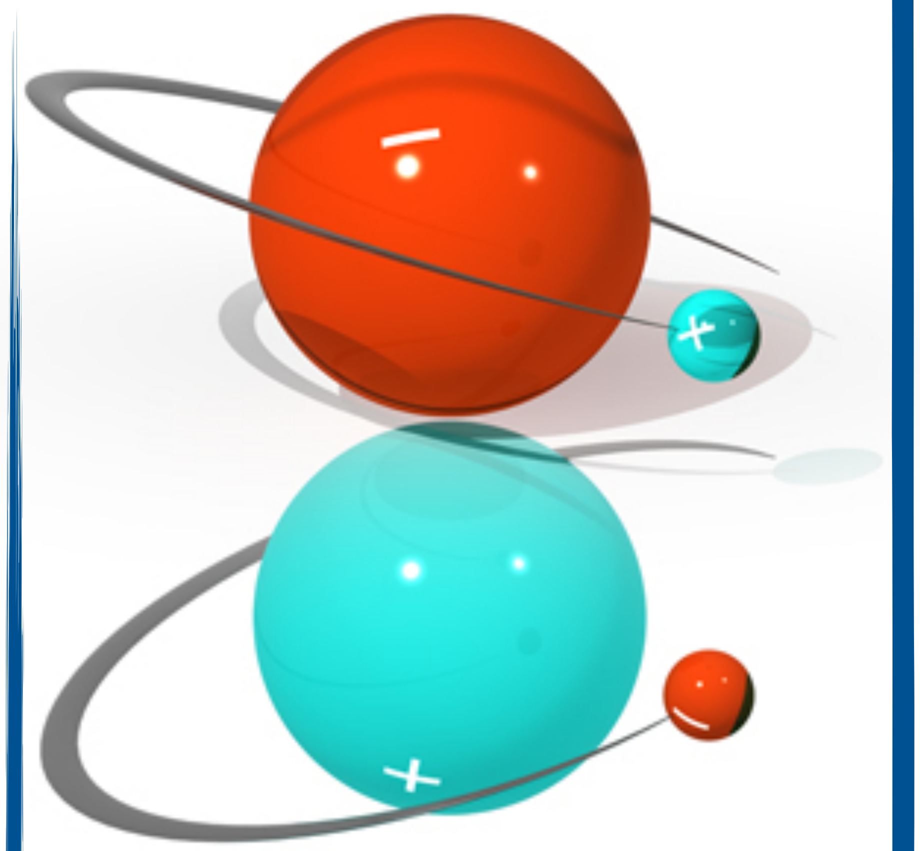

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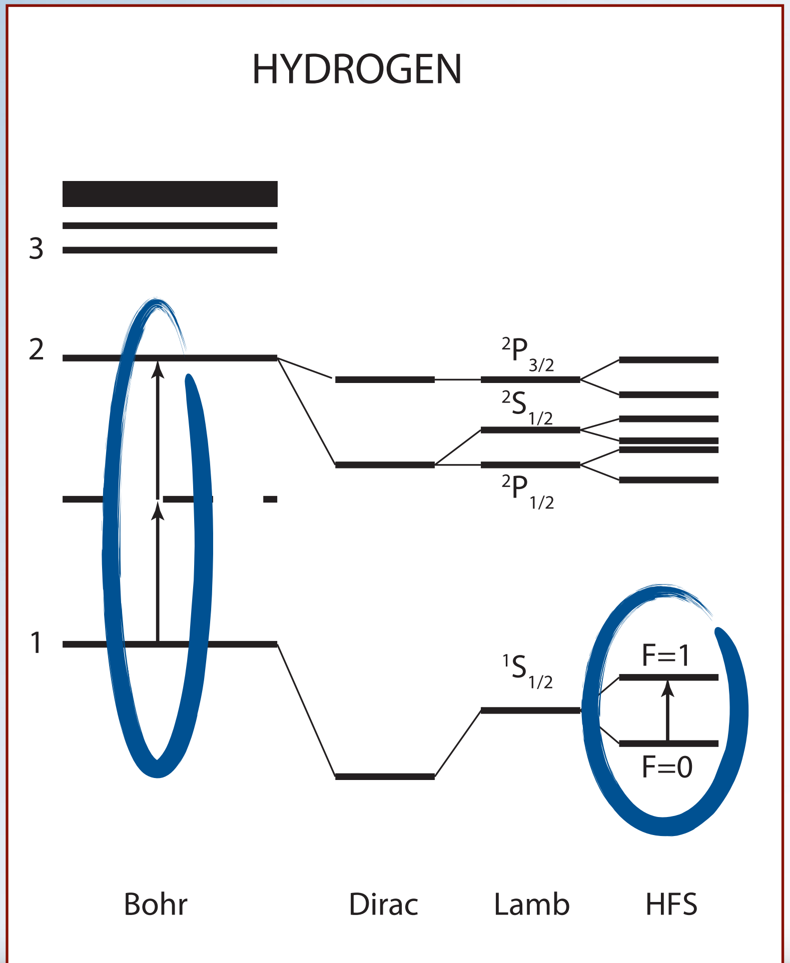
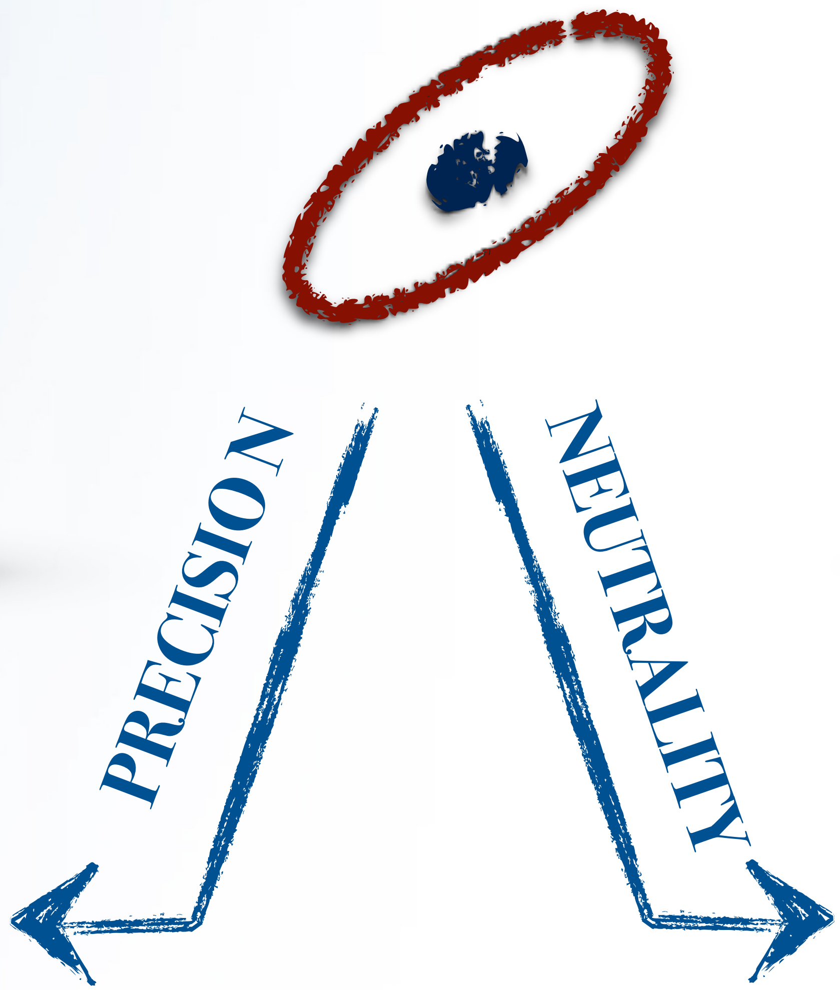
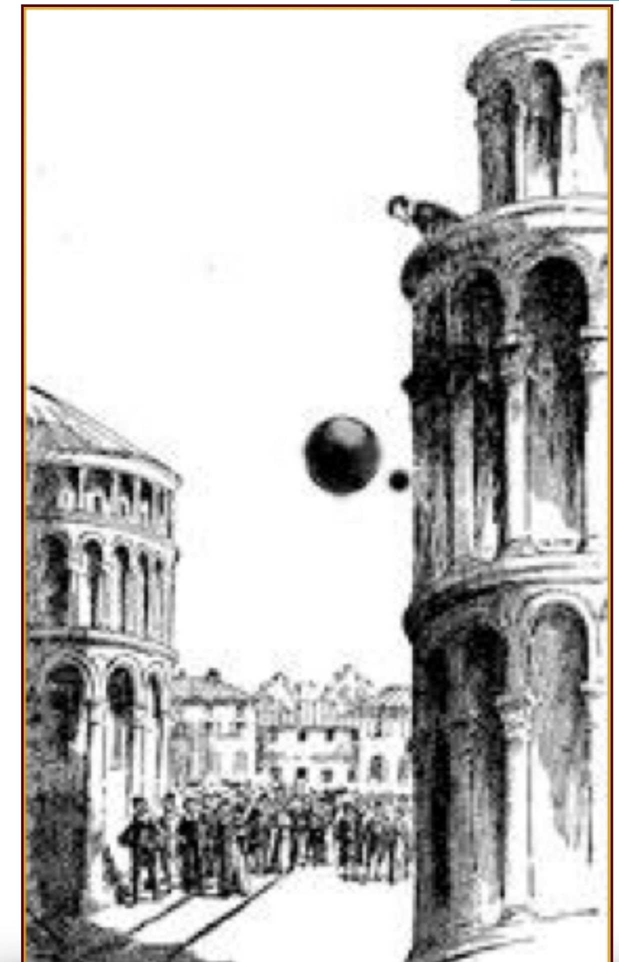
ANTIHYDROGEN EXPERIMENTS







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ALPHA

How to make antihydrogen

$\bar{p}$

e^+

How to make antihydrogen

$\bar{p}$

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

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

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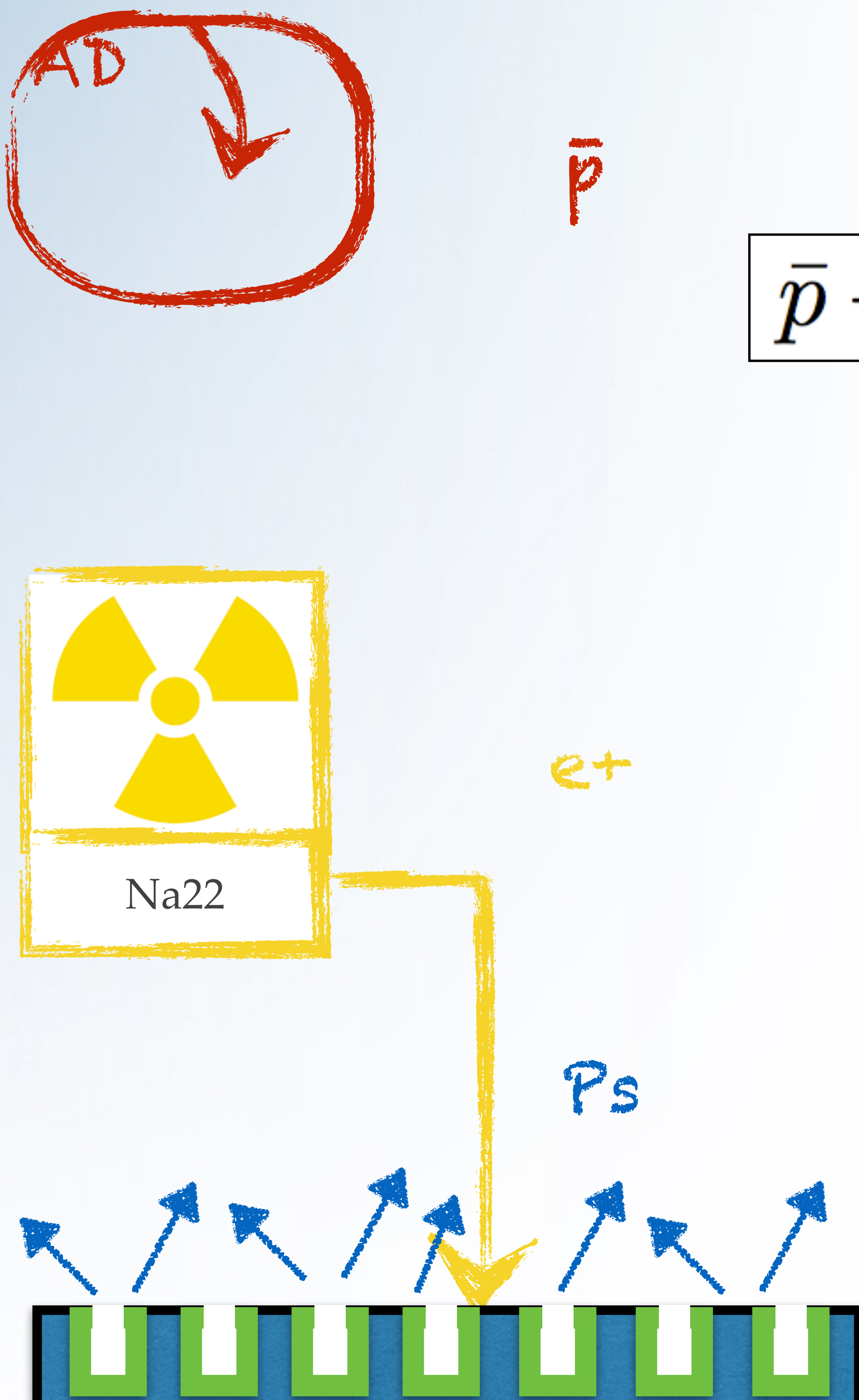
e^+

How to make antihydrogen



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

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

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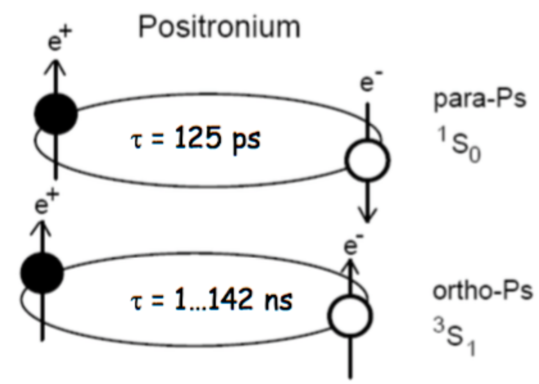
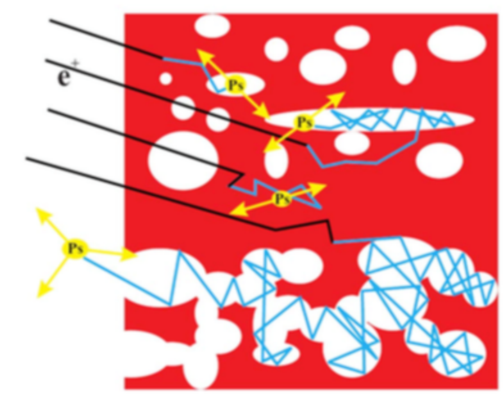
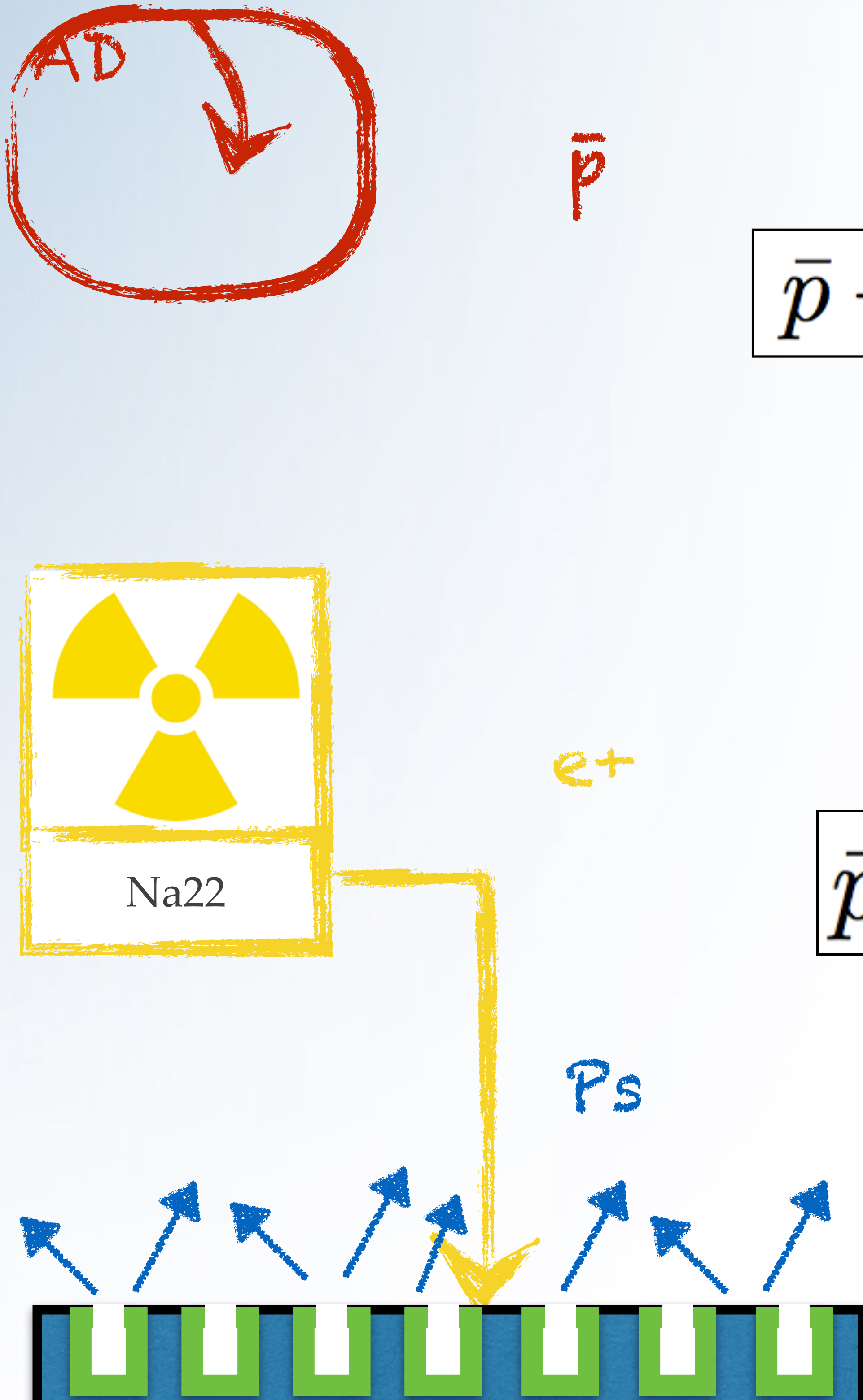




How to make antihydrogen



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

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

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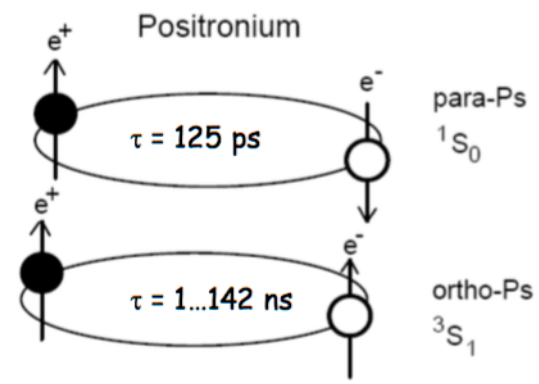

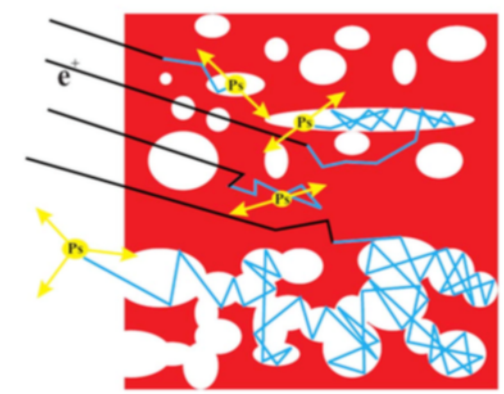

$$\bar{p} + Ps^{\star} \rightarrow \bar{H}^{\star} + e^{-}$$

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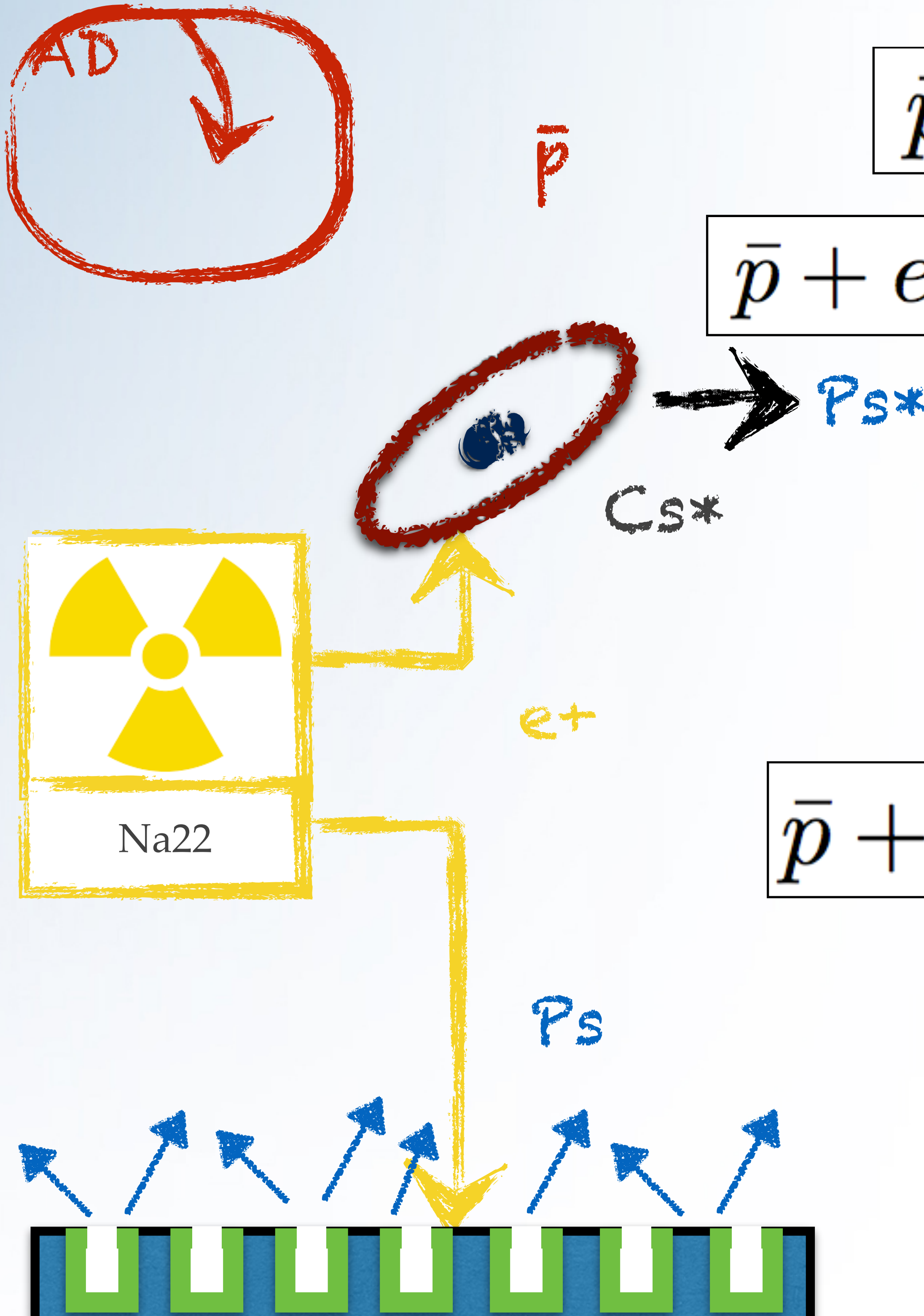
How to make antihydrogen



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

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

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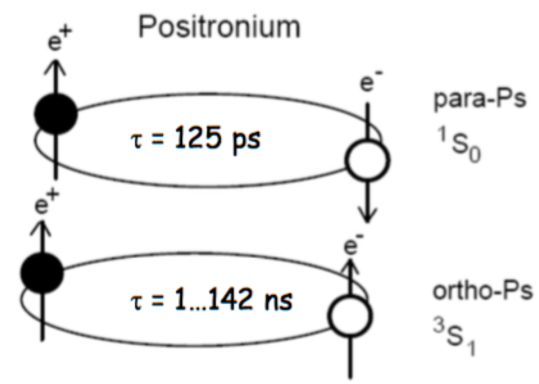

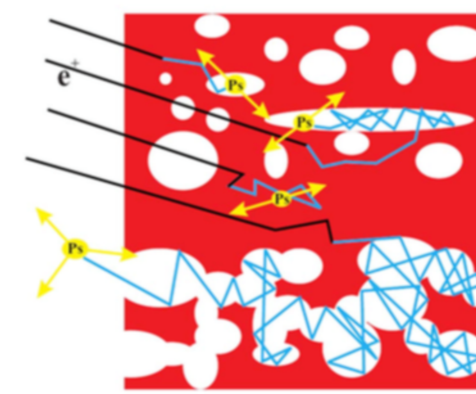

$$\bar{p} + Ps^\star \rightarrow \bar{H}^\star + e^-$$

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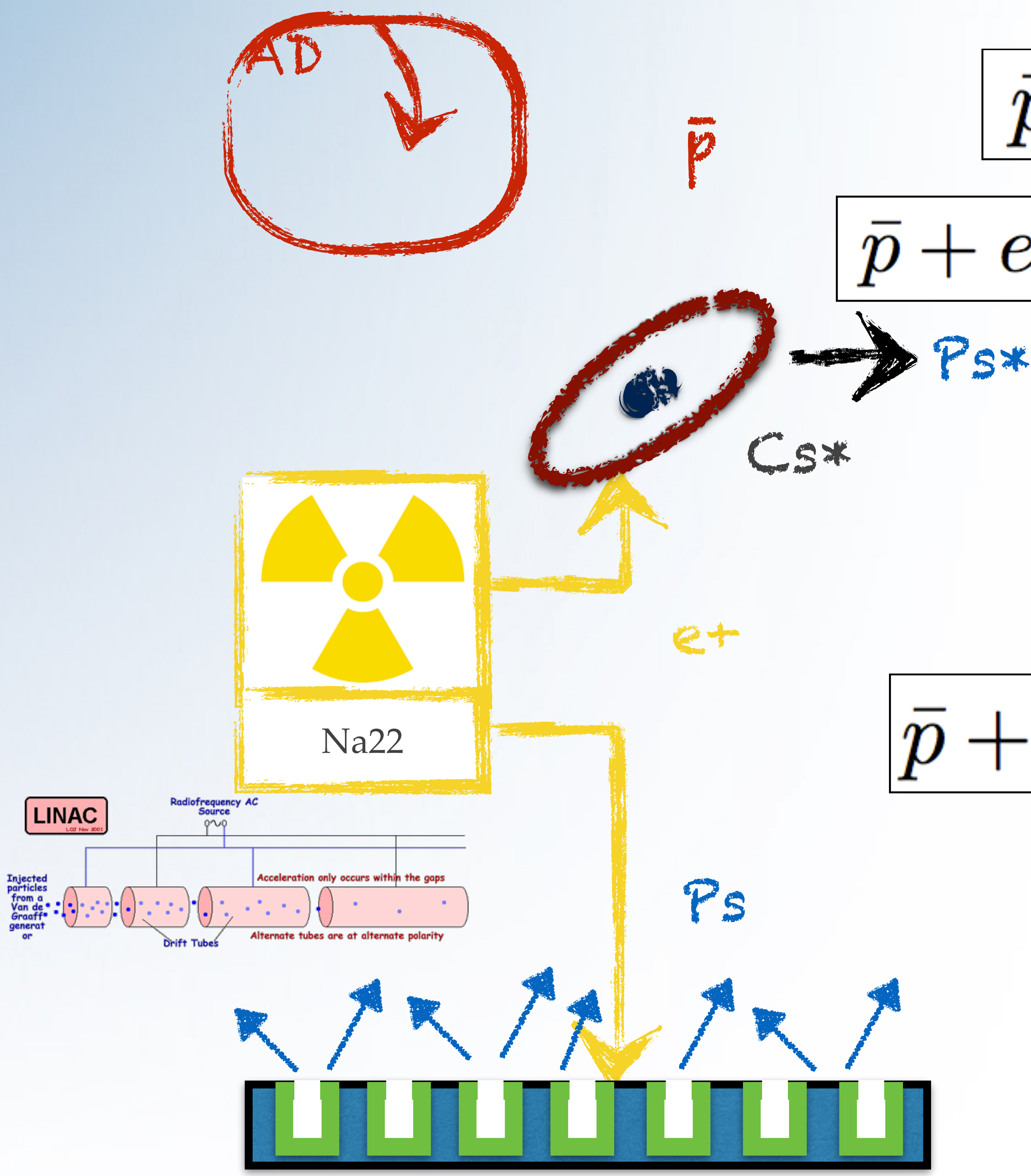
How to make antihydrogen



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

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

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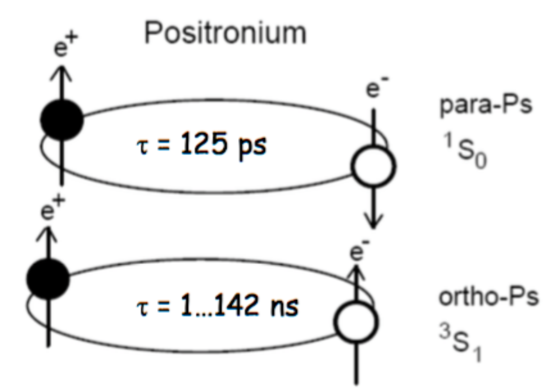

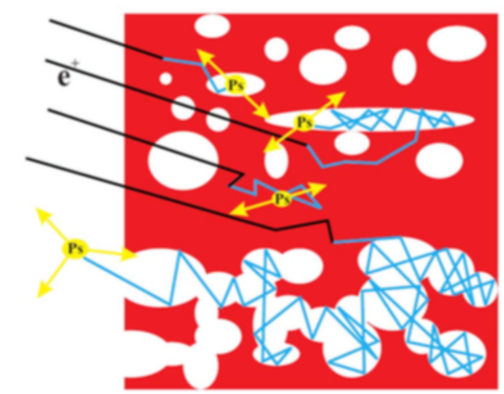

$$\bar{p} + Ps^\star \rightarrow \bar{H}^\star + e^-$$

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Antihydrogen ION !

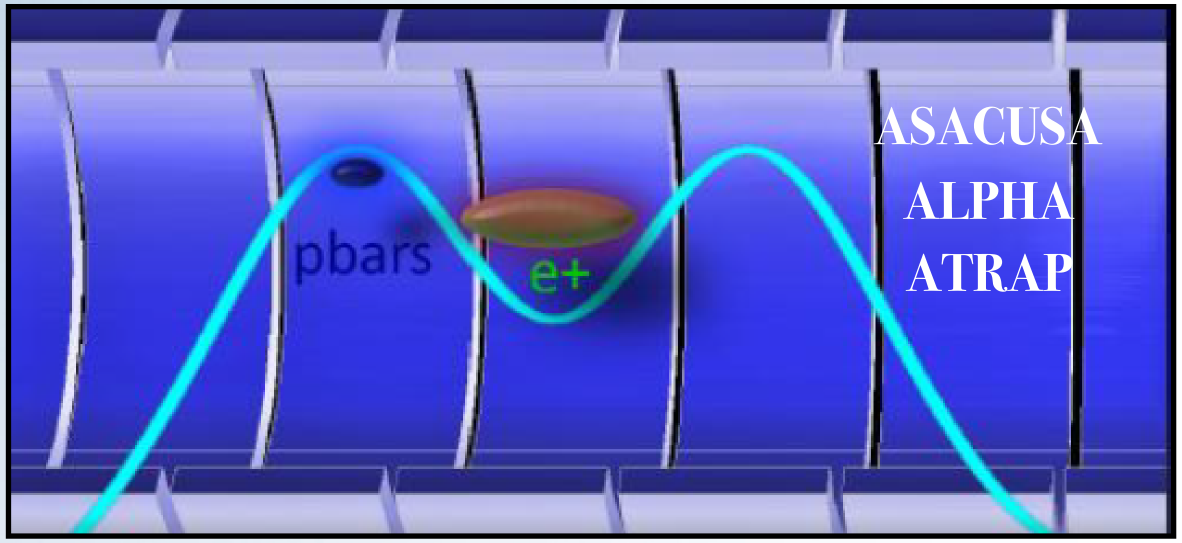
$$\bar{p} + Ps \rightarrow \bar{H} + e^-$$

GBAR

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

EXPERIMENTAL CONCEPTS

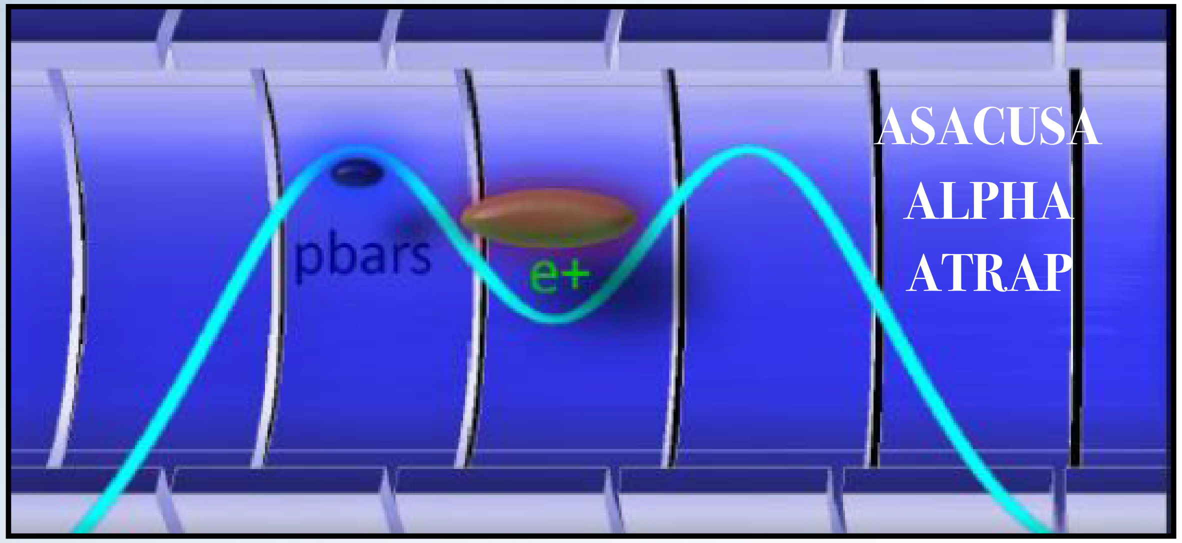
3-body recombination



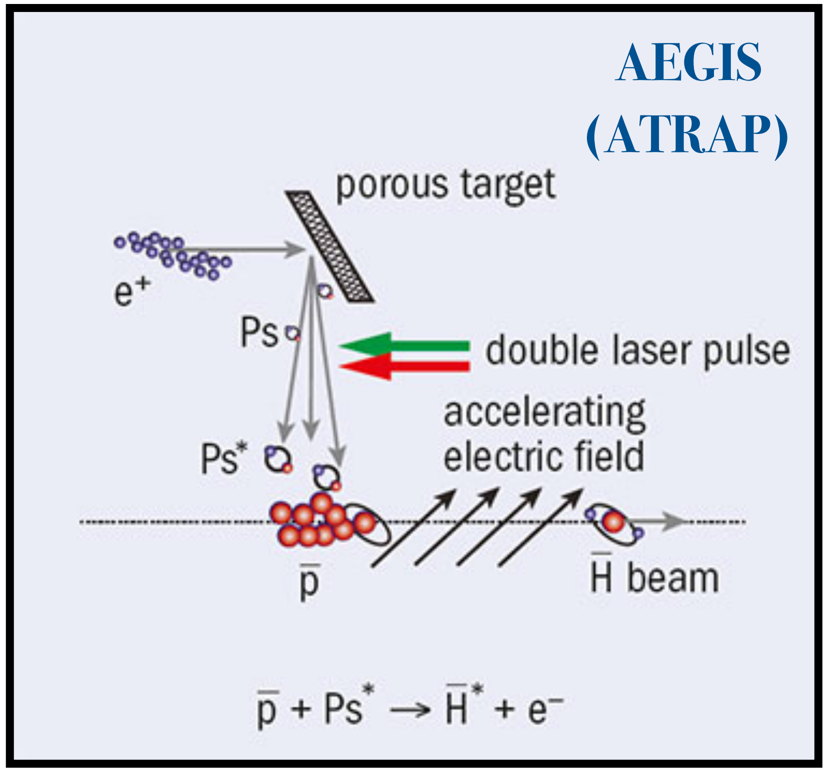
$$\bar{p} + e^{+} + e^{+} \rightarrow \bar{H} + e^{+}$$

EXPERIMENTAL CONCEPTS

3-body recombination Vs. Charge-exchange



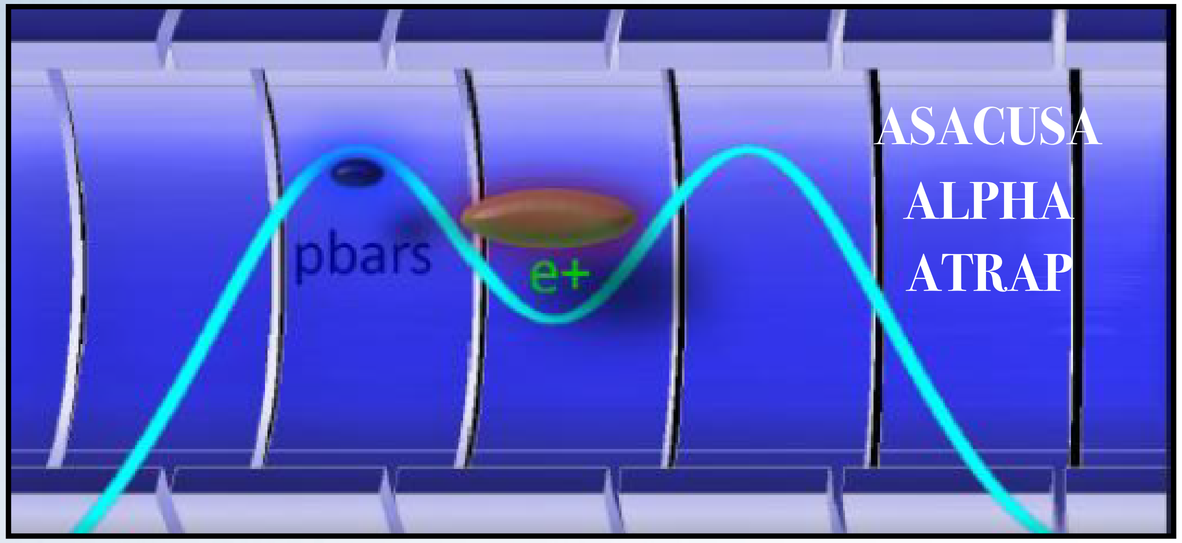
$$\bar{p} + e^{+} + e^{+} \rightarrow \bar{H} + e^{+}$$



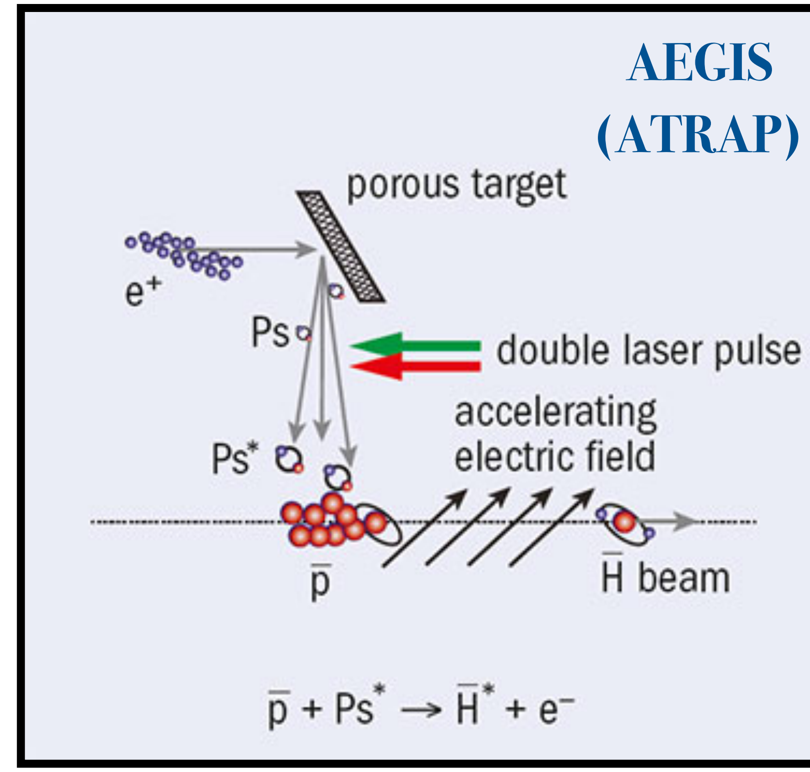
$$\bar{p} + Ps^{\star} \rightarrow \bar{H}^{\star} + e^{-}$$

EXPERIMENTAL CONCEPTS

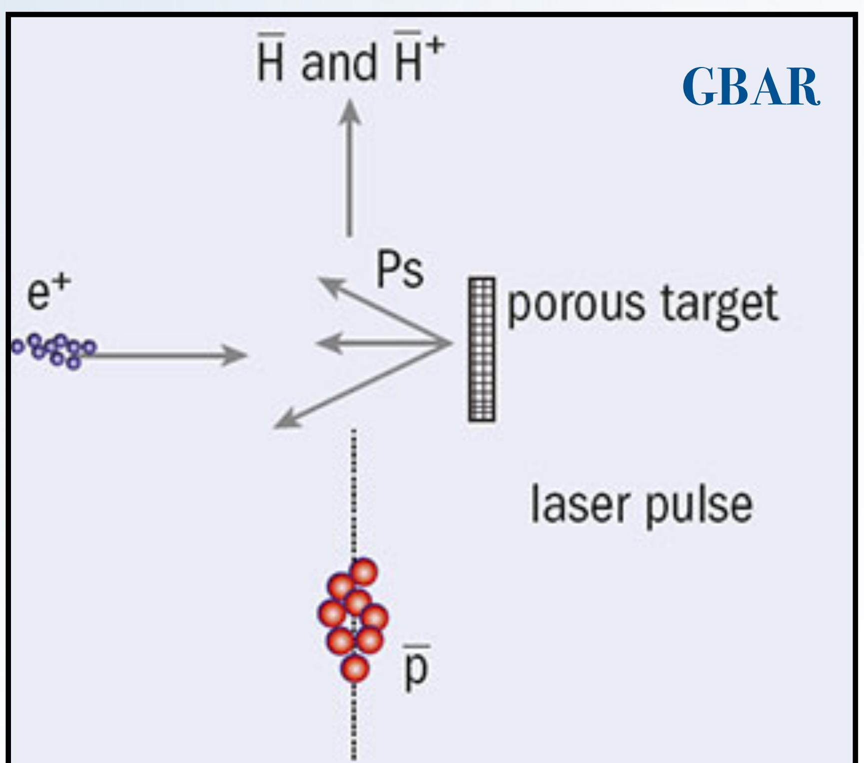
3-body recombination Vs. Charge-exchange



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



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

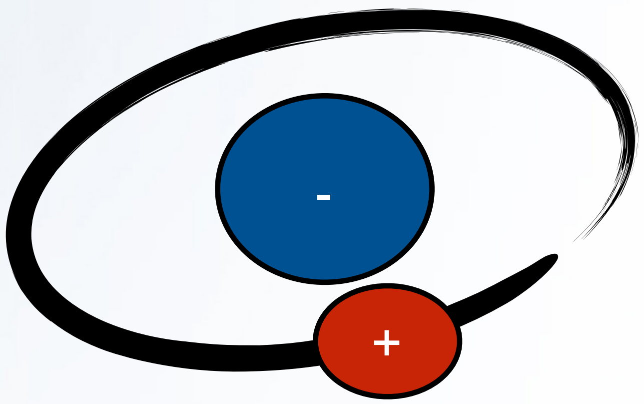


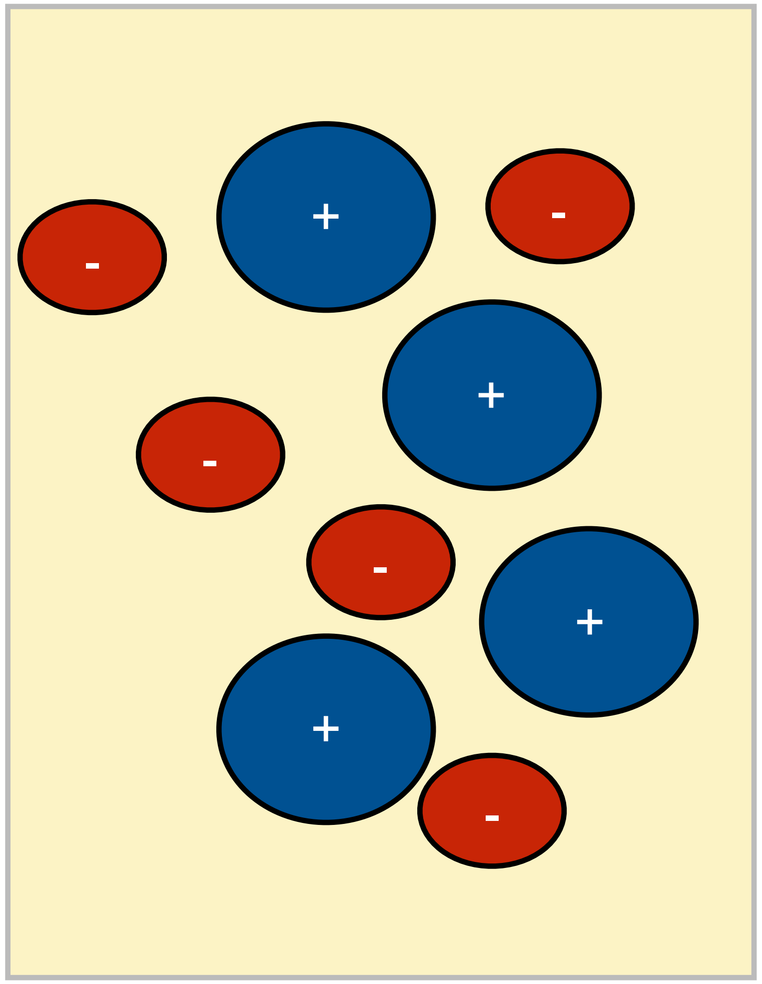
Antihydrogen ion

$$\bar{p} + Ps \rightarrow \bar{H} + e^{-} \quad (1)$$

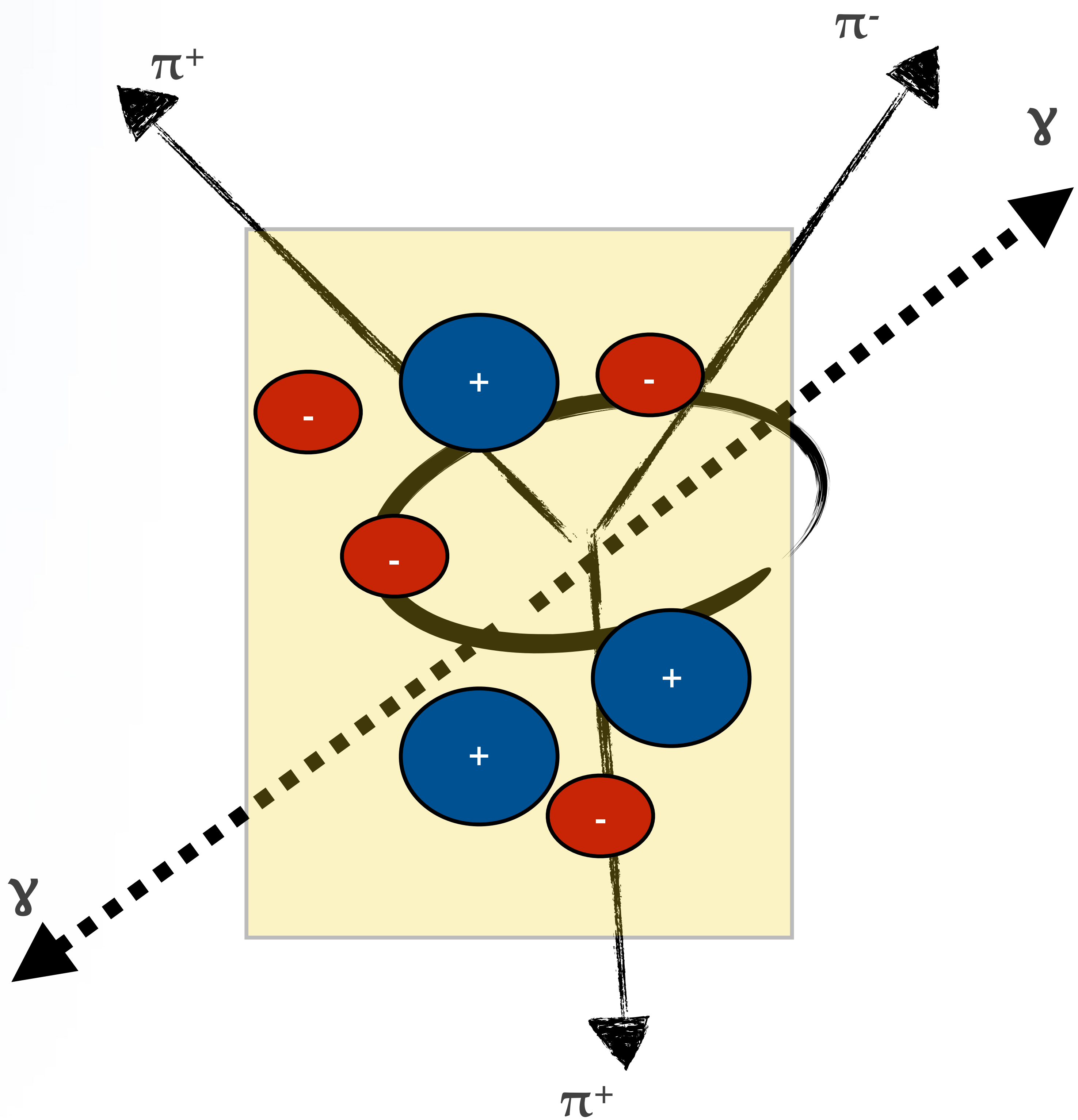
$$\bar{H} + Ps \rightarrow \bar{H}^{+} + e^{-} \quad (2)$$

Antiprotons at lower energies

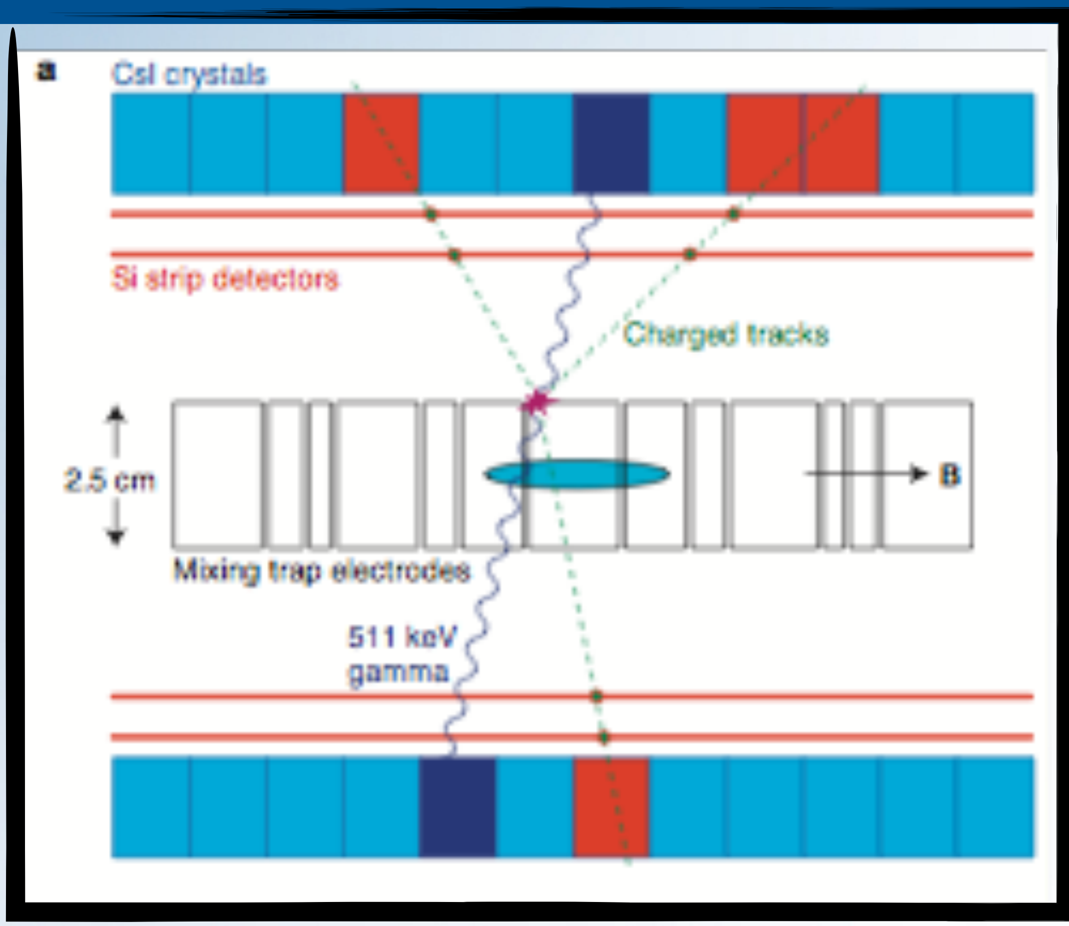




Antiprotons at lower energies



Antiprotons at lower energies



Production and detection of cold antihydrogen atoms

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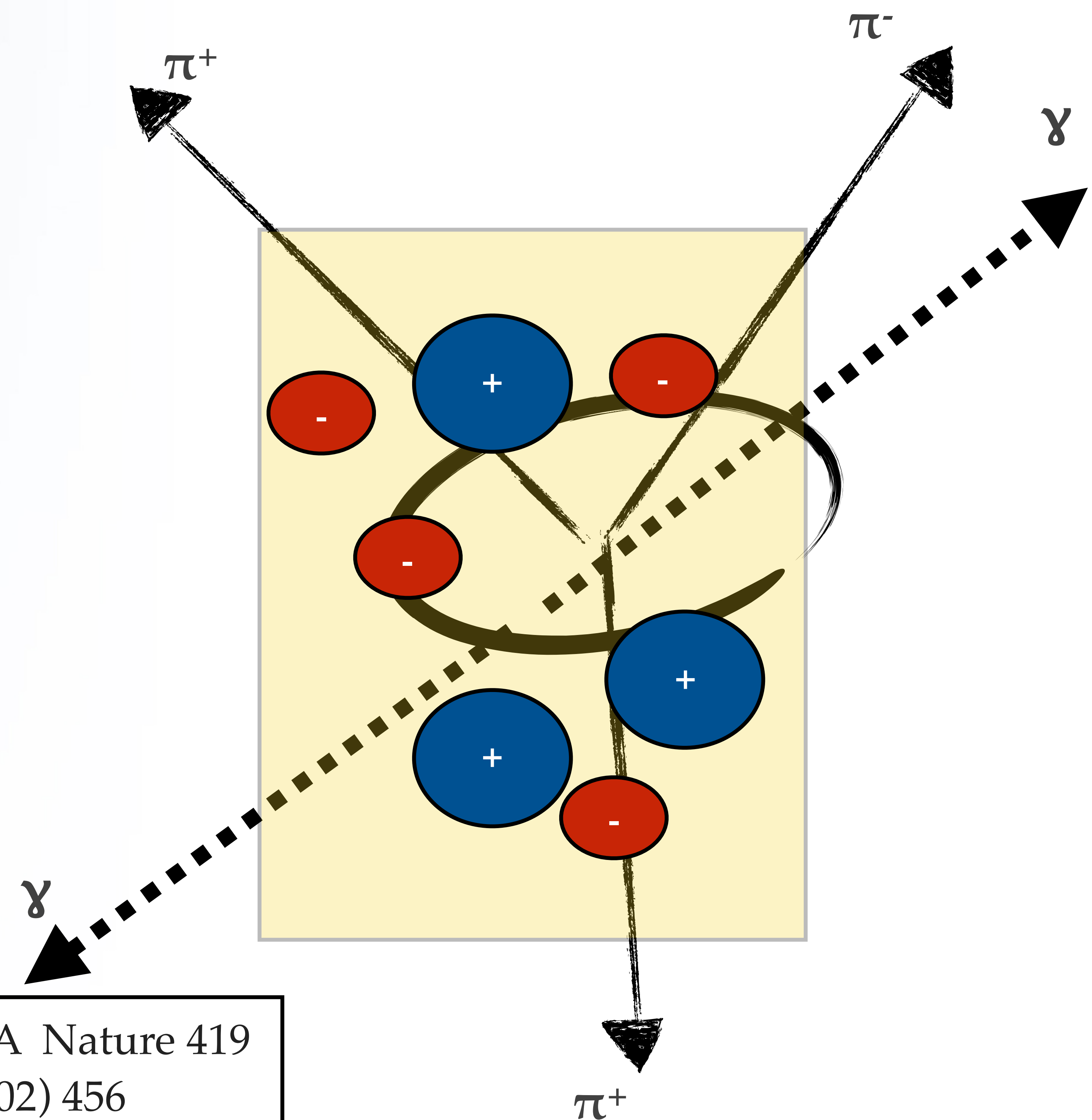
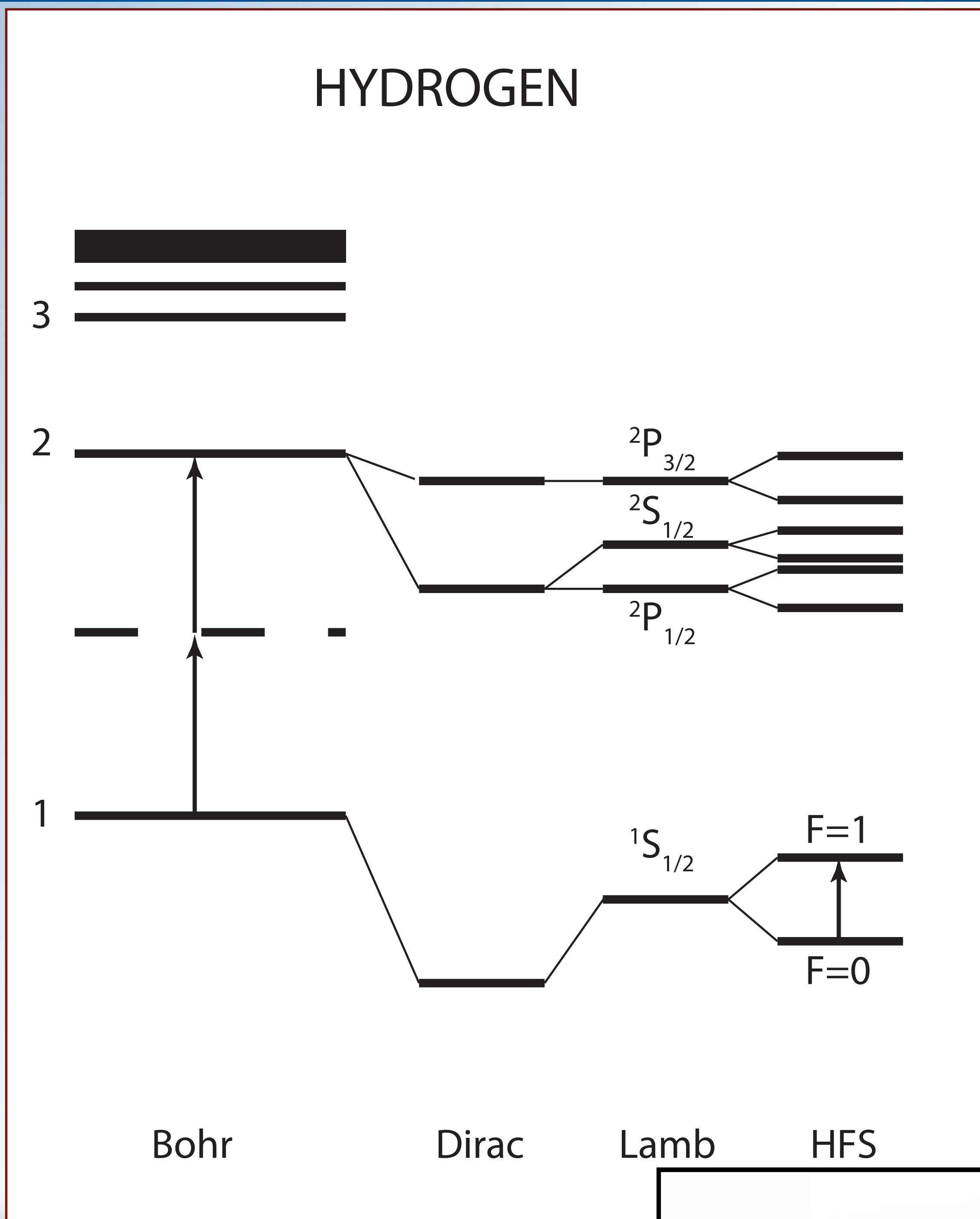
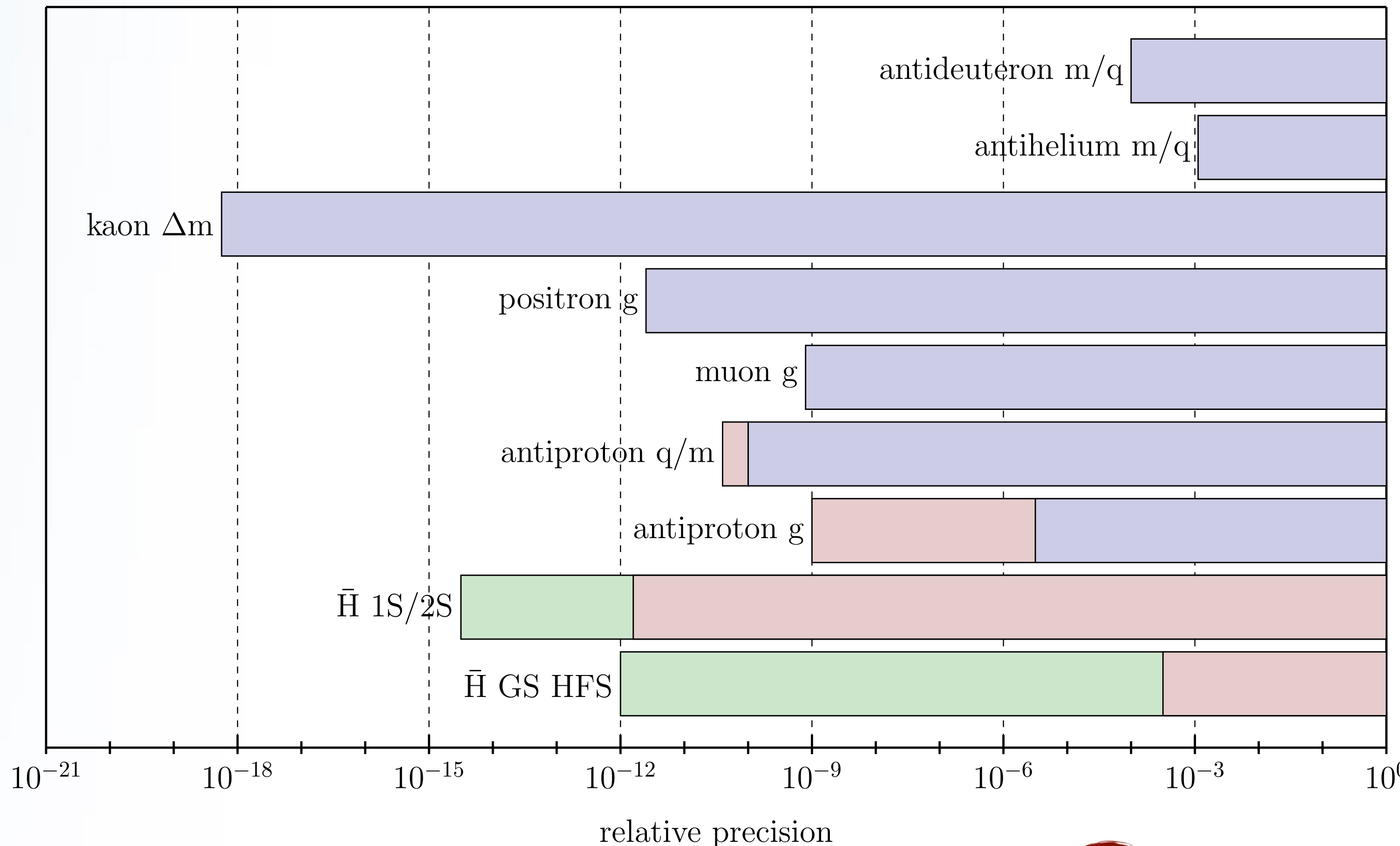
C. Carraro[*], C. L. Cesar[¶], M. Charlton[#], M. J. T. Collier[#], M. Doser[‡],
V. Filippini[☆], K. S. Fine[‡], A. Fontana[☆**], M. C. Fujiwara[††],
R. Funakoshi[††], P. Genova[☆**], J. S. Hangst[‖], R. S. Hayano[††]
M. H. Holzscheiter[‡], L. V. Jørgensen[#], V. Lagomarsino[*‡‡], R. Landua[‡],
D. Lindelöf[†], 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 $\bar{H}$



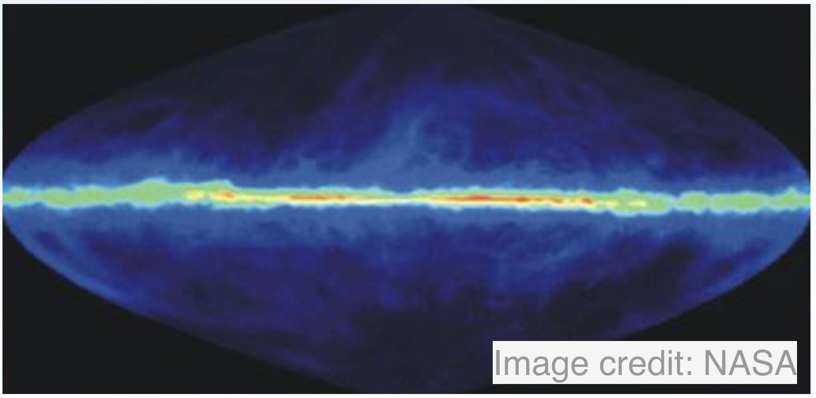


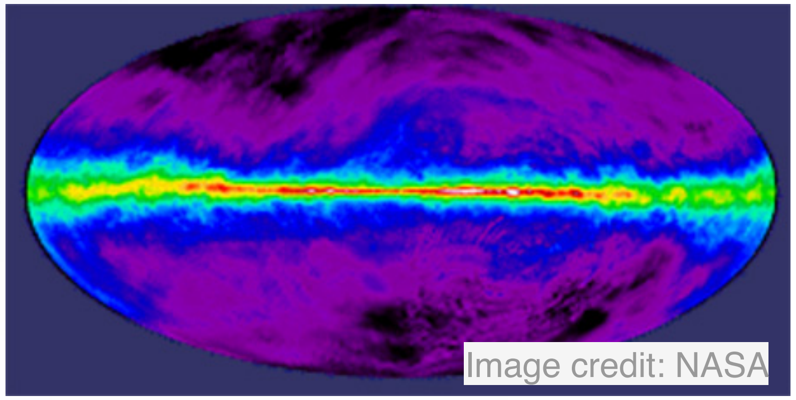
$$\nu_F = \frac{16}{3}\left(\frac{M_p}{M_p + m_e}\right)^3 \frac{m_e}{M_p} \frac{\mu_p}{\mu_N} \alpha^2 c R_y$$

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

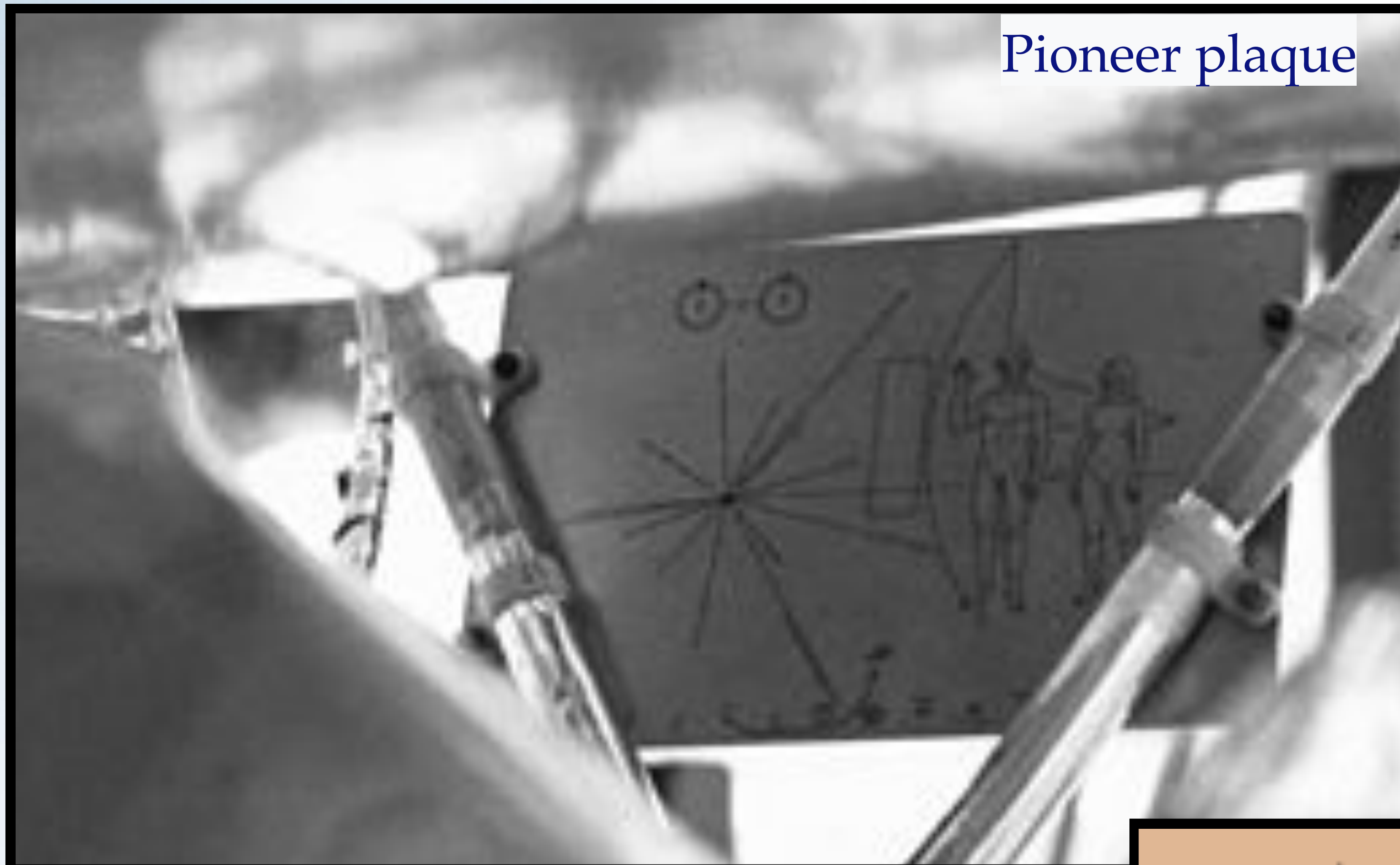
Hyperfine splitting

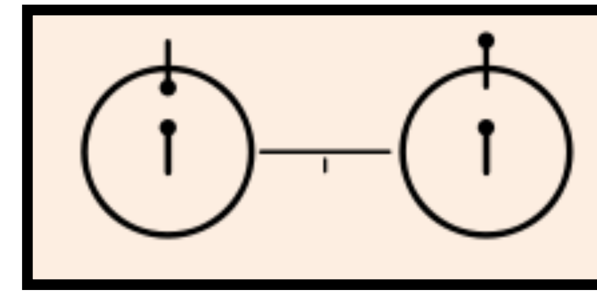
<u>21cm line</u>

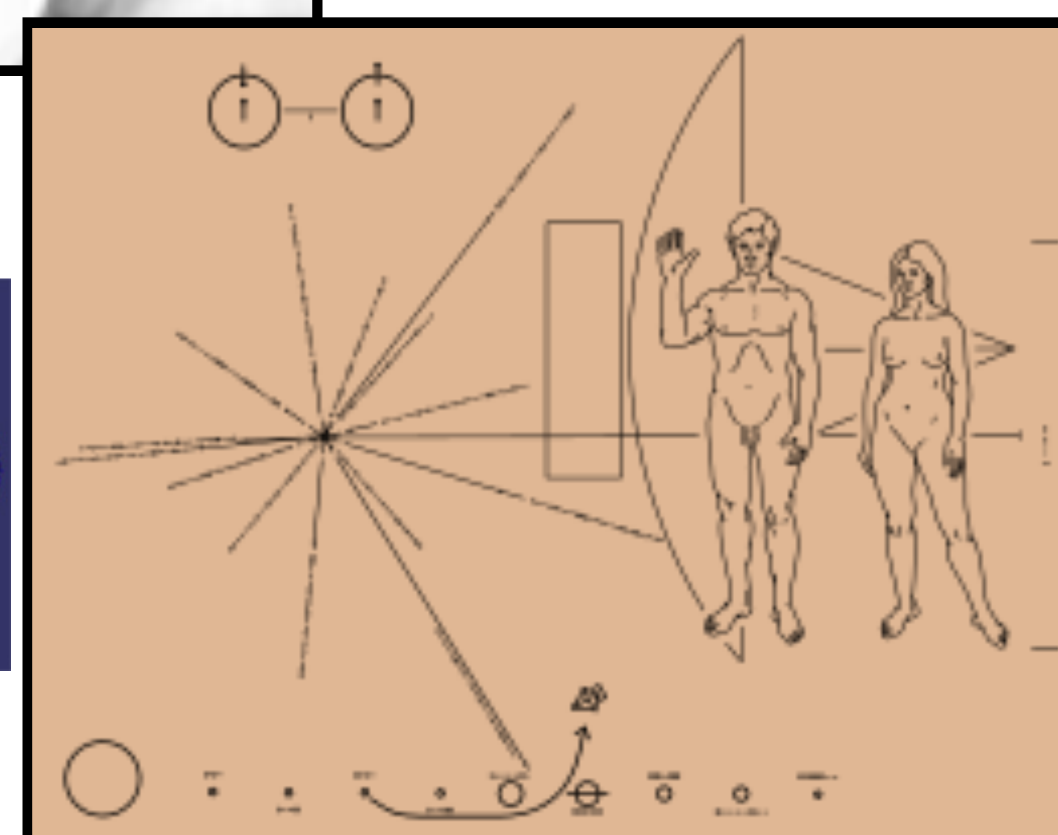




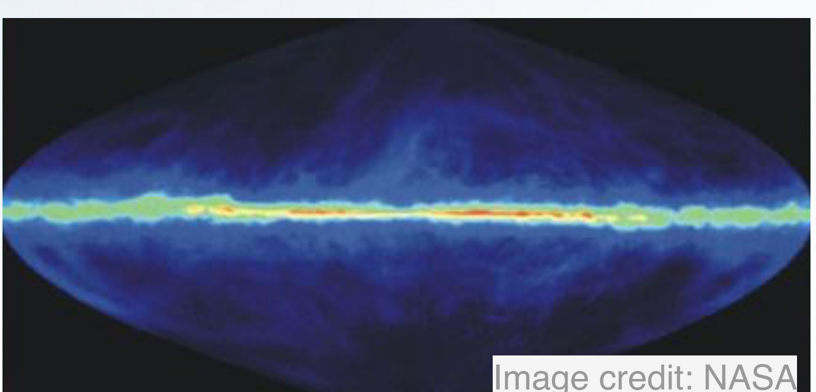
Hyperfine splitting

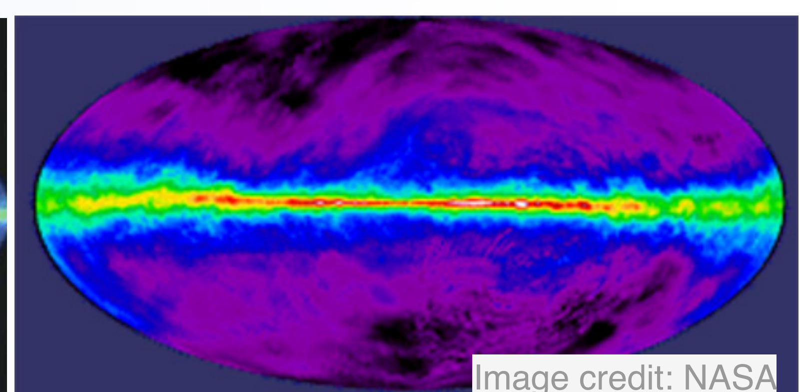






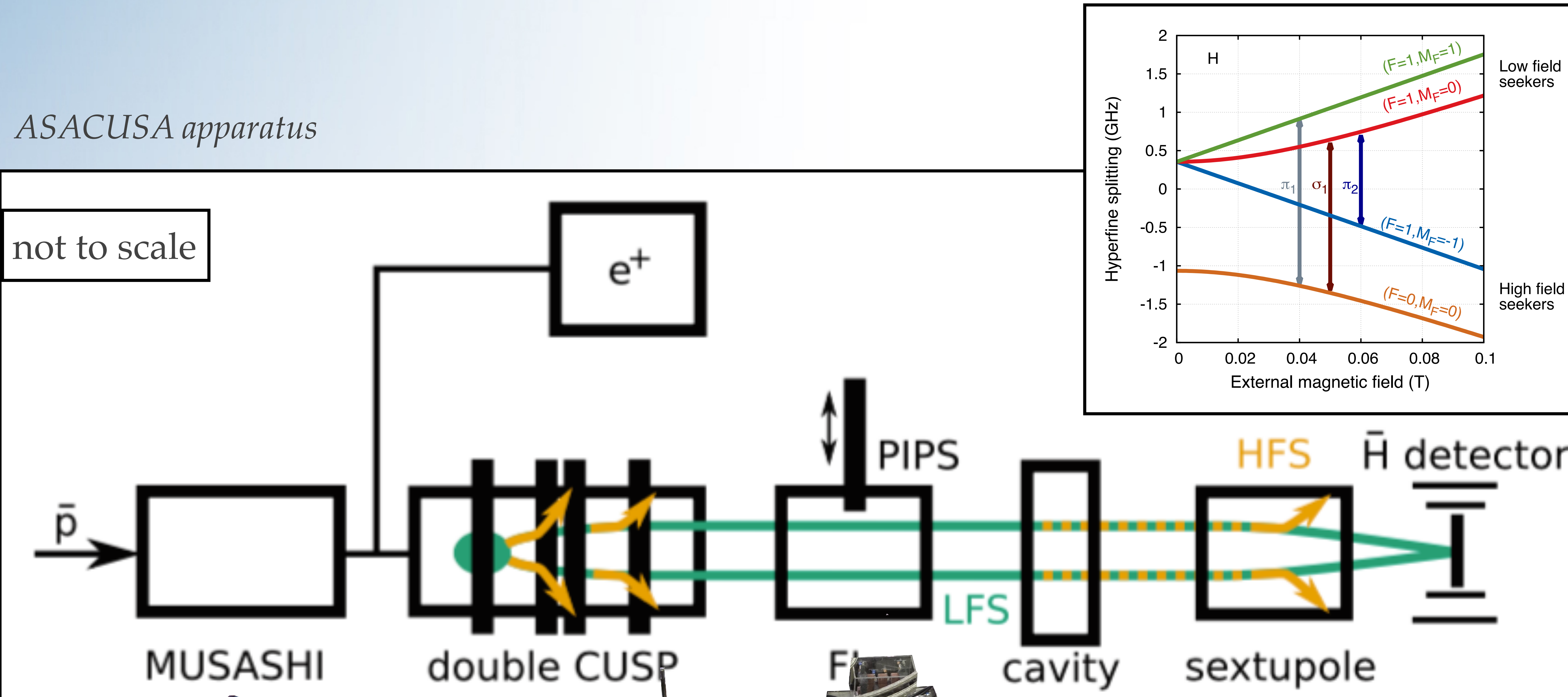
21cm line

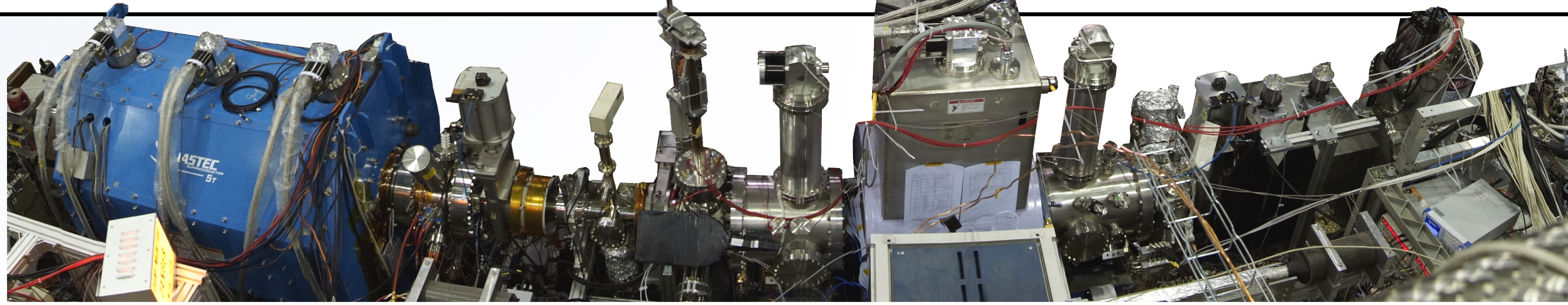


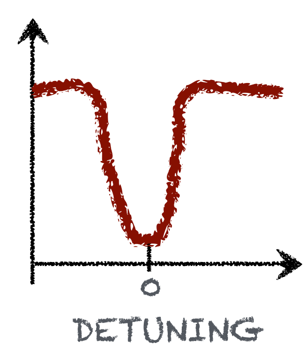


EXPERIMENTAL CONCEPTS

ASACUSA apparatus



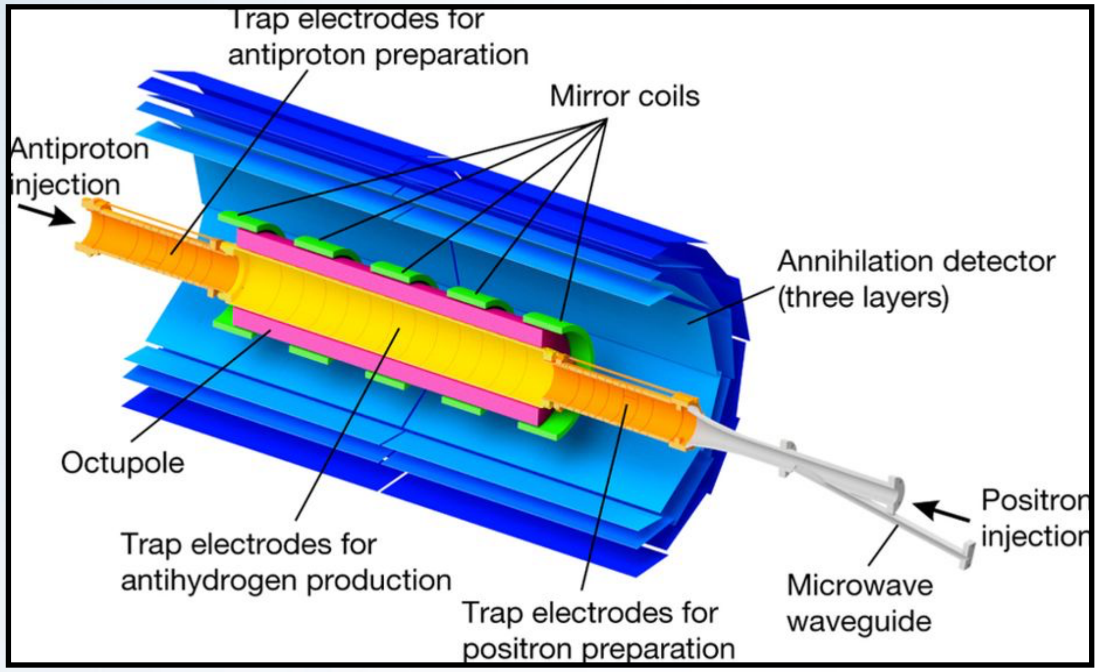




EXPERIMENTAL CONCEPTS

ALPHA-2 apparatus

TRAP

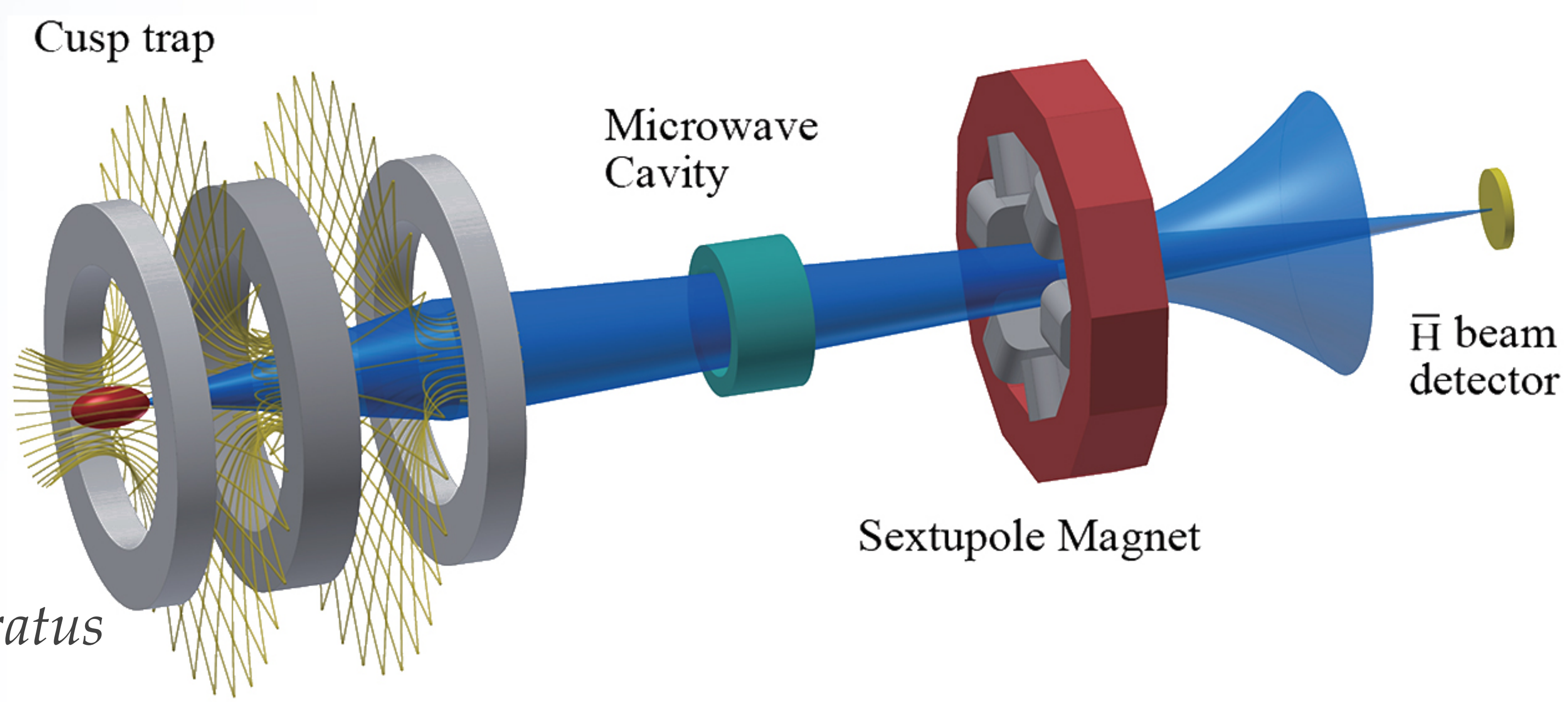


$$kT = \mu(B - B_0)$$

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

BEAM

Vs.

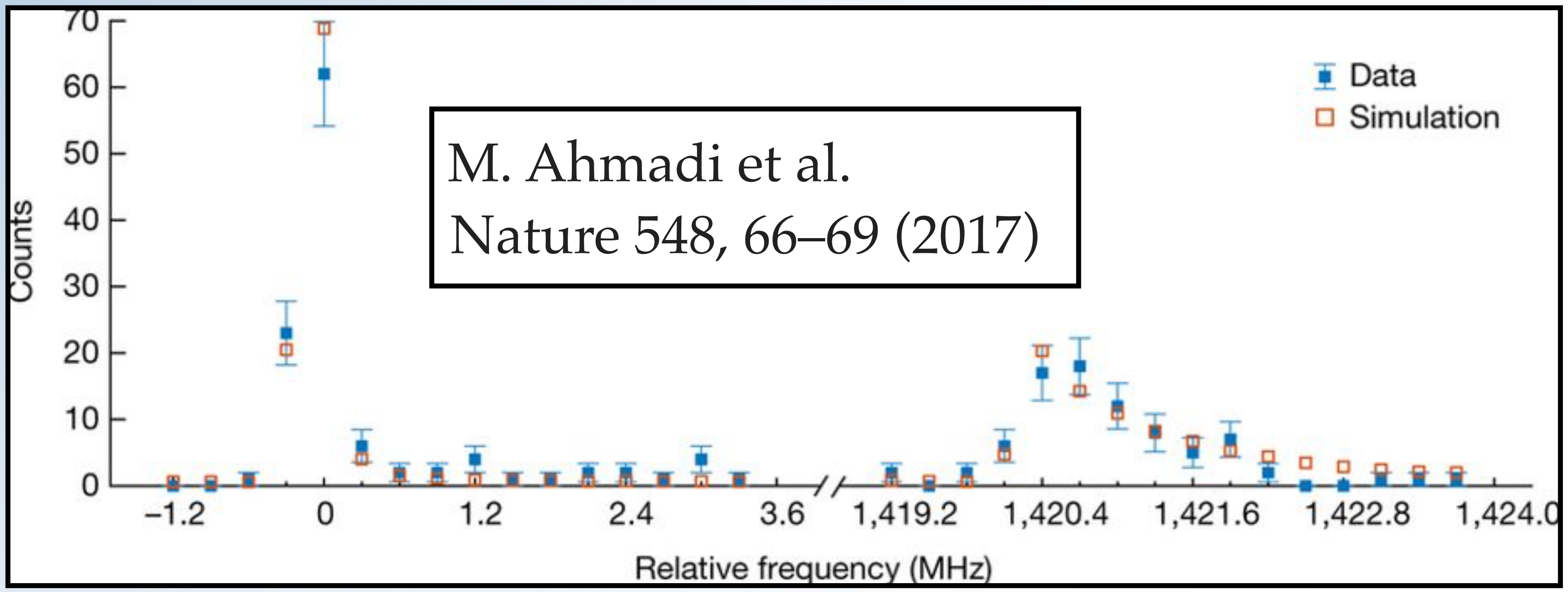


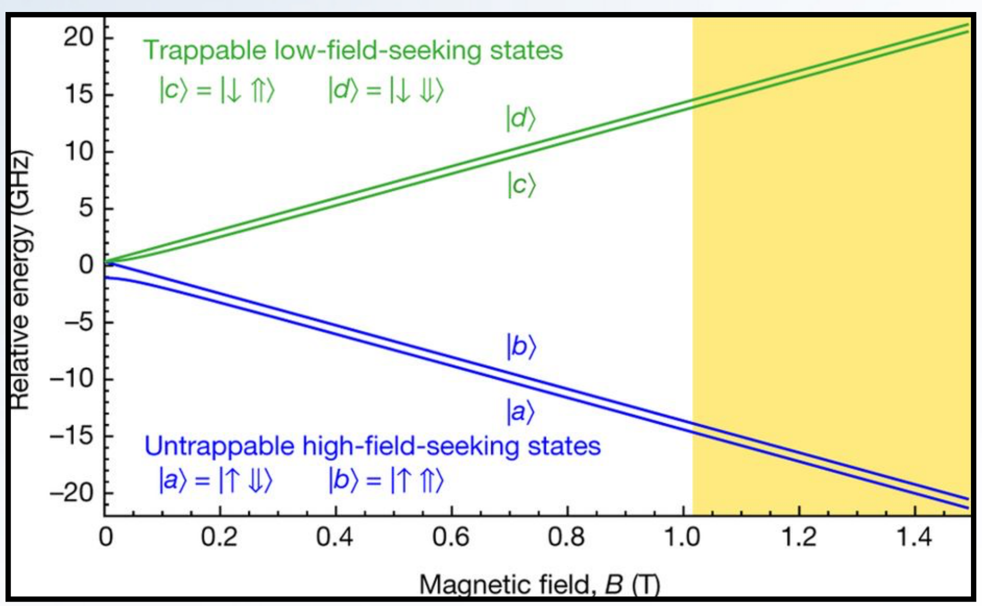
ASACUSA apparatus

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

In a TRAP:

Precision of ~ 500 kHz

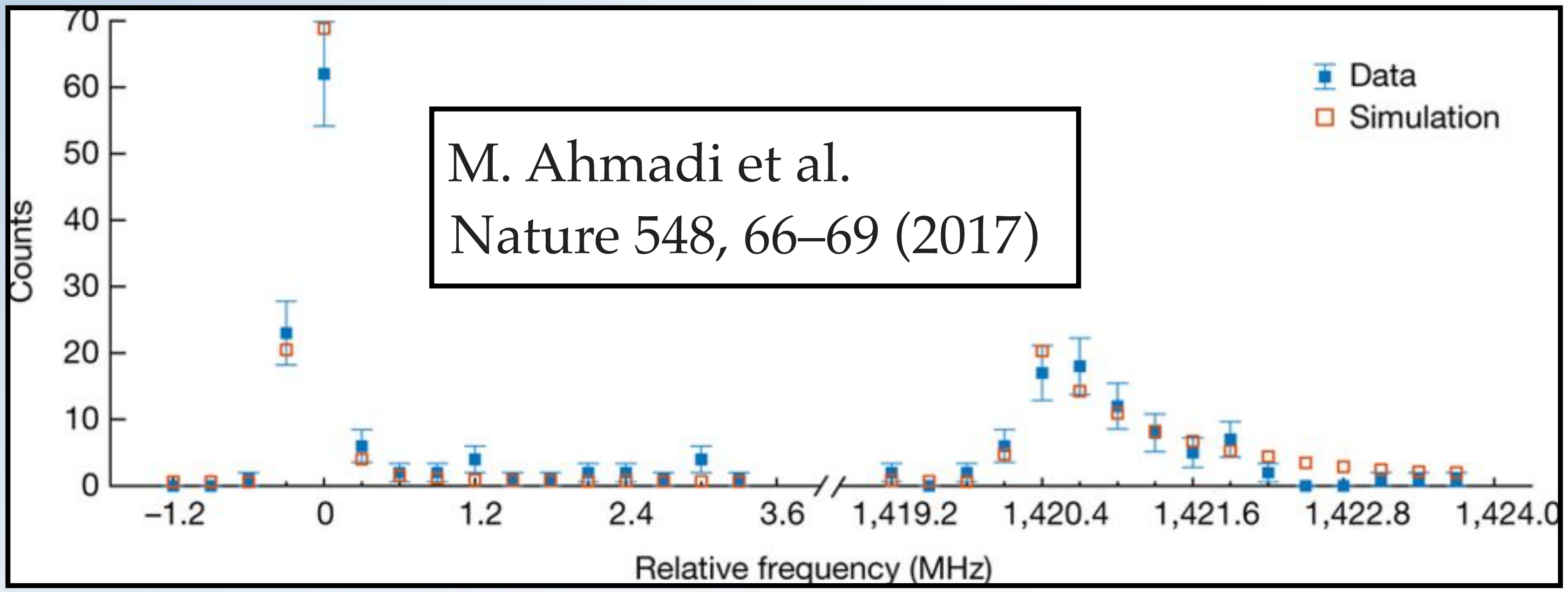




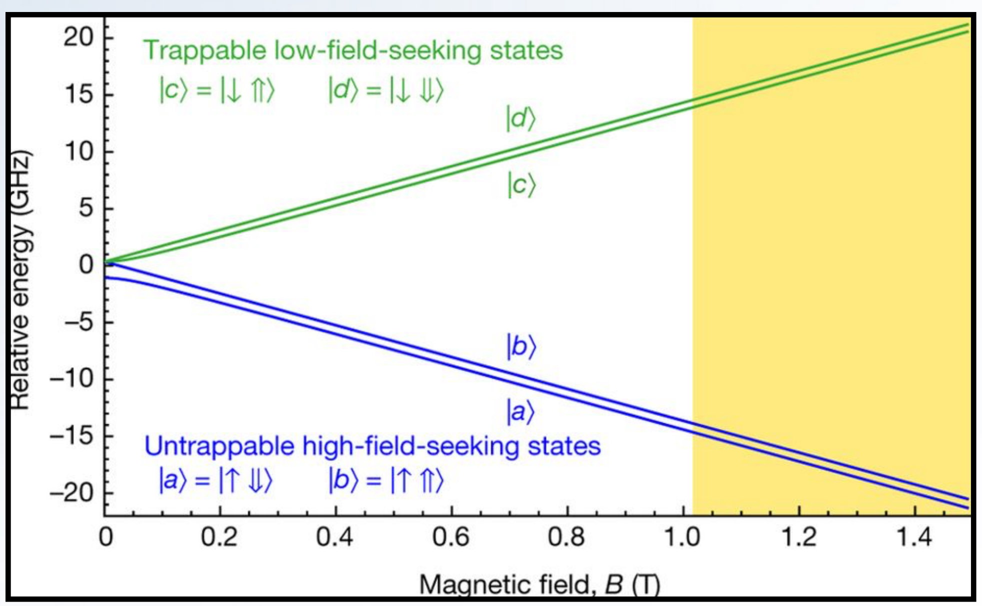
STATUS OF GS-HFS OF H̄/H

In a TRAP:

Precision of ~ 500 kHz

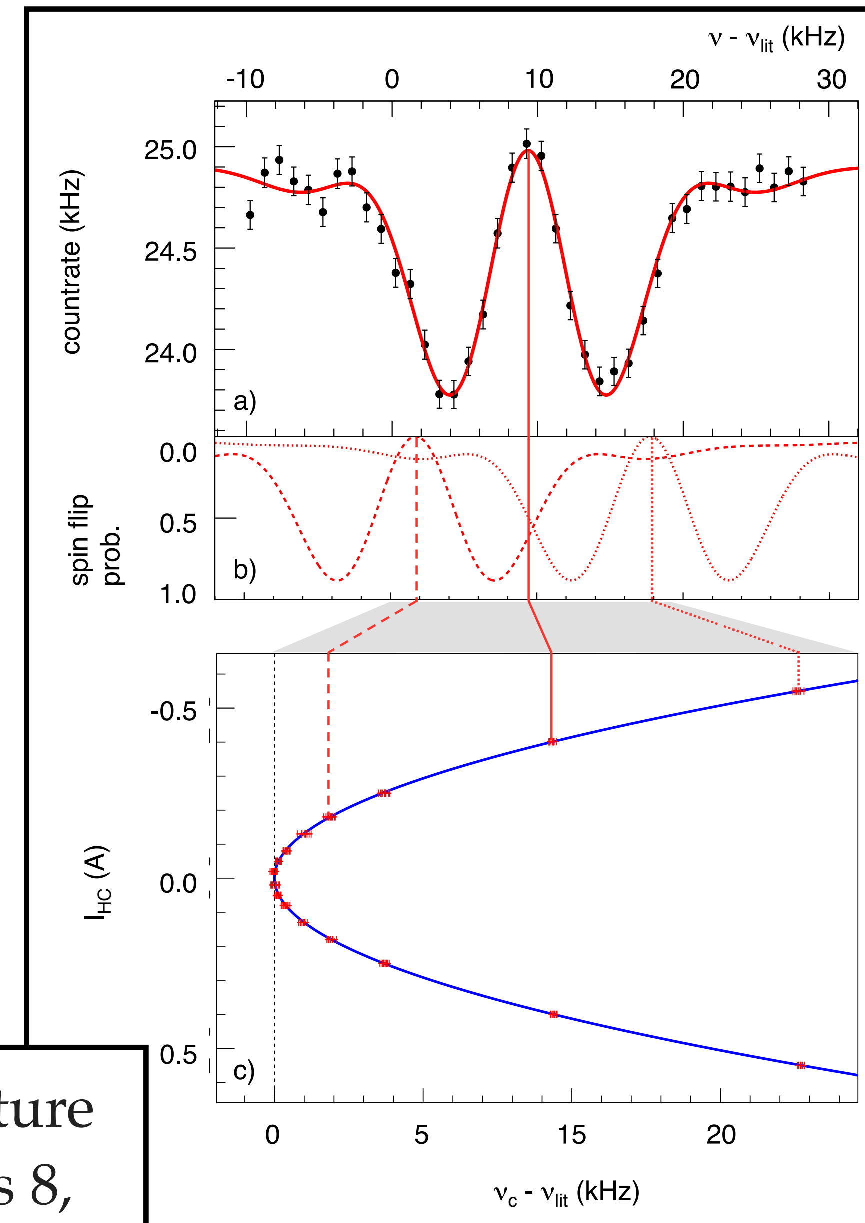


M. Ahmadi et al.
Nature 548, 66–69 (2017)



In a BEAM:

Precision of ~3Hz on HYDROGEN

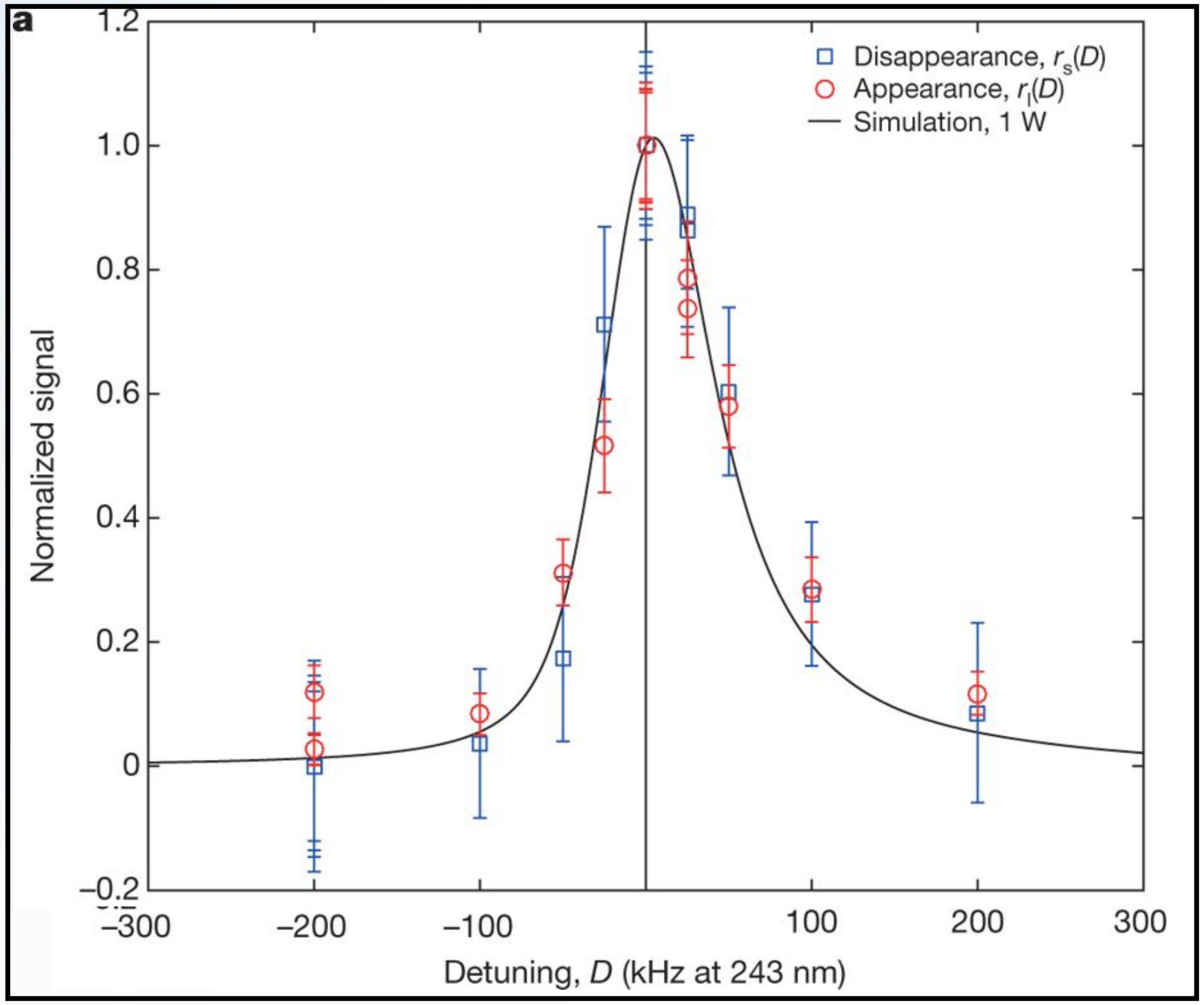


M. Diermaier et al. Nature Communications 8, 15749 (2017)

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 $\bar{H}$

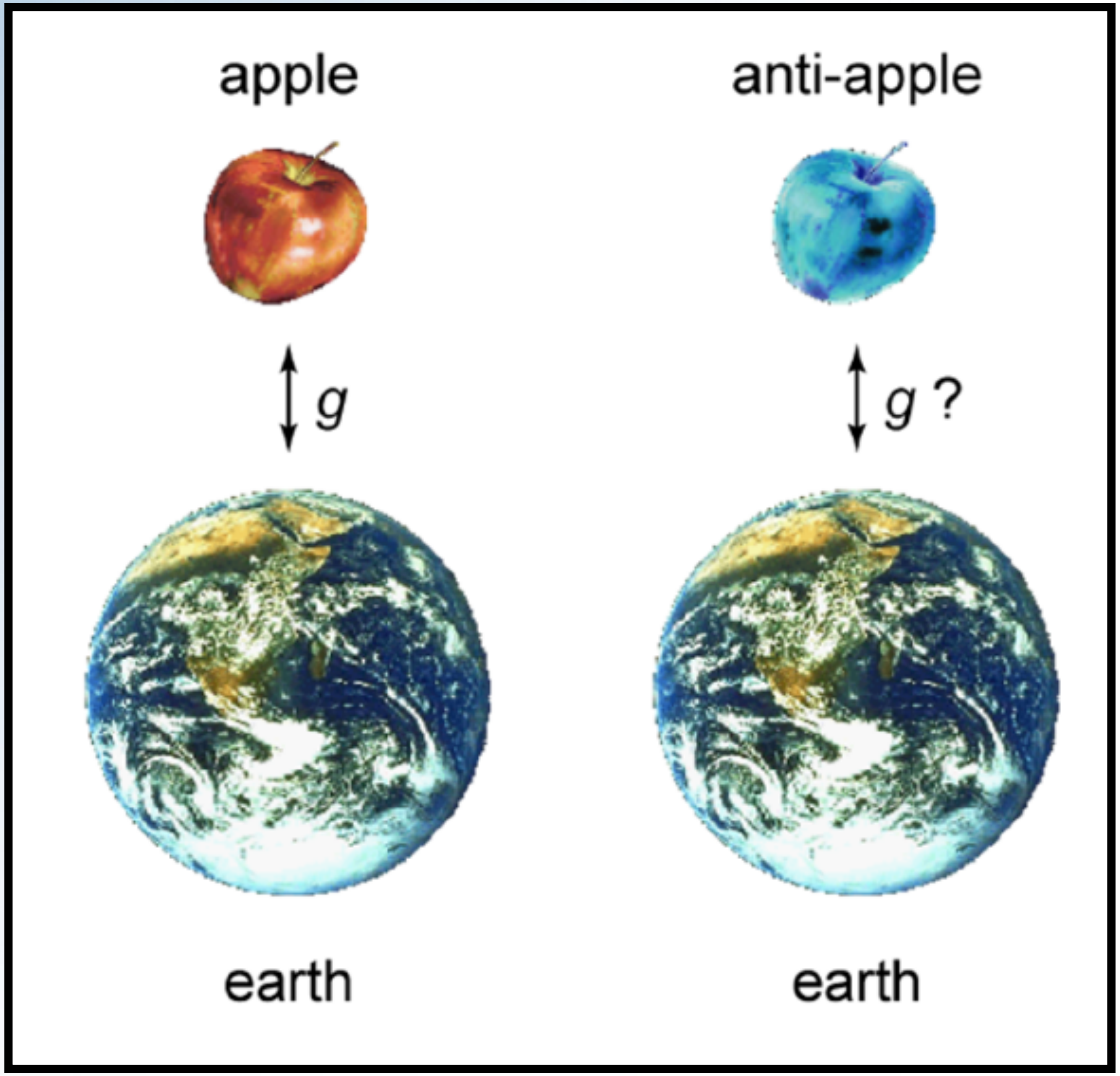
- Control the QS (for beam)

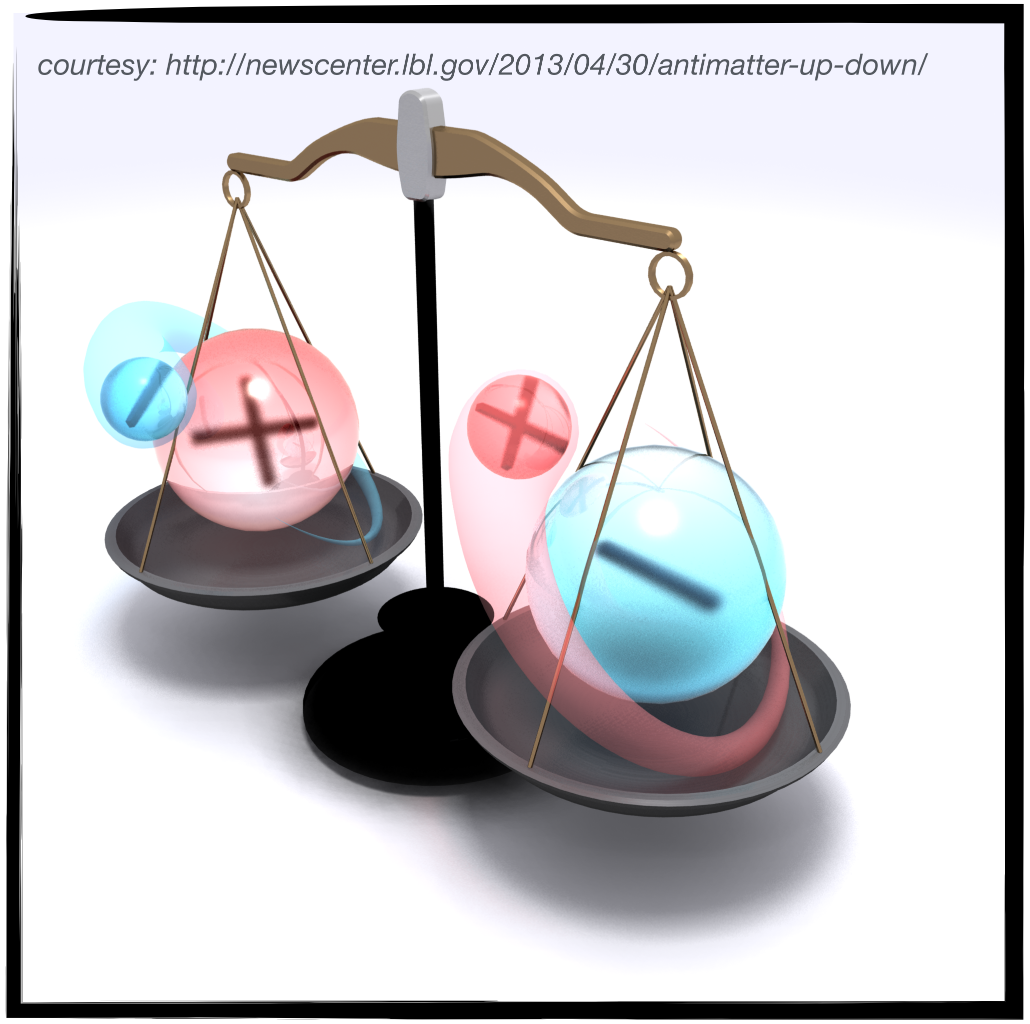
- Colder $\bar{H}$:

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

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

ON THE GRAVITY SIDE





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

ON THE GRAVITY SIDE

Antigravity: $g_{matter} = -g_{antimatter}$
separation of matter and antimatter in Universe

Quantum gravity

Graviton (S=2) → add Gravivector (S=1), Graviscalar (S=0)
simplest case: static potential

$$V = -\frac{Gm_1m_2}{r}(1 \mp a\,e^{-r/v} + b\,e^{-r/s})$$

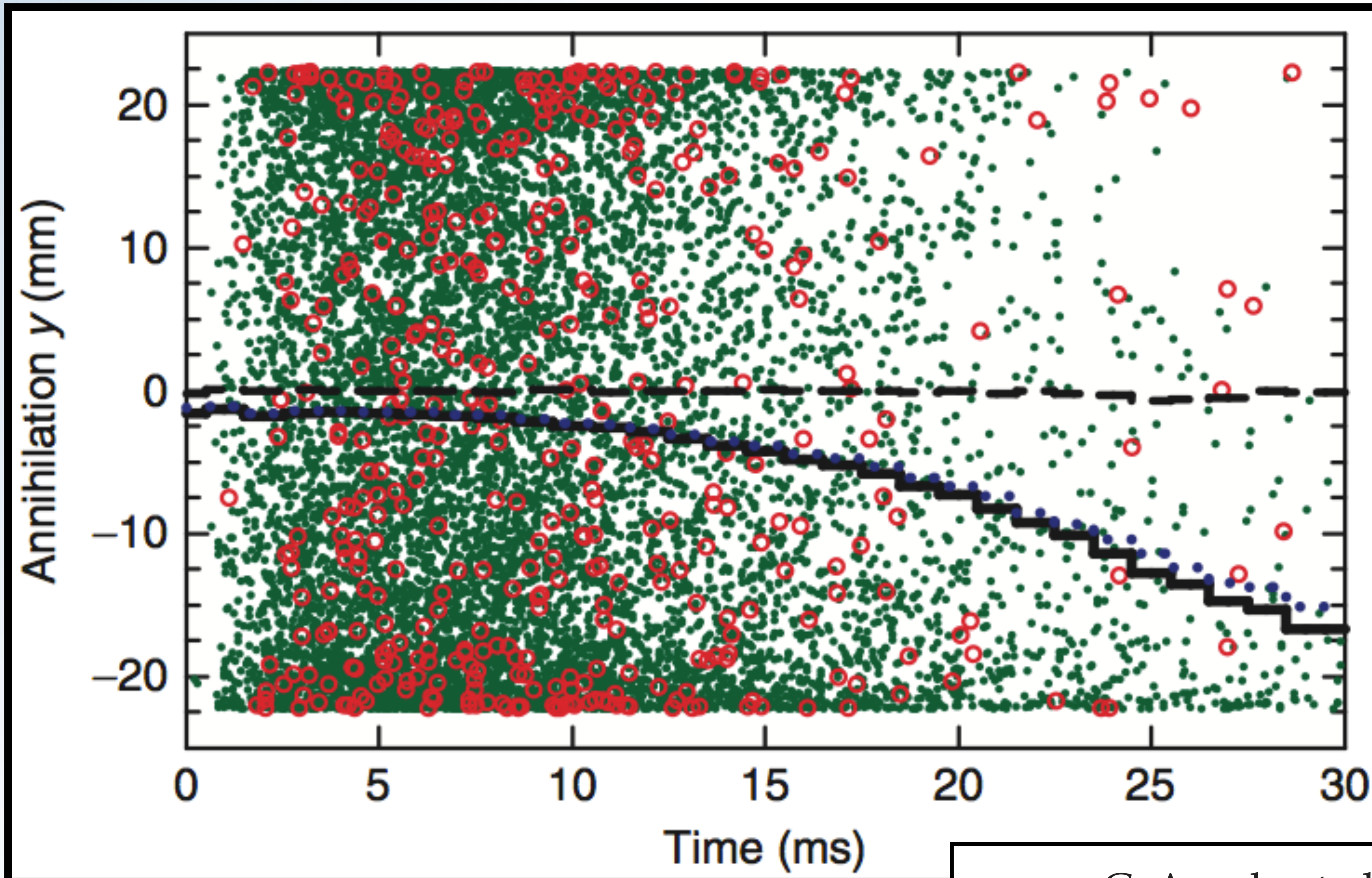
a: Gravivector, b: Graviscalar

– attractive (matter-matter), +: repulsive: matter-antimatter

matter experiments: |a–b|

antimatter: a+b

STATUS OF THE FIELD



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

-65 < g/ḡ < 110

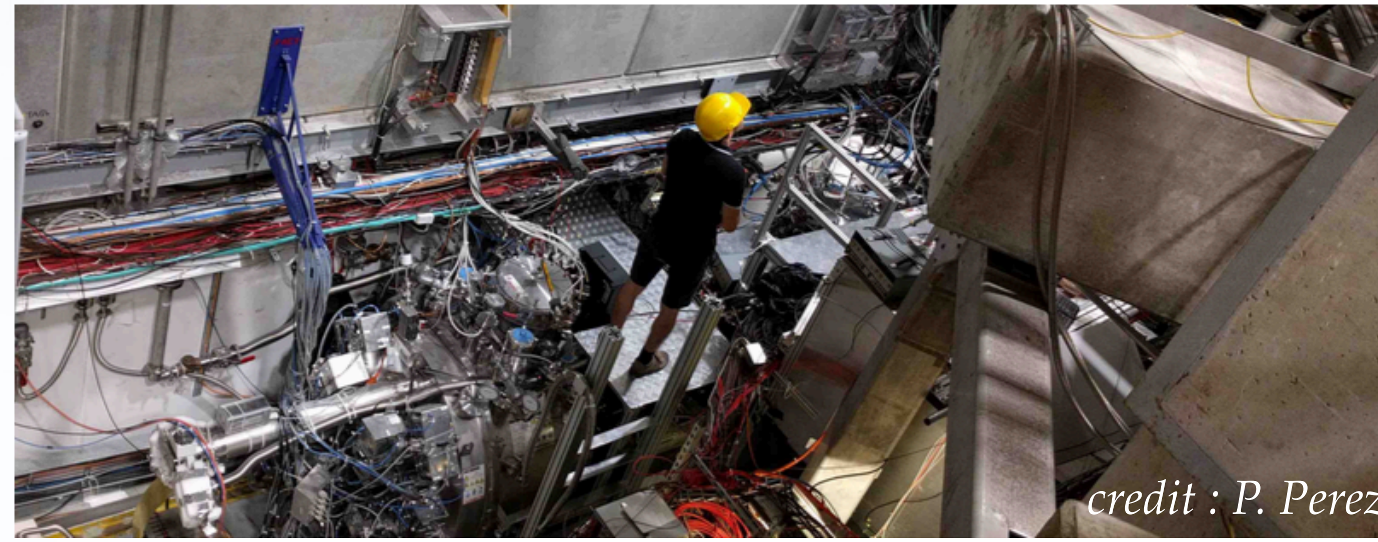
Green dots---simulated annihilations

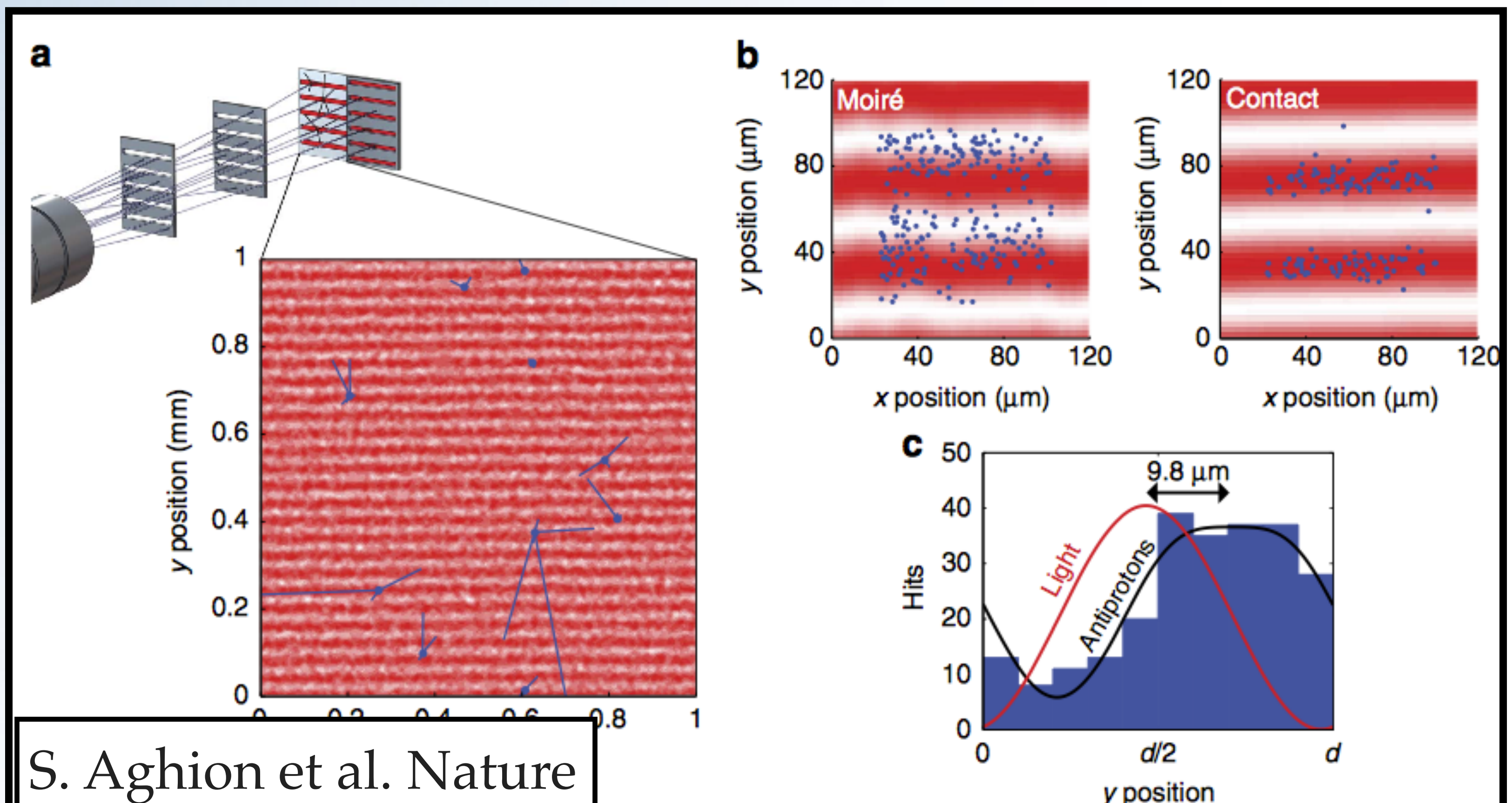
Red circles---434 Observed annihilations

Vertical position of annihilation vertex during release of trapping field

FUTURE GOALS

AEGIS : DEFLECTOMETER

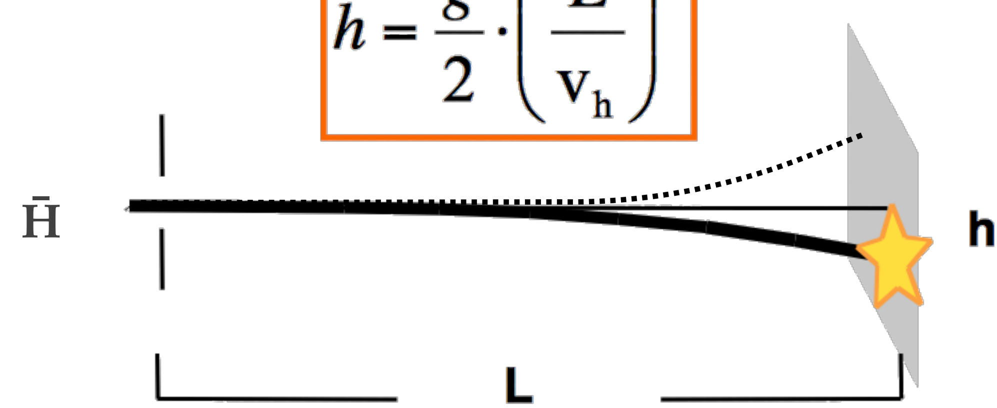




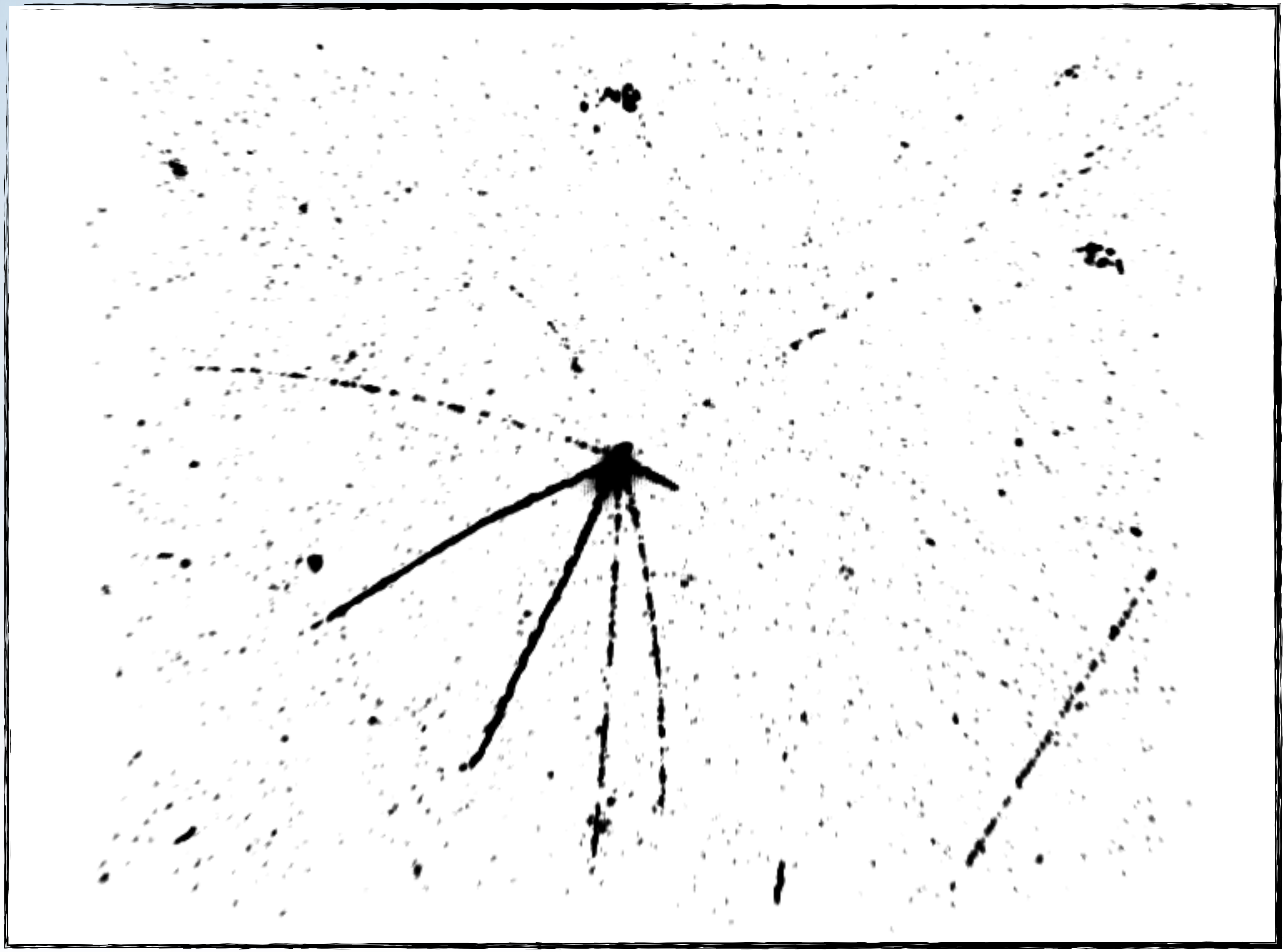
S. Aghion et al. Nature Communications 5 (2014) 4538

~1-10%

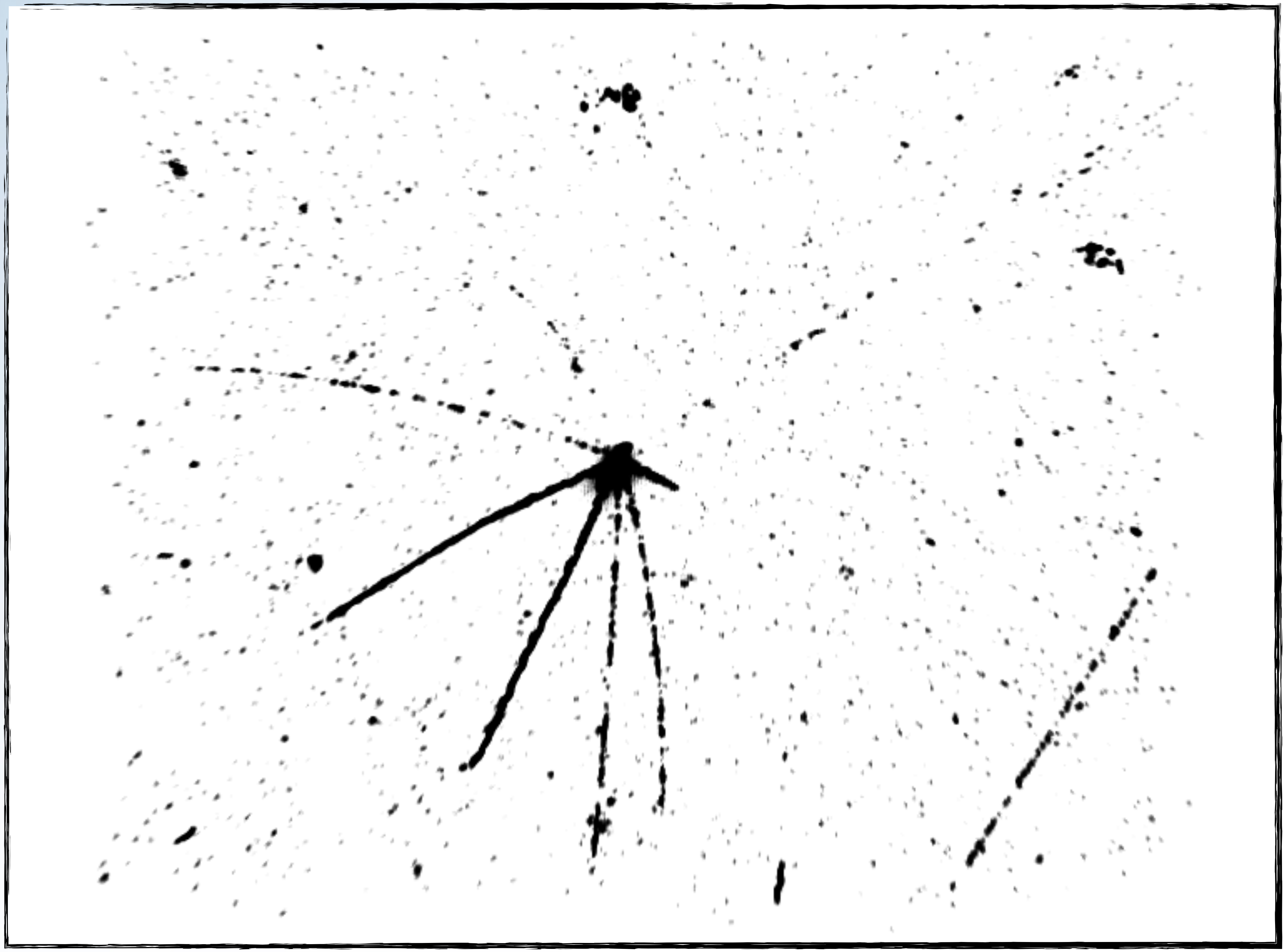
$$h = \frac{g}{2} \cdot \left(\frac{L}{v_h} \right)^2$$



FUTURE GOALS



FUTURE GOALS

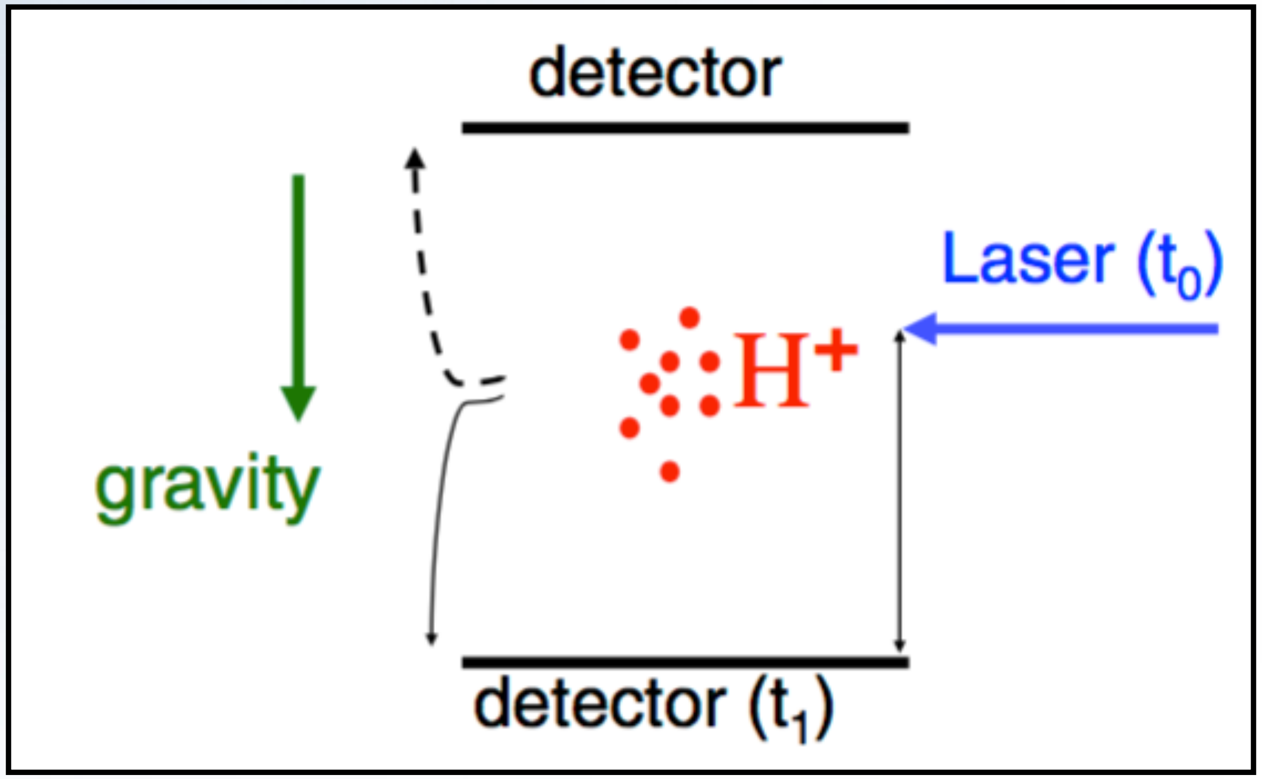


FUTURE GOALS

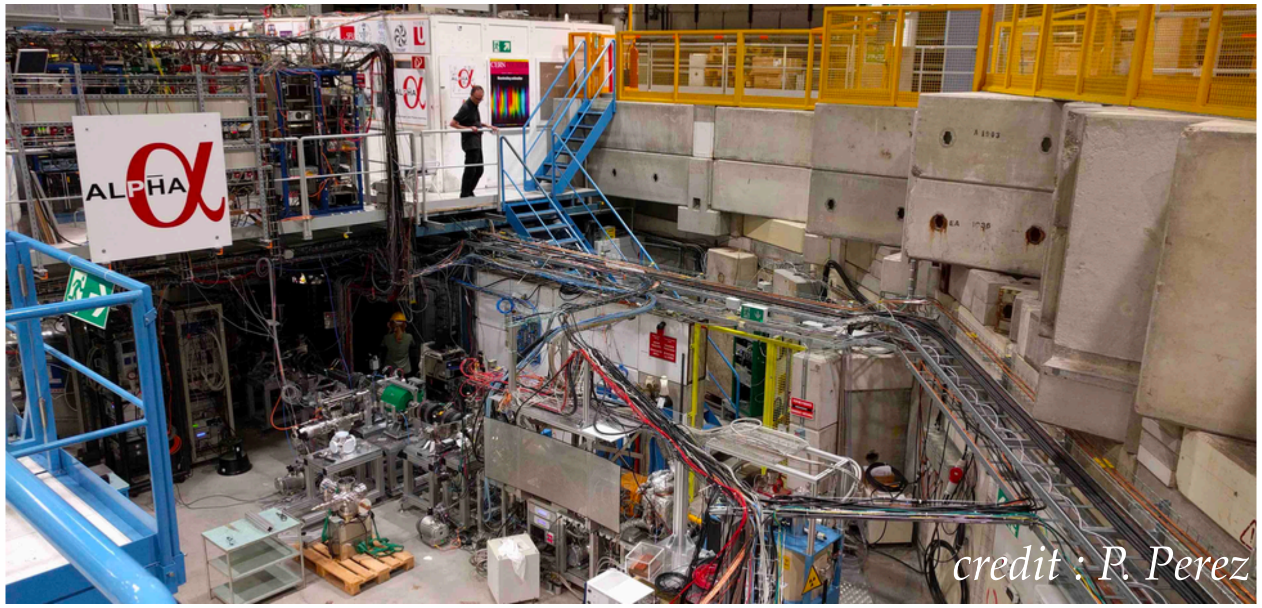
ALPHA : VERTICAL TRAP

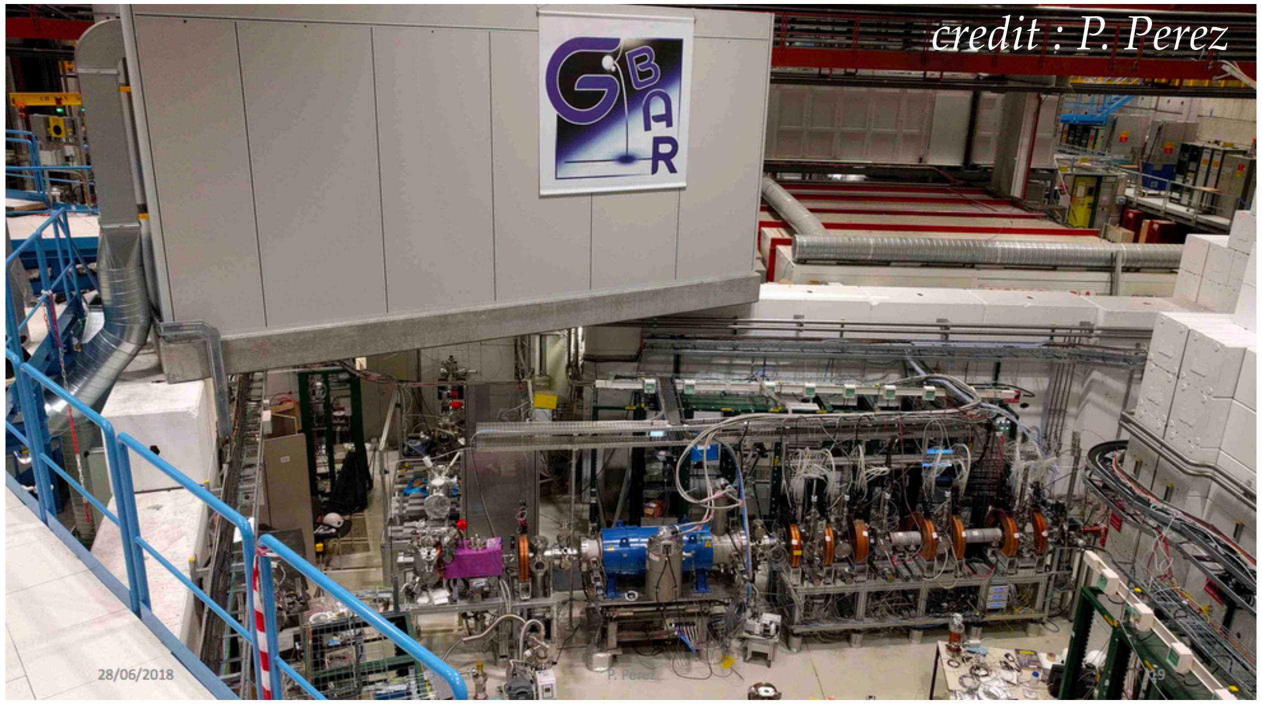
~10% - 1%

GBAR : DROPING EXPERIMENT



~1%





First experiment connected to ELENA

ANTIPROTON EXPERIMENTS

Inject antiprotons along magnetic field axis

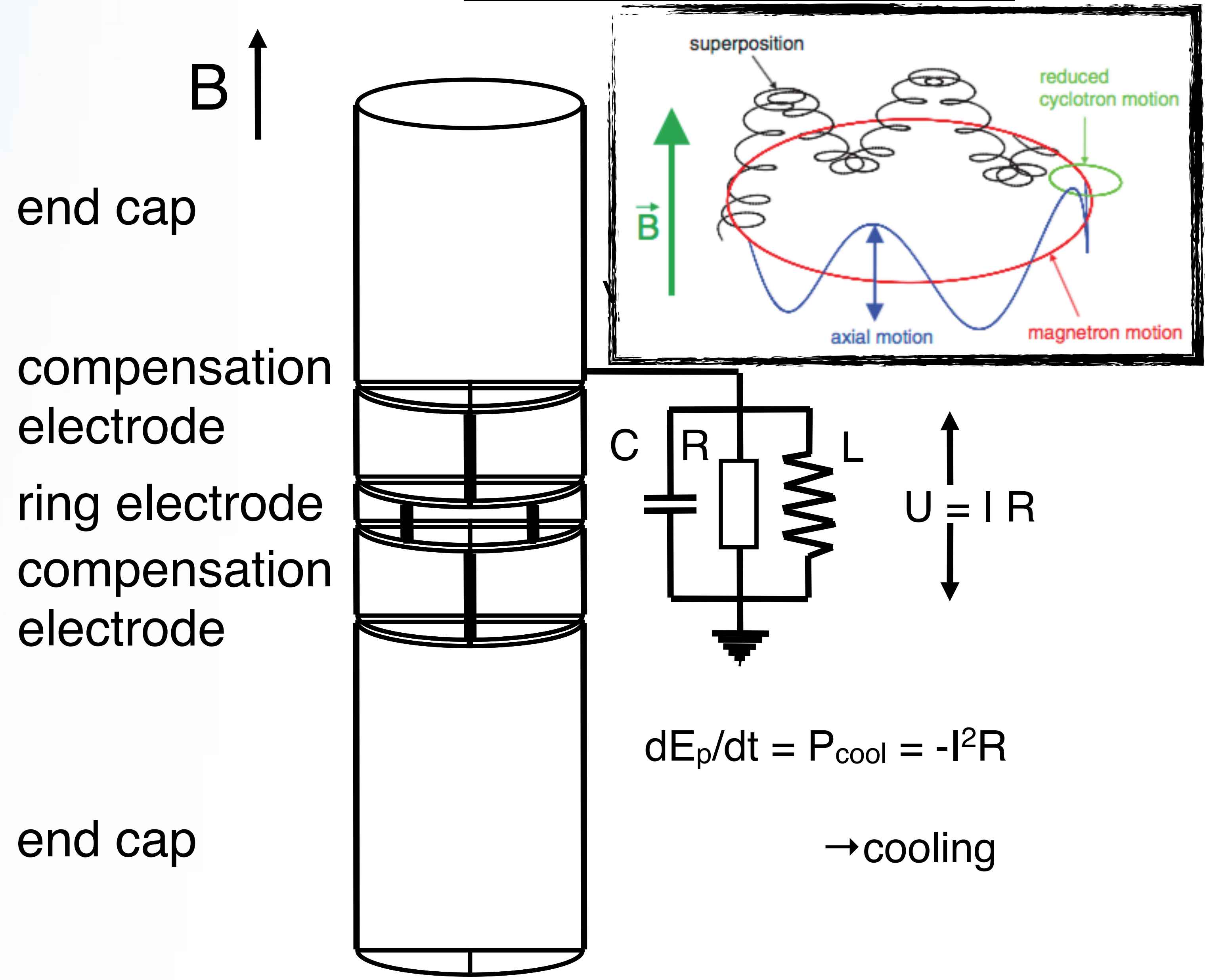
Energy ~ few keV

Precisions measurement : only 1 $\bar{p}$

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

Detection by cryogenic resonance circuit (low noise)

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

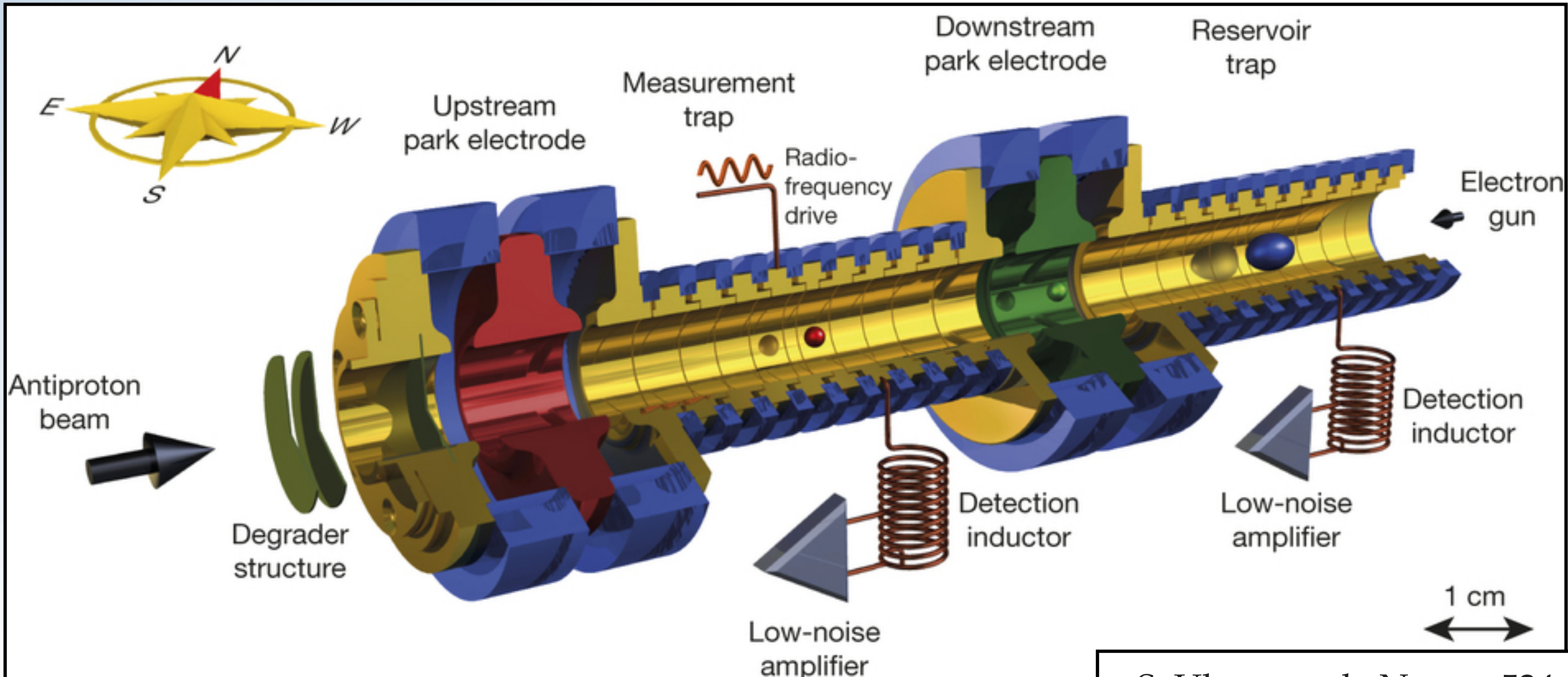


G. Gabrielse, W. Quint (LEAR)

ANTIPROTON EXPERIMENTS

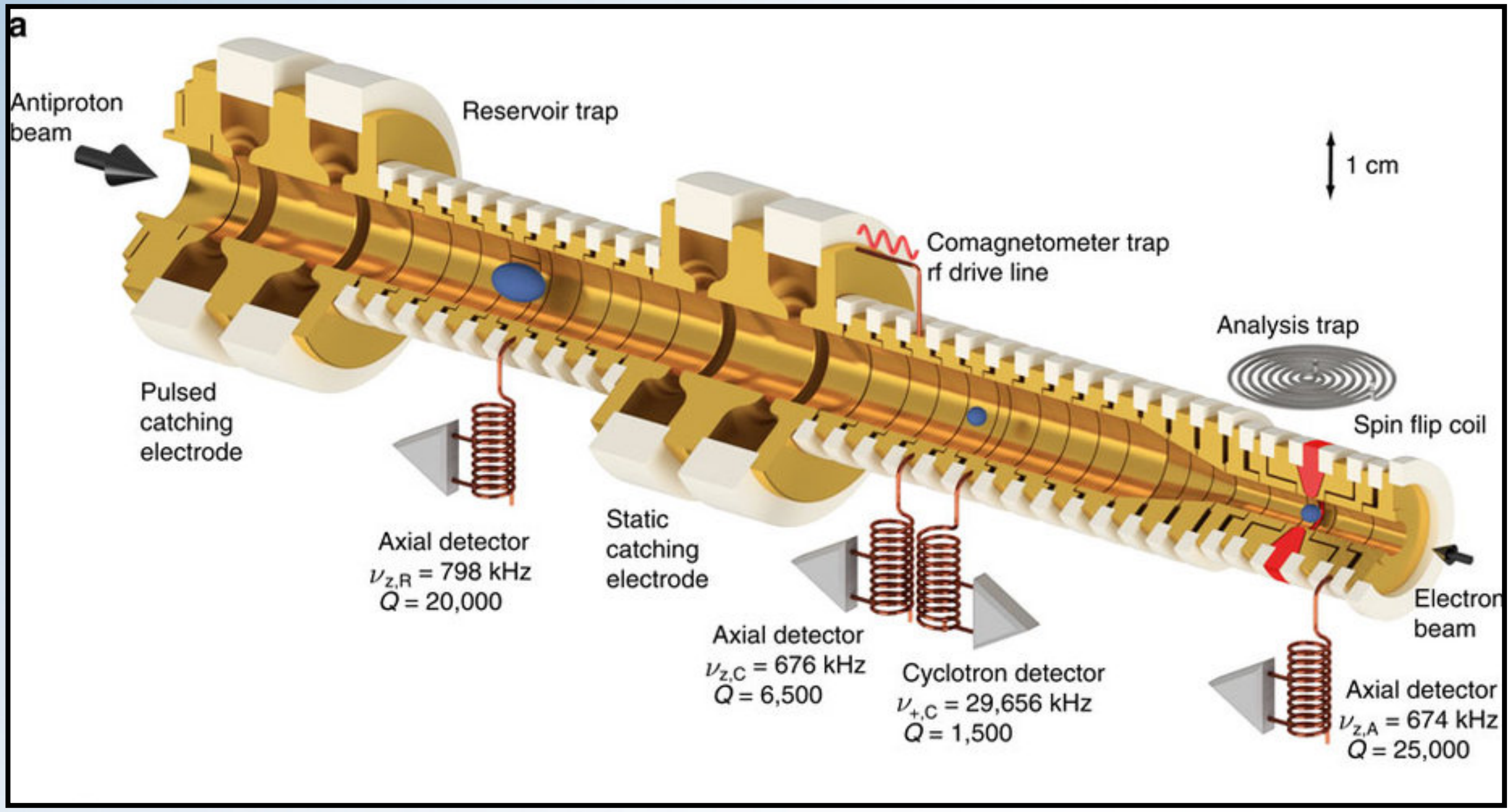
$$\nu_c = \frac{1}{2\pi}\frac{Q_{\bar{p}}}{M_{\bar{p}}}B$$

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



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

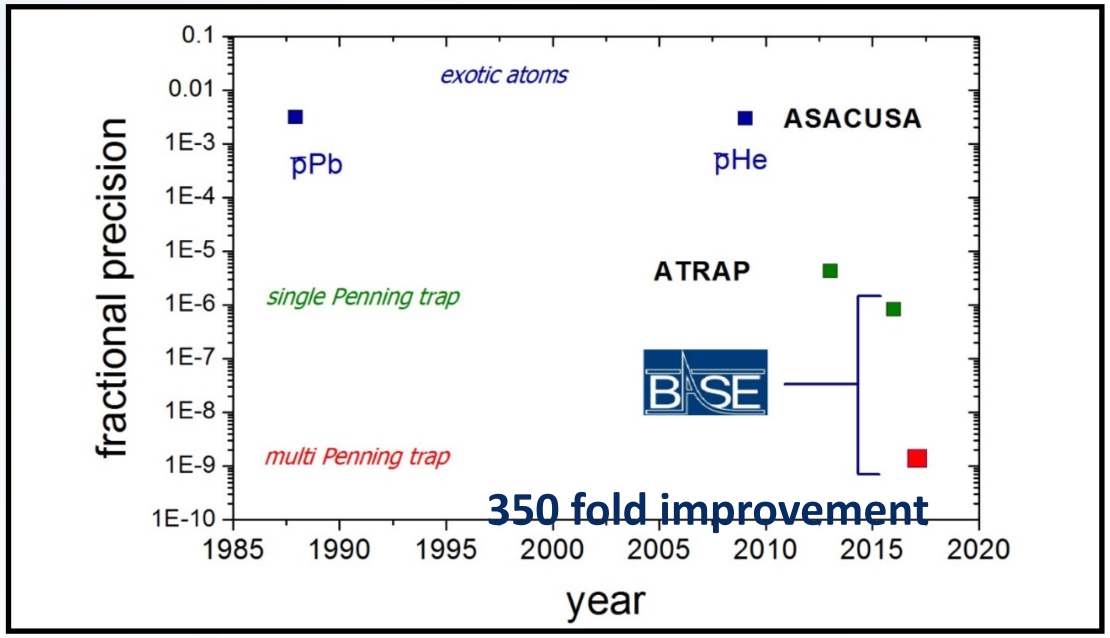
ANTIPROTON EXPERIMENTS



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

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

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



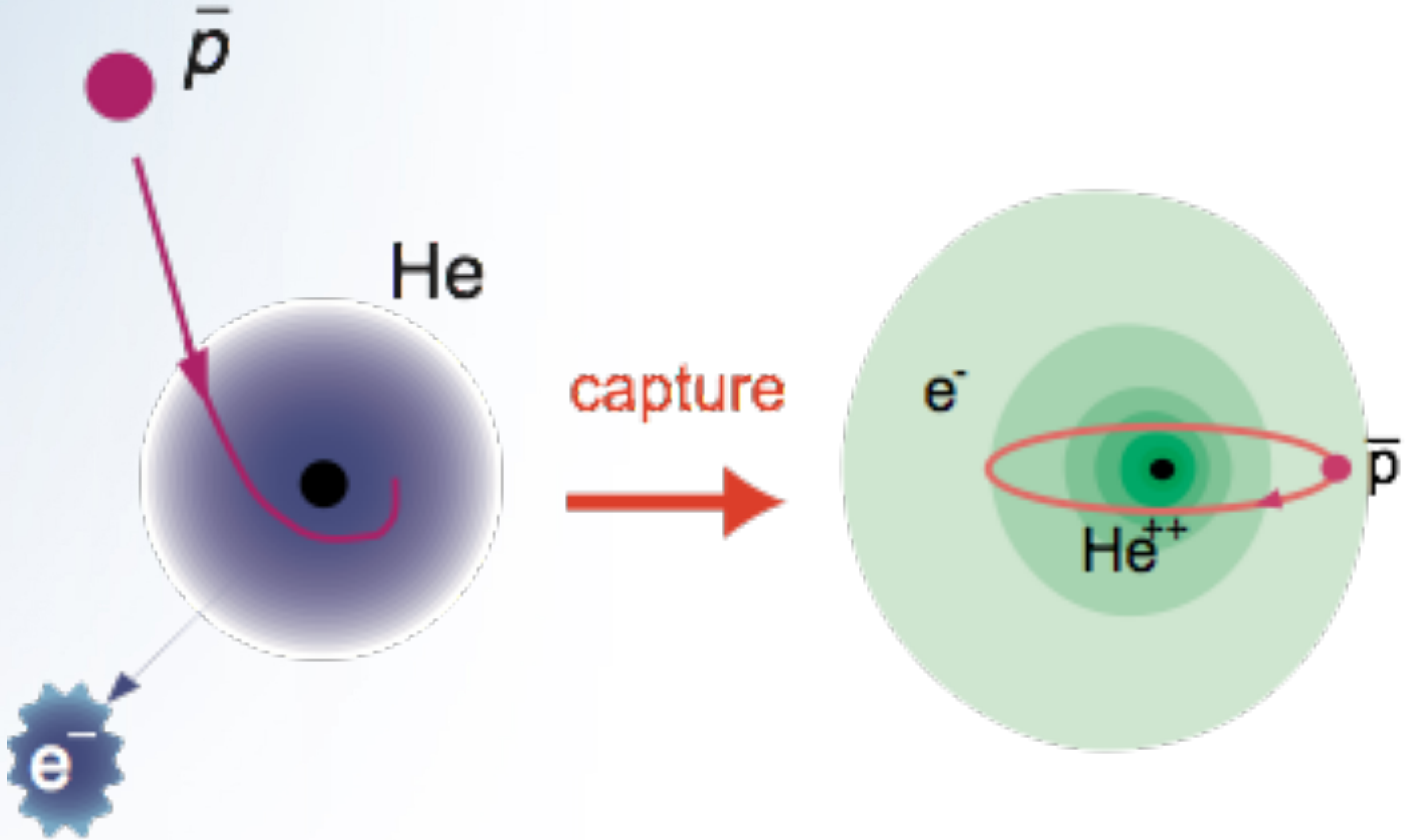
$$\frac{g_{\bar{p}}}{2} = 2.792\,847\,344\,1\,(42)$$

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

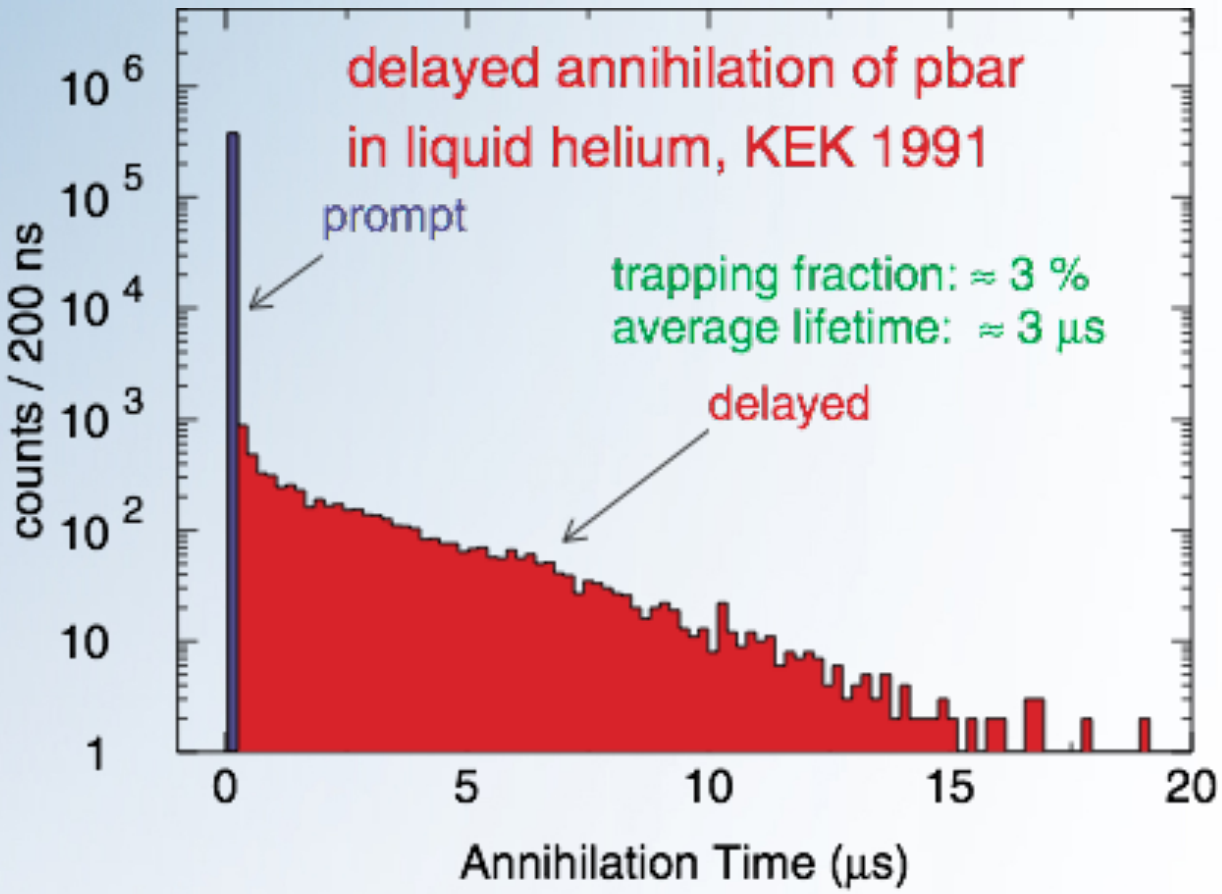
Previous work by the ATRAP collaboration Di Saccia et al. Phys. Rev. Lett. 110, 130801 (2013)

first measurement more precise for antimatter than for matter

ANTIPROTONIC HELIUM



ANTIPROTONIC HELIUM

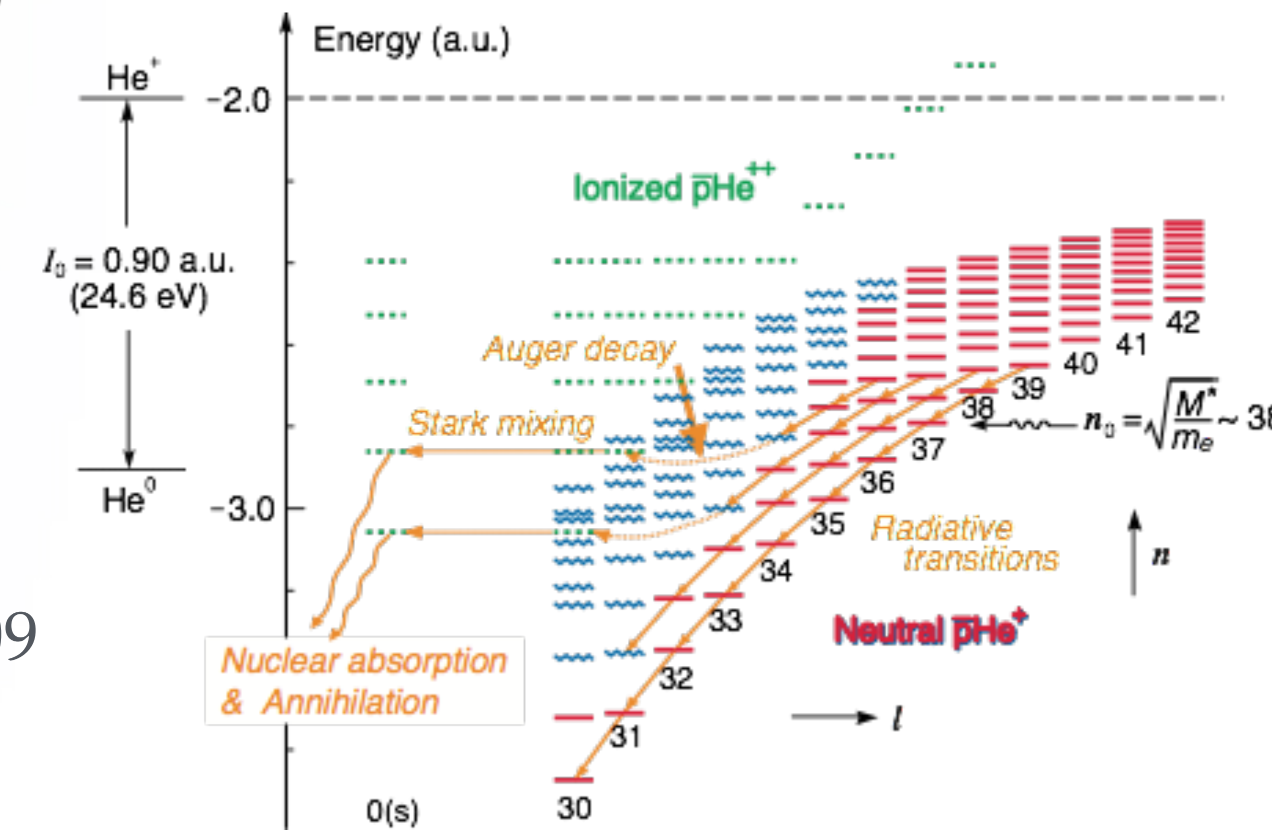


Three-body system $He^{++}e^{-}\bar{p}$,
$\bar{p}$ in highly excited, near circular states (n,l) ~ (38,37)

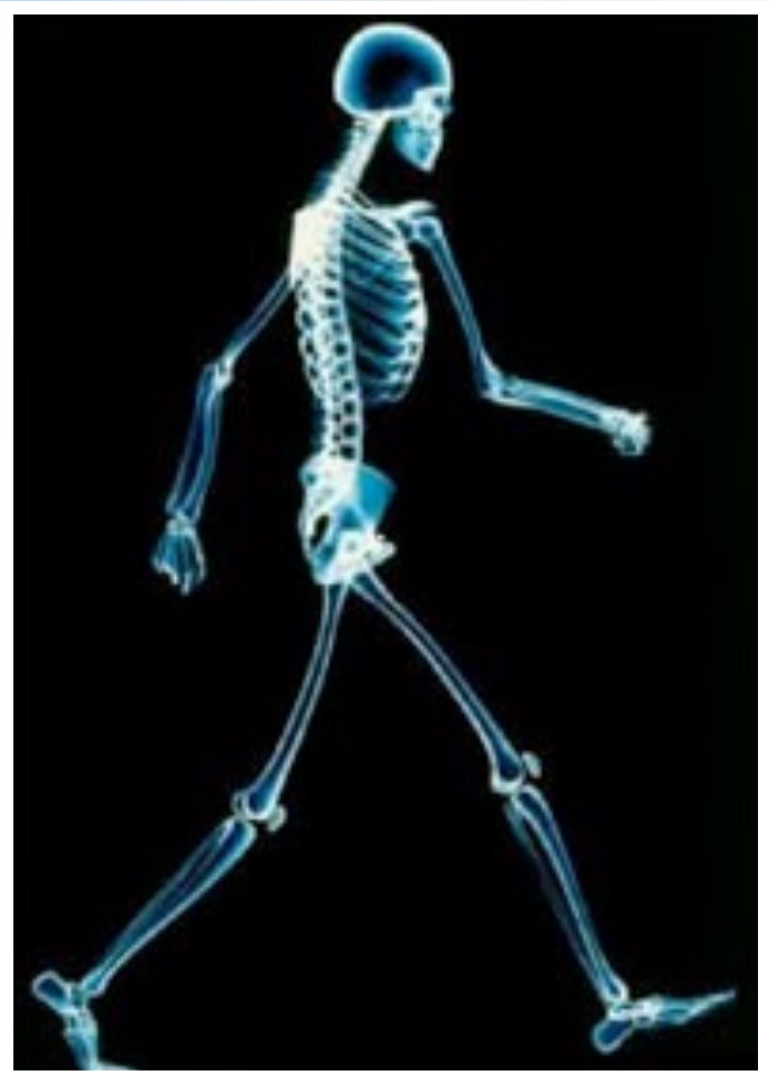
Comparison to 3-body QED calculations that use proton mass, magnetic moment

laser and microwave spectroscopy

CPT test
antiproton properties
mass,charge: 7×10^{-10} 2011
magnetic moment: 2.9×10^{-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.

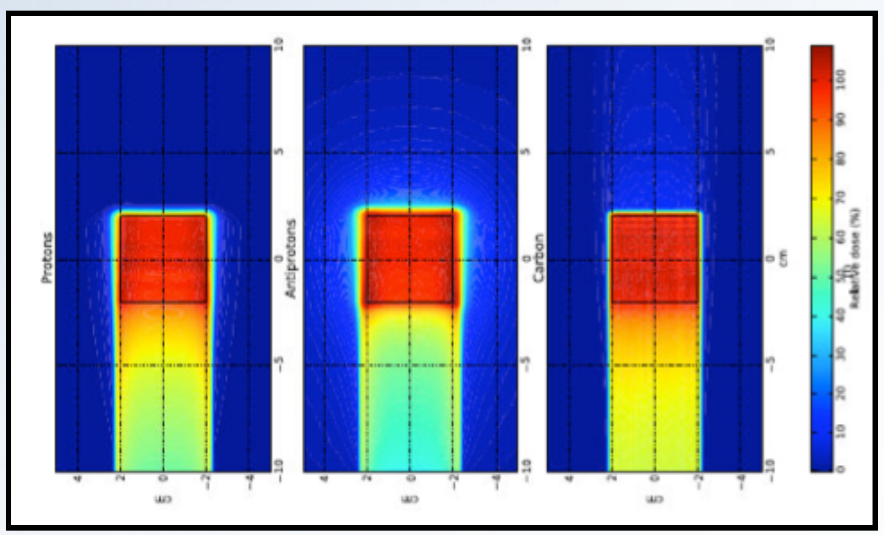
10 e+/s !

"DAILY" APPLICATIONS

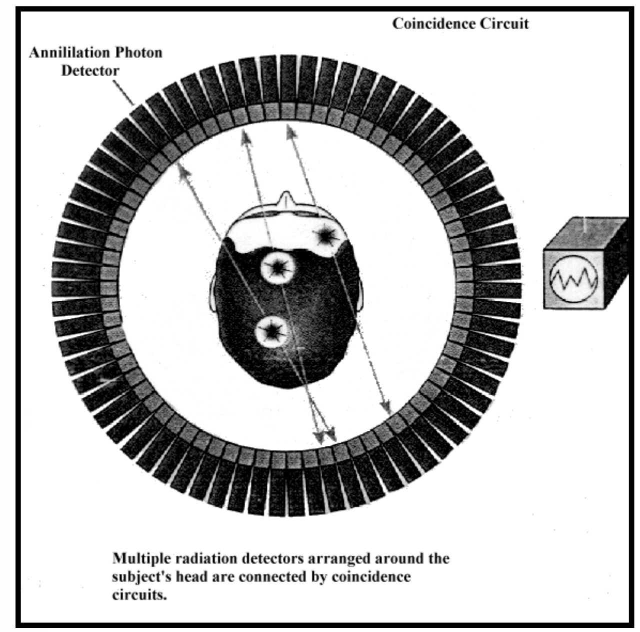
Antiprotons in accelerators!

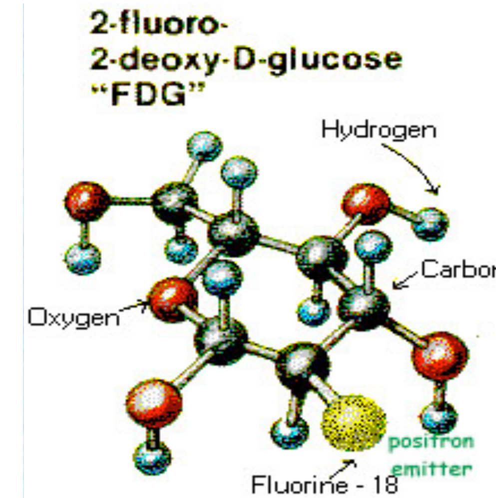
Antiprotons for nuclear studies (PUMA)

Antiproton Therapy (under study)



Medical imaging : PET





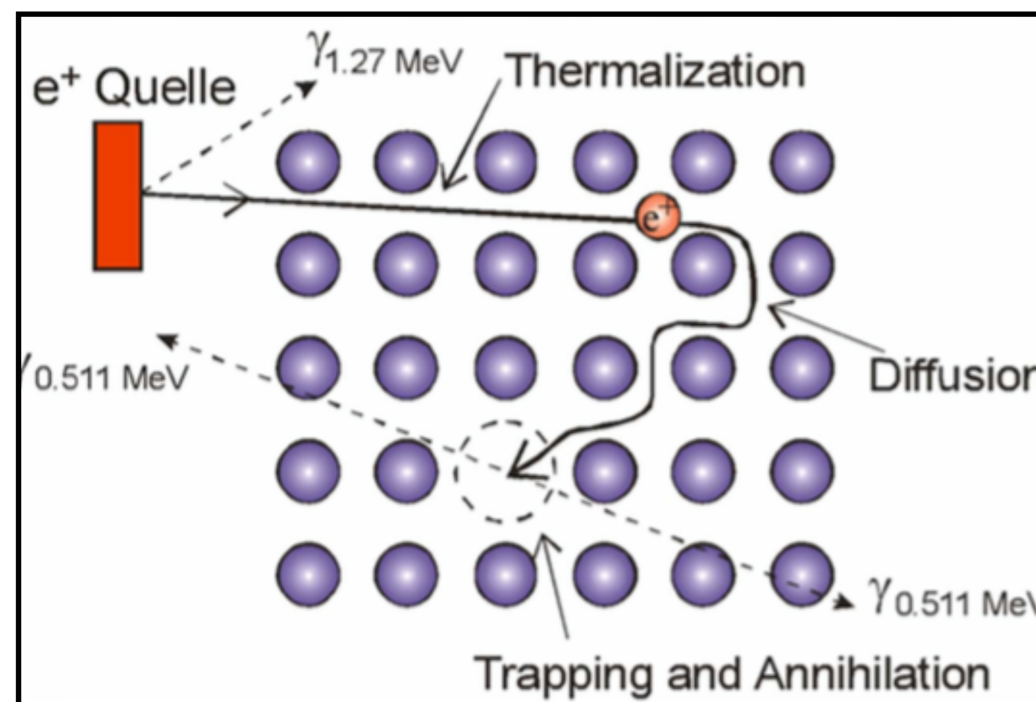
e+ emitting isotope (C-11, N-13, O-15)

(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 $\bar{p}$ ~ 6×10^{23}

CERN produces 3×10^{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!)

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

Energy efficiency is about 10^{-9}
We need ~$9x\ 10^{22}$ J

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

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2 000 000 000 000 000 €

"DAILY "APPLICATIONS

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2 000 000 000 000 000 €

a year of $\bar{p}$ 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!

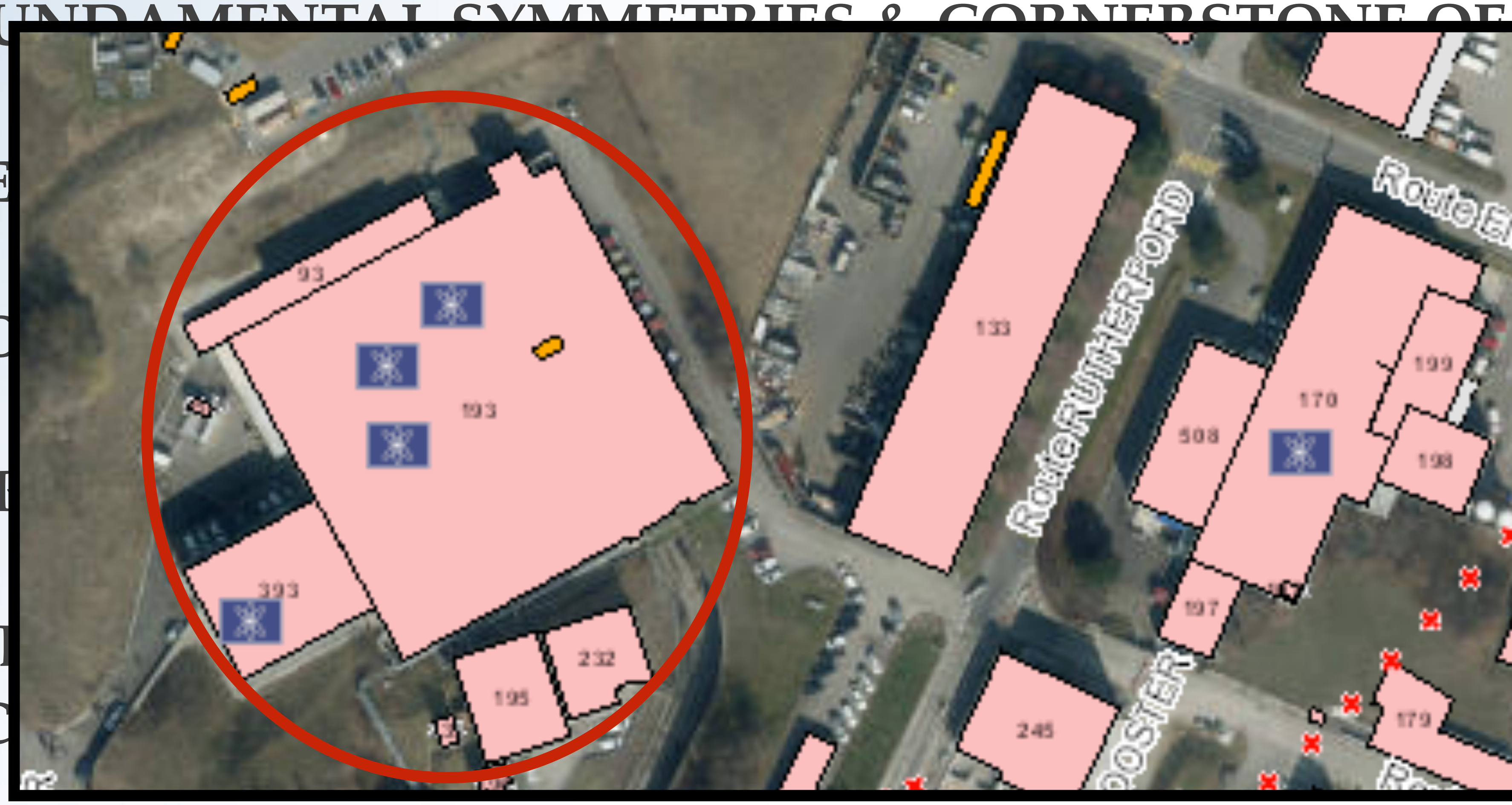
AD PHYSICS PROGRAMME :
TESTING FU… SM

TEST BODIE…

>20 YEARS O…

ENTERING E…

MANY OTHE…
SPECTROSC…



ANTIMATTER AS MEDICAL AND SCIENTIFIC TOOLS

OTHER APPLICATIONS OF ANTIMATTER?