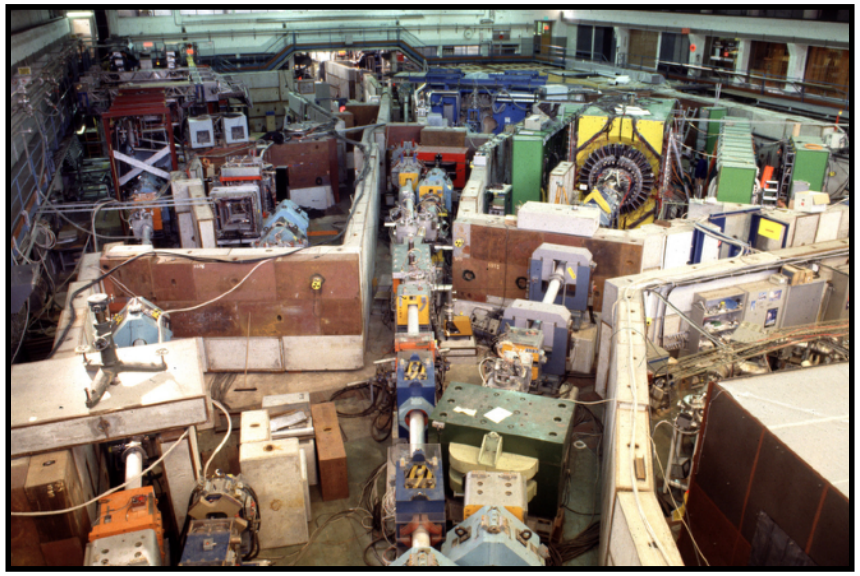
ANTIMATTER IN THE LAB

Q & A SESSION



CERN Summer student 2020

Content of lectures viewed

LECTURE # 1
- What is antimatter?
- Some historical reminders
- Discrete symmetries
- Primordial antimatter search

LECTURE # 2
- 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

Topic of questions asked in advance

- Antimatter (neutron versus antineutron)
- Properties of particles (SPIN)
- Additional information on the 3 gravity experiments at the AD
- Status of the physics (at the AD) since last year

Q1

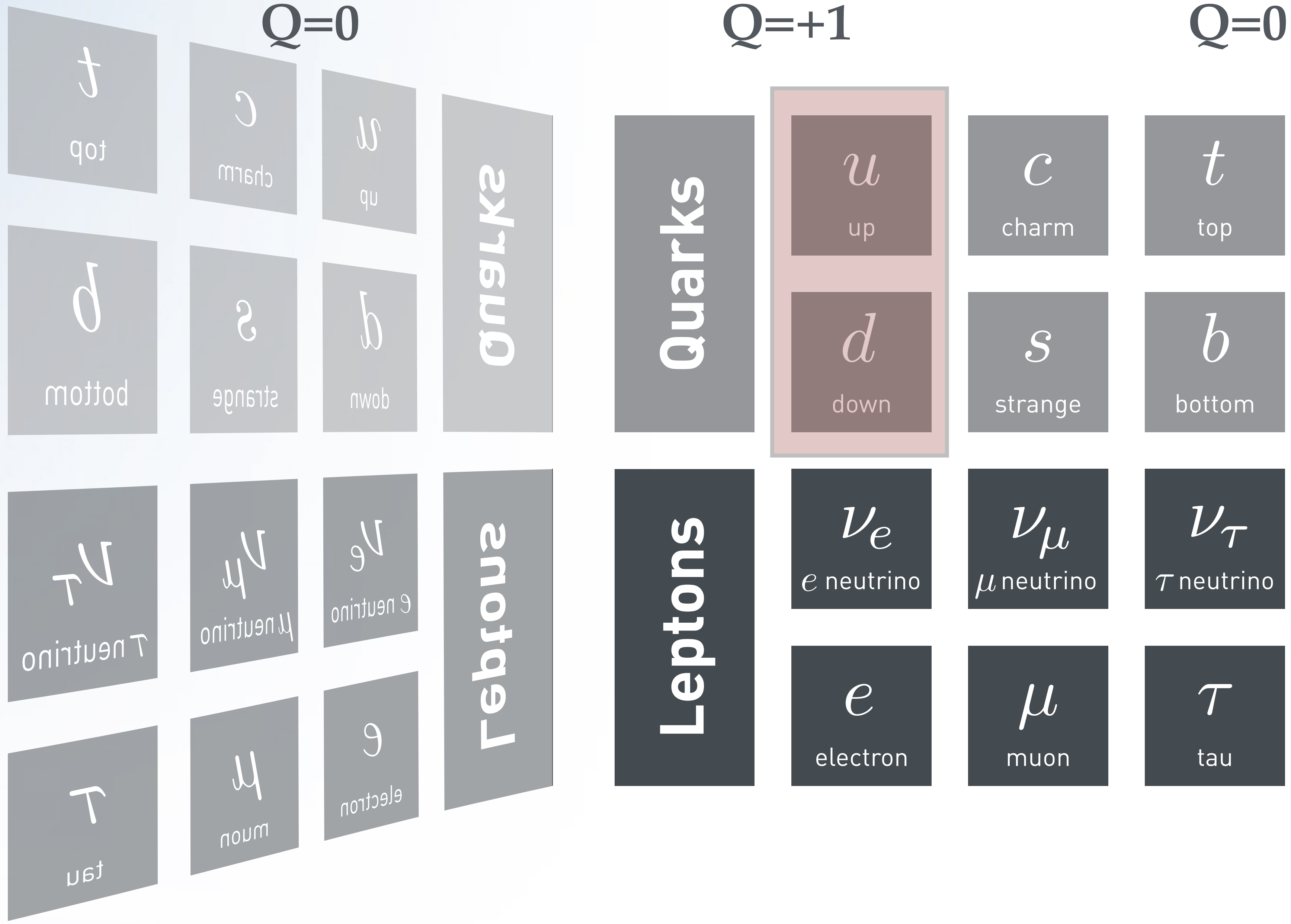
- **How can we distinguish between a neutron and an antineutron? How was it discovered/detected?**

antiproton: $\bar{u}\bar{u}\bar{d}$ Q=-1

antineutron: $\bar{u}\bar{d}\bar{d}$ Q=0

proton: uud Q=+1

neutron: udd Q=0



antiproton discovered in 1955

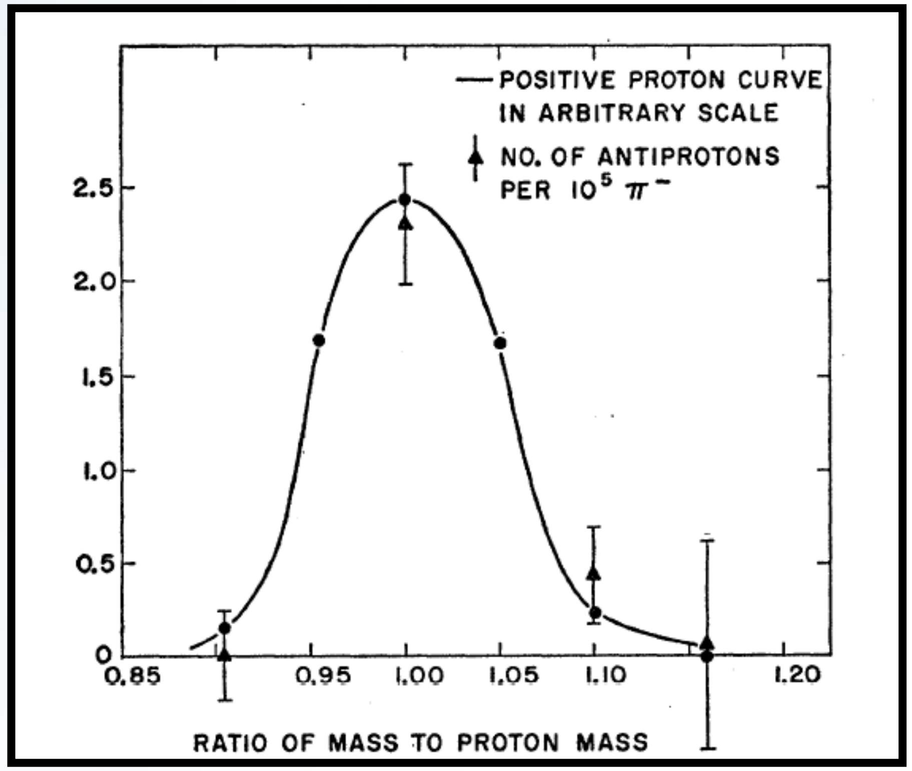
1955 : Discovery of the antiproton (Nobel Prize to Chamberlain & Segré in 1959)

Discovery at the Bevatron

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

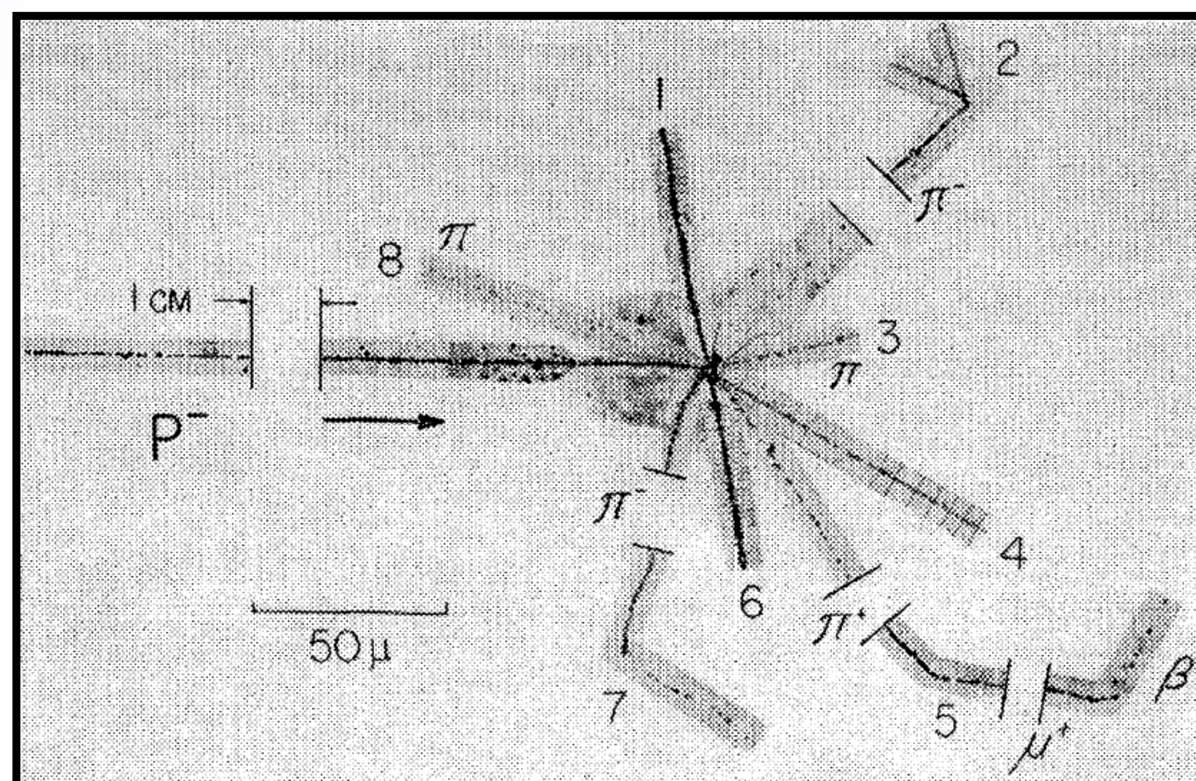
Identified 60 events

Delta m/m ~ 5%



Discrimination against other negatively charged particles via momentum & velocity selection

Annihilation of an antiproton detected in a emulsion a year later : first p̄-N annihilation observed
35 events
—> proof of antimatter character



following year antineutron observed

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

Bevatron was producing 300-600 p̄ / h!

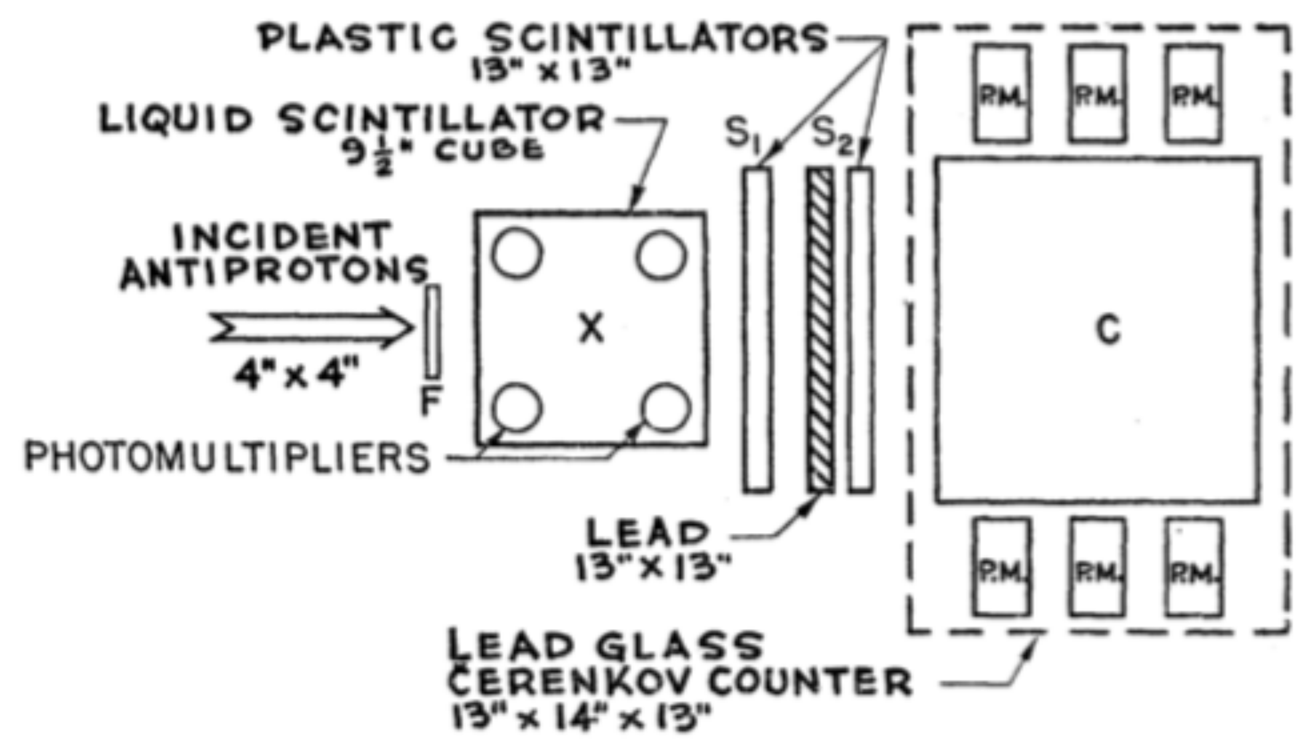
discrimination using energy deposit in different scintillators

Antineutrons Produced from Antiprotons in Charge-Exchange Collisions*

BRUCE CORK, GLEN R. LAMBERTSON, ORESTE PICCIONI,† AND WILLIAM A. WENZEL

Radiation Laboratory, University of California, Berkeley, California

(Received October 3, 1956)

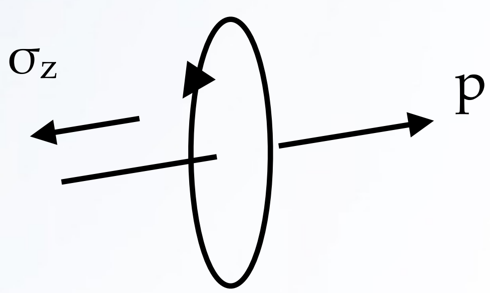


Q2

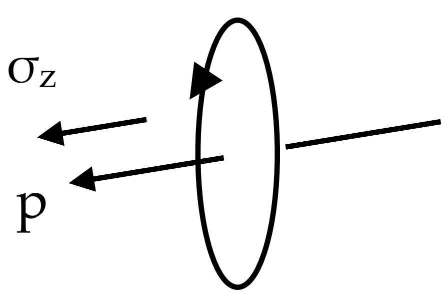
- **intuitive description of spin**
  concept of left/right handedness
  Wave versus particle description

$$L = r \times p$$

Spin: an intrinsic angular moment
helicity: projection of the spin onto the direction of momentum



LH neutrino ν



RH anti-neutrino observed $\bar{\nu}$

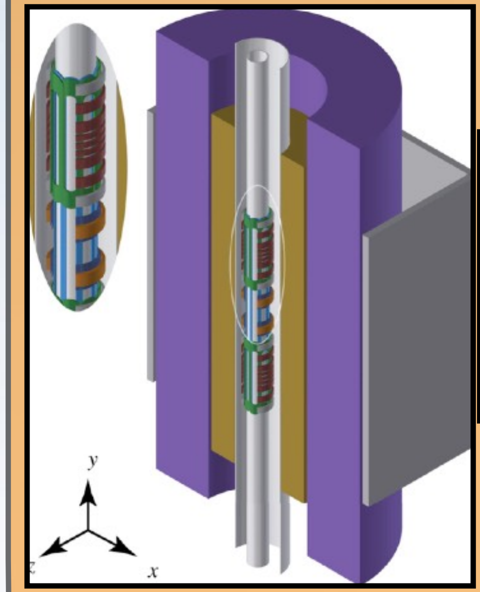
Q3

- **Information on the 3 gravity experiments at the AD**

VERTICAL TRAP

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

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



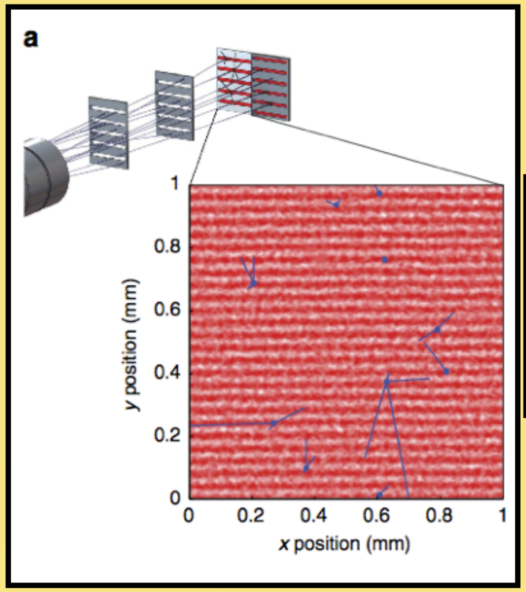
W. A. Bertsche Phil. Trans. R. Soc. A 2018 376 20170265; DOI: 10.1098/rsta.2017.0265. (2018)

ALPHA-G

$\bar{H}$ BEAM

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

Sign measurement targeted



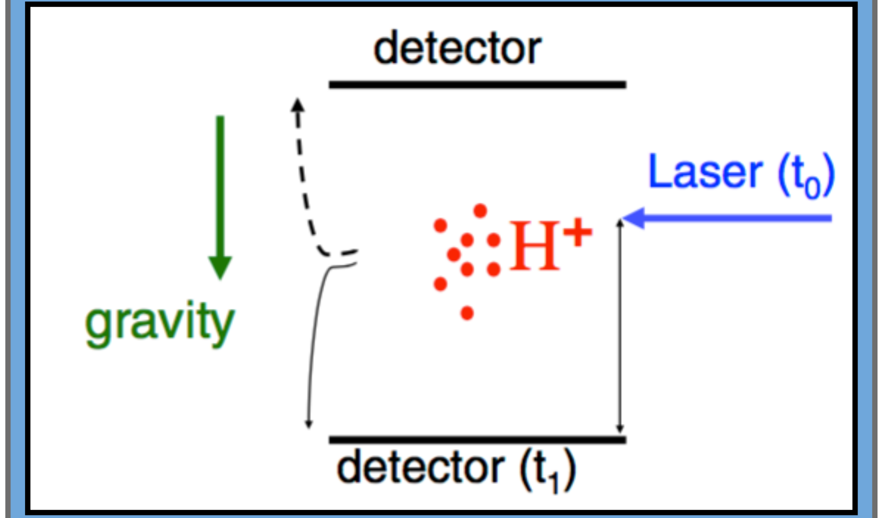
S. Aghion et al. Nature Communications 5 (2014) 4538

AEGIS

$\bar{H}^+$ BEAM

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

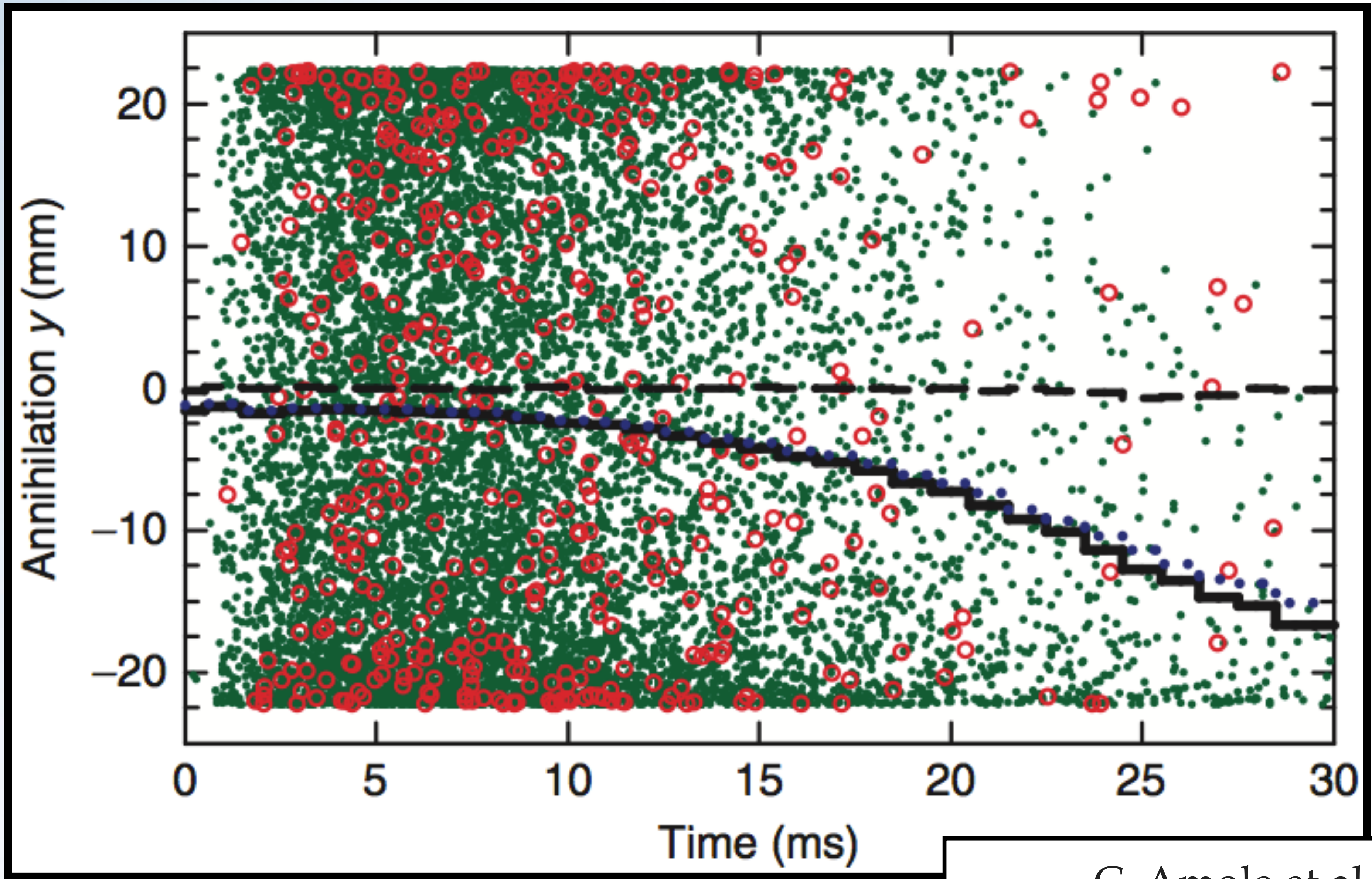
1% measurement targeted



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

GBAR

Q3



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

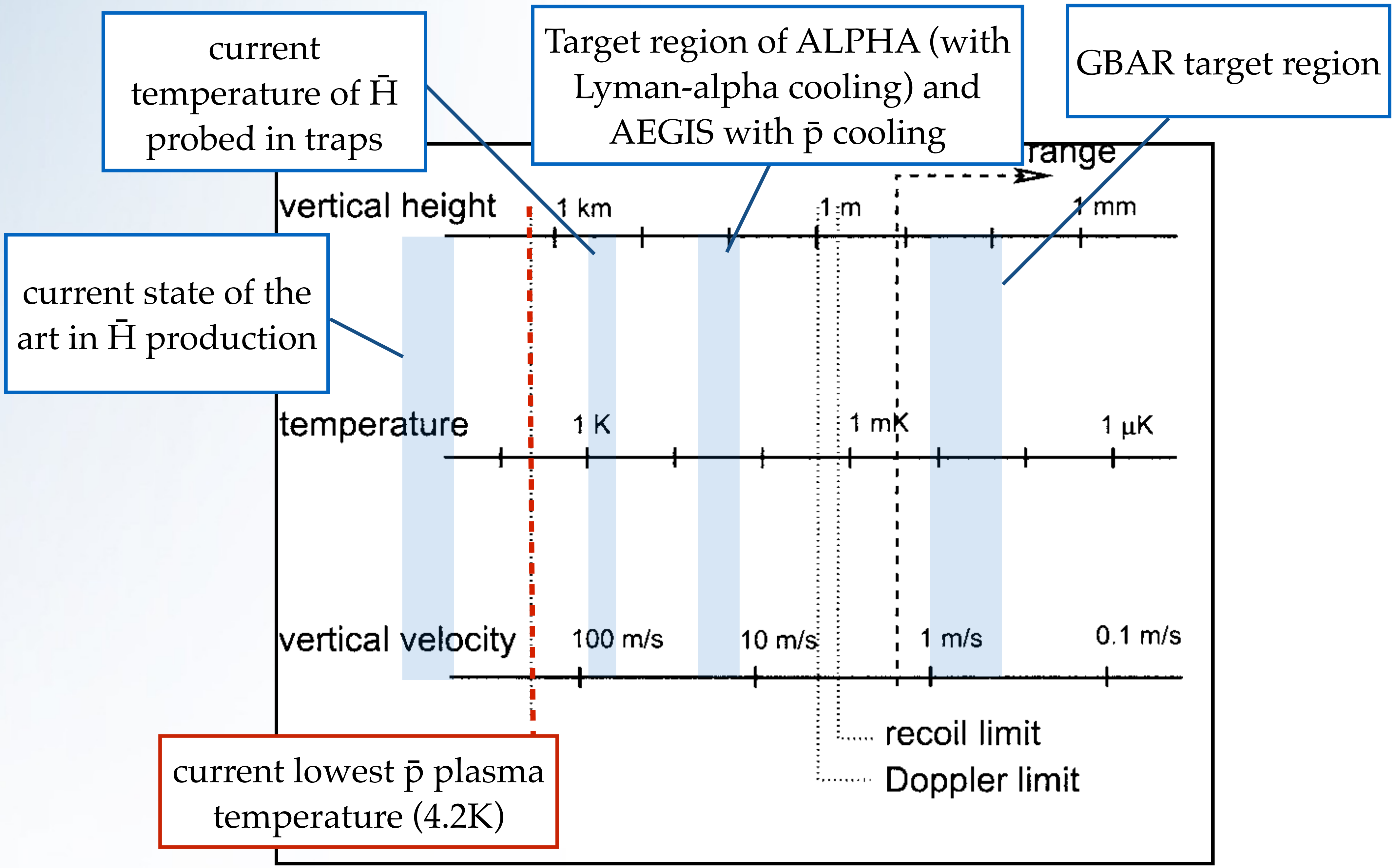
-65 < g/ḡ < 110

Green dots---simulated annihilations

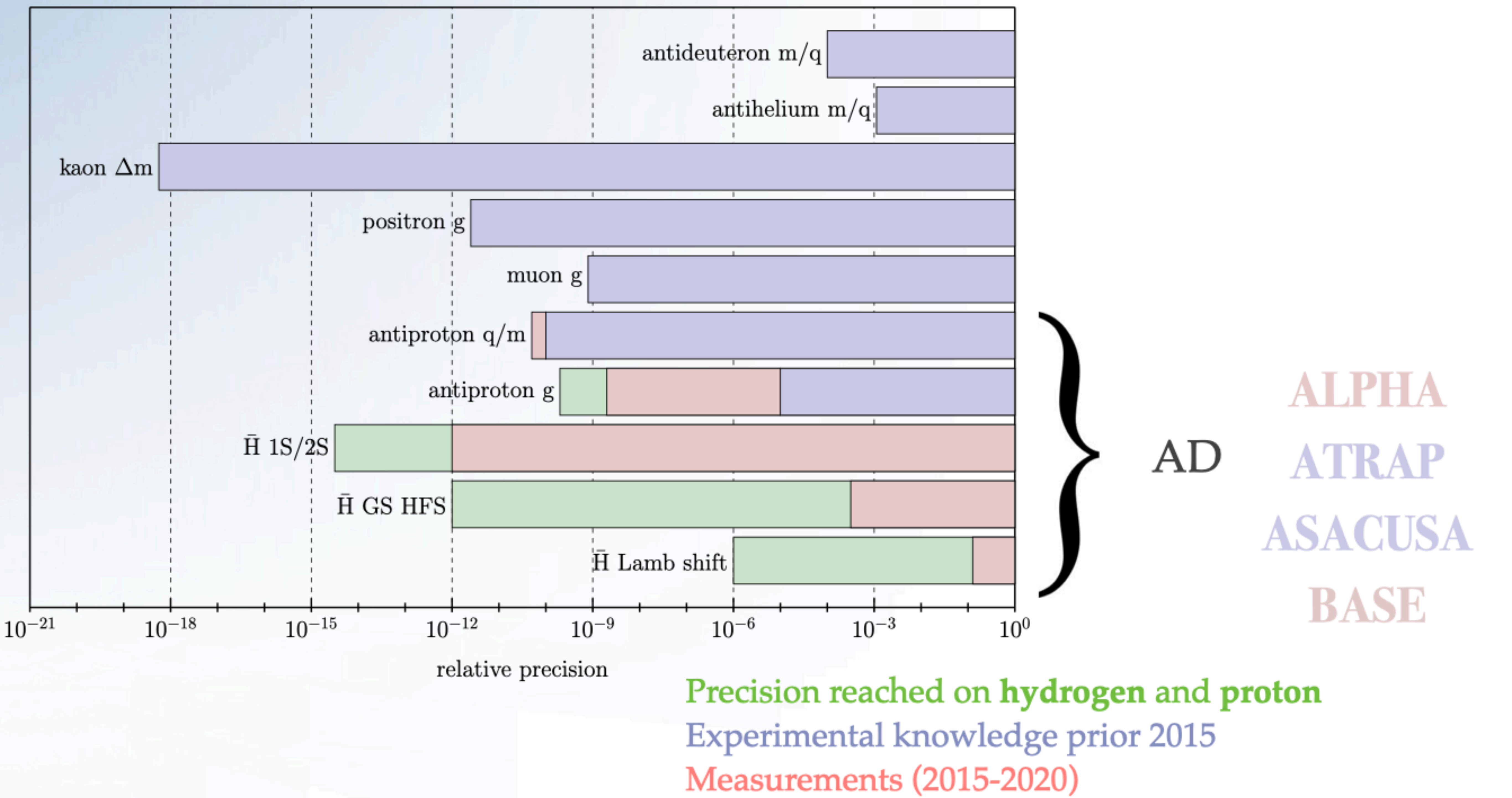
Red circles---434 Observed annihilations

Vertical position of annihilation vertex during release of trapping field

Some numbers to set the scale

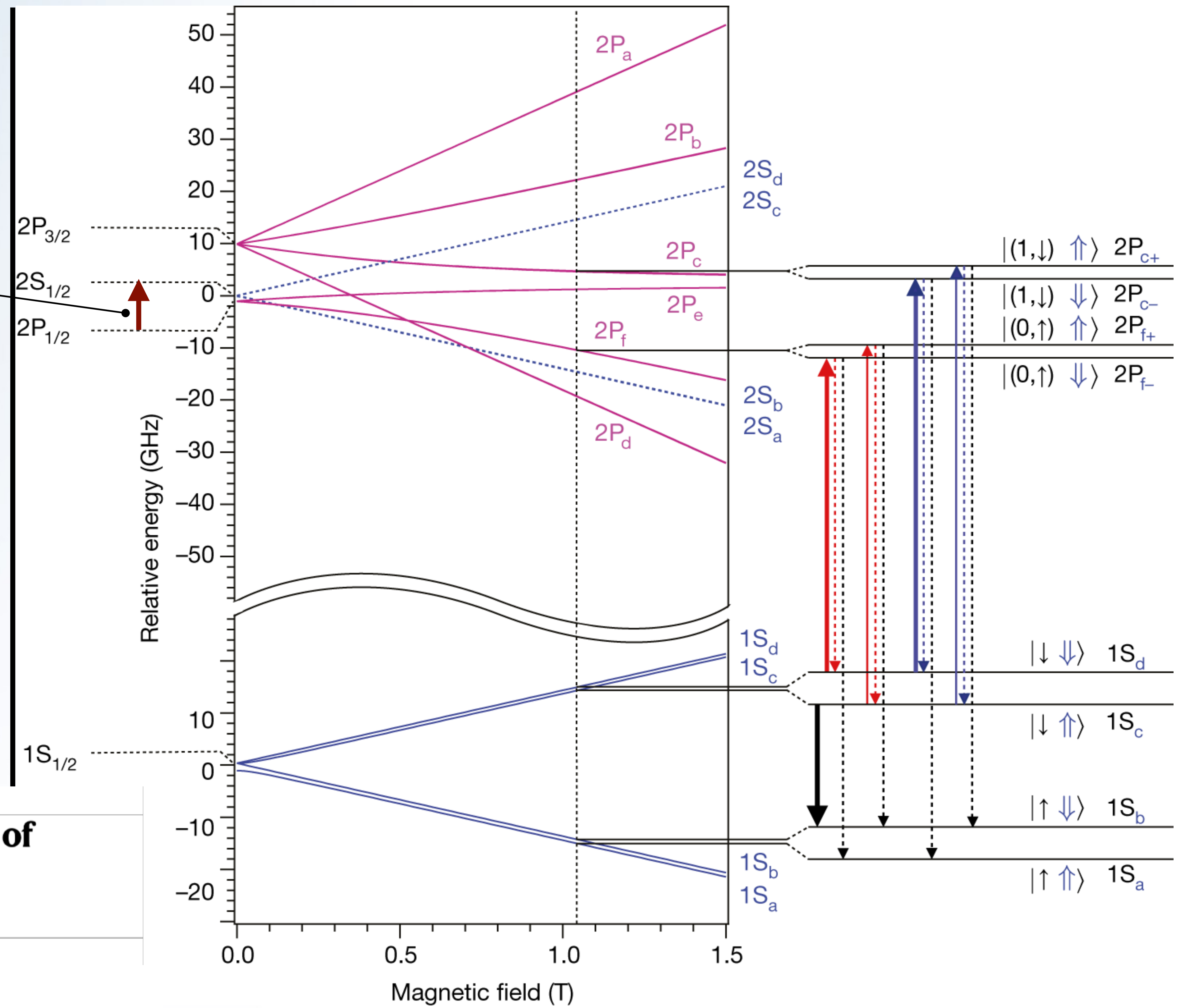


- **Were there any major breakthroughs in the antimatter community between last year and today?**



Q4

Classic Lamb shift



Article

Investigation of the fine structure of antihydrogen

https://doi.org/10.1038/s41586-020-2006-5

Received: 7 December 2018

Accepted: 20 December 2019

Published online: 19 February 2020

The ALPHA Collaboration*

Q4

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 $\bar{H}$

$\bar{H}$ SPECTROSCOPY STUDIES

Lyman-alpha cooling on its way to reach mK $\bar{H}$

New cooling techniques will be further developed during LS2 (sympathetic cooling of + and - charges)

GRAVITATIONAL STUDIES OF $\bar{H}$

First measurements awaited soon after LS2!

New temperature regime probed

ANTIPROTON PROPERTIES

Further improvements foreseen (incl. sympathetic cooling of single $\bar{p}$)

NEW DECELERATOR RING

Colder and better beam : will allow exciting new physics

NEW EXPERIMENTS!

transportable trap

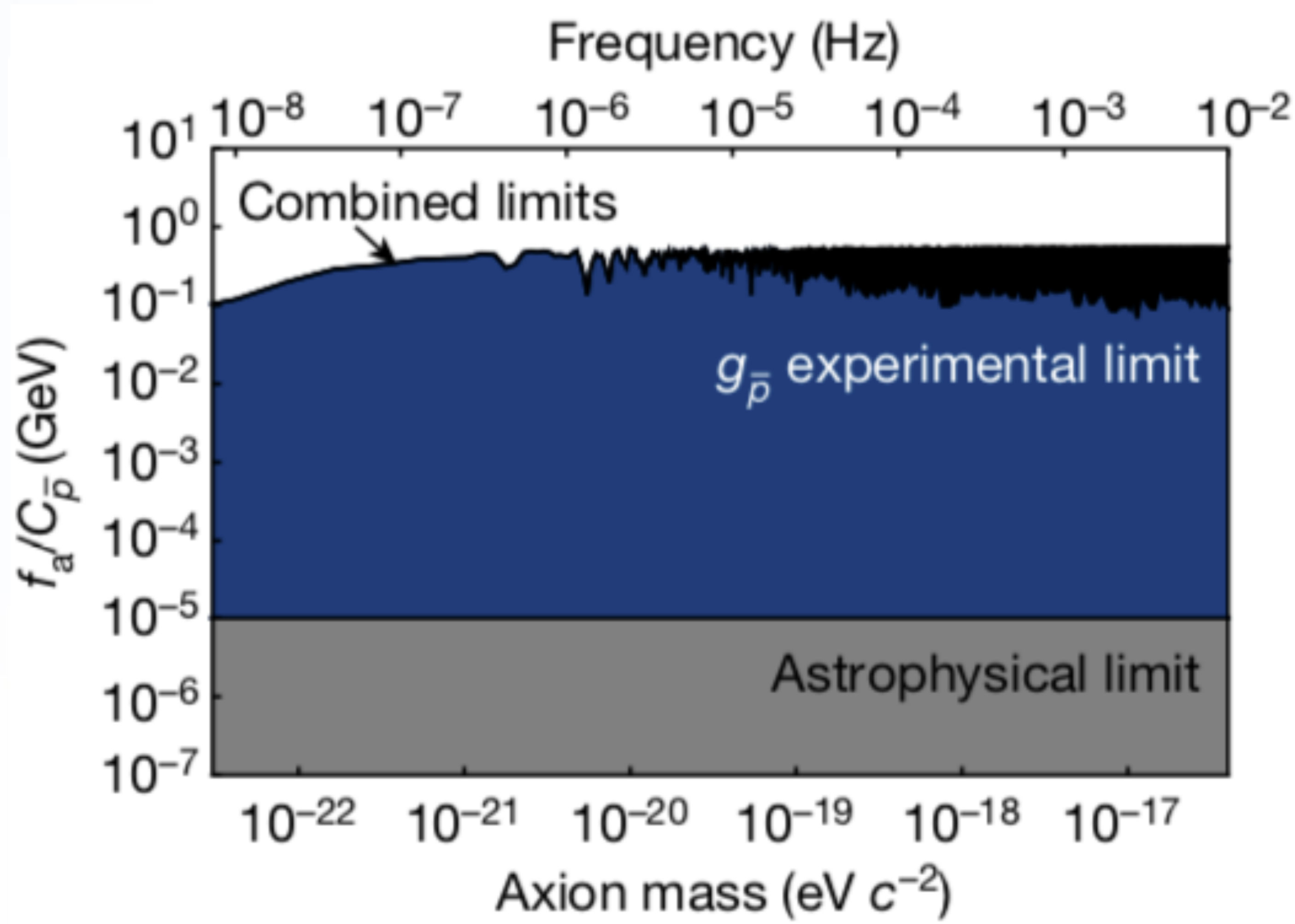
Antiprotons for nuclear studies (PUMA)

Q4

Connection between axion and antimatter?

- baryon asymmetry
- unknown dark matter

Could an ``anomalous'' coupling between the two be the clue to both puzzles?



Article

Direct limits on the interaction of antiprotons with axion-like dark matter

https://doi.org/10.1038/s41586-019-1727-9

Received: 21 May 2019

Accepted: 20 September 2019

Published online: 13 November 2019

C. Smorra[1*], Y. V. Stadnik[2,3], P. E. Blessing[1,4], M. Bohman[1,5], M. J. Borchert[1,6], J. A. Devlin[1,7], S. Erlewein[1,5,7], J. A. Harrington[1,5], T. Higuchi[1,8,12], A. Mooser[1,5], G. Schneider[1,9], M. Wiesinger[1,5], E. Wursten[1,7], K. Blaum[5], Y. Matsuda[8], C. Ospelkaus[5,10], W. Quint[4], J. Walz[2,9], Y. Yamazaki[1], D. Budker[2,11] & S. Ulmer[1*]

Q4

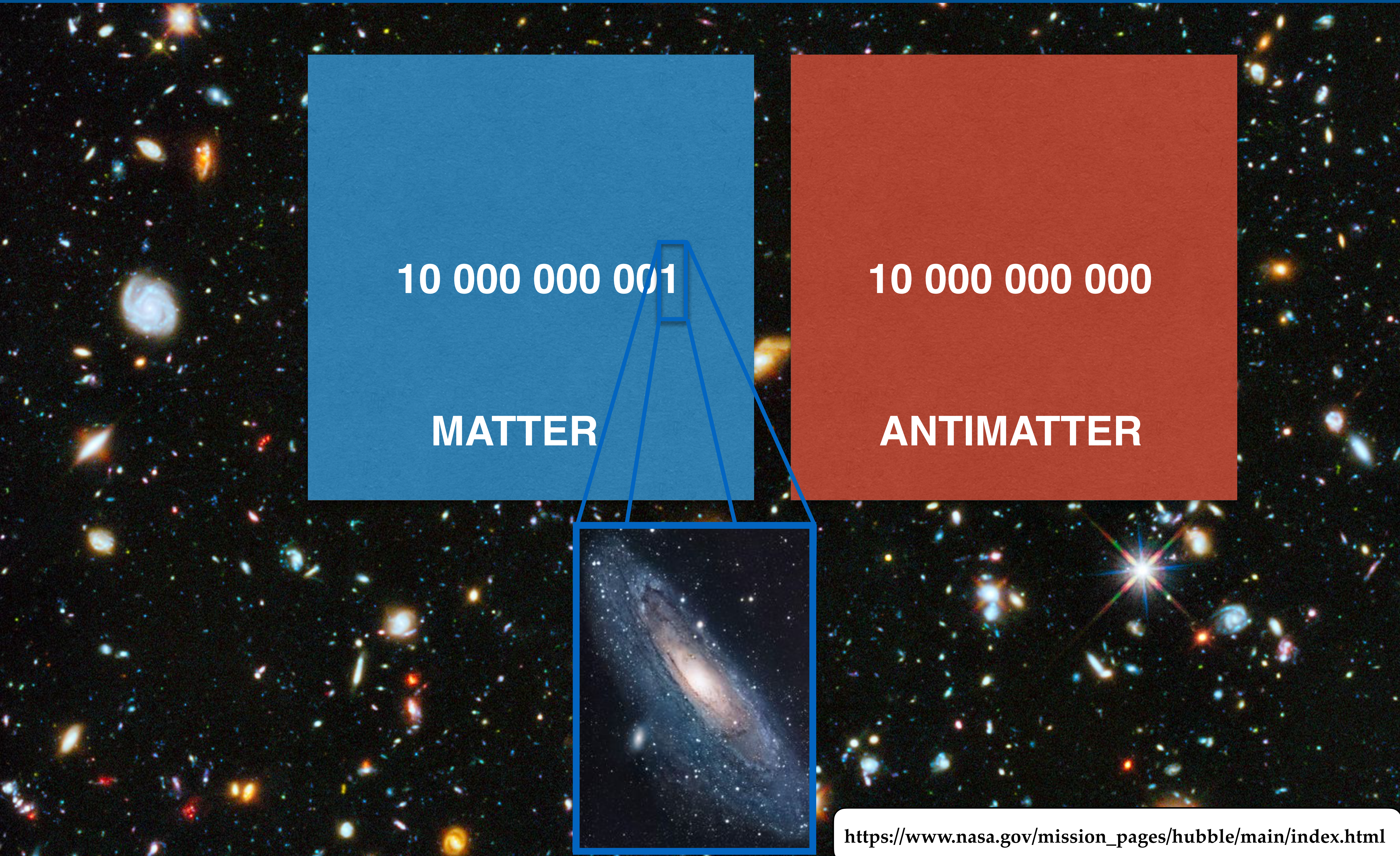
Many other advances outside the AD connected to matter-antimatter asymmetry

CP violation in D mesons (LHCb - 2019)
Indication of possible CP violation in the leptonic sector (2020)
Studies of anti-nuclei (antideuteron - ALICE 2020)
etc

copy of (some of the) lecture slides

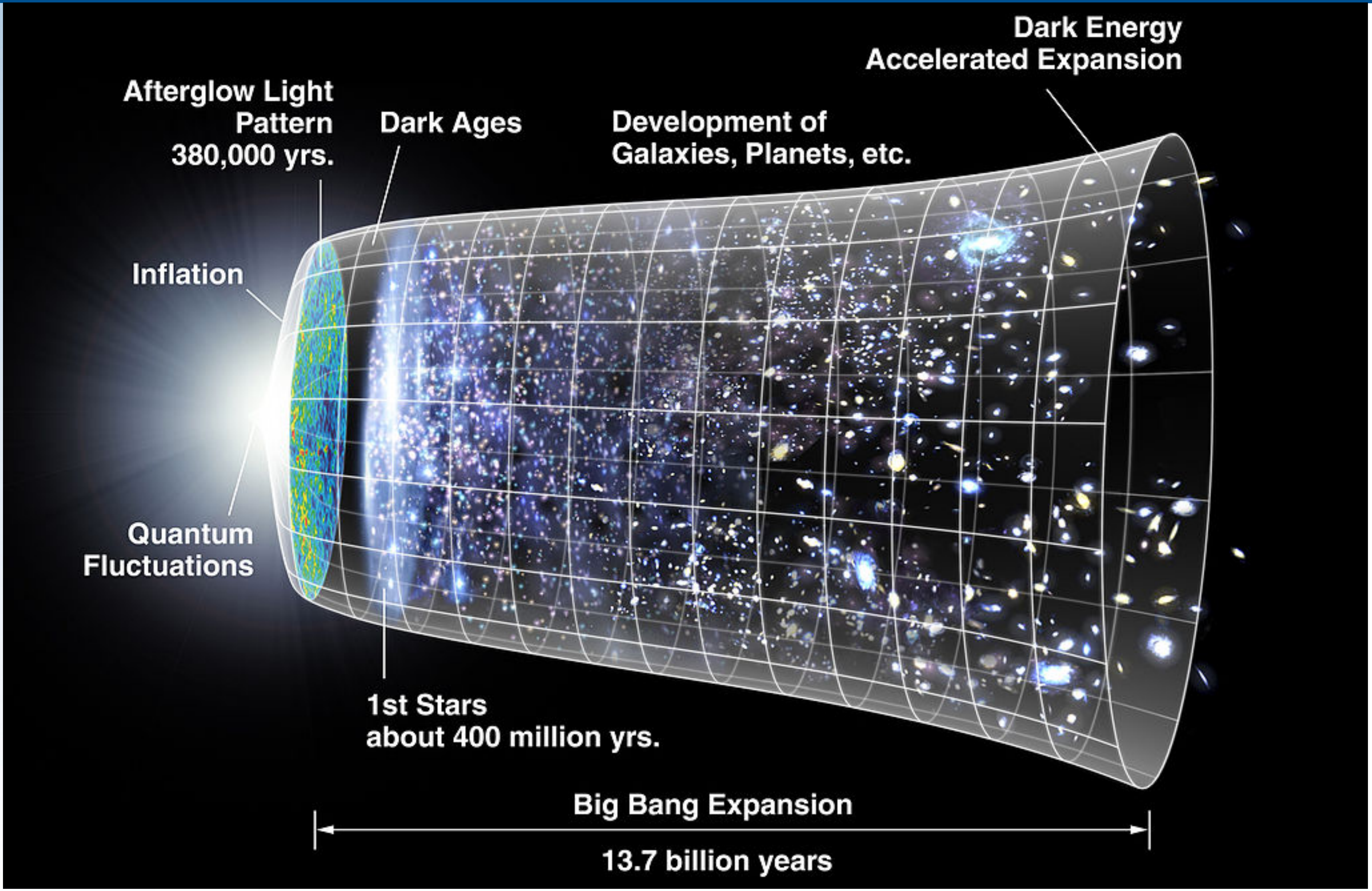
$$E = mc^2$$

Matter - Antimatter asymmetry

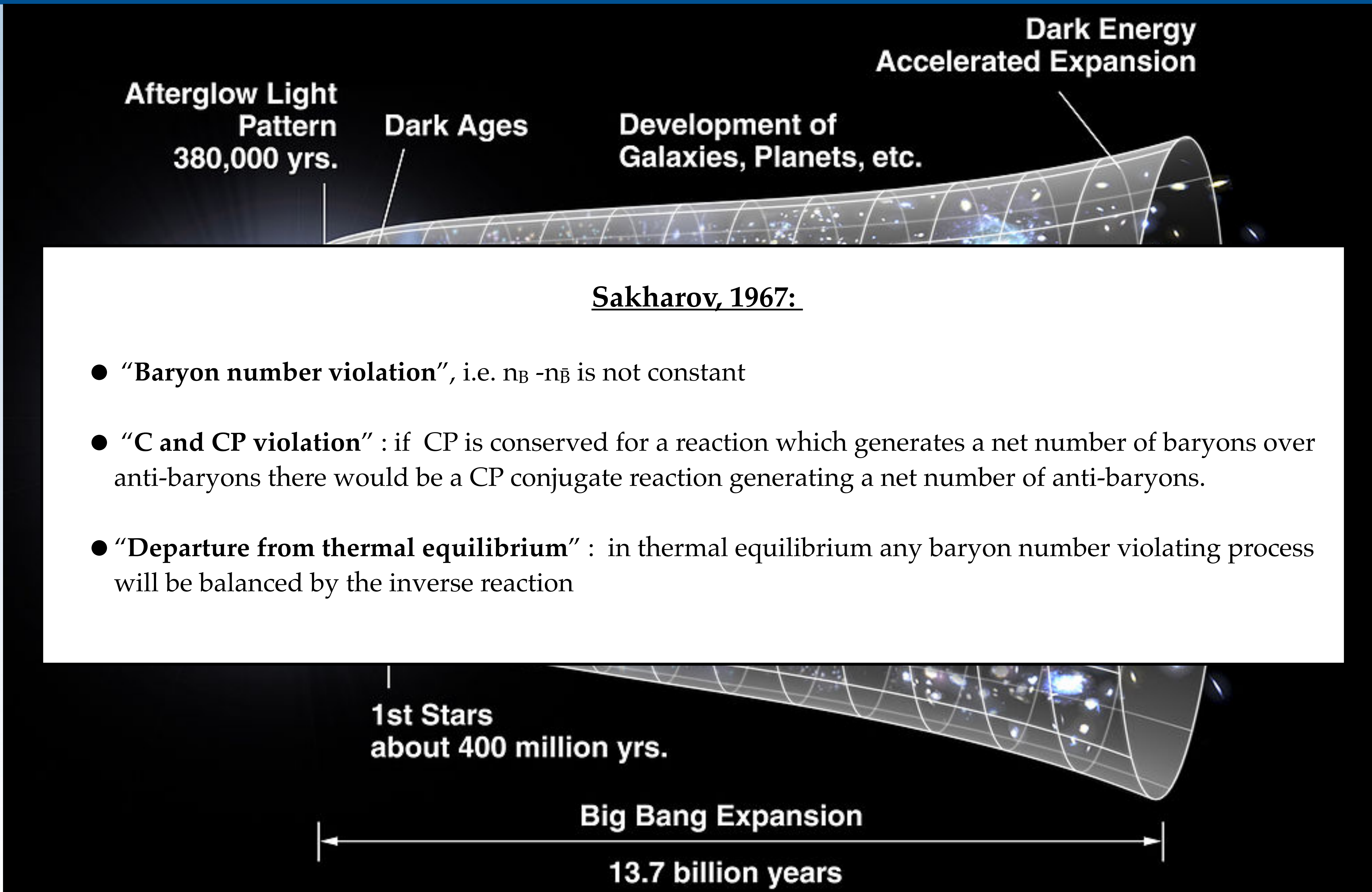


https://www.nasa.gov/mission_pages/hubble/main/index.html

Matter - Antimatter asymmetry



Matter - Antimatter asymmetry



Sakharov, 1967:

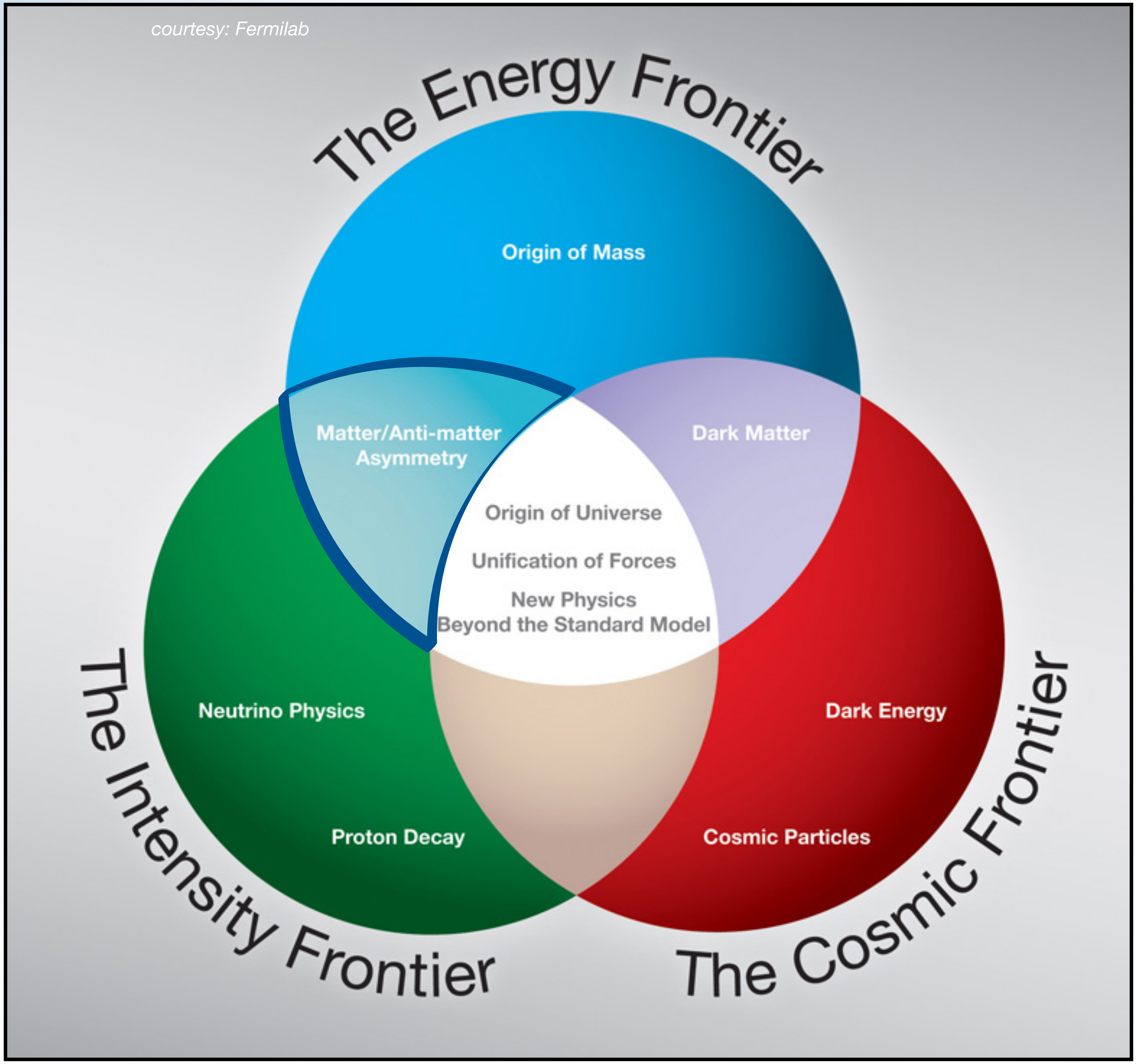
- "**Baryon number violation**", i.e. $n_B - n_{\bar{B}}$ is not constant
- "**C and CP violation**" : if CP is conserved for a reaction which generates a net number of baryons over anti-baryons there would be a CP conjugate reaction generating a net number of anti-baryons.
- "**Departure from thermal equilibrium**" : in thermal equilibrium any baryon number violating process will be balanced by the inverse reaction

The "BIG" questions

Excerpt of the list containing the open questions in particle physics:

- Why is the Higgs boson so light (so-called "naturalness" or "hierarchy" problem) ?
- What is the origin of the matter-antimatter asymmetry in the Universe ?
- Why 3 fermion families ? Why do neutral leptons, charged leptons and quarks behave differently ?
- What is the origin of neutrino masses and oscillations ?
- What is the composition of dark matter (23% of the Universe) ?
- What is the cause of the Universe's accelerated expansion (today: dark energy ? primordial: inflation ?)
- Why is Gravity so weak ?
- …

Frontiers of Particle Physics

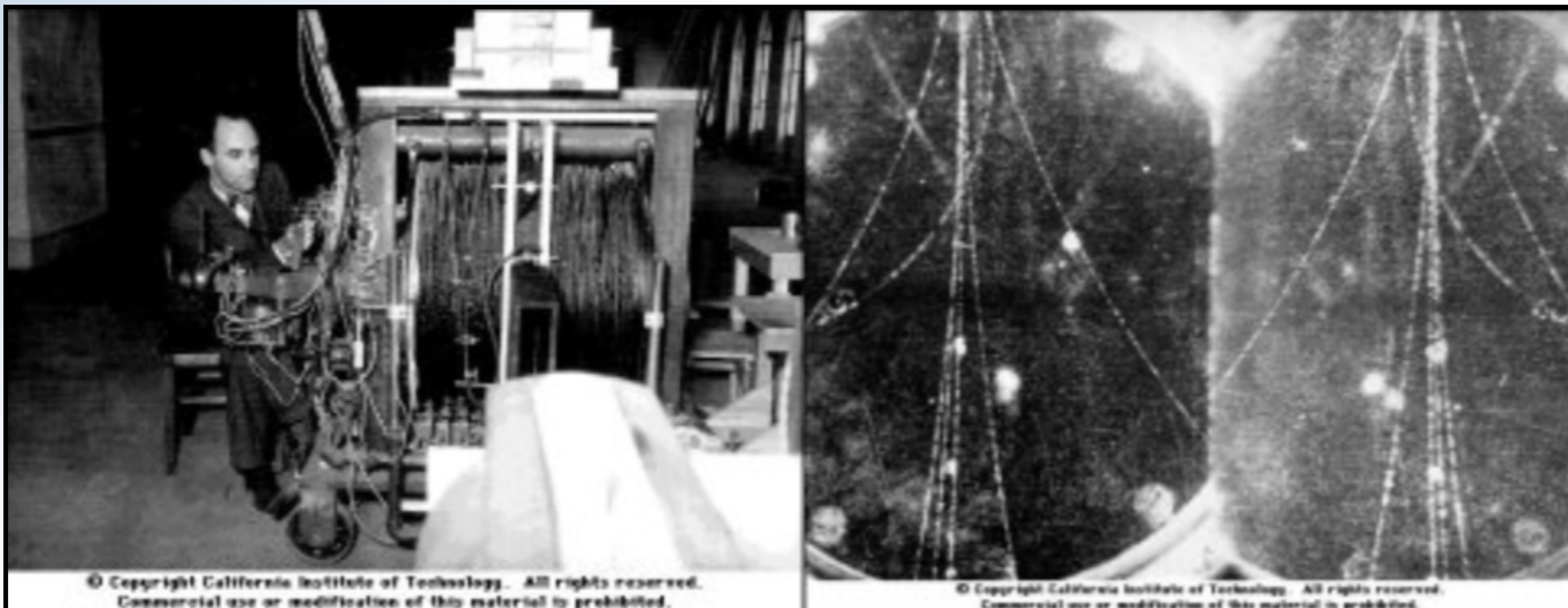


The first antimatter discovery

1932 : Discovery of the positron (Nobel Prize shared with V. Hess in 1936)

C. Anderson

In Cosmic Rays using a Cloud Chamber



Some Bits of History : the Dirac eq.

1928 : The Dirac equation (Nobel Prize in 1933)

$$E = \frac{p^2}{2m} \rightarrow i\hbar\frac{\partial}{\partial t}\psi = -\frac{\hbar^2}{2m}\nabla^2\psi$$

$E \rightarrow i\hbar\frac{\partial}{\partial t}$

$p \rightarrow -i\hbar\nabla$

$$H\psi = (\alpha \cdot \mathbf{P} + \beta m)\psi$$

$$E^2 = p^2 + m^2 \rightarrow -\hbar^2\frac{\partial^2}{\partial t^2}\psi = -\hbar^2\nabla^2\psi + m^2\psi$$

$$H^2\psi = (\alpha_i P_i + \beta m)(\alpha_j P_j + \beta m)\psi$$

$$= (\alpha_i^2 P_i^2 + (\alpha_i\alpha_j + \alpha_j\alpha_i)P_iP_j + (\alpha_i\beta + \beta\alpha_i)P_i m + \beta^2 m^2)\psi$$

=1 =0 =0 =1

$$H^2\psi = (\mathbf{P^2} + m^2)\psi$$

$$(i\gamma^\mu\partial_\mu - m)\psi = 0$$

$$\gamma^0 = \begin{pmatrix} I_2 & 0 \\ 0 & -I_2 \end{pmatrix}, \gamma^1 = \begin{pmatrix} 0 & \sigma_x \\ -\sigma_x & 0 \end{pmatrix},$$

$$\gamma^2 = \begin{pmatrix} 0 & \sigma_y \\ -\sigma_y & 0 \end{pmatrix}, \gamma^3 = \begin{pmatrix} 0 & \sigma_z \\ -\sigma_z & 0 \end{pmatrix}.$$

more antimatter …

1932 Discovery of positron

1948 Discovery of positronium

1955 Discovery of antiproton

1956 Discovery of antineutron

1964 First measurement of a difference between matter & antimatter

1965 Discovery of antideuteron

1970 Discovery of anti- ^{3}He

1978 Discovery of anti-tritium

1996 First creation of relativistic antihydrogen atoms

Discrete Symmetries

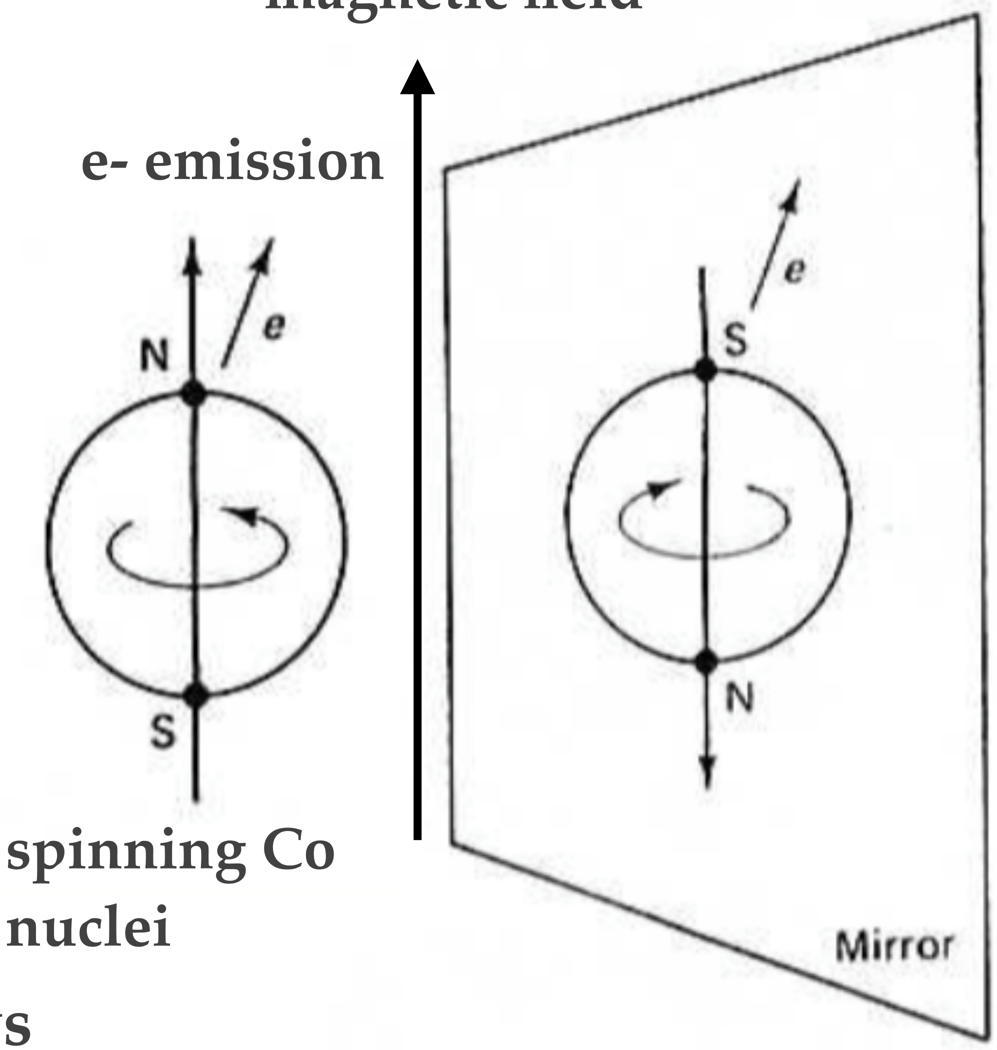
P : Parity transformation. Invert every spatial coordinates

$P(t, r) = P(t, -r)$

fermions and anti-fermions have opposite parity

1956 : Yang and Lee realized that parity invariance had never been tested experimentally for weak interactions

Wu's experiment: recorded the direction of the emitted electron from a ^{60}Co β-decay when the nuclear spin was aligned up and down



P symmetry is MAXIMALLY violated in weak decays

Discrete Symmetries

C : Charge Conjugaison. C reverses every internal additive quantum number (e.g. charge, baryon/lepton number, strangeness, etc.). Exchange of particle and antiparticle

$C\,|p\rangle = |\bar{p}\rangle$

few particles are C-eigenstates

C is conserved in strong and EM interactions

$$C|n\gamma\rangle = (-1)^n\,|\gamma\rangle$$

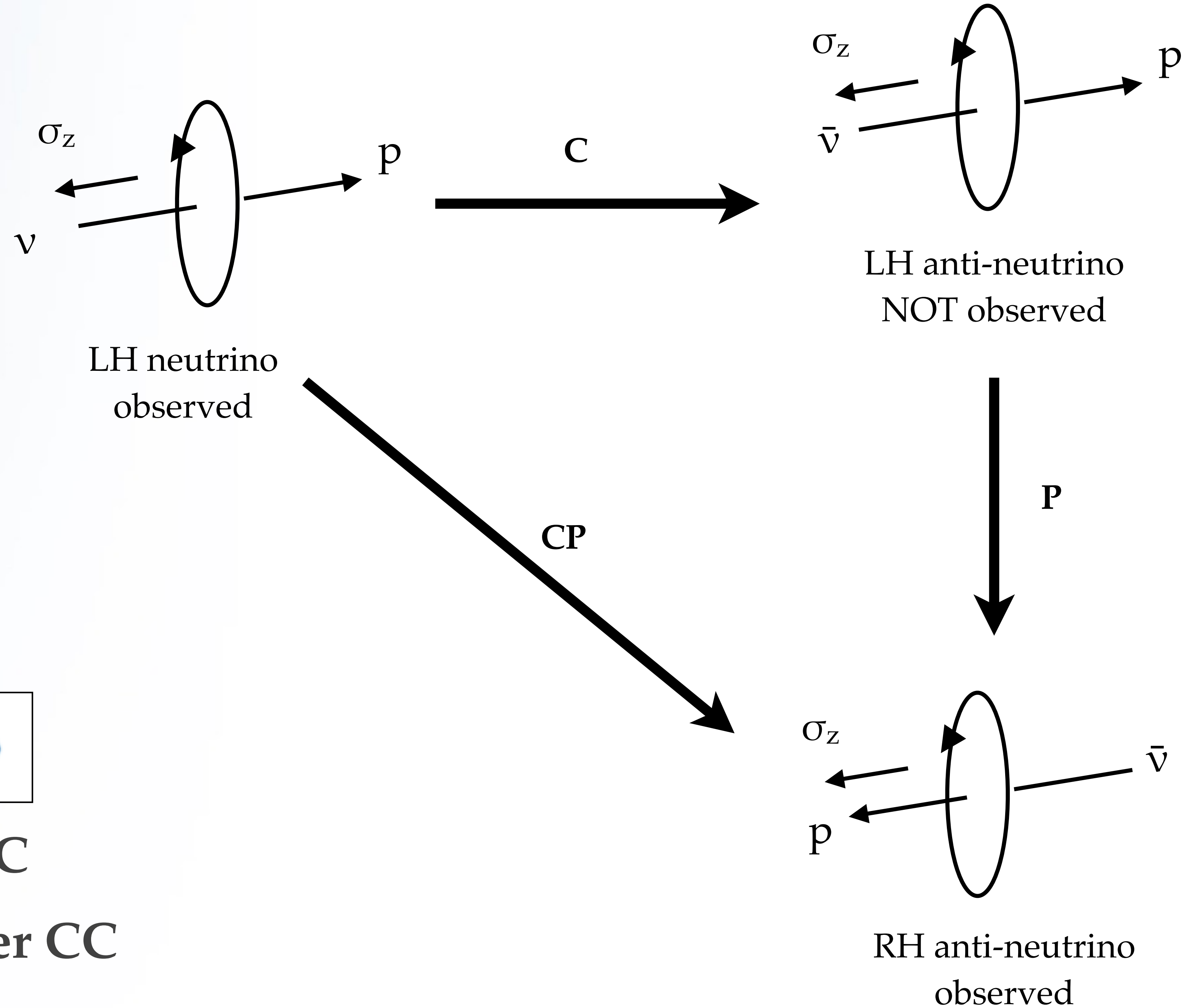
$$C=(-1)^{l+s}$$

$$C|\pi^0\rangle = |\pi^0\rangle$$

$\pi^0 \rightarrow 2\gamma$ is allowed under CC

$\pi^0 \rightarrow 3\gamma$ is not allowed under CC

$< 3.1 \times 10^{-8}$



Discrete Symmetries

CP Violation in Neutral Kaons:

$$K^0 : \quad (d\bar{s}) \quad S = +1$$
$$\bar{K^0} : \quad (s\bar{d}) \quad S = -1$$

Production through $\Delta S=0$
Decay through $\Delta S=+/-\ 1$

Start with a pure K^0 beam

$$|K(t)\rangle = \alpha(t)\,|K^0\rangle + \beta(t)\,|\bar{K^0}\rangle$$

Discrete Symmetries

CP Violation in Neutral Kaons:

$$K^0: \quad (d\bar{s}) \quad S = +1$$
$$\bar{K^0}: \quad (s\bar{d}) \quad S = -1$$

Production through ΔS=0
Decay through ΔS=+/- 1

Start with a pure K⁰ beam

$$|K(t)\rangle = \alpha(t)\,|K^0\rangle + \beta(t)\,|\bar{K^0}\rangle$$

CP Eigenstates :

$$|K_S\rangle = \frac{1}{\sqrt{2}}(|K^0\rangle + |\bar{K^0}\rangle) \quad CP = +1$$
$$|K_L\rangle = \frac{1}{\sqrt{2}}(|K^0\rangle - |\bar{K^0}\rangle) \quad CP = -1$$

$$|K_S\rangle \to 2\pi, \quad CP = +1, \quad \tau \sim 0.9 \times 10^{-10}\,\mathrm{s}$$
$$|K_L\rangle \to 3\pi, \quad CP = -1, \quad \tau \sim 0.5 \times 10^{-7}\,\mathrm{s}$$

Discrete Symmetries

Measured quantity :

$$|\eta_{+-}| = \frac{\text{amplitude}(K_L \to \pi^+\pi^-)}{\text{amplitude}(K_S \to \pi^+\pi^-)} \sim 2.3 \times 10^{-3}$$

Interferences : observed in modulation of the 2 pion signal

Discrete Symmetries

Measured quantity :

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Interferences : observed in modulation of the 2 pion signal

Semi-leptonic mode :

$$K_L \to e^+ + \nu_e + \pi^-$$
$$K_L \to e^- + \bar{\nu_e} + \pi^+$$

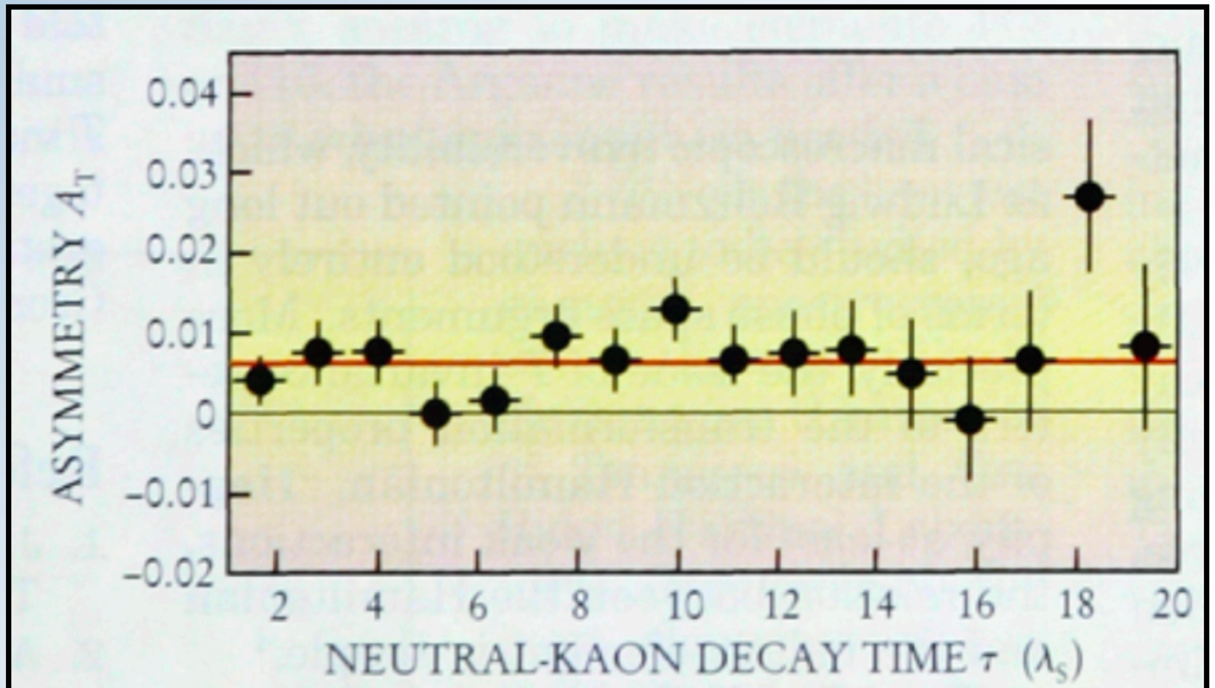
Discrimination criteria between matter and antimatter :

$$\Delta = \frac{\text{rate}(K_L \to e^+ + \nu_e + \pi^-) - \text{rate}(K_L \to e^- + \bar{\nu_e} + \pi^+)}{\text{rate}(K_L \to e^+ + \nu_e + \pi^-) + \text{rate}(K_L \to e^- + \bar{\nu_e} + \pi^+)}$$

$$\Delta \sim 0.3 \times 10^{-2}$$

Discrete Symmetries

T : Time Reversal **@ CPLEAR**



TIME-REVERSAL ASYMMETRY A_T, the observed difference between the rates for $\overline{K}^0 \to K^0$ and $K^0 \to \overline{K}^0$, divided by their sum, is plotted here as a function of the proper time interval τ between the creation of the neutral kaon in the CPLEAR facility at CERN and its subsequent decay from a state of opposite strangeness. The time is given in units of $\lambda_S = 89.3$ ps, the shorter of the two neutral-kaon lifetimes. The red line is the fitted average measured asymmetry, $(6.6 \pm 1.6) \times 10^{-3}$, in good agreement with the theoretical expectation. (Adapted from ref. 2.)

$$\Delta = \frac{\text{rate}(\bar{K}_0 \to K_0) - \text{rate}(K_0 \to \bar{K}_0)}{\text{rate}(\bar{K}_0 \to K_0) + \text{rate}(K_0 \to \bar{K}_0)}$$

Discrete Symmetries

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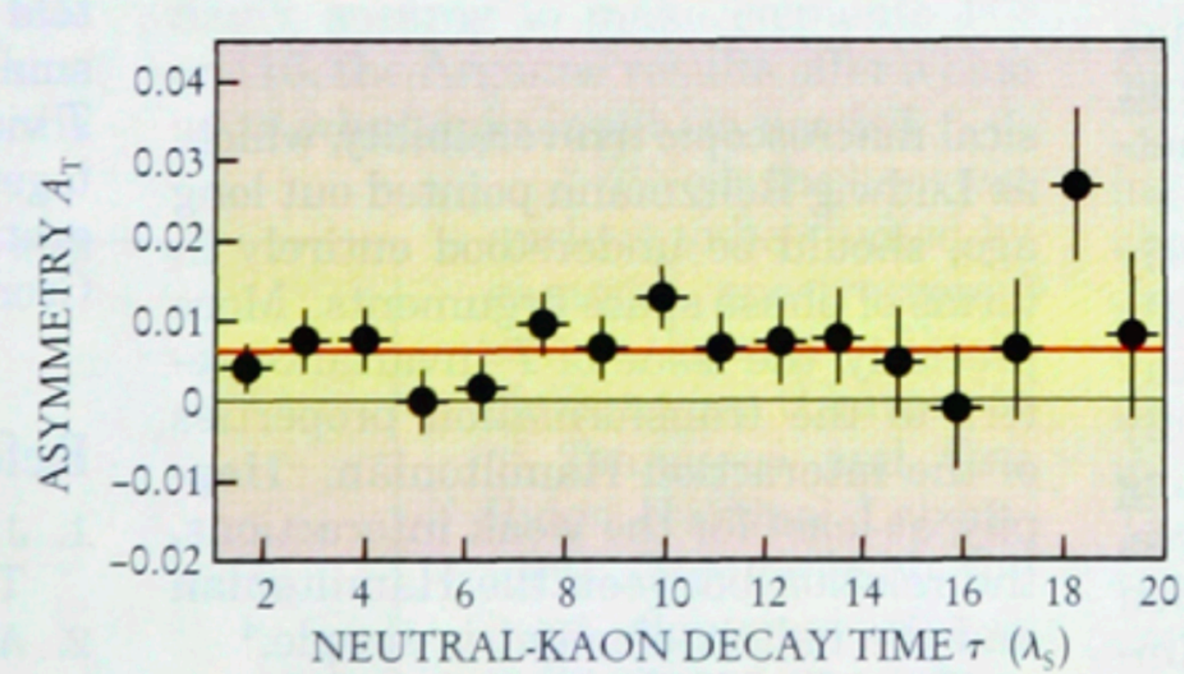

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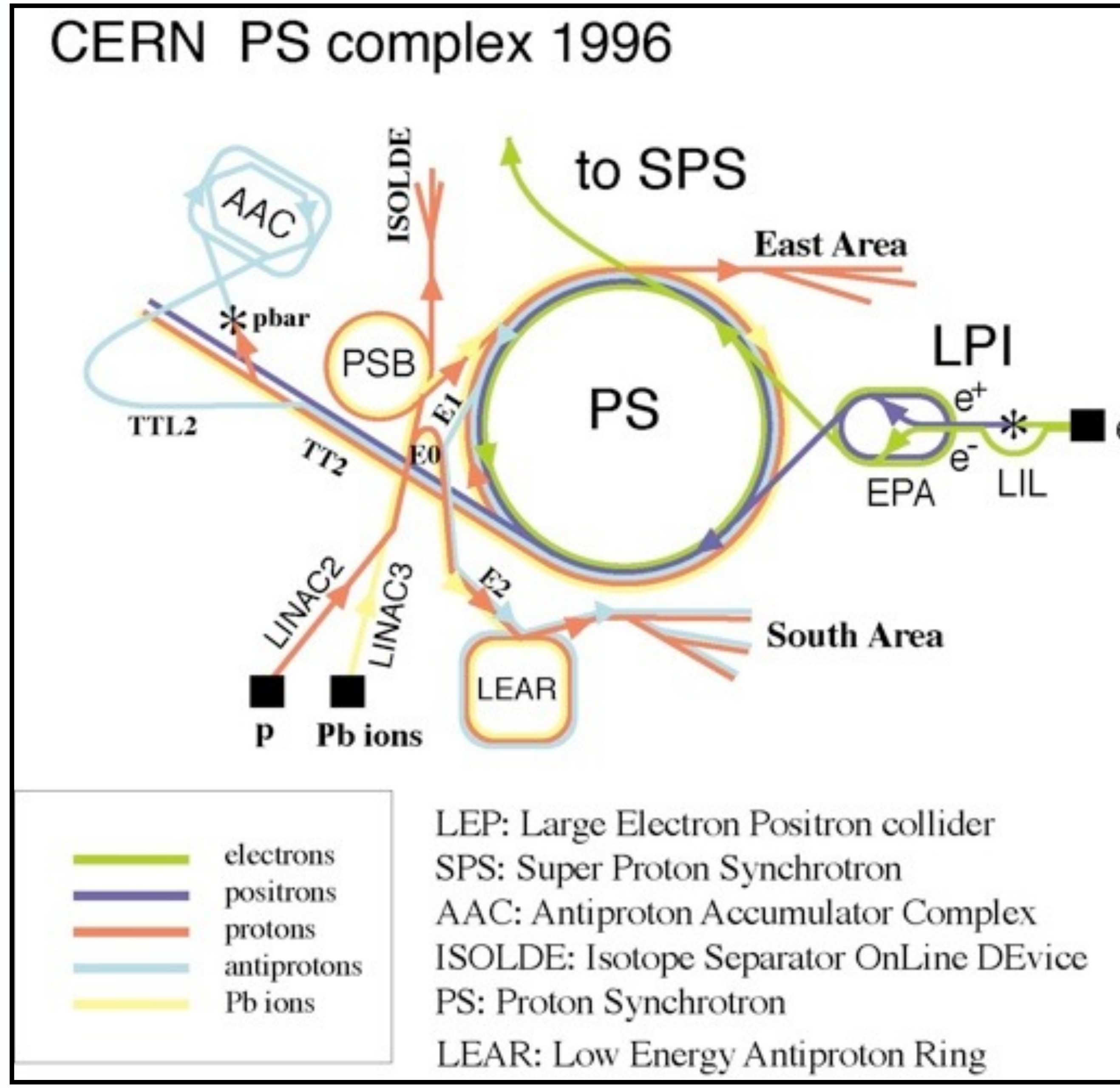
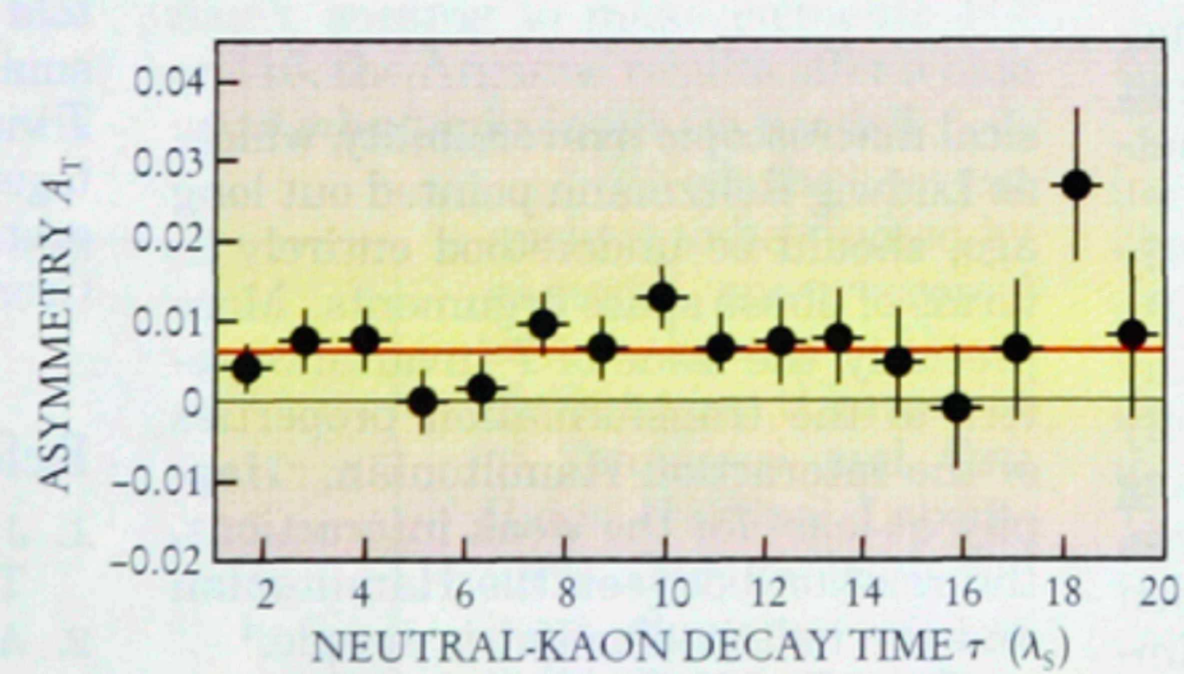


1982-1996 : AAC
3 separate rings
AC, AA, LEAR

Discrete Symmetries

T : Time Reversal @ CPLEAR



TIME-REVERSAL ASYMMETRY A_T, the observed difference between the rates for $\overline{K}^0 \to K^0$ and $K^0 \to \overline{K}^0$, divided by their sum, is plotted here as a function of the proper time interval τ between the creation of the neutral kaon in the CPLEAR facility at CERN and its subsequent decay from a state of opposite strangeness. The time is given in units of $\lambda_S = 89.3$ ps, the shorter of the two neutral-kaon lifetimes. The red line is the fitted average measured asymmetry, $(6.6 \pm 1.6) \times 10^{-3}$, in good agreement with the theoretical expectation. (Adapted from ref. 2.)

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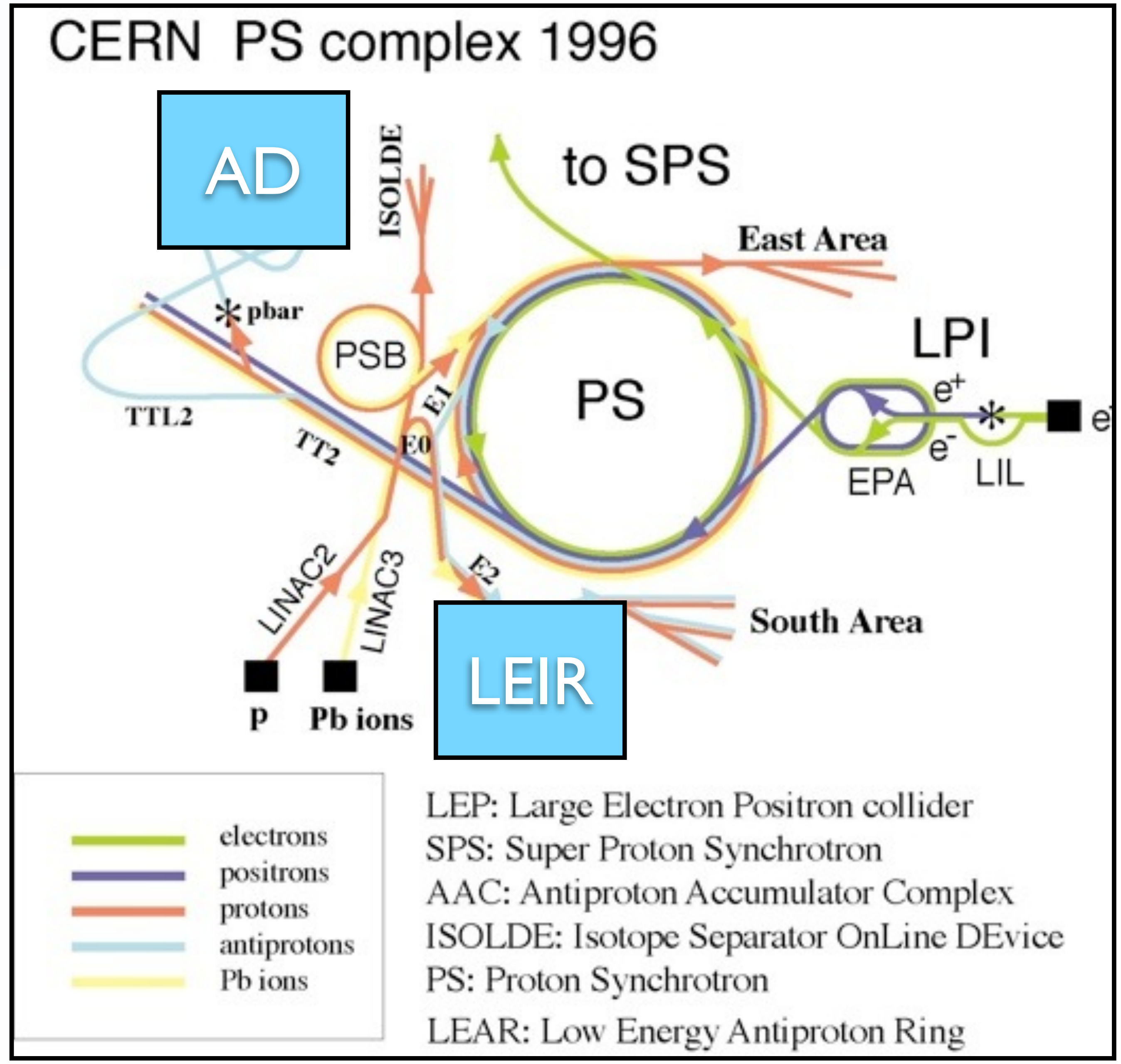

1982-1996 : AAC
3 separate rings
AC, AA, LEAR

Since 2000 :
all-in-one machine : AD

Discrete Symmetries

Summary:

	Interactions		
	Strong	EM	Weak
P	yes	yes	no
C	yes	yes	no
CP (or T)	yes	yes	~10^-3 1964 : K0 decay 1999 (2012) : Direct T Violation 2001: B decay (BELLE, BaBar) 2013 : strange B decay (LHCb)
CPT			

Discrete Symmetries

Summary:

	Interactions		
	Strong	EM	Weak
P	yes	yes	no
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CP (or T)	yes	yes	~10^-3 1964 : K0 decay 1999 (2012) : Direct T Violation 2001: B decay (BELLE, BaBar) 2013 : strange B decay (LHCb)
CPT	yes	yes	yes

Discrete Symmetries

Observation of C, P, T, CP violation, what about CPT?
In the SM, CPT is conserved. So, if T is violated, CP is violated & vice-versa

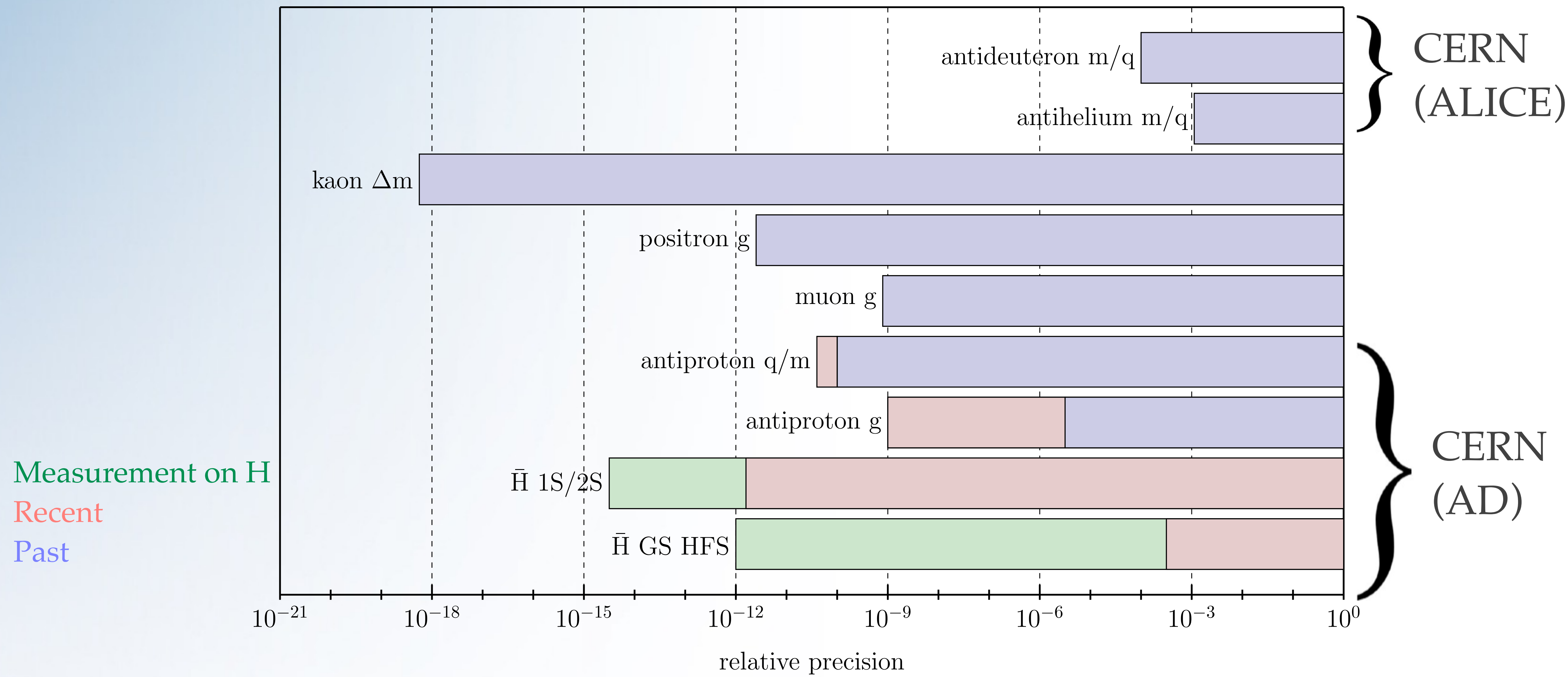
CPT Theorem :

A local, Lorenz invariant theory with canonical spin-statistics relation must be invariant with respect to CPT-transformation

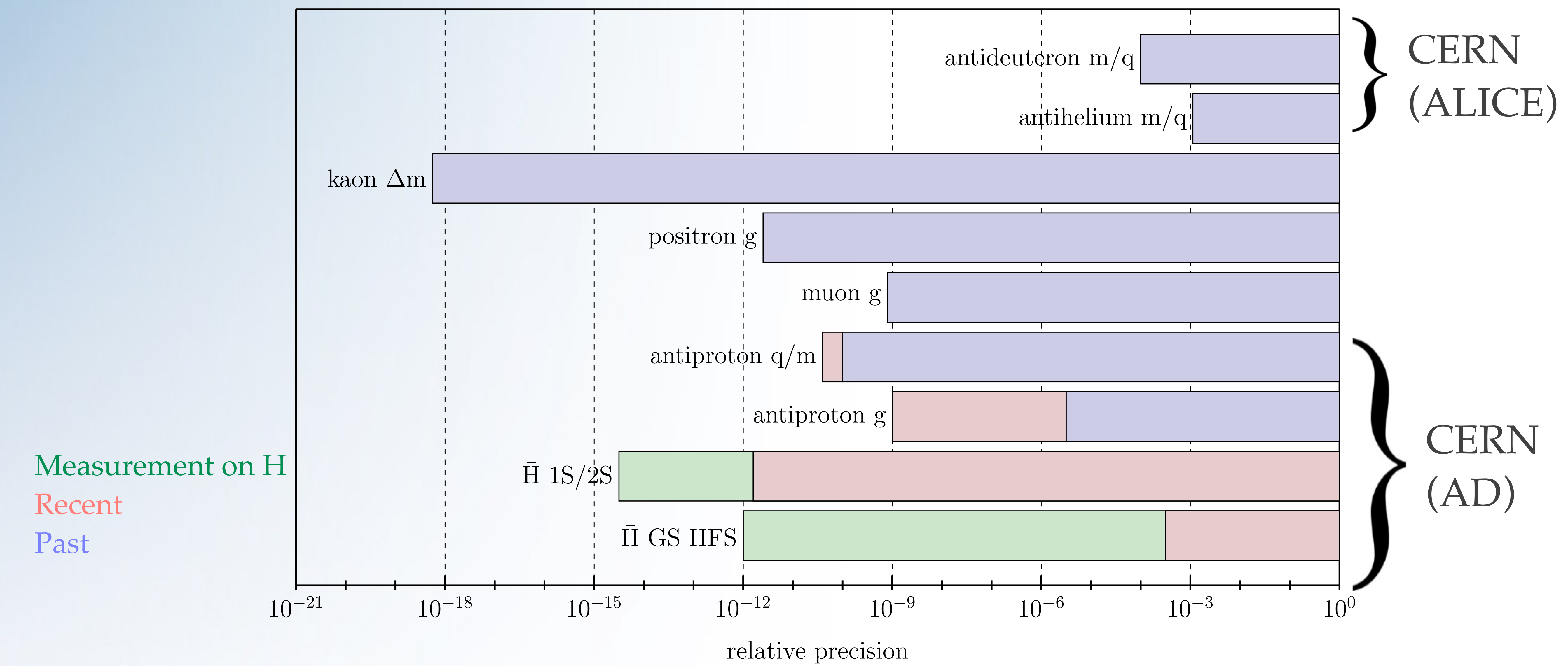
J. Schwinger, Phys. Rev.82, 914 (1951);
G. Lüders, Kgl. Danske Vidensk. Selskab. Mat.-Fys. Medd.28, 5 (1954);
G. Lüders, Ann. Phys.2, 1 (1957);
W. Pauli, Nuovo Cimento,6, 204 (1957);
R. Jost, Helv. Phys. Acta30, 409 (1957);
F.J. Dyson, Phys. Rev.110, 579 (1958).

Implication : properties of matter & antimatter particles should be the same

Tests of CPT Symmetry



Tests of CPT Symmetry



Standard Model Extension

$$(i\gamma^\mu D_\mu - m_e - a^e_\mu \gamma^\mu - b^e_\mu \gamma_5 \gamma^\mu - \frac{1}{2} H^e_{\mu\nu}\sigma^{\mu\nu} + i c^e_{\mu\nu}\gamma^\mu D^\nu + i d^e_{\mu\nu}\gamma_5\gamma^\mu D^\nu)\psi = 0$$

Search for Primordial Antimatter

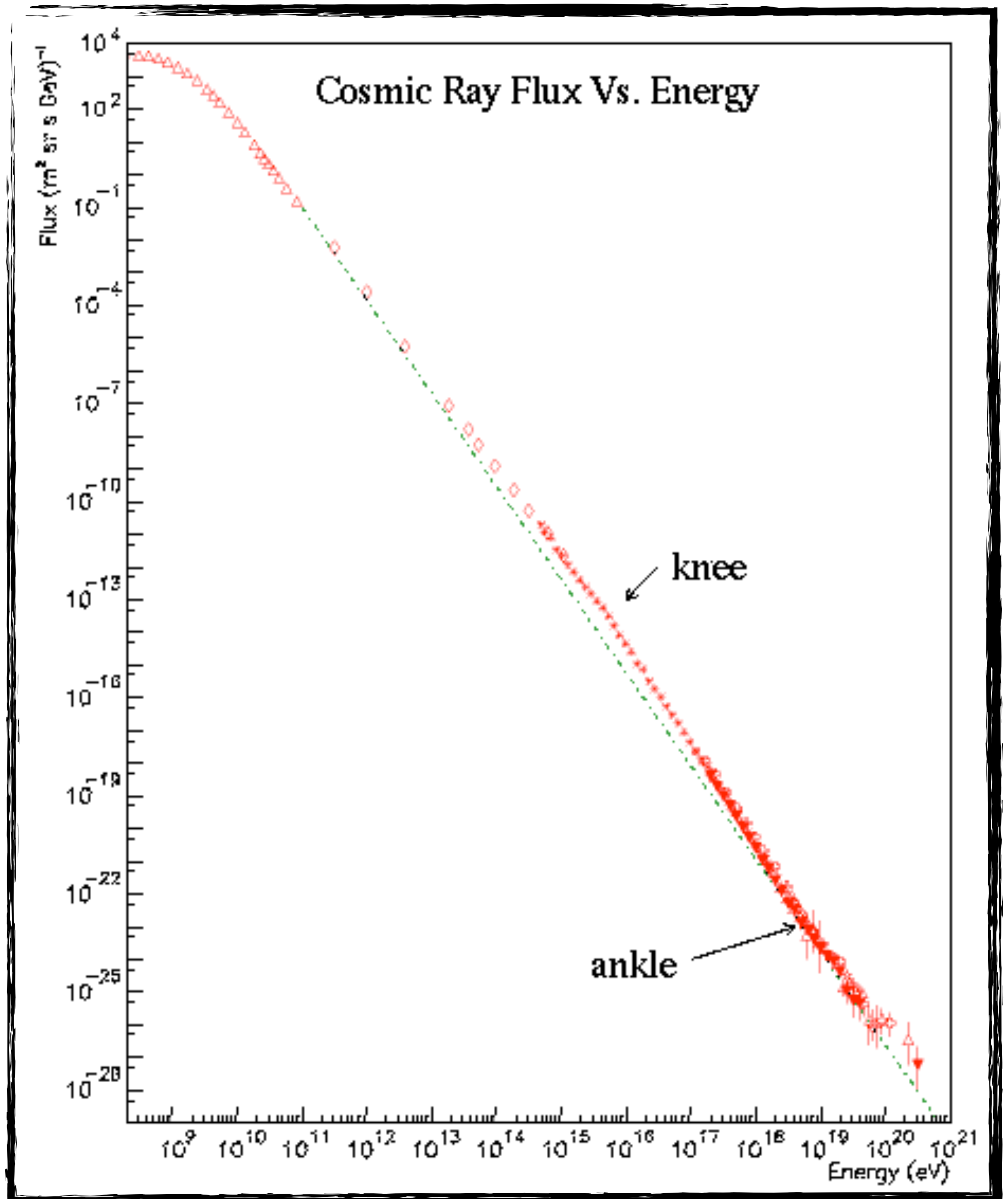
IS THERE ANTIMATTER LEFT IN THE UNIVERSE?

Search for Primordial Antimatter

- **DIRECT SEARCHES IN COSMIC RAYS**

  Creation of Secondaries in IGM : Test source and propagation models for cosmic rays

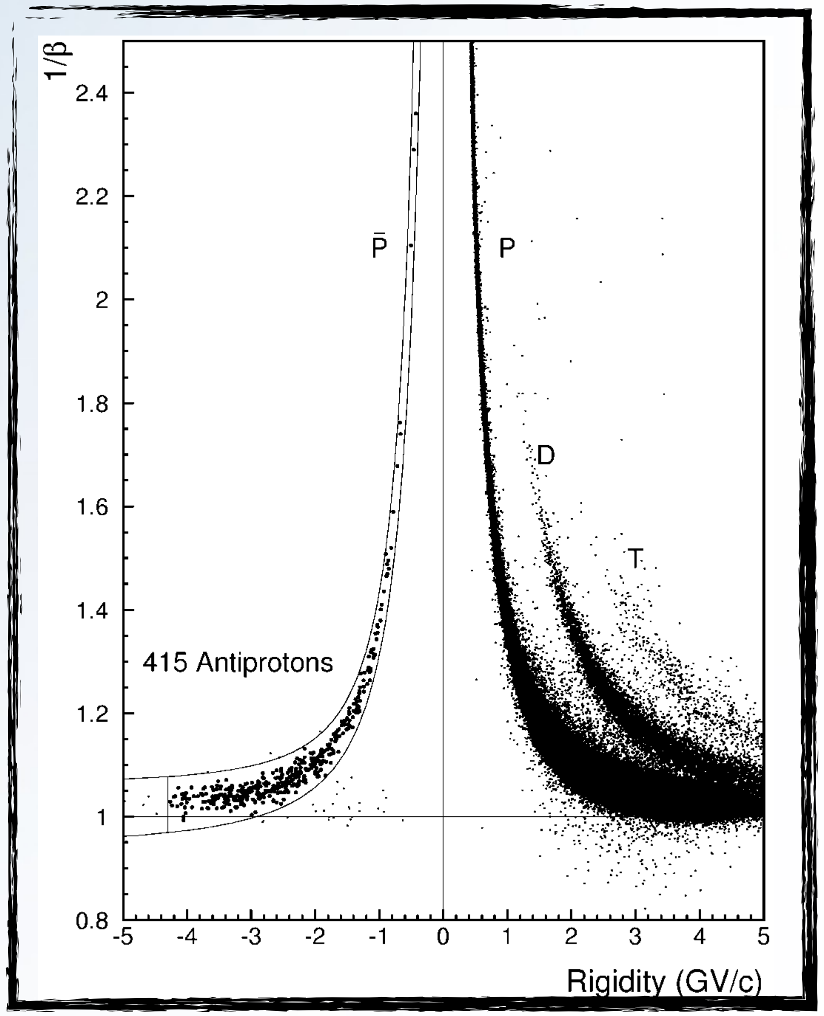
A large part of positrons and antiprotons impinging on Earth are produced in high-energy interactions between cosmic rays nuclei with the interstellar medium. Their spectra can provide an insight on the origin, production and propagation of cosmic rays in our galaxy. Any observed flux larger than that predicted by the Leaky Box Model (LBM), the "standard" model of cosmic ray propagation, could indicate exotic sources of antimatter. The predictions of the propagation models are different above 10 GeV where more refined measurements are needed.

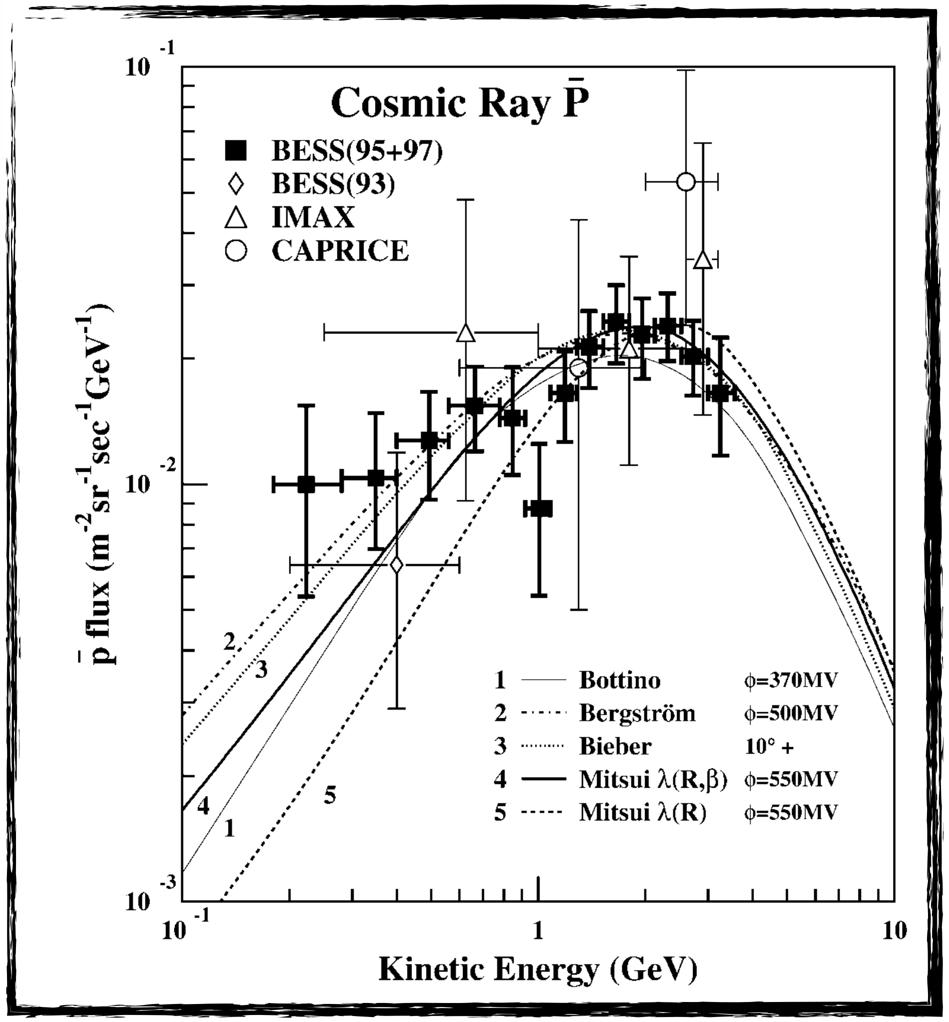


Balloon experiments

Results from CAPRICE/BESS

height of flight = 38 km (top of atmosphere)





PRL 84 (2000) 1078

http://prl.aps.org/pdf/PRL/v84/i6/p1078_1

http://arxiv.org/abs/astro-ph/9809101

subsidiary result (data+propagation model) = $\tau(\bar{p}) > 1.7$ Myr

Space experiments

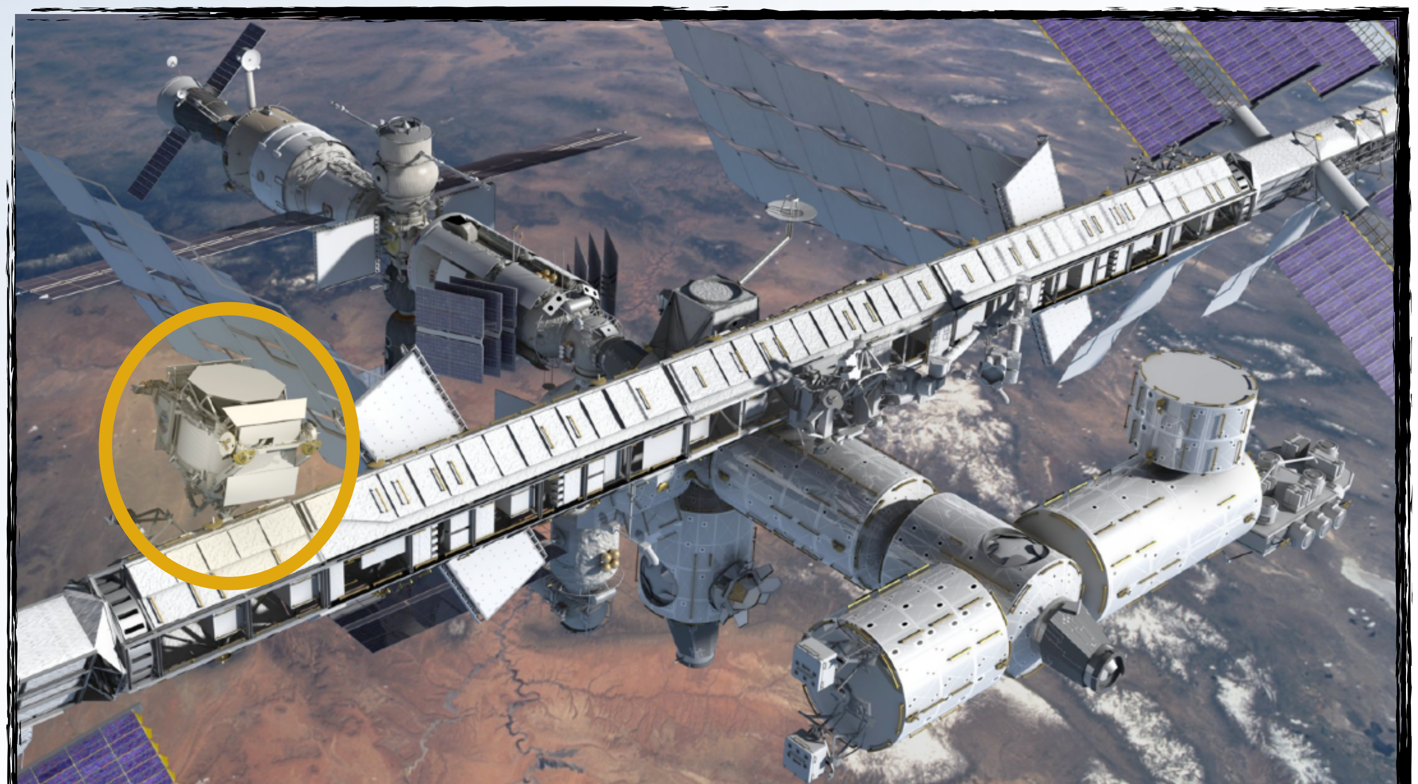
PAMELA (satellite), AMS (space station)

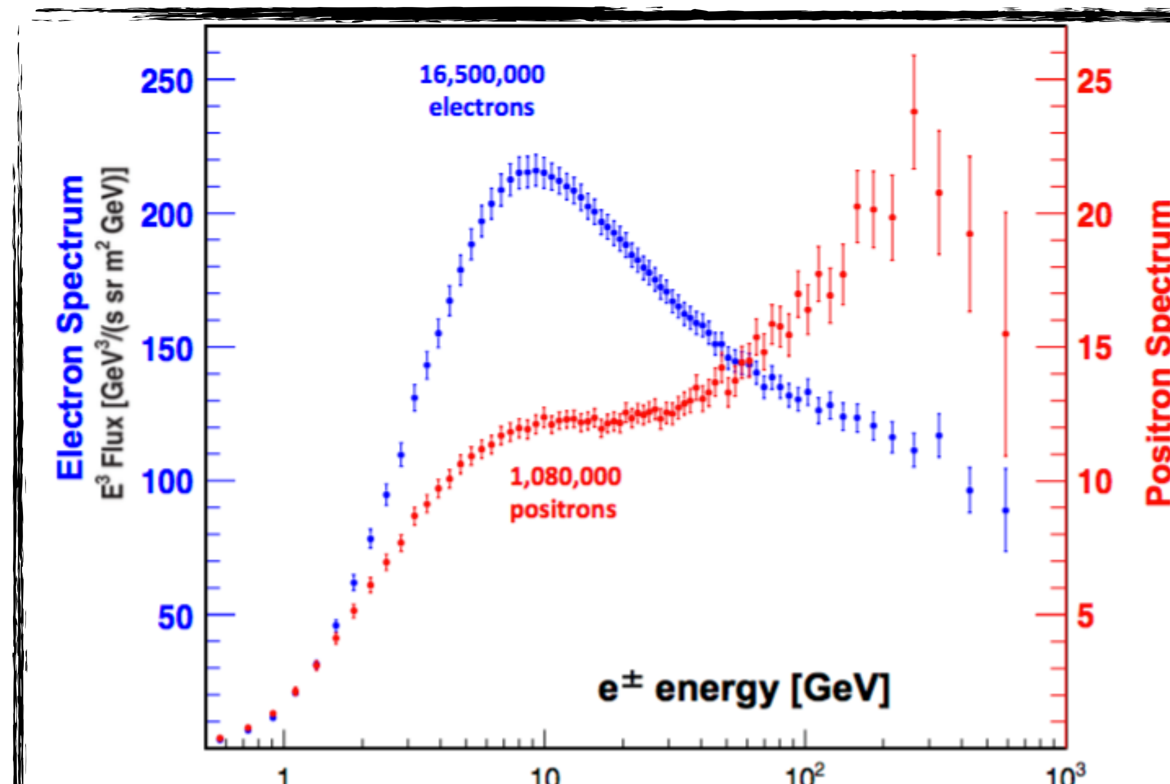
- **SEARCH FOR PRIMARY ANTIMATTER**

e+, p̄, anti-alpha

Note : positrons are difficult to measure/interpret:

- **radiative losses close to sources**
- **possibility of primary positron cosmic rays**





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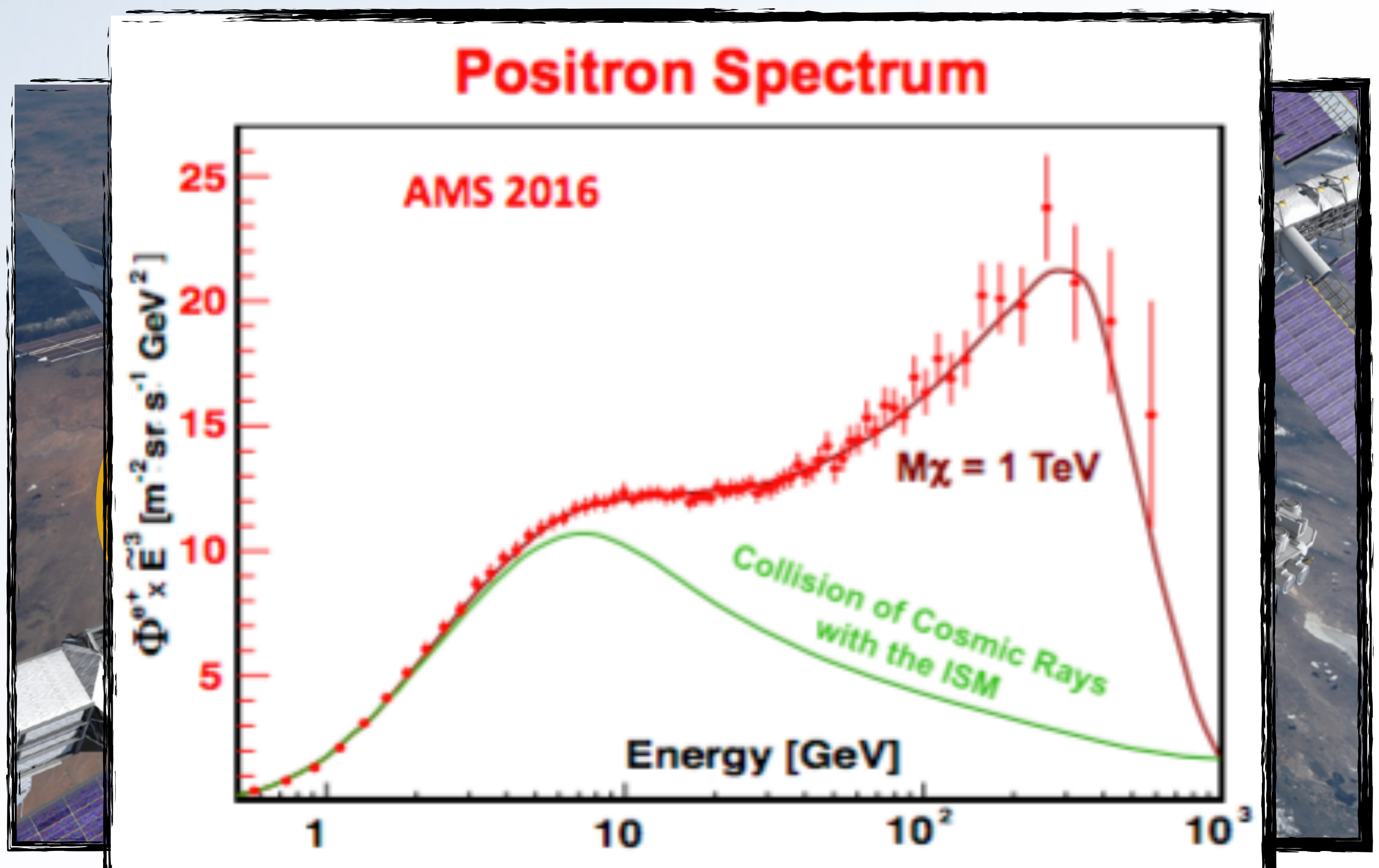
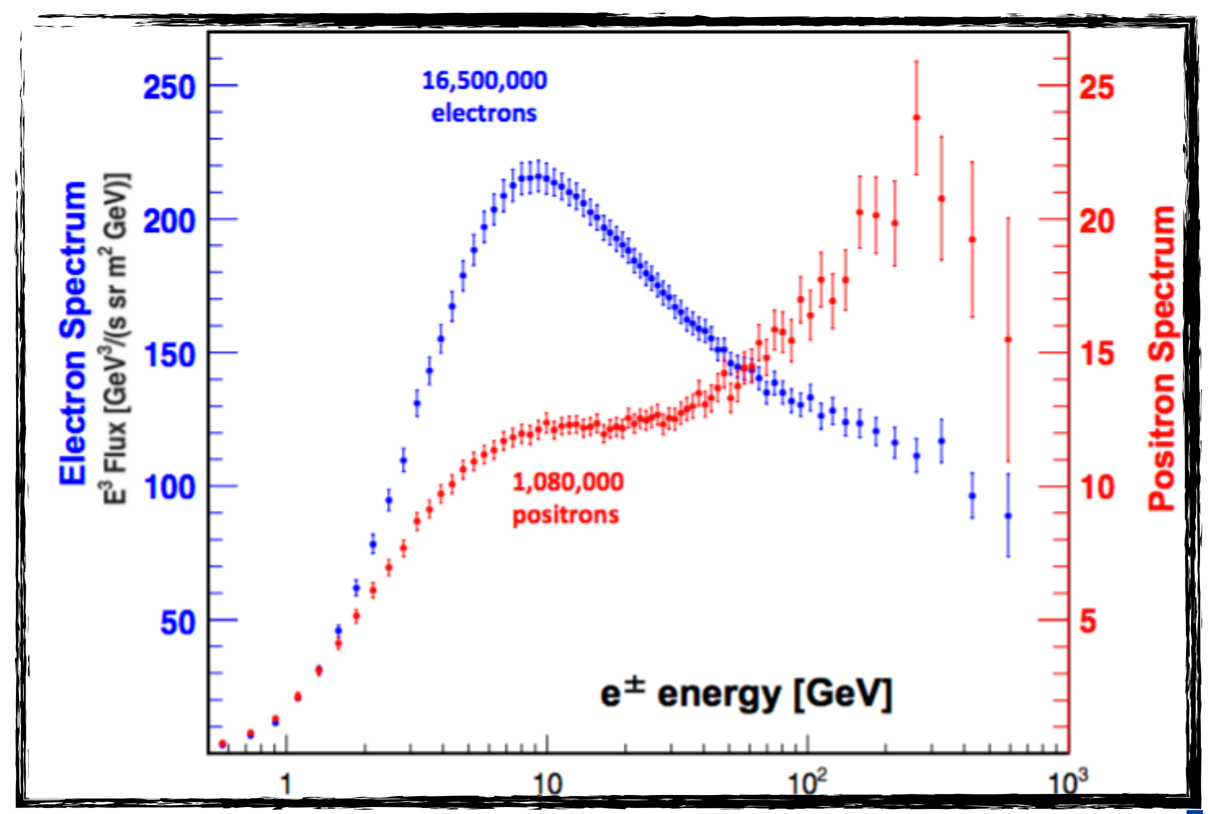
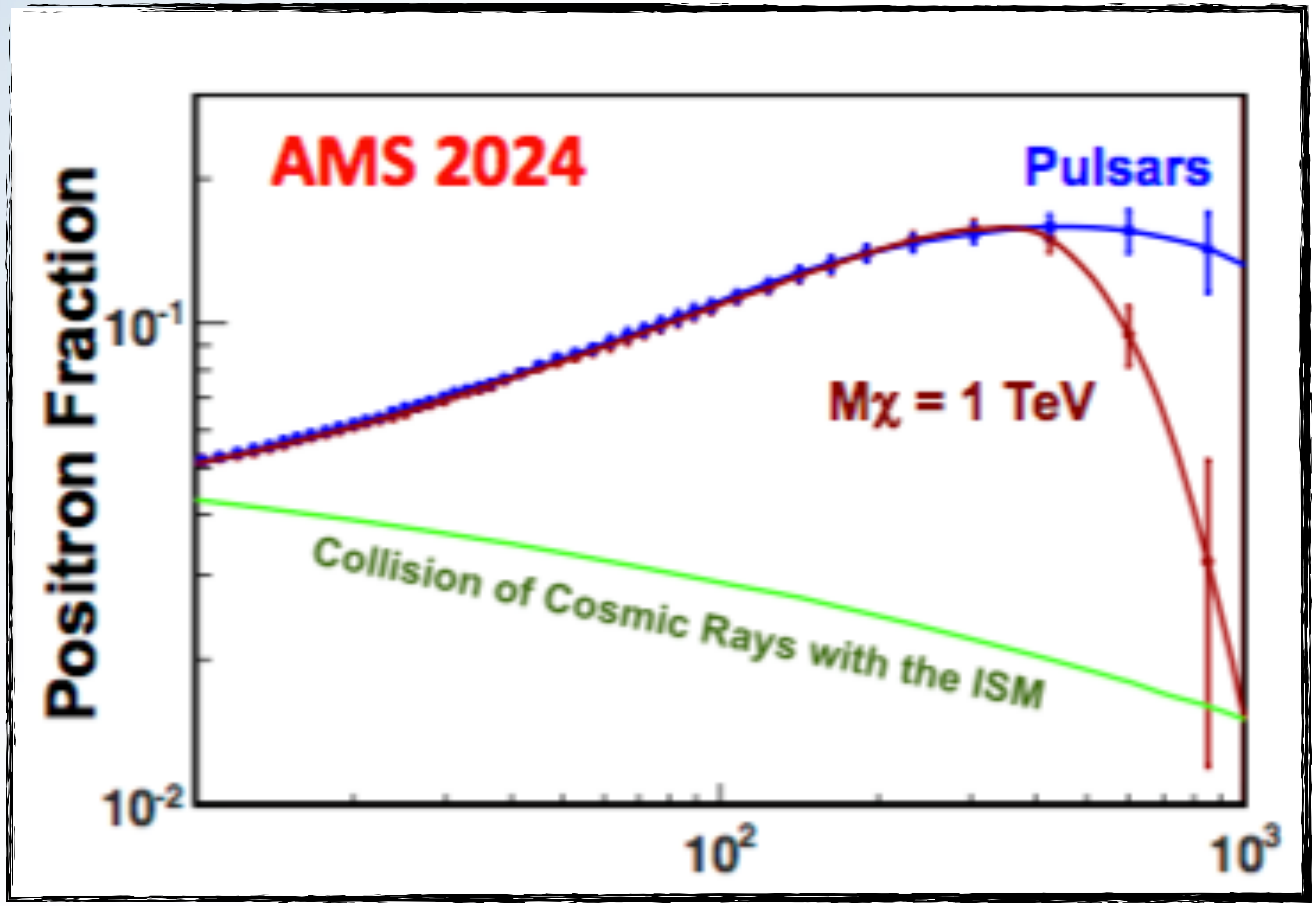




Space experiments

Other sources :

- Modified Propagation of Cosmic Rays, Supernova Remnants, Pulsars



Cosmological Models

Distortions in the CMB:

- CMB would have been affected by late annihilations (if antimatter would have survived longer than expected) & photons from the annihilation would contribute to the diffuse gamma rays

If we accept the view of complete symmetry between positive and negative electric charge so far as concerns the fundamental laws of Nature, we must regard it rather as an accident that the Earth (and presumably the whole solar system), contains a preponderance of negative electrons and positive protons. It is quite possible that for some of the stars it is the other way about, these stars being built up mainly of positrons and negative protons. In fact, there may be half the stars of each kind. The two kinds of stars would both show exactly the same spectra, and there would be no way of distinguishing them by present astronomical methods.

Dirac Nobel lecture 1933

- B=0 universe is mostly excluded by standard cosmology scenarios based on CMB observation (annihilation at boundaries, at least for domains which are smaller than the size of the visible universe)

Cosmological Models

Big Bang Nucleosynthesis

Existence of antimatter during nucleosynthesis would have affected the formation of nuclei (annihilation, formation of $p\bar{p}$ etc.., annihilation gamma rays would photodesintegrate etc)

Estimate the baryon density from SBBN and CMB

Photons are final products of annihilation processes

$$\eta = (\frac{N_B}{N_\gamma})_{T=3\,\mathrm{K}} \quad \eta = (\frac{N_B - N_{\bar{B}}}{N_\gamma})_{T=3\,\mathrm{K}}$$

$$\eta_{SBBN} = (5.80 \pm 0.27) \times 10^{-10}$$
$$\eta_{CMB} = 6.160^{+0.153}_{-0.156} \times 10^{-10}$$

Production of antimatter

The case of antiprotons

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

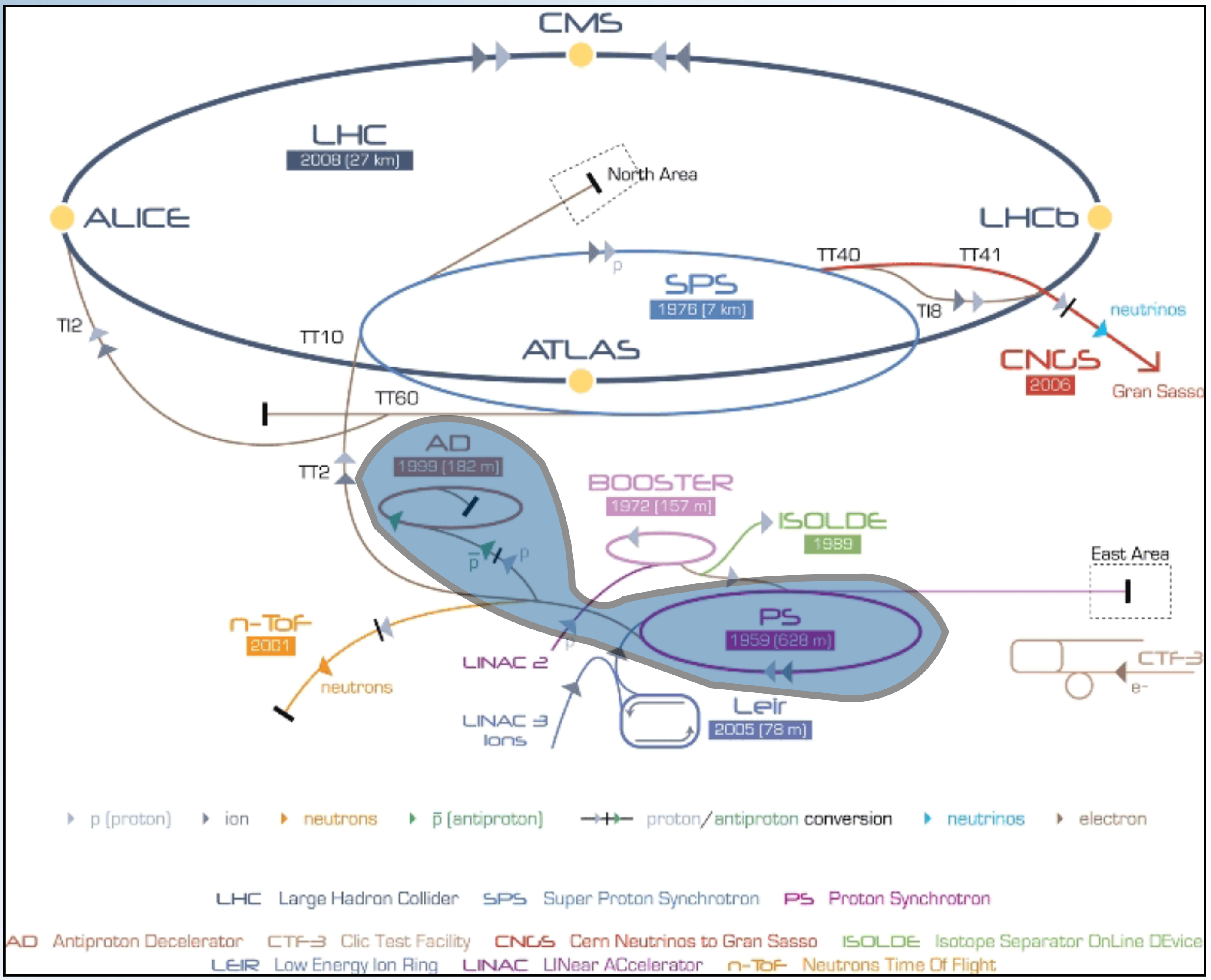
$$\boxed{\sqrt{s} = \sqrt{2m_p^2 + 2E_p m_p}}$$

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

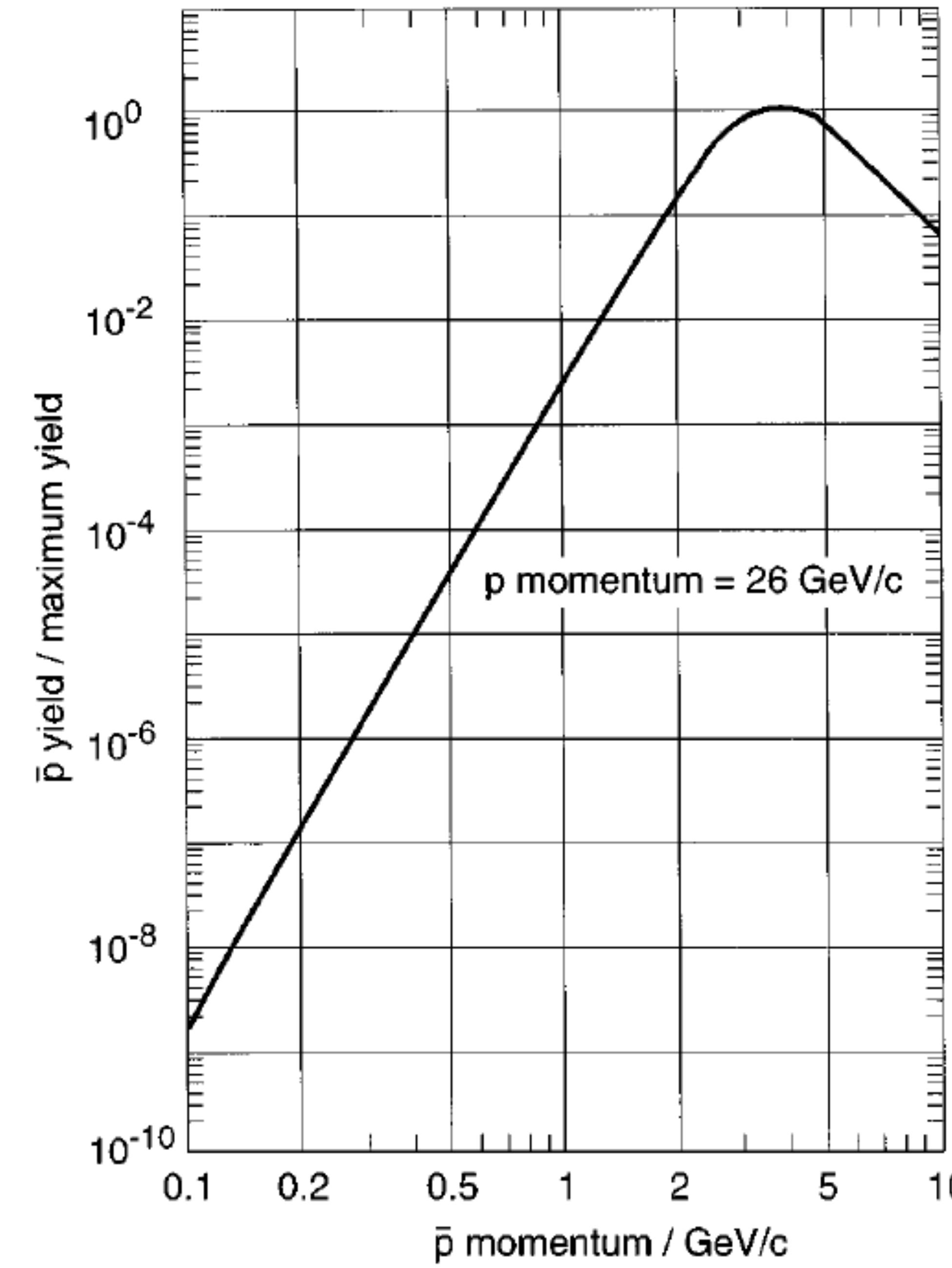
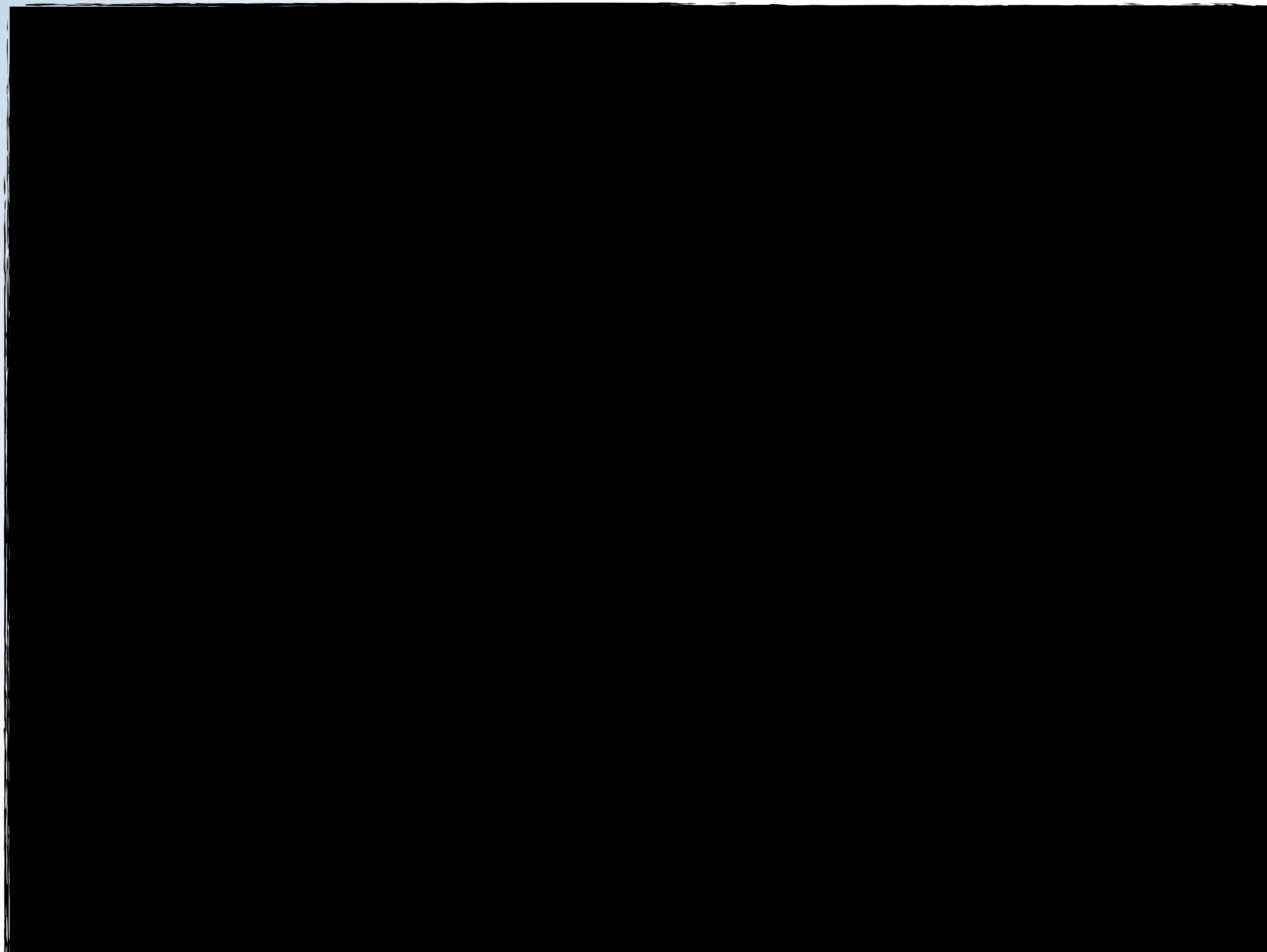


FIG. 1. Normalized antiproton yield (antiprotons per proton) at 26 GeV/*c* proton-beam momentum. The normalization is chosen so that the yield is one at the maximum.

Antiprotons at lower energies



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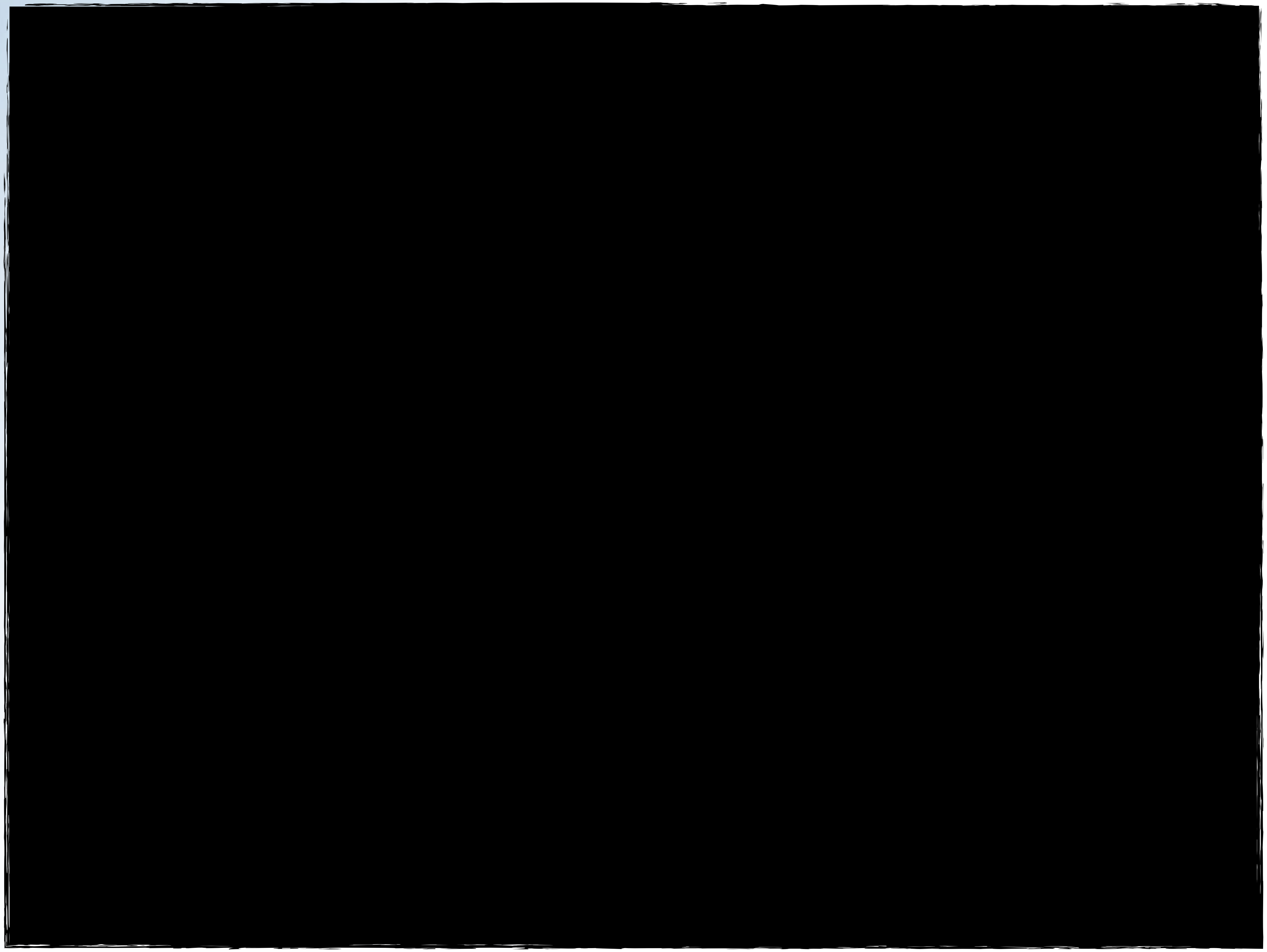


Antiproton Cooling

Cooling : reduce phase space and increase phase-space density

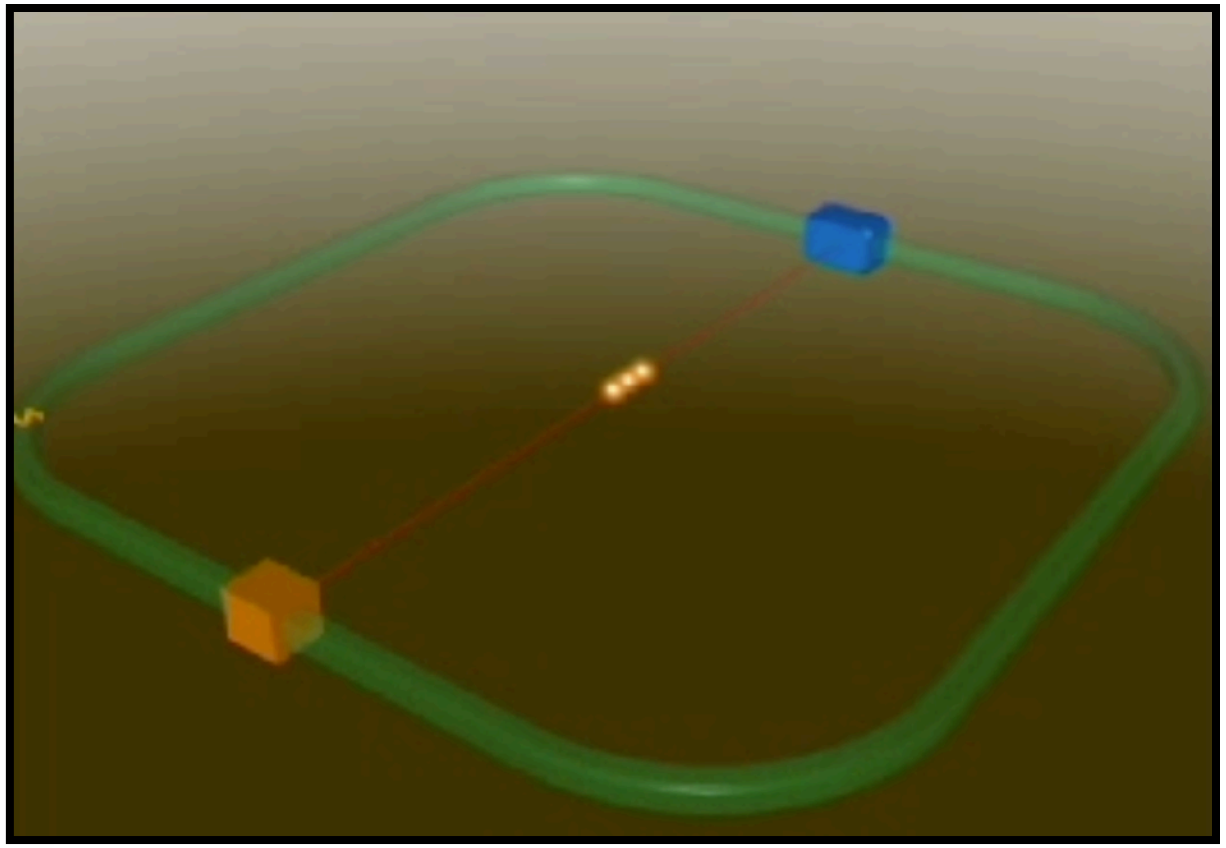
$$D = \frac{N}{\sqrt{E_h E_v L \frac{\Delta p}{p}}}$$

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

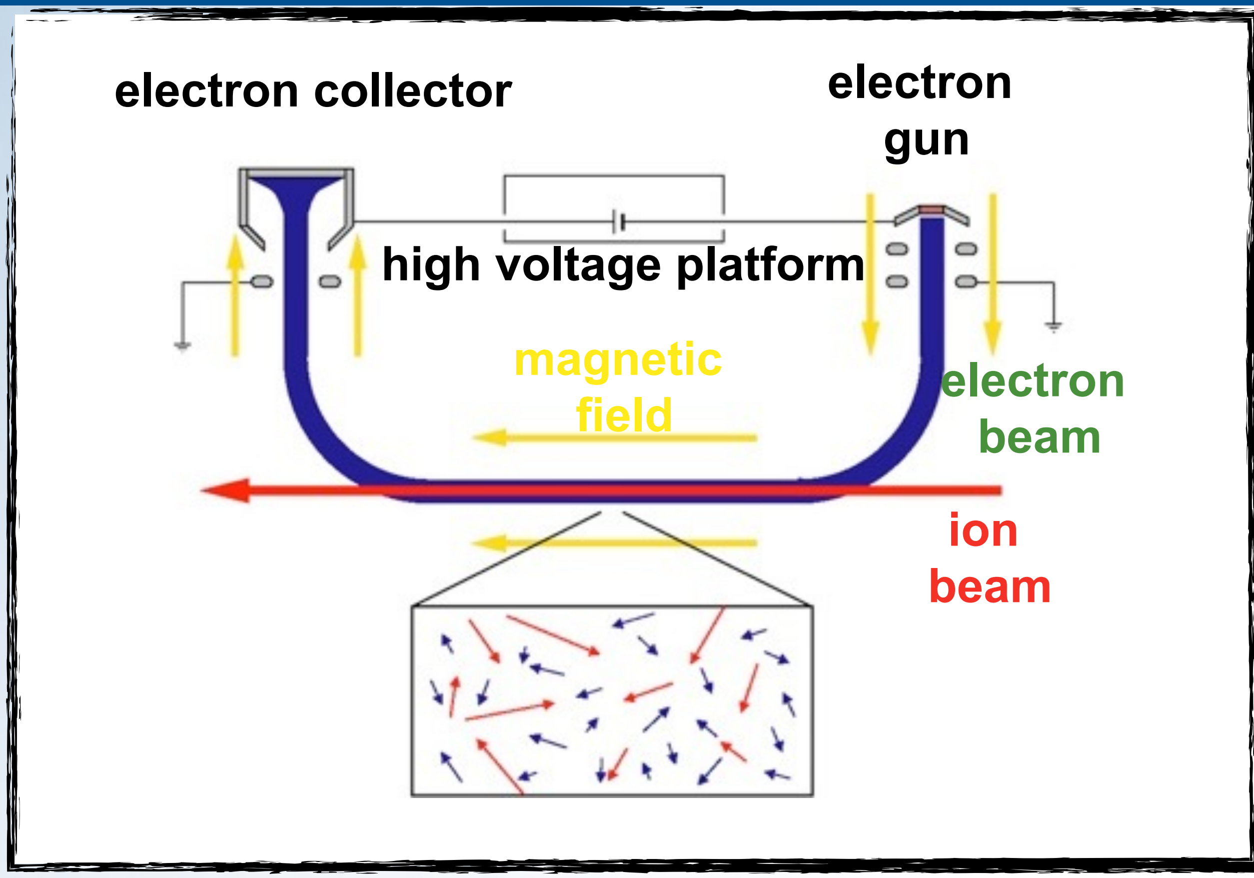
Cooling methods :

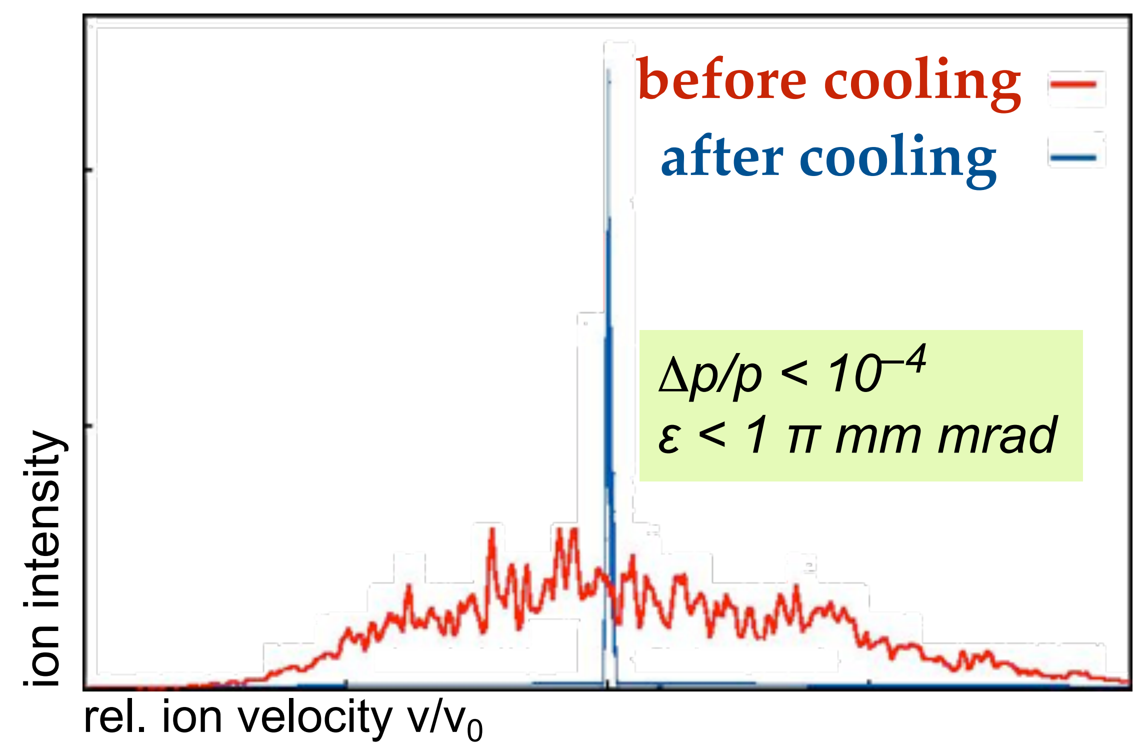
- Stochastic cooling

- Electron cooling

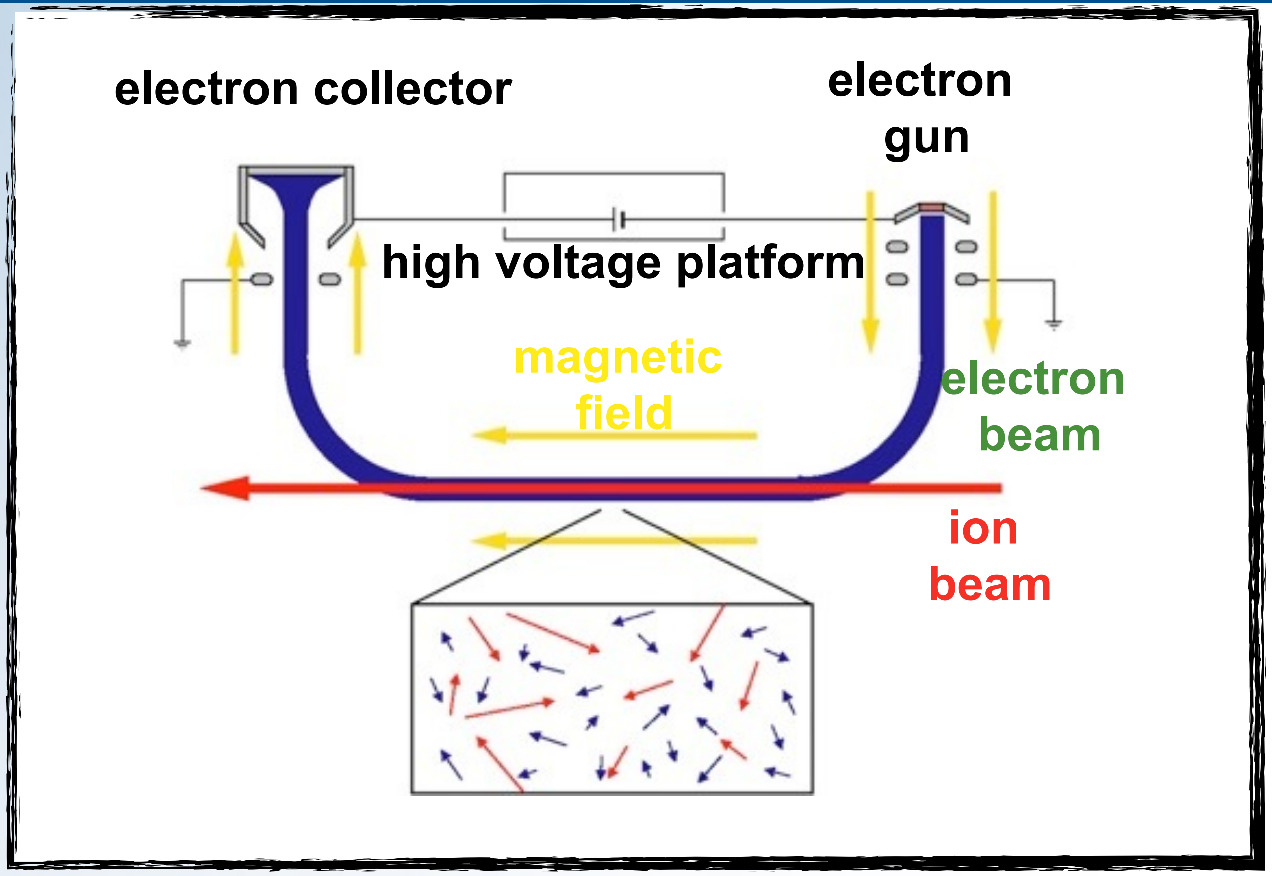


Electron cooling

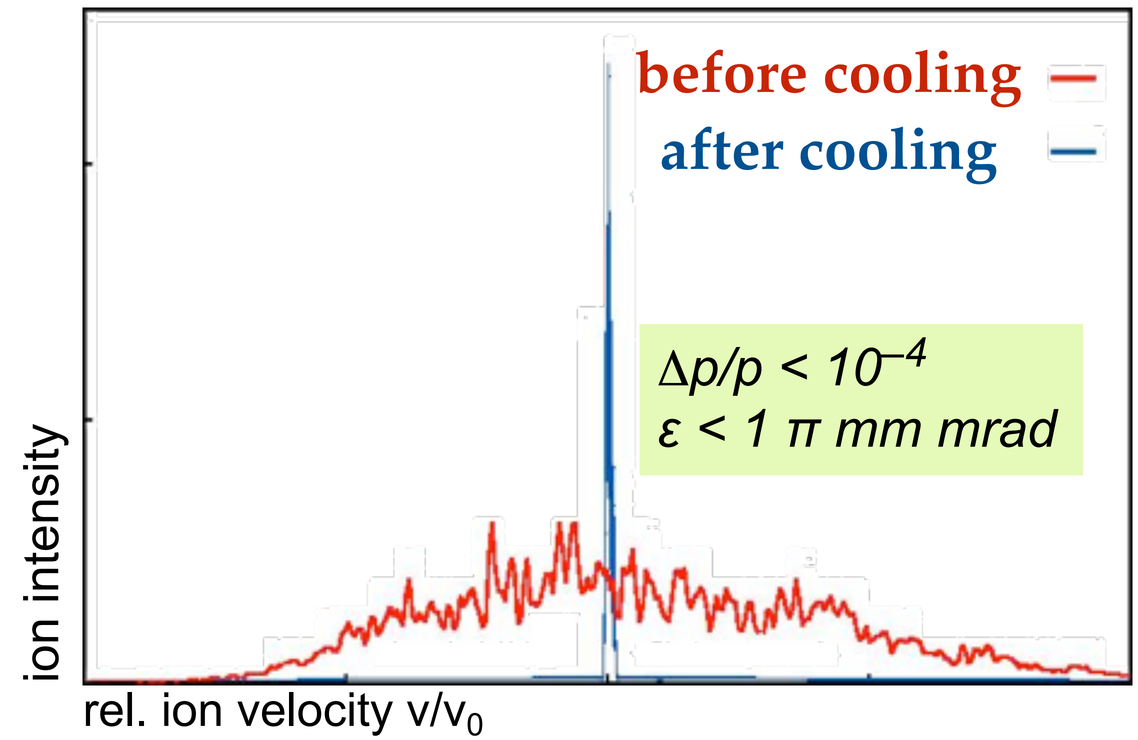




Electron cooling



		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)



Stochastic cooling

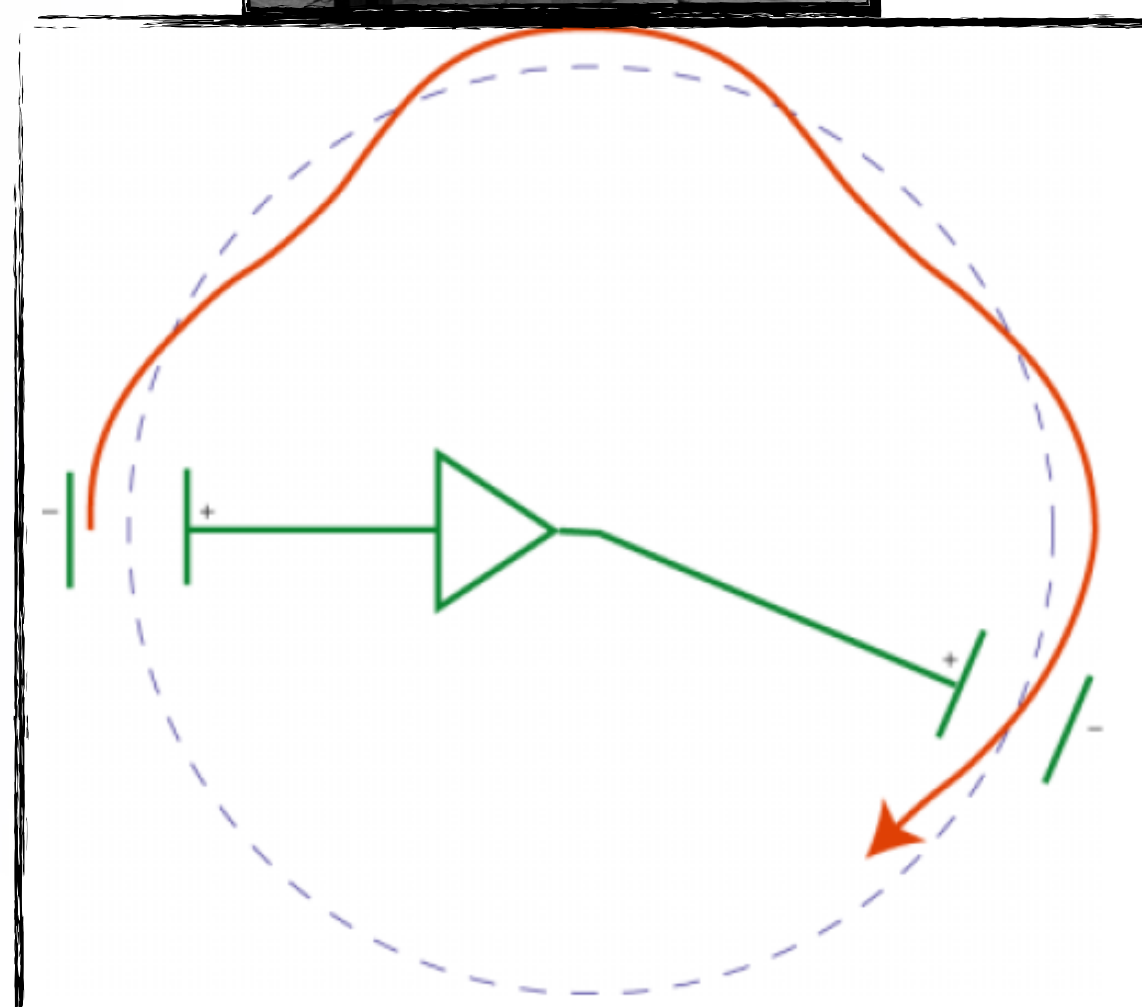
Measure beam center by pick-ups
Correction signal to opposite kicker

Pioneered at CERN for discovery W,Z bosons

Nobel Prize S. van der Meer

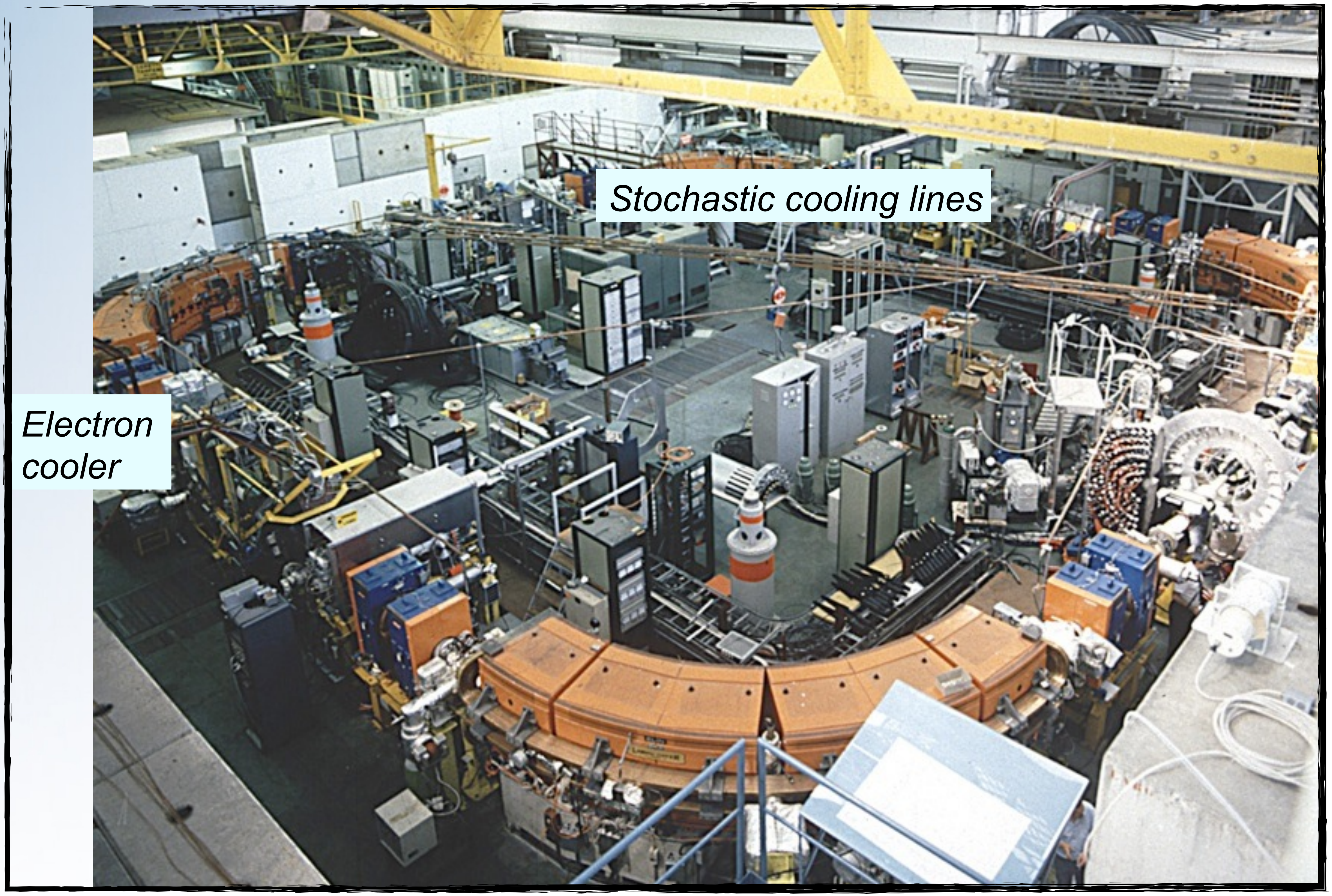
Cooling power decreases with decreasing energy

Cooling time ~ number of particles

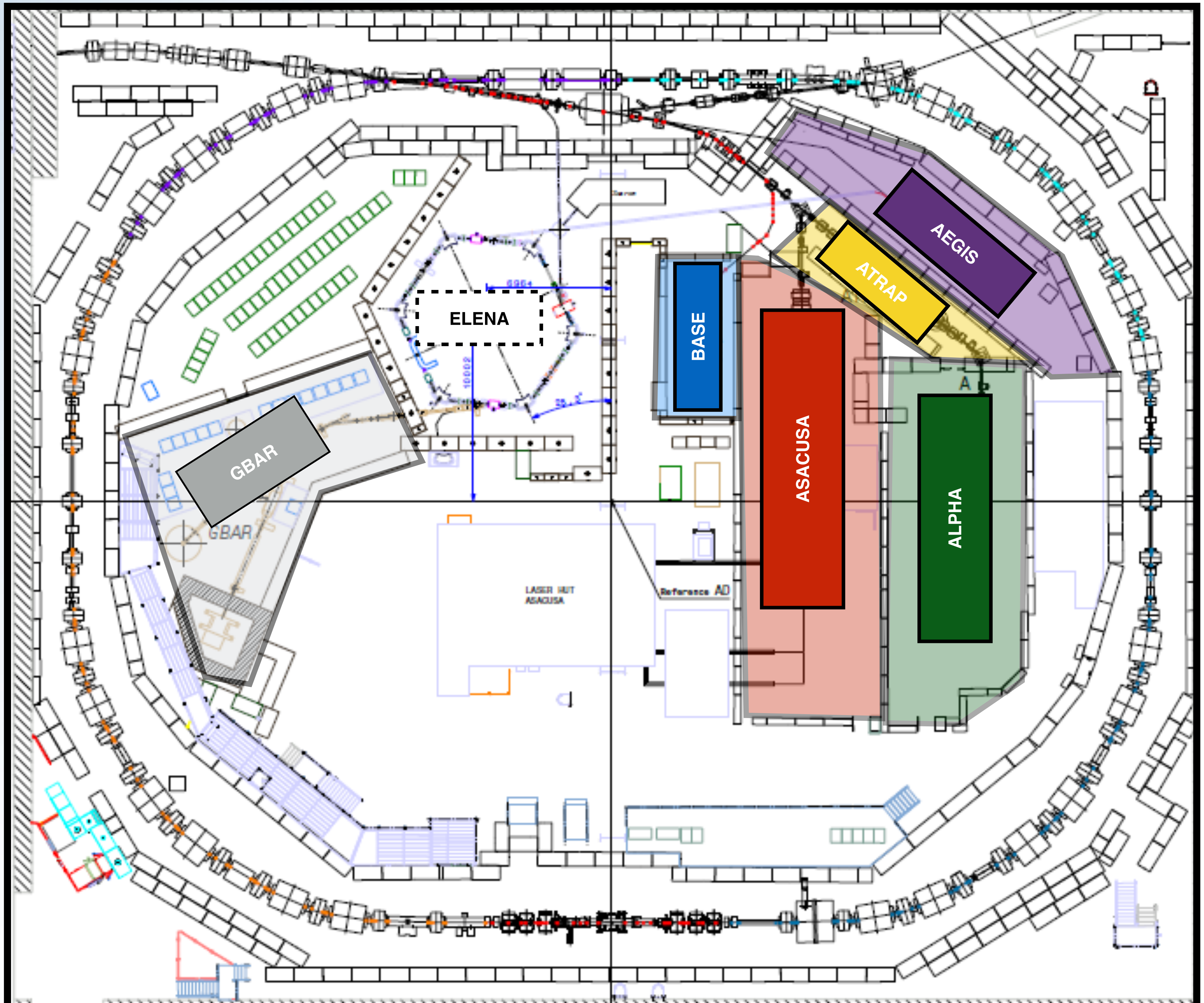


$$\Delta p/p \sim 0.07\%$$
$$\epsilon = 3 - 4 \ \pi\text{mm.mrad}$$

LEAR



The AD Facility



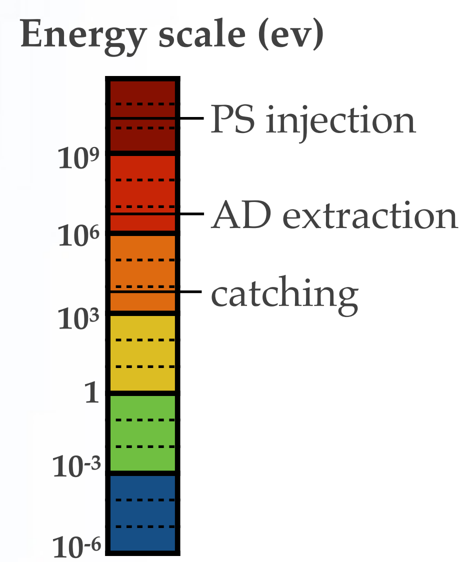
The AD complex

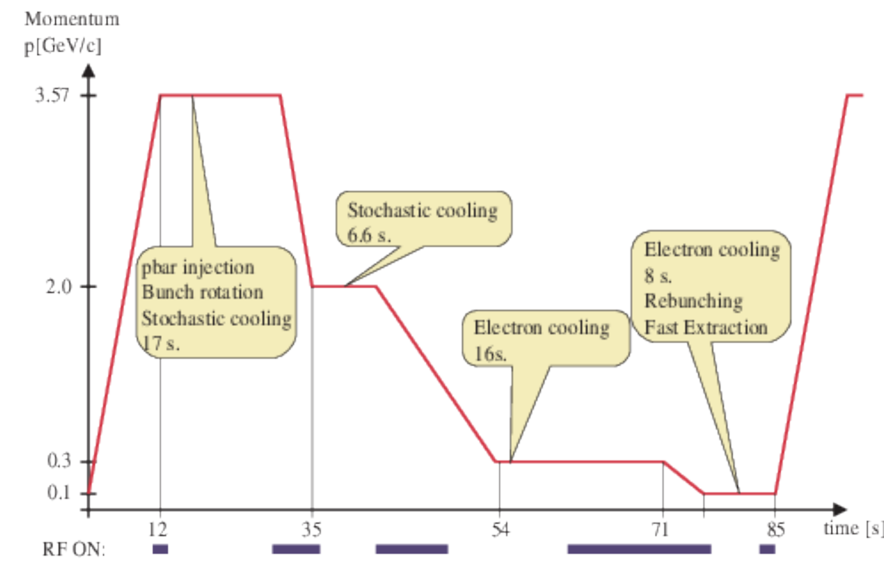
AD

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





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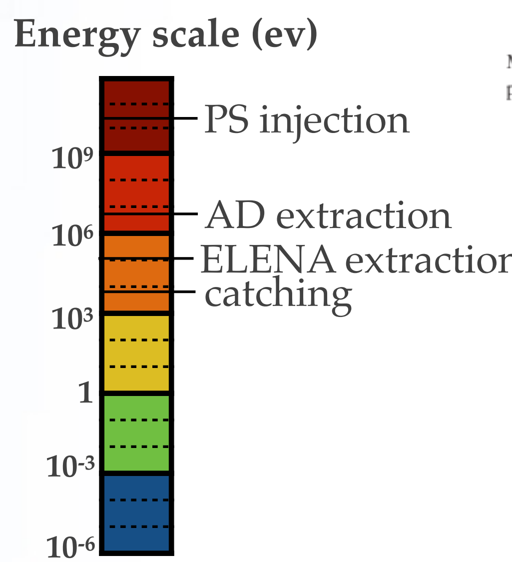
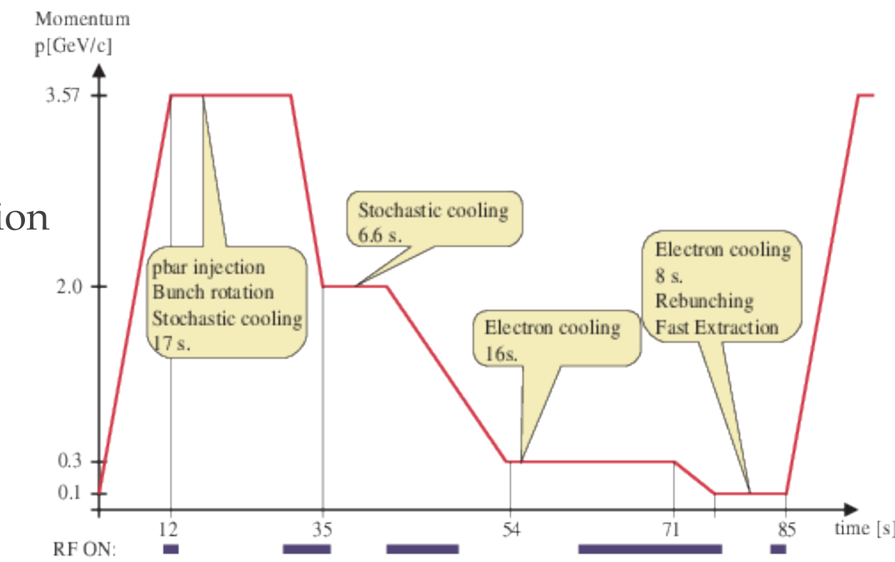




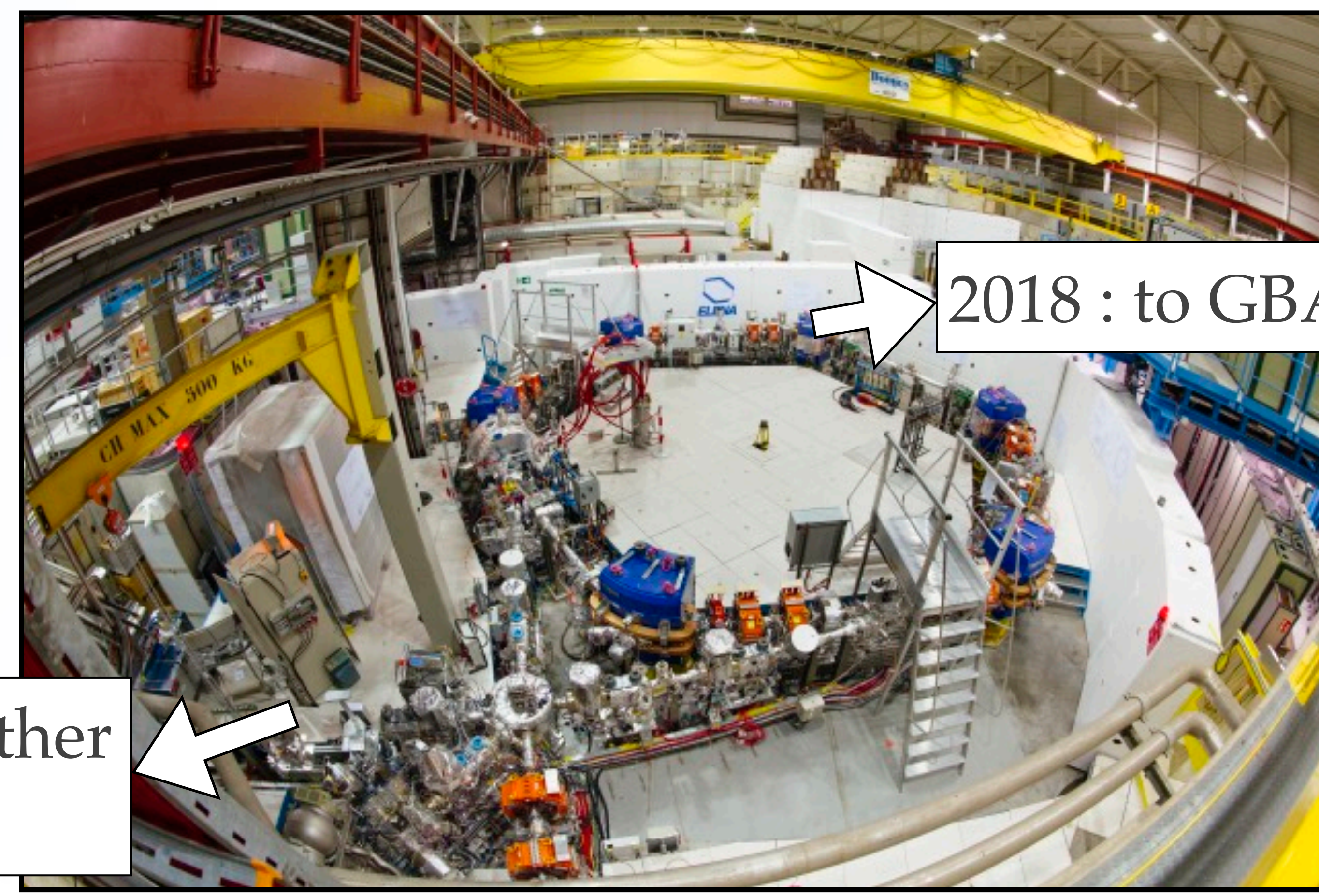
ELENA

$\bar{p}$ 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



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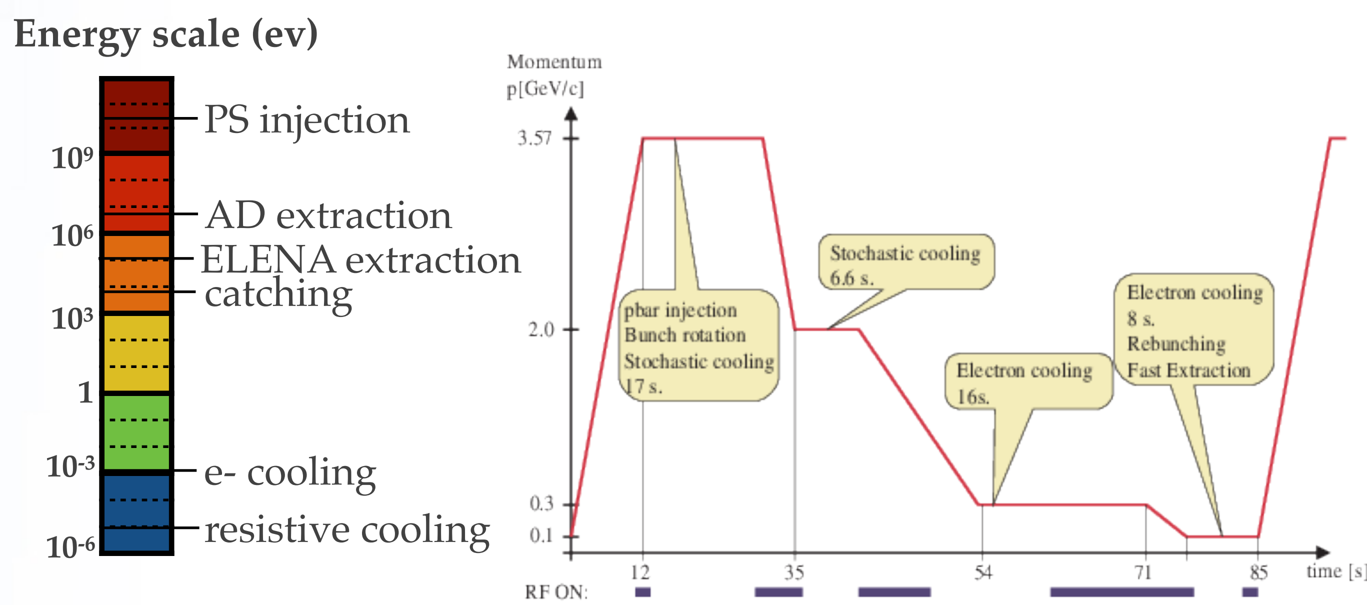

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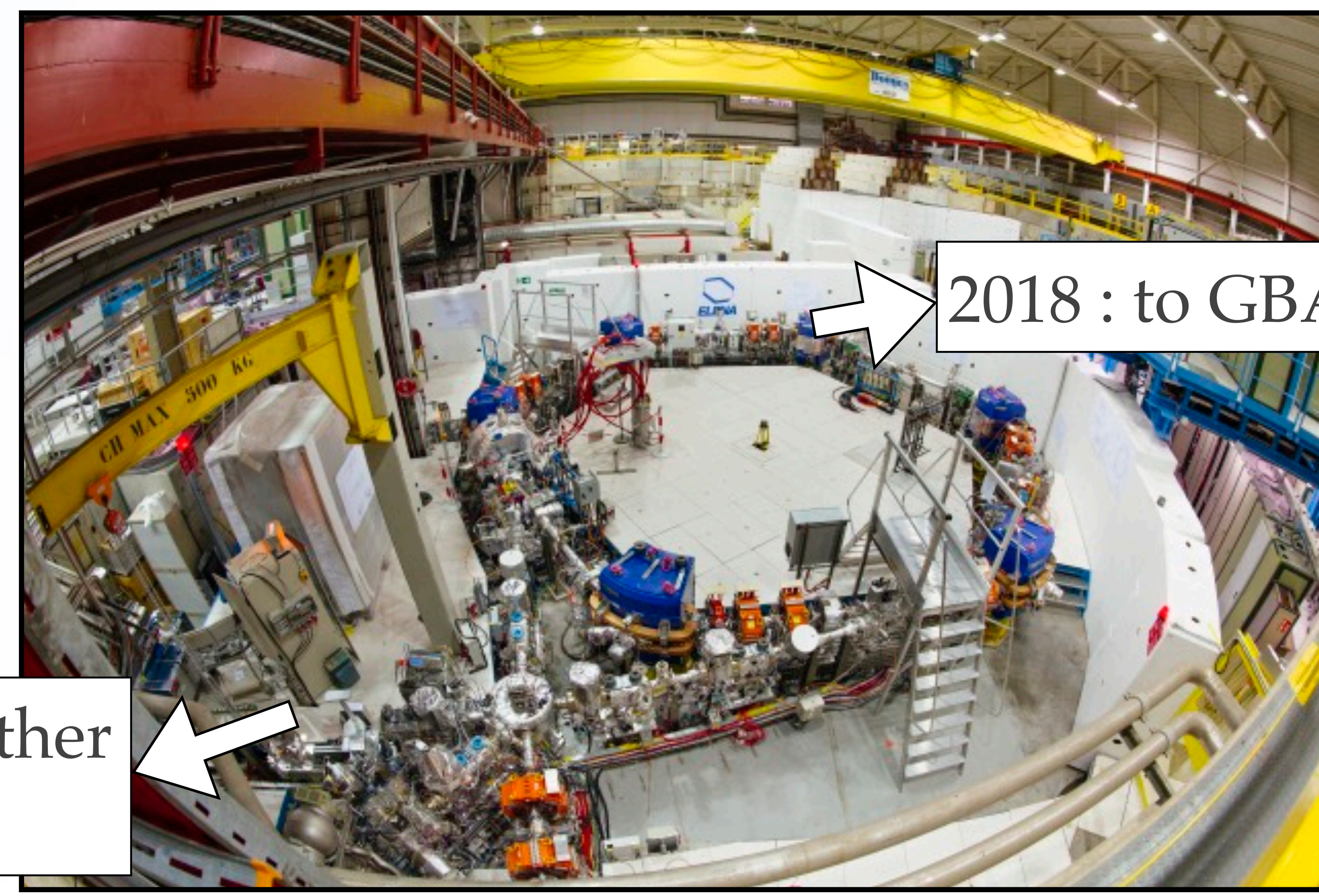
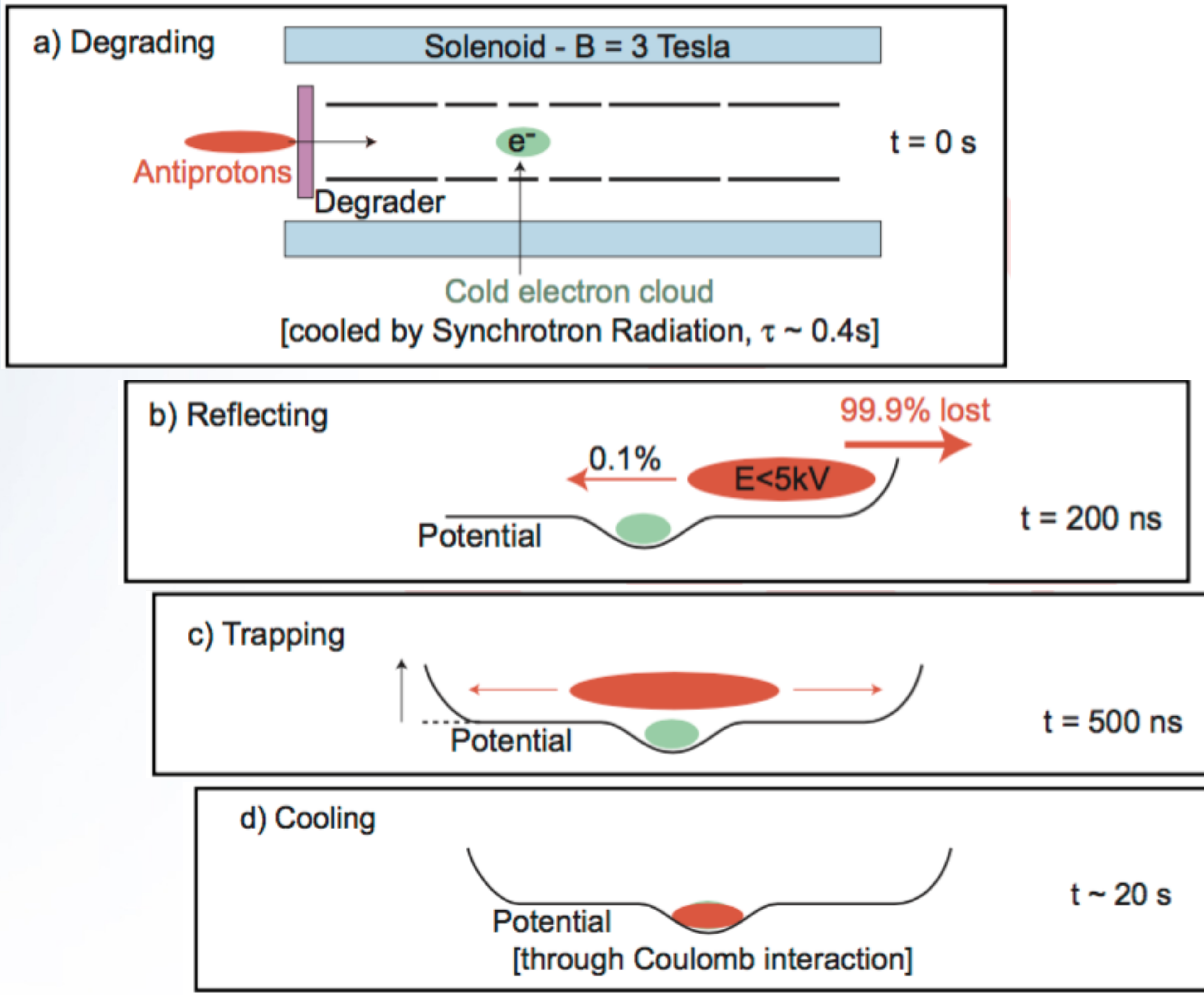


Penning traps

Long trapping times require
good vacuum!



Penning traps

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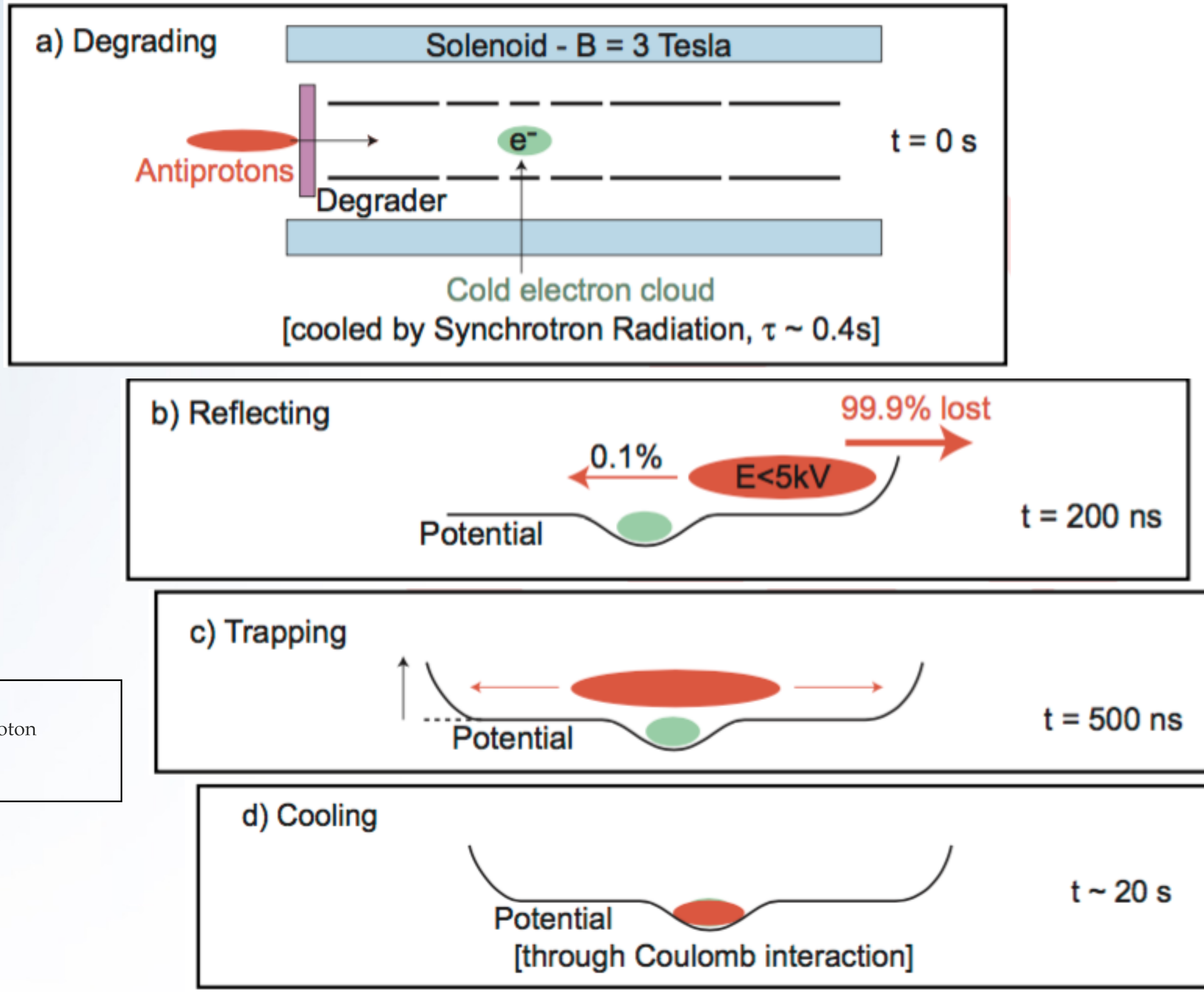
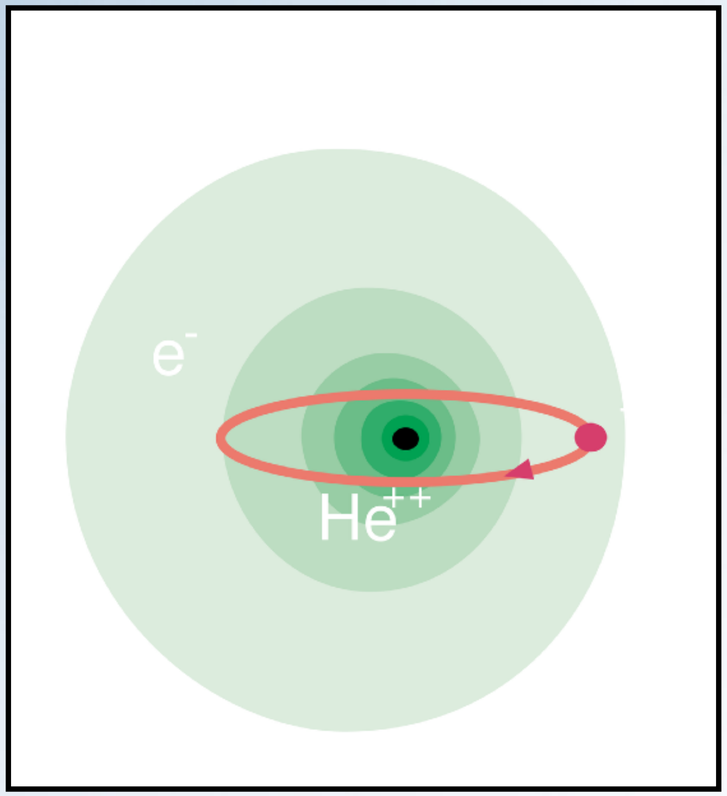
BASE : **P < 2. 10^-18 mbar**
$\boldsymbol{\tau(\bar{p}) > 10.2}$ **years** (68% confidence level)

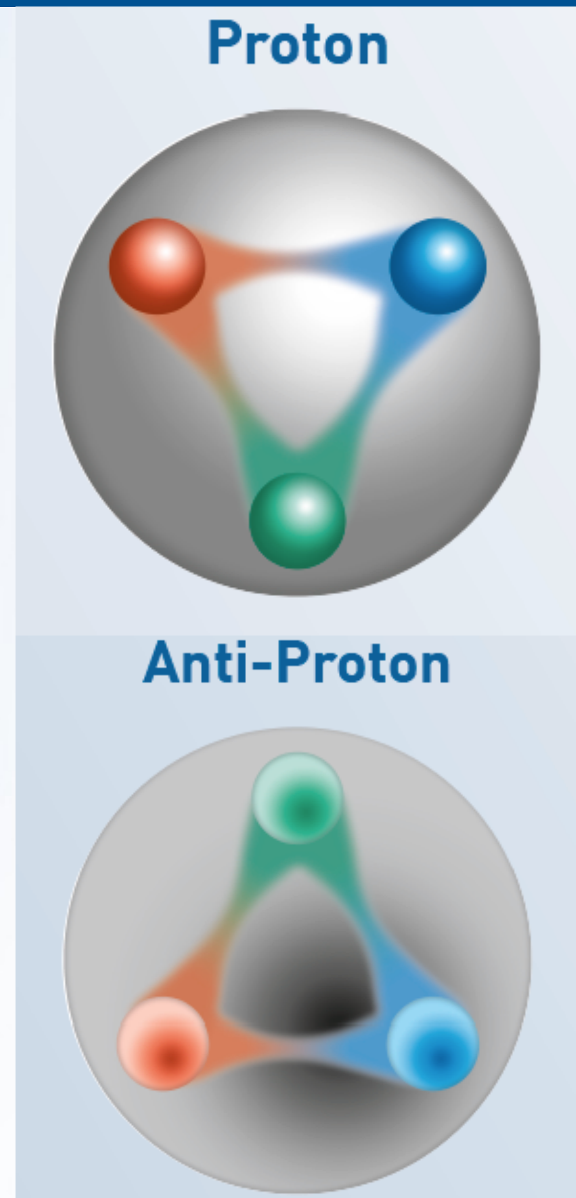
Stefan Sellner et al.
"Improved limit on the directly measured antiproton lifetime"
New Journal of Physics, 19, (2017)



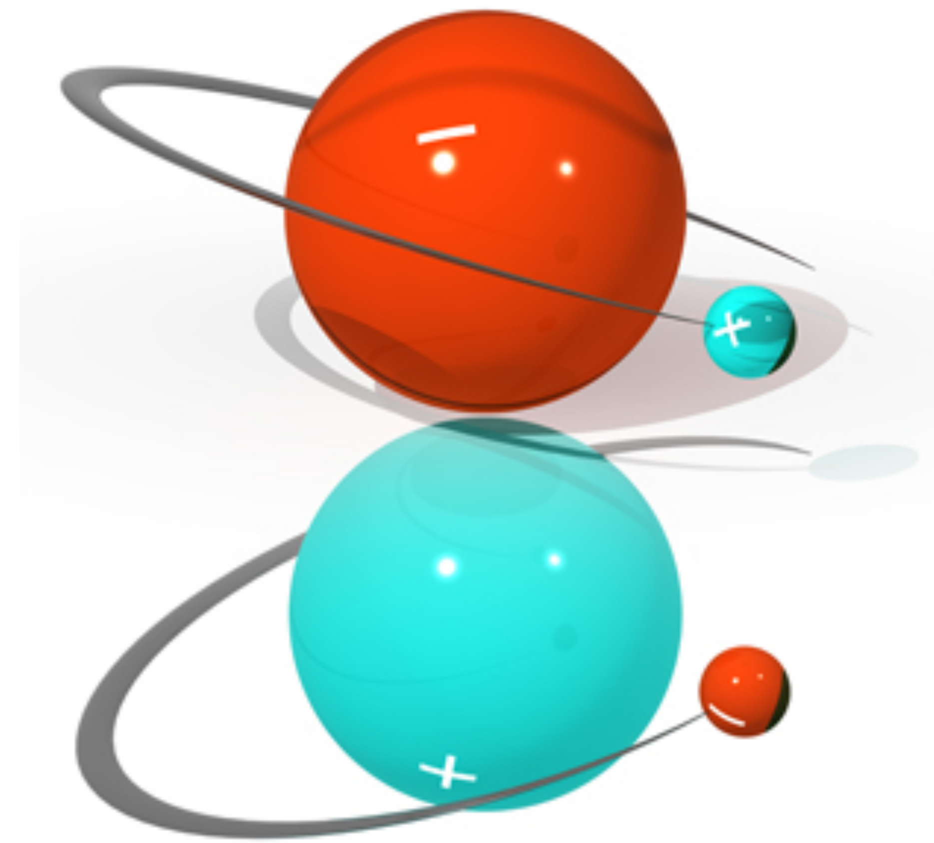
AD experiments



ASACUSA

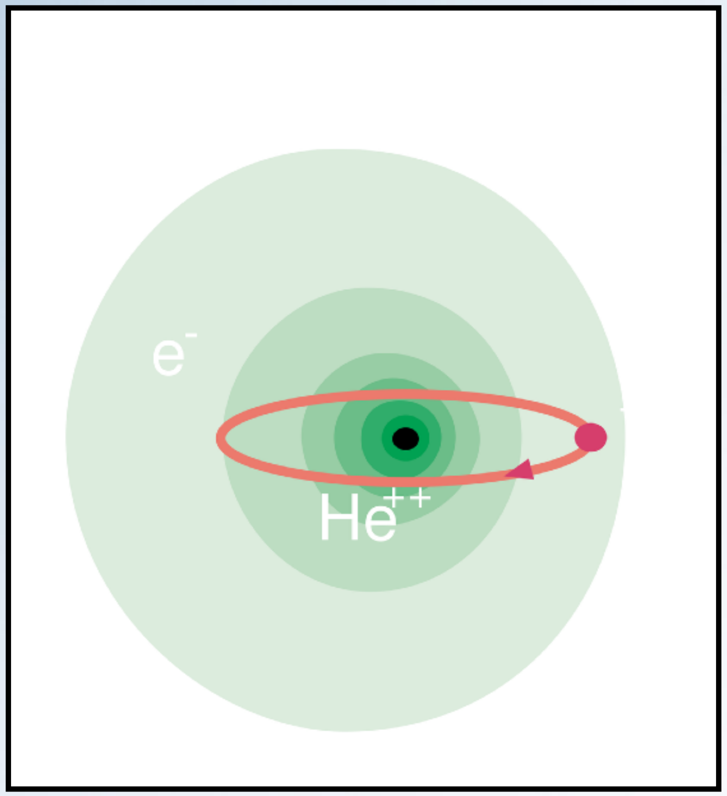


BASE
ASACUSA
ATRAP



ALPHA
ATRAP
ASACUSA
AEGIS
GBAR

AD experiments



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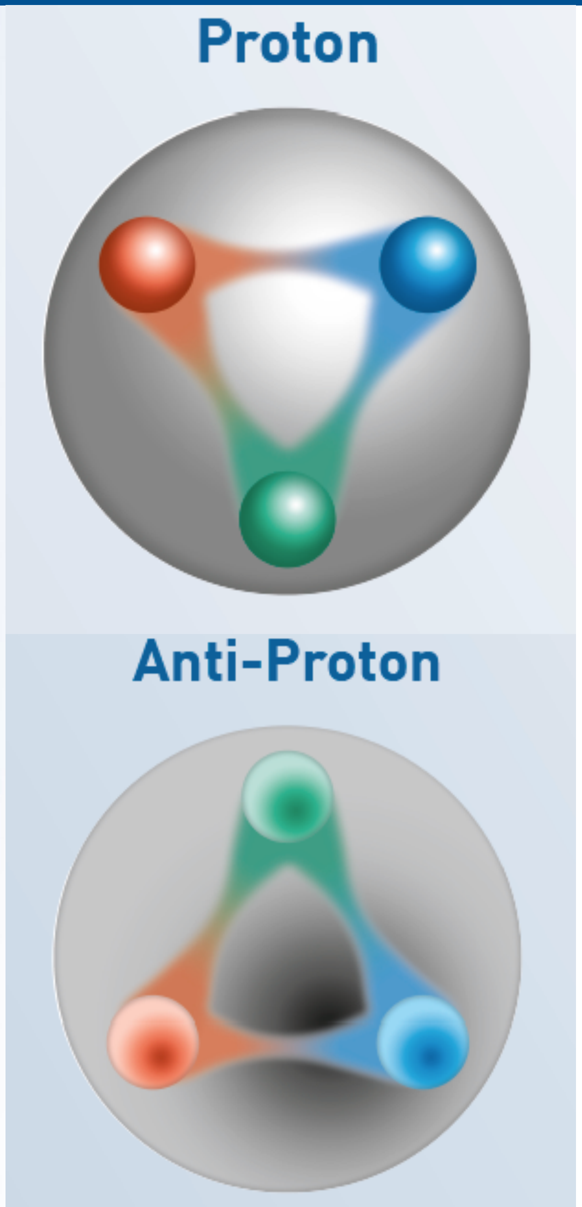

BASE

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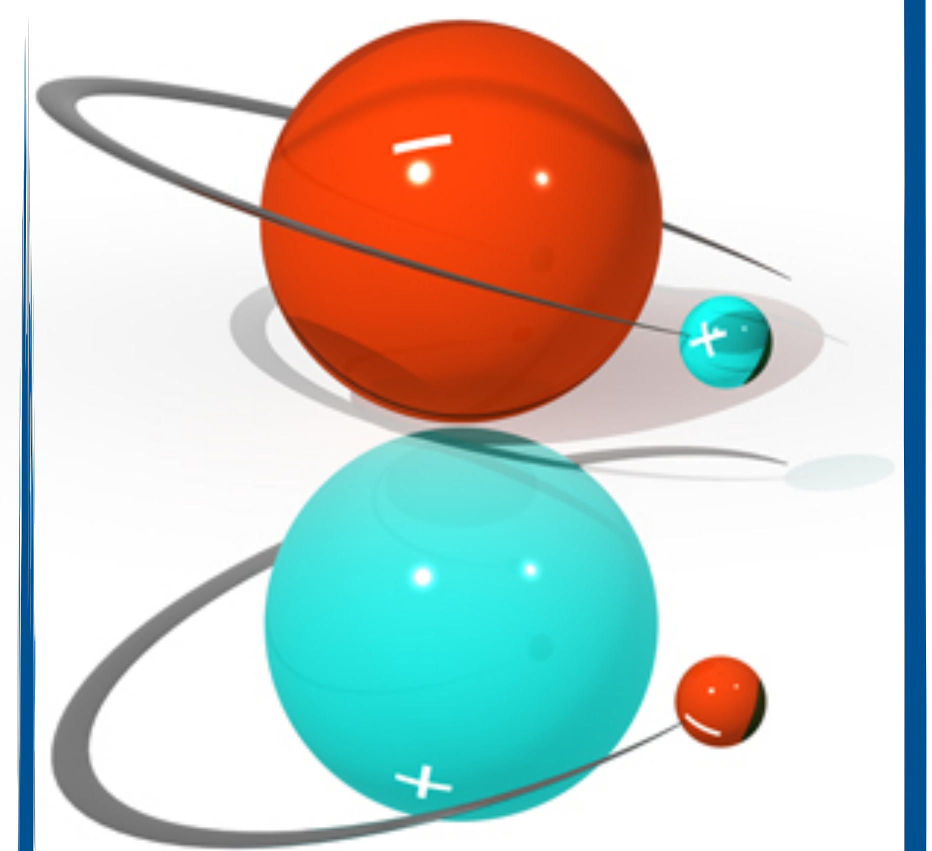


ALPHA

ATRAP

ASACUSA

AEGIS

GBAR

How to make antihydrogen

How to make antihydrogen

$\bar{p}$

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

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

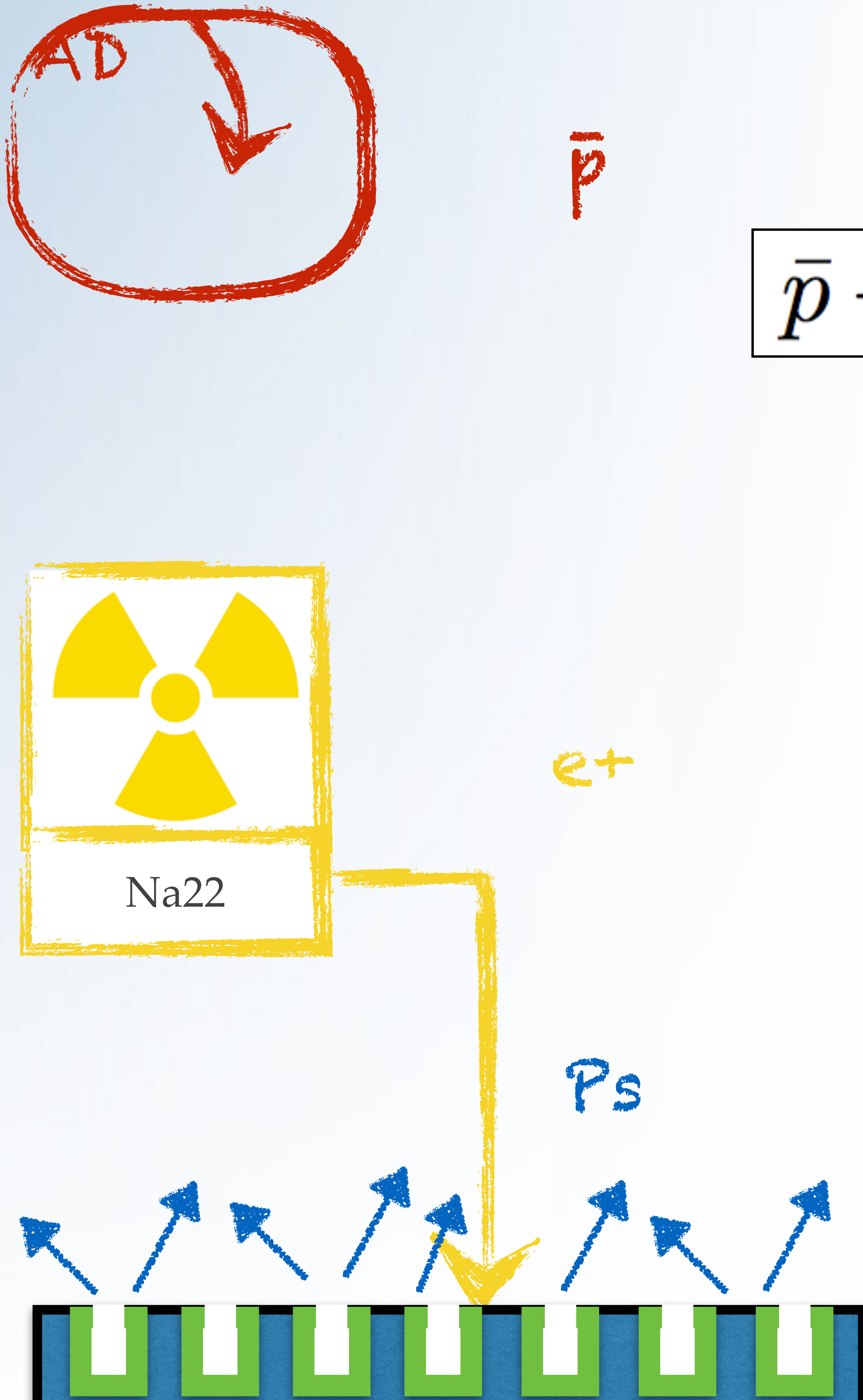
ASACUSA

ALPHA

ATRAP

e^+

How to make antihydrogen



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

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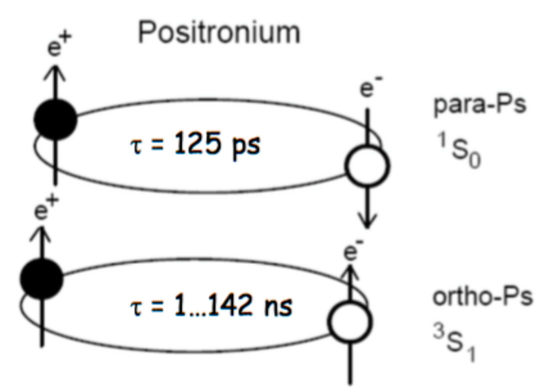
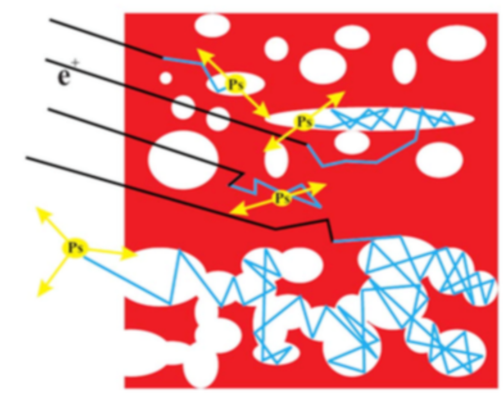
ASACUSA

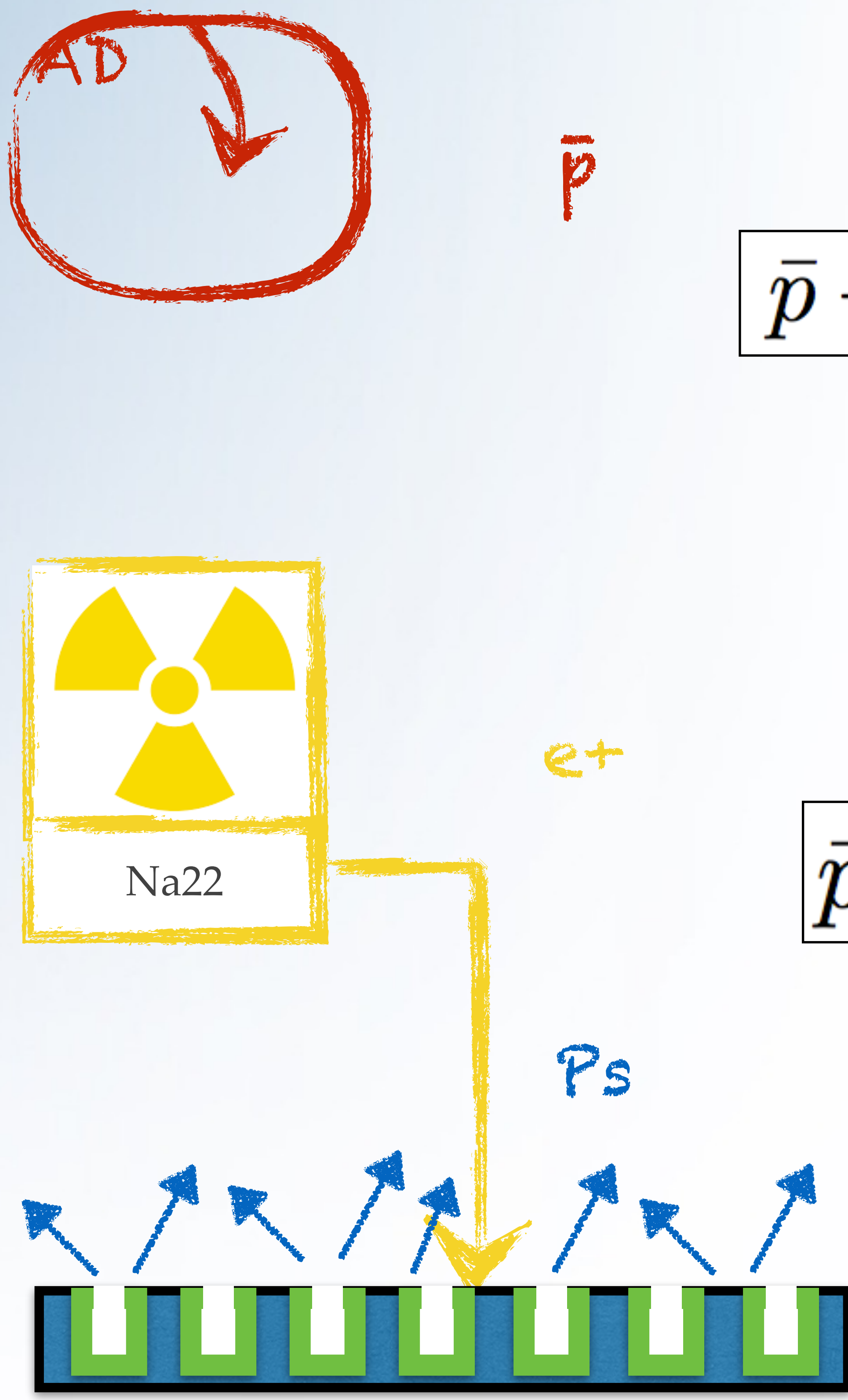
ALPHA

ATRAP





How to make antihydrogen



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

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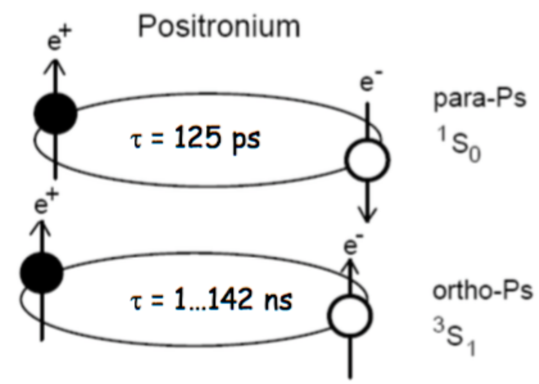
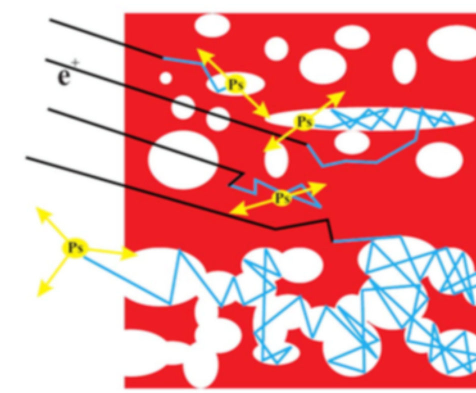
ASACUSA

ALPHA

ATRAP



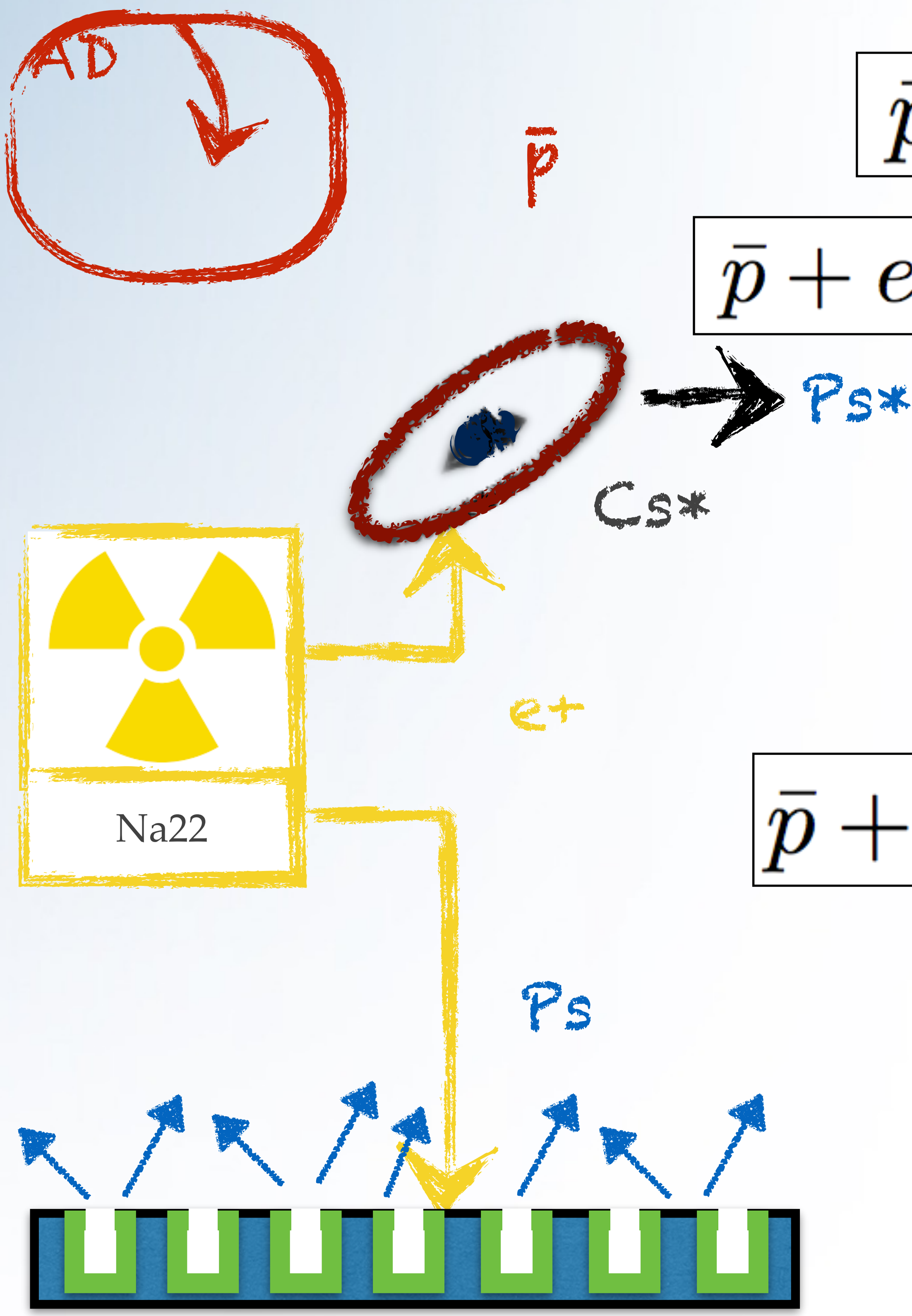


$$\bar{p} + Ps^\star \rightarrow \bar{H}^\star + e^-$$

AEGIS

ATRAP

How to make antihydrogen



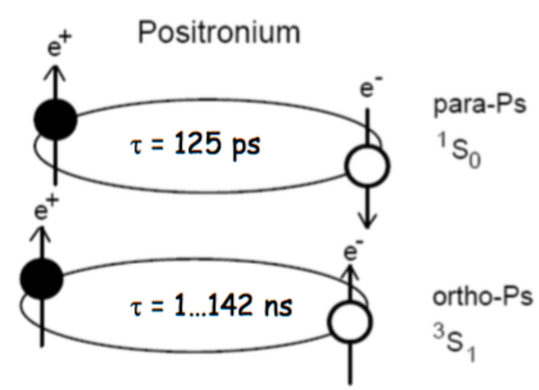
$$\bar{p} + e^{+} \rightarrow \bar{H} + \gamma$$

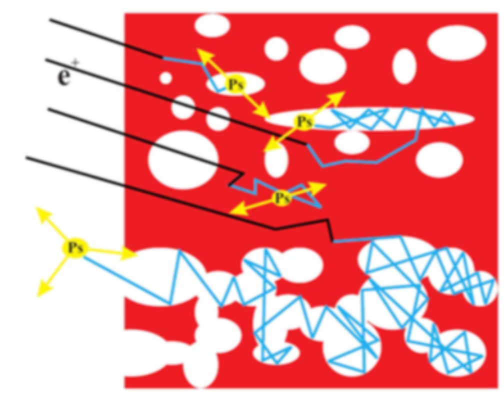
$$\bar{p} + e^{+} + e^{+} \rightarrow \bar{H} + e^{+}$$

ASACUSA

ALPHA

ATRAP



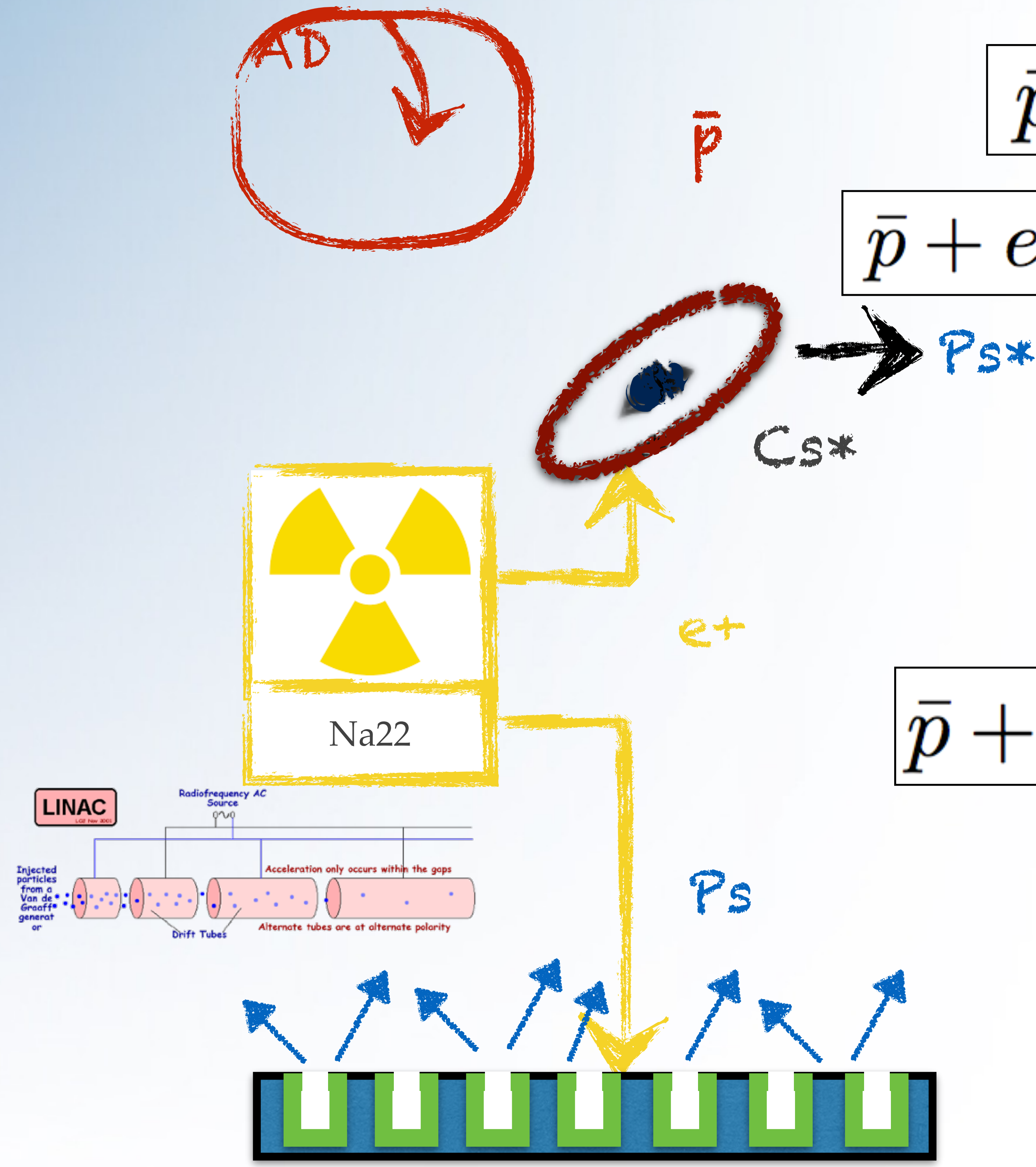


$$\bar{p} + Ps^{\star} \rightarrow \bar{H}^{\star} + e^{-}$$

AEGIS

ATRAP

How to make antihydrogen



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

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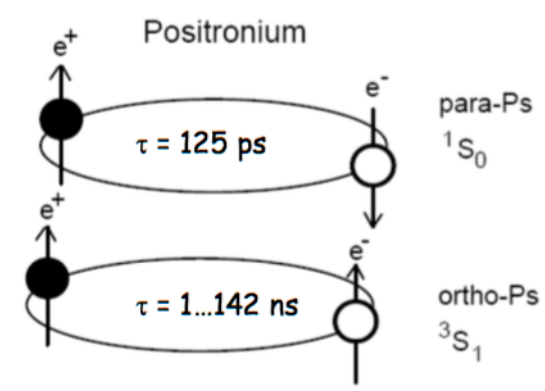
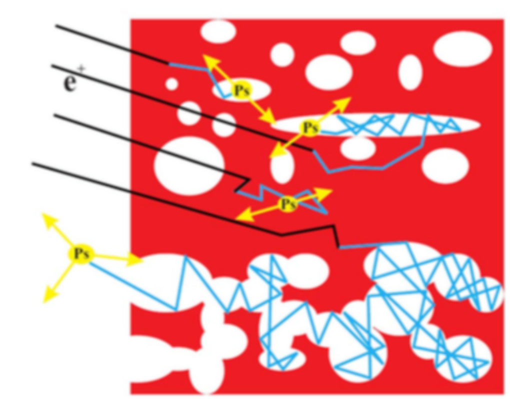
ASACUSA
ALPHA
ATRAP





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

AEGIS
ATRAP

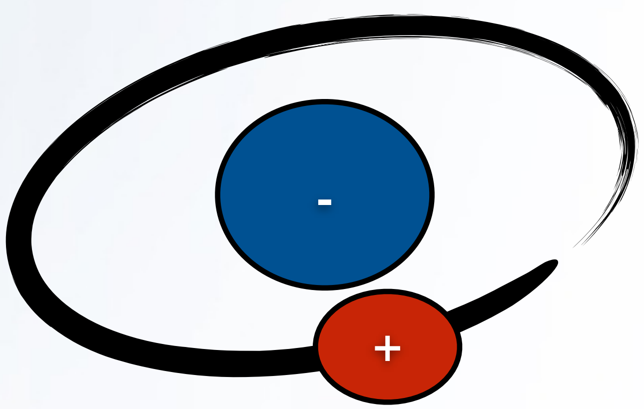
Antihydrogen ION !

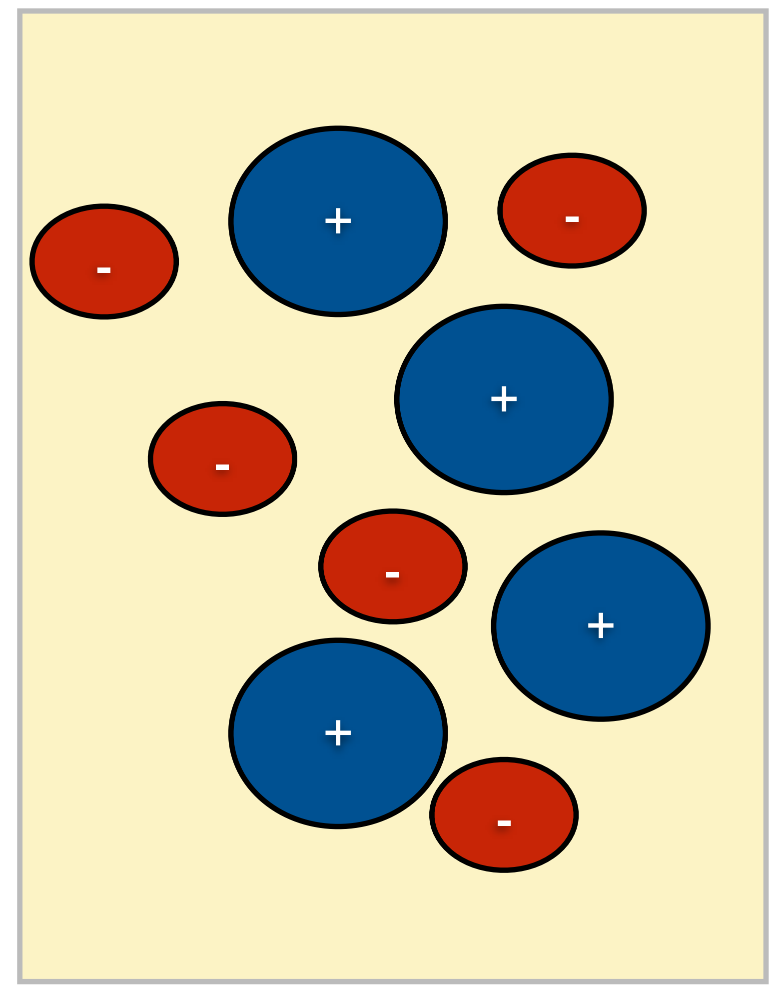
$$\bar{p} + Ps \rightarrow \bar{H} + e^-$$

GBAR

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

Antiprotons at lower energies





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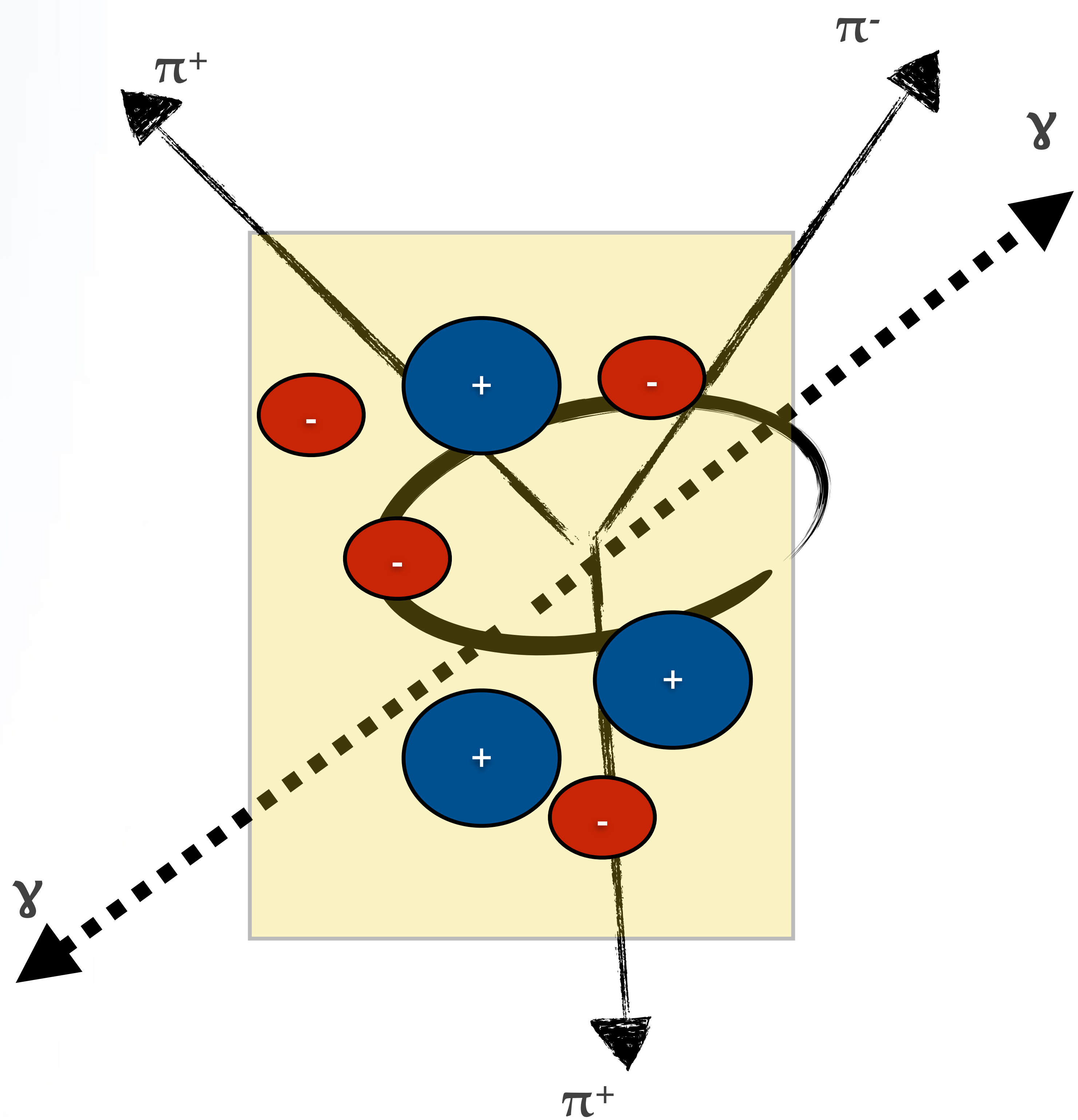
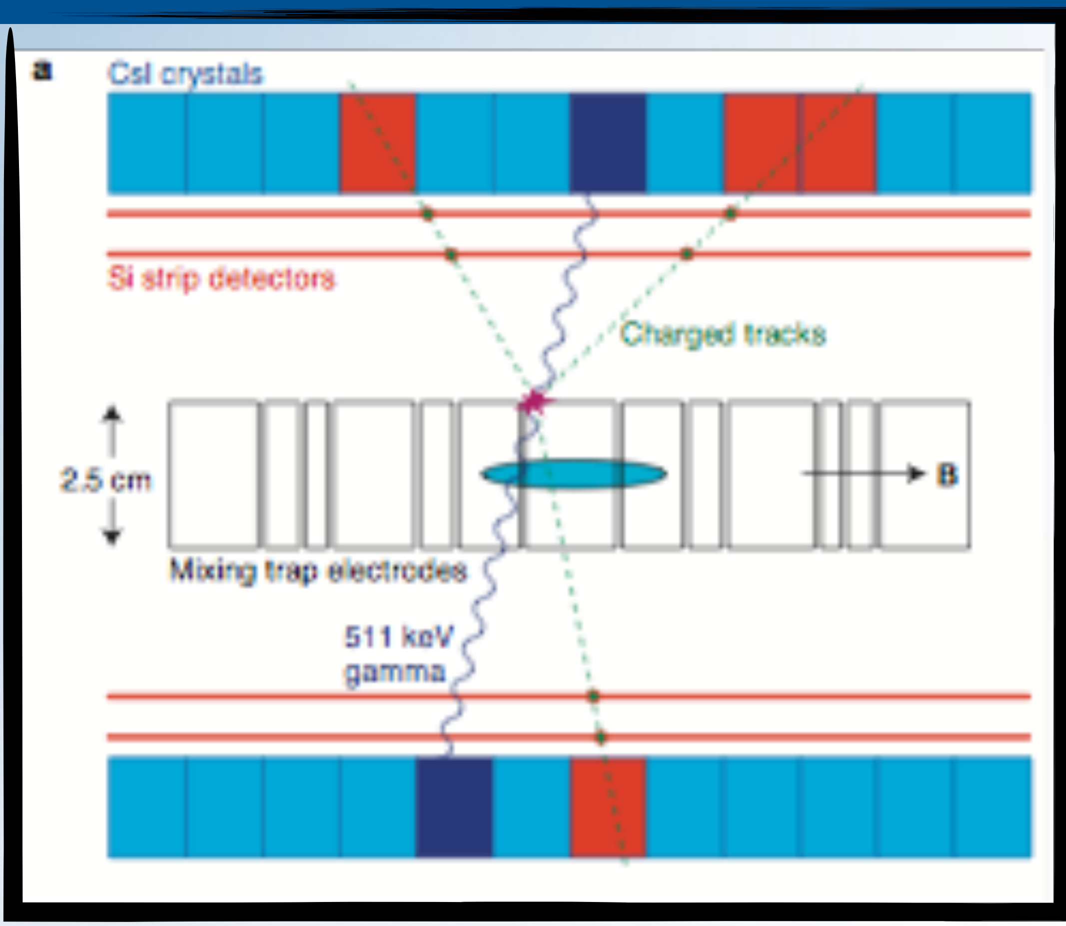
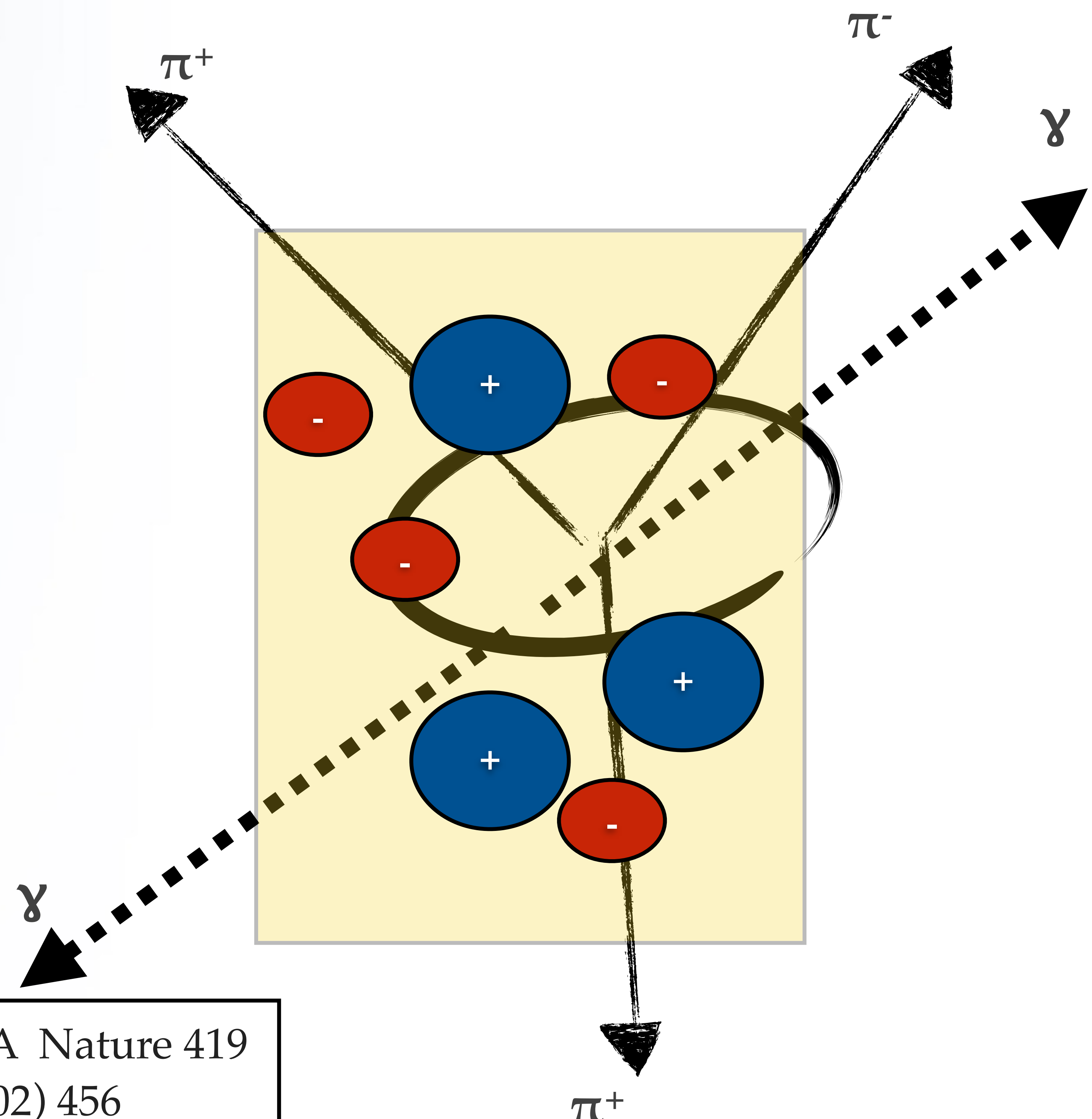


Antiprotons at lower energies



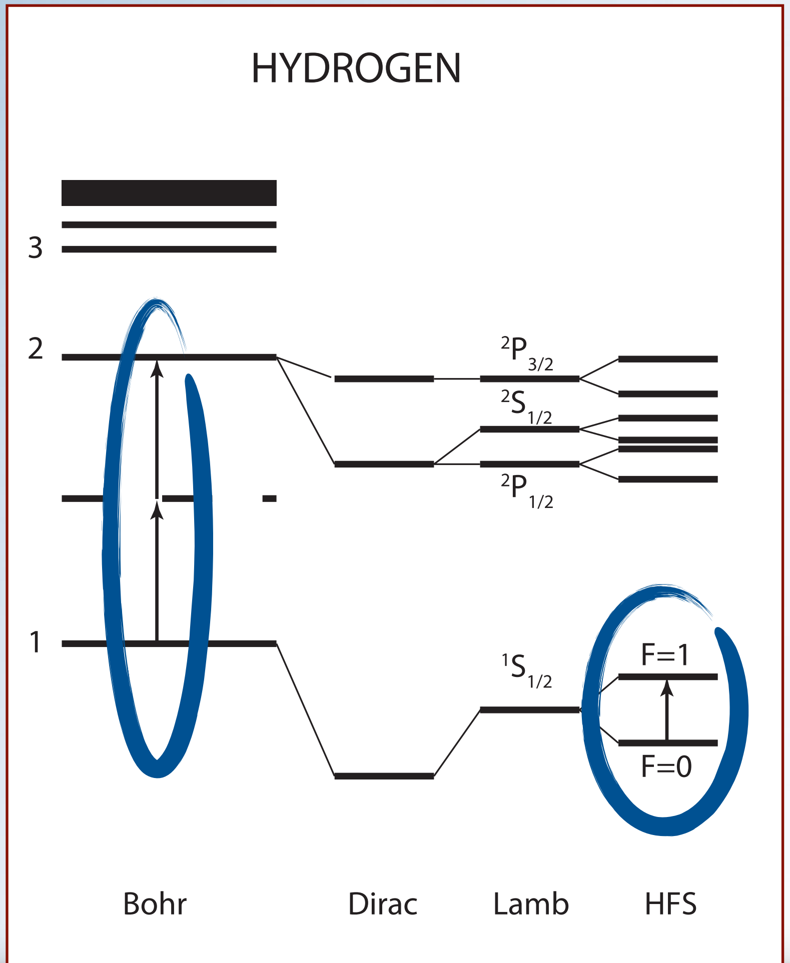


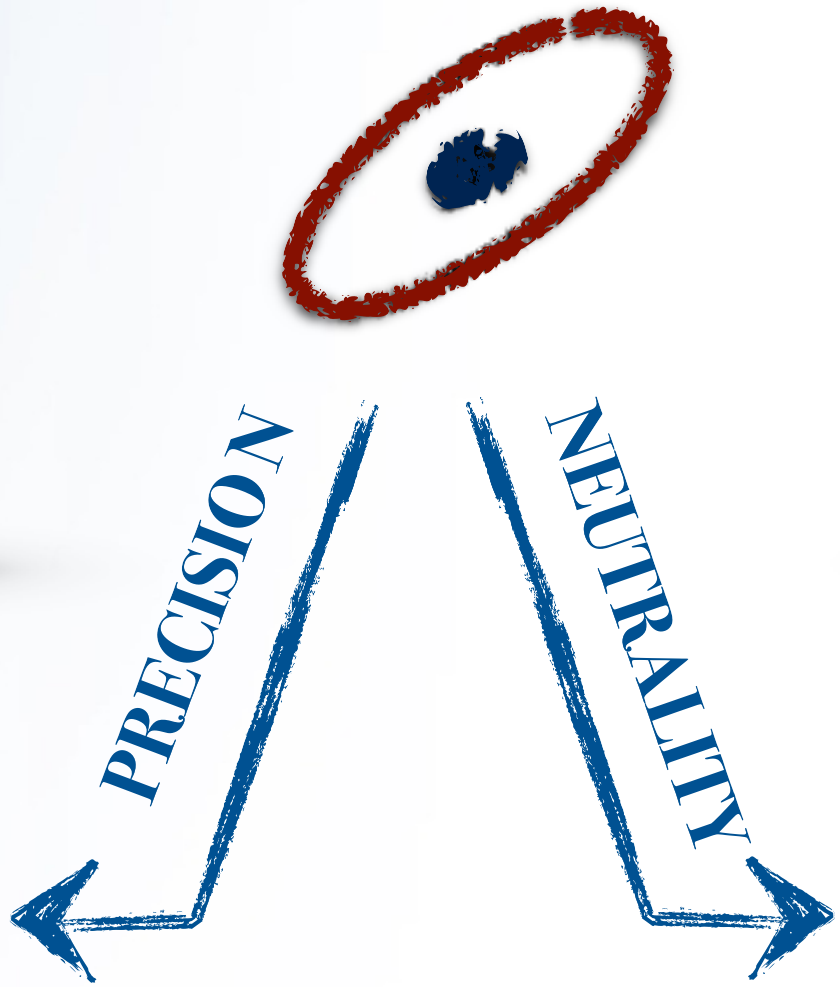
Production and detection of cold antihydrogen atoms

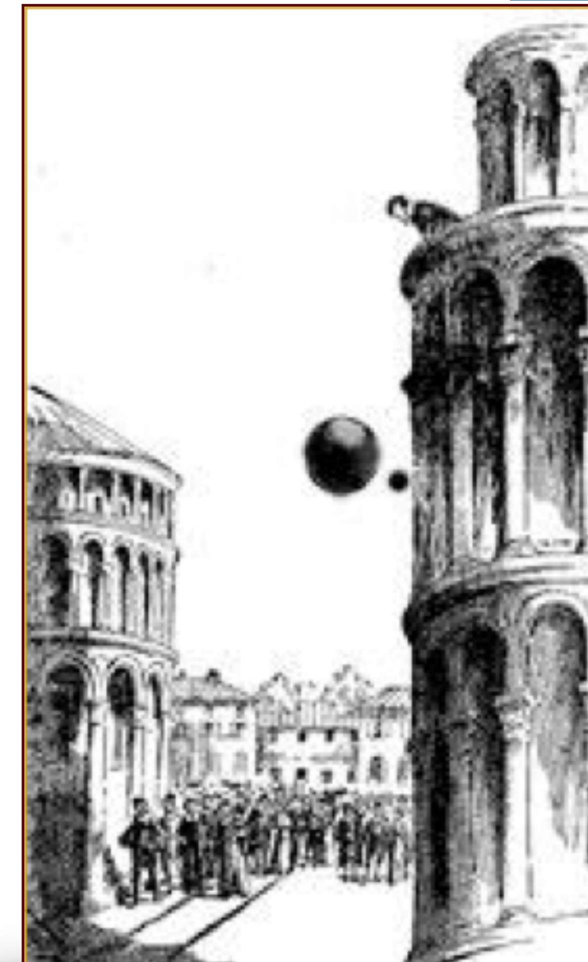
M. Amoretti*, C. Amsler†, G. Bonomi‡§, A. Bouchta‡, P. Bowe‖, C. Carraro*, C. L. Cesar¶, M. Charlton#, M. J. T. Collier#, M. Doser‡, V. Filippini☆, K. S. Fine‡, A. Fontana☆**, M. C. Fujiwara††, R. Funakoshi††, P. Genova☆**, J. S. Hangst‖, R. S. Hayano††, M. H. Holzscheiter‡, L. V. Jørgensen#, V. Lagomarsino*‡‡, 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

Antihydrogen experiments







ASACUSA

ALPHA

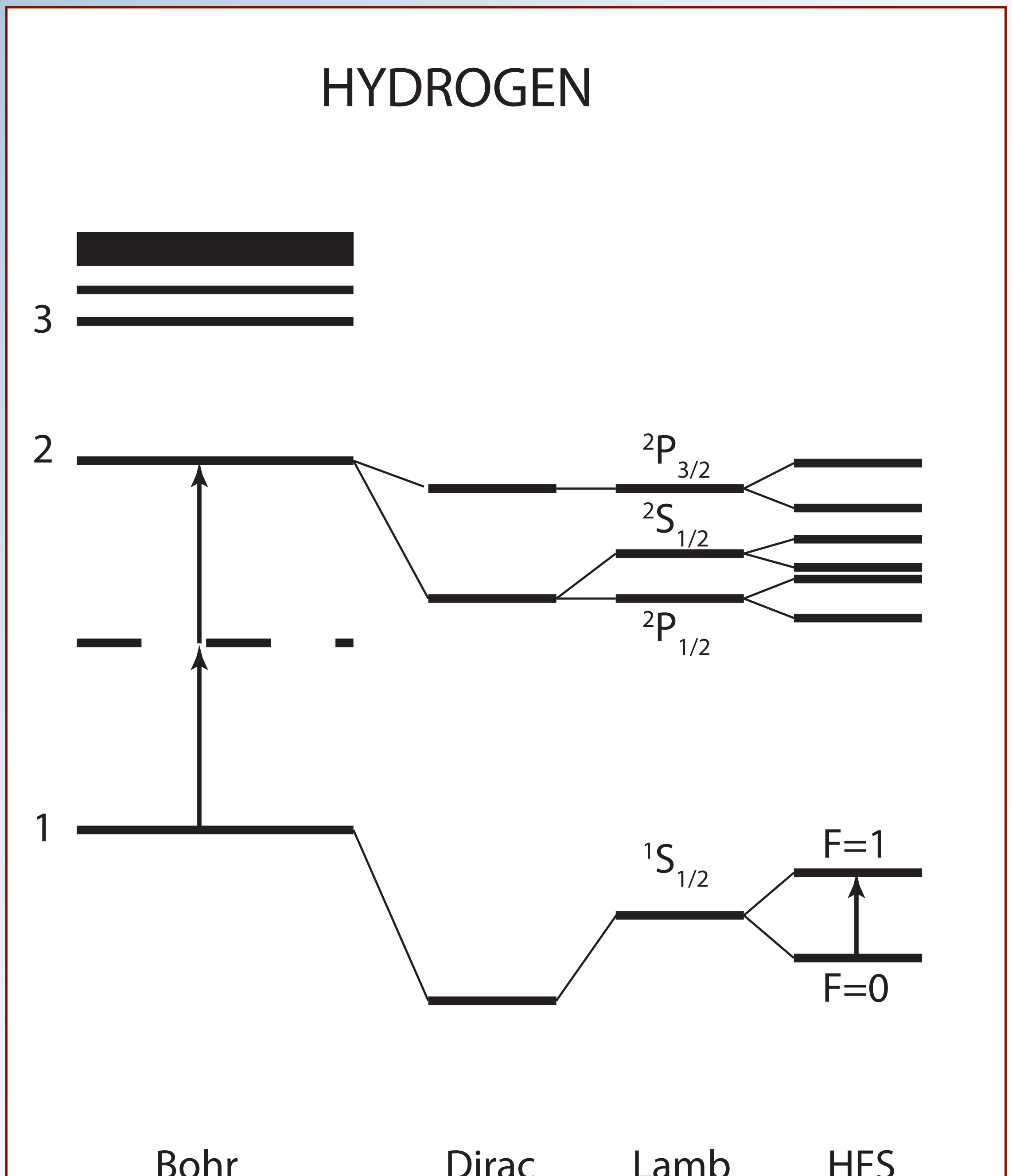
ATRAP

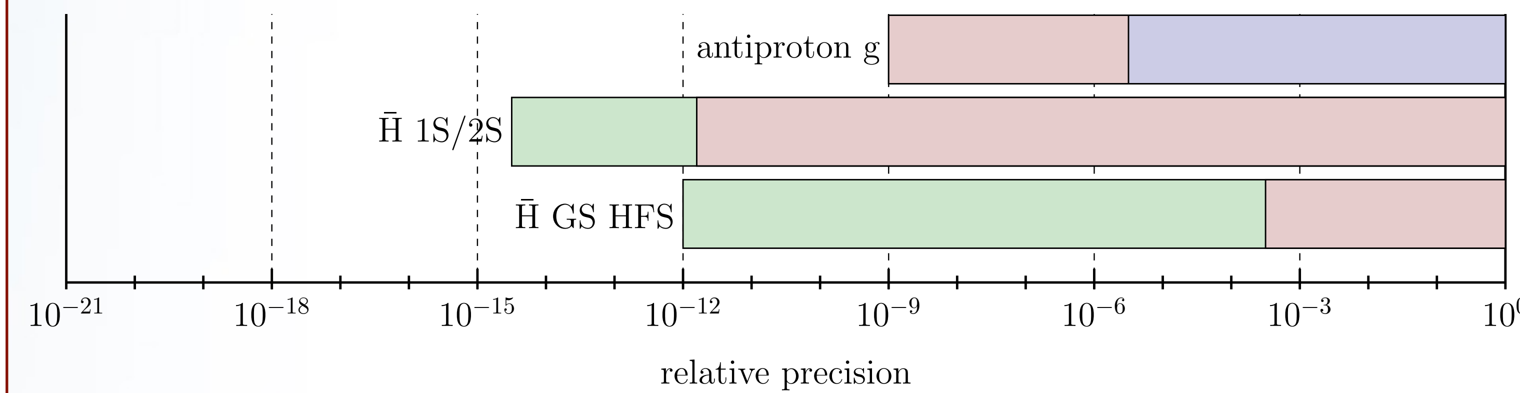
AEGIS

GBAR

ALPHA-G

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





Precision reached on Hydrogen

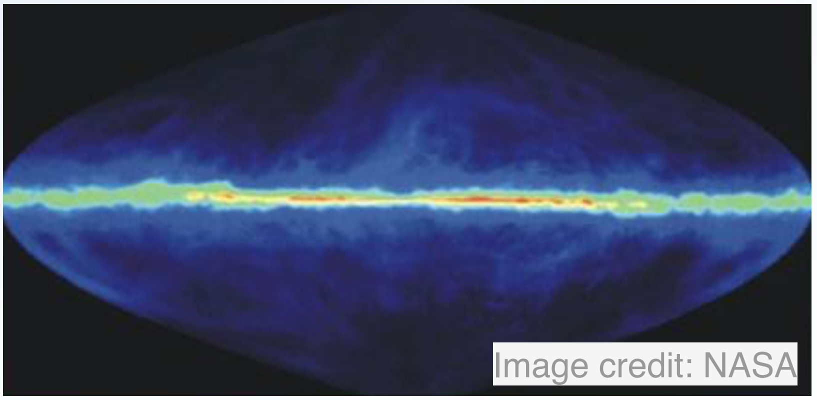
Recent measurements with $\bar{\mathrm{H}}$ and $\bar{\mathrm{p}}$

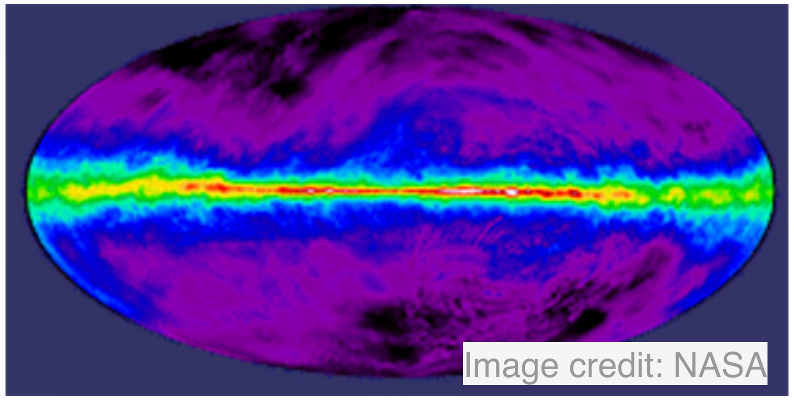
$$\nu_F = \frac{16}{3}\left(\frac{M_p}{M_p + m_e}\right)^3 \frac{m_e}{M_p} \frac{\mu_p}{\mu_N} \alpha^2 c R_y$$

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

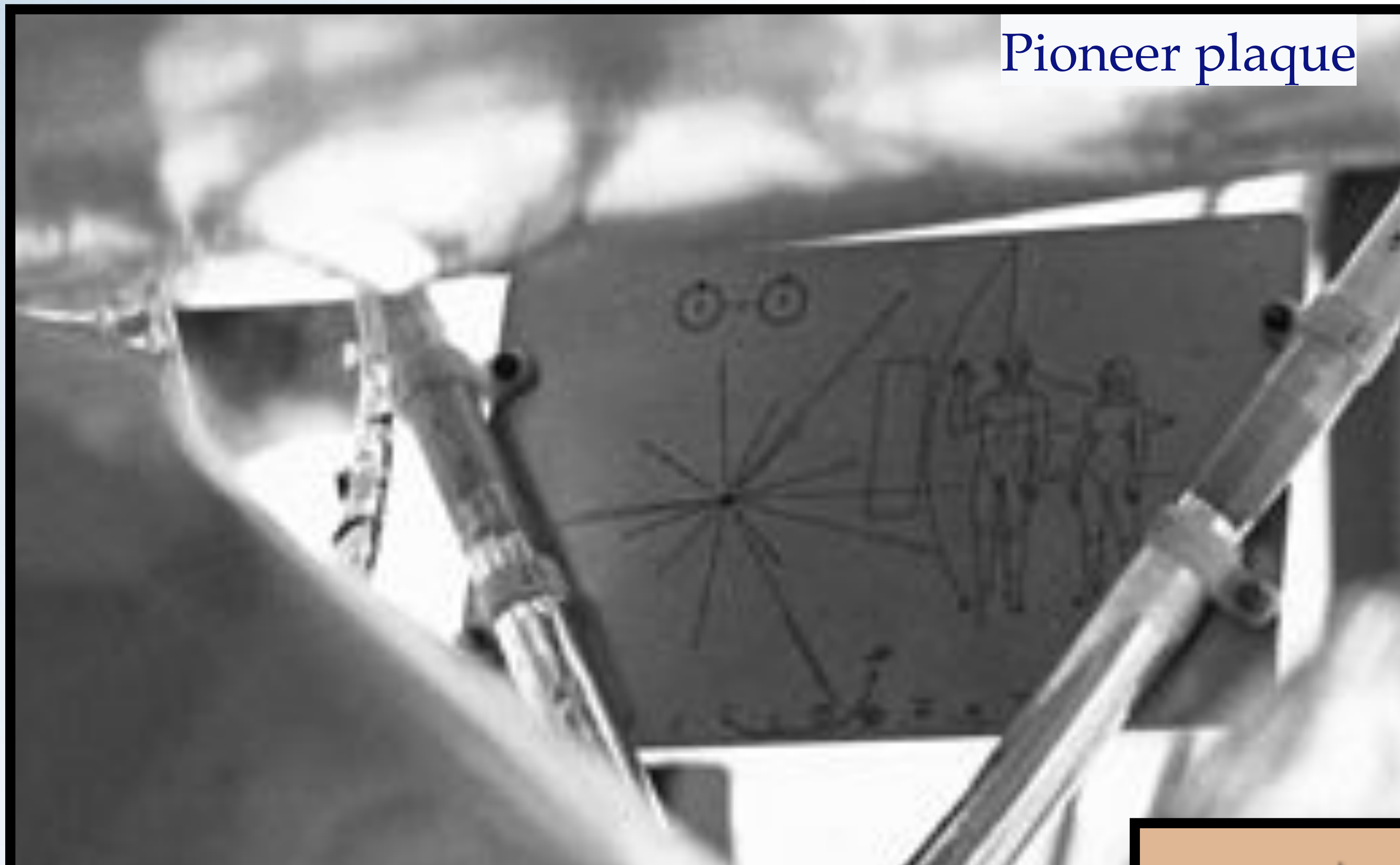
Hyperfine splitting

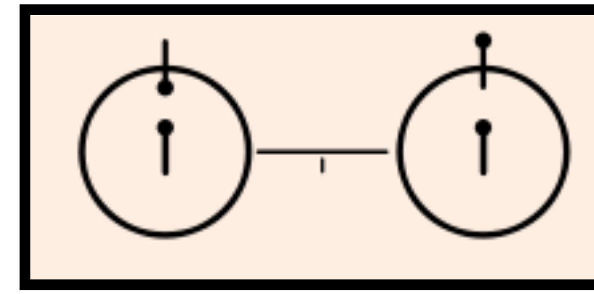
21cm line

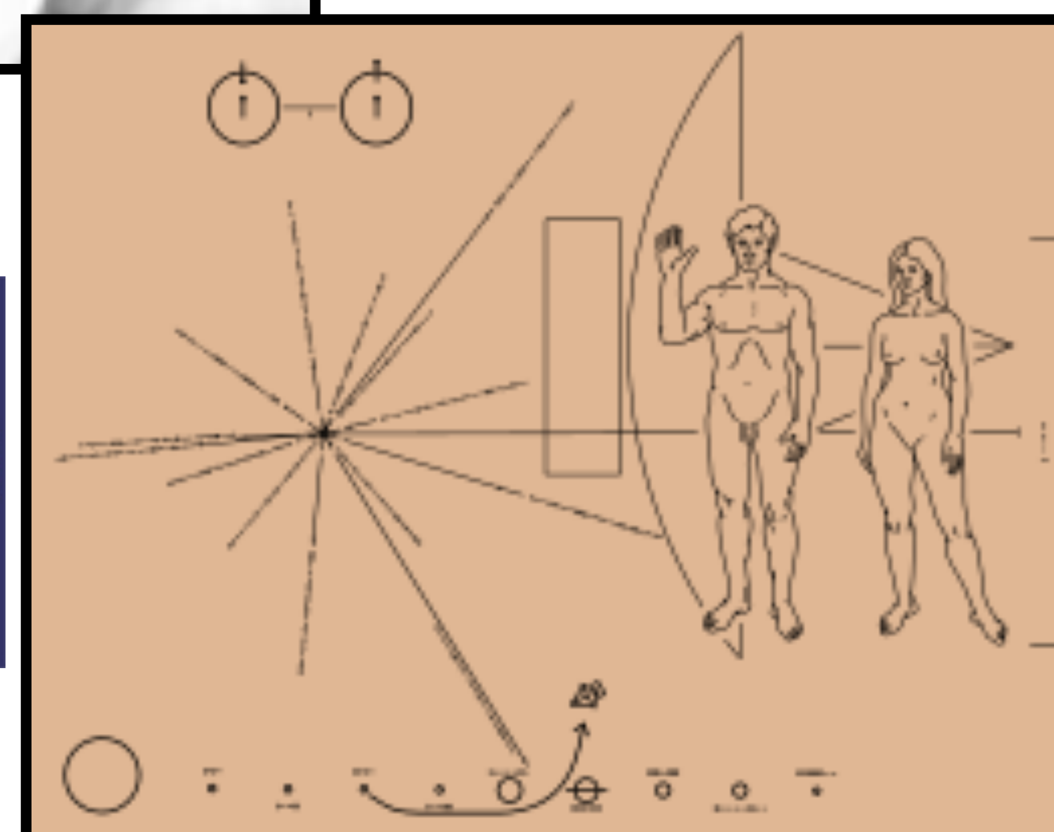




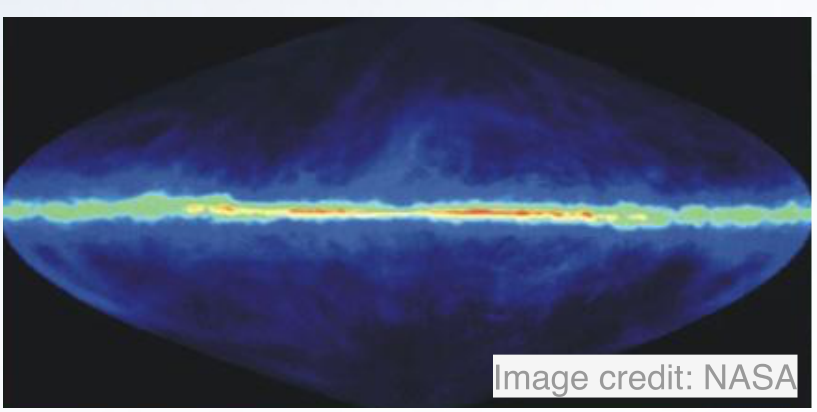
Hyperfine splitting

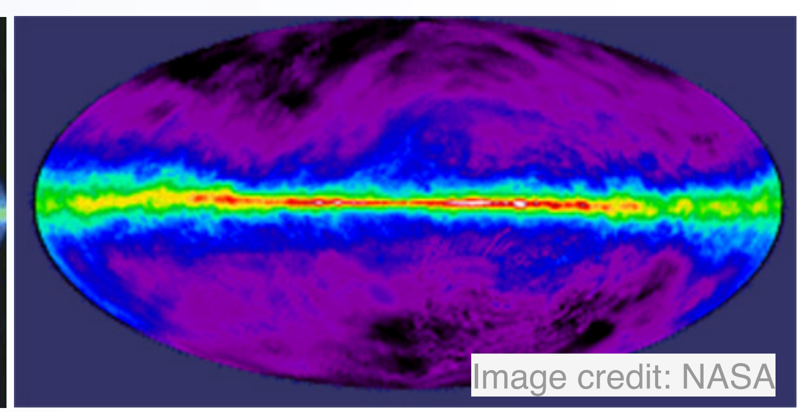






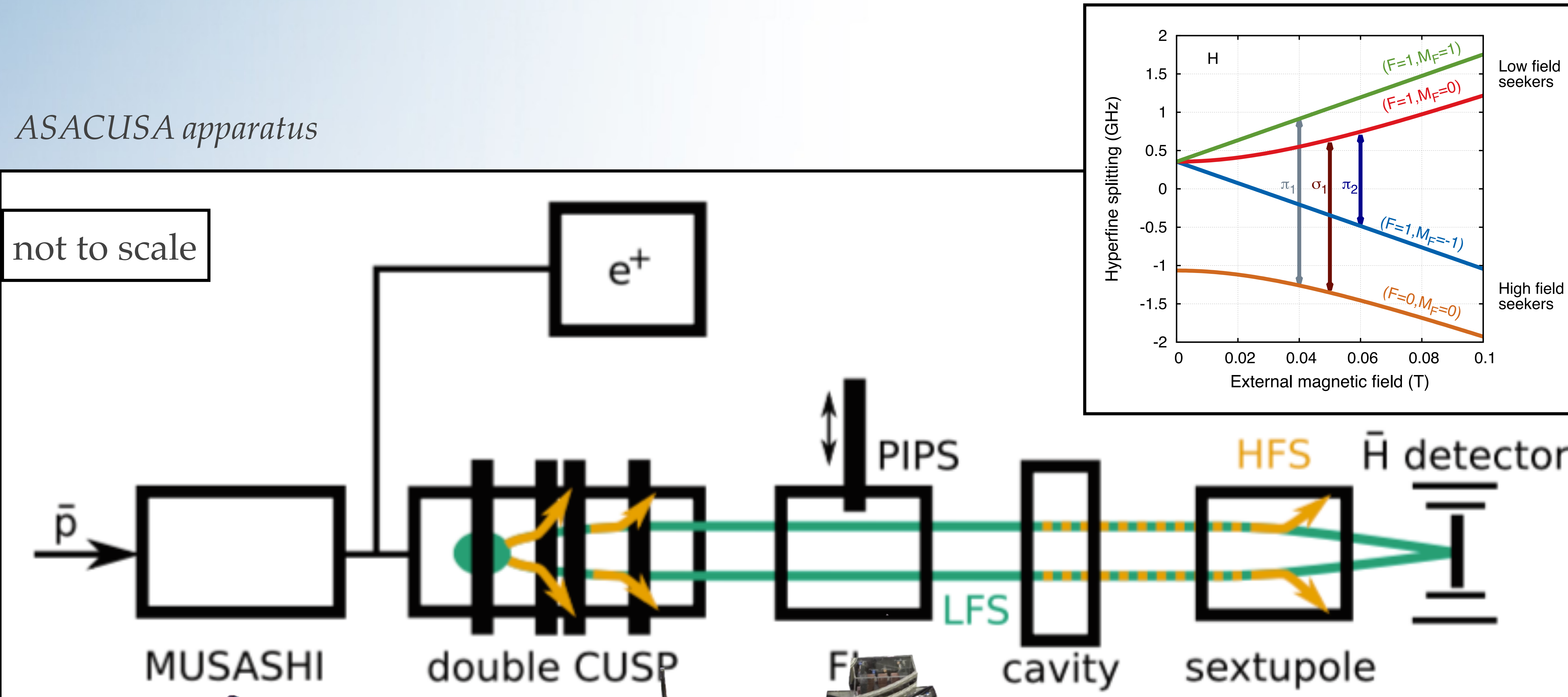
21cm line

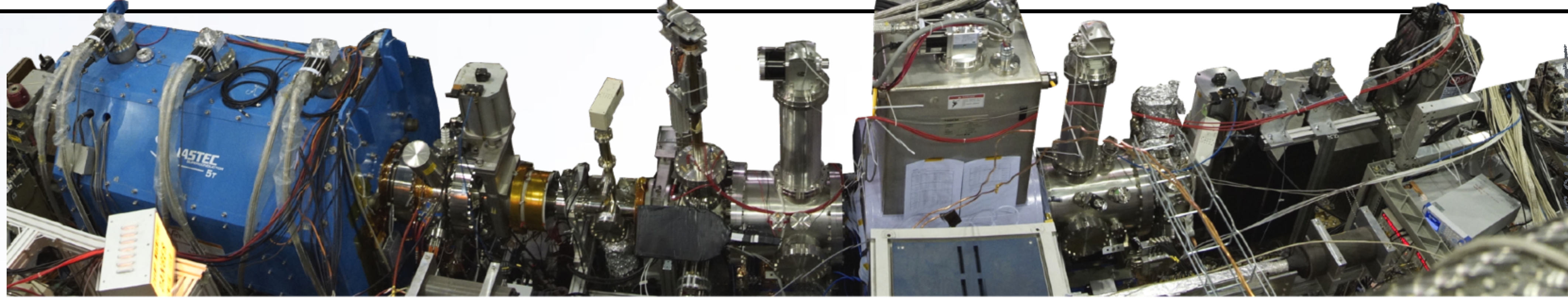


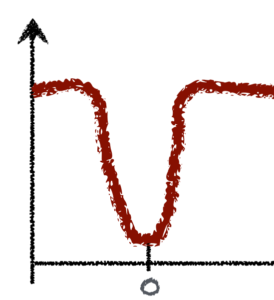


EXPERIMENTAL CONCEPTS

ASACUSA apparatus





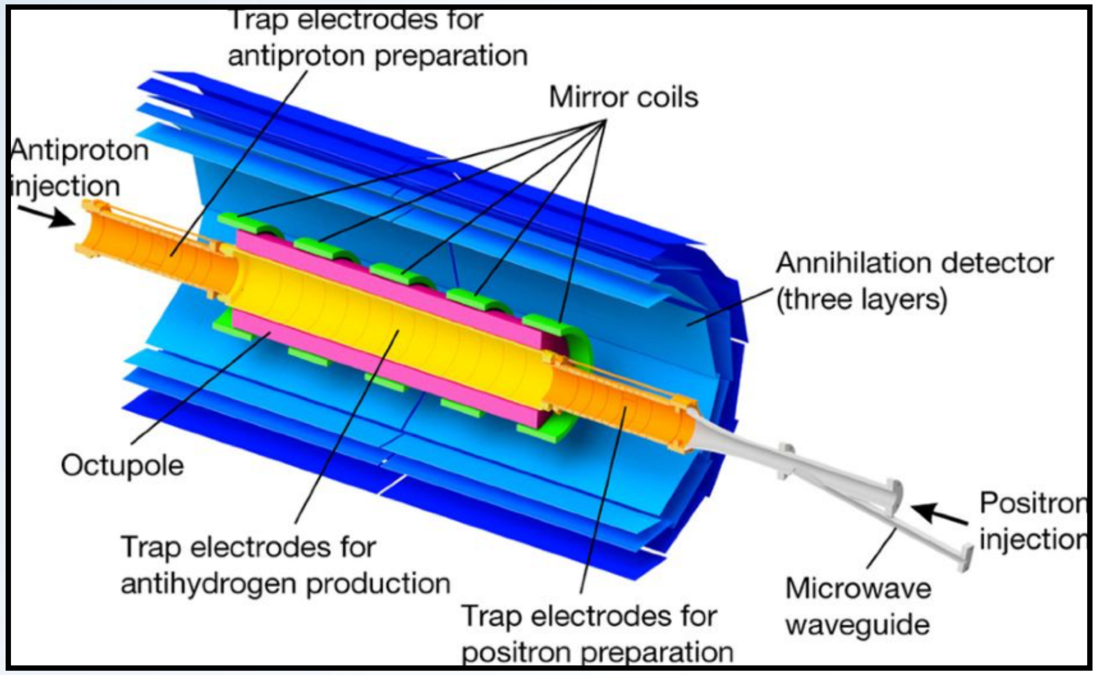


EXPERIMENTAL CONCEPTS

ALPHA-2 apparatus

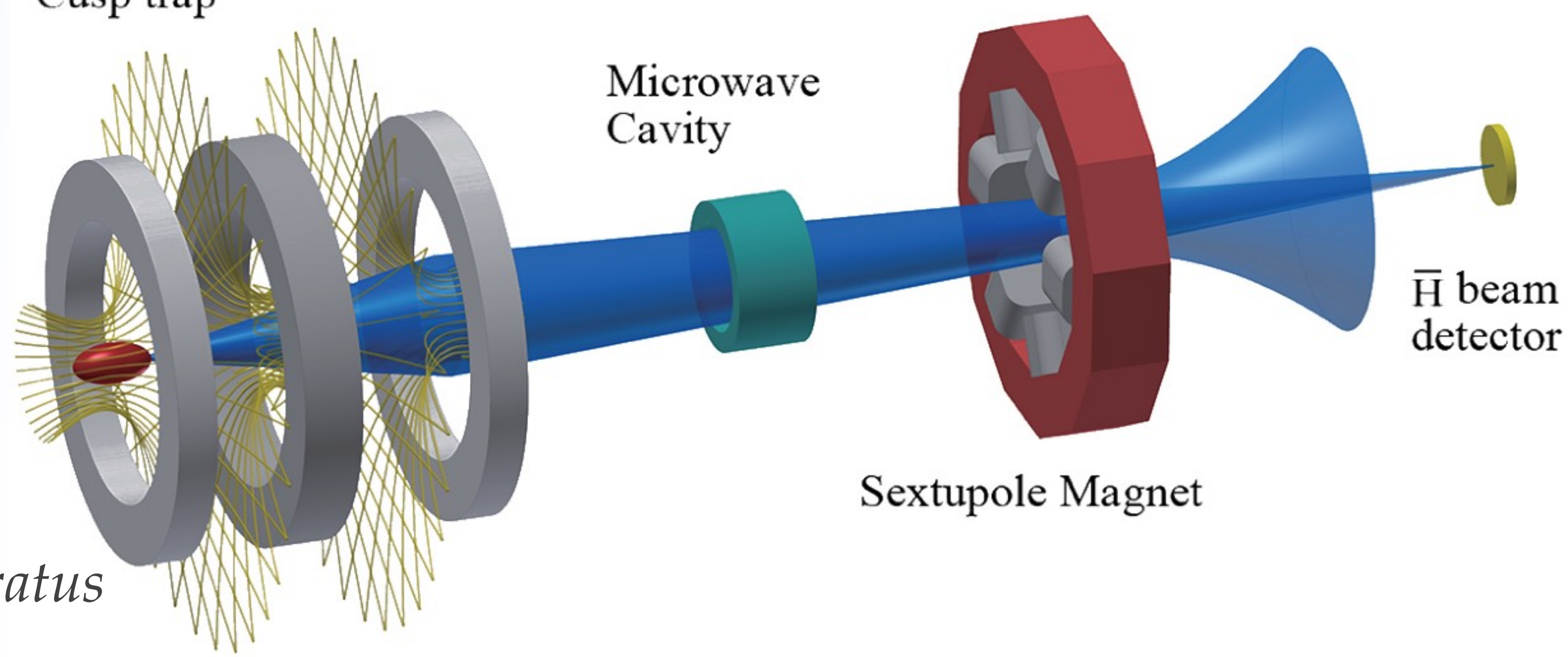
TRAP

$$kT = \mu(B - B_0)$$
$$\frac{\mu_B}{k} = 0.6\,\mathrm{K.T^{-1}}$$



BEAM

Vs.

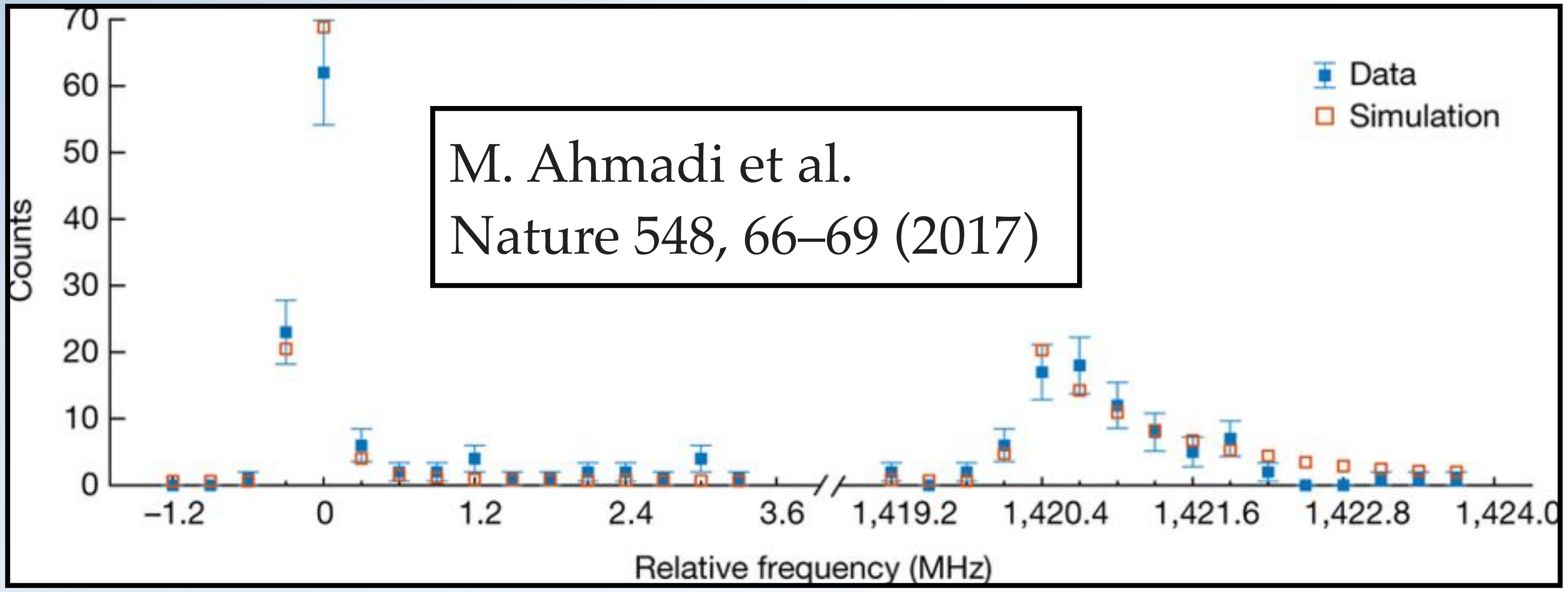


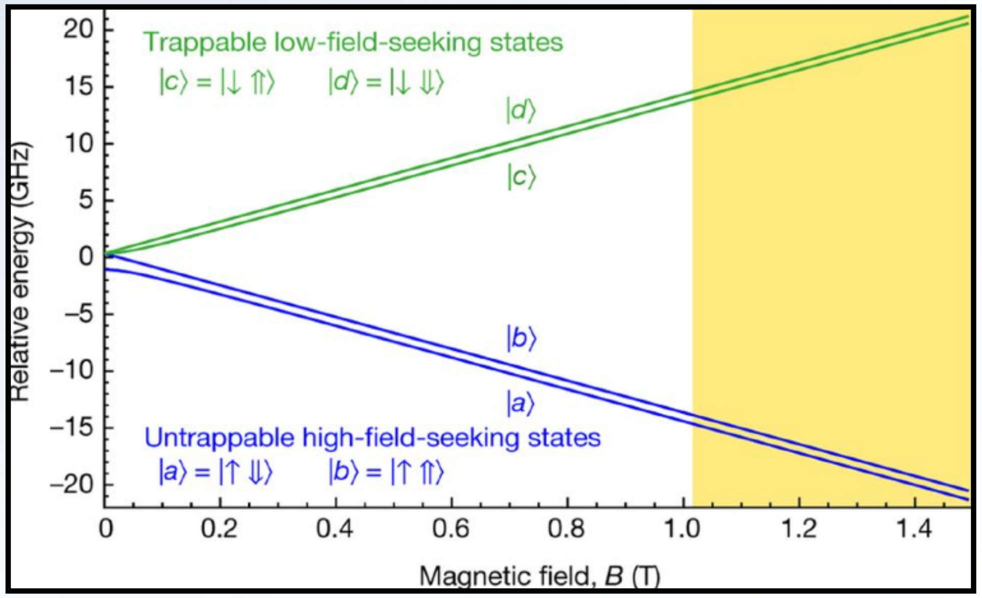
ASACUSA apparatus

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

In a TRAP:

Precision of ~ 500 kHz

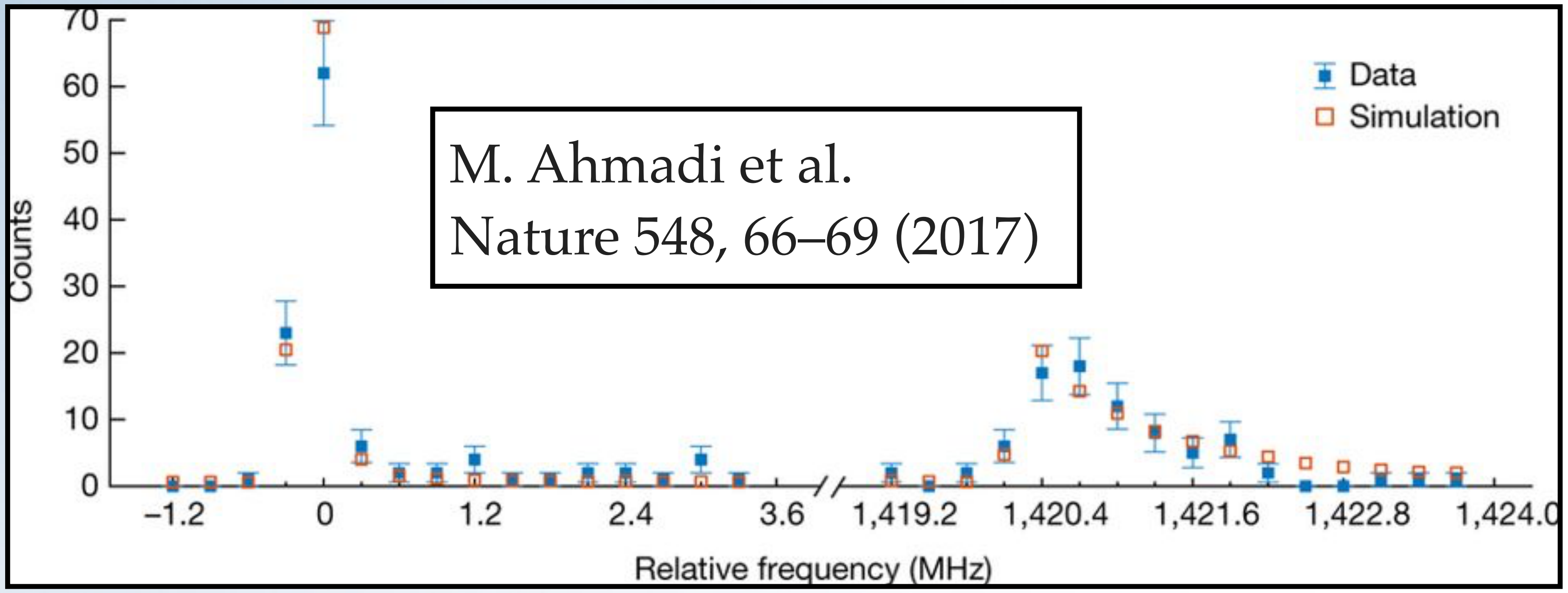




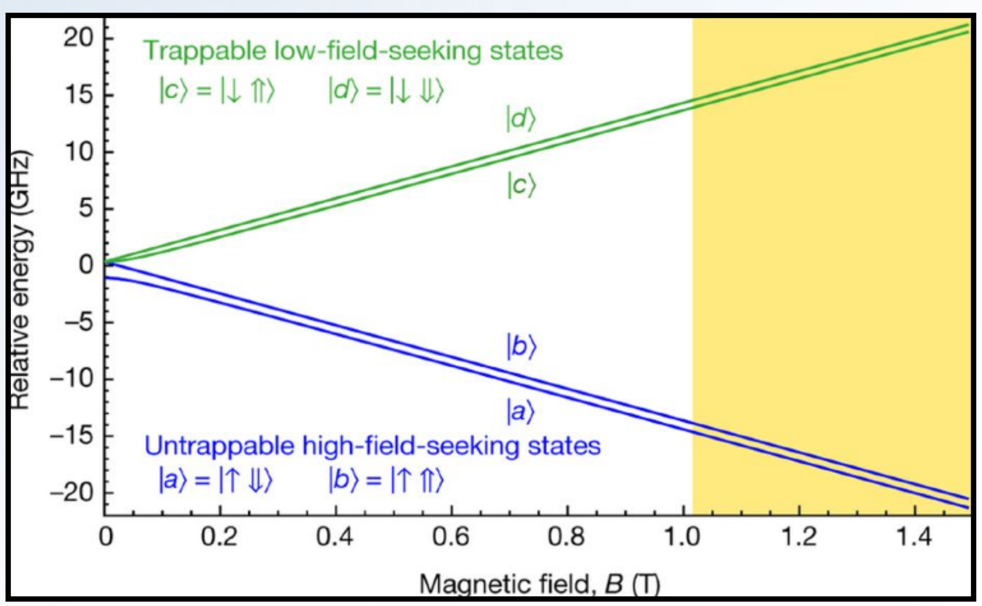
STATUS OF GS-HFS OF $\bar{H}$/H

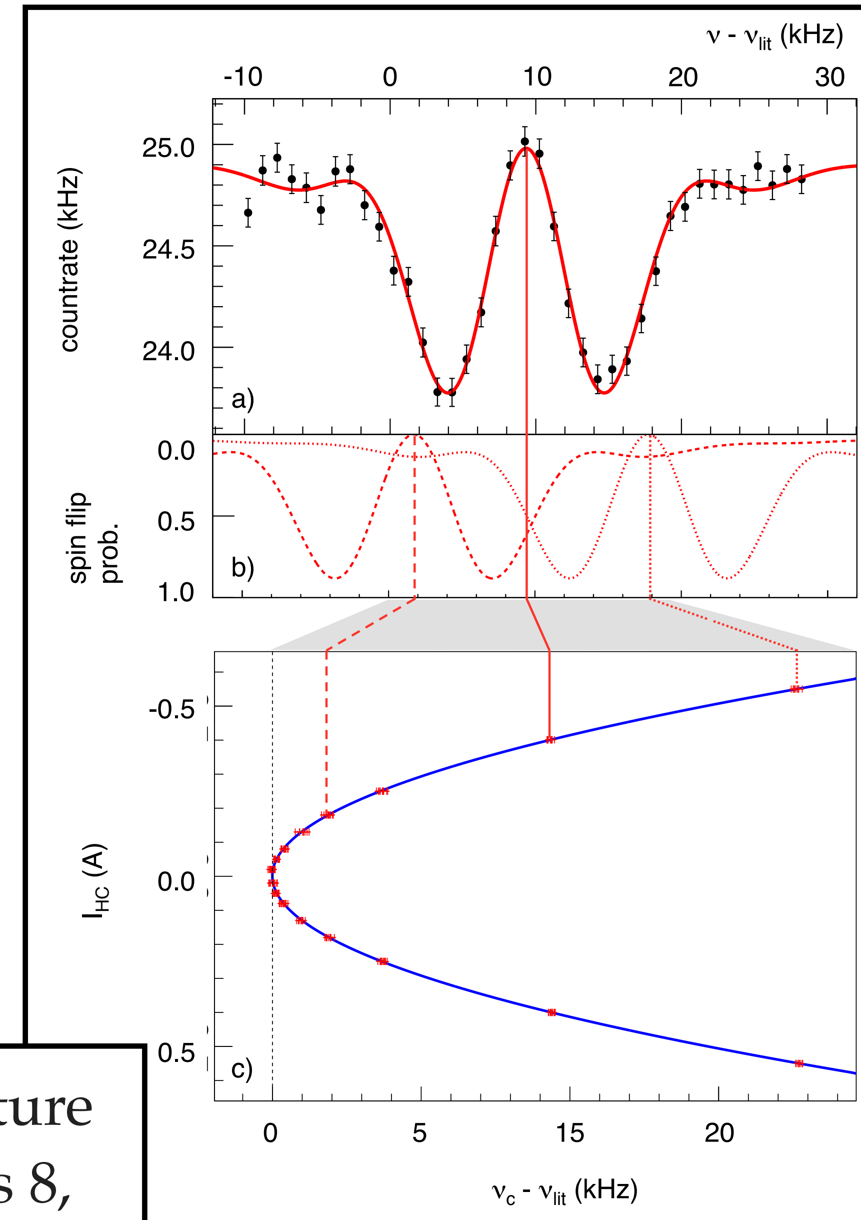
In a TRAP:
Precision of ~ 500 kHz

In a BEAM:
Precision of ~3Hz on HYDROGEN



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



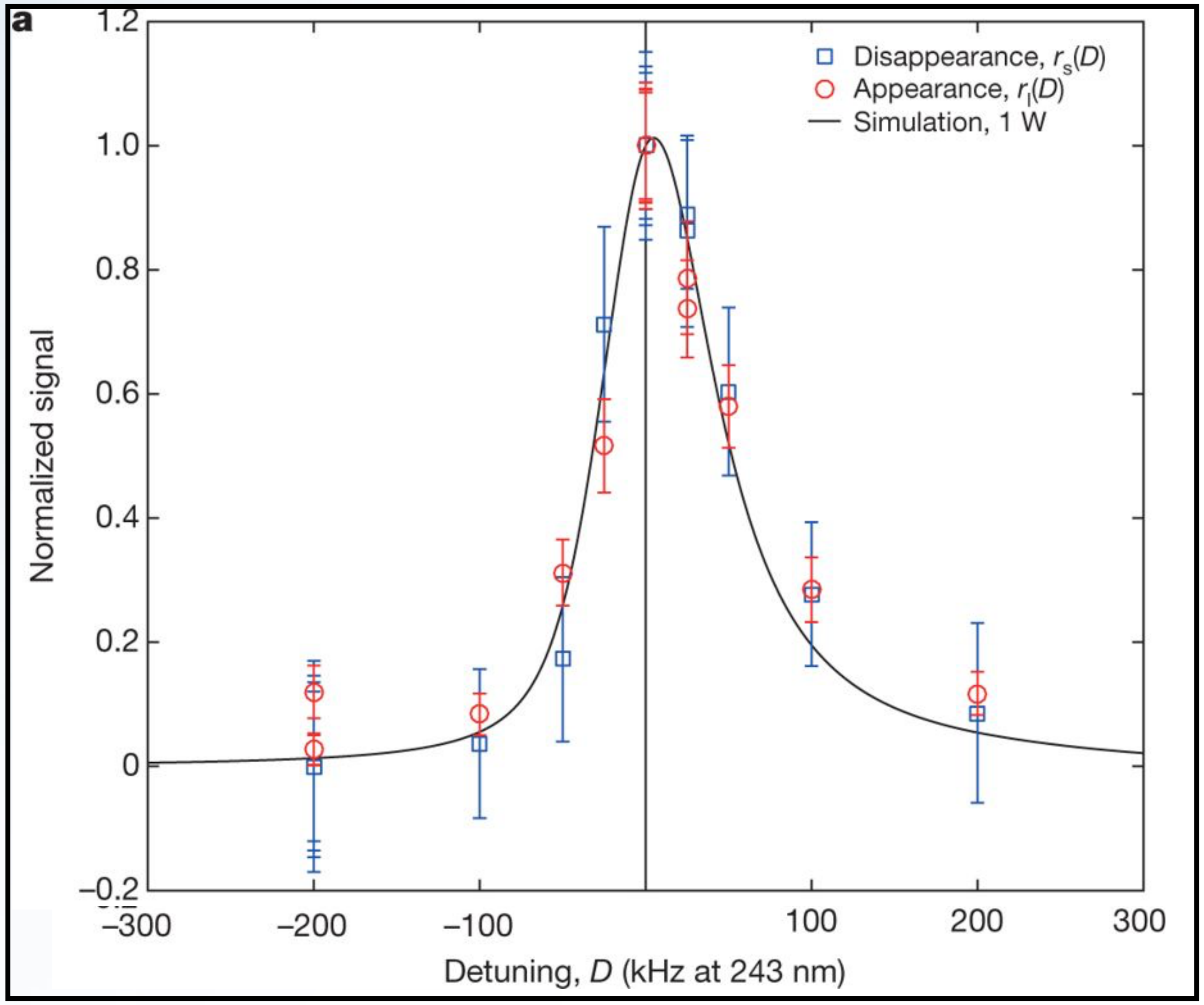


M. Diermaier et al. Nature Communications 8, 15749 (2017)

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

<u>Constraints for further precision</u>

- 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 $\bar{H}$

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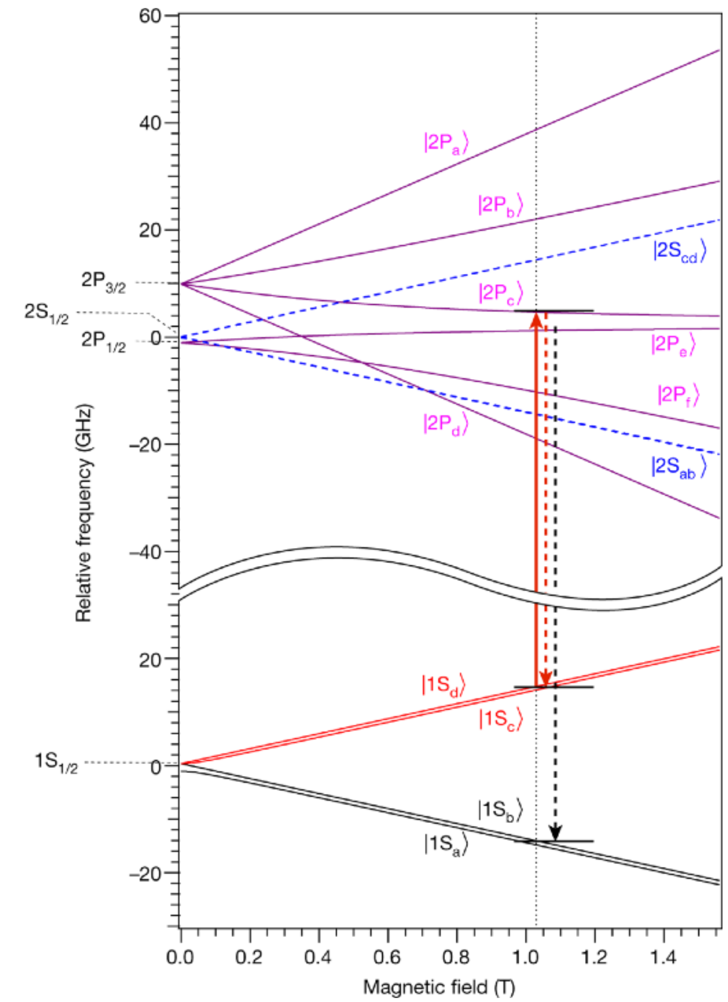
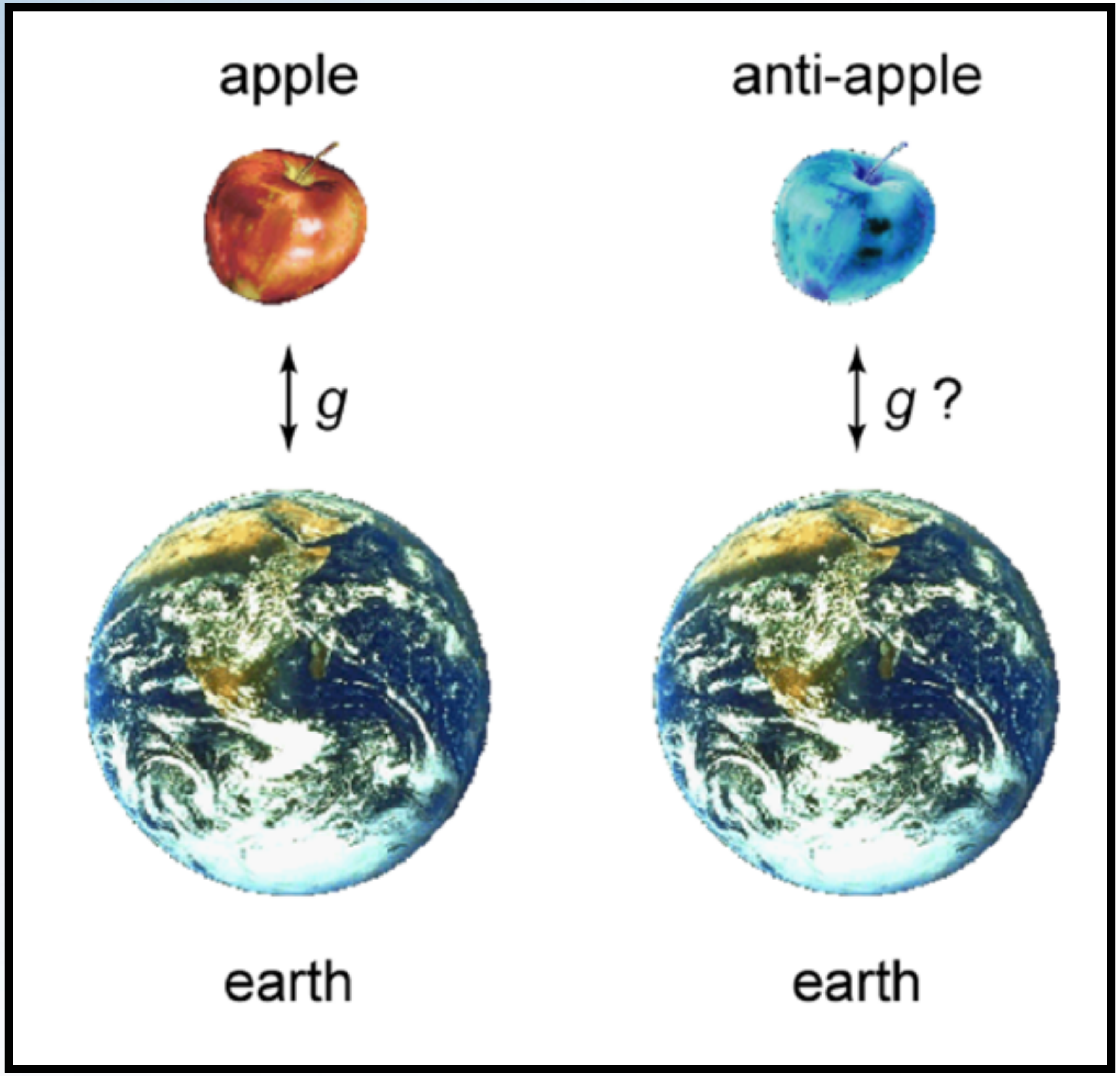
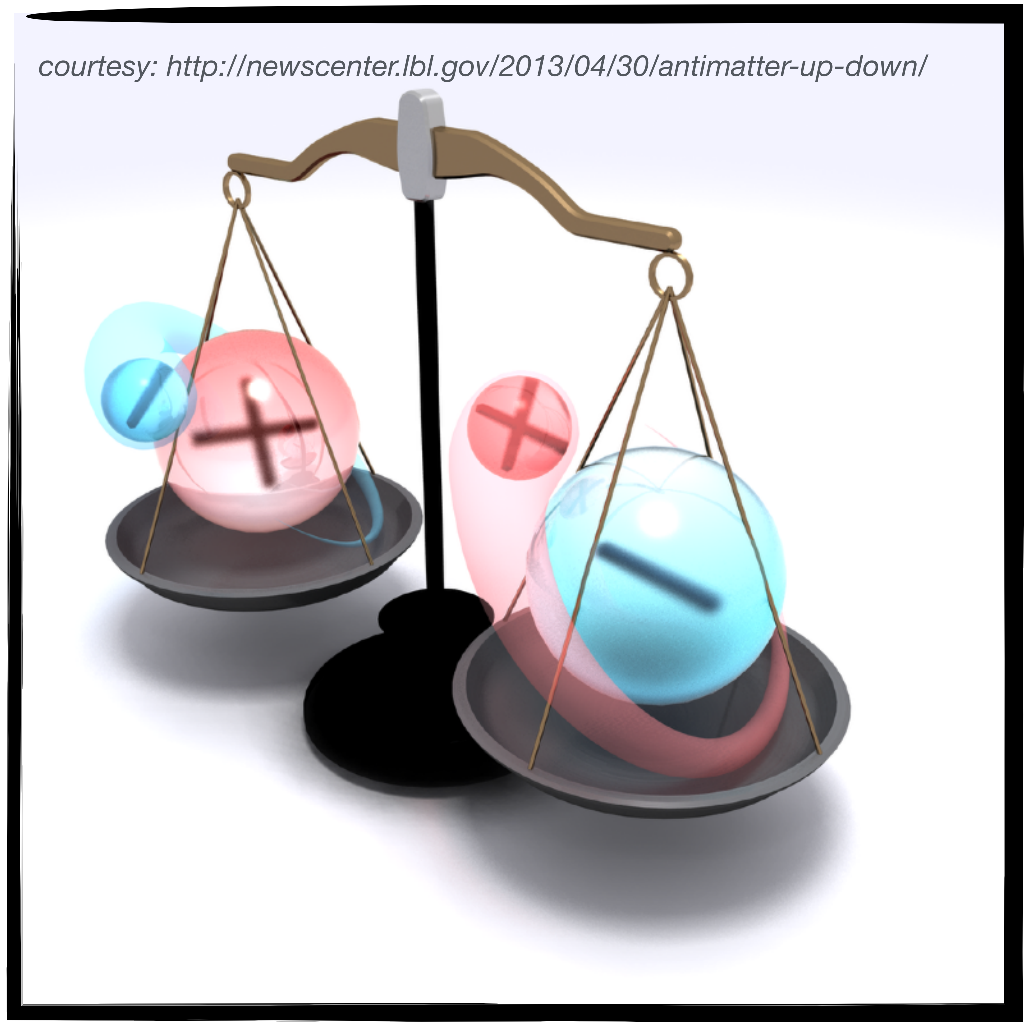


Observation of the 1S–2P Lyman-α transition in antihydrogen
M. Ahmadi et al., Nature 561, 211-215 (2018)

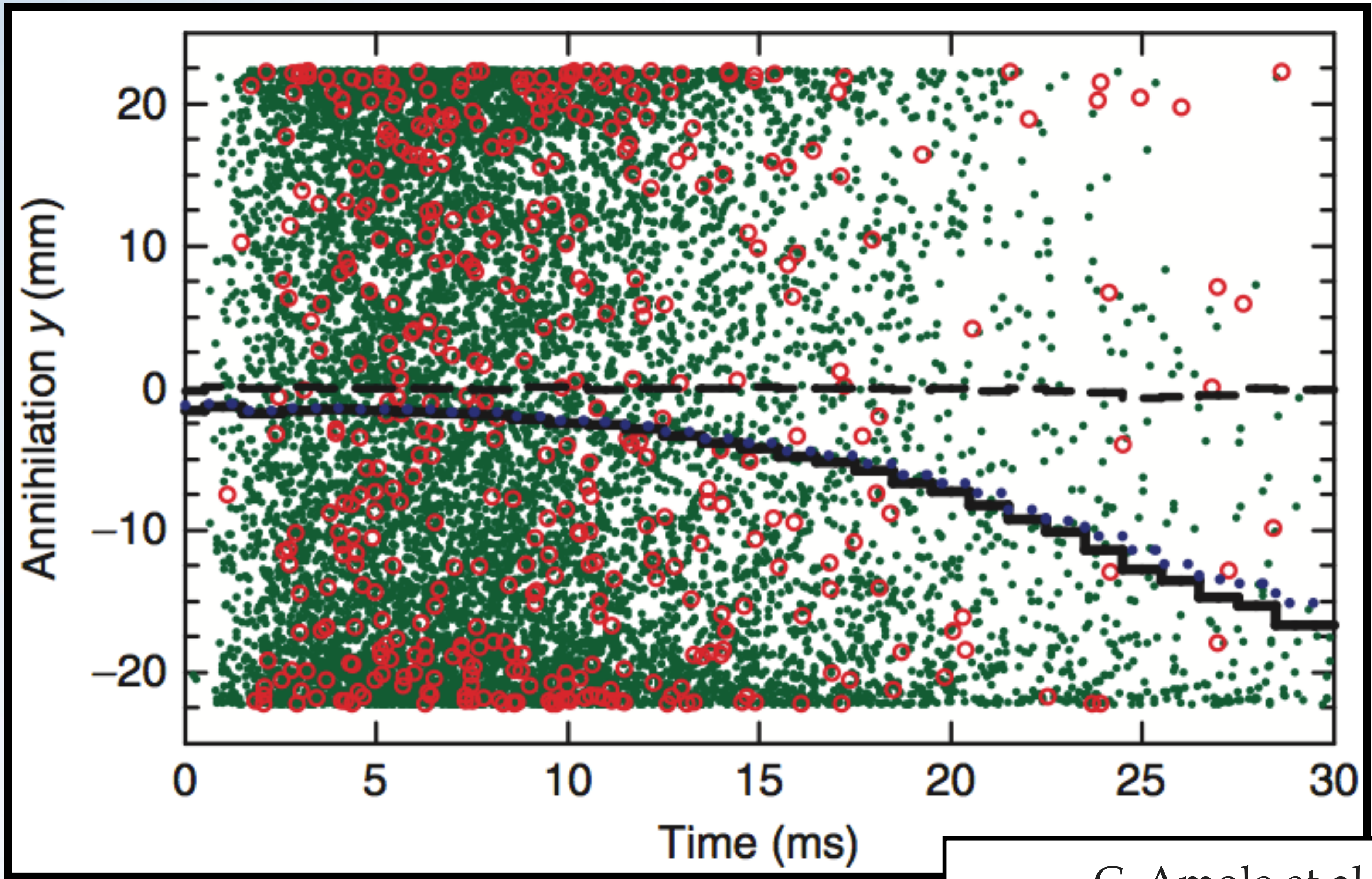
ON THE GRAVITY SIDE





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

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

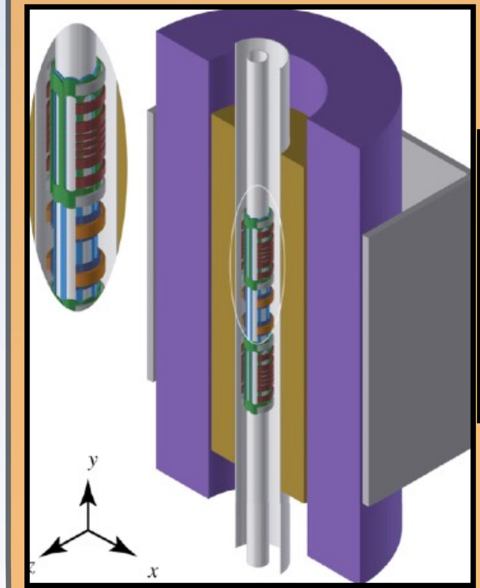
FUTURE GRAVITY GOALS

Plurality of approaches

VERTICAL TRAP

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

Sign measurement planned soon
1% targeted H̄ cooling to ~20 mK and advanced magnetometry



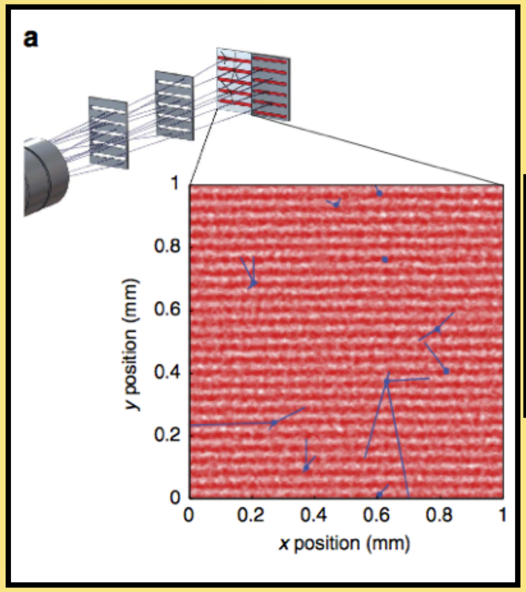
W. A. Bertsche
Phil. Trans. R. Soc. A 2018 376 20170265;
DOI: 10.1098/rsta.2017.0265. (2018)

ALPHA-G

H̄ BEAM

- Sensitivity to ~10 µm deflection needed
- cold antiproton translates in cold H̄ thanks to CE mechanism

Sign measurement targeted



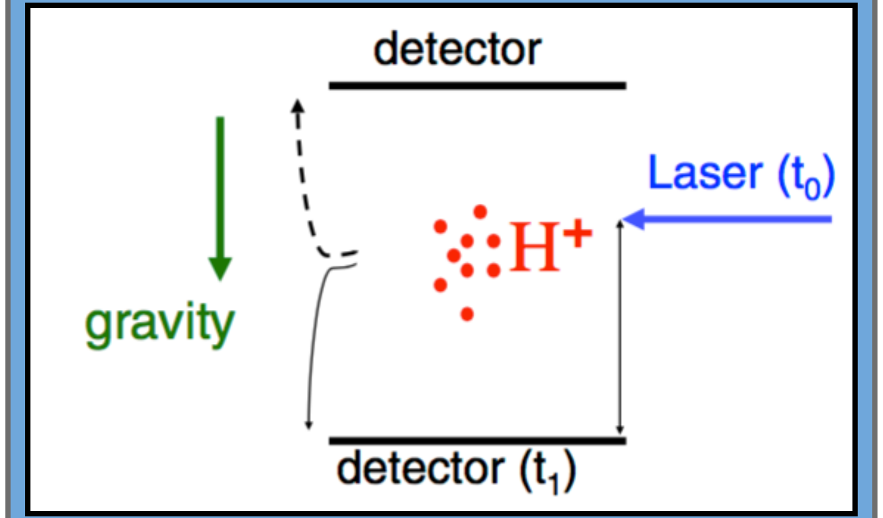
S. Aghion et al.
Nature Communications
5 (2014) 4538

AEGIS

H̄+ BEAM

- Cooling below 1 m/s : Sympathetic cooling of H̄+
- opens new horizons

1% measurement targeted



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

GBAR

ANTIPROTON EXPERIMENTS

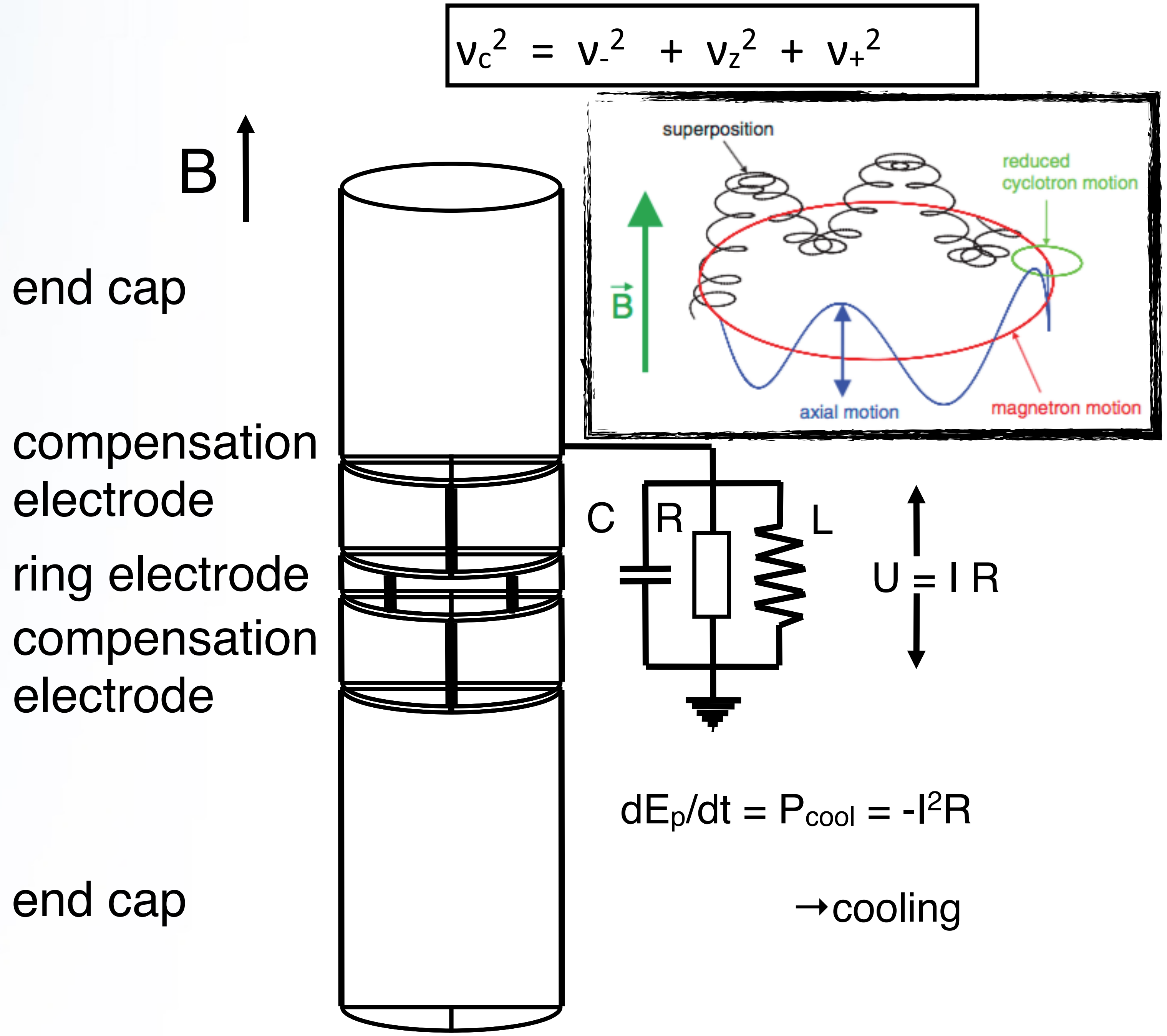
Inject antiprotons along magnetic field axis

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)

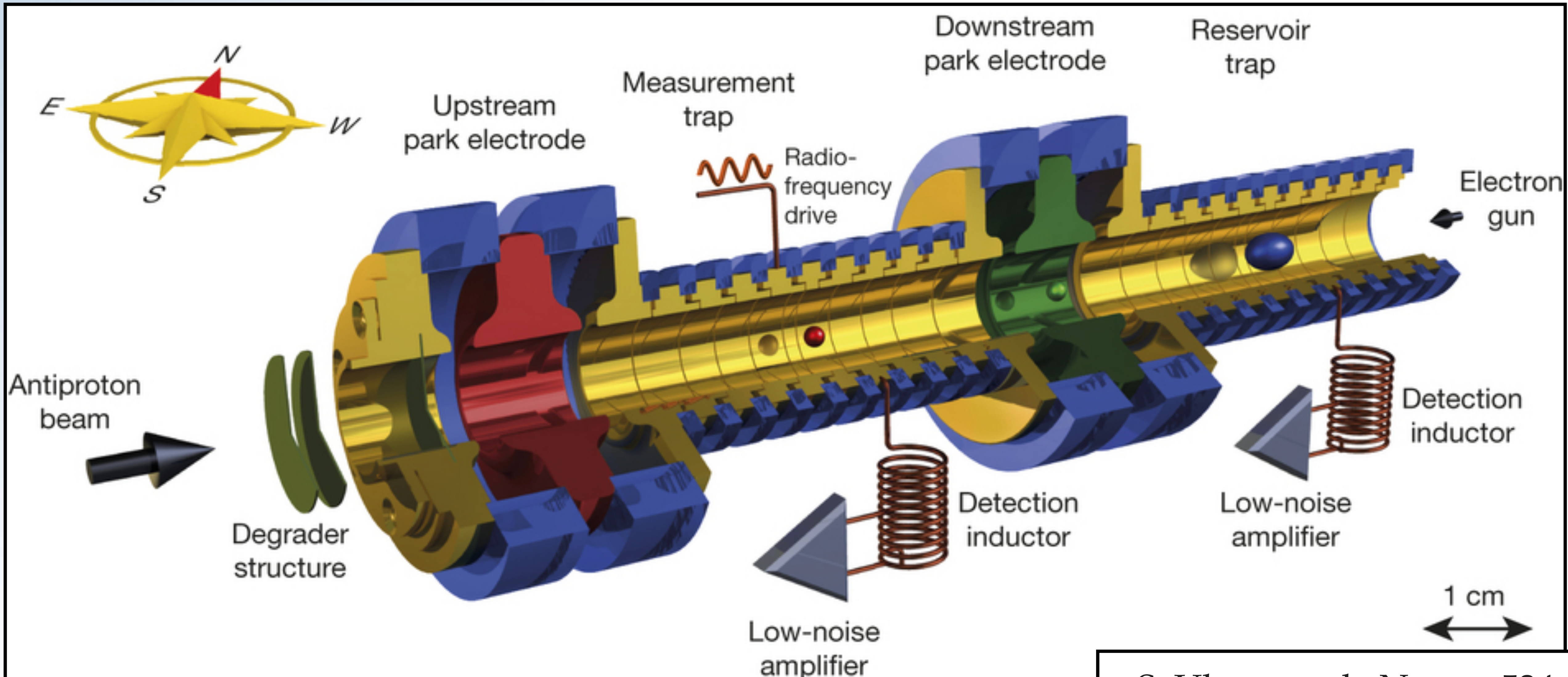


G. Gabrielse, W. Quint (LEAR)

ANTIPROTON EXPERIMENTS

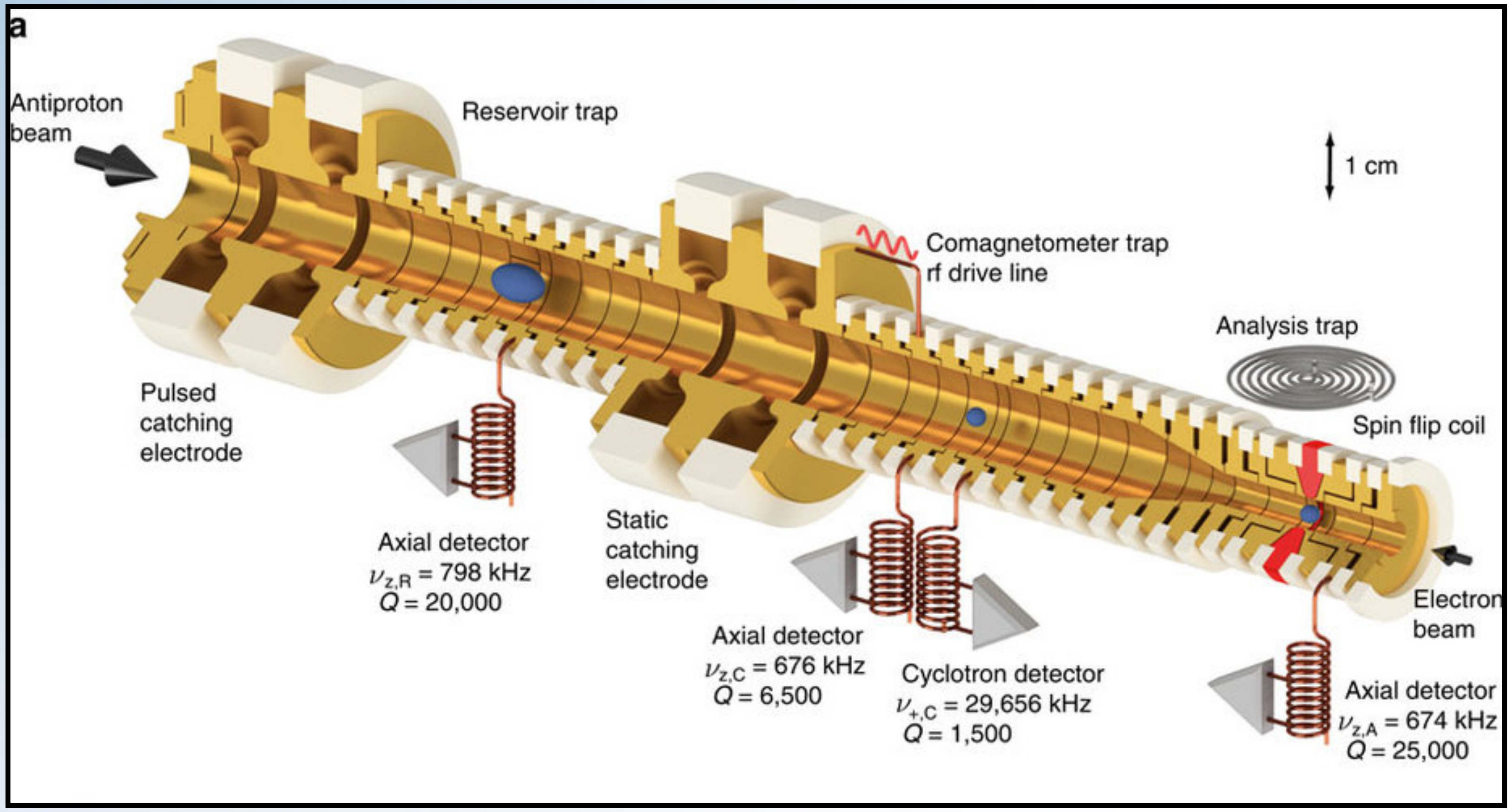
$$\nu_c = \frac{1}{2\pi}\frac{Q_{\bar{p}}}{M_{\bar{p}}}B$$

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



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

ANTIPROTON EXPERIMENTS



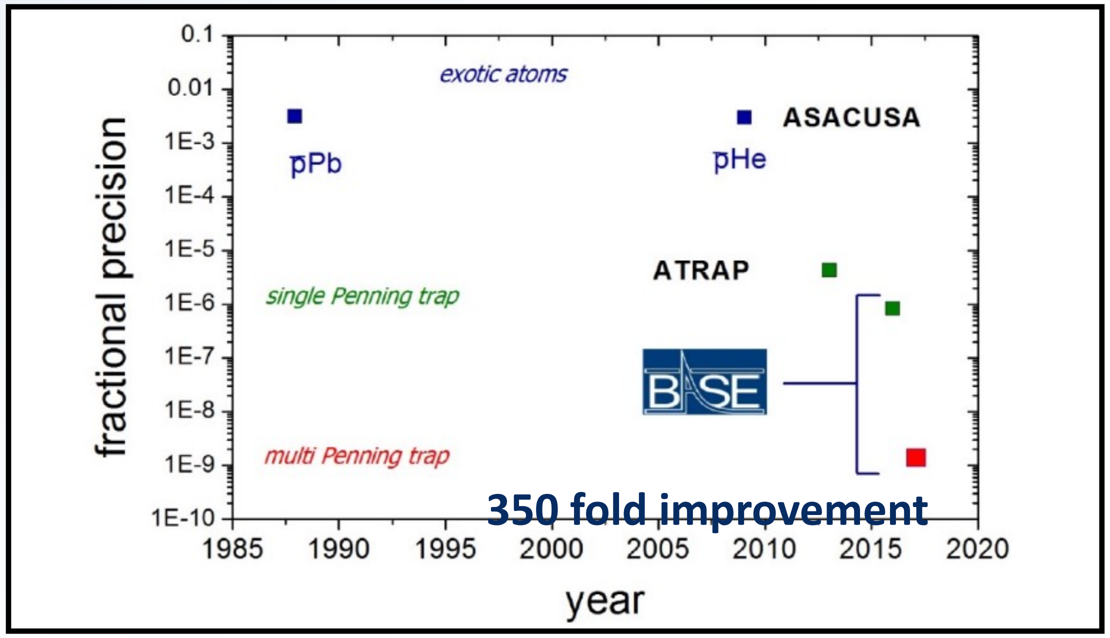
$$\frac{g_{p,\bar{p}}}{2} = \frac{\nu_L}{\nu_c} = \frac{\mu_{p,\bar{p}}}{\mu_N}$$

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

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

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

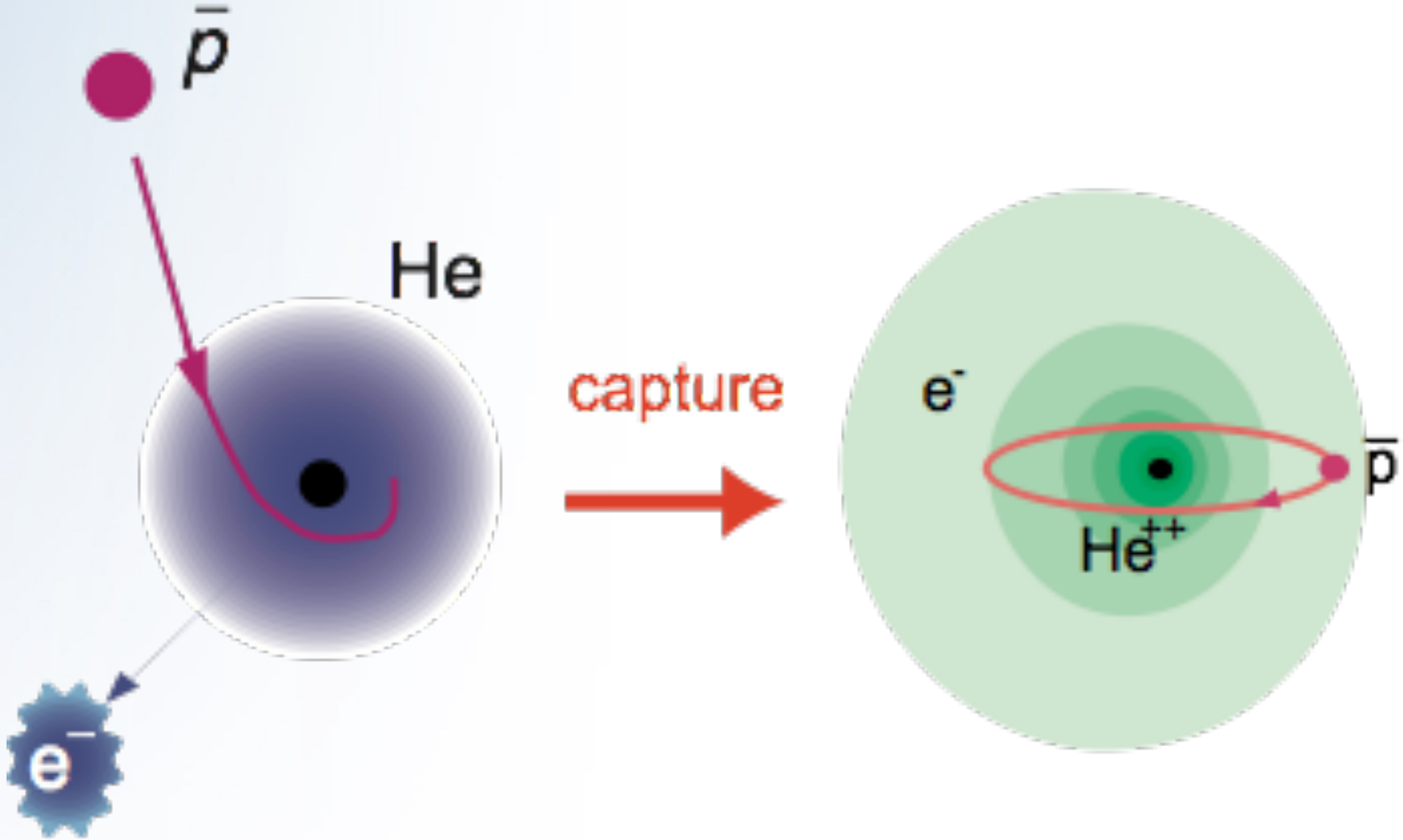
C. Smorra et al., Nature 550, 371 (2017)



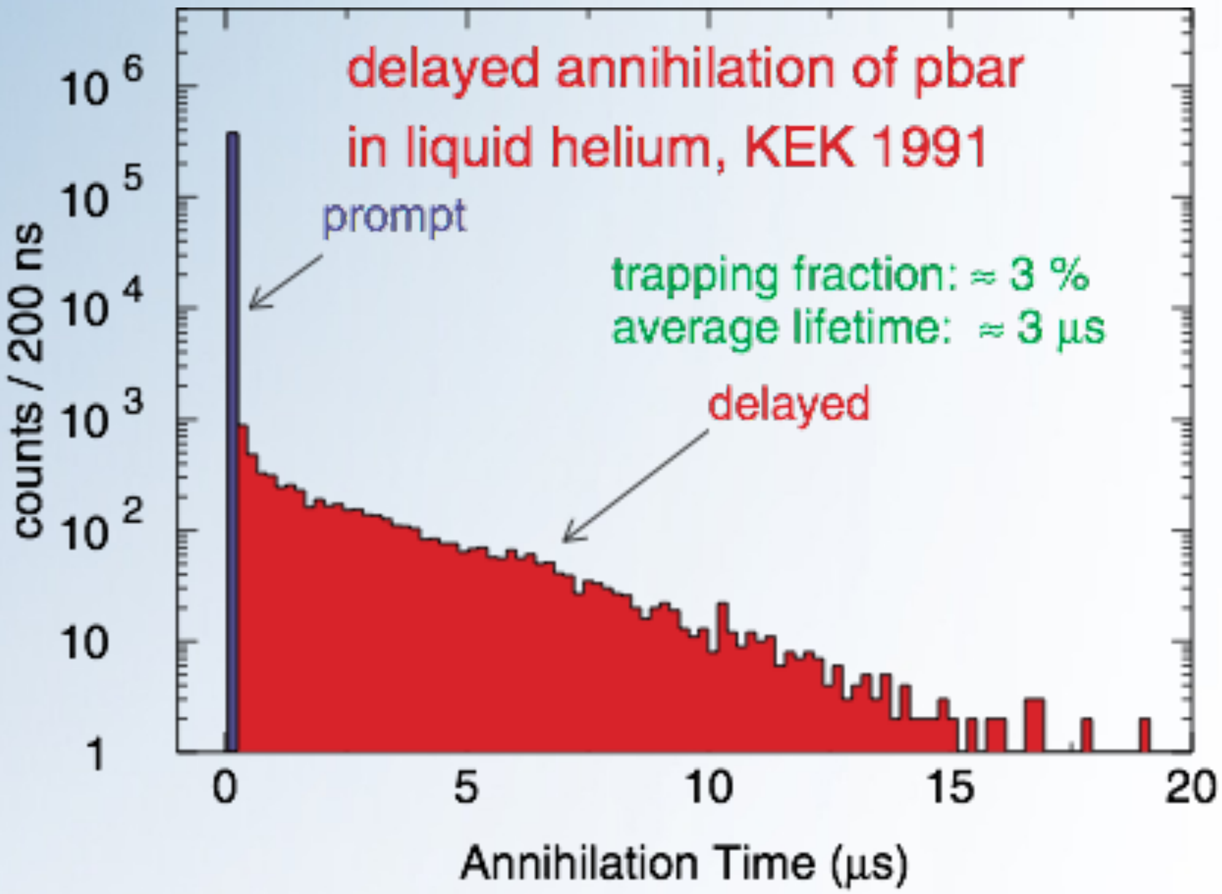
Previous work by the ATRAP collaboration Di Saccia et al. Phys. Rev. Lett. 110, 130801 (2013)

first measurement more precise for antimatter than for matter

ANTIPROTONIC HELIUM



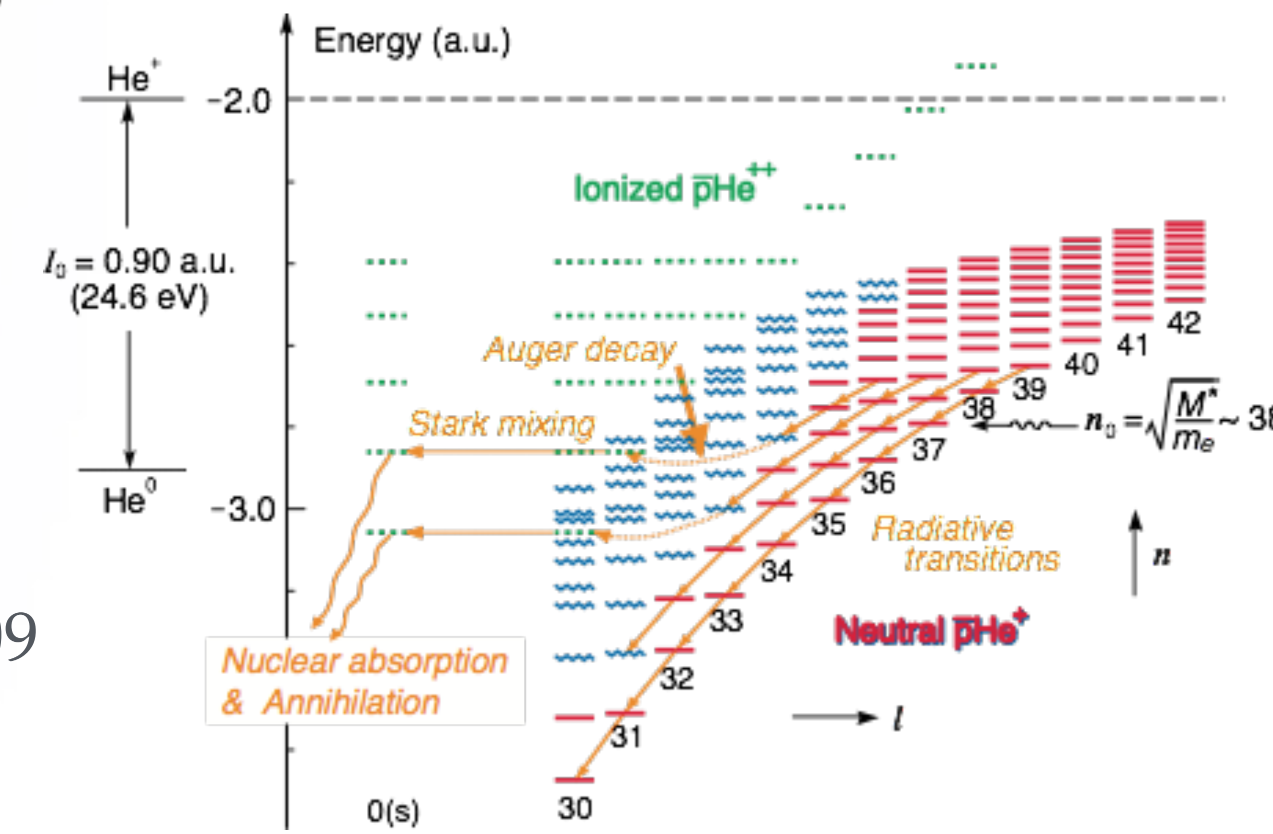
ANTIPROTONIC HELIUM



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

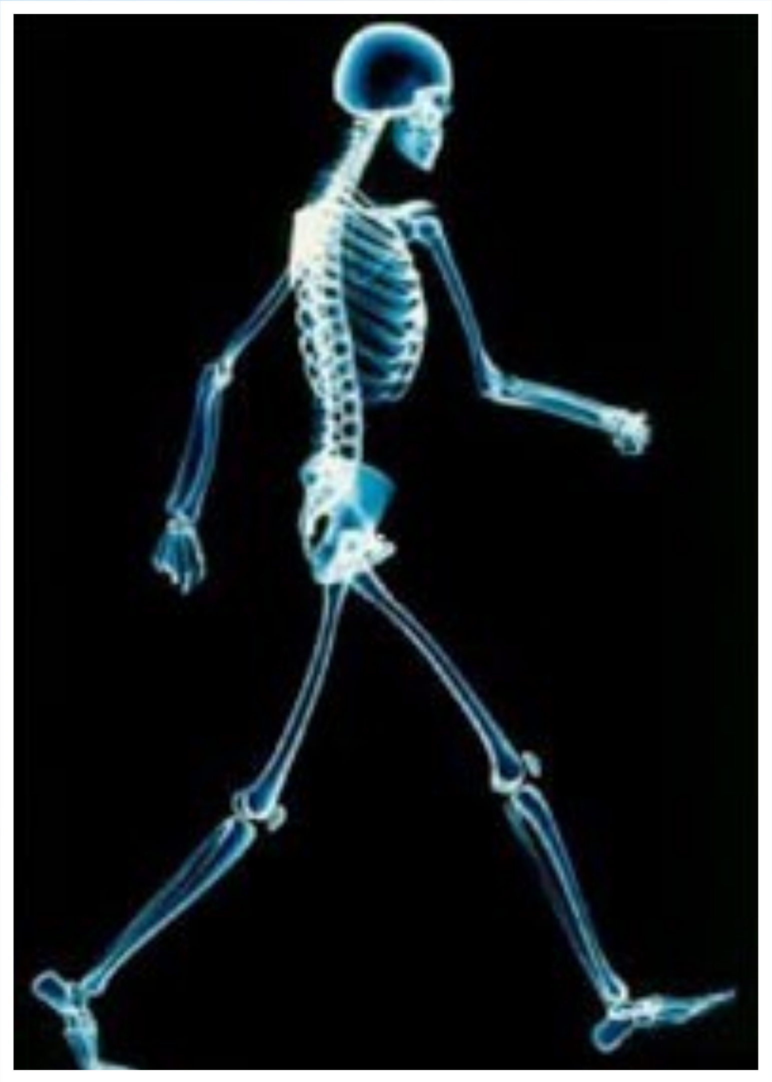
laser and microwave spectroscopy



CPT test
antiproton properties

mass,charge:	$7x10^{-10}$	2011
magnetic moment:	$2.9x10^{-3}$	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.

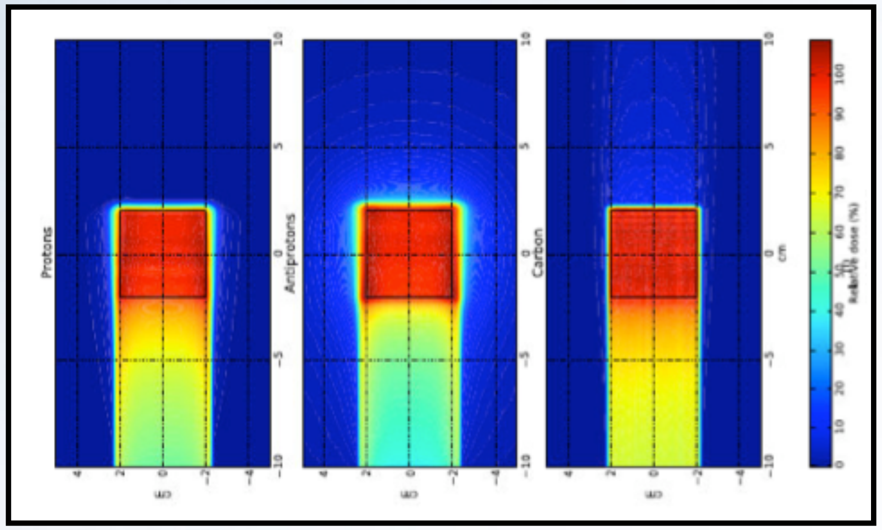
10 e+/s !

"DAILY" APPLICATIONS

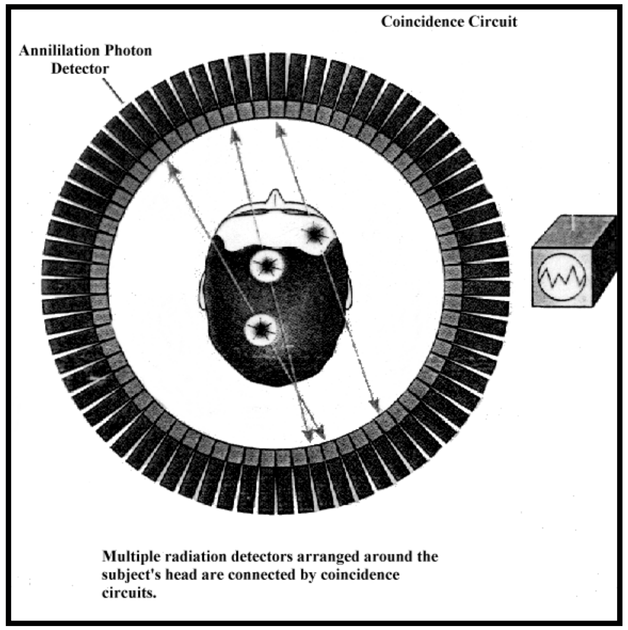
Antiprotons in accelerators!

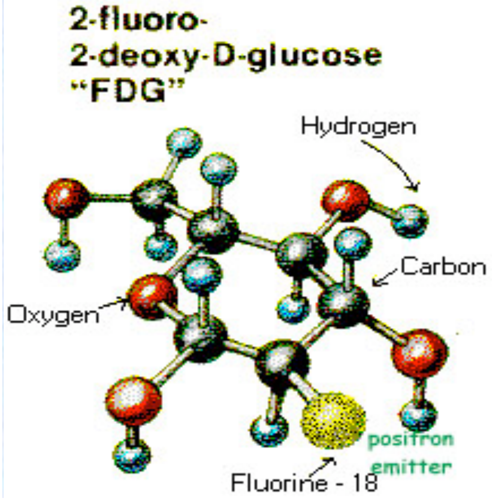
Antiprotons for nuclear studies (PUMA)

Antiproton Therapy



Medical imaging : PET





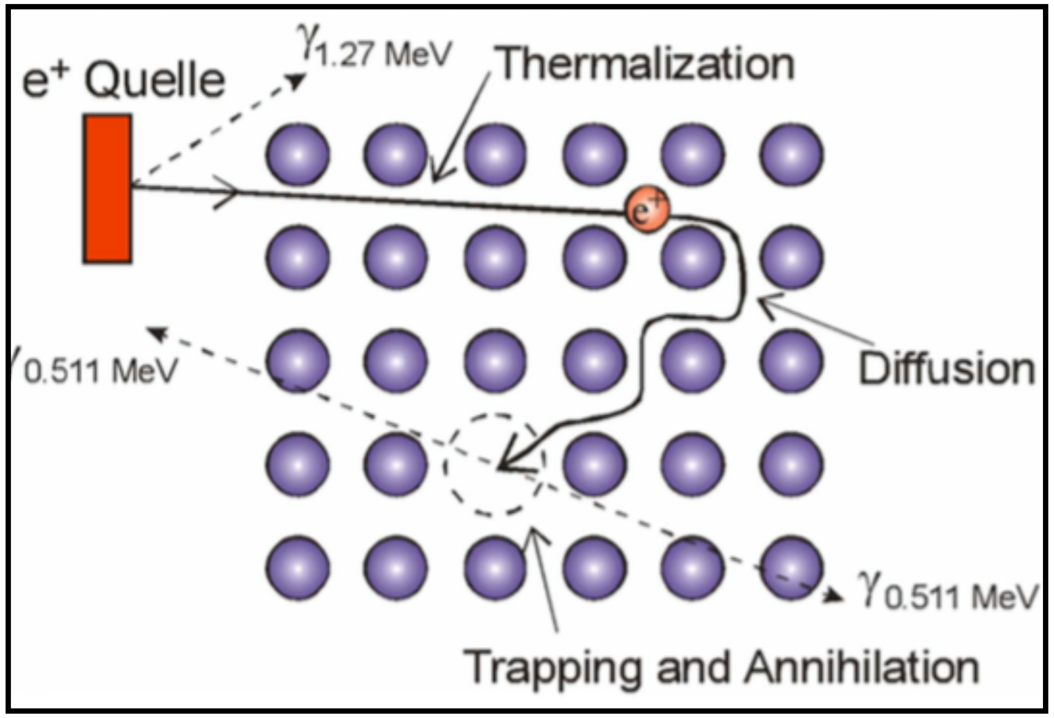
e+ emitting isotope (C-11, N-13, O-15)

(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 $\bar{p}$ ~ $6x10^{23}$

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

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

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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 €

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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

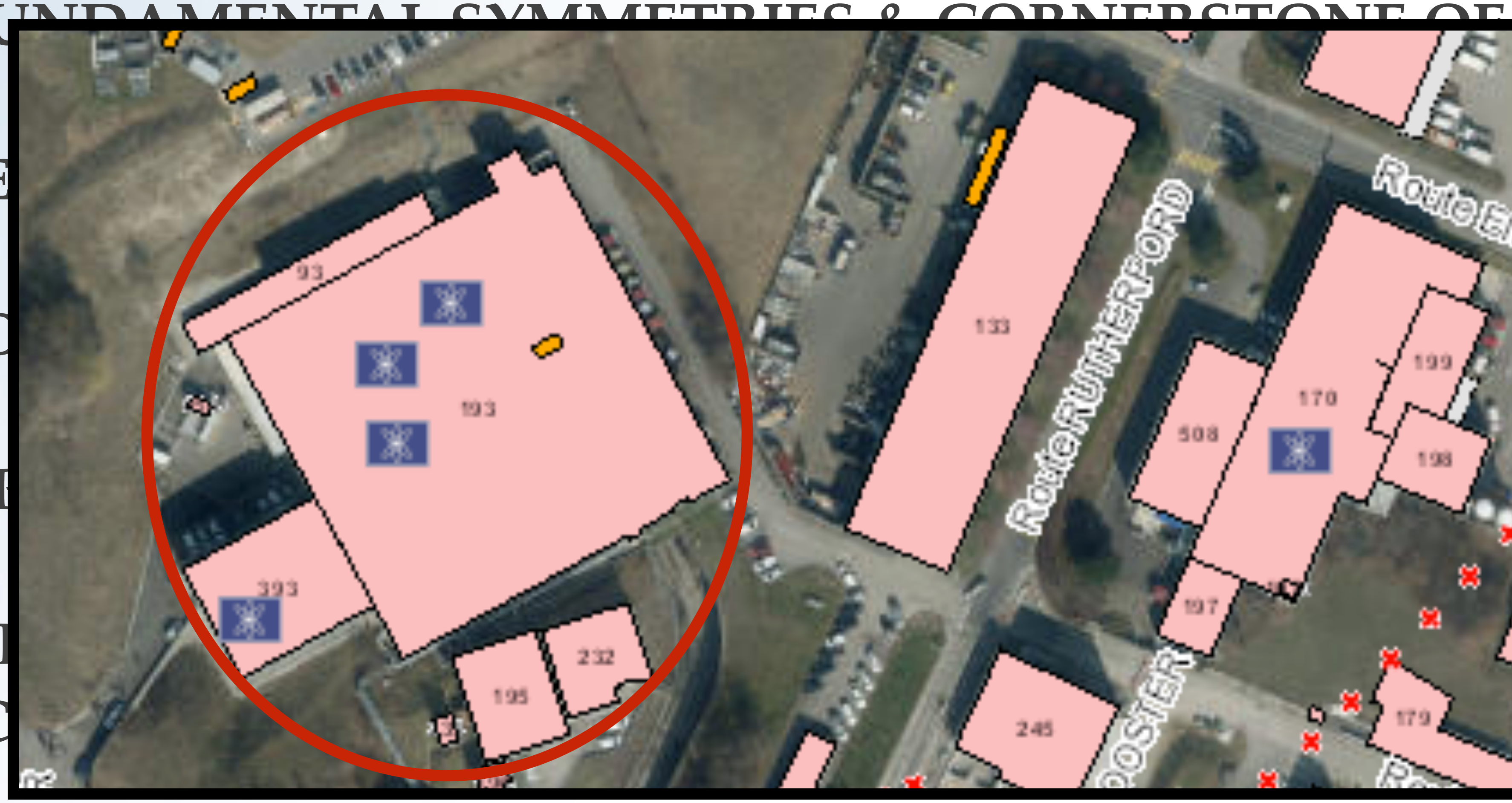
MANY OTHER IDEAS : CHARGE NEUTRALITY, PROTONIUM SPECTROSCOPY, PORTABLE PBAR TRAP …

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?

Question on L1

$$\pi^- + p \rightarrow \Lambda + K^0$$

E_{min} ~ 0.91 GeV

K^0 :	$(d\bar{s})$	$S = +1$
$\bar{K}^0$:	$(s\bar{d})$	$S = -1$

$$\pi^+ + p \rightarrow K^+ + \bar{K}^0 + p$$

E_{min} ~ 1.5 GeV

Question on L1

$$\pi^- + p \to \Lambda + K^0$$

E_{min} ~ 0.91 GeV

$$\pi^+ + p \to K^+ + \bar{K}^0 + p$$

E_{min} ~ 1.5 GeV

$$K^0 : \quad (d\bar{s}) \quad S = +1$$
$$\bar{K}^0 : \quad (s\bar{d}) \quad S = -1$$

CPLEAR

$$p\bar{p} \to K^- \pi^+ K^0$$

B ~ 0.2 %

$$p\bar{p} \to K^+ \pi^- \bar{K}^0$$