Recent highlights and prospects at the Antiproton Decelerator

Chloé Malbrunot
CERN

THE AD COMMUNITY

BASE

ALPHA

GBAR

ASACUSA

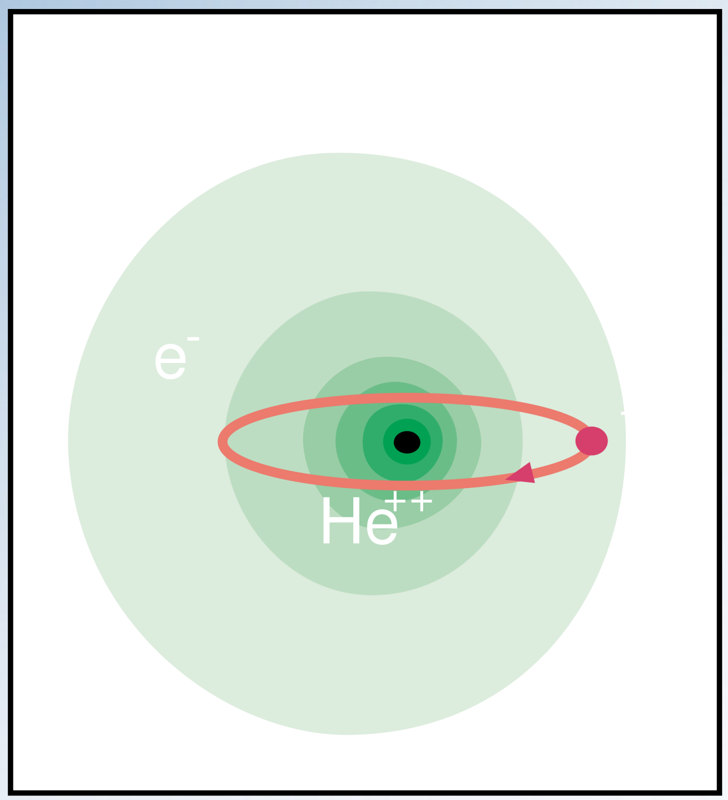
AEGIS

University of Bergen
University of Brescia
CERN, Geneva
University of Genova
Heidelberg University
Max Planck Institute for Nuclear Physics, Heidelberg
University of Trento
University of Lyon
University of Milano
Politecnico di Milano
Institute of Nuclear Research of the Russian Academy of Science, Moscow
University of Oslo
Lab. Aime' Cotton Orsay
University of Pavia
Czech Technical University, Prague
INFN Sections of Genova, Milano, Padova, Pavia, Trento
Stefan Meyer Institute, Vienna

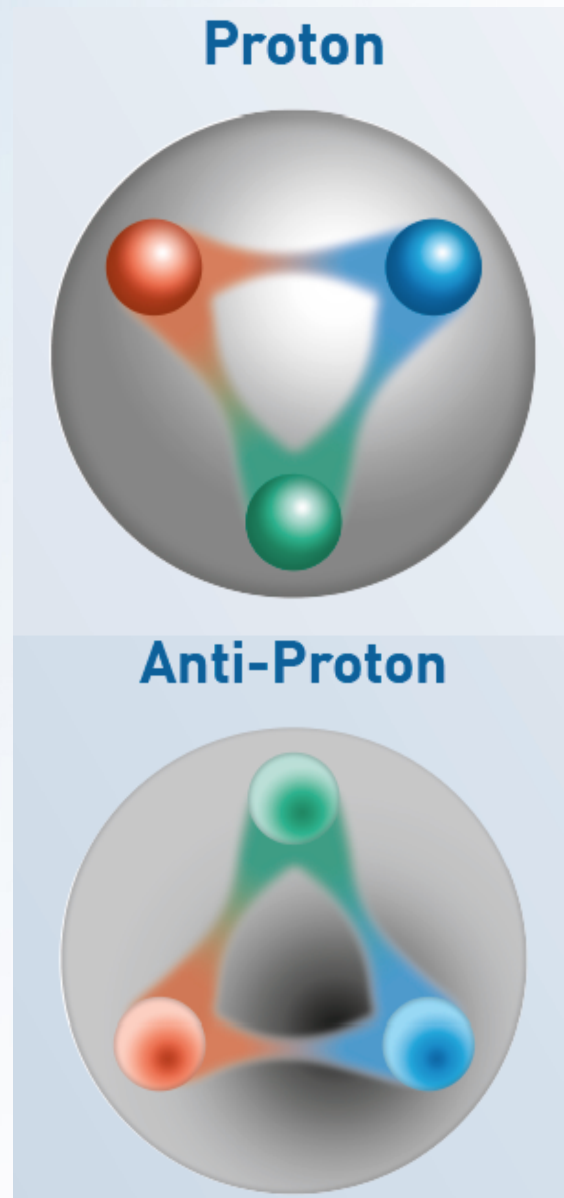
ATRAP

6 collaborations ~ 400 researchers ~ 60 research institutes

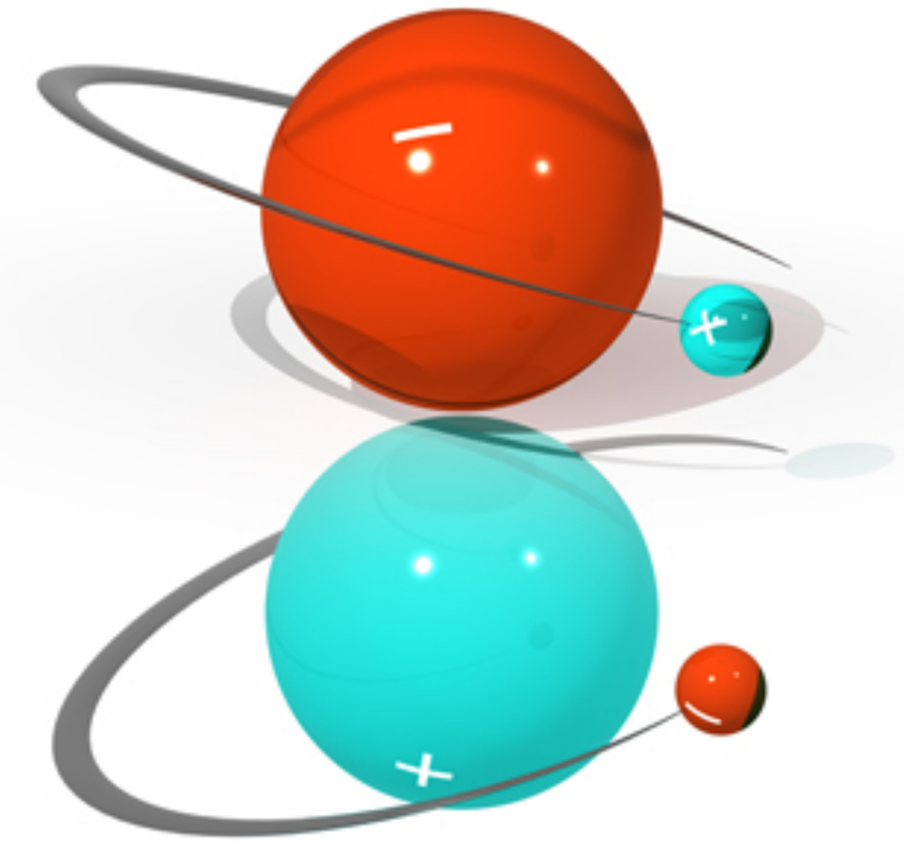
AD EXPERIMENTS



ASACUSA

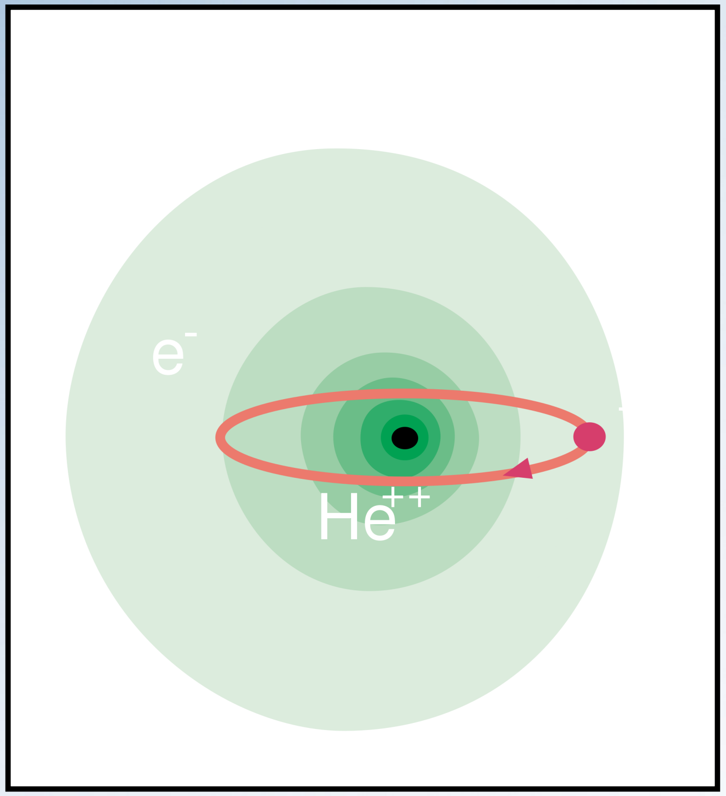


BASE
ASACUSA
ATRAP



ALPHA
ATRAP
ASACUSA
AEGIS
GBAR

AD EXPERIMENTS



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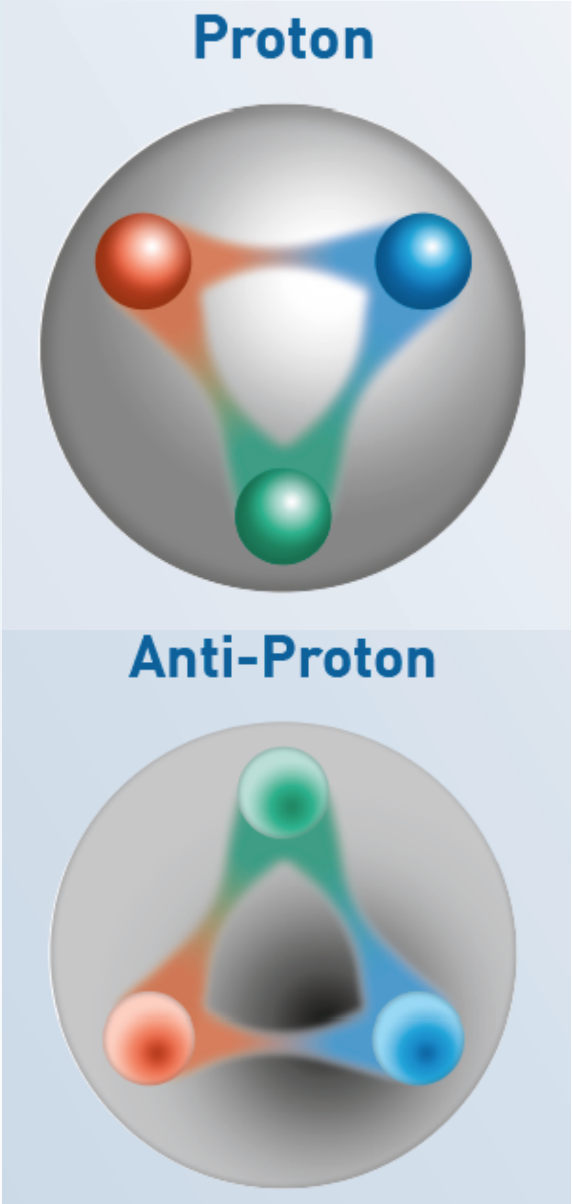

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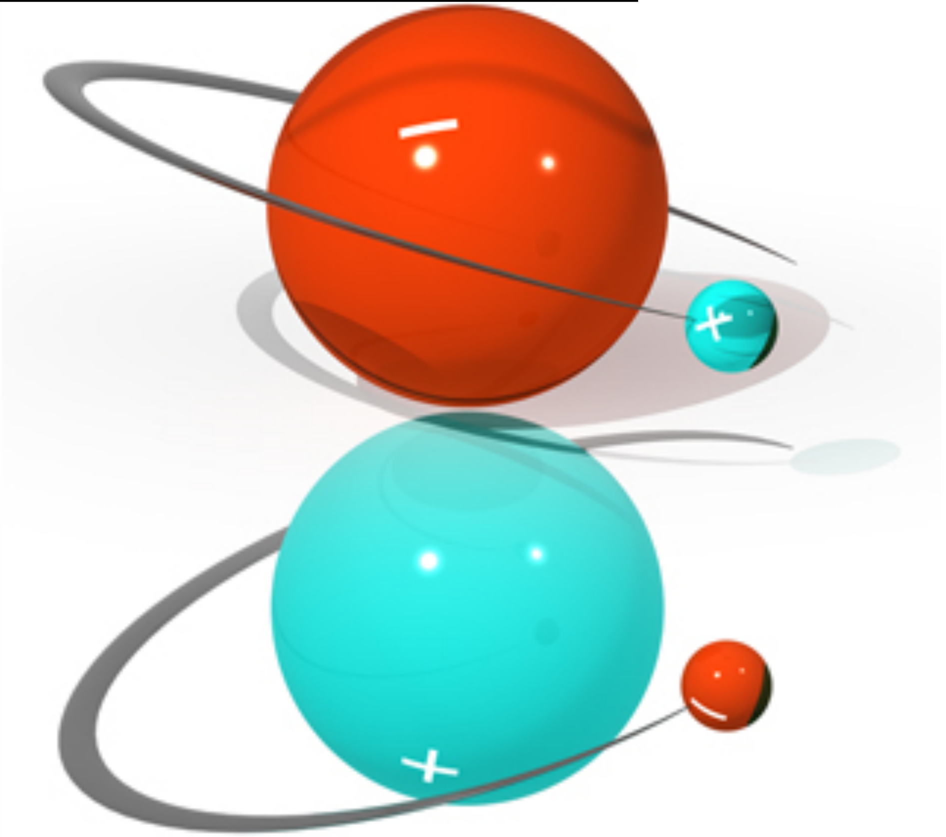
ASACUSA
ATRAP

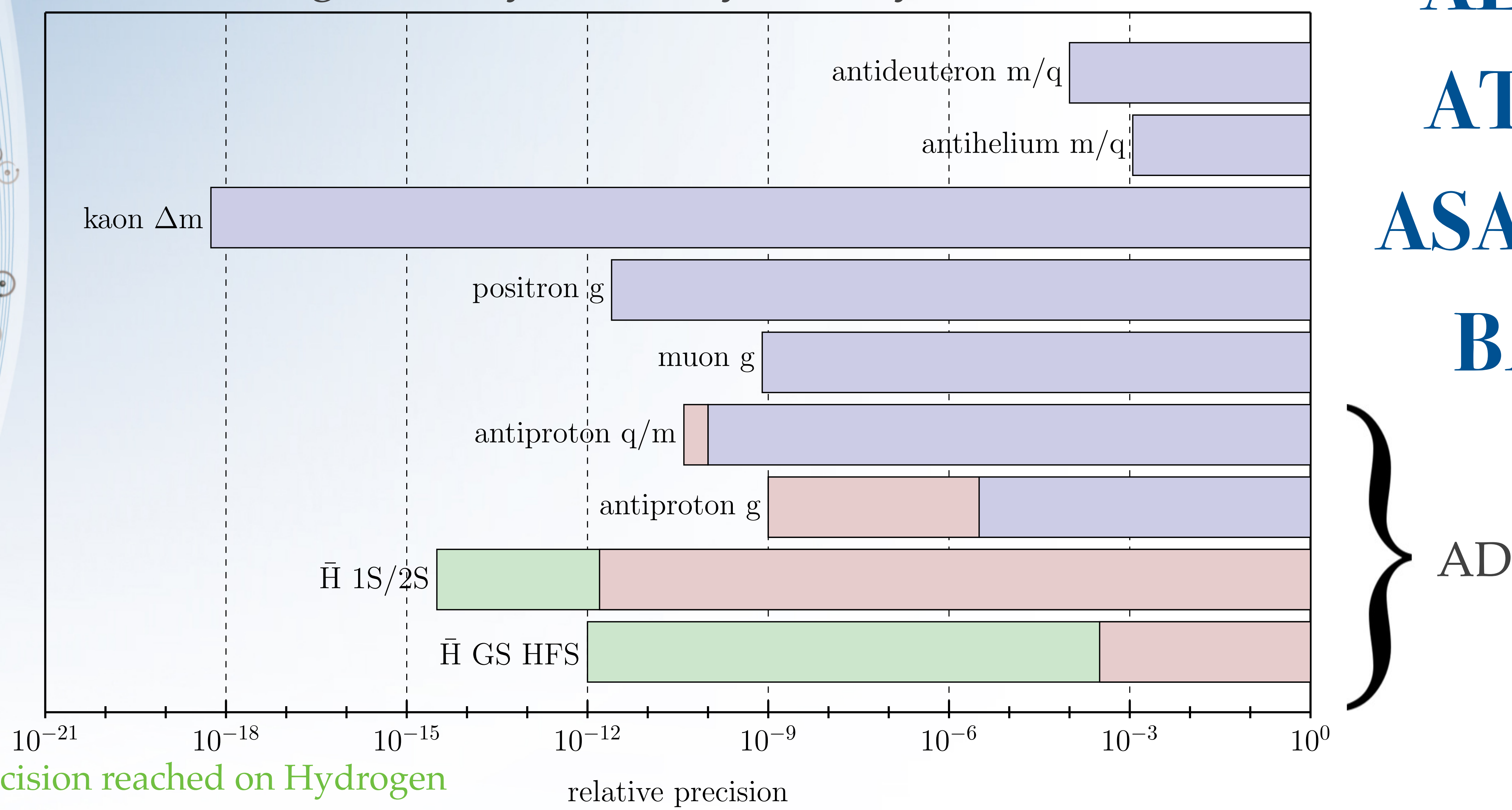


ALPHA
ATRAP
ASACUSA
AEGIS
GBAR

AD PHYSICS

Comparison of fundamental properties of simple baryonic and anti-baryonic systems at **low energy** and with **high precision**

Test of **C**harge - **P**arity - **T**ime symmetry



Precision reached on Hydrogen

Recent measurements

Past measurements

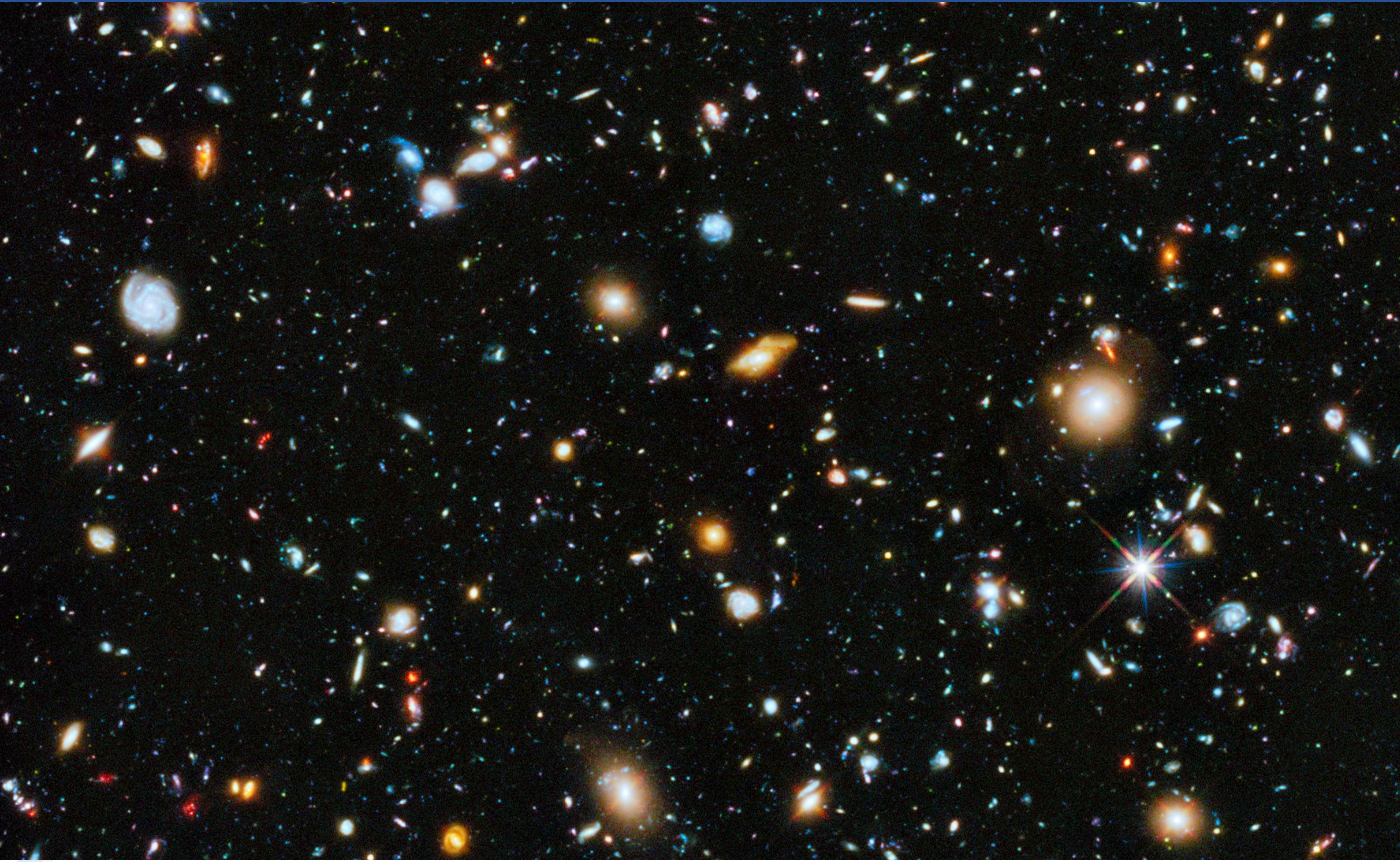
ALPHA

ATRAP

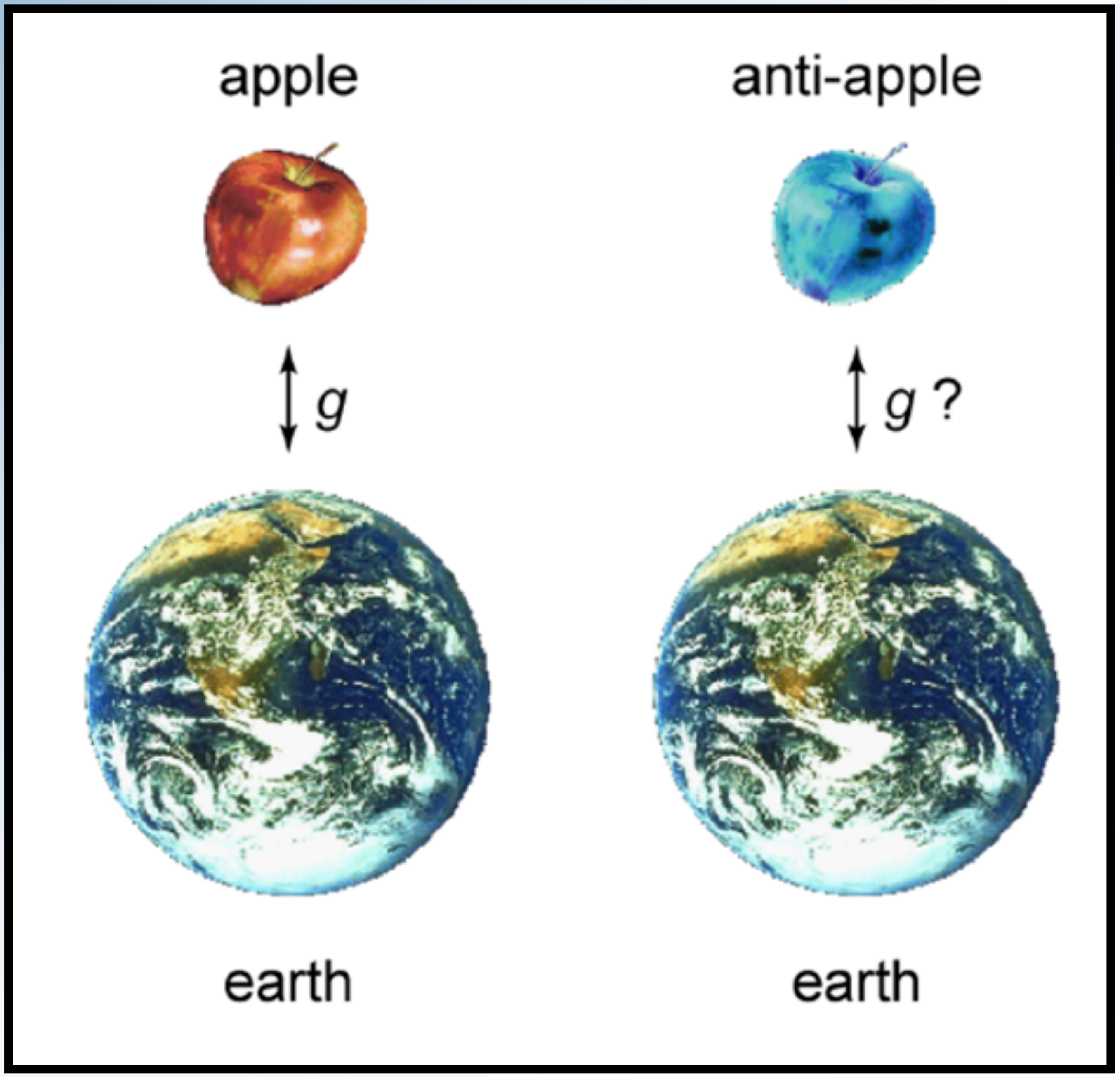
ASACUSA

BASE

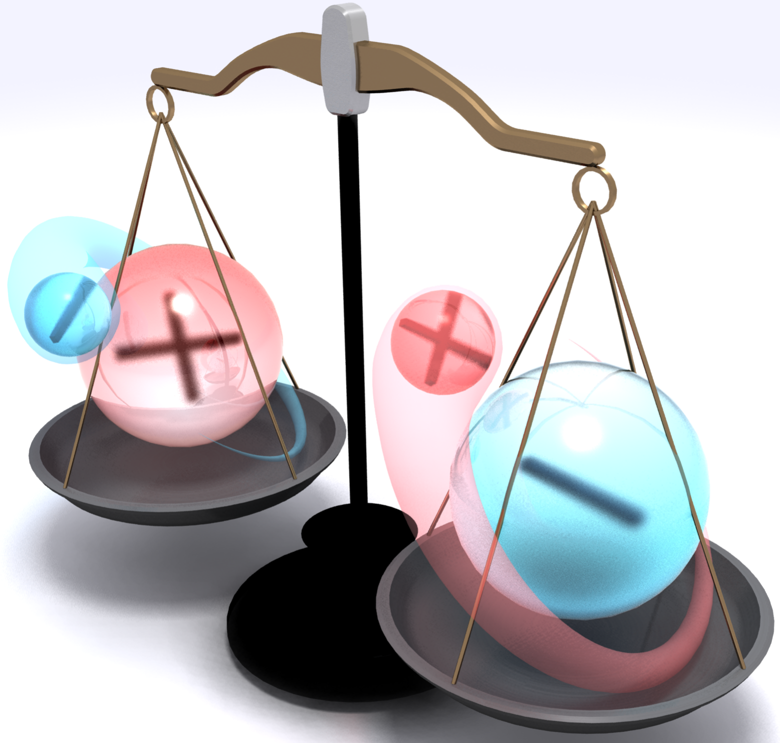
BARYON ASSYMETRY



AD PHYSICS

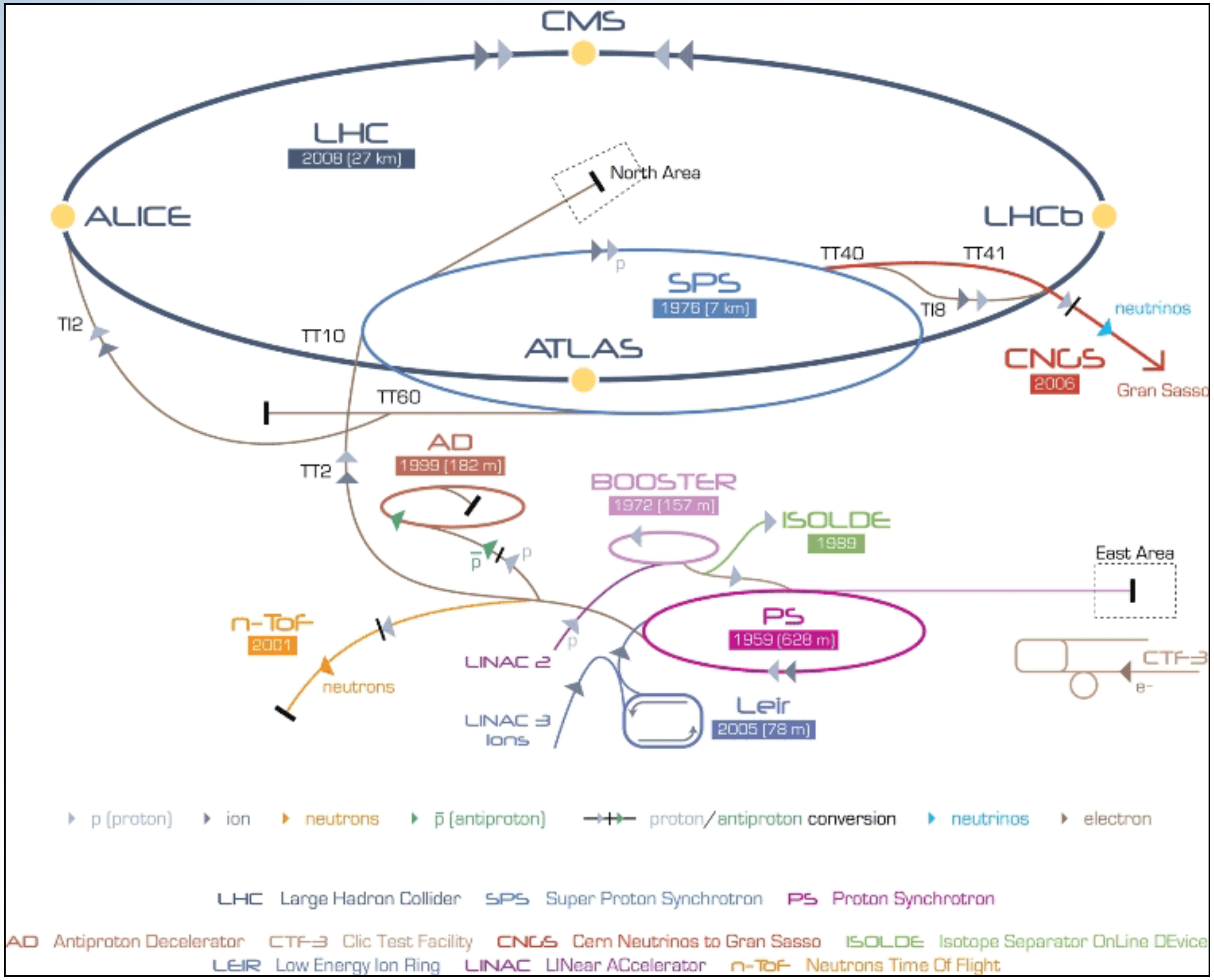


courtesy: http://newscenter.lbl.gov/2013/04/30/antimatter-up-down/

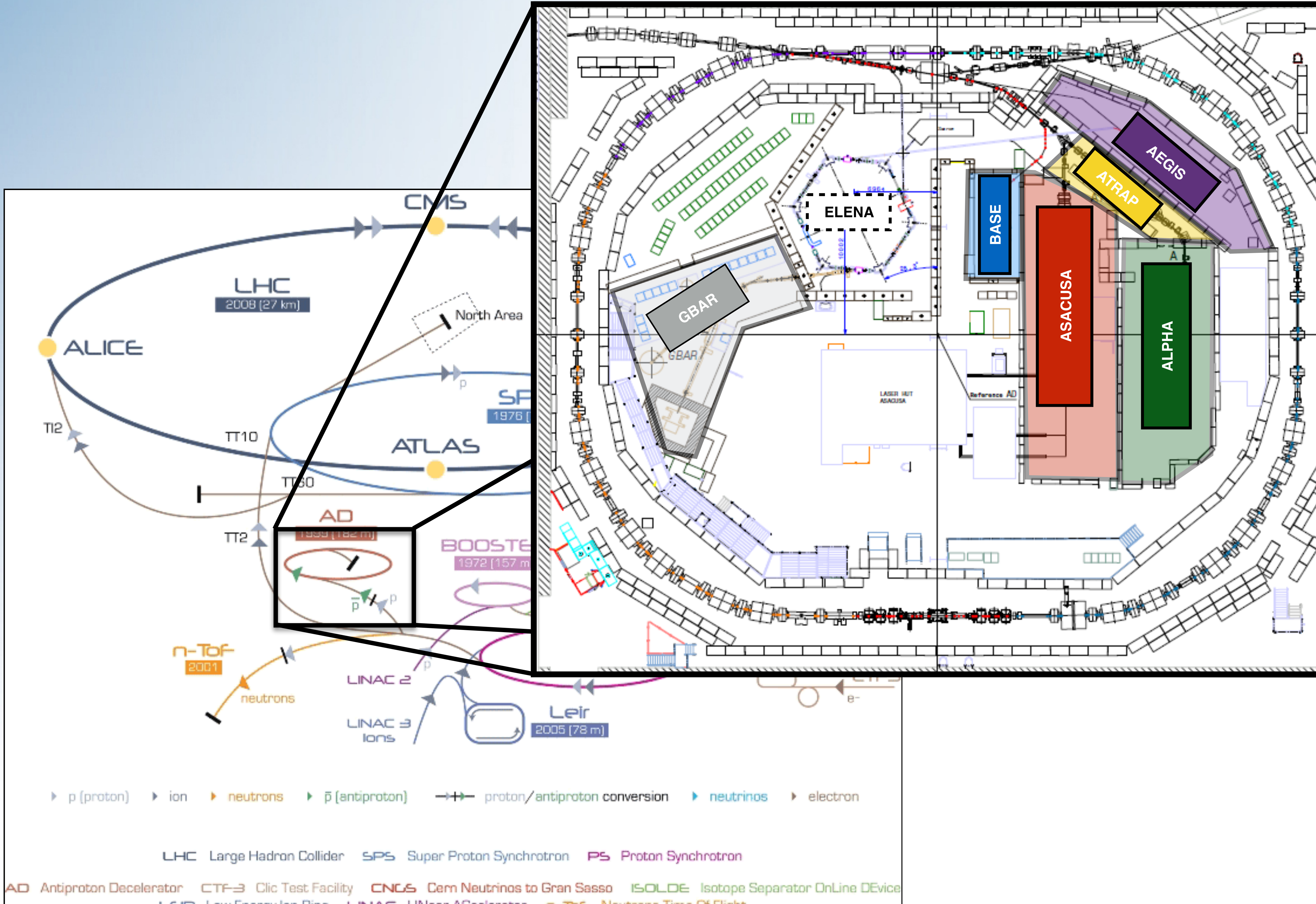


ALPHA-G
AEGIS
GBAR

THE AD COMPLEX



THE AD COMPLEX



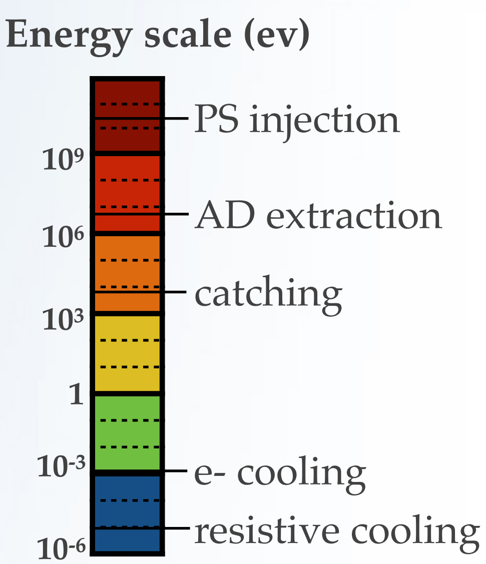
THE AD COMPLEX

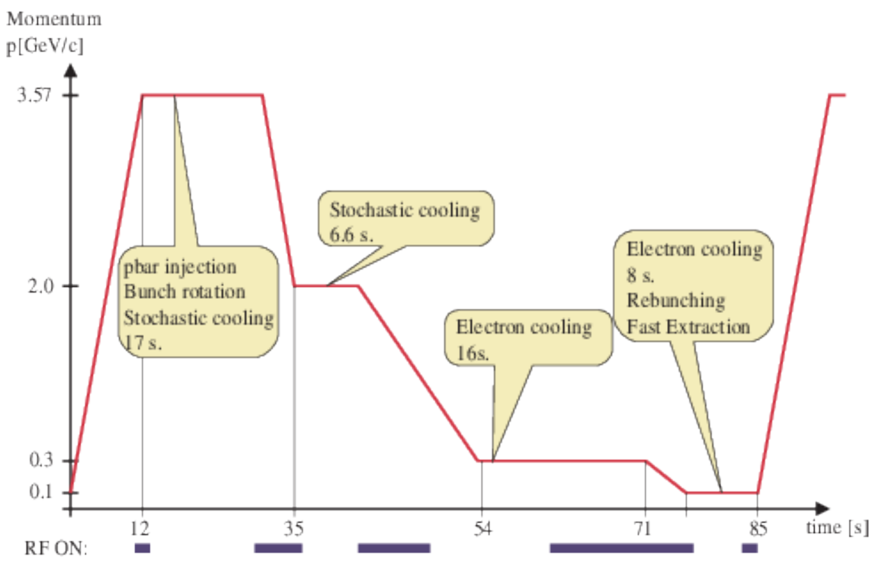
AD

PS : 26 GeV/c proton on target

3×10^{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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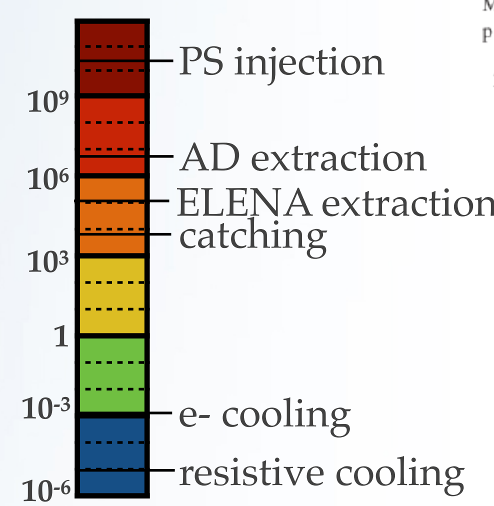
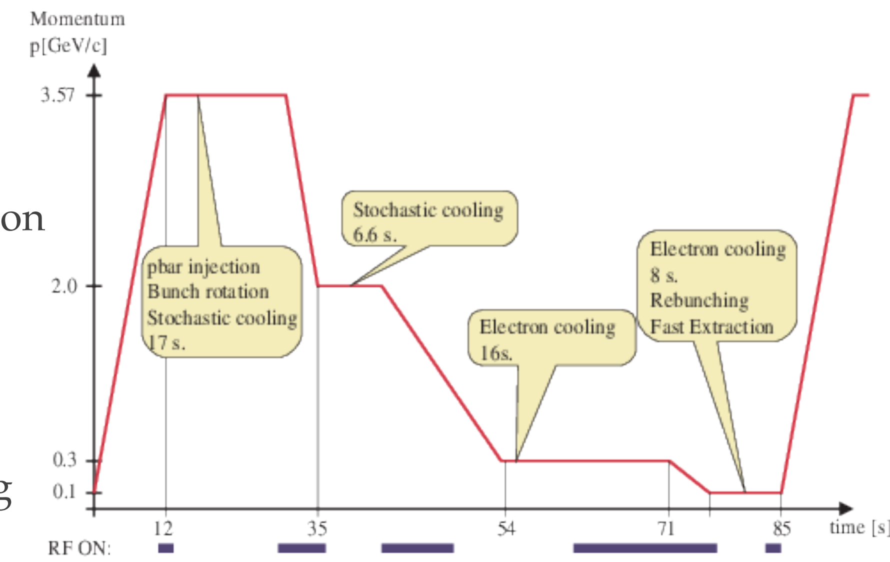




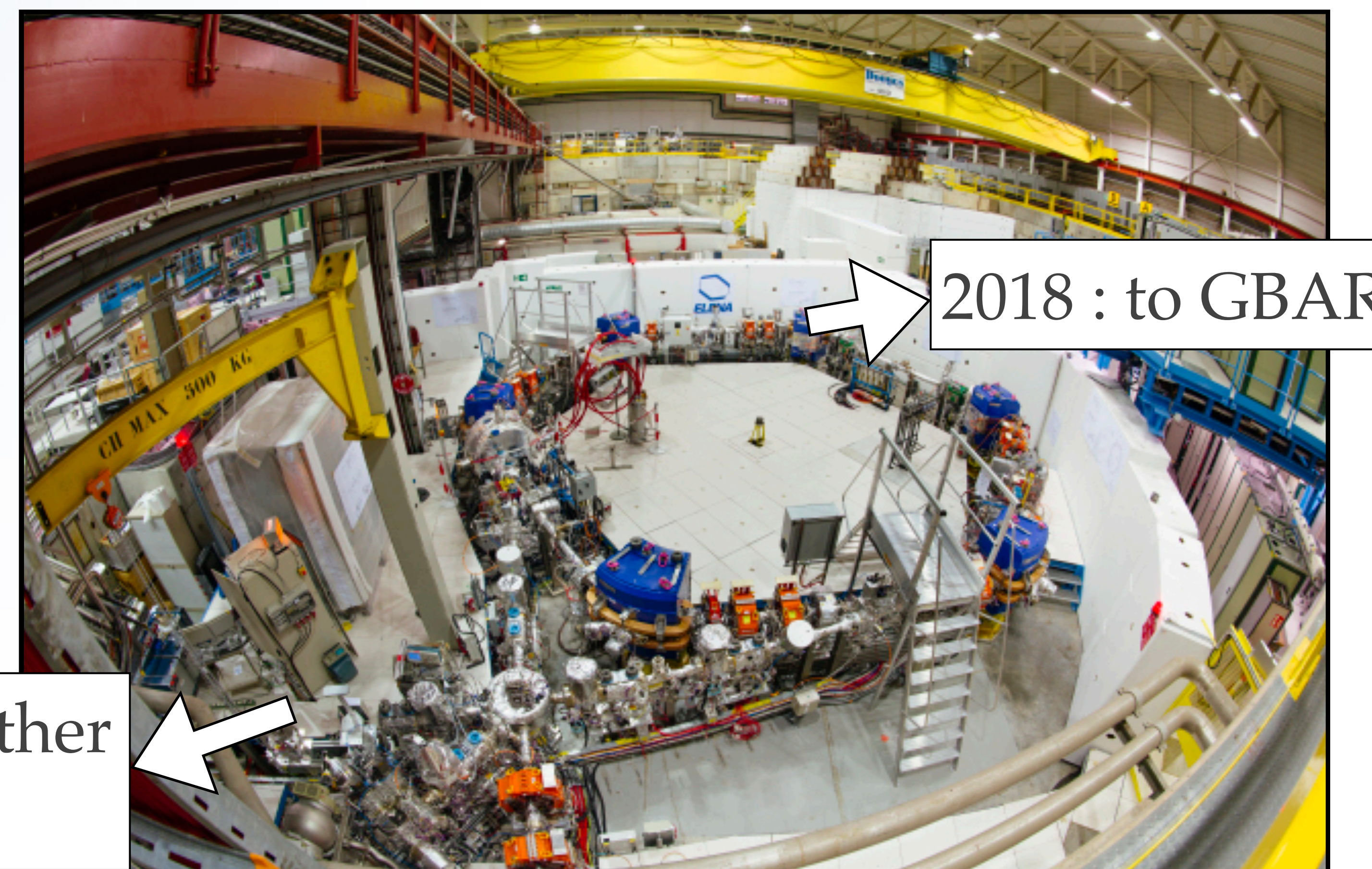
ELENA

$\bar{p}$ at 100 keV at improved beam emittance

all experiments gain a factor 10-100 in trapping efficiency

"simultaneous" delivery to almost all experiments

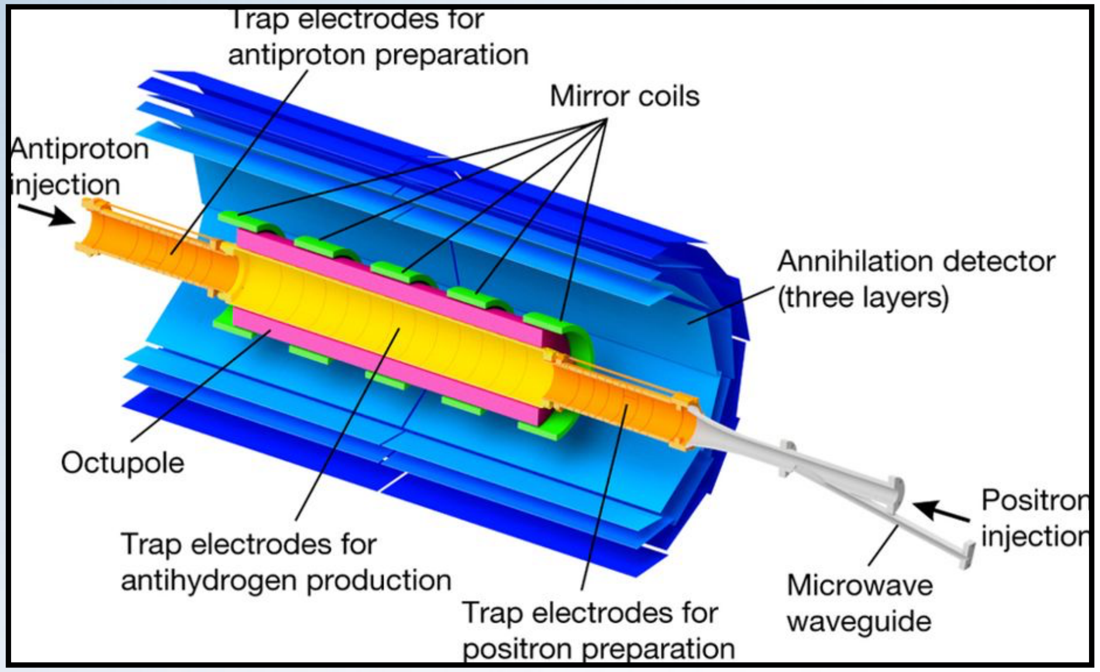
additional experimental zone



EXPERIMENTAL CONCEPTS

ALPHA-2 apparatus

TRAP



Trapping using magnetic moment
Challenge : shallow trap (~0.5K)

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

2018 : 10-20 atoms / trials trapped
Accumulation over 8 hours shift

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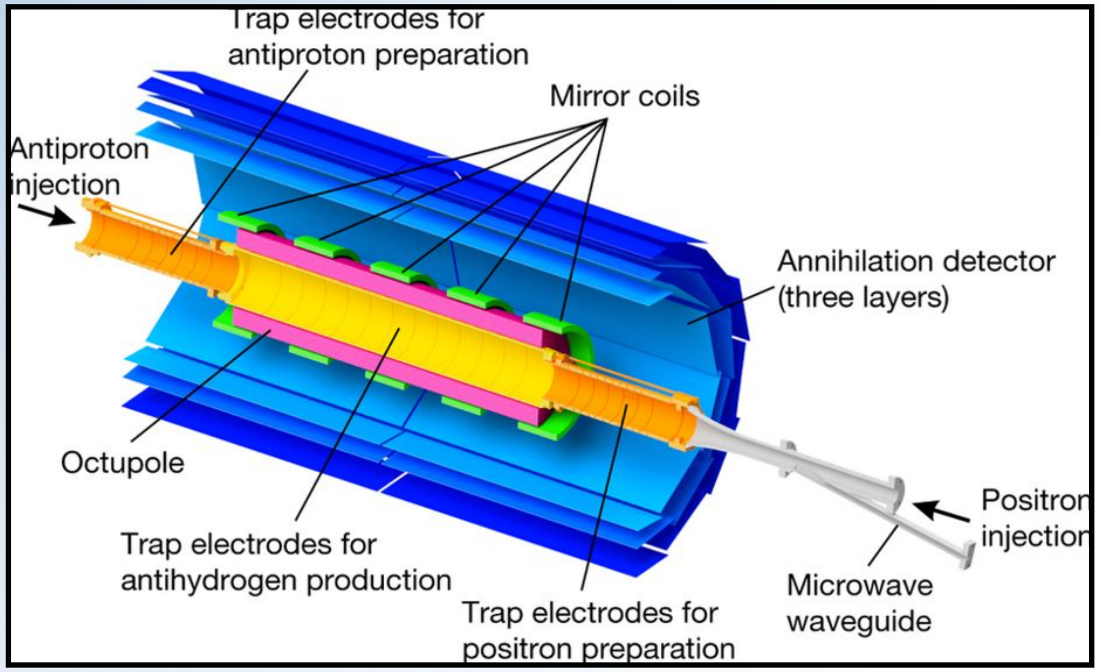

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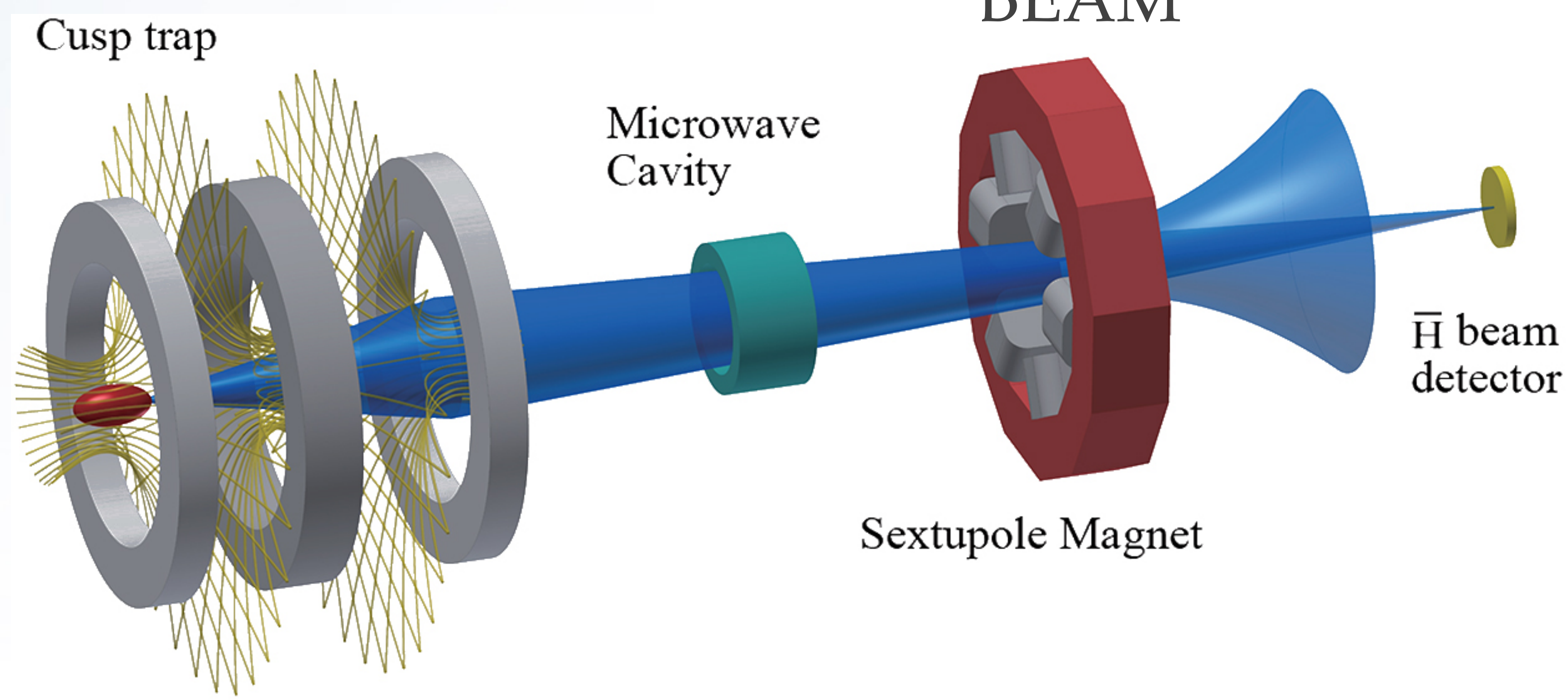
BEAM

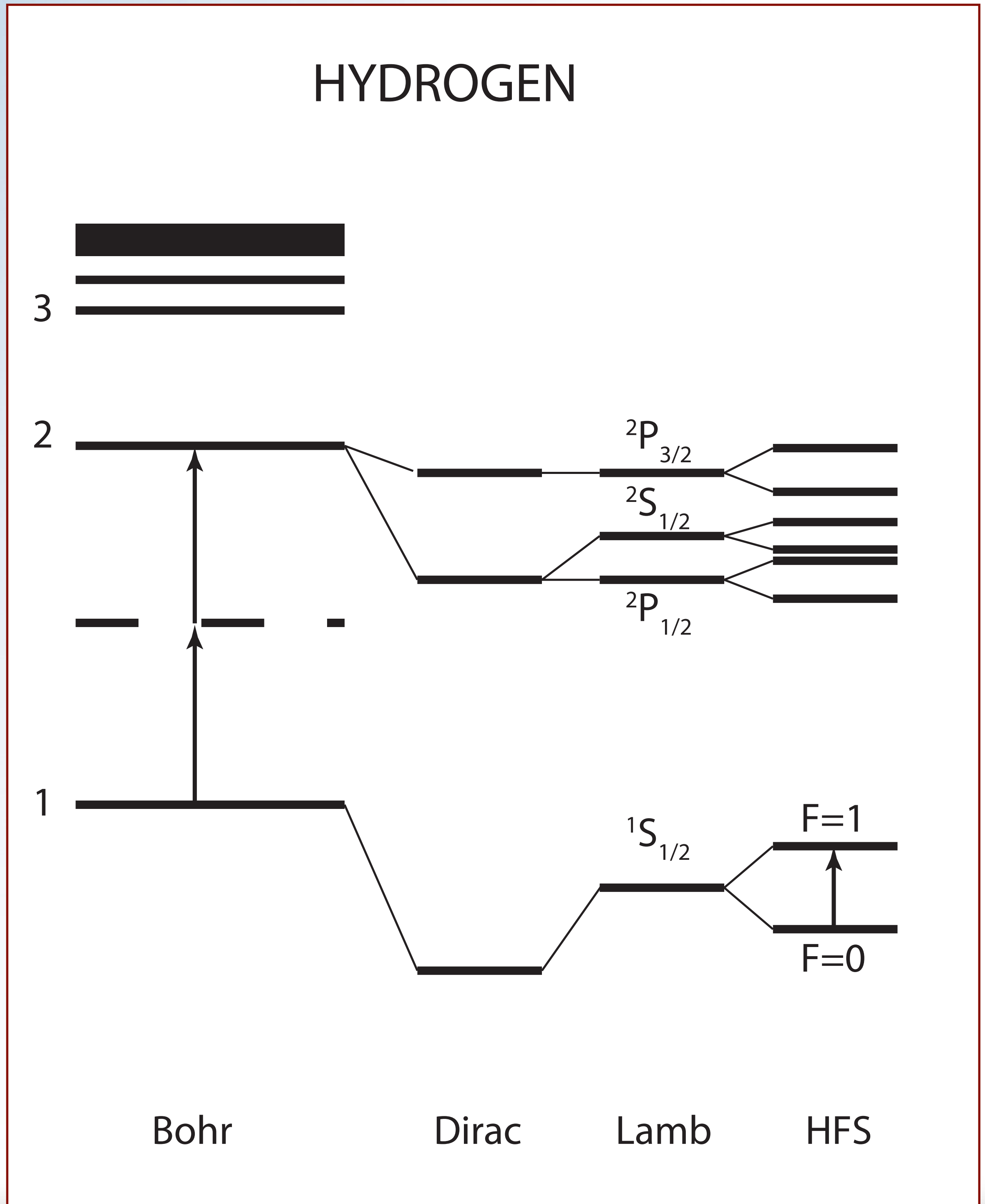


ASACUSA apparatus

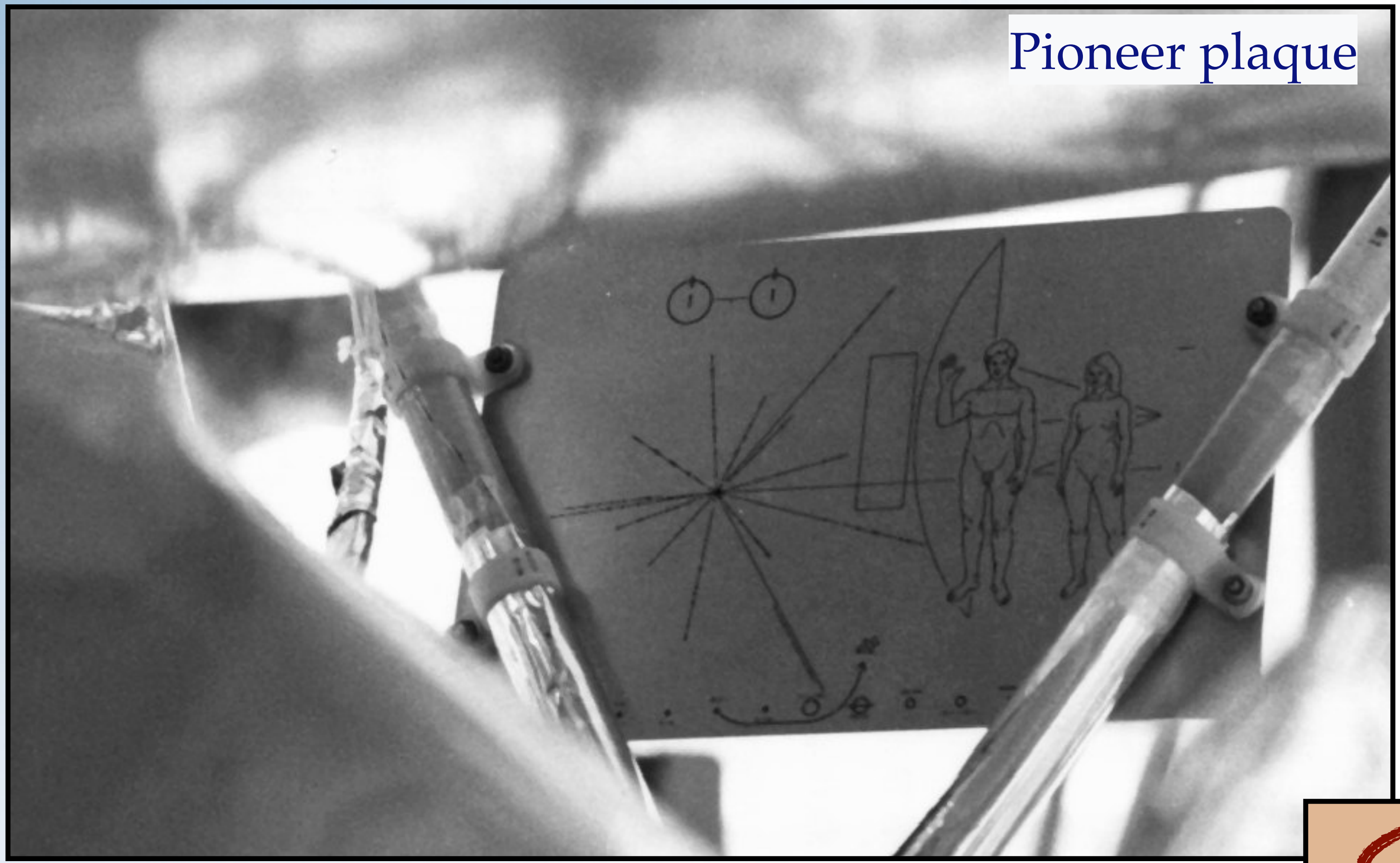
Vs.

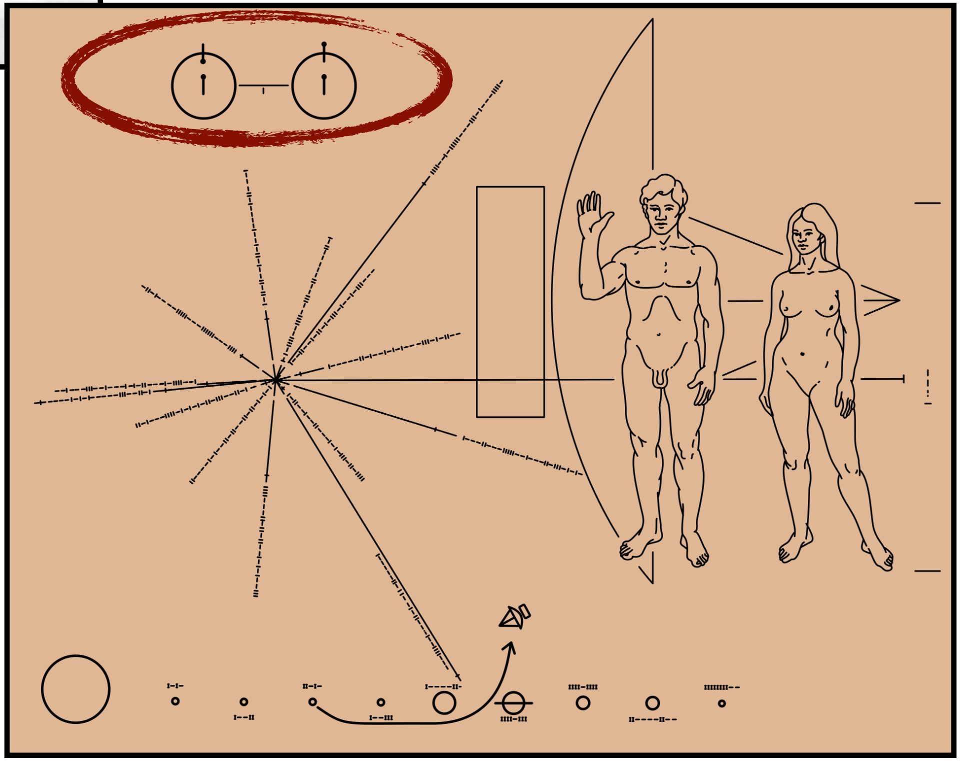
Beam formation through magnetic focussing
Challenge: control of the temperature & quantum state

SPECTROSCOPY OF $\bar{H}$

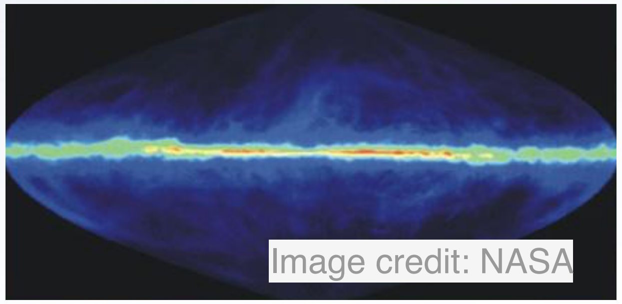


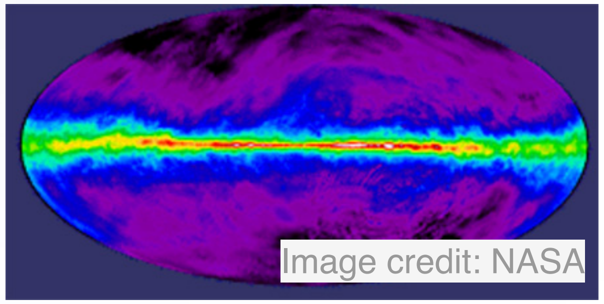
HYPERFINE SPLITTING





21cm line

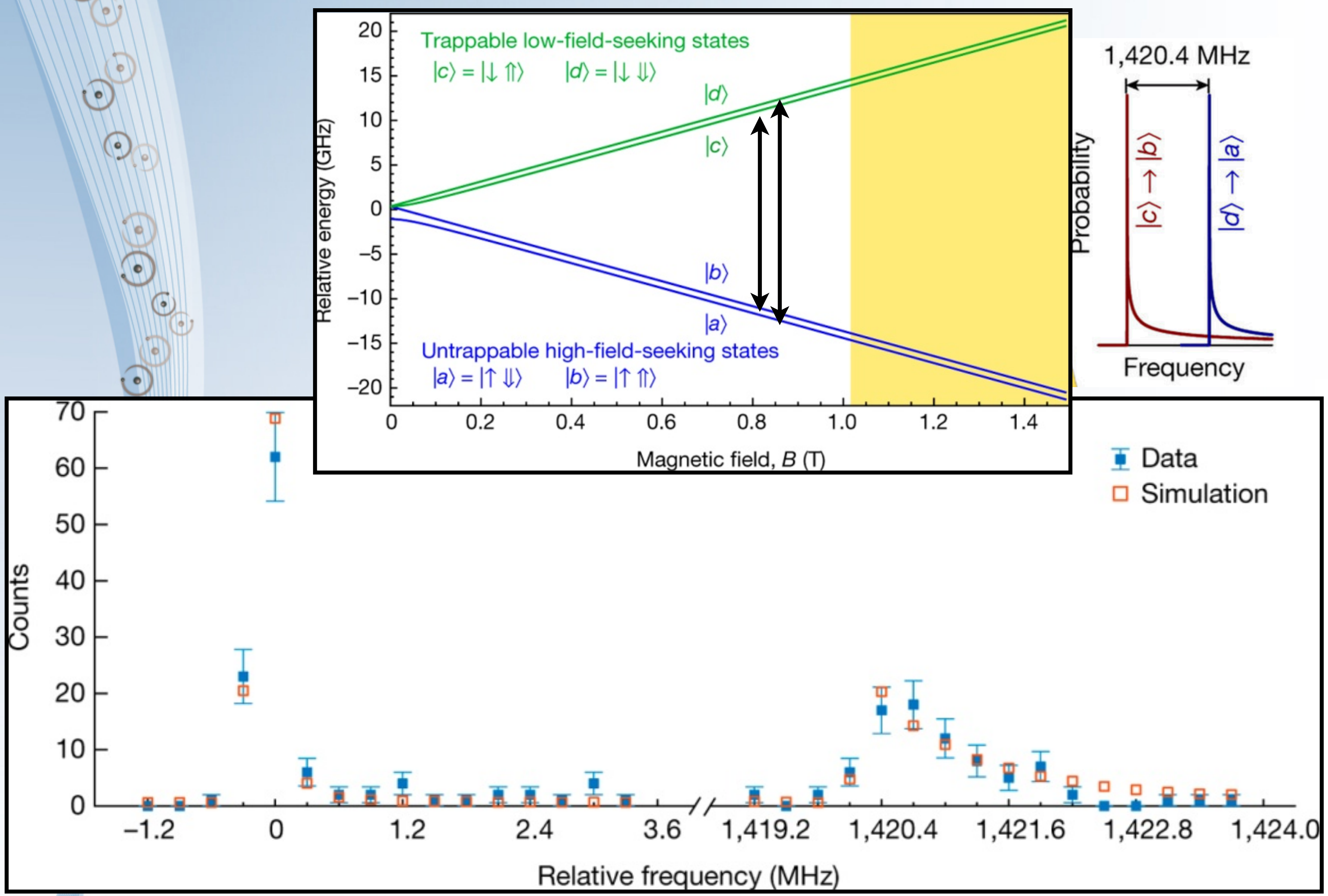




RECENT SPECTROSCOPY HIGHLIGHTS

In a TRAP: **ALPHA**

Precision of 500 kHz (4×10^{-4})



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

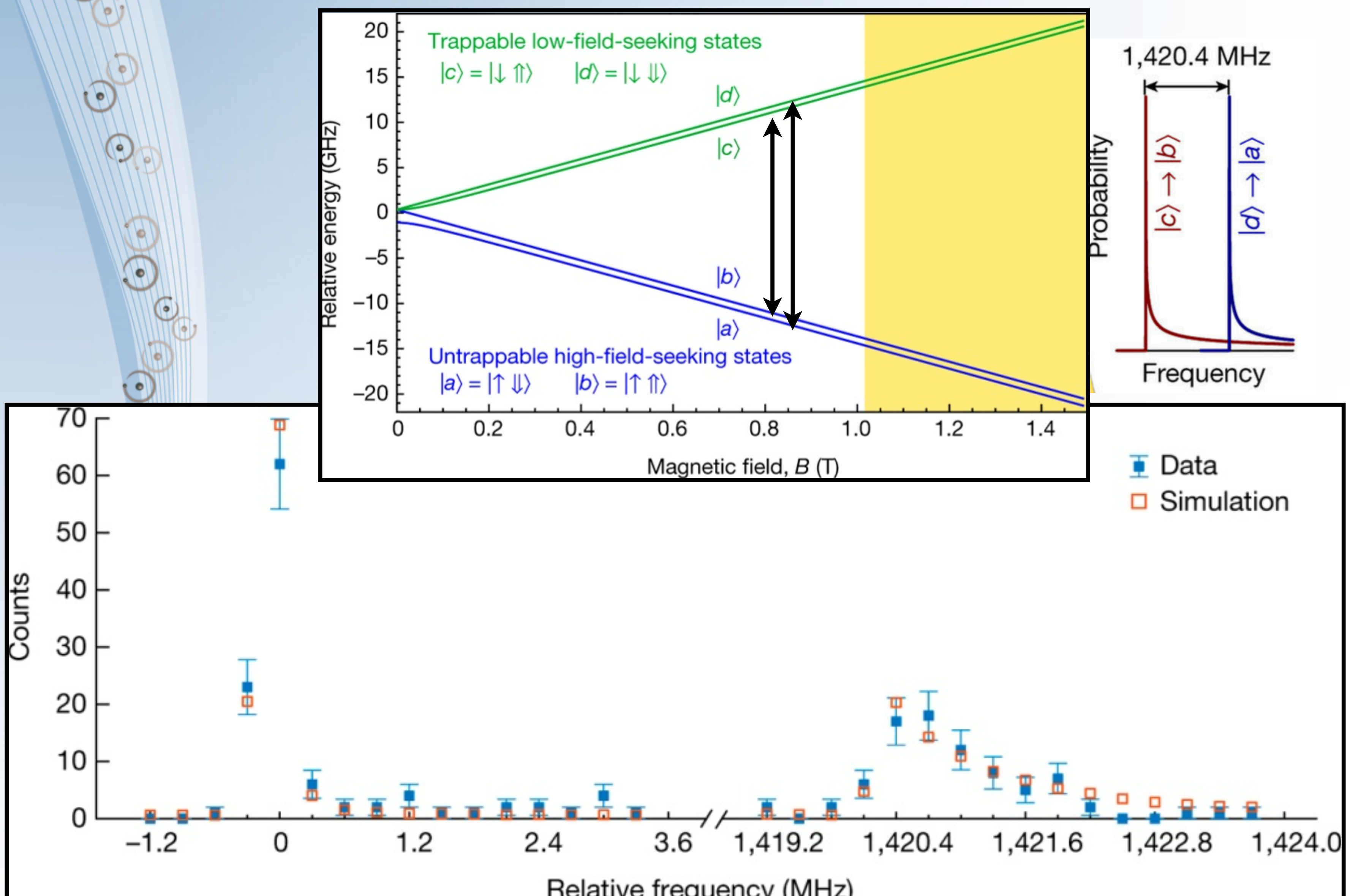
RECENT SPECTROSCOPY HIGHLIGHTS

<u>In a TRAP:</u> **ALPHA**

Precision of 500 kHz (4×10^{-4})

<u>In a BEAM:</u> **ASACUSA**

Precision of ~3Hz (3E-9) on <u>HYDROGEN</u>



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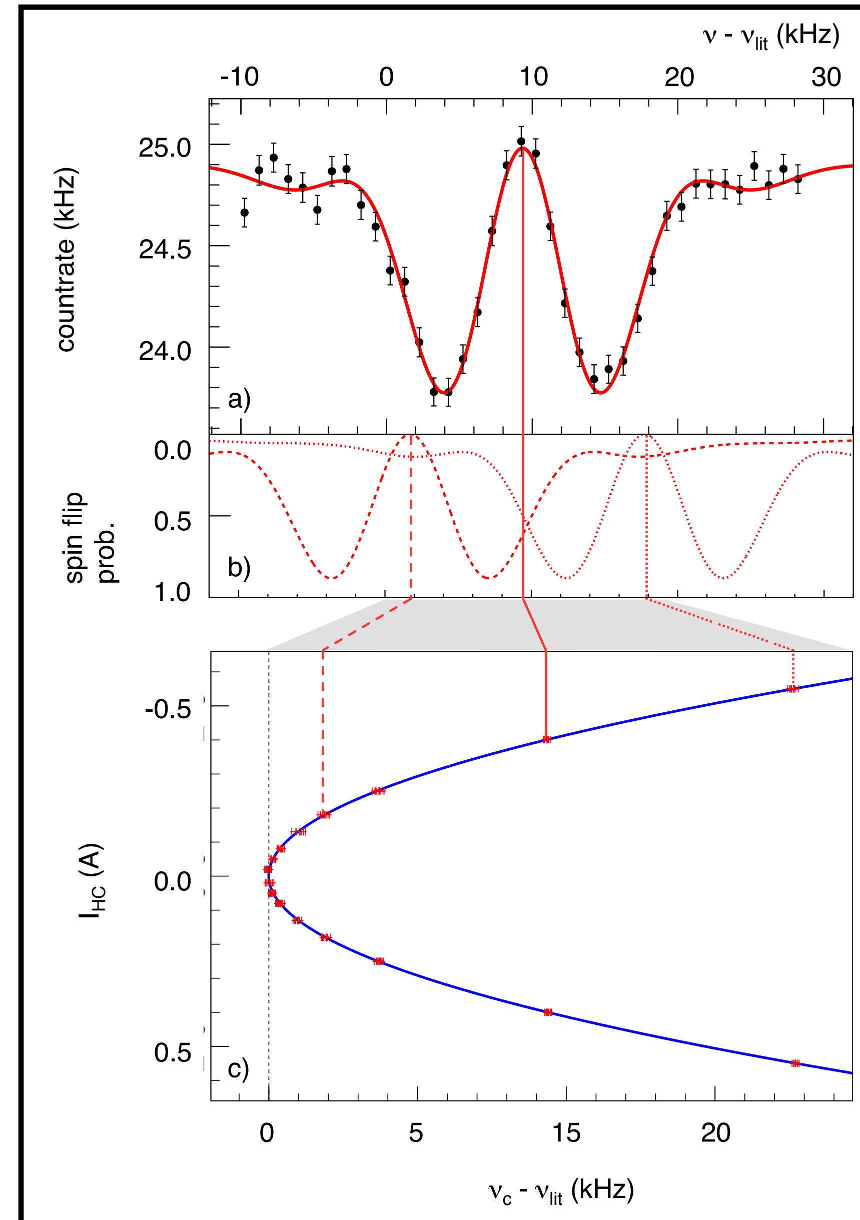


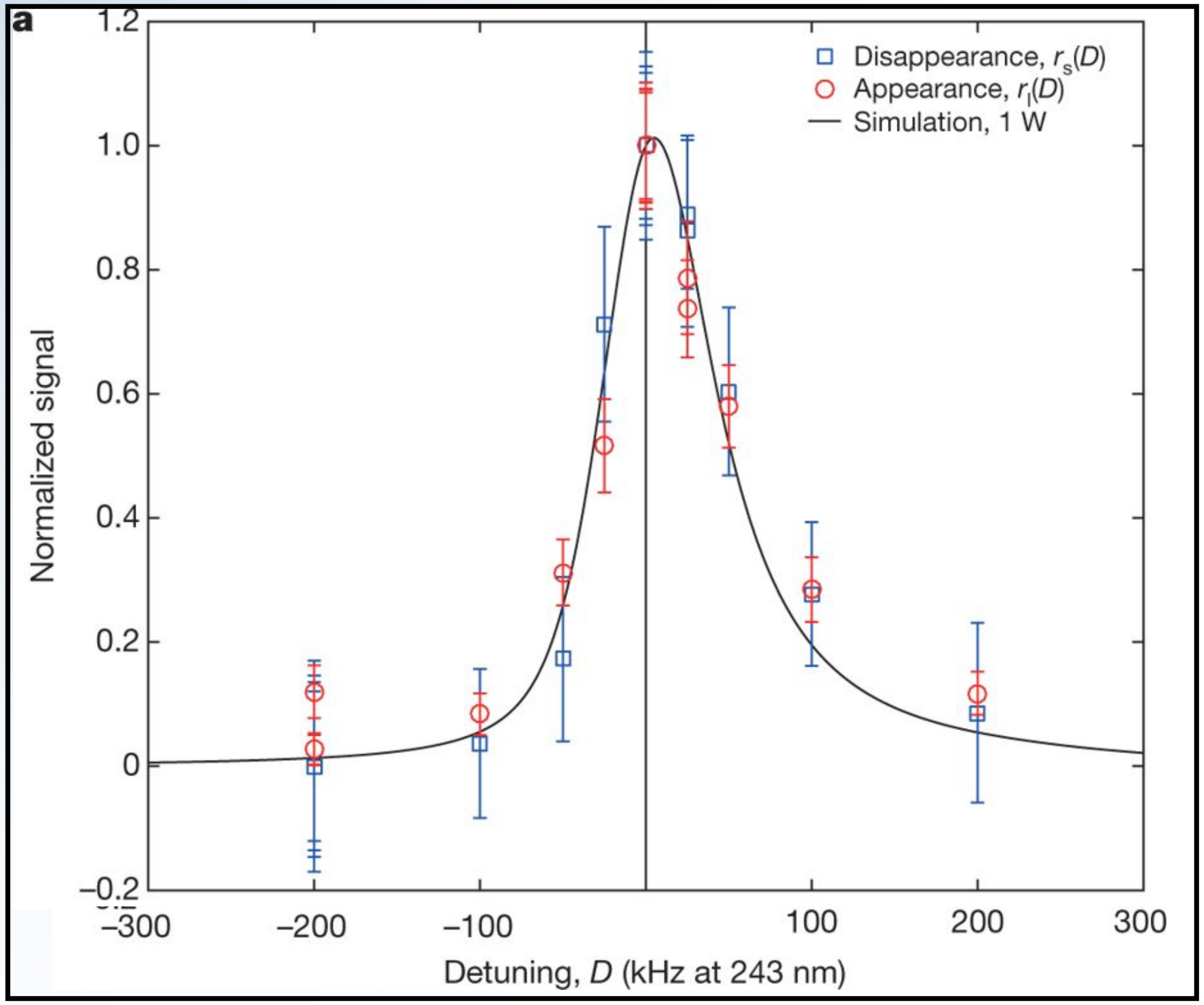
M. Diermaier et al. Nature Communications 8, 15749 (2017)

RECENT SPECTROSCOPY HIGHLIGHTS

ALPHA

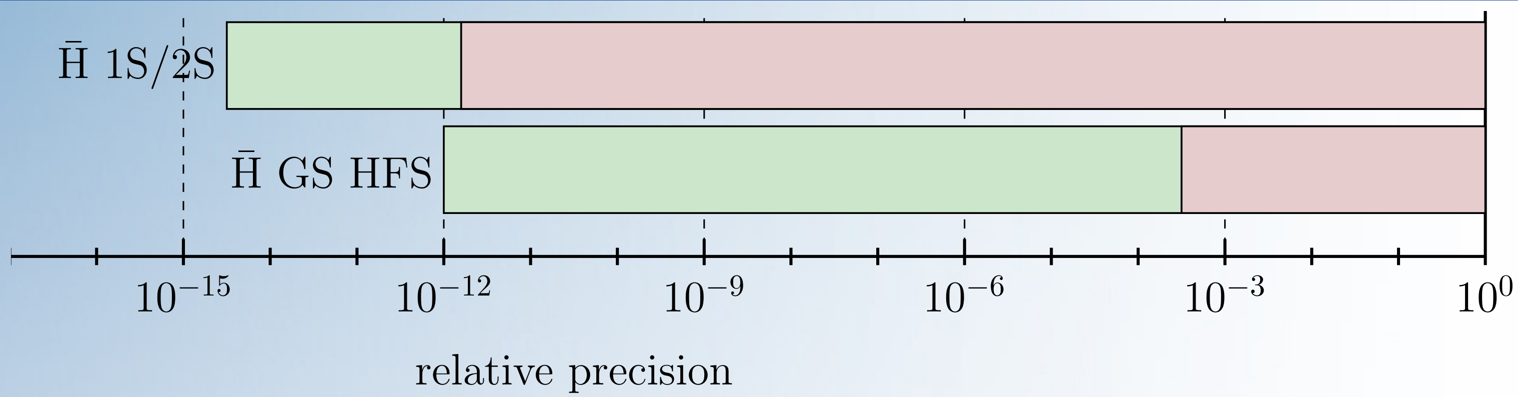
In a TRAP:

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



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

FUTURE SPECTROSCOPY GOALS

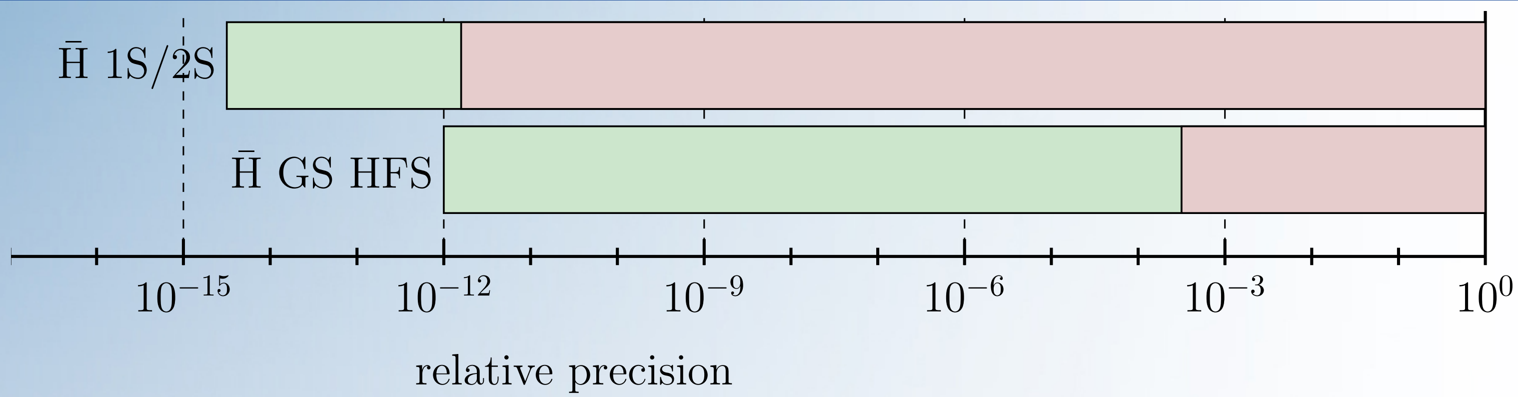


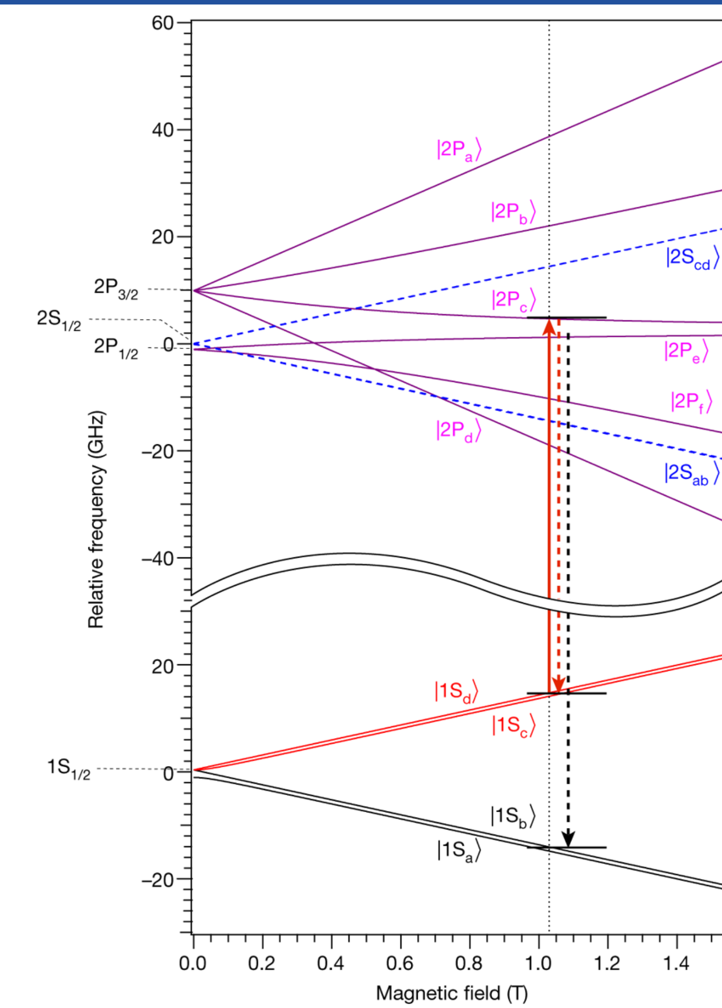
Comparison to H in the same apparatus

<u>For enhanced 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 $\bar{H}$

FUTURE SPECTROSCOPY GOALS





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

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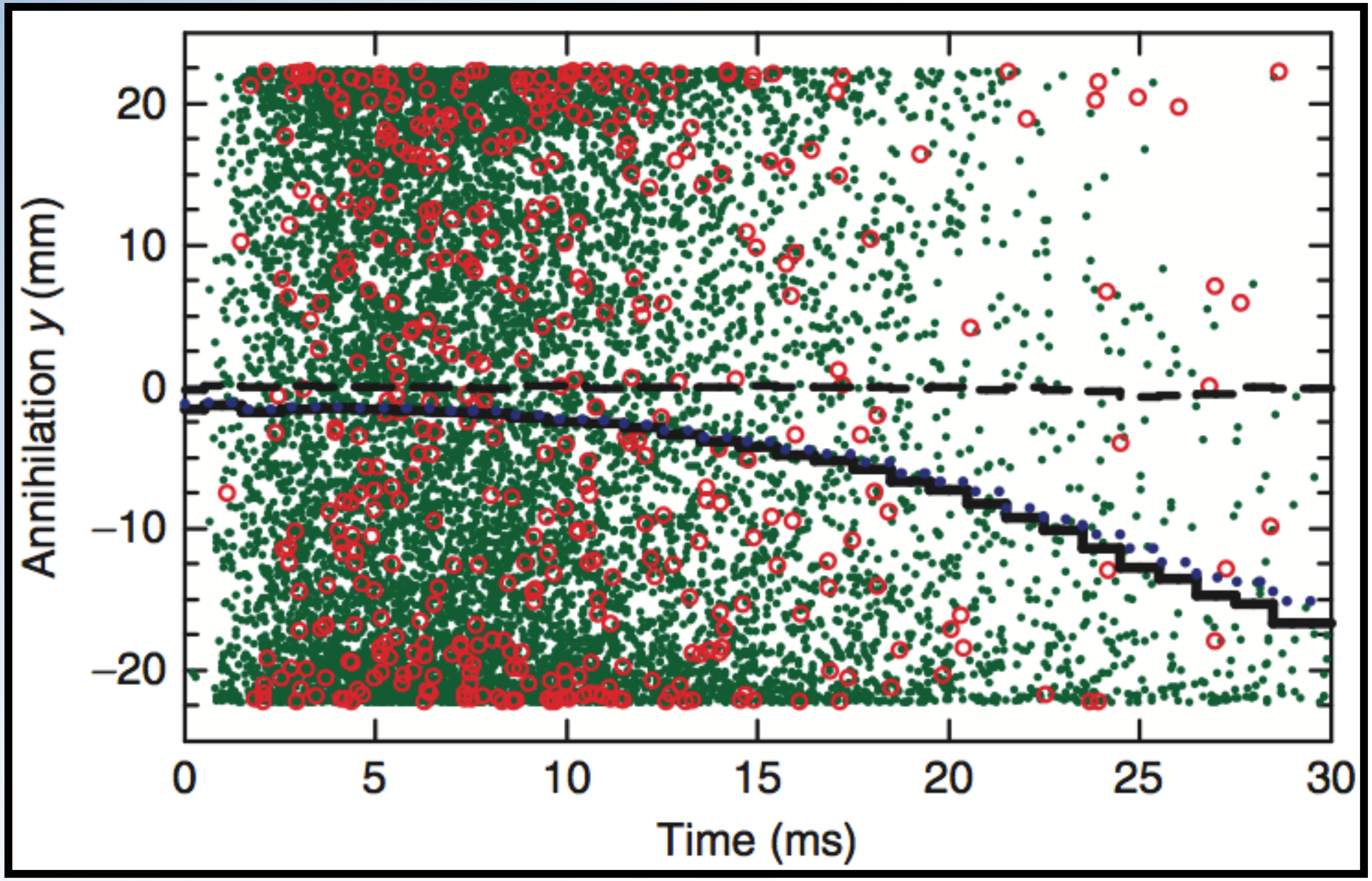
GRAVITY HIGHLIGHTS

ALPHA



-65 < g/ḡ < 110

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

Green dots---simulated annihilations

Red circles---434 Observed annihilations

Vertical position of annihilation vertex during release of trapping field

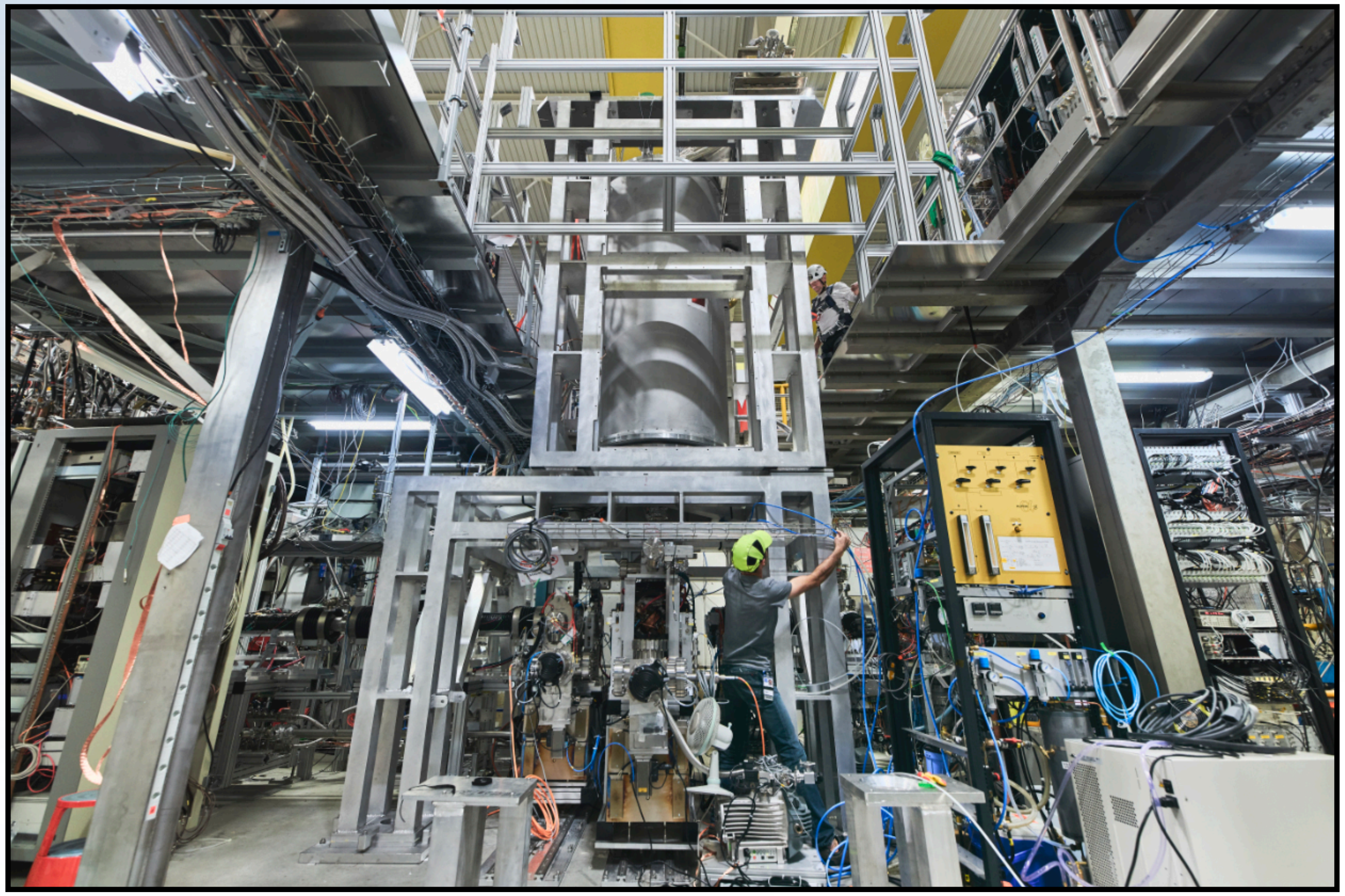
RECENT GRAVITY HIGHLIGHTS

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



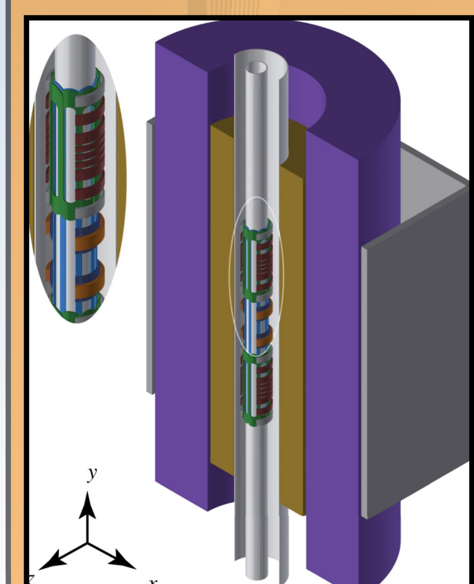
FUTURE GRAVITY GOALS

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 $\bar{H}$ cooling to ~20 mK and advanced magnetometry



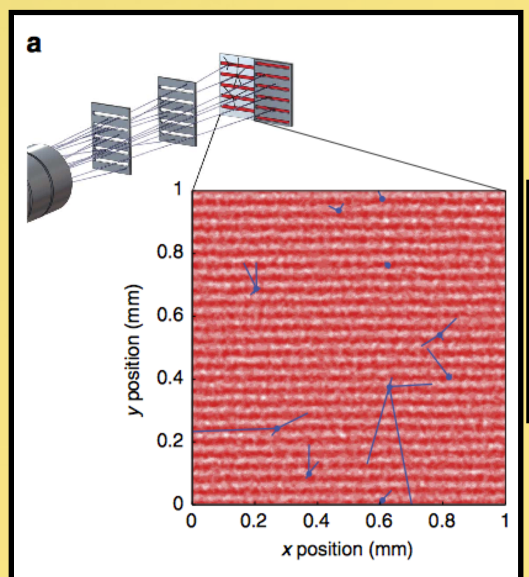
W. A. Bertsche
Phil. Trans. R. Soc. A 2018 376 20170265;
DOI: 10.1098/rsta.2017.0265. (2018)

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



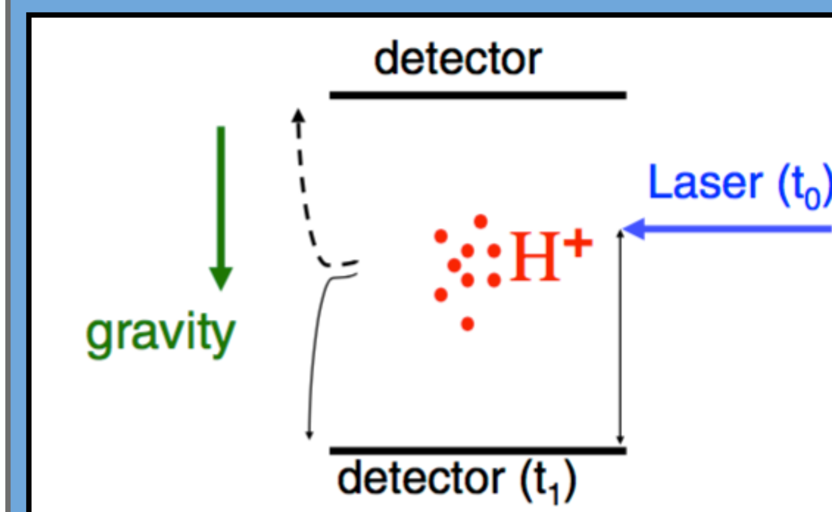
S. Aghion et al.
Nature Communications
5 (2014) 4538

AEGIS

$\bar{H}^+$ BEAM

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

1% measurement targeted

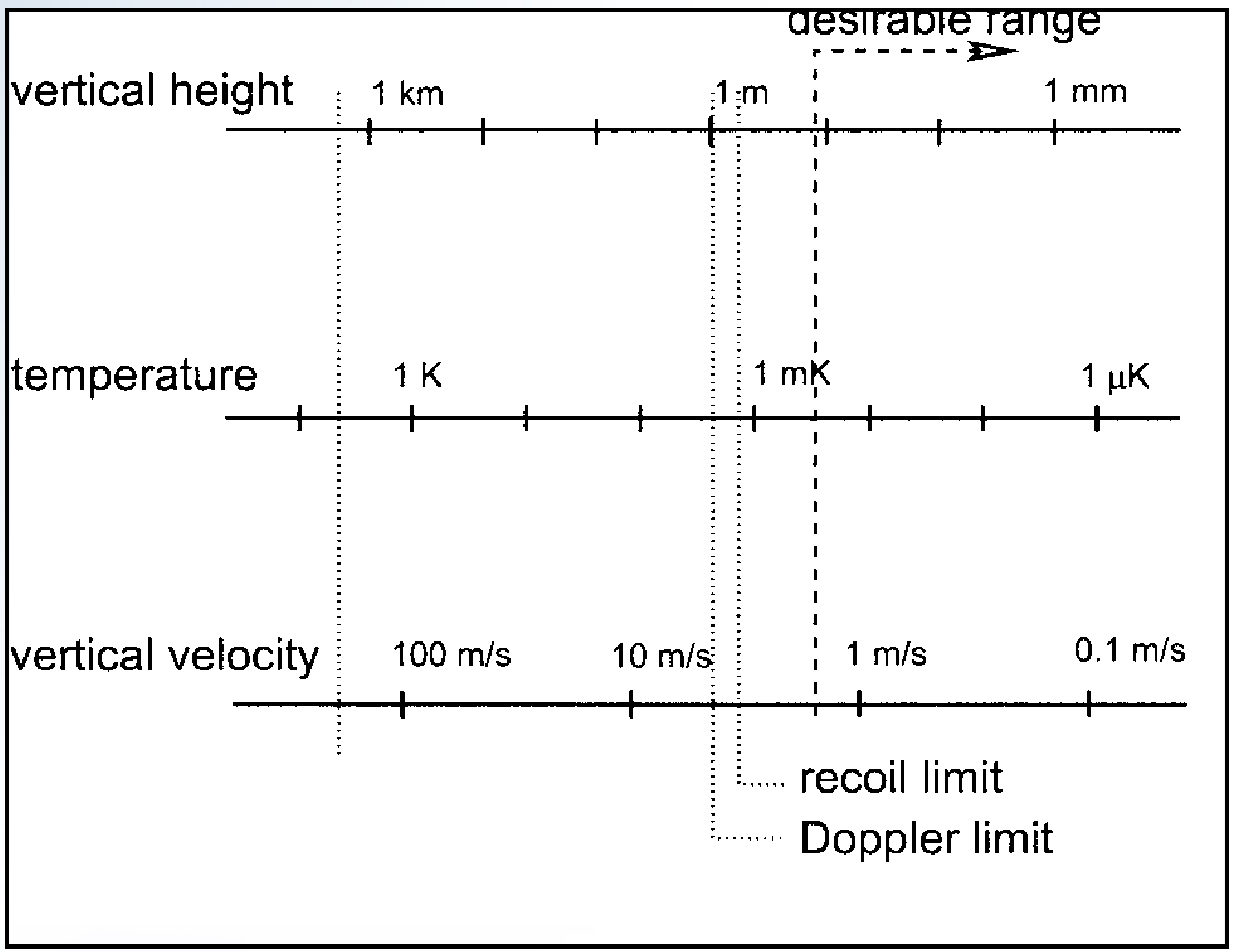


e.g.: The GBAR antimatter gravity experiment
P. Pérez et al., Hyperfine Interactions 233, 21-27 (2015)

GBAR

FUTURE GOALS

Some numbers to set the scale



C. Malbrunot/CERN

FUTURE GOALS

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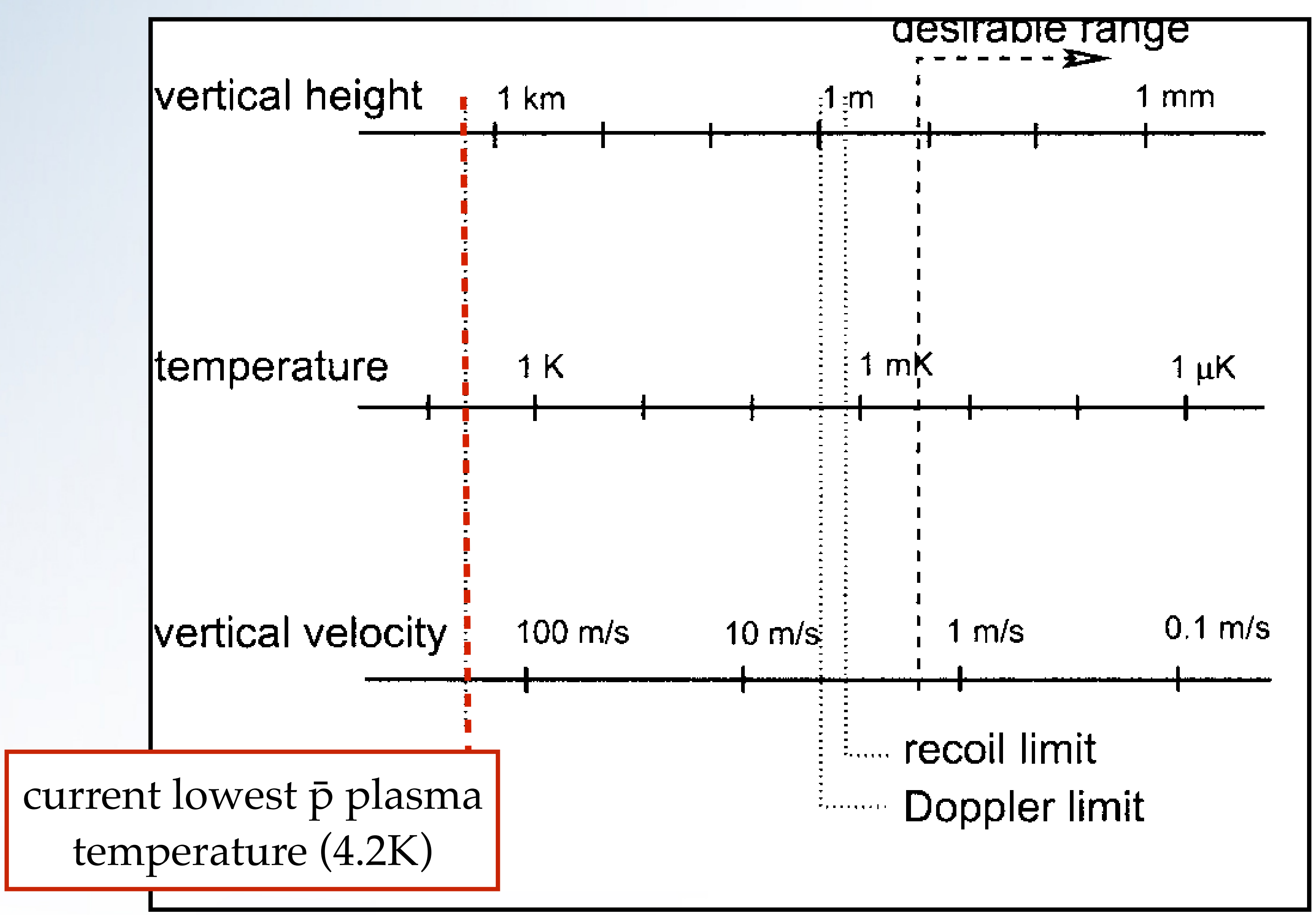

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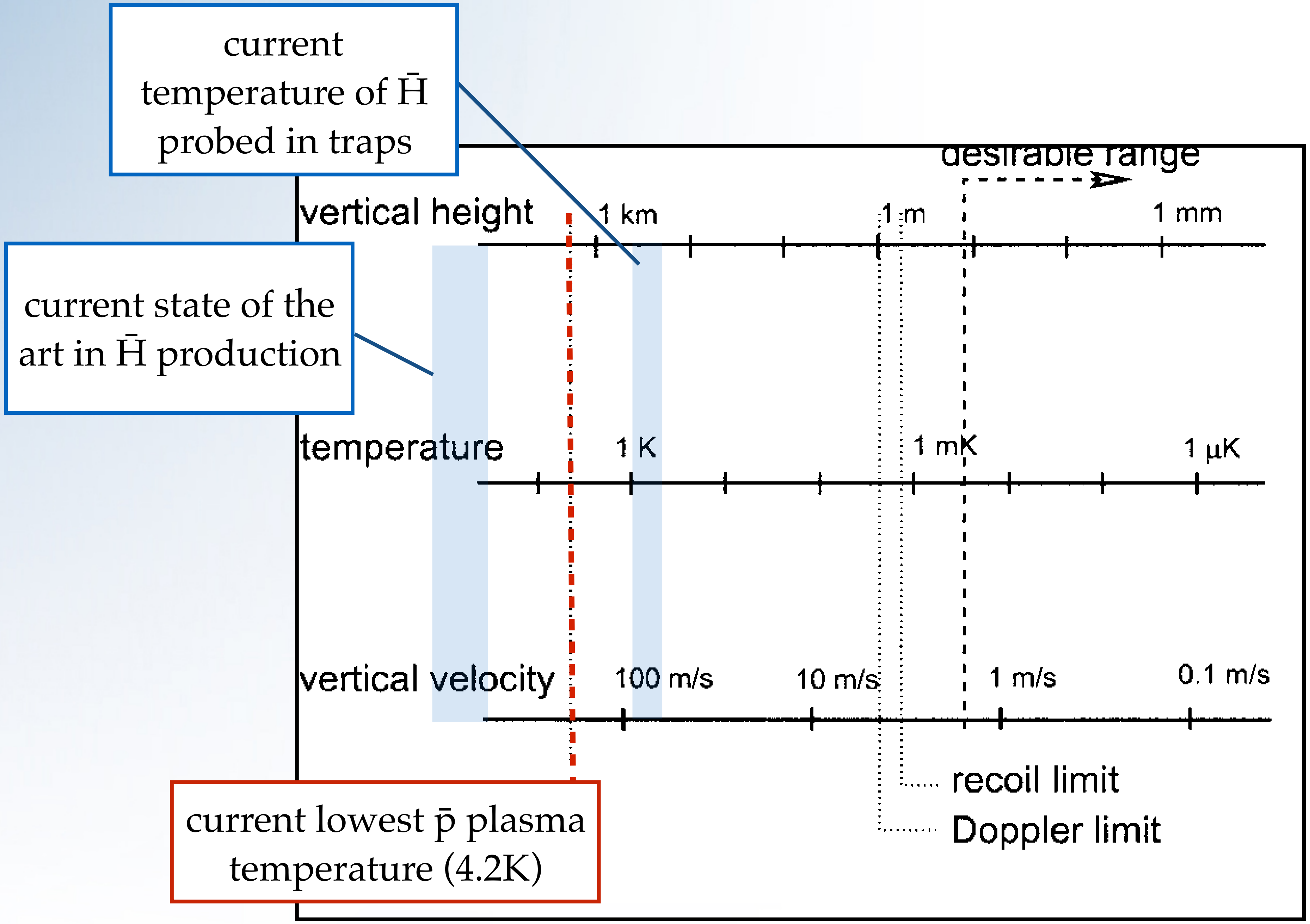

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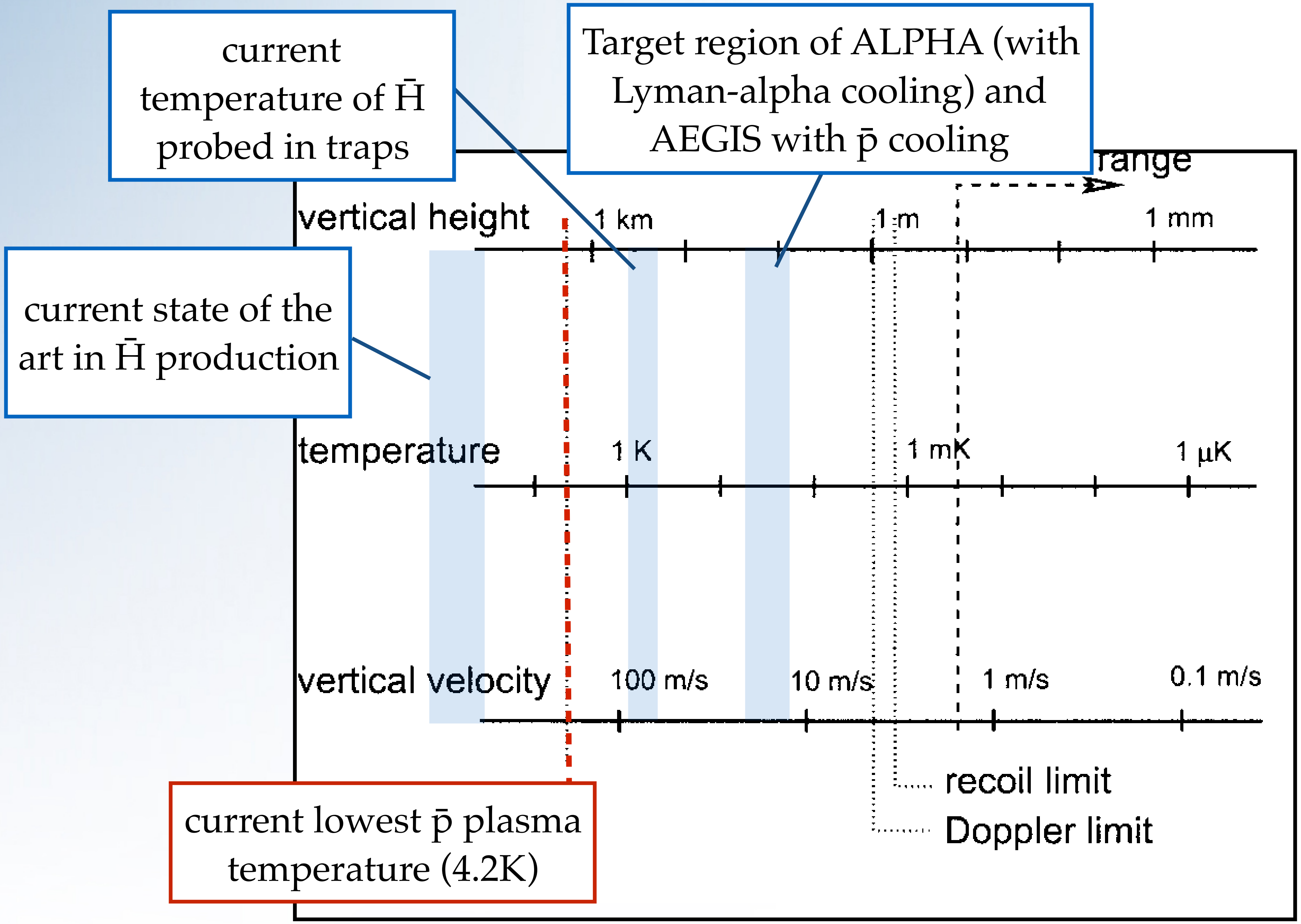

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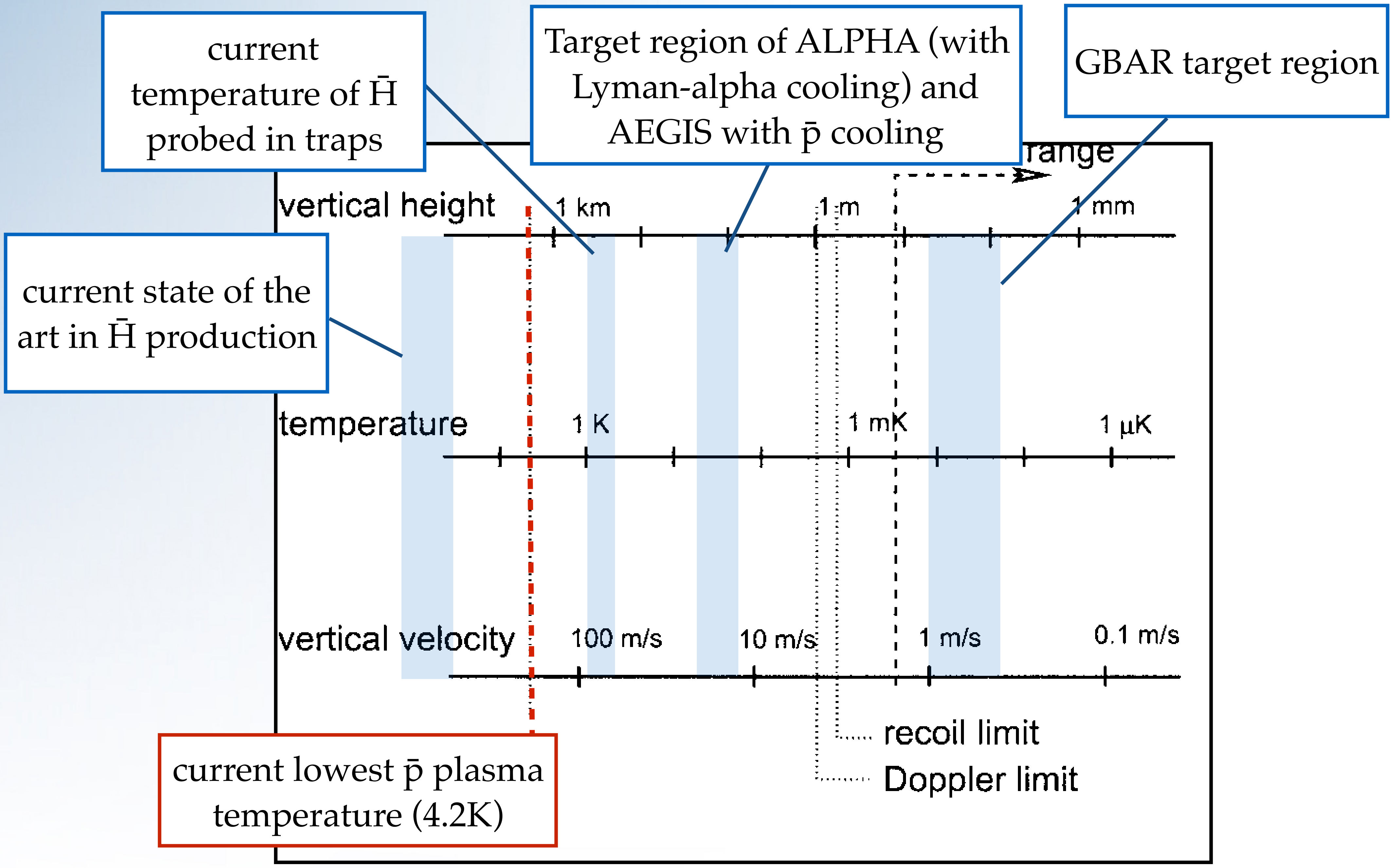


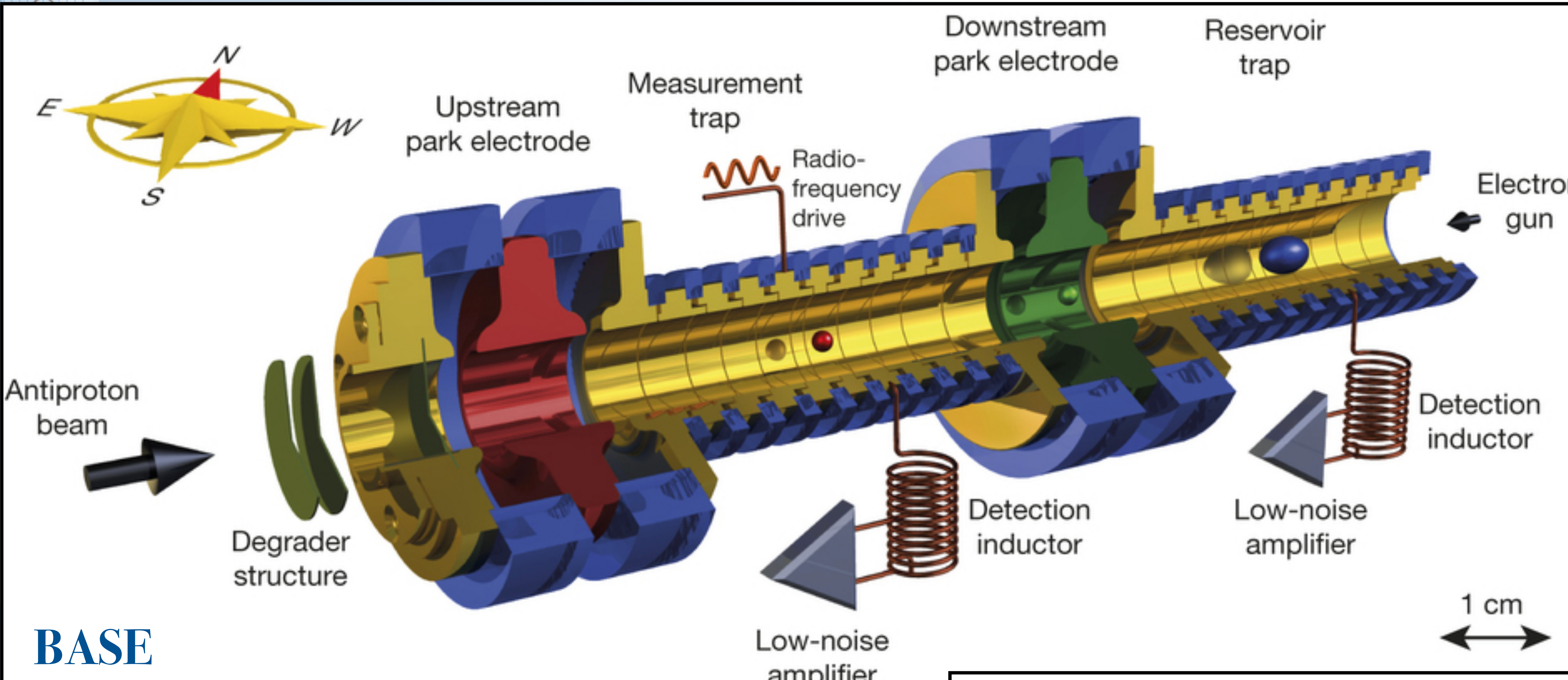
C. Malbrunot/CERN

ANTIPROTON STRUCTURE HIGHLIGHTS

The BASE collaboration :

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

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

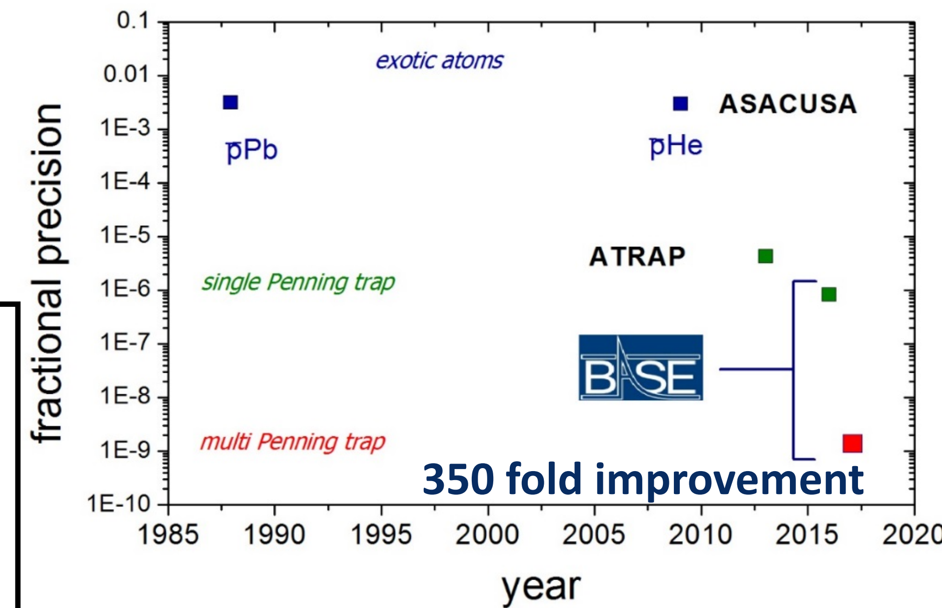


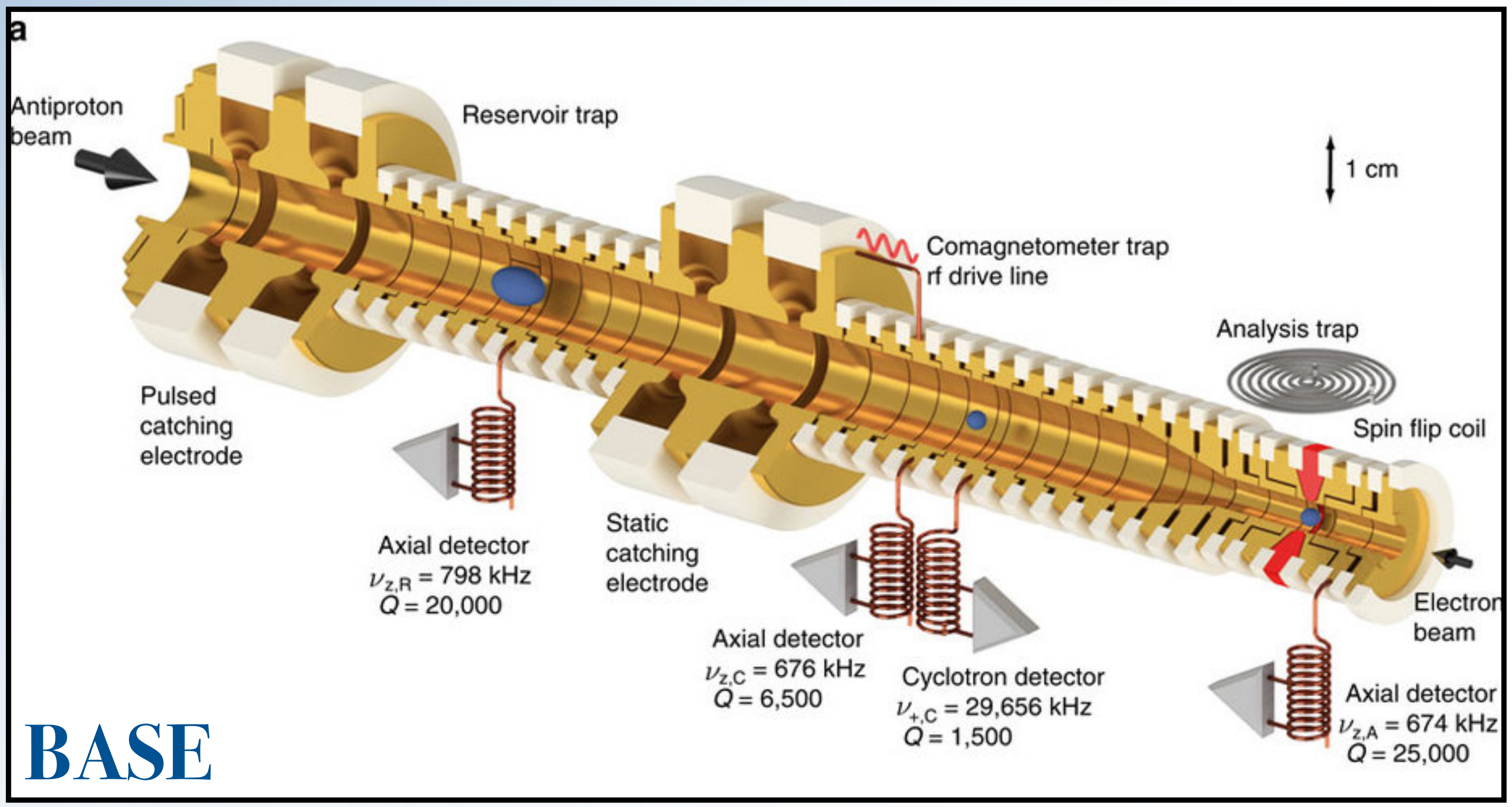
S. Ulmer et al., Nature 524, 196–199 (2015)

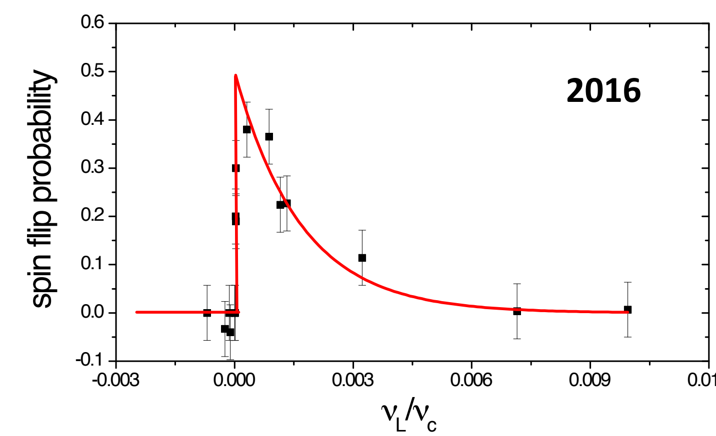
Previous work by the TRAP collaboration (@LEAR)
G. Gabrielse et al. Phys. Rev. Lett. 82, 3198 (1999)

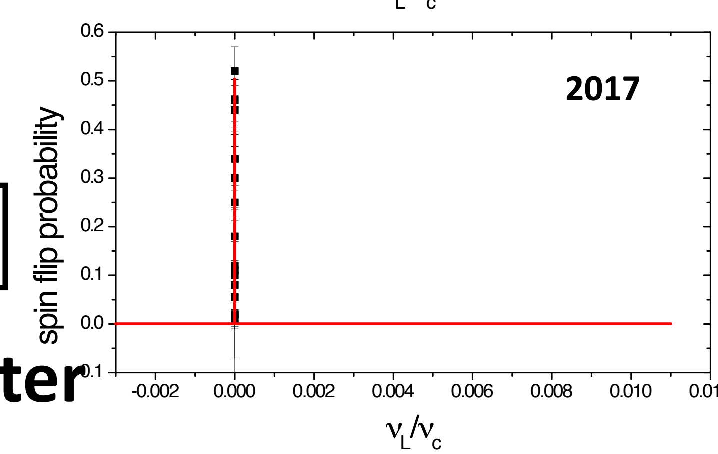
ANTIPROTON STRUCTURE HIGHLIGHTS

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









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

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

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

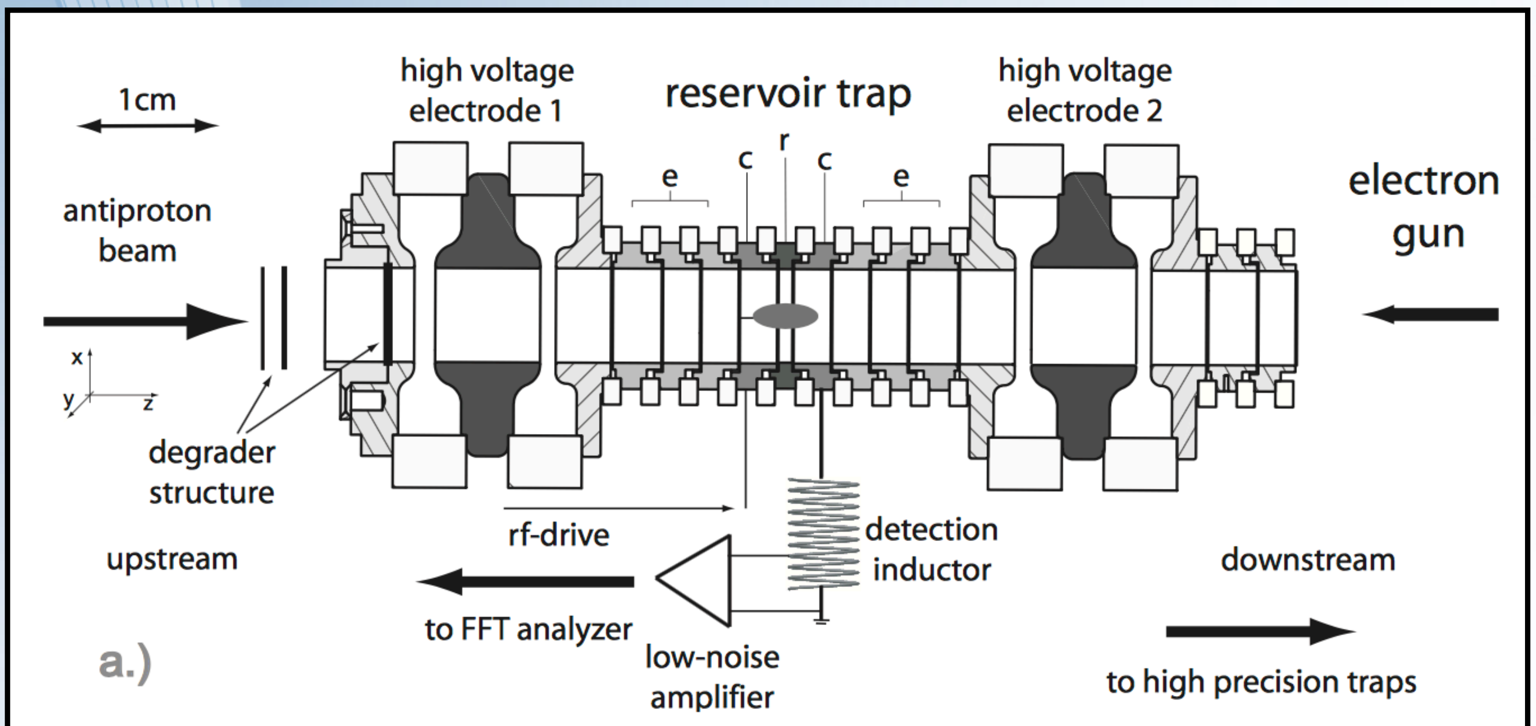
C. Smorra et al., Nature 550, 371 (2017)

first measurement more precise for antimatter than for matter

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

ANTIPROTON STRUCTURE HIGHLIGHTS

Reservoir trap for antiprotons

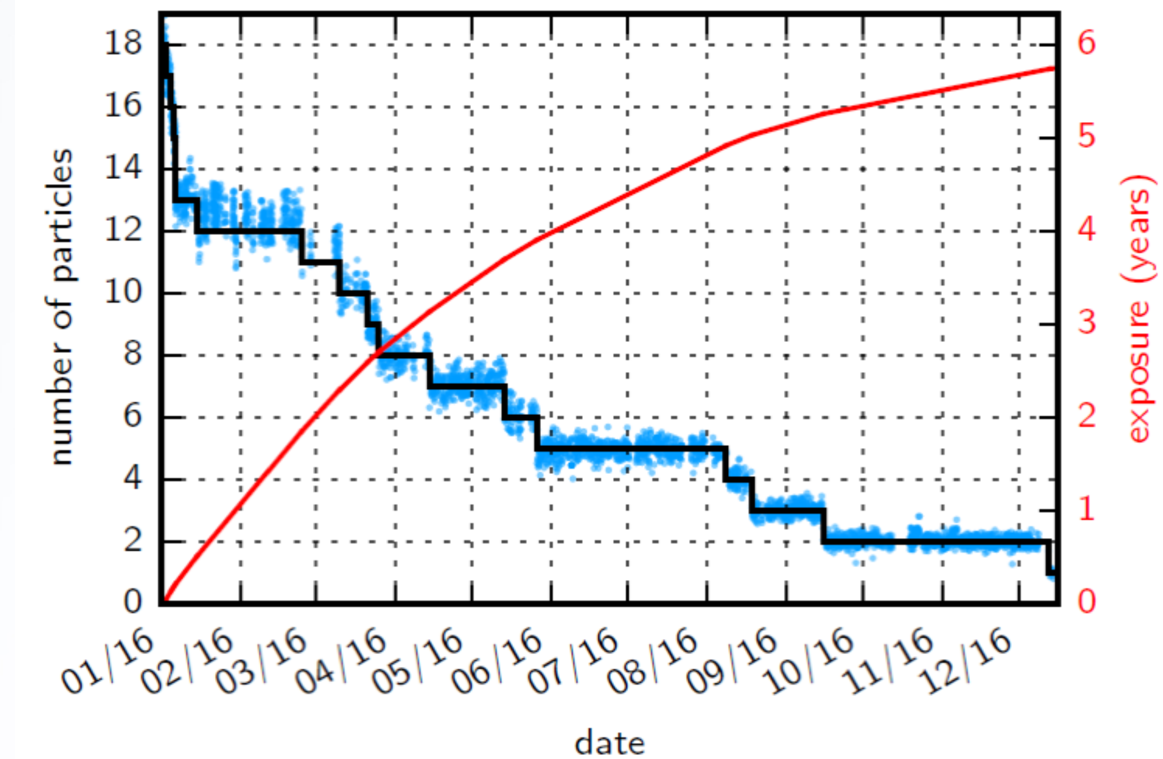


Enables operation with antiprotons independently of accelerator run times.

BASE operates antiproton experiments 365 days per year

C. Smorra, et al., Int. Journ. Mass Spec. 389, 10 (2015).

Antimatter trapping for 405 d



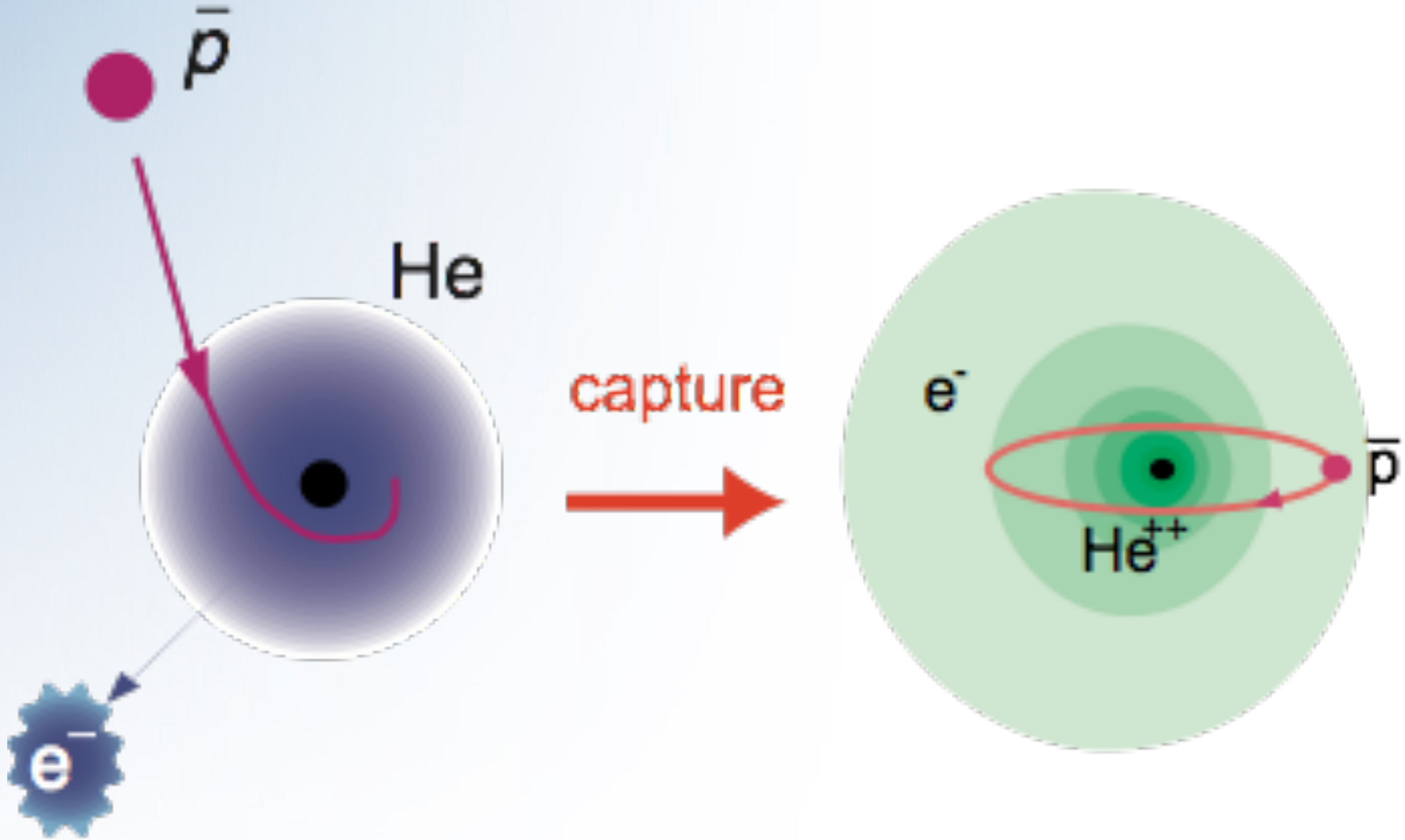
NEW LIMIT

$\tau_{\bar{p}} > 10.2\ a$

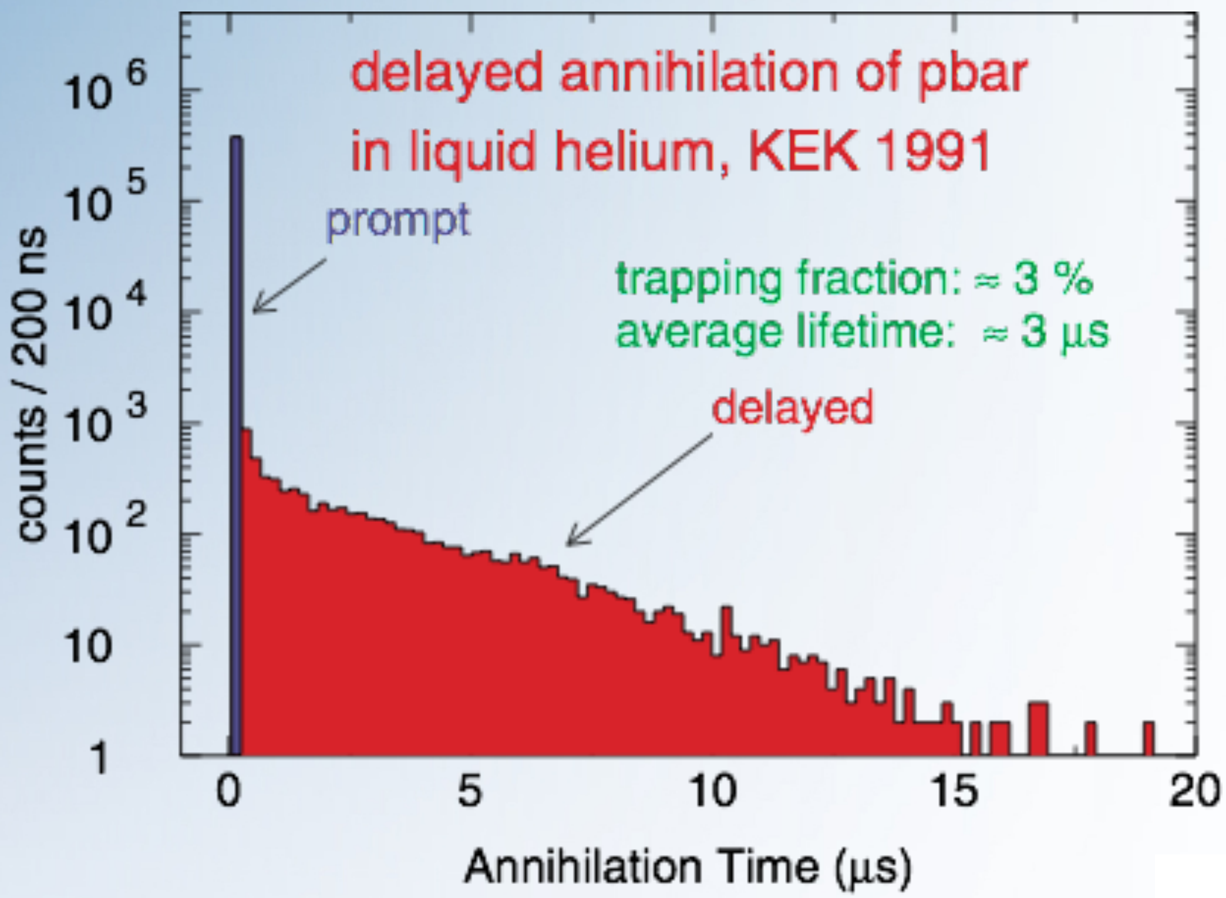
Most stringent limit on directly constrained antiproton lifetime

S. Sellner, New J. Phys. **19**, 083023 (2017)

ANTIPROTONIC HELIUM



ANTIPROTONIC HELIUM



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

Laser and microwave spectroscopy

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

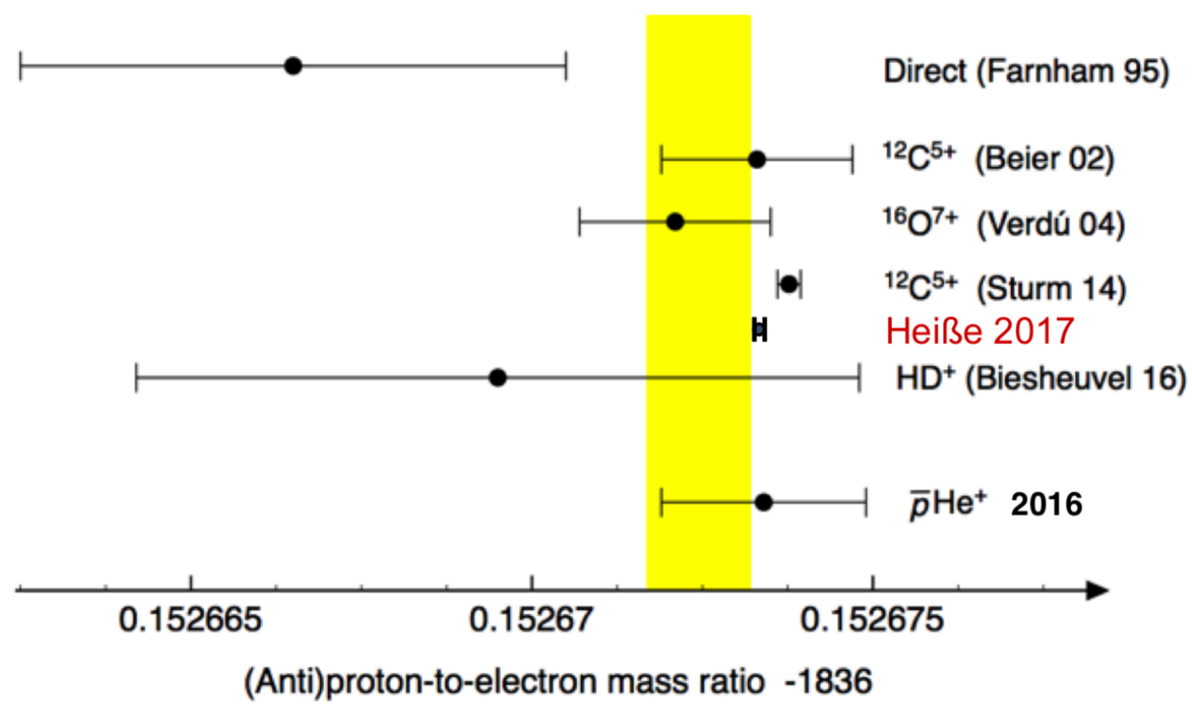
ASACUSA $\bar{p}$ - He

antiproton to electron mass ratio

$$\frac{m_{\bar{p}}}{m_{e^-}} = 1836.1526734(15)$$

$\bar{p}$-He cooled to ~1.5K (buffer-gas cooling)

Masaki Hori et al.
Science Vol. 354, 6312, pp. 610-614 (2016)



SUMMARY OF HIGHLIGHTS

SPECTROSCOPY OF $\bar{H}$

ALPHA : First $\bar{H}$ transitions measured with high precision in magnetic traps

Awaiting new measurements in beam experiments

GRAVITATIONAL STUDIES OF $\bar{H}$

Two new experiments coming online

Plurality of approaches and targeted sensitivities

ANTIPROTON PROPERTIES

More than 2 orders of magnitude improvement on $\bar{p}$ magnetic moment

Improved measurement on the antiproton to electron mass ratio

SUMMARY OF PROSPECTS

$\bar{H}$ 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)

MORE PHYSICS TO COME!