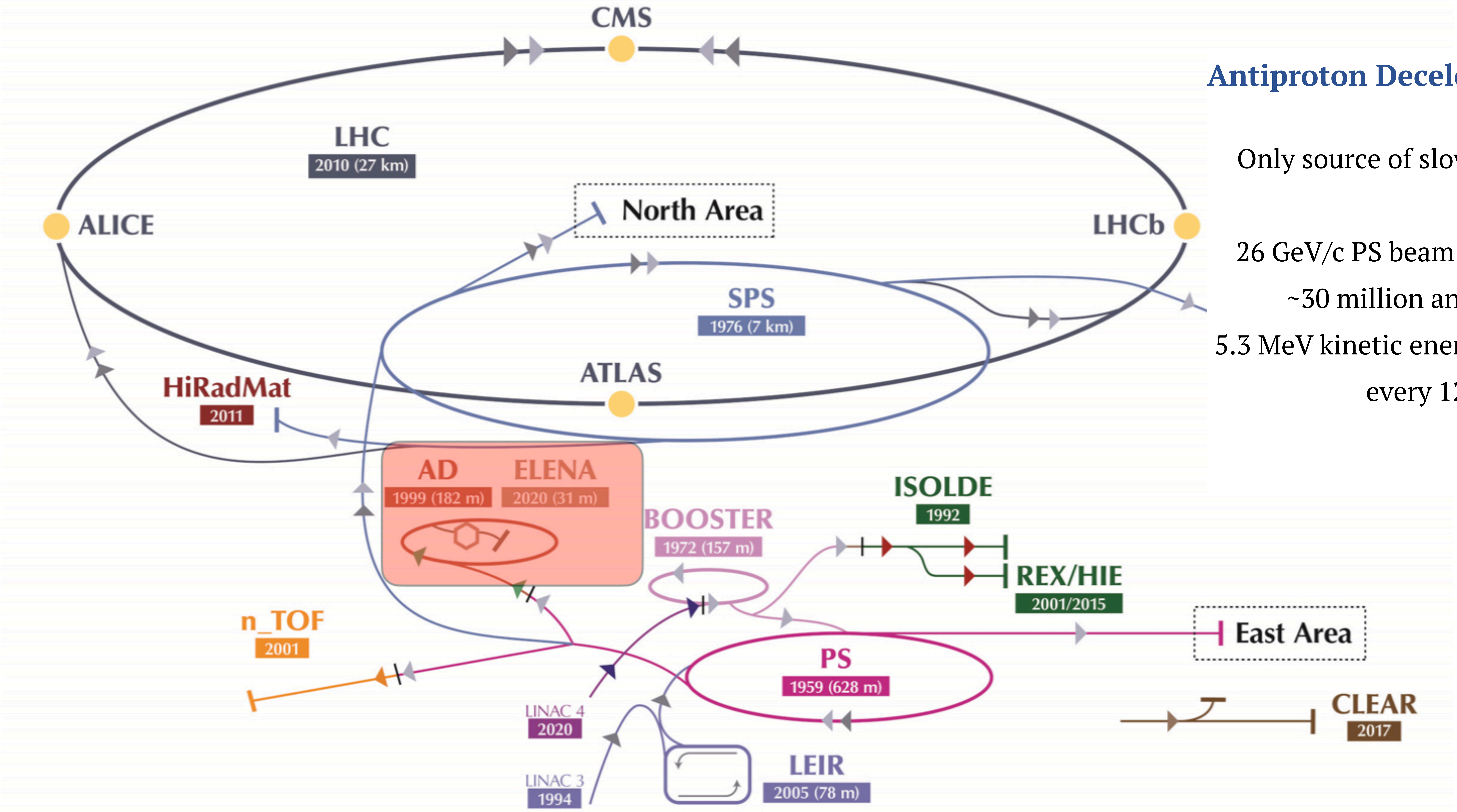
AD/ELENA au CERN
un complexe unique pour des mesures de précision sur l’antimatière

Chloé Malbrunot
CERN

on behalf of the AD experiments



Antiproton Decelerator (AD)

Only source of slow antiprotons

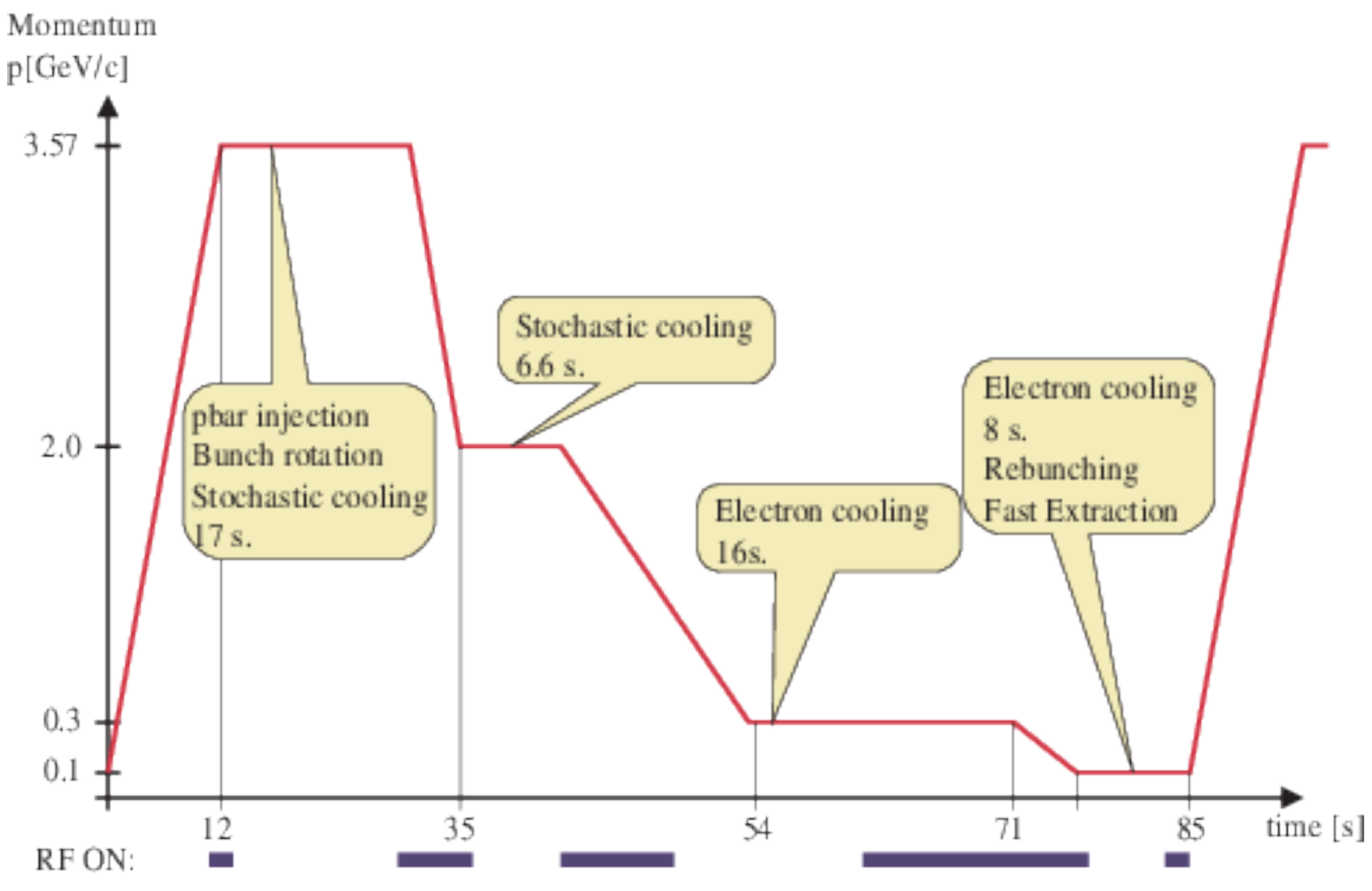
26 GeV/c PS beam onto Ir target

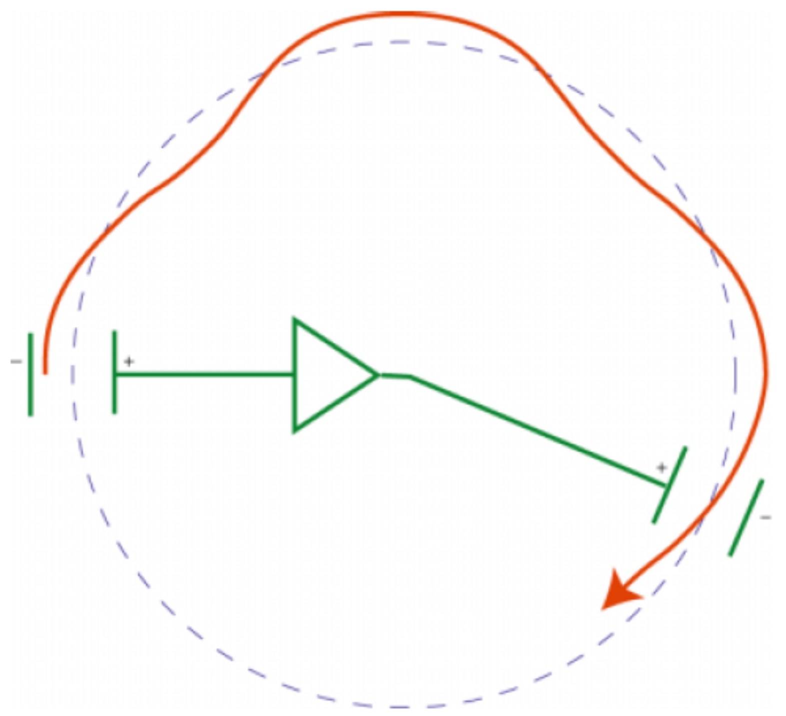
~30 million antiprotons

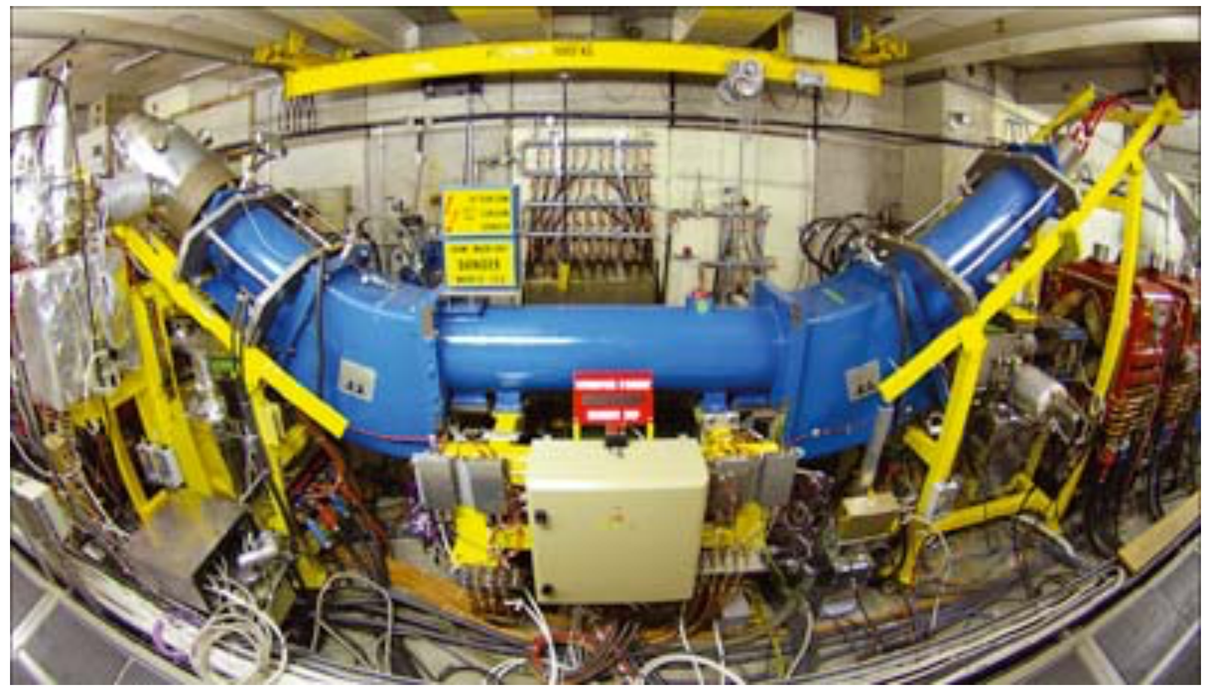
5.3 MeV kinetic energy (100 MeV/c)

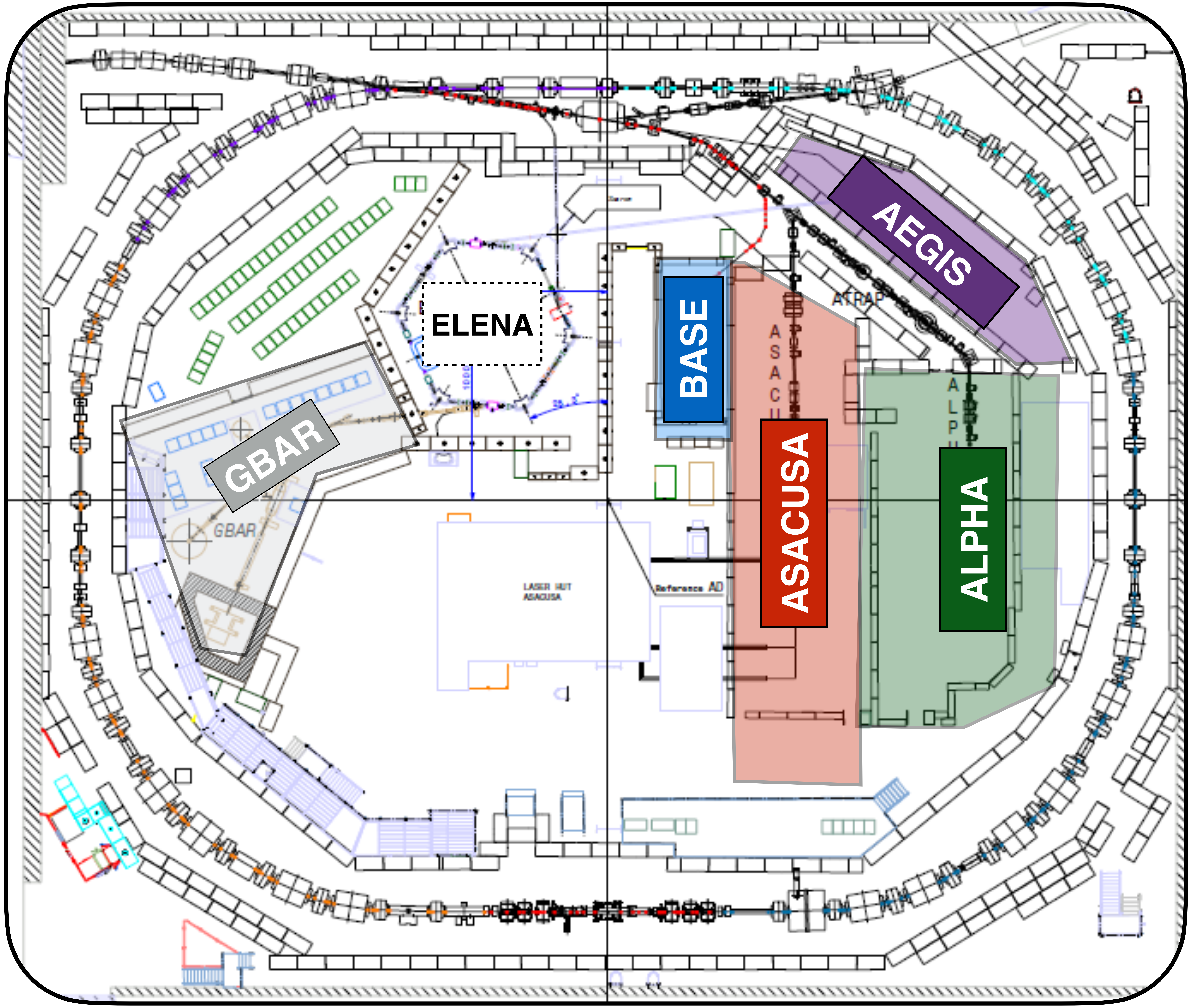
every 120s


CMS
LHC
2010 (27 km)
ALICE
ATLAS
HiRadMat
2011
AD
1999 (182 m)
ELENA
2020 (31 m)
n_TOF
2001
LINAC 3
1994
ELENA
GBAR
BASE
ASACUSA
ALPHA
AEGIS
ATRAP
LASER HUT ASACUSA
Reference AD









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

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

ELENA: a boost to the AD physics programme

AD:

p̄ caught in Penning traps using degraders
➙ 99.9% are lost

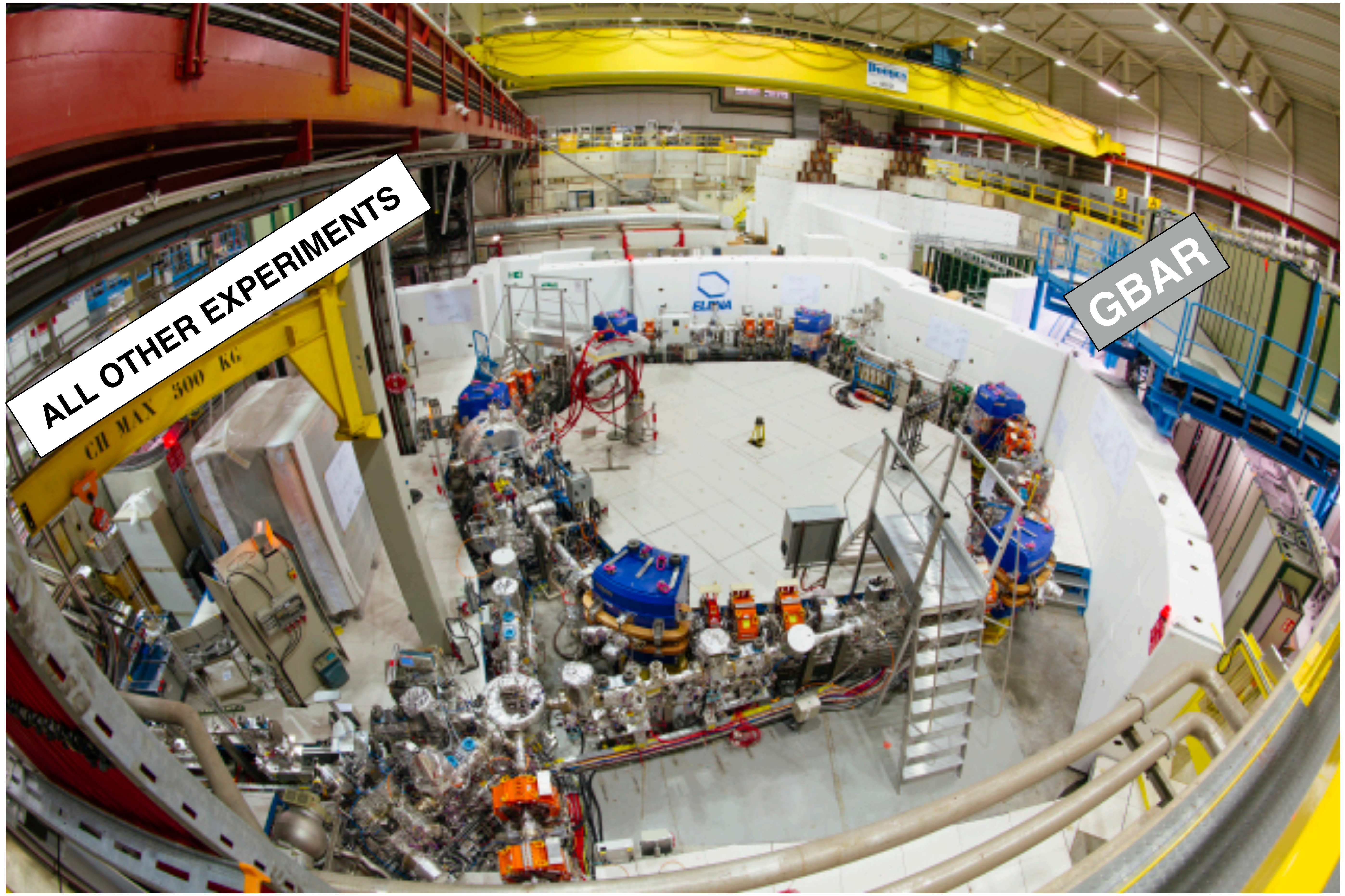
ELENA:

p̄ at 100 keV at improved beam emittance

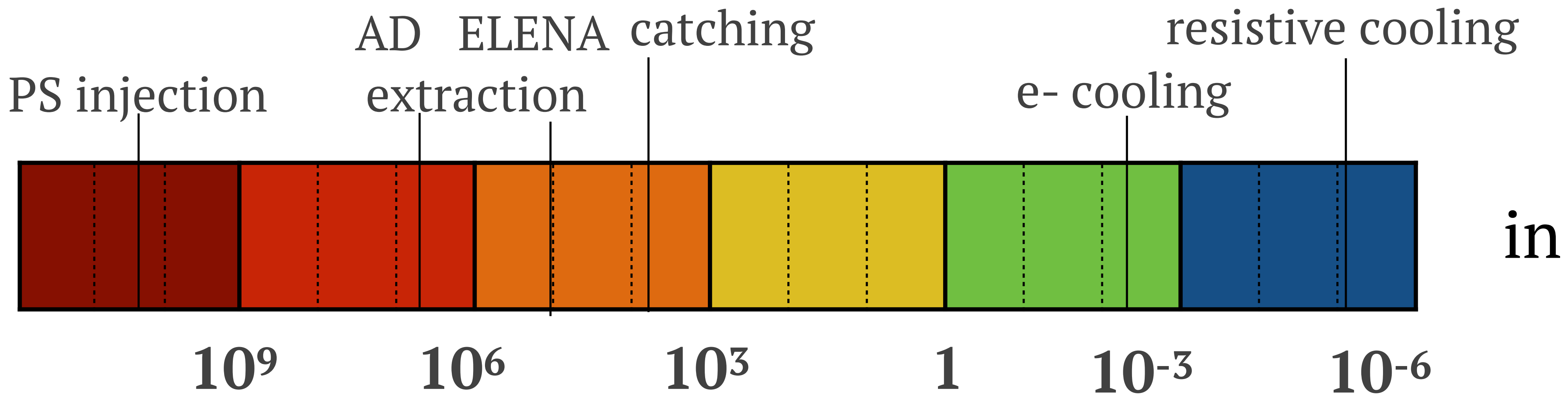
all experiments gain a factor 10-100
in trapping efficiency (degrading at low particle energies is more efficient)

“simultaneous” delivery to almost all experiments
➙ Gain in total beam time

additional experimental zone



Energy scale (ev)



in a few 100s seconds!!

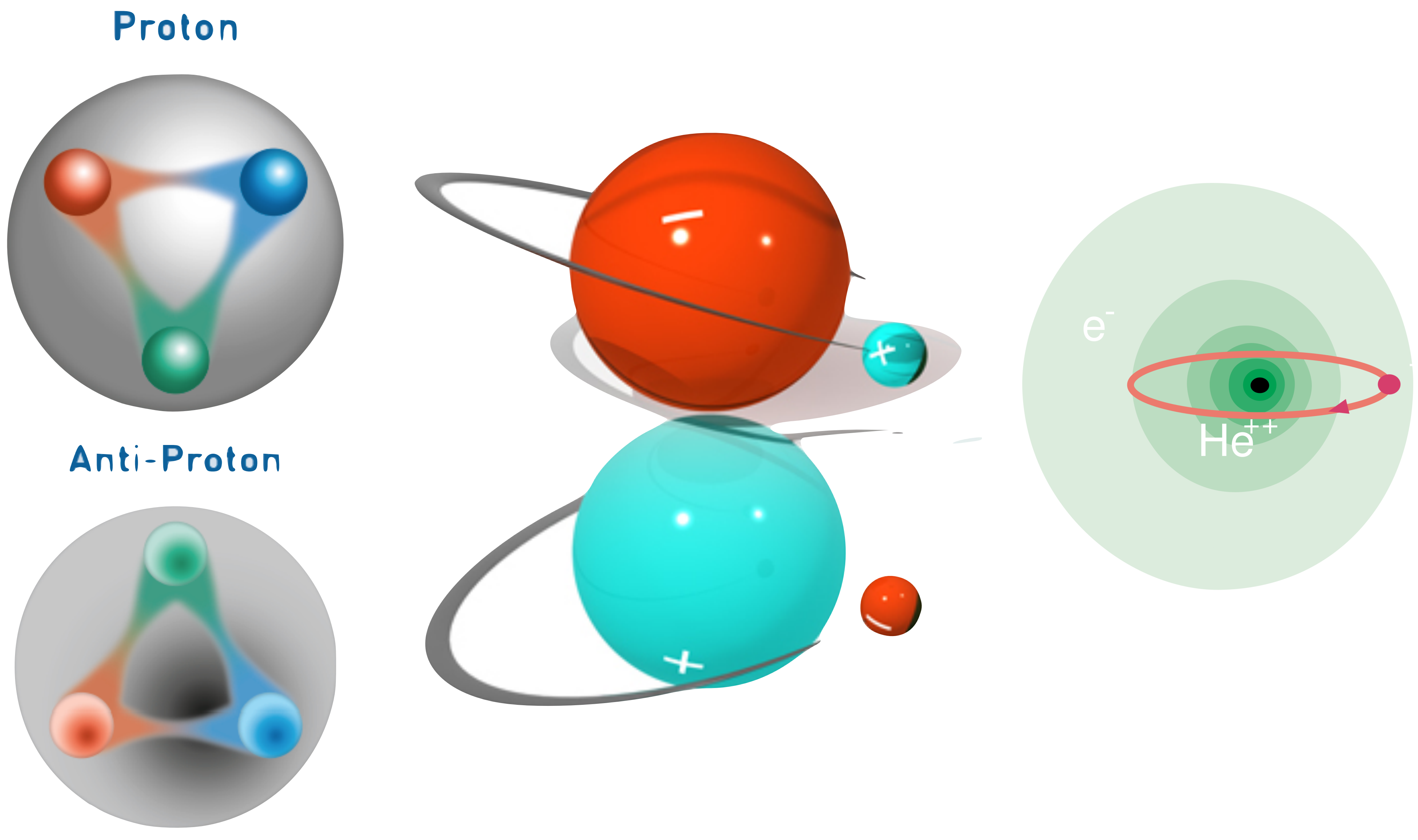
Variety of searches for new physics with low energy antiprotons

BASE ($\bar{p}$ in Penning trap), ASACUSA ($\bar{p}$He)
Fundamental properties of the antiproton

ALPHA
Spectroscopy of 1S-2S in antihydrogen

ASACUSA, ALPHA
Spectroscopy of GS-HFS in antihydrogen

ALPHA, AEgIS, GBAR
Test free fall/equivalence principle with antihydrogen

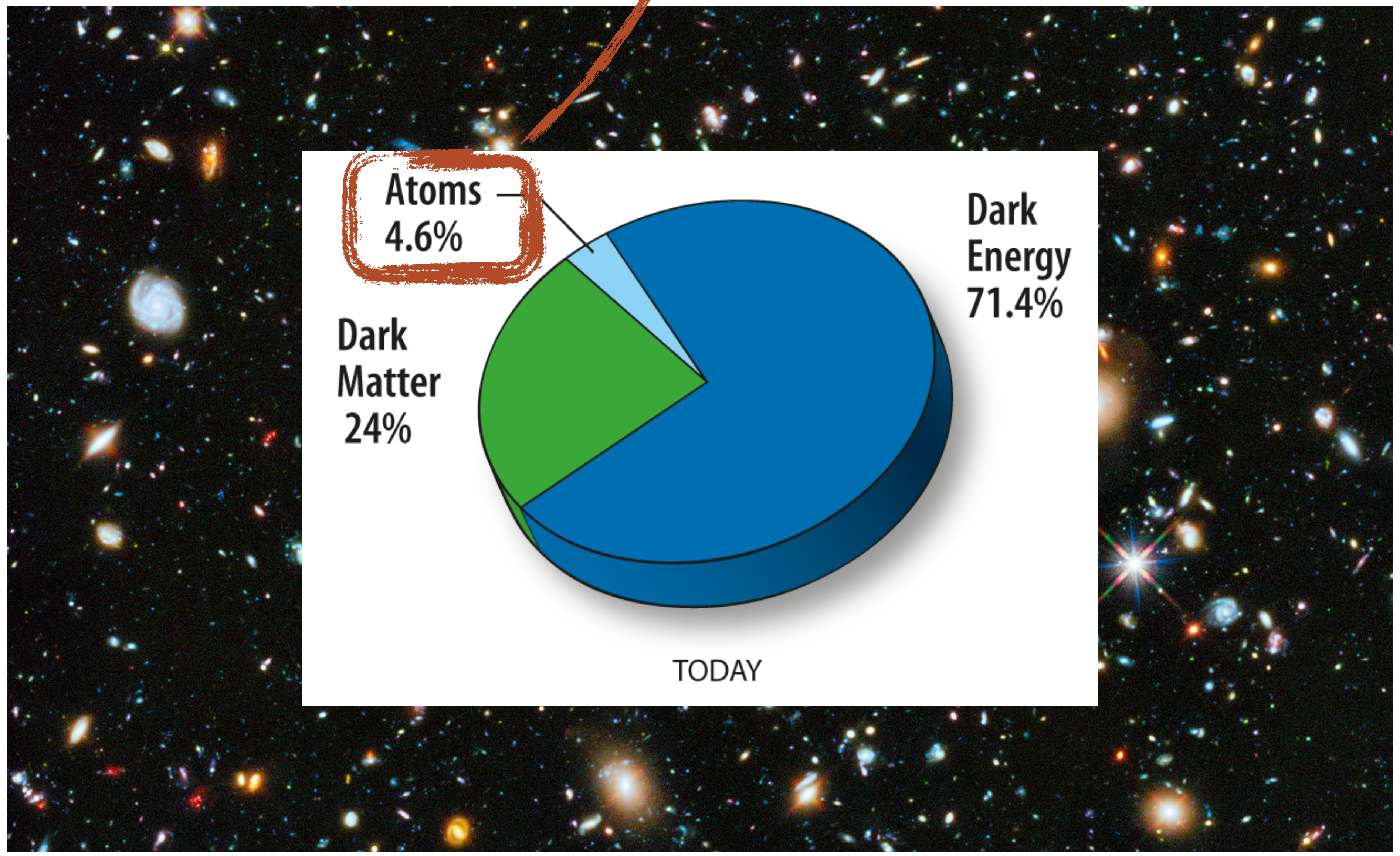


antiproton — antihydrogen — antiprotonic helium

AD community: ~60 research institues/universities - 400 researchers - 5 collaboration (+1 : connection to ISOLDE with the PUMA exp.)

Variety of searches for new physics with low energy antiprotons

Where are the anti-atoms??



Strong baryon asymmetry in the universe

originating from a ~10^{-10} imbalance

CP violation in the SM is by far not enough to explain this imbalance

Variety of searches for new physics with low energy antiprotons

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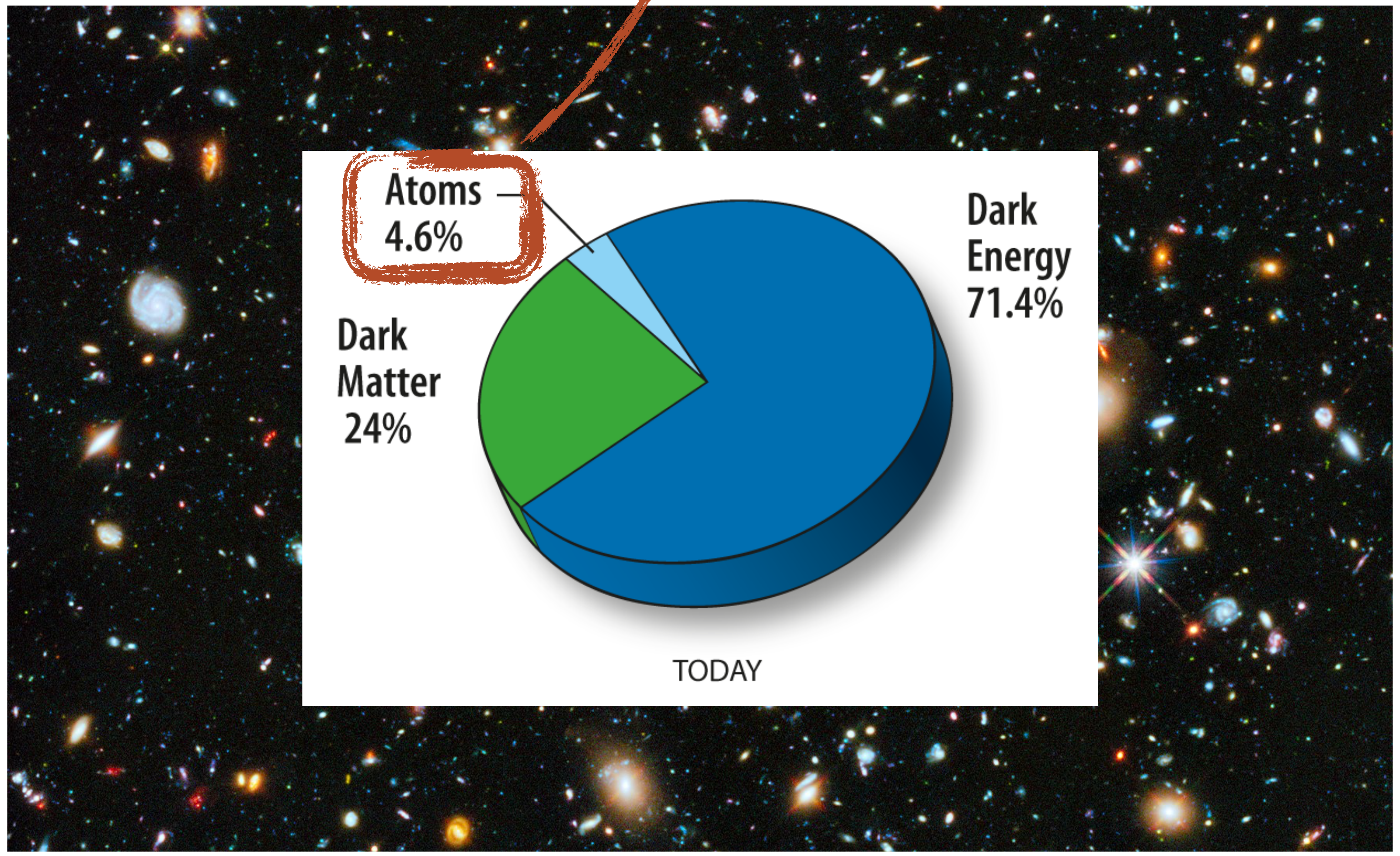

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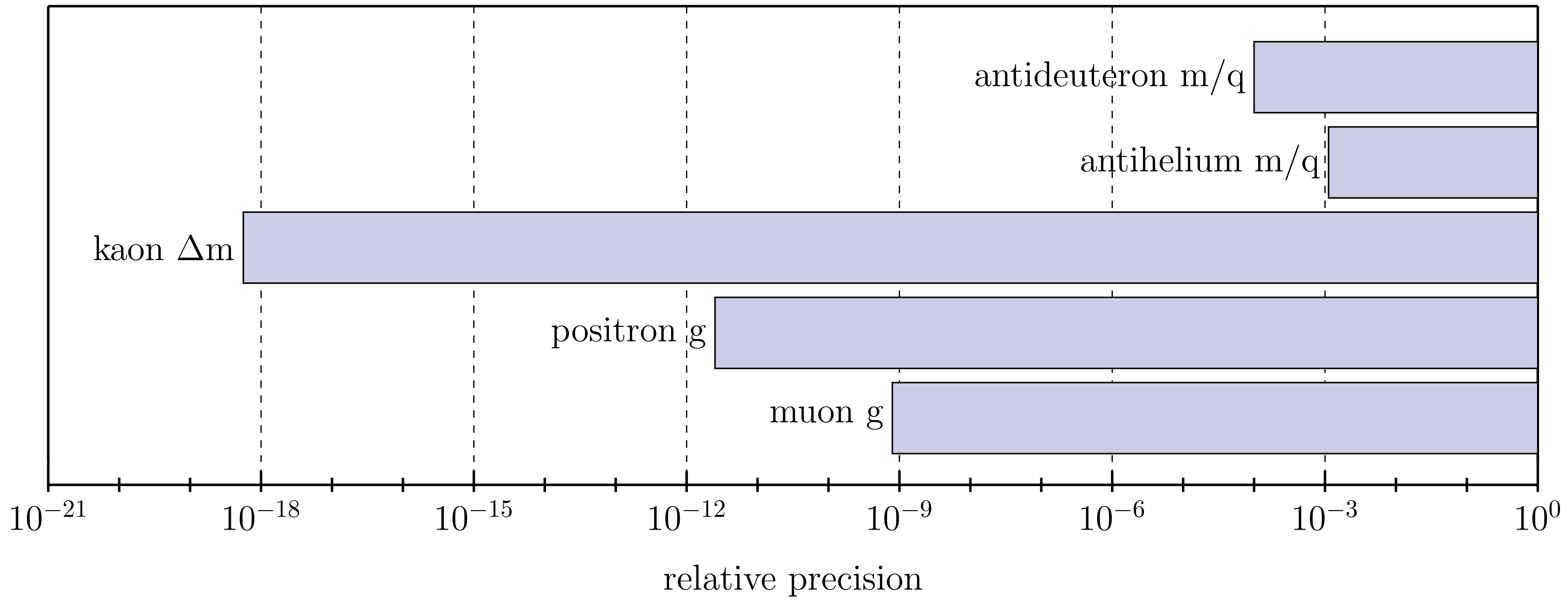
Comparison of fundamental properties of simple baryonic and anti-baryonic systems at low energy and with high precision



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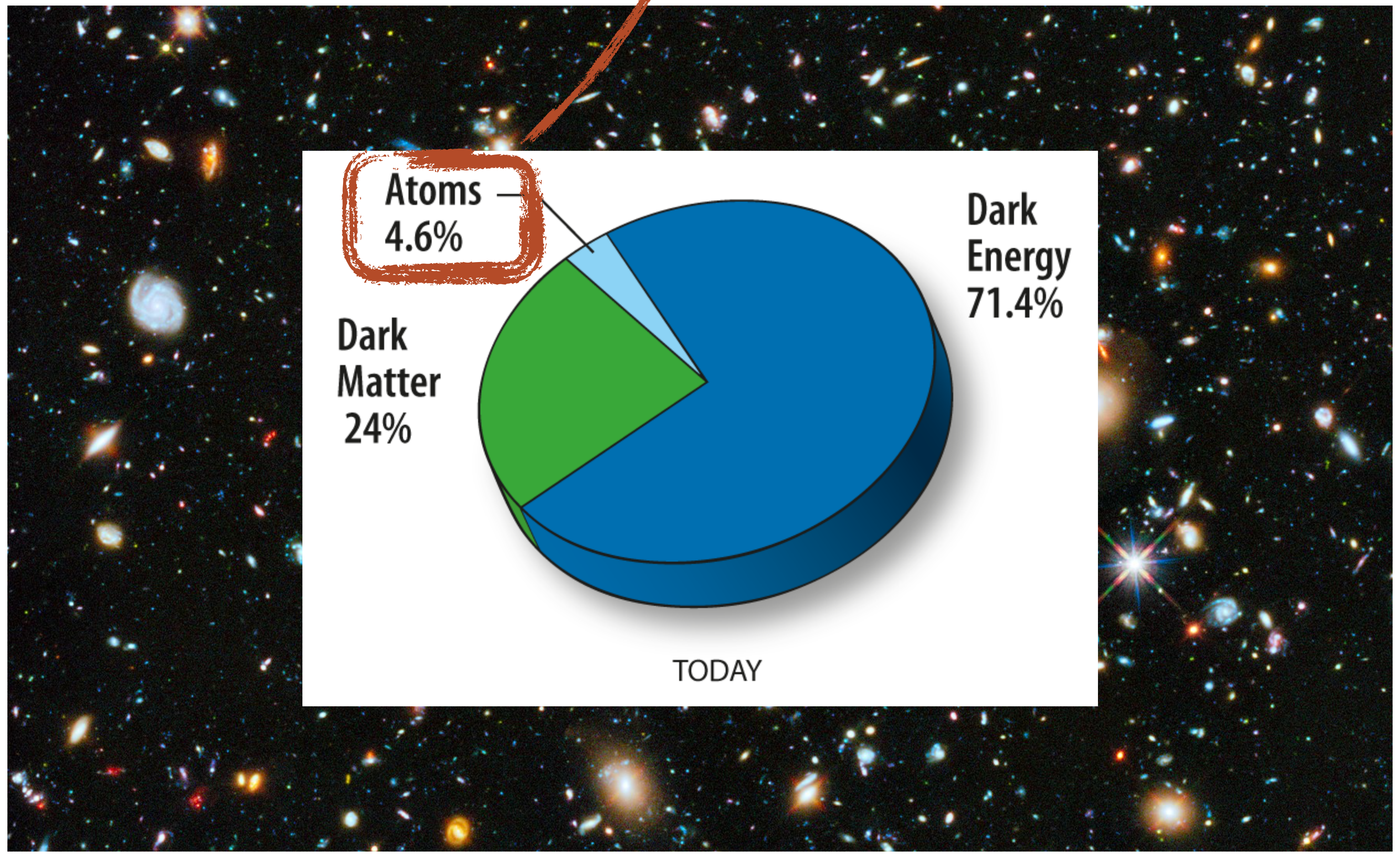

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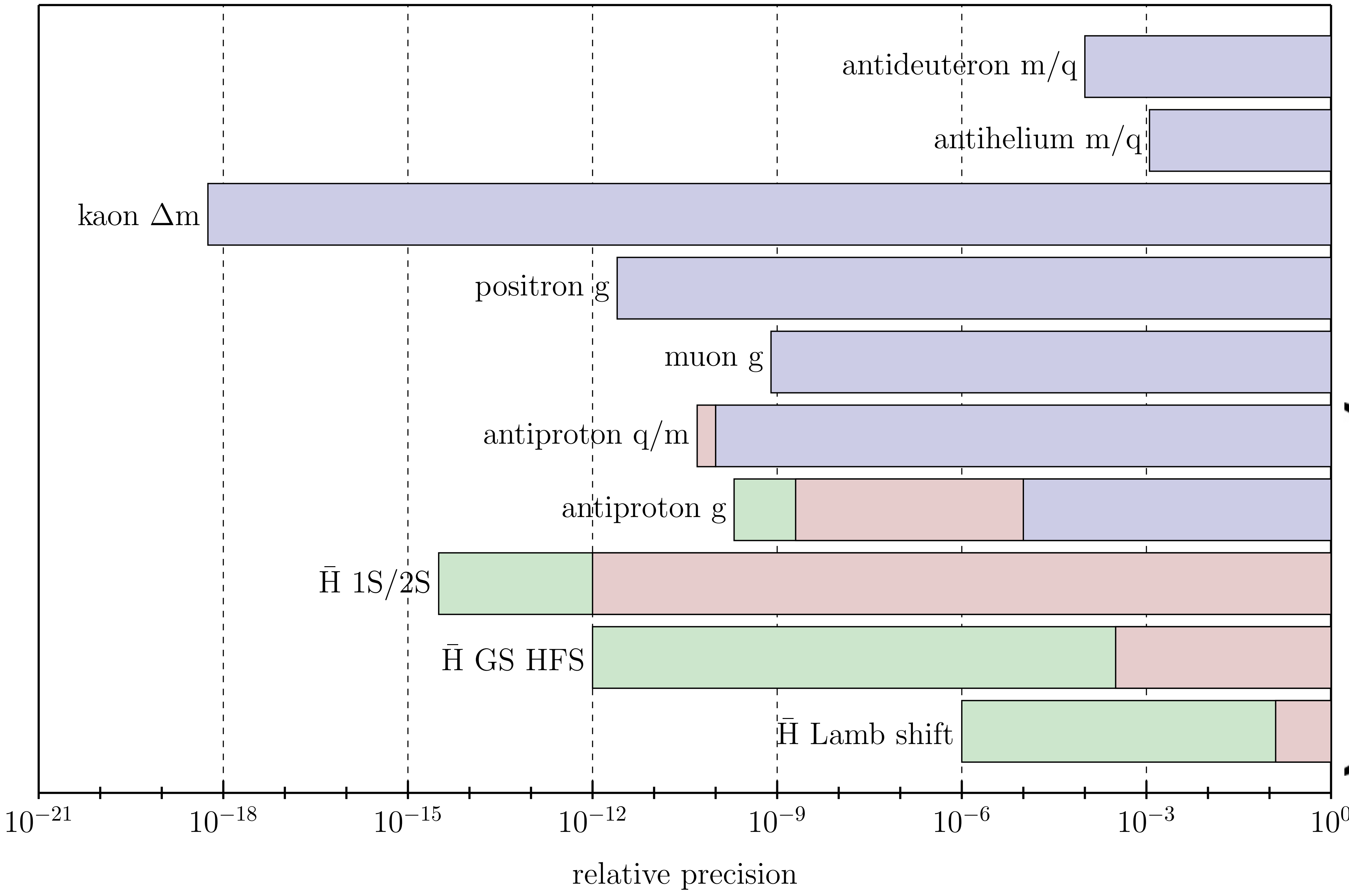

	relative precision	energy resolution [ev]
Kaon	~10^{-18}	~10^{-9}
$\bar{p}$ Q/M	~10^{-10}	~10^{-18}
$\bar{H}$ 1S-2S	~10^{-12}	~10^{-11}
$\bar{H}$ GS-HFS	~10^{-4}	~10^{-10}

In the SME framework absolute energy resolution matters
A. Kostelecky and A. Vargas, Phys. Rev. D 92, 056002 (2015)

AD

Precision reached on **hydrogen** and **proton**
Experimental knowledge prior 2015
Measurements (2015-2020)

Variety of searches for new physics with low energy antiprotons

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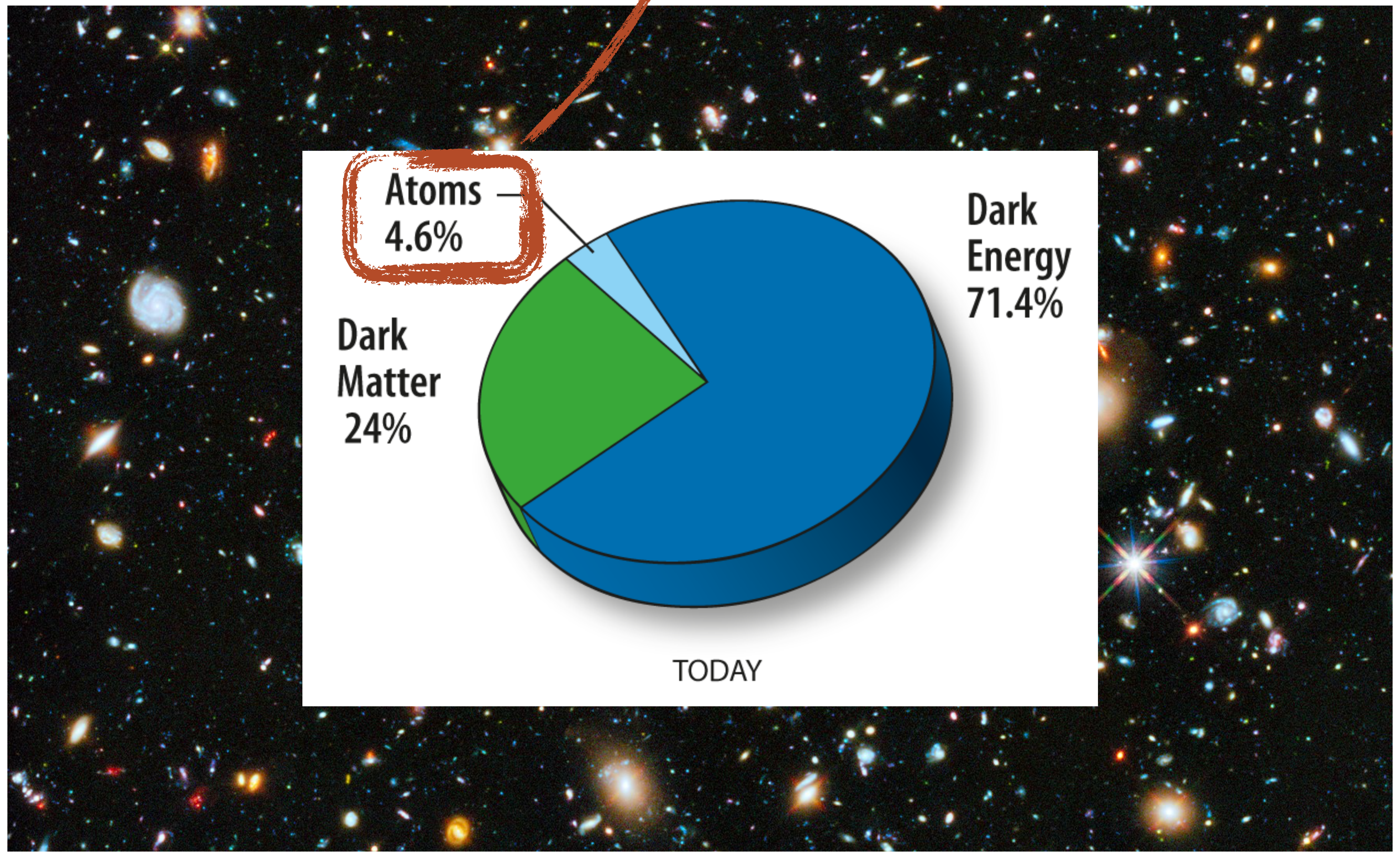

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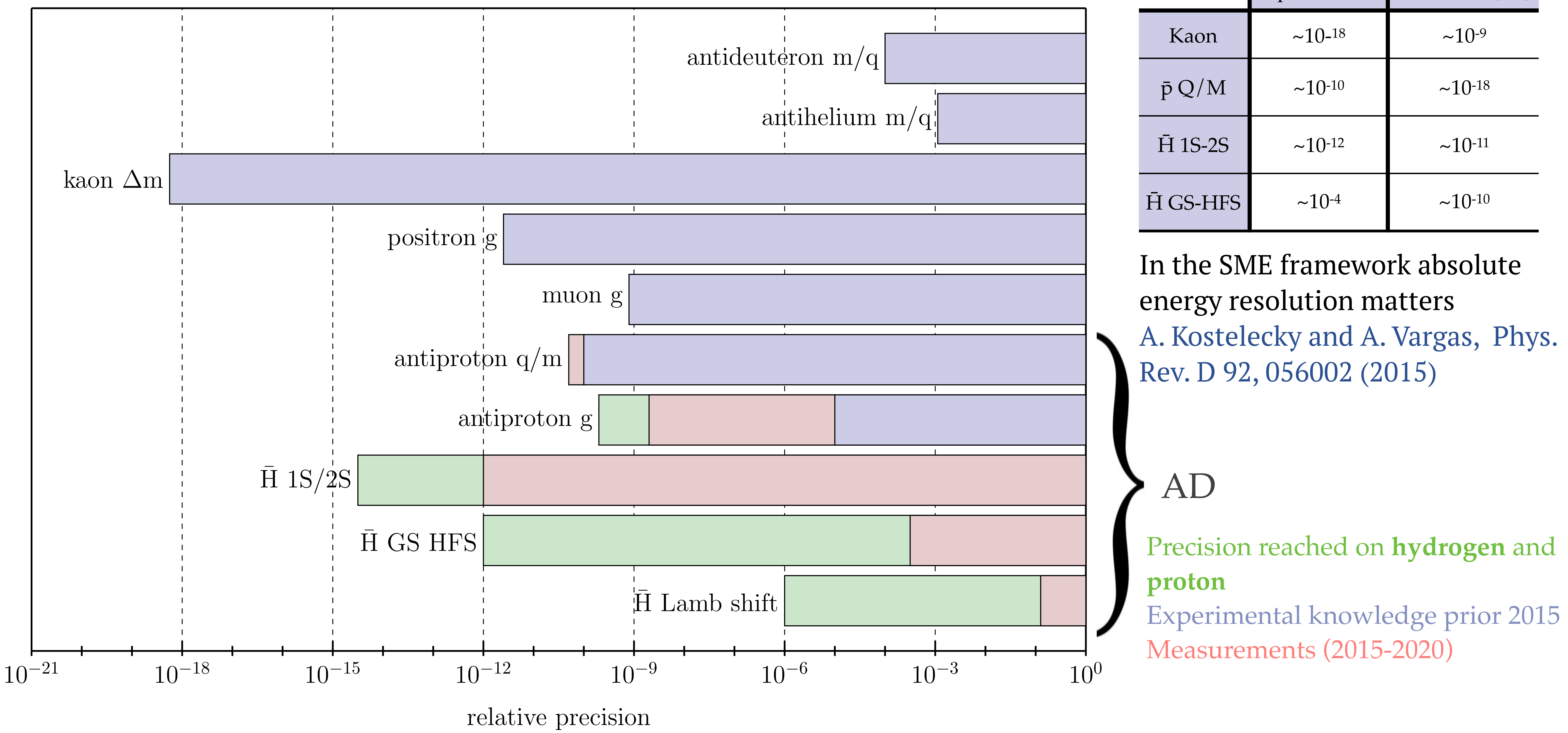

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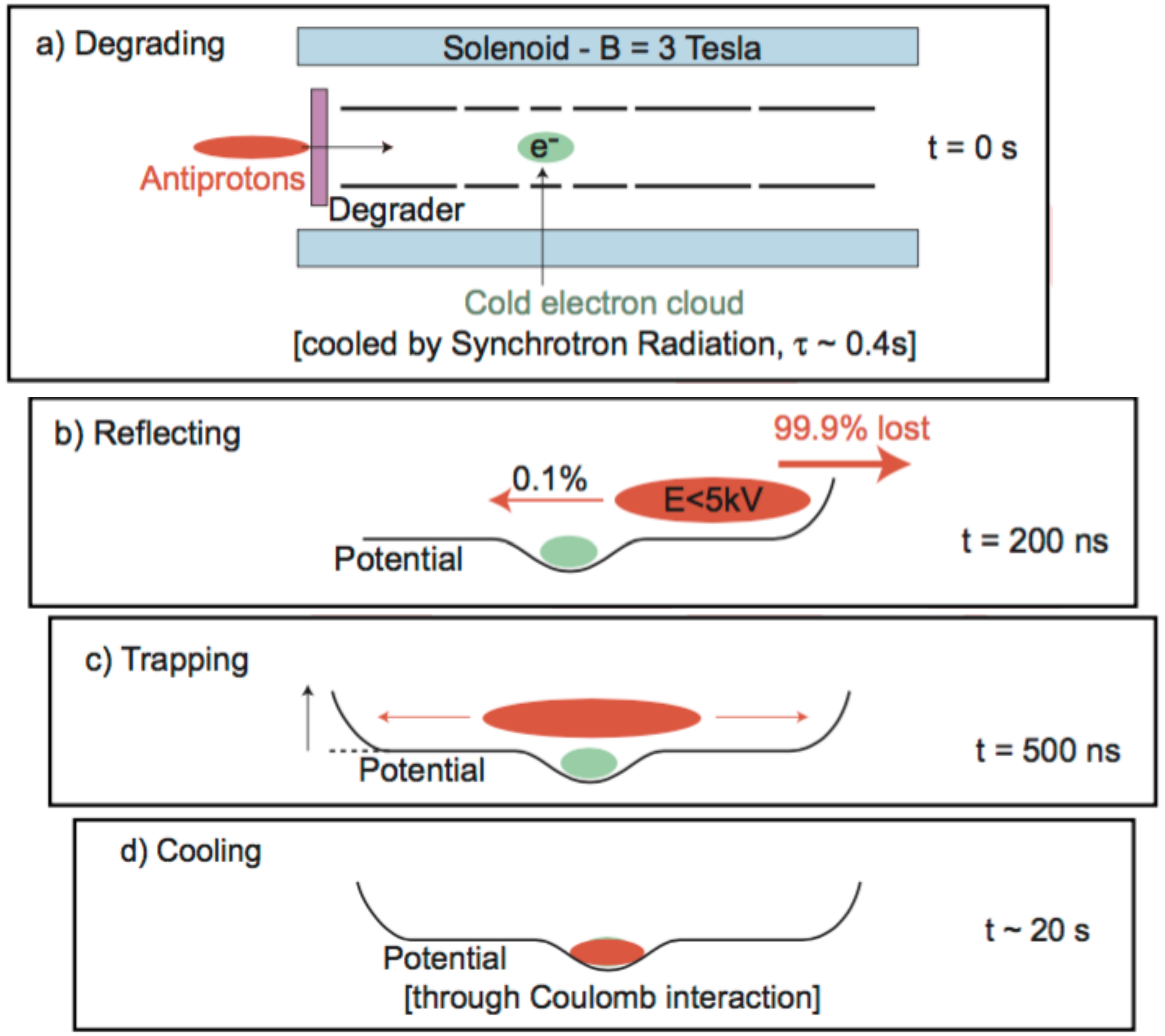
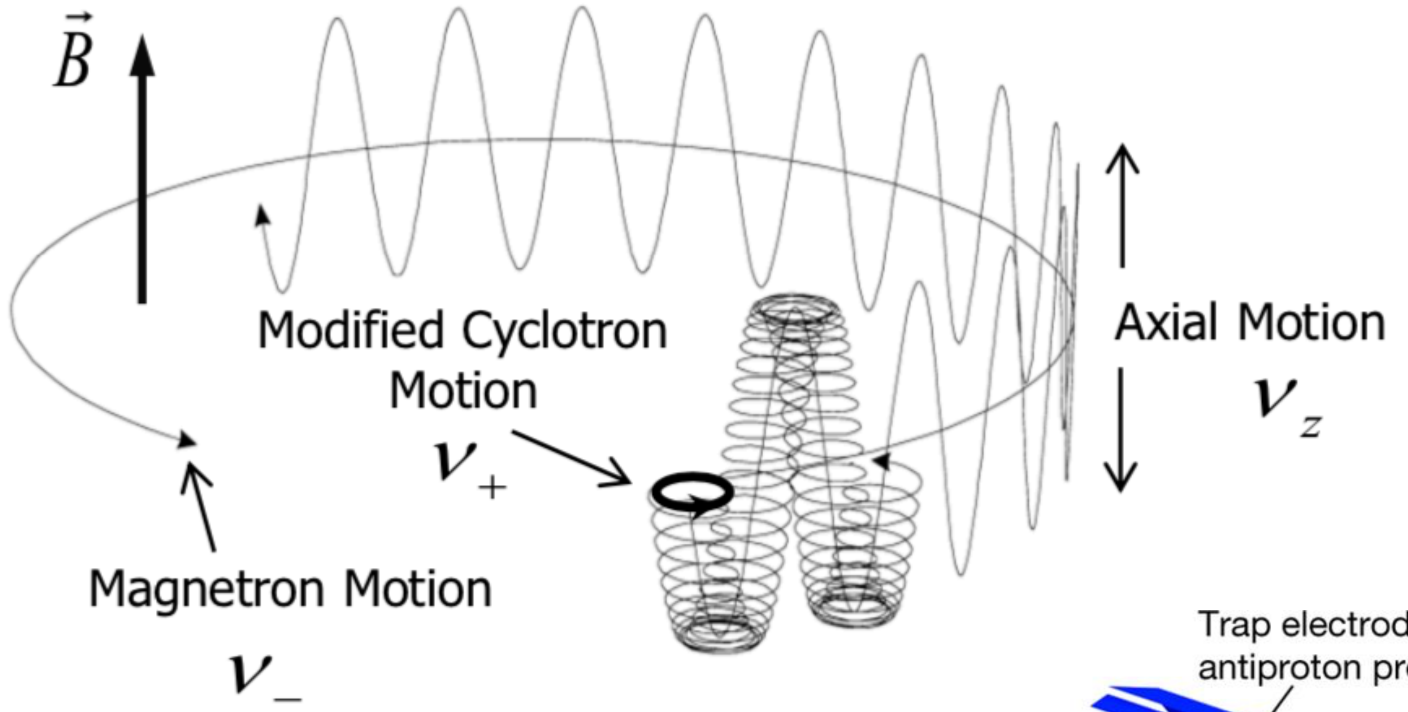
antimatter & gravity

Attempted measurements with charged antiparticles (e^+ in ~1967, p̄ in ~1985)
Indirect limits exists
Universality of free-fall never tested directly on antimatter

Low energy antiprotons for tests of baryon asymmetry

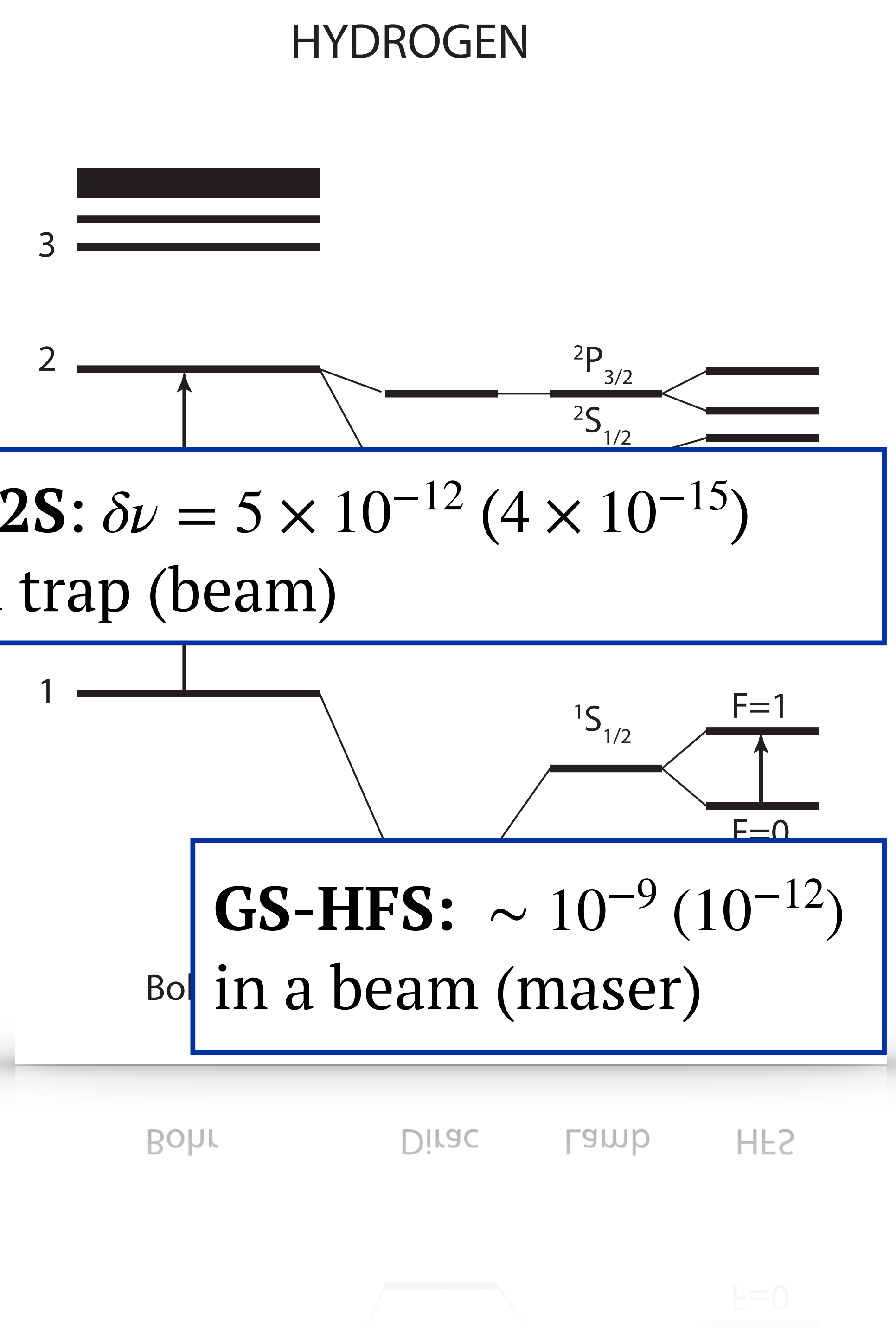
Workhorse Penning trap:





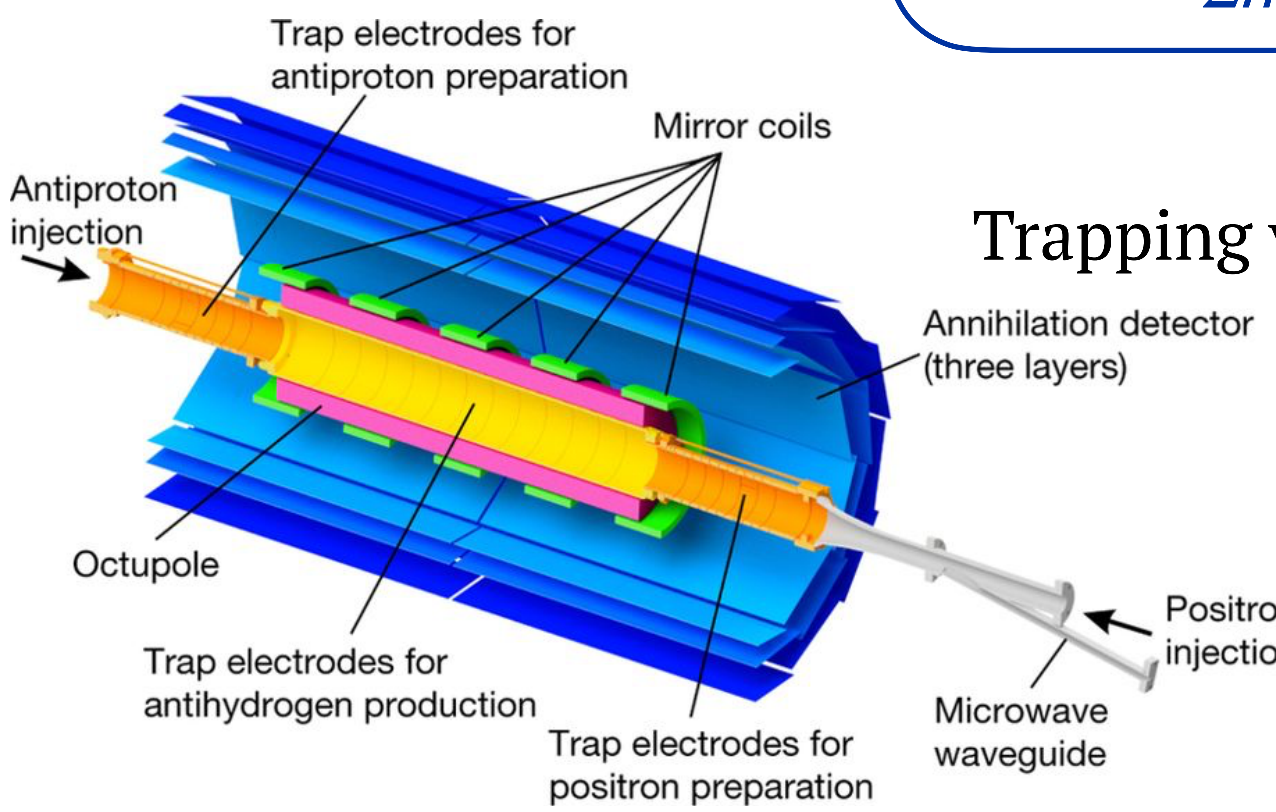
$$\omega_c = \frac{Q_{\bar{p}}}{m_{\bar{p}}} B$$ charge-to-mass ratios

$$\omega_L = g \frac{Q_{\bar{p}}}{2m_{\bar{p}}} B$$ magnetic moments



1S-2S: $\delta\nu = 5 \times 10^{-12}$ (4×10^{-15})
in a trap (beam)

GS-HFS: $\sim 10^{-9}$ (10^{-12})
in a beam (maser)



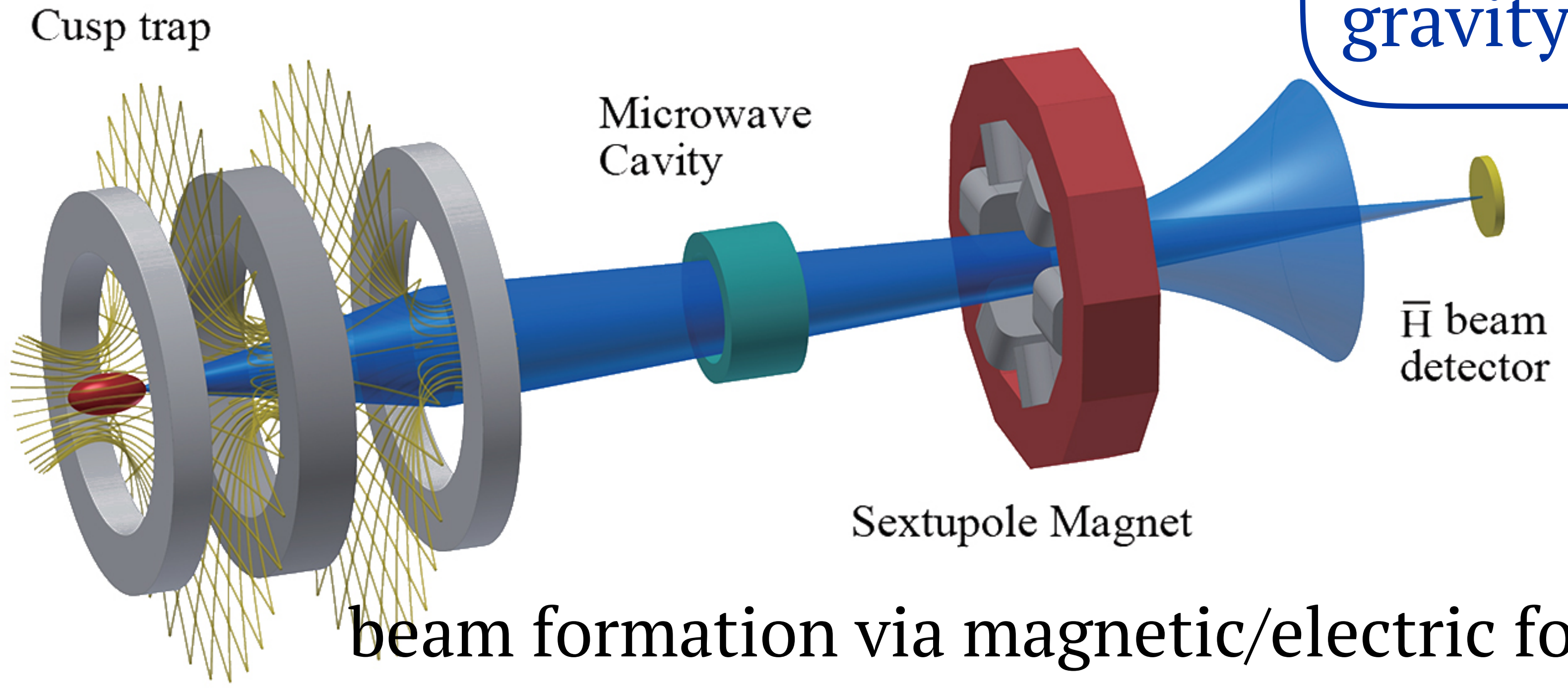
Trapping via magnetic moment

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

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

spectroscopy
1S-2S
GS-HFS
gravity

CHALLENGES
⬆ Temperature limit, inhomogeneous fields
⬇ $\bar{H}$ rate, presence of excited states

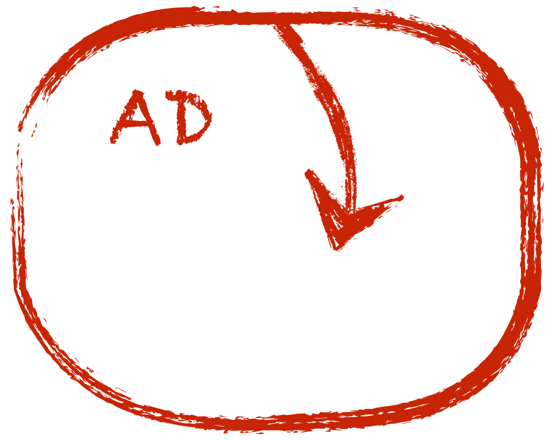


beam formation via magnetic/electric focussing

Long trapping times require good vacuum!

BASE experiment: P < 2. 10^{-18} mbar
$\tau(\bar{p}) > 10.2$ years

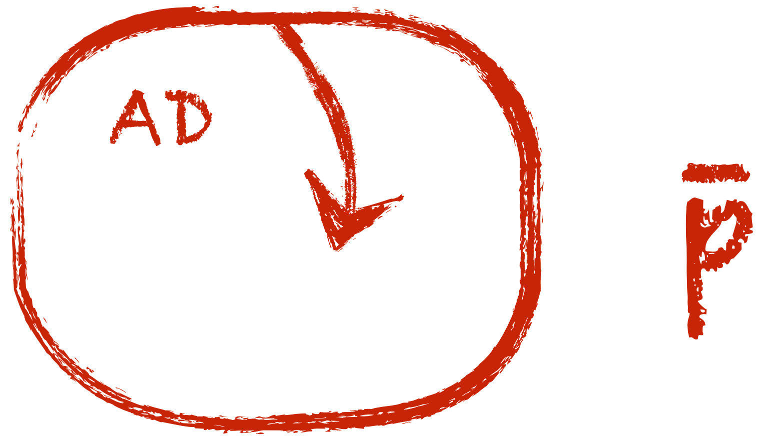
antihydrogen formation: several approaches



$\bar{p}$

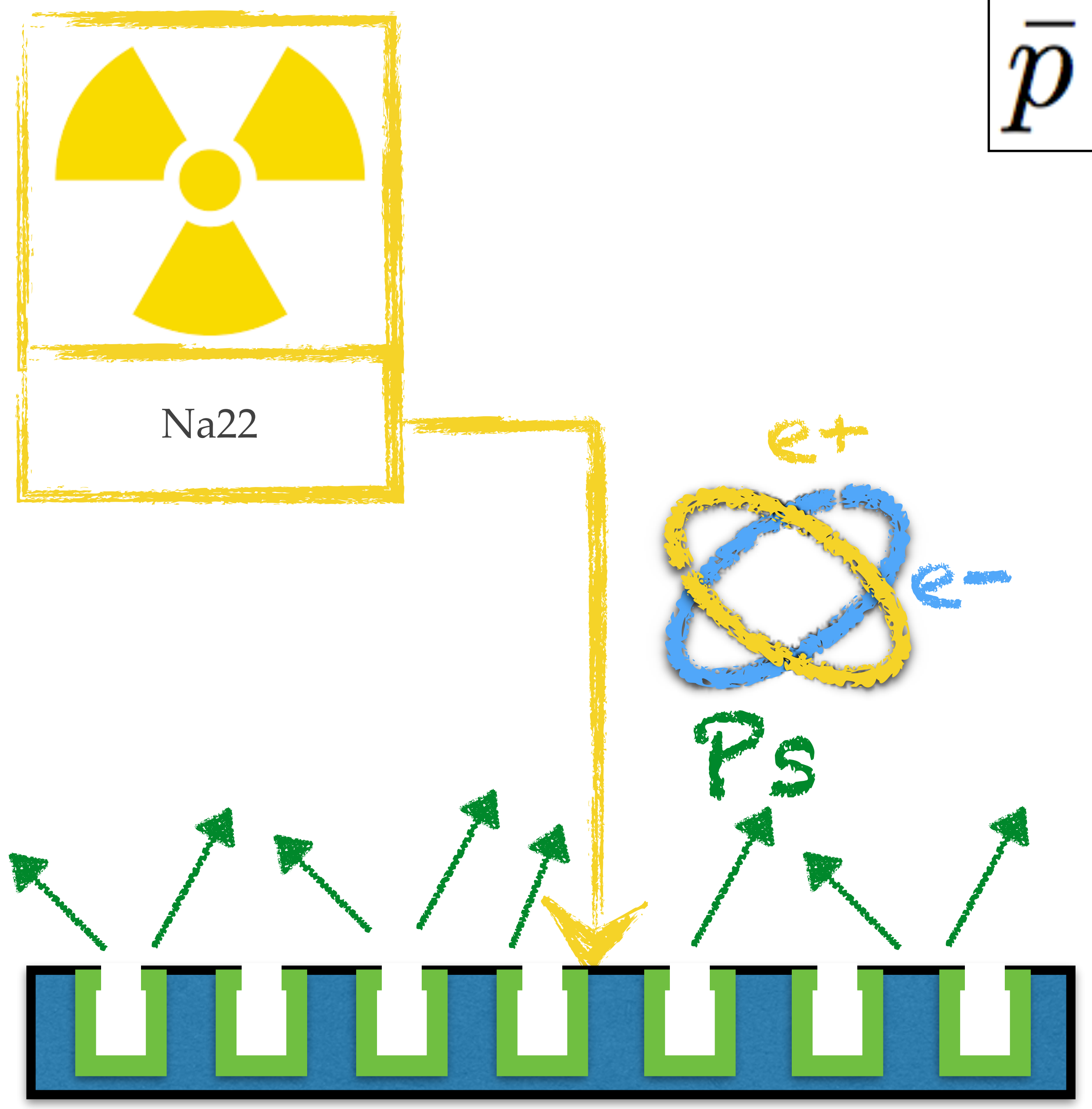
$$\boxed{\bar{p} + e^{+} + e^{+} \rightarrow \bar{H} + e^{+}}$$

antihydrogen formation: several approaches



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

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



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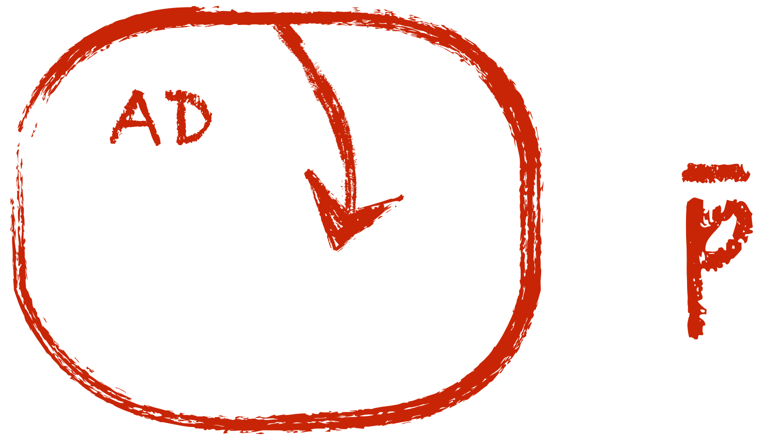
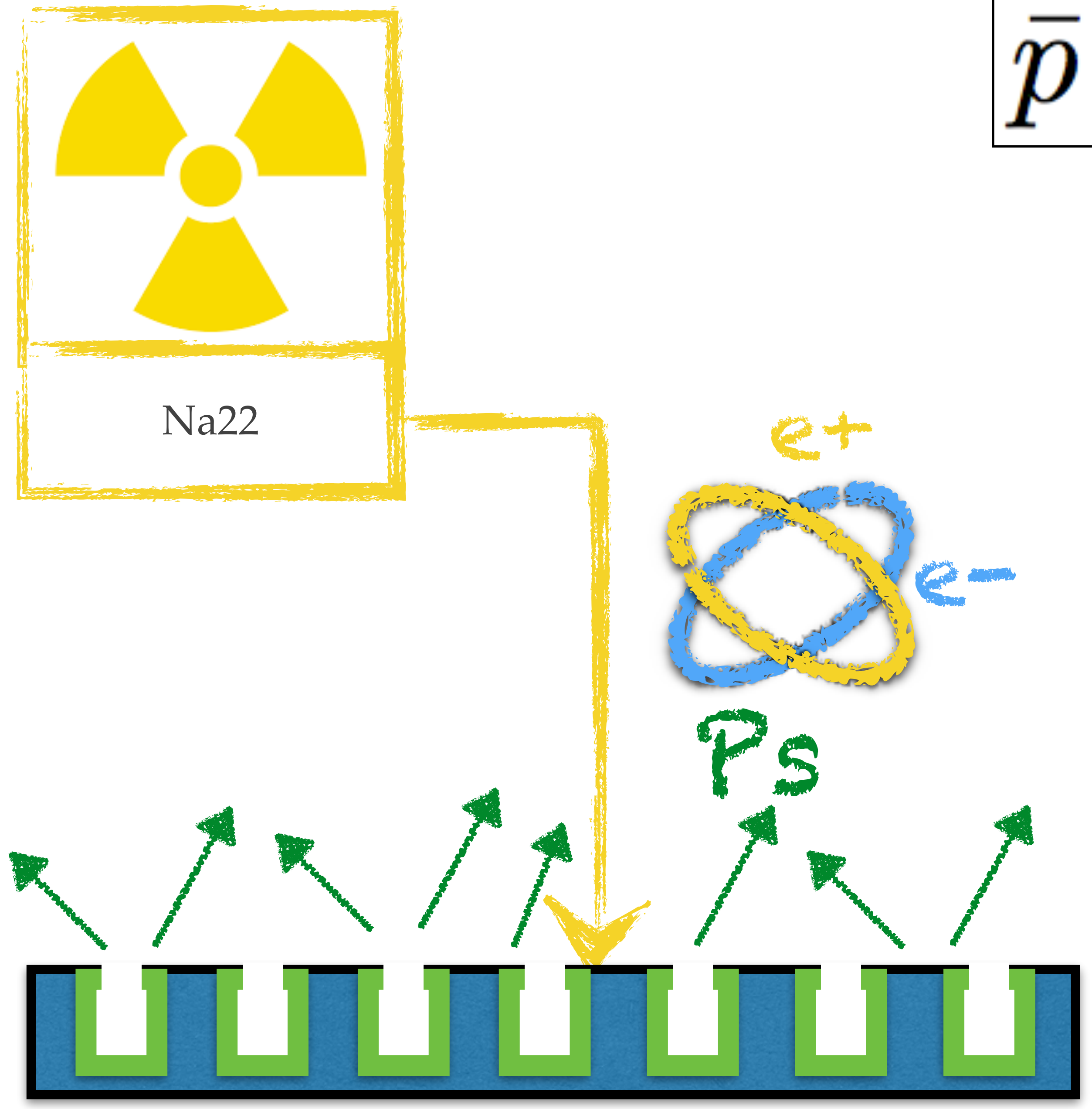
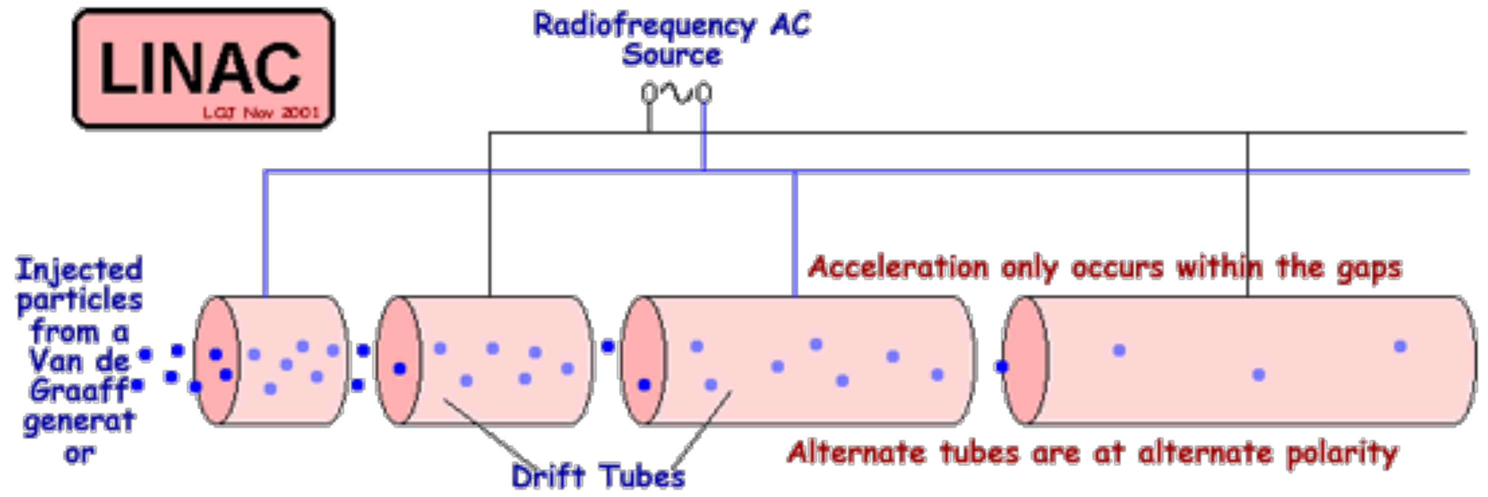


$$\bar{p} + e^+ + e^+ \rightarrow \bar{H} + e^+$$

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



Antihydrogen ION !

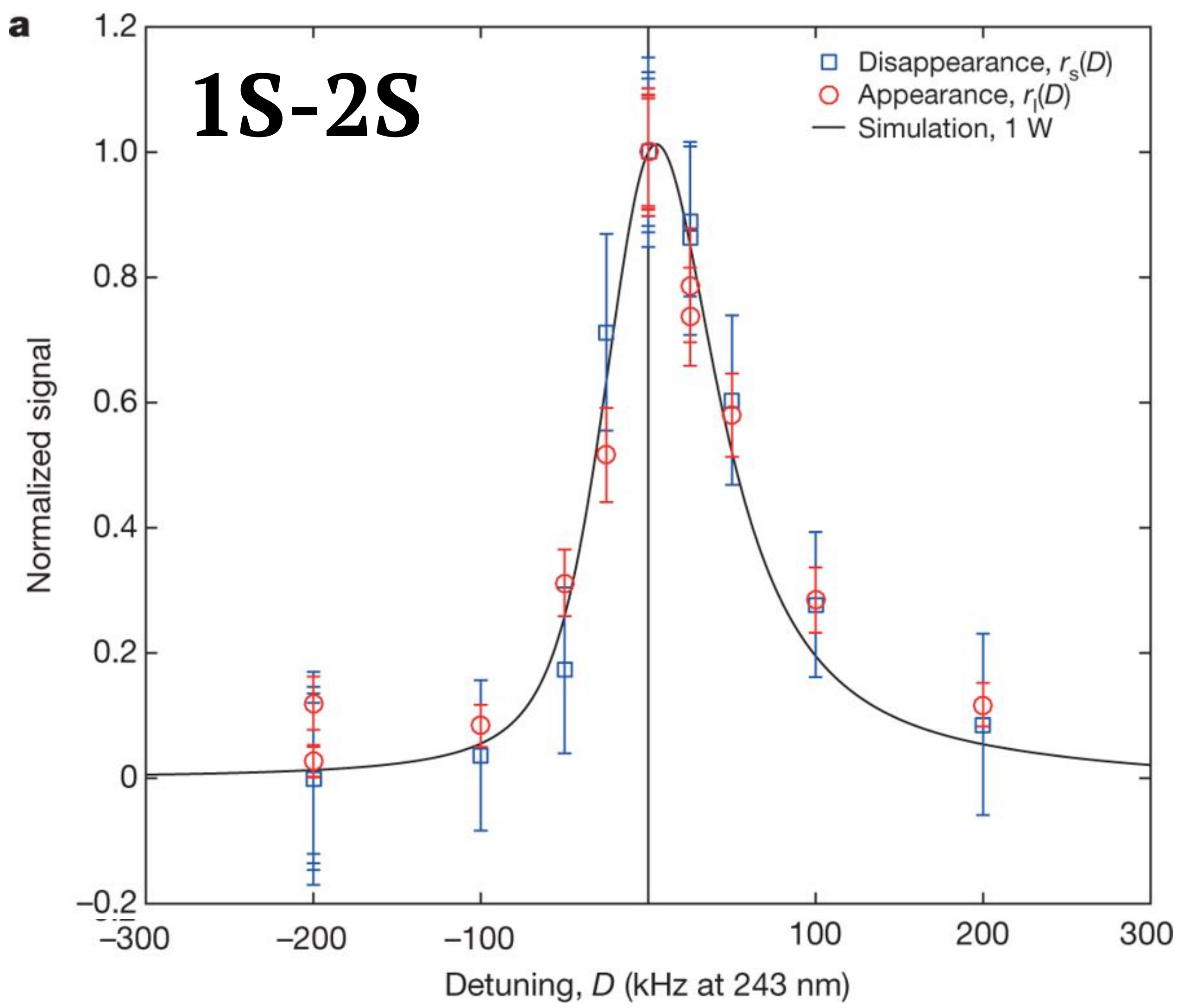


$$\bar{p} + Ps \rightarrow \bar{H} + e^-$$

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

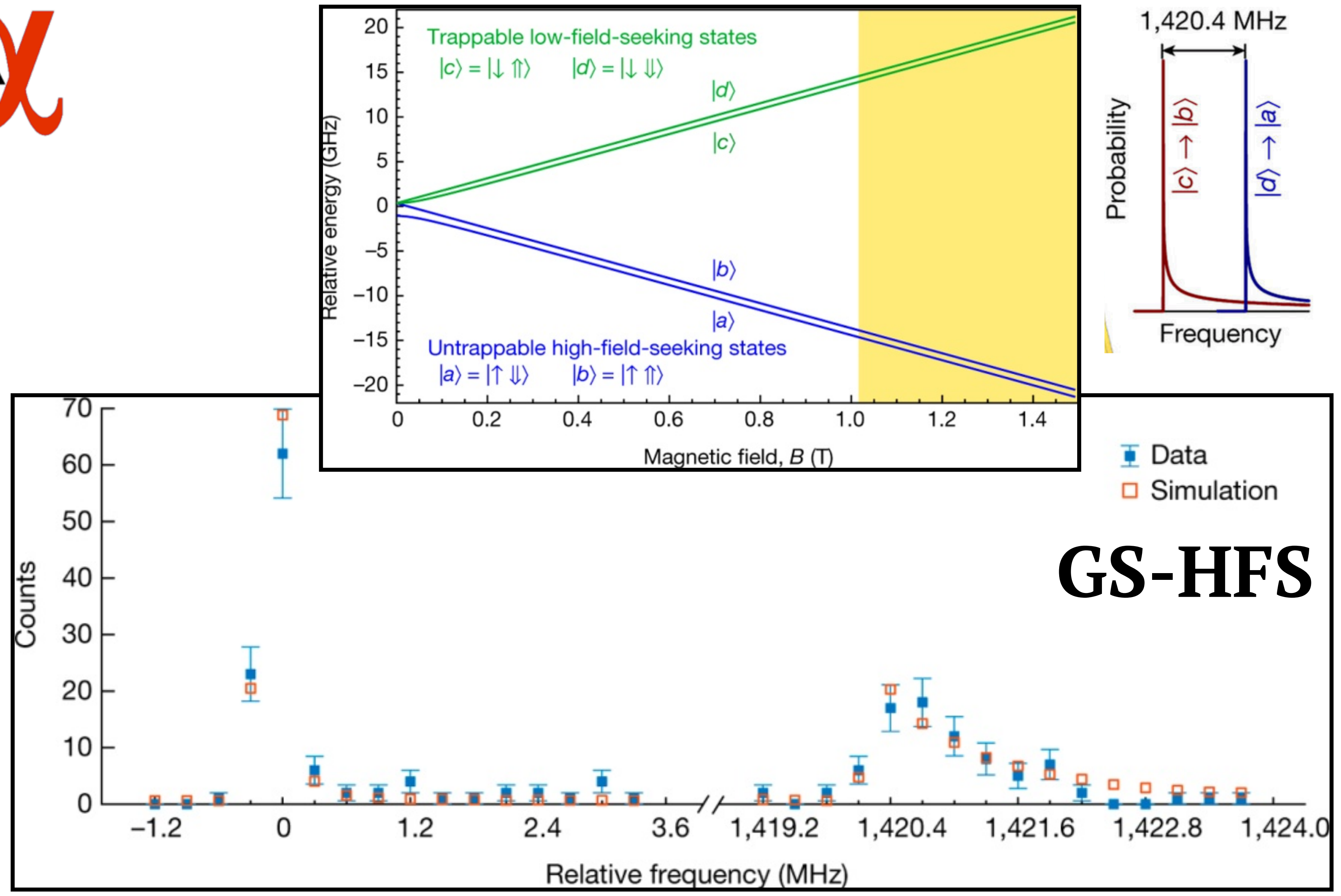
Some spectroscopy highlights with antihydrogen

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



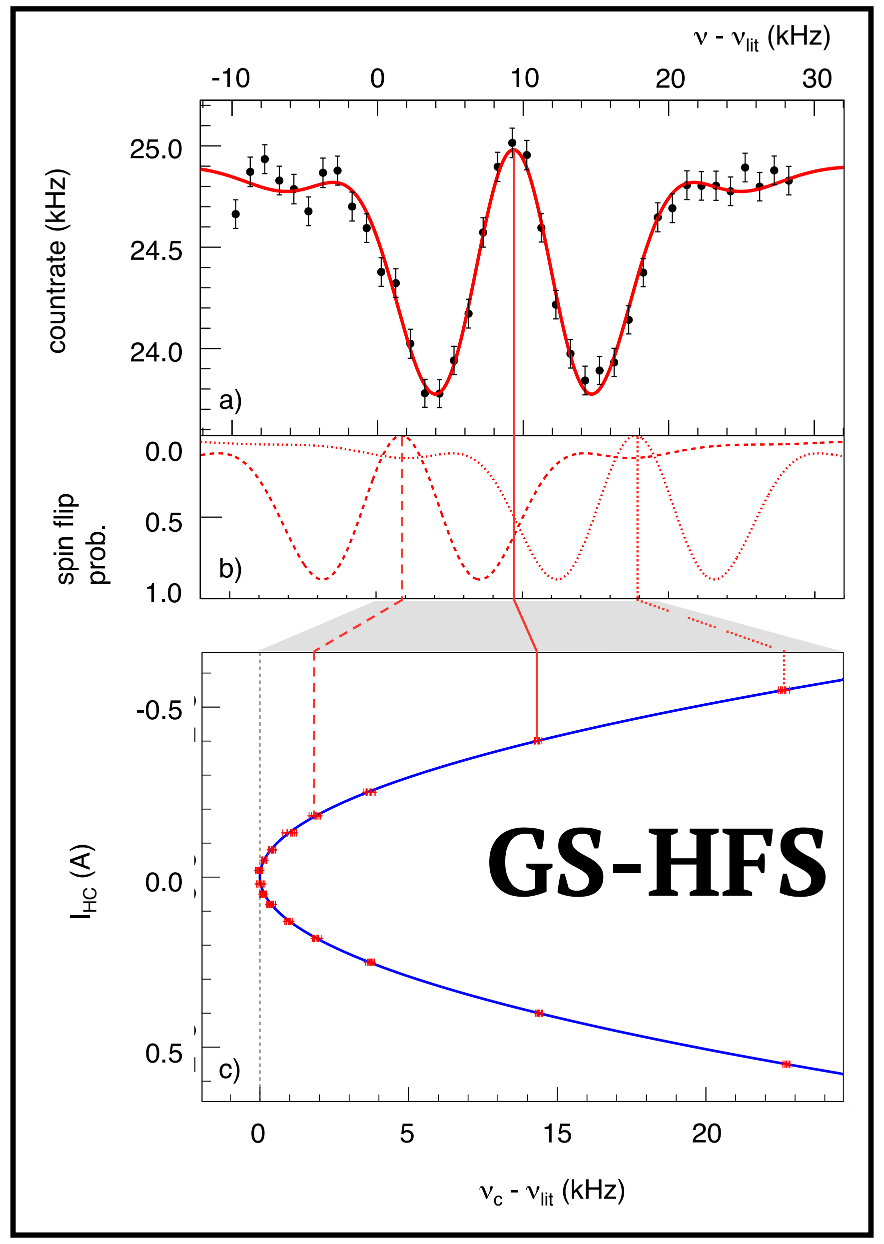
M. Ahmadi et al., Nature 557 71–75 (2018)

In a TRAP:
Precision of 4×10^{-4} (**500 kHz**)



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

In a BEAM:
Precision of 4×10^{-9} (**~3Hz**) on HYDROGEN



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

In a TRAP:
Investigation of the **FINE STRUCTURE** of antihydrogen (~10% precision)
Toward antimatter only determination of the antiproton charge radius (together with 1S-2S precision spectroscopy above)!

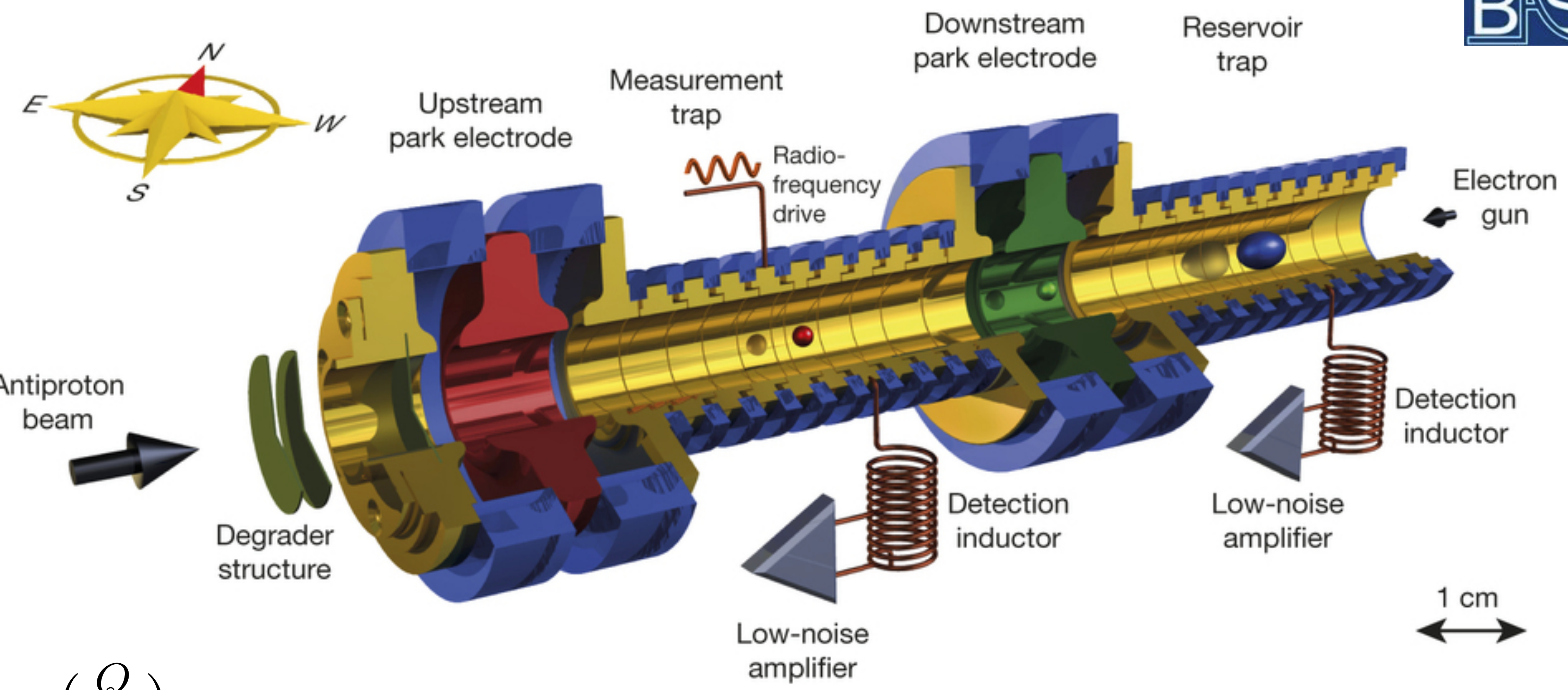
M. Ahmadi et al., Nature 578, 375–380 (2020)

$$\nu_{HF} = \frac{16}{3}\mathcal{R}_y \alpha^2 c \left(\frac{m_{\bar{p}}}{m_{\bar{p}} + m_{e^+}}\right)^3 \frac{m_{e^+}}{m_{\bar{p}}} \frac{\mu_{e^+}}{\mu_B} \frac{\mu_{\bar{p}}}{\mu_N} (1 + \delta_{str} + \delta_{QED})$$

$$\Delta\nu(\text{Zemach}) = \nu_{HF} \frac{2Z\alpha m_e^+}{\pi^2} \int \frac{d^3p}{p^4} \left[\frac{G_{E(\bar{p})}(p^2) G_{M(\bar{p})}(p^2)}{1+\kappa} - 1 \right]$$

Some highlights on antiprotons

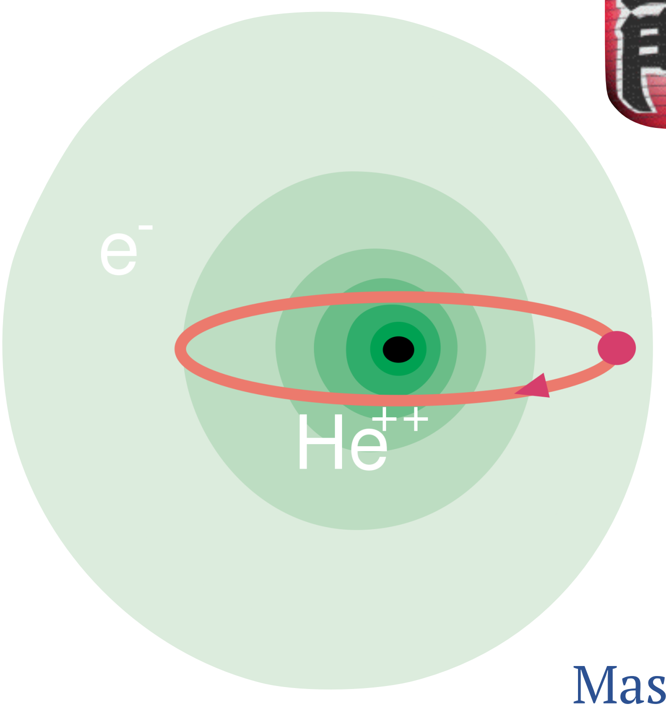
antiproton charge to mass ratio



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

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

antiproton to electron mass ratio

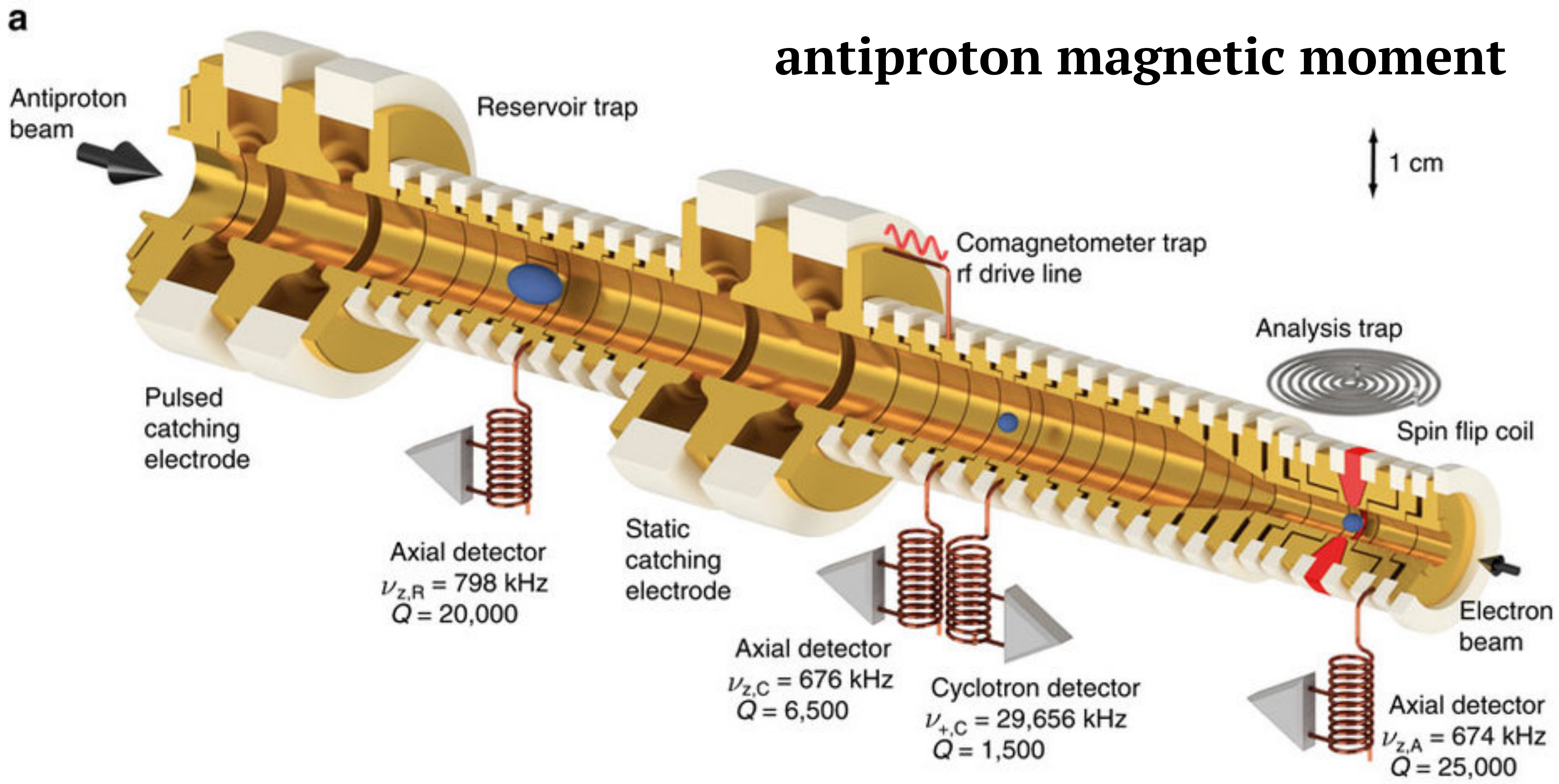


$$\frac{m_{\bar{p}}}{m_{e^-}} = 1836.1526734(15)$$

p̄-He cooled to ~1.5K (buffer-gas cooling)

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

antiproton magnetic moment

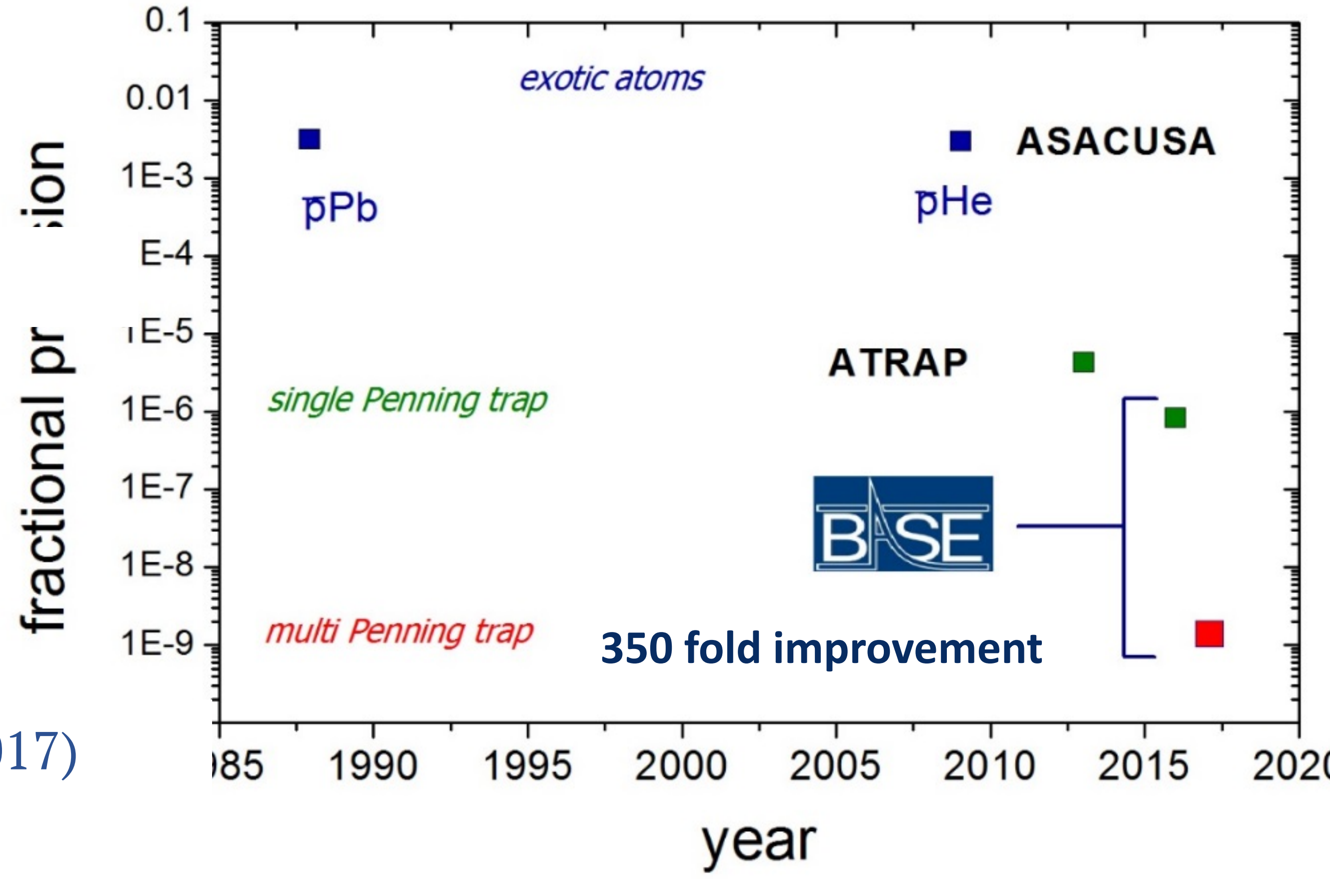


$$\frac{g_{\bar{p}}}{2} = 2.792\,847\,344\,1\,(42)$$

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

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

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



first measurement more precise for antimatter than for matter

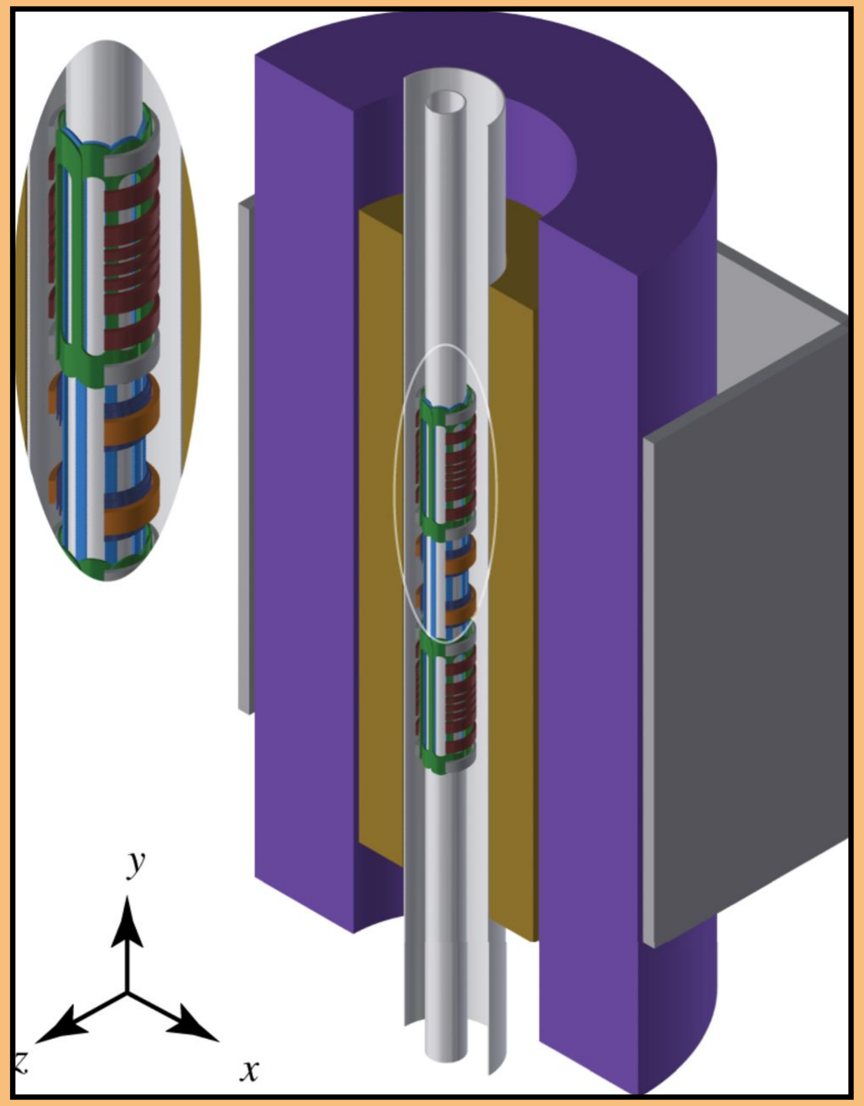
Low energy antiprotons for gravity tests

Plurality of approaches

VERTICAL TRAP

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

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



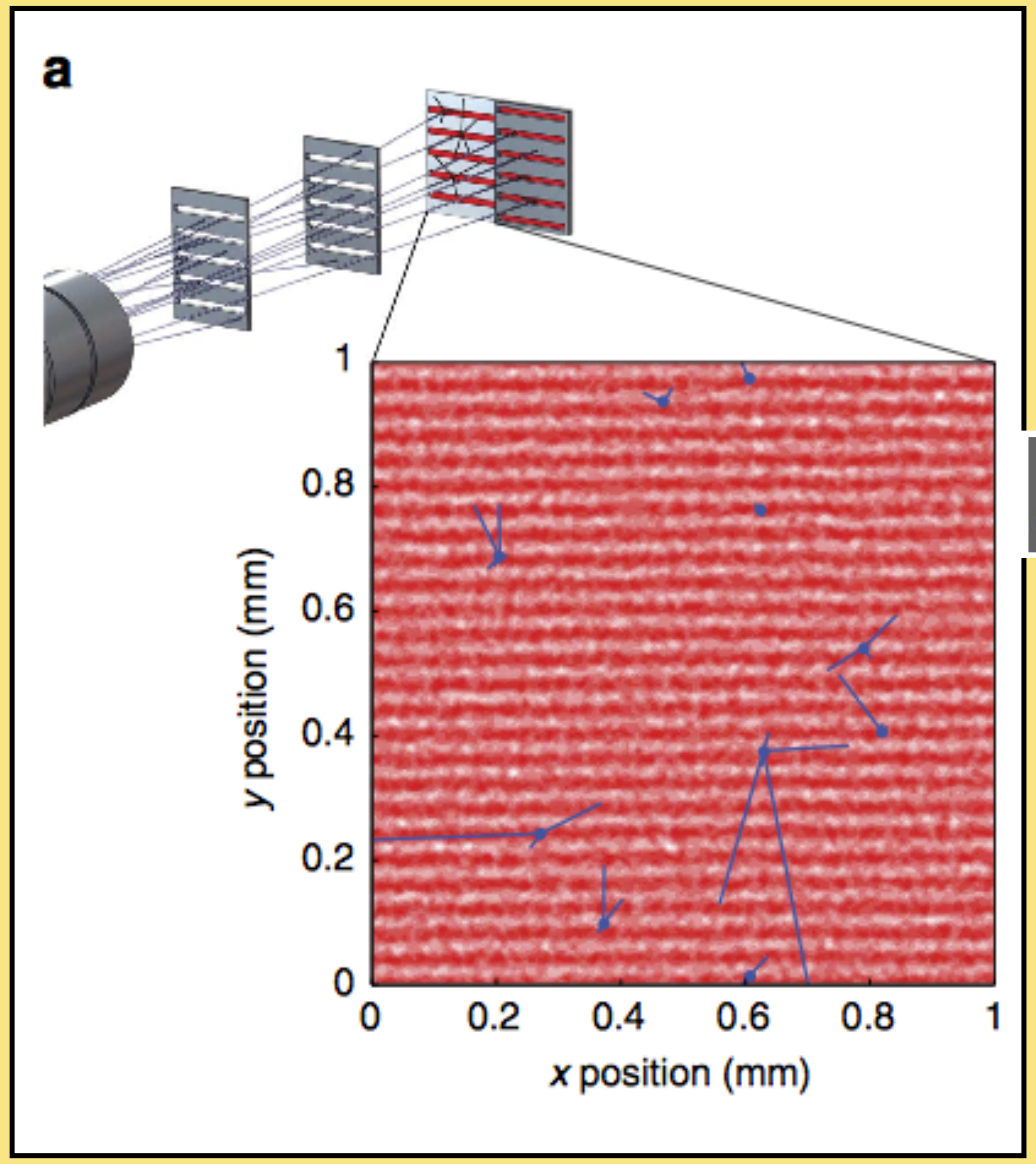
(ALPHA-g)

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

$\bar{H}$ BEAM

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

<u>Sign measurement</u> targeted



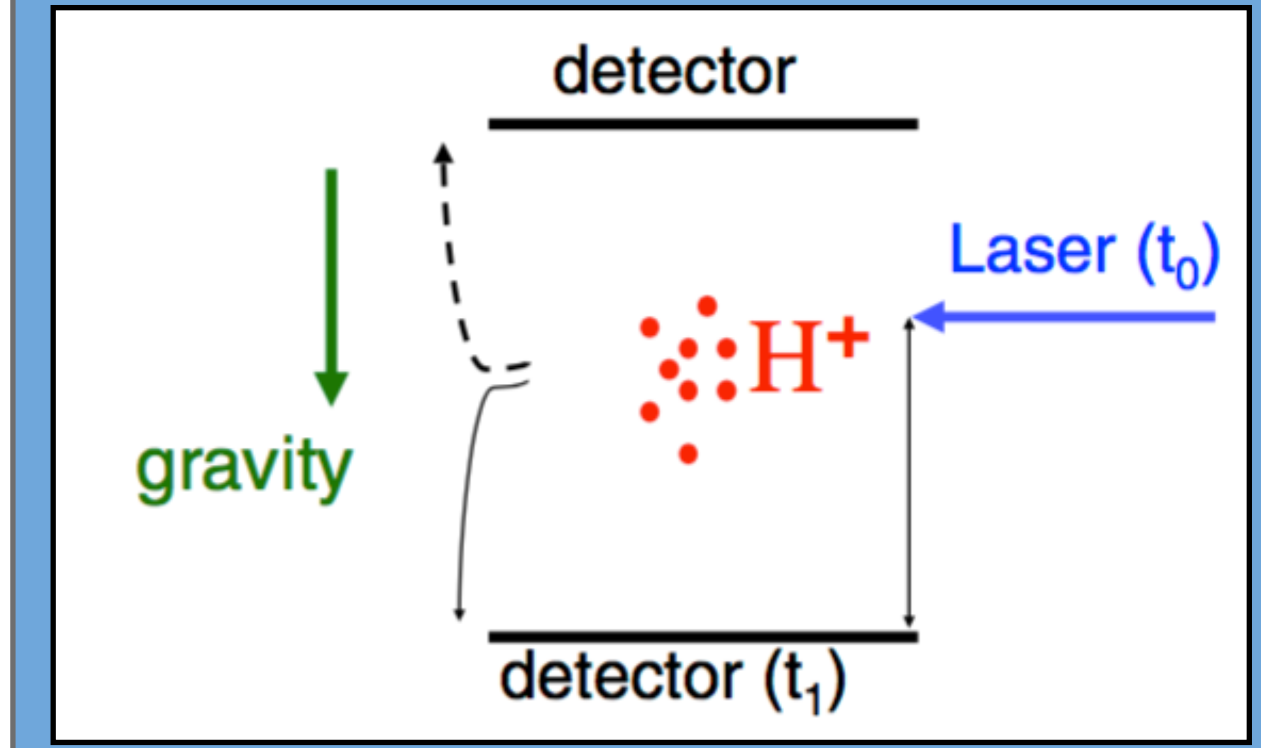
AEgIS

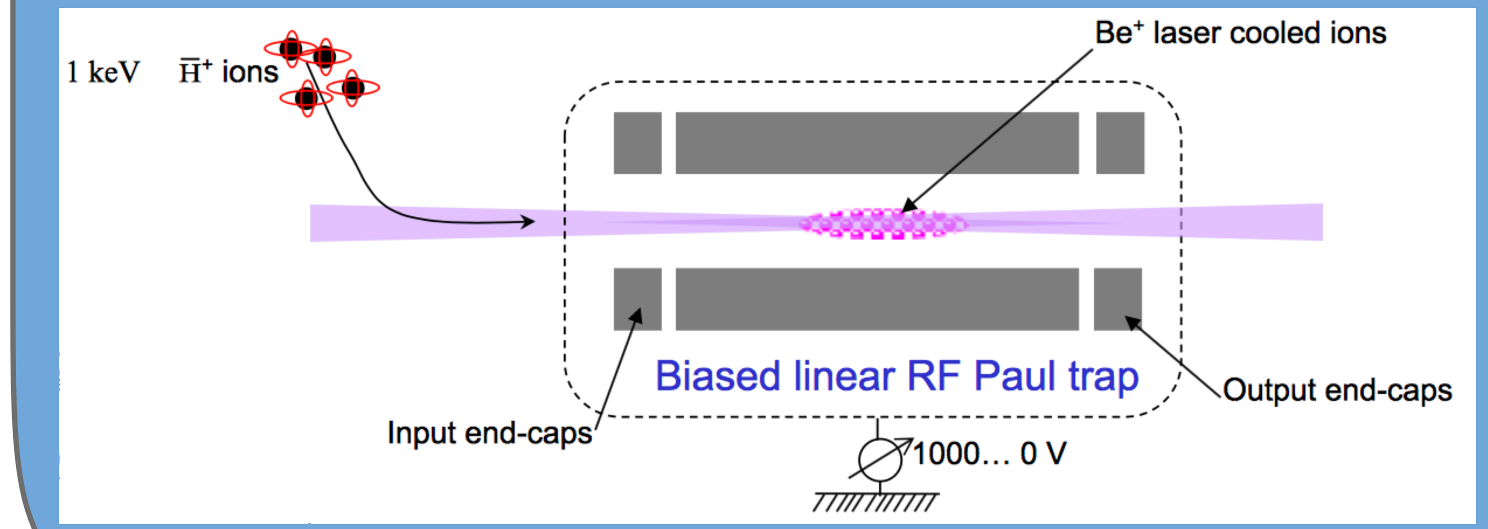
S. Aghion et al. Nature Communications 5 (2014) 4538

$\bar{H}^+$ BEAM

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

<u>1% measurement</u> targeted

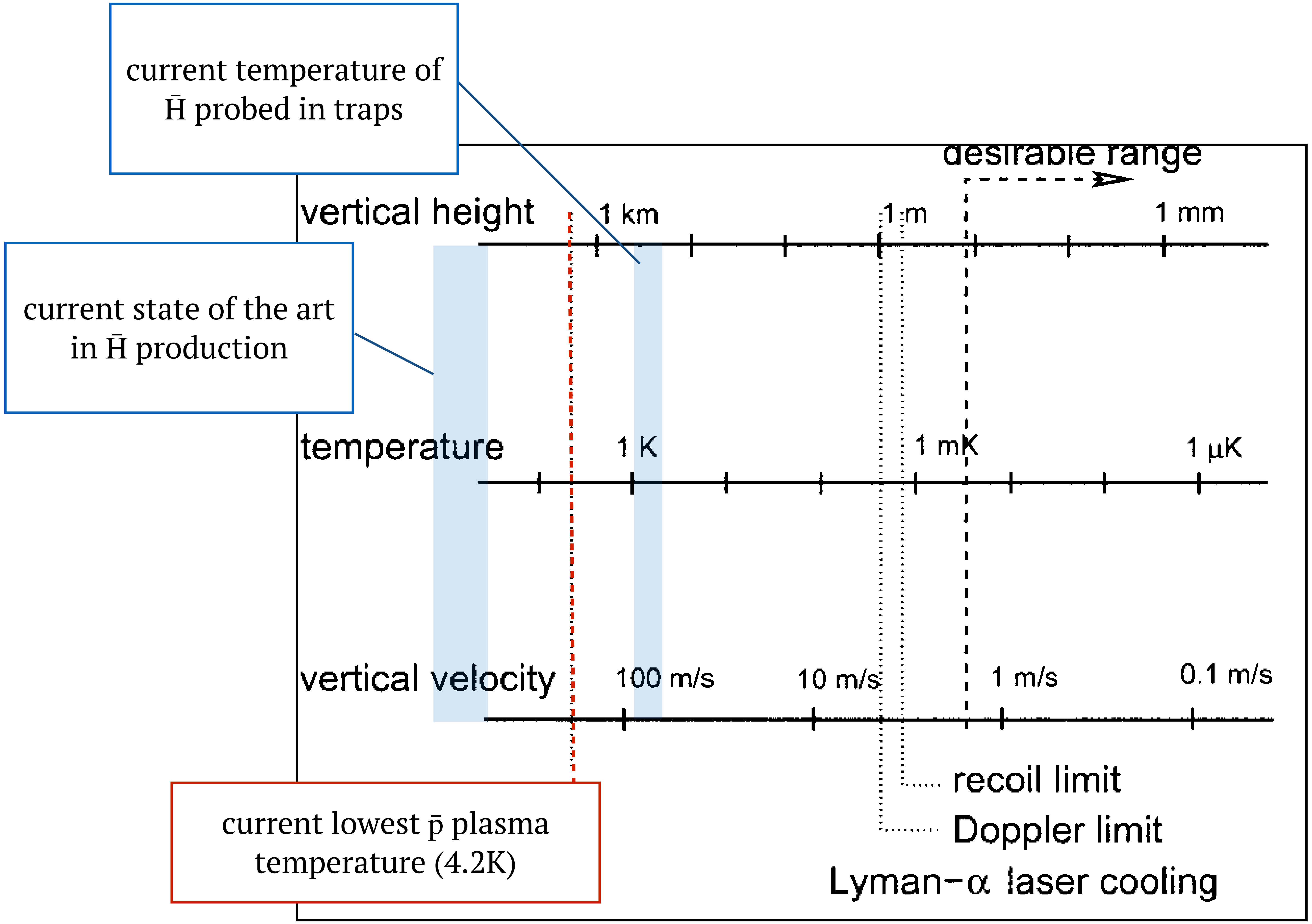




e.g.: The GBAR antimatter gravity experiment
P. Pérez et al., Hyperfine Interactions 233, 21-27 (2015)

Low energy antiprotons for gravity tests

Some numbers to set the scale



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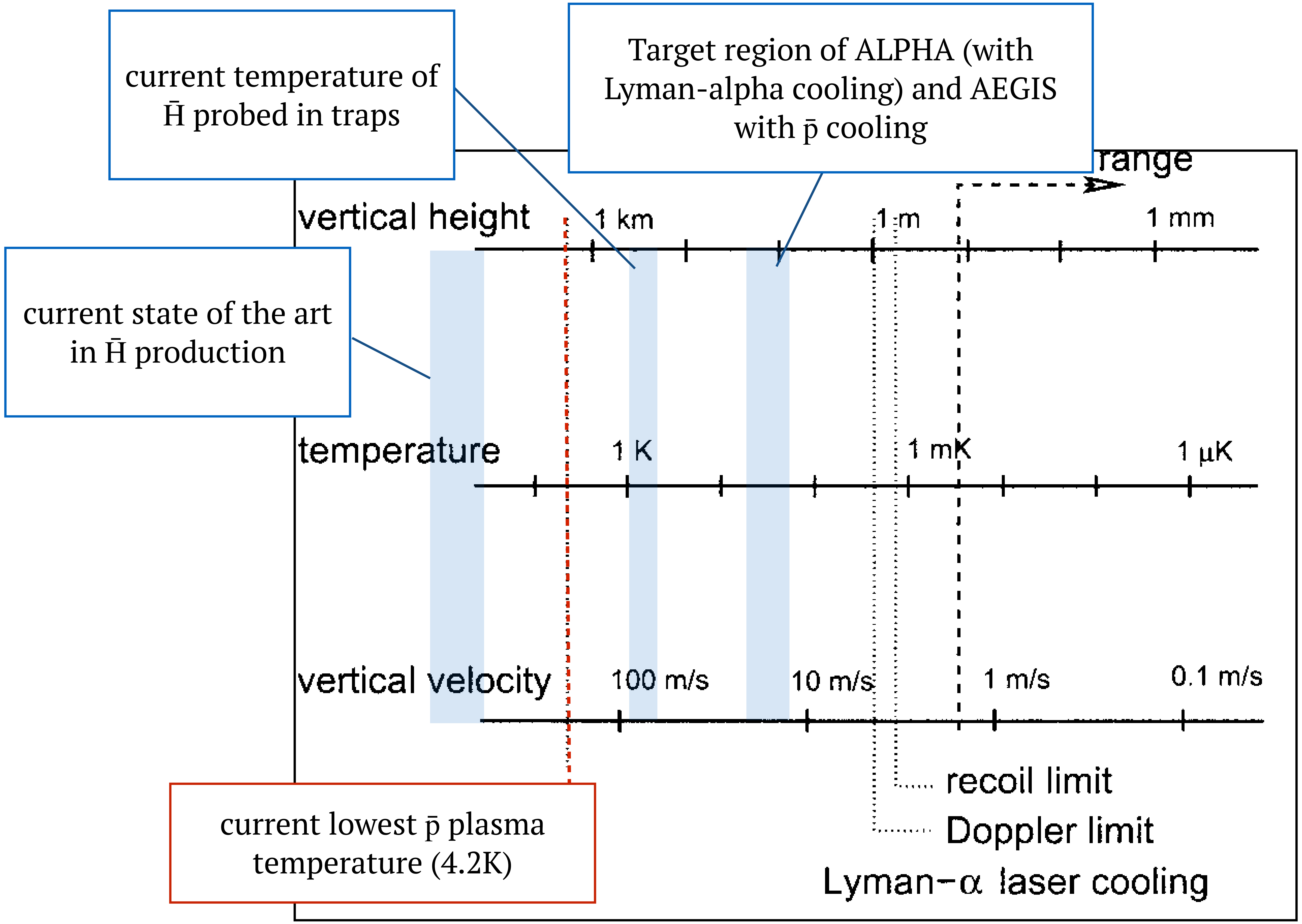

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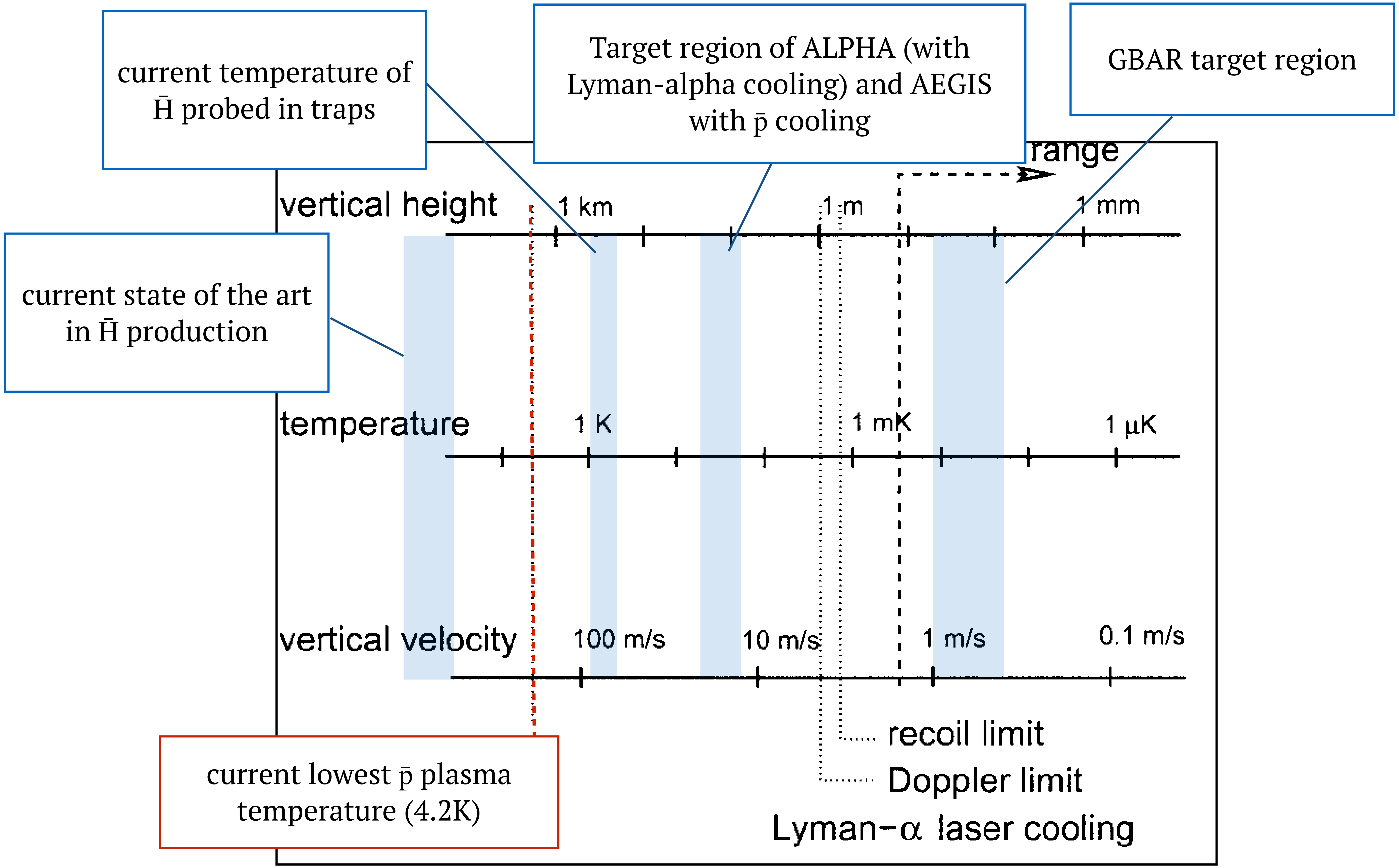

Summary of highlights and prospects

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 (ALPHA-g, GBAR)
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

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

New cooling techniques has been further developed during LS2 (sympathetic cooling of + and - charges)
As well as deexcitation techniques for $\bar{H}$ beam

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First measurements awaited soon after LS2!

New temperature regime probed

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Colder and better beam : will allow exciting new physics beyond current endeavours e.g. $\bar{H}_2^+$

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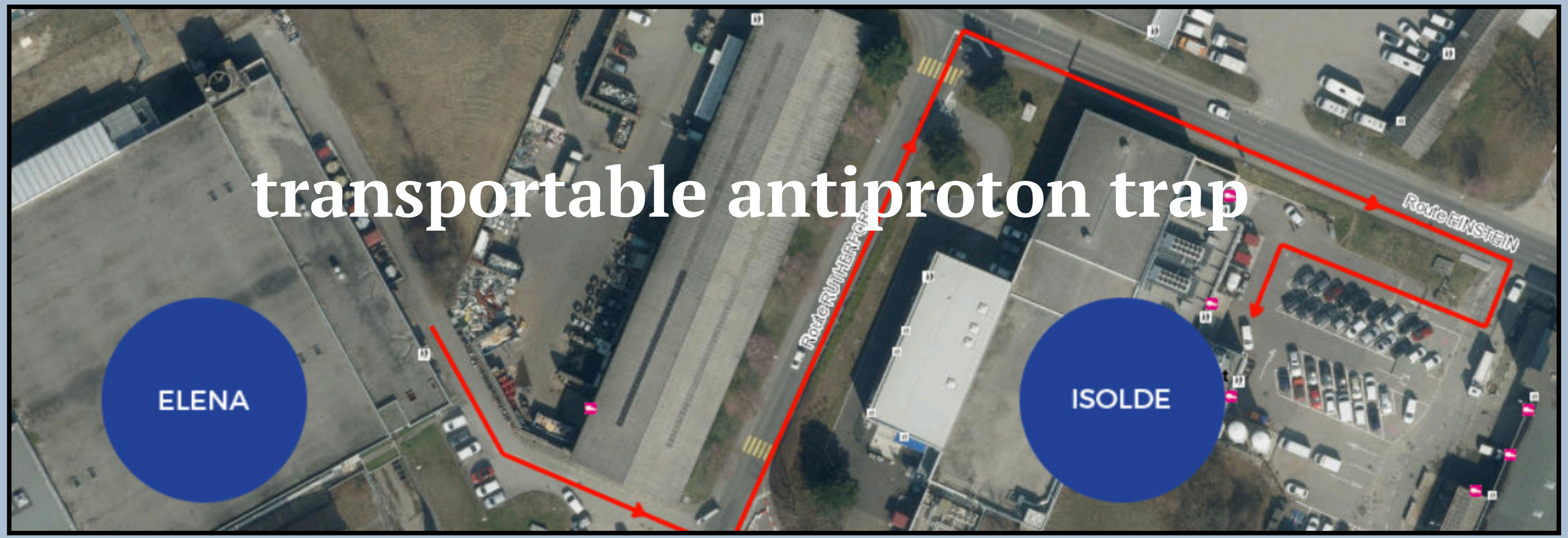
NEW EXPERIMENTS!



Antiprotons for nuclear studies (PUMA)

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