L’antimatière à l’épreuve de la gravité, aperçu des experiences en cours sur l’antihydrogène

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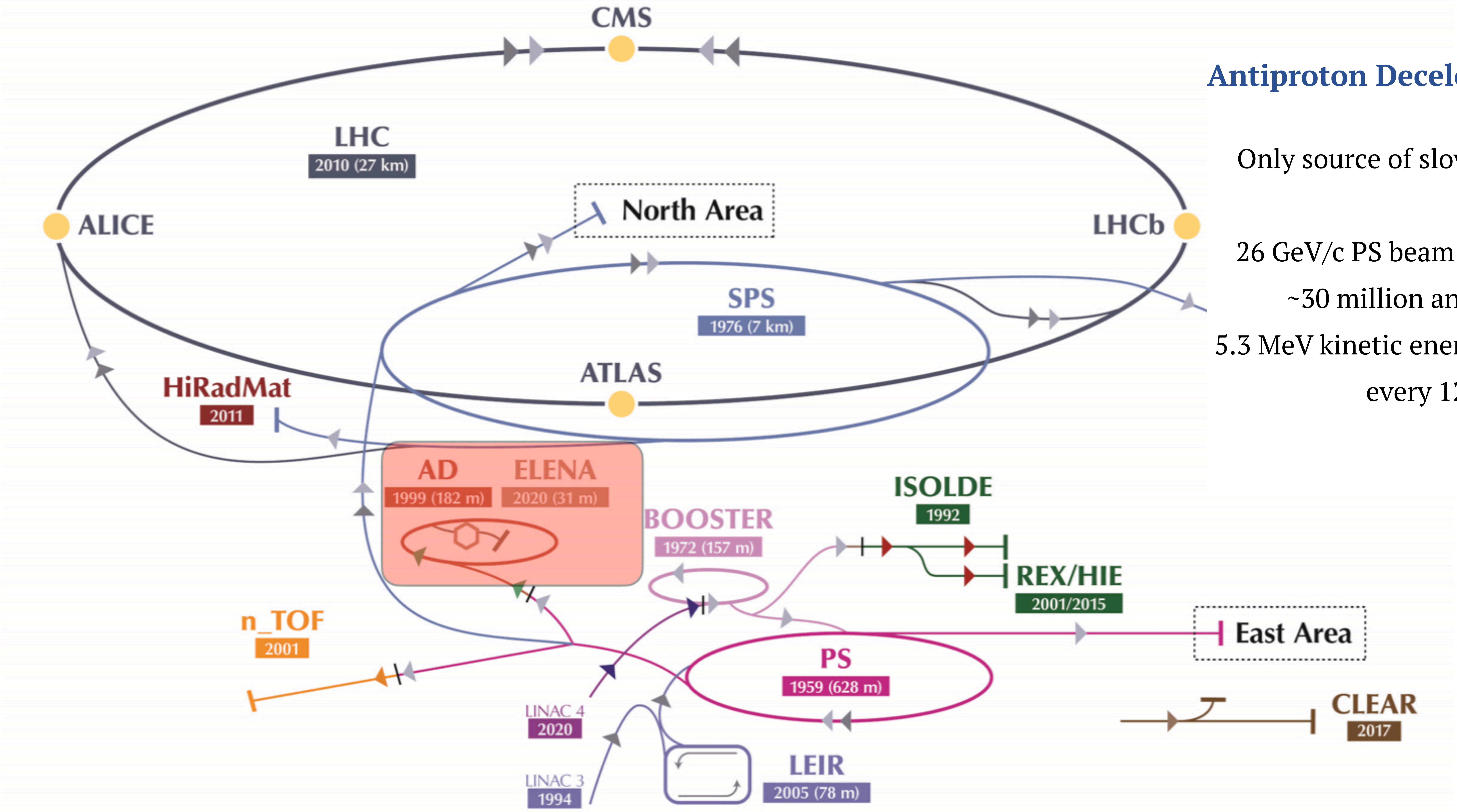


Antiproton Decelerator (AD)

Only source of slow antiprotons

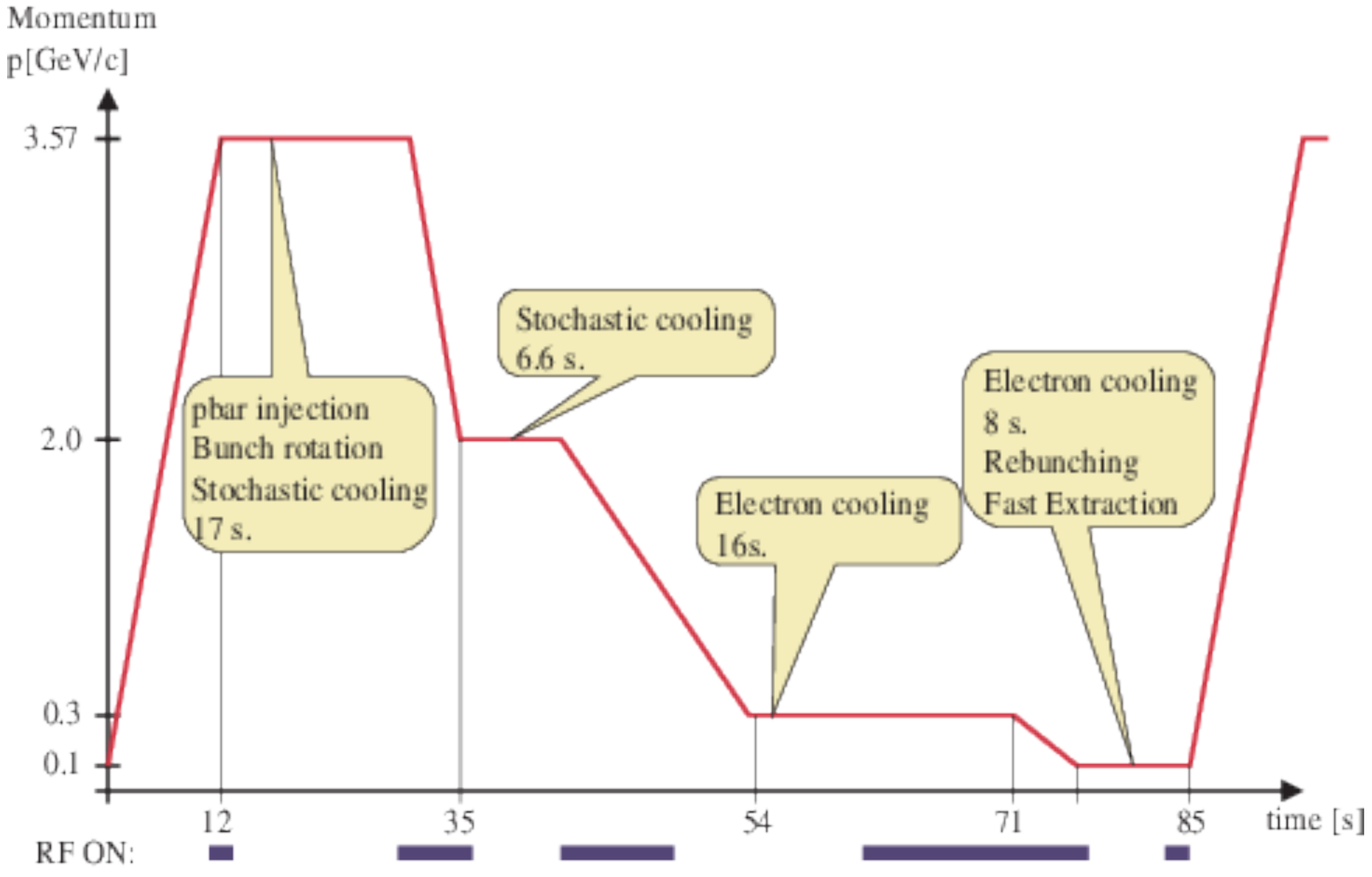
26 GeV/c PS beam onto Ir target

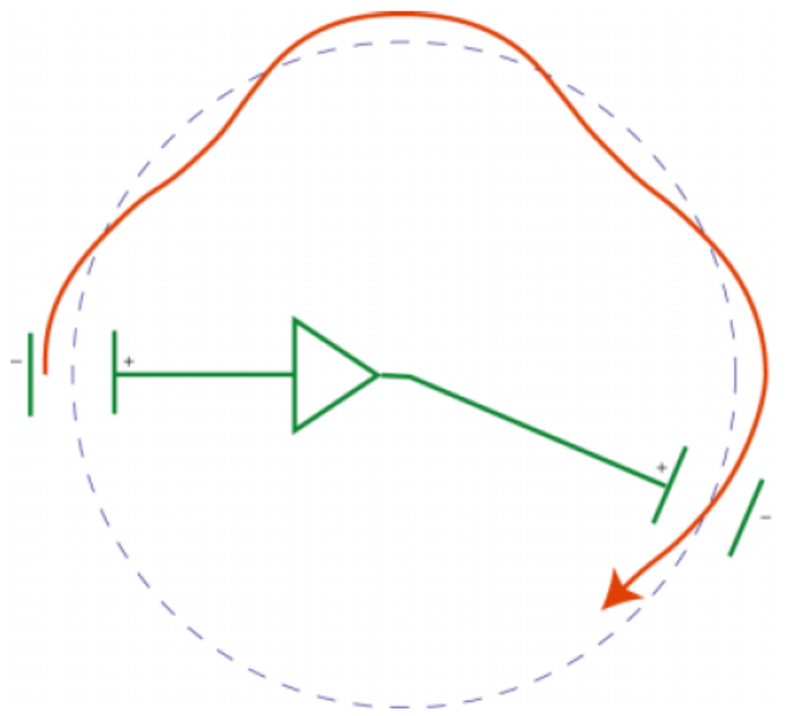
~30 million antiprotons

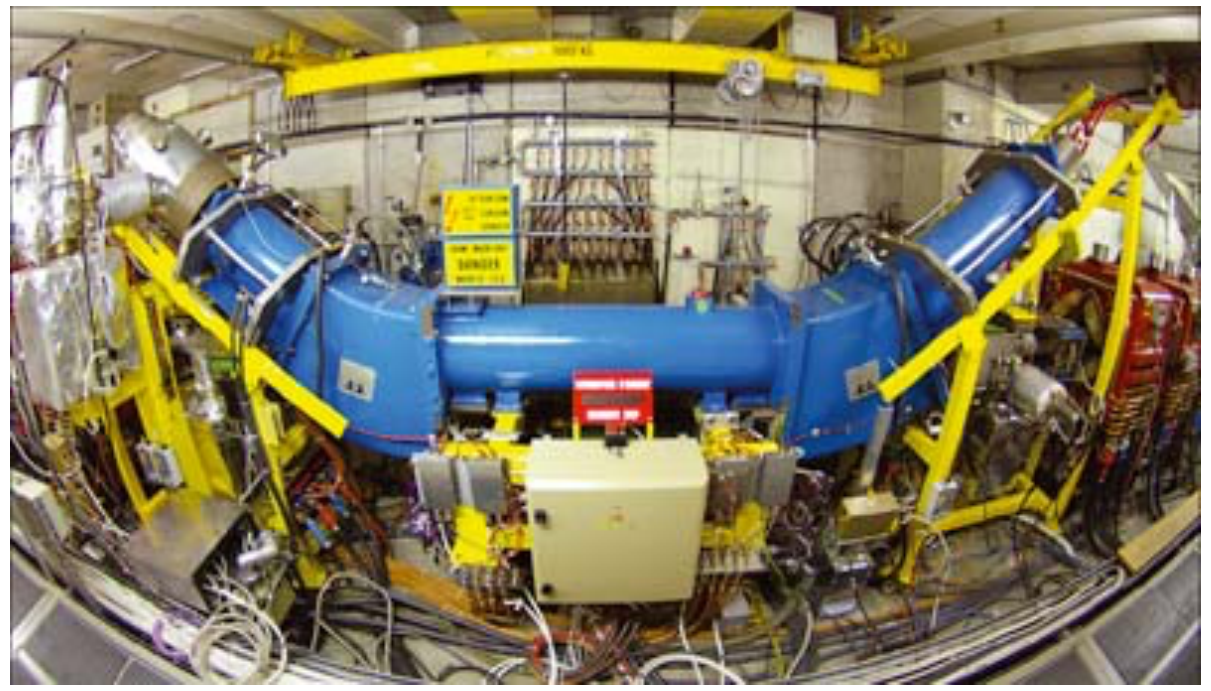
5.3 MeV kinetic energy (100 MeV/c)

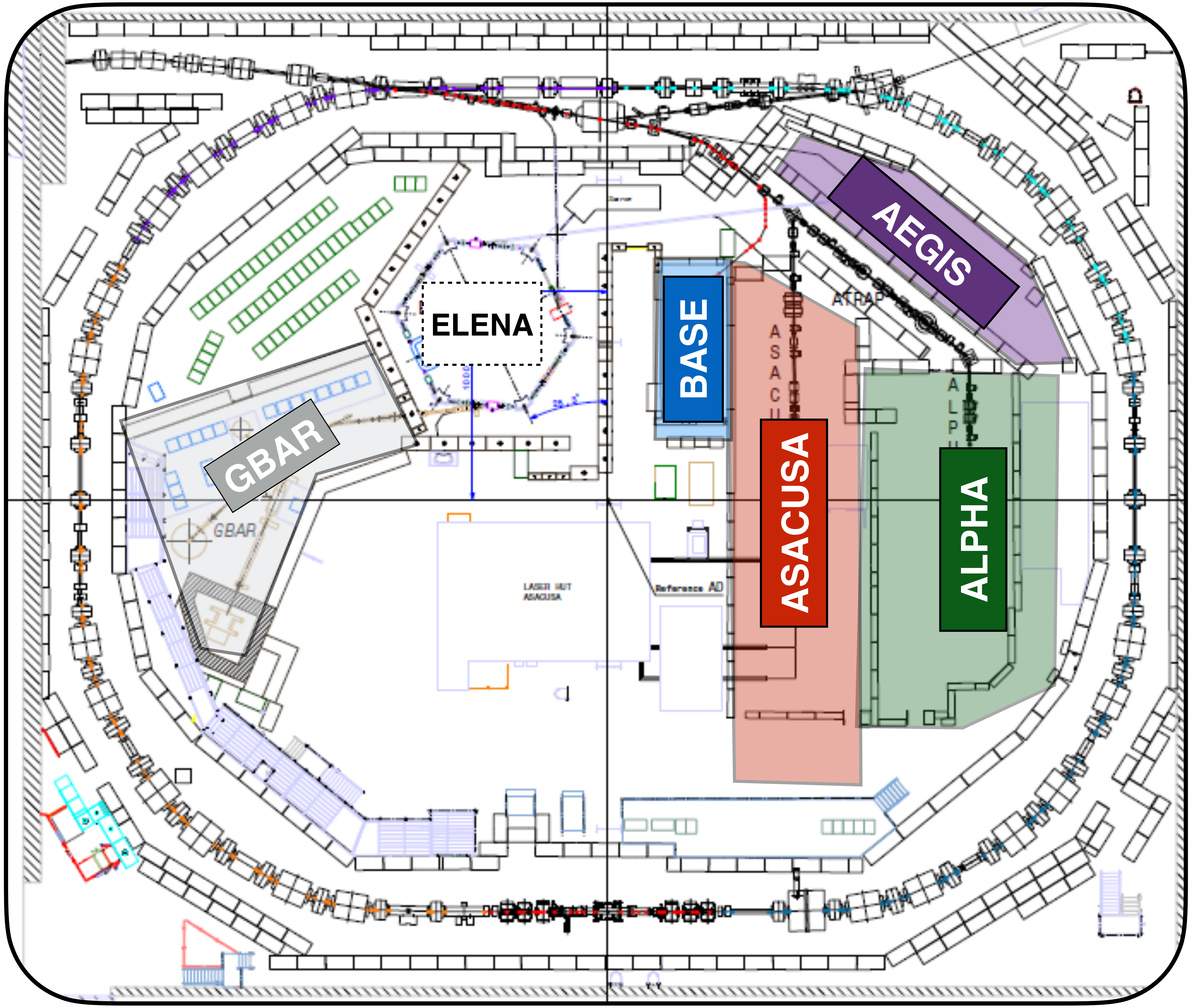
every 120s


CMS
LHC
2010 (27 km)
ALICE
ATLAS
HiRadMat
2011
AD
1999 (182 m)
ELENA
2020 (31 m)
n_TOF
2001
LINAC 4
2020
LINAC 3
1994
AEGIS
ELENA
BASE
GBAR
ASACUSA
ALPHA
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:

$\bar{p}$ caught in Penning traps using degraders
→ 99.9% are lost

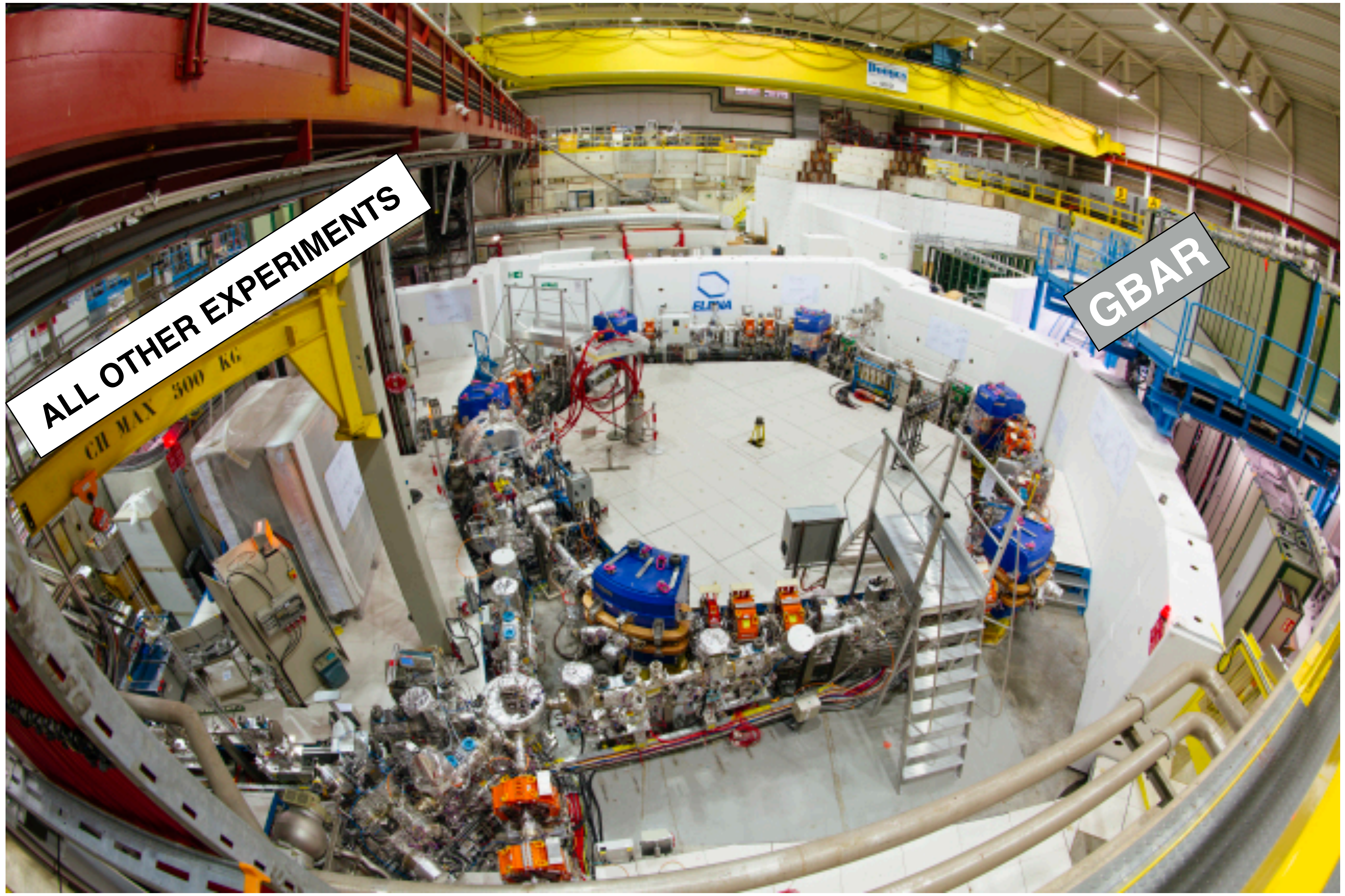
ELENA:

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

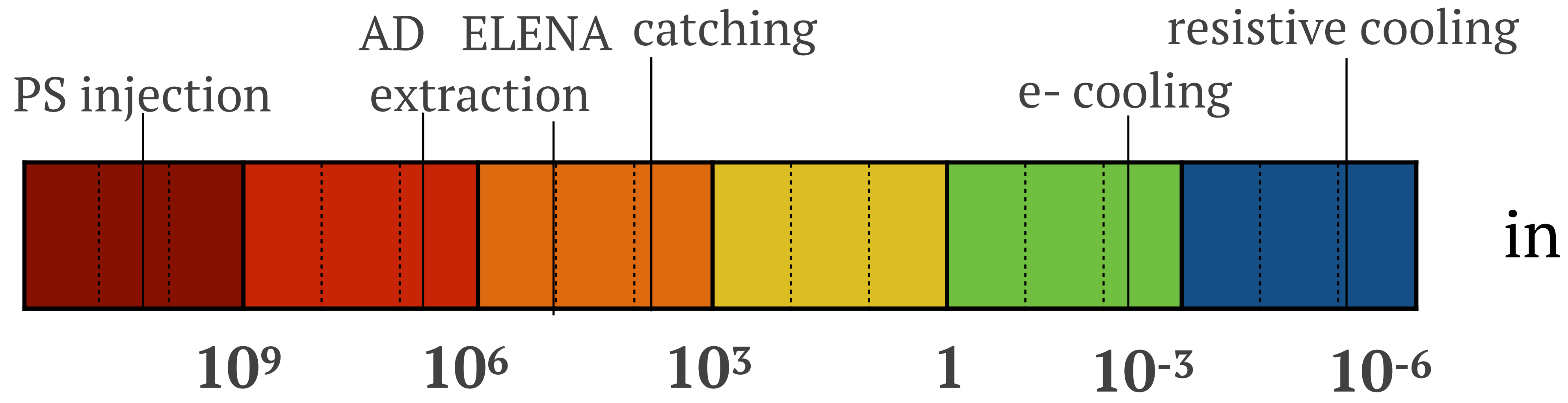
all experiments gain a factor 10-100
in trapping efficiency (degrading at low particle energies is more efficient)

"simultaneous" delivery to almost all experiments
→ Gain in total beam time

additional experimental zone



Energy scale (ev)



in a few 100s seconds!!

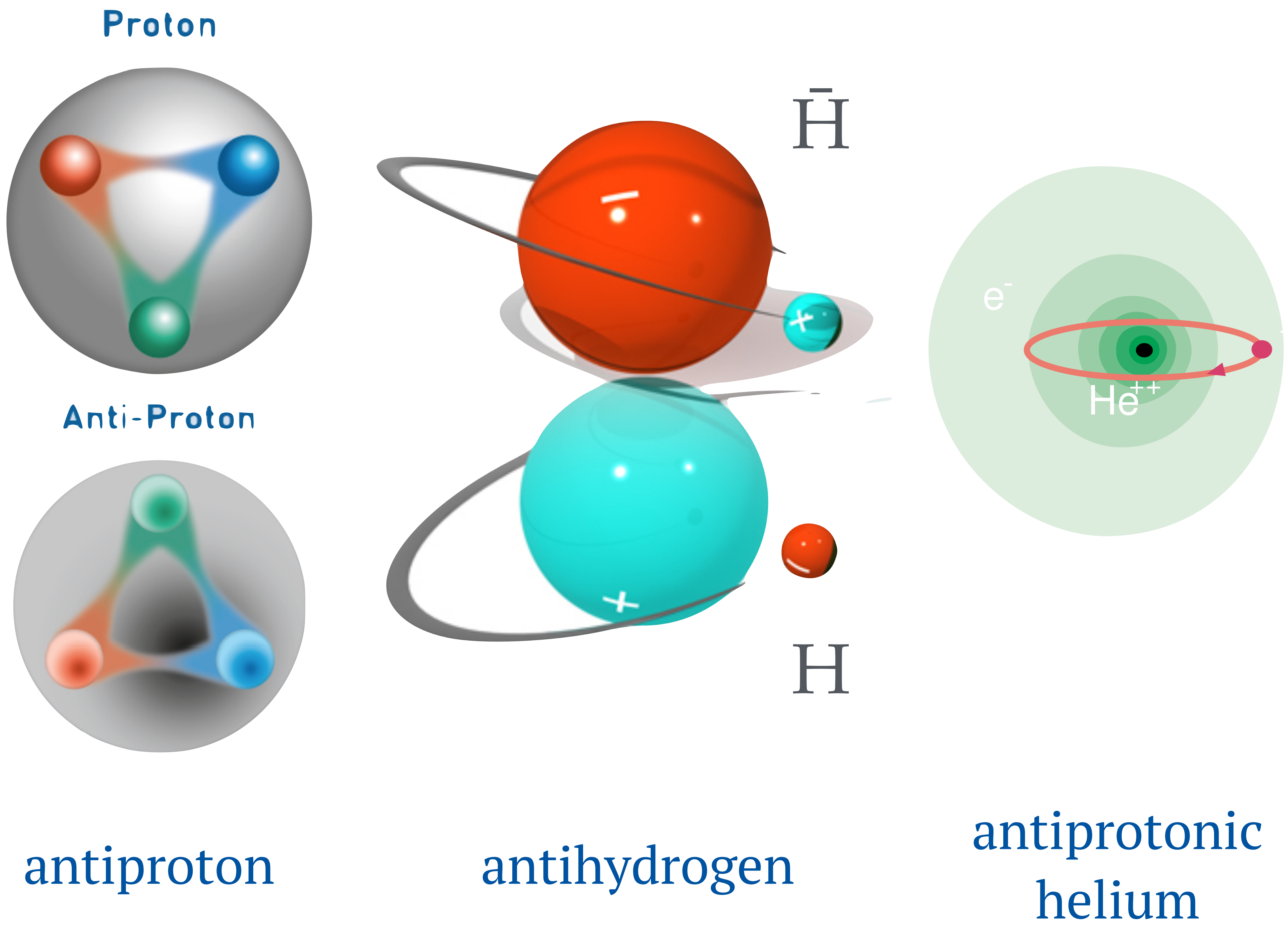
Variety of searches for new physics with low energy antiprotons

BASE/STEP ($\bar{p}$ 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



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

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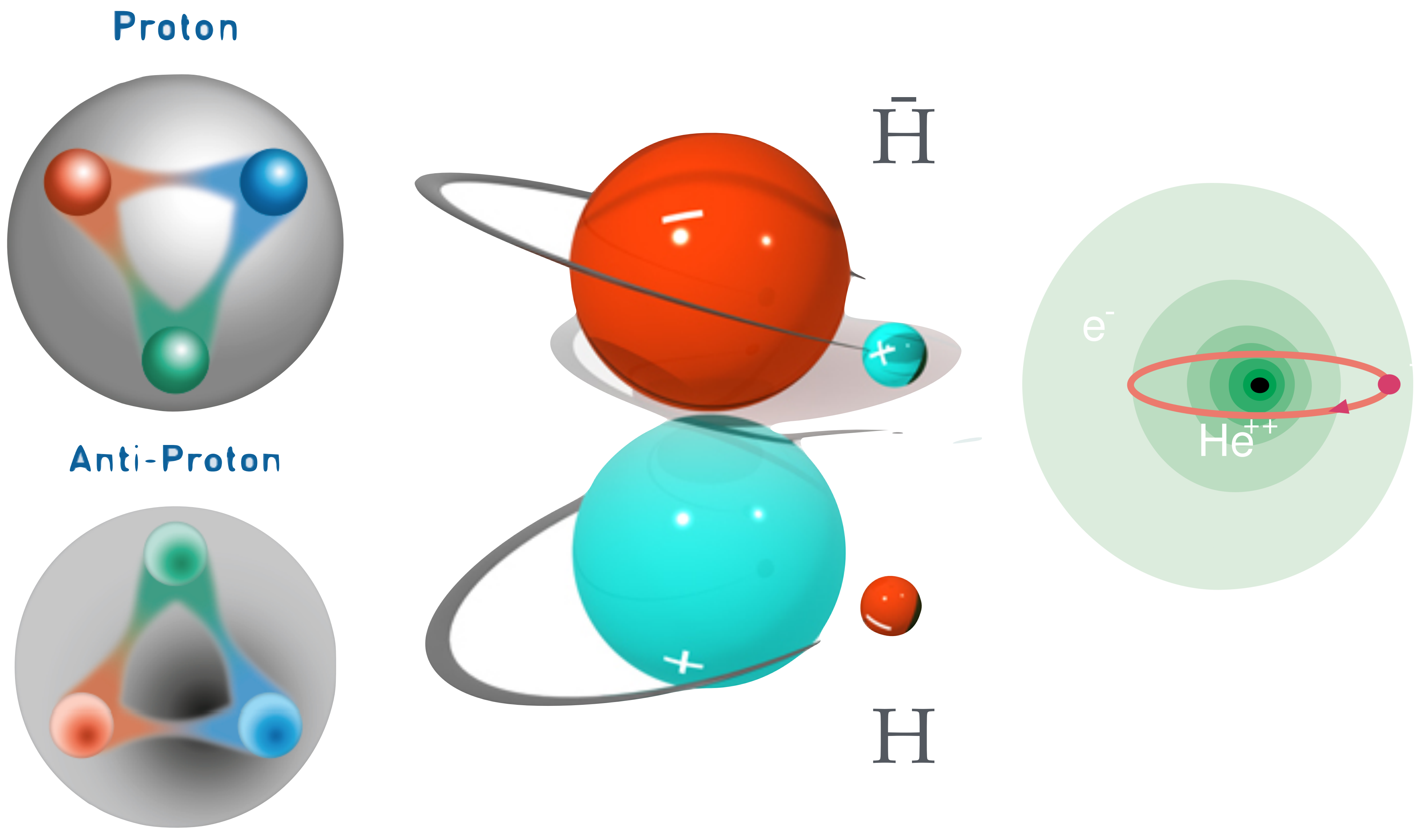


antiproton

antihydrogen

antiprotonic helium

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

Motivations for testing gravity with antihydrogen atoms

Gravity with matter scrutinized via different experimental methods

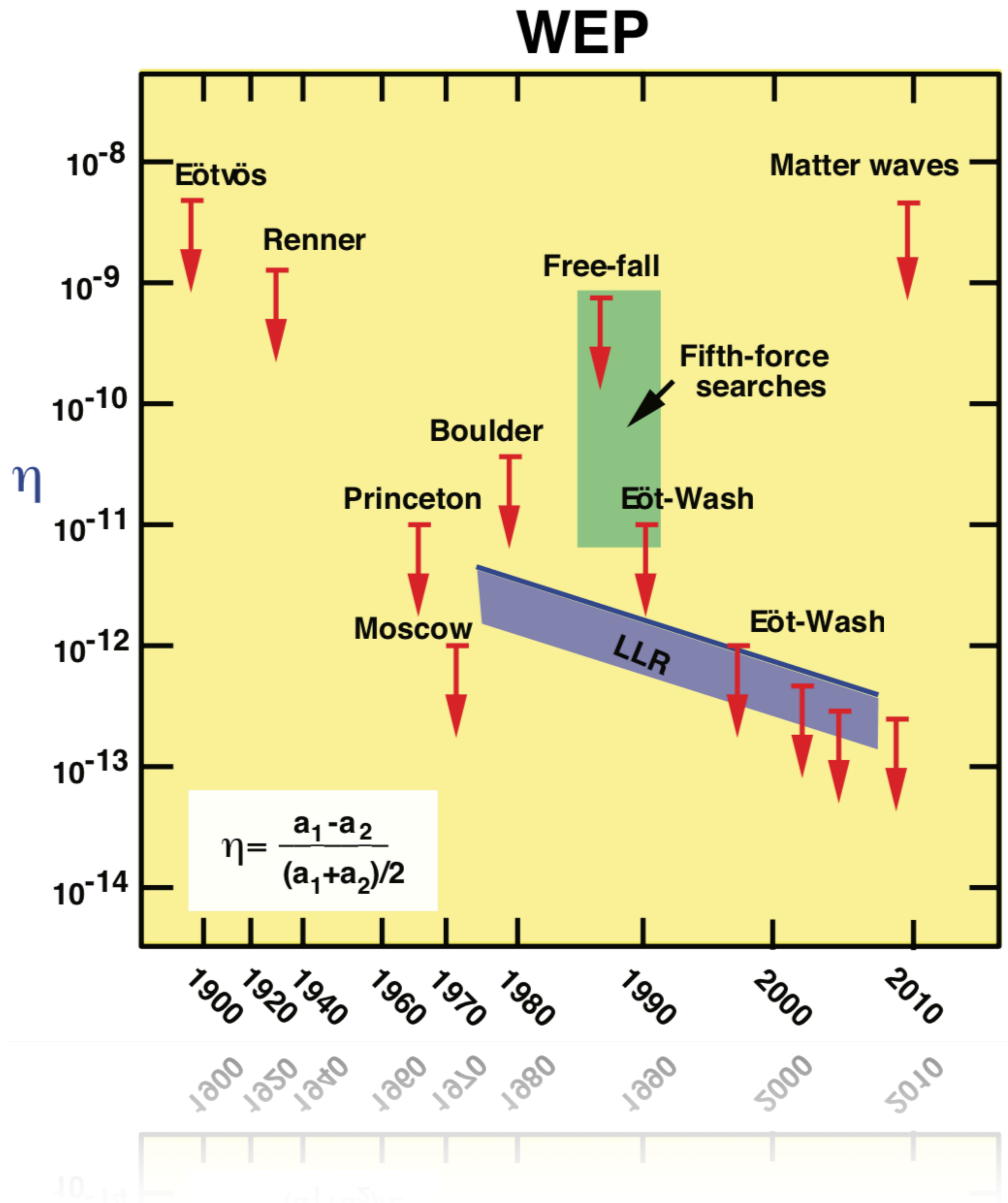
- Universality of free-fall established by Galileo (~450 years go) and Newton
- Weak equivalence principle starting point for Einstein's theory of general relativity (~100 years ago)

Einstein's equivalence principle (EEP) extensively tested experimentally

- WEP

Torsion balance:

$$\eta = \frac{a_1 - a_2}{(a_1 + a_2)/2} > 10^{-13}$$



Motivations for testing gravity with antihydrogen atoms

But gravity is a peculiar force

Very weak force
Lack of consistent quantum treatment

Gravity on antimatter has "never" been directly tested

"Peculiarity" of antimatter :

non detection of primordial antimatter

&

lack of experimental hints for the justification of baryon asymmetry

Need for a free-fall experiment on antimatter

electric field:	gravitational field:
$\mathbf{F} = q \cdot \mathbf{E}$	$\mathbf{F} = m \cdot \mathbf{G}$
$\lvert\mathbf{E}\rvert \propto \frac{Q}{r^2}$	$\lvert\mathbf{G}\rvert \propto \frac{M}{r^2}$
$\lvert\mathbf{a}\rvert \propto q$	$\lvert\mathbf{a}\rvert = \text{const}$

Motivations for testing gravity with antihydrogen atoms

What implications if antimatter behaves differently than matter in a gravitational field?

- GR and WEP would have to be broken?

  validity well tested on matter but not on antimatter
  accelerating expansion of the universe requires dark energy (composition of the universe) but could it be a sign for the need of revised theory?

- New forces : scalar or vector mediators would not necessarily invalidate GR (if similar magnitude cancellation for matter-matter but not for matter-antimatter)

Example:

$$V = -\frac{Gm_1 m_2}{r}(1 \mp a\, e^{-r/v} + b\, e^{-r/s})$$

a: Gravivector, b: Graviscalar

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

matter experiments: |a–b|
antimatter: a+b

Motivations for testing gravity with antihydrogen atoms

Existing <u>indirect</u> bounds

Michael Martin Nieto, T. Goldman,
Physics Reports, Volume 205, Issue 5,1991, Pages 221-281,
https://doi.org/10.1016/0370-1573(91)90138-C.

Mark Fischler, Joe Lykken, Tom Roberts
arXiv.org > hep-th > arXiv:0808.3929v1

GR effect of gravitational redshift
i.e. clocks frequency appear different for an observer in a gravitational potential

cyclotron frequencies of particles are like clocks, so if $\bar{g} \neq g$, the cyclotron frequency (of $\bar{p}$ and p for example) experimentally observed will be different by $(1 - \frac{\bar{g}}{g})\frac{GM}{Rc^2}$

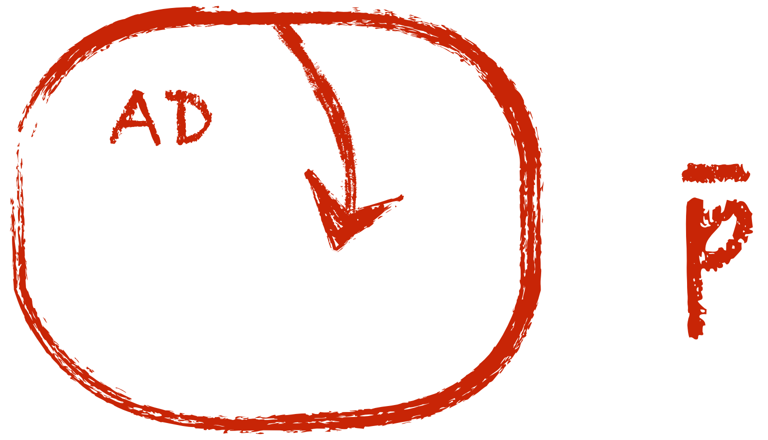
cyclotron frequencies of antiproton and proton measured to ppb precision but :
- "arbitrariness" of the definition of the "absolute gravitational potential" (which sets the upper bound on anomalous antimatter gravity)
- assumes CPT invariance

Need antimatter!
preferentially long-lived, "easily" produced : $\bar{\mathbf{p}}$ **,** $\mathbf{e^+}$
Attempted on those (charged) but too difficult to control stray-fields at a high enough level of precision
($F_G/F_{EM} \sim 10^{-36}$)
anti-neutrons?
Cannot be easily cooled like neutrons (at T~1K, v~140 ms^{-1})

Need for a free-fall experiment on antimatter

an experiment that drop, throw or deflect and measure resulting force
(i.e. independent of framework)

Formation of antihydrogen atoms: several approaches



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

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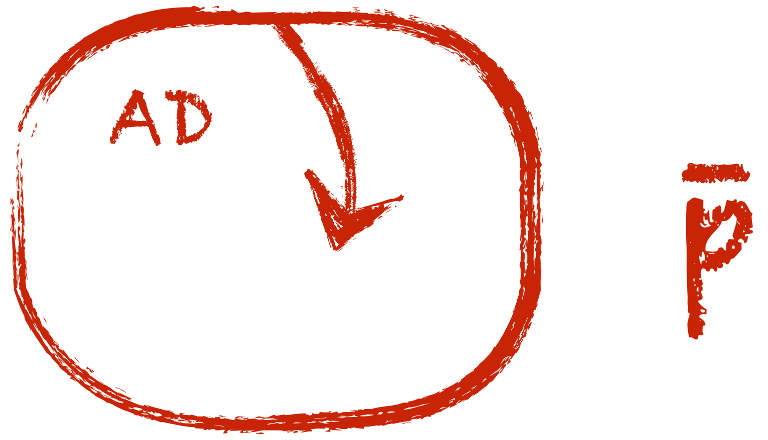
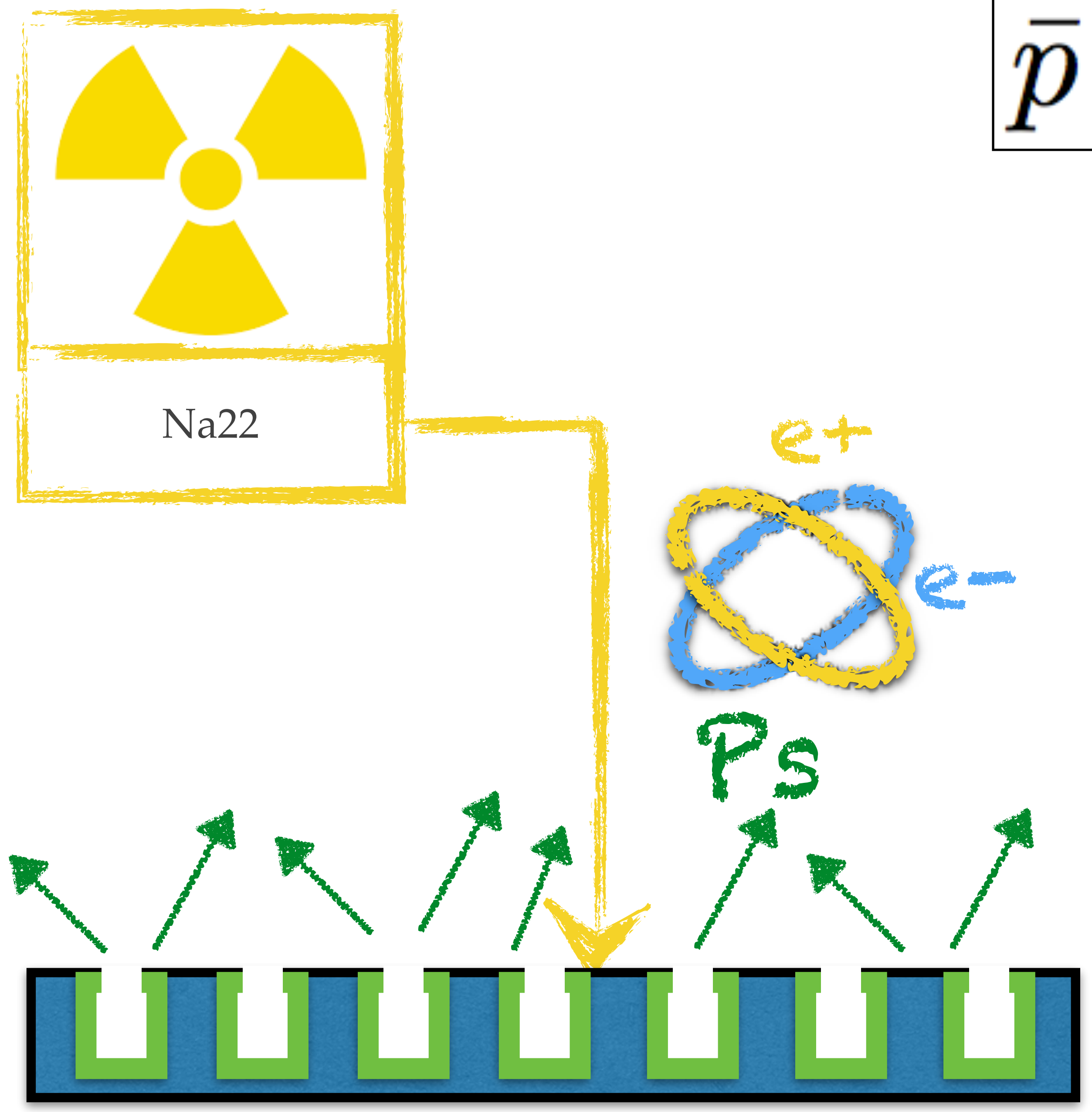


$$\bar{p} + e^{+} + e^{+} \rightarrow \bar{H} + e^{+}$$

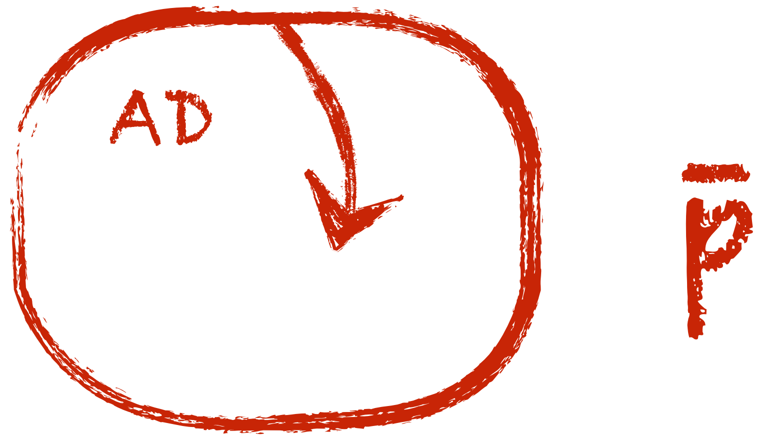
ALPHA



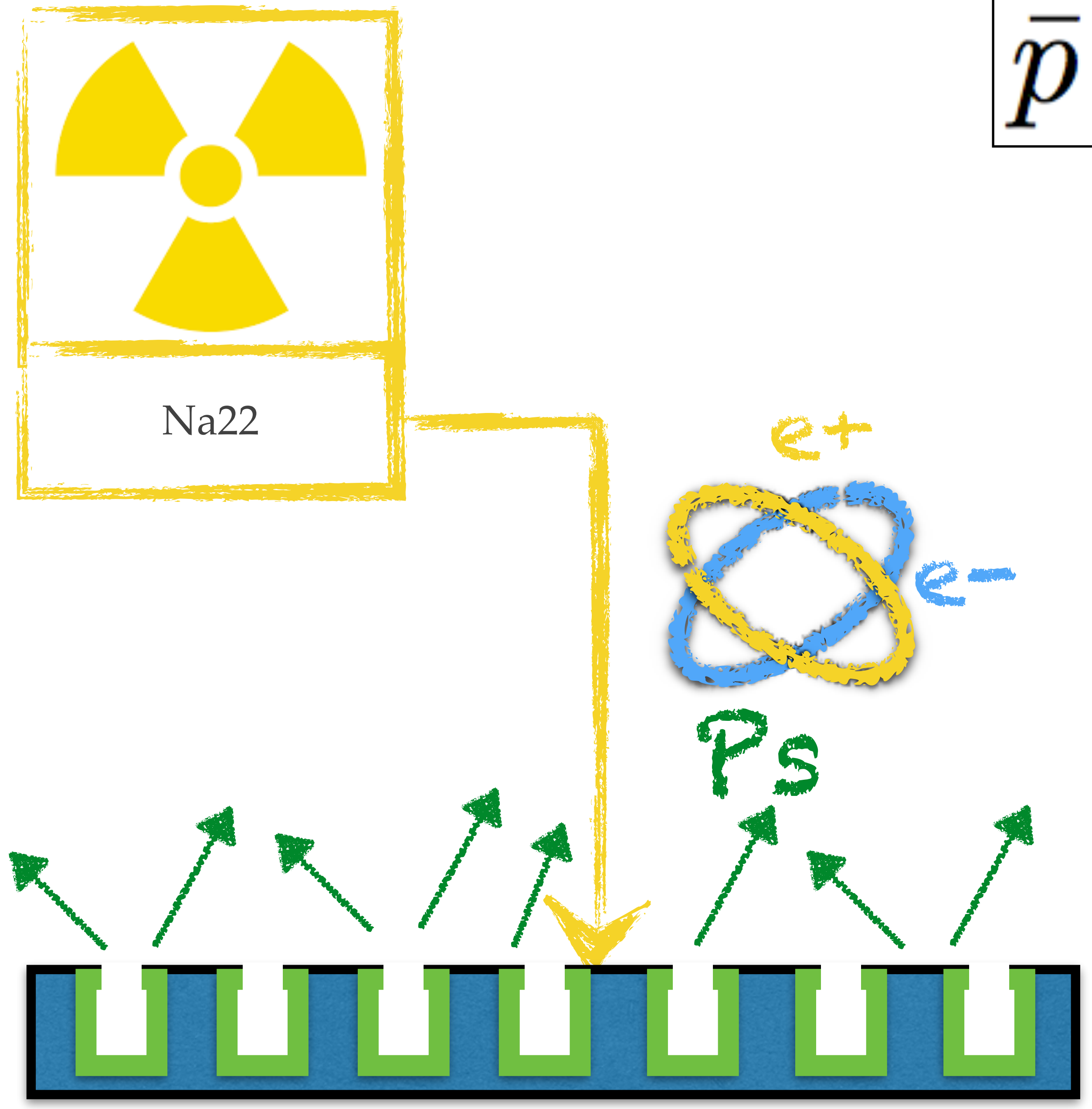
$$\bar{p} + Ps^{\star} \rightarrow \bar{H}^{\star} + e^{-}$$

AEgIS

Formation of antihydrogen atoms: several approaches

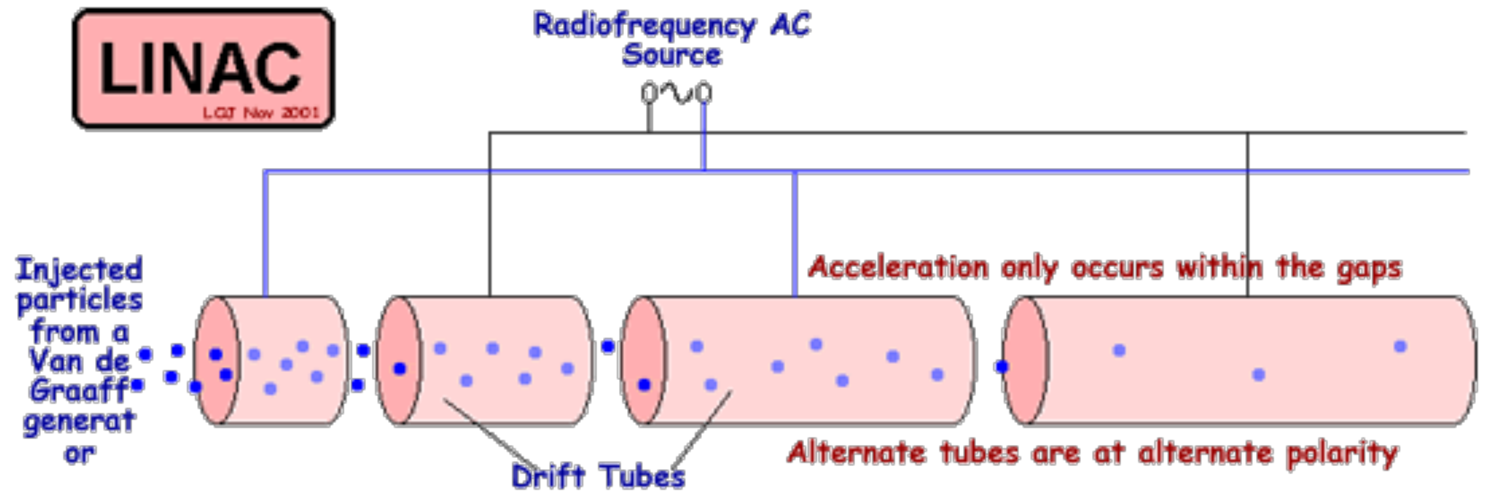


$$\bar{p} + e^+ + e^+ \rightarrow \bar{H} + e^+$$



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

Antihydrogen ION !

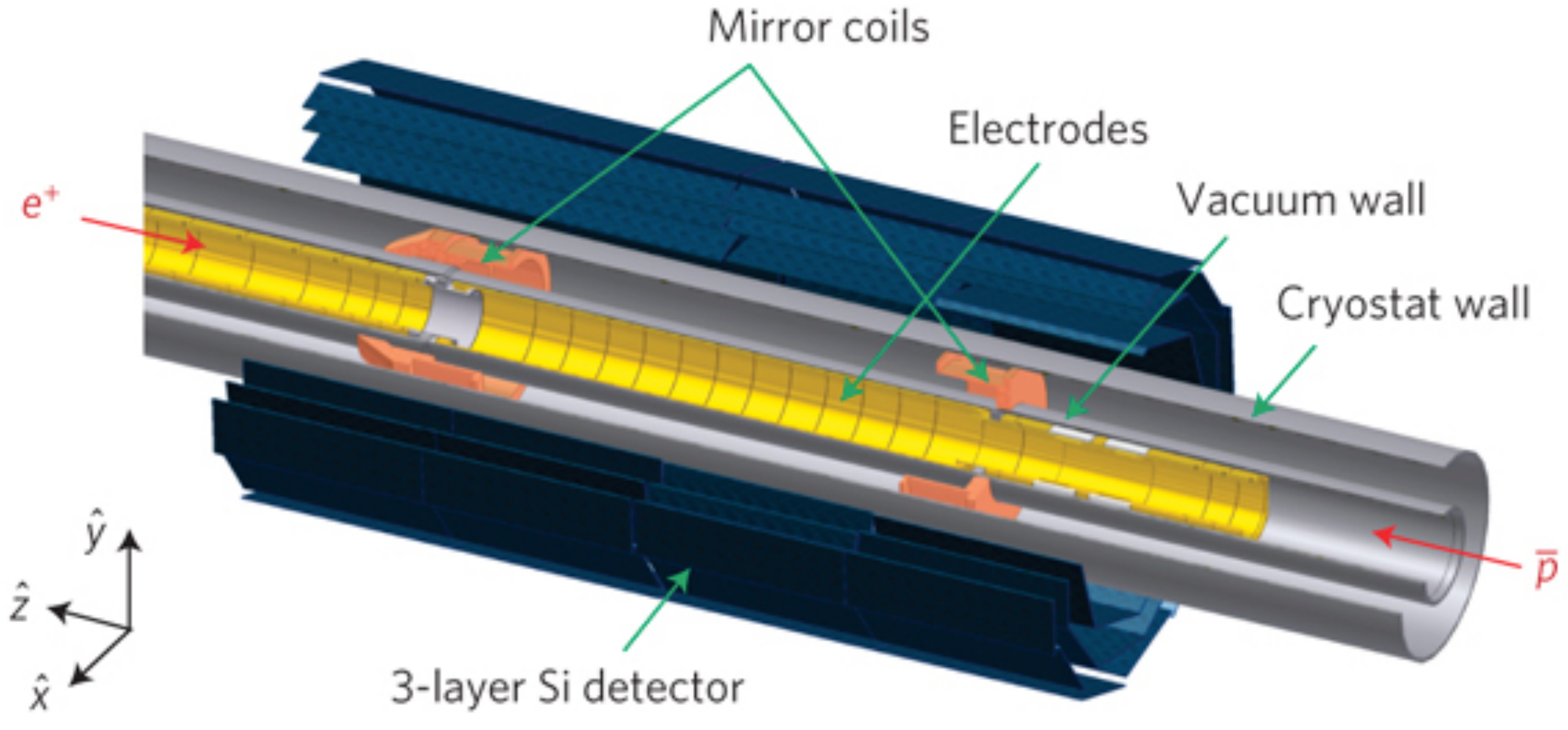


$$\bar{p} + Ps \rightarrow \bar{H} + e^-$$

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

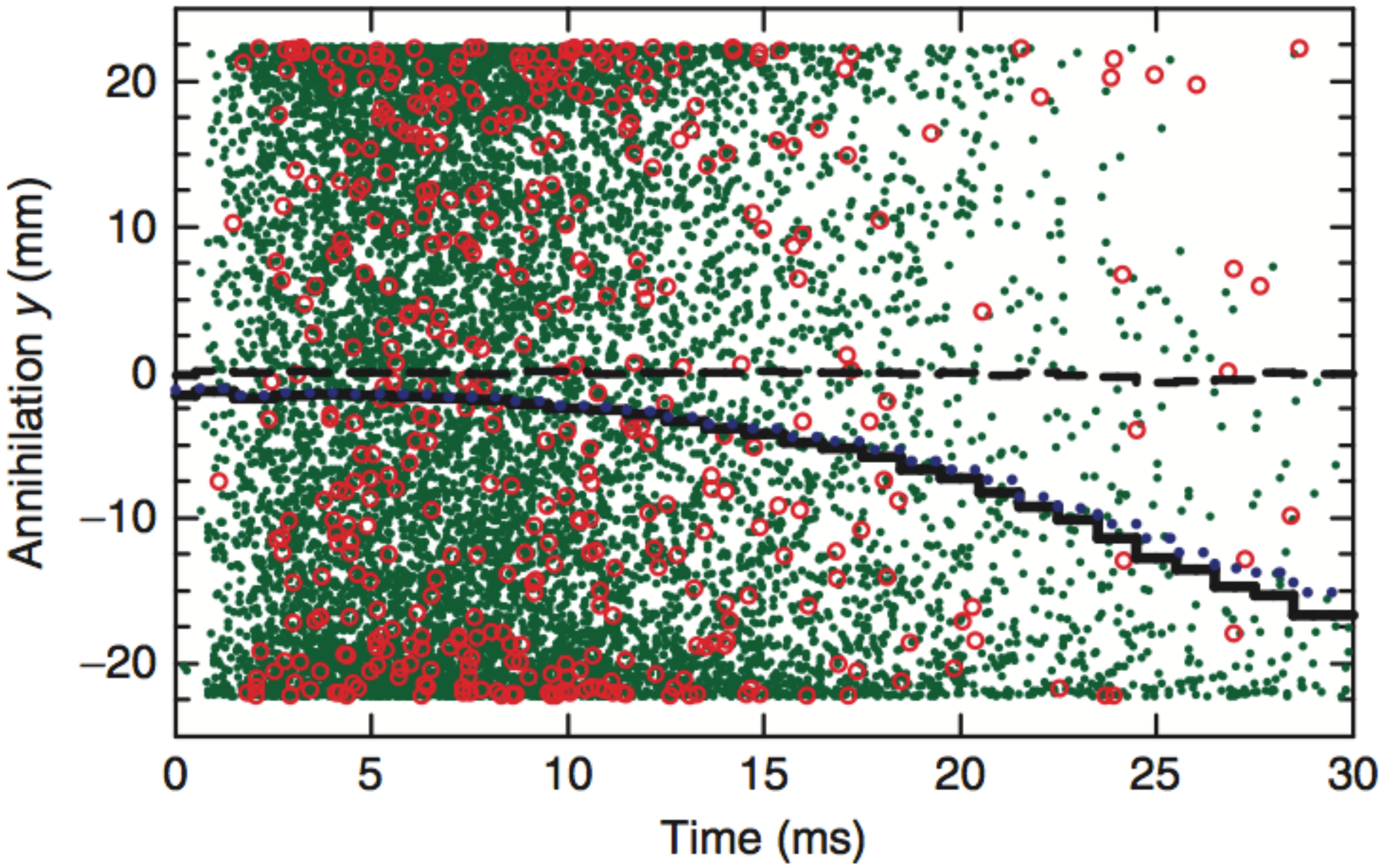
Status of the field

ALPHA
First direct measurement in 2012 (in a magnetic trap!)



-65 < g/ḡ < 110

Vertical position of annihilation vertex during release of trapping field



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

Green dots---simulated annihilations   Red circles---434 Observed annihilations

Status of the field

Now commissioning a VERTICAL TRAP
- increase sensitivity in up/down direction (up to 1.3m trapping range)
- much improved field control

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

Article

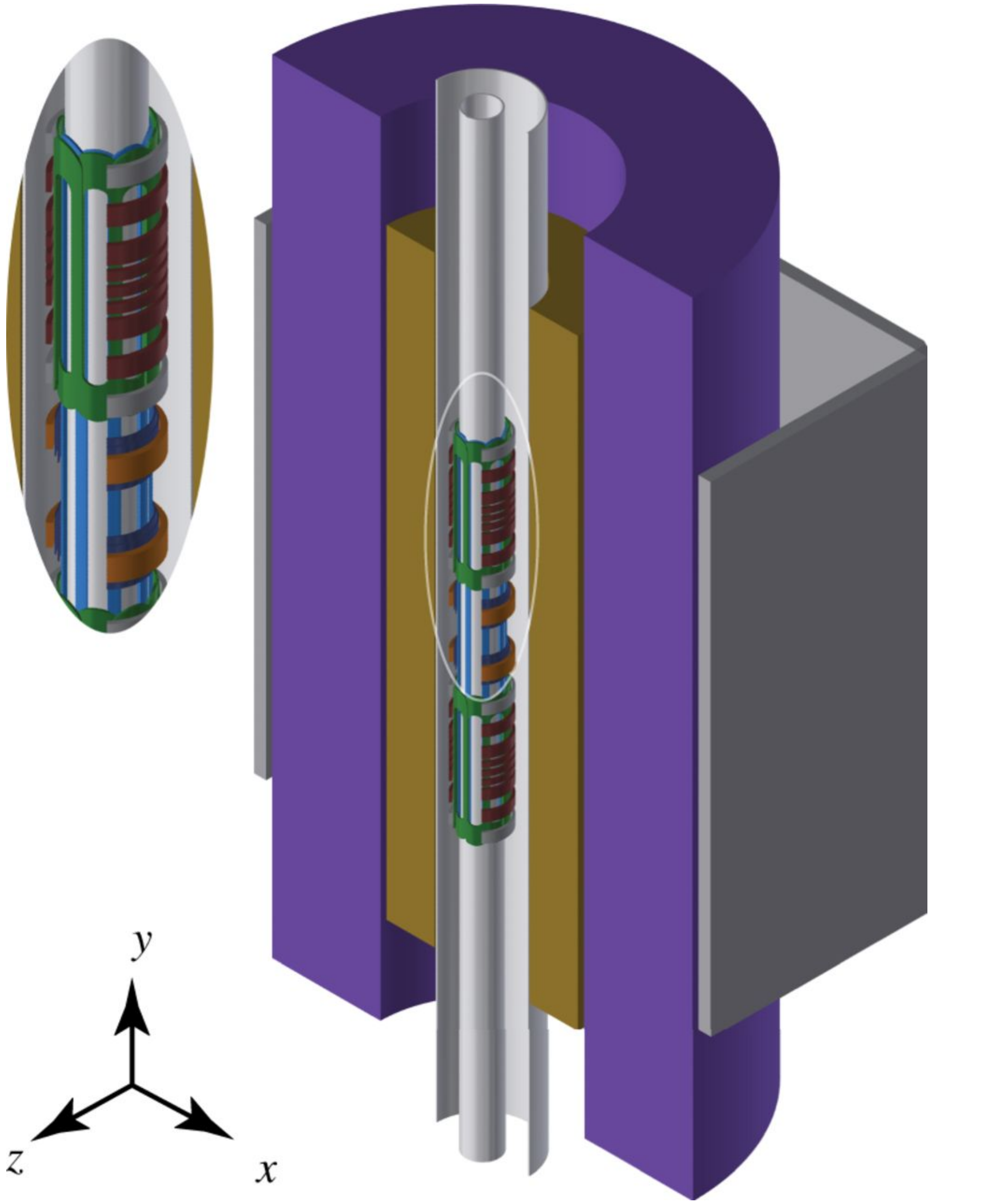
Laser cooling of antihydrogen atoms

https://doi.org/10.1038/s41586-021-03289-6
Received: 21 July 2020
Accepted: 26 January 2021
Published online: 31 March 2021
Open access
Check for updates

ARTICLE

https://doi.org/10.1038/s41467-021-26086-1 OPEN
Check

Sympathetic cooling of positrons to cryogenic temperatures for antihydrogen production

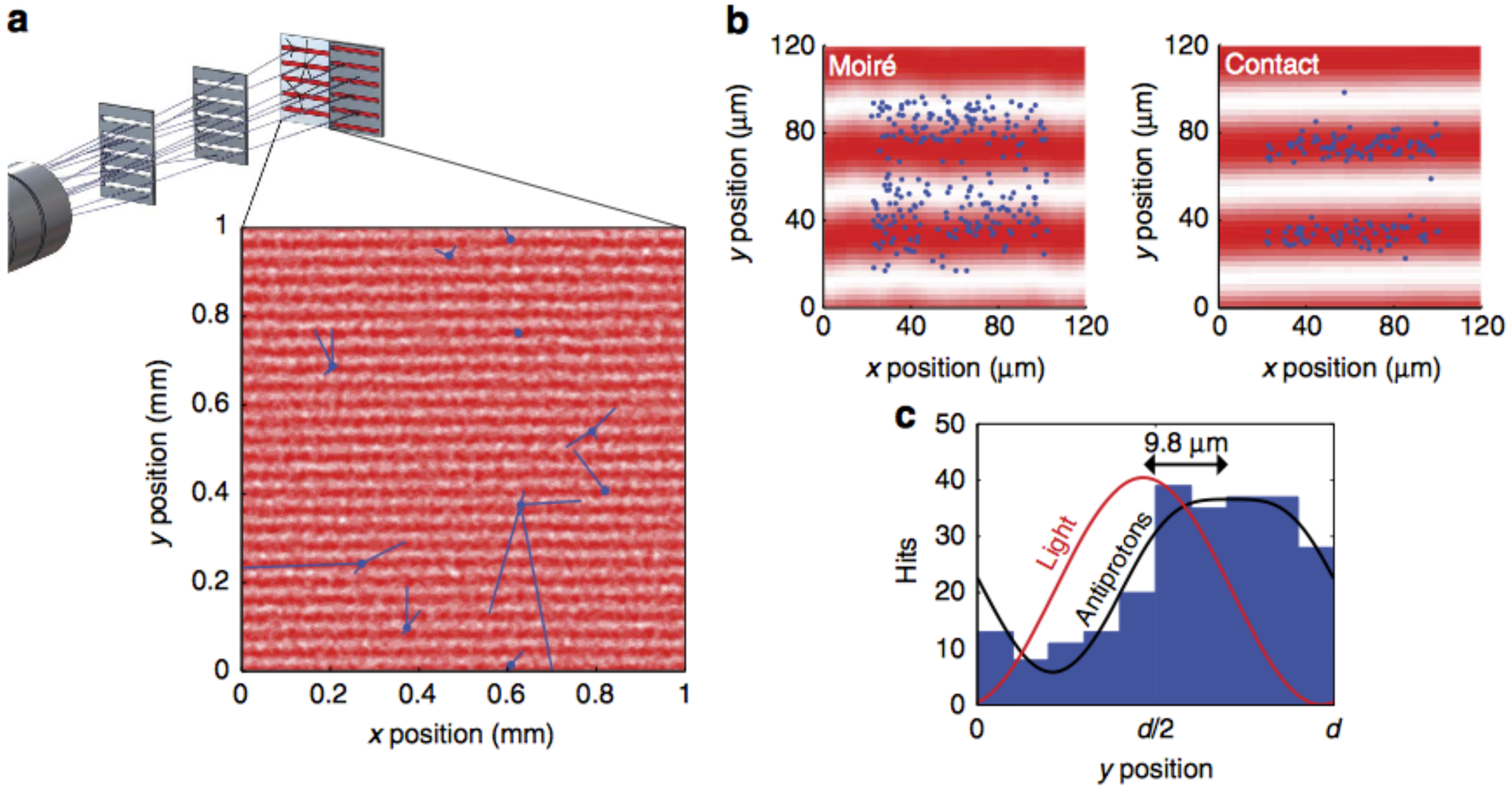


W. A. Bertsche Phil. Trans. R. Soc. A 2018 376 20170265; DOI: 10.1098/rsta.2017.0265. (2018)

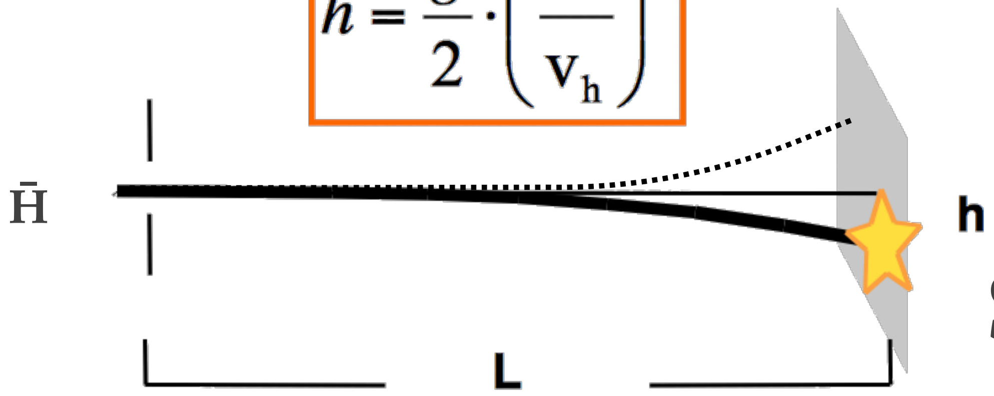
Status of the field

AEGIS : DEFLECTOMETER

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



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



~1-10%

Sensitivity to ~10 μm deflection needed

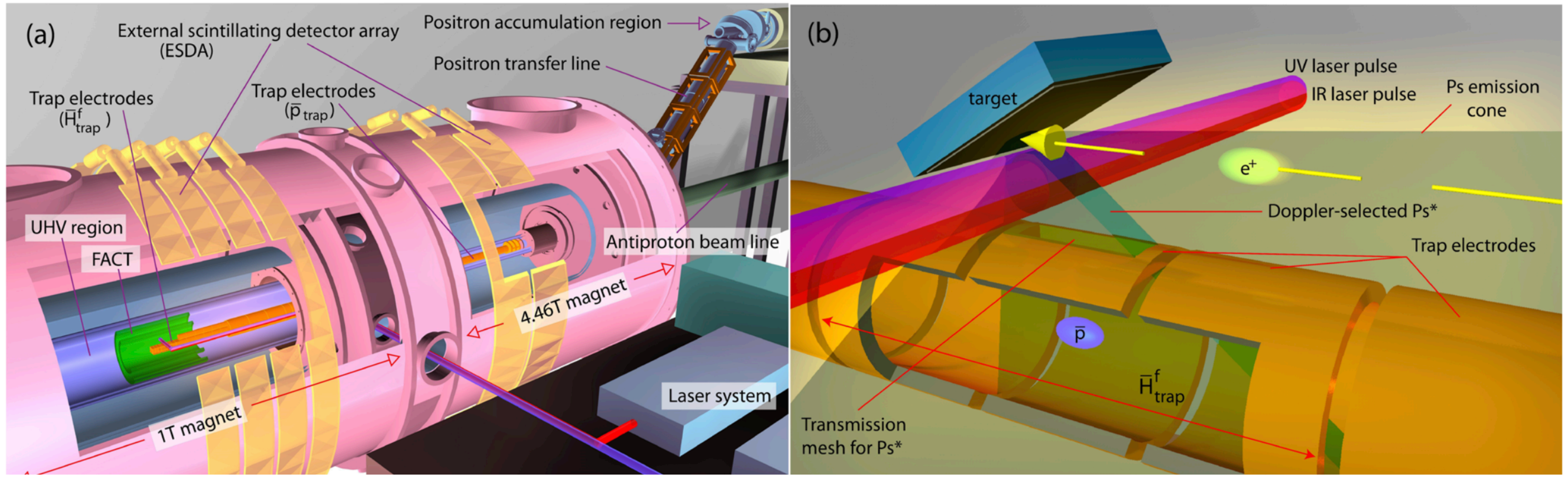
Cold $\bar{H}$ production relying on sympathetic cooling of $\bar{p}$ via laser cooled anions or molecules

E. Jordan et al., Phys. Rev. Lett. 115 113001 (2015)

P. Yzombard et al., Phys. Rev. Lett. 114 213001 (2015)

Recent demonstration of pulsed formation of $\bar{H}$

Communications Physics, volum 4, Article number: 19 (2021)

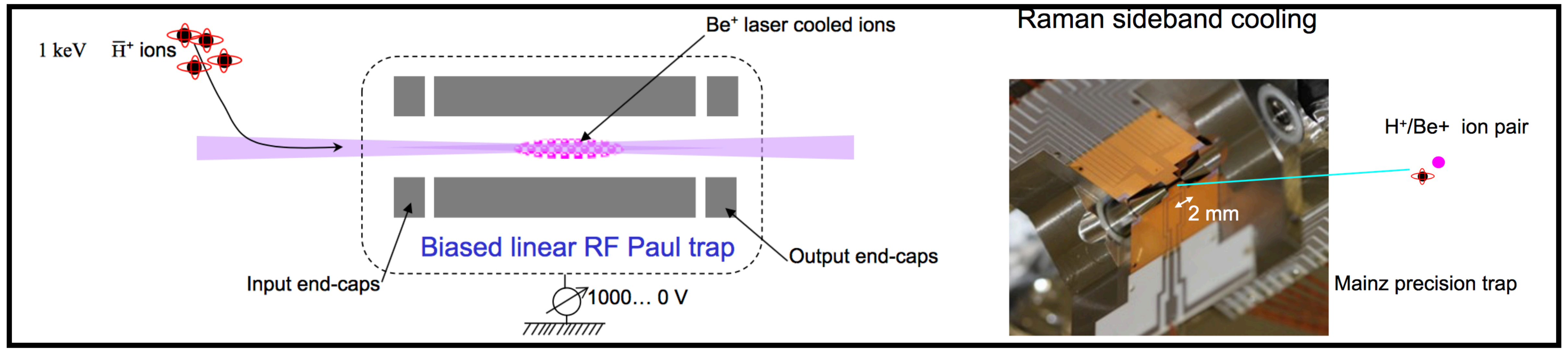


Status of the field

GBAR : USING H̄+

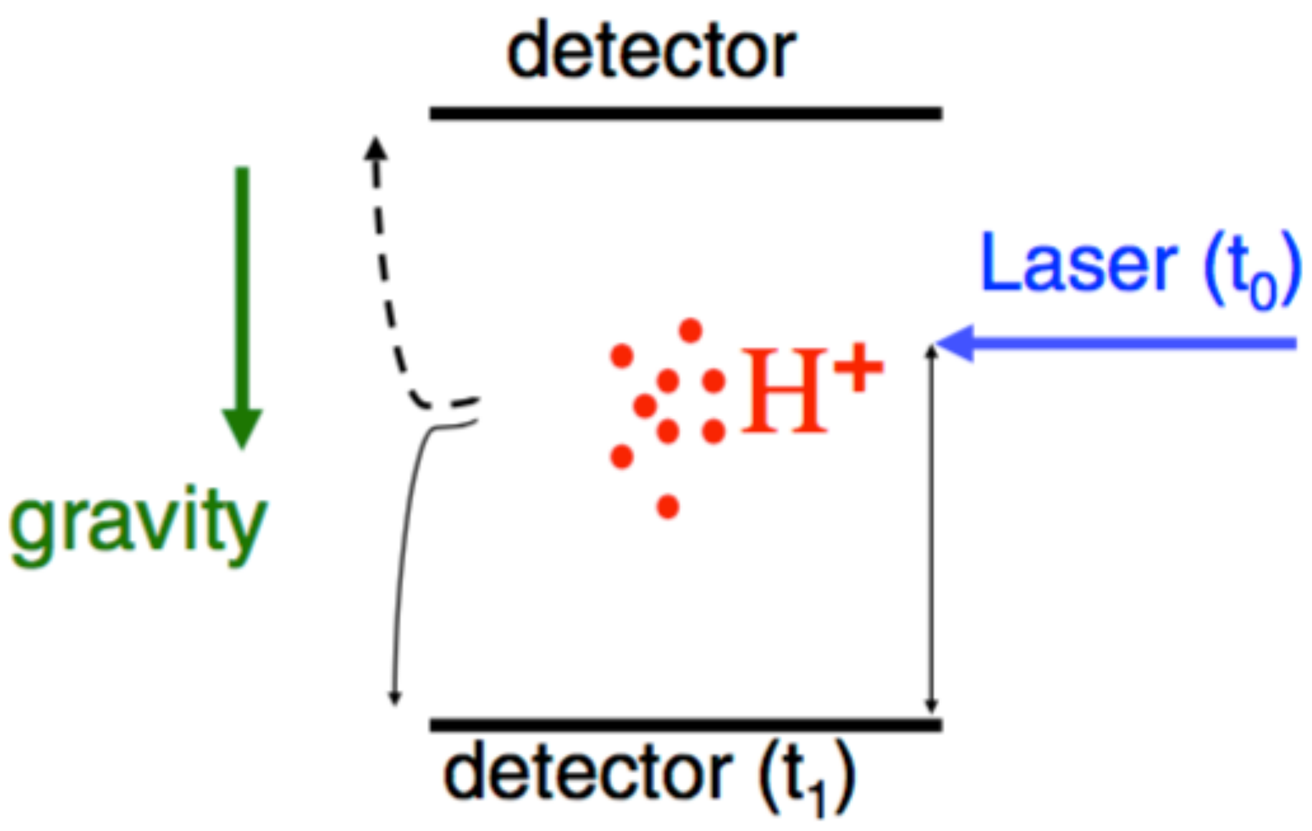
- will produce first ever H̄+ ion
- will bring antimatter to the coldest temperature ever achieved (by several orders of magnitude)

Cooling below 1 m/s : Sympathetic cooling of H̄+



GBAR : DROPING EXPERIMENT

~1%



CASIMIR EFFECT (QUANTUM REFLECTIONS)
—-> spectroscopy of gravitational states!

~0.1%

G. Dufour et al., Eur. Phys. J. C 74 (2014) 2731

Already observed in cold neutrons

V. Nesvizhevsky et al., Nature, 415, 17 (2002)

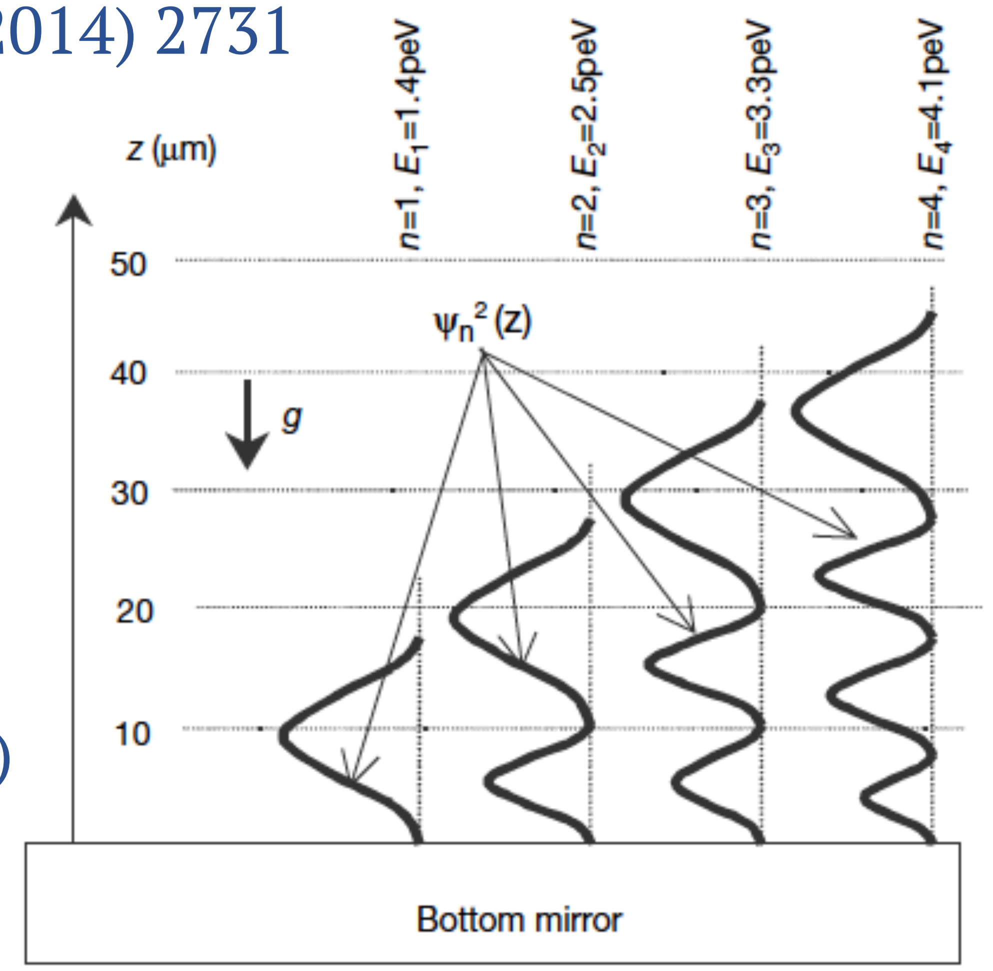
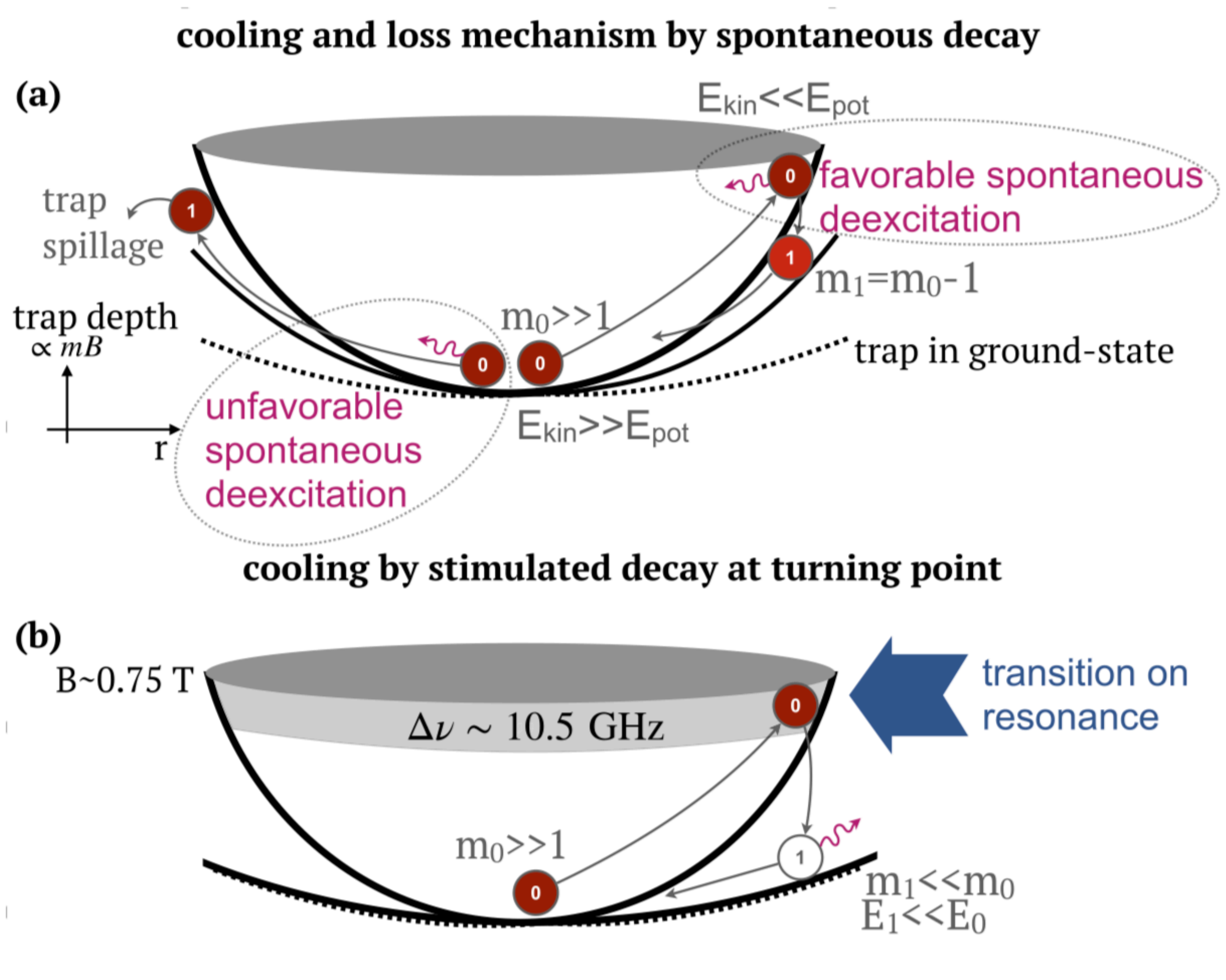


Figure 1 Wavefunctions of the quantum states of neutrons in the potential well formed by the Earth's gravitational field and the horizontal mirror. The probability of finding neutrons at height z, corresponding to the nth quantum state, is proportional to the square of the neutron wavefunction $\psi_n^2(z)$. The vertical axis z provides the length scale for this phenomenon. E_n is the energy of the nth quantum state.

Status of the field

Study of alternative cooling mechanism in a neutral atom trap



C Malbrunot et al 2022 J. Phys. B: At. Mol. Opt. Phys. 55 044003

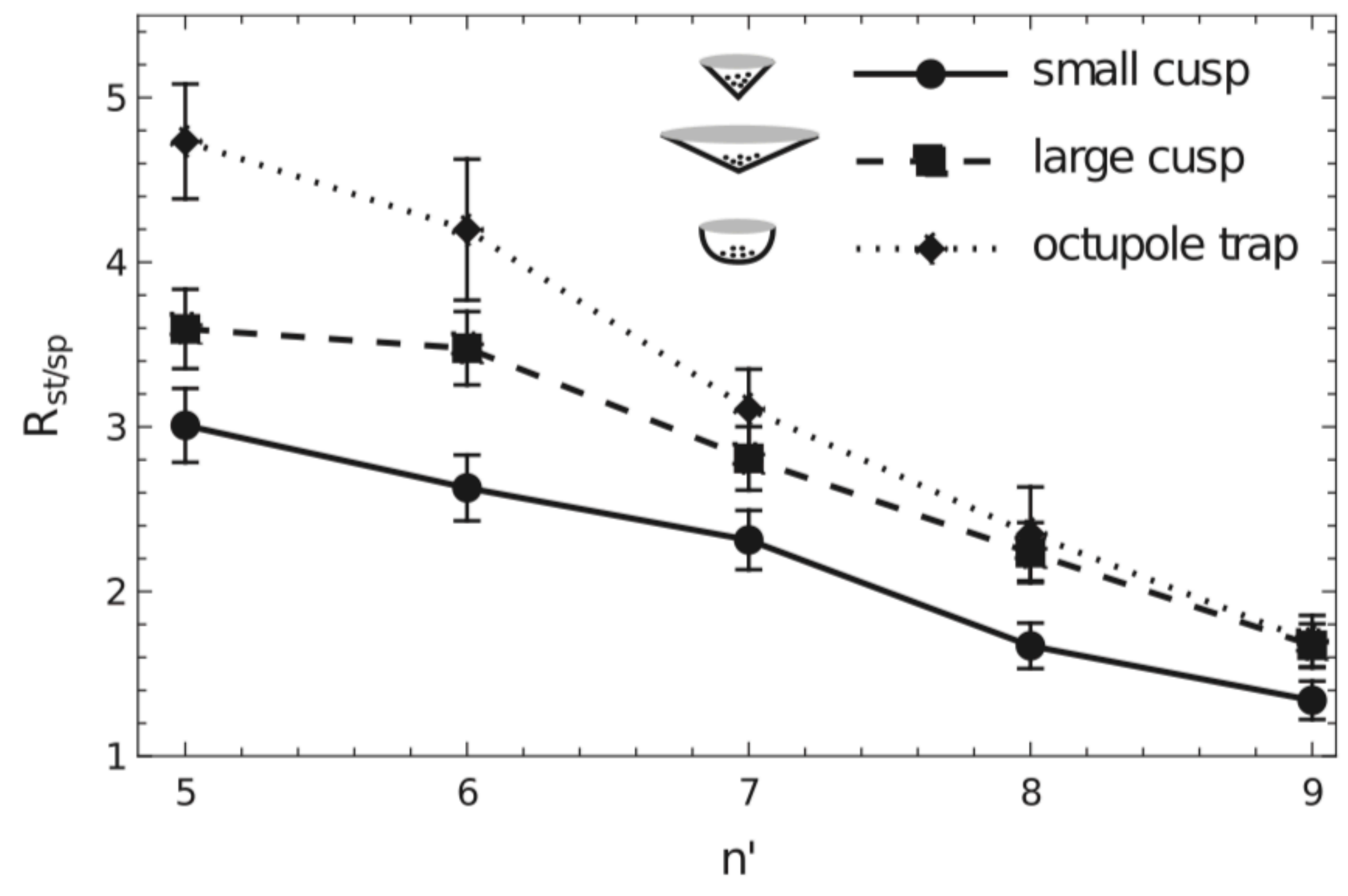


Figure 4. Ratio of trapped atoms with and without THz-stimulated decay ($R_{st/sp}$) as a function of n' for different trap configurations. The stimulated rate is $\Gamma = 4 \times 10^7\ s^{-1}$. The lines are a guide for the eye.

Adiabatic-like cooling by acting on the internal structure of the atoms at an appropriate place in the trap - increase the phase space density

Based on previous work on fast stimulated deexcitation:
e.g. Wolz T, Malbrunot C, Vieille-Grosjean M and Comparat D 2020 *Phys. Rev.* A 101 043412

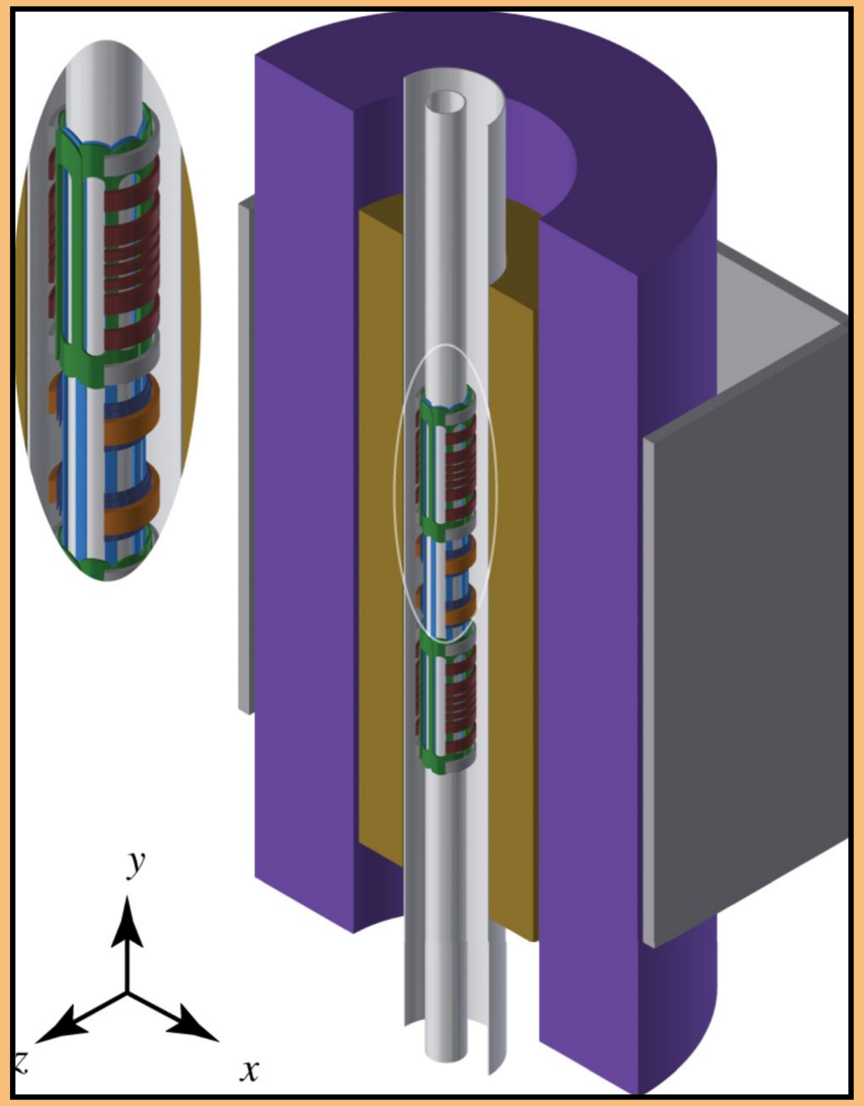
Planned gravity measurements with antihydrogen atoms

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

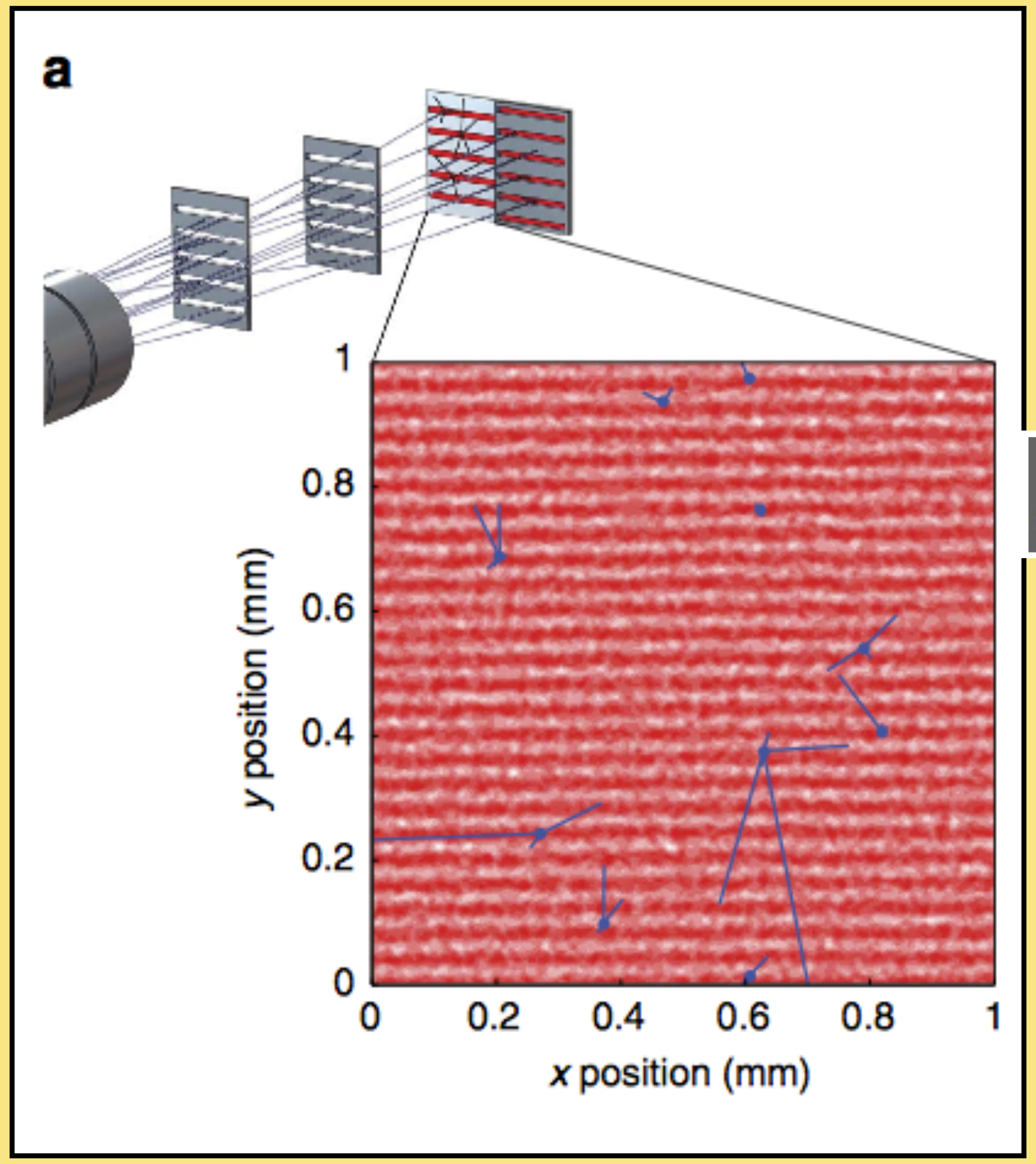


ALPHA
(ALPHA-g)

$\bar{H}$ BEAM

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

Sign measurement targeted



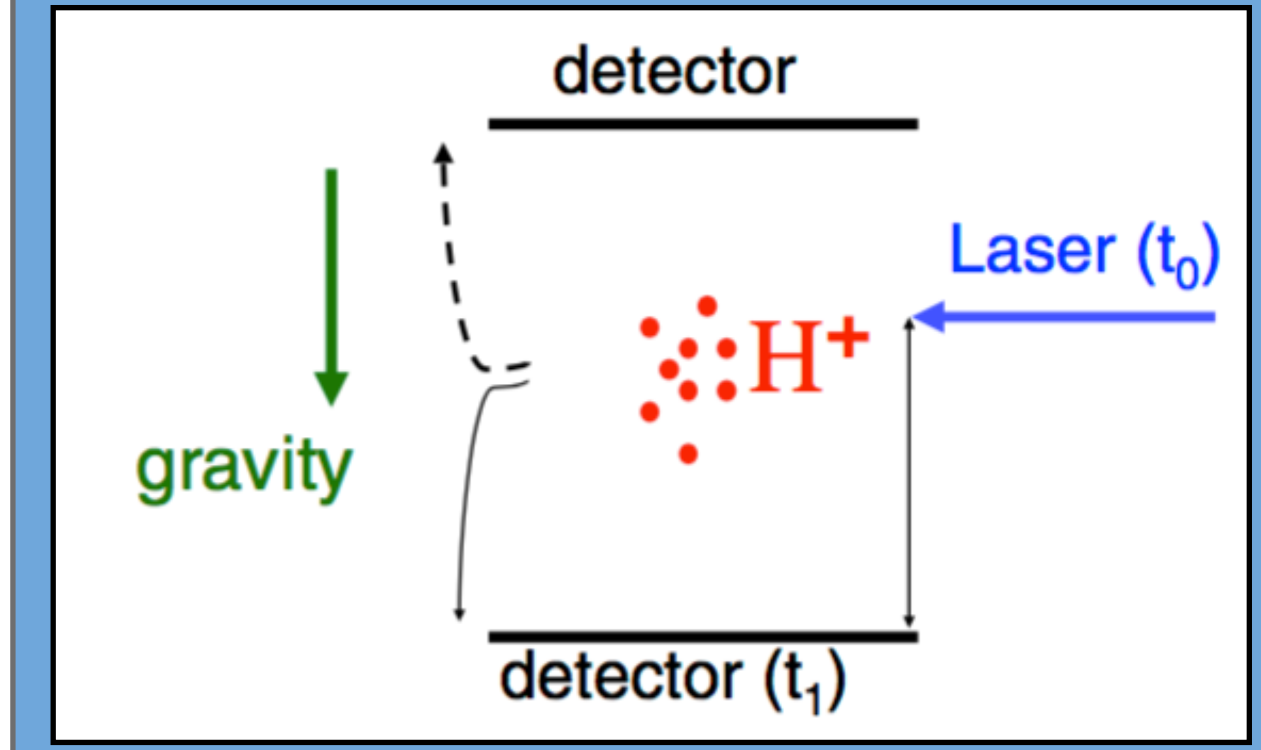
AEgIS

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

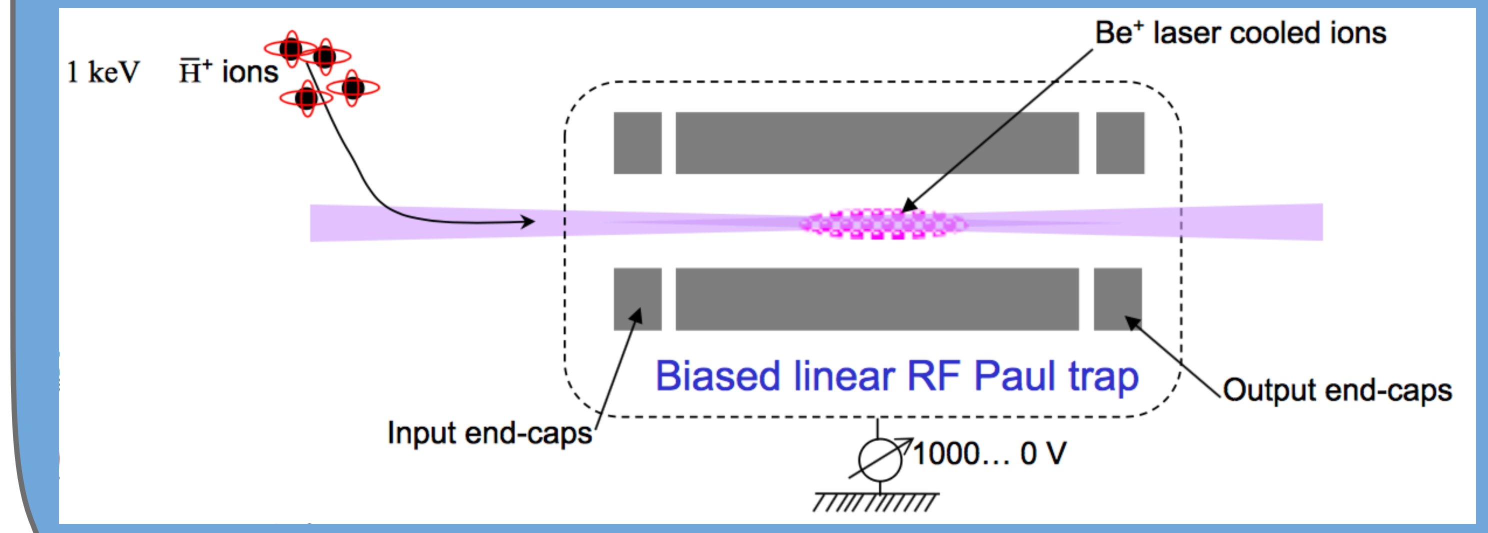
$\bar{H}^+$ BEAM

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

1% measurement targeted



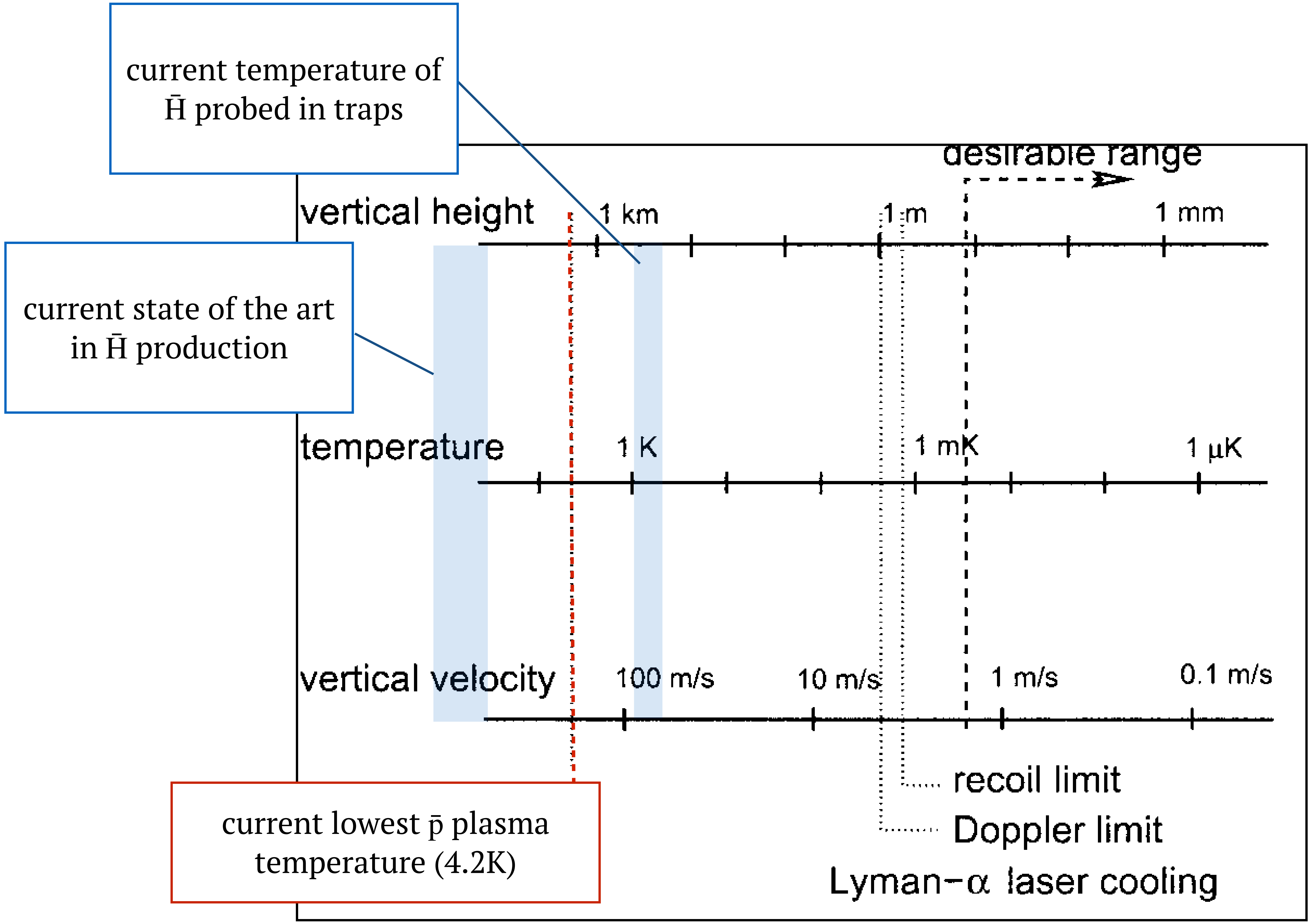
GBAR



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

Planned gravity measurements with antihydrogen atoms

Some numbers to set the scale



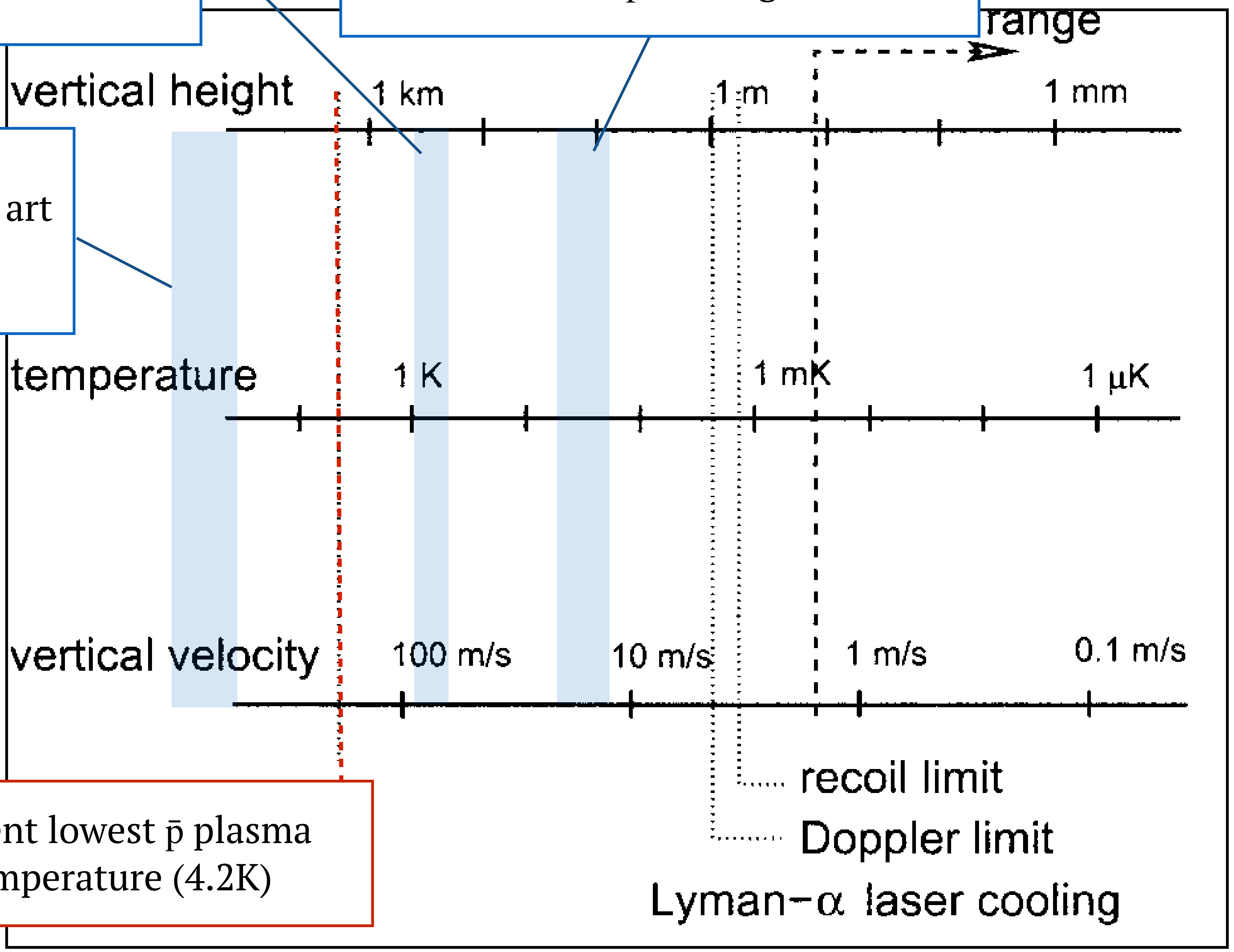
Planned gravity measurements with antihydrogen atoms

Some numbers to set the scale

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

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

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



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

Planned gravity measurements with antihydrogen atoms

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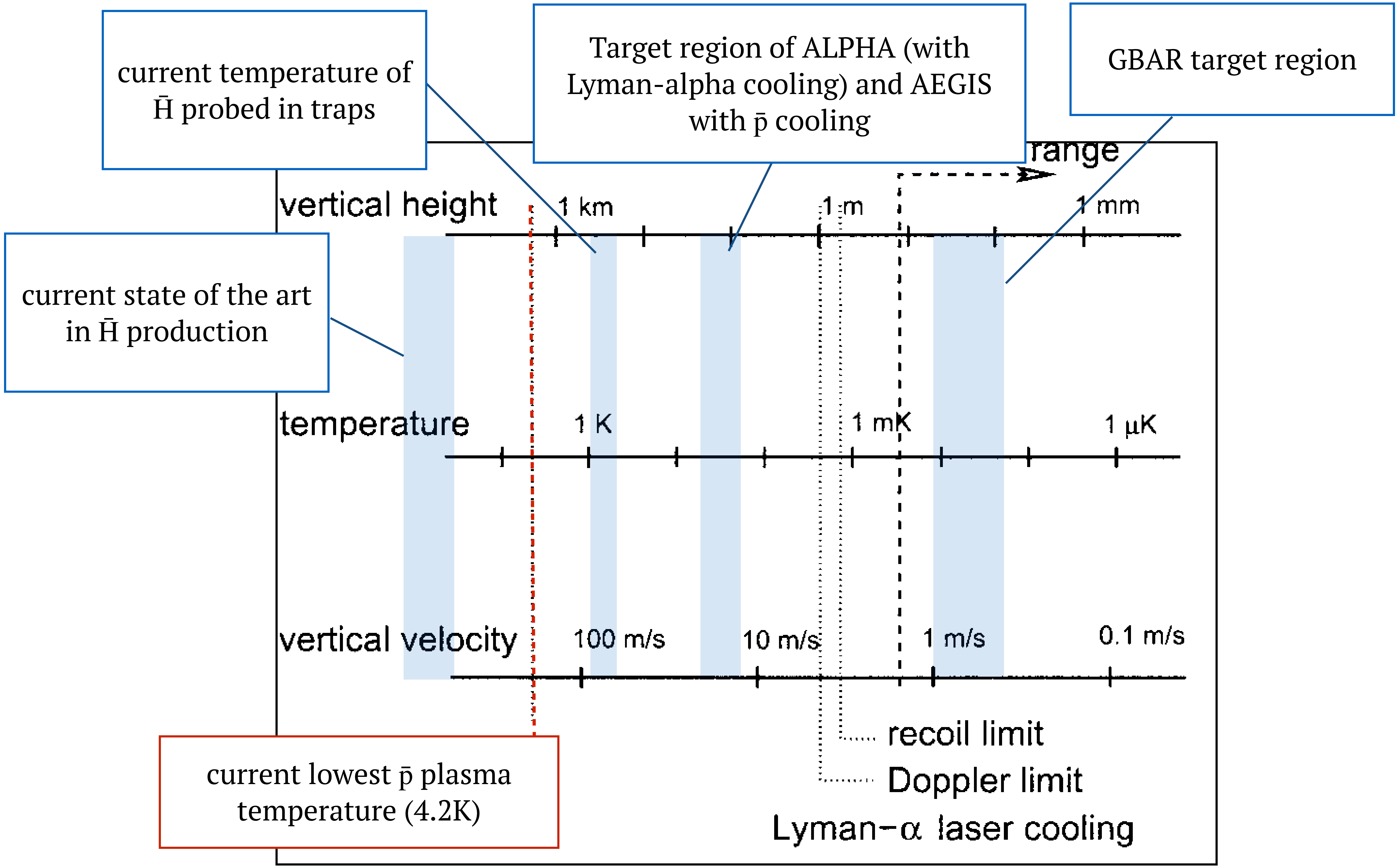

Planned gravity measurements with antihydrogen atoms

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GBAR target region

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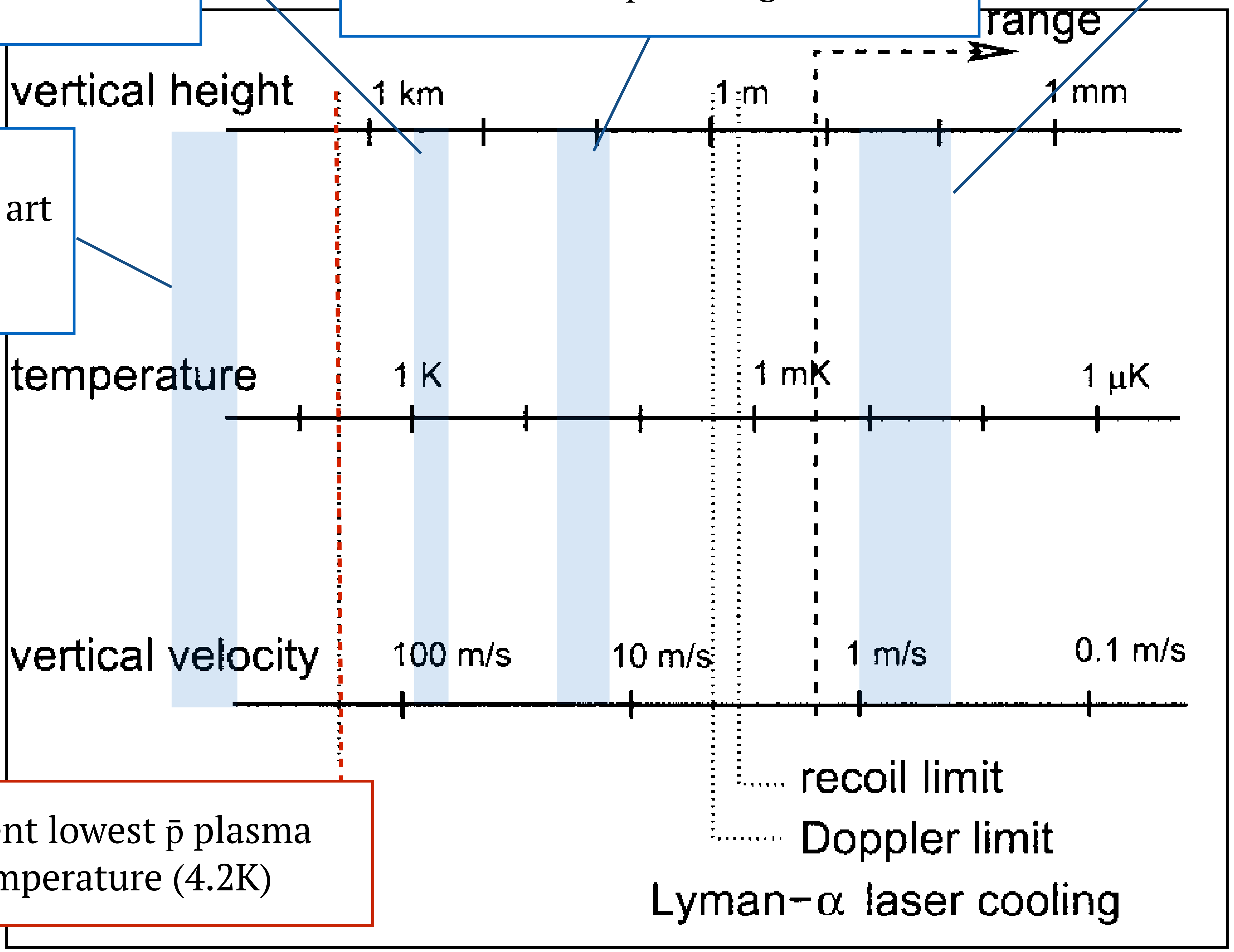
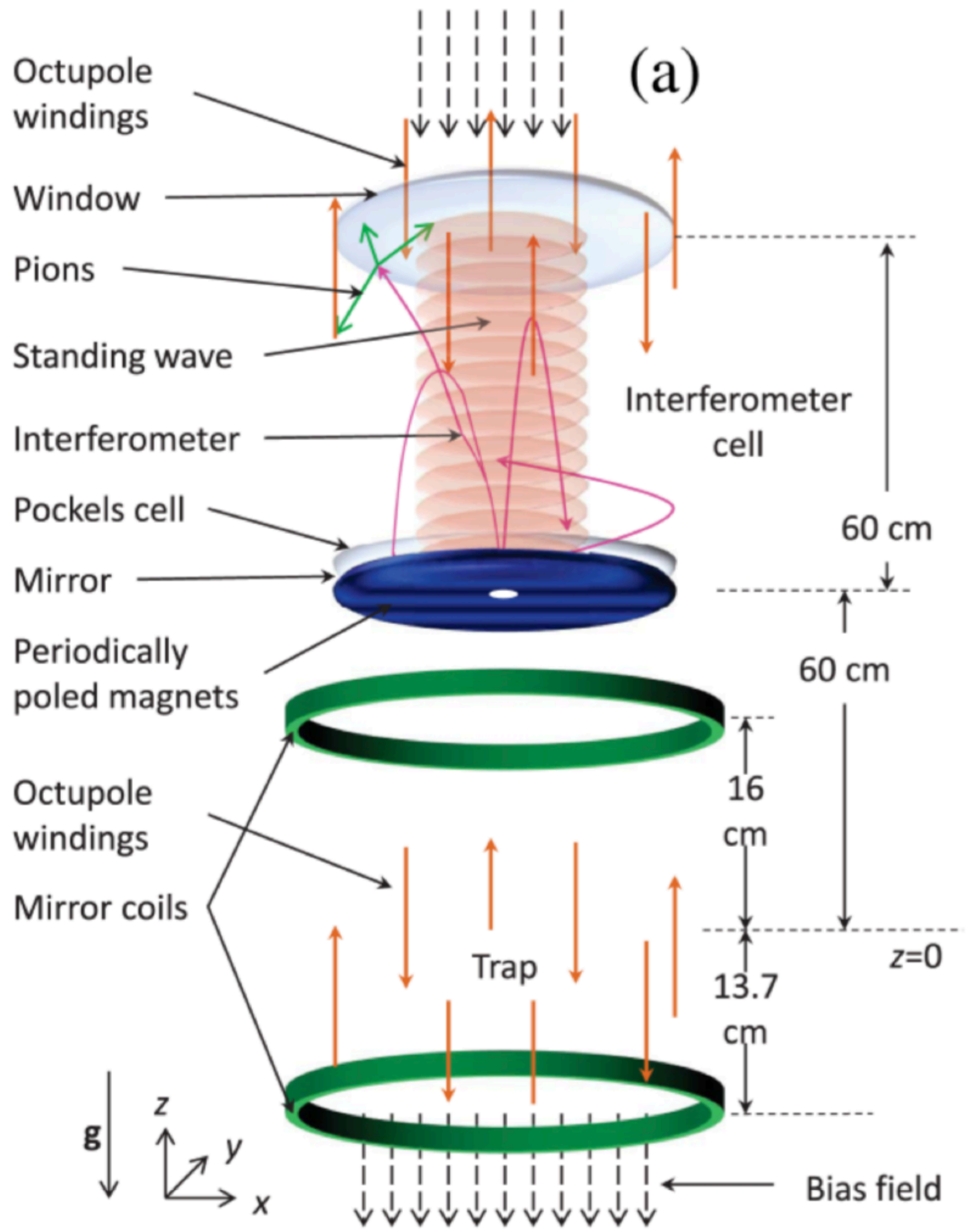


Fountains Interferometry



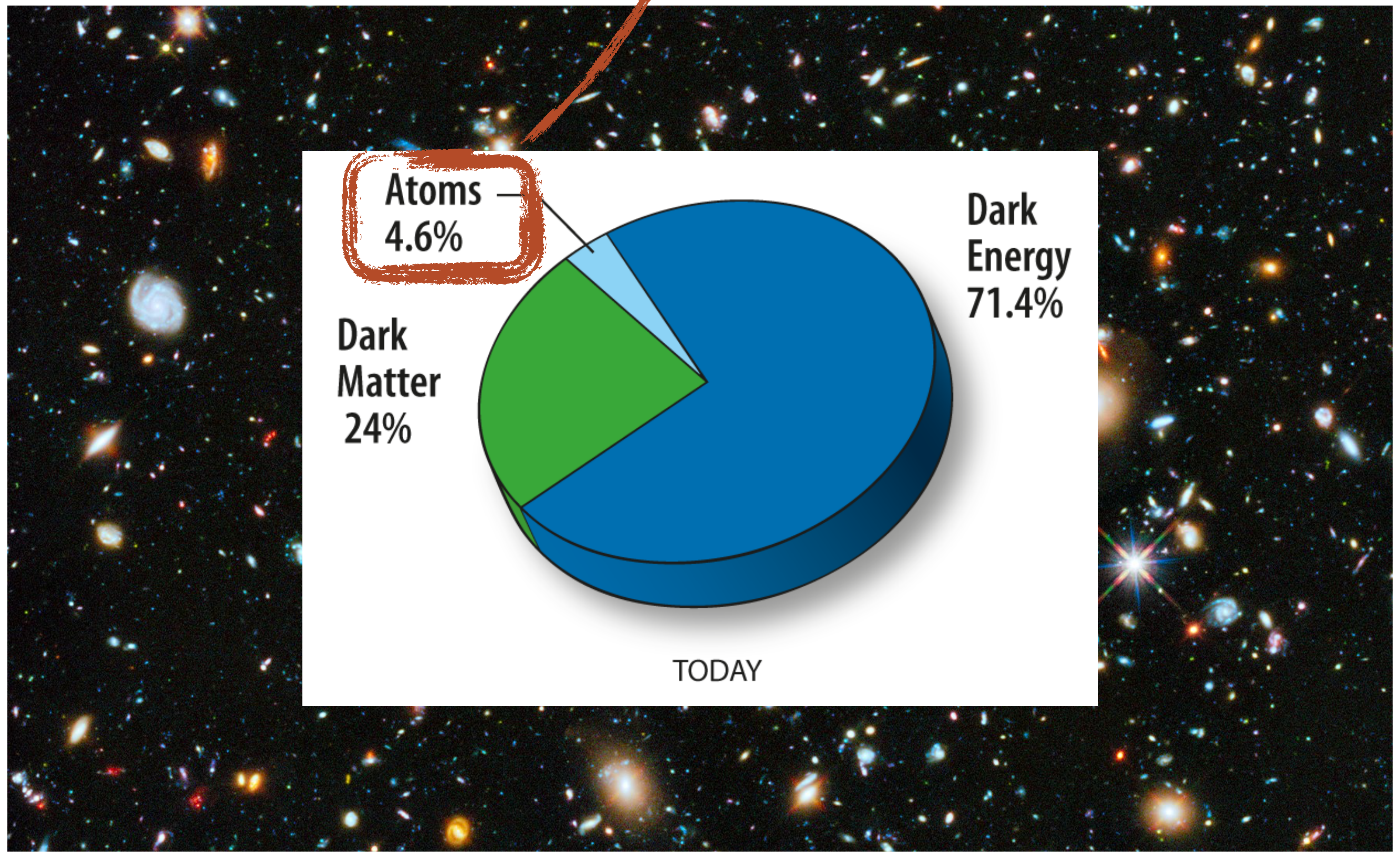
DOI: 10.1103/PhysRevLett.112.121102

Summary

- Uniqueness of the physics question addressed
- Calls for a direct measurement
- $\bar{\text{H}}$ is a tool of choice for such a measurement
- Three collaborations at CERN/AD are taking on the challenge
- A sign measurement is expected soon (~2022/2023)
- Diversity of approaches aims at tackling different sensitivities (with different systematics)
- Typical time-scales involved for new experiments and precision measurements are long (typically >10 years)
- Other "gravity" endeavours with antimatter : muonium (μ^+e^-), positronium (e^+e^-)
  Testing leptonic matter-antimatter systems
  Mu: Testing systems containing 2nd generation particles!

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

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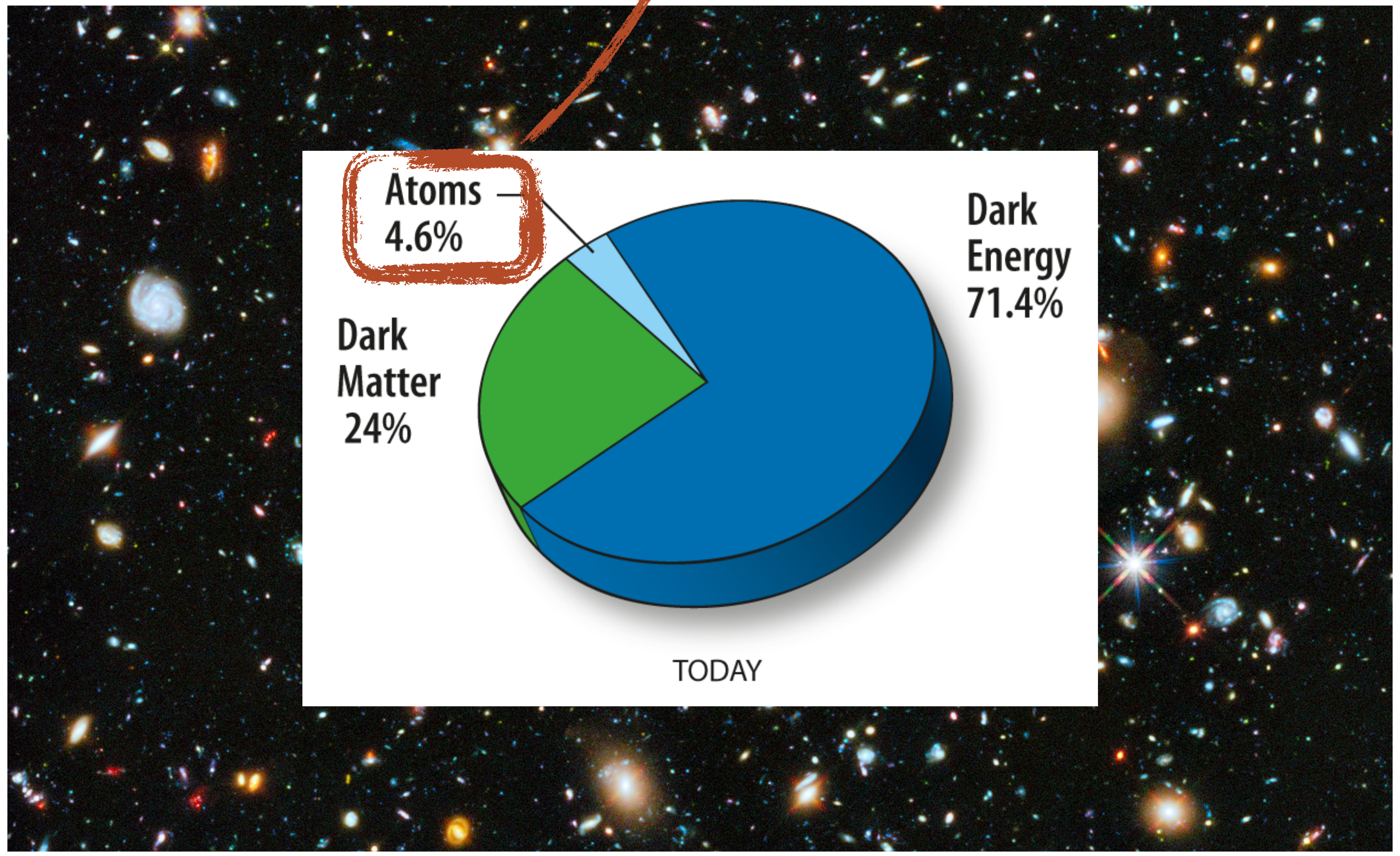

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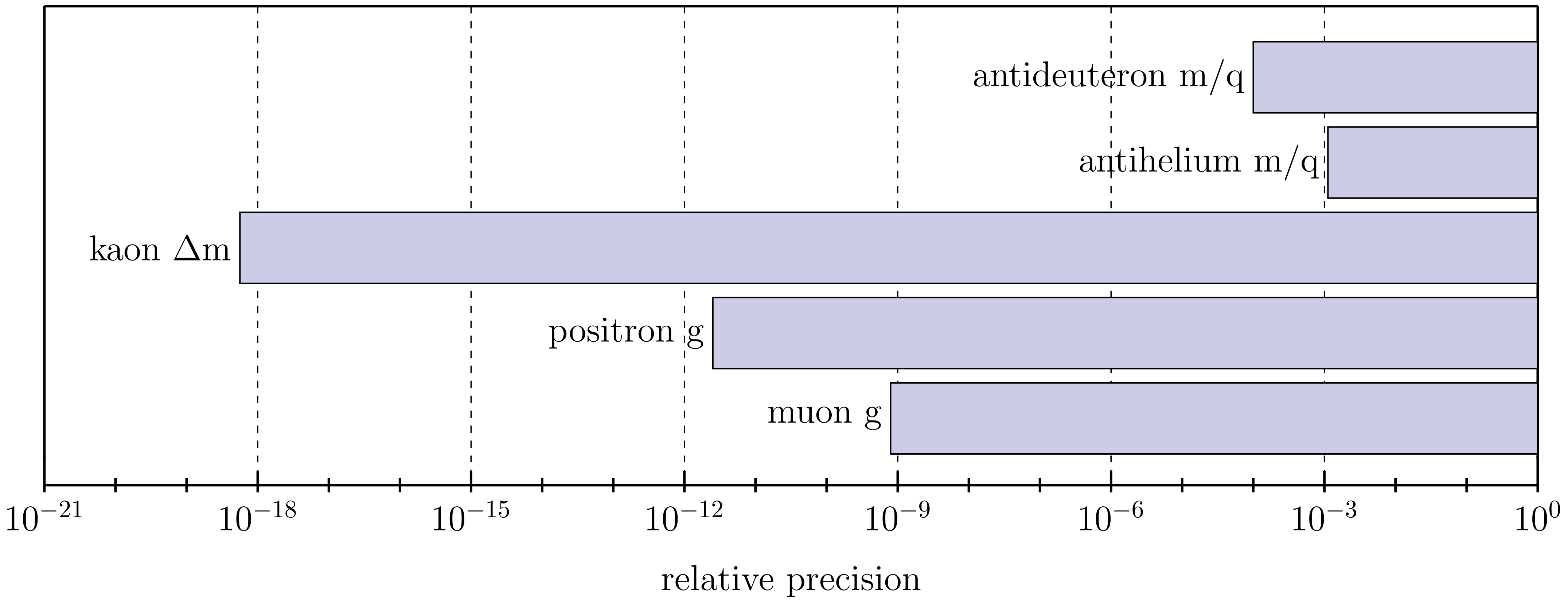
baryon asymmetry:

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



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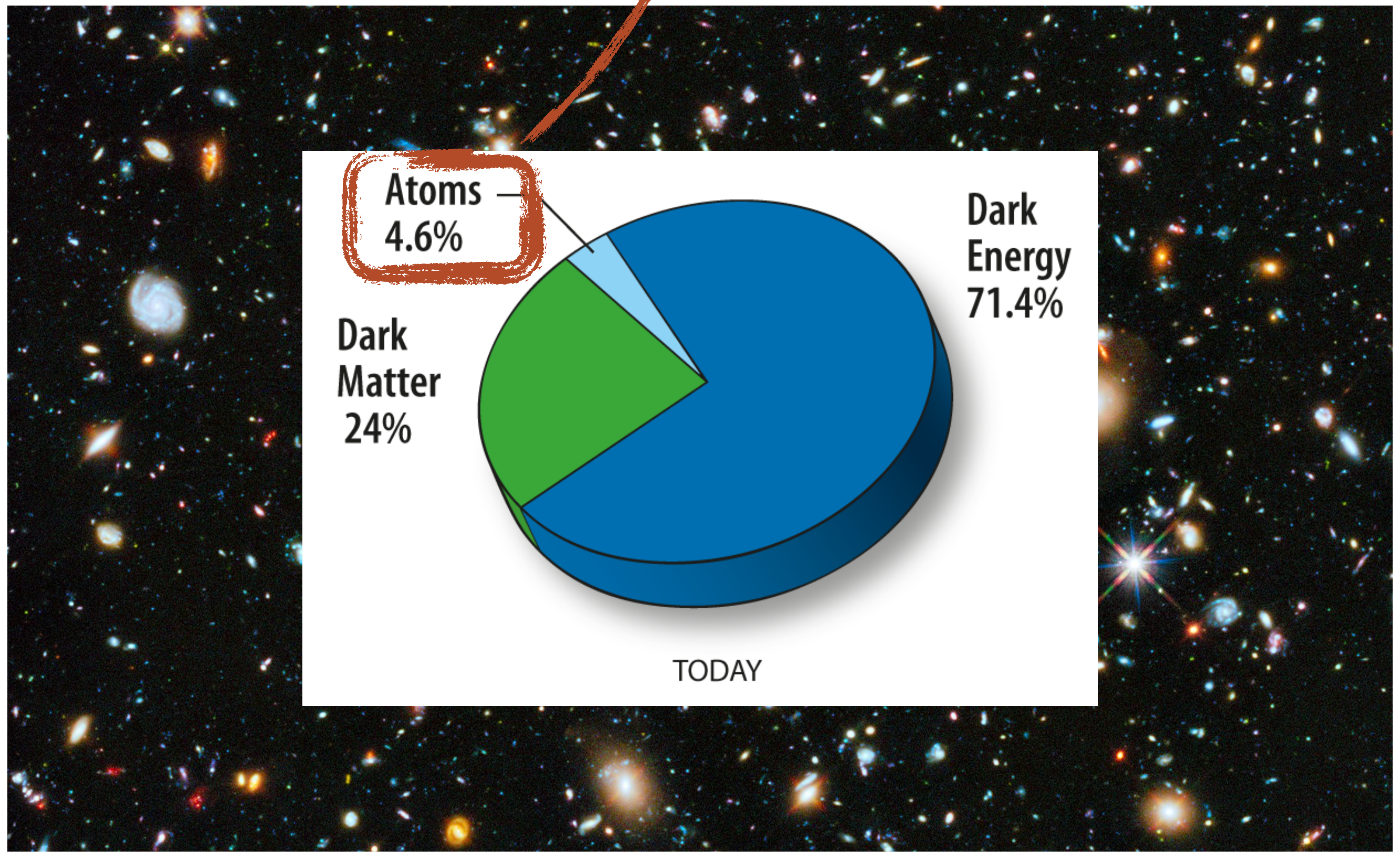

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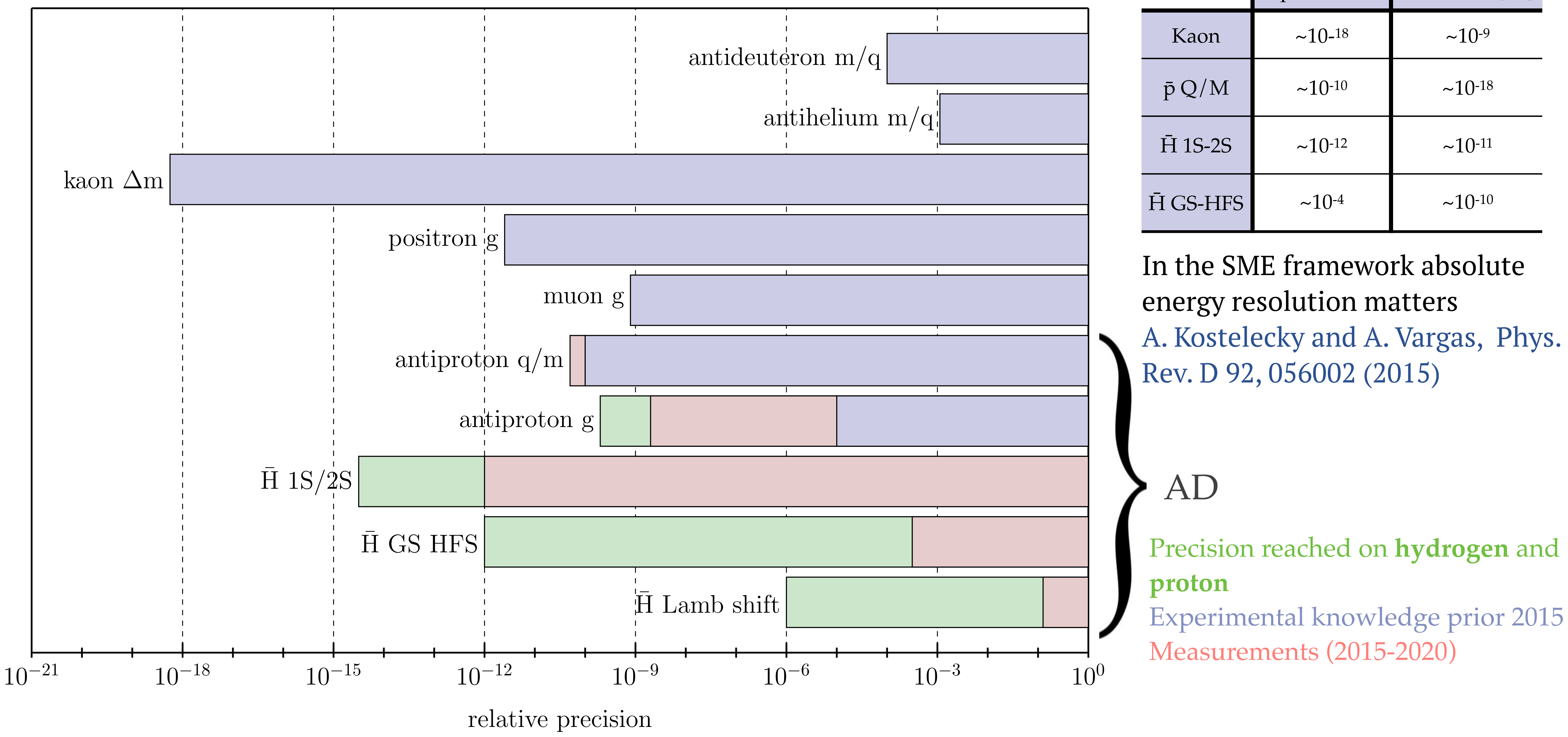


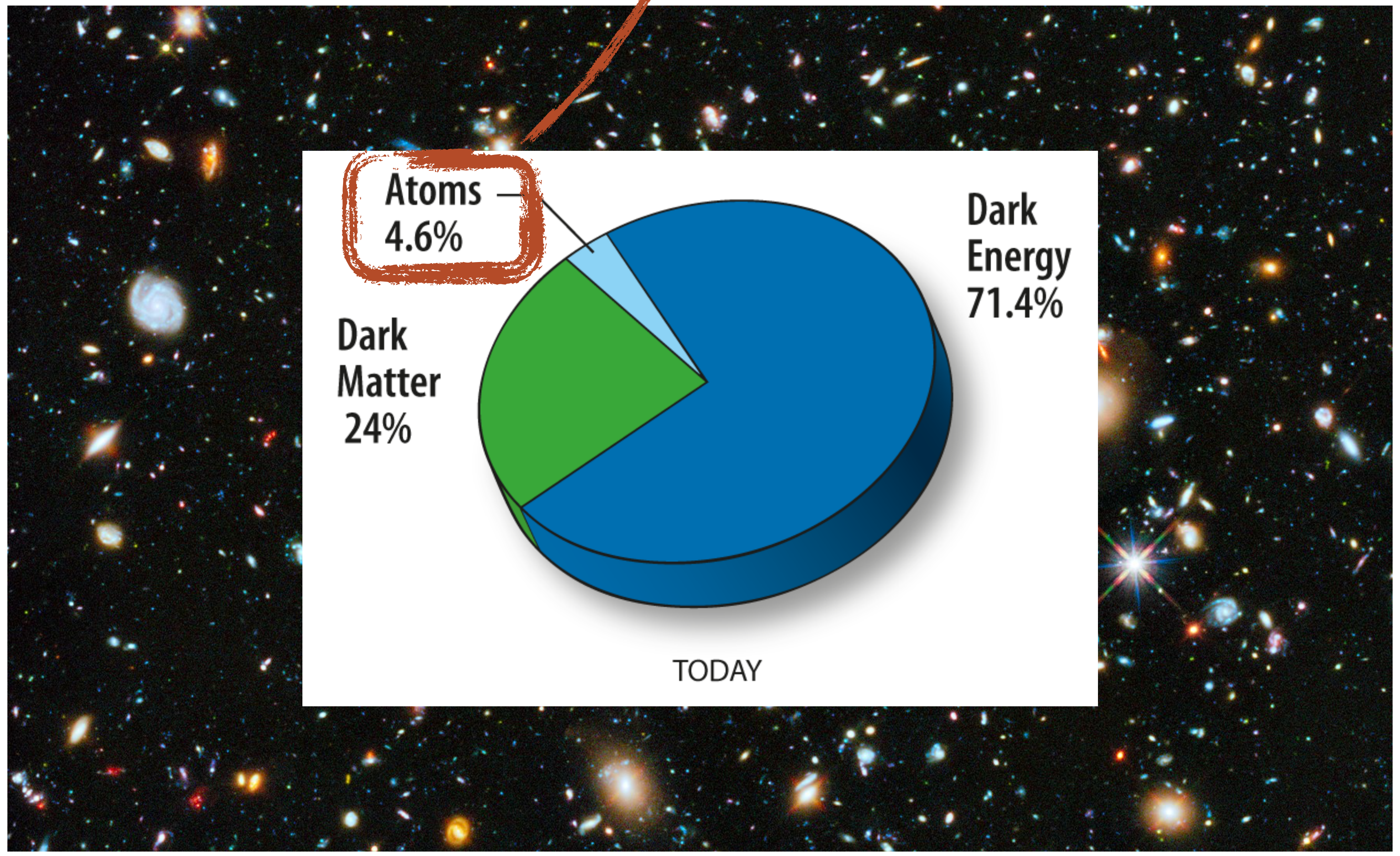
	relative precision	energy resolution [ev]
Kaon	~10^{-18}	~10^{-9}
p̄ Q/M	~10^{-10}	~10^{-18}
H̄ 1S-2S	~10^{-12}	~10^{-11}
H̄ GS-HFS	~10^{-4}	~10^{-10}

In the SME framework absolute energy resolution matters

A. Kostelecky and A. Vargas, Phys. Rev. D 92, 056002 (2015)

Variety of searches for new physics with low energy antiprotons

Where are the anti-atoms??



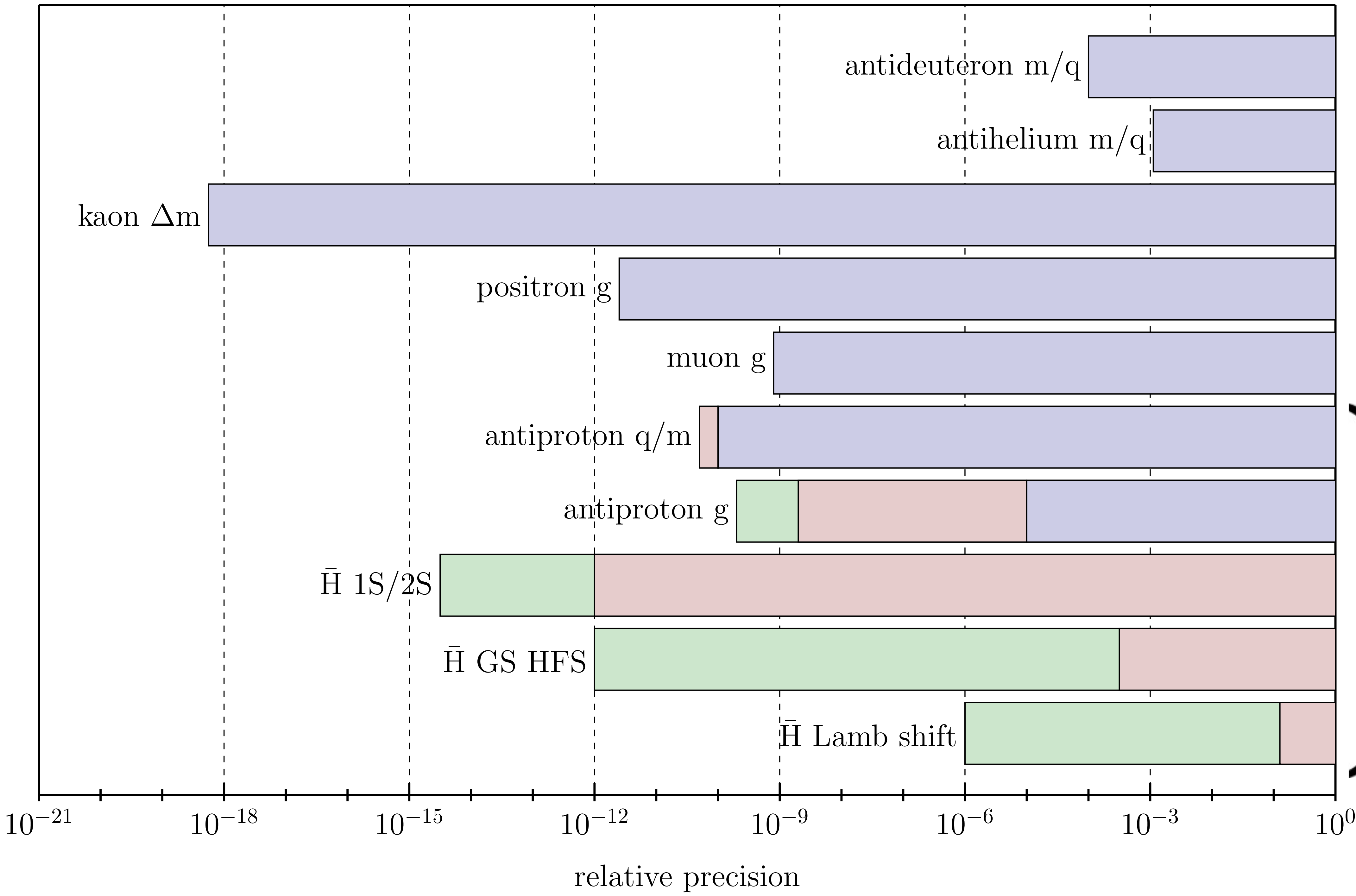
Strong baryon asymmetry in the universe

originating from a ~10^{-10} imbalance

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

baryon asymmetry:

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



	relative precision	energy resolution [ev]
Kaon	~10^{-18}	~10^{-9}
p̄ Q/M	~10^{-10}	~10^{-18}
H̄ 1S-2S	~10^{-12}	~10^{-11}
H̄ 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)

antimatter & gravity

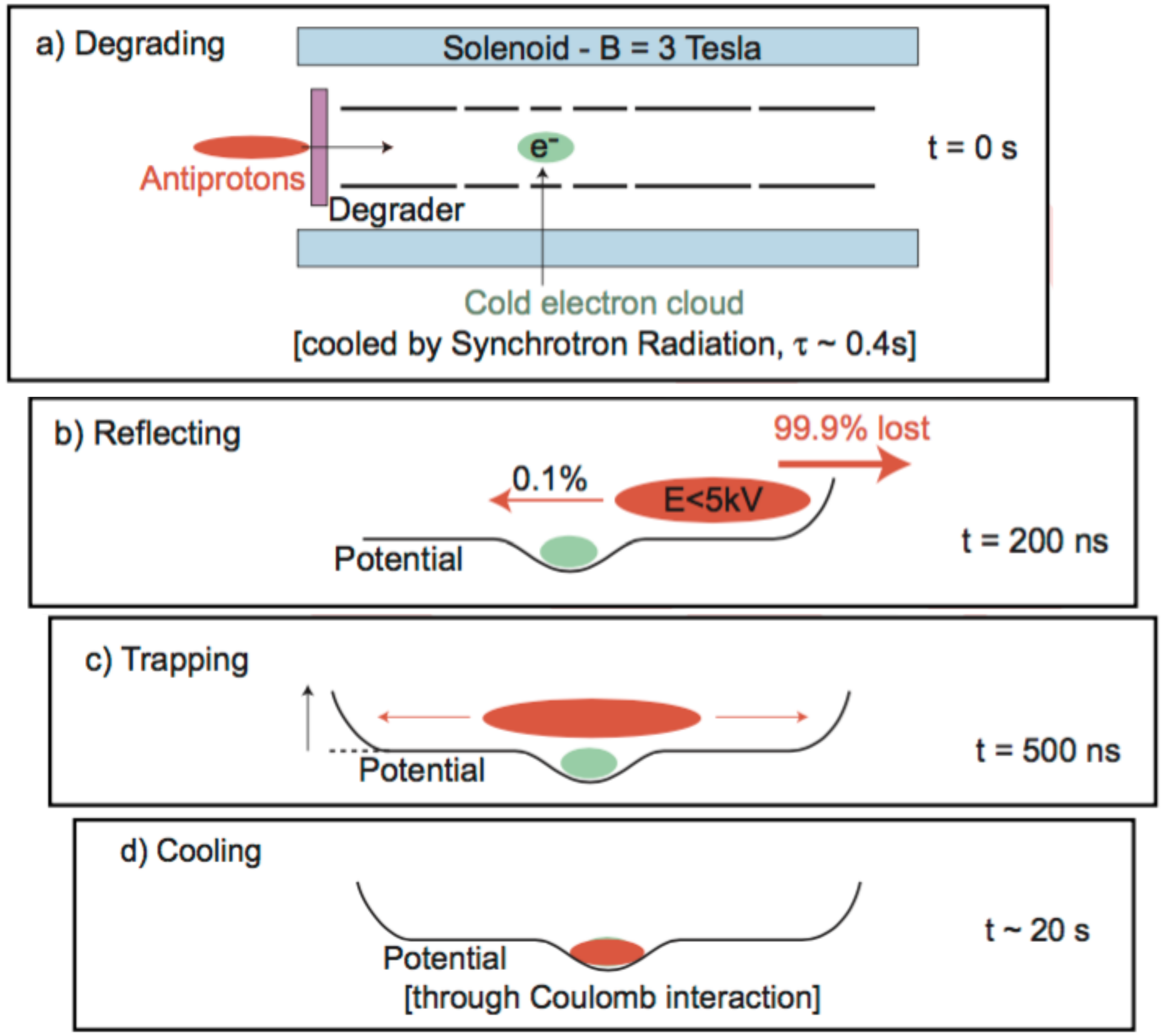
Attempted measurements with charged antiparticles (e^+ in ~1967, p̄ in ~1985)

Indirect limits exists

Universality of free-fall never tested directly on antimatter

Low energy antiprotons for tests of baryon asymmetry

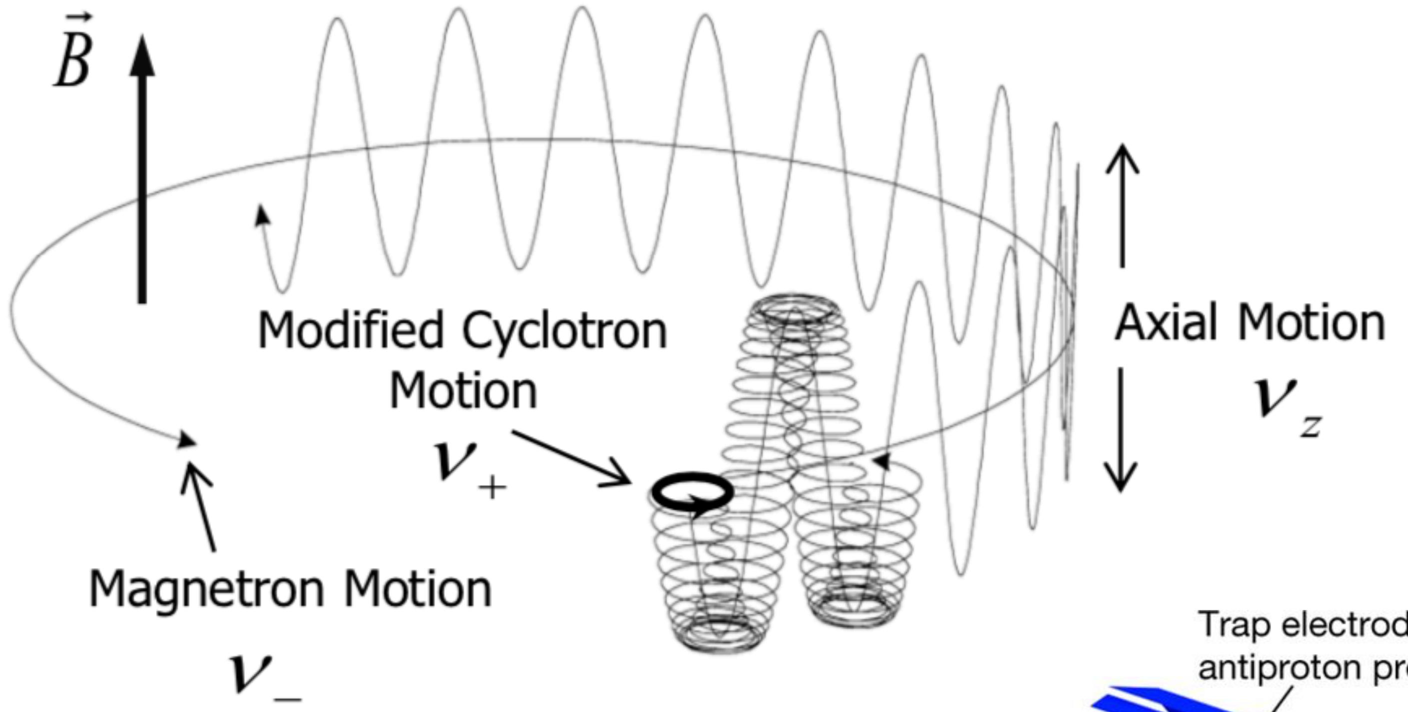
Workhorse Penning trap:



Long trapping times require good vacuum!

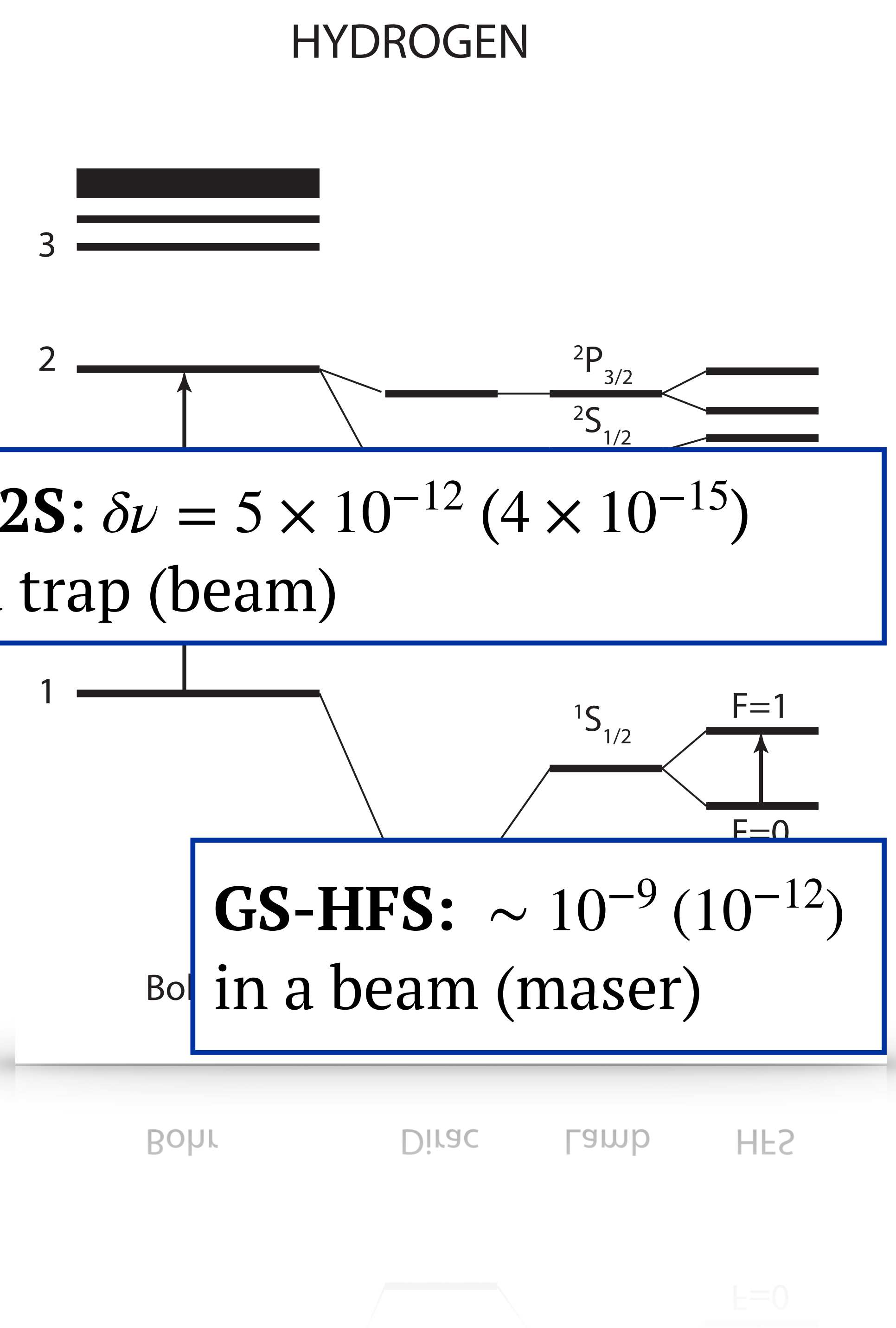
BASE experiment: P < 2. 10^{-18} mbar

$\boldsymbol{\tau}(\bar{p})$ > 10.2 years



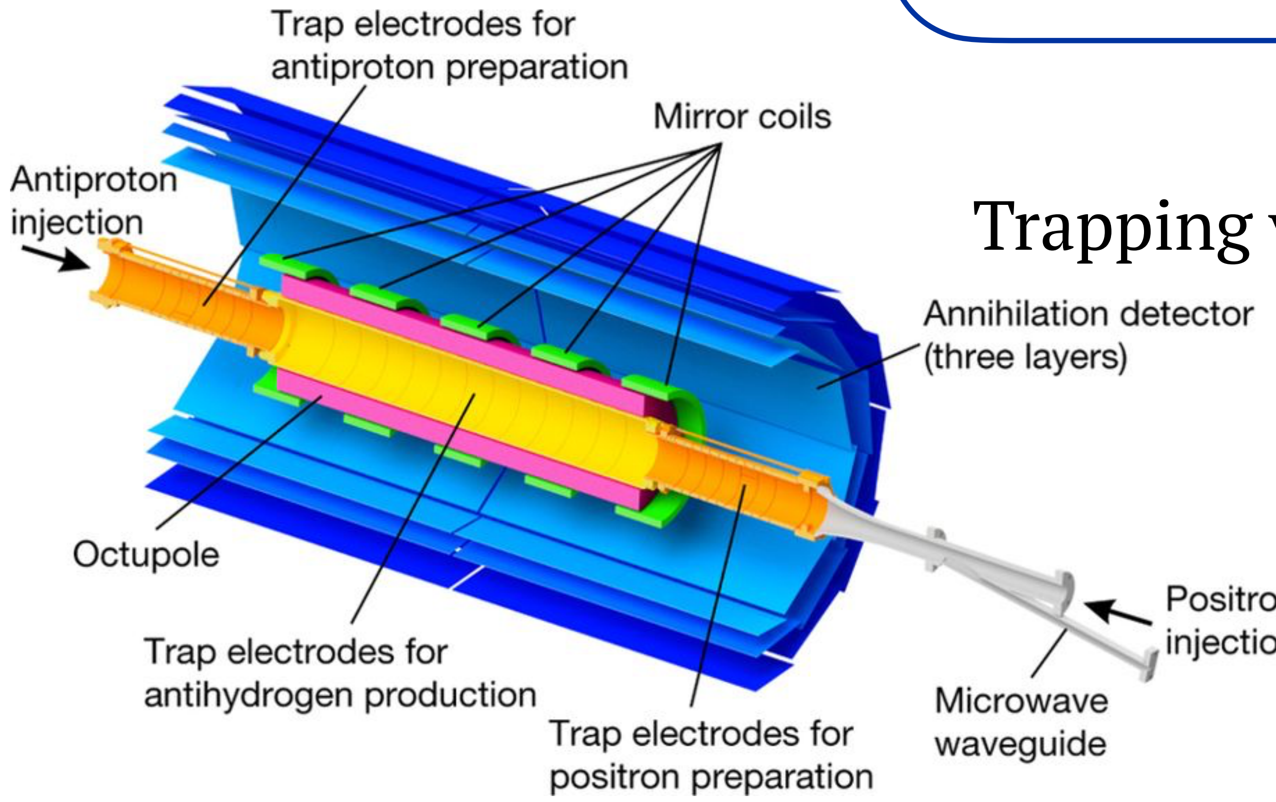
$$\omega_c = \frac{Q_{\bar{p}}}{m_{\bar{p}}} B$$ charge-to-mass ratios

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



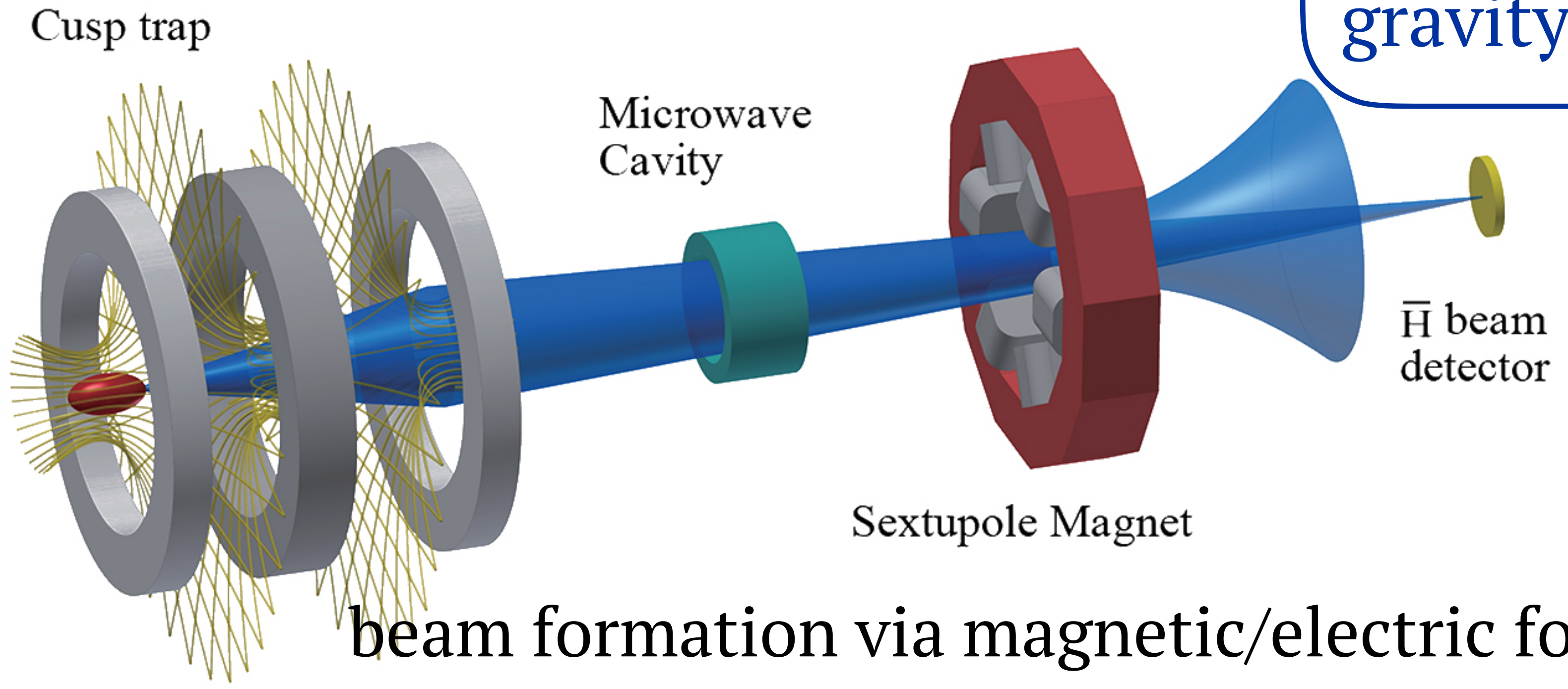
Trapping via magnetic moment

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

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

CHALLENGES
⬆ Temperature limit, inhomogeneous fields
⬇ H̄ rate, presence of excited states

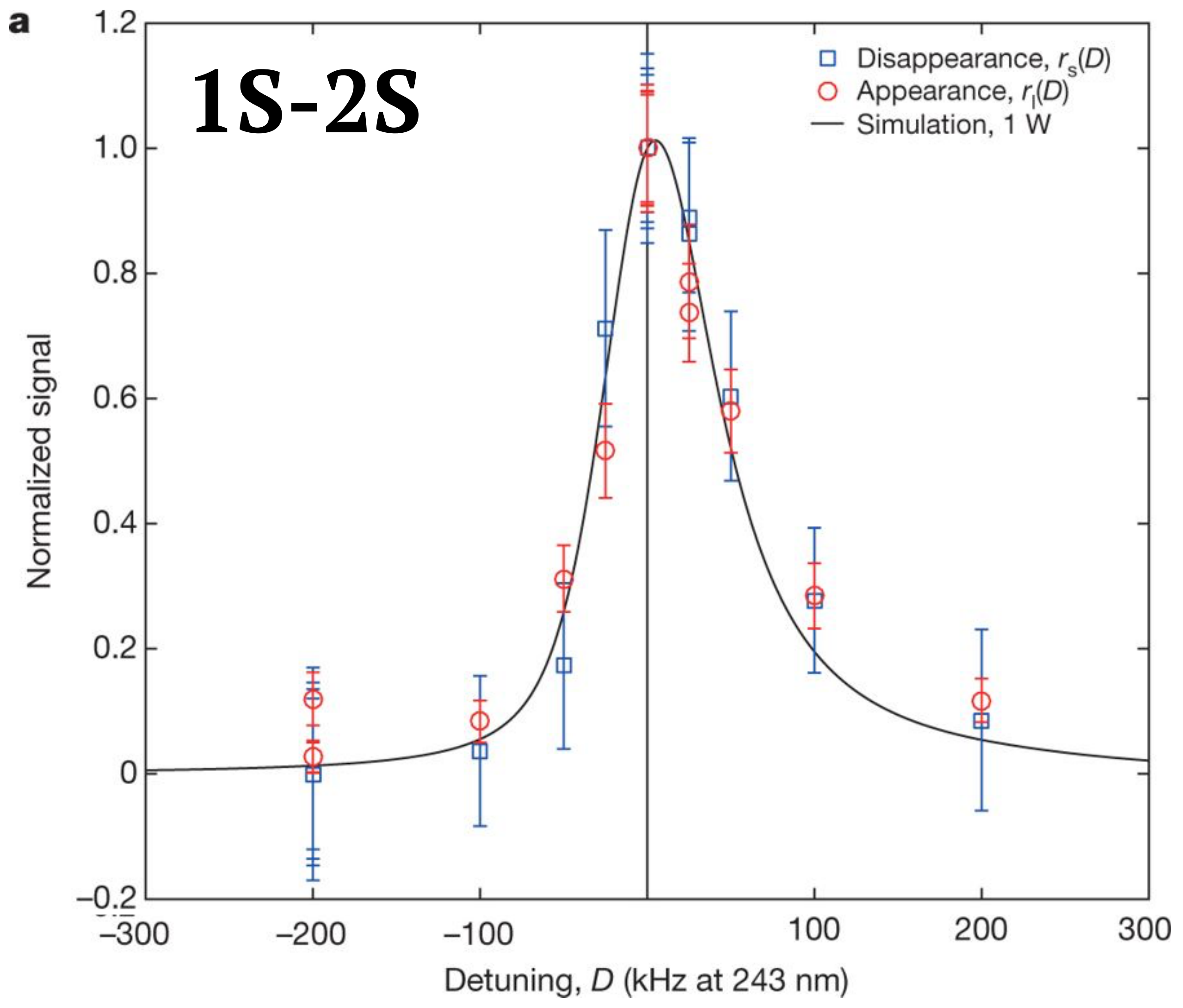
spectroscopy
1S-2S
GS-HFS
gravity



beam formation via magnetic/electric focussing

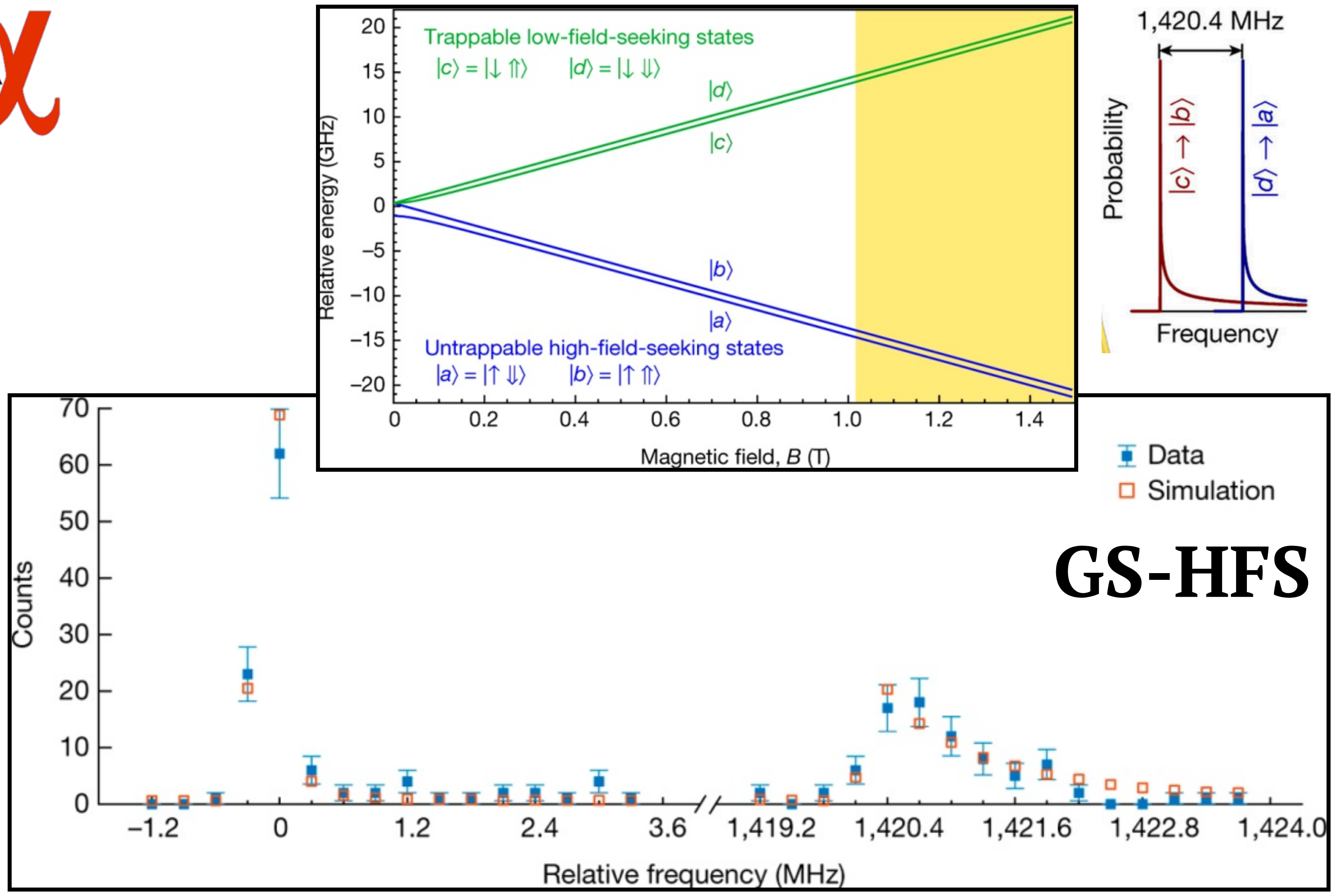
Some spectroscopy highlights with antihydrogen

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



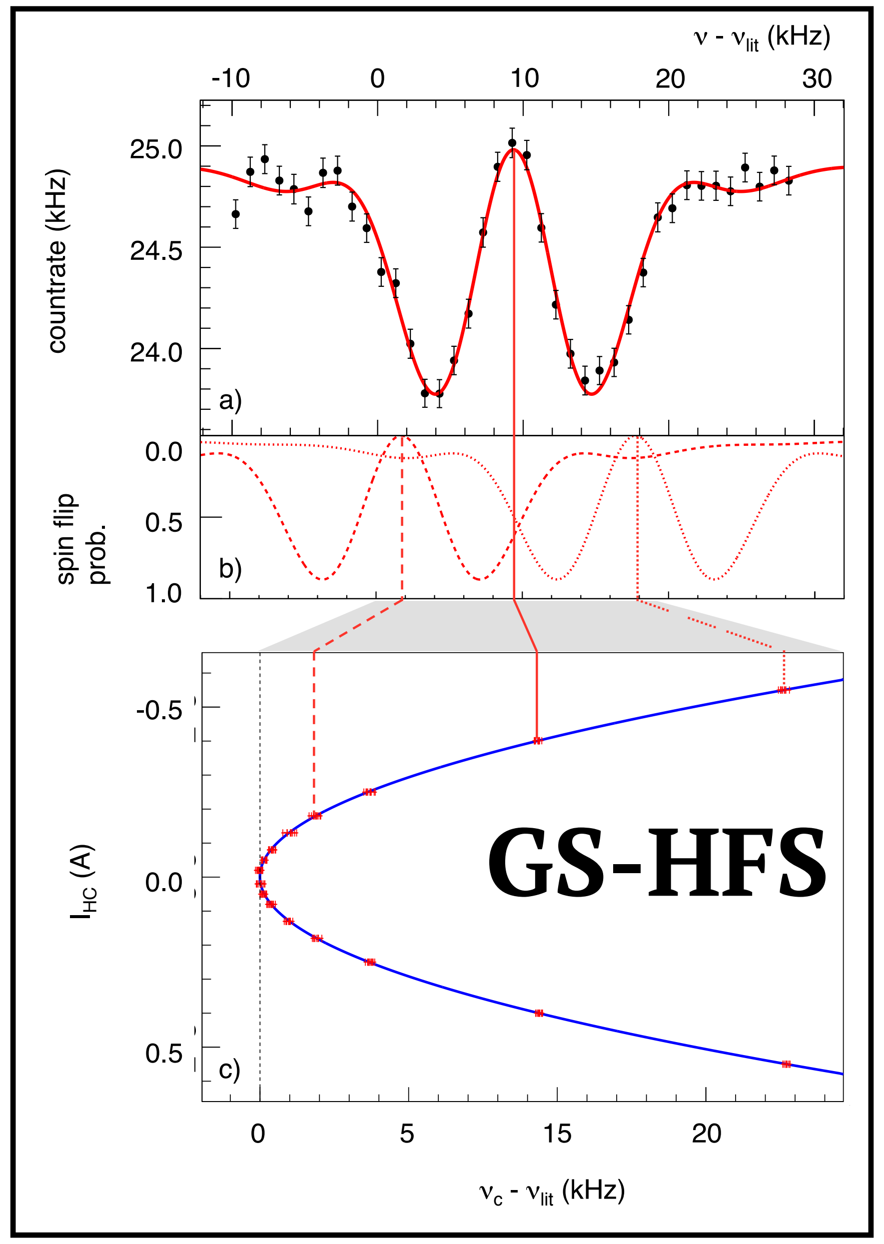
M. Ahmadi et al., Nature 557 71–75 (2018)

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



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

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



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

<u>In a TRAP:</u>
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)!

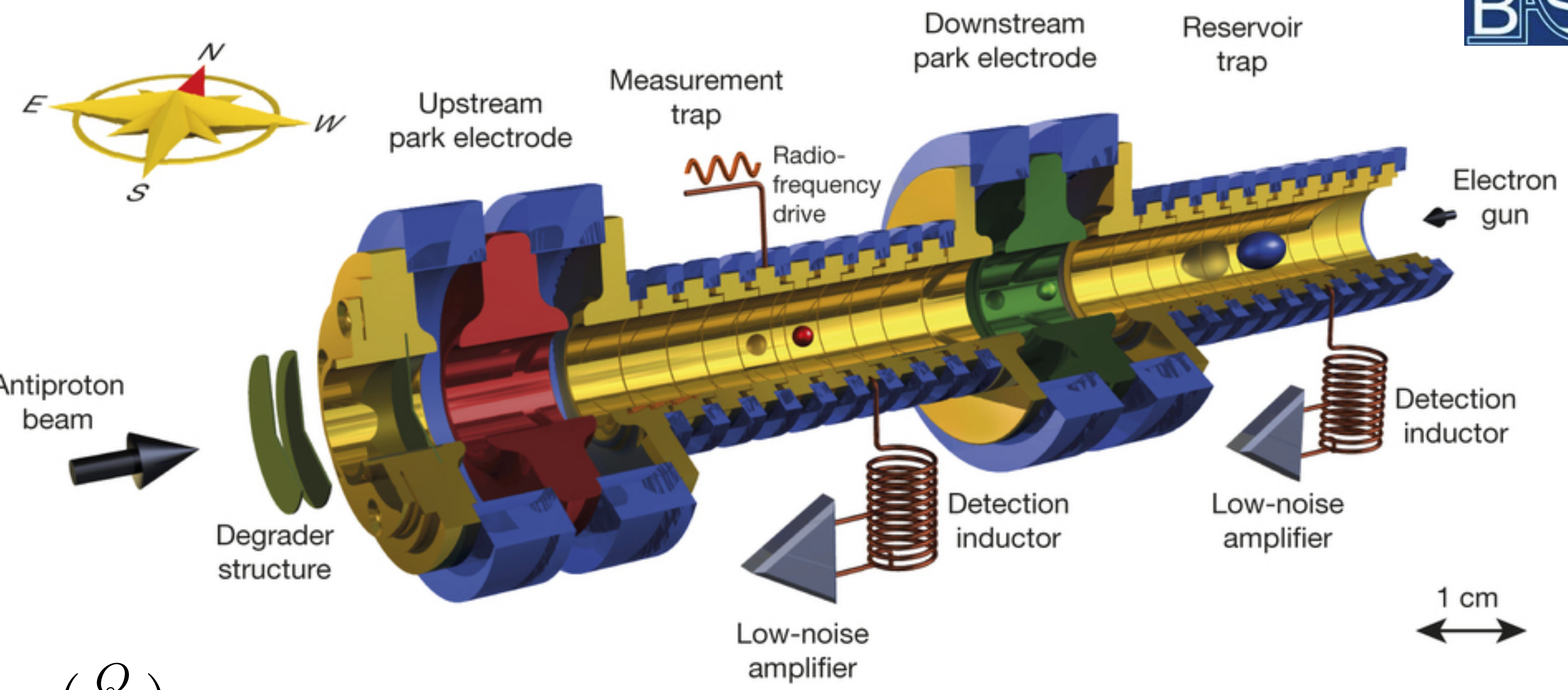
M. Ahmadi et al., Nature 578, 375–380 (2020)

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

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

Some highlights on antiprotons

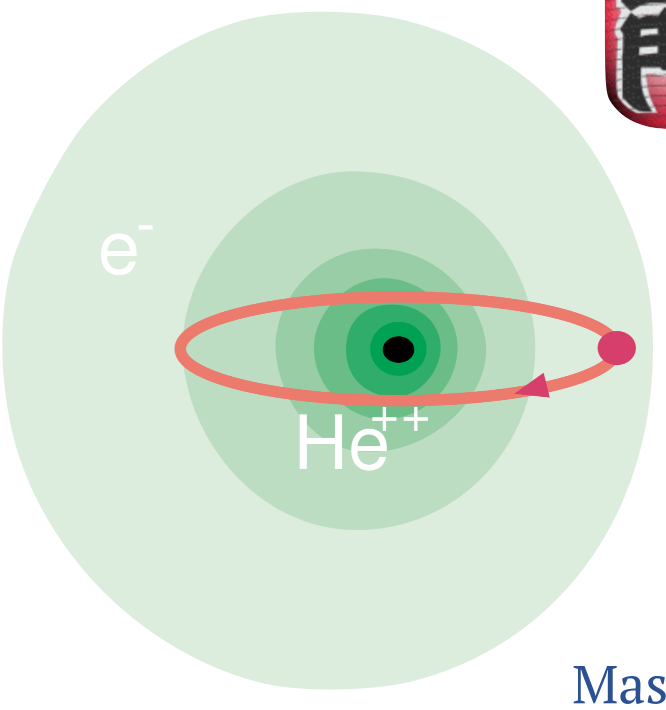
antiproton charge to mass ratio



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

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

antiproton to electron mass ratio

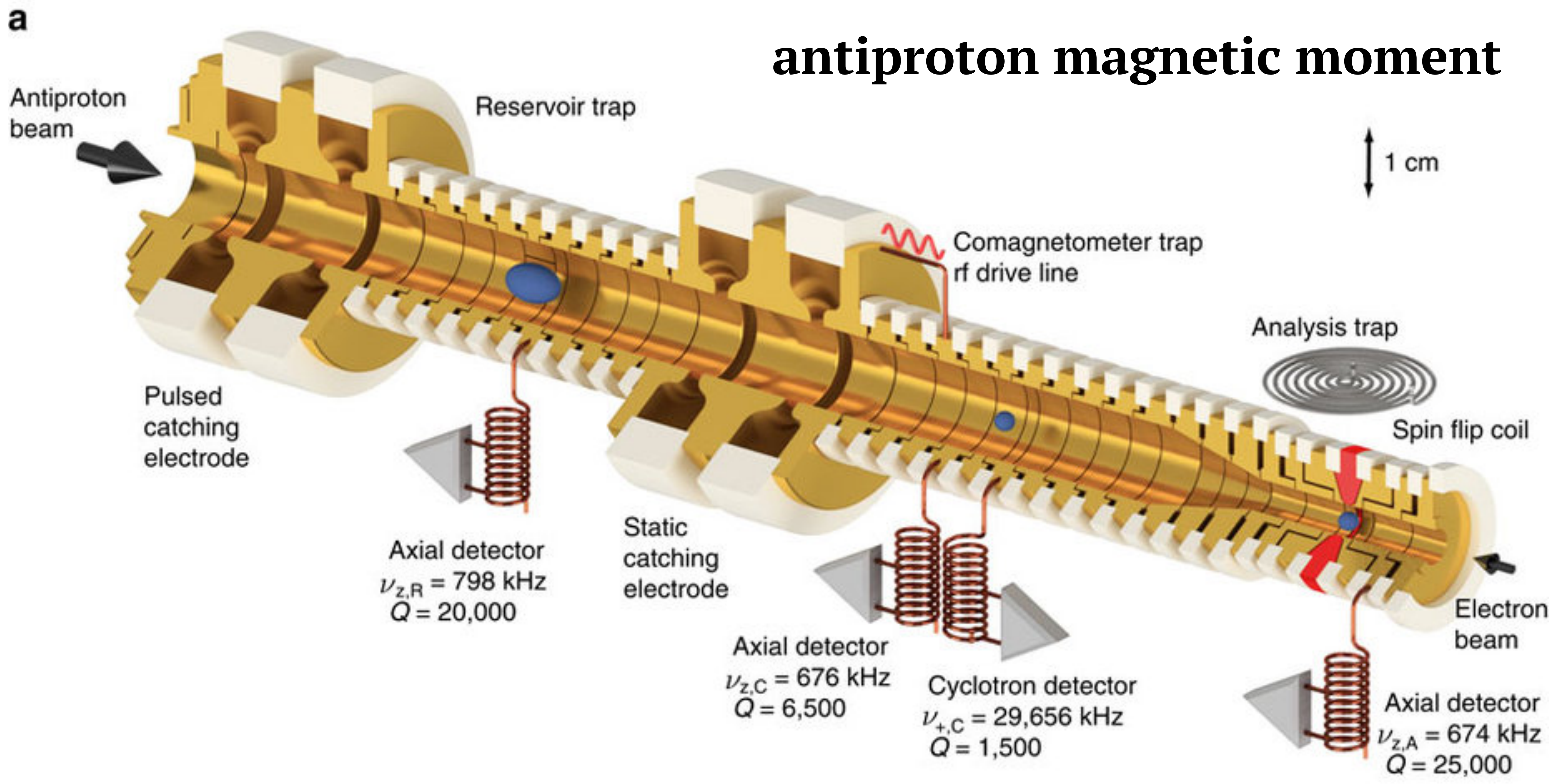


$$\frac{m_{\bar{p}}}{m_{e^-}} = 1836.1526734(15)$$

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

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

antiproton magnetic moment

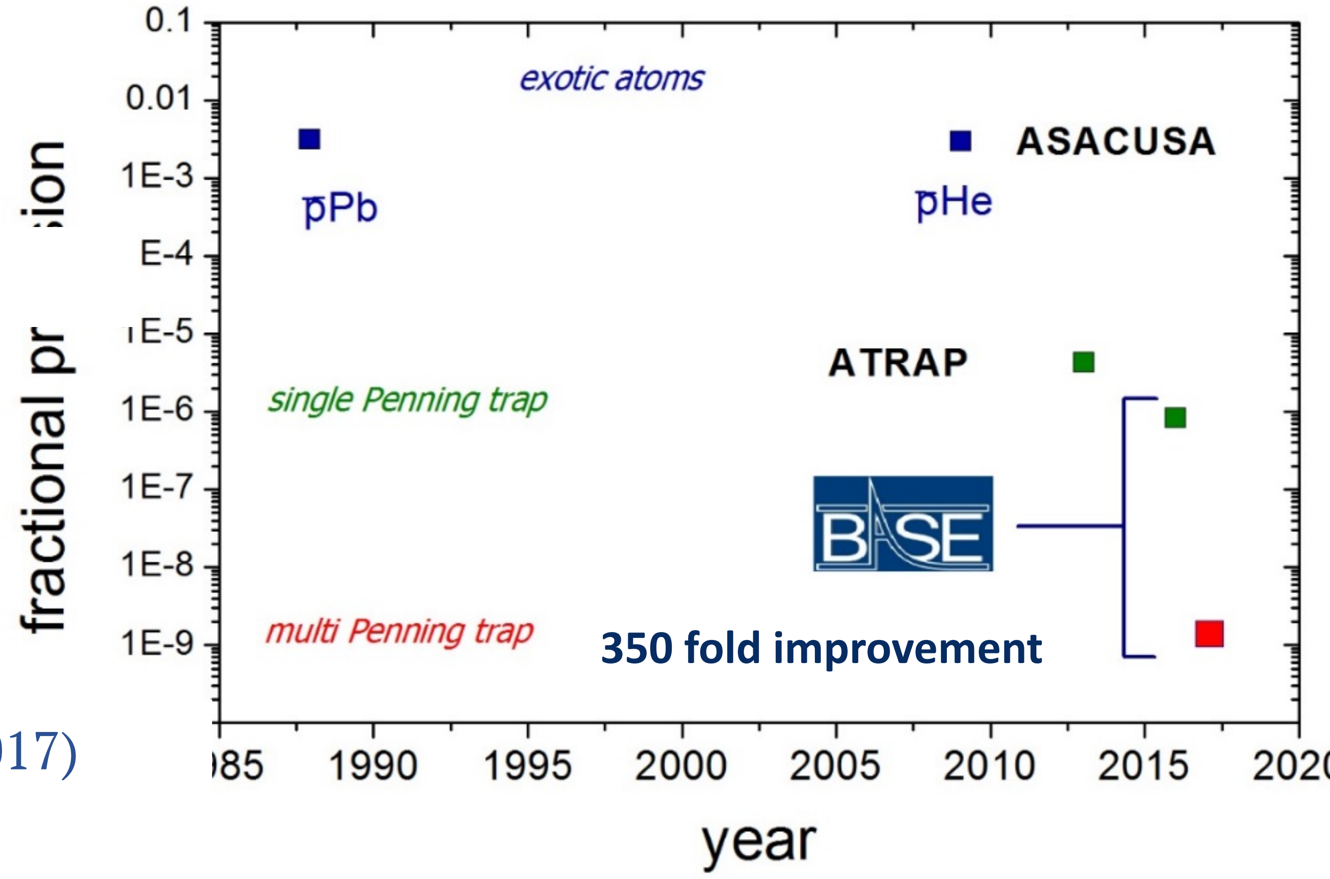


$$\frac{g_{\bar{p}}}{2} = 2.792\,847\,344\,1\,(42)$$

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