Overview of the status of the antihydrogen experiments at CERN

Chloé Malbrunot *

*permanent address: TRIUMF, Vancouver, Canada

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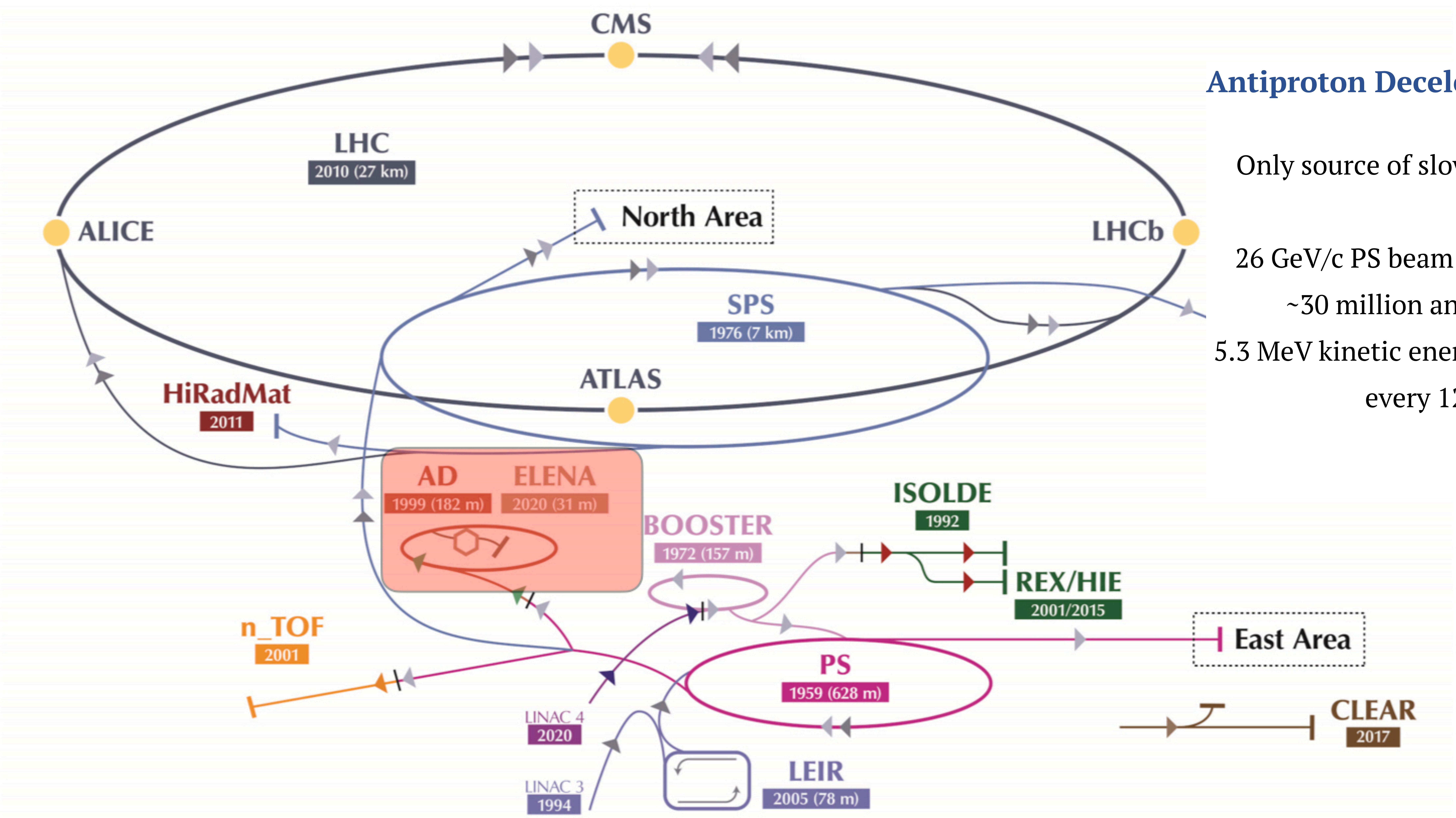


Antiproton Decelerator (AD)

Only source of slow antiprotons

26 GeV/c PS beam onto Ir target

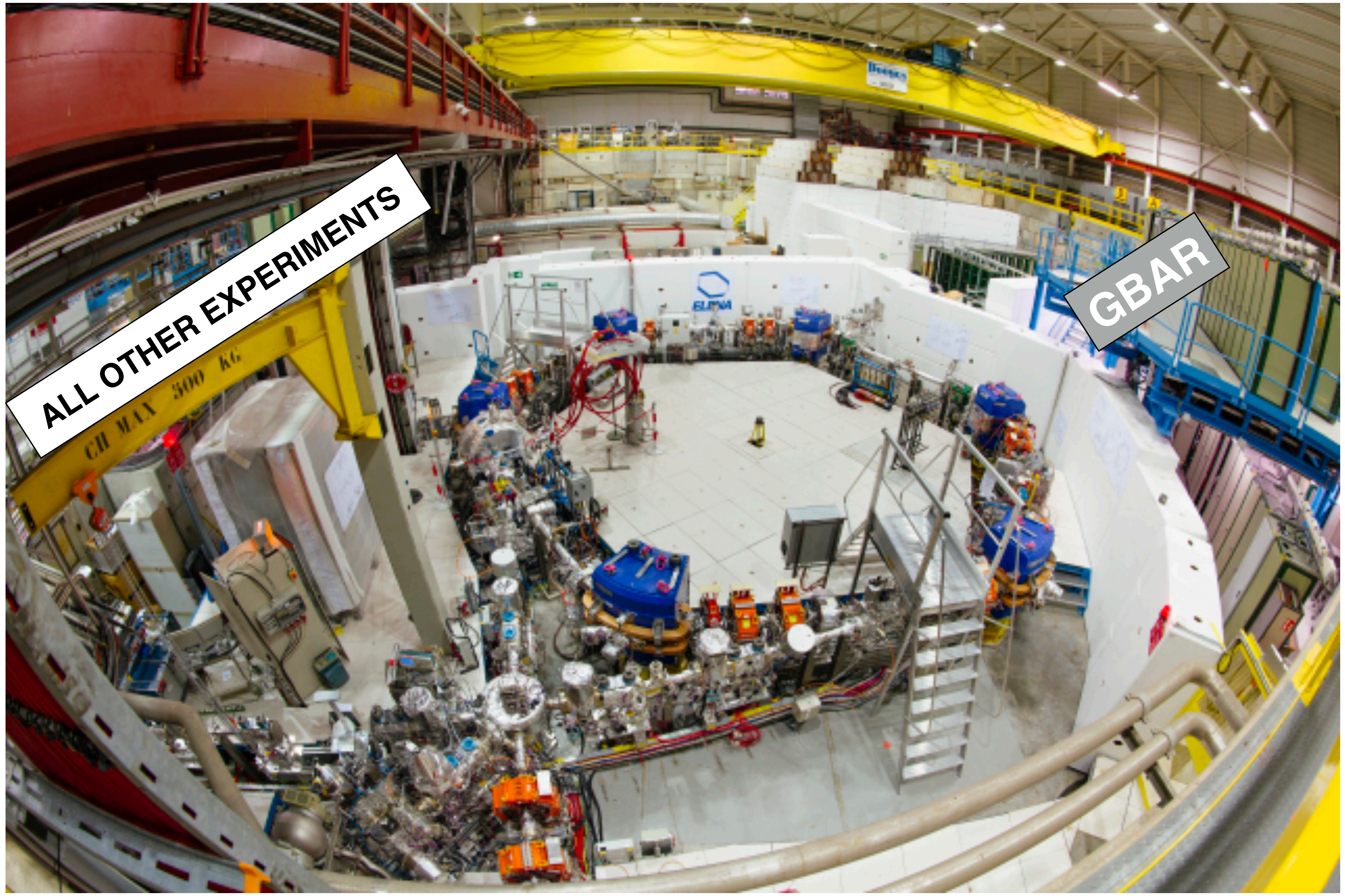
~30 million antiprotons

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 3
1994
ELENA
BASE
AEGIS
ASACUSA
ALPHA
GBAR
PUMA
ATRAP
ALPHA

ELENA: a boost to the AD physics programme



AD:

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

ELENA:

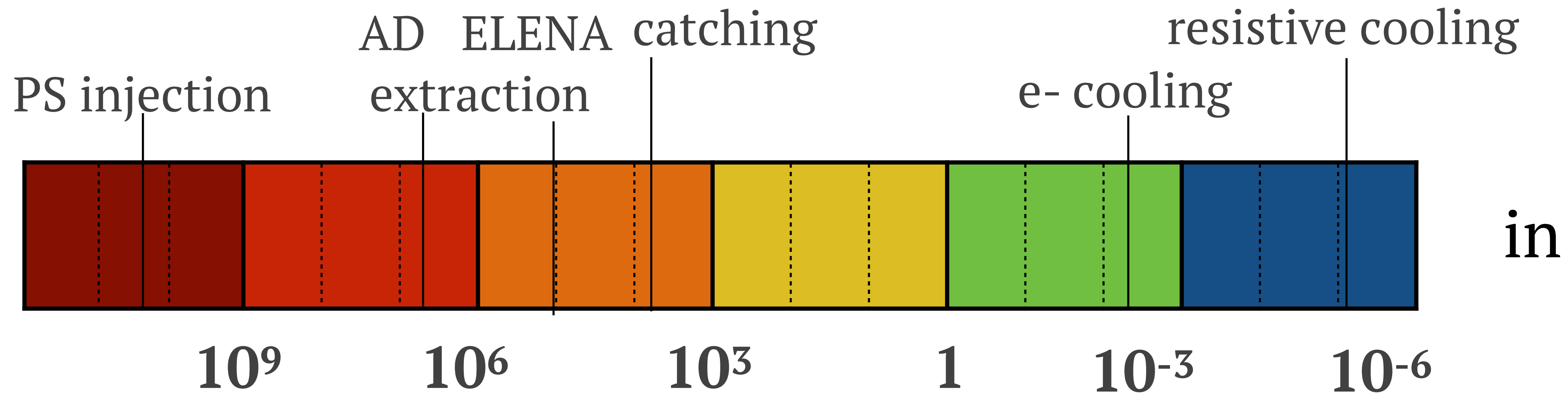
p̄ at 100 keV at improved beam emittance

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!!

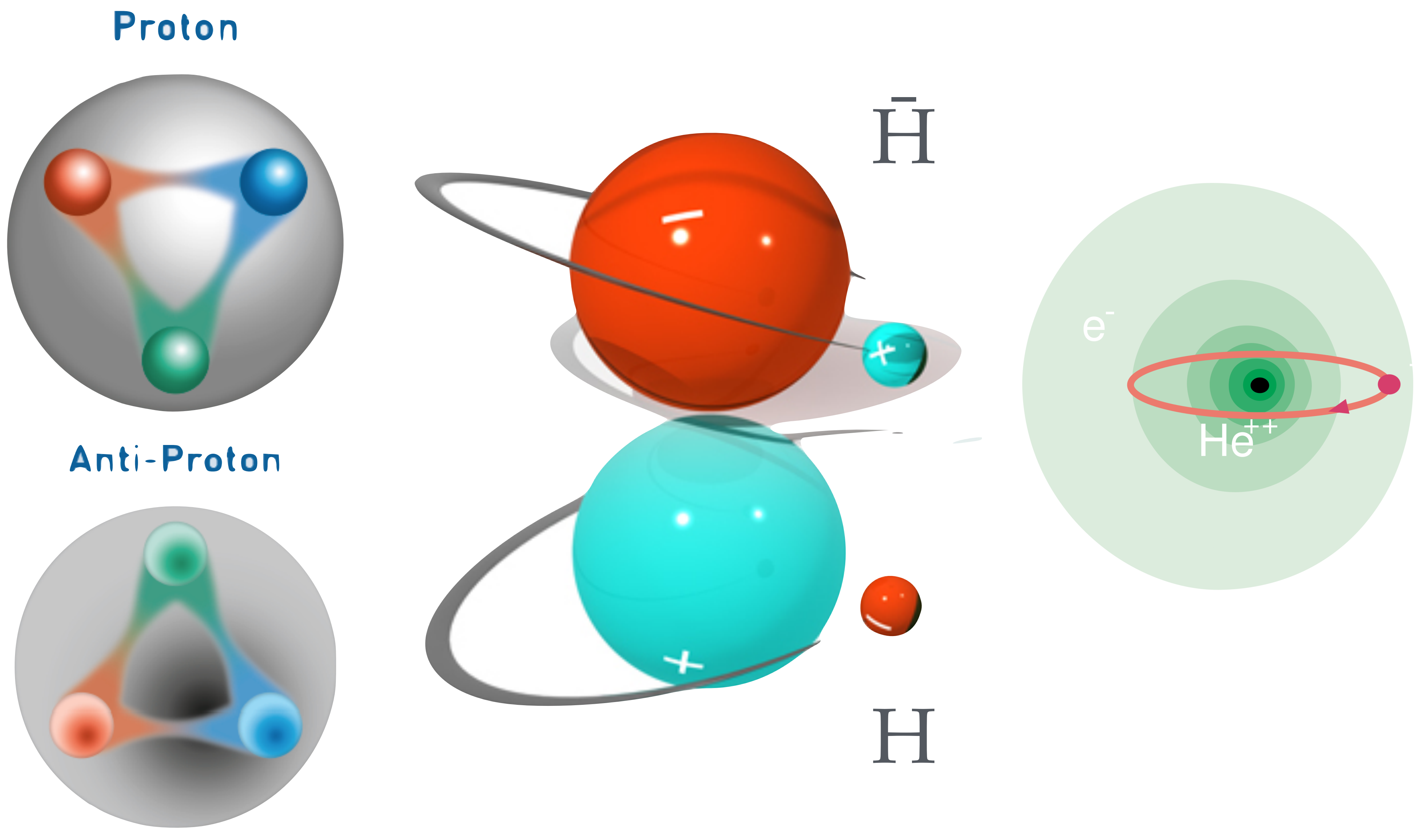
Variety of searches for new physics with low energy antiprotons

BASE/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



antiproton   antihydrogen   antiprotonic helium

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

Motivations for antihydrogen physics

0 **Exciting developments of high precision techniques with antimatter**

- getting close (or even shortly surpass) precision achieved with matter!

1 **Comparison of fundamental properties of simple baryonic and anti-baryonic systems**

- at low energy and with high precision - possible clue to matter/antimatter asymmetry

2 **Neutral antimatter object: testing antimatter gravity**

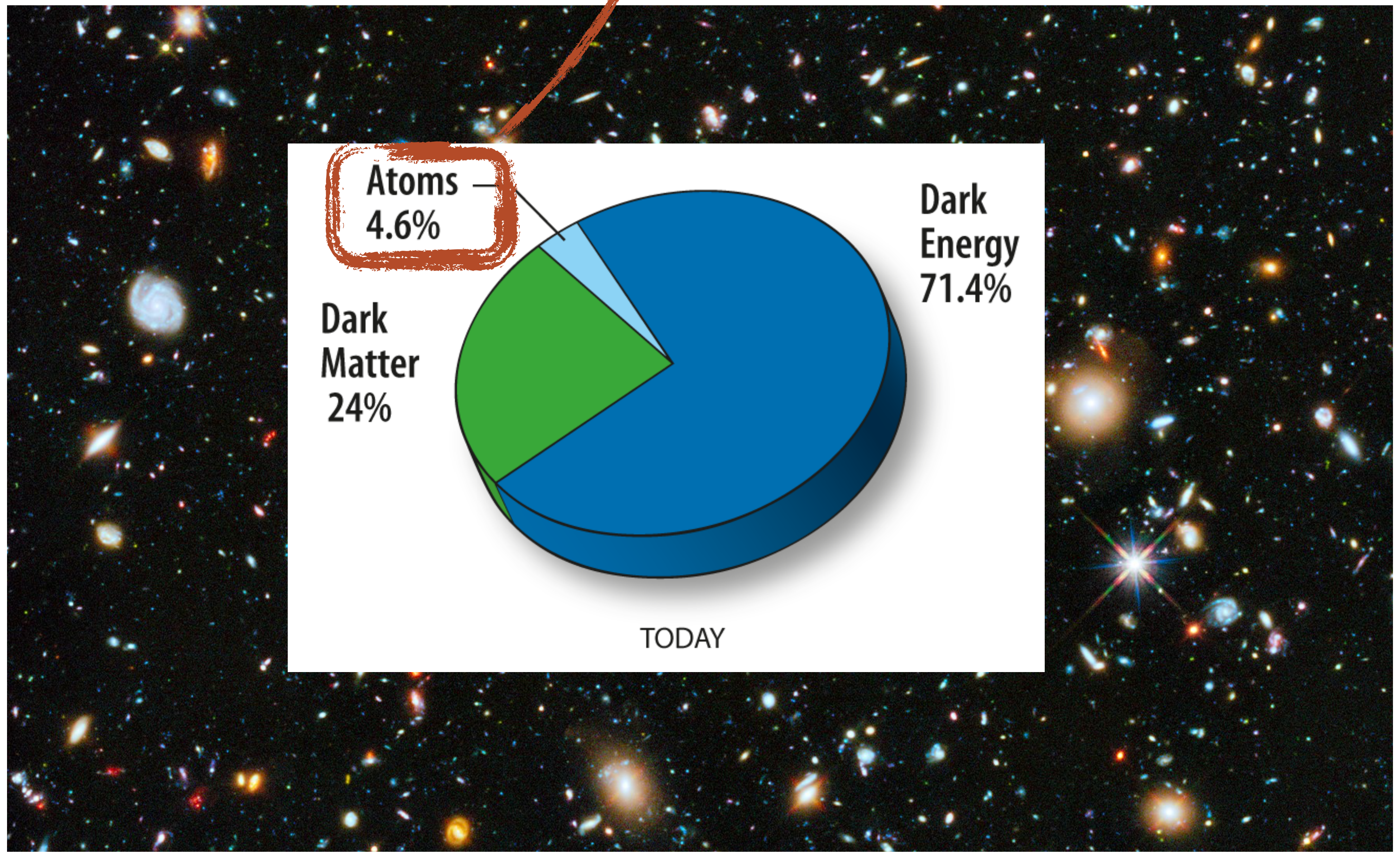
- only neutral antimatter-only system which can be cooled down for a ballistic gravity experiment


credits: NASA, ESA, CSA, and STScI

1

CPT test 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

CPT test with low energy antiprotons

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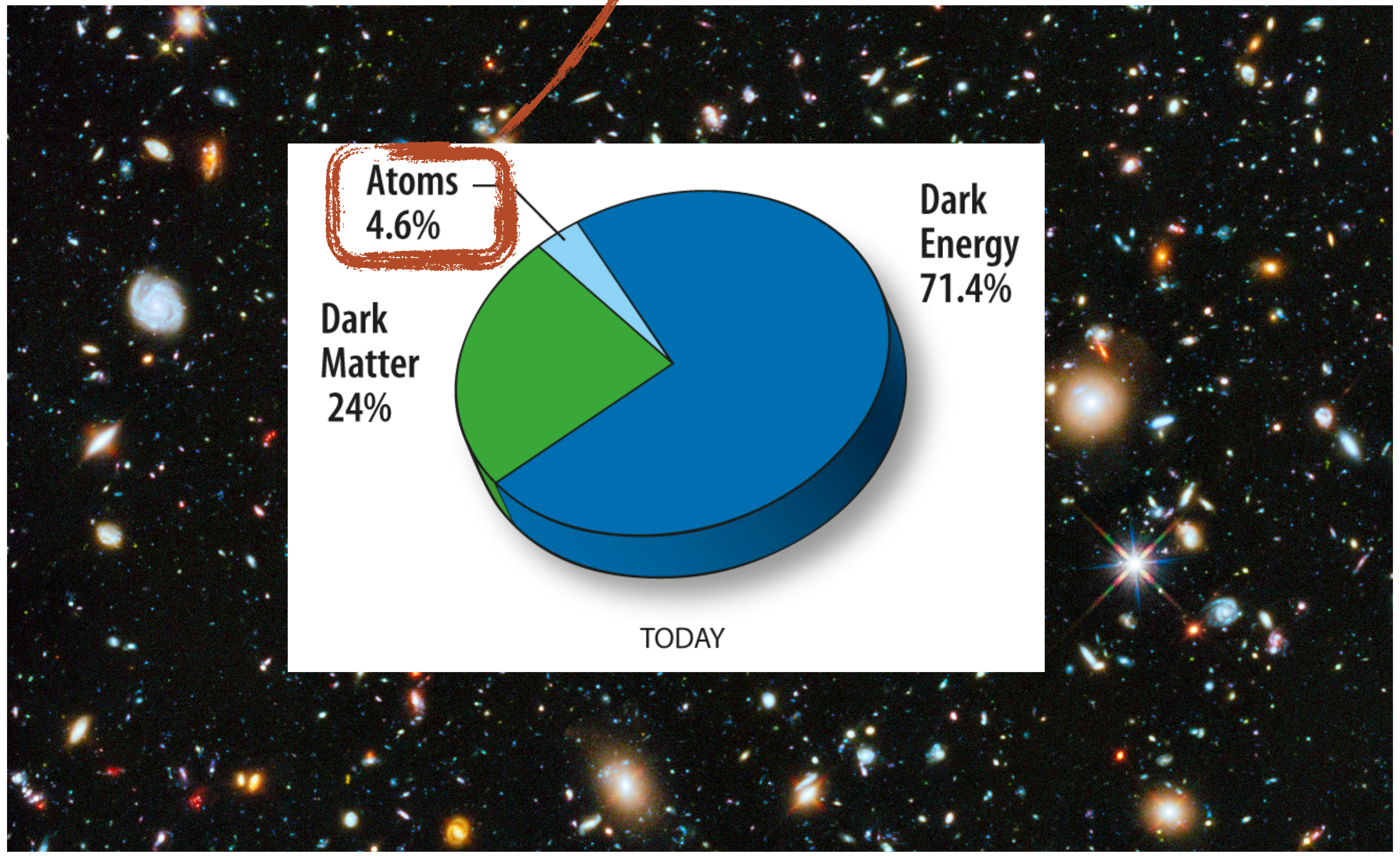


Strong baryon asymmetry in the universe

originating from a ~10^{-10} imbalance

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

Could a difference between matter and antimatter fundamental properties explain baryon asymmetry?

Maybe.....
For sure that would be a sign of new physics

CPT theorem: "cornerstone" of QFT (with Lorentz invariance, locality and unitarity) implies properties of matter&antimatter have to be exactly equal or opposite

Dirac equation in the minimal Standard Model Extension

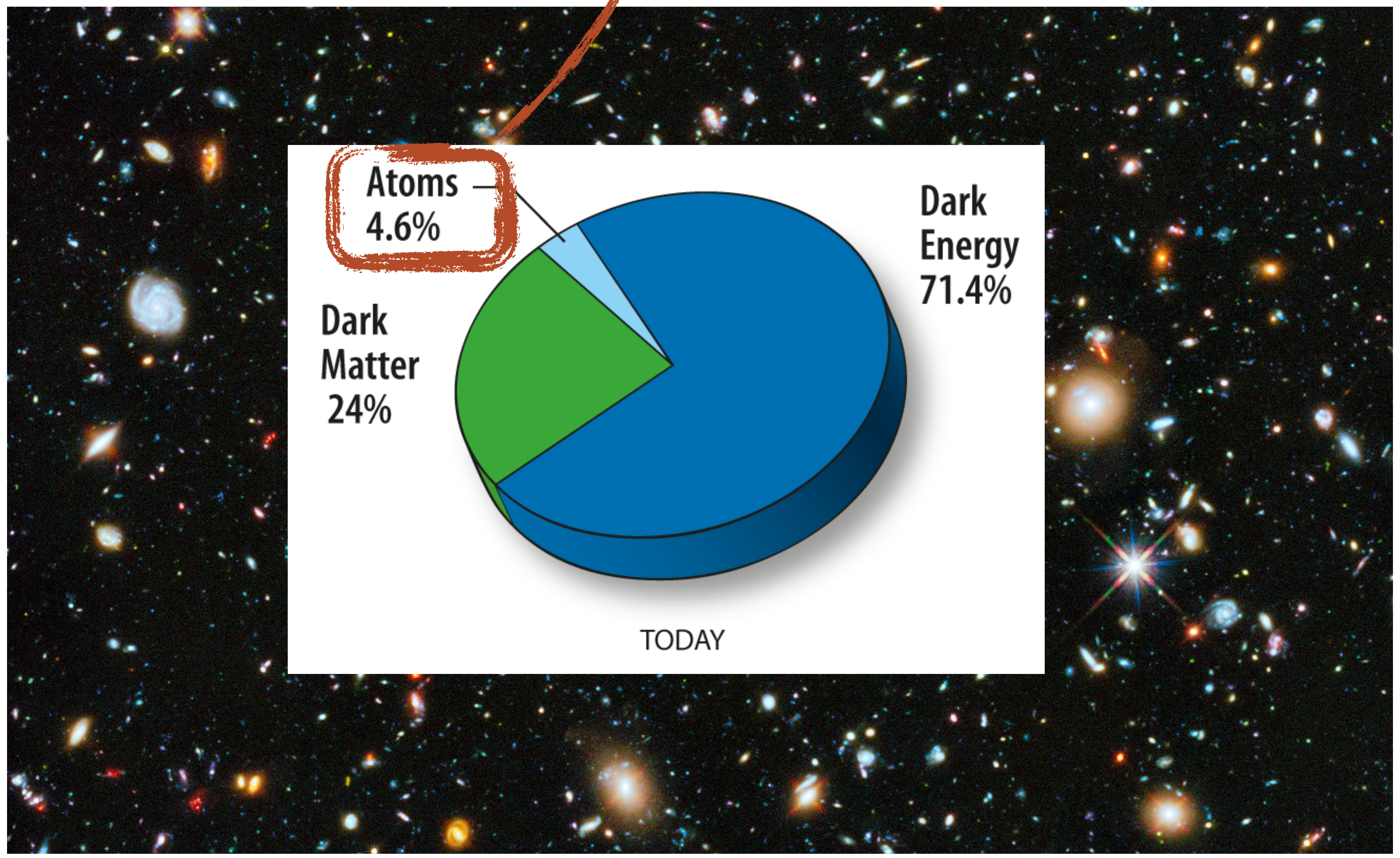
$$(i\gamma^\mu D_\mu - m_e - a^e_\mu \gamma^\mu - b^e_\mu \gamma_5 \gamma^\mu - \frac{1}{2} H^e_{\mu\nu}\sigma^{\mu\nu} + i c^e_{\mu\nu}\gamma^\mu D^\nu + i d^e_{\mu\nu}\gamma_5\gamma^\mu D^\nu)\psi = 0$$

e.g. Lorentz and CPT Tests in Hydrogen, Antihydrogen, and Related Systems, A. Kostelecky and A. Vargas, Phys. Rev. D 92, 056002 (2015)

Different measurements (even of the same quantity) are sensitive (or not) to different SME coefficients

CPT test with low energy antiprotons

Where are the anti-atoms??



Strong baryon asymmetry in the universe

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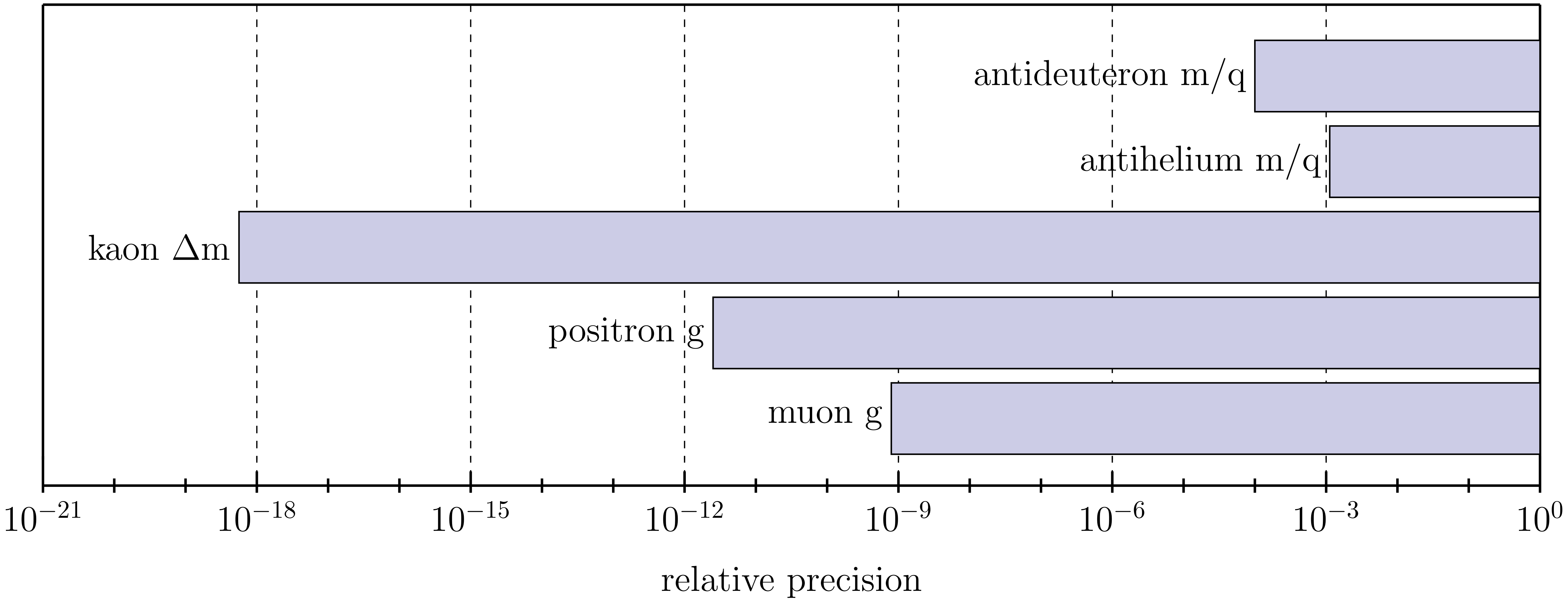
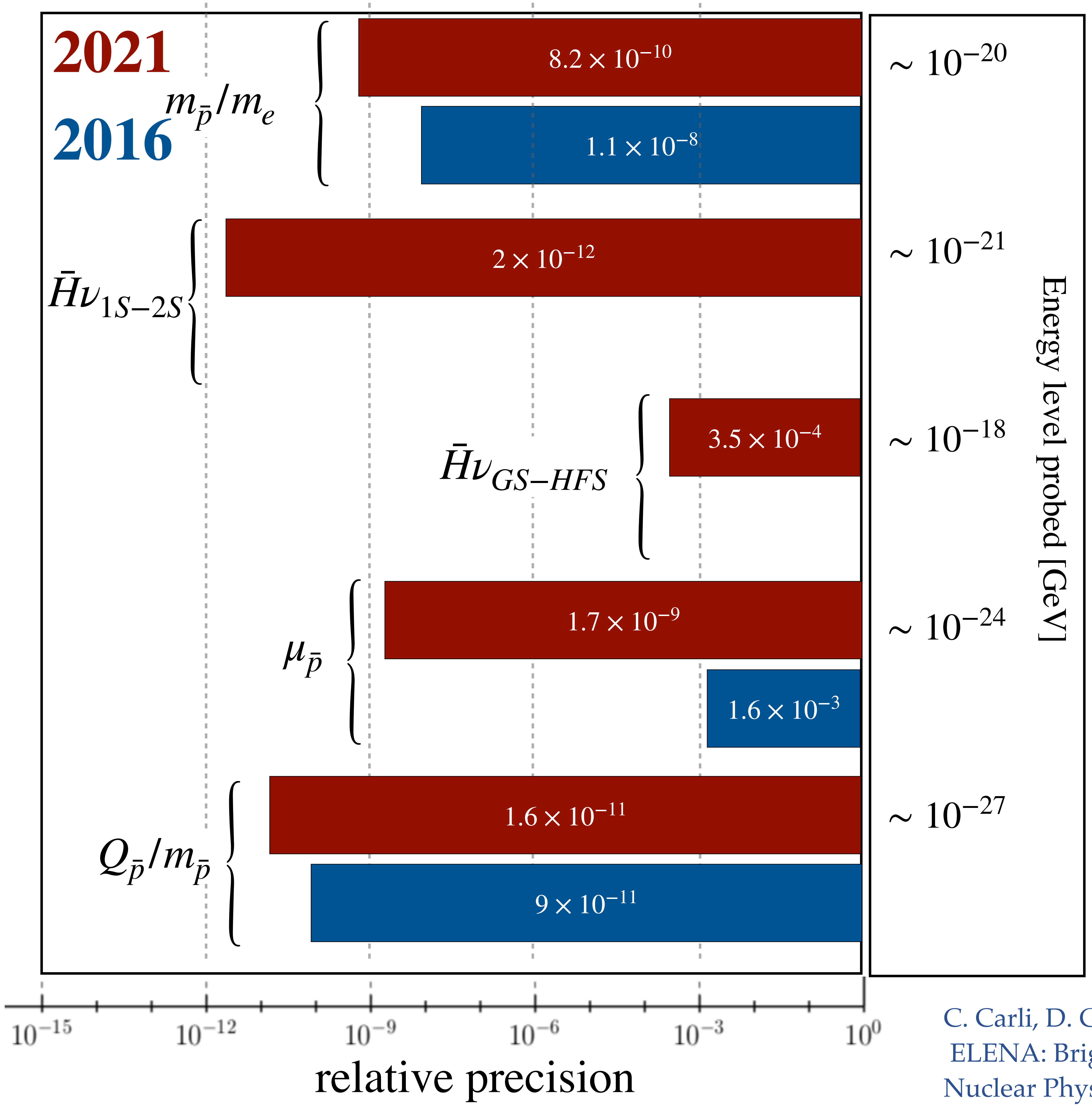
baryon asymmetry:

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



1 Status comparison of matter/antimatter properties at the AD



C. Carli, D. Gamba, C. Malbrunot, L. Ponce & S. Ulmer
ELENA: Bright Perspectives for Low Energy Antiproton Physics
Nuclear Physics News, 32:3, 21-27 (2022)

CPT test with low energy antiprotons

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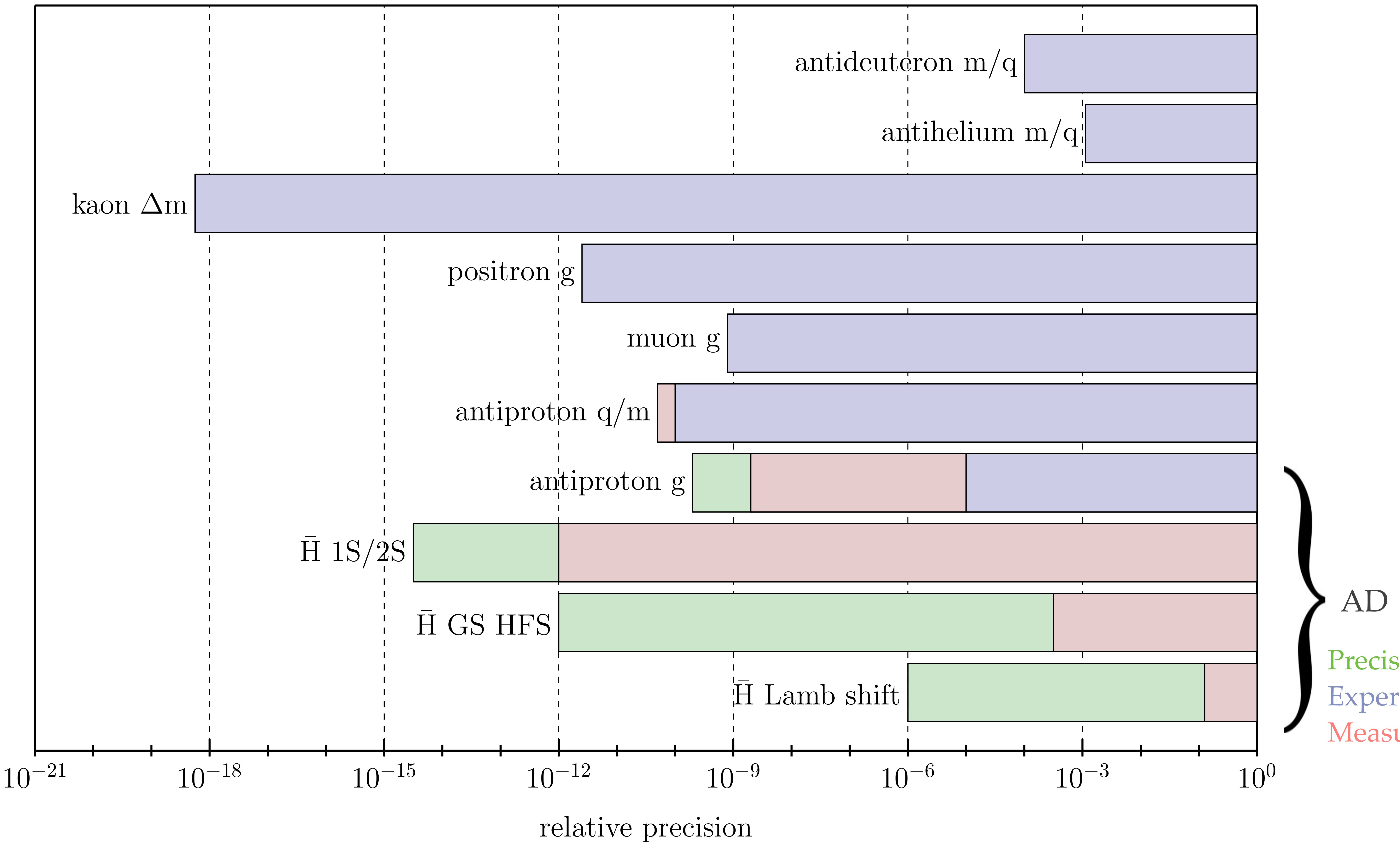


	relative precision	energy resolution [ev]
Kaon	$\sim 10^{-18}$	$\sim 10^{-9}$
p̄ Q/M	$\sim 10^{-10}$	$\sim 10^{-18}$
H̄ 1S-2S	$\sim 10^{-12}$	$\sim 10^{-11}$
H̄ GS-HFS	$\sim 10^{-4}$	$\sim 10^{-10}$

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

② Motivations for testing gravity with antihydrogen atoms

Gravity with <u>matter</u> scrutinized via different experimental methods
Einstein Equivalent principle (EEP) extensively tested experimentally

But gravity is a peculiar force

Very weak force
Lack of consistent quantum treatment

Gravity on antimatter has "never" been directly tested

Anomalous gravity would not necessarily invalidate GR

$$V = -\frac{G m_1 m_2}{r}\left(1 \mp a\, e^{-r/v} + b\, e^{-r/s}\right)$$

a: Gravivector, b: Graviscalar

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

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

"Peculiarity" of antimatter :

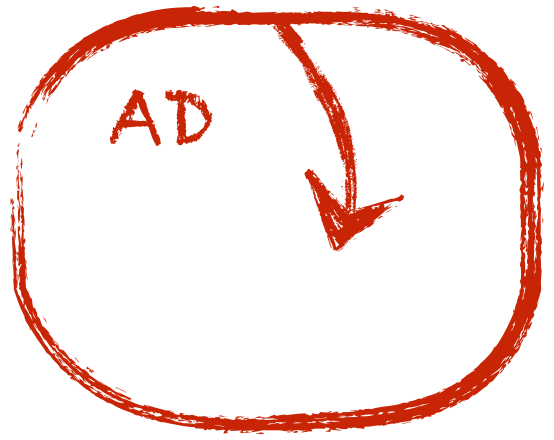
non detection of primordial antimatter

&

lack of experimental hints for the justification of baryon asymmetry

Need for a free-fall experiment on antimatter

Formation of antihydrogen atoms: several approaches

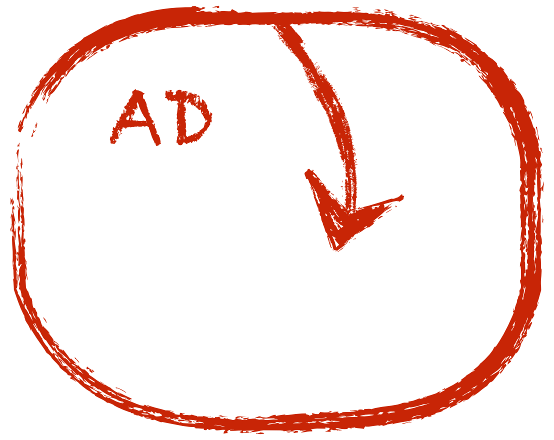


$\bar{p}$

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

ALPHA

Formation of antihydrogen atoms: several approaches



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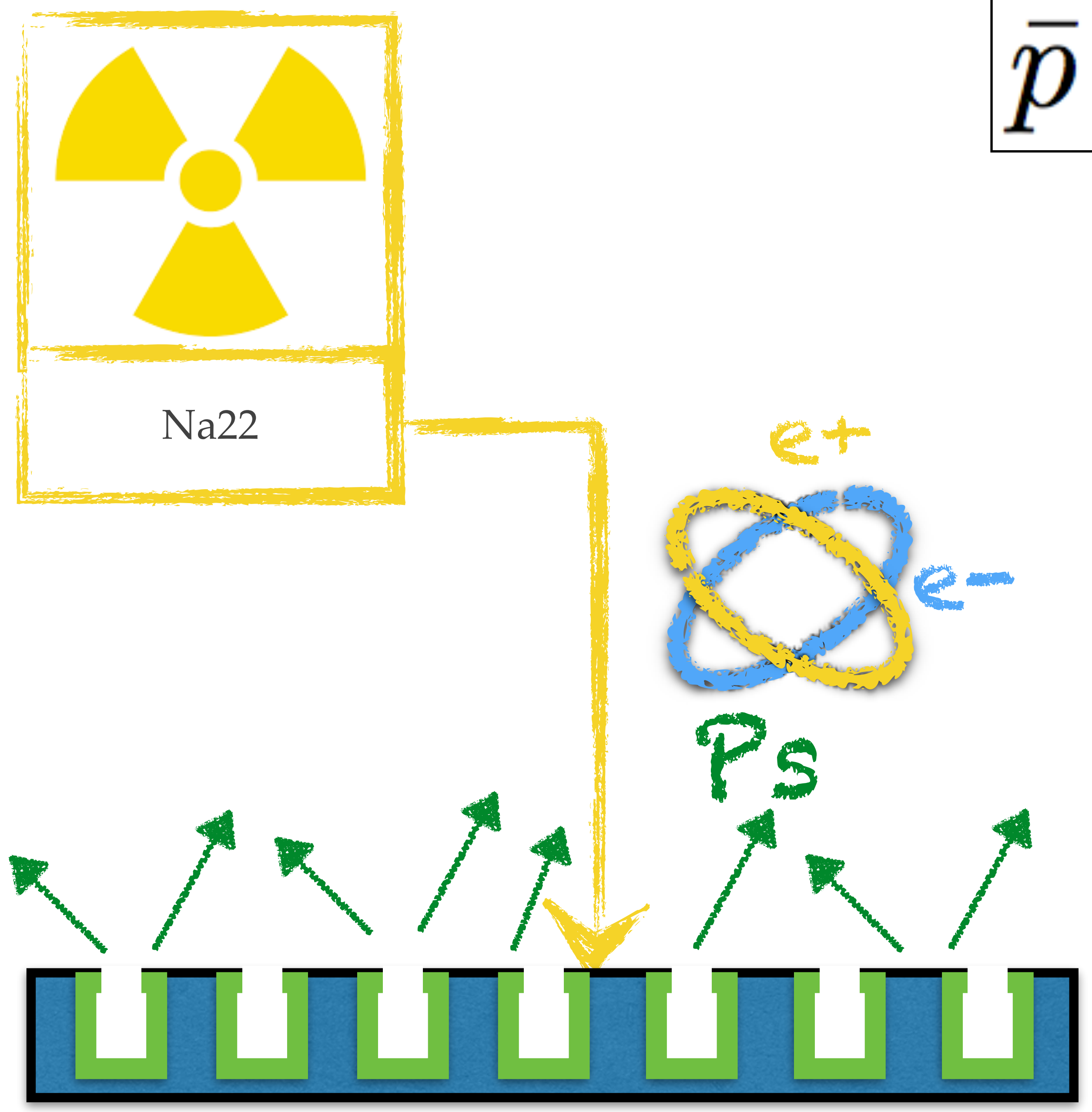

$$\bar{p} + Ps^\star \rightarrow \bar{H}^\star + e^-$$

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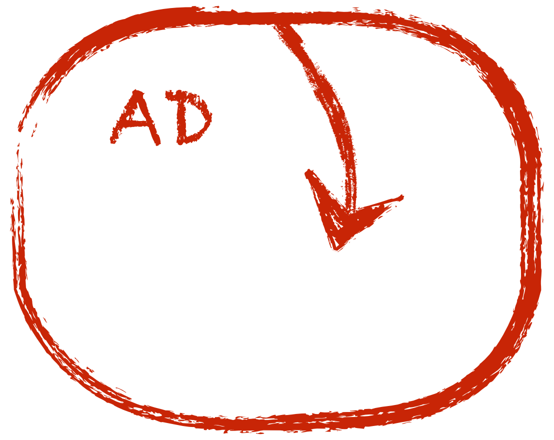

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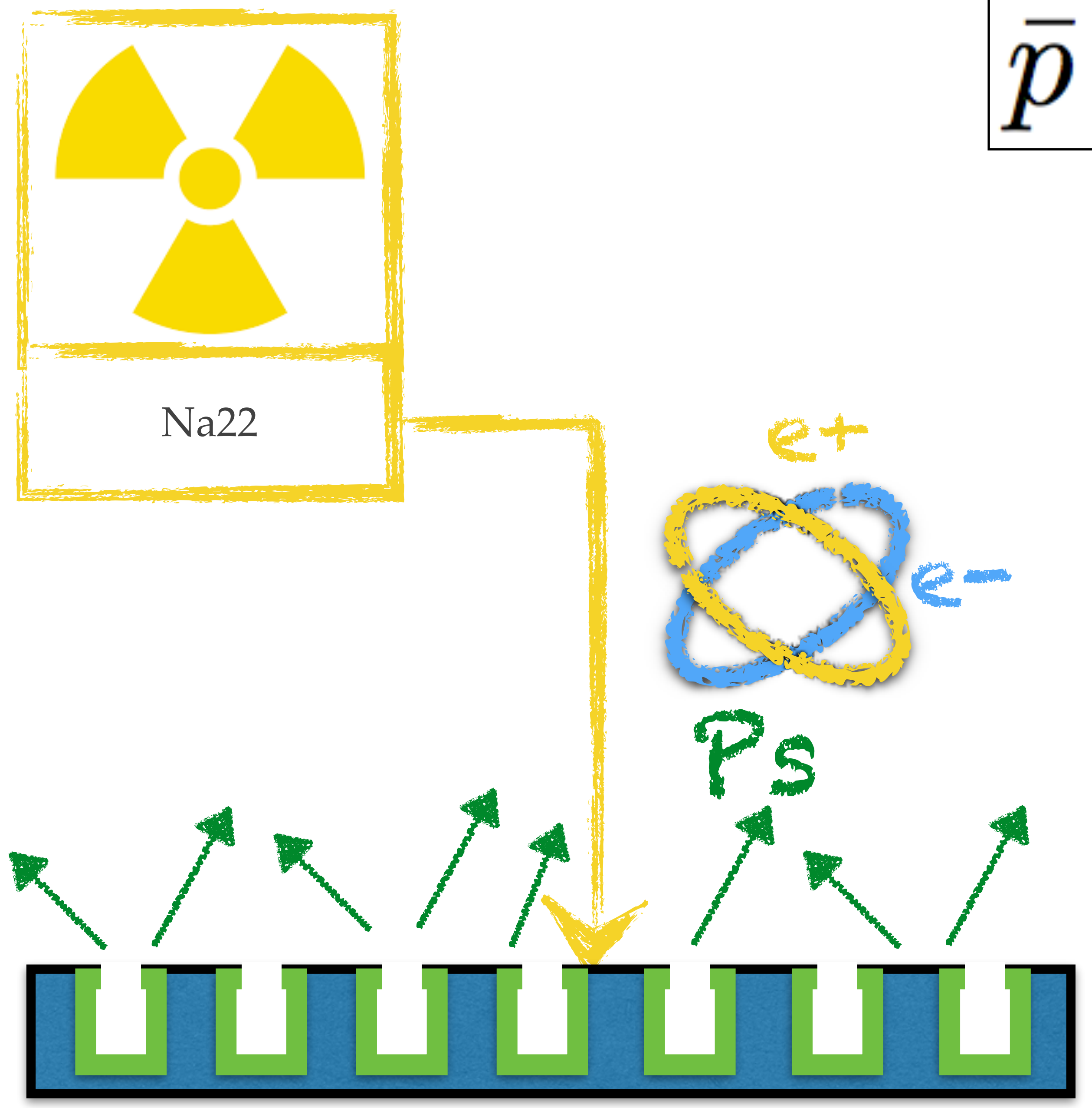
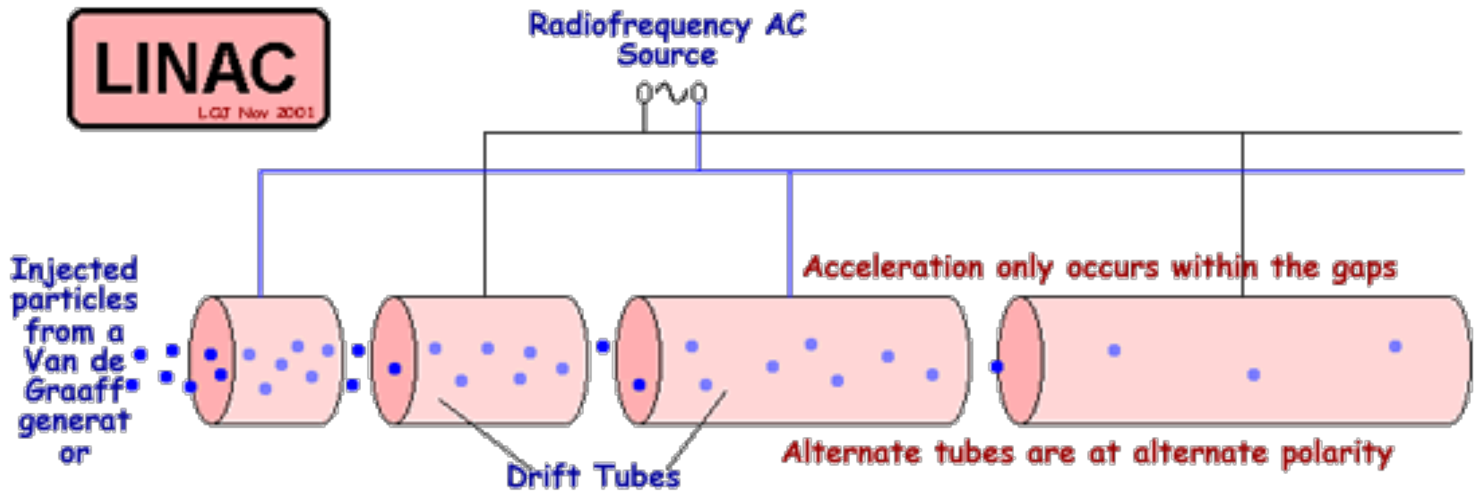
ALPHA



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

AEgIS

Antihydrogen ION !



GBAR

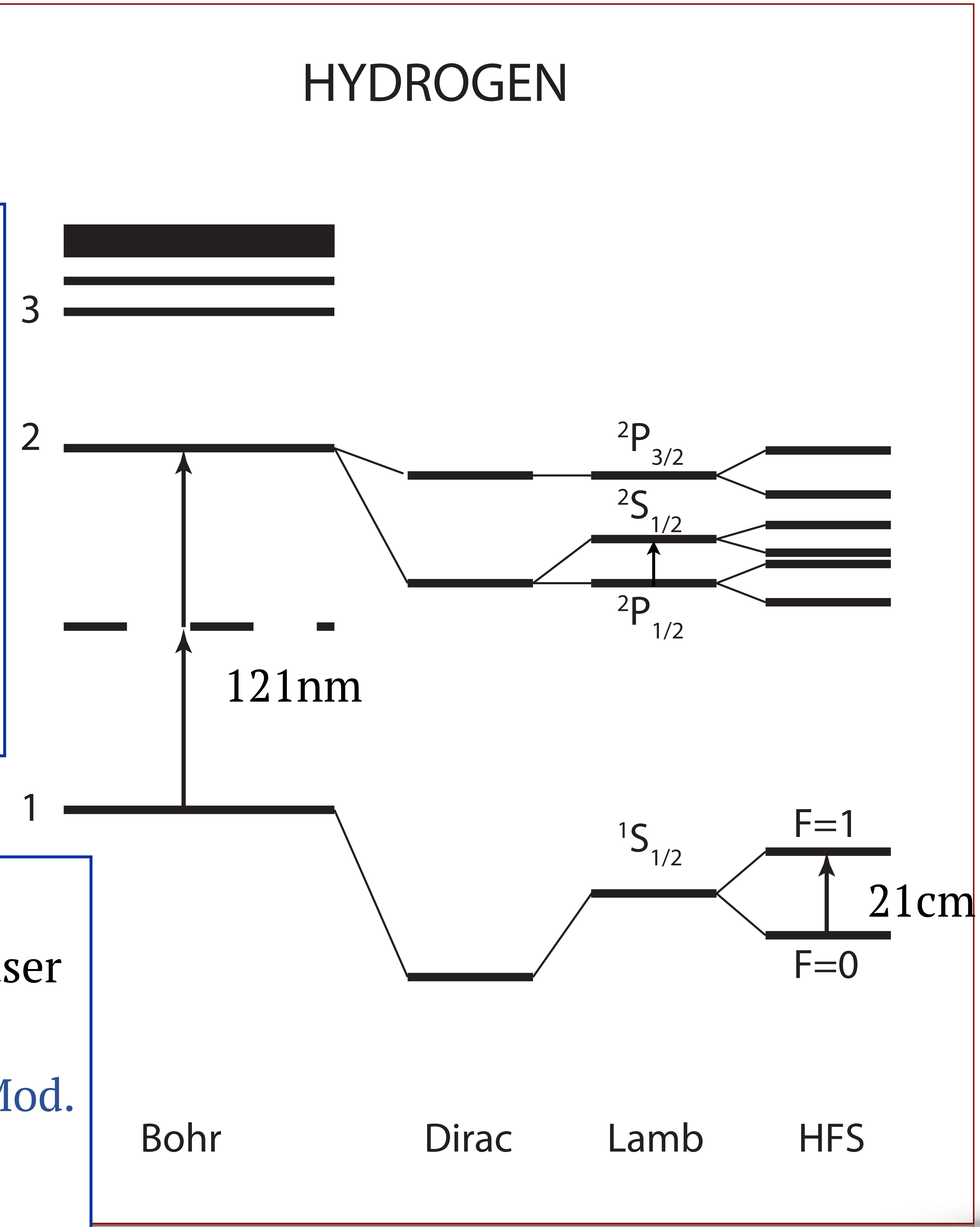
$$\bar{p} + Ps \rightarrow \bar{H} + e^-$$

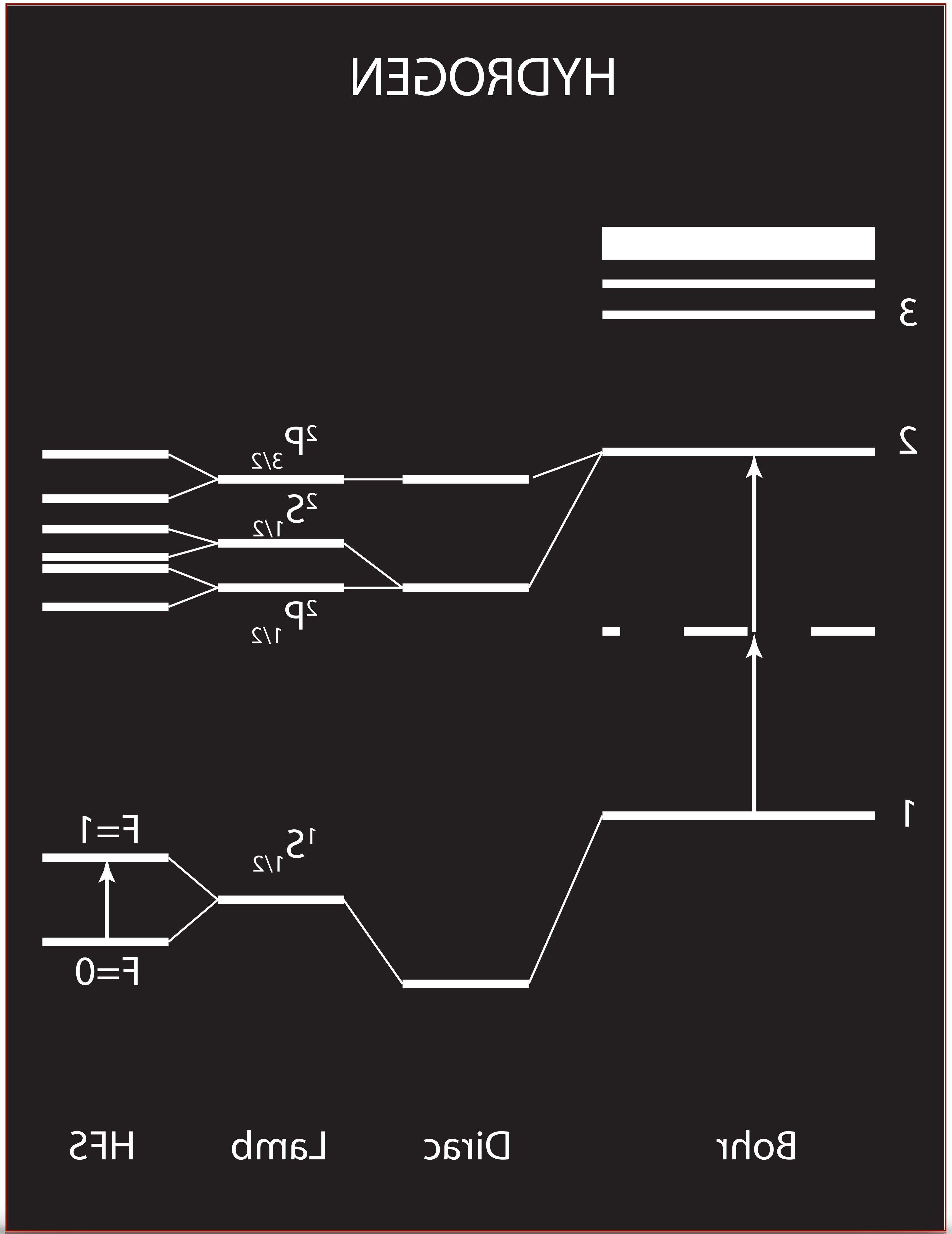
$$\bar{H} + Ps \rightarrow \bar{H}^+ + e^-$$

1

Antihydrogen spectroscopy

1S-2S: two photon transition
4×10^{-15} (~10 Hz)
in a cold (~6K) atomic beam
G. Parthey et al. Phys. Rev. Lett. 107 (2011)





hyperfine splitting measurement in maser
$\sim 10^{-12}$ (~1 mHz)
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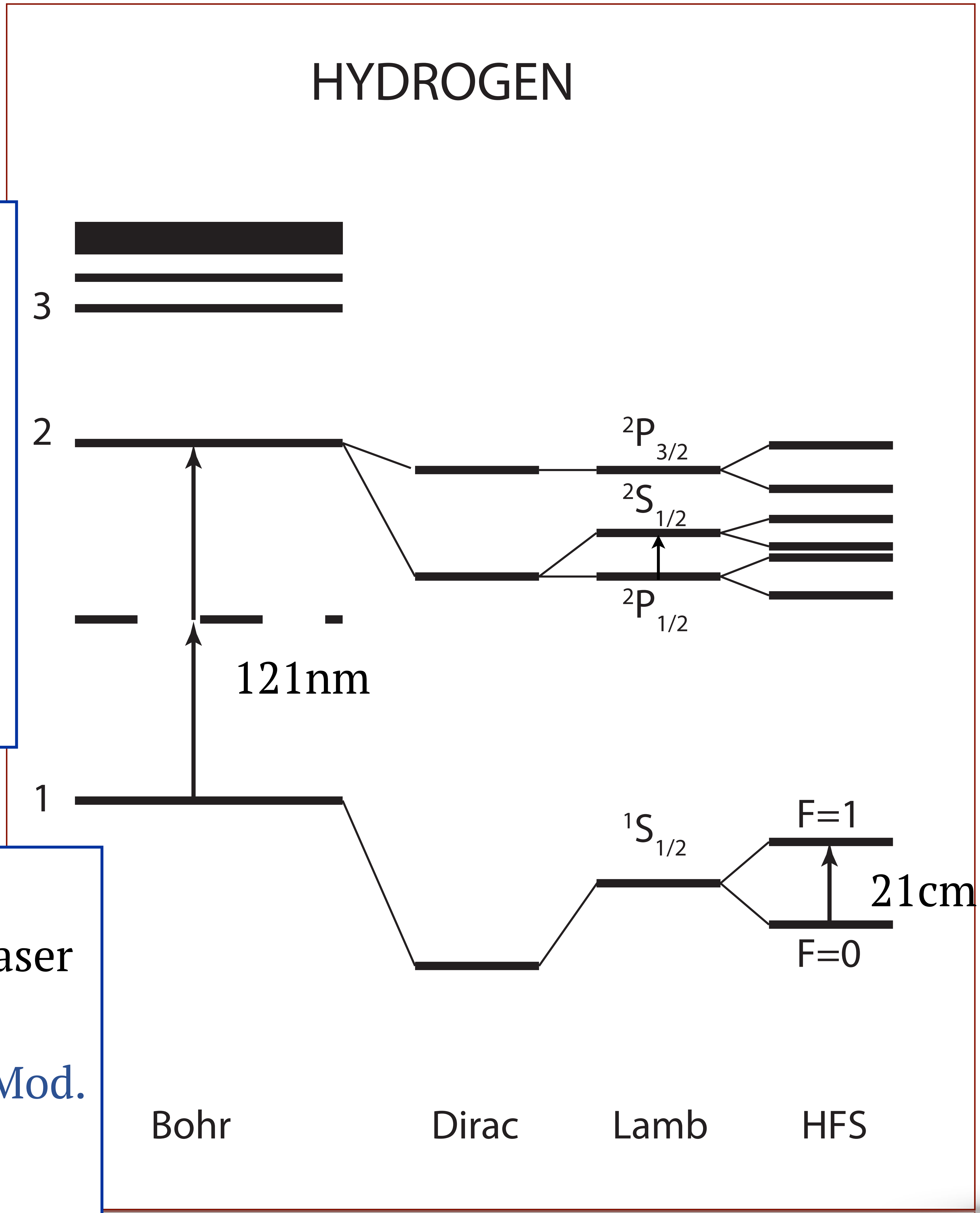

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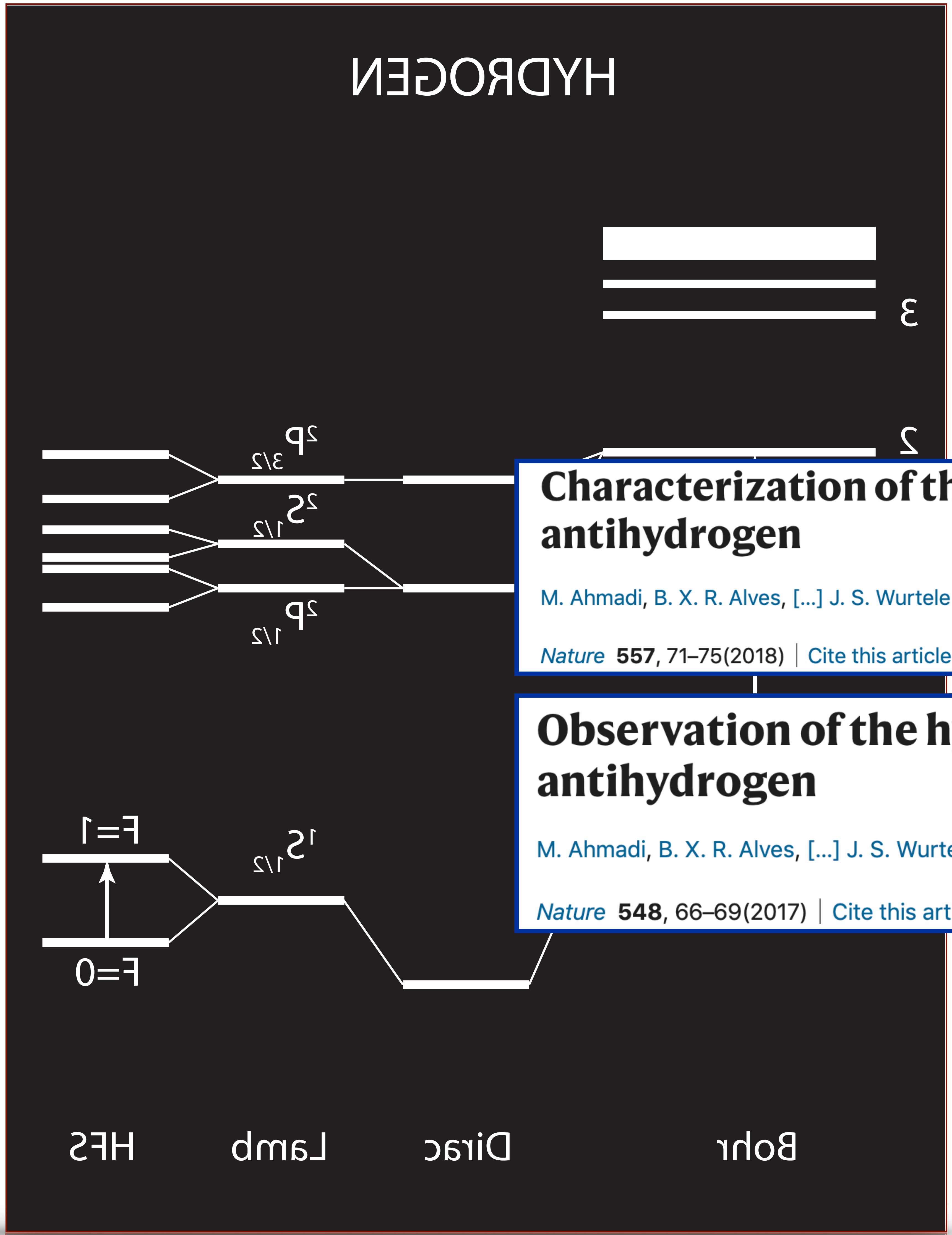


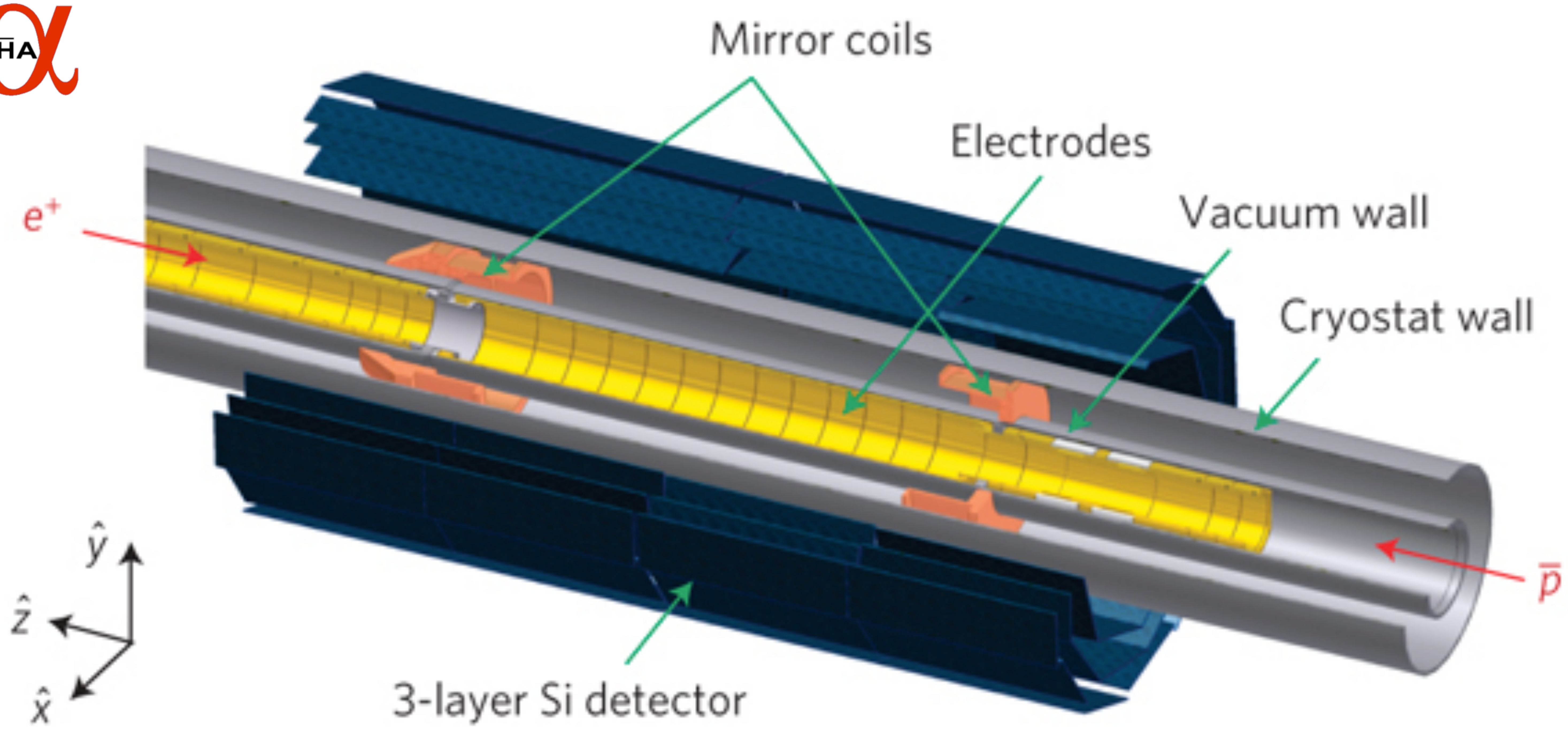
Characterization of the 1S–2S transition in antihydrogen
$\sim 2 \times 10^{-12}$
M. Ahmadi, B. X. R. Alves, [...] J. S. Wurtele
Nature **557**, 71–75(2018) | Cite this article

Observation of the hyperfine spectrum of antihydrogen
$\sim 5 \times 10^{-4}$
M. Ahmadi, B. X. R. Alves, [...] J. S. Wurtele
Nature **548**, 66–69(2017) | Cite this article

ALPHA Collaboration

1

Spectroscopy highlights with antihydrogen



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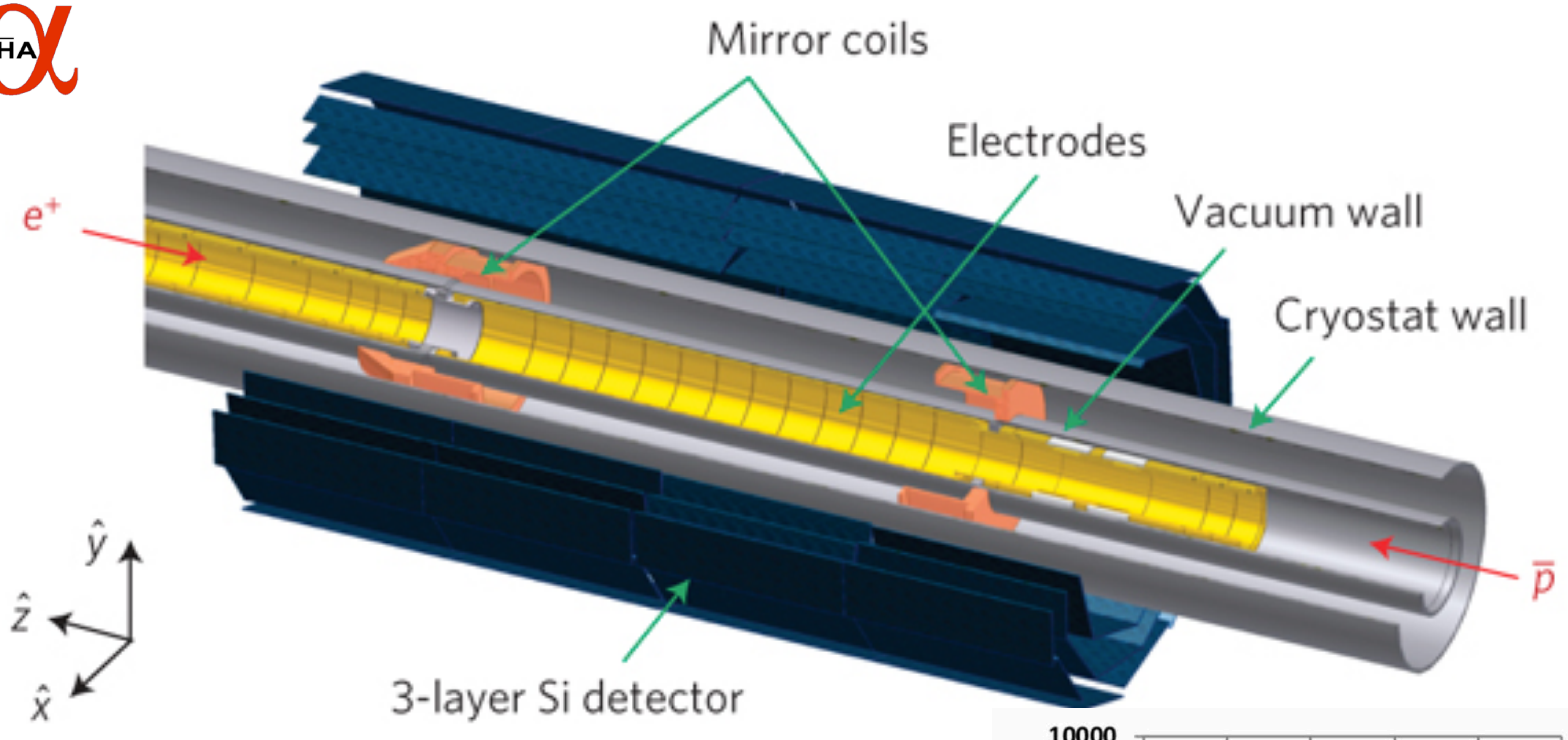
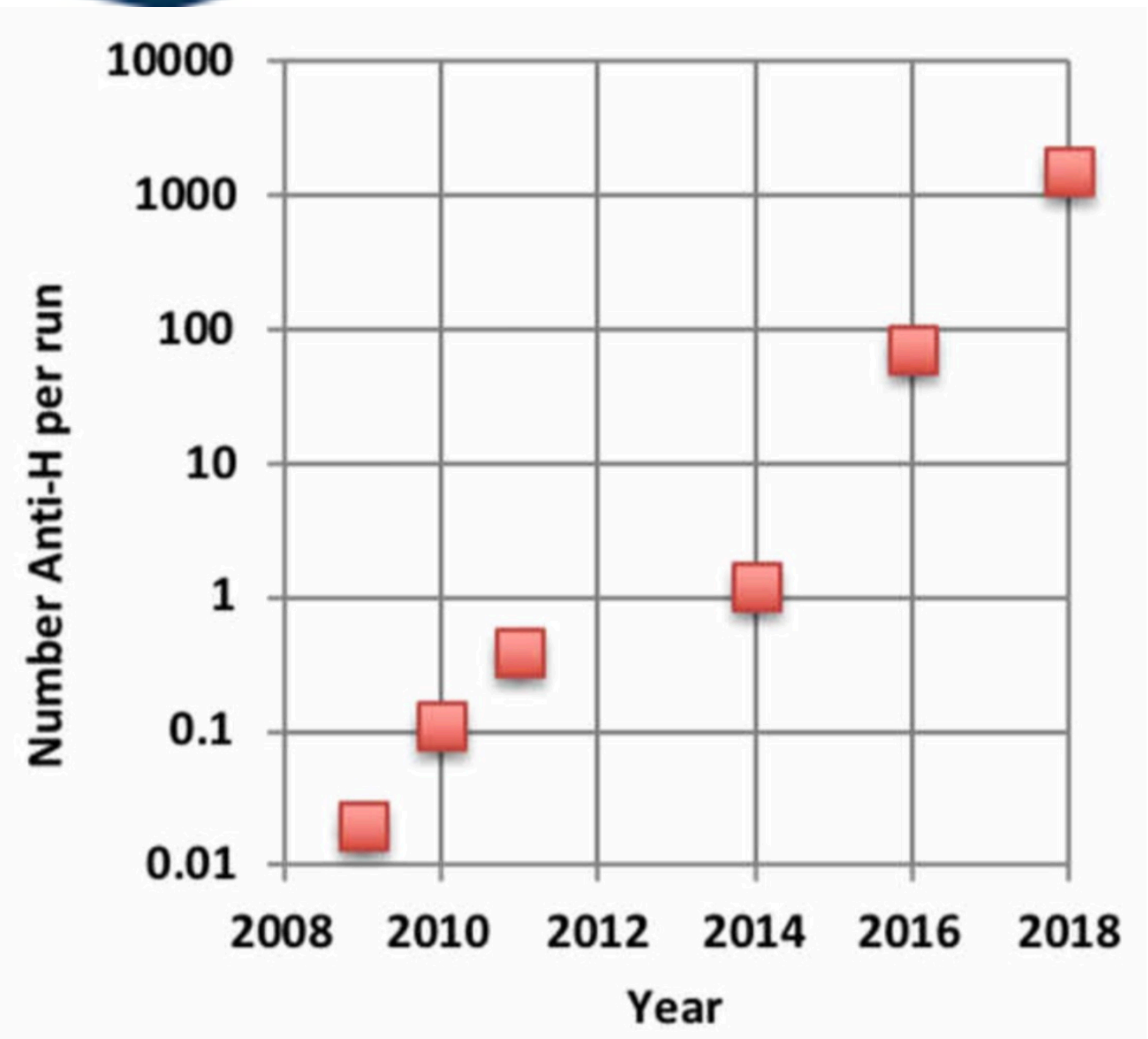


Improvements in trapping rates; now routinely accumulate >1000 $\bar{\text{H}}$ by "stacking"



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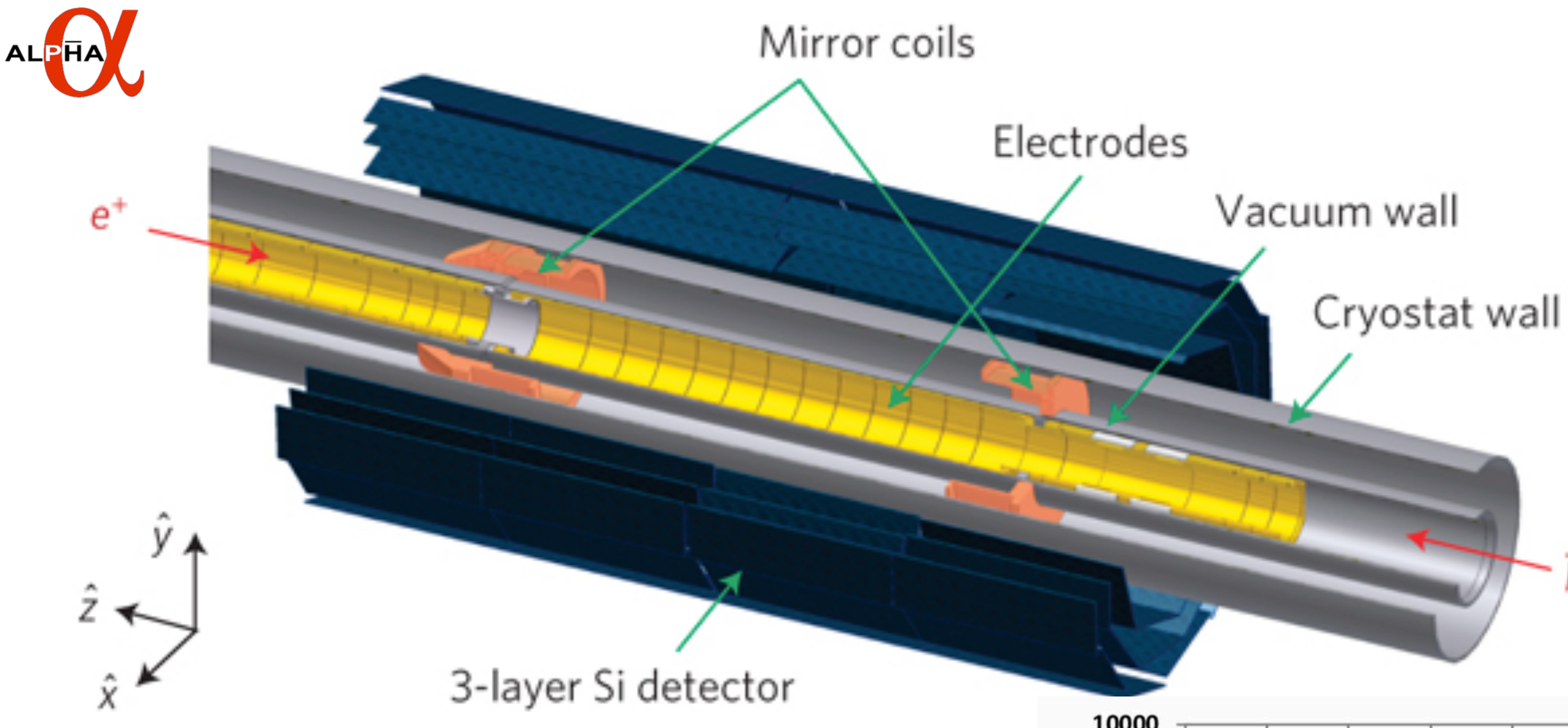
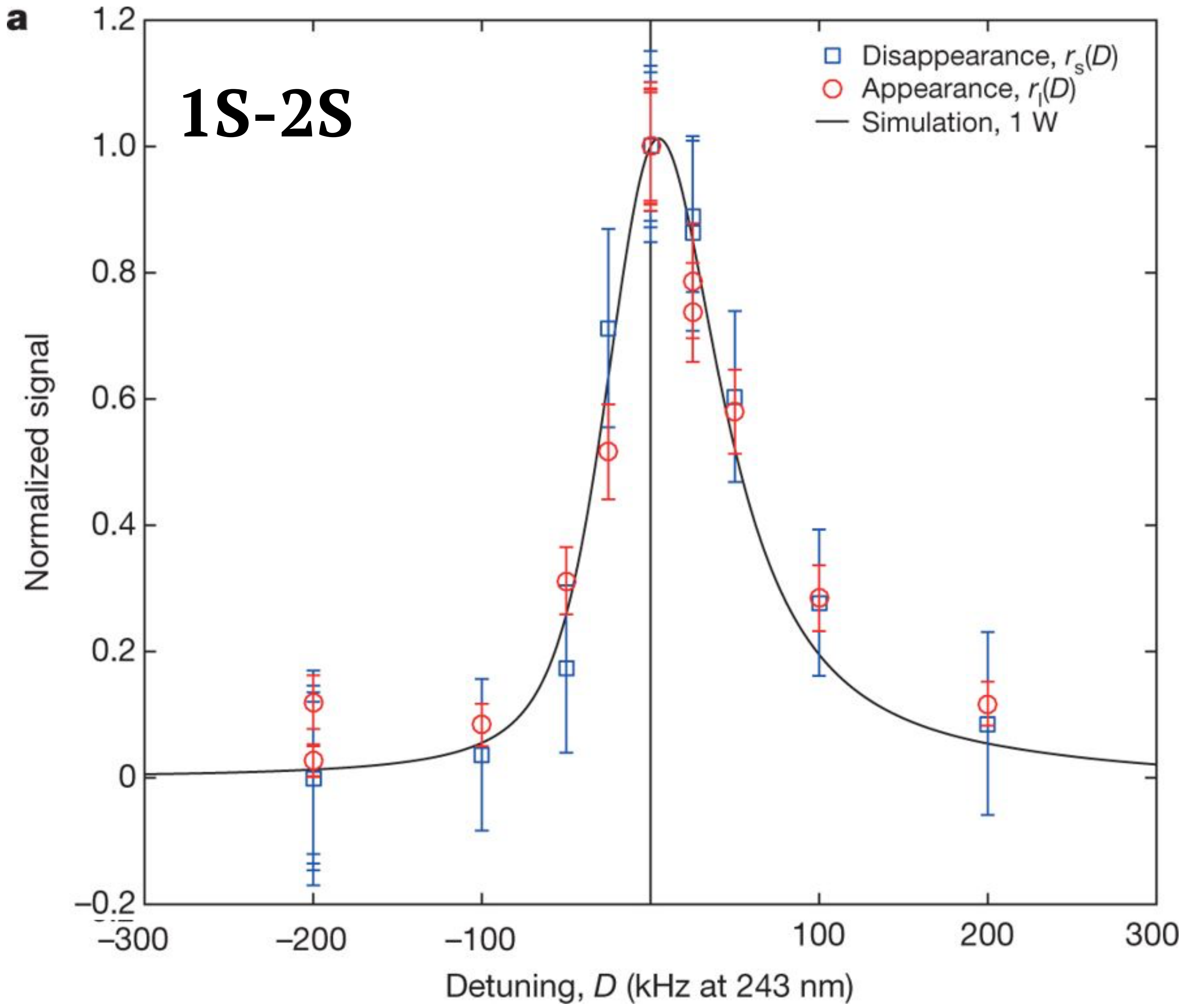


In a TRAP:

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



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

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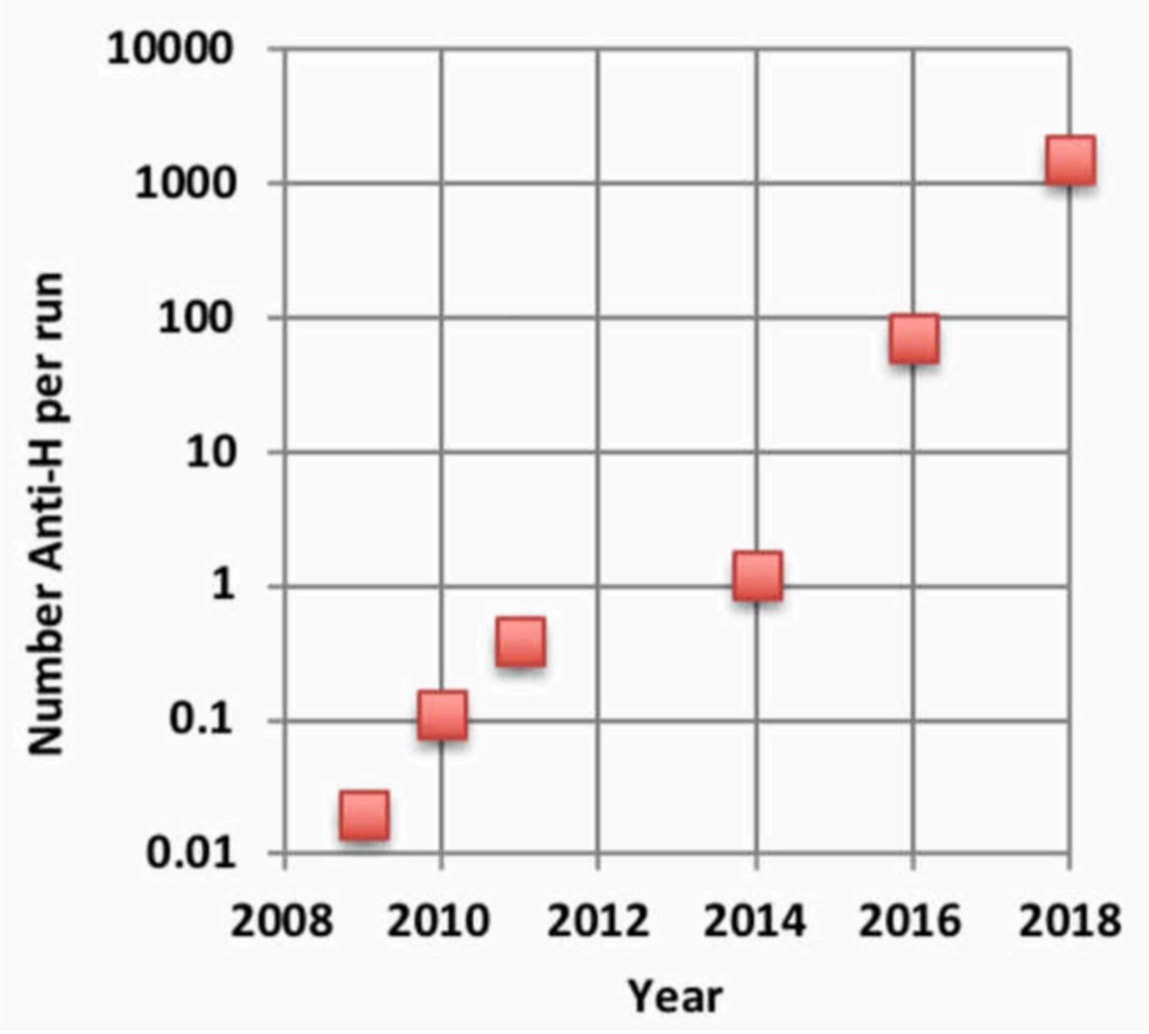
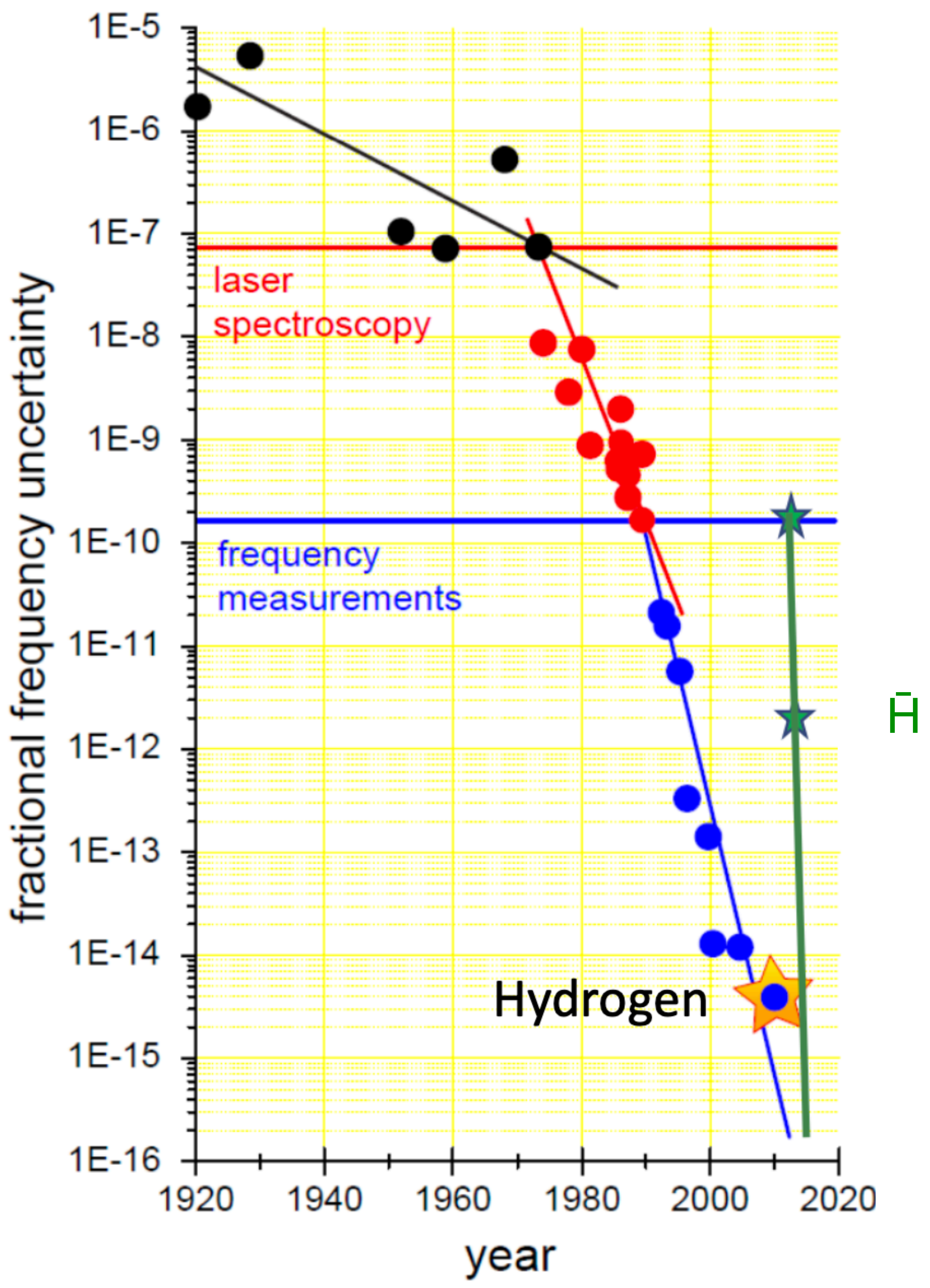
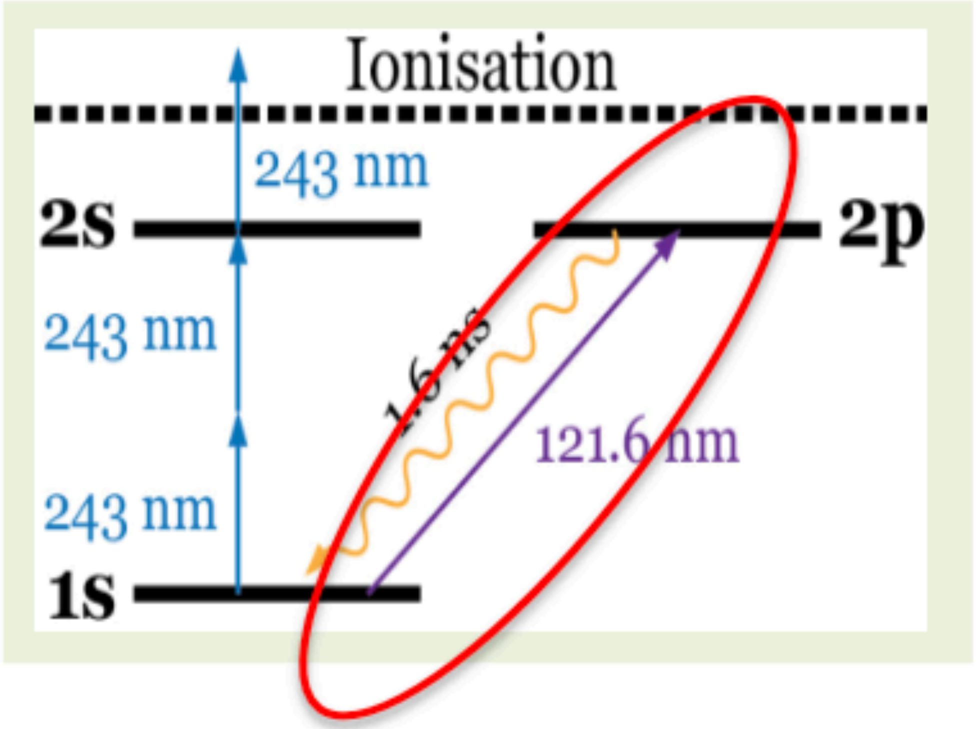
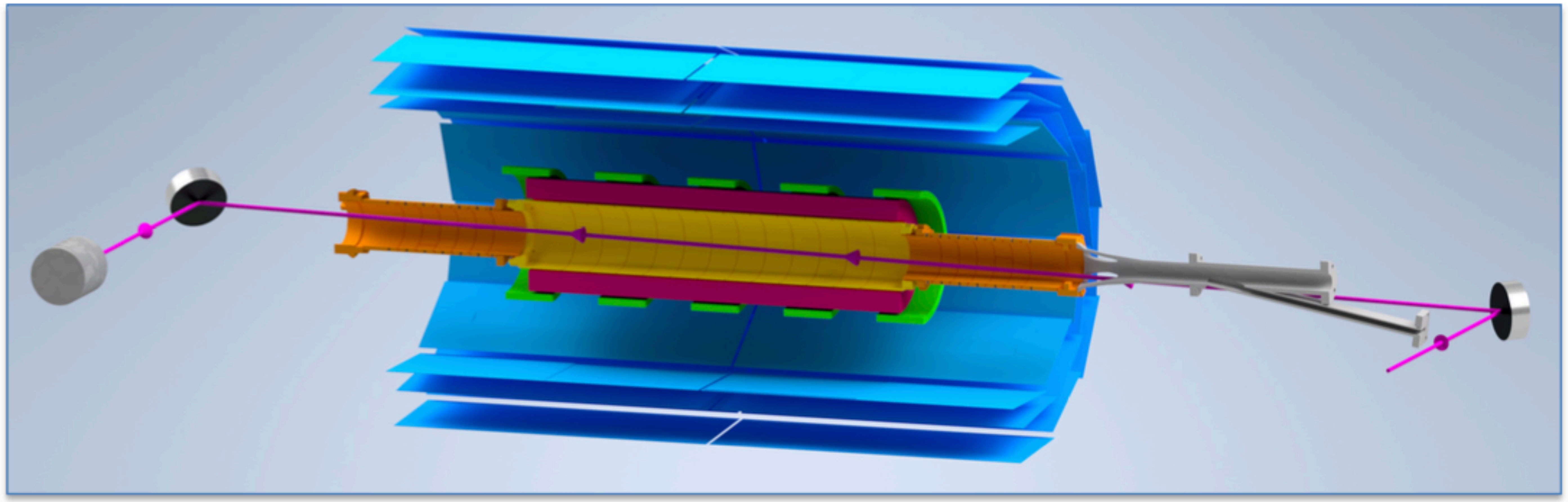


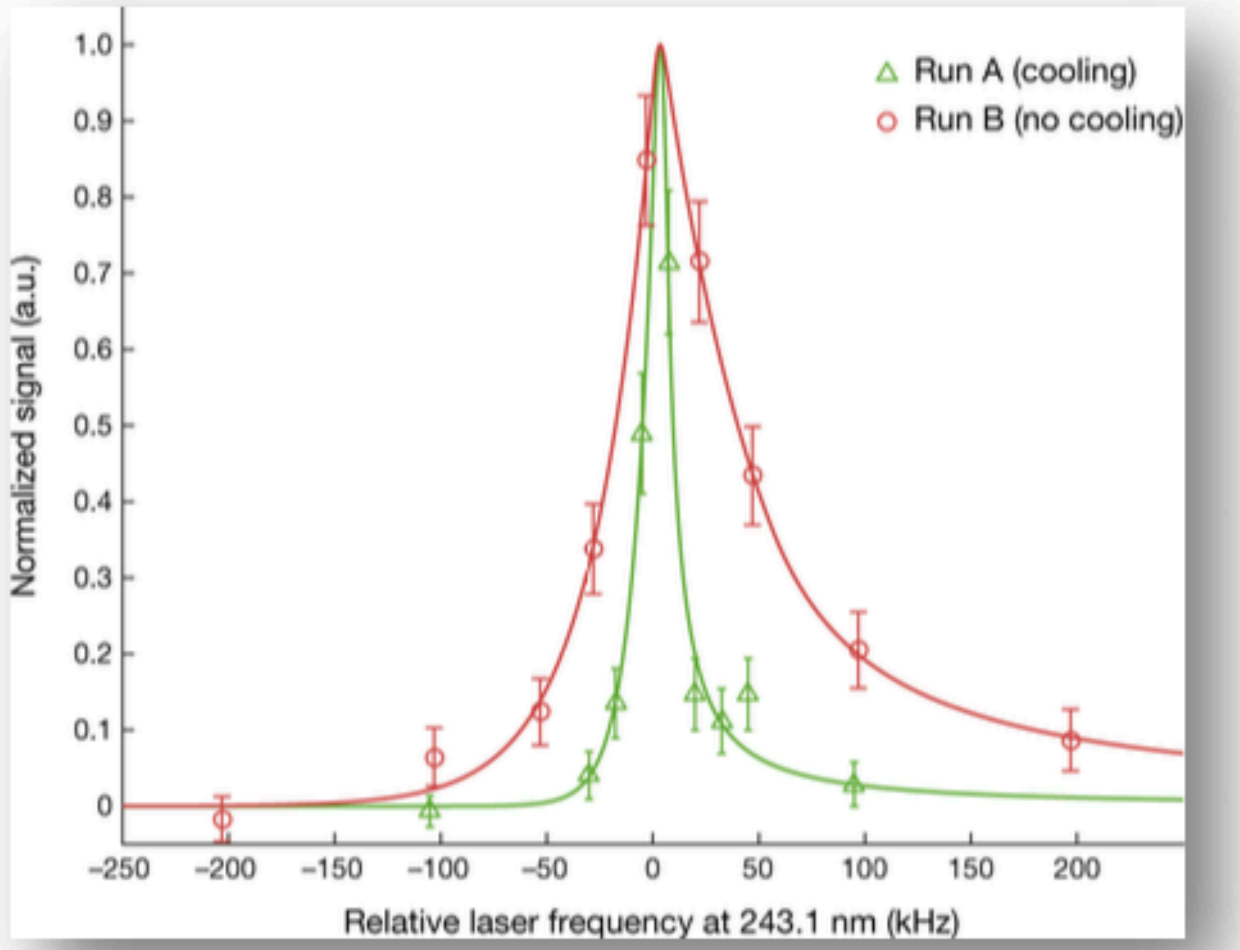

1E-5
1E-6
1E-7
1E-8
1E-9
1E-10
1E-11
1E-12
1E-13
1E-14
1E-15
1E-16
fractional frequency uncertainty
laser
spectroscopy
frequency
measurements
Hydrogen
H̄
1920
1940
1960
1980
2000
2020
year

1

Laser cooling of $\bar{H}$

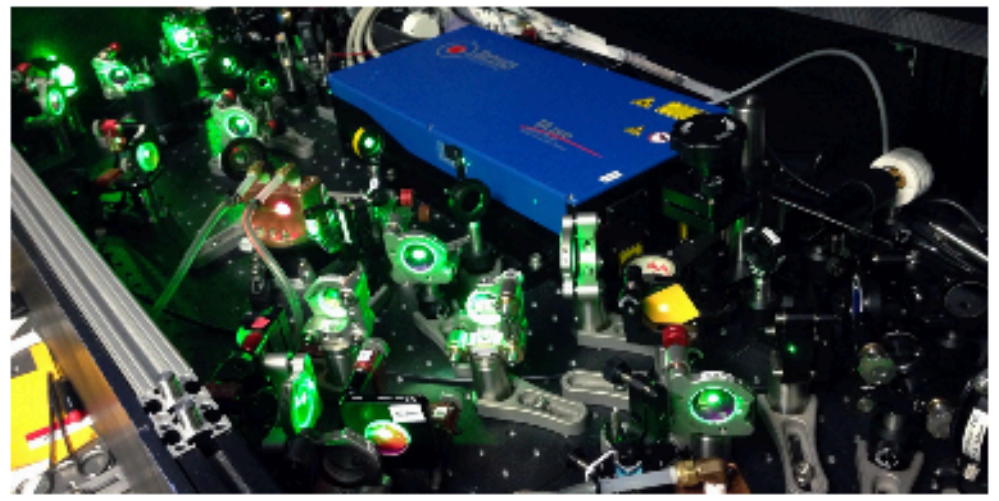






Laser cooling (anti)hydrogen is hard

- 121 nm: vacuum ultraviolet
- Challenging laser built at UBC, Canada
- Cooling takes hours (rather than msec)



Laser cooling a likely game changer in anti-H and H studies

From M. Fujiwara

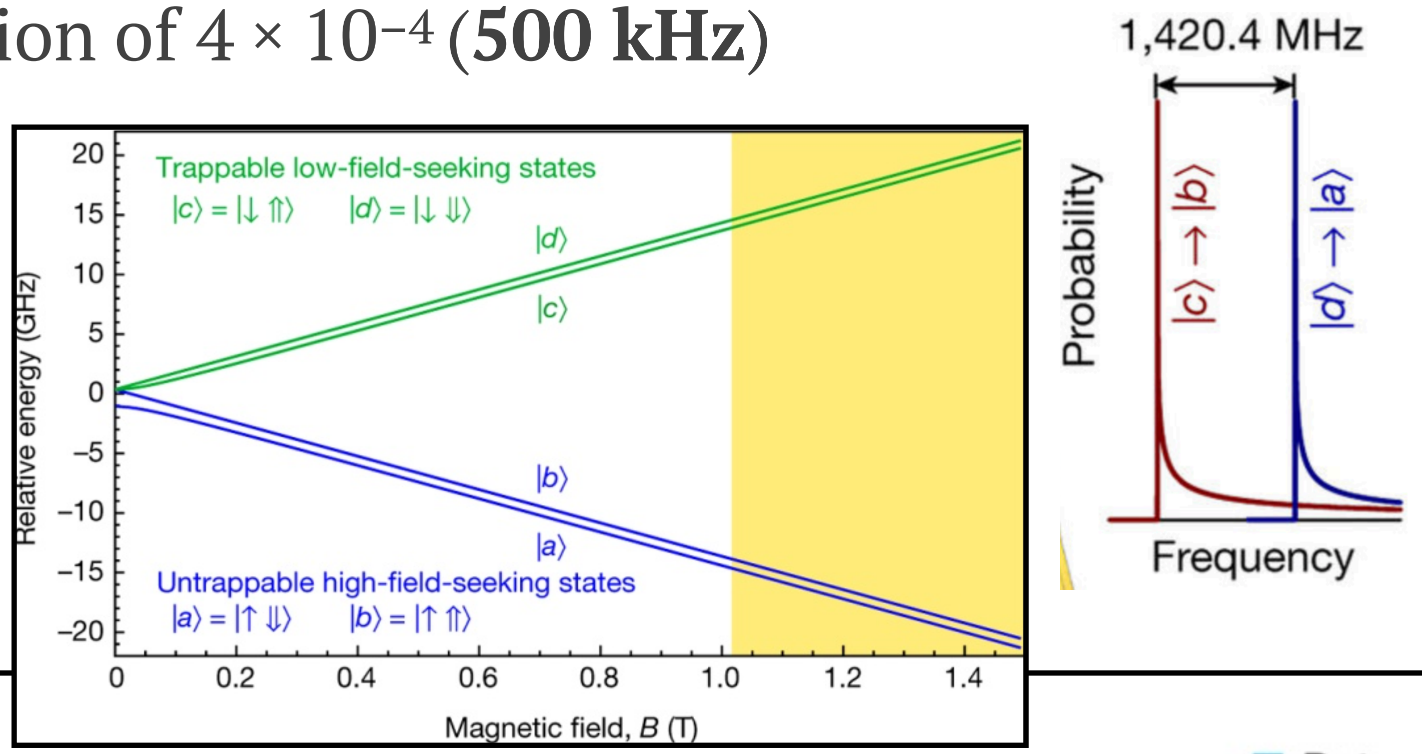
Spectroscopy highlights with antihydrogen

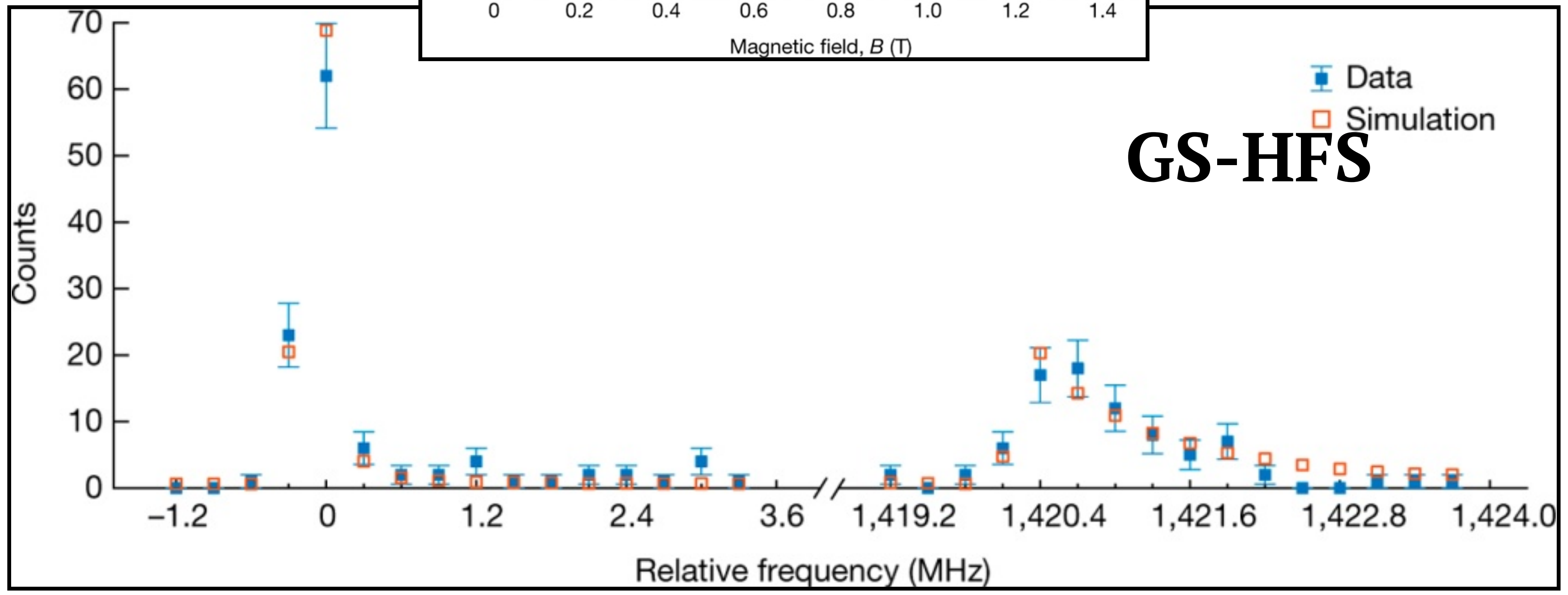
1

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

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

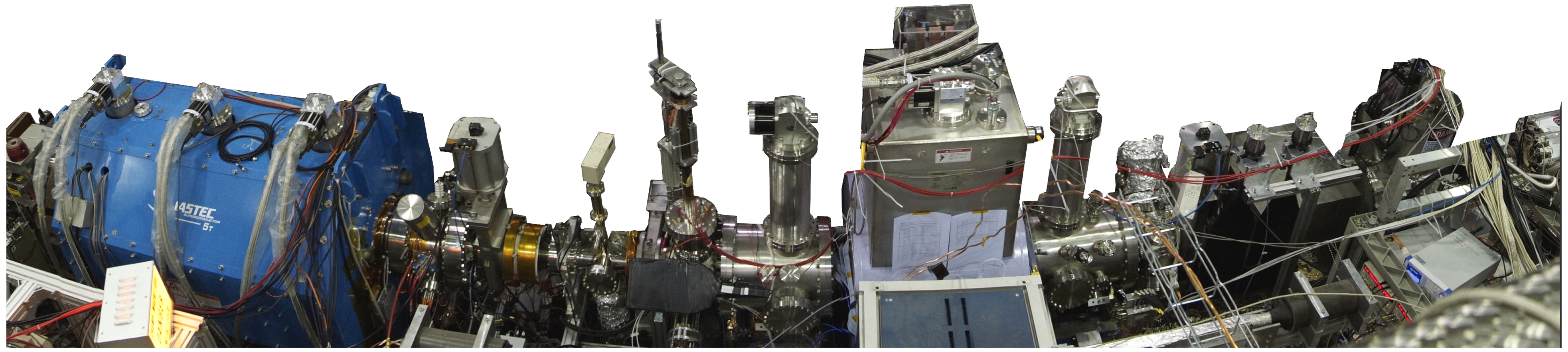
In a TRAP:
Precision of 4 × 10−4 (**500 kHz**)





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

In a BEAM:



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ALPHA

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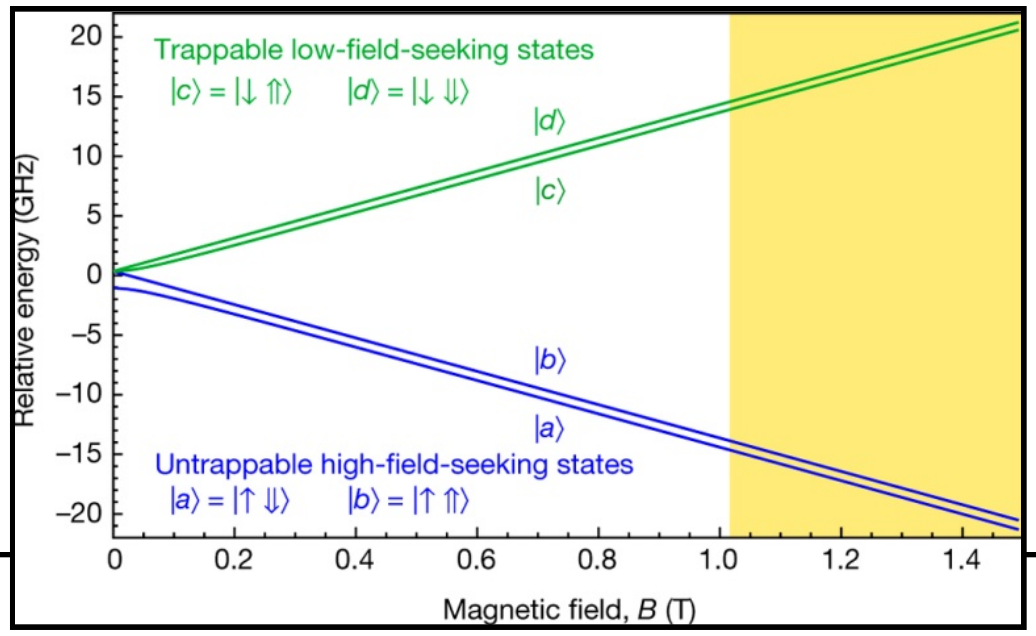
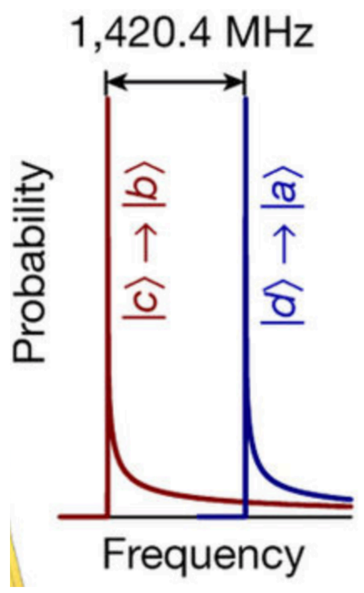
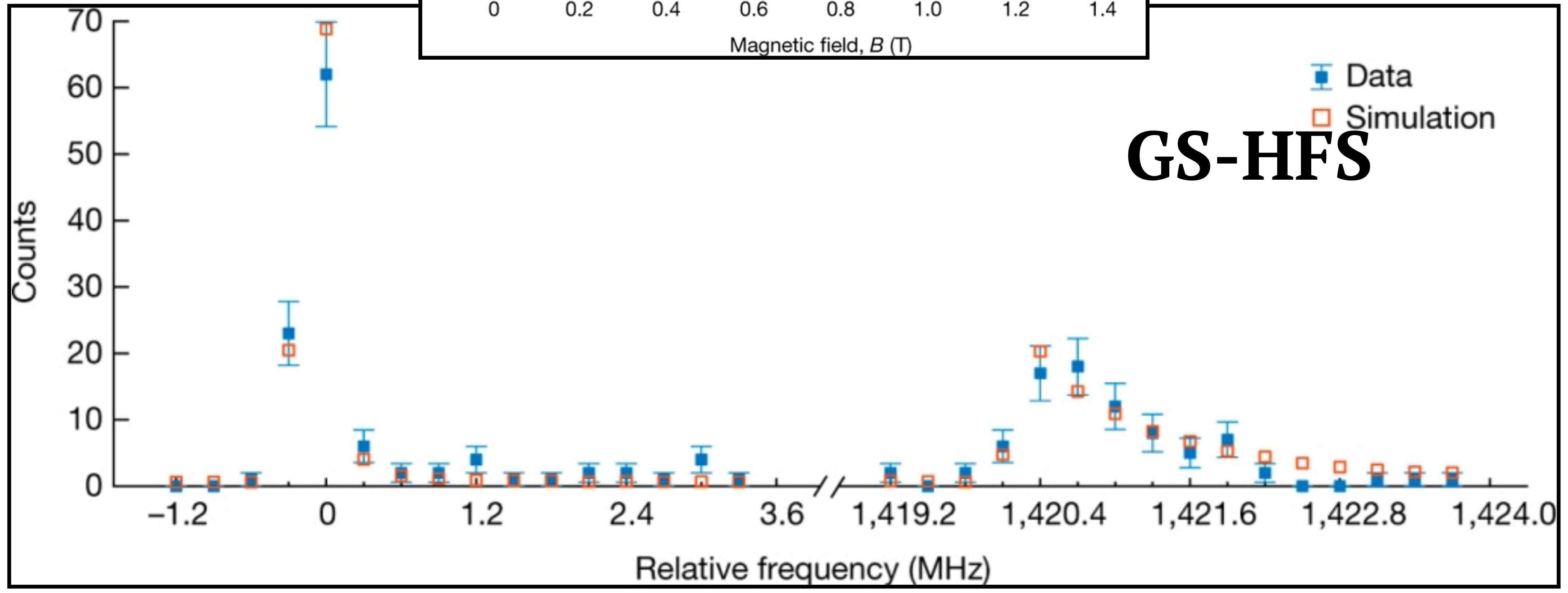
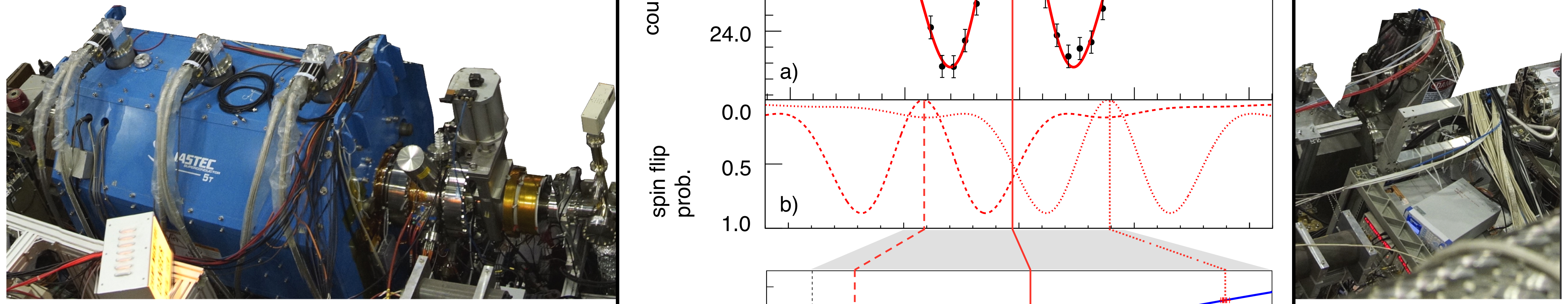


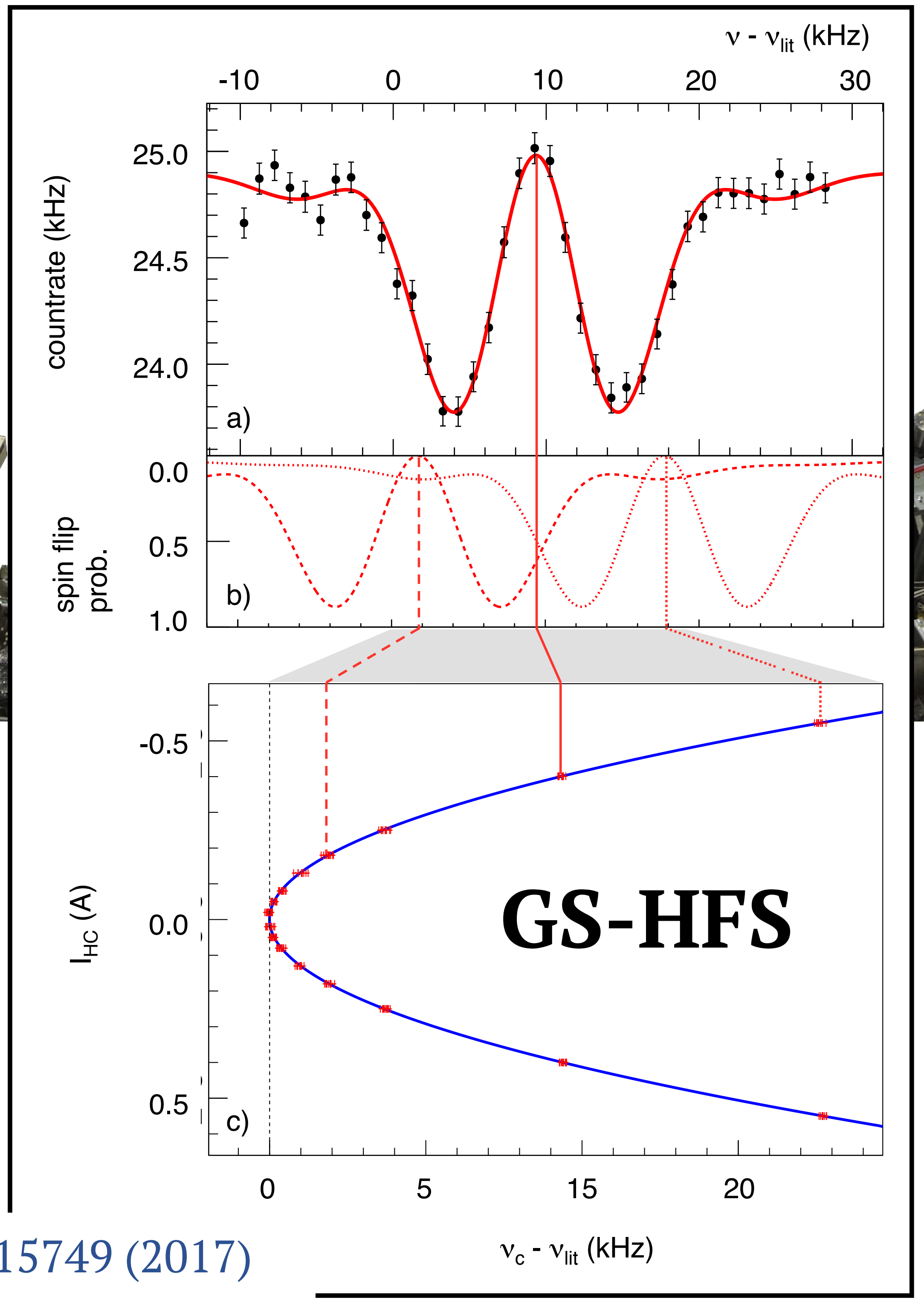




M. Ahmadi et al. Nature 548, 66–69 (2017)

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



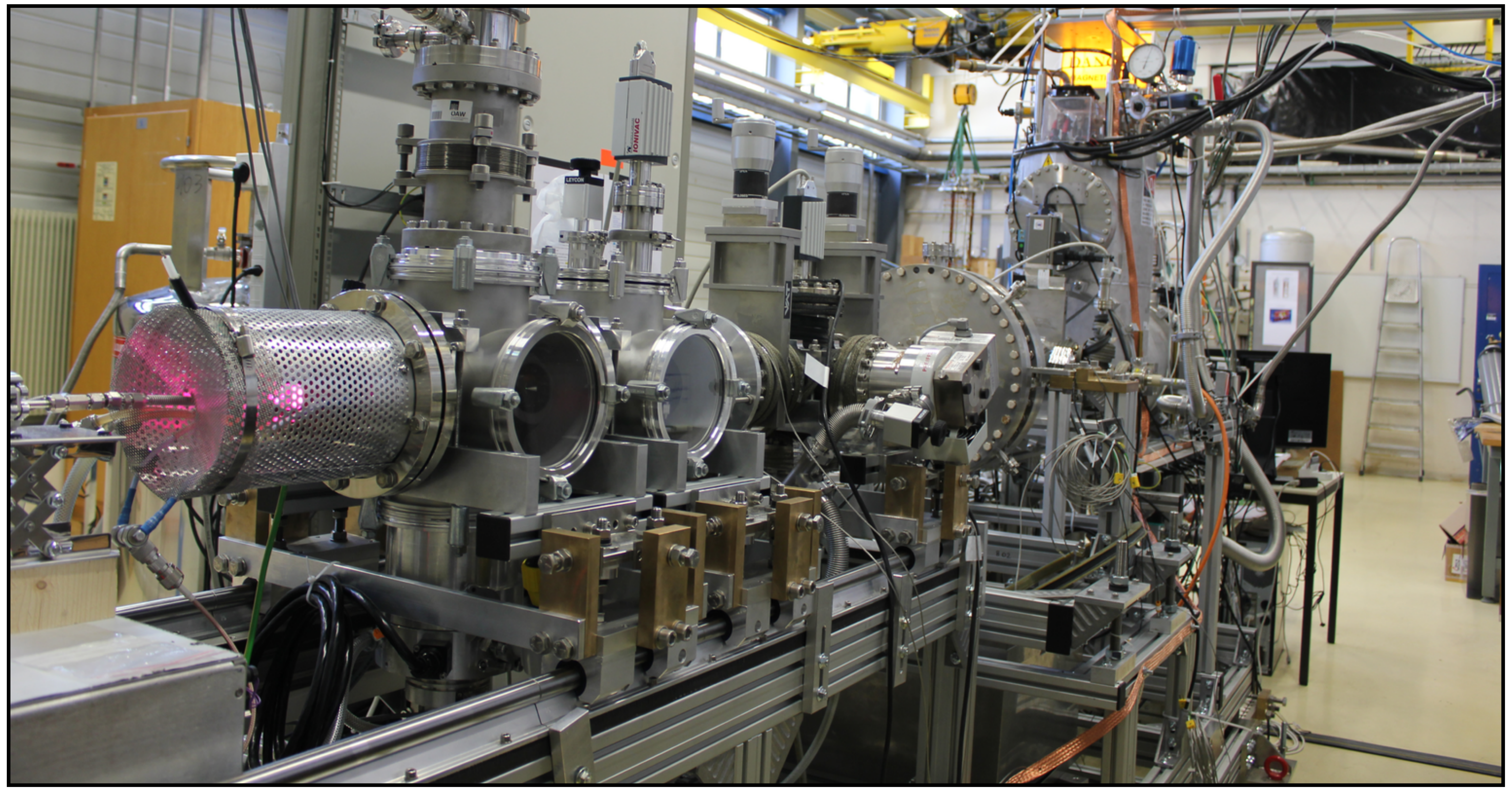


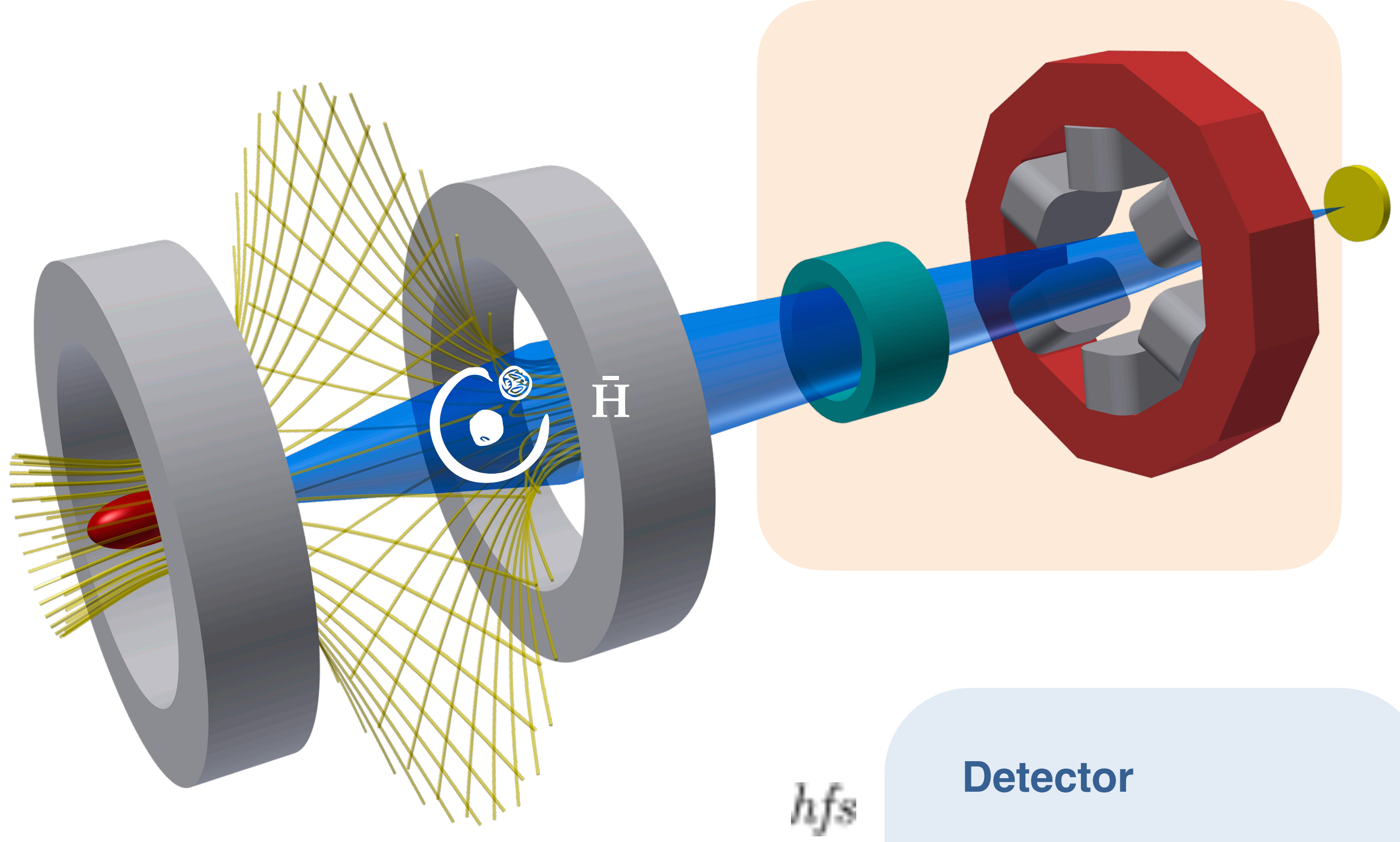
M. Diermaier et al. Nature Communications 8, 15749 (2017)

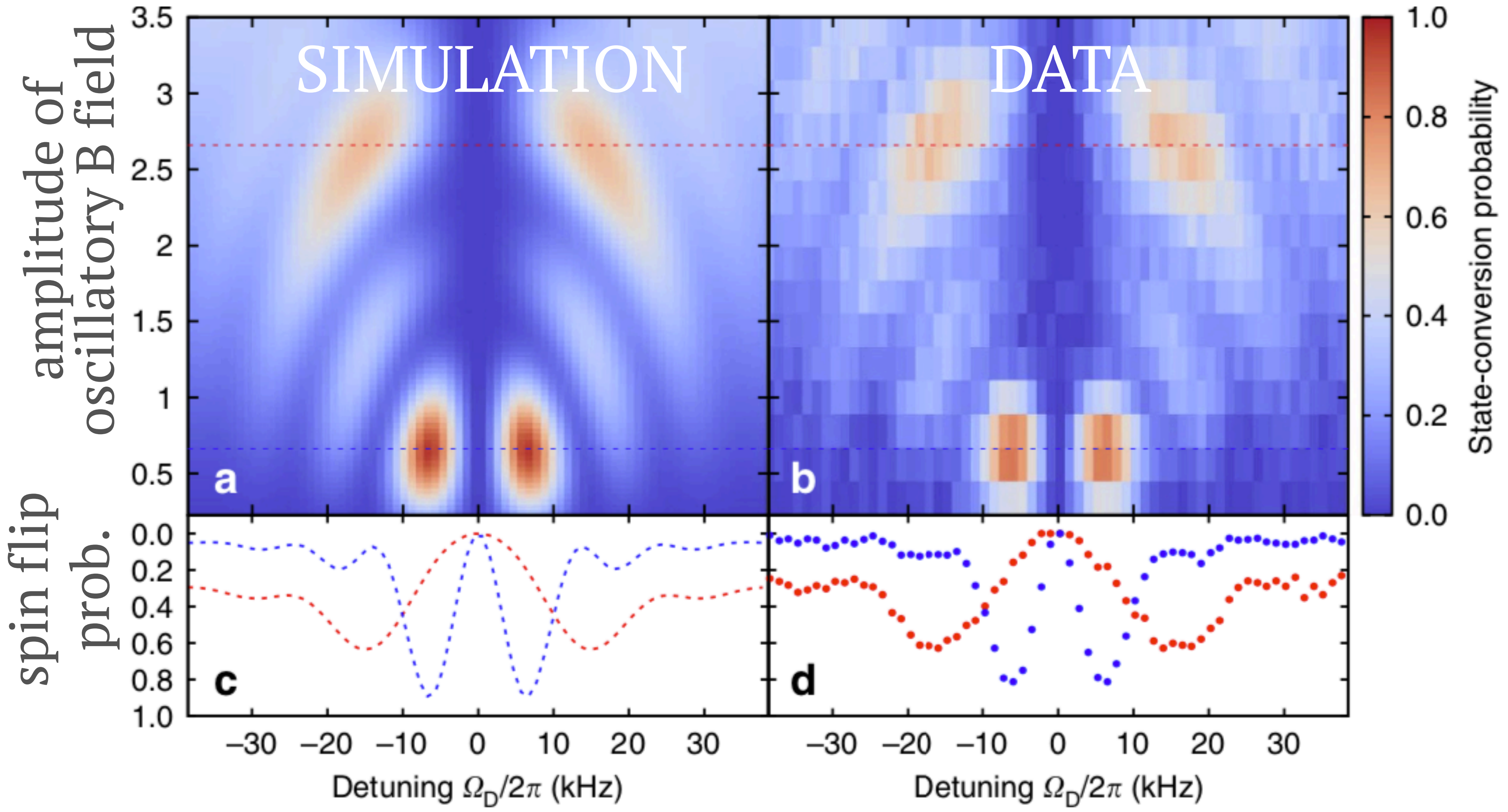
In-beam spectroscopy apparatus

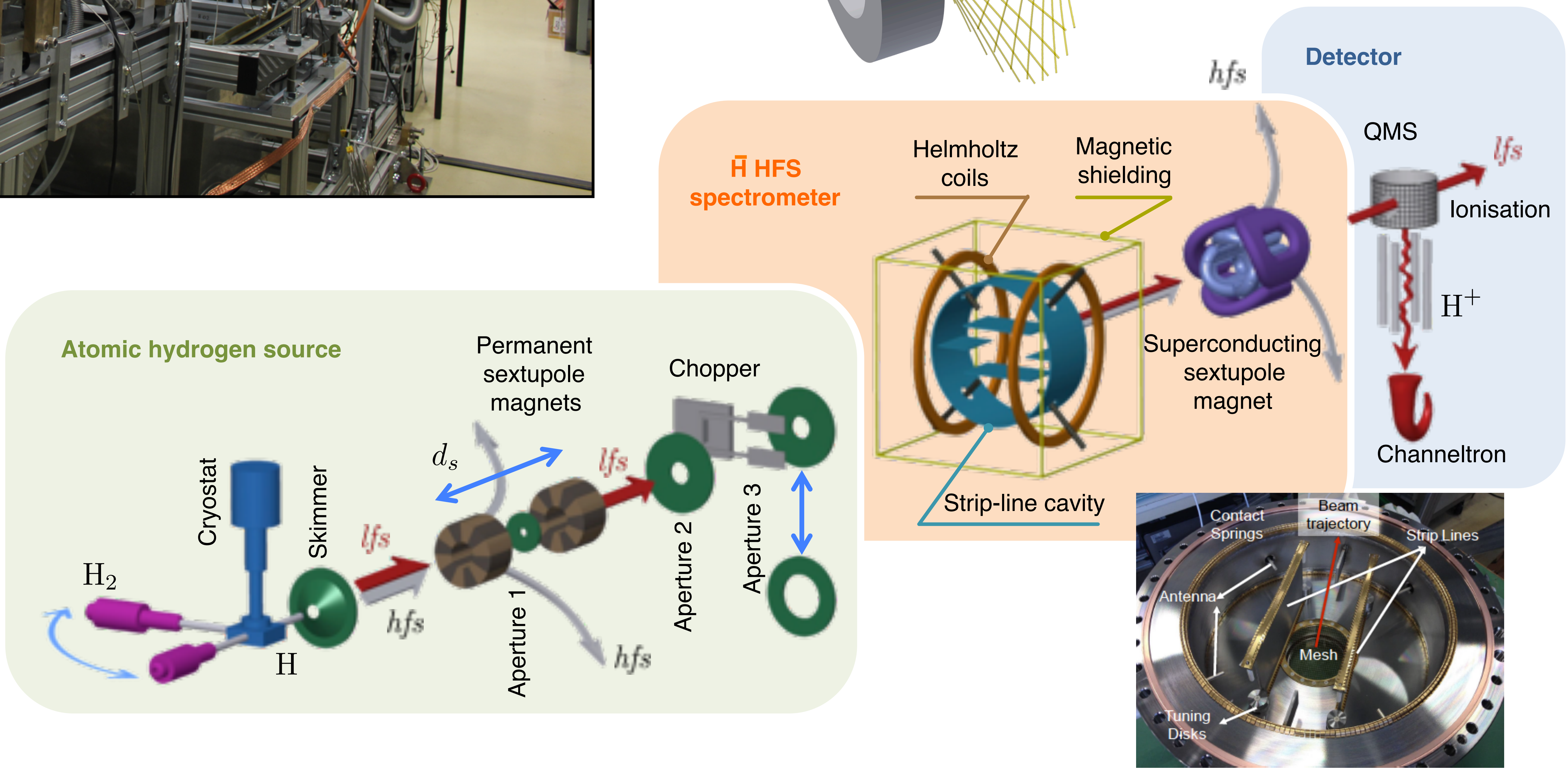
1

Commissioning with a beam of hydrogen from a discharge plasma







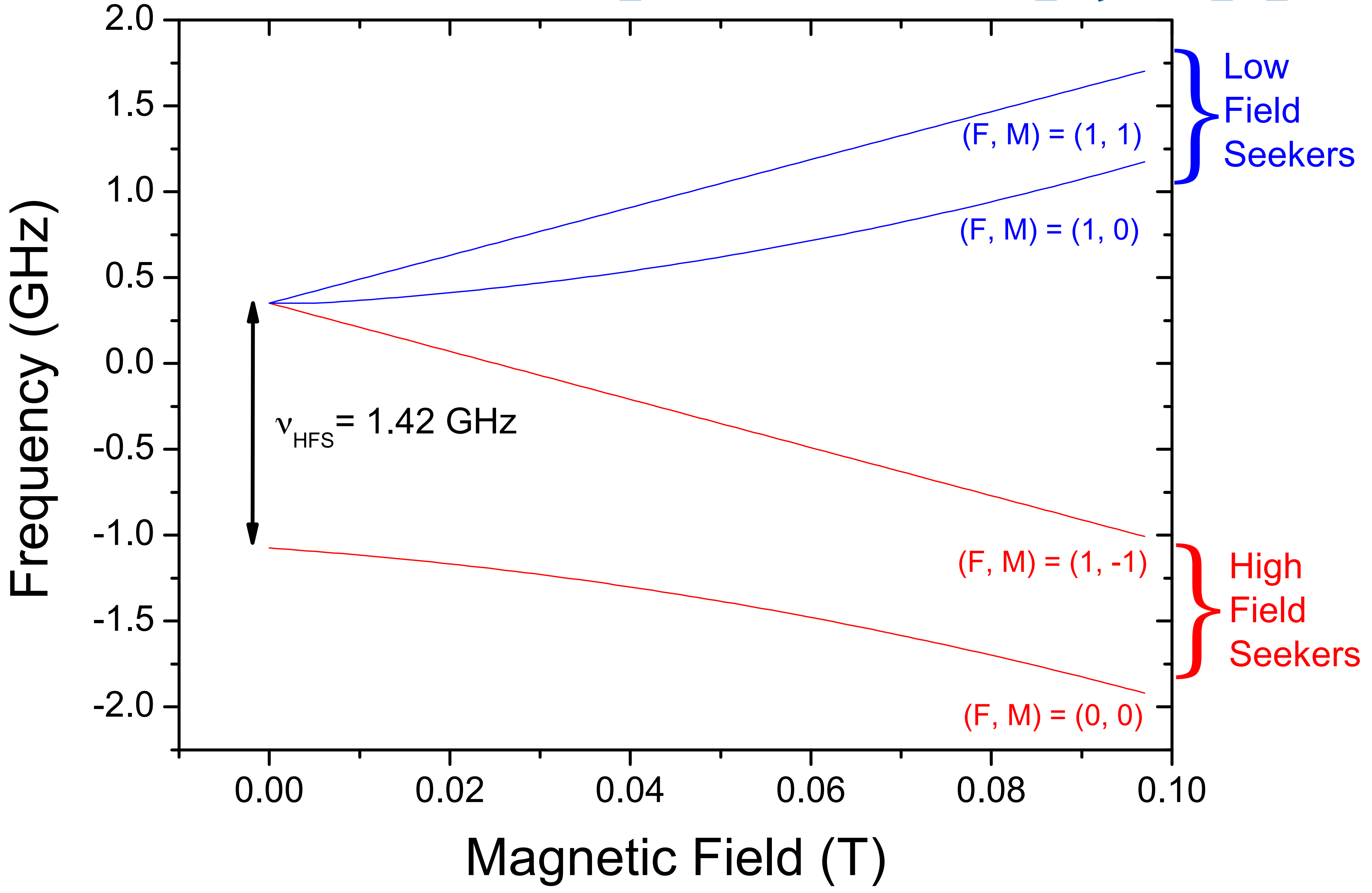


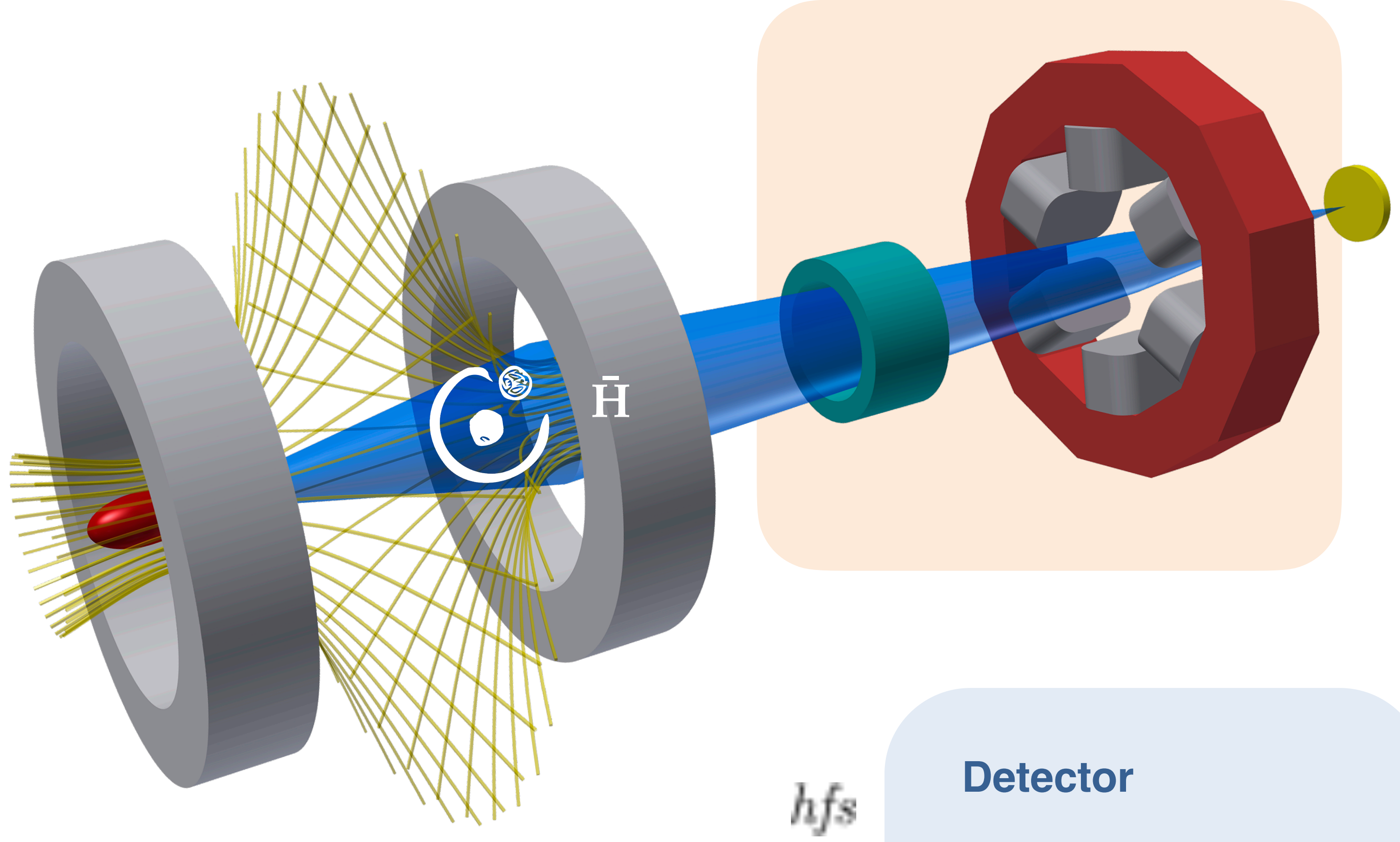
C. Malbrunot et al. NIM A 935 (2019)

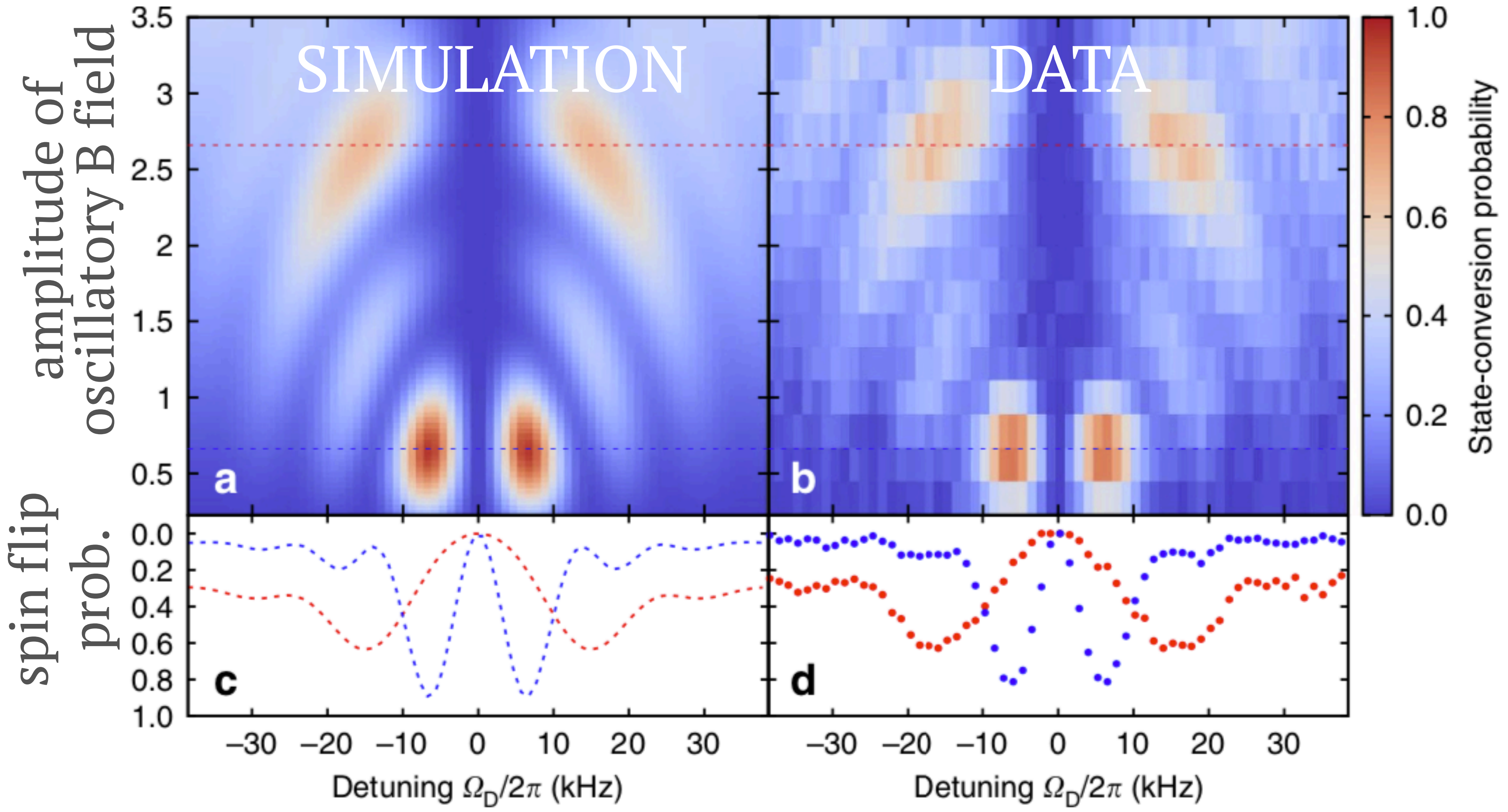
1

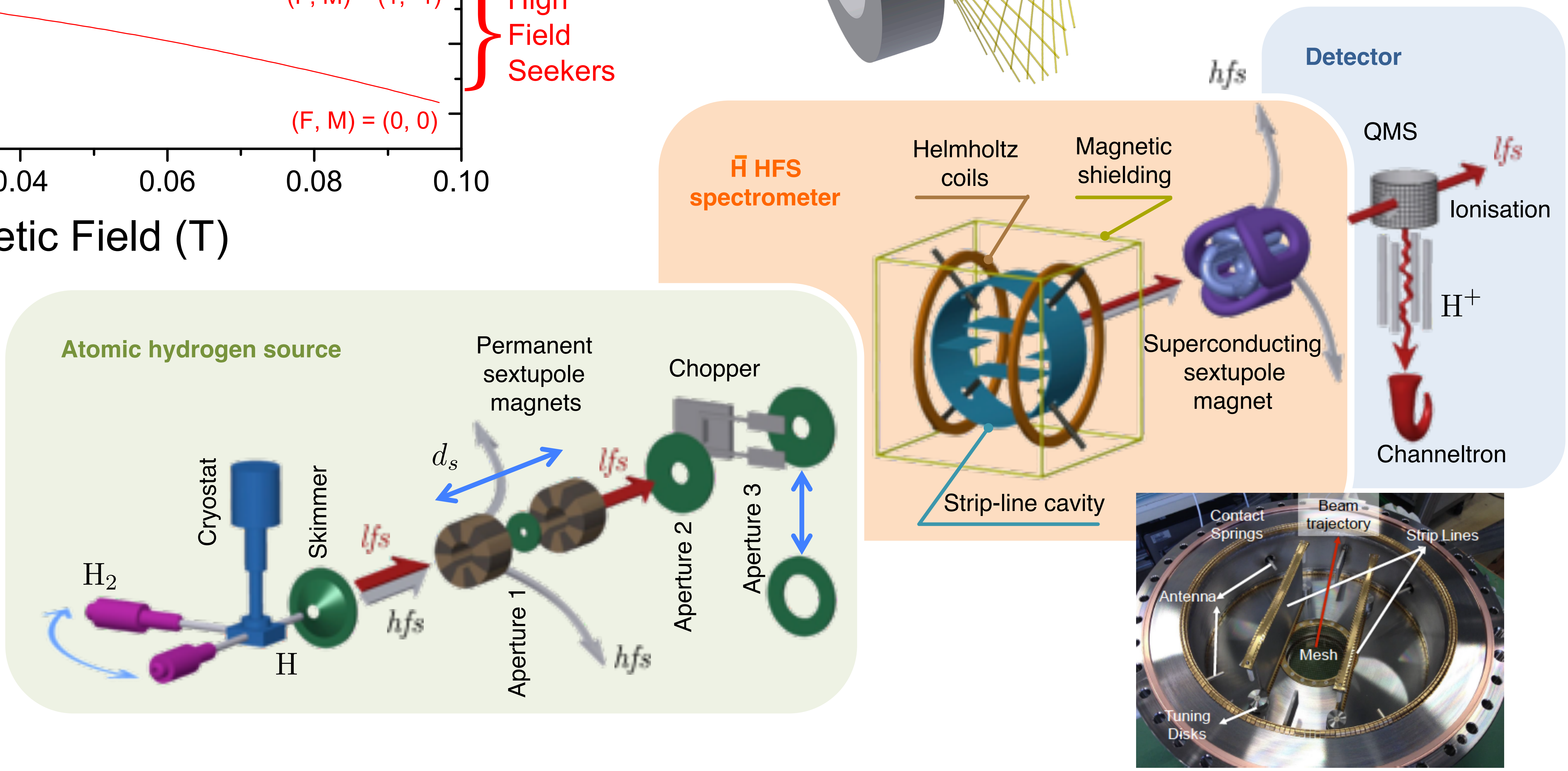
In-beam spectroscopy apparatus

Commissioning with a beam of hydrogen from a discharge plasma









C. Malbrunot et al. NIM A 935 (2019)

In-beam spectroscopy apparatus

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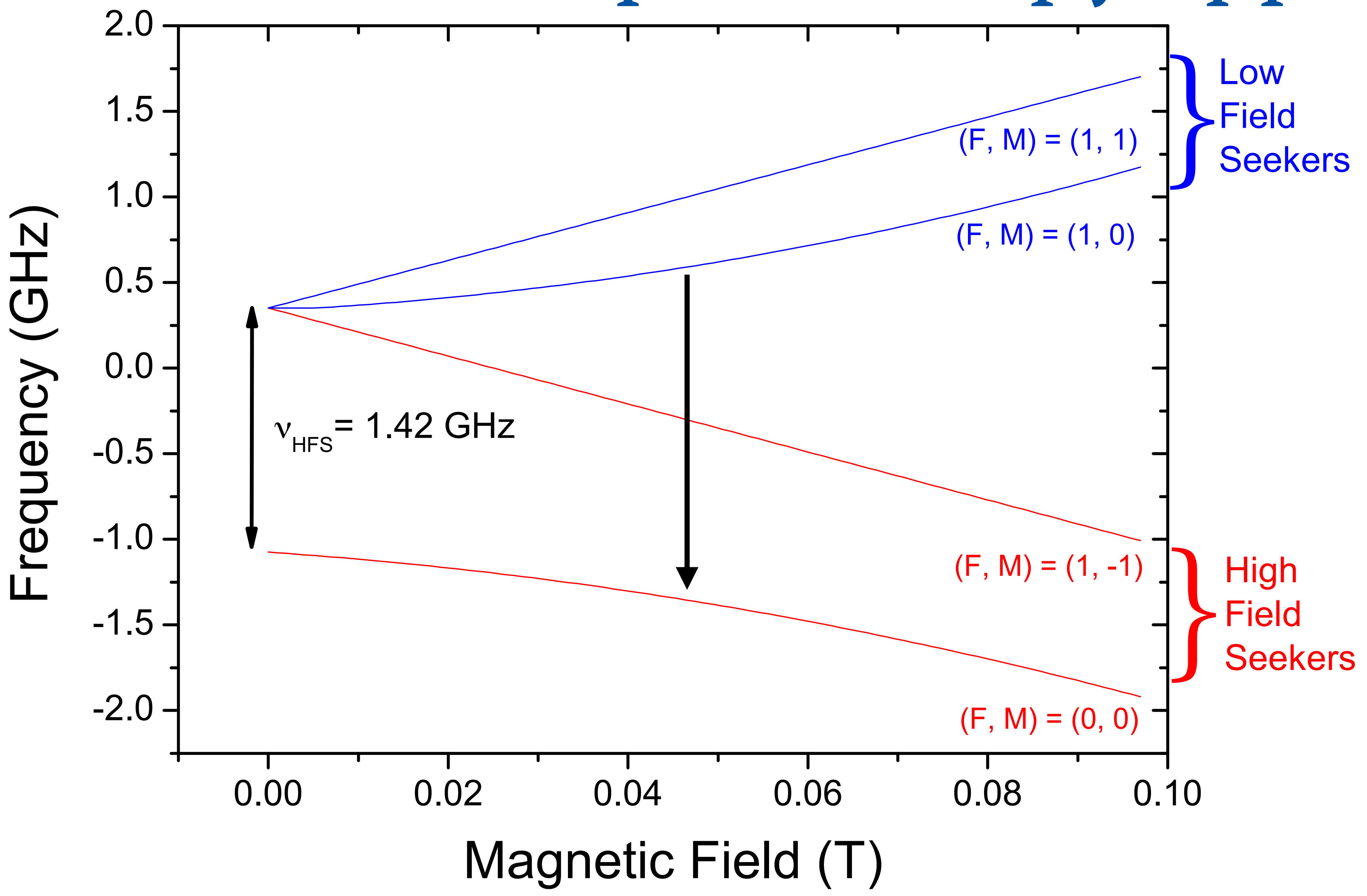
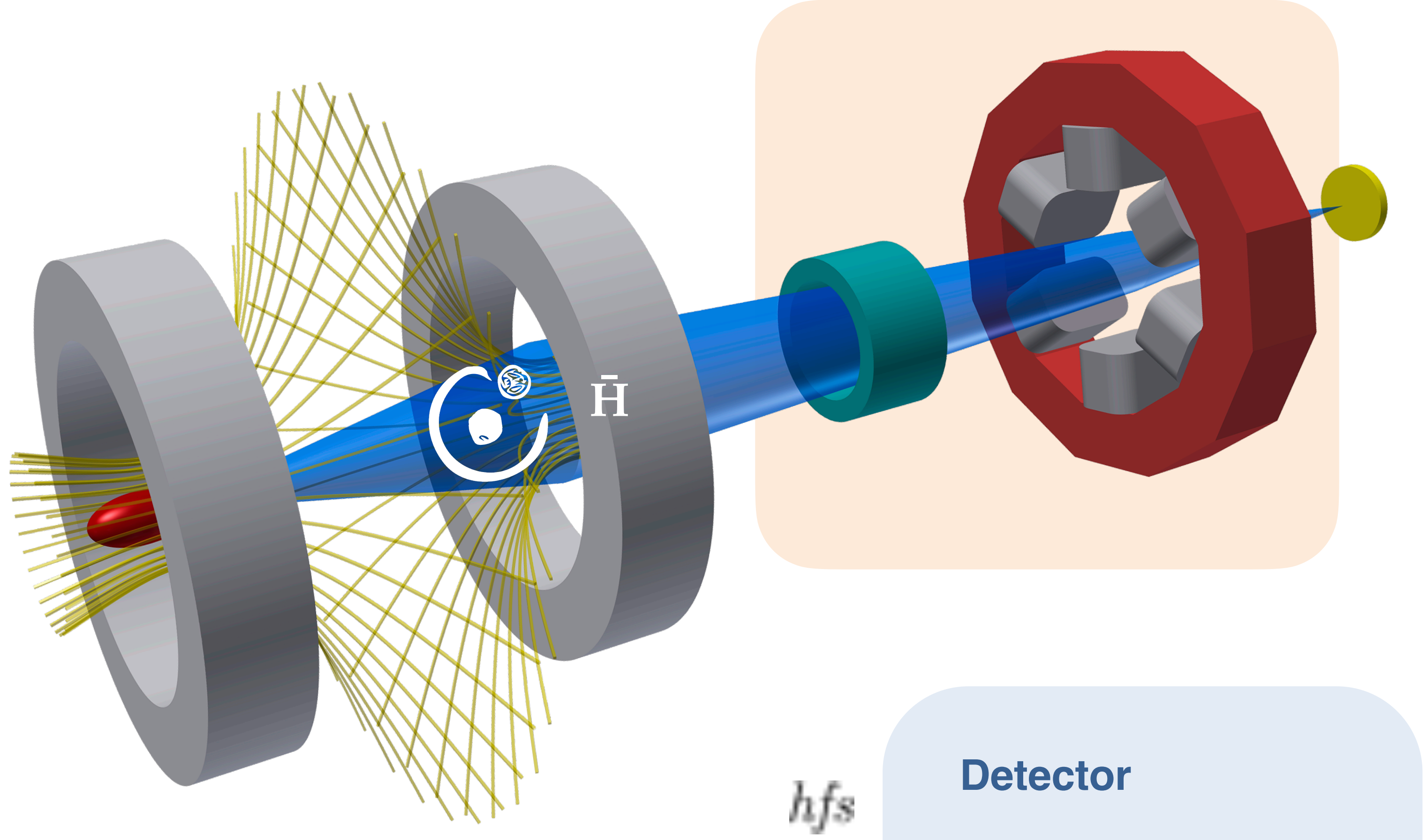
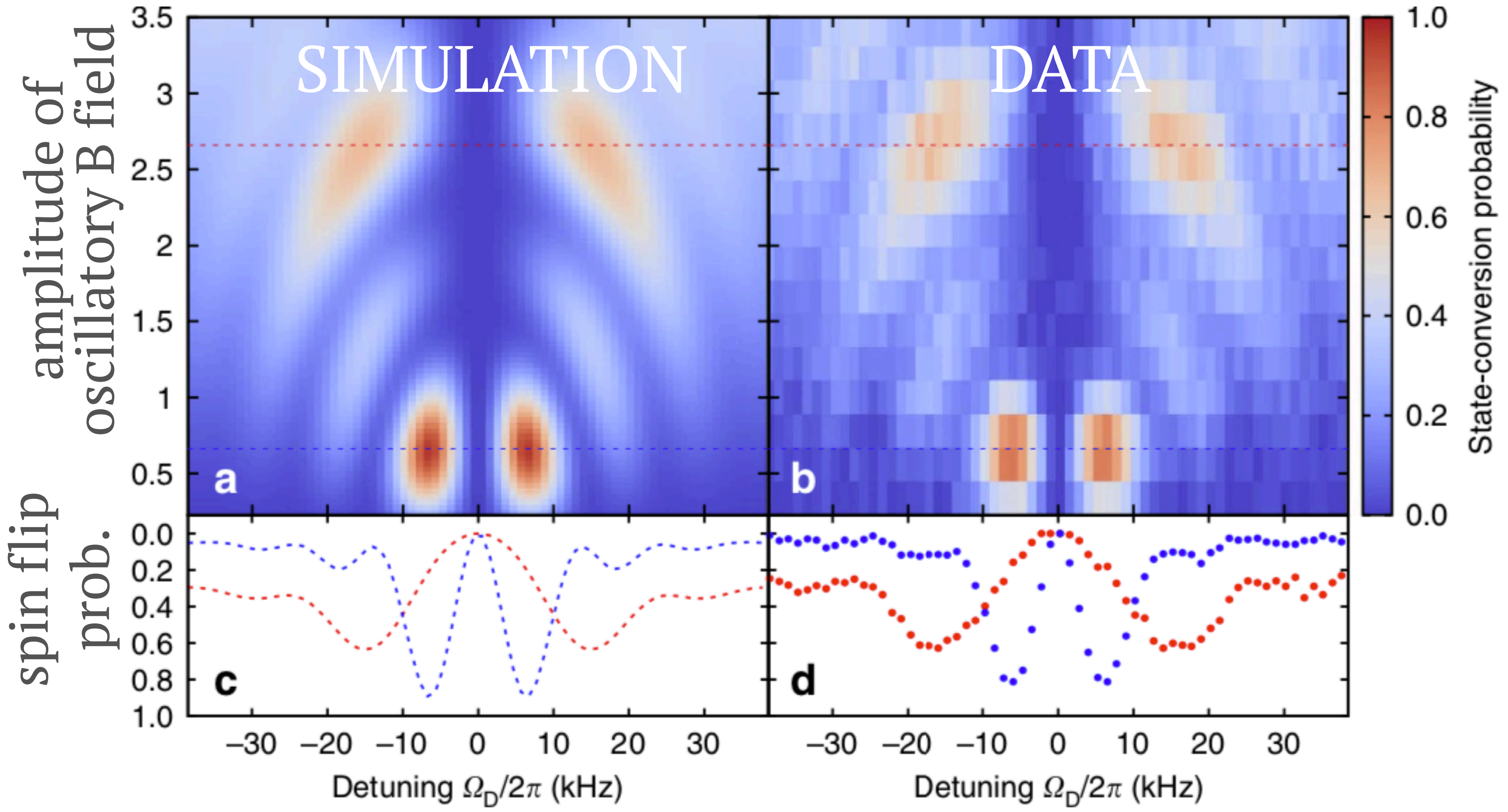
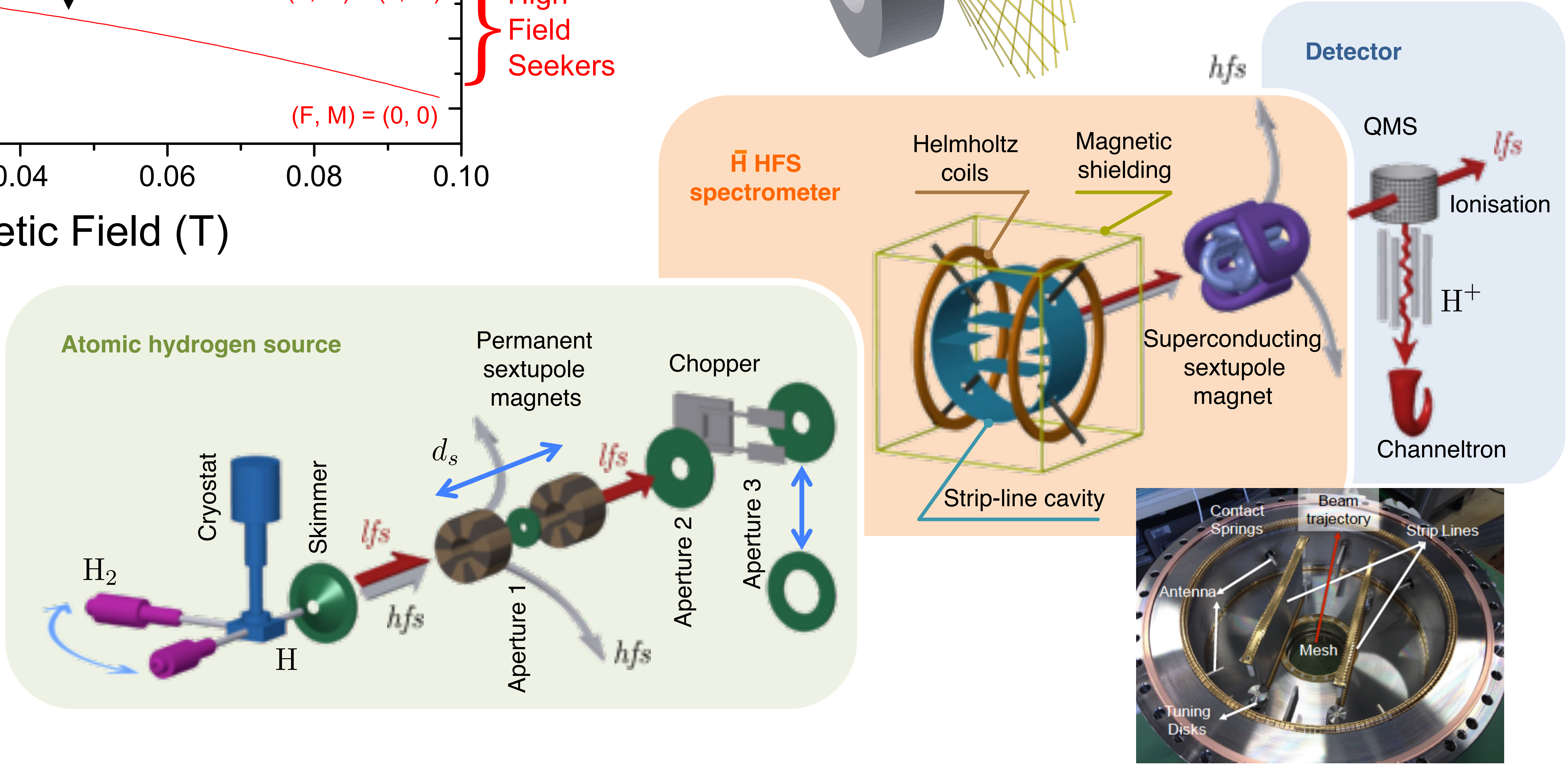
Commissioning with a beam of hydrogen from a discharge plasma







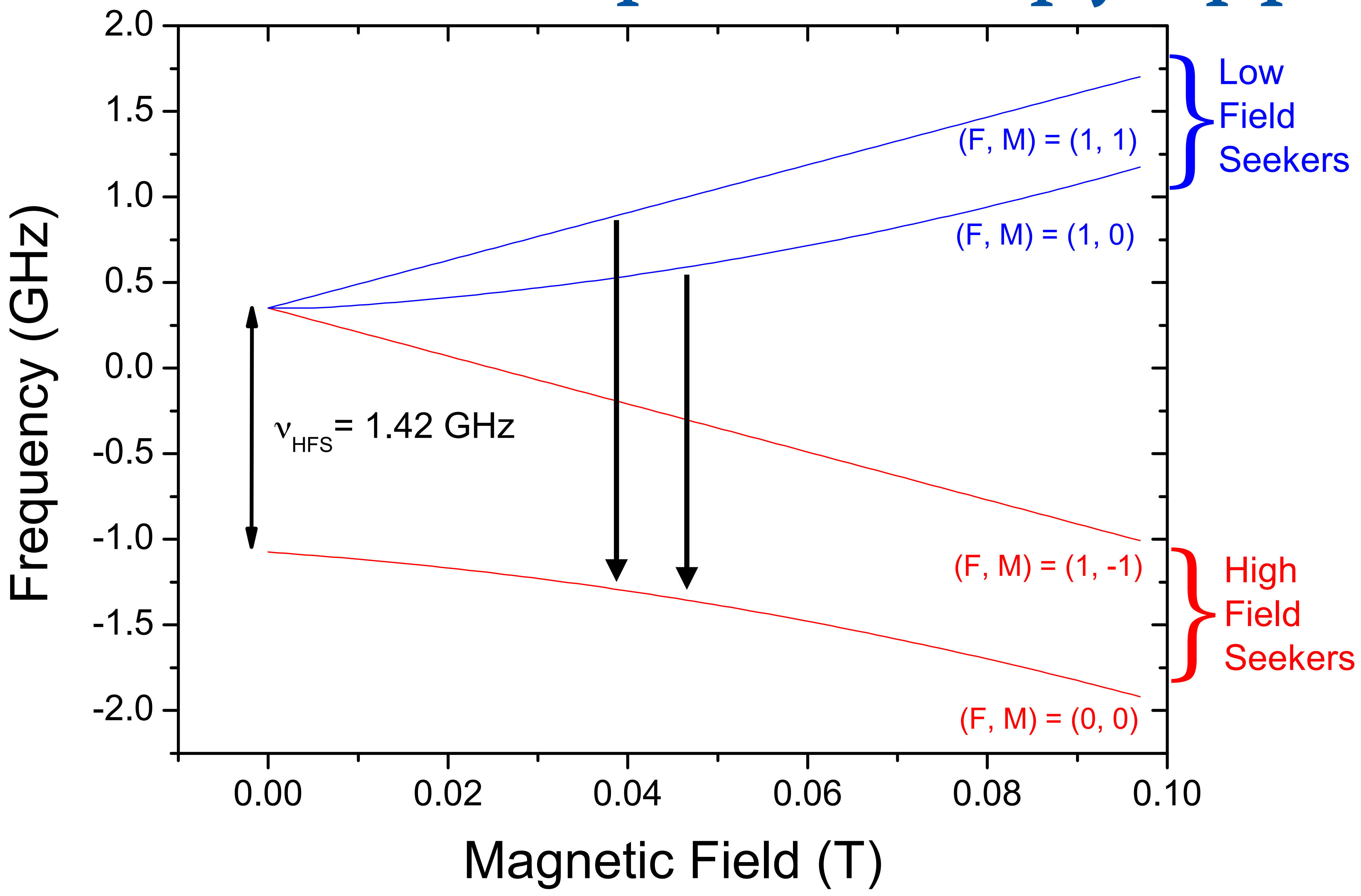


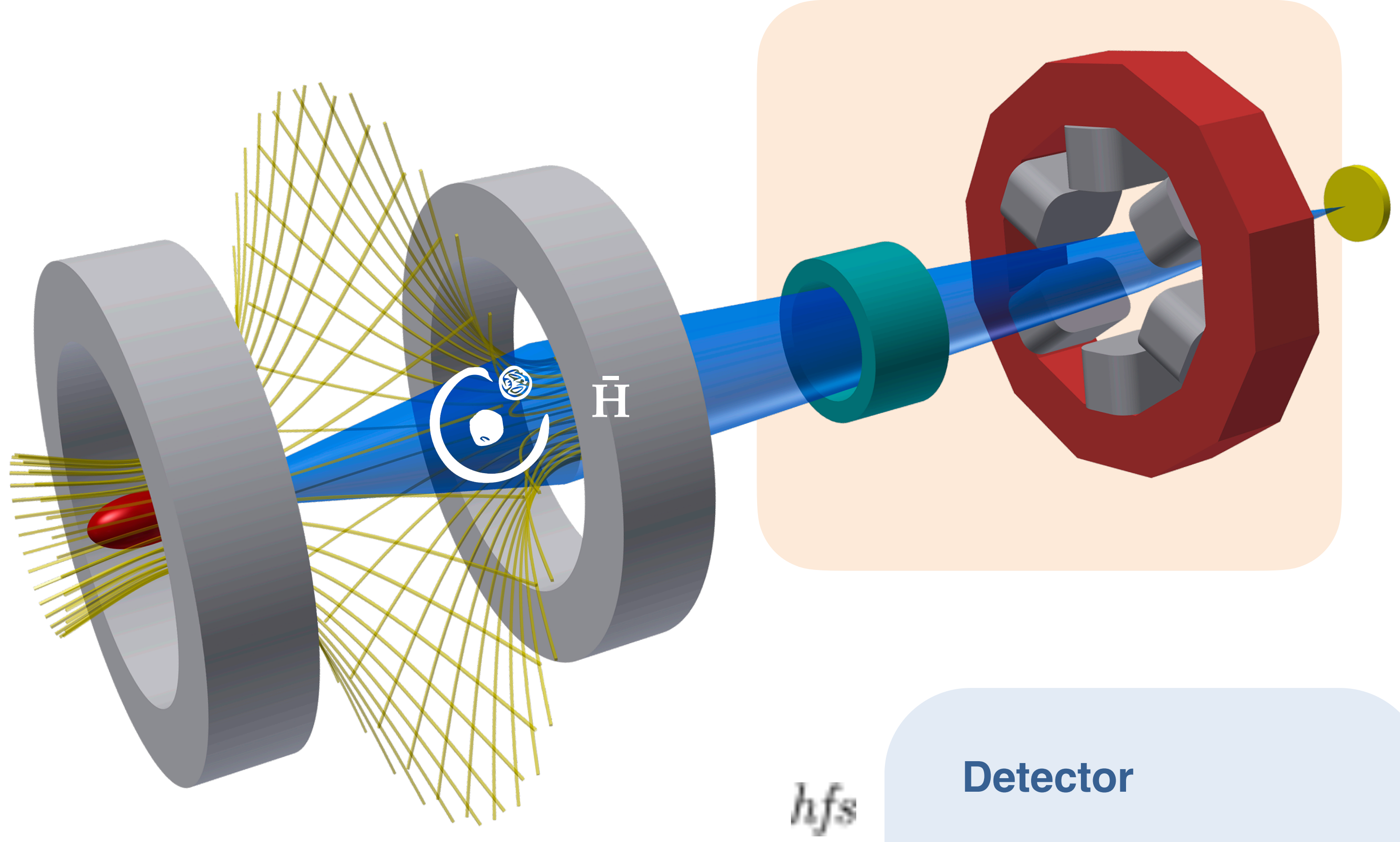
C. Malbrunot et al. NIM A 935 (2019)

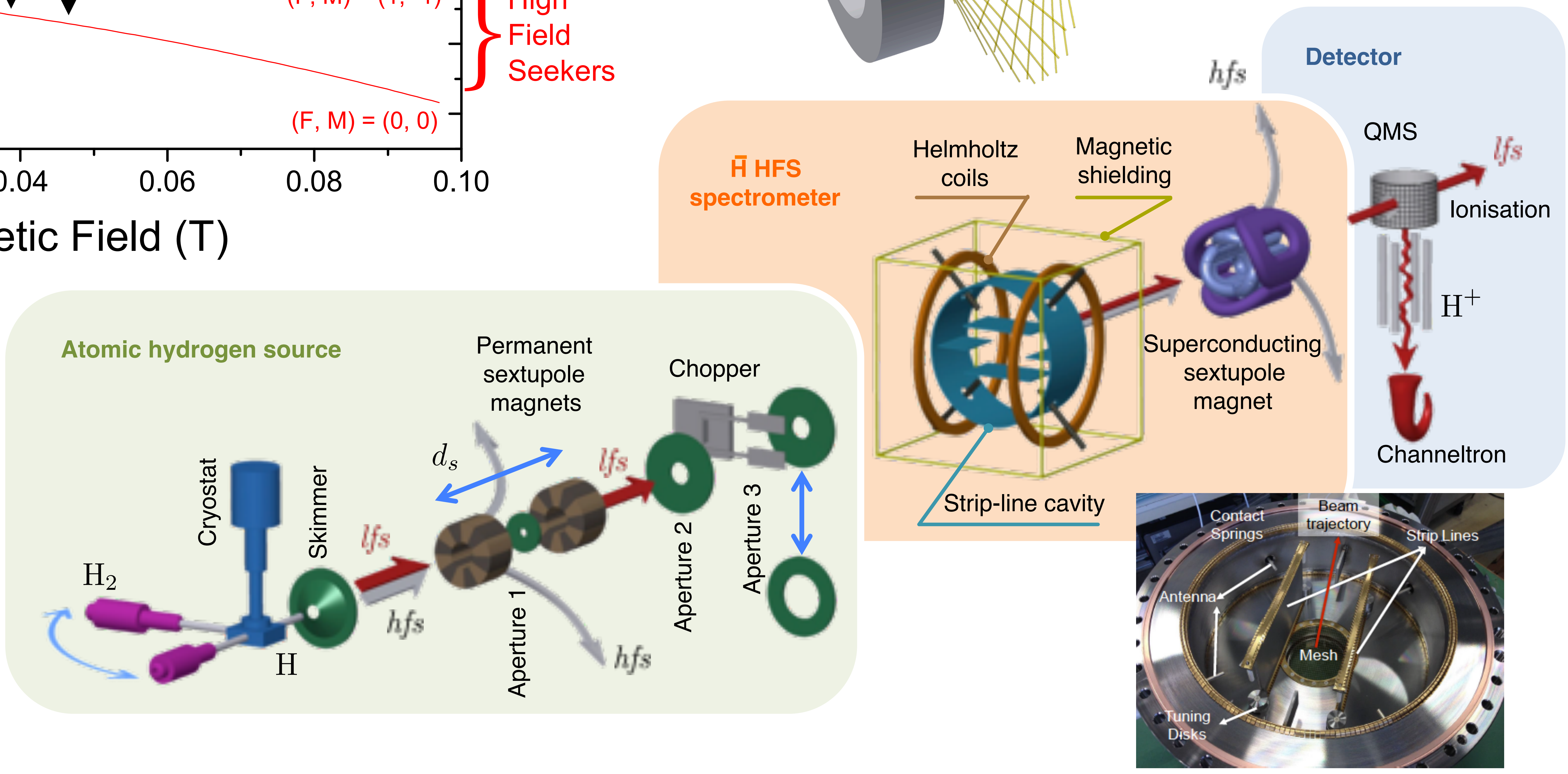
In-beam spectroscopy apparatus

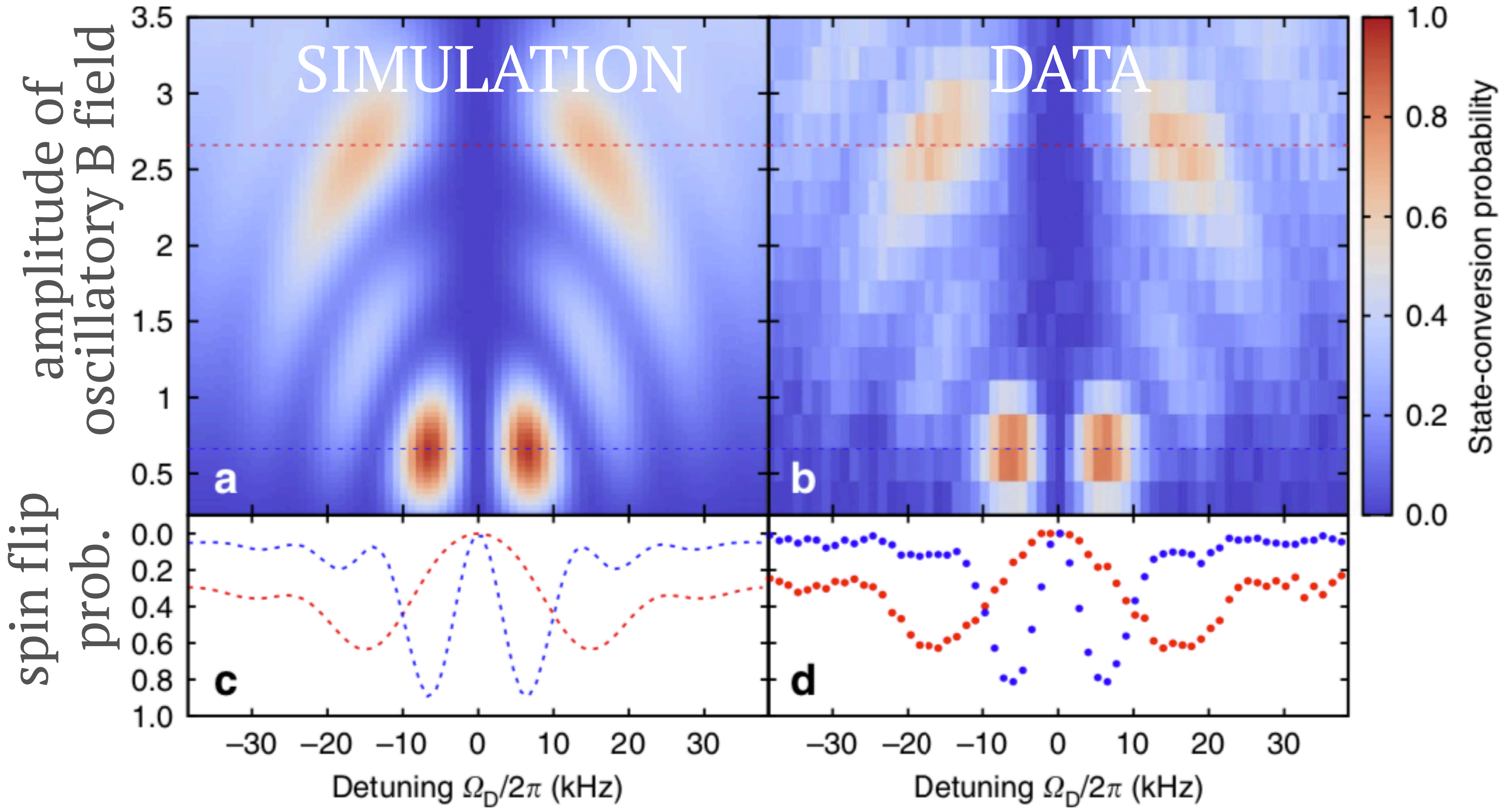
1

Commissioning with a beam of hydrogen from a discharge plasma









C. Malbrunot et al. NIM A 935 (2019)

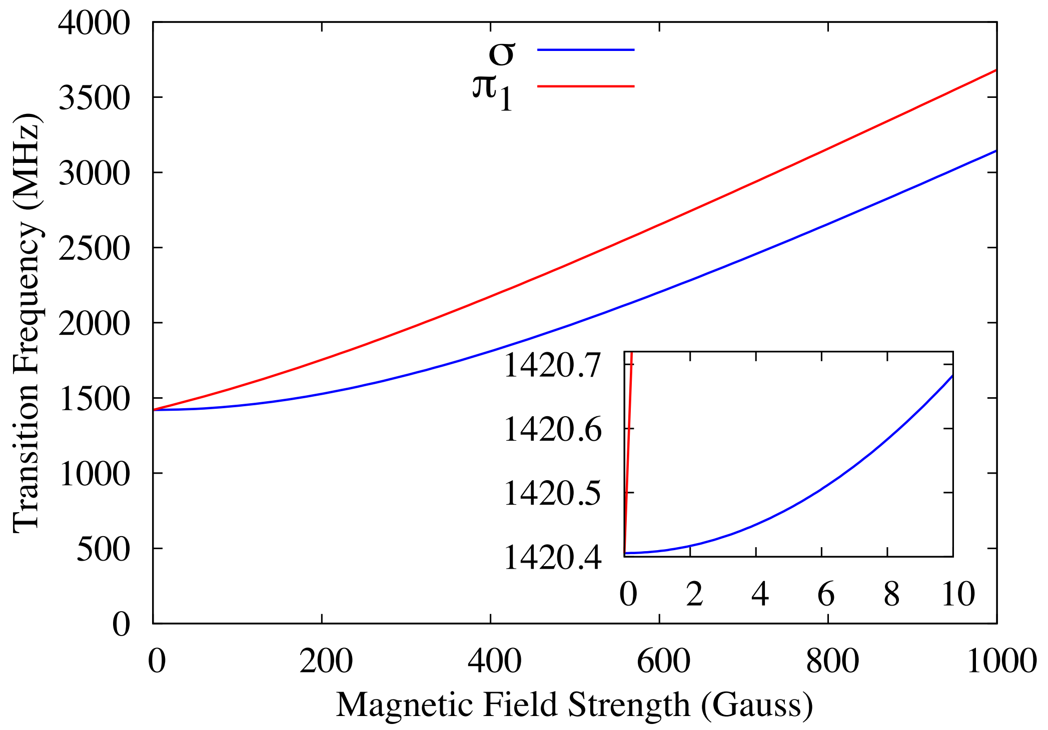
1 Further measurements with H in view of $\bar{H}$

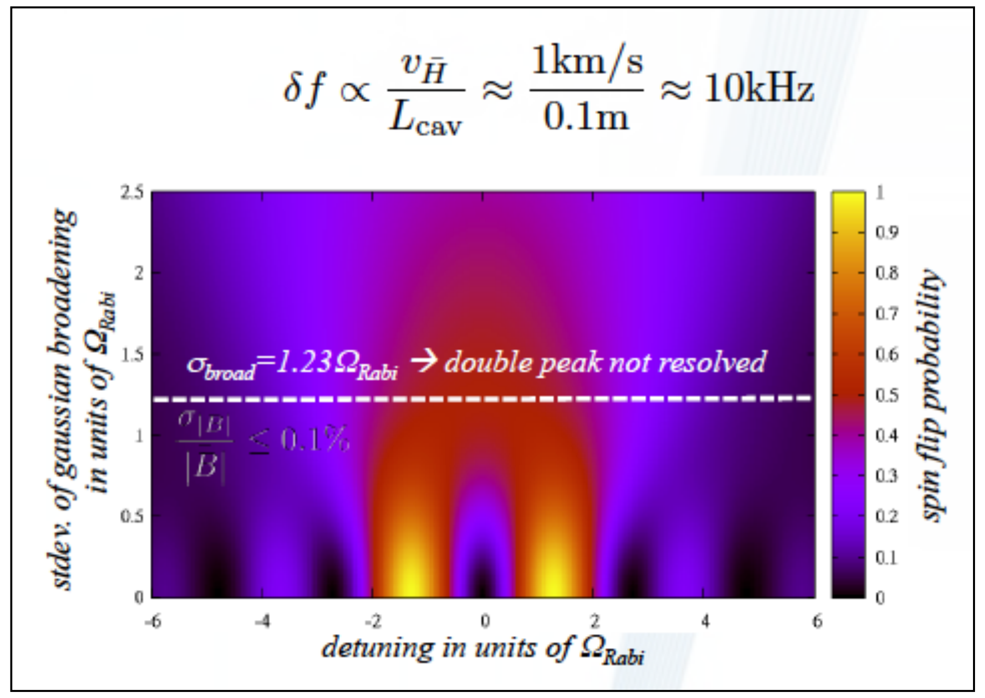
Other possibility :

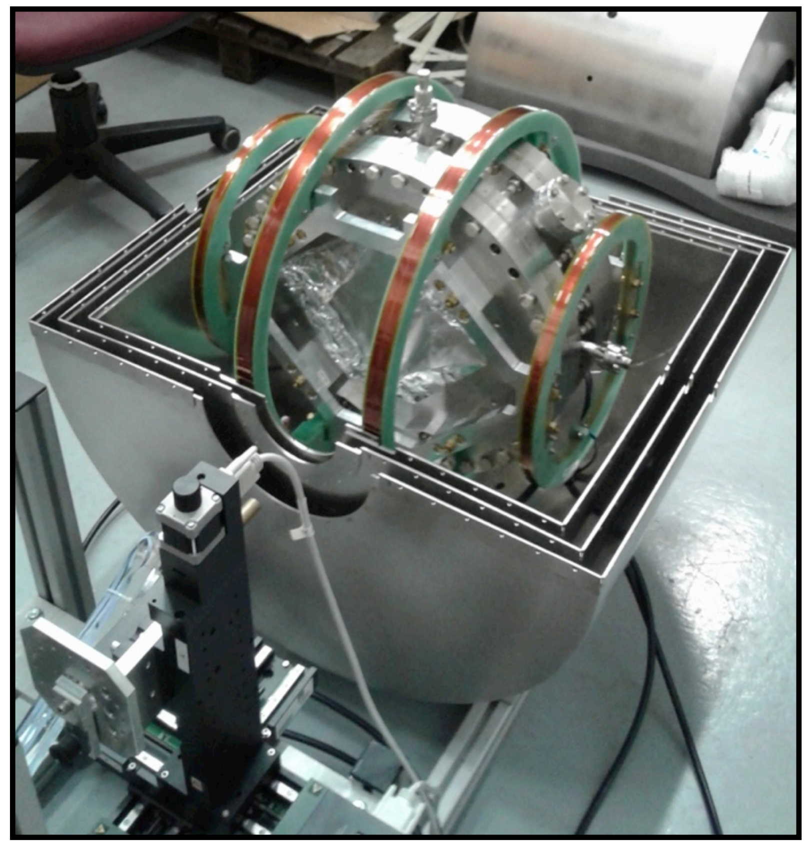
Measure π_1 & σ_1 at the same field : 2 resonances needed, not sensitive to stray field (from the earth or from CUSP in the antihydrogen experiment)

Advantage : π_1 is sensitive to SME coefficients

BUT π_1 more sensitive to magnetic field inhomogeneities



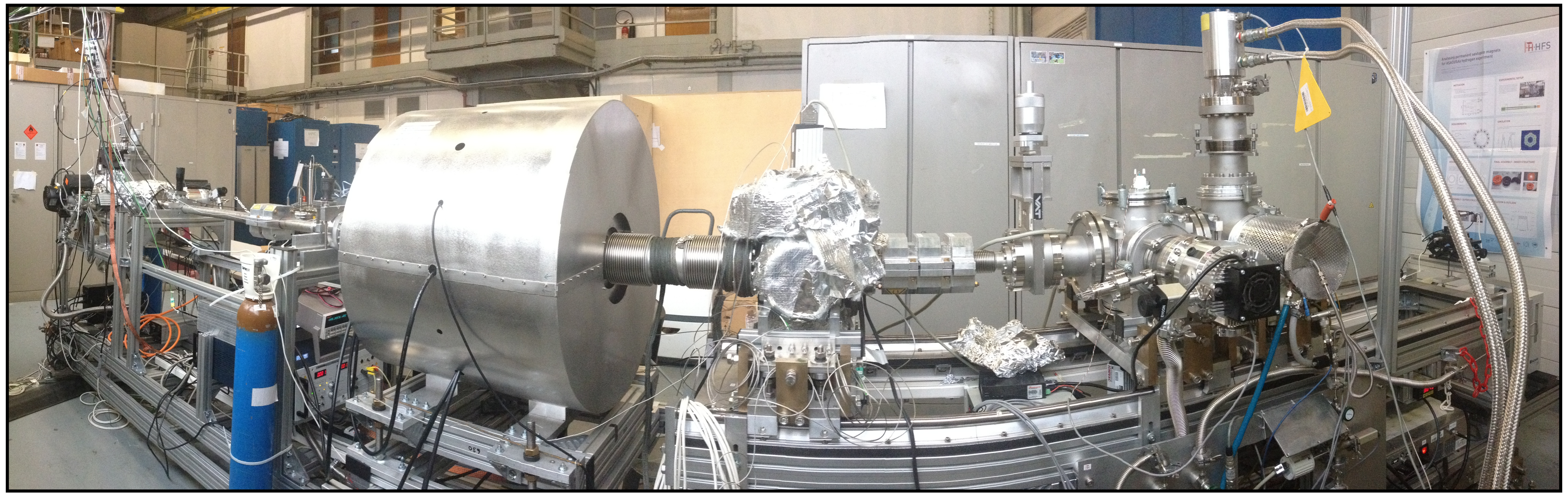


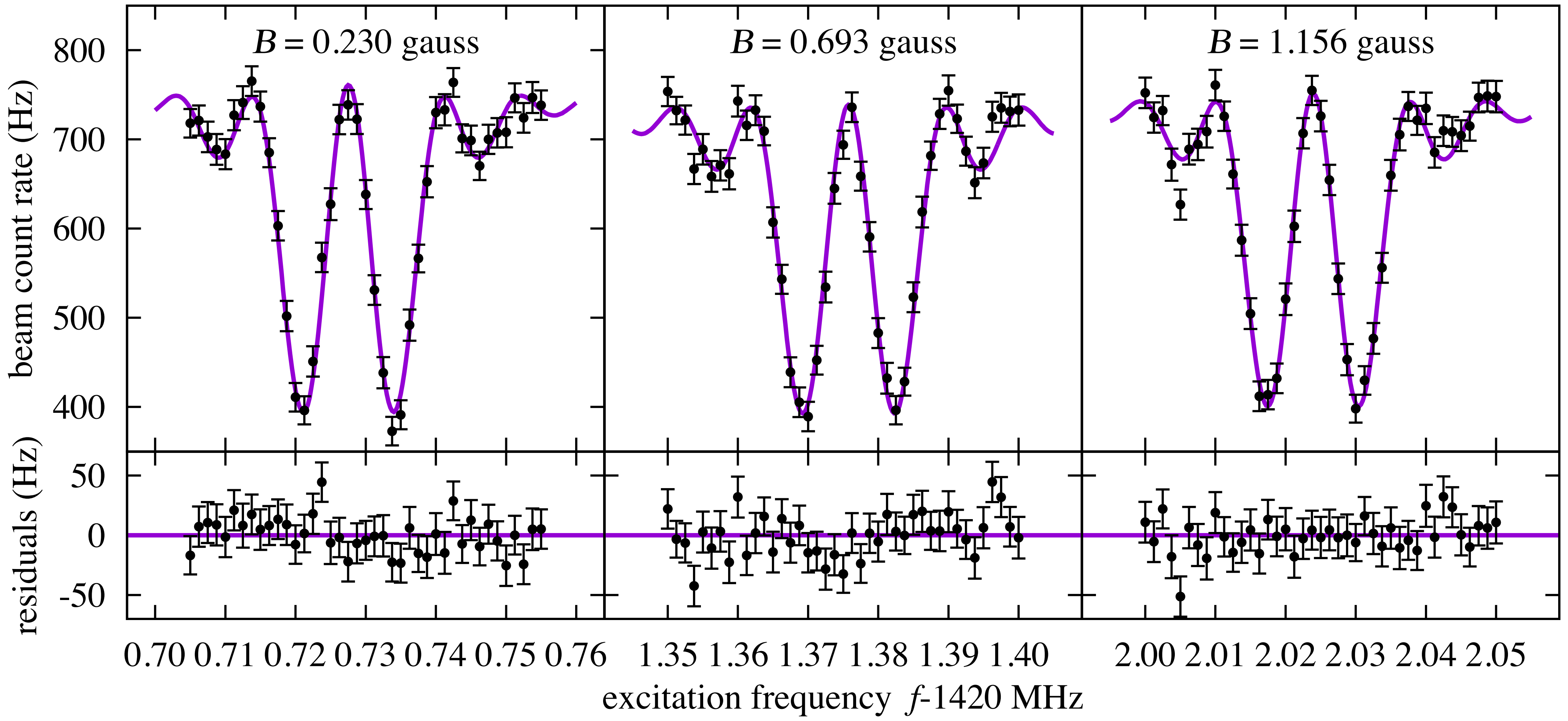


Helmholtz coils with corrections coils

Cavity tilted at 45° to allow both transitions at the same time

3-layers cylindrical shielding





"Simultaneous" measurement of π_1 and σ_1 ➠ **ppb** precision reached!

SME measurements with hydrogen

1

Siderial variations constrained by Harvard-Smithsonian maser at mHz level

PHYSICAL REVIEW A **68**, 063807 (2003)

Testing *CPT* and Lorentz symmetry with hydrogen masers

M. A. Humphrey, D. F. Phillips, E. M. Mattison, R. F. C. Vessot, R. E. Stoner, and R. L. Walsworth
Harvard-Smithsonian Center for Astrophysics, Cambridge, Massachusetts 02138, USA

(Received 4 August 2003; published 9 December 2003)

coefficients in the lab-frame are associated with three independent coefficients in the Sun-centred frame :

$$\mathcal{K}^{Lab}_{w_{k10}} = \mathcal{K}^{Sun}_{w_{k10}} \cos(\theta) - \sqrt{2}\ \Re e(\mathcal{K}^{Sun}_{w_{k11}}) \sin(\theta) \cos(\omega_{\oplus} T_{\oplus}) + \sqrt{2}\ \Im m(\mathcal{K}^{Sun}_{w_{k11}}) \sin(\theta) \sin(\omega_{\oplus} T_{\oplus})$$

angle between B-field and Earth's rotational axis

Earth rotation frequency

sidereal time

72 SME coefficients involved. 48 constrained, 24 remaining and can be constrained by swapping the direction of the static B-field and measuring π_1 while using σ_1 as a proxy

$$2\pi\delta\nu(\Delta M_F) = \frac{\Delta M_F}{2\sqrt{3\pi}} \sum_{q=0}^{2} (\alpha m_r)^{2q} (1 + 4\delta_{q2}) \sum_{w} \left[-g^{0B}_{w(2q)10} + H^{0B}_{w(2q)10} - 2g^{1B}_{w(2q)10} + 2H^{1B}_{w(2q)10} \right]$$

ppb foreseen (Hz level precision) in a first stage :

Improvement possible with slower beam, Ramsey method, higher count rate

see C. Malbrunot et al. RSA, 376, 2116 (2018)

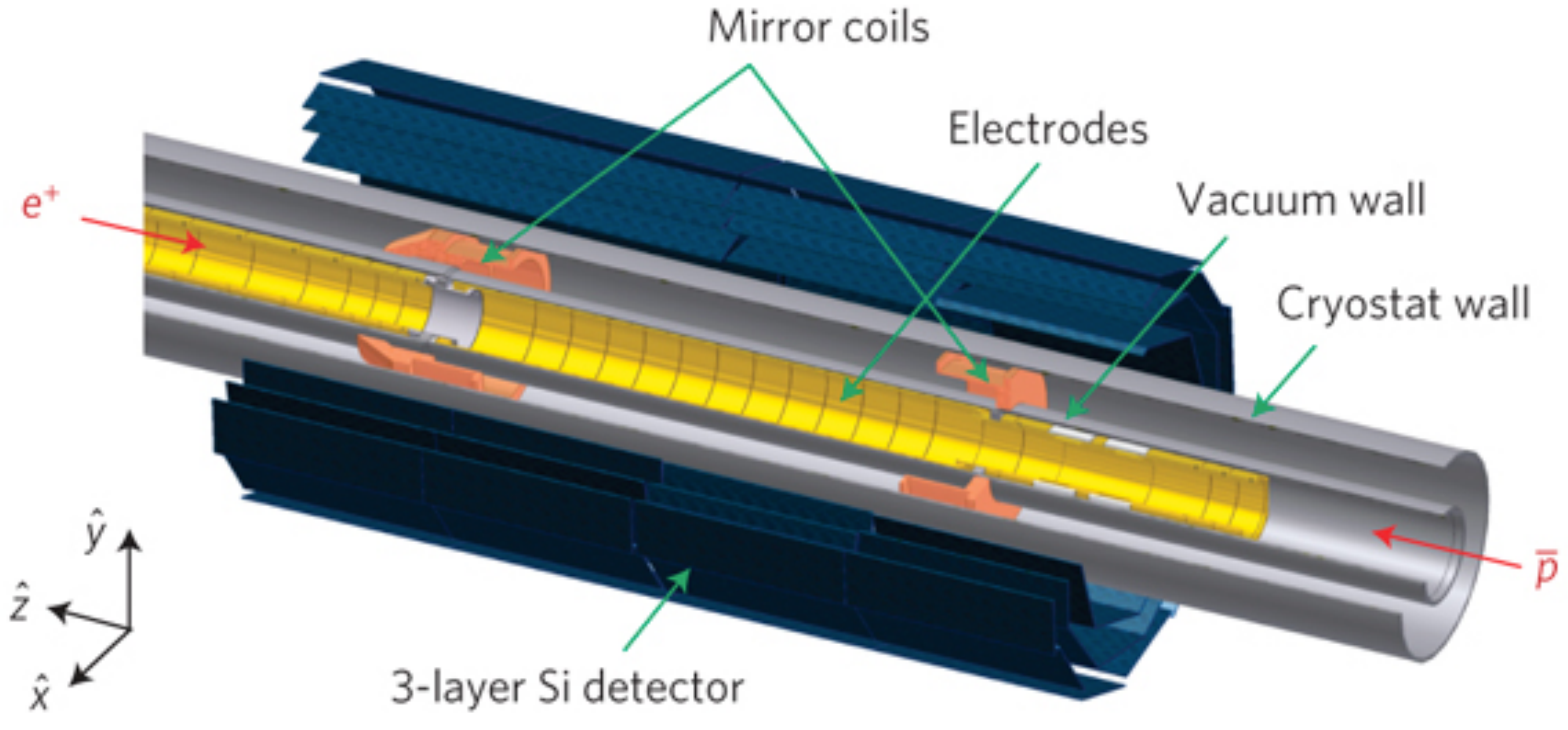
Results coming soon

Gravity with $\bar{H}$: status of the field

2

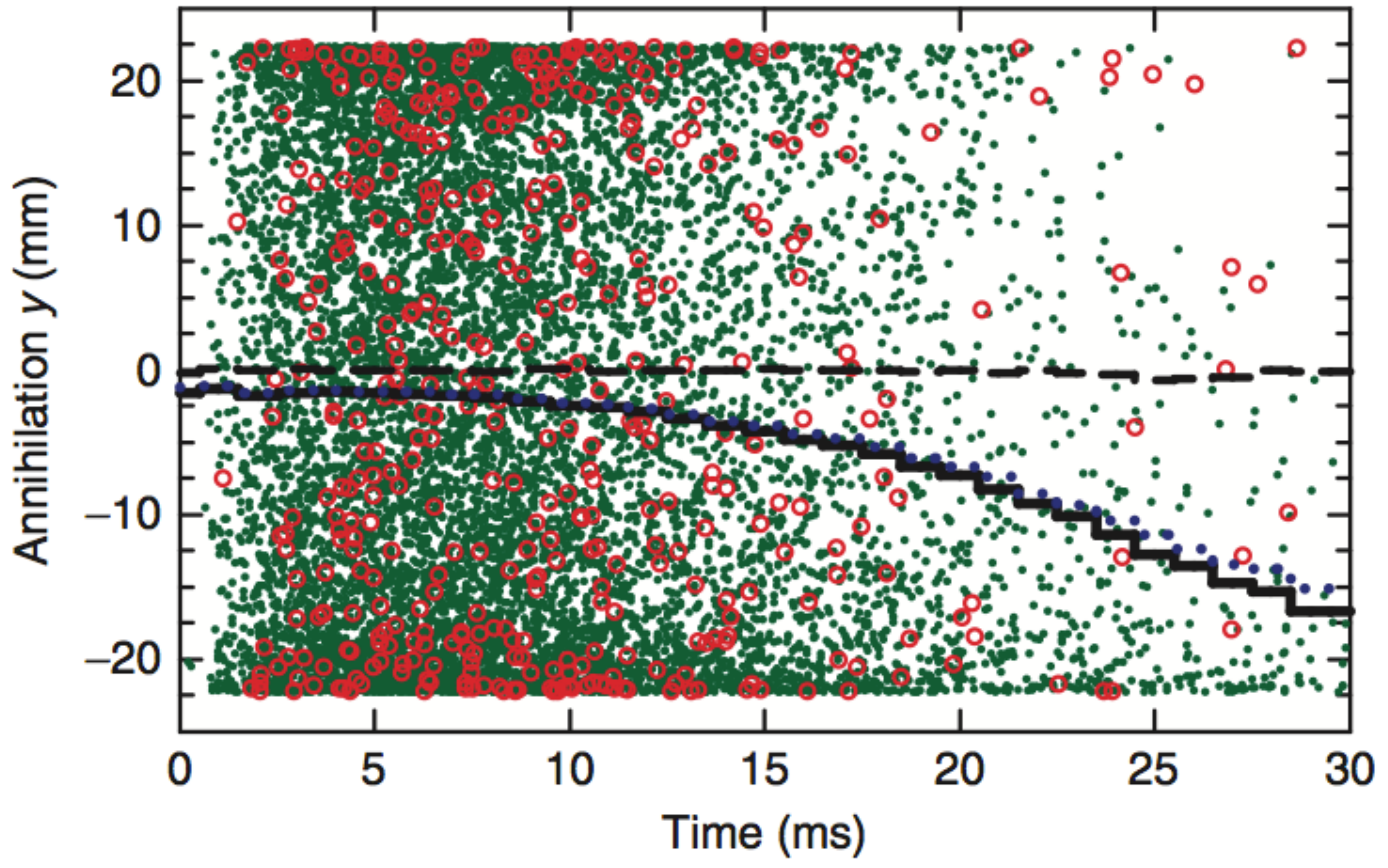
ALPHA

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



$-65 < g/\bar{g} < 110$

Vertical position of annihilation vertex during release of trapping field



Green dots---simulated annihilations

Red circles---434 Observed annihilations

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

2

Gravity with H̄ : status of the field

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

<u>Sign measurement</u> planned rapidly
1% targeted H̄ cooling to ~20 mK
and advanced magnetometry

Article

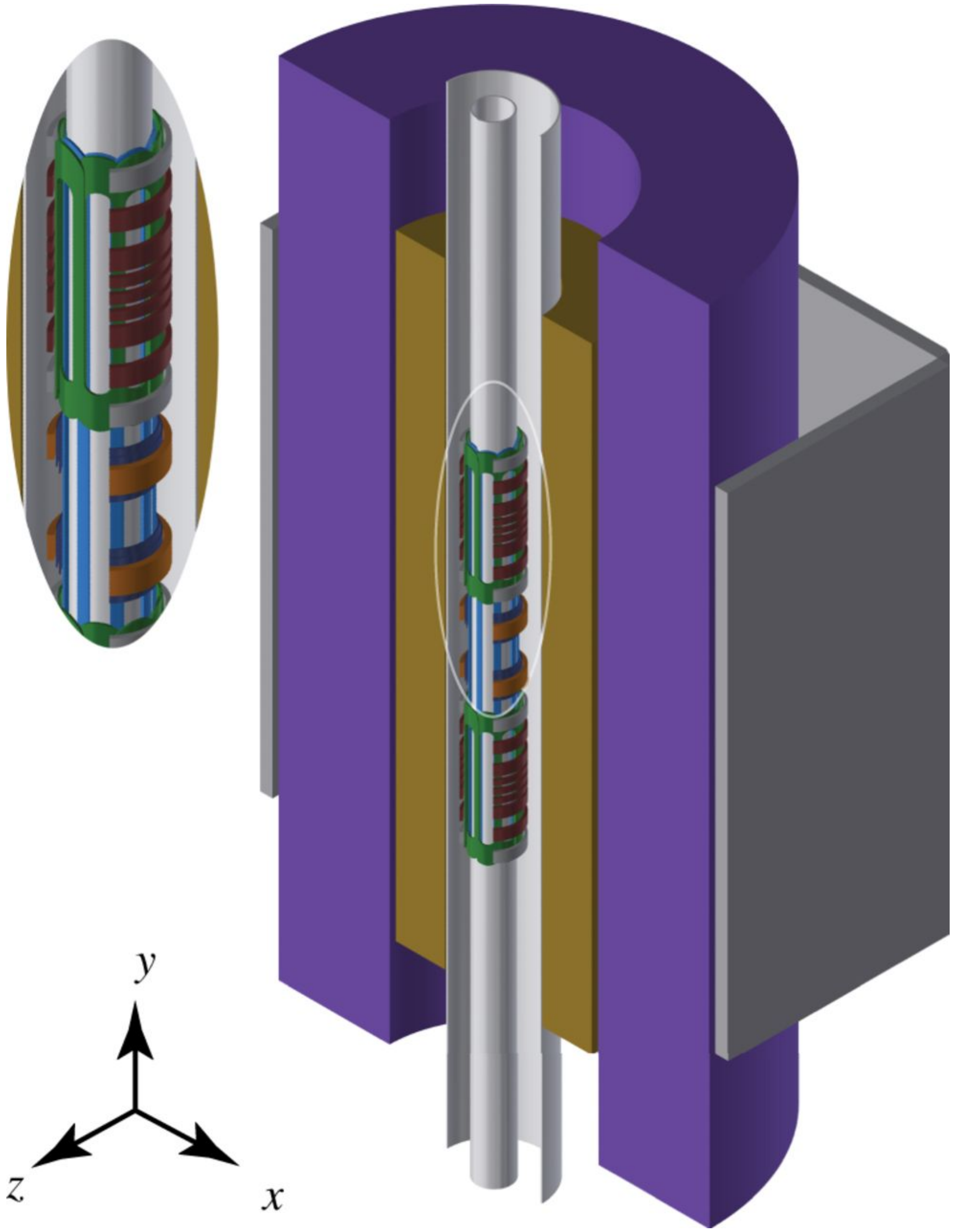
Laser cooling of antihydrogen atoms

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



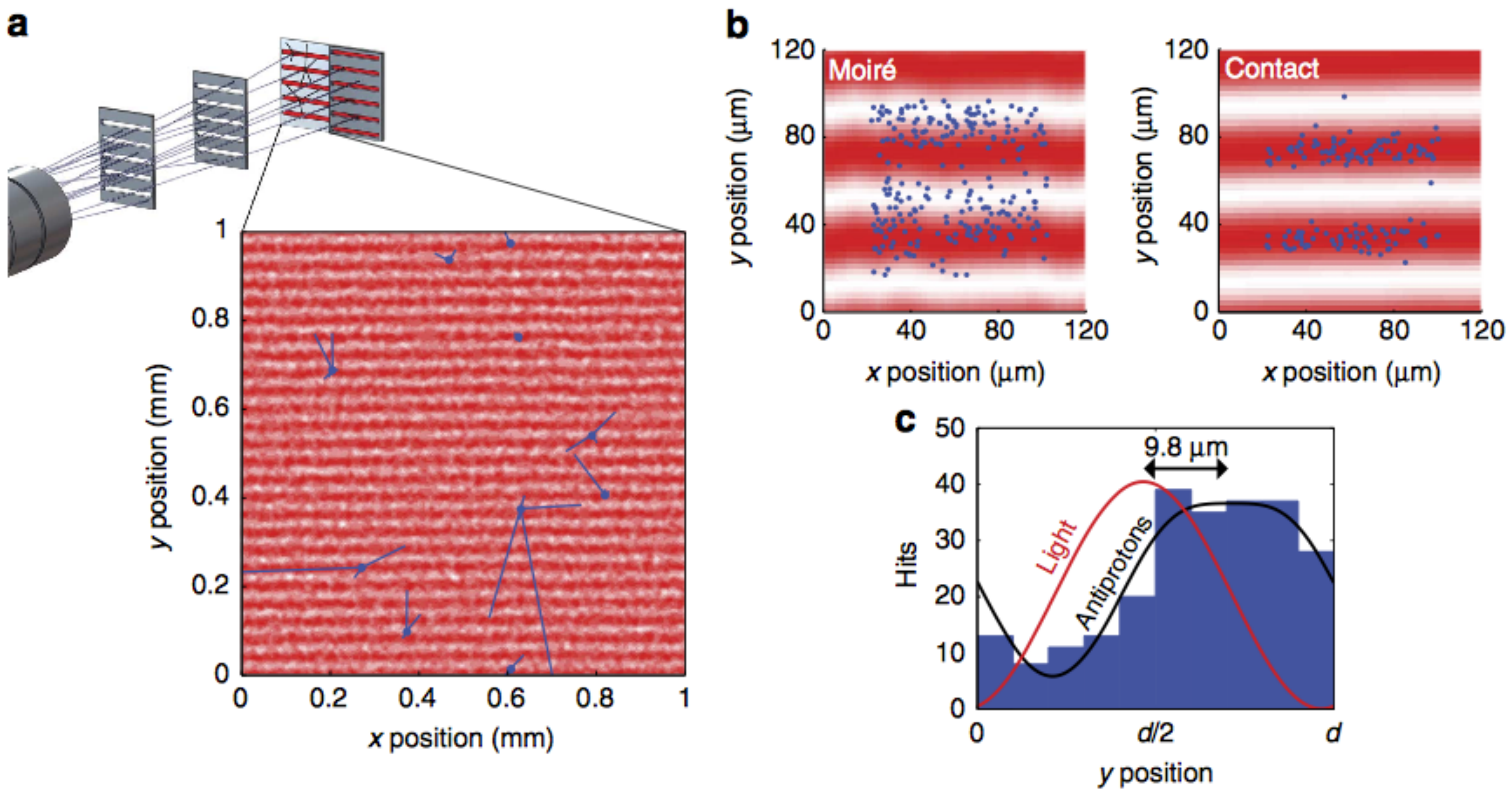
W. A. Bertsche Phil. Trans. R. Soc. A 2018 376 20170265; DOI: 10.1098/rsta.2017.0265. (2018)

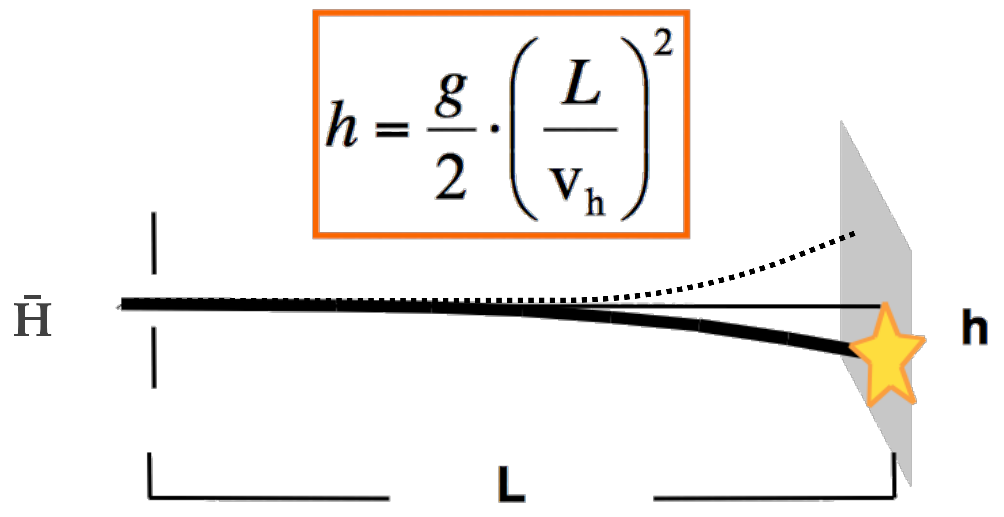
2

Gravity with H̄ : status of the field

AEGIS : DEFLECTOMETER

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



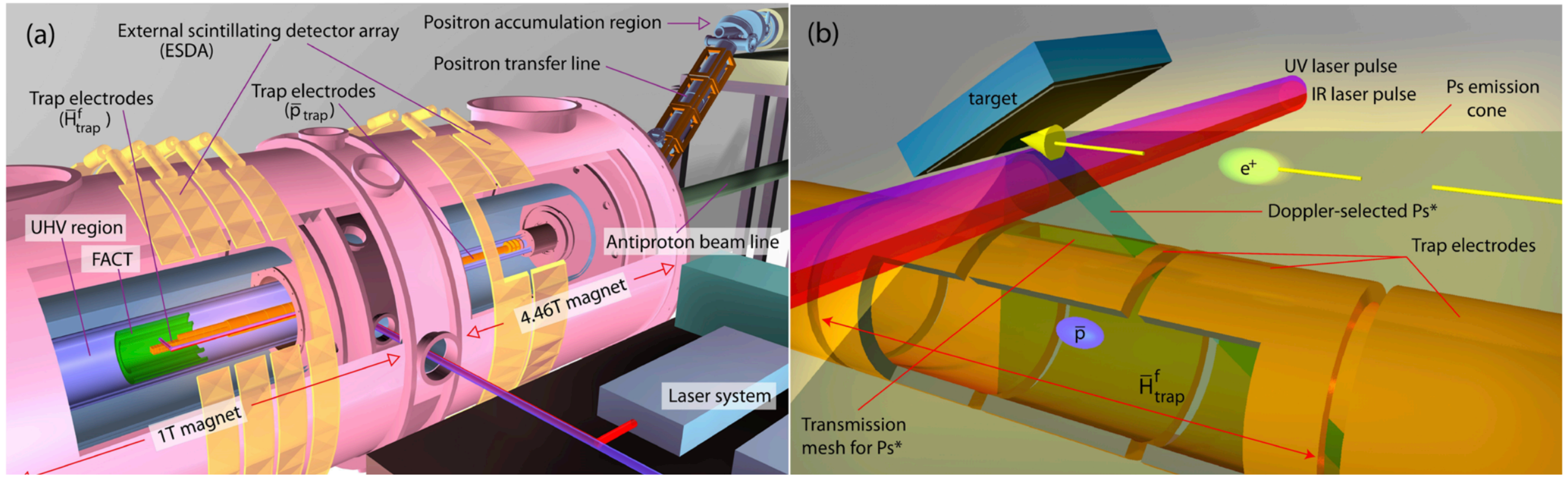


~1-10%

Sensitivity to ~10 μm deflection needed

Recent demonstration of pulsed formation of H̄ (PHASE1 of AEGIS)

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



PHASE 2 (started 2022): Improved apparatus

targeting factor 100 improvement in H̄ production

beam production via adiabatic transfer of p̄ into Ps

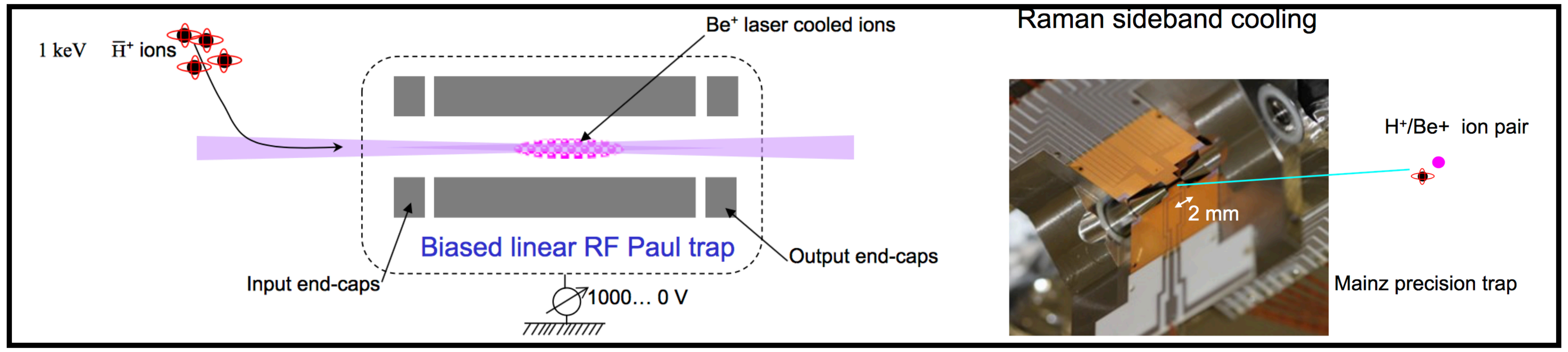
2

Gravity with $\bar{H}$: status of the field

GBAR : USING $\bar{H}$+

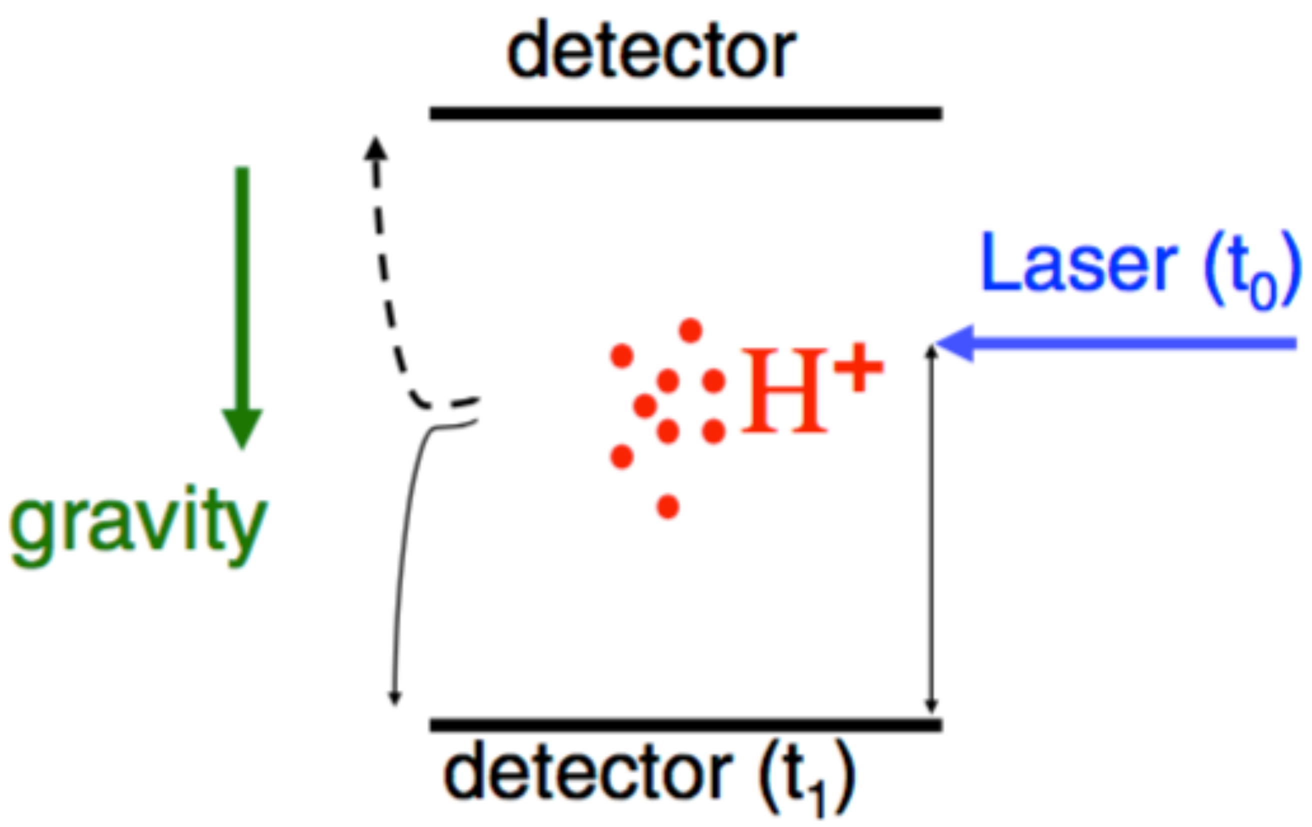
- will produce first ever $\bar{H}^+$ ion
- will bring antimatter to the coldest temperature ever achieved (by several orders of magnitude)

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



GBAR : DROPING EXPERIMENT

~1%



CURRENTLY ATTEMPTING $\bar{H}$ production

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)

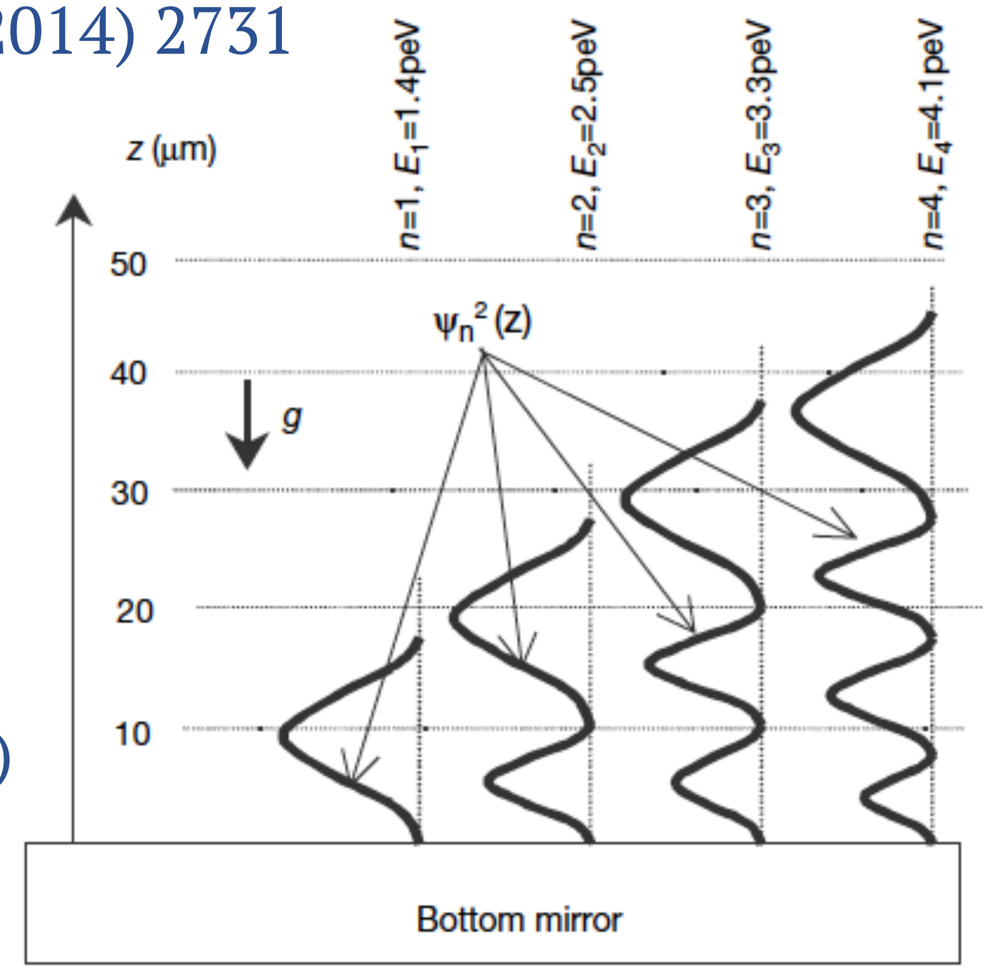


Figure 1 Wavefunctions of the quantum states of neutrons in the potential well formed by the Earth's gravitational field and the horizontal mirror. The probability of finding neutrons at height z, corresponding to the nth quantum state, is proportional to the square of the neutron wavefunction $\psi_n^2(z)$.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

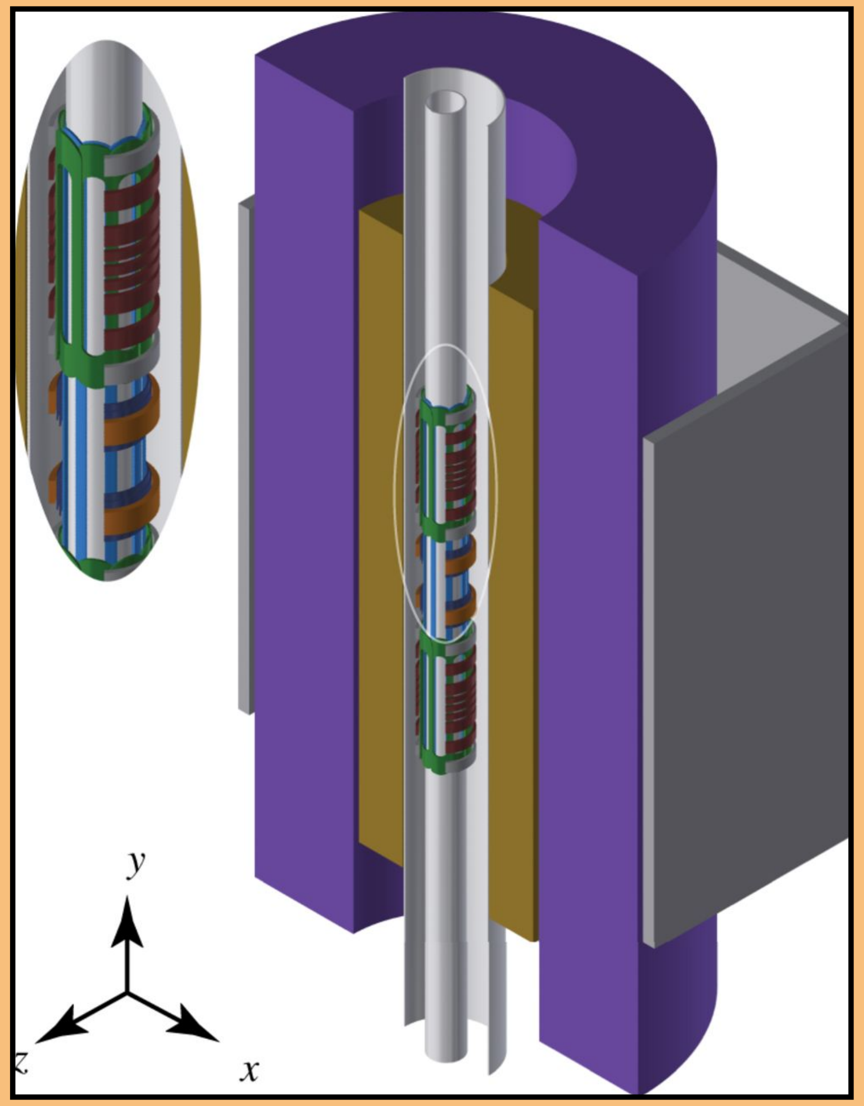
Planned gravity measurements with antihydrogen atoms

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 H̄ cooling to ~20 mK and advanced magnetometry

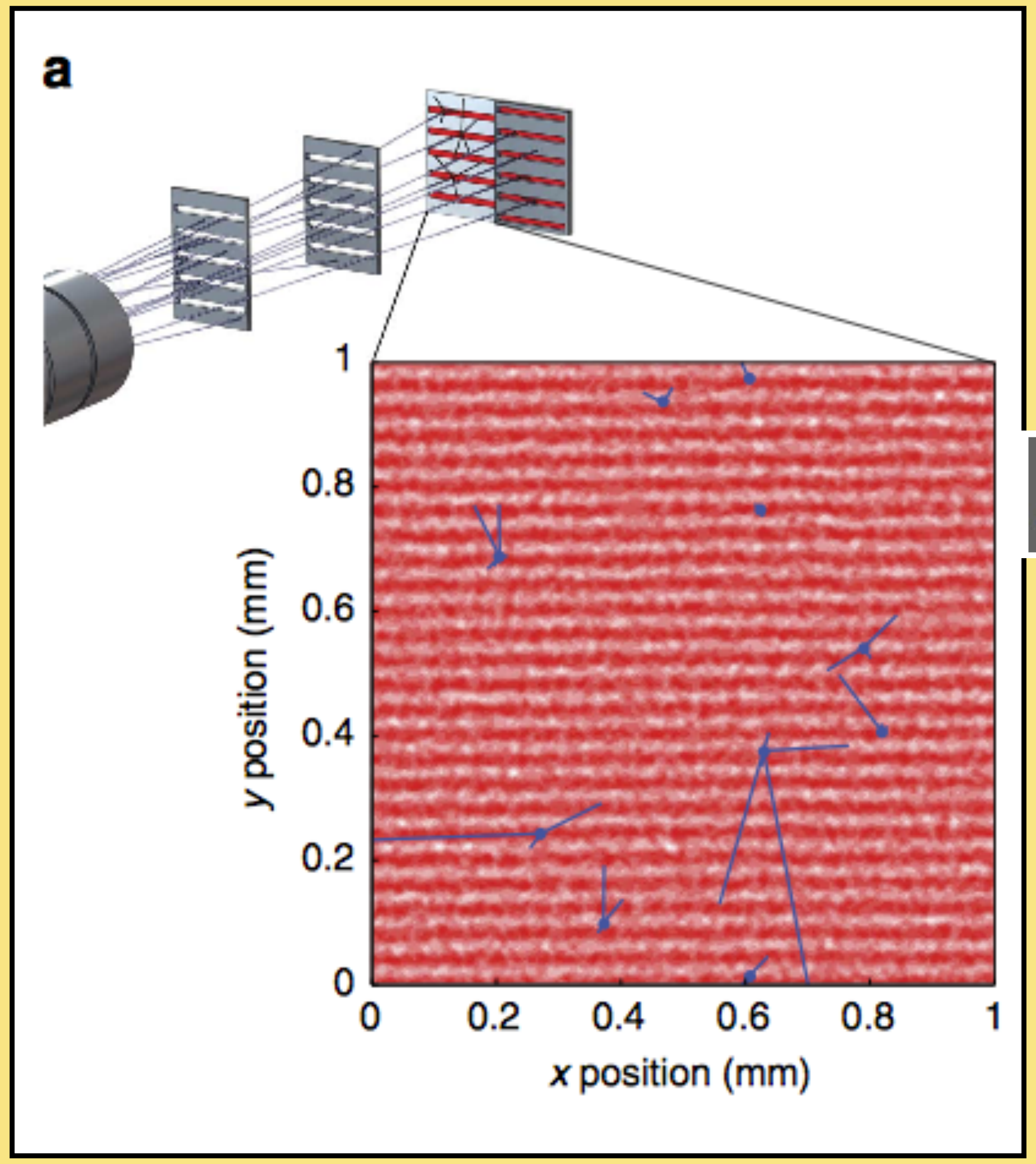


(ALPHA-g)

H̄ BEAM

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

Sign measurement targeted

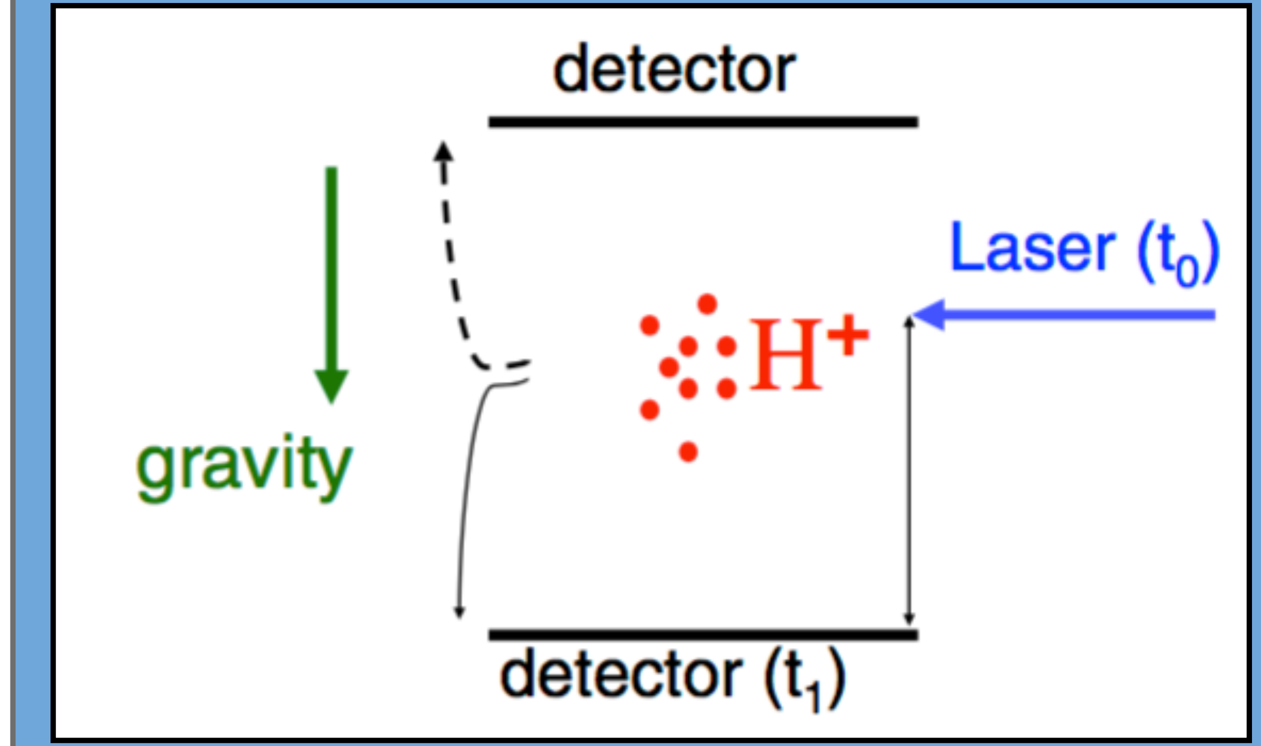


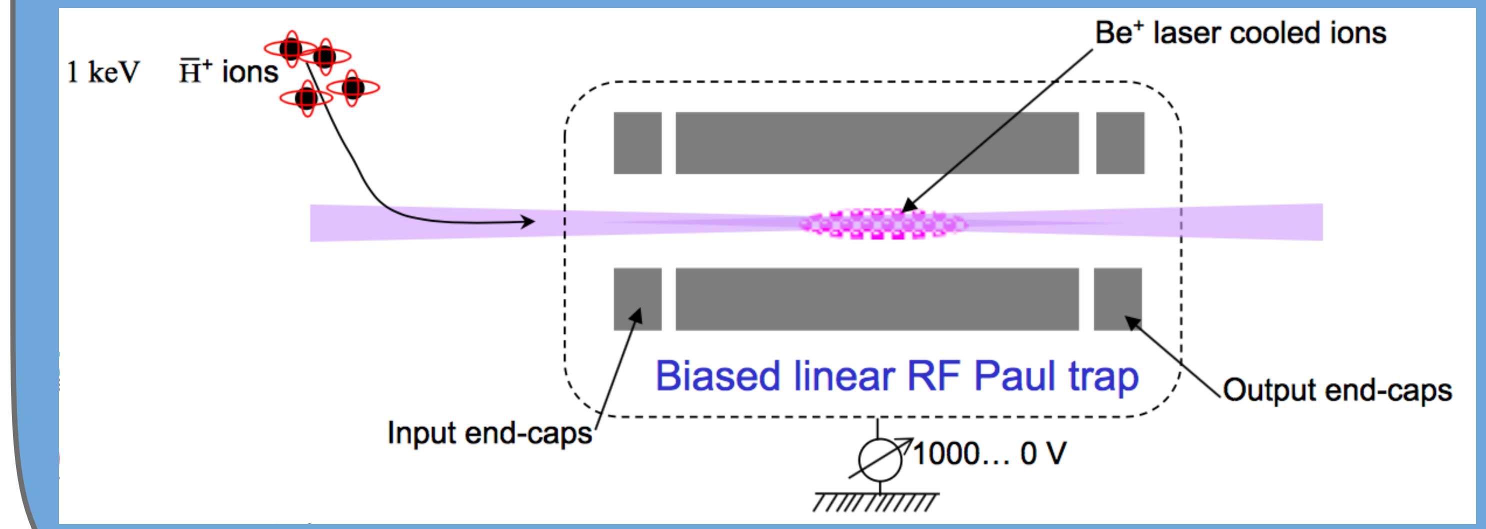
S. Aghion et al. Nature Communications 5 (2014) 4538

H̄⁺ BEAM

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

1% measurement targeted

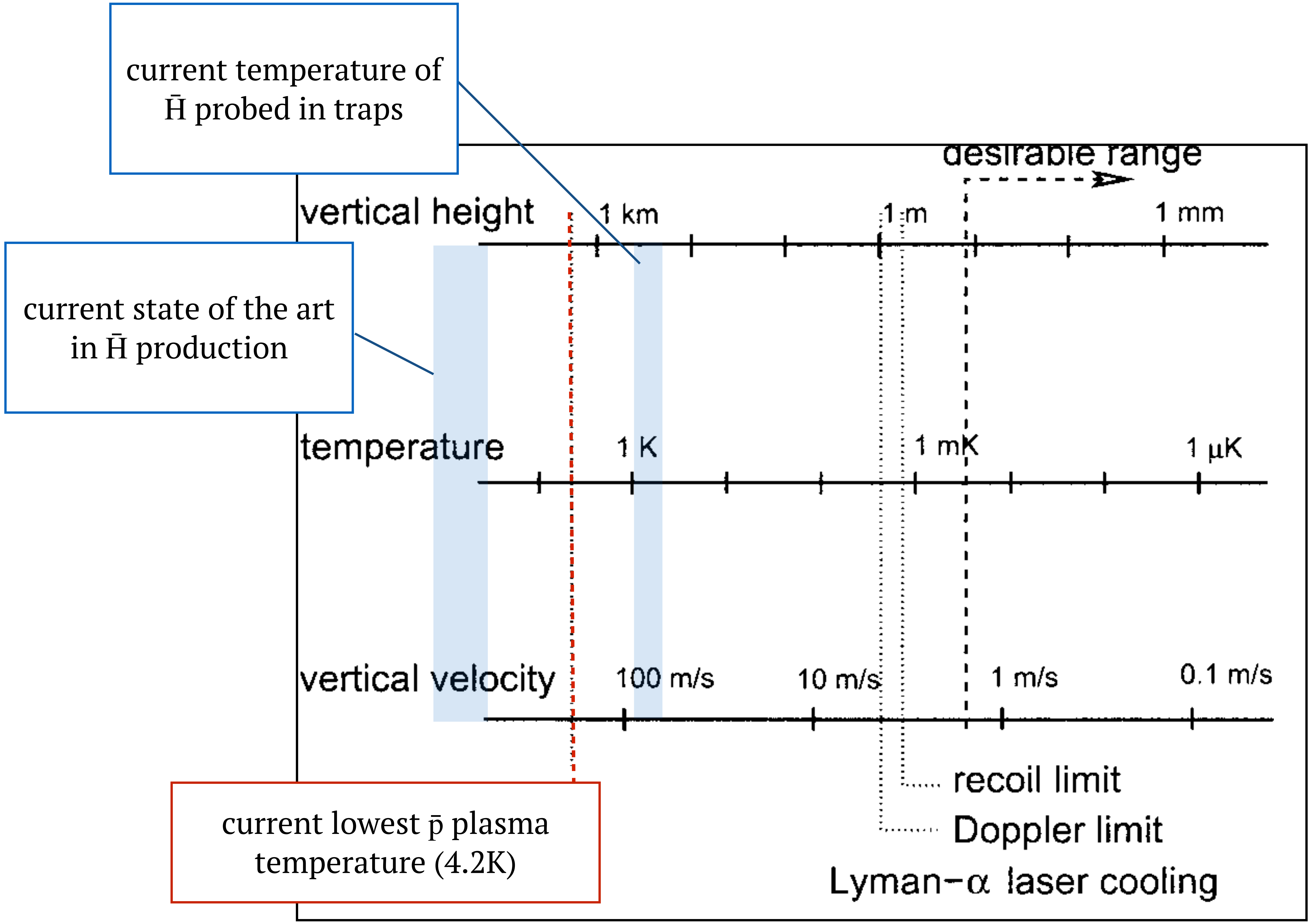




e.g.: The GBAR antimatter gravity experiment
P. Pérez et al., Hyperfine Interactions 233, 21-27 (2015)

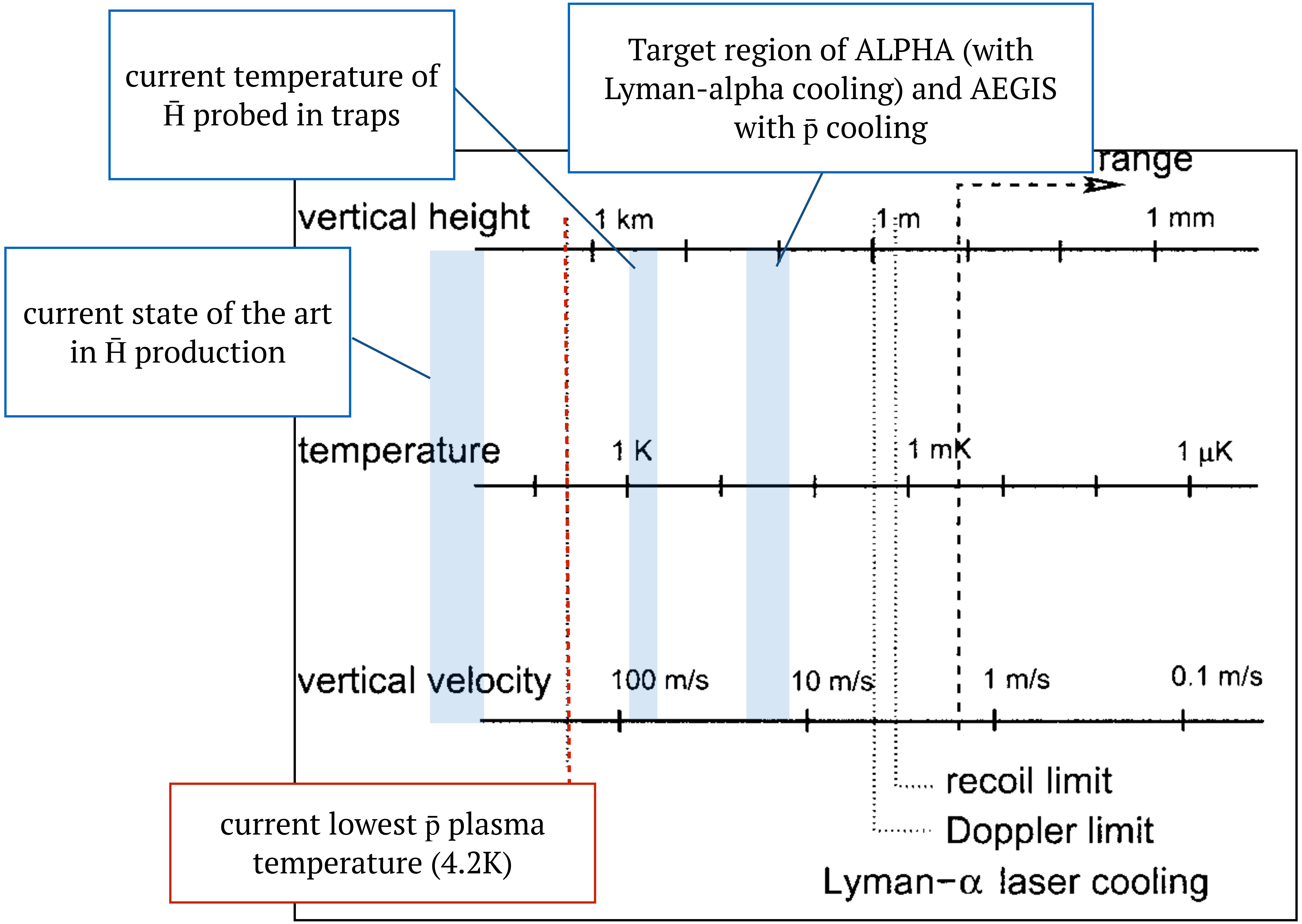
Planned gravity measurements with antihydrogen atoms

Some numbers to set the scale



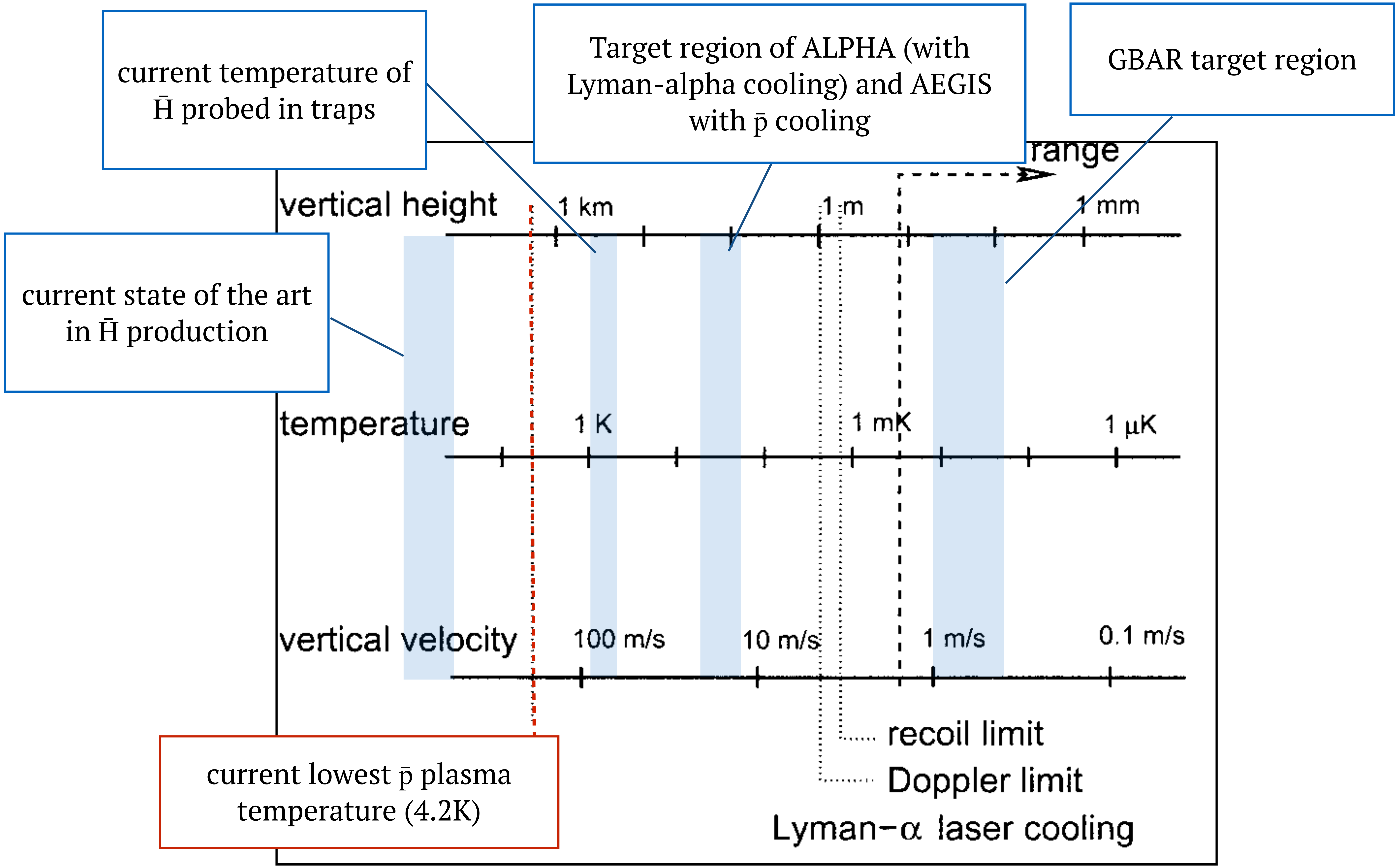
Planned gravity measurements with antihydrogen atoms

Some numbers to set the scale



Planned gravity measurements with antihydrogen atoms

Some numbers to set the scale



Planned gravity measurements with antihydrogen atoms

Some numbers to set the scale

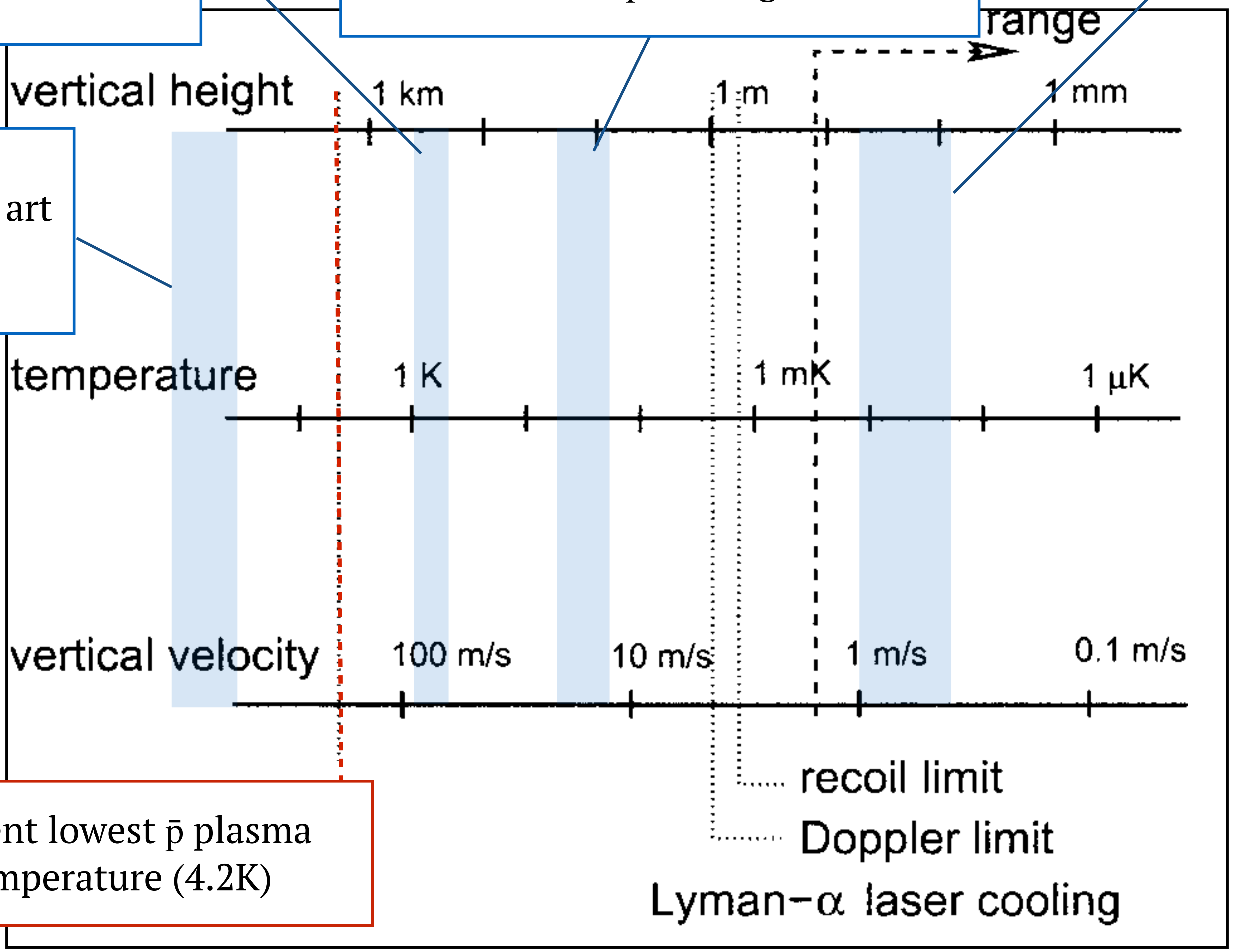
current temperature of $\bar{H}$ probed in traps

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

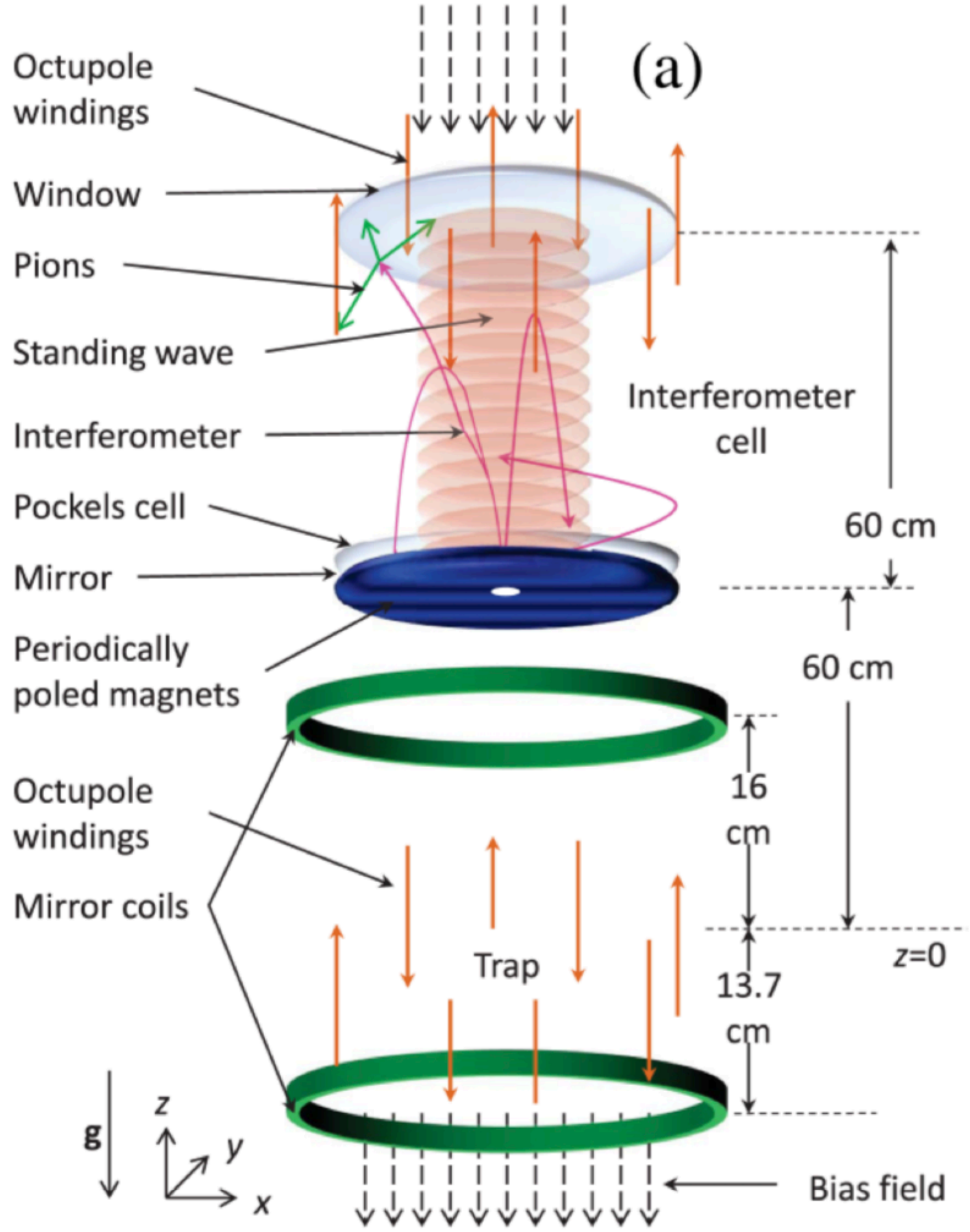
GBAR target region

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

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



Fountains Interferometry



DOI: 10.1103/PhysRevLett.112.121102

Summary

- Uniqueness of the physics question addressed
- $\bar{\mathrm{H}}$ is a tool of choice for CPT and gravity with antimatter tests
- AD has produced impressive results in the last 5 years - more to come. BUT it is an endurance run!
- Driving technological prowess
- Diversity of approaches is important (different challenges and 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
  Muonium: Testing systems containing 2nd generation particles!