RENAFAE

Testes Fundamentais de Física com Antihidrogênio (CPT e WEP) e Trício (Neutrinos)

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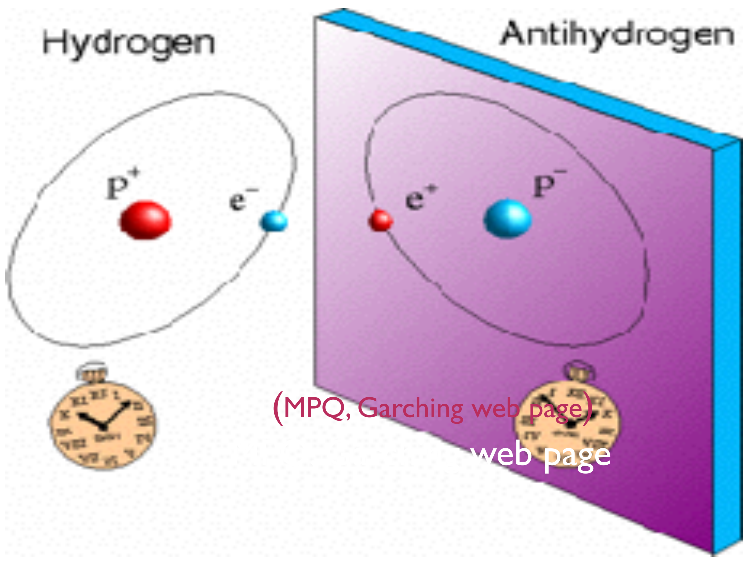
Univ. Fed. Rio de Janeiro, ALPHA Collab. CERN

- background & motivation: CPT symmetry & WEP
- antihydrogen (Hbar) 1S-2S transition frequency = 2,466,061,103,079.4(5.4) kHz :
  2 *ppt* comparison between conjugate species!
- what would be next: cooling & gravity test with Hbar
  what else: positron charge + hyperfine constant + Lamb shift + antiproton radius + …
- what is after, towards *ppq* ? H + Hear trapping: same electromagnetic & gravitational environment
  how : MISu @ UFRJ
- what about tritium ?
- conclusion

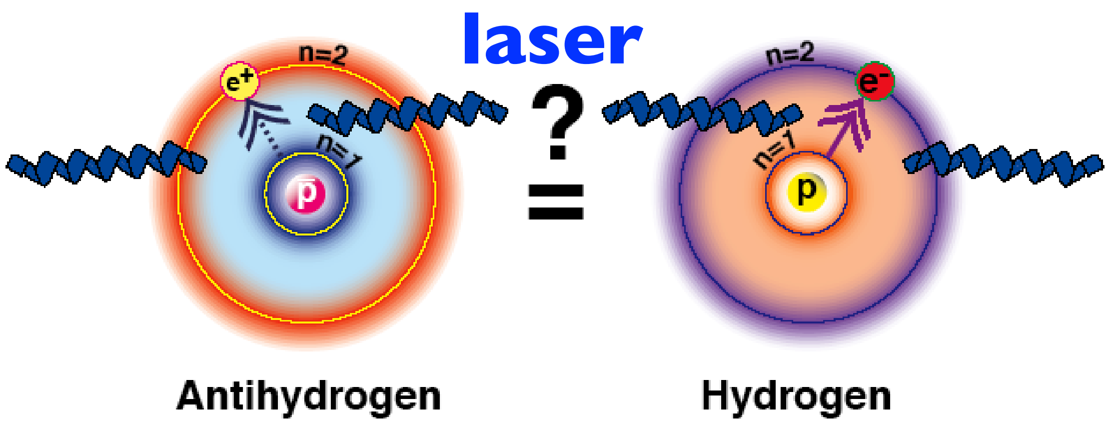
ATHENA/ALPHA Collaboration @ CERN's: Antihydrogen vs. Hydrogen

is $H = \bar{H}$?

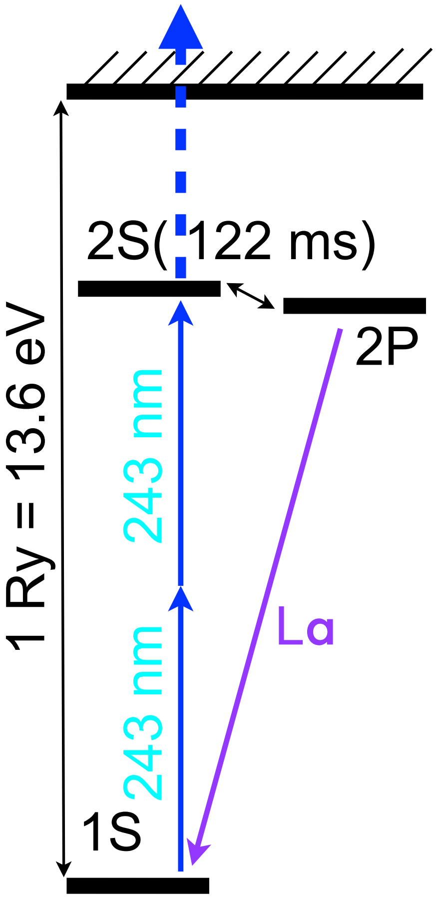
1 - CPT theorem, base of the Standard Model:



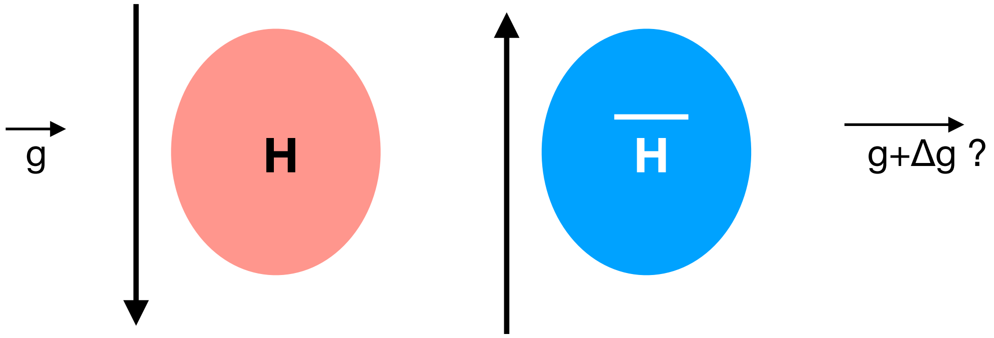
(MPQ, Garching web page)
web page



"CPT and Lorentz Tests in Hydrogen and Antihydrogen", Robert Bluhm, V. Alan Kostelecký, and Neil Russell, PRL 82, 2254 (1999)



2 - Equivalence Principle: g, or g+Δg ??



"Motivations for antigravity in General Relativity", G.Chardin, Hyp. Interact. 109, 83 (1997)

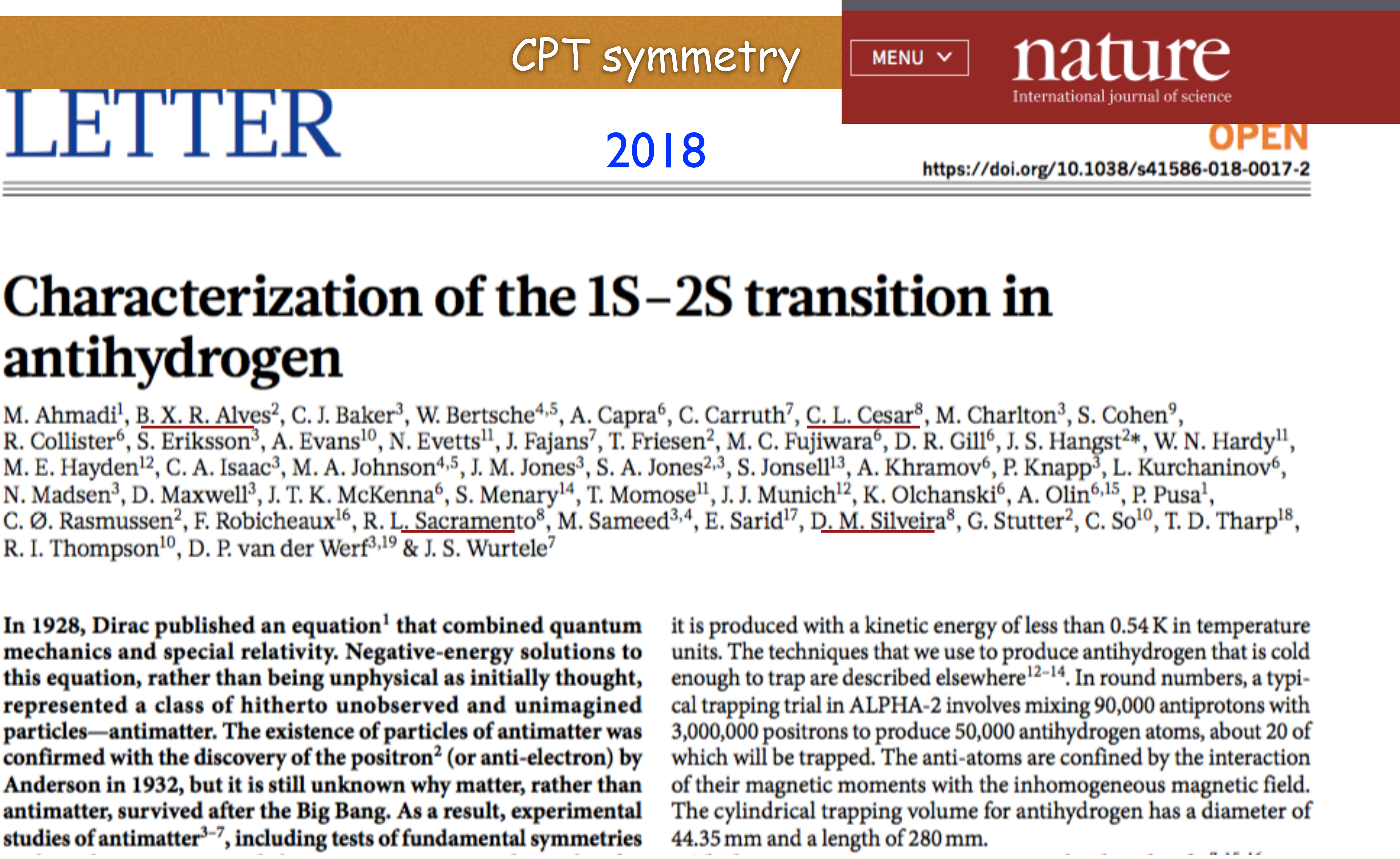
3 - Main Motivation: (Bariogenesis)

- where is the primordial antimatter?

=> Any discrepancy in (**1**) ou (**2**): Major Revolution in Physics - beyond the SM

CPT symmetry

2018



LETTER

OPEN

https://doi.org/10.1038/s41586-018-0017-2

Characterization of the 1S–2S transition in antihydrogen

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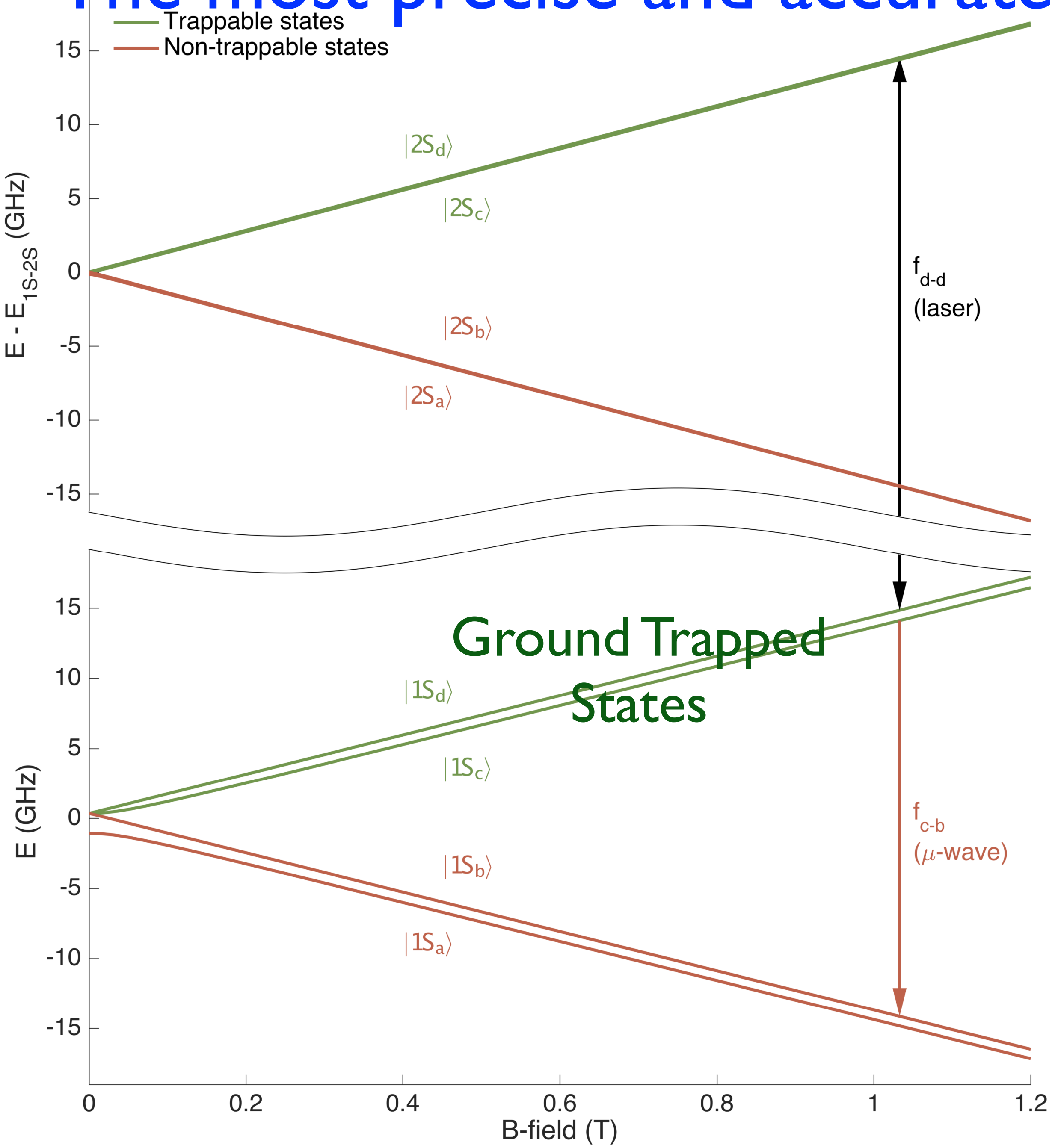
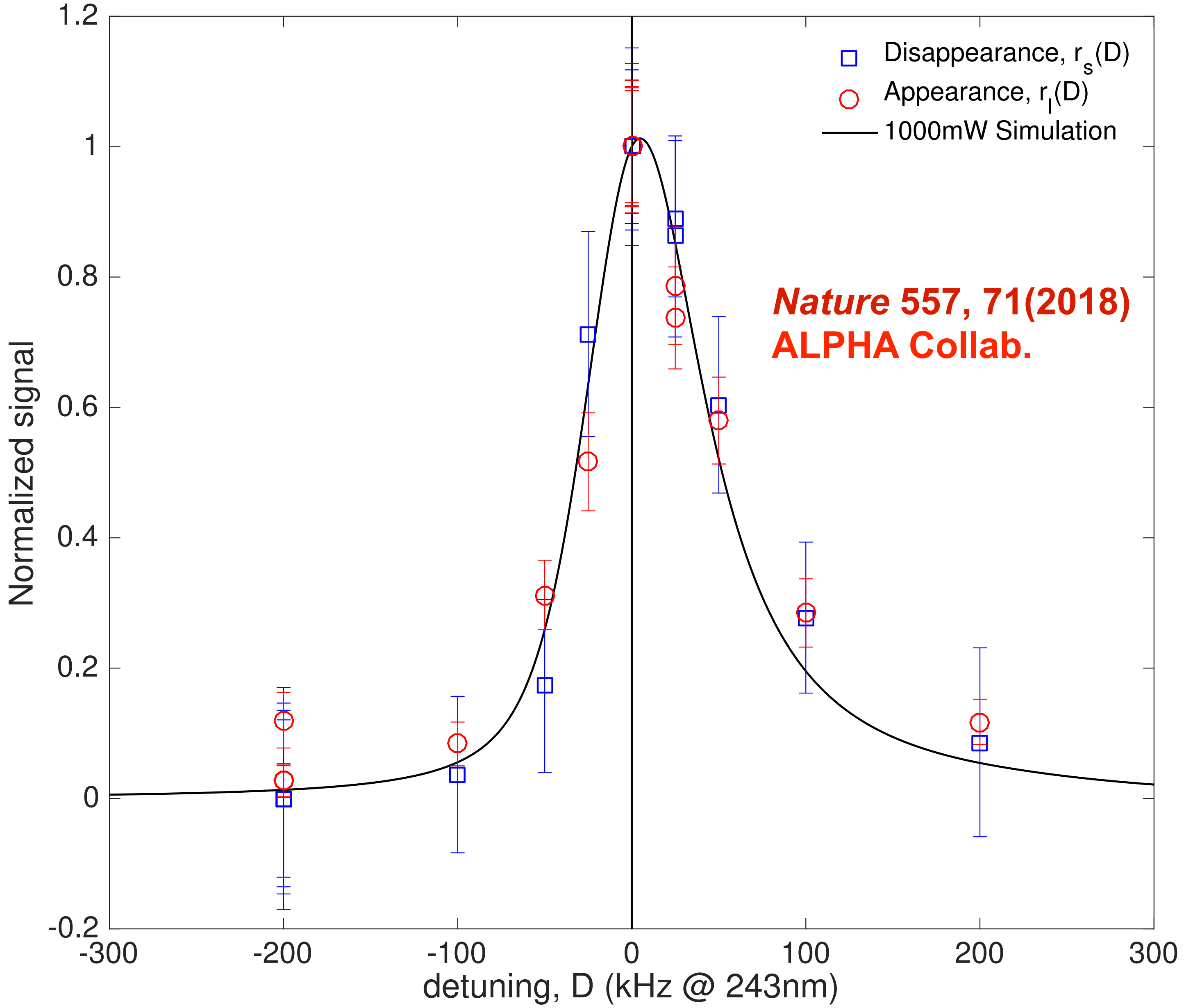
In 1928, Dirac published an equation[1] that combined quantum mechanics and special relativity. Negative-energy solutions to this equation, rather than being unphysical as initially thought, represented a class of hitherto unobserved and unimagined particles—antimatter. The existence of particles of antimatter was confirmed with the discovery of the positron[2] (or anti-electron) by Anderson in 1932, but it is still unknown why matter, rather than antimatter, survived after the Big Bang. As a result, experimental studies of antimatter[3–7], including tests of fundamental symmetries

it is produced with a kinetic energy of less than 0.54 K in temperature units. The techniques that we use to produce antihydrogen that is cold enough to trap are described elsewhere[12–14]. In round numbers, a typical trapping trial in ALPHA-2 involves mixing 90,000 antiprotons with 3,000,000 positrons to produce 50,000 antihydrogen atoms, about 20 of which will be trapped. The anti-atoms are confined by the interaction of their magnetic moments with the inhomogeneous magnetic field. The cylindrical trapping volume for antihydrogen has a diameter of 44.35 mm and a length of 280 mm.

CPT symmetry

The most precise and accurate comparison of conjugated species



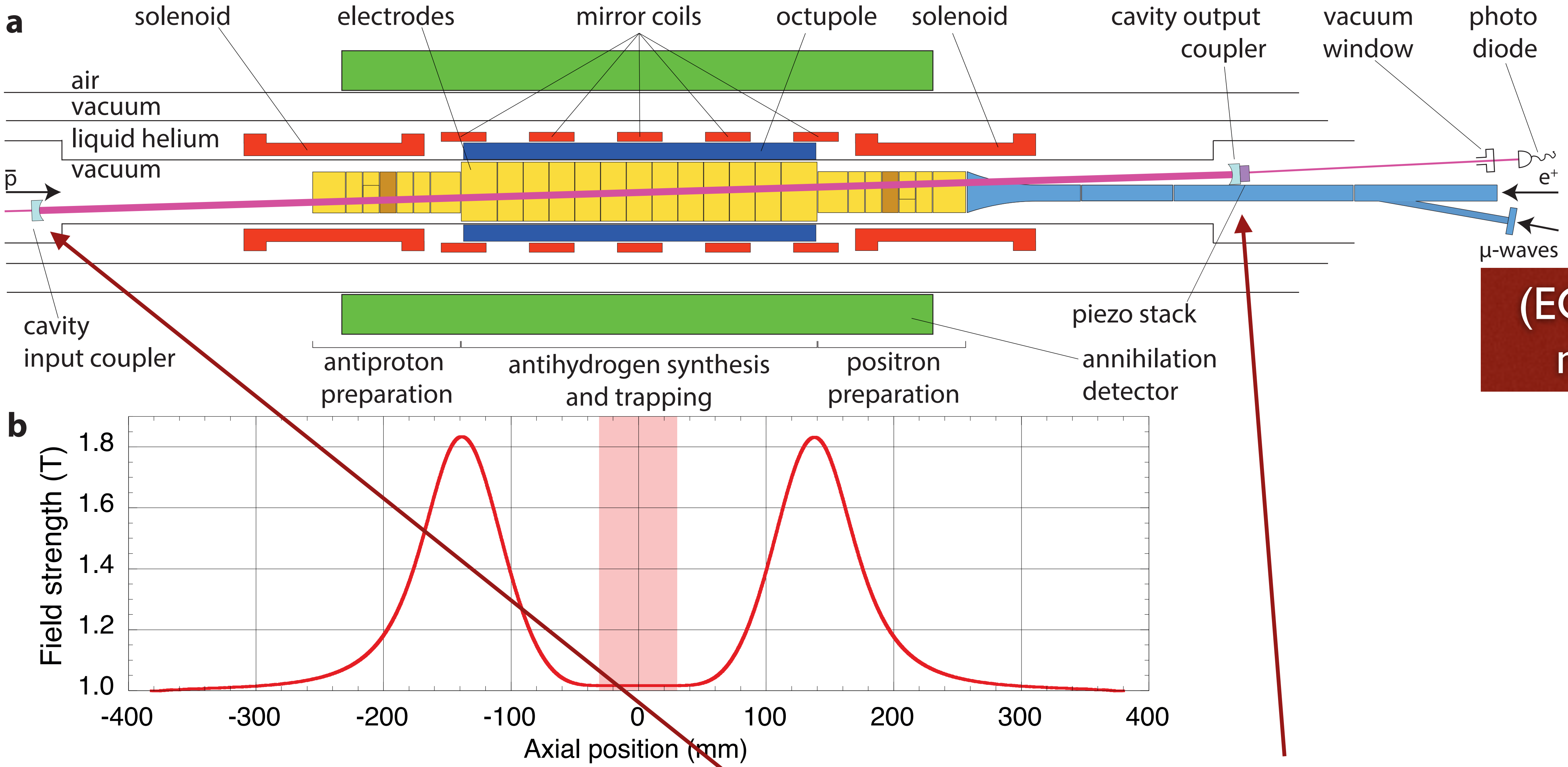


***Nature* 557, 71(2018)**
ALPHA Collab.

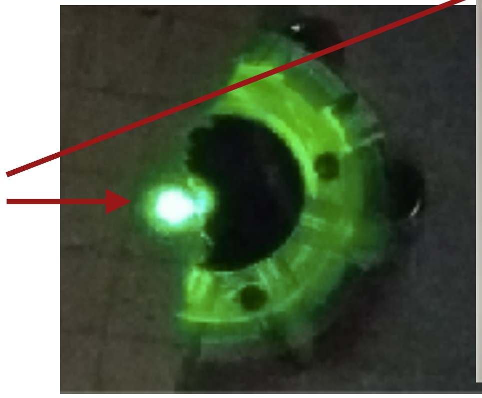
Spectrum and measured frequency:
2 x 10^{-12} compatibility: Hbar & H(projected)

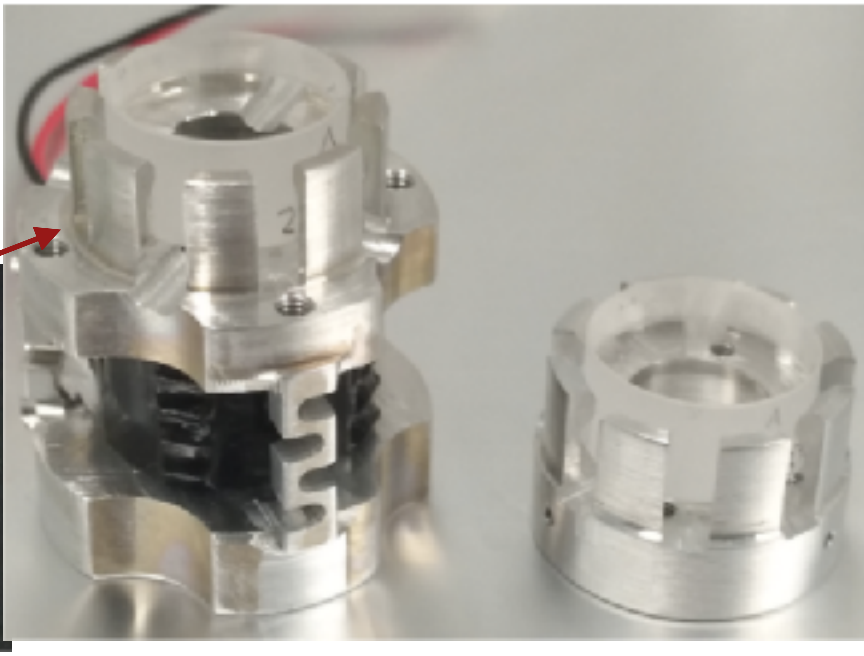
$$f_{\text{d-d}}(\text{H}) = 2{,}466{,}061{,}103{,}080.3(0.6)\text{kHz}$$

$$f_{\text{d-d}}(\text{anti-H}) = 2{,}466{,}061{,}103{,}079.4(5.4)\text{kHz}$$



(ECR)B-field measure

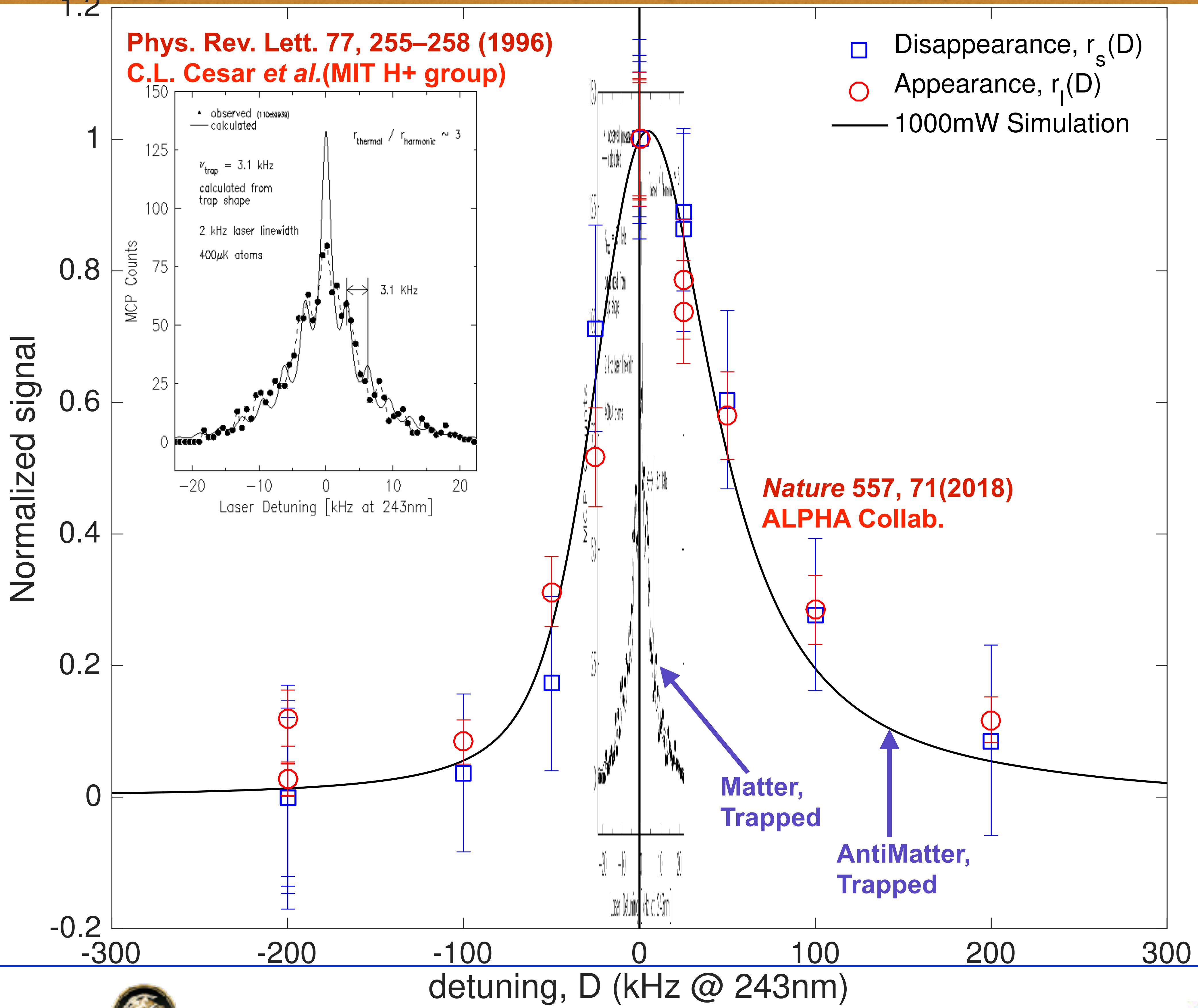




Cryogenic Optical Cavity: designed & made in Brasil

26. Oliveira, A. N. et al. Cryogenic mount for mirror and piezoelectric actuator for an optical cavity. Rev. Sci. Instrum. **88**, 063104 (2017).

Trapped Hbar (2018) in perspective: trapped H (1996)



Phys. Rev. Lett. 77, 255–258 (1996)
C.L. Cesar *et al.*(MIT H+ group)

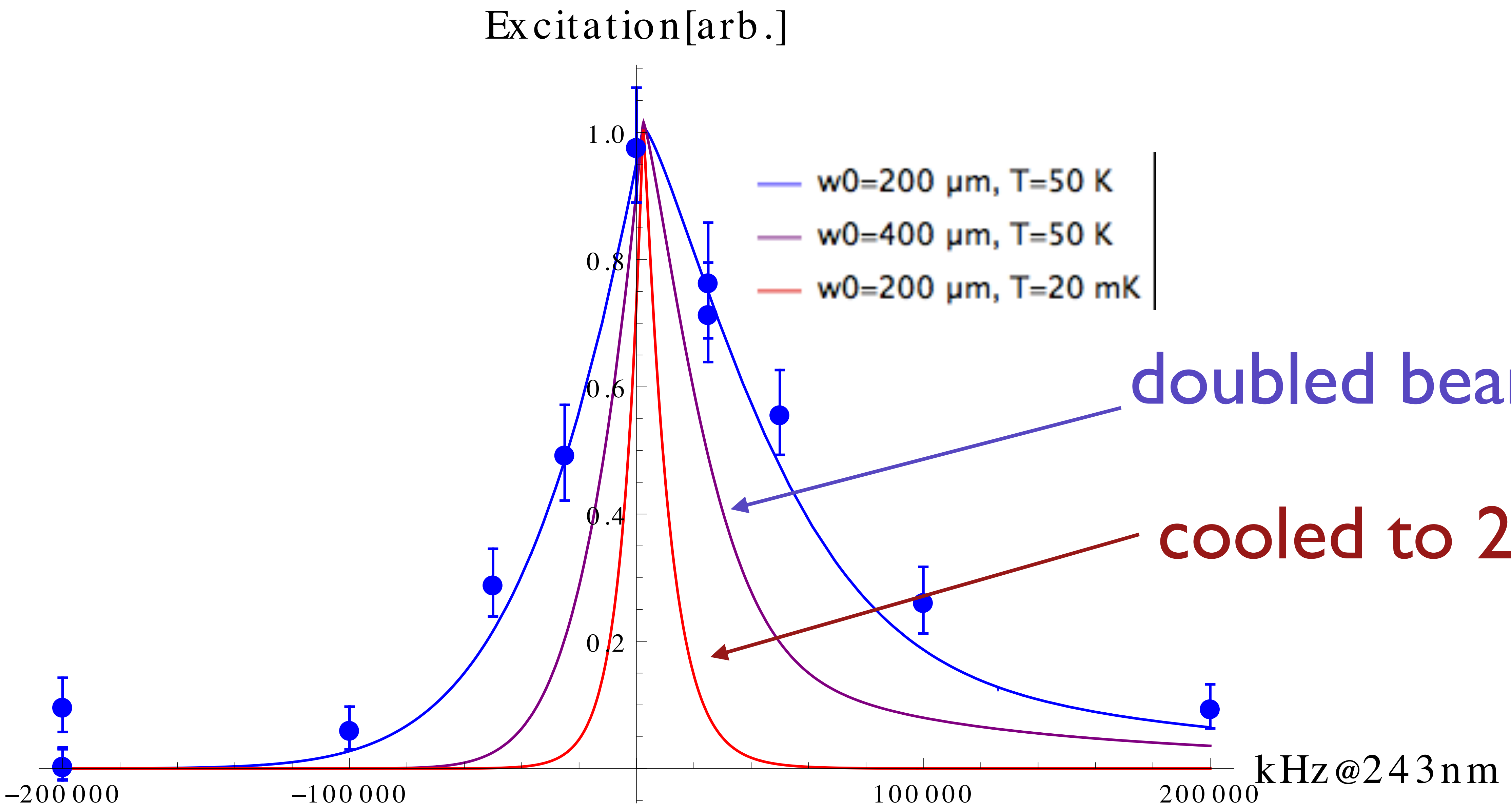
***Nature* 557, 71(2018)**
ALPHA Collab.

Matter, Trapped

AntiMatter, Trapped

Near Future: Linewidth & laser beam waist W0 and Cooling

Approximate Lineshape (perturbation)
- no AC Stark, no saturation -
based on CLC, JPB 49, 074001(2016)

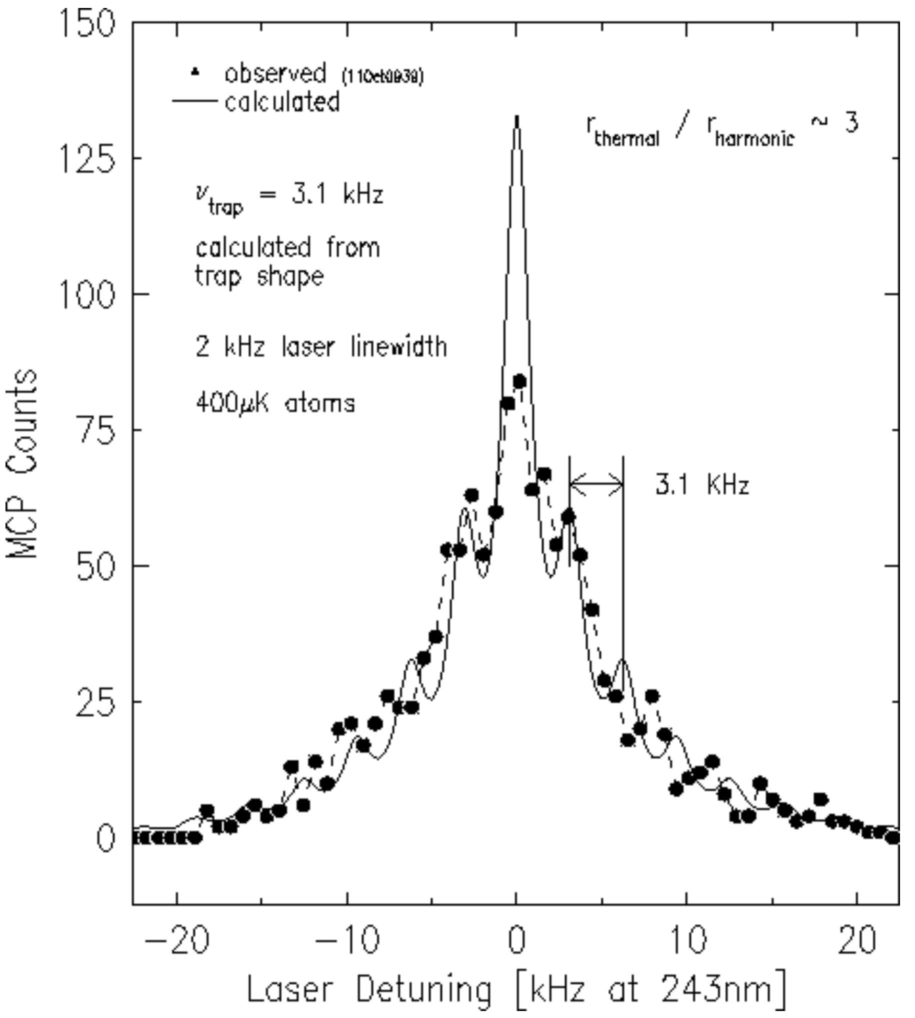


doubled beam waist

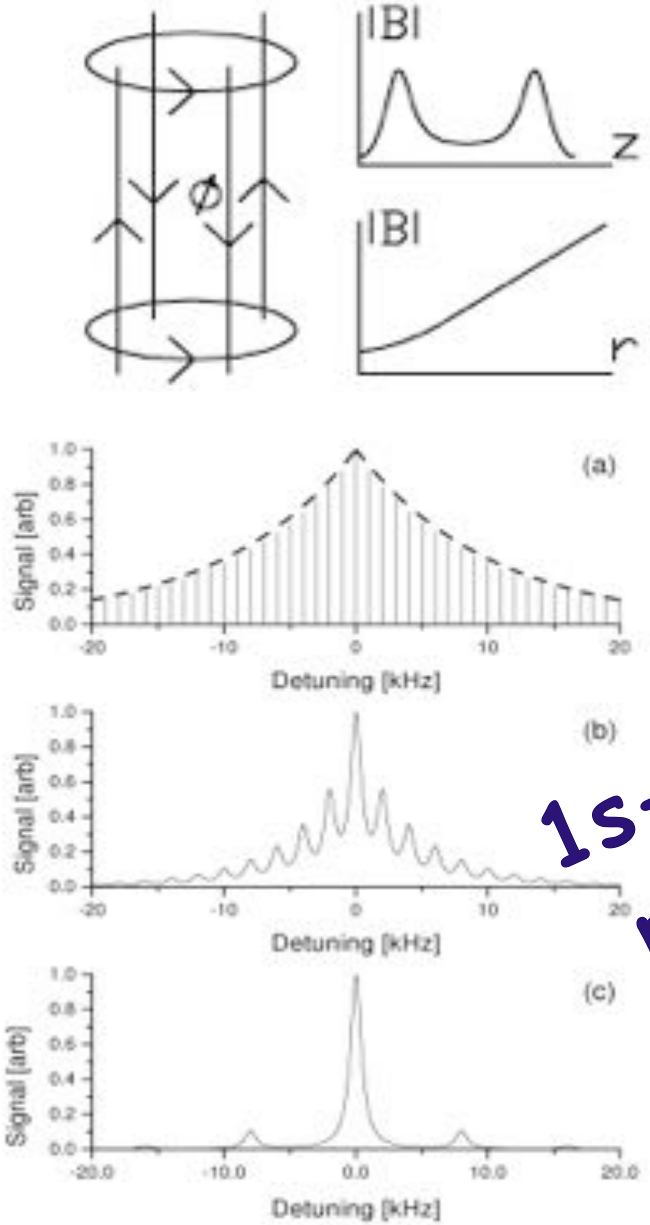
cooled to 20 mK

Hbar Spectroscopy Objectives: resemblance of trapped H!?

- ⭐ 2s - metastable state (122 ms)
- ⭐ 2-counterpropagating photons: Doppler-free
- ⭐ time-of-flight & Zeeman

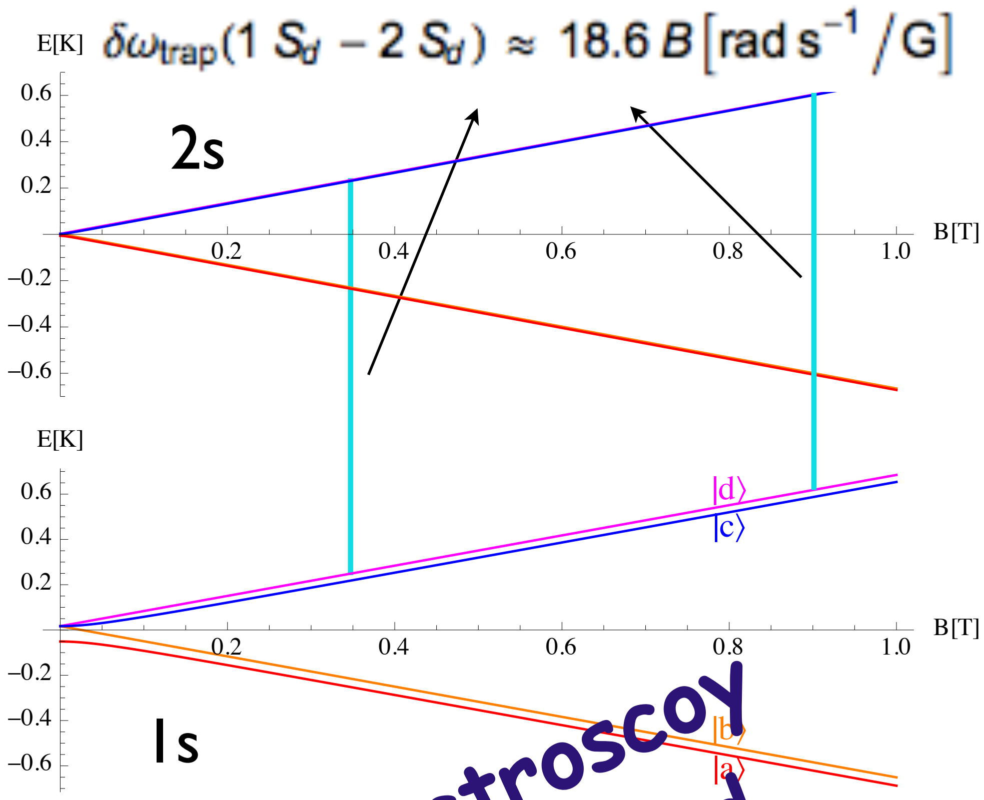


Phys. Rev. Lett. 77, 255–258 (1996)
C.L. Cesar *et al.*(MIT H+ group)

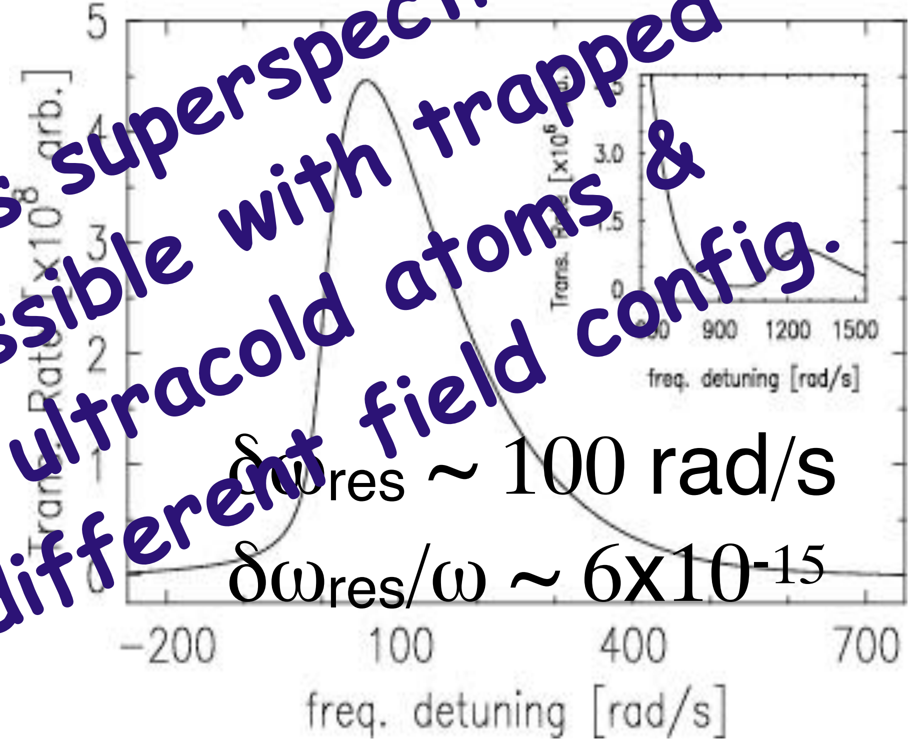


Phys. Rev. A 59, 4564 (1999)

C. Cesar, D. Kleppner



$\delta\omega_{trap}(1\,S_d - 2\,S_d) \approx 18.6\,B\,[\mathrm{rad\,s^{-1}}/\mathrm{G}]$



1s-2s superspectroscoy possible with trapped ultracold atoms & different field config.

$\delta\omega_{res} \sim 100$ rad/s

$\delta\omega_{res}/\omega \sim 6\mathrm{x}10^{-15}$

Phys. Rev. A 64, 023418 (2001)

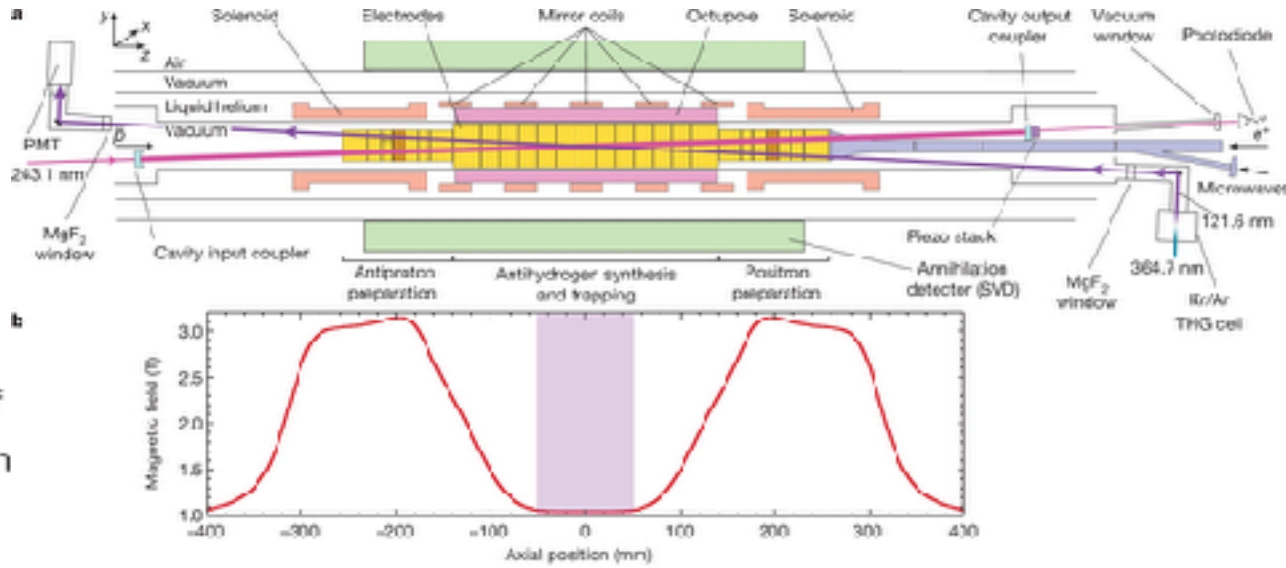
C. Cesar

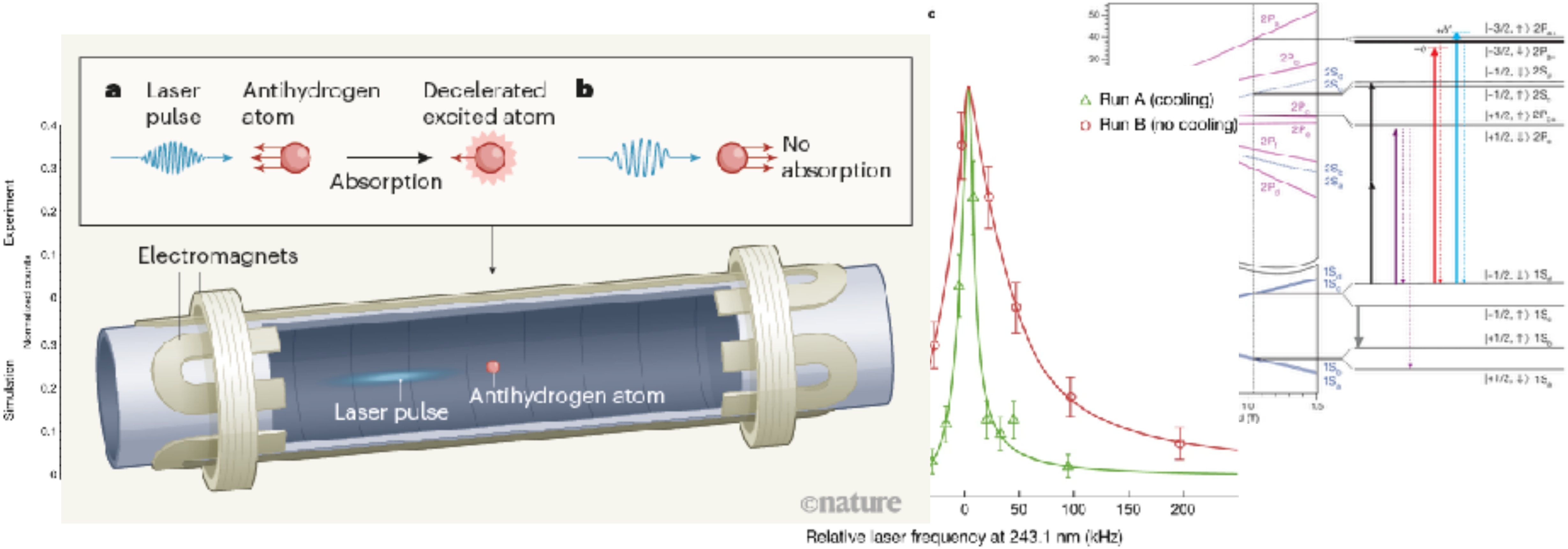
Laser cooling of Hbar: cover page @ Nature (April/21)

Volume 592 Issue 7852, 1 April 2021

Laser-cooled antimatter

Laser cooling — the use of photons to slow the movement of atoms — changed the face of atomic physics when it was first demonstrated 40 years ago. In this week's issue, the ALPHA collaboration takes this technique into fresh territory by successfully applying it to antimatter. Working at CERN's Antiproton Decelerator facility, the researchers trapped atoms of antihydrogen using magnetic fields and then irradiated them with carefully tuned pulses... show more

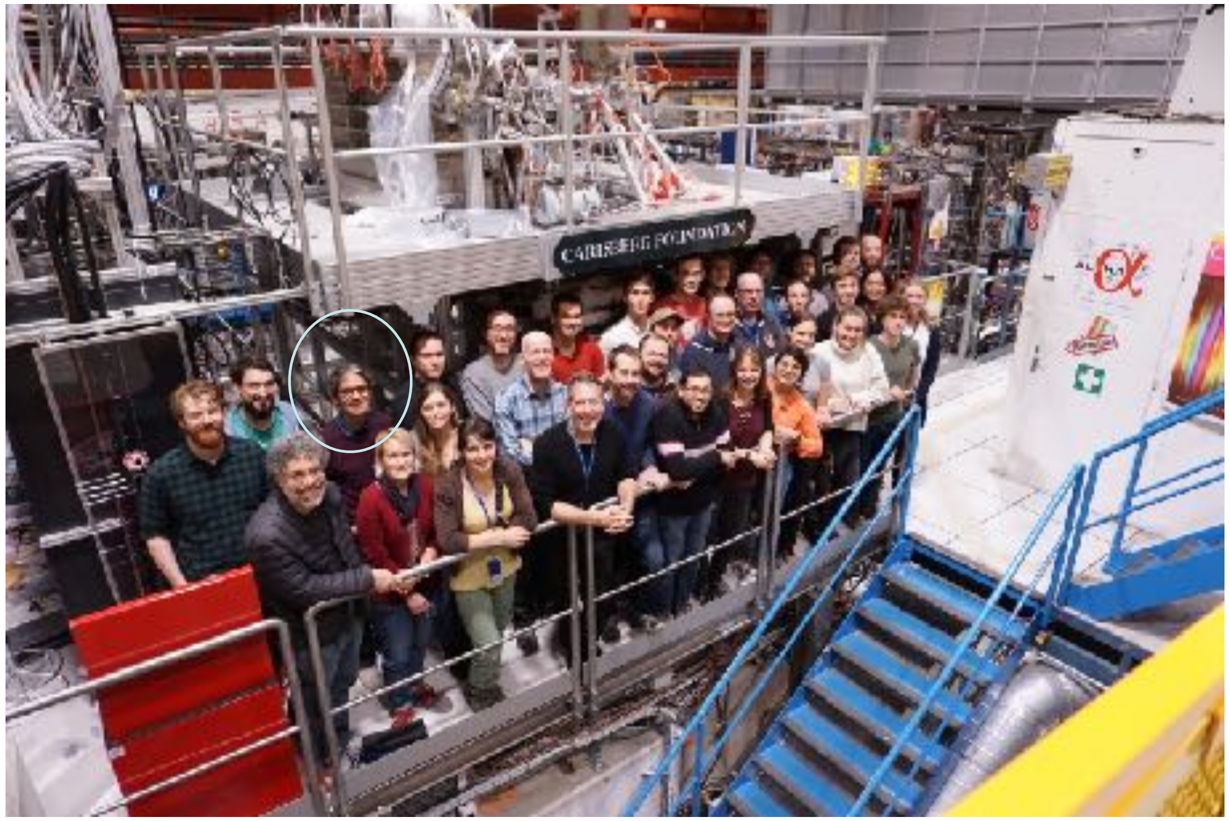


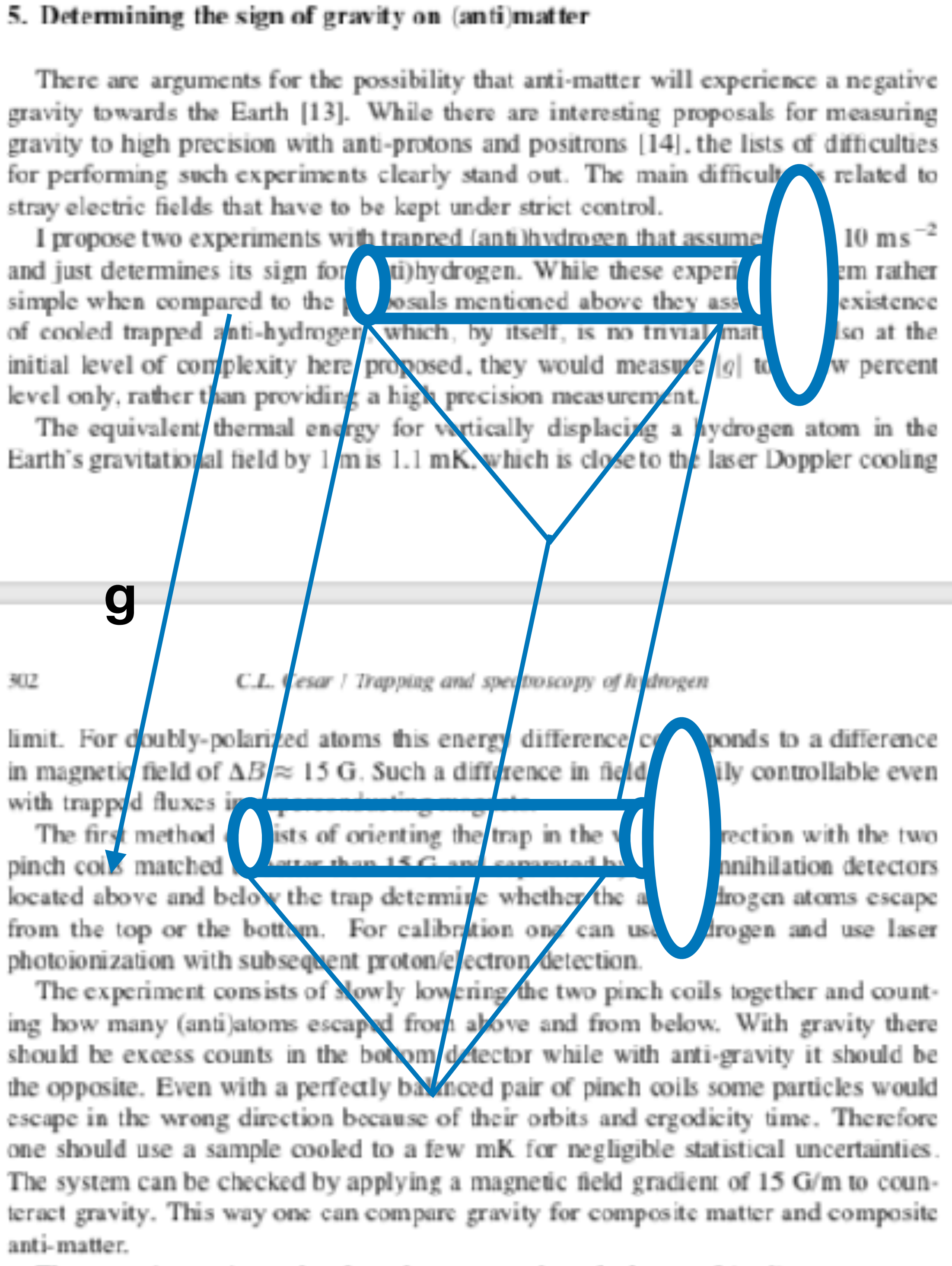


ALPHA-g : towards the observation of antimatter fall

first proposal of this experiment:

CLC, Hyperfine Interactions 109 (1997) 293–304





5. Determining the sign of gravity on (anti)matter

There are arguments for the possibility that anti-matter will experience a negative gravity towards the Earth [13]. While there are interesting proposals for measuring gravity to high precision with anti-protons and positrons [14], the lists of difficulties for performing such experiments clearly stand out. The main difficult s related to stray electric fields that have to be kept under strict control.

I propose two experiments with trapped (anti)hydrogen that assume 10 ms^{-2} and just determines its sign for i)hydrogen. While these experi em rather simple when compared to the p osals mentioned above they ass existence of cooled trapped anti-hydrogen, which, by itself, is no trivial mat lso at the initial level of complexity here proposed, they would measure $|g|$ to w percent level only, rather than providing a high precision measurement.

The equivalent thermal energy for vertically displacing a hydrogen atom in the Earth's gravitational field by 1 m is 1.1 mK, which is close to the laser Doppler cooling

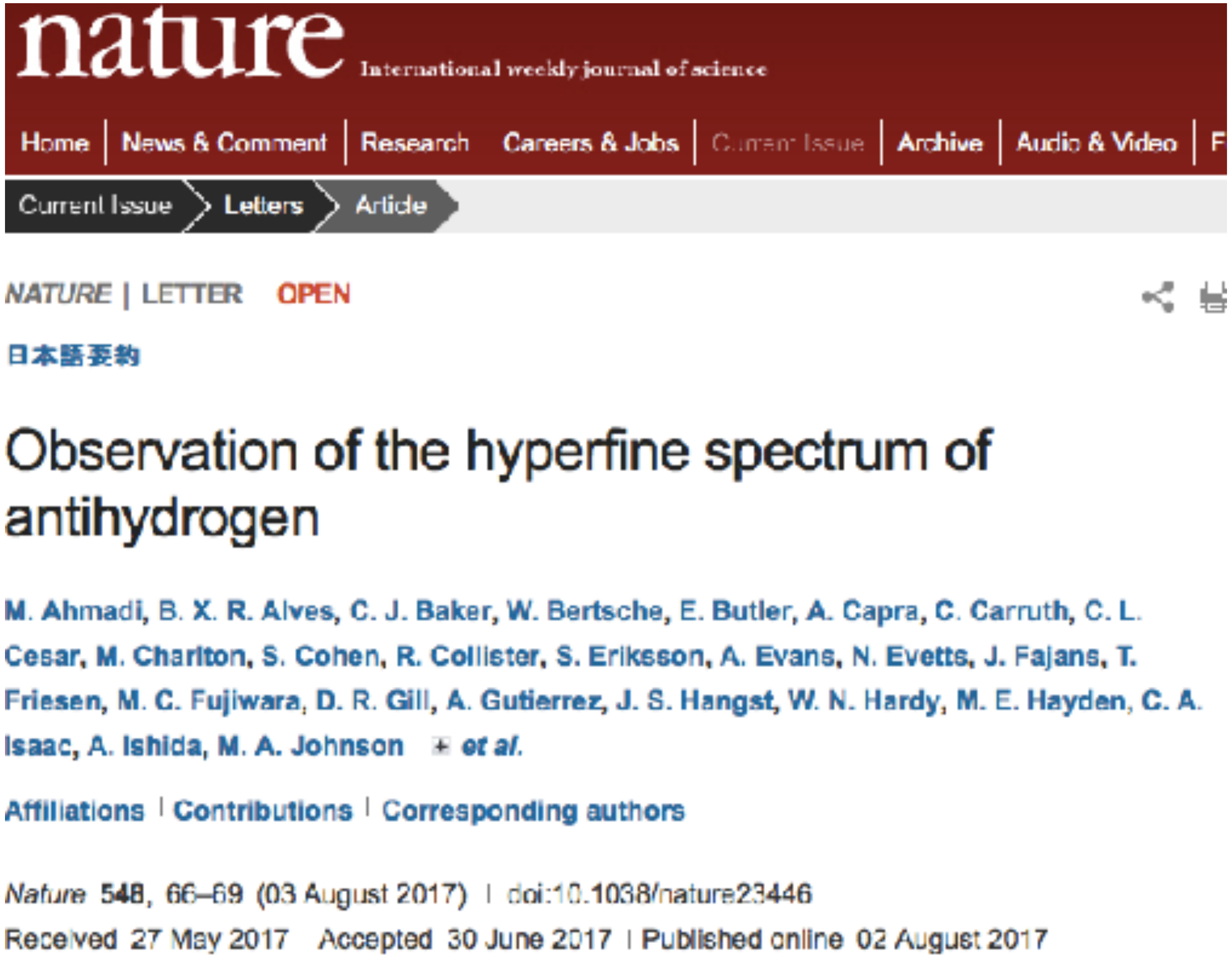
limit. For doubly-polarized atoms this energy difference c ponds to a difference in magnetic field of $\Delta B \approx 15$ G. Such a difference in field ily controllable even with trapped fluxes i

The first method ists of orienting the trap in the rection with the two pinch coils matched nnihilation detectors located above and below the trap determine whether the a drogen atoms escape from the top or the bottom. For calibration one can us drogen and use laser photoionization with subsequent proton/electron detection.

The experiment consists of slowly lowering the two pinch coils together and counting how many (anti)atoms escaped from above and from below. With gravity there should be excess counts in the bottom detector while with anti-gravity it should be the opposite. Even with a perfectly balanced pair of pinch coils some particles would escape in the wrong direction because of their orbits and ergodicity time. Therefore one should use a sample cooled to a few mK for negligible statistical uncertainties. The system can be checked by applying a magnetic field gradient of 15 G/m to counteract gravity. This way one can compare gravity for composite matter and composite anti-matter.

The second experiment involves the construction of a beam of (anti)matter at very

and talking about μW: (anti)hyperfine constant



NATURE | LETTER **OPEN**

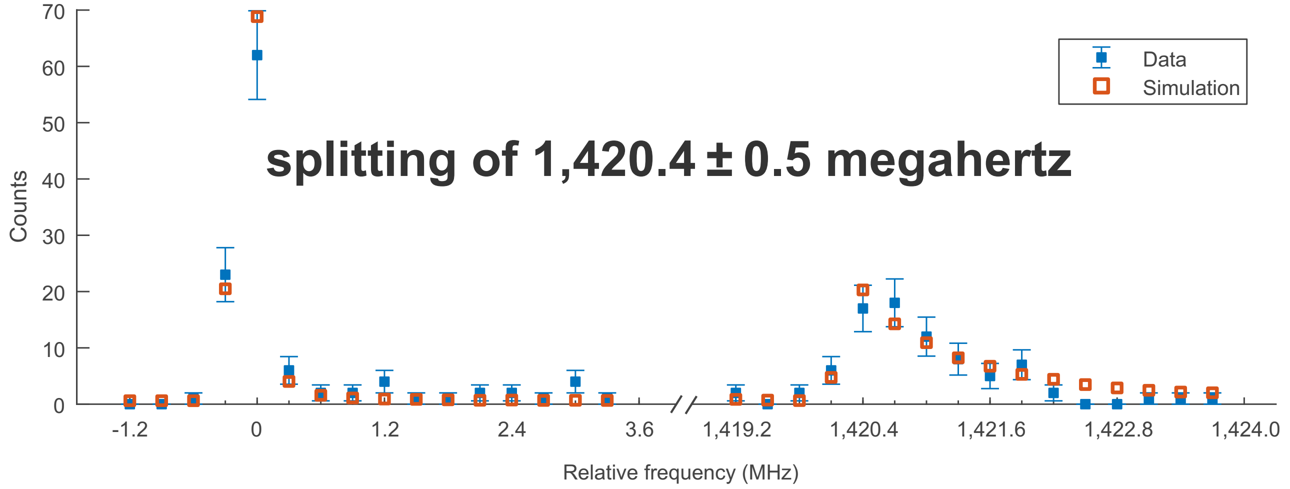
日本語要約

Observation of the hyperfine spectrum of antihydrogen

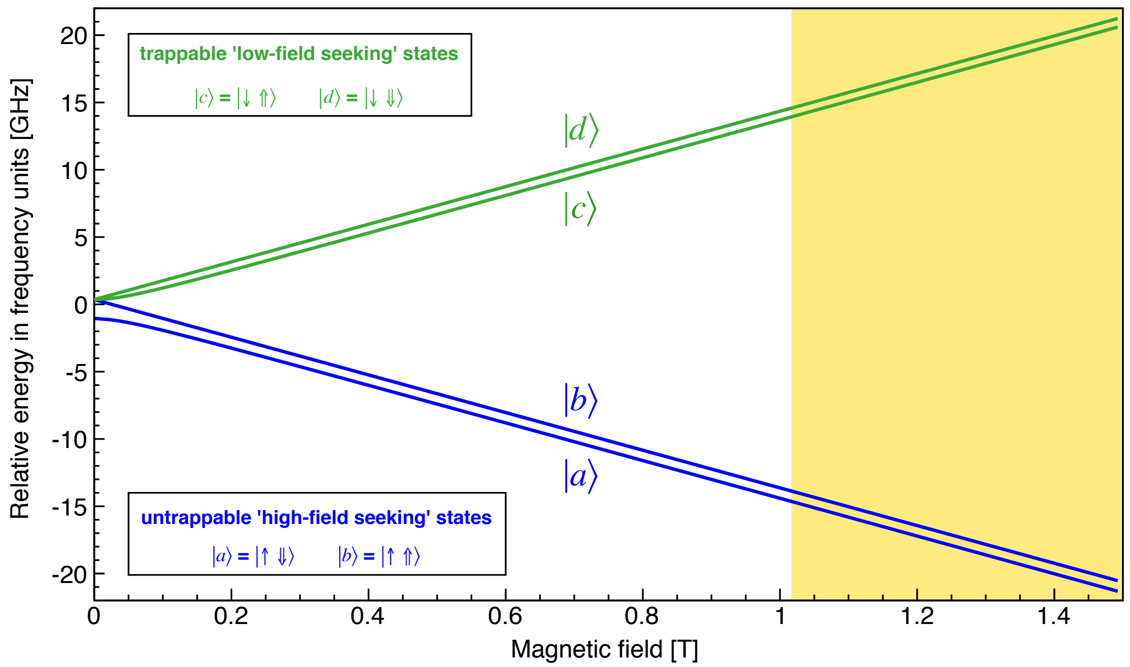
M. Ahmadi, B. X. R. Alves, C. J. Baker, W. Bertsche, E. Butler, A. Capra, C. Carruth, C. L. Cesar, M. Charlton, S. Cohen, R. Collister, S. Eriksson, A. Evans, N. Evetts, J. Fajans, T. Friesen, M. C. Fujiwara, D. R. Gill, A. Gutierrez, J. S. Hangst, W. N. Hardy, M. E. Hayden, C. A. Isaac, A. Ishida, M. A. Johnson + *et al.*

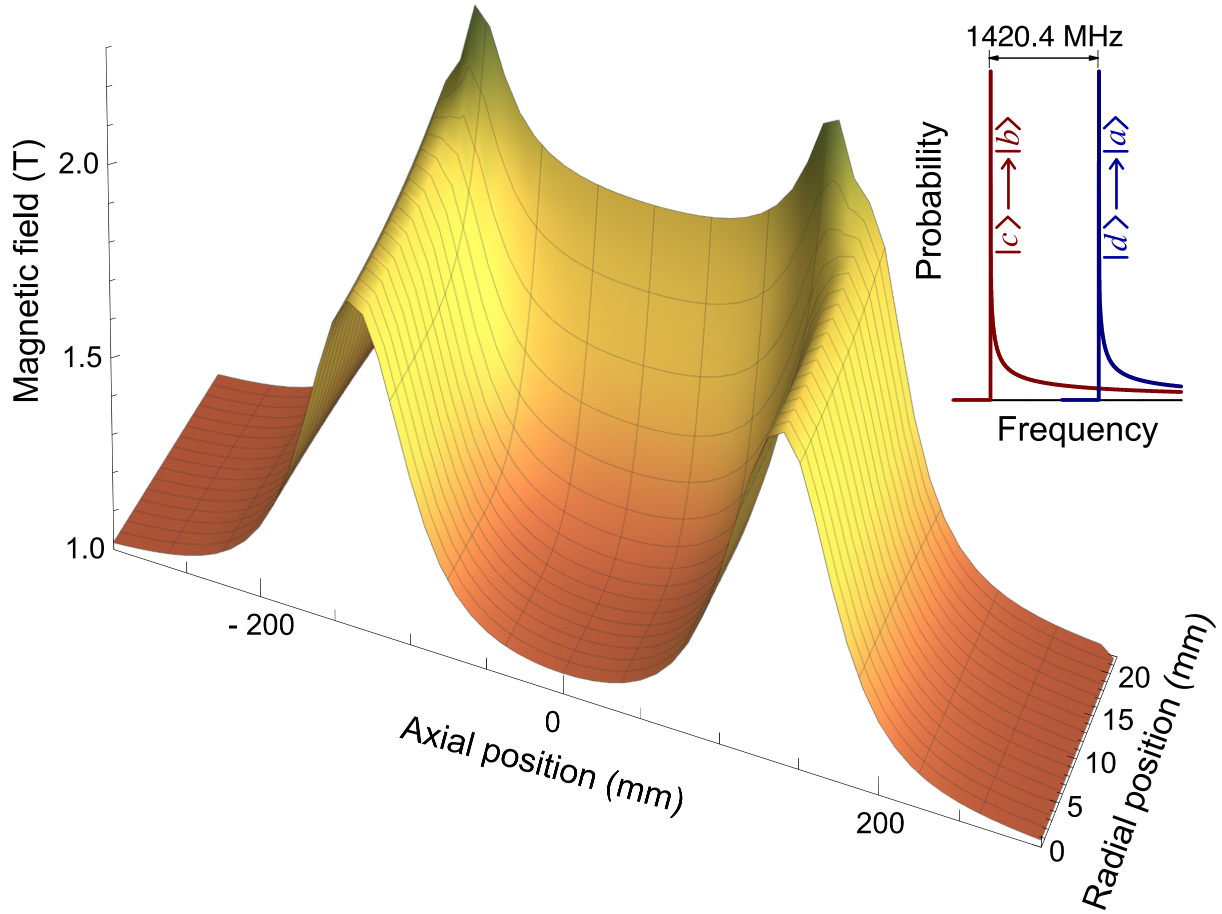
Affiliations | Contributions | Corresponding authors

Nature 548, 66–69 (03 August 2017) | doi:10.1038/nature23446
Received 27 May 2017 Accepted 30 June 2017 | Published online 02 August 2017

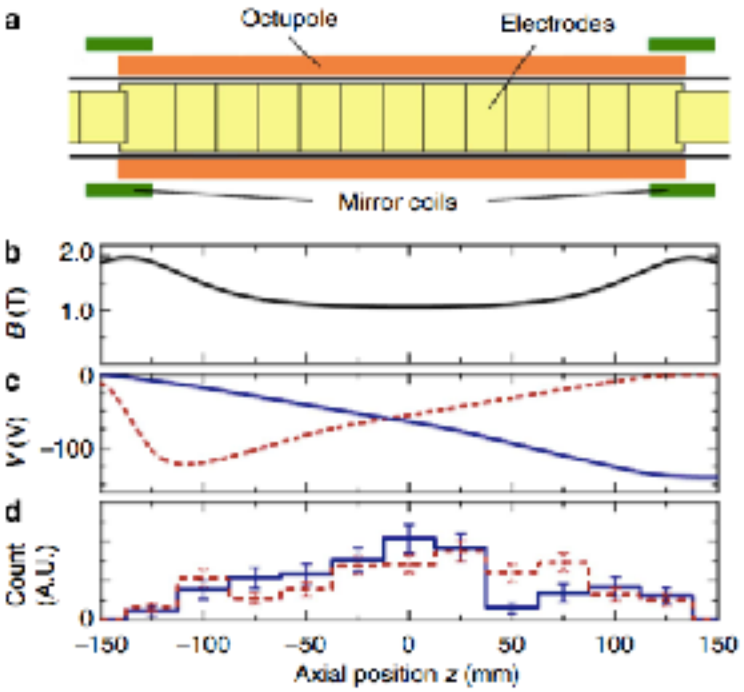


splitting of 1,420.4 ± 0.5 megahertz





Hbar charge
Nature Commun. **5**,3955(2014); Nature **529**, 373(2016)



$Q = (-1.2 \pm 1.1 \pm 0.4) \times 10^{-8}$ e

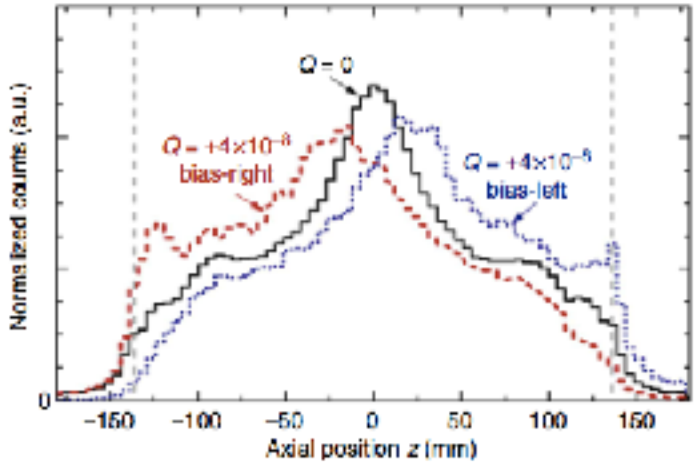
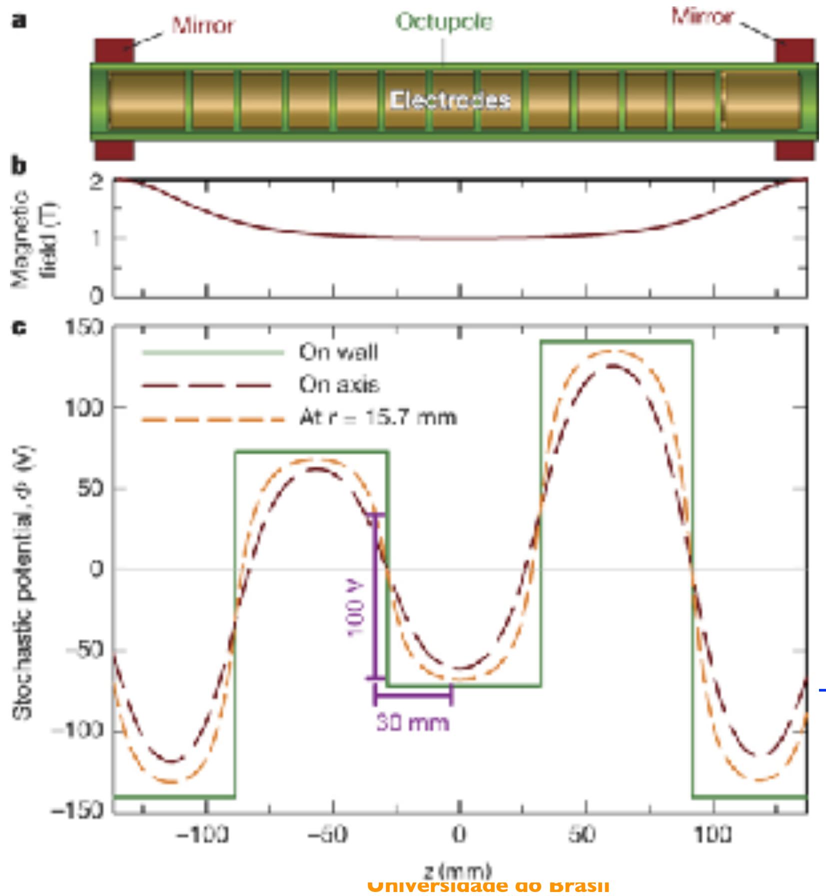


Figure 2 | Simulated annihilation z-distributions. Three simulated annihilation *z*-distributions, for antiatoms with $Q = 0$ (black solid line) and $Q = +4 \times 10^{-8}$ under Bias-Right (red dashed line) and Bias-Left (blue dotted line) conditions. The vertical dashed lines indicate the locations of the cuts at $z = \pm 136$ mm.

An improved limit on the charge of antihydrogen from stochastic acceleration



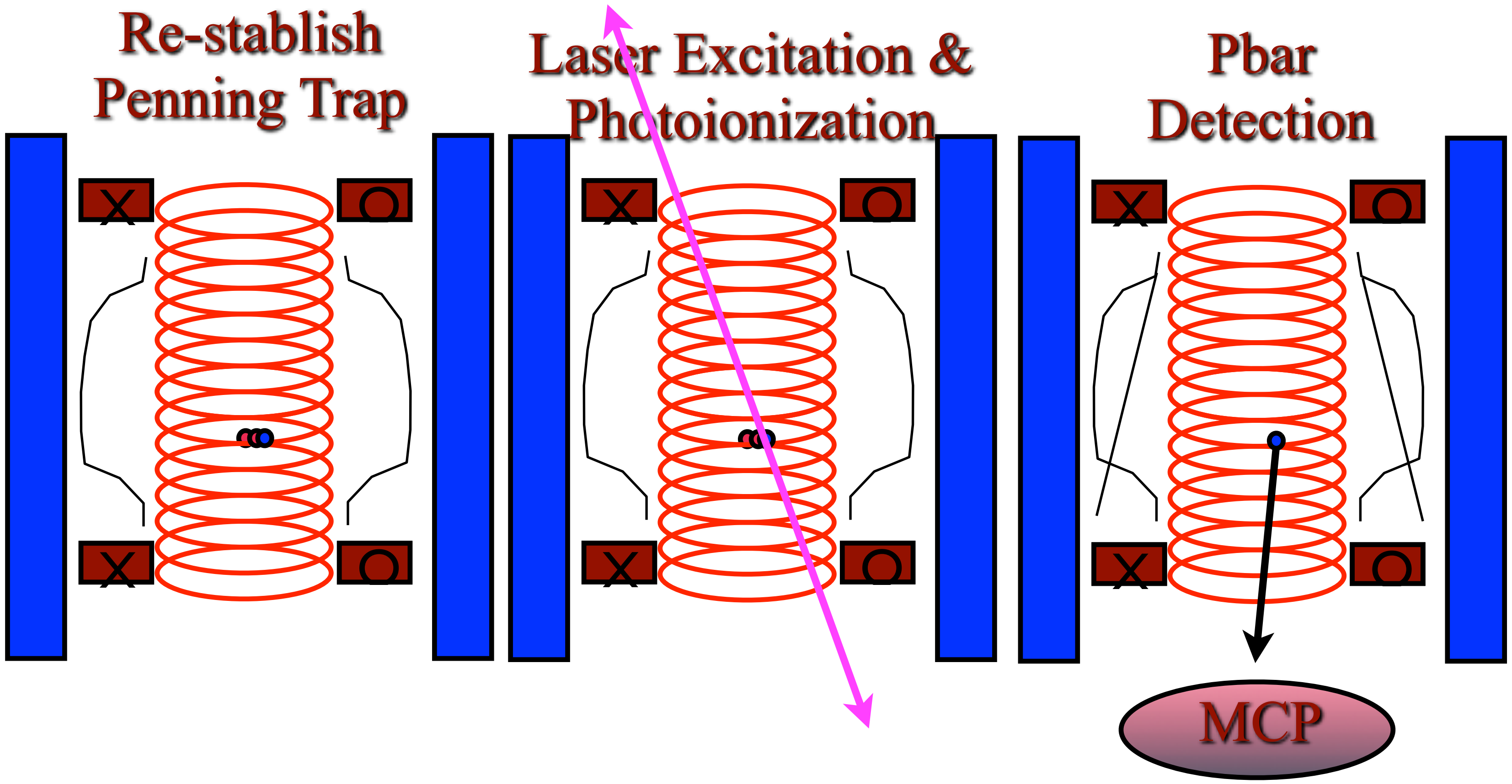
$|Q| < 0.71$ p.p.b. at a 68.3% (1σ) confidence level

combined with ASACUSA measurement of pbar charge

⇒ charge anomaly of the positron to 1 p.p.b. (1σ),

a 25-fold improvement on the best previous bound

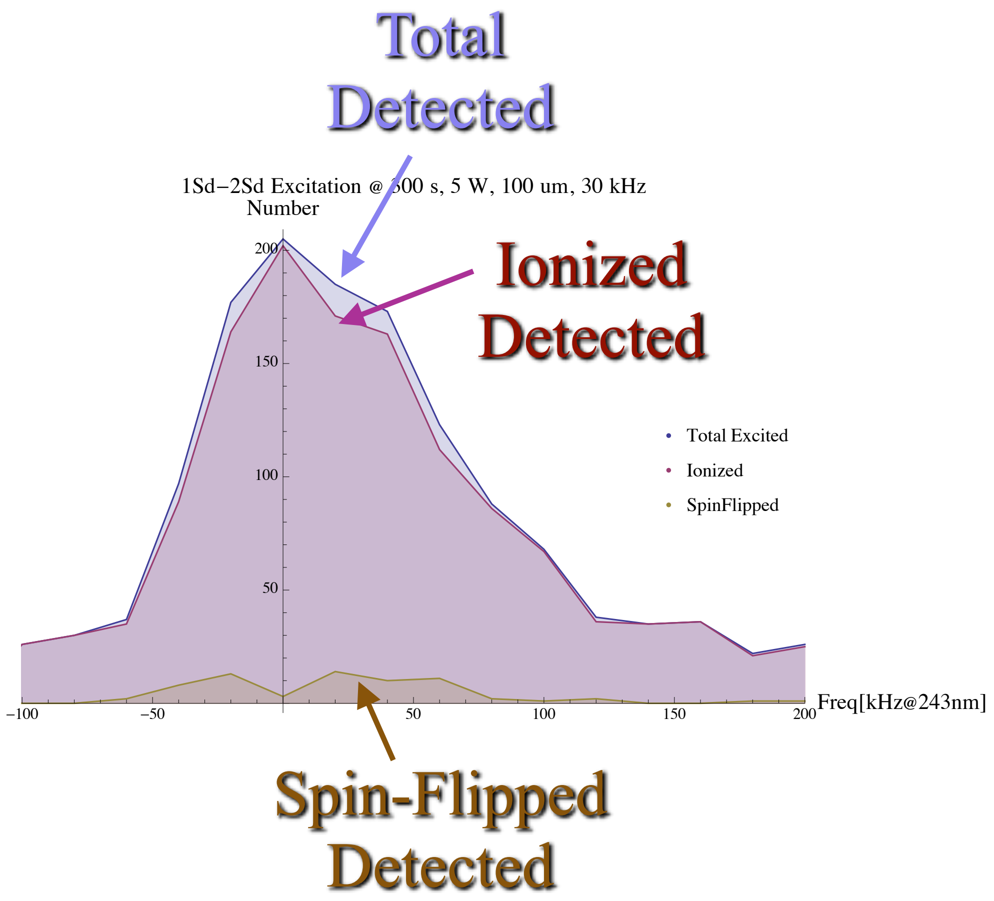
Detection - 1s-2s spectroscopy of trapped (anti)H
H & Hbar in the same trap: gravitational & electromagnetic



Re-stablish Penning Trap

Laser Excitation & Photoionization

Pbar Detection



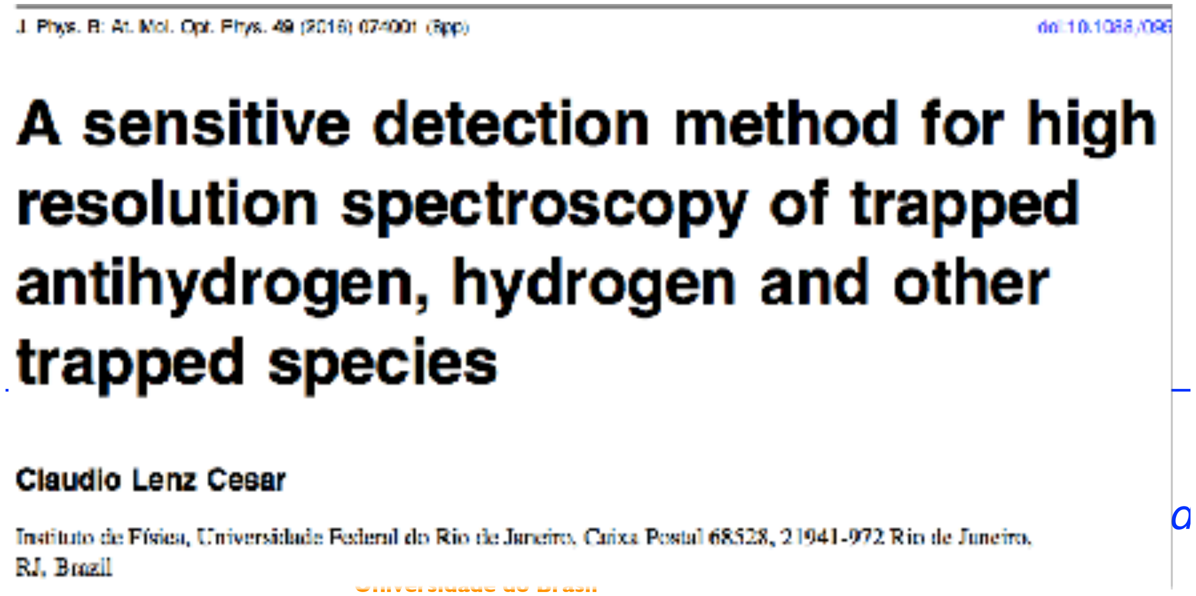
Total Detected

Ionized Detected

Spin-Flipped Detected

Trapping H in ALPHA 2 (same environment)

CLC, J. Phys. B 49 (2016) 074001 (antiH issue)



J. Phys. B: At. Mol. Opt. Phys. 49 (2016) 074001 (8pp) doi:10.1088/09

A sensitive detection method for high resolution spectroscopy of trapped antihydrogen, hydrogen and other trapped species

Claudio Lenz Cesar

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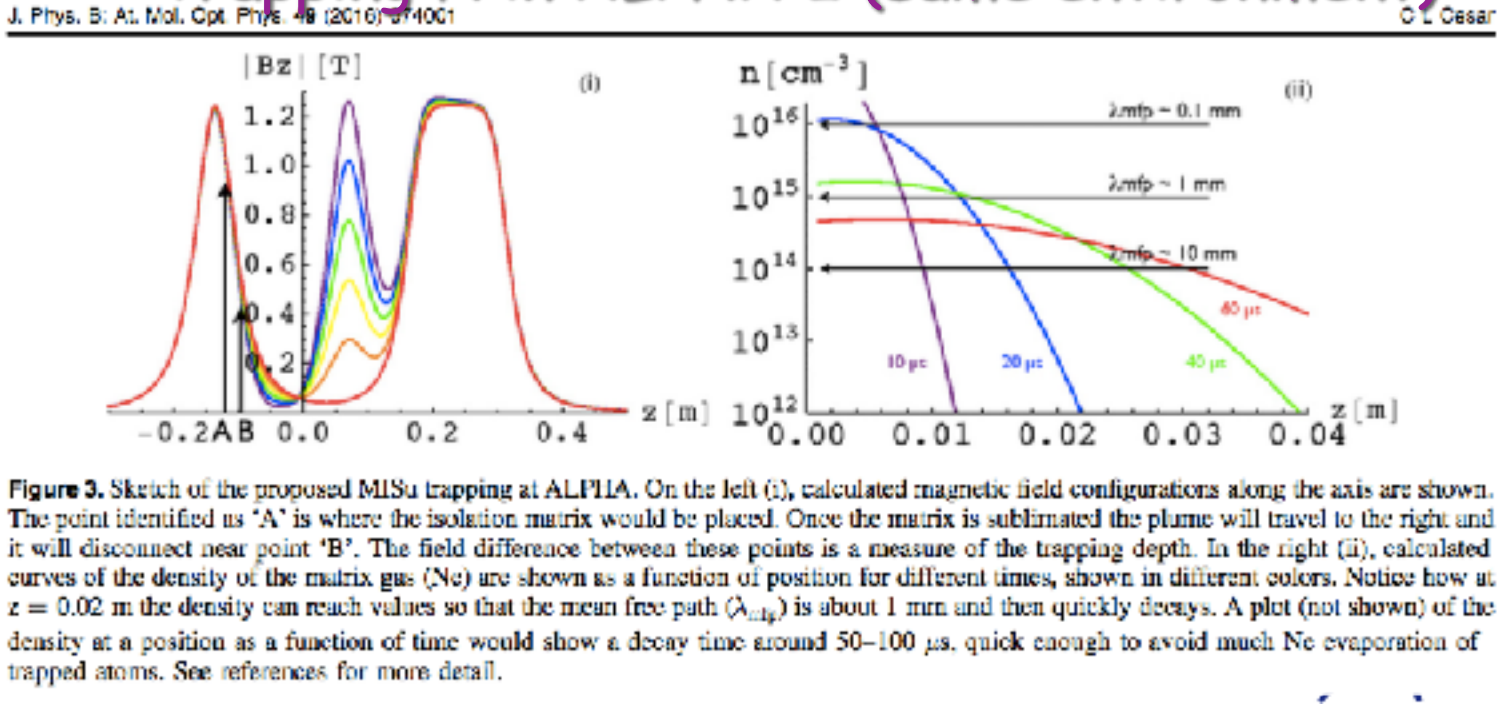


J. Phys. B: At. Mol. Opt. Phys. 49 (2016) 074001 C L Cesar

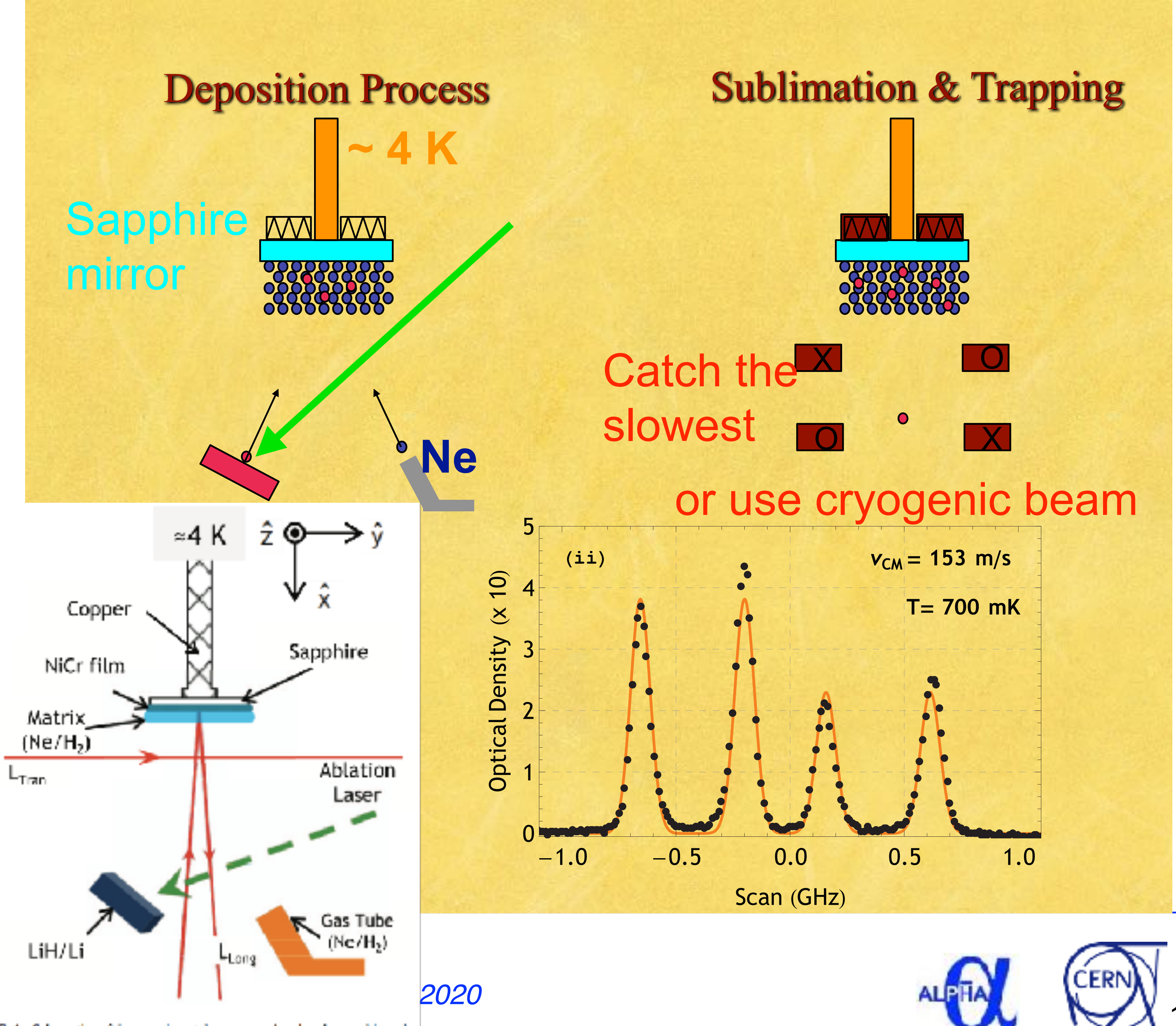
Figure 3. Sketch of the proposed MISu trapping at ALPHA. On the left (i), calculated magnetic field configurations along the axis are shown. The point identified as 'A' is where the isolation matrix would be placed. Once the matrix is sublimated the plume will travel to the right and it will disconnect near point 'B'. The field difference between these points is a measure of the trapping depth. In the right (ii), calculated curves of the density of the matrix gas (Ne) are shown as a function of position for different times, shown in different colors. Notice how at $z = 0.02$ m the density can reach values so that the mean free path (λ_{mfp}) is about 1 mm and then quickly decays. A plot (not shown) of the density at a position as a function of time would show a decay time around 50–100 μs, quick enough to avoid much Ne evaporation of trapped atoms. See references for more detail.

Matrix Isolation Sublimation (MISu): a general technique for cold atoms, molecules and ions

Ne or H2 solid film

Implant species with laser ablation

Sublimate the matriz at cryogenic temperature

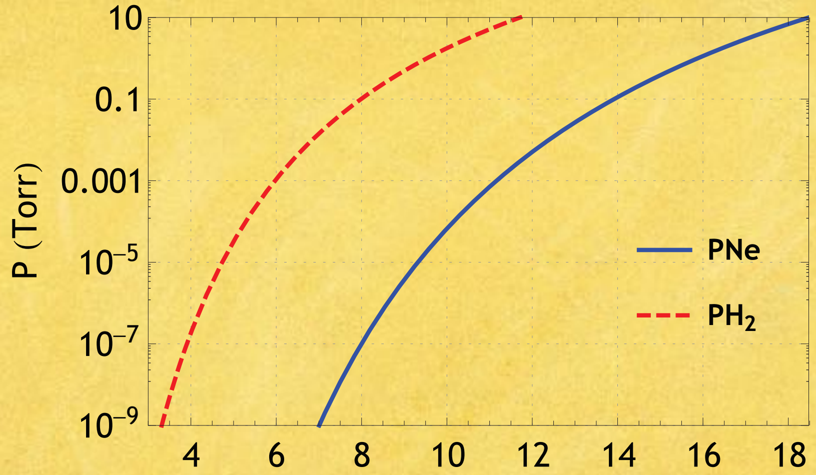


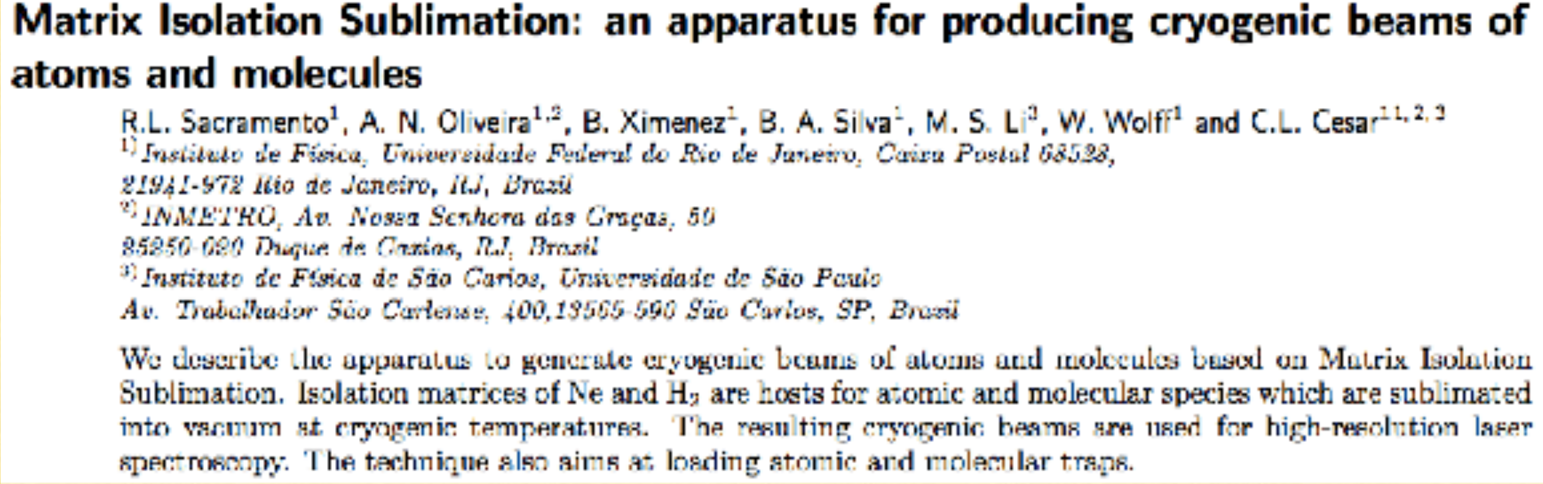
Catch the slowest

or use cryogenic beam

FIG. 1. Schematics of the experimental apparatus showing the sapphire substrate, the NiCr film resistor and the deposited matrix of Ne or H₂ which come

Matrix Isolation Sublimation Apparatus





Matrix Isolation Sublimation: an apparatus for producing cryogenic beams of atoms and molecules

R.L. Sacramento[1], A. N. Oliveira[1,2], B. Ximenez[1], B. A. Silva[1], M. S. Li[3], W. Wolff[1] and C.L. Cesar[1,2,3]

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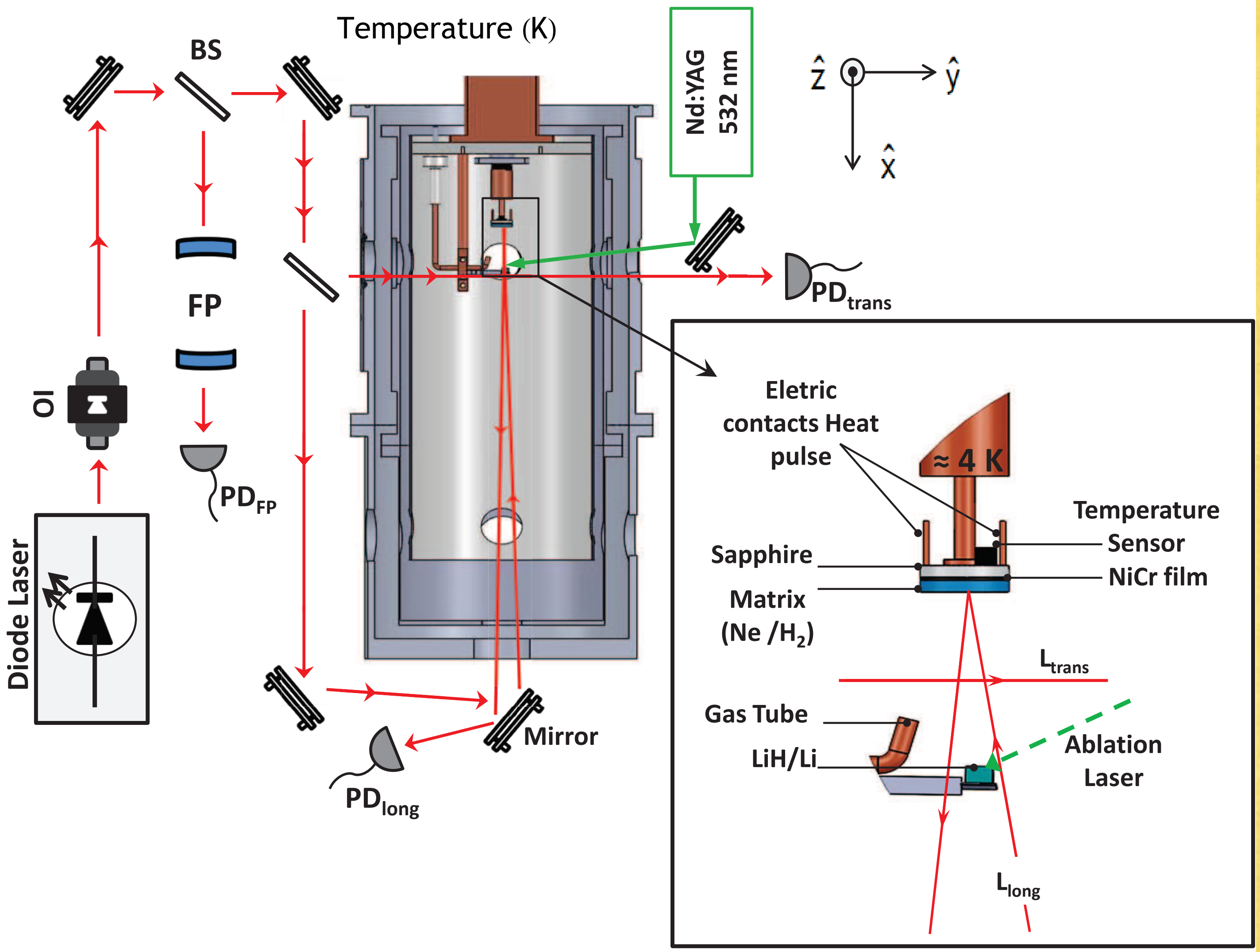
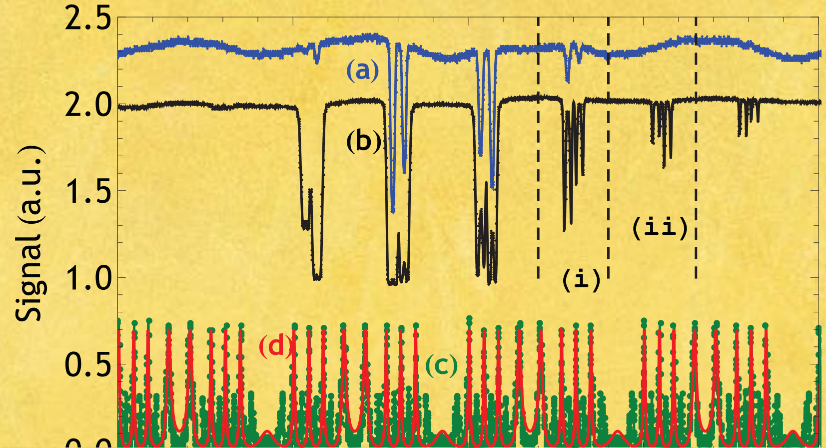
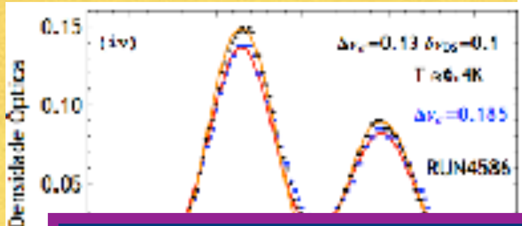
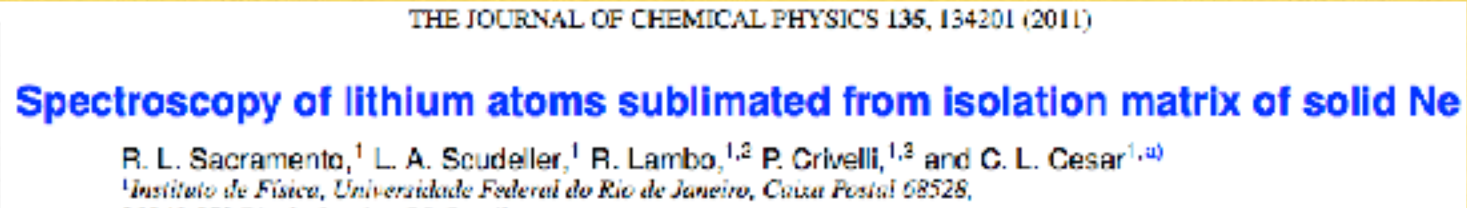
We describe the apparatus to generate cryogenic beams of atoms and molecules based on Matrix Isolation Sublimation. Isolation matrices of Ne and H_2 are hosts for atomic and molecular species which are sublimated into vacuum at cryogenic temperatures. The resulting cryogenic beams are used for high-resolution laser spectroscopy. The technique also aims at loading atomic and molecular traps.





Matrix Isolation Sublimation (MISu): a general technique for cold atoms and molecules



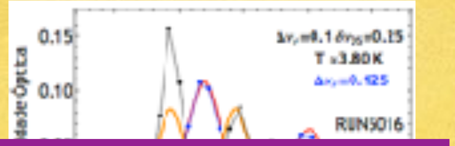

THE JOURNAL OF CHEMICAL PHYSICS 135, 134201 (2011)

Spectroscopy of lithium atoms sublimated from isolation matrix of solid Ne

R. L. Sacramento,[1] L. A. Scudeller,[1] R. Lambo,[1,2] P. Crivelli,[1,3] and C. L. Cesar[1,a)]

[1]*Instituto de Física, Universidade Federal do Rio de Janeiro, Caixa Postal 68528,*

Li in H_2

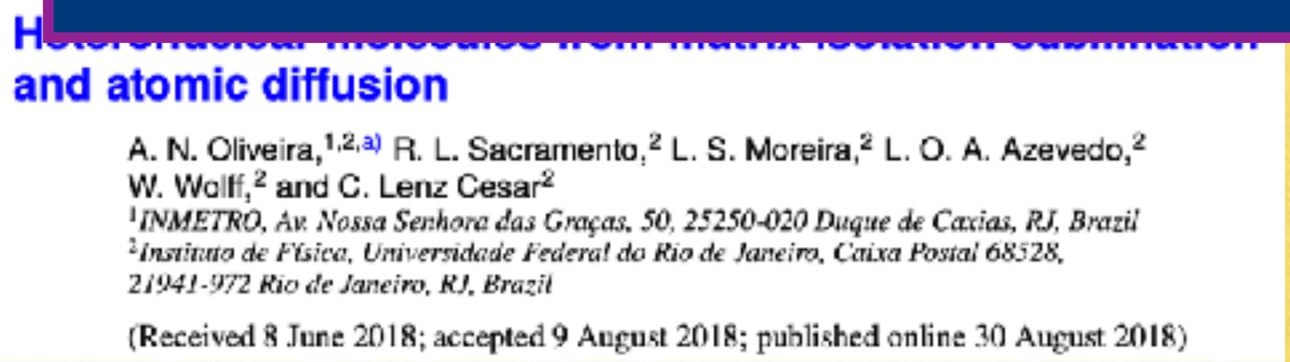


MISu: a made-in-Rio technique to produce cryogenic beams of atoms and molecules:

robust [Rev. Sci. Instrum.86, 073109 (2015)]

Further Developments:

- ⇒ heteronuclear molecules
- ⇒ H/D/T cold beam (~ 1K) spectroscopy
- ⇒ traps for atoms and molecules
- ⇒ H^-/T^- cold beam : transporting into ALPHA & Project8(?)


and atomic diffusion

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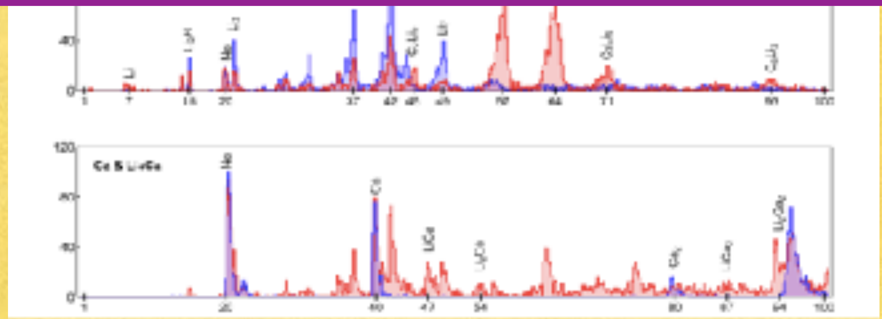
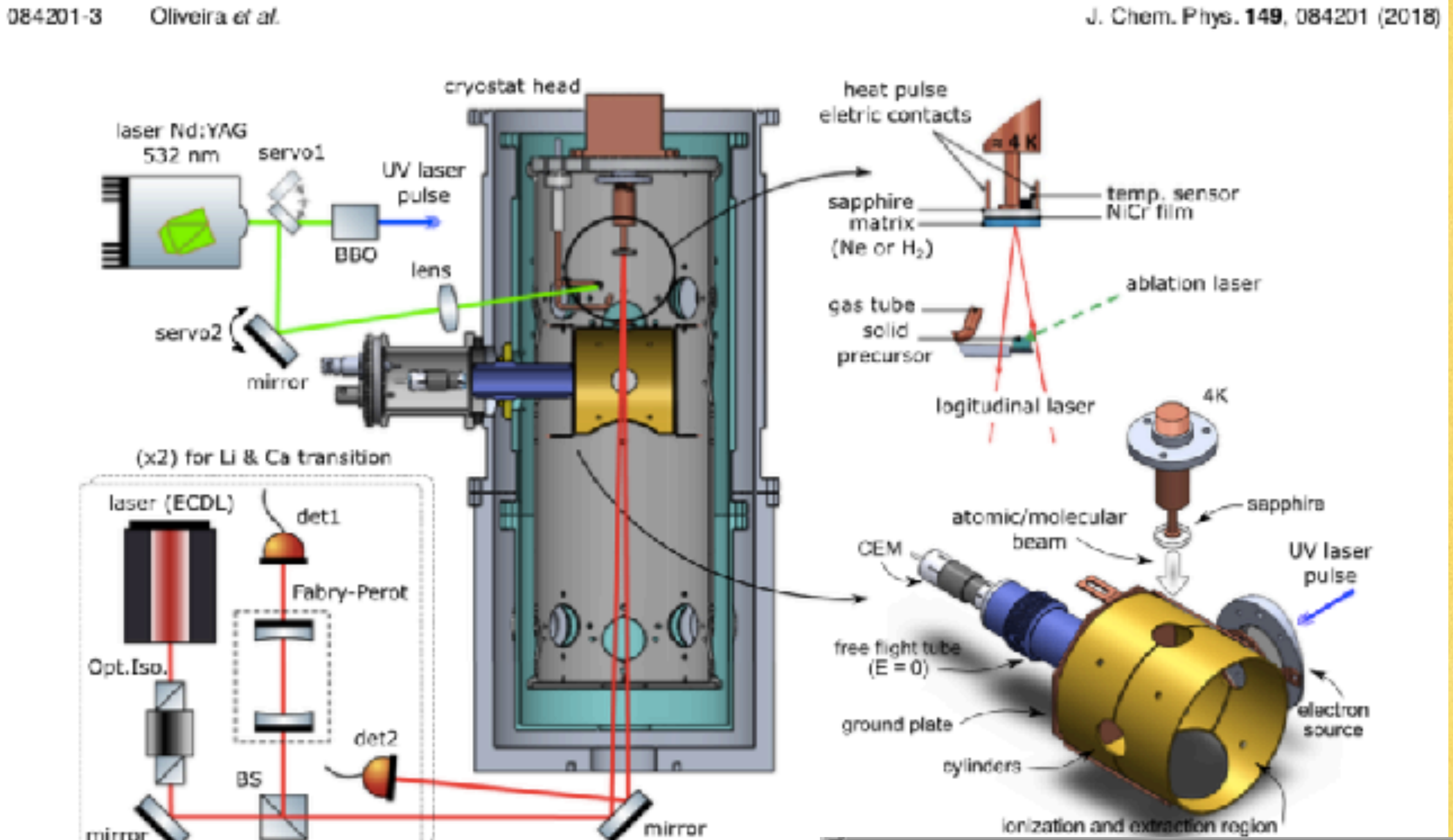
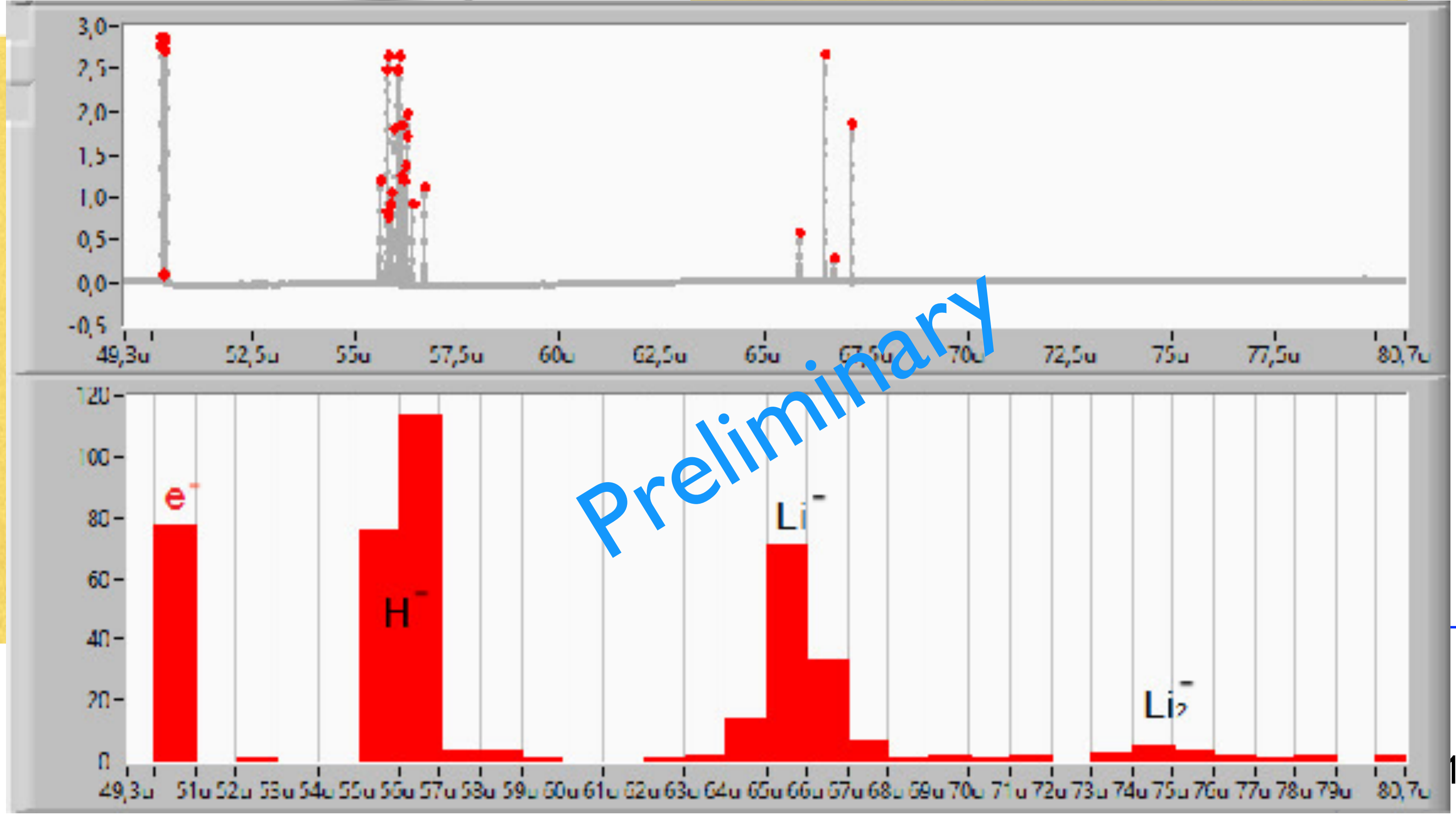


Matrix Isolation Sublimation and Mass Spectrometry: Anions & Cations

084201-3 Oliveira *et al.* J. Chem. Phys. **149**, 084201 (2018)





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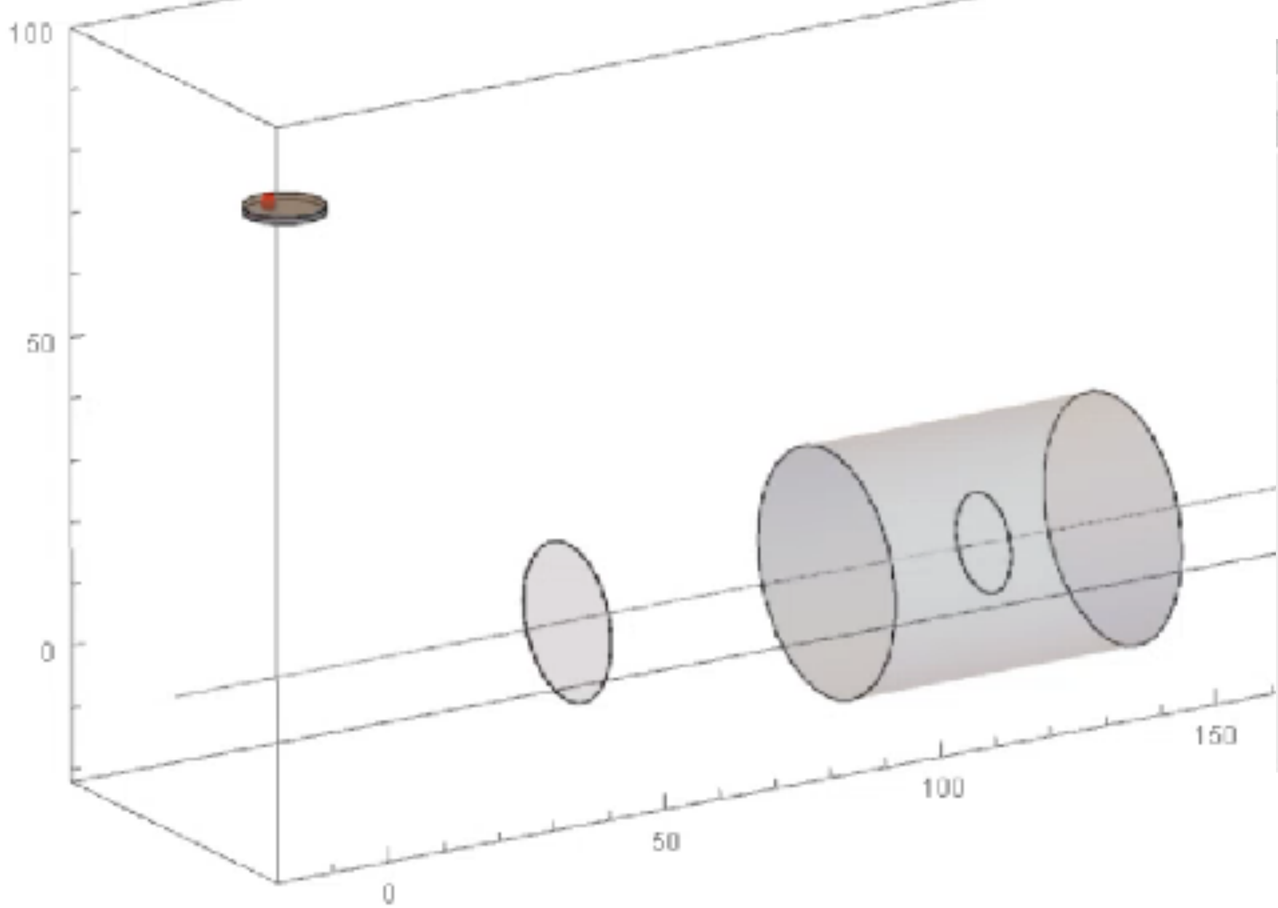
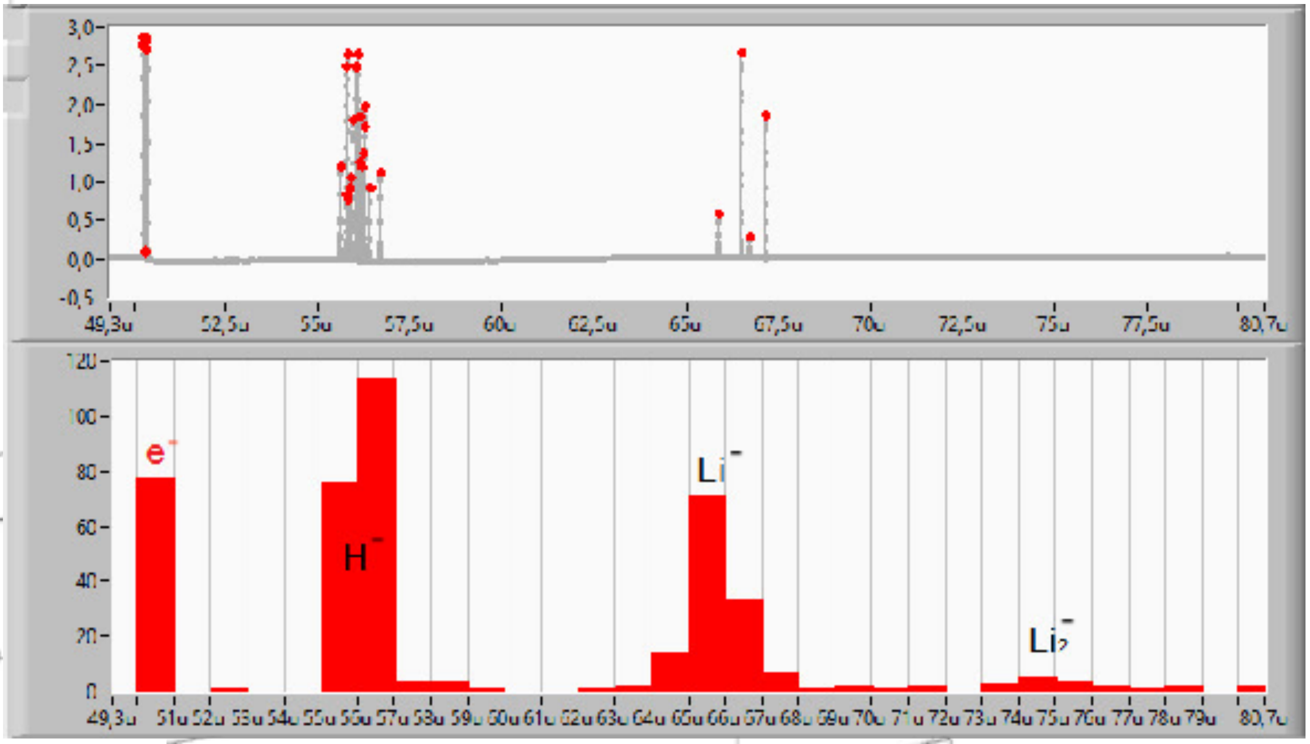
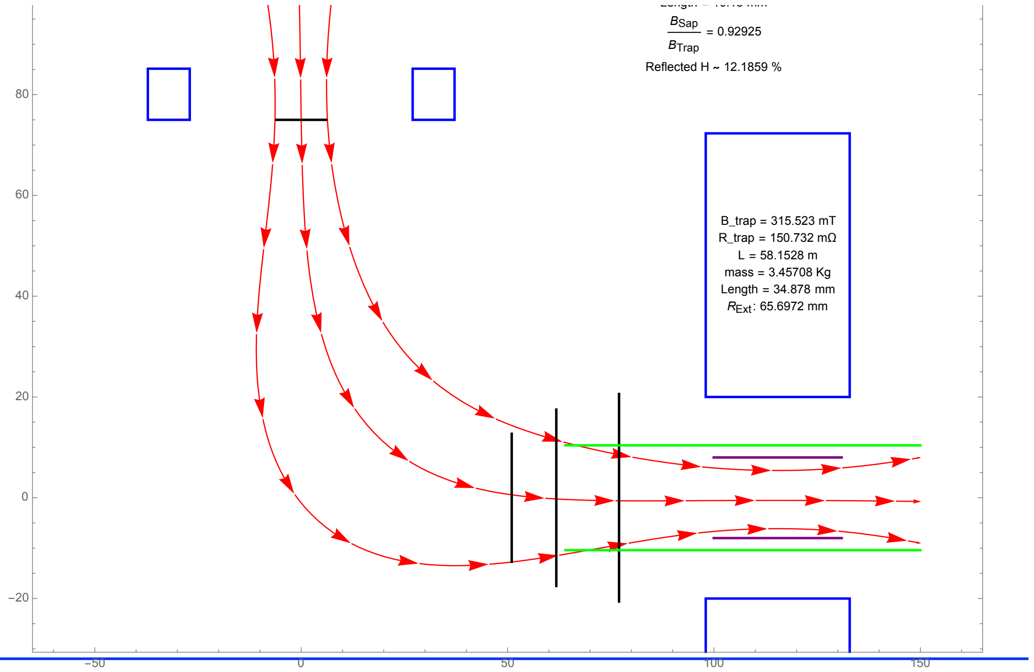
Matrix Isolation Sublimation (MISu):
cold anions (Temático FAPERJ): H-, T-, Li-, Ca-



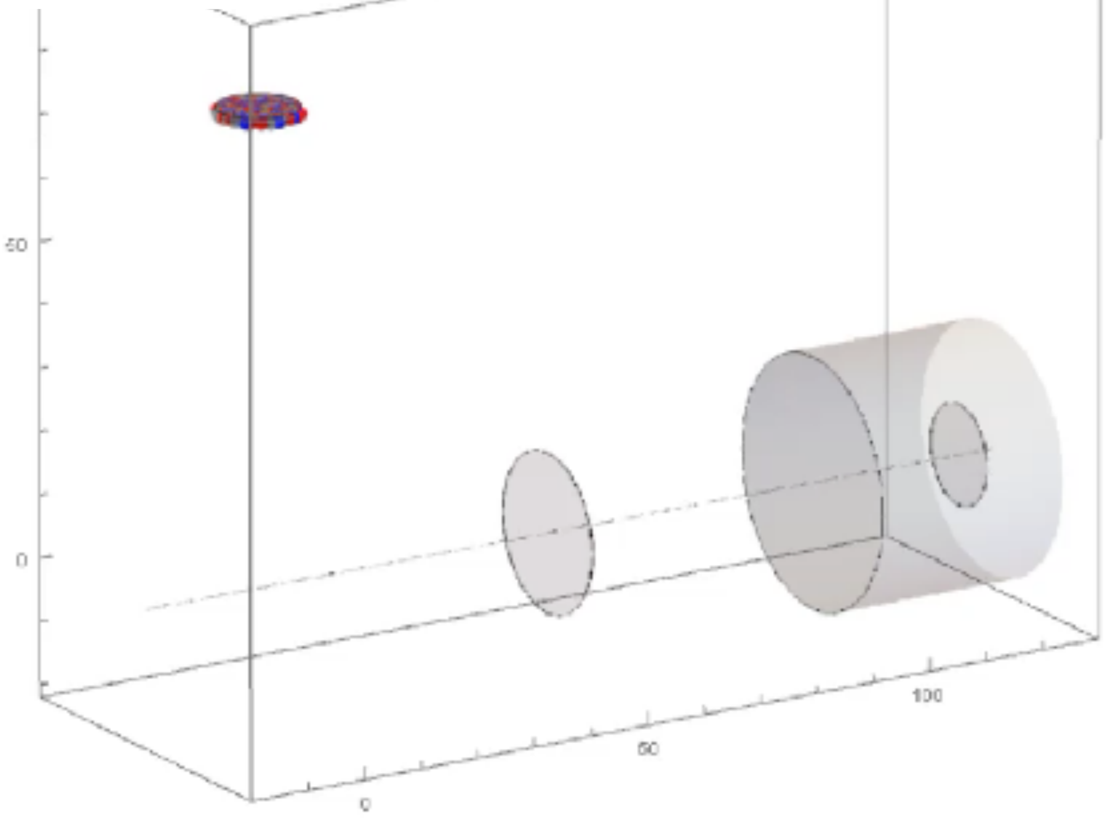




$\frac{B_{Sap}}{B_{Trap}} = 0.92925$

Reflected H ~ 12.1859 %

B_trap = 315.523 mT
R_trap = 150.732 mΩ
L = 58.1528 m
mass = 3.45708 Kg
Length = 34.878 mm
R_{Ext}: 65.6972 mm



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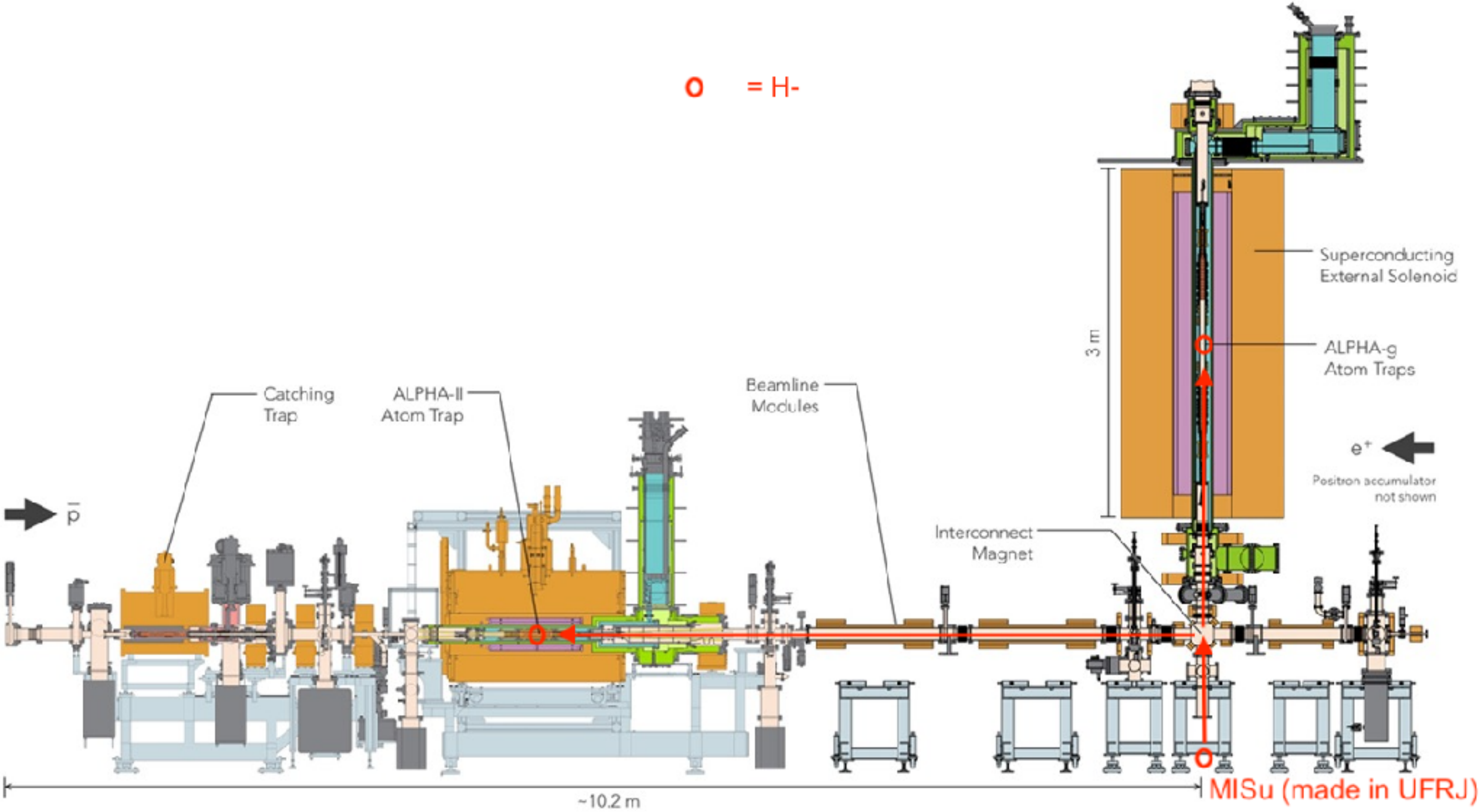
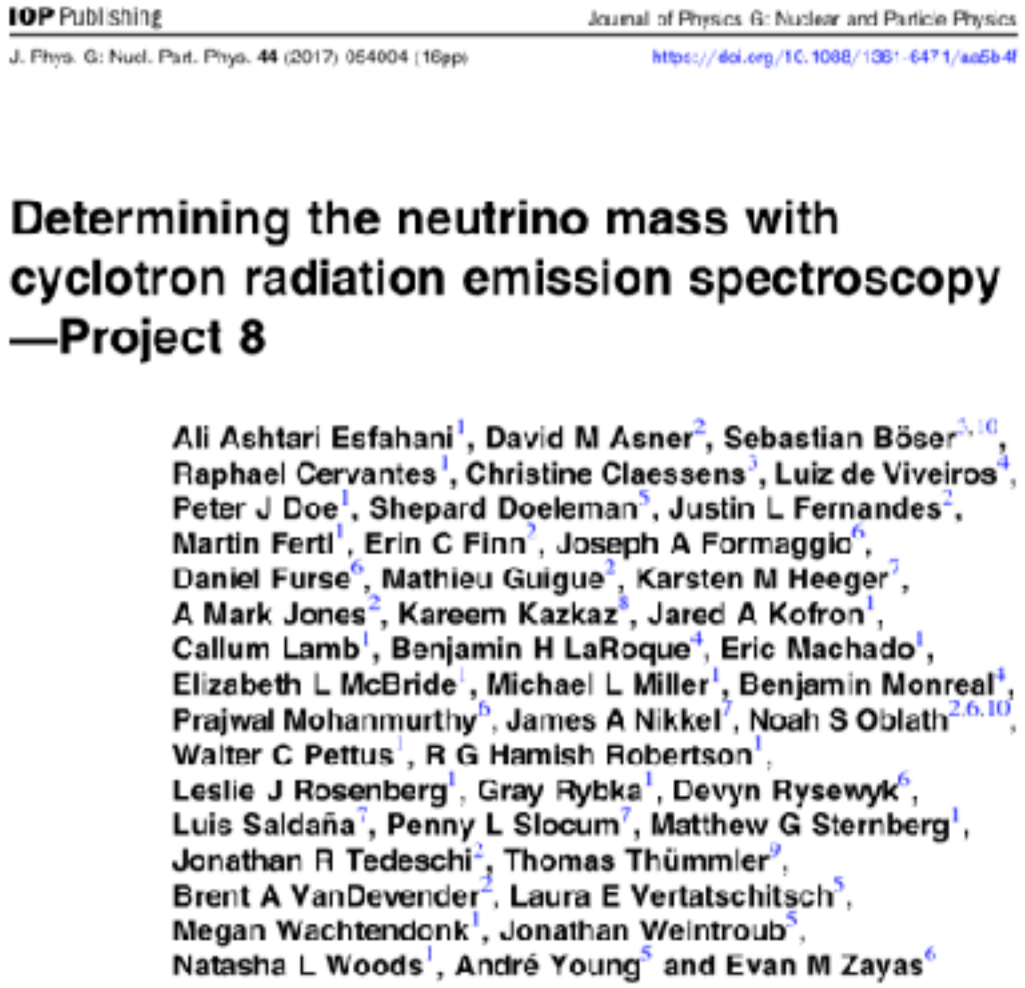
Claudio

Matrix Isolation Sublimation (MISu): cold anions (Temático FAPERJ): H-, T-, Li-, Ca-



PROJECT-8: a compact method to measure neutrino's mass: T decay



IOP Publishing Journal of Physics G: Nuclear and Particle Physics

J. Phys. G: Nucl. Part. Phys. **44** (2017) 054004 (16pp) https://doi.org/10.1088/1361-6471/aa5b4f

Determining the neutrino mass with cyclotron radiation emission spectroscopy—Project 8

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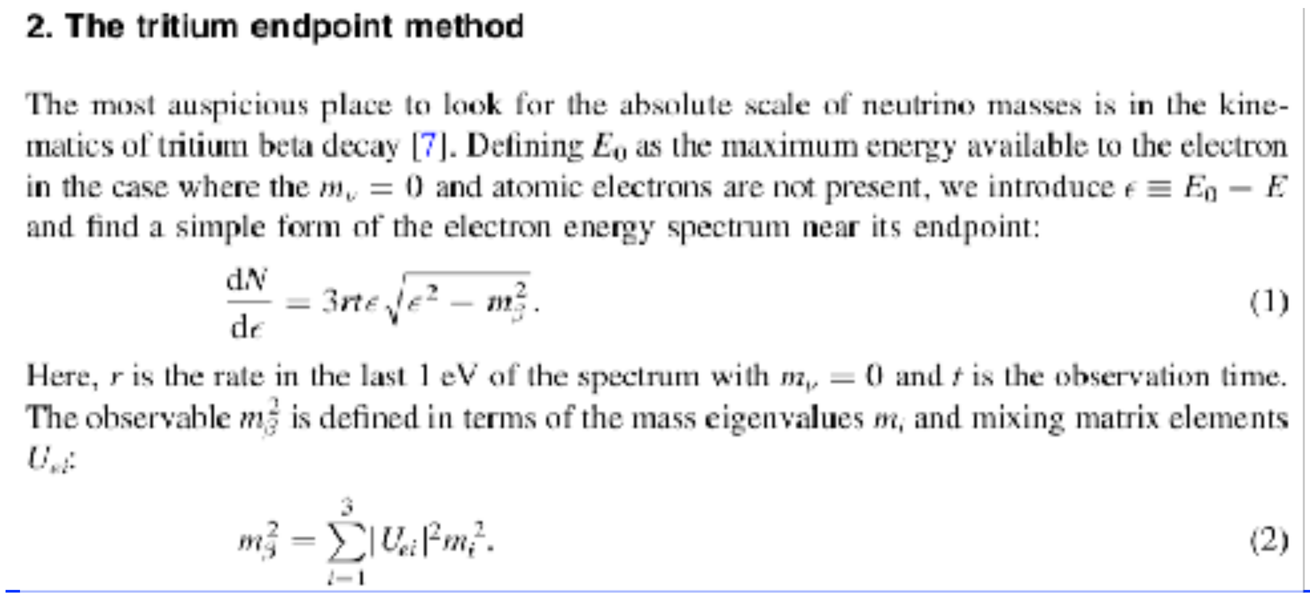


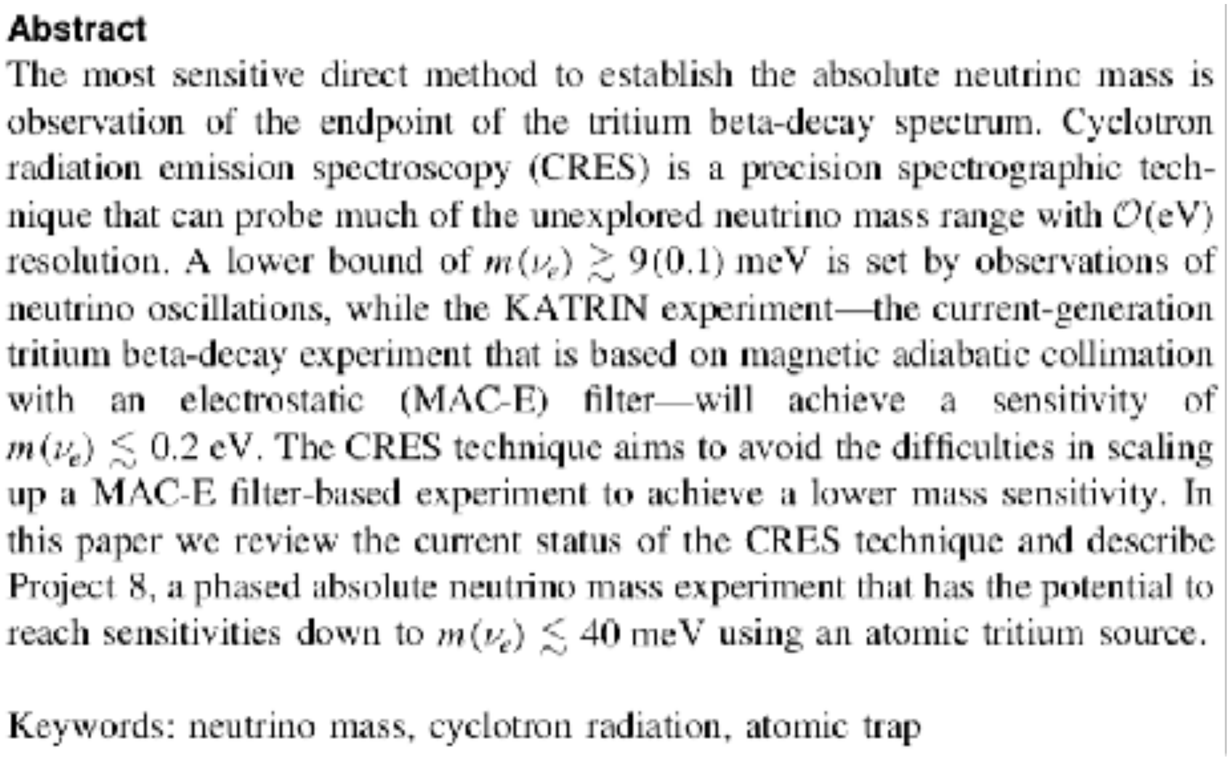
2. The tritium endpoint method

The most auspicious place to look for the absolute scale of neutrino masses is in the kinematics of tritium beta decay [7]. Defining E_0 as the maximum energy available to the electron in the case where the $m_\nu = 0$ and atomic electrons are not present, we introduce $\epsilon \equiv E_0 - E$ and find a simple form of the electron energy spectrum near its endpoint:

$$\frac{dN}{d\epsilon} = 3rt\epsilon\sqrt{\epsilon^2 - m_\beta^2}. \tag{1}$$

Here, r is the rate in the last 1 eV of the spectrum with $m_\nu = 0$ and t is the observation time. The observable m_β^2 is defined in terms of the mass eigenvalues m_i and mixing matrix elements U_{ei}:

$$m_\beta^2 = \sum_{i=1}^{3} |U_{ei}|^2 m_i^2. \tag{2}$$



Abstract

The most sensitive direct method to establish the absolute neutrino mass is observation of the endpoint of the tritium beta-decay spectrum. Cyclotron radiation emission spectroscopy (CRES) is a precision spectrographic technique that can probe much of the unexplored neutrino mass range with $\mathcal{O}$(eV) resolution. A lower bound of $m(\nu_e) \gtrsim 9(0.1)$ meV is set by observations of neutrino oscillations, while the KATRIN experiment—the current-generation tritium beta-decay experiment that is based on magnetic adiabatic collimation with an electrostatic (MAC-E) filter—will achieve a sensitivity of $m(\nu_e) \lesssim 0.2$ eV. The CRES technique aims to avoid the difficulties in scaling up a MAC-E filter-based experiment to achieve a lower mass sensitivity. In this paper we review the current status of the CRES technique and describe Project 8, a phased absolute neutrino mass experiment that has the potential to reach sensitivities down to $m(\nu_e) \lesssim 40$ meV using an atomic tritium source.

Keywords: neutrino mass, cyclotron radiation, atomic trap

PRL **114,** 162501 (2015) PHYSICAL RE

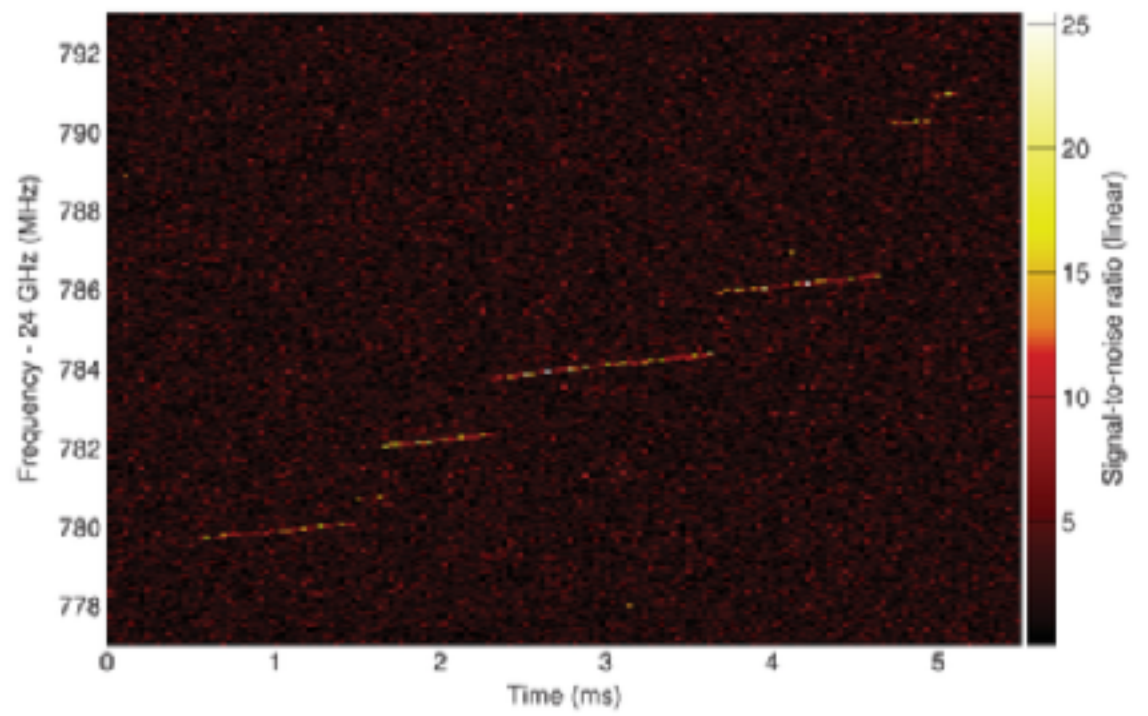


FIG. 2 (color). A typical signal from the decay of $^{83\mathrm{m}}$Kr characterized by an abrupt onset of narrow-band power over the thermal noise of the system. The measured frequency reflects the kinetic energy of the electron, in this case 30 keV. The

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Perspectives with cold Anions: H- , T-, …

- ☆ H- : Easy to guide into ALPHA's antihydrogen Penning+Magnetic Trap
- ☆ Easy to neutralize via photo detachment with a single laser pulse ~100% efficiency

=> Direct comparison of Hbar X H in the same trap: electromagnetic and gravitational field

- ☆ T- : Easy to guide into a magnetic field environment such as PROJECT-8's cell
- ☆ Easy to neutralize via photo detachment with a single laser pulse ~100% efficiency

=> Interesting possibility for neutrino mass measurement via μwave frequency measurement of the highest energy decaying betas.

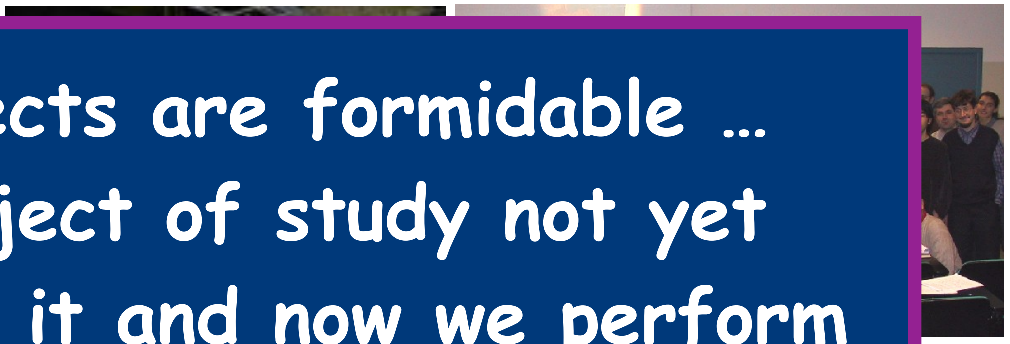
Other anions: astrophysical, molecular, sensors …

InfraStructure - Instrumentation
Being Developed & Desired

- ☆ Superconduting Magnets & HTS Current Leads (High-Tc)
- ☆ Lasers & Frequency Metrology (Optical Frequency Combs, Atomic Clocks)
- ☆ Photodetectors in the UV & VUV (Lyman-ALPHA)
- ☆ Optical Cavities - Cryogenic
- ☆ Mechanical/Electronic Constructions

Conclusions/Perspectives/Acknowledgements

ALPHA @ CERN

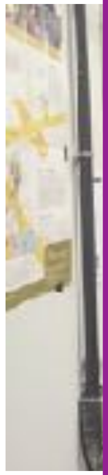


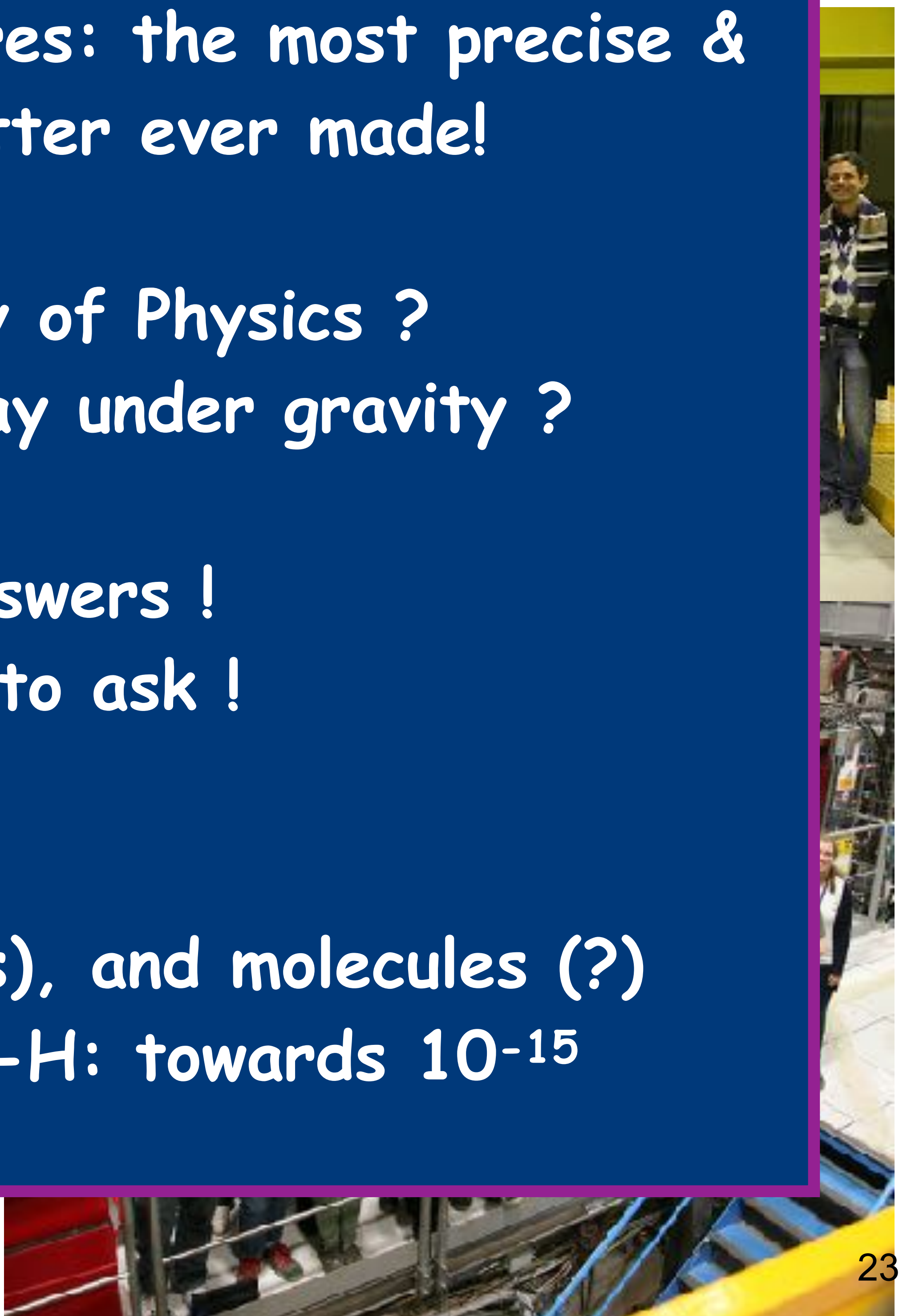
antiHydrogen (ALPHA @ CERN): prospects are formidable …
… we started this program with the object of study not yet existent. We learned to make it, to trap it and now we perform laser spectroscopy to 12 significant figures: the most precise & accurate measurement on antimatter ever made!

- will CPT be a good symmetry of Physics ?
- will antihydrogen fall the same way under gravity ?

only nature has those answers !
but we have learned how to ask !

MISu (@ UFRJ):
a new way of trapping H, T (neutrinos), and molecules (?)
trapping H in the same trap as anti-H: towards 10^{-15}





always looking for interested students:
- se você é um bom estudante, e desejar trabalhar com antimatéria, obter uma formação experimental substancial envolvendo várias técnicas experimentais (vácuo, criogenia, lasers, ótica, eletrônica, RF & μW, supercondutividade, simulação, etc) fazendo física fundamental e quem sabe (talvez) participar de uma revolução na física ...

nos procure: lenz@if.ufrj.br

The End

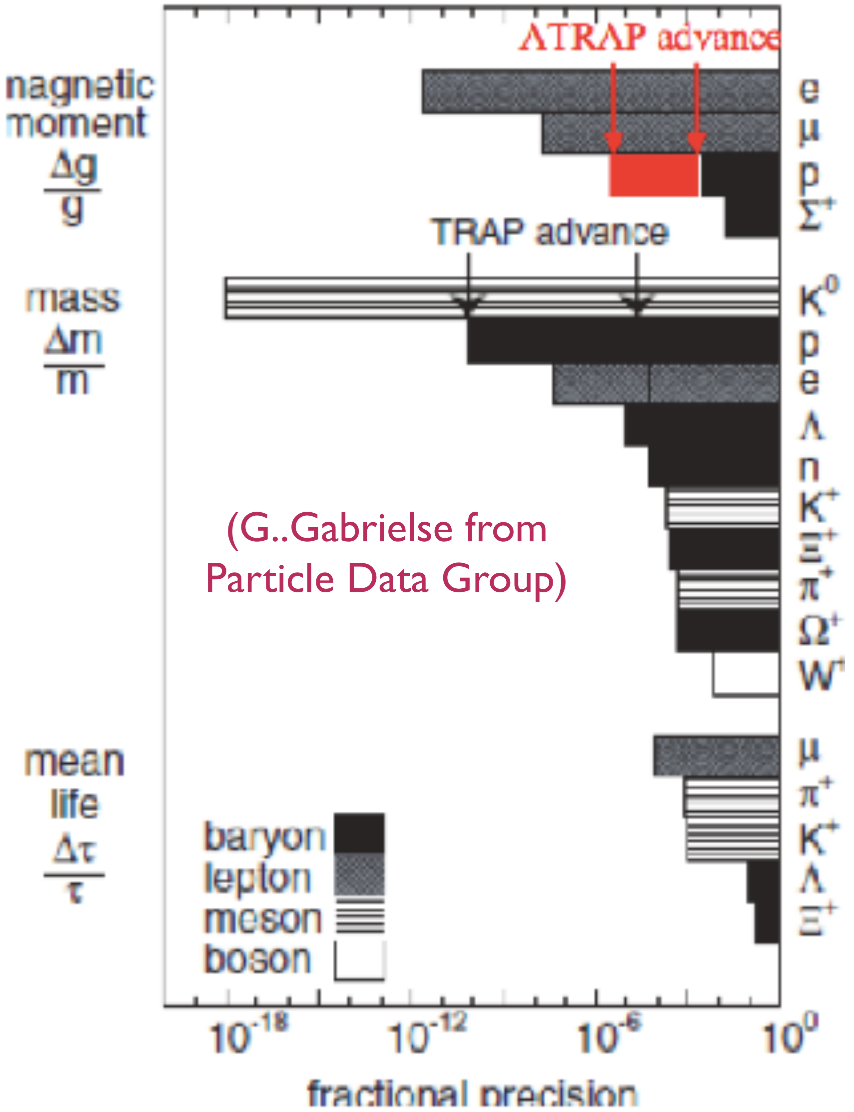
CPT symmetry

Symmetry Operations / Background

"P" - parity, space inversion: -**r** <=> +**r**

"C" - charge conjugation: e- <=> e+

"T" - time reversal: -t <=> +t



(G..Gabrielse from Particle Data Group)

CPT Theorem

Quantum Field Theory
Lorentz Local invariance
Flat space

particles X antiparticles

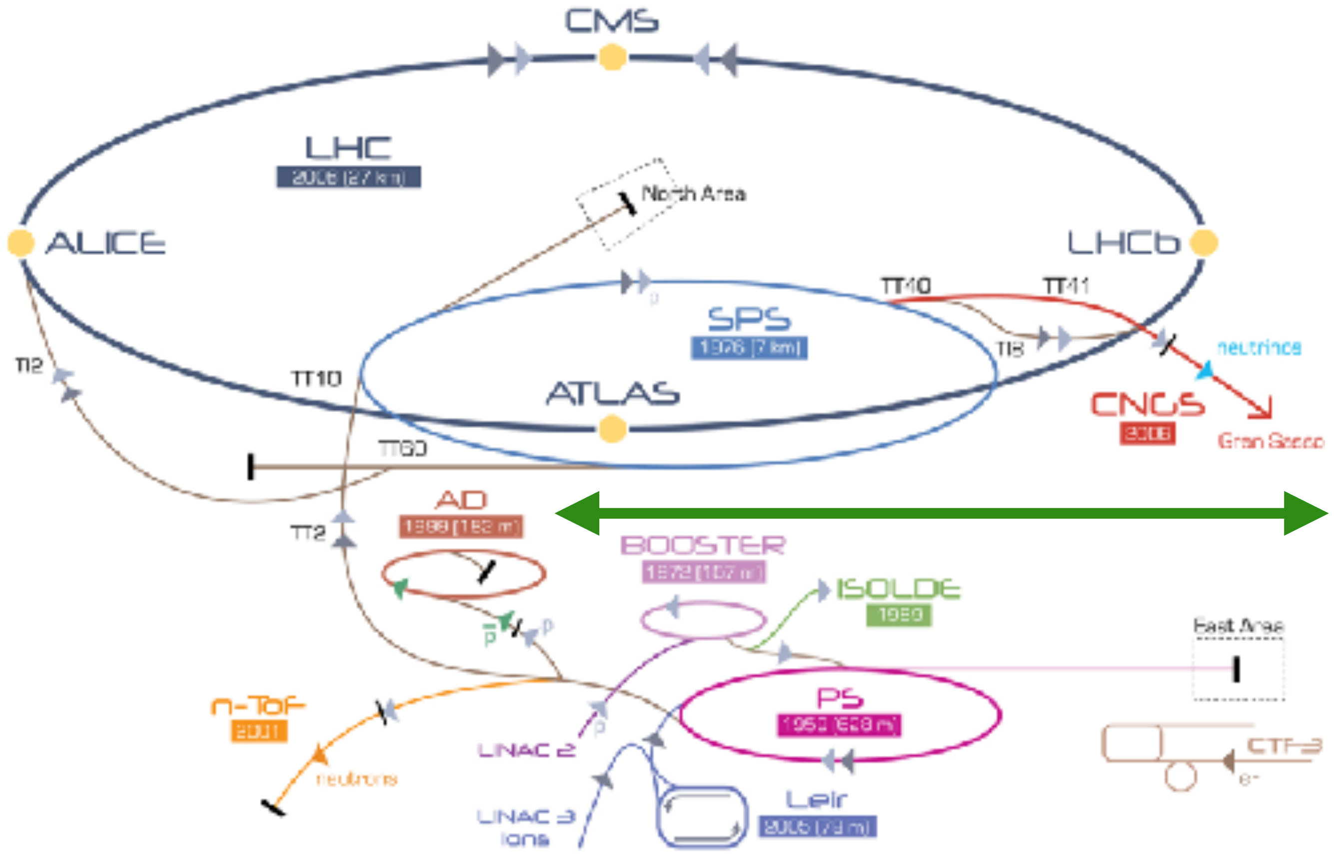
opposite charge, but

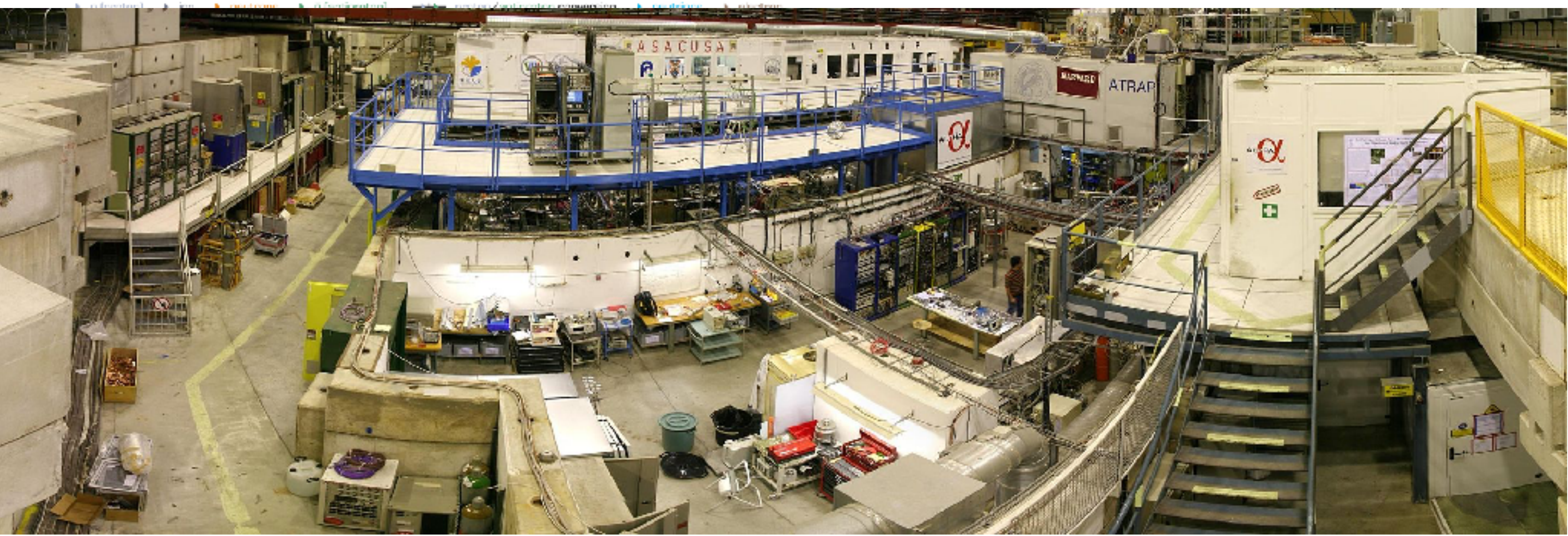
same mass, magnetic moment, mean life, ...

atom X anti-atom

same quantum structure

CERN's Antiproton Decelerator (AD)





ALPHA Collaboration (Est. 2006)

University of Aarhus, Denmark

Auburn University, USA

University of British Columbia, Canada

University of California Berkeley, USA

University of Liverpool, UK

NRCN - Nucl. Res. Center Negev, Israel

RIKEN, Japan

Federal University of Rio de Janeiro, Brazil

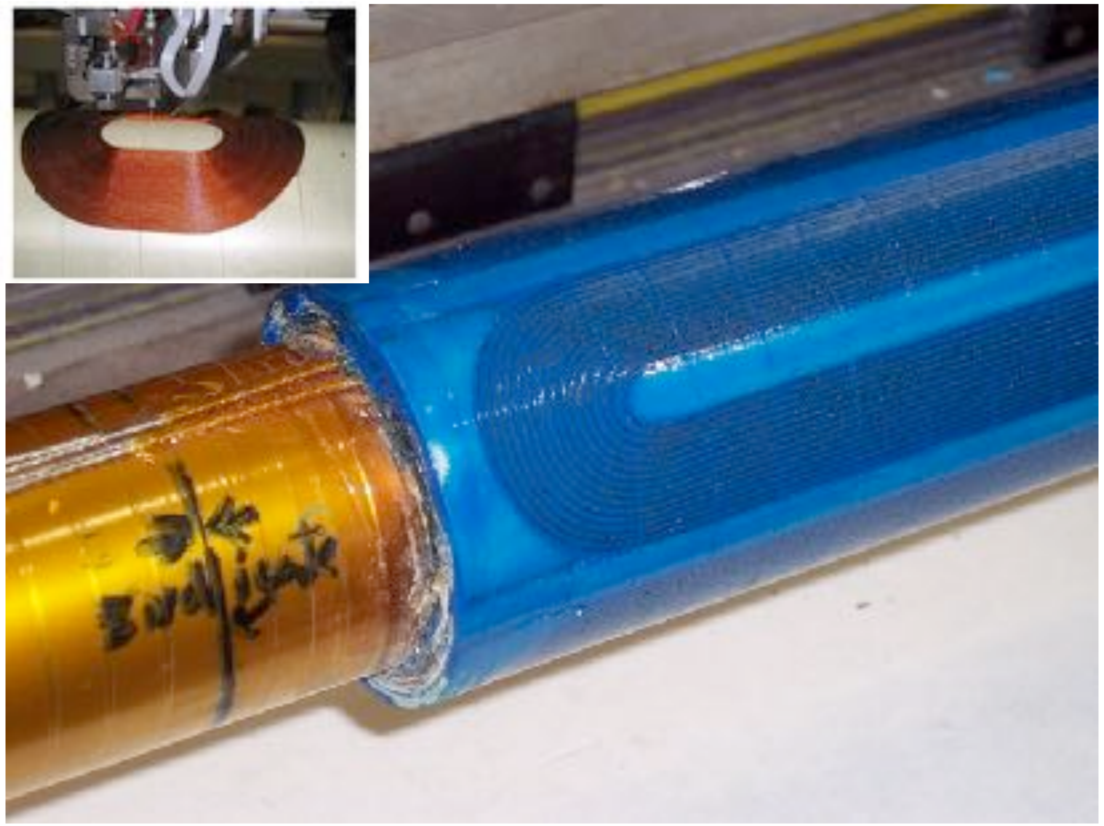
Simon Fraser University, Canada

TRIUMF, Canada

University of Wales Swansea, UK

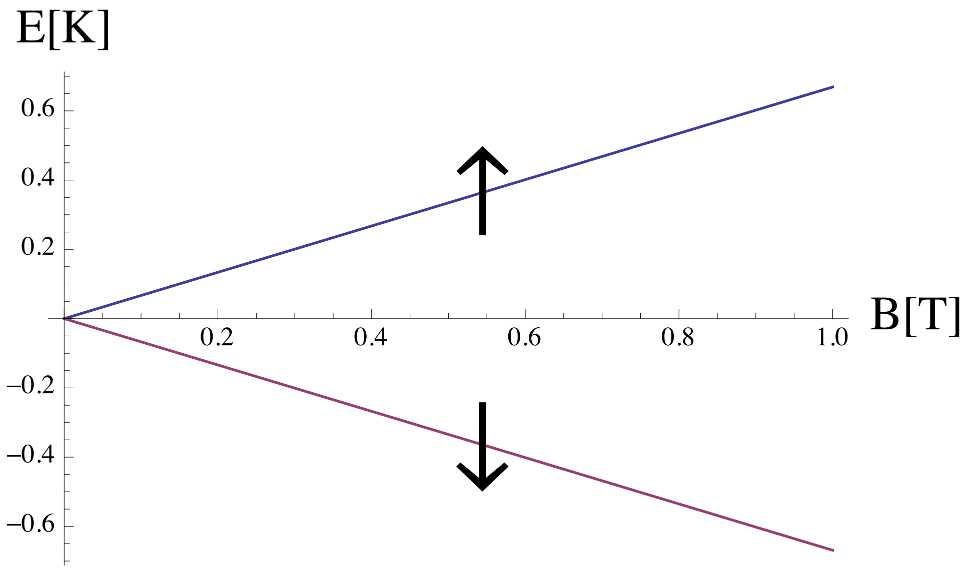
University of Tokyo, Japan

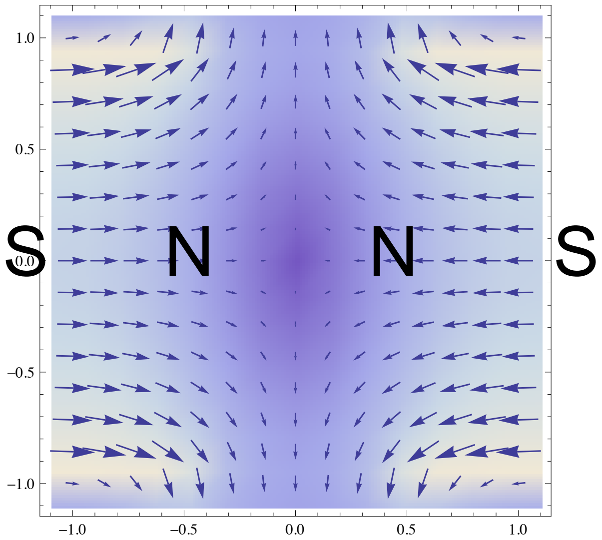
Magnetic Trap

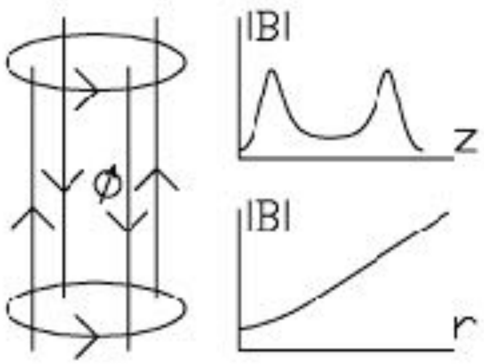


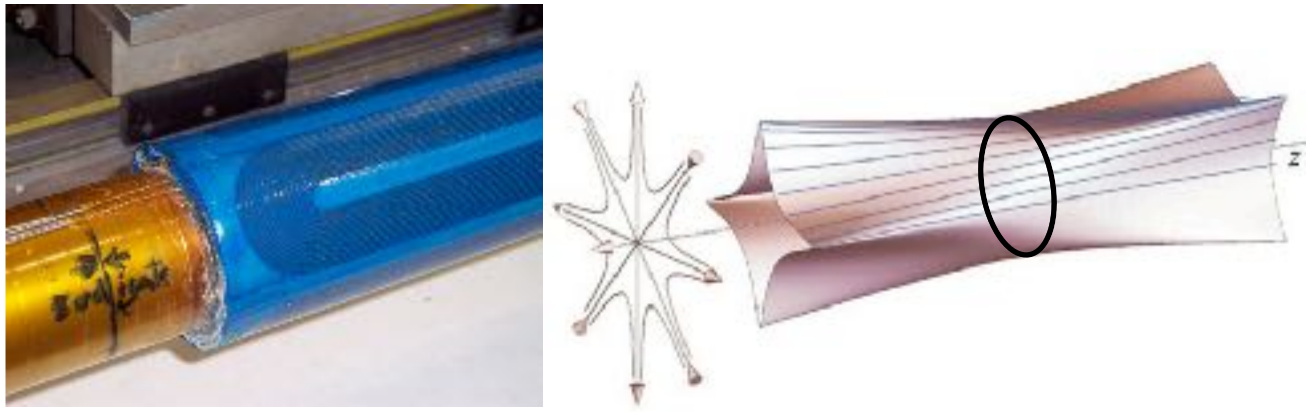
$$U = -\vec{\mu} \cdot \vec{B}$$

$$\vec{F} = -\vec{\nabla} U = \mu \vec{\nabla} B$$



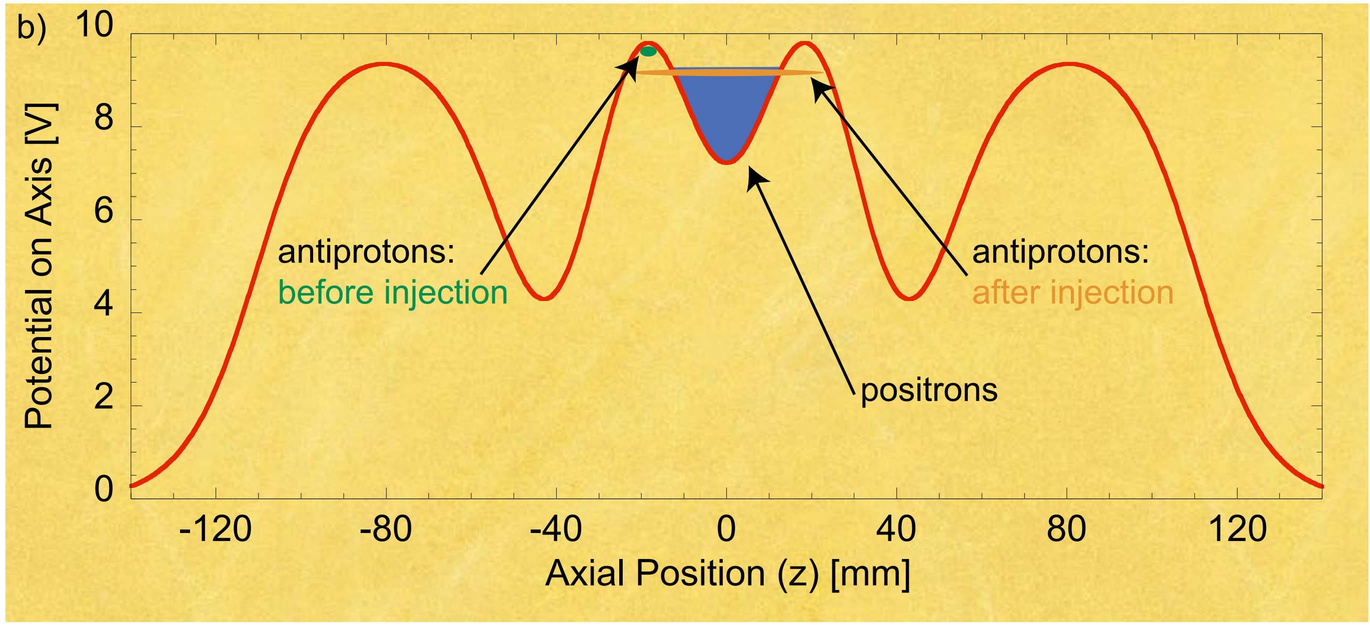


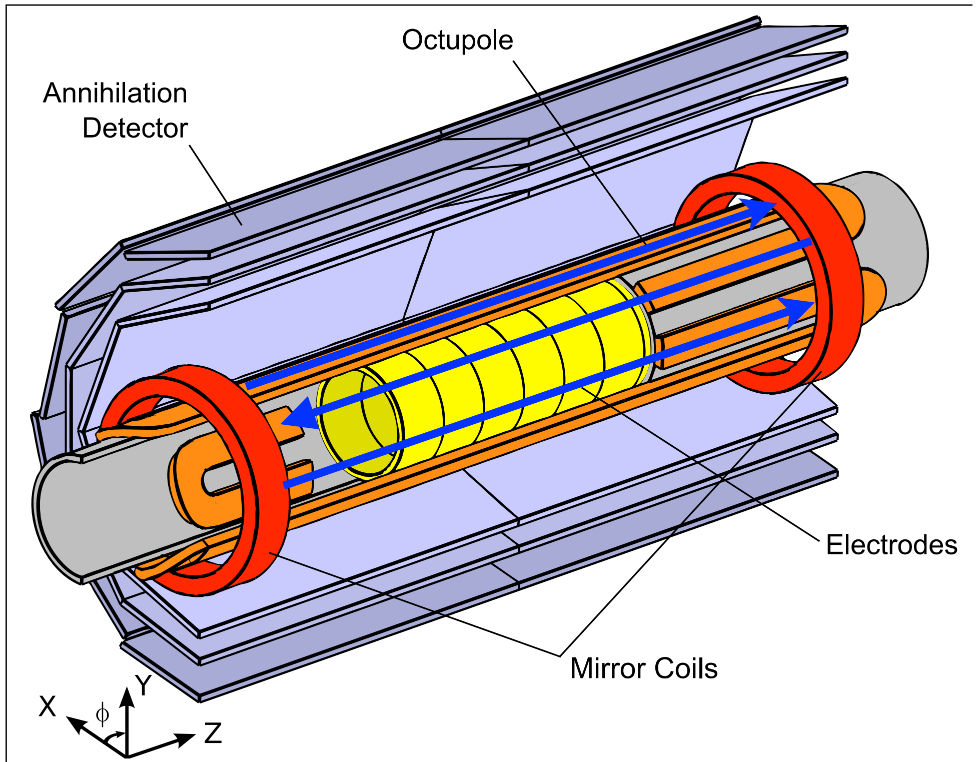


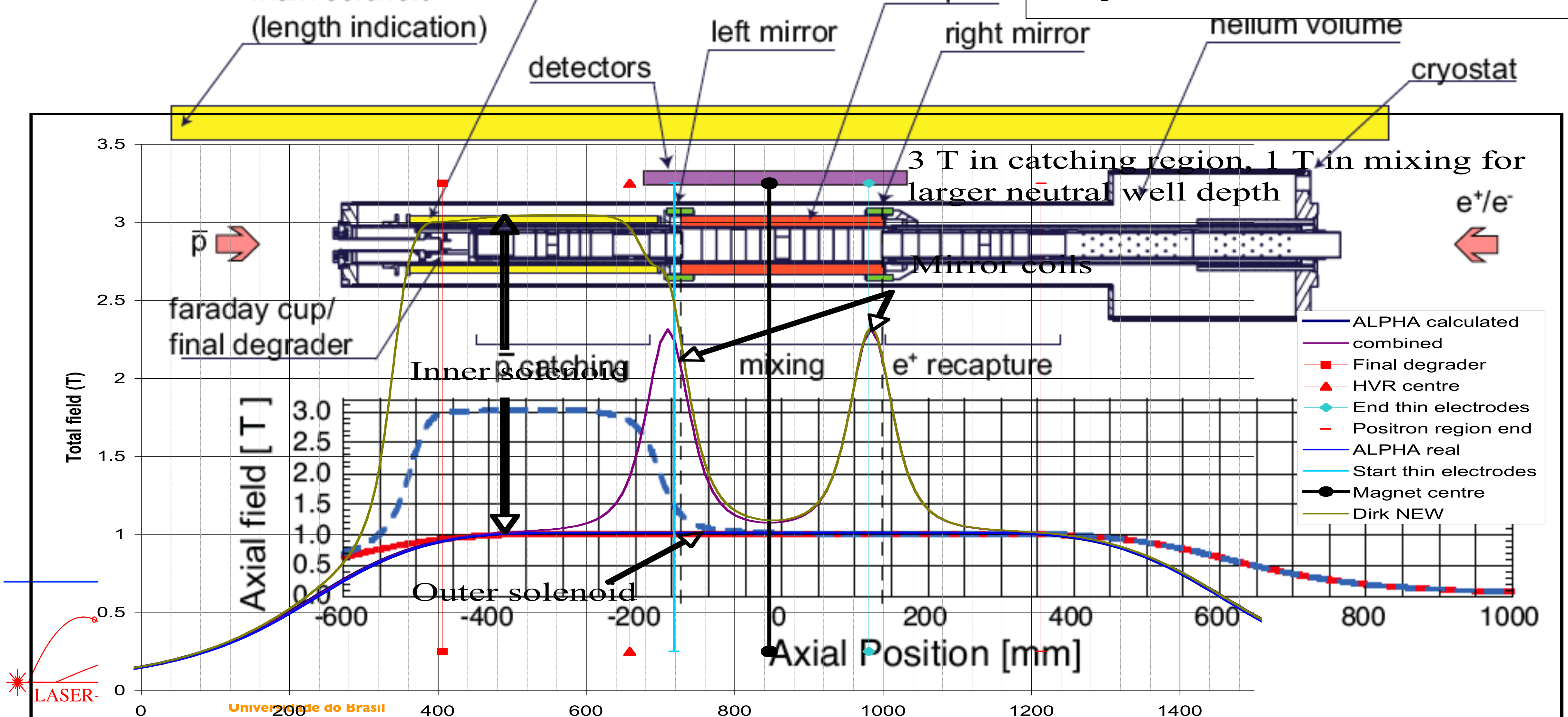


ALPHA ~ Ioffe-Pritchard
8-pole + pinch coils

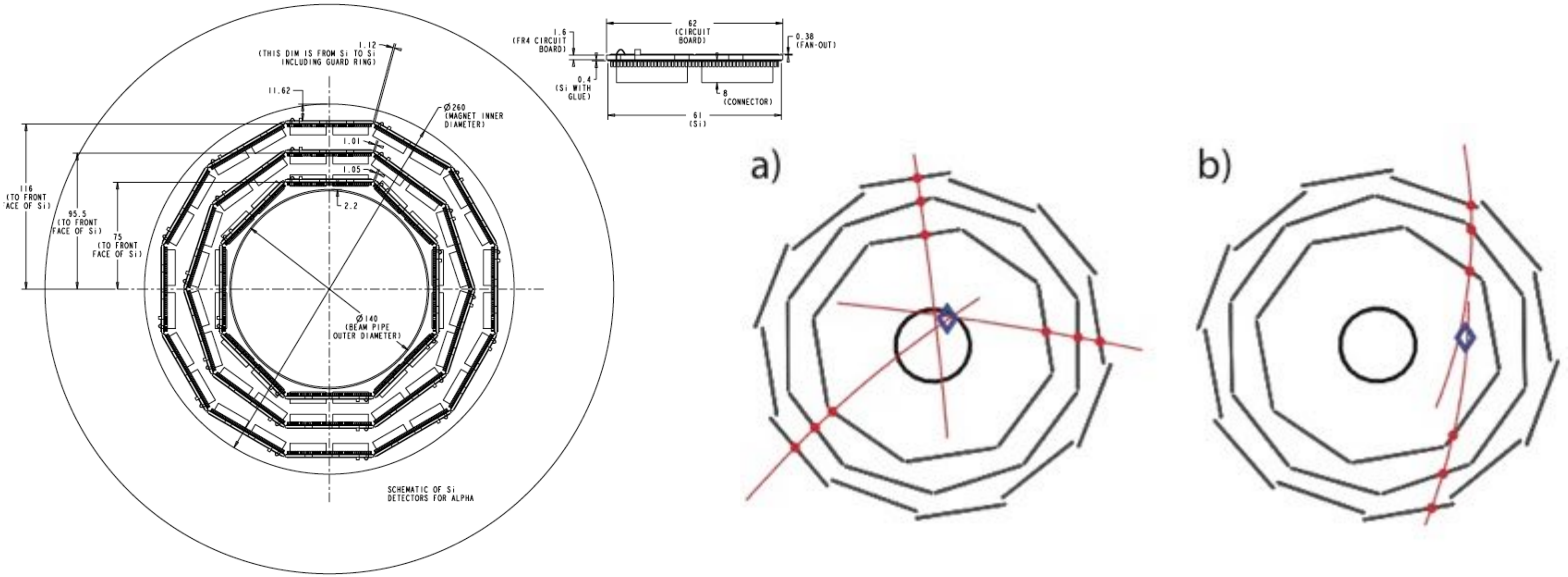
Field Configuration

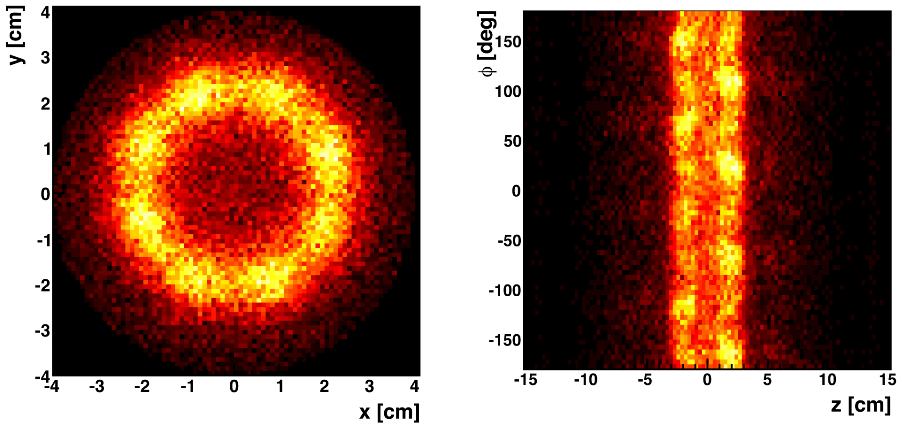




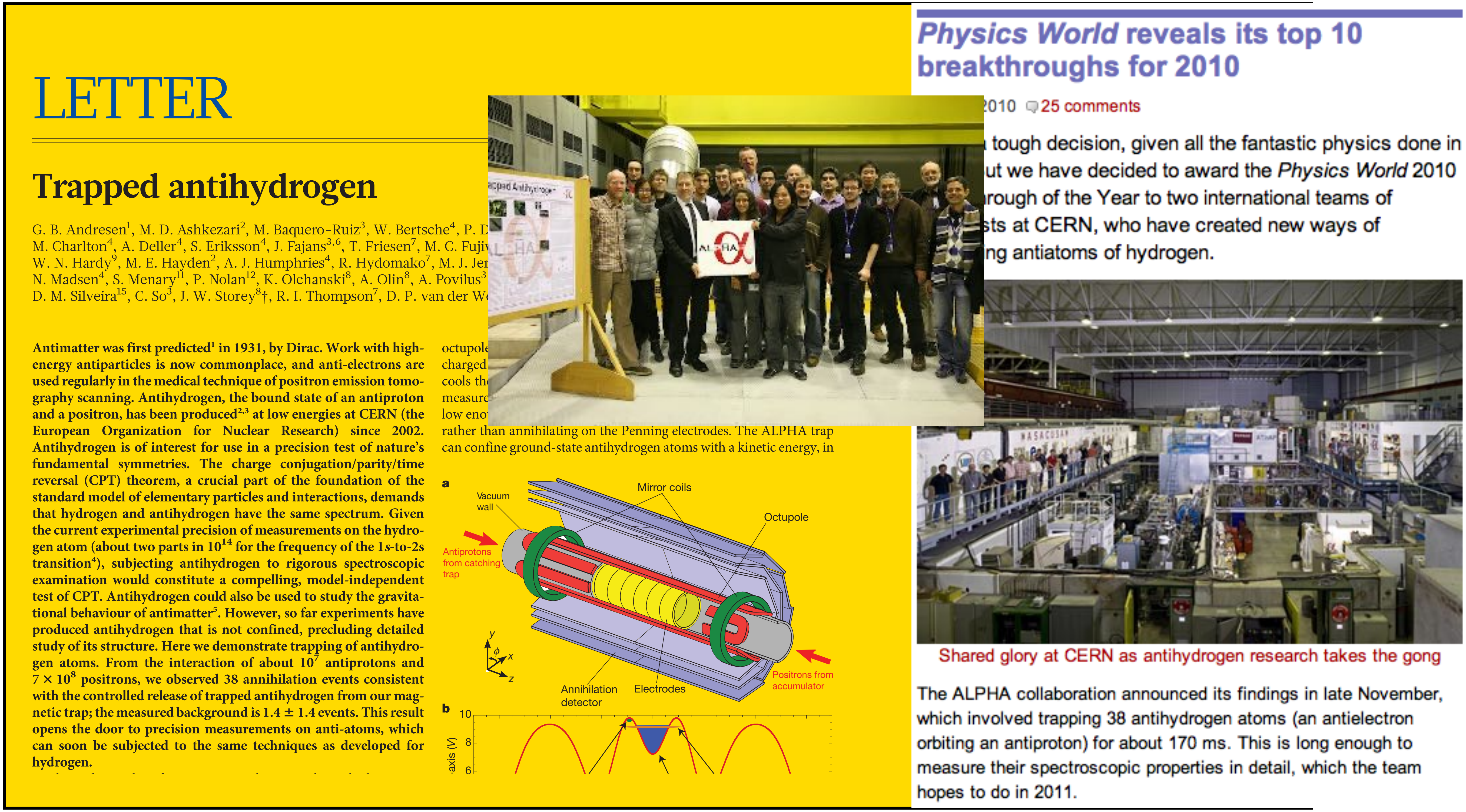


ALPHA: Pbar annihilation = pions imaged in a silicon vertex detector





ALPHA Collaboration @ CERN: First trapped anti-atoms



LETTER

Trapped antihydrogen

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M. Charlton[4], A. Deller[4], S. Eriksson[4], J. Fajans[3,6], T. Friesen[7], M. C. Fujiv
W. N. Hardy[9], M. E. Hayden[2], A. J. Humphries[4], R. Hydomako[7], M. J. Jen
N. Madsen[4], S. Menary[11], P. Nolan[12], K. Olchanski[8], A. Olin[8], A. Povilus[3
D. M. Silveira[15], C. So[3], J. W. Storey[8]†, R. I. Thompson[7], D. P. van der W

Antimatter was first predicted[1] in 1931, by Dirac. Work with high-energy antiparticles is now commonplace, and anti-electrons are used regularly in the medical technique of positron emission tomography scanning. Antihydrogen, the bound state of an antiproton and a positron, has been produced[2,3] at low energies at CERN (the European Organization for Nuclear Research) since 2002. Antihydrogen is of interest for use in a precision test of nature's fundamental symmetries. The charge conjugation/parity/time reversal (CPT) theorem, a crucial part of the foundation of the standard model of elementary particles and interactions, demands that hydrogen and antihydrogen have the same spectrum. Given the current experimental precision of measurements on the hydrogen atom (about two parts in 10^{14} for the frequency of the 1*s*-to-2*s* transition[4]), subjecting antihydrogen to rigorous spectroscopic examination would constitute a compelling, model-independent test of CPT. Antihydrogen could also be used to study the gravitational behaviour of antimatter[5]. However, so far experiments have produced antihydrogen that is not confined, precluding detailed study of its structure. Here we demonstrate trapping of antihydrogen atoms. From the interaction of about 10^7 antiprotons and 7×10^8 positrons, we observed 38 annihilation events consistent with the controlled release of trapped antihydrogen from our magnetic trap; the measured background is 1.4 ± 1.4 events. This result opens the door to precision measurements on anti-atoms, which can soon be subjected to the same techniques as developed for hydrogen.

octupole
charged
cools th
measure
low eno
rather than annihilating on the Penning electrodes. The ALPHA trap can confine ground-state antihydrogen atoms with a kinetic energy, in

Physics World reveals its top 10 breakthroughs for 2010

2010 25 comments

tough decision, given all the fantastic physics done in
ut we have decided to award the *Physics World* 2010
rough of the Year to two international teams of
sts at CERN, who have created new ways of
ng antiatoms of hydrogen.

Shared glory at CERN as antihydrogen research takes the gong

The ALPHA collaboration announced its findings in late November, which involved trapping 38 antihydrogen atoms (an antielectron orbiting an antiproton) for about 170 ms. This is long enough to measure their spectroscopic properties in detail, which the team hopes to do in 2011.