Antihidrogênio X Hidrogênio : Testes de CPT e WEP

espectroscopia e gravidade

FAPERJ
CNPq
Conselho Nacional de Desenvolvimento Científico e Tecnológico
RENAFAE

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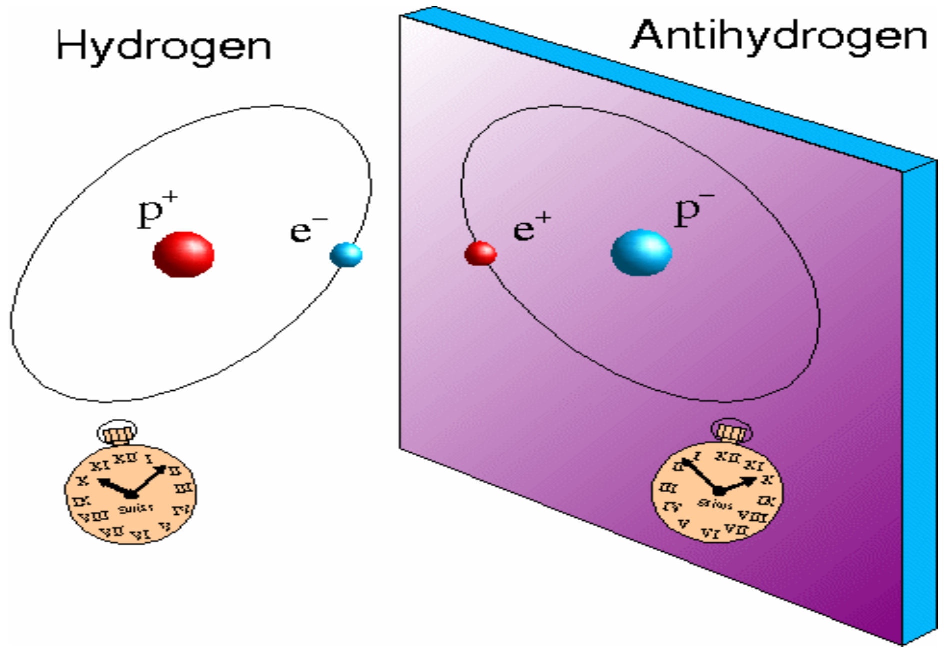
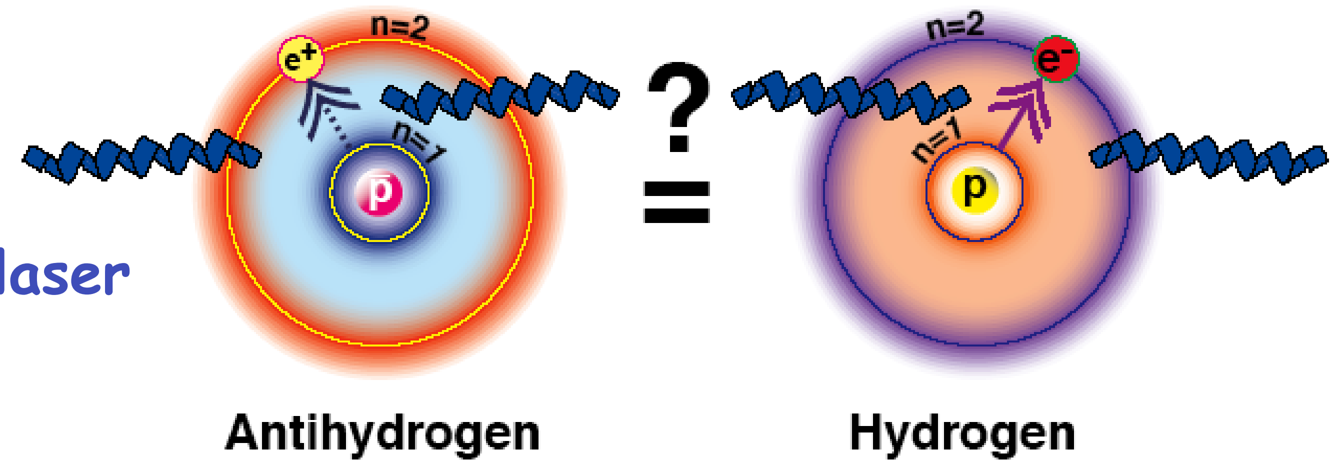
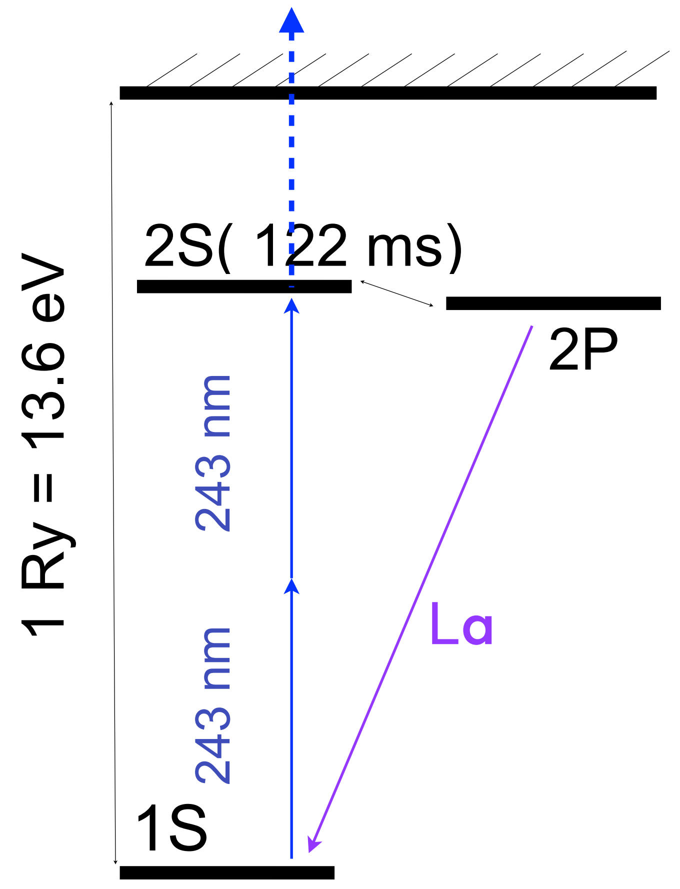


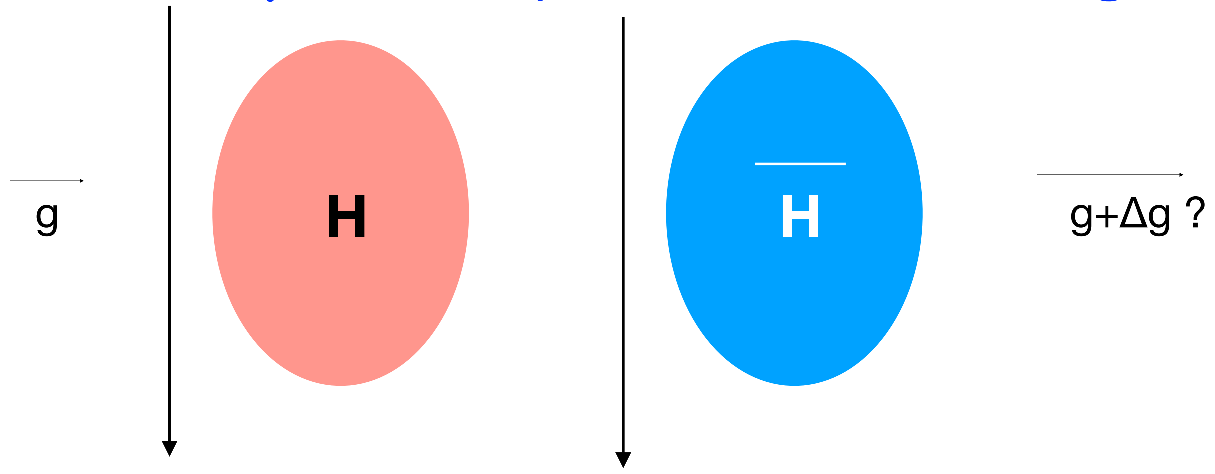
1 - Simetria de CPT, base do Modelo Padrão



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



2 - Princípio de Equivalência Fraco: g ou g+Δg ?



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

0 - Motivações Principais :
(Bariogenesis)

- cadê a antimatéria primordial no Universo? Big-Bang não explica a Matéria em nosso Universo.
- Física além do Modelo Padrão

Além de modelos e teorias …: - anti-átomos só existem em nosso laboratório!

A medida mais precisa e acurada já feita com antimatéria!!!

LETTER

OPEN

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

https://www.nature.com/articles/s41586-018-0017-2 (2018)

Characterization of the 1S–2S transition in antihydrogen

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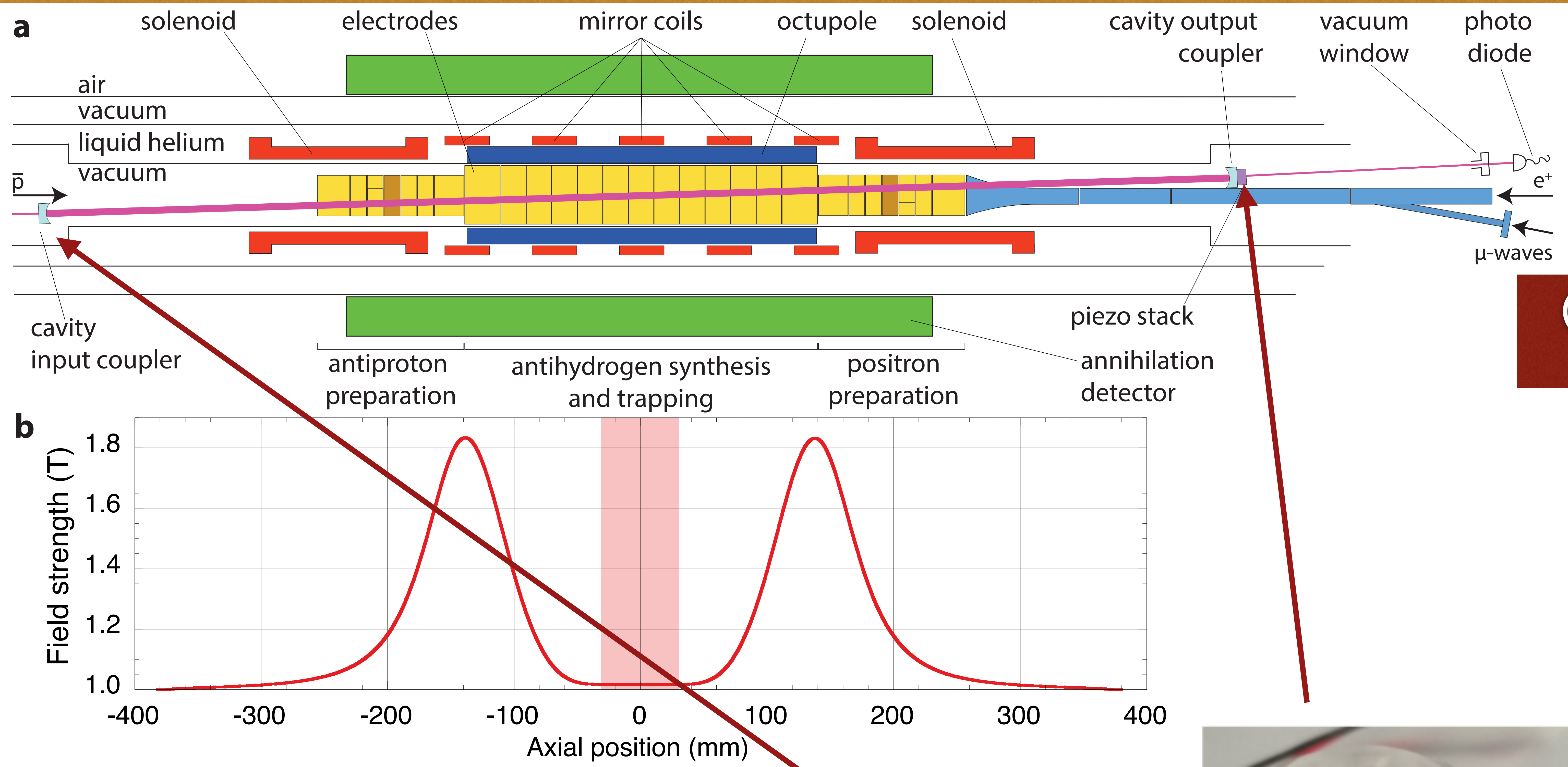
In 1928, Dirac published an equation[1] that combined quantum mechanics and special relativity. Negative-energy solutions to this equation, rather than being unphysical as initially thought, represented a class of hitherto unobserved and unimagined particles—antimatter. The existence of particles of 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.

H vs antiH : comparação da transição 1S-2S (cavidade ótica criogênica made-in-Brasil)

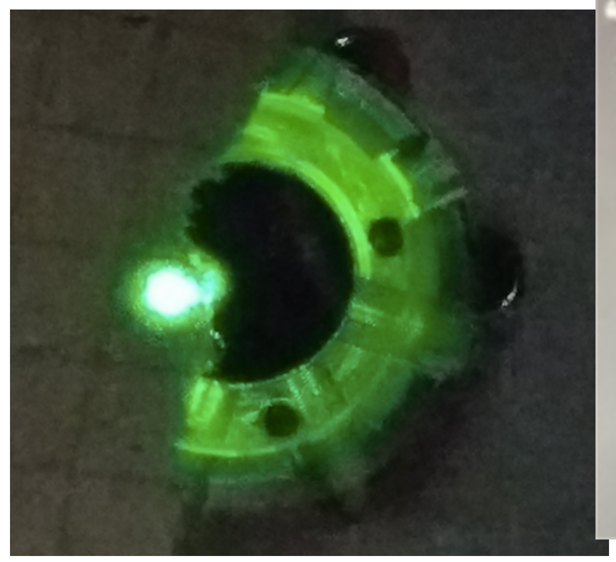


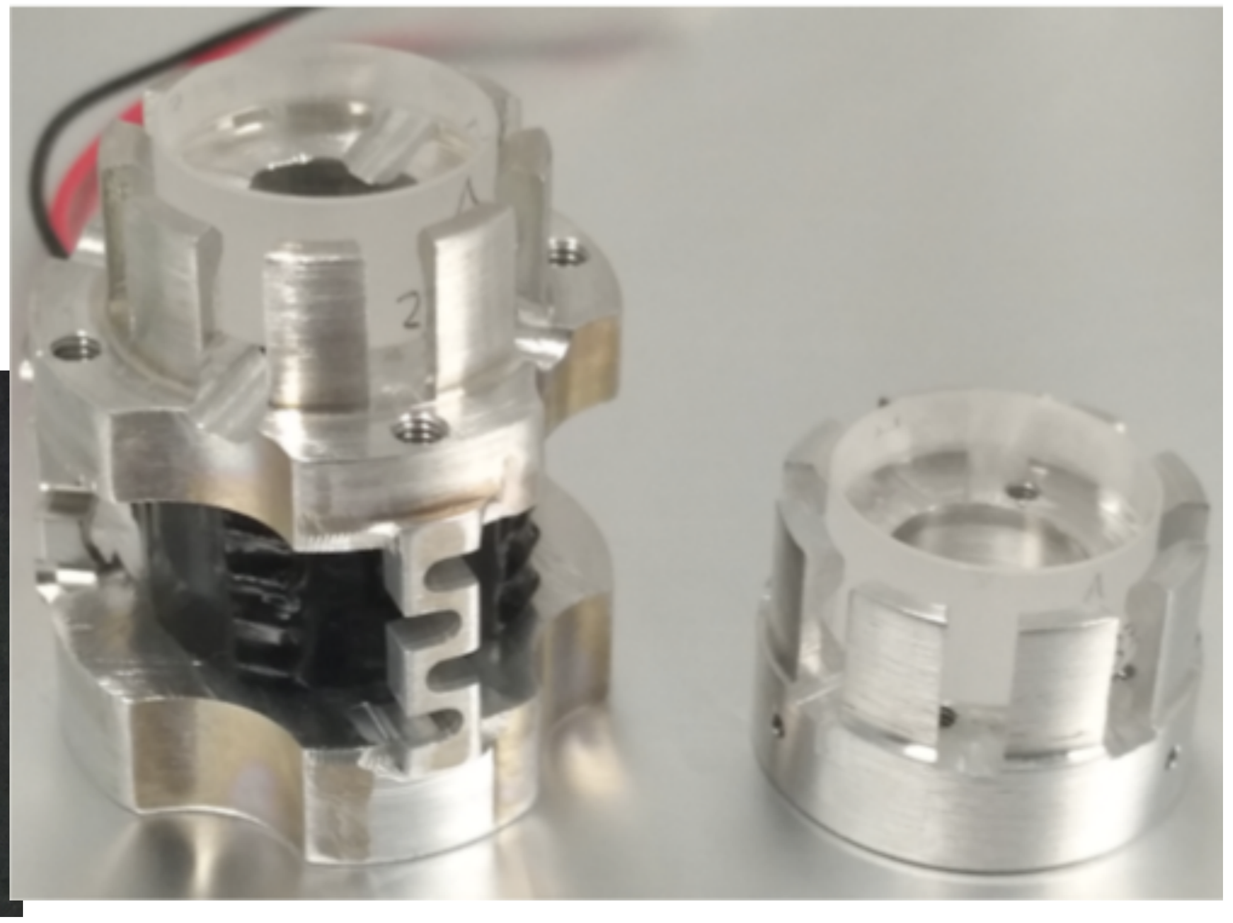
(ECR)B-field measure

https://www.nature.com/articles/s41586-018-0017-2 (2018)

Cavidade Ótica Criogênica (elemento crítico no experimento): projetada & made in Brasil

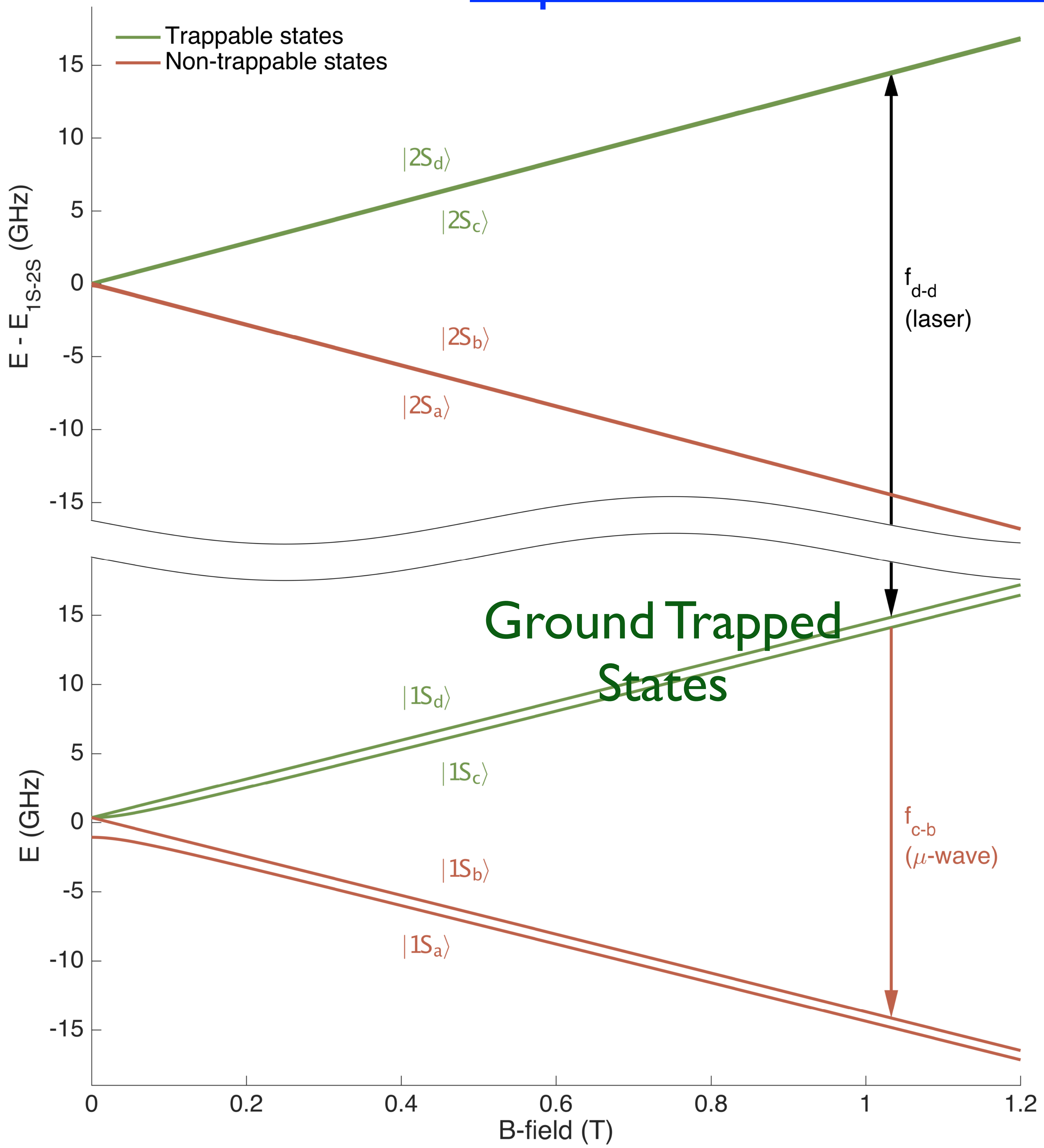
26. Oliveira, A. N. et al. Cryogenic mount for mirror and piezoelectric actuator for an optical cavity. Rev. Sci. Instrum. **88**, 063104 (2017).

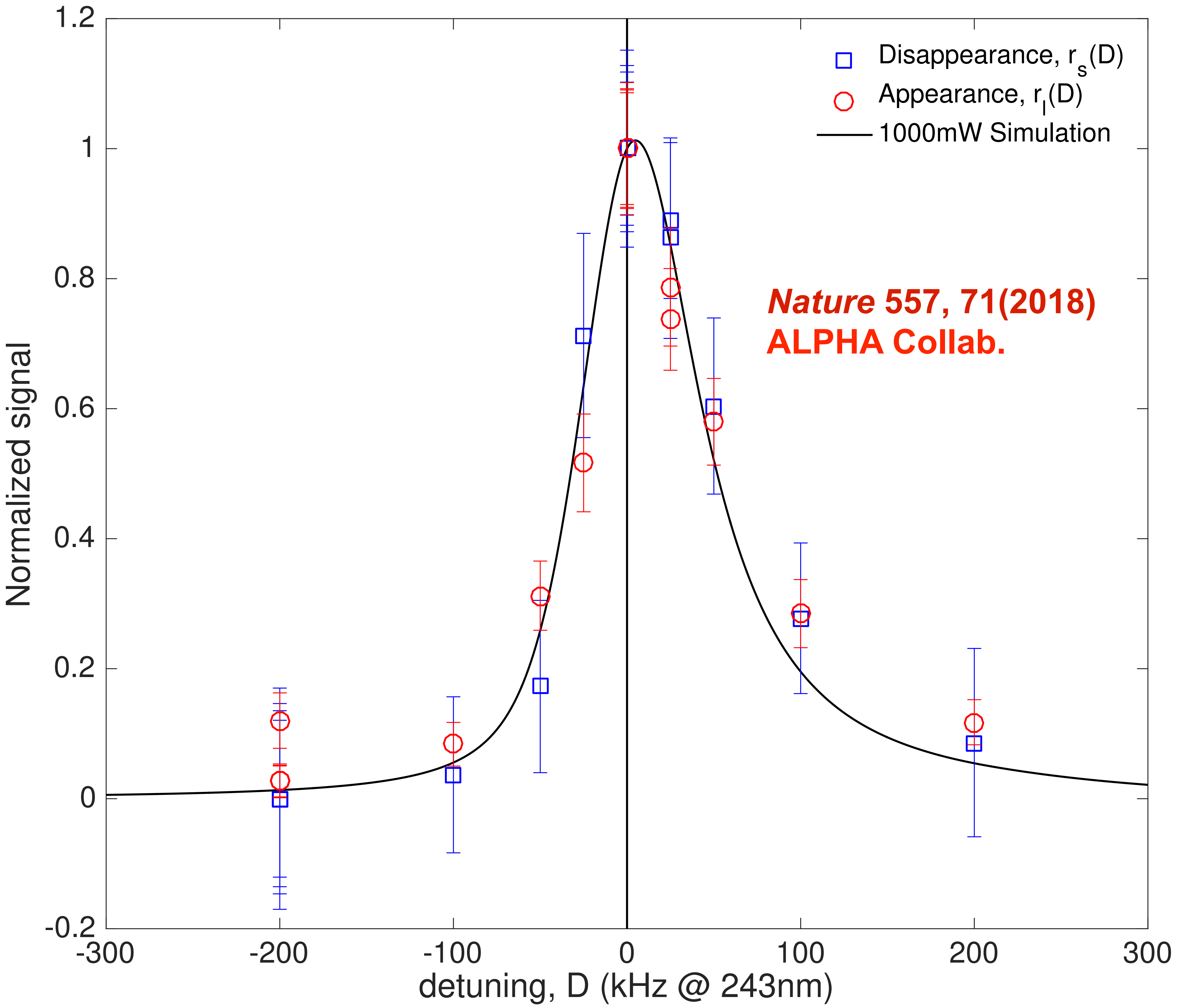




H vs antiH : comparação da transição 1S-2S

https://www.nature.com/articles/s41586-018-0017-2 (2018)

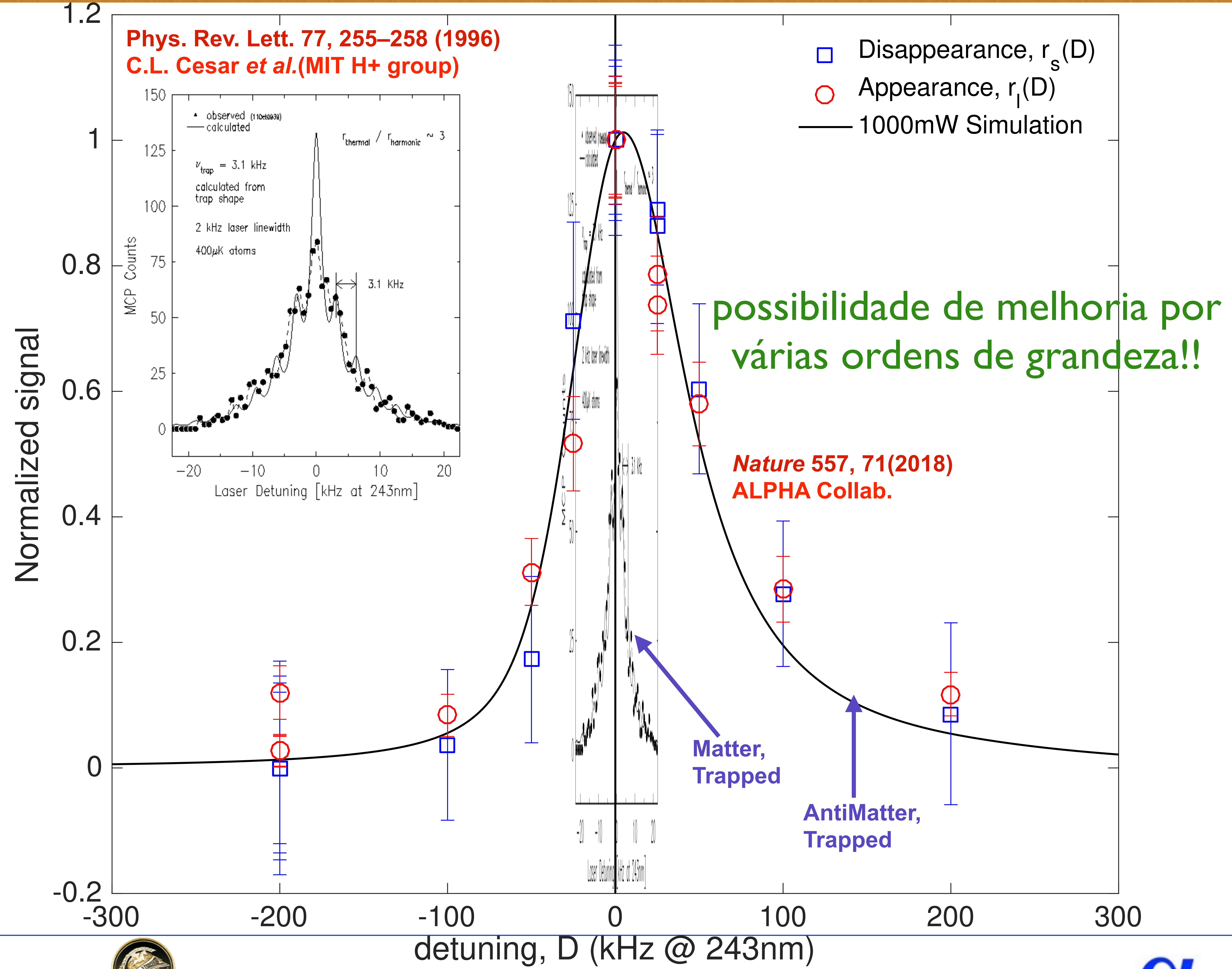




Spectrum e frequência medida:
2×10^{-12} compatibilidade: antiH & H(projected-Hänsch,DE)

f_{d-d}(H) = 2,466,061,103,080.3(0.6)kHz
f_{d-d}(anti-H) = 2,466,061,103,079.4(5.4)kHz

Anti-H (2018) em pespectiva com H (1996)

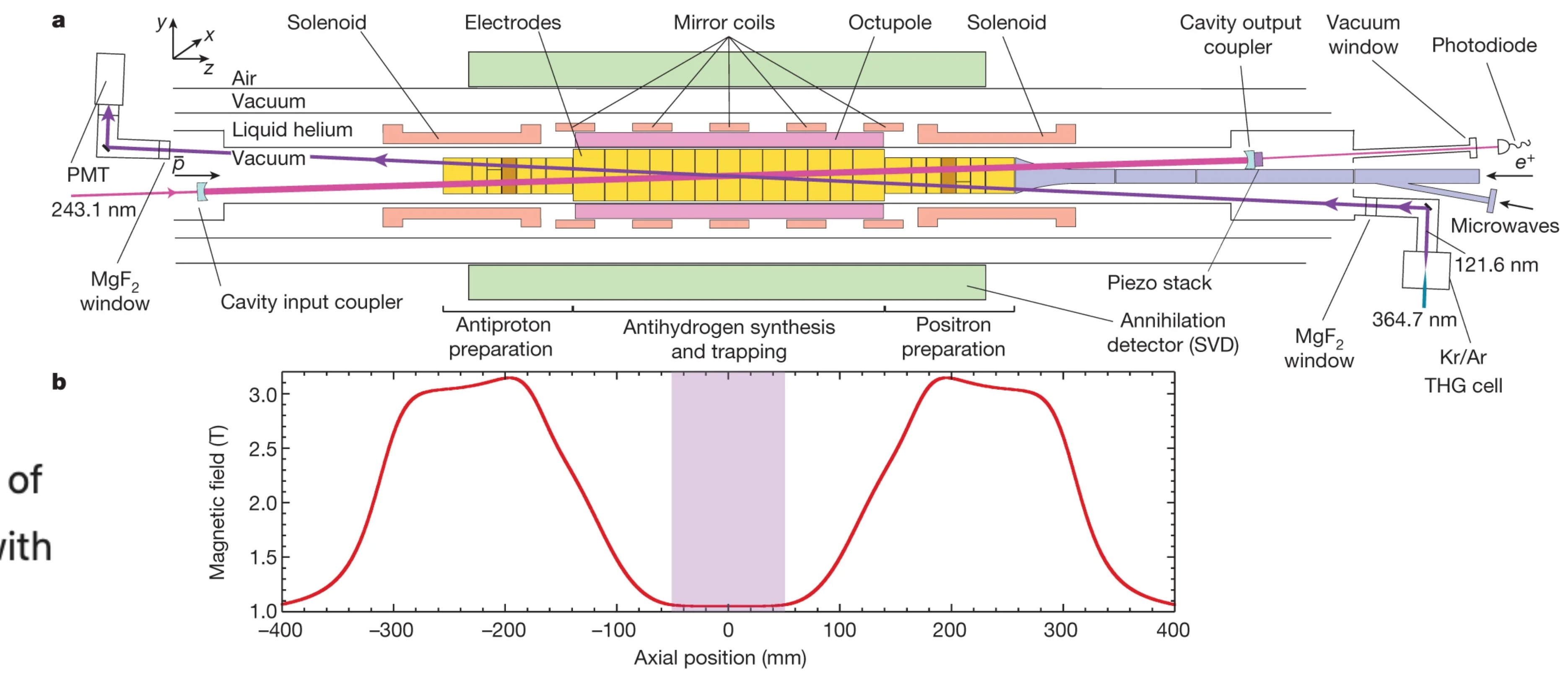


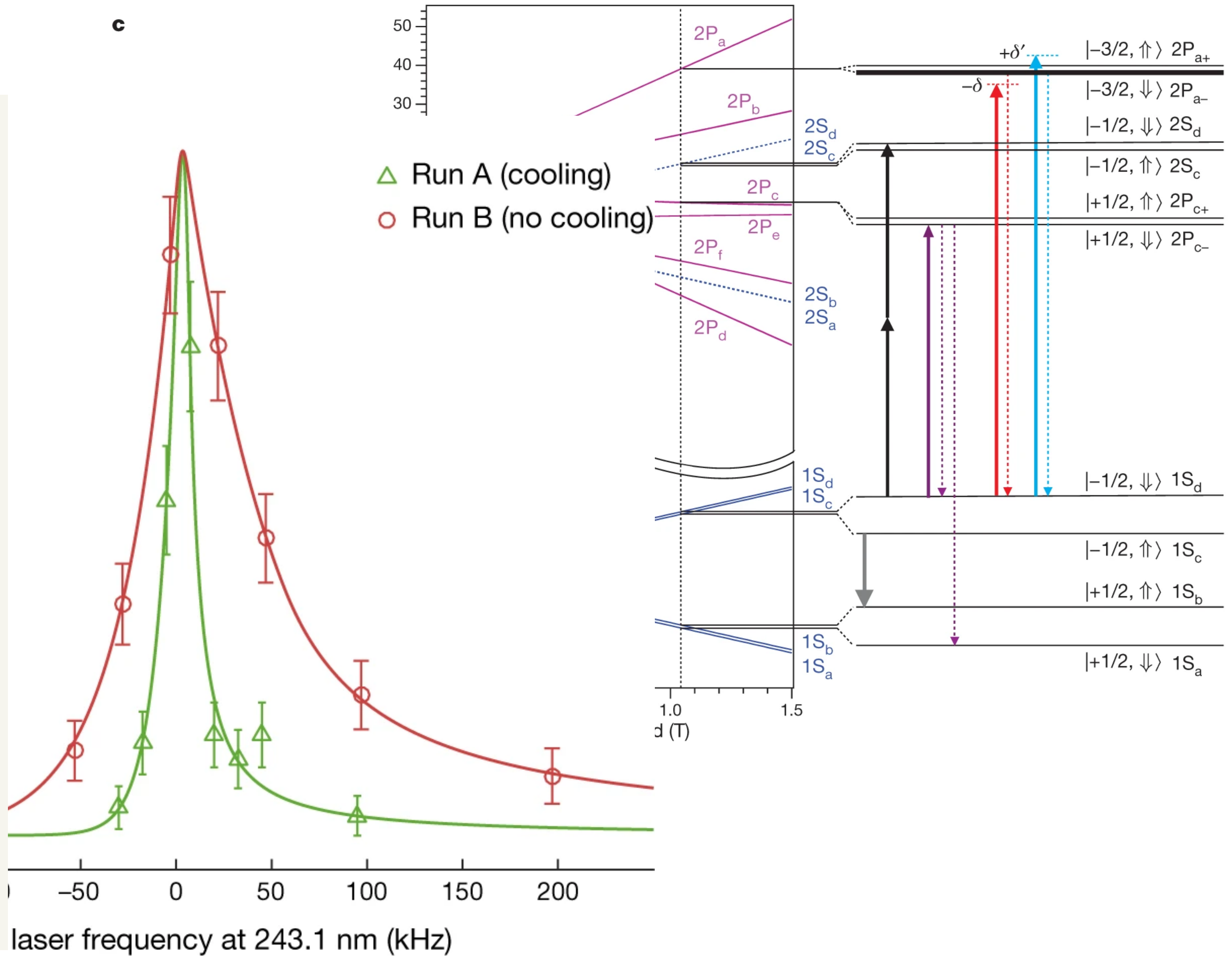
Resfriamento a laser de antiH! Grande melhoria!

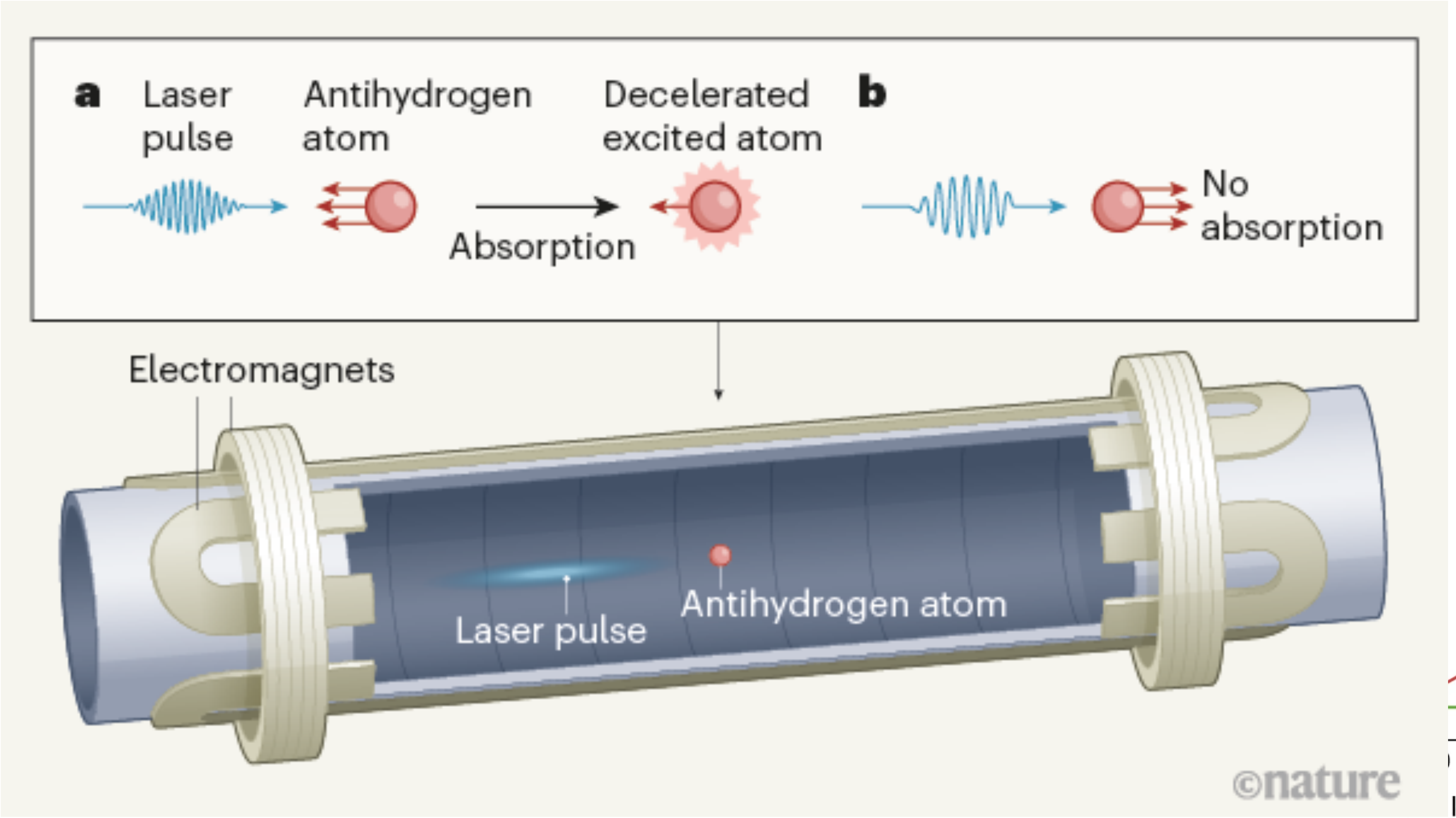
Volume 592 Issue 7852, 1 April 2021

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

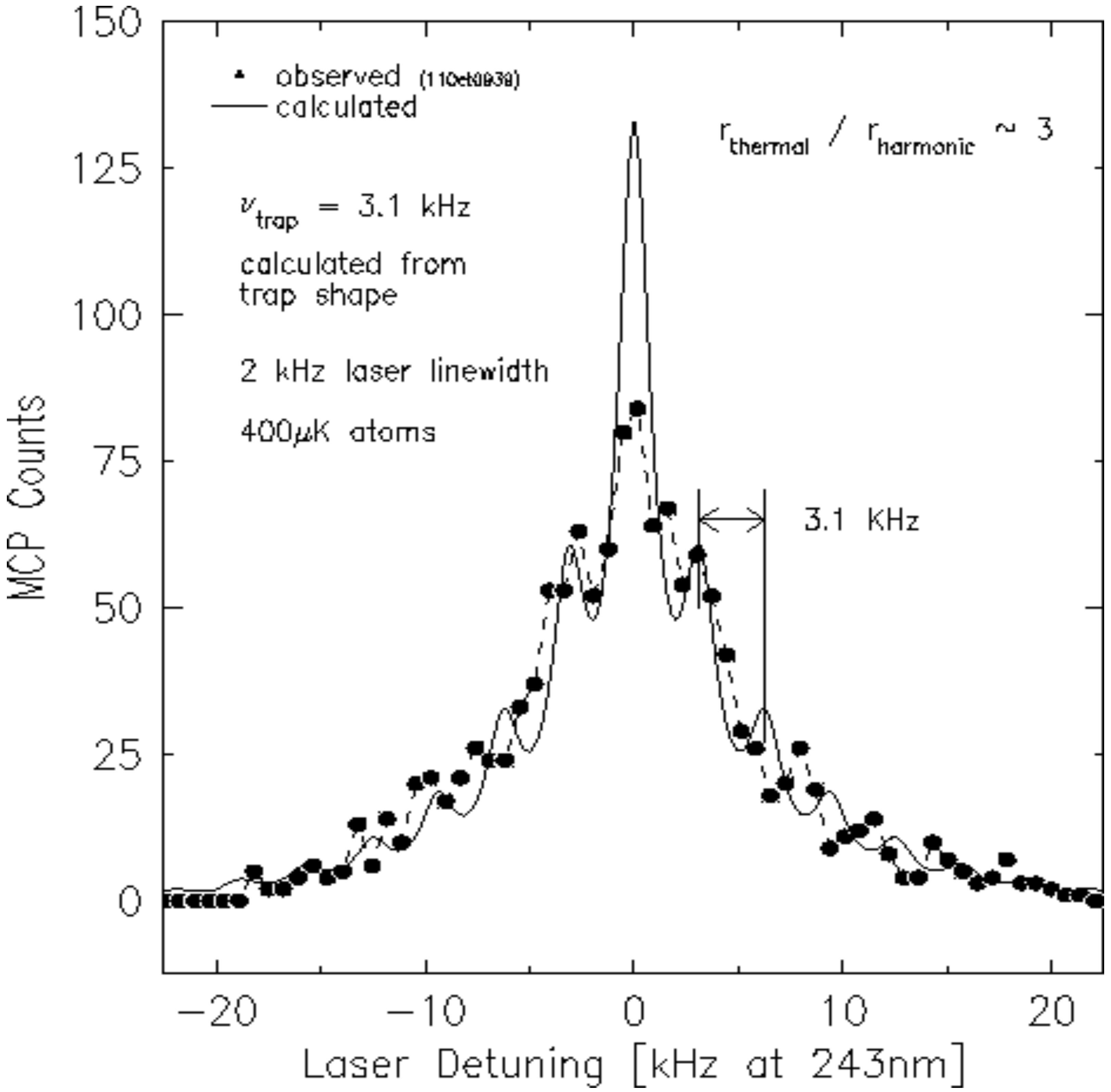




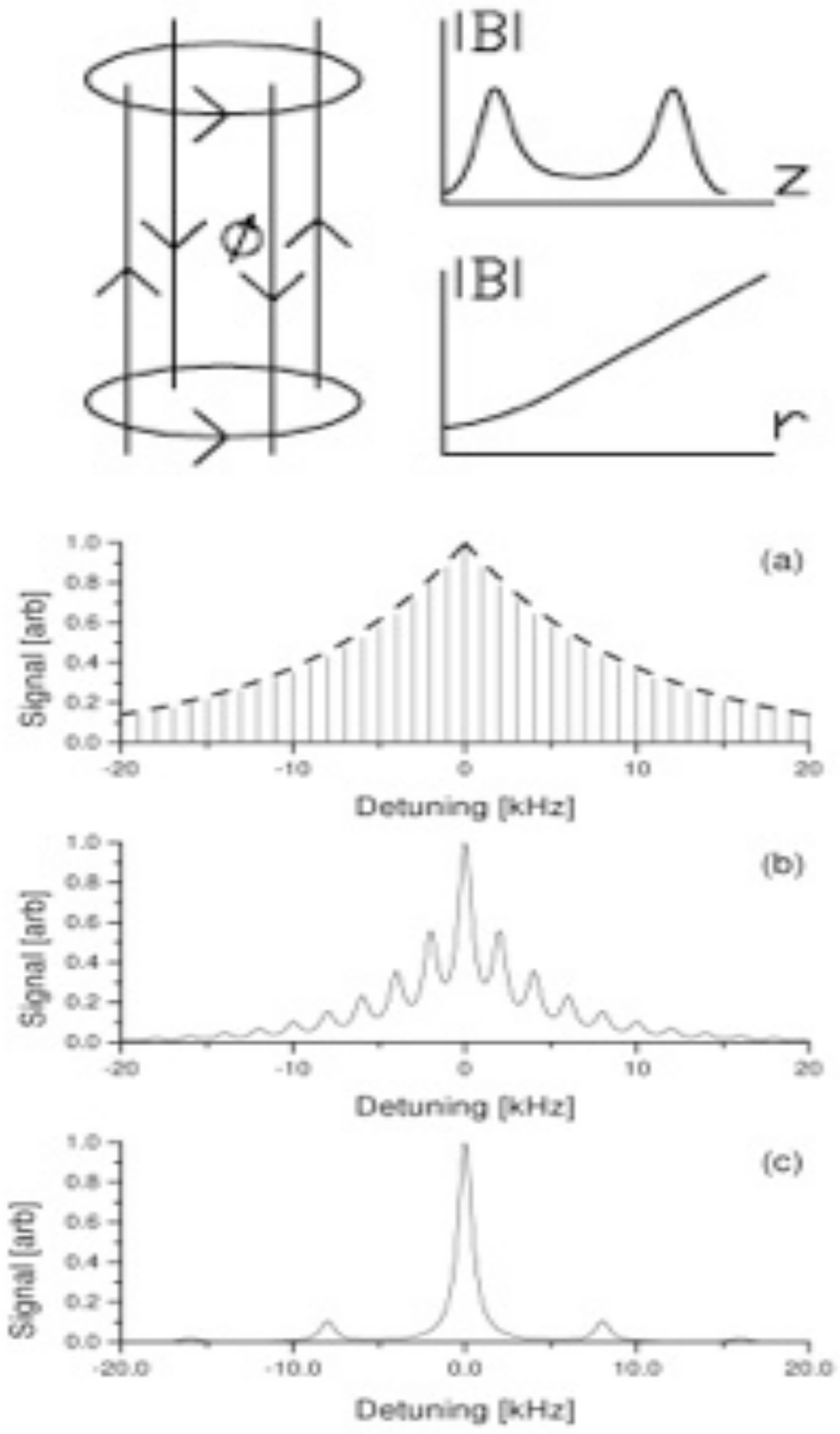


Teoria: quão bom pode a medida avançar? Partes em 10^18 ?

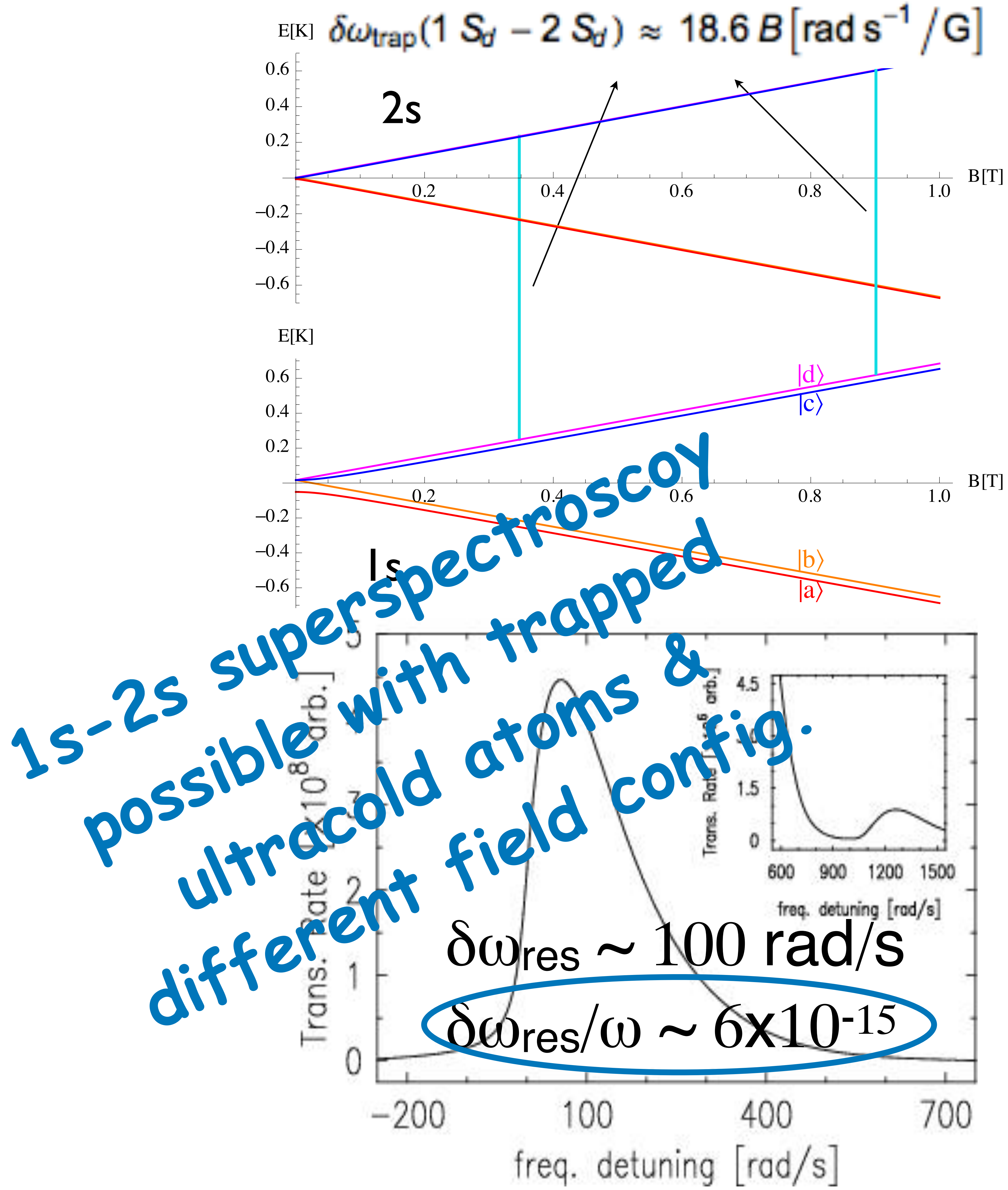
- ☆ 2s - estado metastavel (122 ms)
- ☆ 2-fótons contrapropagantes: livre de Doppler
- ☆ Largura: tempo-de-voo & Zeeman



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



Phys. Rev. A 59, 4564 (1999)
C. L. Cesar, D. Kleppner



Phys. Rev. A 64, 023418 (2001)
C. L. Cesar

ALPHA-g: queda gravitacional de antimatéria segundo proposta original CLC(1997)

Armadilha vertical e baixa lentamente os potenciais magnéticos em cima e embaixo ("abre a lata"): pode compensar g. Alto controle de campos magnéticos necessário!

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 exp... a negative gravity towards the Earth [13]. ... there are interesting propo... measuring gravity to high precision with an... otons and positrons [14], the... difficulties for performing such experiments ... related to stray electric fields that have to be kept under strict control.

I propose two experiments with trapped (anti)hydrogen that assume ... ≈ 10 m s^{-2} and just determines its sign for (anti)hydrogen. While these experiments seem rather simple when compared to the proposals mentioned above they assume the existence of cooled trapped anti-hydrogen, which, by itself, is no trivial matter. Also at the initial level of complexity here proposed, they would measure $|g|$ to a few percent level only, rather than providing a high precision measurement.

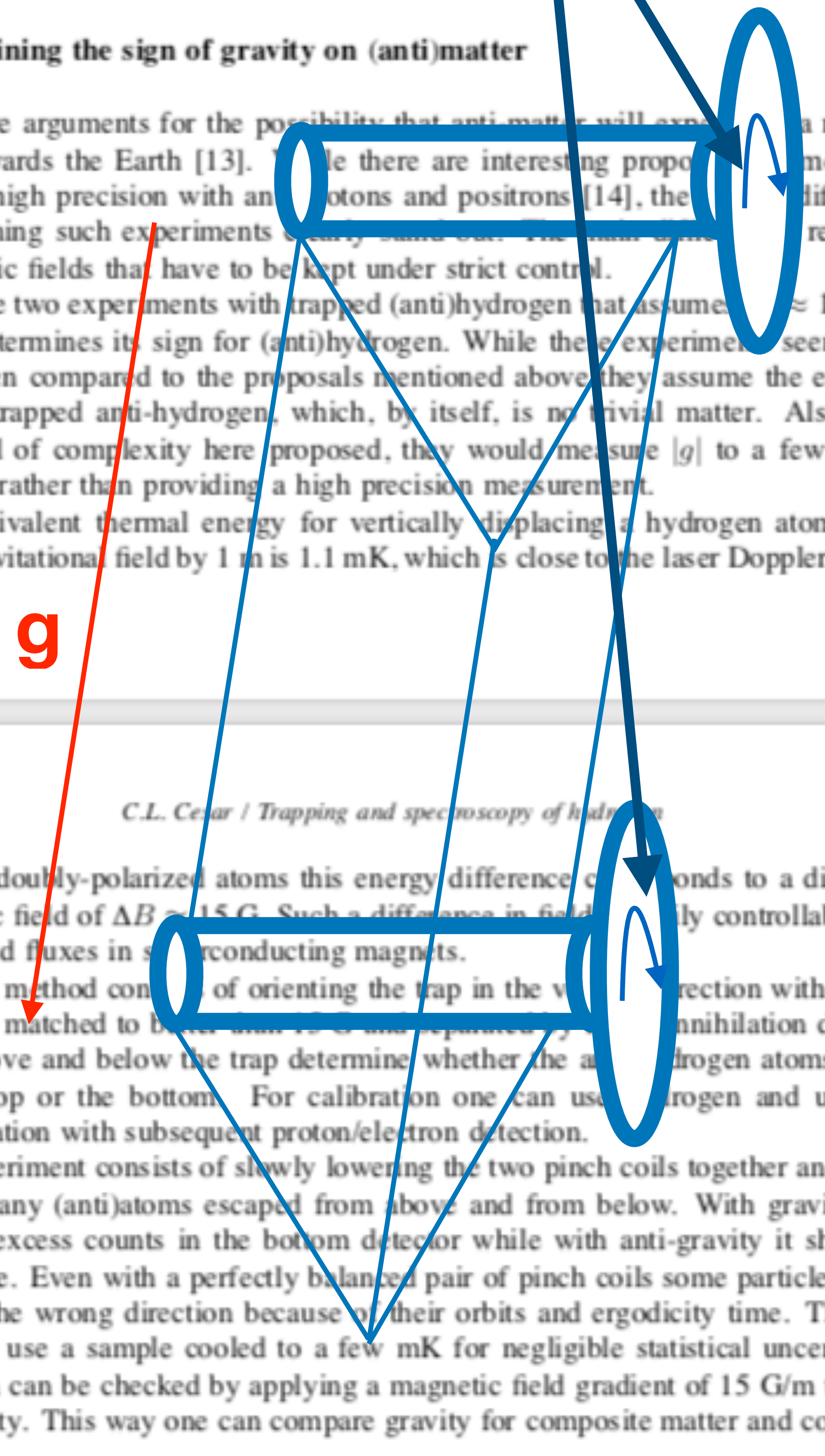
The equivalent thermal energy for vertically displacing a hydrogen atom in the Earth's gravitational field by 1 m is 1.1 mK, which is close to the laser Doppler cooling

limit. For doubly-polarized atoms this energy difference ... onds to a difference in magnetic field of $\Delta B \approx 15$ G. Such a difference in field ... ly controllable even with trapped fluxes in superconducting magnets.

The first method con... of orienting the trap in the v... ection with the two pinch coils matched to b... 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 use ... rogen 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



Article

Observation of the effect of gravity on the motion of antimatter

https://www.nature.com/articles/s41586-023-06527-1 (2023)

https://doi.org/10.1038/s41586-023-06527-1
Received: 6 May 2023
Accepted: 9 August 2023
Published online: 27 September 2023
Open access
Check for updates

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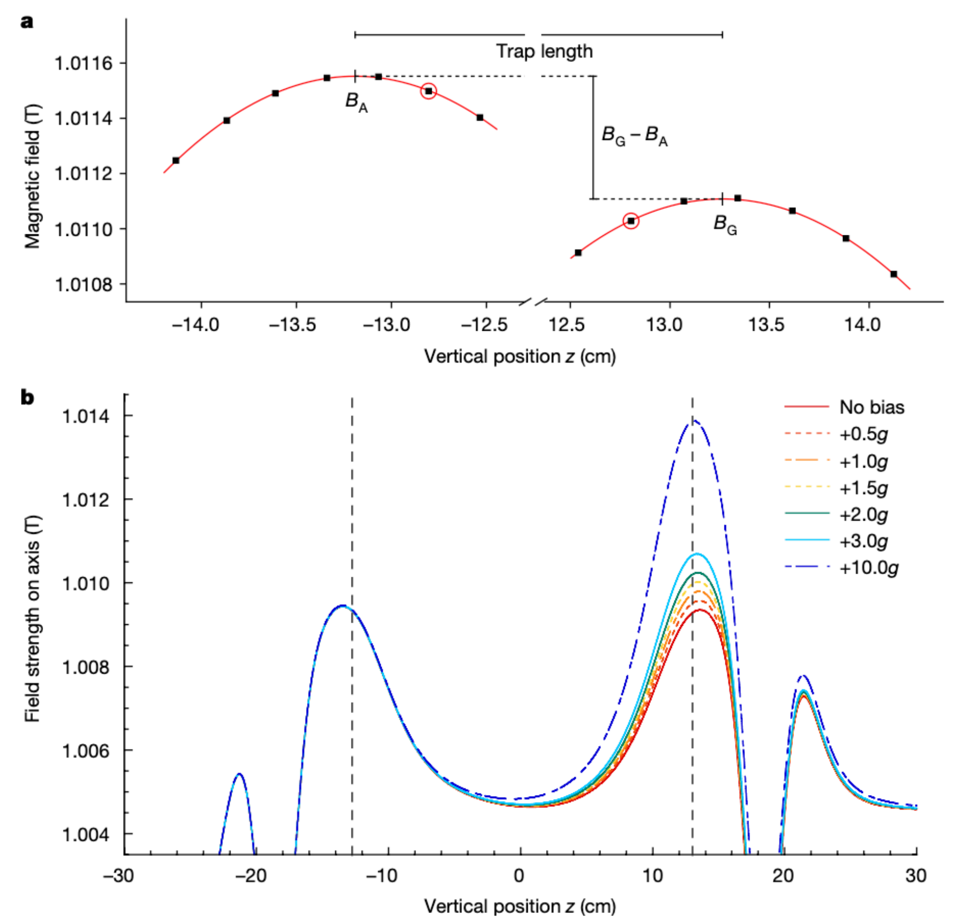
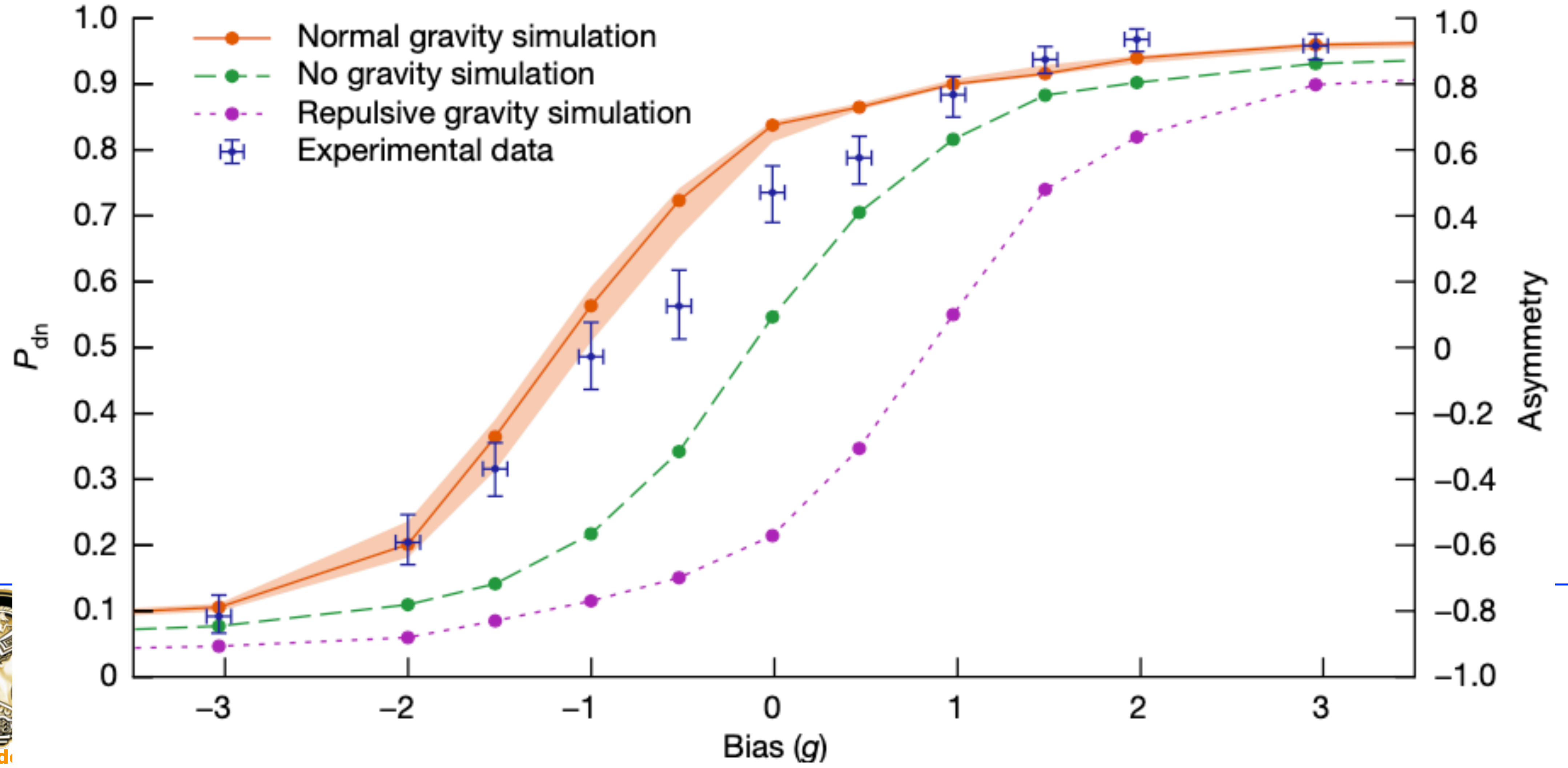
Einstein's general theory of relativity from 1915[1] remains the most successful description of gravitation. From the 1919 solar eclipse[2] to the observation of gravitational waves[3], the theory has passed many crucial experimental tests. Howeve

19. Cesar, C. L. Trapping and spectroscopy of hydrogen. *Hyp. Interact.* **109**, 293–304 (1997).



ig. 2 | Illustrations of the magnetic bias. a, Expanded view of the end-of-ramp mirror coil peak regions for a bias of −1g (note the discontinuous abscissa). The square points represent offline ECR measurements carried out to determine the field profile and to find the peak field location. The points with red circles indicate the axial locations at which ECR measurements were made at the beginning and end of the mirror coil ramp-down for each gravity trial. b, Calculated on-axis final well shapes (after ramp-down) for the positive bias trials. The features at $|z| > 20$ cm are due to the OcB (Fig. 1) end turn windings. The vertical dashed lines represent the physical axial midpoints of mirrors A and G.



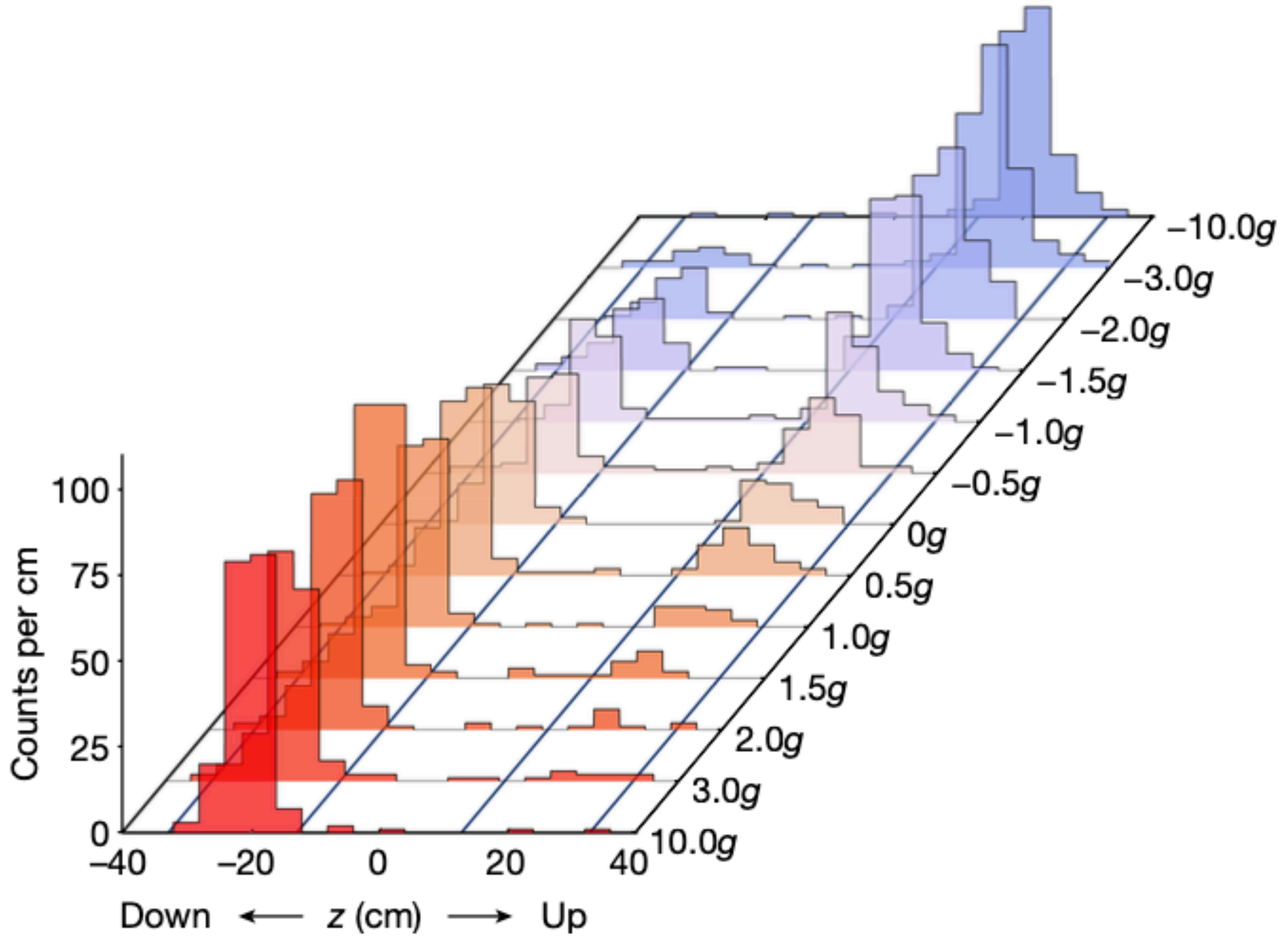


Fig. 3 | Escape histograms. The raw event z-distributions are displayed as histograms for each of the bias values, including the ±10g calibration runs. These are uncorrected for background or detector relative efficiency. The time window represented here is 10 s to 20 s of the magnet ramp-down. The z-cut regions are indicated by the solid, diagonal lines. Explicitly, the acceptance regions in z are [−32.8, −12.8] and [12.8, 32.8] cm for the 'down' and 'up' regions, respectively.

LASER−IF−UFRJ

Universidade

H vs antiH : comparação da transição 1S-2S (dados de 2023-ALPHA e UFRJ)

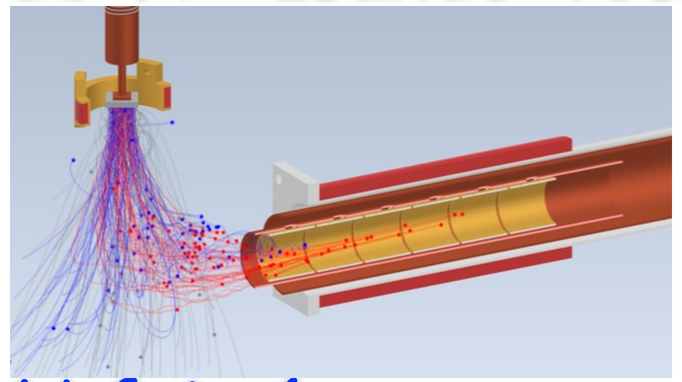
- Análise em andamento da forma de linha espectral e medida da frequência central de antiH com teoria por C.L.Cesar e o aluno de doutorado (em sandwiche no ALPHA) Levi Azevedo (liderança brasileira no principal resultado de 2023)

- Prospectos de atingir 13 algarismos significativos na publicação em preparação (a ser submetida à Nature/2024) (melhoria por x10 frente ao estado-da-arte, do próprio ALPHA)

- Prova de princípio — usando antiH — de técnica proposta por C.L.Cesar (JPB'2016) para detecção de H na mesma armadilha de antiH no ALPHA: abre perspectivas de comparação direta entre as espécies podendo nos levar a partes em 10^15 e adiante!

- Novo software de controle Laser-Metrologia/ALPHA (dentre vários desenvolvimentos): A. N. Oliveira

- Desenvolvimento na UFRJ da primeira armadilha de Penning do País (https://www.nature.com/articles/s42005-023-01228-7) (2023) com o aprisionamento de H- usando técnica "MISu" (made-in-UFRJ) para introduzir H na mesma armadilha de antiH ! (PI rev.2.0: D.M.Silveira)



- Montagem na UFRJ de sistema de espectroscopia de H frio (com prospectos de maior precisão que o do Laureado Nobel T. Hänsch), ou seja, metrologia científica de fronteira no BR: variação de constantes fundamentais? sensibilidade à estrutura do próton e deuteron, efeitos isotópicos, testes de QED e QCD…. (PI: R.L.Sacramento)

ALPHA - Brasil: membros / finanças / necessidades / know-how : spin-offs ?

- Atualmente 3 PhDs pagantes de M&O: CHF 8k/cada-ano. Em breve*(?): + Álvaro Oliveira e Levi Azevedo.
- Recursos para duplicar sistema de MISu e aprisionamento de H- e H da UFRJ no CERN: ~CHF 200k
- Pente de Frequências Óticas + Relógio Atômico de Cs para metrologia científica absoluta no Rio (+3 anos): ~EUR 350k
- Armadilhas (estudos íons & átomos), Espectroscopia H(antiH), D(antiD), e T(antiT), Sensores/Magnetos/Lasers, Interferômetros atômicos (+7 anos): ~EUR 500k
- Know-How / Spin-offs:

1 - Gravímetro ótico em desenvolvimento de fase 2 (de campo) com patente recém depositada pela Petrobrás-UFRJ. Perspectivas da fase 3: licenciamento ou incubação de empresa.
2 - Know-how para construção de lasers (ECDL) para indústria (medições interferométricas em materiais), pesquisa, e ensino -> empresa ?
3 - Know-how para contrução de magnetos supercondutores compactos e barras de correntes supercondutoras de alta temperatura -> empresa ?
*É preciso investimento nos grupos brasileiros, crescente com projeção de longos prazos, para atrair o retorno dos pesquisadores ao BR. Já temos ex-alunos "perdidos", por exemplo, para empresas de computação quântica na França e grande empresa em Liechtenstein.