RENAFAE

Updates on the 1S-2S spectroscopy of antihydrogen at the ALPHA* experiment at CERN

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- ☆ Motivation
- ☆ Making, Trapping and Laser Spectroscopy of Antihydrogen
- ☆ Laser cooled data with analytical lineshape: parts in 10^{13}
- ☆ Proof-of-principle for H in the same anti-H trap: parts in $10^{15,16...}$
- ☆ Brief gravitational fall of antihydrogen
- ☆ Summary and Perspectives

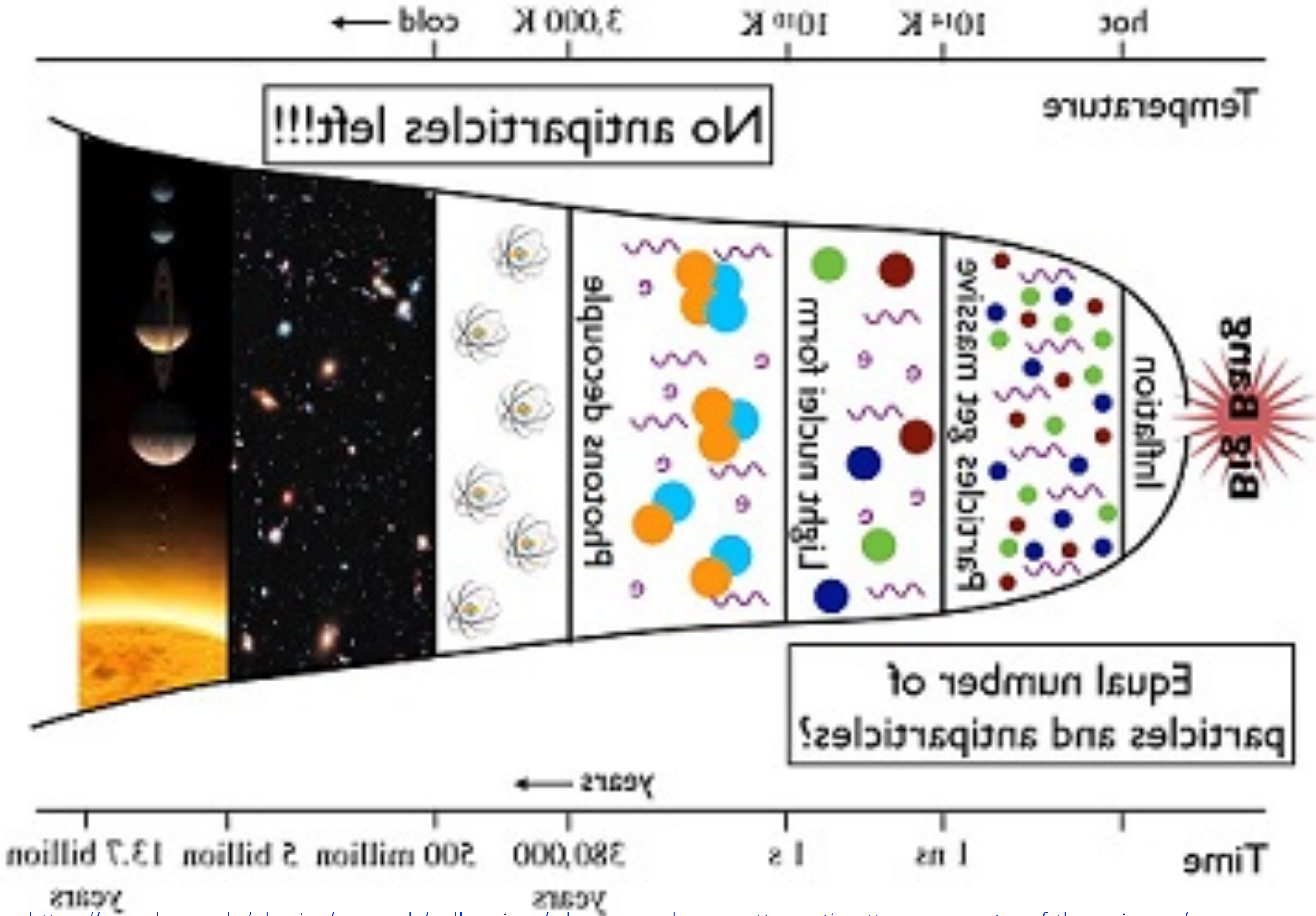
*ALPHA @ PSAS-2026: Abbygale G. Swadling (following talk), Edward Thorpe-Woods (talk Monday-ETH), Maria Beatriz Gomes Goncalves (poster Monday: Be+ cooling of e+)

Let there be particles:
Matter & Antimatter

but … the primordial

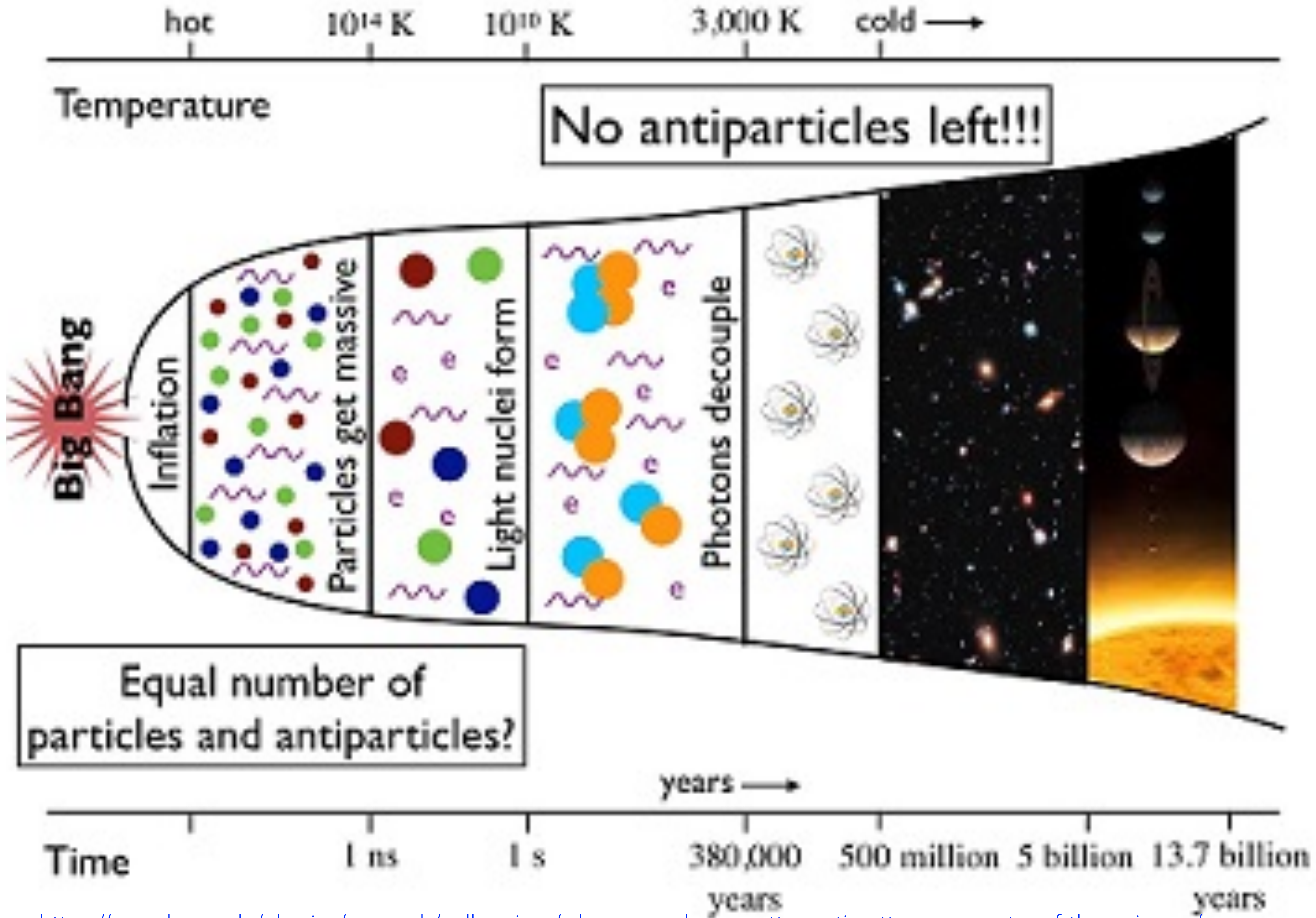
antimatter disappeared

Mirror Universe ?? (speculation yet)

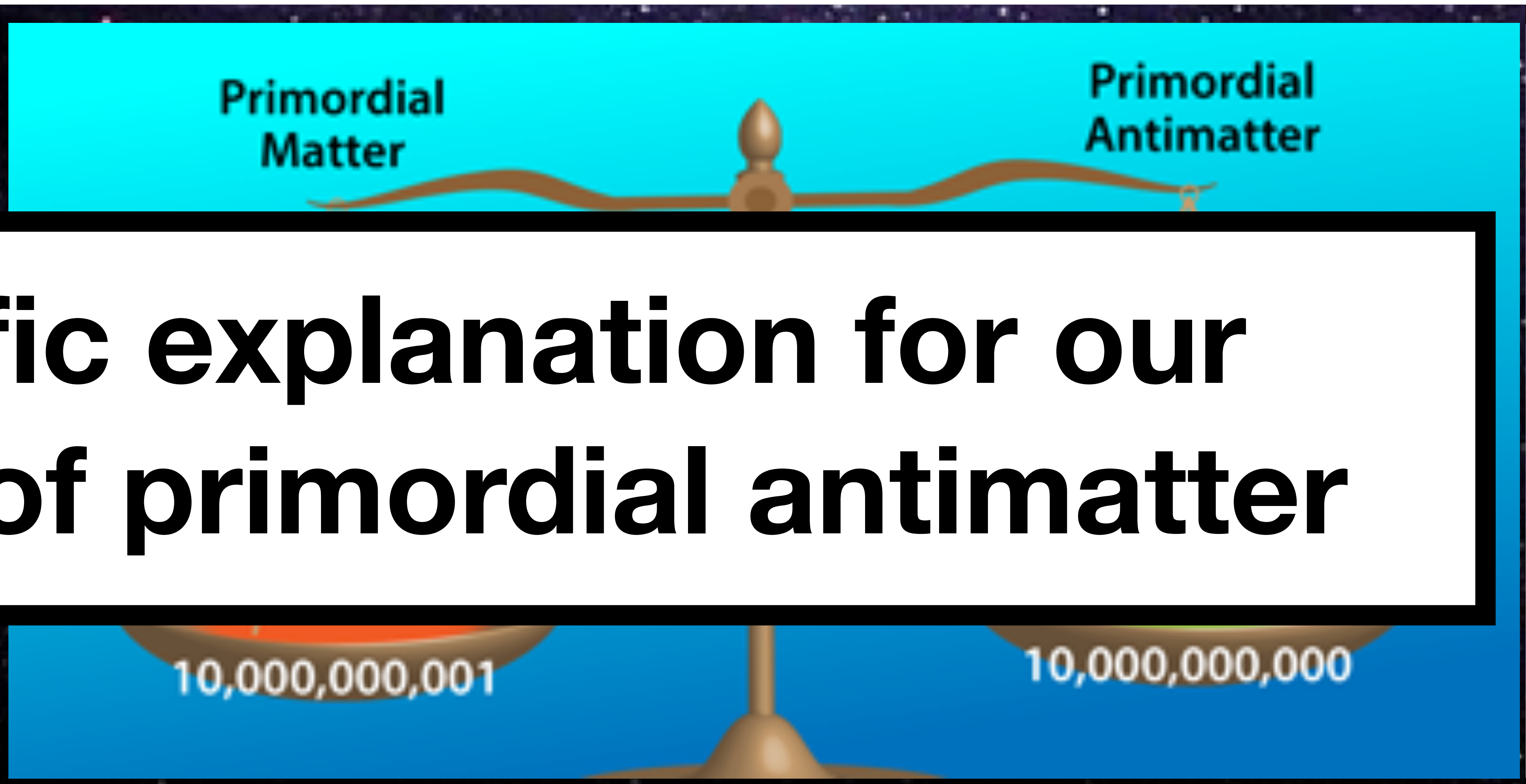


https://www.hmc.edu/physics/research/colloquium/why-are-we-here-matter-antimatter-asymmetry-of-the-universe/

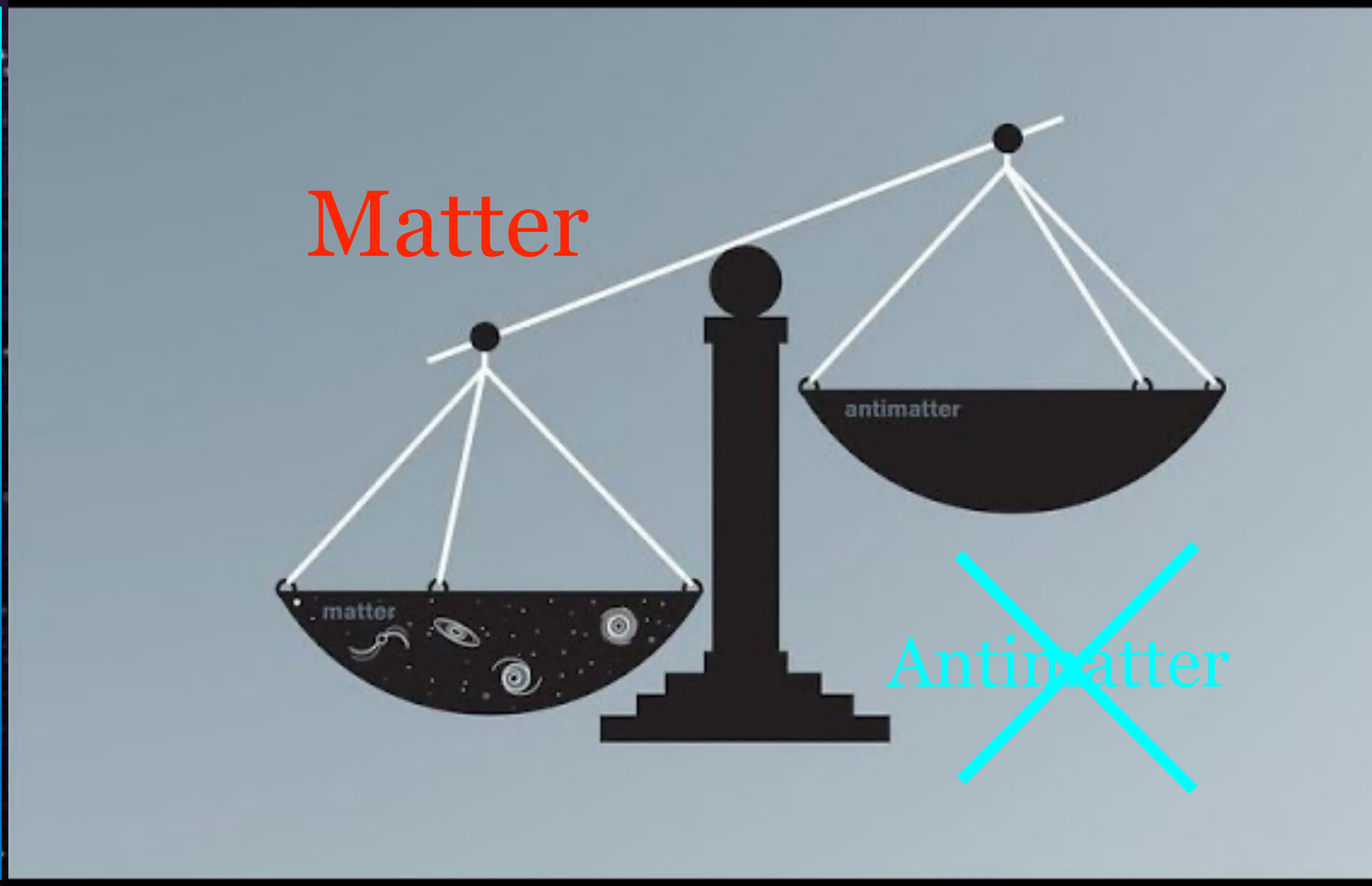
CP violation ?? (not enough seen yet)



https://www.hmc.edu/physics/research/colloquium/why-are-we-here-matter-antimatter-asymmetry-of-the-universe/



no good scientific explanation for our Universe devoid of primordial antimatter



CPT symmetry (base of the Standard Model)

Symmetry Operations / Background

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

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

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

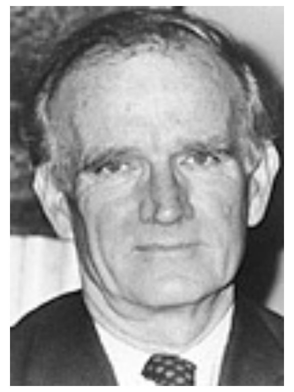
P('57)

C. Yang
1957

T.D.Lee
1957

CP('80)

J. Cronin
1980



V. Fitch
1980

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

CPT symmetry (base of the Standard Model)

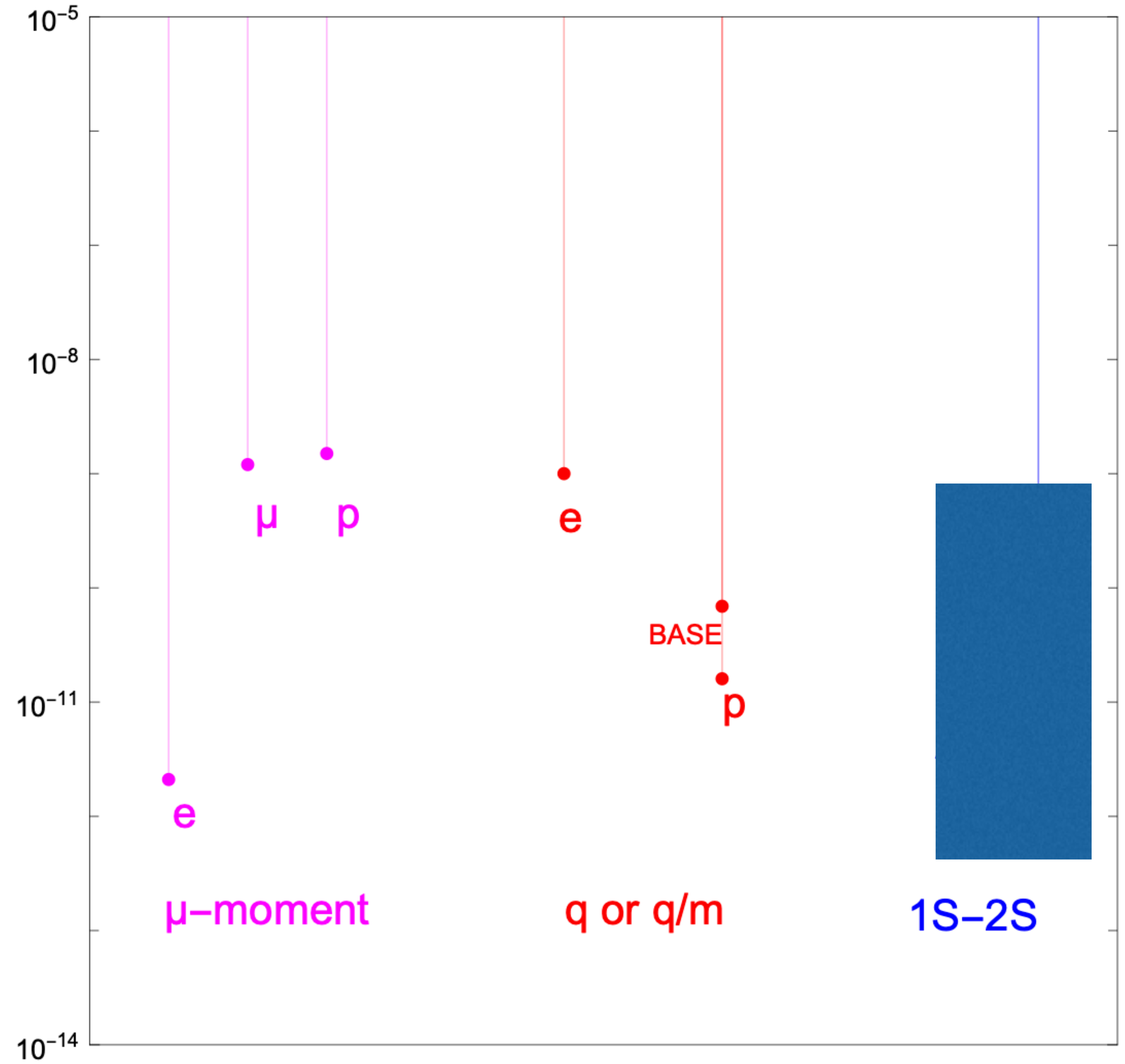
Symmetry Operations / Background

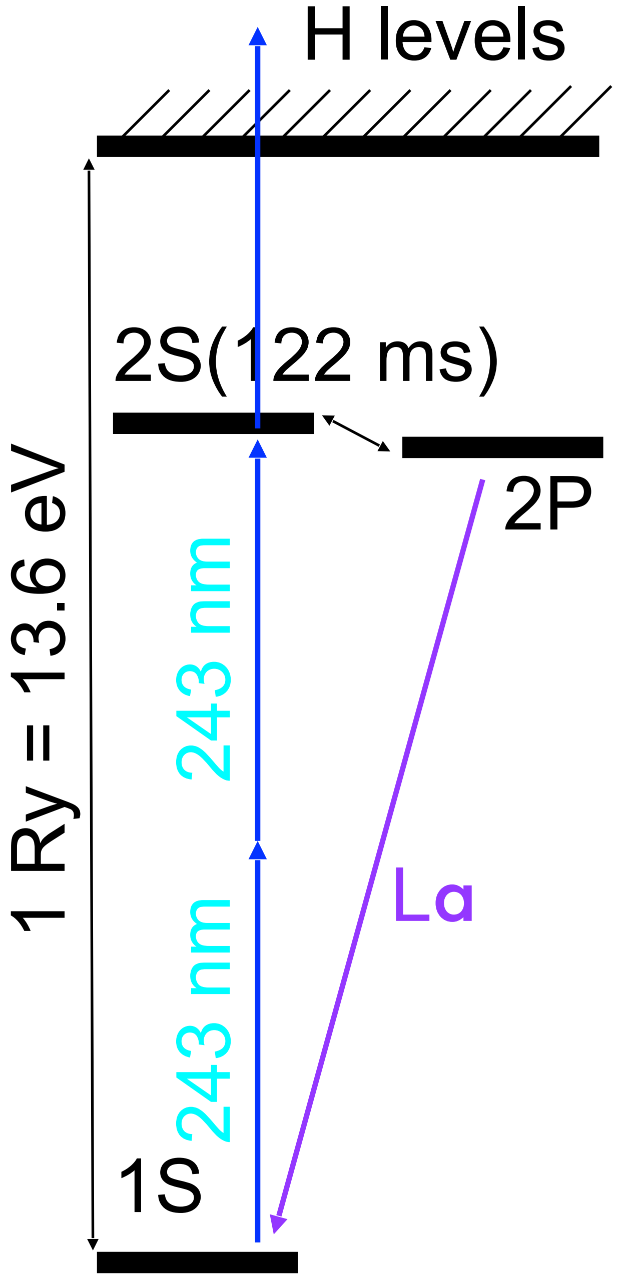
“P” - parity, space inversion: -r <=> +r

“C” - charge conjugation: e- <=> e+

“T” - time reversal: -t <=> +t

Fractional Precision: Matter X Antimatter





Hydrogen (1s-2s)

”Two-Photon Spectroscopy of Trapped Atomic Hydrogen”, Claudio L. Cesar, Dale G. Fried, Thomas C. Killian, Adam D. Polcyn, Jon C. Sandberg, Ite A. Yu, Thomas J. Greytak, and Daniel Kleppner, John M. Doyle, PRL 77, 255 (1996)

2 parts in 10^{12} resolution

“Improved Measurement of the Hydrogen 1S–2S Transition Frequency”, Christian G. Parthey, Arthur Matveev, Janis Alnis, Birgitta Bernhardt, Axel Beyer, Ronald Holzwarth, Aliaksei Maistrou, Randolf Pohl, Katharina Predehl, Thomas Udem, Tobias Wilken, Nikolai Kolachevsky, Michel Abgrall, Daniele Rovera, Christophe Salomon, Philippe Laurent, and Theodor W. Hänsch, PRL 107, 203001(2011)

4 parts in 10^{15} accuracy

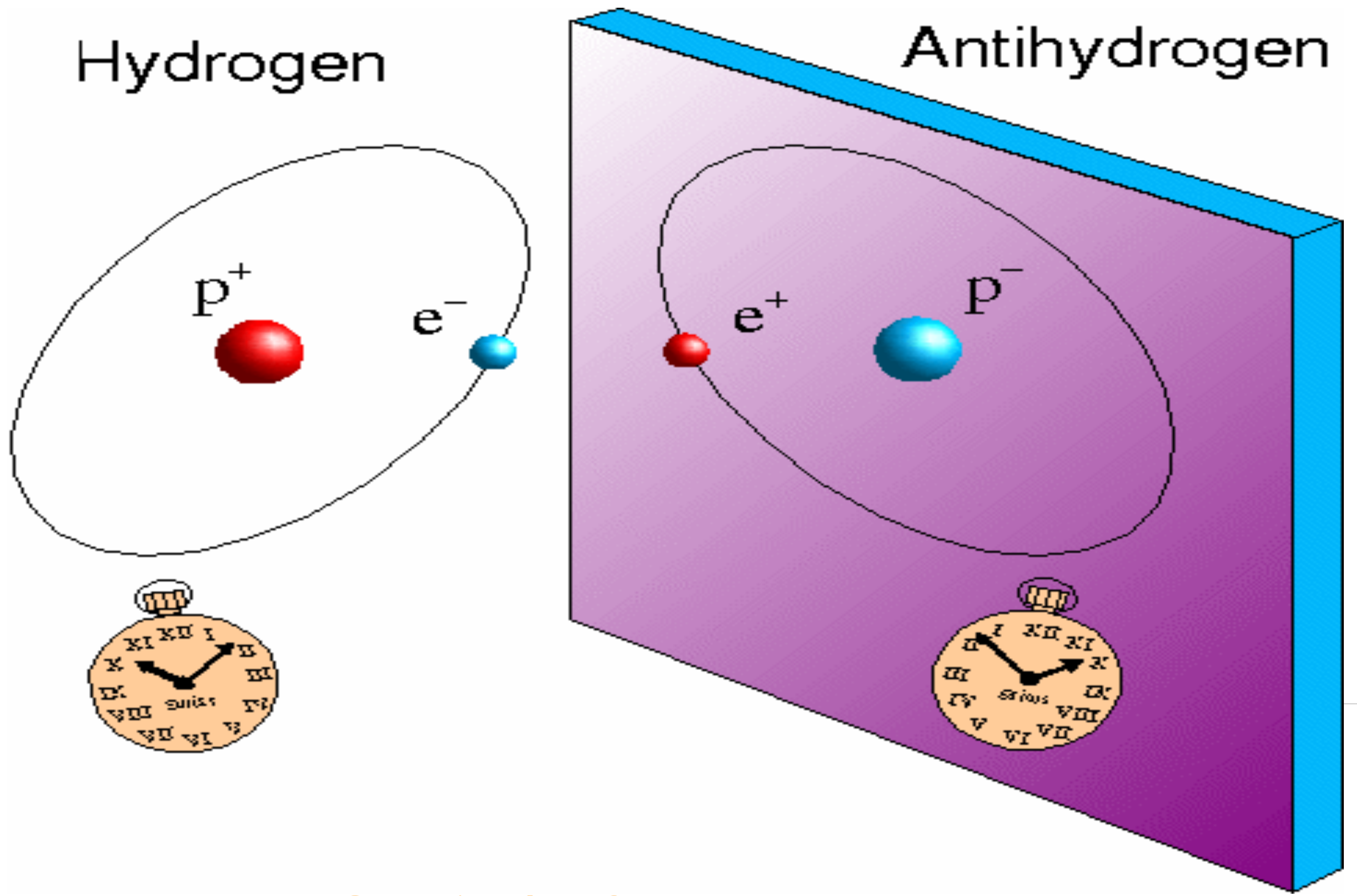
SM: Any reason to doubt?
neutrinos’ masses
μ (g-2) = ?
(Gravity)
Dark Matter
Dark Energy
Early Universe
(primordial antimatter)
Naturalness, fine tuned?
SM parameters ?

Why not test H x Hbar?
- Precision Frontier -

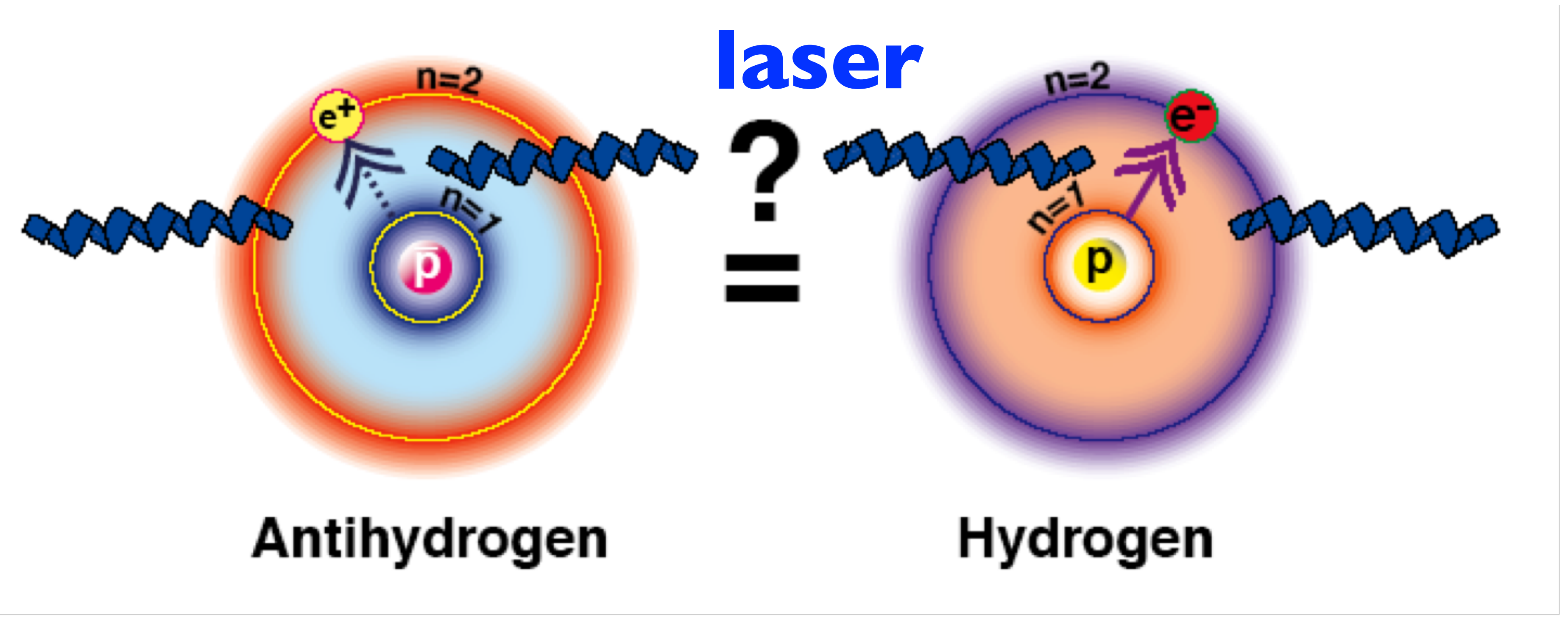
ATHENA(1997)/ALPHA(2006) Collaboration @ CERN's: Antihydrogen vs. Hydrogen

H vs. Hbar

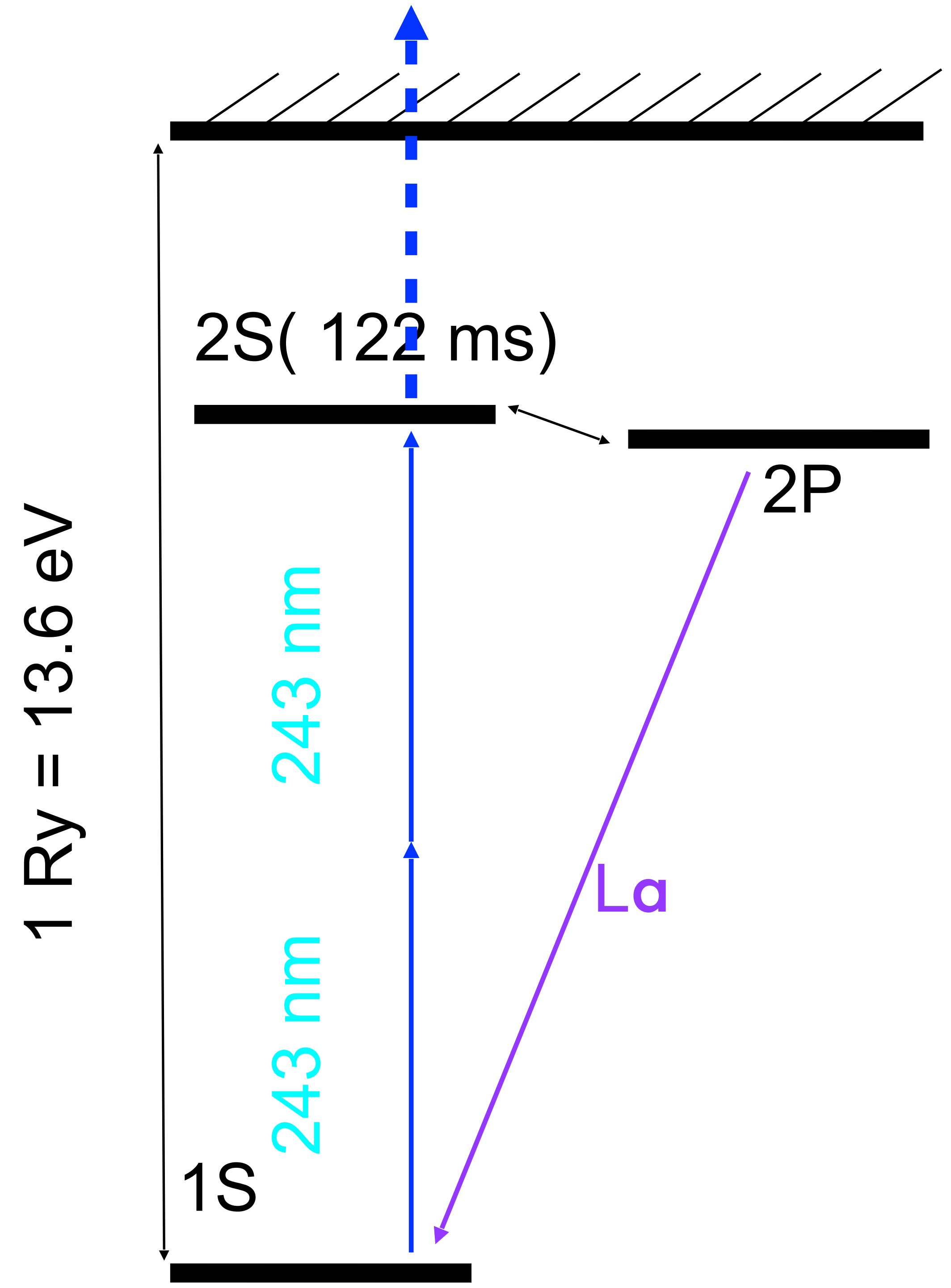
1 - CPT theorem, base of the Standard Model:



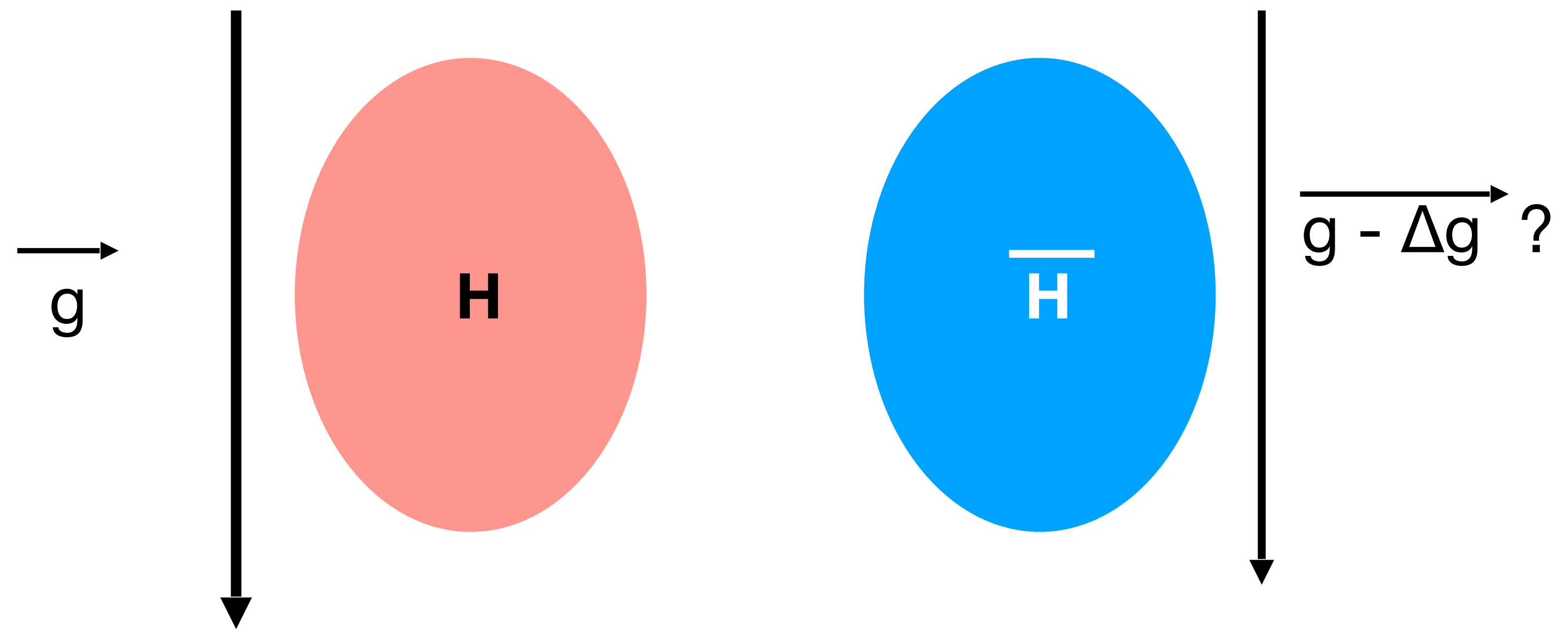
Graching/MPQ webpage



"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 ??



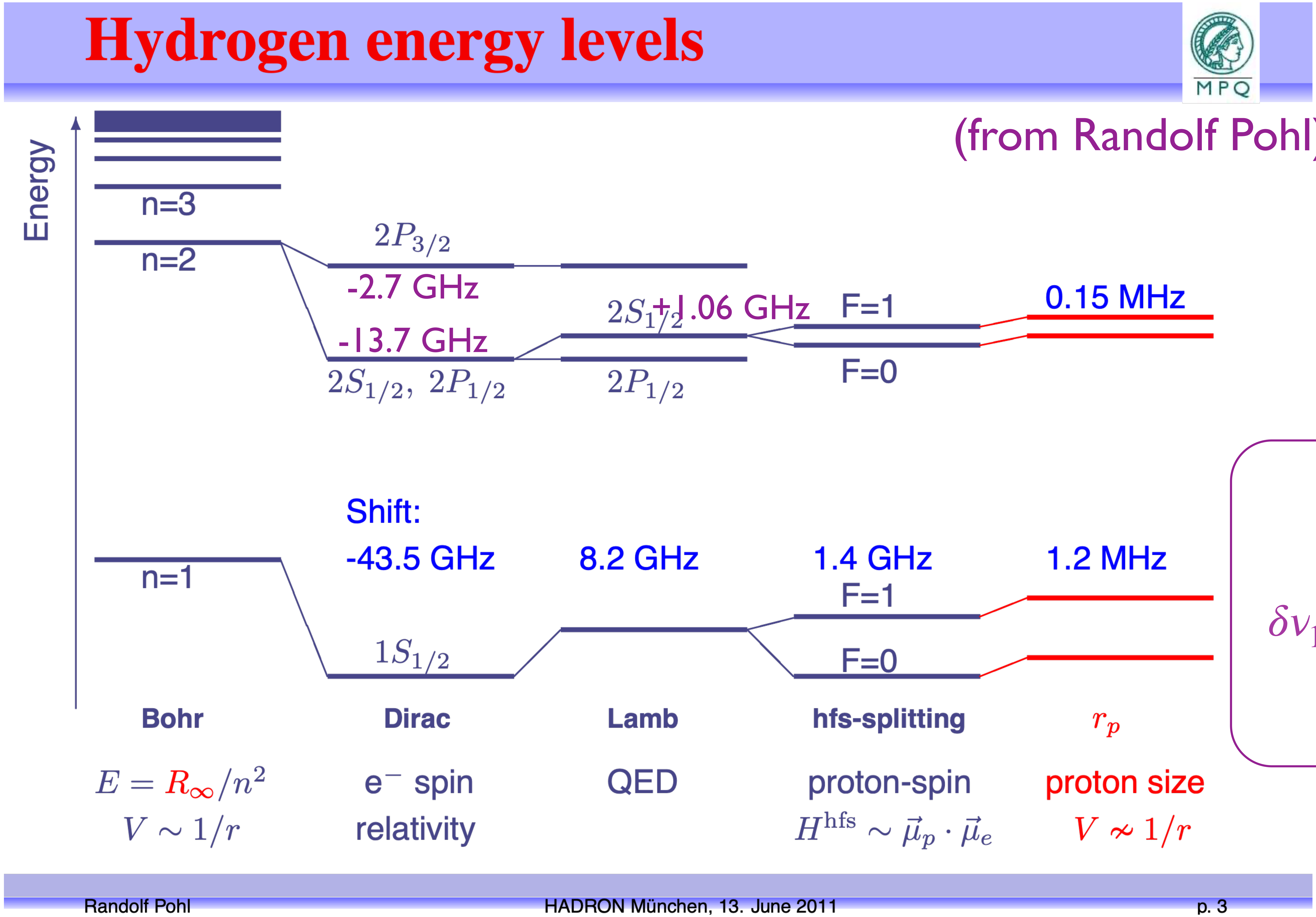
3 - Main Motivation:
(Bariogenesis)

- where is the primordial antimatter?
- Beyond Standard Model physics?

beyond models/theory …:

- neutral, cold antimatter !

H (1S-2S): Bohr, R∞, QED, HFS, QCD=proton charged radius r_p



Hydrogen energy levels

Randolf Pohl HADRON München, 13. June 2011 p. 3

(from Randolf Pohl)

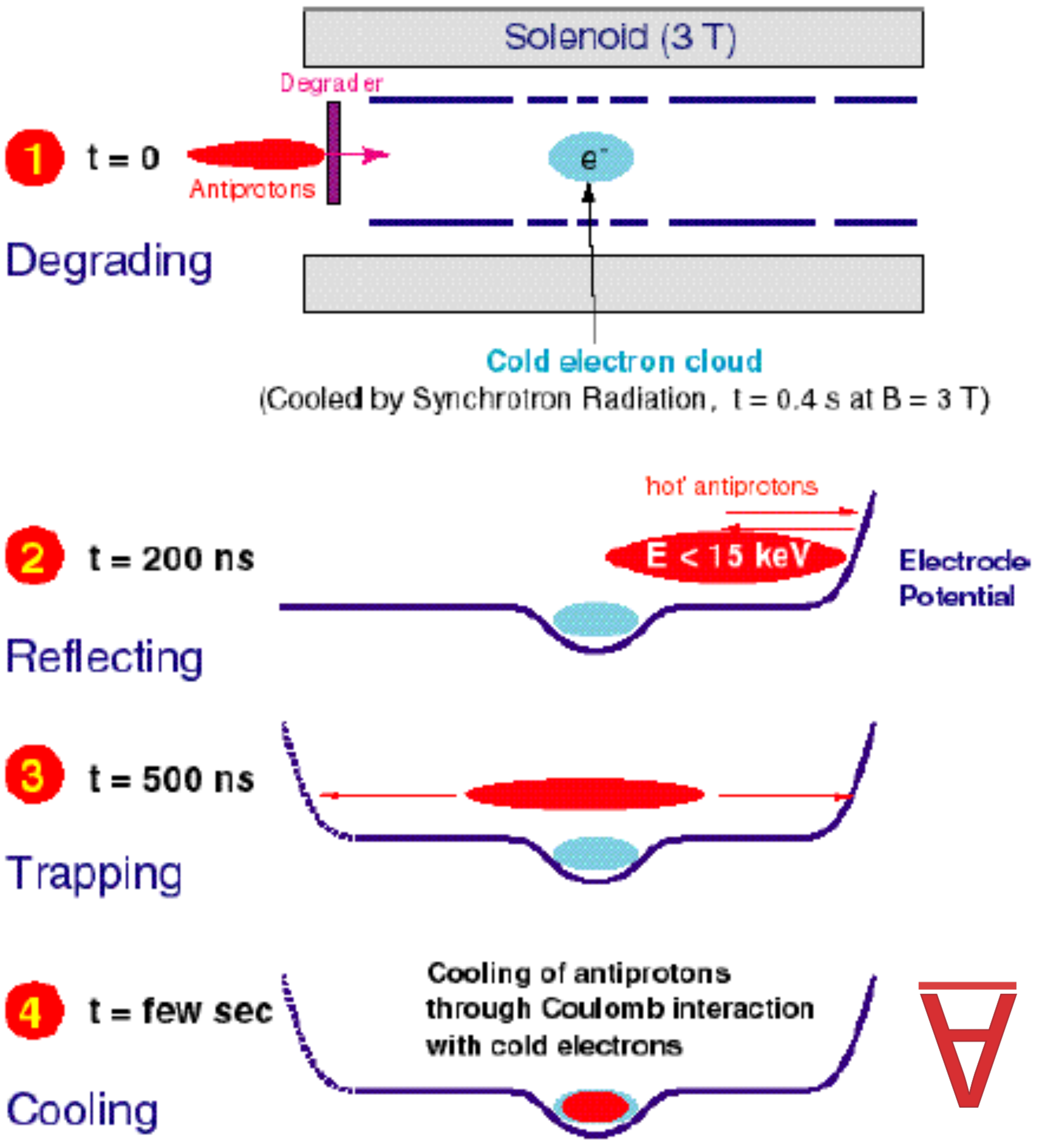
if

$$\delta\nu_{1S-2S} = 120\text{Hz} \Rightarrow$$

$$\delta\nu_{1S-1S}/\nu_{1S-1S} \approx 5 \times 10^{-14}$$

$$\delta r_p/r_p \approx 1 \times 10^{-4}$$

(how) Penning trapping - pbars (dynamic load)



1 t = 0

Degrading

Cold electron cloud

(Cooled by Synchrotron Radiation, t = 0.4 s at B = 3 T)

2 t = 200 ns

Reflecting

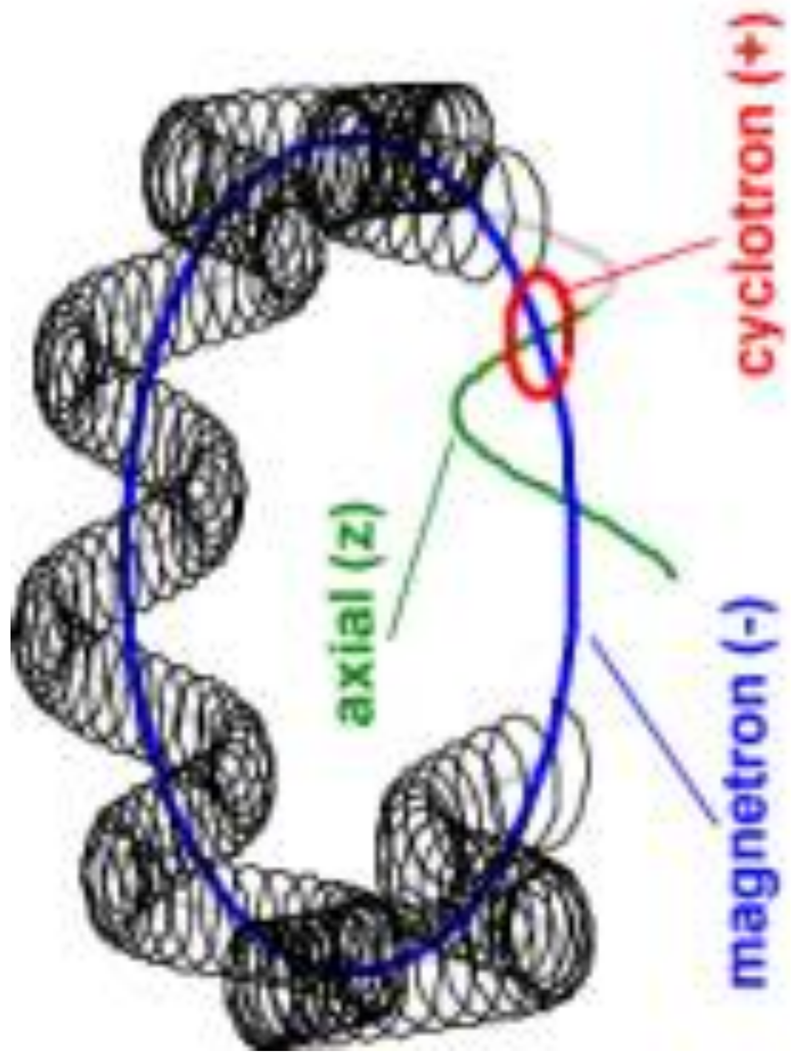
3 t = 500 ns

Trapping

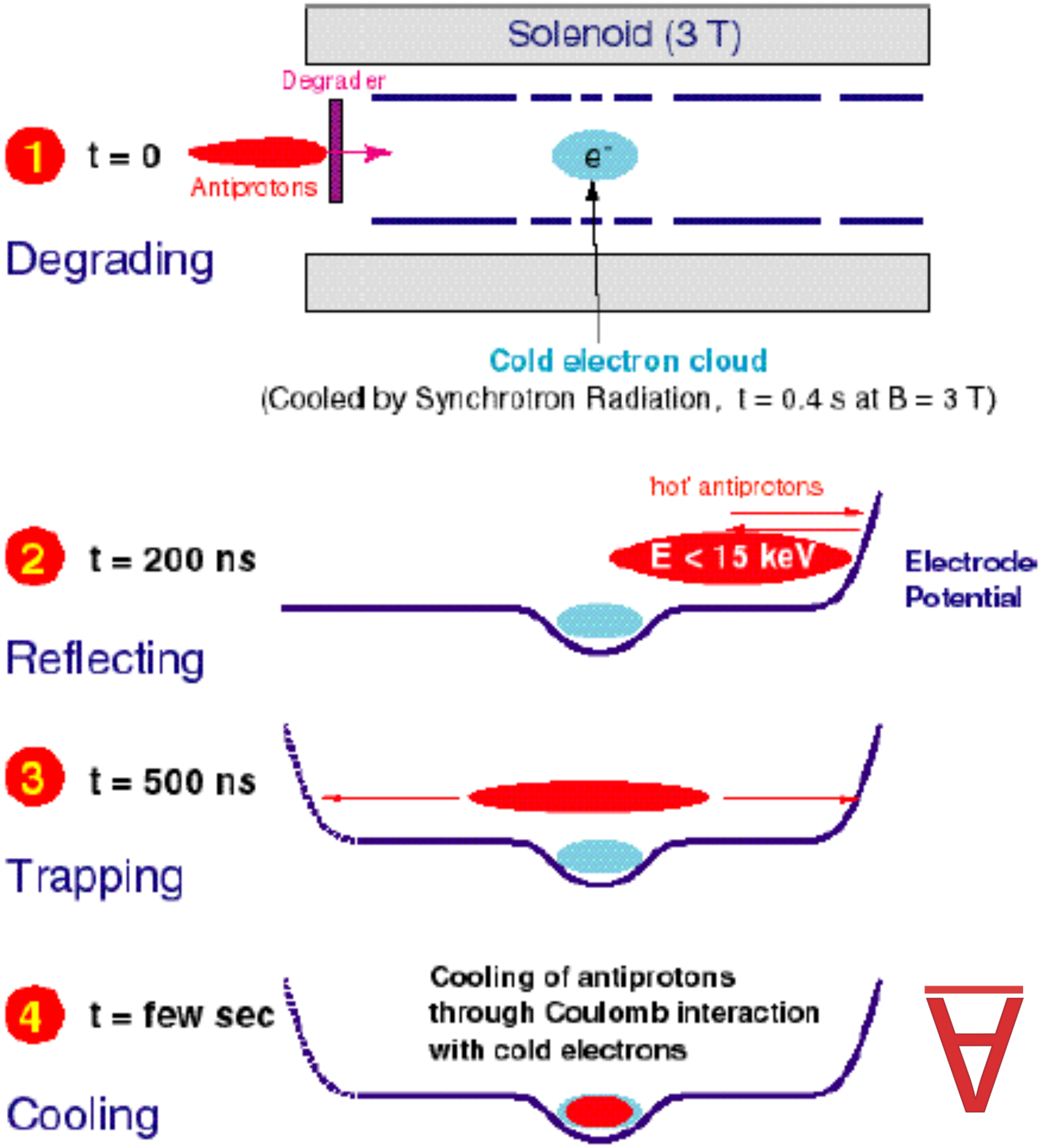
4 t = few sec

Cooling

Cooling of antiprotons through Coulomb interaction with cold electrons



(how) Penning trapping - pbars (dynamic load)



Solenoid (3 T)

Degrader

① t = 0

Antiprotons

e^-

Degrading

Cold electron cloud

(Cooled by Synchrotron Radiation, τ = 0.4 s at B = 3 T)

'hot' antiprotons

② t = 200 ns

E < 15 keV

Electrode Potential

Reflecting

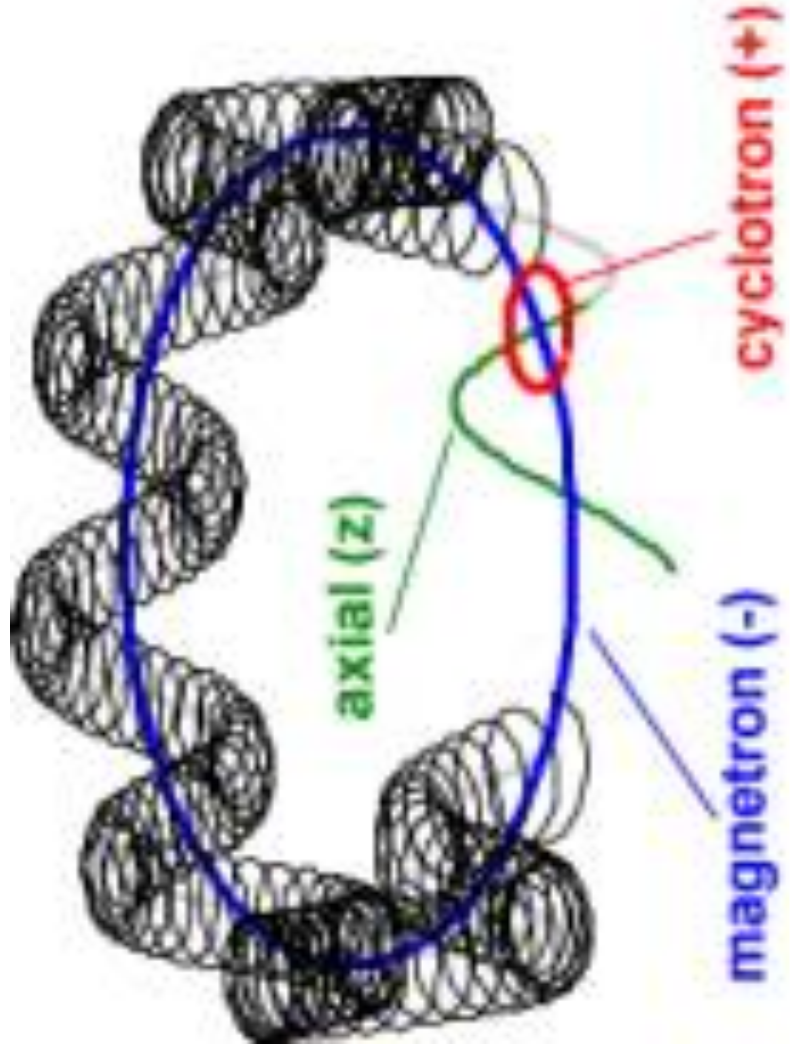
③ t = 500 ns

Trapping

④ t = few sec

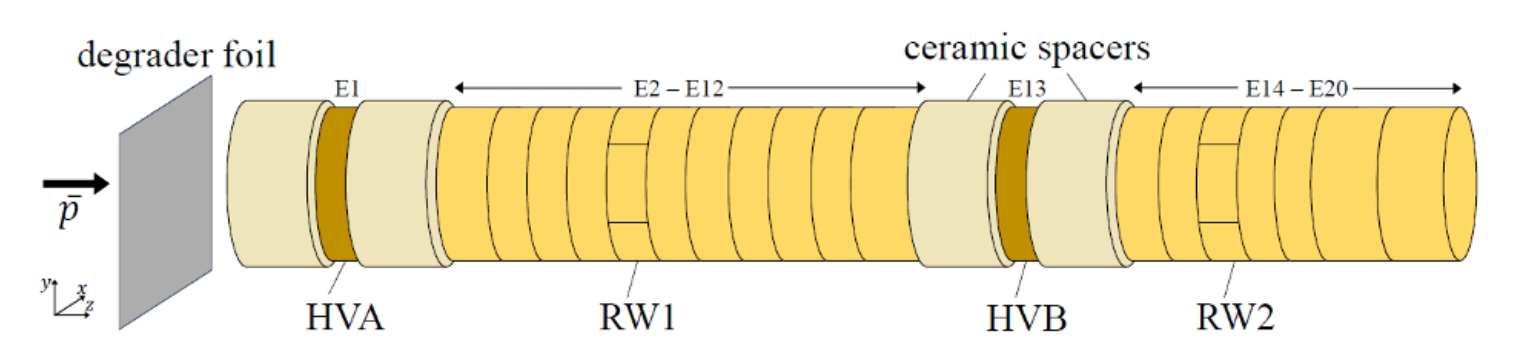
Cooling of antiprotons through Coulomb interaction with cold electrons

Cooling

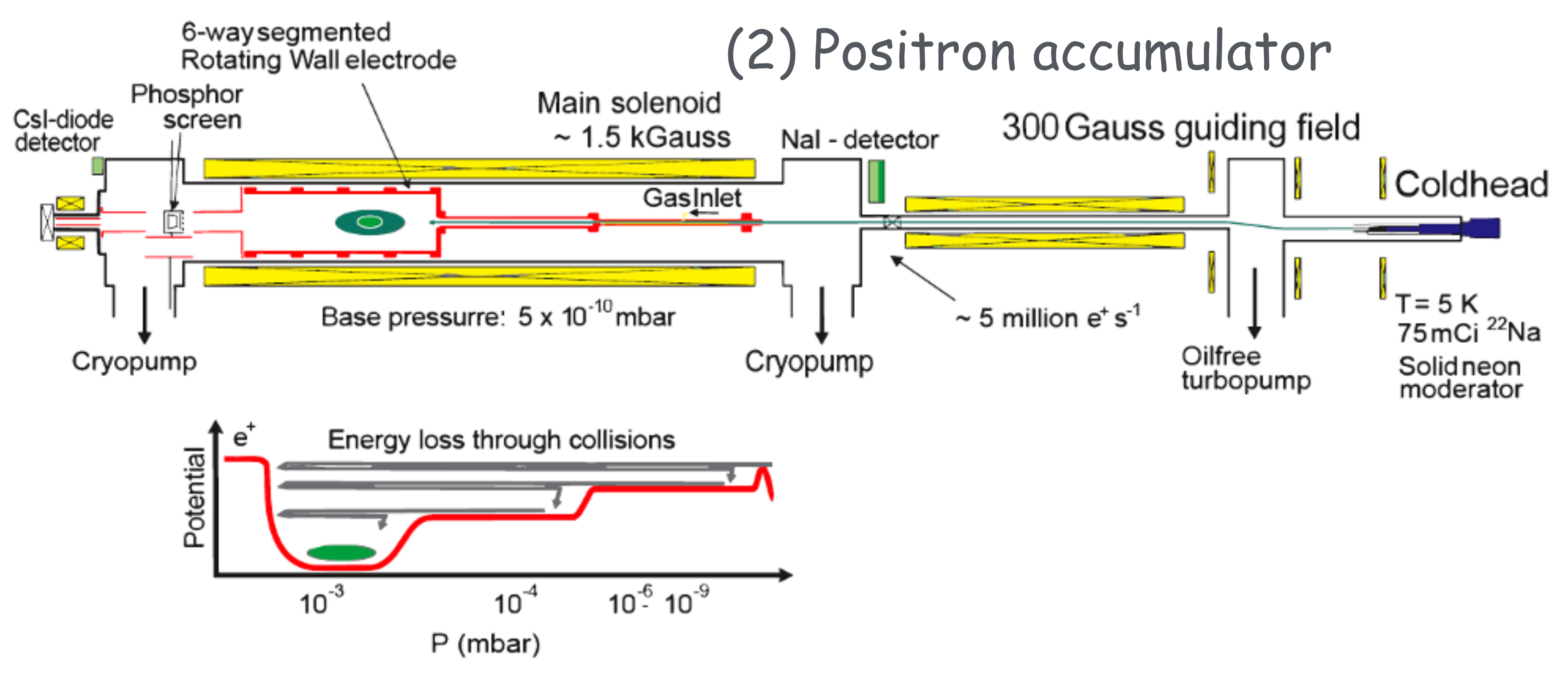


(how) Penning traps - e+ accumulator (Surko type) + Atom atom

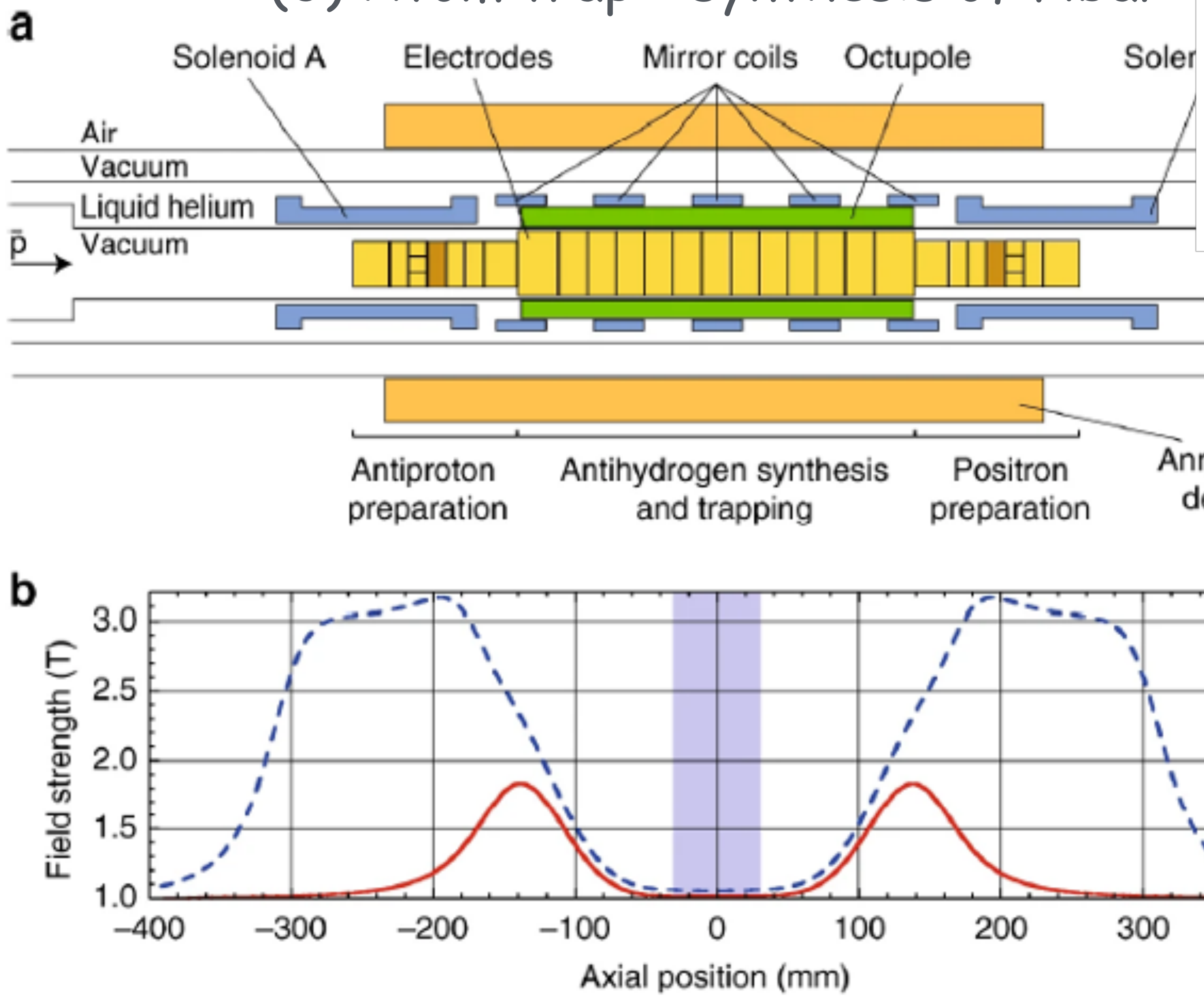
(1) Catching pbars trap



(2) Positron accumulator

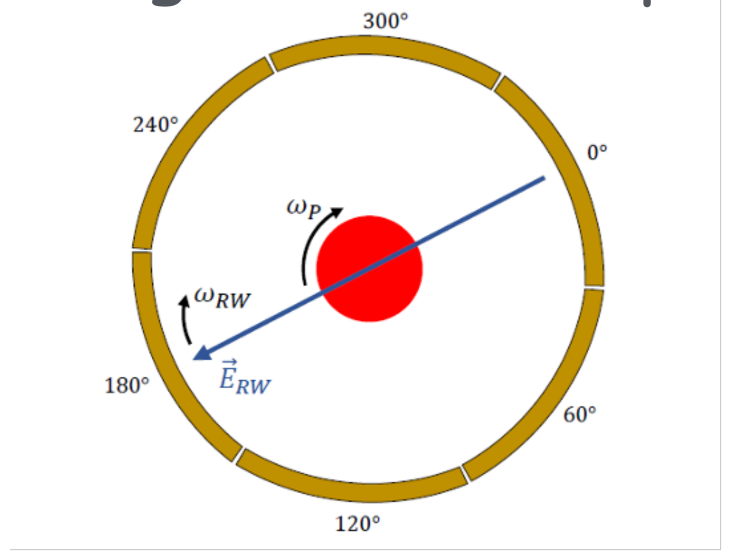


(3) Atom trap - synthesis of Hbar

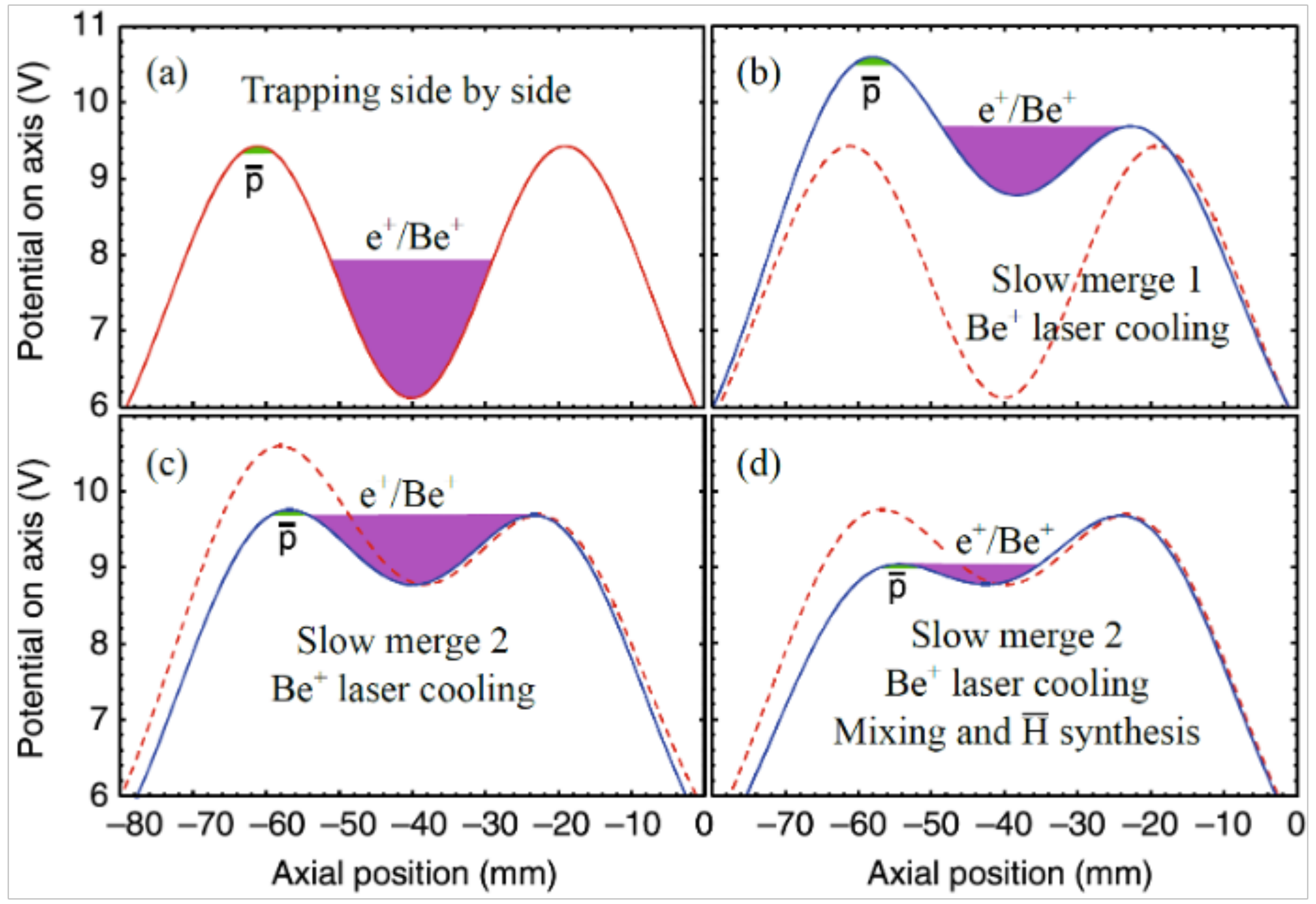


(4)

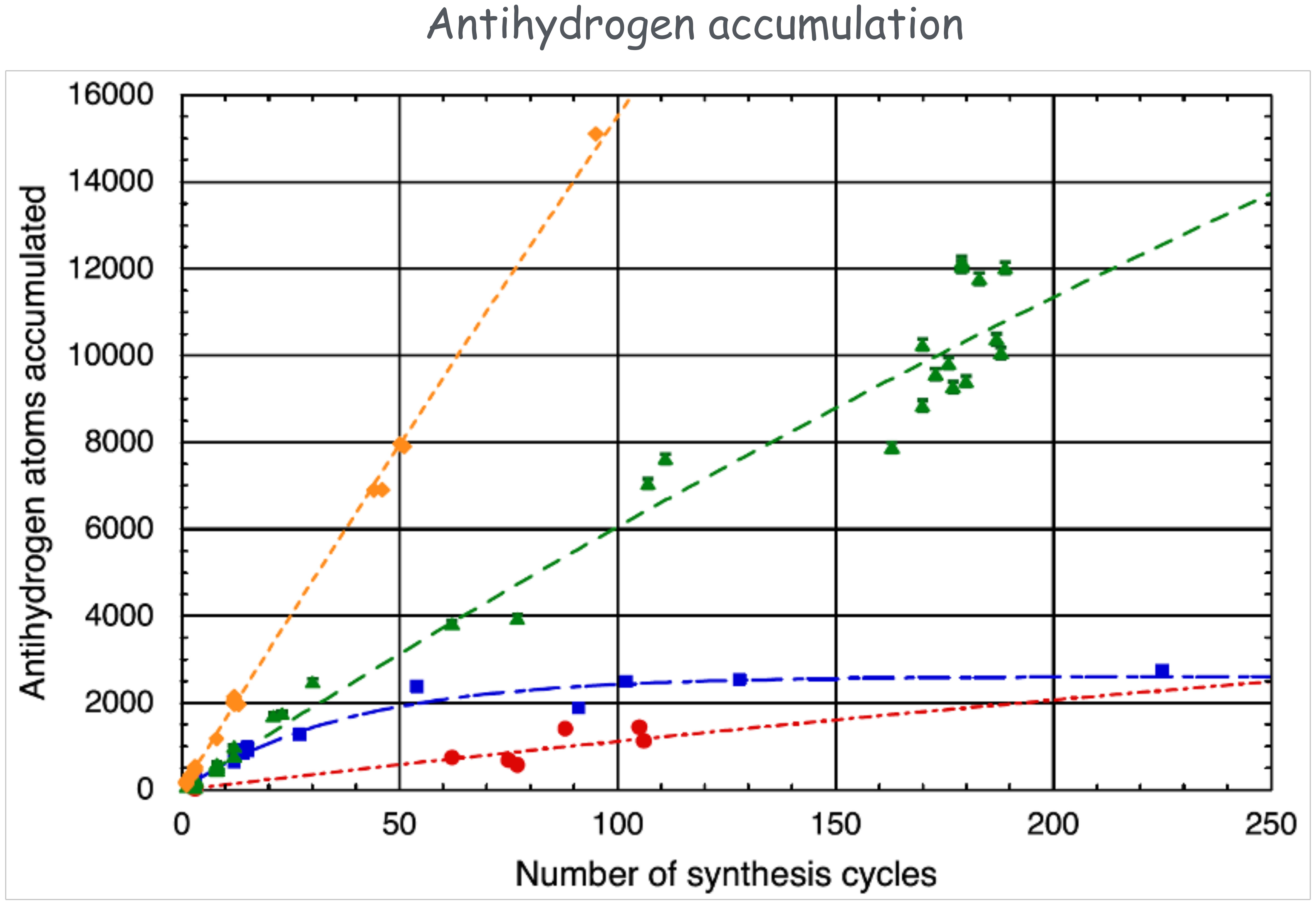
Rotating wall: e+ compressing



(5) Slow merge - synthesis of Hbar

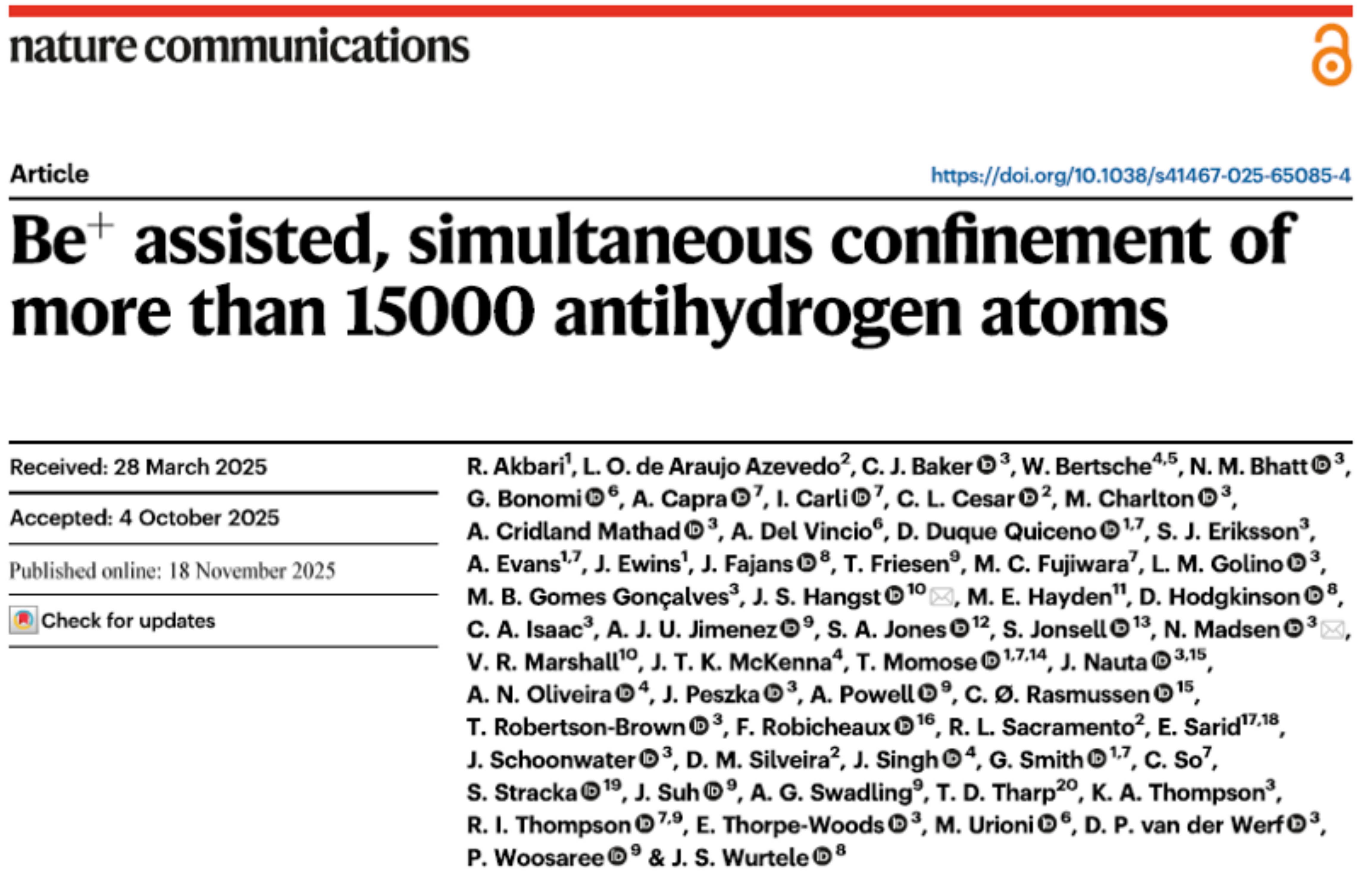


(new) 2025: e⁺ sympathetic cooling by Be⁺ laser cooling


Antihydrogen accumulation

● (Before) Be+ cooling

● (After) optimized Be+ cooling


nature communications

Article https://doi.org/10.1038/s41467-025-65085-4

Be⁺ assisted, simultaneous confinement of more than 15000 antihydrogen atoms

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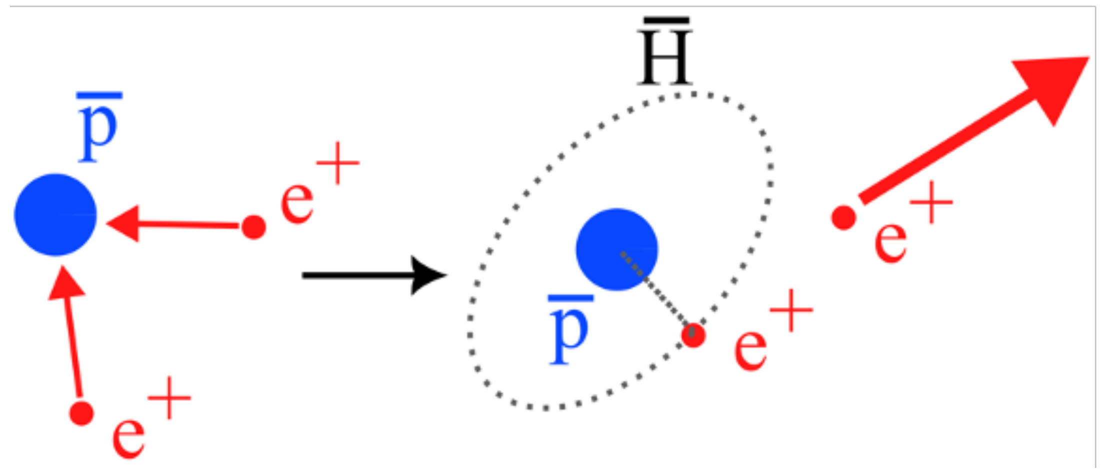
Accepted: 4 October 2025

R. Akbari[1], L. O. de Araujo Azevedo[2], C. J. Baker[3], W. Bertsche[4,5], N. M. Bhatt[3], G. Bonomi[6], A. Capra[7], I. Carli[7], C. L. Cesar[2], M. Charlton[3], A. Cridland Mathad[3], A. Del Vincio[6], D. Duque Quiceno[1,7], S. J. Eriksson[3], A. Evans[1,7], J. Ewins[1], J. Fajans[8], T. Friesen[9], M. C. Fujiwara[7], L. M. Golino[3], M. B. Gomes Gonçalves[3], J. S. Hangst[10], M. E. Hayden[11], D. Hodgkinson[8], C. A. Isaac[3], A. J. U. Jimenez[9], S. A. Jones[12], S. Jonsell[13], N. Madsen[3], V. R. Marshall[10], J. T. K. McKenna[4], T. Momose[1,7,14], J. Nauta[3,15], A. N. Oliveira[4], J. Peszka[3], A. Powell[9], C. Ø. Rasmussen[15], T. Robertson-Brown[3], F. Robicheaux[16], R. L. Sacramento[2], E. Sarid[17,18], J. Schoonwater[3], D. M. Silveira[2], J. Singh[4], G. Smith[1,7], C. So[7], S. Stracka[19], J. Suh[9], A. G. Swadling[9], T. D. Tharp[20], K. A. Thompson[3], R. I. Thompson[7,9], E. Thorpe-Woods[3], M. Urioni[6], D. P. van der Werf[3], P. Woosaree[9] & J. S. Wurtele[8]

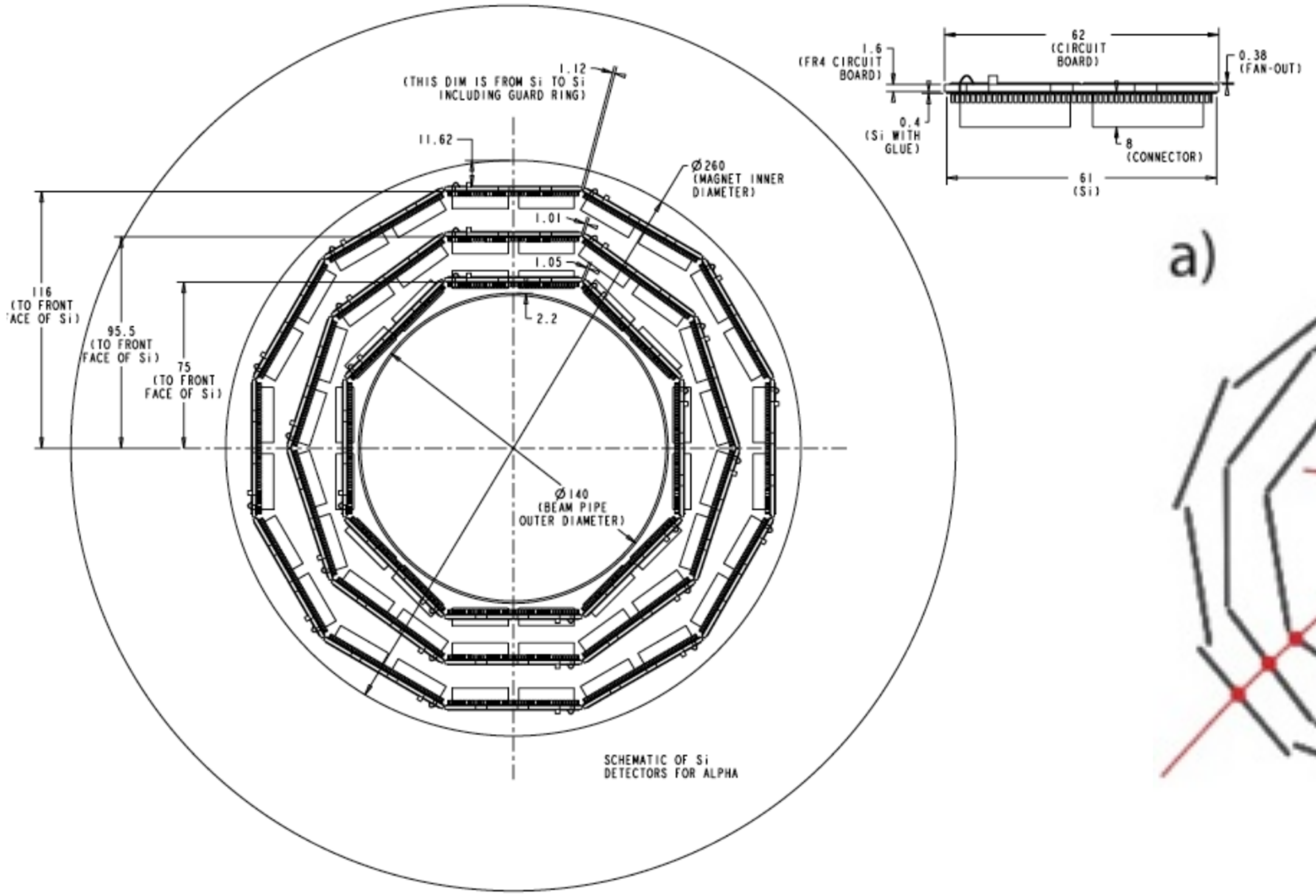


$$\Gamma_{coll} = 6\times10^{-12}\left(\frac{4.2}{T}\right)^{9/2} n_{e+}^2\, s^{-1}$$

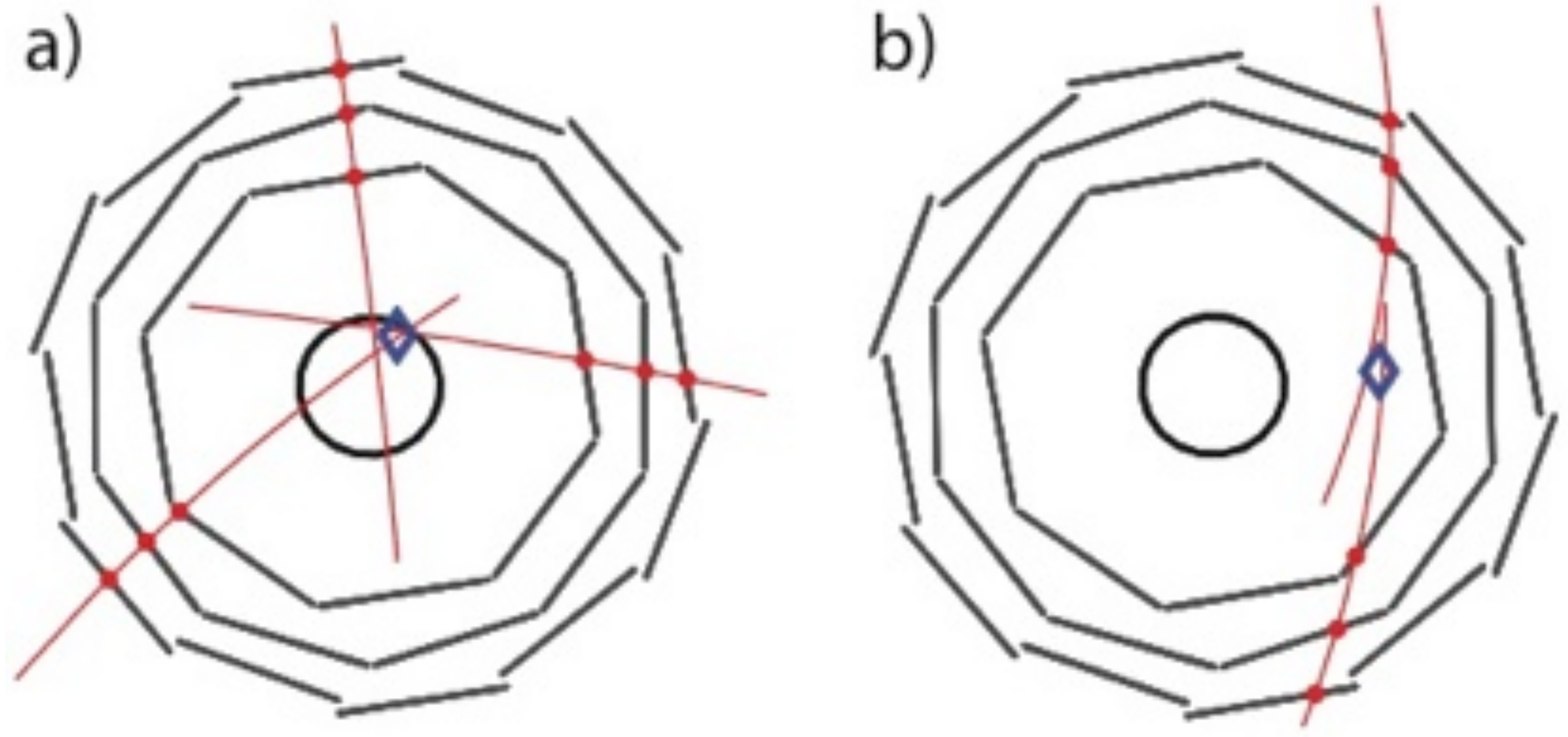
G. Gabrielse et al. Hyperfine Interactions 44.1 (Mar. 1989), pp. 287–293

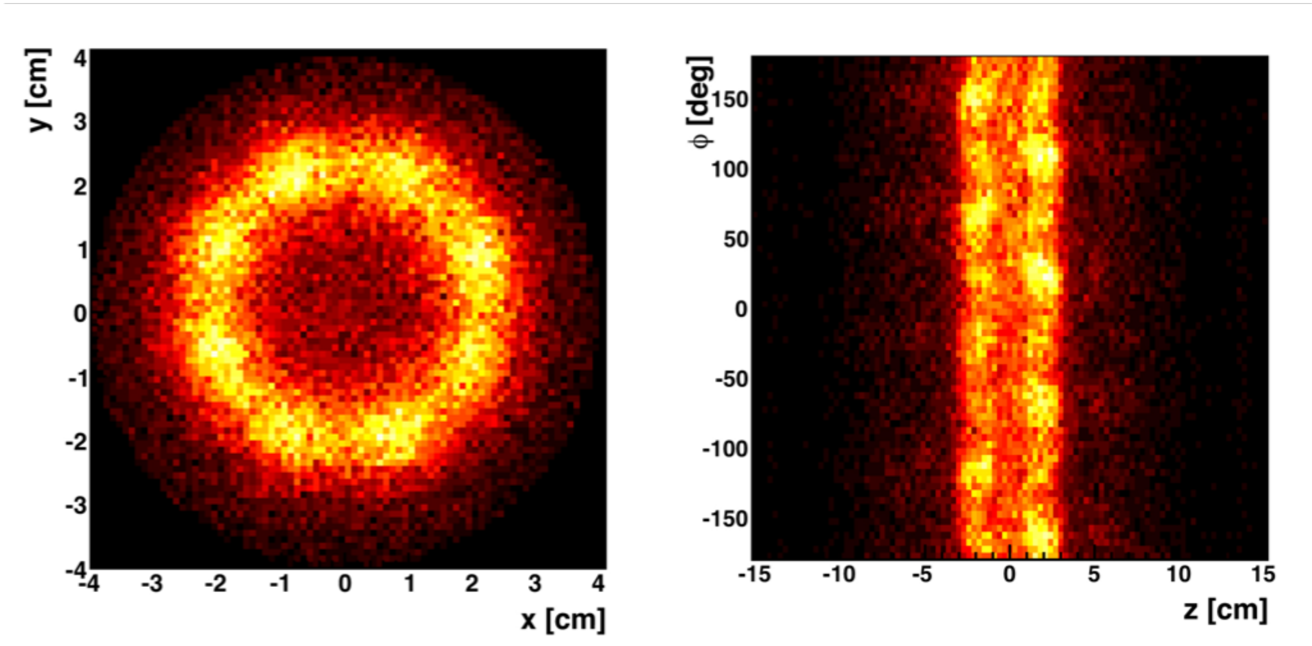
*Maria Beatriz Gomes Goncalves (poster Monday: Be+ cooling of e+)

ALPHA2: Pbar annihilation = pions imaged in a silicon vertex detector

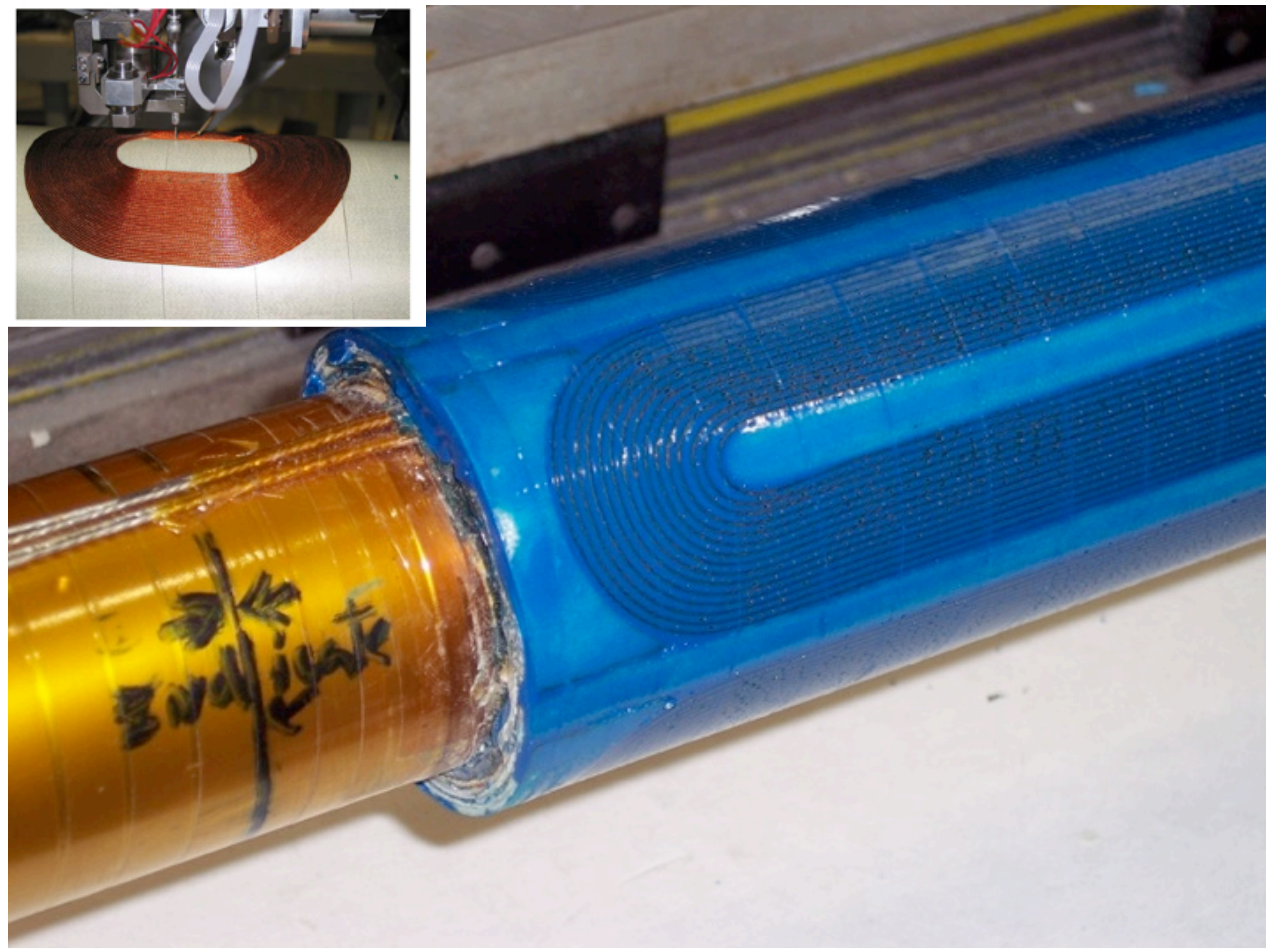


4D tomography



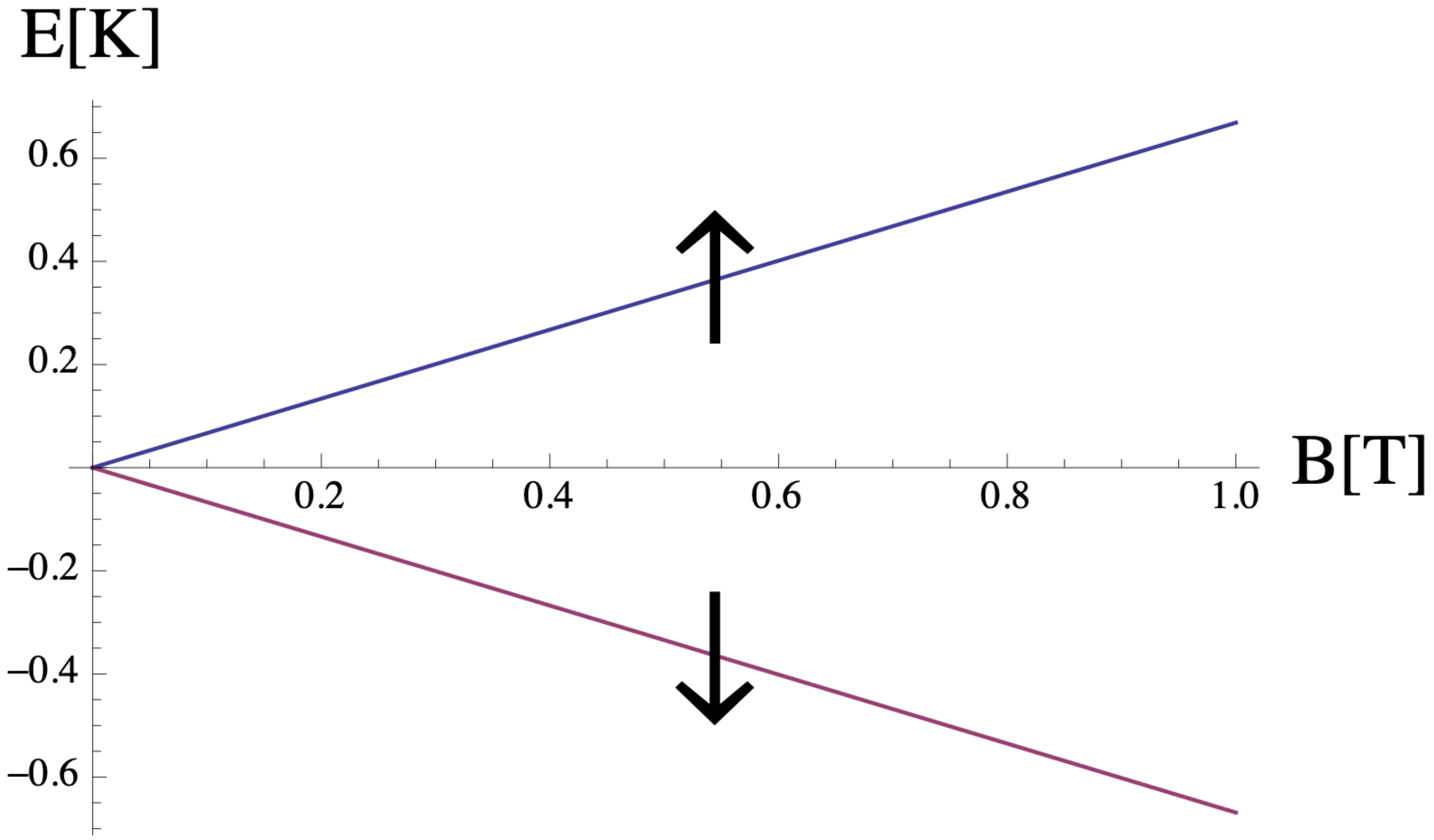


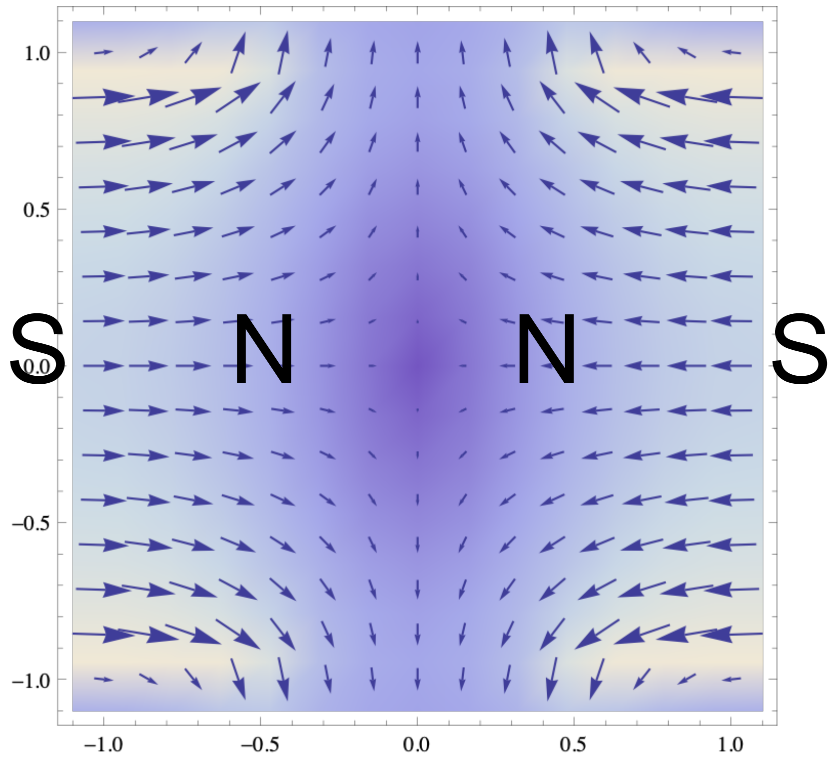
Magnetic Trap: spin = small magnet

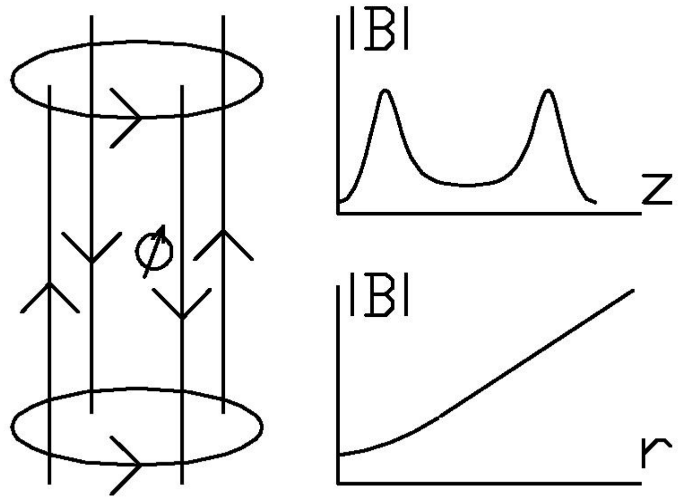


$$\mathbf{U} = -\vec{\mu}\cdot\vec{\mathbf{B}}$$

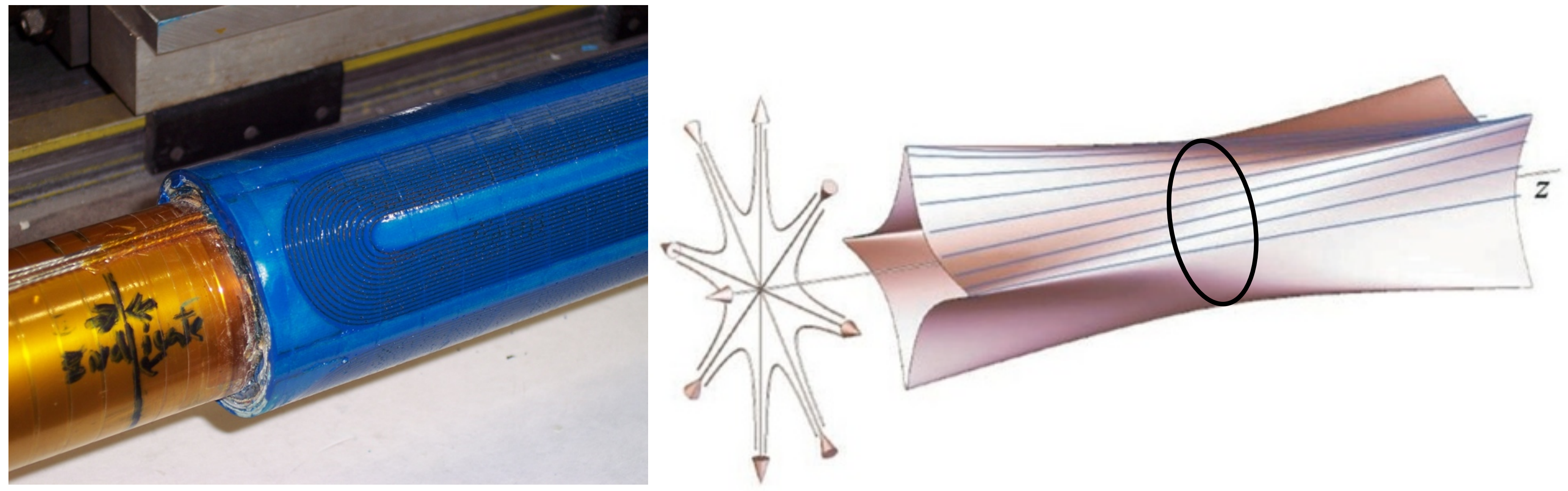
$$\vec{\mathbf{F}} = -\vec{\nabla}\mathbf{U} = \mu\,\vec{\nabla}\,\mathbf{B}$$





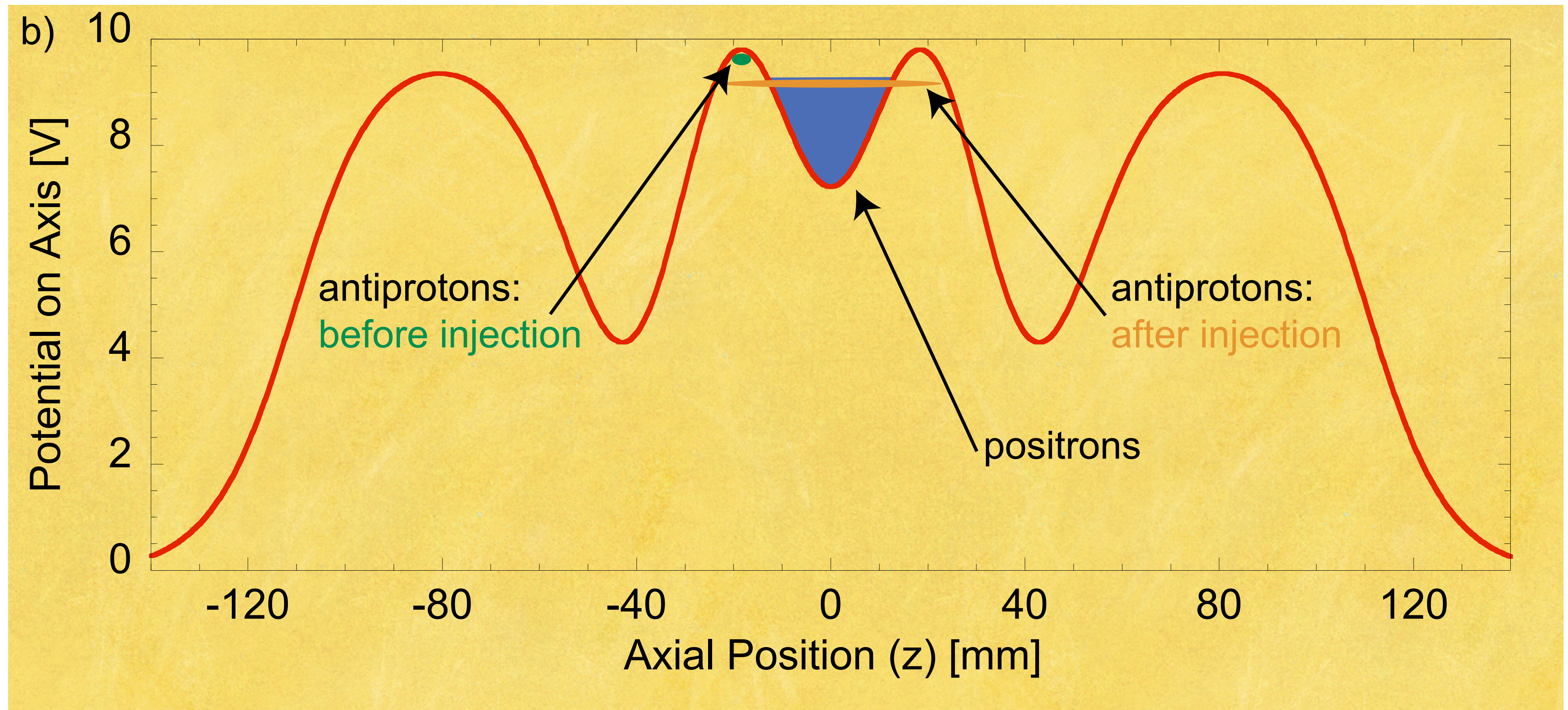


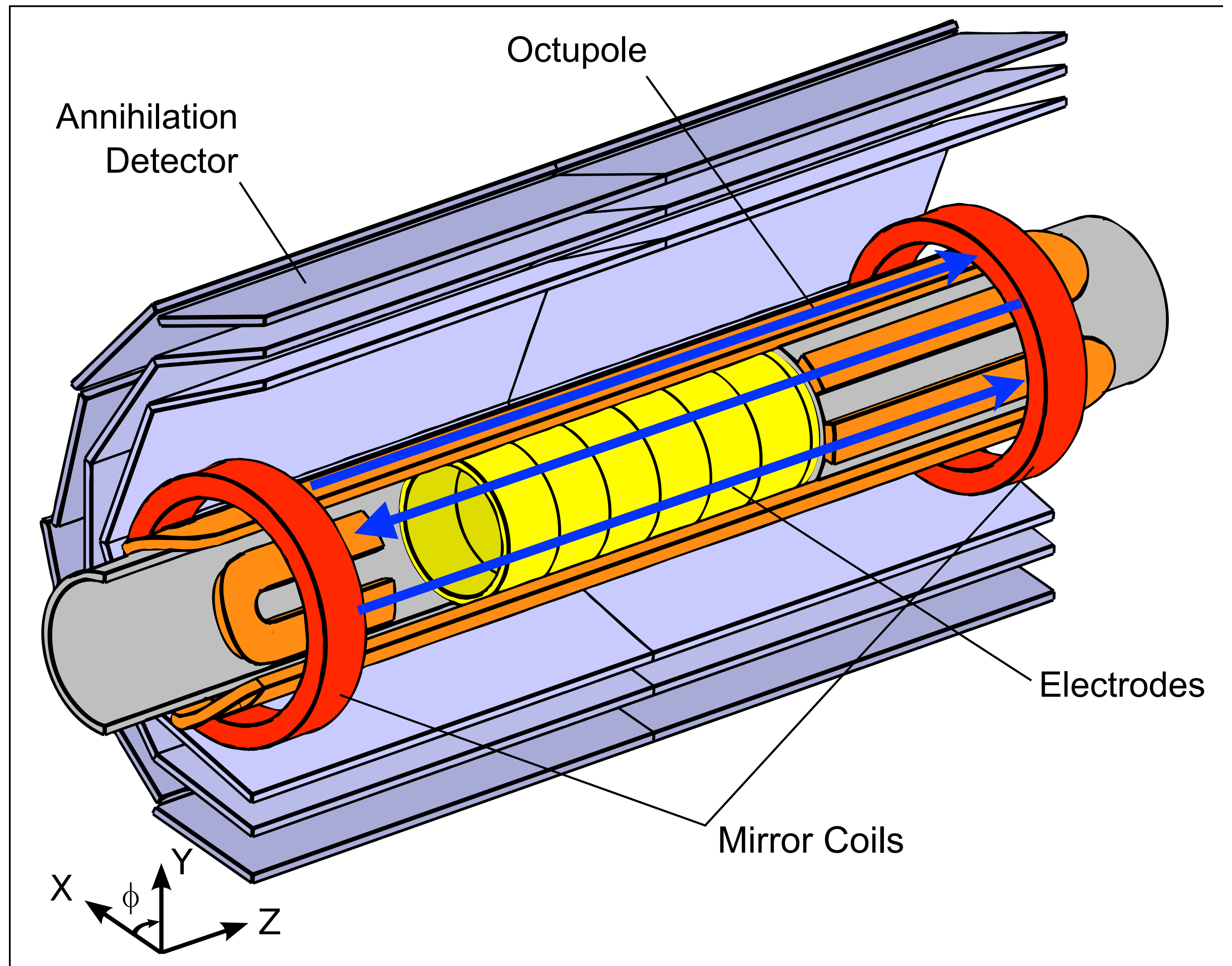
Ioffe-Pritchard 4-poles

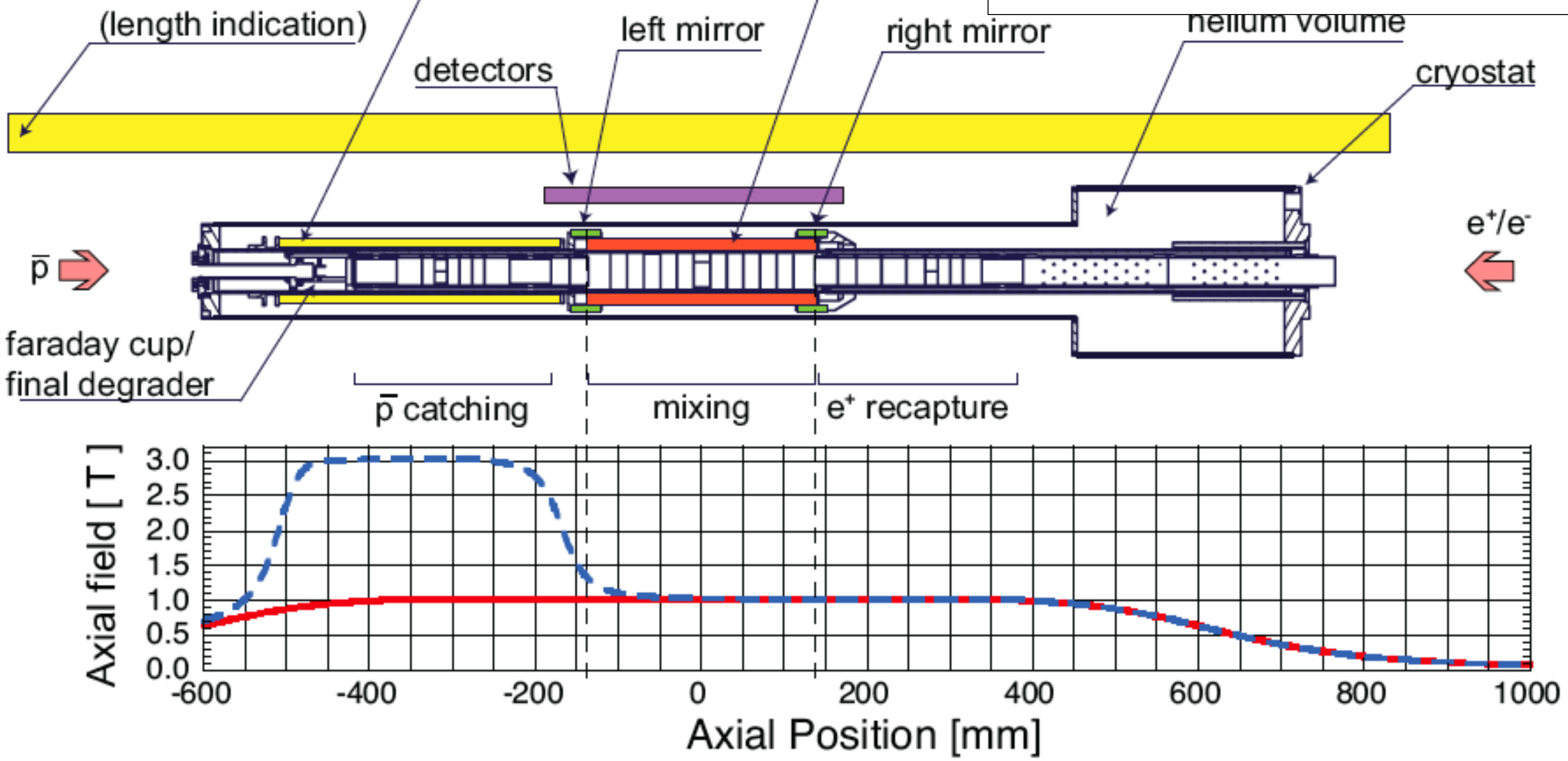


ALPHA ~ Ioffe-Pritchard
8-pole + pinch coils

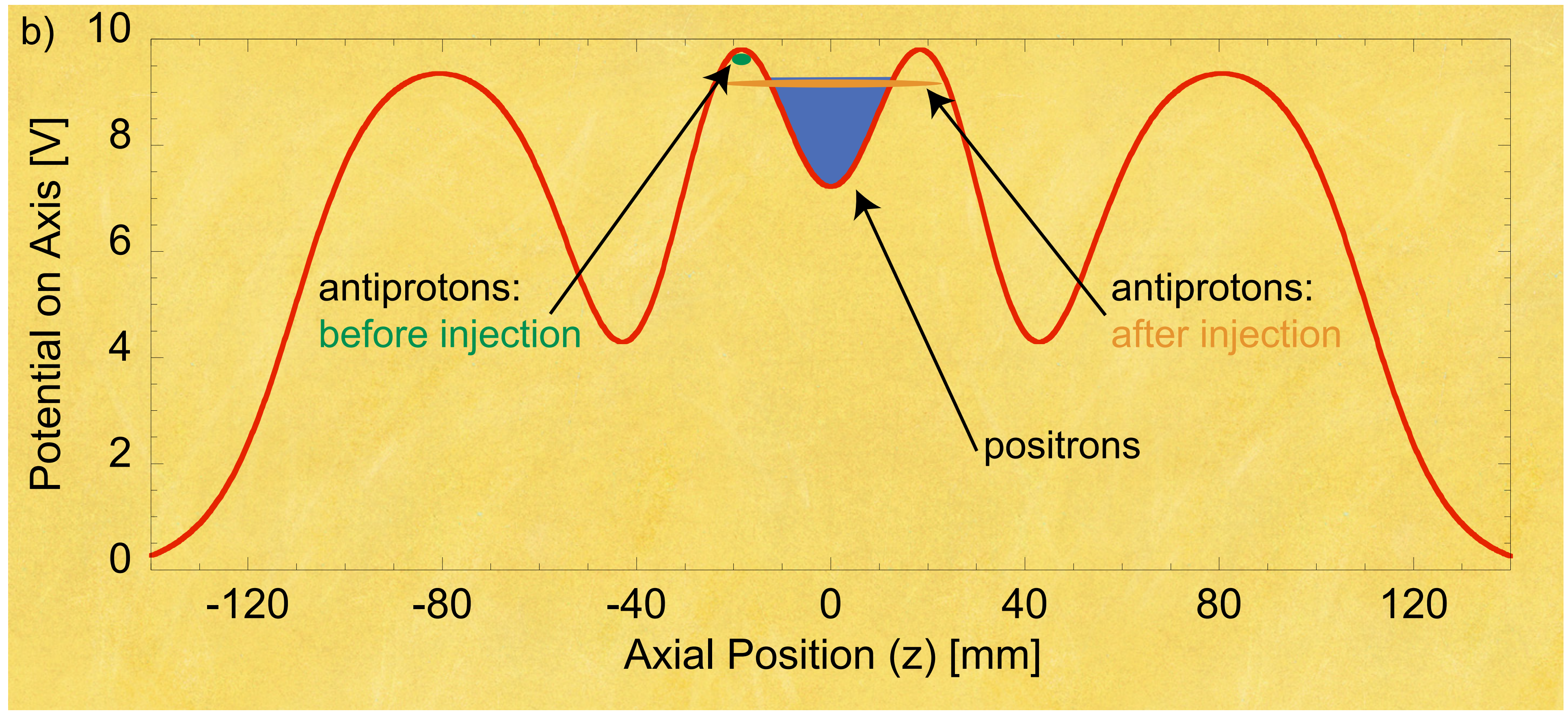
ALPHA-1 Fields' Configuration: Penning and Magnetic Trap

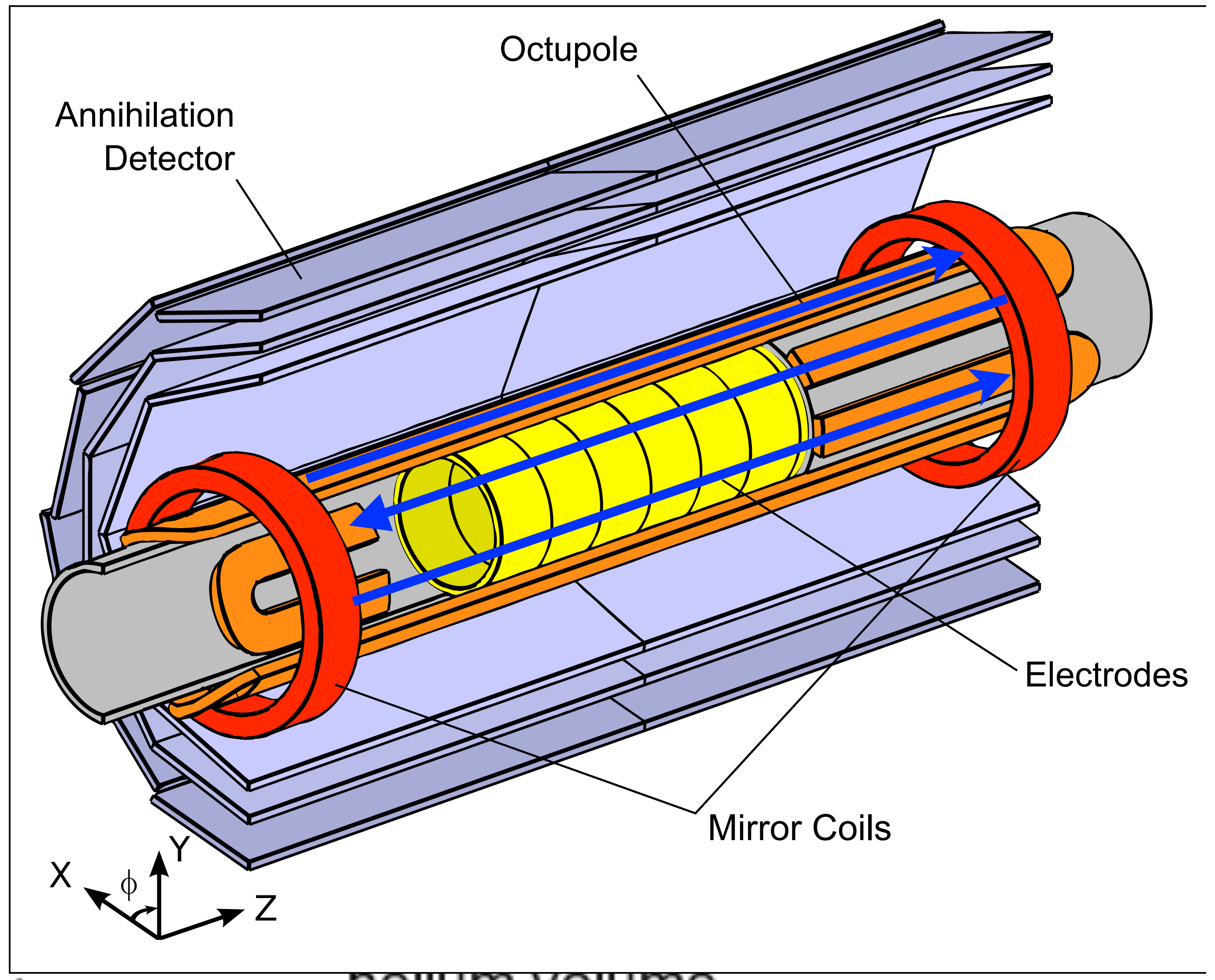


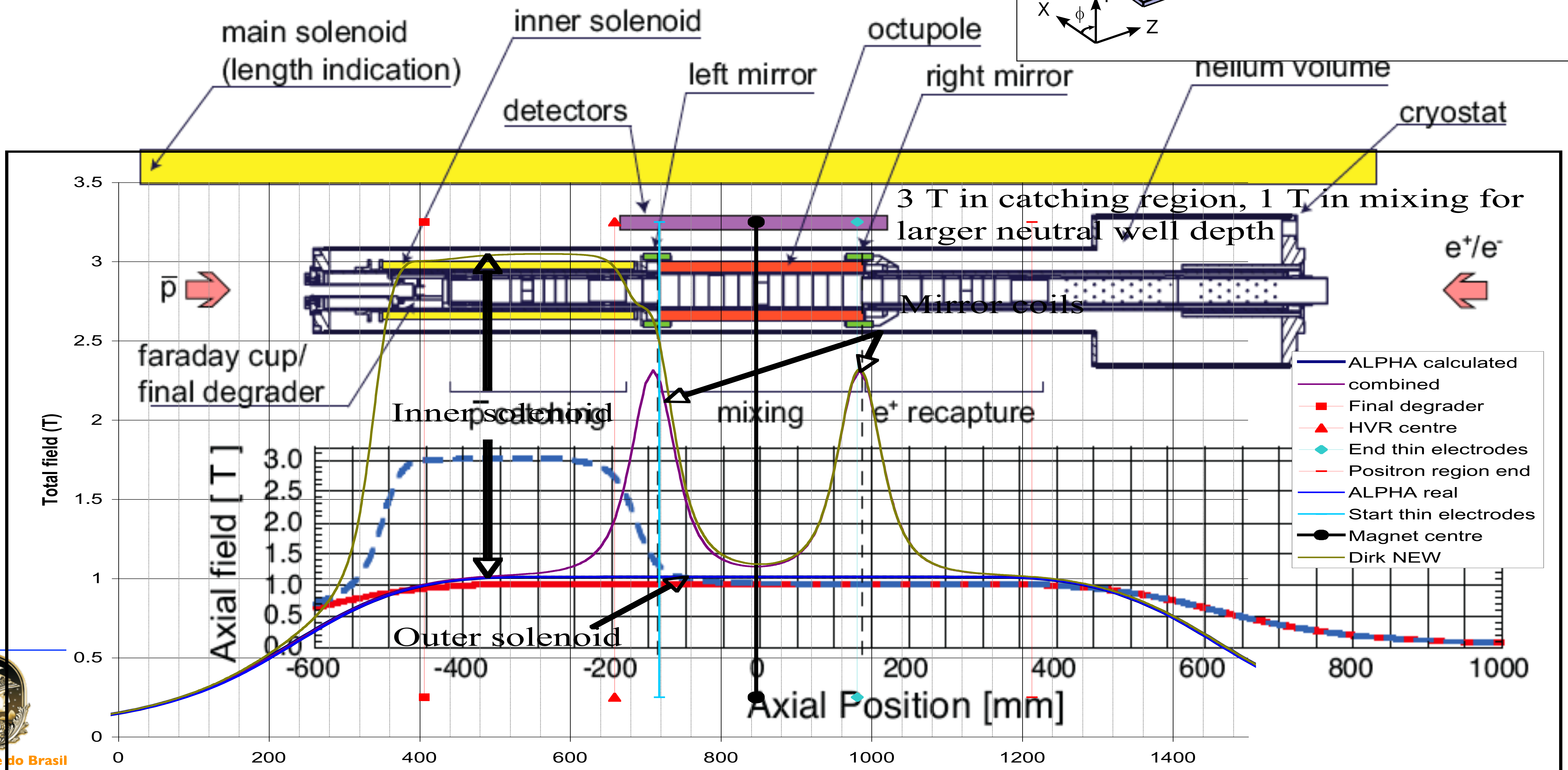




ALPHA-1 Fields' Configuration: Penning and Magnetic Trap







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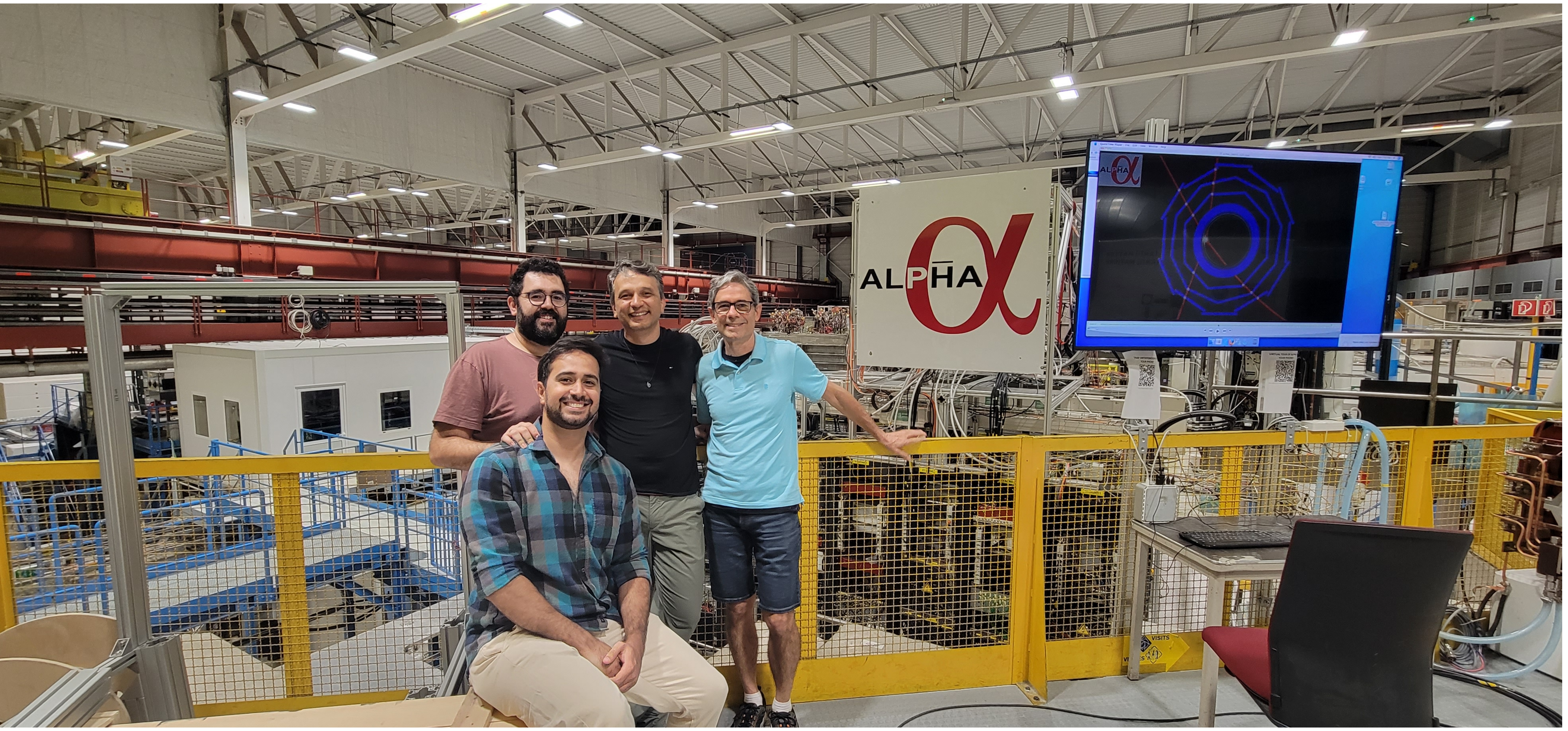
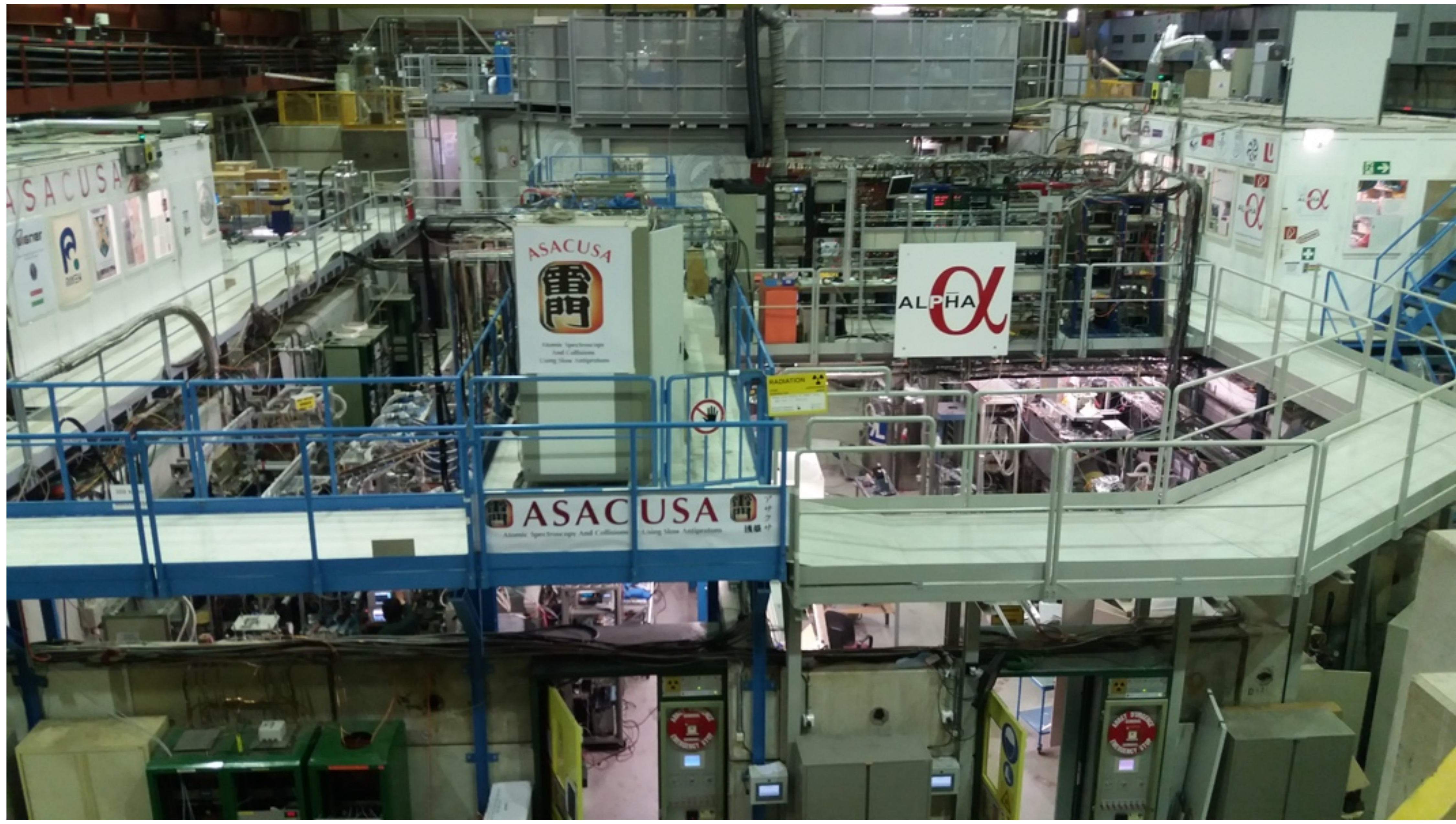
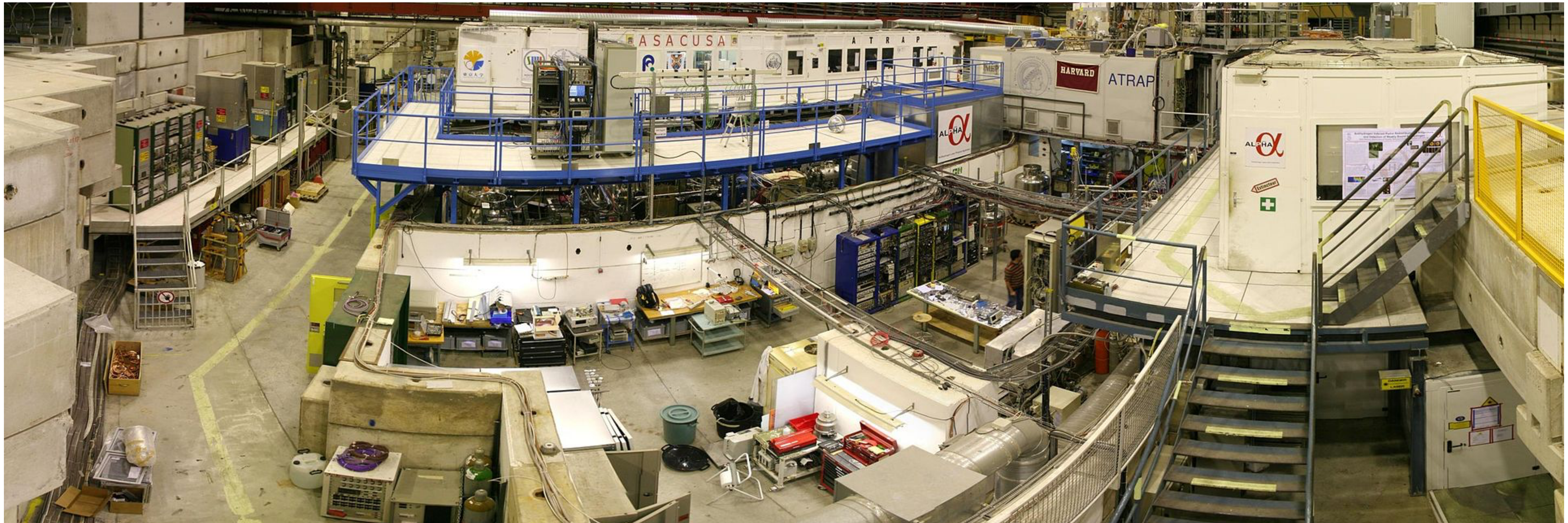
CERN's Antiproton Decelerator (AD)







Hbar formation, trapping, cooling, spectrum, falling

- 1997 Founding of ATHENA - AD (pbars @ 5.3 MeV ~ 6×10^{10} K)
- 2002 First synthesis of slow Hbar ~ 100-1000 K
- 2006 Founding of ALPHA - AD
- 2010 First trapped Hbar ~ 300 mK
- 2013 1st limit on charge anomaly Hbar
- 2016 AD-ELENA : pbars @ 100 keV ~ 10^9 K
- 2018 First 1S-2S Hbar Spectrum ~ 2×10^{-12}
- 2021 Laser cooling (Ly-alpha) ~ 10 mK
- 2023 ALPHA-g first gravitational fall of Hbar
- 2024 Adiabatic expansion cooling of Hbar
- 2025 Laser cooled Be+ (e+ sympathetic) higher production rate
- 2026 many results soon in the press

1 eV ~ 10^4 K

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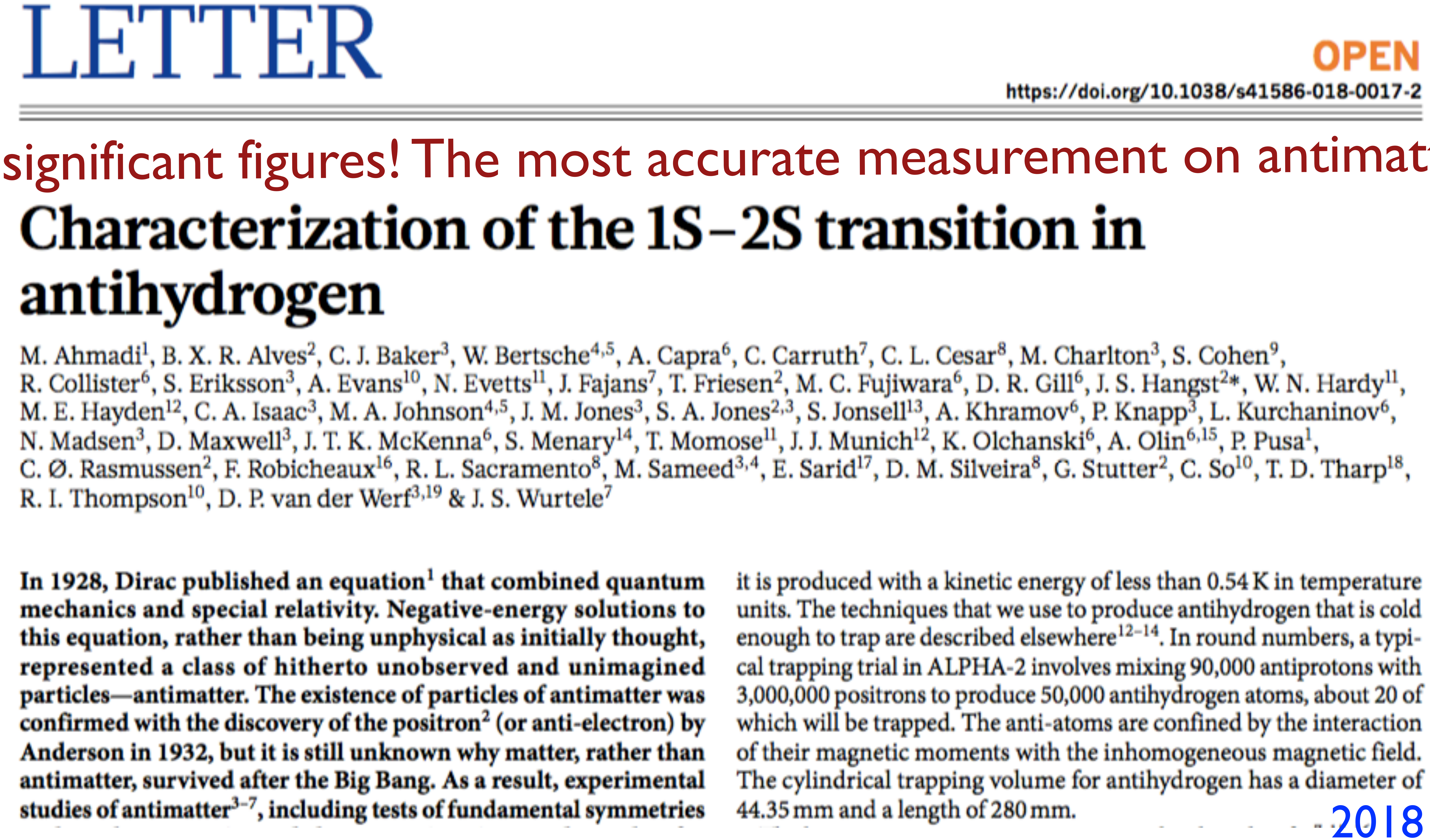
Claudio Lenz Cesar - IQOQI & PSAS - 2026 - ccesar@cern.ch

Hbar laser spectrum



LETTER

OPEN

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

12 significant figures! The most accurate measurement on antimatter!

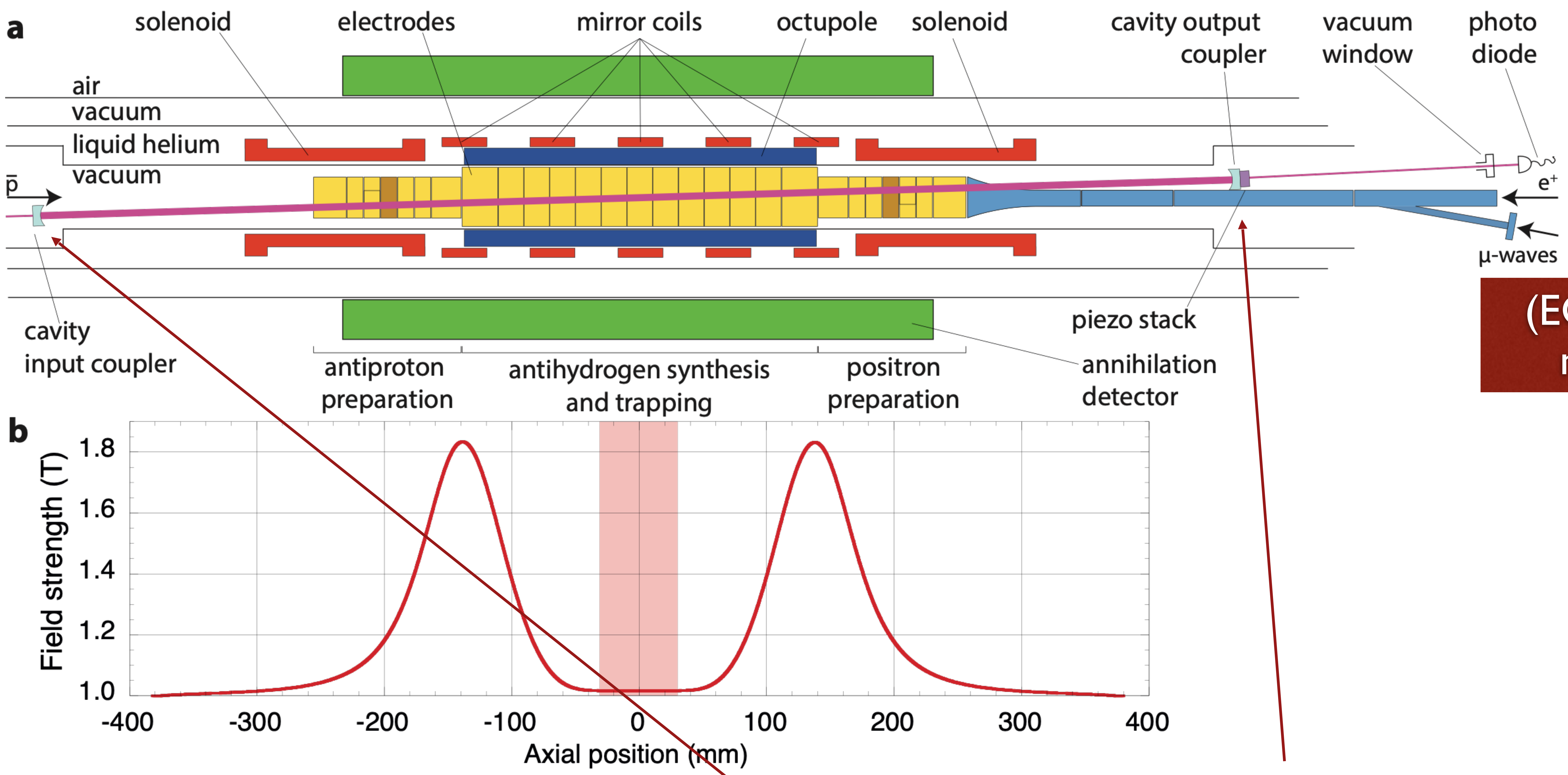
Characterization of the 1S–2S transition in antihydrogen

M. Ahmadi[1], B. X. R. Alves[2], C. J. Baker[3], W. Bertsche[4,5], A. Capra[6], C. Carruth[7], C. L. Cesar[8], M. Charlton[3], S. Cohen[9], R. Collister[6], S. Eriksson[3], A. Evans[10], N. Evetts[11], J. Fajans[7], T. Friesen[2], M. C. Fujiwara[6], D. R. Gill[6], J. S. Hangst[2]*, W. N. Hardy[11], M. E. Hayden[12], C. A. Isaac[3], M. A. Johnson[4,5], J. M. Jones[3], S. A. Jones[2,3], S. Jonsell[13], A. Khramov[6], P. Knapp[3], L. Kurchaninov[6], N. Madsen[3], D. Maxwell[3], J. T. K. McKenna[6], S. Menary[14], T. Momose[11], J. J. Munich[12], K. Olchanski[6], A. Olin[6,15], P. Pusa[1], C. Ø. Rasmussen[2], F. Robicheaux[16], R. L. Sacramento[8], M. Sameed[3,4], E. Sarid[17], D. M. Silveira[8], G. Stutter[2], C. So[10], T. D. Tharp[18], R. I. Thompson[10], D. P. van der Werf[3,19] & J. S. Wurtele[7]

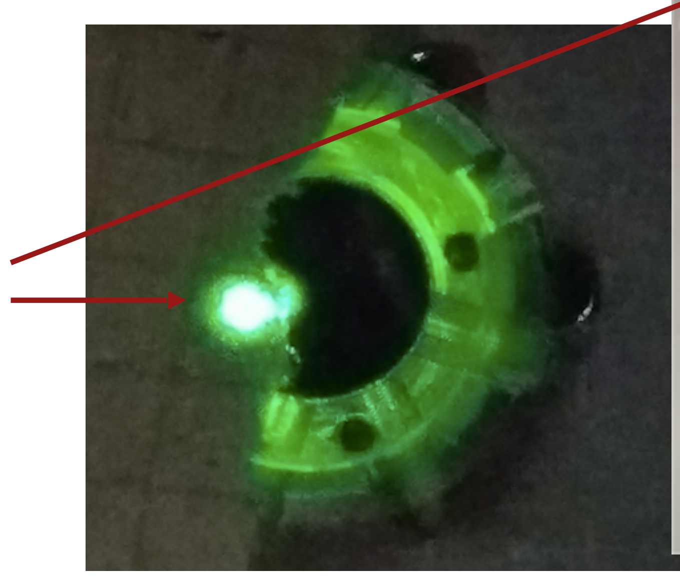
In 1928, Dirac published an equation[1] that combined quantum mechanics and special relativity. Negative-energy solutions to this equation, rather than being unphysical as initially thought, represented a class of hitherto unobserved and unimagined particles—antimatter. The existence of particles of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

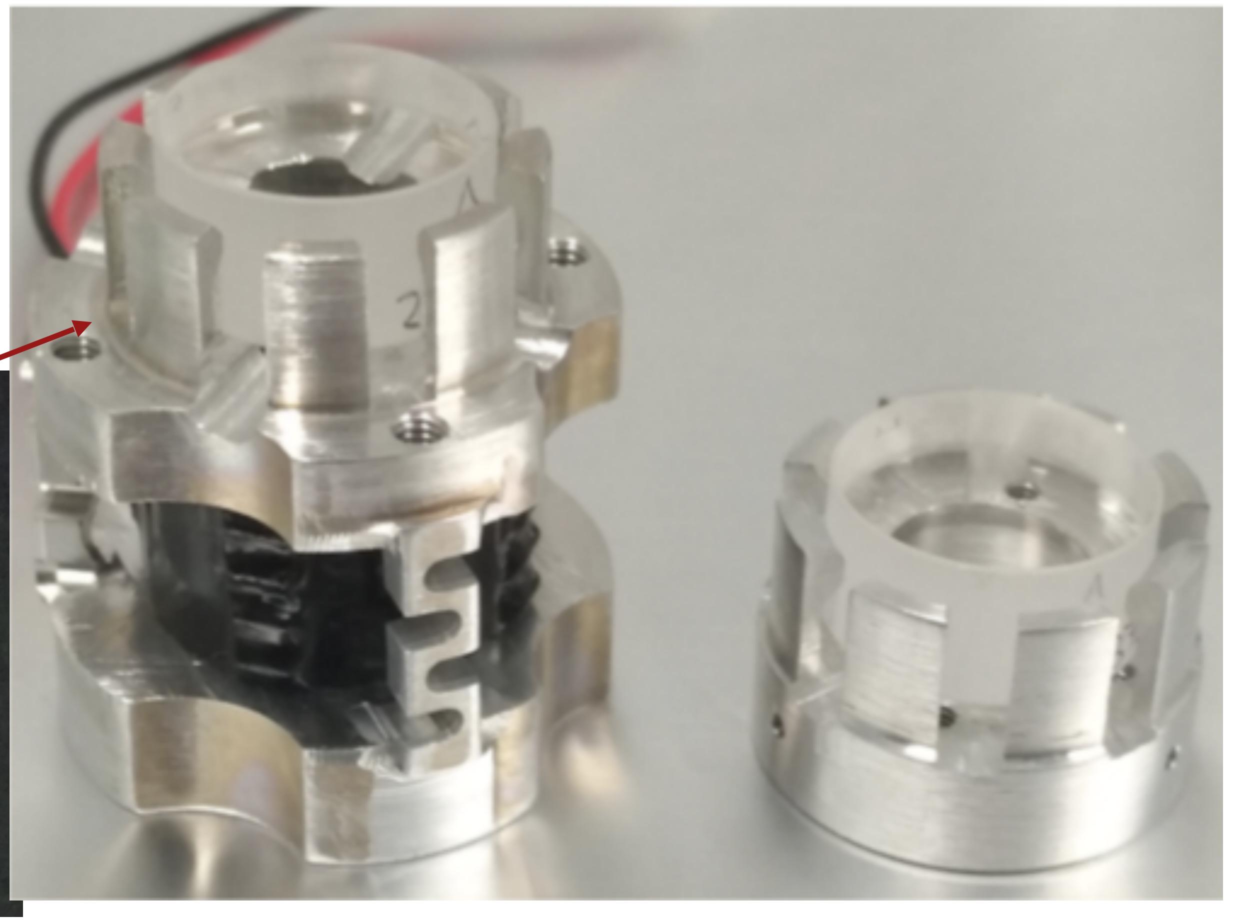
it is produced with a kinetic energy of less than 0.54 K in temperature units. The techniques that we use to produce antihydrogen that is cold enough to trap are described elsewhere[12–14]. In round numbers, a typical trapping trial in ALPHA-2 involves mixing 90,000 antiprotons with 3,000,000 positrons 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.

2018



(ECR)B-field measure

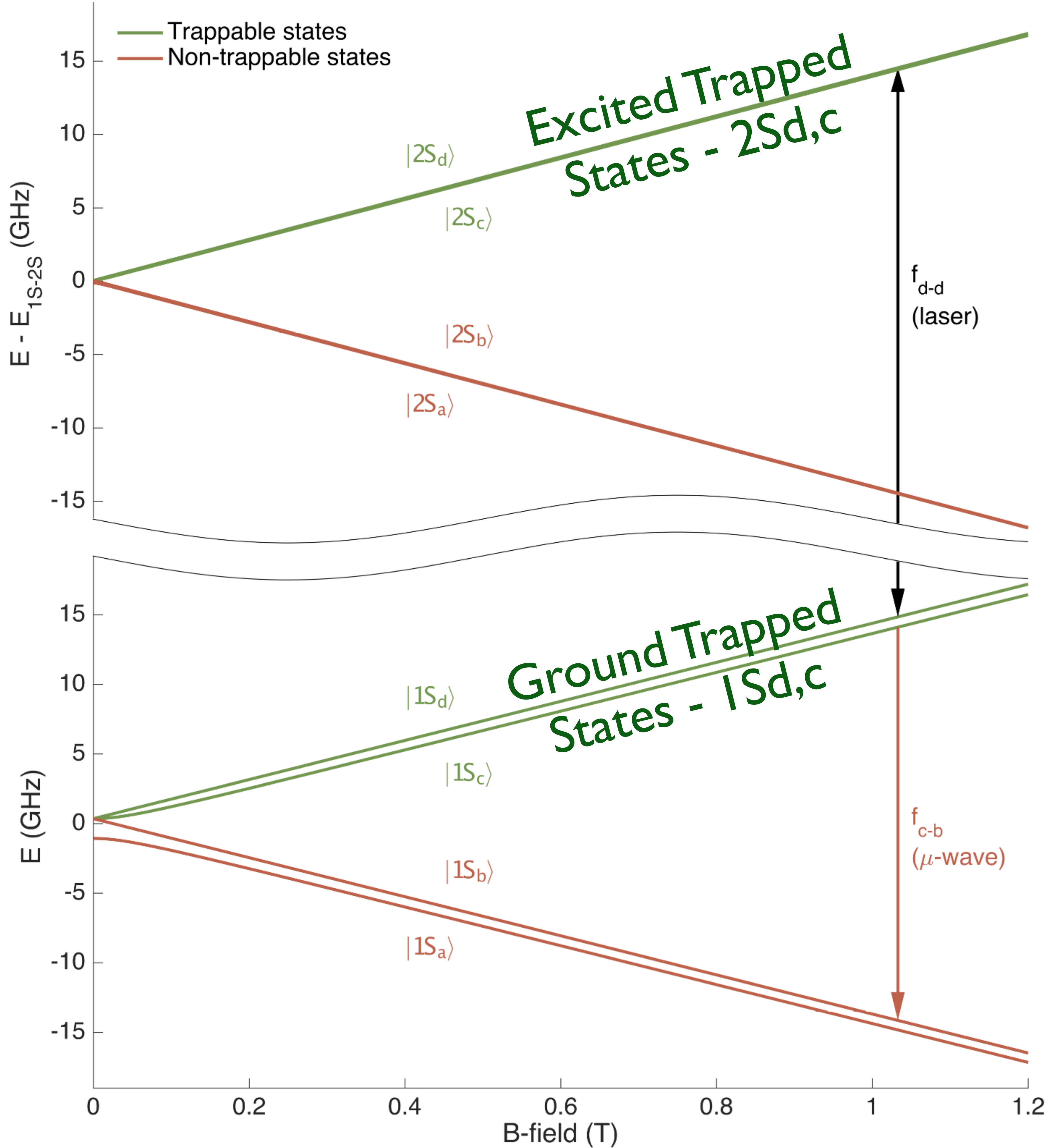


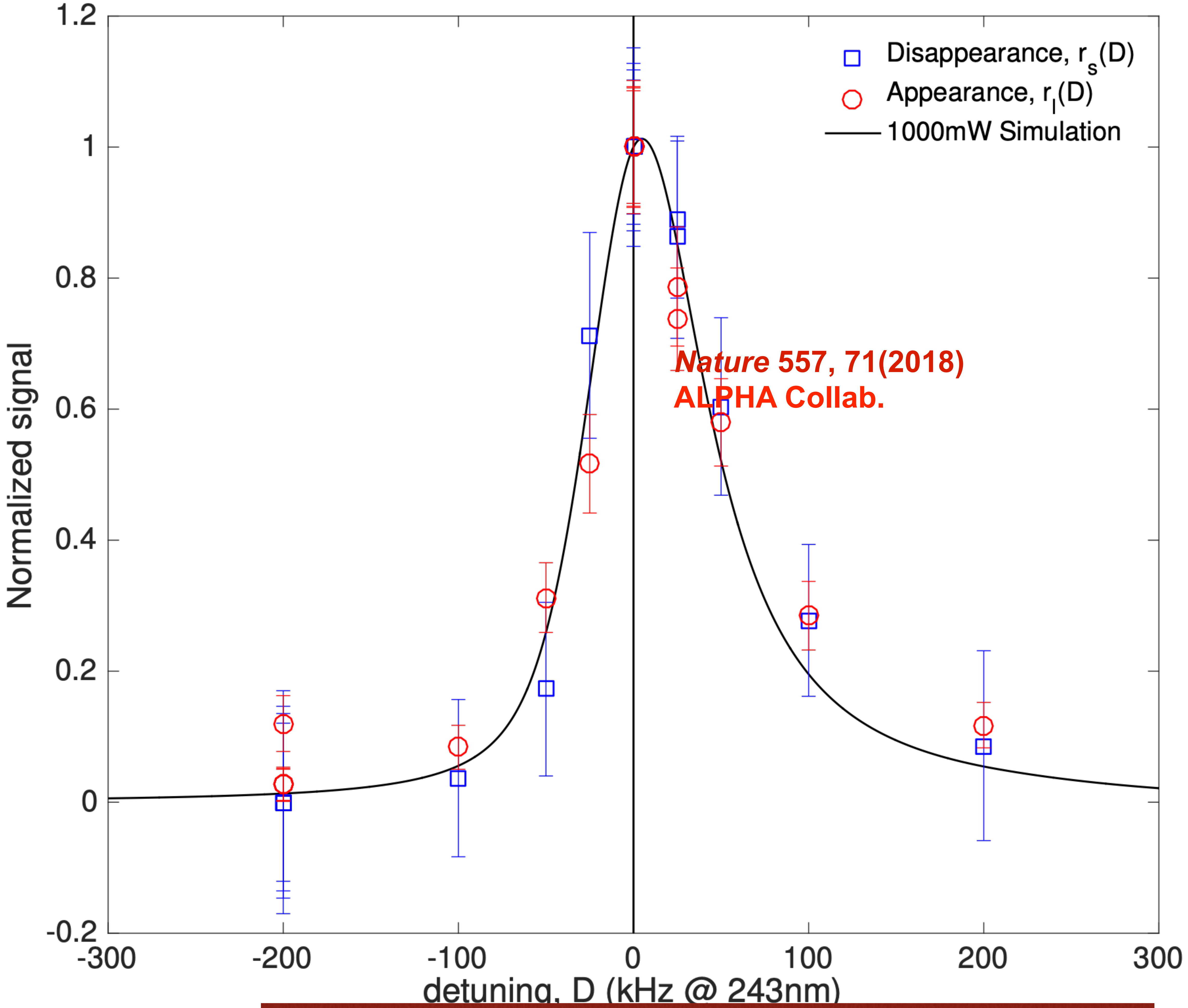


Cryogenic Optical Cavity: designed & made in Brasil

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

H vs Hbar 1S-2S comparison: 2 parts in 10^{12}





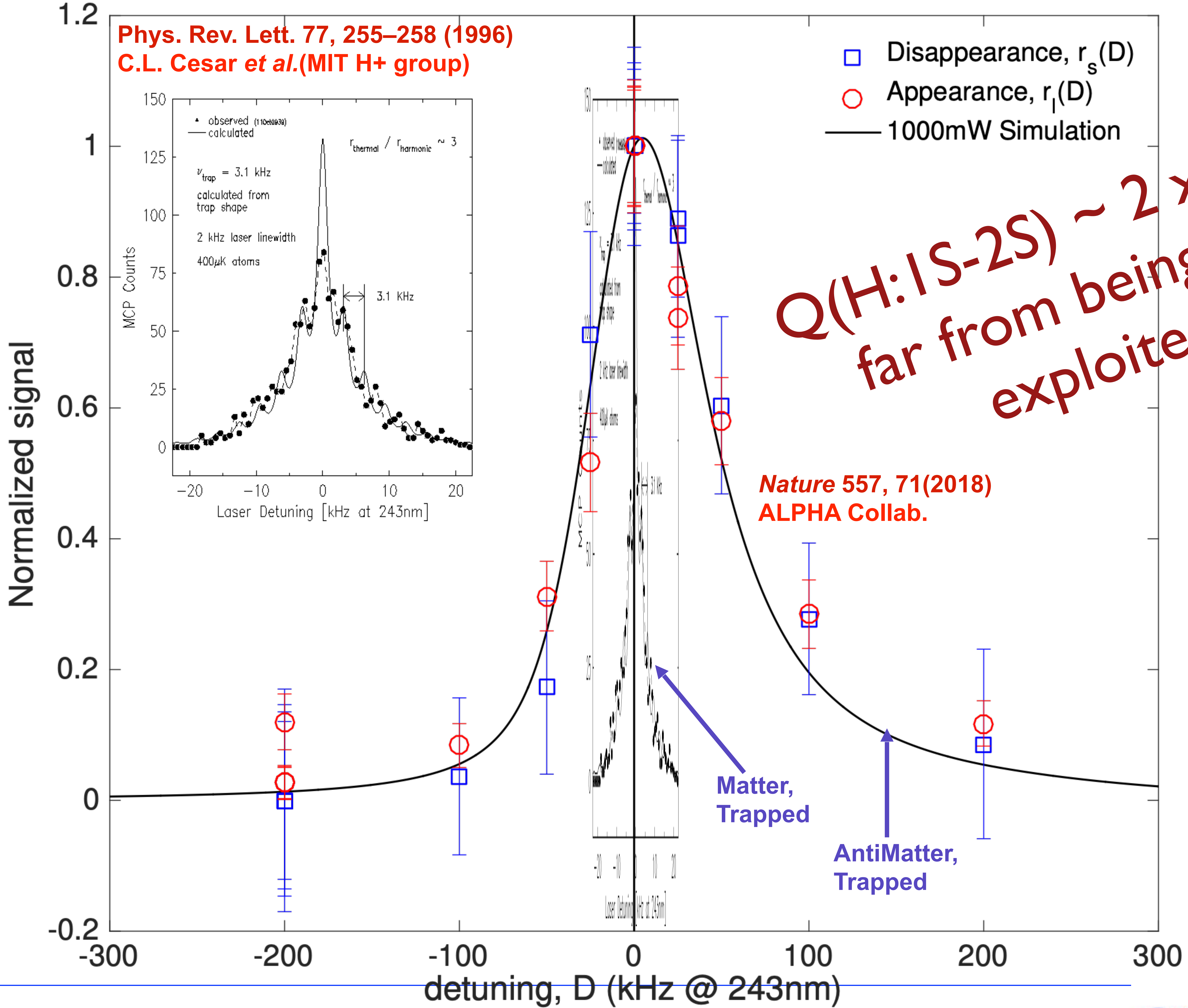
Nature 557, 71(2018)
ALPHA Collab.

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

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

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

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



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

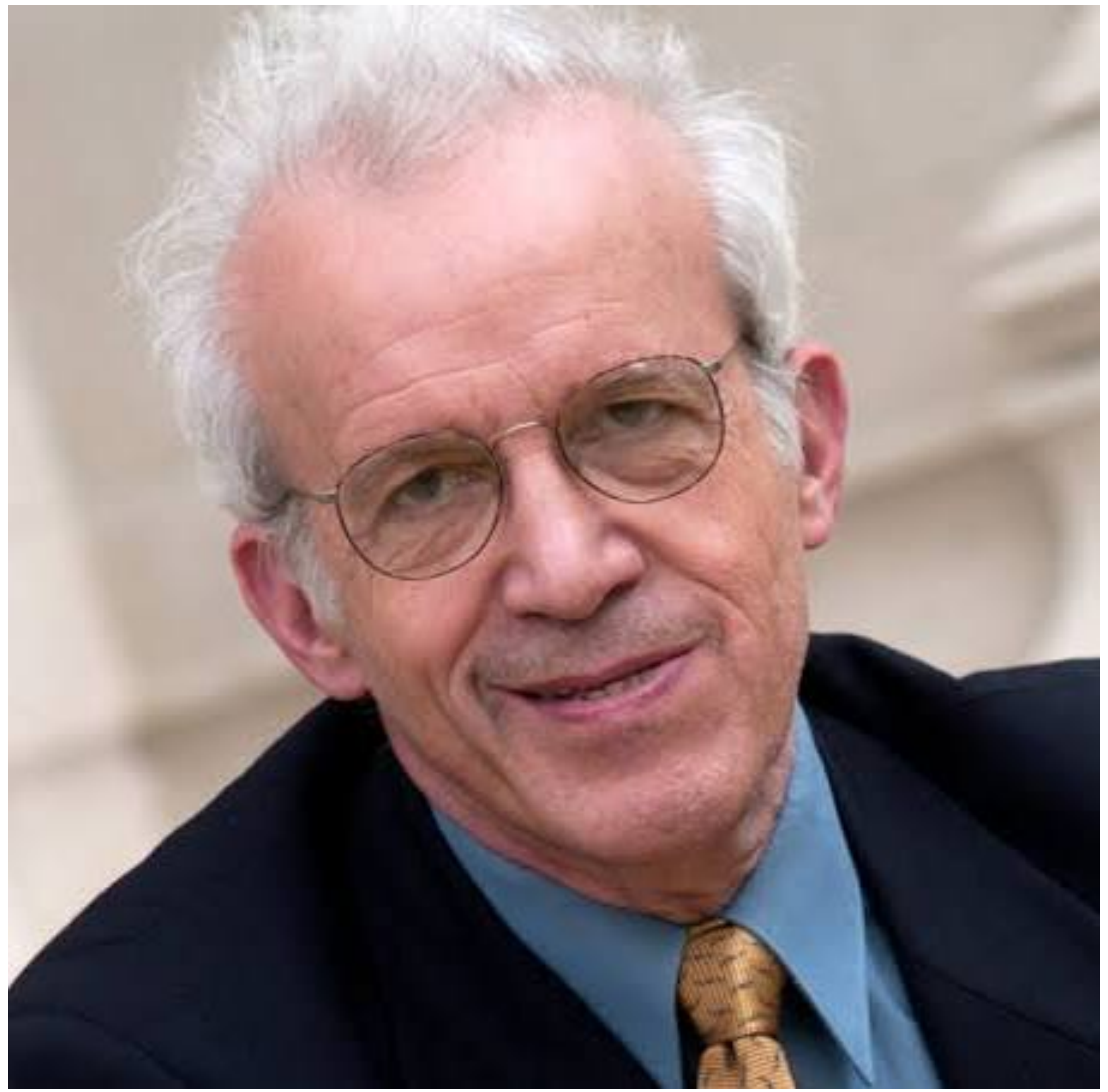
***Nature* 557, 71(2018)**
ALPHA Collab.

Matter, Trapped

AntiMatter, Trapped

Q(H:1S-2S) ~ 2 x 10^{15} !
far from being fully
exploited!

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



Daniel Kleppner (1933-2025)

H-Maser (w/ N. Ramsey)

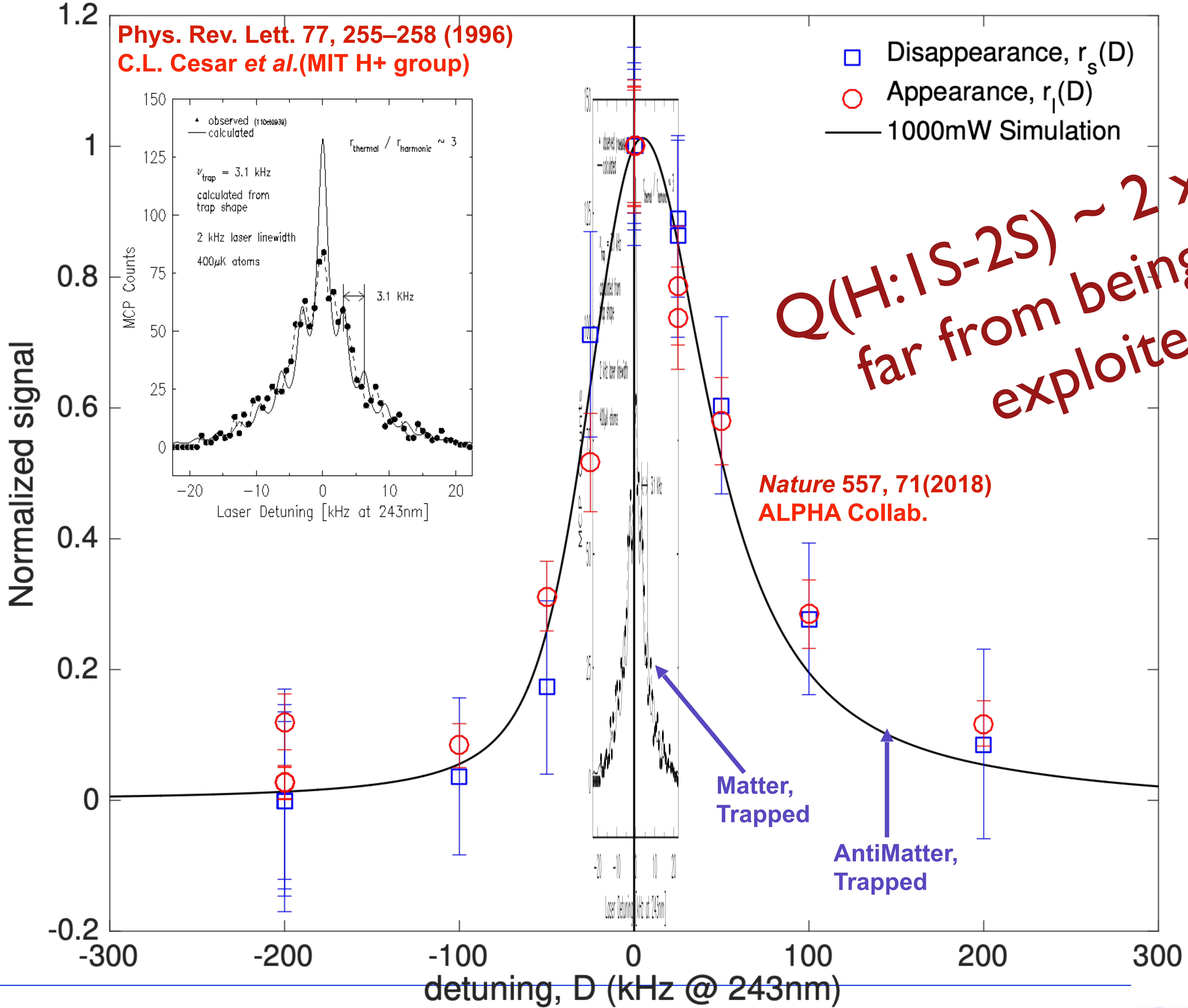
Inhibit spontaneous decay: cavity-QED

Rydberg H/Li in high fields: Q.Chaos

Evaporative Cooling (w/ H.Hess)

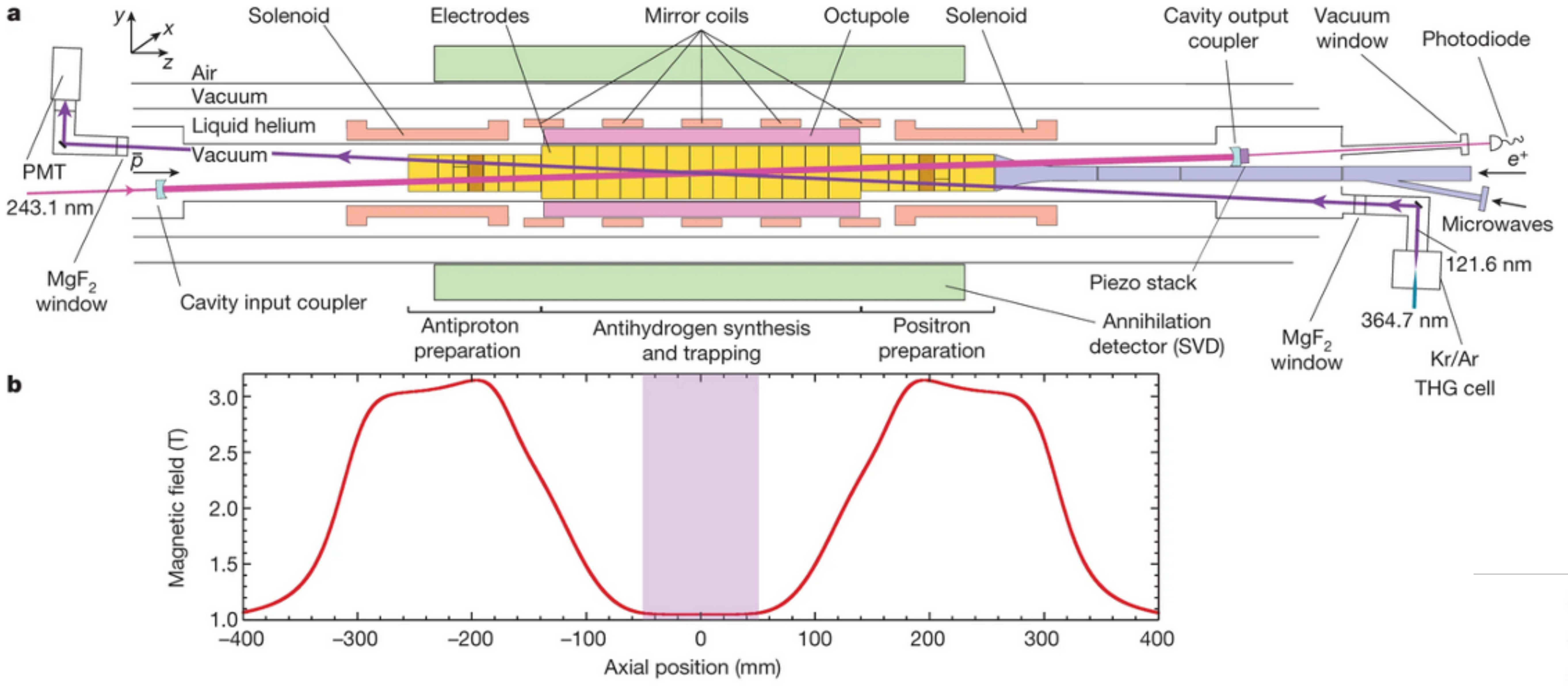
H+ 'BEC father' (w/ T. Greytak)

biggest BEC ever



Q(H:1S-2S) ~ 2 x 10^{15} !
far from being fully
exploited!

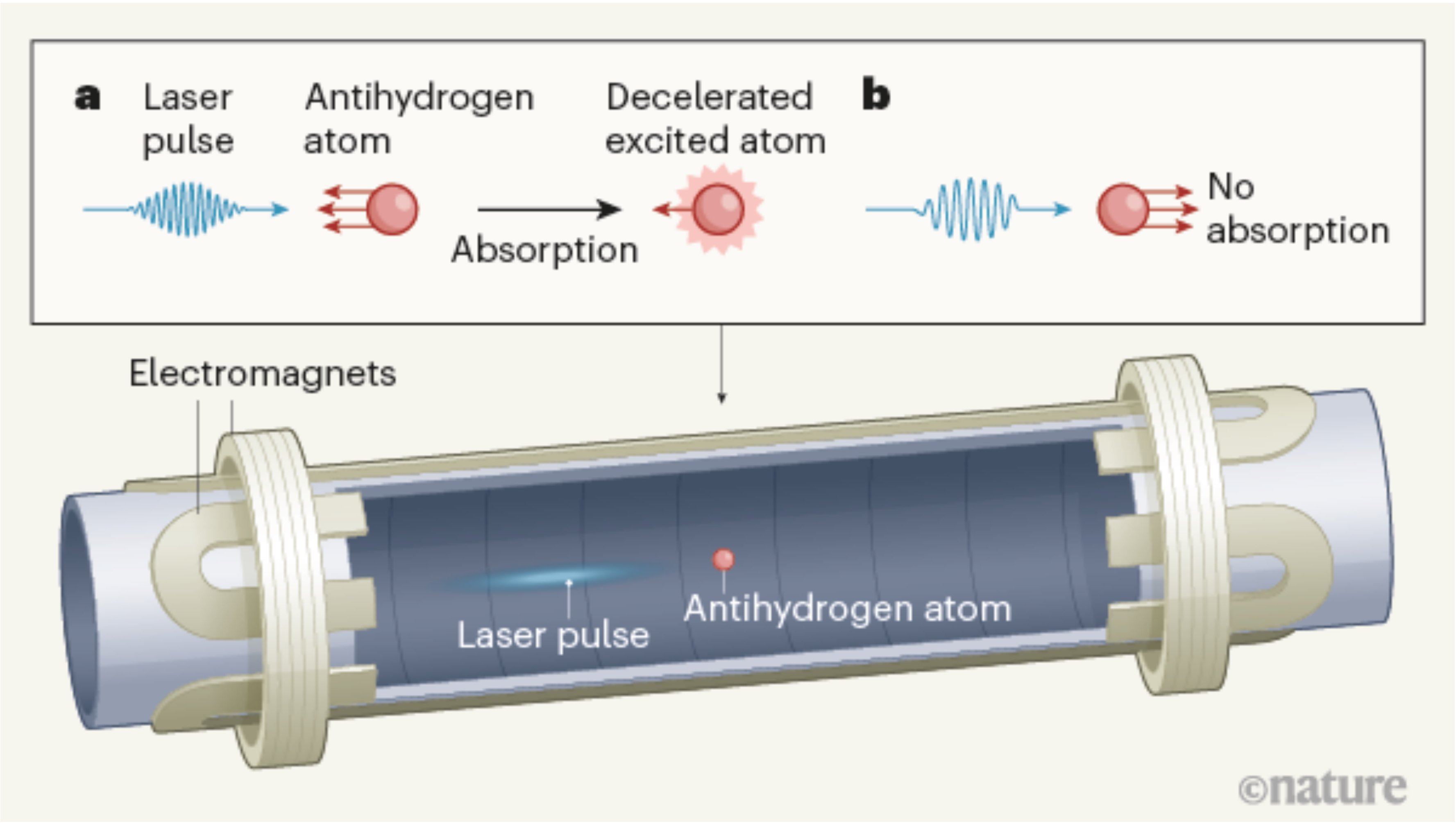
Laser cooling of Hbar : hours of cooling!!

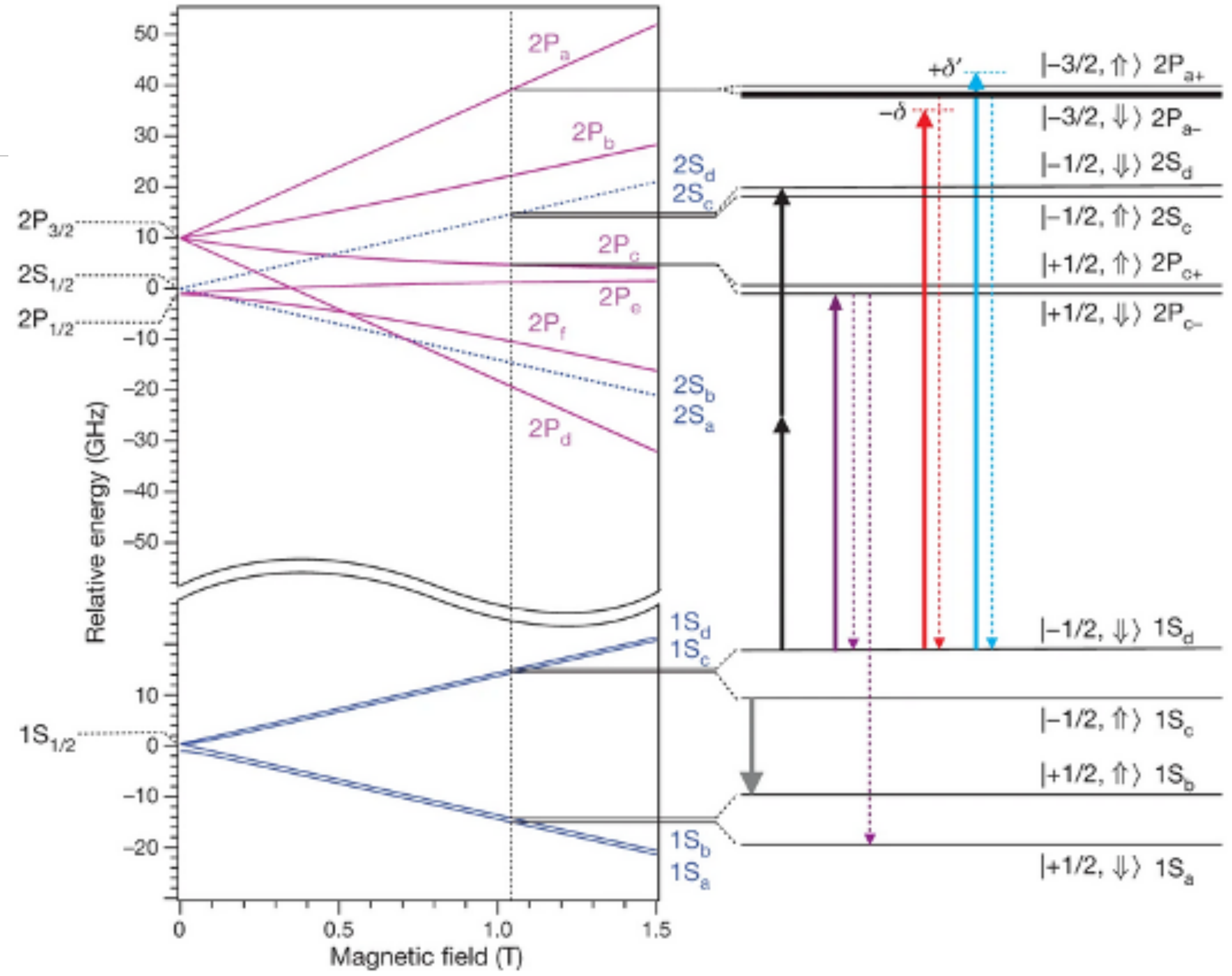


Volume 592 Issue 7852, 1 April 2021

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





Laser cooling of Hbar: tables

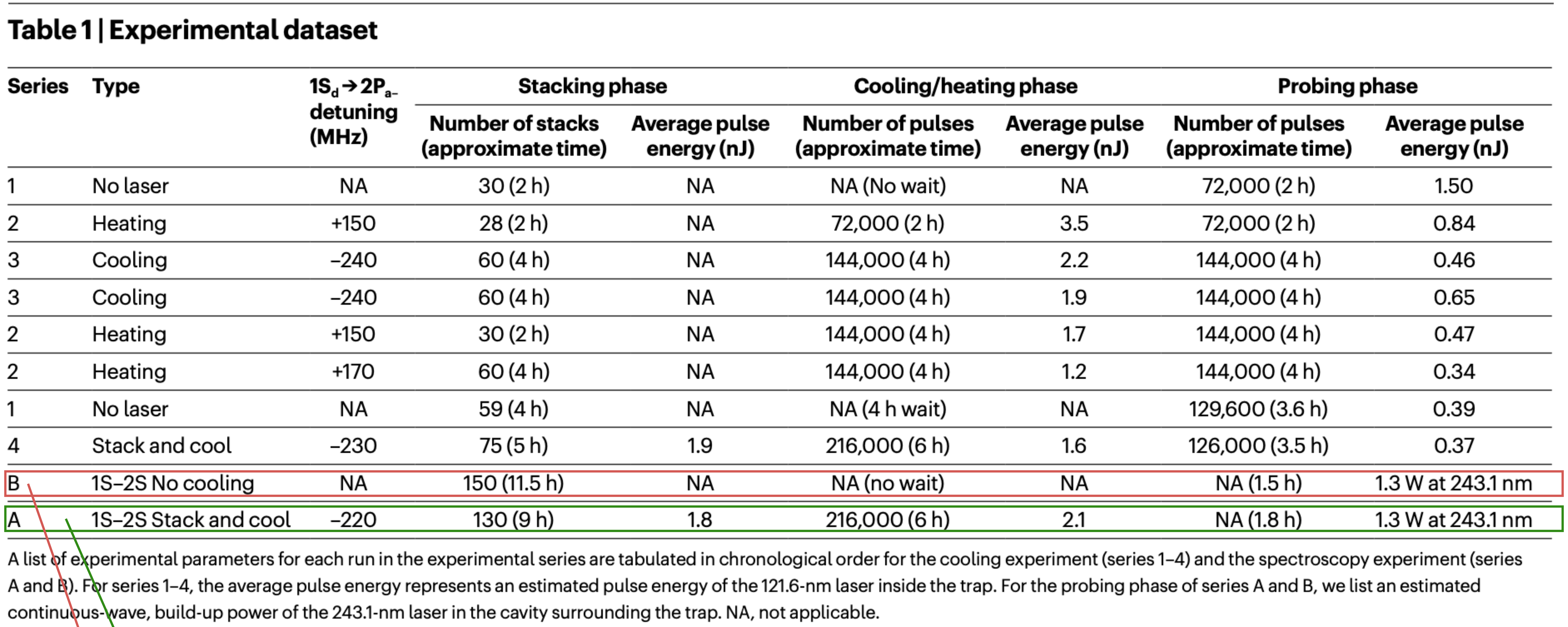
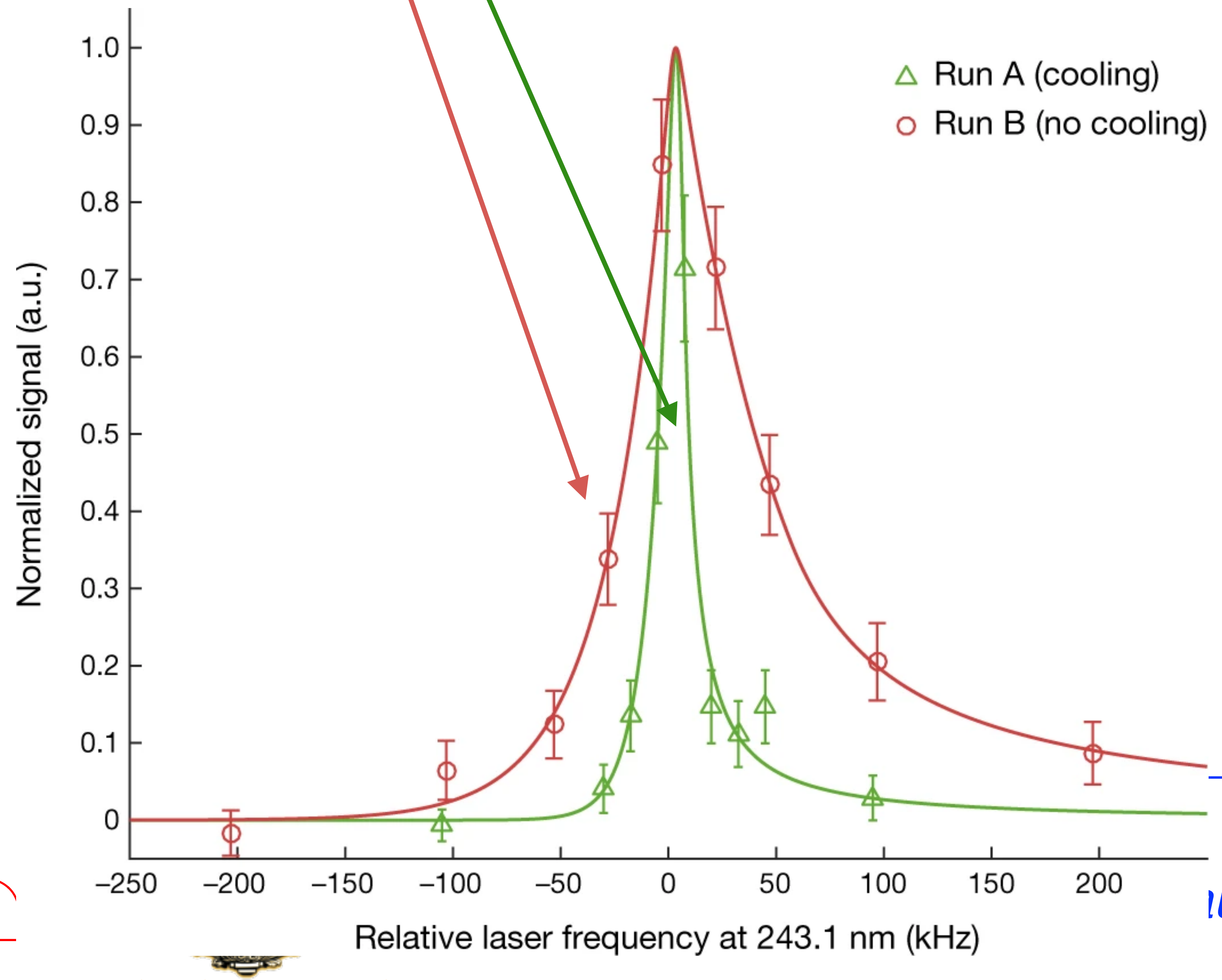


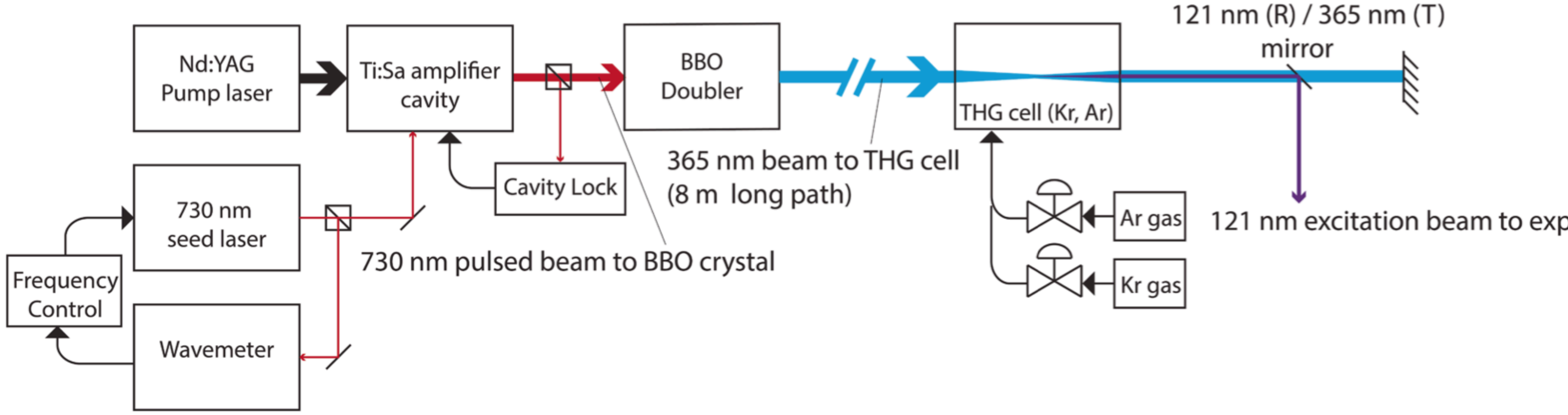
Table 1 | Experimental dataset

Series	Type	$1S_d \rightarrow 2P_{a-}$ detuning (MHz)	Stacking phase		Cooling/heating phase		Probing phase	
			Number of stacks (approximate time)	Average pulse energy (nJ)	Number of pulses (approximate time)	Average pulse energy (nJ)	Number of pulses (approximate time)	Average pulse energy (nJ)
1	No laser	NA	30 (2 h)	NA	NA (No wait)	NA	72,000 (2 h)	1.50
2	Heating	+150	28 (2 h)	NA	72,000 (2 h)	3.5	72,000 (2 h)	0.84
3	Cooling	−240	60 (4 h)	NA	144,000 (4 h)	2.2	144,000 (4 h)	0.46
3	Cooling	−240	60 (4 h)	NA	144,000 (4 h)	1.9	144,000 (4 h)	0.65
2	Heating	+150	30 (2 h)	NA	144,000 (4 h)	1.7	144,000 (4 h)	0.47
2	Heating	+170	60 (4 h)	NA	144,000 (4 h)	1.2	144,000 (4 h)	0.34
1	No laser	NA	59 (4 h)	NA	NA (4 h wait)	NA	129,600 (3.6 h)	0.39
4	Stack and cool	−230	75 (5 h)	1.9	216,000 (6 h)	1.6	126,000 (3.5 h)	0.37
B	1S–2S No cooling	NA	150 (11.5 h)	NA	NA (no wait)	NA	NA (1.5 h)	1.3 W at 243.1 nm
A	1S–2S Stack and cool	−220	130 (9 h)	1.8	216,000 (6 h)	2.1	NA (1.8 h)	1.3 W at 243.1 nm

A list of experimental parameters for each run in the experimental series are tabulated in chronological order for the cooling experiment (series 1–4) and the spectroscopy experiment (series A and B). For series 1–4, the average pulse energy represents an estimated pulse energy of the 121.6-nm laser inside the trap. For the probing phase of series A and B, we list an estimated continuous-wave, build-up power of the 243.1-nm laser in the cavity surrounding the trap. NA, not applicable.

9+6 ~ 15 hr laser cooling





Laser cooling of Hbar: tables

Table 1 | Experimental dataset

Series	Type	$1S_d \rightarrow 2P_{a-}$ detuning (MHz)	Stacking phase		Cooling/heating phase		Probing phase	
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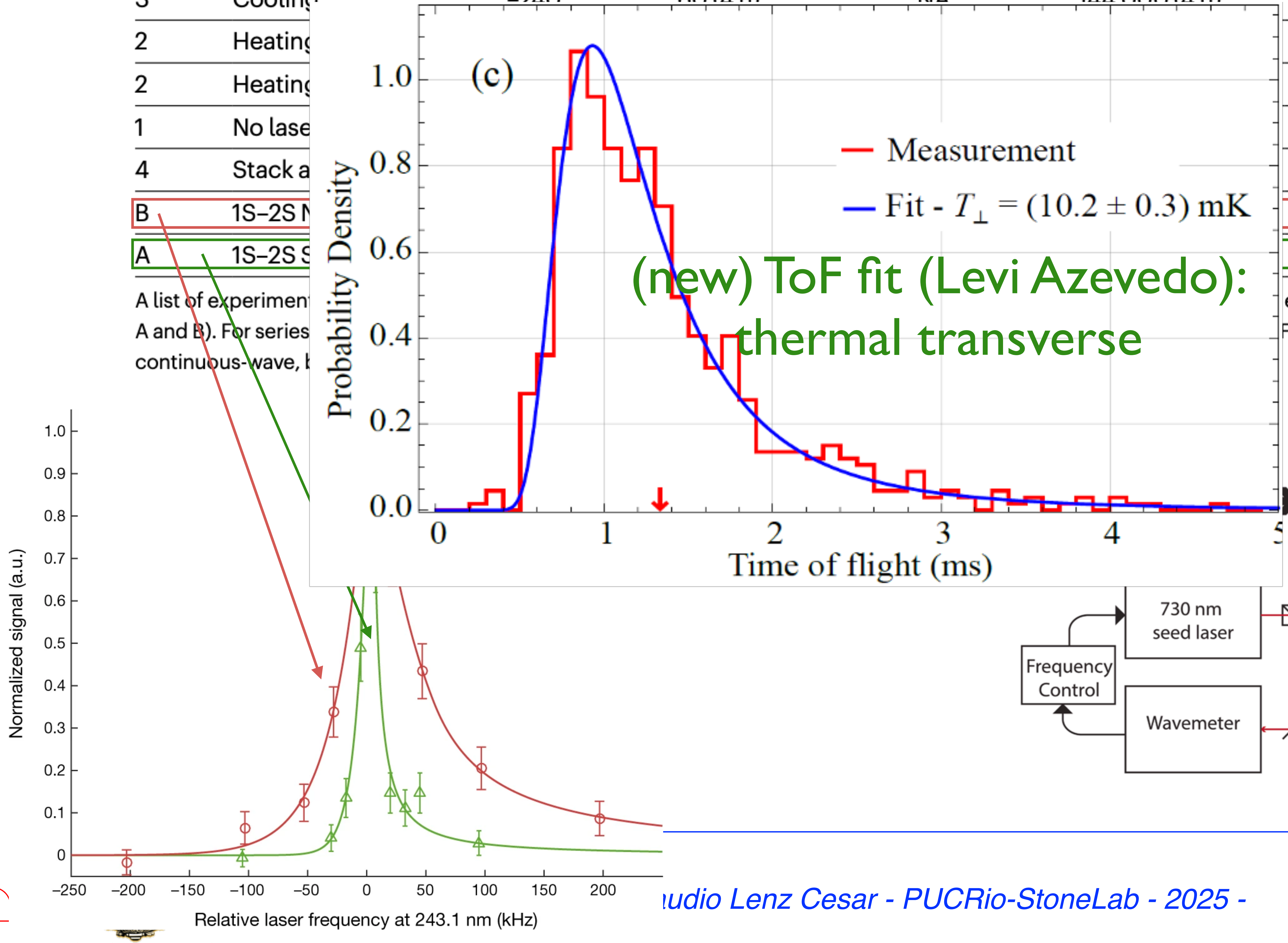
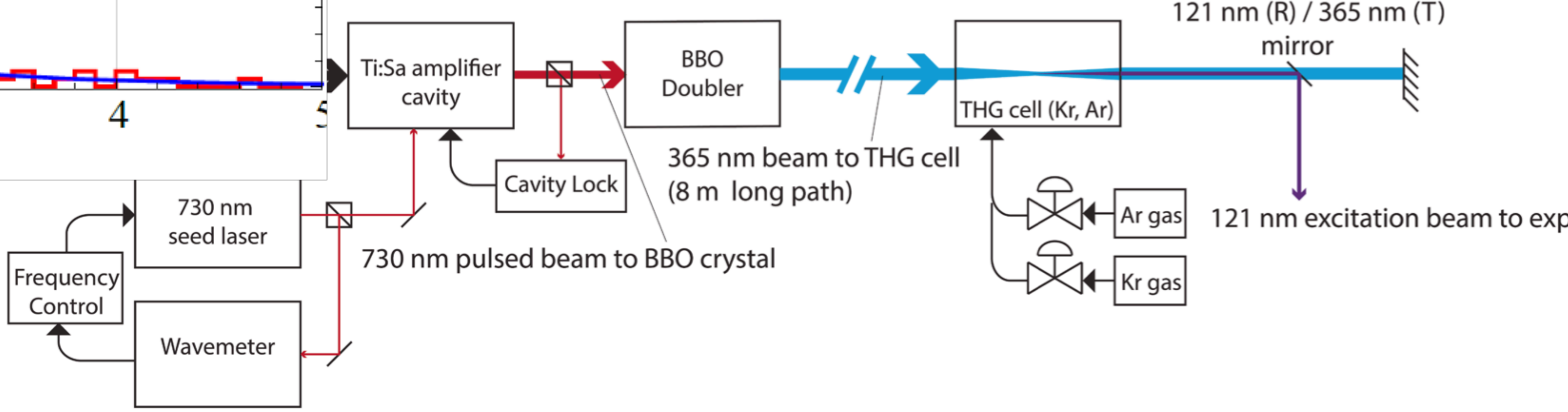
1	No lase					NA	129,600 (3.6 h)	0.39
4	Stack a					1.6	126,000 (3.5 h)	0.37
B	1S–2S N					NA	NA (1.5 h)	1.3 W at 243.1 nm
A	1S–2S S					2.1	NA (1.8 h)	1.3 W at 243.1 nm

A list of experiment … experiment (series 1–4) and the spectroscopy experiment (series
A and B). For series … For the probing phase of series A and B, we list an estimated
continuous-wave, b

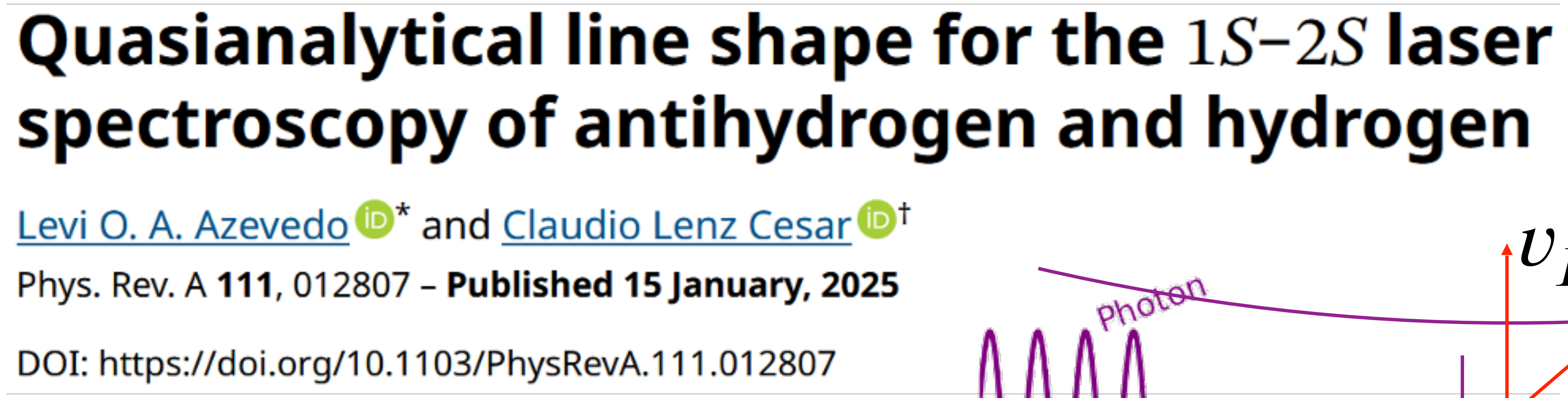
9+6 ~ 15 hr laser cooling



(new) ToF fit (Levi Azevedo): thermal transverse



Quasianalytical Lineshape for (anti-)H 1S-2S spectroscopy

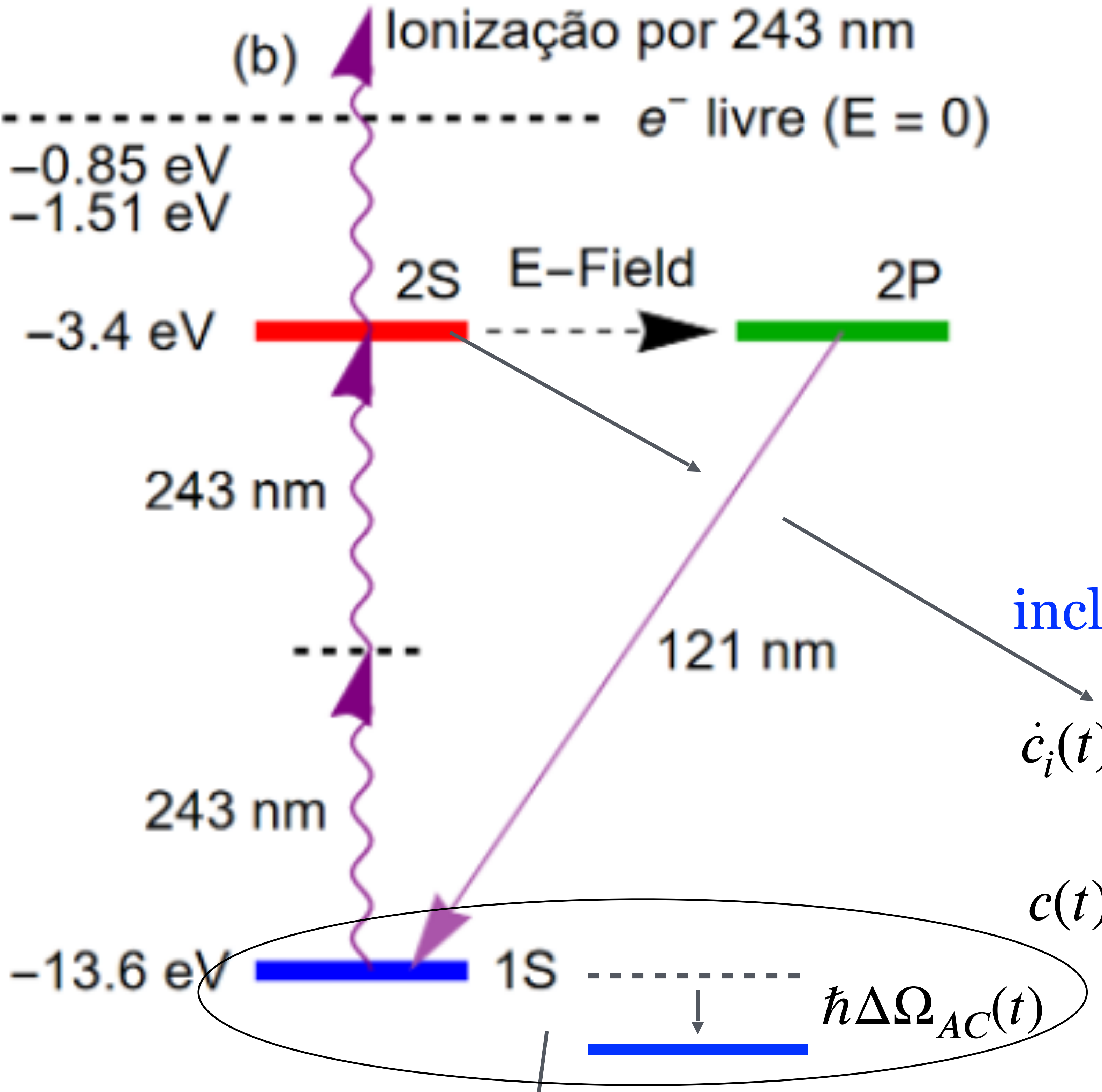


Quasianalytical line shape for the $1S$–$2S$ laser spectroscopy of antihydrogen and hydrogen

Levi O. A. Azevedo* and Claudio Lenz Cesar†

Phys. Rev. A **111**, 012807 – **Published 15 January, 2025**

DOI: https://doi.org/10.1103/PhysRevA.111.012807



include ionization

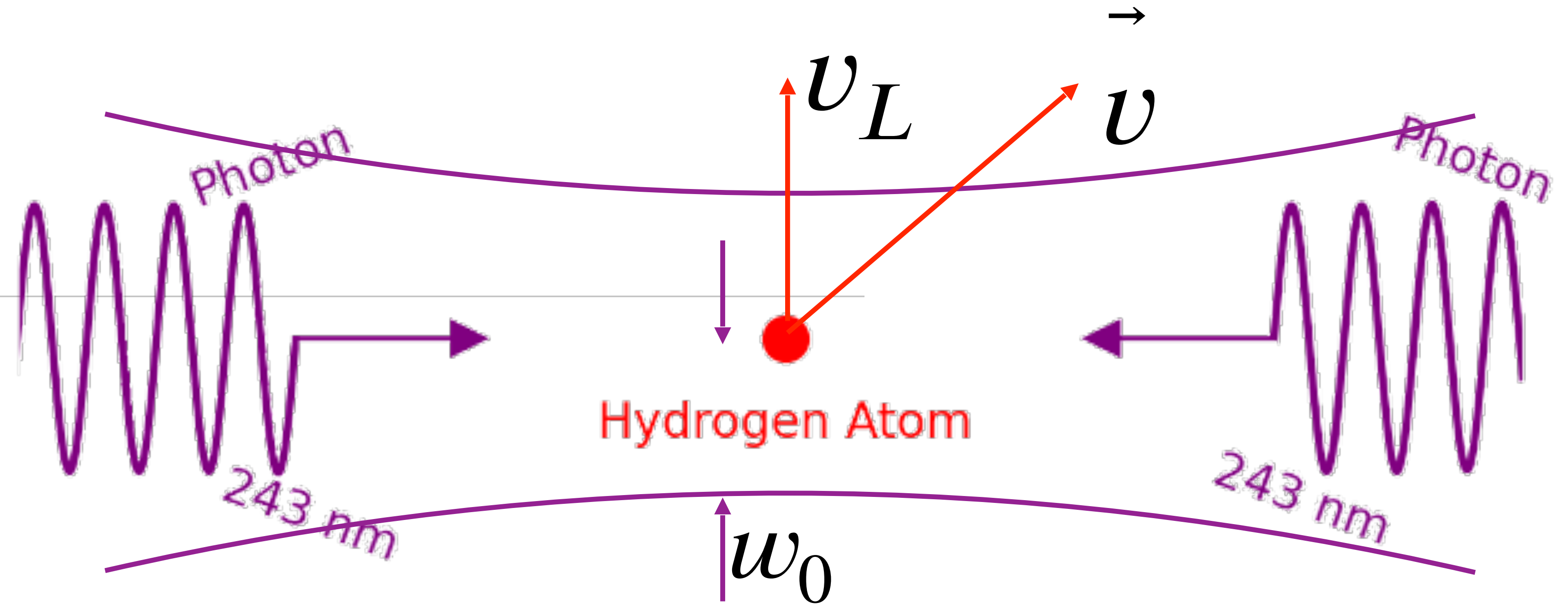
$$\dot{c}_i(t) = -\frac{\gamma_i(t)}{2}c_i(t) \Rightarrow \qquad (|c\rangle \rightarrow |2S\rangle)$$

$$c(t) = c_2(t)\mathrm{Exp}\left(-\frac{\kappa_i w_0\sqrt{\pi/2}}{4v_L}\left(1+\mathrm{Erf}\left(\frac{\sqrt{2}v_L}{w_0}t\right)\right)\right)$$

dress with laser field: ac Stark

$$\dot{a}(t') = i\Delta\Omega_{AC}(t')a(t') \Rightarrow \qquad (|a\rangle \rightarrow |1S\rangle)$$

$$a^{(0)}(t) = \mathrm{Exp}\left(\frac{i\sqrt{8\pi}P\beta_{ac}}{v_L w_0}\left[e^{-2\frac{\rho_L^2}{w_0^2}}\left(1+\mathrm{Erf}\left(\frac{\sqrt{2}v_L}{w_0}t\right)\right)\right]\right)$$



Doppler-free 2 counterpropagating photons

time-of-flight broadening: F. Biraben

Magnetic trap: shift + broadening

some extra approximations

$$\Delta\omega_{AC}(\rho_L) = \sqrt{\frac{2\pi}{3}}\,\frac{4\,P\,\beta_{AC}}{w_0^2}e^{-\frac{2\rho_L^2}{w_0^2}} \longrightarrow \overline{\Delta\omega_{AC}} = \frac{8\sqrt{\pi}P\,\beta_{AC}}{3\,w_0^2}$$

$$v_{\mathrm{ion}} = (\sqrt{8\pi}\,\beta_i P/w_0)e^{-2\,\rho_L^2/w_0^2} \longrightarrow \overline{v_{\mathrm{ion}}} = \frac{4\sqrt{\pi}\beta_i P}{\sqrt{3}\,w_0}$$

Quasianalytical Lineshape for (anti)H 1S-2S spectroscopy

Thermal sample in the trap: $B(z) \rightarrow \delta\omega_{ca}(z), n_{at}(z)$

$$\delta\mathcal{L}(\delta\omega_{ca}) = [n_{\mathrm{at}}(z)\,\delta z] \int_{-\infty}^{\infty} d\rho_{\mathrm{L}} \int_{0}^{\infty} d v_{\mathrm{L}}\, v_{\mathrm{L}}\, f(v_{\mathrm{L}}) |C_{\mathrm{AC\,ion_{approx}}}(\delta\omega_{ca})|^2$$

$$\begin{aligned}\delta\mathcal{L}_{\mathrm{ion}}(\delta\omega_{ca}) = \frac{\pi\,\gamma^2 P^2}{2\,u\,w_0}\Bigg(& e^{-w_0|\delta\omega_{ca}-\overline{\Delta\omega_{\mathrm{AC}}}|/u} - \frac{\overline{v_{\mathrm{ion}}}}{u\sqrt{1+(\overline{v_{\mathrm{ion}}}/u)^2}} e^{-w_0\sqrt{1+(\overline{v_{\mathrm{ion}}}/u)^2}\,|\delta\omega_{ca}-\overline{\Delta\omega_{\mathrm{AC}}}|/\overline{v_{\mathrm{ion}}}} \\ & + \frac{\overline{v_{\mathrm{ion}}}^2}{w_0\,u\,|\delta\omega_{ca}-\overline{\Delta\omega_{\mathrm{AC}}}|}\left(e^{-w_0|\delta\omega_{ca}-\overline{\Delta\omega_{\mathrm{AC}}}|/u} - e^{-w_0\sqrt{1+(\overline{v_{\mathrm{ion}}}/u)^2}\,|\delta\omega_{ca}-\overline{\Delta\omega_{\mathrm{AC}}}|/\overline{v_{\mathrm{ion}}}}\right) \\ & - \frac{2\overline{v_{\mathrm{ion}}}}{\sqrt{\pi}\,u}\left\{\mathcal{K}_{(0)}(w_0|\delta\omega_{ca}-\overline{\Delta\omega_{\mathrm{AC}}}|/u) - \mathcal{K}_{(0)}[w_0\sqrt{1+(\overline{v_{\mathrm{ion}}}/u)^2}\,|\delta\omega_{ca}-\overline{\Delta\omega_{\mathrm{AC}}}|/\overline{v_{\mathrm{ion}}}]\right\}\Bigg) n_{\mathrm{at}}(z)\delta z\end{aligned}$$

$$u = \sqrt{\frac{2k_B T}{m_H}} \approx 128.45\sqrt{\frac{\mathrm{T}}{\mathrm{Kelvin}}}\ \mathrm{m\,s^{-1}}$$

Validity

$$v_{\mathrm{L\,valid}} > 0.5\ \mathrm{ms}^{-1}\left(\frac{P}{200\ \mathrm{mW}}\right)\left(\frac{200\ \mu\mathrm{m}}{w_0}\right),$$

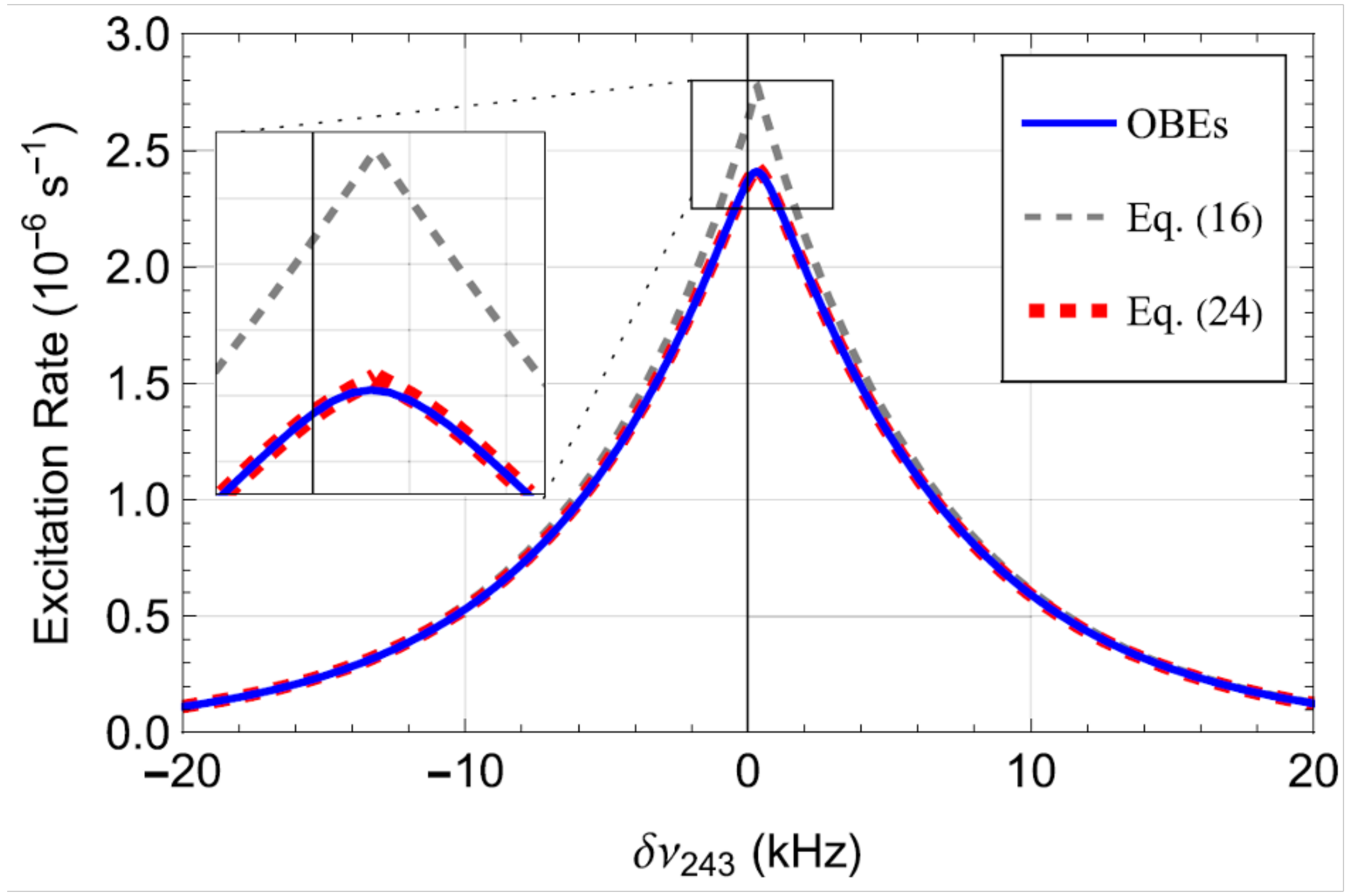
$$T_{\mathrm{validity}} > 300\ \mu\mathrm{K}\left(\frac{P}{200\ \mathrm{mW}}\right)^2\left(\frac{200\ \mu\mathrm{m}}{w_0}\right)^2.$$

Lineshape theory: Levi Azevedo & CLC, PhysRevA.111.012807 (2025)

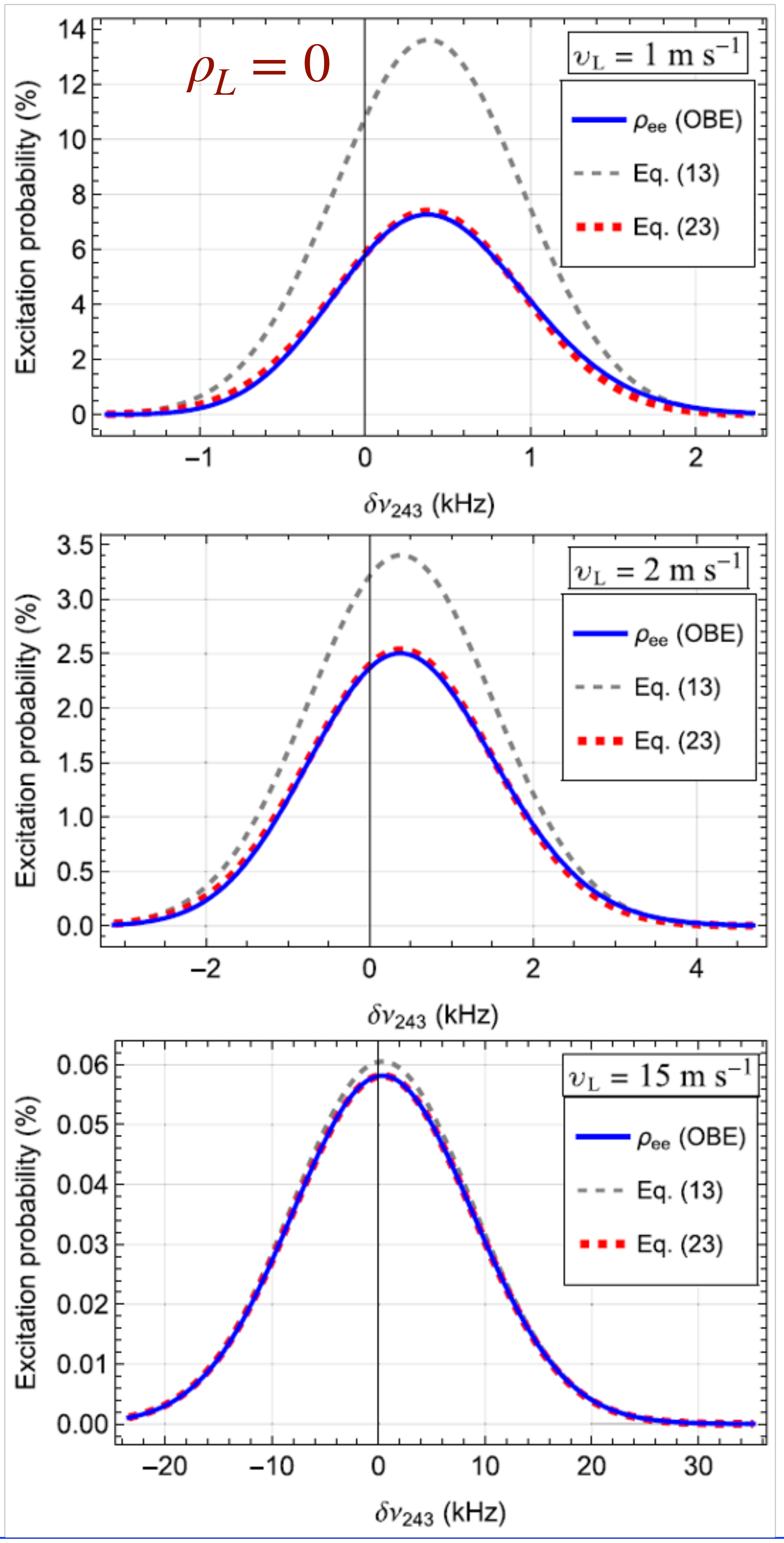
Quasianalytical Lineshape for (anti-)H 1S-2S spectroscopy

Comparison to OBEs ("gas in box")

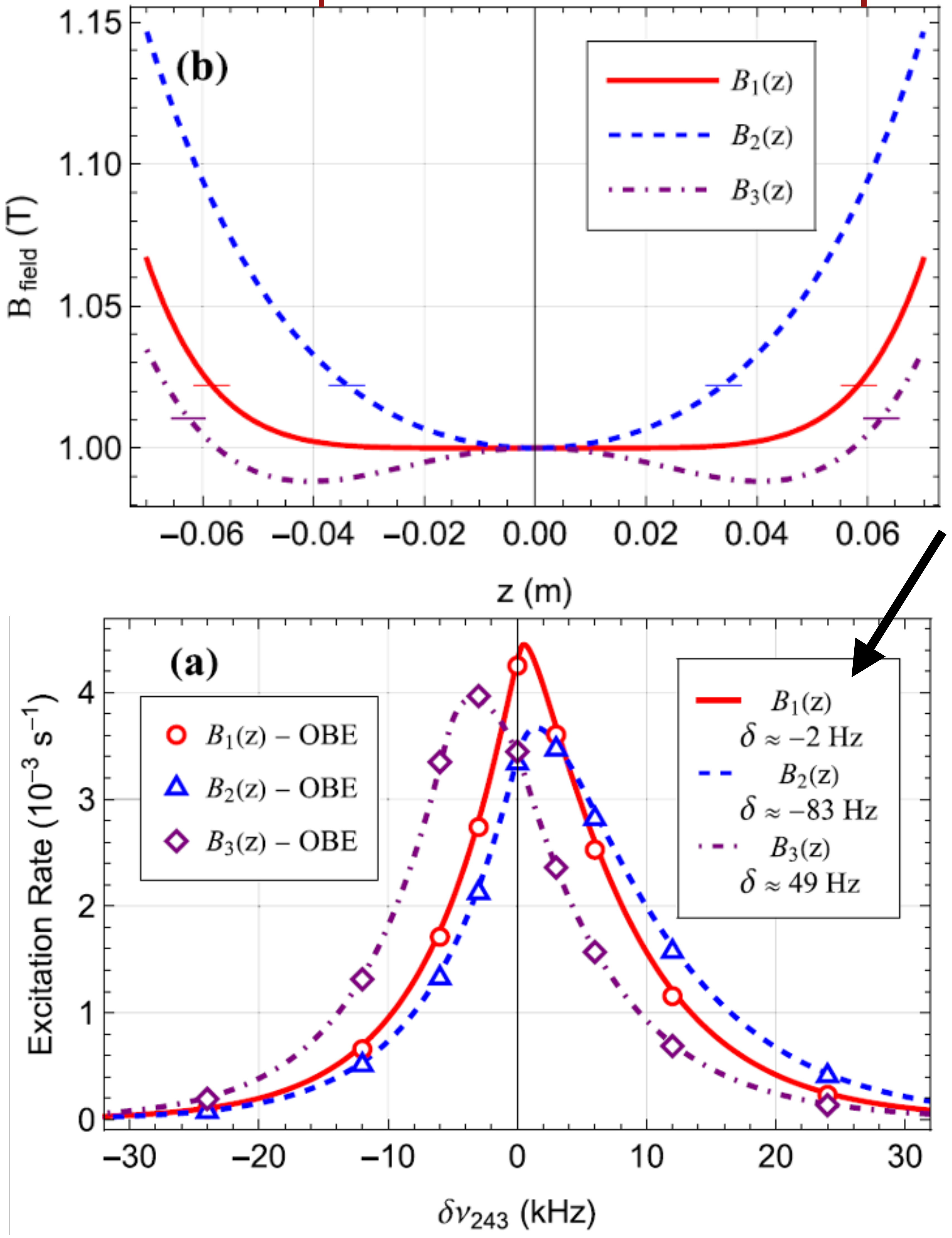
Thermal sample
$w_0 = 196\ \mu\text{m}$
$P = 200\ \text{mW}$
$T = 15\ \text{mK}$



Single atom crossing laser head-on



Comparison to OBEs in trap



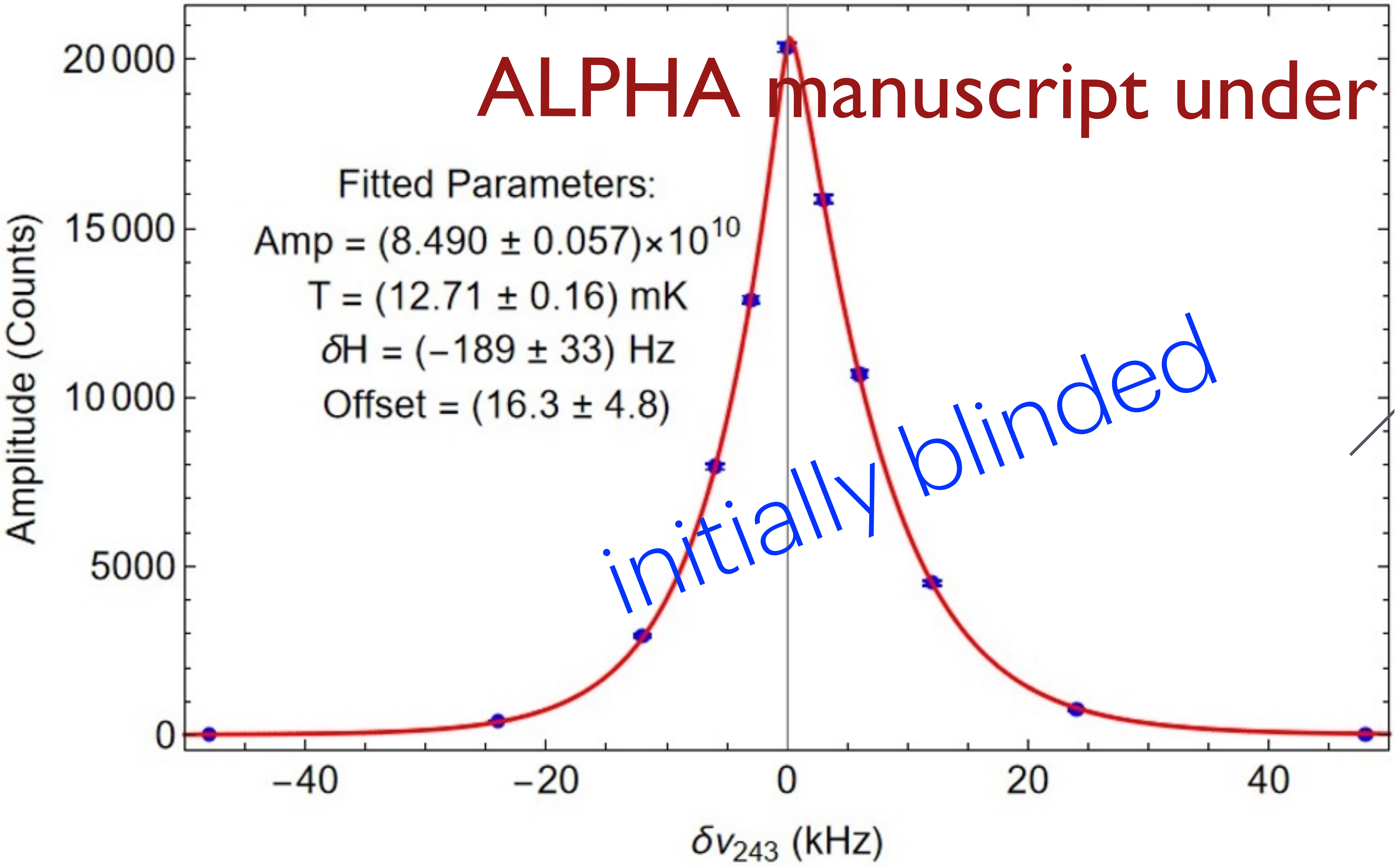
1S-2S Hbar Spectroscopy - Simulation for blind analysis of 2023 data - laser cooled sample

1S-2S Hbar spectroscopy ⇒ parts in $10^{13\text{-}14}$ (2023 data)!!

here only simulation, no meaning of central freq.!

ALPHA manuscript under preparation:keep an eye for it!

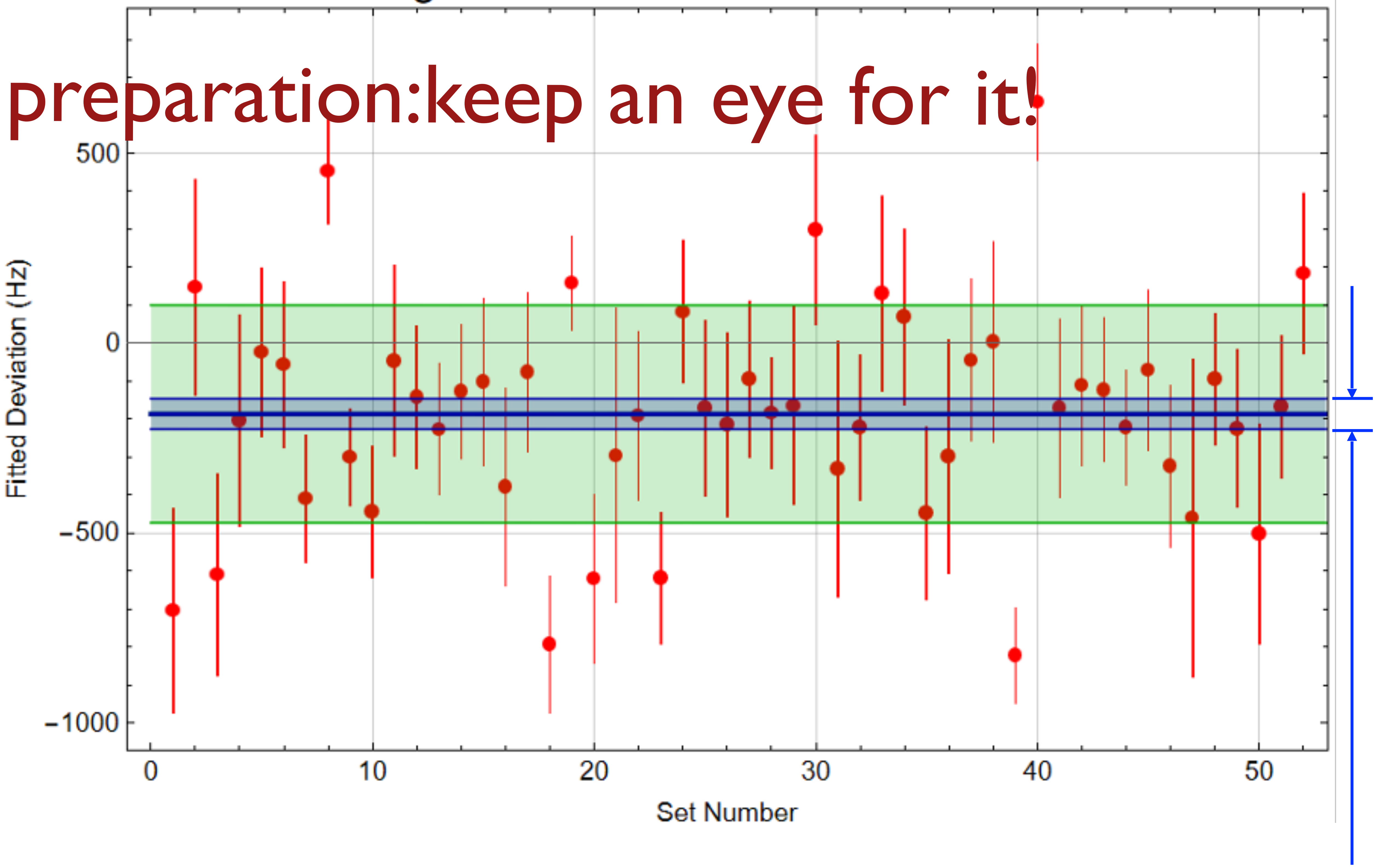
typical ALPHA-2 laser cooled conditions



initially blinded

52 sets of 2750 atoms in each set

Starting from a simulation with 143683 atoms



$\pm 40\text{Hz}$

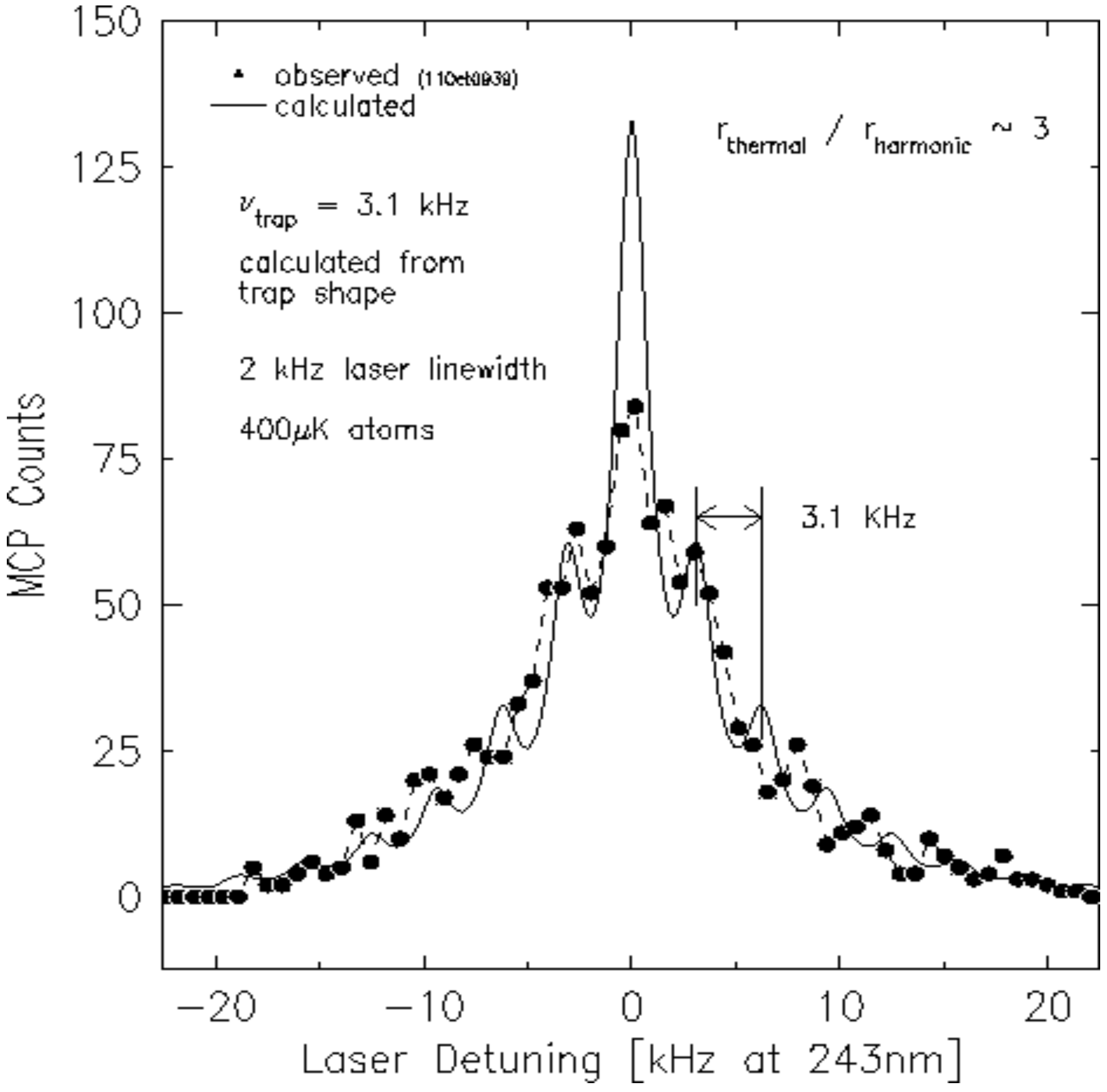
$\Rightarrow \pm 3 \times 10^{-14}$

High-statistics MC Simulation (OBEs) : F. Robicheaux (ALPHA)

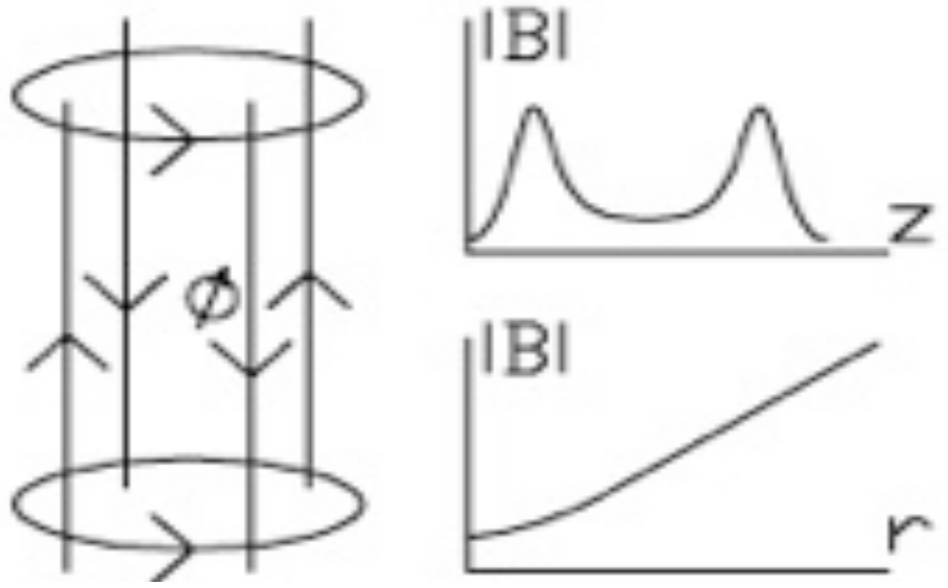
Lineshape Fitting theory: Levi Azevedo & CLC, PhysRevA.111.012807 (2025)

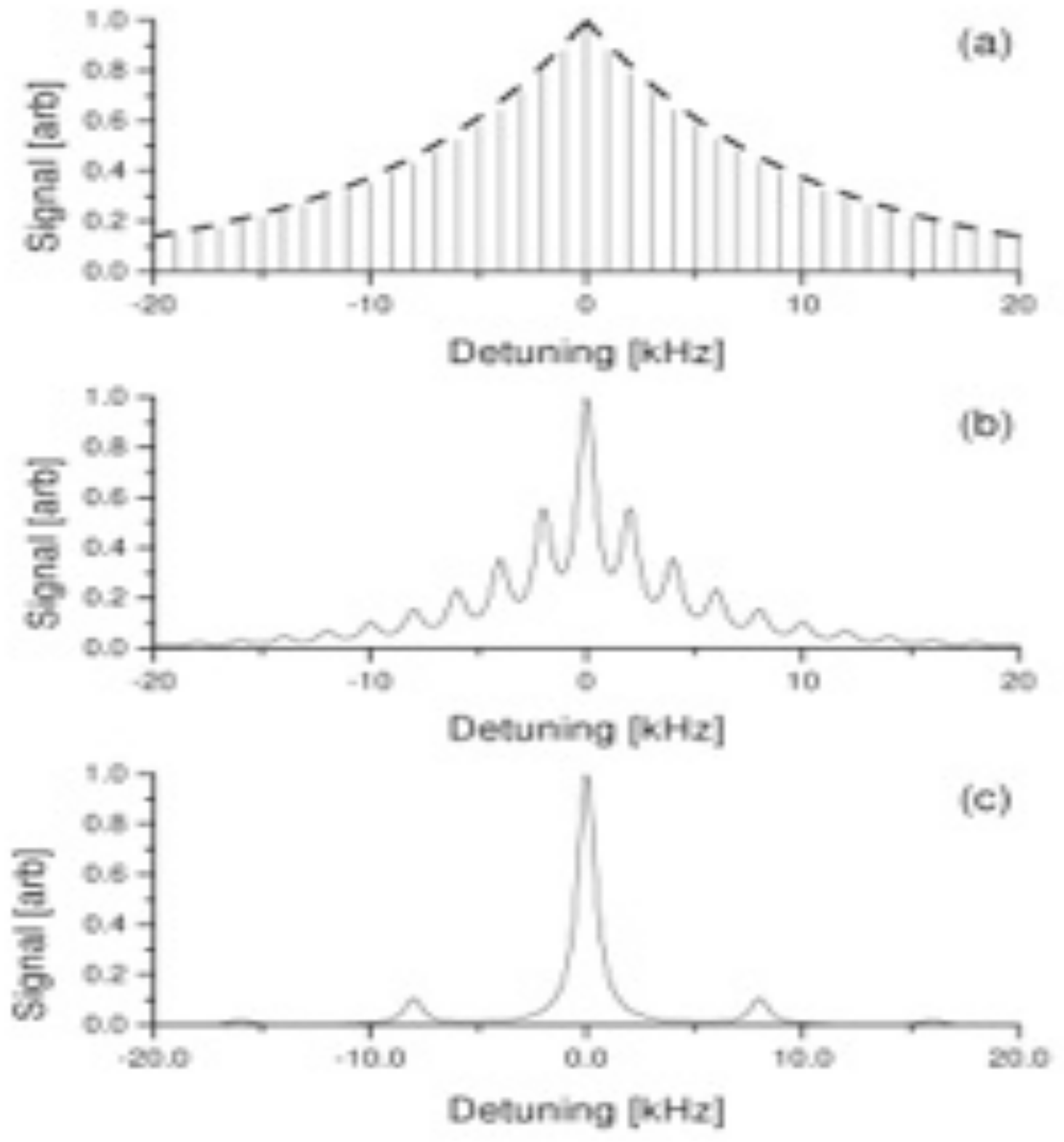
Hbar Spectroscopy Objectives: resemblance of trapped H!?

- ☆ 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. L. Cesar, D. Kleppner

Hbar Spectroscopy Objectives: resemblance of trapped H!?

- 2s - metastable state (122 ms)
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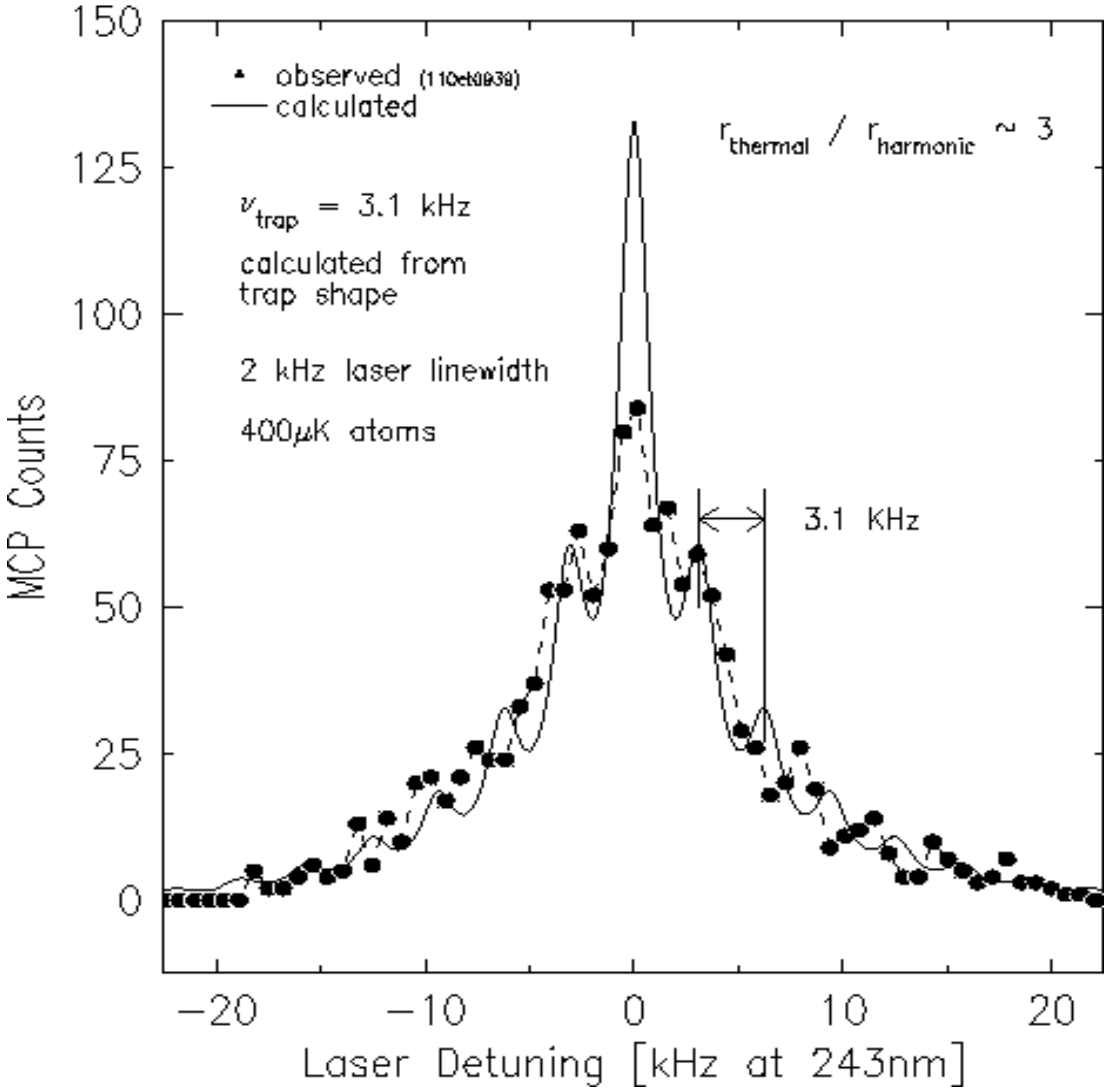
- time-of-flight & Zeeman

reinterpret time-of-flight
as momenta exchange
laser <-> atom+trap



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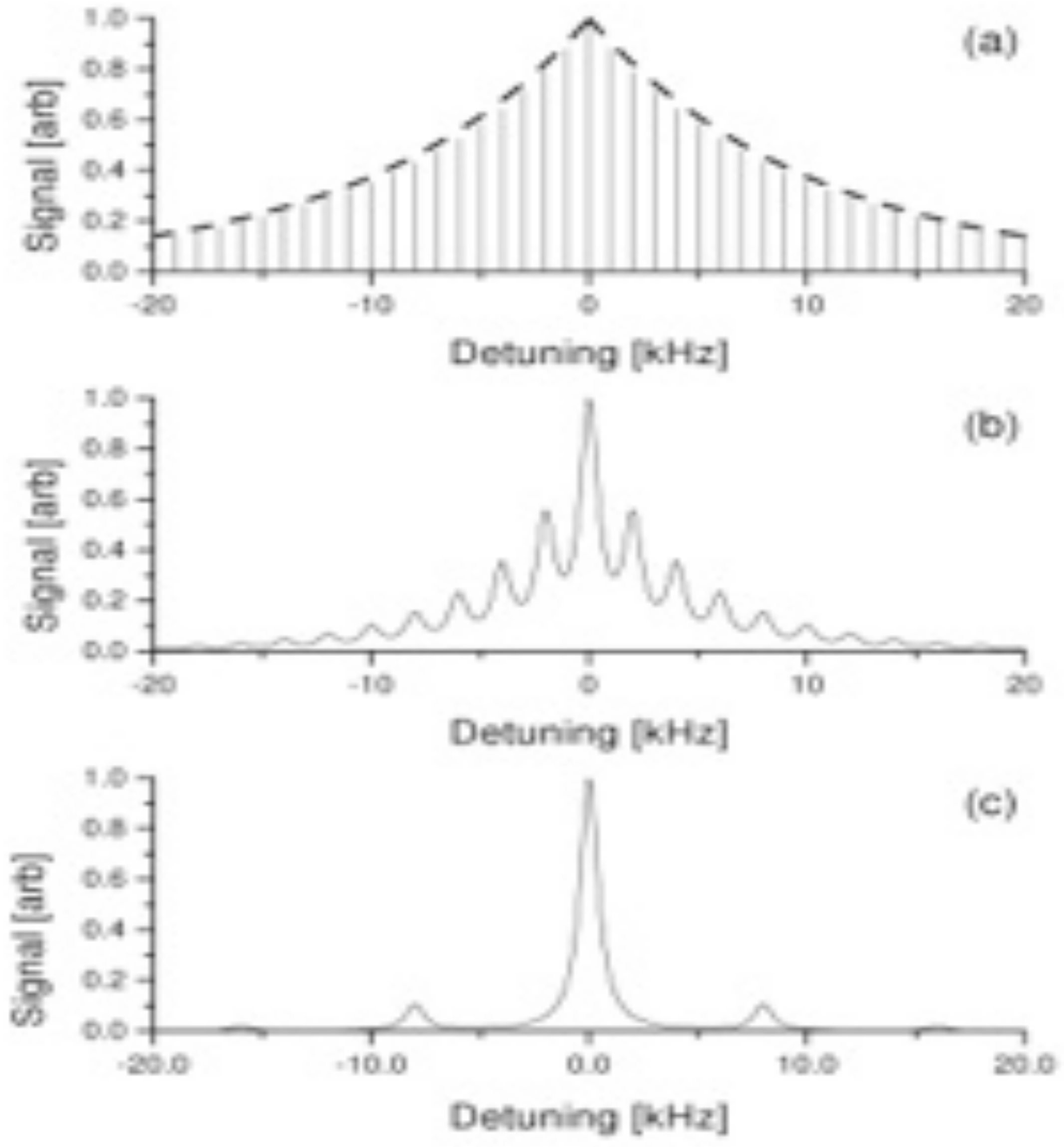

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Hbar Spectroscopy Objectives: resemblance of trapped H!?

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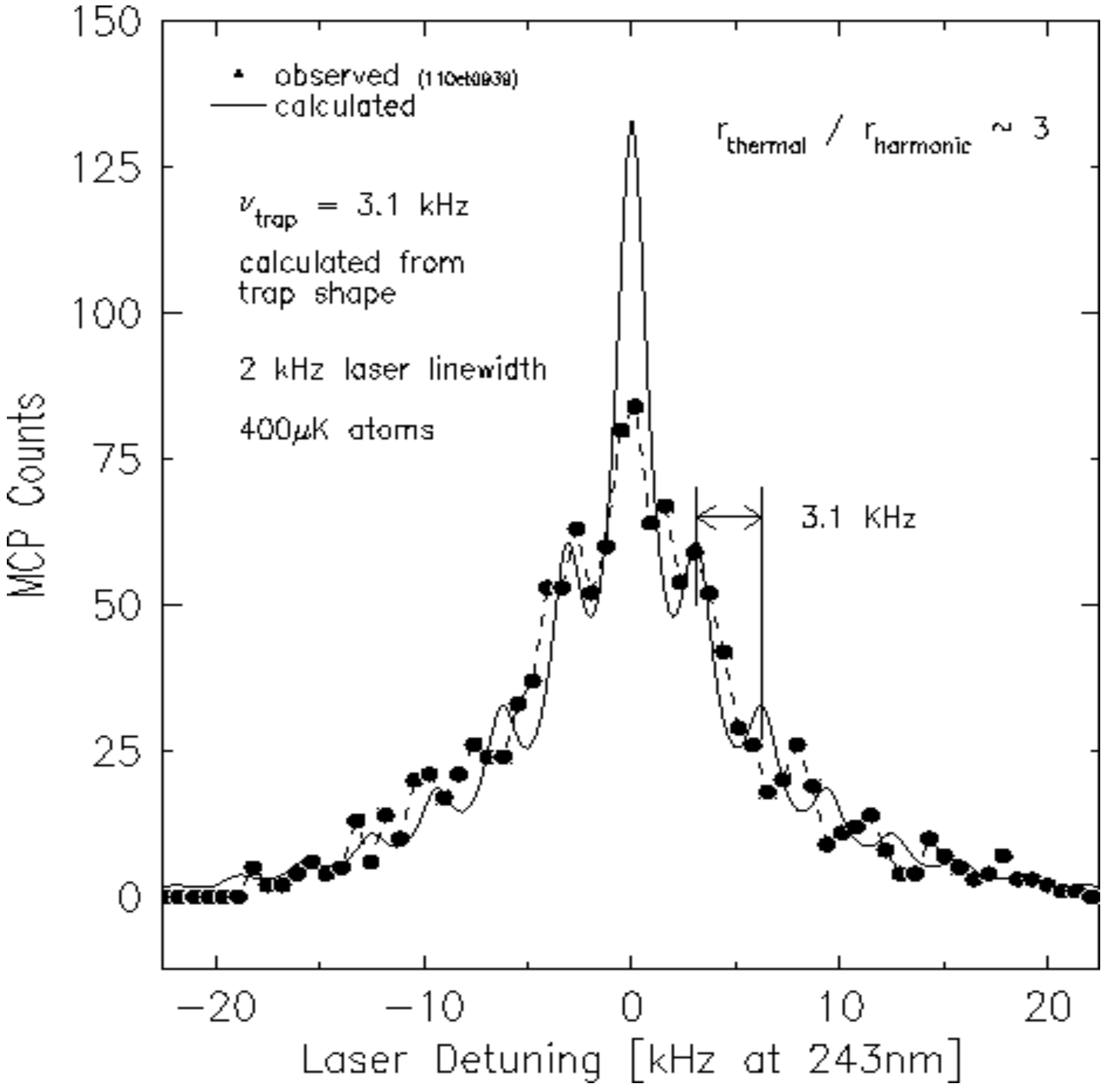
- ⭐ time-of-flight & Zeeman

$\delta\nu_{2S-1S} = (1/2)(186\text{kHz}(B/1\text{T}) + 387\text{kHz}(B/1\text{T})^2)$

Zeeman+Diamagnetic $(e B r)^2/(8 m_e)$



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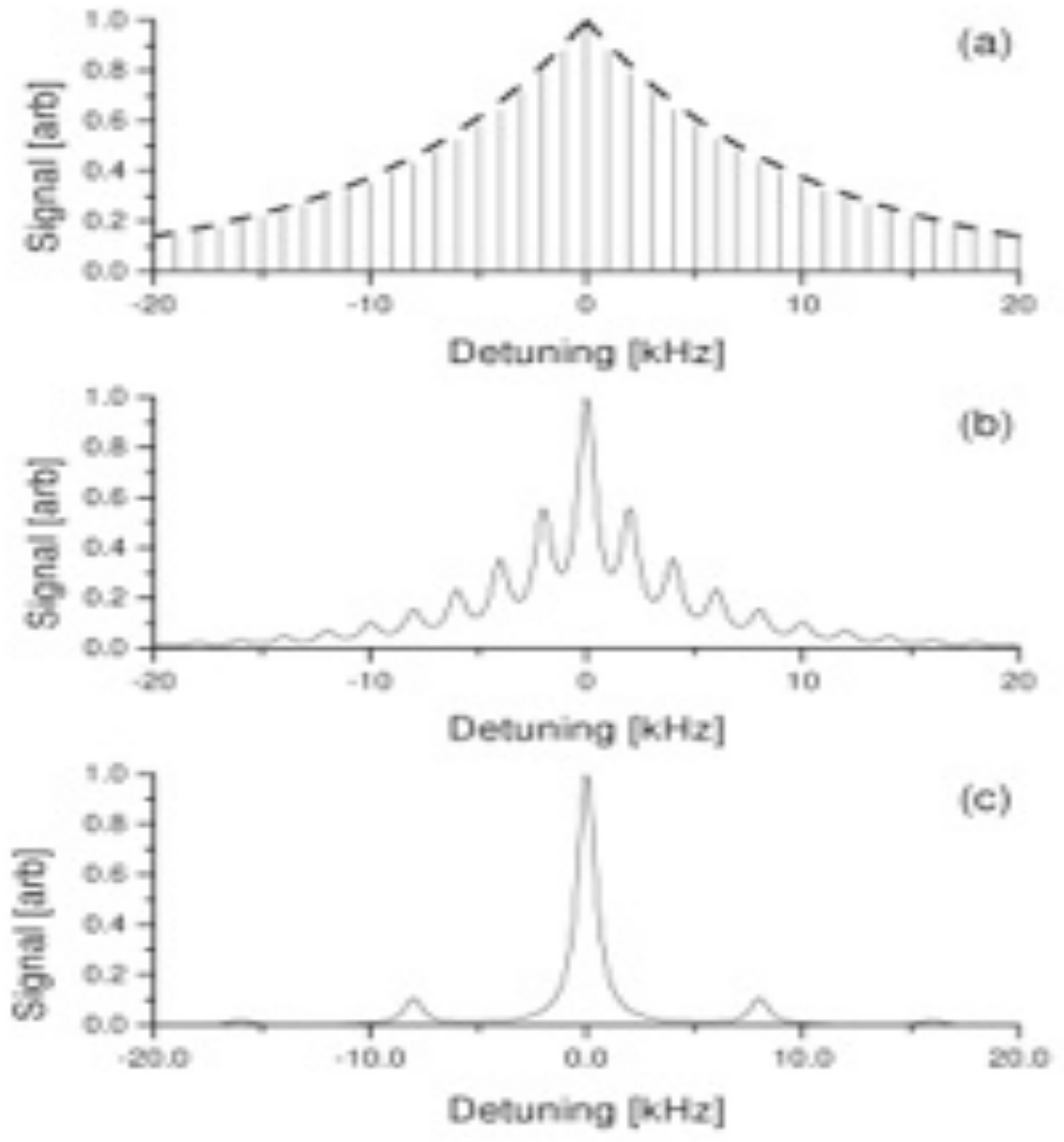

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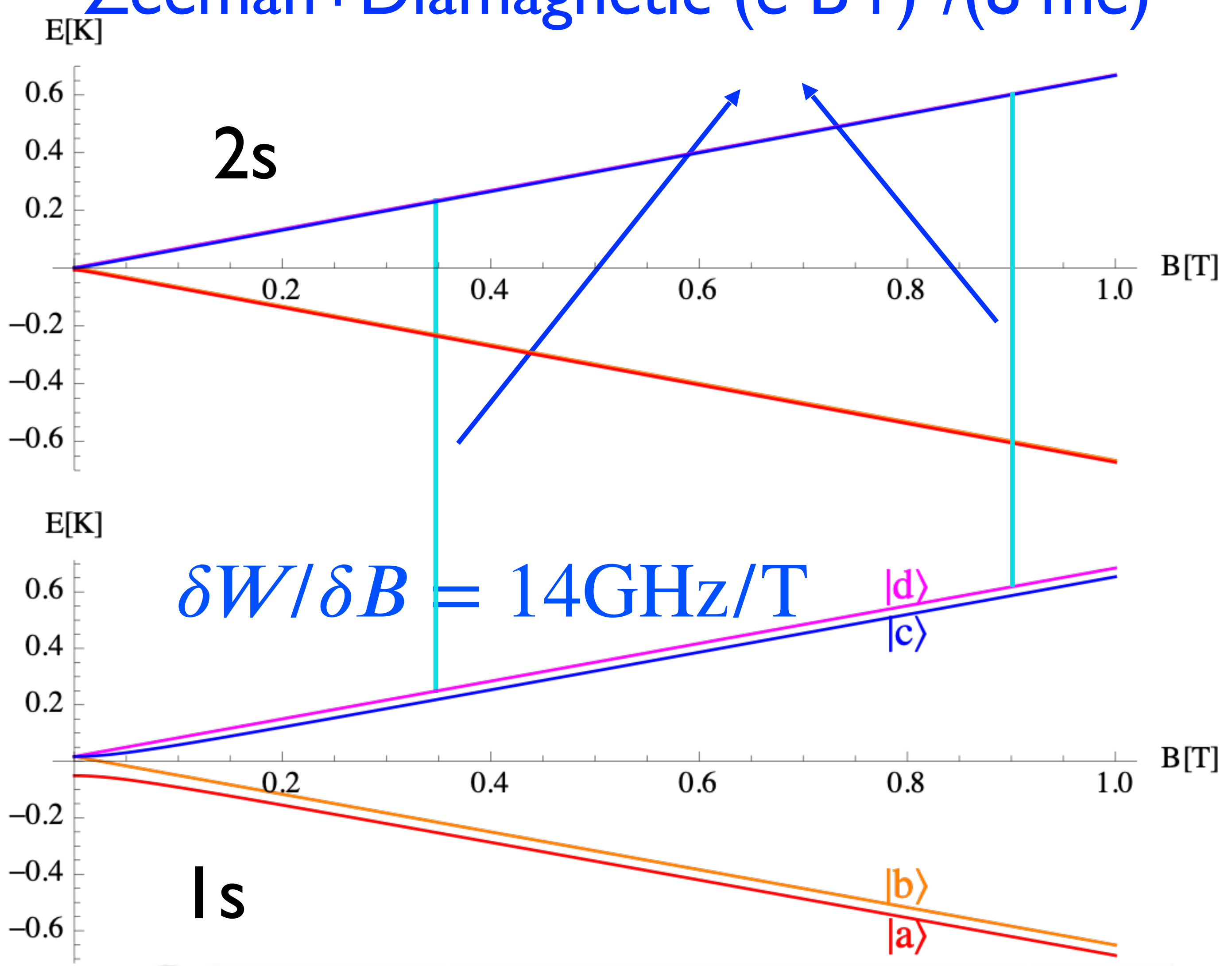
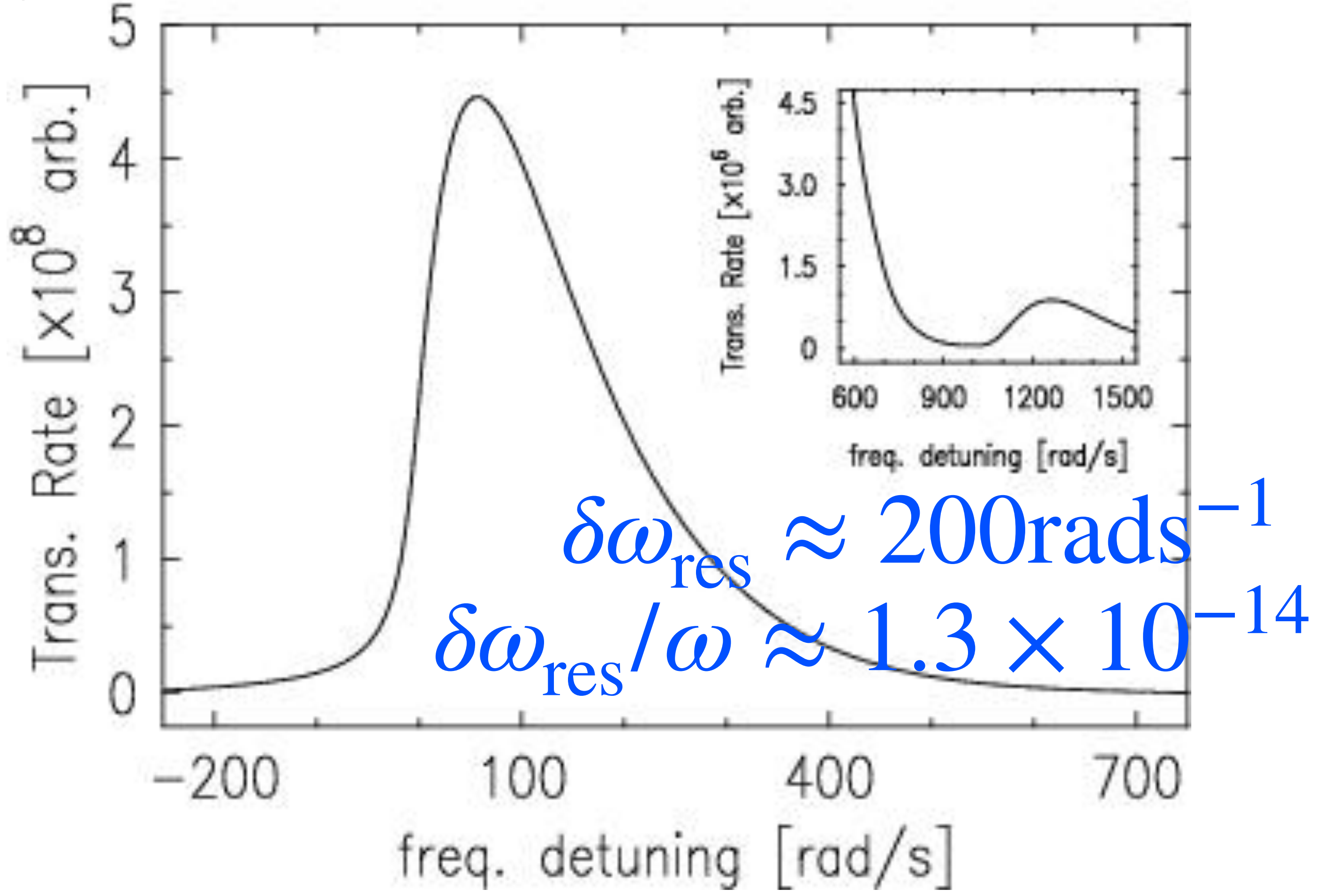


$\delta W/\delta B = 14\text{GHz/T}$



$\delta\omega_{res} \approx 200\text{rads}^{-1}$

$\delta\omega_{res}/\omega \approx 1.3 \times 10^{-14}$

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

Hbar Spectroscopy Objectives: resemblance of trapped H!?

$\delta\nu_{2S-1S} = (1/2)(186\text{kHz}(B/1\text{T}) + 387\text{kHz}(B/1\text{T})^2)$

E[K]

Zeeman+Diamagnetic $(e\,B\,r)^2/(8\,m_e)$

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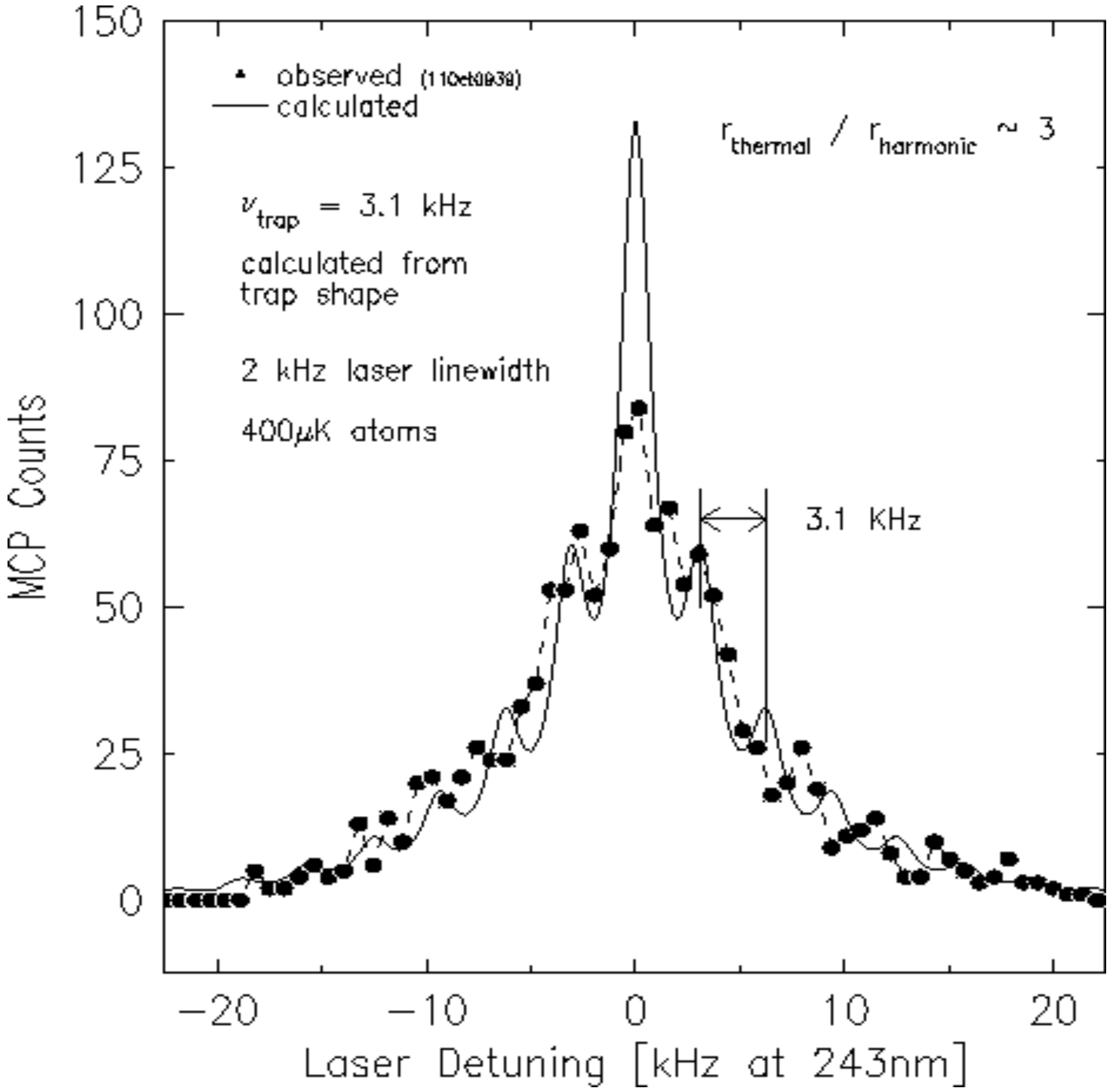

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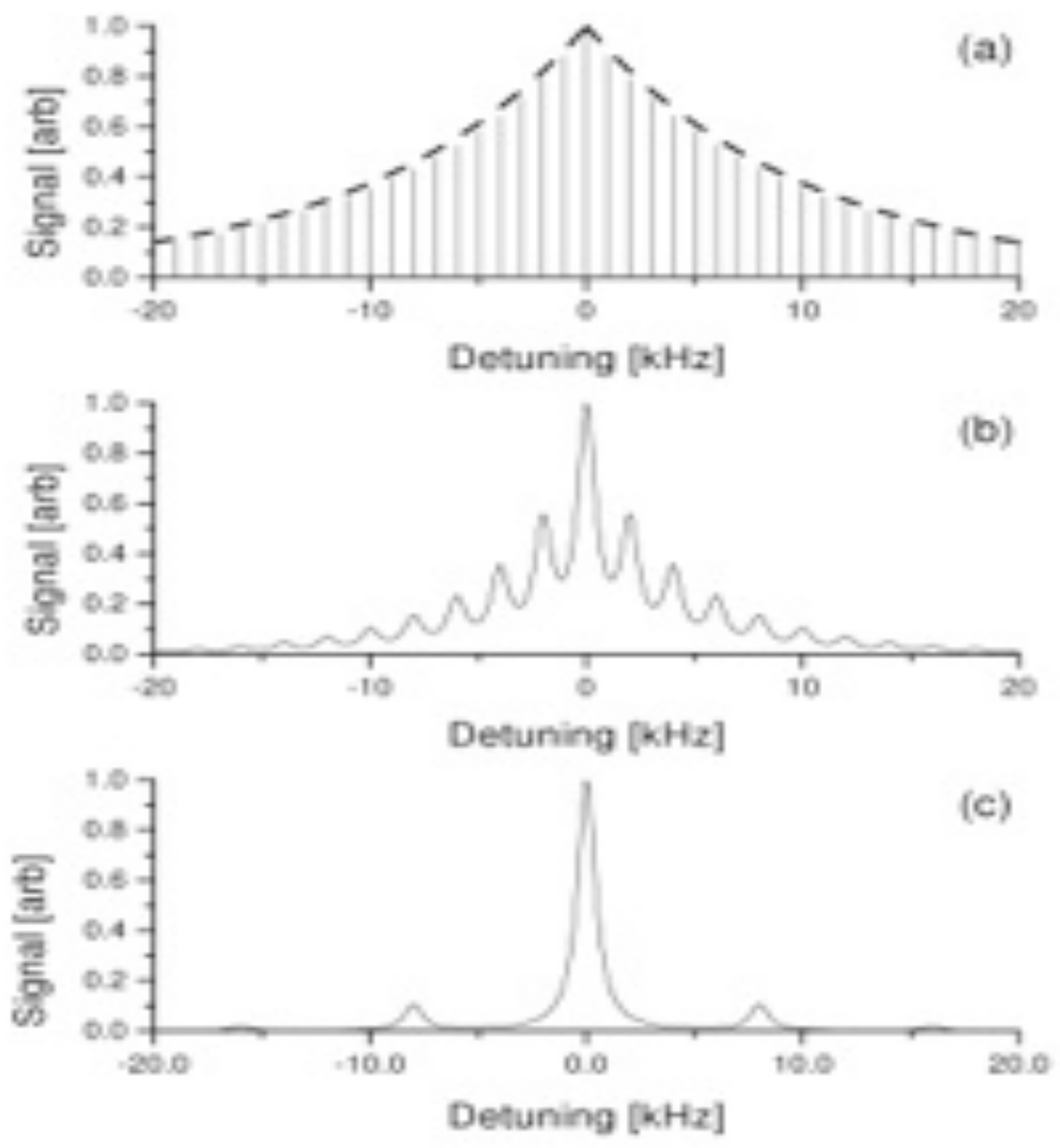
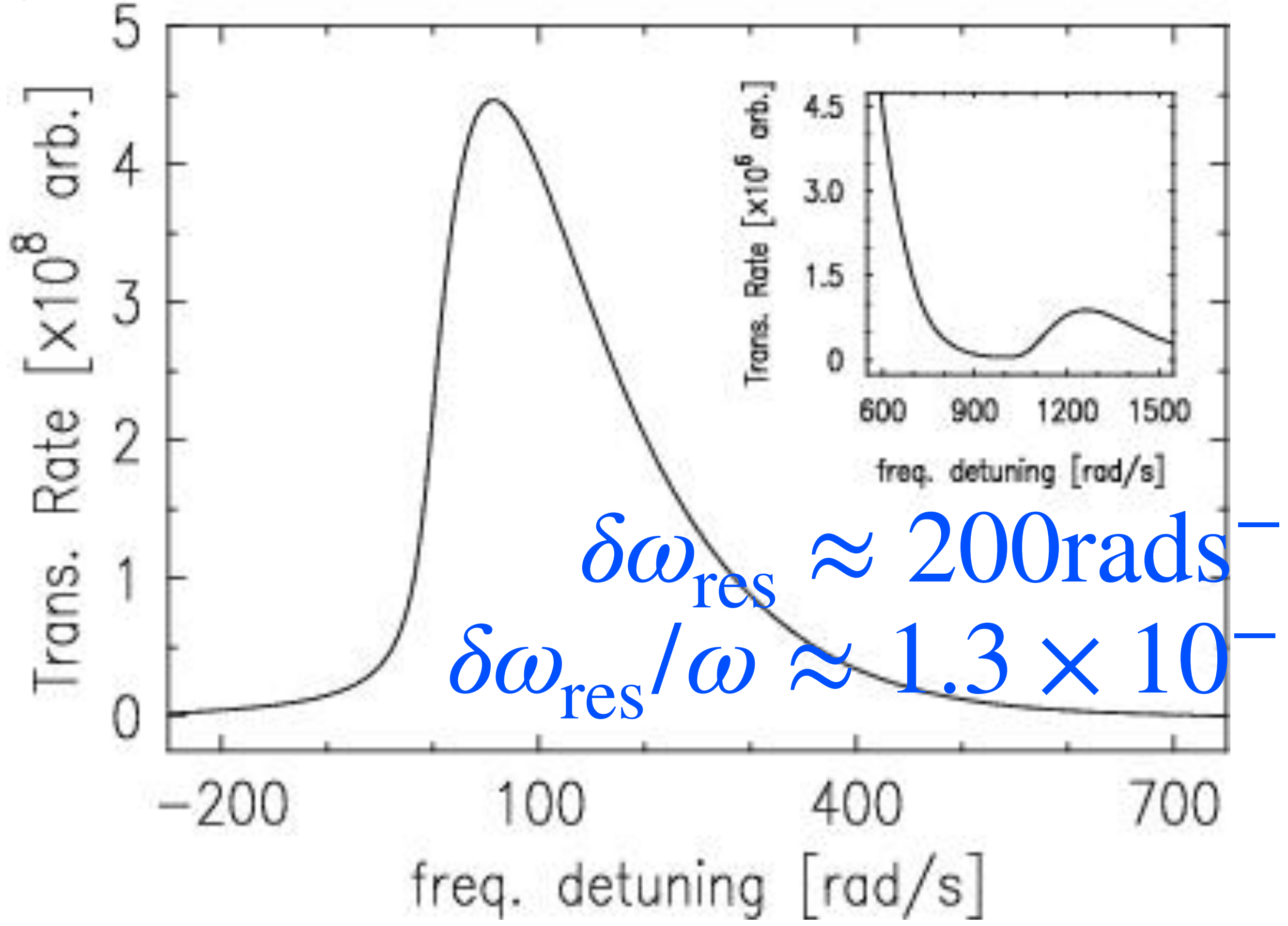


Phys. Rev. A 59, 4564 (1999)
C. L. Cesar, D. Kleppner

1s-2s superspectroscoy
possible with harmonically
trapped cold atoms

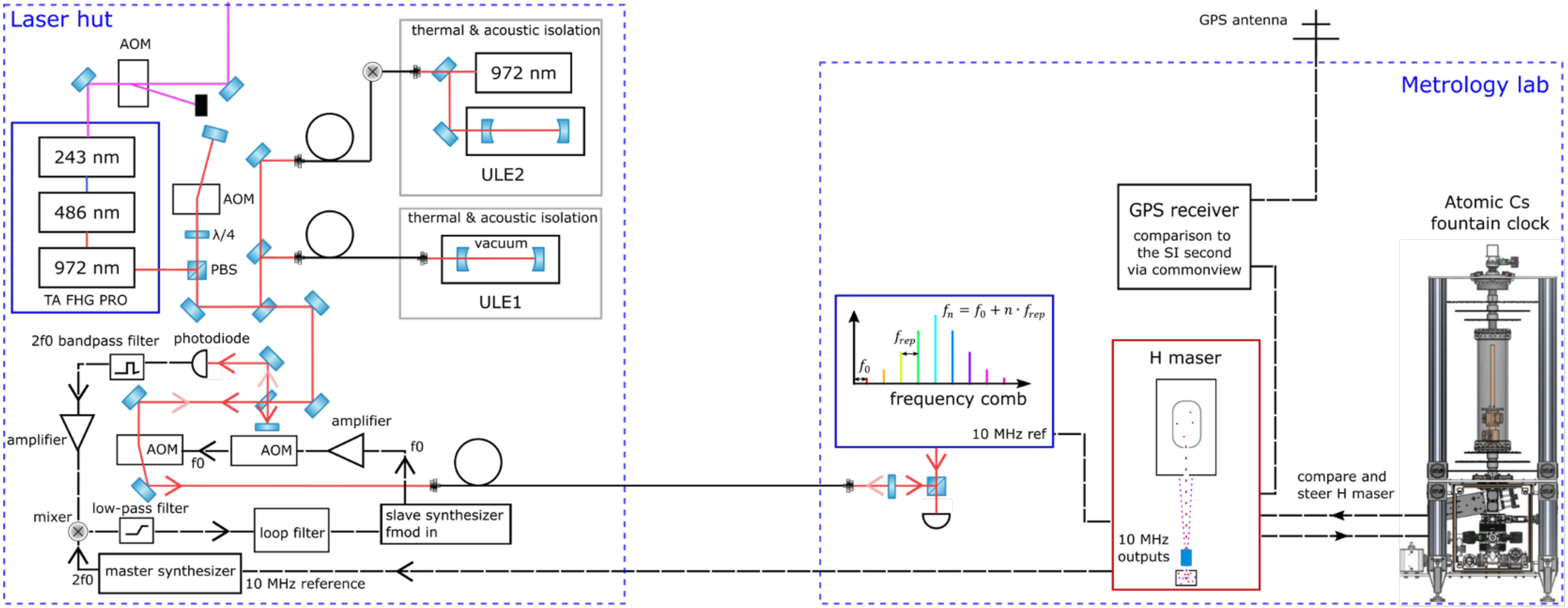


$\delta\omega_{\text{res}} \approx 200\text{rads}^{-1}$

$\delta\omega_{\text{res}}/\omega \approx 1.3 \times 10^{-14}$

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

ALPHA Frequency Metrology



H in the same anti-H trap: direct comparison to parts in 10^{15-18}

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

PAPER

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

Claudio Lenz Cesar

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Antihydrogen and Positronium

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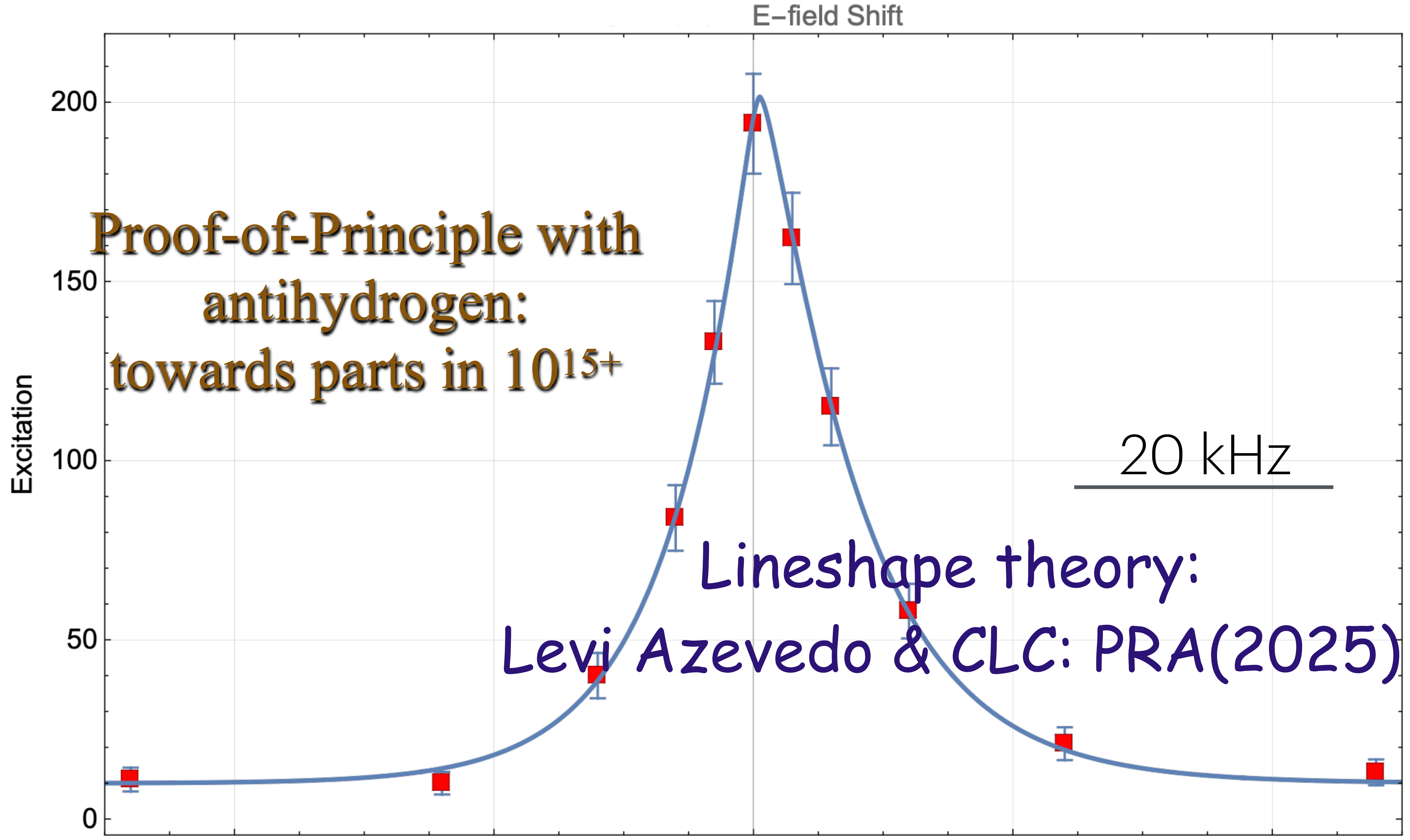
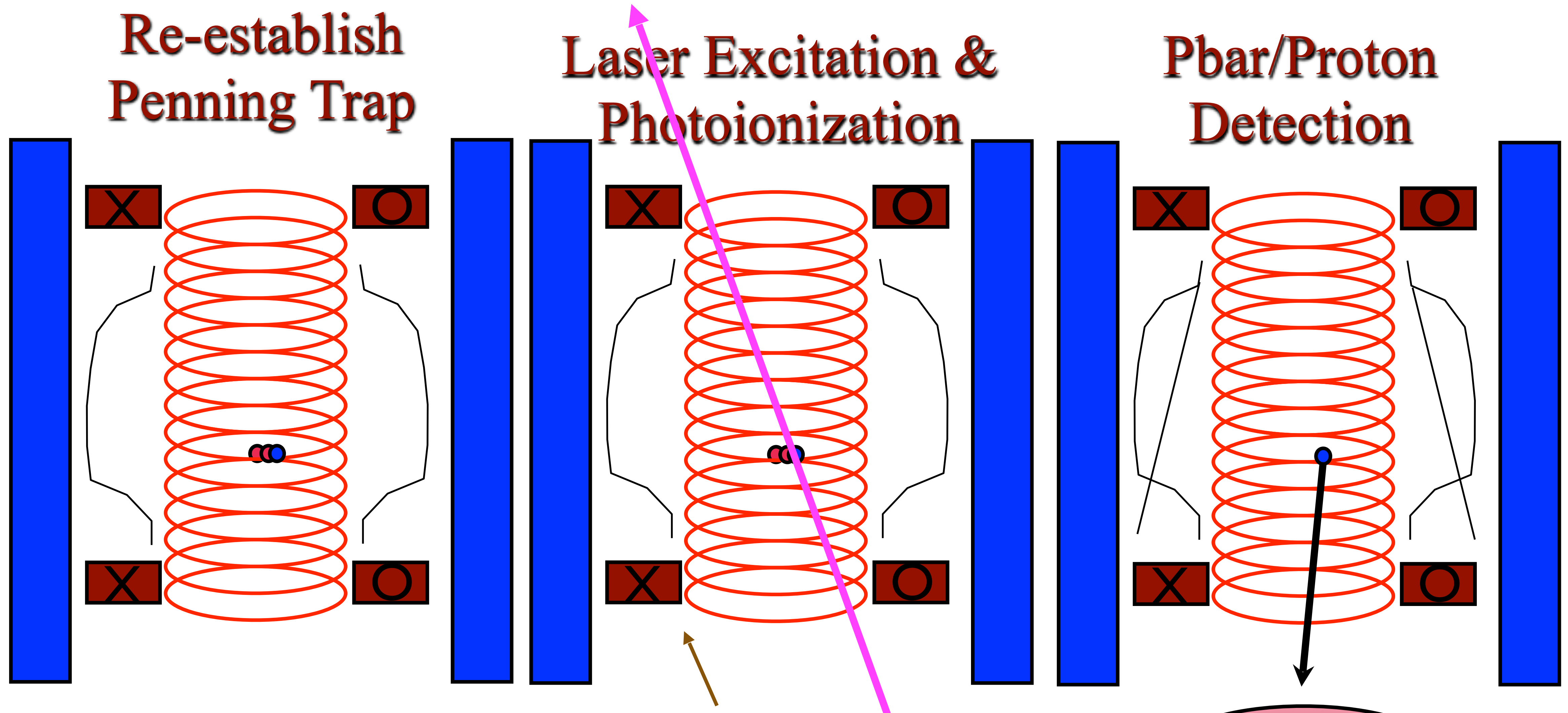
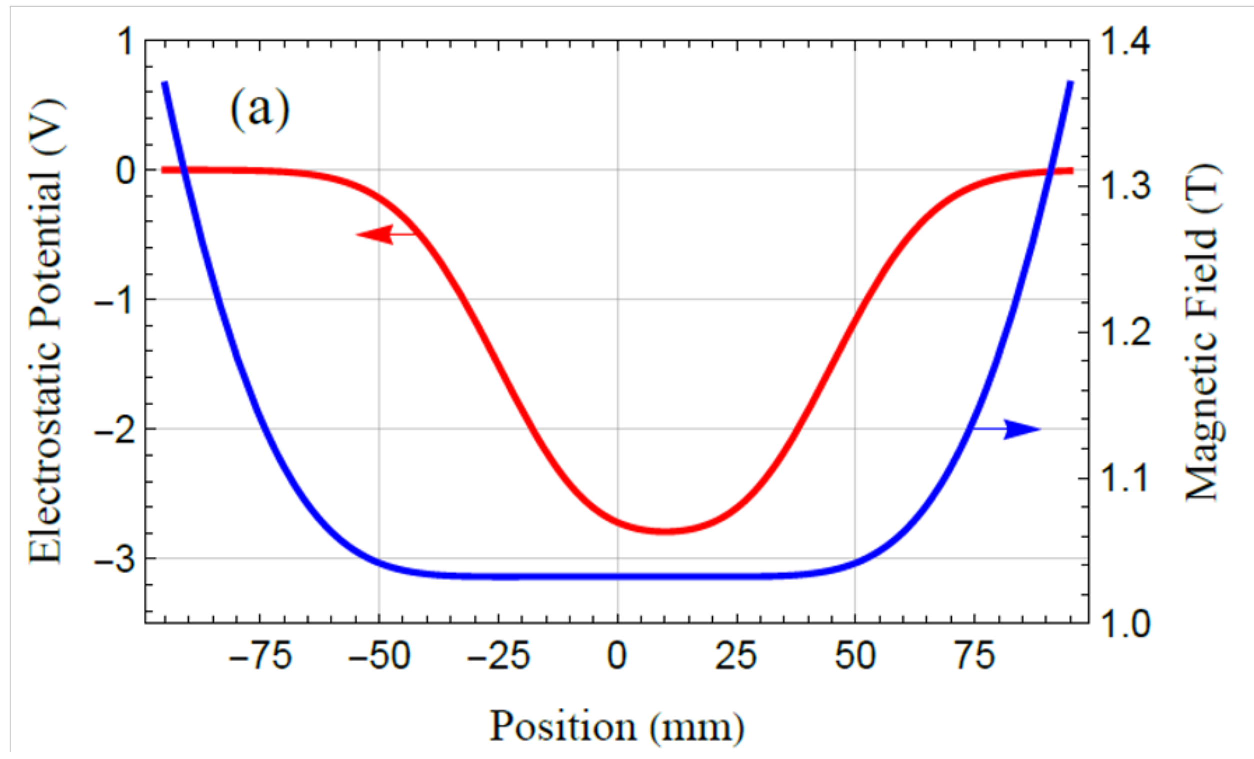
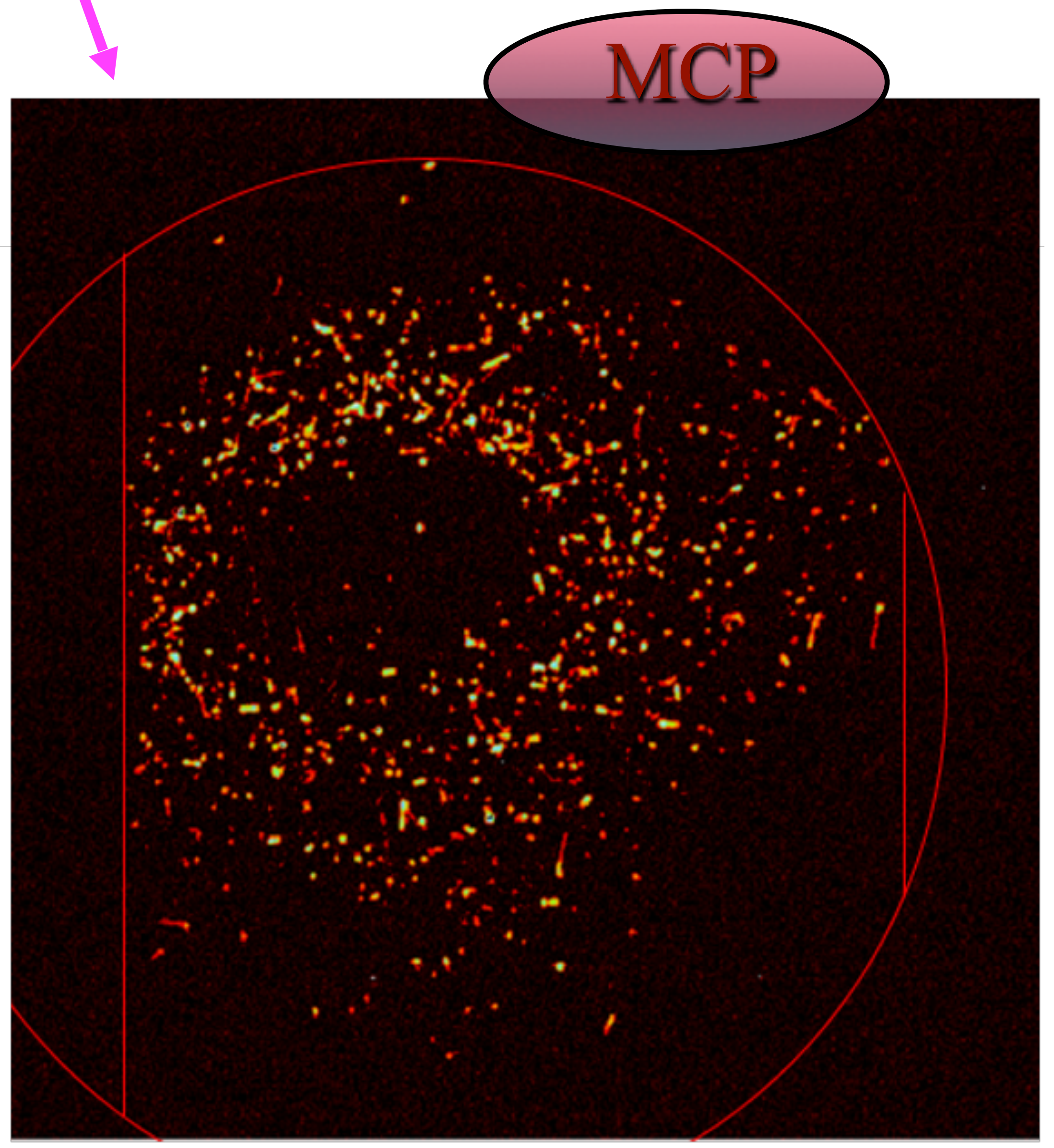


Proof-of-Principle with antihydrogen: towards parts in 10^{15+}

Lineshape theory: Levi Azevedo & CLC: PRA(2025)

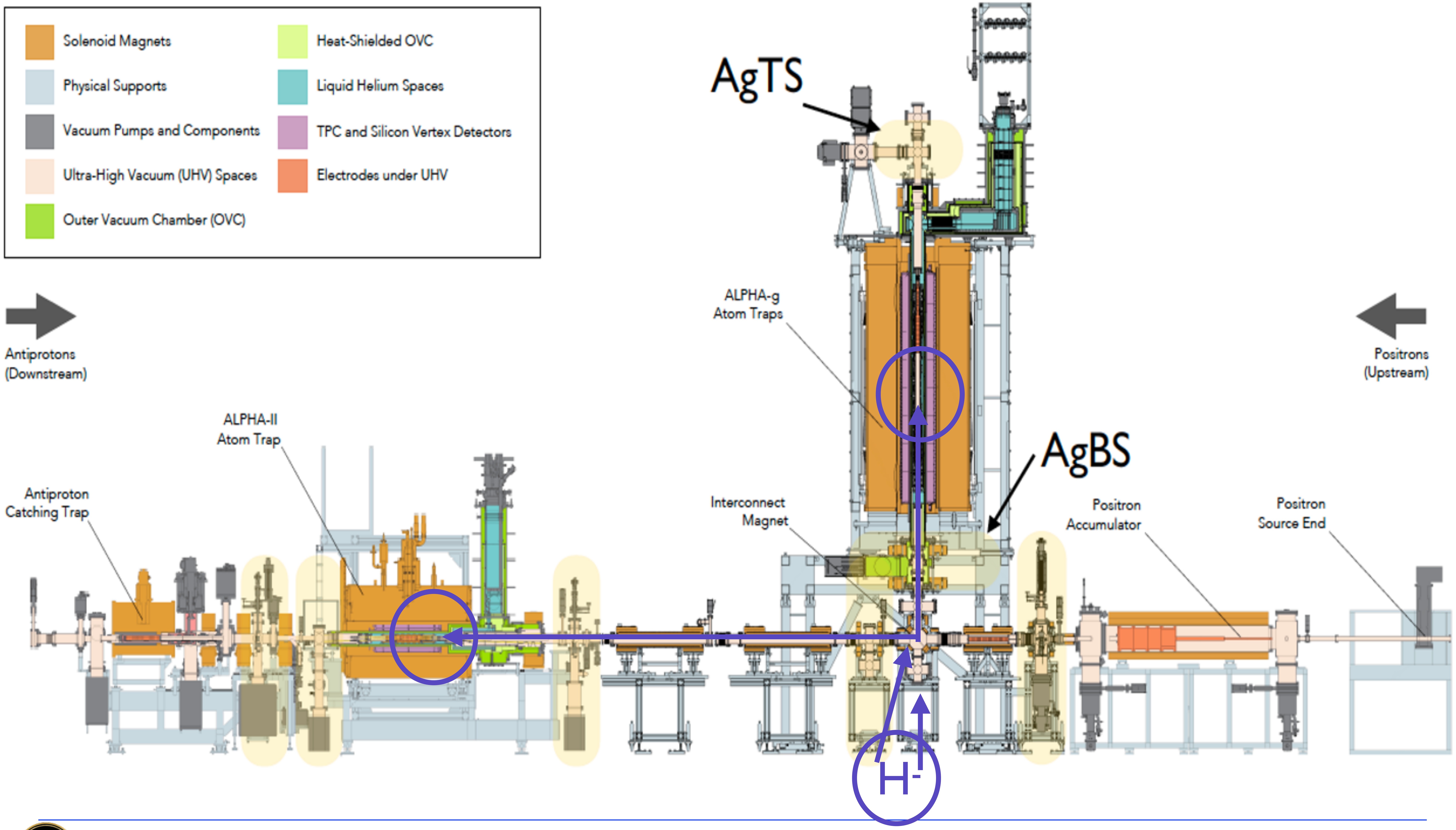




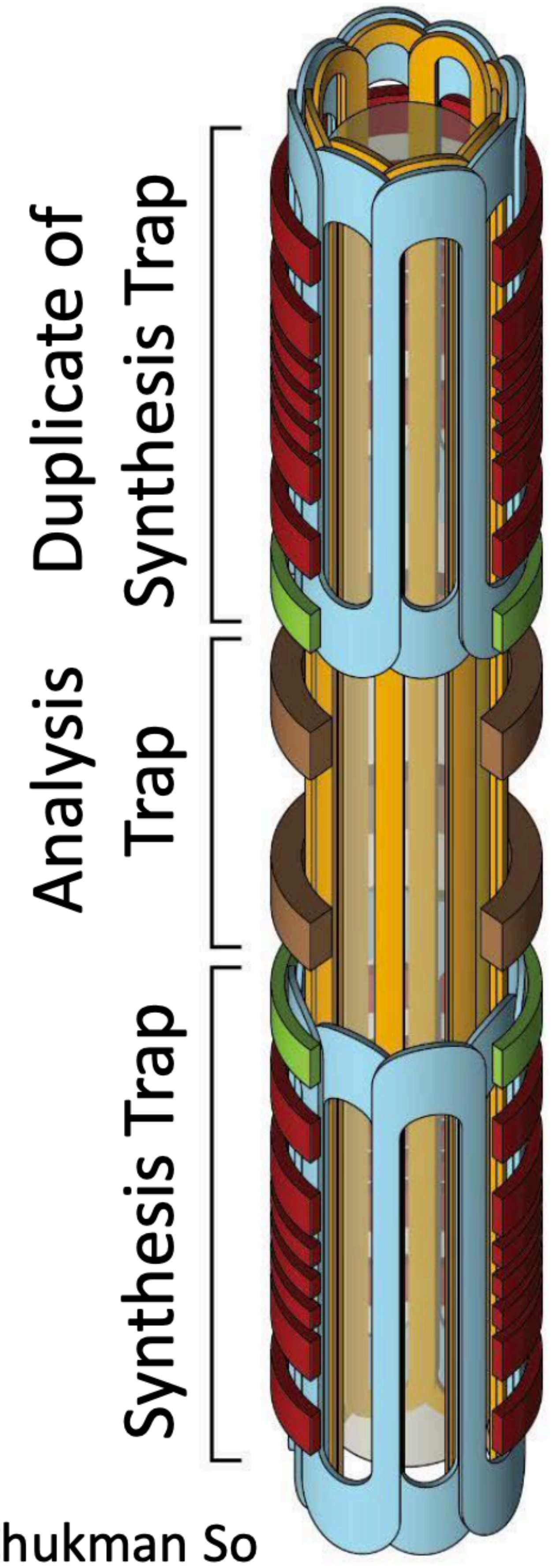


ALPHA (Steven Jones - Groningen) manuscript under revision

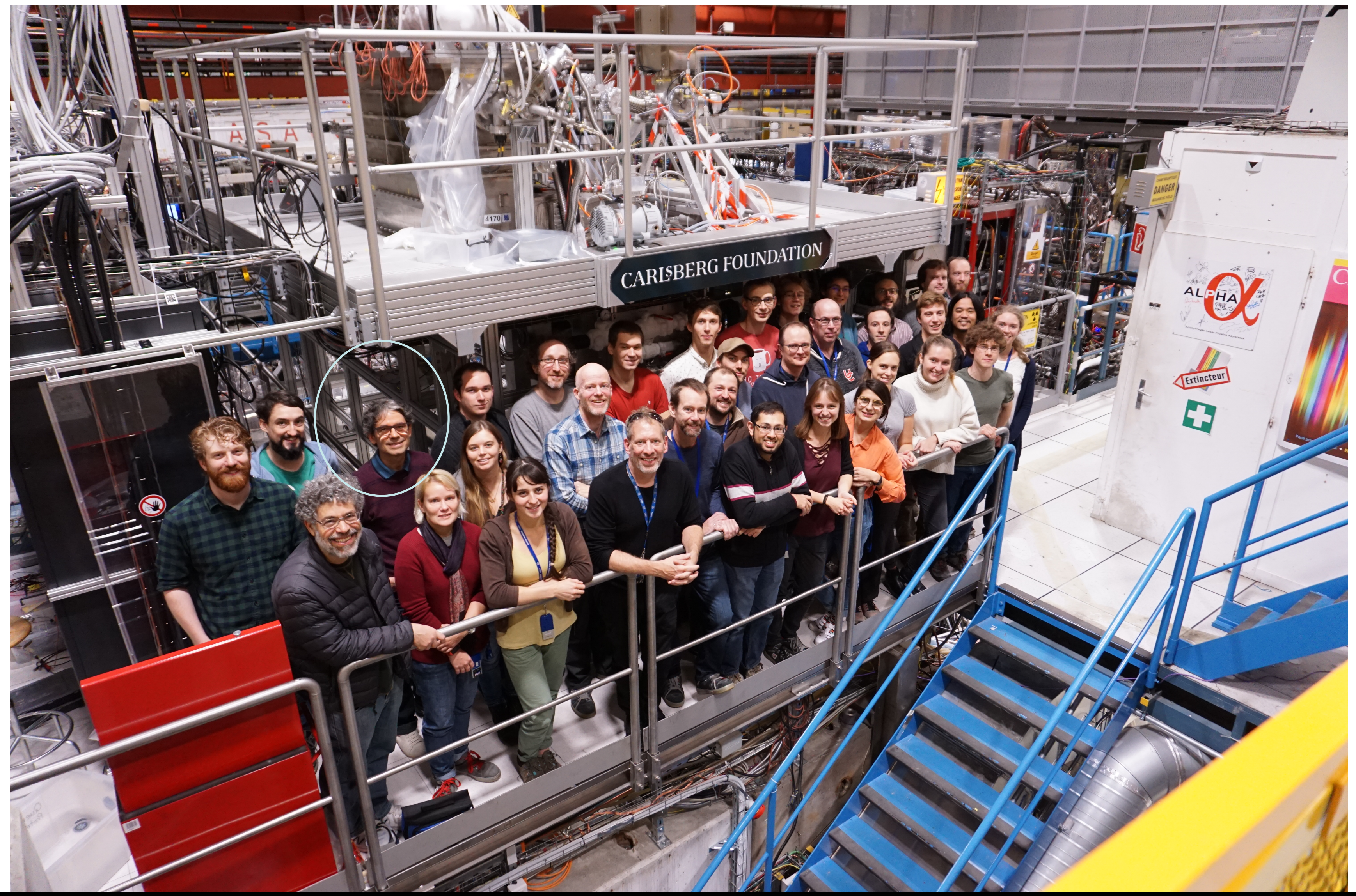
Matrix Isolation Sublimation (MISu):
(PRELIMINARY) proposal: H^- for ALPHA Hbar trap



ALPHA-g : observe antimatter fall down



: Chukman So



[redacted]

$$mgh = k_B T$$

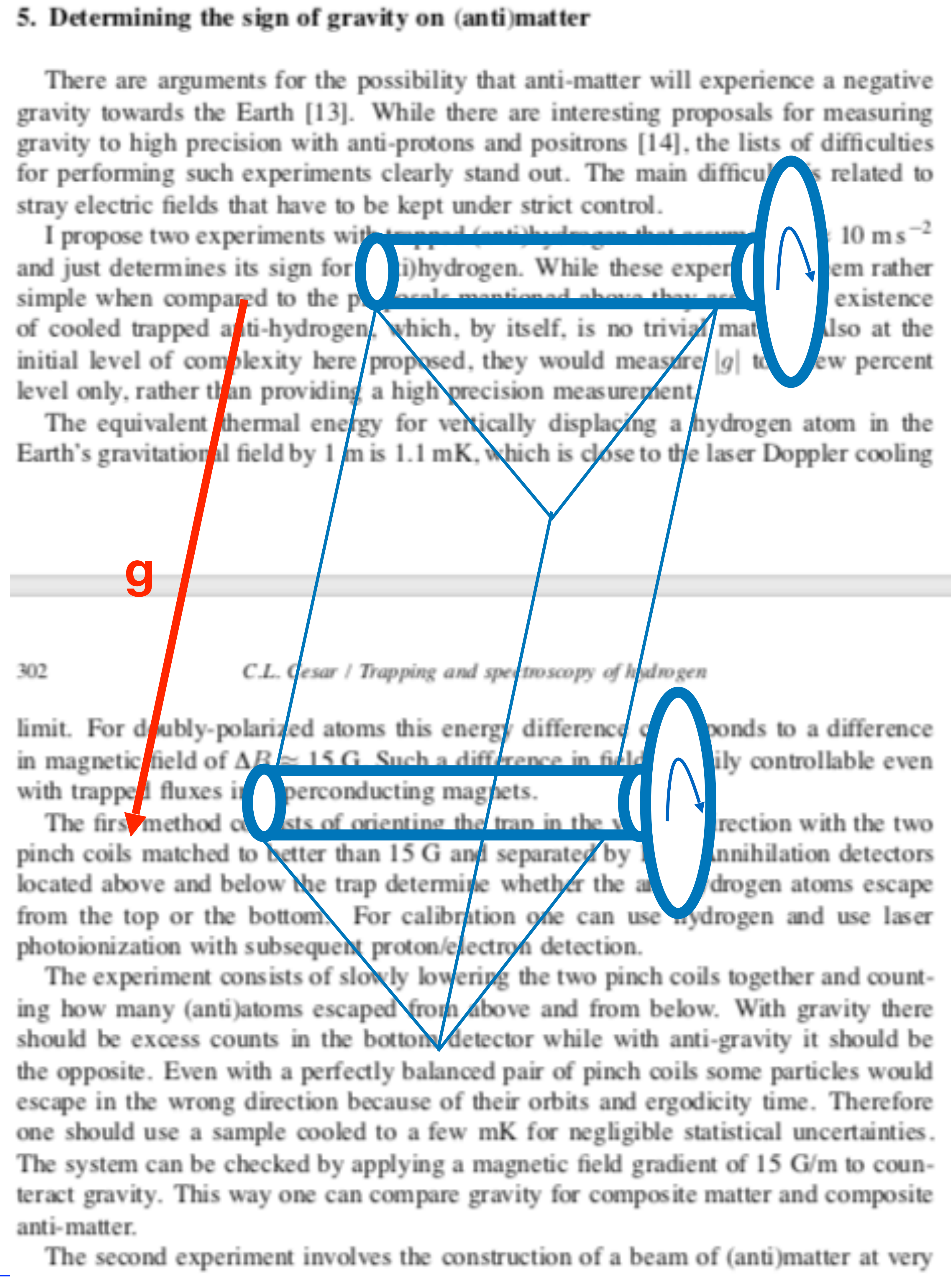
$$300\text{mK} \approx 250\text{m}$$

$$\mu\delta B_{0.5\text{m}} = mg0.5$$

$$\delta B_{0.5\text{m}} \approx 9\text{gauss}$$

in 1 T bias

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 difficul [illegible] s related to stray electric fields that have to be kept under strict control.

I propose two experiments wit [illegible] 10 m s^{-2} and just determines its sign for [illegible] i)hydrogen. While these exper [illegible] em rather simple when compared to the p [illegible] existence of cooled trapped anti-hydrogen, which, by itself, is no trivial mat [illegible] lso at the initial level of complexity here proposed, they would measure $|g|$ to [illegible] ew 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

302 *C.L. Cesar / Trapping and spectroscopy of hydrogen*

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

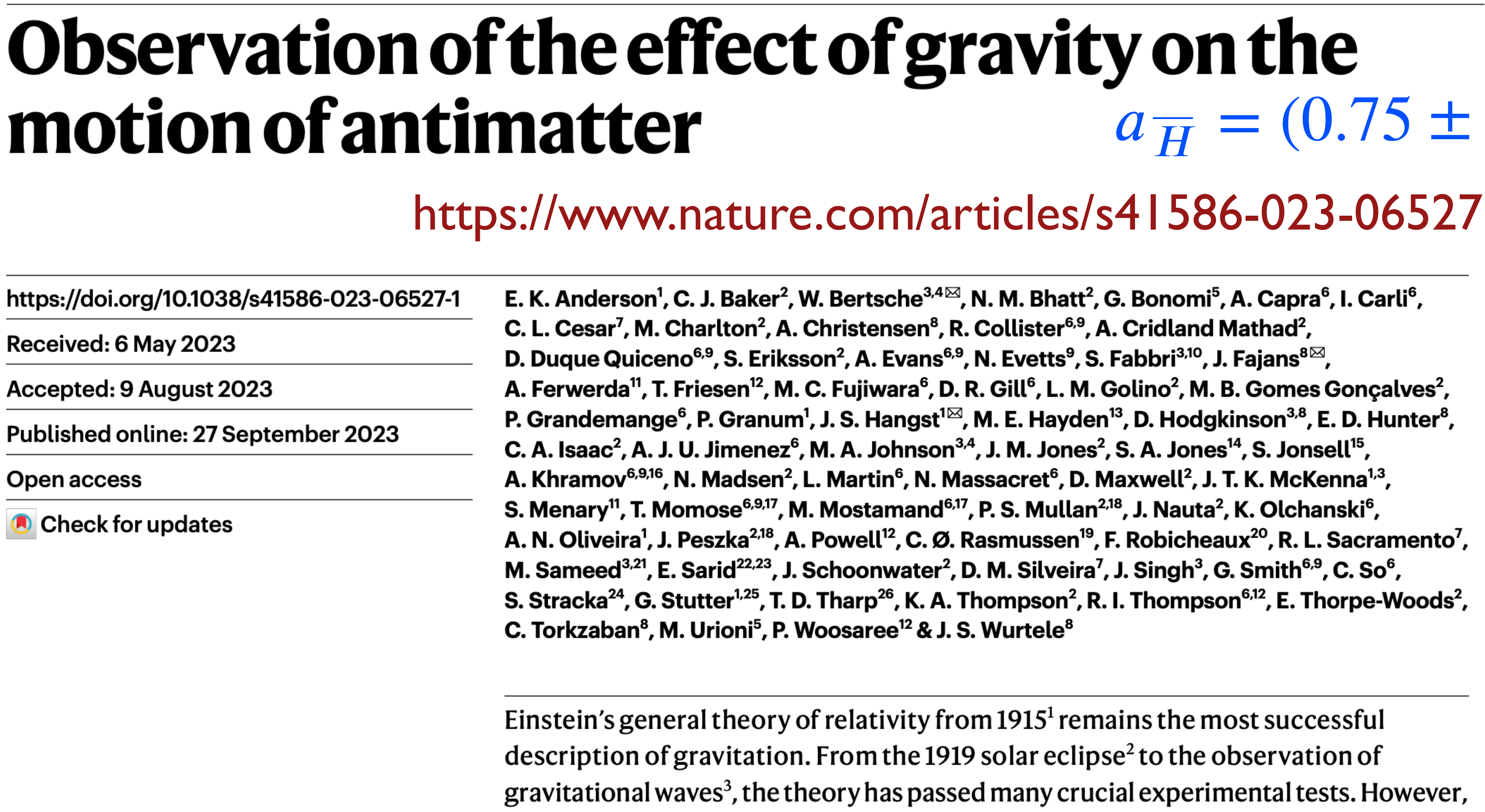
The firs method c [illegible] sts of orienting the trap in the v [illegible] rection with the two pinch coils matched to better than 15 G and separated by [illegible] annihilation detectors located above and below the trap determine whether the a [illegible] drogen atoms escape from the top or the bottom. For calibration one can use [illegible] ydrogen 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

ar@cern.ch

ALPHA-g observation of antimatter fall



Article

Observation of the effect of gravity on the motion of antimatter

$$a_{\overline{H}} = (0.75 \pm 0.13(\text{stat} + \text{syst}) \pm 0.16(\text{sim}))\text{g}$$

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

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E. K. Anderson[1], C. J. Baker[2], W. Bertsche[3,4]⊠, N. M. Bhatt[2], G. Bonomi[5], A. Capra[6], I. Carli[6], C. L. Cesar[7], M. Charlton[2], A. Christensen[8], R. Collister[6,9], A. Cridland Mathad[2], D. Duque Quiceno[6,9], S. Eriksson[2], A. Evans[6,9], N. Evetts[9], S. Fabbri[3,10], J. Fajans[8]⊠, A. Ferwerda[11], T. Friesen[12], M. C. Fujiwara[6], D. R. Gill[6], L. M. Golino[2], M. B. Gomes Gonçalves[2], P. Grandemange[6], P. Granum[1], J. S. Hangst[1]⊠, M. E. Hayden[13], D. Hodgkinson[3,8], E. D. Hunter[8], C. A. Isaac[2], A. J. U. Jimenez[6], M. A. Johnson[3,4], J. M. Jones[2], S. A. Jones[14], S. Jonsell[15], A. Khramov[6,9,16], N. Madsen[2], L. Martin[6], N. Massacret[6], D. Maxwell[2], J. T. K. McKenna[1,3], S. Menary[11], T. Momose[6,9,17], M. Mostamand[6,17], P. S. Mullan[2,18], J. Nauta[2], K. Olchanski[6], A. N. Oliveira[1], J. Peszka[2,18], A. Powell[12], C. Ø. Rasmussen[19], F. Robicheaux[20], R. L. Sacramento[7], M. Sameed[3,21], E. Sarid[22,23], J. Schoonwater[2], D. M. Silveira[7], J. Singh[3], G. Smith[6,9], C. So[6], S. Stracka[24], G. Stutter[1,25], T. D. Tharp[26], K. A. Thompson[2], R. I. Thompson[6,12], E. Thorpe-Woods[2], C. Torkzaban[8], M. Urioni[5], P. Woosaree[12] & J. S. Wurtele[8]

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. However,

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

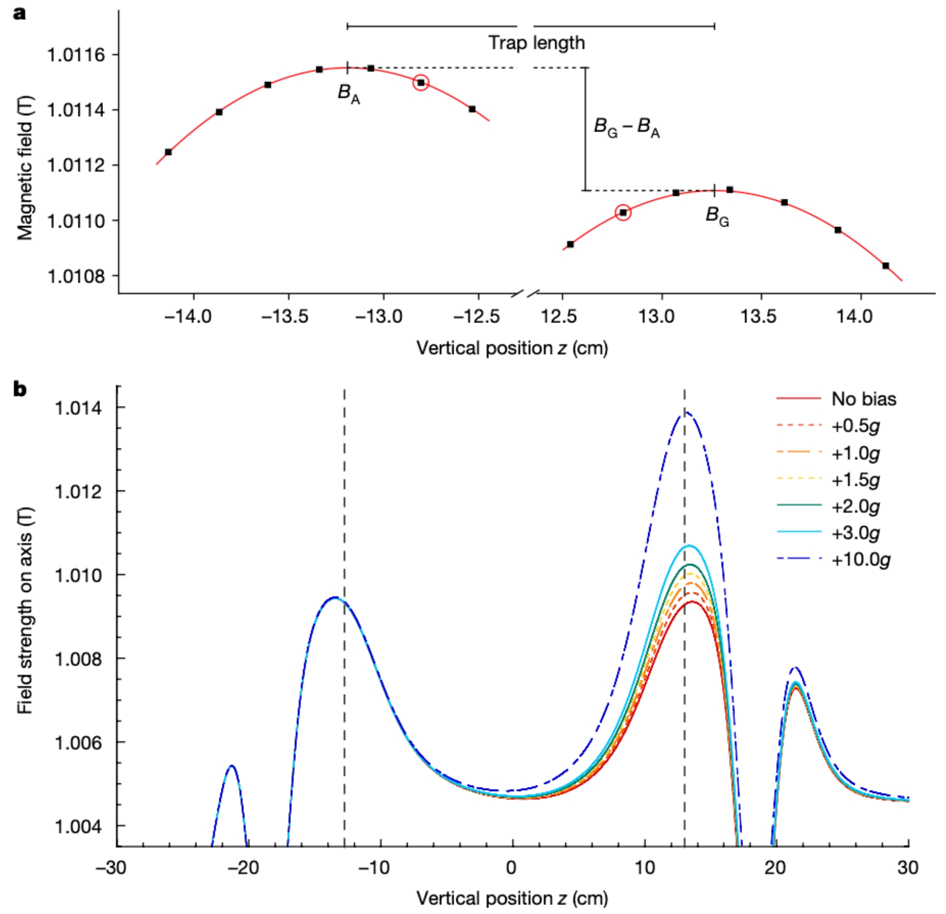
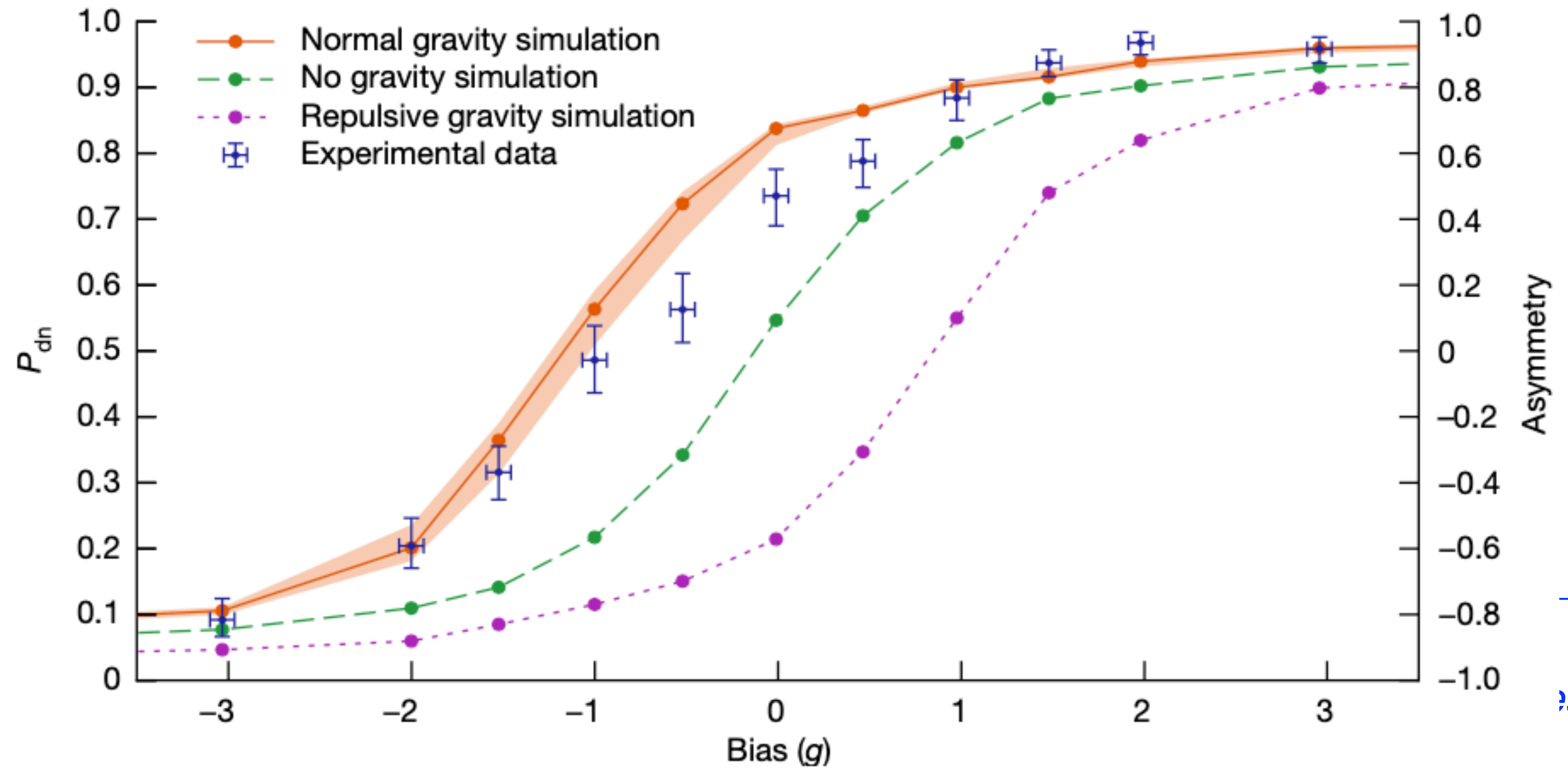


Fig. 2 | Illustrations of the magnetic bias. a, Expanded view of the end-of-ramp mirror coil peak regions for a bias of −1*g* (note the discontinuous abscissa). The square points represent offline ECR measurements carried out to determine the field profile and to find the peak field location. The points with red circles 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



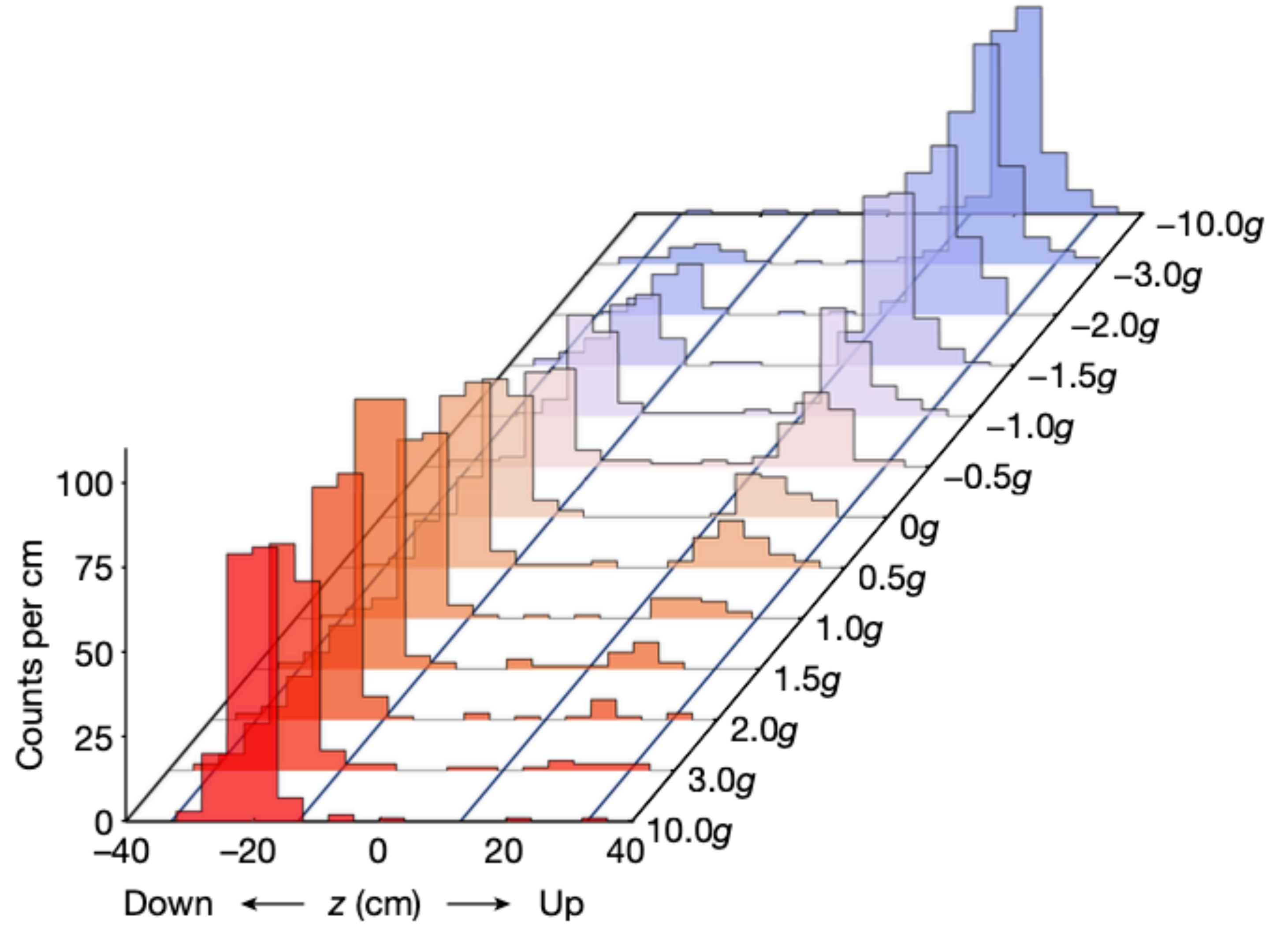


Fig. 3 | Escape histograms. The raw event *z*-distributions are displayed as histograms for each of the bias values, including the ±10*g* calibration runs. These are uncorrected for background or detector relative efficiency. The time window represented here is 10 s to 20 s of the magnet ramp-down. The *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.

ALPHA-g observation of antimatter fall

Article

Observation of the effect of gravity on the motion of antimatter

$$a_{\overline{H}} = (0.75 \pm 0.13(\text{stat}+\text{syst}) \pm 0.16(\text{sim}))g$$

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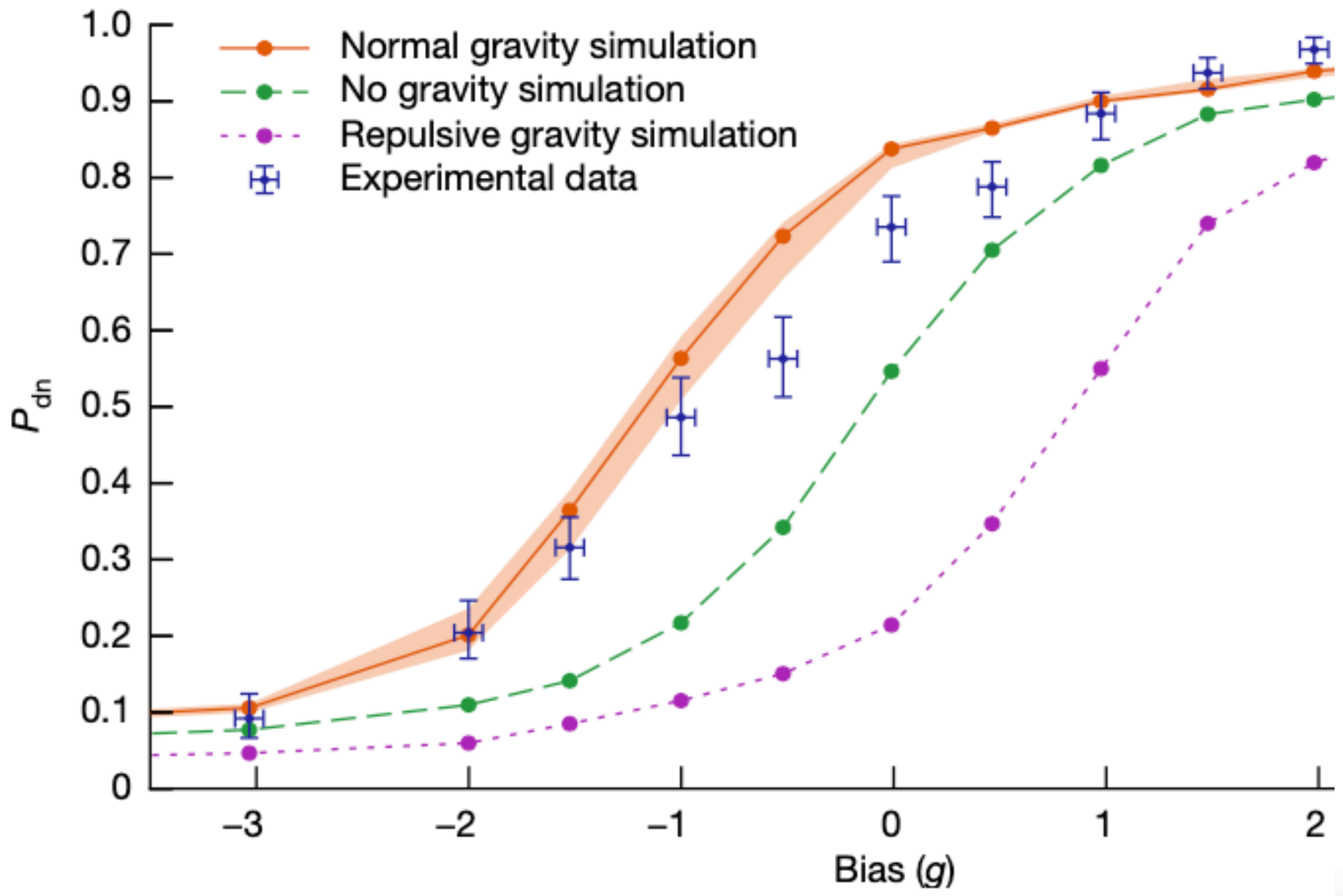
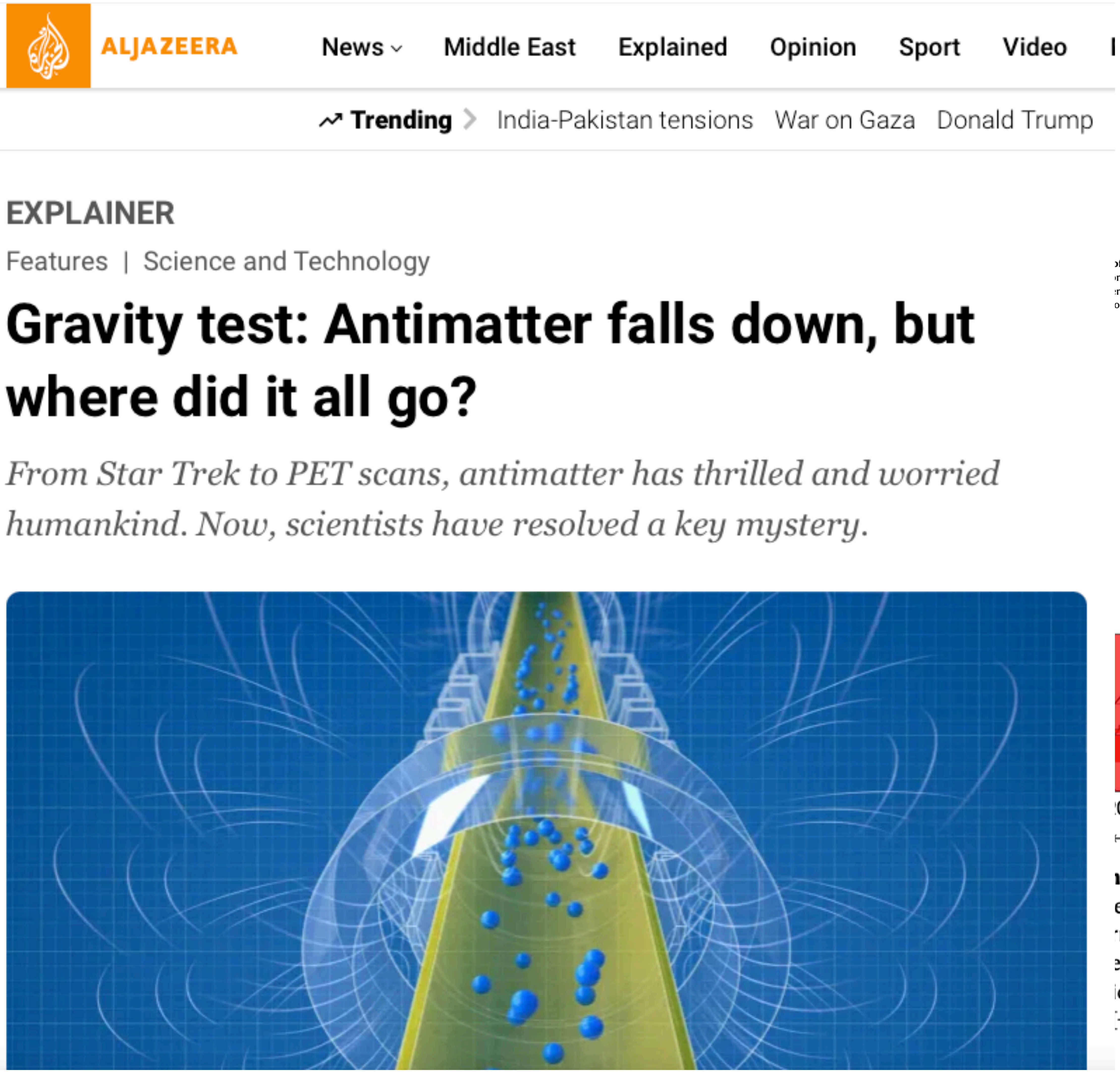


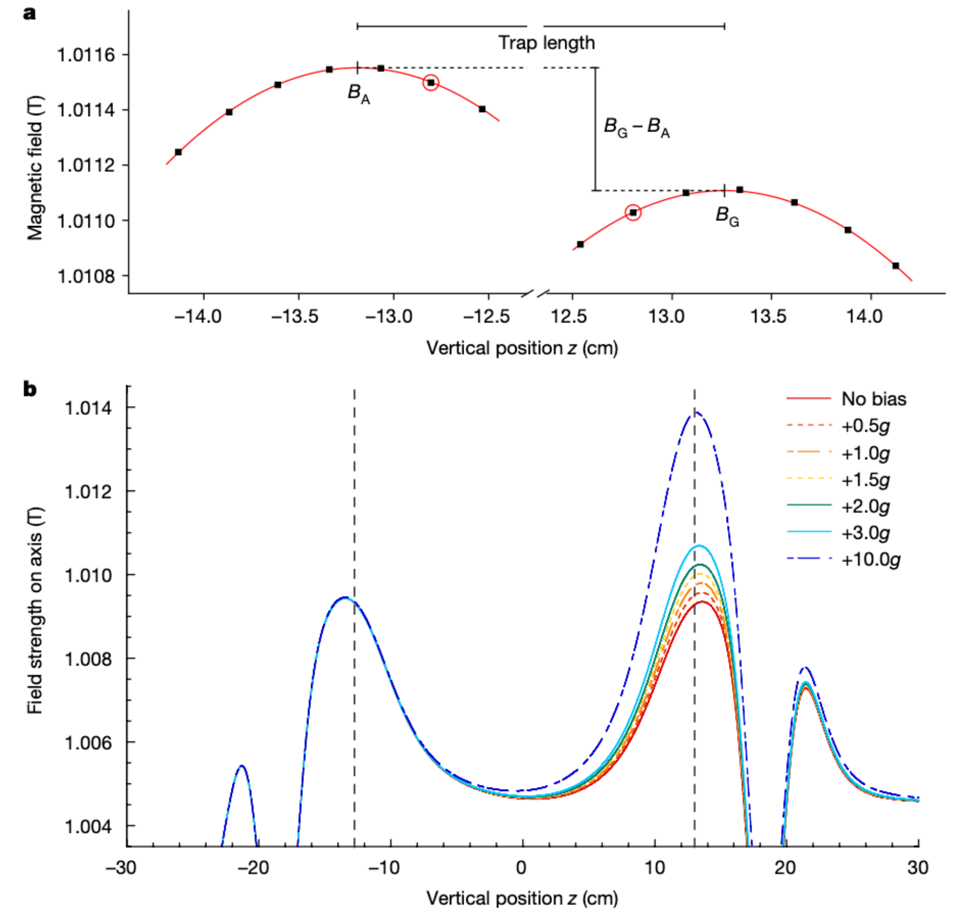


EXPLAINER

Features | Science and Technology

Gravity test: Antimatter falls down, but where did it all go?

From Star Trek to PET scans, antimatter has thrilled and worried humankind. Now, scientists have resolved a key mystery.



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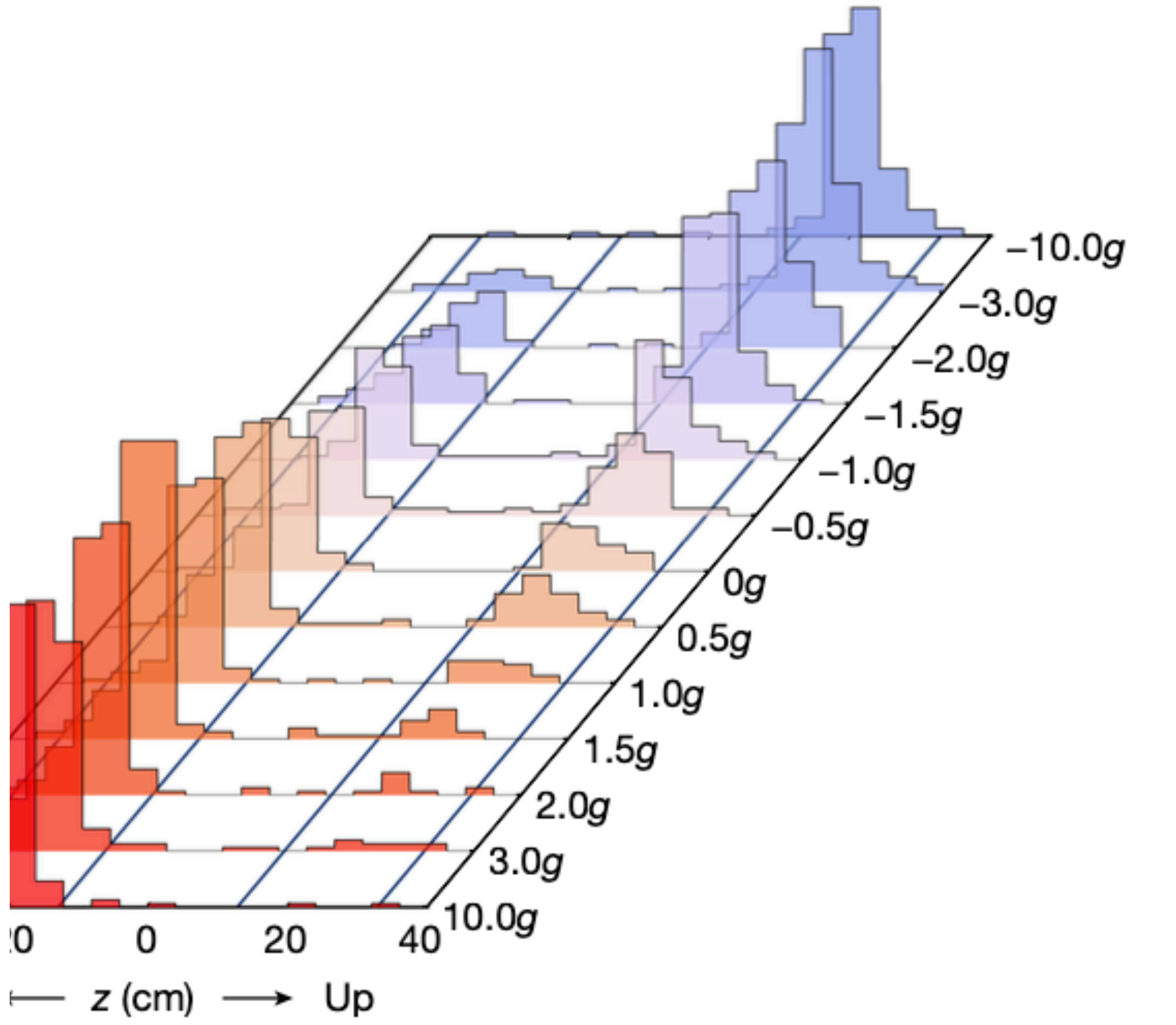

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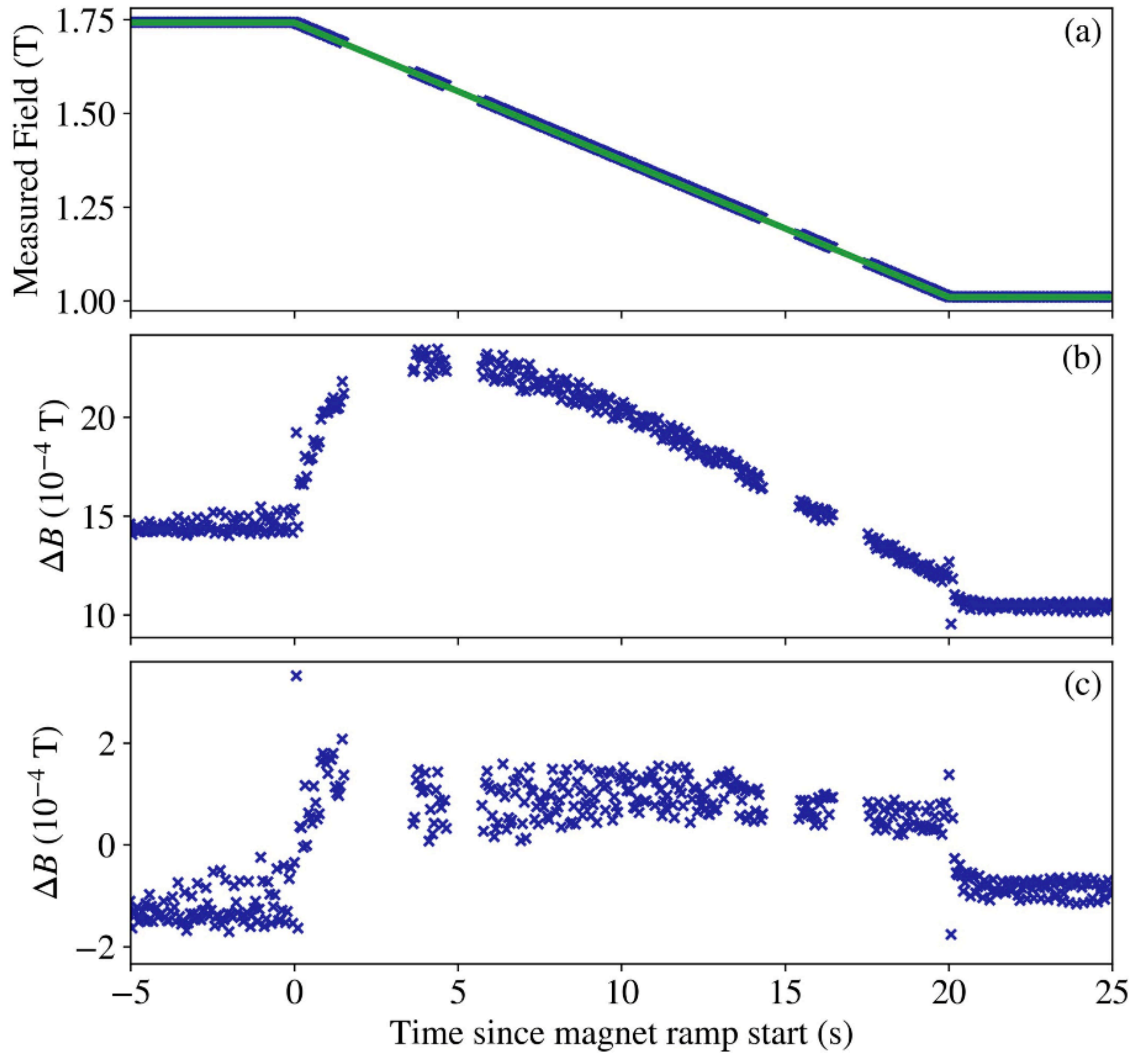
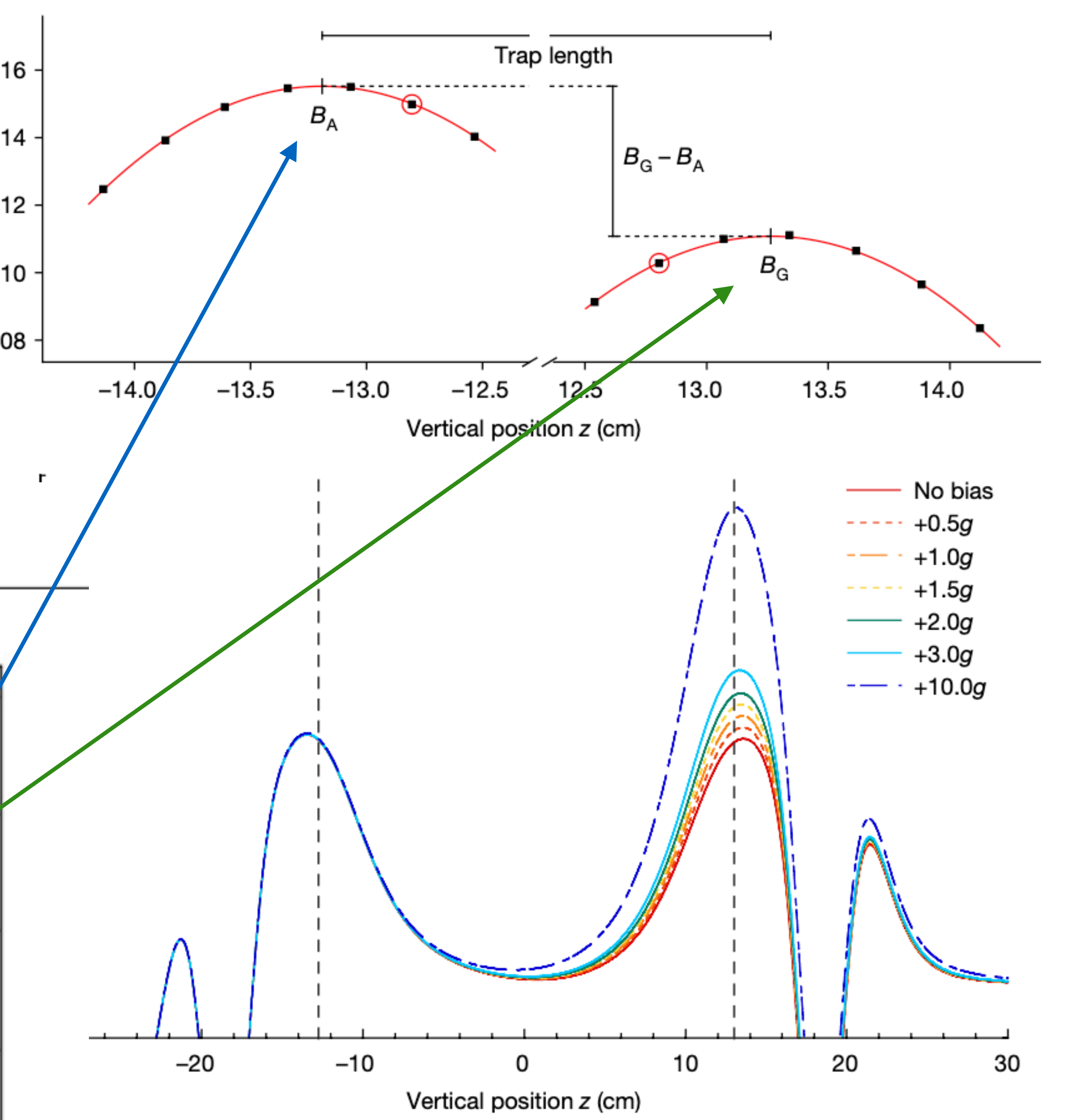


Extended Data Fig. 7 | Magnetic field measurements via the magnetron frequency. Magnetic field measured using the magnetron frequency of electron clouds in the centre of mirror A versus time during the magnet ramp-down. **a** Raw measurements (blue) are compared to the expected linear ramp (green line). **b** The difference between the measurements and the expected linear ramp is plotted versus time. **c** Measurements after accounting for the three corrections described in Methods. The 1–2 s gaps in the data are due to a memory limitation in the FPGA that controls the electrode voltages. New voltage instructions are loaded in this time.



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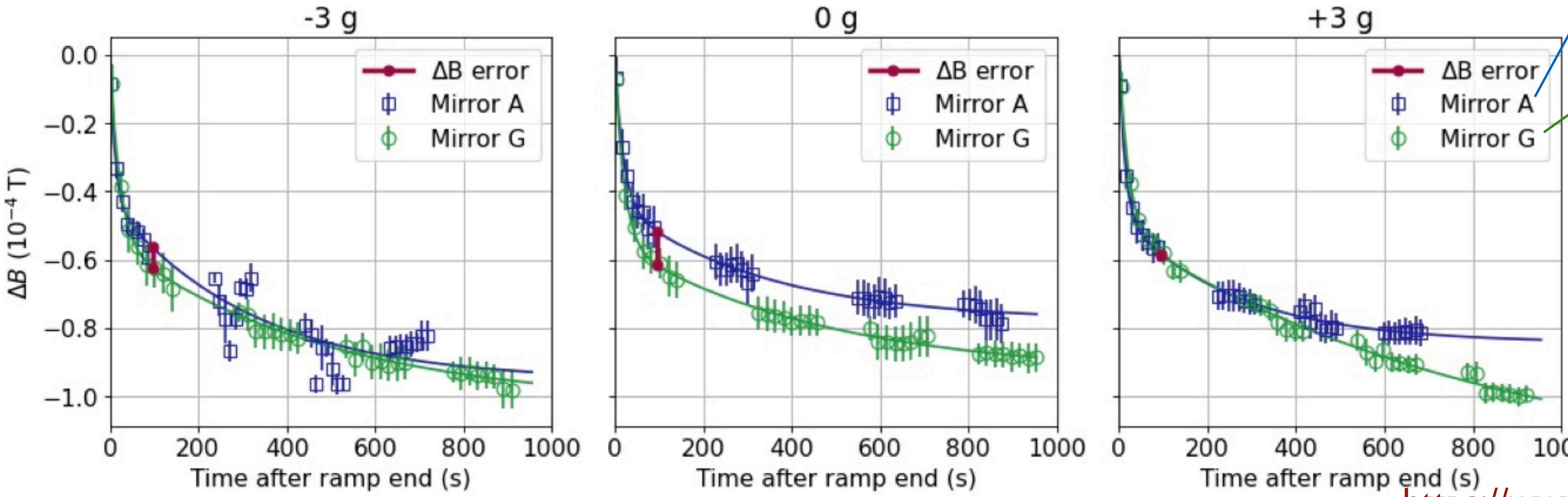


https://www.nature.com/articles/s41586-023-06527

Extended Data Fig. 6 | Decay of persistent fields (offline measurements). The on-axis fields at the axial midpoint (Fig. 2a) of mirrors A and G, as measured by the rapid cycle ECR technique (Methods) to study the decay of persistent fields after the end of the 20 s ramp. The solid lines are fits using two exponential decay times per curve; see Methods. The three plots are for the extreme biases ±3 g and 0 g. The red points represent the extracted systematic error in the magnetic field difference between mirror A and mirror G at each bias, and they are plotted at the approximate time of the ECR resonance in the actual gravity trials. 'Offline' refers to measurements taken independently of the release experiments.

Conclusions/Perspectives/Acknowledgements

ALPHA @ CERN

- 1S-2S spectrum (2018 @ 10^{-12}, 2026 @ $10^{-13,-14}$):
  (E&M, QED, QCD: $r_p \Rightarrow$ 1.2 MHz while ∂f ~ 300 Hz)

⇒ very high precision $10^{-15...-18}$: Hbar & H in same trap (proof-of-principle)

- laser cooling, μW spectroscopy, hyperfine, …
- ALPHA-g gravity fall:

$$a_{\overline{H}} = (0.75 \pm 0.13(\mathrm{stat} + \mathrm{syst}) \pm 0.16(\mathrm{sim}))\mathrm{g}$$

will CPT hold ? WEP ? Nature has the answer !?

LASER−IF−UFRJ

Universidade do Brasil

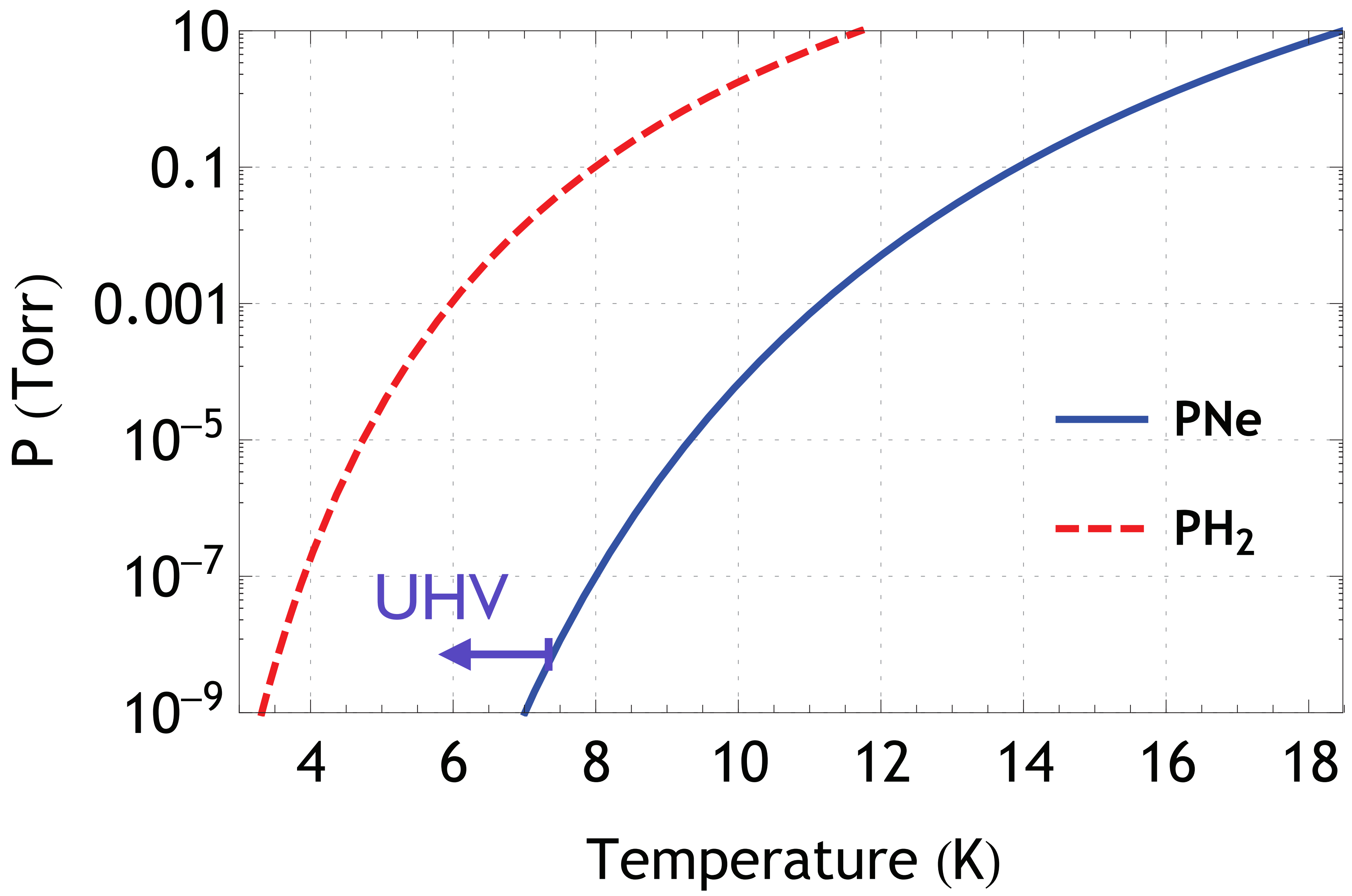
Team UFRJ - moved into new lab in Rio

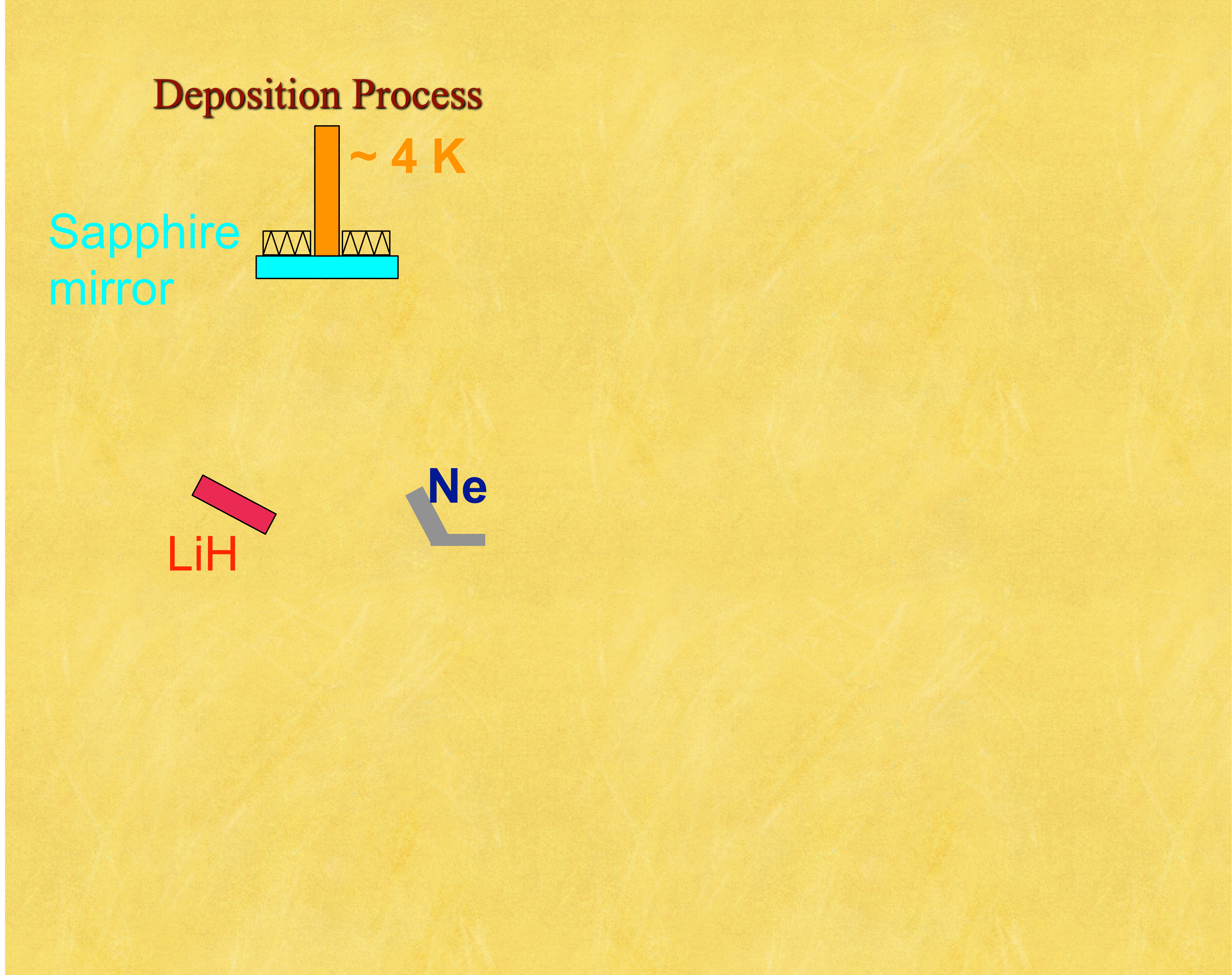
UFRJ - Matrix Isolation Sublimation (MISu): a general technique for cryogenic atoms, molecules, and ions

Ne or H2 solid film

Implant species with laser ablation

Sublimate the matriz at cryogenic temperature





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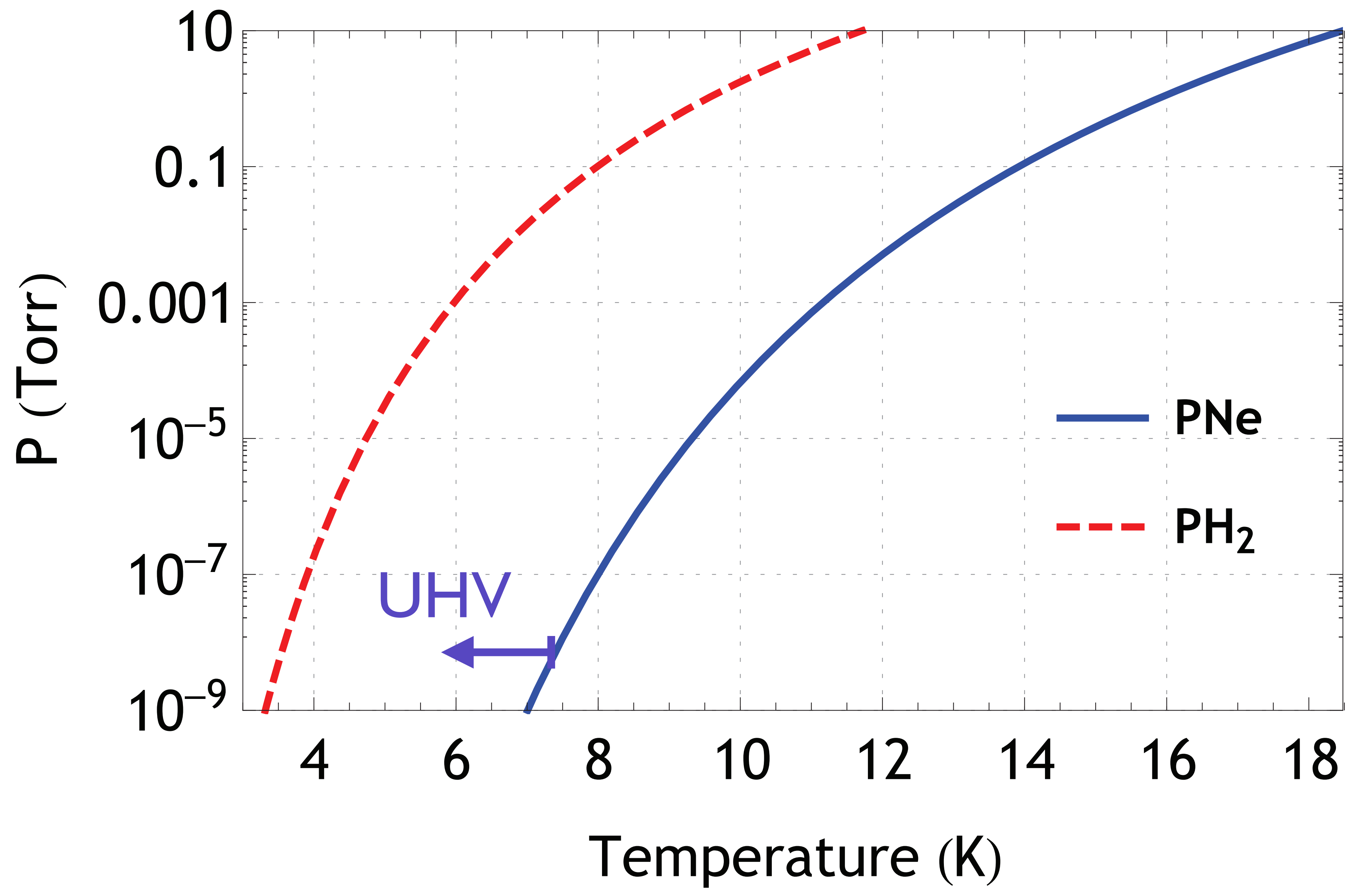

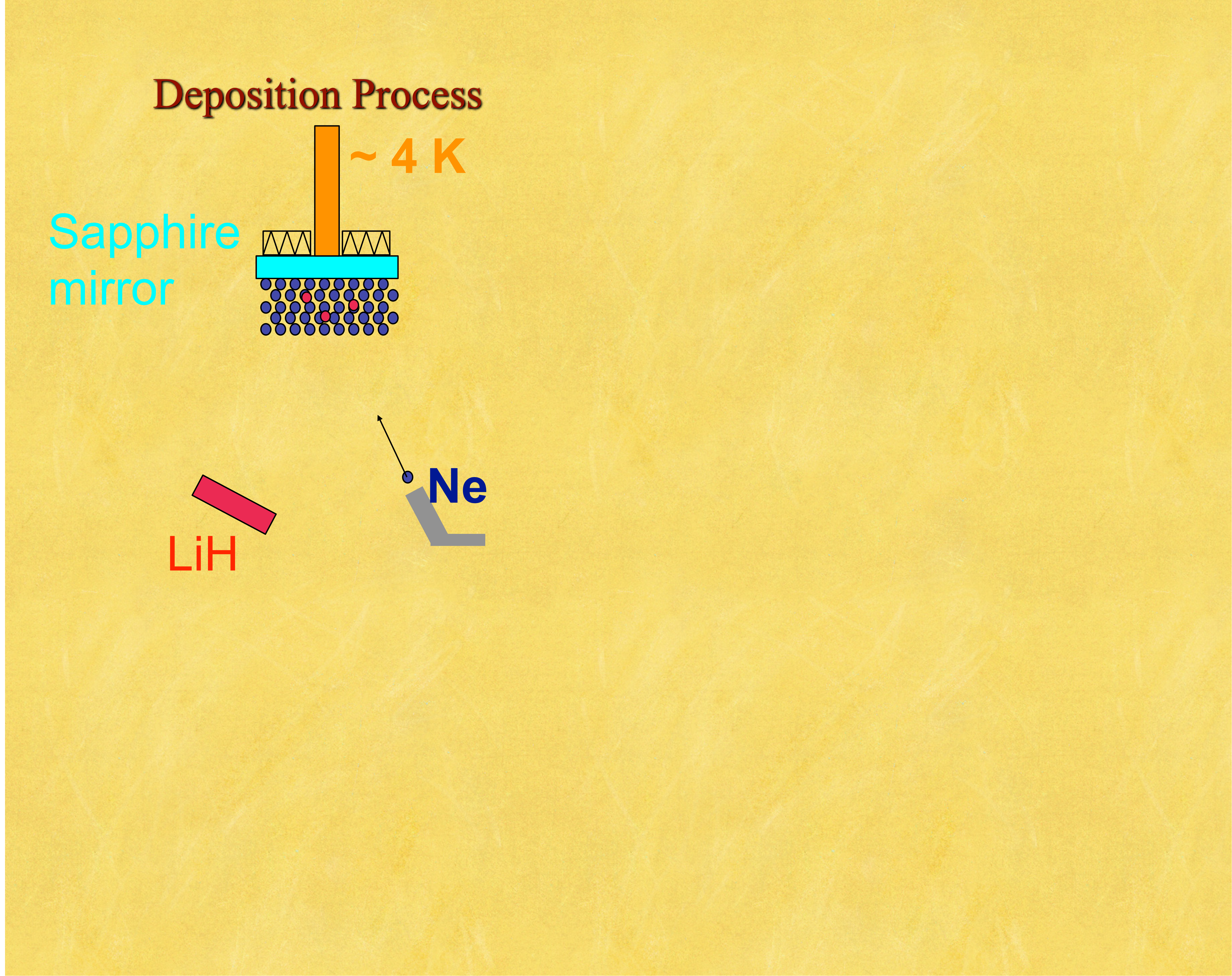

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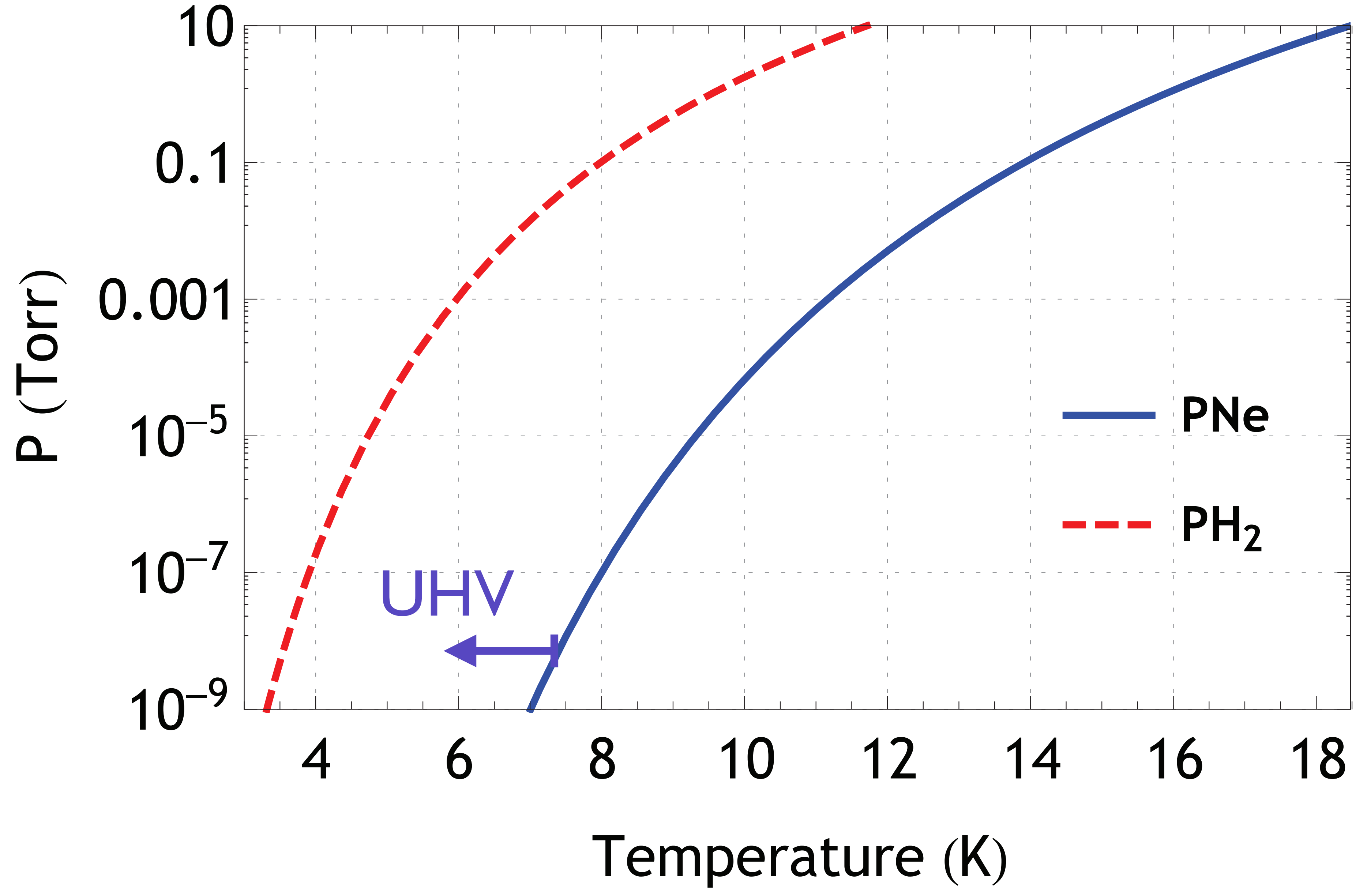

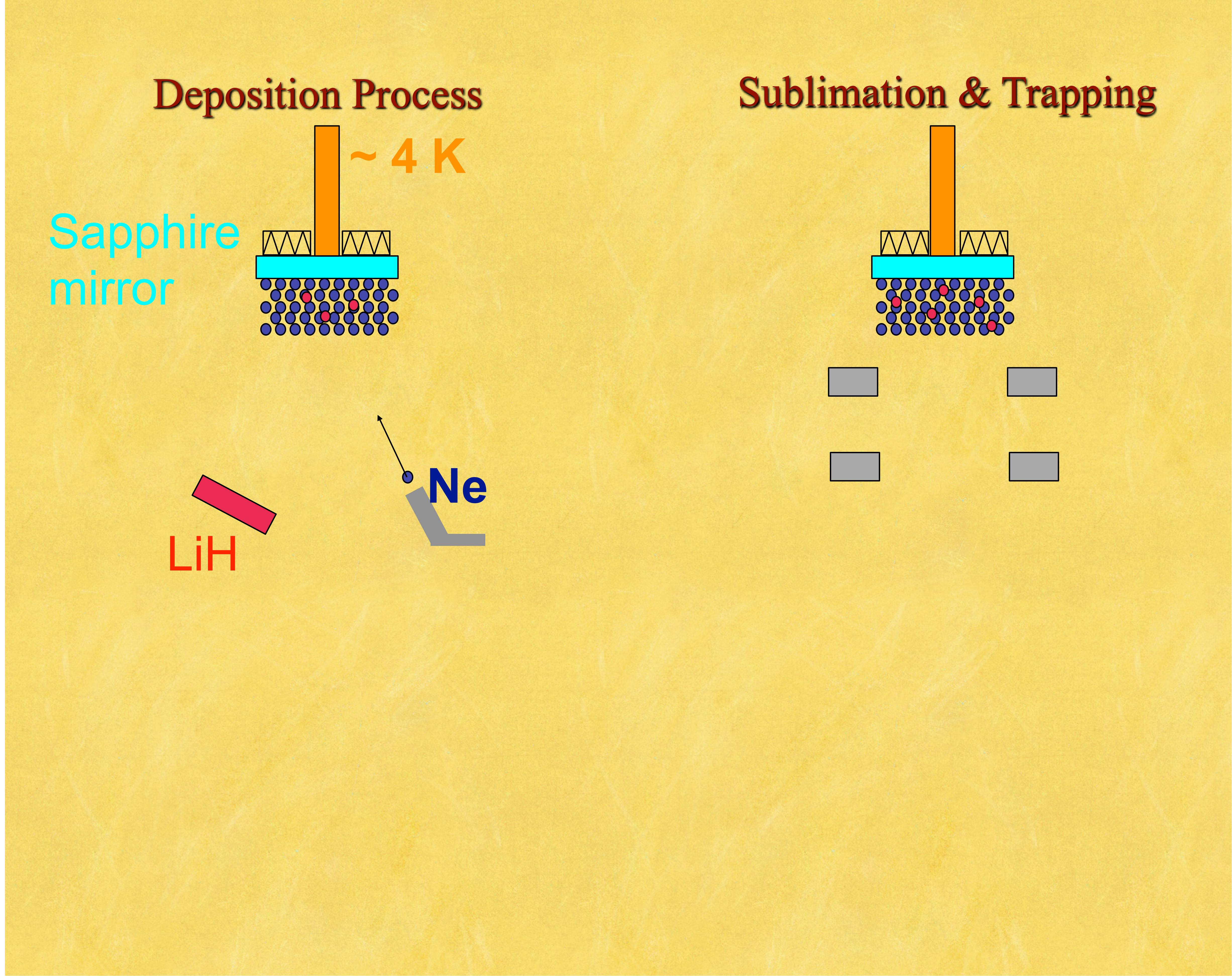

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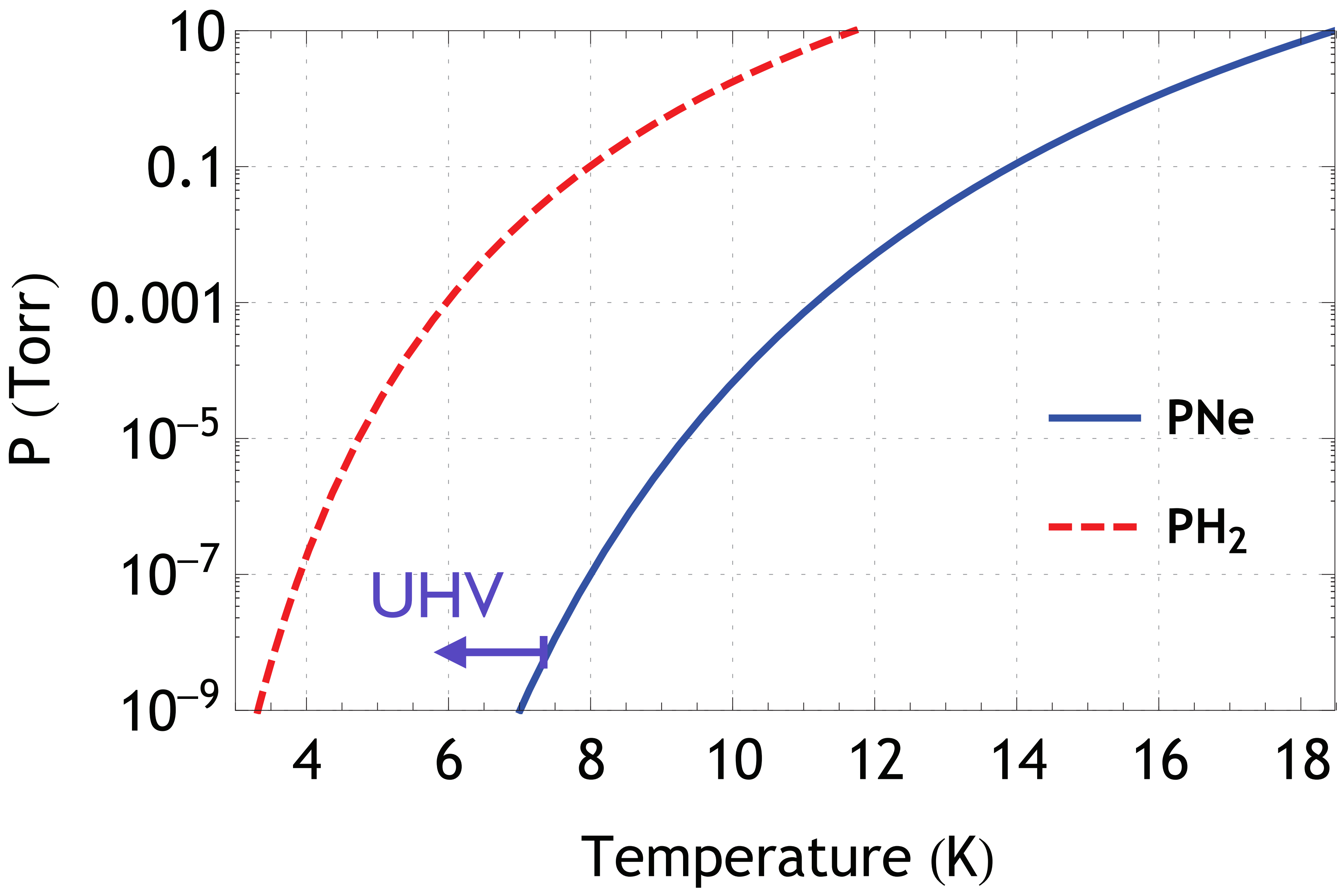
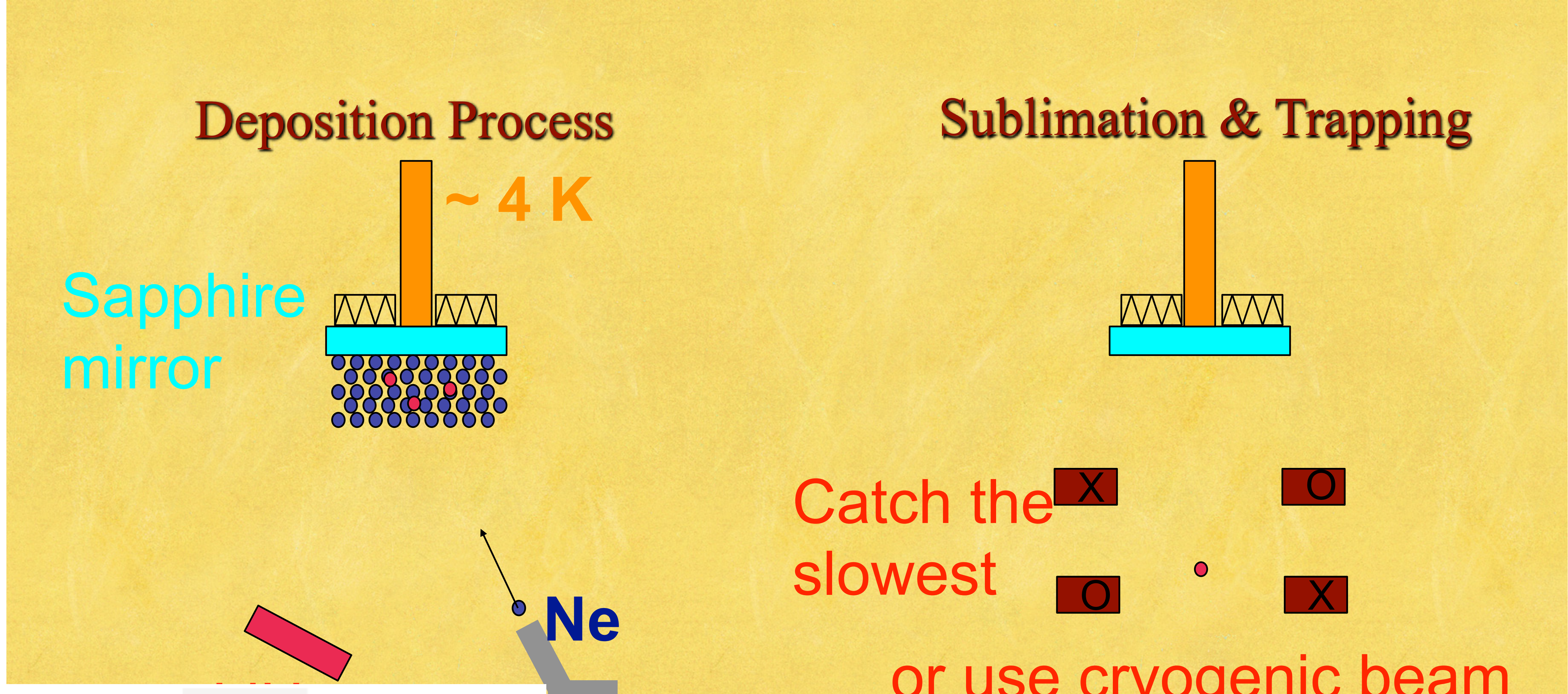




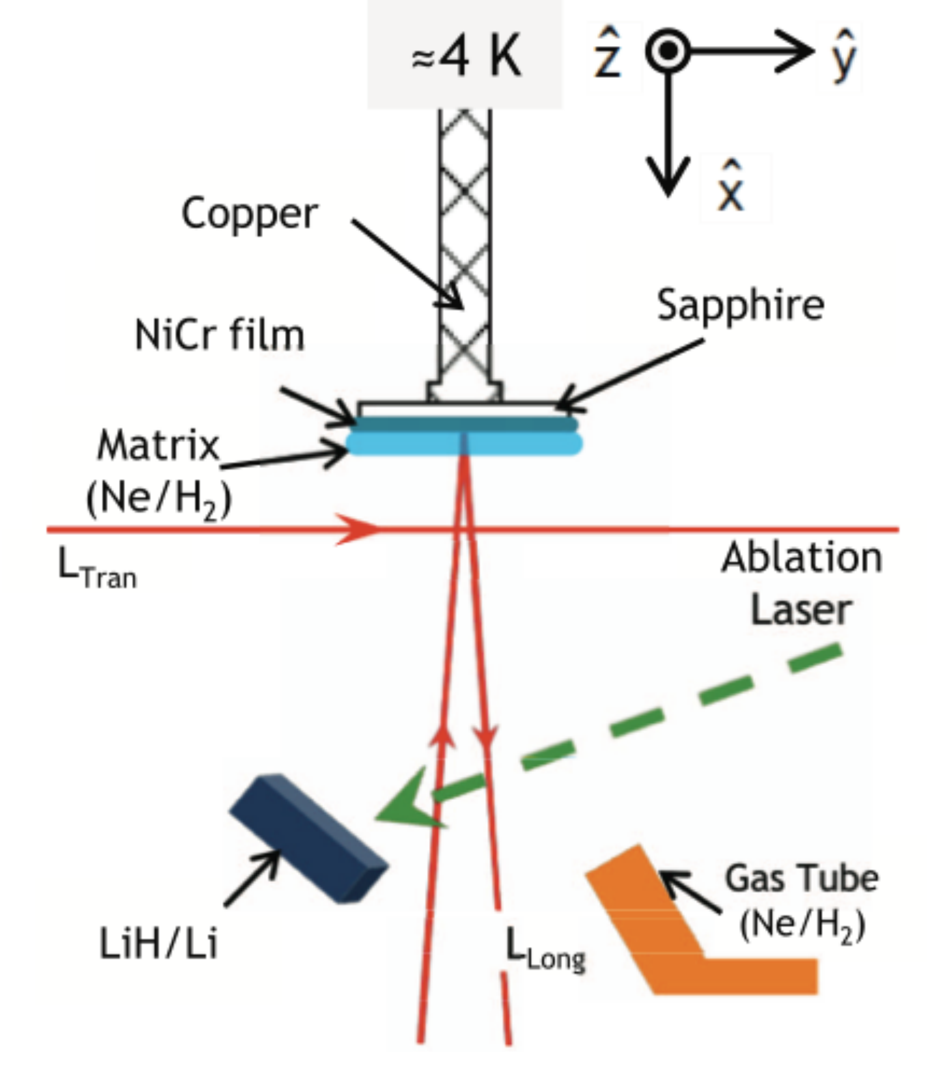
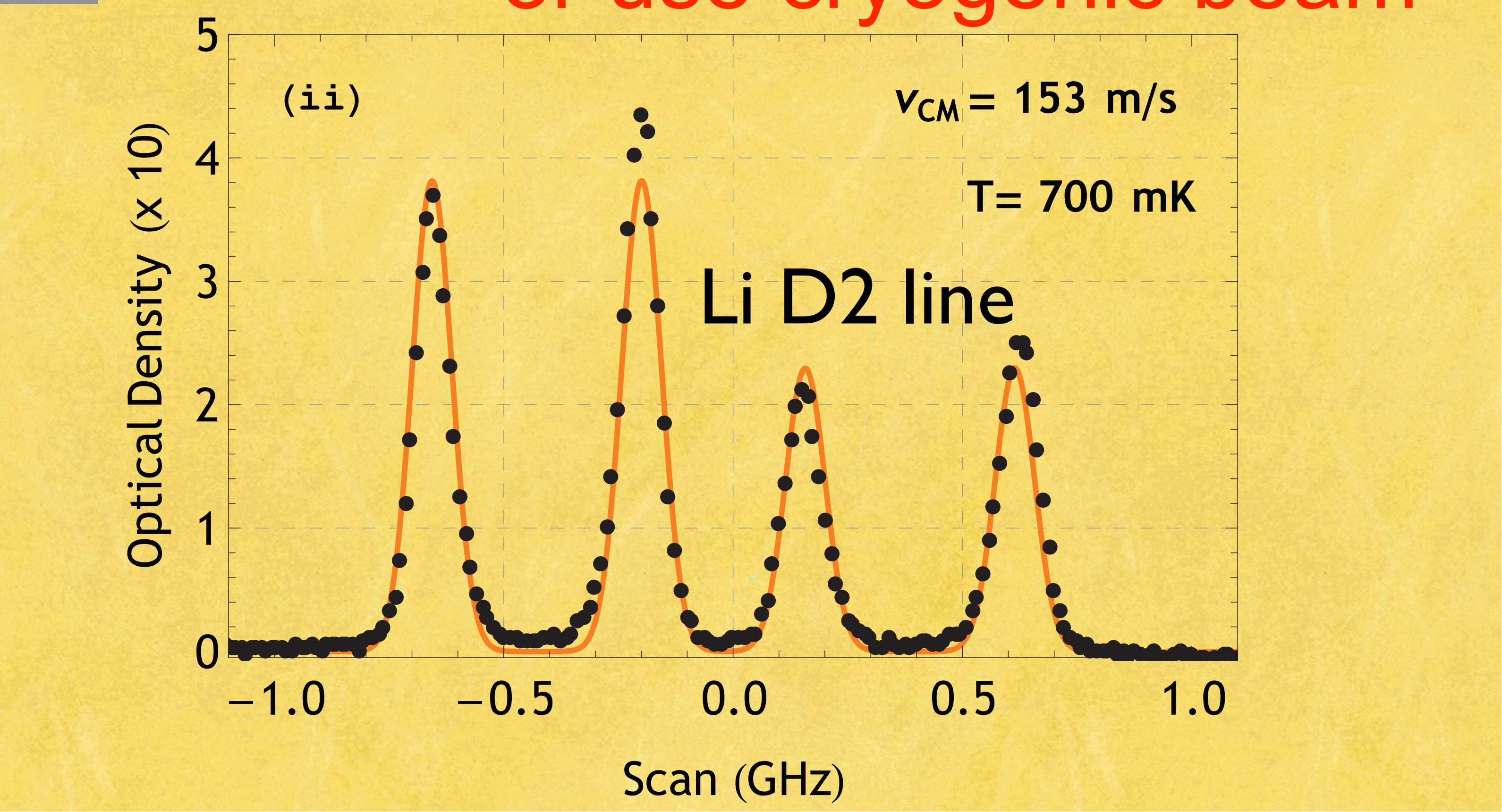
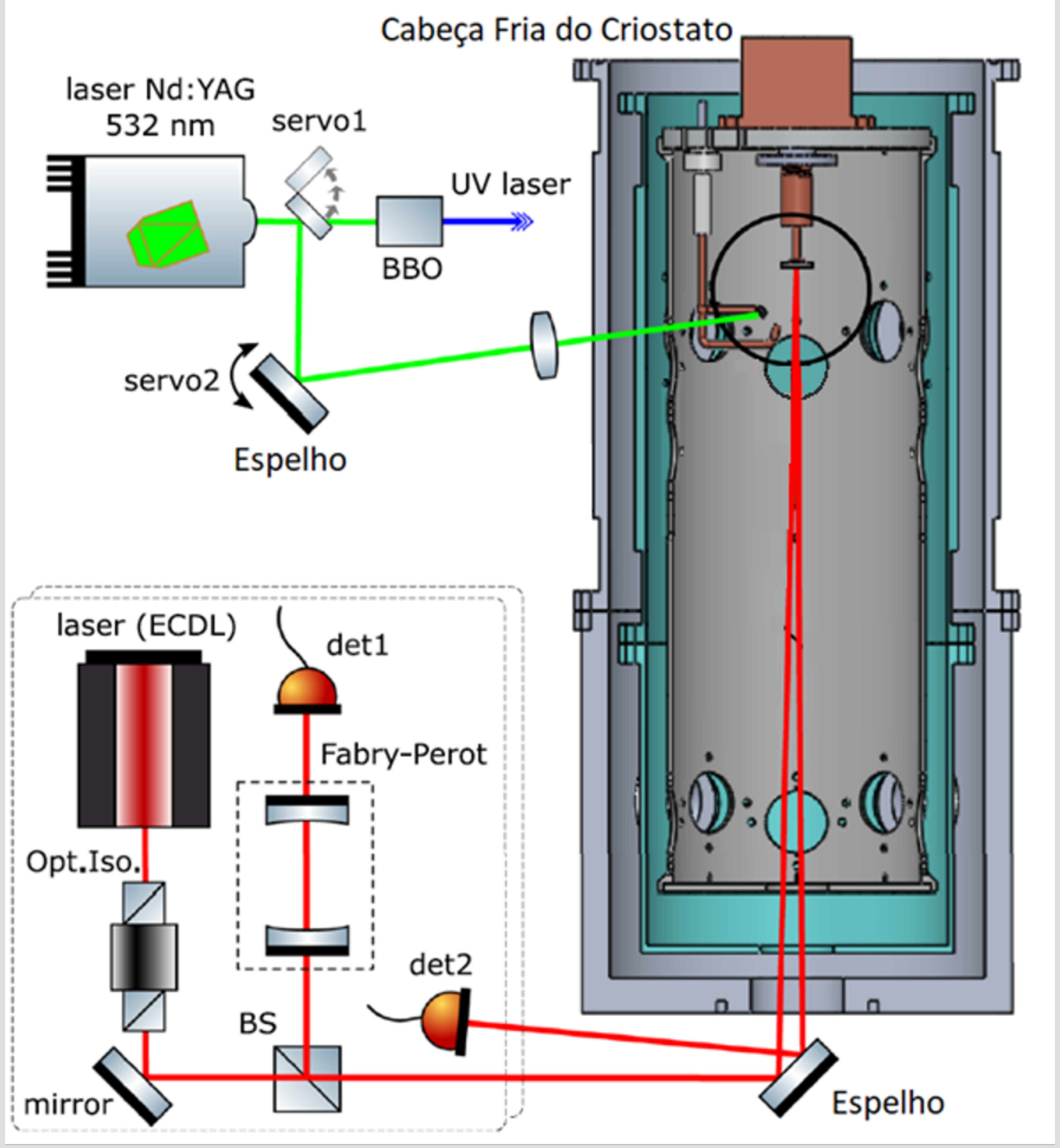
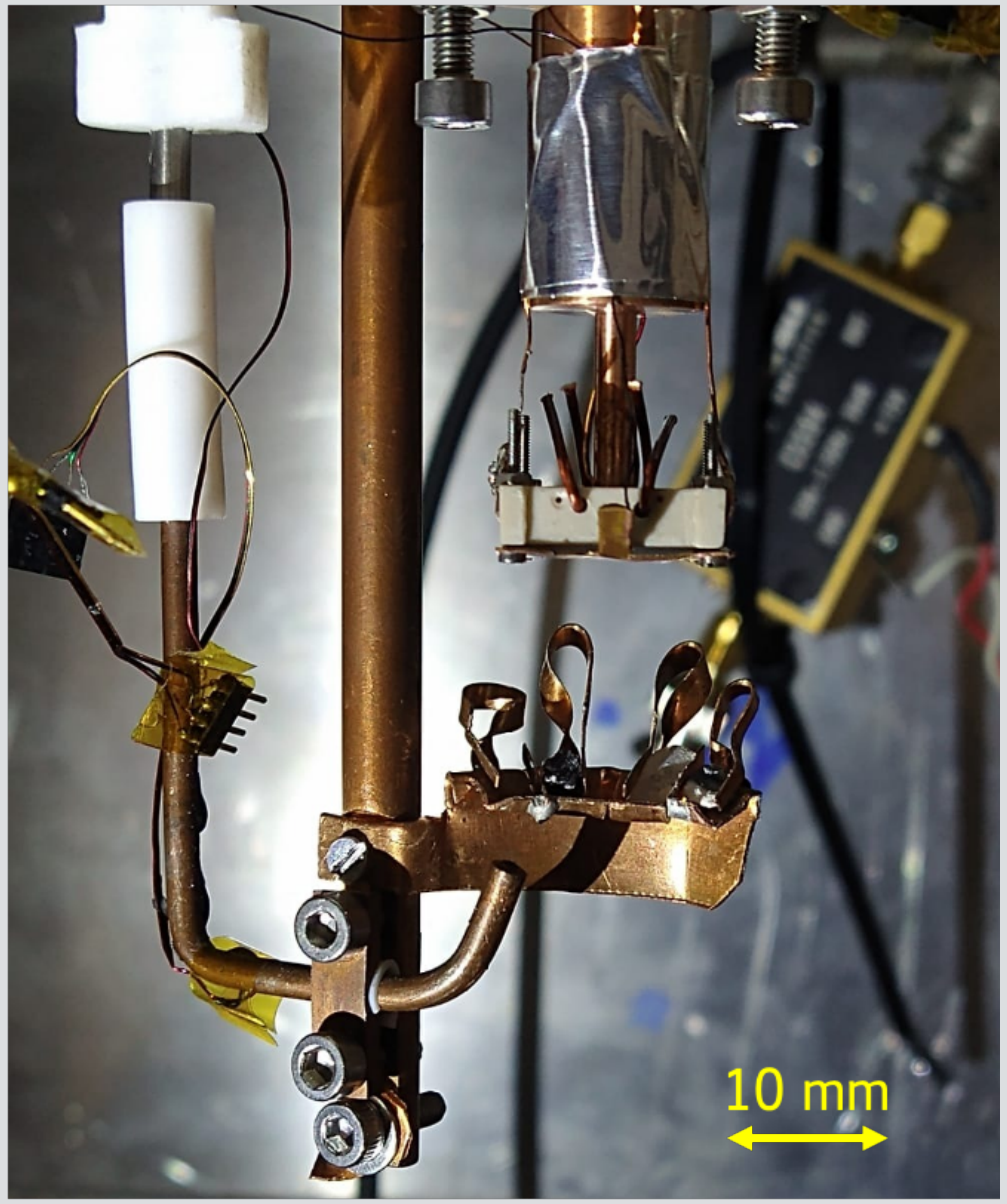


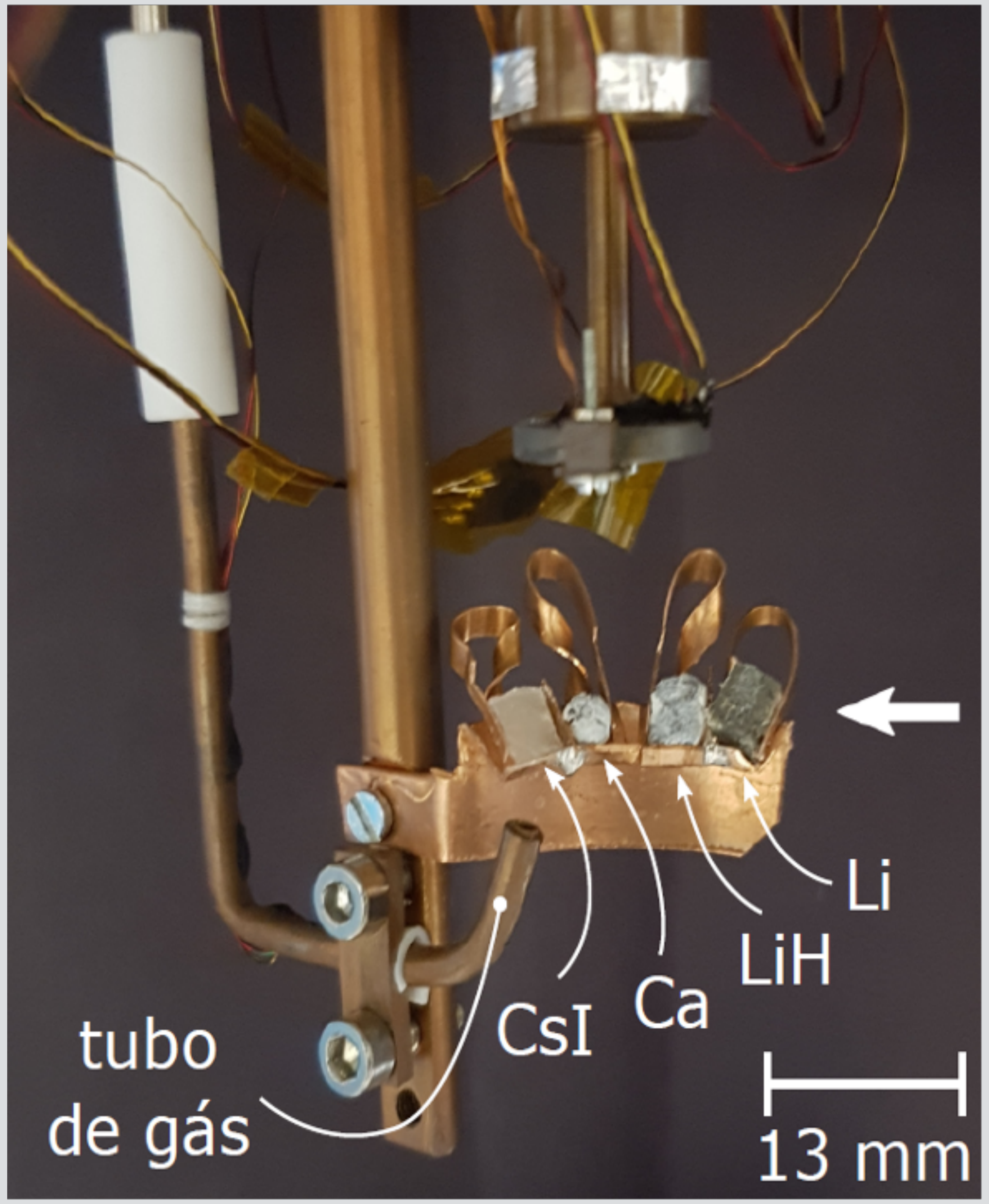
FIG. 1. Schematics of the experimental apparatus showing the sapphire sub-



Matrix Isolation Sublimation Apparatus







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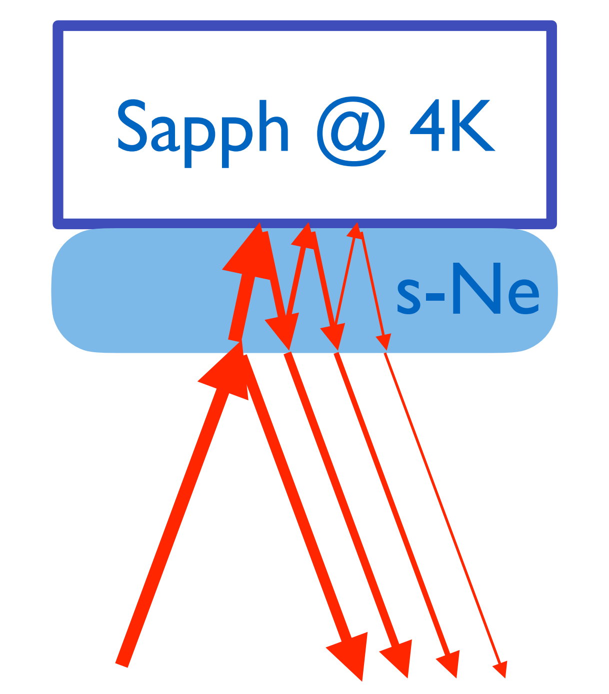
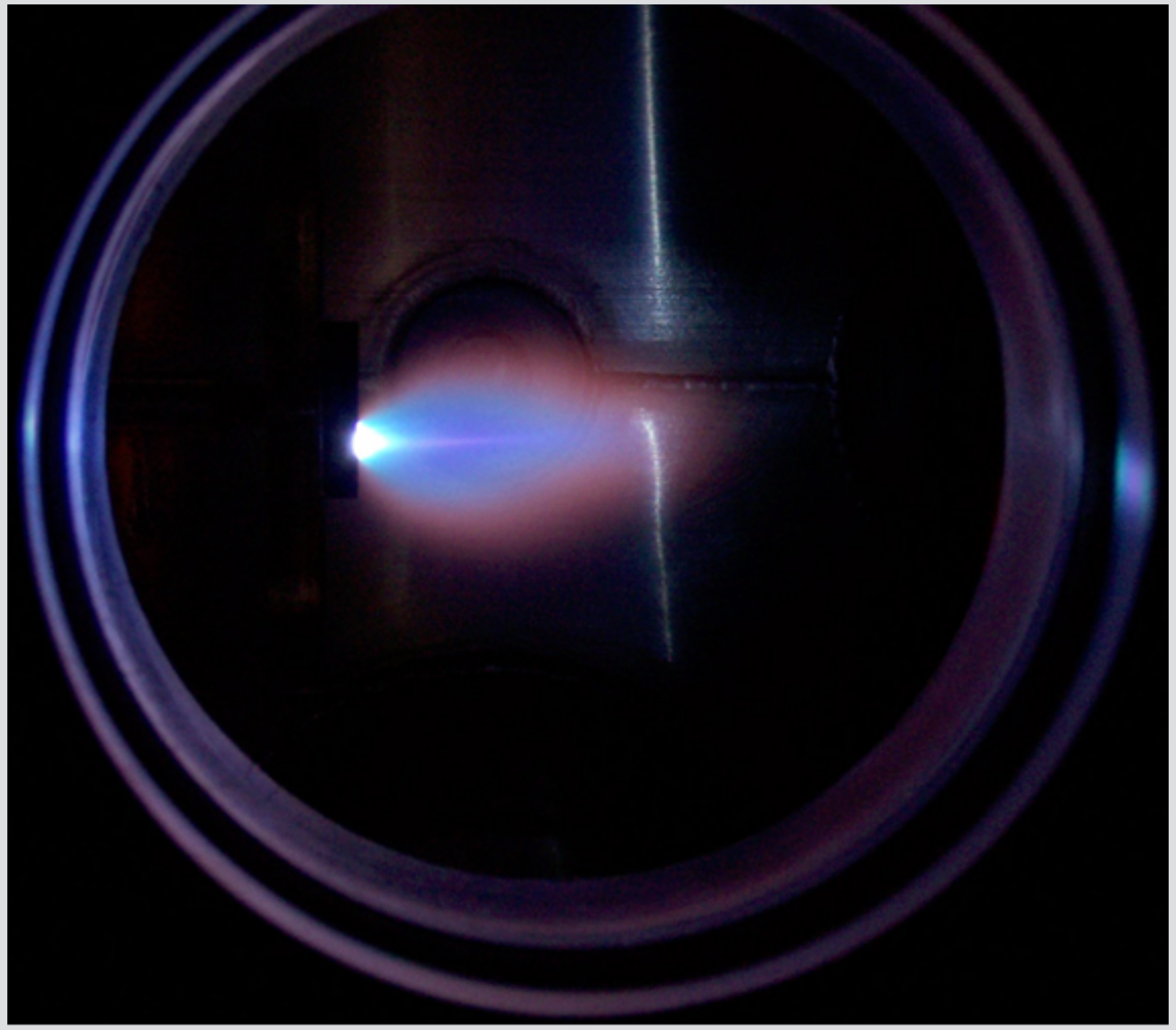
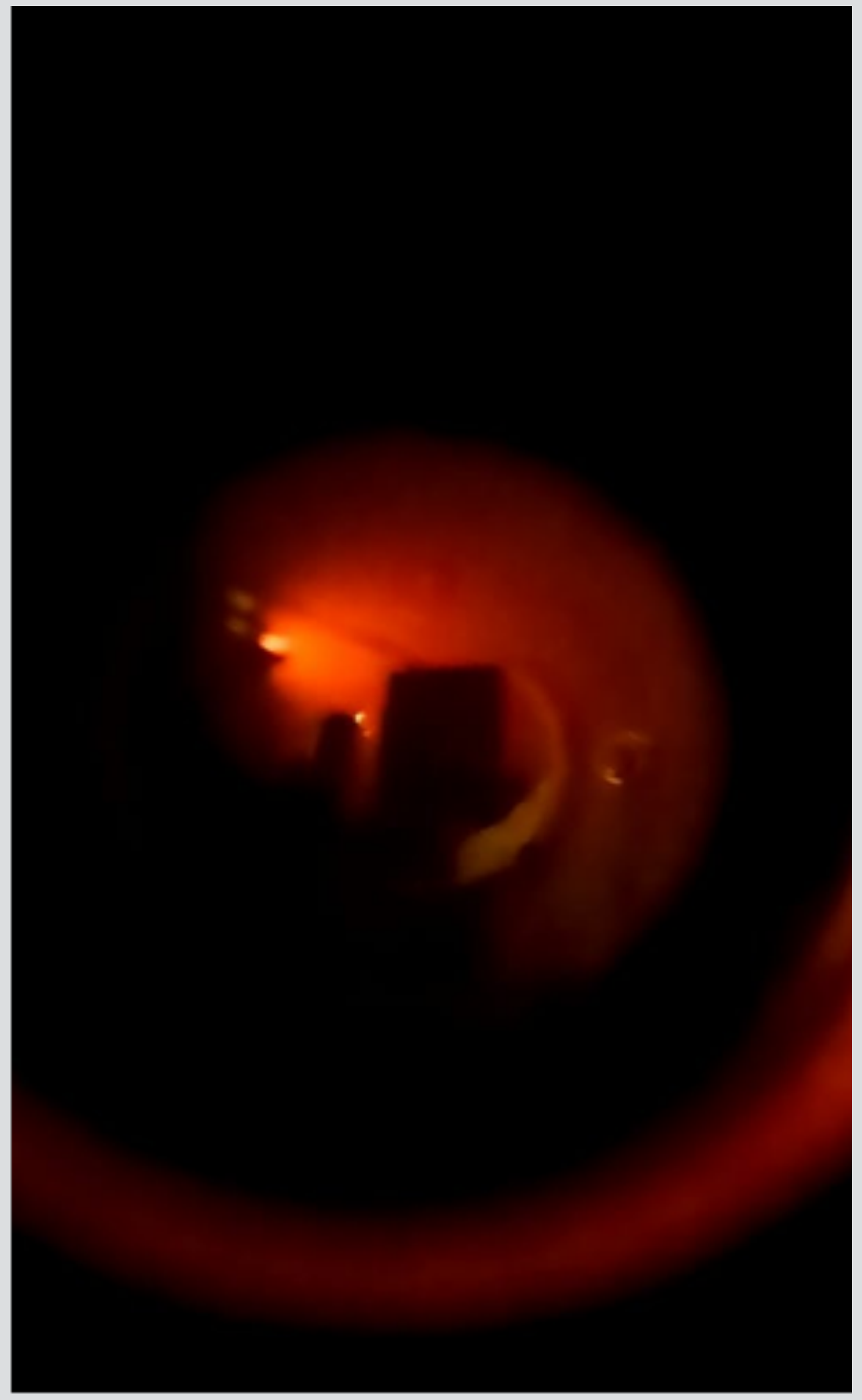
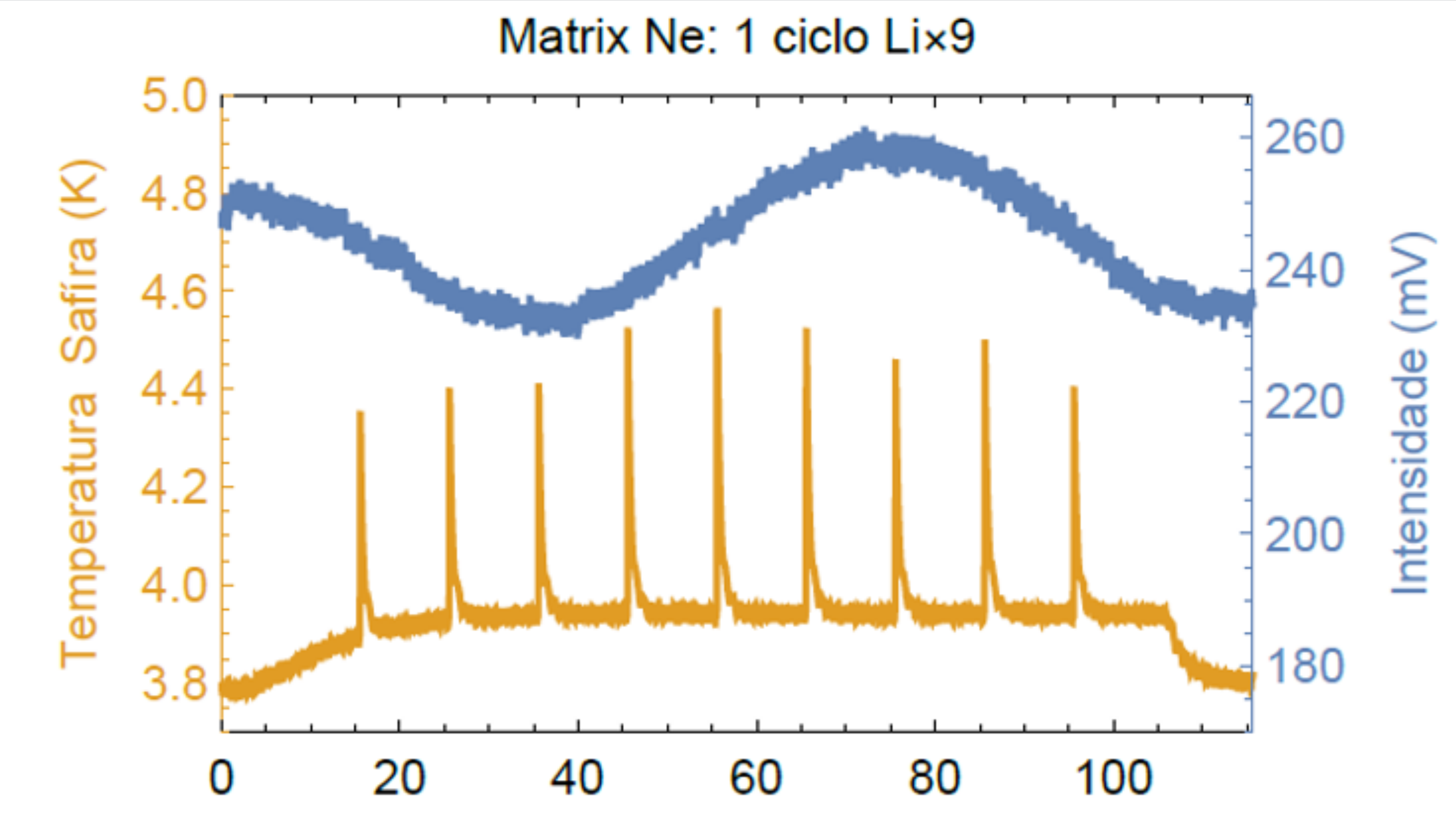


$$Fresnel : R_{NeVc} = (\frac{n_{Ne}-1}{n_{Ne}+1})^2, R_{NeSa} = (\frac{n_{Ne}-n_{Sa}}{n_{Ne}+n_{Sa}})^2$$

$$T = \frac{R_{NeVc} + R_{NeSa} + 2\sqrt{R_{NeVc}R_{NeSa}}\cos(2\pi n_{Ne} l_{Ne} 2/\lambda + \phi)}{1 + R_{NeVc}R_{NeSa} + 2\sqrt{R_{NeVc}R_{NeSa}}\cos(2\pi n_{Ne} l_{Ne} 2/\lambda + \phi)}$$

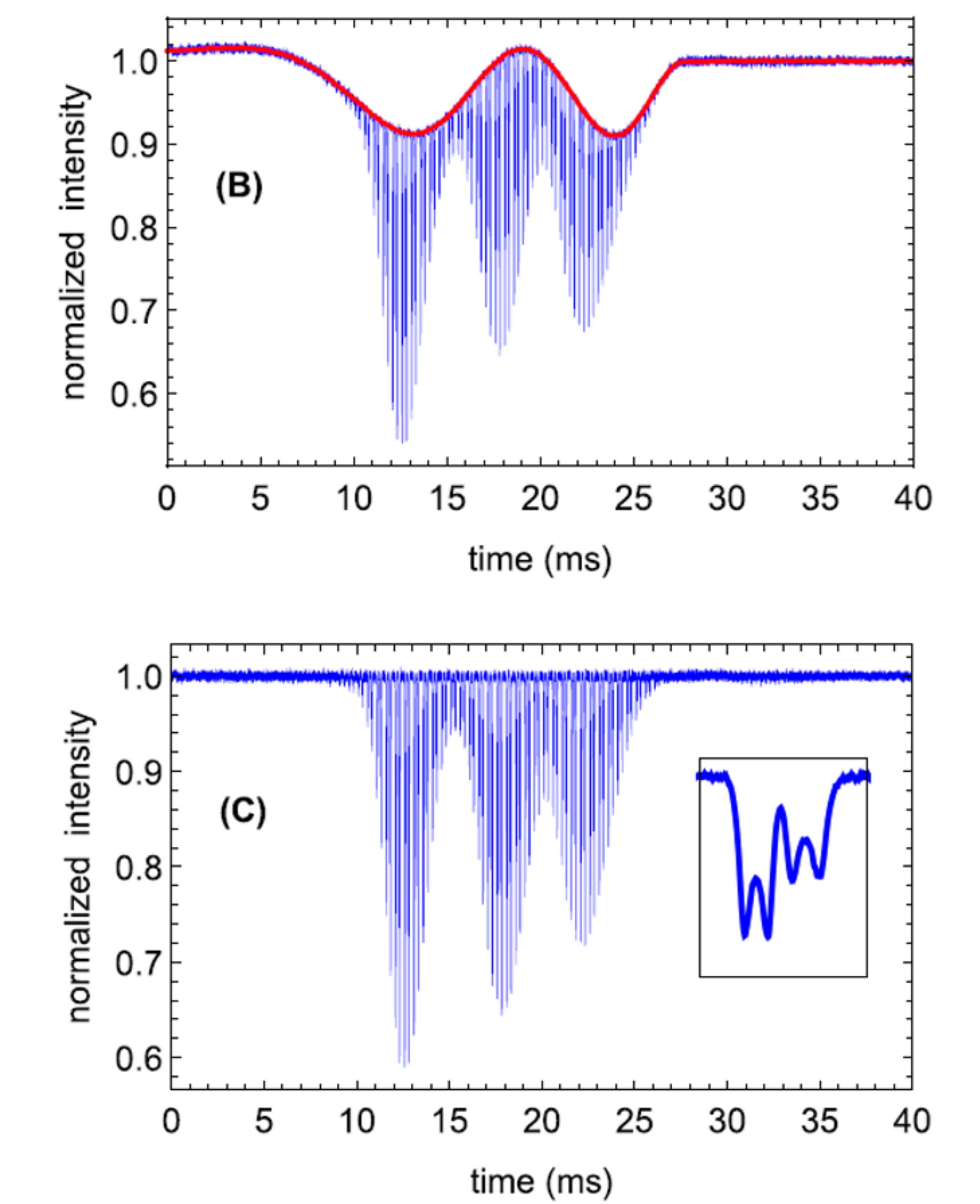


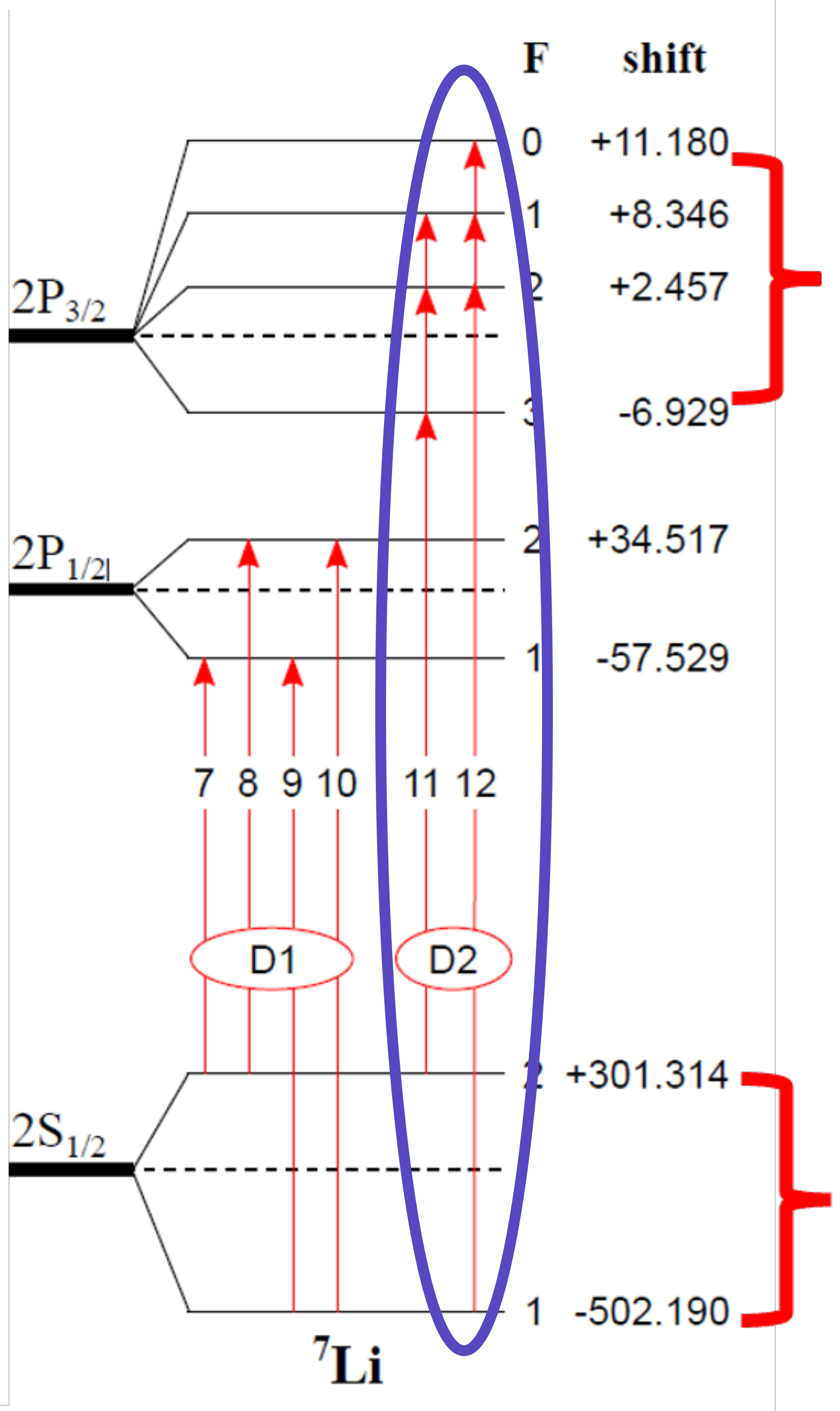




Spectra of Li-7 (D2 line)

3 spaced ablation pulses



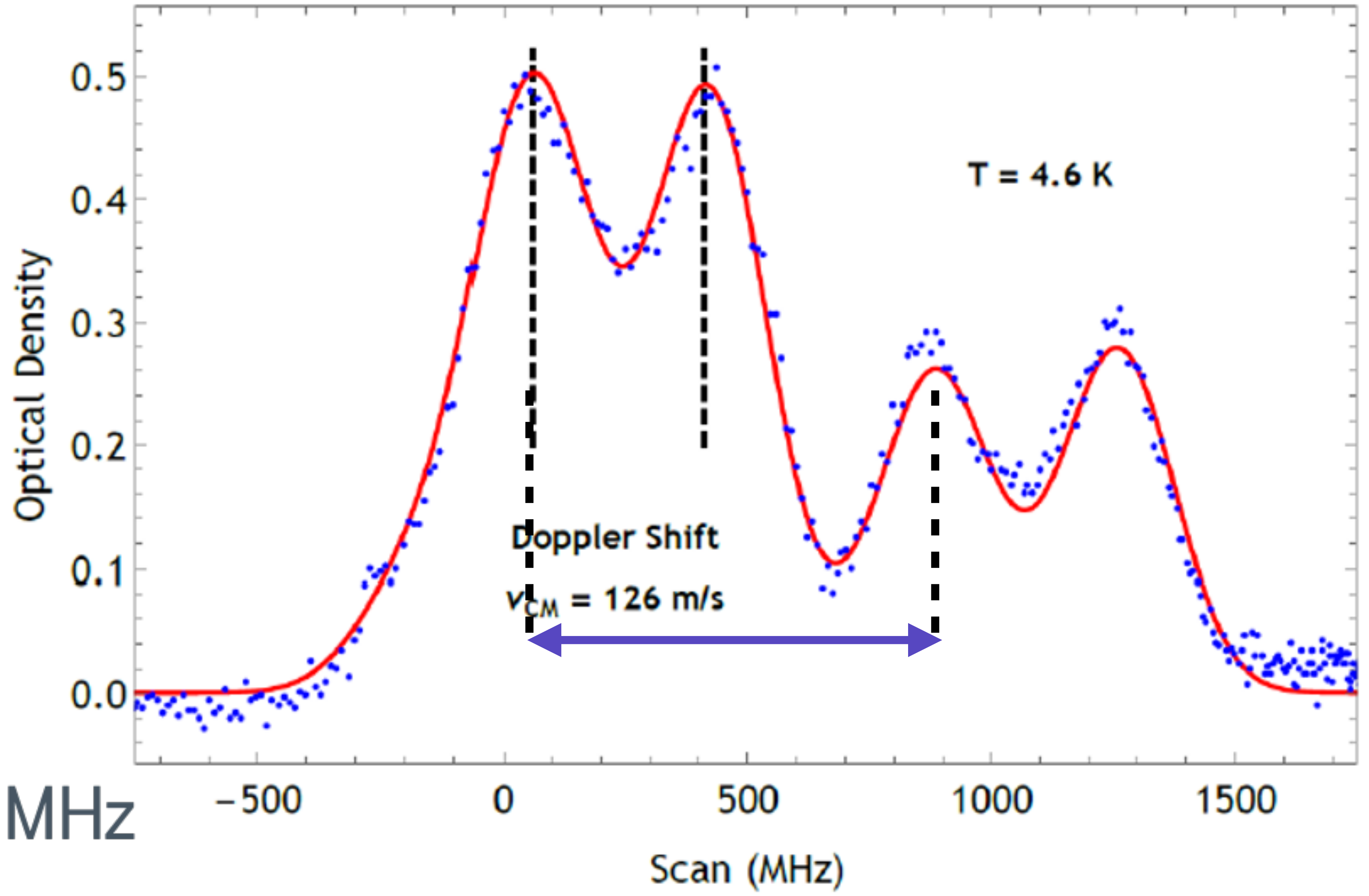


unresolved 17 MHz

803.5 MHz

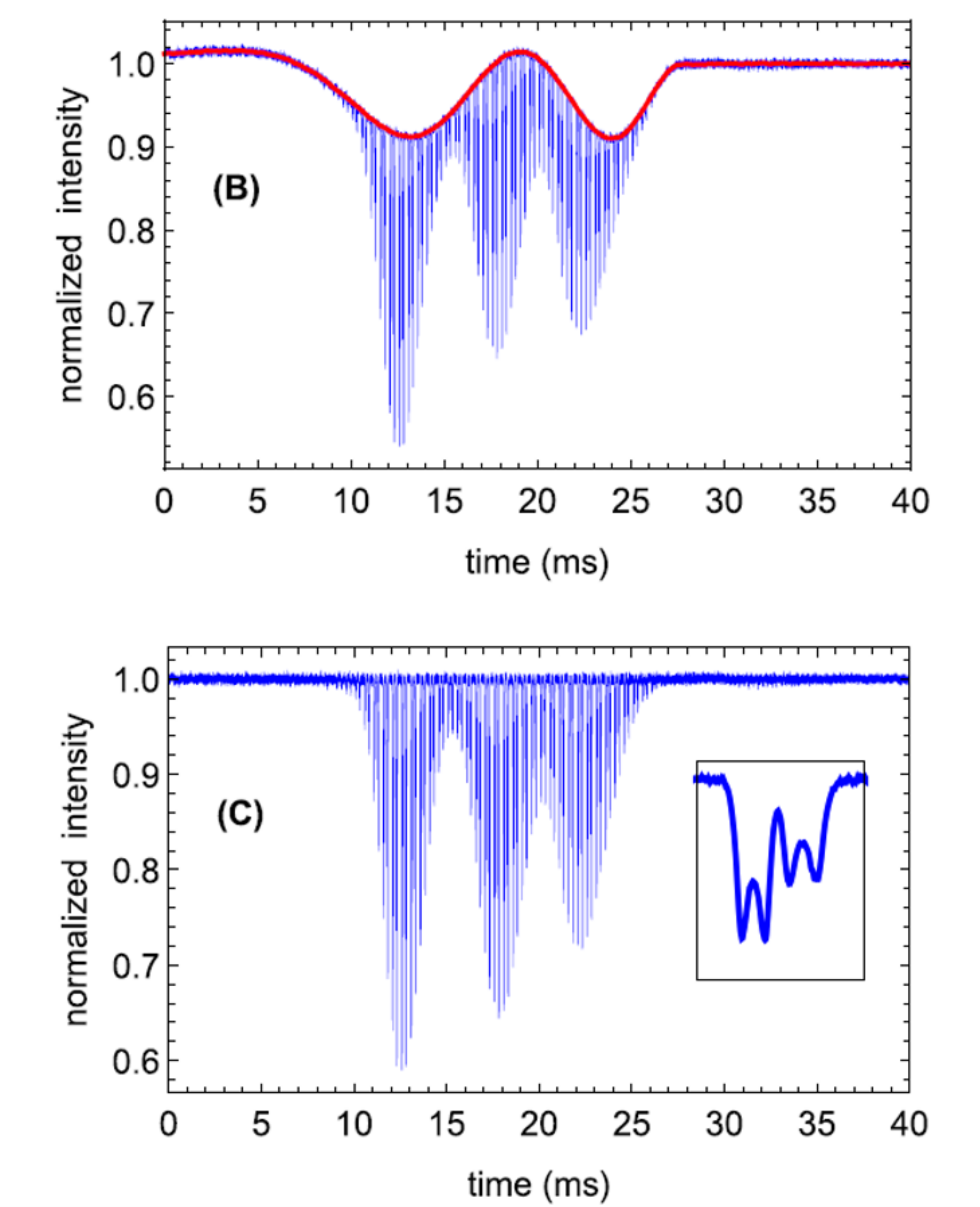
Velocidade → $V = \frac{\lambda \cdot \delta\omega}{2}$

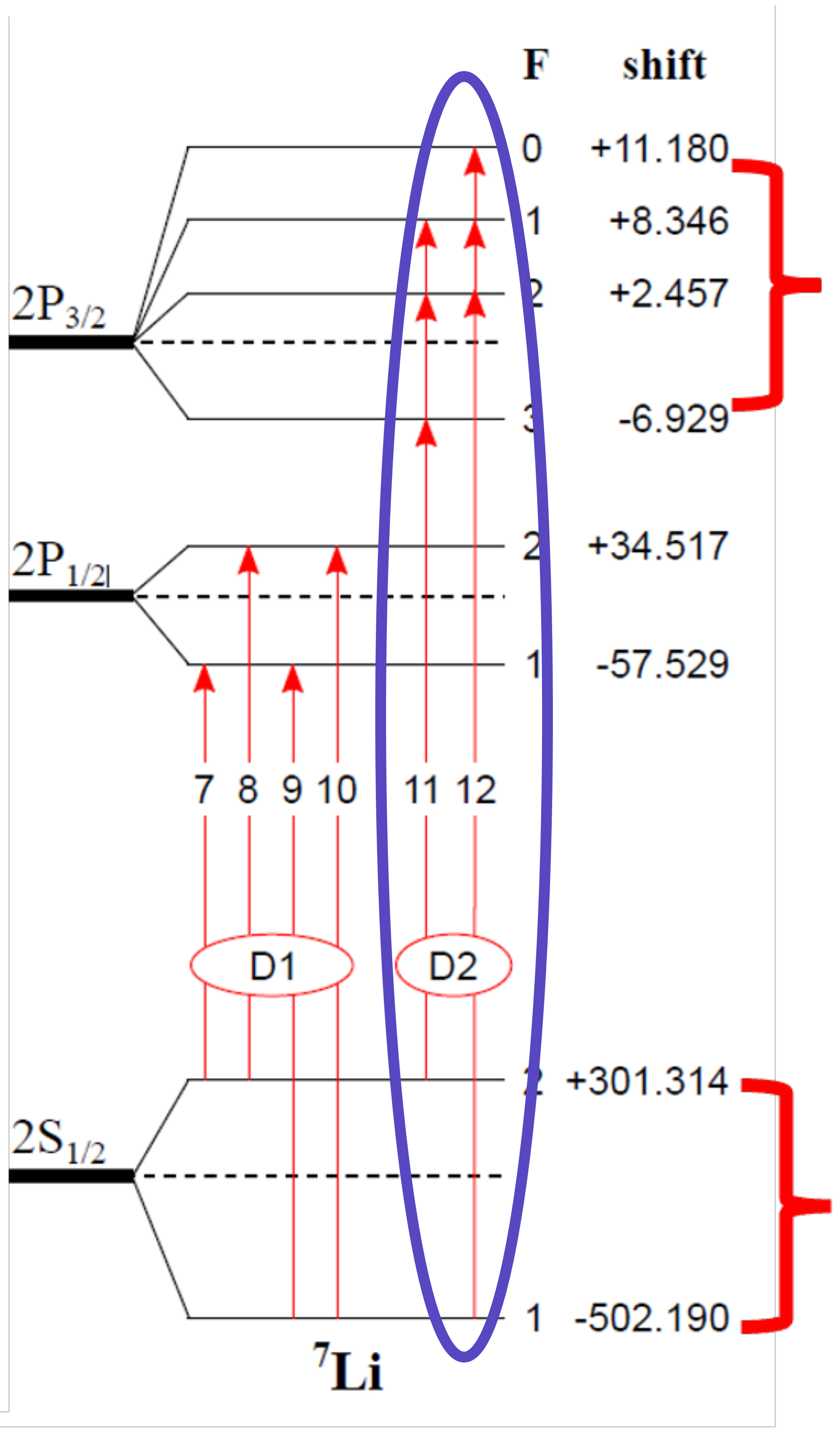
Temperatura → $T = \frac{m\,(\Delta\nu \cdot \lambda)^2}{k_B}$



Spectra of Li-7 (D2 line)

3 spaced ablation pulses





unresolved 17 MHz

803.5 MHz

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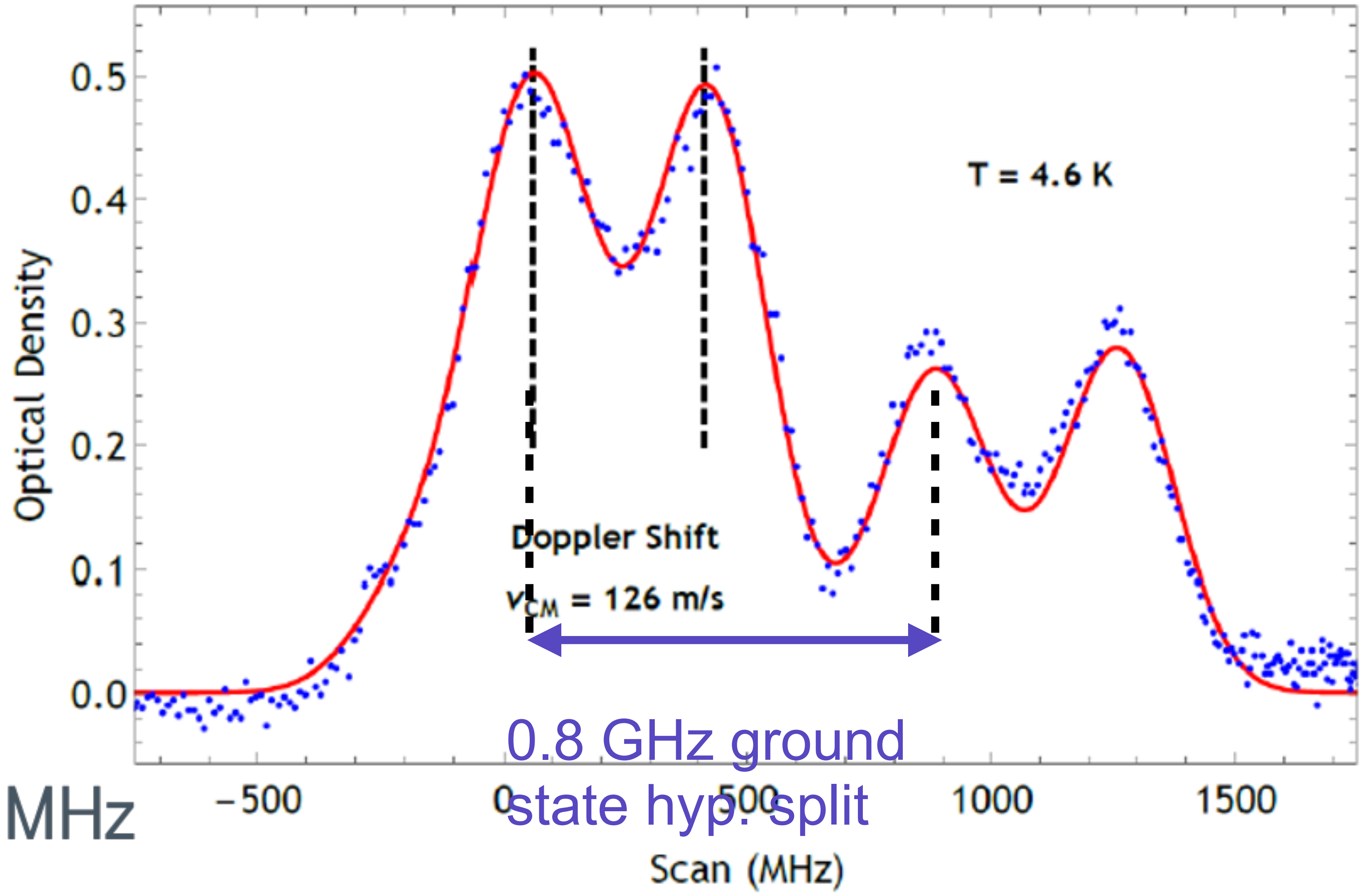
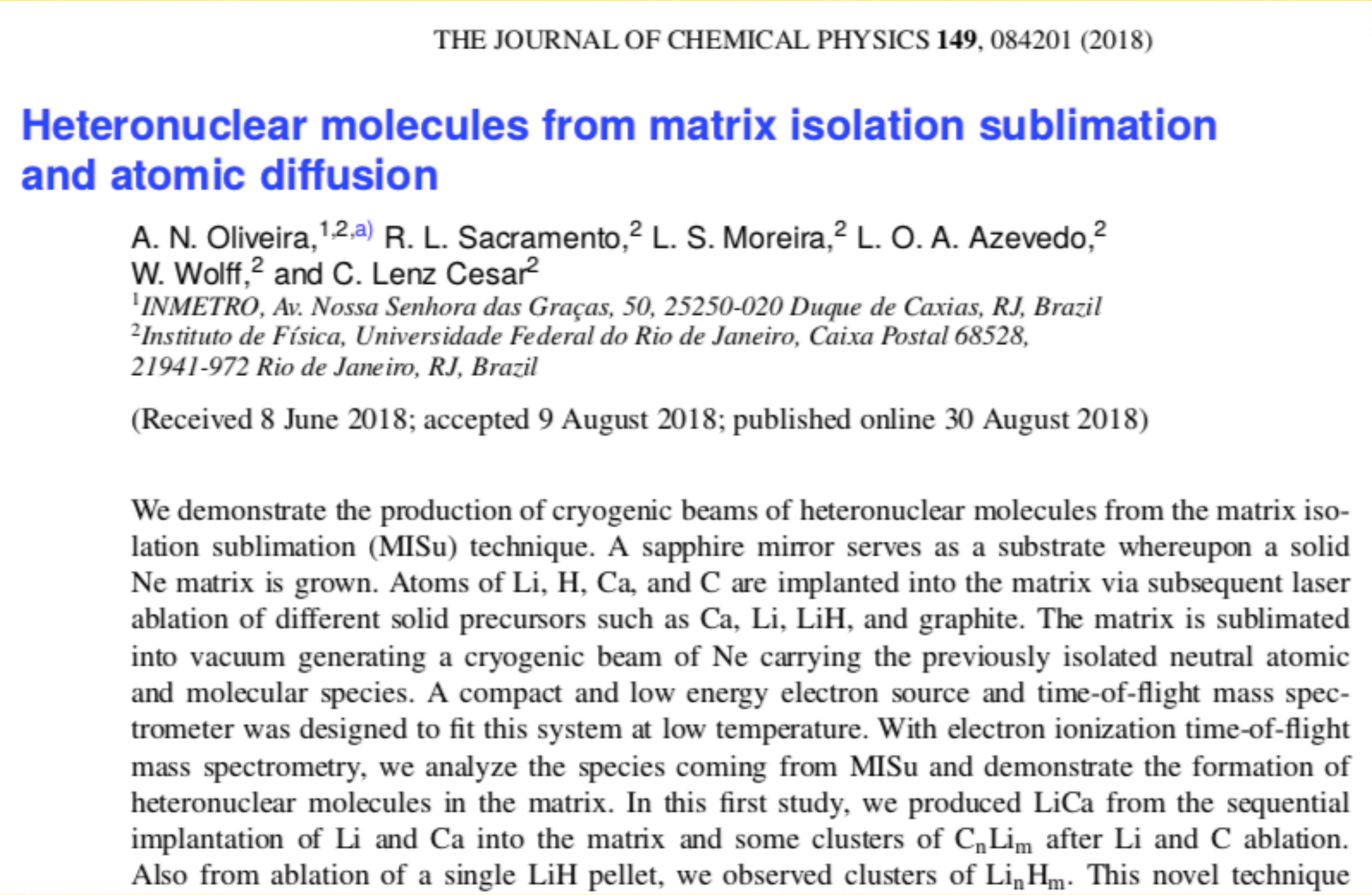


Matrix Isolation Sublimation and Molecular Formation

Heteronuclear Molecules:
(magnetic dipole moment/electric dipole moment)
Formation in the matrix: possibilities for exotic and weakly bound



THE JOURNAL OF CHEMICAL PHYSICS **149**, 084201 (2018)

Heteronuclear molecules from matrix isolation sublimation and atomic diffusion

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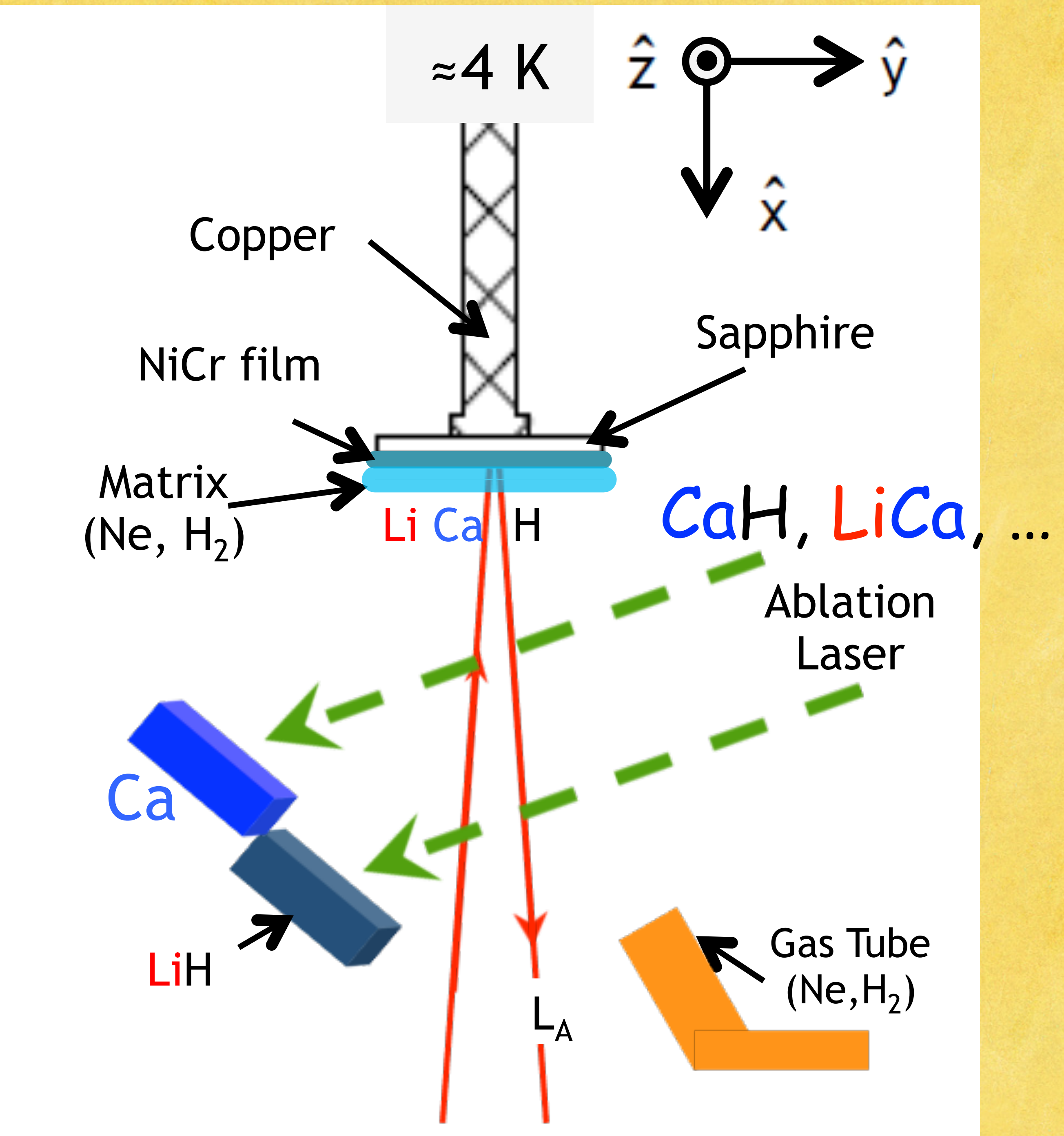
We demonstrate the production of cryogenic beams of heteronuclear molecules from the matrix isolation sublimation (MISu) technique. A sapphire mirror serves as a substrate whereupon a solid Ne matrix is grown. Atoms of Li, H, Ca, and C are implanted into the matrix via subsequent laser ablation of different solid precursors such as Ca, Li, LiH, and graphite. The matrix is sublimated into vacuum generating a cryogenic beam of Ne carrying the previously isolated neutral atomic and molecular species. A compact and low energy electron source and time-of-flight mass spectrometer was designed to fit this system at low temperature. With electron ionization time-of-flight mass spectrometry, we analyze the species coming from MISu and demonstrate the formation of heteronuclear molecules in the matrix. In this first study, we produced LiCa from the sequential implantation of Li and Ca into the matrix and some clusters of C_nLi_m after Li and C ablation. Also from ablation of a single LiH pellet, we observed clusters of Li_nH_m. This novel technique



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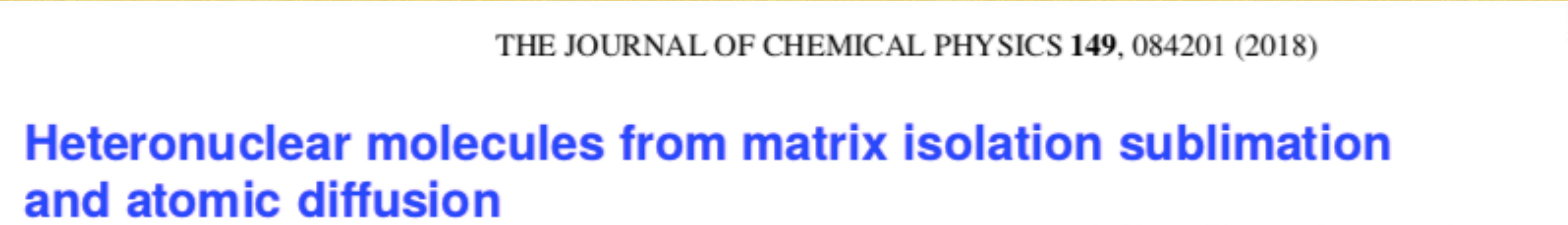
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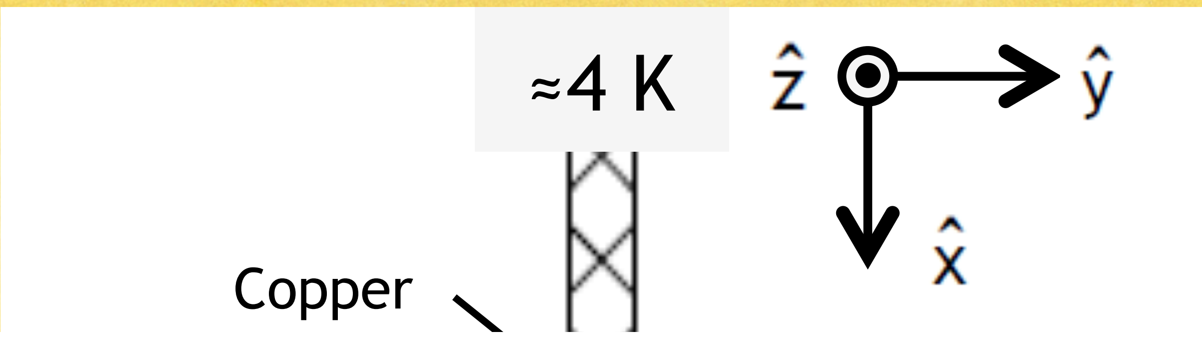
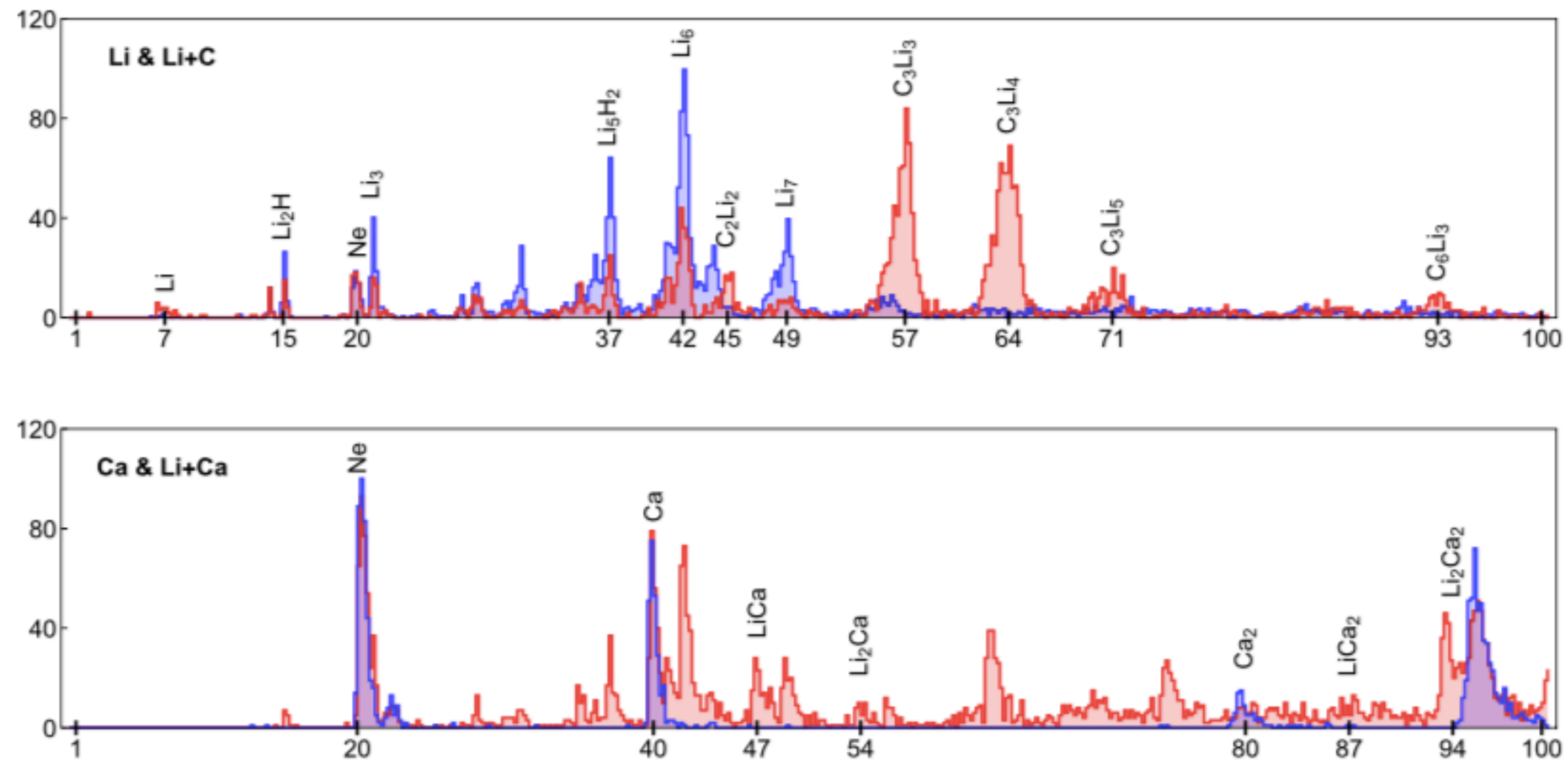
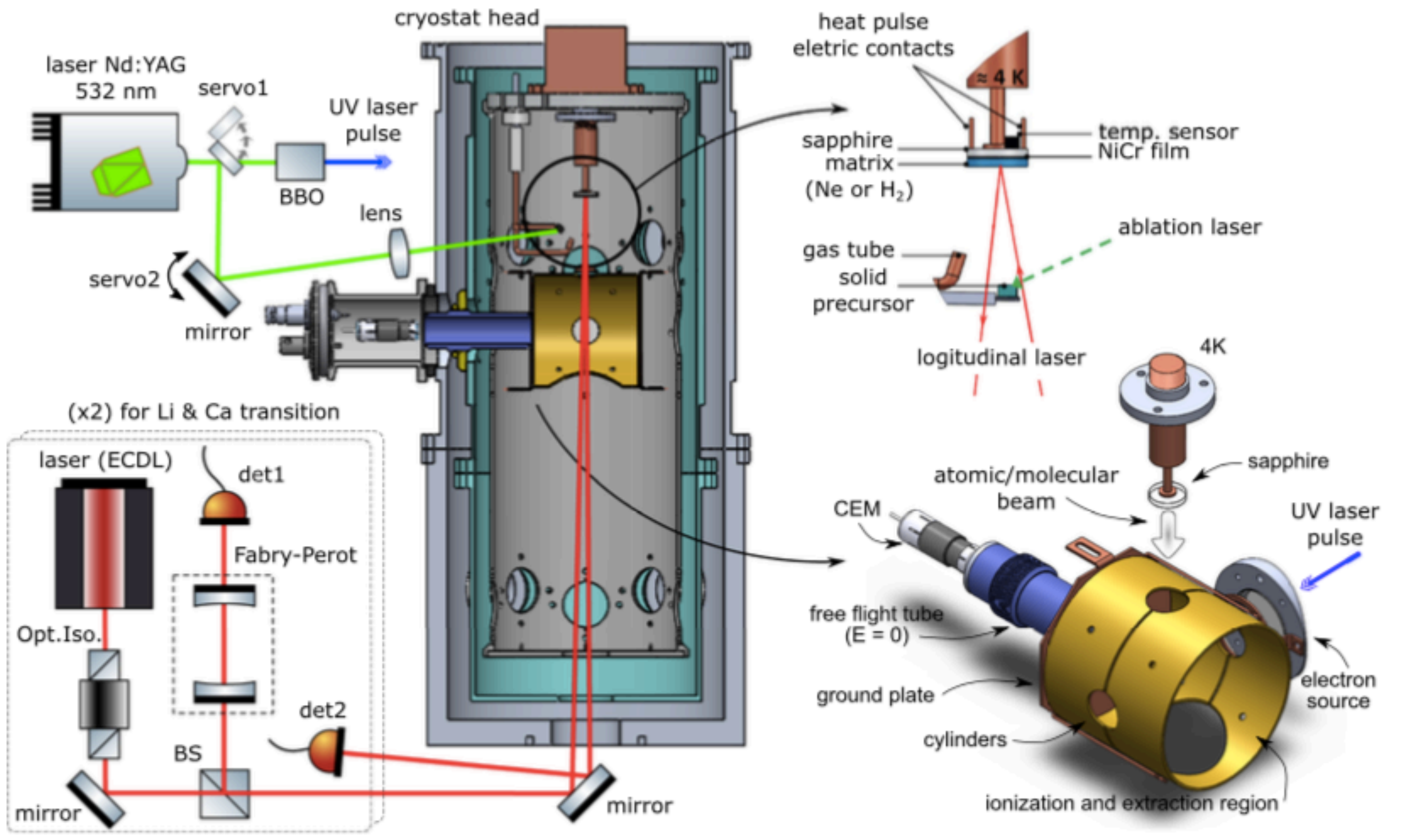


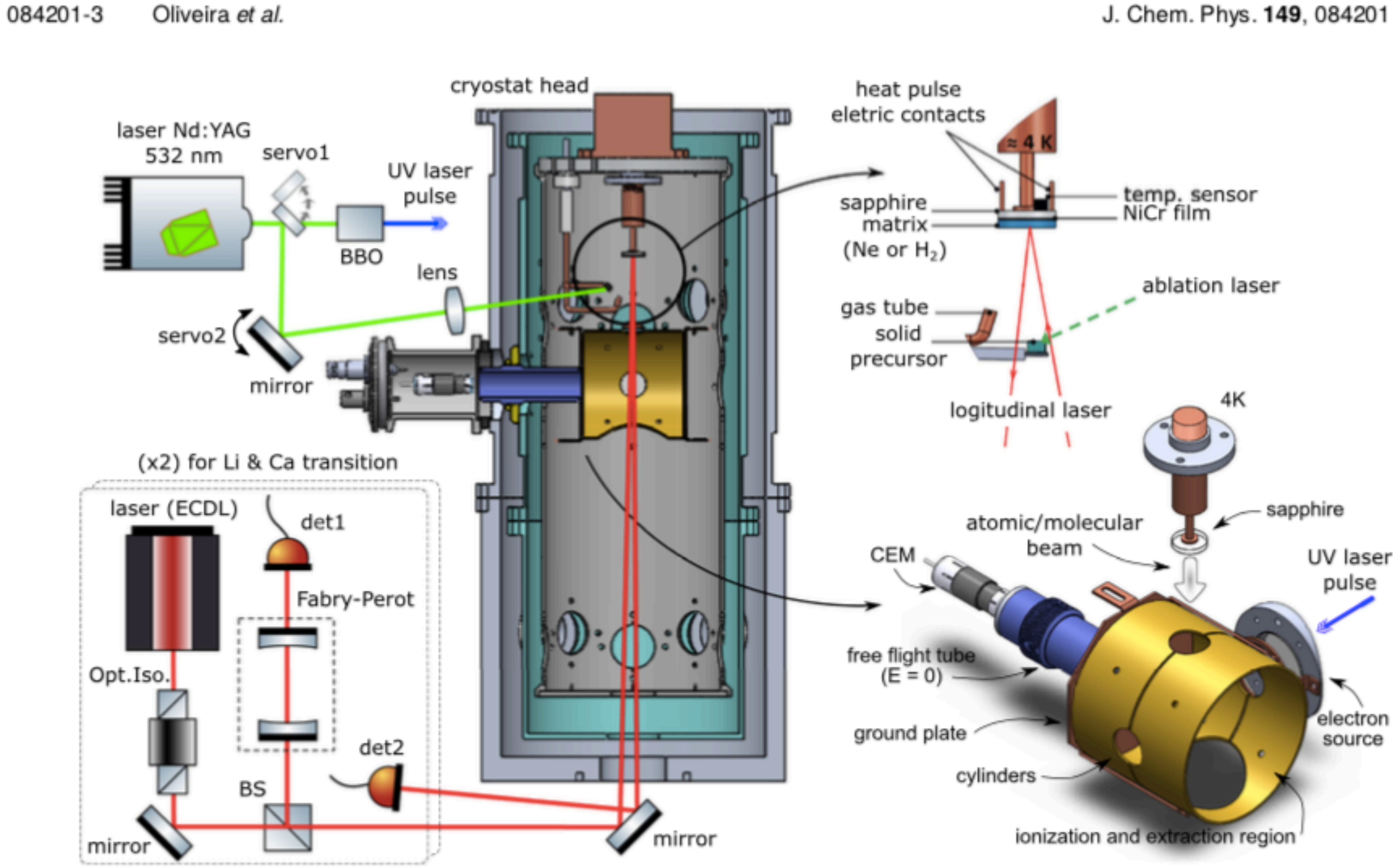
084201-6 Oliveira *et al.* J. Chem. Phys. **149**, 084201 (2018)



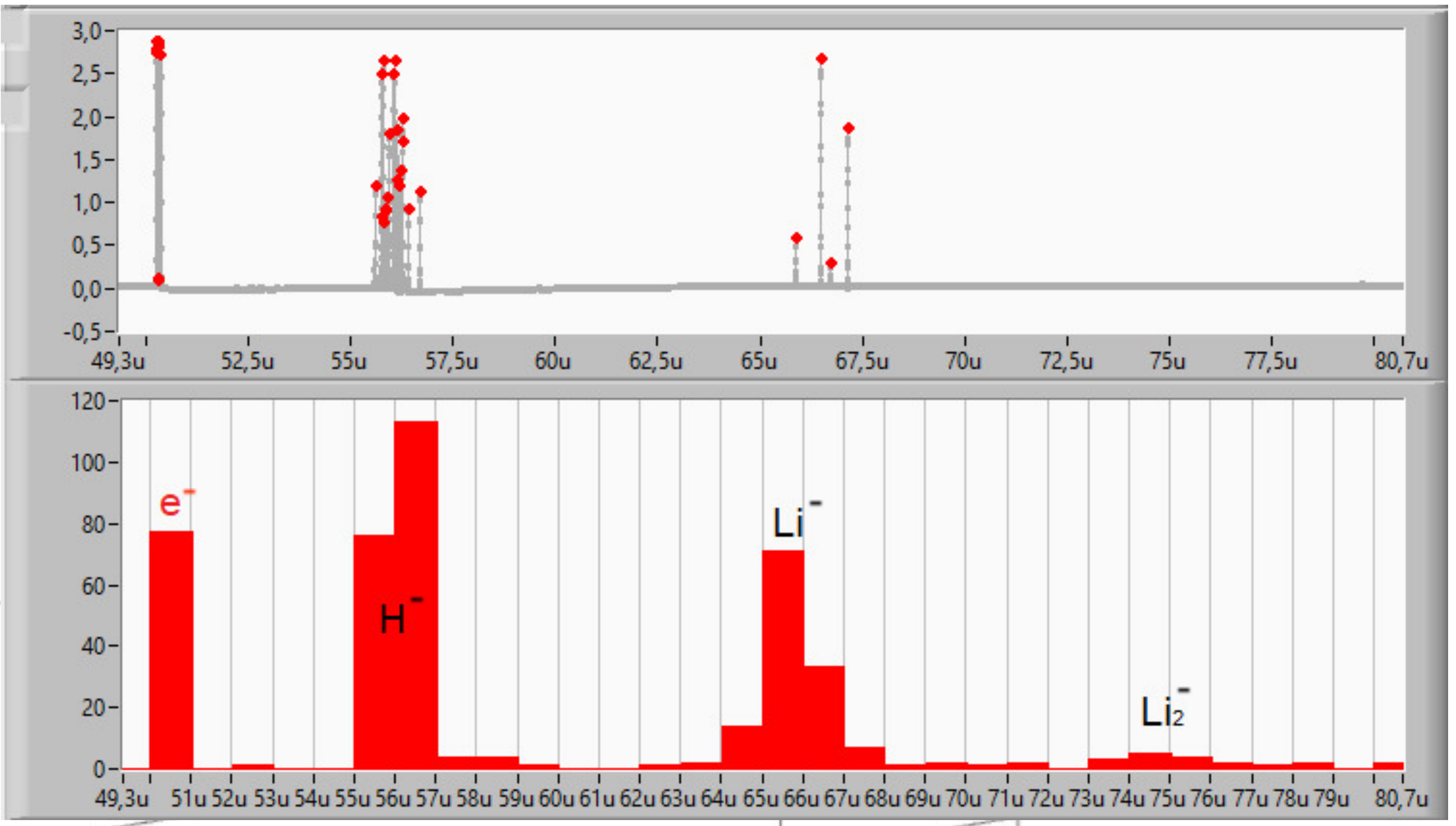
084201-3 Oliveira *et al.* J. Chem. Phys. **149**, 084201 (2018)

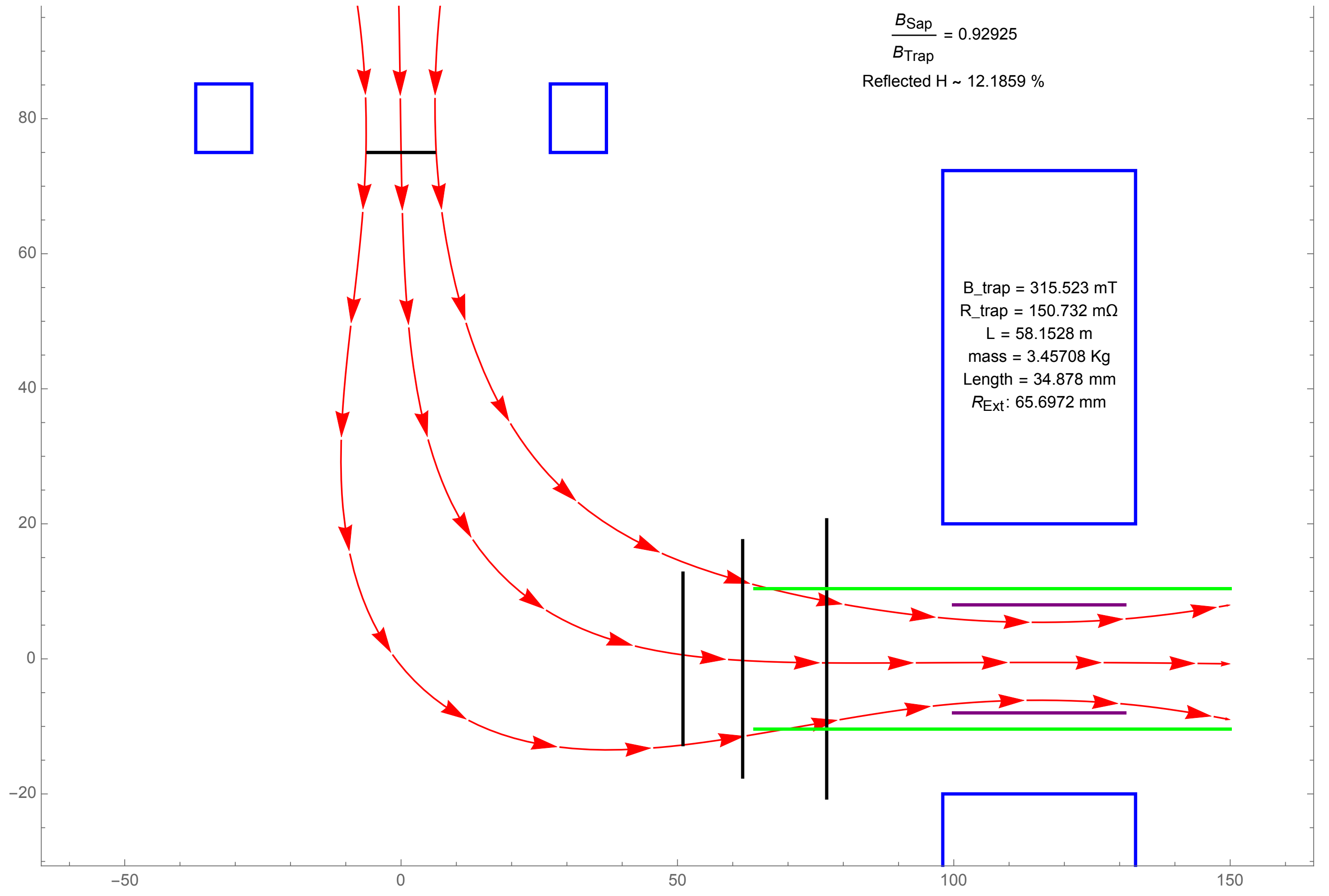


Matrix Isolation Sublimation (MISu): cold anions: H-, Li-, …



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

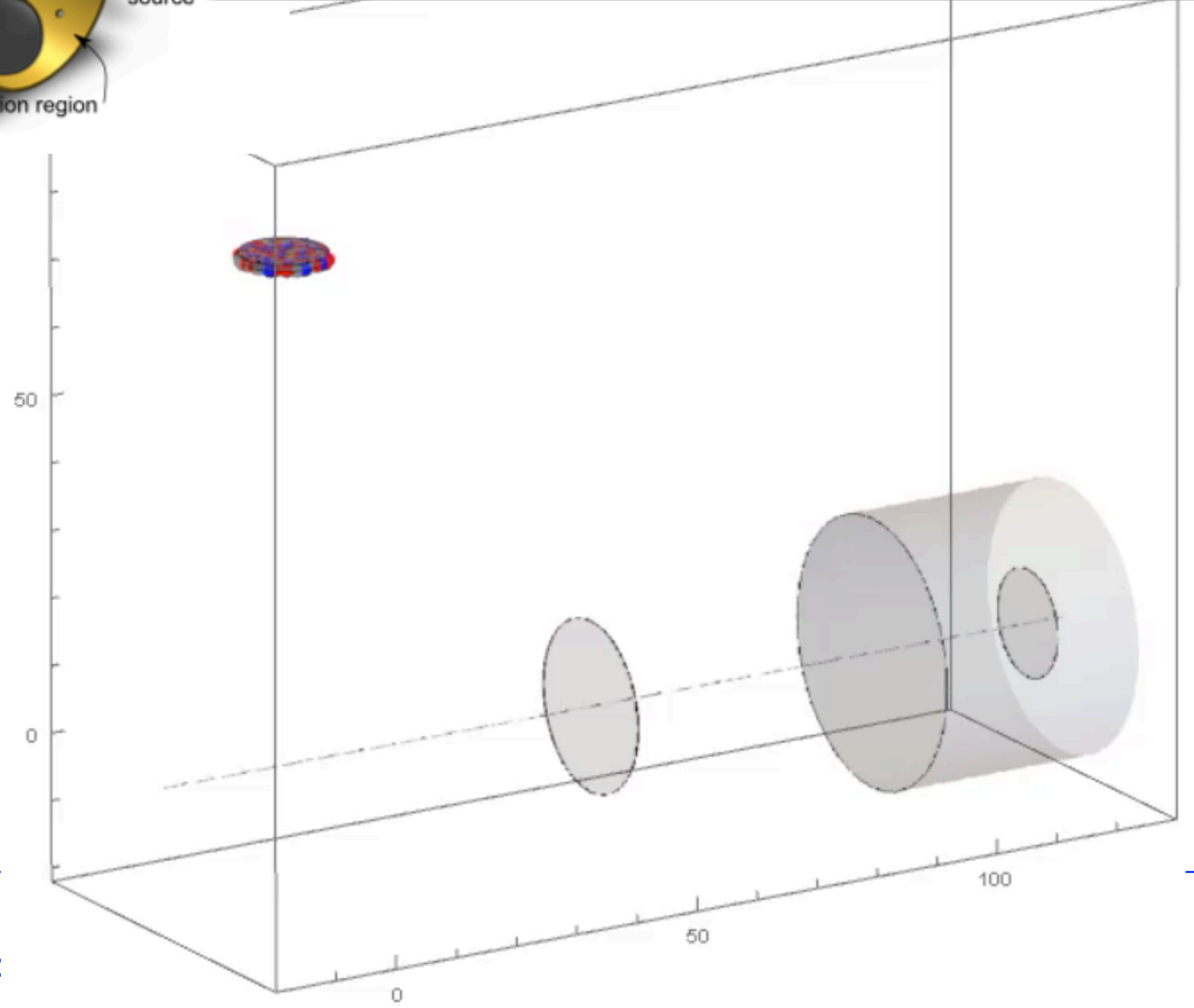




$$\frac{B_{\mathrm{Sap}}}{B_{\mathrm{Trap}}} = 0.92925$$

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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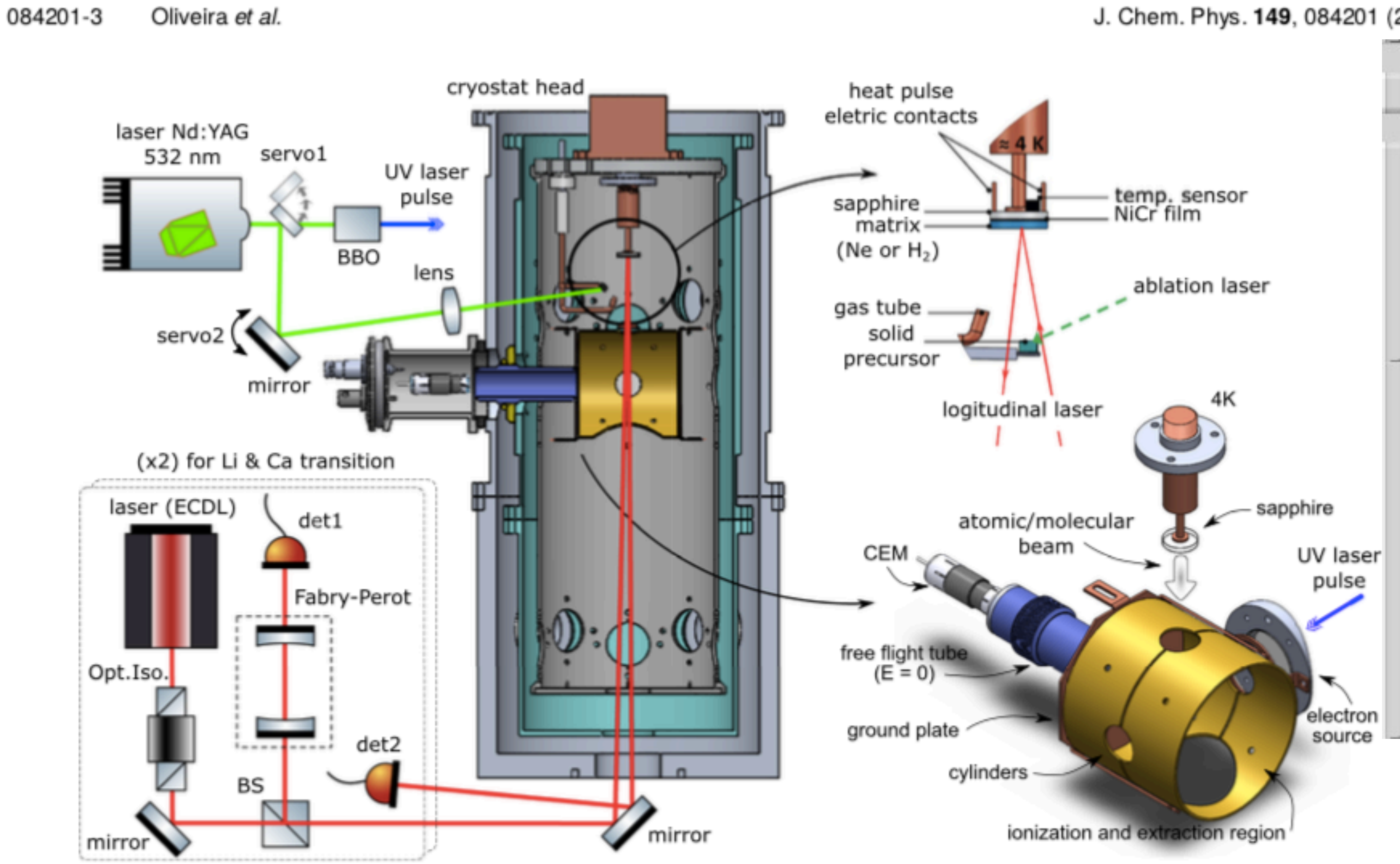

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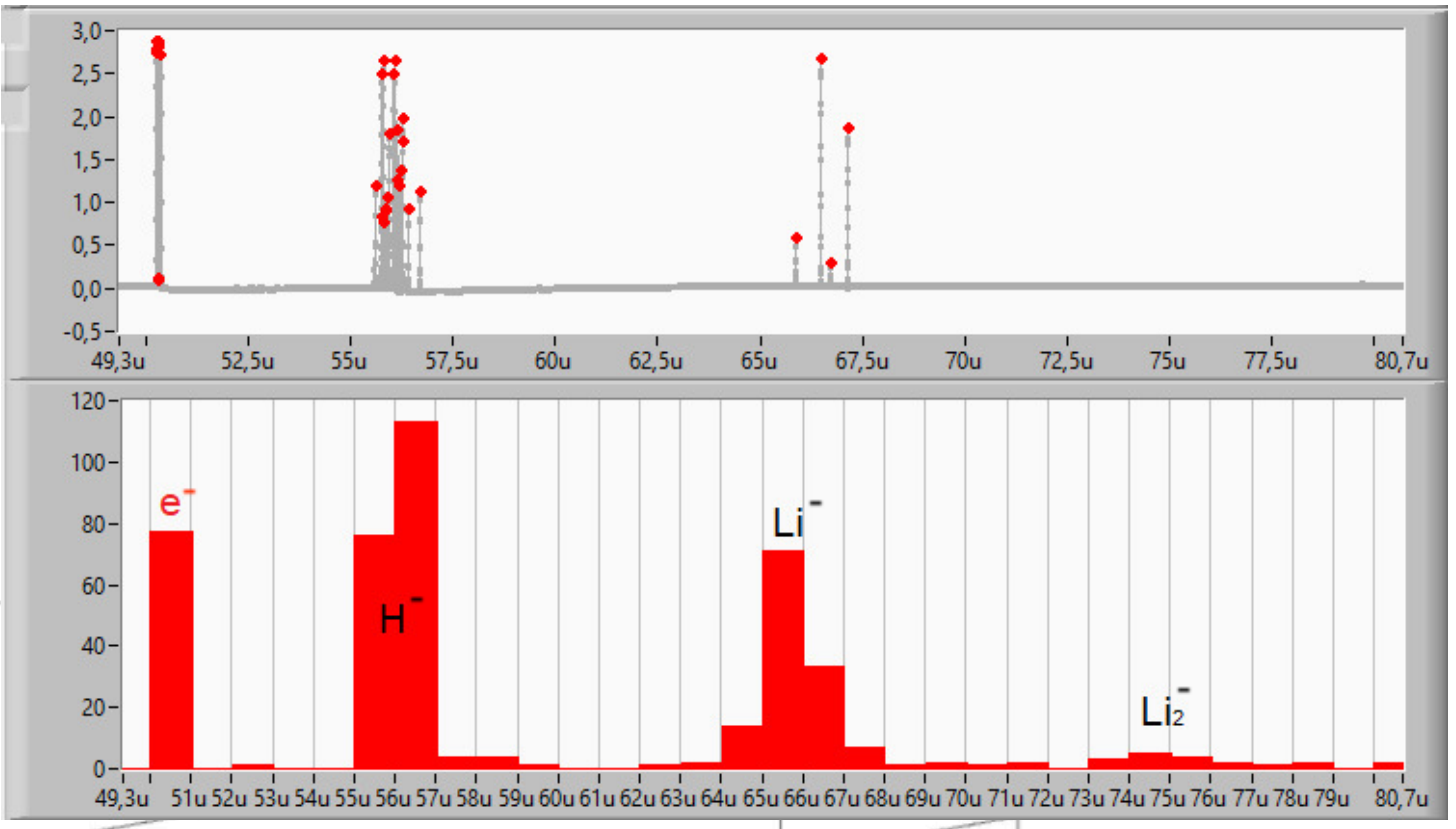

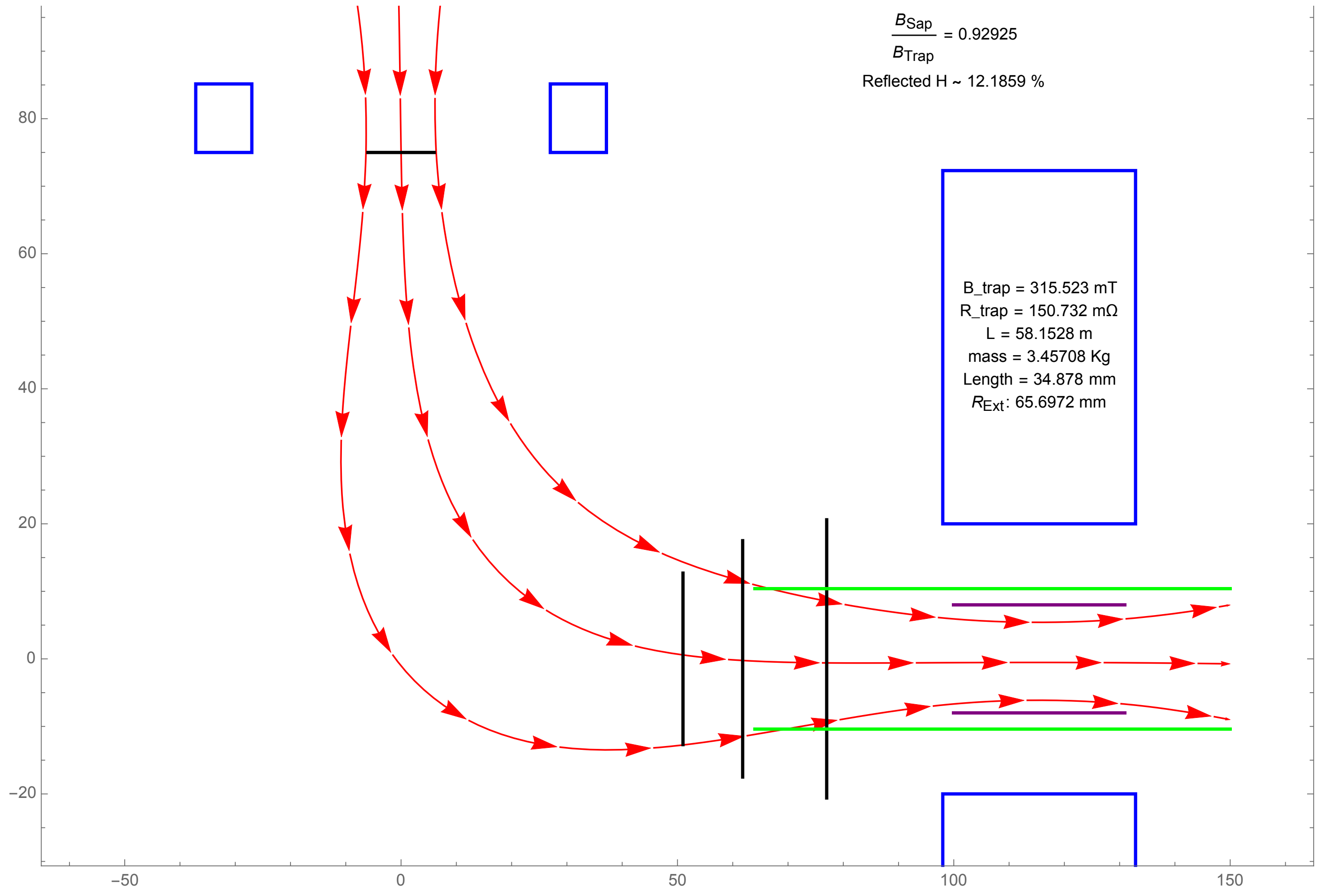

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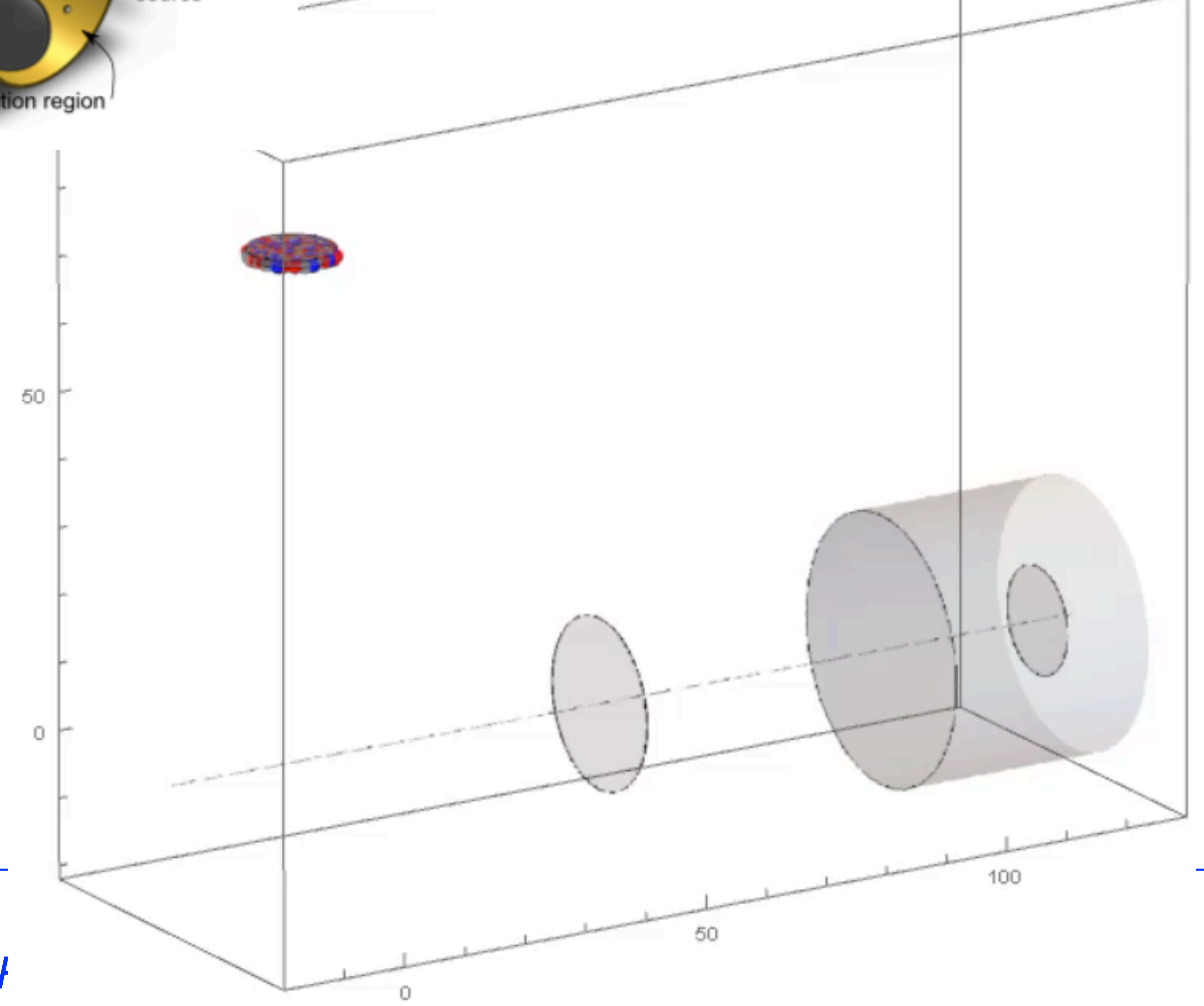

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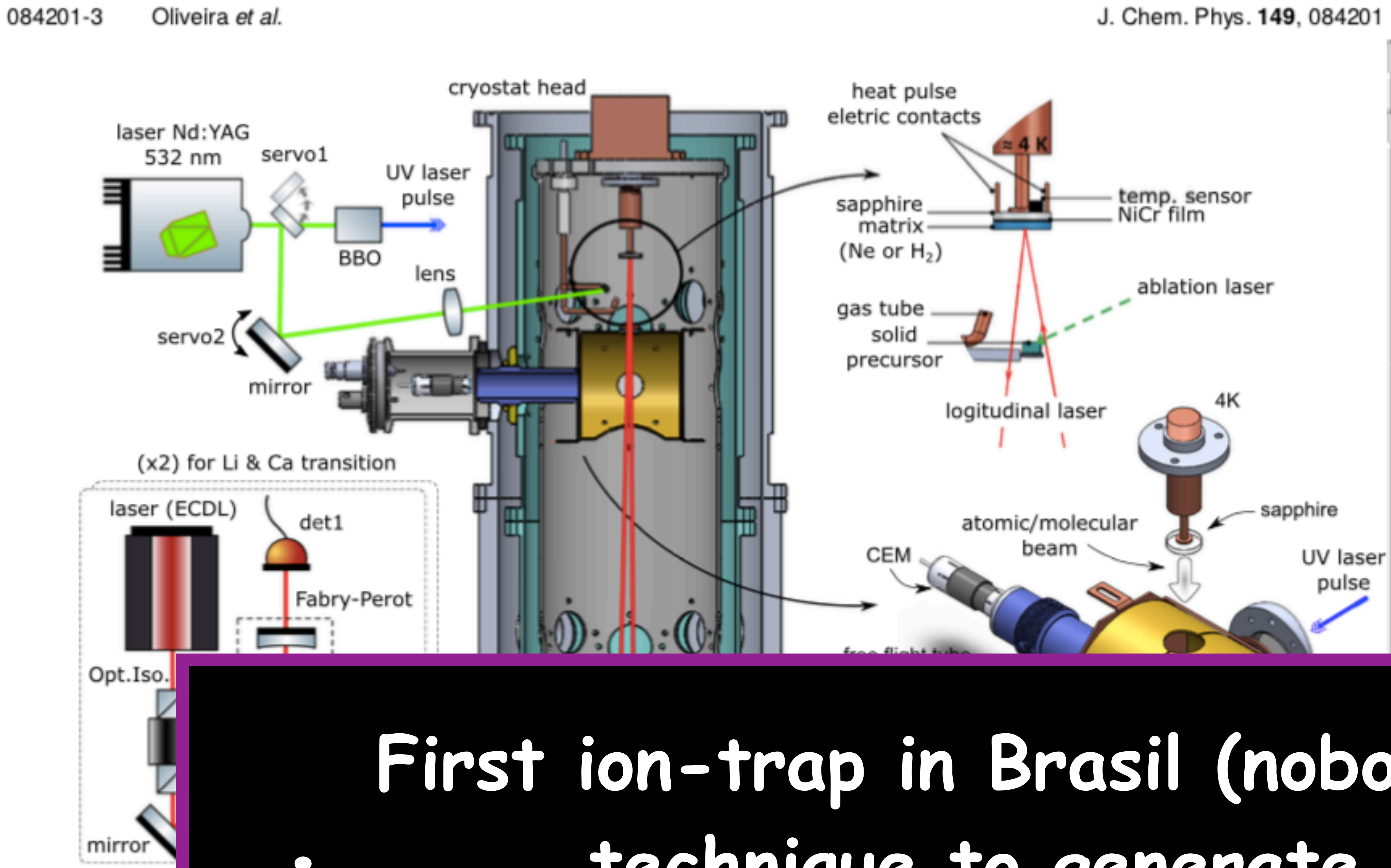

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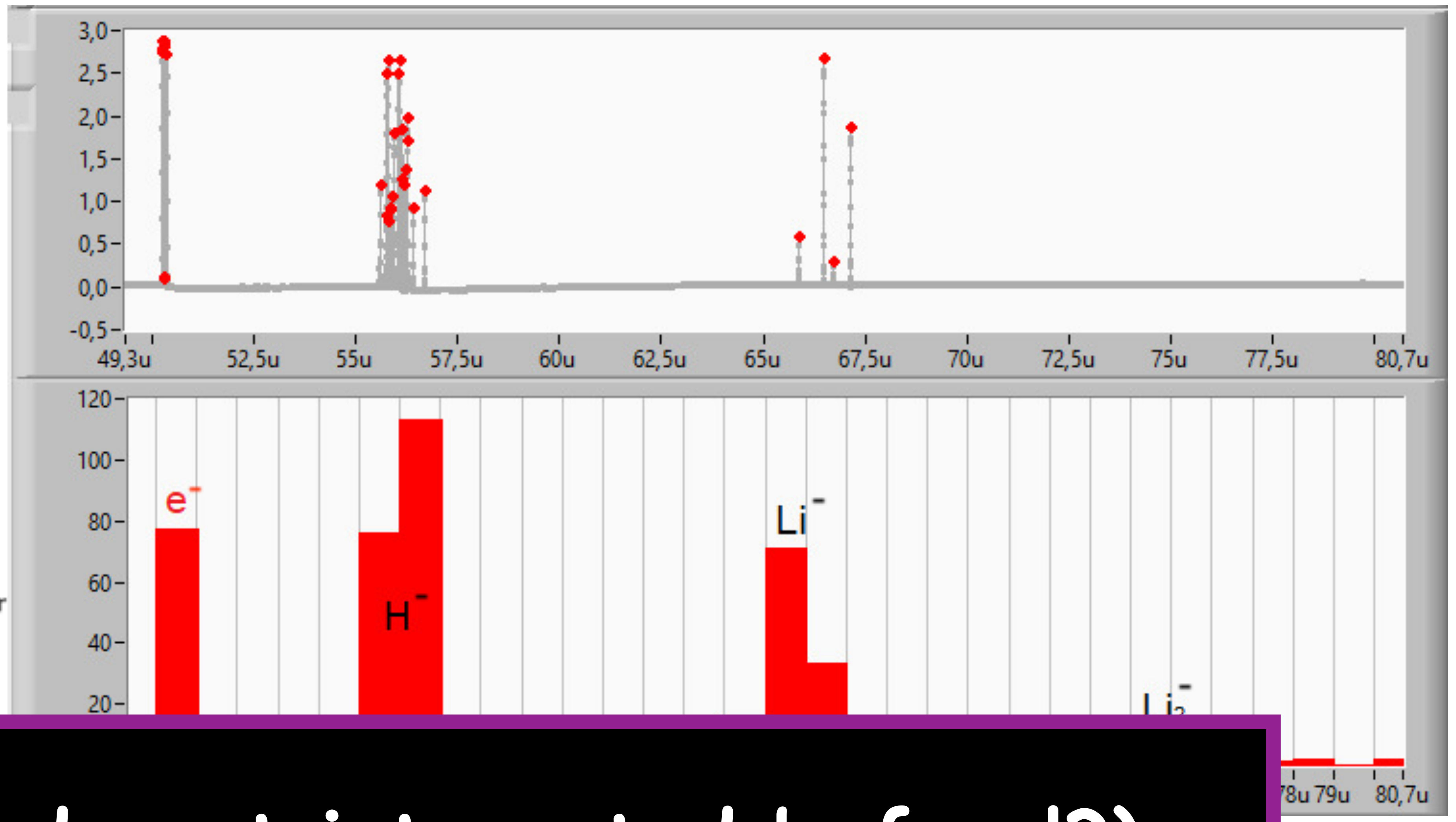
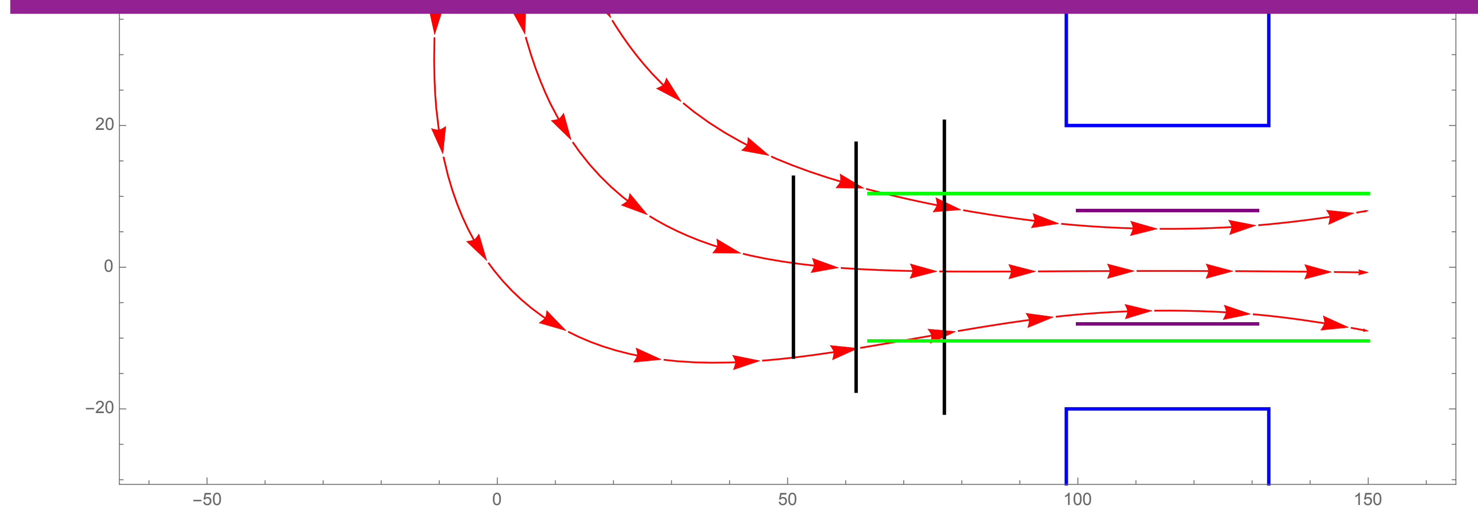
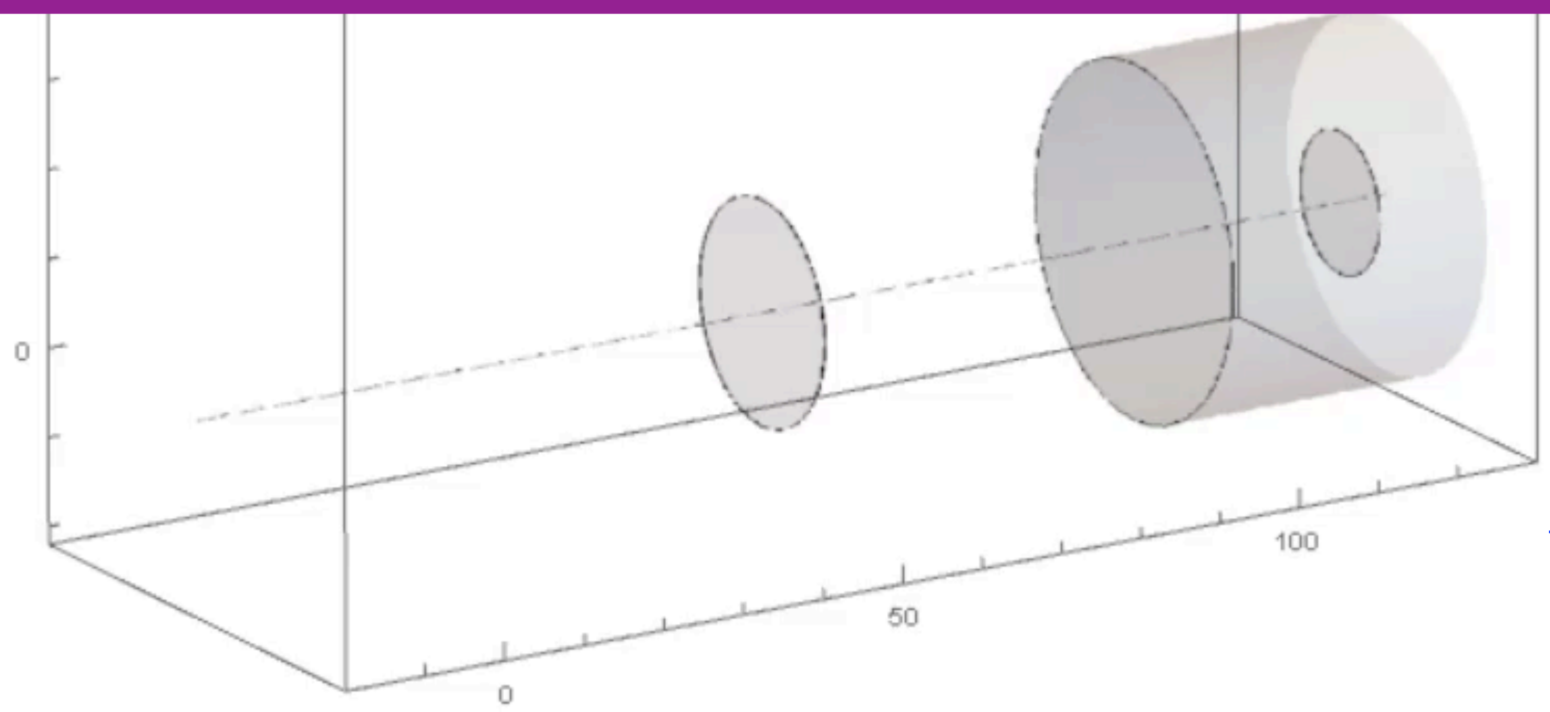


First ion-trap in Brasil (nobody got interested before!?)

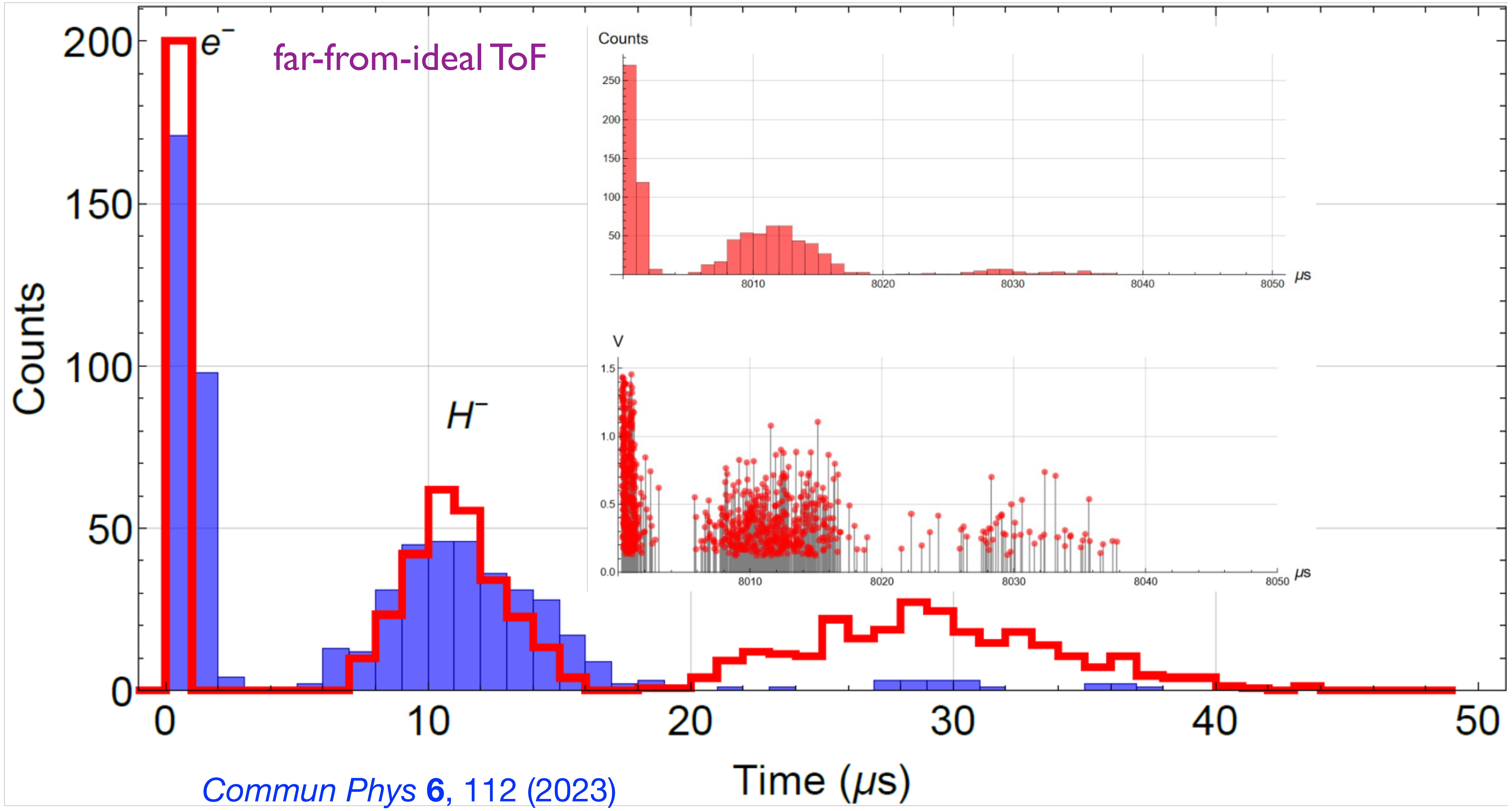
- technique to generate cold cations and anions
- main interest: H- for ALPHA
- but also: Ca+ atom-chip-clock & Q.Computing





Matrix Isolation Sublimation (MISu): trapped cryogenic (mostly e-, …)

Results and Simulation – Negative charged particles



Commun Phys **6**, 112 (2023)

Matrix Isolation Sublimation (MISu): trapped cryogenic (mostly e-, …)

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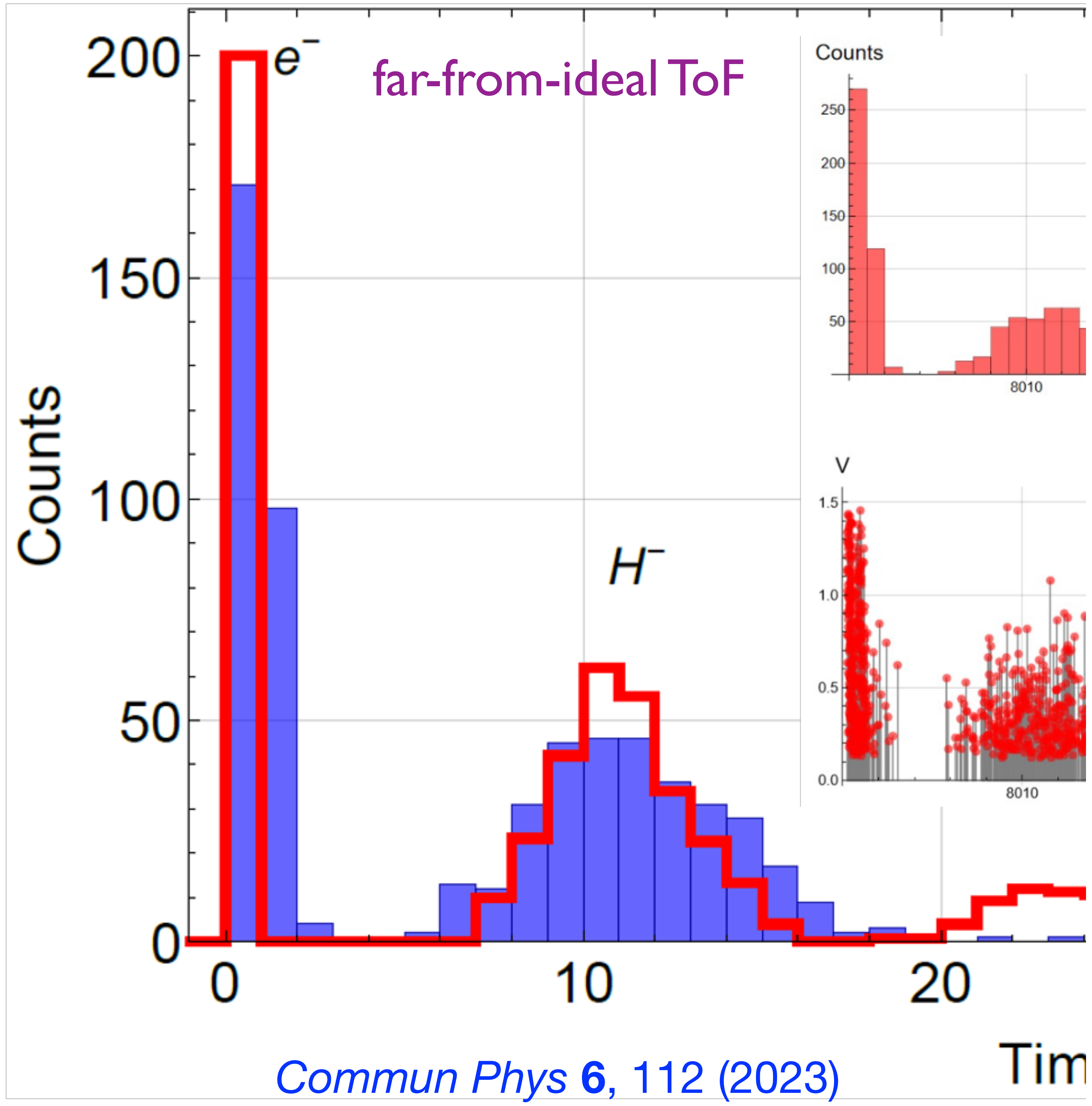
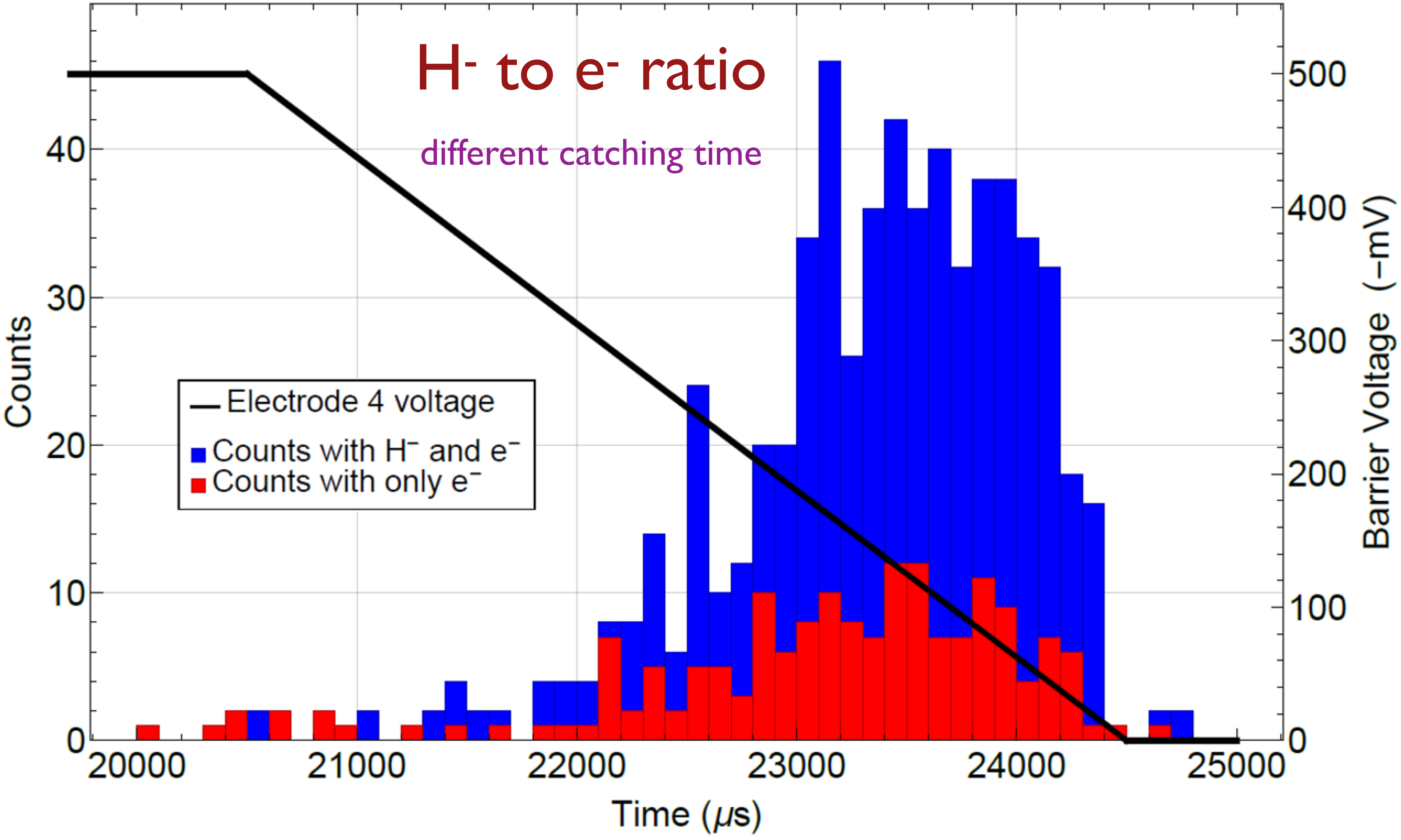


Commun Phys **6**, 112 (2023)

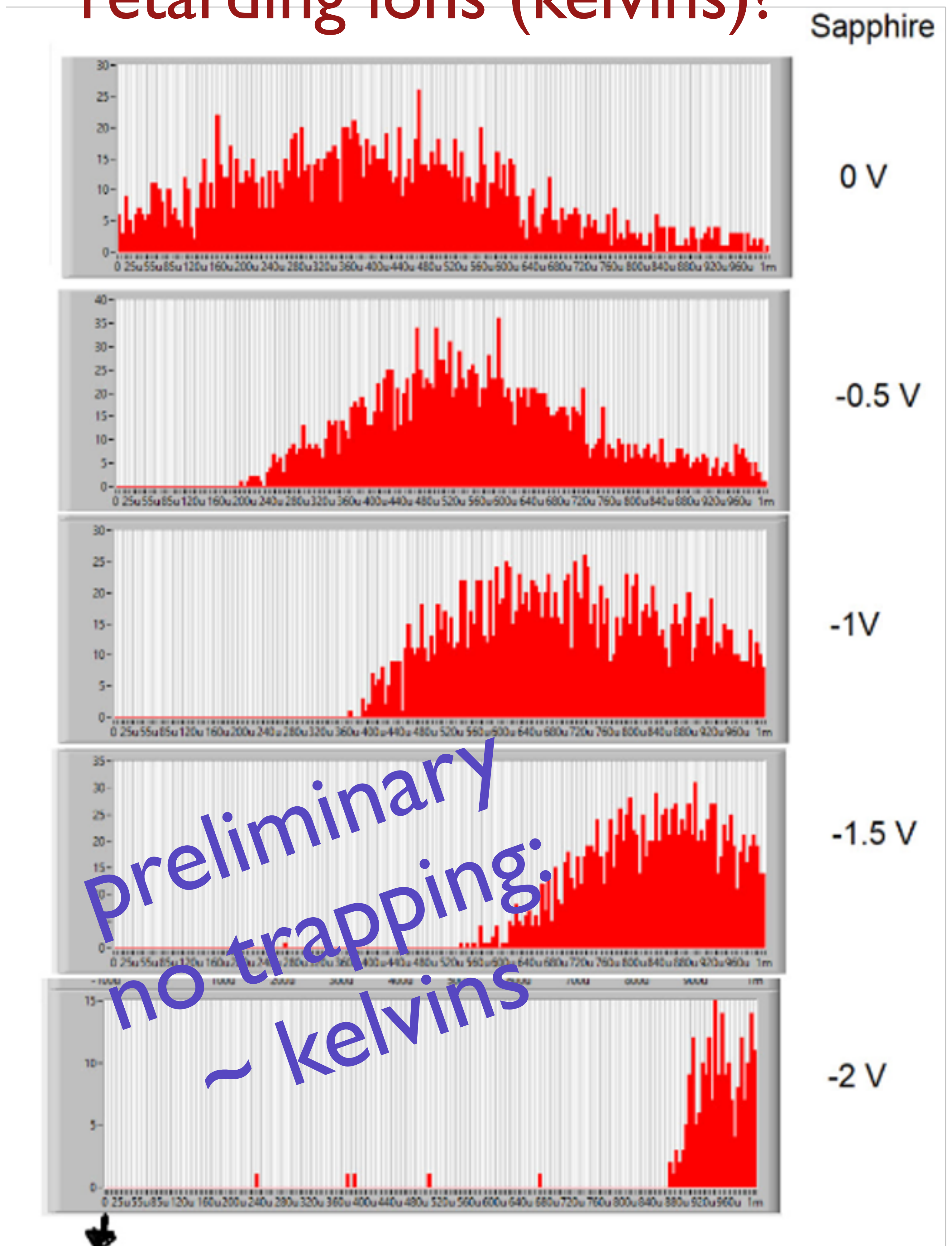


H^- to e^- ratio

different catching time

Matrix Isolation Sublimation (MISu - Rio) : cryogenic ions

retarding ions (kelvins)?

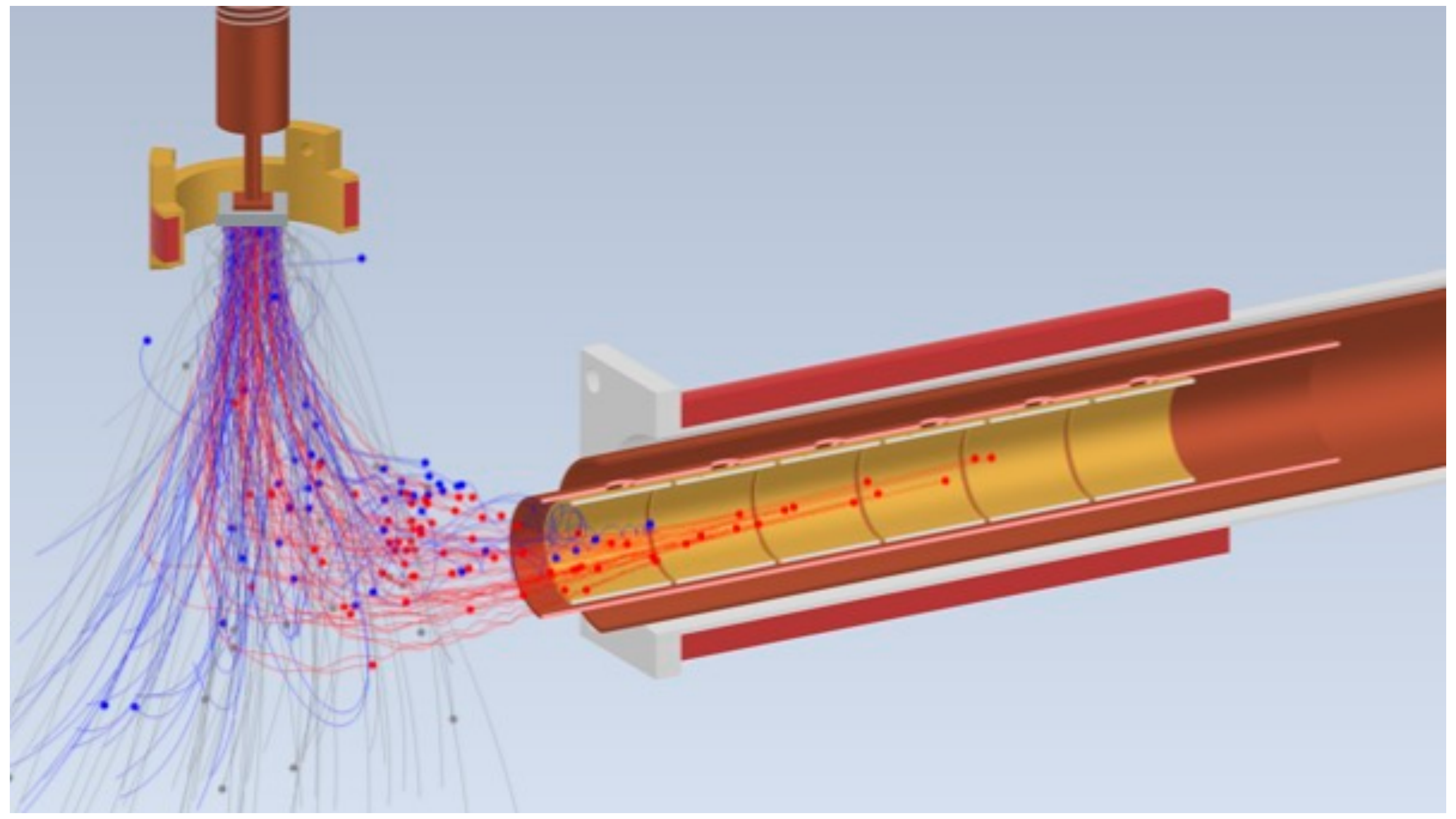


preliminary
no trapping:
~ kelvins

1400 µs após
início do pulso
de calor

LASER−IF−UFRJ

Universidade do Brasil



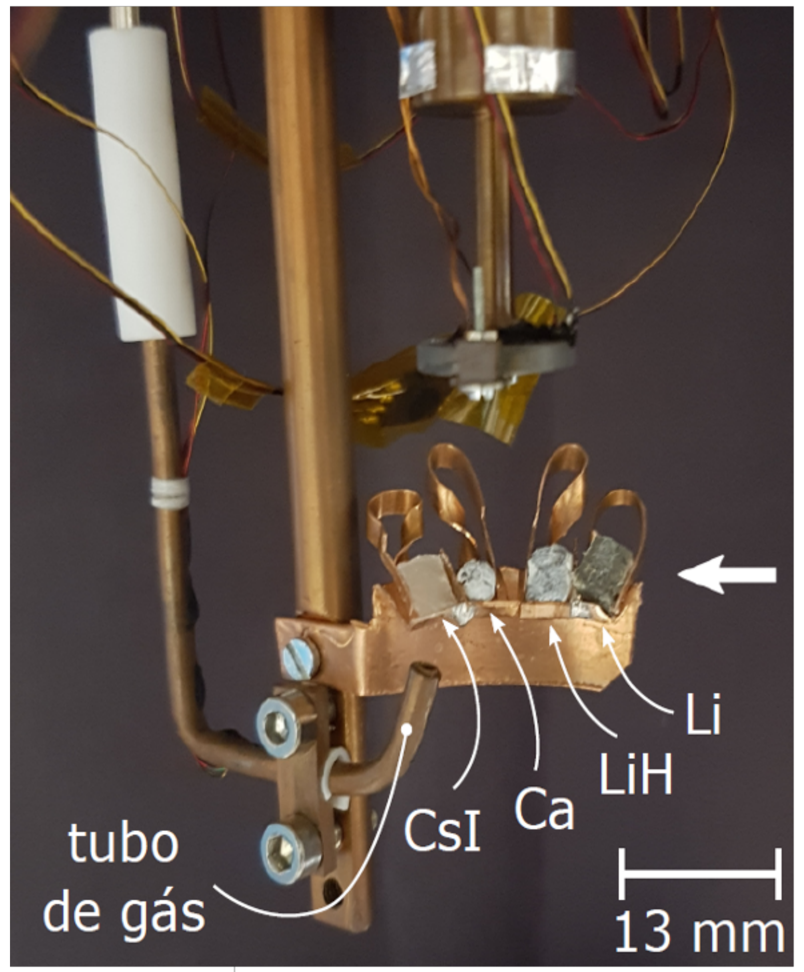
to do:

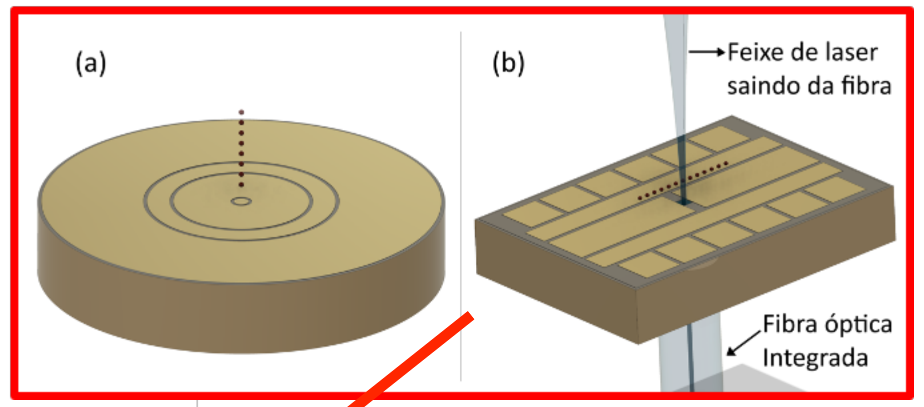
- ☆ Accumulation of H^- / Li^- (?? 40 dB$_\#$??)
- ☆ Axial access for Ca^+ laser spectroscopy (T_{ions} = ?)
- ☆ Two CEM's: detection (-) and (+) simultaneous
- ☆ Molecular formation (triple well) => interesting cases?
  (C^{++} + A^- => CA^+ ?)
- ☆ H^- (& other) Photodetachment (in magnetic field ?)

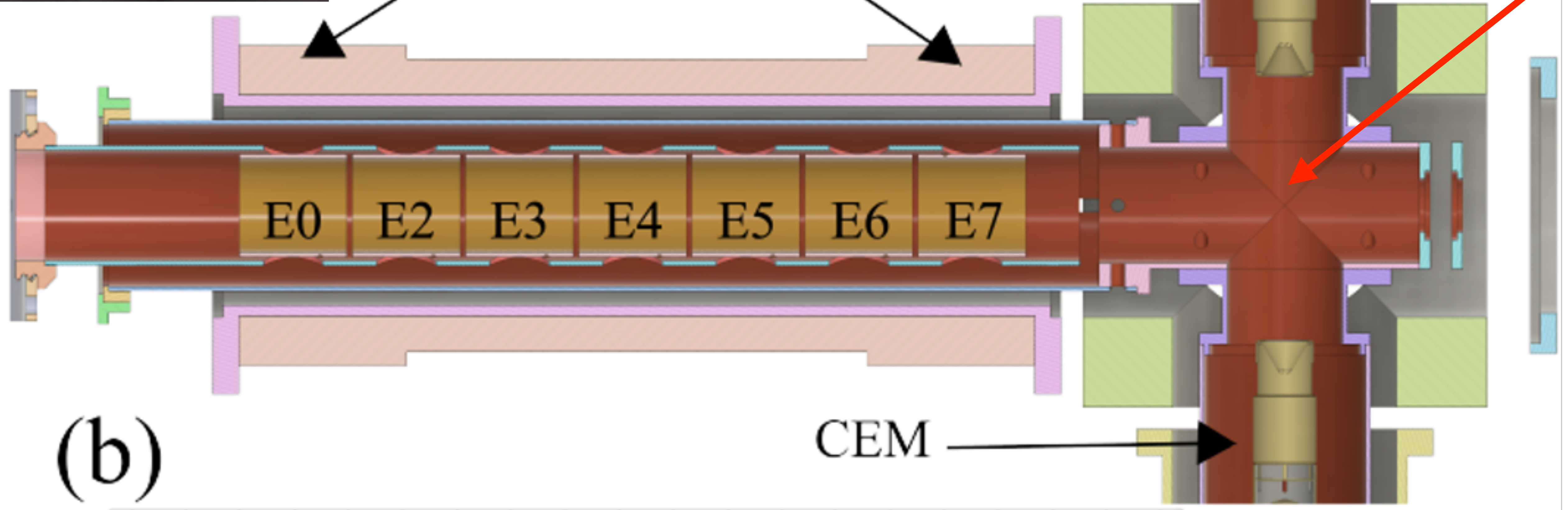
-> H^- (& other) evaporative cooling / scale up numbers and trap time

Matrix Isolation Sublimation (MISu - Rio) : cryogenic ions

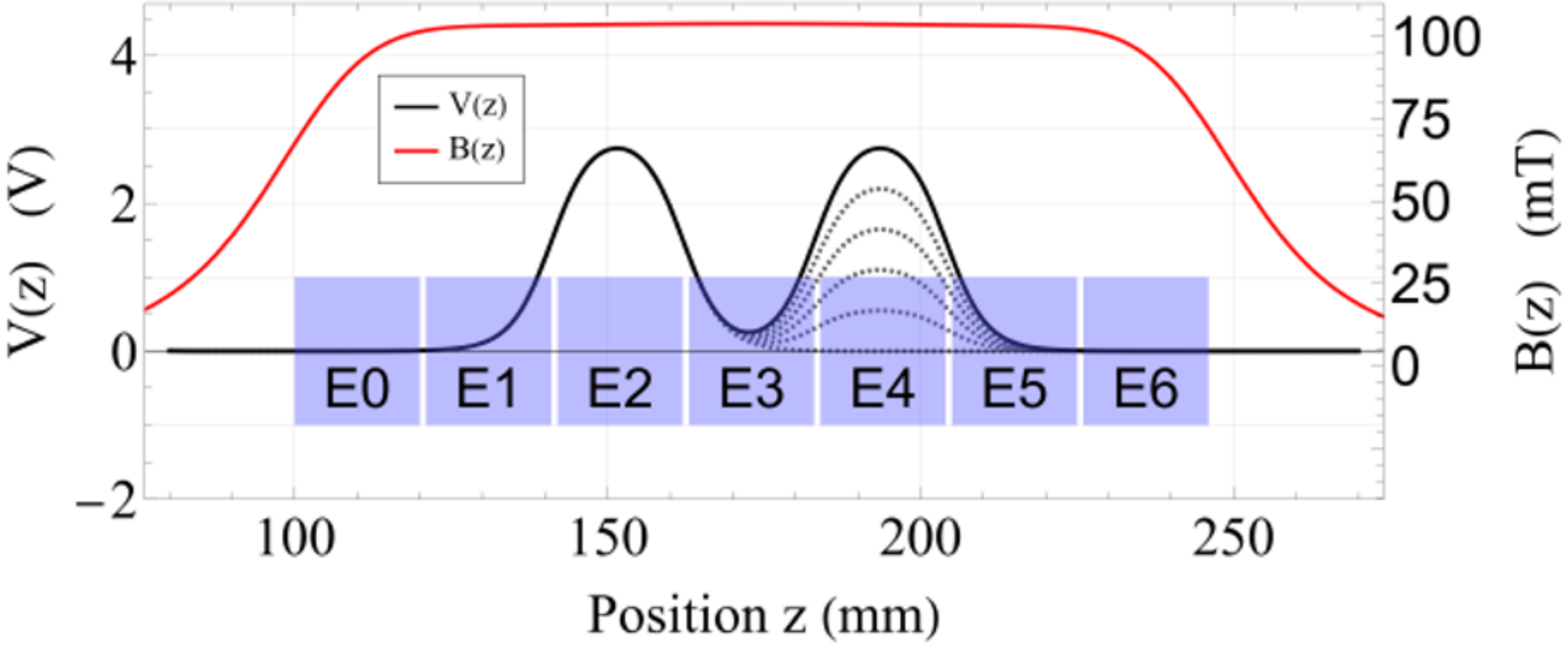
New version: 2026







(b)

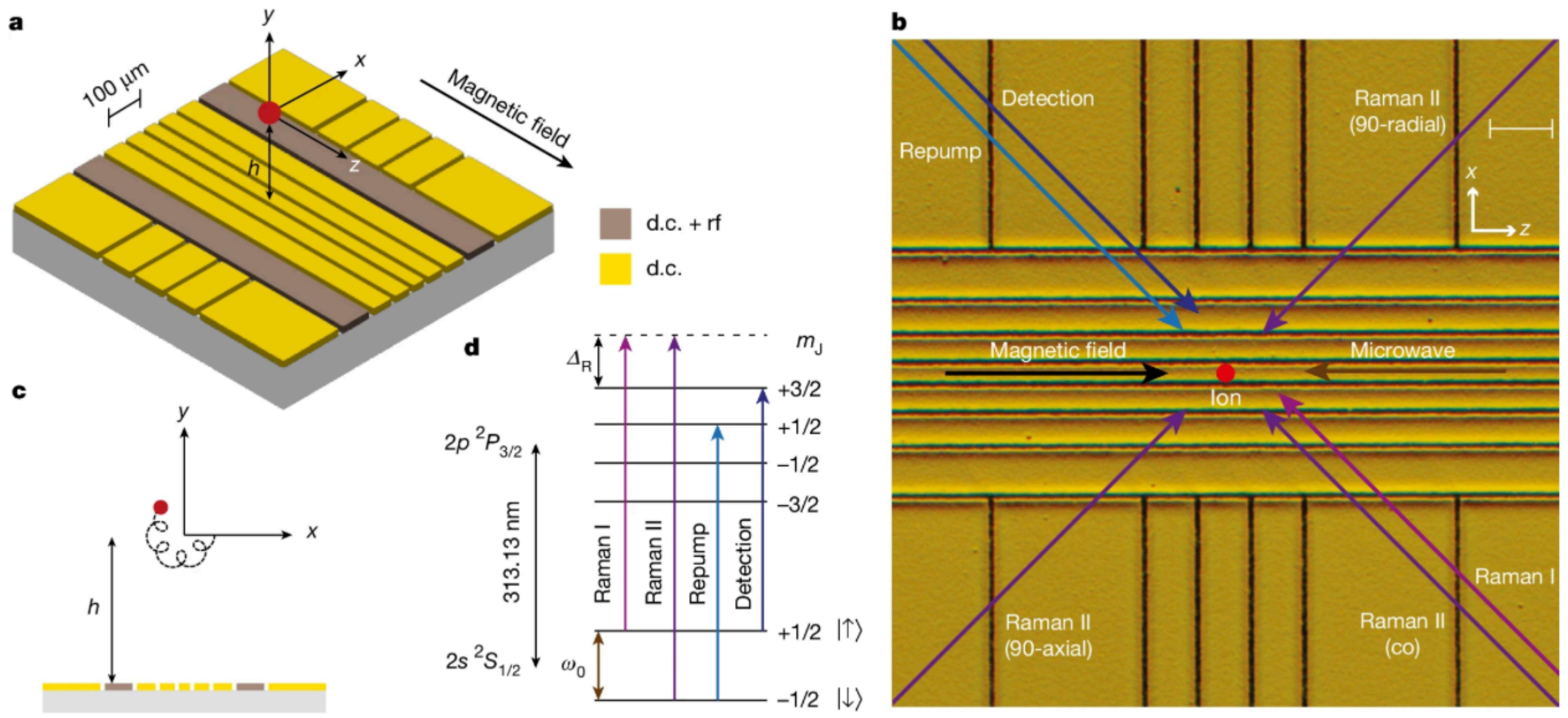


Inspirations:
Zurich and Innsbruck

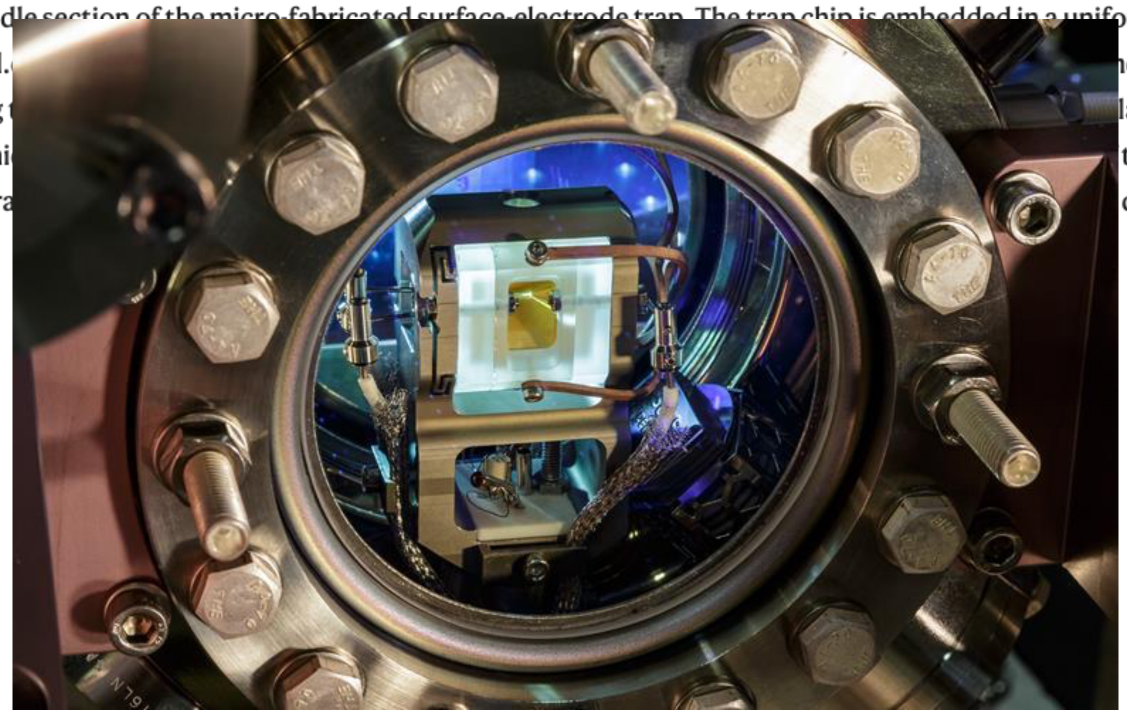
nature
ETH- Zurich

laser

From: Penning micro-trap for quantum computing

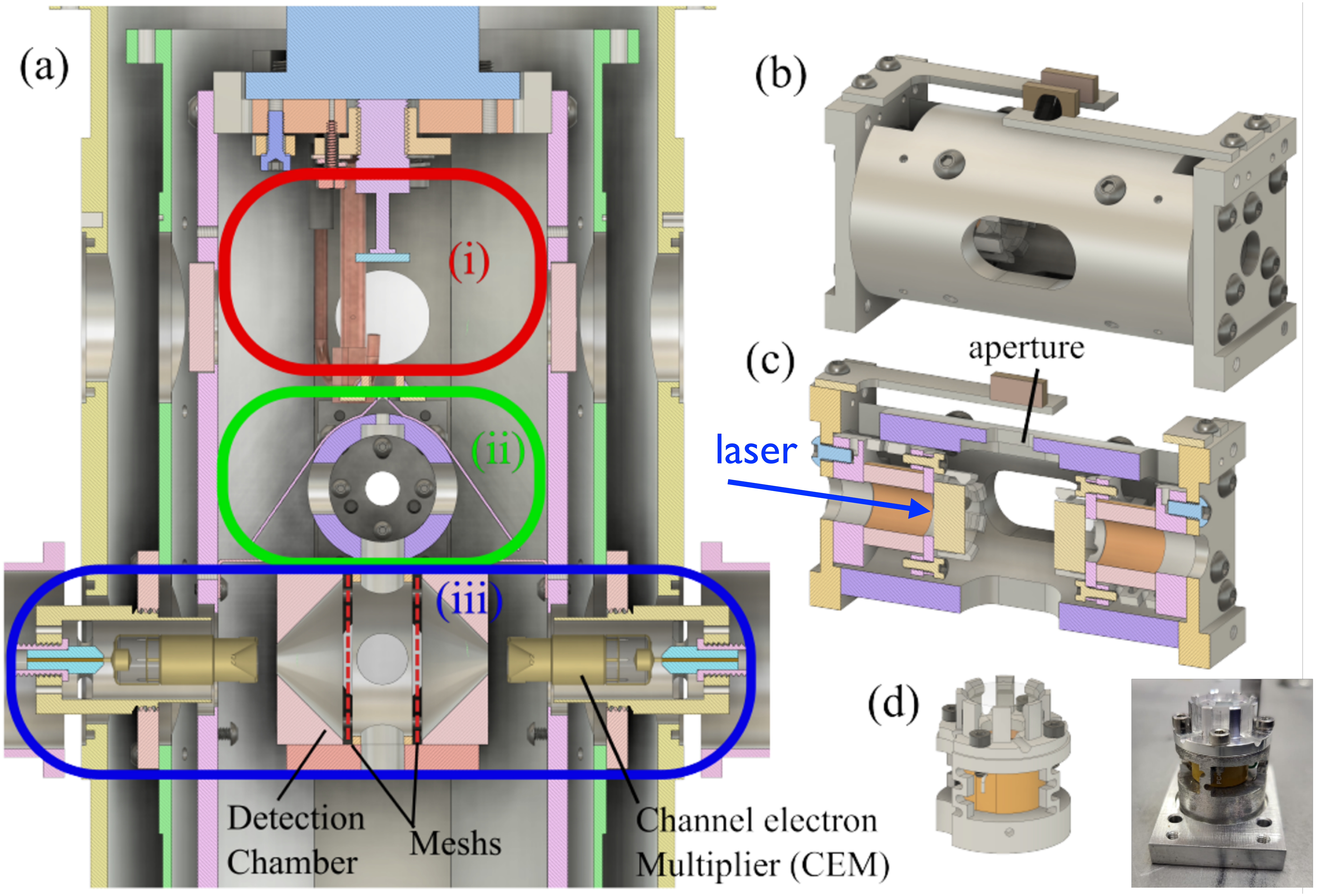


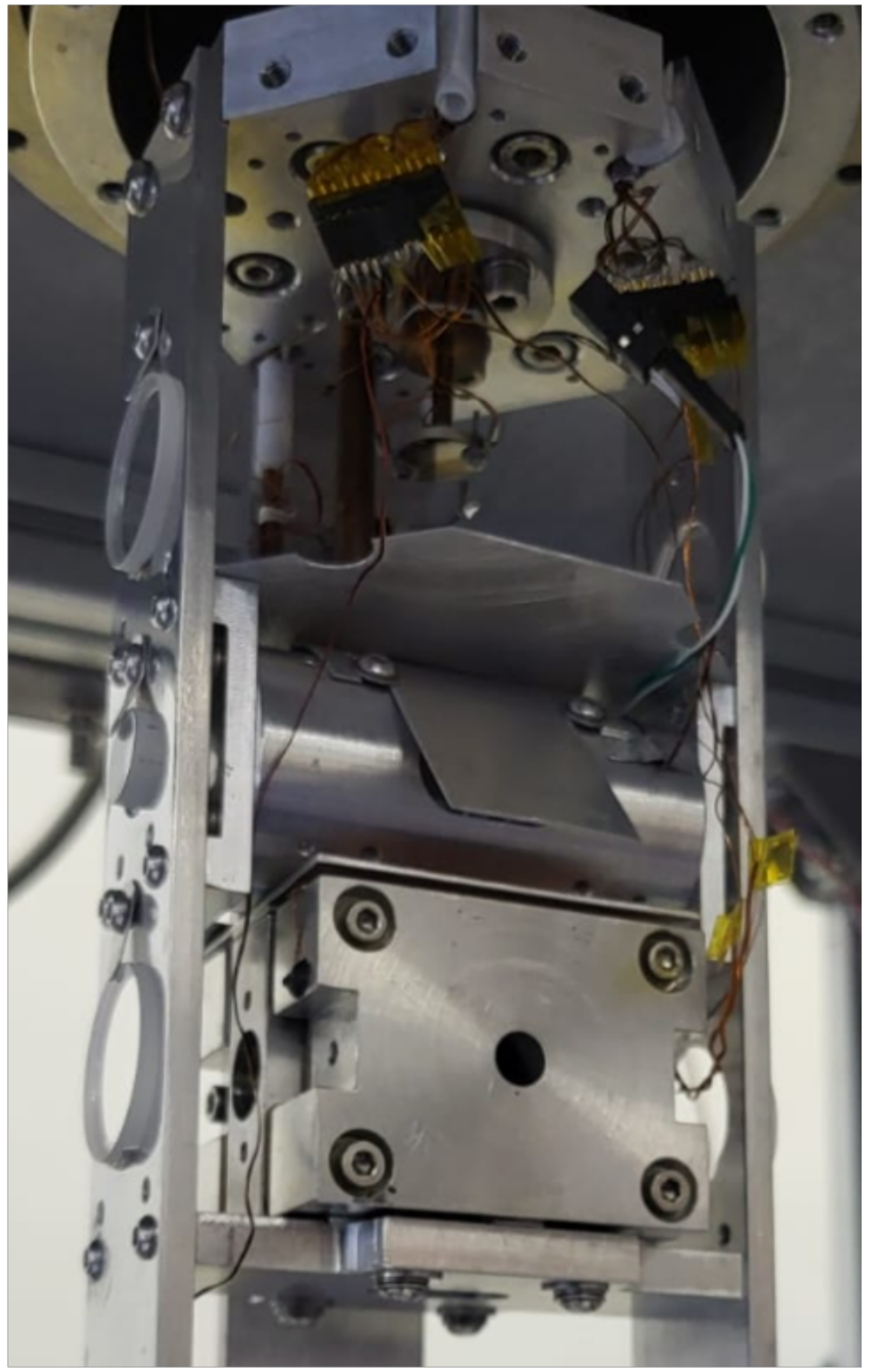
a, Schematic showing the middle section of the micro-fabricated surface-electrode trap. The trap chip is embedded in a uniform magnetic field along the *z* axis, and the application of d. … e surface. Electrodes labelled 'd.c. + rf' are used for coupling … lay of the direction of the laser beams (all near 313 nm) and mi… the ion. All laser beams run parallel to the surface of the tra… delivered to the ion by a horn



Source: © IQOQI / M. R. Knabl
The quantum computer uses trapped calcium ions as qubits

UFRJ: H(e D e T):1S-2S spectroscopy: getting ready!

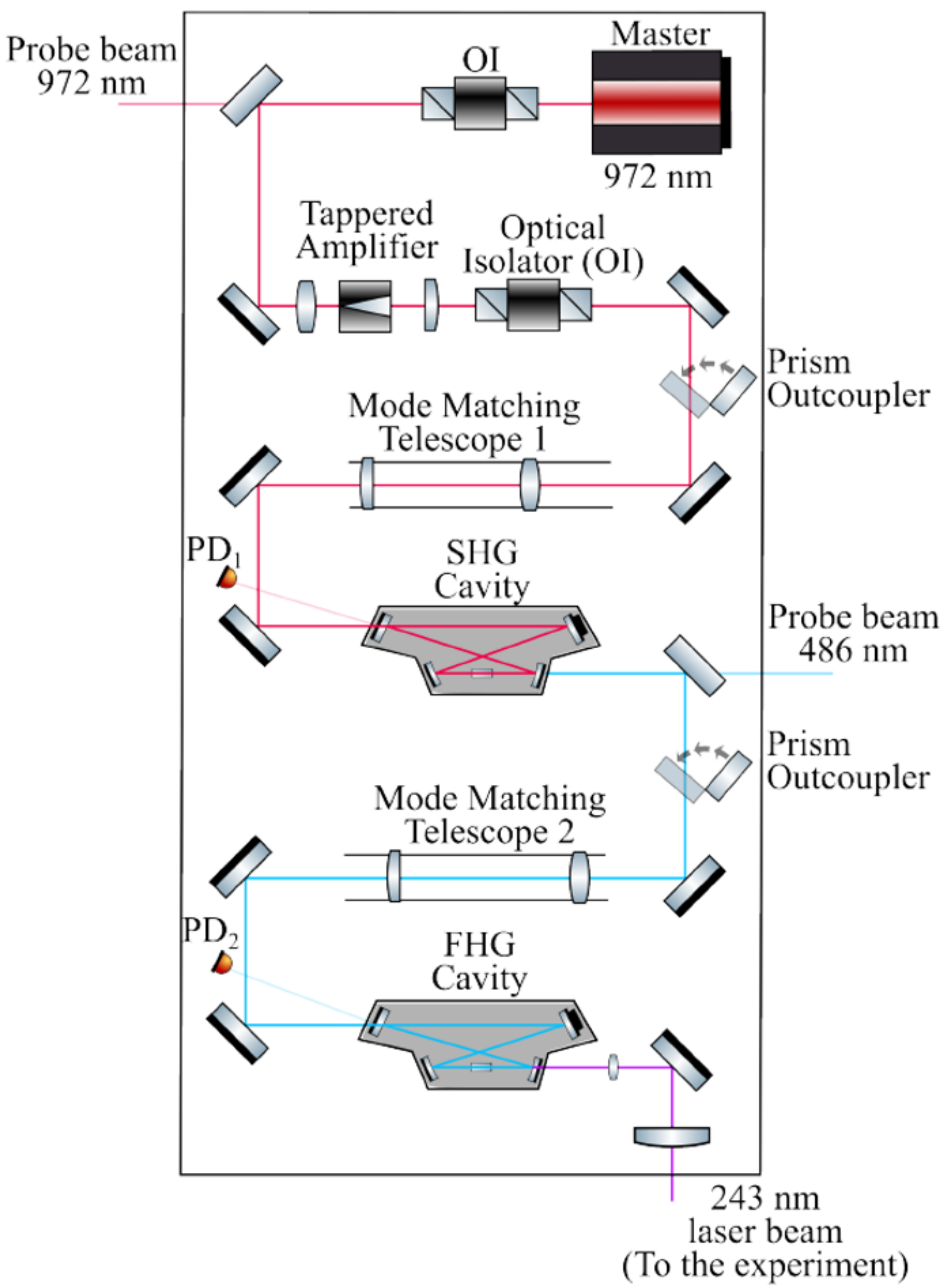




UFRJ: H(e D e T):1S-2S spectroscopy: getting ready!

ULE

Cavity



WS-7 Wavemeter

Te_2 (@486 nm)
Saturated
Spectroscopy

Conclusions/Perspectives/Acknowledgements

ALPHA @ CERN

- 1S-2S spectrum (2018 @ 10^{-12}, 2026 @ $10^{-13,-14}$):
  (E&M, QED, QCD: $r_p \Rightarrow$ 1.2 MHz while ∂f ~ 300 Hz)

⇒ very high precision $10^{-15...-18}$: Hbar & H in same trap (proof-of-principle)

- laser cooling, μW spectroscopy, hyperfine, …

- ALPHA-g gravity fall:

will CPT hold ? WEP ? Nature has the answer !?

$$a_{\overline{H}} = (0.75 \pm 0.13(\text{stat} + \text{syst}) \pm 0.16(\text{sim}))\text{g}$$

LASER @ UFRJ

- MISu technique: => ions, H (D,T) : 1S-2S spectroscopy & trapping
- Application: robust & compact Optical Gravimeter