# Hydrogen, at MIT and UFRJ, and Antihydrogen Laser Spectroscopy, at the ALPHA collaboration at CERN

RENAFAE

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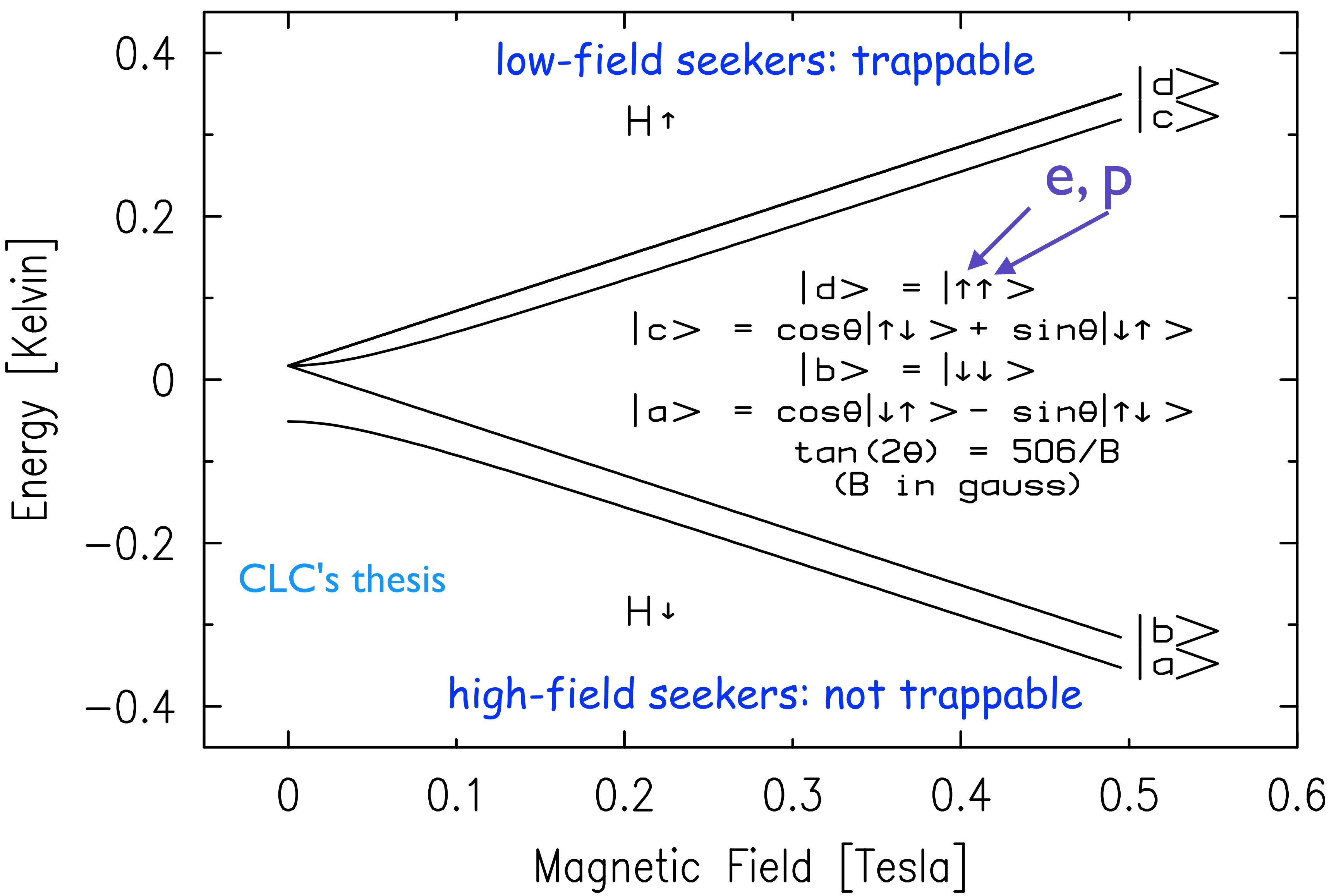
- Trapped Hydrogen @ MIT (Renewed Interest on cold H and techniques - many groups here!)
- Trapped Antihydrogen @ ALPHA : H x Hbar ~ $2\times10^{-12}$
- Matrix Isolation Sublimation: cryogenic atoms, molecules and ions (cations and anions): applications in antihydrogen
- (to do#1 & 2): Direct laser-spectroscopy(1) and trapping(2) of H&D from MISu
- Summary / Perspectives

LASER−IF−UFRJ

Universidade do Brasil

## Hydrogen for Bose-Einstein Condensation

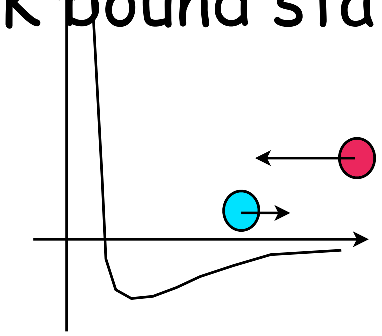
## Detection by μwave -> bolometric technique -> (1s-2s)

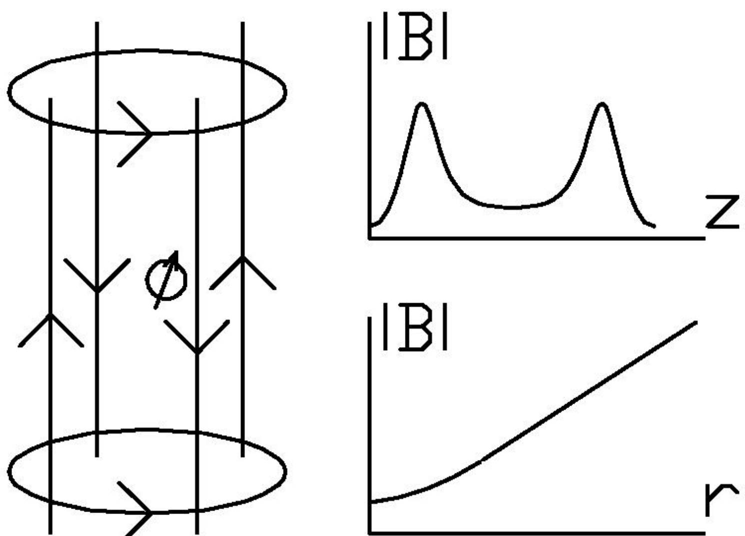


# MIT H+ trapping setup

$^3He$-$^4He$ dilution refrigerator
10 mK (250 mK during discharge)

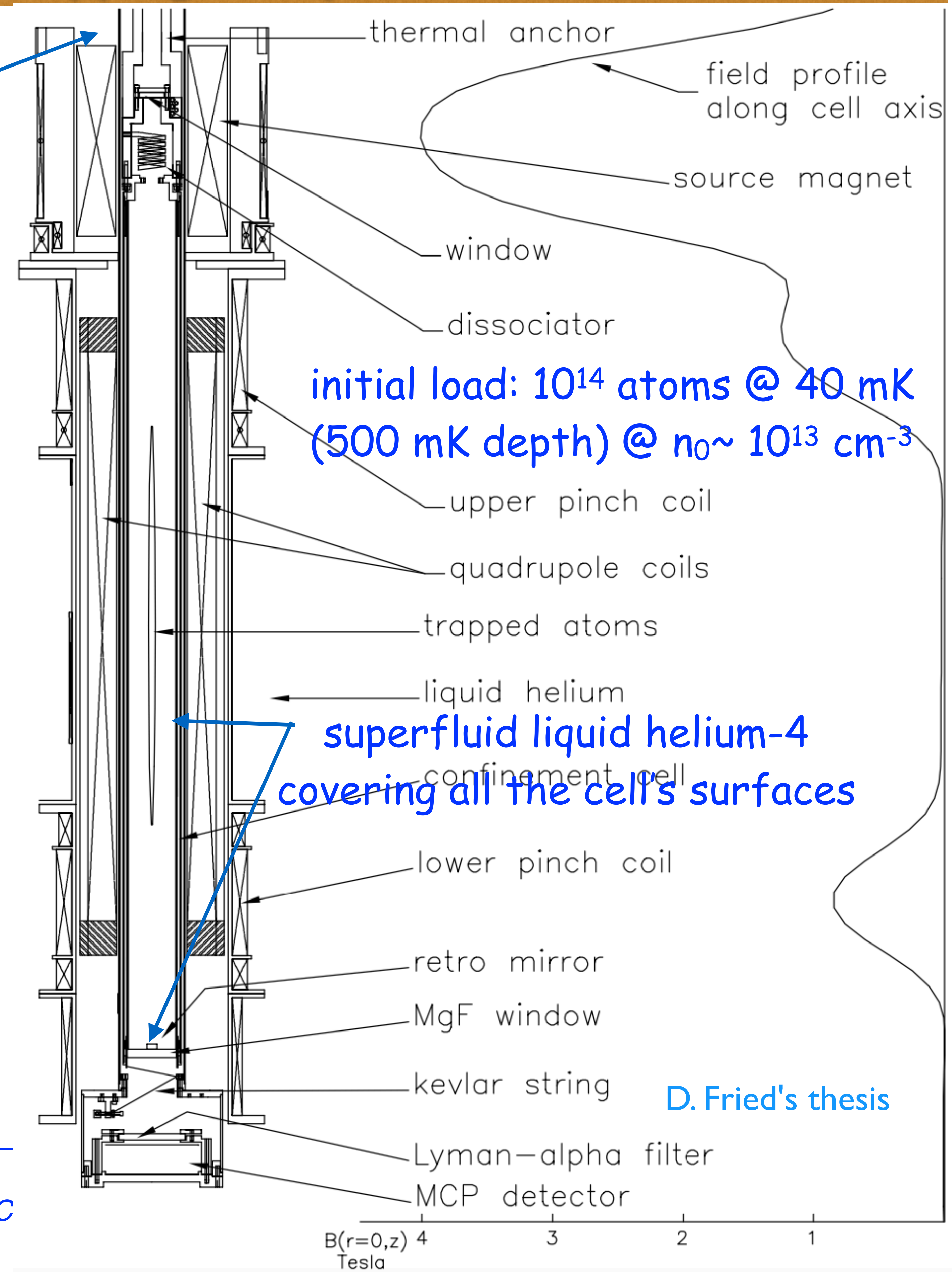
H onto l-He:
1 K bound state






CLC's thesis

Traditional Ioffe-Pritchard trap:
2 mirror/pinch (helmholtz) coils +
radial quadrupole

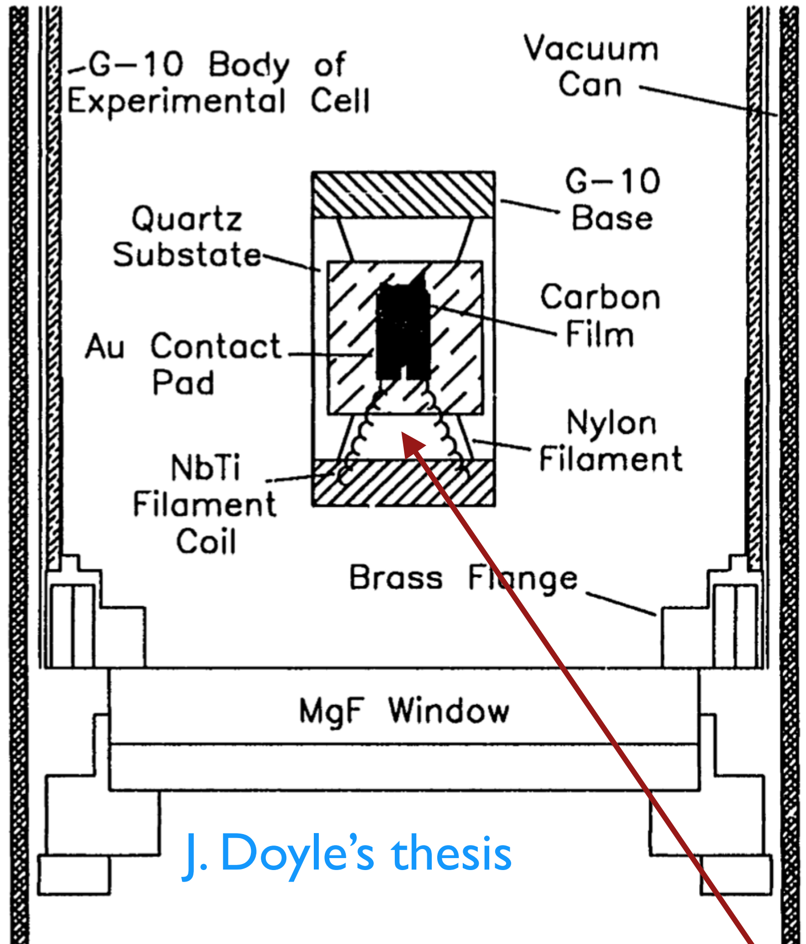



initial load: $10^{14}$ atoms @ 40 mK
(500 mK depth) @ $n_0$~ $10^{13}$ $cm^{-3}$

superfluid liquid helium-4
covering all the cell's surfaces

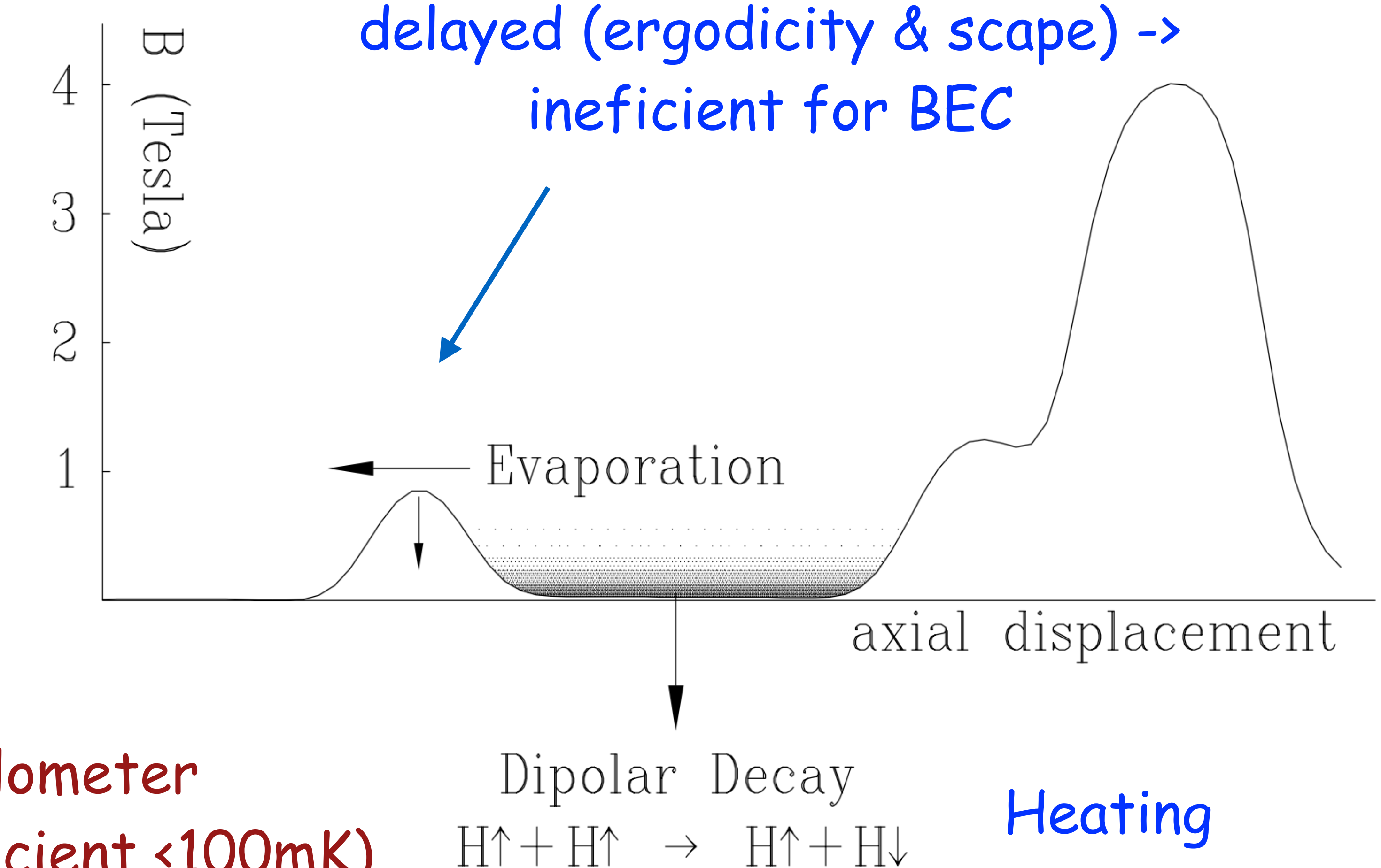
D. Fried's thesis

# MIT H+ trapping evaporative cooling (H. Hess)



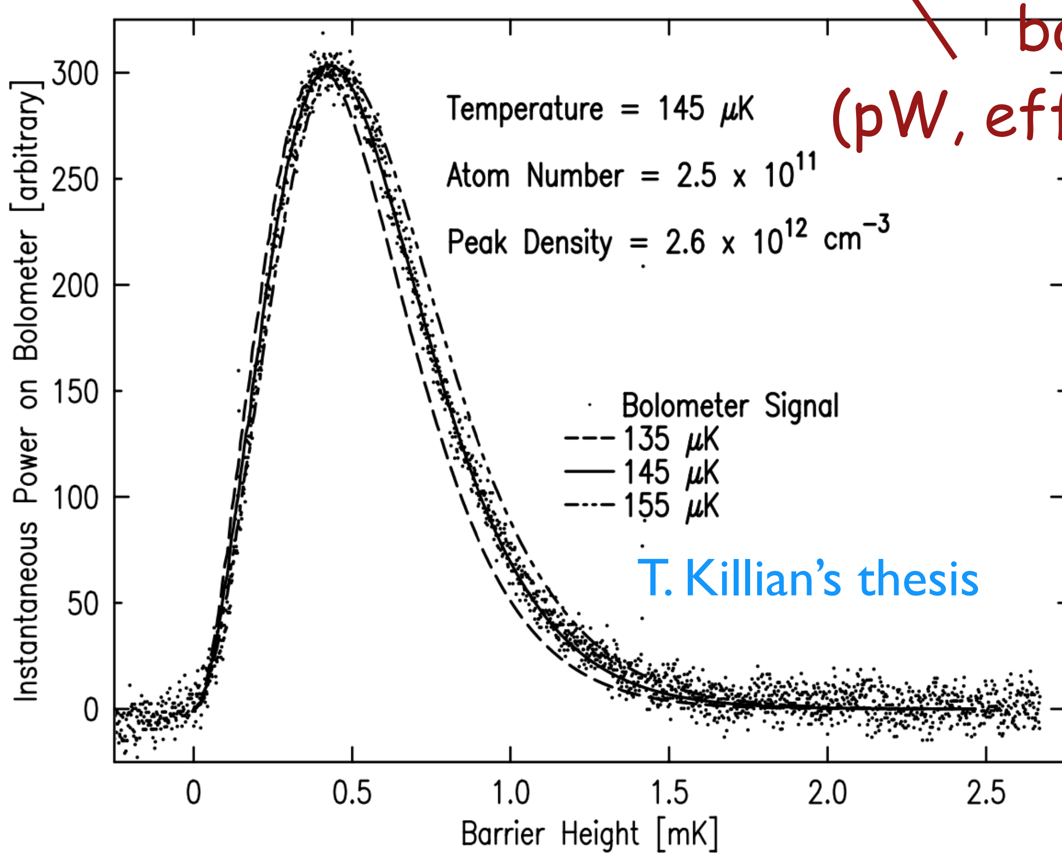

J. Doyle's thesis

saddle point evaporative cooling => 1D -> small hole -> delayed (ergodicity & scape) -> ineficient for BEC




Heating

bolometer (pW, efficient <100mK)

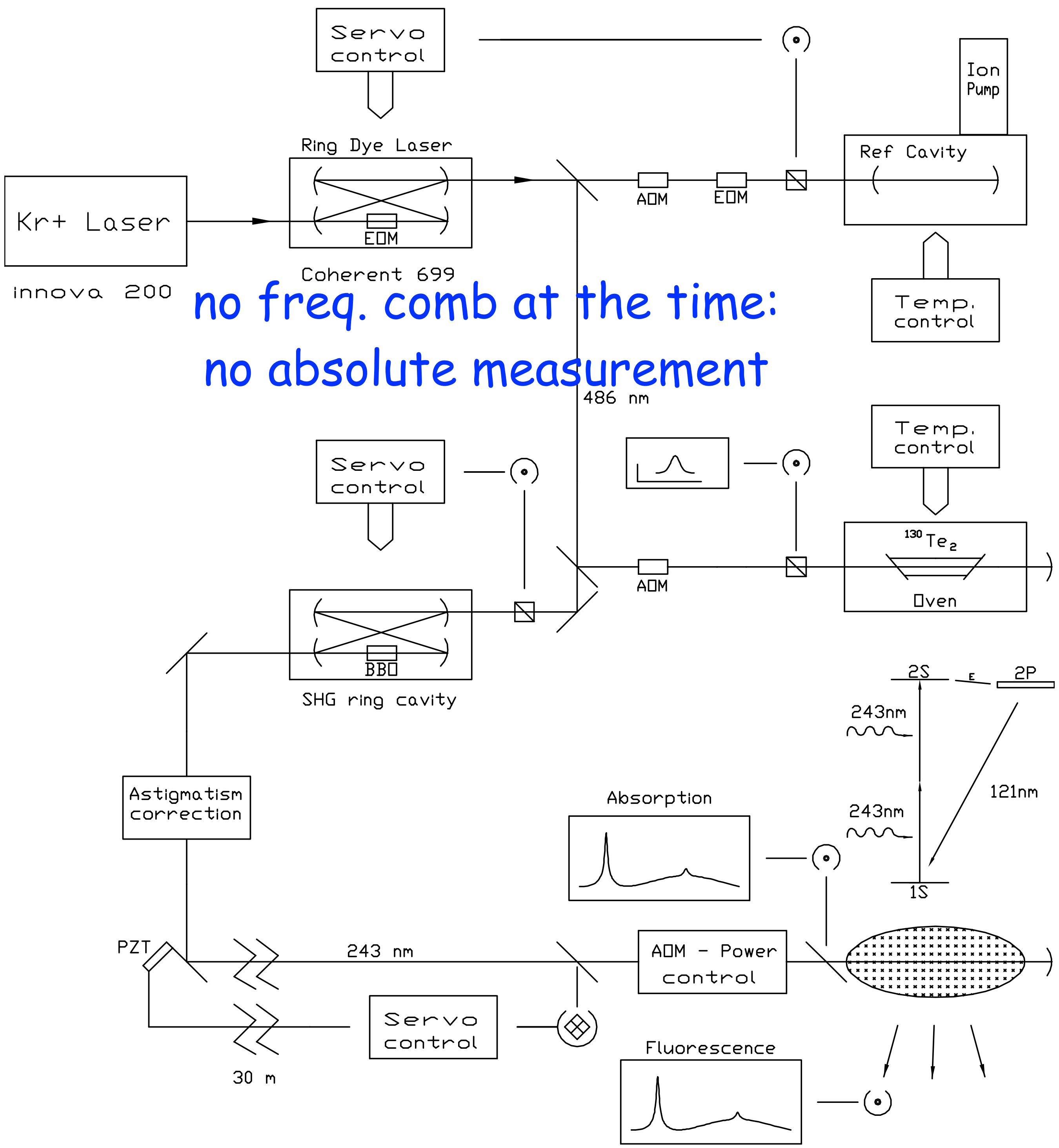



T. Killian's thesis

from 0.8 T to 15-20 x $10^{-4}$T in 5 mins (-> $10^{11}$ atoms @ $10^{14}$ $cm^{-3}$ @ 120 $\mu$K)

T. Killian's thesis

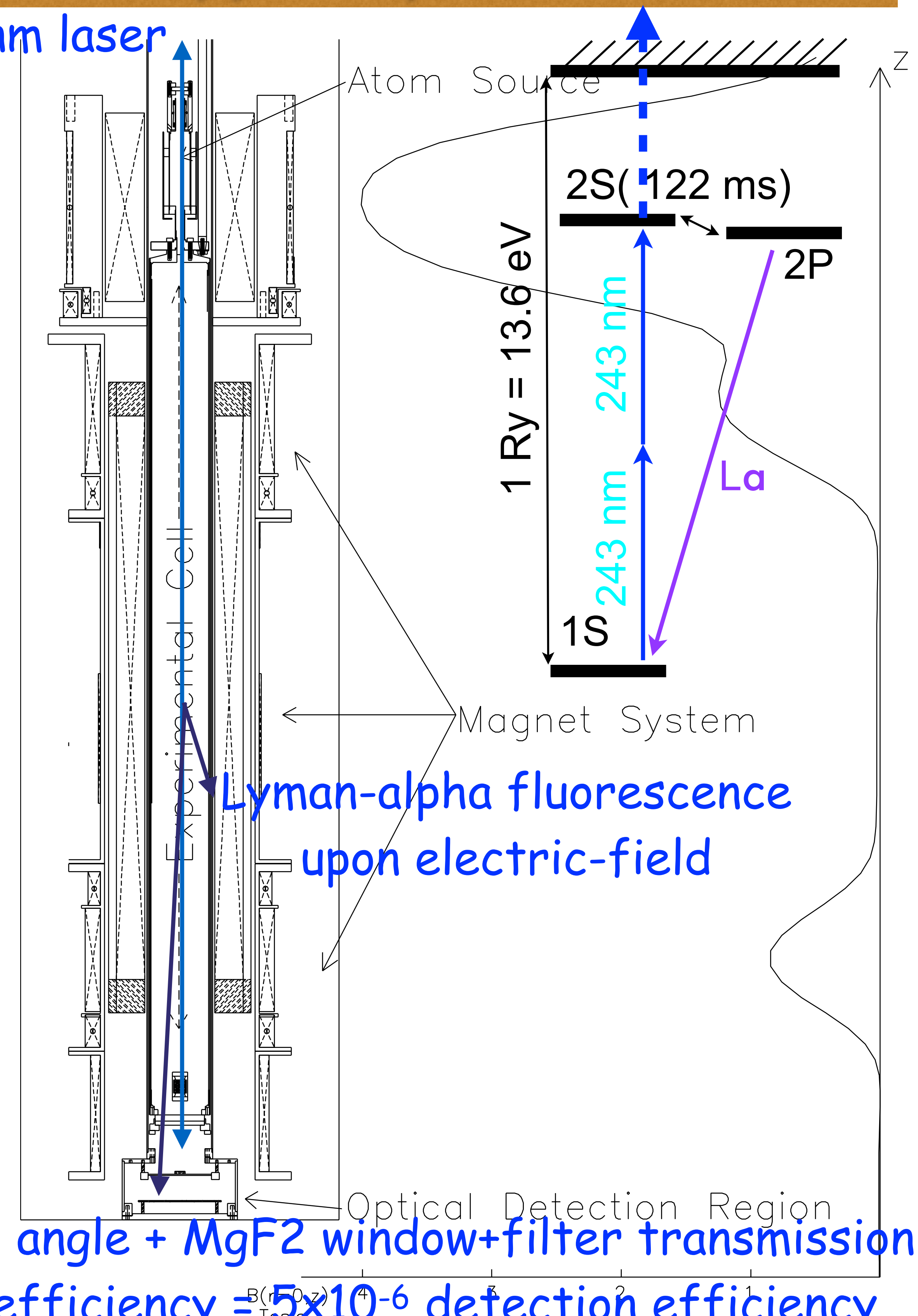
# MIT H+ trapping & spectroscopy setup




no freq. comb at the time:
no absolute measurement

CLC's thesis

243nm laser

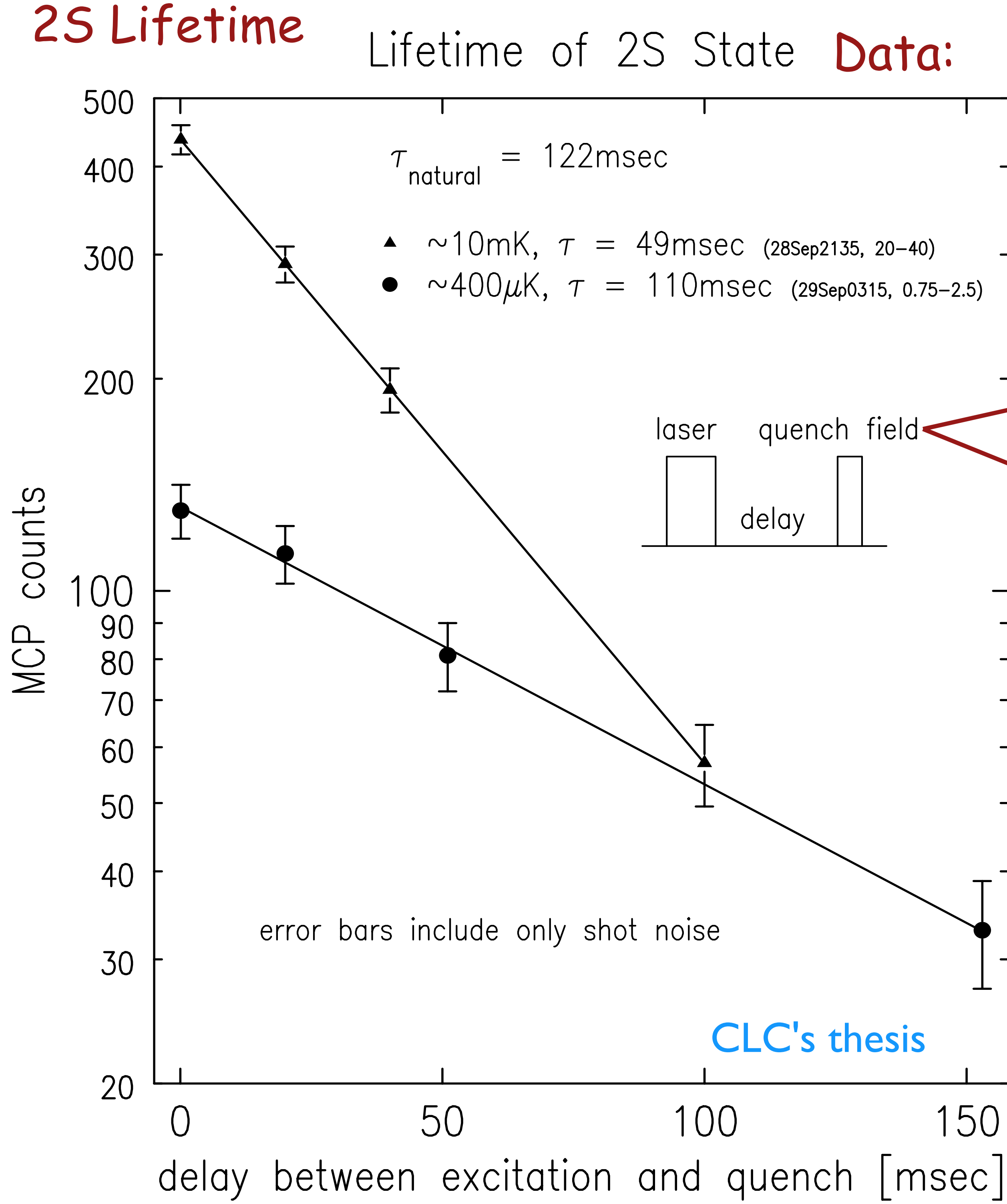


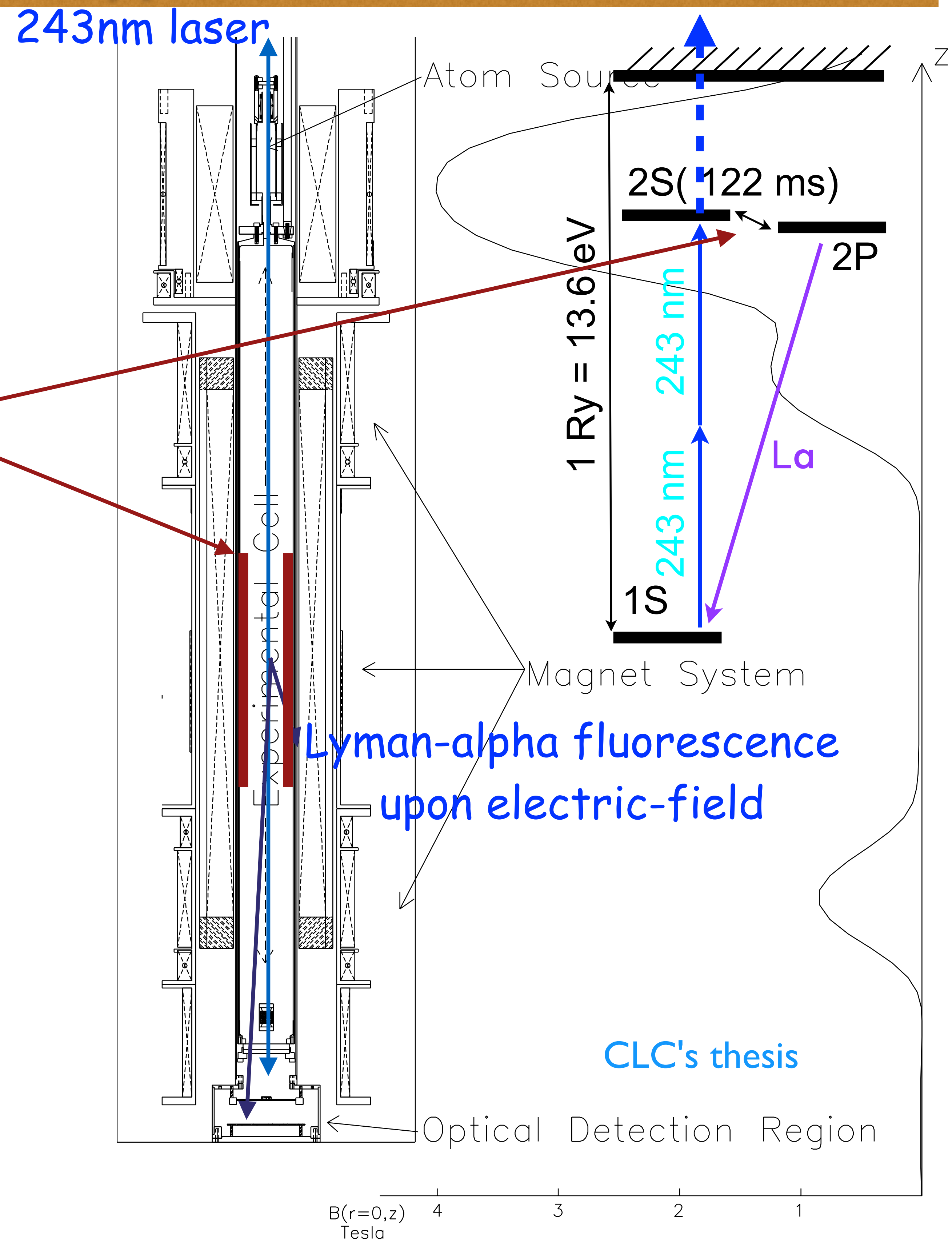

Lyman-alpha fluorescence
upon electric-field

$10^{-4}$ solid angle + MgF2 window+filter transmission
+ MCP efficiency = $5x10^{-6}$ detection efficiency

# MIT H+ Spectroscopy (1S-2S)

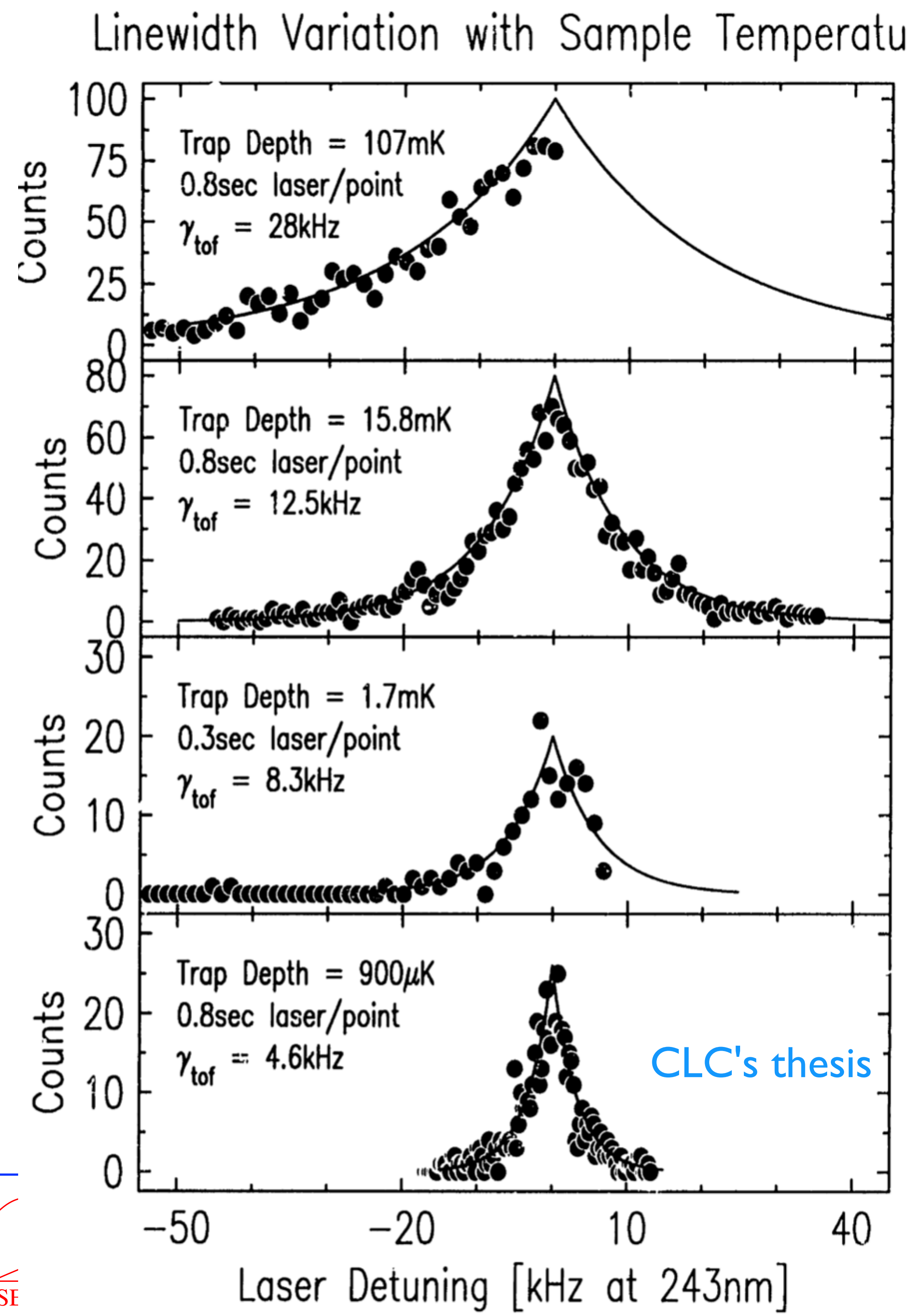
2S Lifetime

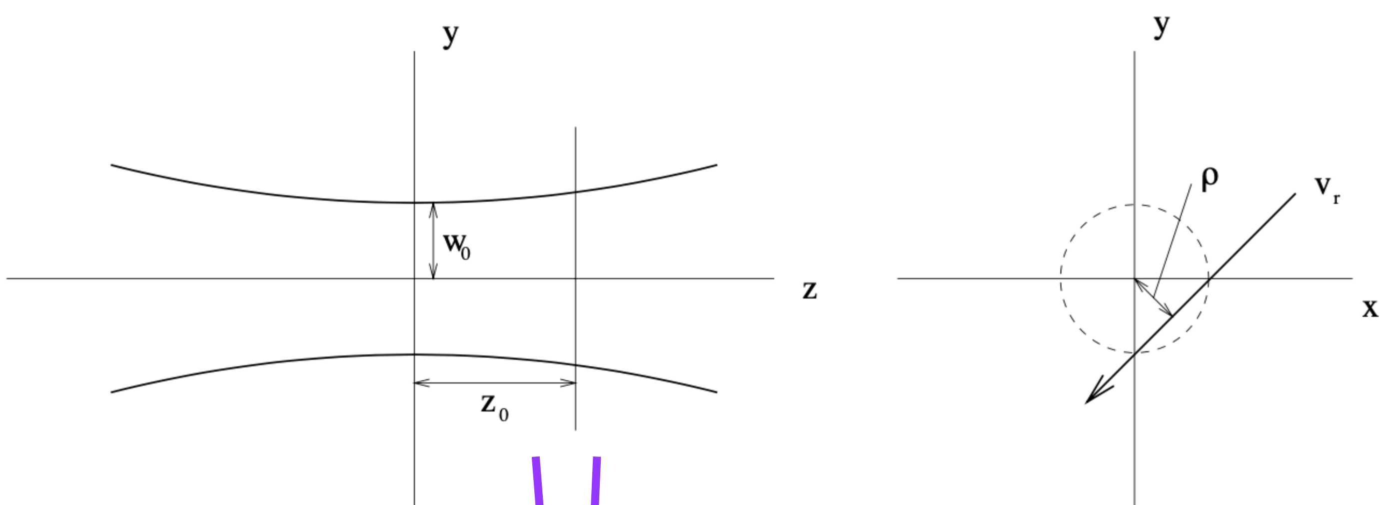


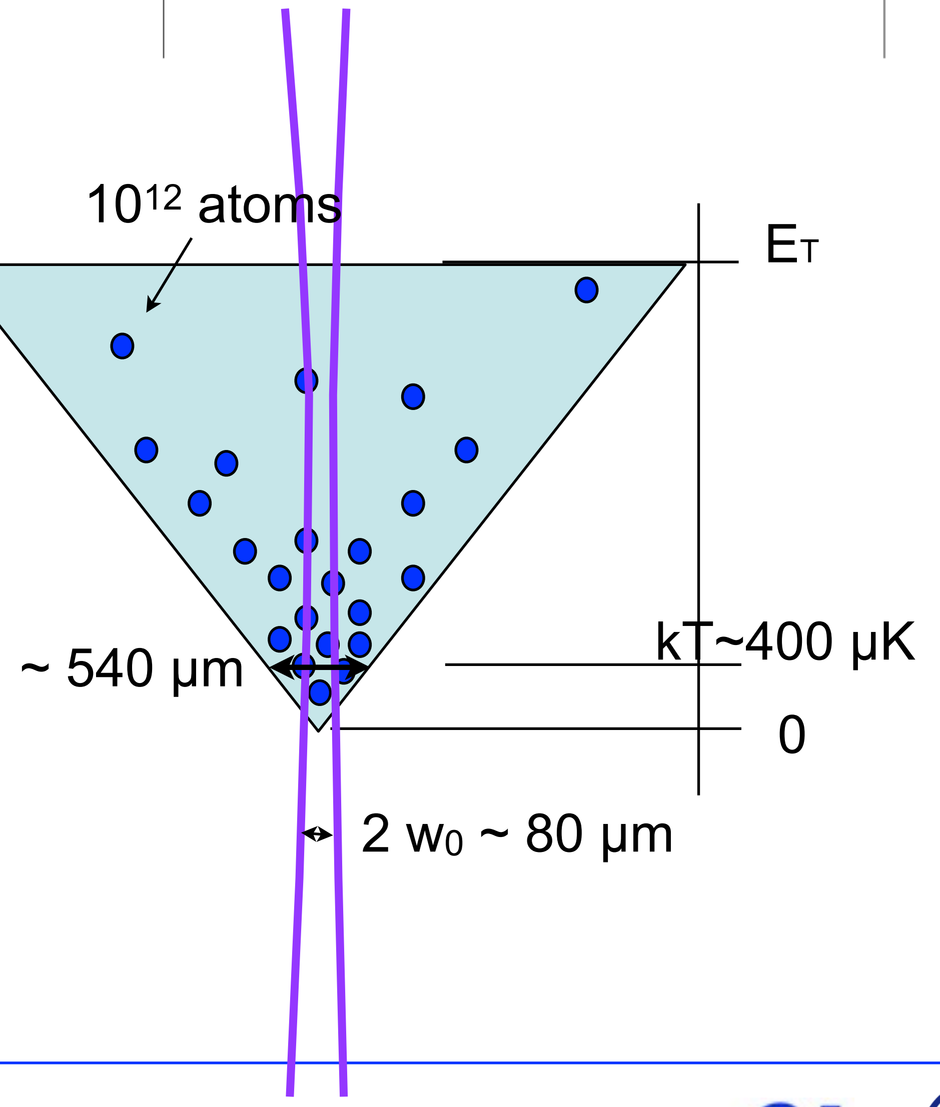



# MIT H+ Spectroscopy (1S-2S) : time-of-flight line shape

time-of-flight lineshape: F. Biraben's Thesis (Cagnac)
(cusped: double exponential)

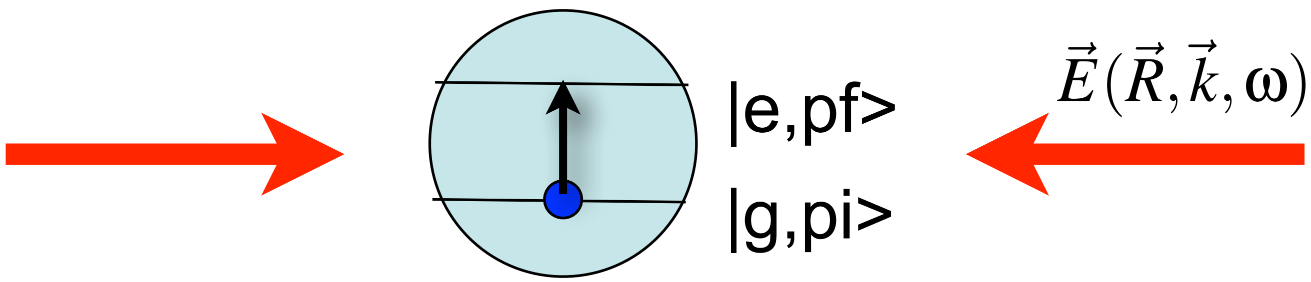


# MIT H+ Spectroscopy: time-of-flight => transverse momenta exchange

Doppler Spectroscopy (plane wave): momentum impart



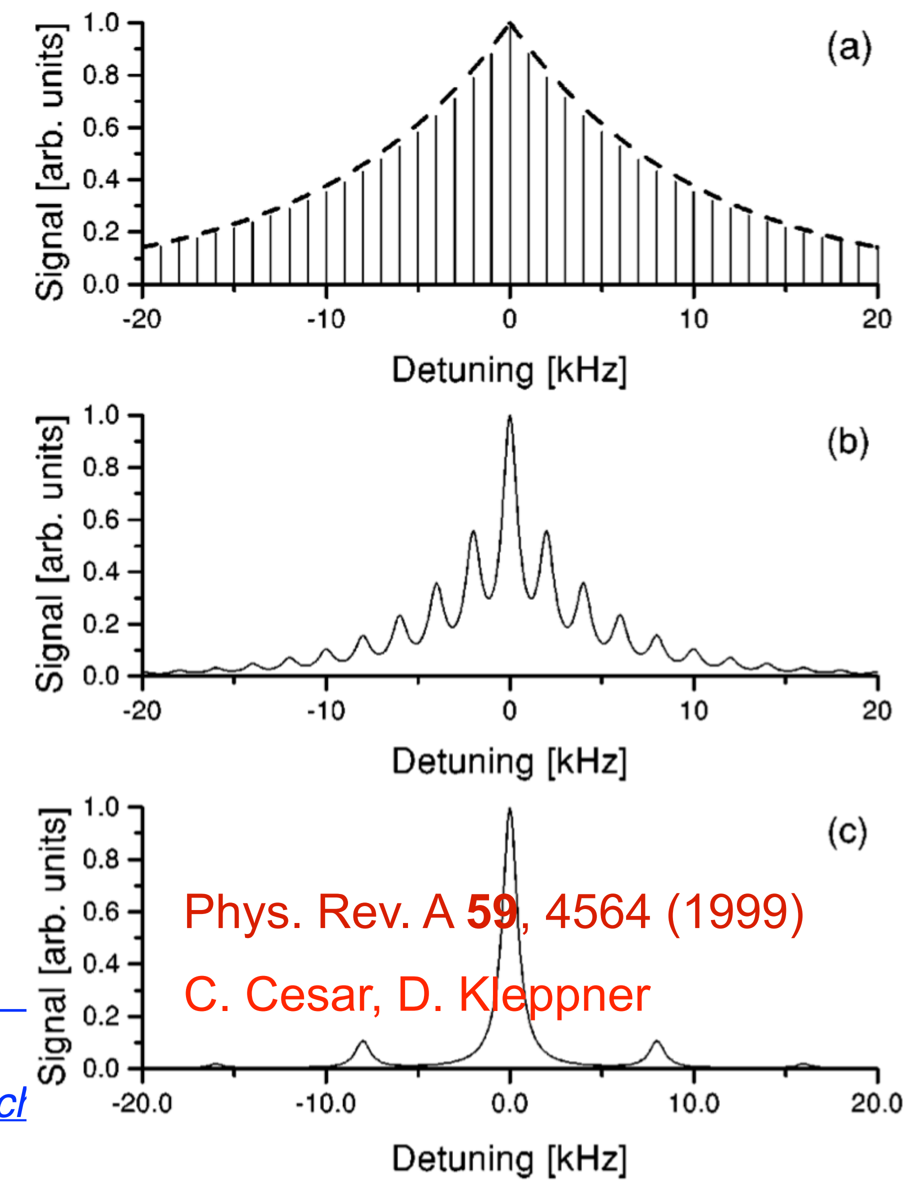

$$w_{g\rightarrow e} \propto < e, \vec{p}_f | e\vec{r}\cdot\vec{E} | g, \vec{p}_i >$$
$$\propto |\mu^j_{eg} < \vec{p}_f | e^{i\vec{k}\cdot\vec{R}} A(\vec{R}) | \vec{p}_i >|^2$$
$$(onda\ plana) \Rightarrow \vec{k}_f = \vec{k}_i + \vec{k}$$
$$\frac{(\hbar k_f)^2}{2m} = \frac{(\hbar k_i)^2}{2m} + \frac{(\hbar)^2 \vec{k}\cdot\vec{k}_i}{m} + \frac{(\hbar k)^2}{2m}$$
$$K_f = K_i + \hbar\Delta\omega_{Doppler} + K_{recuo}$$
$$\Delta\omega_{Doppler} = \vec{k}\cdot\vec{v}$$

time-of-flight lineshape: gaussian beam
(a better quantum mechanical look)

$$A(\vec{R}) \propto e^{-(X^2+Y^2)/(2w^2(Z))} \Rightarrow$$

gaussian beam => Fourier Transform => gaussian line shape for each transverse velocity profile accompanied by transverse momenta exchange

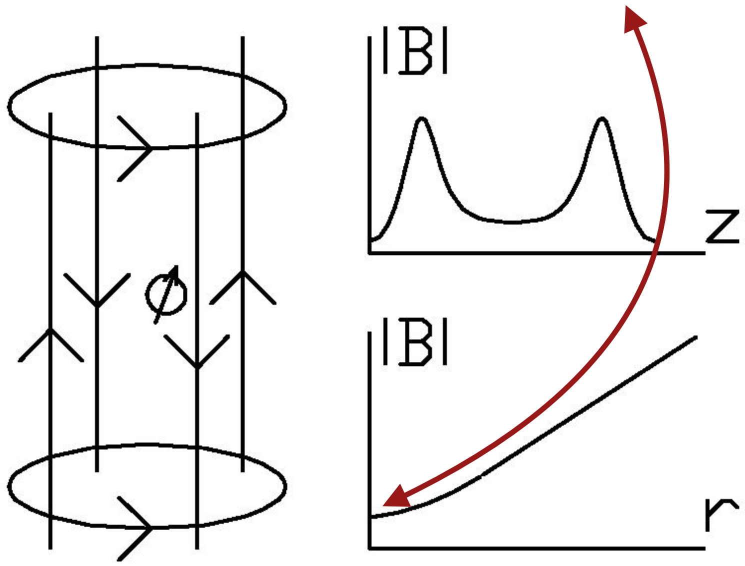
But in a trap: atomic momenta is QUANTIZED
If the trap is harmonic near the bottom:
equally spaced sidebands!
Pictured as:
Raman transition: electronic + 'atom-trap vibration'
or 'Multipass Ramsey Fringes'

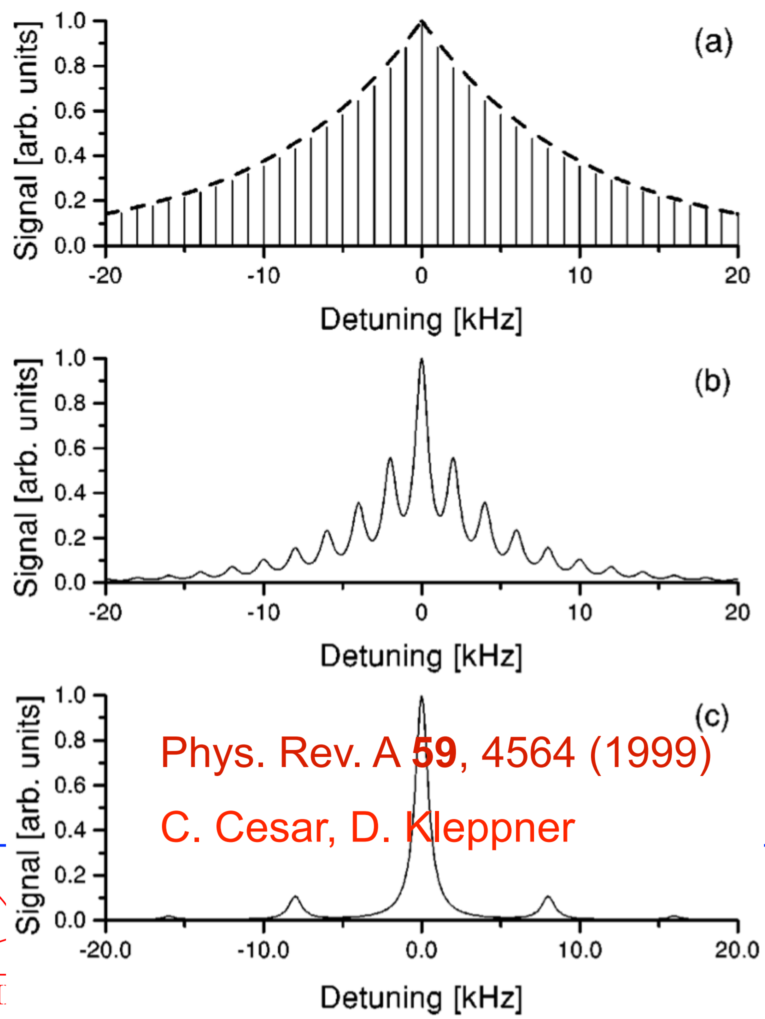



Phys. Rev. A **59**, 4564 (1999)
C. Cesar, D. Kleppner

# MIT H+ Spectroscopy: 1S-2S record resolution (1995)

time-of-flight lineshape: gaussian beam in a quasi-harmonic trap

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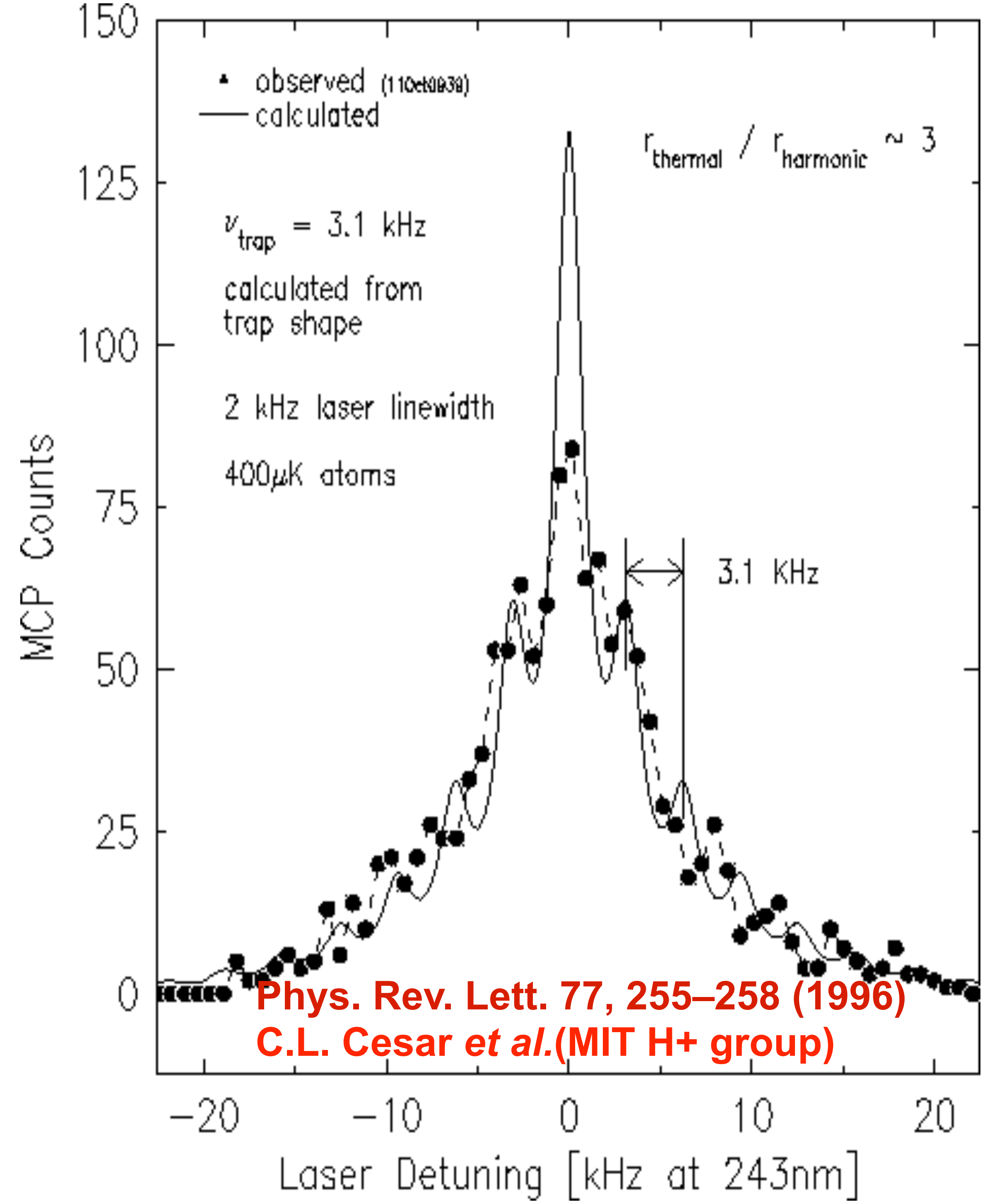



**Phys. Rev. Lett. 77, 255–258 (1996)**

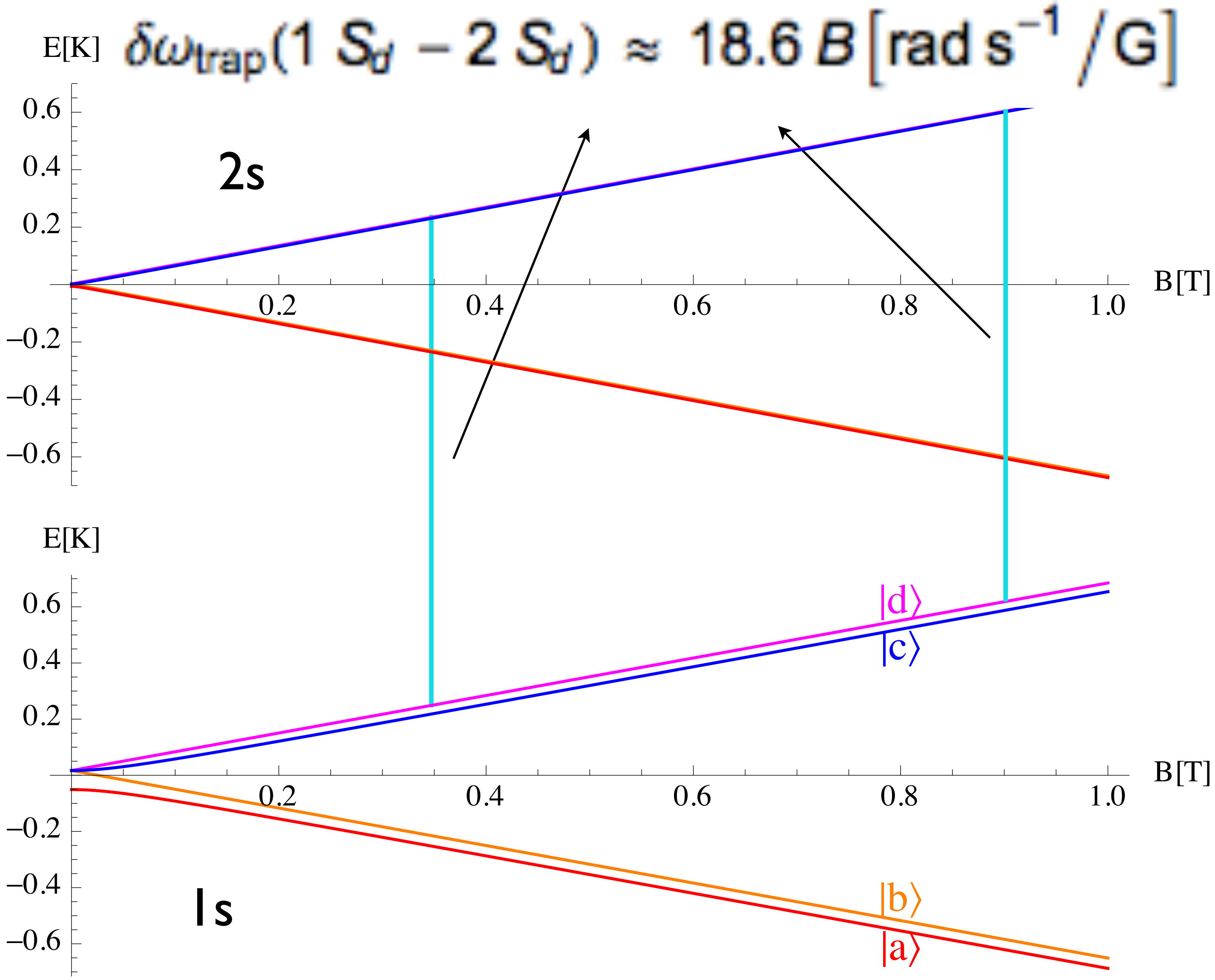
**C.L. Cesar *et al.*(MIT H+ group)**

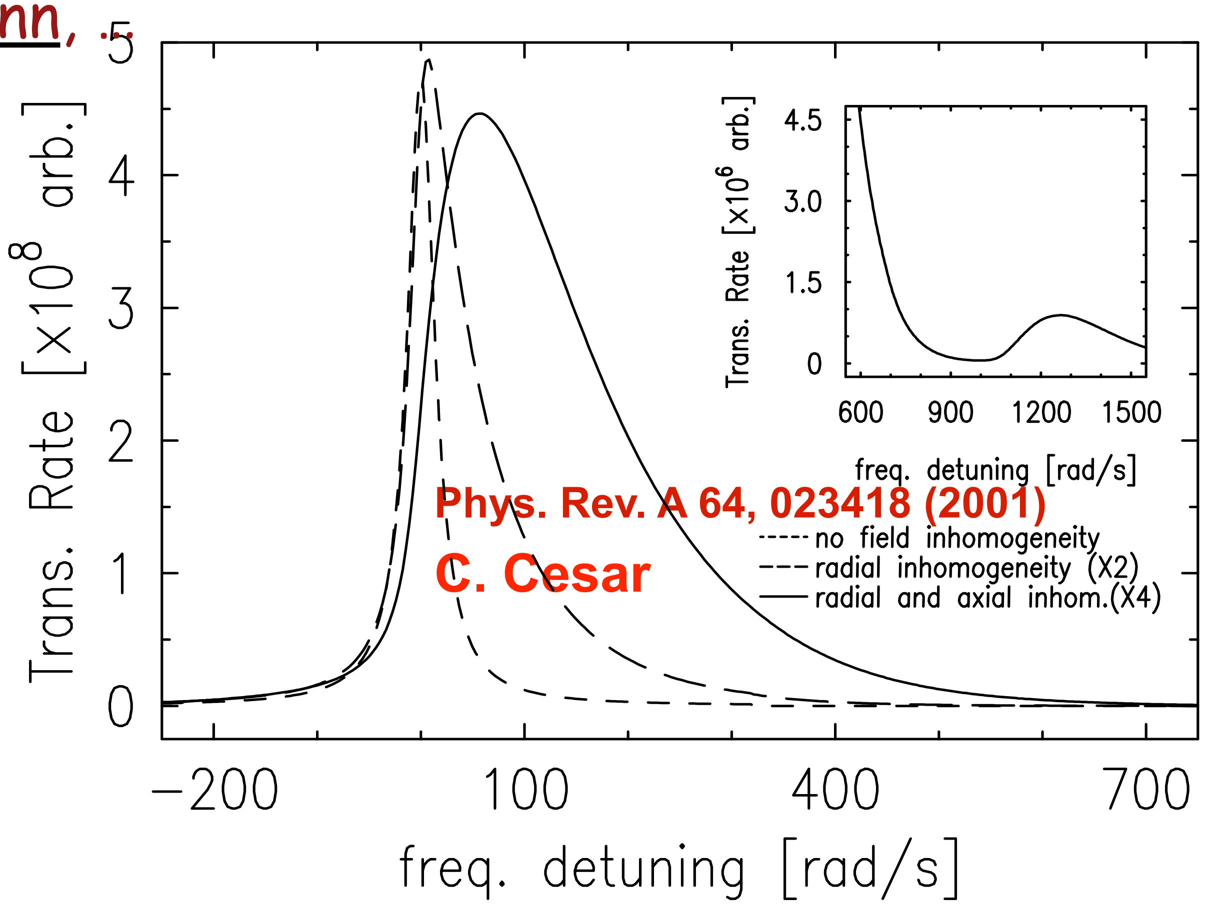
# MIT H+ Spectroscopy: experiment optimized for BEC (not 1S-2S)

BEC: Dale Fried, Thomas Killian, Lorenz Willmann, ...

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

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




$\delta\omega_{res} \sim 100$ rad/s => $\delta\omega_{res}/\omega \sim 6\times10^{-15}$

@ 100 $\mu$K for MIT trap

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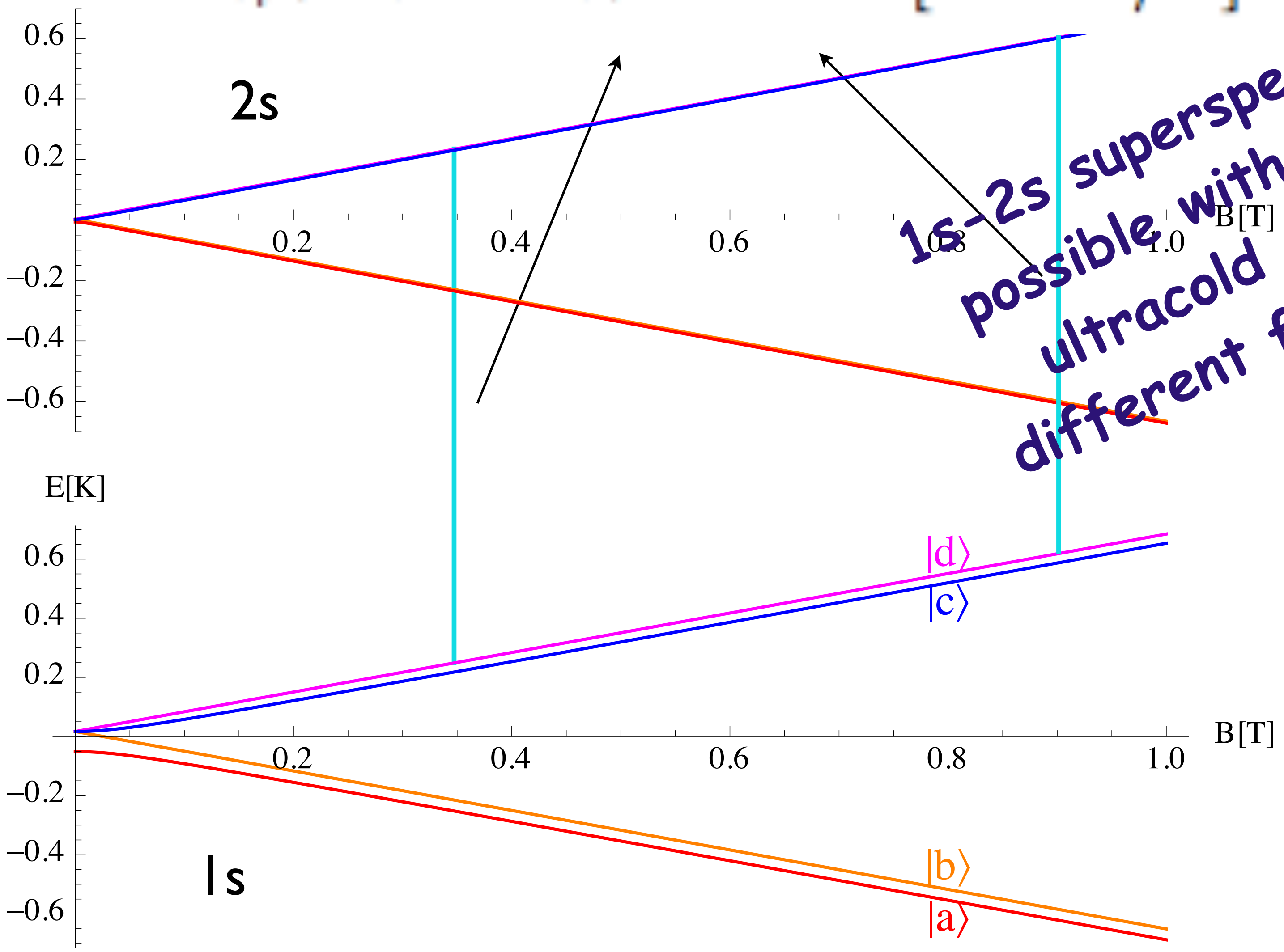
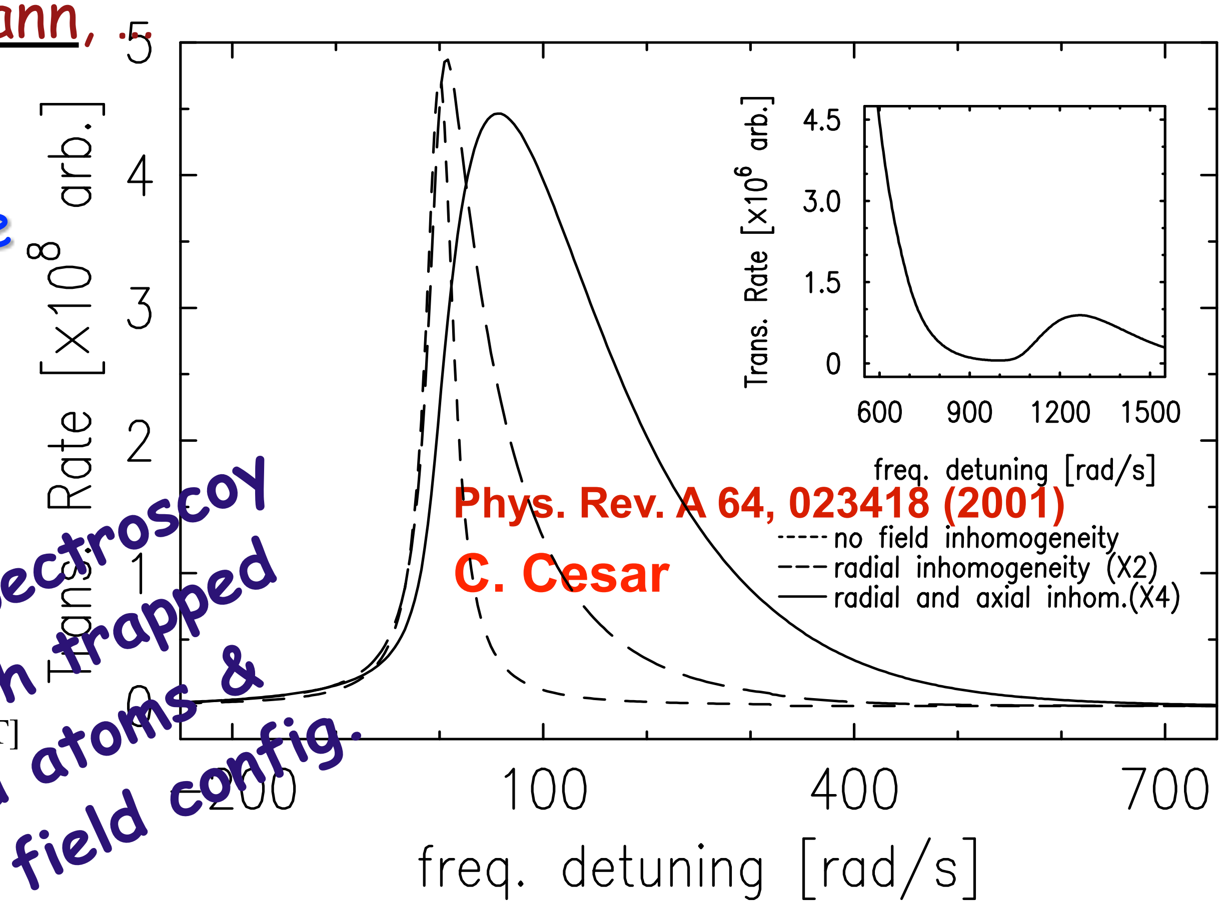



1s-2s superspectroscoy possible with trapped ultracold atoms & different field config.




Phys. Rev. A 64, 023418 (2001)

C. Cesar

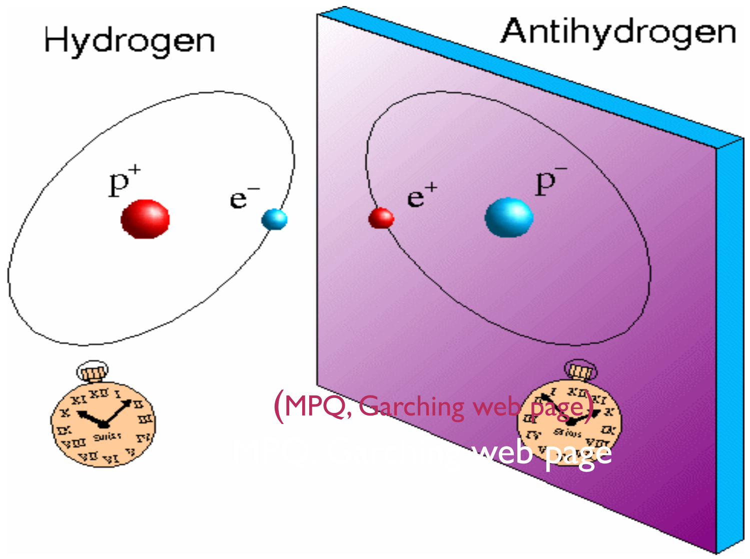
$\delta\omega_{res} \sim 100$ rad/s => $\delta\omega_{res}/\omega \sim 6\mathrm{x}10^{-15}$

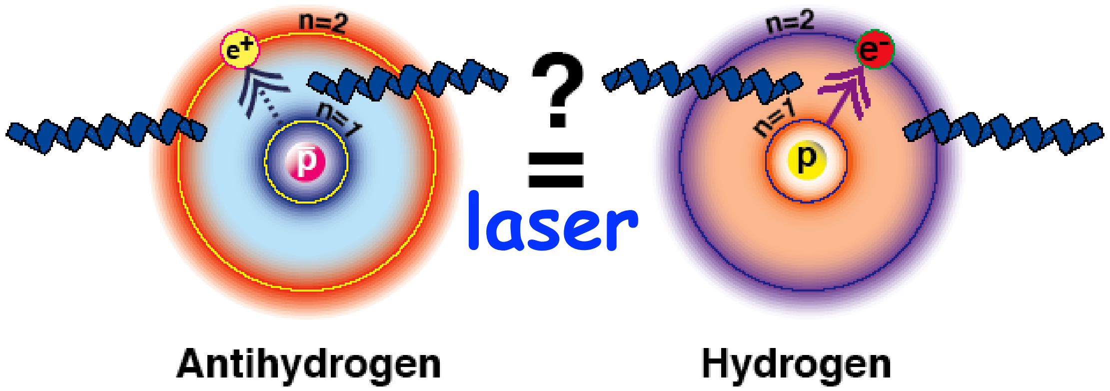
@ 100 $\mu$K for MIT trap

Research discontinued after BEC …
but @CSF Ticino:
Sergey Vasiliev, Thomas Udem, Pauline Yzombard, Paolo Crivelli, Derya Taray, Stephen Hogan, Carina Killian..

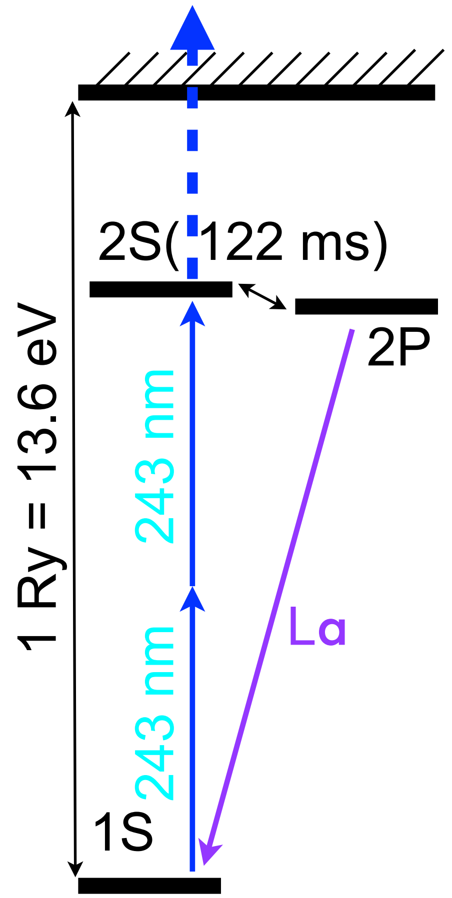
## H vs. Hbar

## 1 - CPT theorem, base of the Standard Model:

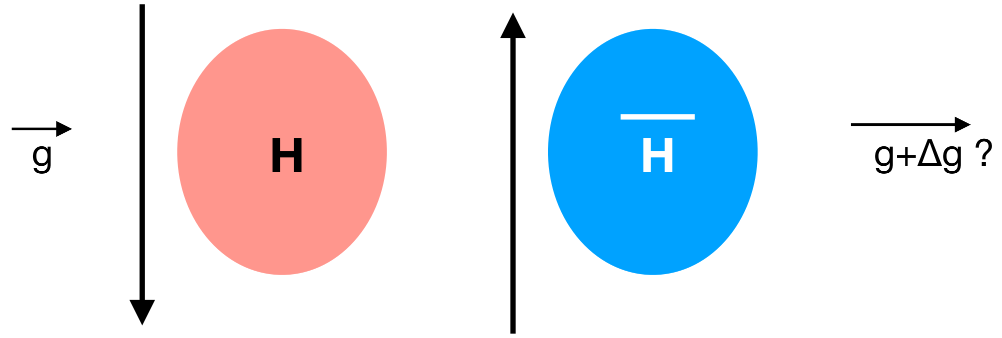



"CPT and Lorentz Tests in Hydrogen and Antihydrogen", Robert Bluhm, V. Alan Kostelecký, and Neil Russell, PRL 82, 2254 (1999)

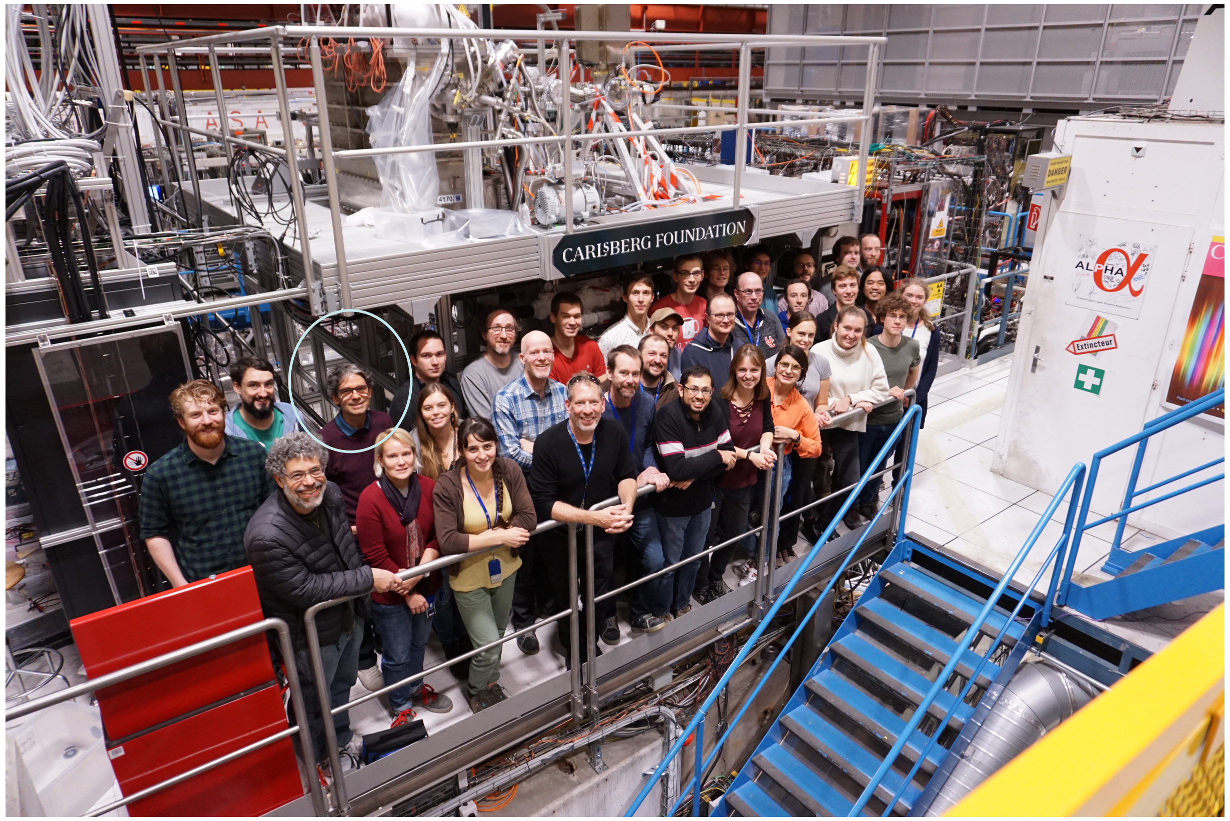


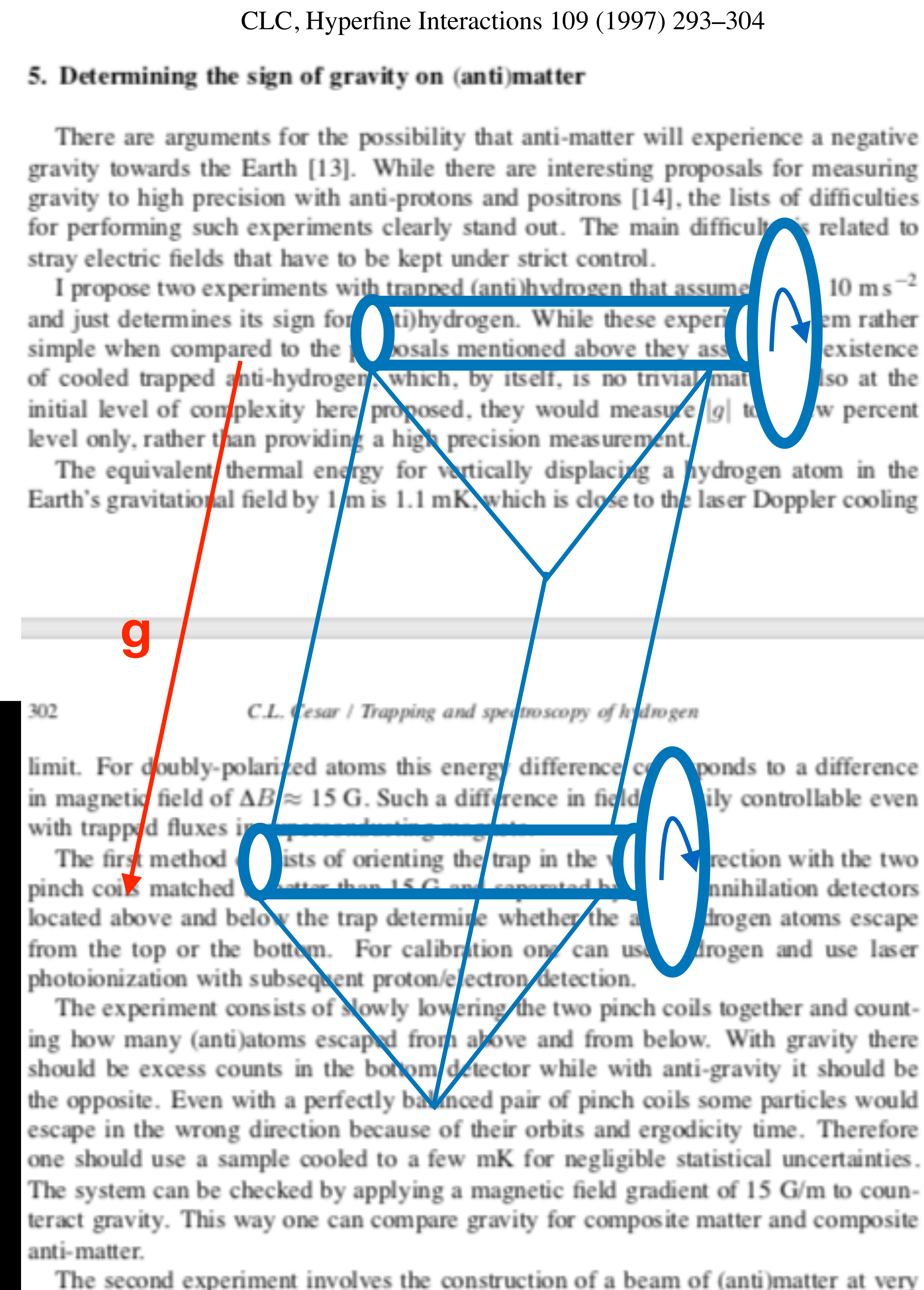

## 2 - Equivalence Principle: g, or g+Δg ??




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

# (ALPHA-g : towards the observation of antimatter fall)




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

I propose two experiments with trapped (anti)hydrogen that assume [illegible] 10 m s$^{-2}$ and just determines its sign fo[illegible]ti)hydrogen. While these experi[illegible]em rather simple when compared to the p[illegible]osals mentioned above they ass[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]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

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 field[illegible]ily controllable even with trapped fluxes i[illegible]

The first method [illegible]ists of orienting the trap in the [illegible]rection with the two pinch coils matched [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]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

[redacted]

[redacted]@cern.ch

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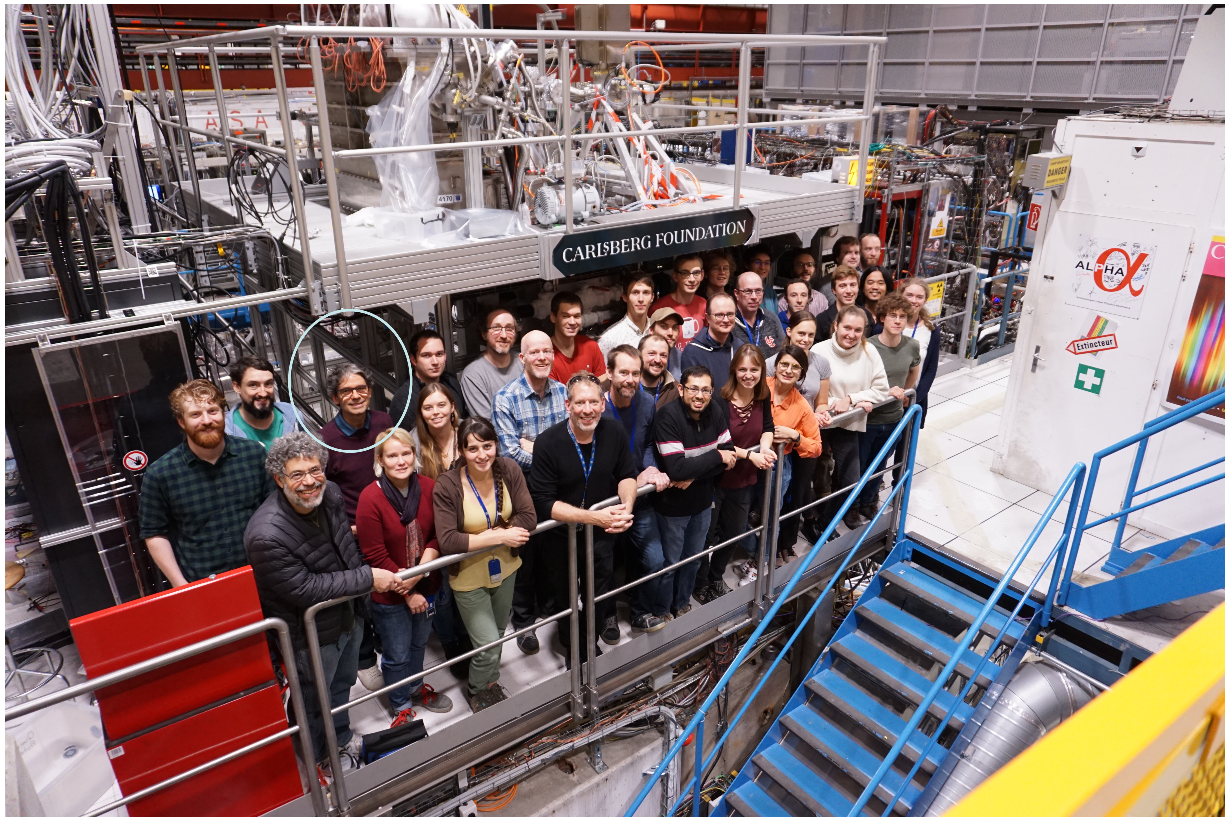


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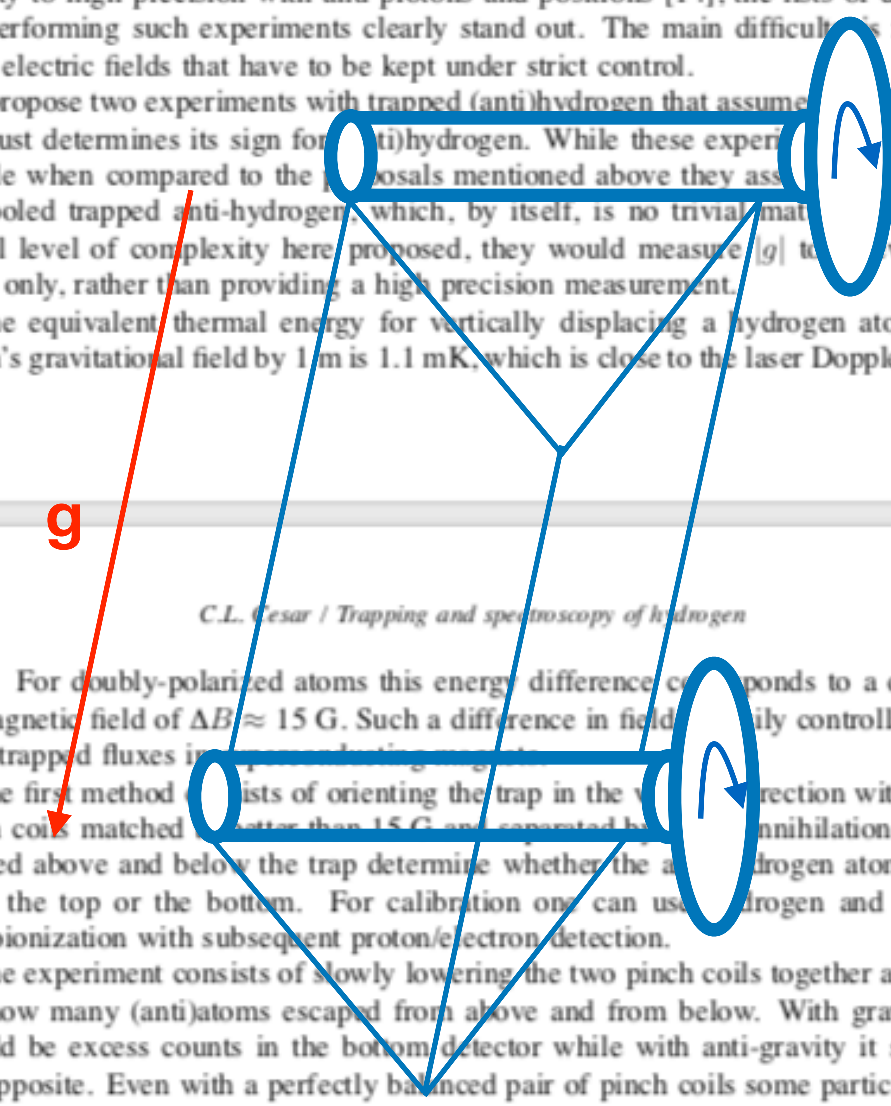


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limit. For doubly-polarized atoms this energy difference corresponds to a difference in magnetic field of $\Delta B \approx 15$ G. Such a difference in field is easily controllable even with trapped fluxes in superconducting magnets.

The first method consists of orienting the trap in the vertical direction with the two pinch coils matched [illegible] annihilation detectors located above and below the trap determine whether the antihydrogen atoms escape from the top or the bottom. For calibration one can use hydrogen and use laser photoionization with subsequent proton/electron detection.

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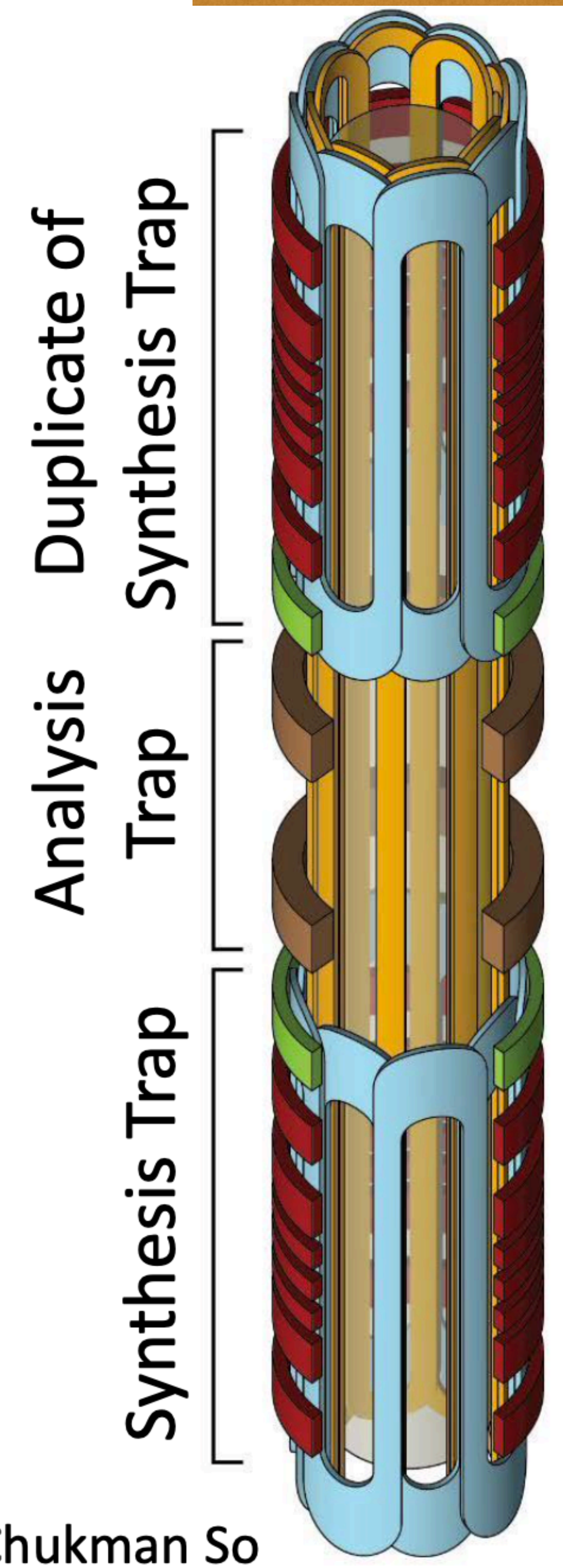
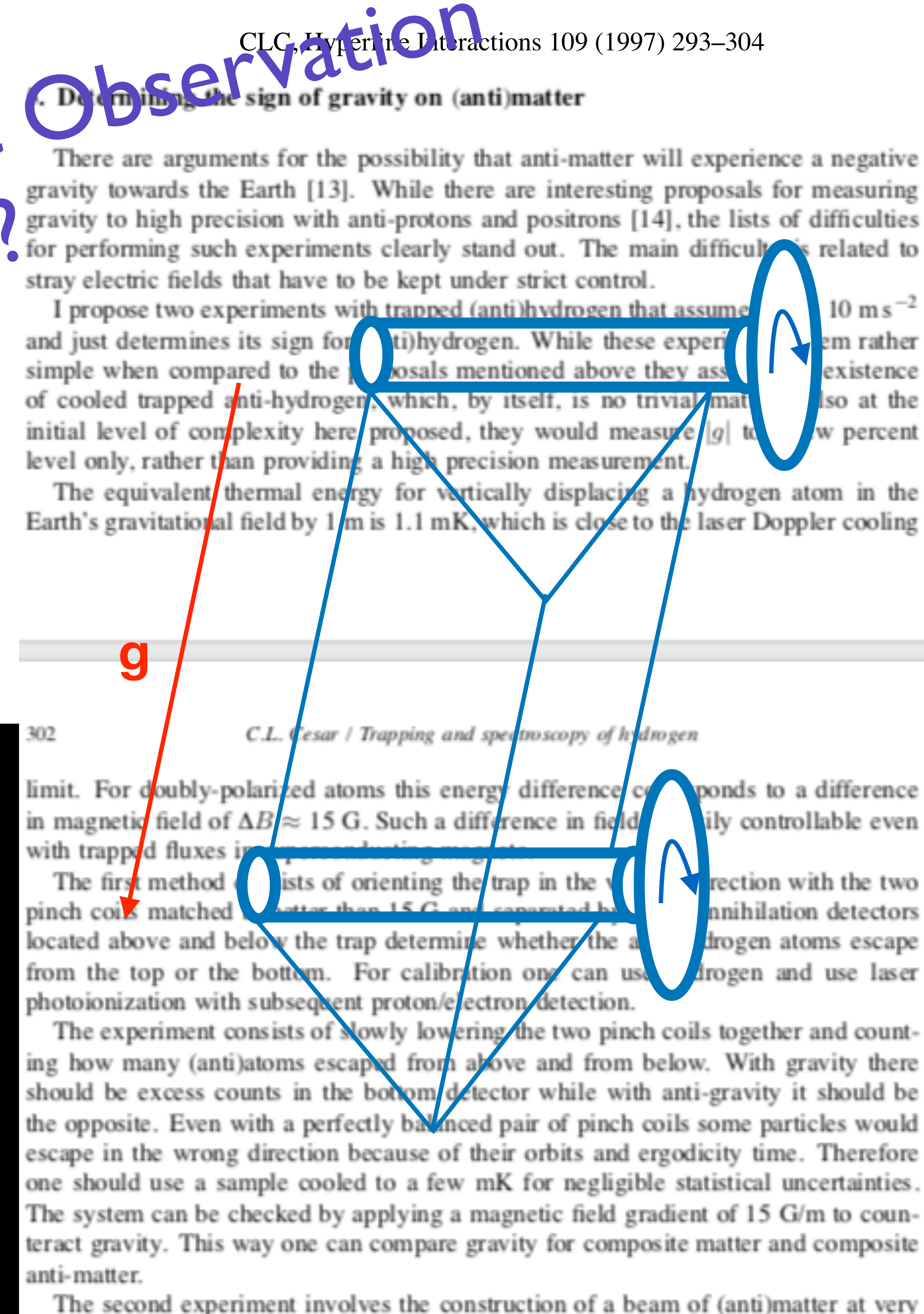




Results Soon of 1st Observation

+ - g ?

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# ALPHA Collaboration @ CERN: ALPHA-2 Laser Spectroscopy

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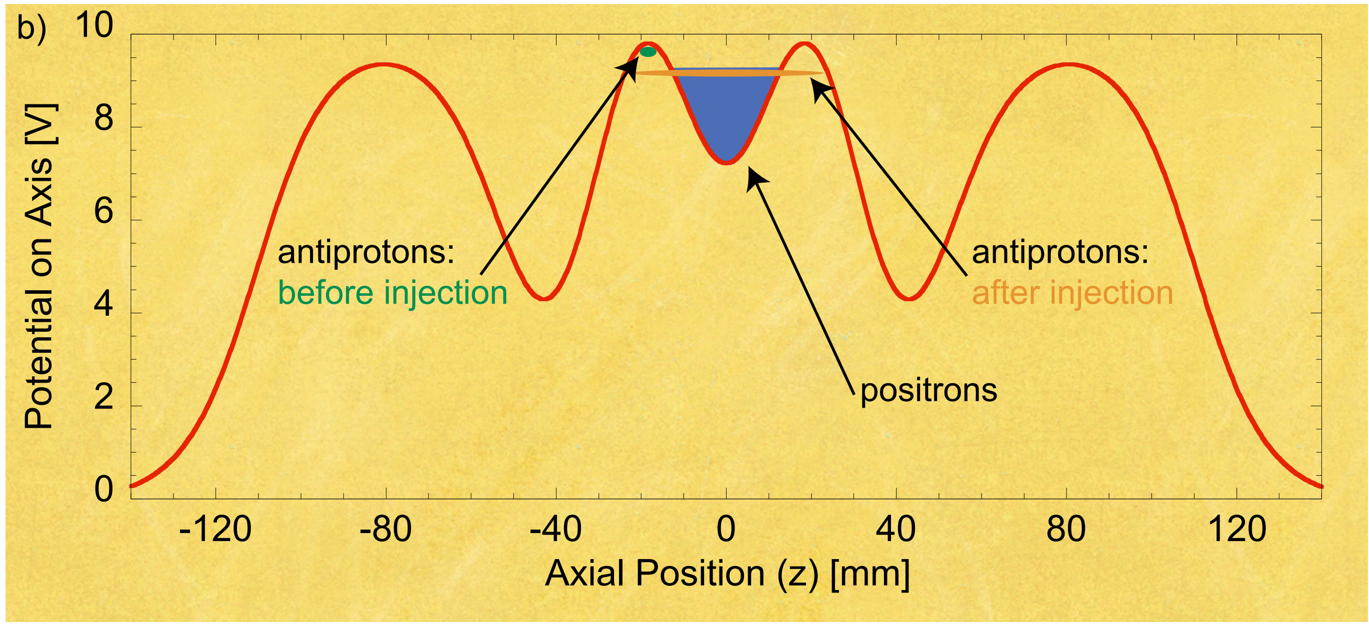
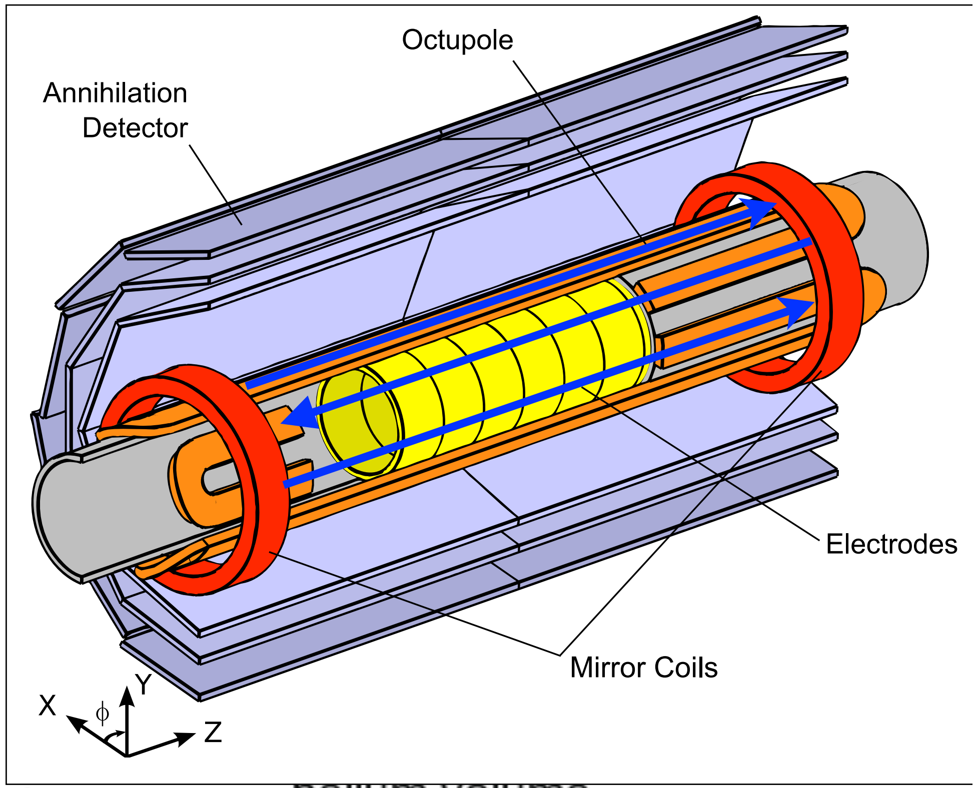
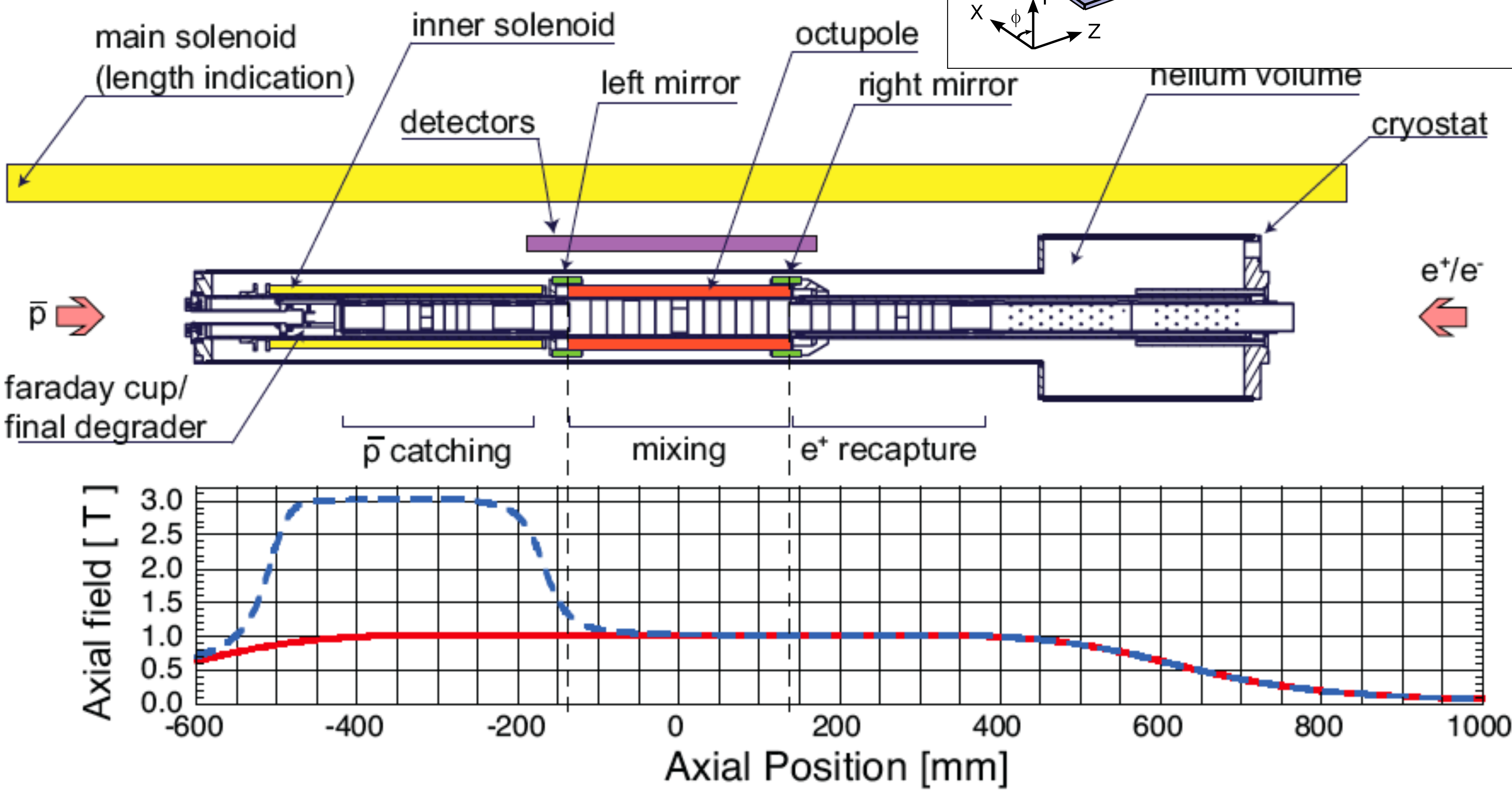
# ALPHA-1 : Fields Configuration



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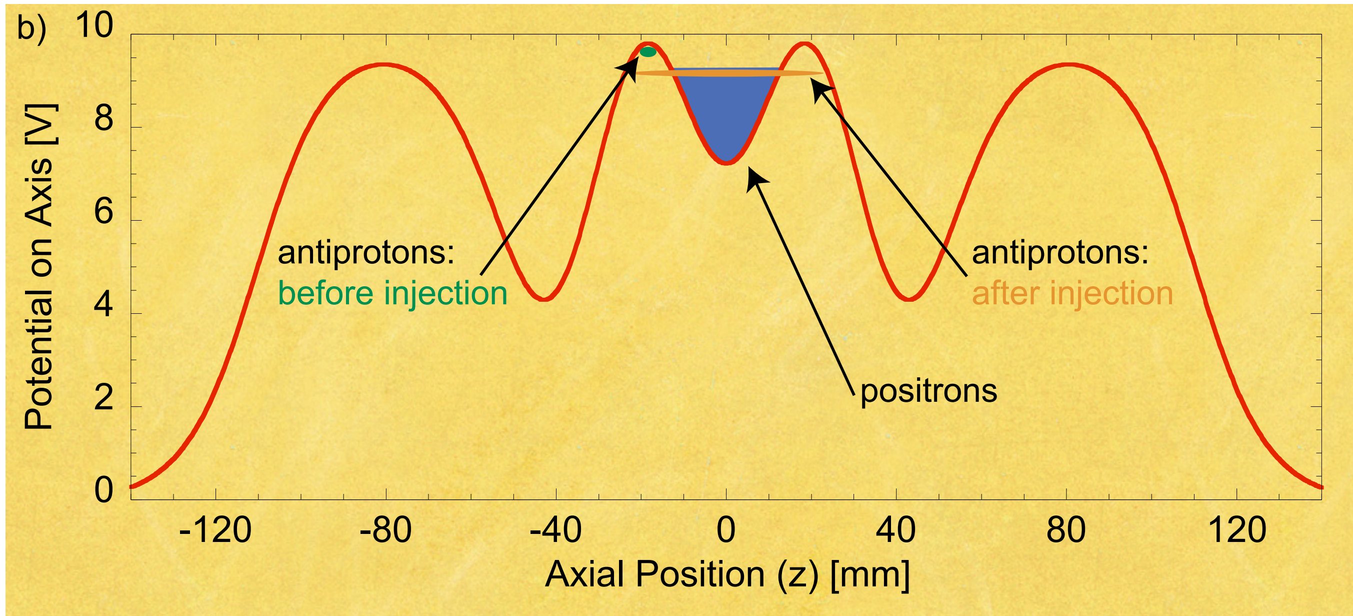


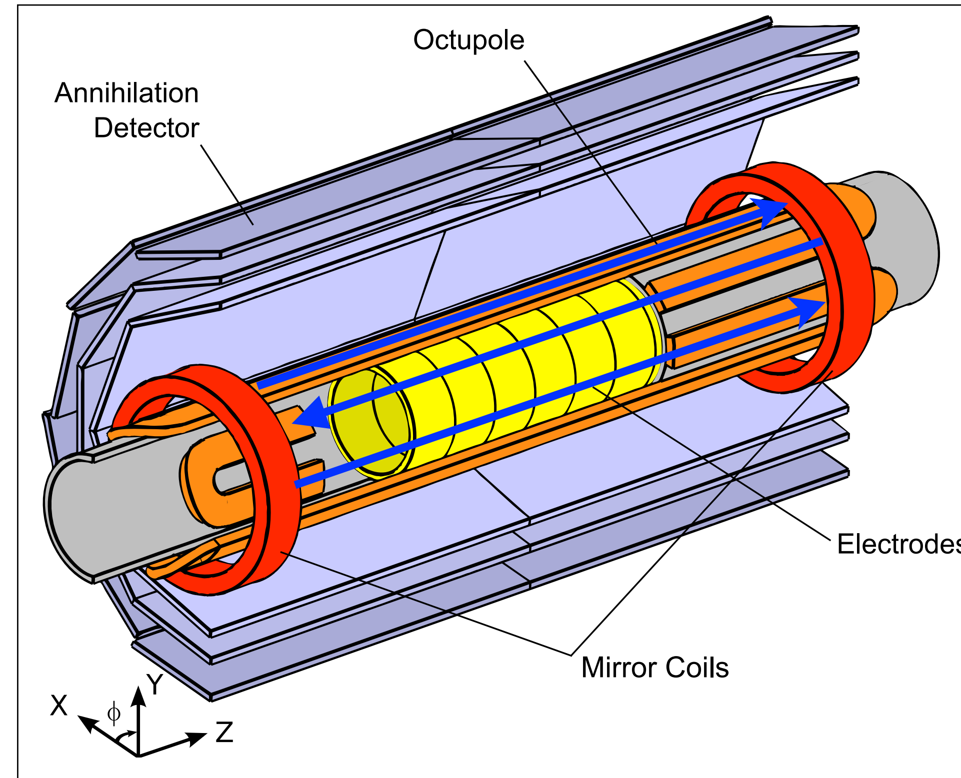


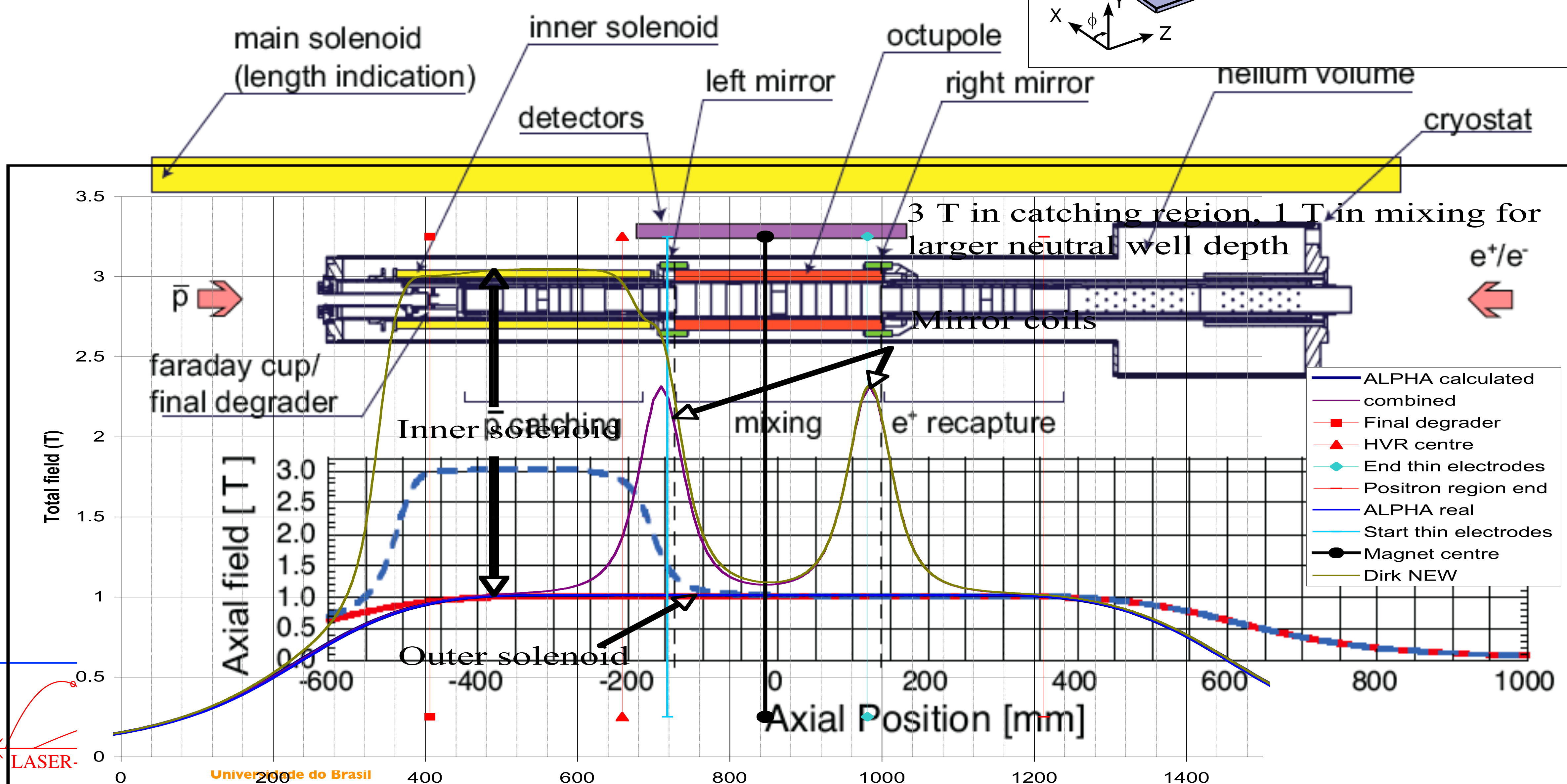


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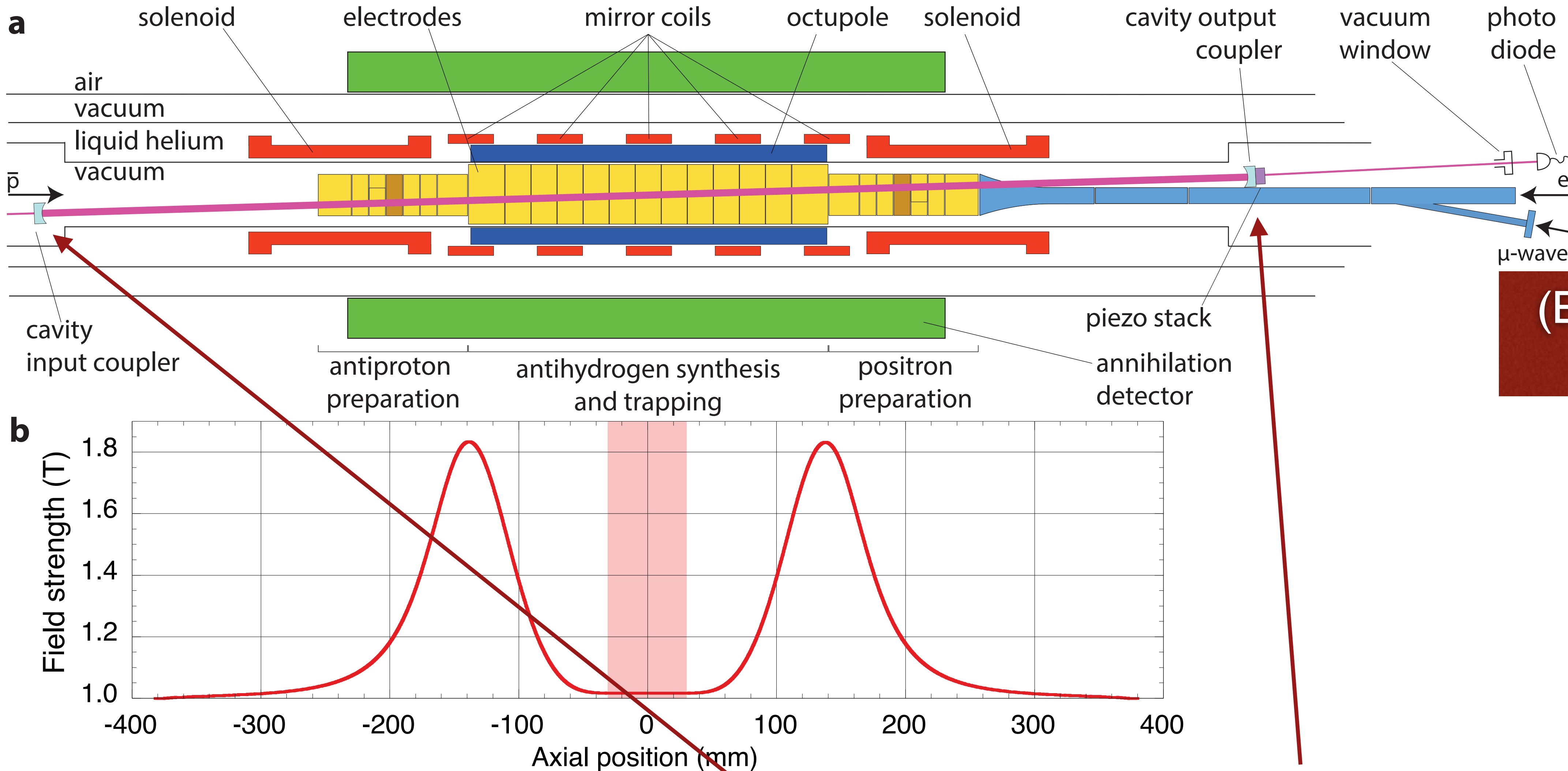
# Characterization of the 1S–2S transition in antihydrogen

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]

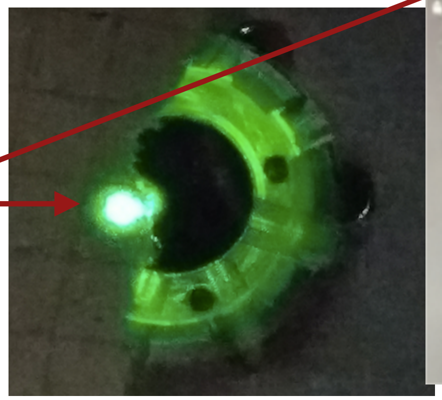
**In 1928, Dirac published an equation[1] that combined quantum mechanics and special relativity. Negative-energy solutions to this equation, rather than being unphysical as initially thought, represented a class of hitherto unobserved and unimagined particles—antimatter. The existence of particles of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

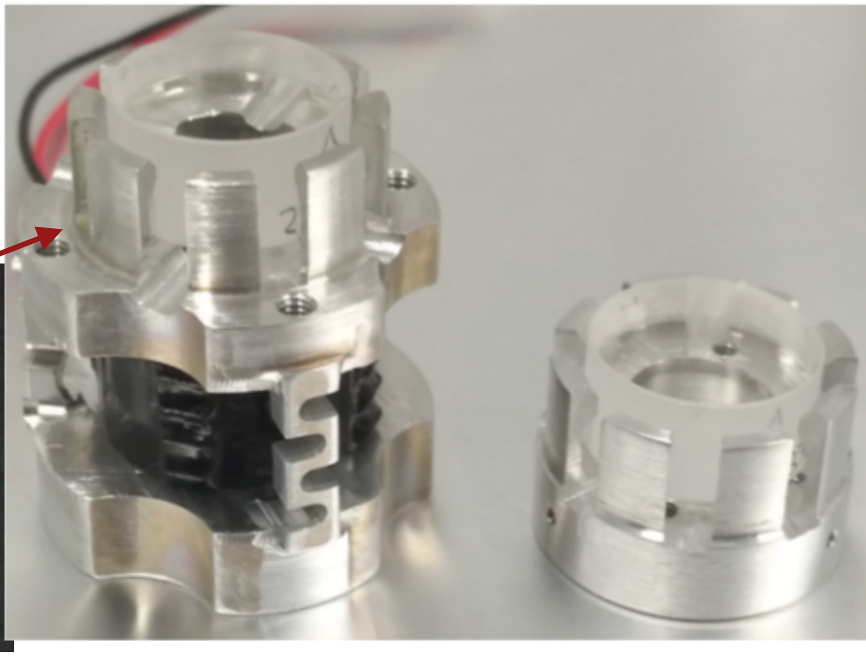
it is produced with a kinetic energy of less than 0.54 K in temperature units. The techniques that we use to produce antihydrogen that is cold enough to trap are described elsewhere[12–14]. In round numbers, a typical trapping trial in ALPHA-2 involves mixing 90,000 antiprotons with 3,000,000 positrons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




(ECR)B-field measure

Cryogenic Optical Cavity: made in Brasil



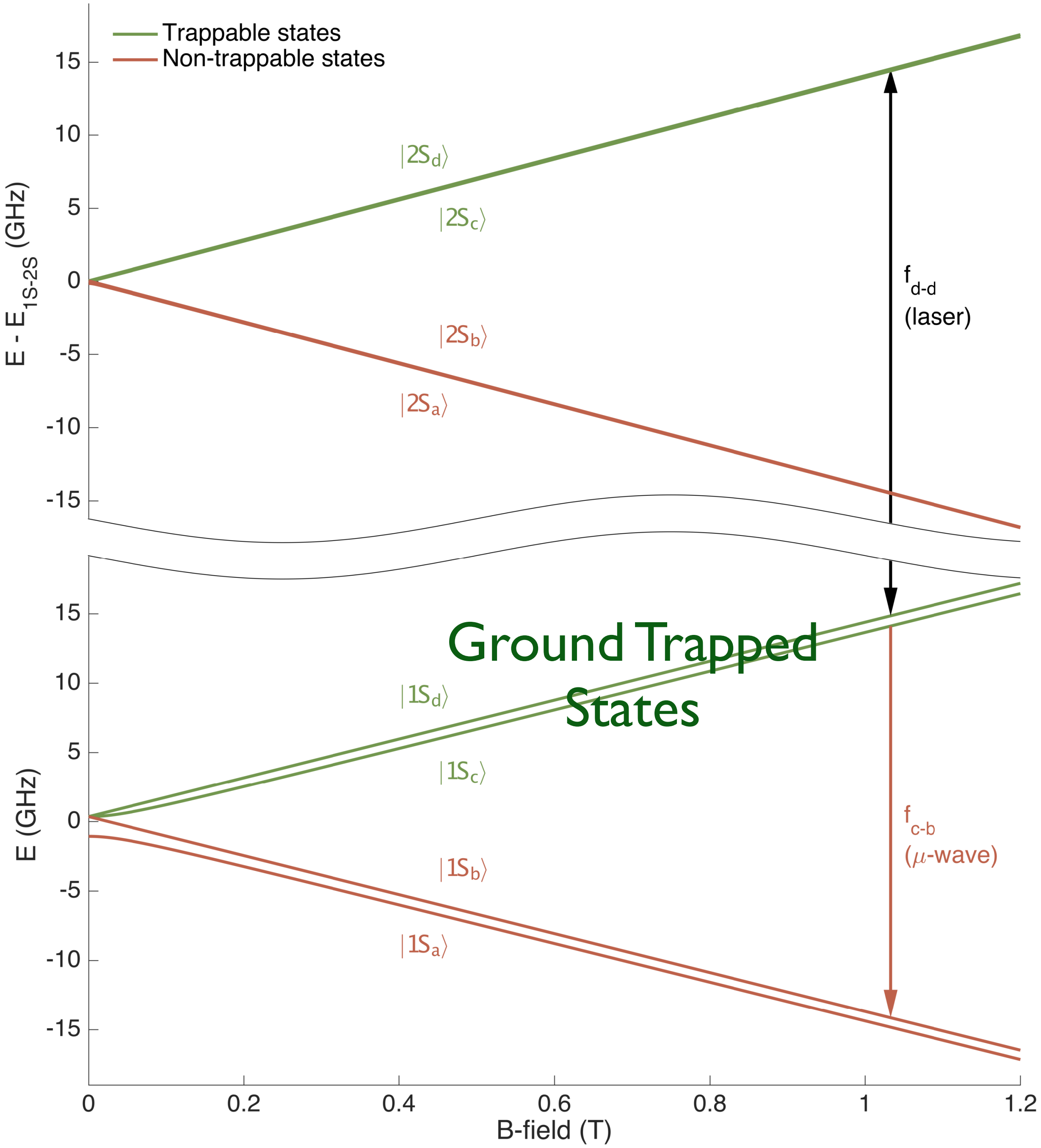


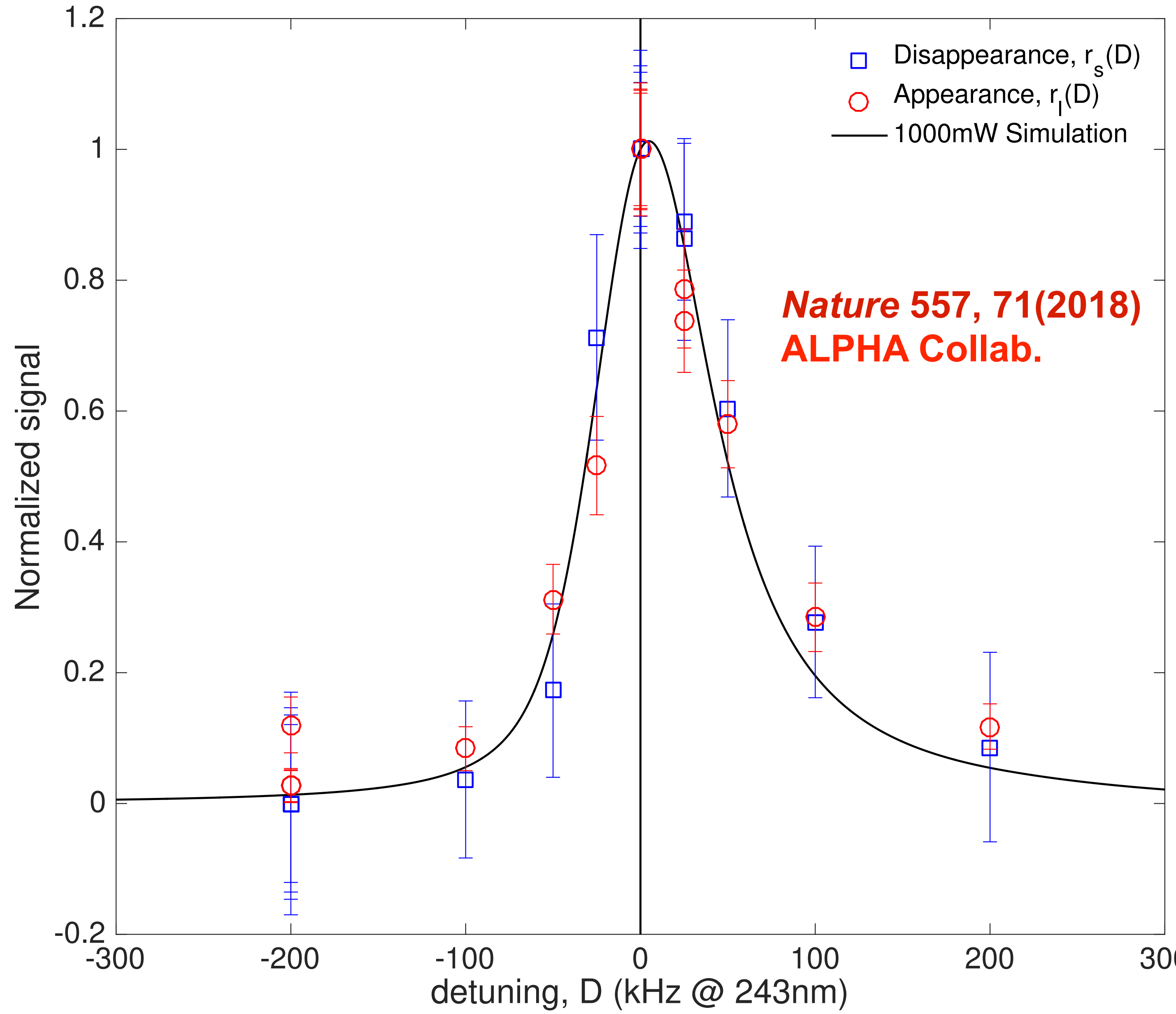
26. Oliveira, A. N. et al. Cryogenic mount for mirror and piezoelectric actuator for an optical cavity. Rev. Sci. Instrum. **88**, 063104 (2017).

# Antihydrogen 1S-2S

## Lineshapes 6

## 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)

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

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

# Systematics

**Table 3 | Summary of uncertainties**

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

| Type of uncertainty | Estimated size (kHz) | Comment | |
|---|---|---|---|
| Statistical uncertainties | 3.8 | Poisson errors and curve fitting to measured data | ↘ * higher stats (2021) |
| Modelling uncertainties | 3 | Fitting of simulated data to piecewise-analytic function | ↘ can do a better job (2022) |
| Modelling uncertainties | 1 | Waist size of the laser, antihydrogen dynamics | can do a better job (2023) |
| Magnetic-field stability | 0.03 | From microwave removal of $1S_c$-state atoms (see text) | |
| Absolute magnetic-field measurement | 0.6 | From electron cyclotron resonance | ↘ vs. H (?), it vanishes(202x) |
| Laser-frequency stability | 2 ↘ | Limited by GPS clock | already addressed (2022) |
| d.c. Stark shift | 0.15 | Not included in simulation | |
| Second-order Doppler shift | 0.08 | Not included in simulation | |
| Discrete frequency choice of measured points | 0.36 ↘ | Determined from fitting sets of pseudo-data | easy & laser cooling (2021) |
| Total | 5.4 | | |

The estimated statistical and systematic errors (at 121 nm) are tabulated.

Other which will dominate in 2021:
laser power (AC StarkShift) & cavity lock
*Statistics: with Hbar stacking: 7-10 weeks in 1 day!

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

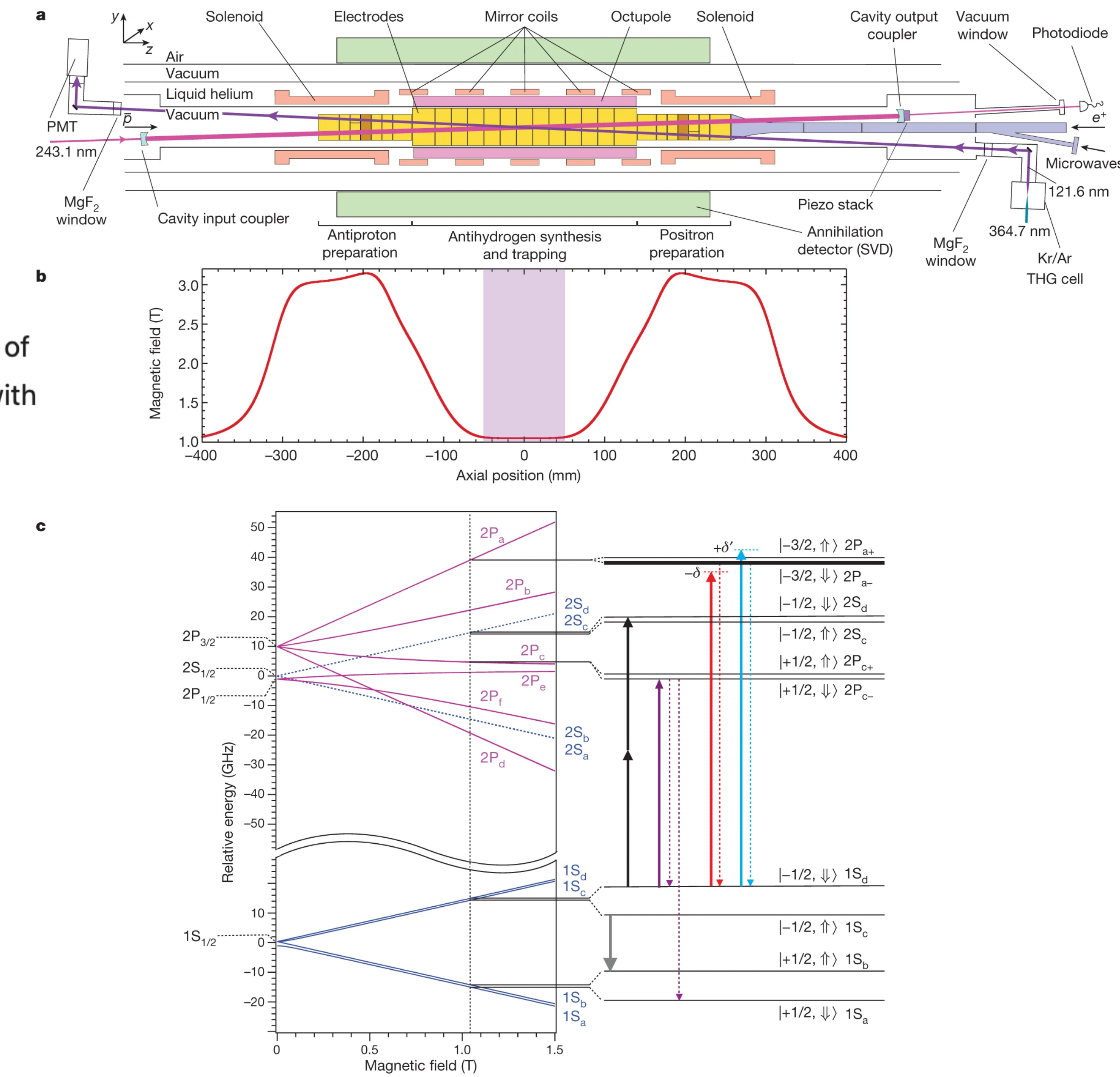
$f_{d-d}$(anti-H) = 2,466,061,103,079.4(5.4)kHz

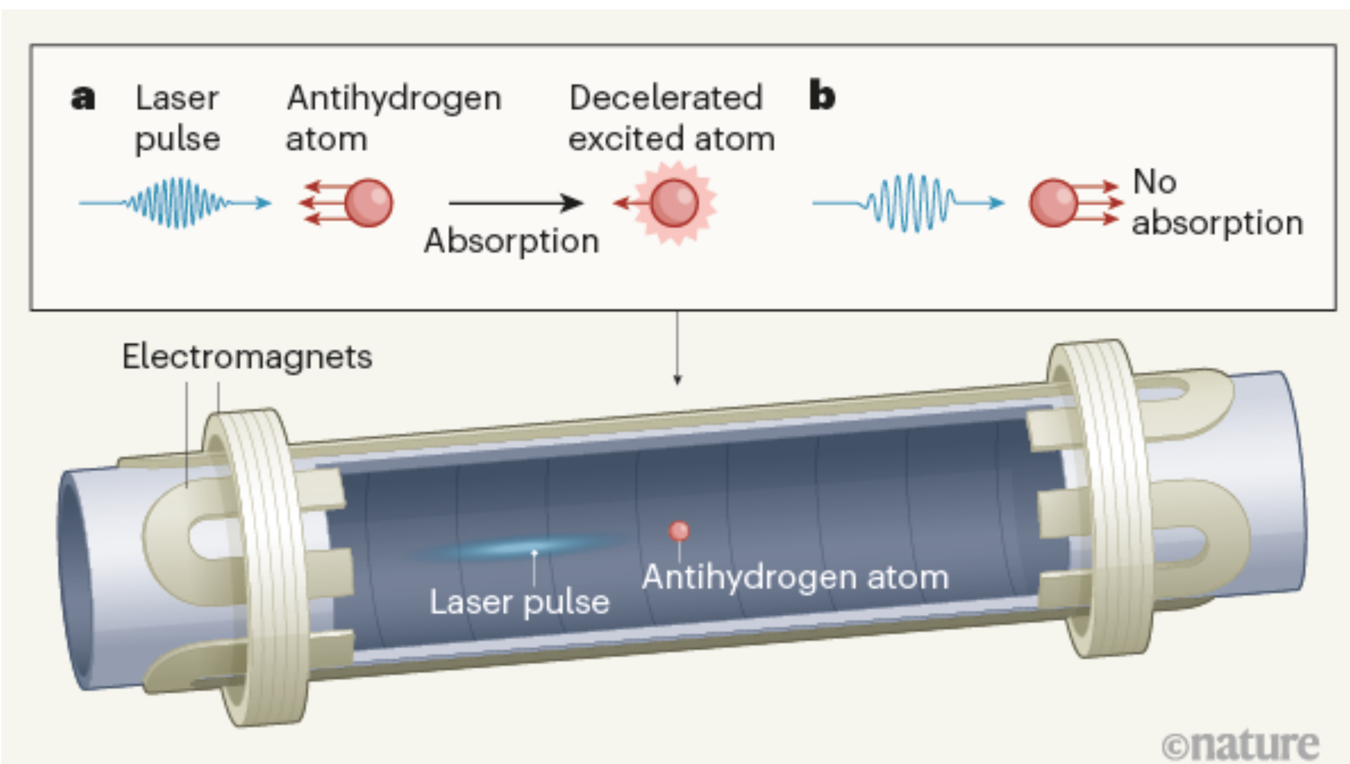
# Laser cooling of Hbar

## 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



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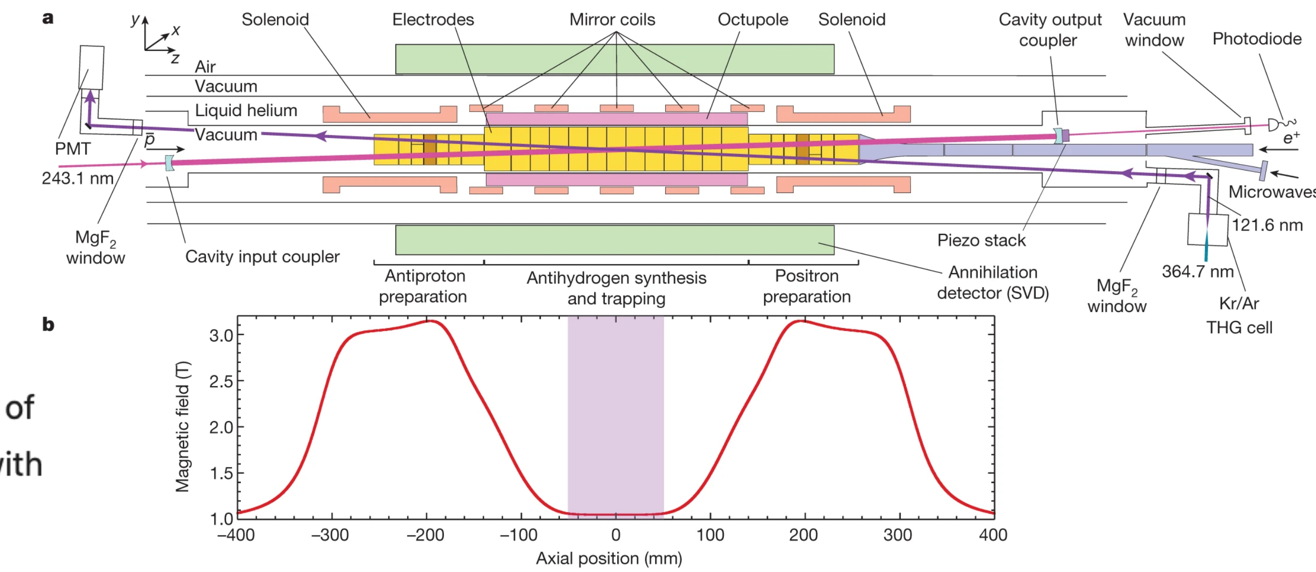
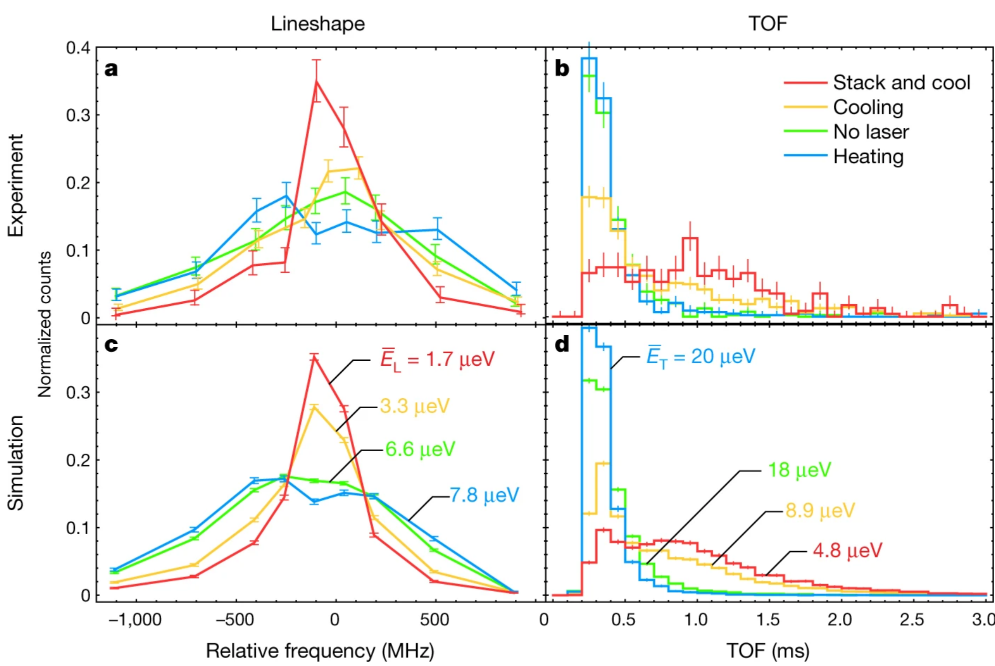
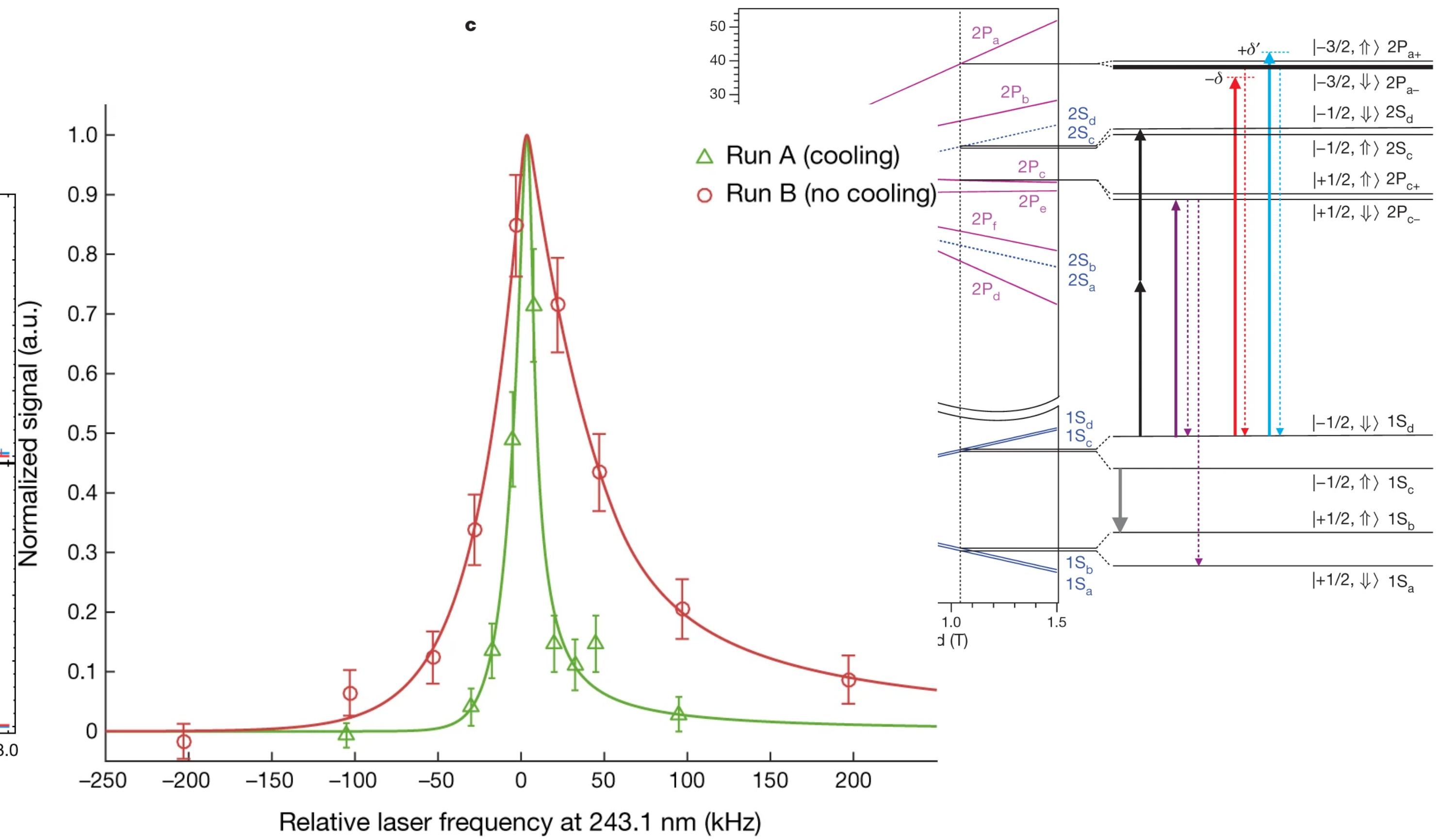


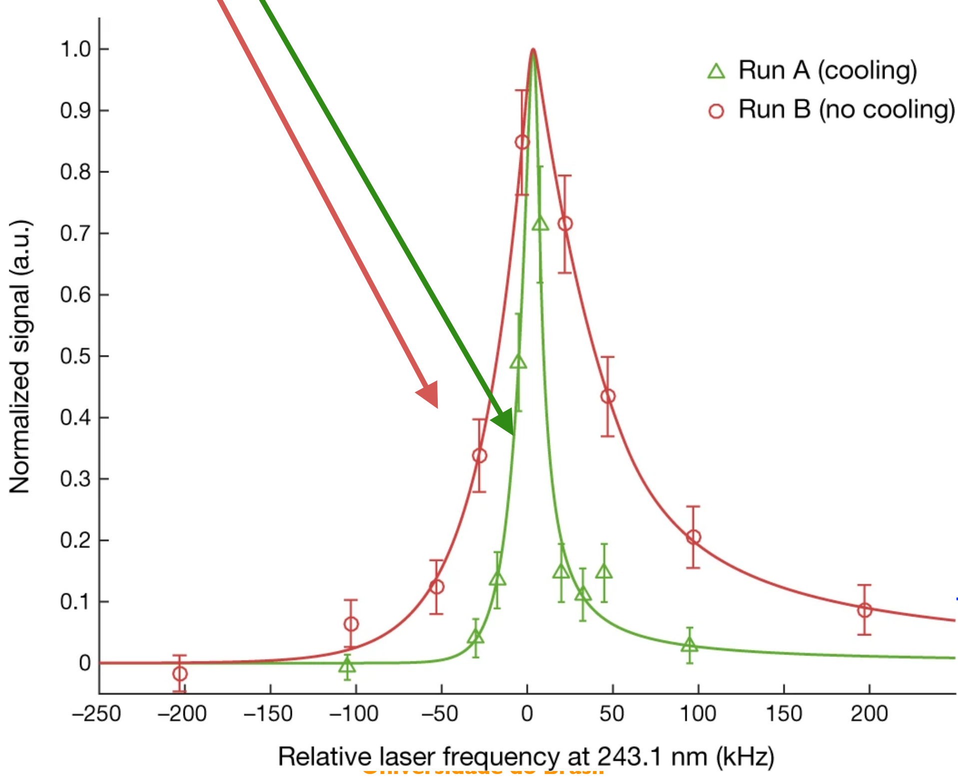



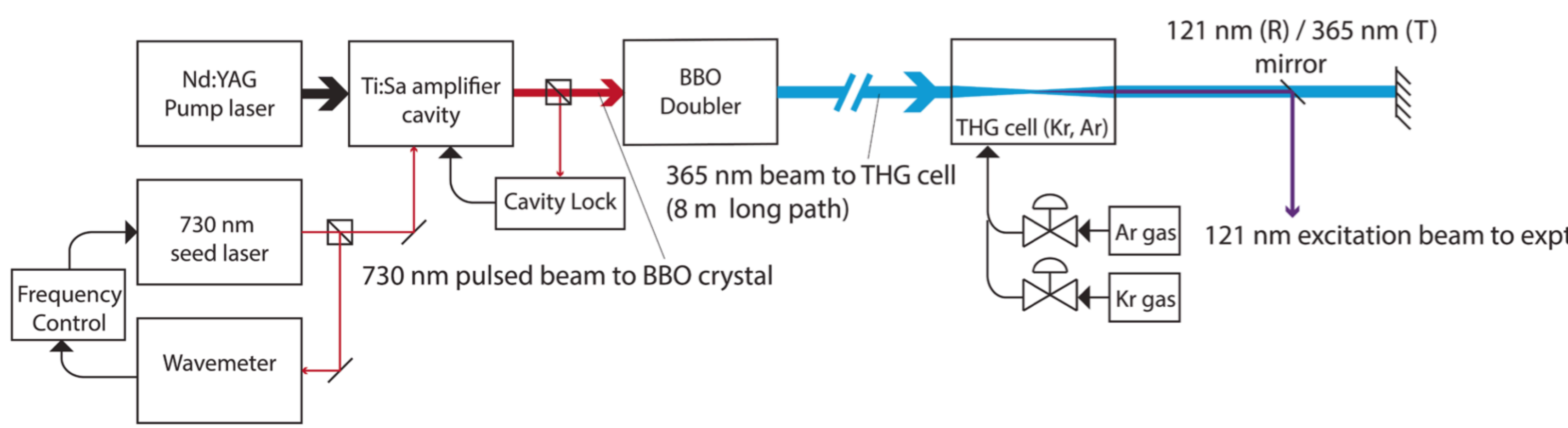
# Laser cooling of Hbar: Tables - new regime

**Table 1 | Experimental dataset**

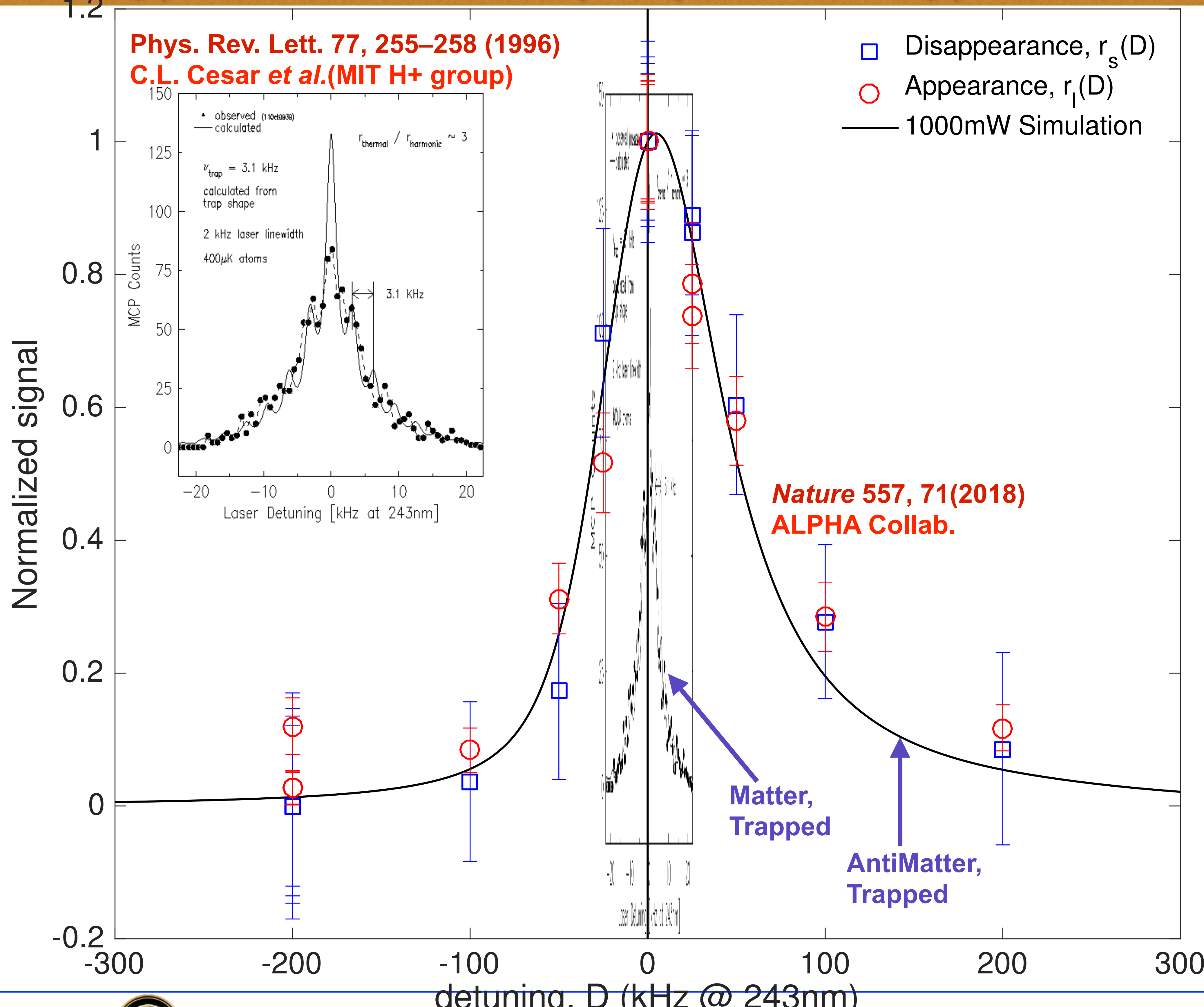
| Series | Type | $1S_d \rightarrow 2P_{a-}$ detuning (MHz) | Stacking phase | | Cooling/heating phase | | Probing phase | |
|---|---|---|---|---|---|---|---|---|
| | | | Number of stacks (approximate time) | Average pulse energy (nJ) | Number of pulses (approximate time) | Average pulse energy (nJ) | 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.



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



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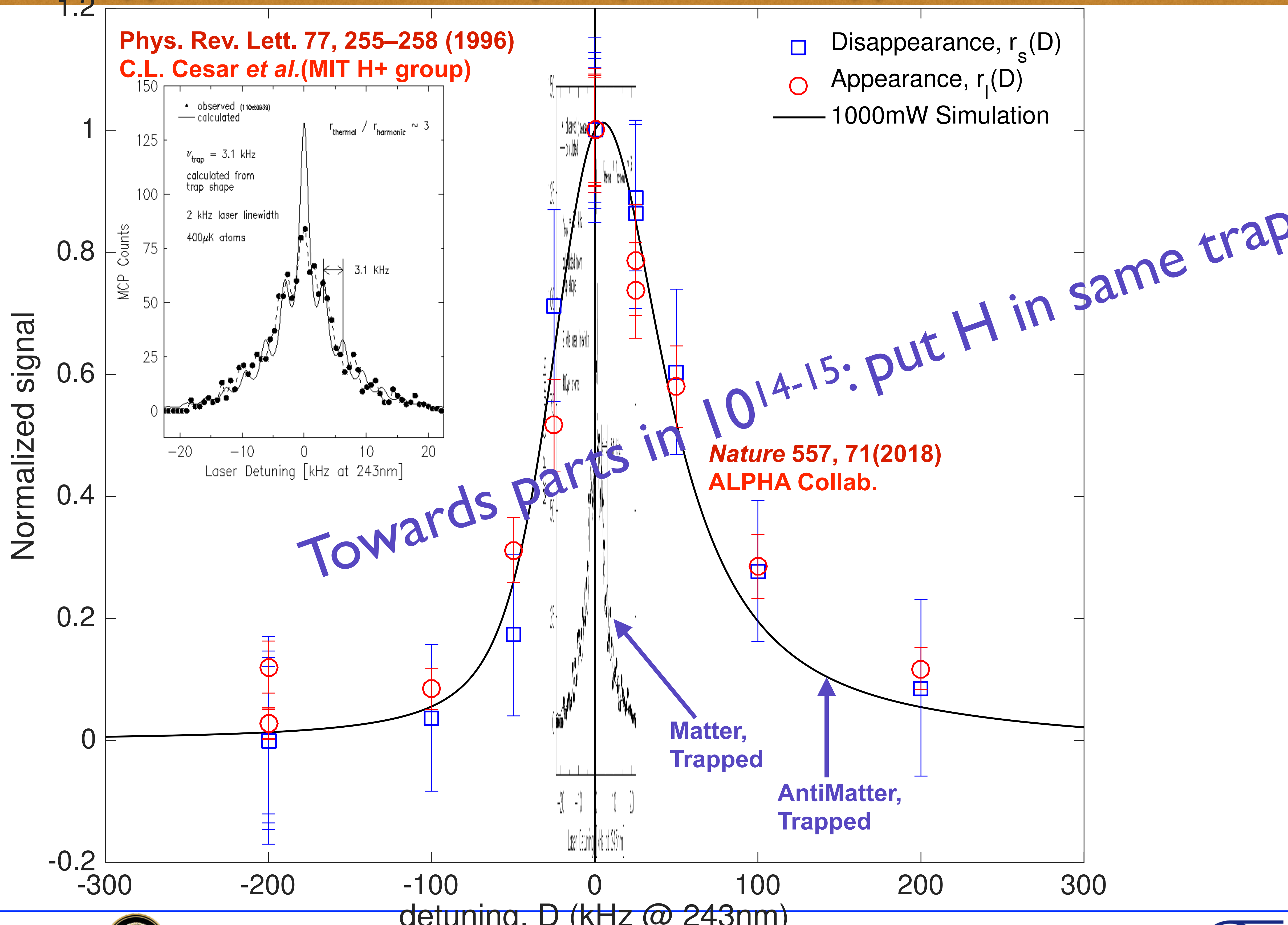
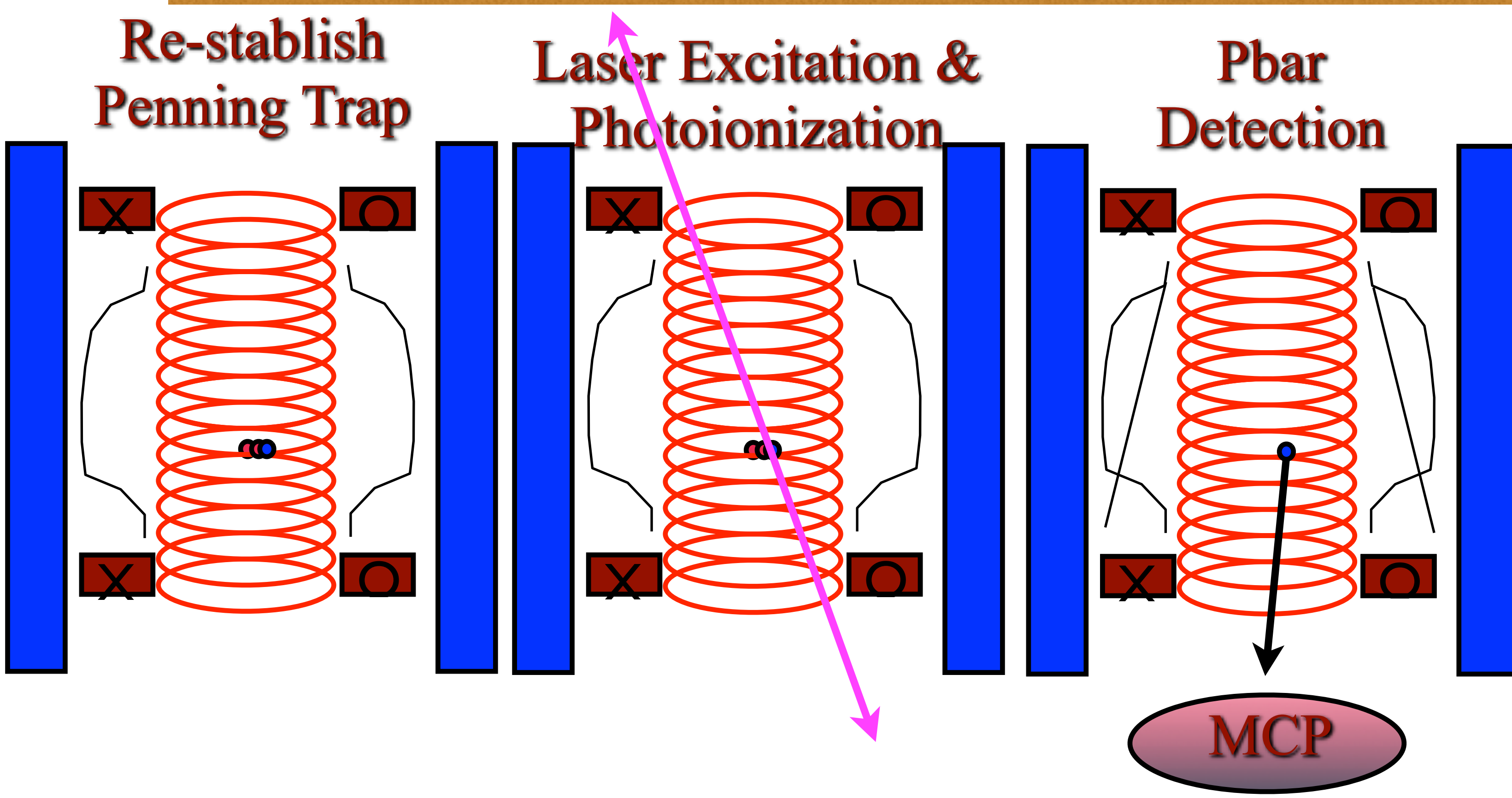
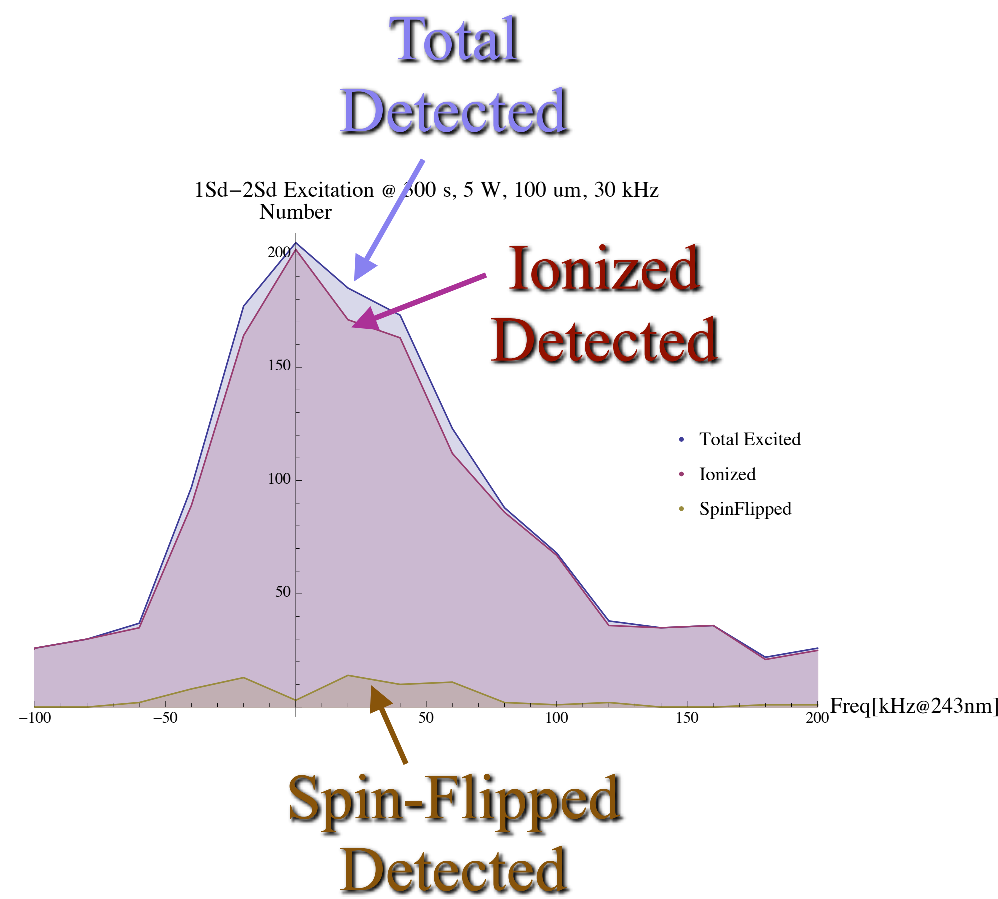


# Detection (how to) - 1s-2s spectroscopy of trapped (anti)H
## H & Hbar in the same trap: gravitational & electromagnetic




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

J. Phys. B: At. Mol. Opt. Phys. **49** (2016) 074001 (8pp) doi:10.1088/095

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

**Claudio Lenz Cesar**

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Calculations for trapping H



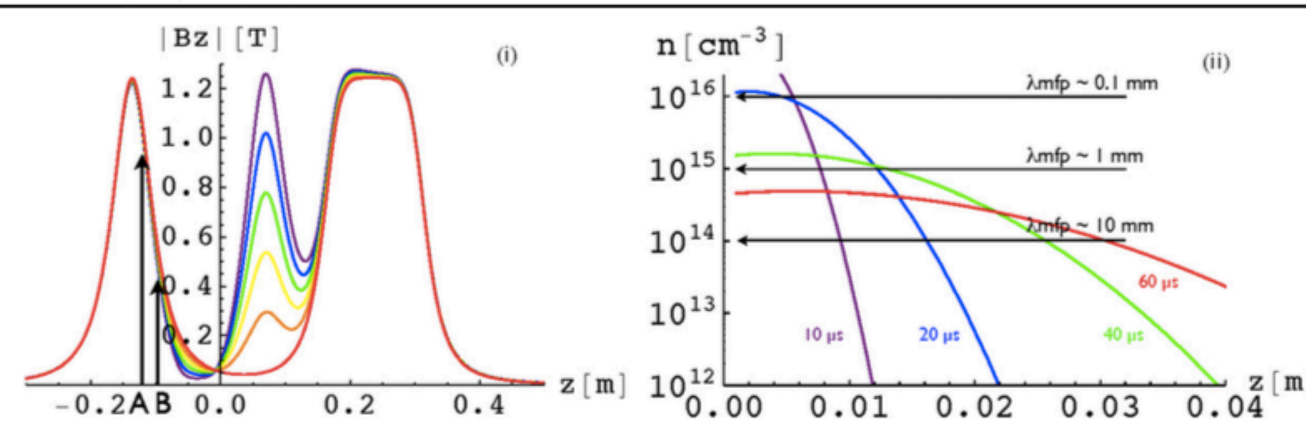


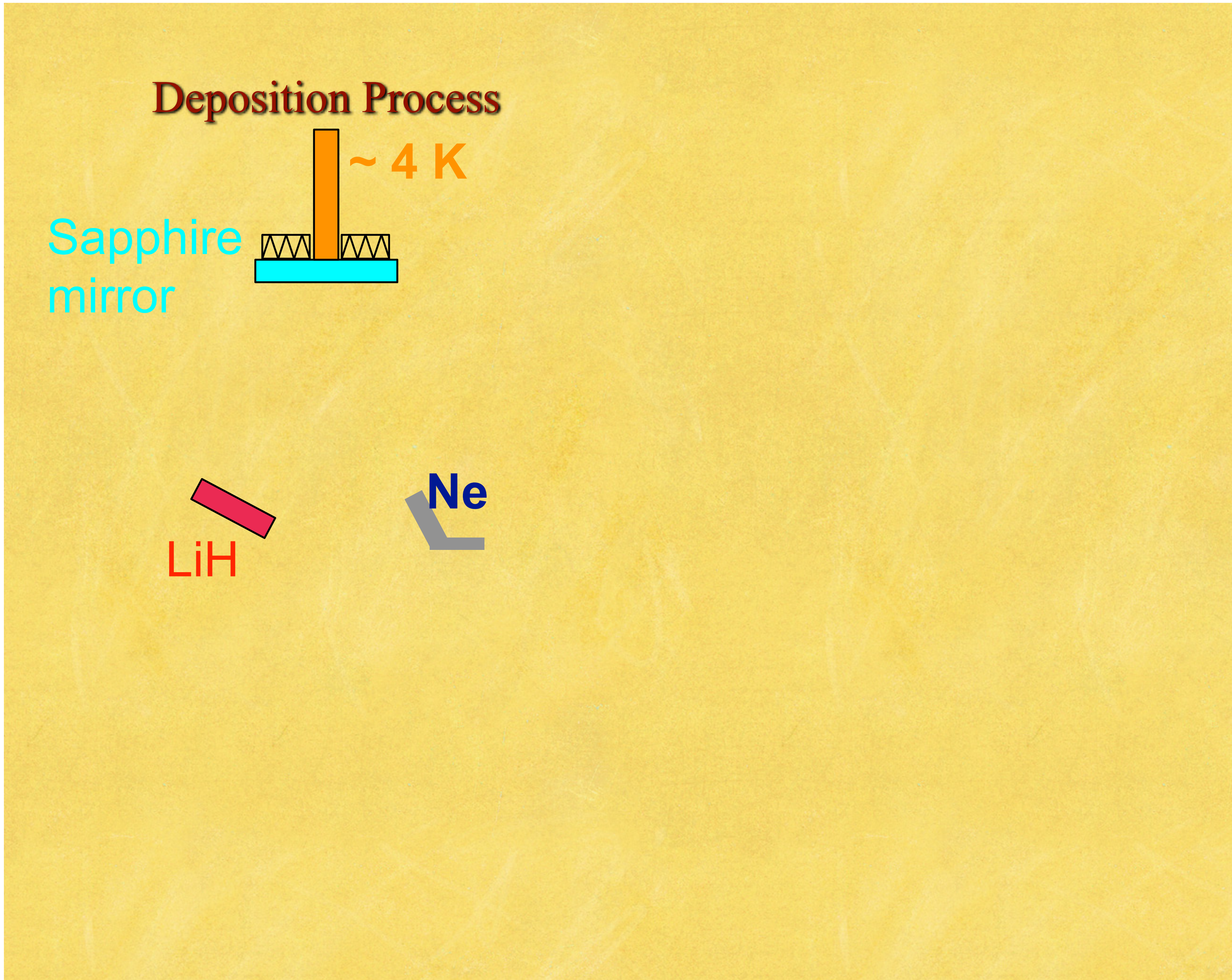

**Figure 3.** Sketch of the proposed MISu trapping at ALPHA. On the left (i), calculated magnetic field configurations along the axis are shown. The point identified as 'A' is where the isolation matrix would be placed. Once the matrix is sublimated the plume will travel to the right and it will disconnect 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 ($\lambda_{mfp}$) 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 $\mu$s, quick enough to avoid much Ne evaporation of trapped atoms. See references for more detail.

# 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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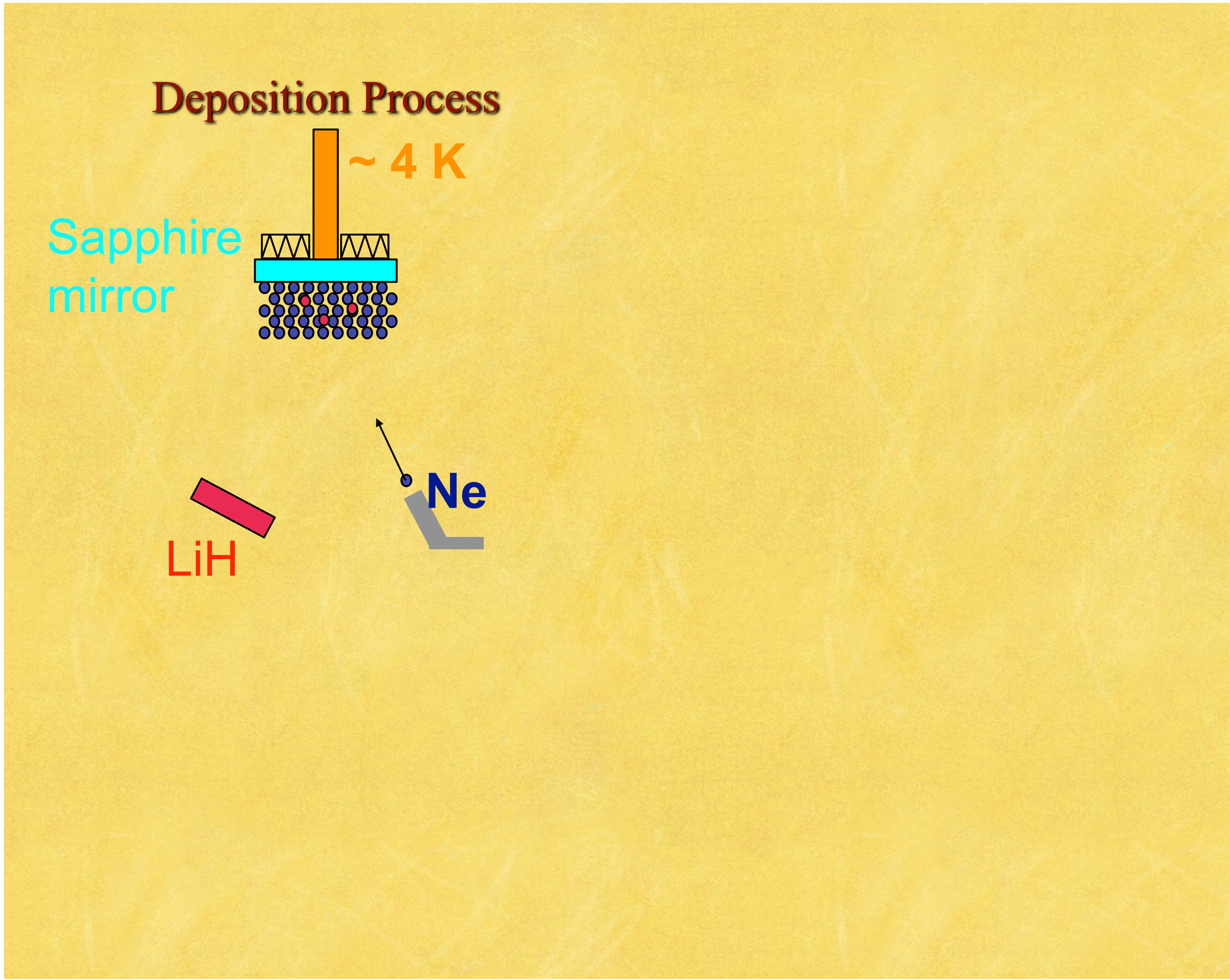

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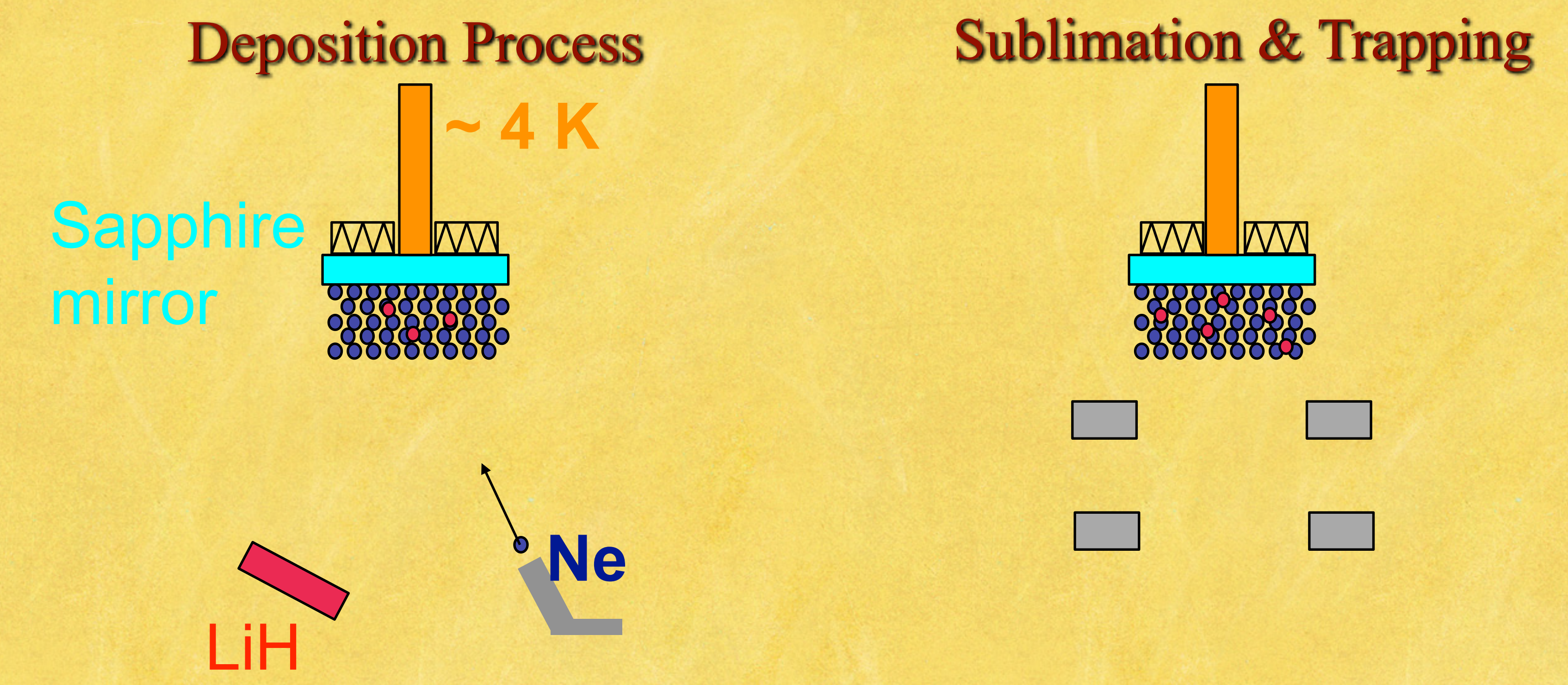

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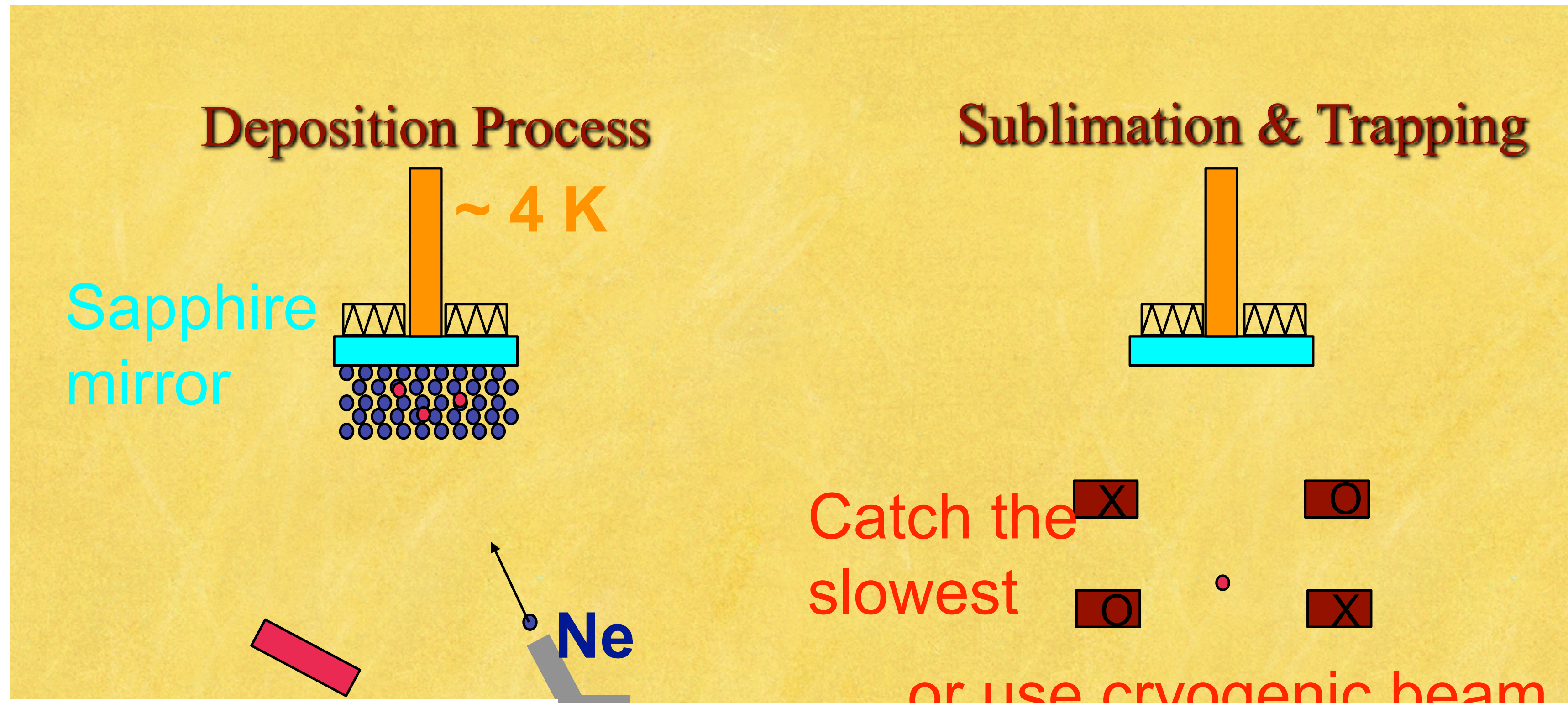


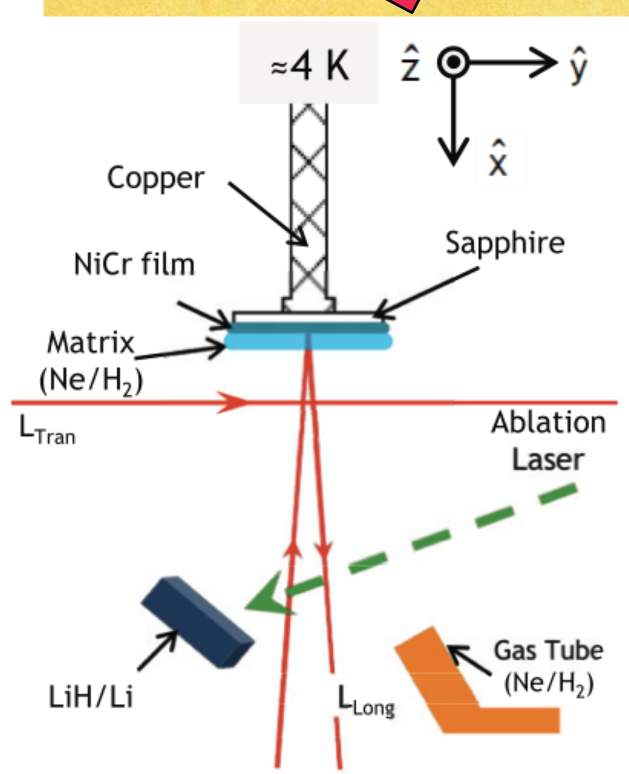


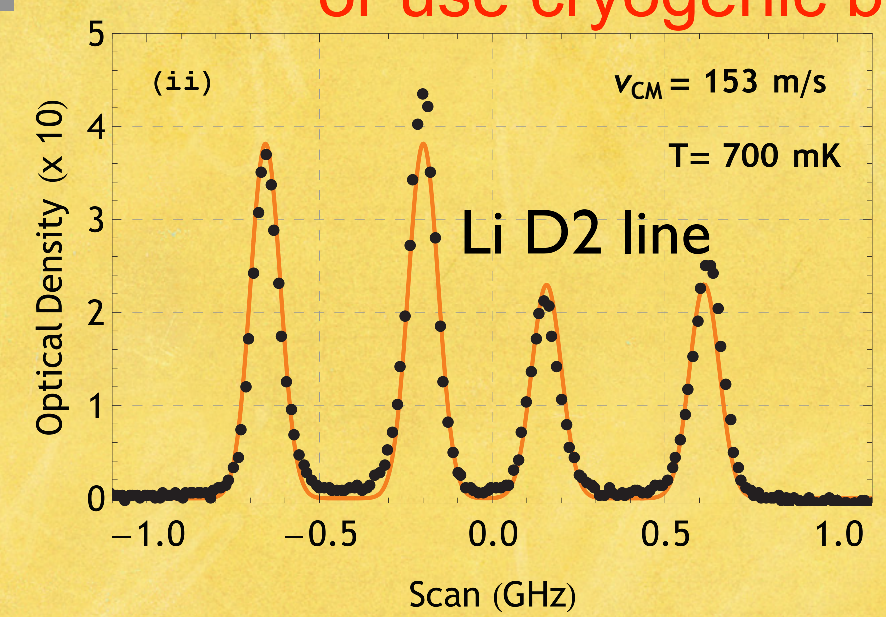


FIG. 1. Schematics of the experimental apparatus showing the sapphire substrate, the NiCr film resistor and the deposited matrix of Ne or $H_2$ which come from the gas tube. The Li atoms are implanted via laser ablation (shown in dashed green) on a solid Li or LiH precursor. Two beams from the spec-

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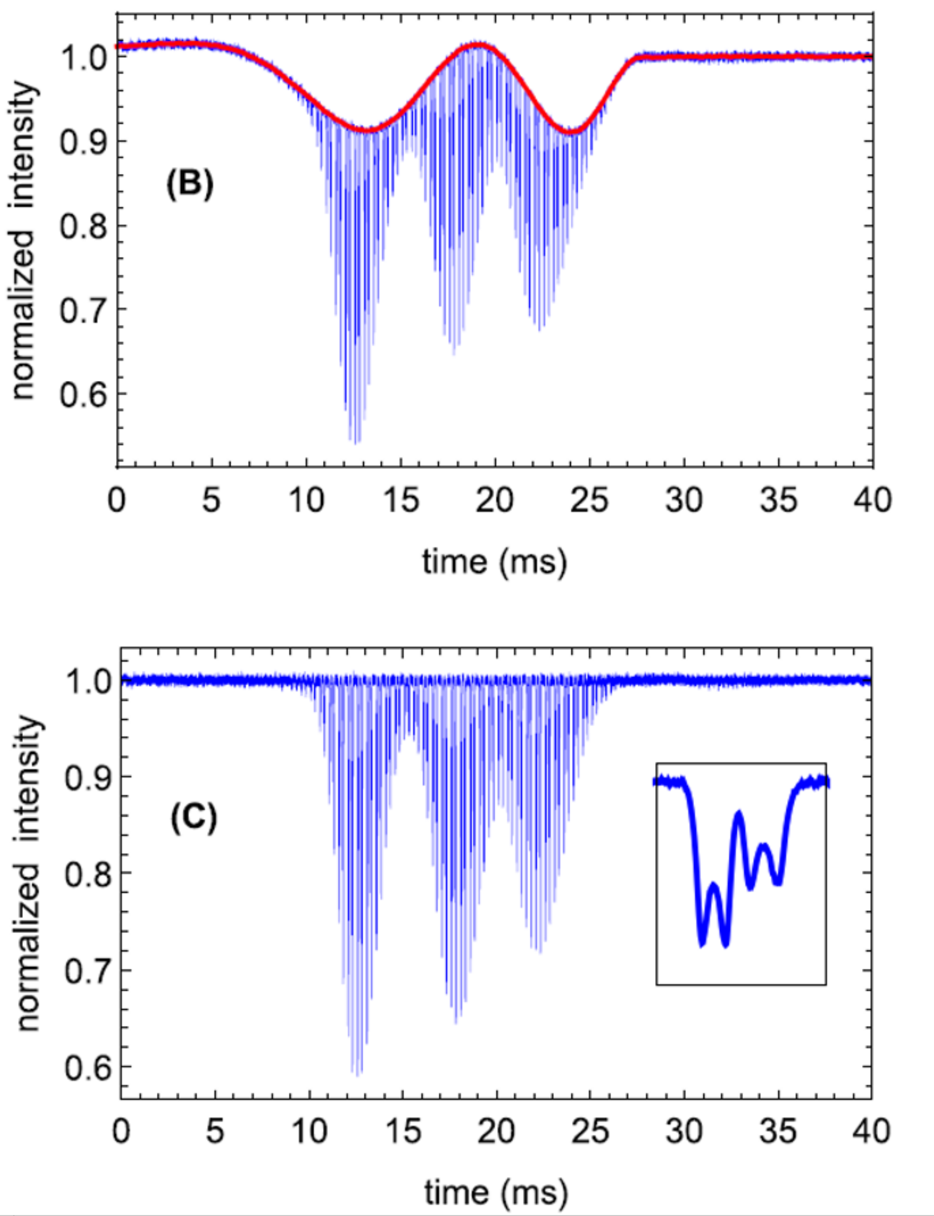
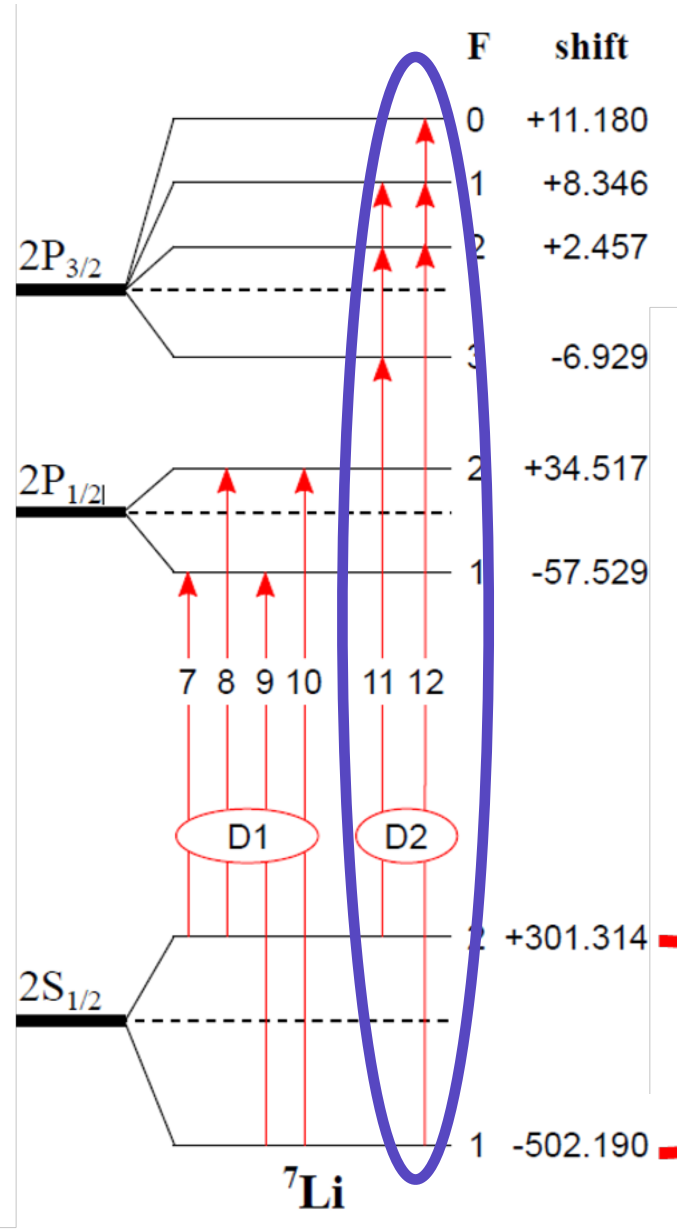
# Spectra of Li-7 (D2)

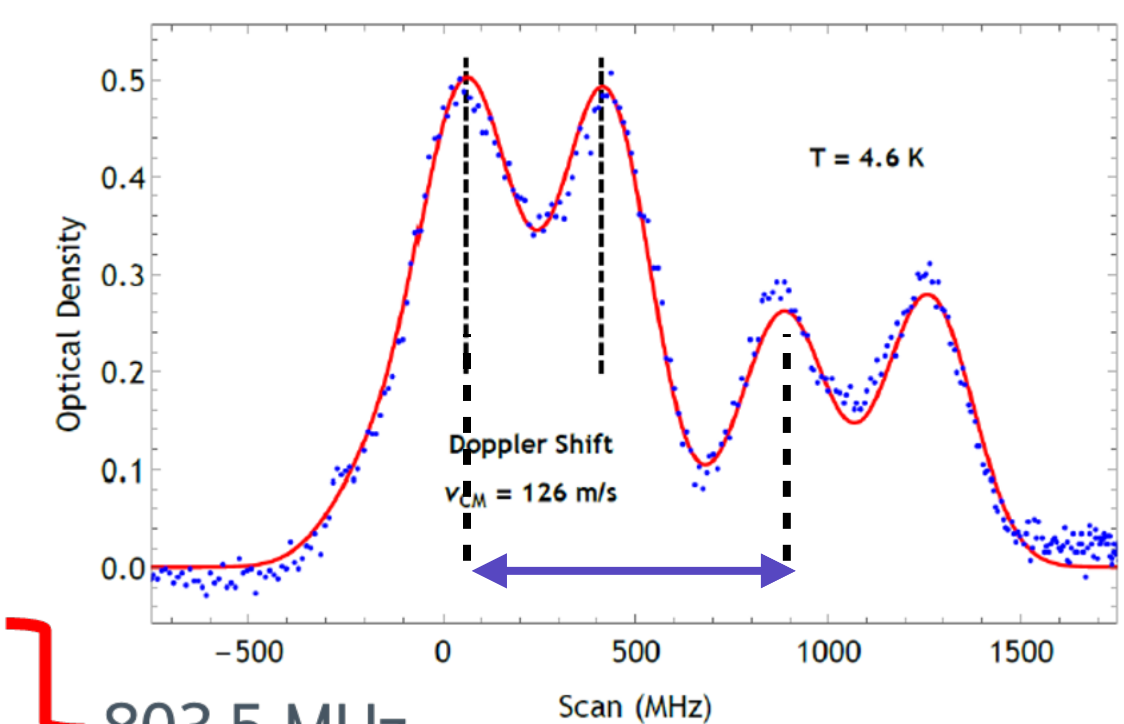
## 3 spaced ablation pulses



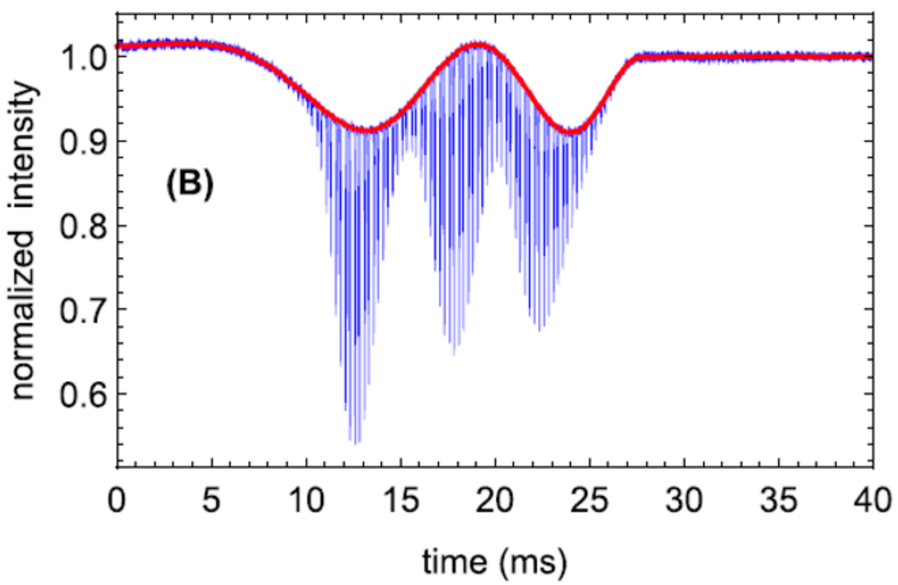

Velocidade → $V = \frac{\lambda \cdot \delta\omega}{2}$

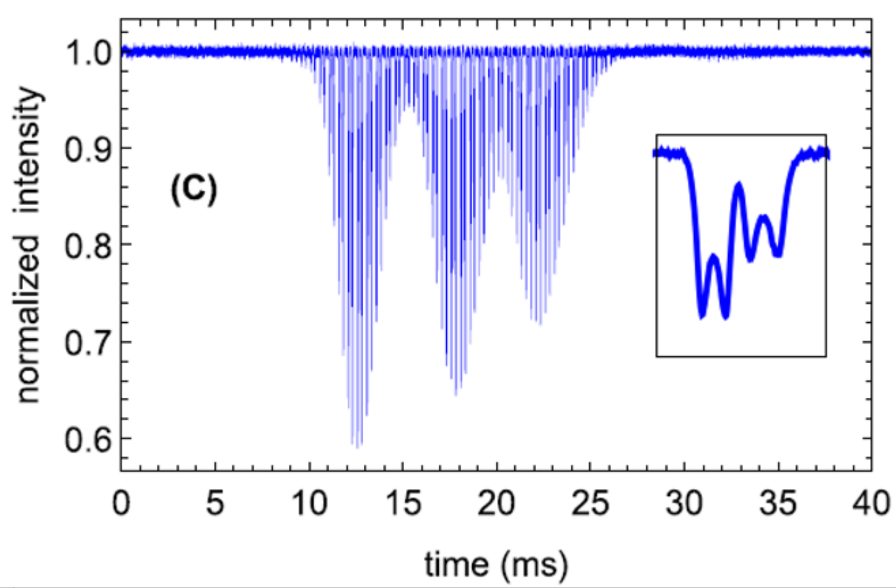
Temperatura → $T = \frac{m\,(\Delta\nu \cdot \lambda)^2}{k_B}$

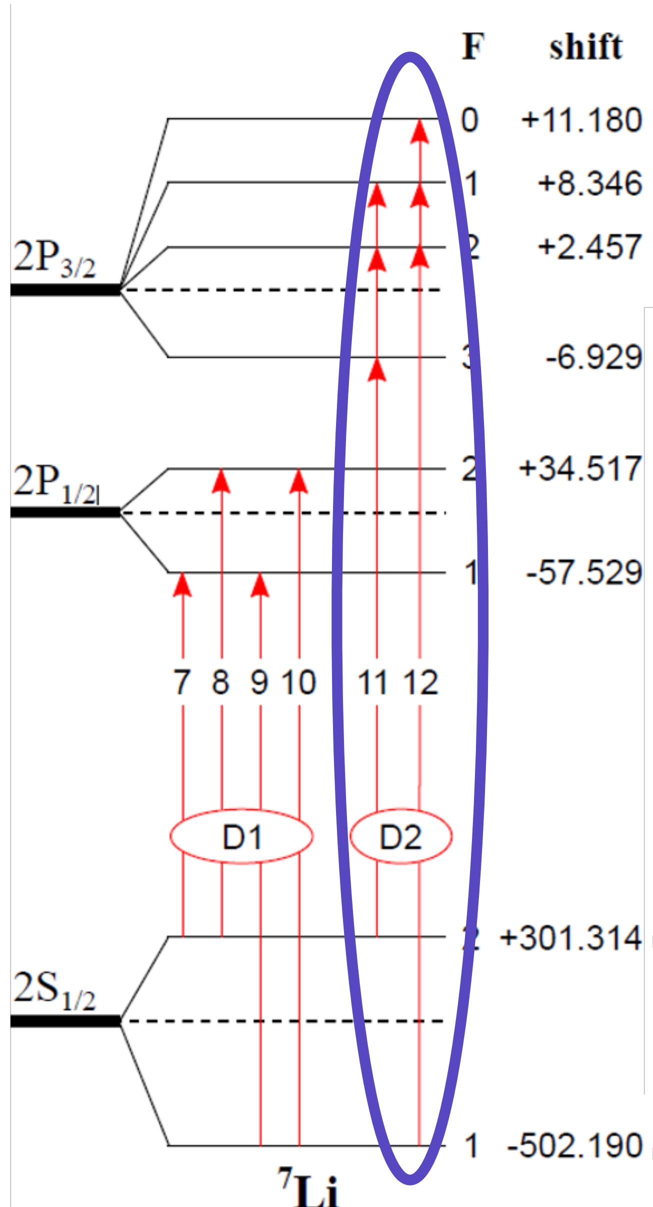



803.5 MHz

## 3 spaced ablation pulses

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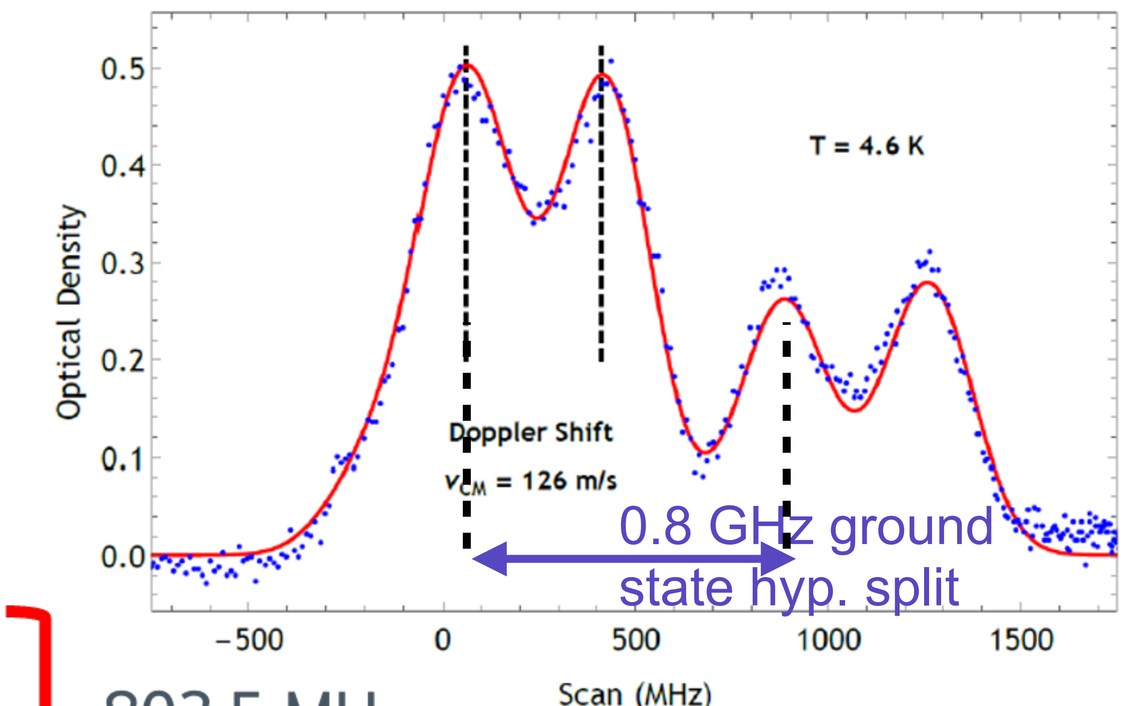

# Matrix Isolation Sublimation and Mass Spectrometry

## 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

A. N. Oliveira,[1,2,a)] R. L. Sacramento,[2] L. S. Moreira,[2] L. O. A. Azevedo,[2] W. Wolff,[2] and C. Lenz Cesar[2]
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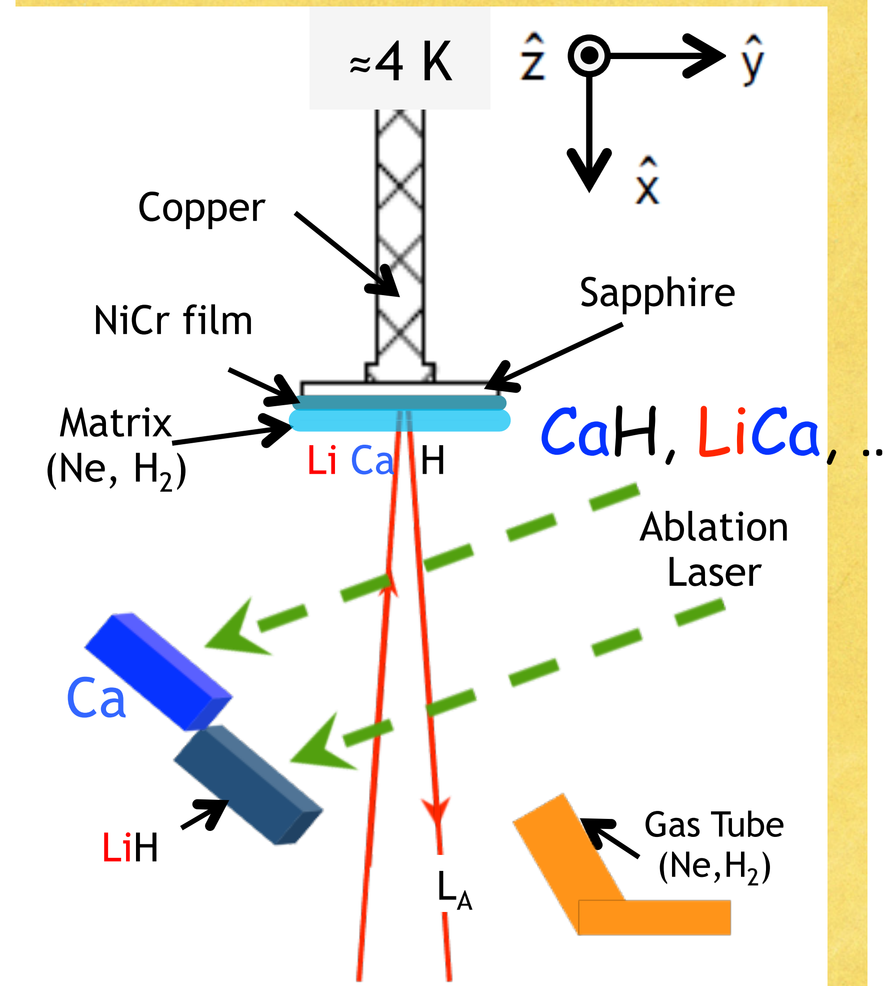
(Received 8 June 2018; accepted 9 August 2018; published online 30 August 2018)

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



# Matrix Isolation Sublimation and Mass Spectrometry

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

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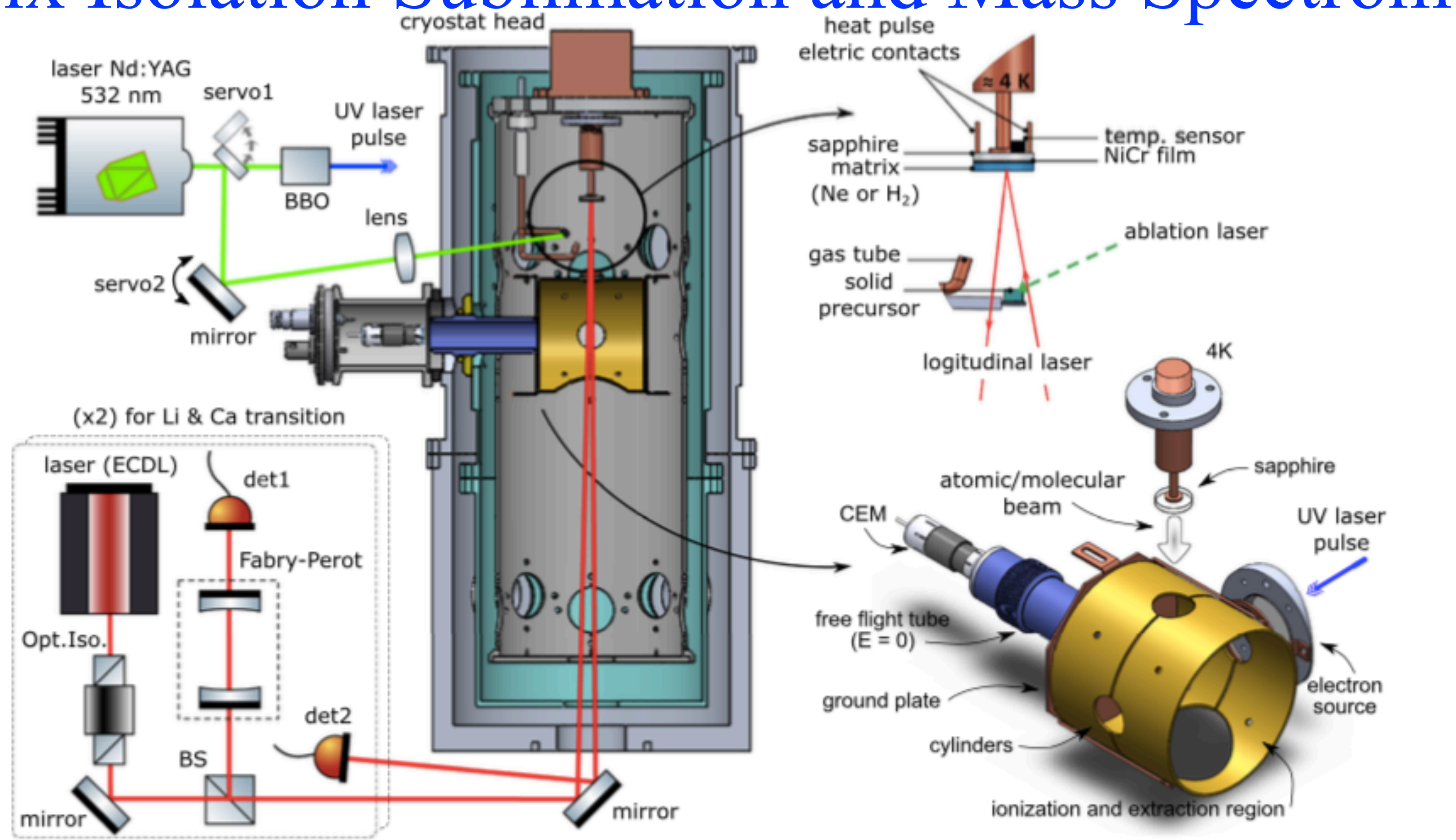


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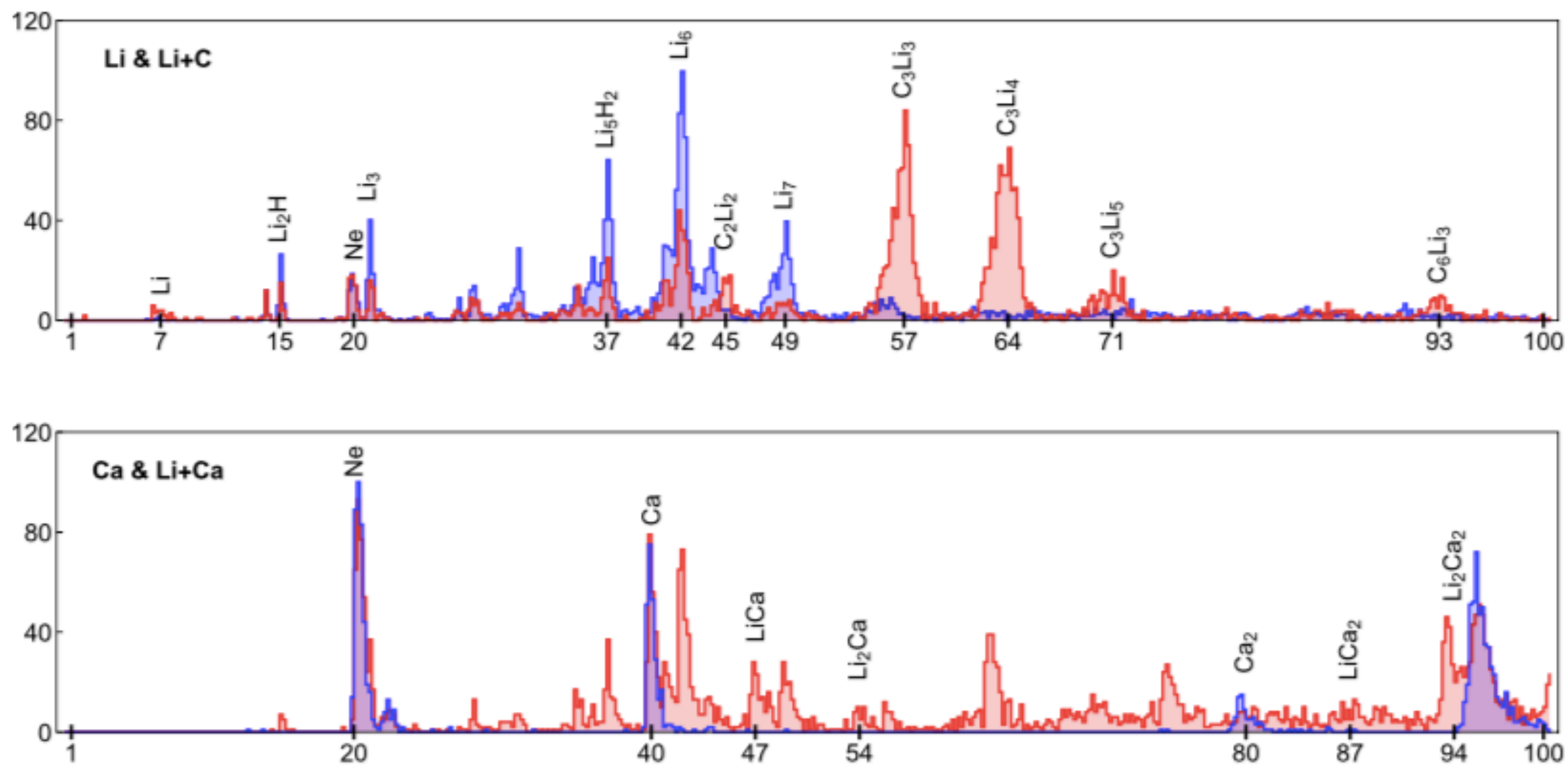
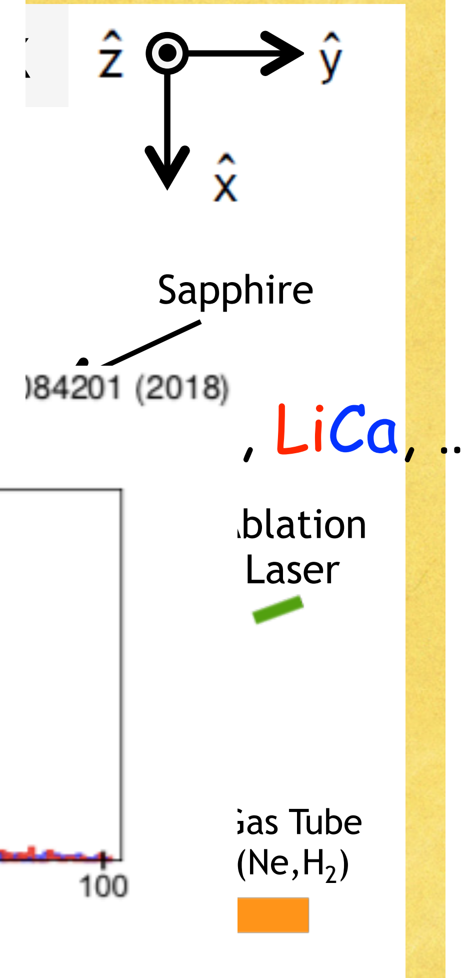
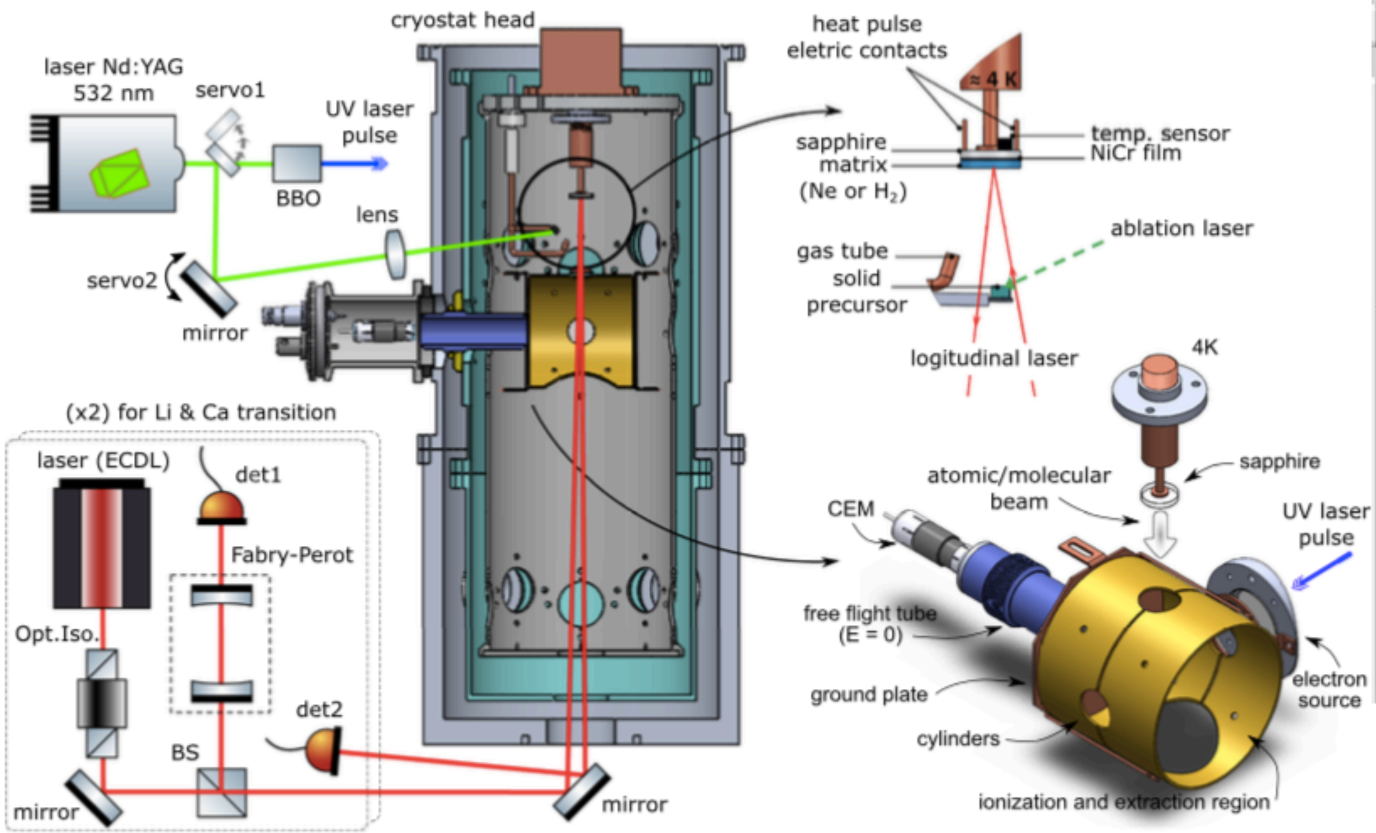
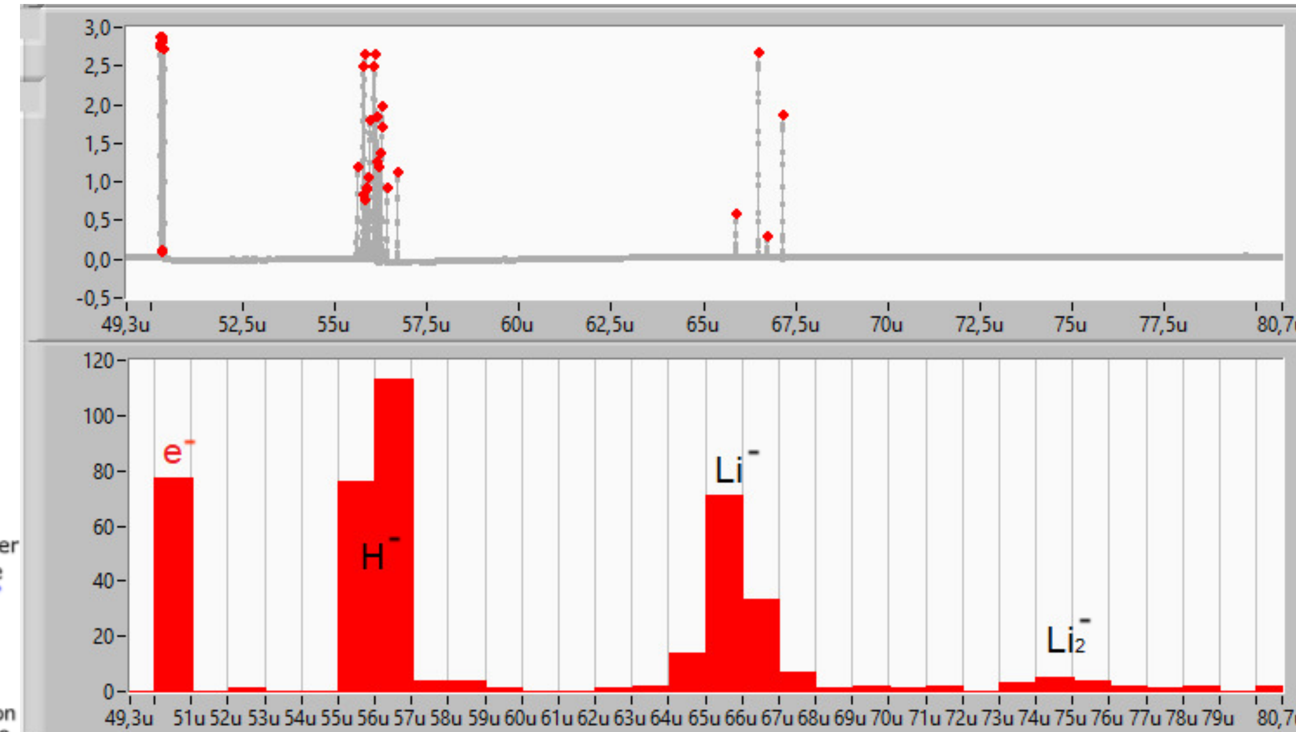


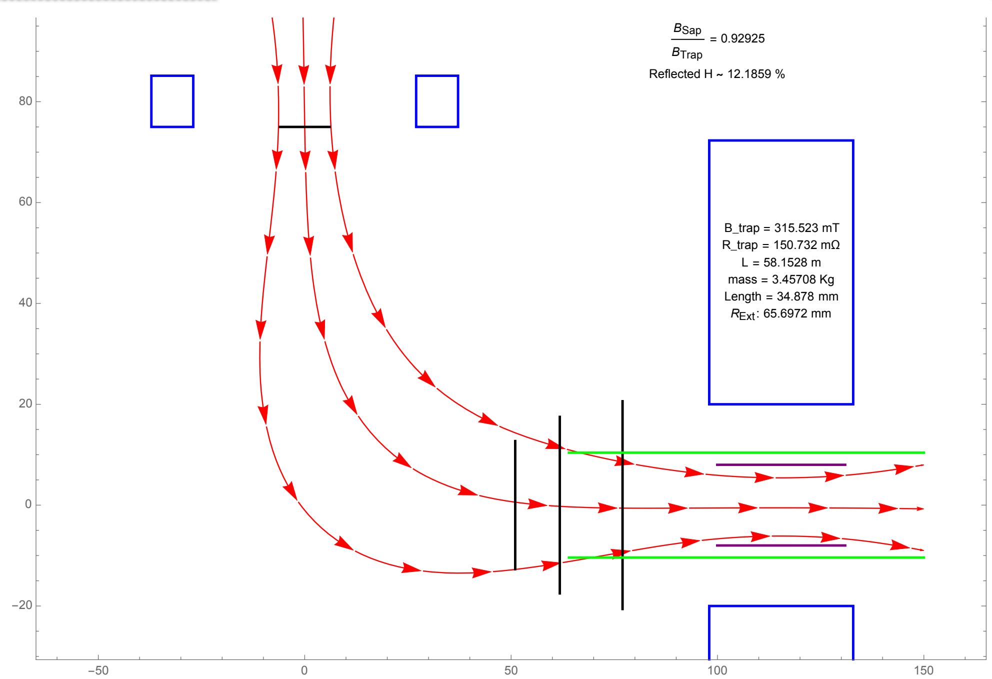



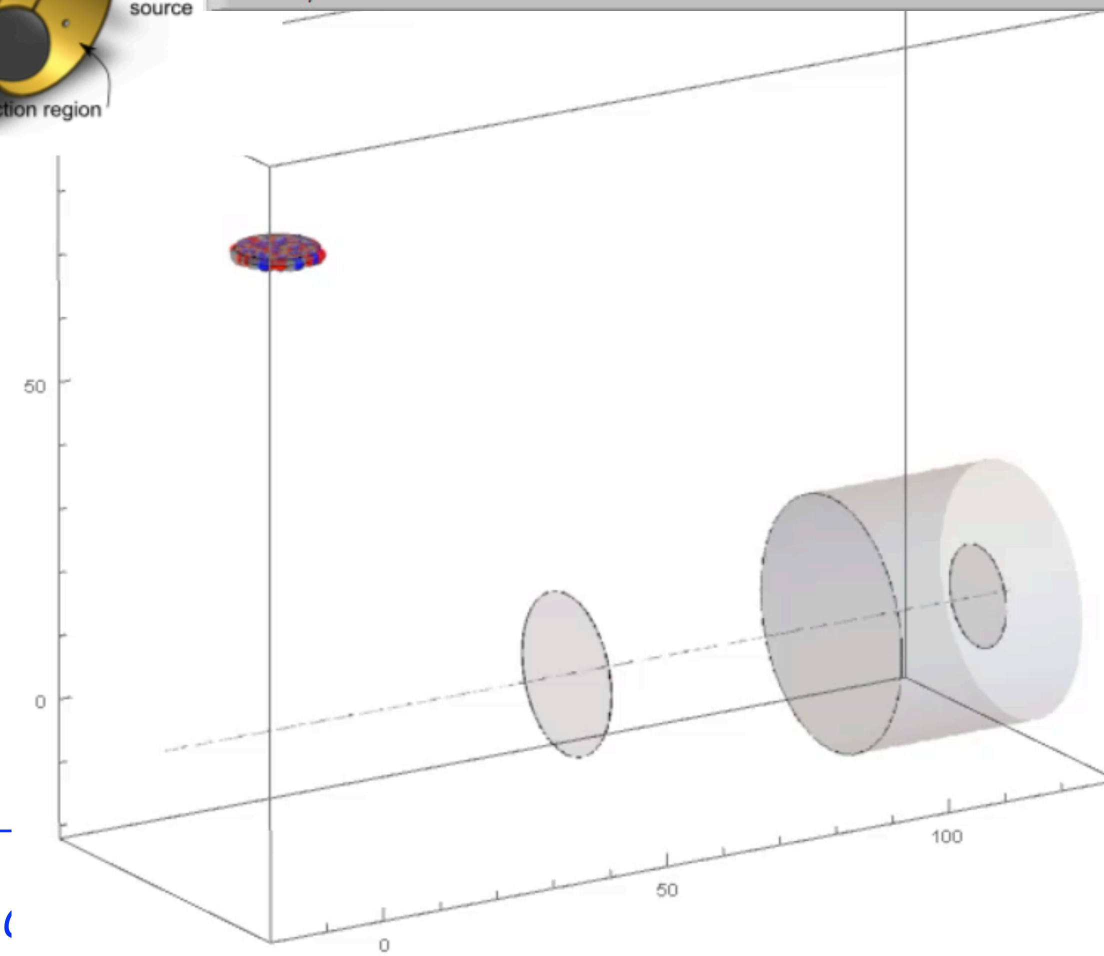
# Matrix Isolation Sublimation (MISu): cold anions: H-, Li-, …

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



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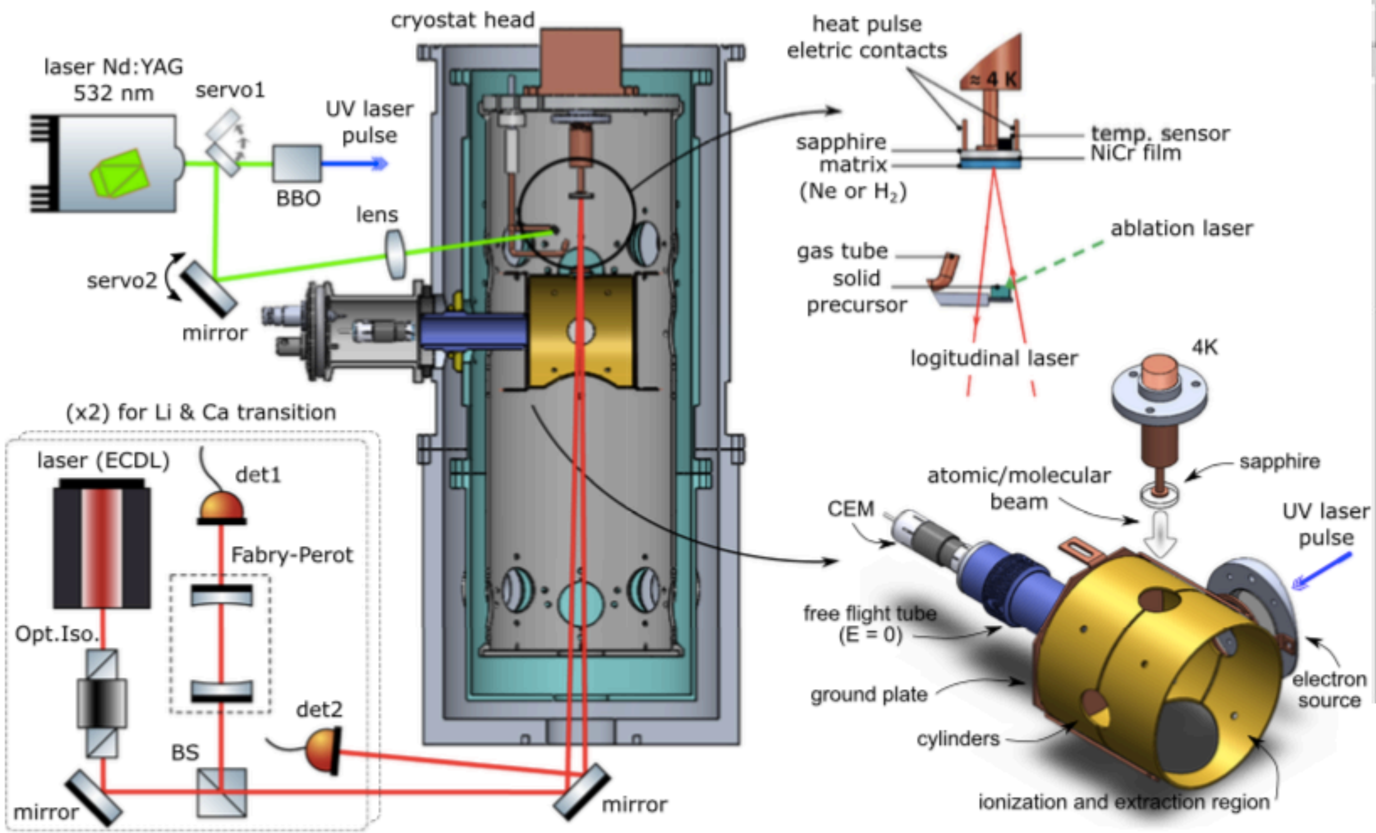
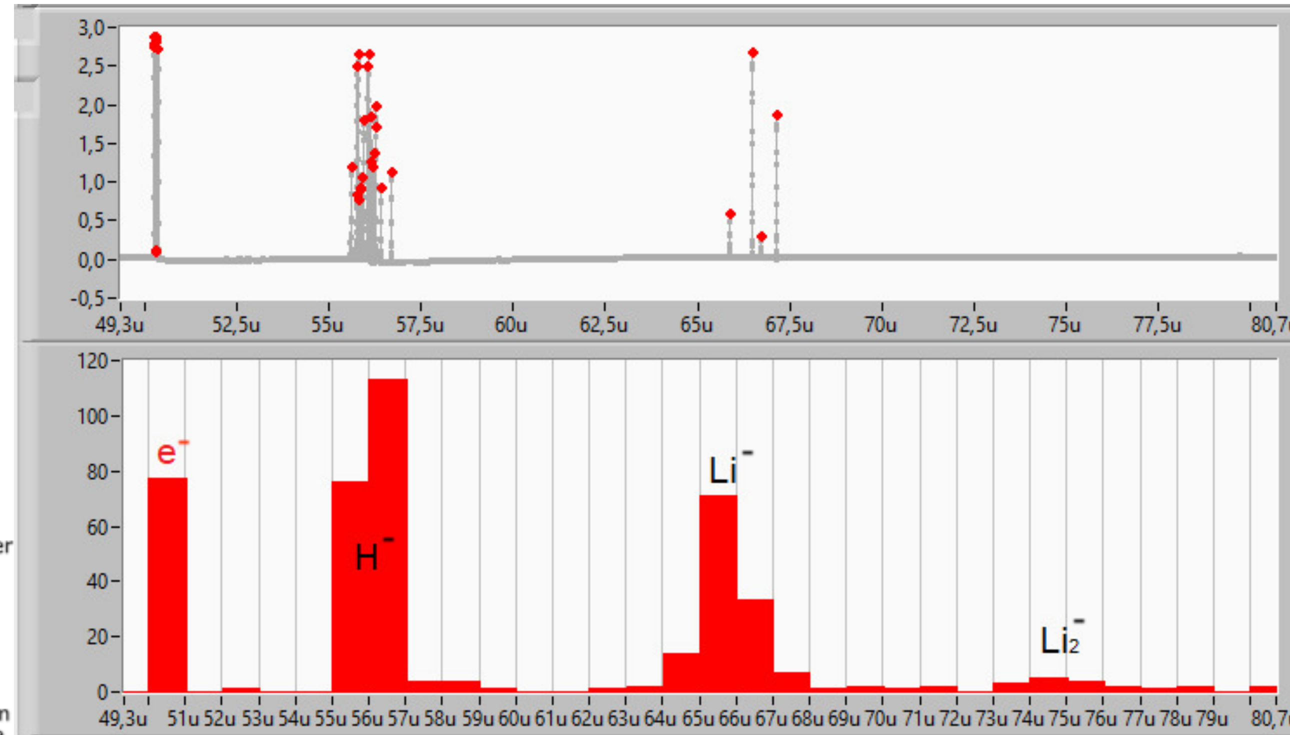
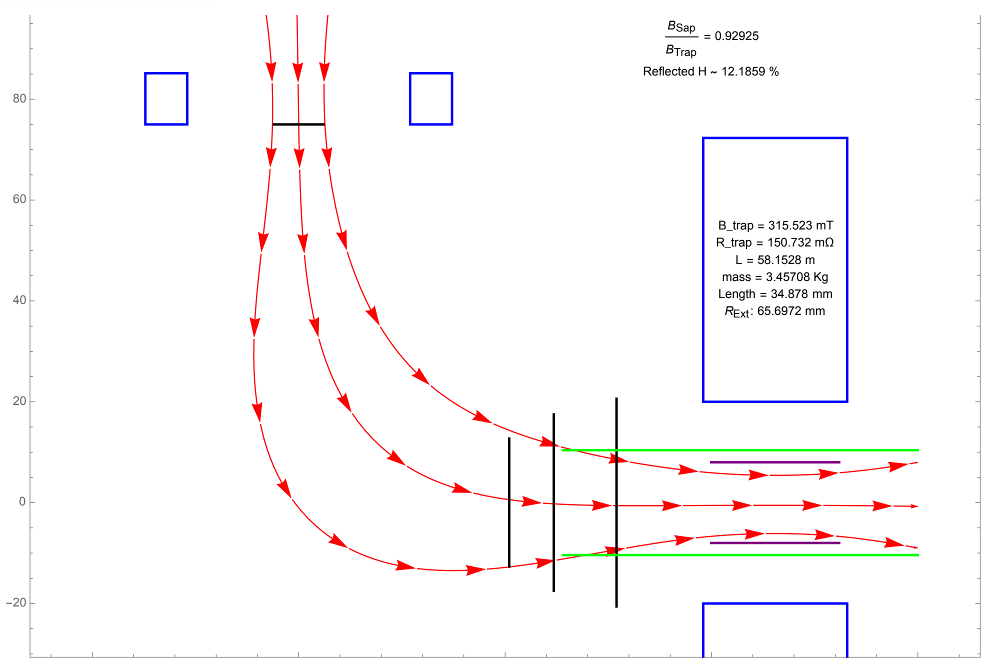
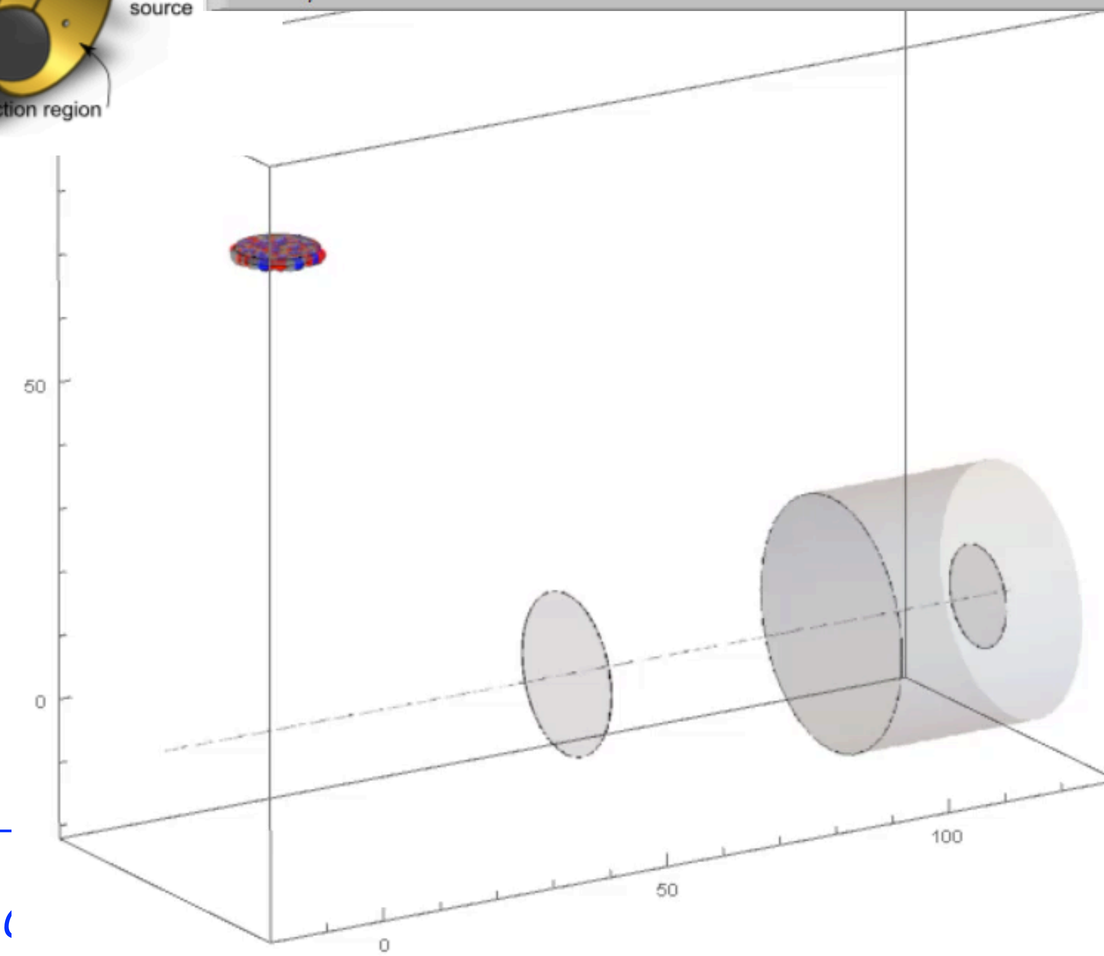


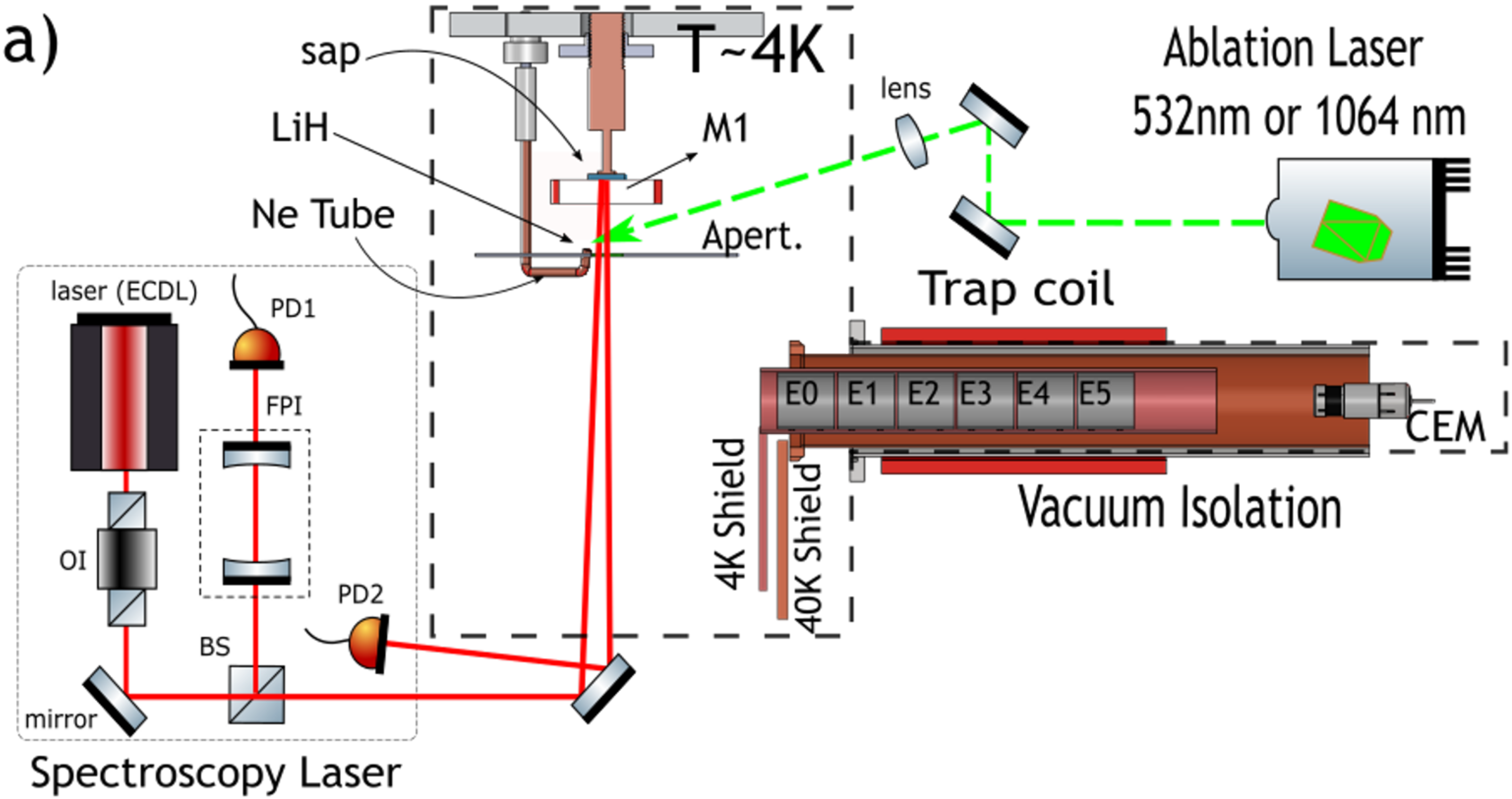



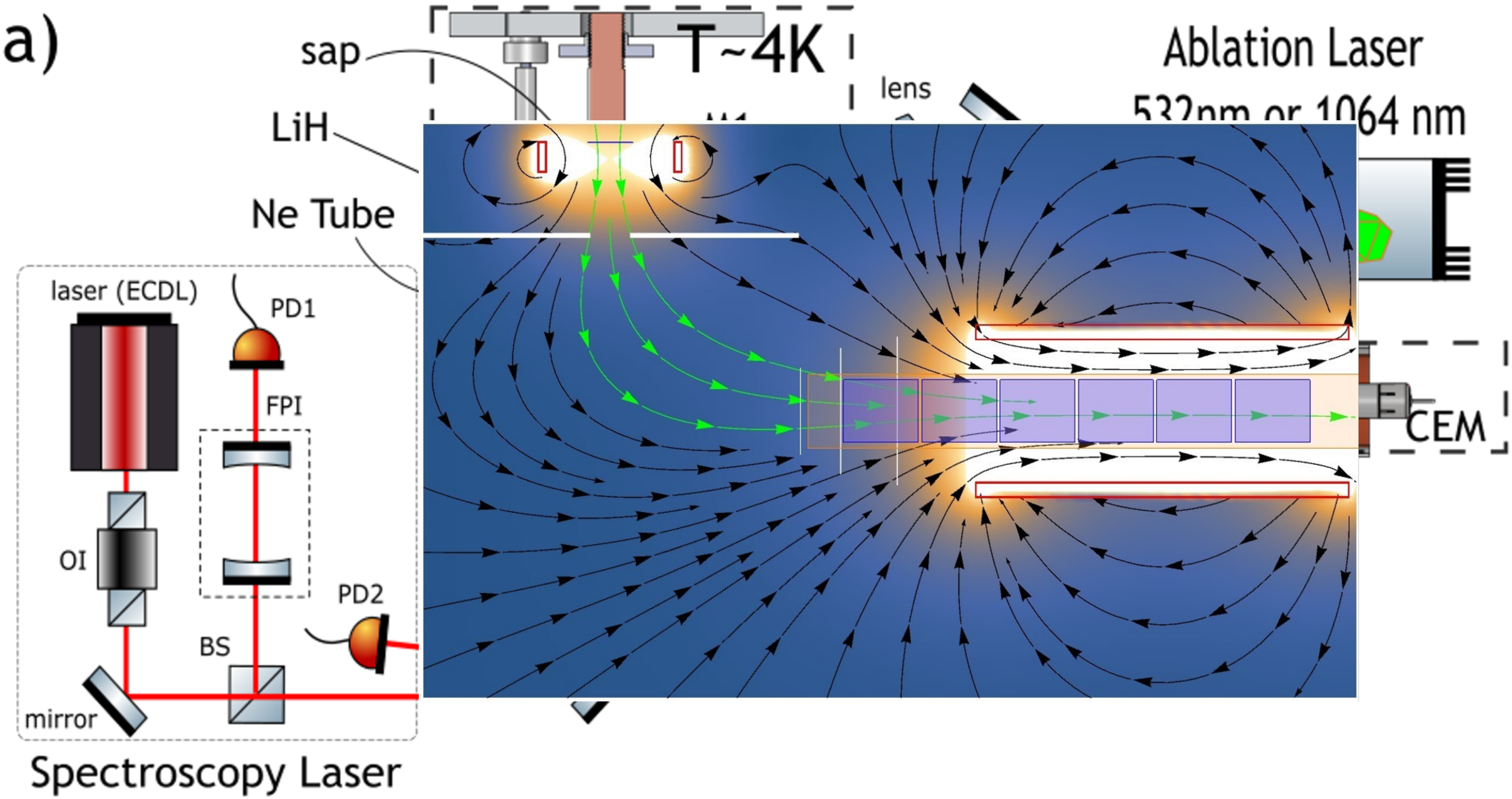



Matrix Isolation Sublimation (MISu):
trapped ions (cations..)

# LASER Penning Trap

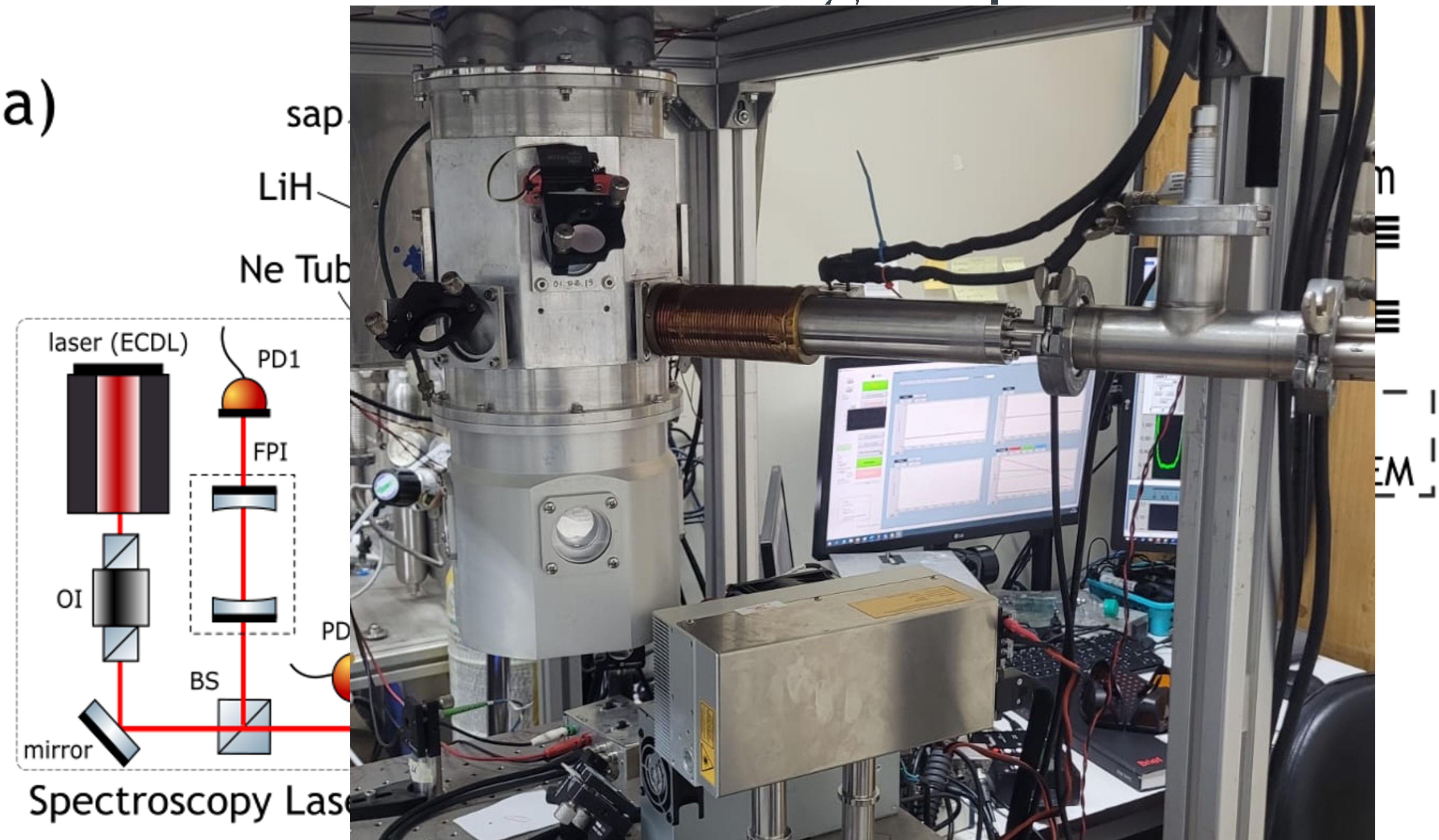


# LASER Penning Trap

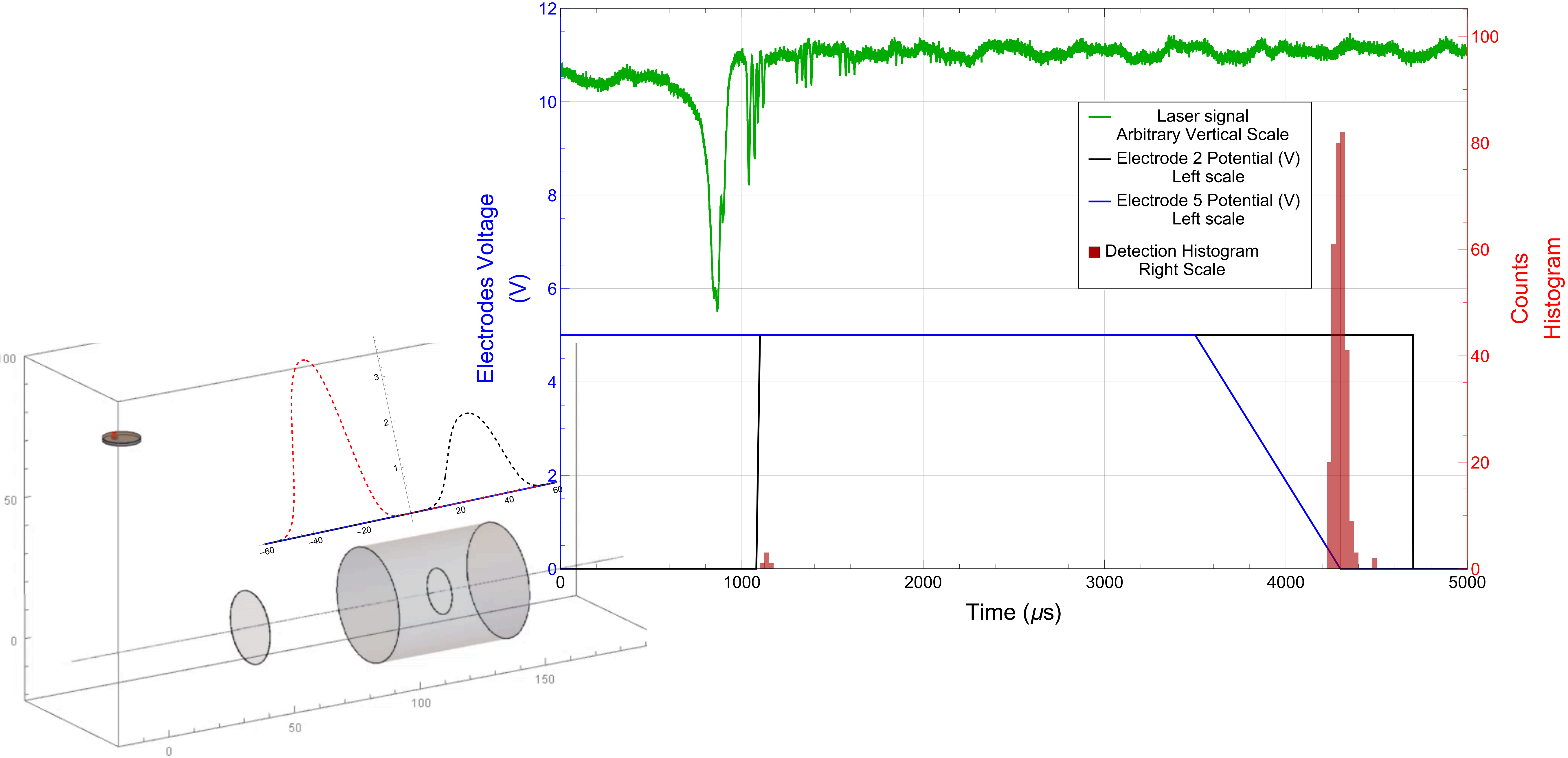


# Matrix Isolation Sublimation (MISu): trapped ions (cations..)

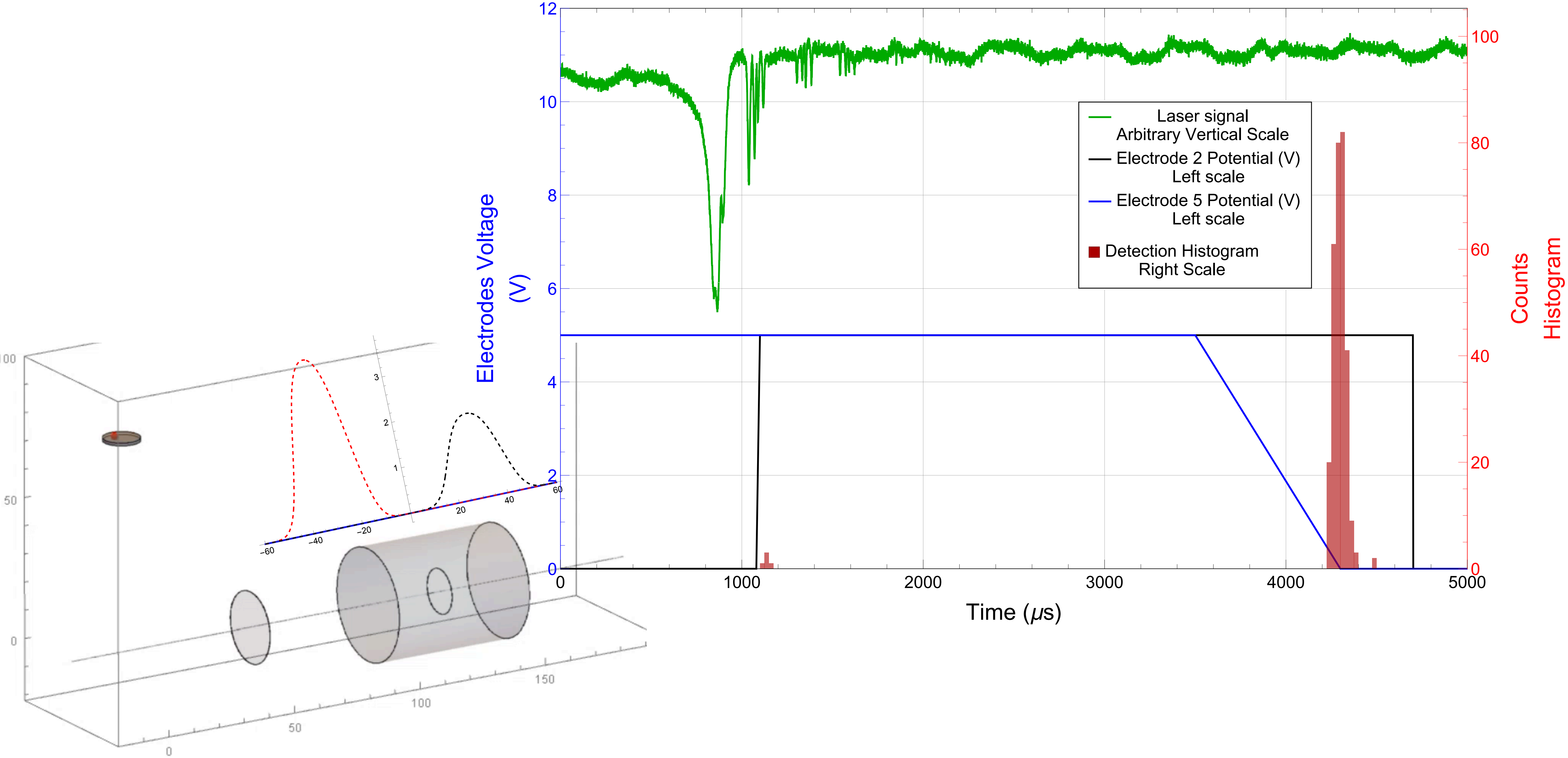
## LASER Penning Trap



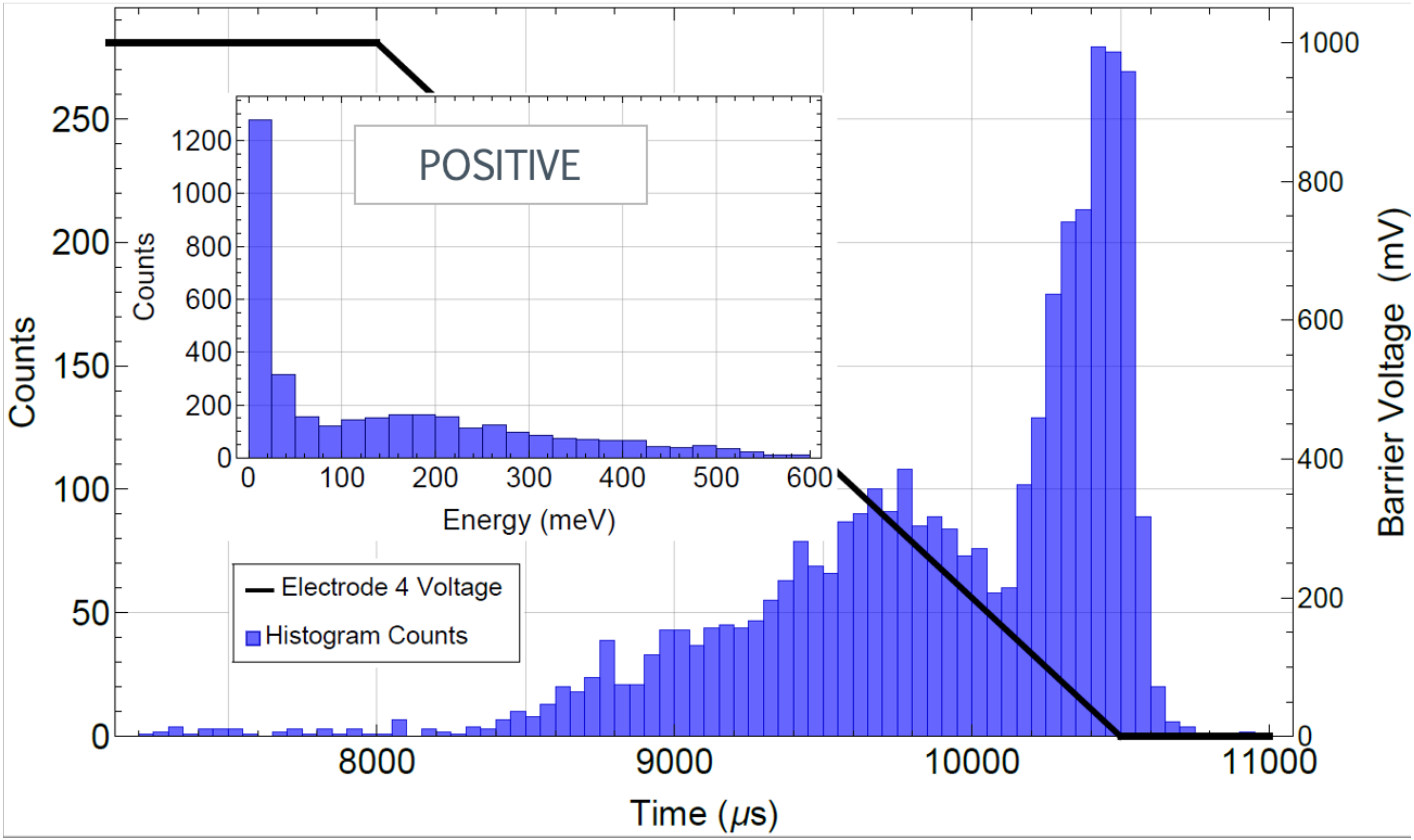
# Matrix Isolation Sublimation (MISu): trapped ions (cations: mostly H+ …)

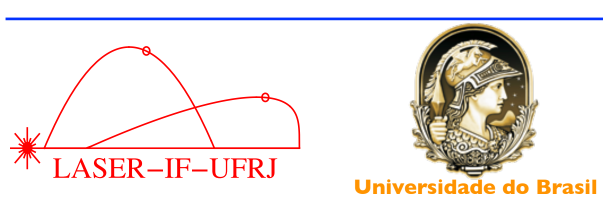


# Matrix Isolation Sublimation (MISu): trapped ions (cations: mostly H+ …)

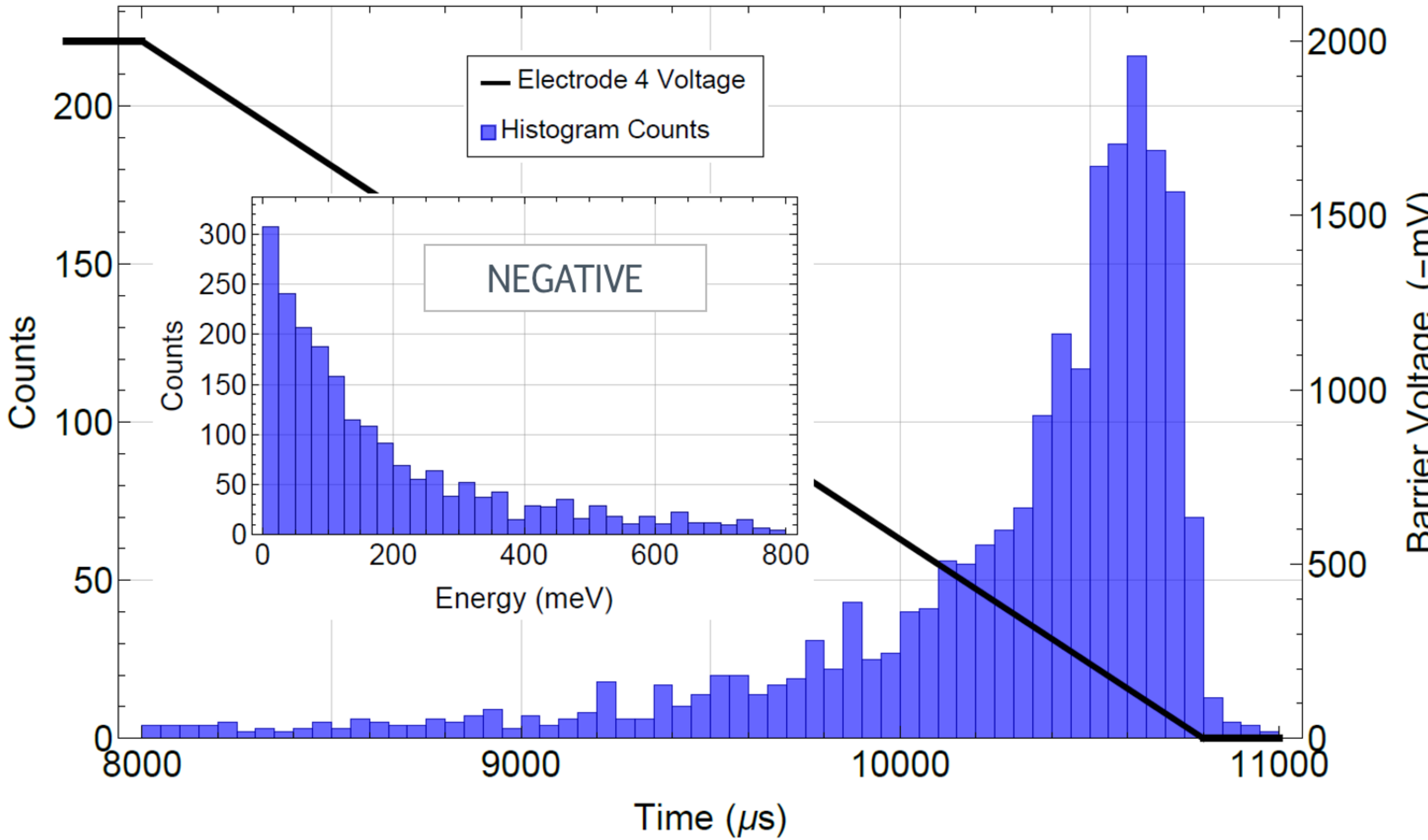


# Matrix Isolation Sublimation (MISu): trapped cryogenic (mostly p, ...)



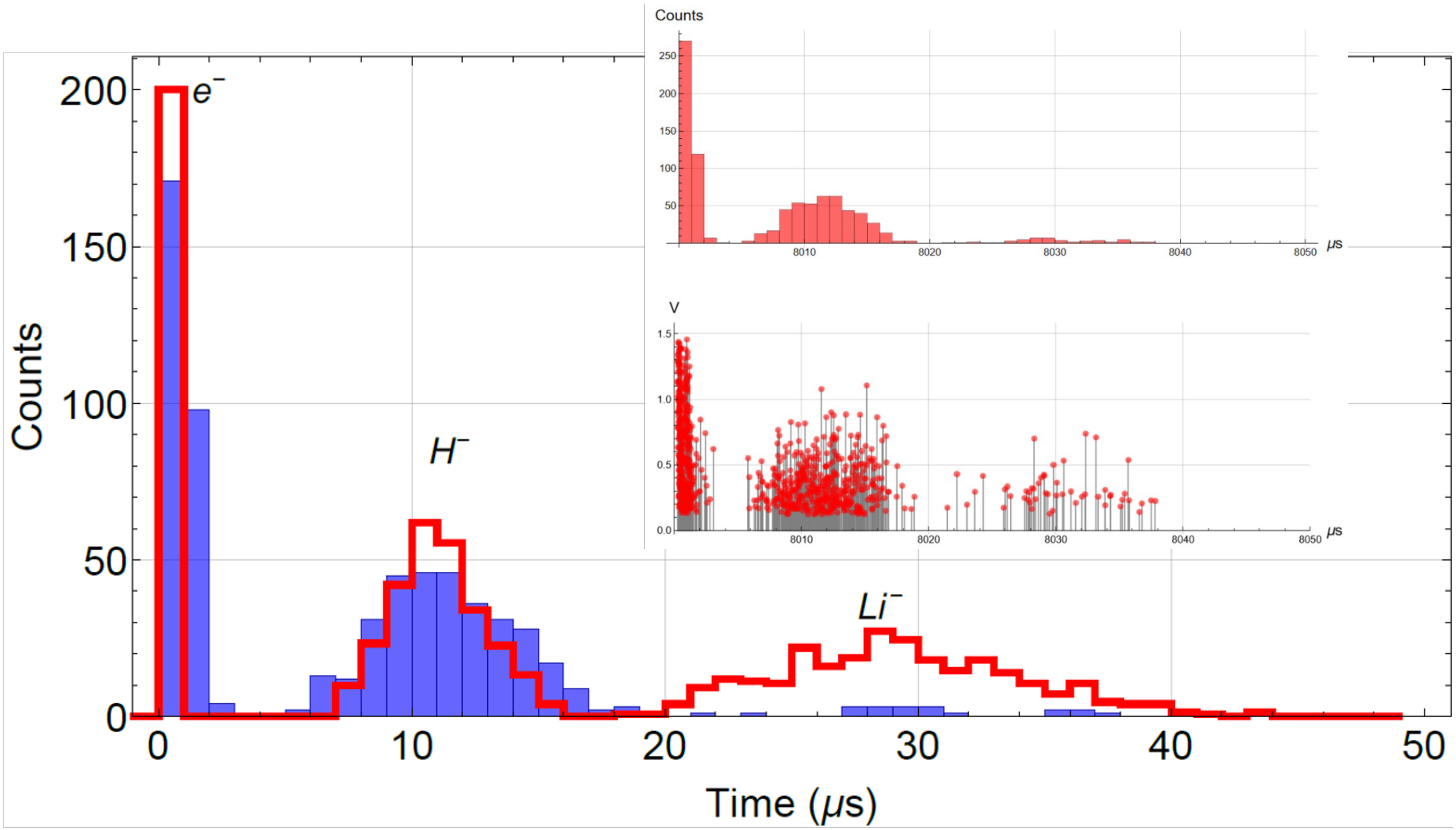



# Matrix Isolation Sublimation (MISu): trapped cryogenic (mostly $H^-$ [3/4], $e^-$ ...)



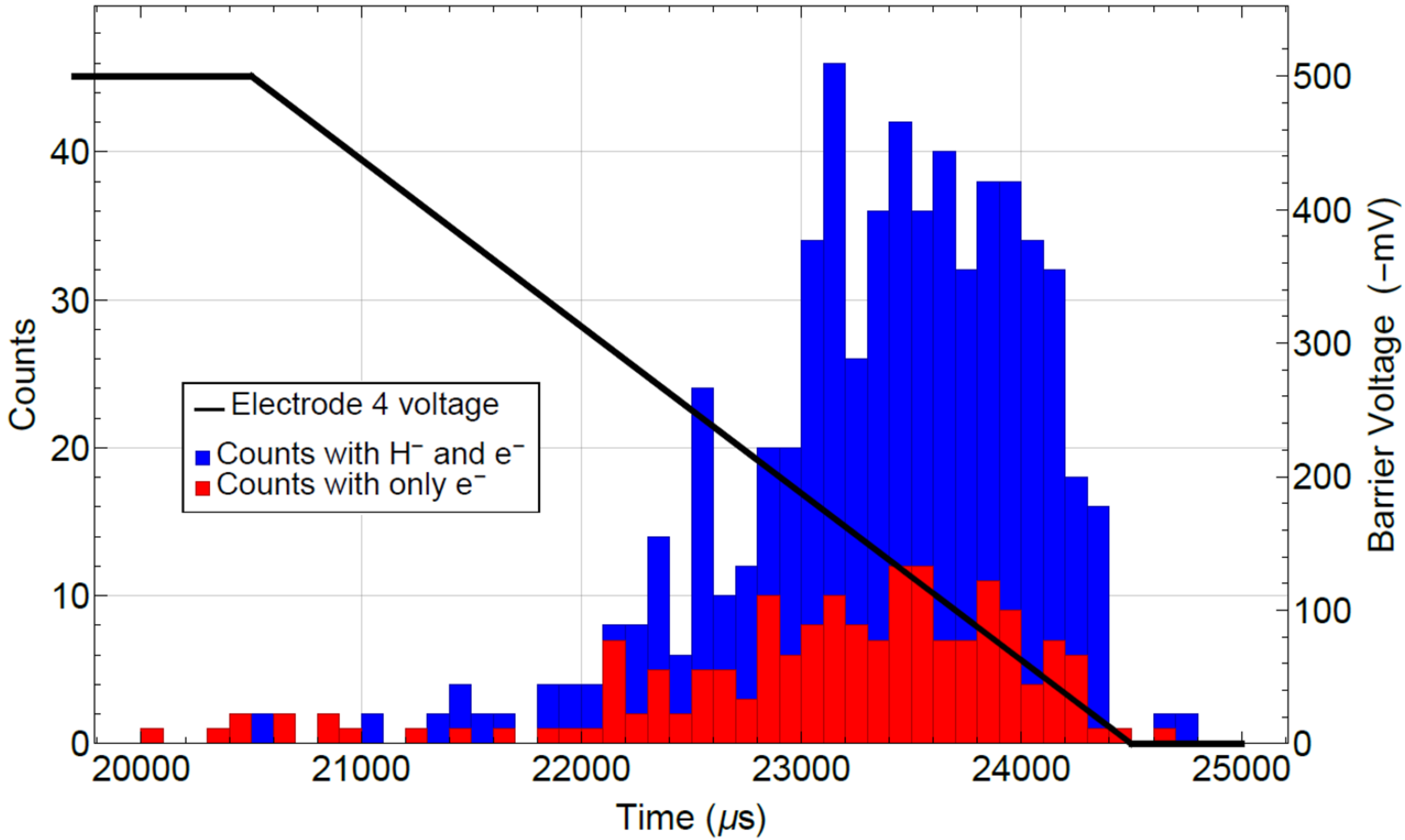
# Matrix Isolation Sublimation (MISu): trapped cryogenic (mostly e-, ...)

## Results and Simulation – Negative charged particles



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

## $H^-$ to $e^-$ ratio



# Matrix Isolation Sublimation (MISu): cryogenic ions

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## Adaptable platform for trapped cold electrons, hydrogen and lithium anions and cations

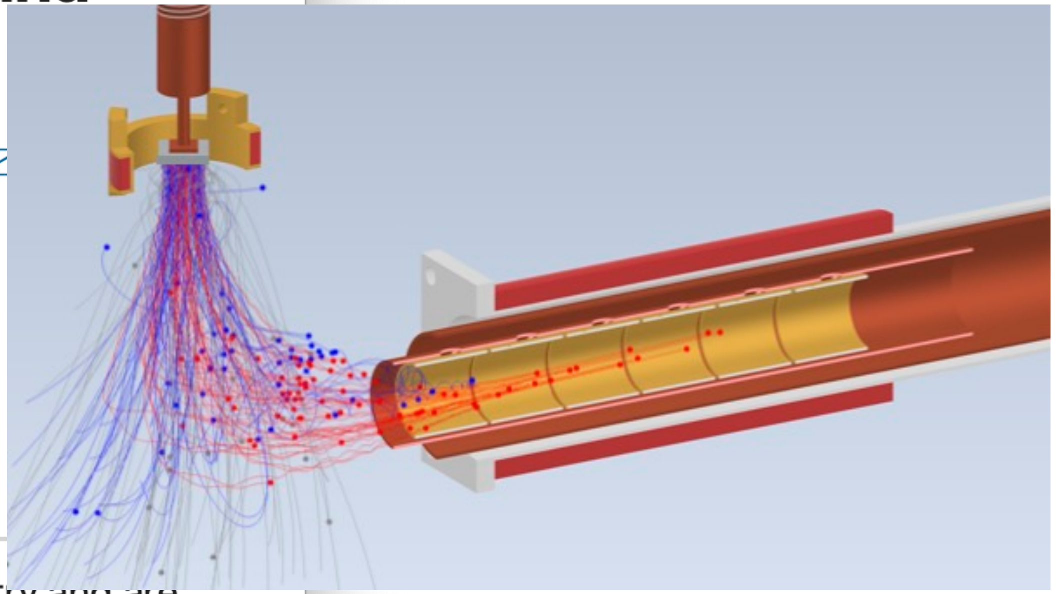
L. O. A. Azevedo, R. J. S. Costa, W. Wolff, A. N. Oliveira, R. L. Sacramento, D. M. Silveira & C. L. Cesar

*Communications Physics* **6**, Article number: 112 (2023) | Cite this article



cryoCrystals
@ CSF(Ticino):
Eric Hessels,
Giovanni Carugno
...(Paolo Crivelli)

https://www.nature.com/articles/s42005-023-01228-7

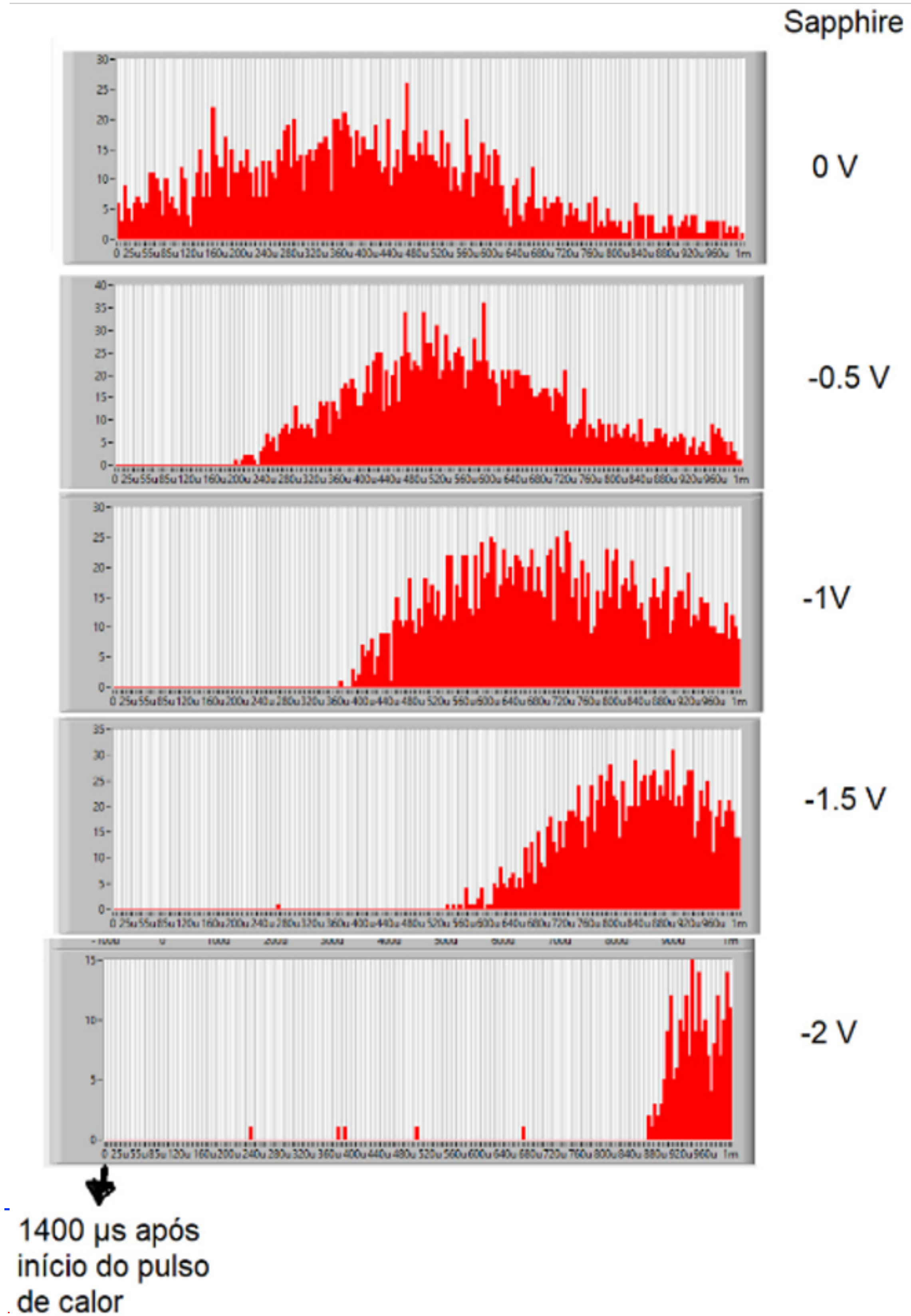


### Abstract

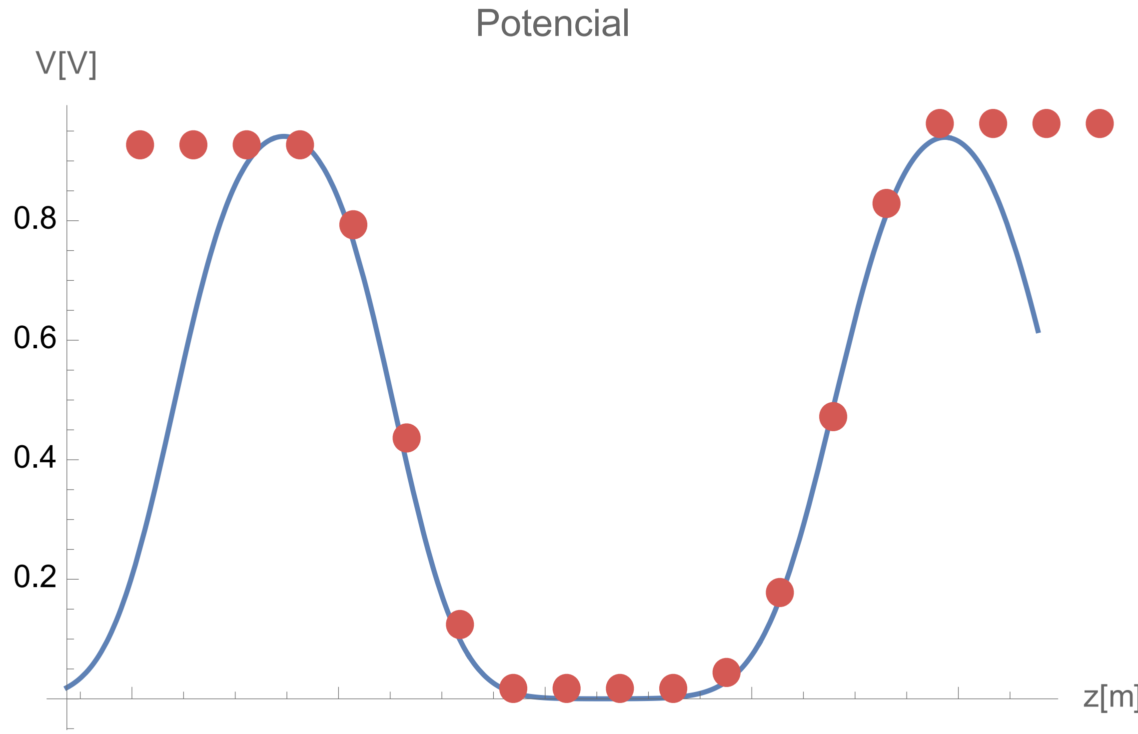
Cold cations, electrons and anions are ubiquitous in space, participate in star formation chemistry and are relevant to studies on the origin of molecular biology homochirality. We report on a system to generate and trap these species in the laboratory. Laser ablation of a solid target (LiH) facing a sublimating Ne matrix generates cold electrons, anions, and cations. Axial energy distributions (of $e^-$, $H^\pm$ and $Li^\pm$) peaked at 0–25 meV are obtained in a Penning trap at 90 mT and 0.5 eV barrier. Anions can be guided and neutralized with low

ALPHA CERN

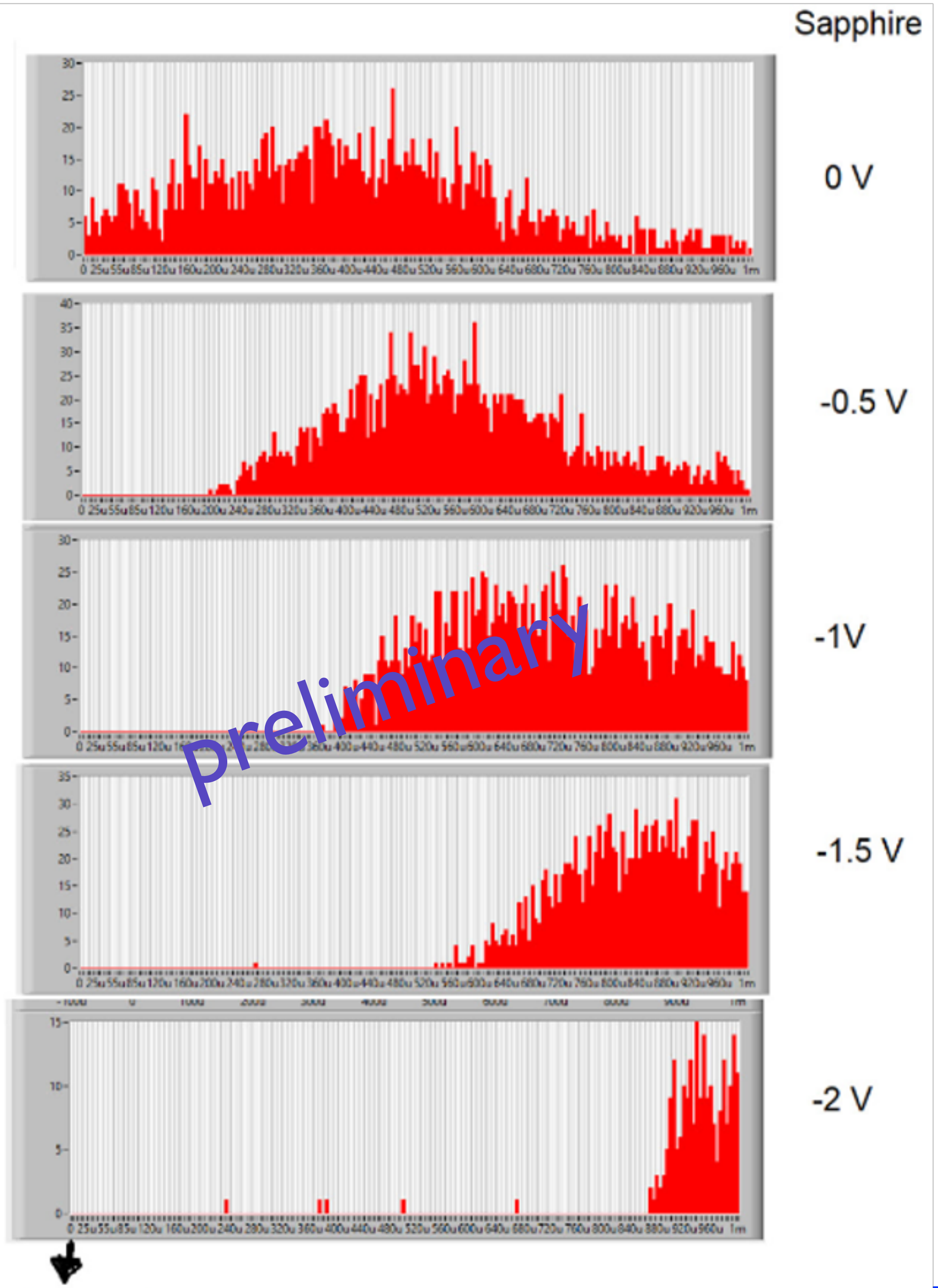
# Beyond the manuscript (kelvins): retarding ions




Without trap: real cryogenic
Trap raises energy

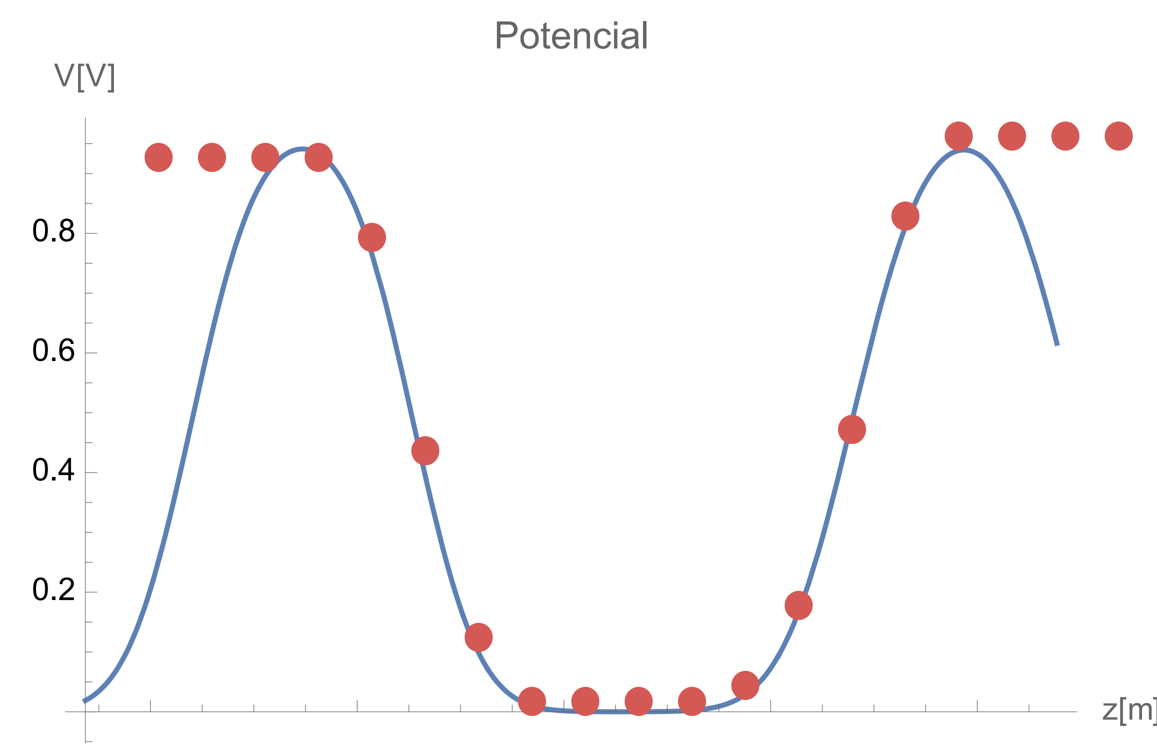


# Beyond the manuscript (kelvins): retarding ions

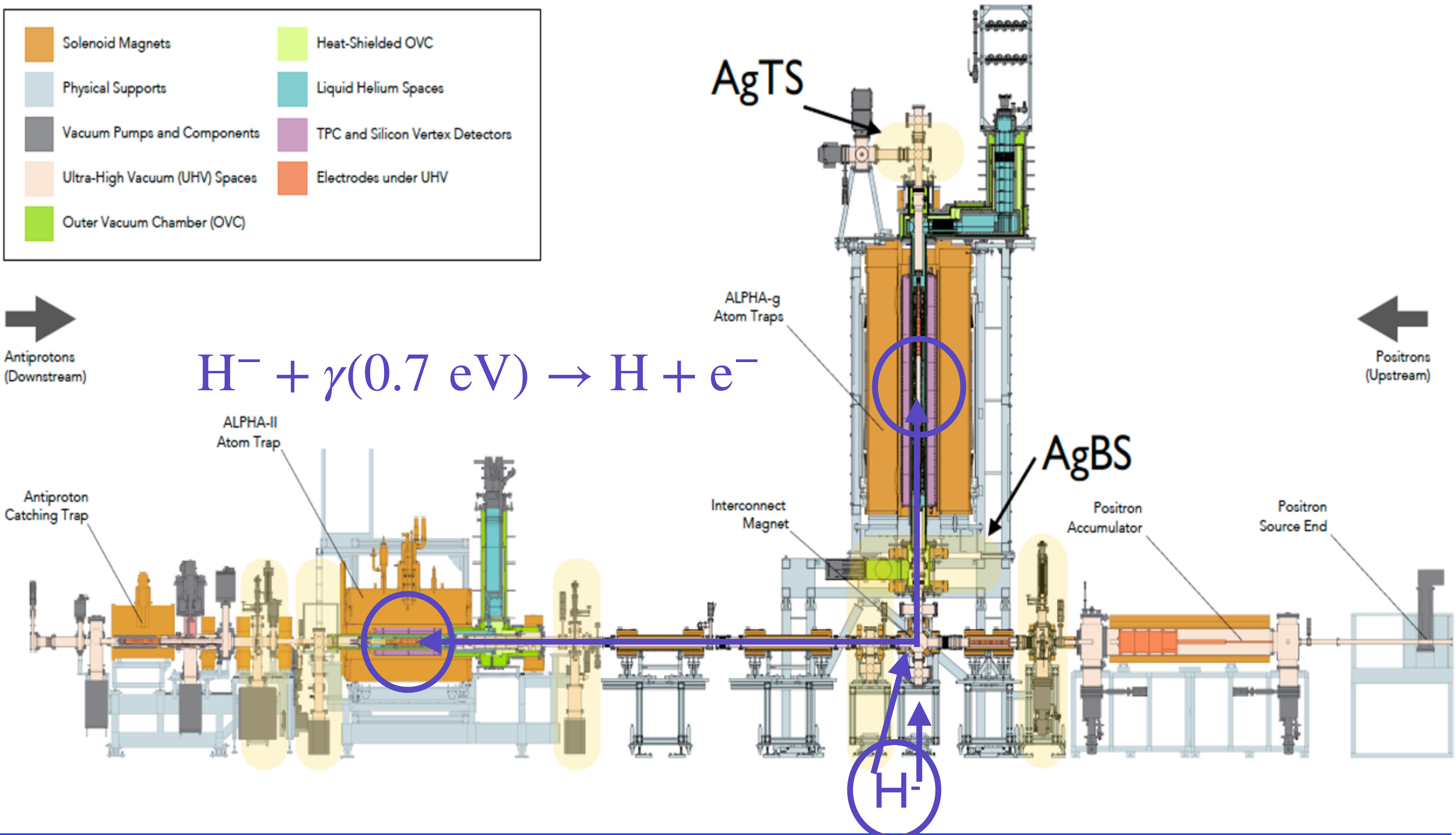



1400 µs após
início do pulso
de calor

Without trap: real cryogenic
Trap raises energy



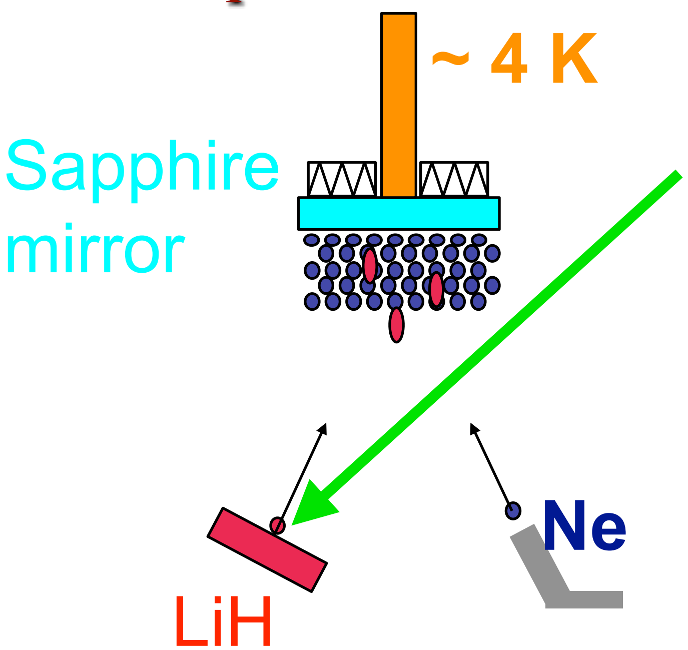
# Matrix Isolation Sublimation (MISu): (PRELIMINARY) proposal: $H^-$ for ALPHA Hbar trap

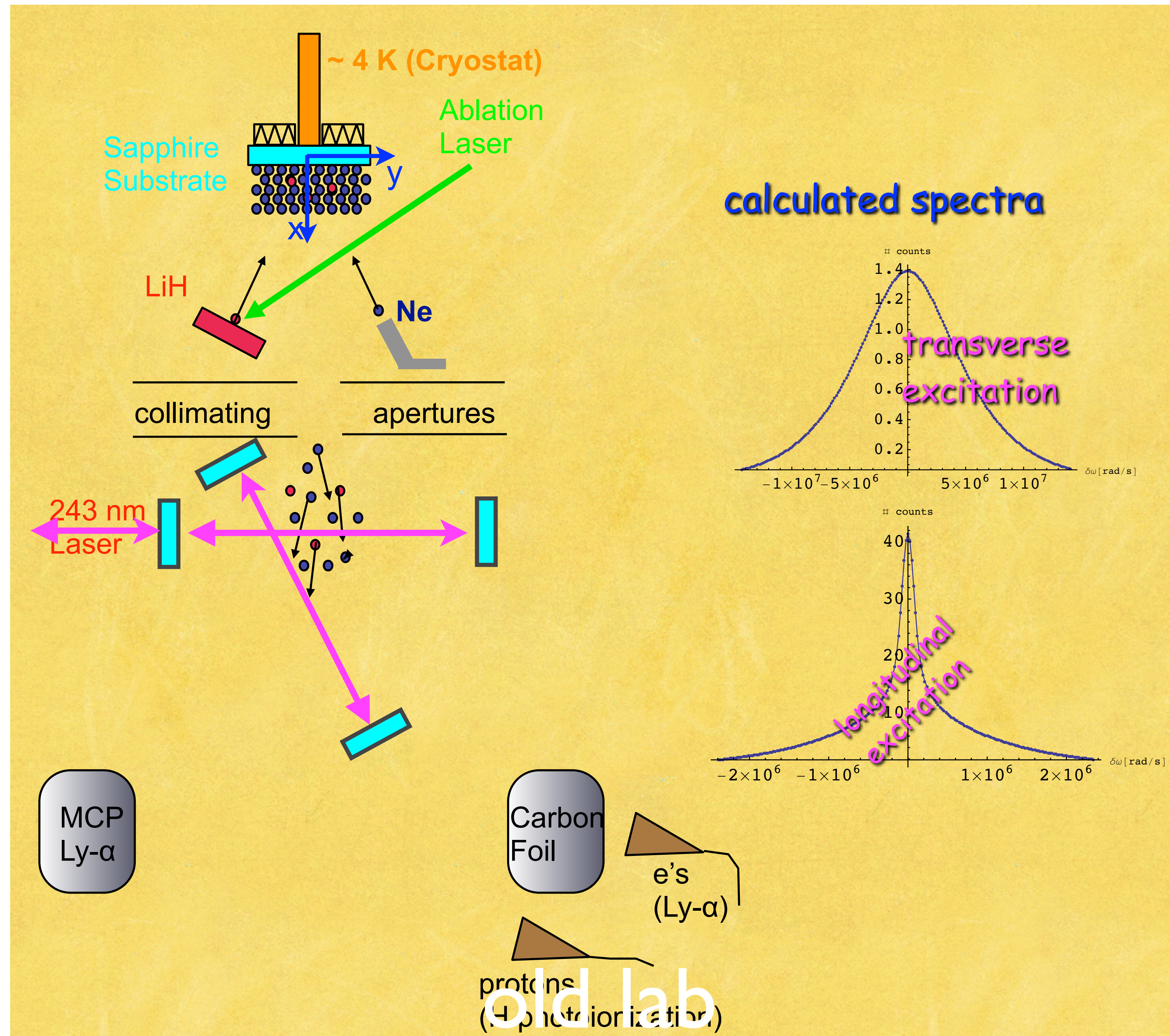



$$H^- + \gamma(0.7\ \mathrm{eV}) \rightarrow H + e^-$$

# To Do #1: Matrix Isolation Sublimation: Direct H(1s-2s, 2s-...)/D/T.. spectroscopy from MISu

**Deposition Process**



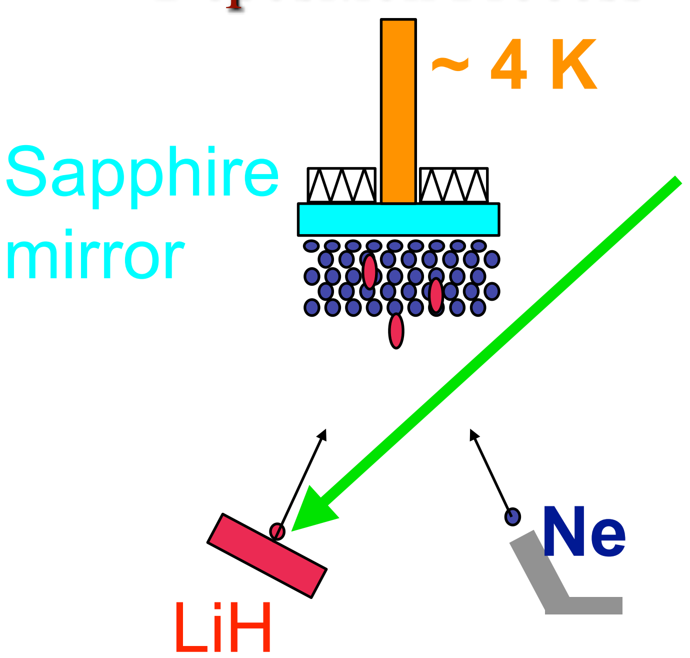

H,D,T beam spectroscopy

heteronuclear molecular formation (process ?)

trapping of H, Li, OH, CaH, KRb ...

# To Do #1: Matrix Isolation Sublimation:
# Direct H(1s-2s, 2s-...)/D/T.. spectroscopy from MISu

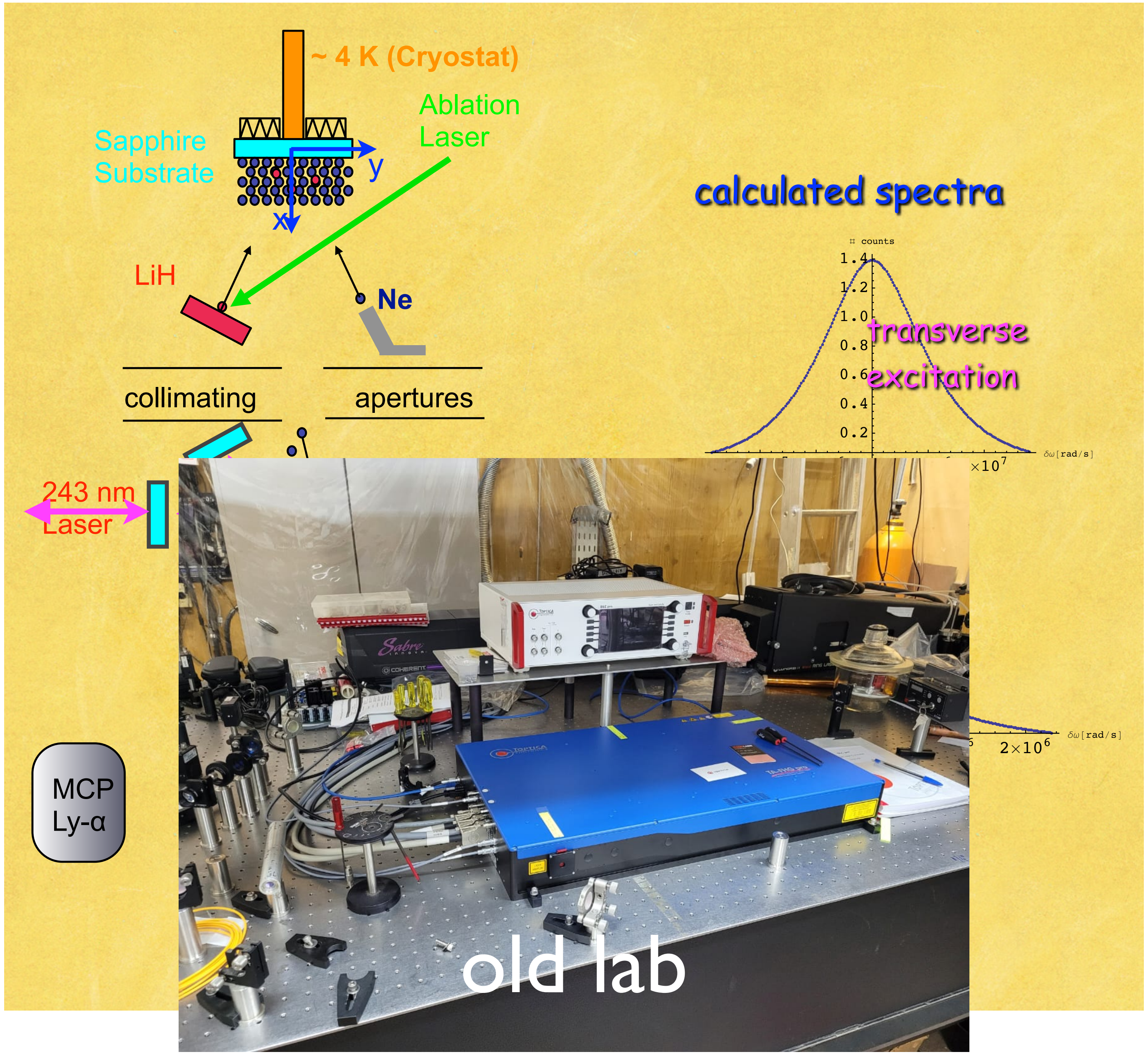
**Deposition Process**




**H,D,T beam spectroscopy**

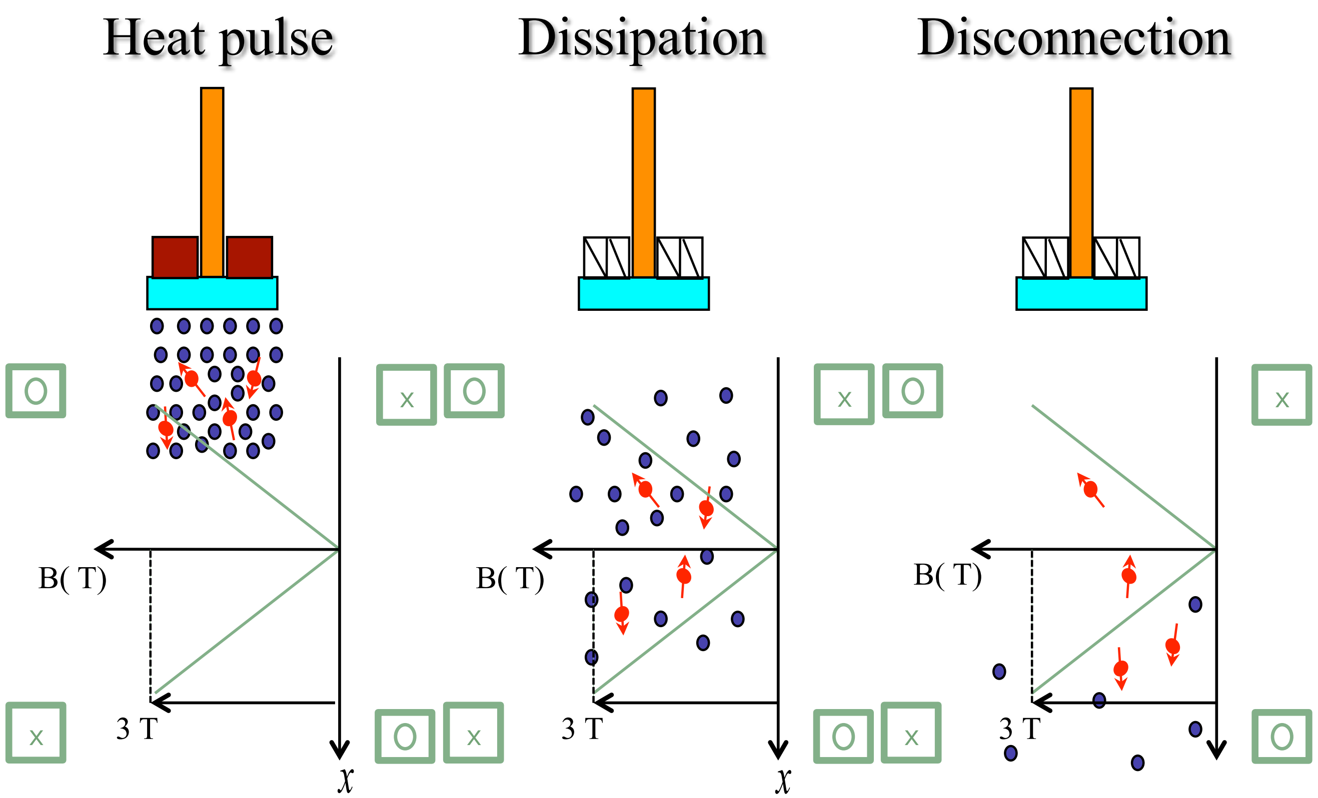
**heteronuclear molecular formation (process ?)**

**trapping of H, Li, OH, CaH, KRb ...**

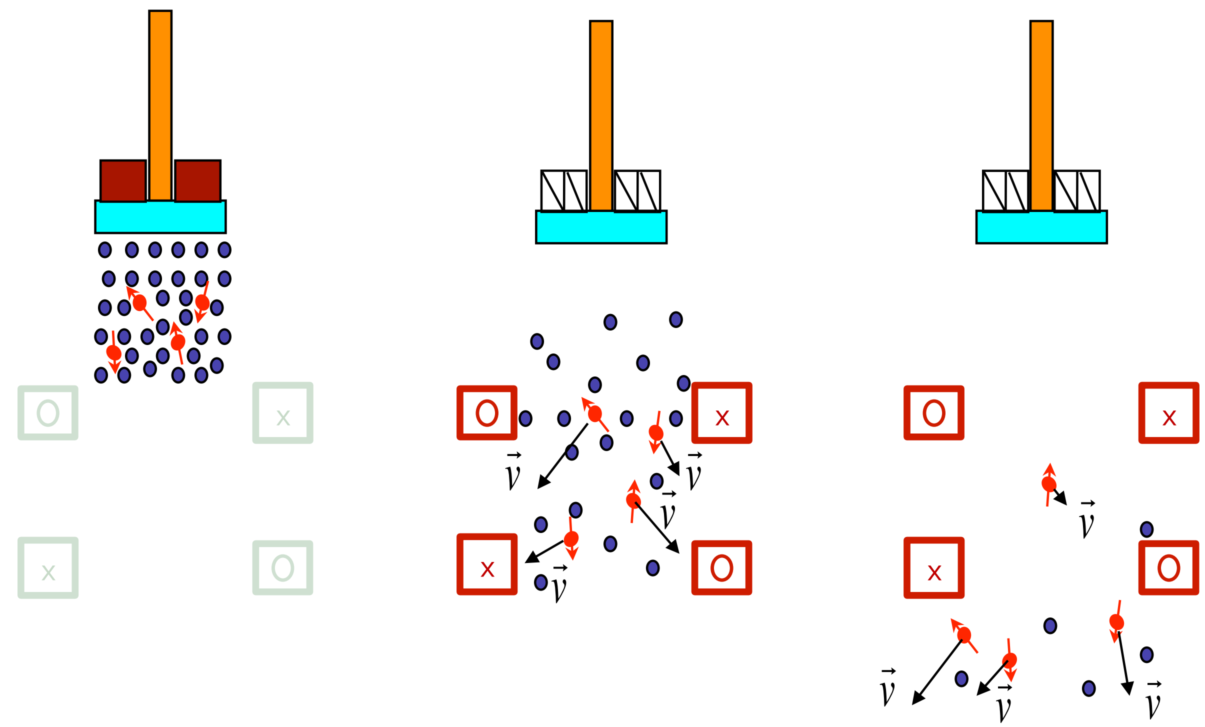


# To Do #2: Direct Trap from Matrix Isolation Sublimation

## Route 1: 3 T high-L CW magnet




## Route 2: 1 T low-L switched magnet



Build a new magnet
(dicussing details w/S.Vasiliev)

CLC, J. Phys. B 49 (2016) 074001 (antiH issue)
~$10^7$ - $10^9$ trapped H

THE JOURNAL OF CHEMICAL PHYSICS **131**, 054302 (2009)

http://dx.doi.org/10.1063/1.3180822

**Trapping hydrogen atoms from a neon-gas matrix: A theoretical simulation**

S. Bovino,[1] P. Zhang,[1,a)] V. Kharchenko,[1,2] and A. Dalgarno[1,b)]
[1]*Institute for Theoretical Atomic, Molecular and Optical Physics, Harvard-Smithsonian Center for Astrophysics, Harvard University, Cambridge, Massachusetts 02138, USA*
[2]*Department of Physics, University of Connecticut, Storrs, Connecticut 06269, USA*

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

$H^-$ : Possible 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 same local

Other cryogenic anions/cations: astrophysical, molecular, sensors …

⇒ (next months) Scale **UP** production numbers & lower temperatures:

solution looking for problems

# Perspectives with cryogenically cold H/D atoms & Molecules

☆ Laser Spectroscopy 1S-2S, 2S-xxxx @ subK (?) beam samples

☆ Direct trapping paramagnetic atoms & molecules from MISu

Thanks to: MIT & ALPHA collaborators, and to team at UFRJ(Rio): Levi Azevedo, Rodolfo Costa, Alvaro Nunes de Oliveira, Rodrigo Sacramento, Daniel Silveira, Wania Wolff

— Looking forward to collaborations —


new undergraduate students
assemblying the system


7,5 m
s com os lasers: a sala dos lasers
isolada acústicamente (e de poeira)
aboratório e em bom controle térmico.
a com uma sala/mezanino.
new lab: 2023

Thank you Paolo et al.
CSF team