Hyperfine Microwave Spectroscopy of Ground-State Antihydrogen

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Canada

The hyperfine splitting of ground state hydrogen ($\nu_{\mathrm{H}}^{\mathrm{hfs}}$) can be measured to 13 significant figures.

Cold antihydrogen has been magnetically-trapped,[1] and a rudimentary measurement of $\nu_{\overline{\mathrm{H}}}^{\mathrm{hfs}}$ has been obtained.[2]

What are the prospects for precision comparisons of $\nu_{\mathrm{H}}^{\mathrm{hfs}}$ and $\nu_{\overline{\mathrm{H}}}^{\mathrm{hfs}}$, as tests of CPT invariance?

[1]ALPHA Collaboration, *Nature* ***468****, 673 (2010)*

[2]ALPHA Collaboration, *Nature* ***483*** *, 439 (2012)*

Outline

Review
- Hyperfine splitting (hfs) in ground state H/ $\overline{\text{H}}$
- Signatures for CPT symmetry violation

Experiment: magnetic resonance of cold trapped $\overline{\text{H}}$
- Apparatus and methods
- Data
- Implications

What next?
- Prospects for a precision test of CPT based on hfs spectroscopy of H and $\overline{\text{H}}$

The ALPHA Collaboration

Other Presentations

Monday 12:00

- **Niels Madsen** (Swansea): Antihydrogen and Fundamental Physics

Tuesday 15:30 (Poster Session)

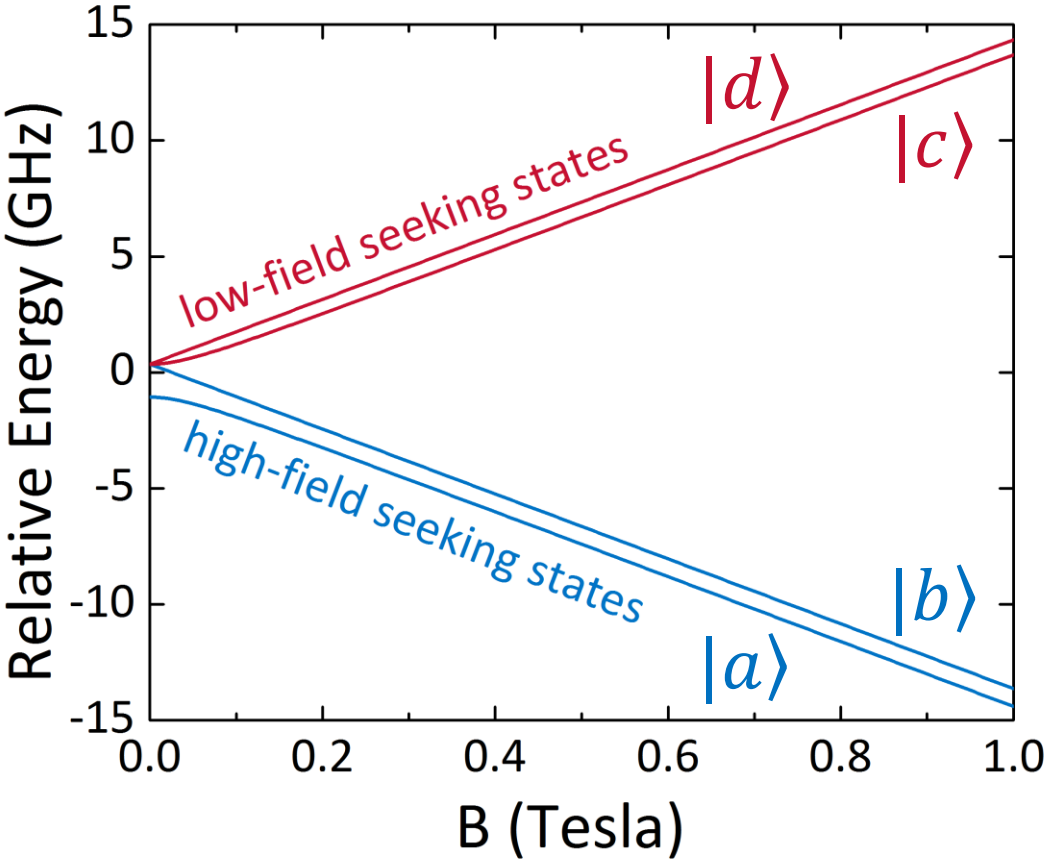
- **Makoto Fujiwara** (TRIUMF): Lyman-alpha source for spectroscopy and laser cooling of antihydrogen
- **Dirk van der Werf** (Swansea): Metastable states in antihydrogen production
- **Joseph McKenna** (Liverpool): The role of the Silicon Vertex Detector in the ALPHA Experiment
- **Andrey Zhmoginov** (Berkeley): Nonlinear dynamics of antihydrogen in magnetostatic traps: gravitational measurements and laser cooling

Friday 9:30

- **Joel Fajans**: Description and first application of a new technique to measure the gravitational mass of antihydrogen

Hyperfine Structure

Electronic (positronic) ground state of the H ($\overline{H}$) atom



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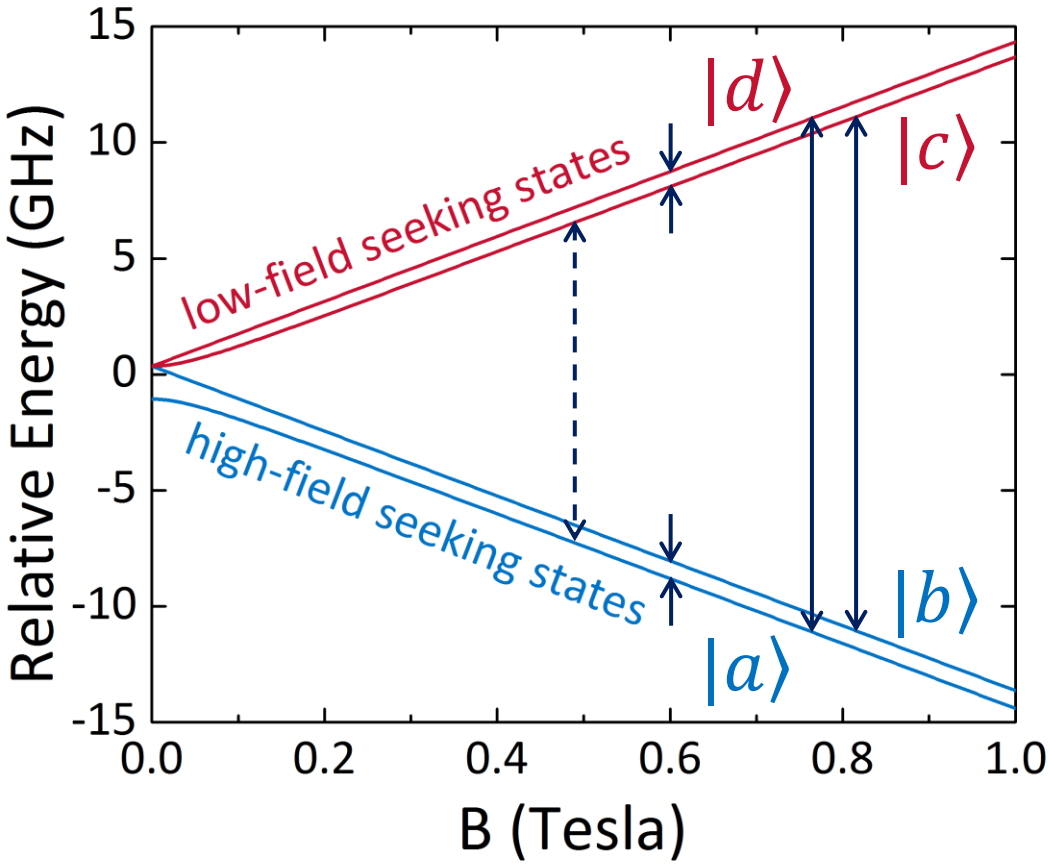


Apply RF Field $\vec{B}_1$

→ Allowed transitions

Character in large B_0

$\vec{B}_1 \perp \vec{B}_0$

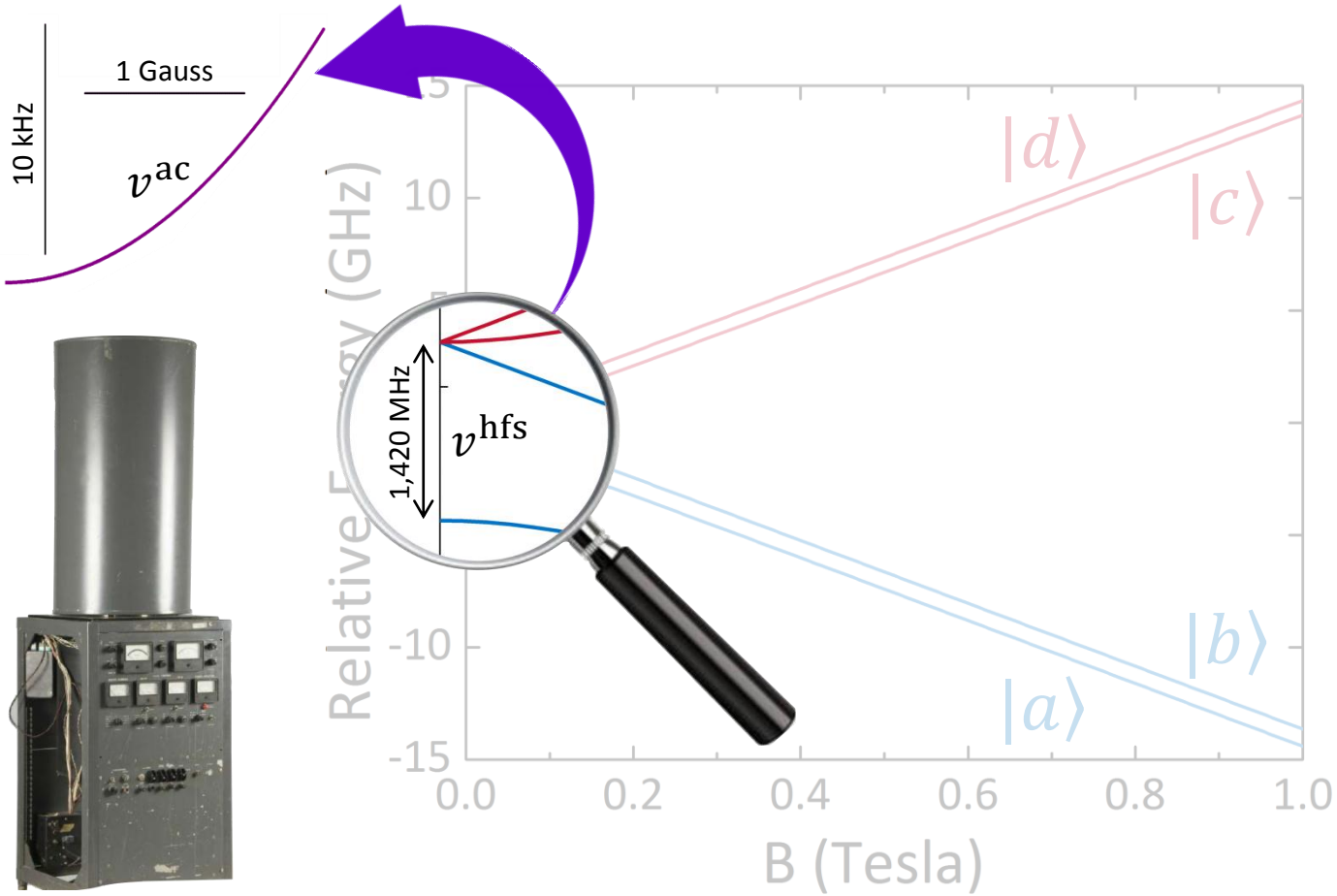
$|b\rangle$-$|c\rangle$, $|a\rangle$-$|d\rangle$ } ESR/PSR

$|c\rangle$-$|d\rangle$, $|a\rangle$-$|b\rangle$ } NMR

$\vec{B}_1 \parallel \vec{B}_0$

$|a\rangle$-$|c\rangle$ } combined

Hyperfine Structure



H Maser: ν^{ac} is insensitive to B

Hyperfine Structure

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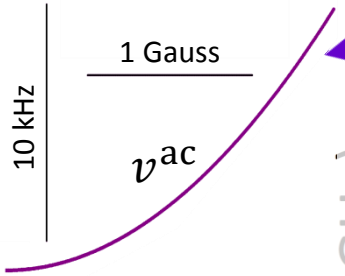
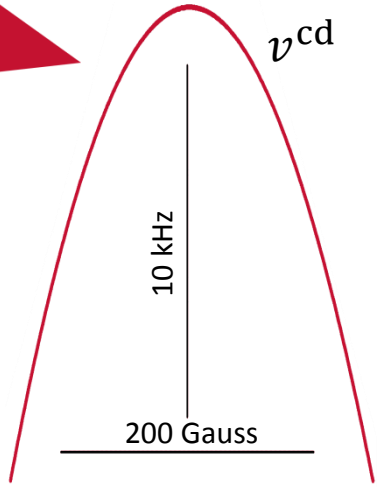
$B' = 0.65$ Tesla

Hyperfine Structure





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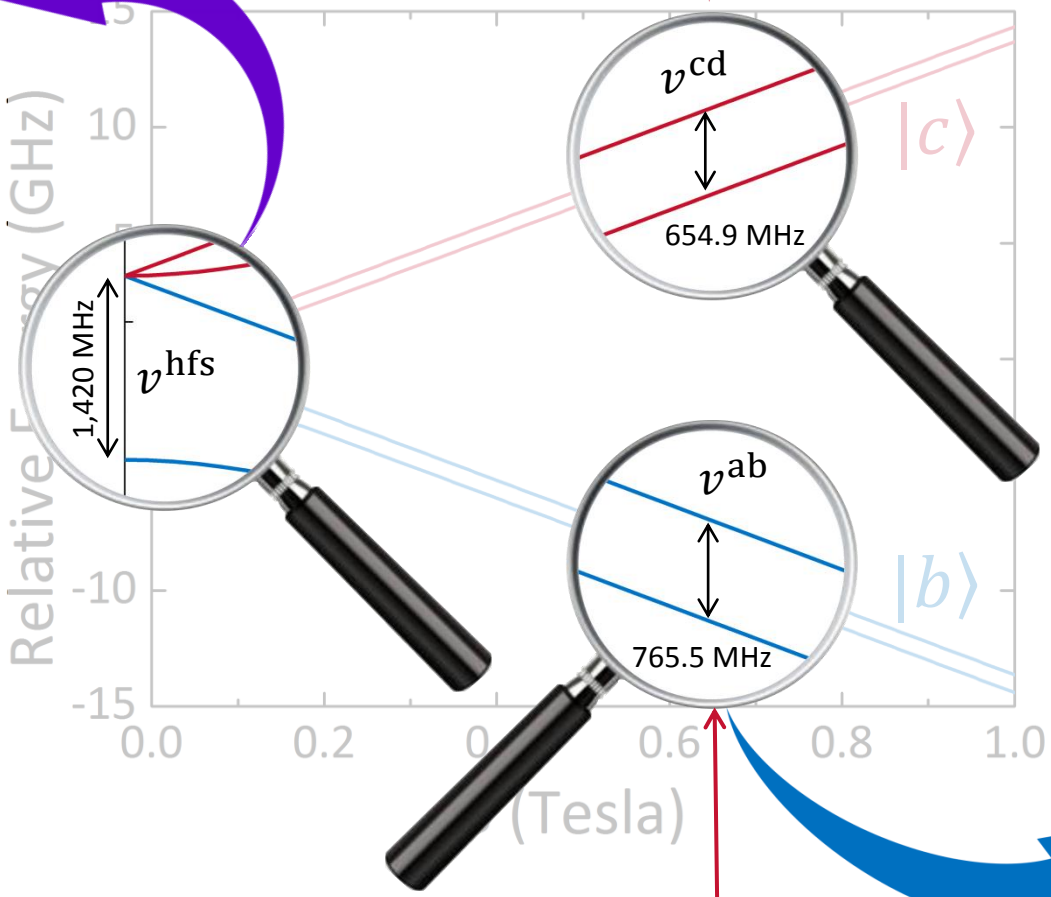

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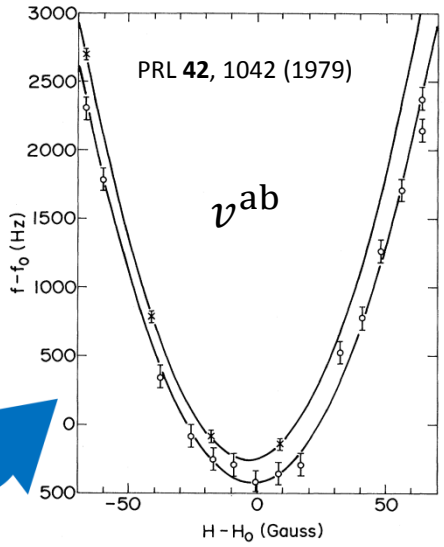
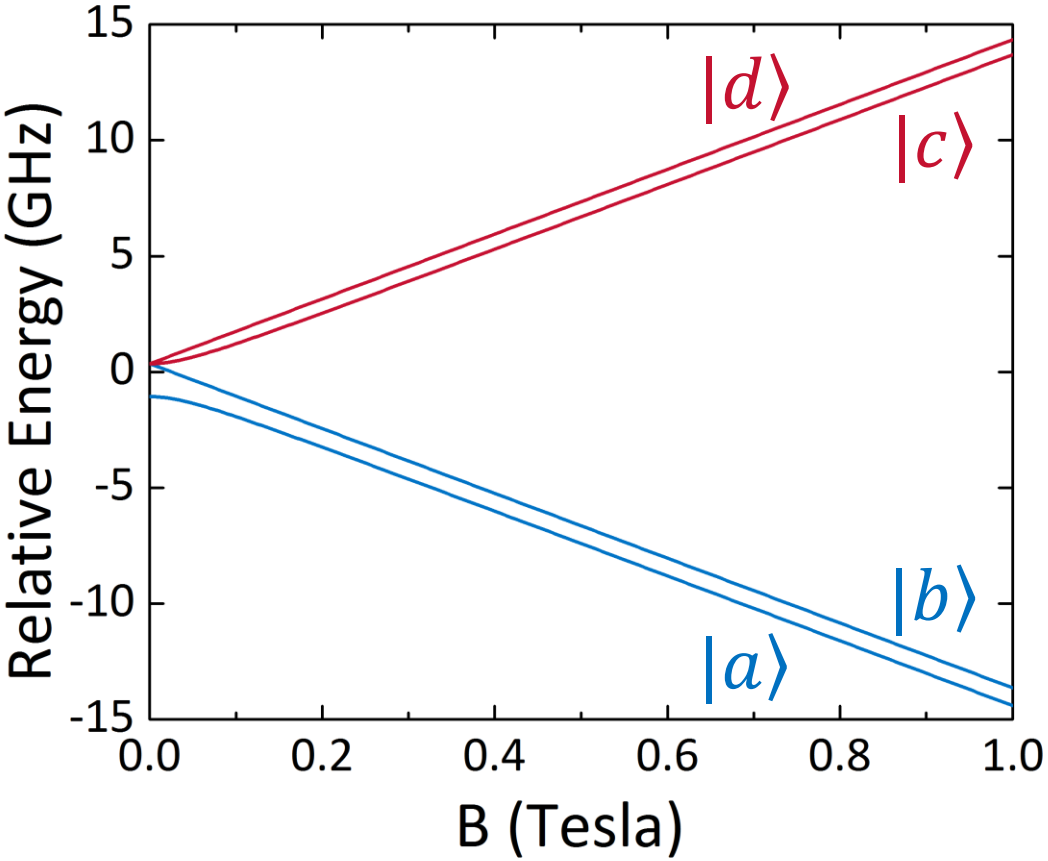


Signatures for CPT Violation

SME[1]: framework for evaluating the influence of Lorentz and CPT violation; points to effects that might arise in the spectra of H and $\overline{H}$.[2]



[1]Colladay & Kostelecký, *Phys Rev D* **55**, 6760 (1997)
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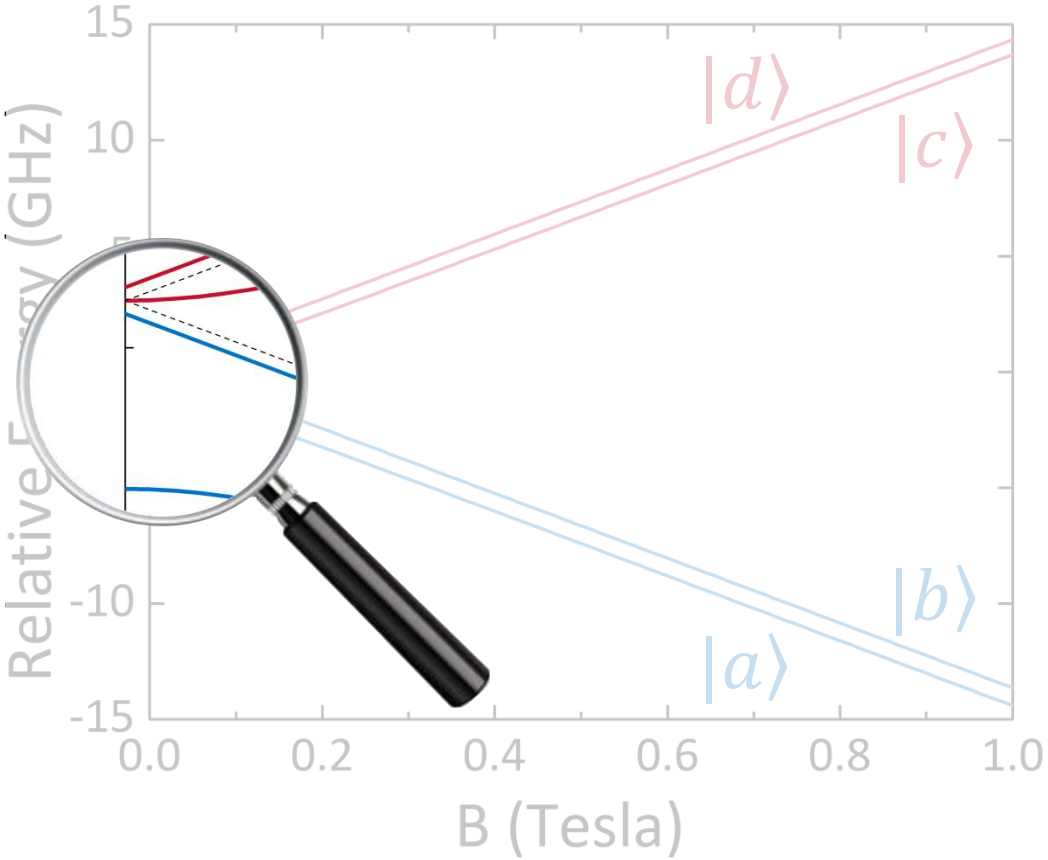

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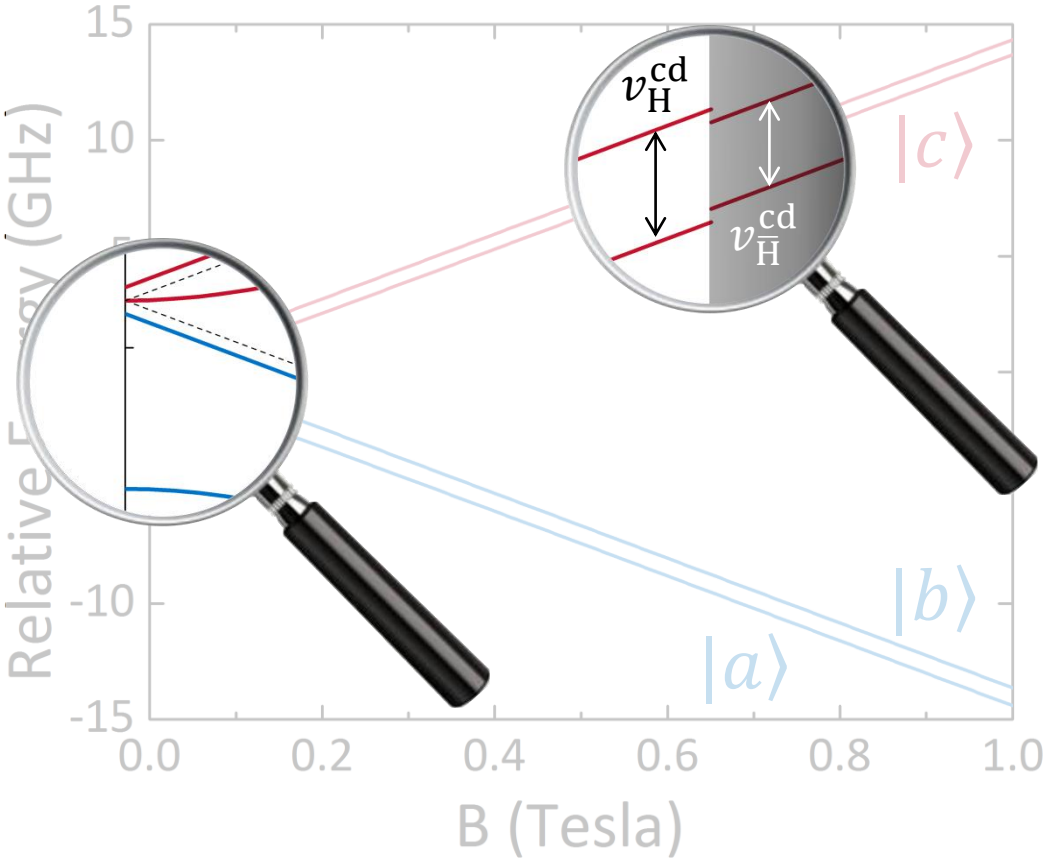

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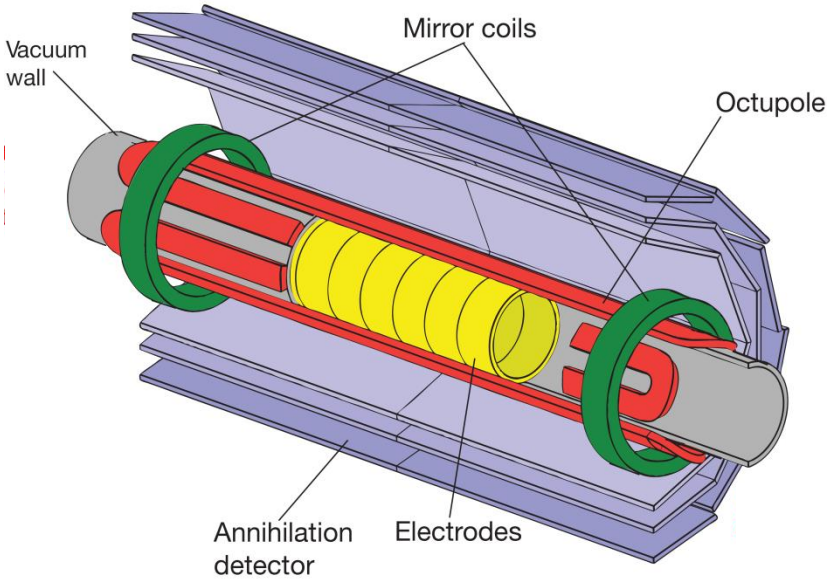
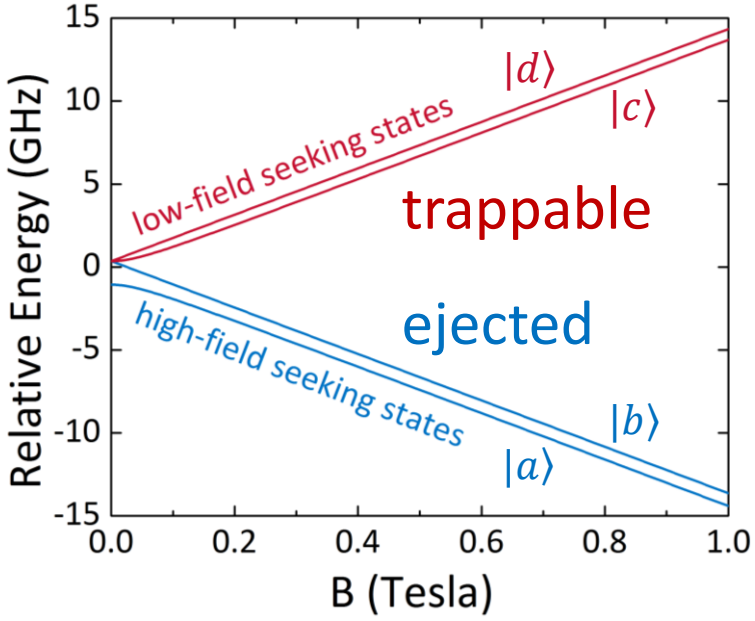
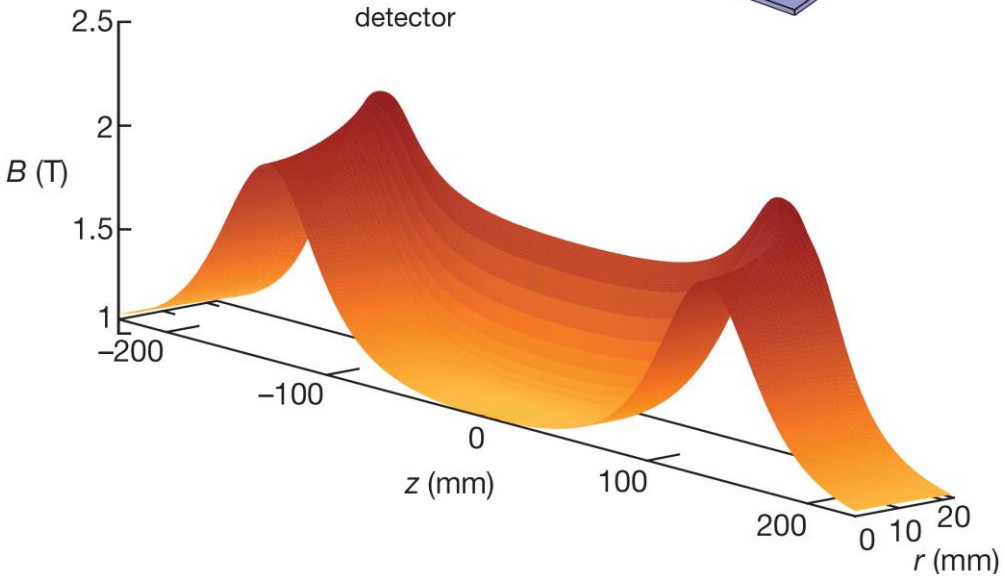
Apparatus

*Nature **468**, 673 (2010)*
*Nature Phys **7**, 558 (2011)*
*Phys Lett B **695**, 95 (2011)*







Magnetic potential well

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

depth: 0.54 K

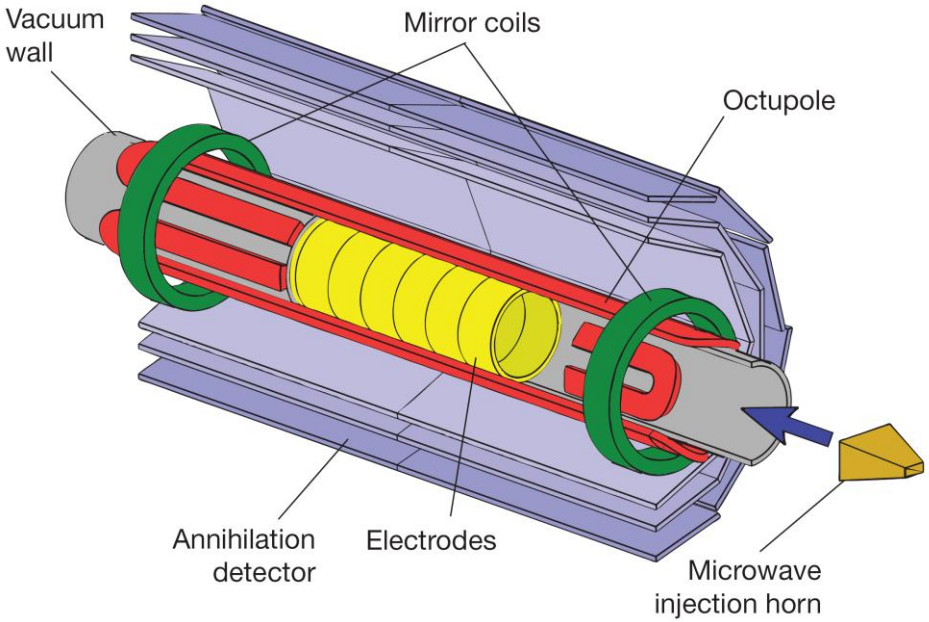
$\bar{H}$: synthesized at midpoint

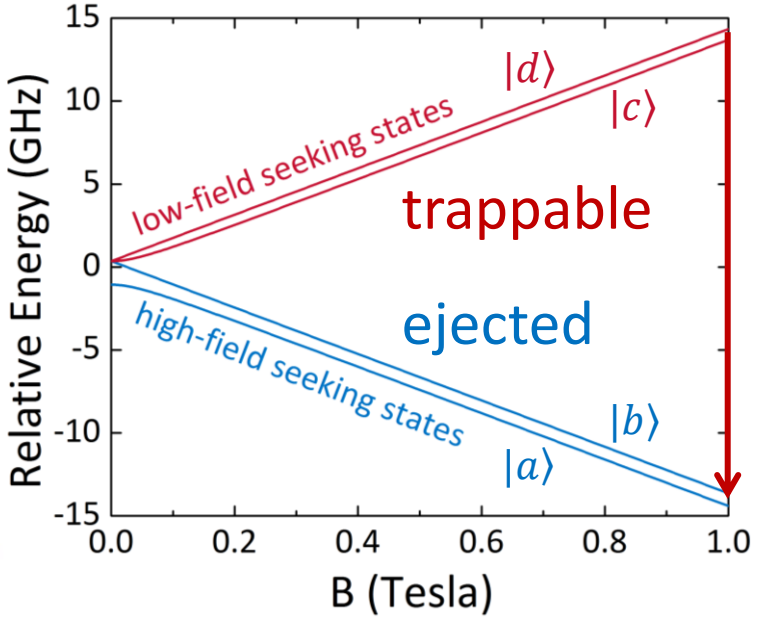
Storage time: ~10^3 s

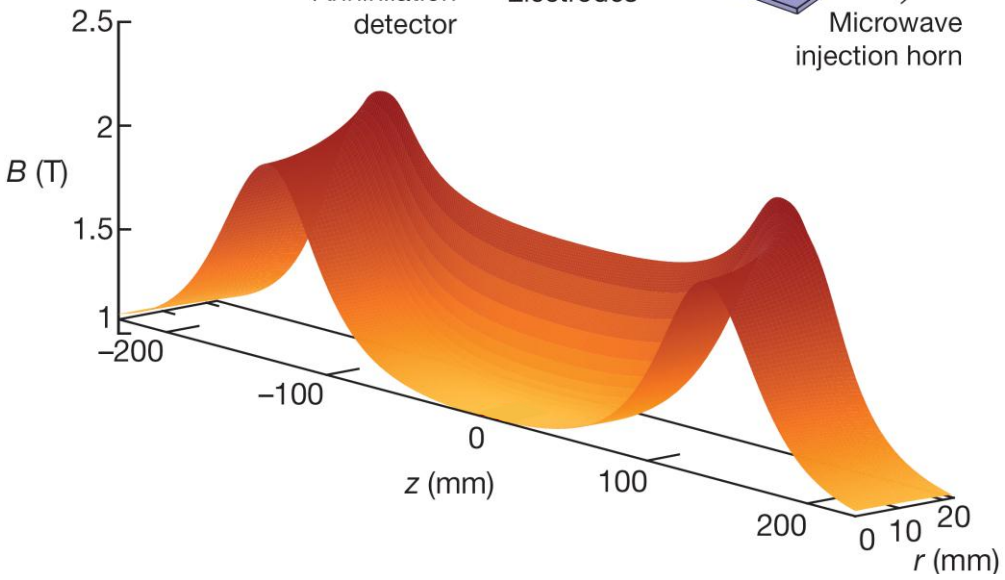
B_{min} = 1 Tesla

Experiment

Nature ***468***, *673 (2010)*
Nature Phys ***7***, *558 (2011)*
Phys Lett B ***695***, *95 (2011)*







Inject microwaves (28-30 GHz)

↓

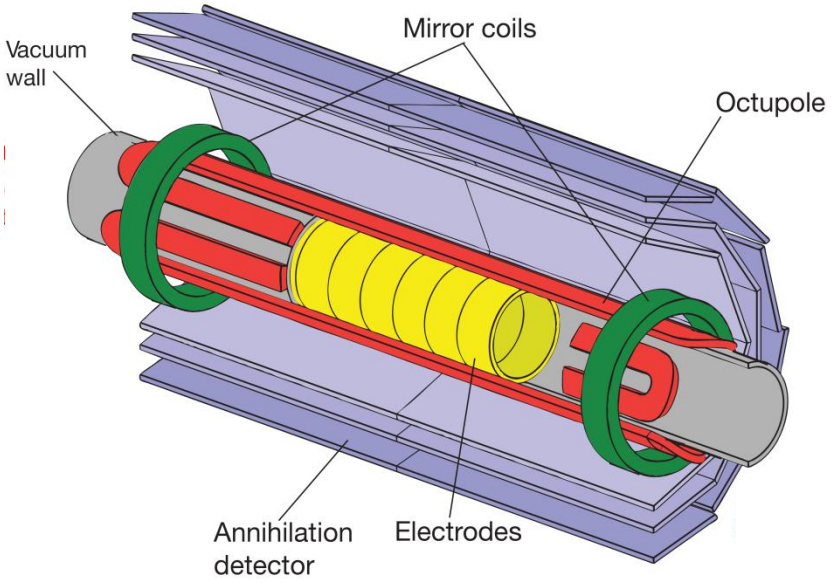
Induce spin flip transitions

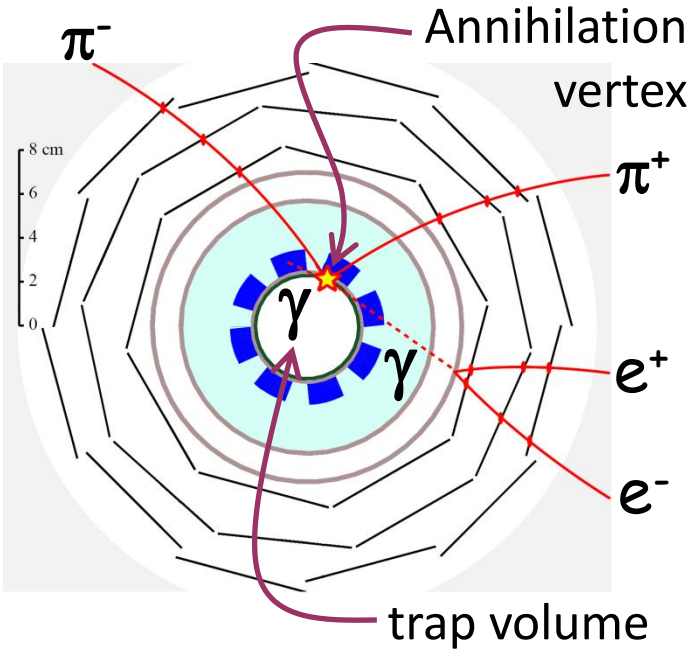
↓

Monitor annihilation events

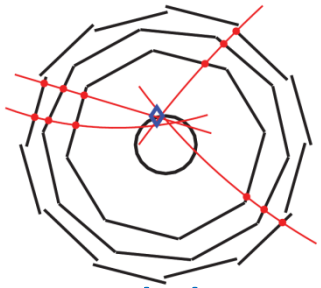
Detector

Nucl. Instrum. Meth. A. **684**, 73 (2012)
New J Phys **14**, 105010 (2012)

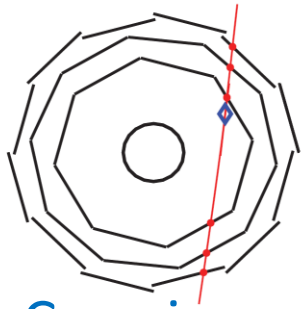




Reconstruction



Annihilation



Cosmic ray

Vertex resolution

z : 5.6 mm | r : 8.7 mm | ϕ : 21.4°

Efficiencies[1] :

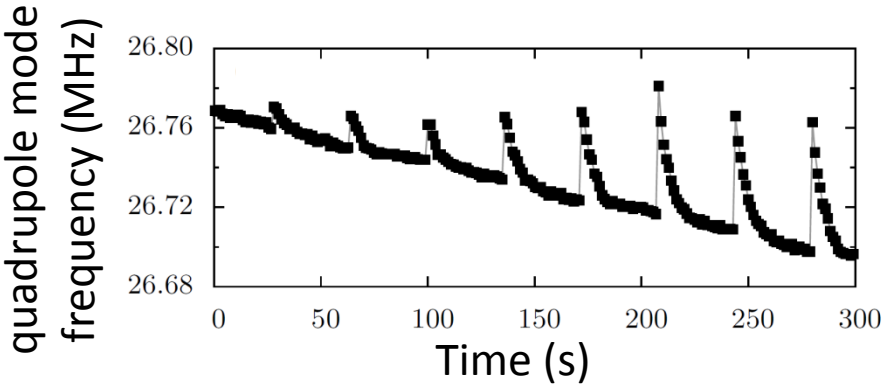
57±6%: $\bar{p}$ annihilation

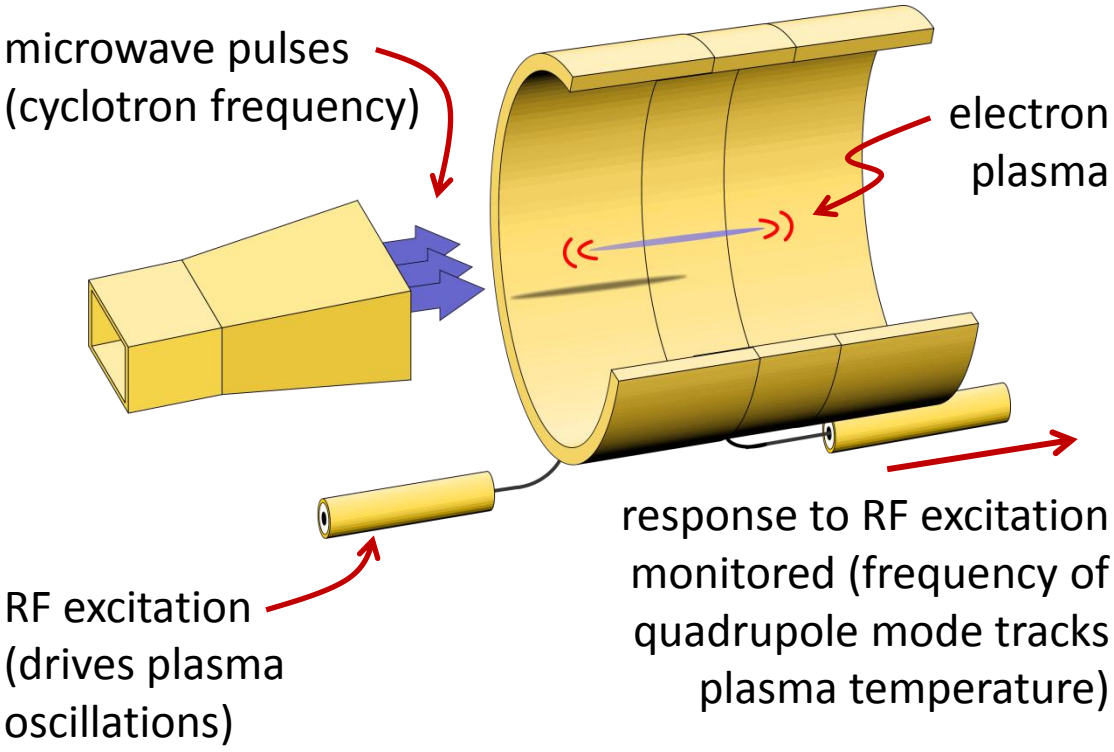
99.5%: cosmic rejection

[1]standard event acceptance criteria

Characterization

Electron Cyclotron Resonance used as an in-situ probe of:
(a) Static magnetic field
(b) Microwave fields





AIP Conf Proc **1521**, 123 (2013)
Hyperfine Interact **212**, 117 (2012)
Hyperfine Interact **199**, 39 (2011)

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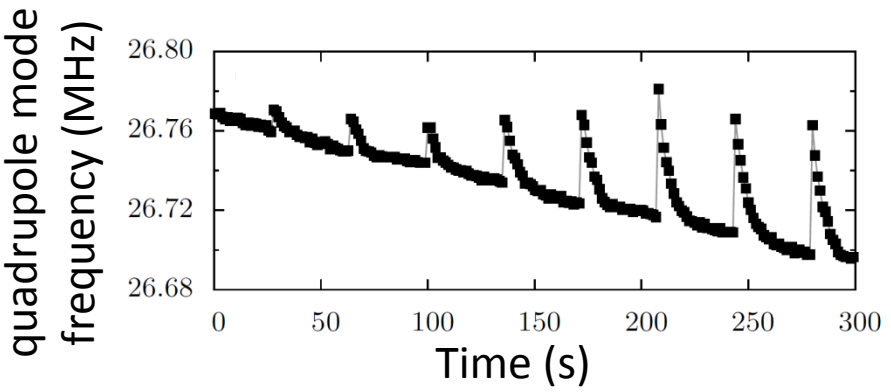
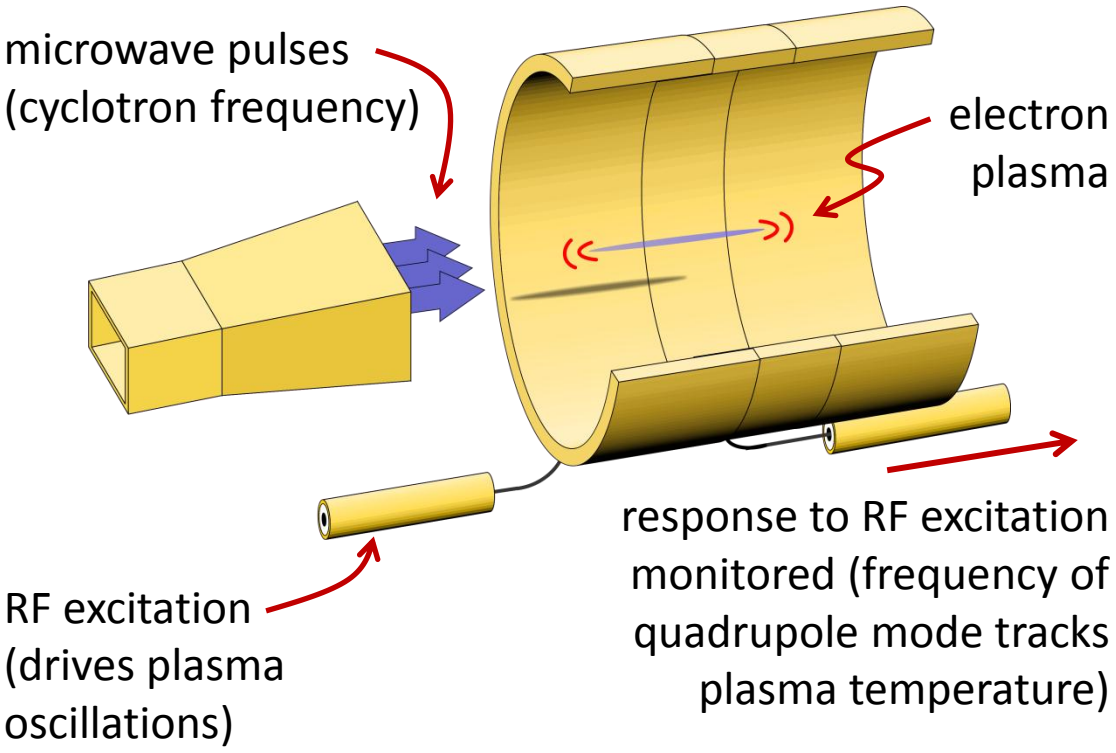




Minimum in trapping field: reproducibly ±0.7 Gauss ≡ ±2 MHz

Confirms balancing of microwave electric fields (all resonance conditions)

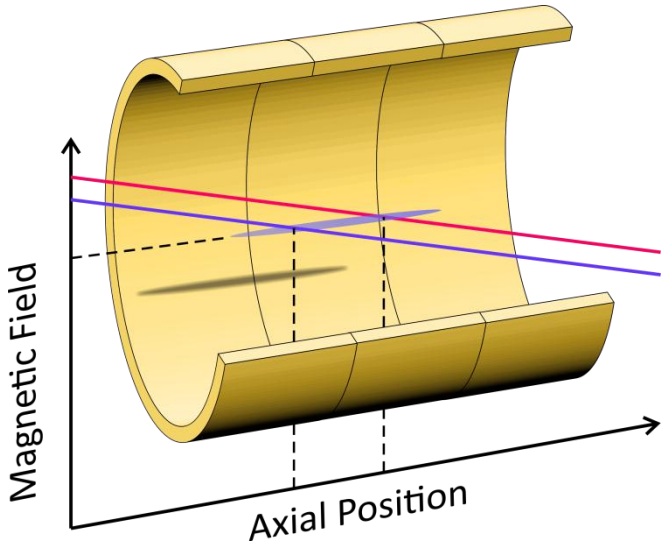
Rabi frequency: ~10^4 rad/s (inferred)

AIP Conf Proc **1521**, 123 (2013)
Hyperfine Interact **212**, 117 (2012)
Hyperfine Interact **199**, 39 (2011)

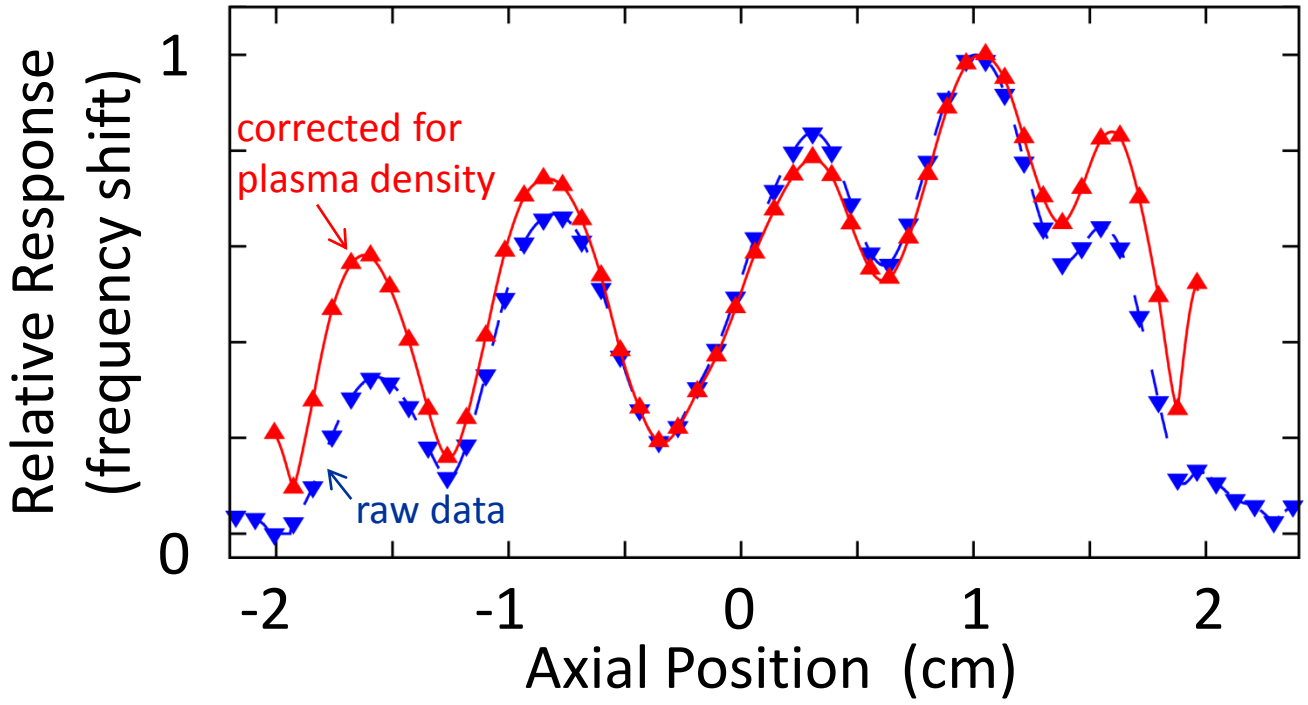
Imaging

- Apply Magnetic Field Gradient
- Measure Plasma Response
- Increment Uniform Field

repeat



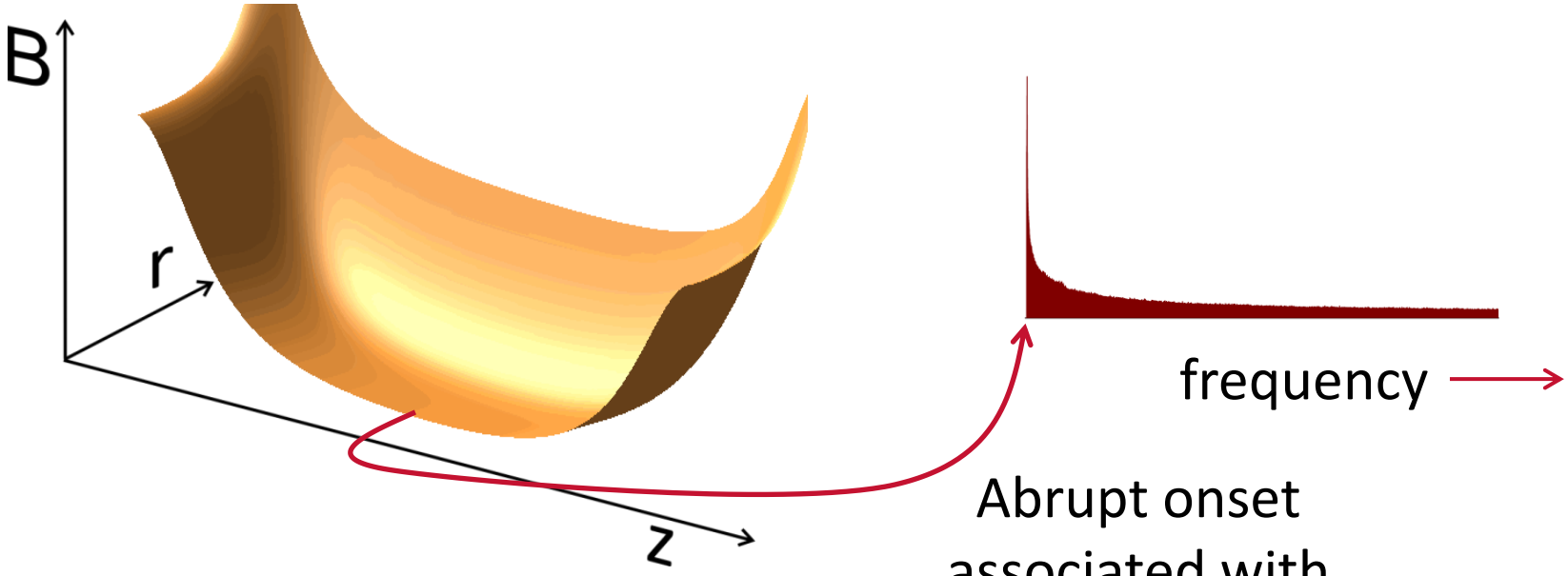
Plasma



Maps microwave fields

AIP Conf Proc **1521**, 123 (2013)
Hyperfin Interact **212**, 117 (2012)
Hyperfin Interact **199**, 39 (2011)

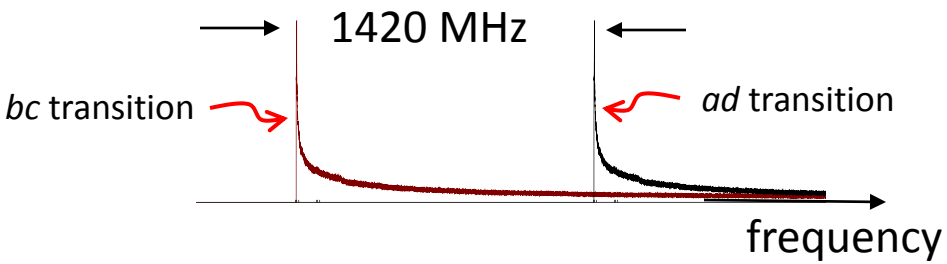
PSR Lineshape

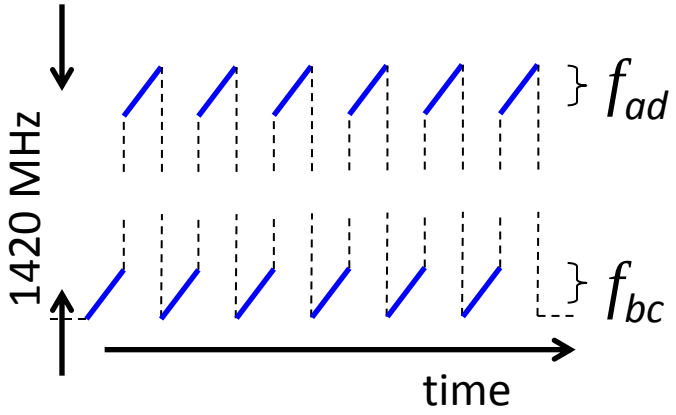


Abrupt onset associated with minimum in field

(r,z: not to scale)

Strategy





Synthesize

↓

Trap

↓

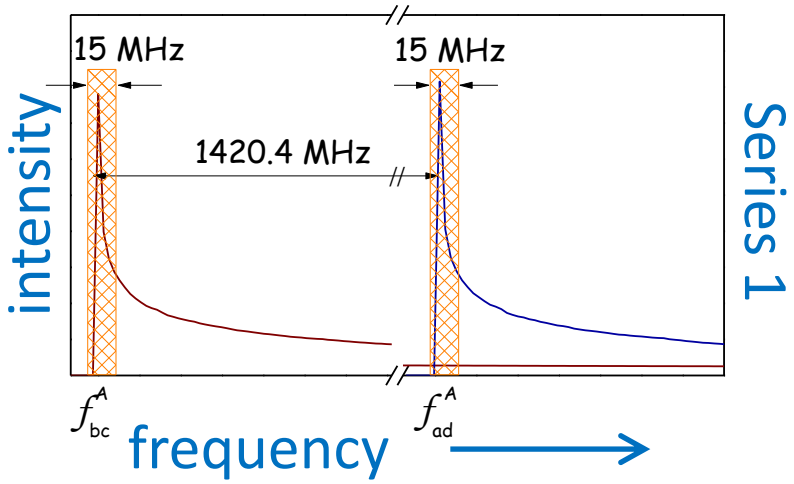
Irradiate → Observe (‘appearance mode’)

↓

Release → Observe (‘disappearance mode’)

Strategy

On resonance
(field A/sweep A)

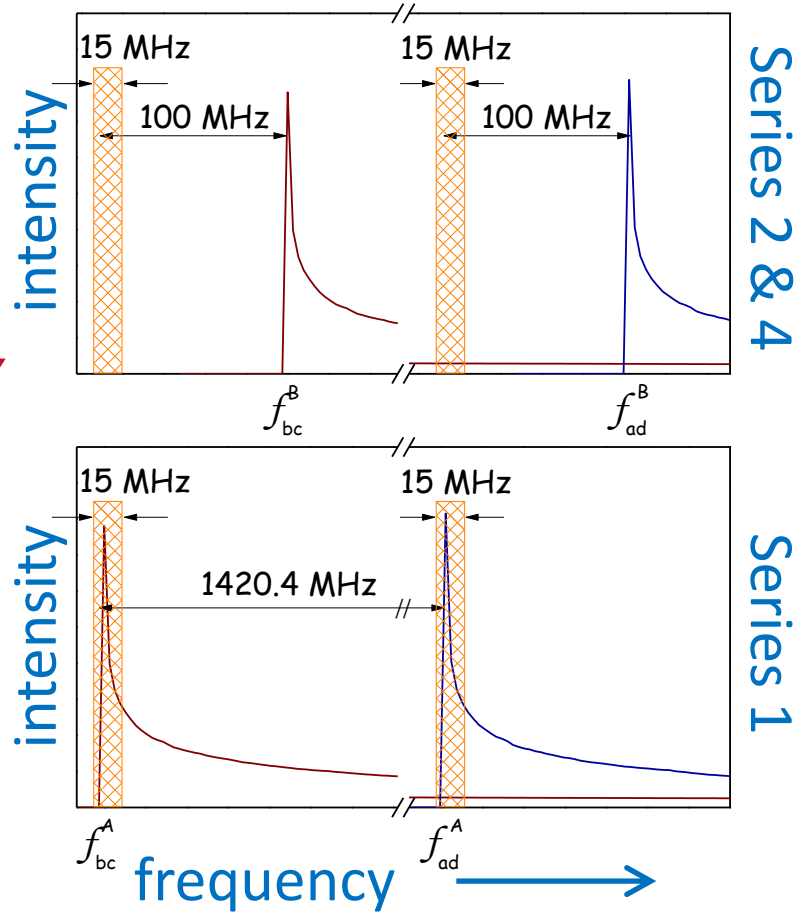


Strategy

Off resonance
(field B/sweep A)

increase
mag field

On resonance
(field A/sweep A)



Strategy

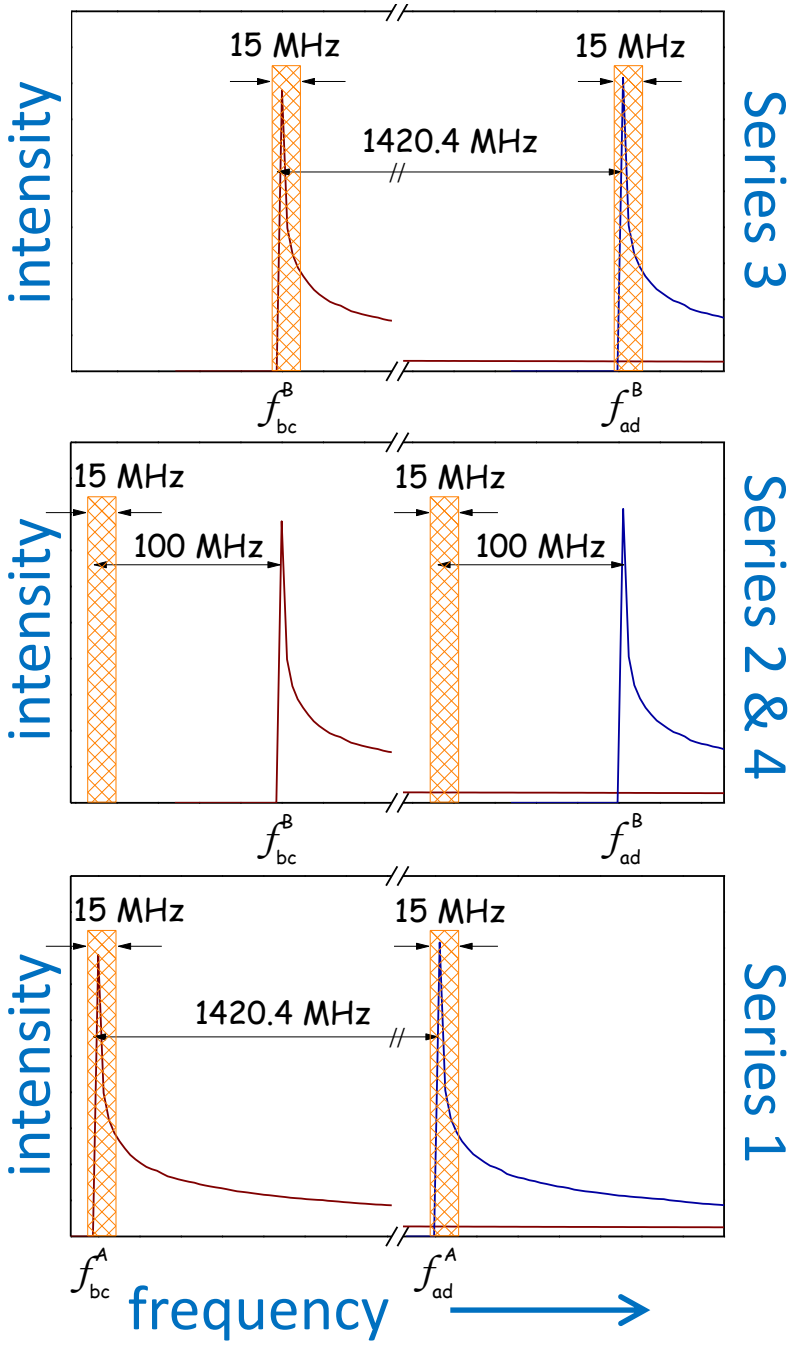
On resonance
(field B/sweep B)

increase
frequency

Off resonance
(field B/sweep A)

increase
mag field

On resonance
(field A/sweep A)



Strategy

On resonance
(field B/sweep B)

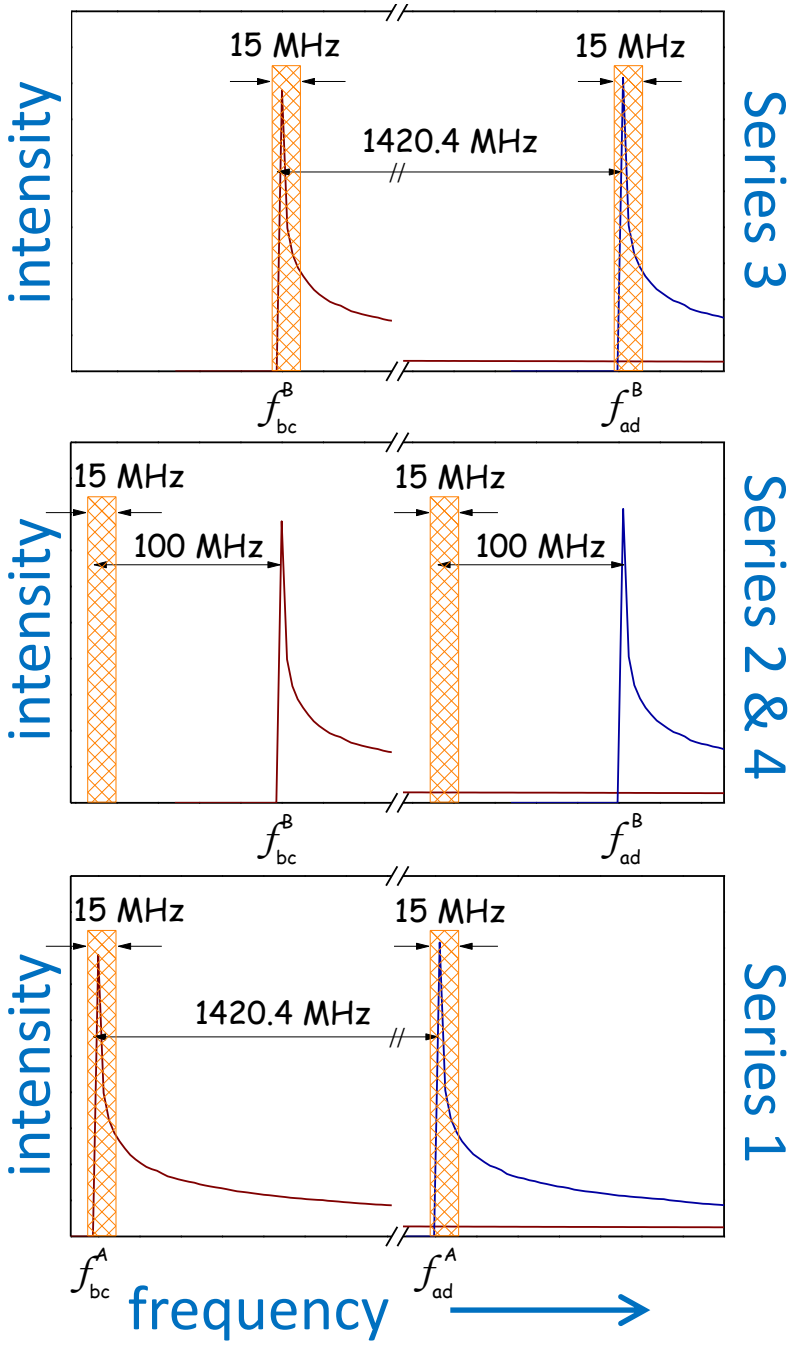
increase
frequency

Off resonance
(field B/sweep A)

increase
mag field

On resonance
(field A/sweep A)

No microwaves;
Series 5 (field A)
Series 6 (field B)



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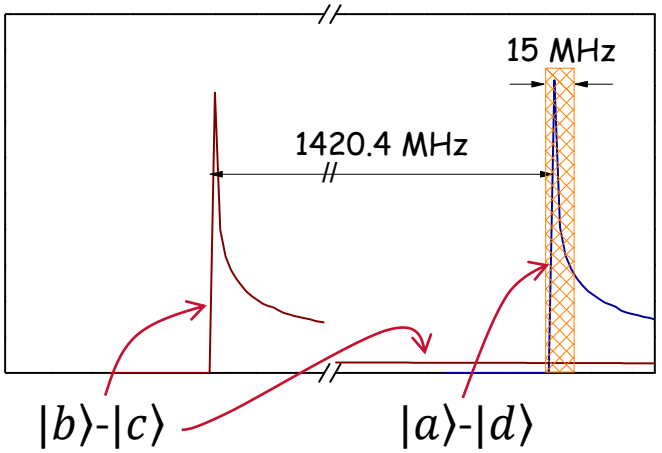
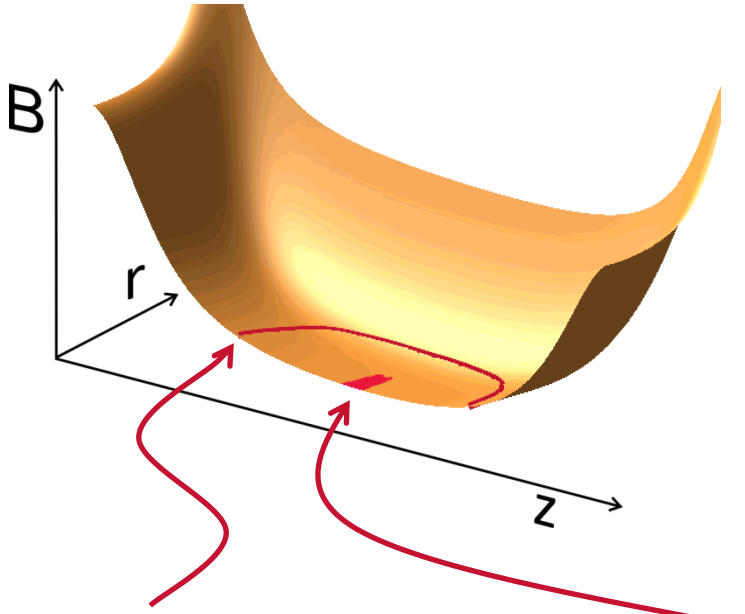




Tail of $|b\rangle$-$|c\rangle$ transition

Onset of $|a\rangle$-$|d\rangle$ transition

(r,z: not to scale)

Disappearance Mode

Nature **483**, 439 (2012)

Totals for 'disappearance mode' measurements

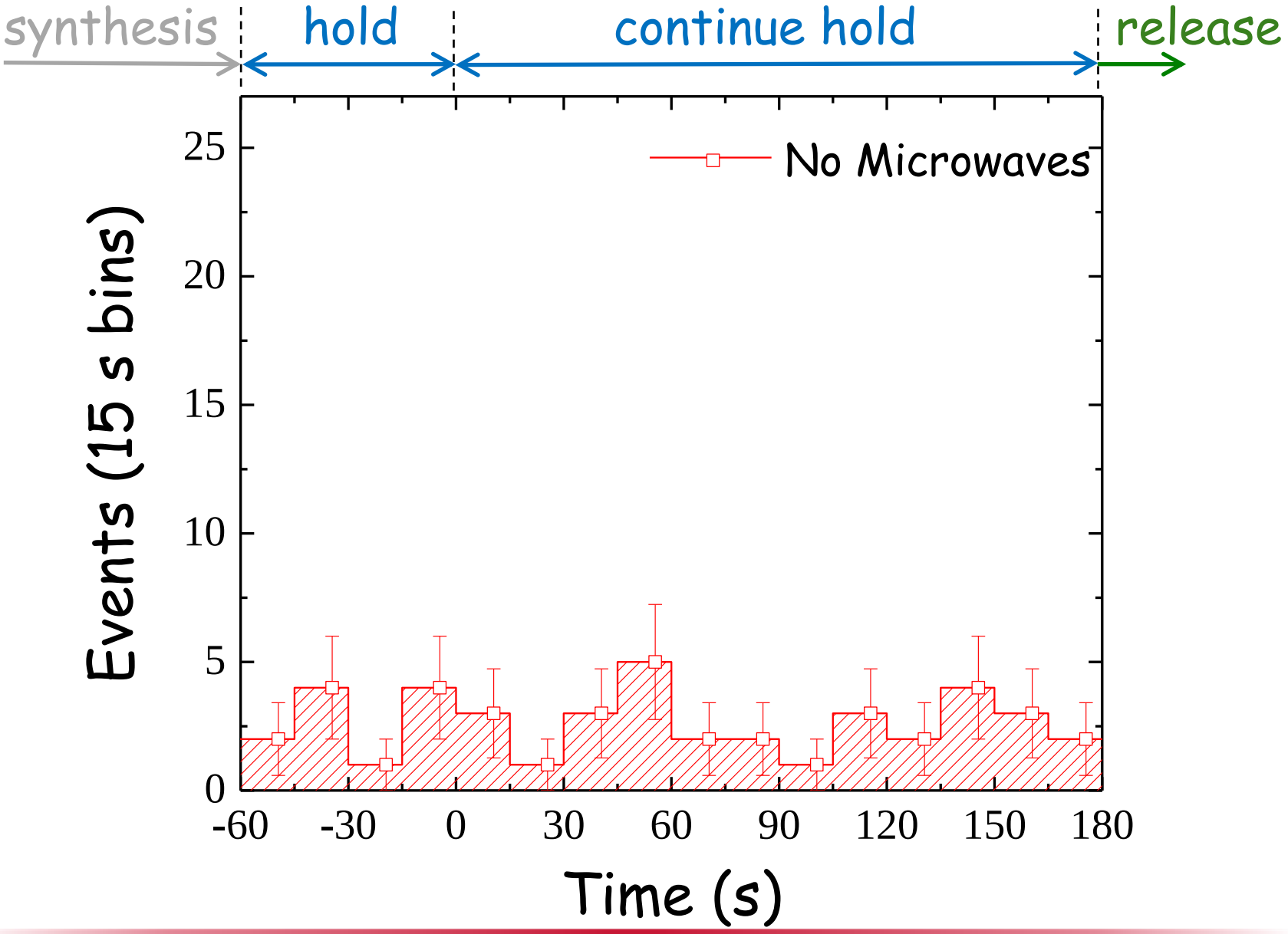
	Number of attempts	Detected antihydrogen	Rate
On resonance (1 + 3)	103	2	0.02 ± 0.01
Off resonance (2 + 4)	110	23	0.21 ± 0.04
No microwaves (5 + 6)	100	40	0.40 ± 0.06

Series summaries for 'disappearance mode' measurements

Series	Relative microwave frequency	Relative magnetic field	Number of attempts	Antihydrogen detected at trap shutdown	Rate	Comment
1	0 MHz	0 mT ($B_{min}^{axis} = B^{A}$)	79	1	0.01 ± 0.01	On resonance
2	0 MHz	+3.5 mT ($B_{min}^{axis} = B^{B}$)	88	16	0.18 ± 0.05	Off resonance
3	+100 MHz	+3.5 mT ($B_{min}^{axis} = B^{B}$)	24	1	0.04 ± 0.04	On resonance
4	0 MHz	+3.5 mT ($B_{min}^{axis} = B^{B}$)	22	7	0.32 ± 0.12	Off resonance
5	Off	0 mT ($B_{min}^{axis} = B^{A}$)	52	17	0.33 ± 0.08	No microwaves
6	Off	+3.5 mT ($B_{min}^{axis} = B^{B}$)	48	23	0.48 ± 0.10	No microwaves

Appearance Mode

Nature **483**, 439 (2012)



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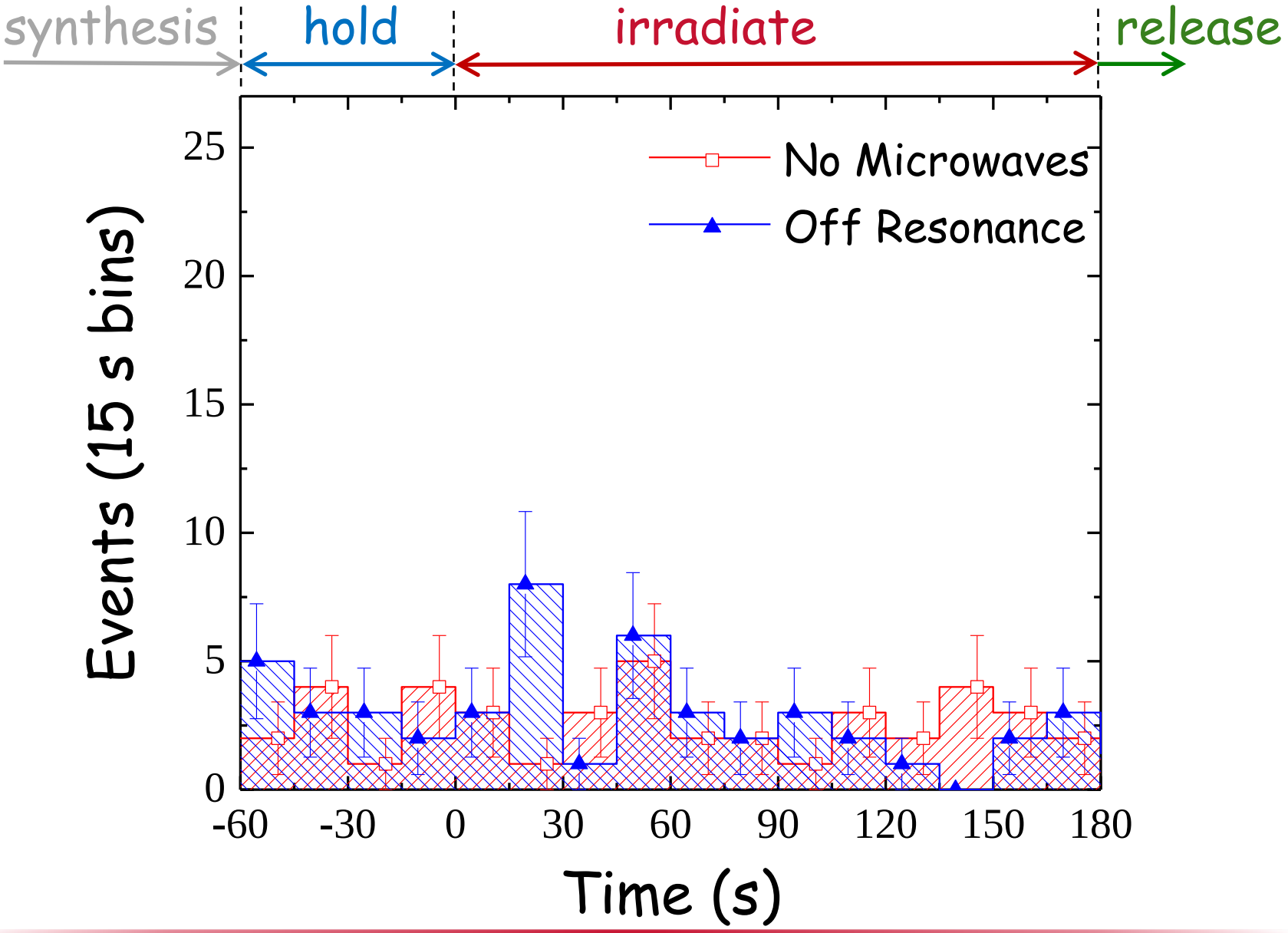
Nature **483**, 439 (2012)



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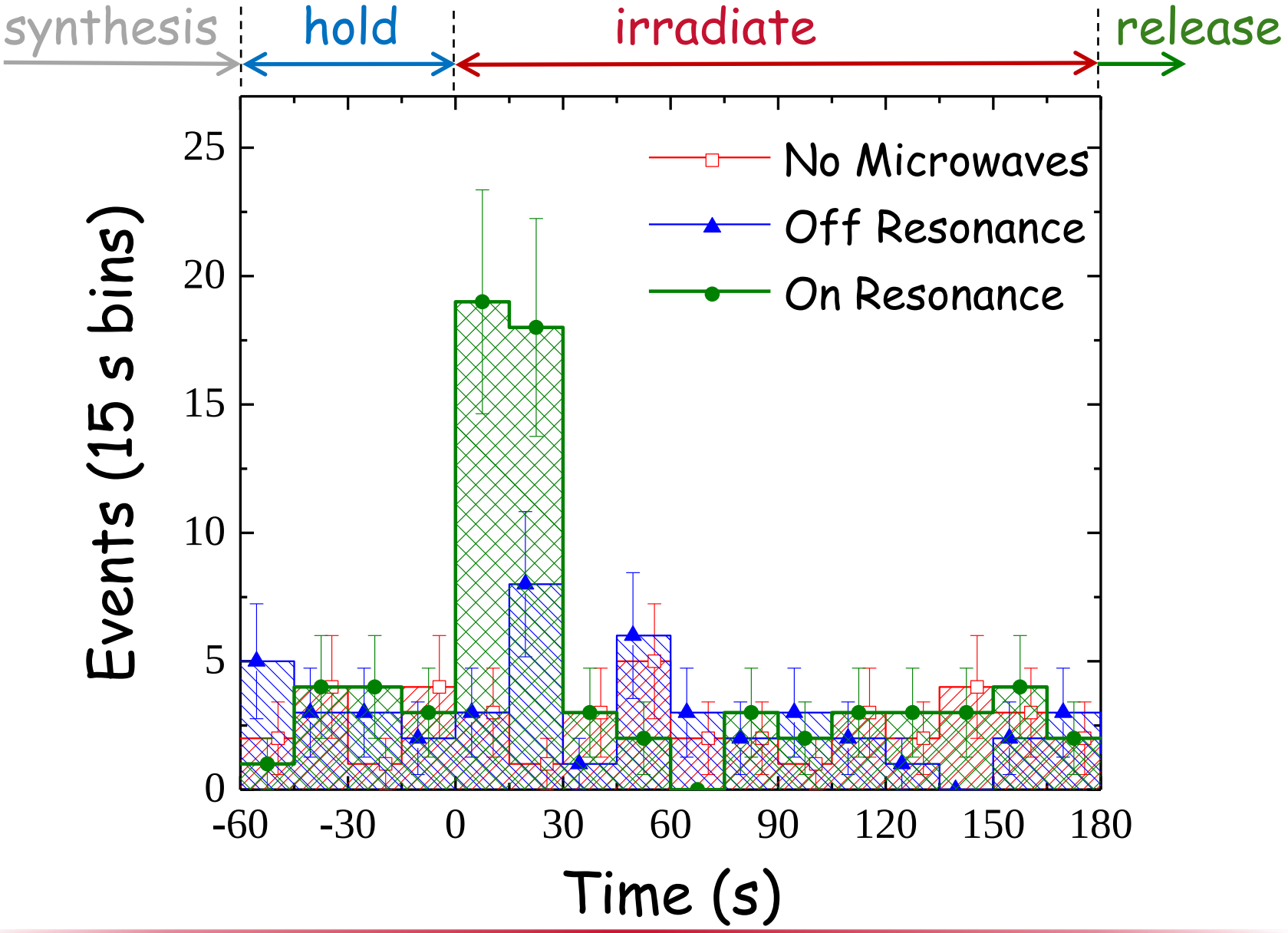

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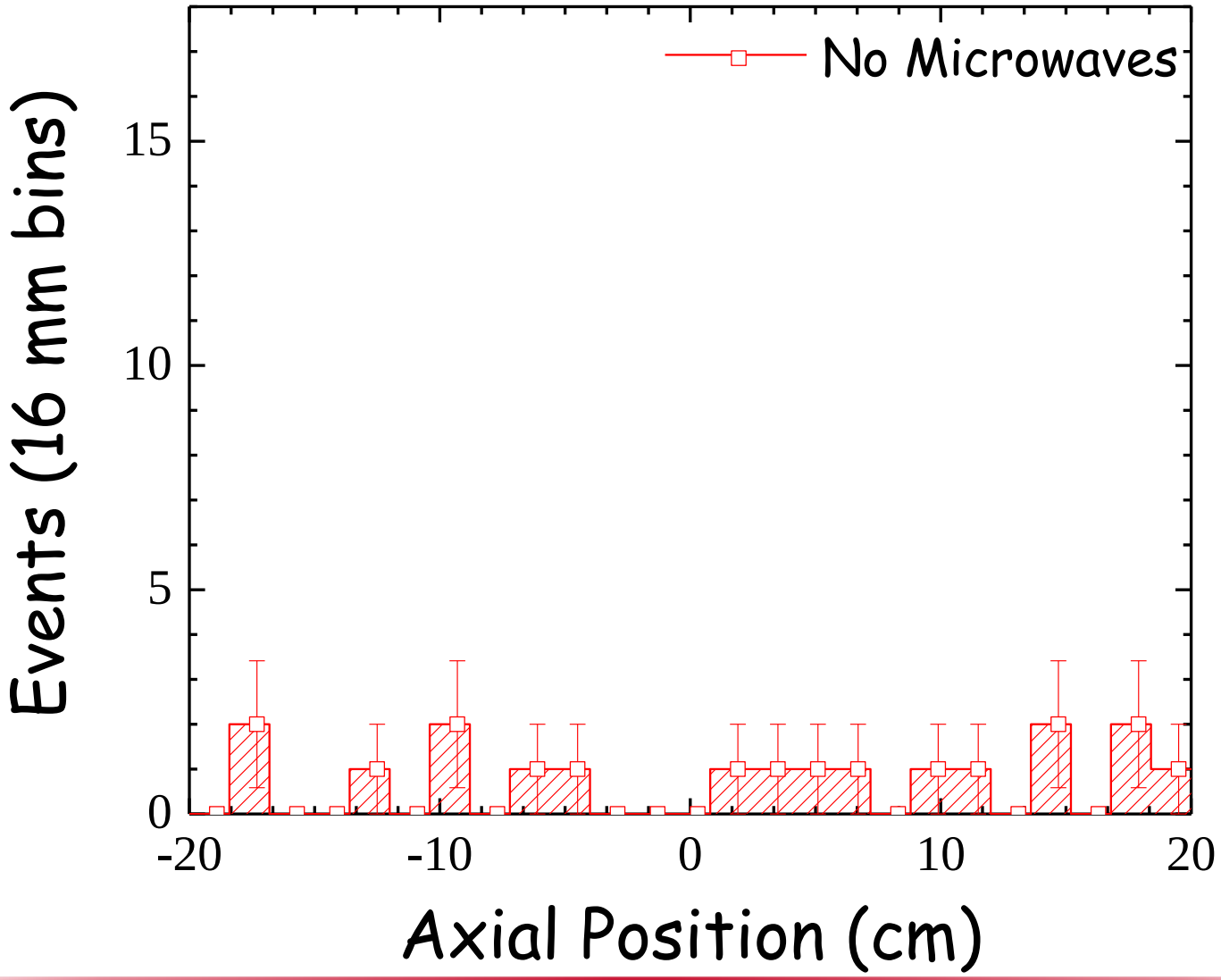

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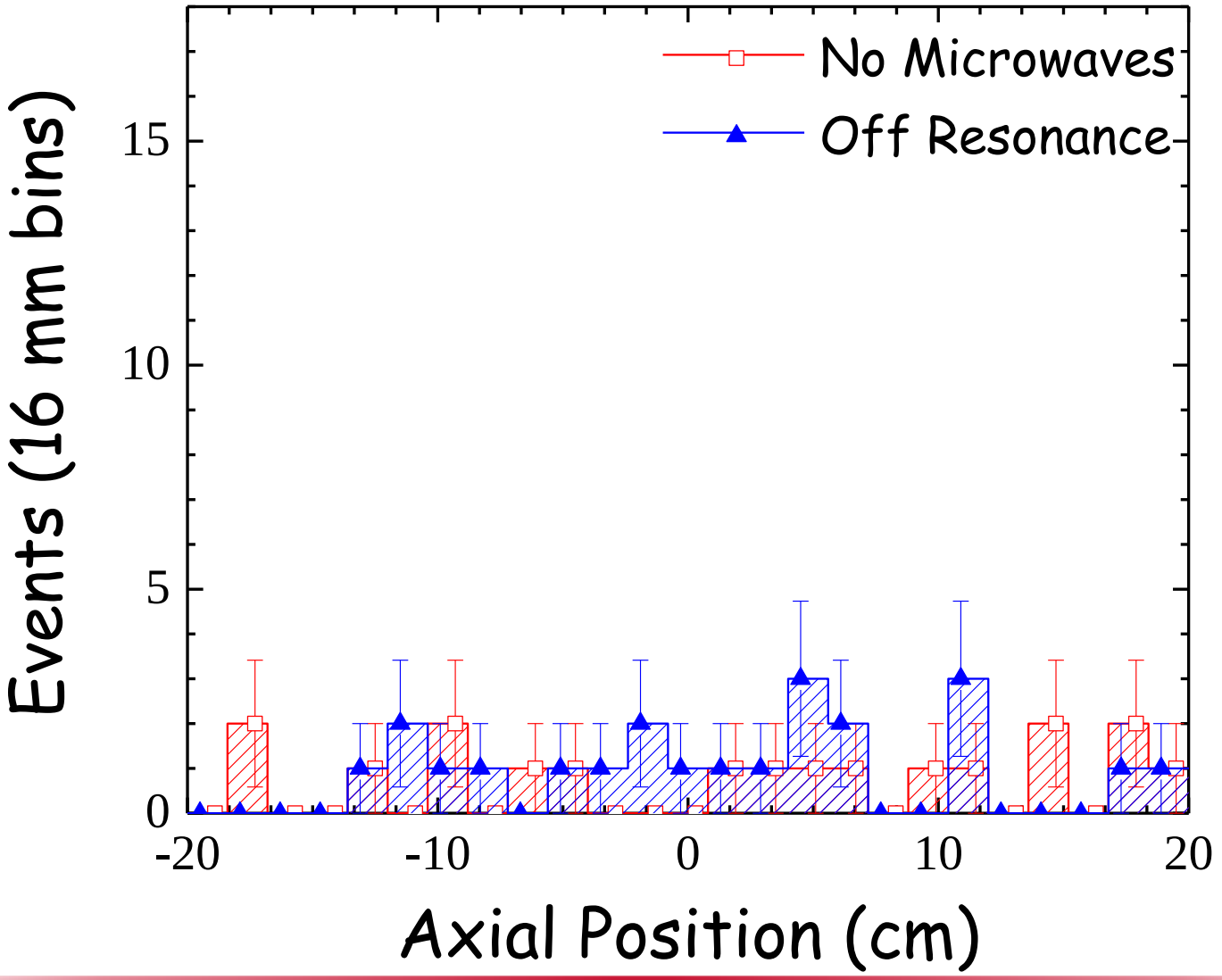

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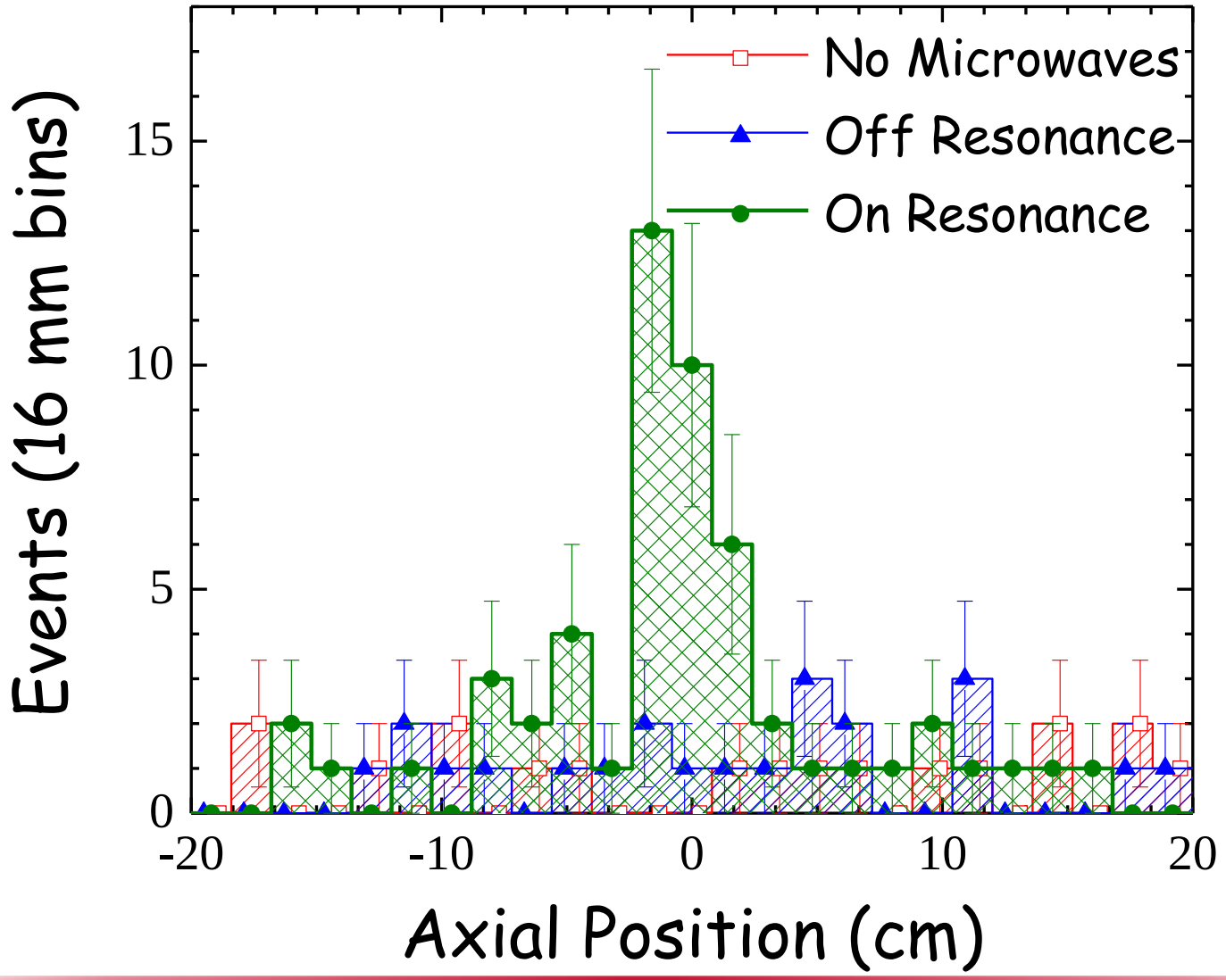

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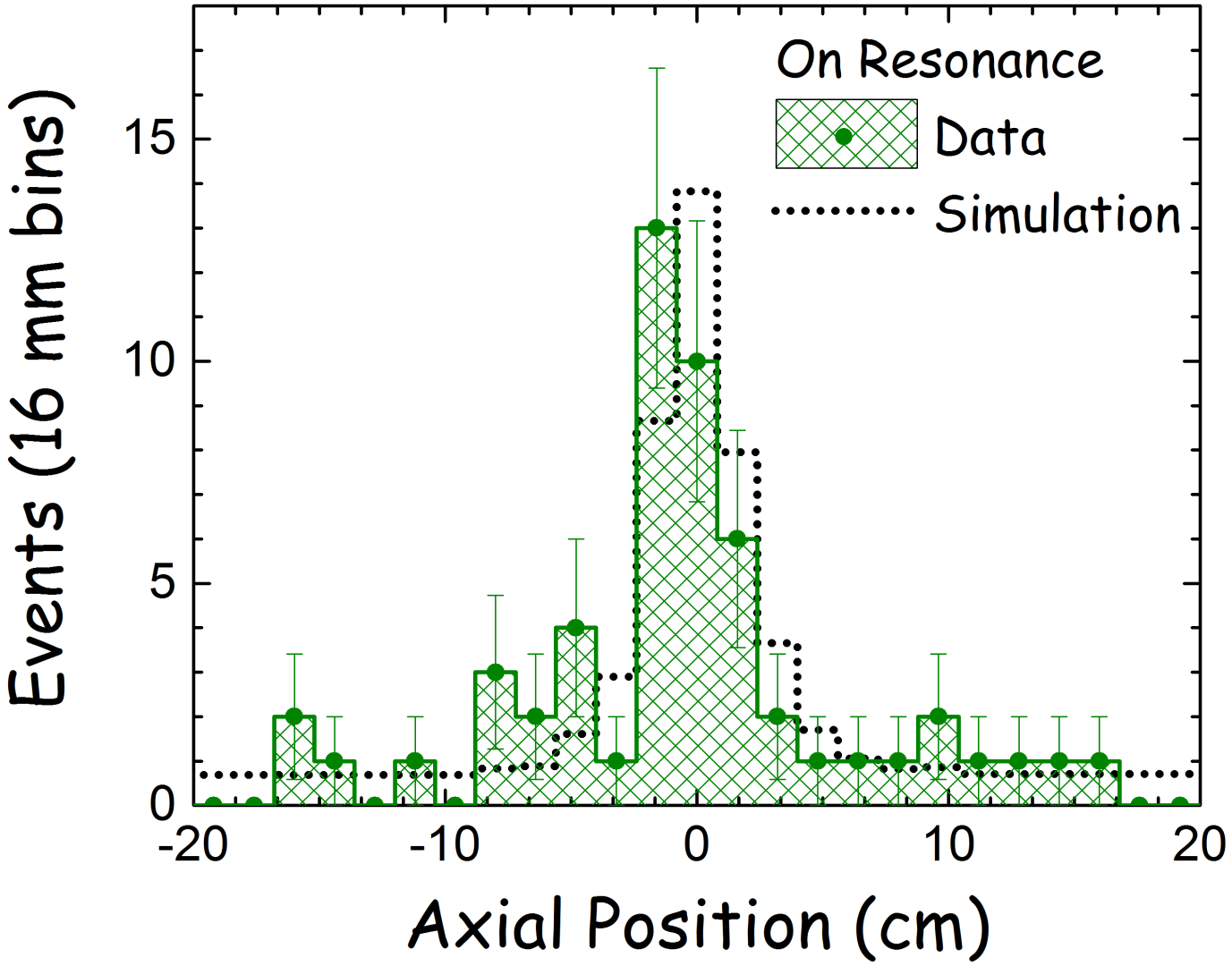
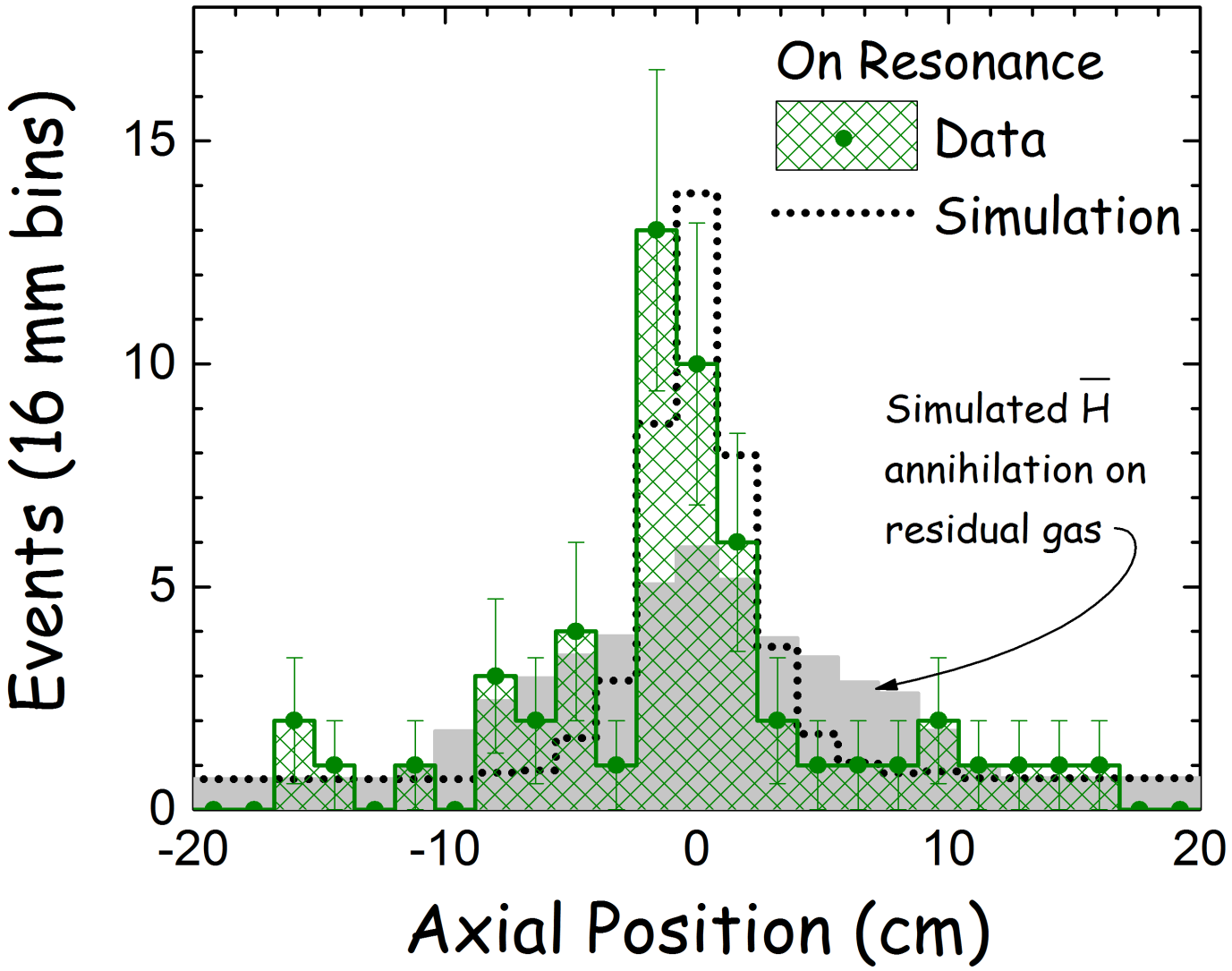


Appearance Mode



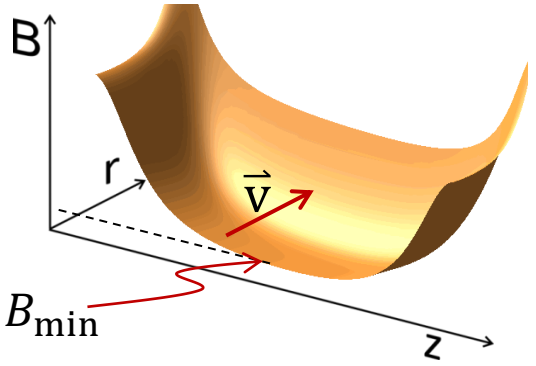
Summary

- Proof of principle experiment: controlled resonant interaction with antihydrogen
- Analyses of appearance & disappearance mode data yield consistent picture of H spin flips
- Demonstrates viability of working with small numbers of trapped anti-atoms

  Bonus: experimental bounds, limited by procedure (100 MHz offset between scans); no attempt to localize onset of lines
- PSR frequencies: 4×10^{-3} relative precision
- $\nu_{\overline{\mathrm{H}}}^{\mathrm{hfs}} \approx 1.42 \pm 0.10$ GHz

What Next?

NMR Broadening Estimate



Tune $B_{\min}$ to $B' = 0.65$ Tesla

Set trap depth: 0.5K

typical speed: $v = 70$ m/s

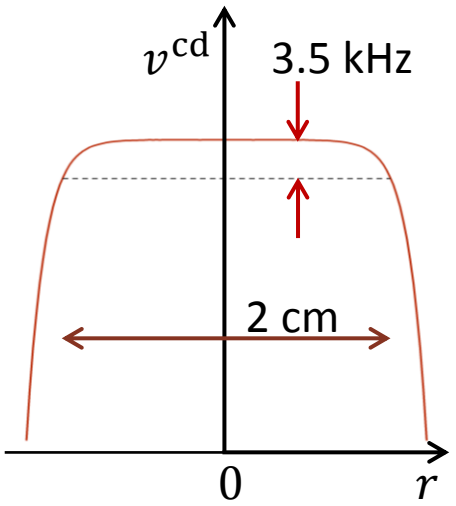
Induce $|c\rangle$-$|d\rangle$ transitions: apply B_1 at $v \sim v_{\max}^{cd}$

Atom travelling radially through midpoint; length scale (l) over which B_1 is effective satisfies:

$$\frac{v}{l} = \Delta v = v_{\max}^{cd} - v^{cd}\Big|_{r=\frac{l}{2}}$$

Gives $l \sim 2$ cm and $\Delta v \sim 3.5$ kHz

$$\Delta v / v^{hfs} \sim 2 \times 10^{-6}$$

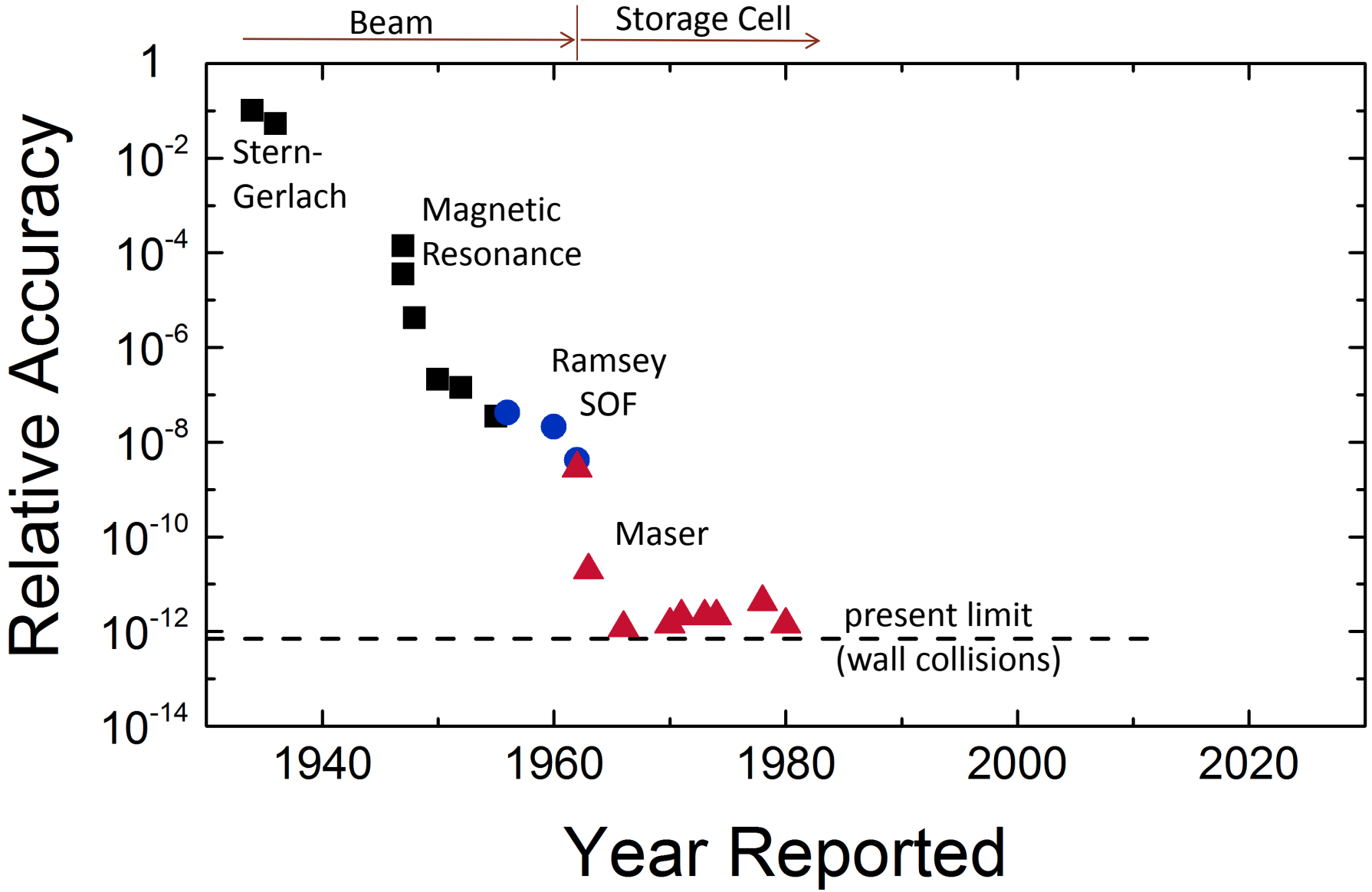


$$B_{oct} \propto r^3$$

$$B_{tot} - B_{min} \propto r^6$$

$$v^{cd} - v_{max}^{cd} \propto r^{12}$$

History of ν^{hfs} Measurements



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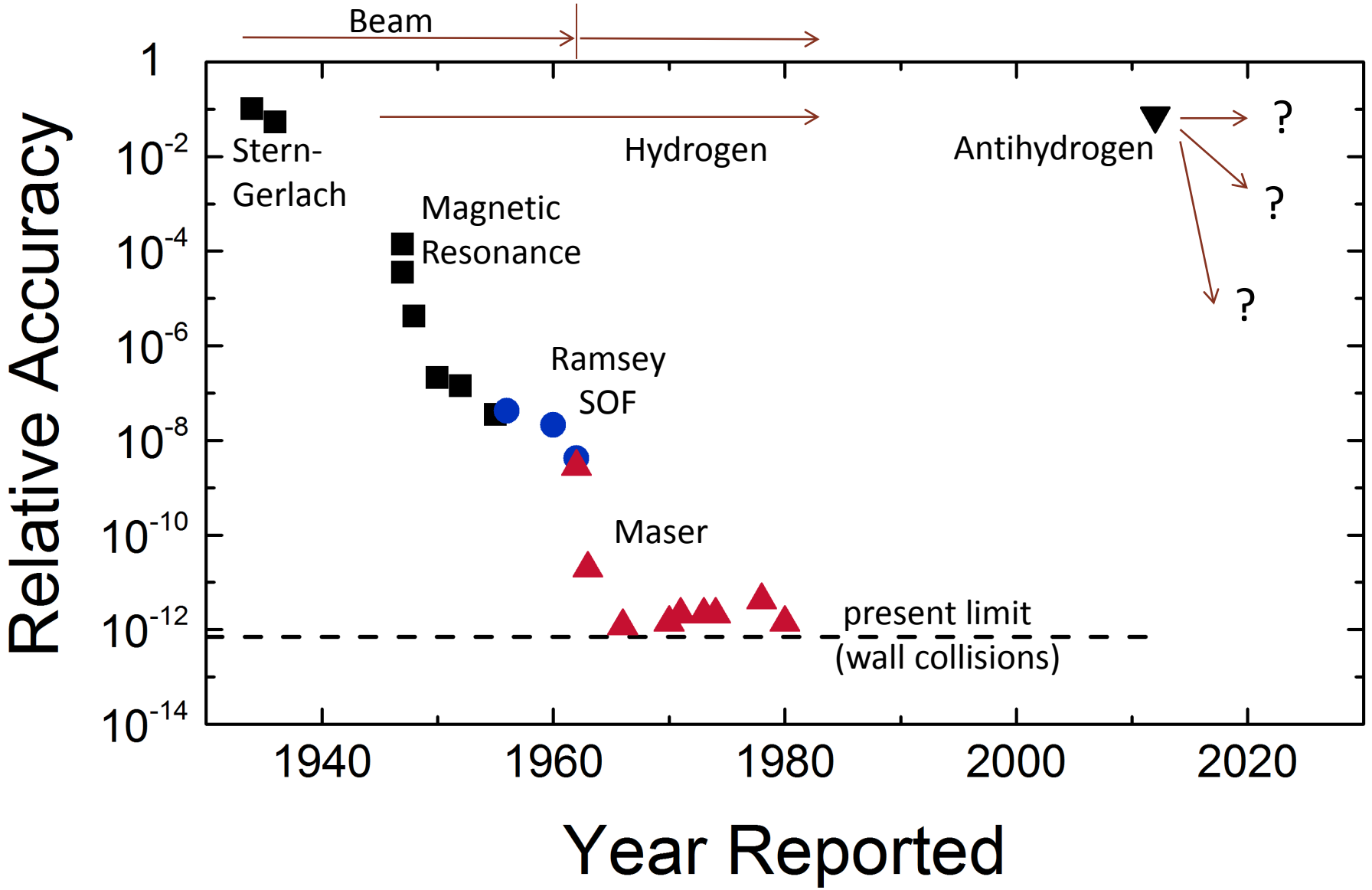
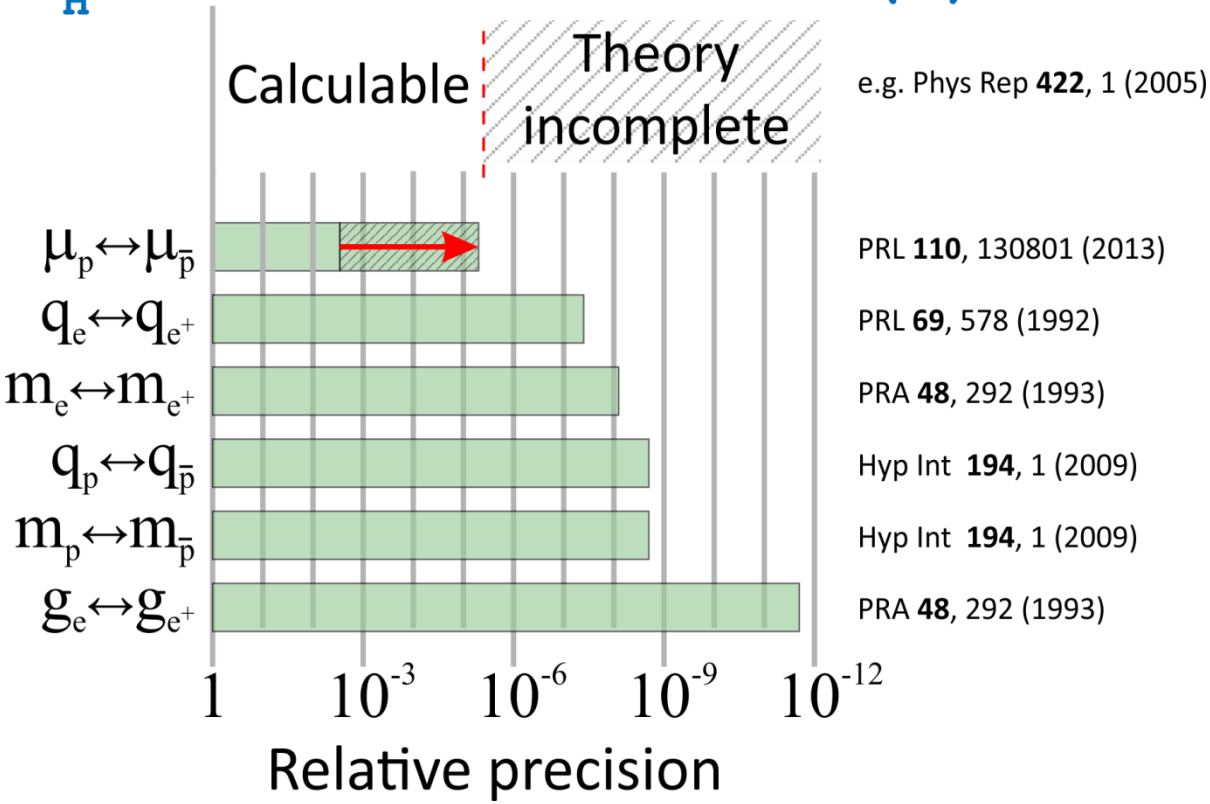


Empirical Bounds on Anomalies

$$\nu^{\mathrm{hfs}} = \frac{16}{3}\left(\frac{m_p}{m_p + m_e}\right)^3 \frac{m_e}{m_p}\frac{\mu_p}{\mu_N}\alpha^2 \mathrm{c\ Ry} + \text{corrections}$$

Antihydrogen $\nu_{\bar{H}}^{hfs} = 1.42\ (10)\ \mathrm{GHz}$ Nature **483**, 439 (2012)

Hydrogen $\nu_{H}^{hfs} = 1.420405751768\ (1)\ \mathrm{GHz}$



e.g. Phys Rep **422**, 1 (2005)

PRL **110**, 130801 (2013)

PRL **69**, 578 (1992)

PRA **48**, 292 (1993)

Hyp Int **194**, 1 (2009)

Hyp Int **194**, 1 (2009)

PRA **48**, 292 (1993)

Figure of Merit?

Beringer *et al. Phys Rev D* **86**, 01001 (2012)

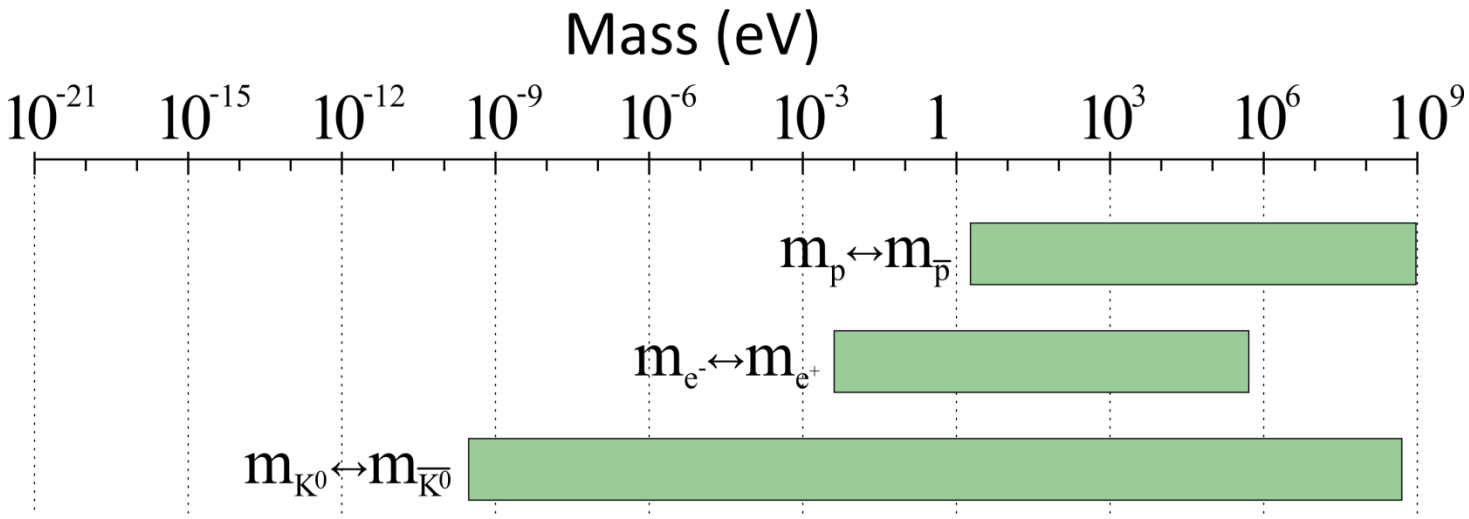
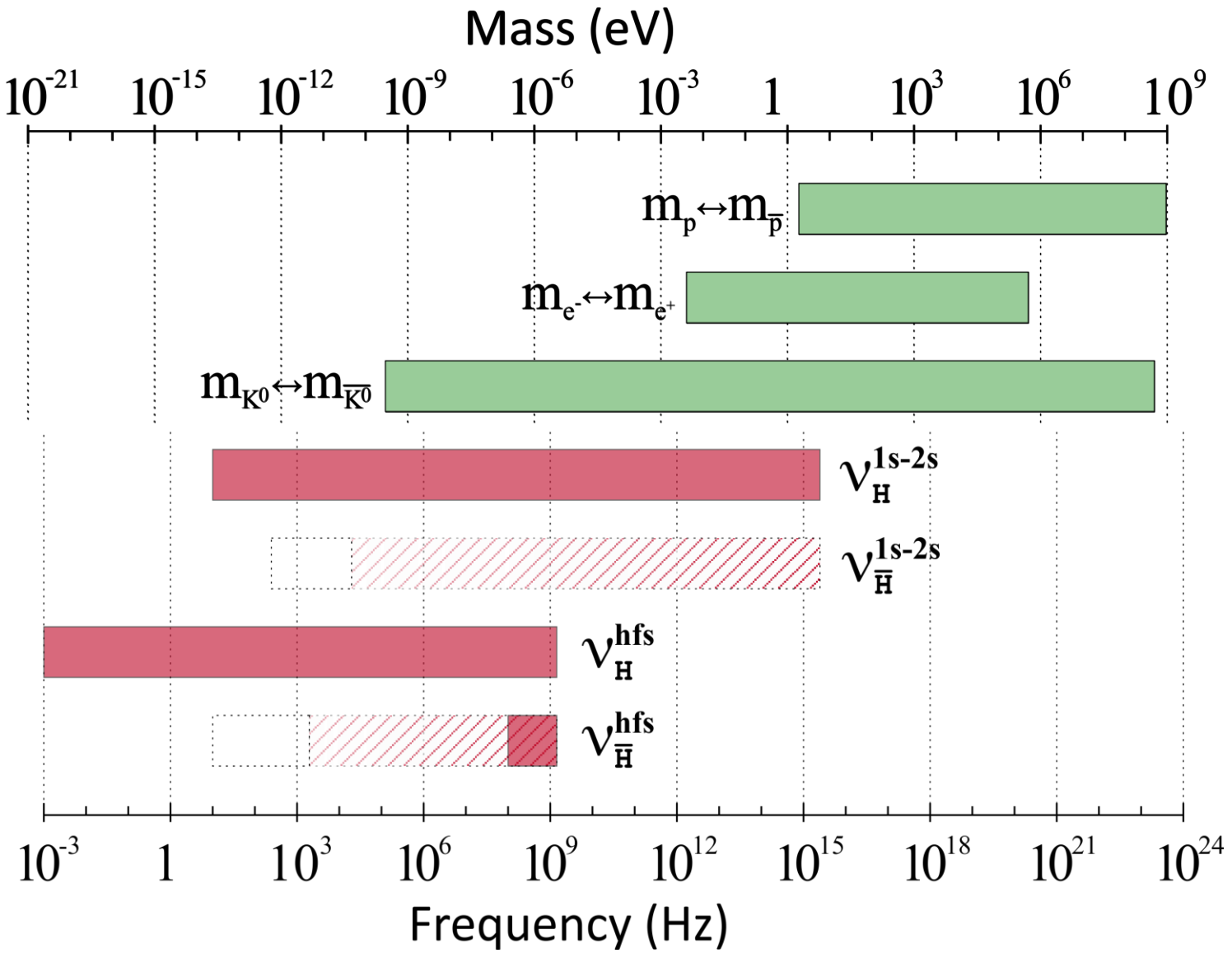


Figure of Merit?

Beringer *et al. Phys Rev D* **86**, 01001 (2012)



Summary

- Proof of principle experiment: controlled resonant interaction with antihydrogen
- Analyses of appearance & disappearance mode data yield consistent picture of H spin flips
- Demonstrates viability of working with small numbers of trapped anti-atoms

  Bonus: experimental bounds, limited by procedure (100 MHz offset between scans); no attempt to localize onset of lines
- PSR frequencies: 4×10^{-3} relative precision
- $\nu_{\overline{\mathrm{H}}}^{\mathrm{hfs}} \approx 1.42 \pm 0.10$ GHz
- $\Delta\nu/\nu^{\mathrm{hfs}} \sim 2 \times 10^{-6}$ plausible for NMR spectroscopy at $B = B'$; factor 10-100 better, with many colder atoms?