Toward SME-Sensitive Antihydrogen Hyperfine Spectroscopy

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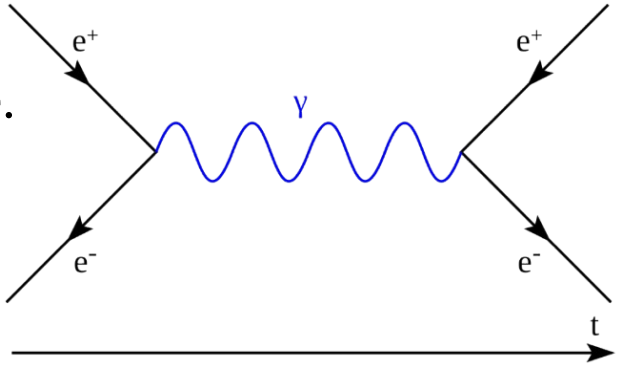
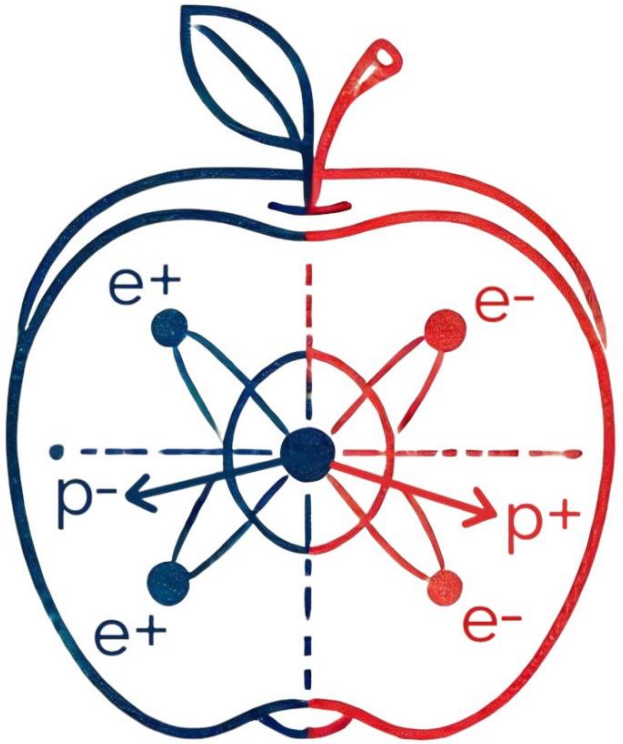
Matter-Antimatter

- Equal amount of Matter and Antimatter were created 14 B years ago.
- Whenever they meet, they annihilate.



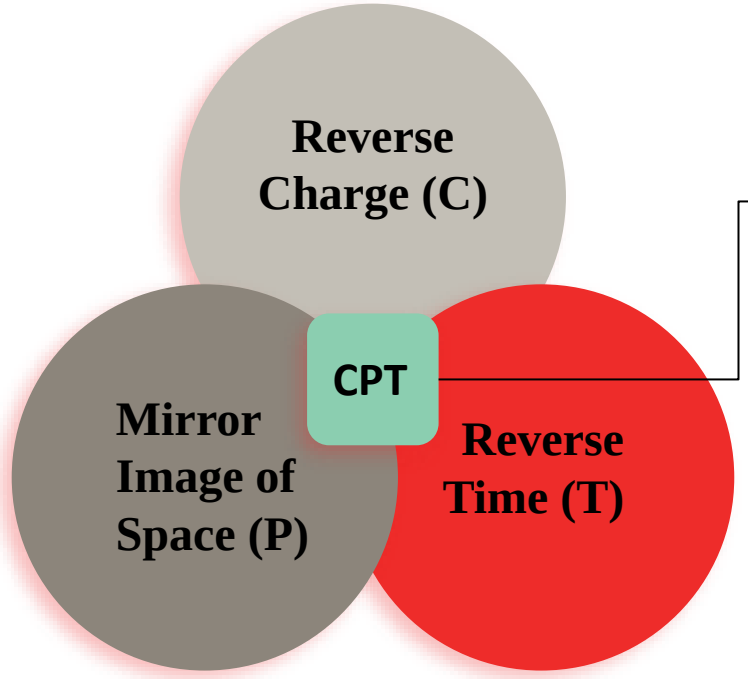
- For every billion pairs of matter and antimatter, one extra matter existed.
- After Annihilation, leftover matter formed the universe.



Antimatter Matter

CPT and Lorentz Symmetry

- Where is the Antimatter?



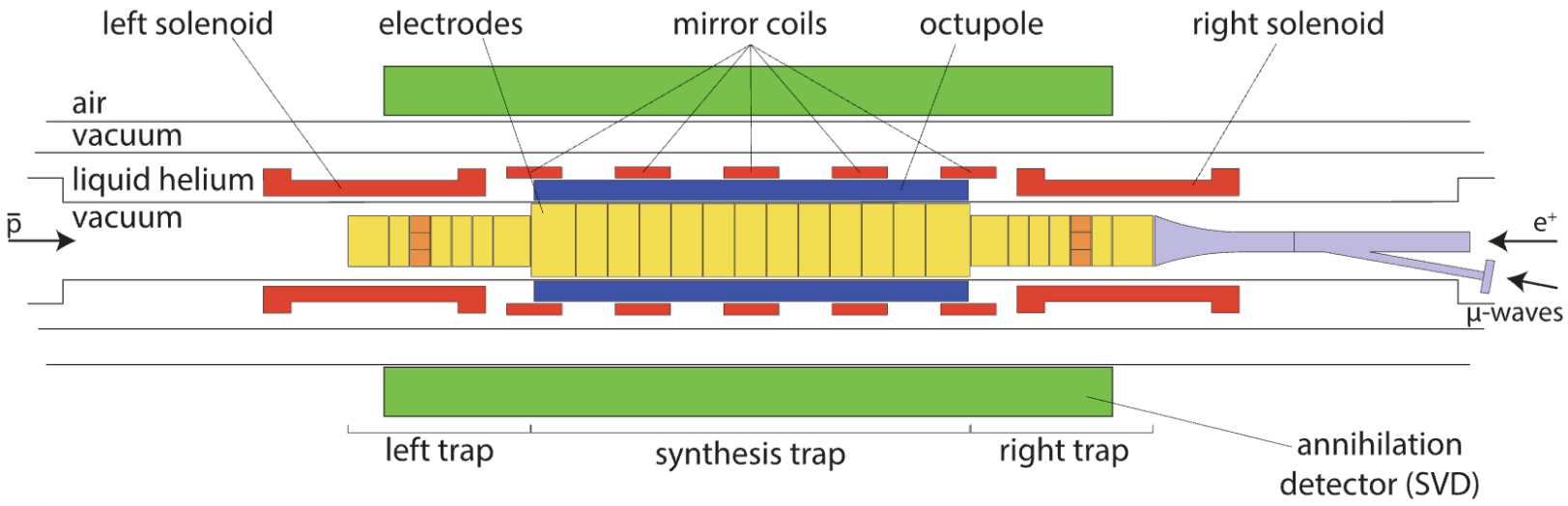
All the Laws of Physics should remain the same

Any deviation from CPT Symmetry ⟶ Could explains why the universe is made of matter

- **Lorentz Symmetry:** The laws of physics should be unchanged under rotations and boosts of the observer's reference frame.

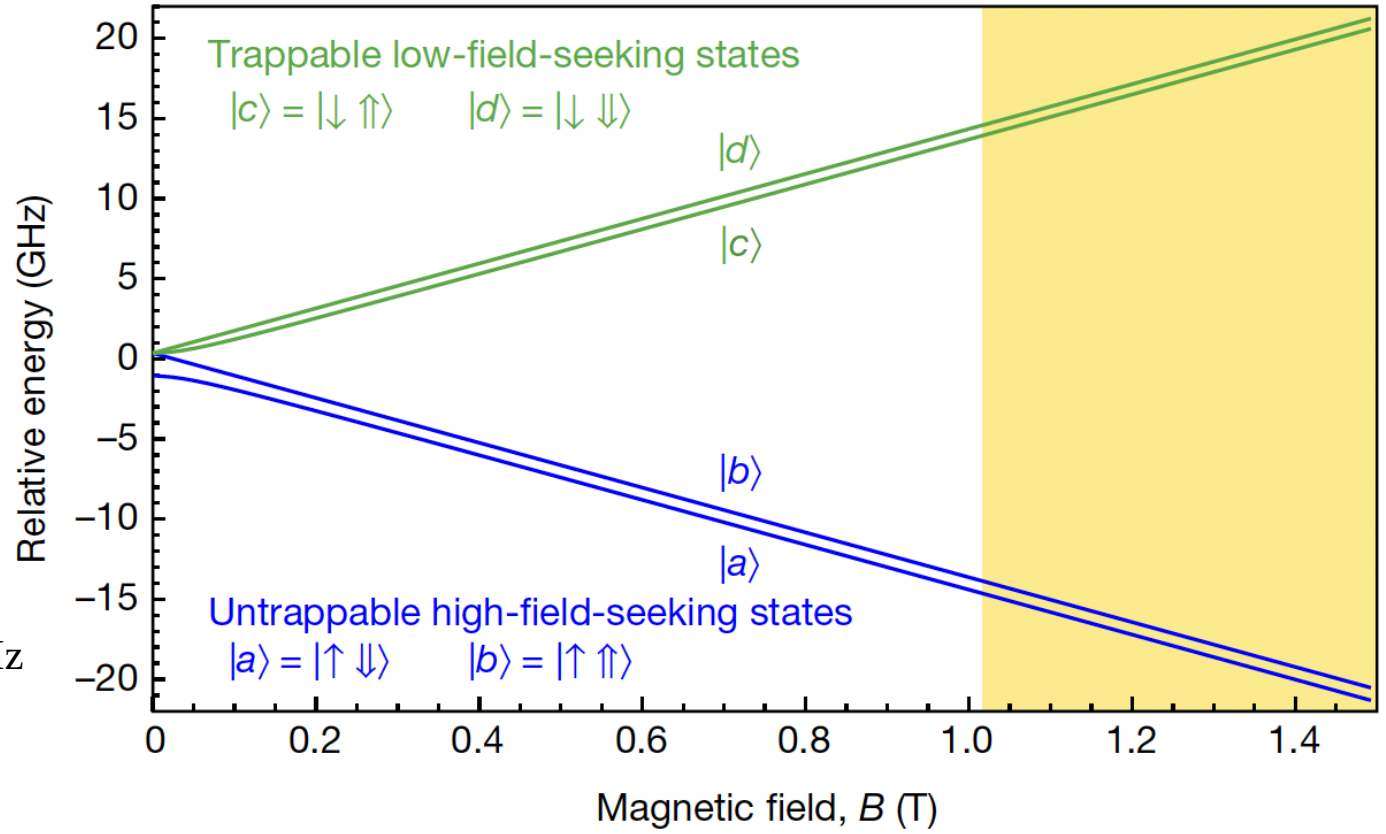
ALPHA Experiment

- ALPHA (Antihydrogen Laser Physics Apparatus)
- Located at Antiproton Decelerator (AD) facility at CERN
- At its core is a cylindrical Penning-Malmberg trap superposed with a magnetic minimum neutral atom trap.
- e^+ produced by the beta-plus decay
- The antiprotons and positrons are confined, manipulated, and mixed.
- $\bar{H}$ atoms are trapped by a three-dimensional magnetic minimum generated by superconducting magnets.



Hyperfine Splitting in ALPHA

$$\mathrm{GSHFS} = f_{da}(B_{\min}) - f_{cb}(B_{\min})$$



Antihydrogen: $\nu_{\bar{H}}^{HFS,1S}$=1,420,404.8 ± 1.1($stat.$) ± 5.6 ($sys.$)kHz

Hydrogen: $\nu_{H}^{HFS,1S}$=1,420,405.751768 ± 2×10^{-6} kHz

Hellwig, H. W. et al. IEEE TIM 19 (1970): 200-209

Akbari, R et al. (ALPHA Collaboration) Nature 653, 1022–1026 (2026)

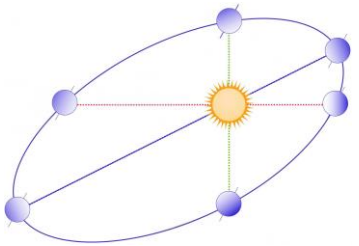
Standard Model Extension

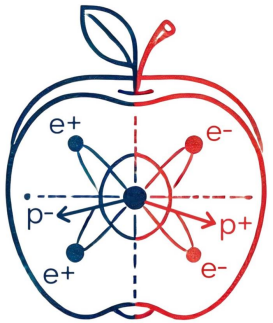
- SME=Standard Model + all Lorentz/CPT-violating terms

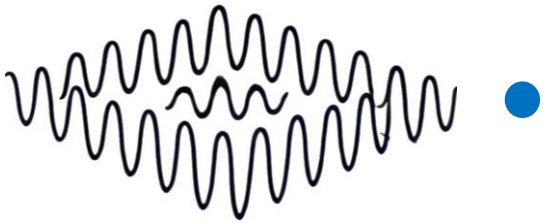
1. Signals that vary with Earth's rotation
   Sidereal/annual modulation

2. Matter-antimatter comparisons
   H vs $\overline{H}$

3. Precision spectroscopy / static bounds
   Static spectroscopy bounds







Lehnert, R., *The Standard-Model Extension*, EPJ Web of Conferences 282, 01004 (2023)

SME Hyperfine Prediction

Spin independent

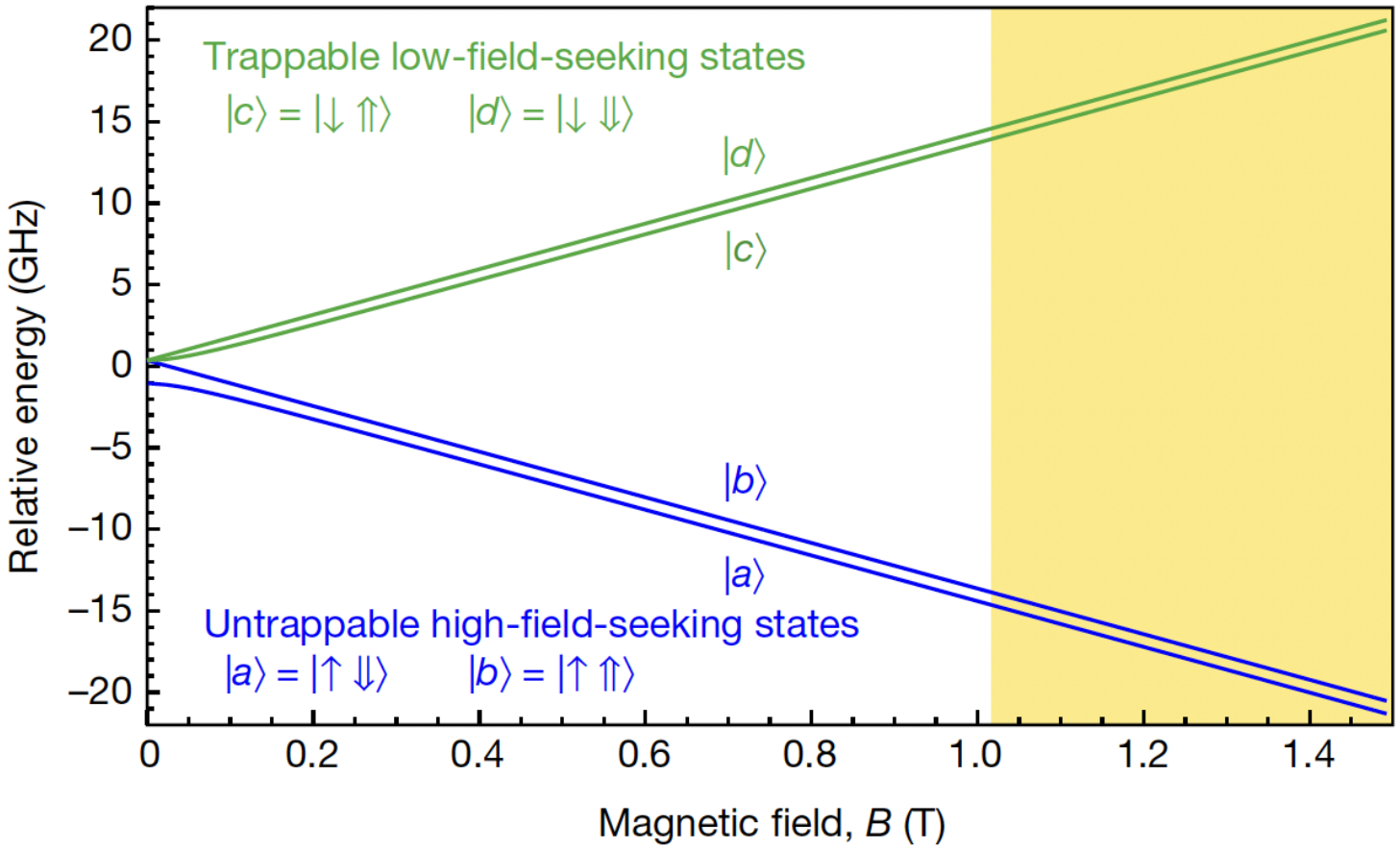
Spin dependent

$$E_d^{SME} = A^e + A^p - \left(B_3^e + B_3^p\right)$$

$$E_c^{SME} = A^e + A^p - \cos(2\theta_1)\left(B_3^e - B_3^p\right)$$

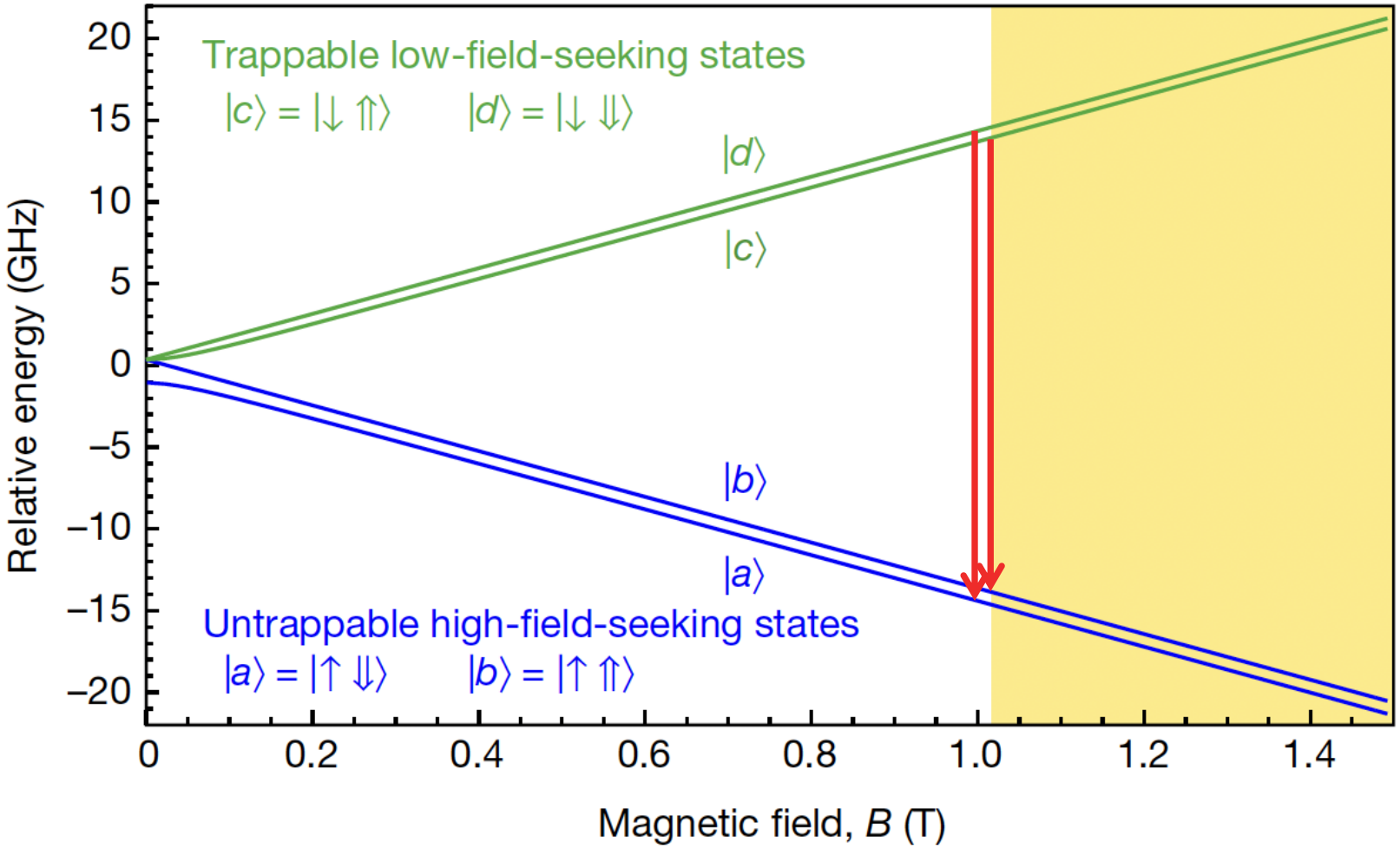
$$E_b^{SME} = A^e + A^p + \left(B_3^e + B_3^p\right)$$

$$E_a^{SME} = A^e + A^p + \cos(2\theta_1)\left(B_3^e - B_3^p\right).$$



$$\Delta E_{d\leftrightarrow a}^{\bar{H},SME} = \Delta E_{c\leftrightarrow b}^{\bar{H},SME} = -2\cos^2\theta_1\ B_3^e - 2\sin^2\theta_1\ B_3^p$$

M. Charlton, S. Eriksson, and G. M. Shore, *Testing Fundamental Physics in Antihydrogen Experiments*, arXiv:2002.09348 (2020).


Trappable low-field-seeking states
$|c\rangle = |\downarrow \Uparrow\rangle$ $|d\rangle = |\downarrow \Downarrow\rangle$
$|d\rangle$
$|c\rangle$
$|b\rangle$
$|a\rangle$
Untrappable high-field-seeking states
$|a\rangle = |\uparrow \Downarrow\rangle$ $|b\rangle = |\uparrow \Uparrow\rangle$
Relative energy (GHz)
20
15
10
5
0
−5
−10
−15
−20
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Magnetic field, B (T)

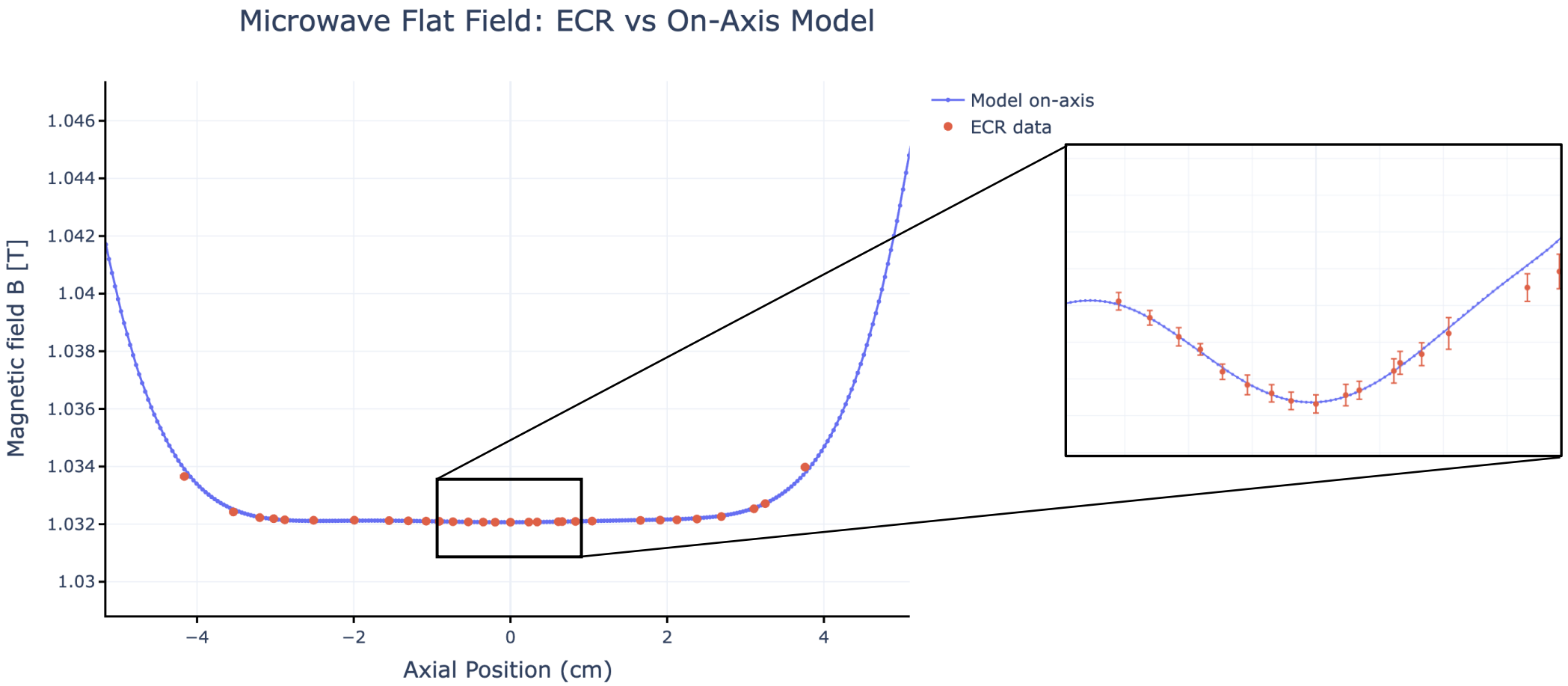
Why are individual transition frequencies challenging?

- Magnetic field consideration:
  - Zeeman sensitivity
  - On-axis ECR vs 3D effective field
  - Magnetic field drift and stability
  - Non-uniform field

$$\frac{\partial f}{\partial B} \approx 2.8 MHz/G$$

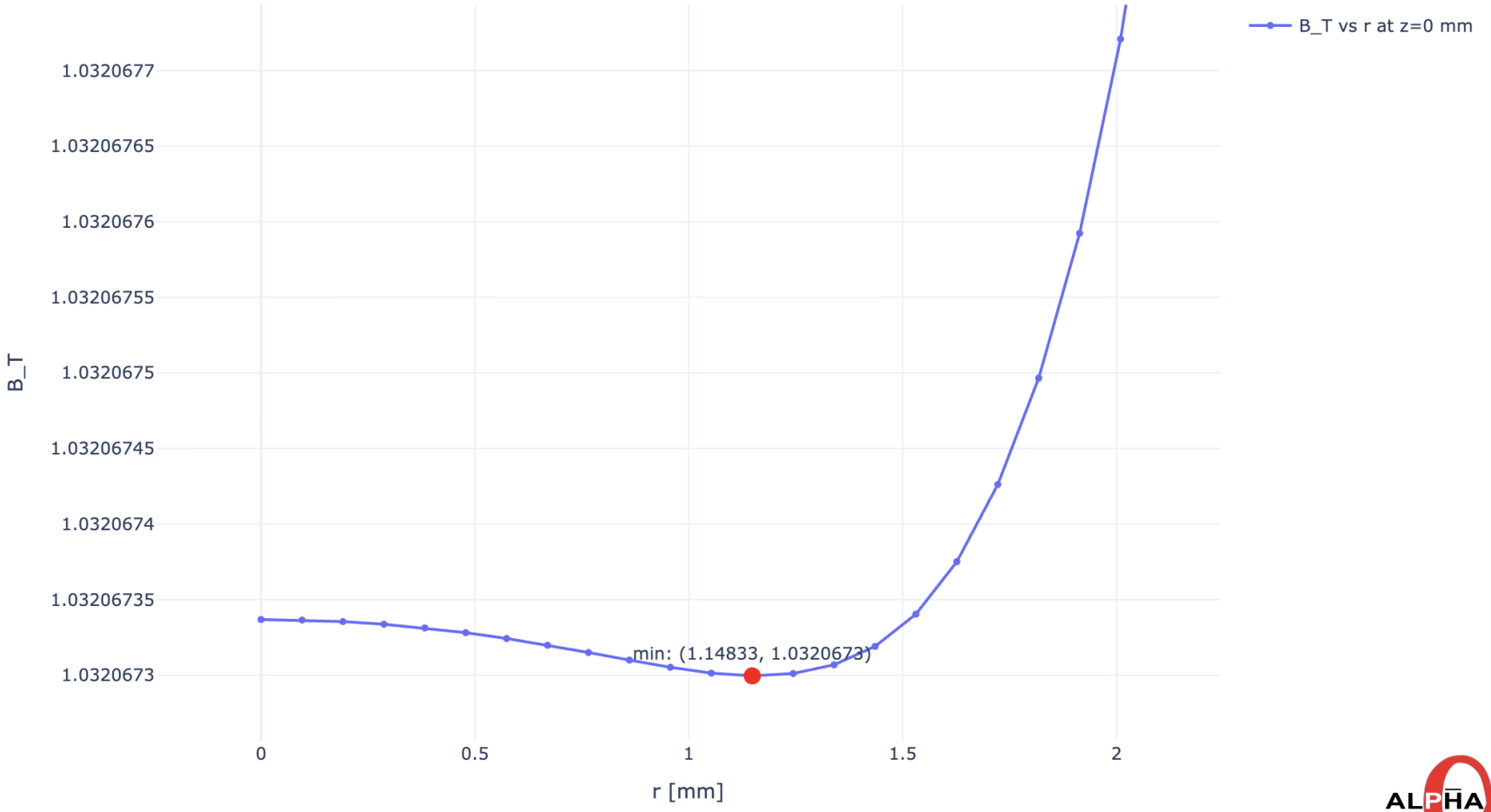
- Spectroscopy extraction challenges:
  - Empirical onset/lineshape model
  - Microwave coupling and power dependence
  - Broadening
  - Reproducibility and binning

ECR-Constrained Magnetic Field Model



ECR-Constrained Magnetic Field Model

Radial Magnetic Field Profile Near the Trap Minimum



Preliminary Magnetic Field Effects for Individual Transitions

- Reproducibility
- Binning
- Signal model

Contribution	Shift in Frequency	Uncertainty
Off-axis extrapolation	~165 kHz	TBD
Local on-axis ECR/model uncertainty	NA	~56 kHz
ECR field precision	NA	~30 kHz
B-drift / Timing correction	~30 kHz	~10 kHz

Preliminary magnetic field contribution only.

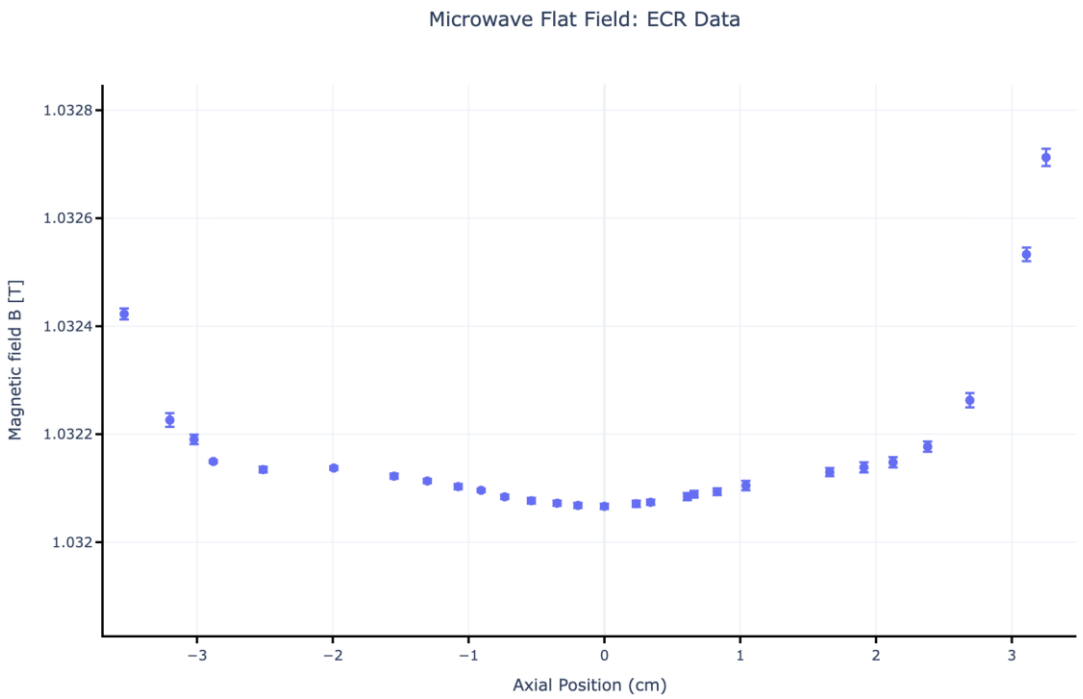
Summary

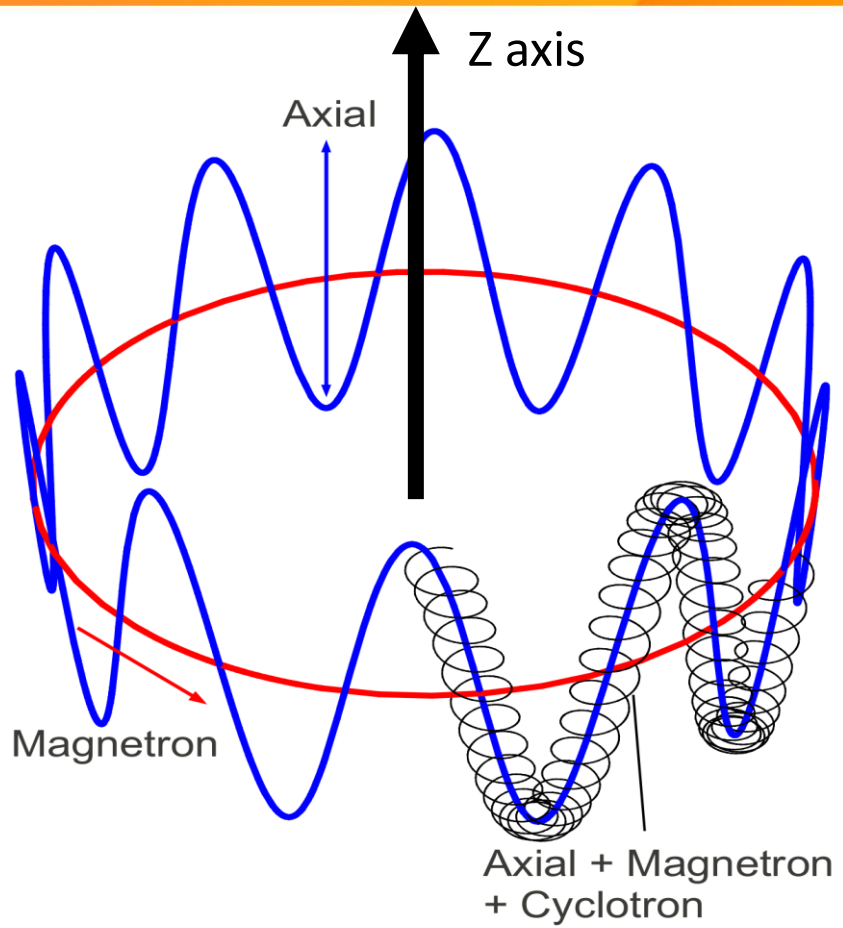
- ALPHA measures antihydrogen ground-state hyperfine transitions using microwave-induced spin flips.
- The published hyperfine splitting uses $f_{da}(B_{\min}) - f_{cb}(B_{\min})$ cancels the leading order of the magnetic field dependence and SME sensitive terms.
- SME sensitive interpretation motivates extracting individual transition.
- Individual transitions require careful magnetic field studies.

THαNK YOU!

Electron Cyclotron Resonance (ECR) Method

$$f_c = \frac{q\,|\vec{B}|}{2\,\pi\,m}$$





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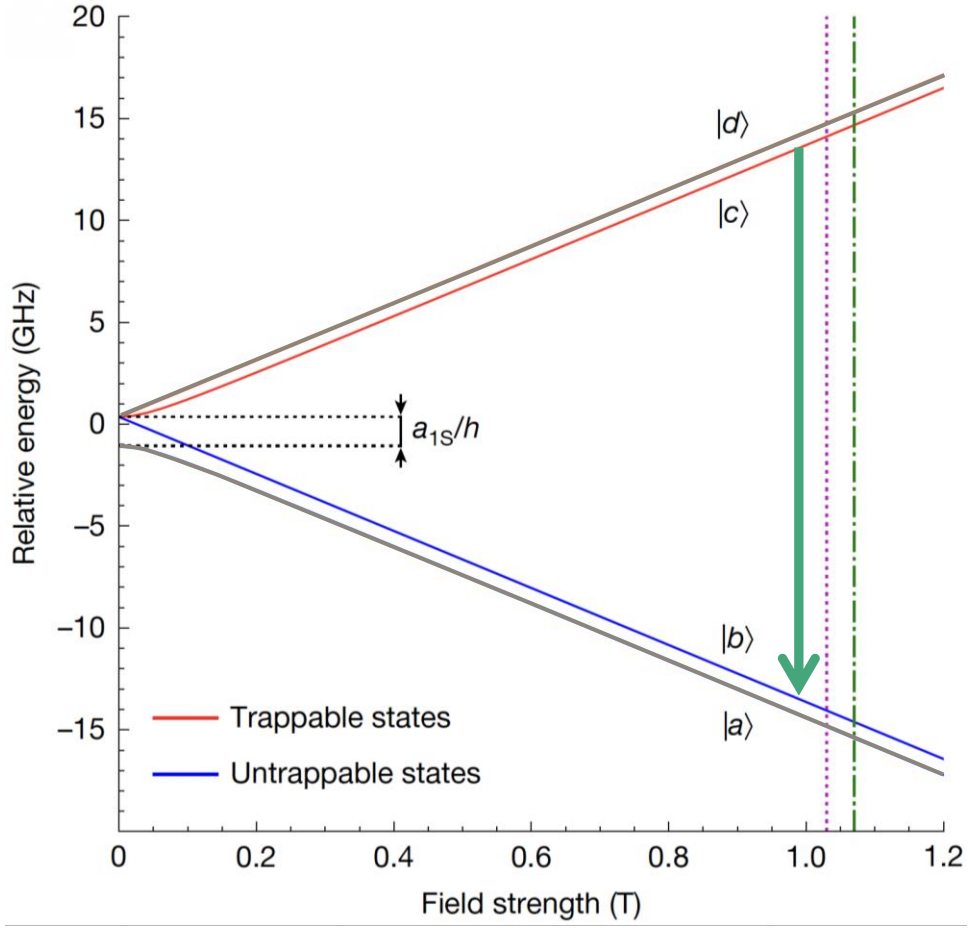
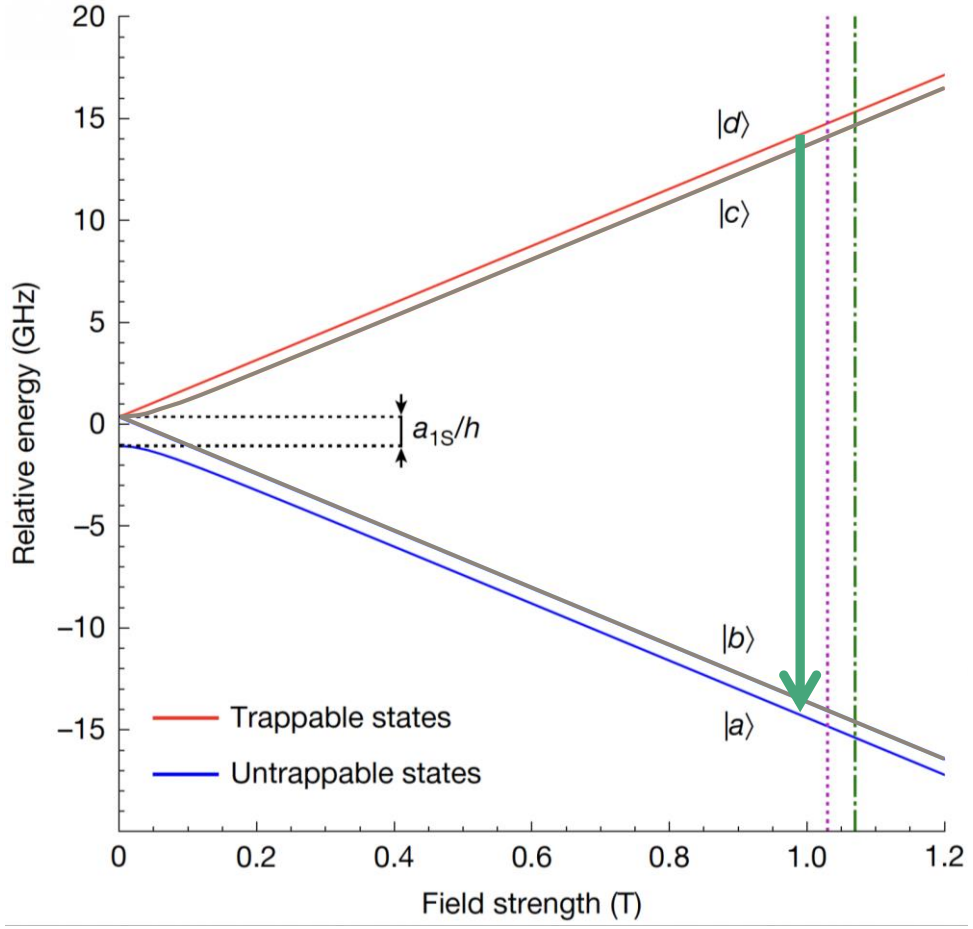
Individual Transition Frequencies





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