Spin-Dependent Interactions and Fundamental Physics

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Particle Astrophysics Seminar

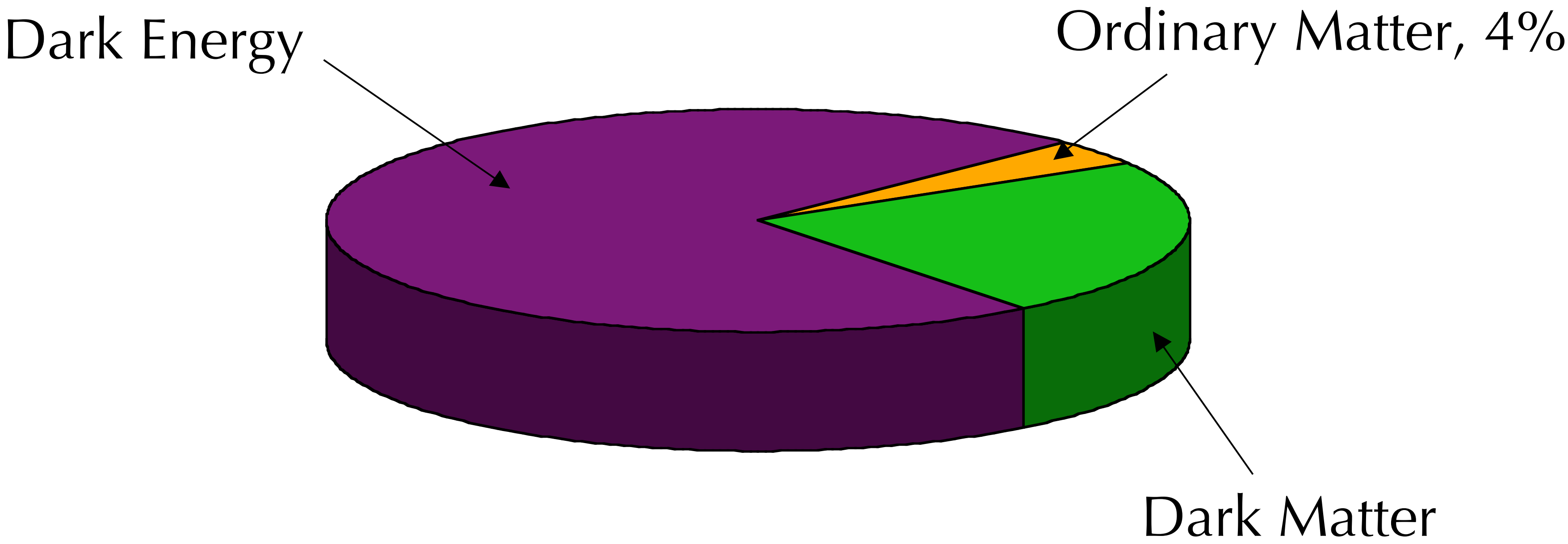
Fermilab, Batavia IL

22 October, 2007

We Would Like to Know:

1. What the universe is made of
2. How the universe works

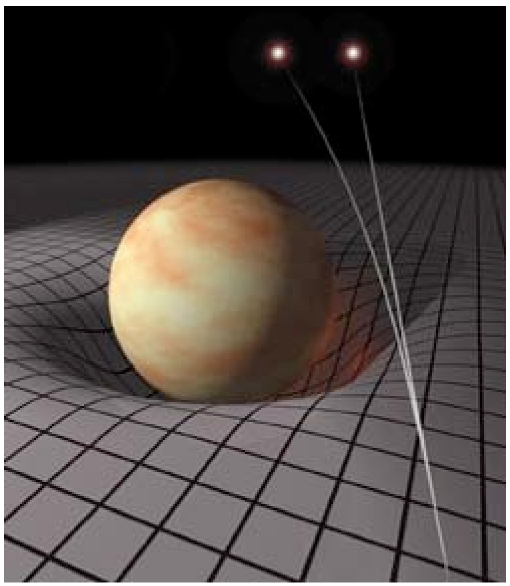
What is the Universe Made of?



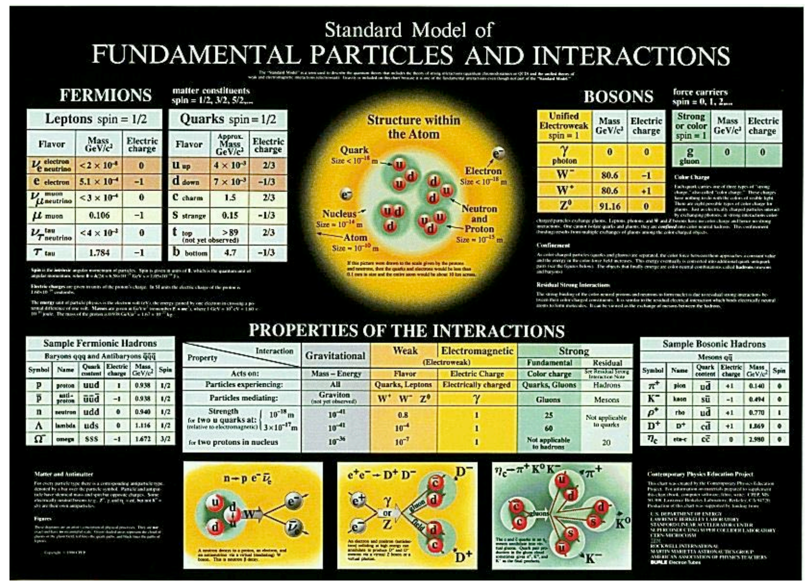
96% new particles and fields
that we may be able to detect
in the laboratory

How Does the Universe Work?

General Relativity



the Standard Model



assume Lorentz symmetry, CPT, EP, causality, etc.

Spin-coupled Interactions

1. Preferred-frame effects: broken rotational or boost symmetry
2. Dynamical effects of broken Lorentz symmetry
3. “New” particles
4. Non-commutative geometries
5. Torsion, the role of spin in gravity

Lorentz and CPT violation

Spontaneous breaking of Lorentz symmetry

⇨ spin-coupled background field:

$$H = -\tilde{b}^{e}_{j}\,\sigma^{j}_{e}$$

R. Bluhm and V.A. Kostelecky, Phys. Rev. Lett. **84**, 1381 (2000)

Dynamical Effects of Lorentz and CPT violation

Spontaneous breaking of Lorentz symmetry

⇨ Nambu-Goldstone ghost bosons

1. Ghost condensate defines a preferred frame
2. Cosmological constant: $M \sim 1$ meV
3. Dark matter: $M \sim 1$ eV

N. Arkani-Hamed, *et al.*, JHEP **7**, 29 (2005)

Ghost Condensate Potential #1

$$V = \frac{M^2}{F}\vec{s}\cdot\vec{v}$$

- Lorentz and CPT-violating
- distinguishes between left and right helicity

Ghost Condensate Potential #2

The GC mediates a novel spin-spin interaction:

$$V_\pi(\vec{r},\vec{v}) = \frac{1}{8\pi}\left(\frac{M}{F}\right)^2 (\vec{s}_1\cdot\vec{\nabla})(\vec{s}_2\cdot\vec{\nabla})\int\frac{d^3k}{(2\pi)^3}\frac{e^{i\vec{k}\cdot\vec{r}}}{M^2(\vec{v}\cdot\vec{k})-k^4}$$

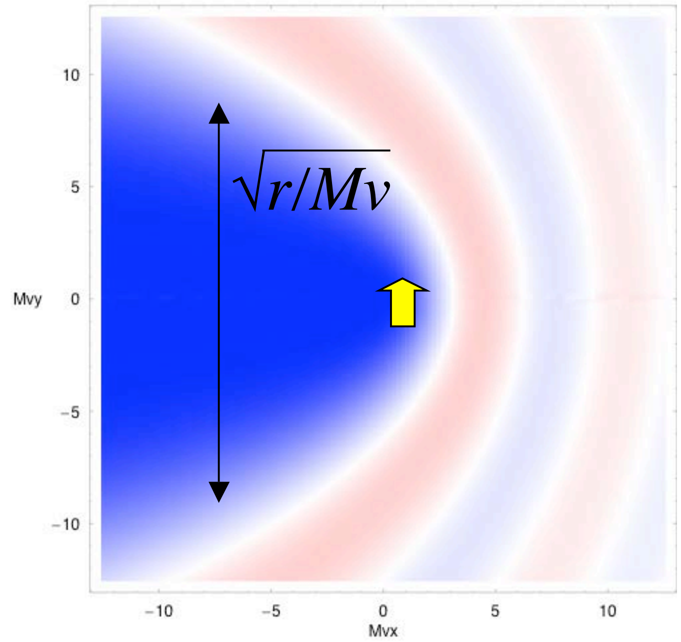
If v=0,

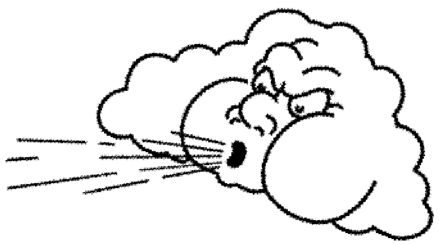
$$V_\pi(\vec{r},0) = -\frac{1}{8\pi}\left(\frac{M}{F}\right)^2\frac{(\vec{s}_1\cdot\vec{s}_2)-(\vec{s}_1\cdot\hat{r})(\vec{s}_2\cdot\hat{r})}{r}$$

Ghost Condensate Potential #2

Velocity dependence

⇨ non-uniform spatial profile





Numerical calculation: Jesse Thaler

Low-mass Boson Exchange, Part 1

Generically, we can look for three interactions between polarized spins and unpolarized matter:

$$V(\vec{r}) = \frac{g_p g_s}{\hbar c}\frac{\hbar^2}{8\pi m_e}(\sigma \cdot \hat{r})\left(\frac{1}{r\lambda}+\frac{1}{r^2}\right)e^{-r/\lambda}$$

$$+\frac{f_\perp}{\hbar c}\frac{\hbar^2}{8\pi m_e}(\sigma \times \hat{r})\left(\frac{1}{r\lambda}+\frac{1}{r^2}\right)e^{-r/\lambda}$$

$$+\frac{f_v}{\hbar c}\frac{\hbar c}{8\pi}(\sigma \cdot \vec{v})\frac{e^{-r/\lambda}}{r}$$

B.A. Dobrescu and I. Mocioiu, JHEP **11**, 5 (2006)
J.E. Moody and F. Wilczek, Phys. Rev. D **30**, 130 (1984)

Low-mass Boson Exchange, Part 2

And three more interactions between two polarized spins:

$$V(\vec{r}) = \frac{g^2}{4\pi\hbar c}\frac{\hbar^3}{4m_e^2 c}\left[(\sigma_1\cdot\sigma_2)\left(\frac{1}{r\lambda}+\frac{1}{r^2}\right)-(\sigma_1\cdot\hat{r})(\sigma_2\cdot\hat{r})\left(\frac{1}{\lambda^2 r}+\frac{3}{\lambda r^2}+\frac{3}{r^3}\right)\right]e^{-r/\lambda}$$

$$+D_1\hbar c(\sigma_1\cdot\sigma_2)\frac{e^{-r/\lambda}}{r}$$

$$+D_2\frac{\hbar^2}{m_e}((\sigma_1\times\sigma_2)\cdot\hat{r})\left(\frac{1}{\lambda r}+\frac{1}{r^2}\right)e^{-r/\lambda}$$

B.A. Dobrescu and I. Mocioiu, JHEP **11**, 5 (2006)
J.E. Moody and F. Wilczek, Phys. Rev. D **30**, 130 (1984)

Spin-coupled Interactions

1. Preferred-frame effects: broken rotational or boost symmetry
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5. Torsion, the role of spin in gravity

Low-Energy Experimental Searches

Electron sector: torsion balance

Proton sector: hydrogen maser

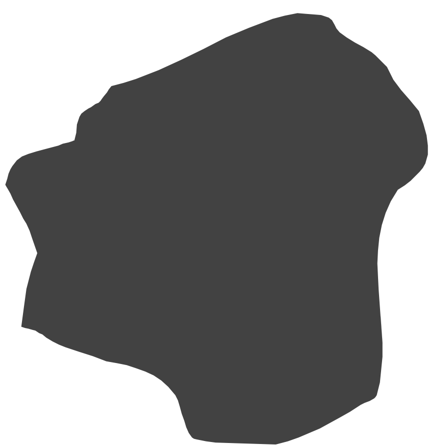
Neutron sector: noble gas maser

The Electron Sector:
Torsion Balance Experiments

C.C., B.R. Heckel, E.G. Adelberger
Center for Nuclear Physics and Astrophysics
University of Washington

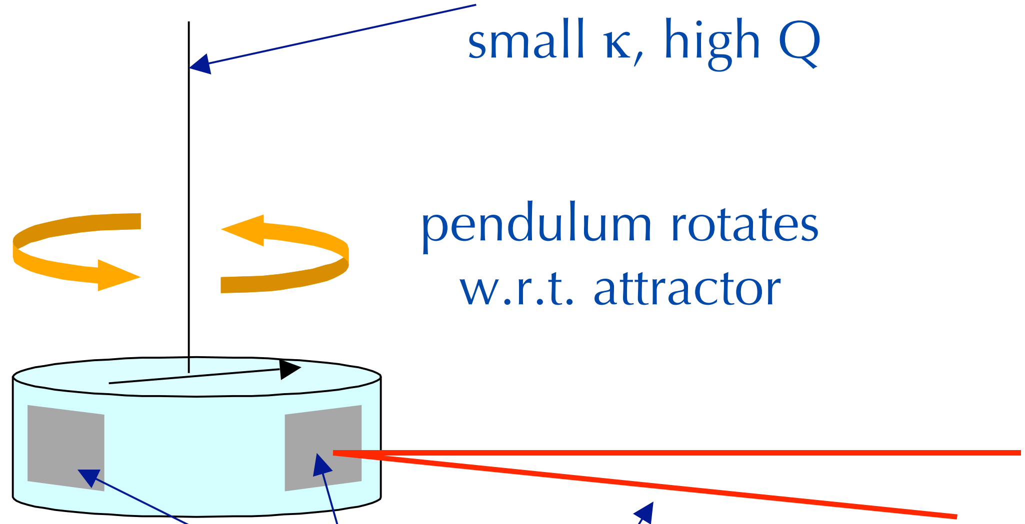
A Generic Torsion Pendulum

attractor:
something we made, a background field, a distant mass . . .



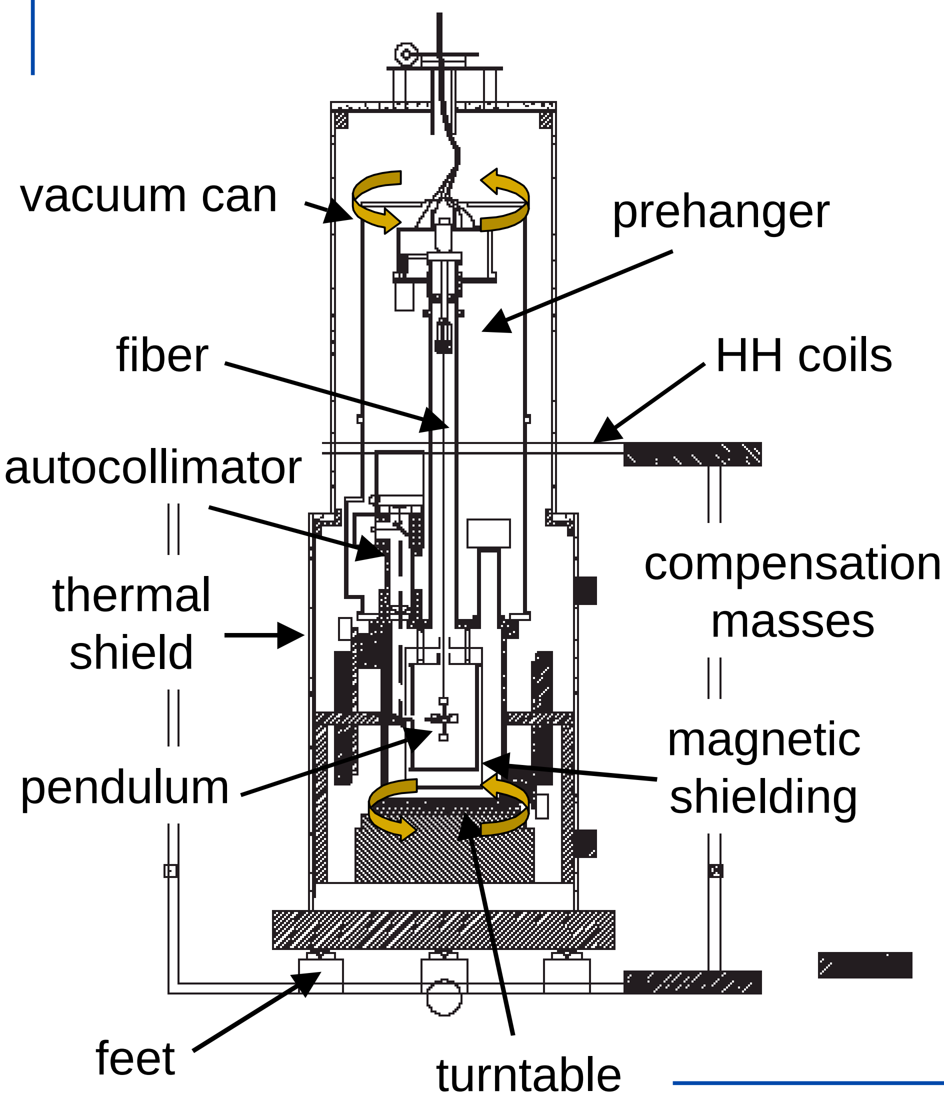
thin fiber:
small κ, high Q

pendulum rotates w.r.t. attractor



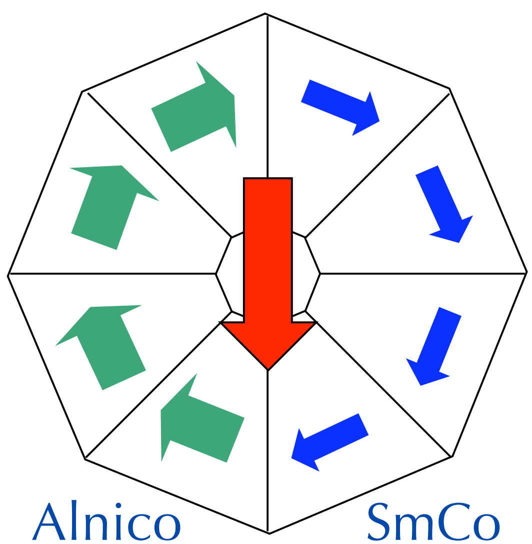
mirrors:
use retroreflected laser beam to detect angular deflection,
long path length ⇒ resolve small angles

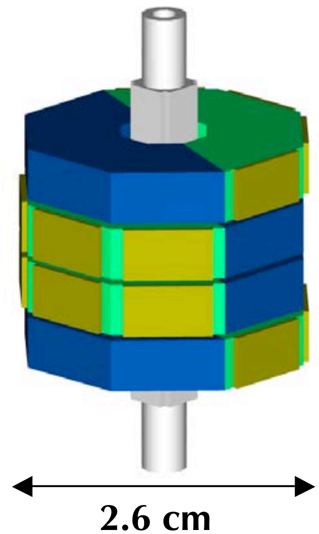
The Torsion Balance Apparatus



The Spin Pendulum

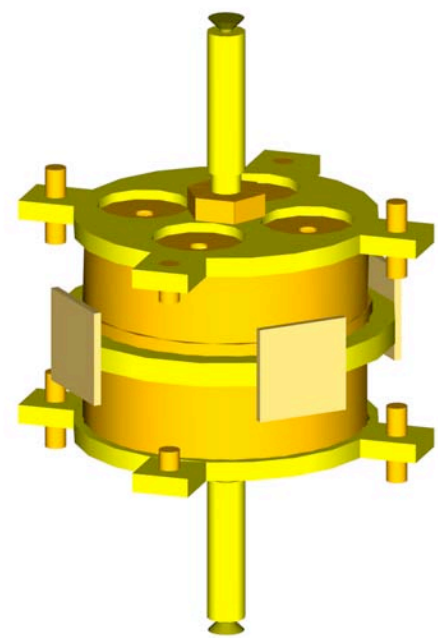
- 10^{23} polarized electron spins
- negligible external magnetic field





- minimal composition dipole
- negligible higher order gravitational moments

- gold-plated
- magnetically shielded
- 4 mirrors



The Gyrocompass Effect

The pendulum experiences a torque in the rotating frame:

$$\tau_z = -(\Omega \times J) \cdot \hat{n}$$
$$= -S\Omega \cos\lambda \cos\phi$$
$$= -\frac{N_p \hbar}{2} \Omega \cos\lambda \cos\phi$$

So the pendulum wants to point south by an amount proportional to its net spin

The Pendulum’s Net Spin

Calculated Estimate:

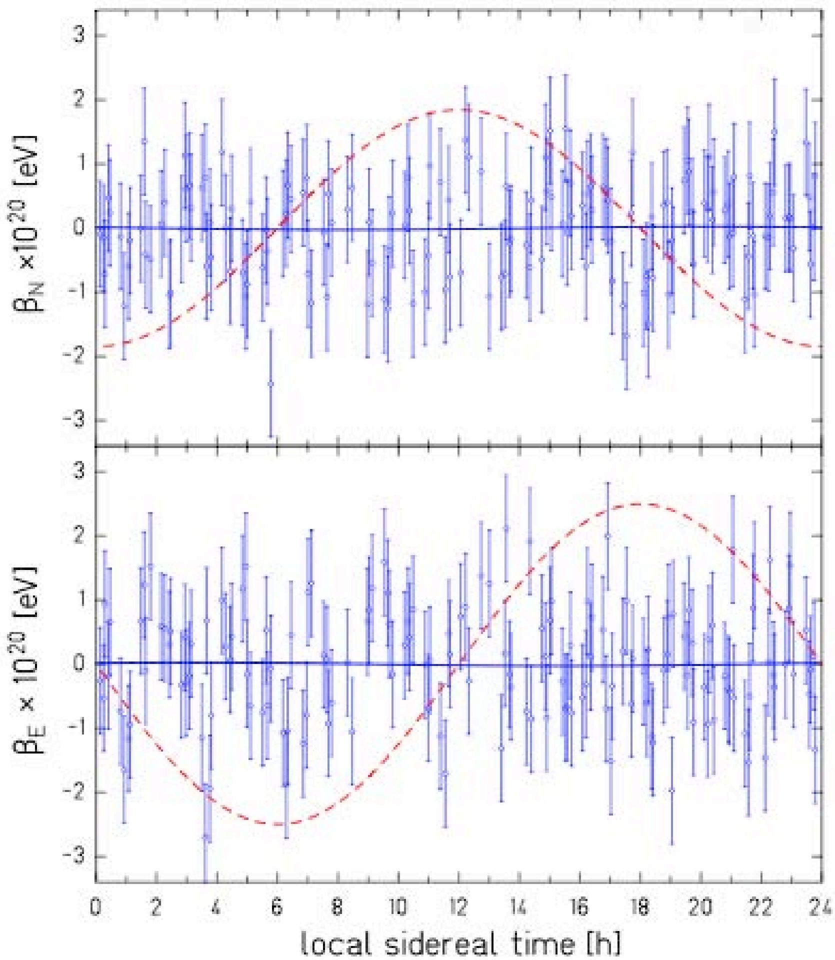
$$(9.7 \pm 2.7) \times 10^{22} \text{ spins}$$

Measured Value:

$$(9.78 \pm 0.25) \times 10^{22} \text{ spins}$$

Spin Pendulum Analysis

$$E = -N_p \vec{\sigma} \cdot \vec{\beta}$$



- 4 days of data
- binned over sidereal day
- fit to:

$$V = \vec{\sigma} \cdot \vec{A}$$

best fit:

$A_x = (-0.20 \pm 0.76) \times 10^{-21}$ eV

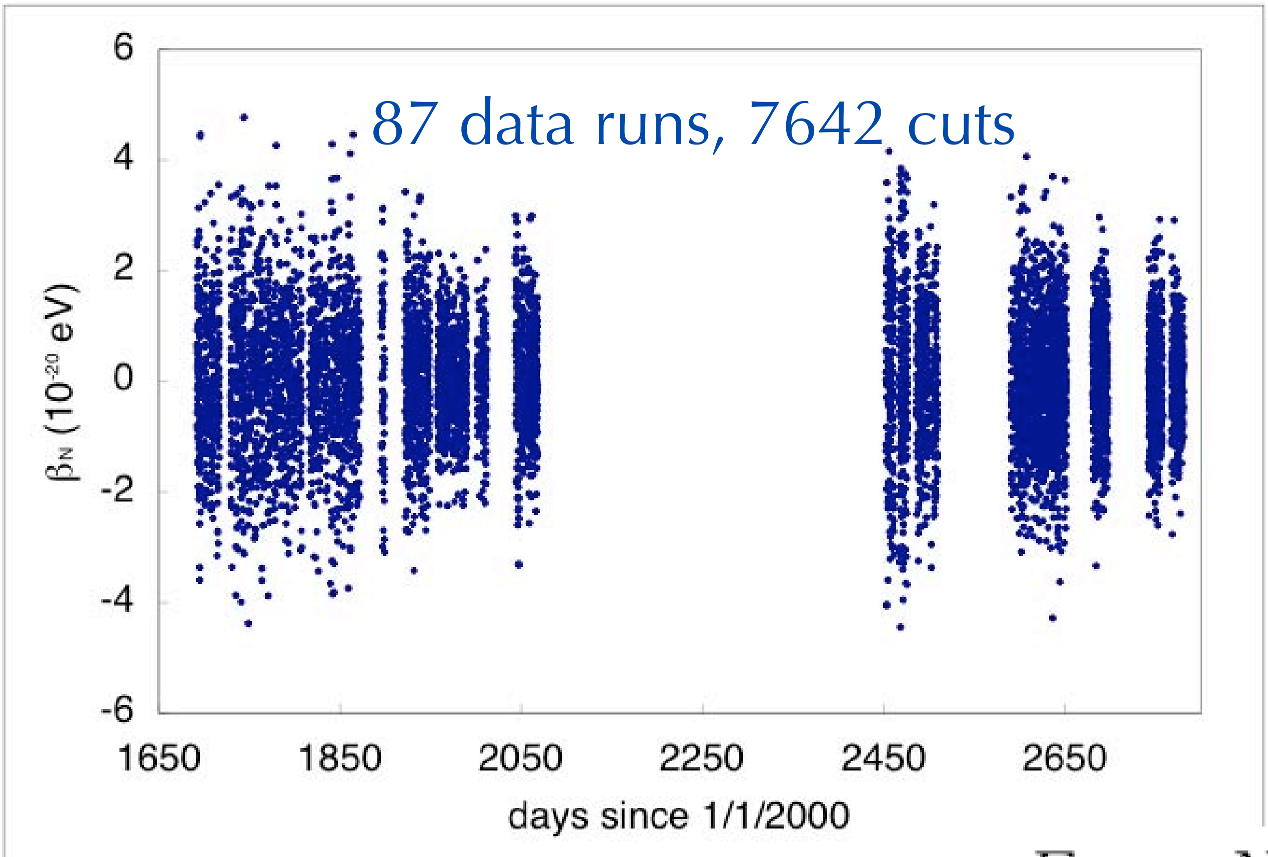
$A_y = (-0.23 \pm 0.76) \times 10^{-21}$ eV

hypothetical signal:

$A_x = 2.5 \times 10^{-20}$ eV

Spin Pendulum Data Set

linear regression fit to global data set



$$E = -N_p \vec{\sigma} \cdot \vec{\beta}$$

Torsion Pendulum Result

$$\tilde{b}^e_x = -0.91 \pm 1.44 \times 10^{-22}$$

$$\tilde{b}^e_y = 0.84 \pm 1.44 \times 10^{-22}$$

$$\tilde{b}^e_z = -3.7 \pm 21.2 \times 10^{-22}$$

benchmark value: $m_e^2/M_{Planck} = 10^{-17}$ eV

The Proton Sector: Hydrogen Maser Experiments

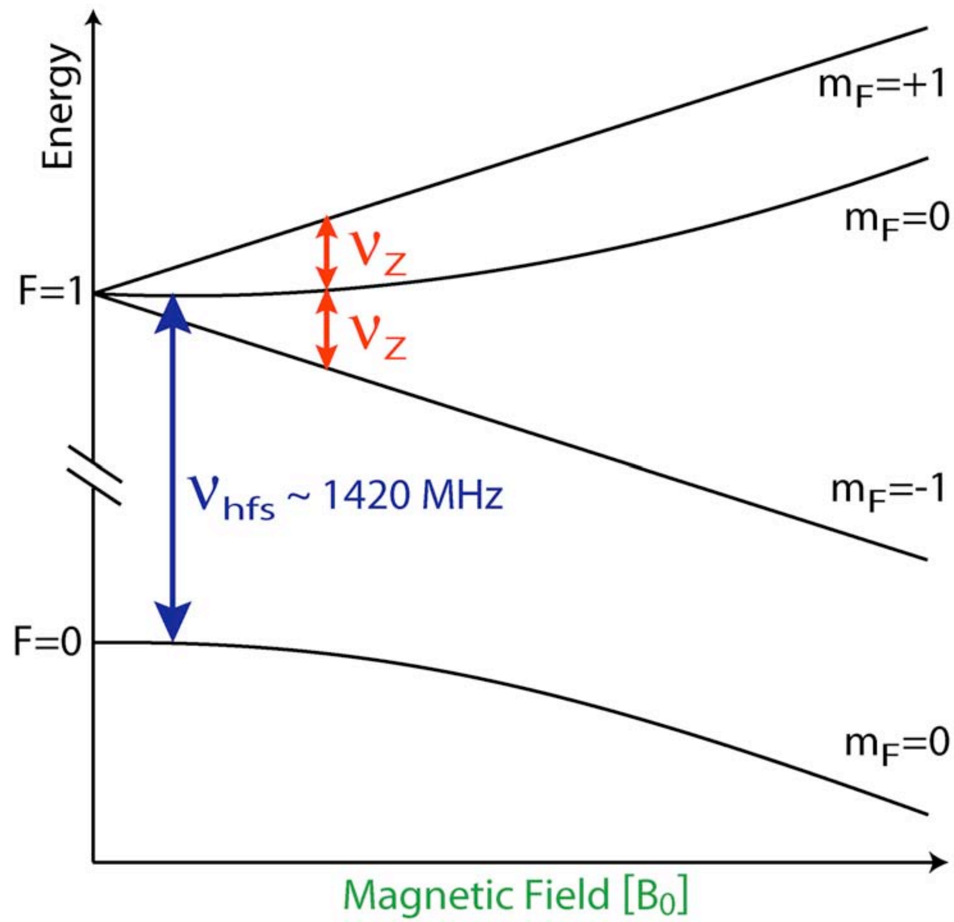
M.A. Humphrey, D.F. Phillips, R.L. Walsworth
Harvard-Smithsonian Center for Astrophysics
Harvard University

Hydrogen Atom Transitions

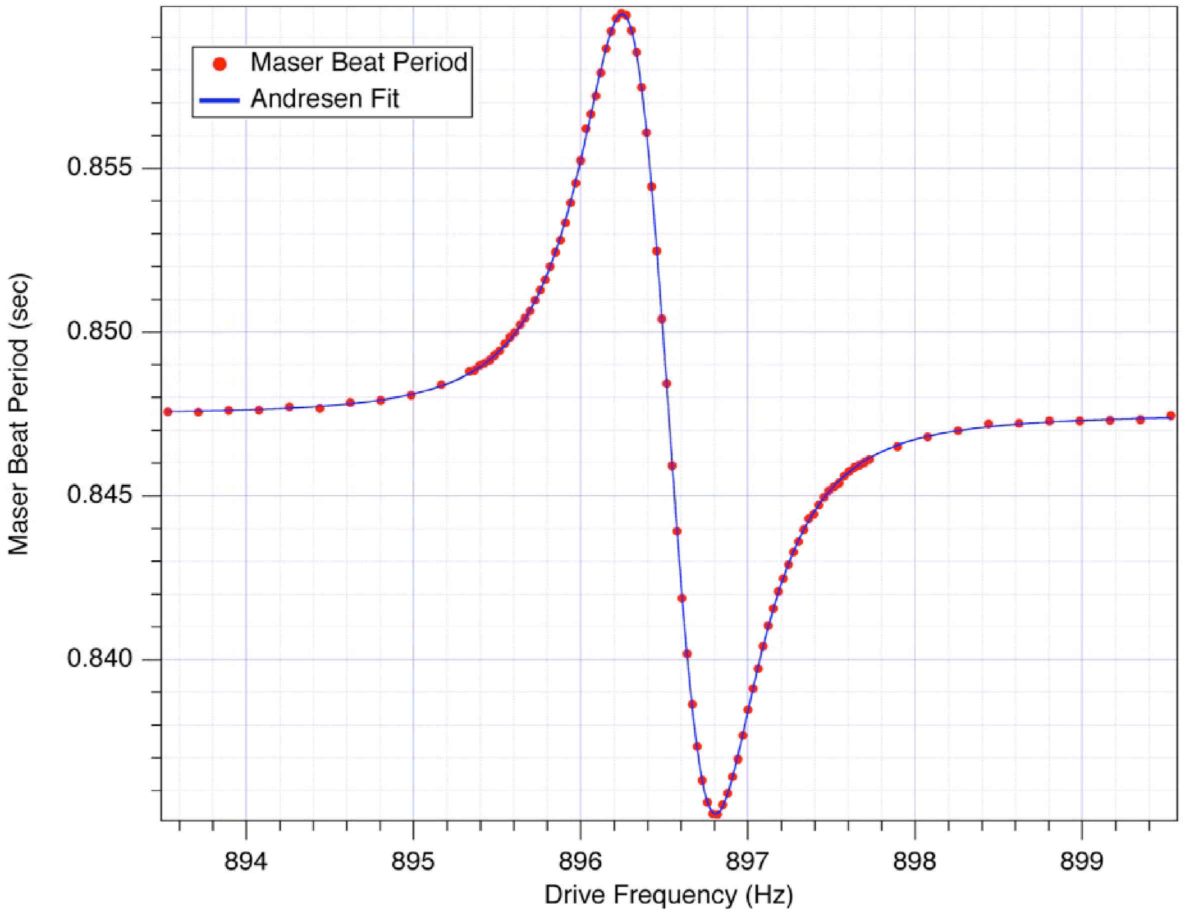
- Maser frequency (ν_{hfs}) insensitive to magnetic and spin-coupled interactions
- Fractional frequency stability $<10^{-14}$ for up to a few weeks

- Zeeman frequency (ν_Z) sensitive to Lorentz violation

$$|\tilde{b}^p + \tilde{b}^e| \leq 2\pi\delta\nu_z$$

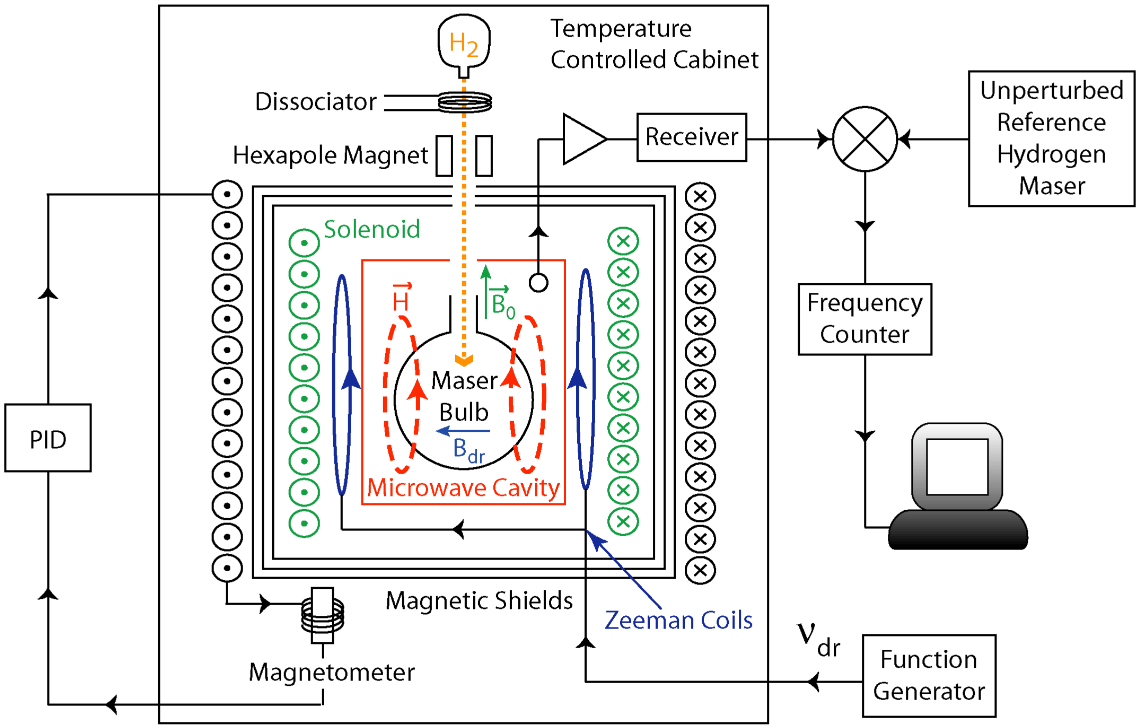


Measuring the Zeeman Frequency



- Apply static field B_0 to fix quantization axis, ν_Z
- Apply oscillating field $B_{dr} \perp$ to B_0
- Induced shift in maser frequency is anti-symmetric fn of $\nu_{dr} - \nu_Z$
- When $\nu_{dr} = \nu_Z$, the maser frequency is unperturbed
- Sweep ν_{dr} through resonance, fit resulting lineshape

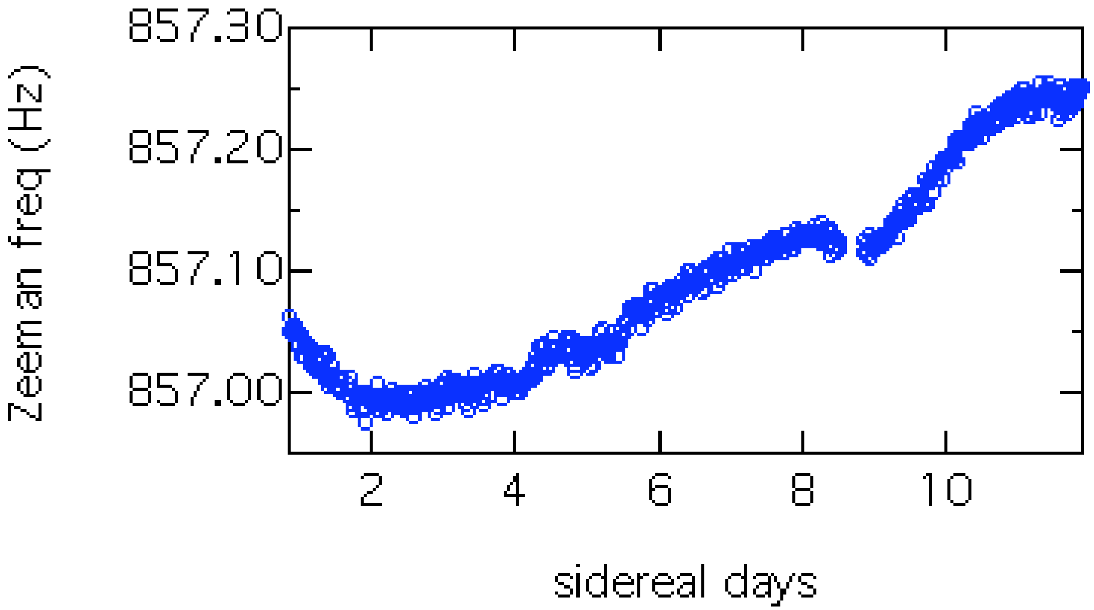
Hydrogen Maser Apparatus



- hexapole magnet selects states for population inversion
- static 1 mG field defines quantization axis
- 4 layers of magnetic shielding
- active stabilization of solenoid current removed daily fluctuations in B-field
- referenced to unperturbed H-maser

The Hydrogen Maser

Hydrogen Maser Result



$$|\tilde{b}^p + \tilde{b}^e| \leq 2 \times 10^{-18}\ \mathrm{eV}$$

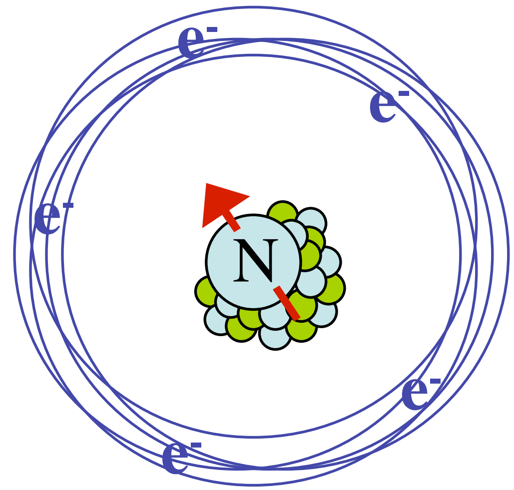
benchmark value: $m_p{}^2/M_{Planck} = 10^{-13}$ eV

D.F. Phillips, *et al.*, Phys. Rev. D **63**, 111101(R) (2000)

The Neutron Sector: Dual-Species Maser Experiments

A. Glenday, D. Bear, F. Cane,
D.F. Phillips, R.E. Stoner, R.L. Walsworth
Harvard-Smithsonian Center for Astrophysics
Harvard University

^{3}He and ^{129}Xe Comagnetometer



- no net electronic spin
- spin 1/2 nuclei
- nuclear spin from neutron
- maser frequencies:

$$\omega_{He} = \gamma_{He} B_0 + \omega_{LV}$$

$$\omega_{Xe} = \gamma_{Xe} B_0 + \omega_{LV}$$

- use Xe to lock B_0

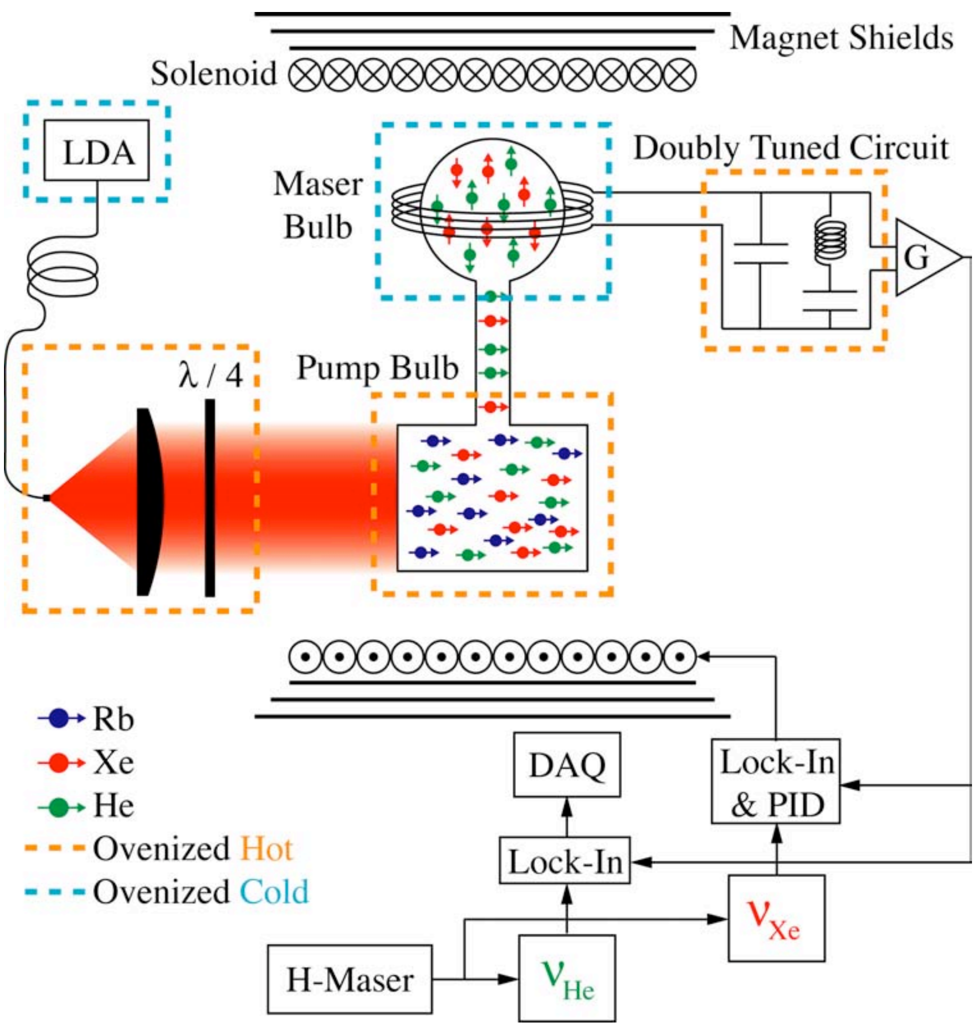
Sensitivity to Lorentz-Violation

$$\omega_{He} = \underbrace{\frac{\gamma_{He}}{\gamma_{Xe}}\omega_{Xe}}_{\text{constant}} + \underbrace{\left(1 - \frac{\gamma_{He}}{\gamma_{Xe}}\right)\omega_{LV}}_{\text{varying sidereally}}$$

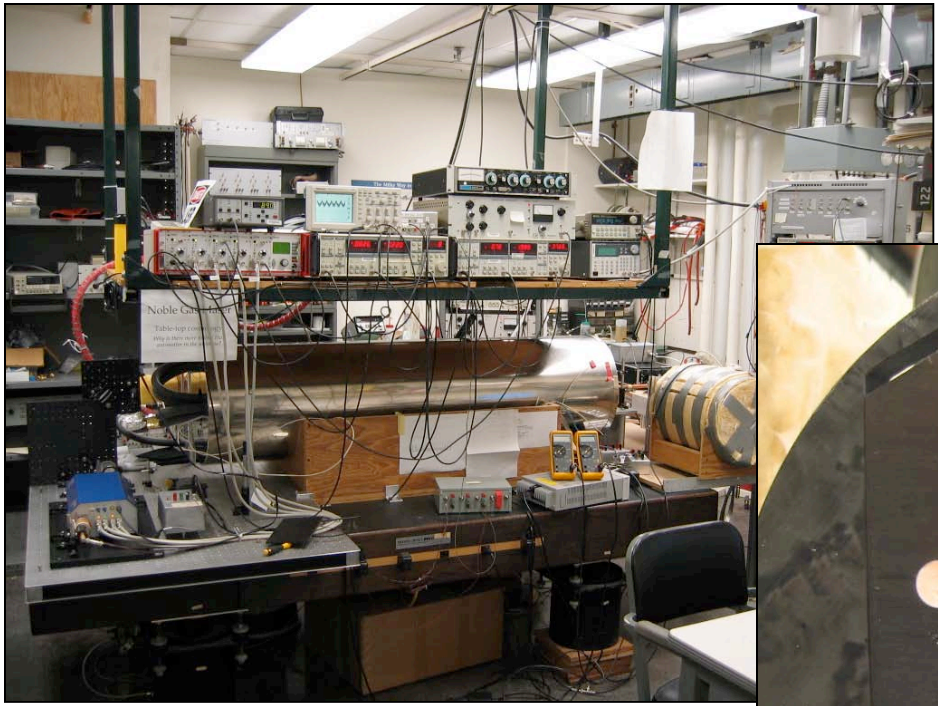
$$\frac{\gamma_{He}}{\gamma_{Xe}} = 2.75$$

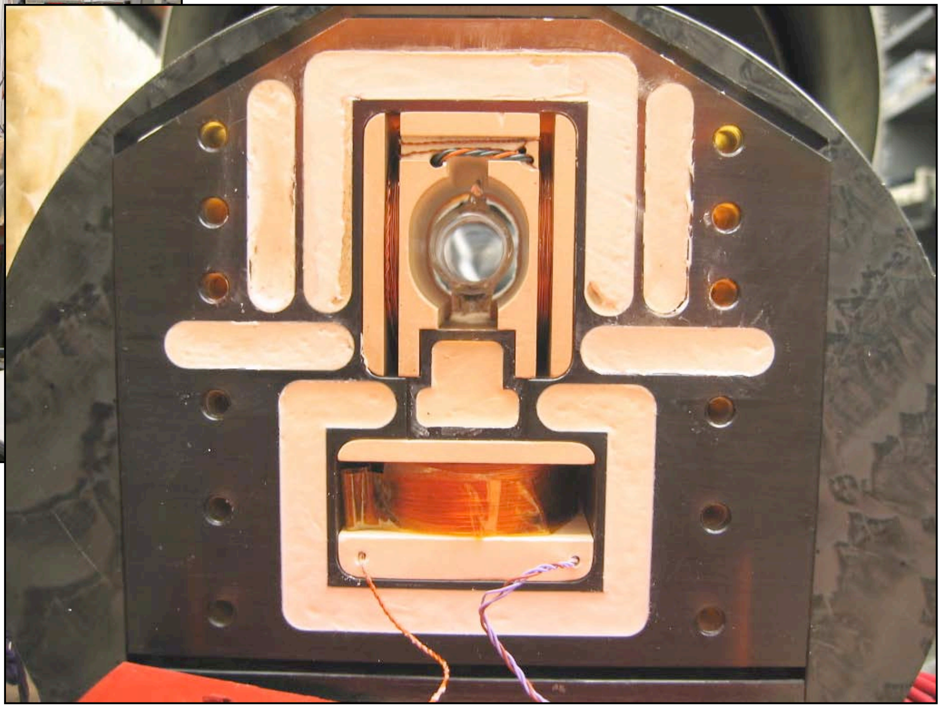
Dual-Species Maser Apparatus

- Double-bulb glass cell
- 30-50 Torr of ^{129}**Xe**,
- 600 -1000 Torr of ^{3}**He**,
- 80 Torr of N_2 (buffer gas)
- **Rb** metal
- σ^+ light, Rb D_1 transition
- $B_0 \approx 6$ G
- Field gradients ≤ 30 ppm/cm
- $\nu_{Xe}, \nu_{He} \approx 7, 20$ kHz
- referenced to H-maser

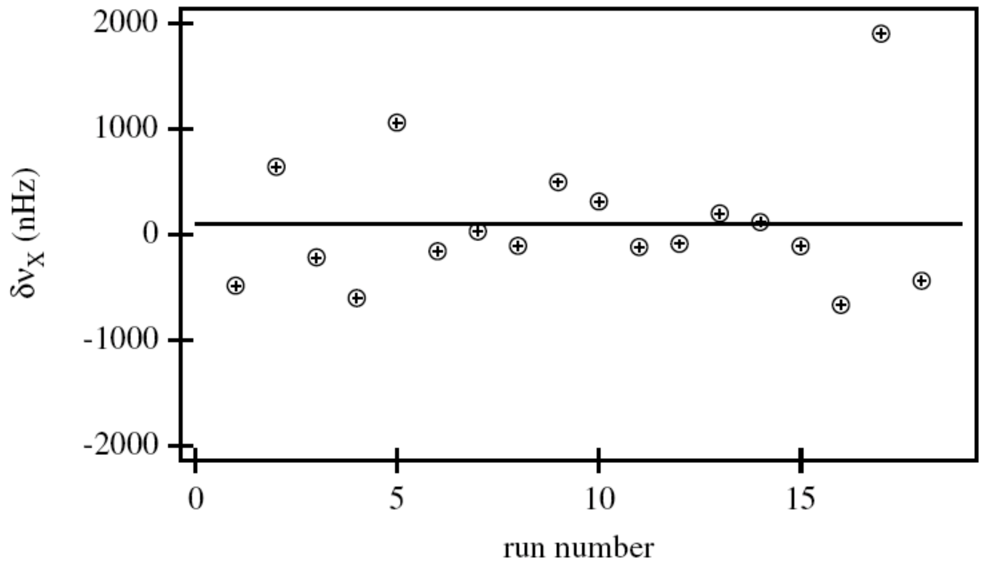


Dual-Species Maser Apparatus





Dual-Species Maser Result

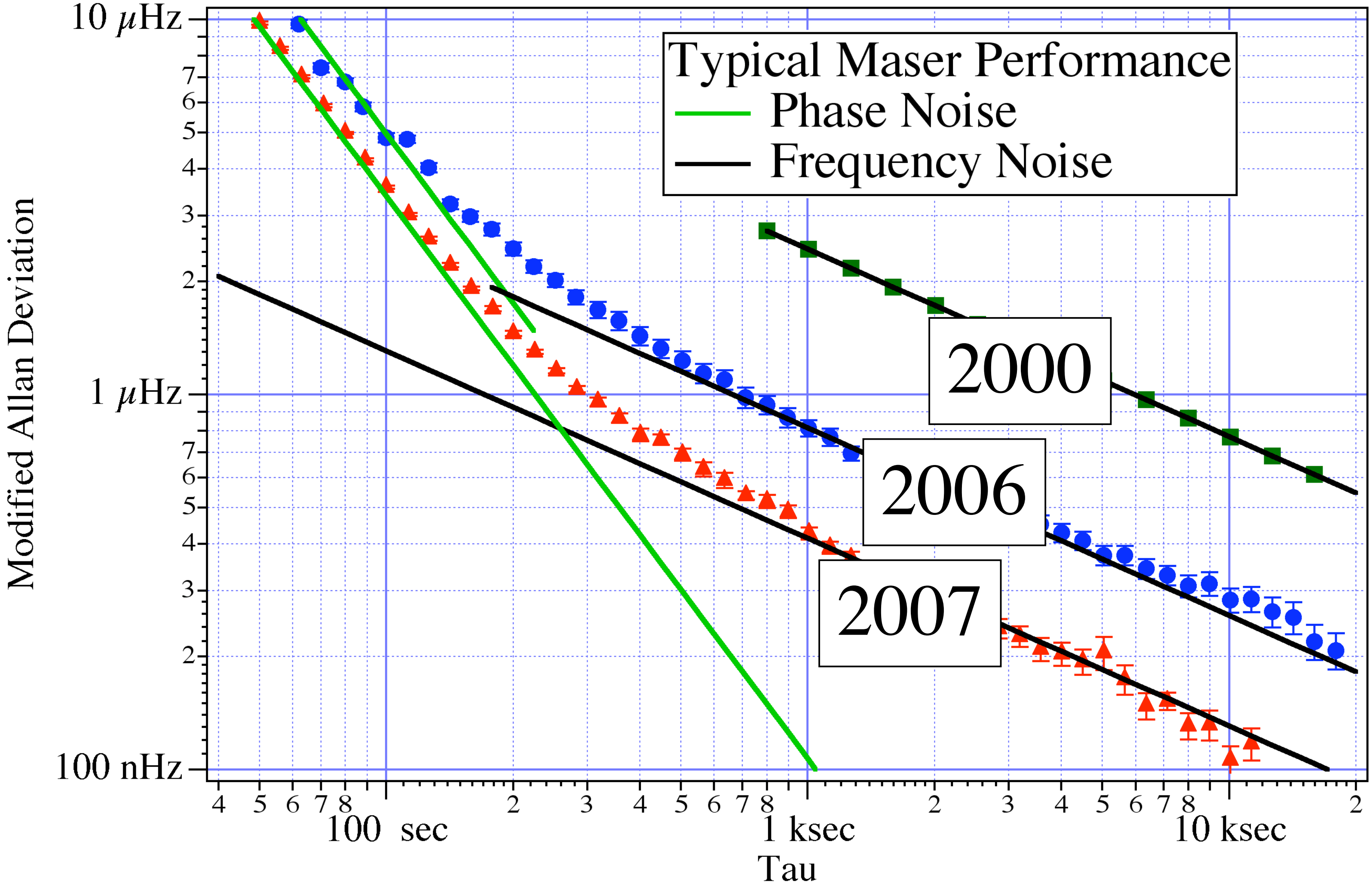


$$\tilde{b}^n = 6.4 \pm 5.4 \times 10^{-23}\ \text{eV}$$

benchmark value: $m_n^2/M_{Planck} = 10^{-13}$ eV

D. Bear, *et al.*, PRL **85**, 5038 (2000)

Improved Maser Performance

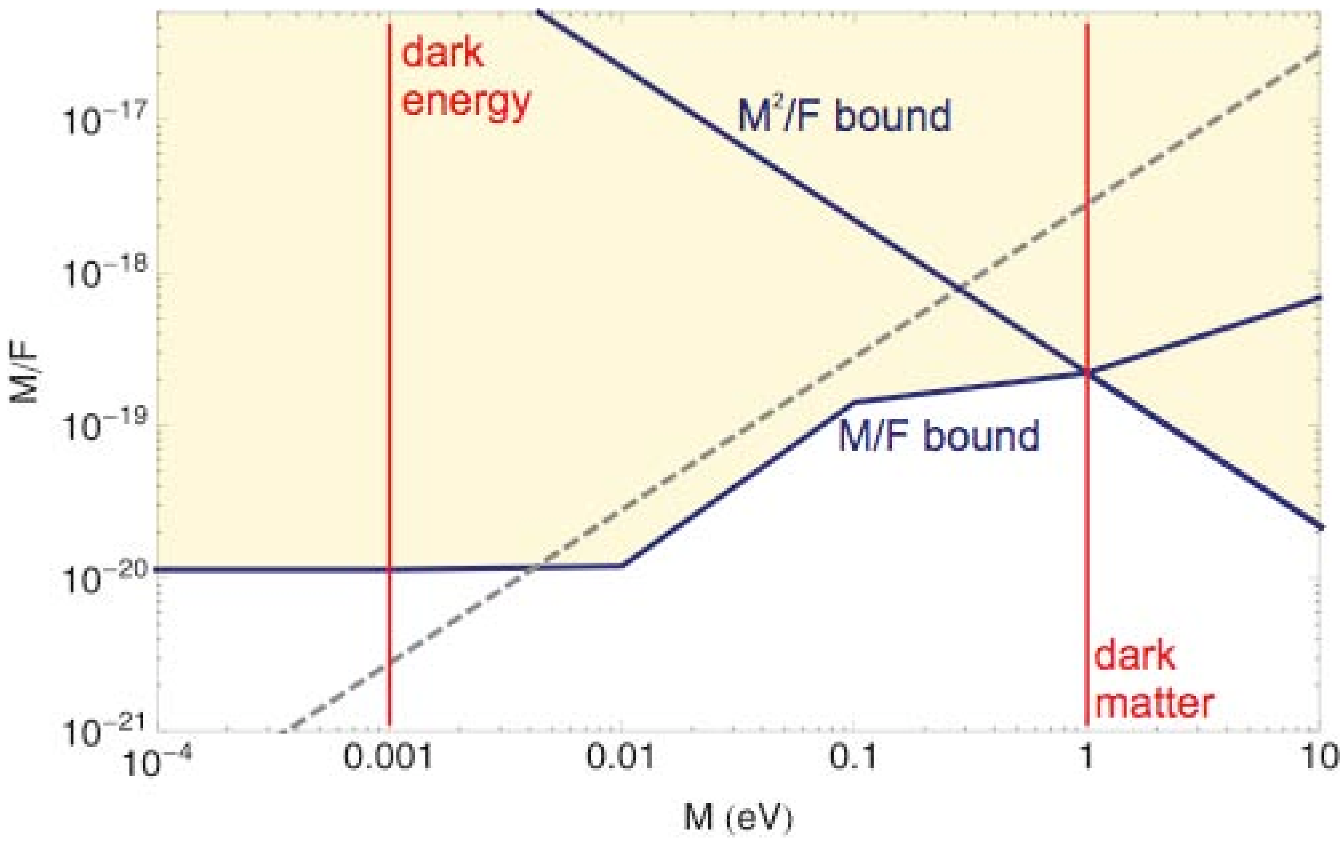


Current Status of Lorentz/CPT measurements

Experiment	$b_\perp^e$ (GeV)	$b_\perp^p$ (GeV)	$b_\perp^n$ (GeV)
^{129}Xe/^{3}He maser (Harvard)			10^{-32}
^{199}Hg-^{123}Cs precession (UW)	10^{-27}	10^{-27}	10^{-30}
H-maser double resonance (Harvard)	10^{-27}	10^{-27}	
K-^{3}He comagnetometer (Princeton)	10^{-28}	10^{-30}	10^{-31}
Spin-polarized torsion pendulum (UW)	10^{-31}		

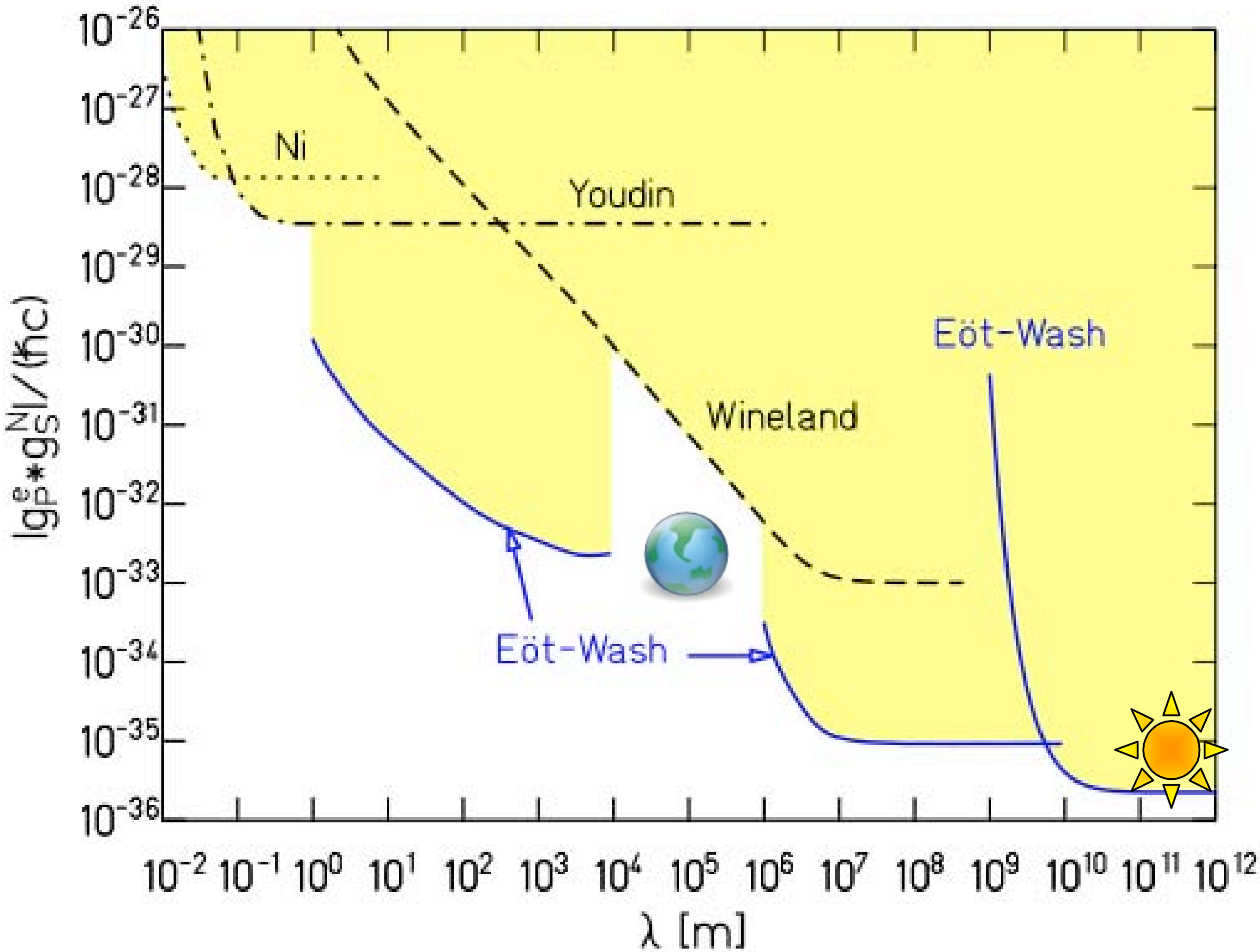
Results: Ghost Condensate

95% confidence level exclusion limits



Results: ALP monopole-dipole

95% confidence level exclusion limits



Results: Low-Mass Boson Monopole-dipole Interactions

$g_p g_s/\hbar c = (-4.8 \pm 8.5) \times 10^{-37}$

$f_v/\hbar c = (0.96 \pm 2.5) \times 10^{-56}$

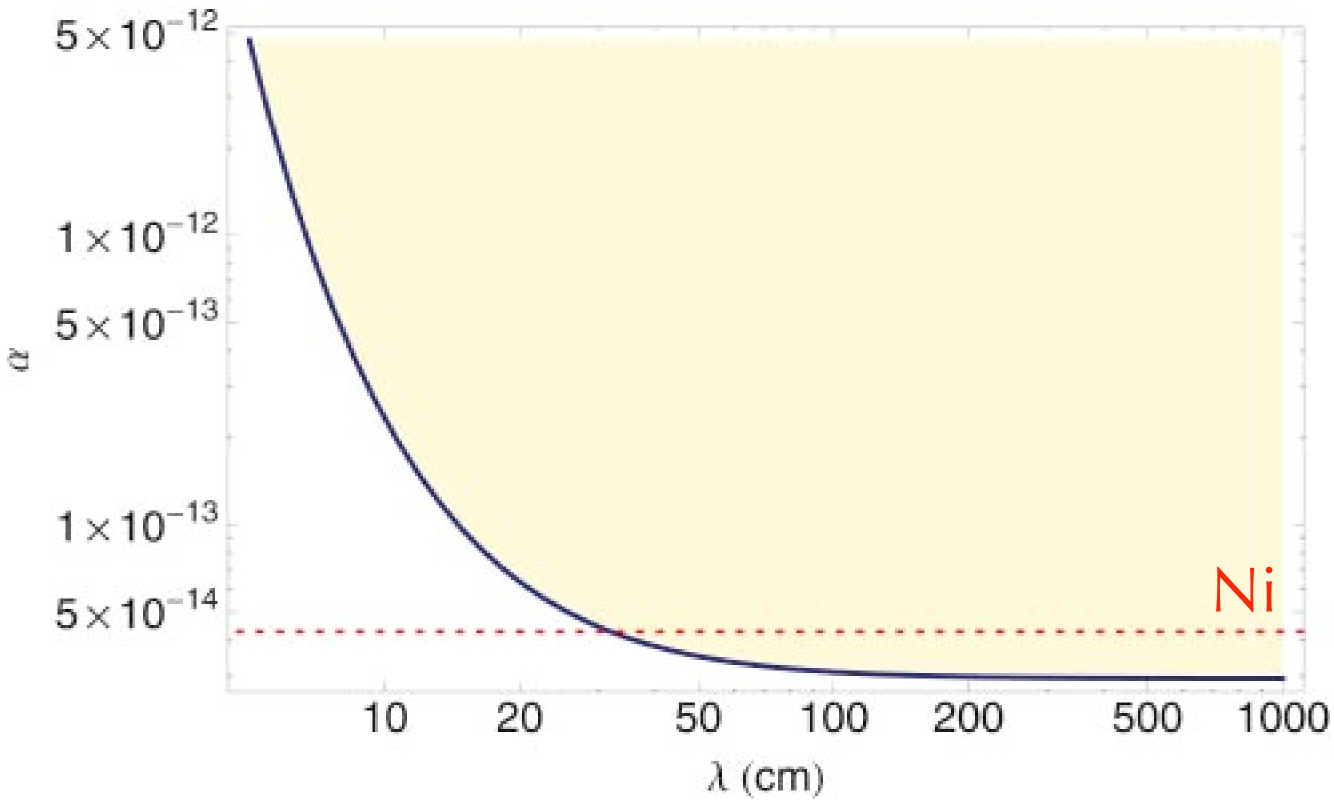
$f_\perp/\hbar c = (0.39 \pm 1.08) \times 10^{-32}$

$$V(\vec{r}) = \frac{g_p g_s}{\hbar c}\frac{\hbar^2}{8\pi m_e c}(\sigma \cdot \hat{r})\left(\frac{1}{r\lambda} + \frac{1}{r^2}\right)e^{-r/\lambda} + \frac{f_v}{\hbar c}\frac{\hbar c}{8\pi}(\sigma \cdot \hat{v})\frac{e^{-r/\lambda}}{r} + \frac{f_\perp}{\hbar c}\frac{\hbar^2}{8\pi m_e}(\sigma \times \hat{r})\left(\frac{1}{r\lambda} + \frac{1}{r^2}\right)e^{-r/\lambda}$$

Results: ALP dipole-dipole

Compared to a magnetic dipole: $\alpha = (-0.8 \pm 1.8) \times 10^{-14}$

95% confidence level exclusion limits



Results: Low-Mass Boson Dipole-dipole Interactions

$$D_1 = (-1.5 \pm 3.6) \times 10^{-41}$$

$$D_2 = (-0.5 \pm 1.3) \times 10^{-28}$$

$$V(\vec{r}) = D_1 \hbar c (\sigma_1 \cdot \sigma_2) \frac{e^{-r/\lambda}}{r} + D_2 \frac{\hbar^2}{m_e} ((\sigma_1 \times \sigma_2) \cdot \hat{r}) \left(\frac{1}{\lambda r} + \frac{1}{r^2} \right) e^{-r/\lambda}$$

Conclusions

- We can make very precise low energy measurements of forces coupled to electron, proton and neutron spins
- These measurements set stringent limits on fundamental symmetry breaking and couplings to "new" particles
- We may also set limits on extensions to GR and the role that spin may play in determining the geometry of space-time
- New experiments will soon push these limits even further . . .