



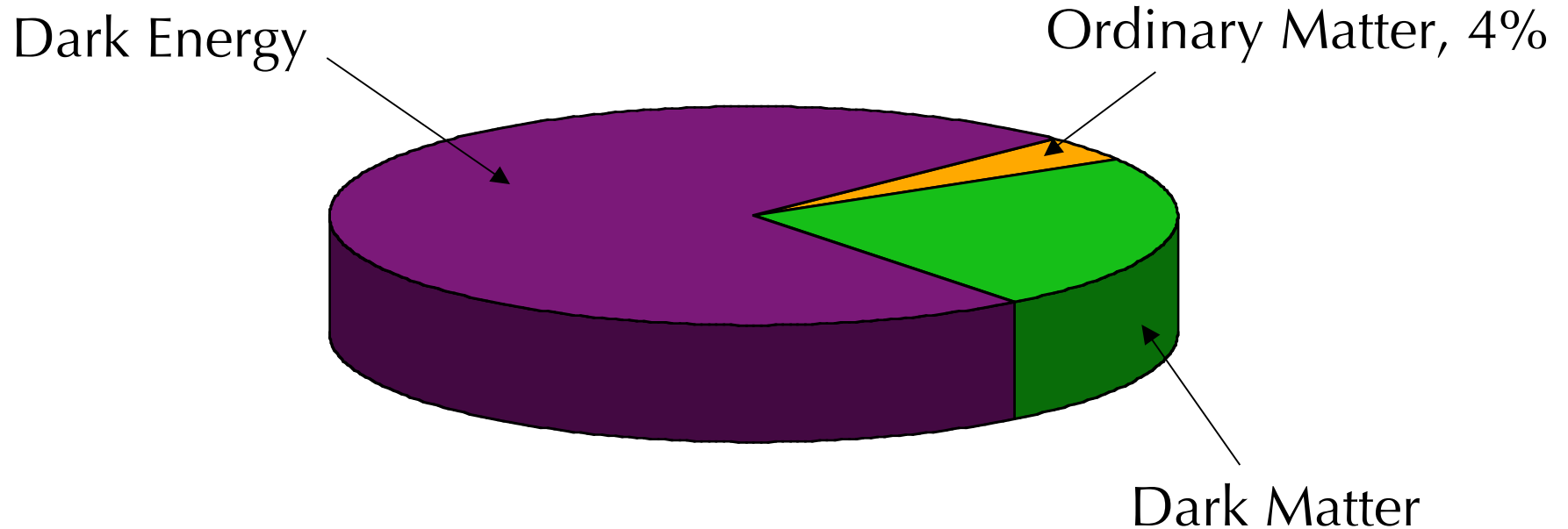
# Spin-Dependent Interactions and Fundamental Physics

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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

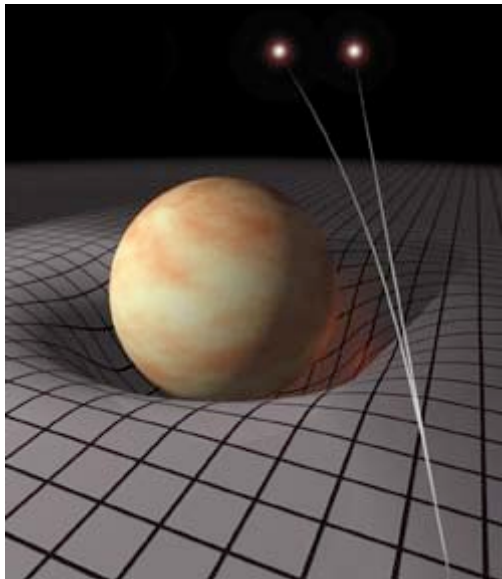
# What is the Universe Made of?



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

**Standard Model of FUNDAMENTAL PARTICLES AND INTERACTIONS**

The Standard Model is a set of quantum field theories that describe the behavior of elementary particles and their interactions. It is the most successful theory of physics to date, having been tested to high precision in a wide range of experiments.

FERMIONS				matter constituents			
Leptons spin = 1/2				Quarks spin = 1/2			
Flavor	Mass (GeV/c <sup>2</sup> )	Electric charge	Spin	Flavor	Approx. Mass (GeV/c <sup>2</sup> )	Electric charge	Spin
$e^-$ electron	$< 2 \times 10^{-6}$	0	1/2	$u$ up	$4 \times 10^{-2}$	2/3	1/2
$\mu^-$ muon	$1.057$	-1	1/2	$d$ down	$7 \times 10^{-2}$	-1/3	1/2
$\tau^-$ tau	$1.784$	-1	1/2	$c$ charm	$1.5$	2/3	1/2
$\nu_e$ electron neutrino	$< 10^{-6}$	0	1/2	$s$ strange	$0.15$	-1/3	1/2
$\nu_\mu$ muon neutrino	$< 4 \times 10^{-6}$	0	1/2	$t$ top (not observed)	$> 89$	2/3	1/2
$\nu_\tau$ tau neutrino	$< 1.8$	0	1/2	$b$ bottom	$4.7$	-1/3	1/2

**Structure within the Atom**

BOSONS				force carriers			
Unified Electroweak spin = 1				Strong or color spin = 1			
Symbol	Mass (GeV/c <sup>2</sup> )	Electric charge	Spin	Symbol	Mass (GeV/c <sup>2</sup> )	Electric charge	Spin
$\gamma$ photon	0	0	1	$g$ gluon	0	0	1
$W^\pm$	80.6	-1 / +1	1	$\Delta$ Delta baryons	1.1 - 1.6	0	3/2
$Z^0$	91.16	0	1	$\Lambda$ Lambda baryons	1.116	0	3/2

**PROPERTIES OF THE INTERACTIONS**

Property	Interaction	Gravitational		Weak (Electroweak)		Strong	
		Mass-Energy	Flavor	Electric Charge	Color Charge	Fundamental	Residual
Acts on:	All	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons	
Particles mediating:	Graviton (not yet observed)	$W^\pm, Z^0$	$\gamma$	Gluons	Mesons		
Strength (for two quarks at $1.3 \times 10^{-16}$ m)		$10^{-38}$	$10^{-5}$	1	25	Not applicable to quarks	
Range		$10^{-17}$ m	$10^{-16}$ m	$10^{-16}$ m	60	Not applicable to hadrons	

**Sample Fermionic Hadrons**

Symbol	Name	Quark Content	Mass (GeV/c <sup>2</sup> )	Spin
$p$	proton	$uud$	1	1/2
$n$	neutron	$udd$	0.940	1/2
$\Lambda$	lambda	$uds$	1.116	1/2
$\Sigma$	sigma	$uus, uds, dds$	1.073	1/2

**Sample Bosonic Hadrons**

Symbol	Name	Quark Content	Mass (GeV/c <sup>2</sup> )	Spin
$\pi^\pm$	pion	$u\bar{d}, d\bar{u}$	0.140	0
$K^\pm$	kaon	$u\bar{s}, s\bar{u}$	0.494	0
$D^\pm$	charm meson	$c\bar{u}, c\bar{d}$	1.869	0
$B_c^\pm$	charm meson	$c\bar{c}, c\bar{s}$	3.690	0

**Contemporary Physics Education Project**

This project is a part of the Contemporary Physics Education Project, which aims to provide a comprehensive and up-to-date resource for students and educators alike. It covers a wide range of topics in modern physics, from quantum mechanics to particle physics, and is designed to be both accessible and engaging.

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:

$$H = -\tilde{b}_j^e \sigma_e^j$$

# 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:  $M \sim 1 \text{ meV}$
3. Dark matter:  $M \sim 1 \text{ eV}$

# 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:

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

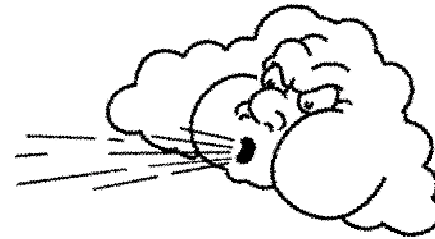
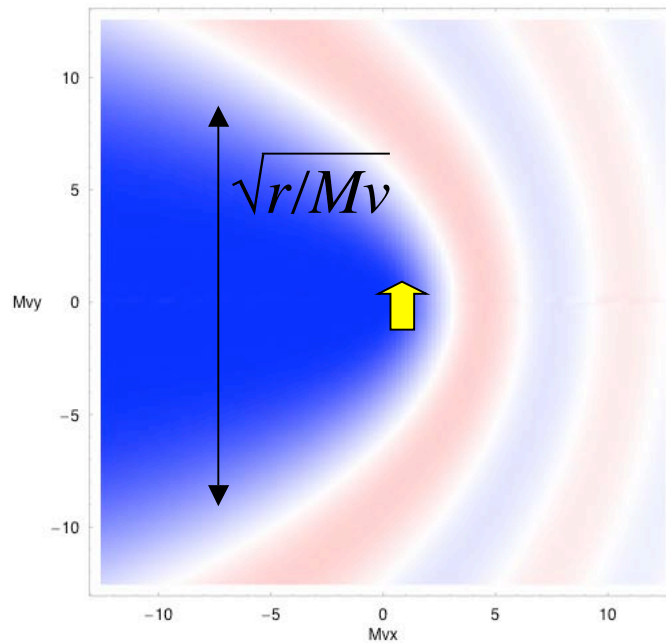
If  $\vec{v}=0$ ,

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

# 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:

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

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
2. Dynamical effects of broken Lorentz symmetry
3. “New” particles
4. Non-commutative geometries
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

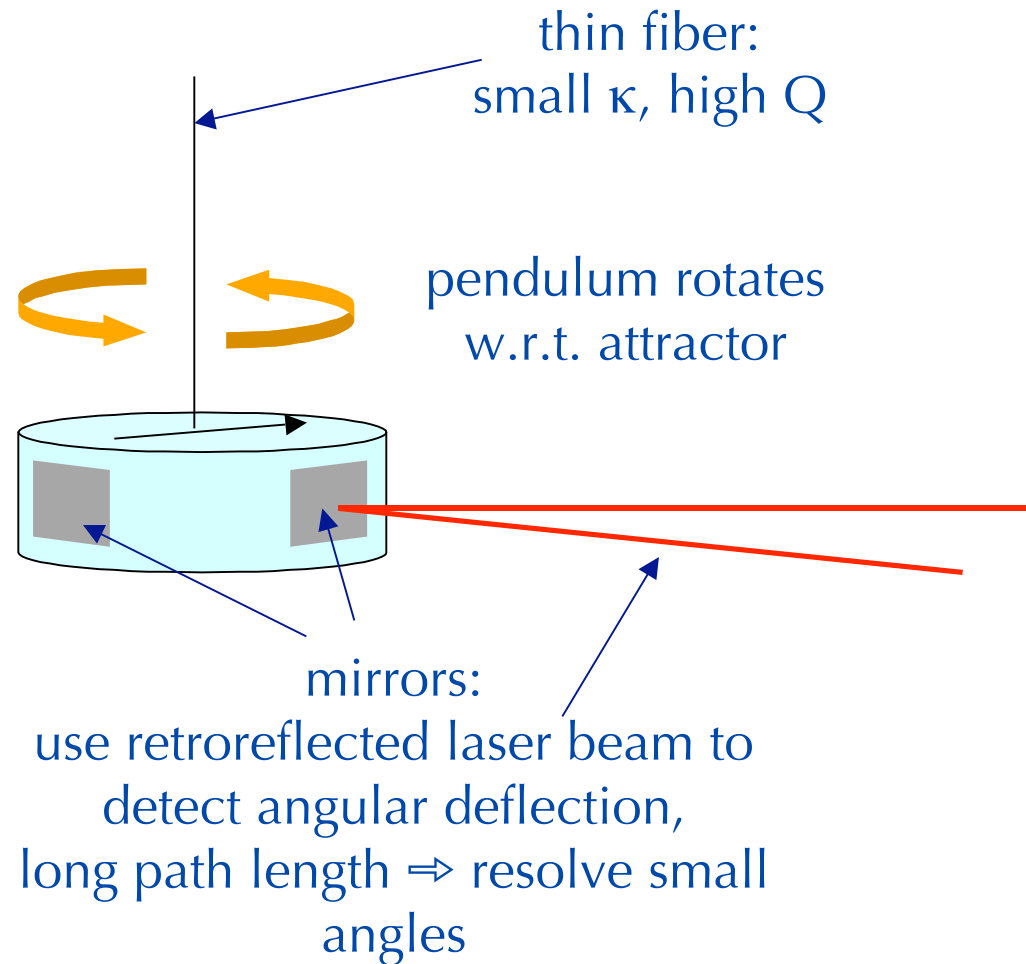


# The Electron Sector: Torsion Balance Experiments

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

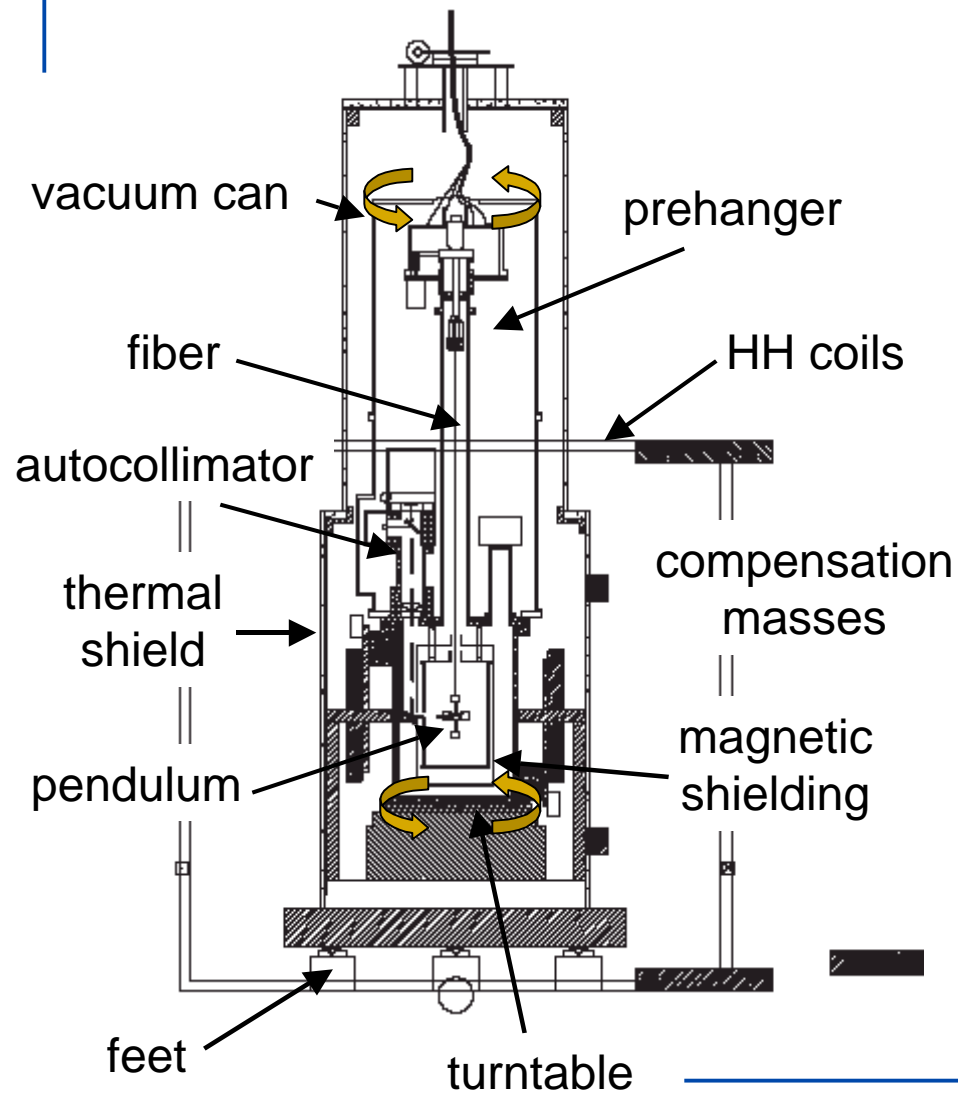
# A Generic Torsion Pendulum

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



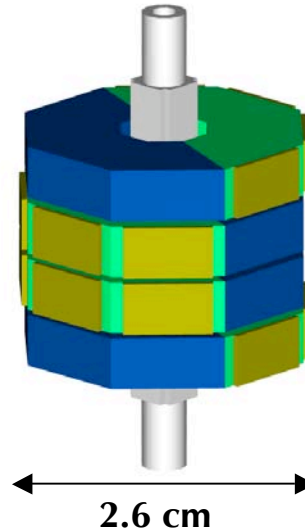
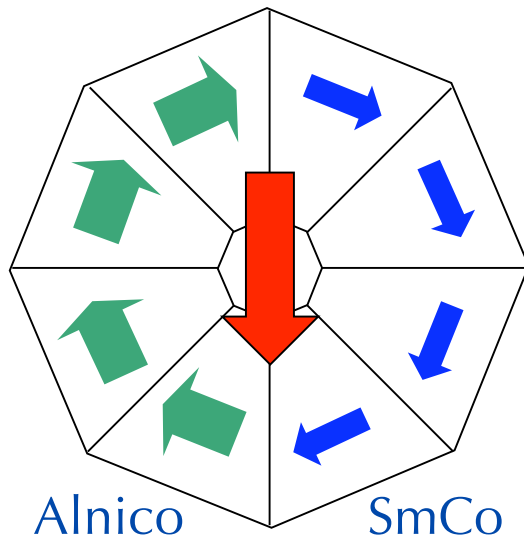


# The Torsion Balance Apparatus

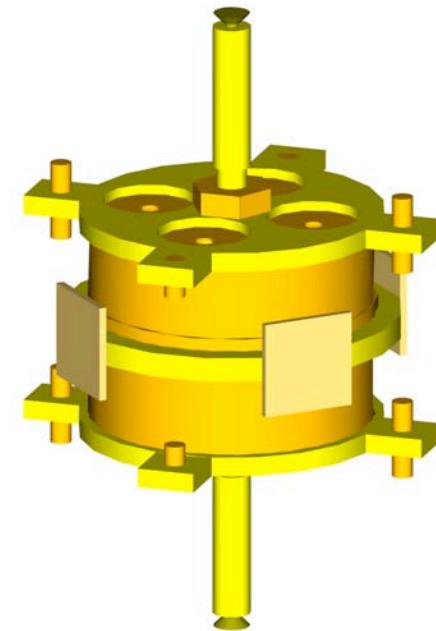


# The Spin Pendulum

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



- gold-plated
- magnetically shielded
- 4 mirrors



- minimal composition dipole
- negligible higher order gravitational moments

# The Gyrocompass Effect



The pendulum experiences a torque in the rotating frame:

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

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

# The Pendulum's Net Spin

Calculated Estimate:

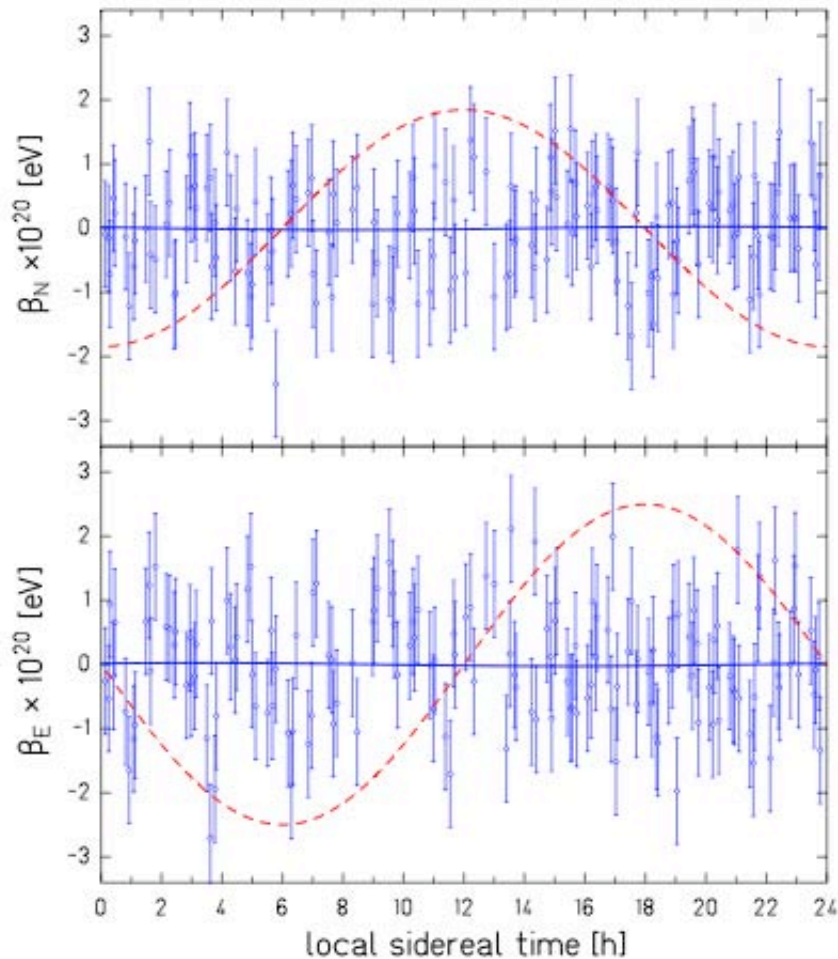
$$(9.7 \pm 2.7) \times 10^{22} \text{ spins}$$

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:

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

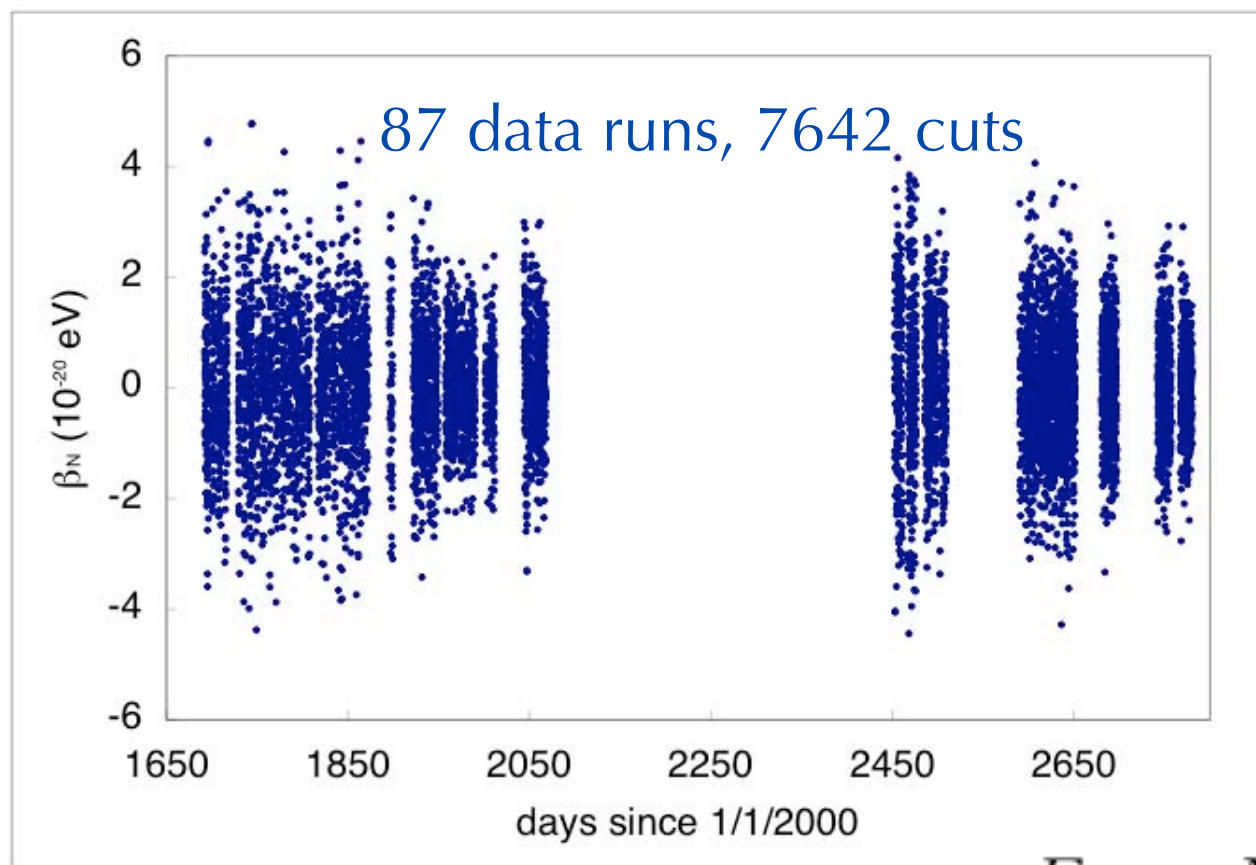
$$A_y = (-0.23 \pm 0.76) \times 10^{-21} \text{ eV}$$

hypothetical signal:

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

# Spin Pendulum Data Set

linear regression fit to global data set



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

# Torsion Pendulum Result

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

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

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

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



# The Proton Sector: Hydrogen Maser Experiments

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

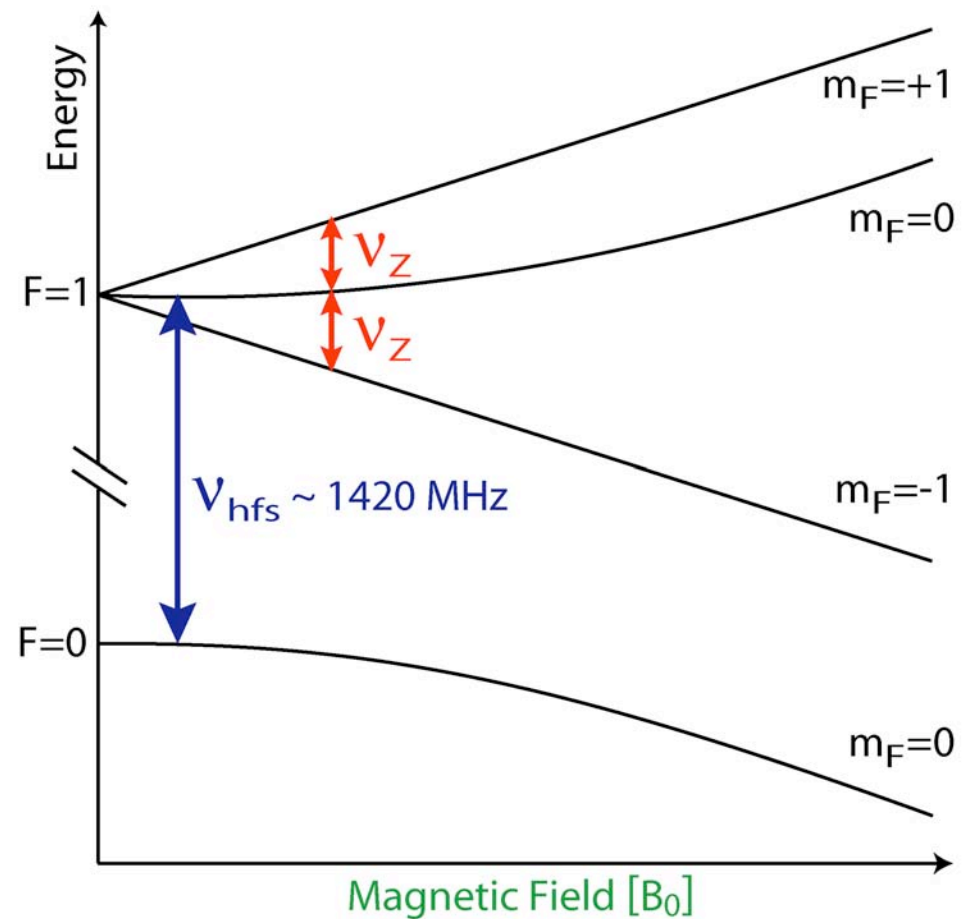


# Hydrogen Atom Transitions

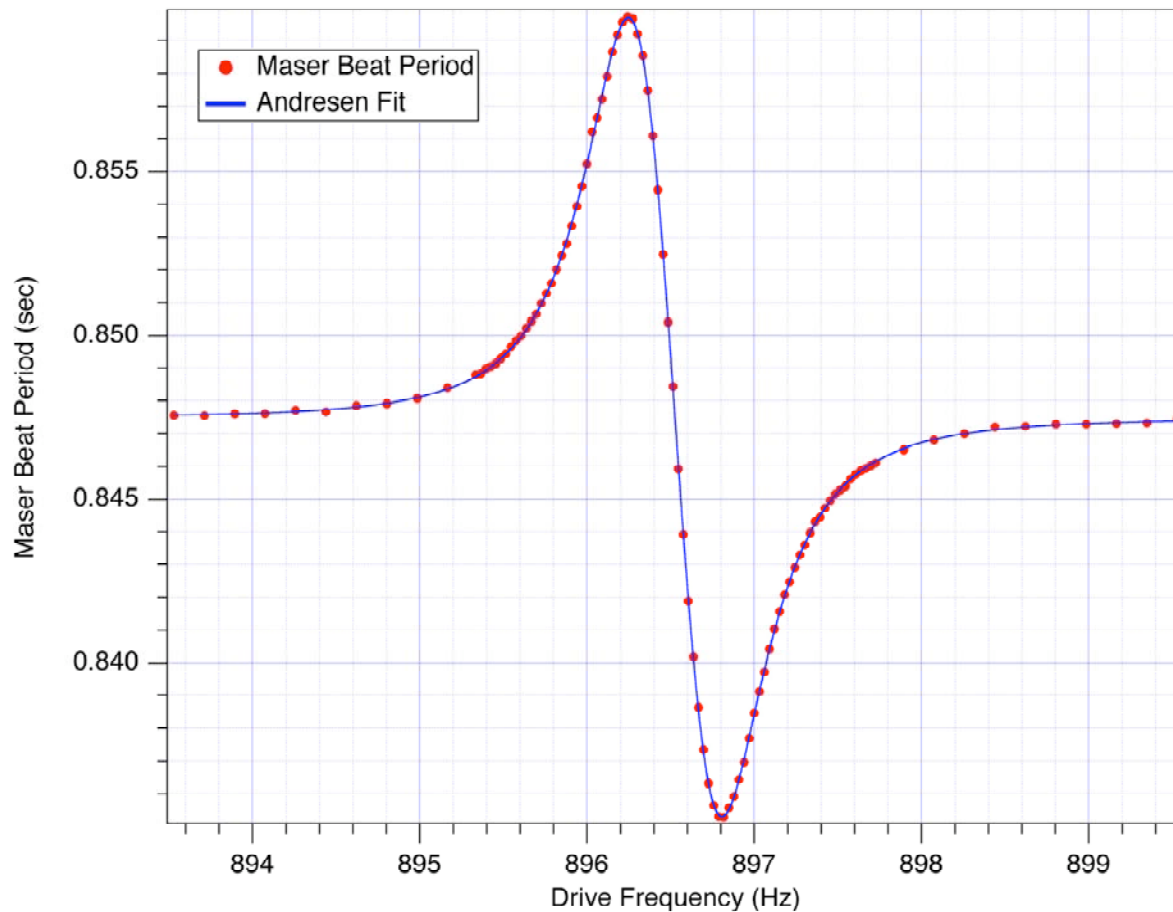
- Maser frequency ( $\nu_{\text{hfs}}$ ) insensitive to magnetic and spin-coupled interactions
- Fractional frequency stability  $< 10^{-14}$  for up to a few weeks

- Zeeman frequency ( $\nu_z$ ) sensitive to Lorentz violation

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

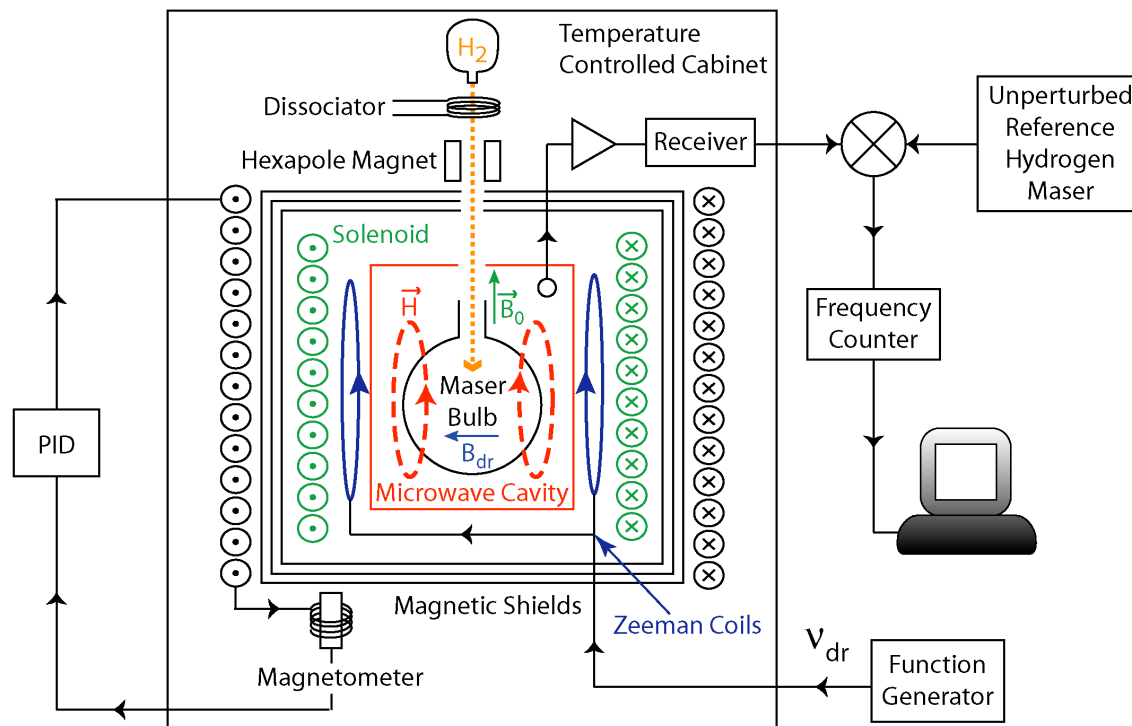


# Measuring the Zeeman Frequency



- Apply static field  $B_0$  to fix quantization axis,  $\nu_Z$
- 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  $\nu_{dr}$  through resonance, fit resulting lineshape

# Hydrogen Maser Apparatus

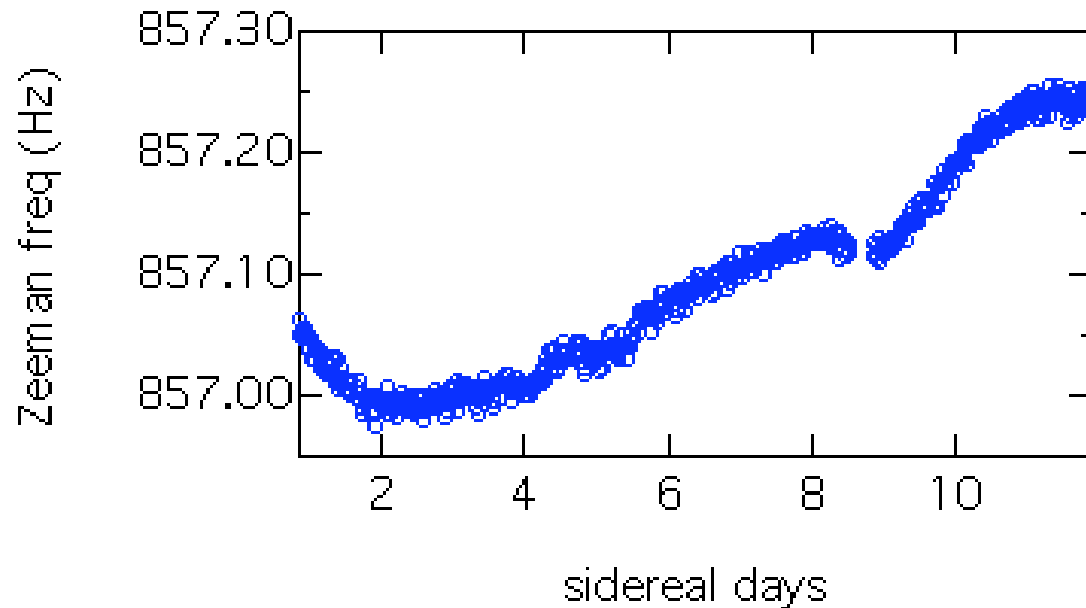


- hexapole magnet selects states for population inversion
- static 1 mG field defines quantization axis
- 4 layers of magnetic shielding
- active stabilization of solenoid current removed daily fluctuations in B-field
- referenced to unperturbed H-maser

# The Hydrogen Maser



# Hydrogen Maser Result



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

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

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

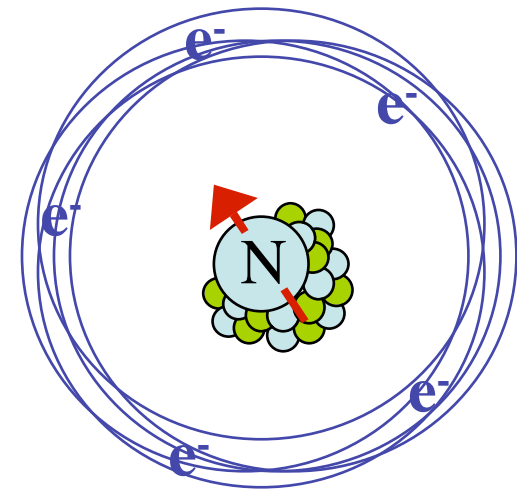


# The Neutron Sector: Dual-Species Maser Experiments

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

# $^3\text{He}$ and $^{129}\text{Xe}$ 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

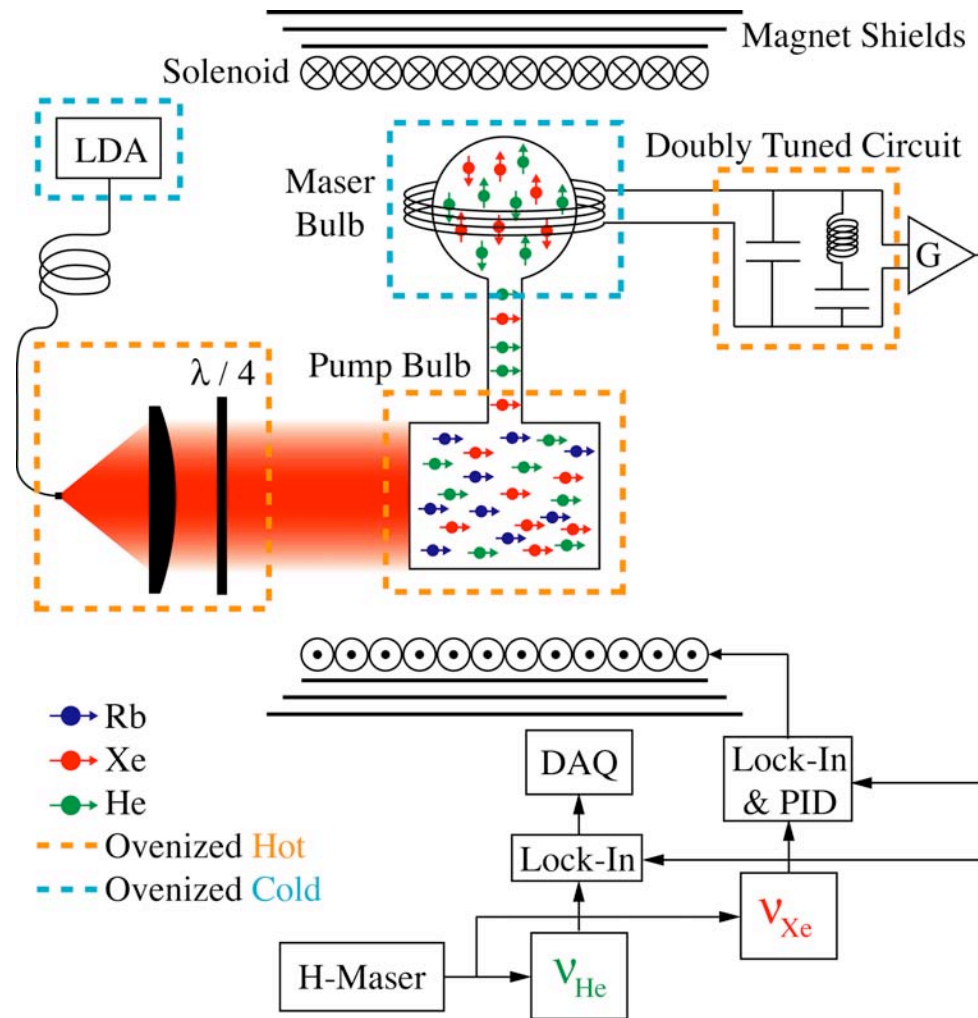
$$\omega_{He} = \underbrace{\frac{\gamma_{He}}{\gamma_{Xe}} \omega_{Xe}}_{\text{constant}} + \underbrace{\left(1 - \frac{\gamma_{He}}{\gamma_{Xe}}\right) \omega_{LV}}_{\text{varying sidereally}}$$

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

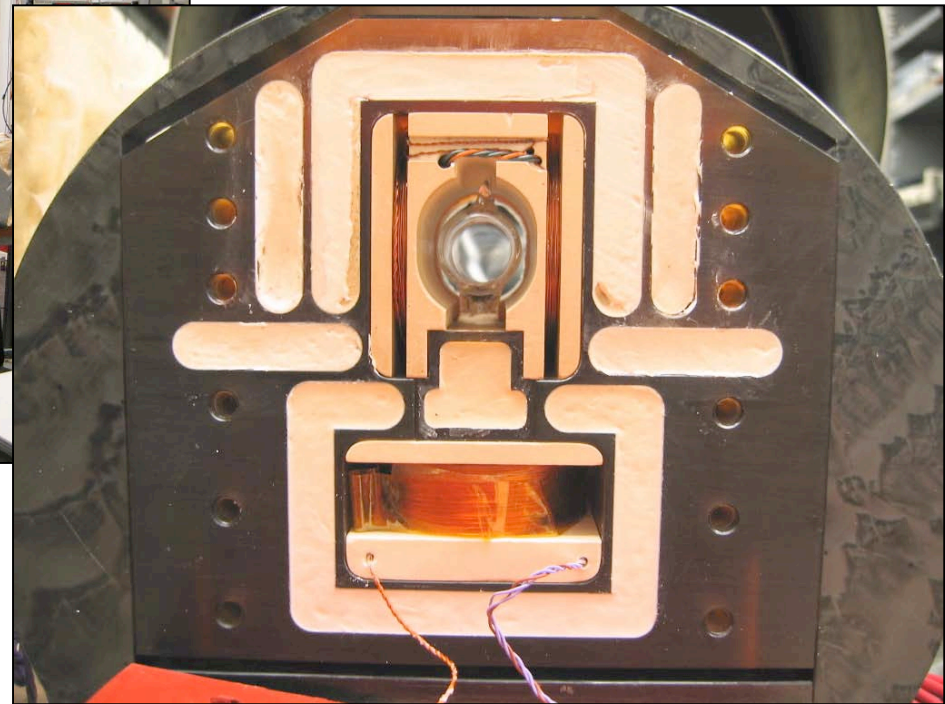
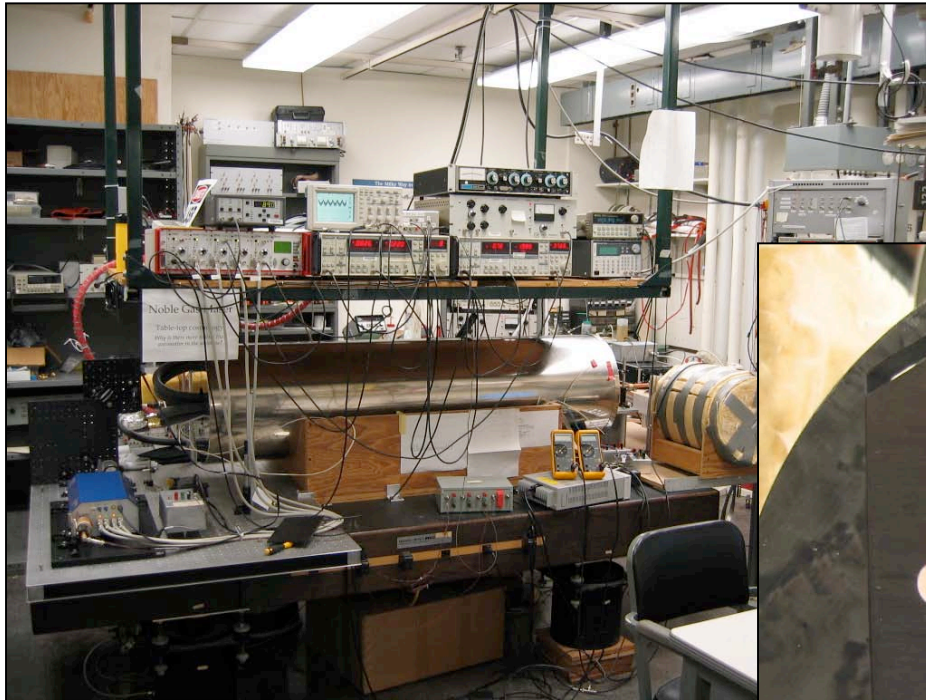


# Dual-Species Maser Apparatus

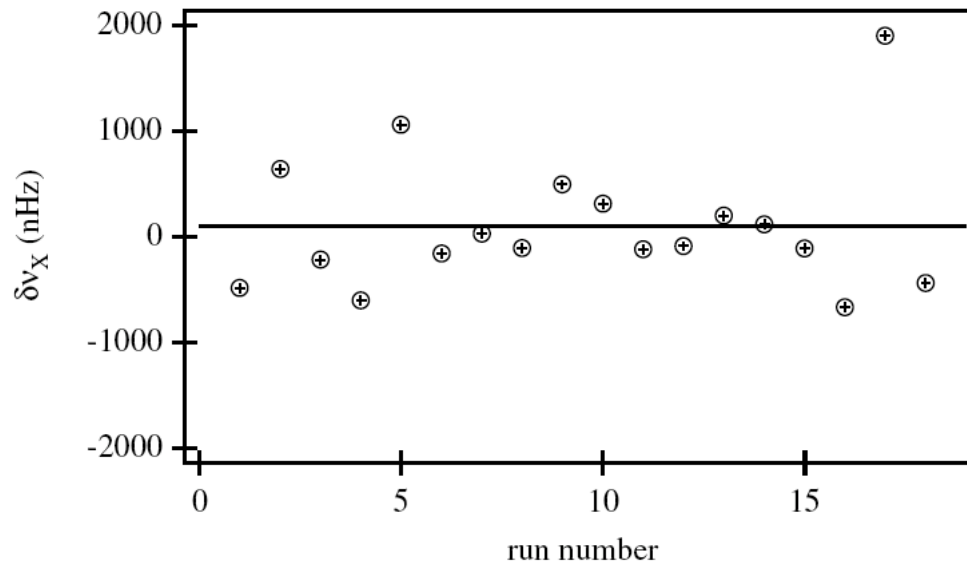
- Double-bulb glass cell
- 30-50 Torr of  $^{129}\text{Xe}$ ,
- 600 -1000 Torr of  $^3\text{He}$ ,
- 80 Torr of  $\text{N}_2$  (buffer gas)
- **Rb** metal
- $\sigma^+$  light, Rb  $D_1$  transition
- **$B_0 \approx 6 \text{ G}$**
- Field gradients  $\leq 30$  ppm/cm
- $\nu_{\text{Xe}}, \nu_{\text{He}} \approx 7, 20 \text{ kHz}$
- referenced to H-maser



# Dual-Species Maser Apparatus



# Dual-Species Maser Result

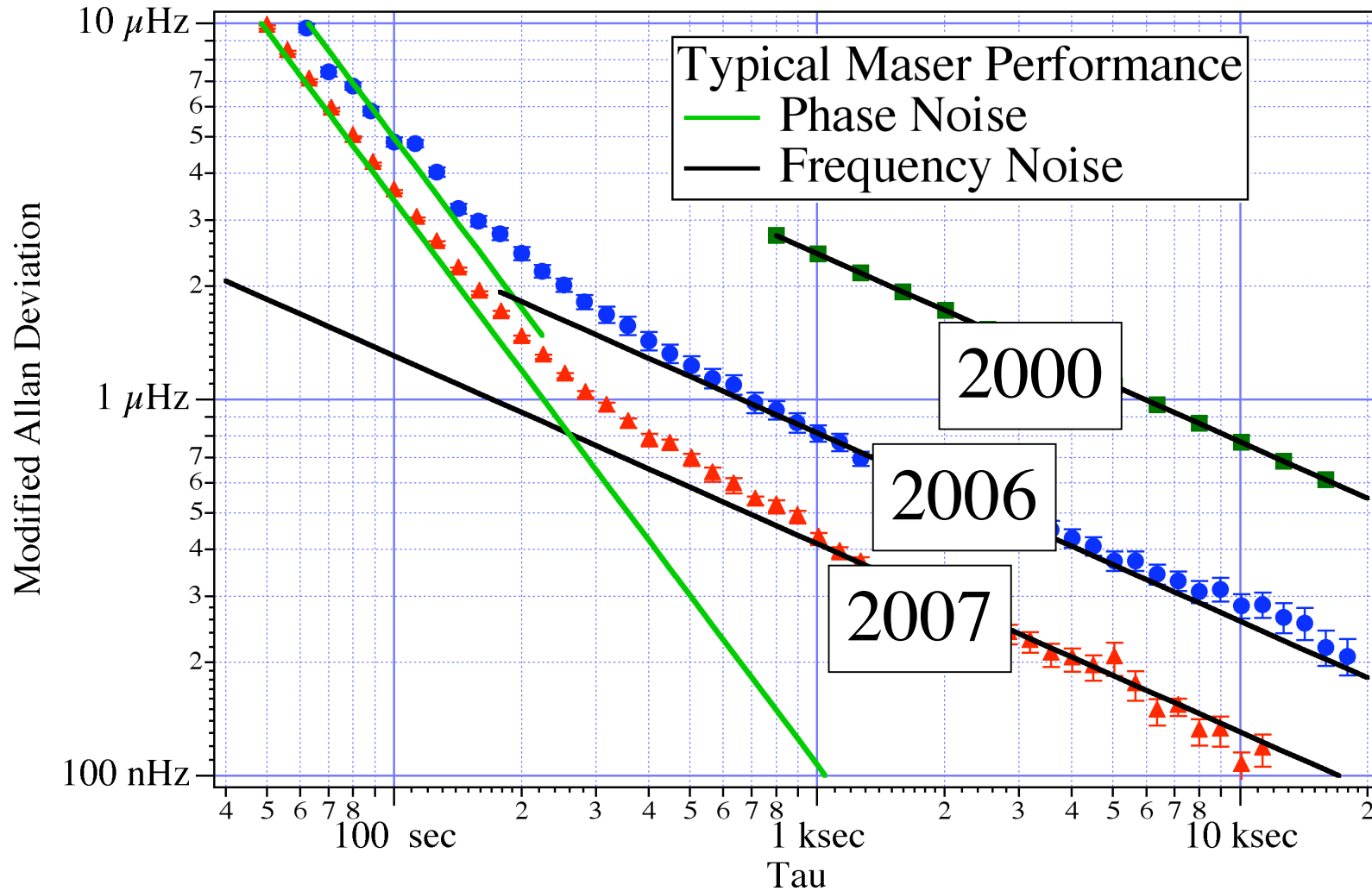


$$\tilde{b}^n = 6.4 \pm 5.4 \times 10^{-23} \text{ eV}$$

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

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

# Improved Maser Performance

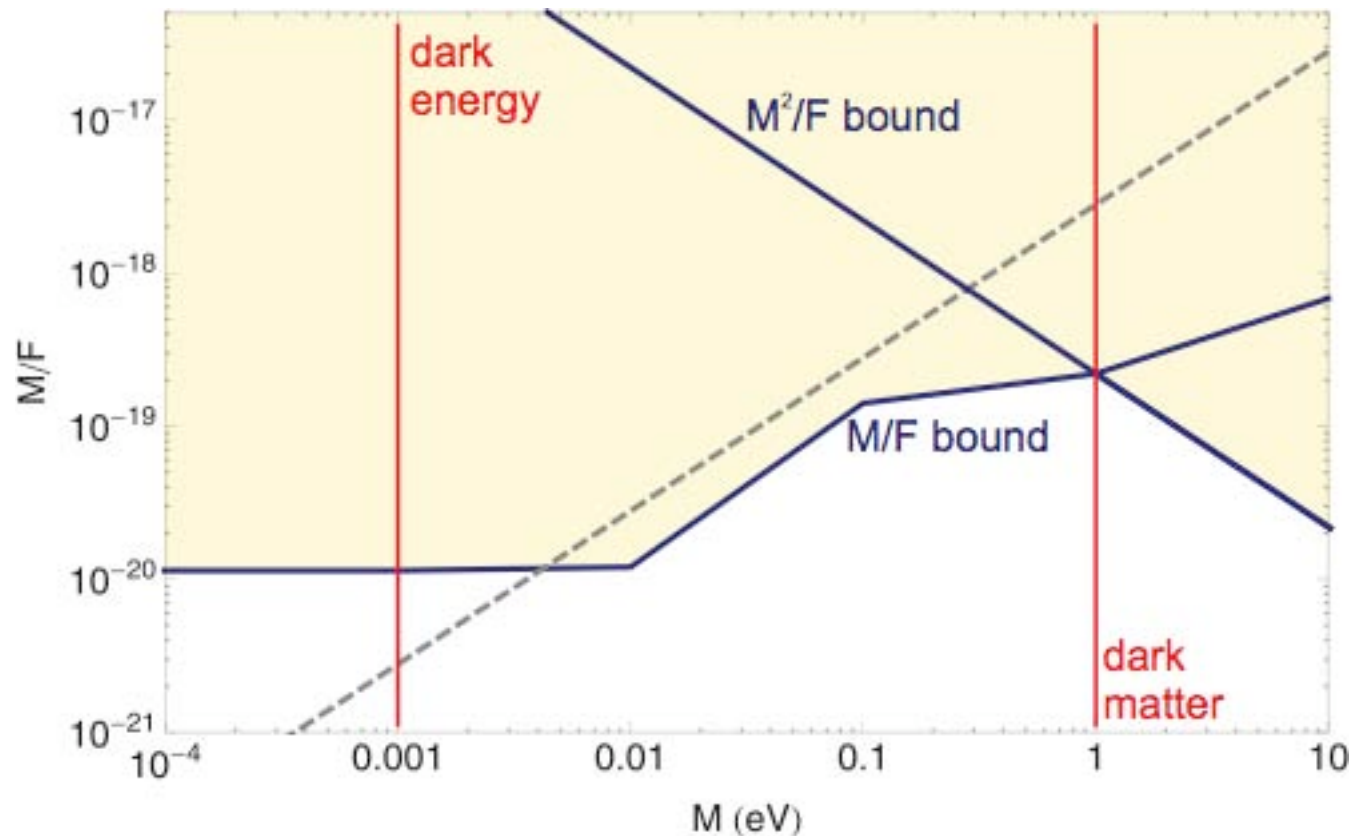


# Current Status of Lorentz/CPT measurements

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

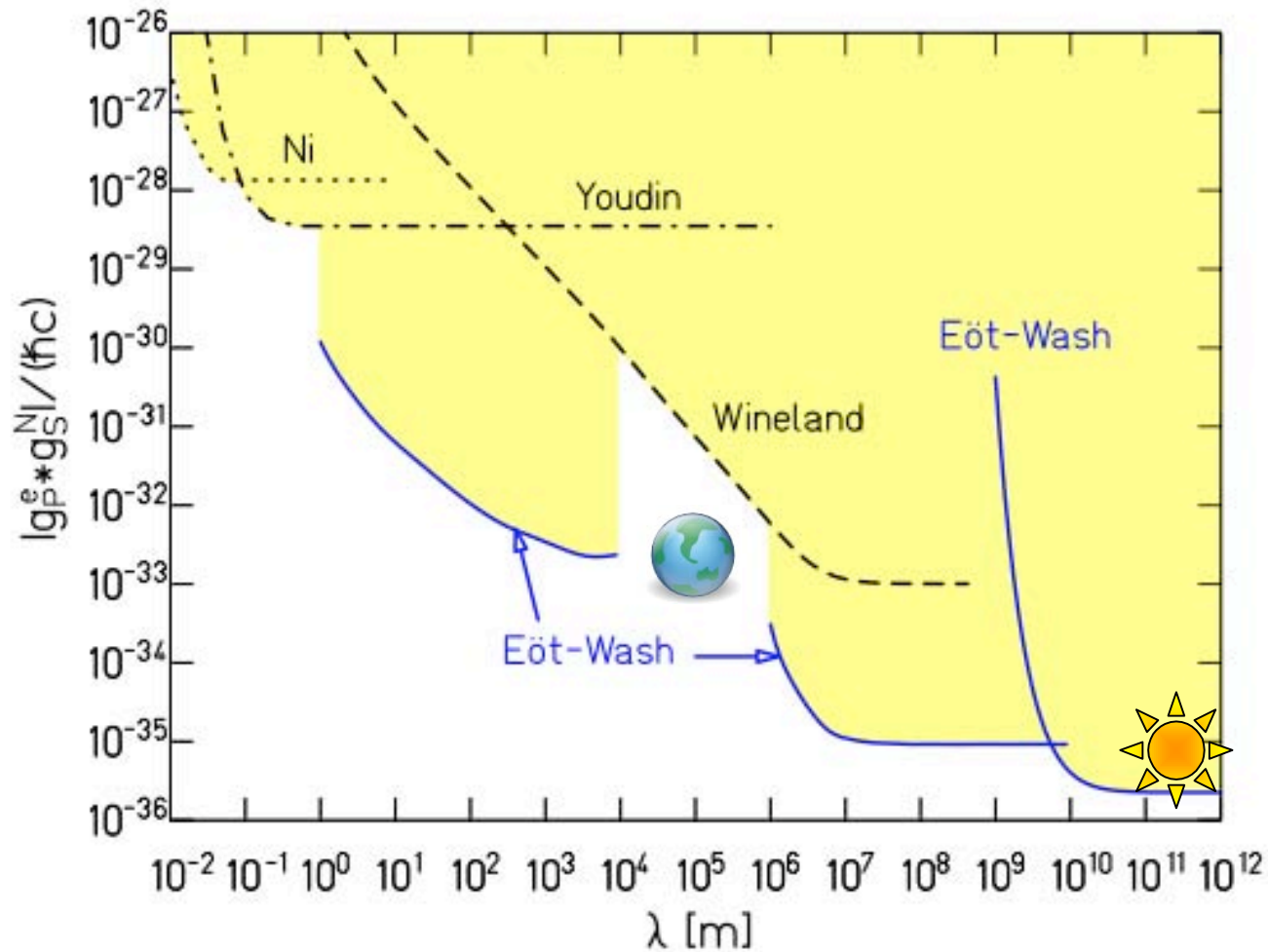
# Results: Ghost Condensate

95% confidence level exclusion limits



# Results: ALP monopole-dipole

95% confidence level exclusion limits



# Results: Low-Mass Boson Monopole-dipole Interactions

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

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

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

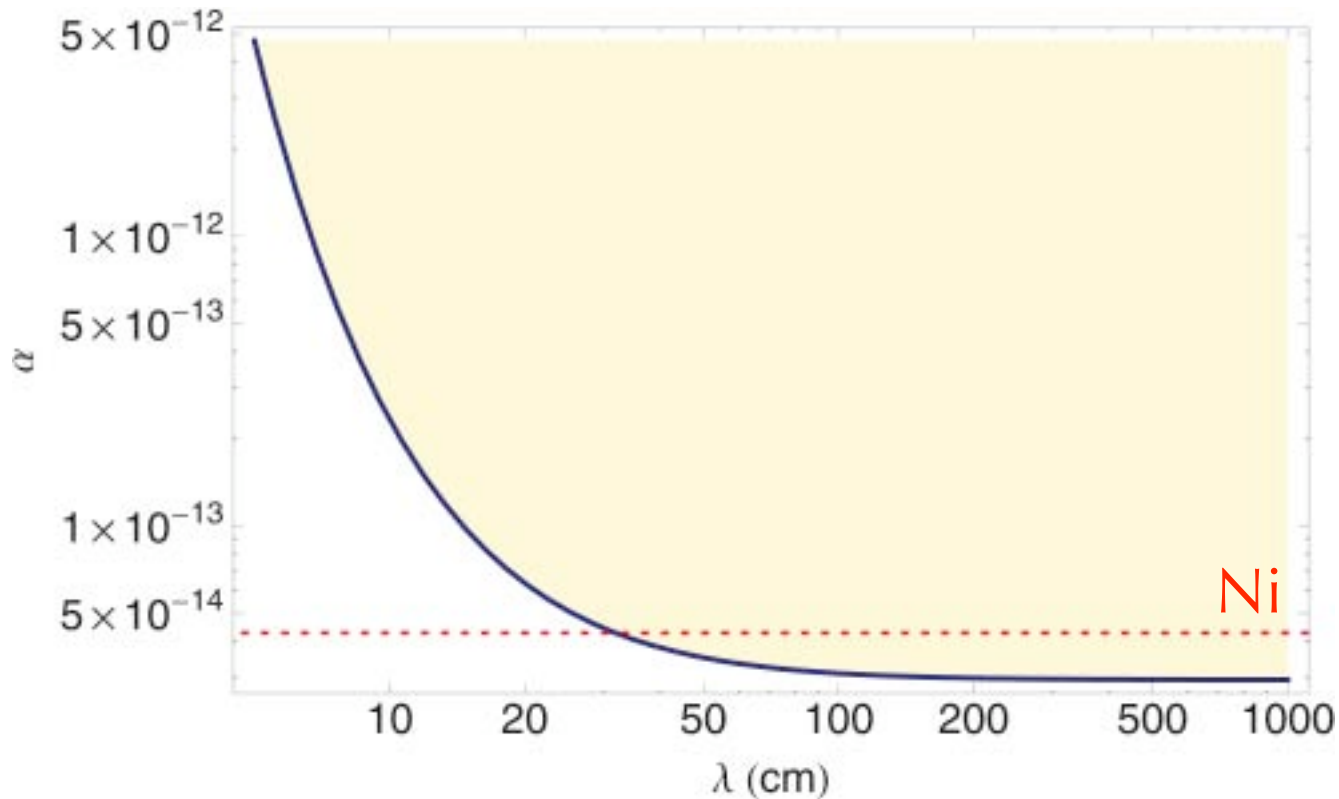
$$V(\vec{r}) = \frac{g_p g_s}{\hbar c} \frac{\hbar^2}{8\pi m_e c} (\sigma \cdot \hat{r}) \left( \frac{1}{r\lambda} + \frac{1}{r^2} \right) e^{-r/\lambda} \\ + \frac{f_v}{\hbar c} \frac{\hbar c}{8\pi} (\sigma \cdot \hat{v}) \frac{e^{-r/\lambda}}{r} + \frac{f_{\perp}}{\hbar c} \frac{\hbar^2}{8\pi m_e}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



# 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 . . .