Exotic spin-dependent interactions of electrons (and a bit about neutrons)

E. G. Adelberger
University of Washington

will discuss motivations, principles and results:

- polarized-electron test-body technology
- Plank-scale preferred-frame experiments
- non-commutative geometries
- spin-spin interactions of exotic bosons
- pseudo-Goldstone bosons and new global symmetries
- ultra-low-mass axion-like dark matter
- ultra-low-mass vector dark matter

A bit of history

In 1986 Blayne Heckel and I, motivated by Fischbach's "discovery' of a 5^{th} force, formed a small group and began developing instruments to probe sub-gravitational forces.

It was unexpectedly easy for us to demonstrate that Fischbach's 5^{th} force did not exist, and the experience suggested that excellent sensitivity to ultra-feeble interactions provided a way to probe lots of interesting issues. So, with NSF support, we continued to upgrade our torsion balance instruments and attained a powerful hammer we used for equivalence principle tests. We are grateful to our theory colleagues who continue to provide interesting nails for our hammers.

In the mid-nineties, motivated by the naïve idea of testing the symmetry properties of gravity we began developing electron-polarized test bodies.
I've been asked to discuss the results of the work based on that technology.

the Eöt-Wash® group

Faculty
- EGA
- Jens Gundlach
- Blayne Heckel

Current Grad students
- Kerkira Stockton
- John Lee
- Erik Shaw
- Will Terrano

Staff scientist
- Erik Swanson

Sabbatical Visitor
- Andy Kim

Postdocs
- Krishna Venkateswara (LIGO)
- Charlie Hagedorn

Current undergrad
- Michael Ross

EP
$1/r^2$
spin
technology

Primary support from NSF Gravitational Physics

our spin experiments exploit the properties of 2 different magnetic materials:

Alnico – a soft ferromagnet with high spin density:
magnetization comes from pairs of aligned electron spins

$SmCo_5$ – a hard ferromagnet with low spin density:
Sm magnetization has large spin and orbital angular contributions that essentially cancel

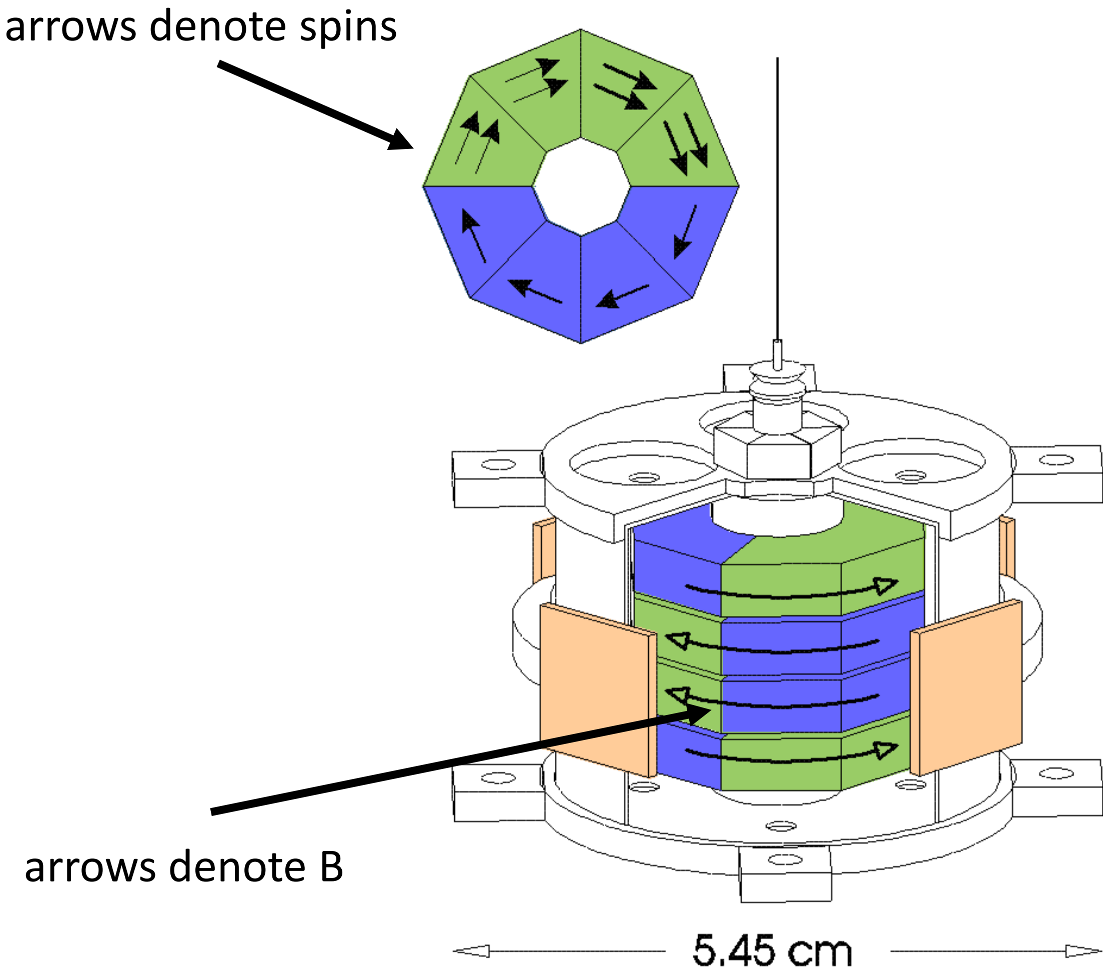
Simplified explanation for remarkable properties of $SmCo_5$:

The Sm in $SmCo_5$ crystal exists in a 3+ ionic state with 5 valence f electrons.
The repulsive e-e interaction forces the space function to be maximally antisymmetric.
m_L = (+3) + (+2) + (+1) + (0) + (-1) = 5 i.e. L=5

The spin function must be maximally symmetric i.e. S=5/2 .
Therefore the spin and orbital contributions to the $SmCo_5$ are equal.
Hund's Rule says that at beginning of a shell the two contributions cancel.

Hence the magnetic moment of $SmCo_5$ comes almost entirely from the 10 polarized Co electrons, but the total spin of $SmCo_5$ is only S=10-5=5, i.e. roughly ½ of that in a typical ferromagnet

the Eöt-Wash spin pendulum



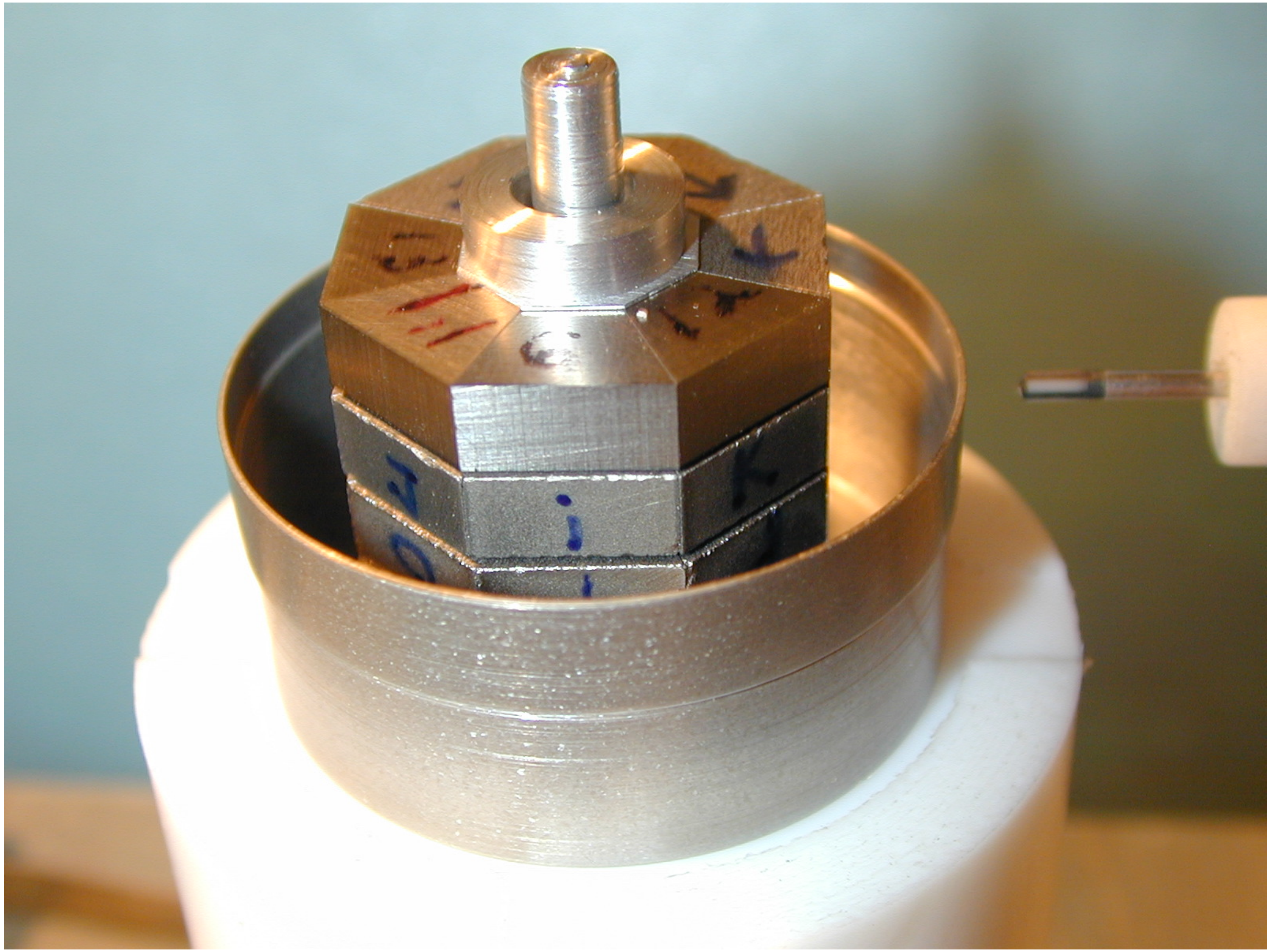
- 9.8×10^{22} polarized electrons
- negligible mass asymmetry
- negligible composition asymmetry
- flux of B confined within octagons
- negligible external B field

- Alnico: all B comes from electron spin: spins point opposite to B

- $SmCo_5$: Sm 3^+ ion spin points along total B and its spin B field is nearly canceled by its orbital B field--so B of $SmCo_5$ comes almost entirely from the Co's electron spins

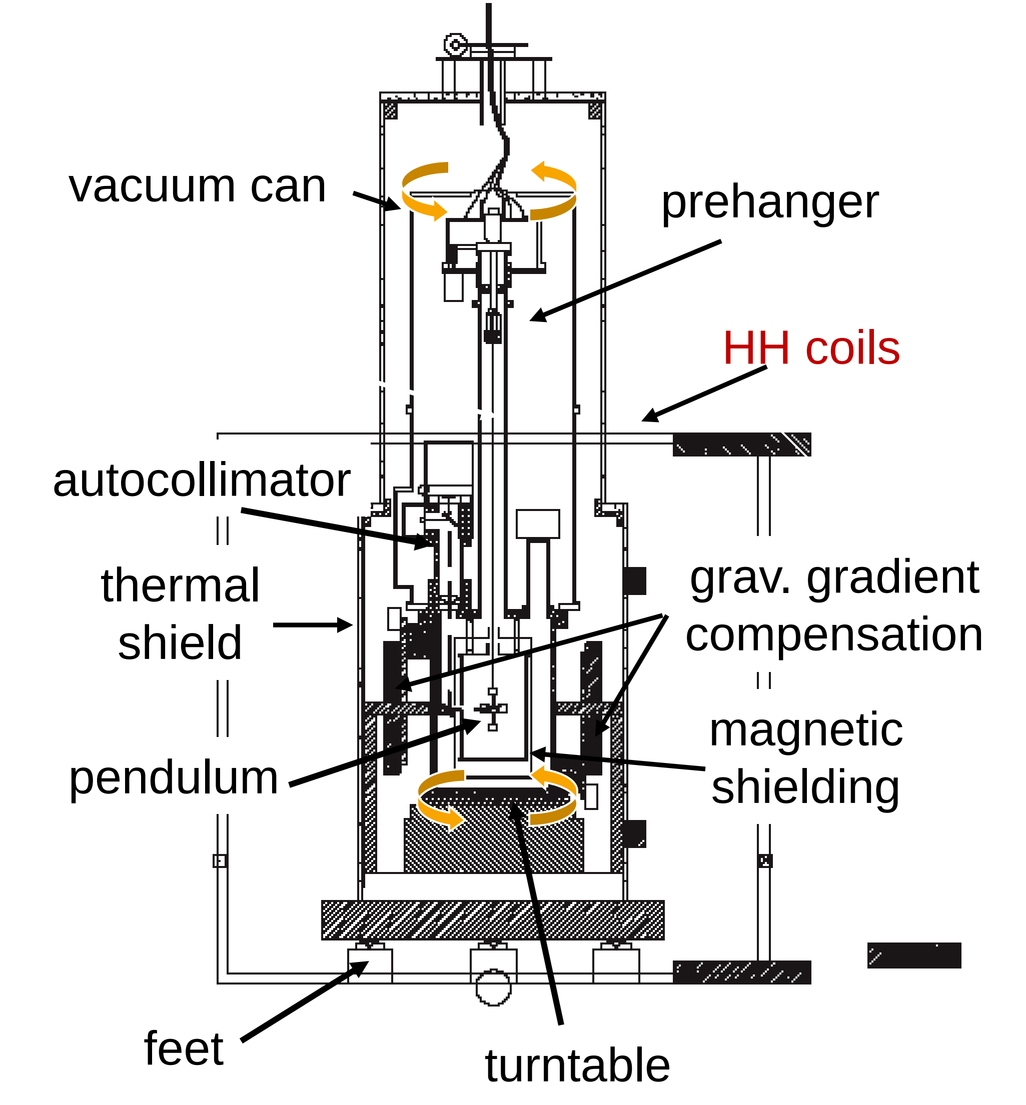
- therefore the spins of Alnico and Co form a closed loop and pendulum's net spin comes from the Sm. Because $B_{Sm} \propto 2S_{Sm} + L_{Sm} \approx 0$ we find
- $J_{Sm} = - S_{Sm}$

measuring the stray magnetic field of the spin pendulum



B inside = 9.6±0.2 kG B outside ≈ few mG

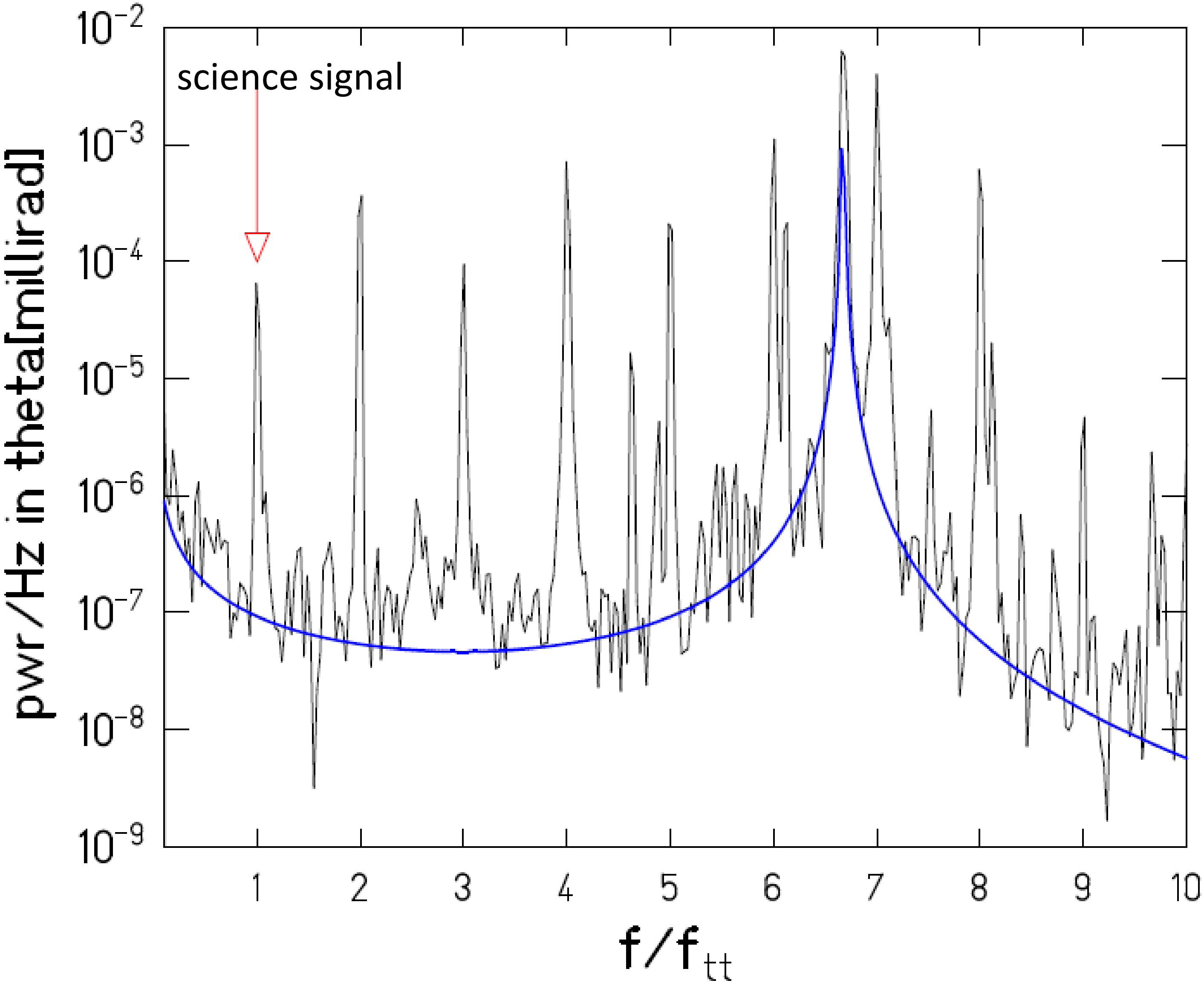
the Eöt-Wash rotating torsion balance

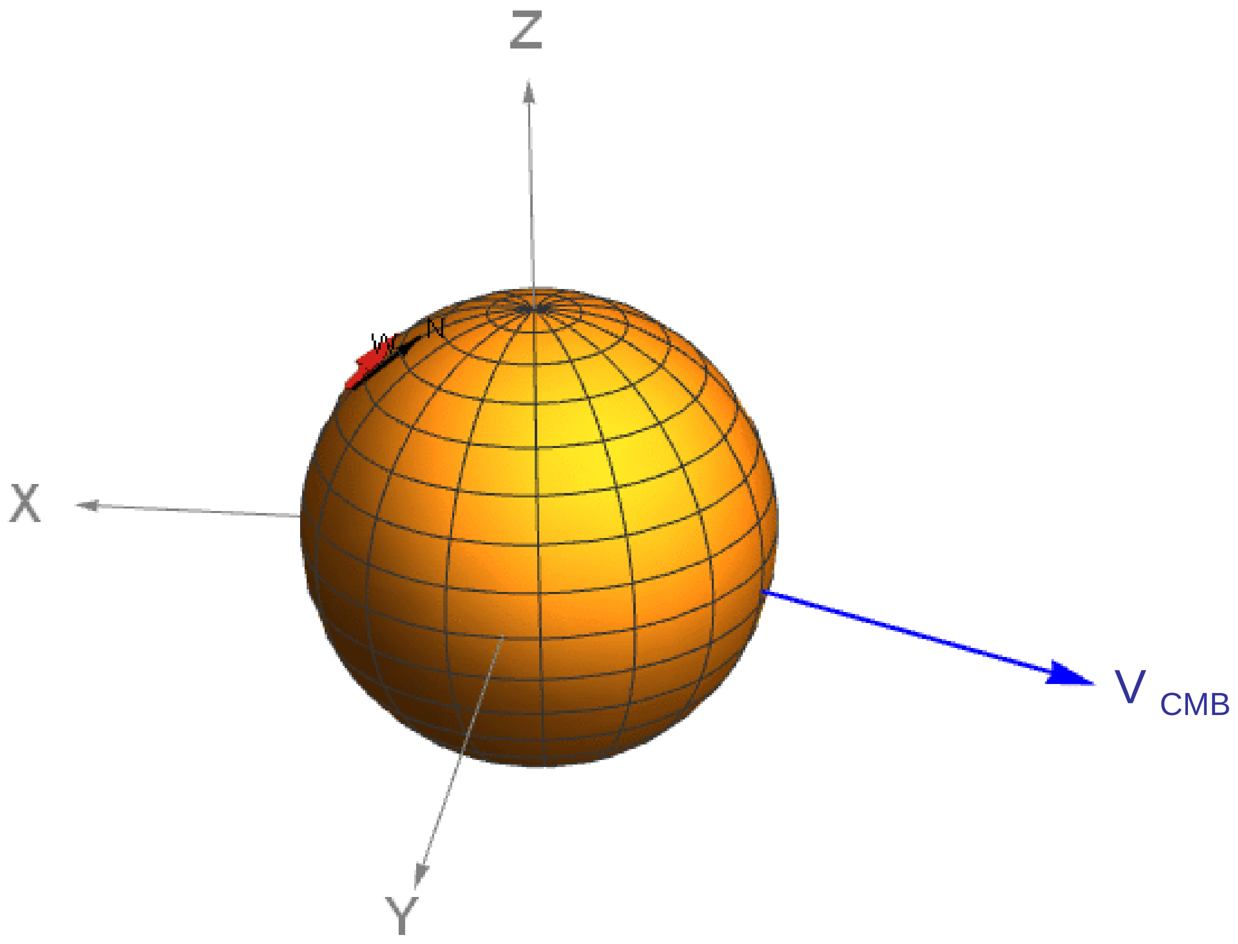


power spectrum of the spin-pendulum twist

Peaks at due to repeatable irregularities in the turntable rotation rate. Odd multiples are eliminated by combining data with two opposite orientations of the pendulum or by looking for astronomical modulation of the science signal.

Note that the noise background Is thermal.




Z
W
N
X
V CMB
Y

nail #1: cosmic preferred frames?

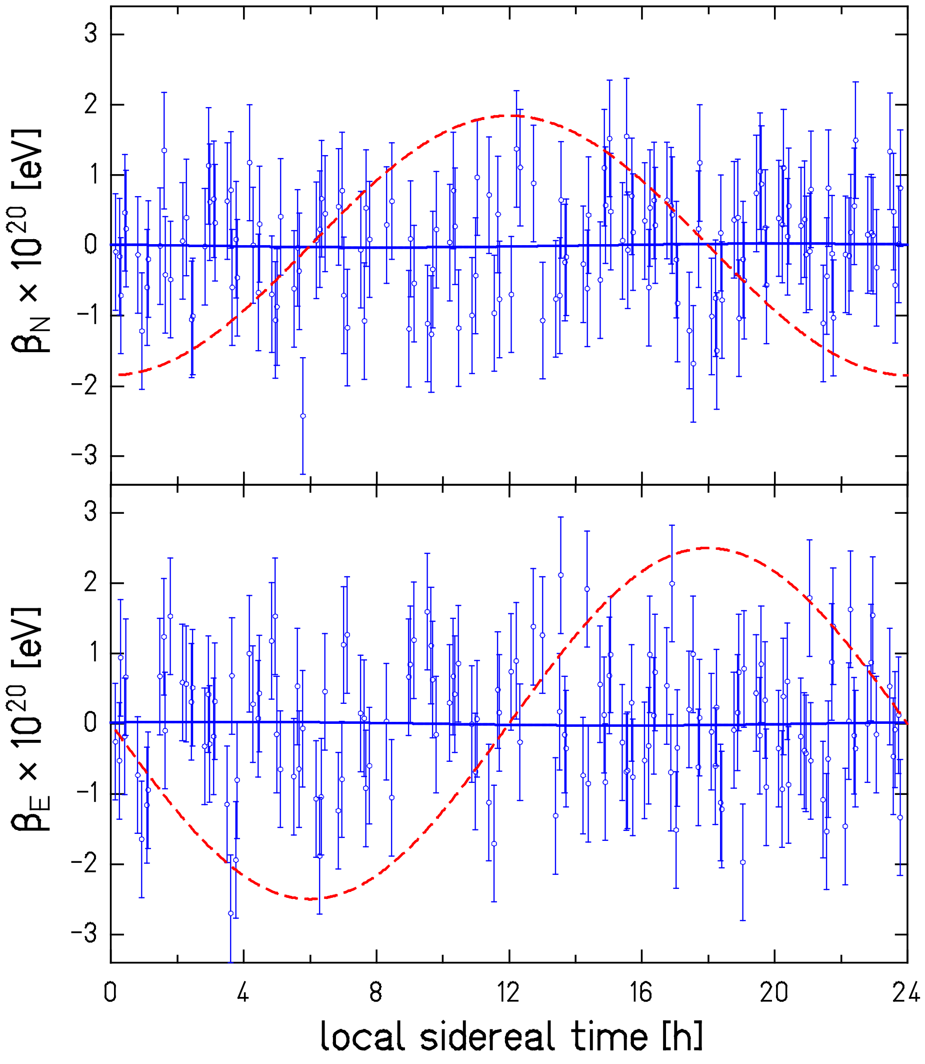
We all were taught that there are no preferred frames. But the Universe defines a frame in which the CMB is essentially isotropic. Could there be other preferred frame effects defined by the Universe?

Kostelecky et al. developed a scenario where vector and axial-vector fields were spontaneously generated in the early universe and then inflated to enormous extents;

Particles couple to these preferred-frame fields in Lorentz-invariant manners.

This “Standard Model Extension” predicts lots of new observables many of which violate CPT. One such observable is $E = \sigma_e \cdot \tilde{b}_e$ where $\tilde{b}_e$ is fixed in inertial space - its benchmark value is $m_e^2 / M_{\mathbf{Planck}} \approx 2 \times 10^{-17}$ eV

spin-pendulum data span a period of 36 months
a 113 hour stretch is shown below



definition of **β:**

$E_{pend} = -N_p\, \boldsymbol{\beta \cdot \sigma}$

2ß=energy needed to flip a spin

- - - - - -

simulated signal from assumed $b_x = 2.5 \times 10^{-20}$ eV

———

best fit out-of-phase sine waves--corresponds to preferred-frame signal:

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

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

The gyrocompass

Anschütz's gyrocompass.

Anschuetz-Kaempfe and Sperry separately patented gyrocompasses in UK and US. In 1915 Einstein ruled that Anschütz's patent was valid.

conventional gyrocompass

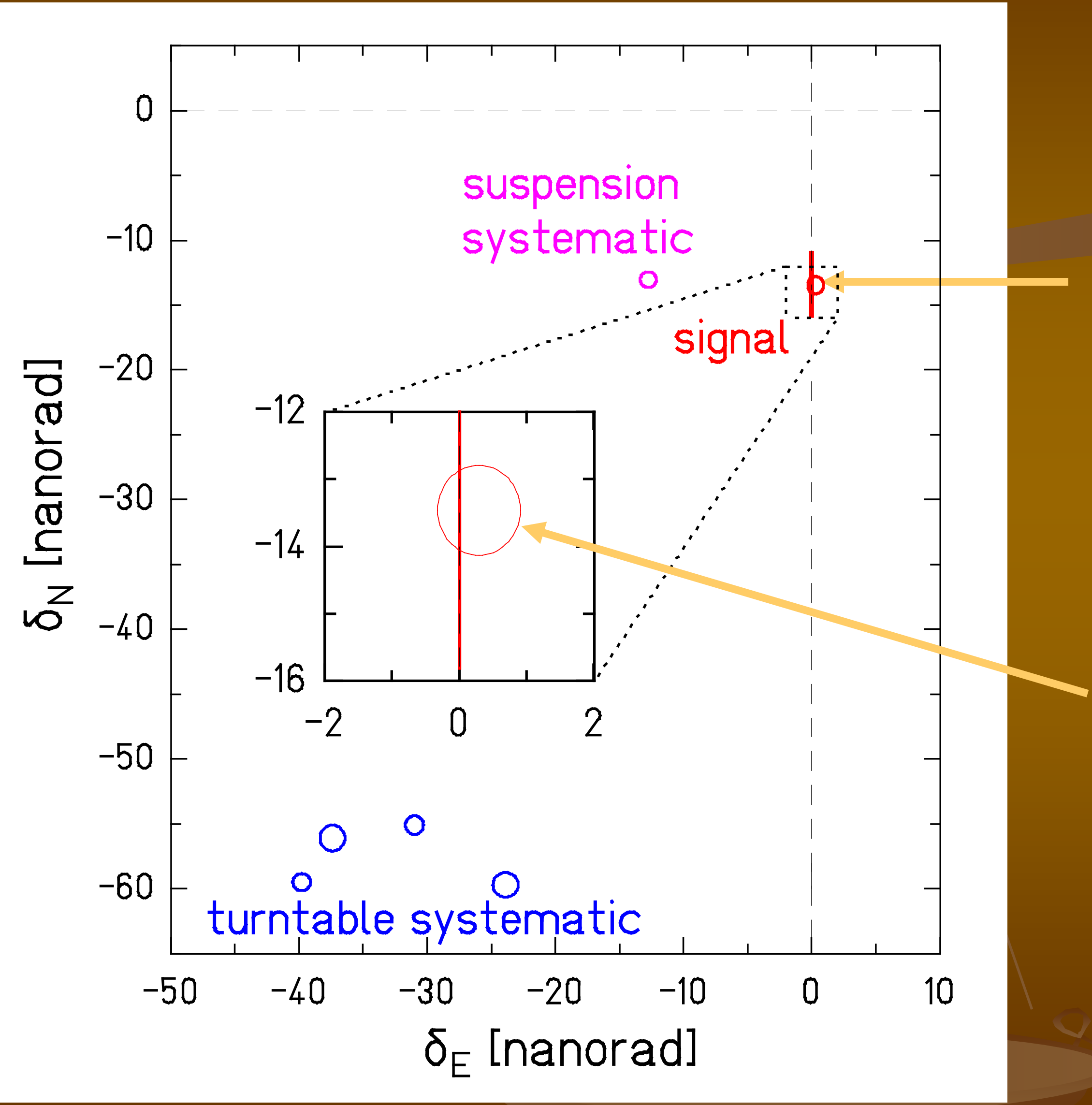
angular momentum J of a spinning flywheel in a lossy gimbal will eventually point true North where the gimbals do not dissipate energy

our gyrocompass.

Earth's rotation Ω acting on J of pendulum produces a steady torque along suspension fiber

$| \Omega \times J \cdot n |$ where n is unit vector along local vertical. Because $S = -J$ this is equivalent to $\beta_N = -1.616 \times 10^{-20}$ eV

lab-fixed spin pendulum signal



gyrocompass effect:
The vertical bar shows expected effect based on 2 previous discordant measurements of $SmCo_5$ spin density

The ellipse shows our result when we use the Coriolis effect to calibrate the spin density

Lorentz-symmetry violating rotation parameters is there a preferred direction in space?

$$E = \sigma_e \cdot \tilde{b}_e$$

TABLE IX: 1σ constraints on the Lorentz-symmetry violating $\tilde{b}^e$ parameters. Units are 10^{-22} eV.

parameter	electron	proton	neutron
	our work		
$\tilde{b}_X$	-0.67 ± 1.31	$\lesssim 2 \times 10^4$	0.22 ± 0.79
$\tilde{b}_Y$	-0.18 ± 1.32	$\lesssim 2 \times 10^4$	0.80 ± 0.95
$\tilde{b}_Z$	-4 ± 44		

Cane et al, PRL 93(2004) 230801

Phillips et al, PRD 63(2001) 111101

These should be compared to the benchmark value $m_e^2/M_{\rm Planck} = 2 \times 10^{-17}$ eV.

Lorentz-symmetry violating boost parameter
Is there a preferred helicity in space?

$$V = -B\boldsymbol{\sigma} \cdot \boldsymbol{v}/c\ ,$$

where $\boldsymbol{v}$ is the velocity of the spin with respect to the CMB rest-frame.

Our 1 sigma spin-pendulum result

$$B = (+0.50 \pm 1.13) \times 10^{-19}\ \mathrm{eV}$$

an amusing number

- our upper limit on the energy required to invert an electron spin about an arbitrary axis fixed in inertial space is ~10^{-22} eV
- this is comparable to the electrostatic energy of two electrons separated by ~ 90 astronomical units

nail #2: non-commutative space-time geometry?

string theorists have suggested that the space-time coordinates may not commute, i.e. that

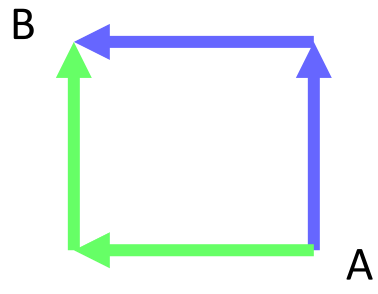
$$[\widehat{x}_\mu, \widehat{x}_\nu] = i\theta_{\mu\nu}$$

where Θ_{ij} has units of area and represents the mimimum observable patch of area, just as the commutator of x and p_x represents the minimum observable product of $\Delta x \, \Delta p_x$

"Review of the Phenomenology of Noncommutative Geometry"
I. Hinchliffe, N Kersting and Y.L. Ma
hep-ph/0205040

effect of non-commutative geometry on a point-like spin

non-commutative geometry is equivalent to a “pseudo-magnetic” field and thus couples to spins



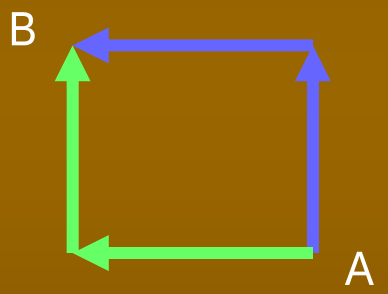
$$\mathcal{L}_{eff} = \frac{3}{4} m \Lambda^2 \left(\frac{e^2}{16\pi^2} \right)^2 \theta^{\mu\nu} \overline{\psi} \sigma_{\mu\nu} \psi$$

Anisimov, Dine, Banks and Graesser
Phys Rev D 65, 085032 (2002)

Λ is a cutoff which is assumed to be 1TeV for electrons

effect of non-commutative geometry on spin

$$\mathcal{L}_{eff} = \frac{3}{4} m\Lambda^2 \left(\frac{e^2}{16\pi^2}\right)^2 \theta^{\mu\nu}\overline{\psi}\sigma_{\mu\nu}\psi$$



Λ is a cutoff assumed to be 1TeV
Anisimov, Dine, Banks and Graesser
hep-ph/2010039

minimum observable patch of area implied by our results

$$|\theta^{\mu\nu}| \approx 6 \times 10^{-58}\ \mathrm{m}^2$$

6×10^{-58} m^2 seems very small
and indeed it is

but in another sense it is also quite large
6×10^{-58} m^2 $\sim$ $(10^6\ L_P)^2$
where L_P is the Planck Length
$\sqrt{(\hbar G/c^3)} = 1.6 \times 10^{-35}$ m

or $\sim$ $(10^3\ L_U)^2$
where L_U is the Grand Unification length
$L_U = \hbar c\ /10^{16}$ GeV

but $10^{\mathbf{13}}$ GeV is pretty good for a table-top result

nail #3: spin-spin exchange potentials mediated by ultra-low mass vector bosons?

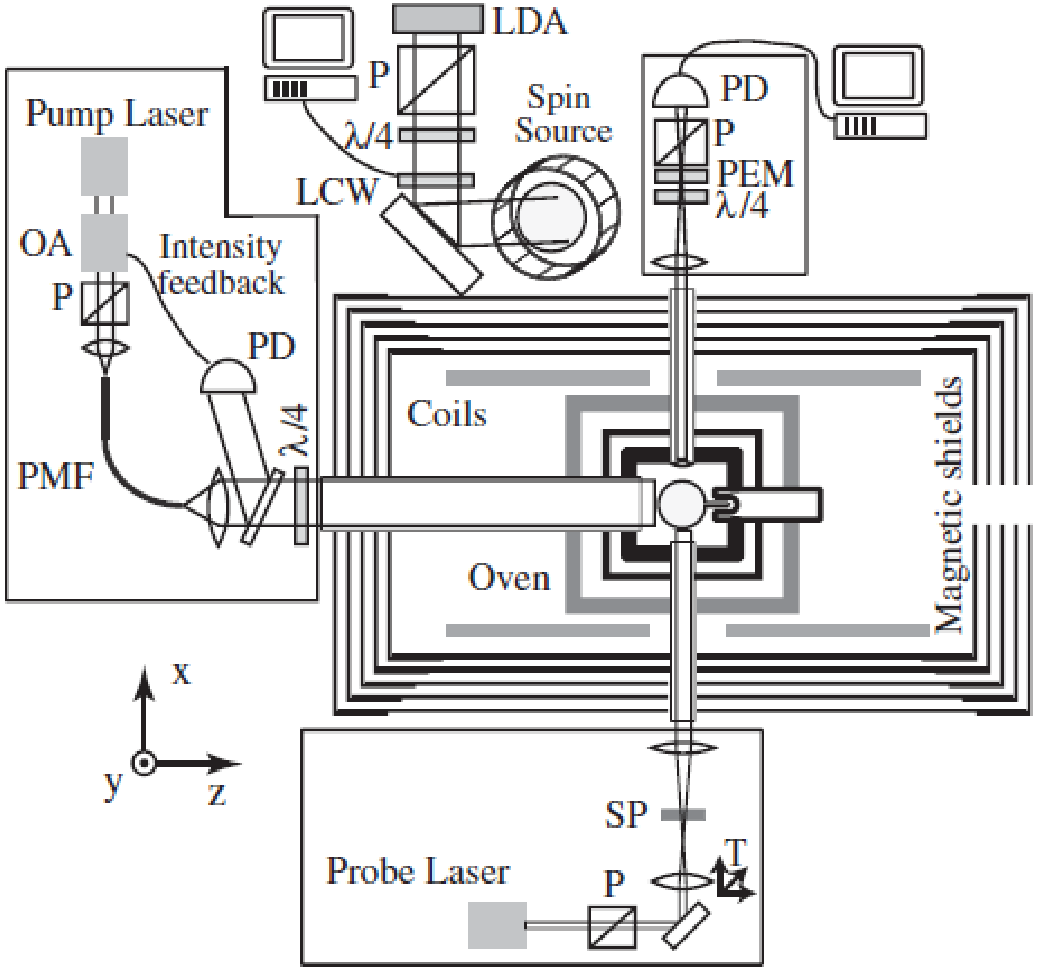
$$V_1 = \frac{g_A^2}{4\pi r}(\hat{\boldsymbol{\sigma}}_1 \cdot \hat{\boldsymbol{\sigma}}_2)e^{-r/\lambda}$$

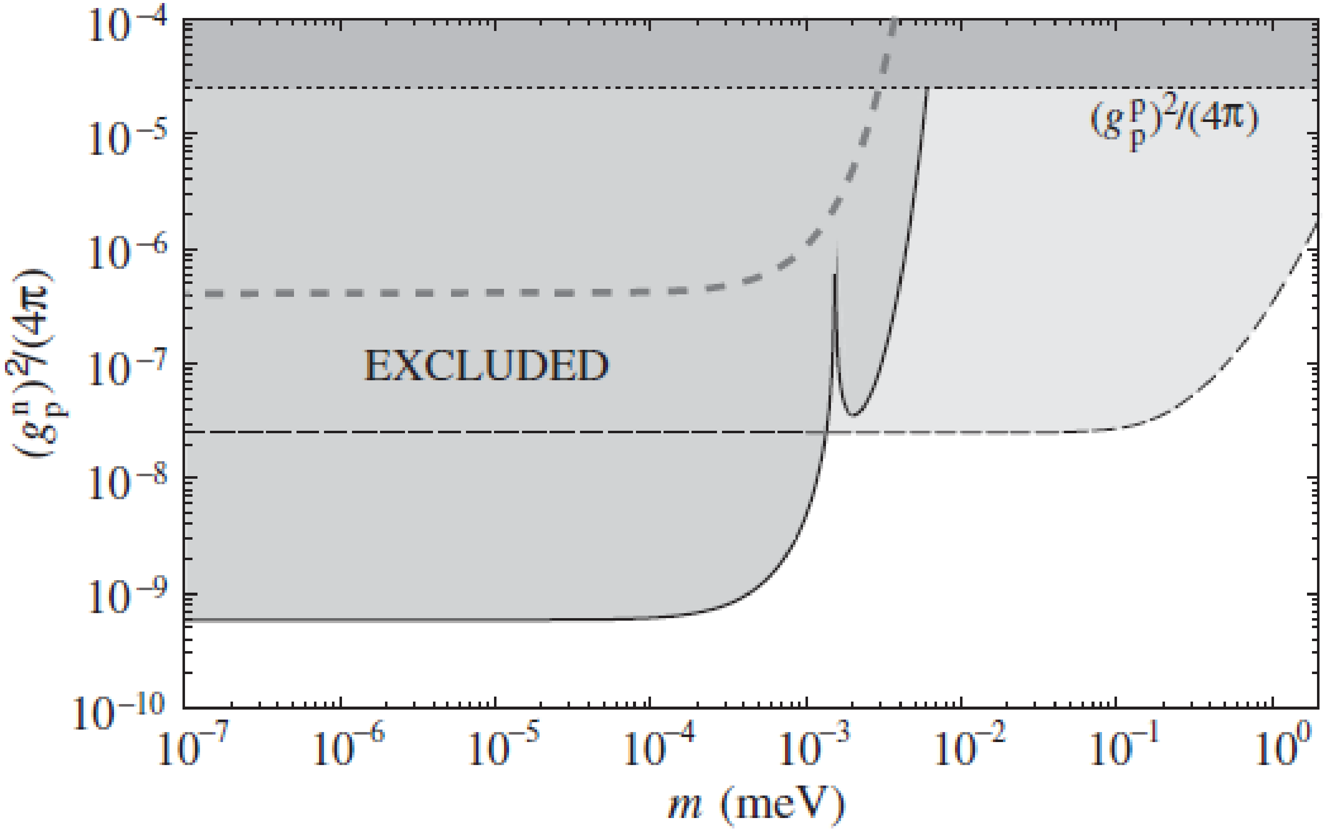
$$V_2 = -\frac{g_A g_V \hbar}{4\pi m_e c r^2}(\hat{\boldsymbol{\sigma}}_1 \times \hat{\boldsymbol{\sigma}}_2 \cdot \hat{\boldsymbol{r}}) \left(1 + \frac{r}{\lambda}\right) e^{-r/\lambda}$$

$$V_3 = -\frac{(g_A^2 + g_V^2)\hbar^2}{16\pi m_e^2 c^2 r^3}\left[(\hat{\boldsymbol{\sigma}}_1 \cdot \hat{\boldsymbol{\sigma}}_2)\left(1 + \frac{r}{\lambda}\right) - (\hat{\boldsymbol{\sigma}}_1 \cdot \hat{\boldsymbol{r}})(\hat{\boldsymbol{\sigma}}_2 \cdot \hat{\boldsymbol{r}})\left(3 + \frac{3r}{\lambda} + \frac{r^2}{\lambda^2}\right)\right] e^{-r/\lambda}$$

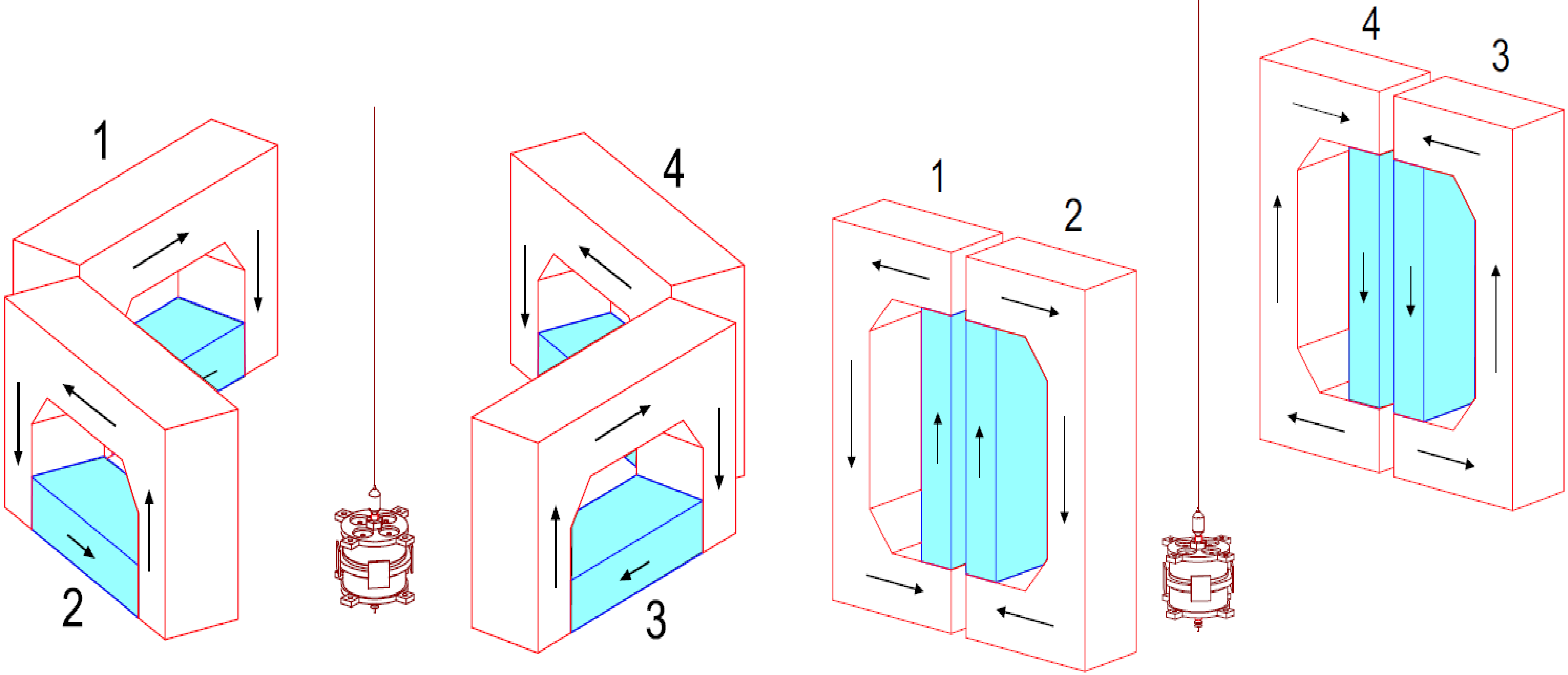
Princeton study of V1, V2 & V_3 interactions of neutrons (actually ^3He) using spin exchange with optically pumped alkalis

G. Vasilakis et al. PRL 103,261801 (2009)





We probed V1, V2 and V3 interactions by surrounding the rotating spin pendulum with stationary spin sources



Shaded bars are SmCo5, return yokes are iron

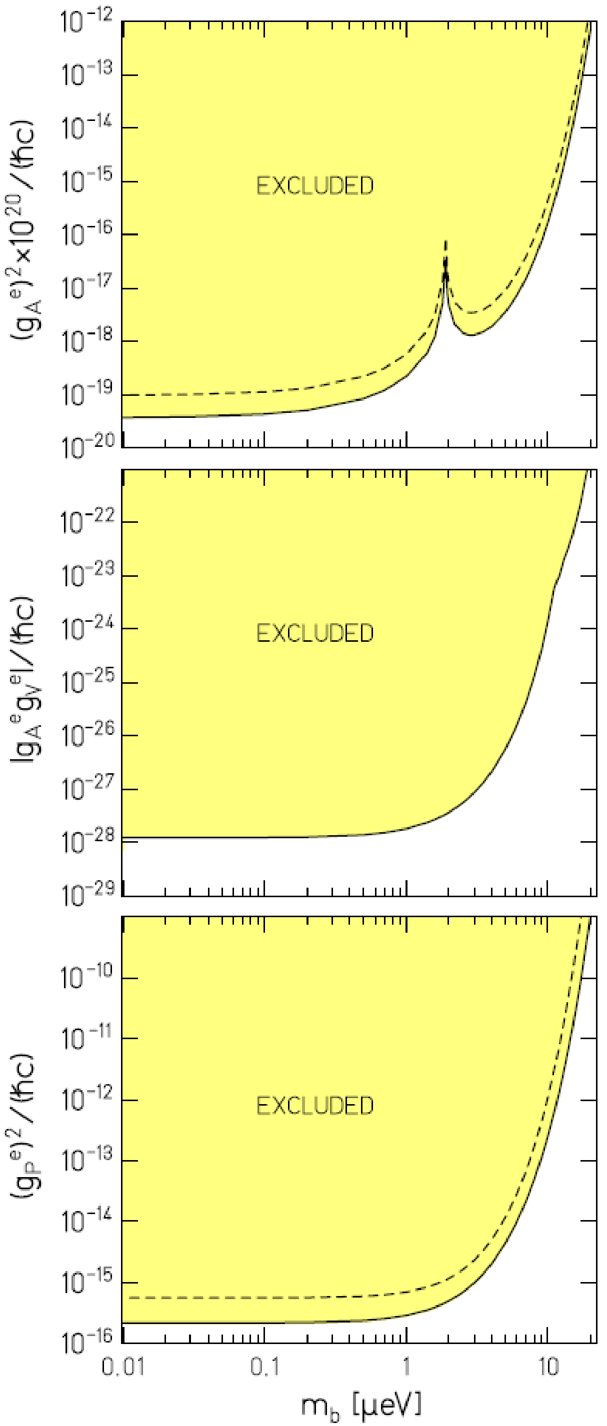


TABLE II. 68.5% confidence bounds on coupling to electrons of bosons with $m_b \leq 0.1$ μeV.

Potential	Coupling	Value: e (this work)	Value: n (Ref. [9])
V_1	$g_A^2/(\hbar c)$	$(-1.6 \pm 3.5) \times 10^{-40}$	1.5×10^{-40}
V_2	$g_A g_V/(\hbar c)$	$(9.2 \pm 6.5) \times 10^{-29}$	4.9×10^{-25}
V_3	$g_P^2/(\hbar c)$	$(-1.0 \pm 1.9) \times 10^{-16}$	7.3×10^{-9}

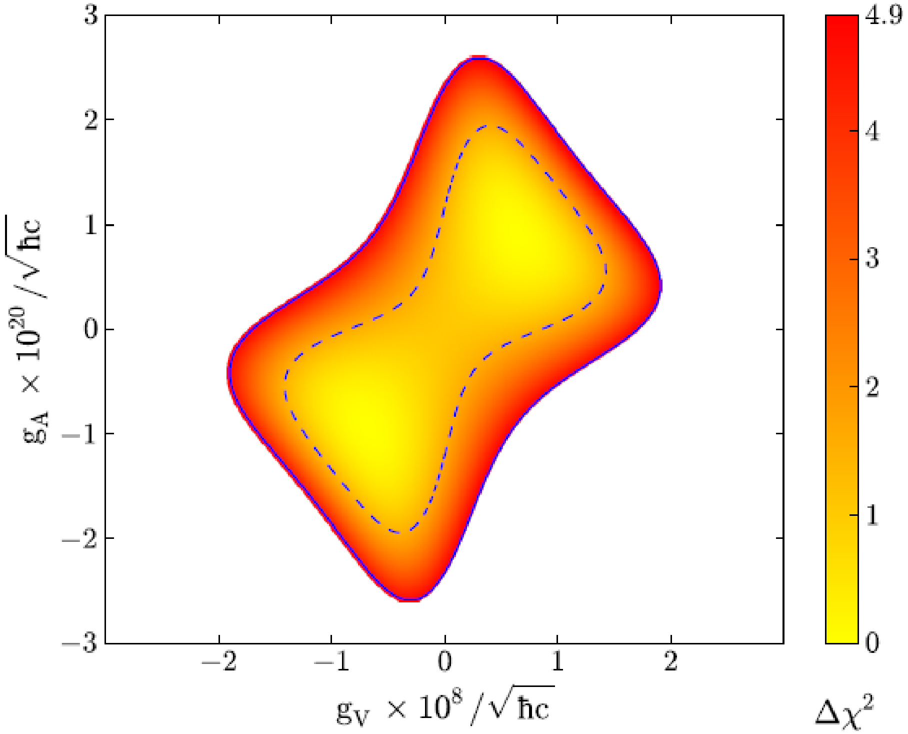


FIG. 5 (color online). Constraints on axial and vector couplings g_A^e and g_V^e of spin-1 bosons with mass less than 0.1 μeV. The solid and dashed contours correspond to 68.5% and 95.3% confidence levels determined from 10 000 simulated data sets.

nail #4: new spontaneously-broken symmetries?

Spontaneously broken global symmetries always generate massless pseudoscalar Goldstone bosons that couple to fermions with $g_p = m_f/F$ where F is the symmetry-breaking energy scale.

If the symmetry is explicitly broken as well the resulting pseudo Goldstone bosons acquire a mass $m_b = \frac{\Lambda^2}{F}$.

Sensitive searches for the fermionic interactions of these bosons can probe for new hidden symmetries broken at very high scales.

familiar example of a pseudo-Goldstone boson (pGb):
the pion from spontaneous breaking of chiral symmetry

Speculations about additional pGb's:

- axions
- familons
- majorons
- closed-string axions
- accidental pGb's

see A. Ringwald, arXiv:1407.0546 for a nice review

forces mediated by pseudoscalar boson exchange are purely spin-dependent

$$V_{\rm dd} = \frac{g_p^2 \hbar^2}{16\pi m_e^2 c^2 r^3}\left[(\hat{\boldsymbol{\sigma}}_1 \cdot \hat{\boldsymbol{\sigma}}_2)\left(1 + \frac{r}{\lambda}\right) - 3(\hat{\boldsymbol{\sigma}}_1 \cdot \hat{\boldsymbol{r}})(\hat{\boldsymbol{\sigma}}_2 \cdot \hat{\boldsymbol{r}})\left(1 + \frac{r}{\lambda} + \frac{r^2}{3\lambda^2}\right)\right] e^{-r/\lambda}$$

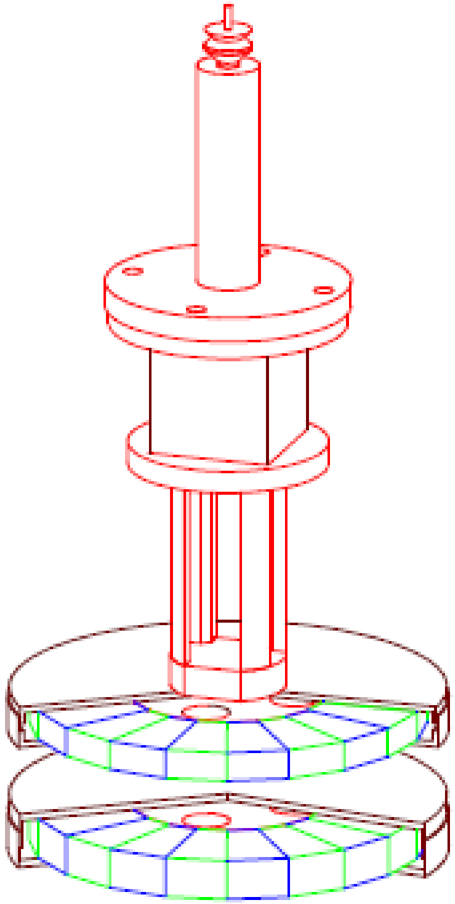
$$\lambda = \hbar/(m_b c).$$

If the boson also has a scalar coupling g_s (cf axion or axion-like particle ALP) a CP-violating interaction is also generated

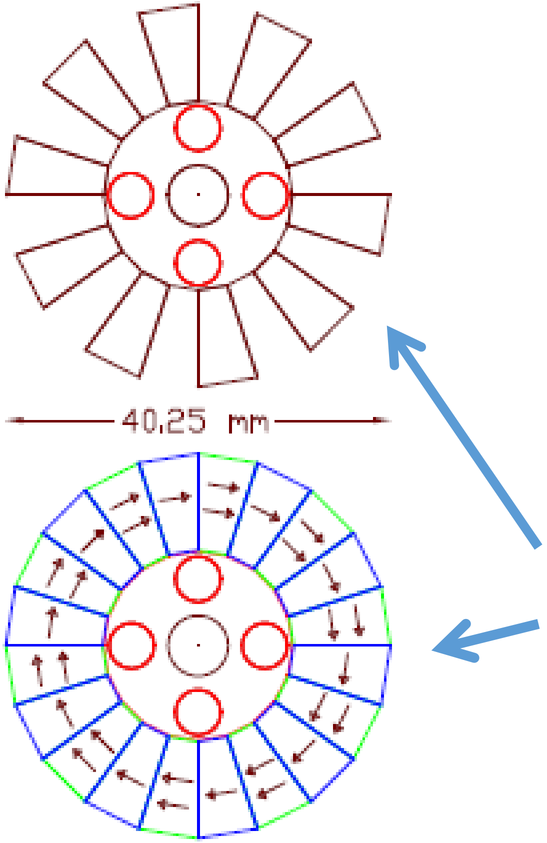
$$V_{\rm md} = \frac{\hbar g_s g_p}{8\pi m_e c}\left[(\hat{\boldsymbol{\sigma}} \cdot \hat{\boldsymbol{r}})\left(\frac{1}{r\lambda} + \frac{1}{r^2}\right)\right] e^{-r/\lambda}$$

Eöt-Wash pseudo-Goldstone boson detector

developed by Will Terrano (PhD 2015)



unpolarized mass attractor

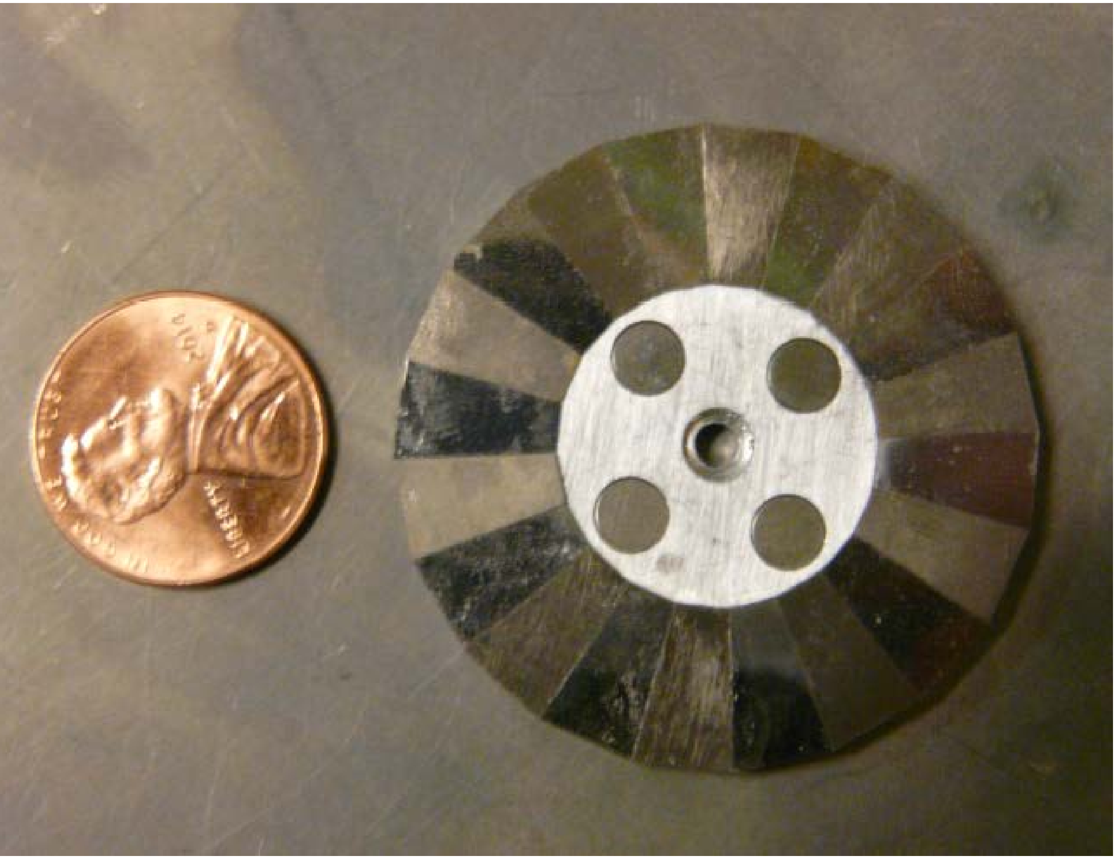


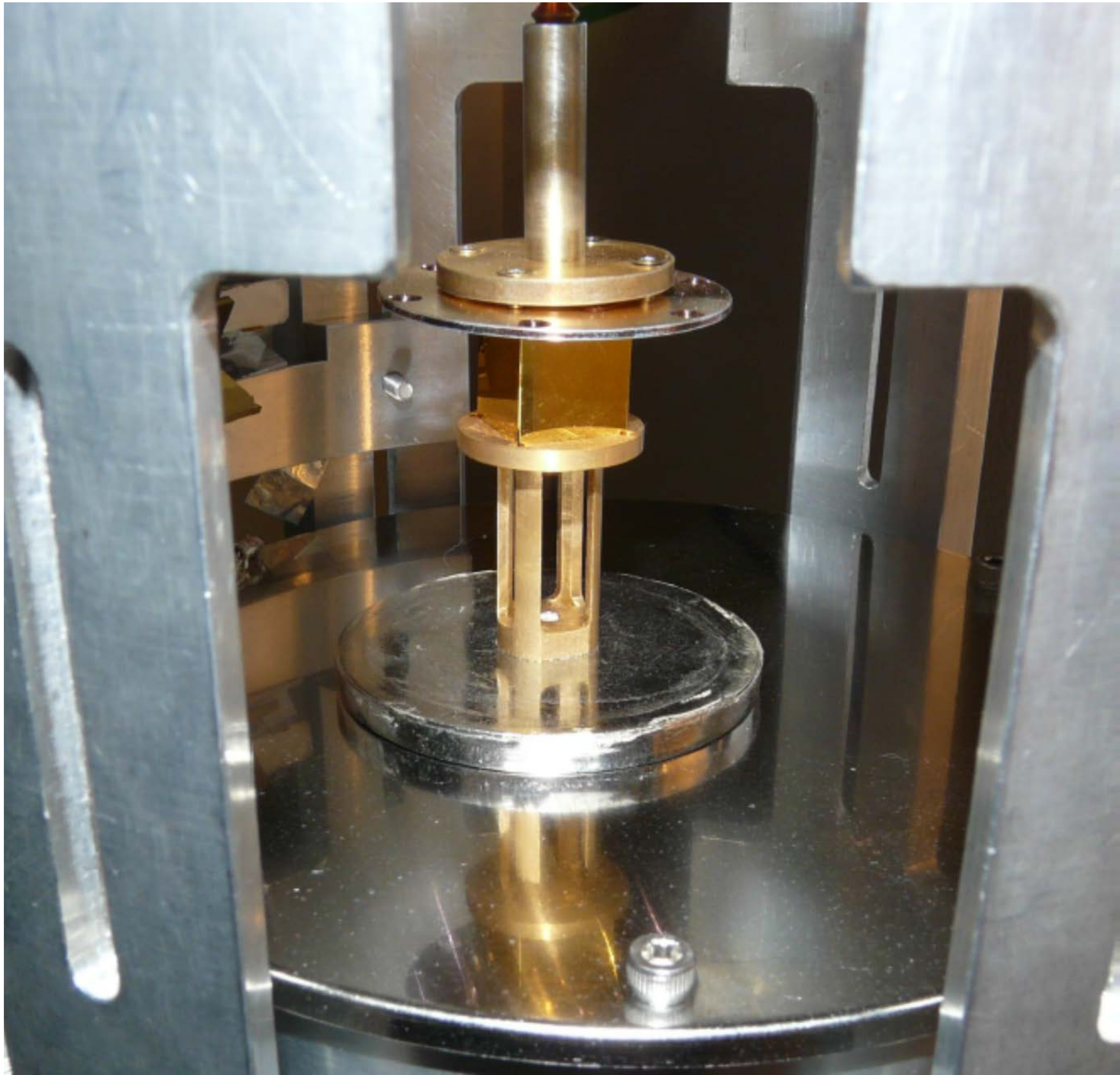
polarized spin attractor

stationary pendulum- rotating attractor instrument with 20-pole azimuthal symmetry

compact setup with sophisticated magnetic shielding

probes
monopole-dipole &
dipole-dipole interactions

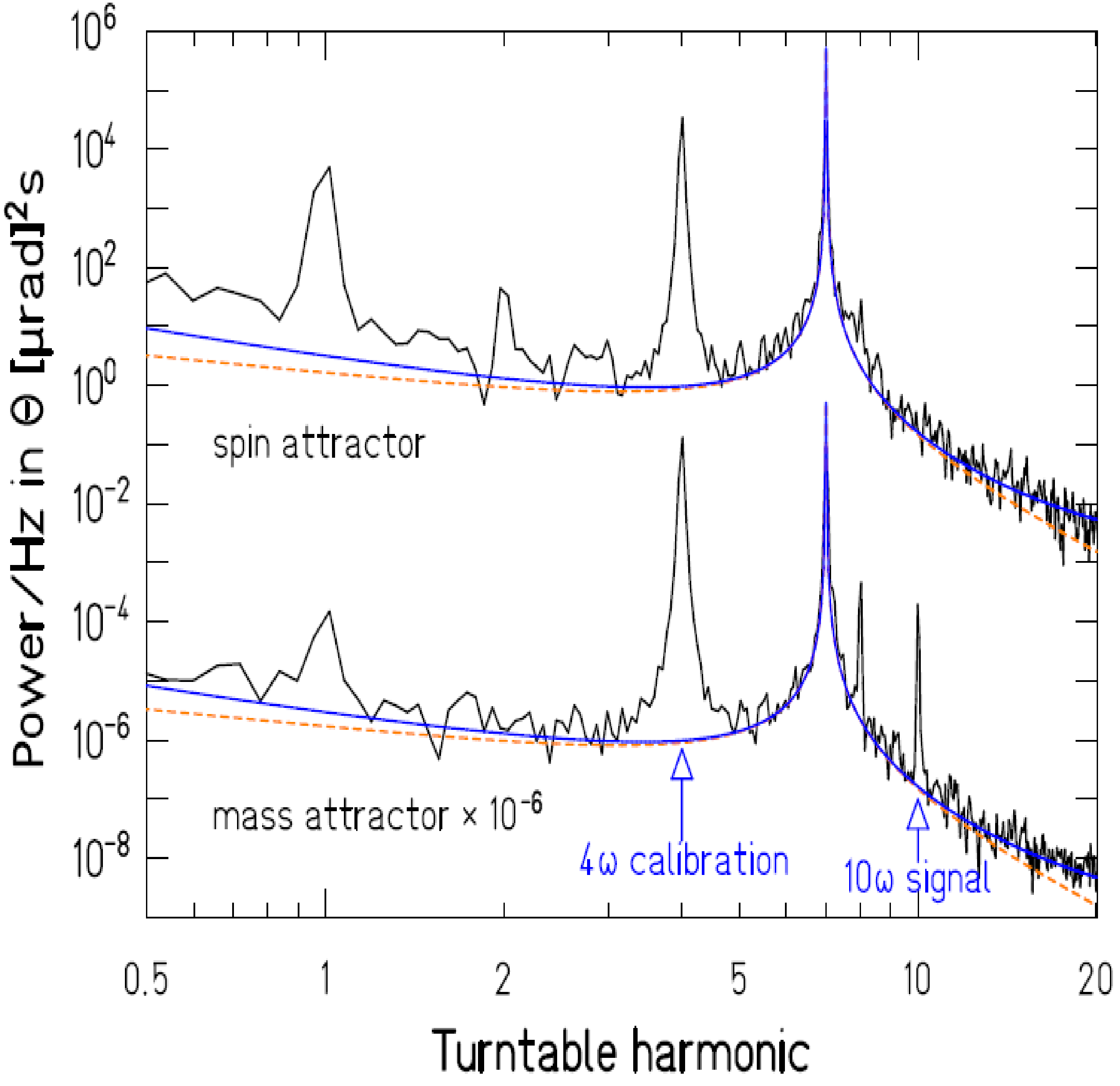




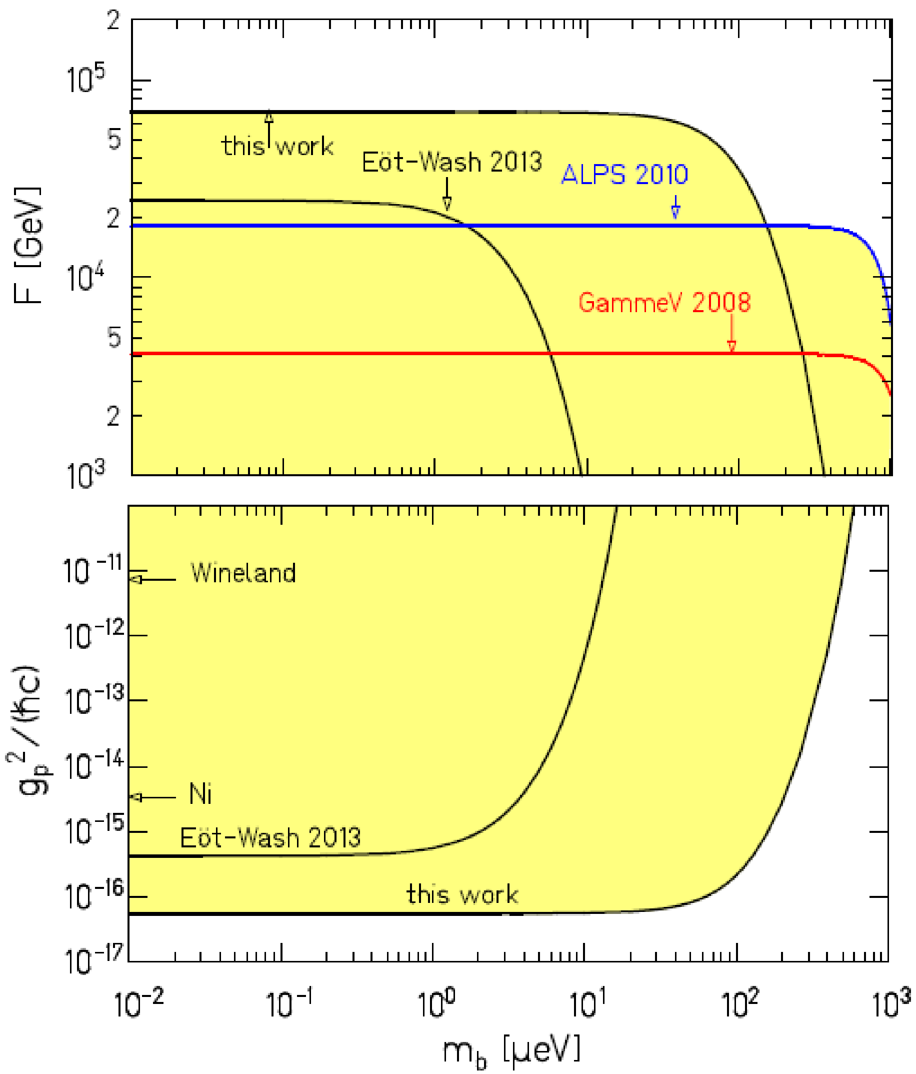
unprecedented aN m torque sensitivity

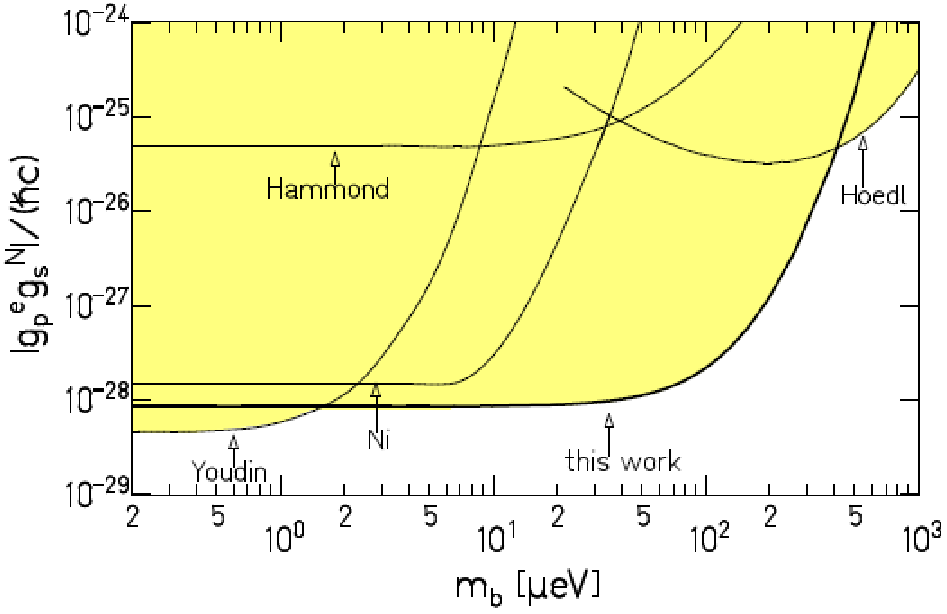
TABLE I. Observed 4ω and 10ω torques. Amplitudes A are in units of aN m, phases ϕ are in degrees, and separations s are in millimeters. The 1σ uncertainties do not include systematic effects. If $V_{\mathrm{md}} = 0$, we expect $\Delta\phi = \phi_{10\omega} - \phi_{4\omega} = -9.0°$.

Attractor	T_{att}/T_0	$A_{4\omega}$	$A_{10\omega}$	$\phi_{10\omega} - \phi_{4\omega}$
Spin: $s = 4.12$	7	2855 ± 5	0.7 ± 2.9	$+3 \pm 25$
Spin: $s = 4.12$	6	2863 ± 4	2.9 ± 2.8	-7.9 ± 5.5
Spin: $s = 4.12$	$6 + 7$	2860 ± 3	1.3 ± 2.0	-6.1 ± 8.6
Mass: $s = 1.98$	7	5611 ± 8	344 ± 4	-9.47 ± 0.08



95% confidence exclusion limits from the pseudo-Goldstone boson detector



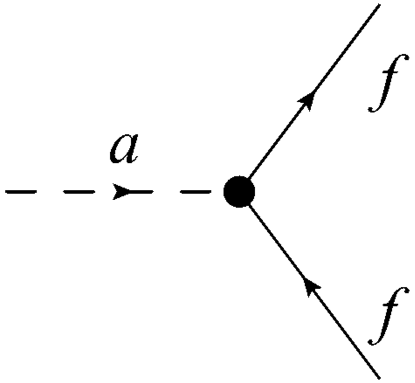


ALPS and GammeV are light shining thru wall expts
At DESY and FermiLab

W.A. Terrano et al., PRL 115, 201801 (2015)

nail #5 "Axion Wind" Effect (Axion and ALPs)

[Flambaum, *Patras Workshop*, 2013], [Stadnik, Flambaum, *PRD* **89**, 043522 (2014)]

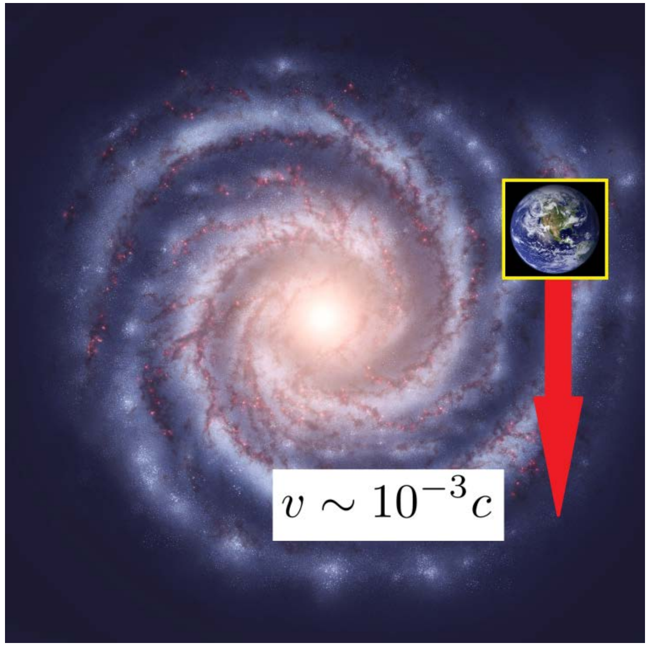


$$\mathcal{L}_{aff} = -\frac{C_f}{2f_a}\partial_i[a_0\cos(\varepsilon_a t - p_a\cdot r)]\bar{f}\gamma^i\gamma^5 f$$

$$=> \quad H_{\text{eff}}(t) \simeq \frac{C_f a_0}{2f_a}\sin(m_a t)\ p_a\cdot\sigma_f$$

$$a_0\vec{p}_a = \vec{v}_a\sqrt{2\rho_{\text{DM}}}$$

$$v_a \approx 10^{-3}$$



$$H_{\text{eff}}(t) \simeq \sqrt{\rho_{\text{DM}}/2}\,\frac{C_f}{f_a}\sin\left(m_a t + \phi_a\right)\vec{v}_a\cdot\vec{\sigma}_f$$

τ_0	200 s	$m_a = 2.1\times10^{-17}$ eV
τ_{cut}	2700 s	$m_a = 1.5\times10^{-18}$ eV
1 y	$\pi\times10^7$ s	$m_a = 1.3\times10^{-22}$ eV

"Axion Wind" Effect (Axion and ALPs)

[Flambaum, *Patras Workshop*, 2013], [Stadnik, Flambaum, *PRD* **89**, 043522 (2014)]

$$H_{\text{eff}}(t) \simeq \frac{C_f a_0}{2 f_a} \sin(m_a t)\, p_a \cdot \sigma_f$$

$$\omega_1 \approx \frac{m_a c^2}{\hbar}$$

$$\omega_2 = \frac{2\pi}{T_{\text{sidereal}}}$$

If CDM is entirely axions

$a_0 \sim (4\times10^{-2}\text{ eV})/m_a$

axion wind velocity ~ 10^{-3}

so a signal of 10^{-22} eV would correspond to $f_a/C_e \sim 4\times10^{17}$ eV

DFSZ axion has $C_e \sim 1$

KSVZ axion has $C_e \sim 10^{-3}$

Analysis procedure (collaboration with Will Terrano)

analyse data cuts (typically containing exactly 2 turntable revolutions and lasting about 3000 s) to extract lab-fixed signals β_N and β_W where

$E_{pend} = -N_p \, \boldsymbol{\beta} \cdot \boldsymbol{\sigma}$

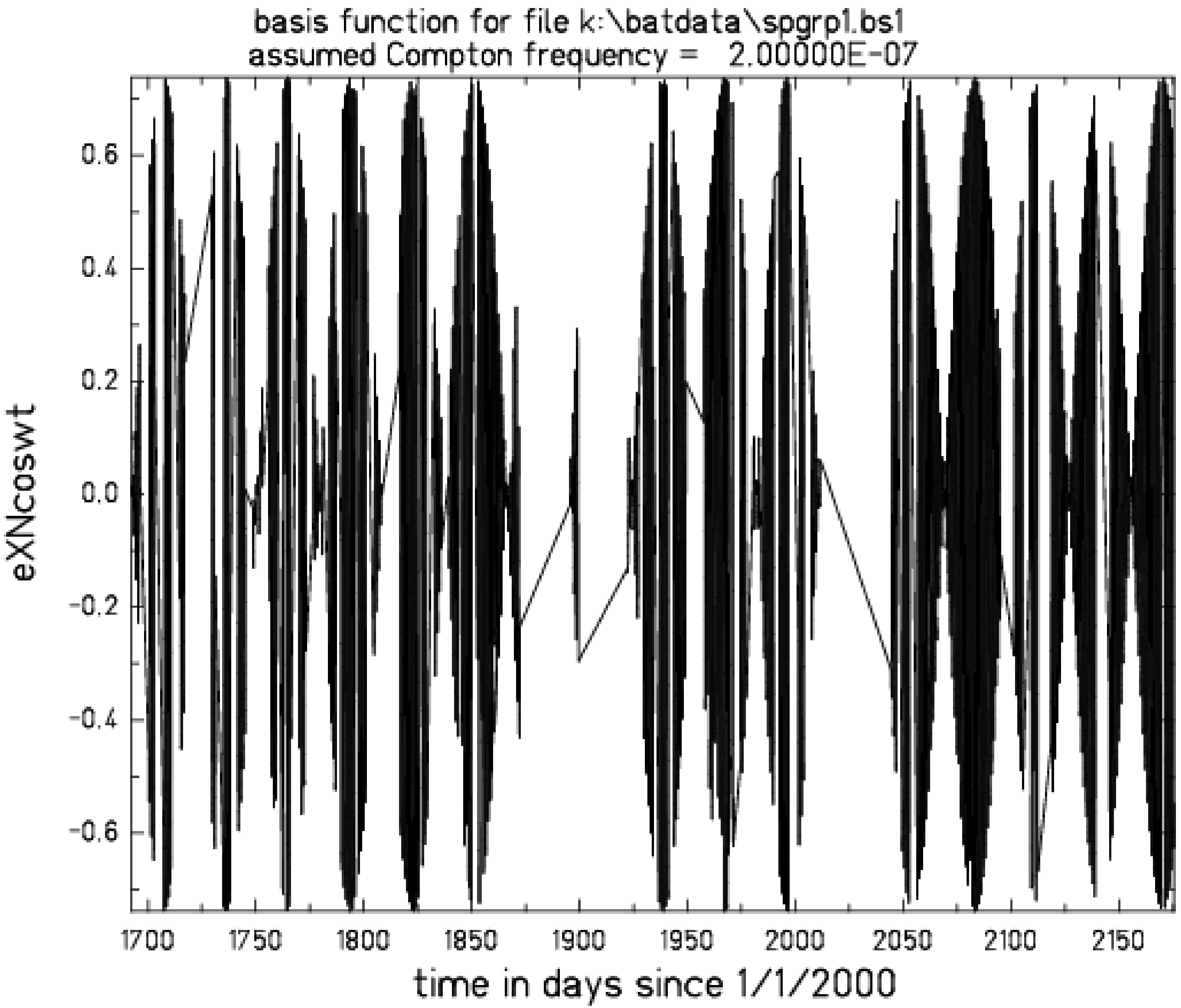
convert these signals to equatorial frame β_X and β_Y

pick an assumed Compton frequency ω_c and make a linear fit of the β_N and β_W time series in terms of 4 parameters:

X_cos ($\omega_c t$) X_sin ($\omega_c t$) Y_cos ($\omega_c t$) Y_ ($\omega_c t$) where X and Y are equatorial coordinates

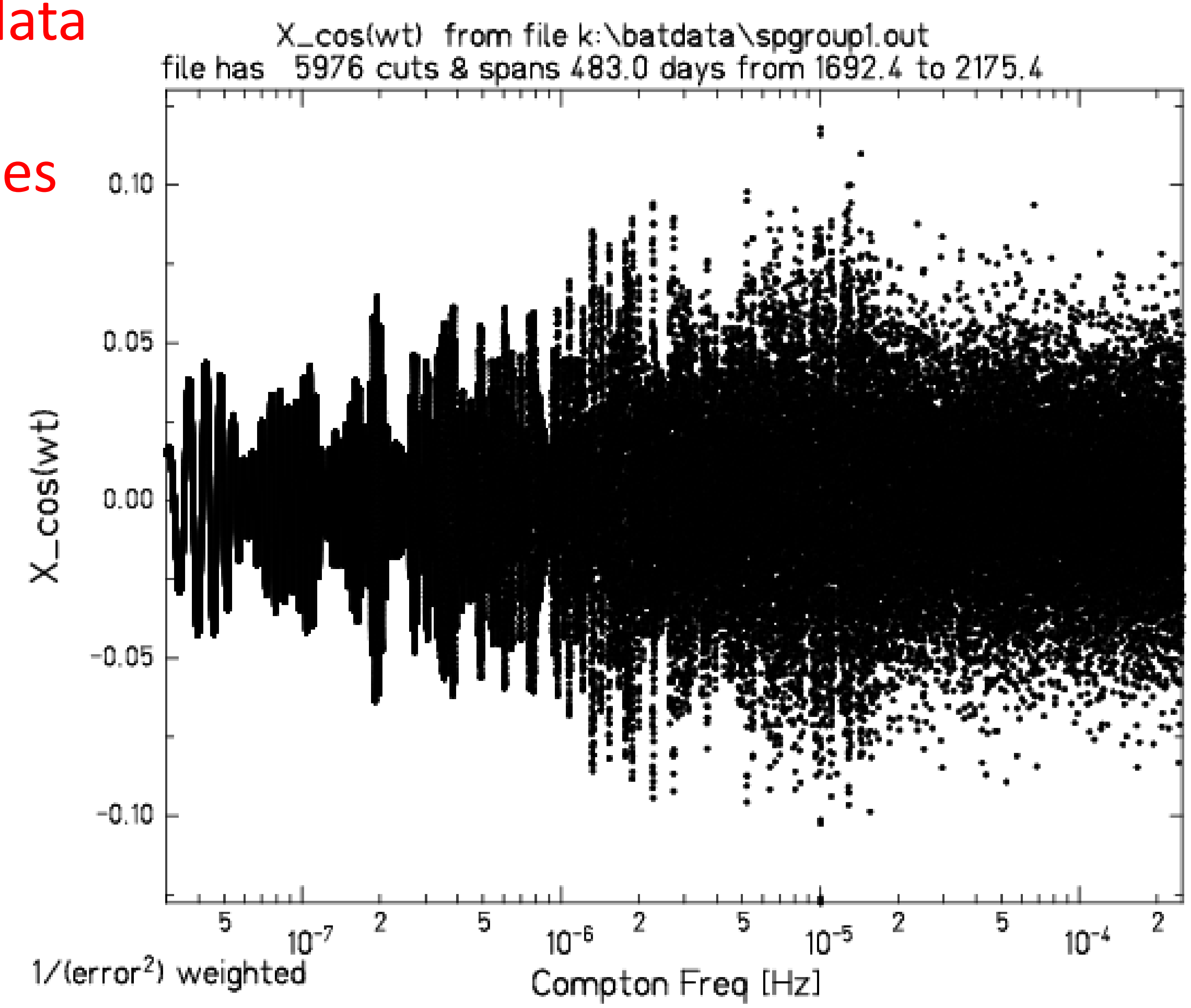
repeat this last step over a dense scan of logarithmically spaced ω_c

deduce uncertainty from spread in the results


basis function for file k:\batdata\spgrp1.bs1
assumed Compton frequency =   2.00000E-07
eXNcoswt
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
1700
1750
1800
1850
1900
1950
2000
2050
2100
2150
time in days since 1/1/2000

1 of the 4 fit amplitudes
extracted from roughly ½ of our data

results from the other 3 amplitudes
are very similar

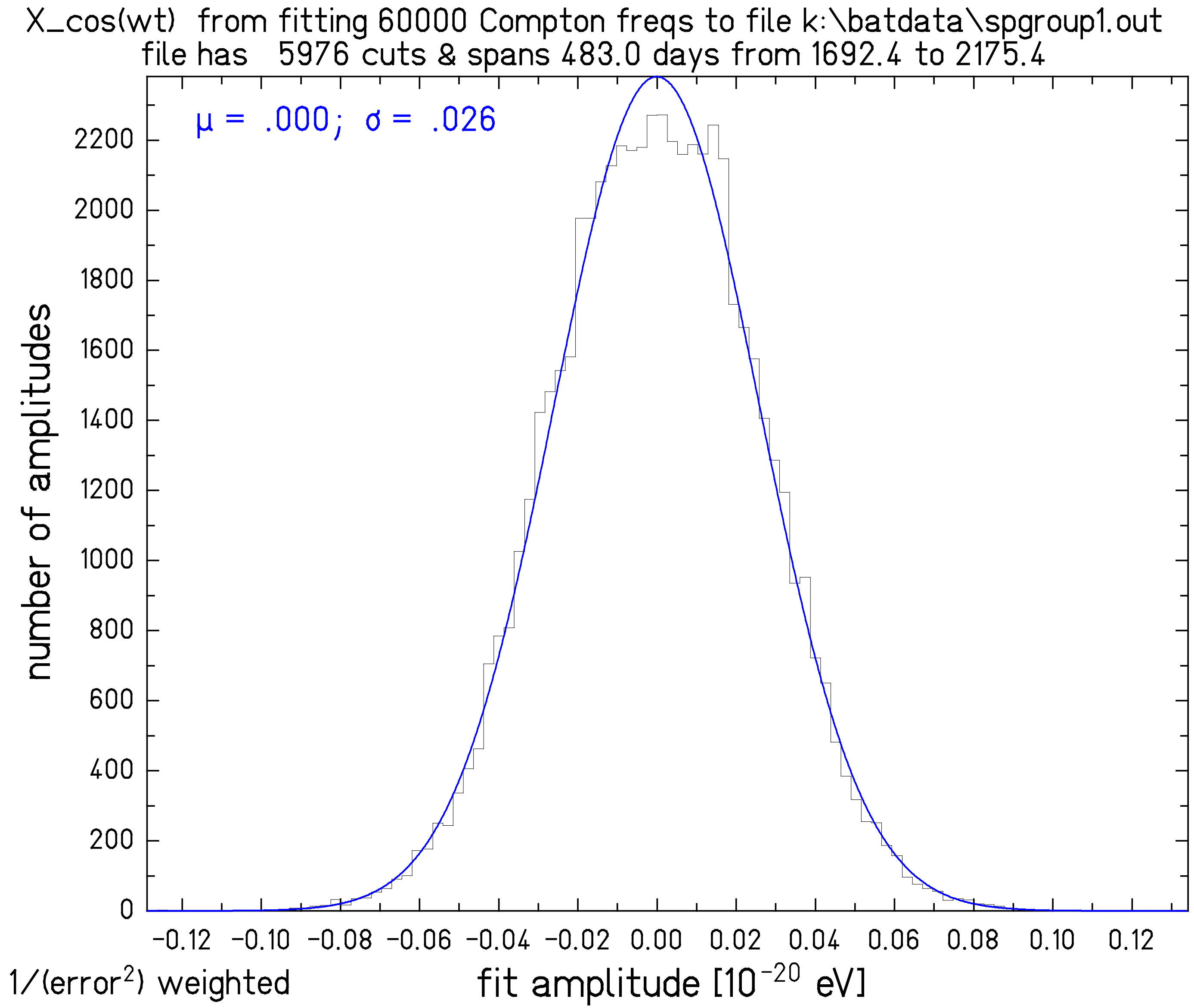


Histogram of 1 of the 4 fit amplitudes summed over Compton frequencies between 3×10^{-8} Hz to 2.5×10^{-4} Hz (this is only part of our data)

signal is expected to be coherent over $\approx10^{6}$ cycles i.e.over our entire data span in the range of frequencies we consider

95% confidence upper limit is 5.2×10^{-22} eV

preliminary



nail #6: ultra-low mass vector dark matter coupled to B-L?

Our newest project: stationary torsion balance with a Be/Al pendulum (good sensitivity to B-L)

replaced our usual tungsten fiber (Q's around 5000)
by fused silica suspension fiber (Q's around 500,000) for much better thermal noise

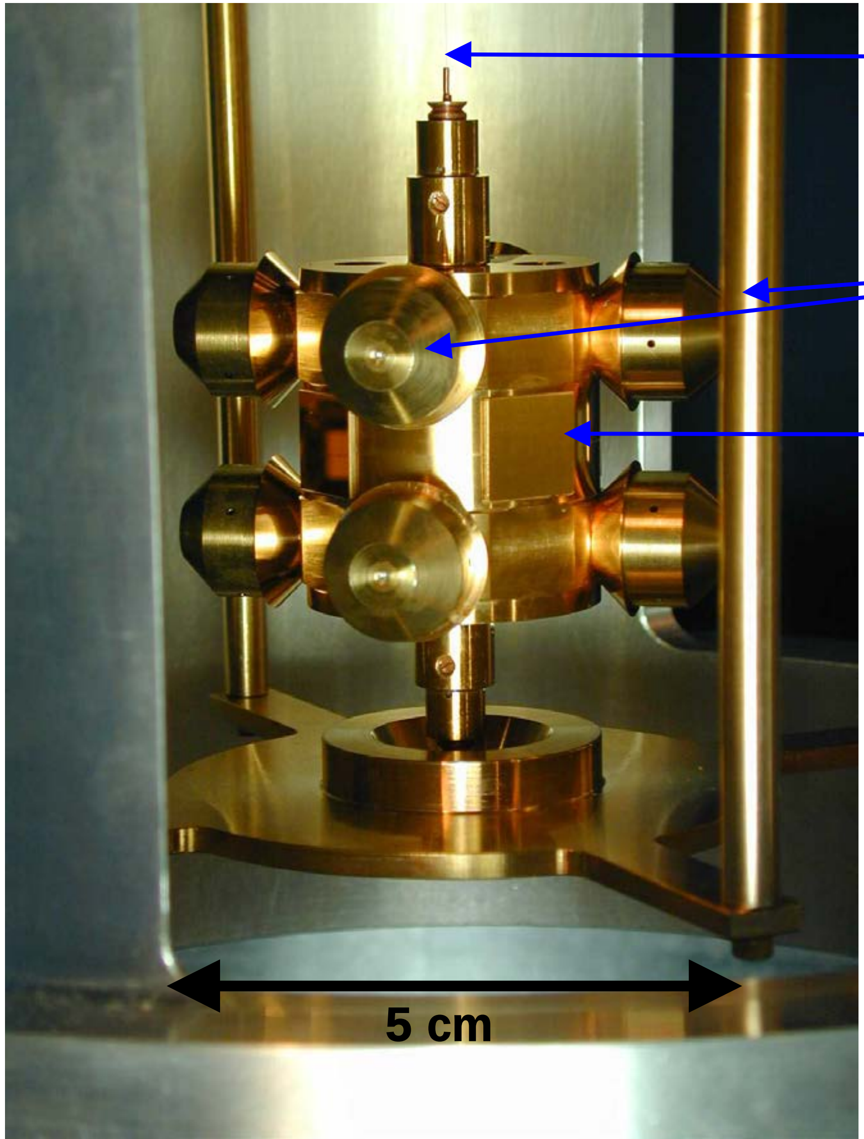
more sensitive twist-angle readout

do analysis like that in nail #5

hope to get decent results in 0.01 mHz to 10 mHz regime

B-L torsion pendulum of the recent WEP test

T. A. Wagner et al., Class. Quant. Grav. 29, 184002 (2012)



20 μm diameter tungsten fiber

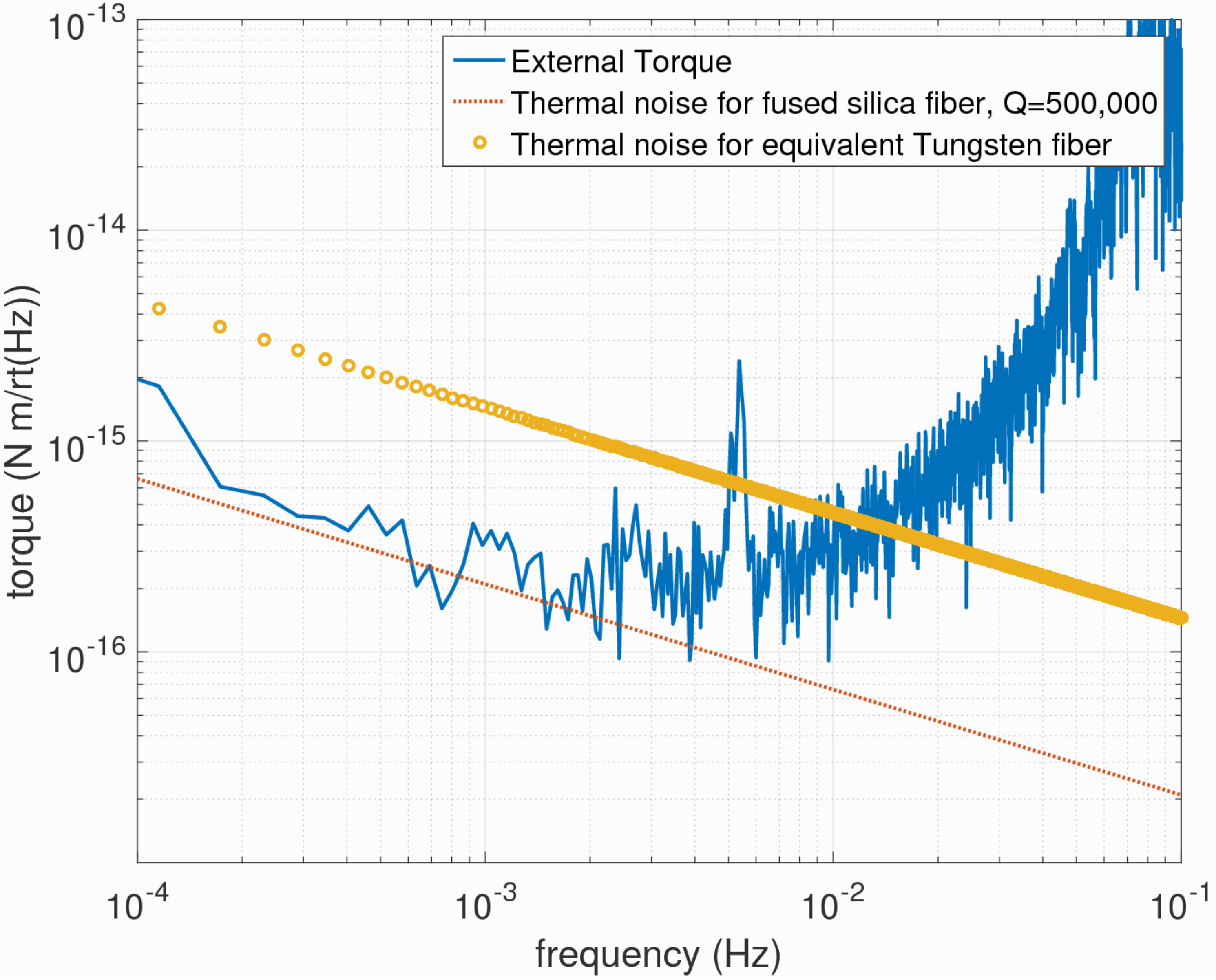
eight 4.84 g test bodies
4 Be & 4 Al

4 mirrors for measuring pendulum twist

symmetrical design suppresses false effects from gravity gradients, etc.

free osc freq:	1.261 mHz
quality factor:	4000
machining tolerance:	5 μm
total mass :	70 g

Erik Shaw’s excellent fused silica torsion fibers



references

- Planck-scale preferred-frame tests

  B.R. Heckel et al., PR D 78, 092006 (2008)

- exotic spin-spin potentials

  B.R. Heckel et al., PRL 111, 151802 (2013) electrons

  G. Vasilakis et al. PRL 103,261801 (2009) neutrons

- pseudo-Goldstone bosons & spontaneously broken symmetries

  W.A. Terrano et al., PRL 115, 201801 (2015)

- ultra-light bosonic dark matter

  P.W. Graham et al., PRD 93, 075029 (2016) vector bosons

  Y.V. Stadnik and V.V. Flaubaum, PRD 89, 043522 (2014) axions (ALP)s