Exotic spin-dependent interactions
plus
Progress in Lunar Laser ranging

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will discuss motivations, principles and results:

- polarized-electron test-body technology
- Plank-scale preferred-frame experiments
- non-commutative geometries
- pseudo-Goldstone bosons and new global symmetries
- ultra-low-mass axion-like dark matter
- lunar laser ranging in the APOLLO era

the Eöt-Wash® group

Faculty
EGA
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Postdocs
Krishna Venkateswara (LIGO)
Charlie Hagedorn

Current undergrad
Michael Ross

Current Grad students
Kerkira Stockton
John Lee
Erik Shaw
Will Terrano

Sabbatical Visitor
Andy Kim

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

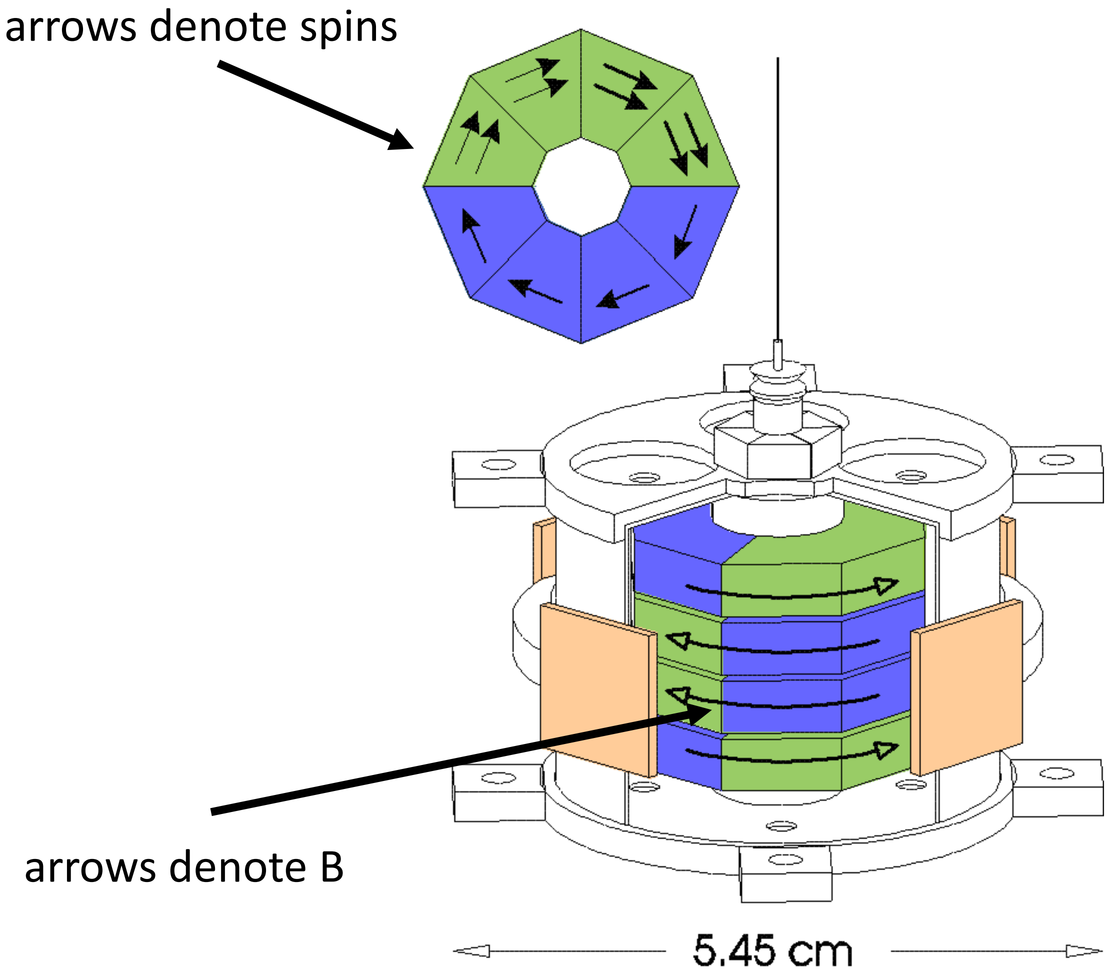
Simplified explanation for remarkable properties of $SmCo_5$:

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 <u>maximally antisymmetric</u>.
m_L = (+3) + (+2) + (+1) + (0) + (-1) = 5 <u>i.e. L=5</u>

The spin function must be <u>maximally symmetric i.e. S=5/2</u> .
Therefore the spin and orbital contributions to the Sm magnetic moment 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



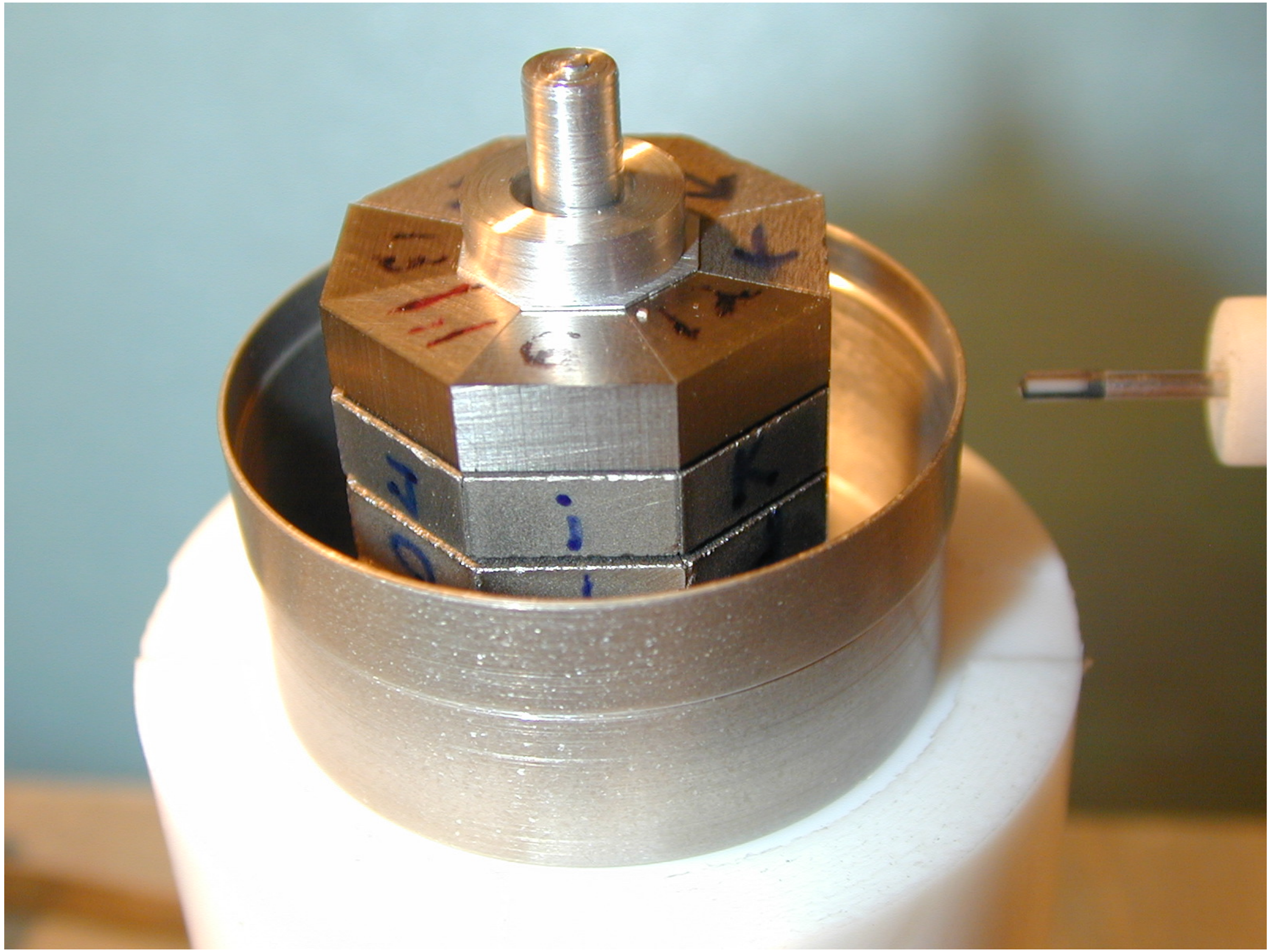
- 9.8 x 10^{22} polarized electrons
- negligible mass asymmetry
- negligible composition asymmetry
- flux of B confined within octagons
- negligible external B field

- 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
- $J_{Sm} = - S_{Sm}$

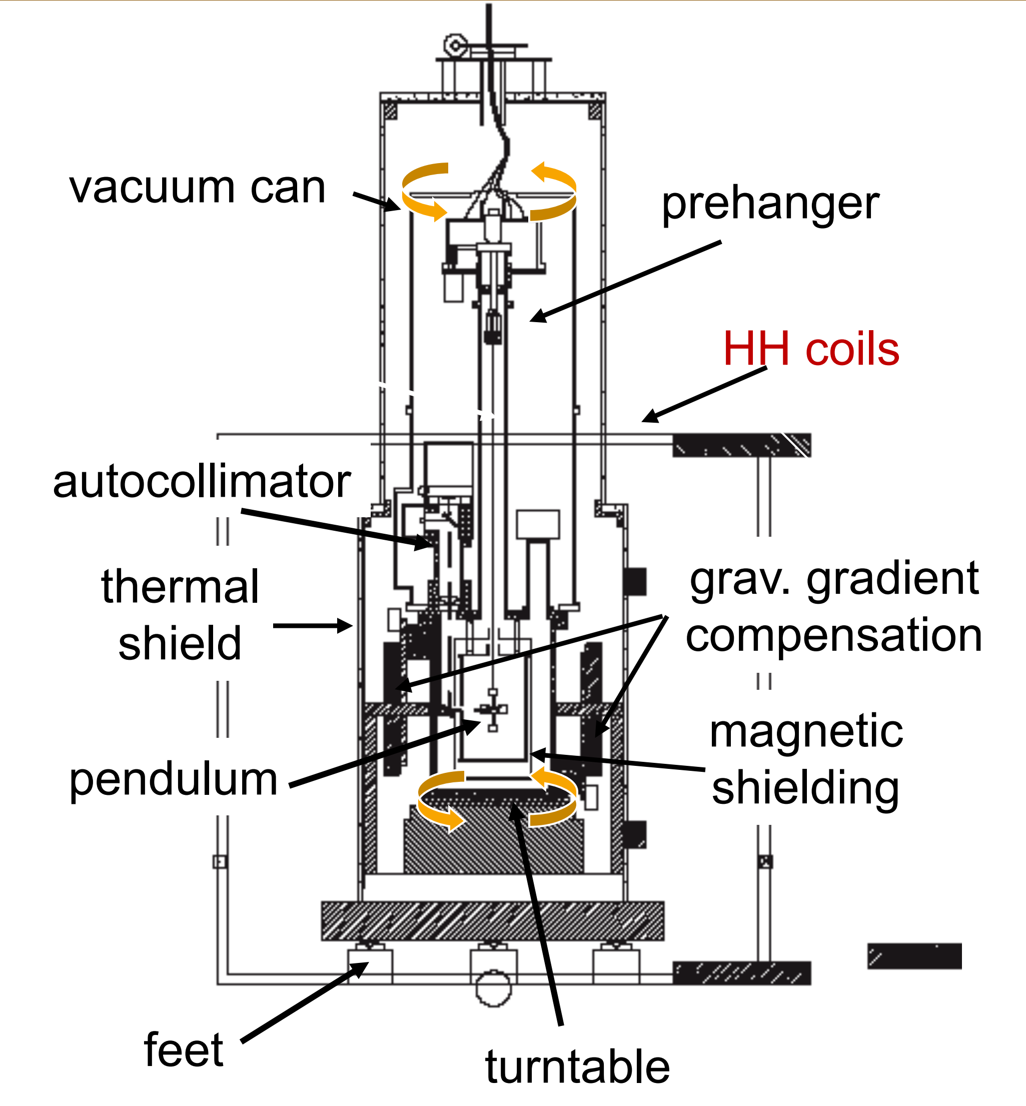
measuring the stray magnetic field of the spin pendulum



B inside = 9.6±0.2 kG

B outside ≈ few mG

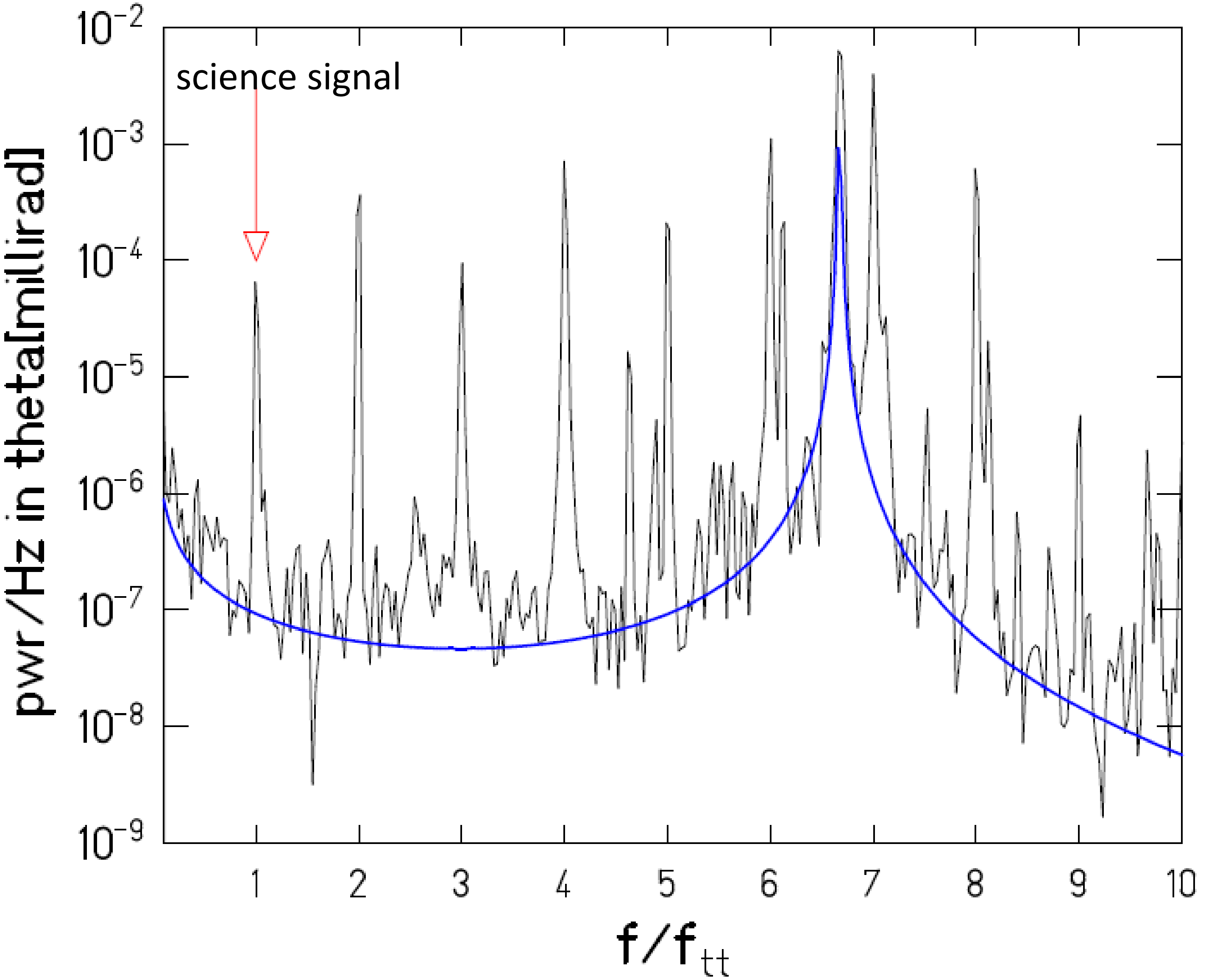
the Eöt-Wash rotating torsion balance

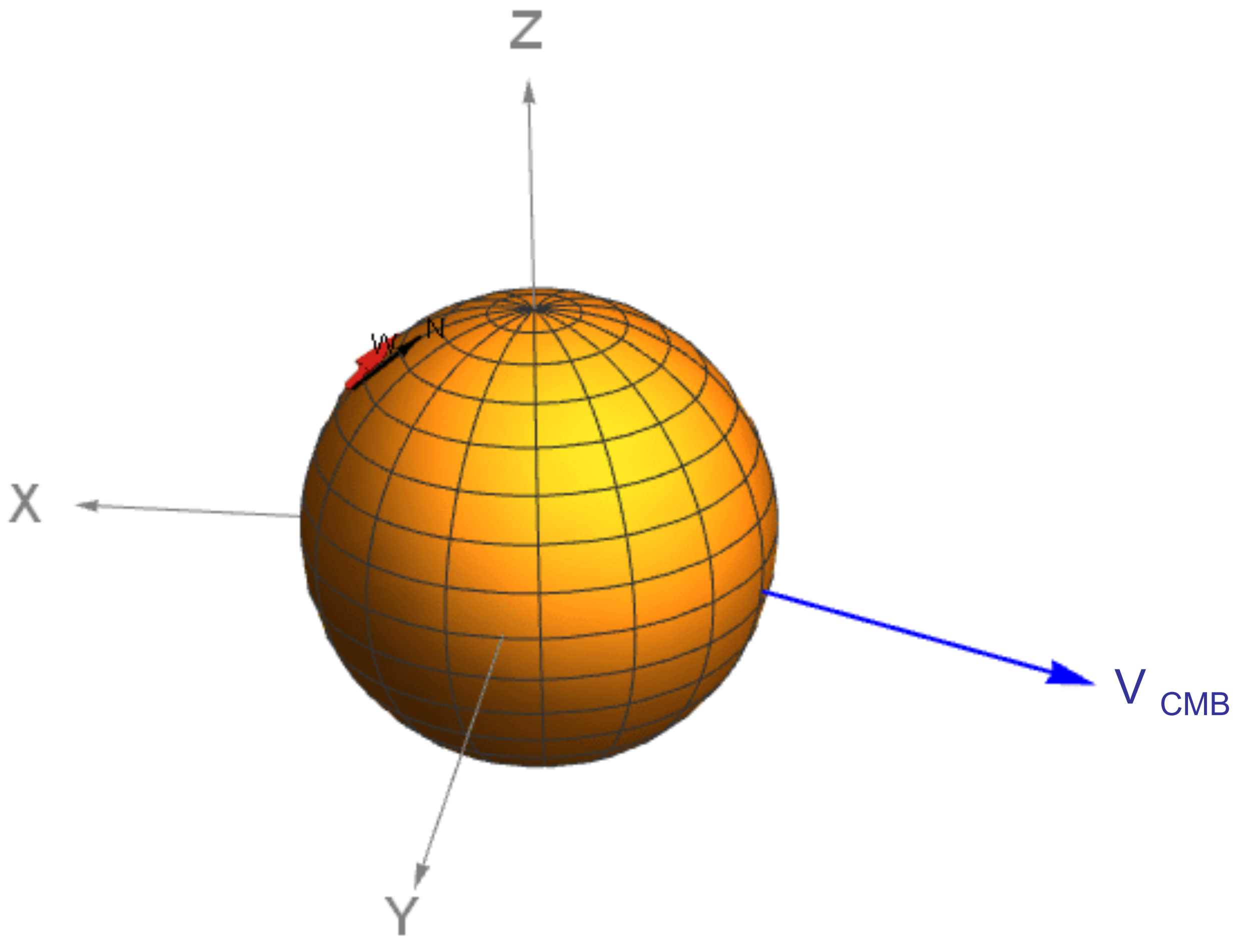


power spectrum of the spin-pendulum twist

Peaks are 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
X
Y
W
N
V CMB

cosmic preferred frames?

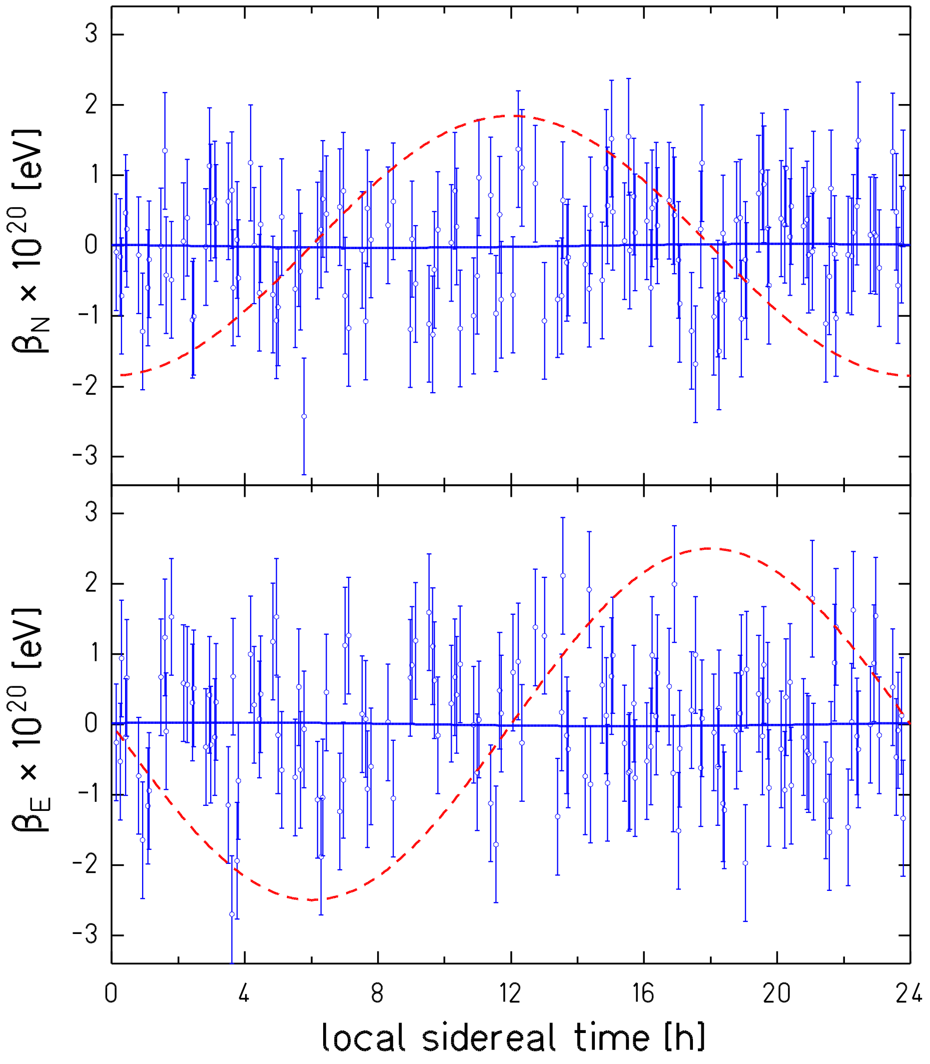
We all were taught that there are no preferred frames. But the Universe defines a frame in which the CMB is essentially isotropic. Could there be other preferred frame effects defined by the Universe?

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 $b_x=2.5\times10^{-20}$ eV

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

$b_x=(-0.20\pm0.76)\times10^{-21}$ eV

$b_y=(-0.23\pm0.76)\times10^{-21}$ 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

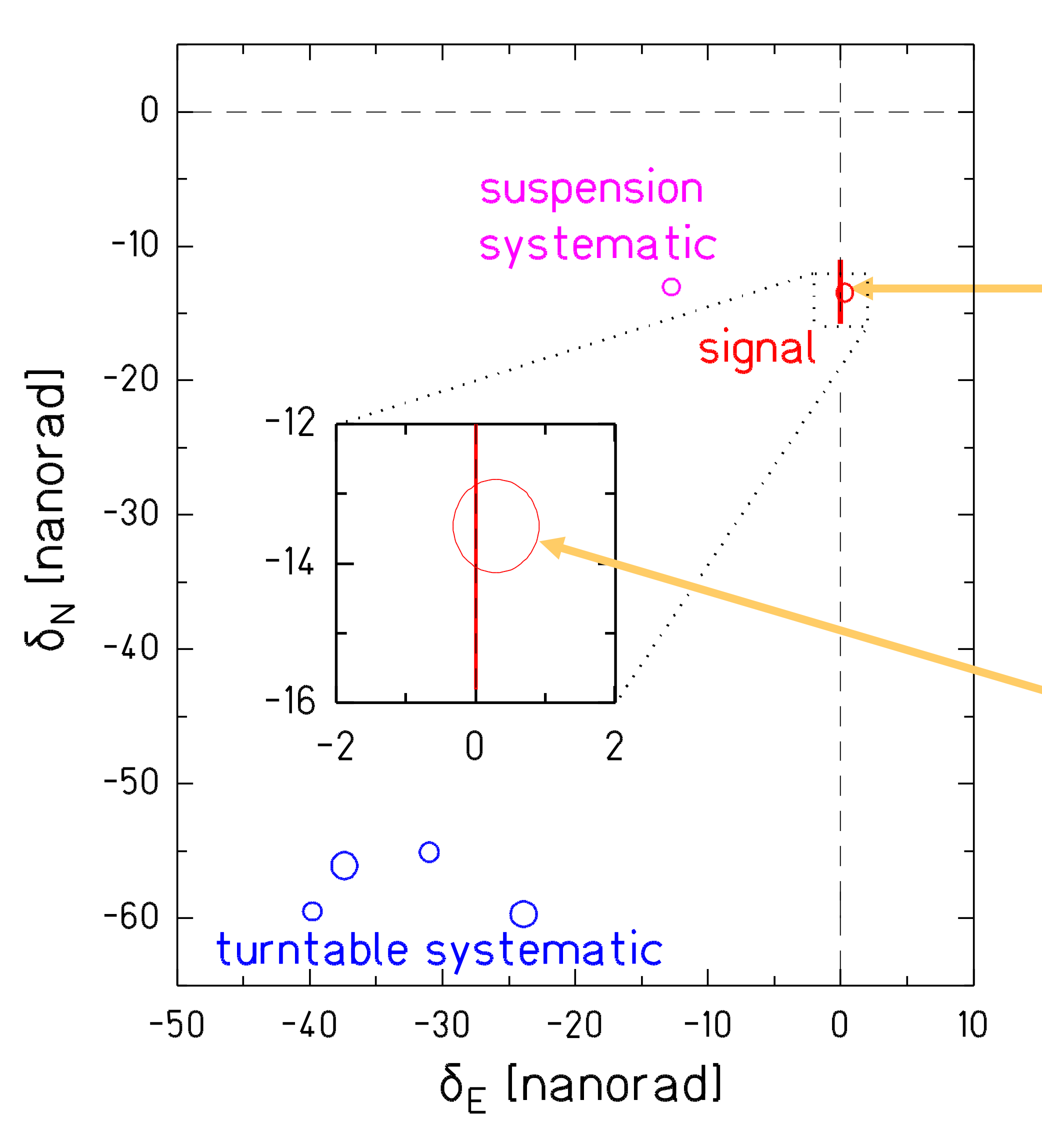
angular momentum J of a spinning flywheel in a lossy gimbal will eventually point true North where the gimbals do not dissipate energy

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 rather than previous polarized neutron and X-ray scattering data.

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	$\leq 2 \times 10^4$	0.22 ± 0.79
$\tilde{b}_Y$	-0.18 ± 1.32	$\leq 2 \times 10^4$	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 $m_e^2/M_{\text{Planck}} = 2 \times 10^{-17}$ 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

non-commutative space-time geometry?

string theorists have revived an earlier suggestion that the space-time coordinates may not commute, i.e. that

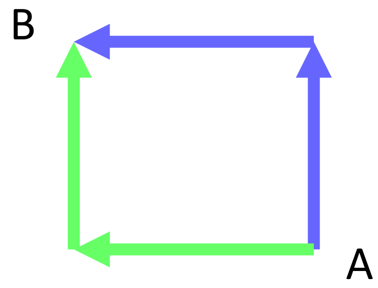
$$[\widehat{x}_\mu, \widehat{x}_\nu] = i\theta_{\mu\nu}$$

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

Our results imply $\theta \leq 6 \times 10^{-58}$ m^2
which 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 not bad for a table-top result

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

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

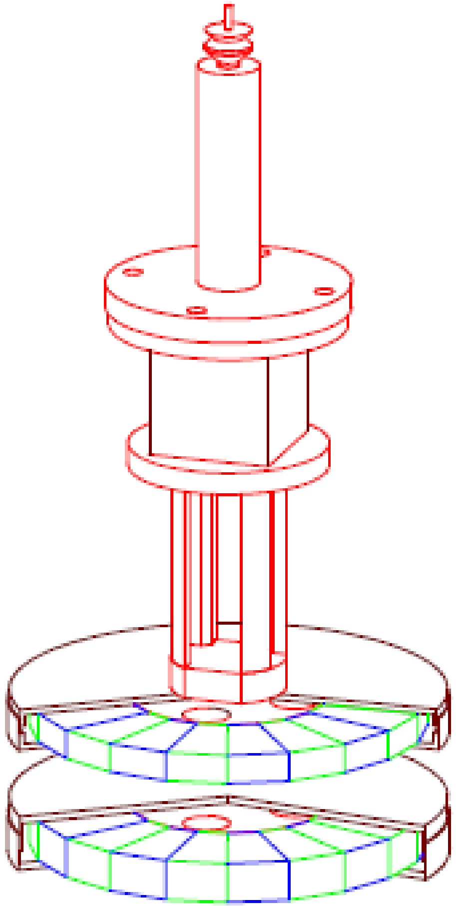
$$\lambda = \hbar/(m_b c).$$

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

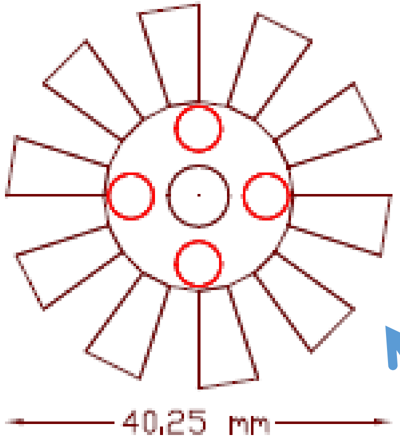
$$V_{\mathrm{md}} = \frac{\hbar g_s g_p}{8\pi m_e c} \left[(\hat{\boldsymbol{\sigma}} \cdot \hat{\boldsymbol{r}}) \left(\frac{1}{r\lambda} + \frac{1}{r^2} \right) \right] e^{-r/\lambda}$$

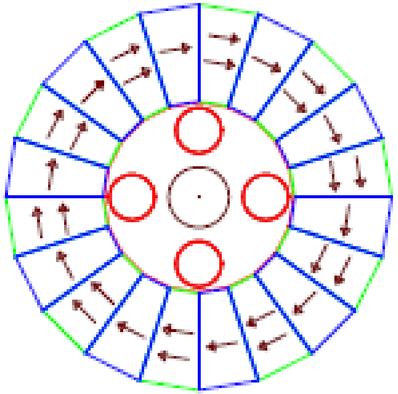
Eöt-Wash pseudo-Goldstone boson detector

developed by Will Terrano (PhD 2015)



unpolarized mass attractor



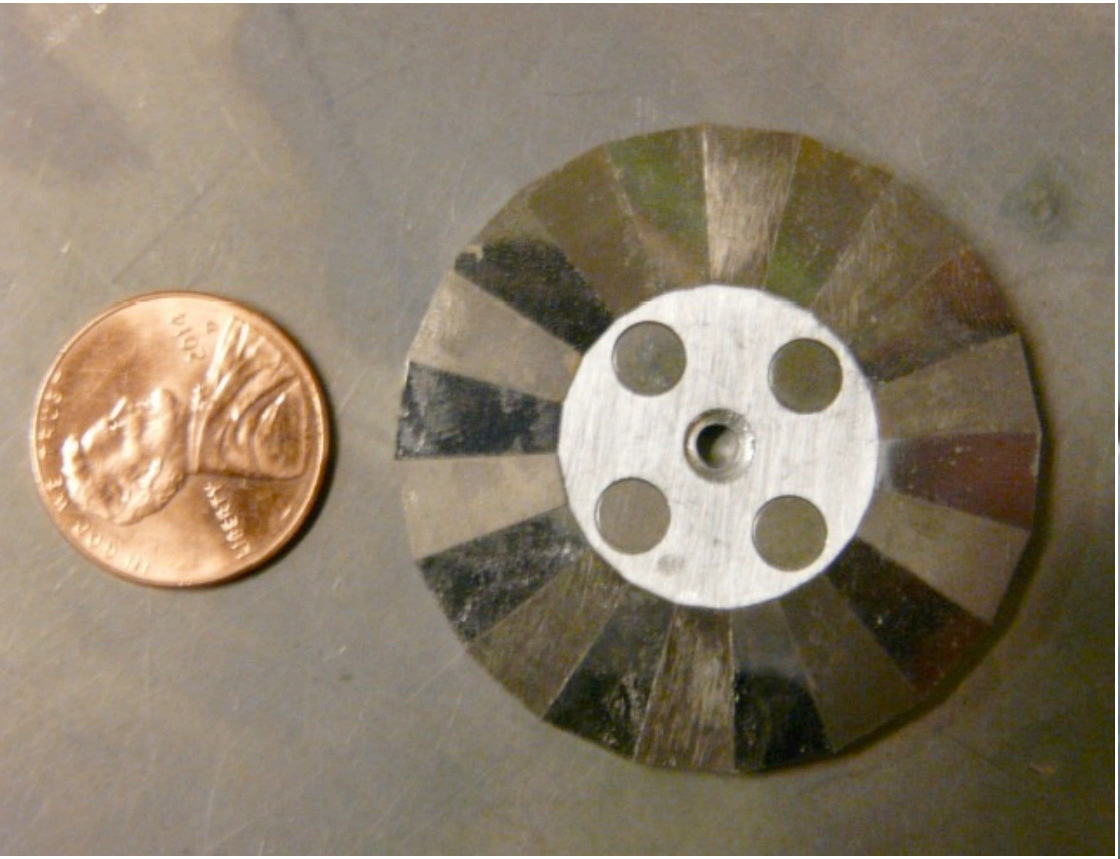


polarized spin attractor

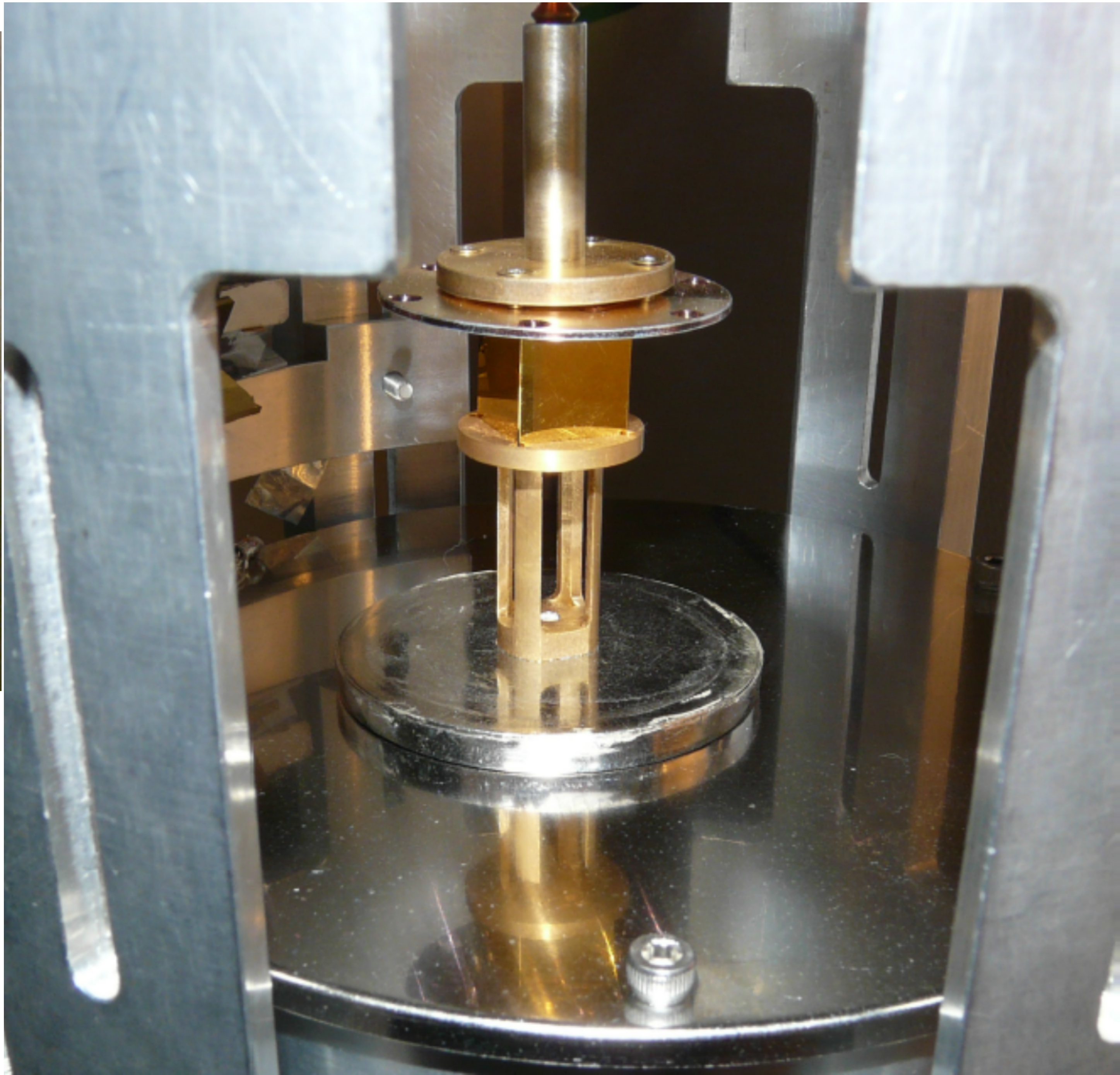
stationary pendulum- rotating attractor instrument with 20-pole azimuthal symmetry

compact setup with sophisticated magnetic shielding

we probed both monopole-dipole & dipole-dipole interactions



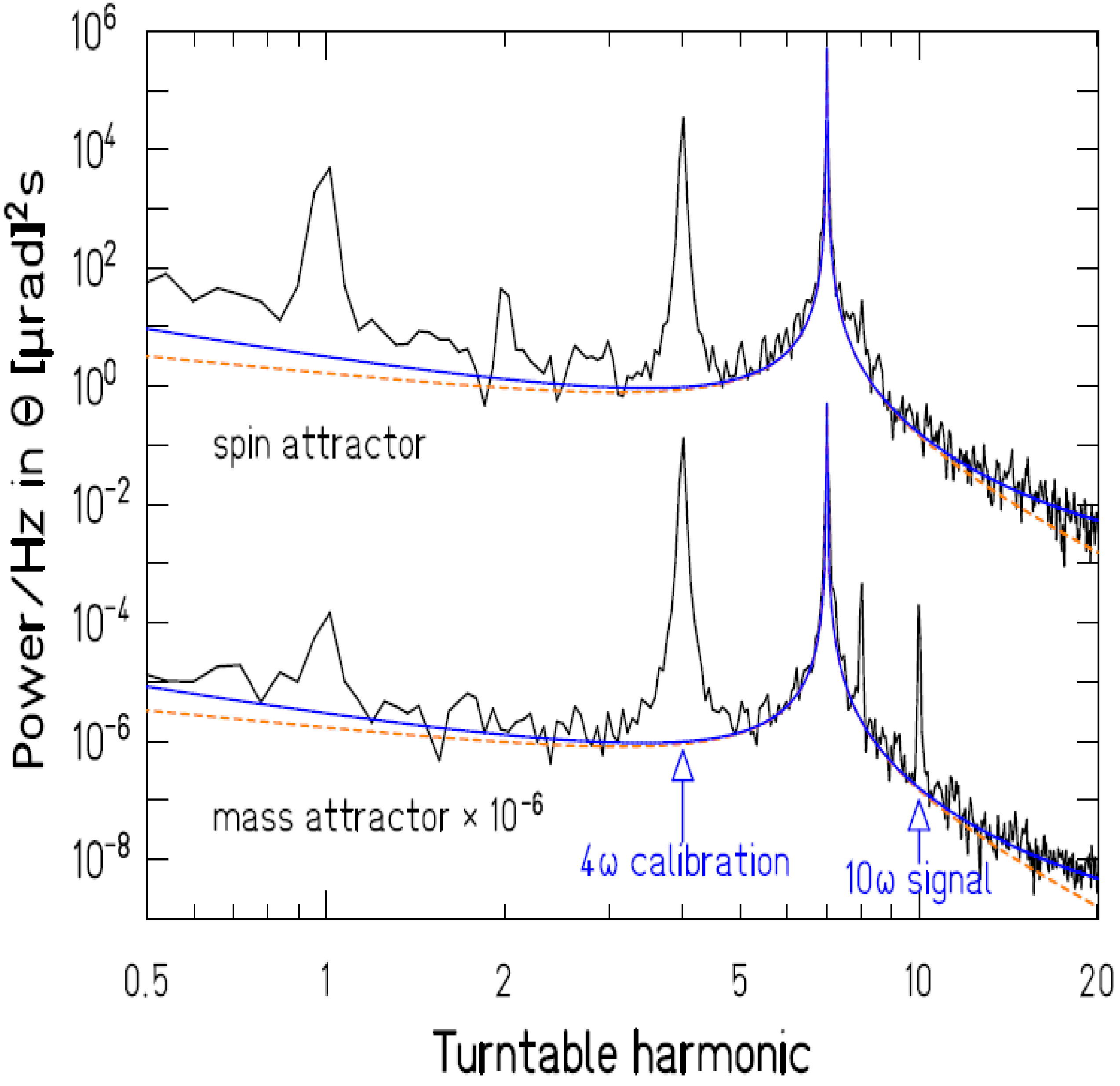
4 small tungsten cylinders provide continuous gravitational calibration of the torque scale



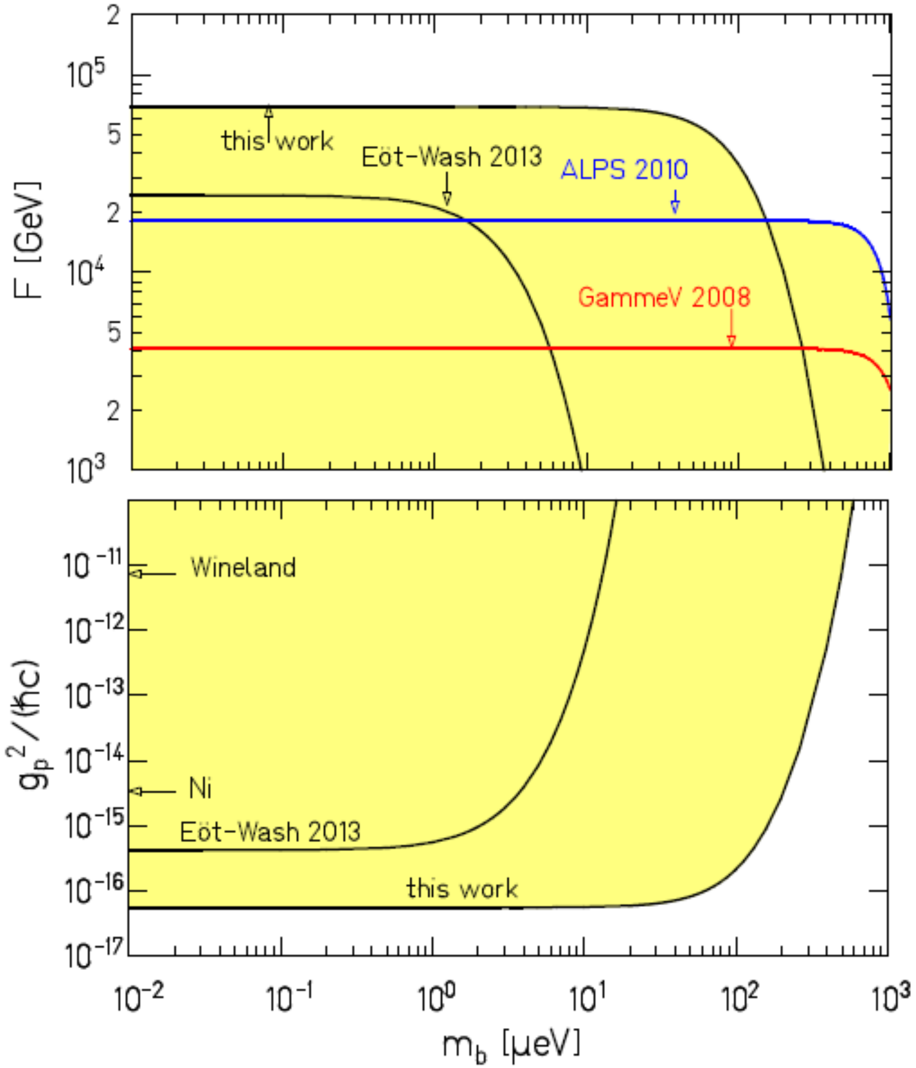
unprecedented aN m torque sensitivity

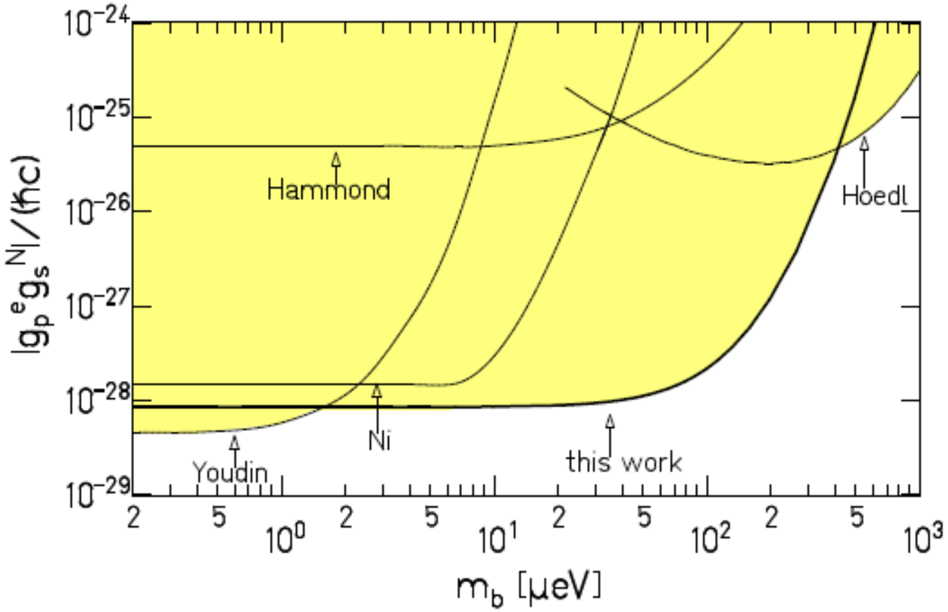
TABLE I. Observed 4ω and 10ω torques. Amplitudes A are in units of aN m, phases ϕ are in degrees, and separations s are in millimeters. The 1σ uncertainties do not include systematic effects. If $V_{\mathrm{md}} = 0$, we expect $\Delta\phi = \phi_{10\omega} - \phi_{4\omega} = -9.0°$.

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



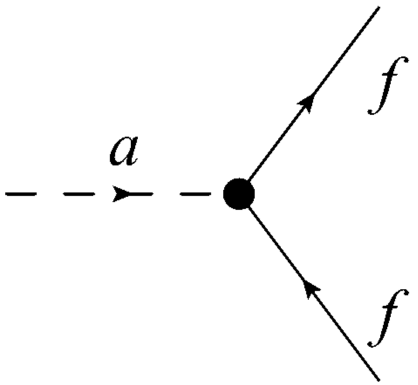


ALPS and GammeV are light shining thru wall expts at DESY and FermiLab

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

"Axion Wind" Effect (Axion and ALPs)

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

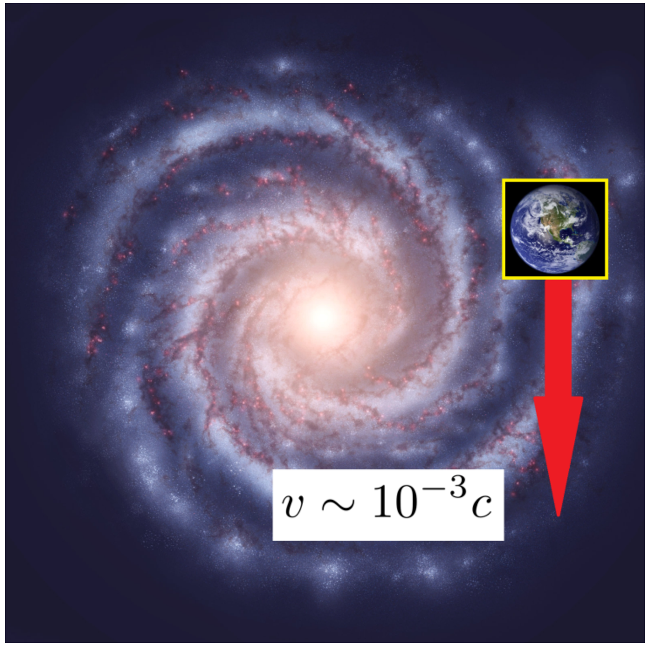


$$\mathcal{L}_{aff} = -\frac{C_f}{2f_a}\partial_i[a_0\cos(\varepsilon_a t - p_a \cdot r)]\bar{f}\gamma^i\gamma^5 f$$

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

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

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



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

τ_0	200 s	$m_a = 2.1 \times 10^{-17}$ eV
τ_{cut}	2700 s	$m_a = 1.5 \times 10^{-18}$ eV
1 y	$\pi \times 10^7$ s	$m_a = 1.3 \times 10^{-22}$ eV

“Axion Wind” Effect (Axion and ALPs)

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

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

$$\boxed{\omega_1 \approx \frac{m_a c^2}{\hbar}} \qquad \boxed{\omega_2 = \frac{2\pi}{T_{\mathrm{sidereal}}}}$$

If CDM is entirely axions

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

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 (work with W. Terrano and C. Hagedorn)

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

$E_{\mathbf{pend}} = -N_{\mathbf{p}}\, \boldsymbol{\beta} \cdot \boldsymbol{\sigma}$

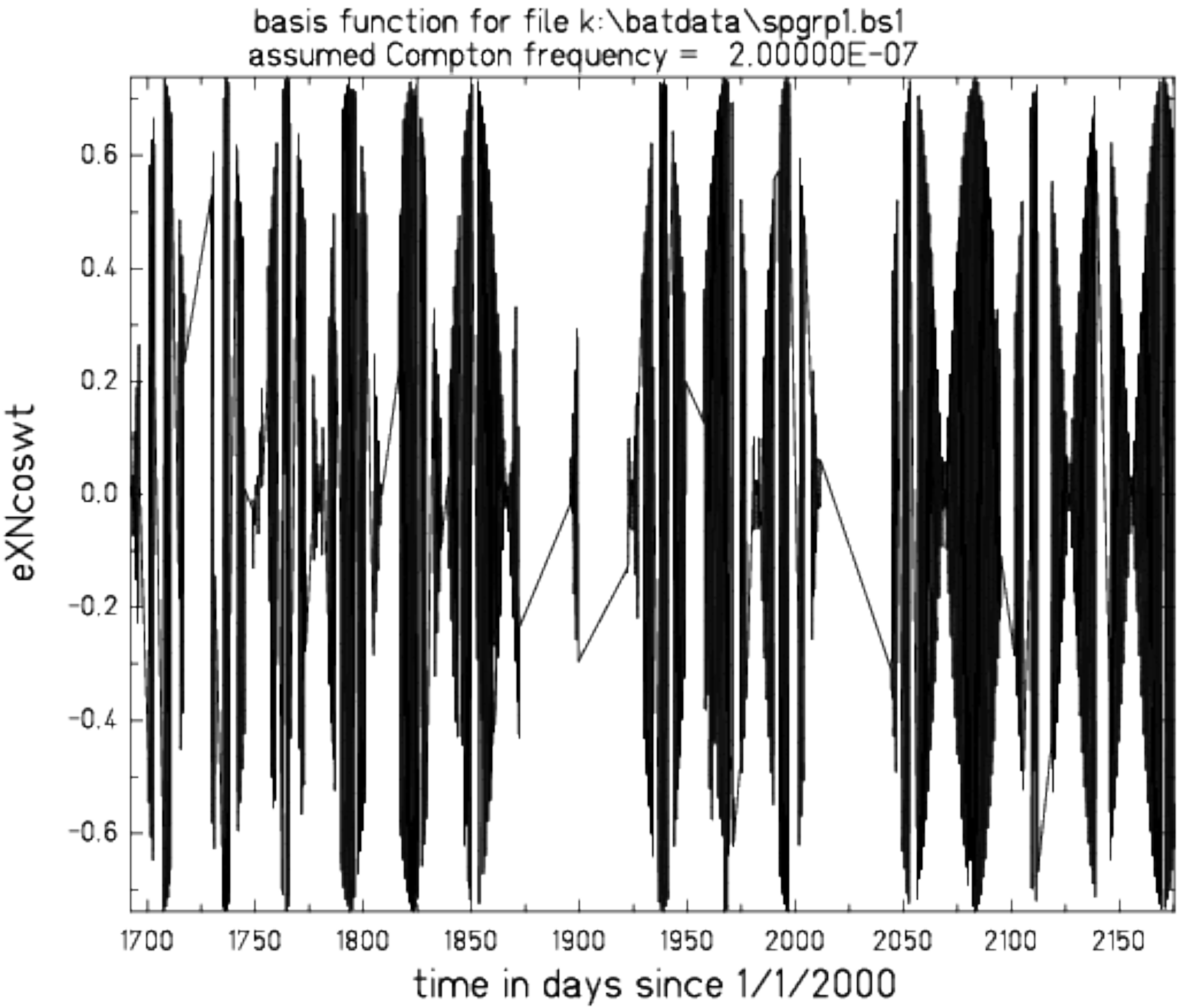
convert these signals to equatorial frame β_X and β_Y

pick an assumed Compton frequency $\omega_{\mathbf{c}}$ and make a linear fit of the β_N and β_W time series in terms of 4 parameters:

X_cos $(\omega_{\mathbf{c}} t)$ X_sin $(\omega_{\mathbf{c}} t)$ Y_cos $(\omega_{\mathbf{c}} t)$ Y_ $(\omega_{\mathbf{c}} t)$ where X and Y are equatorial coordinates; combine sin & cos terms in quadrature to get amplitudes along X and Y

repeat this last step over a dense scan of logarithmically spaced $\omega_{\mathbf{c}}$

deduce uncertainty from spread in the results

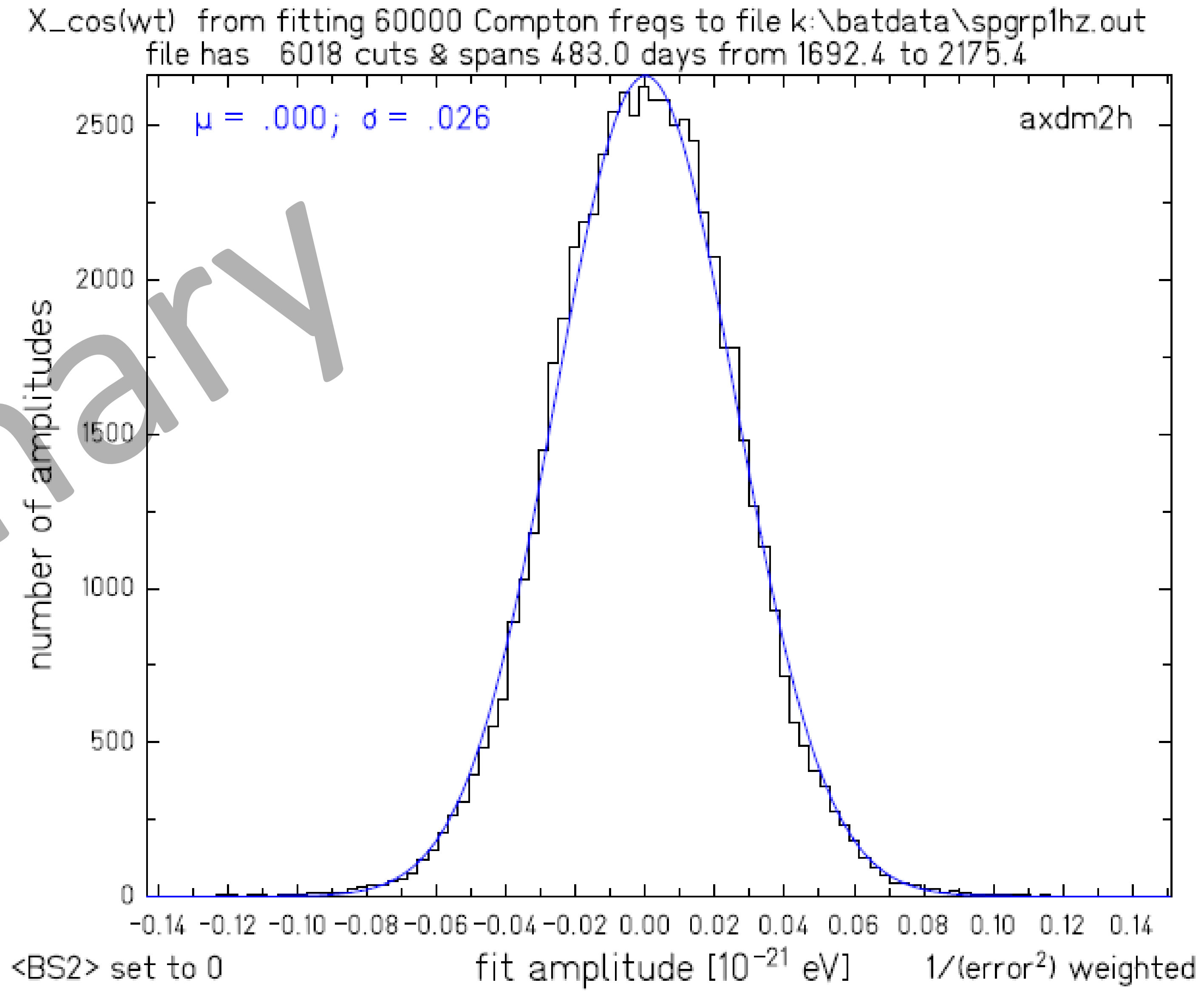


basis function for file k:\batdata\spgrp1.bs1
assumed Compton frequency = 2.00000E-07
eXNcoswt
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
1700
1750
1800
1850
1900
1950
2000
2050
2100
2150
time in days since 1/1/2000

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)

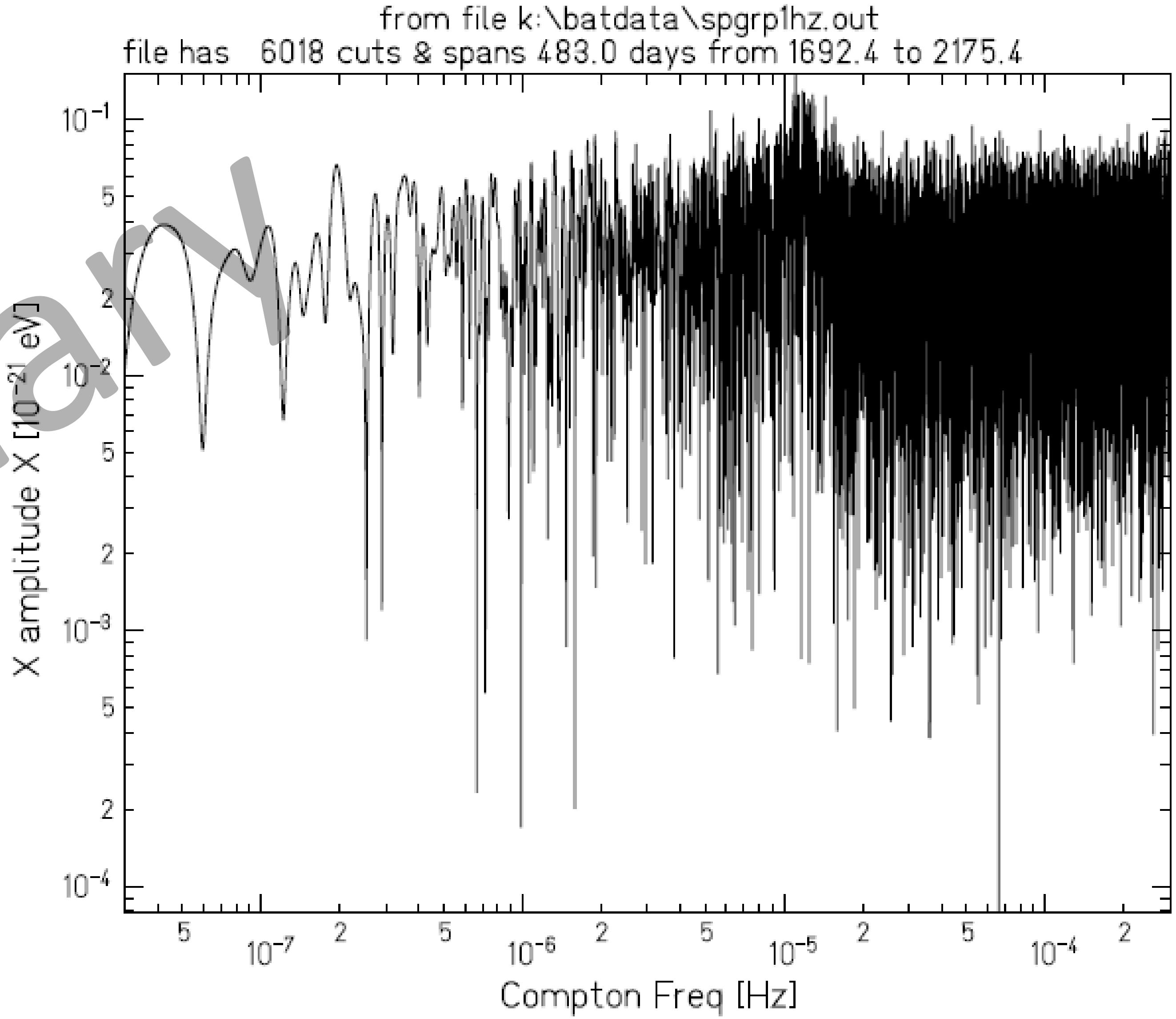
signal is expected to be coherent over $\approx10^{6}$ cycles i.e.over our entire data span in the range of frequencies we consider

95% confidence upper limit is 5.2×10^{-23} eV



X amplitude vs. Compton frequency extracted from roughly ½ of our data

results for Y amplitude are are very similar



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 lower thermal noise

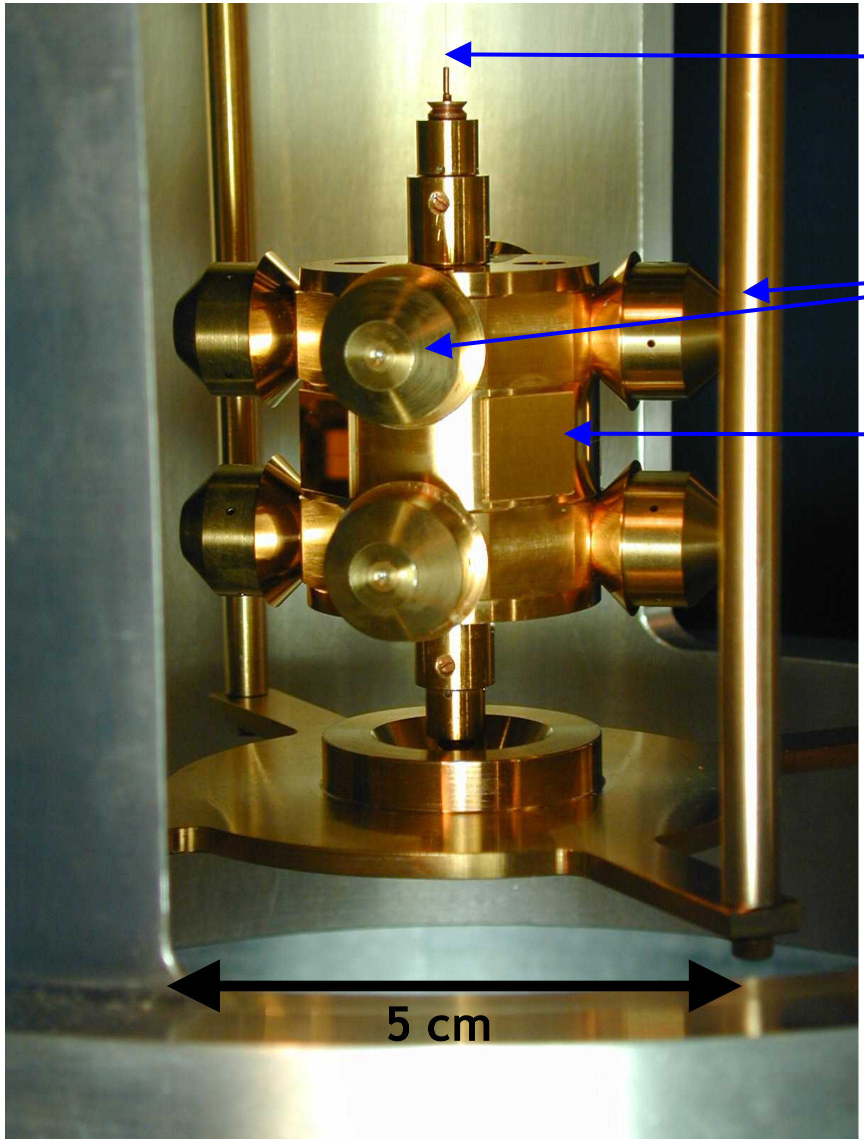
more sensitive twist-angle readout

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

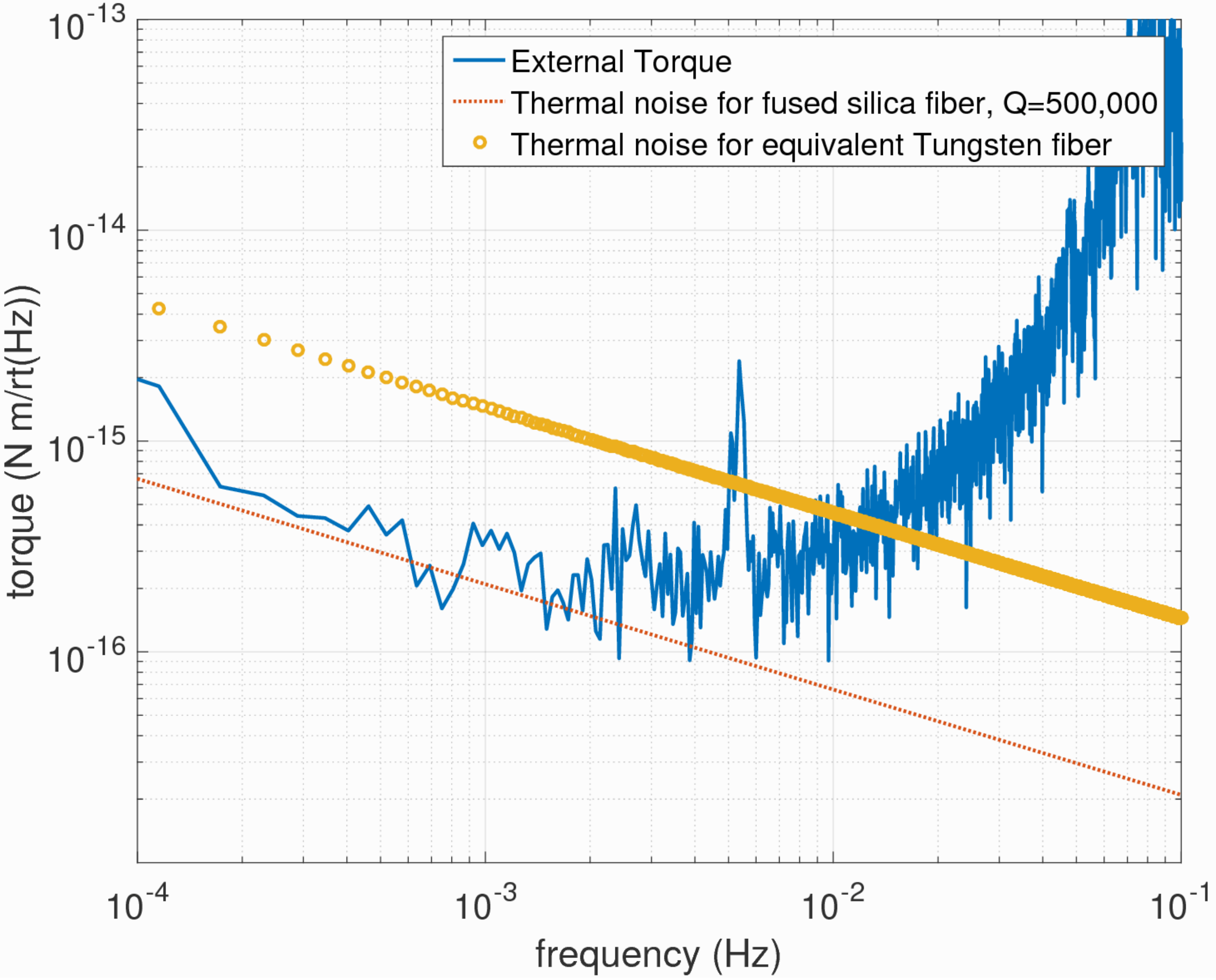
eight 4.84 g test bodies
4 Be & 4 Al

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



Lunar Laser Ranging currently provides the best tests of:

time-rate-of-change of *G*

fractional change < 10^{-12} per year

$1/r^2$ force law

violations < 10^{-10} times gravity at 10^8 m scales

strong equivalence principle

(does gravitational binding energy fall like everything else?)

$\Delta a/a \approx 10^{-13}$; gravity reduces earth's mass by 0.46 ppb => SEP verified to 4×10^{-4}

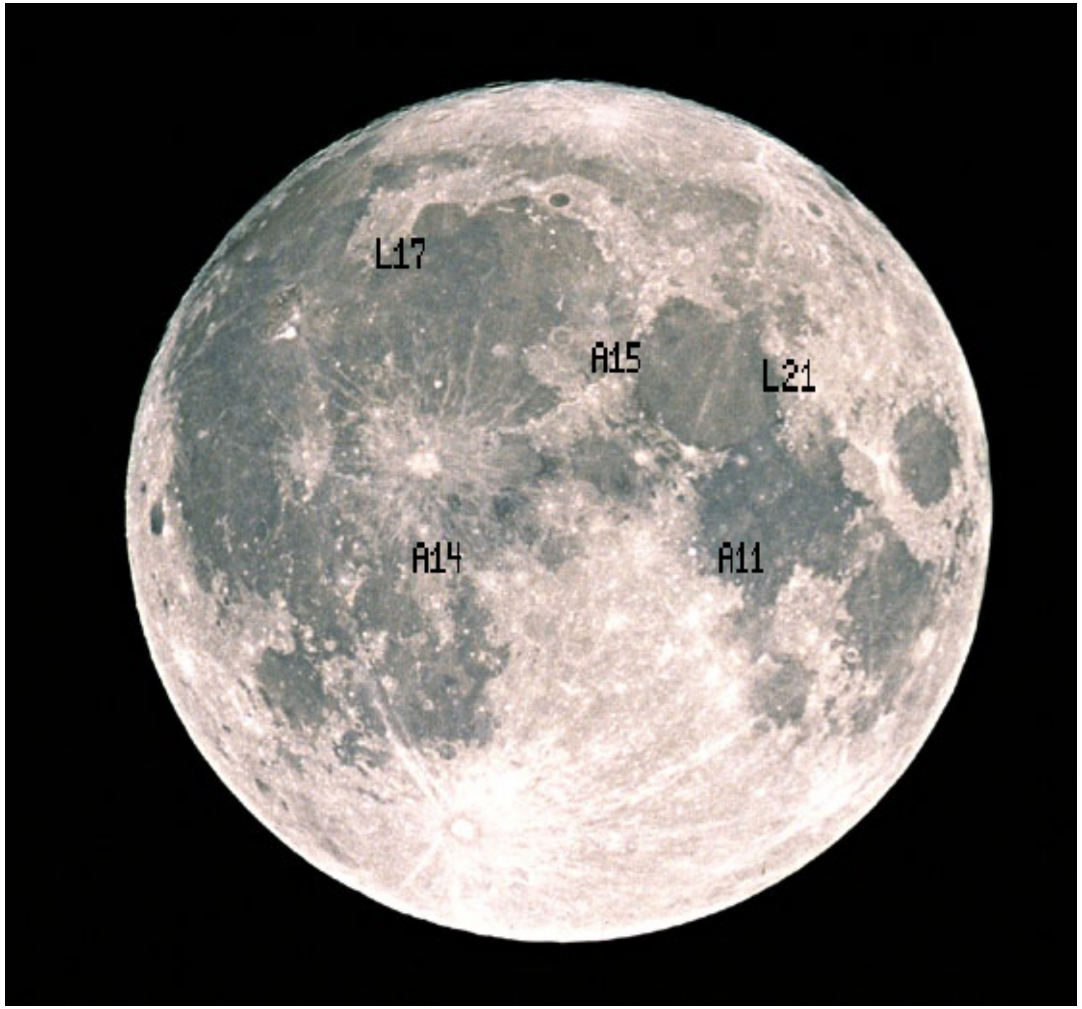
pulsar timing will soon give better constraints

preferred frames

equality of active and passive gravitational masses

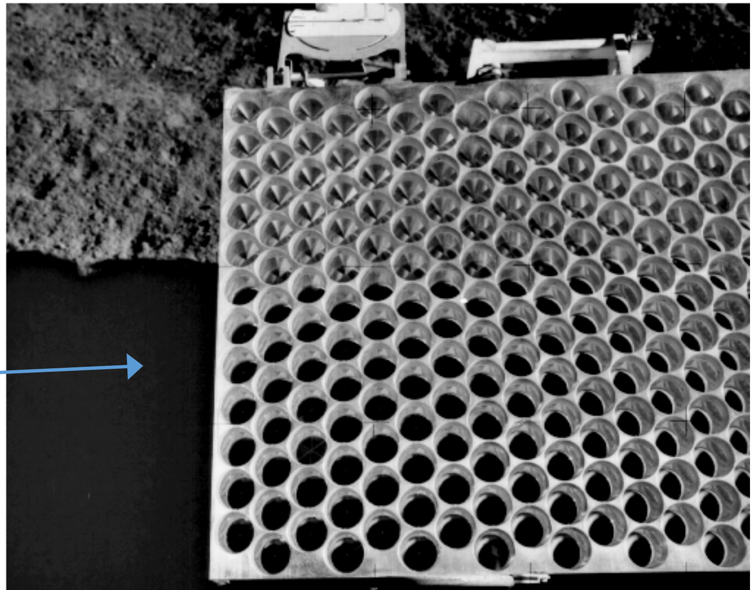
Williams, Turyshev and Boggs, Int. J. Mod. Phys. D 18 (2009) 1129

The Lunar Retro-reflectors



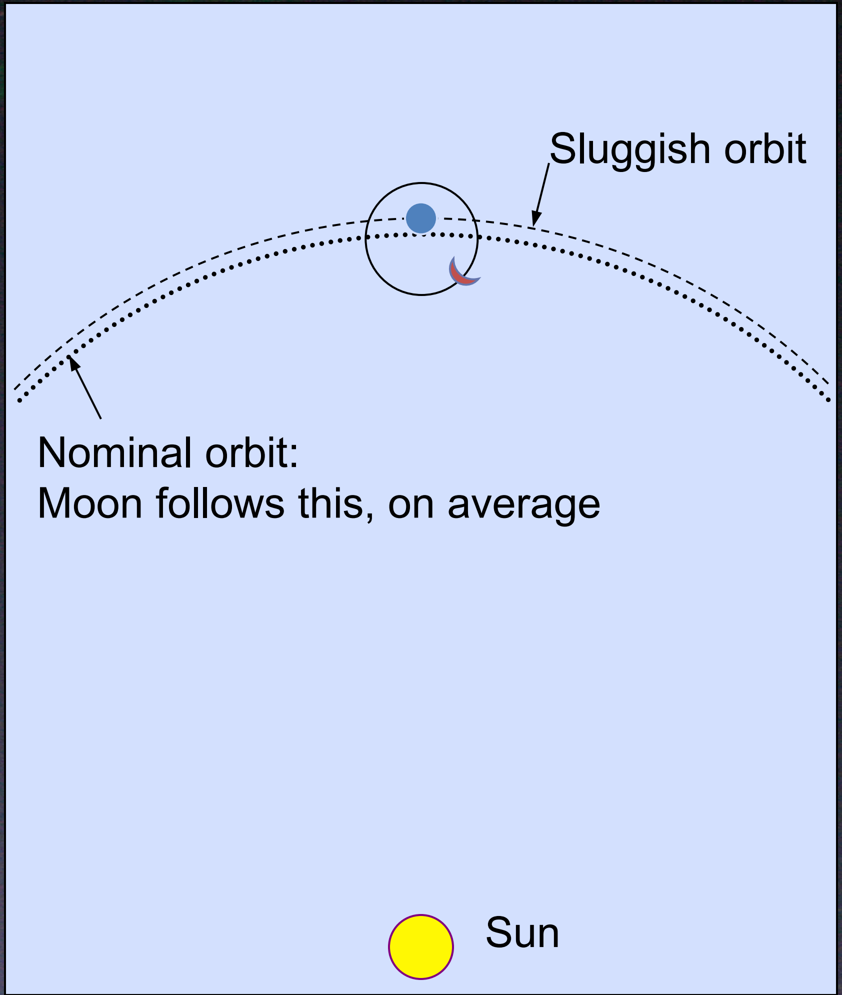
- Three Apollo missions placed reflectors on the moon
  - Apollo 11: 100-element
  - Apollo 14: 100-element
  - Apollo 15: 300-element
- Two French-built, Soviet-landed reflectors, similar in size to A11 & A14 were placed on rovers
  - Luna 17 (originally inaccessible)
  - Luna 21

A15

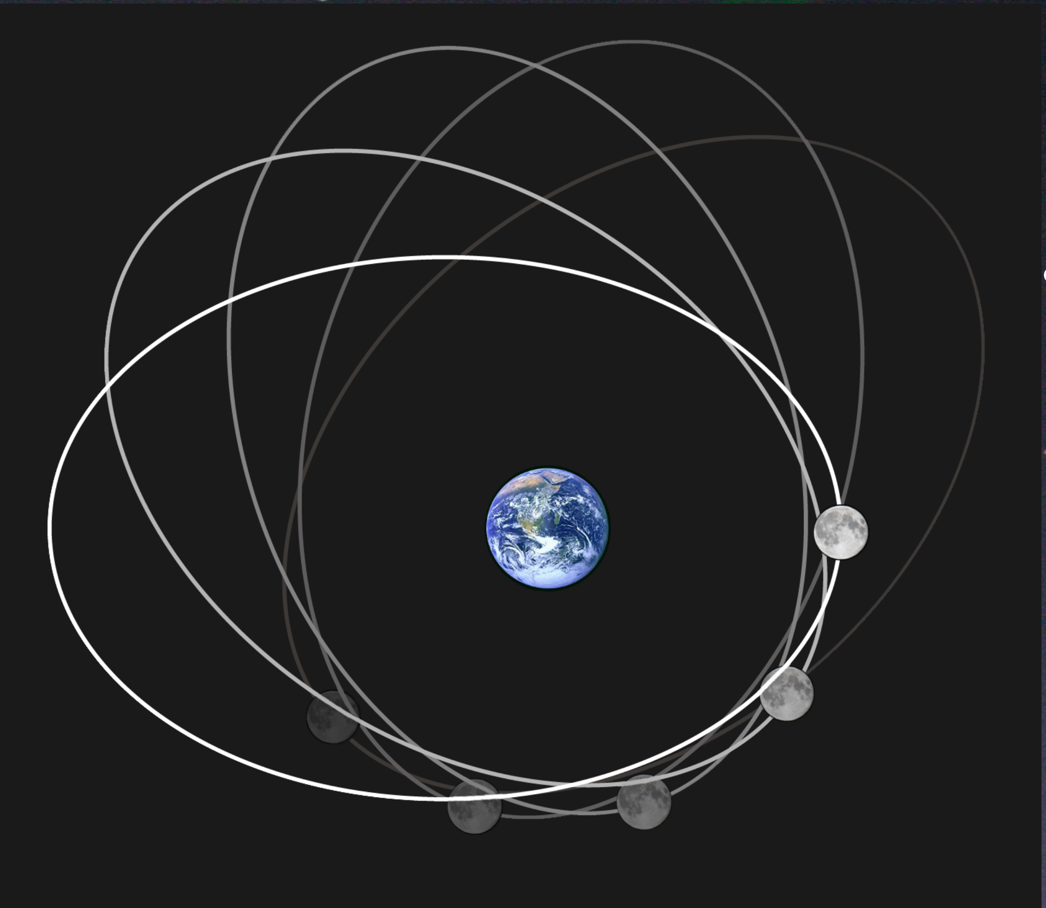


equivalence principle signal

- If earth had smaller gravitational to inertial mass ratio than the moon, the earth's orbit around sun would have larger radius than the moon's. It would appear that moon's orbit is *shifted* toward sun



Yukawa ISL violation signal



- LLR observations precisely determine moon's orbit precession of about 40.7 deg/y
- LLR model predicts precession arising from other solar-system bodies, quadrupole component of earth's field and relativistic effects
- 2σ upper limit on any residual anomalous precession is only 27 μas/y. This leads to the strong Yukawa constraint for λ~a/2 shown on an earlier slide.

G dot signal

- LLR tidal friction causes moon’s orbit to expand steadily (by coincidence at nearly the Hubble rate)

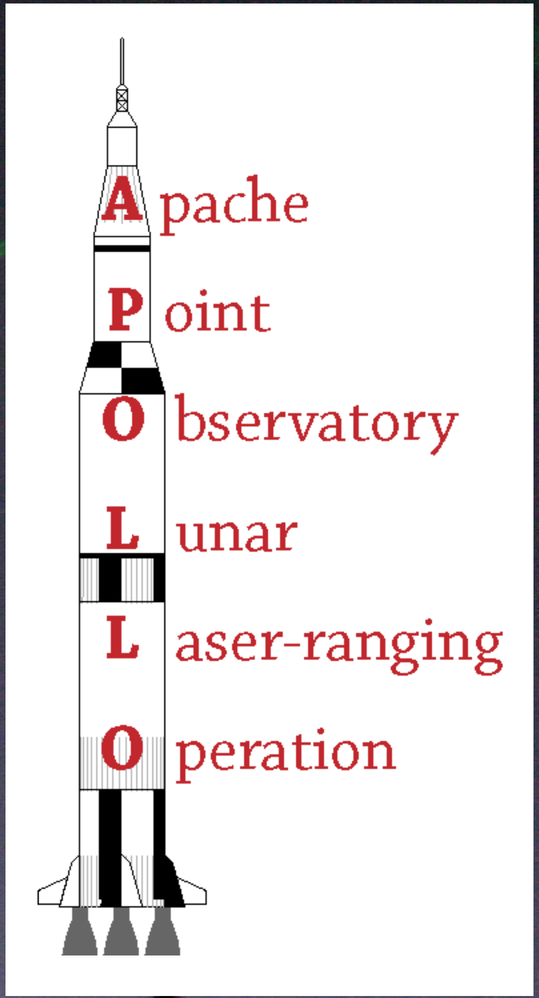
- LLR can distinguish this from changing G because the friction effect does not violate Kepler’s Third Law while G dot does

APOLLO: a next-generation LLR facility

UCSD, APO, Washington, Harvard, Humboldt State,

Northwest Analysis collaboration led by Tom Murphy at UCSD

and funded by NASA & NSF



APOLLO provides factor of 10 improvement in range precision (from cm to mm) and

factor of 100 improvement in data rates by:

- using a 3.5 meter telescope with good seeing
- firing 20 pulses/sec
- gathering multiple photons/shot with 16 element detector array

APOLLO's high precision, high data rate, and our focus on understanding systematic error make it possible to take lunar laser-ranging to a new level.

LLR measures ranges between telescope and lunar reflectors:

APOLLO increases range precision from cm to mm

APOLLO can operate during full moon to sample wider portion of moon's orbit

APOLLO can range to all 5 lunar reflectors providing info on lunar orientation & tides

Gravitational science relies on models to convert these ranges into the distance between centers of mass of Earth and Moon.

Models must account for solar system dynamics, plus atmospheric, terrestrial and lunar solid-body effects

APOLLO's high data rate and ancillary instrumentation allow us to probe systematic errors in both ranges and models

APO 3.5 m, New Mexico, 2800 m elevation

Examples of APOLLO’s capabilities

- found the lost L17 reflector
- routinely range to all 5 reflectors

  ranges to 3 reflectors give 1 distance and 2 angles

  ranges to 5 reflectors add 2 measures of moon’s tidal deformation

  A recent 1-hour session with very good “seeing” cycled twice through all 5 reflectors, and counted ~45,000 photons.

  This is about as many photons as OCA (best previous LLR station) gathered in 1 year.

- regularly range in full moon

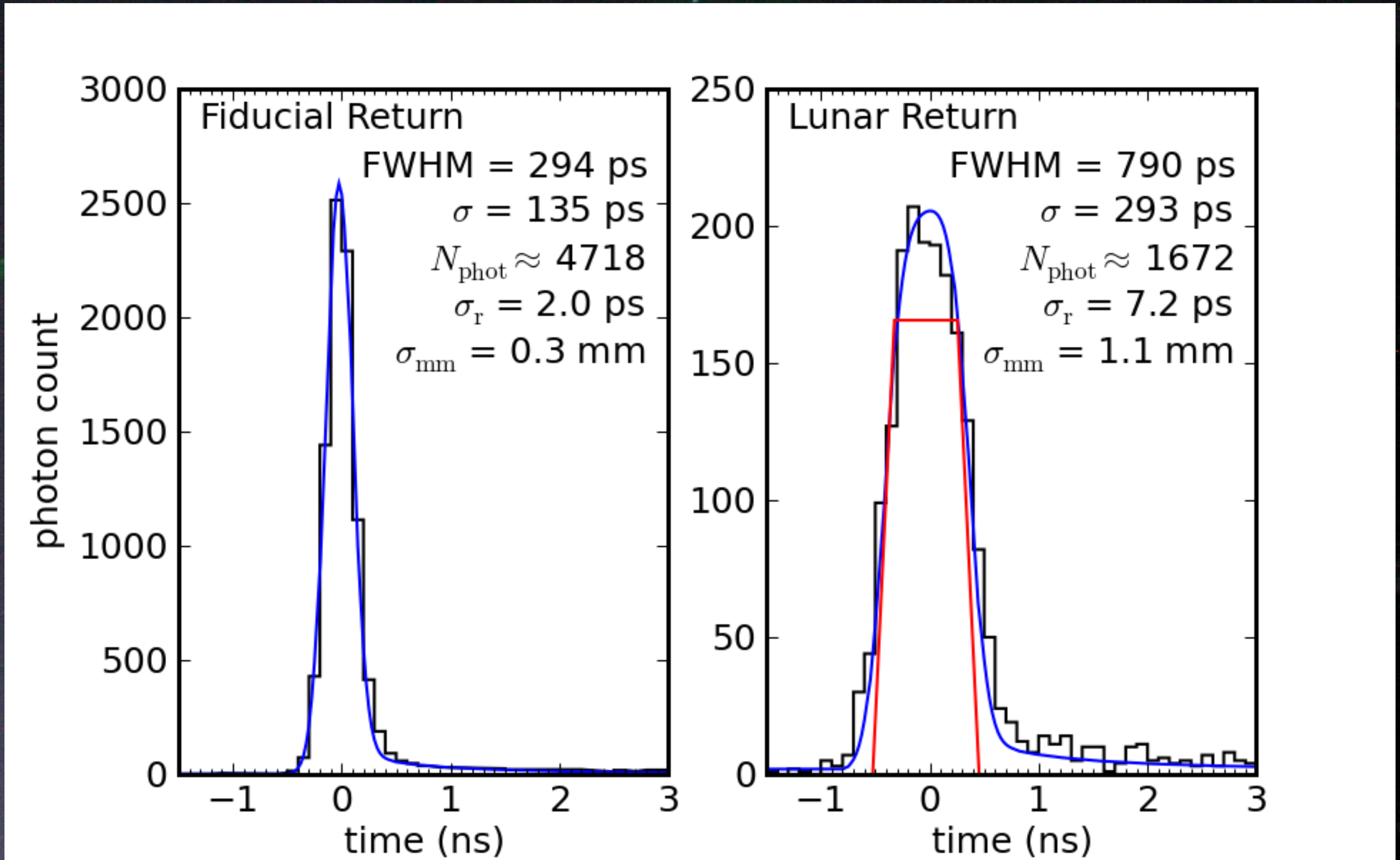
  samples lunar cycle more uniformly

- high data rate allows systematic investigations

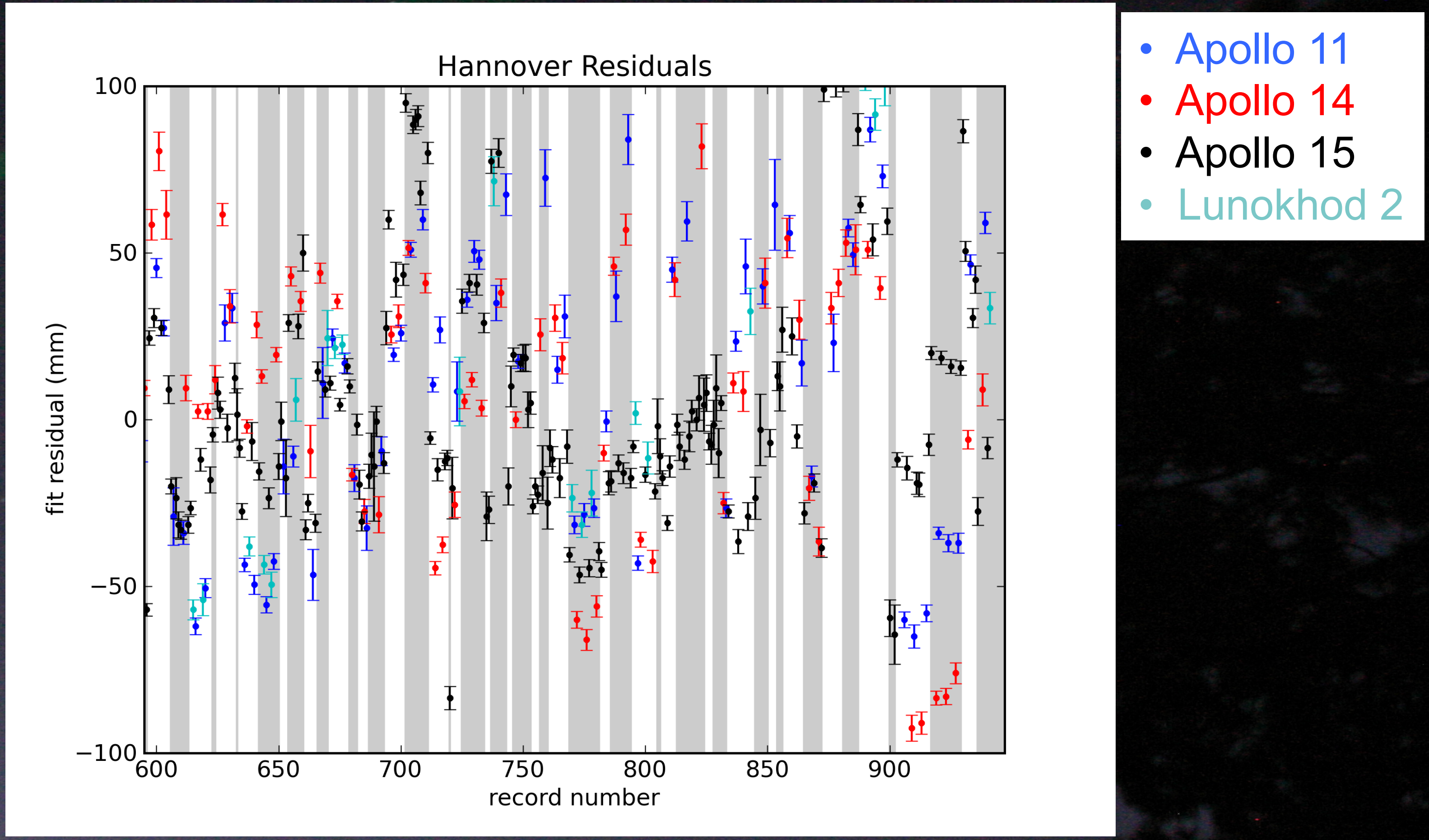
  studied degradation and thermal properties of reflectors

  Important for plans to place new optical devices on the moon

Fitting the Return & Reflector Trapezoid

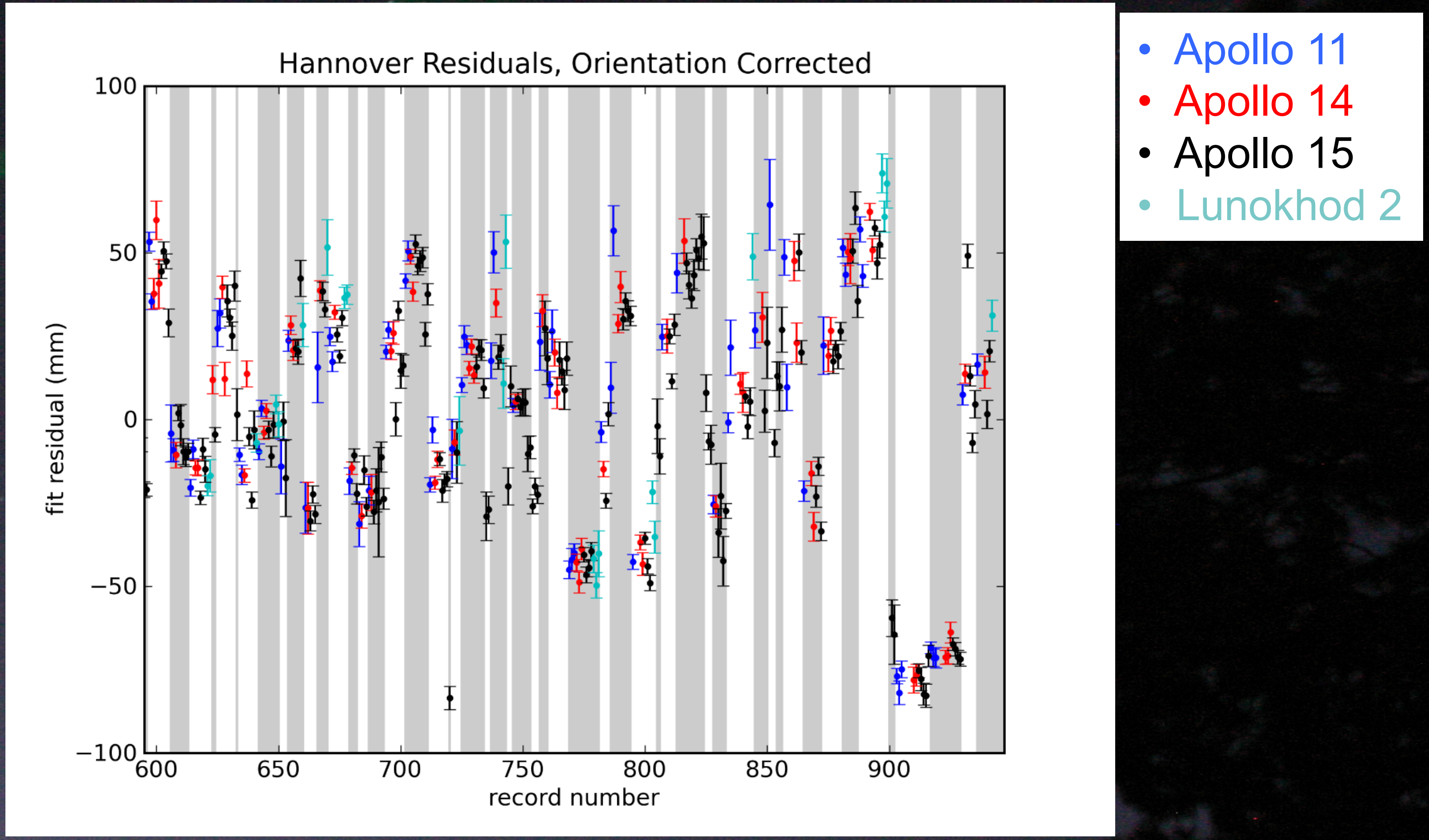


APOLLO data clearly require nightly adjustment of the predicted lunar orientation

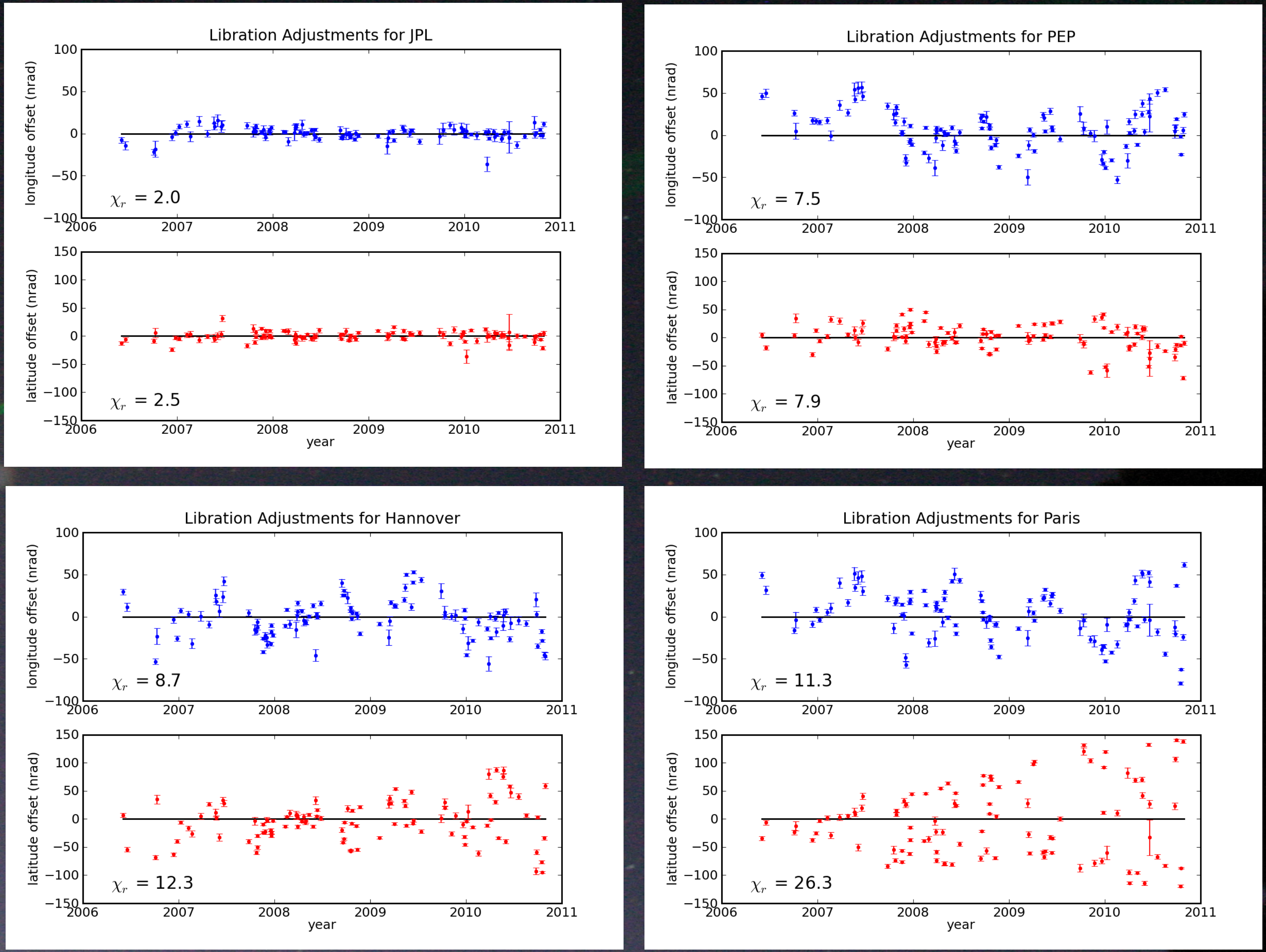


(vertical bands show individual nights)

Example: tweaking the model's lunar orientation

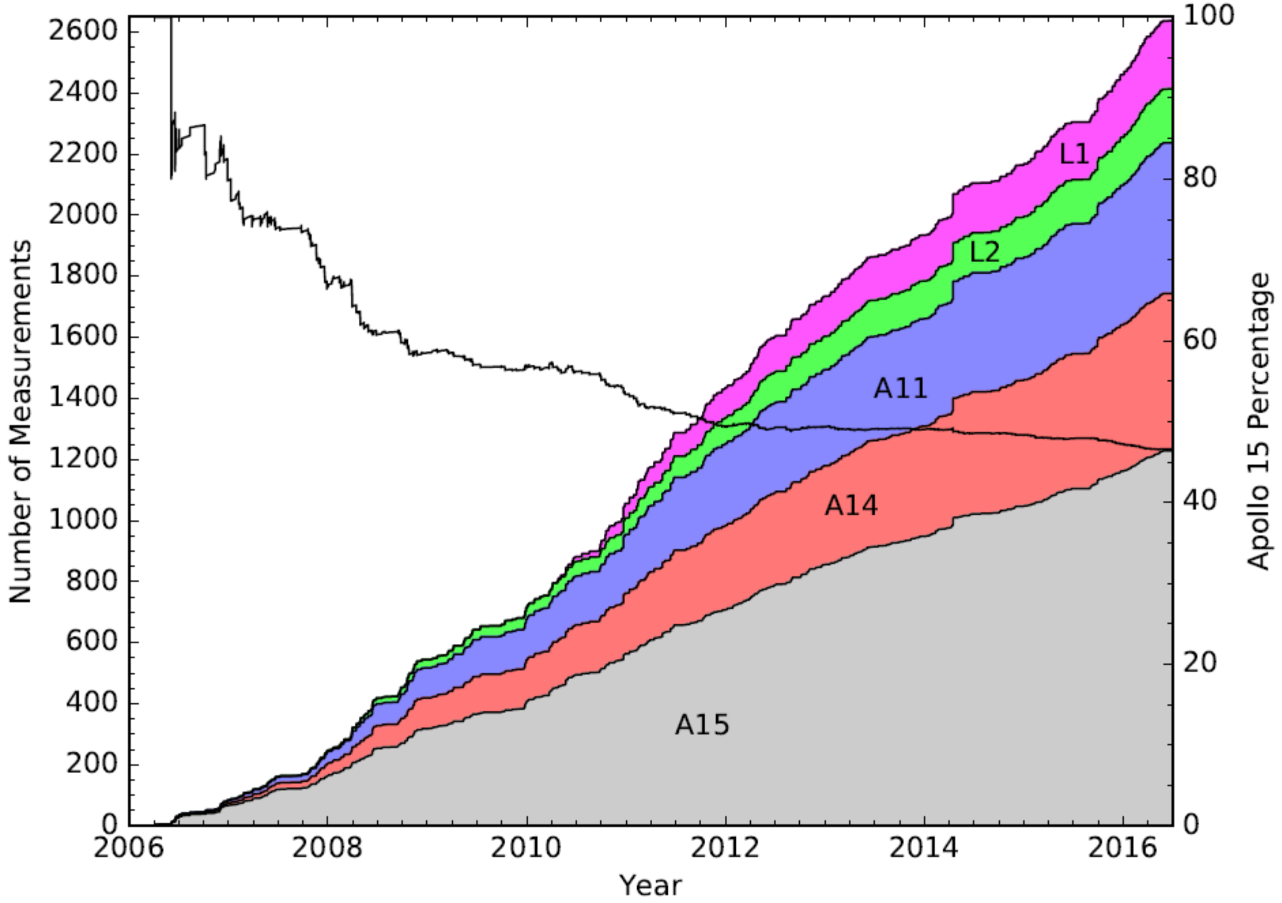


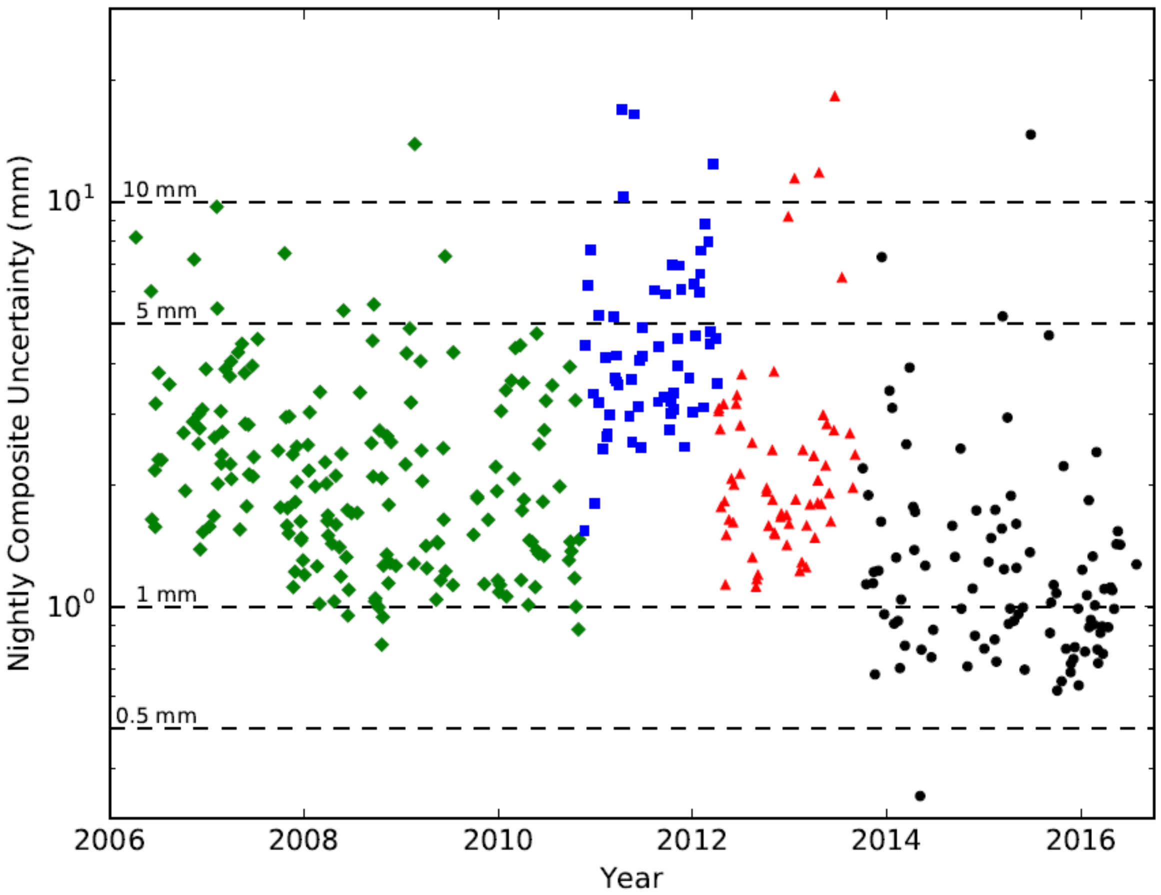
adjusting moon orientation to fit APOLLO data



Ranges are very sensitive to lunar orientation; 1 nrad is 1.7 mm at moon's surface. Here we tweaked lunar orientation each night to minimize the spread between residuals for different reflectors

APOLLO performance history





How good is the terrestrial component of the LLR model?
Observed APOLLO site motion relative to that of the North American plate

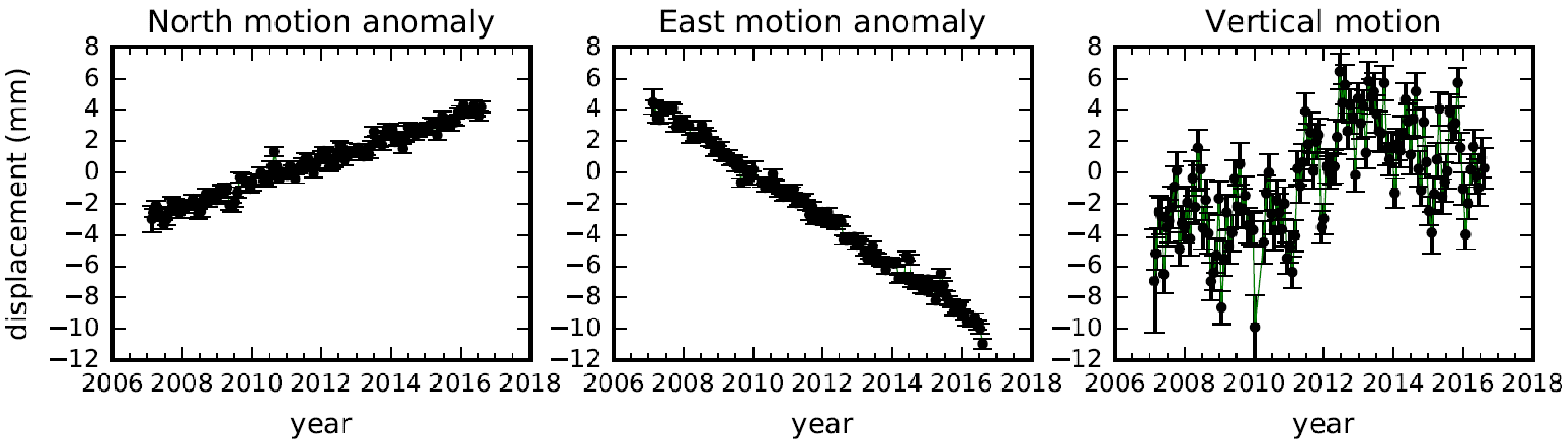
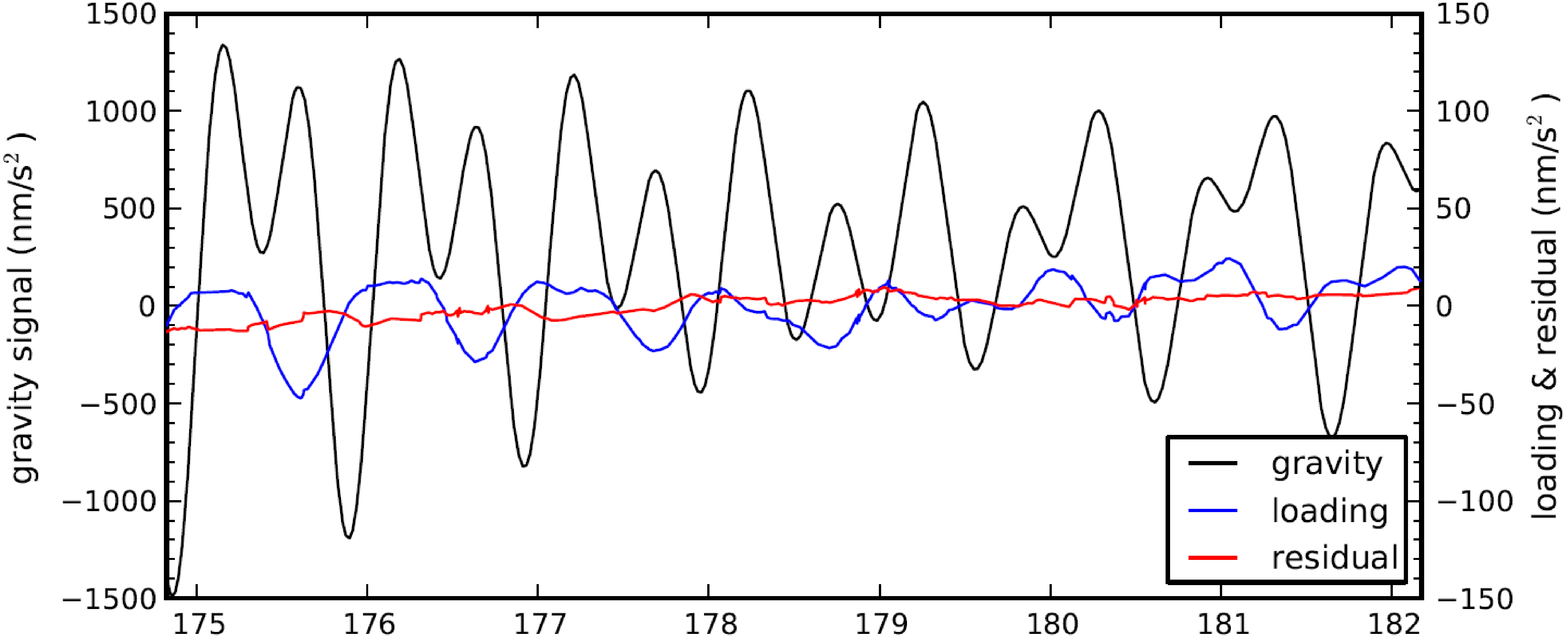


Figure 4: GPS data from the P027 PBO station located 2.5 km away from the Apache Point Observatory (on a similar summit). Data are binned in lunar-monthly units. Motions are shown *relative to* the North American plate, moving at (−6.3, −11.5, −0.6) mm/yr in the north, east, and up directions. The net motion of station P027 with respect to the global frame becomes (−5.6, −13.0, +0.1) mm/yr. The vertical motion indicates peak-to-peak site motions exceeding 1 cm, highlighting the need to incorporate geodetic measurements into millimeter-quality LLR analysis.

Terrestrial models must also explain the high-sensitivity gravity data from a superconducting gravimeter located the APOLLO site.

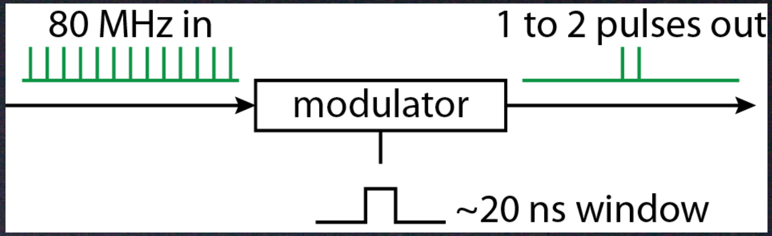
A 1 week sample is shown



Step changes reflect rotation of the telescope dome

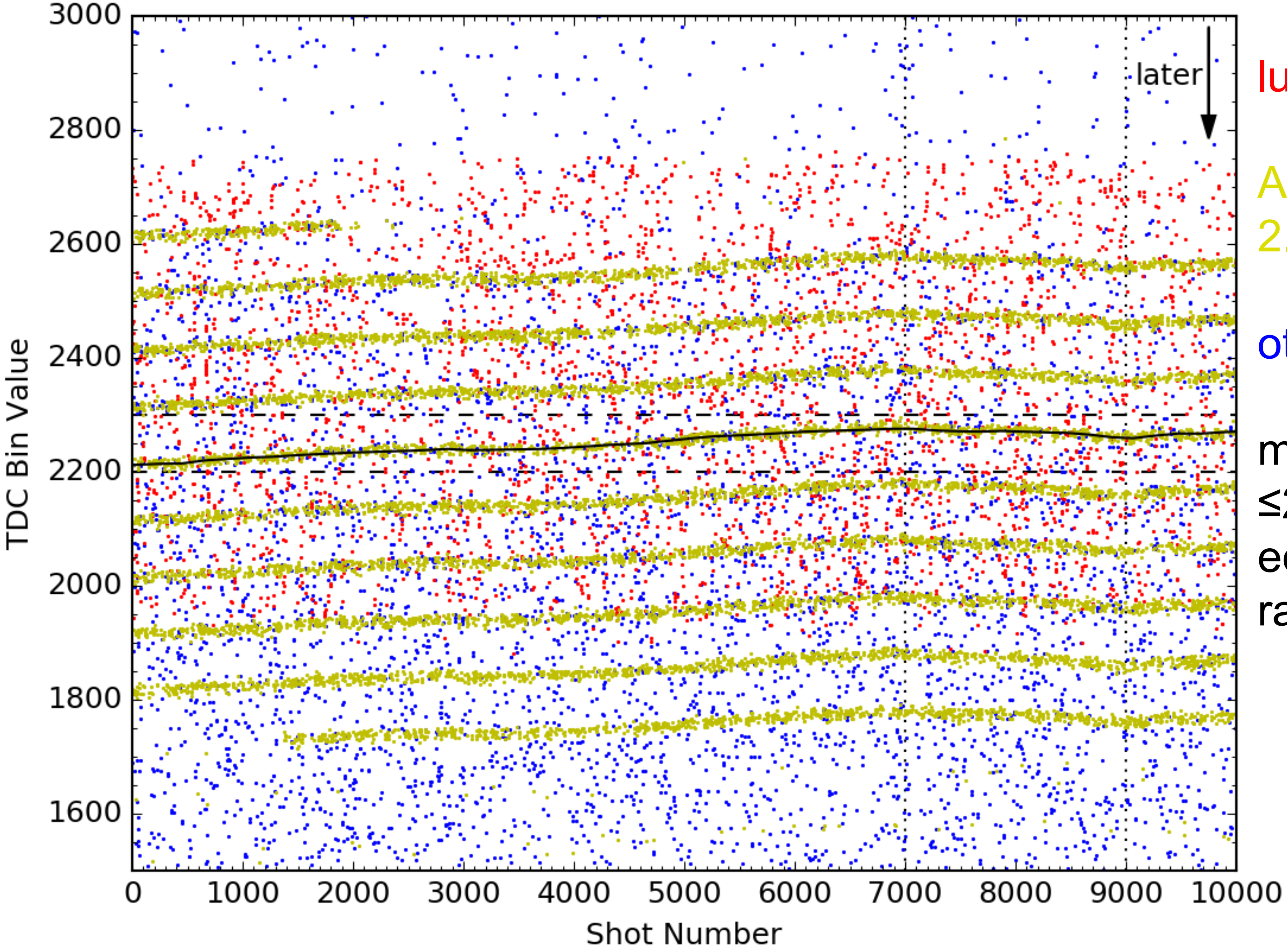
New Development: Precision → Accuracy

- Ranges prior to 2015 based on APOLLO's GPS-steered Rb clock
- Absolute Calibration System (ACS) installed August 2016
- 80 MHz, 10 ps fiber laser, locked to cesium clock with precision < 1 ps
- Can pick pulses out around lunar return time & overlay



- Likewise for local fiducial corner cube return
- Provides reference photons at APD "on time"
  - tick marks on calibrated ruler, measured exactly like lunar photons
- Also allows offline tests and characterization of systematics

First run with ACS: 2016.09.12 still using GPS-steered Rb clock



lunar photons

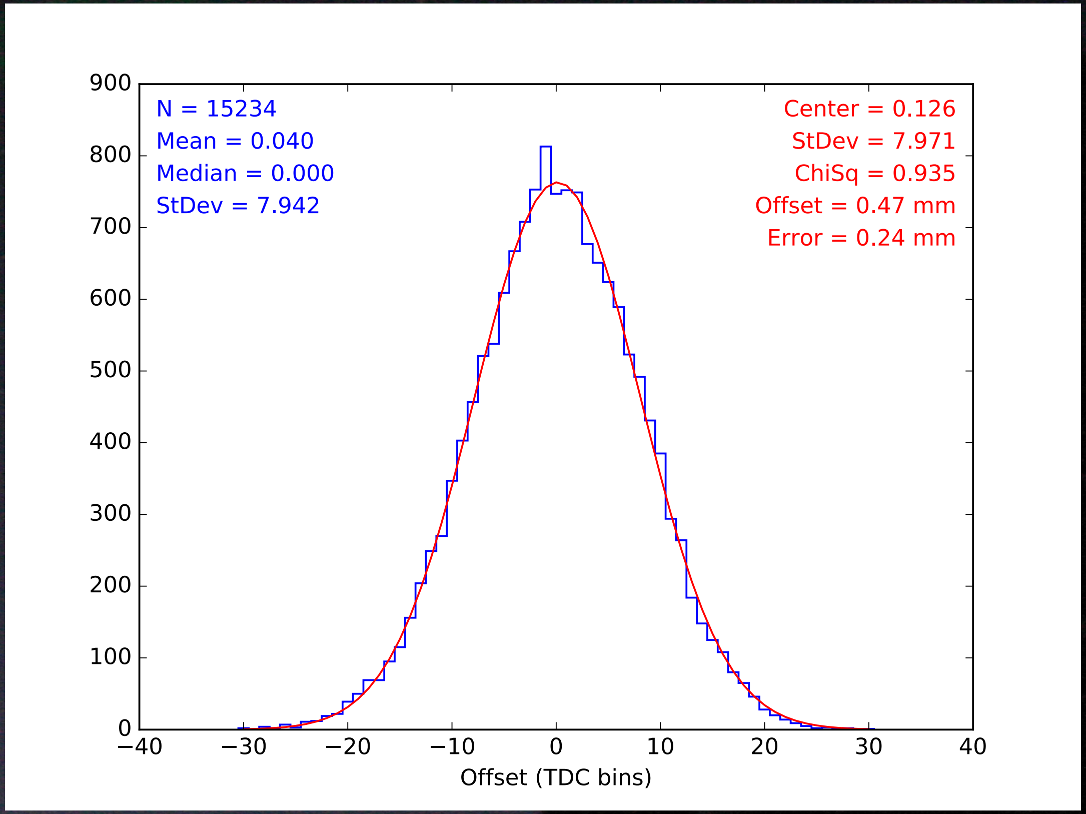
ACS photons provide 2.5 ns “comb” spacing

other events

measured clock drift ≤2 ns in 200s equivalent to 1.5 mm range error

Encouraging prospects

- Have sub-mm statistical range uncertainities
- ACS shows our prior data had 1 to 2 mm systematic errors
- Clock drift readily visible
- See channel-dependent timing characteristics
  - known/corrected, but took months to gather data for assessment; now takes 10 minutes



Next Step: Model Development

To extract fundamental science from new LLR data one must model all effects that influence telescope-retroreflector ranges at the mm level:

- relativistic gravity in solar system
- tidal effects
- atmospheric propagation delays
- terrestrial and lunar orientations
- geophysics + selenophysics

This is a challenging problem, and it is <u>vital</u> to have several independent codes

The best (JPL) LLR model currently gives 15 mm APOLLO residuals. This allows them to fit the characteristic EP signature with 4 mm uncertainty.

With APOLLO's ACS we expect to quote normal points with verified 2 mm absolute uncertainty which will put real pressure on the models

The ball is now increasingly in the modeler's court!

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