

# Exotic spin-dependent interactions plus Progress in Lunar Laser ranging

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University of Washington

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

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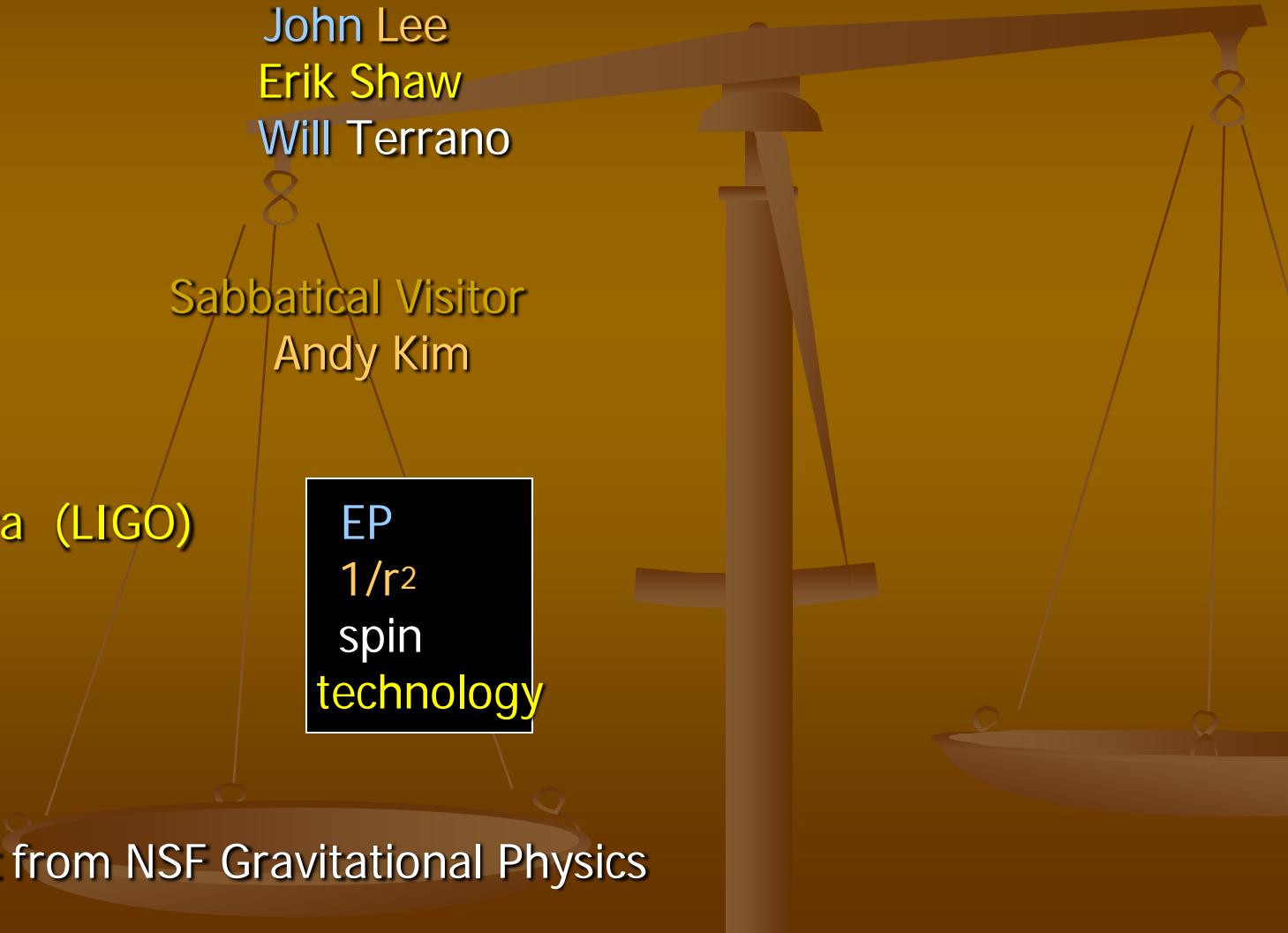
Will Terrano

## 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<sub>5</sub>** – 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<sub>5</sub>:

The Sm in SmCo<sub>5</sub> 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.

$$m_L = (+3) + (+2) + (+1) + (0) + (-1) = 5 \quad \text{i.e. } L=5$$

The spin function must be maximally symmetric i.e. S=5/2.

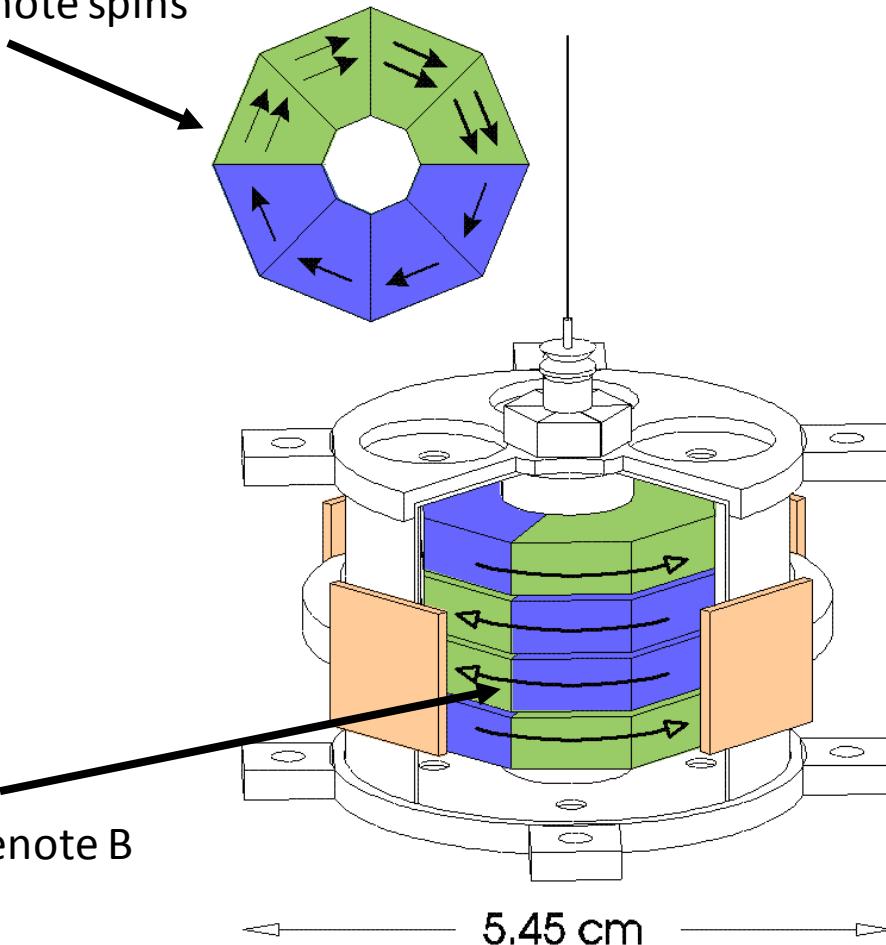
Therefore the spin and orbital contributions to the Sm magnetic moment are equal.

Hund's Rule says that at beginning of a shell the two contributions cancel.

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

# the Eöt-Wash spin pendulum

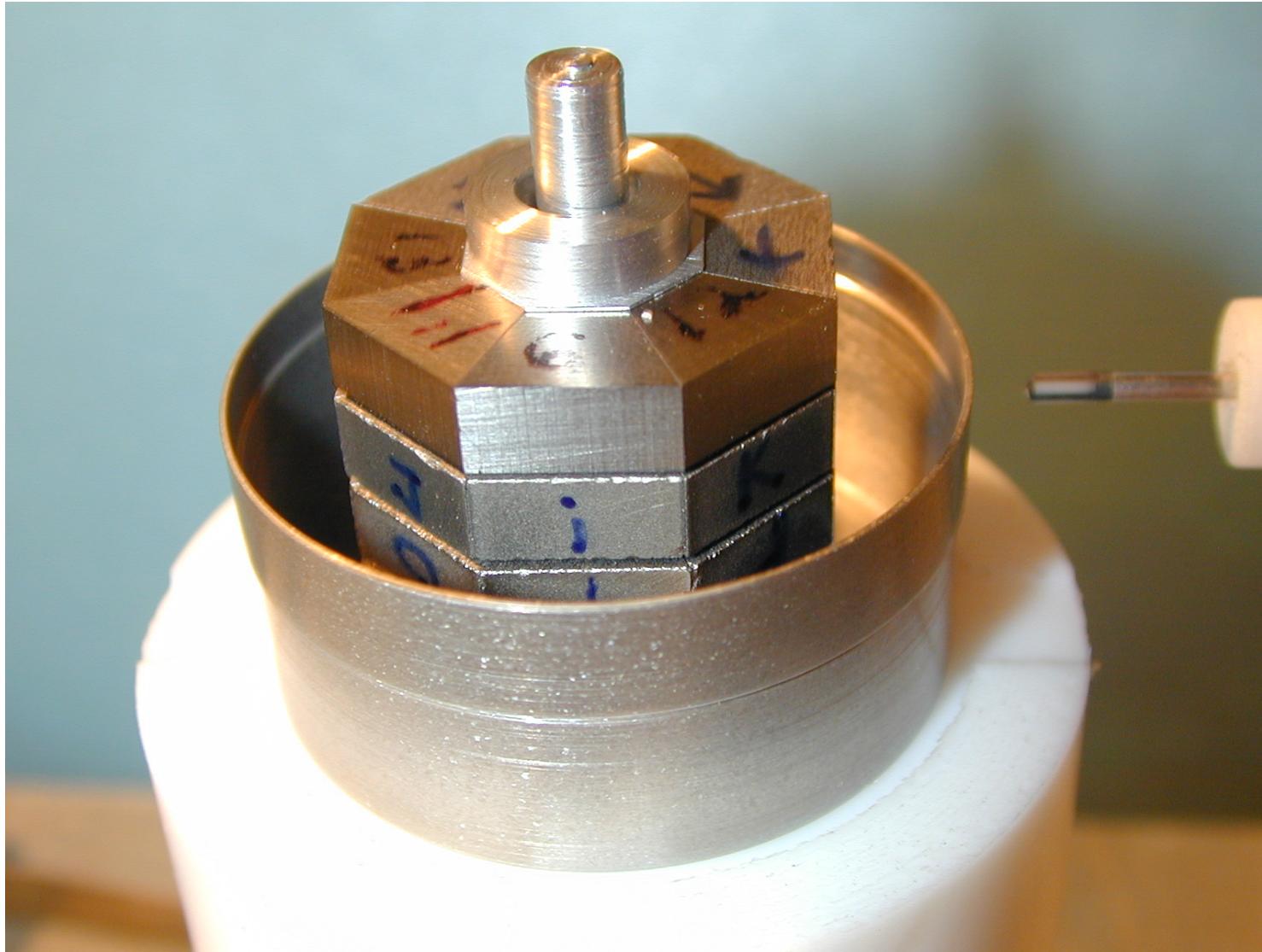
arrows denote spins



arrows denote B

- $9.8 \times 10^{22}$  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
- $\text{SmCo}_5$ : Sm  $3^+$  ion spin points along total B and its spin B field is nearly canceled by its orbital B field--so B of  $\text{SmCo}_5$  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  $B_{\text{Sm}} \propto 2S_{\text{Sm}} + L_{\text{Sm}} \approx 0$  we find  
$$J_{\text{Sm}} = - S_{\text{Sm}}$$

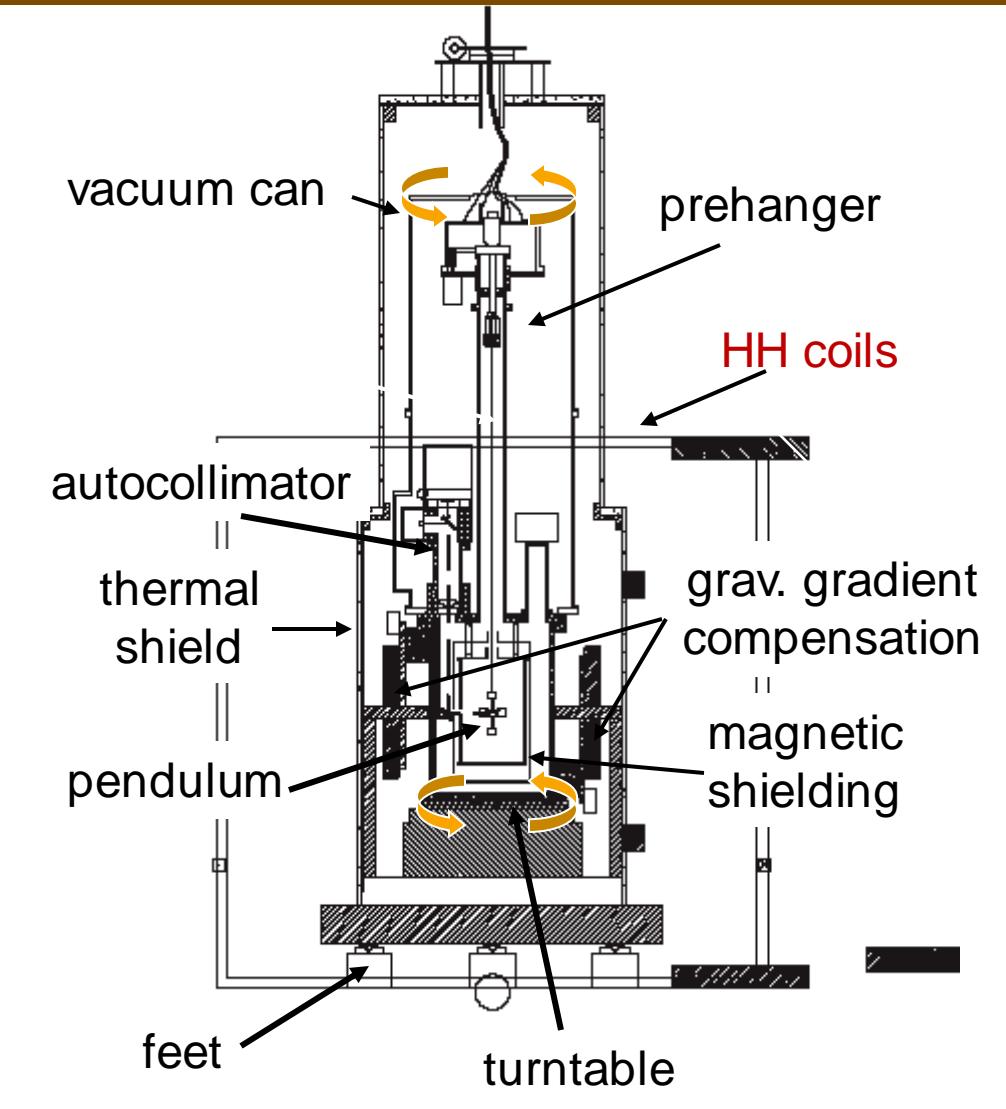
# measuring the stray magnetic field of the spin pendulum



$B$  inside =  $9.6 \pm 0.2$  kG

$B$  outside  $\approx$  few mG

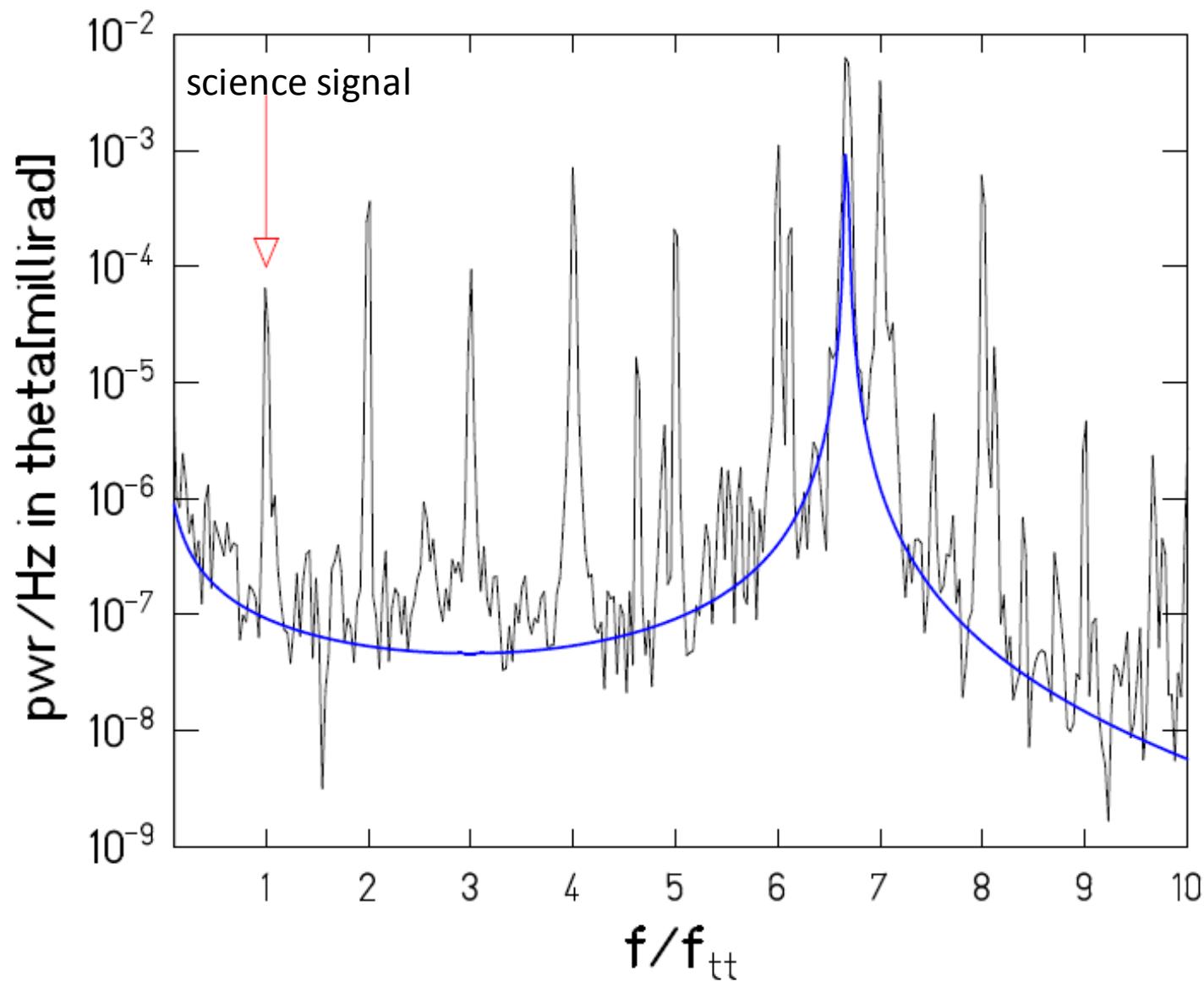
# the Eöt-Wash rotating torsion balance

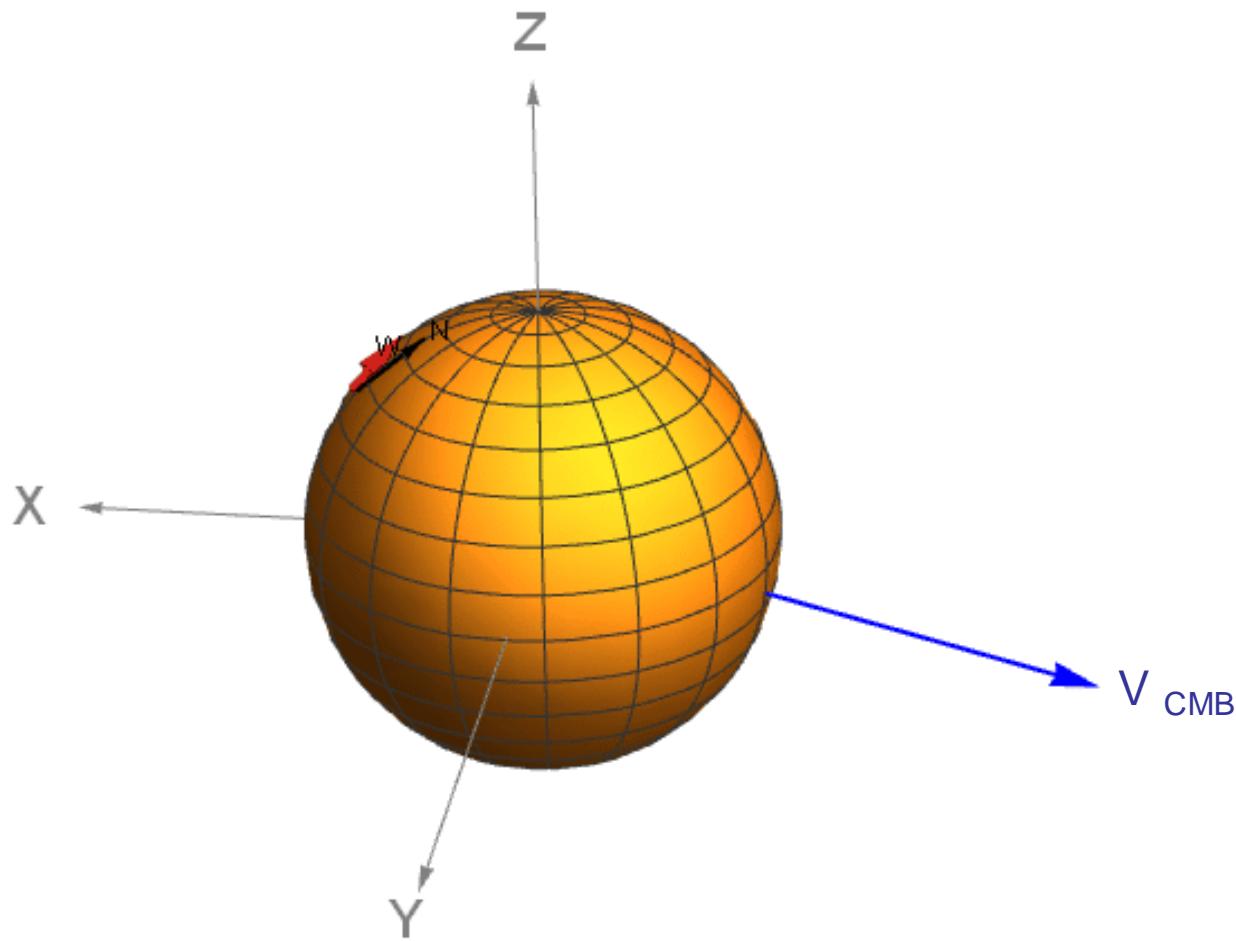


# power spectrum of the spin-pendulum twist

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.





# cosmic preferred frames?

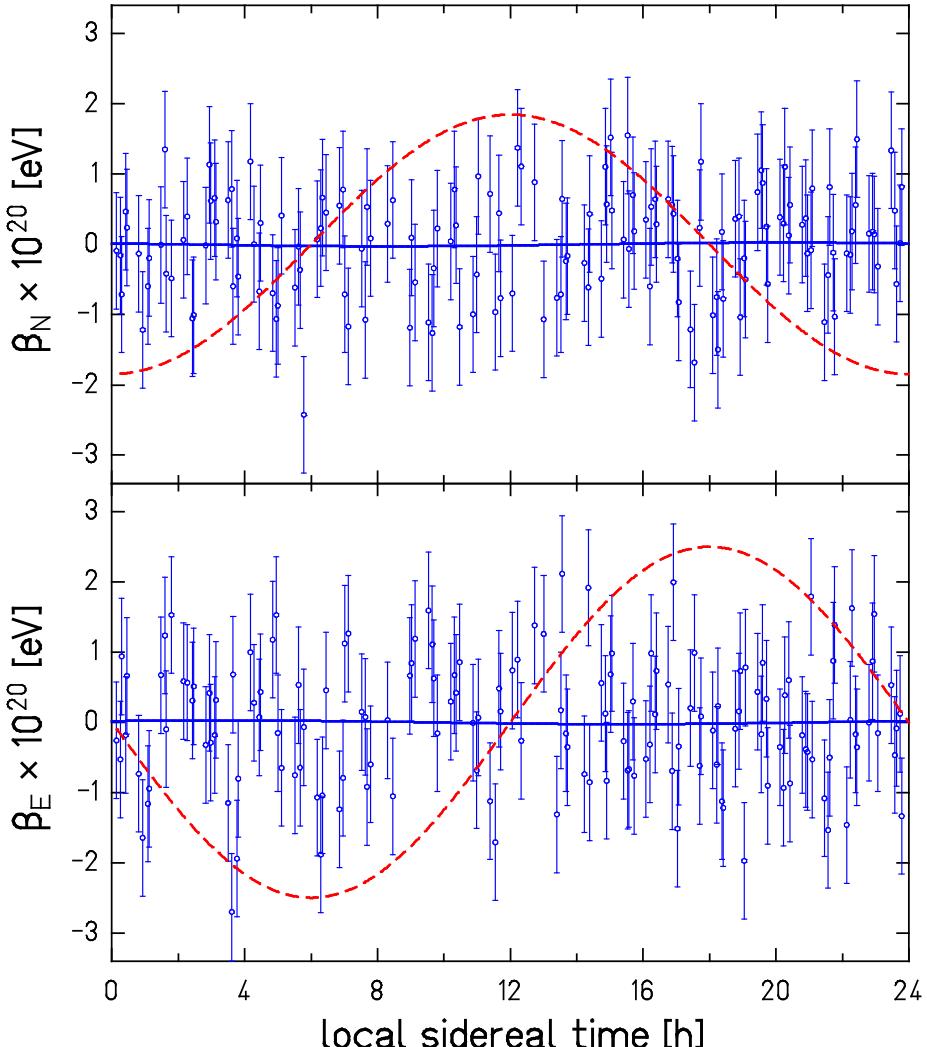
We all were taught that there are no preferred frames. But the Universe defines a frame in which the CMB is essentially isotropic. Could there be other preferred frame effects defined by the Universe?

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  $m_e^2/M_{\text{Planck}} \approx 2 \times 10^{-17}$  eV

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



definition of  $\beta$ :

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

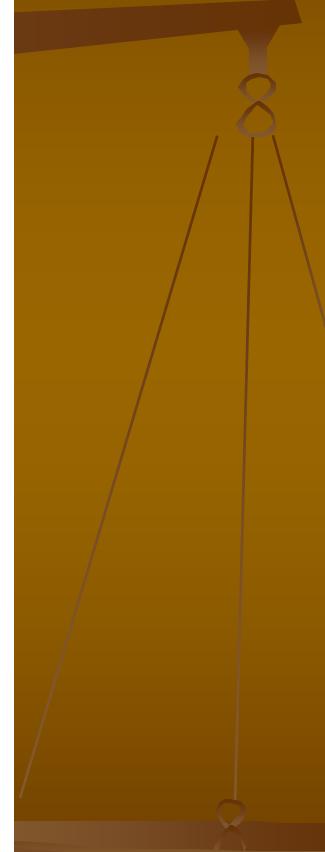
$2\beta$ =energy needed  
to flip a spin

— — — — —

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

---

best fit out-of-phase sine  
waves--corresponds to  
preferred-frame signal:  
 $b_x = (-0.20 \pm 0.76) \times 10^{-21} \text{ eV}$   
 $b_y = (-0.23 \pm 0.76) \times 10^{-21} \text{ eV}$



# 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

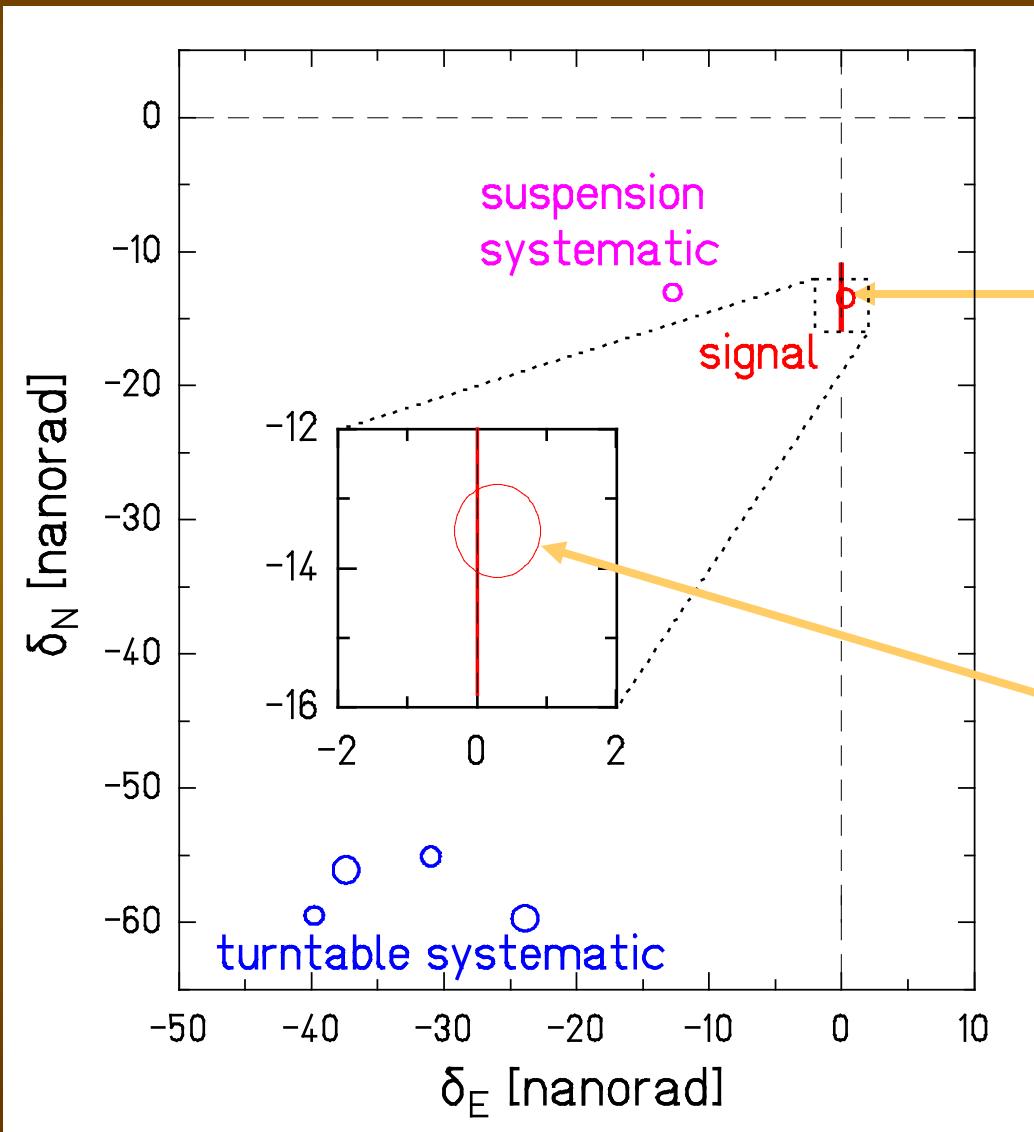
angular momentum  $J$  of a spinning flywheel in a lossy gimbal will eventually point true North where the gimbals do not dissipate energy

## our gyrocompass.

Earth's rotation  $\Omega$  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  $\beta_N = - 1.616 \times 10^{-20} \text{ eV}$

# lab-fixed spin pendulum signal



gyrocompass effect:  
The vertical bar shows  
expected effect based on  
2 previous discordant  
measurements of  $\text{SmCo}_5$   
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:  $1\sigma$  constraints on the Lorentz-symmetry violating  $\tilde{b}^e$  parameters. Units are  $10^{-22}$  eV.

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



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?

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

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

Our 1 sigma spin-pendulum result

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

# an amusing number

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

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

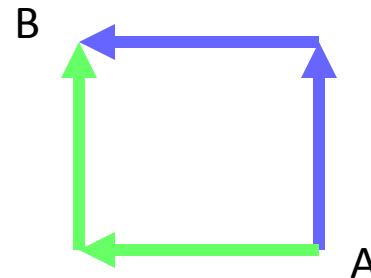
where  $\Theta_{ij}$  has units of area and represents the minimum observable patch of area, just as the commutator of  $x$  and  $p_x$  represents the minimum observable product of  $\Delta x \Delta p_x$

“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



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

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

$\Lambda$  is a cutoff which is assumed to be 1TeV for electrons

Our results imply  $\theta \leq 6 \times 10^{-58} \text{ m}^2$   
which seems very small and indeed it is

but in another sense it is also quite large

$$6 \times 10^{-58} \text{ m}^2 \sim (10^6 L_P)^2$$

where  $L_P$  is the Planck Length

$$\sqrt{\hbar G/c^3} = 1.6 \times 10^{-35} \text{ m}$$

or  $\sim (10^3 L_U)^2$

where  $L_U$  is the Grand Unification length

$$L_U = \hbar c / 10^{16} \text{ GeV}$$

but  $10^{13} \text{ GeV}$  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

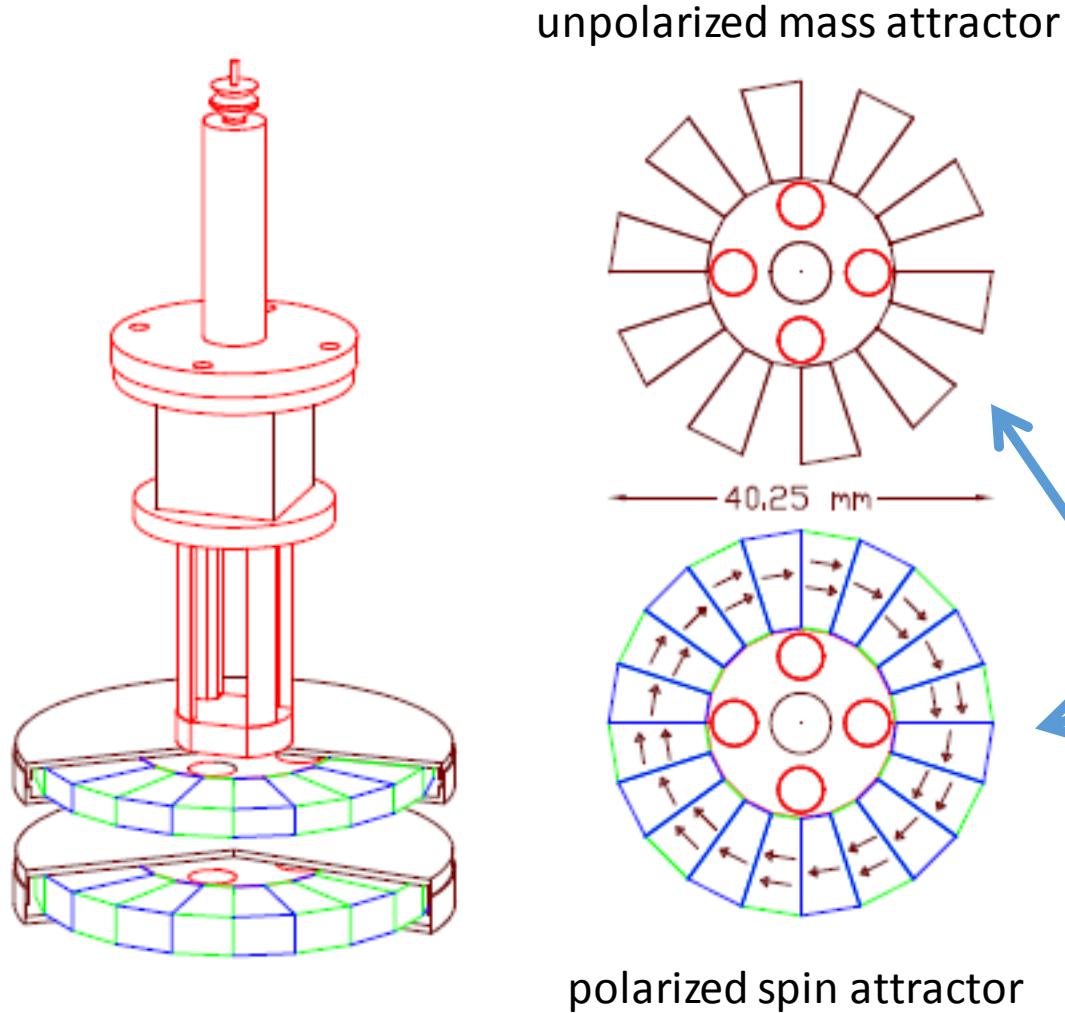
$$V_{dd} = \frac{g_p^2 \hbar^2}{16\pi m_e^2 c^2 r^3} \left[ (\hat{\sigma}_1 \cdot \hat{\sigma}_2) \left( 1 + \frac{r}{\lambda} \right) - 3(\hat{\sigma}_1 \cdot \hat{r})(\hat{\sigma}_2 \cdot \hat{r}) \left( 1 + \frac{r}{\lambda} + \frac{r^2}{3\lambda^2} \right) \right] e^{-r/\lambda}$$
$$\lambda = \hbar/(m_b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

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

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

# Eöt-Wash pseudo-Goldstone boson detector

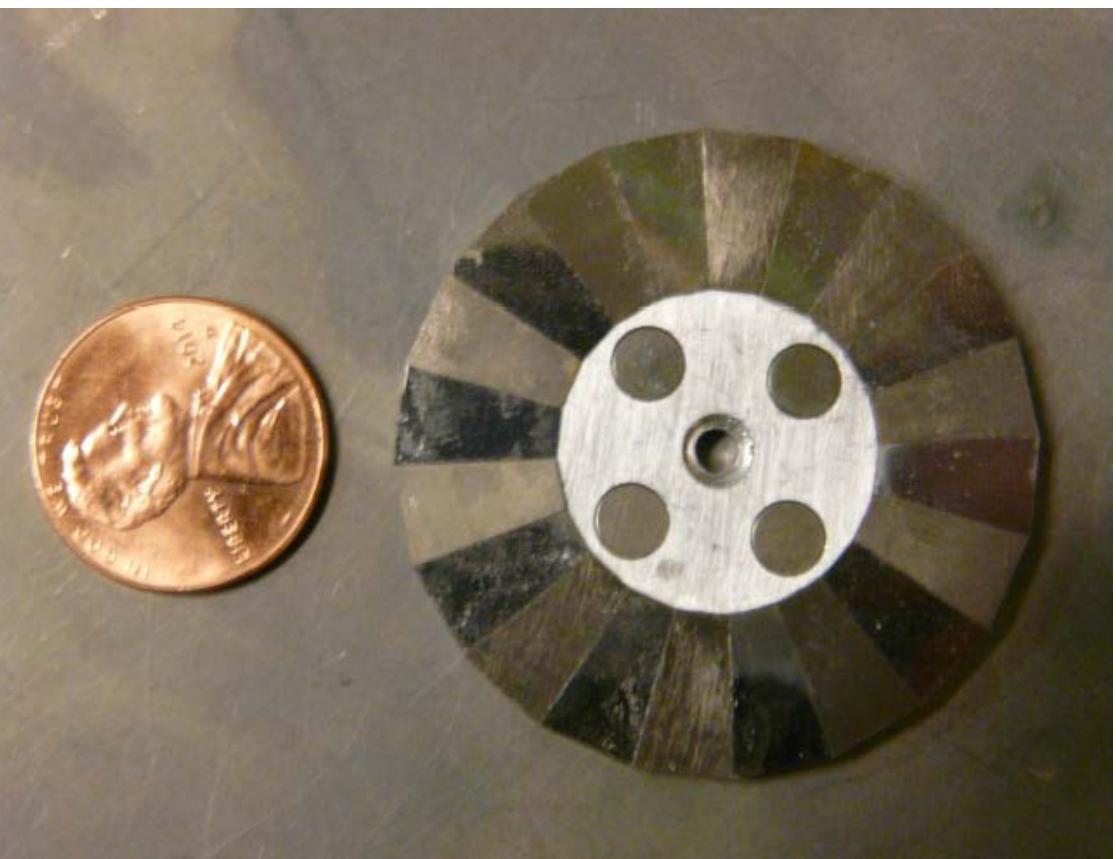
developed by Will Terrano (PhD 2015)



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

compact setup with sophisticated magnetic  
shielding

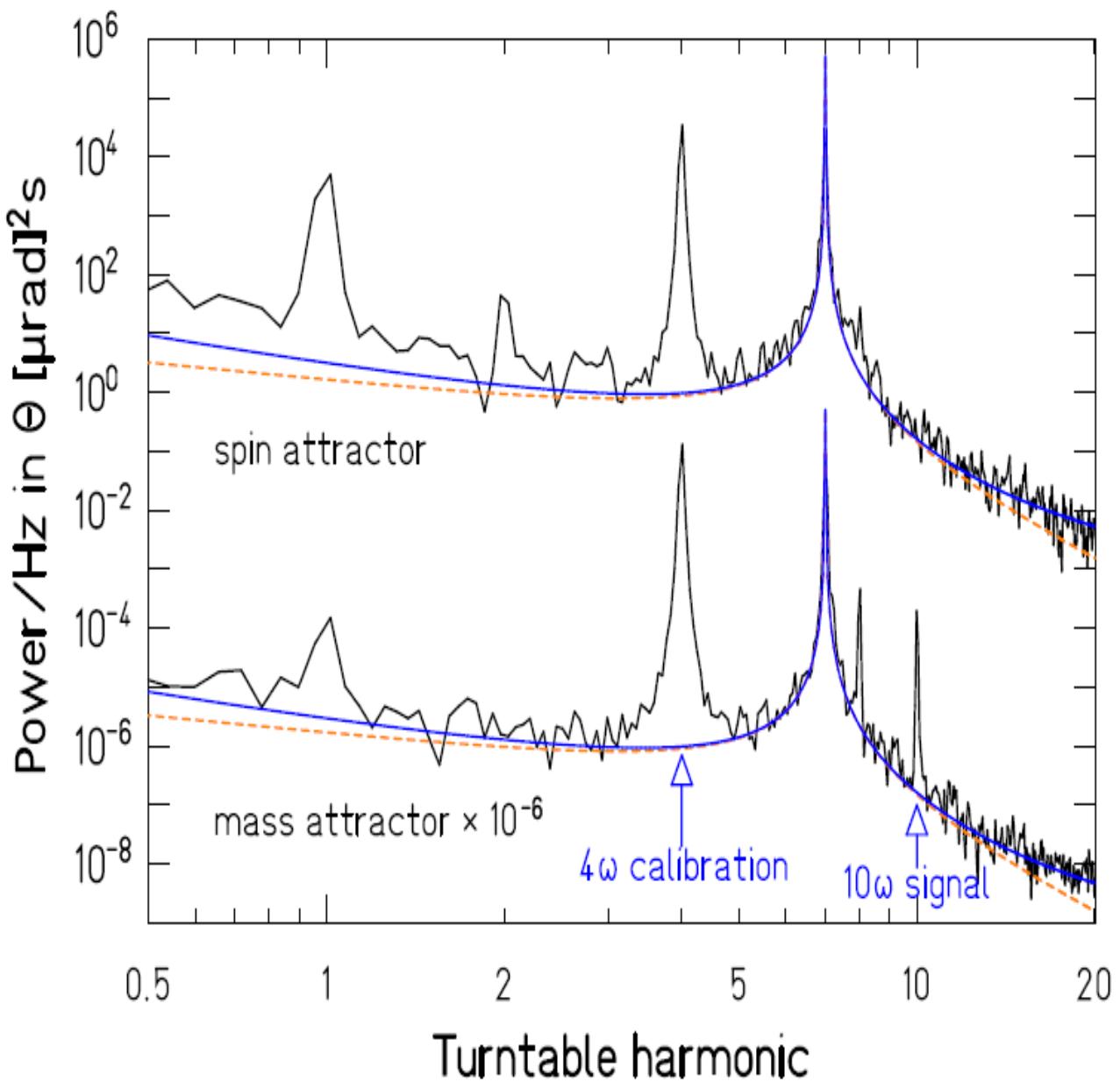
we probed both  
monopole-dipole &  
dipole-dipole interactions



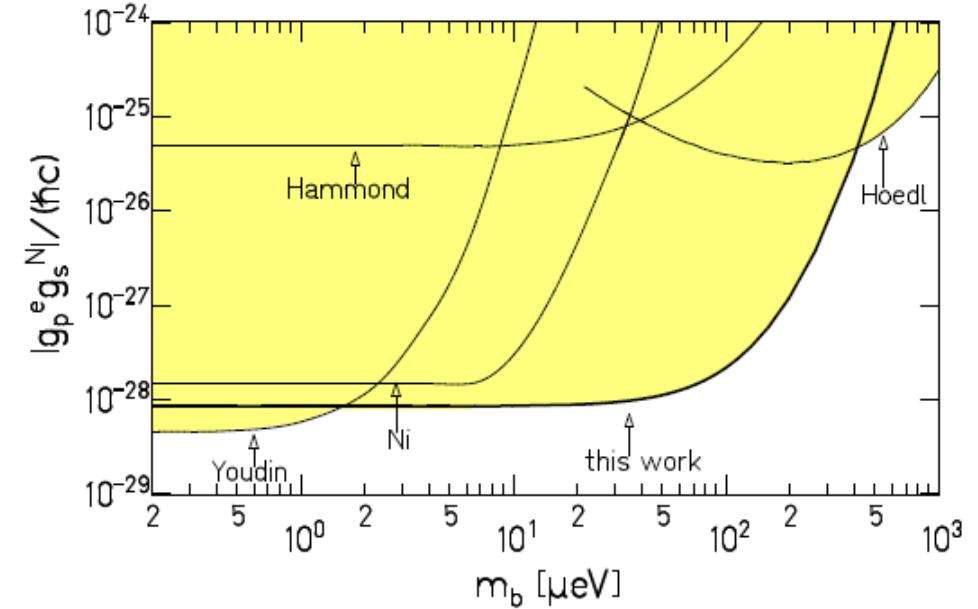
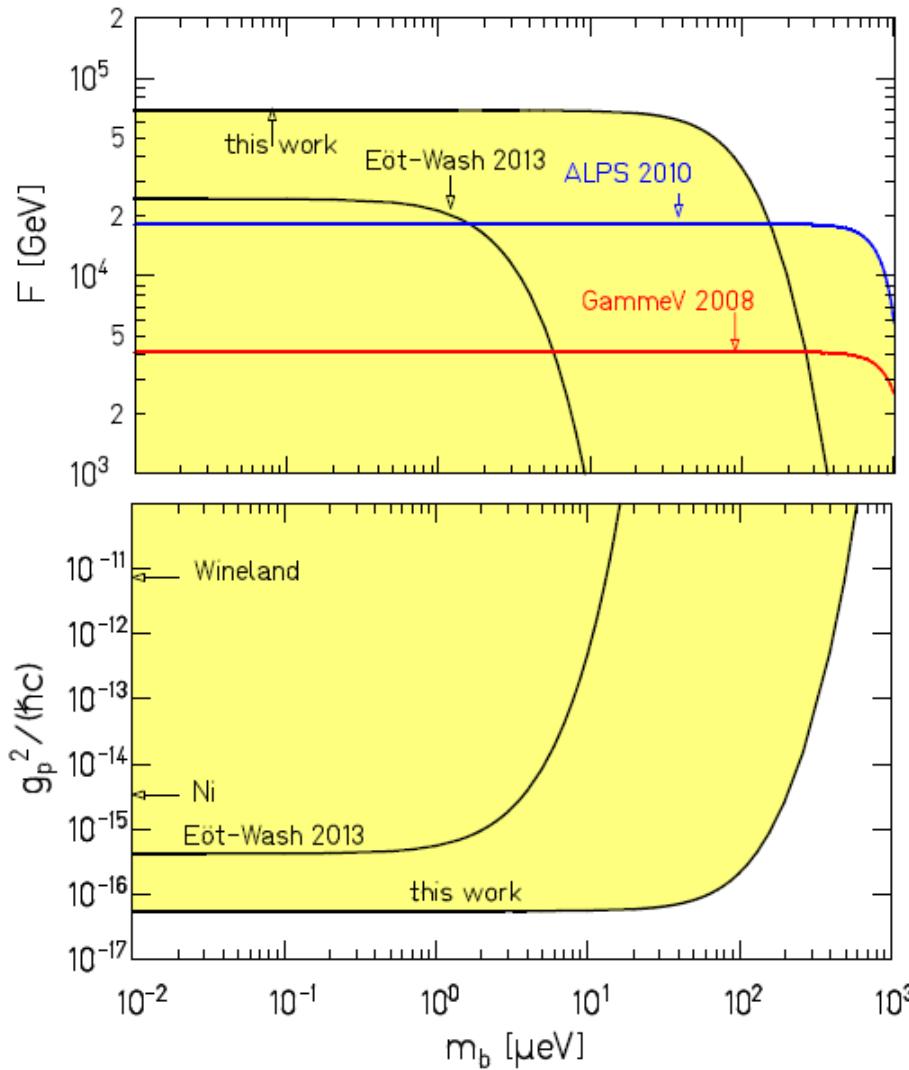
unprecedented aN m  
torque sensitivity

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

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



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

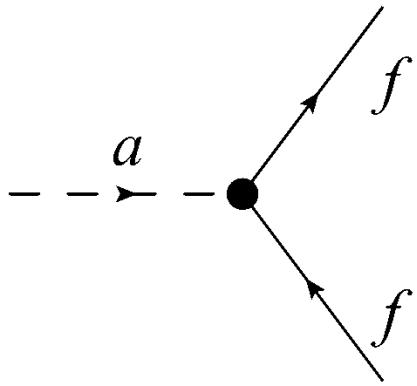


ALPS and GammeV are light shining thru wall expts  
at DESY and FermiLab

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)]



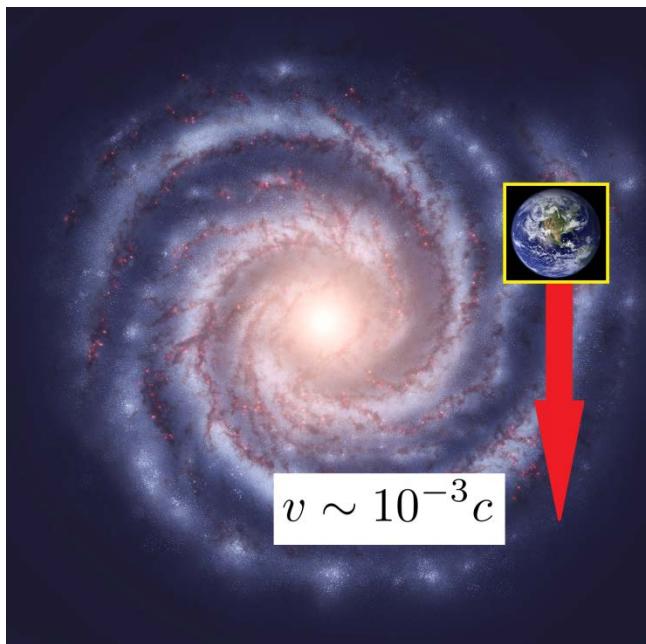
$$\mathcal{L}_{aff} = -\frac{C_f}{2f_a} \partial_i [a_0 \cos(\varepsilon_a t - p_a \cdot r)] \bar{f} \gamma^i \gamma^5 f$$

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

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

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

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



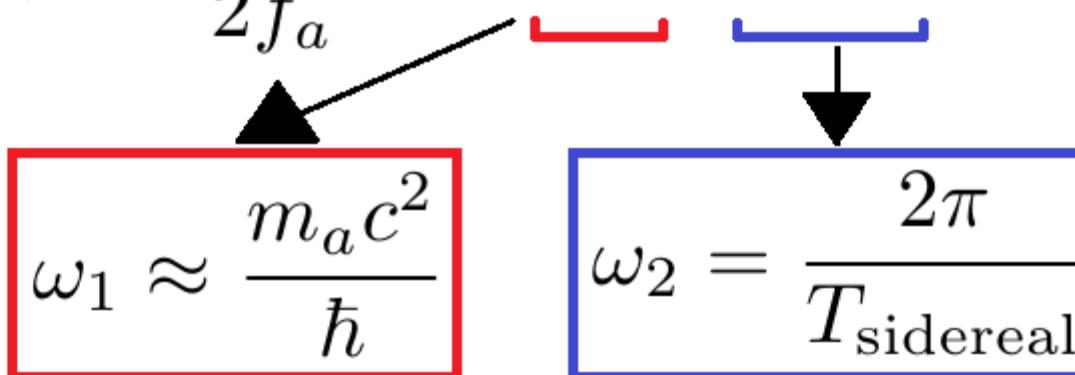
$$\tau_0 \quad 200 \text{ s} \quad m_a = 2.1 \times 10^{-17} \text{ eV}$$

$$\tau_{\text{cut}} \quad 2700 \text{ s} \quad m_a = 1.5 \times 10^{-18} \text{ eV}$$

$$1 \text{ y} \quad \pi \times 10^7 \text{ s} \quad m_a = 1.3 \times 10^{-22} \text{ eV}$$

# “Axion Wind” Effect (Axion and ALPs)

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

$$H_{\text{eff}}(t) \simeq \frac{C_f a_0}{2 f_a} \sin(m_a t) \underbrace{p_a \cdot \sigma_f}_{\omega_2 = \frac{2\pi}{T_{\text{sidereal}}}}$$

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

If CDM is entirely axions  
 $a_0 \sim (4 \times 10^{-2} \text{ eV})/m_a$

axion wind velocity  $\sim 10^{-3}$   
so a signal of  $10^{-22} \text{ eV}$  would correspond to  $f_a/C_e \sim 4 \times 10^{17} \text{ eV}$

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  $\beta_N$  and  $\beta_W$  where  
 $E_{\text{pend}} = -N_p \cdot \beta \cdot \sigma$

convert these signals to equatorial frame  $\beta_X$  and  $\beta_Y$

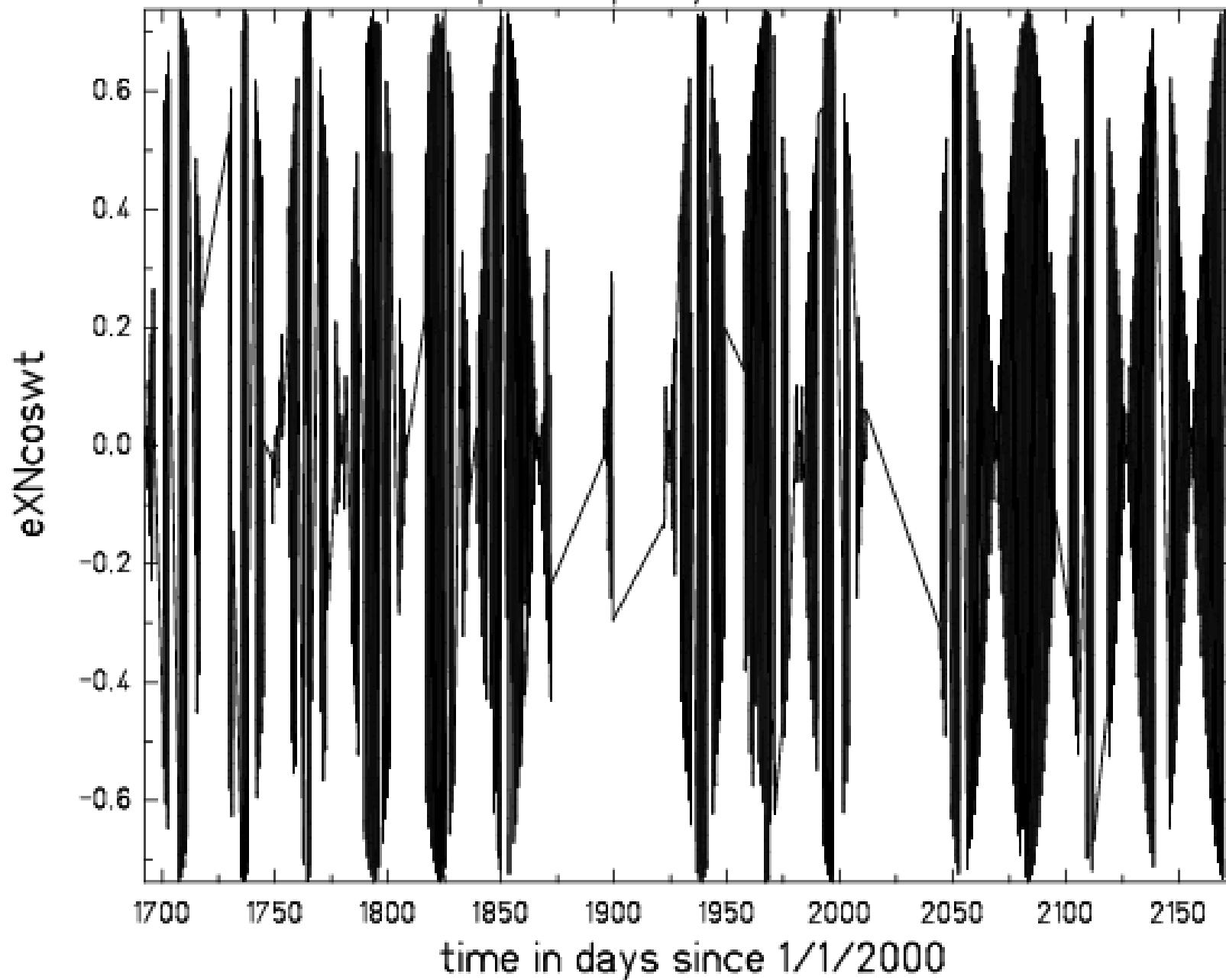
pick an assumed Compton frequency  $\omega_C$  and make a linear fit of the  $\beta_N$  and  $\beta_W$  time series in terms of 4 parameters:

$X_{\text{cos}}(\omega_C t)$   $X_{\text{sin}}(\omega_C t)$   $Y_{\text{cos}}(\omega_C t)$   $Y_{\text{sin}}(\omega_C t)$  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  $\omega_C$

deduce uncertainty from spread in the results

basis function for file k:\batdata\spgrp1.bs1  
assumed Compton frequency = 2.00000E-07

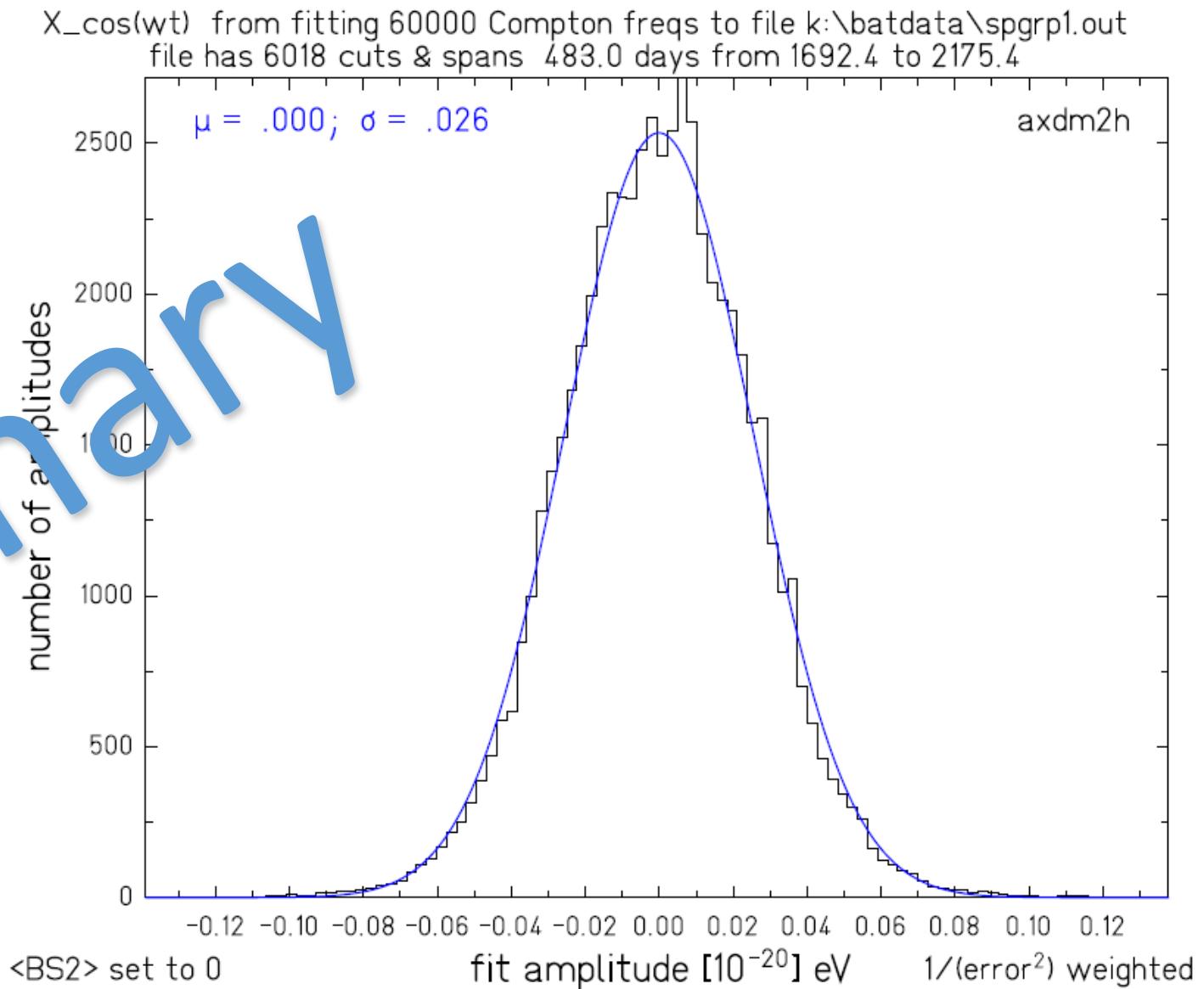


# Histogram of 1 of the 4 fit amplitudes summed over Compton frequencies between $3 \times 10^{-8}$ Hz to $2.5 \times 10^{-4}$ Hz (this is only part of our data)

signal is expected to be coherent over  $\approx 10^6$  cycles i.e. over our entire data span in the range of frequencies we consider

95% confidence upper limit is  $5.2 \times 10^{-22}$  eV

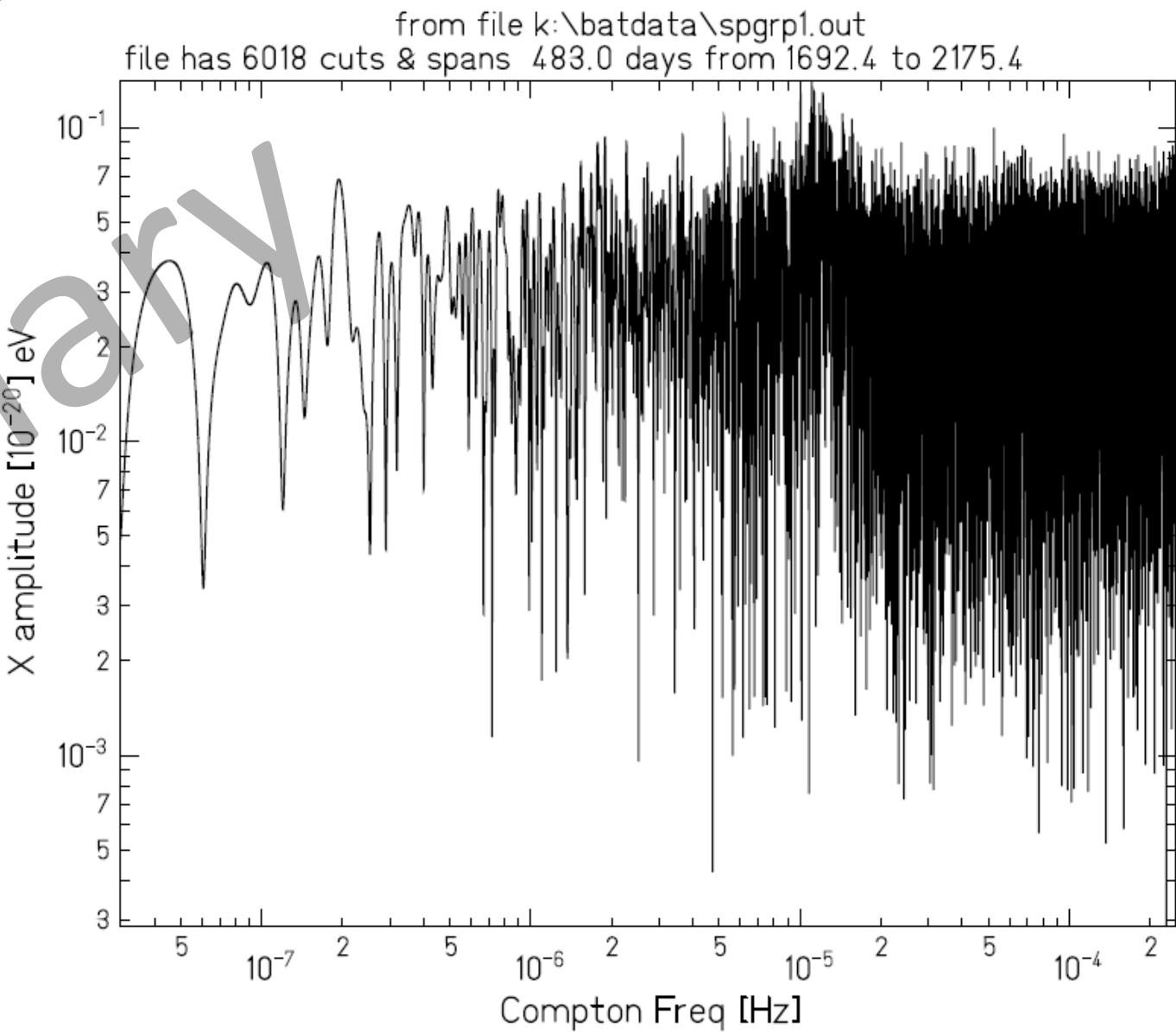
preliminary



X amplitude vs. Compton frequency  
extracted from roughly  $\frac{1}{2}$  of our data

results for Y amplitude are  
are very similar

preliminary



## 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

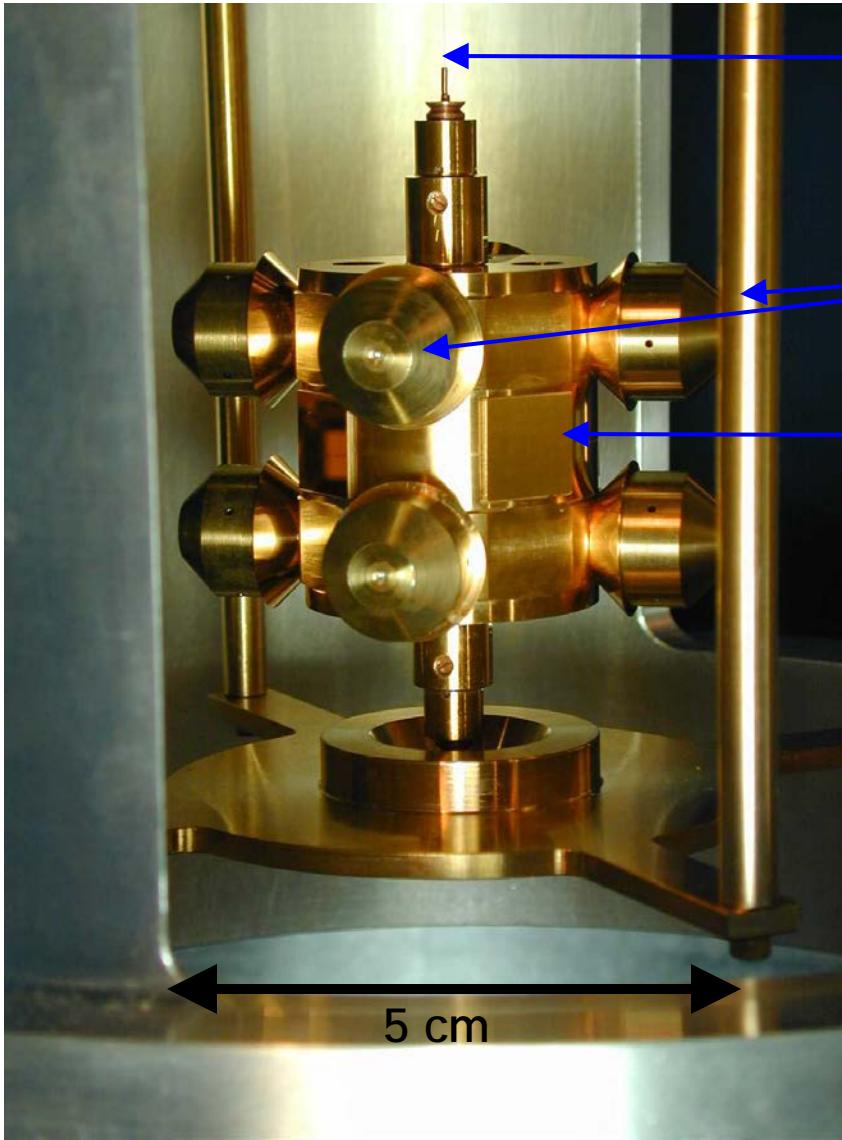
more sensitive twist-angle readout

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  $\mu\text{m}$  diameter tungsten fiber

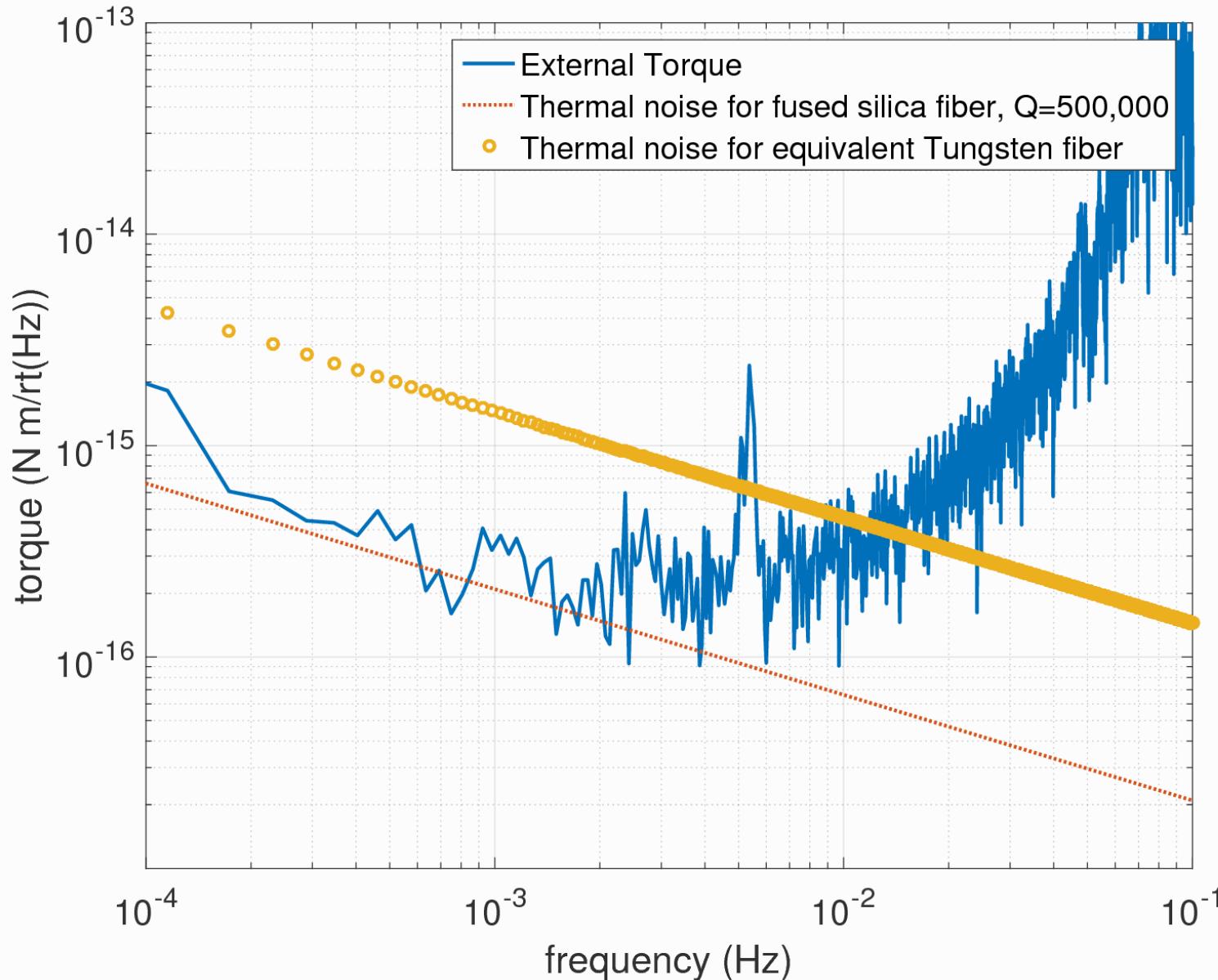
eight 4.84 g test bodies  
4 Be & 4 Al

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 $\mu\text{m}$
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?)

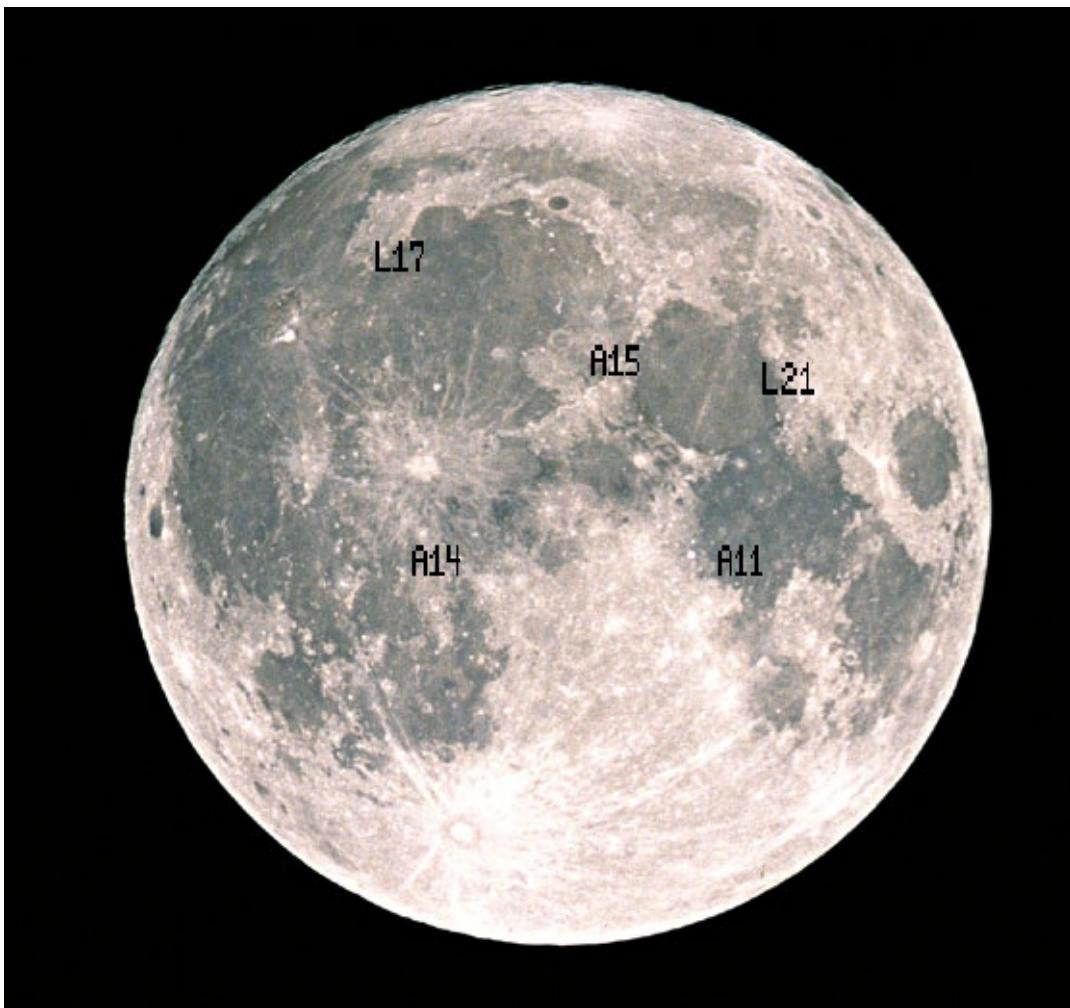
$\Delta a/a \approx 10^{-13}$ ; gravity reduces earth's mass by  
0.46 ppb  $\Rightarrow$  SEP verified to  $4 \times 10^{-4}$

pulsar timing will soon  
give better constraints

preferred frames

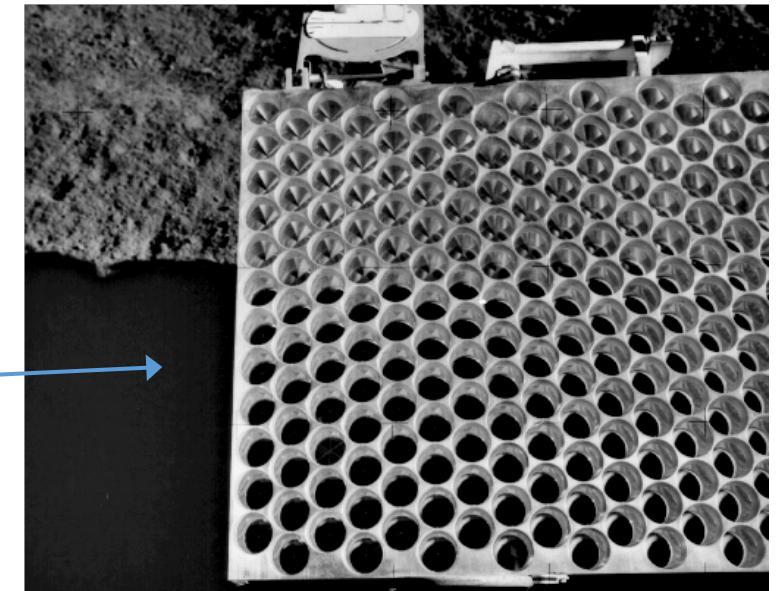
equality of active and passive gravitational masses

# The Lunar Retro-reflectors



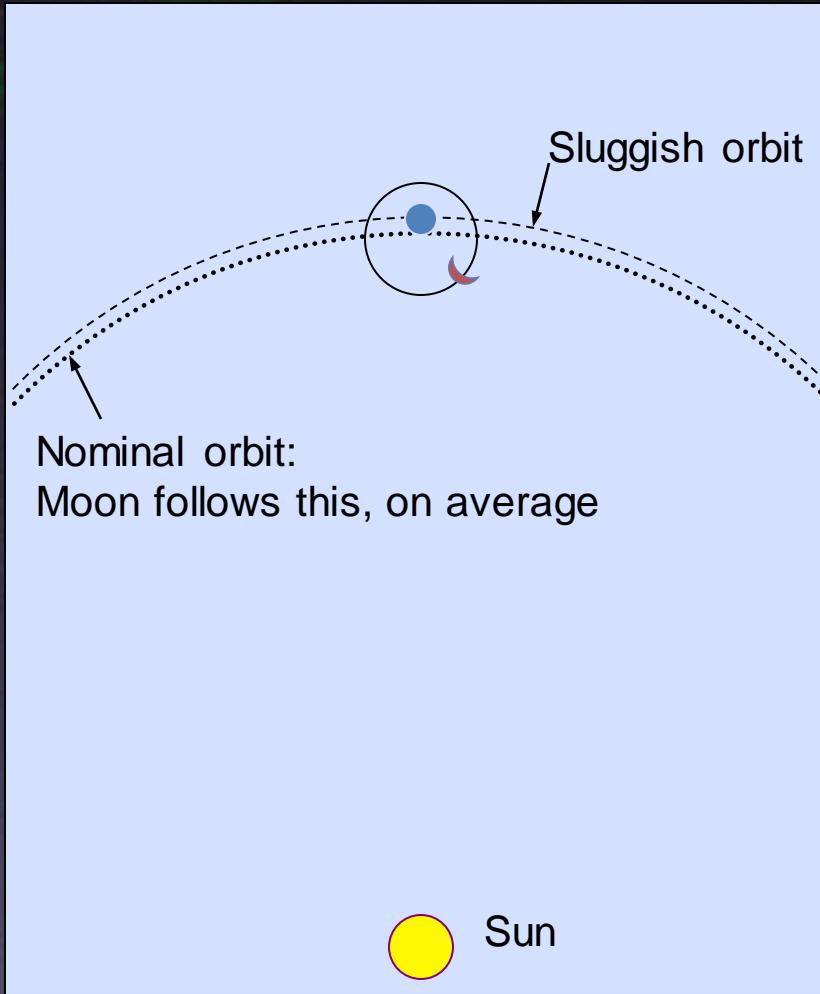
- Three Apollo missions placed reflectors on the moon
  - Apollo 11: 100-element
  - Apollo 14: 100-element
  - Apollo 15: 300-element
- Two French-built, Soviet-landed reflectors, similar in size to A11 & A14 were placed on rovers
  - Luna 17 (originally inaccessible)
  - Luna 21

A15 →



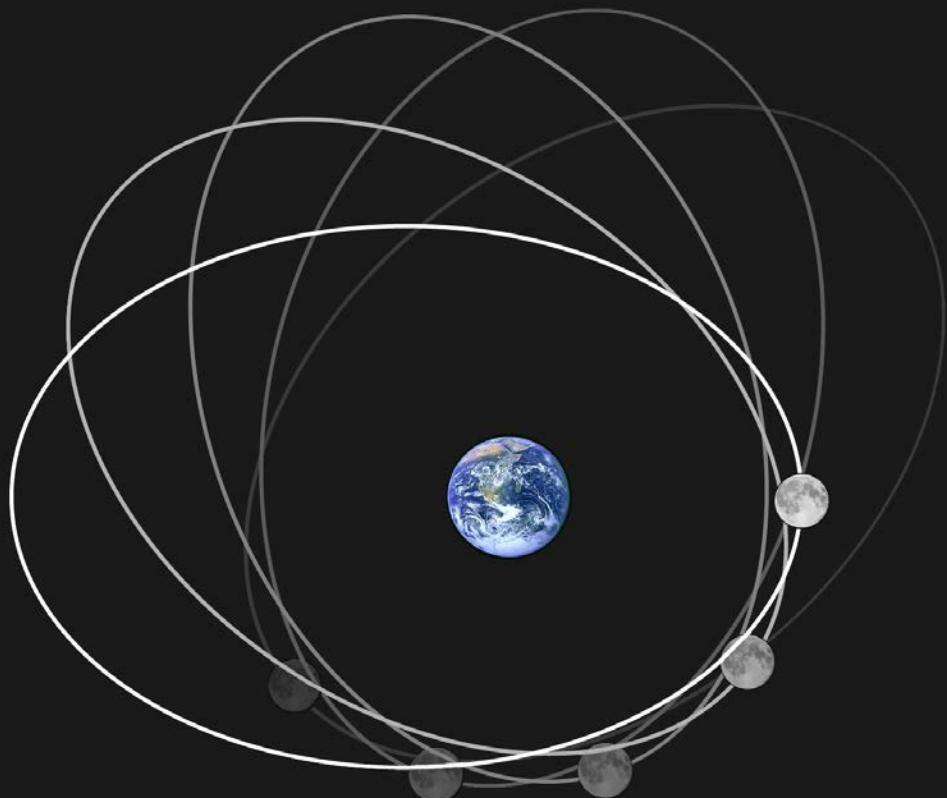
# equivalence principle signal

- 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
- $2\sigma$  upper limit on any residual anomalous precession is only  $27 \mu\text{as}/\text{y}$ . This leads to the strong Yukawa constraint for  $\lambda \sim a/2$  shown on an earlier slide.

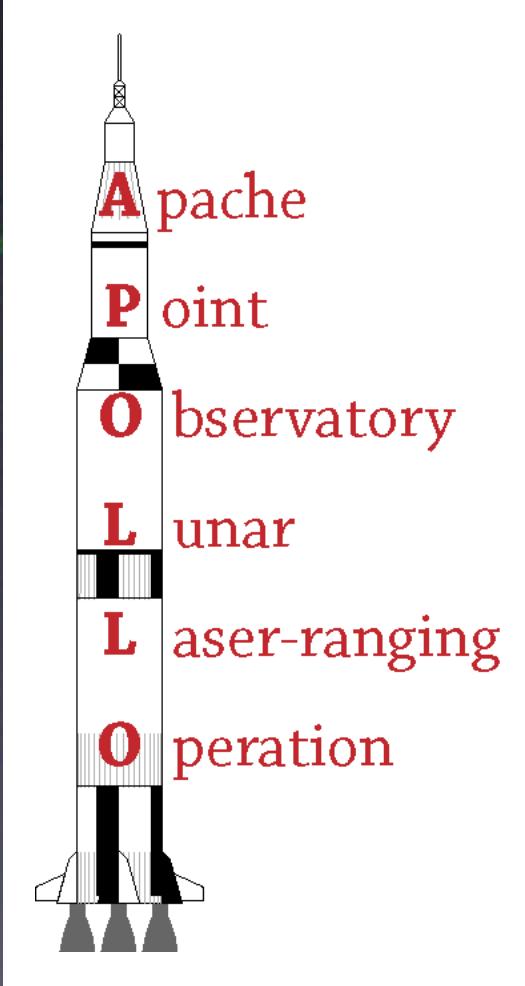


## G dot signal

- 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

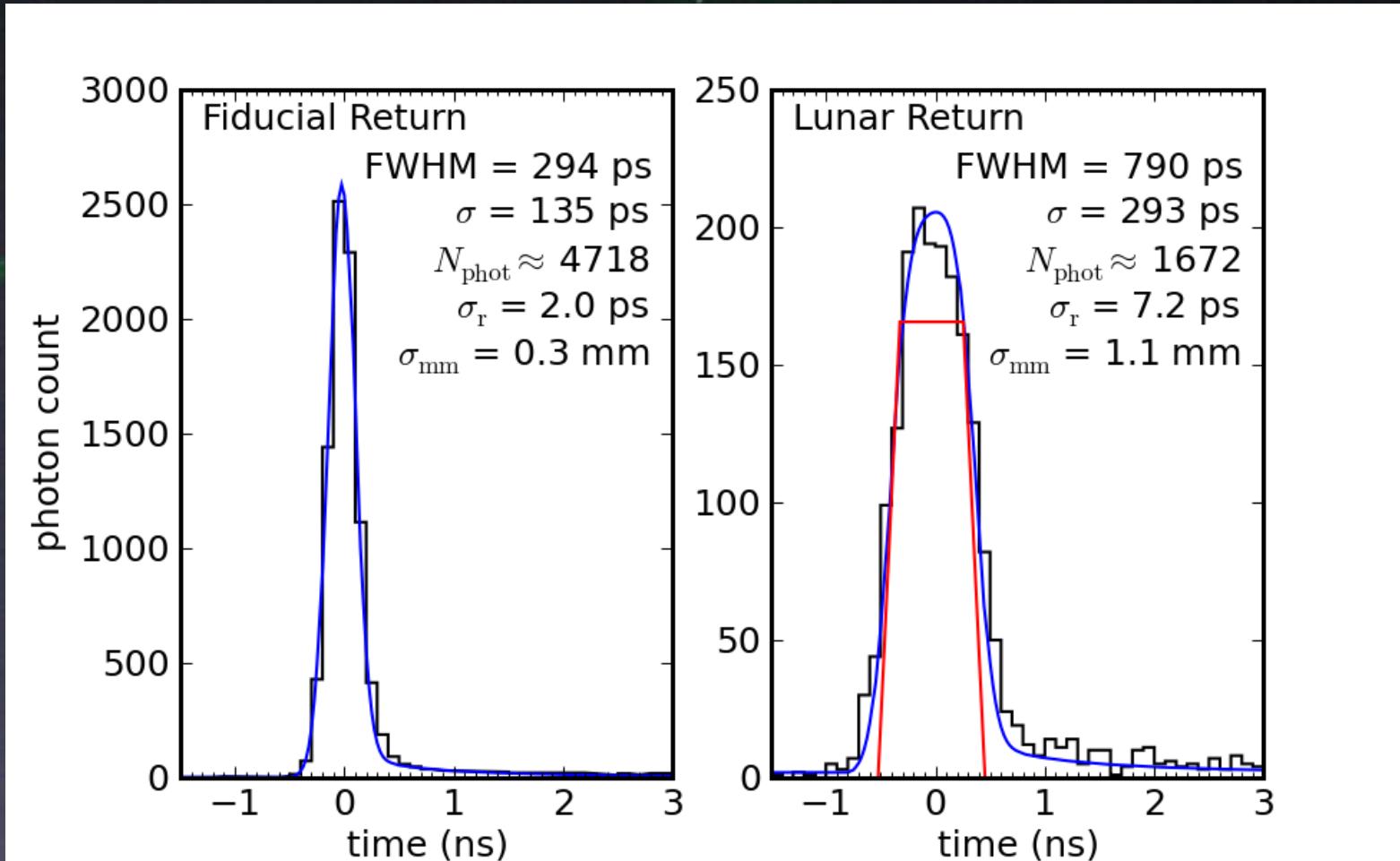
# APO 3.5 m, New Mexico, 2800 m elevation



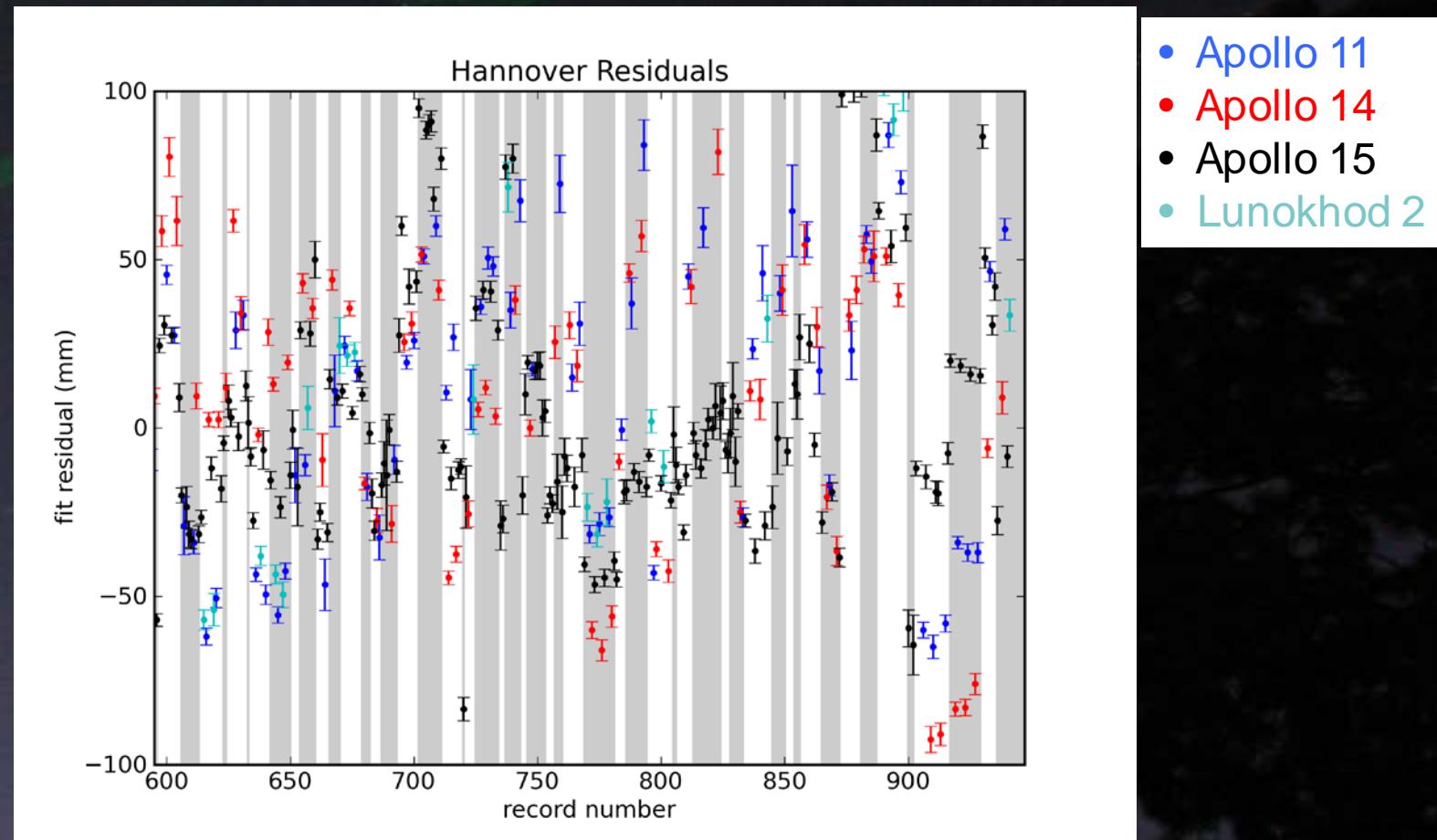
# Examples of APOLLO's capabilities

- 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

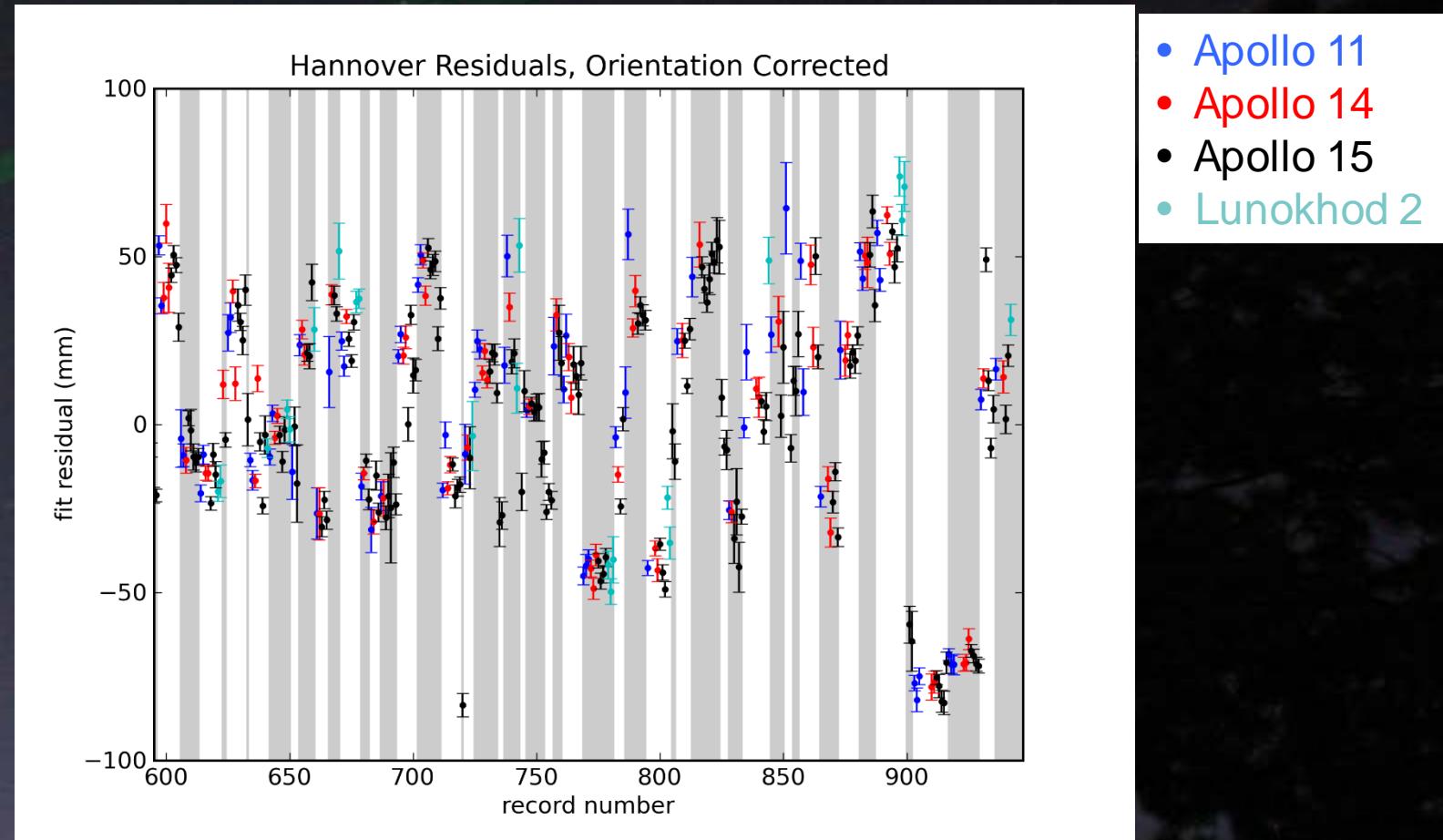


# APOLO data clearly require nightly adjustment of the predicted lunar orientation

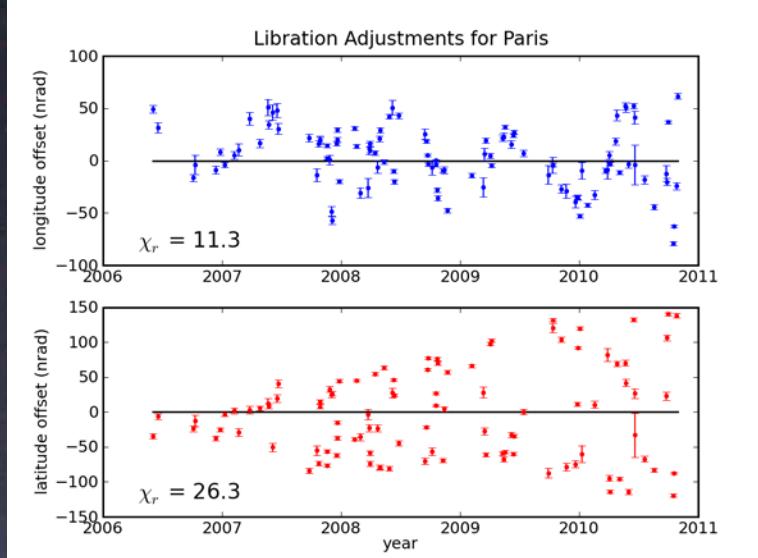
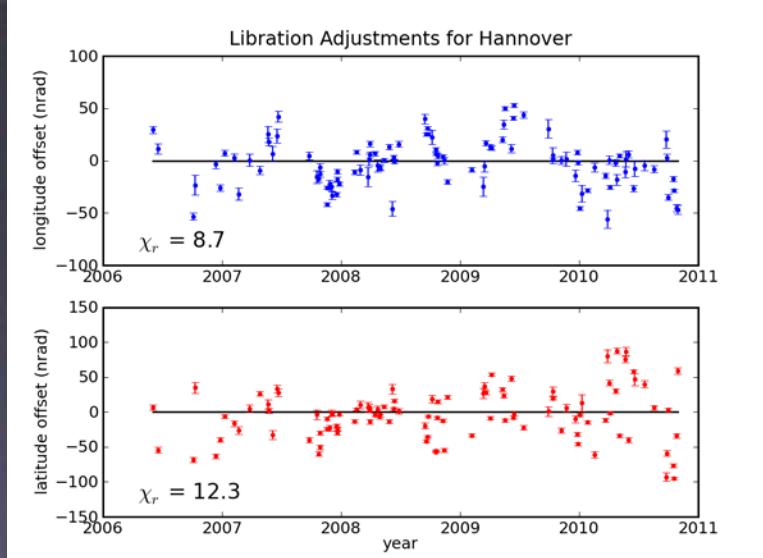
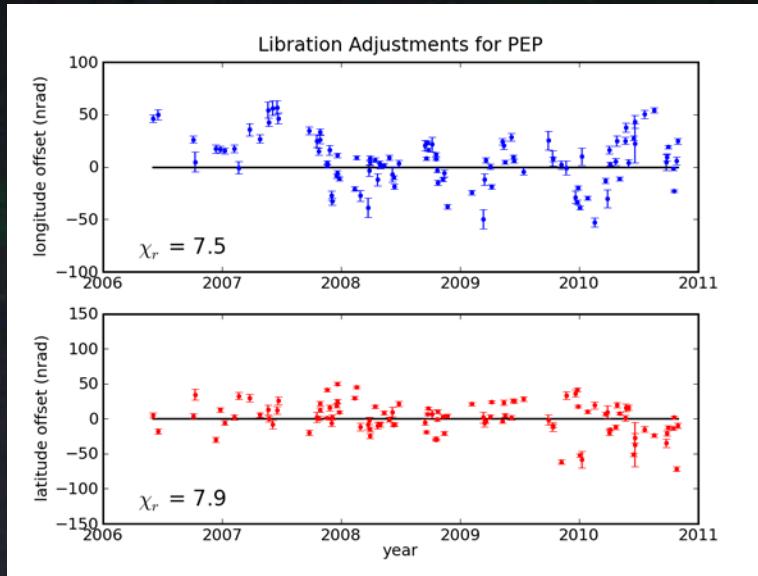
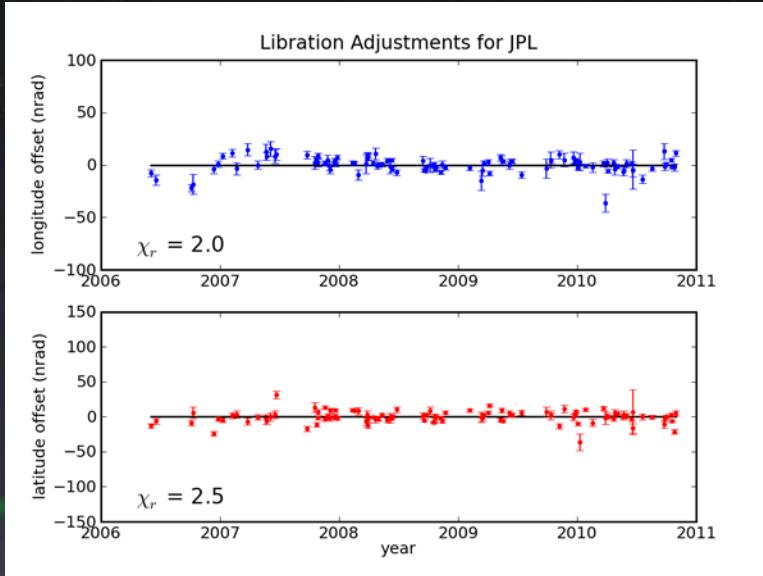


(vertical bands show individual nights)

# Example: tweaking the model's lunar orientation

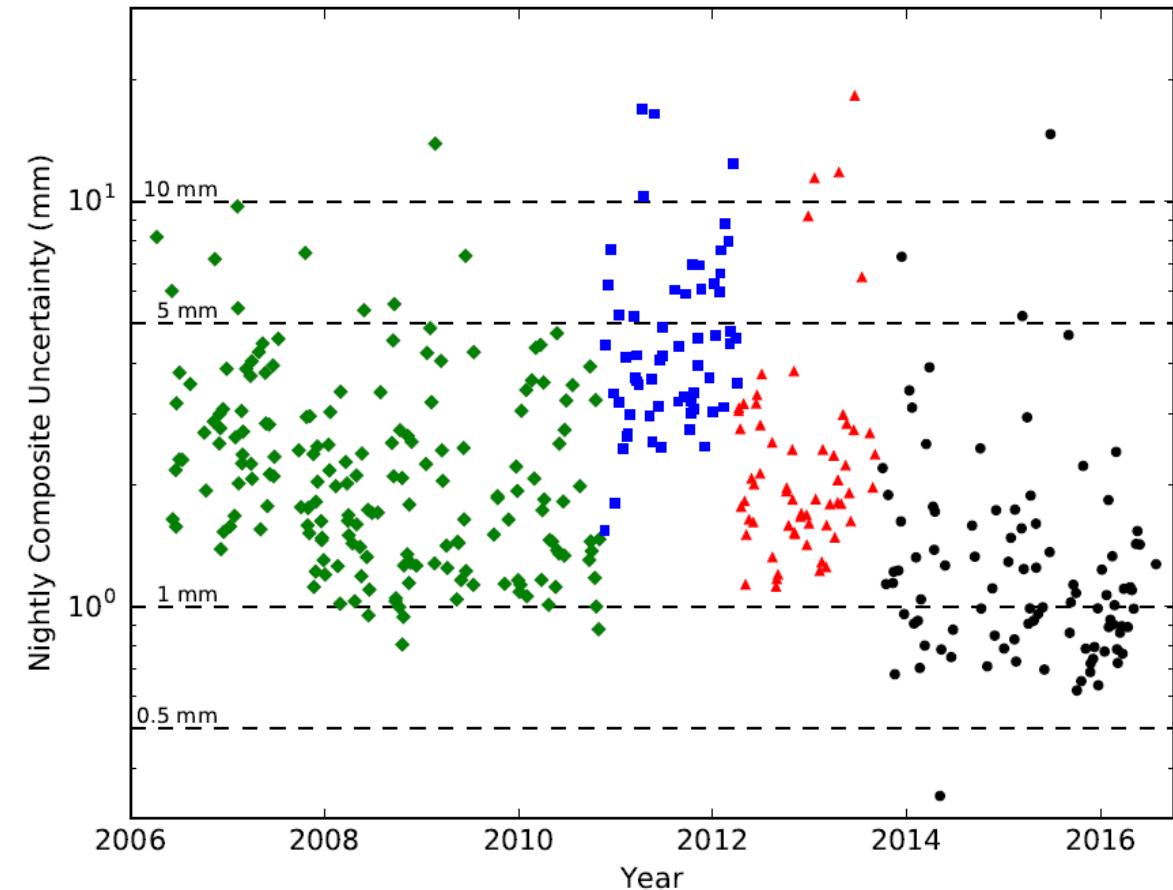
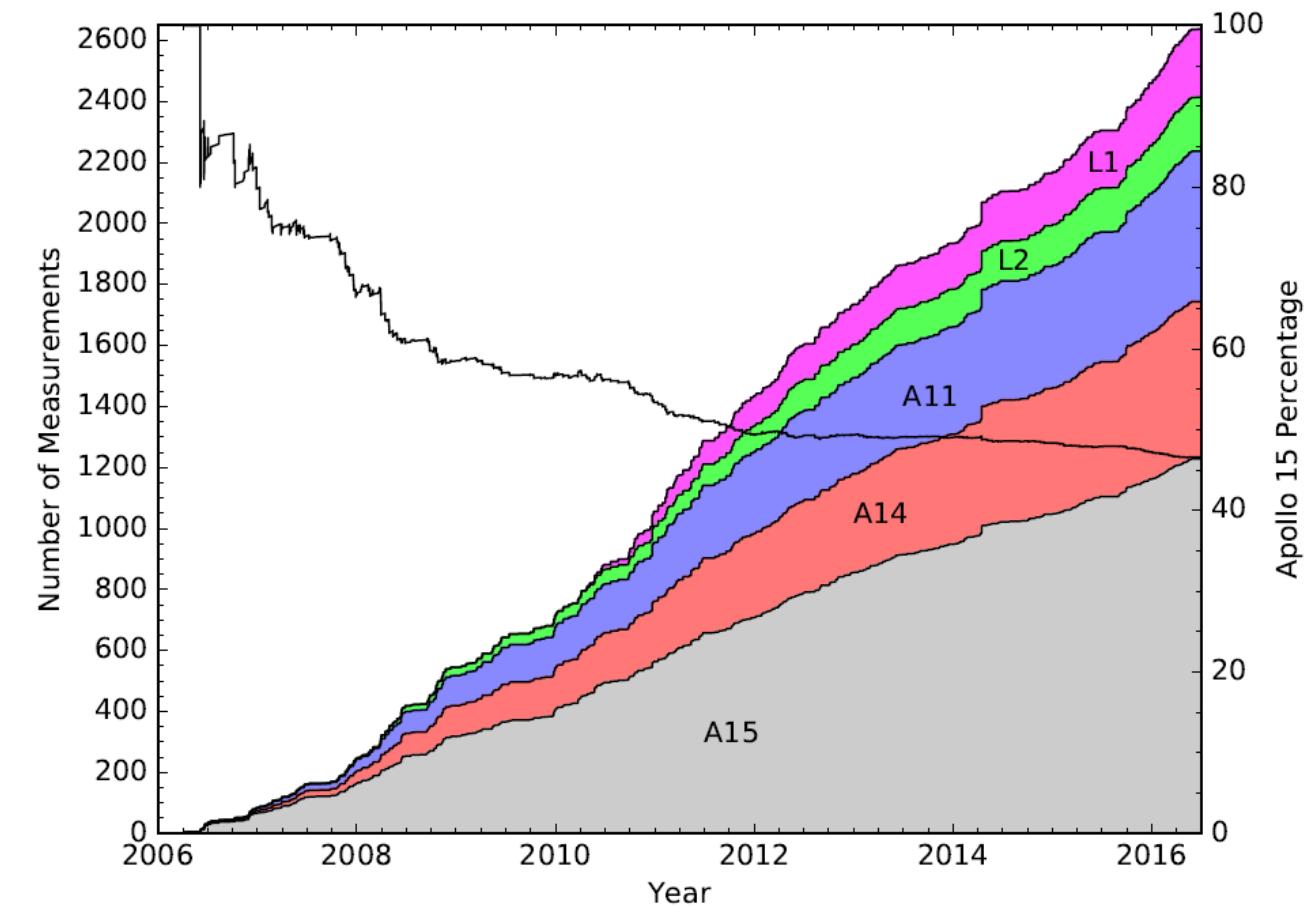


# adjusting moon orientation to fit APOLLO data



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

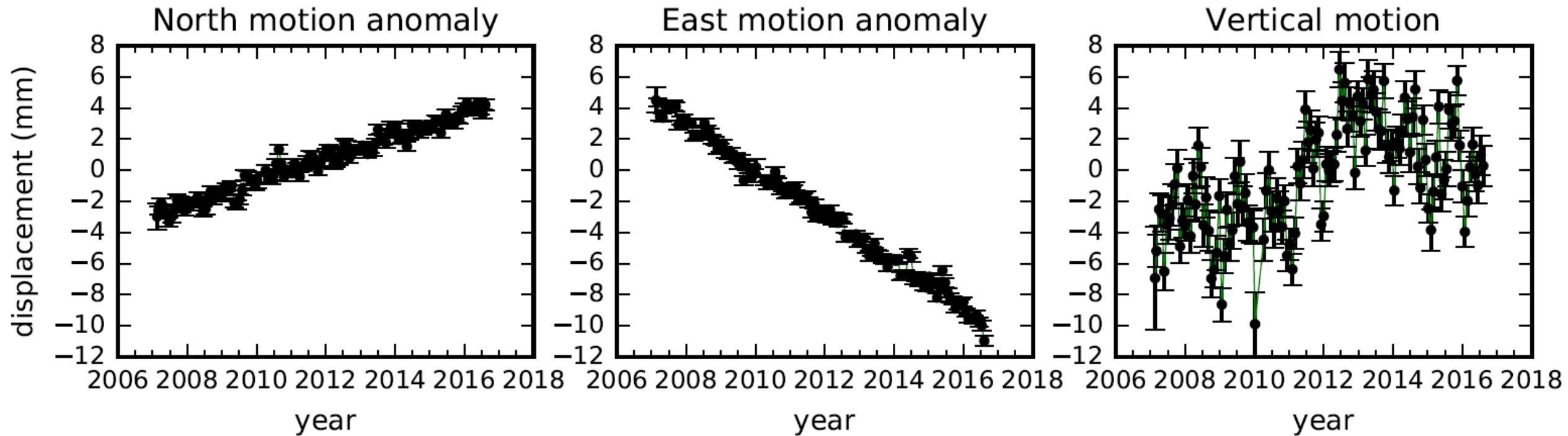
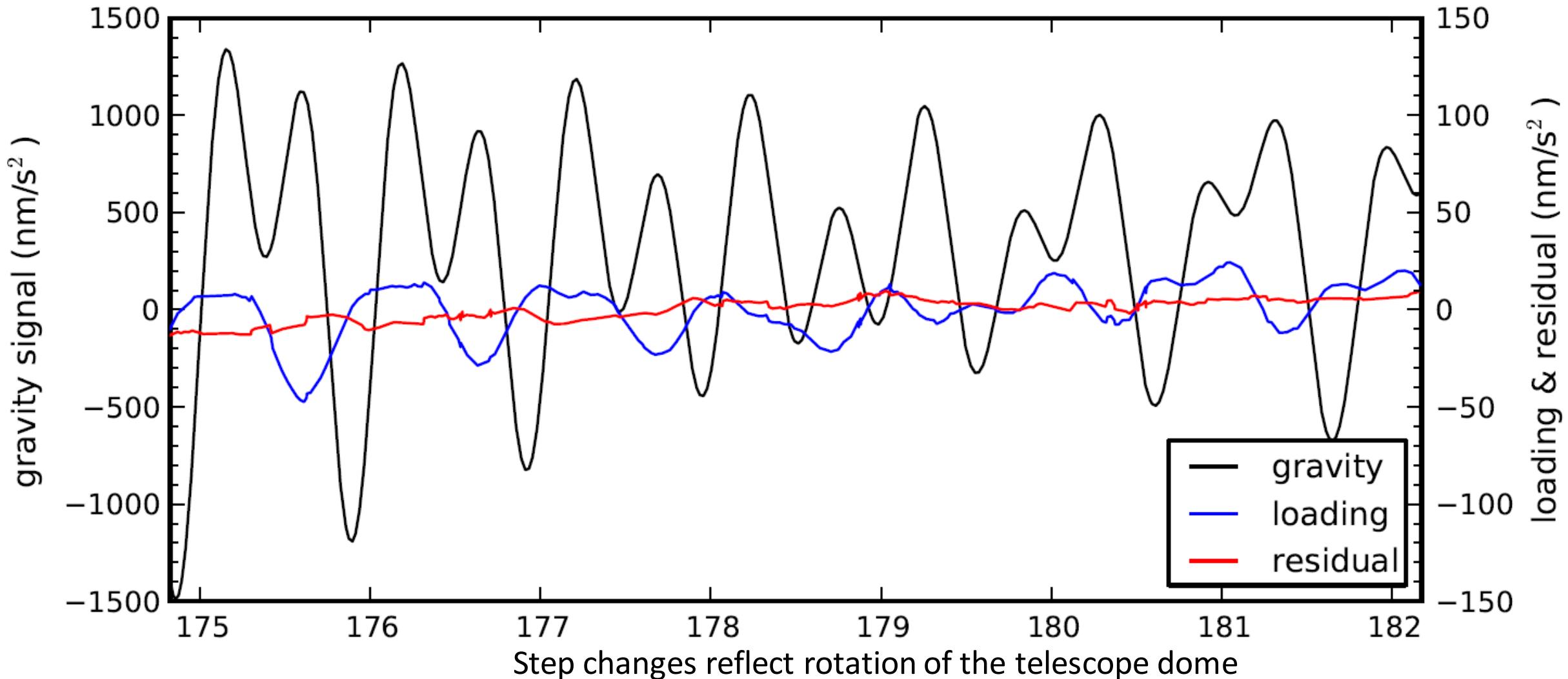


Figure 4: GPS data from the P027 PBO station located 2.5 km away from the Apache Point Observatory (on a similar summit). Data are binned in lunar-monthly units. Motions are shown *relative to* the North American plate, moving at  $(-6.3, -11.5, -0.6)$  mm/yr in the north, east, and up directions. The 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.

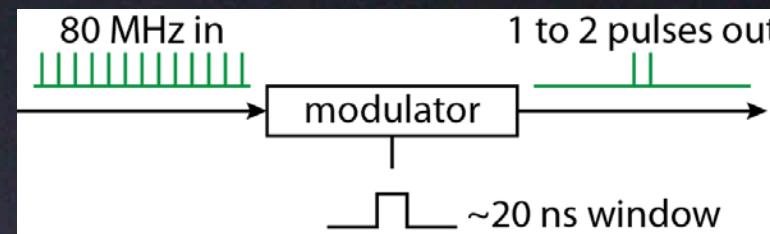
Terrestrial models must also explain the high-sensitivity gravity data from a superconducting gravimeter located the APOLLO site.

A 1 week sample is shown



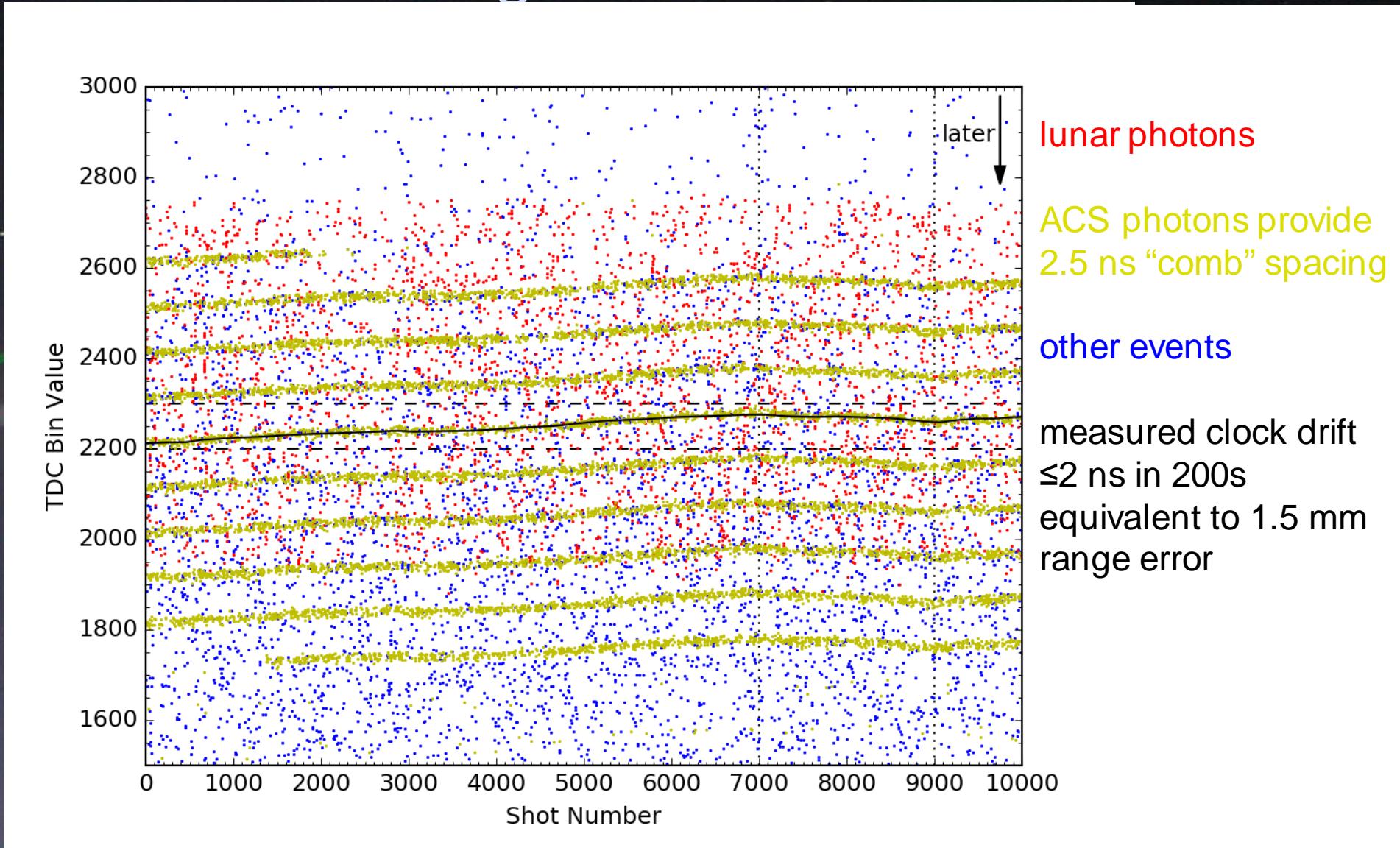
# New Development: Precision → Accuracy

- 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



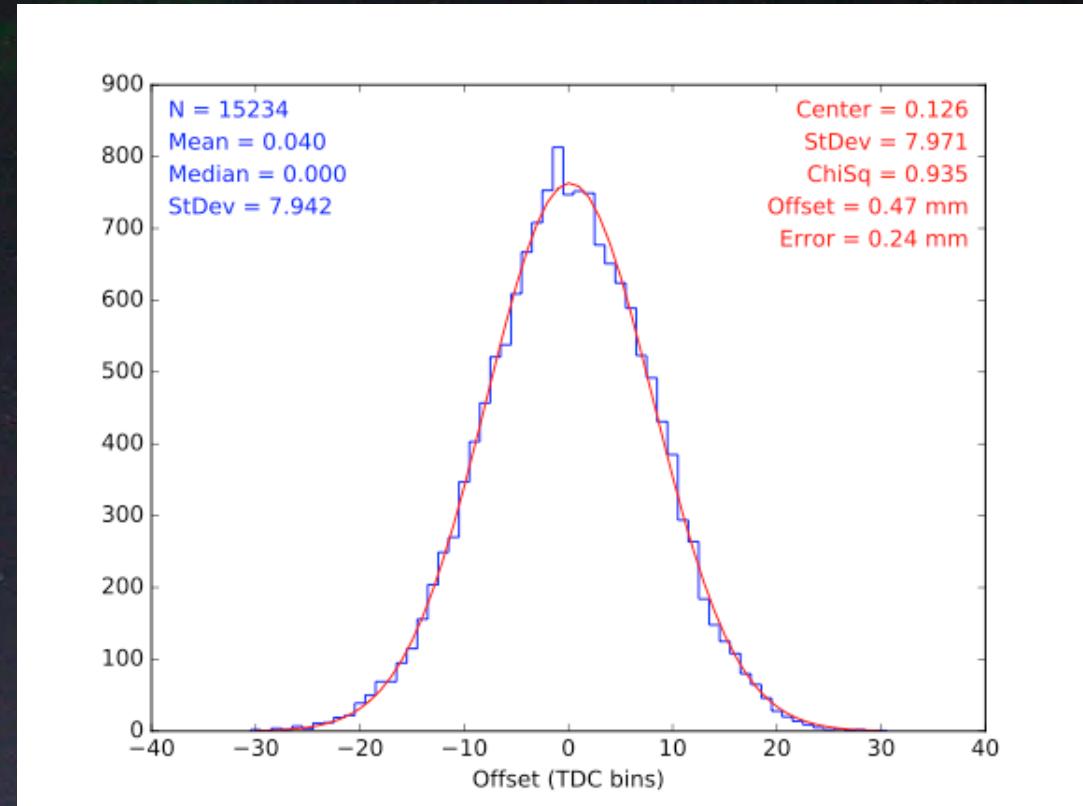
- Likewise for local fiducial corner cube return
- Provides reference photons at APD “on time”
  - tick marks on calibrated ruler, measured exactly like lunar photons
- Also allows offline tests and characterization of systematics

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



# Encouraging prospects

- Have **sub-mm statistical range uncertainties**
- 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 vital 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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