Tests of Lorentz invariance using spinning fermions and laser-ranging to the moon

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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?
- Could Lorentz Invariance break down at the Planck scale?
- If so, can low-energy experiments be sensitive to such Planck-scale physics?

Kostelecky and his coworkers developed a preferred-frame scenario, the “Standard Model Extension”, in which vector, axial-vector and tensor 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.

The "Standard Model Extension" is an ever-expanding field-theoretic framework, recently extended to include the gravitational sector, that predicts many new observables some of which violate CPT.

One rotation-noninvariant observable is $E = \sigma^{e} \cdot \tilde{b}^{e}$

where $\tilde{b}^{e}$ is an axial vector fixed in inertial space –

its benchmark value is $m_e^2 / M_{Planck} \approx 2 \times 10^{-17}$ eV

Additional boost-noninvariant terms lead to generalized helicities

$E = C_{IJ}\, \sigma_I^{e}\, v_J / c$

non-commutative space-time geometry

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

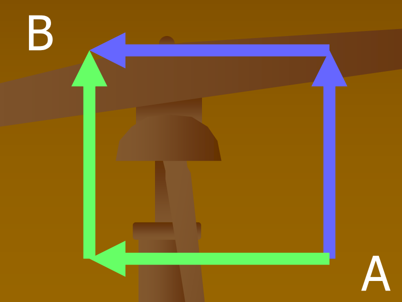
$$[\widehat{x}_\mu, \widehat{x}_\nu] = i\theta_{\mu\nu}$$

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 spin

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

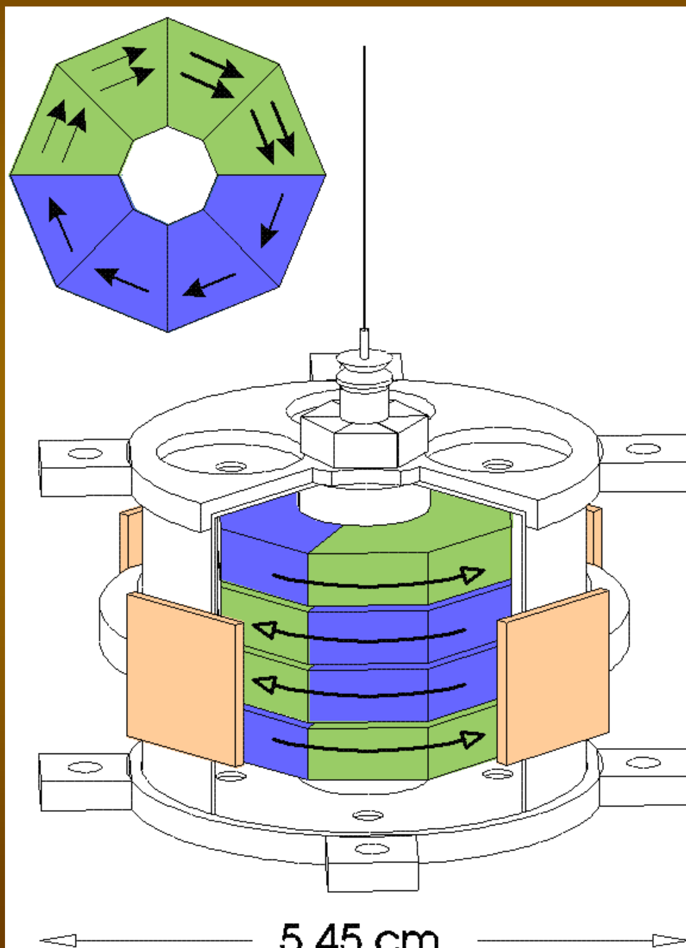


$$\mathcal{L}_{eff} = \frac{3}{4} m\Lambda^2 \left(\frac{e^2}{16\pi^2}\right)^2 \theta^{\mu\nu}\overline{\psi}\sigma_{\mu\nu}\psi$$

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

Λ is a cutoff assumed to be 1TeV

the Eöt-Wash spin pendulum



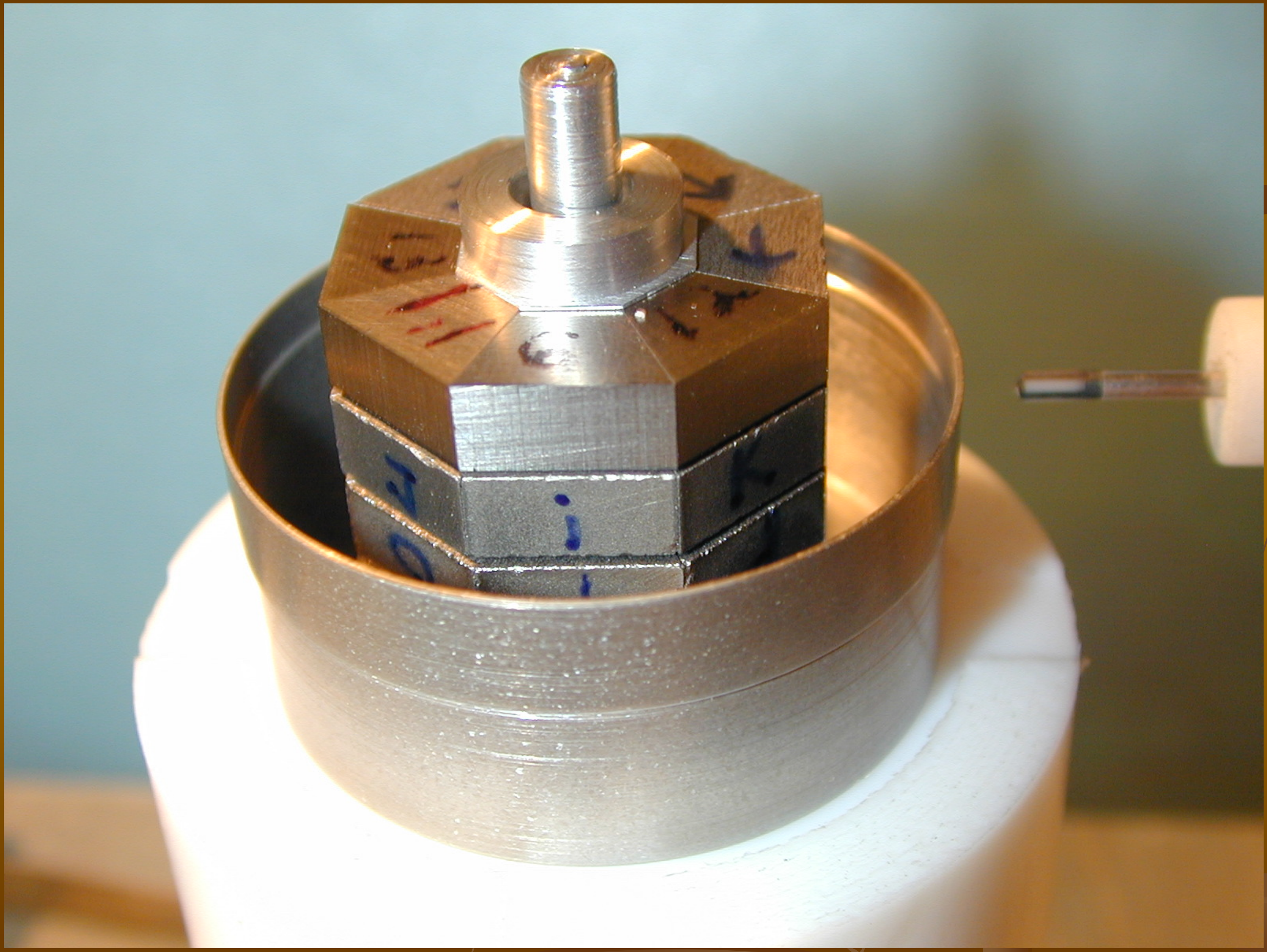
- 9.8×10^{22} polarized electrons
- negligible external B field because B is confined within octagons
- negligible mass asymmetry
- negligible composition asymmetry

- Alnico: all B comes from electron spin: spins point <u>opposite</u> to B

- $SmCo_5$: Sm 3^+ ion has spin pointing <u>along</u> 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

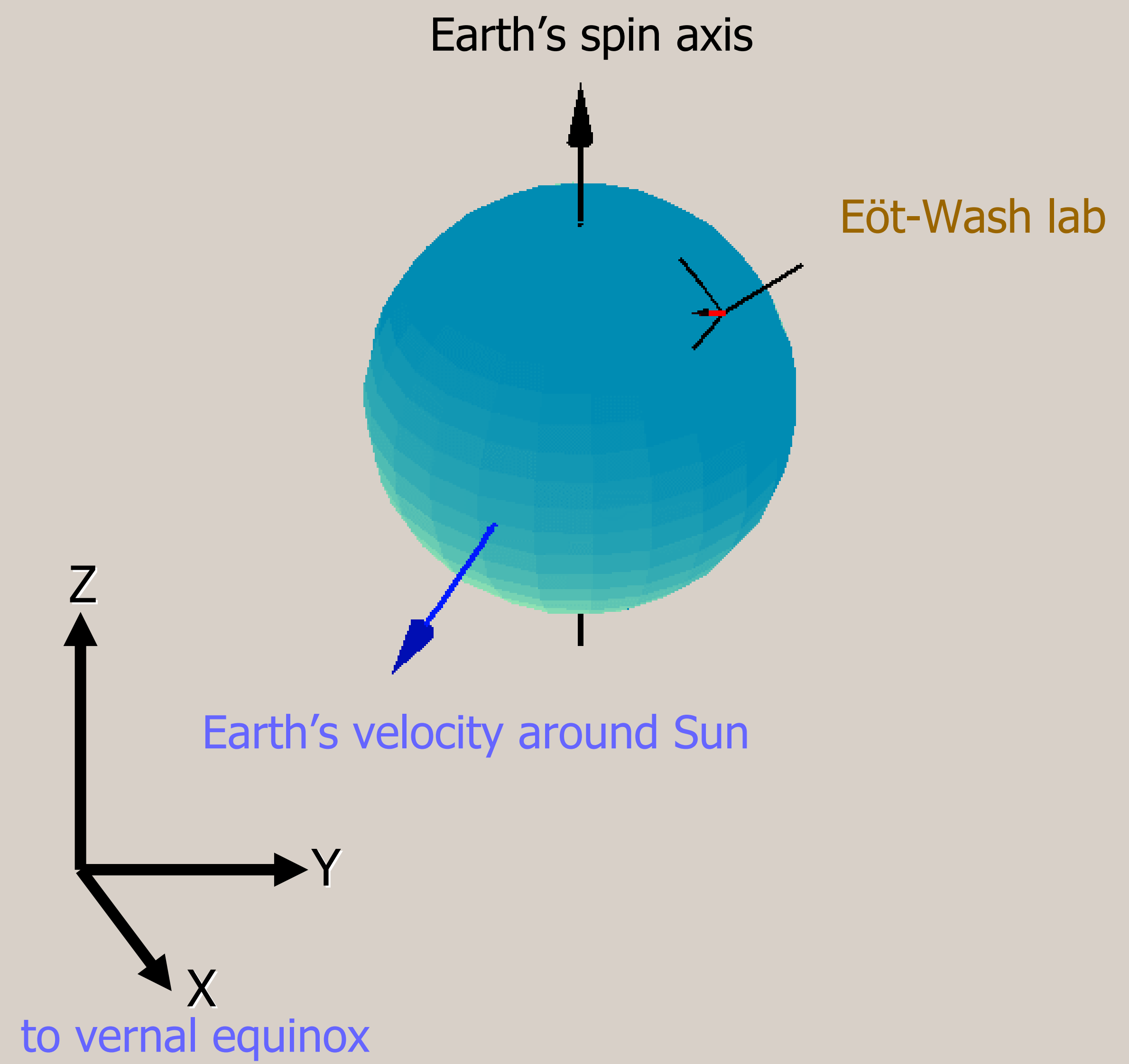
- therefore the spins of Alnico and Co cancel and pendulum's net spin comes from the Sm giving J = – S

measuring the stray magnetic field of the spin pendulum

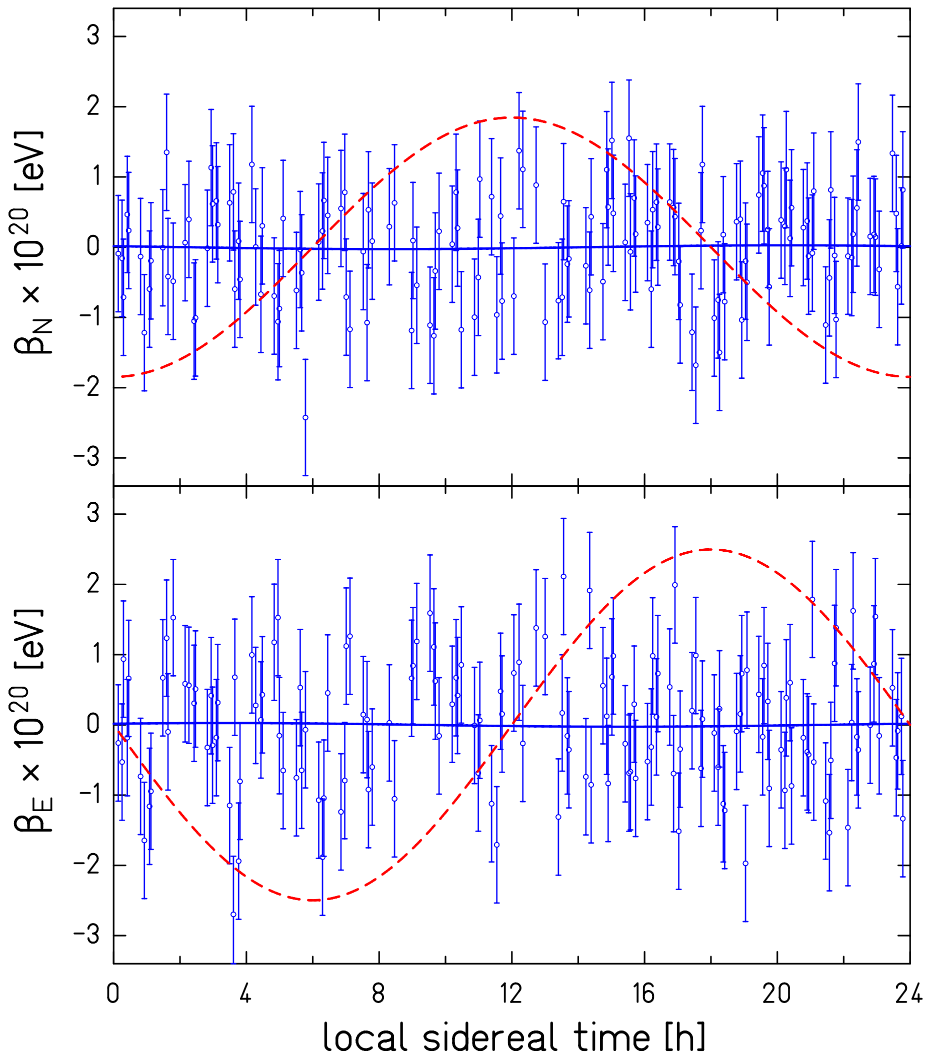


B inside = 9.6±0.2 kG

B outside ≈ few mG


Earth's spin axis
Eöt-Wash lab
Z
Earth's velocity around Sun
Y
X
to vernal equinox

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



definition of **β**:

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

2ß=energy needed to flip a spin

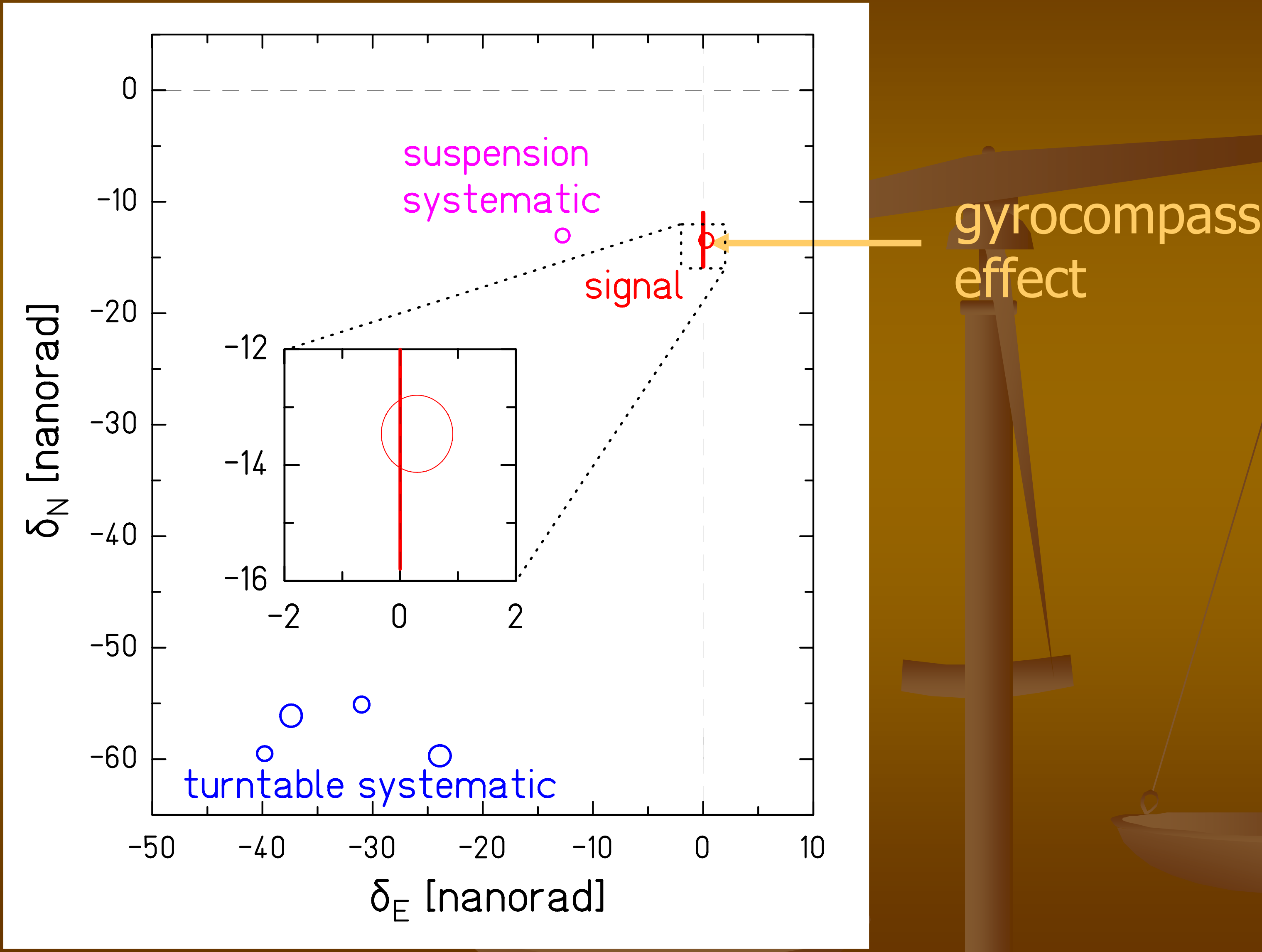
simulated signal from assumed $b_x = 2.5\times10^{-20}$ eV

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

lab-fixed spin pendulum signal



The gyrocompass

Anschütz's gyrocompass.

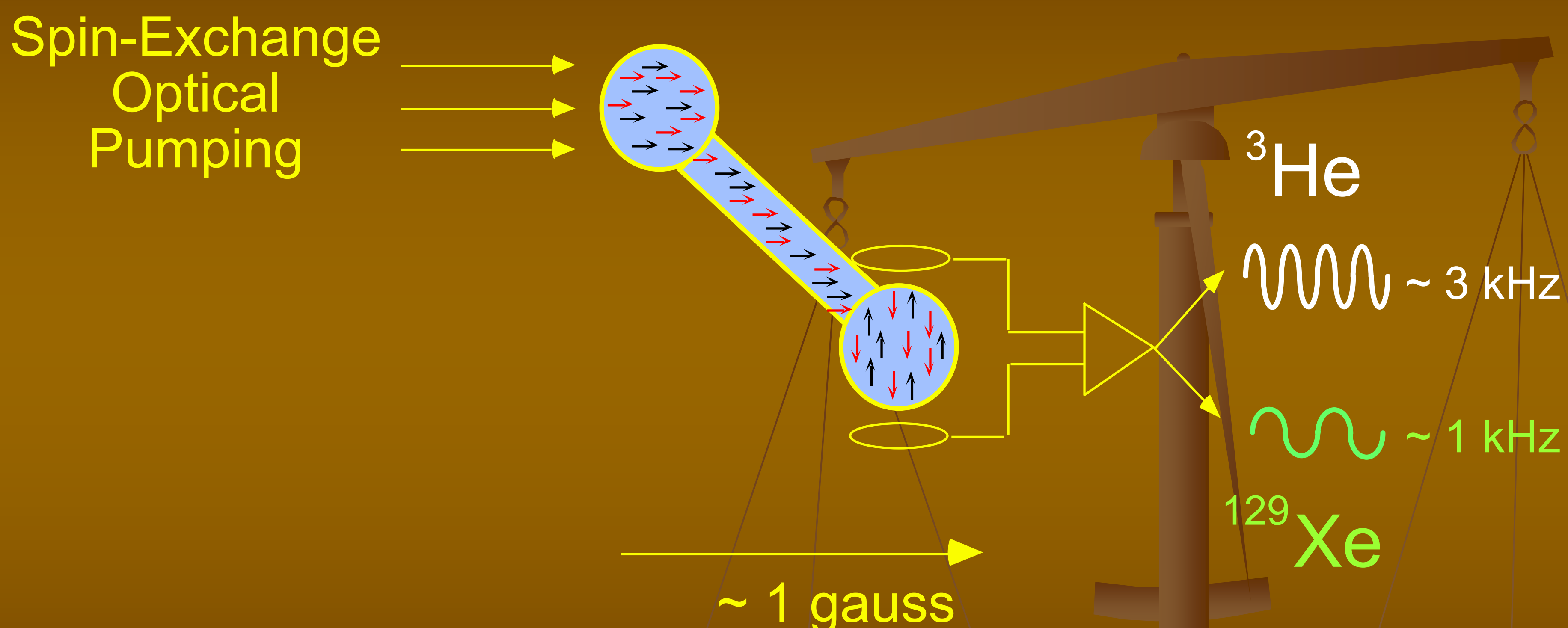
Anschuetz-Kaempfe and Sperry separately patented gyrocompasses in UK and US. In 1915 Einstein ruled that Anschütz's patent was valid.

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

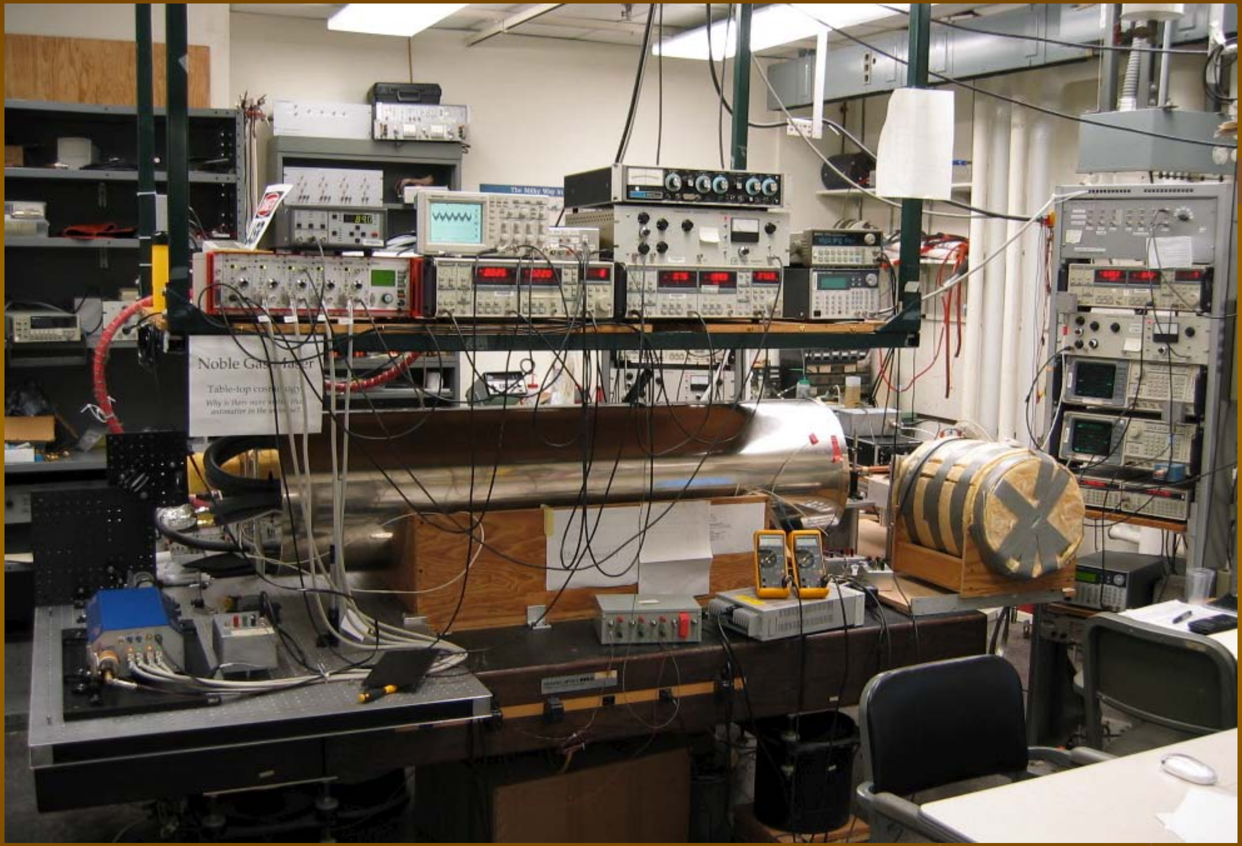
CfA Two-Species Noble Gas Maser



One species serves as a magnetometer, the other free-runs

~ 100 nanohertz frequency sensitivity on timescale of hours

Walsworth Group: ^{3}He/^{129}Xe & Hydrogen masers



They study daily and annual variations in maser frequency to constrain rotation and boost sensitive terms

Lorentz-symmetry violating rotation parameters

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

Heckel et al, PRD 78 (2008)092006

parameter	electron	proton	neutron
$\tilde{b}_X$	-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		

Phillips et al, PRD 63(2001) 111101 Cane et al, PRL 93(2004) 230801

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

Earth's motion around the Sun gives sensitivity to boost terms generalized helicities

PHYSICAL REVIEW D **78,** 092006 (2008)

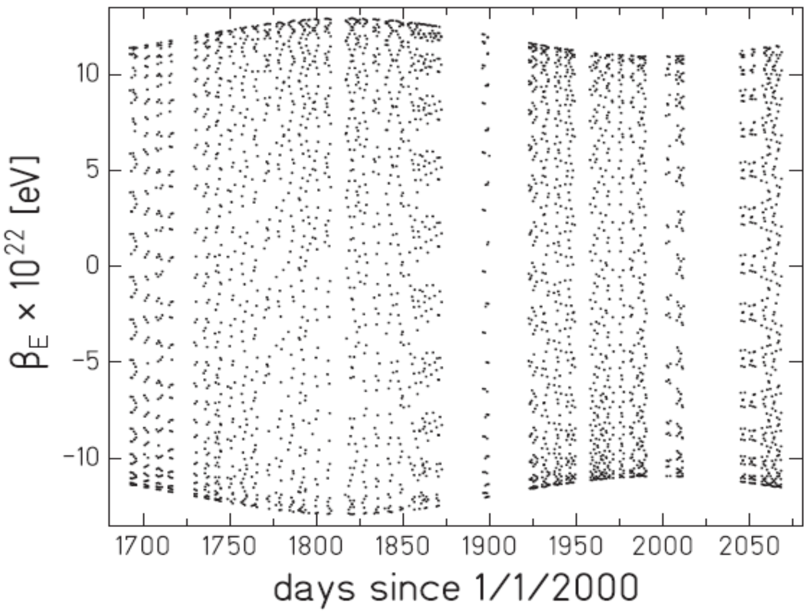
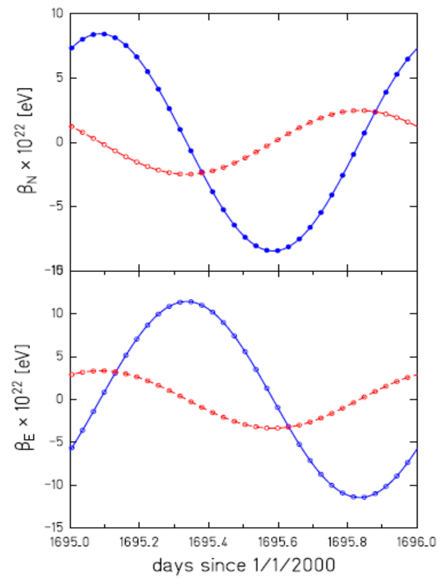


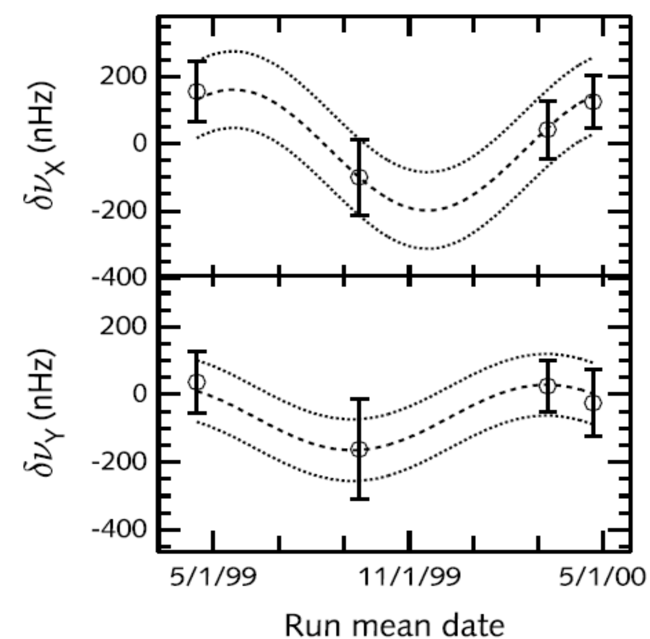
FIG. 6. Expected β_E signal corresponding to $C_{XX} = 10^{-18}$ eV. Each point is placed at the time of one of the cuts in our complete data set. Almost 4000 additional data points extending out to 2825 on the horizontal axis are omitted to keep the figure readable. The annual modulation arises from $\boldsymbol{v}_{\odot}$, the steady component comes from $\boldsymbol{v}_{\mathrm{CMB}}$.

Eöt-Wash



CfA

PRL **93,** 230801 (2004)

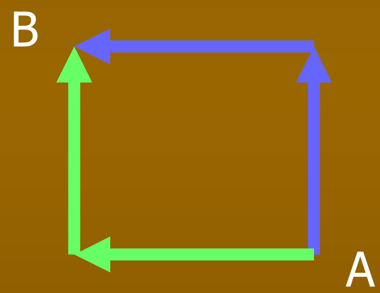


an amusing number

- 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

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

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

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

Lunar Laser Ranging (LLR): a comprehensive probe of weak-field gravity

- nearly 4 decades of ranging data during which range precision has improved by factor greater than 100
- shape of moon’s orbit currently known to 4 mm: relativisic effects have 6 meter amplitude
- some implications of these data

    Gdot/G < 1 part in 10^{12}/year

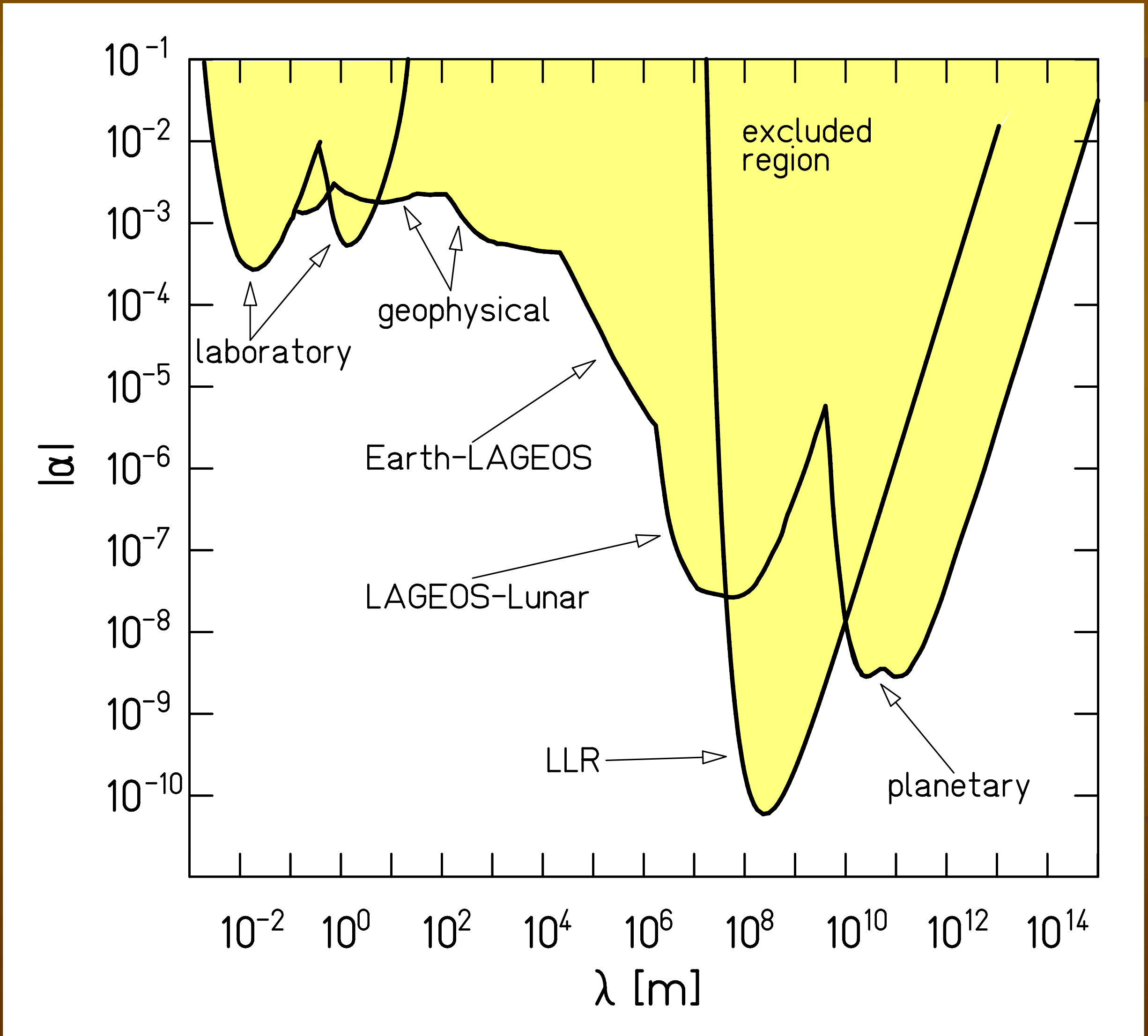
    anisotropy of G < few parts in 10^{12}

    best test of strong EP

    most precise test of the gravitational $1/r^2$ law

    constraints on Lorentz violation in gravitational sector

95% confidence limits as of 2000 on Yukawa violations of the gravitational $1/r^2$ law



archival LLR data provide bounds on 6 linear combinations of dimensionless SME gravitational parameters

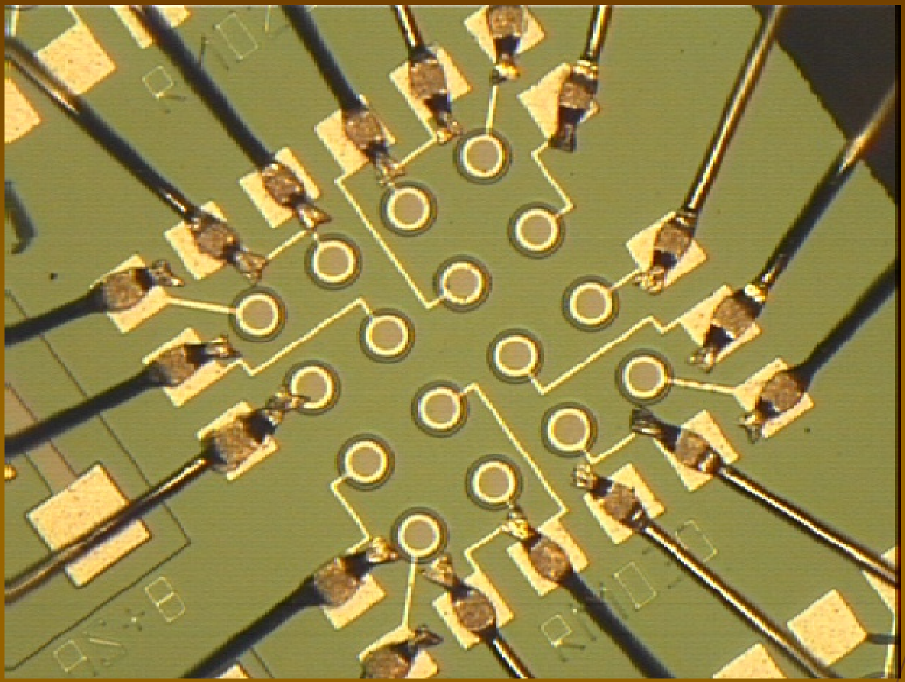
Parameter	Predicted sensitivity	This work
$\bar{s}^{11}-\bar{s}^{22}$	10^{-10}	$(1.3 \pm 0.9) \times 10^{-10}$
$\bar{s}^{12}$	10^{-11}	$(6.9 \pm 4.5) \times 10^{-11}$
$\bar{s}^{02}$	10^{-7}	$(-5.2 \pm 4.8) \times 10^{-7}$
$\bar{s}^{01}$	10^{-7}	$(-0.8 \pm 1.1) \times 10^{-6}$
$\bar{s}_{\Omega_\oplus c}$	10^{-7}	$(0.2 \pm 3.9) \times 10^{-7}$
$\bar{s}_{\Omega_\oplus s}$	10^{-7}	$(-1.3 \pm 4.1) \times 10^{-7}$

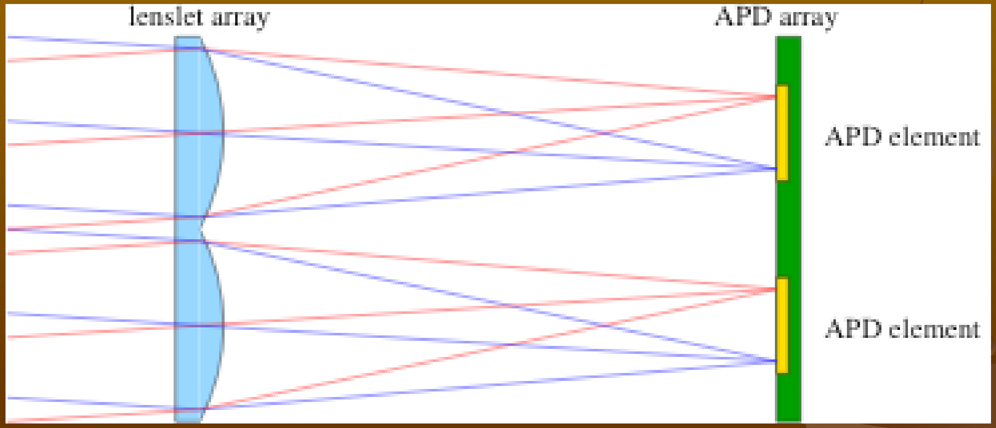
Battat et al. PRL 99 (2007) 241103

APOLLO
a next-generation LLR facility

- UCSD, UW, MIT, Humboldt State, Harvard, APO collaboration: Tom Murphy (UCSD) is PI
- based on 3.5 m APO telescope at 9200′ elevation in southern New Mexico
- instrumented for remote operation
- 2W laser delivers 90ps pulses of 532nm light at 20Hz
- return and time-zero photons detected in 16-element APD array

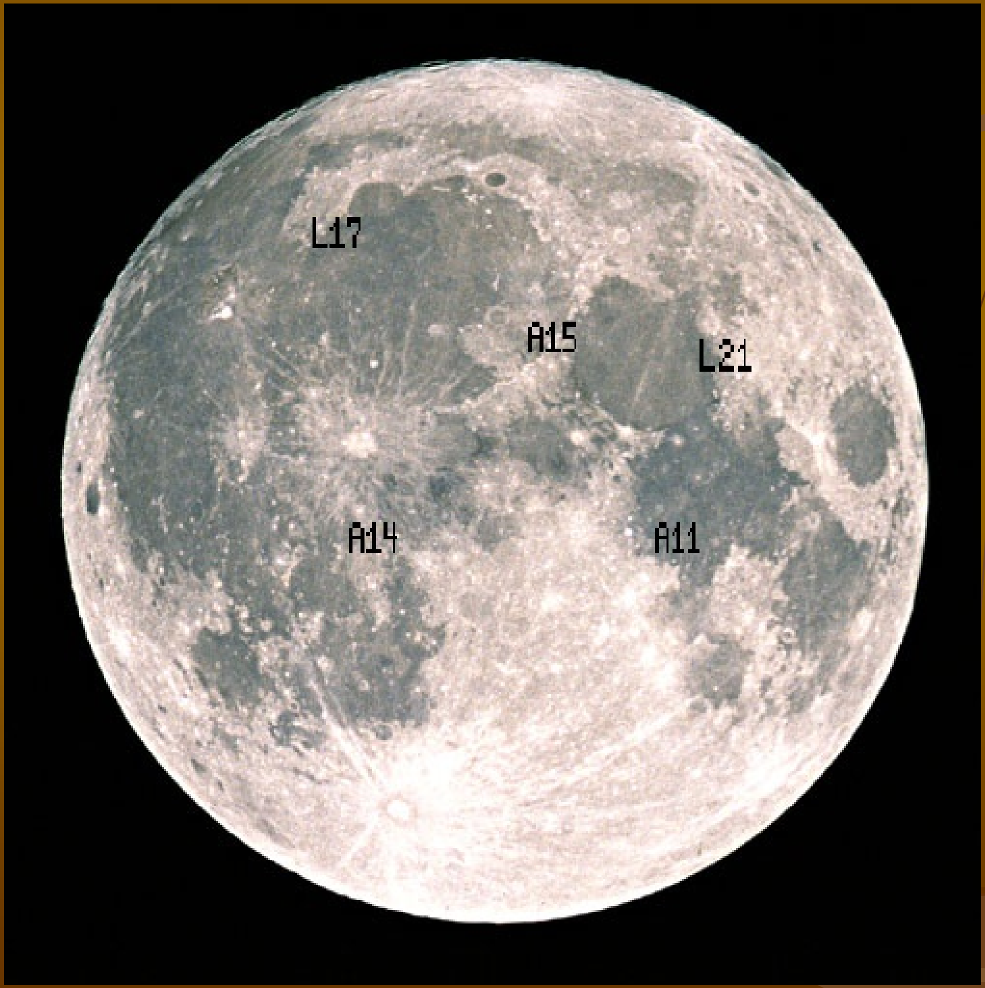
Catching All the Photons





- Several photons per pulse necessitates multiple "buckets" to time-tag each
  - Avalanche Photodiodes (APDs) respond only to *first* photon
- Lincoln Labs prototype APD arrays are perfect for APOLLO
  - 4×4 array of 30 μm elements on 100 μm centers
- Lenslet array in front recovers full fill factor
  - Resultant field is 1.4 arcsec on a side
  - Focused image is formed at lenslet
  - 2-D tracking capability facilitates optimal efficiency

Lunar retroreflectors



Three Apollo missions delivered reflectors

- Apollo 11: 100-element
- Apollo 14: 100-element
- Apollo 15: 300-element

Two French-built, Soviet-landed reflectors were placed on rovers

- Lunokhod 1 (inaccessible)
- Lunokhod 2

similar in size to A11, A14

Some limiting factors in LLR:

- converting telescope-to-reflector range into distance between centers of mass
- uneven coverage throughout the lunar cycle
- low photon counting rate limits systematic studies

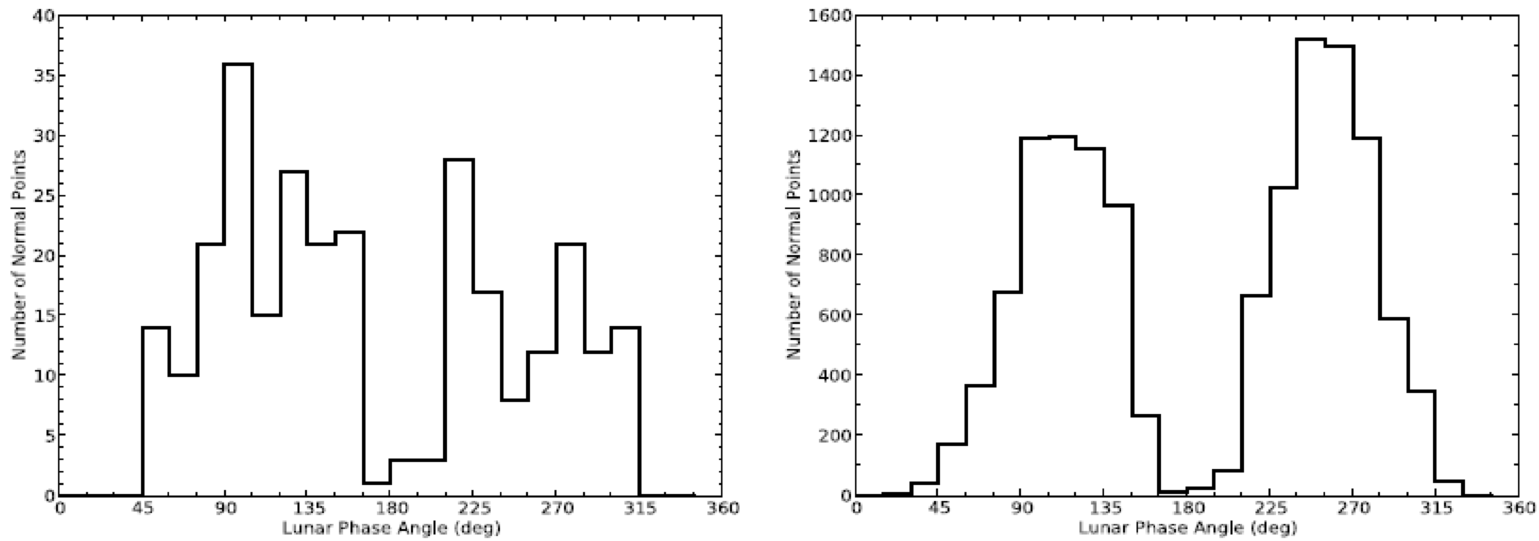
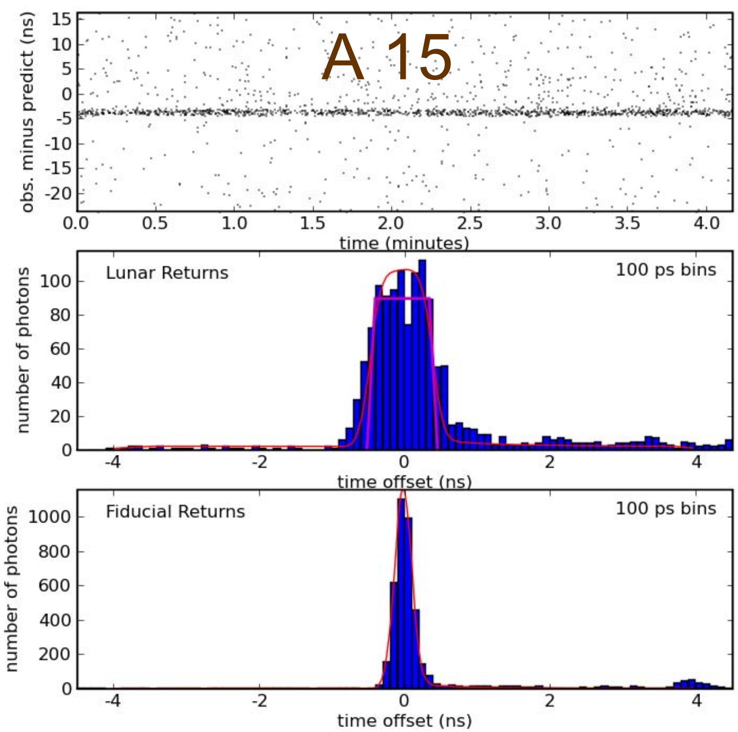


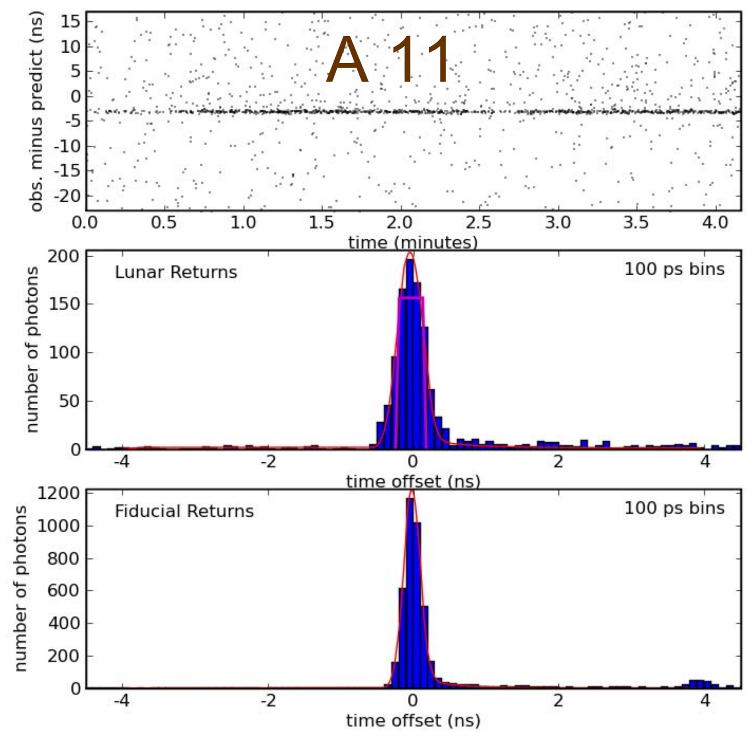
FIG. 2.—(*Left*): Lunar-phase coverage of the APOLLO data set. (*Right*): The same plot for the archival LLR data from 1984 to 2008. Phase angles of 0°, 90°, and 180° correspond to new, first quarter, and full moon, respectively.

APOLLO's performance

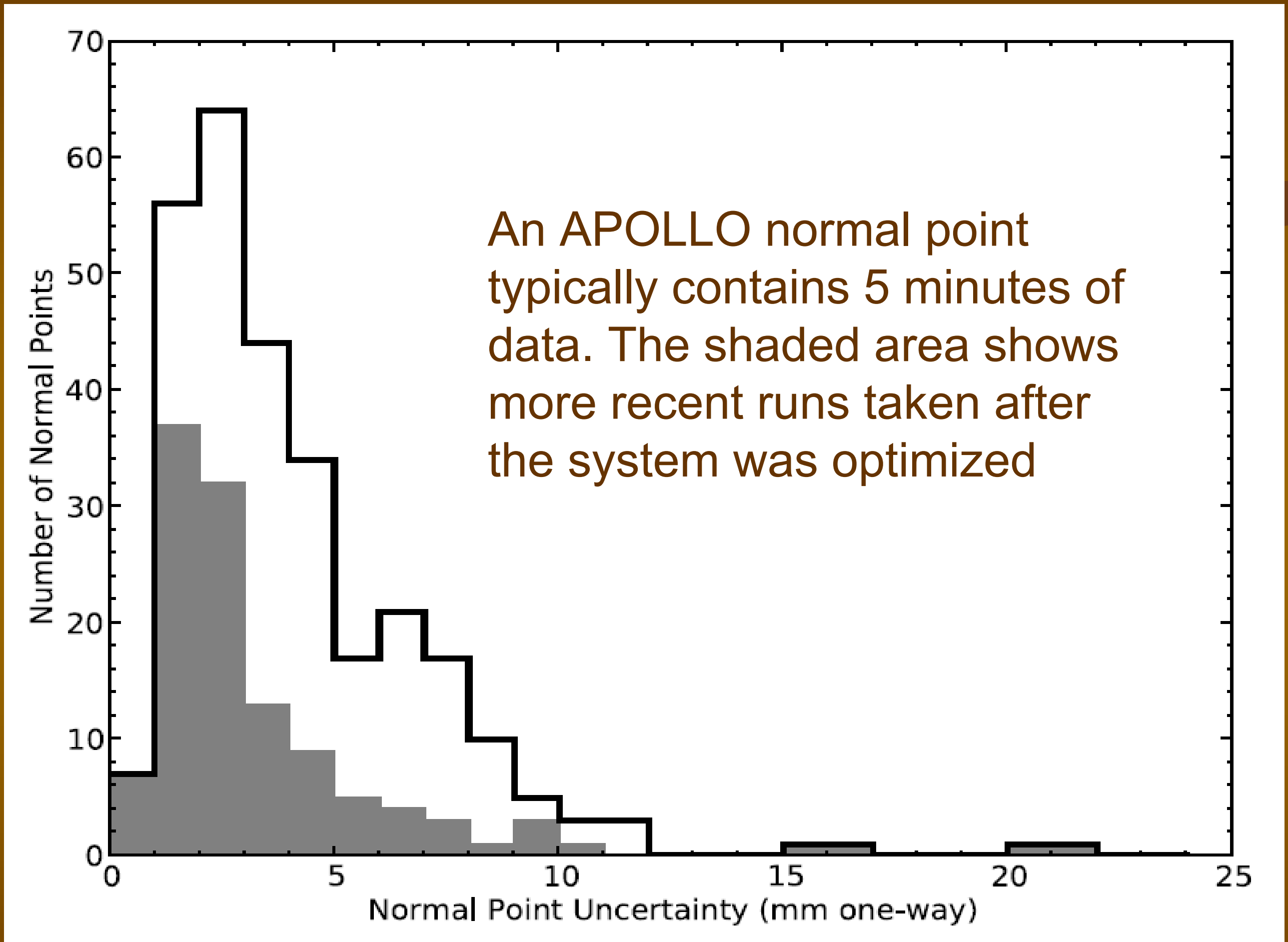
Table 1: Summary of APOLLO record runs

Reflector	Date	Laser Shots	Photons detected (× prev. record)	Photons/minute (× prev. record)	Phot/shot
Apollo 11	2008-10-17	5000	4497 (26×)	1079 (65×)	0.90
Apollo 14	2008-10-17	5000	7606 (36×)	1825 (69×)	1.52
Apollo 15	2008-10-17	5000	15730 (26×)	3775 (67×)	3.15
Lunokhod 2	2008-09-22	5000	750 (11×)	180 (31×)	0.15





APOLLO range precision is now at the mm level



APOLLO’s high data rate and precision allow us to make systematic error tests that coud not be done in the past

An interesting possibility for the future

place a microwave beacon on the moon near one of the retroreflectors

this will tie the VLBI system together with LLR allowing a very precise test of the relation between the local inertial frame and that of the distant quasars

conclusions

- Experiments with classical bodies (permanent magnets and masers) have good sensitivity for potential Planck-scale violations of Lorentz invariance in the matter sector. No evidence for this is found at the 10^{-31} GeV level.

- Battat used LLR data to bound Lorentz-violating effects in the pure gravity sector at the 10^{-6} to 10^{-10} level

- powerful new LLR (APOLLO) facility is now operating. To fully exploit this instrument, a modern, flexible ranging code incorporating detailed earth and moon solid-body effects as well as GR is needed

- Kostelecky and Tasson's new mechanism for potentially large Lorentz violation in the matter-gravity is testable with gravitational experiments (EP tests, LLR, atom interferometry, etc) These tests are currently being done.

PRL 100, 031101 (2008) PHYSICAL REVIEW LETTERS week ending 25 JANUARY 2008

Atom-Interferometry Tests of the Isotropy of Post-Newtonian Gravity

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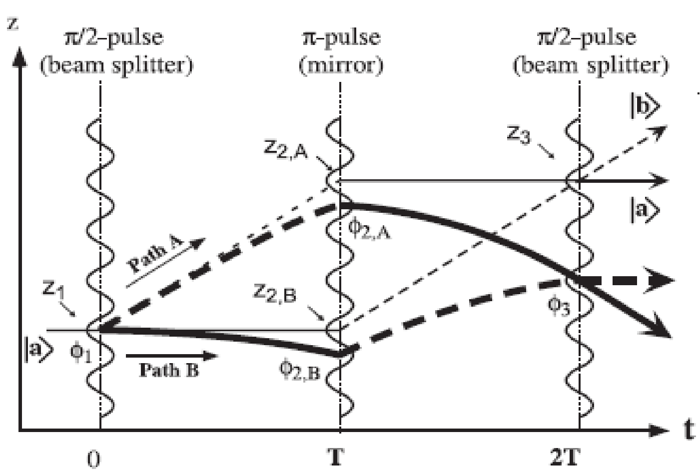
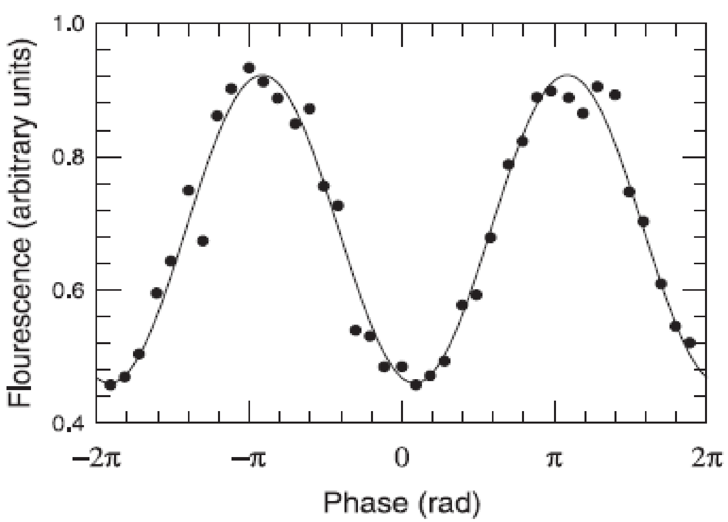
(Received 19 October 2007; published 22 January 2008)





references

Experimental papers:

- Heckel et al., PRD 78 (2008) 092006 (electrons)
- Canè et al., PRL 93 (2004) 230801 (neutrons)
- Battat et al., PRL 99 (2007) 241103 (LLR)
- Müller et al., PRL 100 (2008) 031101 (Cs atoms)

Standard Model Extension papers:

- Kostelecký & Lane, PRD 60 (1999) 116010 (matter)
- Bailey & Kostelecký, PRD 74 (2006) 045001 (pure-gravity)
- Kostelecký & Tasson, PRL 102 (2009) 010402 (gravity-matter)

2σ upper limits on $g_P^e\, g_S^N$ for axion-like particles