Title: Recent Gravitational Experiments and their Implications for Particle Physics

Date: Sep 11, 2007 08:30 AM

URL: http://pirsa.org/07090036

Abstract:

TOPICS COVERED

- Equivalence Principle tests
- short-range Inverse-square Law tests
- cosmic preferred-frame tests

WILL SUMMARIZE

- motivations
- techniques
- results

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WILL SUMMARIZE

- motivations
- techniques
- results

the Eöt-Wash® group in experimental gravitation

Faculty
- EGA
- Jens Gundlach
- Blayne Heckel

Staff
- Erik Swanson

Postdocs
- Seth Hoedl
- CD Hoyle
- Stephan Schlamminger

Current Grad students
- Claire Cramer
- Ted Cook
- Charlie Hagedorn
- William Terrano
- Todd Wagner

$1/r^2$
EP
spin

Part of this talk is based on PhD thesis work of recent graduate Dan Kapner (currently Kavli Fellow KCCP in Chicago)

Primary support from NSF Grant PHY0355012 with supplements from the DOE Office of Science and to a lesser extent NASA

unifying gravity with the other forces in physics is the central problem in fundamental science

string or M theory provides the only known framework for doing this

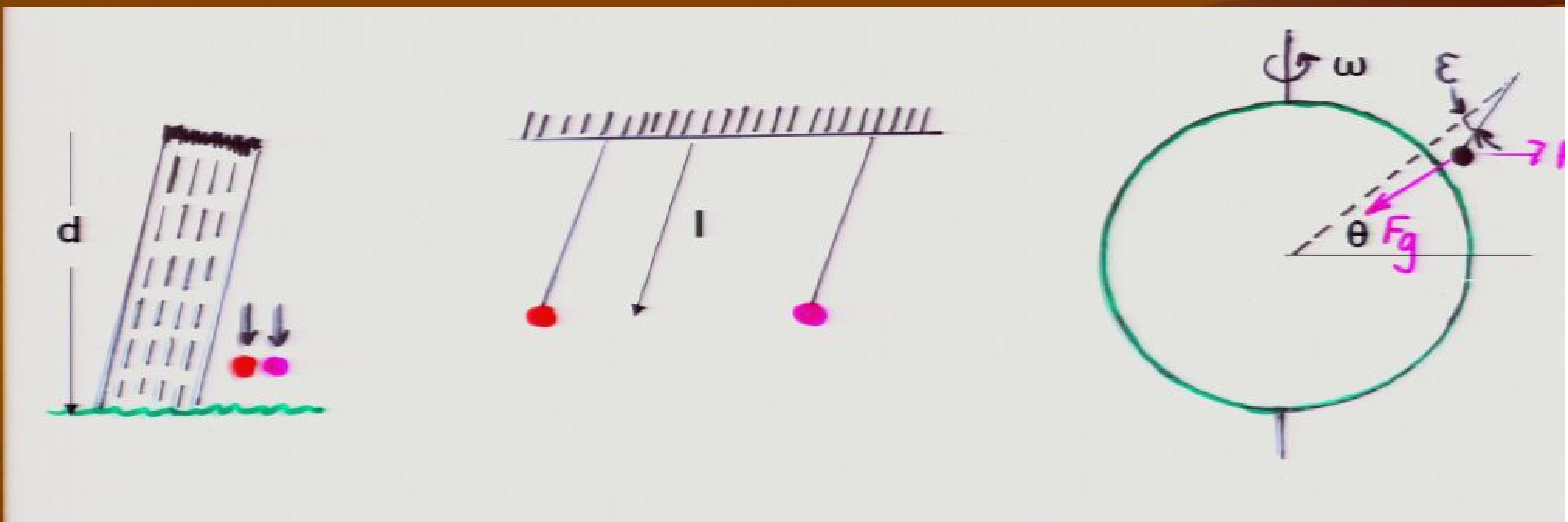
BUT: it inherently contains features that have to be hidden from experiment:
10 or 11 dimensions
hundreds of massless scalar particles

must find a way to account for the extreme weakness of gravity and the observed dark energy

some of these new features could show up in Equivalence Principle and/or inverse-square law tests

A brief history of Equivalence Principle tests:
Do all materials have the same m^i/m^g?

Galileo test | Newton-Bessel test | Eötvös test

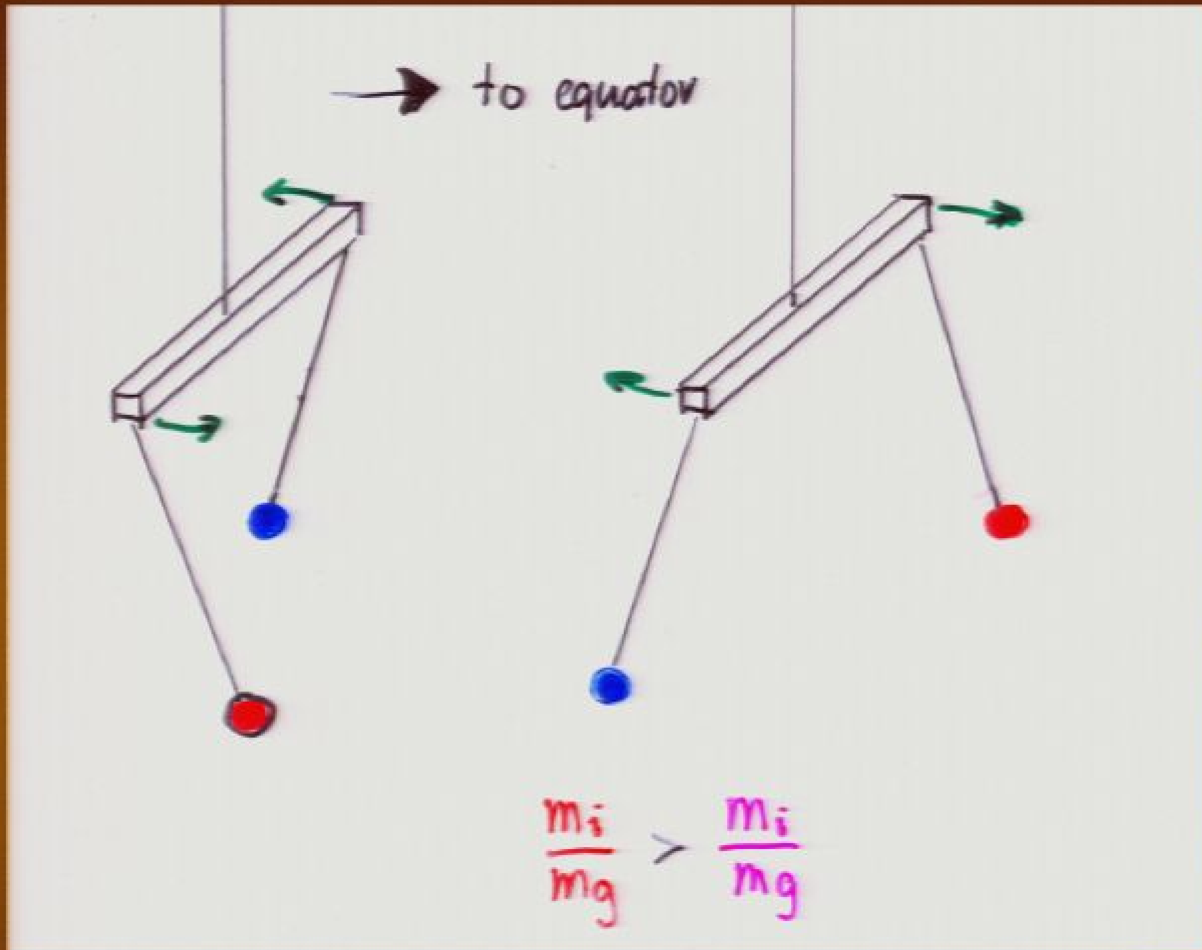


are fall times equal? | are periods equal? | are angles equal?

$T=\sqrt{(2d/g\ (m^i/m^g))}$ | $T=2\pi\ \sqrt{(l/g\ (m^i/m^g))}$ | $\varepsilon=\omega^2 R \sin 2\theta/(2g)\ (m^i/$

$\Delta a/a \leq 0.1$ | $\Delta a/a \leq 10^{-4}$ | $\Delta a/a \leq 10^{-9}$

implementation as a null experiment

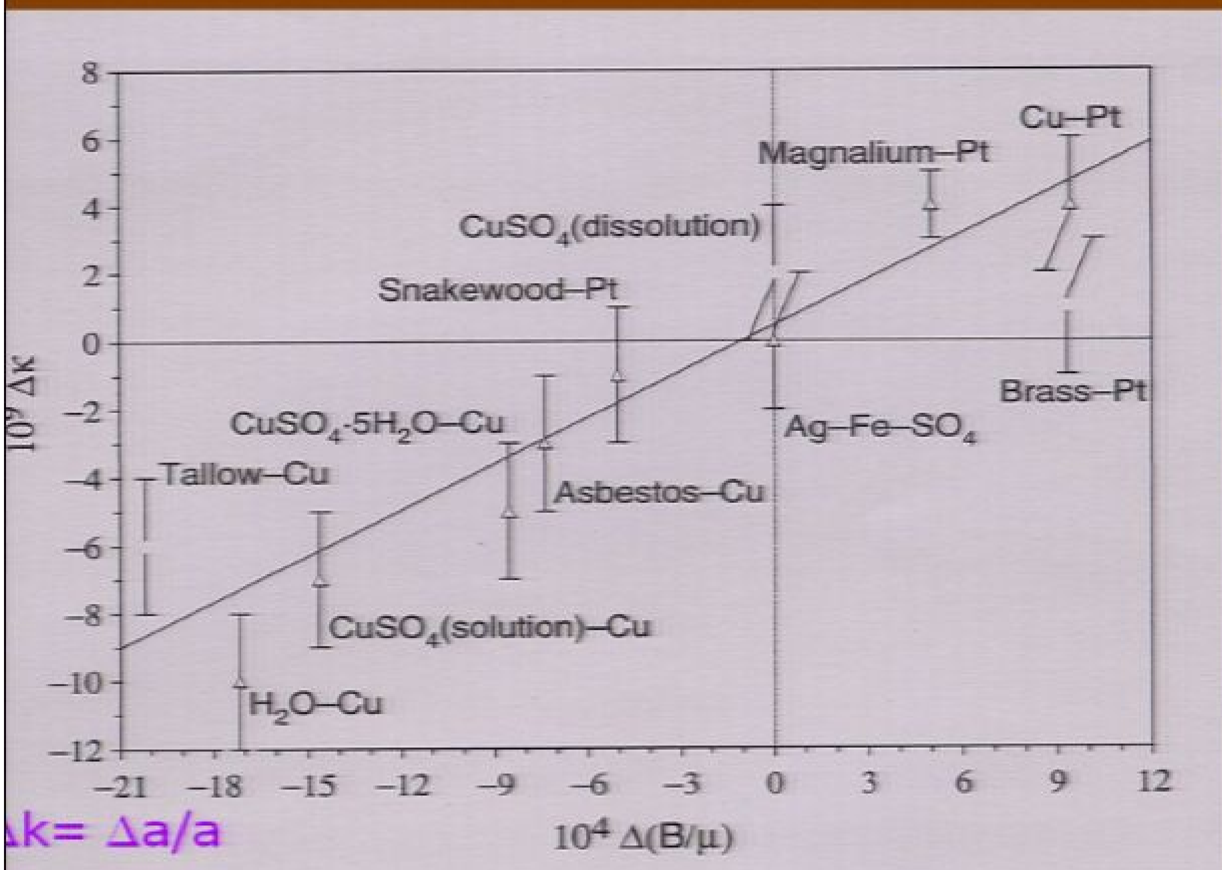


balance twists only if force vectors are not parallel

if the EP is violated down is not a unique direction
but gravity gradients also make vectors nonparallel

modern era in EP tests was ushered in by Fischbach's reanalysis of Eötvös's results

Fischbach at el., PRL 56, 3 (1986)



This result along with geophysical measurement was taken as evidence for a "5th force"

$$V(r) = V_N \left(1 + \tilde{\alpha} \left[\frac{B}{u}\right] \left[\frac{B}{u}\right]\right) \exp(-$$

with

$\alpha \approx .01$

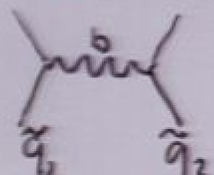
$30\text{m} \le \lambda \le 1000\text{m}$

2 WAYS TO THINK ABOUT EP TESTS

- test a key prediction of Einstein's theory of gravity

  is $m_i = m_g$?

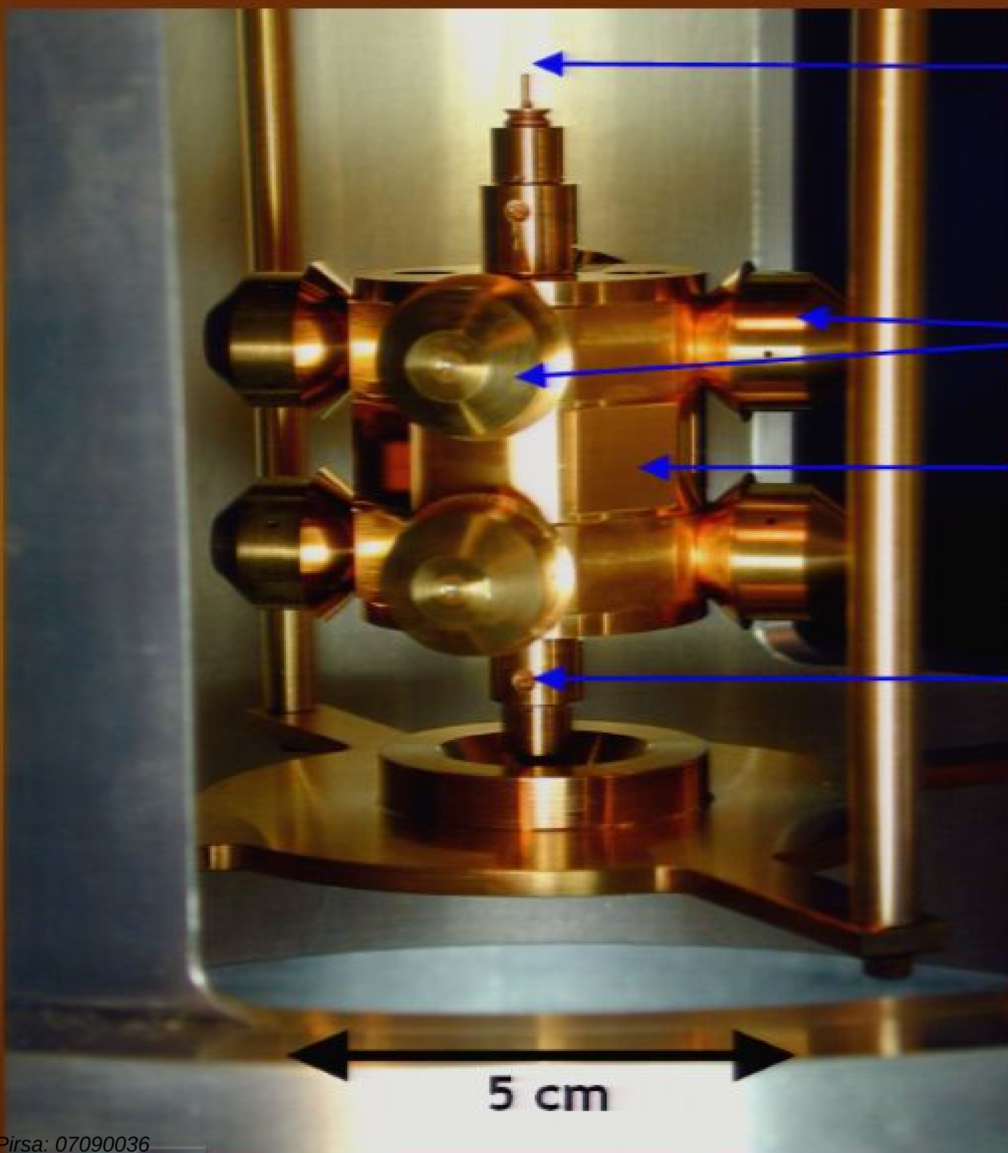
- assume EP is exact for gravity: use tests to probe for new quantum exchange forces even weaker than gravity

> any quantum exchange force will violate the EP
>
> 
>
>
> $$F_{12} \propto \tilde{q}_1 \tilde{q}_2 \frac{1}{r^2}\left(1+\frac{r}{\lambda}\right) e^{-r/\lambda}$$
>
> $$\lambda = \frac{\hbar}{m_b c}$$
>
> $$a_1 = \frac{F_{12}}{m_1} \propto \frac{\tilde{q}_1}{m_1}$$ ← "charge"-to-mass ratio cannot be exactly the same for all objects!
>
> recall EM
>
> $$(q/m)_{electron} = -(q/m)_{positron} \approx -2000\,(q/m)_{proton}$$

- most of the ideas for solving the big problems in physics predict effects that could show up in EP tests

  e.g. string theory dilaton

torsion pendulum of the new Eöt-Wash EP test



20 μm diameter 108 cm long
tungsten fiber

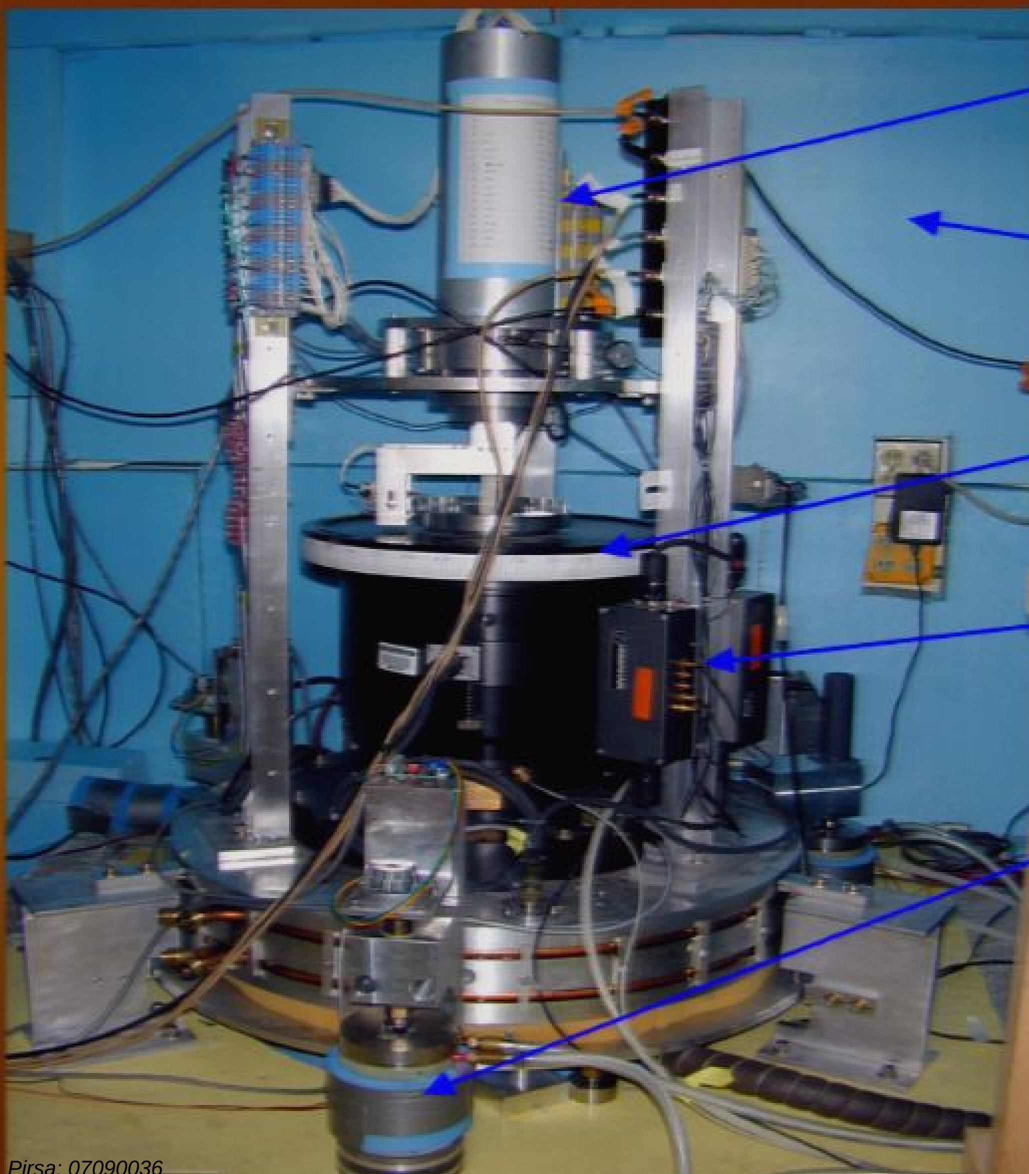
eight 4.84 g test masses
(4 Be & 4 Ti) or (4 Be & 4

4 mirrors

tuning screws adjust the mas
multipole moments & minimi
sensitivity to gravity gradient

free osc freq:	1.261 m
quality factor:	4000
decay time:	11d 6.5
machining tolerance:	5 μm
total mass :	70 g

turntable of the new EP balance



servoed rotary contactor
for electric signals

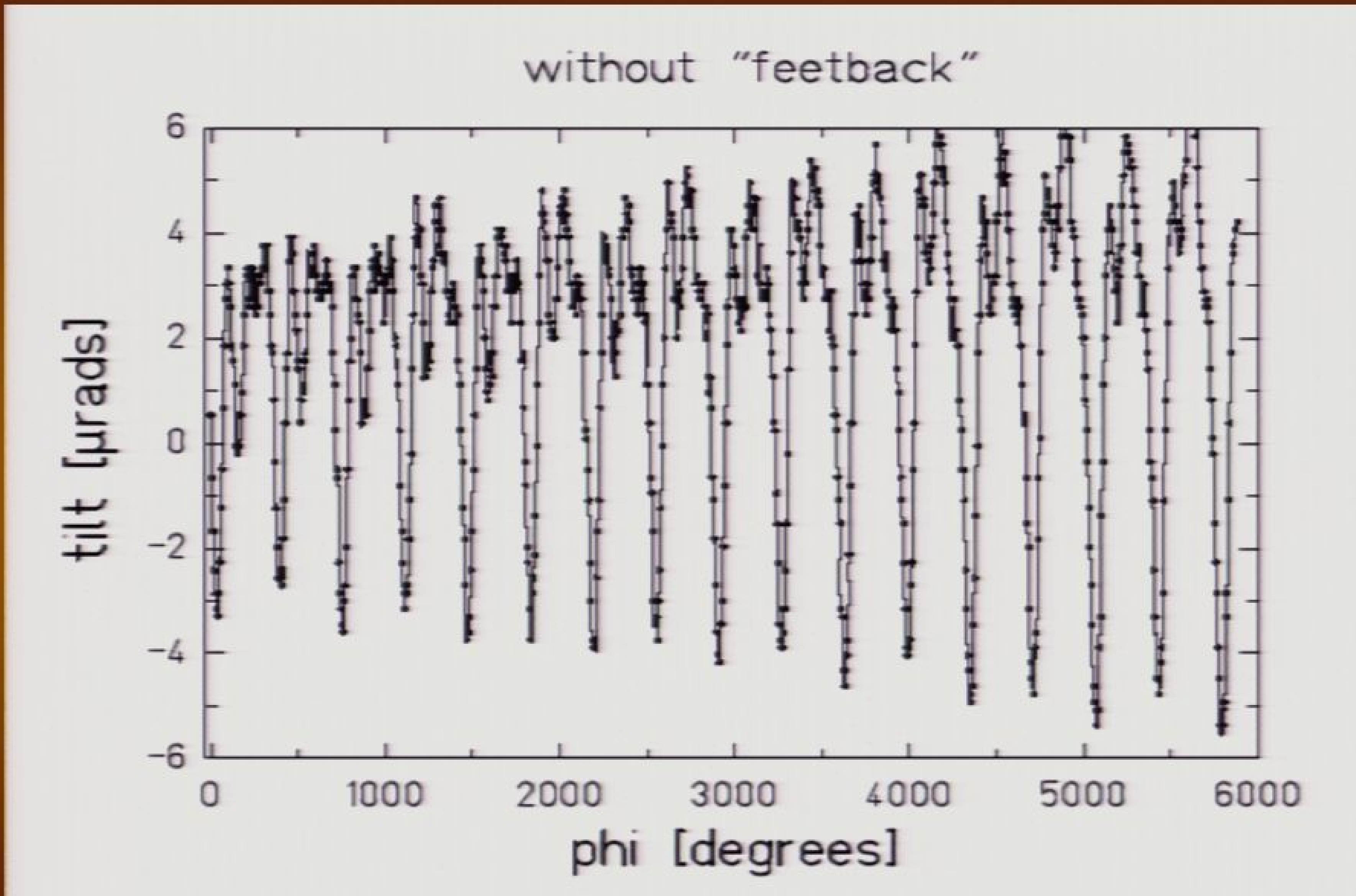
thermal insulation

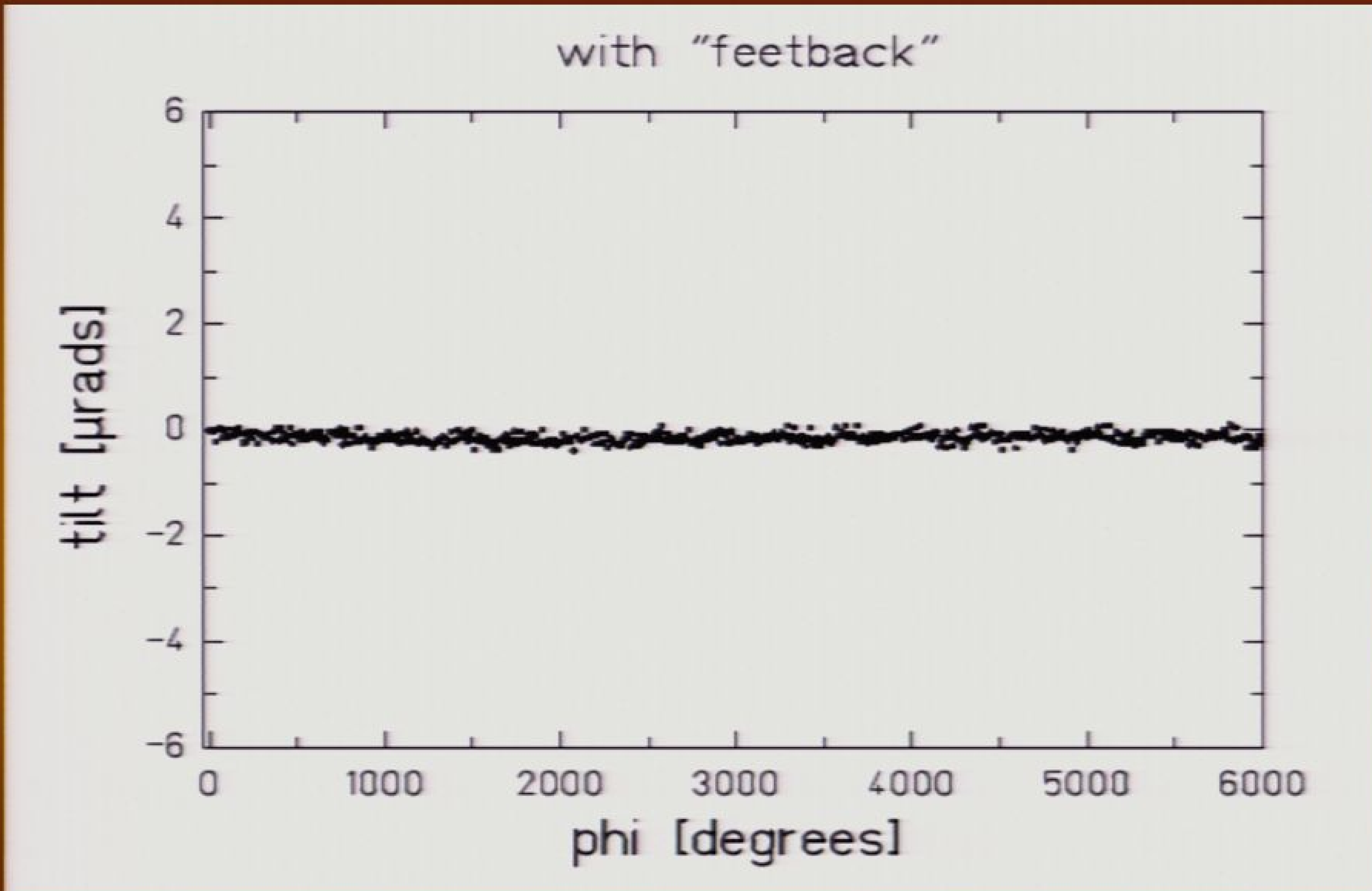
air-bearing turntable

angle encoder electronics

thermal expansion feet
fedback to keep turntable
rotation axis level

torsion balance hangs
from the bearing which
rotates at 0.833 mHz


without "feetback"
tilt [μrads]
phi [degrees]
6
4
2
0
−2
−4
−6
0
1000
2000
3000
4000
5000
6000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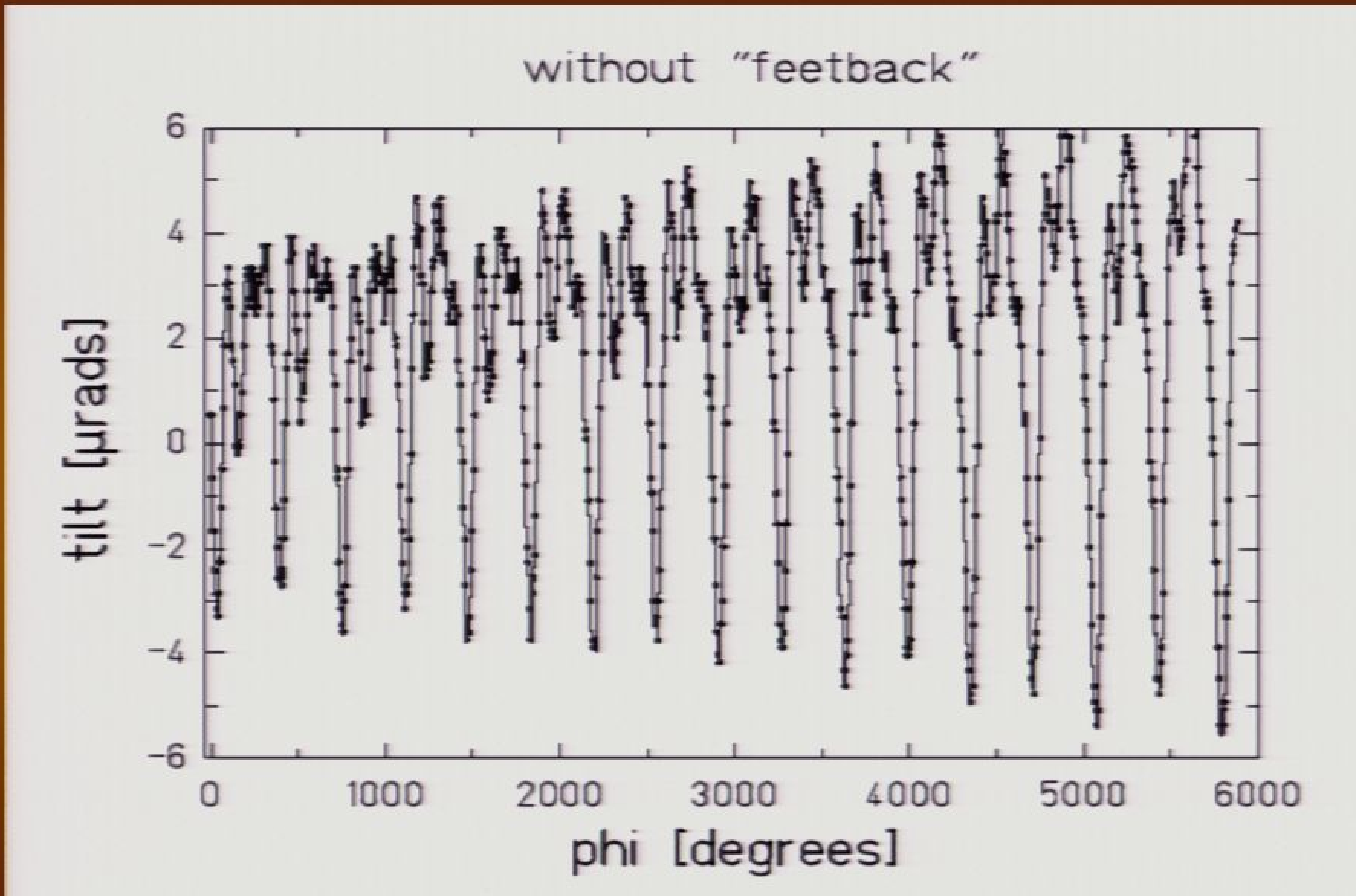
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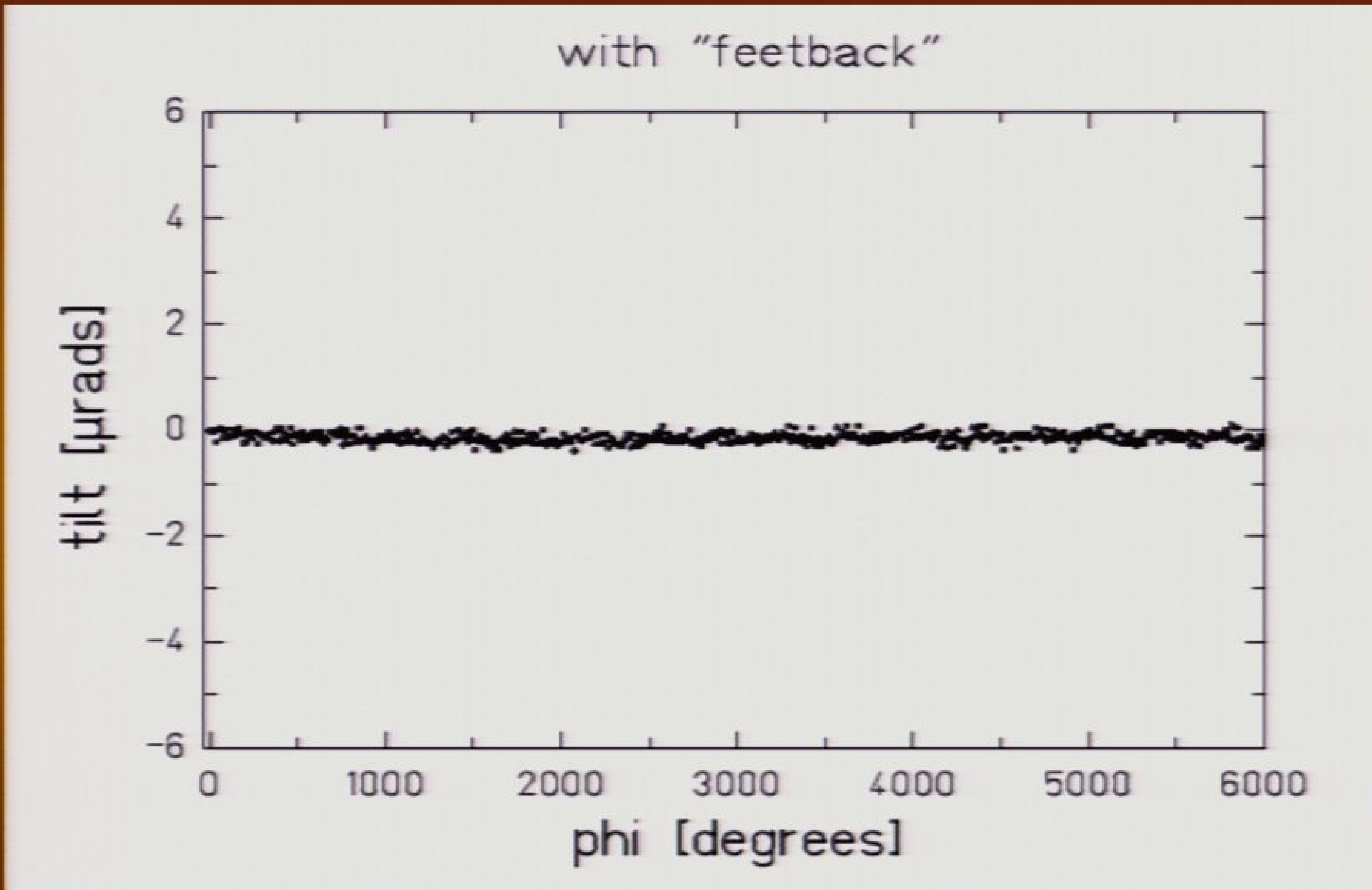
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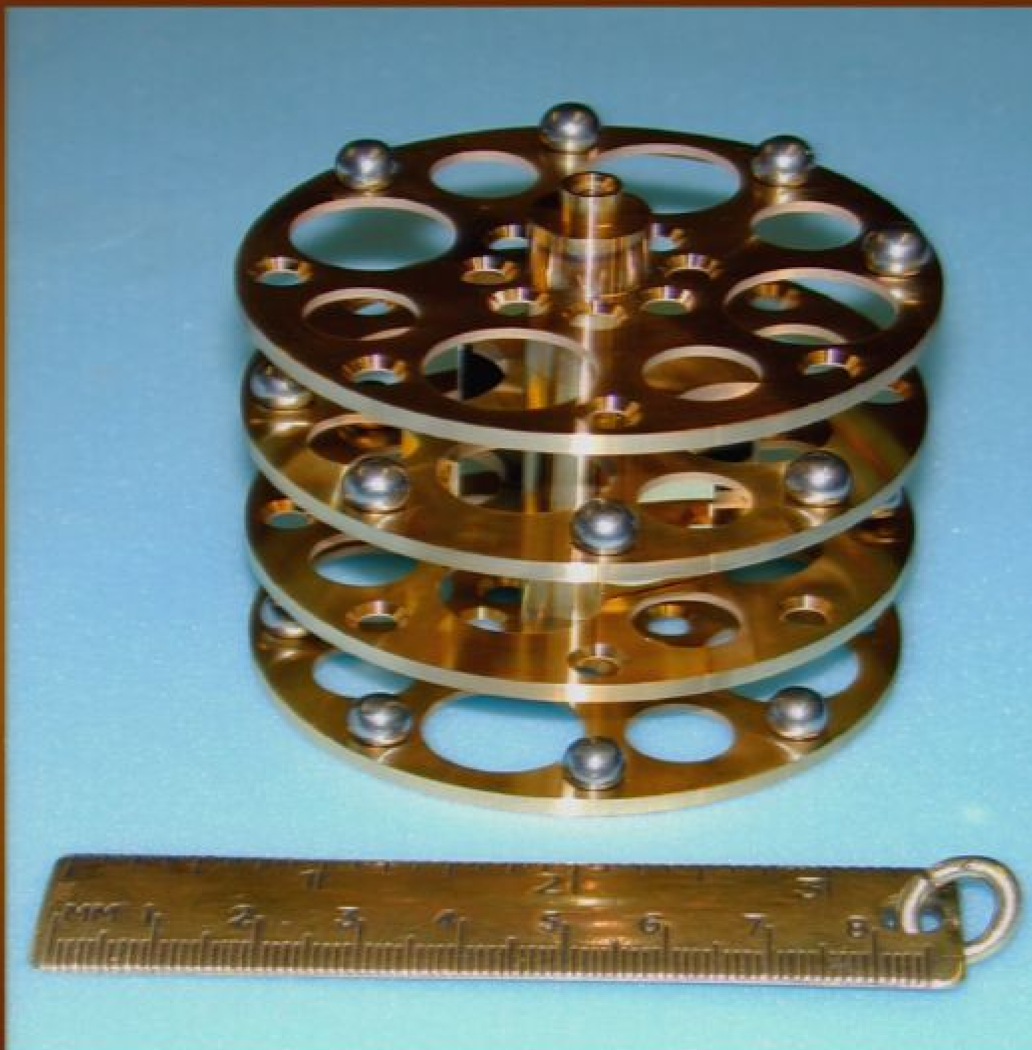
phi [degrees]

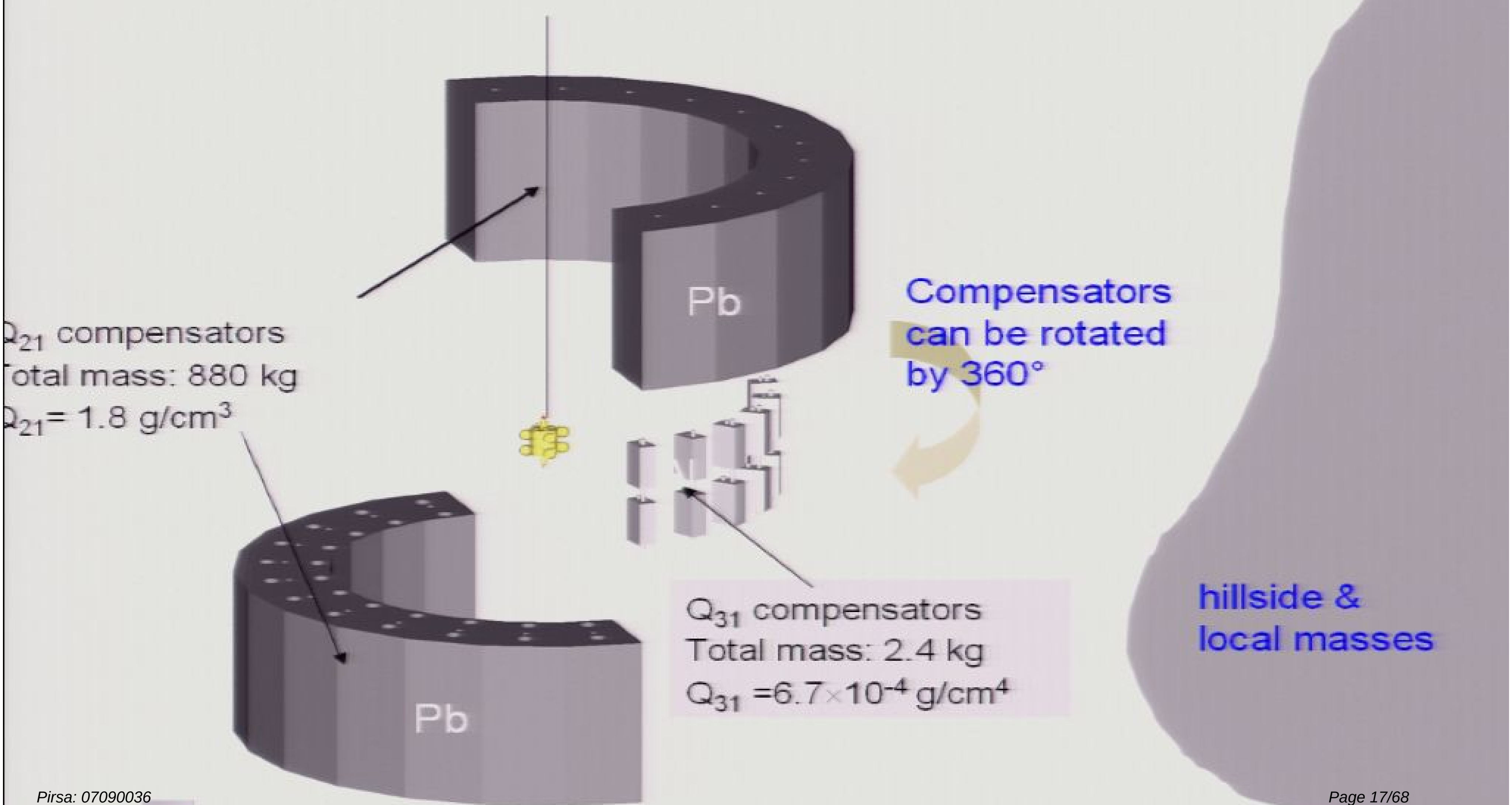
gravity-gradiometer pendulums



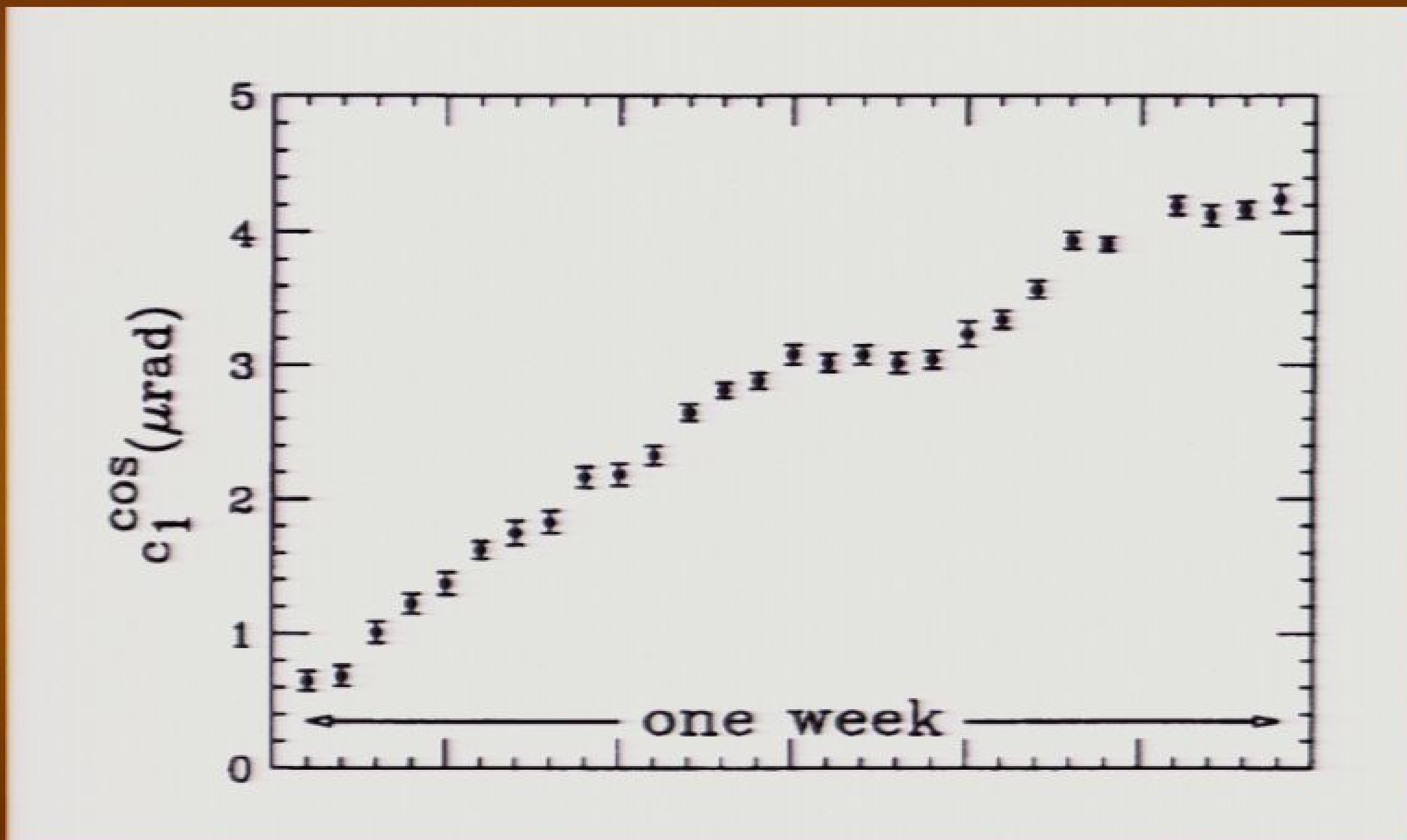
q_{41} configuration on a table

q_{21} configuration instal

gravity-gradient compensation

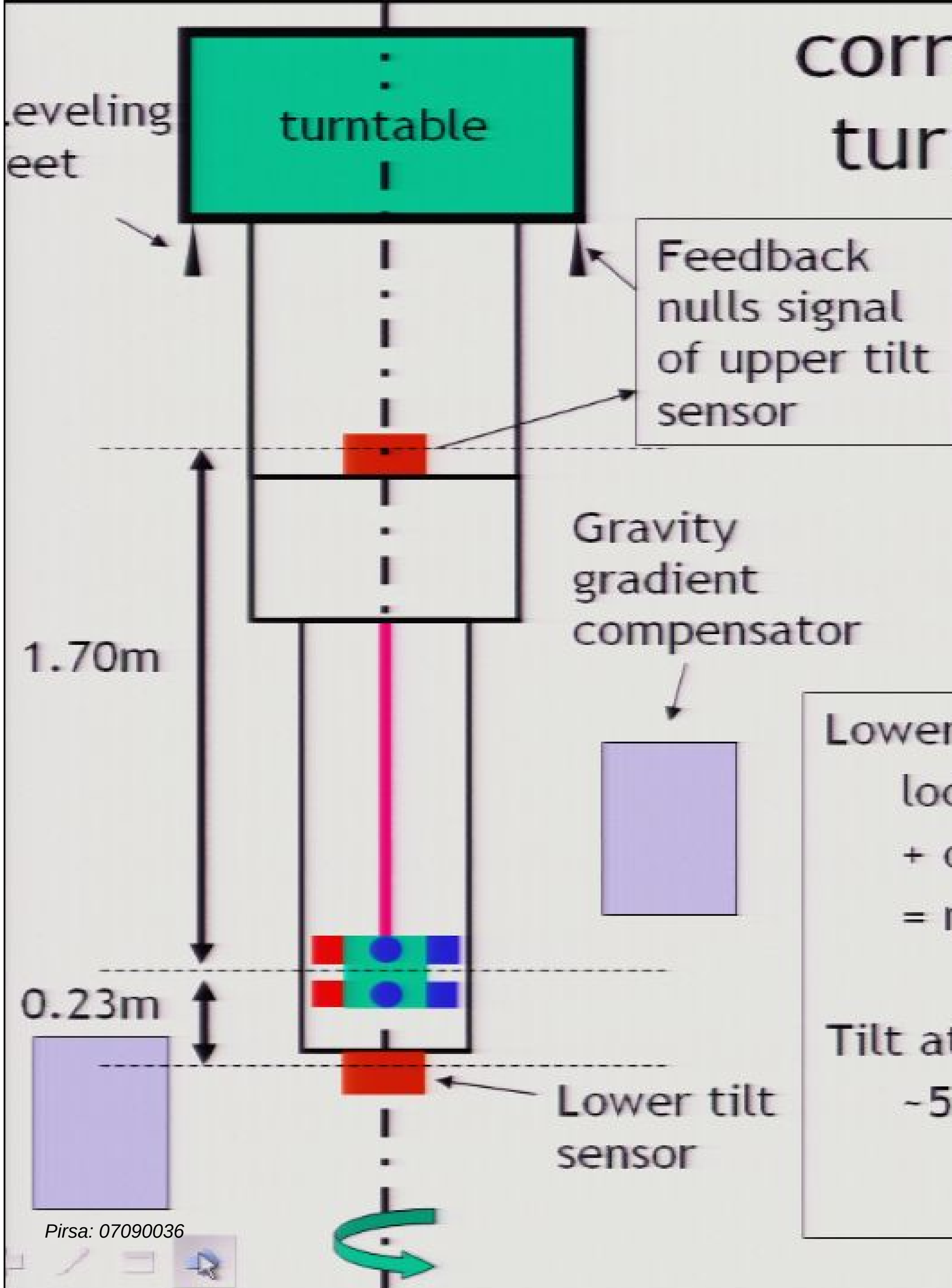


limitations on gradient cancellation



these data were taken in early November

correction for tilt of the turntable rotation axis



- Feedback removes tilt at upper t sensor
- However, local vertical varies wi height
  - gives a spurious deflection of the pendulum due to residual tilt

Lower tilt sensor measures:

local earth field (~60 nrad)

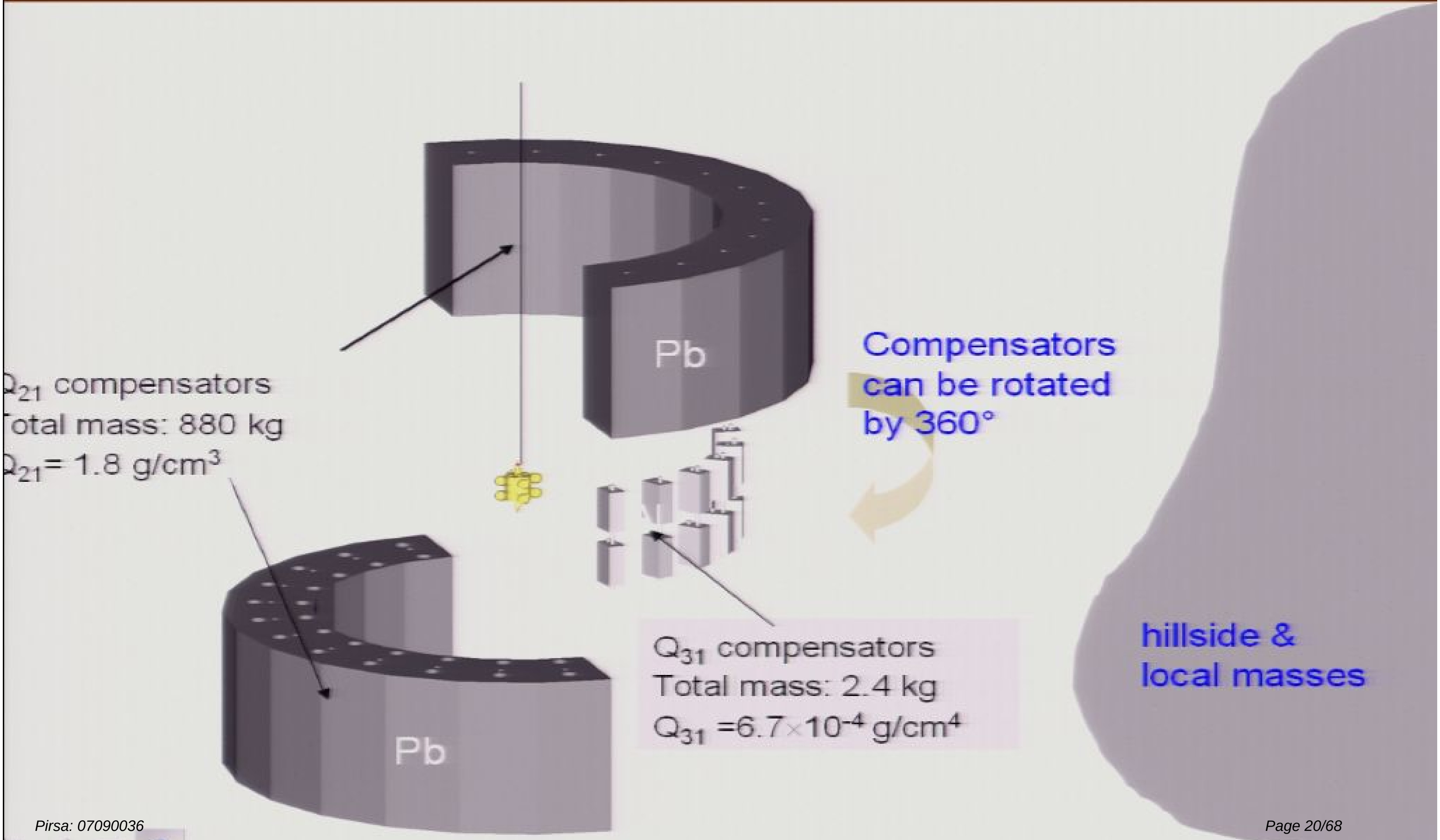
+ off-center compensator field (~–15 nrad

= measured tilt (~45 nrad)

Tilt at pendulum is only due to local earth fie

~50 nrad of tilt → ~2.5 nrad correction to pendulum signal

gravity-gradient compensation



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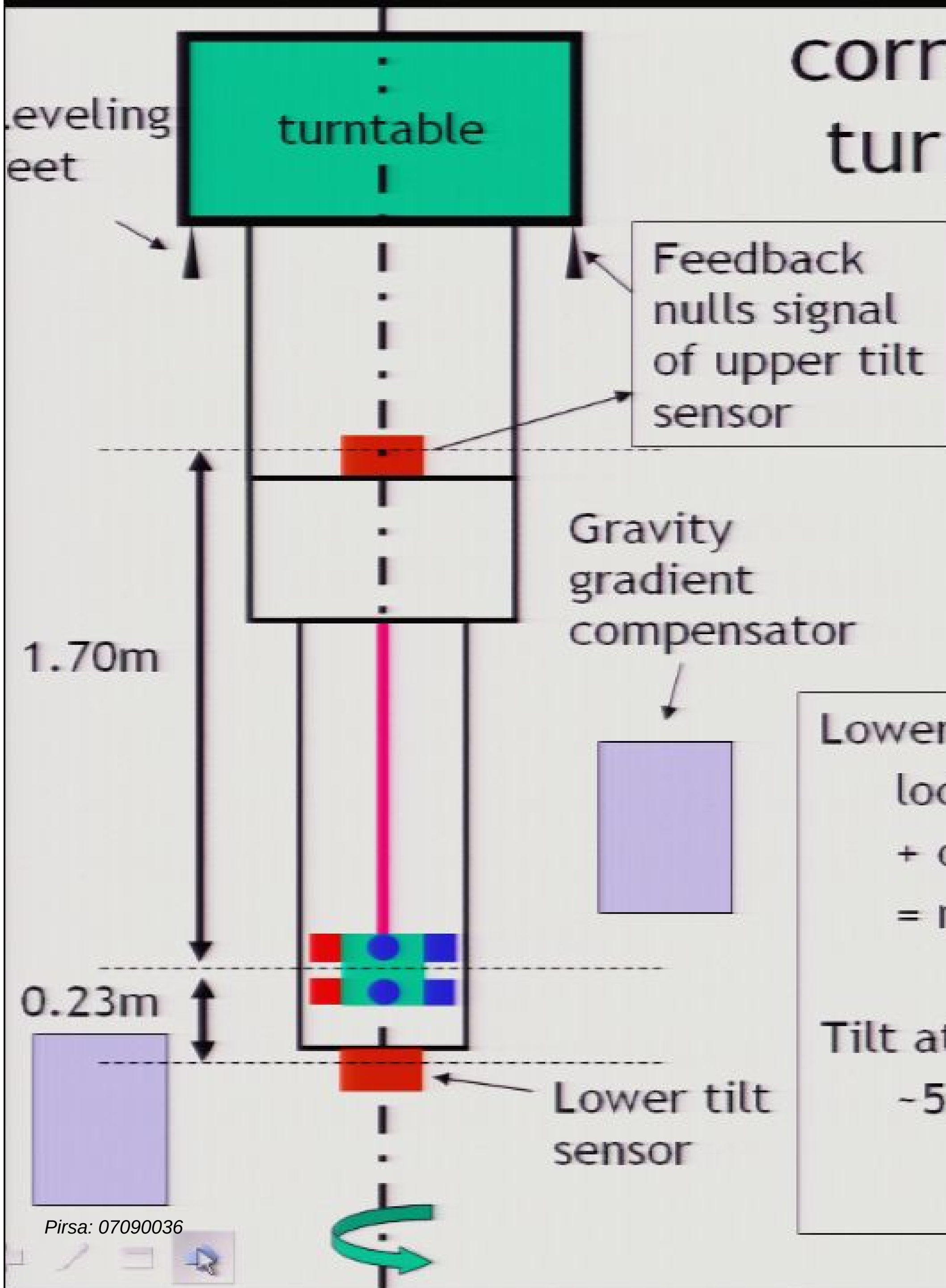

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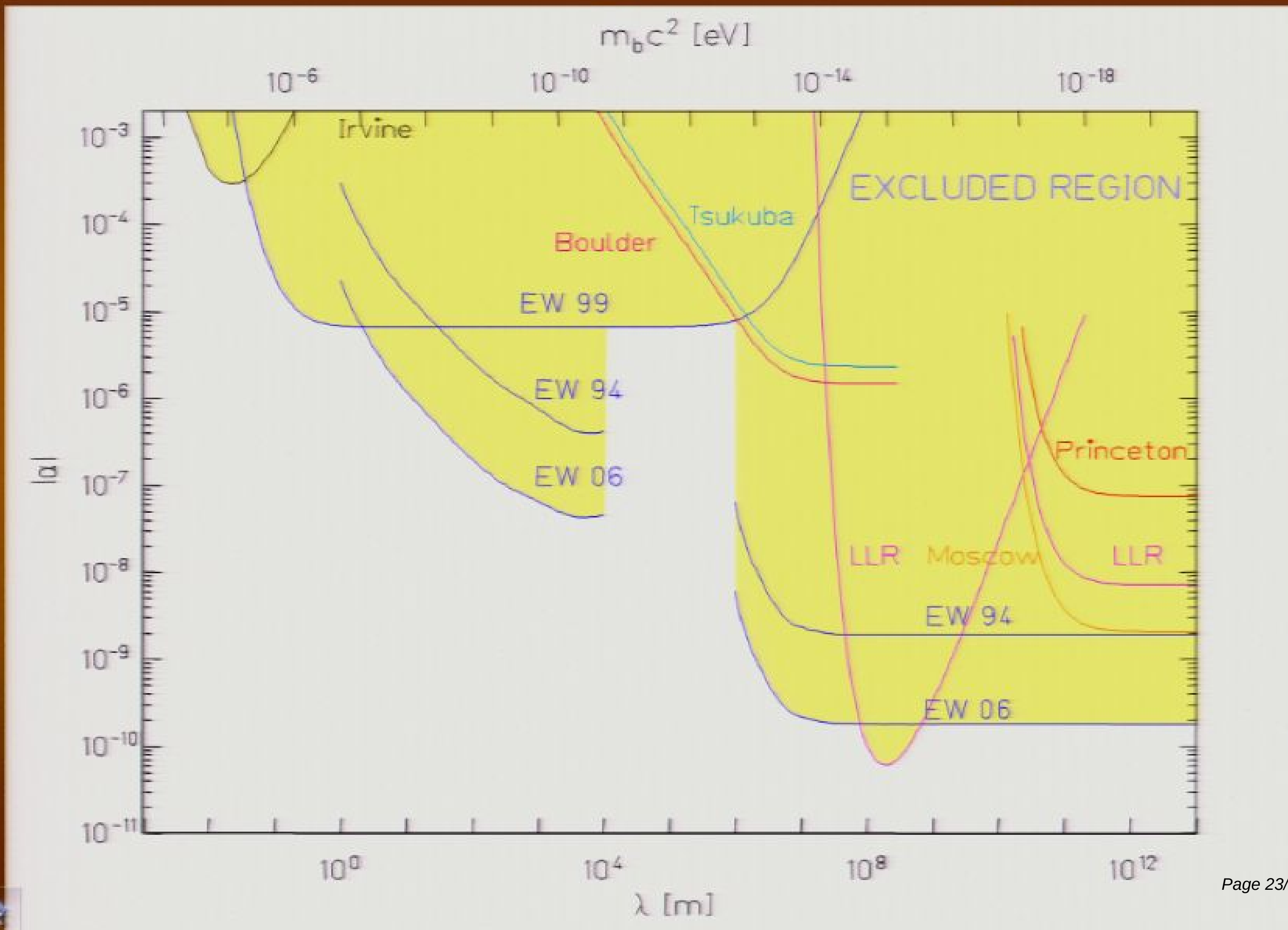
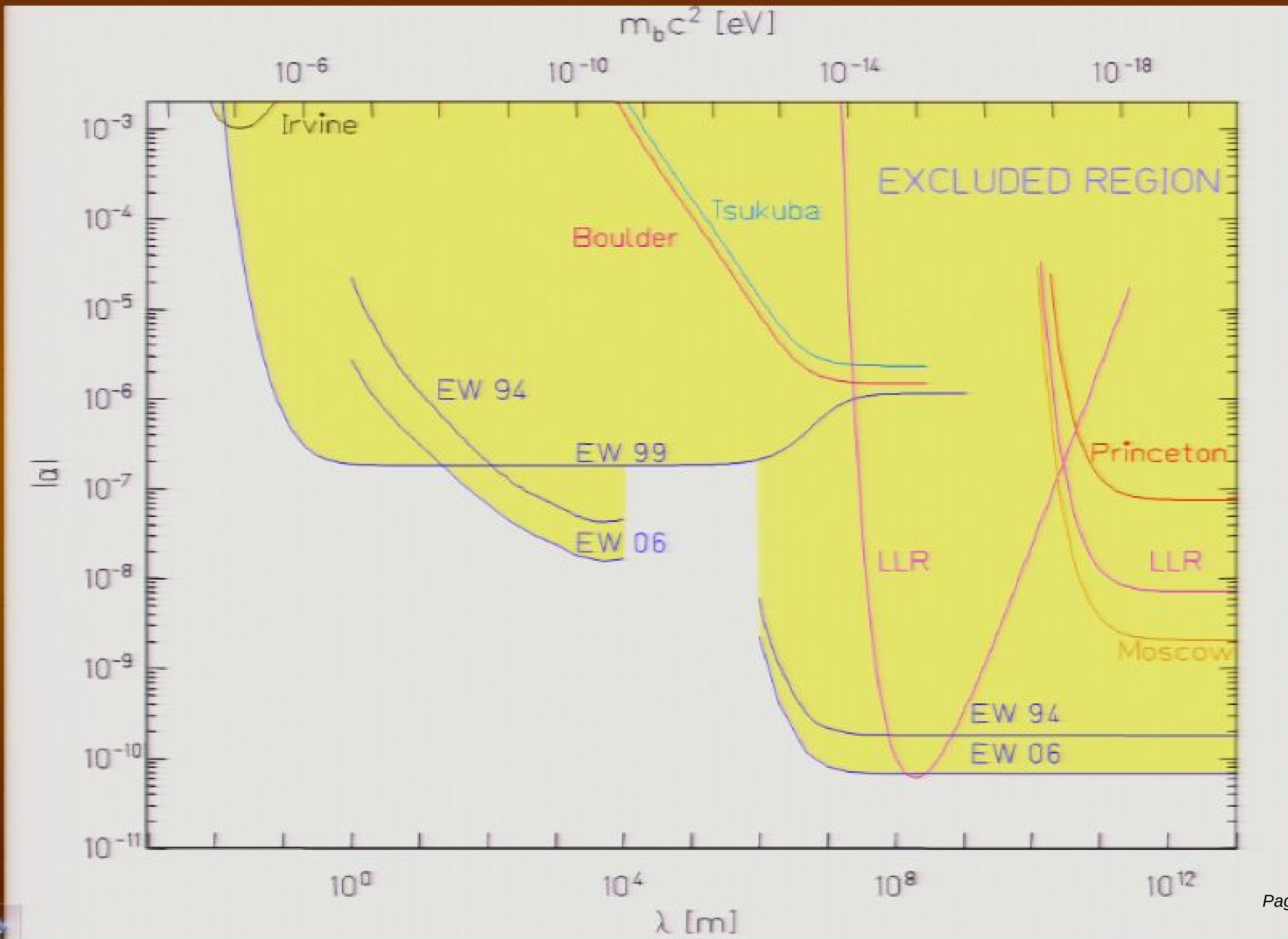
1σ statistical + systematic uncertainties from our Equivalence Principle experiment with beryllium and titanium test bodies

Source	Δa (cm/s^2)	$\Delta a / a_{source}$
Earth	$(-1.0 \pm 3.6) \times 10^{-13}$	$(-0.6 \pm 2.2) \times 10$
Sun	$(1.2 \pm 2.7) \times 10^{-13}$	$(2.1 \pm 4.6) \times 10$
Galaxy	$(0.0 \pm 3.0) \times 10^{-13}$	$(0.0 \pm 1.6) \times 10$
CMB	$(3.0 \pm 2.6) \times 10^{-13}$	$(1.8 \pm 1.5) \times 10$

95% confidence level exclusion plot for interactions coupled to baryon number

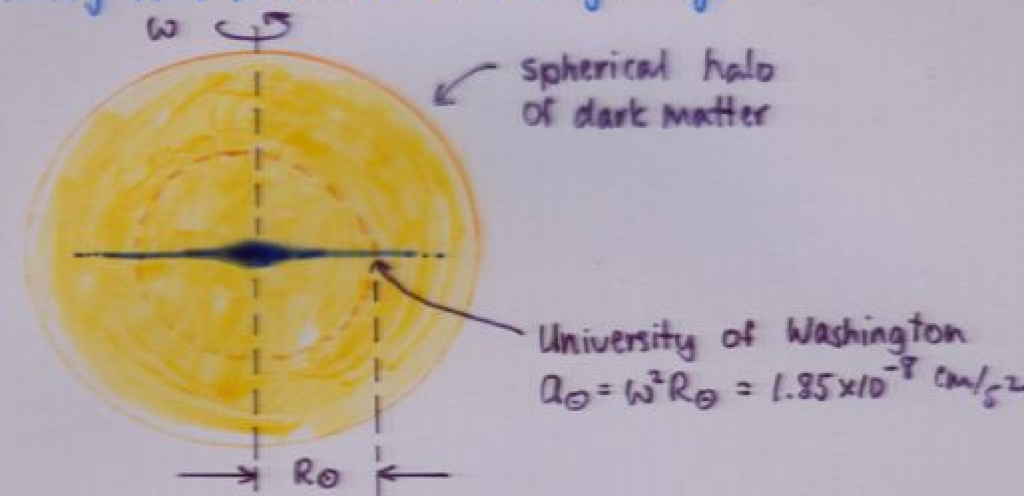


95% confidence level exclusion plot for interactions coupled to B - L



Is gravity the only long-range force between dark and luminous matter?

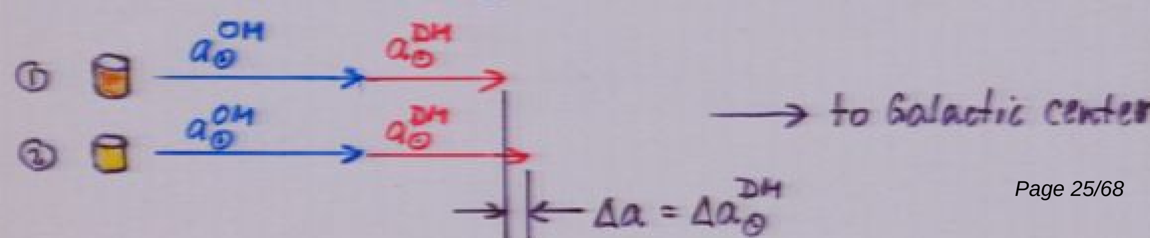
Check universality of free fall for different materials falling toward center of our galaxy.



although 90% of galaxy mass is thought to be DM much of it lies outside $R_\odot$, so

$$a_\odot^{DM} = 25\text{–}30\%\, a_\odot \Rightarrow a_\odot^{DM} \approx 5\times10^{-9}\ \text{cm/s}^2$$

we can make interesting statement about non-grav. component of $a_\odot^{DM}$ if we can detect differential accels. with a sensitivity of $10^{-3} a_\odot^{DM} \sim 5\times10^{-12}$ cm/s



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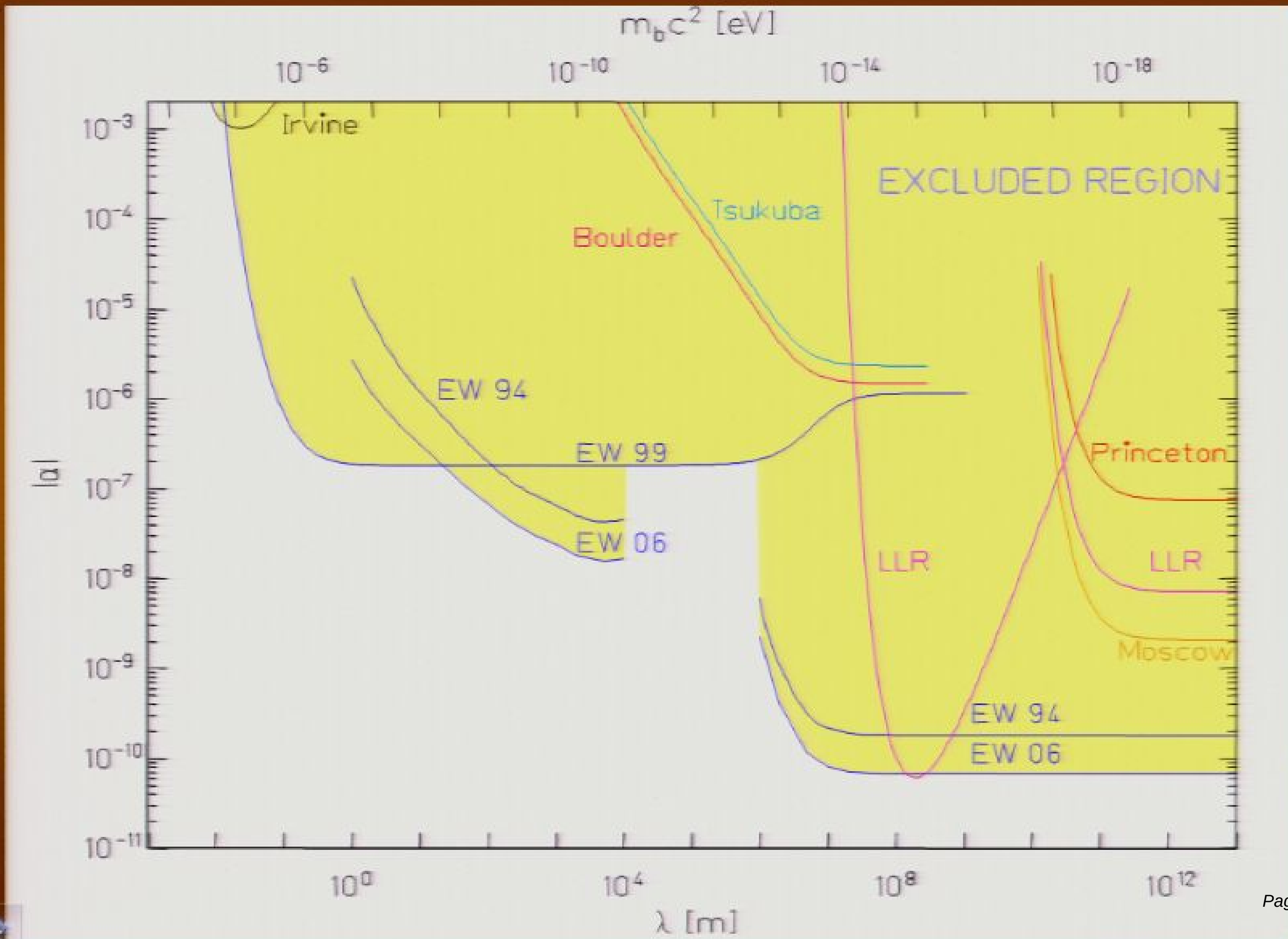

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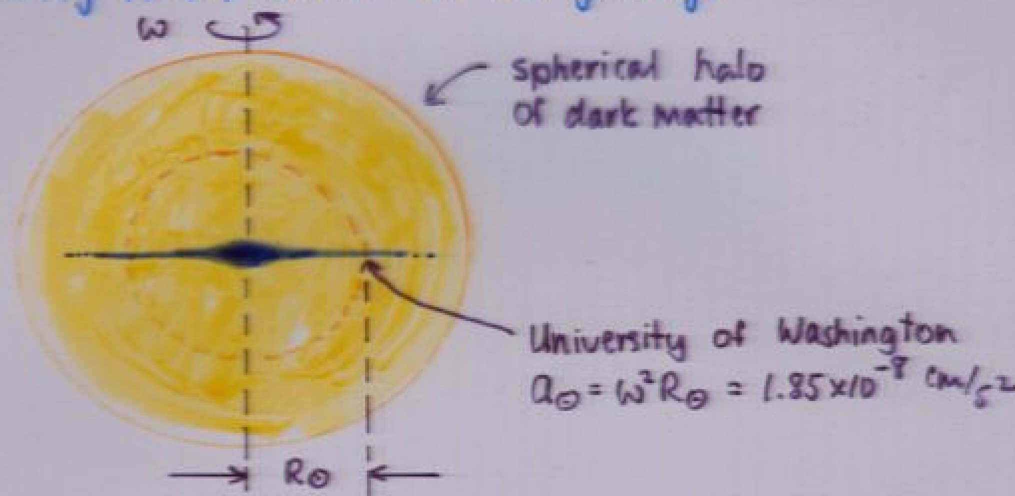

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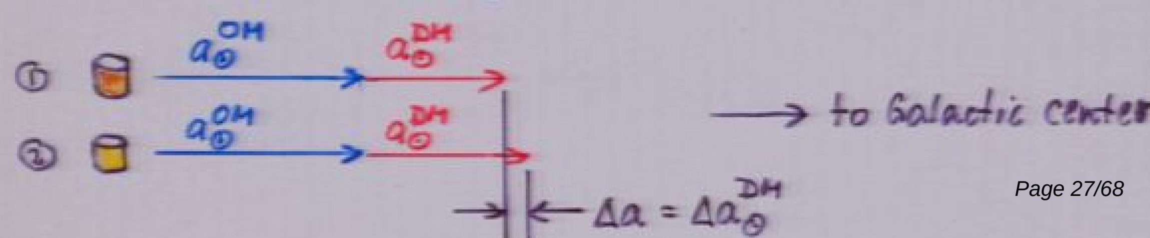


assume $a_\odot^{DM} \equiv g_\odot^{DM} + \tilde{a}_\odot^{DM}$ where $a_\odot^{DM} \sim 5\times10^{-9}\ cm/s^2$

we want this

$\hookrightarrow \tilde{a}_\odot^{DM}(H^\circ) \propto \langle \tilde{q}_\odot \rangle^{DM} \left(\frac{\tilde{q}}{m}\right)^{H^\circ}$

but measure this

$\hookrightarrow \Delta\tilde{a}_\odot^{DM}(EP) \propto \langle \tilde{q}_\odot \rangle^{DM} \Delta\left(\frac{\tilde{q}}{m}\right)^{\text{tbodies}}$

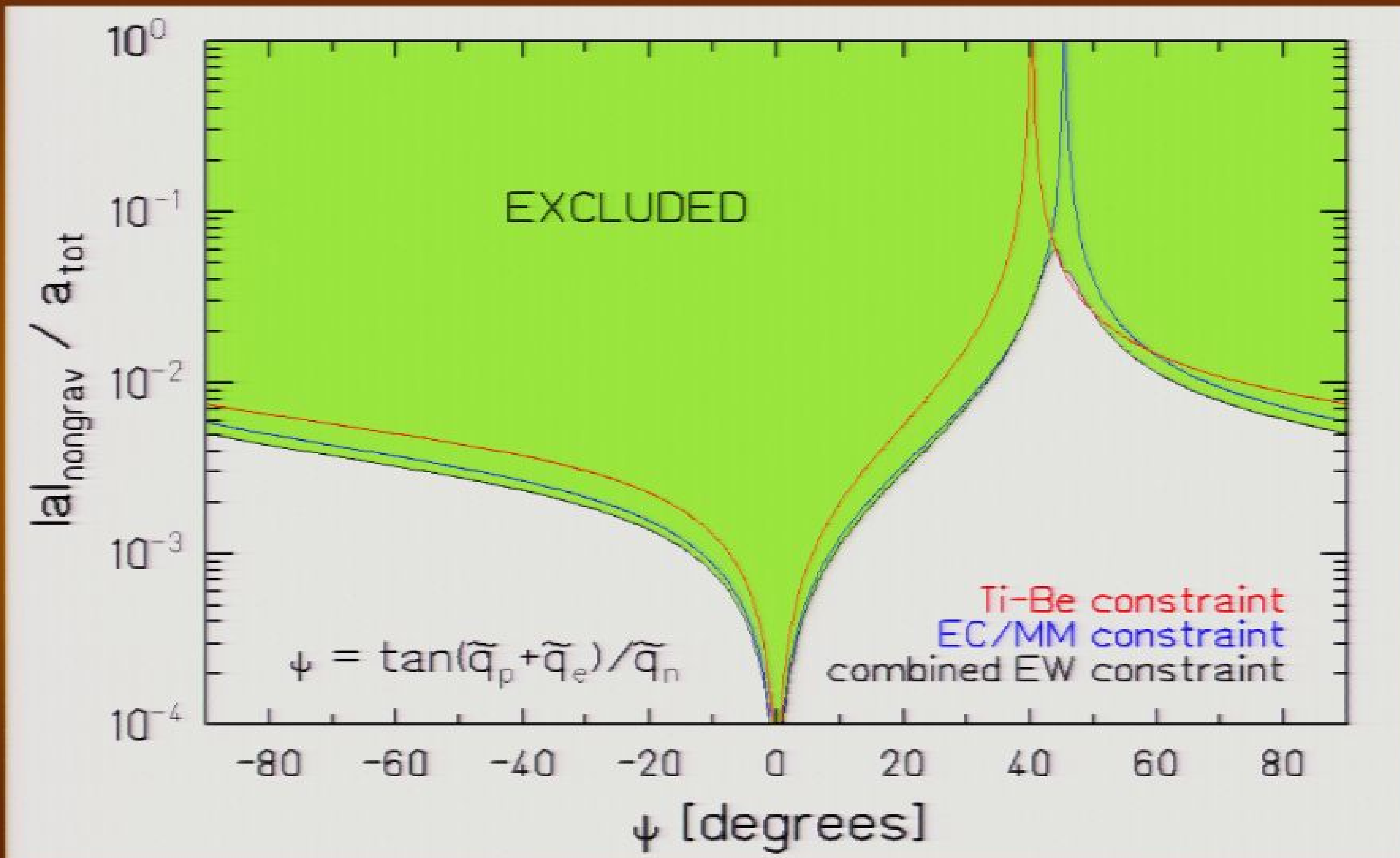
- make no assumptions about $\langle \tilde{q}_\odot \rangle^{DM}$
- parameterize $\tilde{q}$ of ordinary, electrically neutral matter $\tilde{q} = Z(\tilde{q}_e + \tilde{q}_p) + N\tilde{q}_n$

our 1d results:

$\Delta\tilde{a}_\odot^{DM}(Ti-Be) = (0.0 \pm 3.0)\times10^{-13}\ cm/s^2$

$\Delta\tilde{a}_\odot^{DM}(EC-MM) = (3.3 \pm 3.2)\times10^{-13}\ cm/s^2$

95% confidence limits on non-gravitational acceleration of hydrogen by galactic dark matter



at most 5% of the acceleration can be non-gravitational

motivations for sub-millimeter tests of the inverse-square law

- untested regime
- probes the dark energy length scale
- large extra dimensions?
- chameleons?
- "fat gravitons"?

Parameterising breakdowns of $1/r^2$ law

- Old-fashioned way

$$F(r) = G\frac{m_1 m_2}{r^{2+\epsilon}}$$

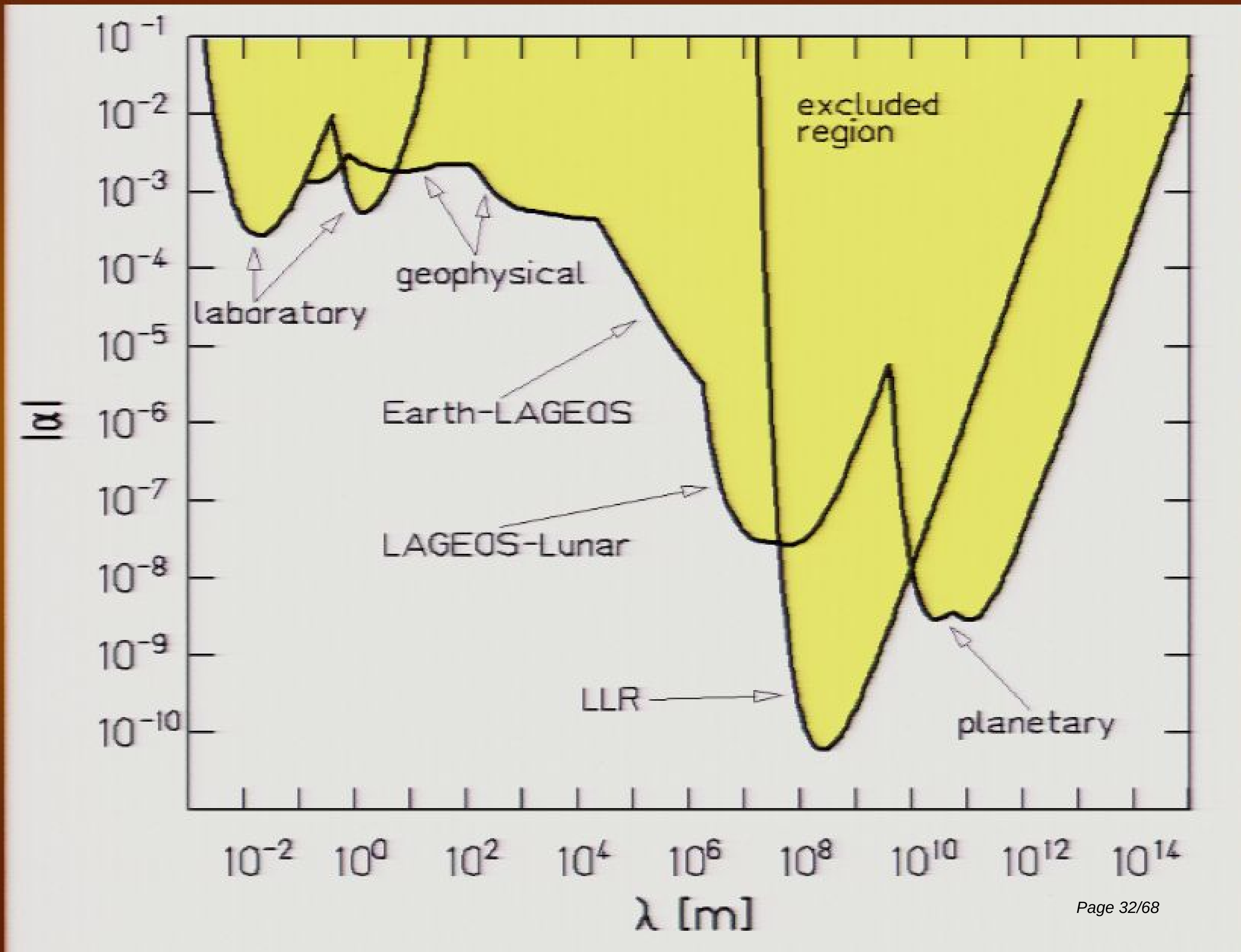
↑ no theoretical basis

- modern way

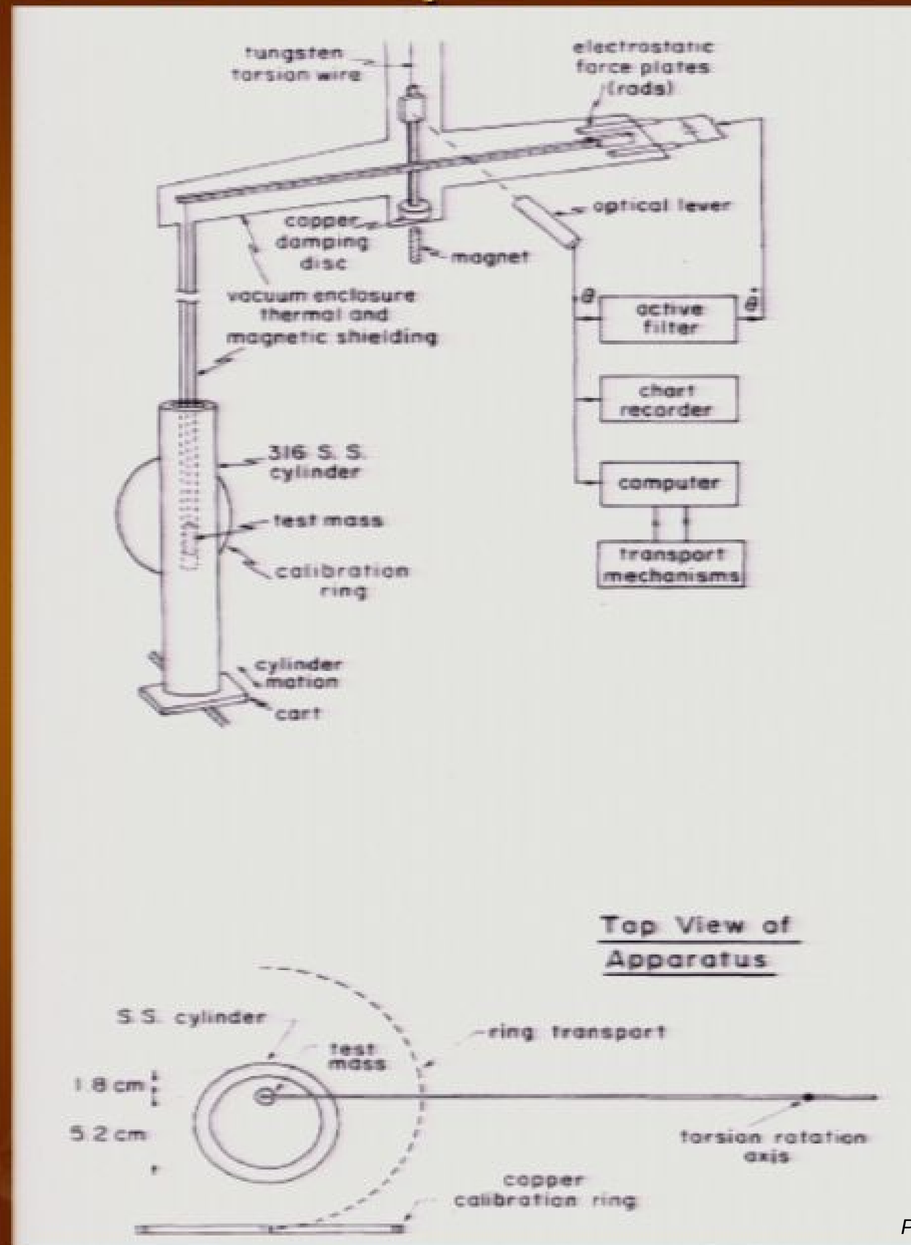
$$F(r) = G\frac{m_1 m_2}{r^2}\left[1 + \alpha\left(1+\frac{r}{\lambda}\right)e^{-r/\lambda}\right]$$

↑
- exchange of boson with $m \neq 0$
- extra dimensions scenario when $r \sim R^*$

95% confidence limits as of 2000



the Irvine experiment



Hoskins et al. PRD 32, 3084 (1985)

Does dark energy define a new fundamental length scale in physics?

$$\rho_{\mathrm{d}} \approx 3.8\ \mathrm{keV/cm^3}$$

$$\lambda_{\mathrm{d}} = \sqrt[4]{\hbar c/\rho_{\mathrm{d}}} \approx 85\ \mu\mathrm{m}$$

a second “Planck length”?

Gauss's Law and extra dimensions

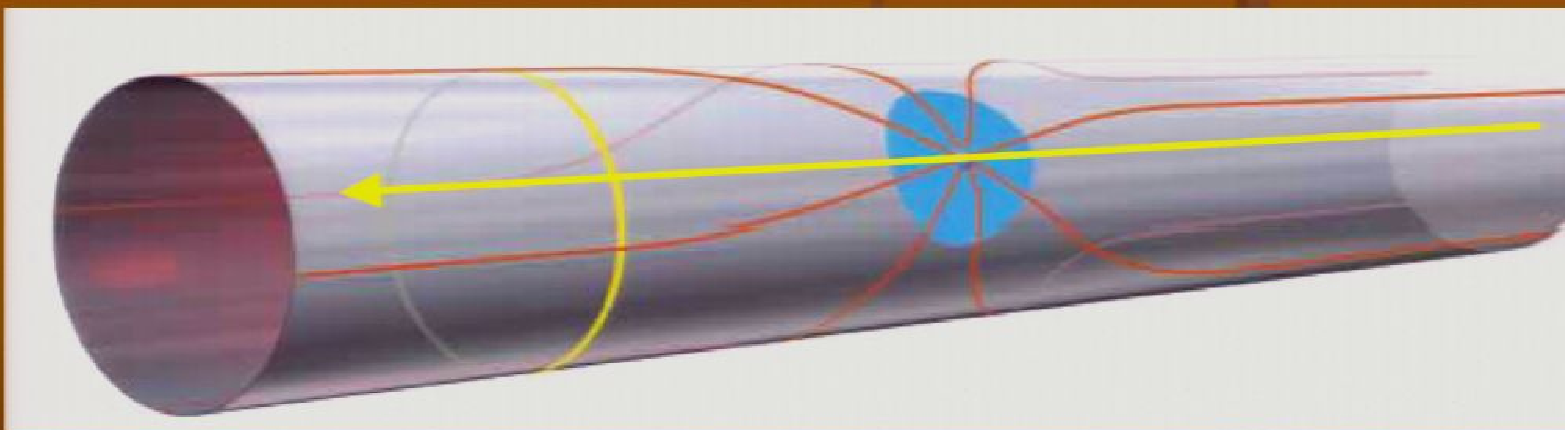
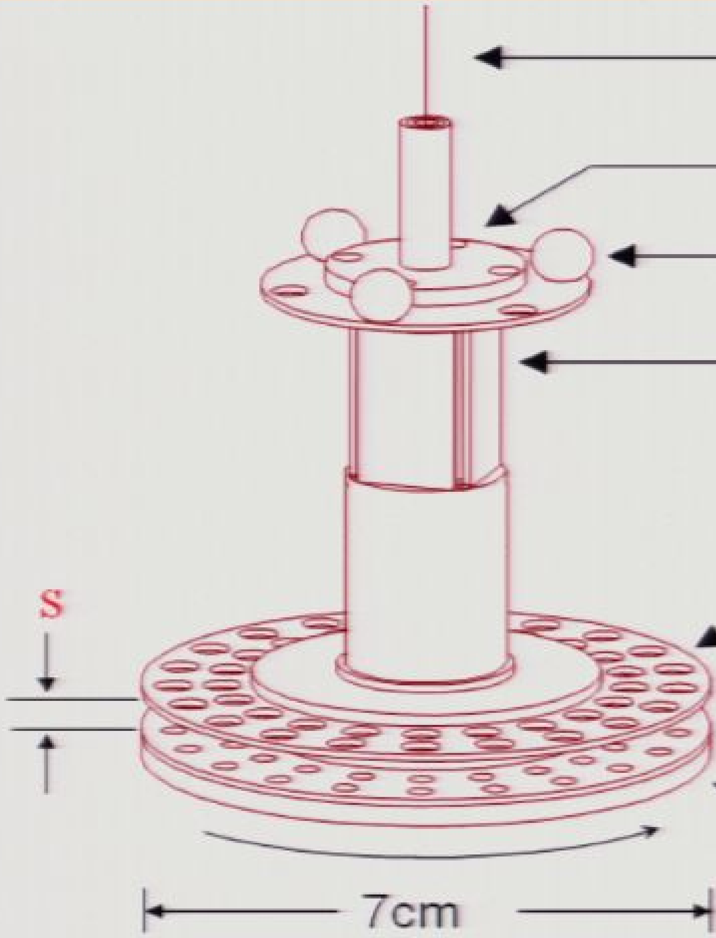


illustration from Savas Dimopoulis

the 42-hole inverse-square law pendulum



tungsten fiber, 20μm diameter, 80cm lengt

leveling mechanism

3 aluminum calibration spheres

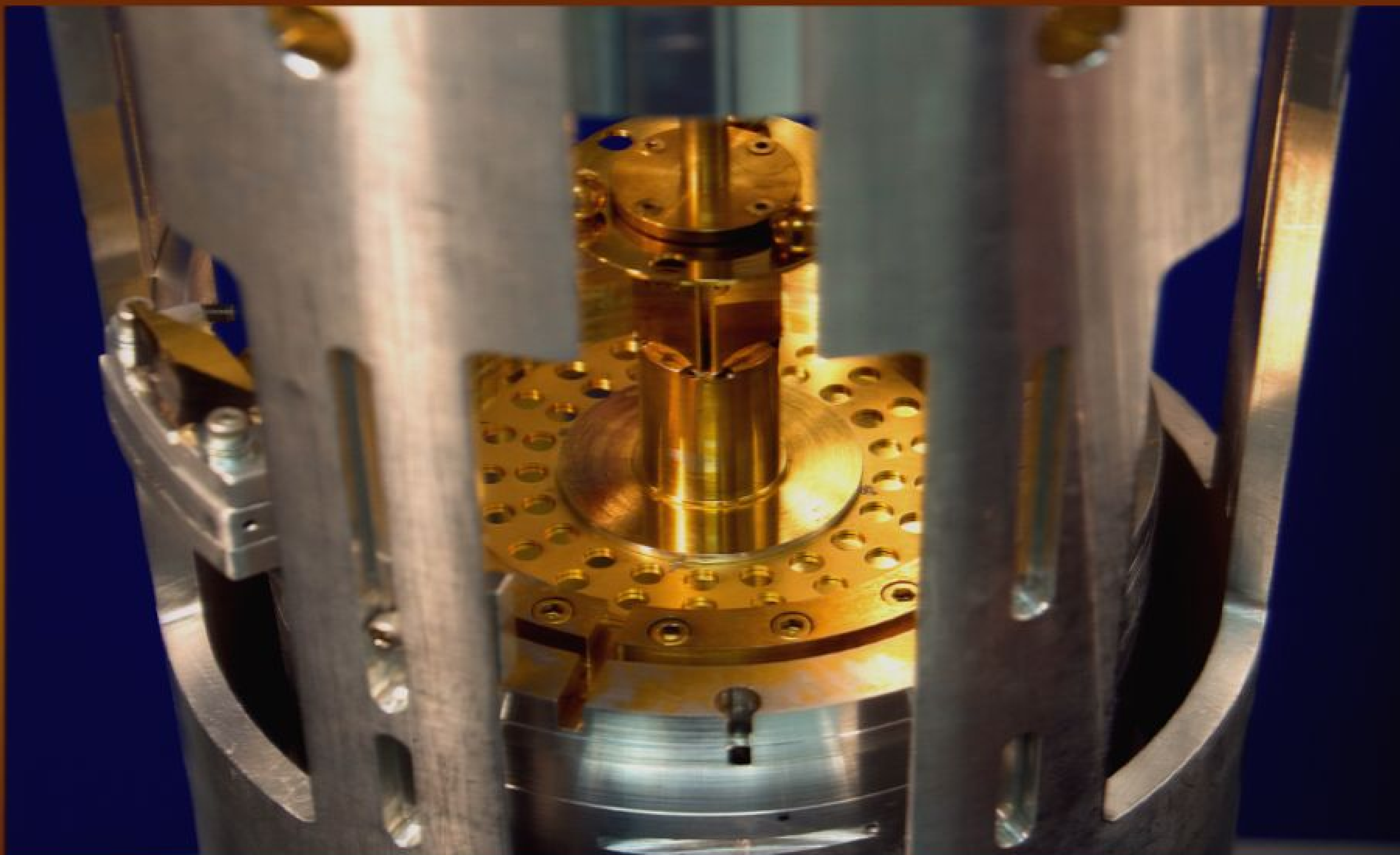
4 mirrors for tracking angle of deflection

detector: 1mm thick molybdenum ring with 42 holes arranged in 21-fold rotational symmetry

not pictured, 10μm thick Au-coated BeCu membrane, electrostatic shield

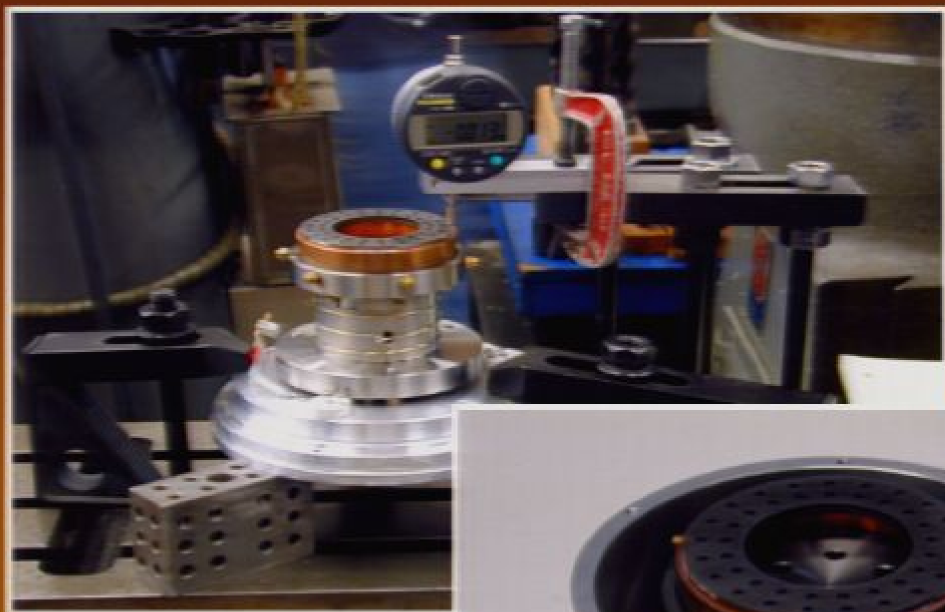
attractor : **rotating pair** of discs with 21-fold rotational symmetry, holes in lower attractor out of phase with holes in upper attractor to **cancel Newtonian gravity**

PhD project of Dan Kapner

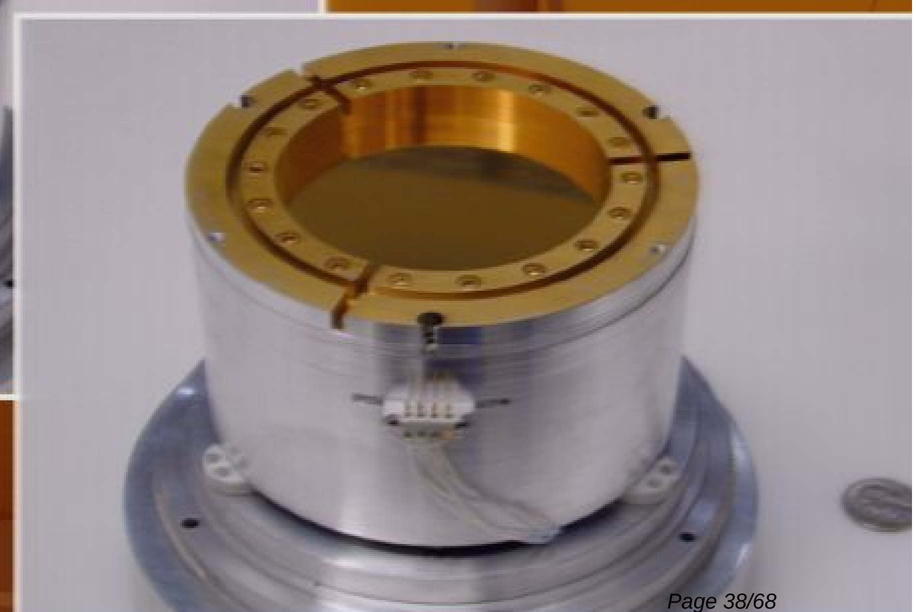


Mary Levin photo

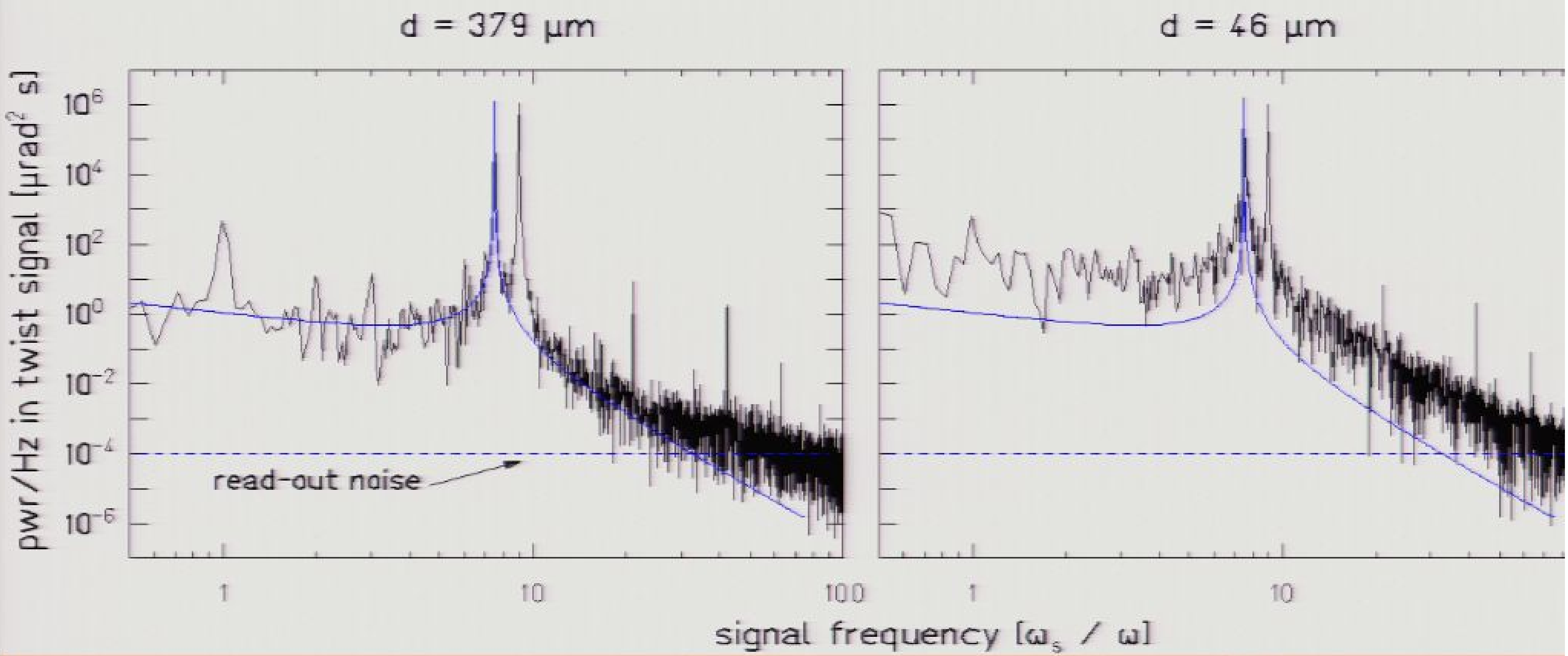
rotating attractor and its electrostatic shield



- tightly stretched 10- μm thick, Au-coated BeCu foil shields electrostat effects.
- placed 12 μm above rotating attractor

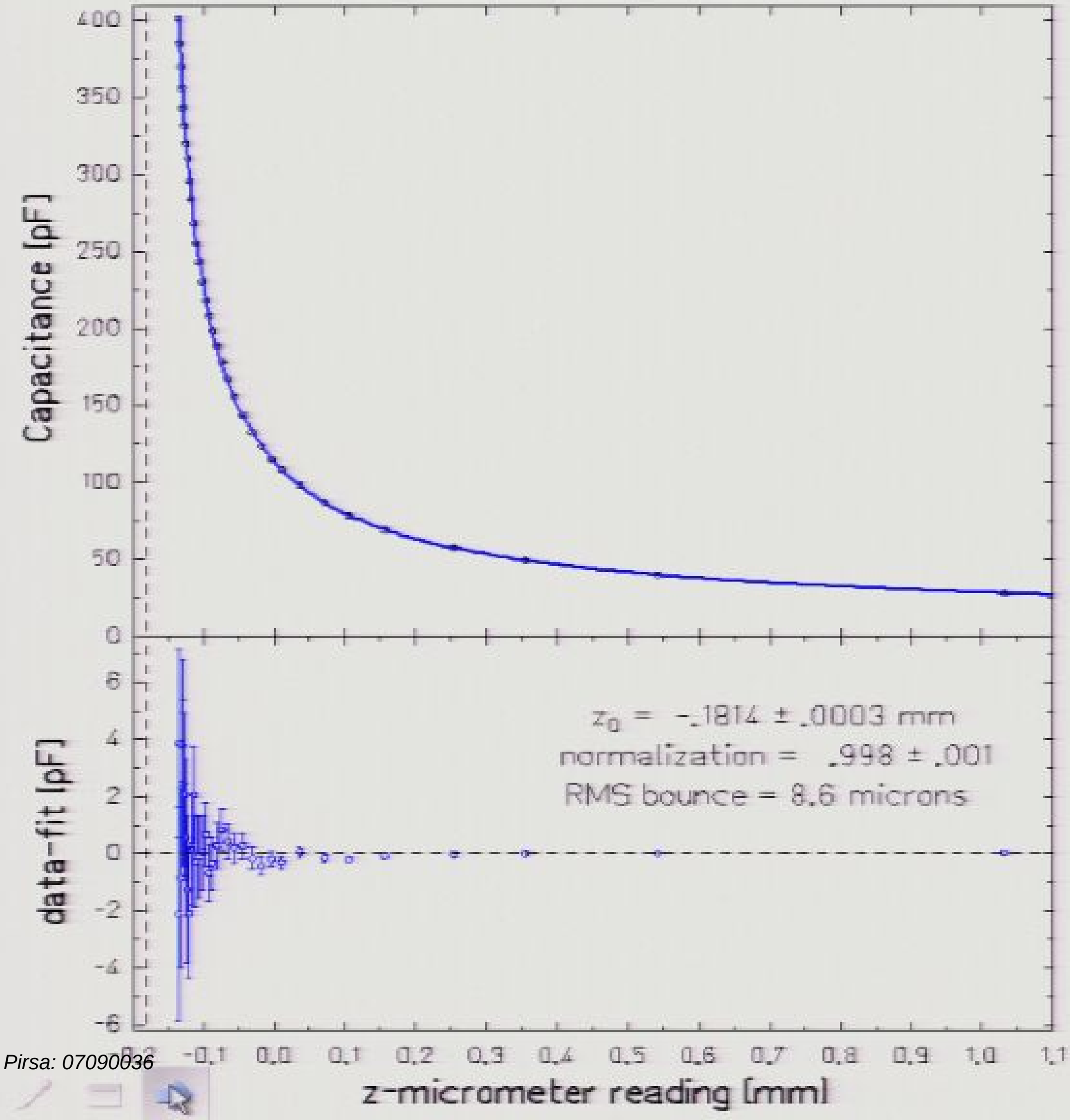


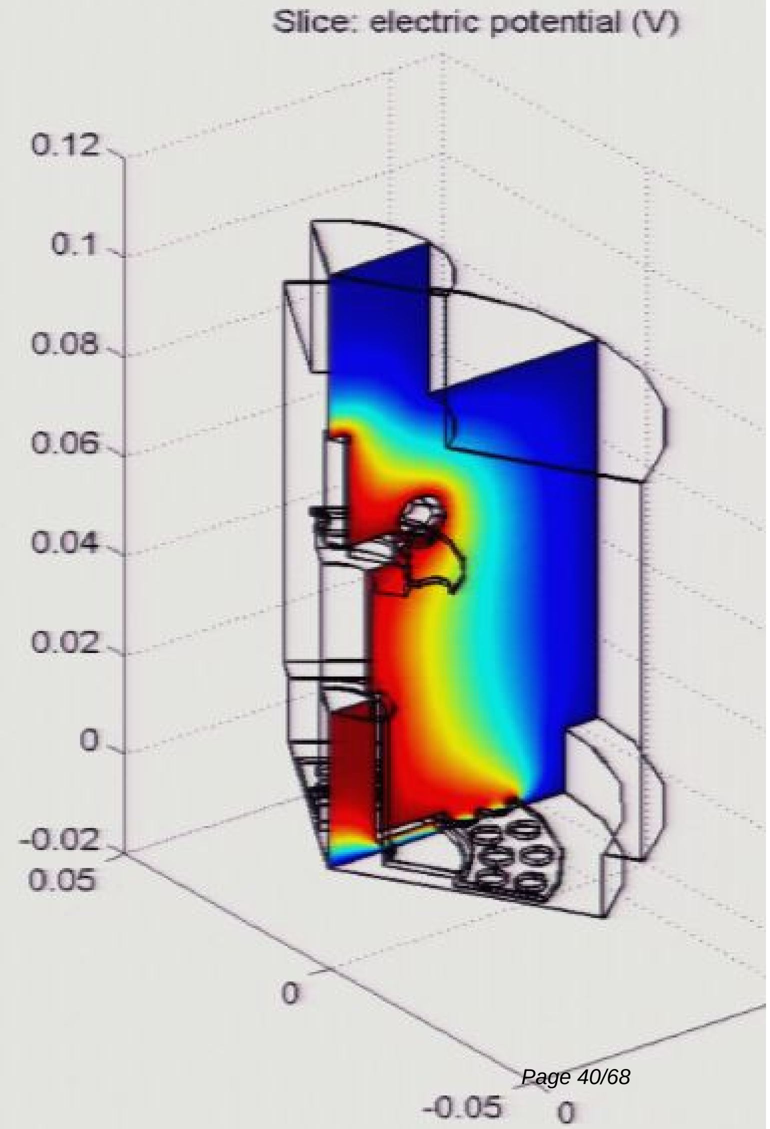
power spectral density of twist noise



d = detector/foil separation

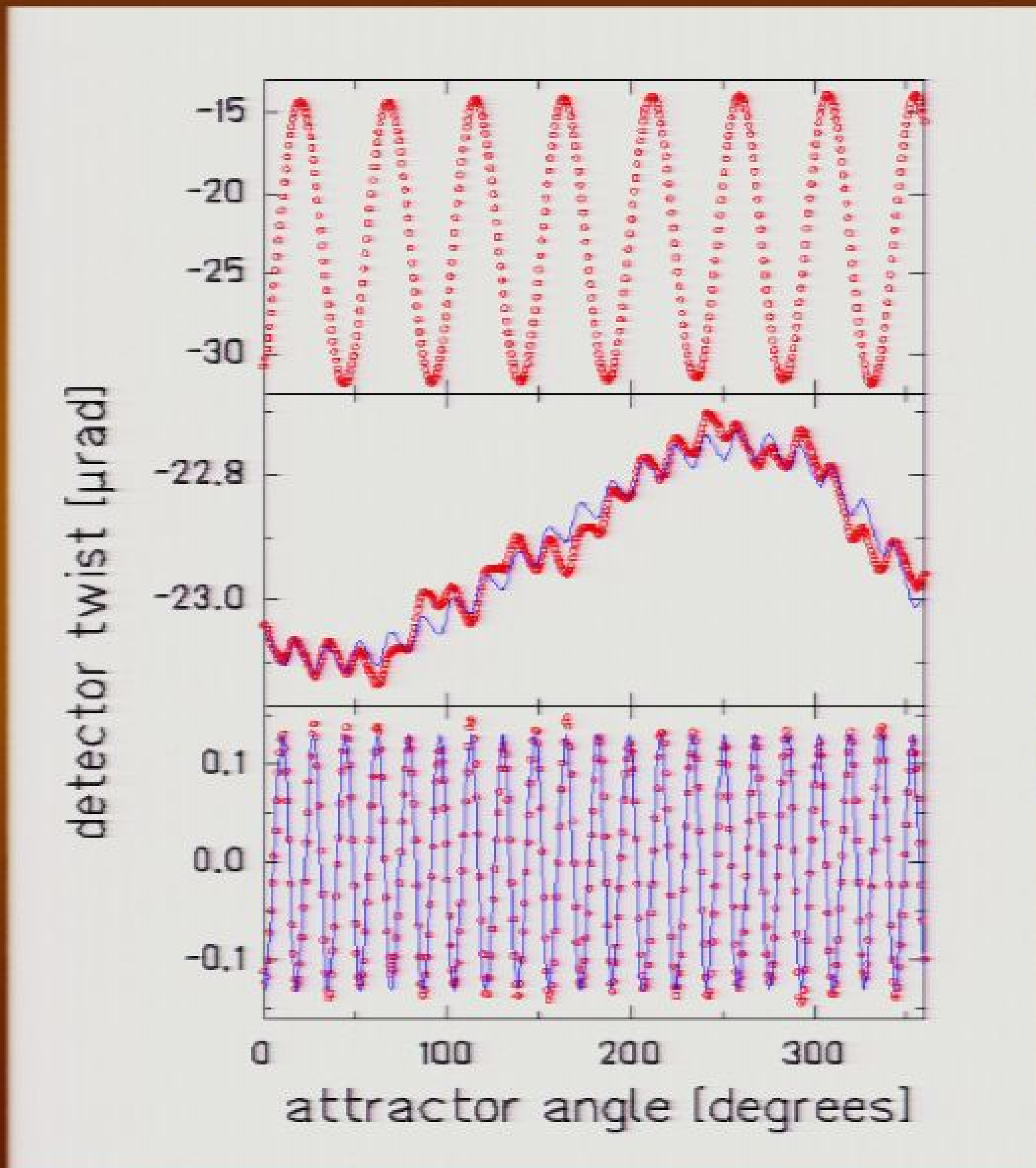
measuring the detector-membrane separation





signal processing

these data were taken with the calibration turn-table stationary

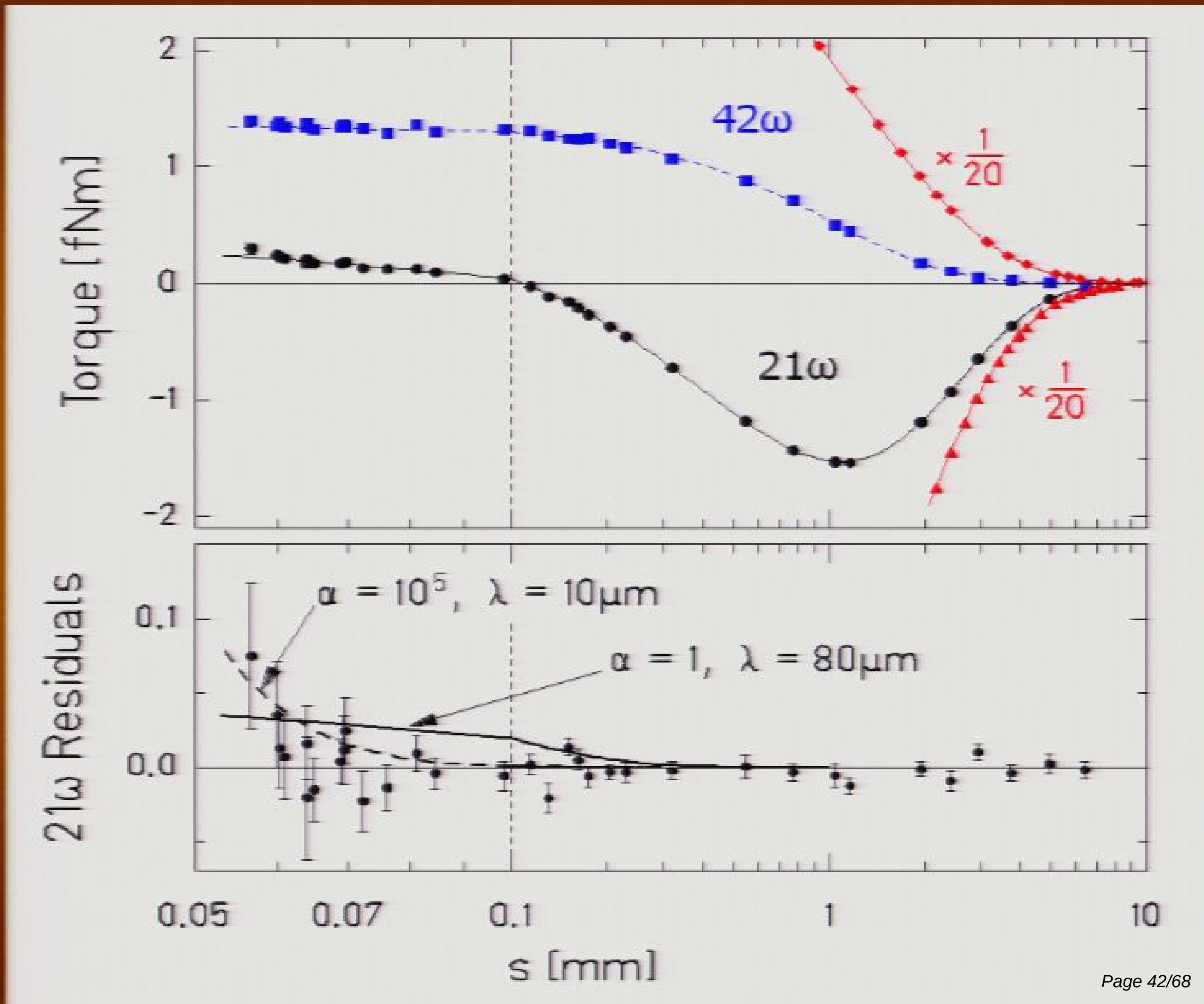


raw signal

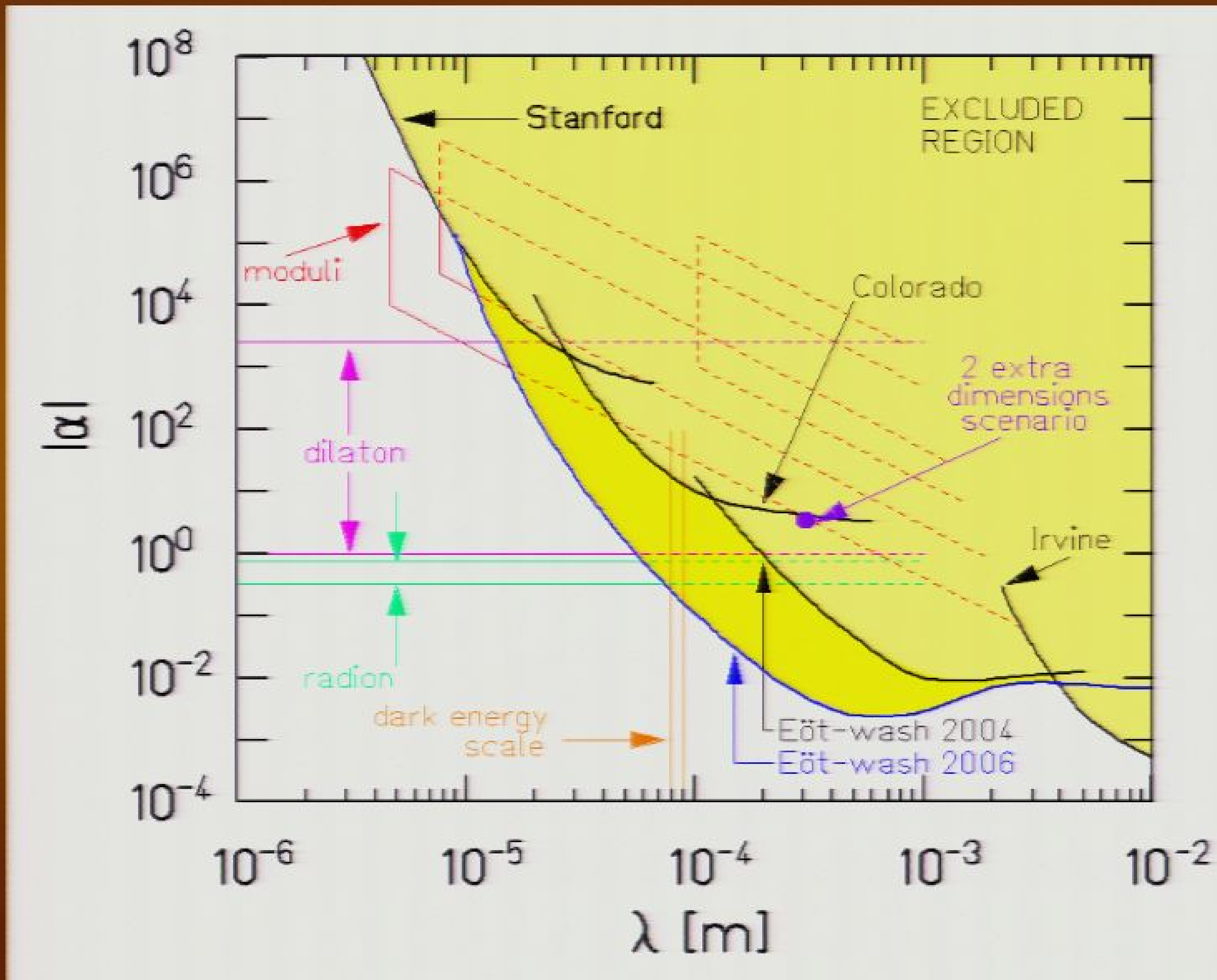
2-pt digital fil
used in our earlier work

5-pt digital fil

data from 42-hole experiment III



95% confidence upper limits on ISL violation



some 2σ implications of our data

- inverse-square law holds down to 56 microns
- largest possible size of an extra dimension is R = $\lambda(\alpha=8/3)$ = 44 microns
- for ADD's 2 equal extra dimensions scenario $M^* \geqslant 3.4$ TeV/c^2
- radion exchange with n extra dimensions gives a Yukawa force with $\alpha=n/(n+2)$ and $\lambda \approx 2.4$ mm [1 TeV/M^*c^2]; this implies $M^*(n=6) \approx 6.4$ TeV/c^2
- dilaton must have mass $mc^2 \geqslant 3.5$ meV

the chameleon mechanism

can circumvent experimental evidence against string theory's gravitationally coupled low-mass scalars by adding a self-interaction term to the effective potential density

$$V_{\mathrm{eff}}(\phi,\vec{x}) = \frac{1}{2}m_\phi^2\phi^2 + \frac{\gamma}{4!}\phi^4 - \frac{\beta}{M_{\mathrm{Pl}}}\rho(\vec{x})\phi$$

natural values of β & γ are 1

in presence of matter, massless chameleons acquire an effective mass

$$m_{\mathrm{eff}}(\rho) = \frac{\hbar}{c}\left(\frac{9}{2}\right)^{1/6}\gamma^{1/6}\left(\frac{\beta\rho}{M_{\mathrm{Pl}}}\right)^{1/3}$$

so that an object's external field comes only from a thin skin of material of thickness ~ $1/m_{\mathrm{eff}}$ (≈ 60μm)

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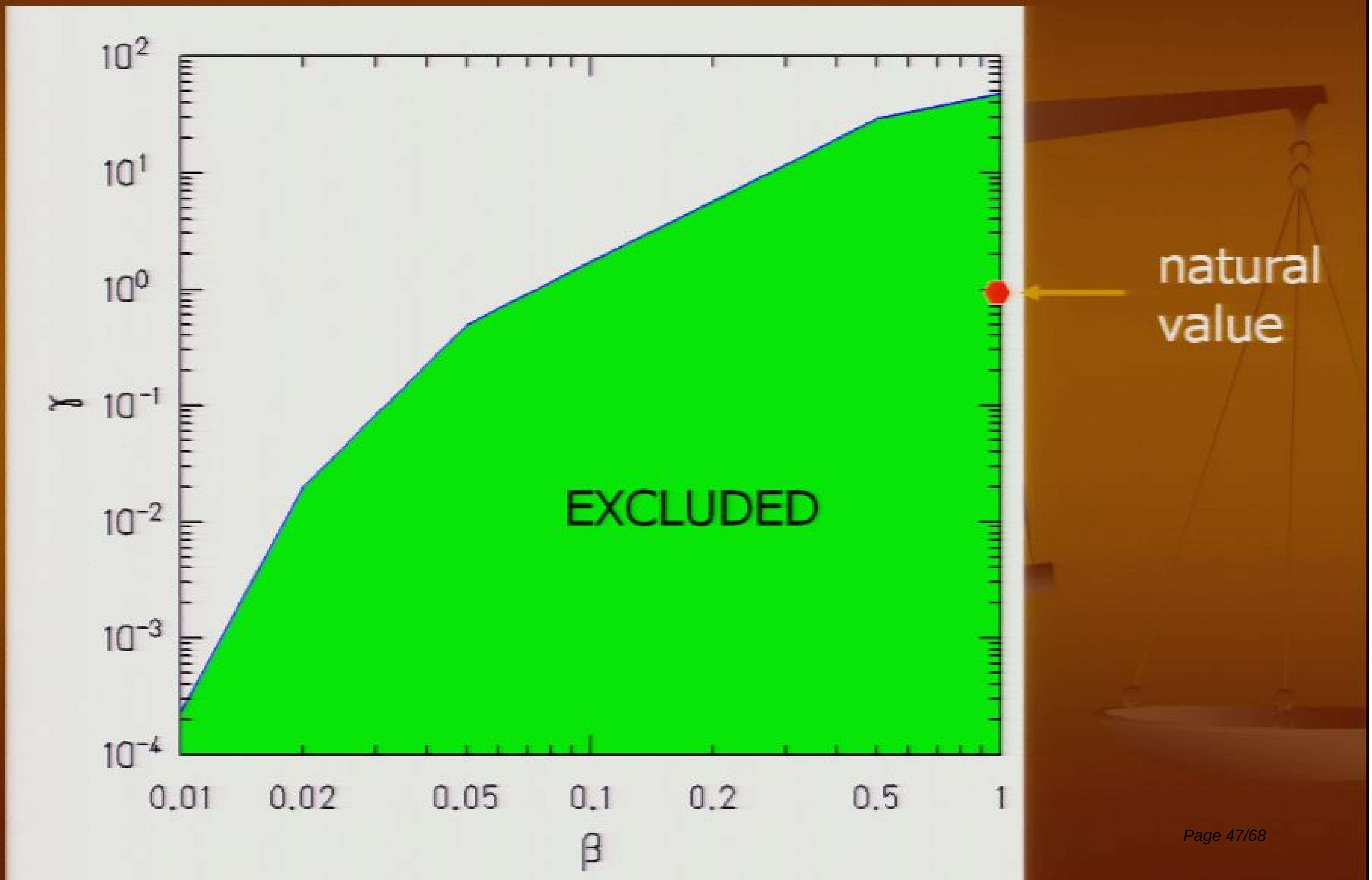
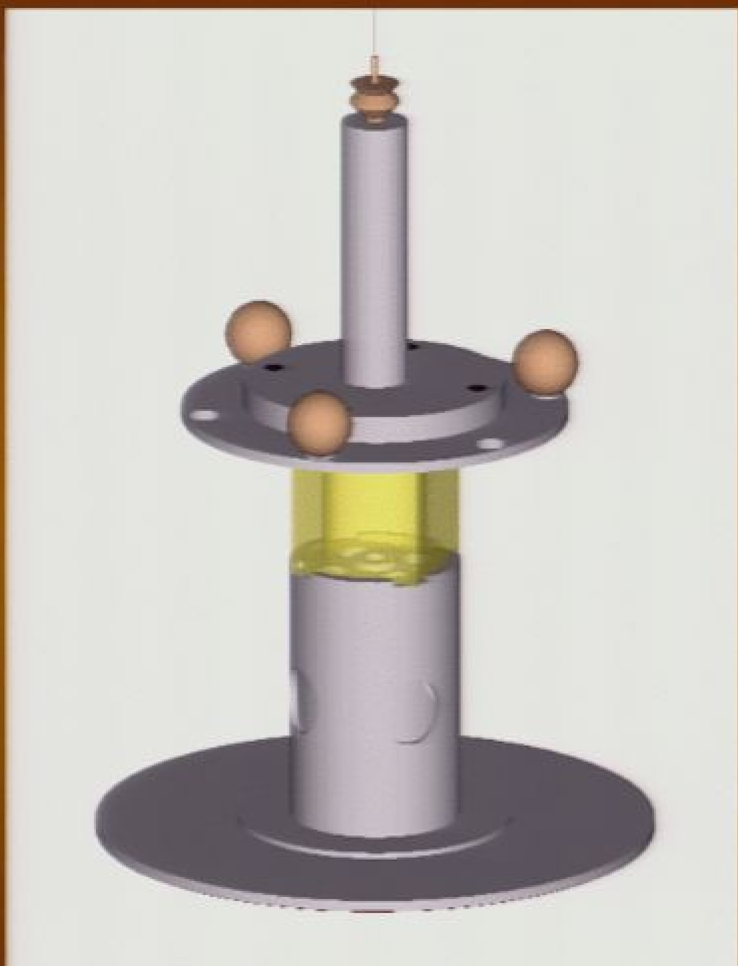
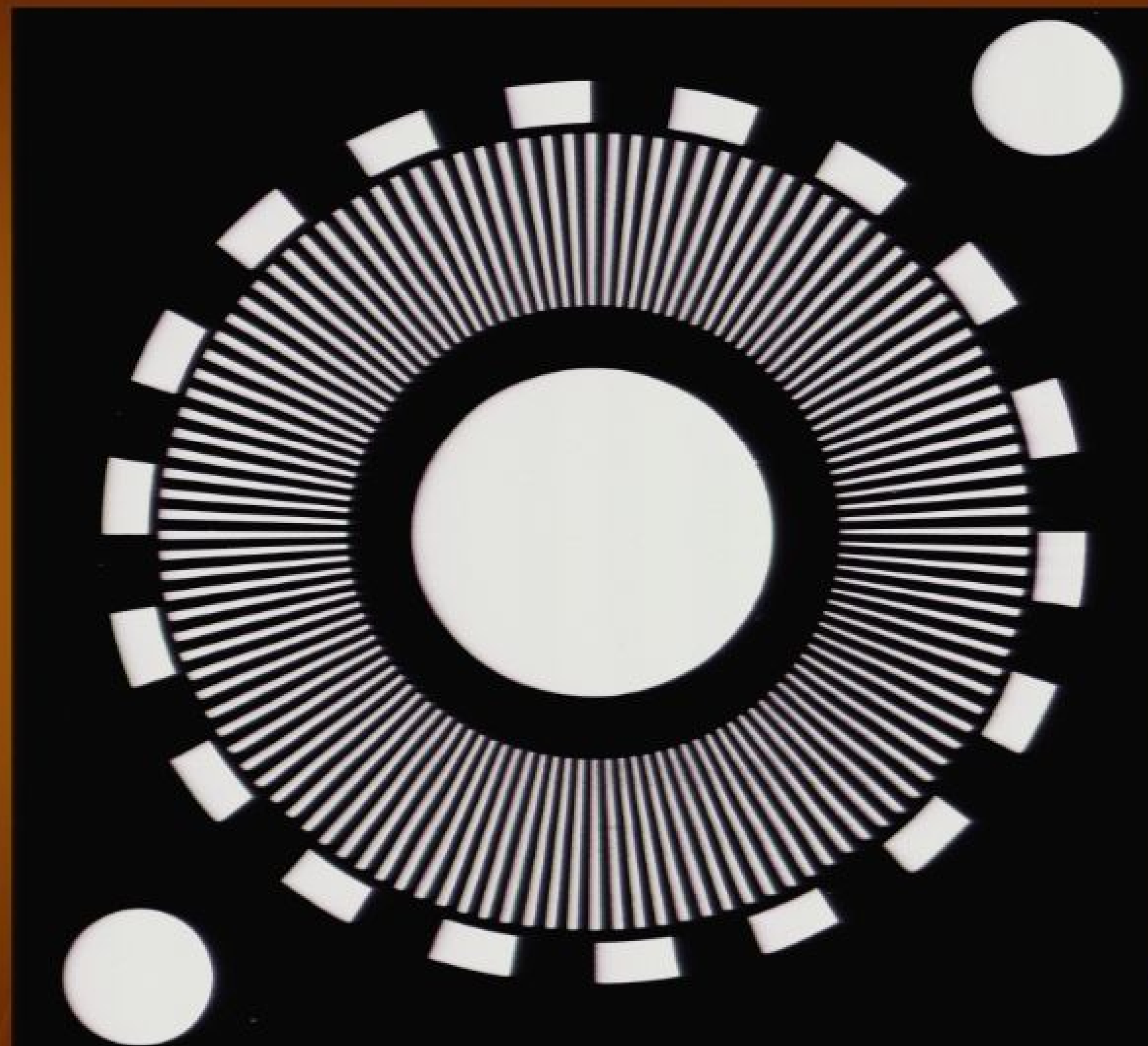
2σ chameleon constraints



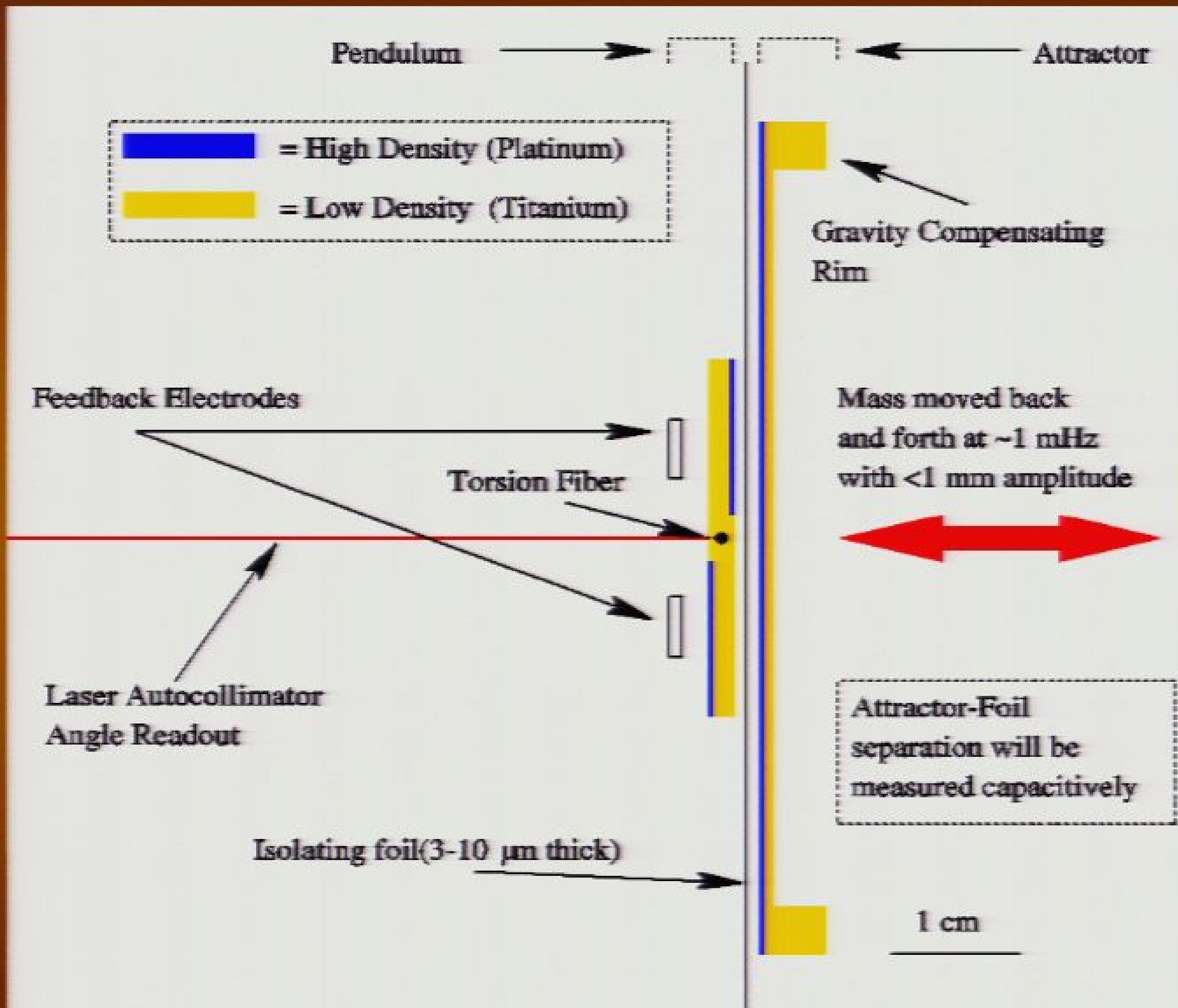
the Fourier-Bessel pendulum





will be the PhD project of Ted Cook

the plate pendulum



This will be the PhD project of Charlie Hagedorn

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 observable is $E = \sigma_e \cdot \tilde{b}_e$ where $\tilde{b}_e$ is fixed in inertial space - its benchmark value is $m_e^2/M_{Planck} \approx 2 \times 10^{-17}$ eV

non-commutative space-time geometry

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

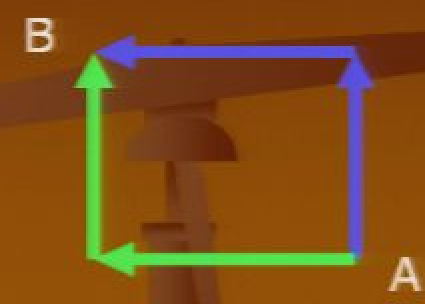
$$[\widehat{x}_\mu, \widehat{x}_\nu] = i\theta_{\mu\nu}$$

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 spin

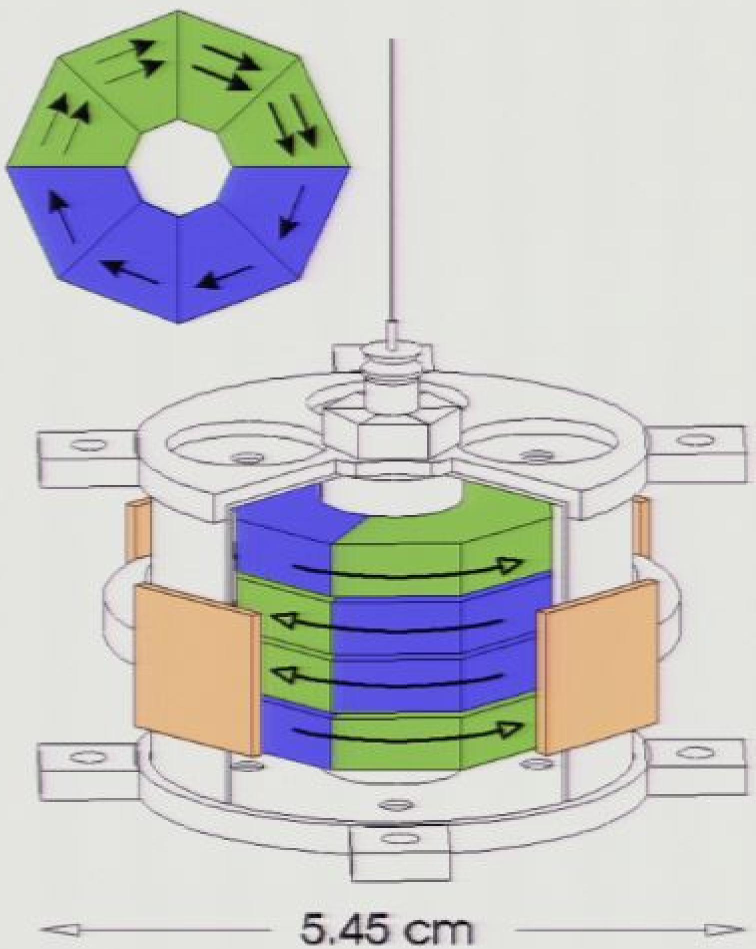
non-commutative geometry is equivalent to a "pseudo-magnetic" field and thus couples to spins



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

Anisimov, Dine, Banks and Graesser
Phys Rev D 65, 085032 (2002)
Λ is a cutoff assumed to be 1TeV

the Eöt-Wash spin pendulum



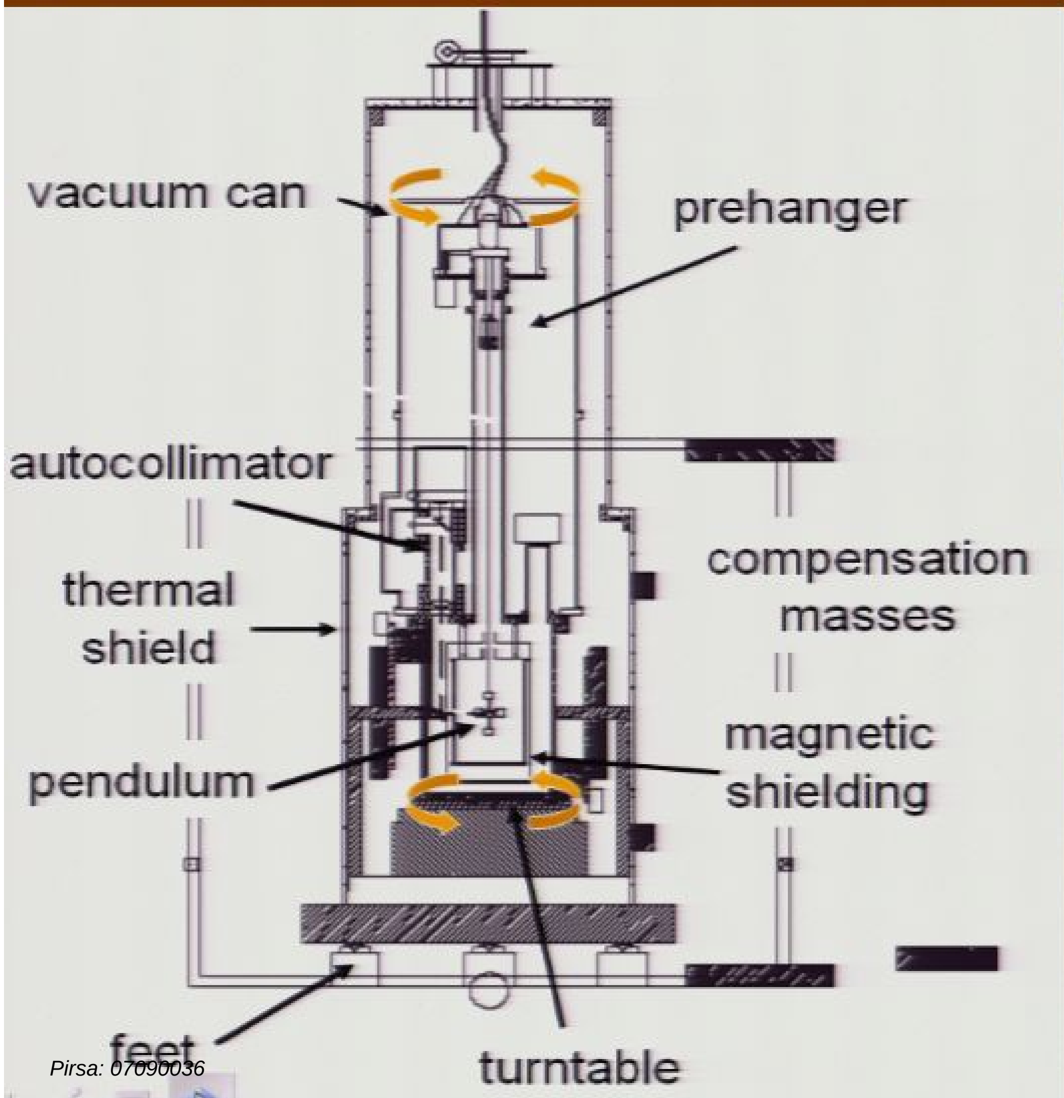
- 9.8×10^{22} polarized electrons
- negligible mass asymmetry
- negligible composition asymmetry
- flux of B confined within octagons
- negligible external B field

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

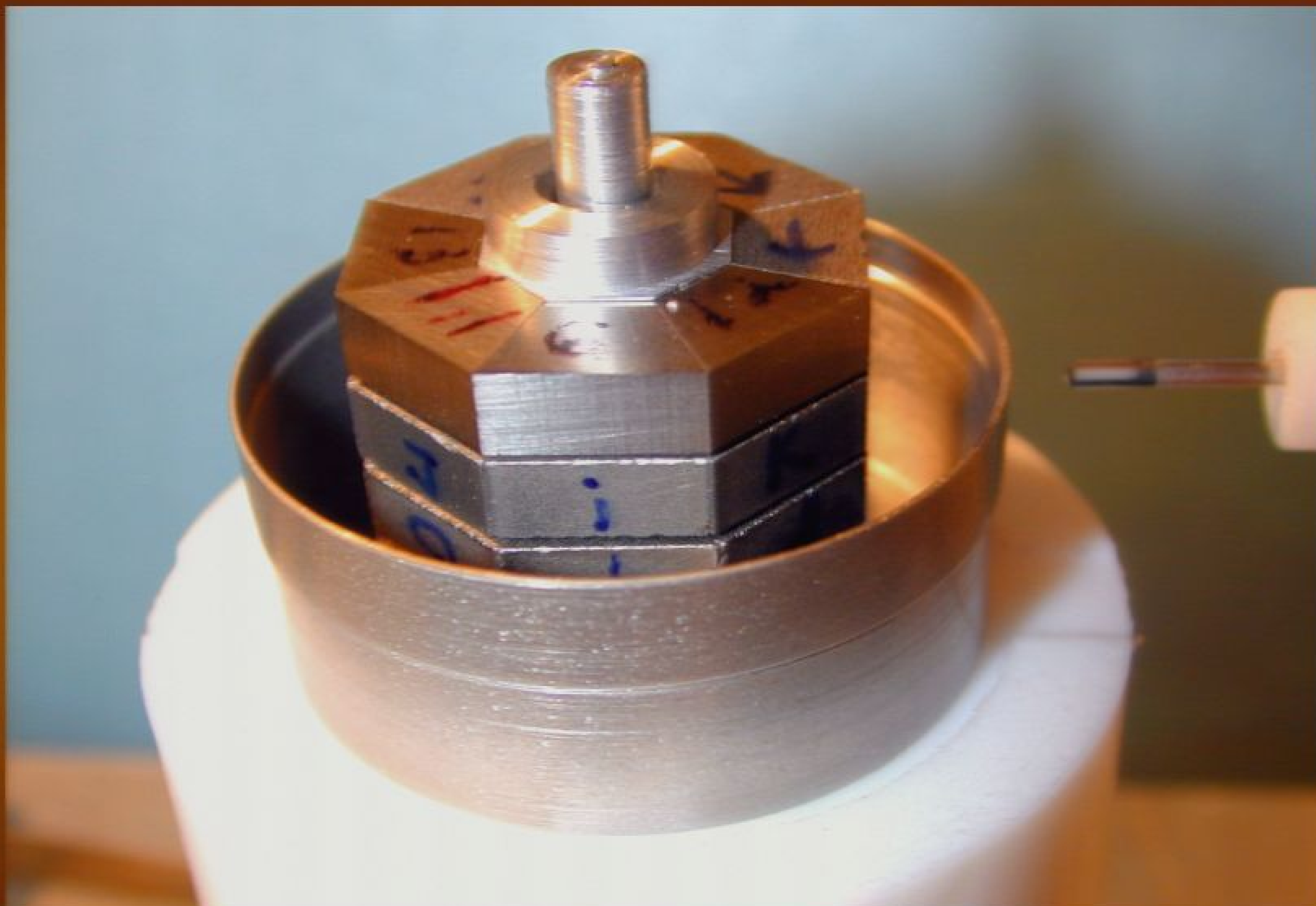
- $SmCo_5$: Sm 3^+ ion has spin pointing <u>along</u> total B and its spin B field is nearly canceled by its orbital B field--so B of $SmCo_5$ comes almost entirely from the Co's electron spins

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

the Eöt-Wash rotating torsion balance



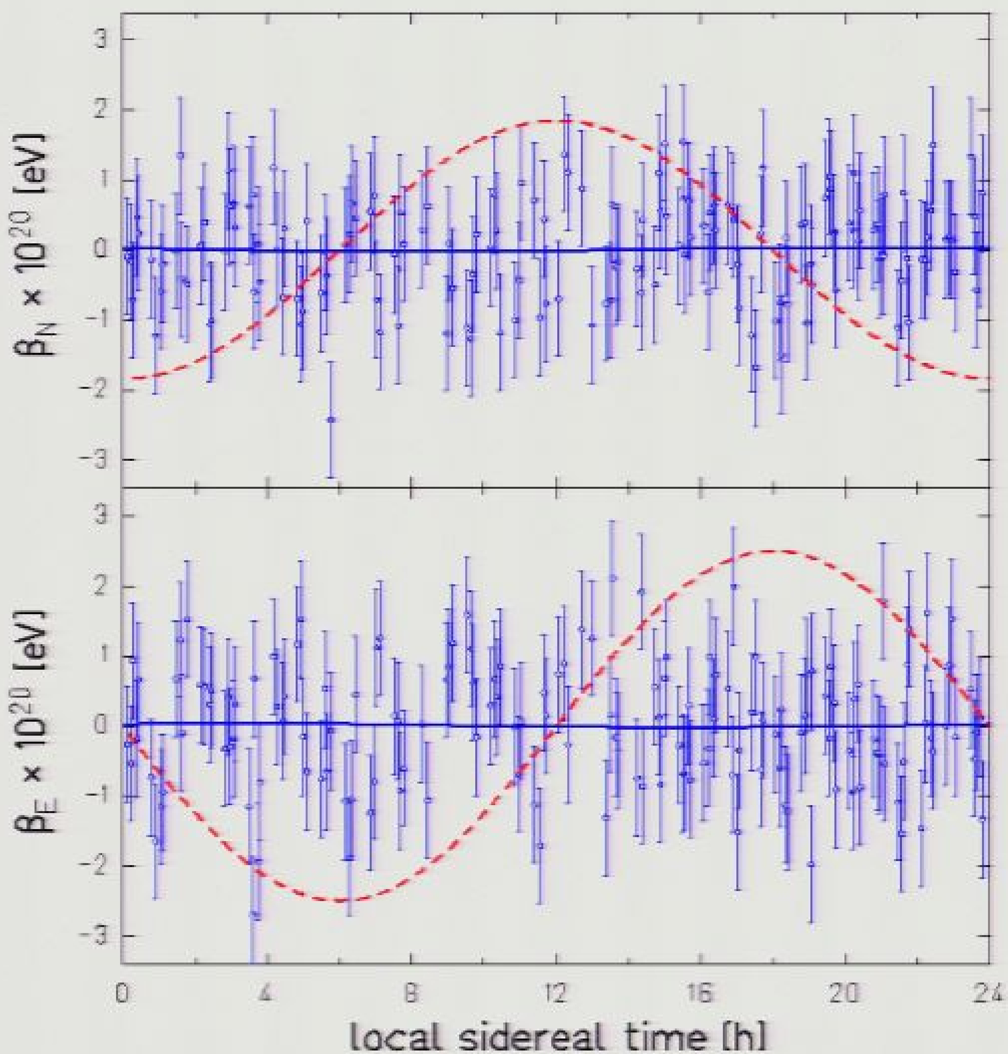
measuring the stray magnetic field of the spin pendulum



B inside = 9.6±0.2 kG

B outside ≈ few mG

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

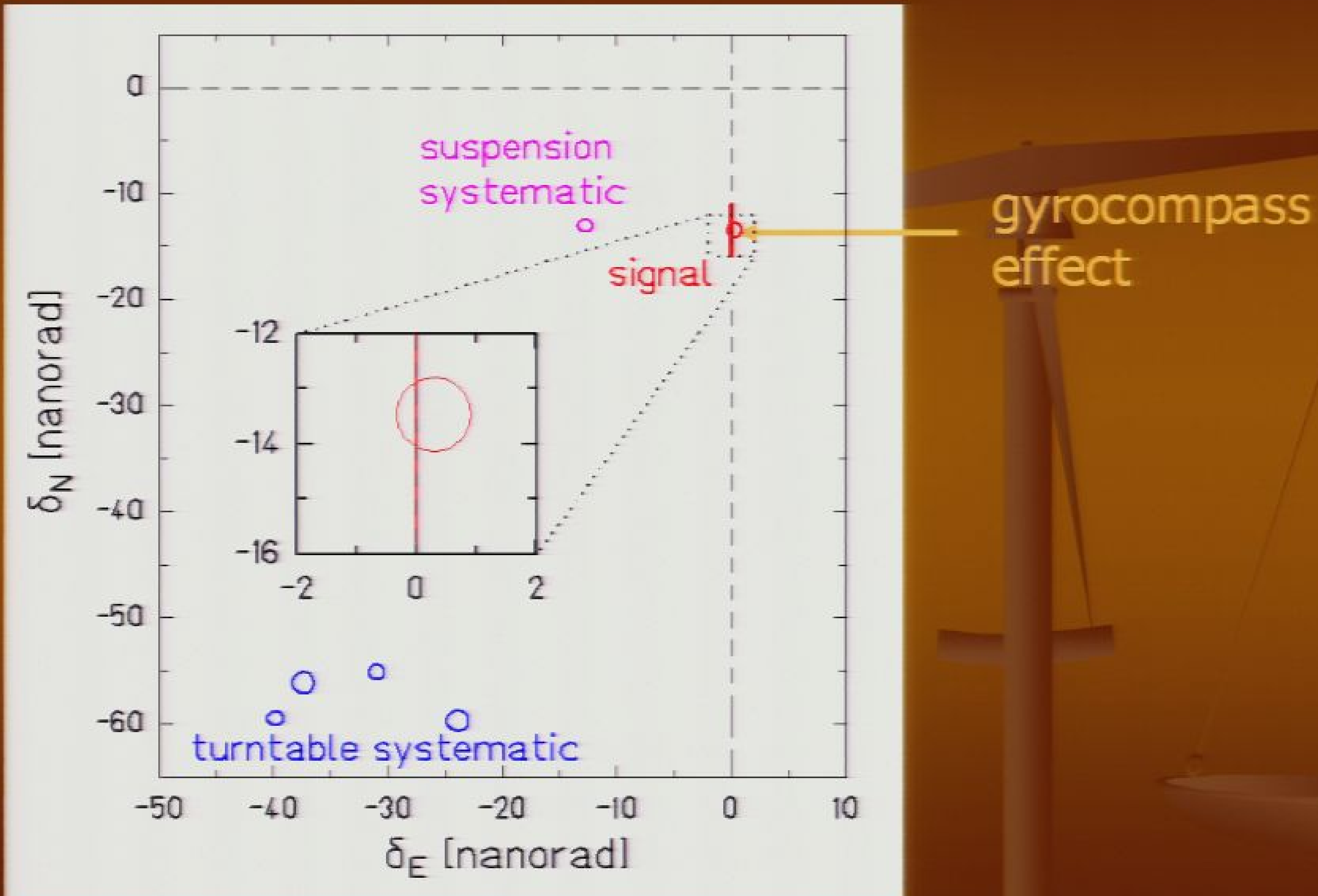


definition of β:
$E_{pend} = -N_p\, \beta \cdot \sigma$

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

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

Lorentz-symmetry violating rotation parameters

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

parameter	electron[a]	proton[b]	neutron[c]
$\tilde{b}_X$	$+1.0 \pm 1.5$	$\leq 2 \times 10^4$	0.22 ± 0.79
$\tilde{b}_Y$	-0.6 ± 1.5	$\leq 2 \times 10^4$	0.80 ± 0.95
$\tilde{b}_Z$	$+3.7 \pm 21.2$		

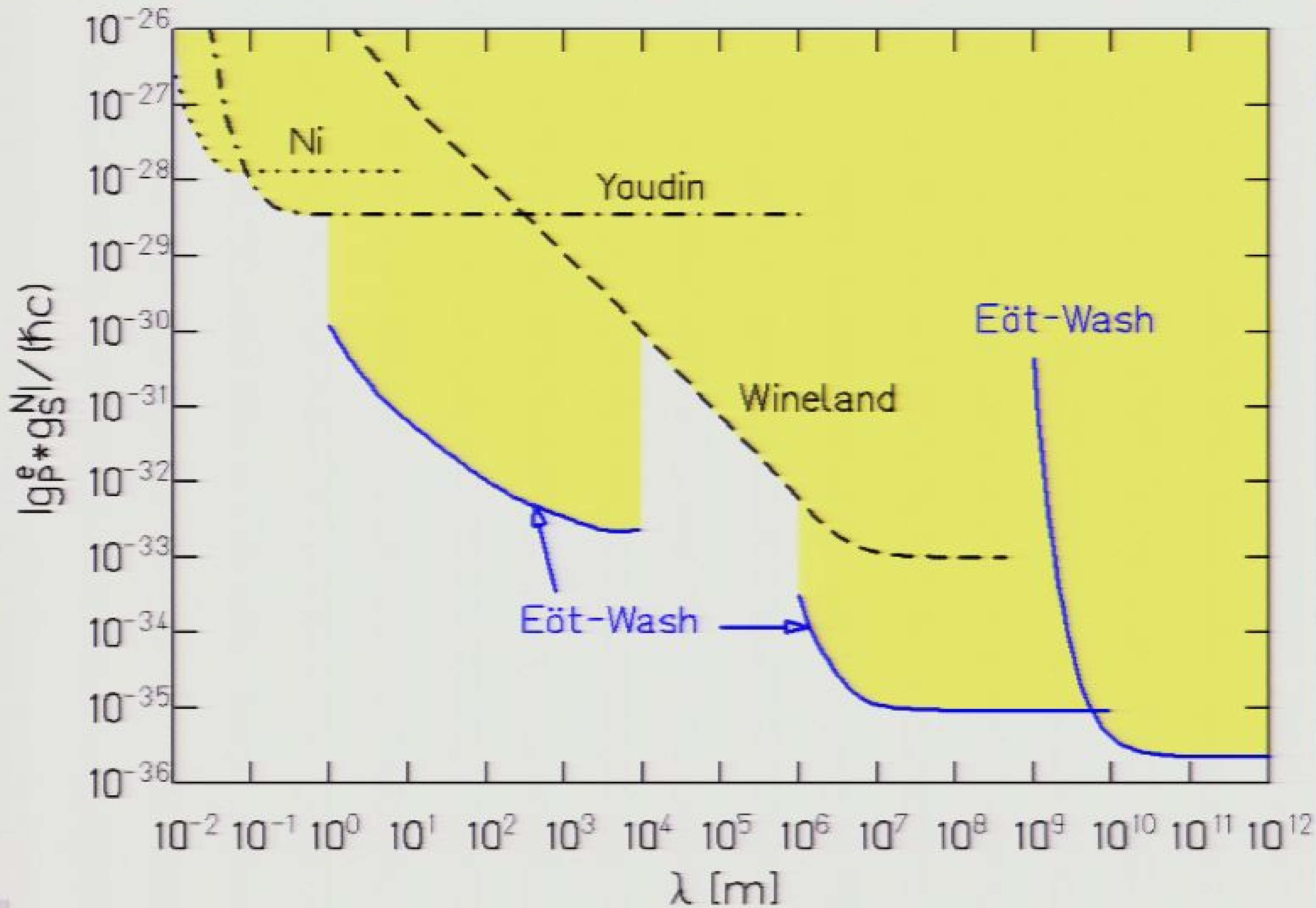
Cane et al, PRL 93(2004) 230801 Phillips et al, PRD 63(2001) 111101

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

an amusing number

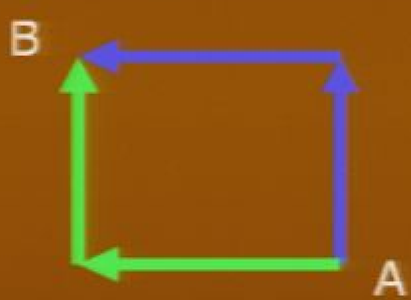
- our upper limit on the energy required to invert an electron spin about an arbitrary axis fixed in inertial space is $\sim 10^{-22}$ eV
- this is comparable to the electrostatic energy of two electrons separated by ~ 90 astronomical units

95% confidence upper limits on CP-violating monopole-dipole interactions



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.

In another sense it is also still 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^{13} GeV is pretty good for a table-top result!

We are now studying the interactions
between our spin pendulum and a larger spin source based on the same principles as those used in the pendulum

some motivations:

- test for the spin-spin interactions predicted by Arkani-Hamed's "ghost condensate" modification of gravity

- test for proposed torsion fields that couple to intrinisic spin

references

- Equivalence Principle tests
  - Y. Su et al., PRD 50, 3614 (1994)
  - S. Baessler et al., PRL 83, 3585 (1999)
  - G.L. Smith et al., PRD 61, 022001 (2000)
- Inverse-square law tests
  - D.J. Kapner et al., PRL 98, 021101 (2007)
  - E.G. Adelberger et al., PRL 98, 13104 (2007)
- Preferred-frame tests
  - B.R. Heckel et al., PRL 97, 021603 (2006)

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