Title: Laboratory tests of the Equivalence Principle and the Inverse Square Law

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Abstract:

Tests of the Equivalence Principle (WEP & SEP) and the Gravitational Inverse-Square Law

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University of Washington

- results (emphasis on recent work)
- how they were obtained

the University of Washington

EÖT-WASH® GROUP

in experimental gravitation

faculty

$1/r^2$ → Eric Adelberger
$1/r^2$ → Blayne Heckel
Jens Gundlach ← EP

professional staff

Erik Swanson

post docs

Seth Hoedl
$1/r^2$ → CD Hoyle
Stephan Schlamminger ← EP

grad students

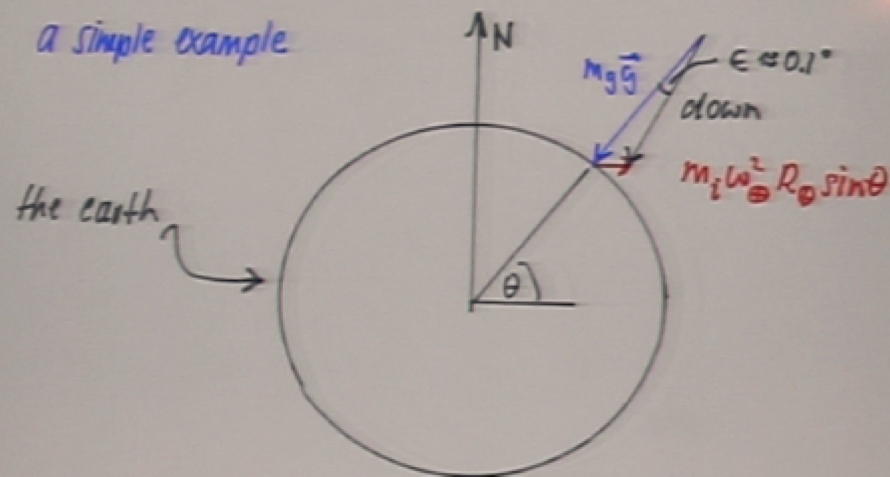
K-Y Choi ← EP
$1/r^2$ → Ted Cook
$1/r^2$ → Dan Kapner
Frank Marcoline

undergrads

→ Rogan Carr   Caleb Hotchkiss

- if the EP is violated, "down" is not a unique direction, but depends on the material that falls

a simple example



- torsion-balance test of the EP compare the "down" direction (the horizontal components of $\vec{a}_g$) for different materials

- results are interpreted as constraints on a potential

$$V(r) = G\frac{m_1 m_2}{r}\left\{1 + \tilde{\alpha}\left(\frac{\tilde{q}}{m}\right)_1\left(\frac{\tilde{q}}{m}\right)_2\right\}$$

scalar interactions have $\alpha > 0$
vector " " $\alpha < 0$

what length scales are interesting in these tests?

all length scales are interesting

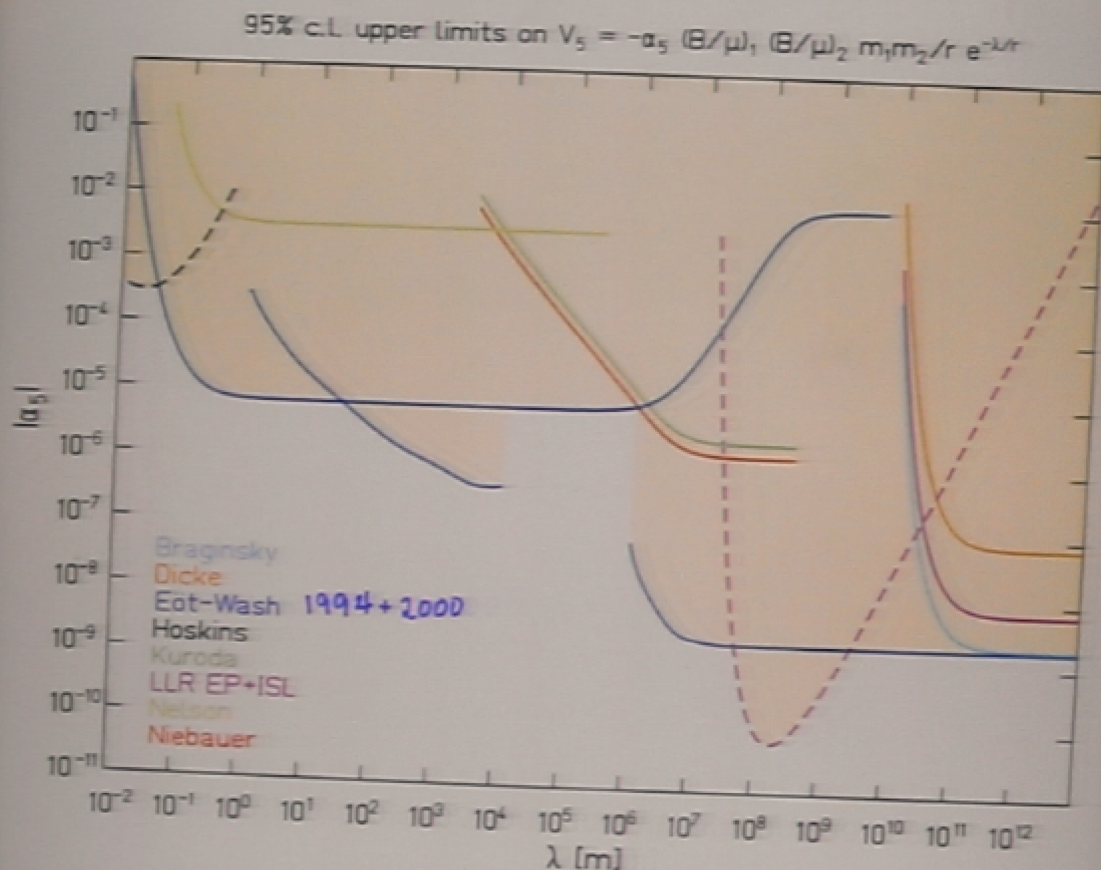
from	$\lambda = \infty$	$m = 0$
to	$\lambda = 1.6 \times 10^{-33}$ cm	$m = m_{Planck} = \sqrt{\hbar c / G}$

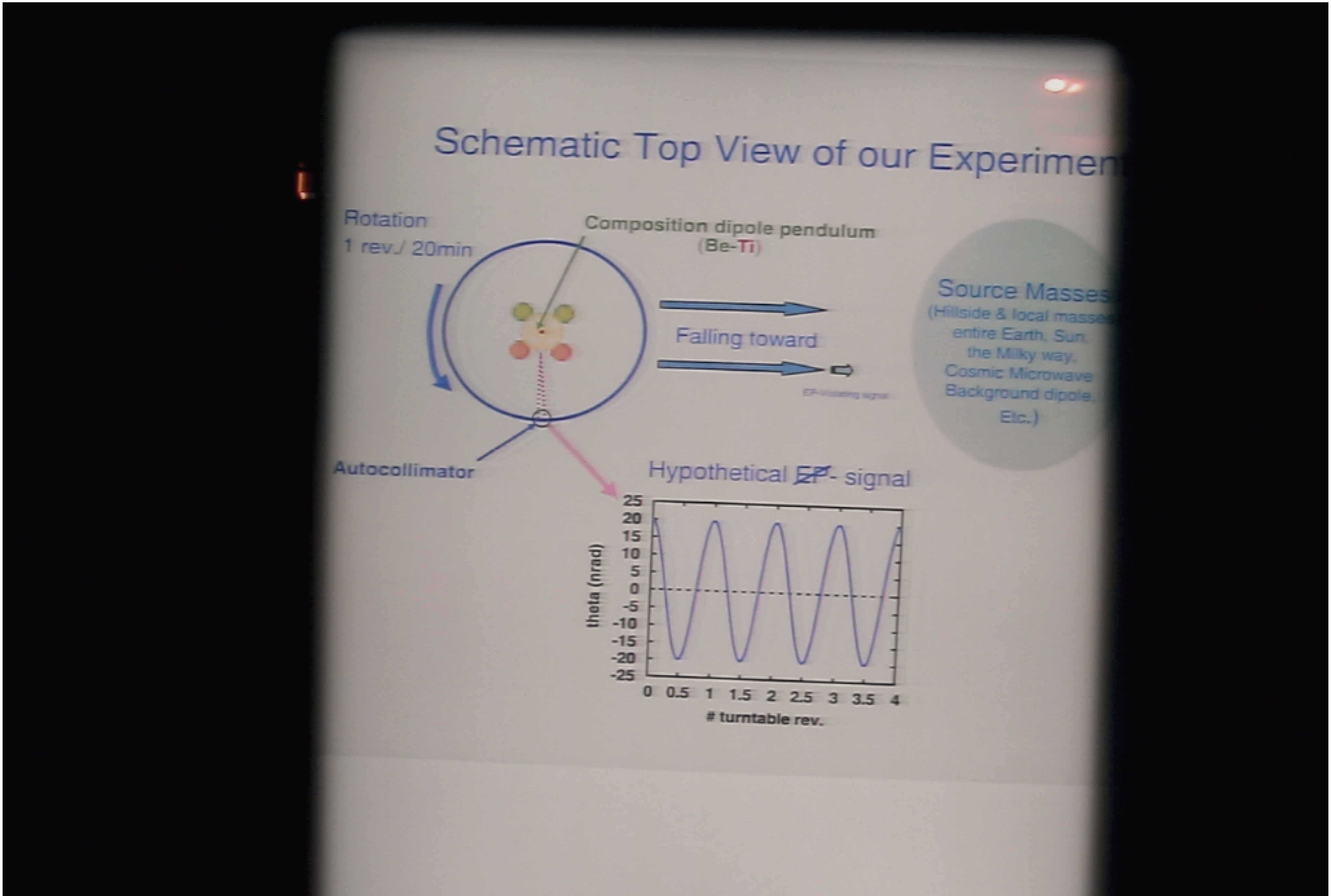
all scales are equal, but some are are more equal than others

$m = 0$	$\lambda = \infty$
$m = (M_Z)^2 / M_P$	$\lambda \sim 30$ cm
$m = (1\,\mathrm{TeV})^2 / M_P$	$\lambda \sim 0.2$ mm
$m = M_P$	$\lambda = 1.6 \times 10^{-33}$ cm

— from EP tests

--- from $1/r^2$ tests




Schematic Top View of our Experimen
Rotation
1 rev./ 20min
Composition dipole pendulum
(Be-Ti)
Falling toward
Source Masses
(Hillside & local masse
entire Earth, Sun,
the Milky way,
Cosmic Microwave
Background dipole,
Etc.)
Autocollimator
Hypothetical EP- signal
theta (nrad)
25
20
15
10
5
0
-5
-10
-15
-20
-25
0 0.5 1 1.5 2 2.5 3 3.5 4
turntable rev.

Gravity gradients (I)

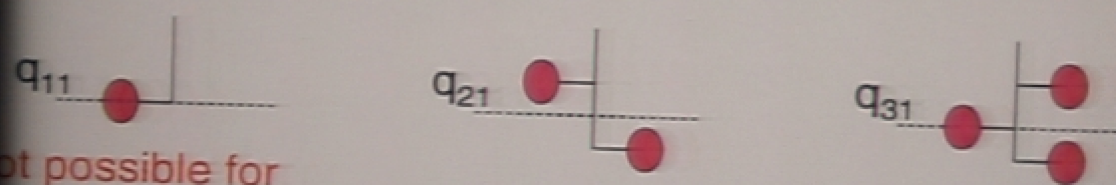
Gravitational potential energy between the pendulum an
the source masses is given by

$$\mathrm{w} = -4\pi G \sum_{l=0}^{\infty} \frac{1}{2l+1} \sum_{m=-l}^{l} Q_{lm} q_{lm} e^{-im\phi}$$

$Q_{lm} = \int d^3r' \rho_{source}(\vec{r}')\, r'^{-(l+1)}\, Y_{lm}(\hat{r}')$ gravity gradient field

$q_{lm} = \int d^3r\, \rho_{pend}(\vec{r})\, r^l\, Y_{lm}^*(\hat{r})$ gravity multipole momen

Torque for 1ω (m=1) signal: $\tau = 8\pi G \frac{1}{2l+1} |q_{l1}| |Q_{l1}|$



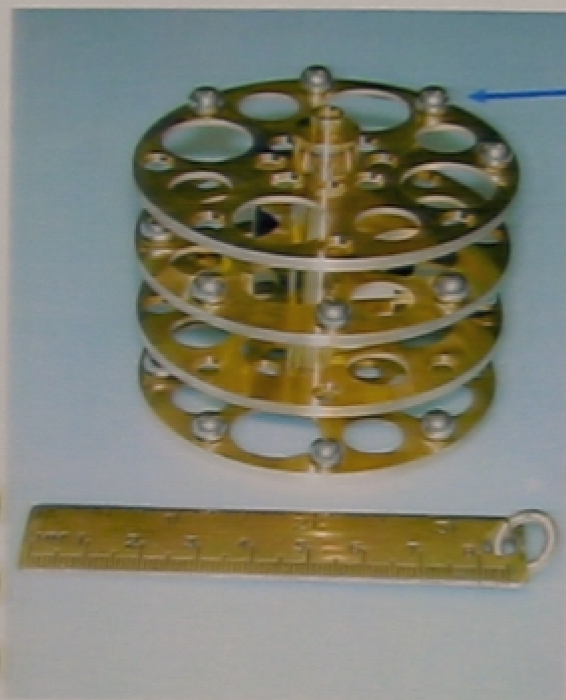
ot possible for
torsion pendulum

Gravity gradients (III)

Total mass
69 g

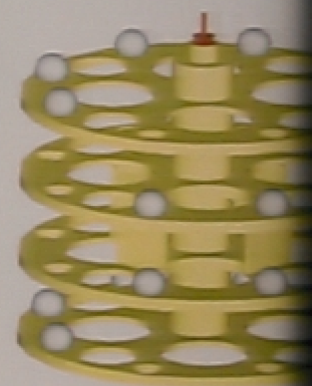
pendulum

q_{21} = 35.78 gcm²



Φ 7mm 1
Ti Balls
(m_{ave} =
0.795 g)

q_{31} pendul

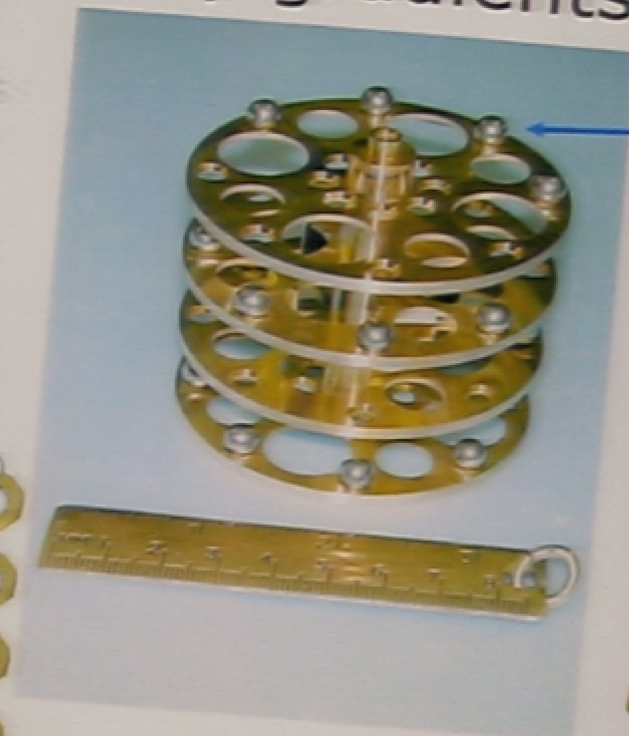


q_{31} = 105.22 gc

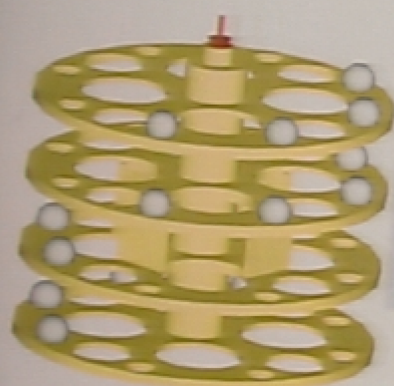
Gravity gradients (III

Total mass
69 g

q_{21} pendulum

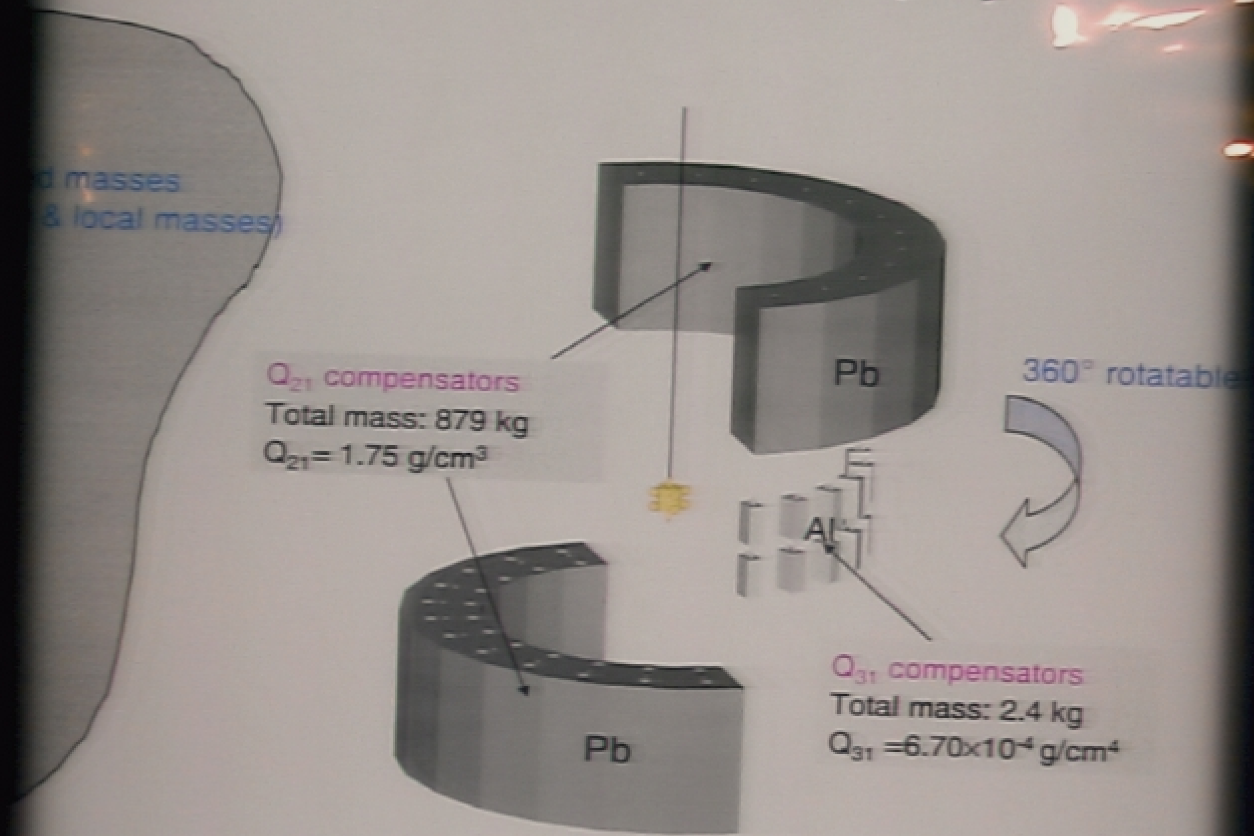


q_{21} = 35.78 gcm²



q_{31} = 105

Gravity gradients (II)



EP Torsion Pendulum

20 μm diameter tungsten
(length: 108 cm)

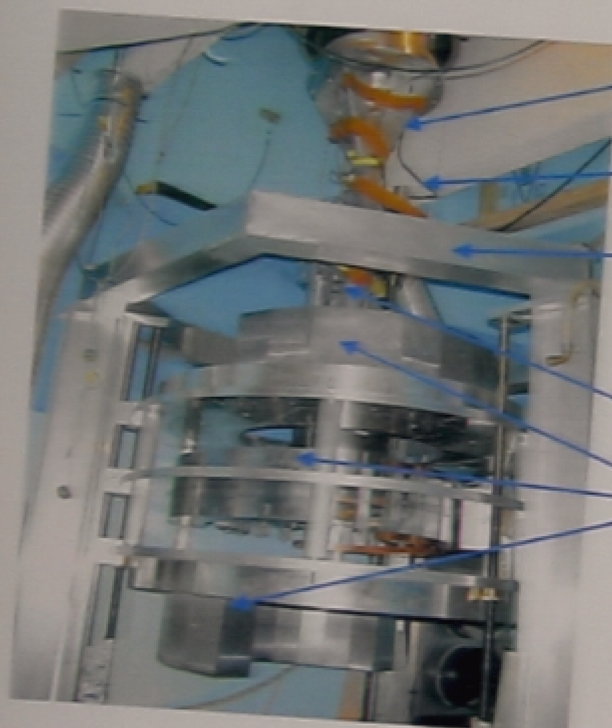
8 test masses (4 Be &
4.84 g each (within 0.1 m

4 mirrors

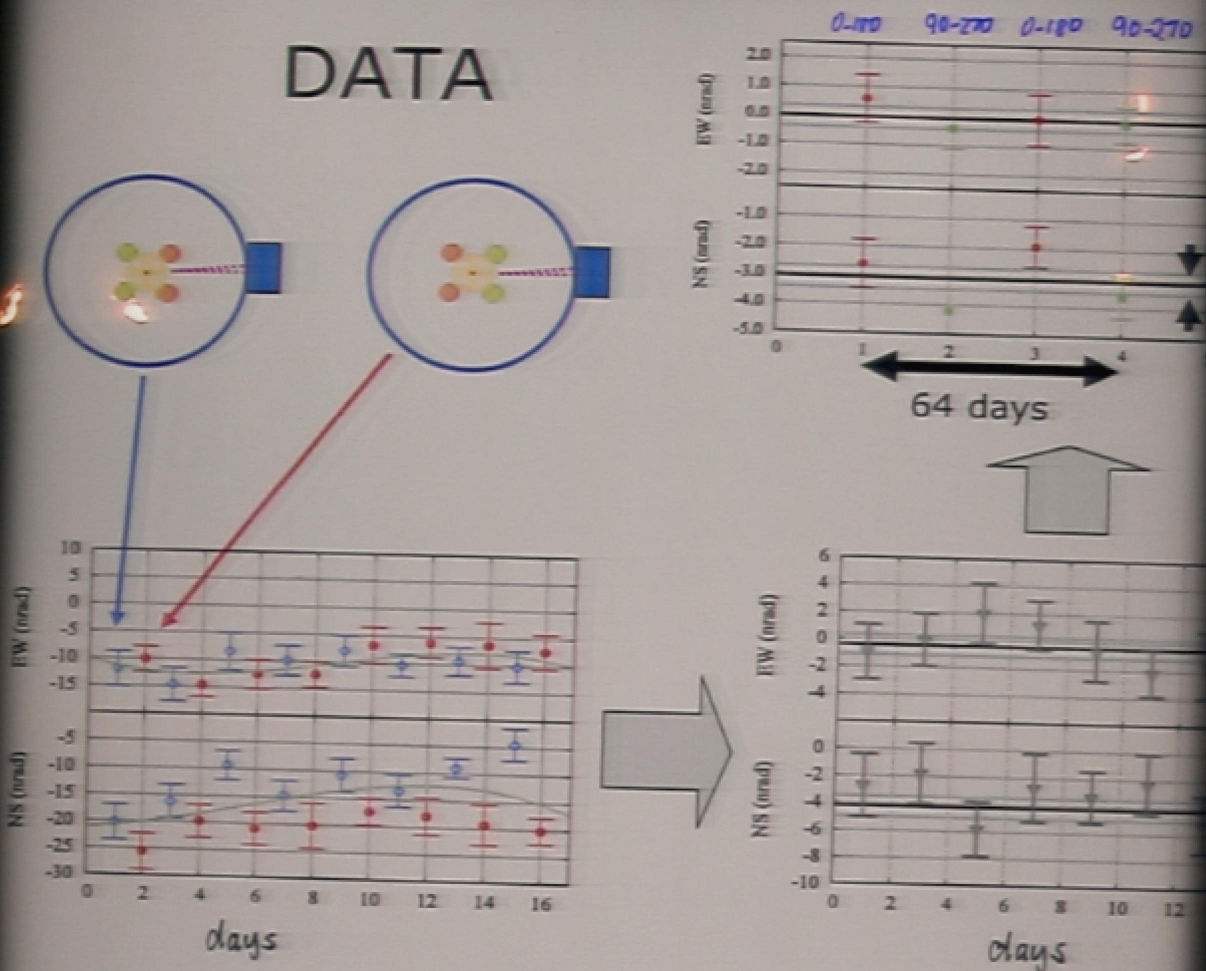
tuning screws for adjusti
gravity multipole momen
to null the gravitational c

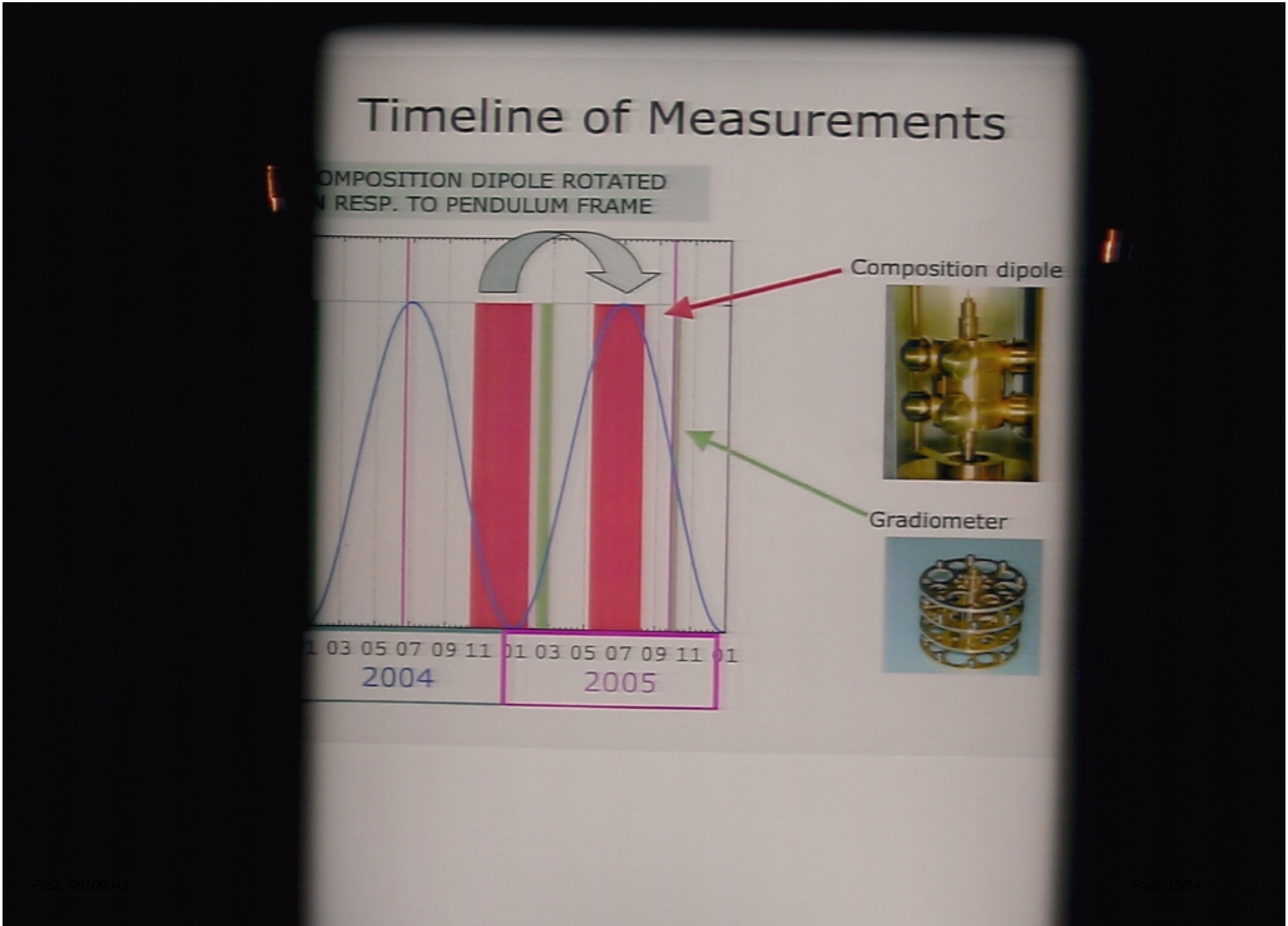
frequency:	1.261
quality factor:	4000
decay time:	11d 6.
machining tolerance:	5 μm
total mass :	70 g

The Lower Part of the Apparatus

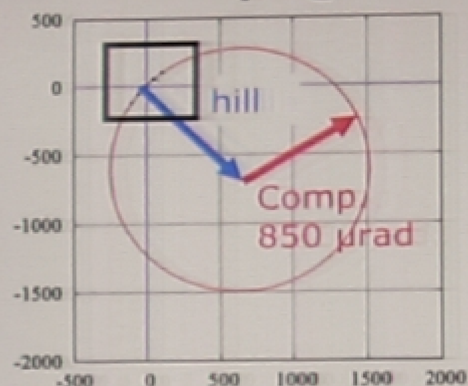


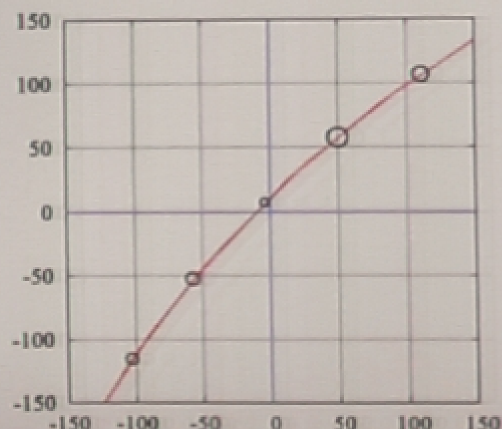
DATA

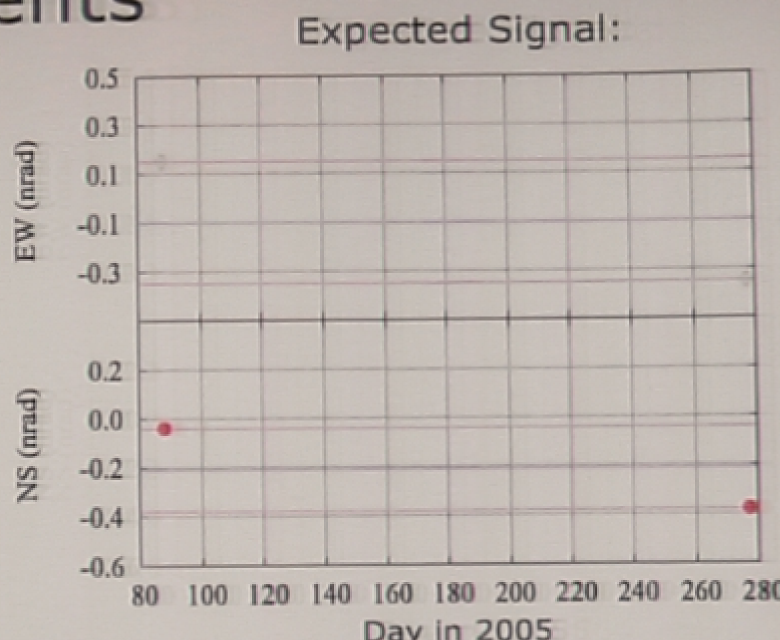

0-180
90-270
0-180
90-270
EW (nrad)
NS (nrad)
64 days
EW (nrad)
NS (nrad)
days
EW (nrad)
NS (nrad)
days


Timeline of Measurements
OMPOSITION DIPOLE ROTATED
N RESP. TO PENDULUM FRAME
Composition dipole
Gradiometer
1 03 05 07 09 11 01 03 05 07 09 11 01
2004
2005

Gravity gradients

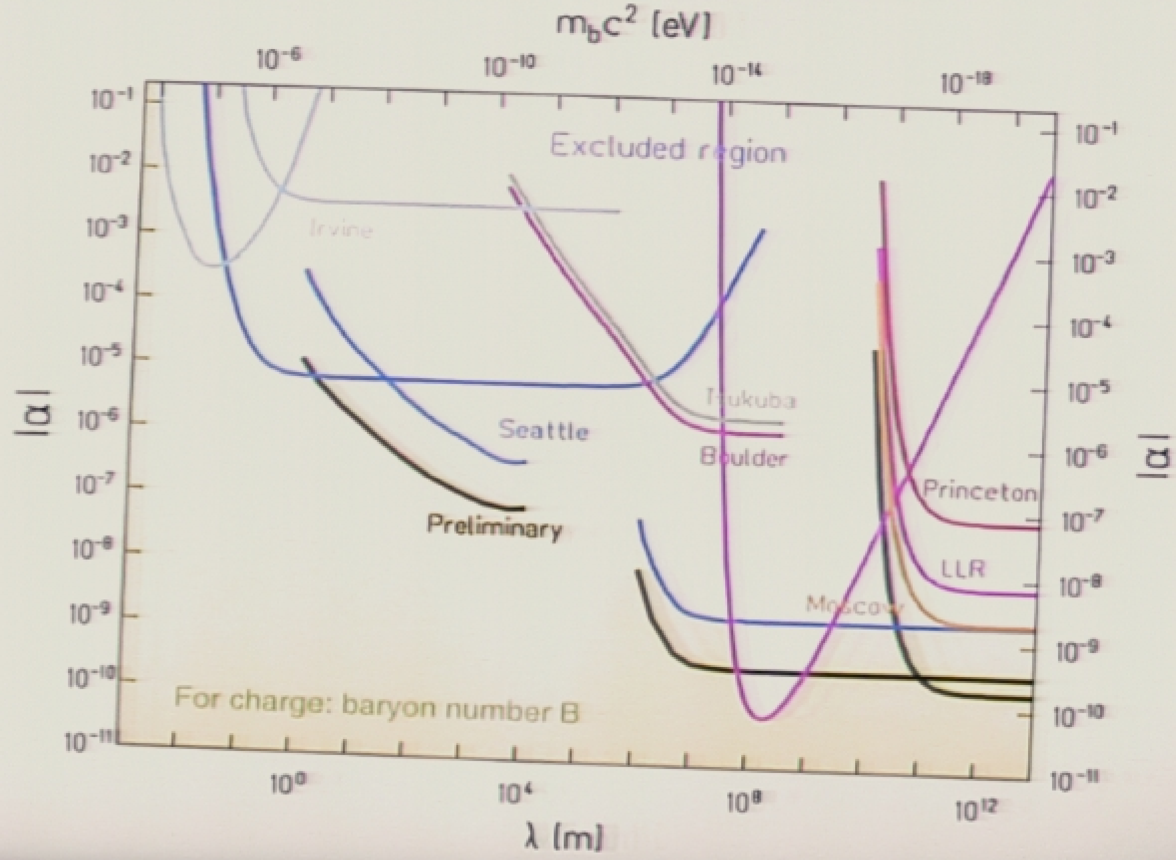






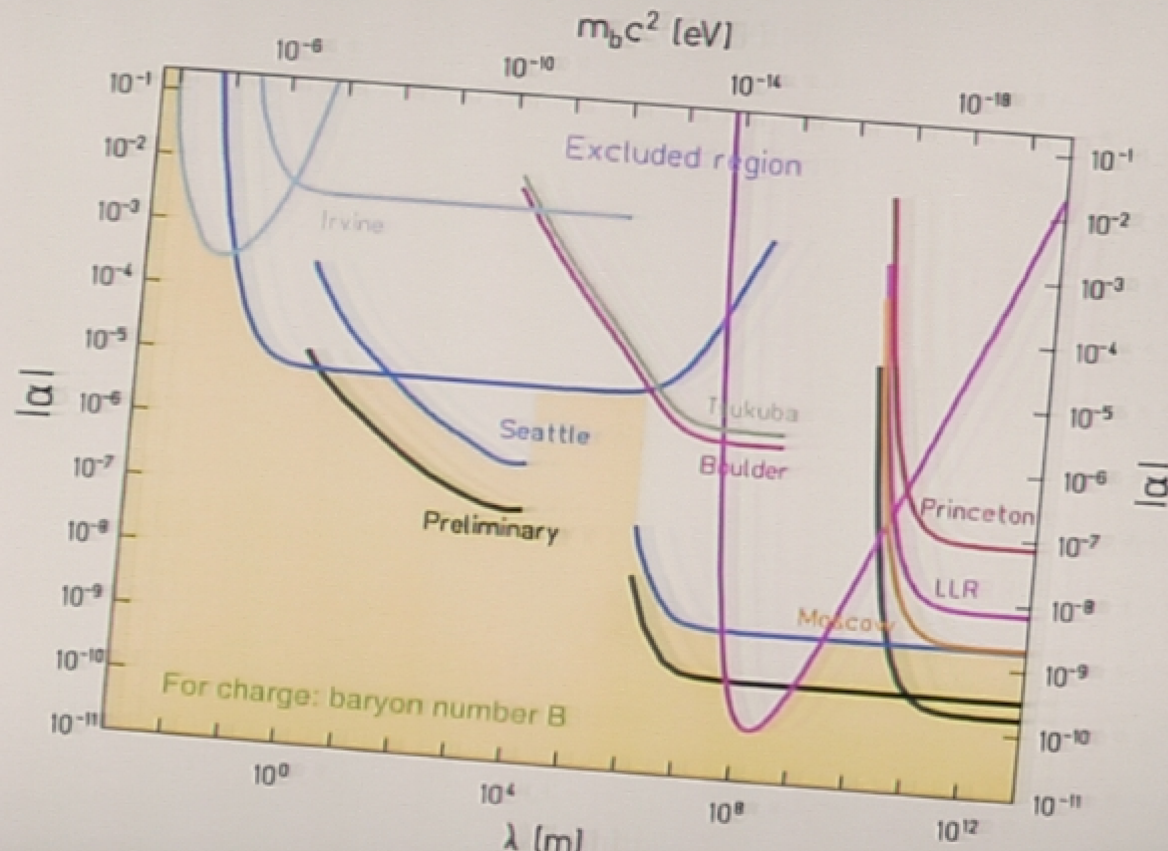
	mean	sigma
EW	**-0.10 nrad**	**0.25 nrad**
NS	**-0.21 nrad**	**0.17 nrad**

Results



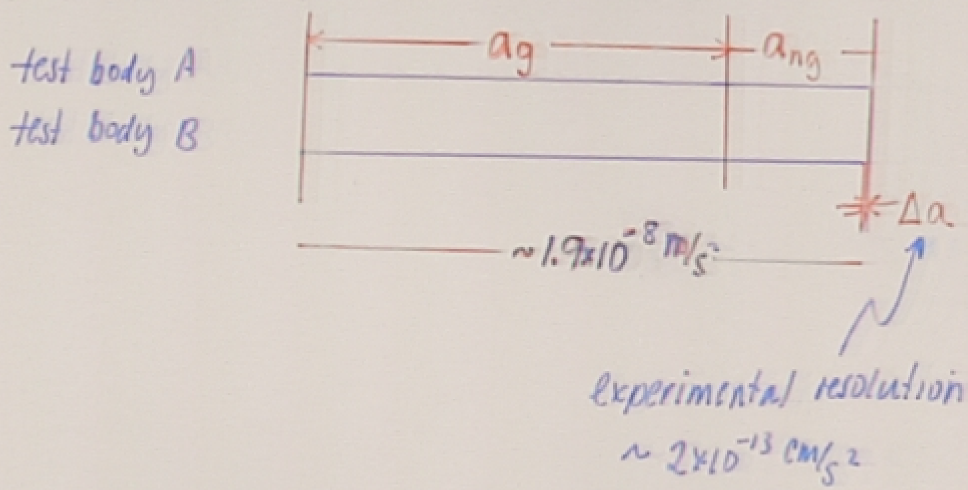
$m_b c^2$ [eV]
10^{-6}
10^{-10}
10^{-14}
10^{-18}
Excluded region
Irvine
Tsukuba
Seattle
Boulder
Preliminary
Princeton
LLR
Moscow
For charge: baryon number B
$|\alpha|$
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{0}
10^{4}
10^{8}
10^{12}
λ [m]

Results



$m_b c^2$ [eV]
Excluded region
Irvine
Seattle
Preliminary
Tsukuba
Boulder
Princeton
LLR
Moscow
For charge: baryon number B
|α|
λ [m]

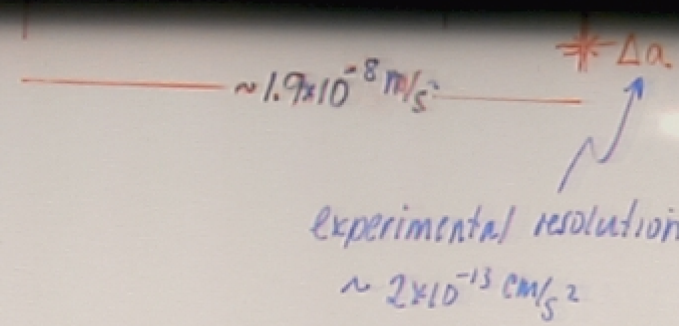
Acceleration of luminous matter to galactic dark matter



a_{ng} must arise from scalar interaction

vector interaction would blow apart dark matter halo

tree-level approximation for electrically neutral bodies



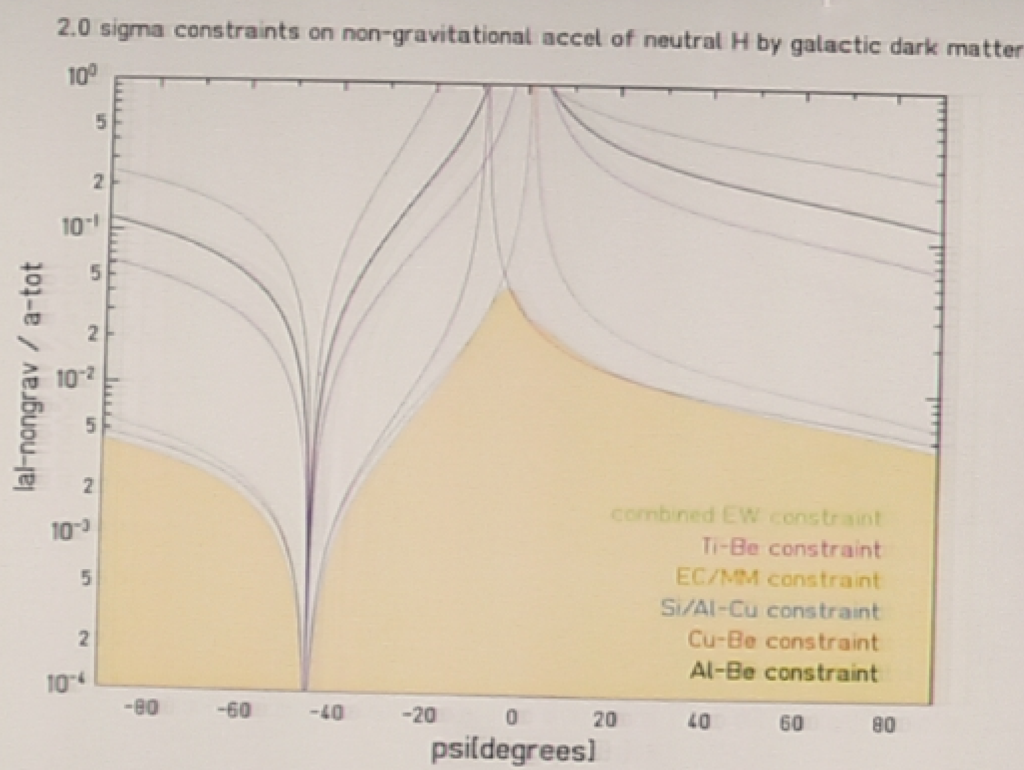
a_{ng} must arise from scalar interaction

vector interaction would blow apart dark matter halo

tree-level approximation for electrically neutral bodies

$$q_s(Z,N) = (q_s^e + q_s^p) Z + q_s^n N$$

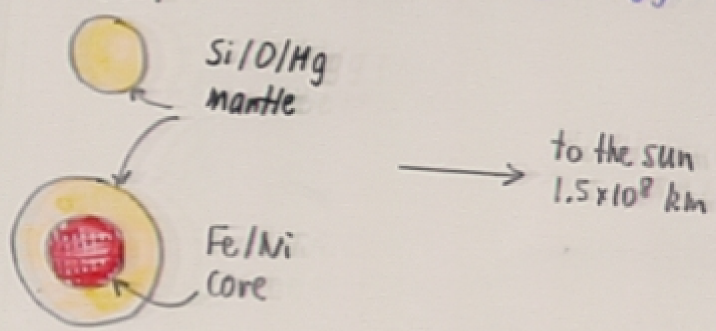
$$\text{let } \psi = \tan^{-1} \frac{(q_s^e + q_s^p) - q_s^n}{q_s^n}$$


2.0 sigma constraints on non-gravitational accel of neutral H by galactic dark matter
|a|-nongrav / a-tot
10^0
5
2
10^{-1}
5
2
10^{-2}
5
2
10^{-3}
5
2
10^{-4}
-80
-60
-40
-20
0
20
40
60
80
psi[degrees]
combined EW constraint
Ti-Be constraint
EC/MM constraint
Si/Al-Cu constraint
Cu-Be constraint
Al-Be constraint

'Model-independent' test of equivalence principle for gravitational binding energy

2×10^{-11} of mass in grav. binding energy

moon



earth

46×10^{-11} of mass in grav. binding energy

composition-dependent accelerations the same in both cases

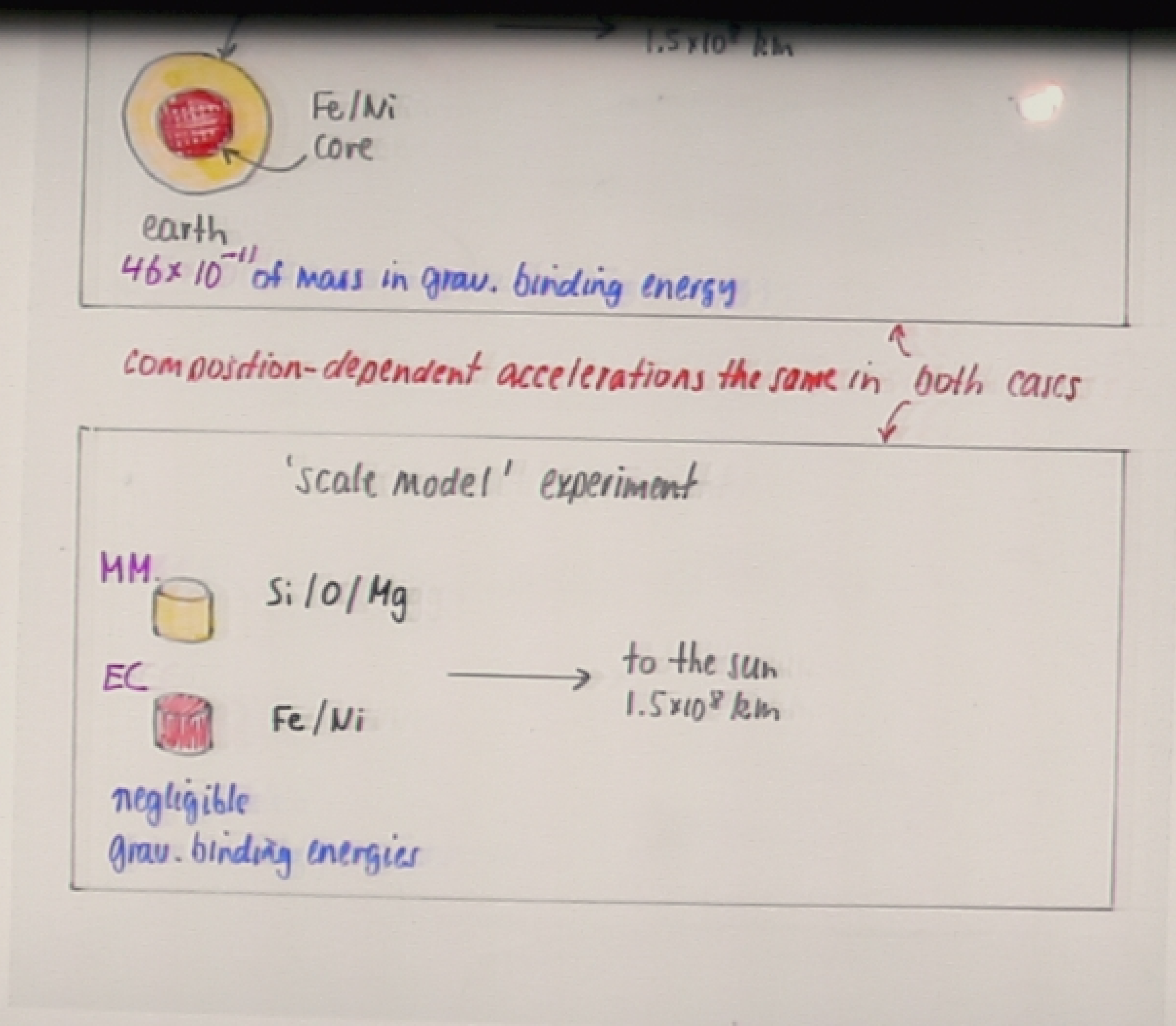
'scale model' experiment

MM.

Si/O/Mg

EC

to the sun


Fe/Ni
core
earth
46×10^-11 of mass in grav. binding energy
composition-dependent accelerations the same in both cases
'scale model' experiment
MM
Si/O/Mg
EC
Fe/Ni
to the sun
1.5×10^8 km
negligible
grav. binding energies

UNAMBIGUOUS TESTS OF THE SEP

$$\eta_{SEP} = \left.\frac{\Delta a}{a}\right|_{SEP} \frac{1}{(46-2)\times 10^{-11}}$$

$$\left.\frac{\Delta a}{a}\right|_{SEP} = \left.\frac{\Delta a}{a}\right|_{LLR} - \left.\frac{\Delta a}{a}\right|_{CD}$$

- 1999 result

$$\left.\frac{\Delta a}{a}\right|_{LLR} = (3.2 \pm 4.6)\times 10^{-13}$$

Williams et al., PRD 53, 6730 (1996)

$$\left.\frac{\Delta a}{a}\right|_{CD} = (0.1 \pm 2.7)\times 10^{-13}$$

Baessler et al., PRL 83, 3585 (1999)

$$\eta_{SEP} = (0.7 \pm 1.2)\times 10^{-3}$$

- new result

$$\left.\frac{\Delta a}{a}\right|_{LLR} = (-0.7 \pm 1.5)\times 10^{-13}$$

Anderson & Williams, Class. Quant. Grav. 18, 2447 (2001)

$$\left.\frac{\Delta a}{a}\right|_{SEP} = \left.\frac{\Delta a}{a}\right|_{LLR} - \left.\frac{\Delta a}{a}\right|_{CD}$$

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- new result

$$\left.\frac{\Delta a}{a}\right|_{LLR} = (-0.7 \pm 1.5)\times 10^{-13}$$

Anderson & Williams, Class. Quant. Grav. 18, 2447 (2001)

$$\left.\frac{\Delta a}{a}\right|_{CD} = (-1.3 \pm 1.3)\times 10^{-13}$$

U. Schmidt et al., unpublished

$$\eta_{SEP} = (1.4 \pm 4.3)\times 10^{-4}$$

LLR Science

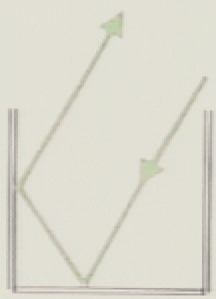
Gravitational Physics:

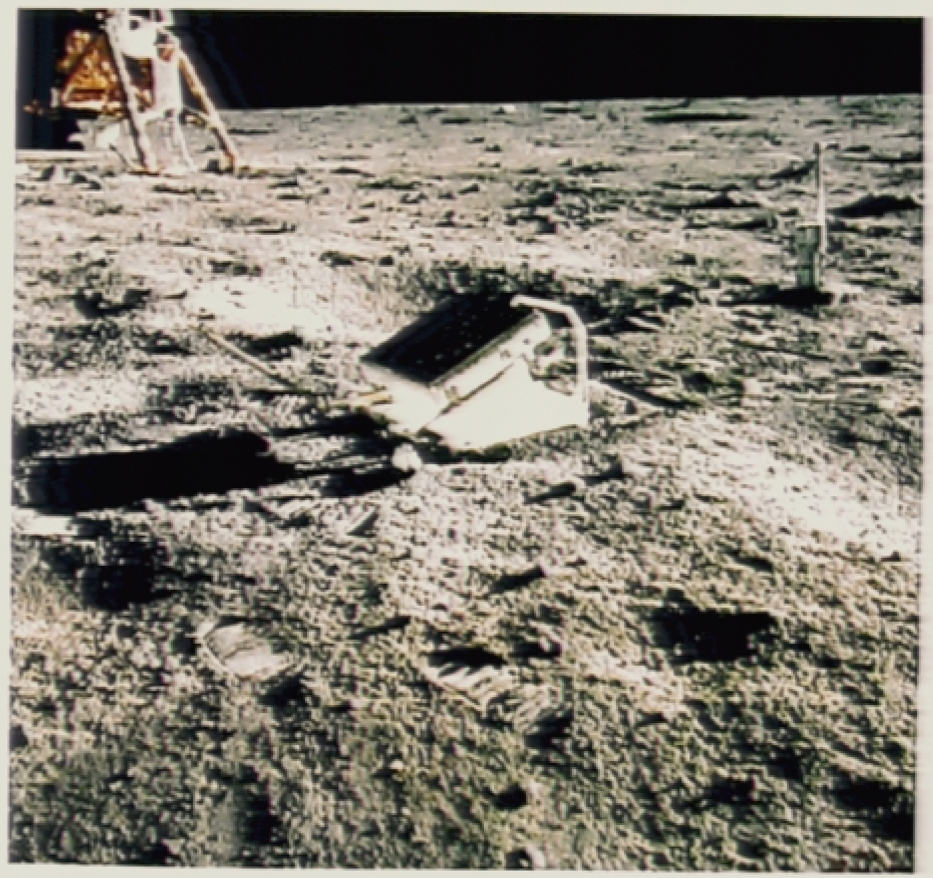
- The *best* test available of the strong equivalence principle (EP)
- A *leading* test of the weak (composition-dependent) EP
- The *best* test of time-variation of Newton's constant, G
- The *best* test of gravitomagnetism ($\cos D$ term)
- Currently the *best* probe of relativistic geodetic precession
- The *most sensitive* test of $1/r^2$ law

By-products:

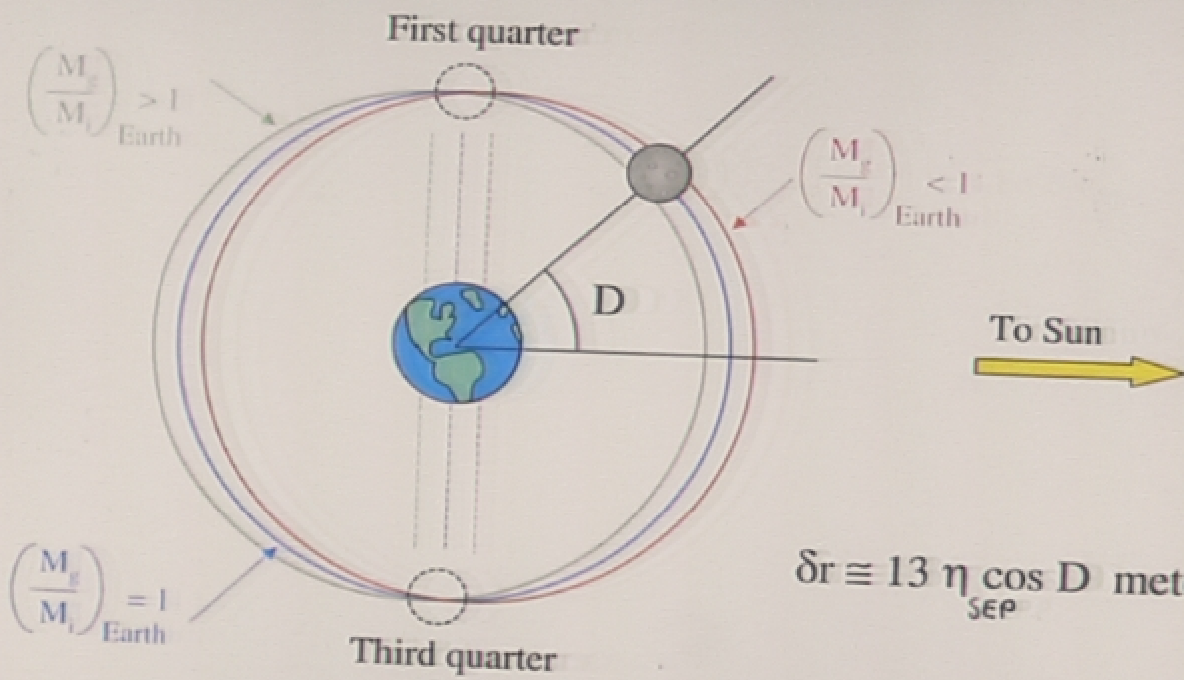
- Lunar interior
- Coordinate systems
- Geophysics

Apollo 11 reflector

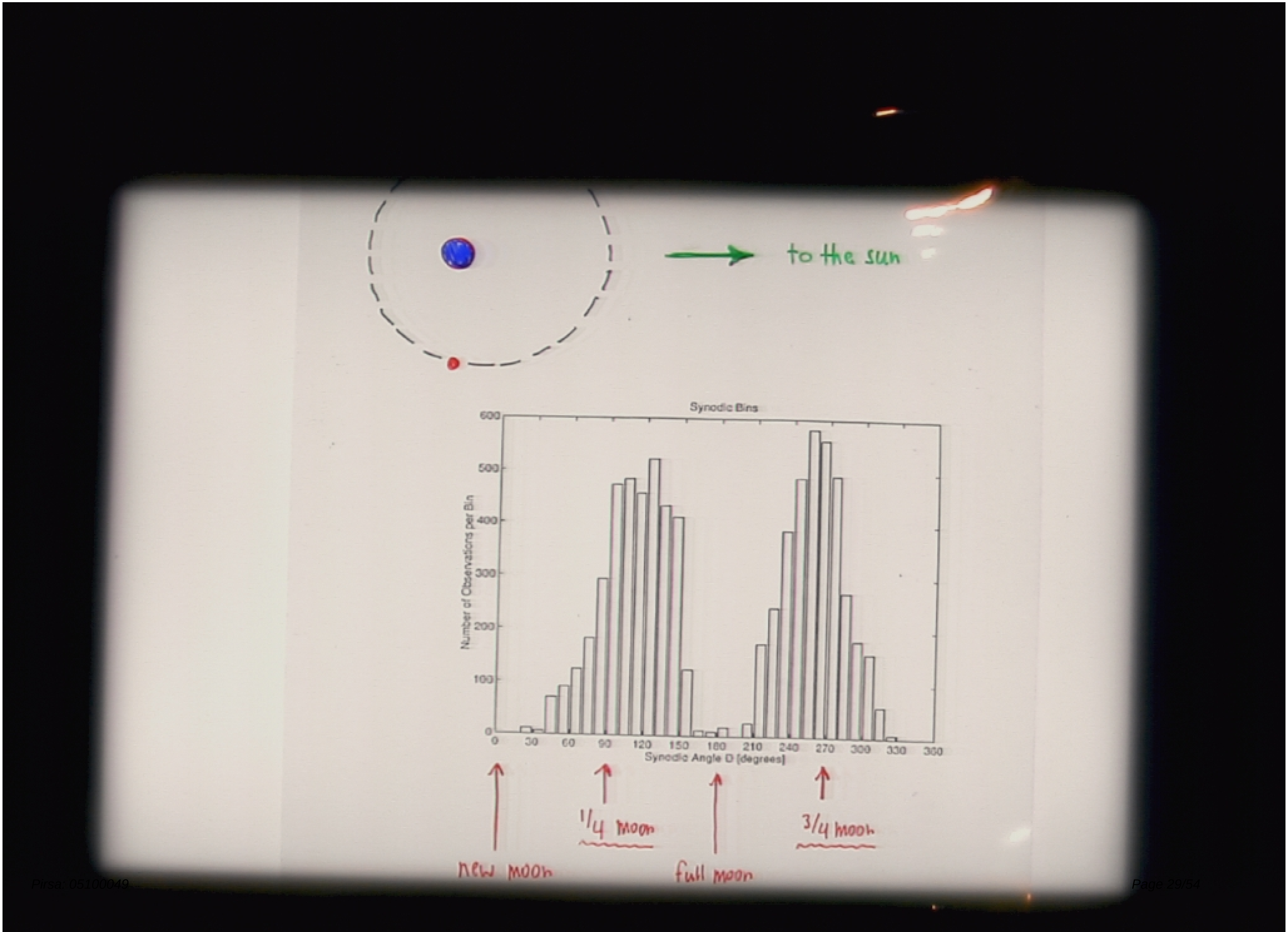

Retro-reflector

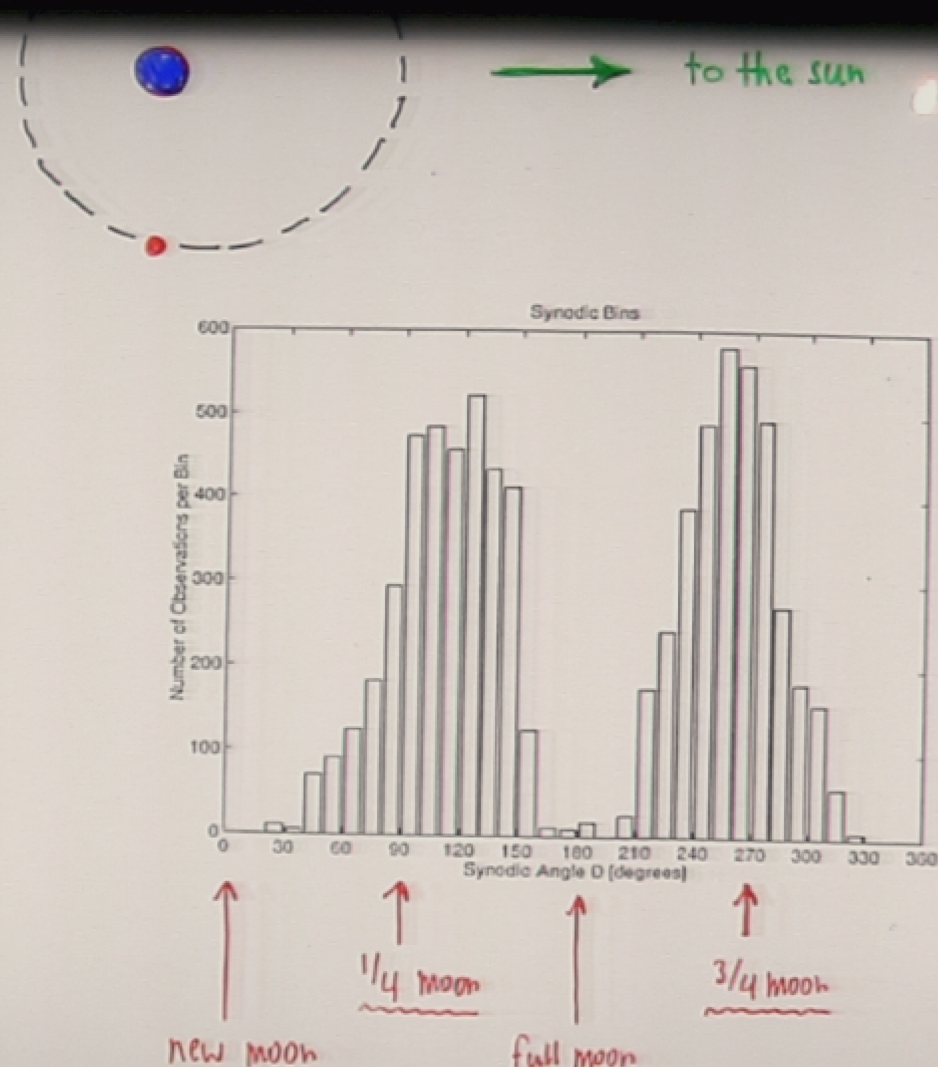


Orbital Perturbations



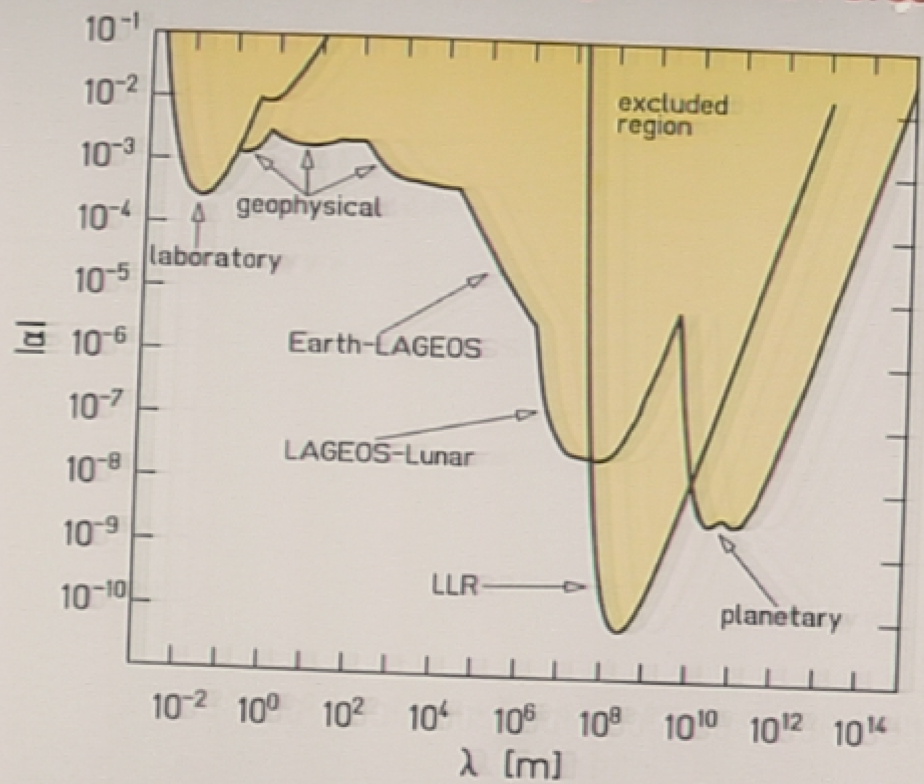
$$\delta r \cong 13\, \eta_{SEP} \cos D \ \text{meters}$$


to the sun
Synodic Bins
Number of Observations per Bin
Synodic Angle D [degrees]
0 30 60 90 120 150 180 210 240 270 300 330 360
0 100 200 300 400 500 600
new moon
1/4 moon
full moon
3/4 moon



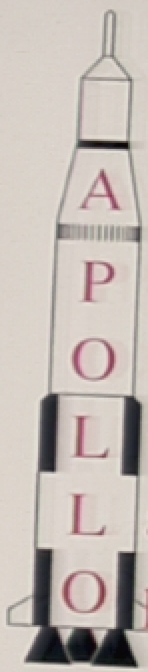
Müller & Nordtvedt Phys Rev D 58 (1998) 062001

Constraints on Long-Range Yukawa Forces



APOLLO: Next-Generation Lunar Laser Ranging

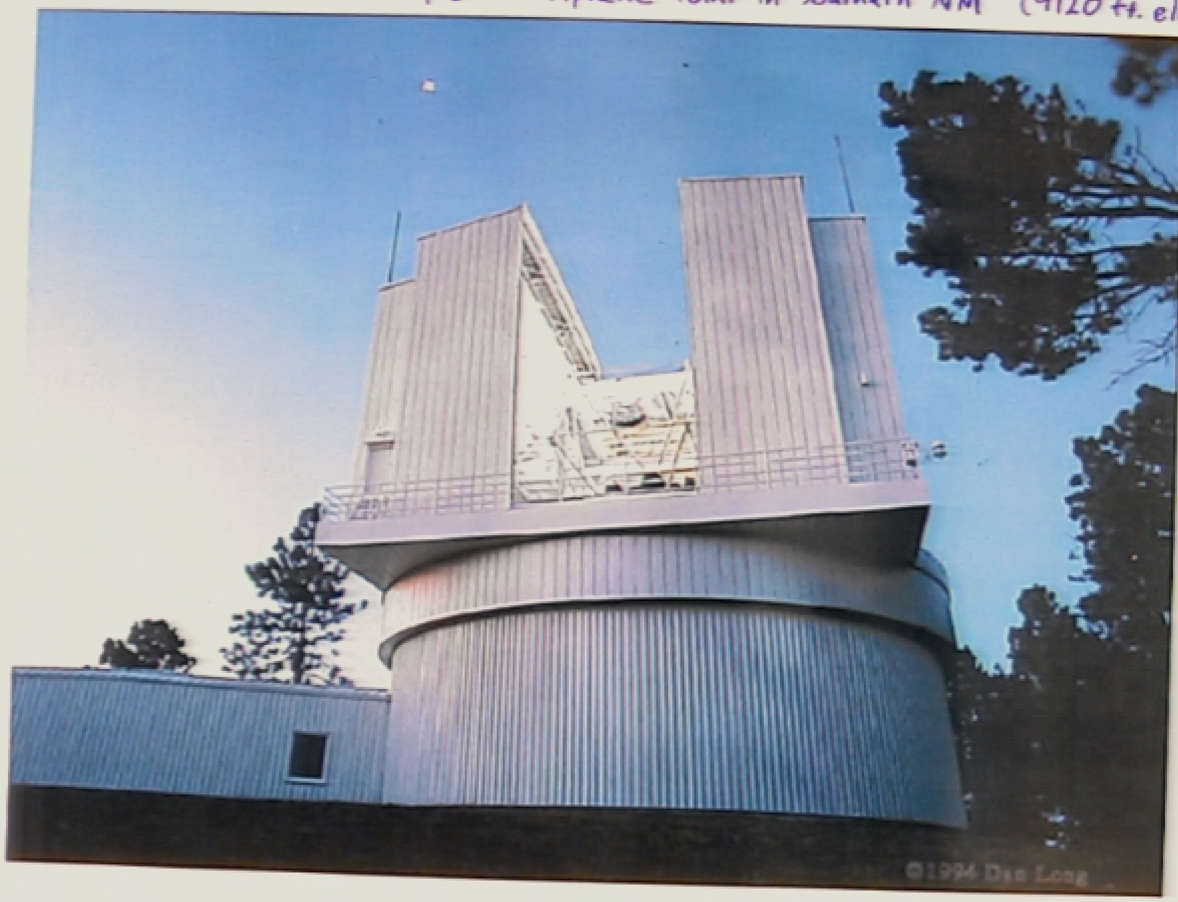
will give more than 100 times greater event rate and can sample almost the entire lunar cycle



Apache
Point
Observatory
Lunar
Laser–ranging
Operation

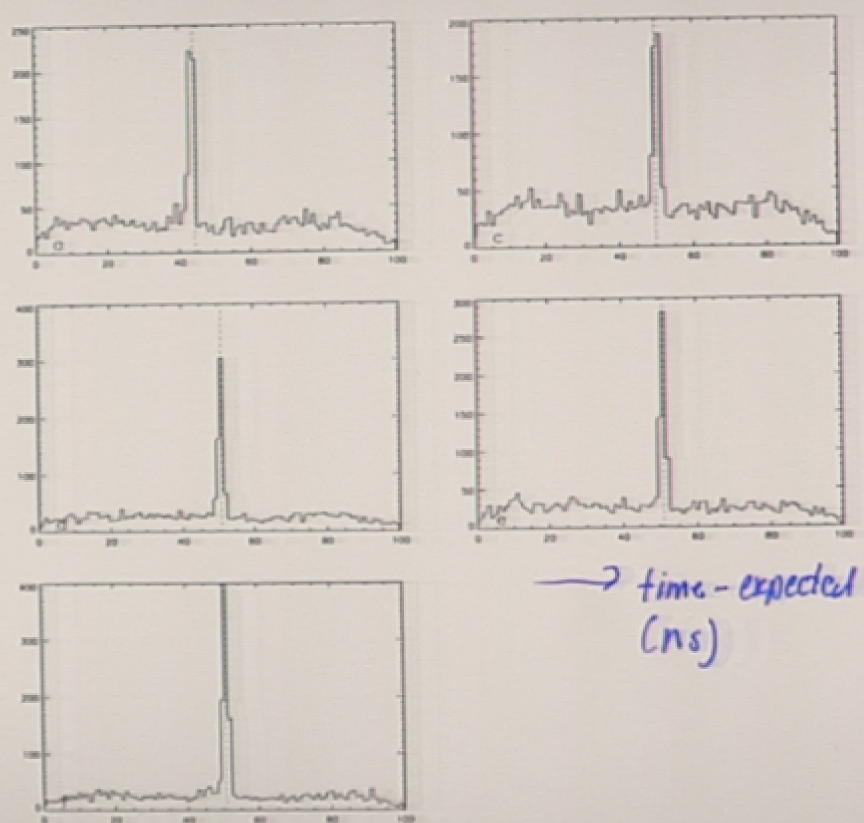
Tom Murphy	UCSD
Eric Adelberger	UW
Chris Stubbs	Harvard
Ken Nordtvedt	Northwest Analysis
Jim Williams	JPL
Jean Dickey	JPL
Bruce Gillespie	Apache Point Observatory
John Goodkind	UCSD

3.5 meter telescope at Apache Point in Southern NM (9120 ft. elev.)



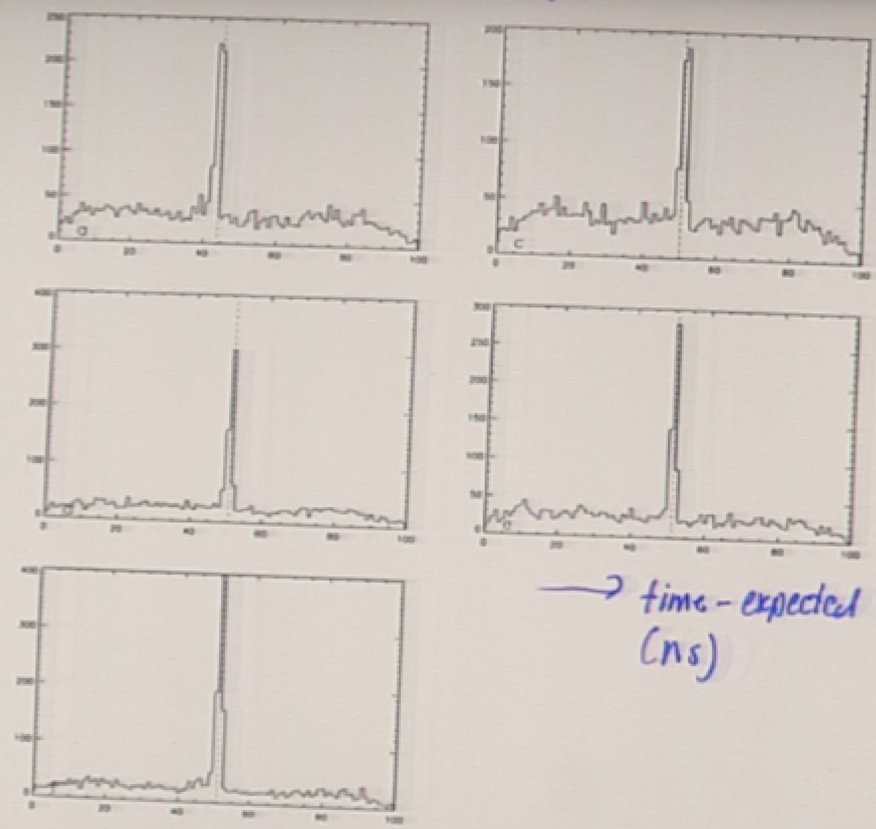
APOLLO ranges to the <u>full moon</u>

30 minutes of data



→ time - expected time (ns)

30 minutes of data



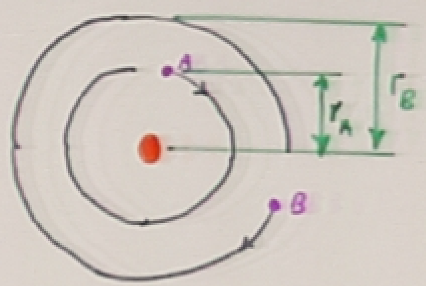
→ time - expected time (ns)

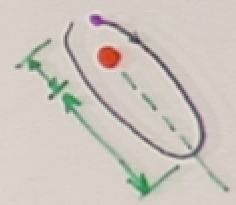
In 30 minutes we got as many photon returns as McDonald LLR facility did in 3 yrs (2000-2003)

APOLLO Expectations for 1σ Uncertainties

- One-millimeter RMS normal point precision
- Strong EP to $\eta_{SEP} \approx 3 \times 10^{-5}$: (2 years; $t^{-\frac{1}{2}}$ thereafter)
- Weak EP to $\Delta a/a \approx 10^{-14}$: (2 years; $t^{-\frac{1}{2}}$ thereafter)
- Gravitomagnetism to 10^{-4}: (2 years; $t^{-\frac{1}{2}}$ thereafter)
- $\dot{G}/G$ to 10^{-13} yr^{-1}: (5 years; $t^{-\frac{5}{2}}$ thereafter)
- Geodetic precession to $\approx 3 \times 10^{-4}$: (10 years; $t^{-\frac{3}{2}}$ thereafter)
- Similar order-of-magnitude gains in lunar science, coordinate determinations, etc.

Any given test of the $1/r^2$ law is sensitive to a restricted range of length scales



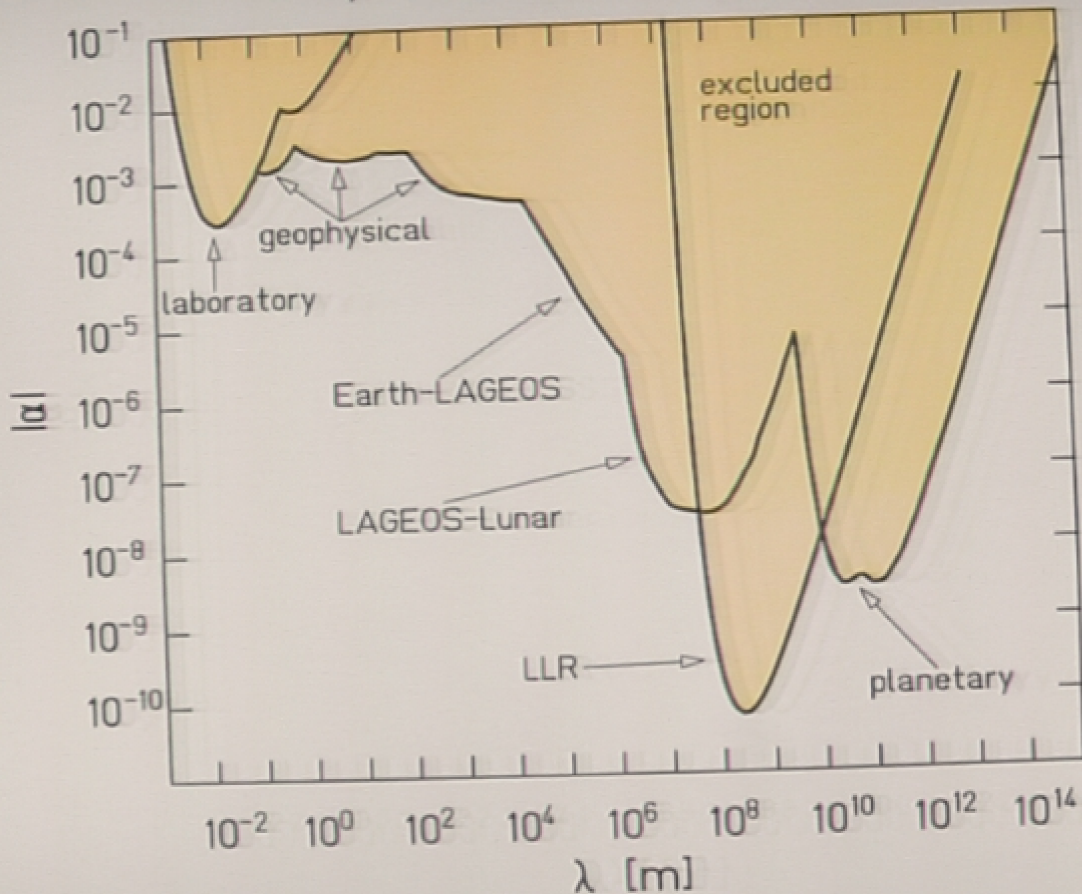


$$\frac{T_A^2}{r_A^3} = \frac{T_B^2}{r_B^3} \ ?$$

precession of perigee?

∴ need many different approaches to cover a wide range of length scales

95% confidence limits



What might be special about gravity at $r \lesssim 1$ mm?

- mass scale of gravity

  $M_P = \sqrt{\hbar c / G} \sim 10^{16}$ TeV

  can be unified with mass scale of particle physics

  $M_{part} \sim 1$ TeV

  if 2 of the extra dimensions a "large" with size ~ 1 mm

- cosmological constant from distant supernovae + CMB

  $\Lambda \sim 4\ \mathrm{keV/cm^3}$

  corresponds to a length ~ 0.1 mm

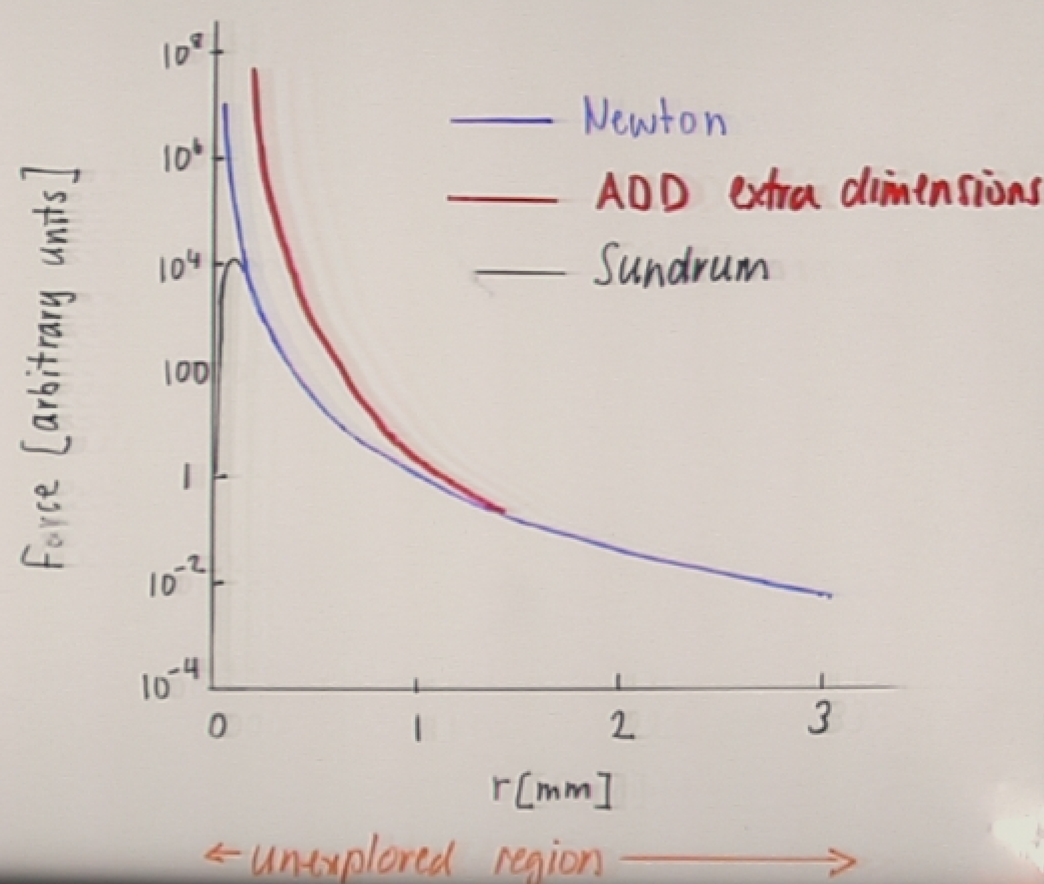
- generically interesting mass scale

  $(M_{part})^2 / M_P$

  corresponds to a length ~ 1 mm

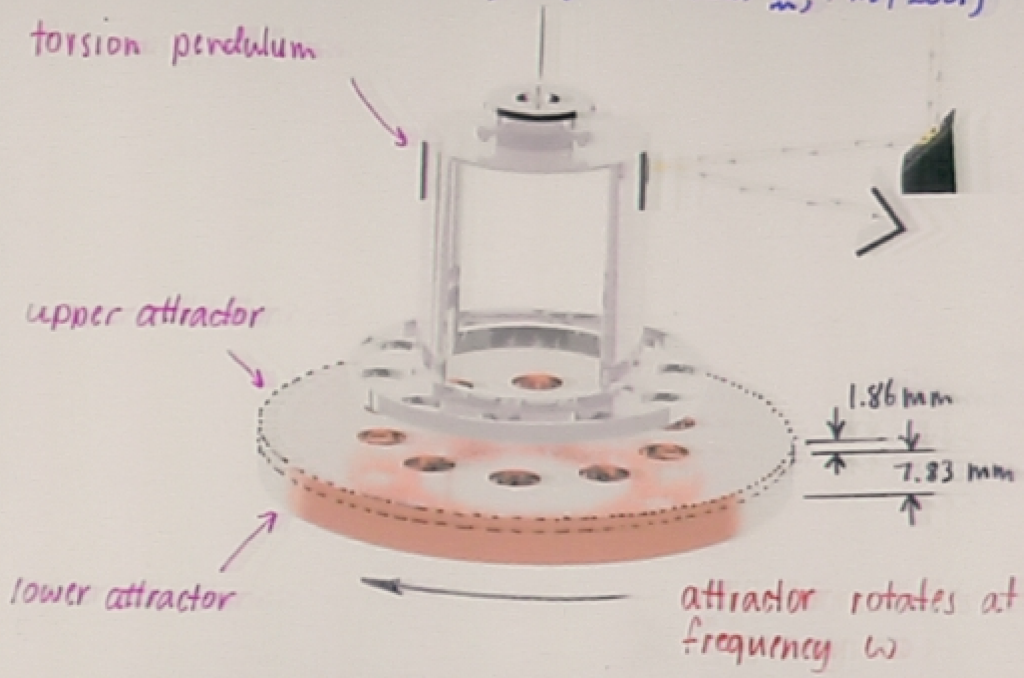
- essentially nothing is known about gravity

PREDICTIONS FOR $1/r^2$ LAW BREAKDOWN



Washington short-range instrument

Hoyle et al., Phys. Rev. Lett. 86, 1418 (2001)



- the 10 holes in the lower attractor are "out of phase" with the holes in the upper attractor.
- this cancels Newtonian gravity torque

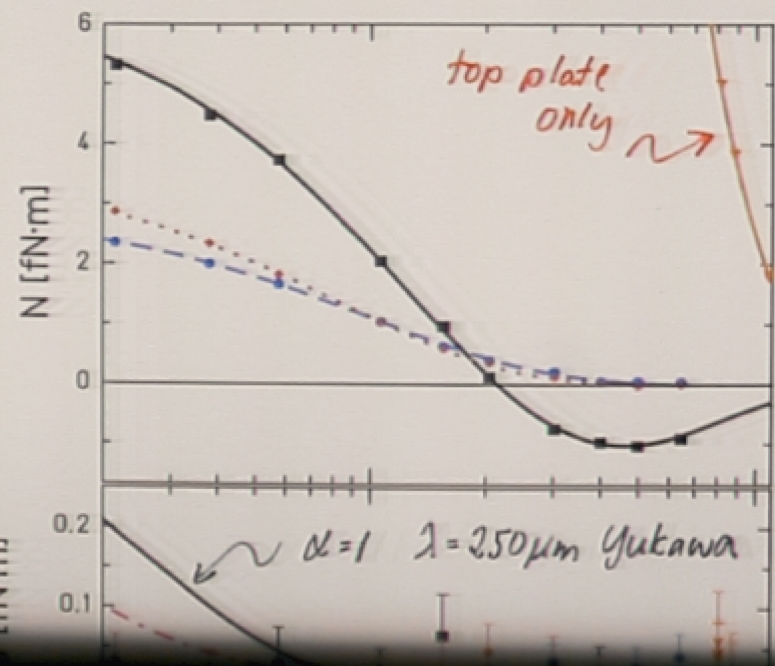
Eöt-Wash Mark II short-range instrument

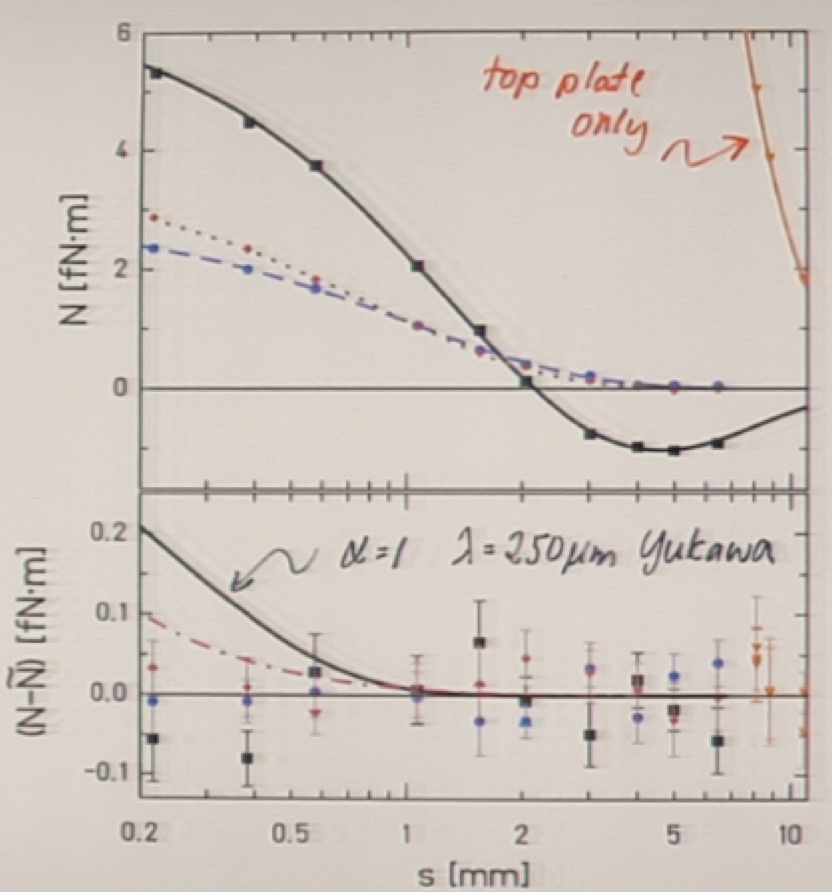
Hoyle et al. 10-hole data

— 10ω torque

- - - 20ω torque

• • • • 30ω torque

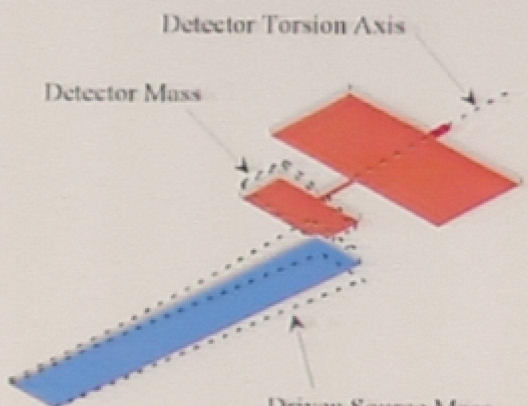




top plate only
α=1 λ=250μm Yukawa
N [fN·m]
(N-Ñ) [fN·m]
s [mm]
0.2
0.5
1
2
5
10
6
4
2
0
0.2
0.1
0.0
-0.1

Long et al., Nature 421, 922 (2003)

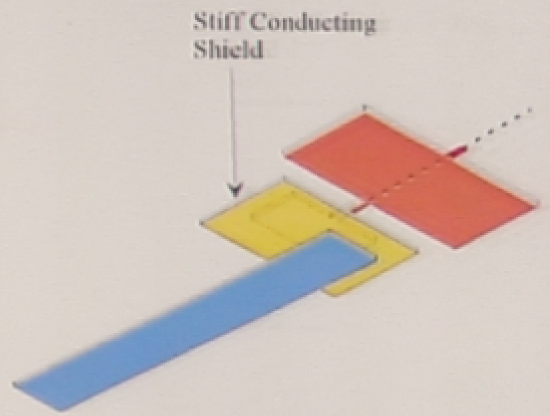
Planar Geometry



$F_Y(\alpha=1,\ \lambda=100\,\mu m)$

$\approx 1\times10^{-14}\ N$

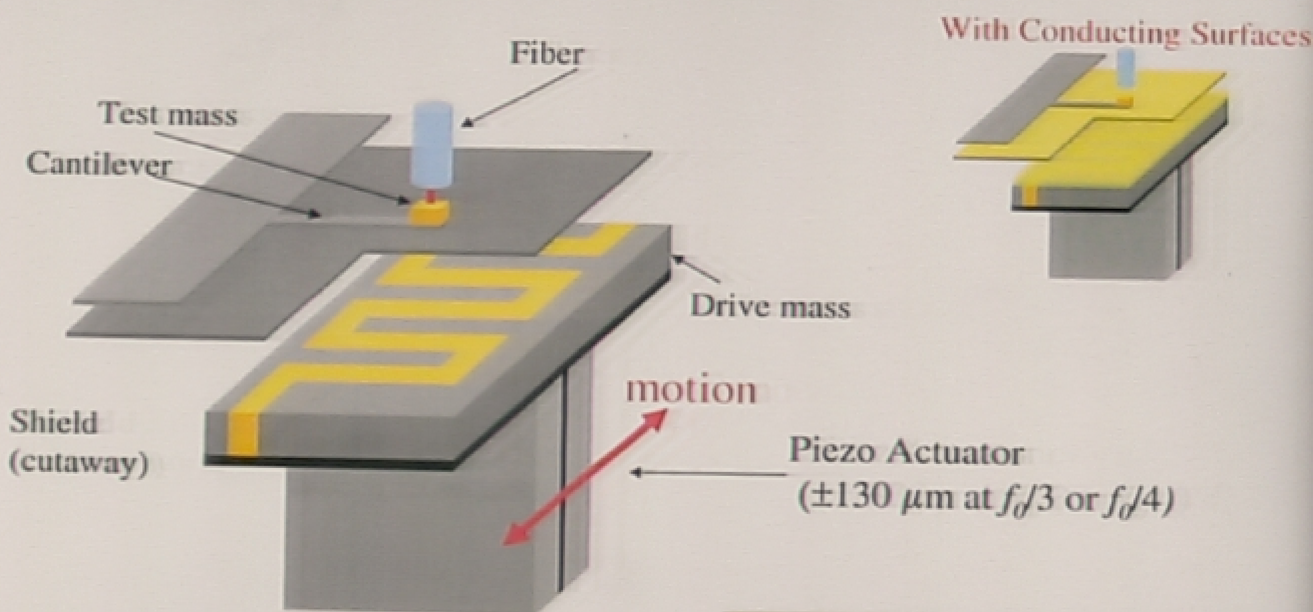
Source and Detector
Oscillators



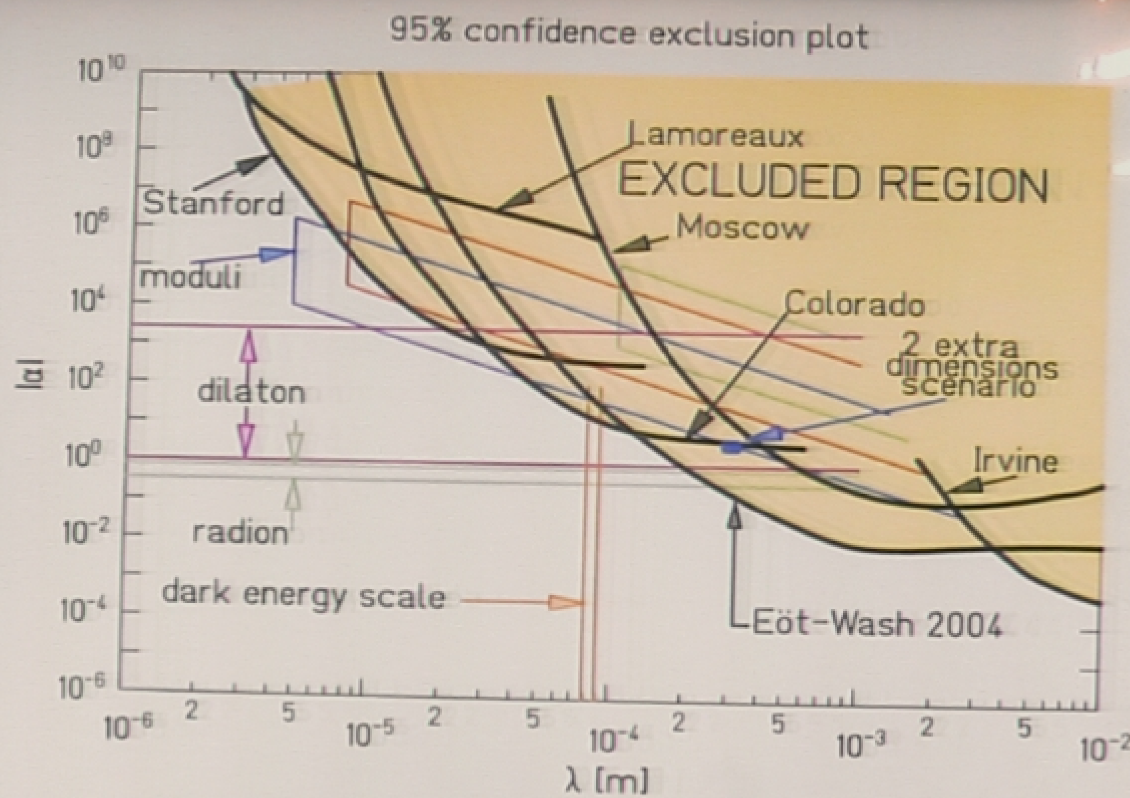
Shield for Background
Suppression

Stanford's Experiment

Chiaverini et al., Phys. Rev. Lett. 90, 151101 (2003)

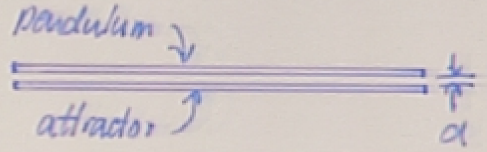


Cantilever resonance (f_0): ~300 Hz
Drive frequency($f_0/3$): ~100Hz


95% confidence exclusion plot
EXCLUDED REGION
Lamoreaux
Stanford
Moscow
moduli
Colorado
2 extra dimensions scenario
dilaton
Irvine
radion
dark energy scale
Eöt-Wash 2004
|α|
λ [m]
10^{10}
10^{8}
10^{6}
10^{4}
10^{2}
10^{0}
10^{-2}
10^{-4}
10^{-6}
10^{-5}
10^{-3}
10^{-2}

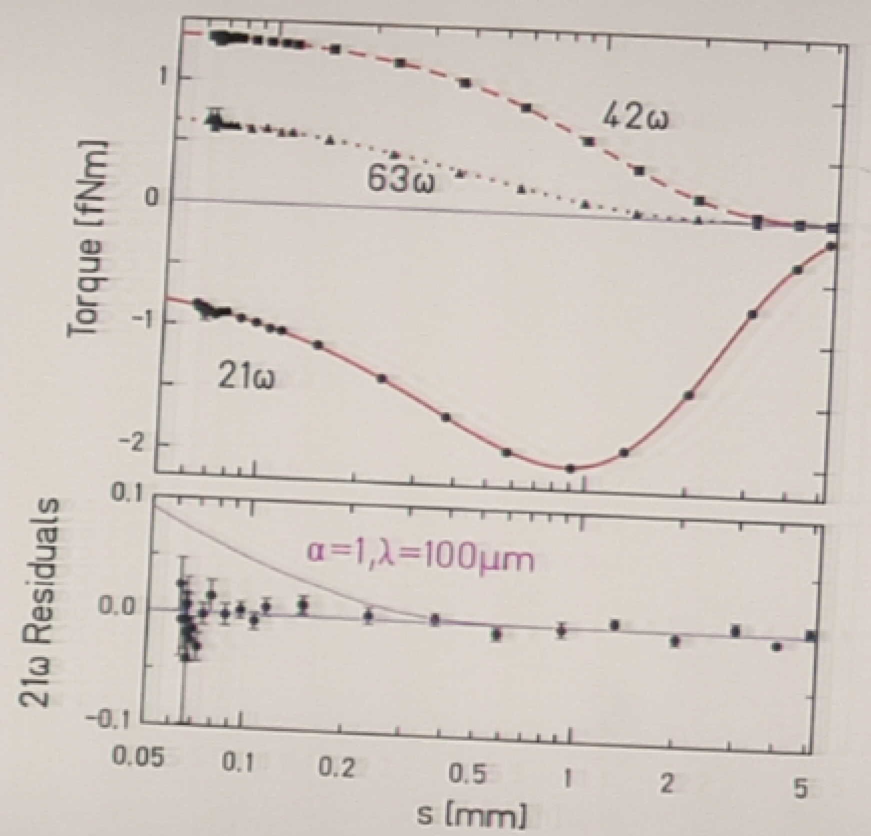
Scaling relations for detector sensitivity to new short-range physics

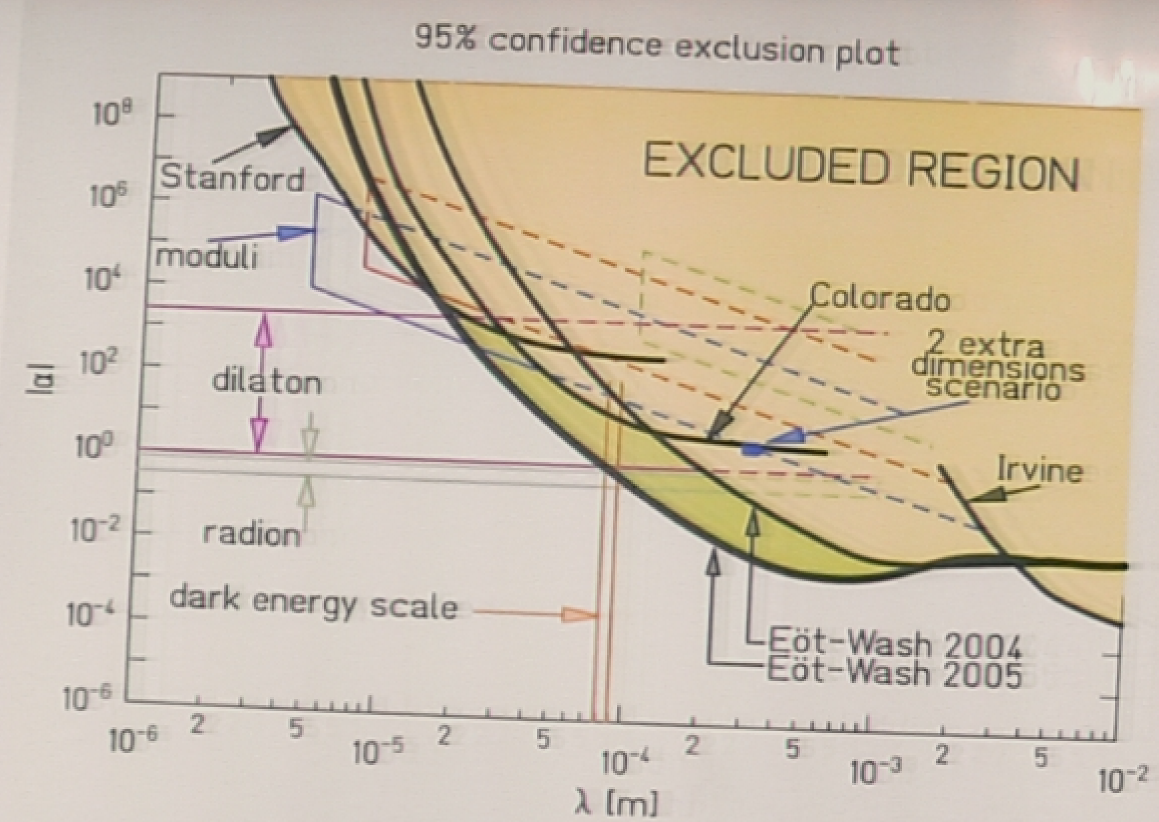
torque $= N_{s.r.} = \dfrac{\Delta E_{s.r}}{\Delta \theta}$

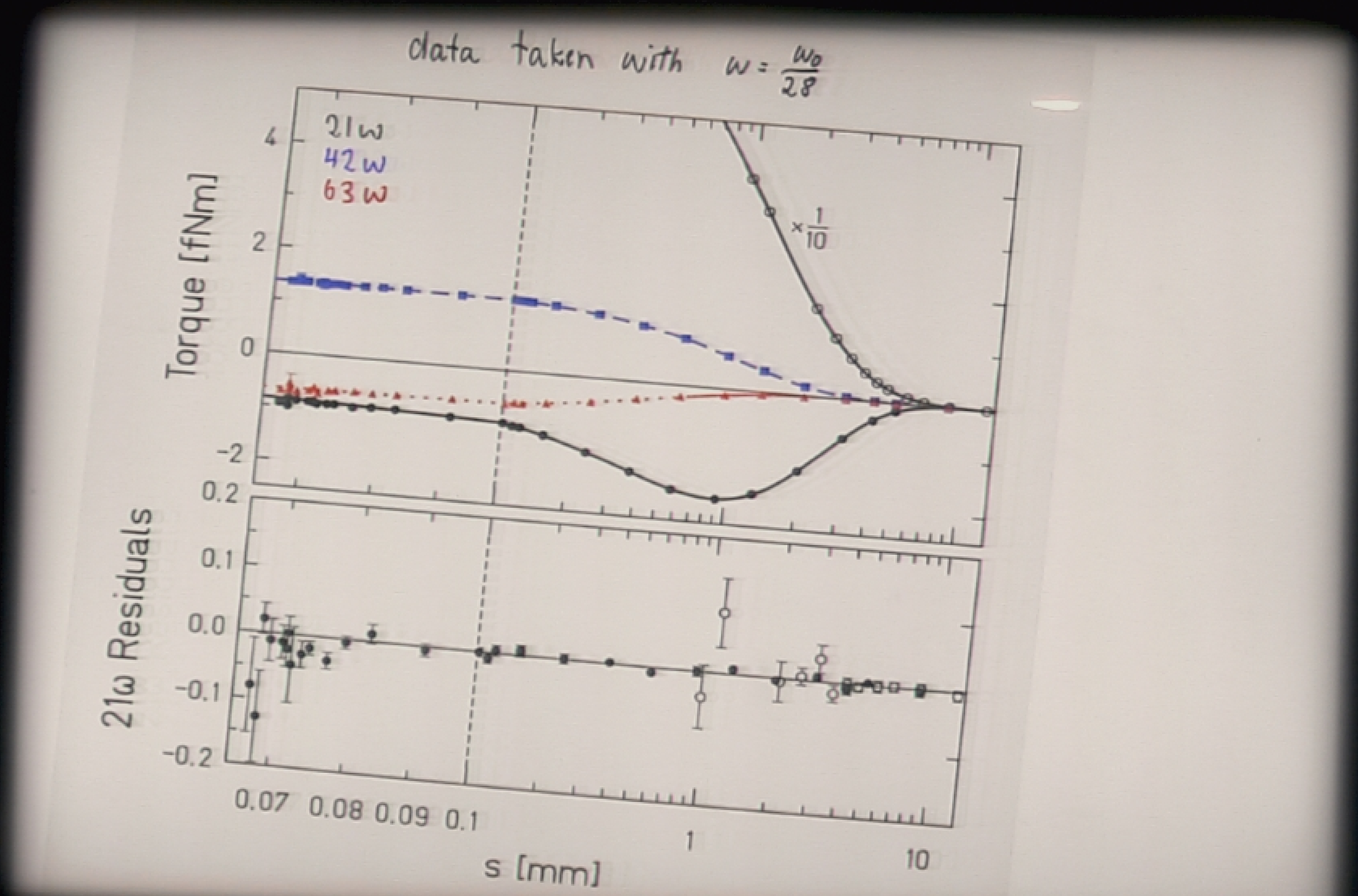


$$E_{s.r} = A \rho_1 \rho_2 \lambda^3 e^{-d/\lambda}$$

$$N_{s.r} = \frac{\Delta A}{\Delta \theta} \rho_1 \rho_2 \lambda^3 e^{-d/\lambda}$$


42ω
63ω
21ω
Torque [fNm]
1
0
-1
-2
0.1
0.0
-0.1
21ω Residuals
α=1,λ=100μm
0.05
0.1
0.2
0.5
1
2
5
s [mm]


95% confidence exclusion plot
EXCLUDED REGION
Stanford
moduli
dilaton
radion
dark energy scale
Colorado
2 extra dimensions scenario
Irvine
Eöt-Wash 2004
Eöt-Wash 2005
|α|
λ [m]


data taken with ω = ω0/28
21ω
42ω
63ω
×1/10
Torque [fNm]
4
2
0
-2
0.2
0.1
0.0
-0.1
-0.2
21ω Residuals
0.07
0.08
0.09
0.1
1
10
s [mm]

- We see an apparent deviation at small distances ($s < 100\mu m$)

- Is this real?

    - check for experimental artifact by shaving $140\mu m$ off lower attractor plate

      greatly reduces Newtonian 21ω torque, but has essentially no effect on short-range interaction

    - if anomaly persists, must distinguish between new 'gravitational' physics & subtle EM effect

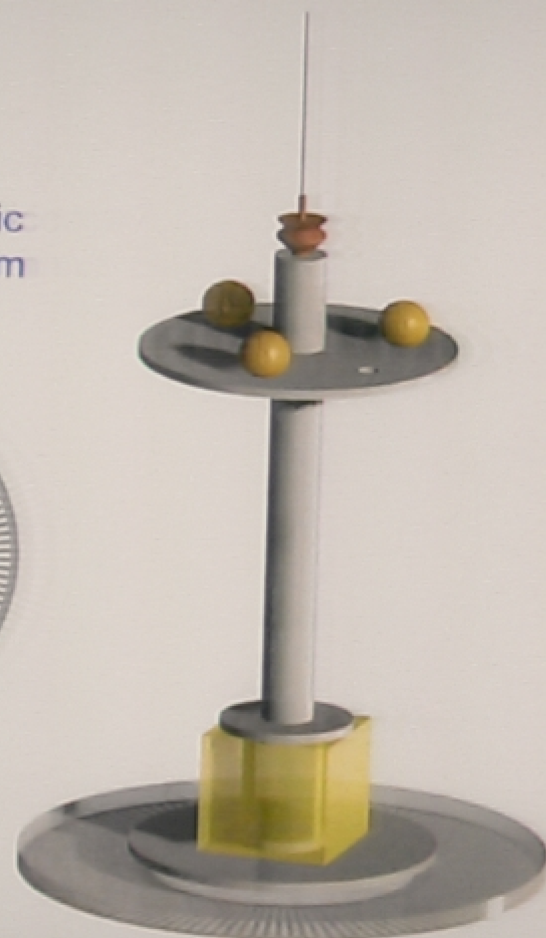
      replace Mo detector ring with Al ring of same dimensions

        gravity force reduced by ρ_{Al}/ρ_{Mo}
        but EM effects virtually unchanged

Wedge Pendulum

120 Fold Symmetric
~~Tungsten~~ Pendulum
(50μm Thick)

Rhenium



(Preliminary Design)

SUMMARY

- to probe the true geometry of the Universe must study gravity
- this is done most directly by testing the $1/r^2$ law
- our tests have shown that $1/r^2$ law holds down to $\lambda \sim 80\mu m$ ($|\alpha| = 1$) at 95% confidence
  - ⇒ largest extra dimension must have size $R_* \leq 63\mu m$ ($\alpha = 8/3$)
  - ⇒ 2 equal extra dimensions require $R_* \leq 53\mu m$ ($\alpha = 16/3$) and a unification scale $M_* \geq 2.4$ TeV
- we do see anomalies at shorter length scales (apparent weakening of gravity or new repulsive force)