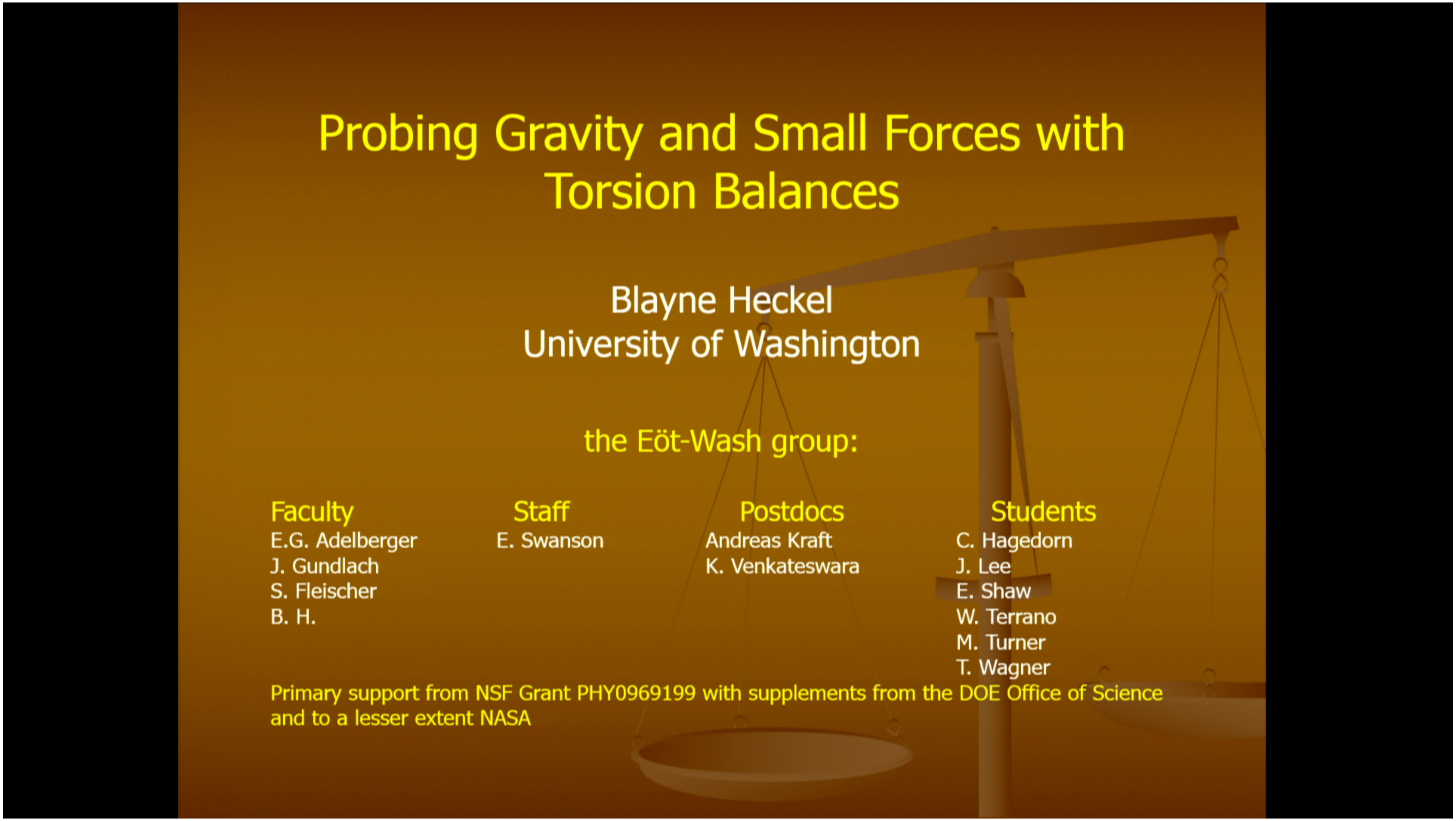
Title: Probing Gravity and Small Forces with Torsion Balances

Date: Jun 17, 2014 01:30 PM

URL: http://pirsa.org/14060018

Abstract: The EotWash group at the University of Washington has developed a set of torsion balance
 instruments to probe the properties of gravity and to search for new weak forces. Current efforts
 focus on improved tests of the principle of equivalence, the inverse square law at short distances,
 and spin-coupled interactions. These experiments and prospects for the future will be discussed.



Probing Gravity and Small Forces with Torsion Balances

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University of Washington

the Eöt-Wash group:

Faculty	Staff	Postdocs	Students
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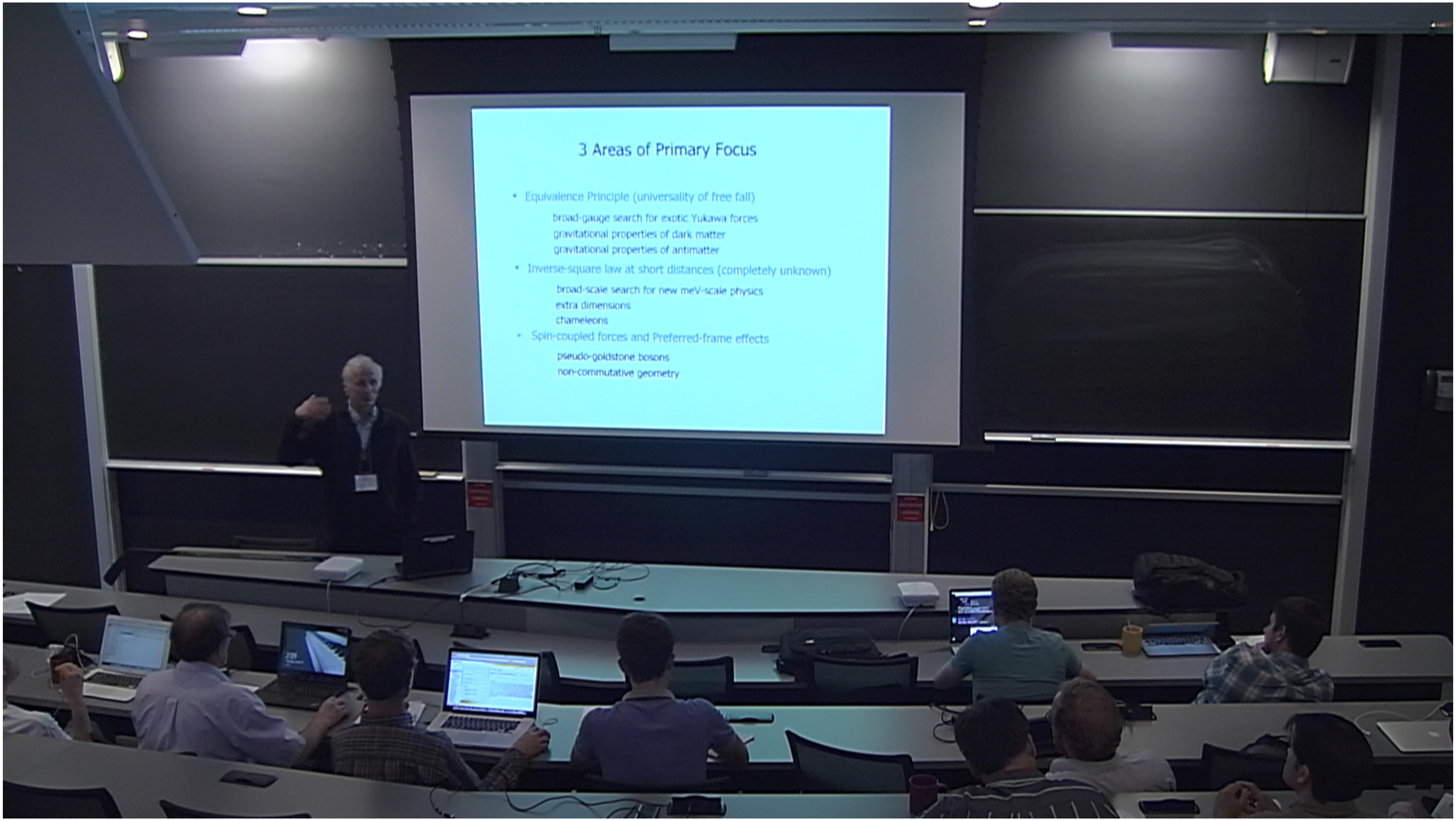
			M. Turner
			T. Wagner

Primary support from NSF Grant PHY0969199 with supplements from the DOE Office of Science and to a lesser extent NASA

3 Areas of Primary Focus

- Equivalence Principle (universality of free fall)
  - broad-gauge search for exotic Yukawa forces
  - gravitational properties of dark matter
  - gravitational properties of antimatter
- Inverse-square law at short distances (completely unknown)
  - broad-scale search for new meV-scale physics
  - extra dimensions
  - chameleons
- Spin-coupled forces and Preferred-frame effects
  - pseudo-goldstone bosons
  - non-commutative geometry



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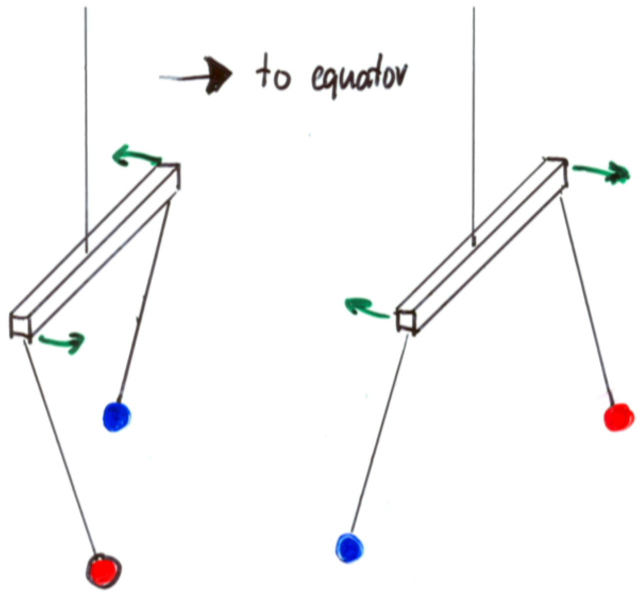
Testing the WEP by watching things fall sideways



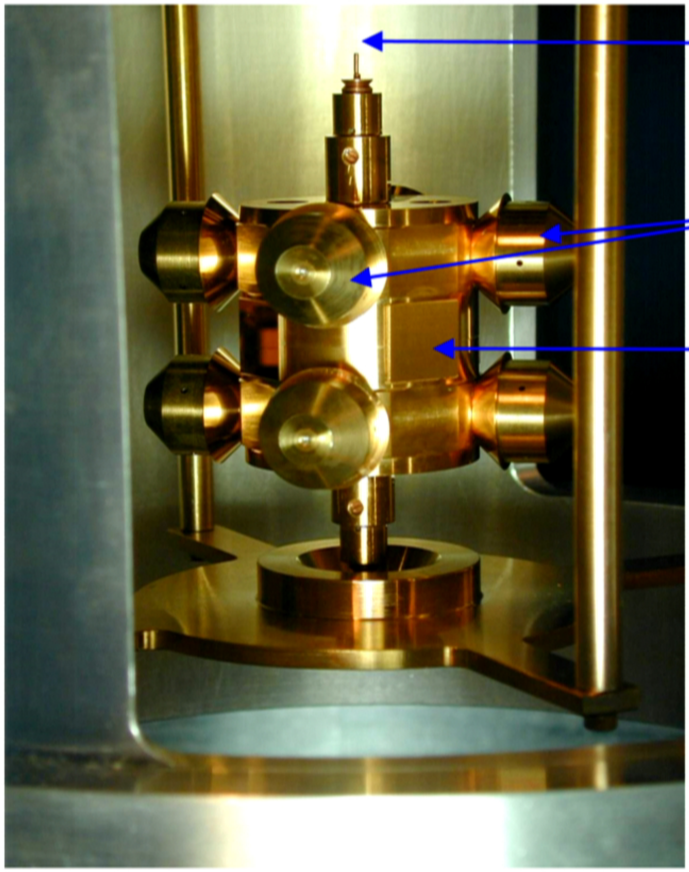
$$\frac{m_i}{m_g} > \frac{m_i}{m_g}$$

Balance only twists if force vectors are not parallel

Down is not a unique direction if the EP is violated or if the gravity field is not uniform

torsion pendulum of our recent EP test

T. A. Wagner et al., Class. Quant. Grav. 29, 184002 (2012)



20 μm diameter tungsten fiber

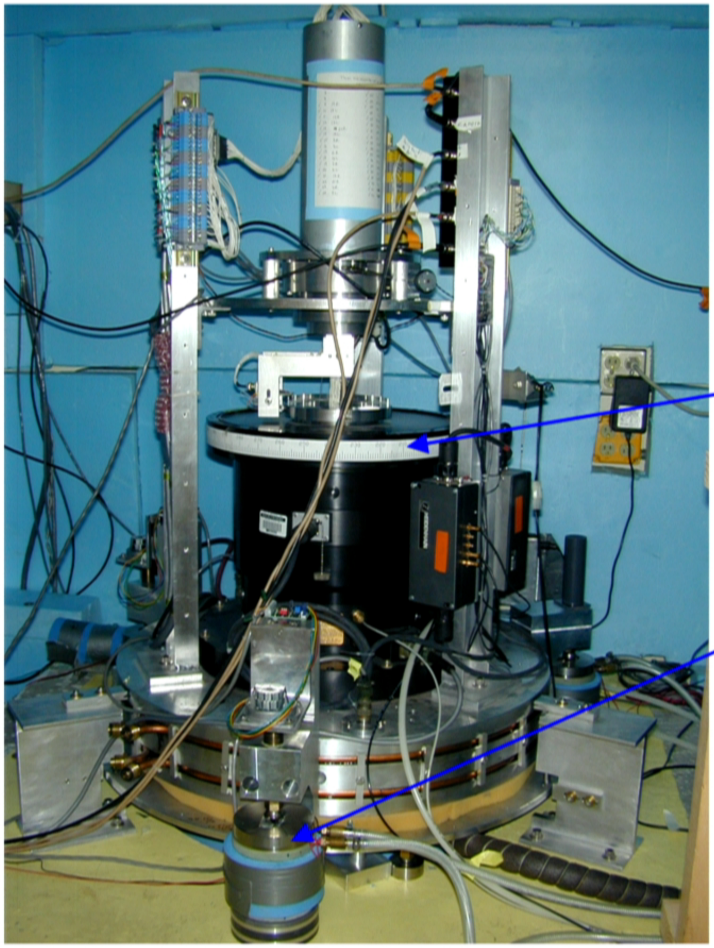
eight 4.84 g test bodies
(4 Be & 4 Ti) or (4 Be & 4 Al)

4 mirrors for measuring
pendulum twist

symmetrical design
suppresses false effects
from gravity gradients, etc.

free osc freq:	1.261 mHz
quality factor:	4000
machining tolerance:	5 μm
total mass :	70 g

Eöt-Wash torsion balance hangs from turntable that rotates at about 0.833 mHz



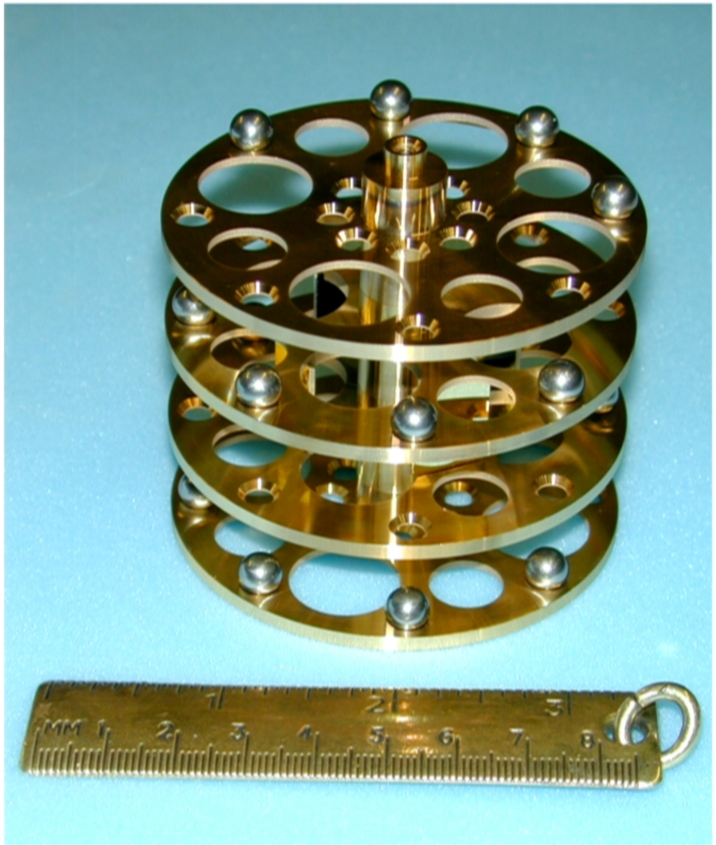
turntable requirements:

1) constant rotation rate
2) rotation axis must be along the suspension fiber

air-bearing turntable

thermal expansion feet feedback to keep turntable rotation axis level

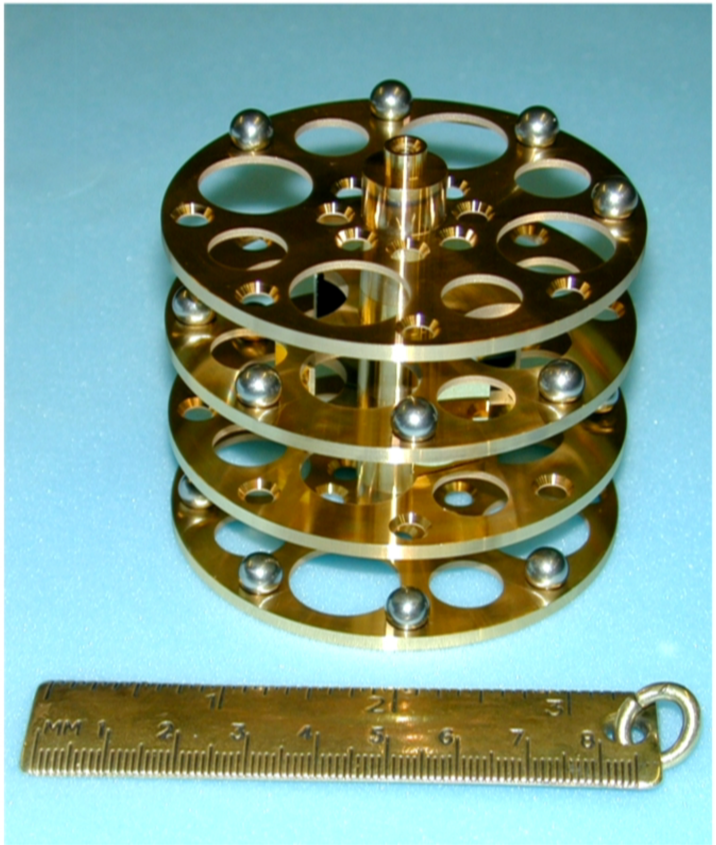
gravity-gradiometer pendulums



q_{41} configuration on a table

q_{21} configuration installed

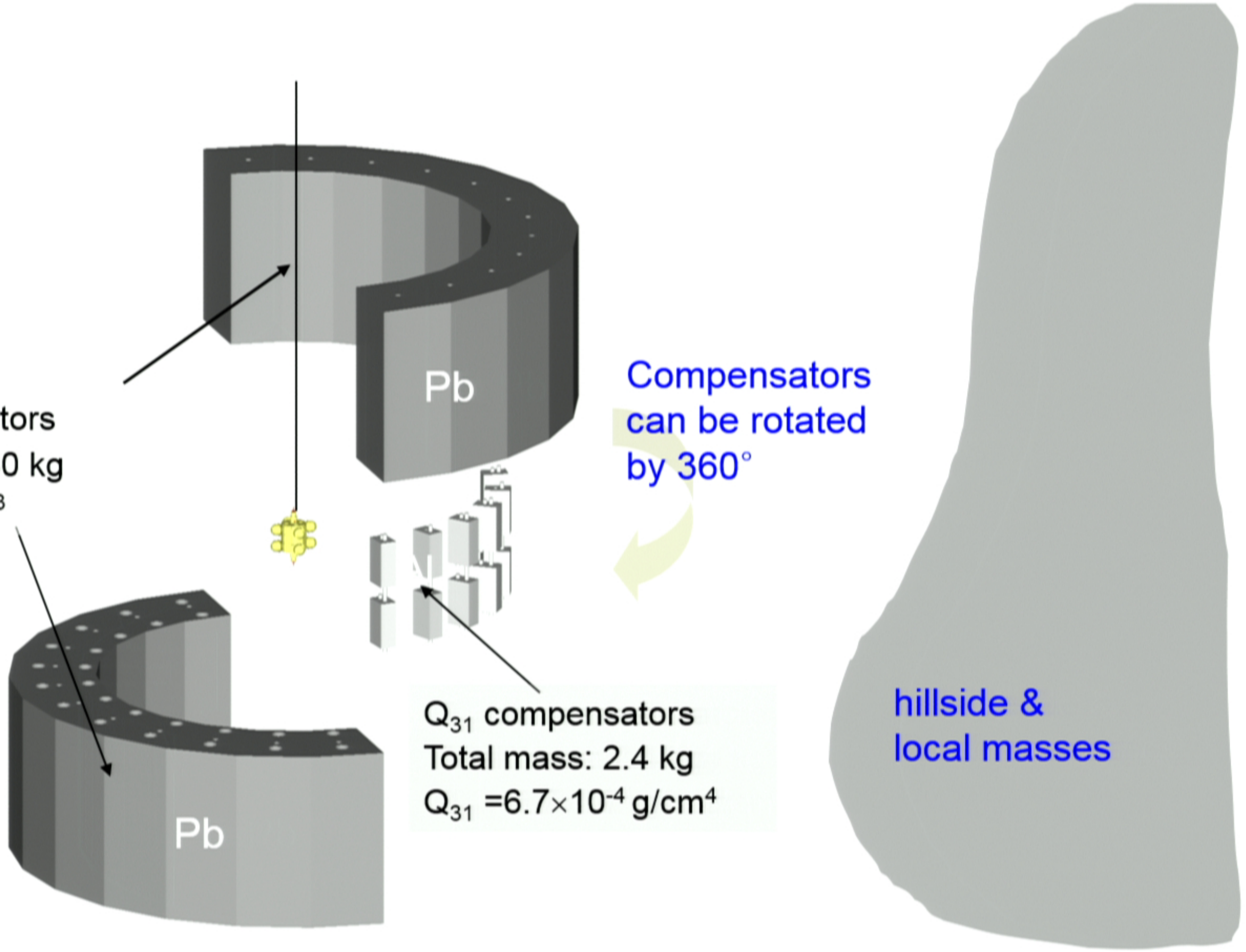
gravity-gradiometer pendulums



q_{41} configuration on a table

q_{21} configuration installed

gravity-gradient compensation



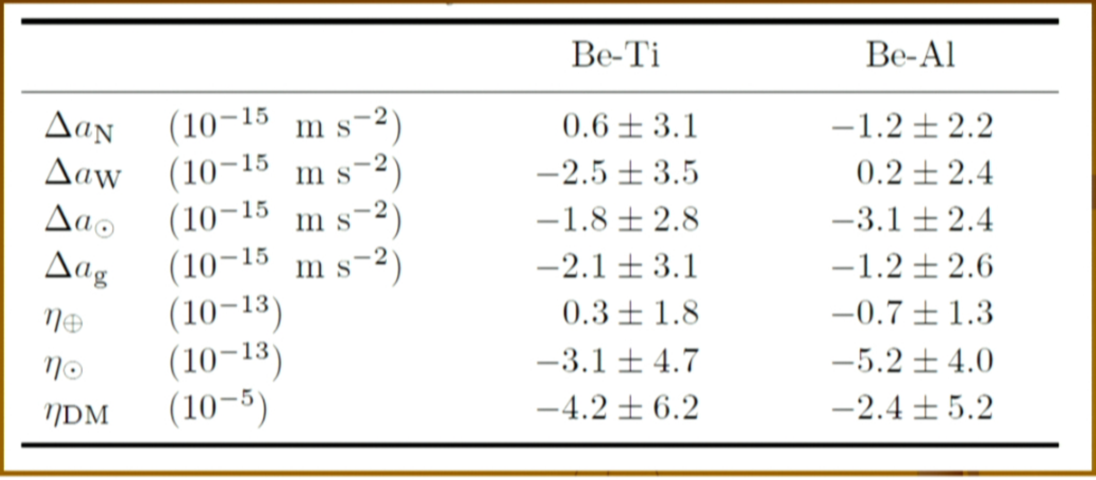
Q_{21} compensators
Total mass: 880 kg
Q_{21}= 1.8 g/cm^3

Compensators
can be rotated
by 360°

Q_{31} compensators
Total mass: 2.4 kg
Q_{31} =6.7×10^{-4} g/cm^4

hillside &
local masses

results with 1σ uncertainties



		Be-Ti	Be-Al
Δa_{N}	$(10^{-15}\ \mathrm{m\ s^{-2}})$	0.6 ± 3.1	-1.2 ± 2.2
Δa_{W}	$(10^{-15}\ \mathrm{m\ s^{-2}})$	-2.5 ± 3.5	0.2 ± 2.4
$\Delta a_{\odot}$	$(10^{-15}\ \mathrm{m\ s^{-2}})$	-1.8 ± 2.8	-3.1 ± 2.4
Δa_{g}	$(10^{-15}\ \mathrm{m\ s^{-2}})$	-2.1 ± 3.1	-1.2 ± 2.6
$\eta_{\oplus}$	(10^{-13})	0.3 ± 1.8	-0.7 ± 1.3
$\eta_{\odot}$	(10^{-13})	-3.1 ± 4.7	-5.2 ± 4.0
η_{DM}	(10^{-5})	-4.2 ± 6.2	-2.4 ± 5.2

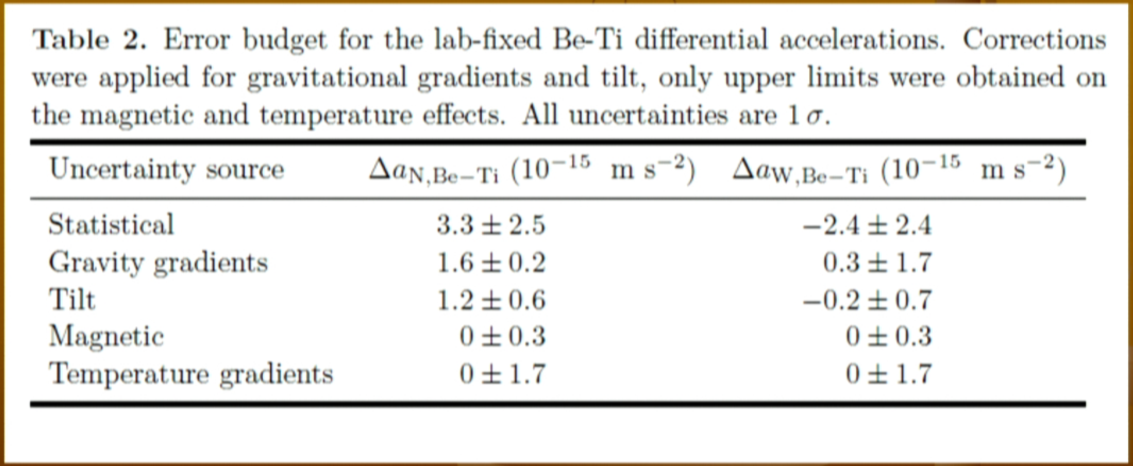
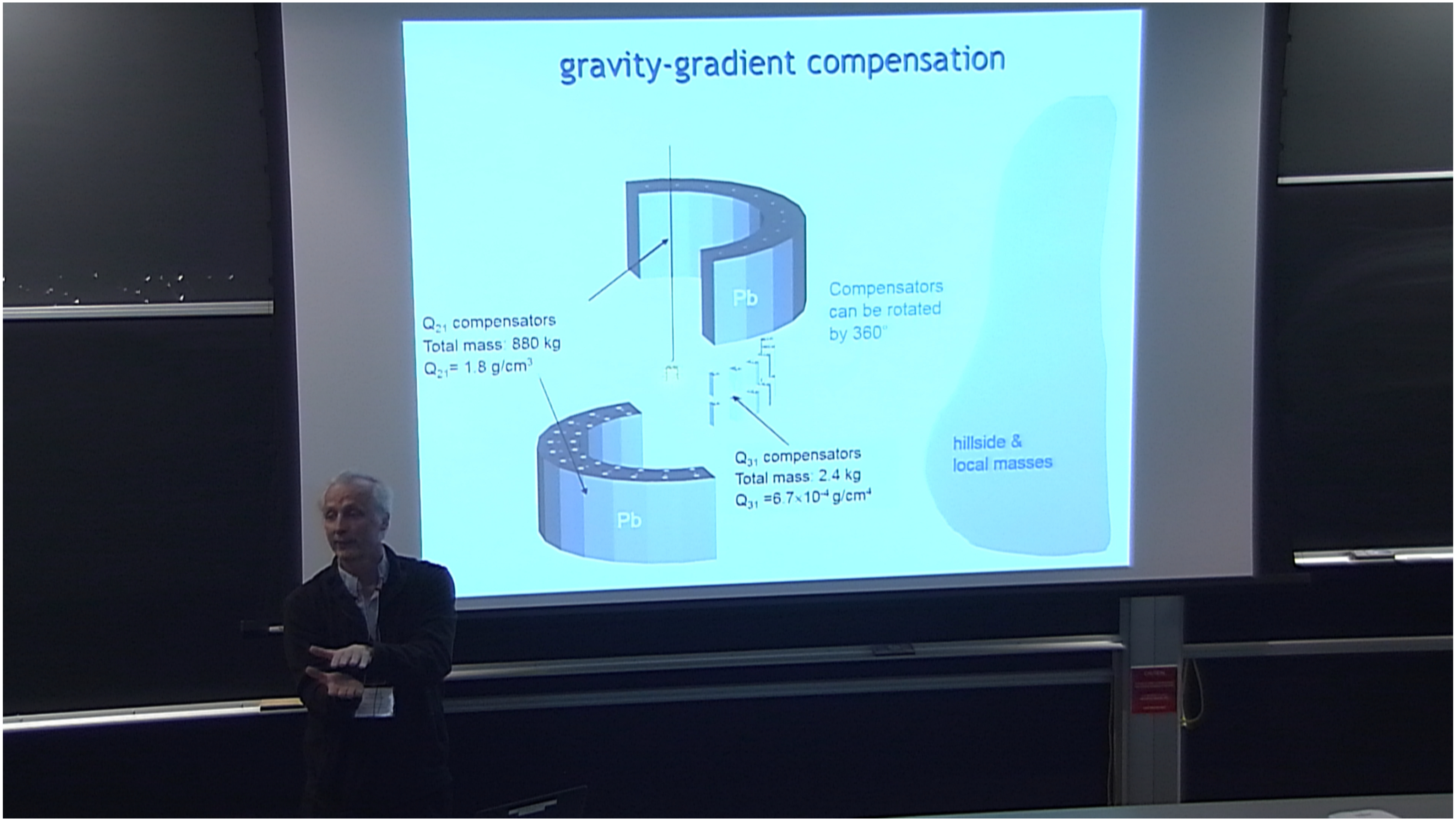


Table 2. Error budget for the lab-fixed Be-Ti differential accelerations. Corrections were applied for gravitational gradients and tilt, only upper limits were obtained on the magnetic and temperature effects. All uncertainties are $1\,\sigma$.

Uncertainty source	$\Delta a_{\mathrm{N,Be-Ti}}$ $(10^{-15}\ \mathrm{m\ s^{-2}})$	$\Delta a_{\mathrm{W,Be-Ti}}$ $(10^{-15}\ \mathrm{m\ s^{-2}})$
Statistical	3.3 ± 2.5	-2.4 ± 2.4
Gravity gradients	1.6 ± 0.2	0.3 ± 1.7
Tilt	1.2 ± 0.6	-0.2 ± 0.7
Magnetic	0 ± 0.3	0 ± 0.3
Temperature gradients	0 ± 1.7	0 ± 1.7

PhD project of Todd Wagner



gravity-gradient compensation

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Total mass: 880 kg
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hillside &
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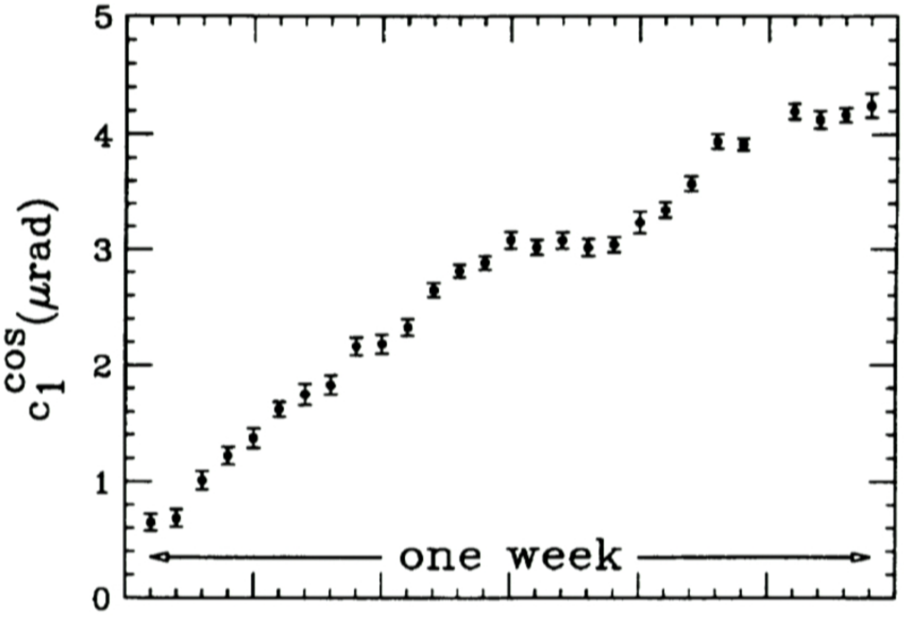
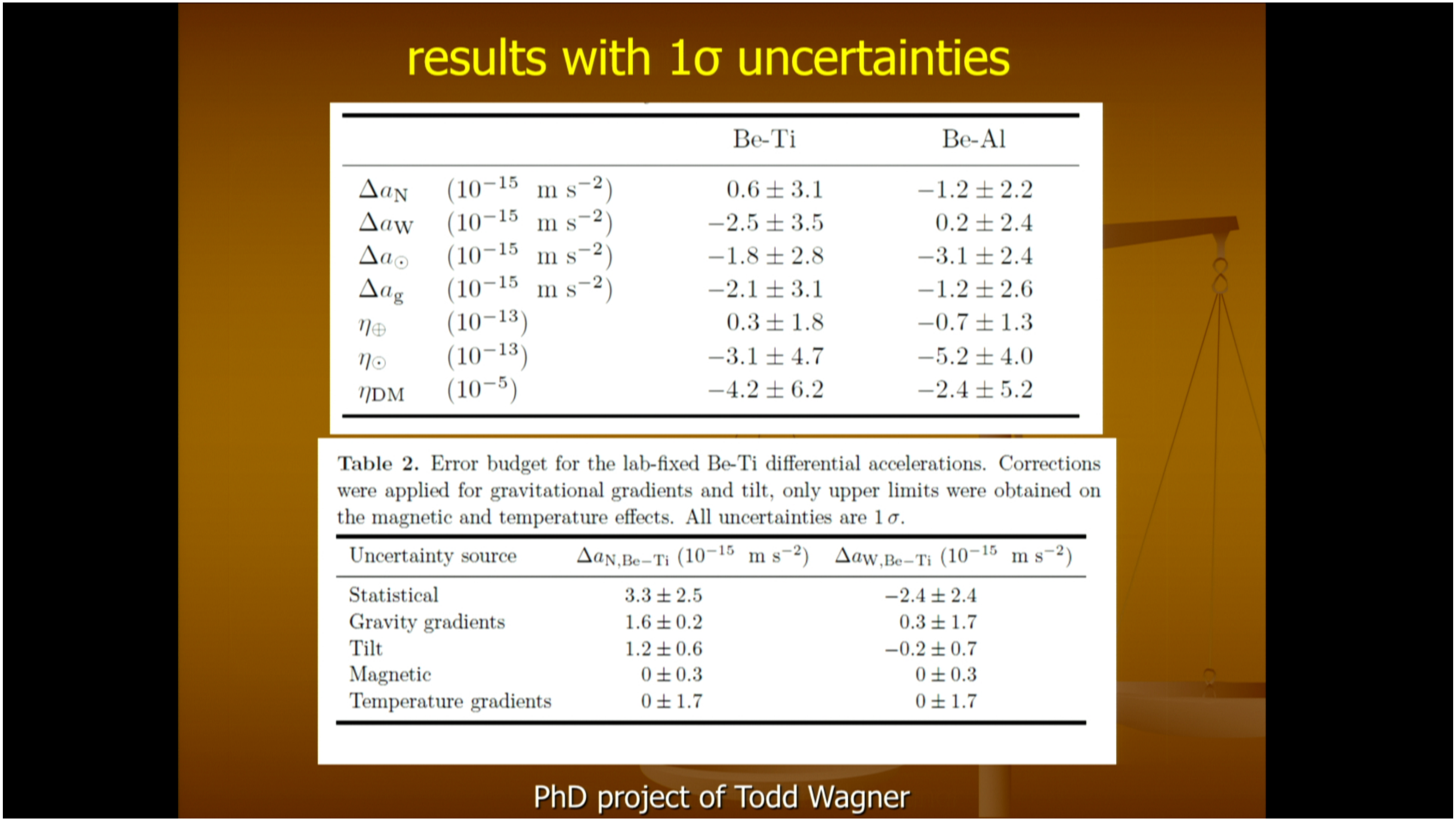
limitations on gradient cancellation



these data were taken in early November



results with 1σ uncertainties

		Be-Ti	Be-Al
$\Delta a_{\rm N}$	$(10^{-15}\ \rm m\ s^{-2})$	0.6 ± 3.1	-1.2 ± 2.2
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$\Delta a_{\odot}$	$(10^{-15}\ \rm m\ s^{-2})$	-1.8 ± 2.8	-3.1 ± 2.4
$\Delta a_{\rm g}$	$(10^{-15}\ \rm m\ s^{-2})$	-2.1 ± 3.1	-1.2 ± 2.6
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$\eta_{\rm DM}$	(10^{-5})	-4.2 ± 6.2	-2.4 ± 5.2

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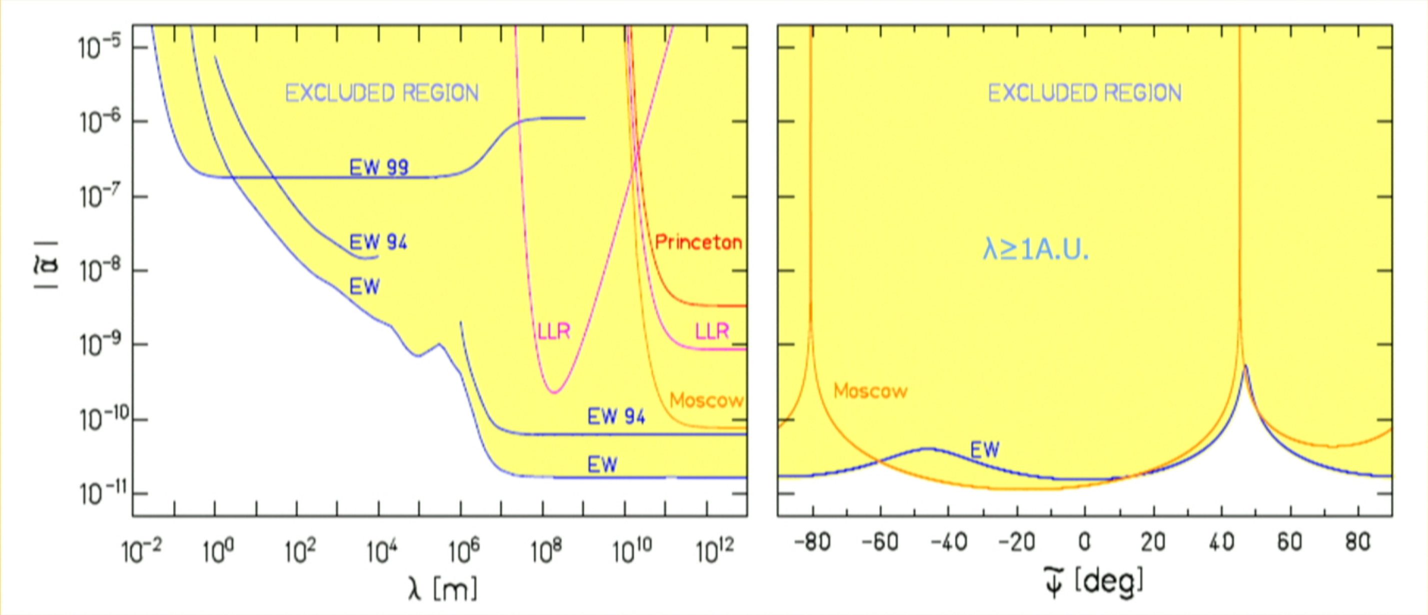
PhD project of Todd Wagner

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



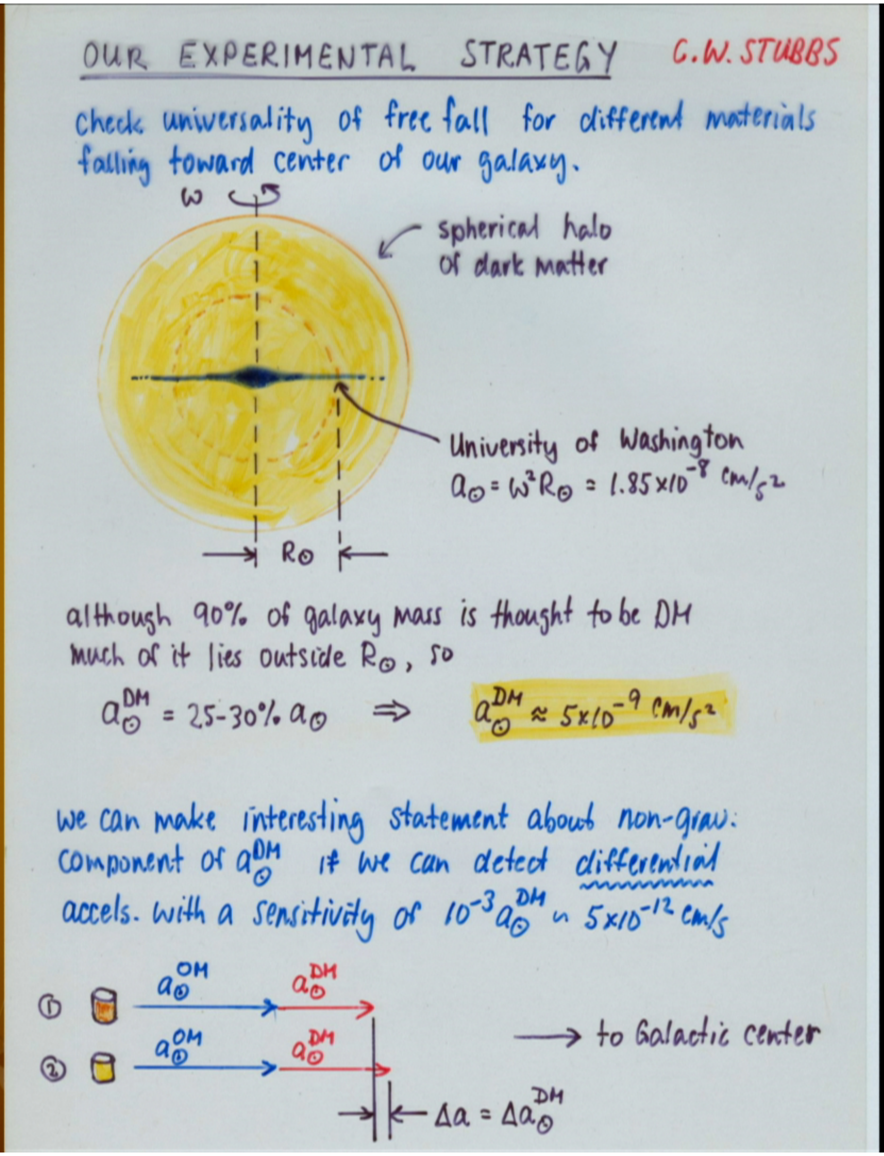
Yukawa attractor integral based on:

0.5m<λ<5m	lab building and its major contents
1m< λ<50km	topography
5km< λ<1000km	USGS subsurface density model
1000km< λ<10000km	PREM earth model

T. A. Wagner et al., Class. Quant. Grav. 29, 184002 (2012)

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

Could there be a long-range scalar interaction that couples dark-matter & standard-model particles?



OUR EXPERIMENTAL STRATEGY

C.W. STUBBS

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

ω

spherical halo of dark matter

University of Washington

$a_\odot = \omega^2 R_\odot = 1.85 \times 10^{-8}$ cm/s²

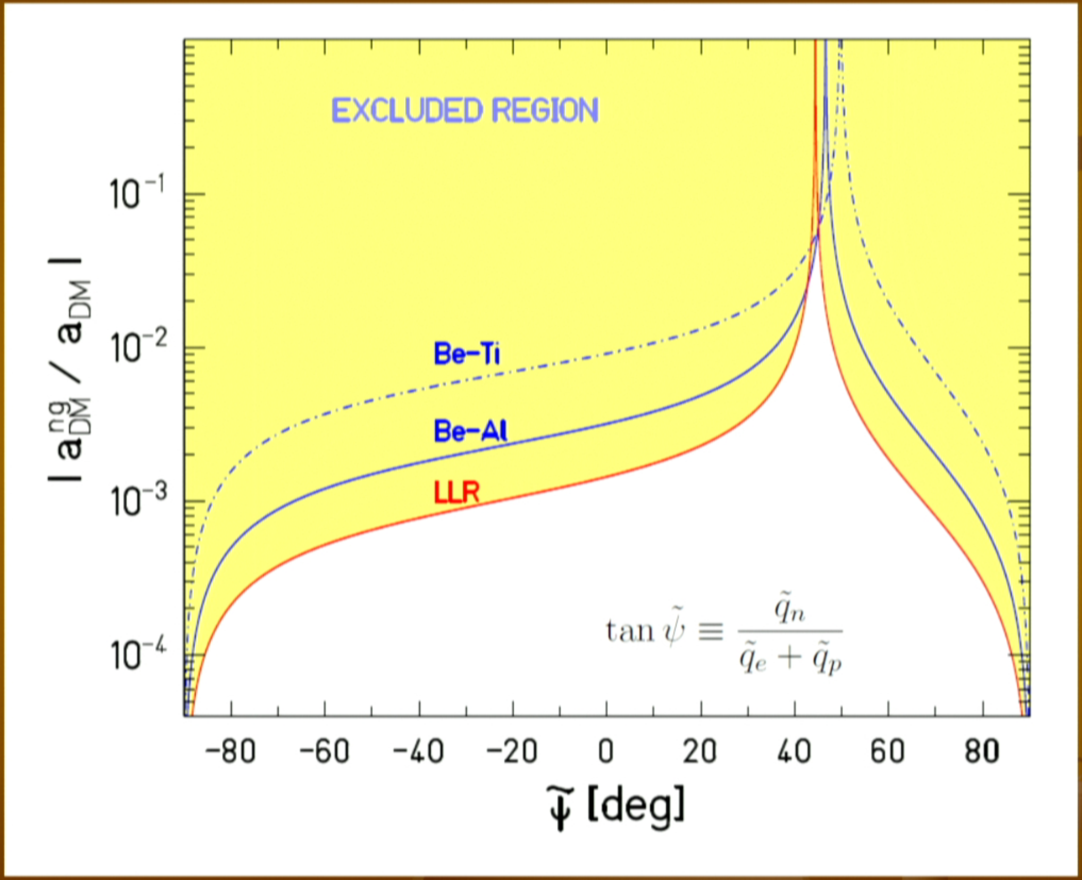
$R_\odot$

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

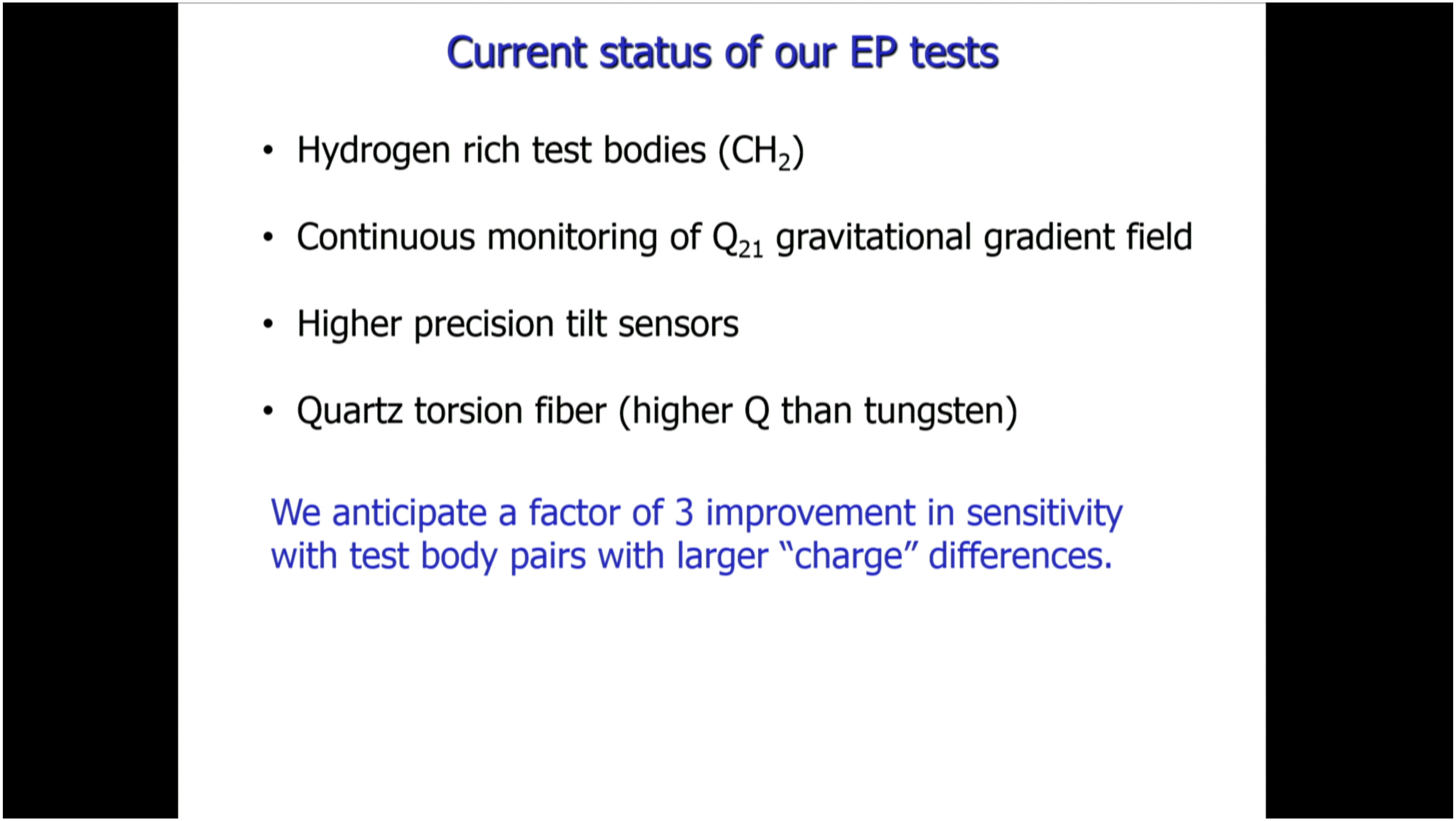
$$a_\odot^{DM} = 25\text{-}30\%\, a_\odot \Rightarrow a_\odot^{DM} \approx 5\times10^{-9}\ \text{cm/s}^2$$

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

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



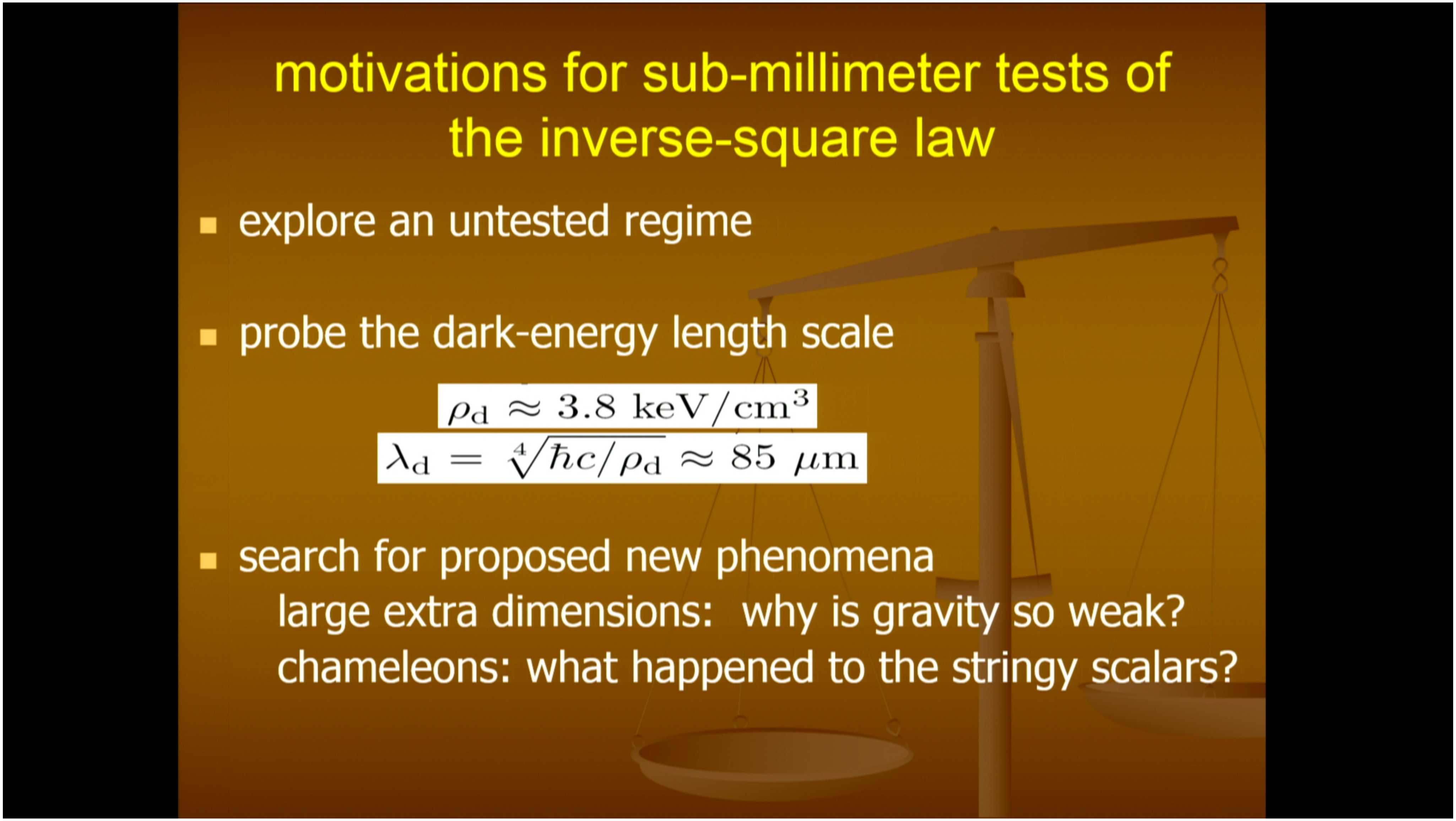
at most 6% of the acceleration can be non-gravitational



Current status of our EP tests

- Hydrogen rich test bodies (CH_2)
- Continuous monitoring of Q_{21} gravitational gradient field
- Higher precision tilt sensors
- Quartz torsion fiber (higher Q than tungsten)

We anticipate a factor of 3 improvement in sensitivity with test body pairs with larger “charge” differences.



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

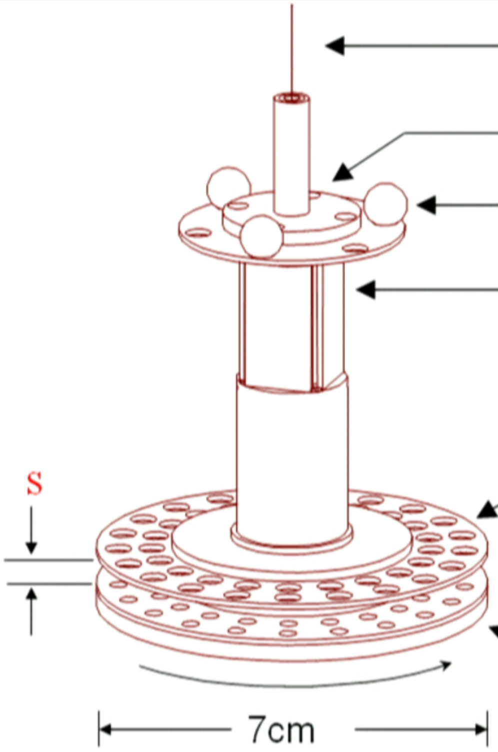
- explore an untested regime
- probe the dark-energy length scale

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

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

- search for proposed new phenomena
  large extra dimensions: why is gravity so weak?
  chameleons: what happened to the stringy scalars?

the 42-hole ISL pendulum



tungsten fiber, 20μm diameter, 80cm length

leveling mechanism

3 aluminum calibration spheres

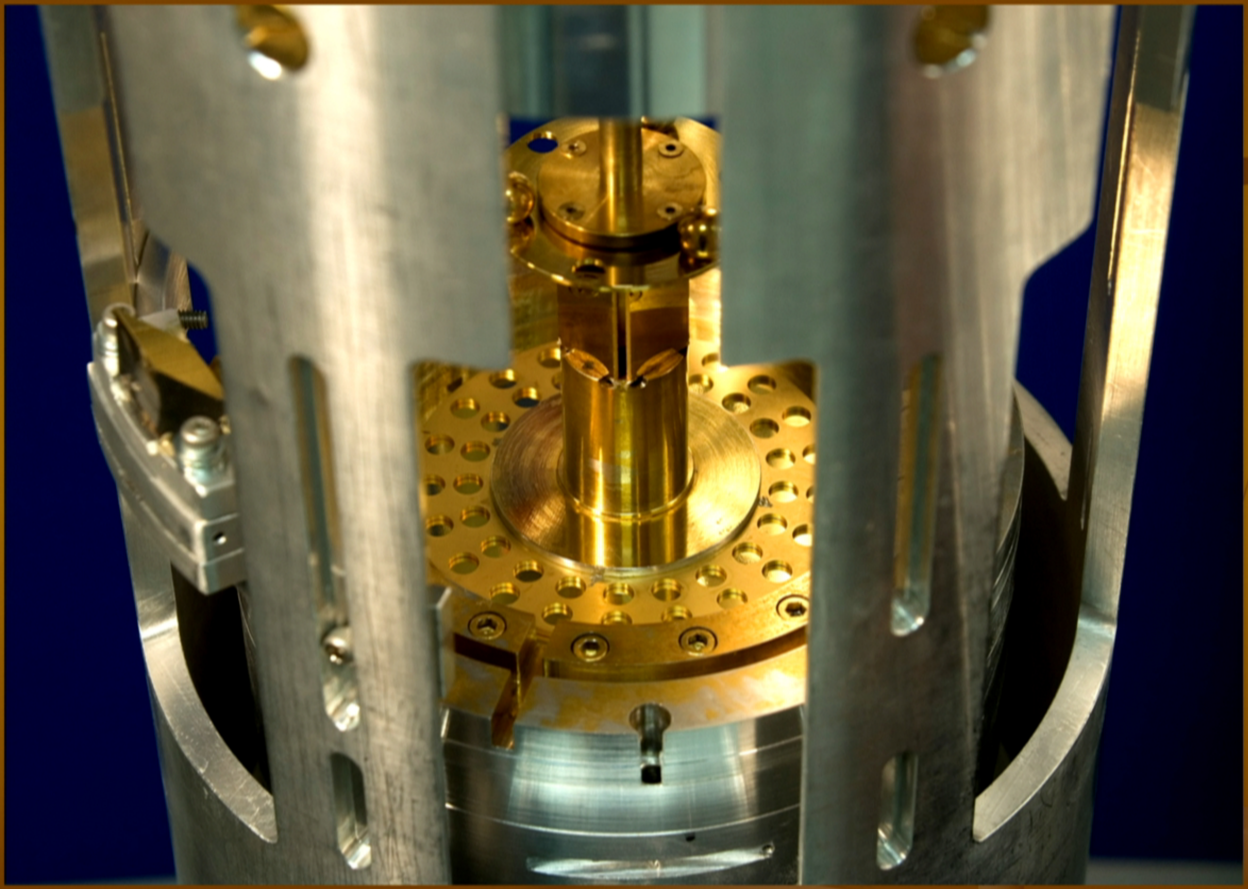
4 mirrors for tracking angle of deflection

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

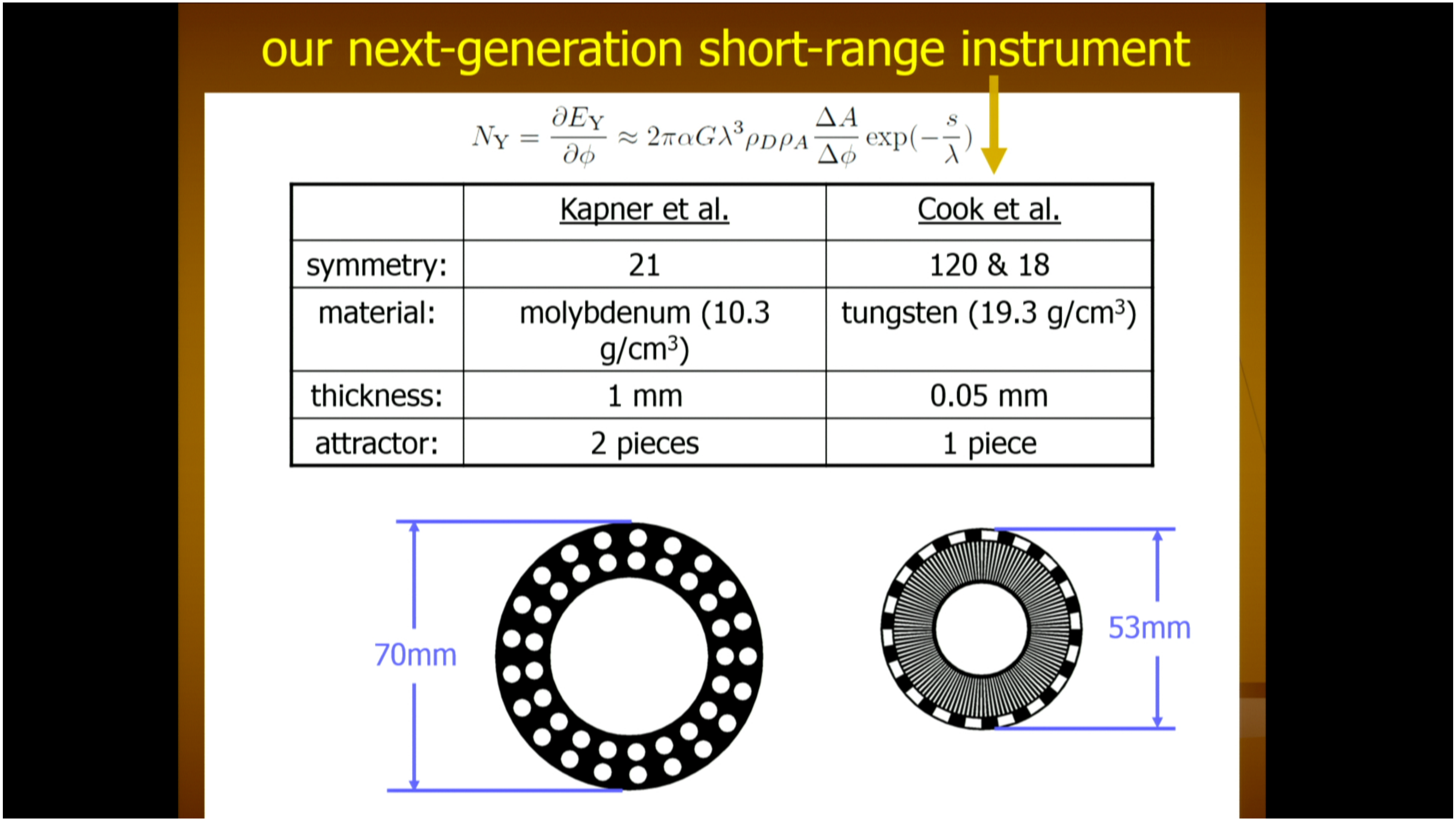
not pictured, 10μm thick Au-coated BeCu membrane, electrostatic shield

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**

D.J. Kapner et al., PRL 98, 021101(2007)



Mary Levin photo

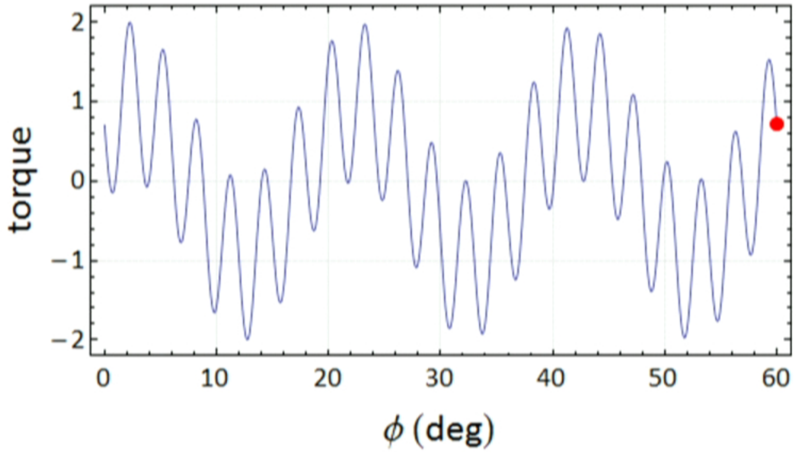


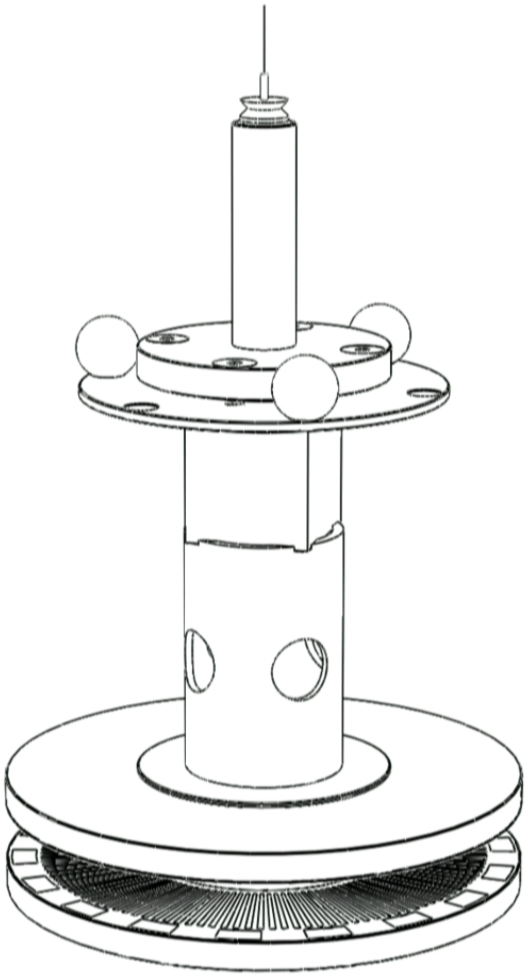
our next-generation short-range instrument

$$N_{\mathrm{Y}} = \frac{\partial E_{\mathrm{Y}}}{\partial \phi} \approx 2\pi\alpha G\lambda^3 \rho_D \rho_A \frac{\Delta A}{\Delta \phi} \exp(-\frac{s}{\lambda})$$

	Kapner et al.	Cook et al.
symmetry:	21	120 & 18
material:	molybdenum (10.3 g/cm^3)	tungsten (19.3 g/cm^3)
thickness:	1 mm	0.05 mm
attractor:	2 pieces	1 piece

Cook et al.'s Experiment

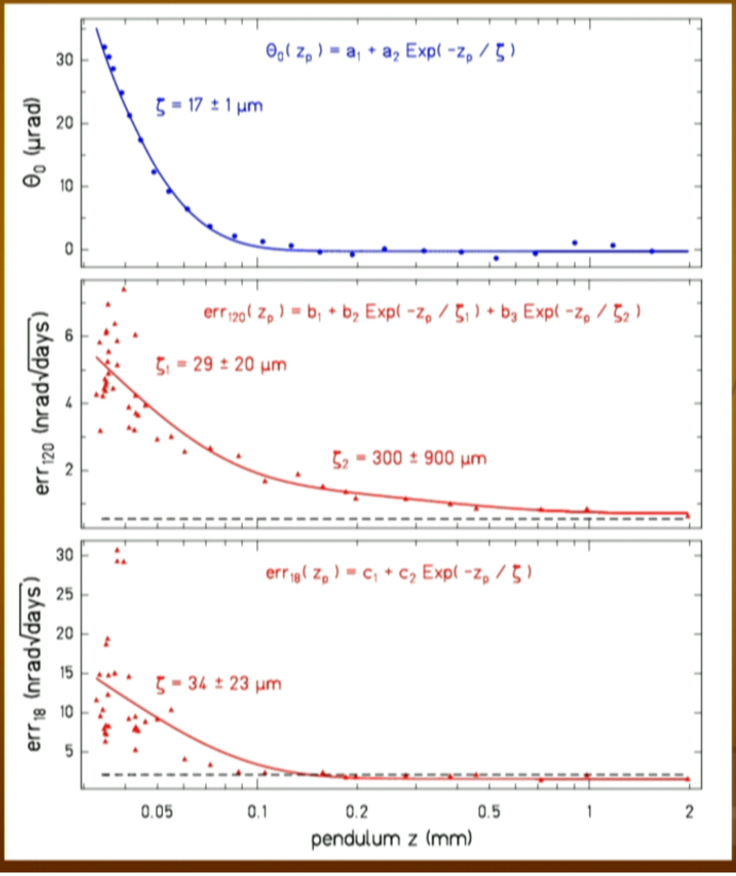




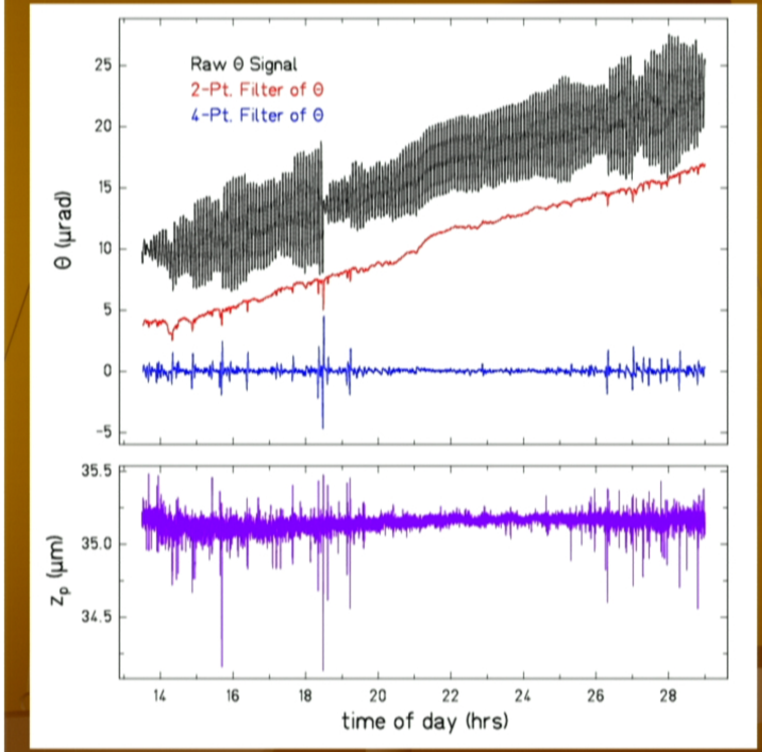
simulation is speeded up by
factor of ≈1000

patch fields

patch field potential minimum
not aligned with fiber minimum

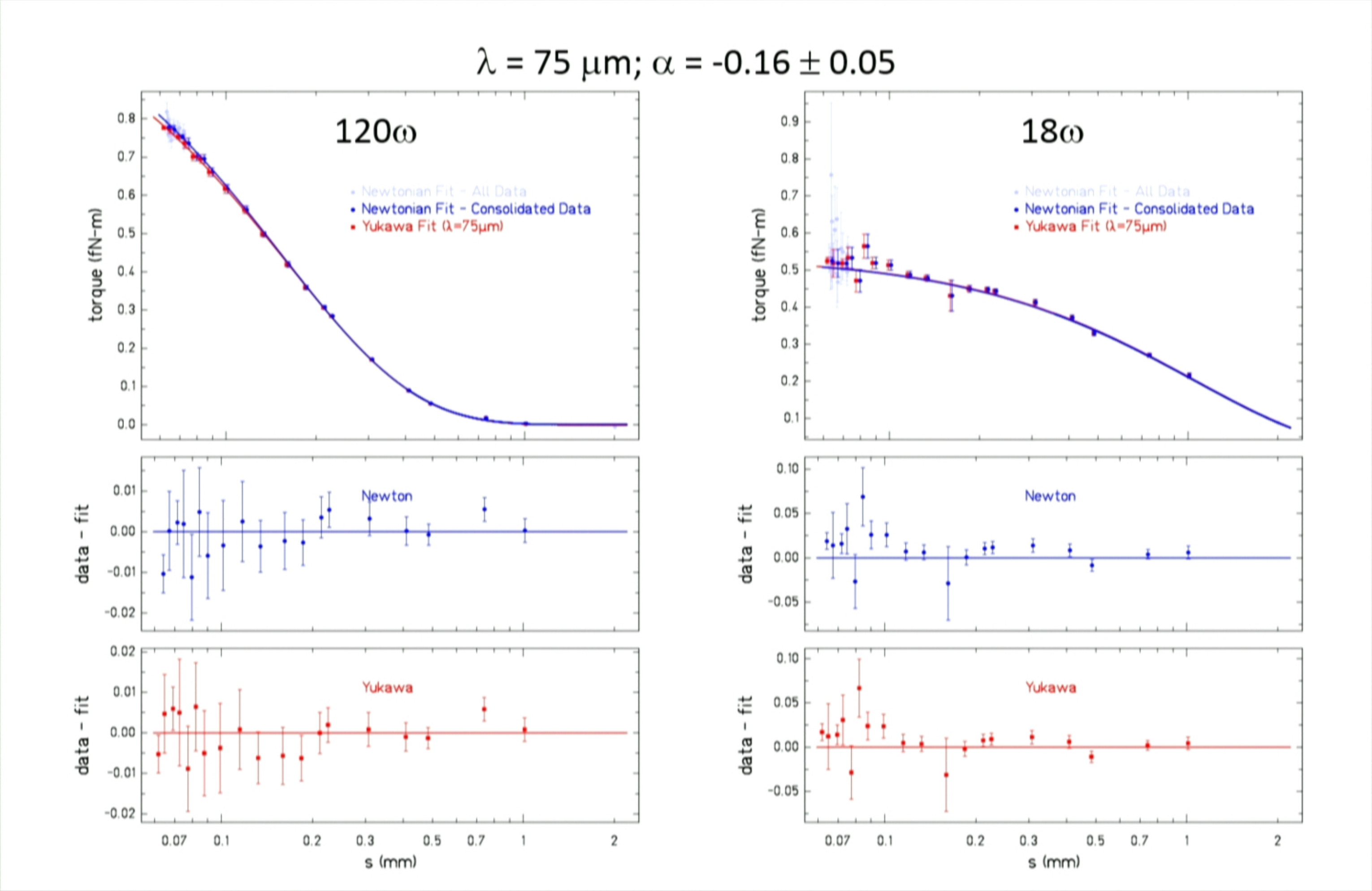


vibrations



(attractor not turning)

Data Fit

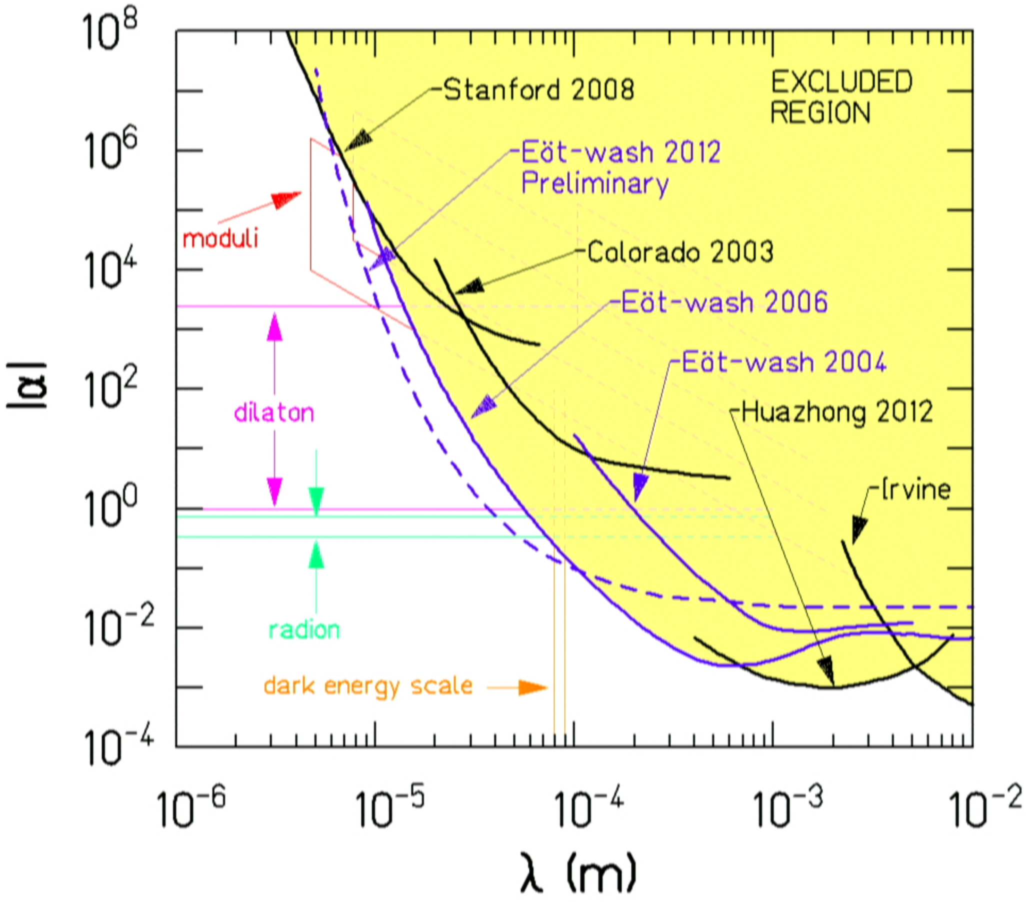


λ = 75 μm; α = -0.16 ± 0.05

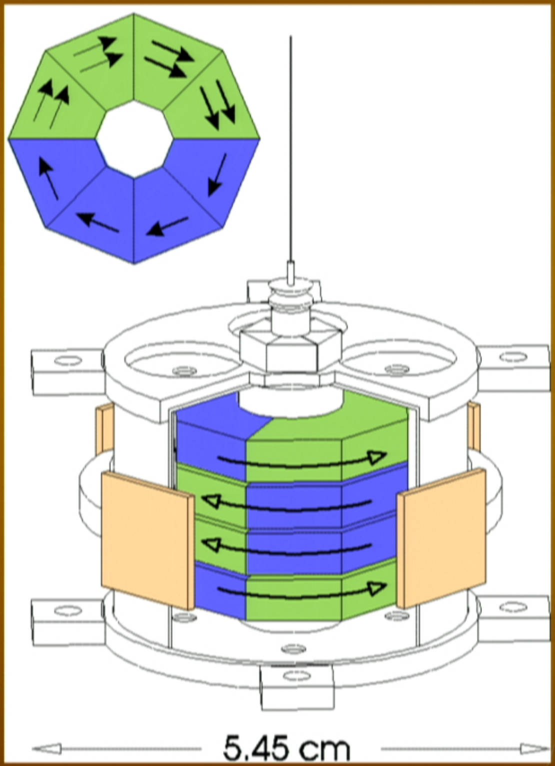
Cook's preliminary 95% C.L. results

order of magnitude higher sensitivity below 40 μm:

We hope to do significantly better in the an improved iteration of Cook's device



the Eöt-Wash spin pendulum



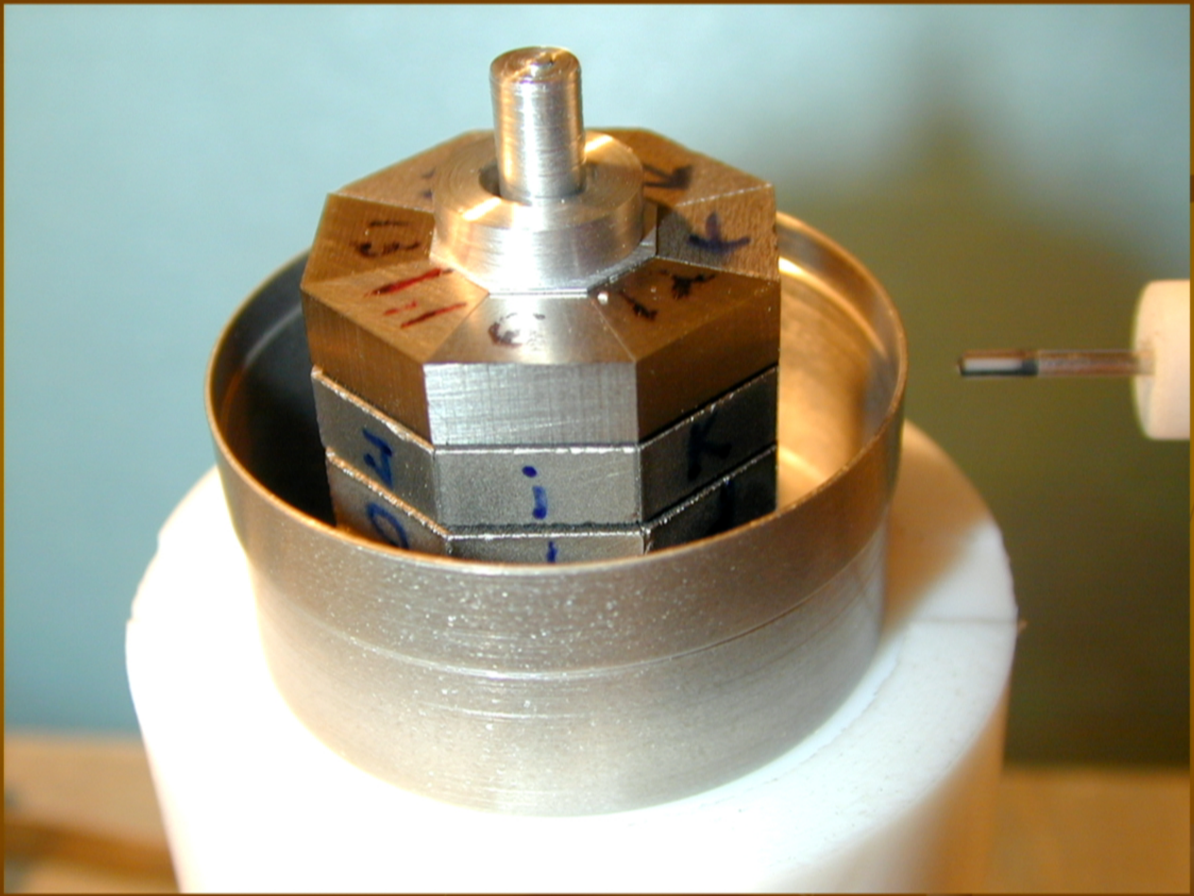
- 9.8 x 10^{22} polarized electrons
- negligible mass asymmetry
- negligible composition asymmetry
- flux of B confined within magnets
- negligible external B field

- Alnico: all B comes from electron spin: spins point opposite to B

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

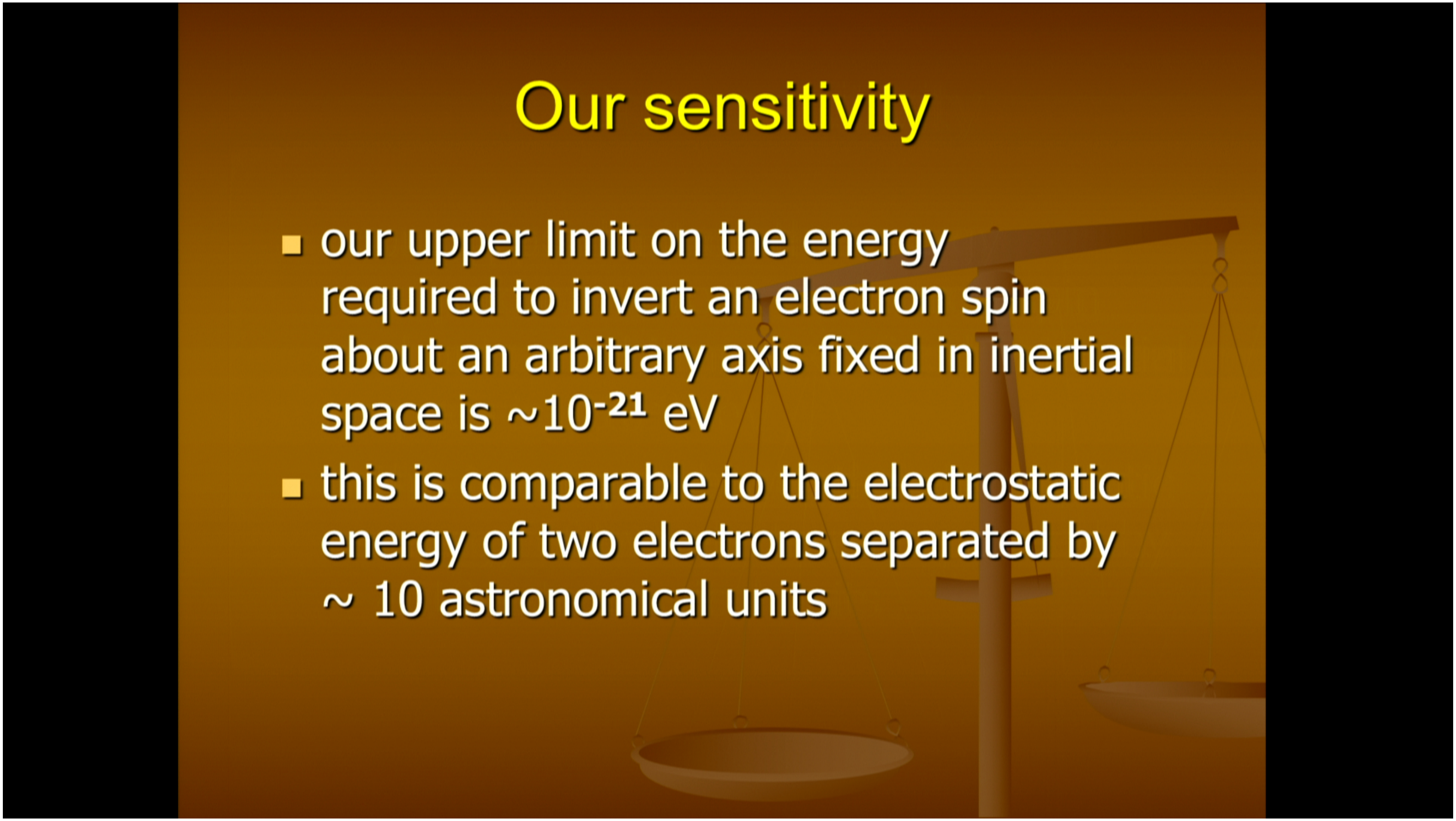
- therefore the spins of Alnico and Co cancel and pendulum's net spin comes from the Sm and J = 📫 S

measuring the spin pendulum's stray B field



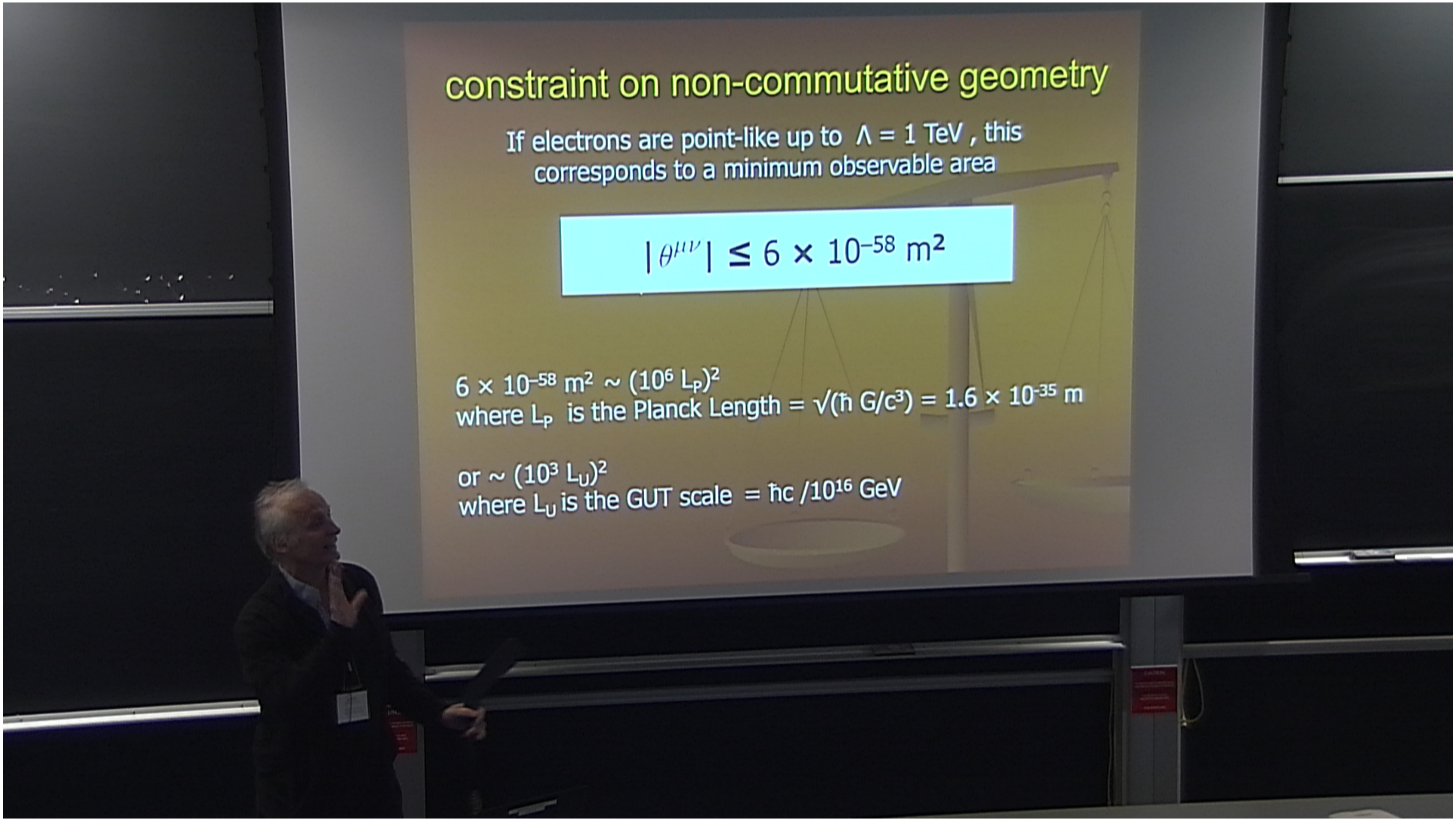
B inside = 9.6±0.2 kG

B outside ≈ few mG



Our sensitivity

- our upper limit on the energy required to invert an electron spin about an arbitrary axis fixed in inertial space is ~10^{-21} eV
- this is comparable to the electrostatic energy of two electrons separated by ~ 10 astronomical units



constraint on non-commutative geometry

If electrons are point-like up to $\Lambda = 1$ TeV , this corresponds to a minimum observable area

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

$6 \times 10^{-58}\ \mathrm{m}^2 \sim (10^6 L_P)^2$
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 GUT scale = $\hbar c / 10^{16}$ GeV

Recent limits on short range spin-spin coupling

$$V_{ee}(\vec{r}) = g_P^2 \frac{\hbar^2}{16\pi m_e^2 c^2} (\vec{\sigma}_1 \cdot \vec{\nabla}_1)(\vec{\sigma}_2 \cdot \vec{\nabla}_2) \frac{e^{-r/\lambda}}{r}$$