I’ve had the pleasure of working with Wick since 1980
and we’ve been friends and scientific colleagues ever since.

We’ve written 6 papers together on

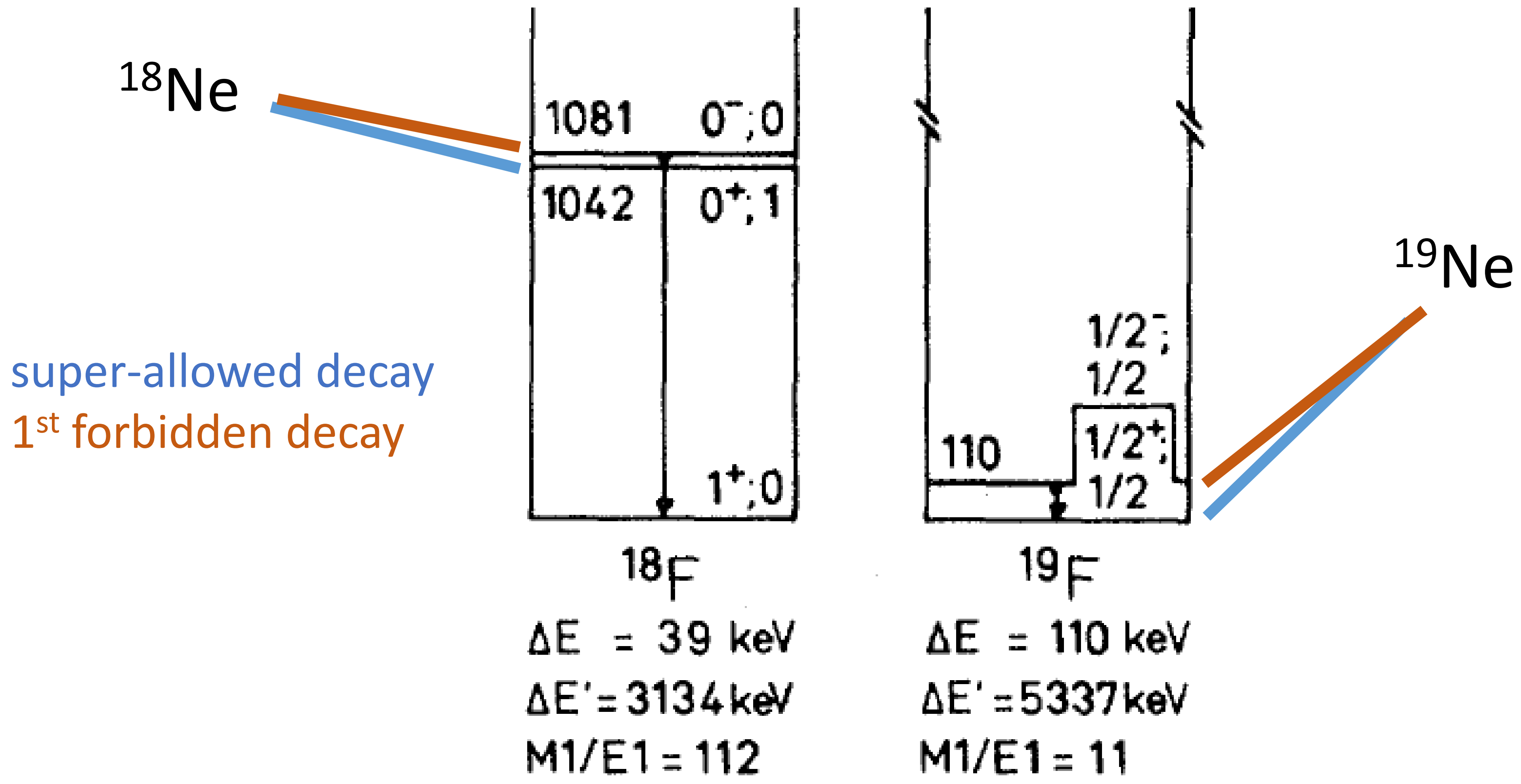
- the parity non-conserving NN interaction
- nuclear physics of solar neutrino detectors
- solar fusion cross sections

We’ve had some great bike rides together at workshops

- Icefields Highway at Lake Louise
- Steamboat Springs
- 90 mile loop in Yellowstone

I really appreciate your no-nonsense approach to physics
and am in awe of your pedaling power

parity-nonconserving NN interaction



Beta Decays of ^{18}Ne and ^{19}Ne and their Relation to Parity-Mixing in ^{18}F and ^{19}F
EGA, …. and WCH, Phys. Rev. C27 2833 (1983)

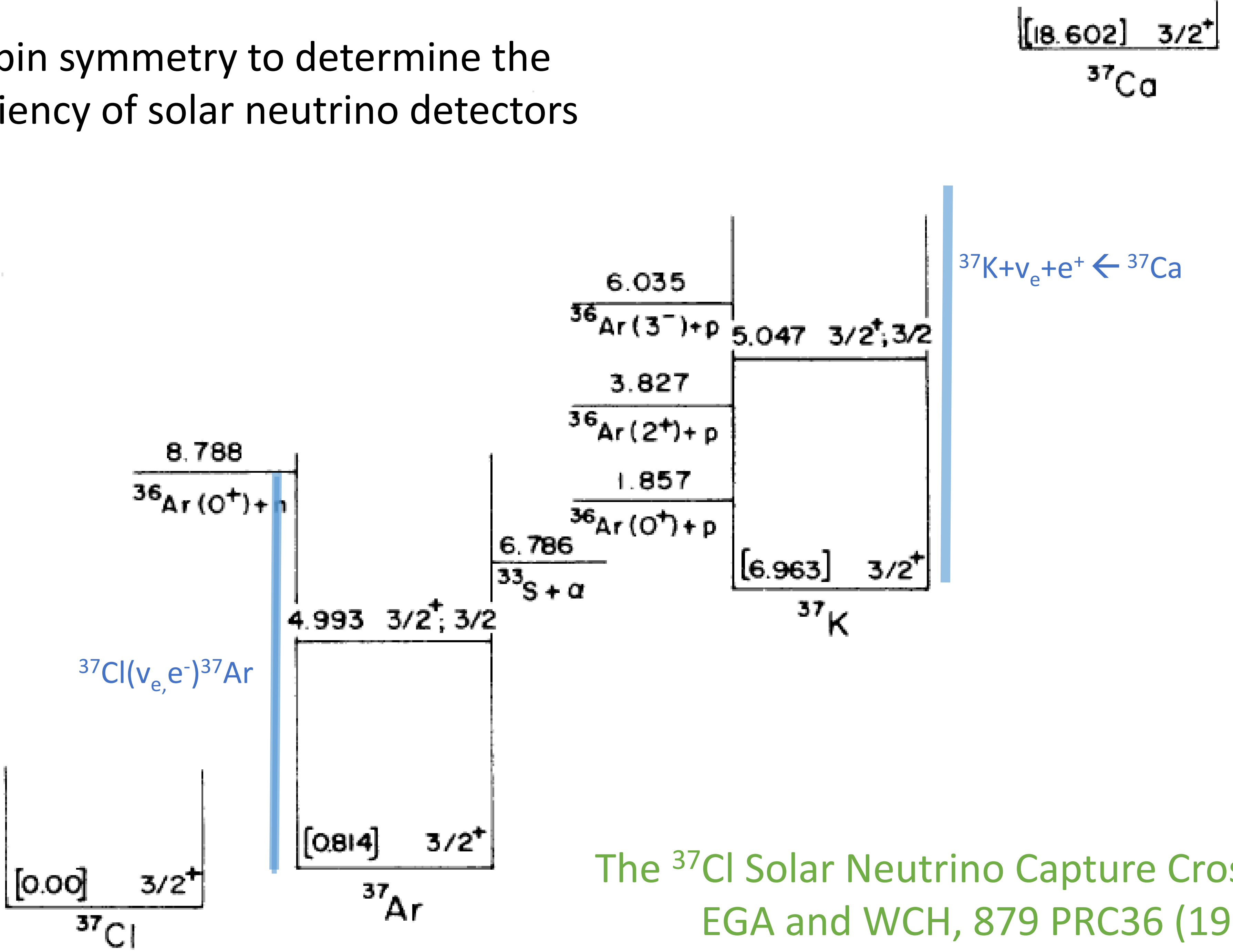
"The Parity Nonconserving Nucleon-Nucleon Interaction," E.G. Adelberger and W.C. Haxton, Ann. Rev. of Nuclear and Particle Science **35**, 501 (1985).

I always thought that I was a picky writer who cared a lot about style, but when it came to writing this paper together I met my match

"which" vs. "that"
"since" vs. "because"

EGA ``that sounds better than which in this sentence"
WCH ``actually it should be the other way around"
EGA ``no, I really prefer that"
WCH "but Laura is an English teacher and she says it should be which"
EGA "OK – you win"

exploiting isospin symmetry to determine the detection efficiency of solar neutrino detectors



The ^{37}Cl Solar Neutrino Capture Cross Section
EGA and WCH, 879 PRC36 (1987)

In 1986 Wick told me about Ephriam Fischbach's "fifth force" and invited Ephraim to spend some time in Seattle. This got me and a wonderful colleague in atomic and neutron physics (Blayne Heckel), interested in "gravitational physics". A good background in nuclear physics, and none in gravitational physics were big advantages.

my own prejudice:

symmetrical apparatus is extremely important

theoretical tools from nuclear physics:

spherical multipole expansion

Fourier-Bessel expansion

The rest of my talk deals with our latest test of short-distance gravity

motivations for sub-millimeter tests of the inverse-square law (ISL)

- explore an untested regime of gravity

    look for new very weakly coupled Yukawa forces

$$V(r) = V_N(r)[1 + \alpha \exp(-r/\lambda)]$$

- probe the dark-energy length scale

$$\rho_{\rm d} \approx 3.8\ \mathrm{keV/cm^3}$$
$$\lambda_{\rm d} = \sqrt[4]{\hbar c/\rho_{\rm d}} \approx 85\ \mu\mathrm{m}$$

- search for proposed new stringy phenomena

  large extra dimensions: why is gravity so weak?

    n extra dimensions change potential from 1/r to 1/r^(1+n)

    if dimensions are smaller than closest separation Yukawa is good approximation

  the extra nominally massless "gravitationally" coupled particles of string theory

    dilatons, moduli, radions, heavy gravitons, etc. would produce Yukawa interactions

Gauss's Law and extra dimensions

moral: to see the true strength of gravity
you have to get really close

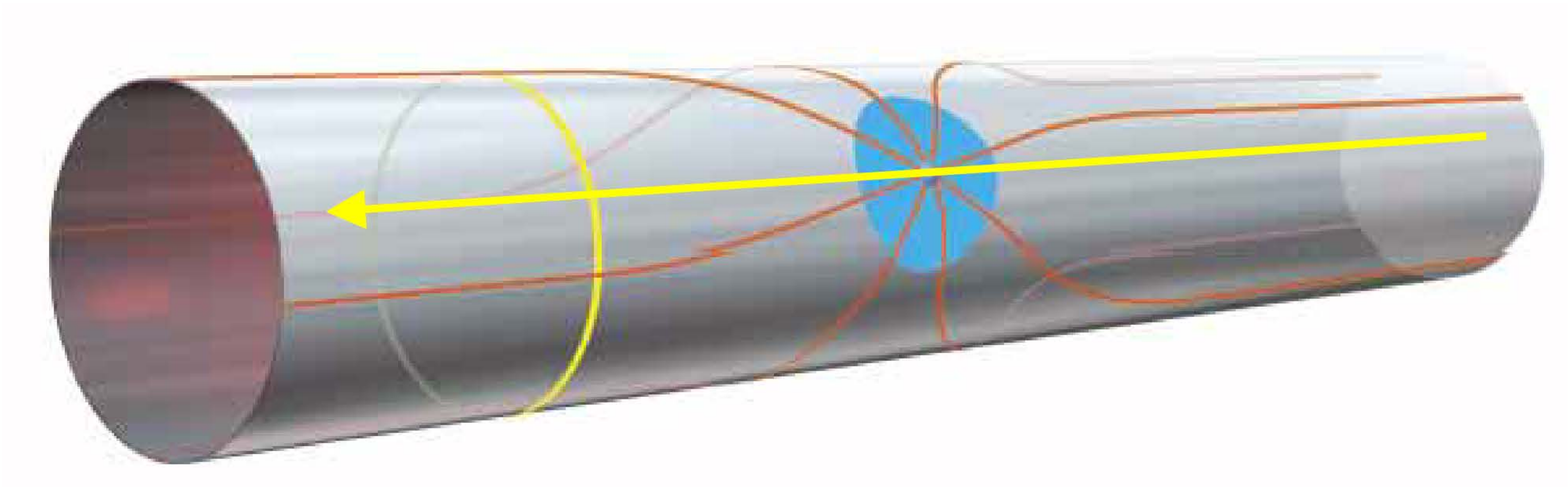
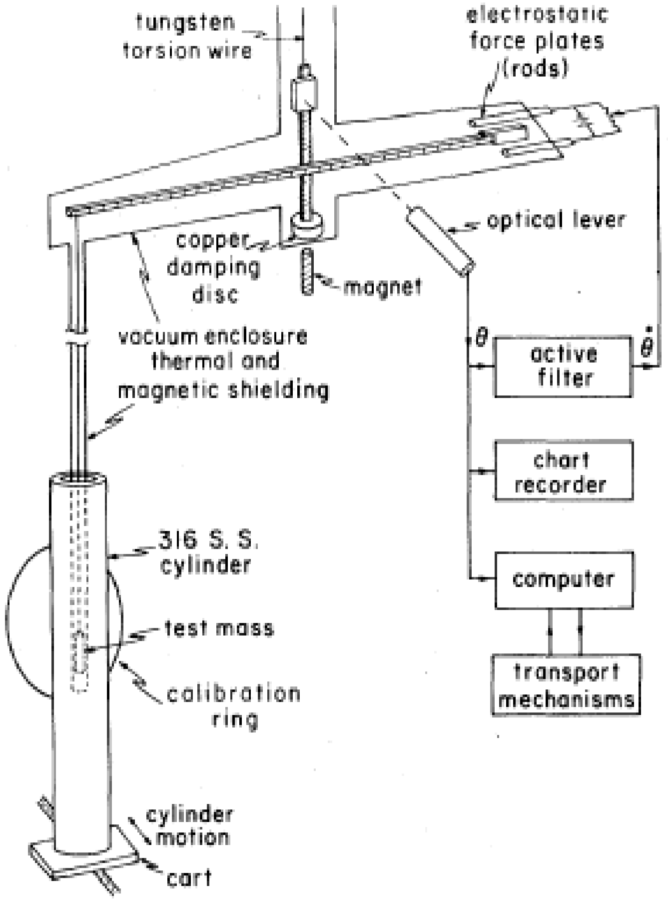


illustration from Savas Dimopoulos

Irvine and Eöt-Wash torsion-balance tests of the ISL

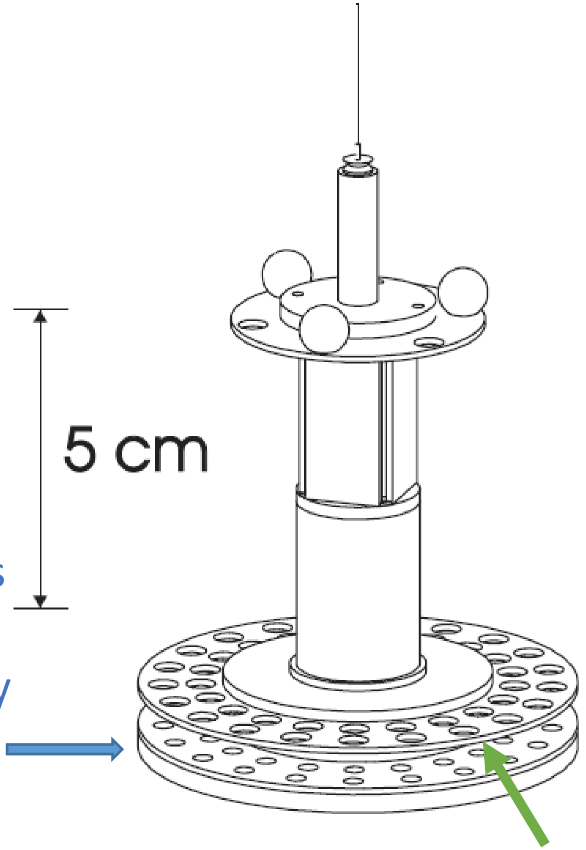
Hoskins et al. PRD 32, 3084 (1985)

Does a cylinder inside an "infinitely long" cylindrical shell feel a force?



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

Does the torque on "missing masses" of the pendulum's 42 holes exerted by the 42 holes in the rotating attractor agree with Newton's Law?



Attractor consists of 2 plates: Lower plate is thicker and has holes rotated by π/21. This suppresses Newtonian gravity but has little effect on a short-range force

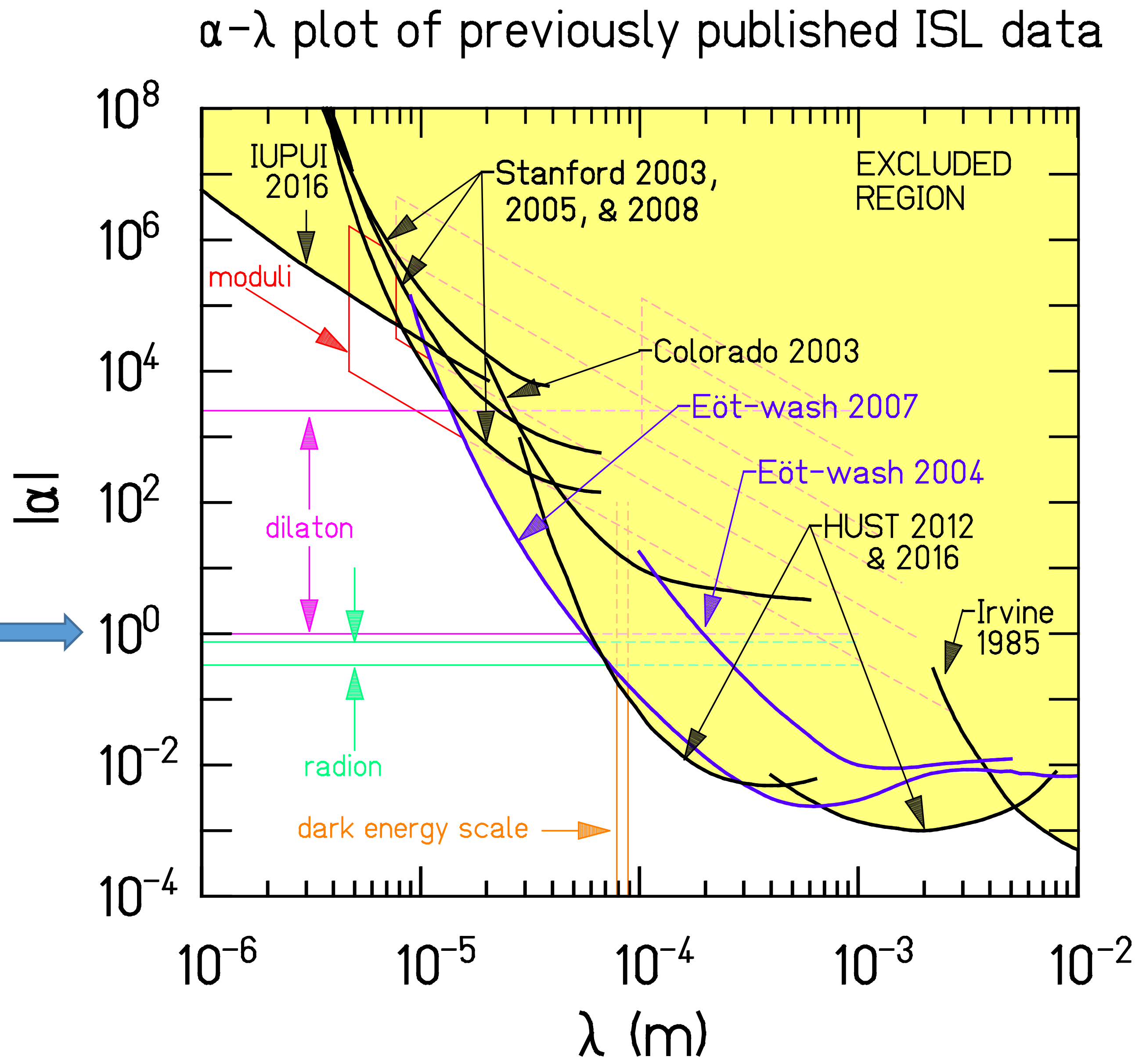
tightly stretched10 µm thick Cu foil between pendulum and attractor

short-distance gravity experiments are challenging

force is very weak– will see just how weak in a few slides later
alignment is tricky– need to align 6 cm sized objects (1 of them hanging from an 83 cm fiber) with μm accuracy--final alignment done using gravity itself
unshielded backgrounds are enormous – need rigid conducting foil between source and pendulum, for $s < 50$ μm patch effect noise dominates
cleanliness is essential – 1 speck of dust between plates will ruin measurement

patch effects+vibrations are limiting factors

summary of published ISL tests of short-distance gravity

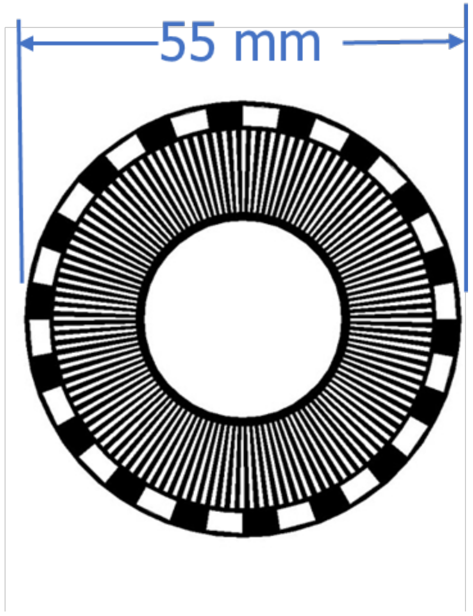


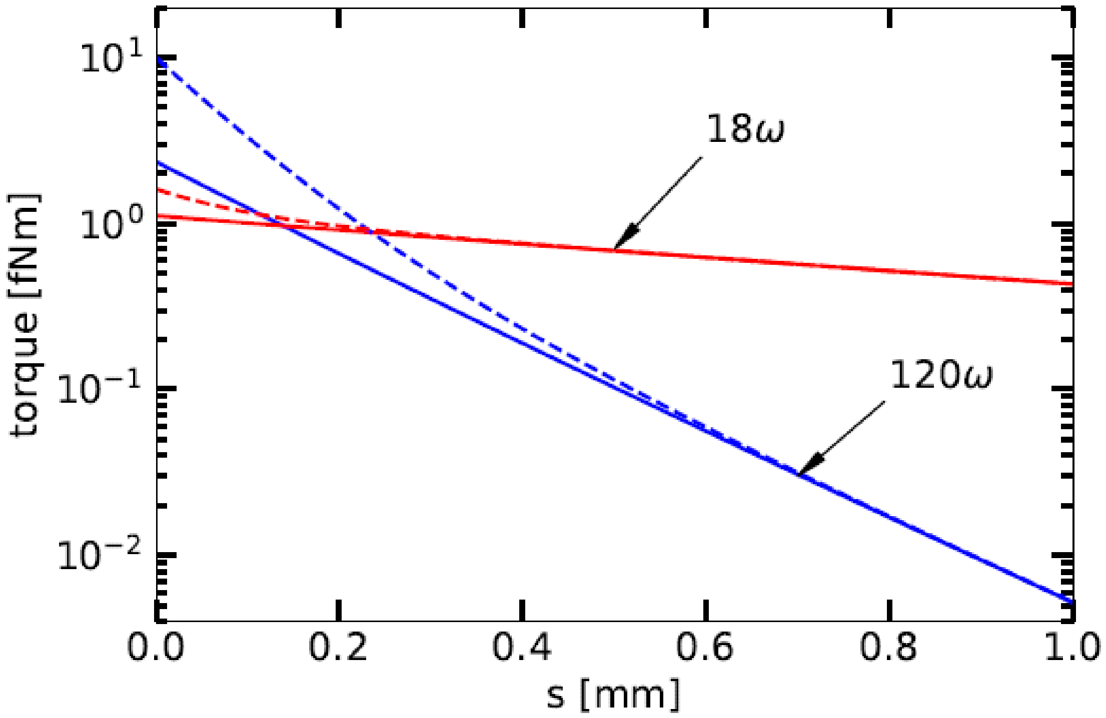
to test gravity sensitivity must be below this level

Fourier-Bessel geometry

an optimized test body design for ISL tests that fully exploits cylindrical symmetry

- enhanced sensitivity for short-range Yukawa interactions
- identical geometries for pendulum and attractor test-bodies
- analytic solutions for Newtonian and Yukawa interactions and for
- dipole-dipole and monopole-dipole interactions between magnetized test bodies
- combination of 2 different azimuthal symmetries(m=18 and m=120) provides
- simultaneous tests at 2 different length scales
- 50% transparent pattern optimizes torque signal and minimizes sensitivity to pattern imperfections





solid lines: Newton

dashed lines: Newton + λ=80μm, α=10 Yukawa

UW Mark 2 Fourier-Bessel ISL instrument

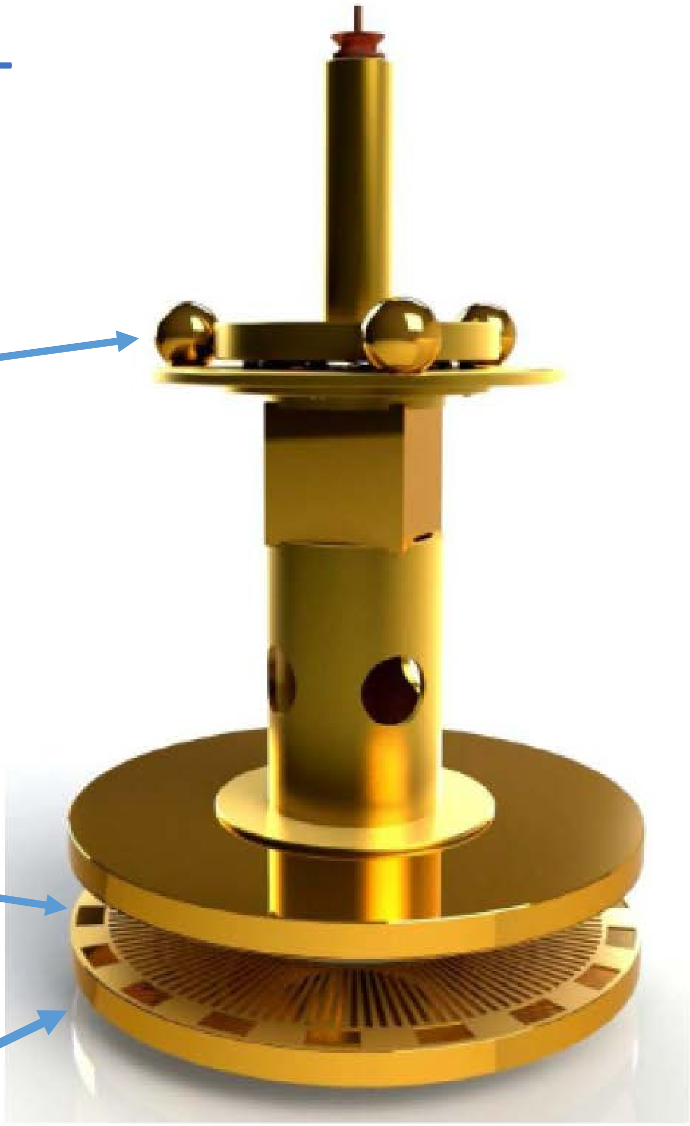
John Lee's 2019 PhD project

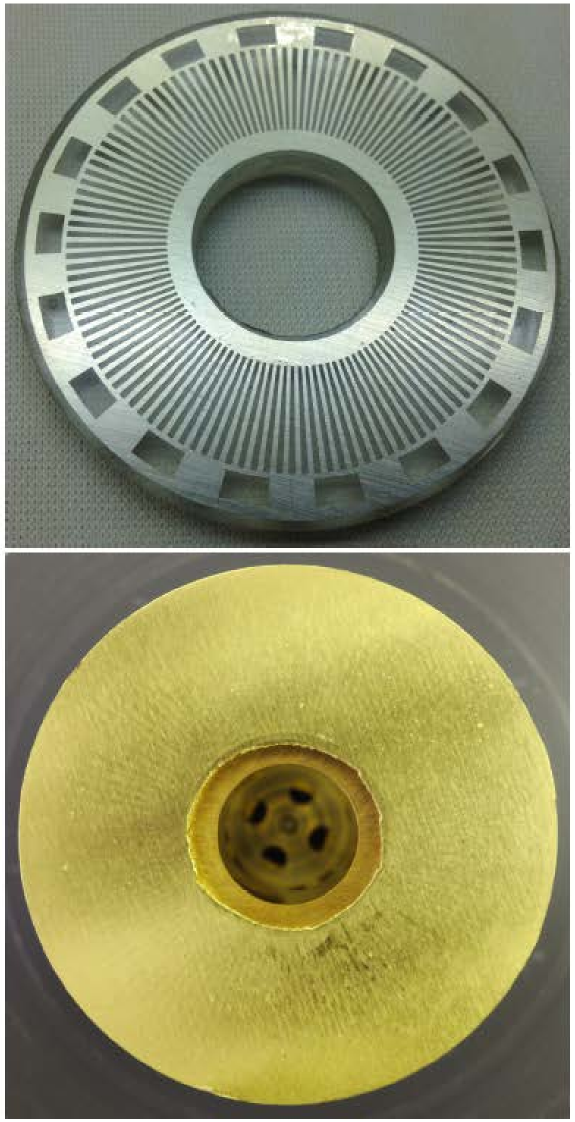
torque on 3 small spheres exerted by 3 large spheres on an external turntable provide absolute calibration.

This work can be thought of as measuring G_N at separations down to 50µm

separation, s, between facing surfaces of test bodies is greatly exaggerated

attractor rotating at frequency ω exerts harmonic torques varying at 18ω, 120ω and 54ω (3rd harmonic of 18-fold signal)





52 mm diameter hole pattern

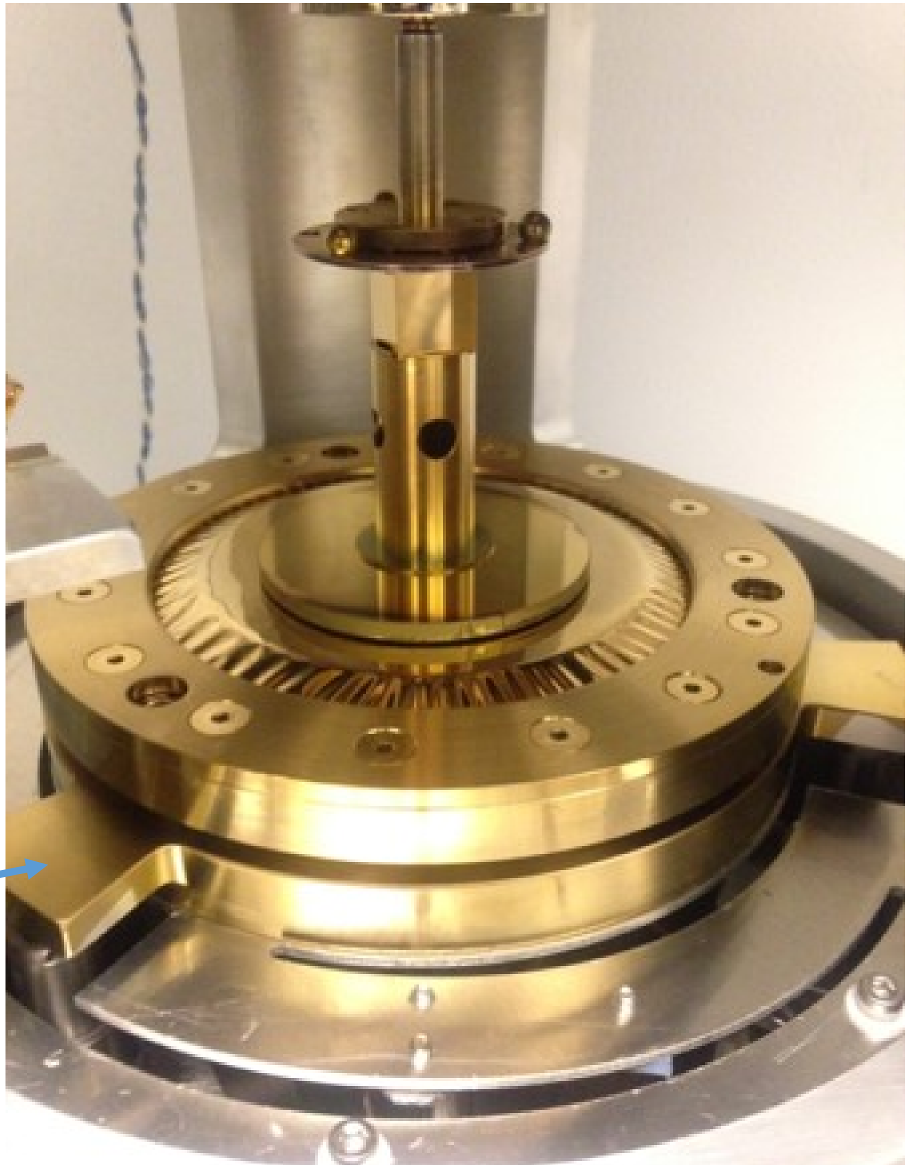
Test bodies were cut from 54 and 99 thick Pt foils and epoxied to BK glass annuli using a technique that filled the holes with glue, leaving them flat to within ±2µm

Upgraded features of UW Mark 2 Fourier-Bessel instrument

John Lee's 2019 PhD project

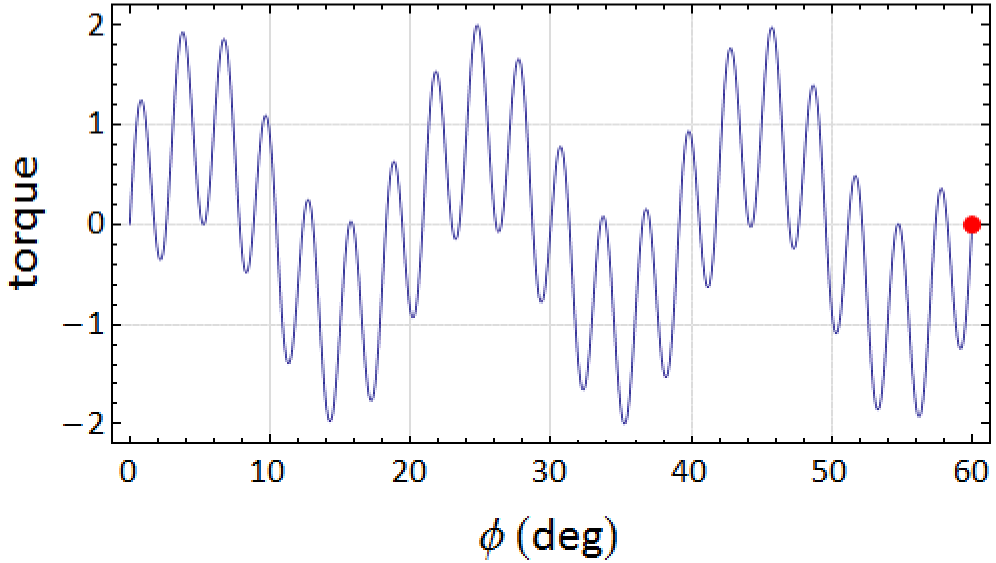
- new test body materials   Pt instead of W
- new test-body fabrication technique
- remotely adjustable 3 DOF isolation-foil positioner
- new vacuum chamber and accessories
- improved analysis with weekly octupole gravitational calibration of the torque scale

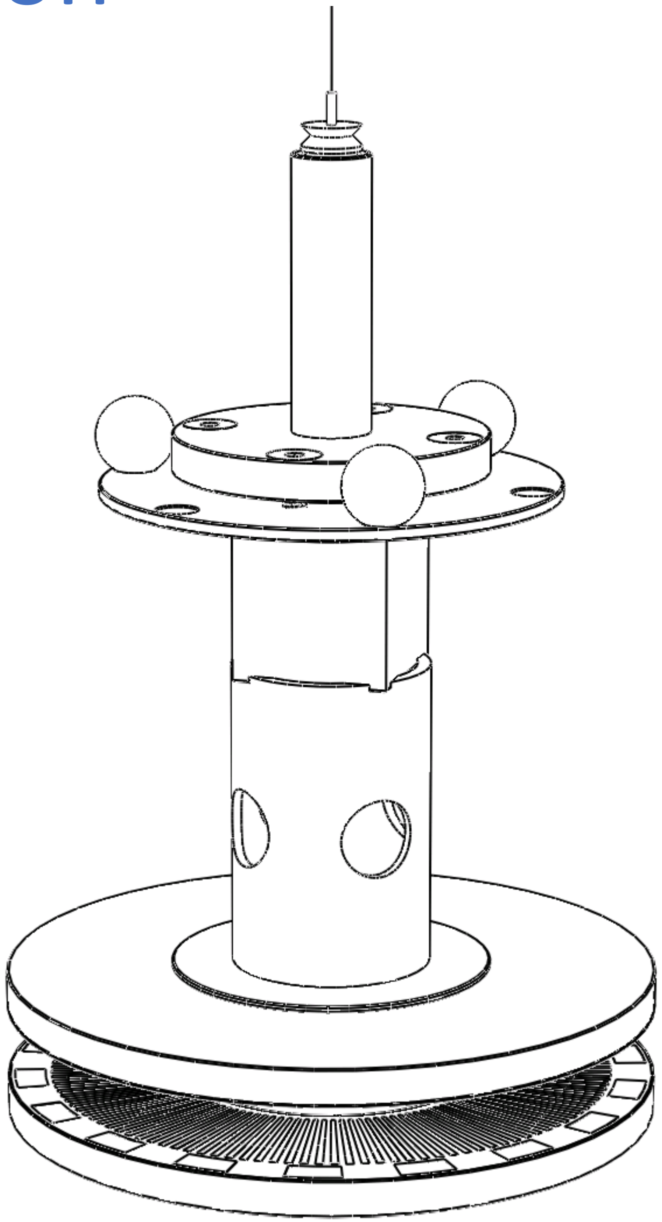
1 of 3 remotely adjustable isolation foil positioners



Fourier-Bessel simulation

T.E. Cook





simulation is speeded up by factor of ≈1000

John Lee testing for magnetic systematics

3 outer spheres on the gravitational calibration turntable

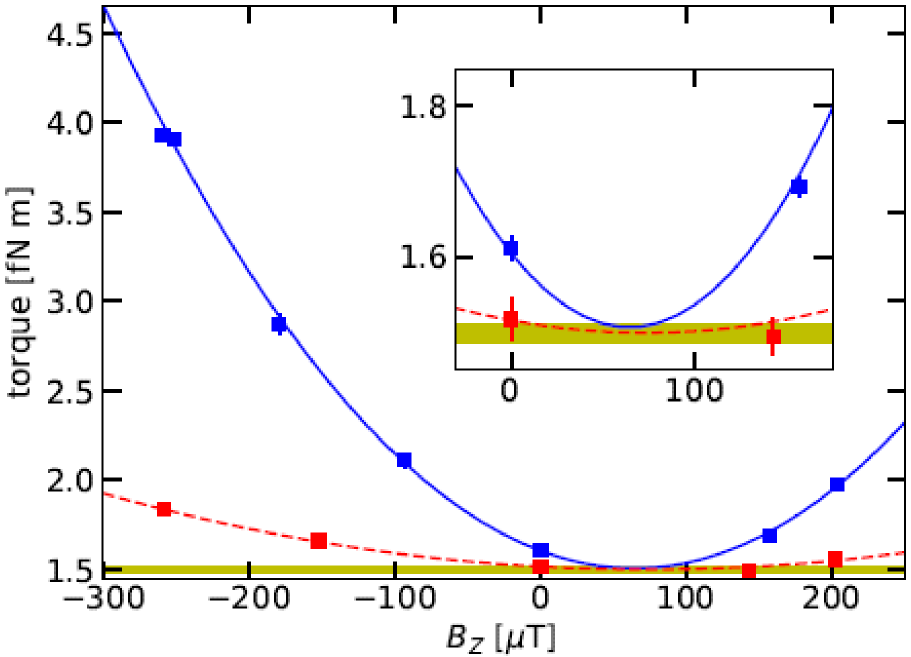
systematic errors

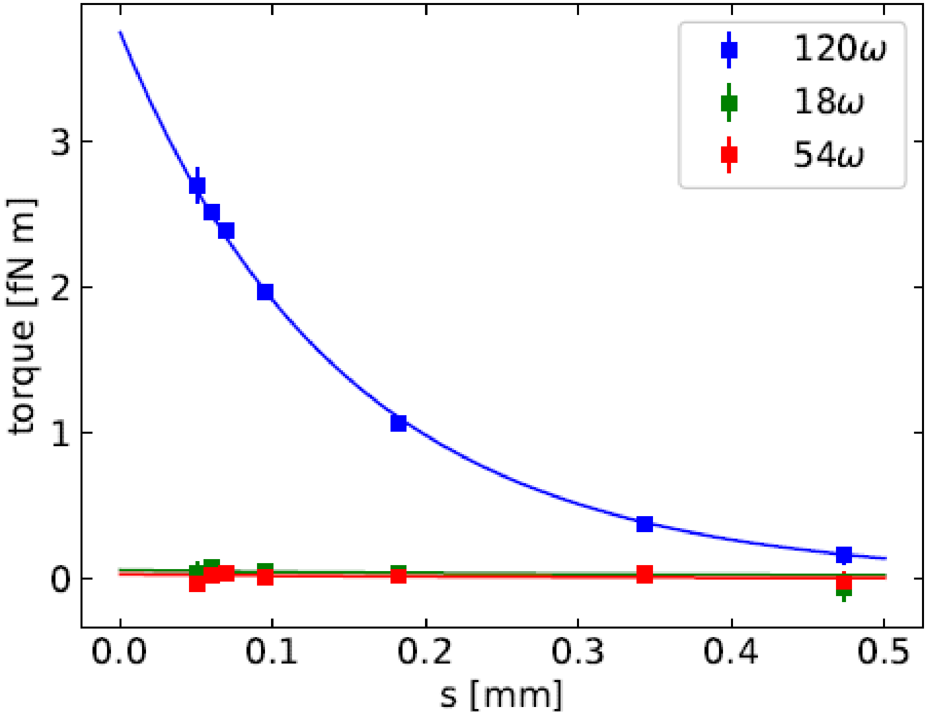
Made usual tests by varying temperatures and temperature gradients,
applied electrical and magnetic fields, etc.

Magnetic fields showed the only significant effect:
an ambient B field weakly polarizes the Pt test bodies.
The resulting dipole-dipole interaction induces a non-gravitational force:

vertical B gives an attractive interaction
horizontal B gives repulsive interaction

Fourier-Bessel calculations give excellent account of magnetic results with a single overall normalization.
Effect was only significant for vertical fields and for the 120ω torque where it required a –1.1% correction





analysis procedure

gravity itself can determine some instrumental parameters (dimensions, centering, autocollimator scale, glue film thickness) more precisely than conventional methods (micrometers, measuring microscopes, electronic scales); we allow these to float within the uncertainties of conventional measurements..

measured torque

predicted torque

m=18,54,120

3D separation

instrumental parameters

$$\chi^2(\lambda) = \sum_{j=1}^{95} \sum_{m} \frac{[N_m(\vec{\zeta}_j) - \tilde{N}_m(\vec{\zeta}_j, \vec{\eta}, \lambda)]^2}{(\delta N_m)^2 + \left(\delta s_j \frac{\partial \tilde{N}_m}{\partial s_j}\right)^2} + \sum_{i=1}^{17} \left[\frac{\eta_i^{exp} - \eta_i}{\delta \eta_i^{exp}}\right]^2$$

number of measurements

uncertainty in the measured torque

externally measured experimental parameter and its uncertainty

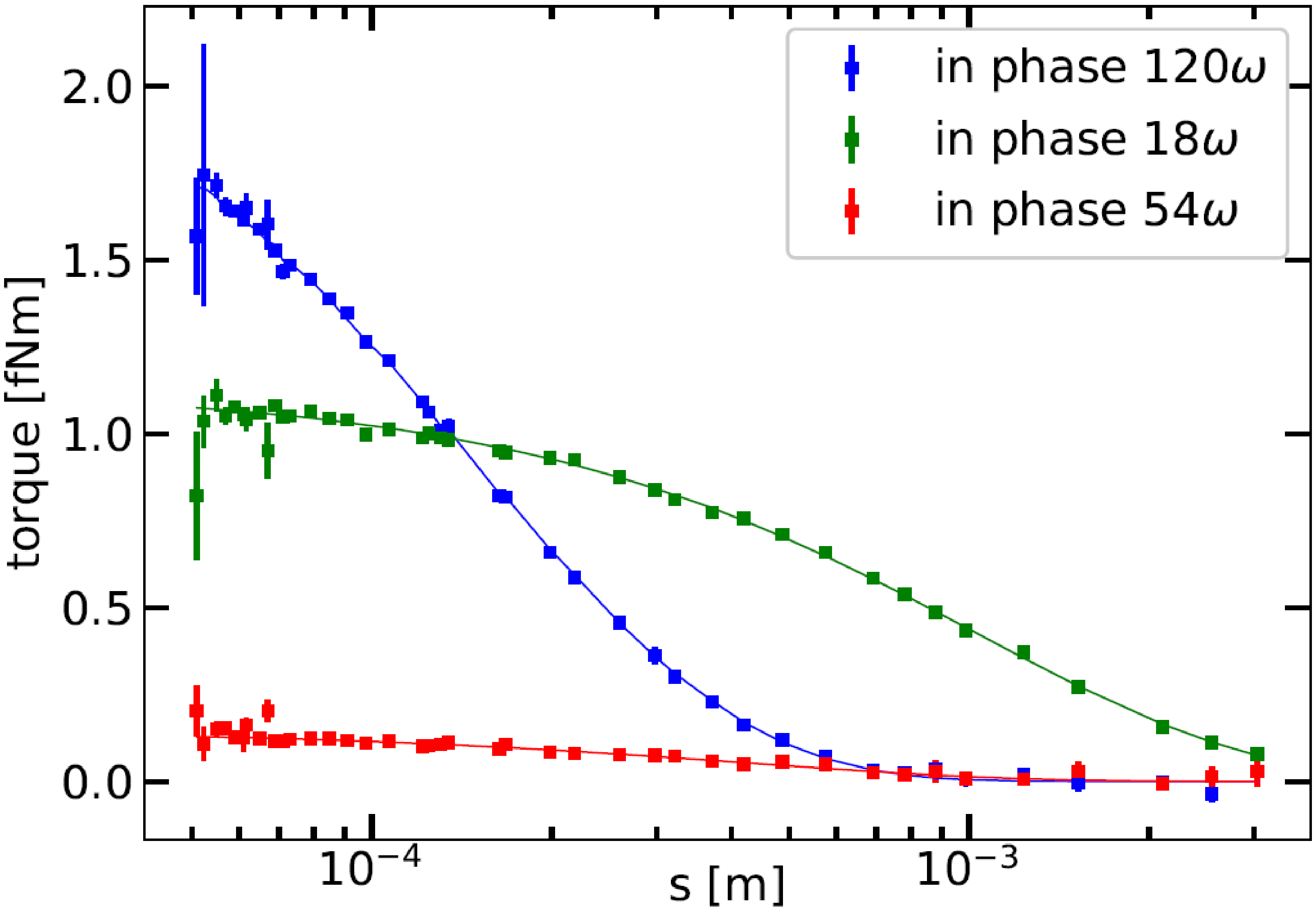
Instrumental parameters include 4 masses and 4 thicknesses of material removed to make the holes, glue density, thickness of glue film on the test body faces, autocollimator scale, etc. The total chisqr from 12 of the parameters was less than 1. We simplified things my leaving these fixed at their externally measured values.

Newtonian fit is excellent

$$\chi^2 = 275.0 \text{ with } \nu = 285$$
$$P = .654$$

1 fN m torque ≈ 1/10 the weight of
1 E.coli placed at the end of a massless
1 m long lever arm

.01 fN m error bar ≈ 1/1000 the weight of
1 E.coli placed at the end of a massless
1 m long lever arm



95% exclusion plot

We added a single Yukawa term with λ between 5μm and 9mm and minimized chisqr, varying η independently at each λ. None of these Yukawas improved chisqr at the 2σ level

$$(\Delta\chi^2 = 6.2):$$

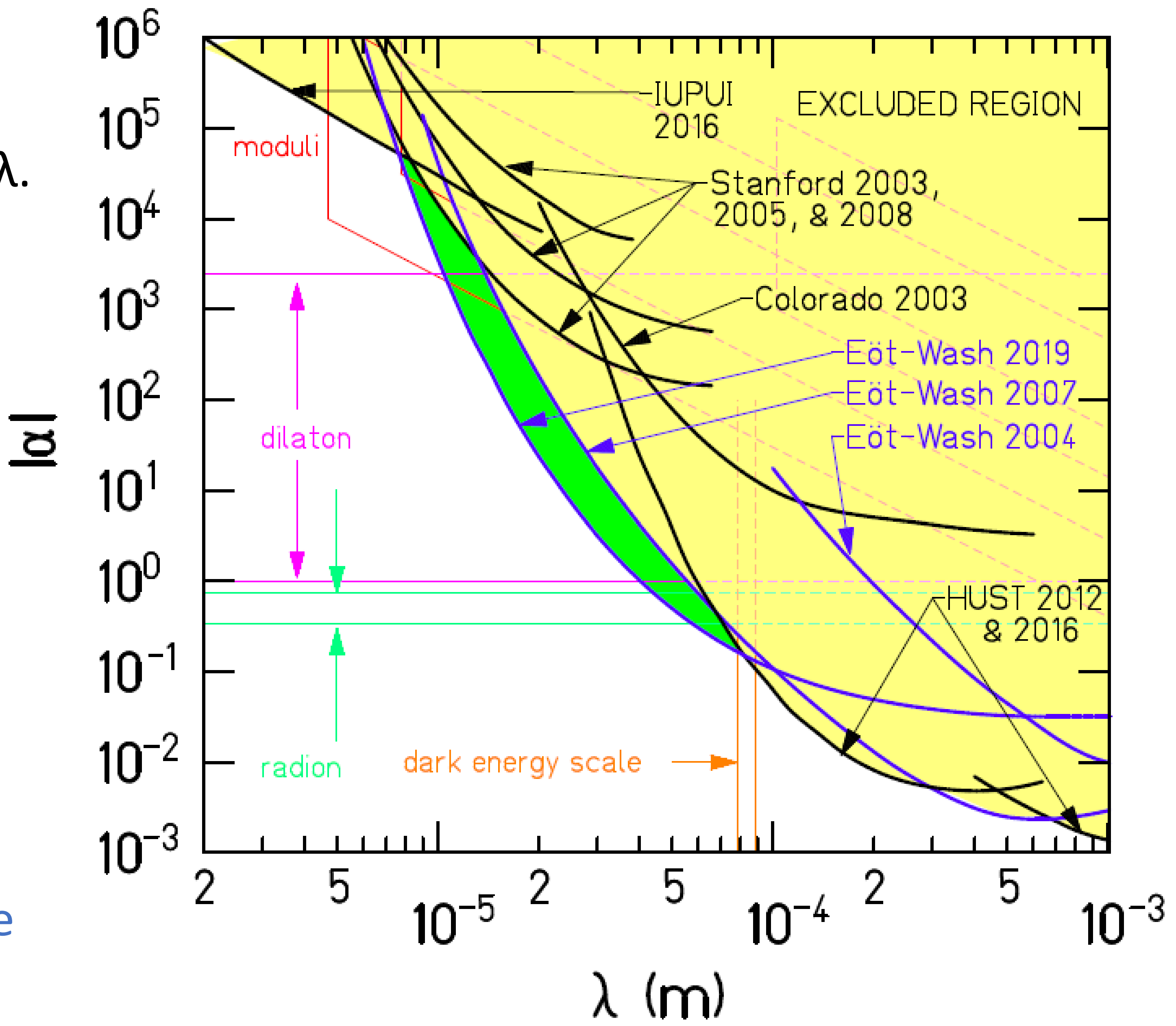
The most probable Yukawa had

$$\Delta\chi^2 = 3.3$$
$$\lambda = 7.1\mu m$$

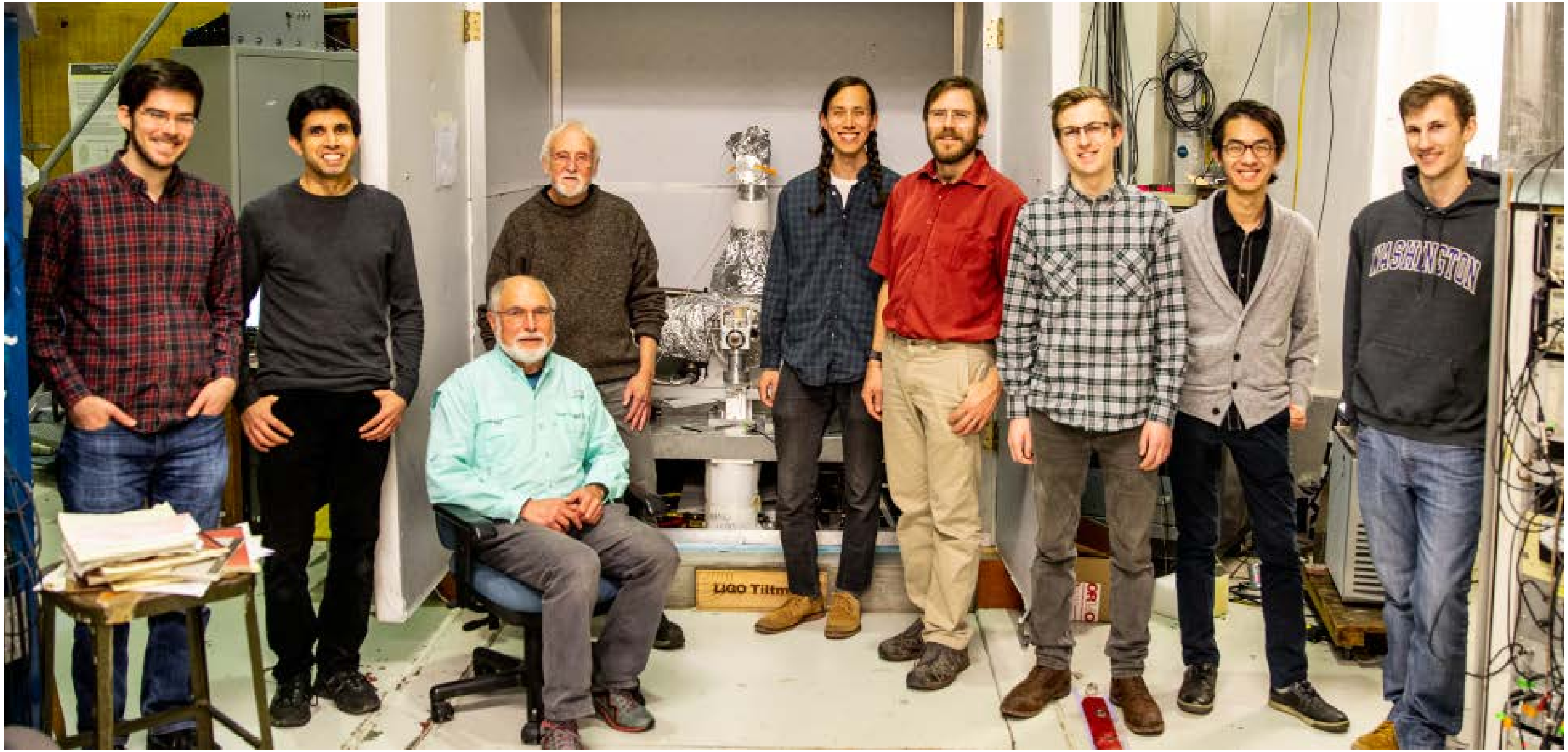
some implications of this result:

dilaton or heavy graviton must have masses > 5.1 meV

largest single extra dimension must have toroidal radius < 30μm



The Eöt-Wash group:
where there's always a new twist



members not in this photo: Jens Gundlach (PI on sabbatical in Switzerland) and Blayne Heckel (co-PI and department chair)

primary support from NSF Gravitational Physics

Wick,

I'm sure that you'll enjoy your <u>nominal</u> retirement and the freedom to do only those things you really want to do, including physics