SHORT-RANGE SEARCHES FOR NON-NEWTONIAN GRAVITY:

NEW PHYSICS AT SMALL SCALES

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PHYSICS 135c
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THE INVERSE SQUARE LAW

NEWTONIAN ISL: $F_G = -G\frac{m_1 m_2}{r^2}$

- **ASSUMED RANGE OF VALIDITY:** ∞ TO $R_P = \sqrt{G\hbar/c^3} = 1.6 \cdot 10^{-35} m$

- **GEOMETRIC IN ORIGIN:** $F_G = -G\frac{m_1 m_2}{r^{n-1}}$

- **ONLY WITHIN A DECADE GRAVITY PRECISELY TESTED BELOW 1mm**
  - INTRINSICALLY WEAK COMPARED TO E&M
  - THERMAL, SEISMIC, ETC. BACKGROUNDS POSE CHALLENGES
  - DIFFICULTY IN BRINGING TEST MASSES ARBITRARILY CLOSE

- **COMPARED TO RANGE OF COULOMB'S ISL MEASUREMENT**:
  - TESTED DOWN TO SEPARATIONS $\sim 10^{-18} m$
  - IN e^+e^- LEPTONIC INTERACTIONS IN HIGH-ENERGY COLLIDERS

POTENTIAL PARAMETRIZATIONS

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

  - GENERALLY DESCRIBES SHORT-RANGE FORCE CARRIED BY PARTICLE OF MASS:
    $$m = \hbar / c\lambda$$
  - α = dimensionless strength parameter, $\propto$ squared product of coupling constants
  - λ = length scale

  - VALID FOR:
    - BOSON-EXCHANGE FORCES
    - APPROX FOR LARGE EXTRA DIMENSIONS DOWN TO SEPARATIONS ~ SIZE EXTRA DIM'S

- **POWER-LAW:** $$V(r) = -G\frac{m_1 m_2}{r}\left(1 + \beta_k\left[\frac{1mm}{r}\right]^{k-1}\right)$$

  - VALID FOR EXCHANGE OF 2 MASSLESS PARTICLES
  - β_k COEFFICIENTS DEPEND ON PARTICLES EXCHANGED

THEORETICAL MOTIVATION

- **GAUGE HEIRARCHY PROBLEM:**
  - WHY IS GRAVITY SO WEAK COMPARED TO OTHER FORCES?

$$M_{EW} \sim 100GeV << M_{PL} = \sqrt{\hbar c / G} = 1.2 \cdot 10^{16} TeV / c^2$$

  - HIGGS MASS: $M_H \sim 100GeV$
  - QM CORRECTIONS PULL M_H UP TO M_{PL}
    UNLESS PHYSICS "CUTS OFF" AT LOWER SCALE
  - OTHERWISE REQUIRES "FINE-TUNING"… CANCELLATION OF QM CORRECTIONS IN L

- **COSMOLOGICAL CONSTANT PROBLEM:**
  - SCALE FOR C.C. SHOULD BE: $E_\lambda \sim M_{PL} \sim 10^{19} GeV$
    - SECOND-QUANTIZATION QM SHO
  - OBSERVED VALUE: $E_\lambda \sim 10^{-4} eV$
  - CONTRIBUTIONS FROM ALL PARTICLES/FIELDS HAVE TO CANCEL OUT -> "FINE-TUNING"

- **NON-GRAVITATIONAL PHYSICS:**
  - SM PREDICTS VERY-LOW-MASS SCALAR OR VECTOR BOSONS
  - PRODUCE SHORT-RANGE EXCHANGE FORCES => ISL VIOLATIONS

SOLVING THE HEIRARCHY PROBLEM

- **SUPERSYMMETRY (SUSY):**
  - SUPERSYMMETRIC PARTNERS CANCEL OUT QUANTUM CORRECTIONS
  - FINE-TUNING NOT NEEDED!
  - CANCELLED UP TO $M_{\tilde{t}} \sim 100 GeV$
  - PREDICTS NEW PARTICLES AT 100 GeV SCALE

- **STRING / M-THEORY:**
  - 3+1 DIM BRANE IN 10+1 DIM BULK (7 DIM CURLED UP)
  - SM PARTICLES OPEN STRINGS TERMINATED ON BRANE
  - GRAVITONS CLOSED STRINGS PROPOGATE IN BULK

STRING / M-THEORY SOLUTION

- **A SOLUTION (1998 ARKANI-HAMED, DIMOPOULOS & DIVALI):**
  - **MAYBE MPL ISN'T** $10^{16} TeV$
  - **ACTUALLY CLOSER TO** M_{EW}

    TRUE PLANCK MASS: $M_* \sim 100 GeV$

  - **GRAVITY ACTUALLY STRONGER THAN OBSERVED AT SMALL-RANGE:**

    $$M_{PL} \propto 1/\sqrt{G}$$

    - WE SEE WEAKER GRAVITY BECAUSE IT LEAKS INTO EXTRA DIMENSIONS
    - THE GREATER # OF COMPACT DIMENSIONS , THE WEAKER GRAVITY
    - GRAVITONS PROPOGATE IN 10+1 DIM BULK, OTHER SM PARTICLES ON BRANE

  - **CONSISTENT WITH OBSERVATIONS OF ELECTROMAGNETIC INTERACTIONS**

"LARGE" EXTRA DIMENSIONS

- **M-THEORY EXPERIMENTAL PREDICTIONS:**
  - SOME EXTRA DIM'S COULD BE "LARGE" ENOUGH TO BE EXPERIMENTALLY ACCESSIBLE

$$R_* >> R_{PL} = 1.6 \cdot 10^{-35} m$$

  - EFFECTIVE ISL:

$$r >> R_* \Rightarrow V(r) \propto 1/r^2$$

$$r << R_* \Rightarrow V(r) \propto 1/r^{2+n}$$

$$r \geq R_* \Rightarrow V(r):$$

$$\lambda = R_*$$

$$\alpha = 8n/3$$

  - GRAVITY WILL BE STRONGER AT DISTANCES ~ "LARGE" EXTRA DIM'S
  - WHERE TO LOOK:

$$R_* = \left[\frac{M_{PL}}{M_*}\right]^{2/n} \left[\frac{\hbar}{2\pi c M_*}\right]$$

$$R_* \approx \frac{1}{\pi} 10^{-17+32/n} cm \qquad \begin{matrix} n=1 \\ n=2 \end{matrix} \Rightarrow \begin{matrix} R_* = 3 \cdot 10^{12} m \\ R_* = .3mm \end{matrix}$$

THE COSMOLOGICAL CONST. PROBLEM

- **REDUCE QM PREDICTION FOR VACUUM ENERGY DENSITY:**
  - SECOND-QUANTIZATION (QM SHO W/ NON-ZERO REST ENERGY) TOO HIGH!

- **REDUCE THE GRAVITATIONAL COUPLING TO STANDARD VACUUM ENERGY:**
  - FOR LOCAL EFFECTIVE QFT, NATURALNESS => NEW GRAV. PHYSICS AT LENGTH SCALES ~1mm WOULD CUT OFF SHORTER DISTANCE CONTRIBUTIONS TO VAC. ENERGY
  - "FAT" GRAVITONS

- **EXPERIMENTAL PREDICTIONS:**
  - GRAVITY "SHUTS OFF" AT LENGTH SCALES < 100 μm
  - YUKAWA ISL VIOLATION: $\alpha = -1$ $\lambda = .1$mm
  - OPPOSITE OF M-THEORY PREDICTION

OTHER ISL-VIOLATING PREDICTIONS

- **BOSON-EXCHANGE FORCES:**
  - VIOLATES WEAK EQUIVALENCE PRINCIPLE
  - DISTINGUISH FROM EXTRA DIM BY EQUIVALENCE PRINCIPLE TESTS

- **RADION-MEDIATED FORCES:**
  - DYNAMICAL VARYING SPACETIME GEOMETRY, RADII OF NEW DIMENSIONS FLUCTUATE
  - RADIONS: LOW-MASS SPIN-0 FIELDS STABILIZE VOLUME OF EXTRA DIMENSIONS
  - MAY BE LONGEST-RANGE EFFECT, AND DOESN'T DEPEND ON # DIM

- **"MODULI" PARTICLES:**
  - LARGE # OF WEAKLY-COUPLED MASSLESS SCALAR FIELDS == MODULI
  - COUPLE TO SUSY-BREAKING OF GROUND STATES OF STRING THEORY
  - DILATON
    - BEST UNDERSTOOD MODULUS PARTICLE
    - SCALAR PARTICLE, DETERMINES STRENGTH OF GAUGE COUPLINGS
    - IMPORTANT AS SMOKING GUN FOR STRING THEORY

- **AXION-EXCHANGE FORCES:**
  - AXIONS: PSEUDO-SCALAR PARTICLES EXPLAIN SMALL UPPER LIMIT ON Θ_{QCD}
  - GIVES SPIN-INDEPENDENT YUKAWA POTENTIAL BETWEEN NUCLEONS

- **MULTI-PARTICLE EXCHANGE FORCES:**
  - 2 MASSLESS PARTICLES EXCHANGING SIMULTANEOUSLY
  - GIVES RISE TO THE POWER-LAW POTENTIAL

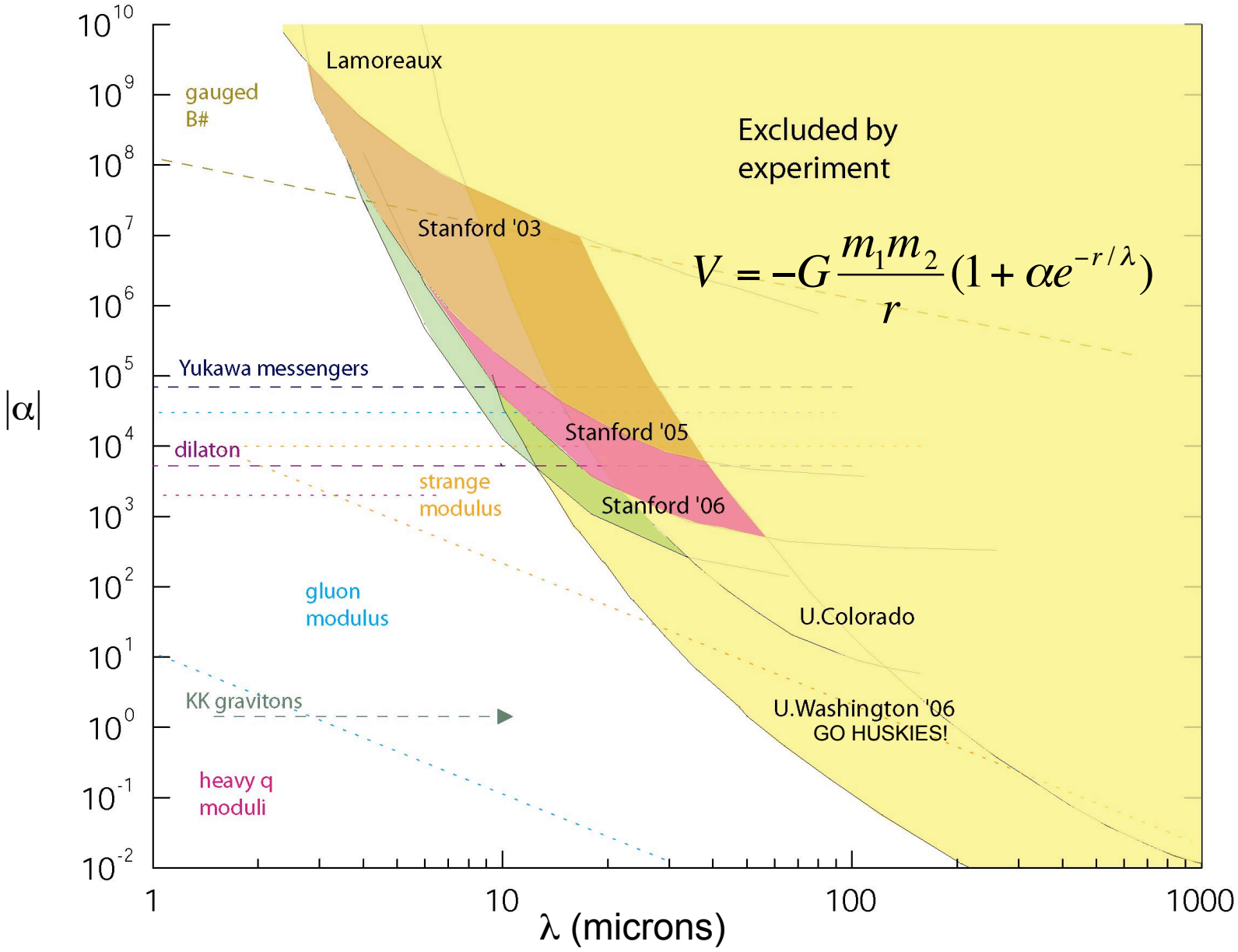
ISL EXPERIMENTS SEARCH FOR NEW PARTICLE PHYSICS BEYOND STANDARD MODEL

DISTINGUISHING ISL-VIOLATIONS

- **CURRENTLY EXPERIMENTS ARE PUSHING DOWN CONSTRAINTS IN PARAMETER SPACE…**
- **WHAT IF A NON-ISL FORCE IS DETECTED?**
- **COULD BE DUE TO:**
  - LARGE EXTRA DIMENSIONS
  - "FAT" GRAVITONS
  - NEW PARTICLE EXCHANGES
  - ETC…
- **COMPOSITION DEPENDENT FORCE?**
  - TEST THE EQUIVALENCE PRINCIPLE
  - IF COMPOSITION-DEPENDENT CANNOT BE DUE TO LARGE EXTRA DIMENSIONS
  - E.G. BOSON-EXCHANGE VIOLATES EP
- **HOW DOES ISL CHANGE WITH DISTANCE?**
  - MODELS GIVE PREDICTIONS FOR STRENGTH OF FORCE AND LENGTH SCALE
  - FITS OF YUKAWA POTENTIAL PARAMETERS αAND λWILL RESTRICT MODELS
  - E.G. RADION LONGEST RANGE EFFECT

LATEST EXPERIMENTAL CONSTRAINTS:

95% CONFIDENCE LEVEL CONSTRAINTS ON A YUKAWA VIOLATION OF GRAVITATIONAL ISL



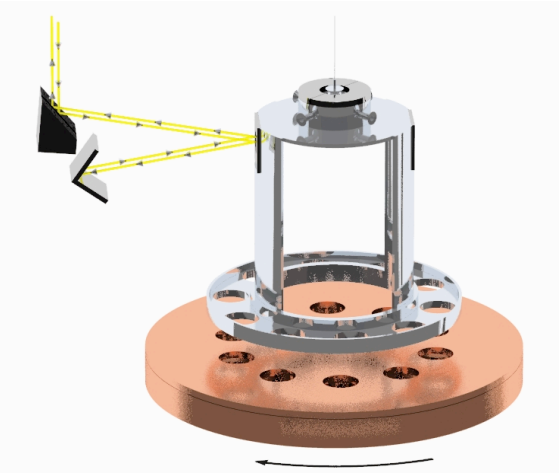
TYPES OF EXPERIMENTS

- **TORSION PENDULUMS**
  - HISTORICALLY BEST TOOL FOR MAKING MEASUREMENTS OF WEAK FORCES
    - DENSITY OF EARTH (MITCHELL, 1750)
    - ELECTROSTATIC FORCE (COULOMB, 1785)
    - GRAVITATIONAL CONSTANT (CAVENDISH, 1798)
    - EQUIVALENCE PRINCIPLE (EÖTVOS, 1890)
    - HIGH-PRECISION G, LORENTZ SYMMETRY (TODAY)
    - OF COURSE, ISL VIOLATIONS!

- **MICROCANTILEVER**
  - NEWER TECHNOLOGY NOT YET AS SENSITIVE AS TORSION
  - ALLOWS FOR MUCH SMALLER TEST MASS SEPARATIONS
  - FABRICATION TECHNIQUES ALLOW FOR BETTER ALIGNMENT
  - LESS SENSITIVE TO SEISMIC FLUCTUATIONS

- **CASIMIR EFFECT**
  - HYBRIDIZATION OF TORSION AND CANTILEVER APPROACHES
  - PHYSICS IS IMPORTANT FOR NANOFABRICATION TECHNOLOGY
  - LESS EXPERIMENTAL HISTORY FOR THESE TESTS

TORSION PENDULUMS



- **BASIC COMPONENTS:**
  - TEST MASSES
  - FIBER PENDULUM (SUSPENDING TEST MASSES)
  - ATTRACTOR MASSES
  - LIGHT BEAM BOUNCES OFF MIRROR ON PENDULUM (TO MEASURE TWIST)

- **NATURALLY SUITED TO GRAVITATIONAL MEASUREMENTS**
  - NATURALLY SUITED TO GRAVITATIONAL MEASUREMENTS
  - ROTATION INDEPENDENT OF g
  - INSENSITIVE TO NET FORCES ACTING ON CENTER OF MASS
  - DECOUPLED FROM EXTERNAL FLUCTUATIONS (HOW?)
  - VERY SENSITIVE TO FORCE:
    - TORQUE SENSITIVITY: $10^{-18} N \cdot m$
    - LENGTH OF PENDULUM: ~1cm
    - FORCE SENSITIVITY: $10^{-16} N$

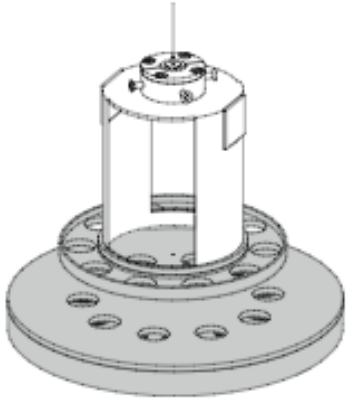
- **EXPERIMENTAL CHALLENGES ABOUND**
  - SHIELDING FROM EXTERNAL INFLUENCES
  - PRECISION SEPARATIONS OF TEST MASSES

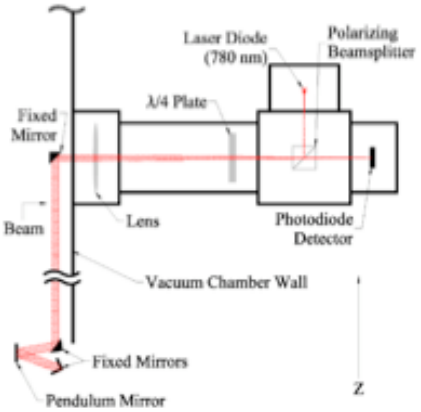
EÖT-WASH TORSION BALANCE

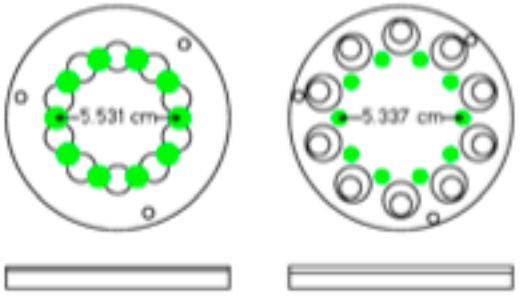
- **ADELBERGER @ UNIVERSITY OF WASHINGTON**
  HIGHEST PRECISION TORSION EXPERIMENT TO DATE

- **EXPERIMENTAL SETUP:**

  - "MISSING MASS" TEST BODIES IN PARALLEL PLATES
    - BORE & POSITION PRECISELY KNOWN/MEASURED → MISSING MASS
    - CORRECTIONS FOR BUOYANCY OF AIR!
    - GOLD PLATING
  - TORSION PENDULUM
    - TORSION FIBER
    - FIBER POSITIONING (x-y-z-θ STAGE)
    - THIN TEST MASS RING
    - PASSIVE MAGNETIC DAMPER
  - UNIFORMLY ROTATING ATTRACTOR DISK SET
    - UPPER & LOWER ATTRACTOR MASSES
    - ATTRACTOR ROTATION DRIVE
  - CAPACITIVE SEPARATION & TILT SENSORS
  - AUTOCOLLIMATOR (PENDULUM TWIST)
    - MODULATED LASER BEAM
    - POSITION-SENSITIVE DETECTOR
    - MIRRORS
  - VACUUM VESSEL
  - MECHANICAL SUPPORT & SHIELDING
    - ELECTROSTATIC
    - VIBRATION-DAMPENED KINEMATIC MOUNT ON CYCLTRON MAGNET
    - MU-METAL SHIELDS
    - THERMAL ISOLATION
    - SEISMIC MONITORING
  - CALIBRATION TURNTABLE
    - 2 BRASS SPHERES
    - ROTATES AROUND VAC. VESSEL



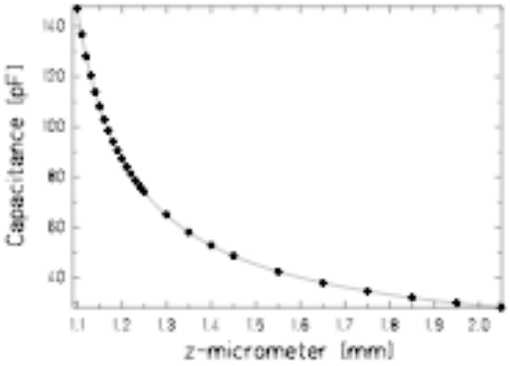


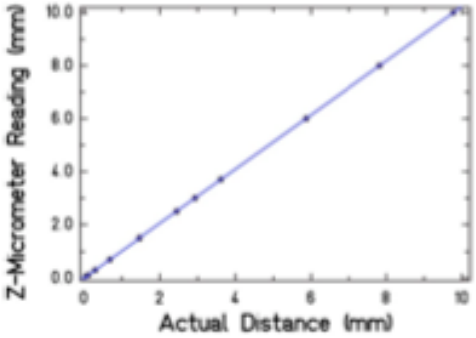


EÖT-WASH TORSION BALANCE

ALIGNMENT & POSITIONING

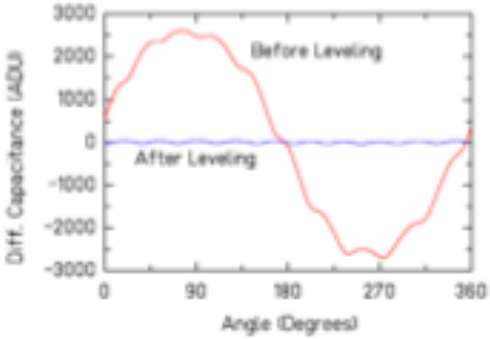
- **SEPARATION:**
  - THE MOST IMPORTANT EXPERIMENTAL PARAMETER
  - CURRENTLY DOWN TO s ~ 50μm (HALF DIA. HAIR)
  - LIMITED BY:
    - SEISMIC VIBRATIONS
    - DUST PARTICLES
    - ALIGNMENT UNCERTAINTIES





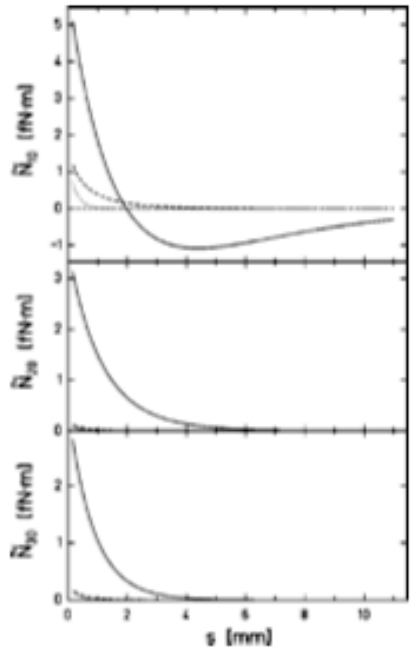
- **TILT:**
  - PENDULUM (CAPACITANCE WITH REMOVABLE SEMI-CIRCLES)
  - ATTRACTOR (CAPACITANCE WITH MEMBRANE)

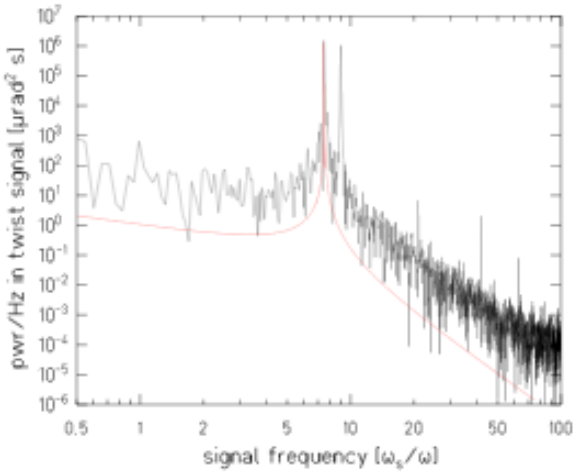
- **CENTERING:**
  - ATTRACTOR - PENDULUM
  - BASED ON GRAVITATIONAL TORQUE SYMMETRIC ABOUT X & Y

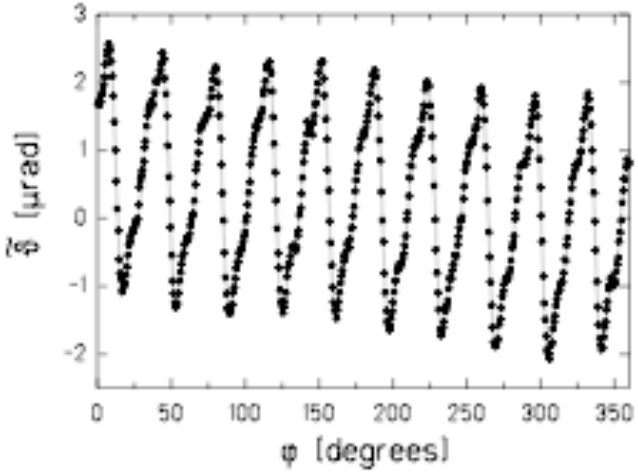


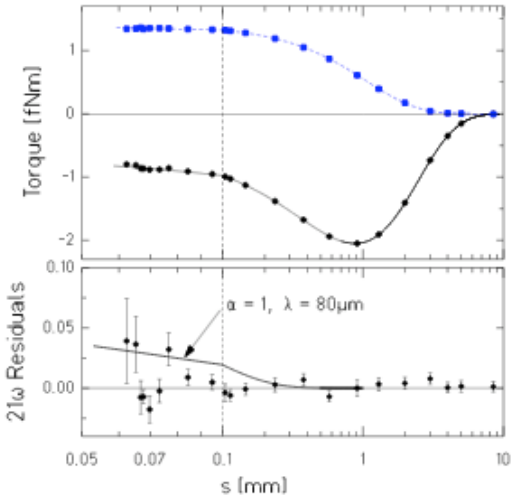
EÖT-WASH TORSION BALANCE

- **EXPERIMENTAL SIGNAL:**
  - HOLES CAUSE TORQUE ALONG FIBER
  - TORQUE SIGNAL MODULATED AT ω
  - SENSITIVE TO HARMONICS OF TORQUE: 10ω, 20ω, & 30ω
    - NEWTONIAN 10 ω TORQUE REDUCED BY NULL EFFECT OF BOTTOM ATTRACTORS
    - 20ω & 30ω REDUCED LESS
  - MEASURE TORQUES ($\tilde{N}_{10}, \tilde{N}_{20}, \tilde{N}_{30}$) AS FUNCTION OF SEPARATION **s**
  - INFER HARMONIC COMPONENTS OF TORQUE VIA PEND. TWIST
  - MEASUREMENTS OF TORQUES COMPARED TO CALCULATIONS (FIG)
  - SIGNATURES DISTINGUISHING NEWTONIAN GRAV. FROM NEW PHYSICS:
    - SHAPE OF NEWTONIAN 10 ω TORQUE
    - HIGH HARMONIC CONTENT OF NEWTONIAN TORQUE
    - DISCERN SYSTEMATICS



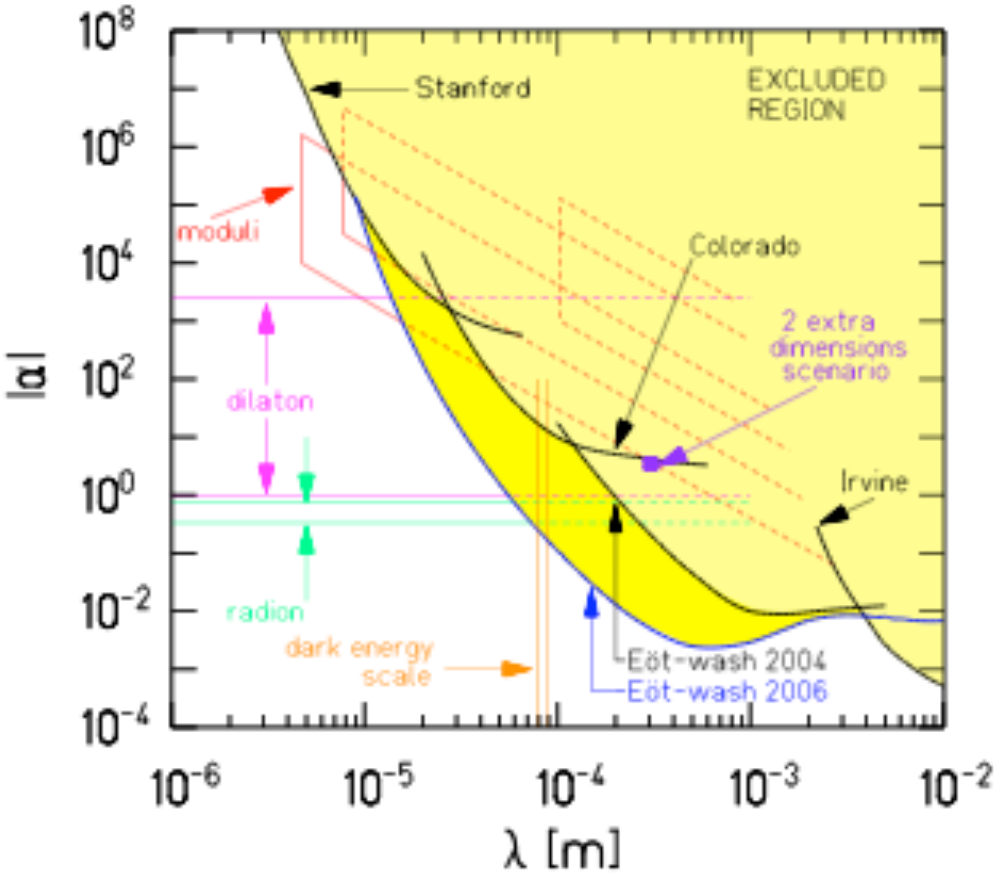






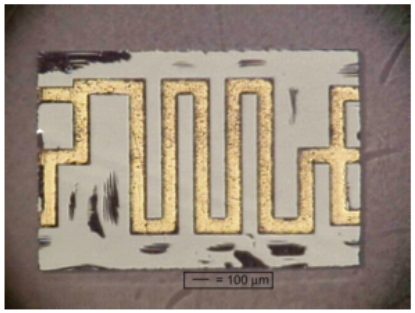
EÖT-WASH TORSION BALANCE

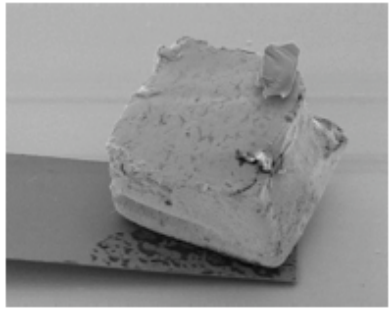
- **RESULTS:**
  - MOST RECENT INCARNATION PROBED DOWN TO $\lambda_d = \sqrt[4]{\hbar c/\rho_d} \approx 85\ \mu m.$
  - TESTED ISL FOR SEPARATIONS FROM 9.5mm to 55μm
  - 95% CONFIDENCE ISL HOLDS DOWN TO 56μm
  - MODEL INDEPENDENT UPPER-LIMITS ON SIZE OF COMPACT-EXTRA DIMENSION: R<44μm

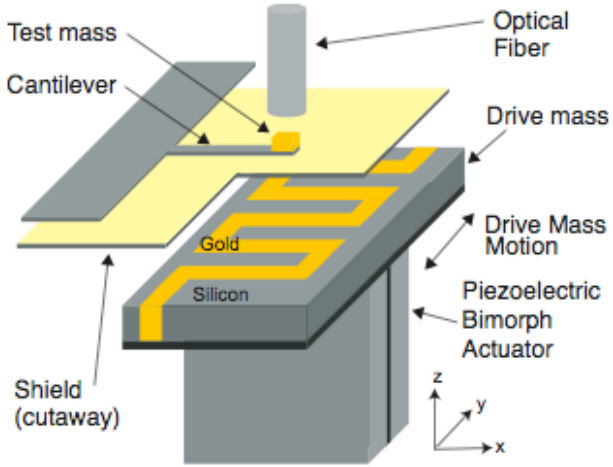


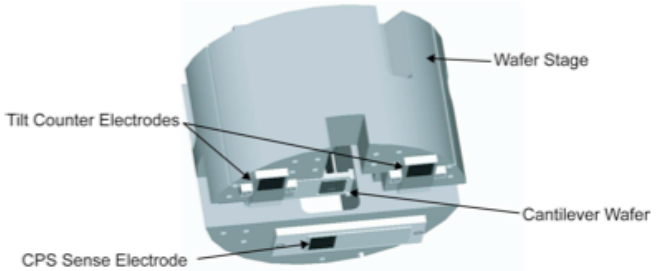
STANFORD MICROCANTILEVER

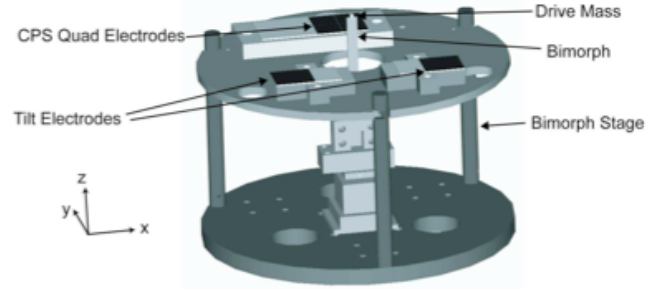
- **BEST RESULTS TO DATE FOR RANGE:** $\lambda = 6 - 20\mu m$
- **EXPERIMENTAL SETUP:**
  - CANTILEVER
    - SINGLE-CRYSTAL MICROMACHINED SILICON
    - RESONANT FREQUENCY: $\omega_0^2 = k/m_t$
    - TRANSFER FUNCTION: $x(f_o) = F(f_o)Q/k$
  - TEST MASS
    - MOLDED GOLD PRISM, MAG-TYPE NICKEL-COATED
  - DRIVE MASS
    - GOLD / SILICON MEANDER →AC GRAVITATIONAL FIELD
    - MEANDER CURRENT FOR SPATIALLY-VARYING B FIELD
    - OPERATED AT SUBHARMONIC OF ω_0
  - SHIELD MEMBRANE
    - ISOLATE ELECTROSTATIC & CASIMIR EXCITATIONS
    - STIFF METALLIZED SILICON-NITRIDE (VS. CANTI)
  - PIEZOELECTRIC BIMORPH ACTUATOR
    - DRIVEN AT $f_0/3$ OR $f_o/4$
  - VIBRATION ISOLATION
  - CAPACITIVE POSITION & TILT SENSORS
  - CRYOGENIC APPARATUS ~10K
    - LIMIT THERMAL NOISE IN CANTILEVER MOTION $S_f = \sqrt{4kk_bT/Q\omega_o}$
  - INTERFEROMETER
    - FIBER INTERFEROMETER TO DEDUCE FORCE ON TEST MASS
    - WORKS WITH PIEZO STACK TO MAINTAIN FRINGE ALIGN.









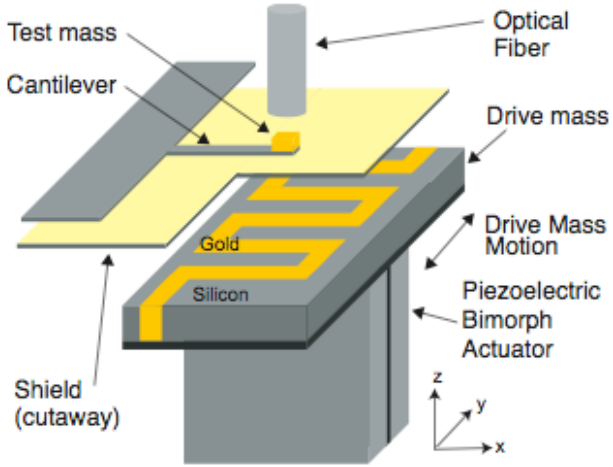


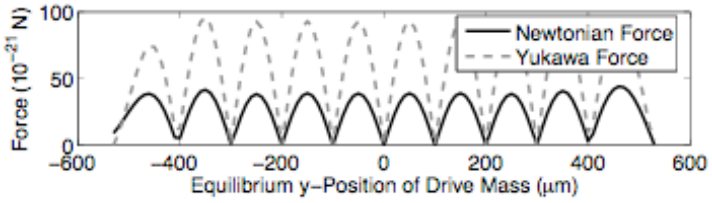
STANFORD MICROCANTILEVER

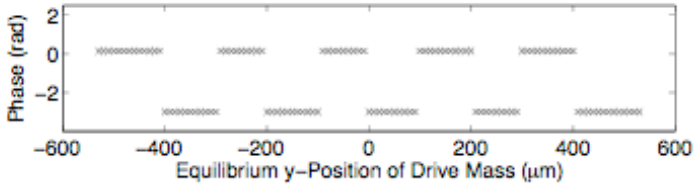
- **MEASURE FORCE VS. Y-POSITION**
  - ANY COUPLING BETWEEN MASSES WILL SHOW PERIODICITY
  - COMPARE MEASUREMENT TO PREDICTIONS BASED ON FEA
  - GIVES A BOUND ON YUKAWA-TYPE DEVIATIONS
  - USE SPATIAL PHASE-SENSITIVE DETECTION

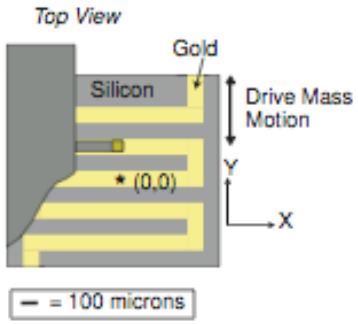
- **MEASUREMENT SCHEME:**
  - GRAVITATIONAL TESTS:
    - MEANDER GROUNDED
    - 100μm FORCE PERIODICITY
  - MAGNETIC TESTS:
    - APPLY AC CURRENT THROUGH MEANDER , BIMORPH STILL
    - DRAW DC CURRENT, BIMORPH MOVING
    - SAME RESULT: SEE MAGNETIC COUPLING B/W MASSES
    - 200μm FORCE PERIODICITY, PI PHASE CHANGE

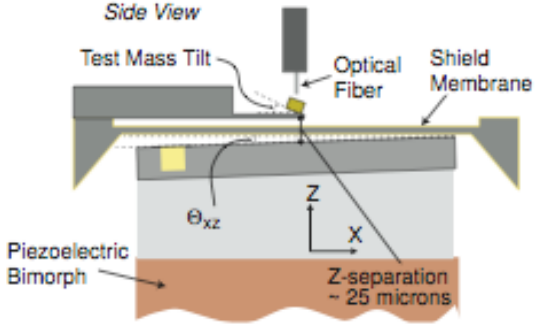
- **ALIGNMENT MEASUREMENTS:**
  - FEA SENSITIVE TO ALIGNMENTS MUST MEASURE
  - TILTS SHIMMED & 3-AXIS POSITIONERS USED
  - Z DETERMINED BY CANTI-SHIELD TOUCH THEN BACKED OFF









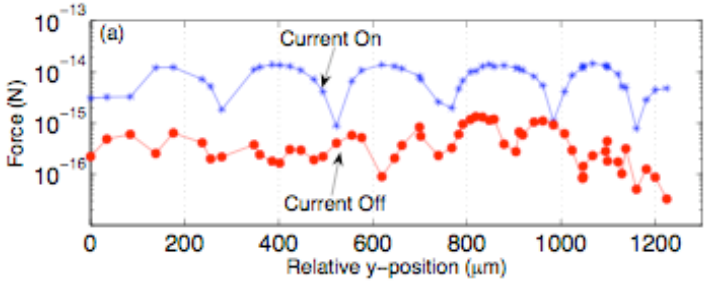


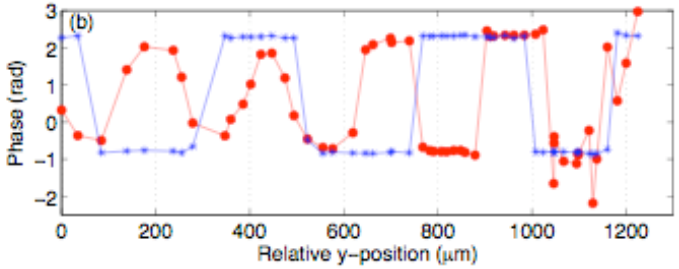
STANFORD MICROCANTILEVER

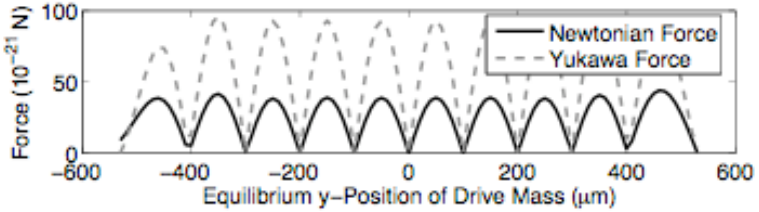
- **MAGNETIC ANALOG EXPERIMENT:**
  - BIMORPH MOVING, 1/3 RESONANT FREQUENCY
  - STEP THROUGH Y-POSITION, MEASURE FORCE
  - MEASURE CURRENT ON == MAGNETIC CASE
  - MEASURE CURRENT OFF == GRAVITATIONAL CASE

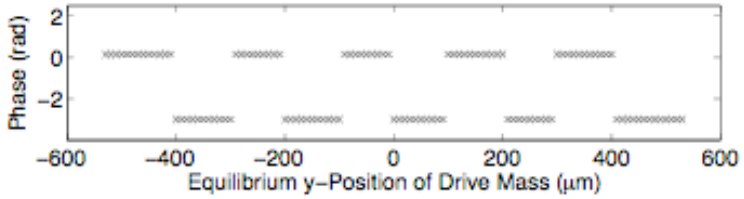
- **RESULTS:**
  - CONFIRMS ALIGNMENT B/W MASSES
  - FEA PREDICTIONS OF FORCE PERIODICITY
  - NO DRIVE CURRENT WAY TOO BIG FOR GRAVITY
    - NOT DUE TO CASIMIR / ELECTROSTATIC
    - PURELY MAGNETIC
    - DRIVE MASS MAGNETIZED BY AMBIENT FIELD
    - TEST MASS A MAGNETIC SUSCEPTOMETER
  - SUSCEPTOMETER PLACES LIMIT ON GRAVITATIONAL SENSITIVITY WITH MAG. TEST MASS

  - VERIFICATION OF FORCE SENSITIVITY OF CANTILEVER!!



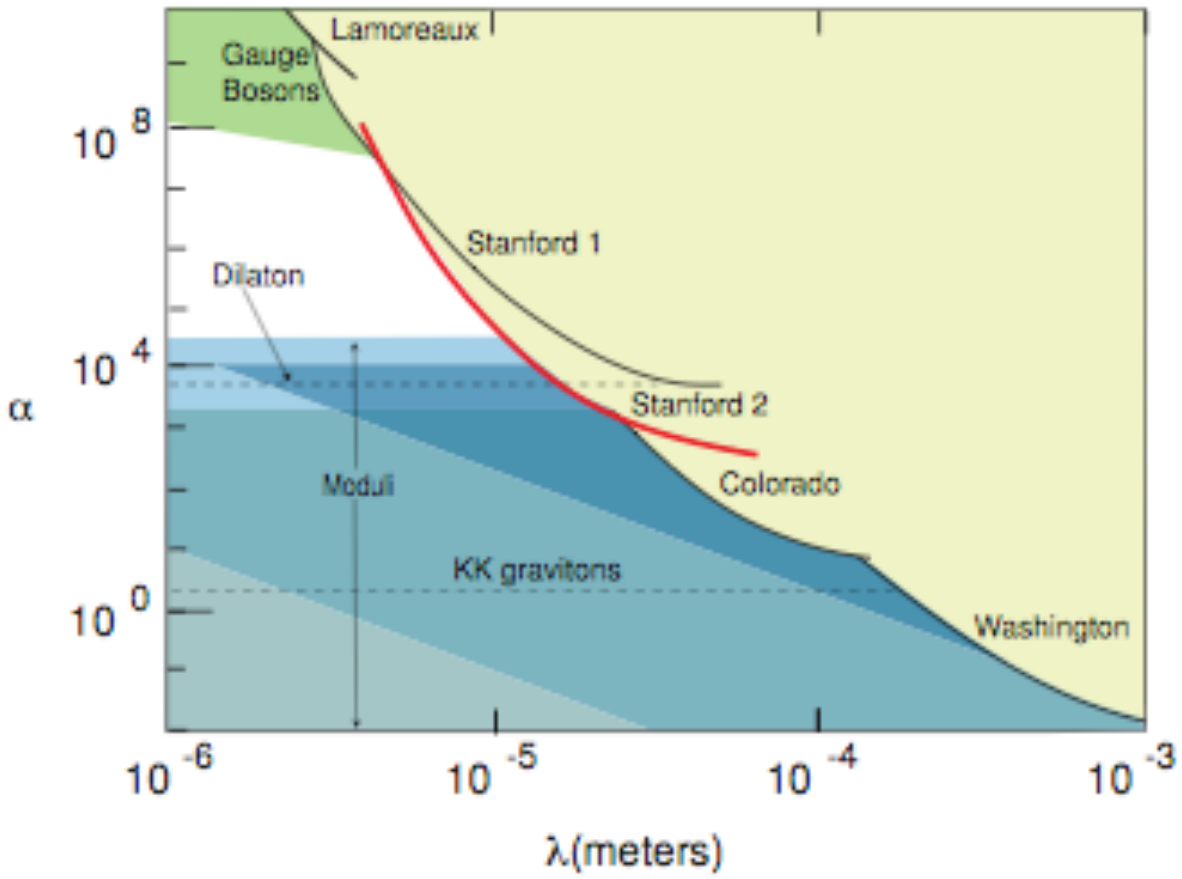






STANFORD MICROCANTILEVER

- **RESULTS:**
  - ORDER OF MAGNITUDE IMPROVEMENT OVER PREVIOUS RESULTS AT λ~20μm
  - MOST STRINGENT CONSTRAINTS ON YUKAWA POTENTIALS: 6 - 20μm
  - CONSTRAINS PREDICTIONS OF MODULI & GAUGE BOSONS
  - DOES NOT RULE OUT M-THEORY / LARGE EXTRA DIMENSIONS



CASIMIR EFFECT: SKIMMING

- **RESULTS STRENGTHEN CONSTRAINTS FOR λ~ 30-86nm**
- **MICROMECHANICAL TORSION OSCILLATOR**
- **MEASURES CASIMIR PRESSURE BETWEEN GOLD-COATED PLATES OR PLATE AND SPHERE**
- **RESONANT FREQUENCY OF OSCILLATOR RELATED TO CASIMIR FORCE**
  - SHIFT OF RESONANCE GIVES $\partial F(z)/\partial z$ BY: $$\omega_r^2 = \omega_0^2 \left[1 - \frac{b^2}{I\omega_0^2} \frac{\partial F(z)}{\partial z}\right]$$
  - CASIMIR PRESSURE IS THEN: $$P(z) = -\frac{1}{2\pi R} \frac{\partial F(z)}{\partial z}.$$
- **EXPERIMENTAL DATA:**