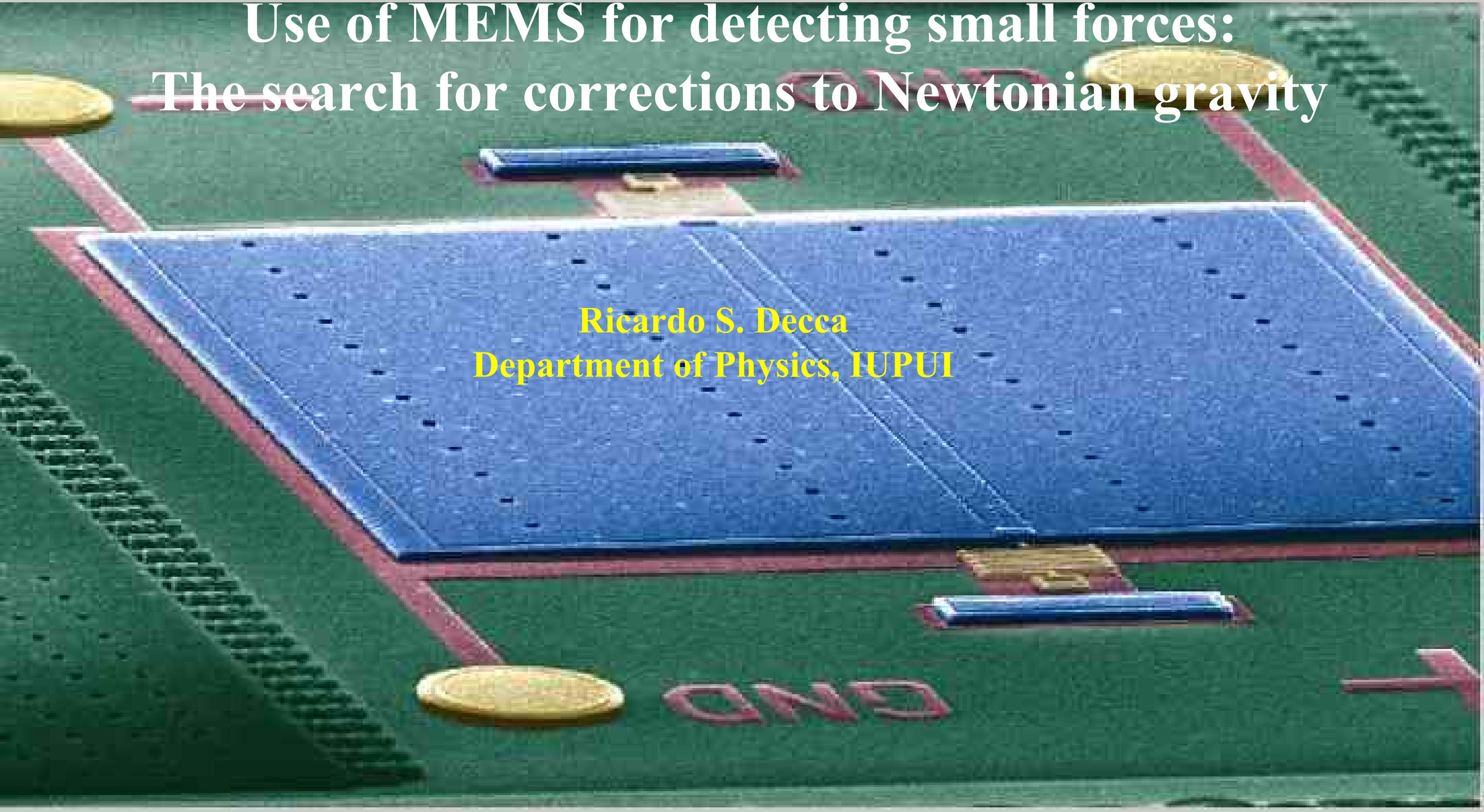
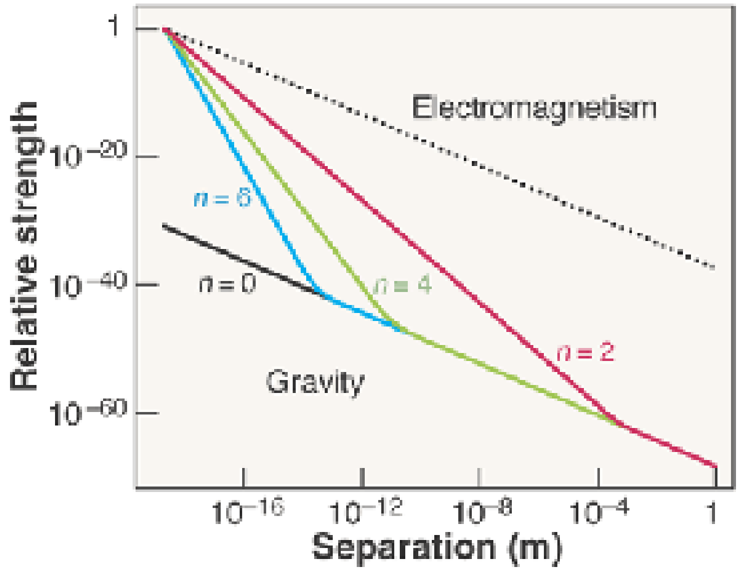
Use of MEMS for detecting small forces: The search for corrections to Newtonian gravity

Ricardo S. Decca
Department of Physics, IUPUI



Collaborators

Daniel López	Lucent Technologies
Ho Bun Chan	University of Florida
Ephraim Fischbasch	Purdue University
Dennis E. Krausse	Wabash College and Purdue University
Valdimir M. Mostepanenko	Universidade Federal da Paraíba
Galina L. Klimchitskaya	Universidade Federal da Paraíba
Chris Jamell	IUPUI
Mark Hanni	IUPUI



Jonathan L. Feng, Science **301**, 795 ('03)

The strength of gravity for various numbers of large extra dimensions n, compared to the strength of electromagnetism (dotted)

Without extra dimensions, gravity is weak relative to the electromagnetic force for all separation distances.

With extra dimensions, the gravitational force rises steeply for small separations and may become comparable to electromagnetism at short distances.

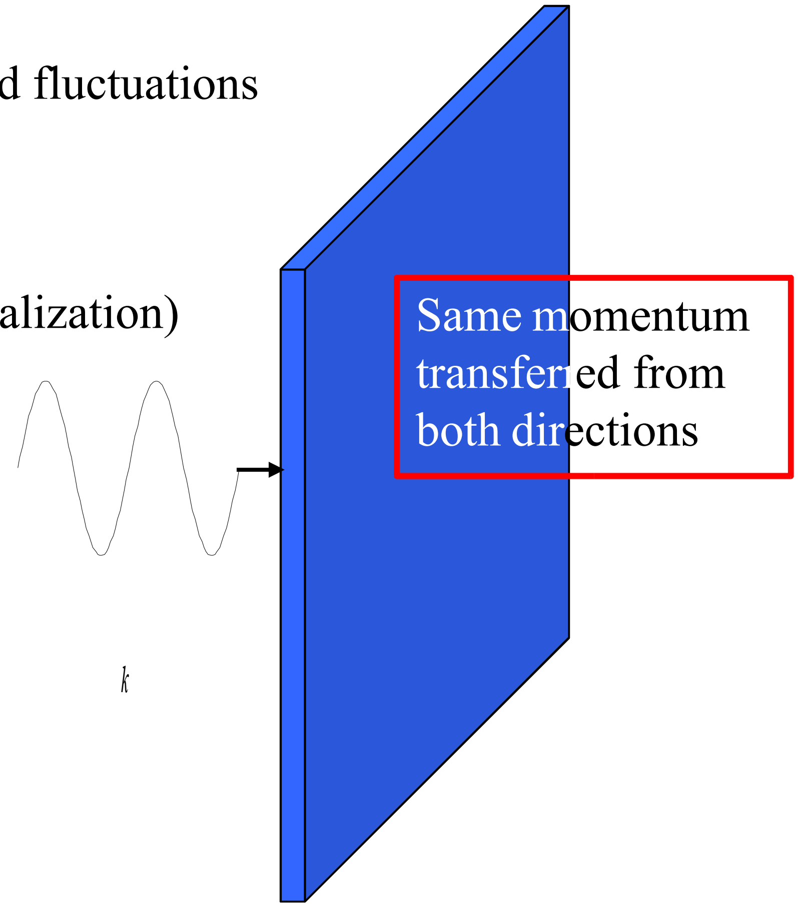
What is the background?

Outline

- Casimir forces
- Why Mems?
- Limits from Casimir forces experiments
- Improved "Casimir-less" experiments
- Next generation

What is the Casimir force?

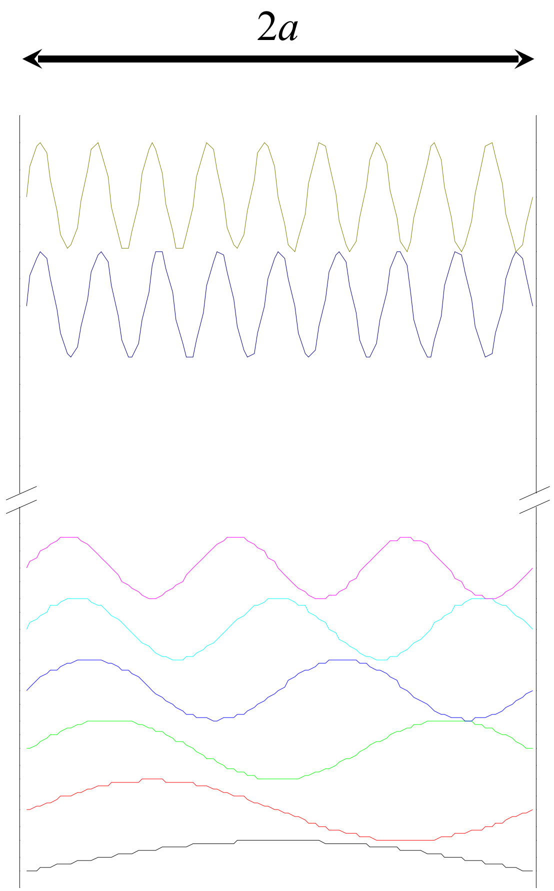
- Zero-point vacuum electromagnetic field fluctuations
- Macroscopic quantum effect
- H. G. B. Casimir, 1948 (Energy renormalization)

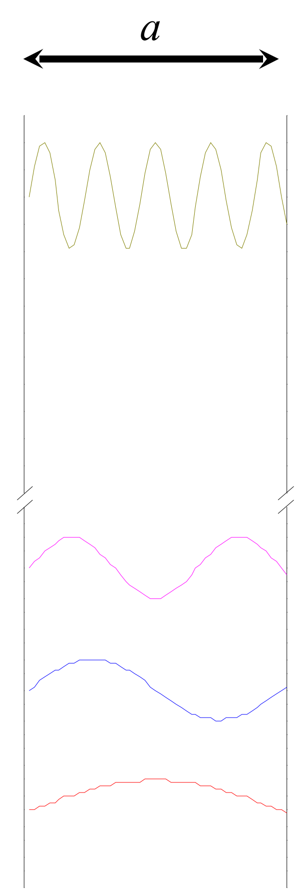


$$\langle 0|E|0\rangle = \langle 0|B|0\rangle = 0$$

$$\frac{1}{2}\langle 0|(E^2+B^2)|0\rangle = \langle 0|E^2|0\rangle = \frac{1}{2\Omega}\sum_{\omega,k}\omega_k$$

$$(\hbar = c = 1)$$





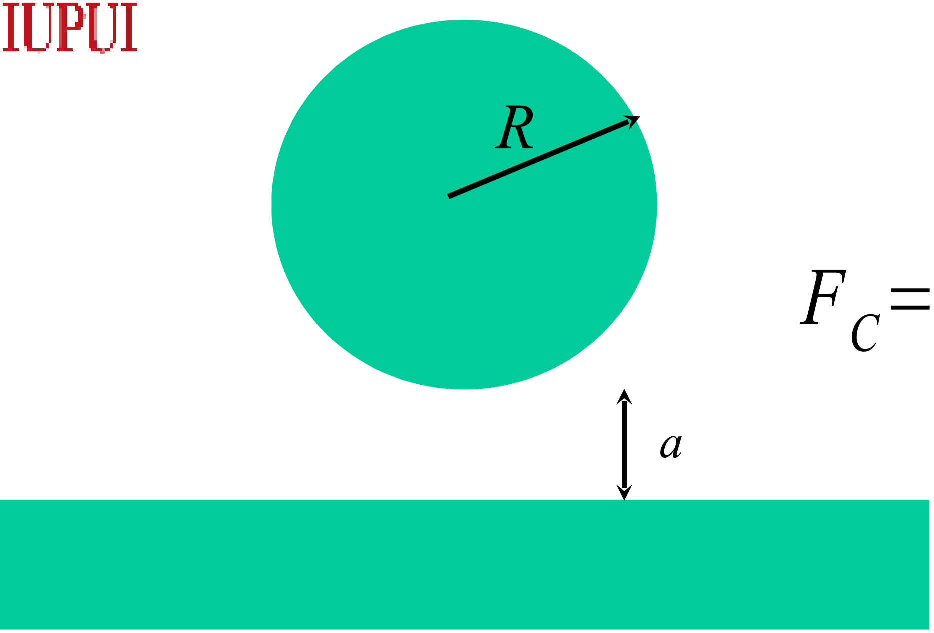
Attractive force!

$$P_C = -\frac{\pi^2 \hbar c}{240 a^4}$$

- Dominant electronic force at small (~ 1 nm) separations
- Non-retarded: van der Waals
- Retarded: Casimir

No mode restriction on the outside

Proximity force theorem



$$F_C = 2\pi R \times E_C = 2\pi R \times \left(\frac{1}{2\Omega} \sum_{,k} \hbar \quad {}_k \right)$$

E_C: energy density

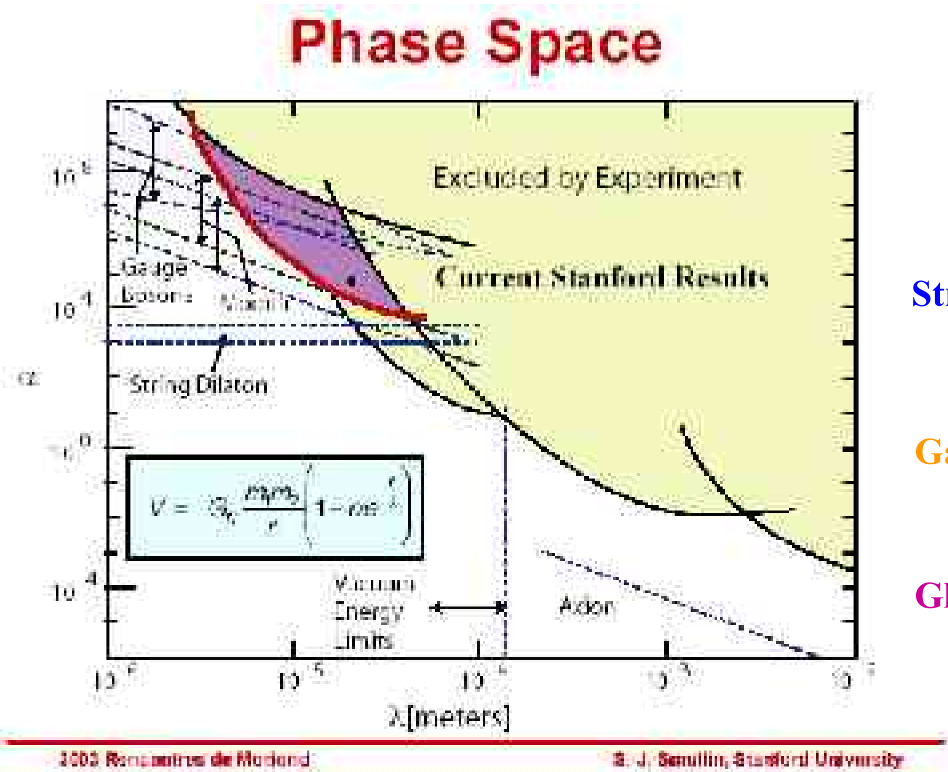
Believed to be exact for Casimir interaction.
Proved to produce errors smaller than *a/R ~ 1/1000*

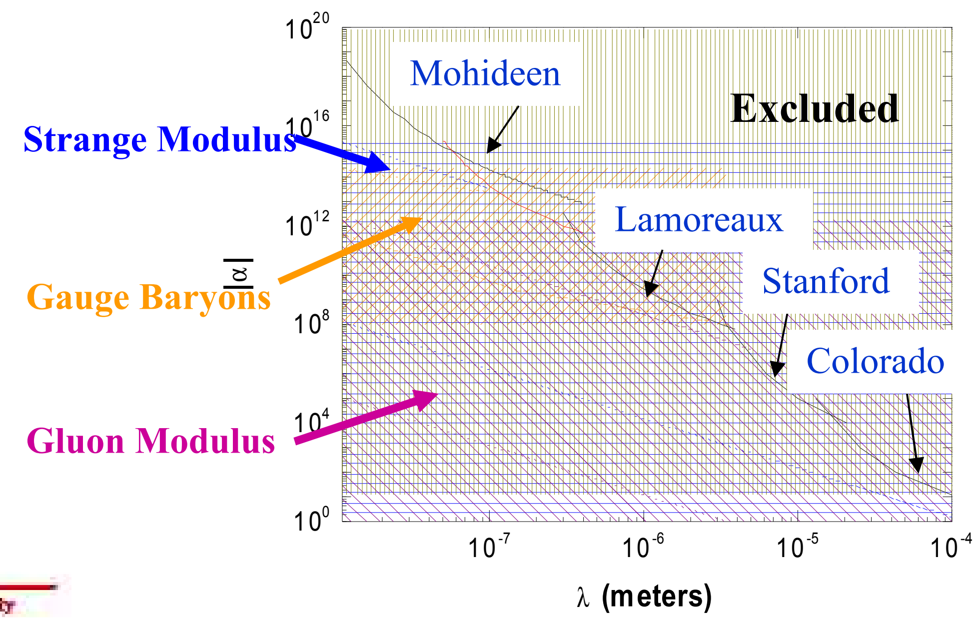
Yukawa-like potential

$$V(r) = -G\frac{m_1 m_2}{r}\left(1+\alpha \cdot e^{-r/\lambda}\right)$$

Arises from very different pictures:

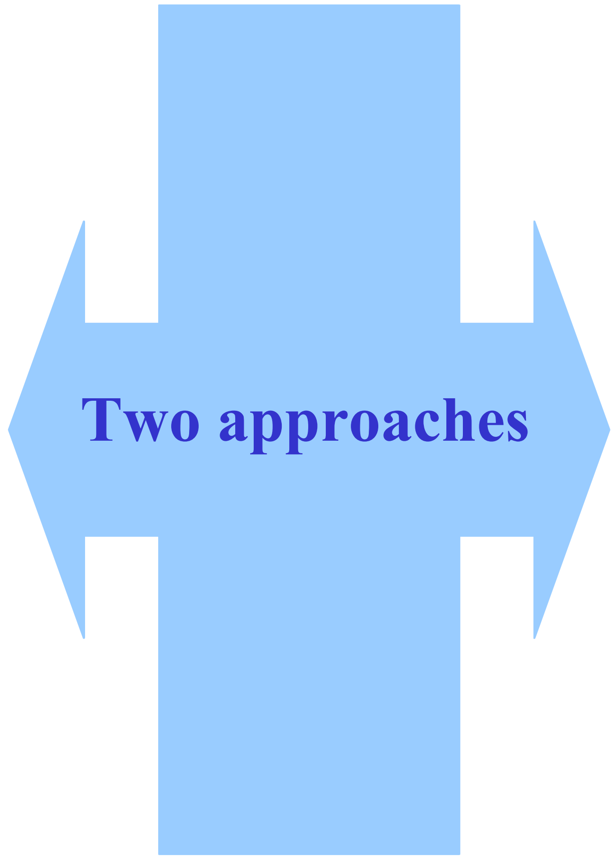
- Compact extra-dimensions
- Exchange of light (but massive, $\mu = 1/\lambda$) bosons
  - -Moduli
  - -Graviphotons
  - -Dilatons
  - -Hyperphotons
  - -Axions





Approaches

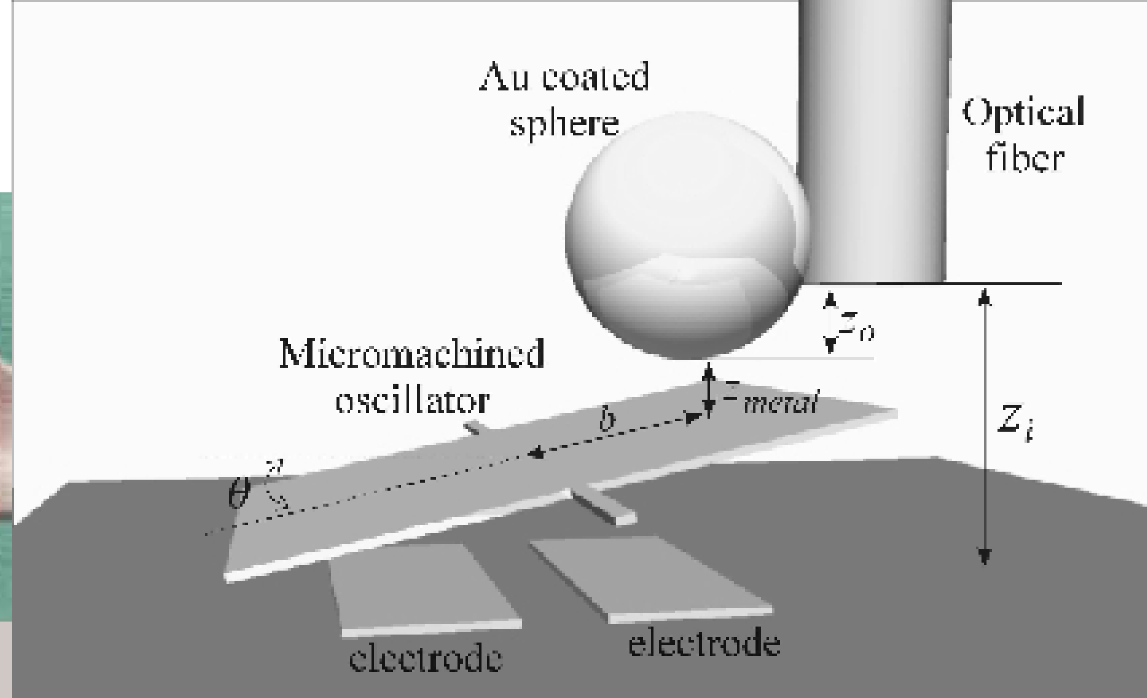
Measure and understand the Casimir force very well

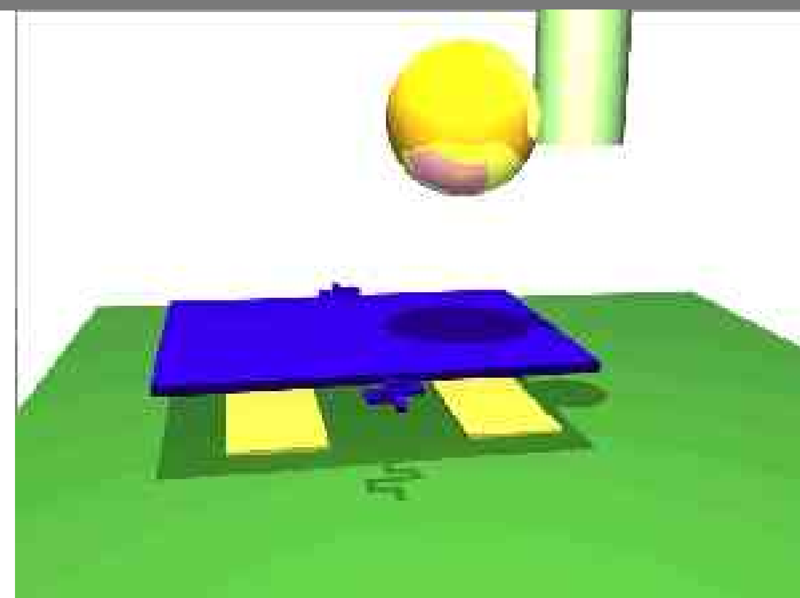


Work in an environment with the effect of the Casimir force minimized

Experimental setup

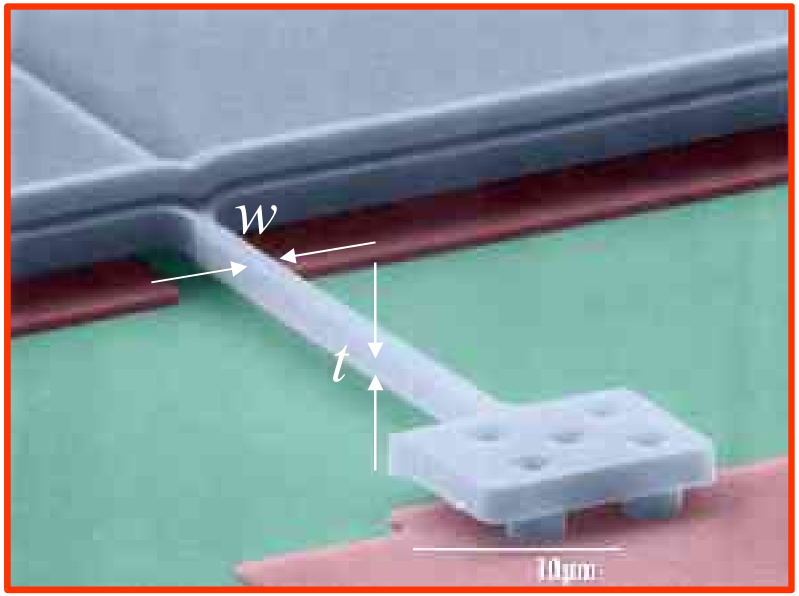
$$z_{metal} = z_i - z_o - z_g - b\Theta$$



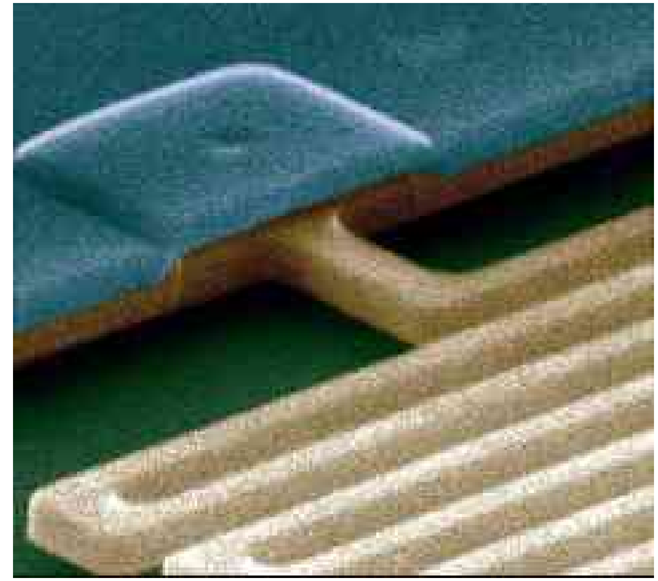


IUPUI

$$\delta F = \sqrt{\frac{(2 k_B T \kappa)}{\pi f_r Q}}\,\frac{1}{b}$$



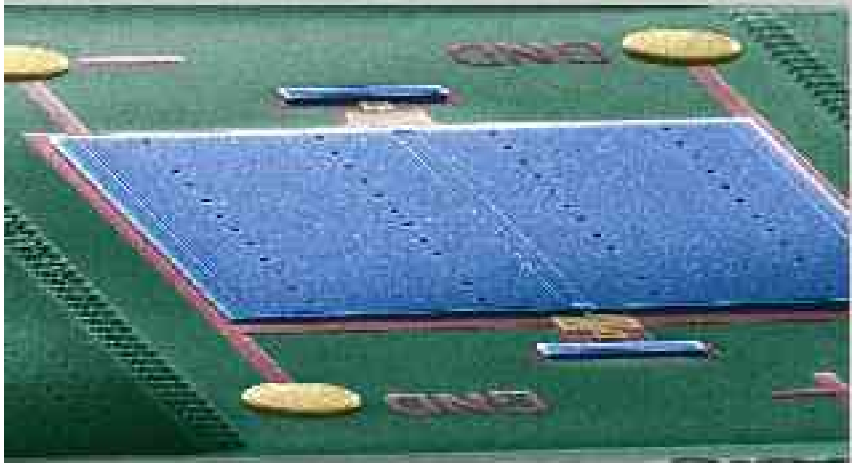
$w,\ t = 2\mu m$

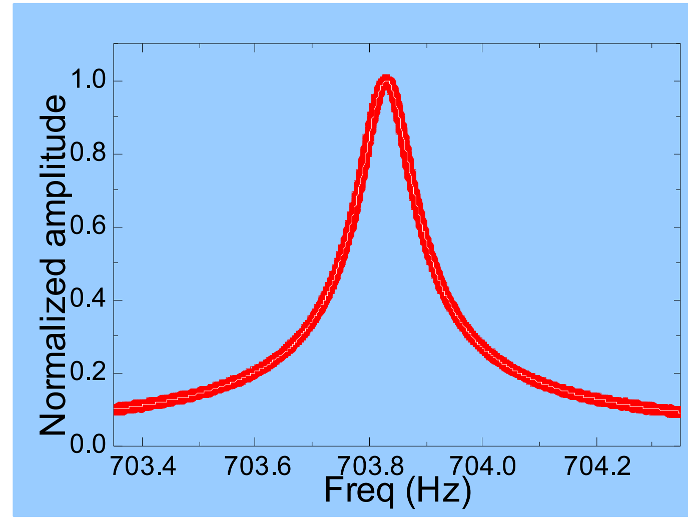


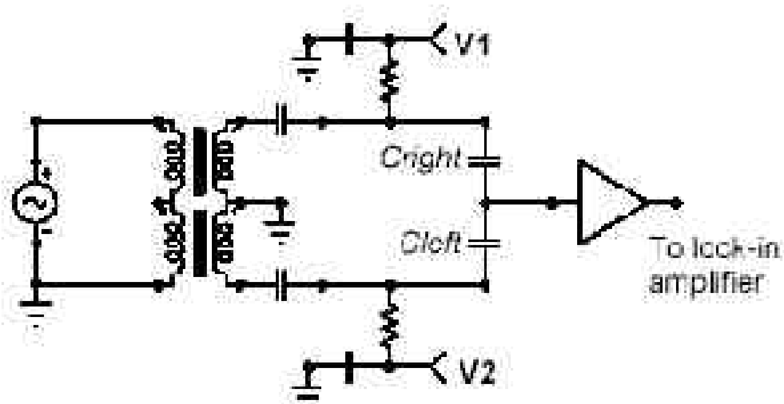
$$\kappa_s = \frac{w t^3 E_{Si}}{6 L_{serp}}$$

$$\kappa_r \approx \frac{2 w^3 t E_{Si}}{3L}$$

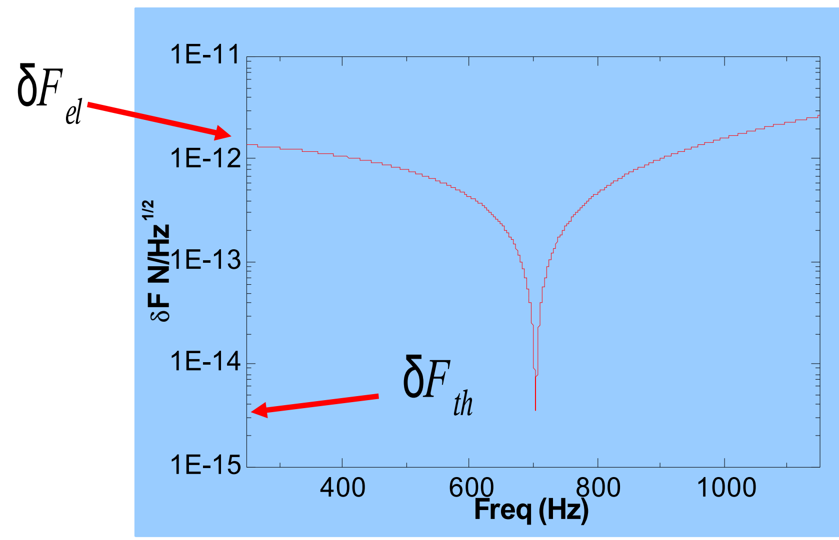
$$\kappa_s \approx \kappa_r / 40$$





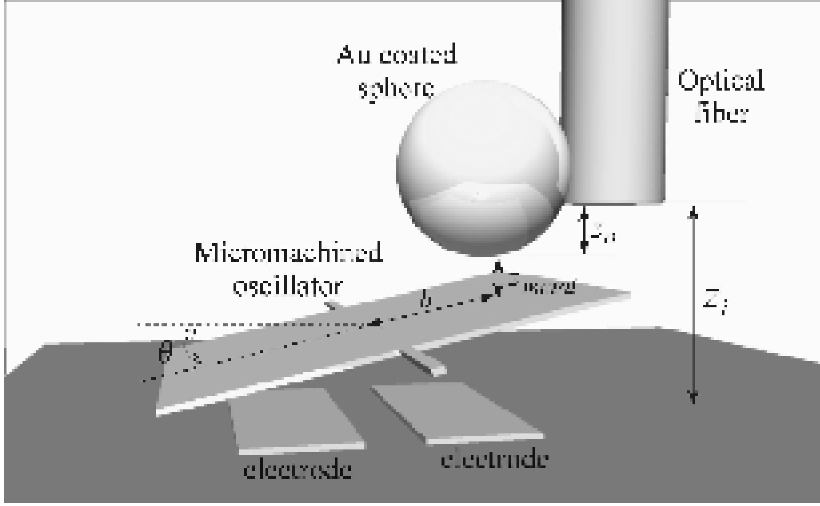


$\delta\theta \approx 10^{-9}\,\mathrm{rad}/\sqrt{\mathrm{Hz}}$

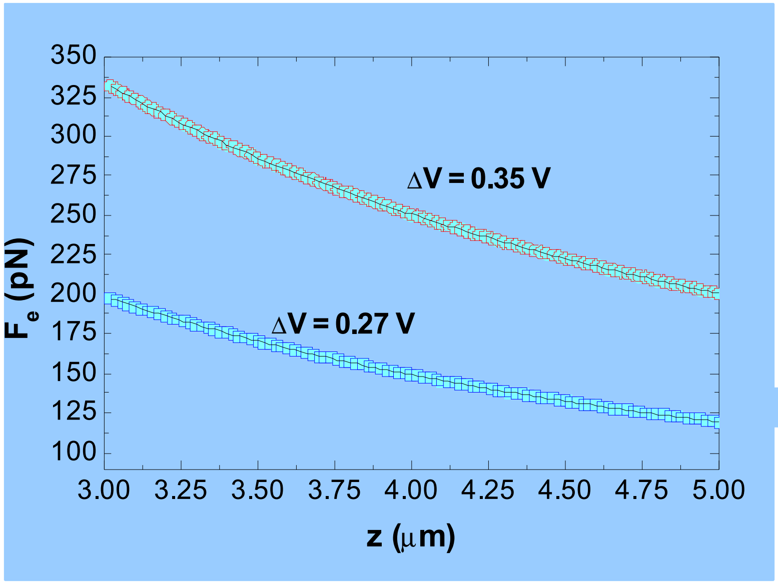


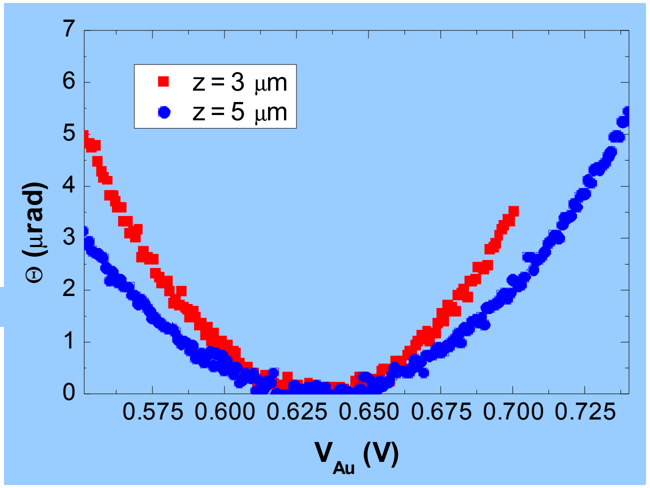
$$\delta F = \frac{1}{b}\sqrt{\left(\frac{4k_B T\kappa}{\omega_0 Q}\right) + \left(\frac{\delta\theta\,\kappa_{el}}{A(\omega)}\right)^2} = \sqrt{(\delta F_{th})^2 + (\delta F_{el})^2}$$

Static measurements



Calibration

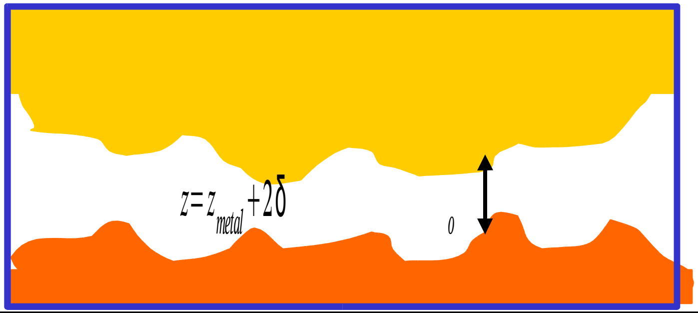


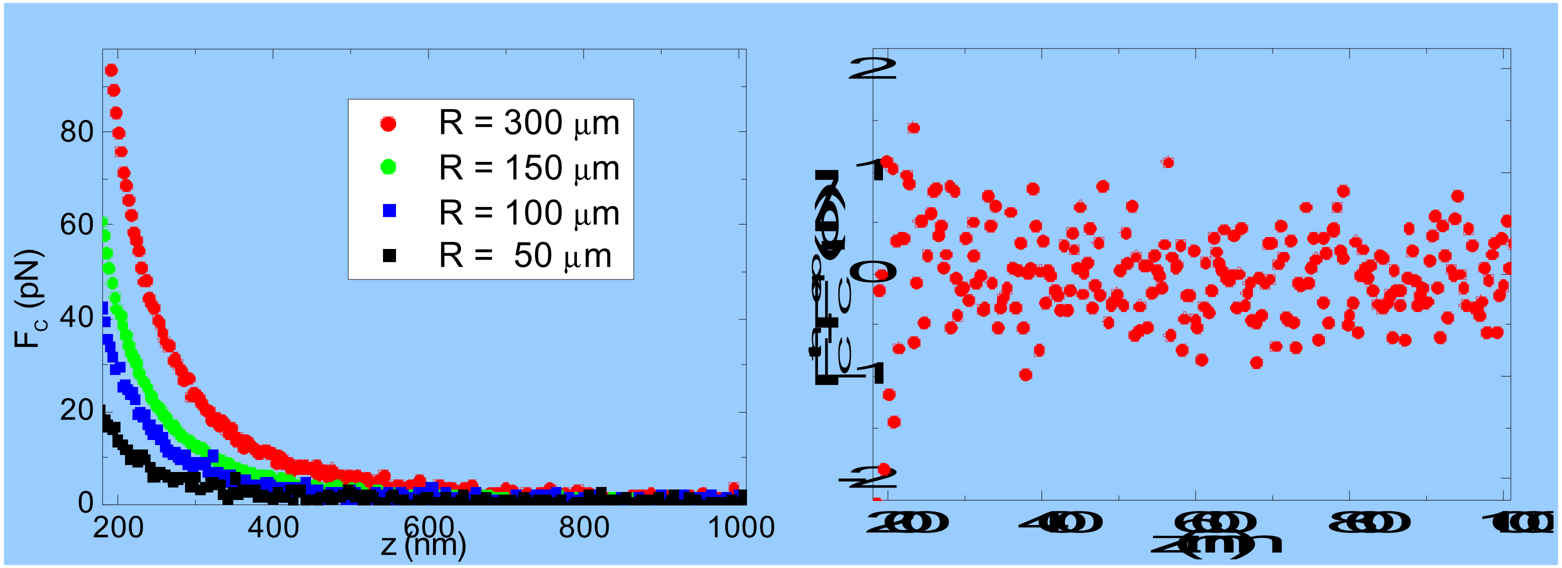


$$F_e \approx \pi\varepsilon_0 (V - V_{Au})^2 \frac{R}{(z_{metal} + 2\delta_0)}$$

Fit:

- R
- V_{Au}
- δ_o
- κ





Theory considers:

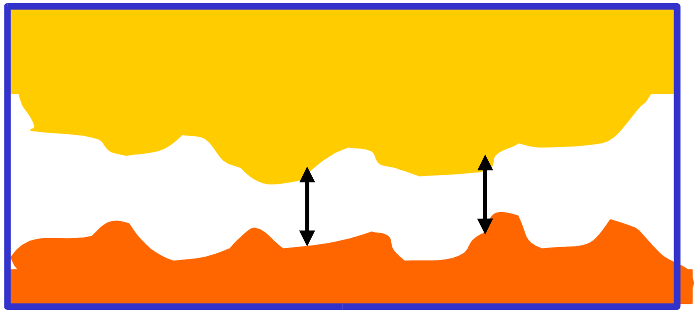
Agreement: 1.3 %

- Finite conductivity corrections
- Roughness

$$F_{CS}(z)=\frac{\hbar}{2\pi c^2}R\int_0^\infty \xi^2 d\xi\int_1^\infty p\left\{\ln\left[1-\frac{(s_1-p)(s_2-p)}{(s_1+p)(s_2+p)}e^{-2p\xi z/c}\right]+\ln\left[1-\frac{(s_1-\varepsilon_1 p)(s_2-\varepsilon_2 p)}{(s_1+\varepsilon_2 p)(s_2+\varepsilon_2 p)}e^{-2p\xi z/c}\right]\right\}dp$$

$$F_C=\sum_i v_i F_{CS}(z)$$

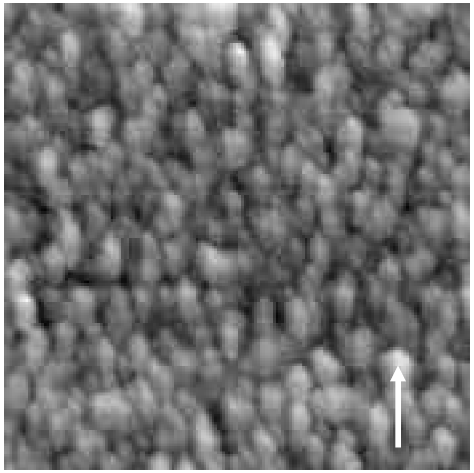
$$s_i=\sqrt{\varepsilon_i-1+p^2}$$

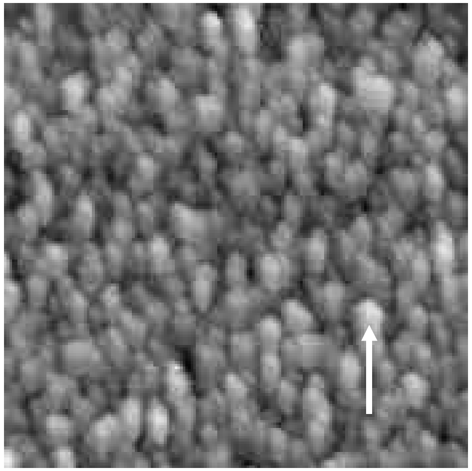


$$F_C = \sum_i v_i F_{CS}(z)$$

v_i: Fraction of the sample at separation zi

AFM image of the Au plane

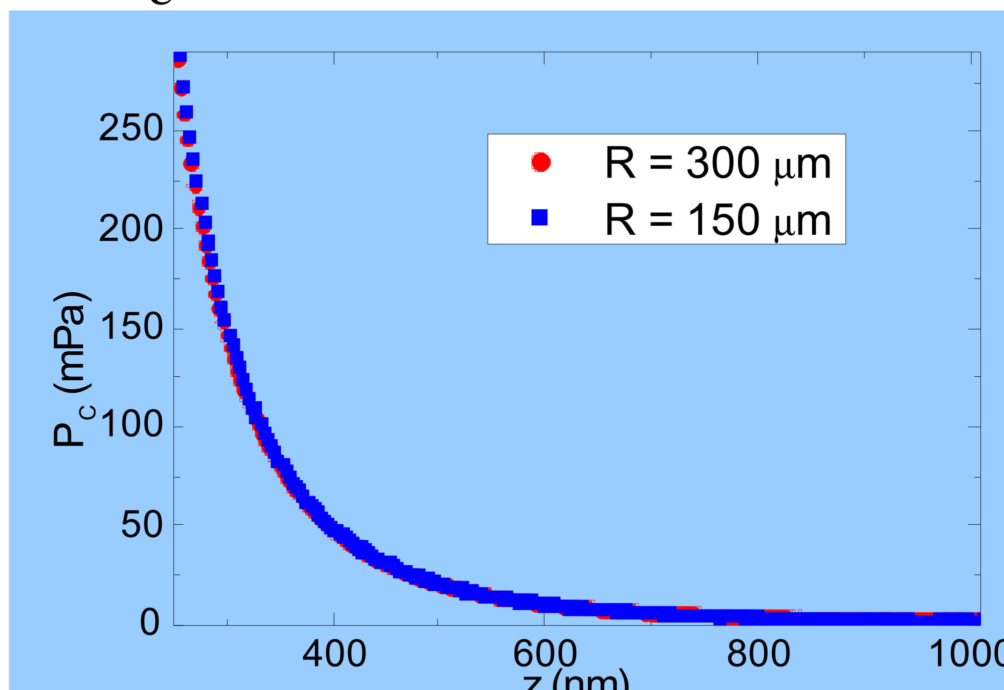




Dynamic measurements

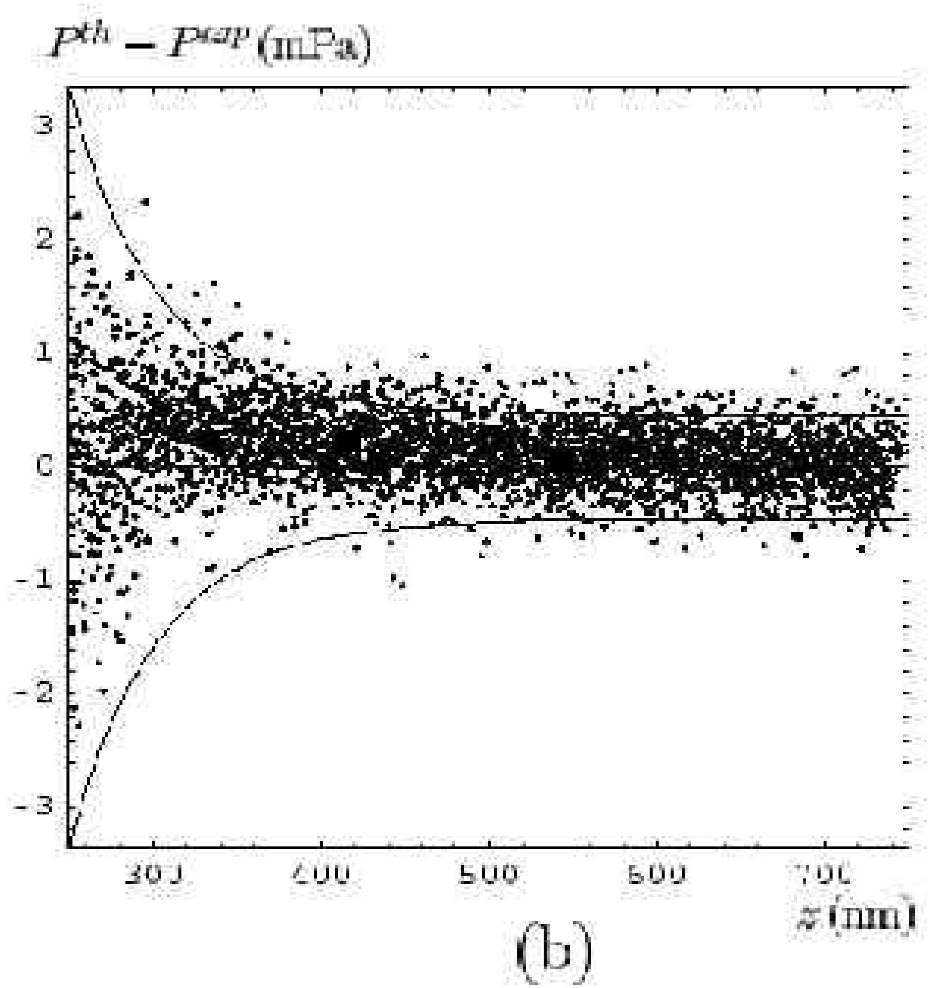
$$\omega_r^2 = \omega_0^2\left(1 - \frac{b^2}{I\omega_0^2}\frac{\partial F_C}{\partial z}\right)$$

$$F_C = 2\pi R \times E_C \Rightarrow \frac{\partial F_C}{\partial z} = 2\pi R \times P_C$$



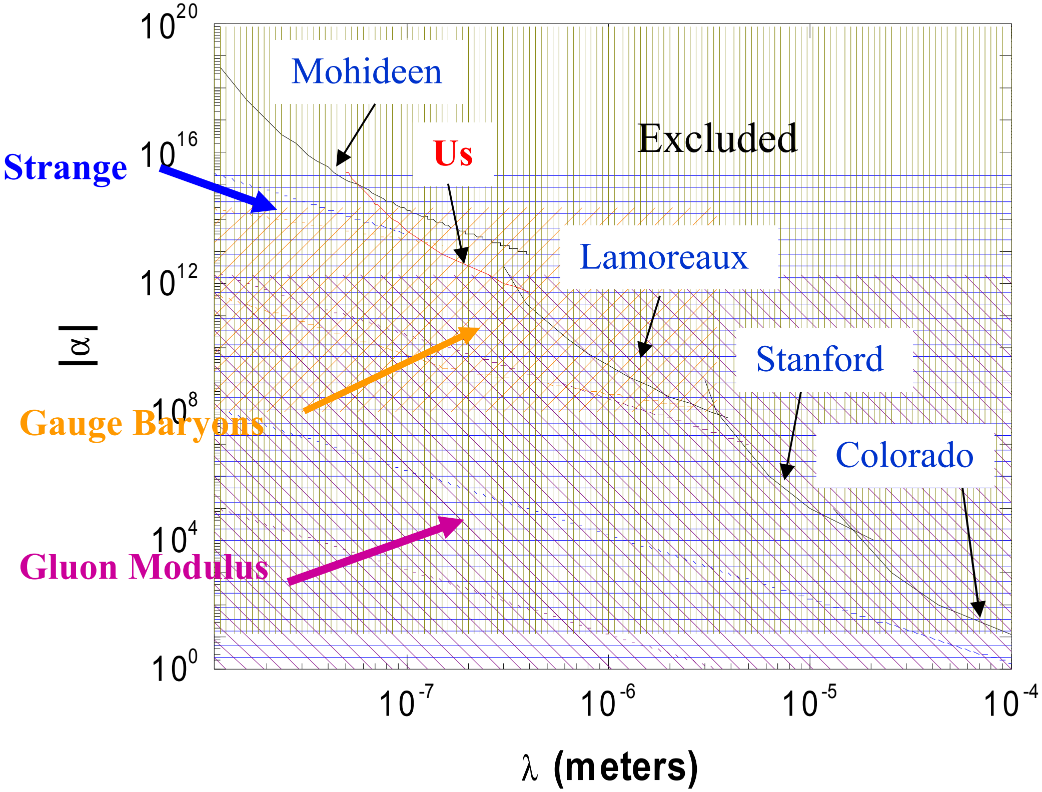
14 sets of measurements

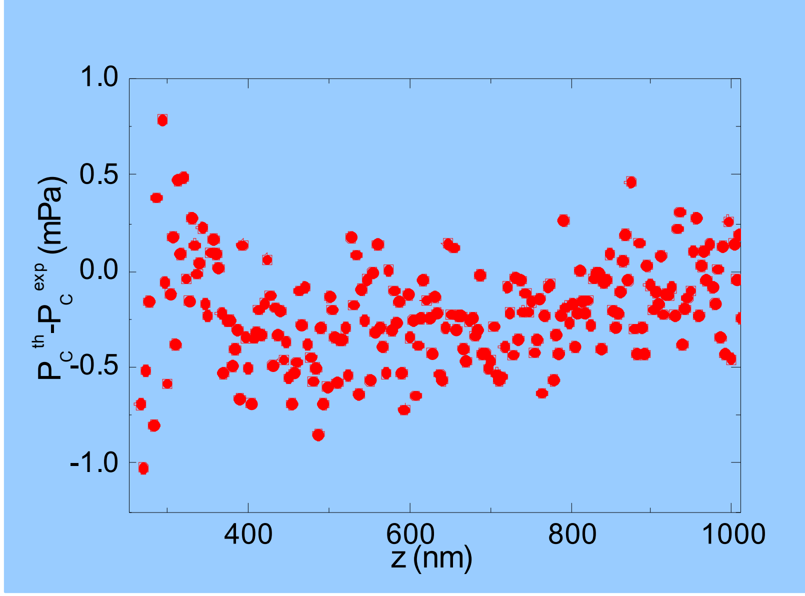
The solid lines represent
95% confidence level



Agreement ~ 1.5%!!!

Limits on Extra Dimensions and New Forces: Sub-micron Limits



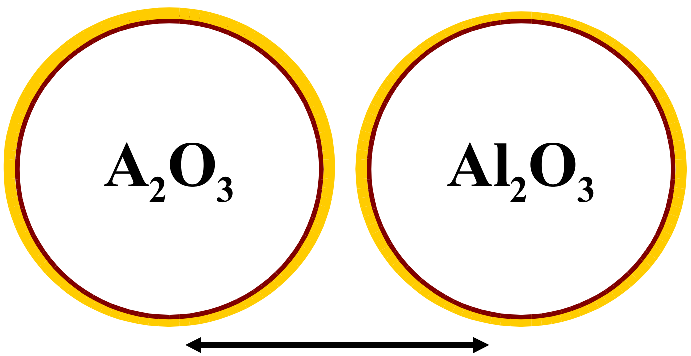


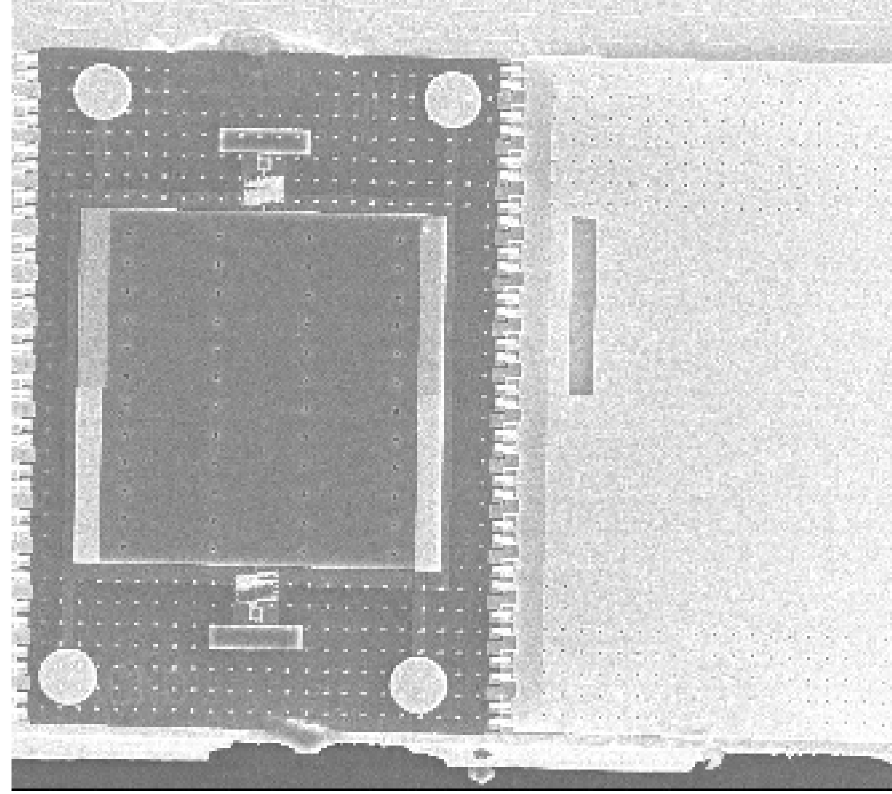
$$V(r)=-G\frac{m_1m_2}{r}\left(1+\alpha \cdot e^{-r/\lambda}\right)$$

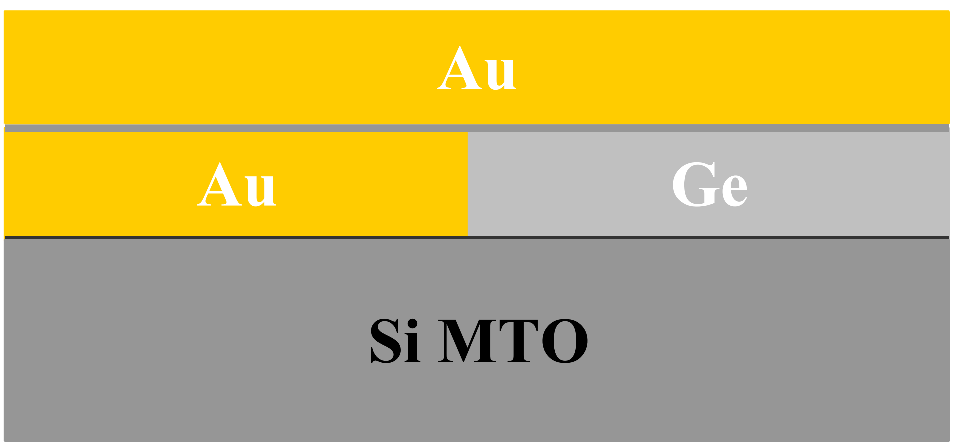
$$P_Y = P_C^{th} - P_C^{exp}$$

Over 1 order of magnitude improvement

“Casimir-less” experiments







$$\Delta F_{hyp} = -4\pi^2 G \alpha \lambda^3 e^{-z/\lambda} R K_s K_p$$

$$K_s = \left[\rho_{Au} - (\rho_{Au} - \rho_{Cr}) e^{-d^s_{Au}/\lambda} - (\rho_{Cr} - \rho_s) e^{-(d^s_{Au} + d_{Cr})/\lambda}\right]$$

$$K_p = \left[\rho_{Au} - \rho_{Ge} e^{-(d^p_{Au} + d_{Pt})/\lambda} \left(1 - e^{-(d_{Ge})/\lambda}\right)\right]$$

IUPUI

$$\Delta F_{hyp} = -4\pi^2 G \alpha \lambda^3 e^{-z/\lambda} R K_s K_p$$

$$K_s = \left[\rho_{Au} - (\rho_{Au} - \rho_{Cr}) e^{-d^s_{Au}/\lambda} - (\rho_{Cr} - \rho_s) e^{-(d^s_{Au} + d_{Cr})/\lambda}\right]$$

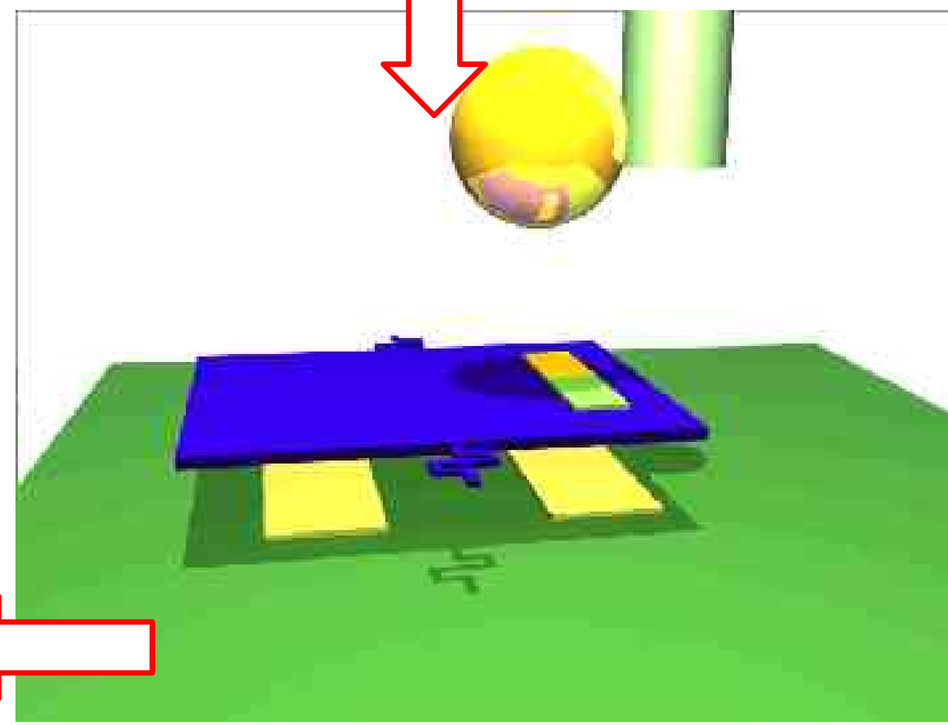
$$K_p = \left[\rho_{Au} - \rho_{Ge} e^{-(d^p_{Au} + d_{Pt})/\lambda}\left(1 - e^{-(d_{Ge})/\lambda}\right)\right]$$

Signal optimization:

Work at ω_r!!!

Alternate

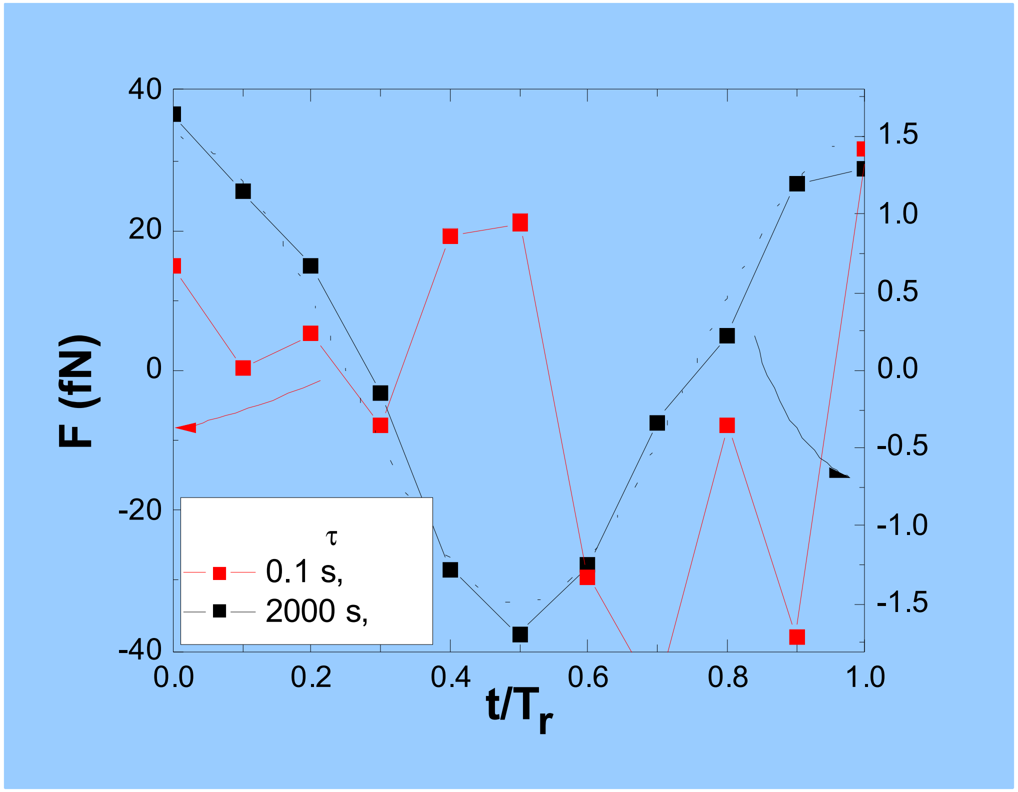
Oscillate plate at f_1, sphere at f_2 such that $f_1 + f_2 = f_r$



$$e^{-z/\lambda} \propto \cos(2\pi f_1 t); \quad \rho_{Au} - \rho_{Ge} \propto \cos(2\pi f_2 t)$$

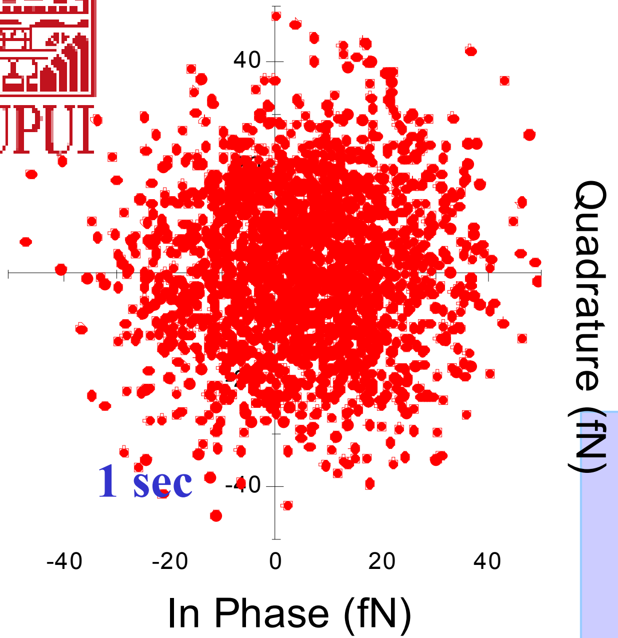
$$\Delta F_{hyp} \propto \cos(2\pi f_r t)$$

Effect of time averaging

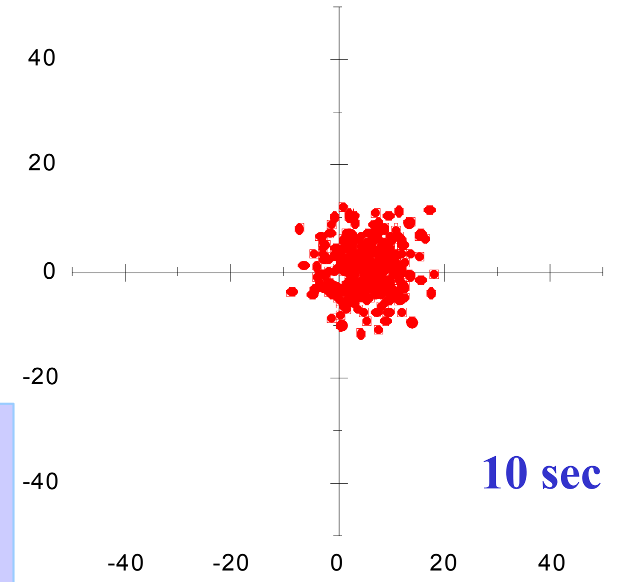


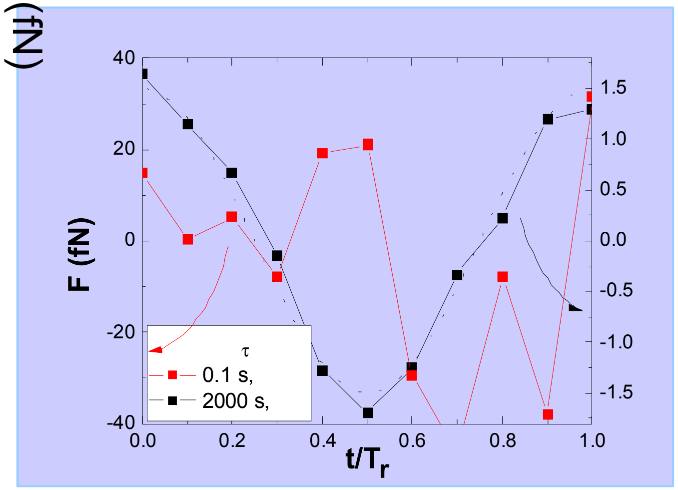
Separation: z_{mo} = 300 nm

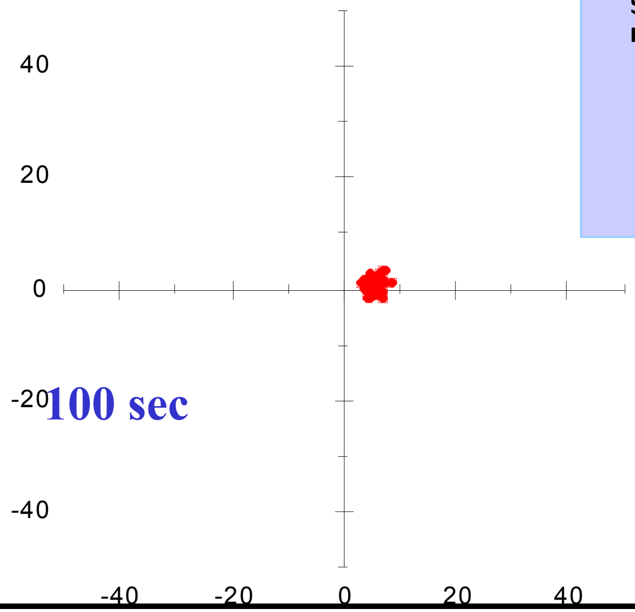
$$F(t) = F_P \cos(\omega_0 t) + F_Q \sin(\omega_0 t)$$

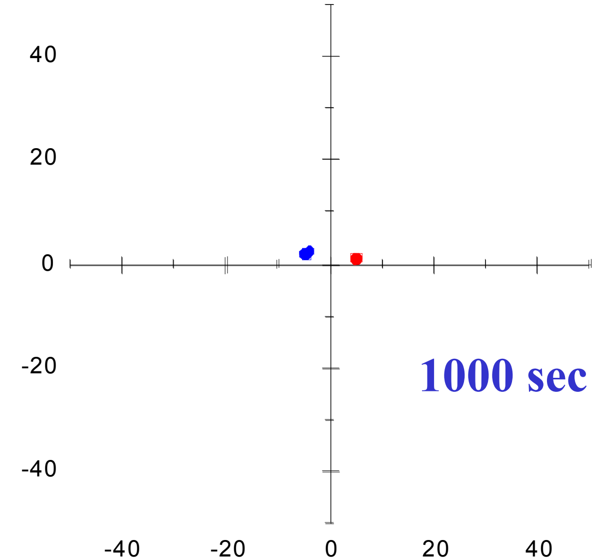


Separation: z_{mo} = 200 nm









IUPUI

Signal optimization:

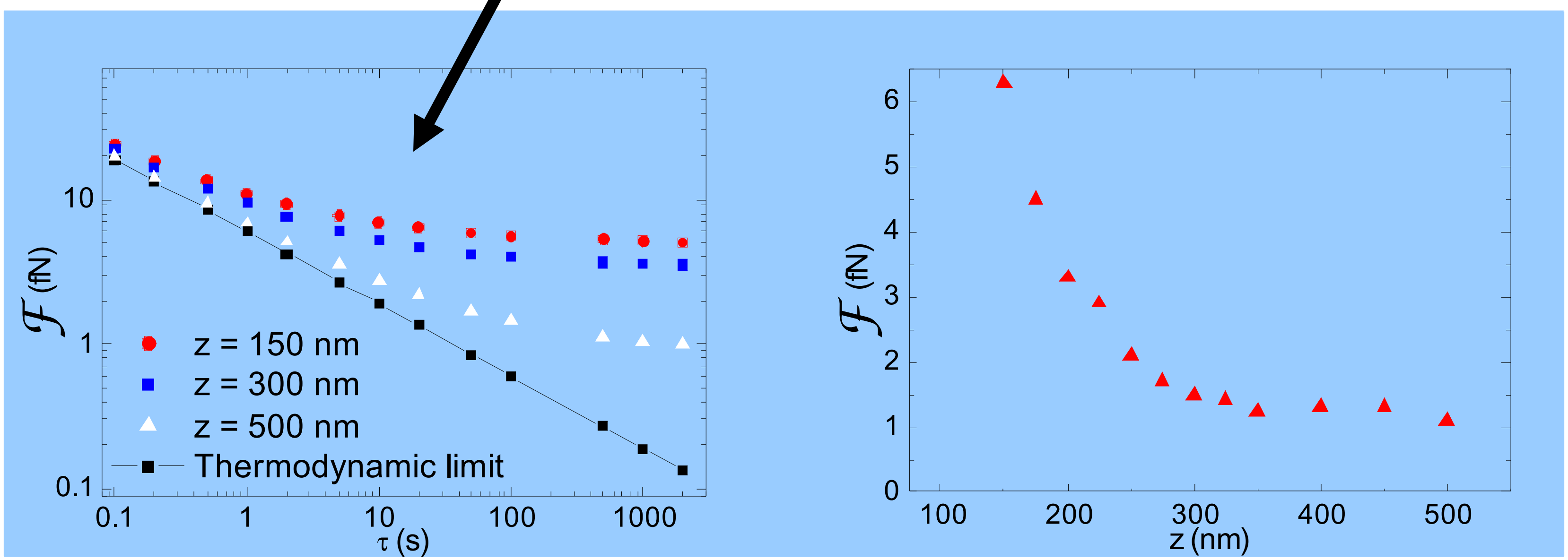
Work at ω_r!!!

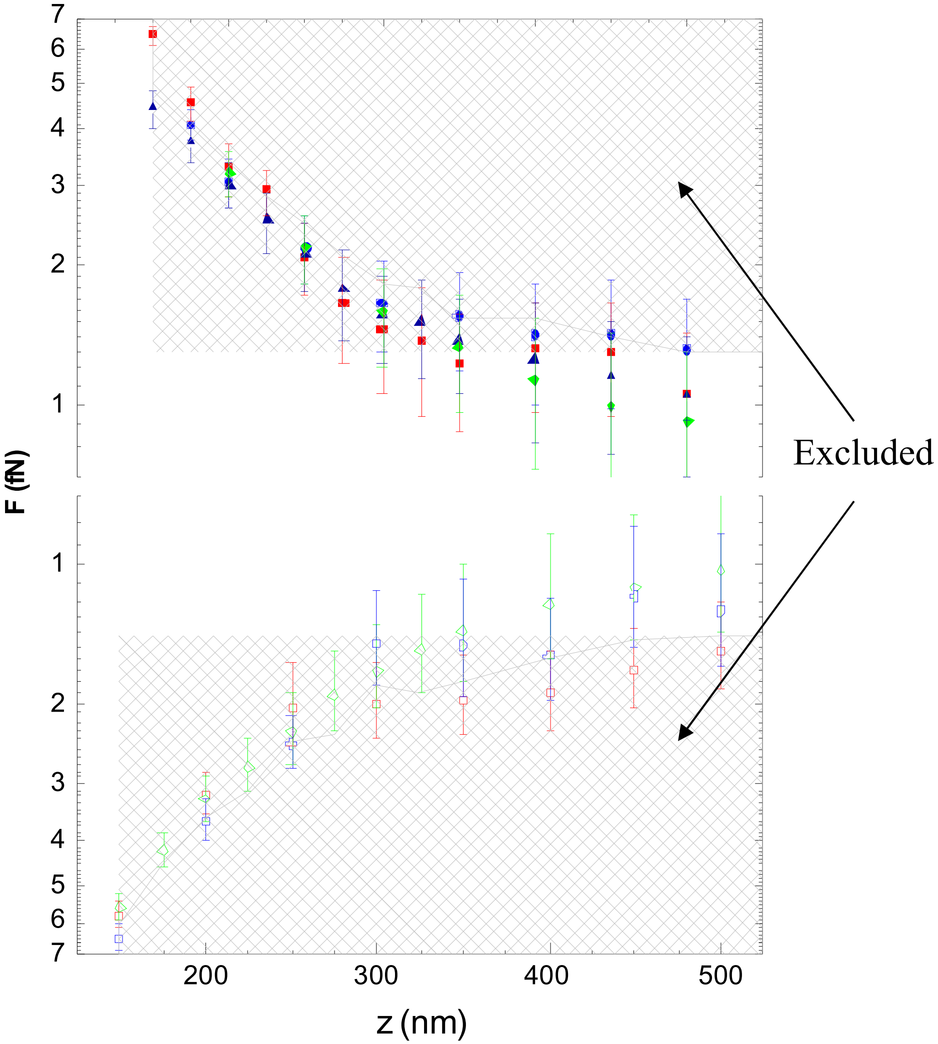
Oscillate plate at f_1, sphere at f_2 such that $f_1 + f_2 = f_r$

$$e^{-z/\lambda} \propto \cos(2\pi f_1 t);\ \rho_{Au} - \rho_{Ge} \propto \cos(2\pi f_2 t)$$

$$\Delta F_{hyp} \propto \cos(2\pi f_r t)$$

95% confidence level



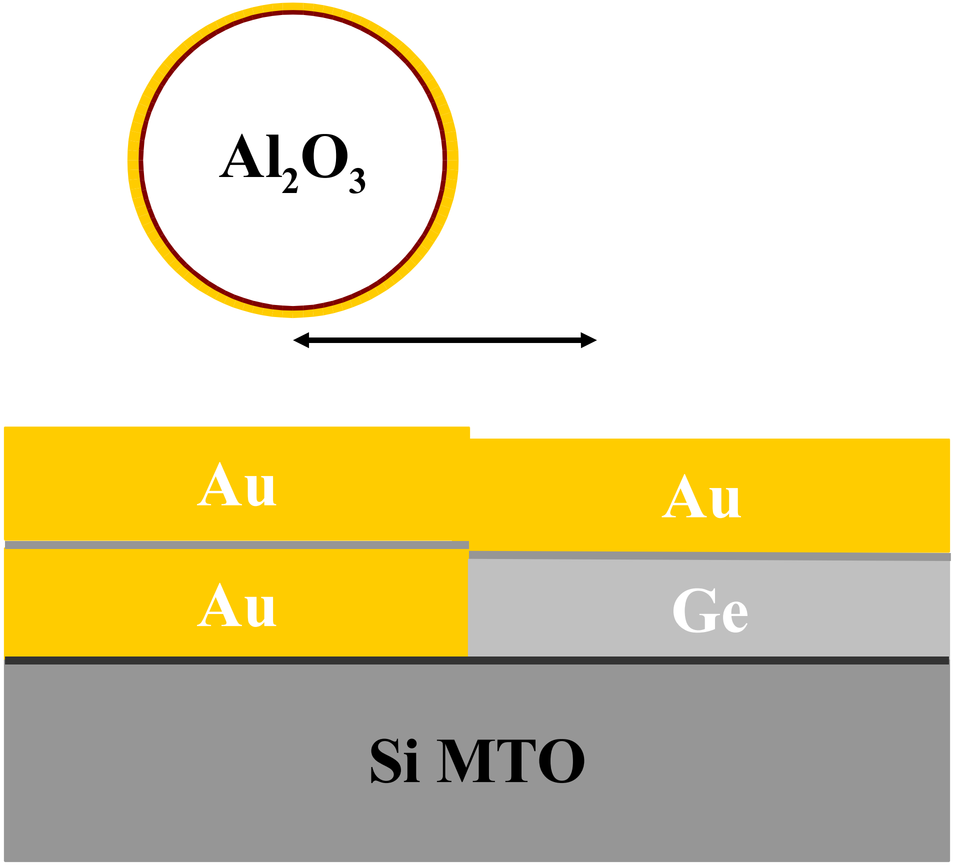


Error bars: 95% confidence level

$$F = \bar{F} \pm t_{6,0.975} \times s_6$$

We used the 95% confidence level of the minimum value

Background



Motion not parallel to the axis
(too small)

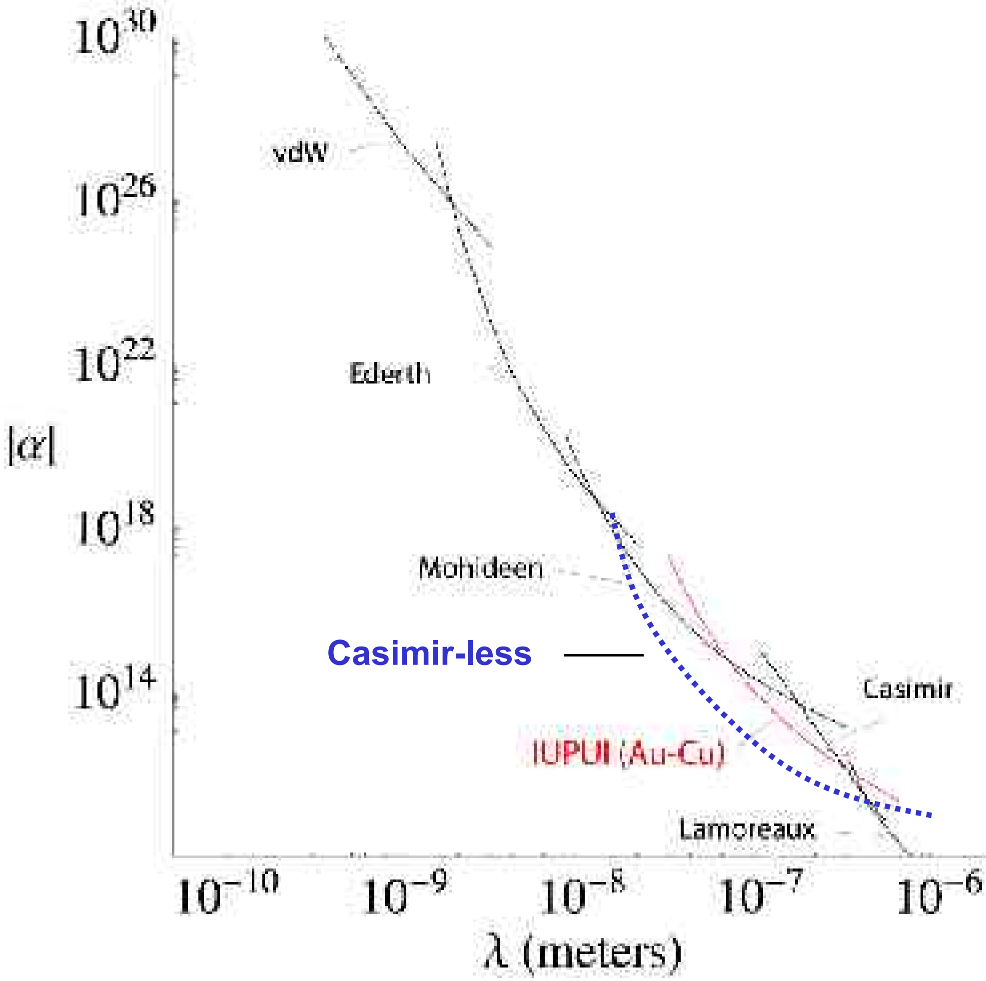
Step
(0.1 nm needed)

Difference in electrostatic force
(0.1 mV needed)

Difference in Au coating
(unlikely)

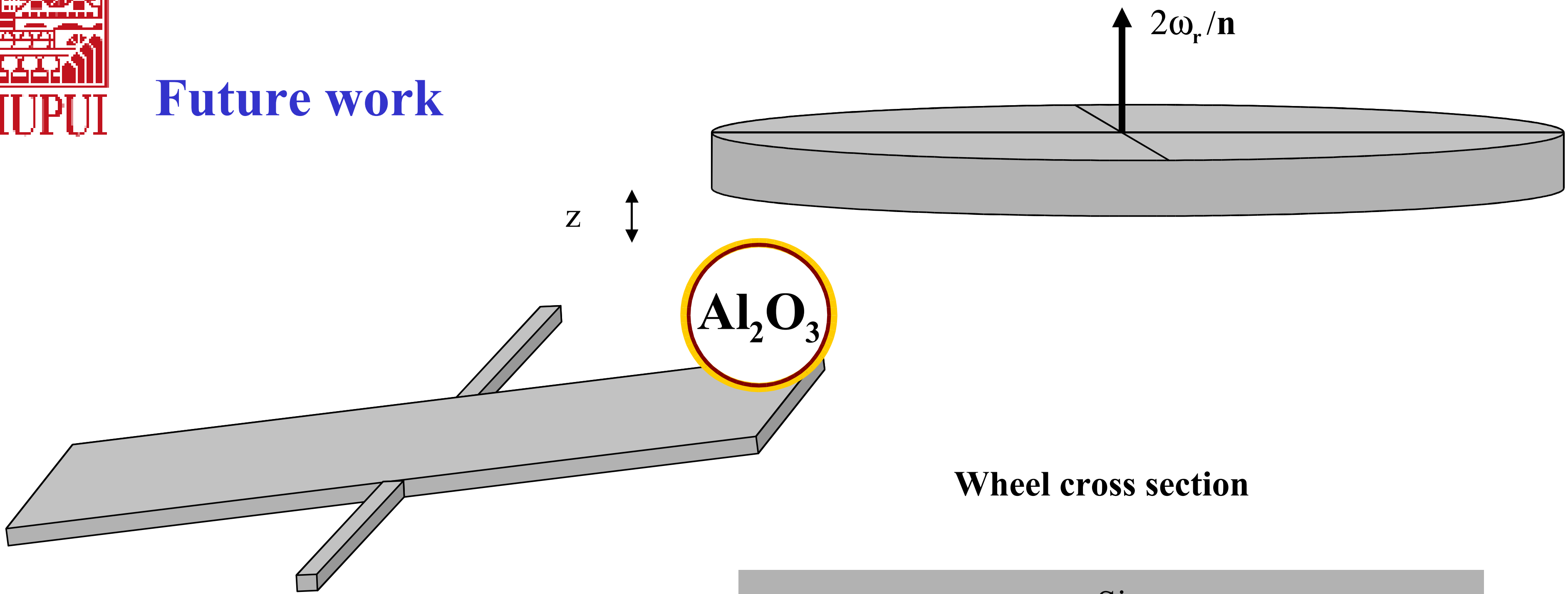
Au coating not thick enough
(unlikely)

Newtonian gravity
(nice try: 4×10^{21} N)

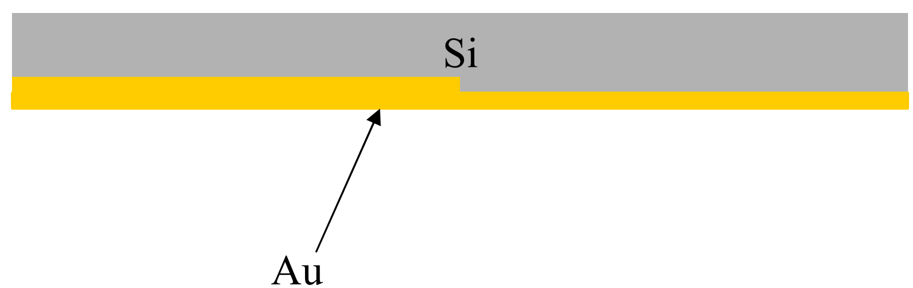


Two orders of magnitude improvement!!!

Future work



Wheel cross section



Advantages

- $\Delta F_{hyp}(z,t) = \frac{\pi}{4} \frac{\Delta F_{hyp}(z_0)}{2} \cos(\omega_r t)$
- Lower background

Disadvantage

- **Sensitive to Newtonian gravity**

IUPUI

Conclusions

- **Most sensitive measurements** of the Casimir Force and Casimir Pressure

- **Unprecedented agreement with theory**

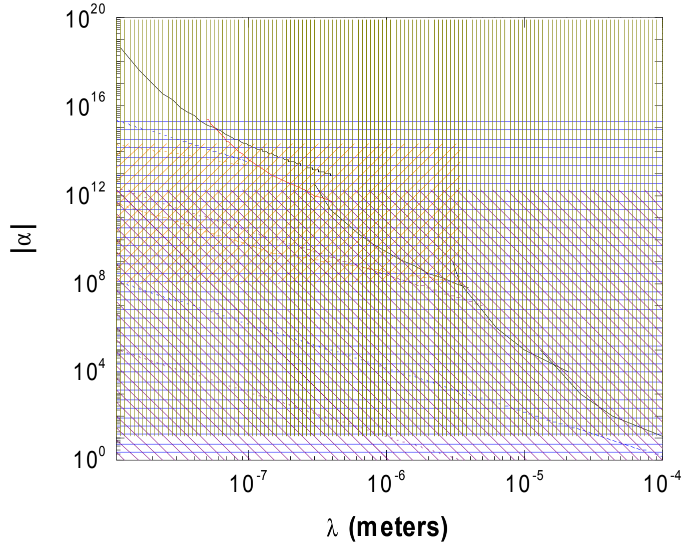
- **First realization** of a **"Casimir-less"** experiment

- **Improvement** of about **two orders of magnitude** in Yukawa-like hypothetical forces

Questions

- How low in |α| can we go?

  Most likely down to ~ 10^6



- Can we set limits for warped extra dimensions?

  Very likely (Marginal with current setup)

- When do we need to improve the signal-to-noise ratio?

Collaborators

Daniel López	Lucent Technologies
Ho Bun Chan	University of Florida
Ephraim Fischbasch	Purdue University
Dennis E. Krausse	Wabash College and Purdue University
Valdimir M. Mostepanenko	Universidade Federal da Paraíba
Galina L. Klimchitskaya	Universidade Federal da Paraíba
Chris Jamell	IUPUI
Mark Hanni	IUPUI