Casimir effect and short-range gravity tests

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www.lkb.ens.fr, www.lkb.upmc.fr

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R. Decca, E. Fischbach (IUPUI Indianapolis) …

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casimir-network.org

Search for scale dependent modifications of the gravity force law

- Exclusion plot for deviations with a generic Yukawa form

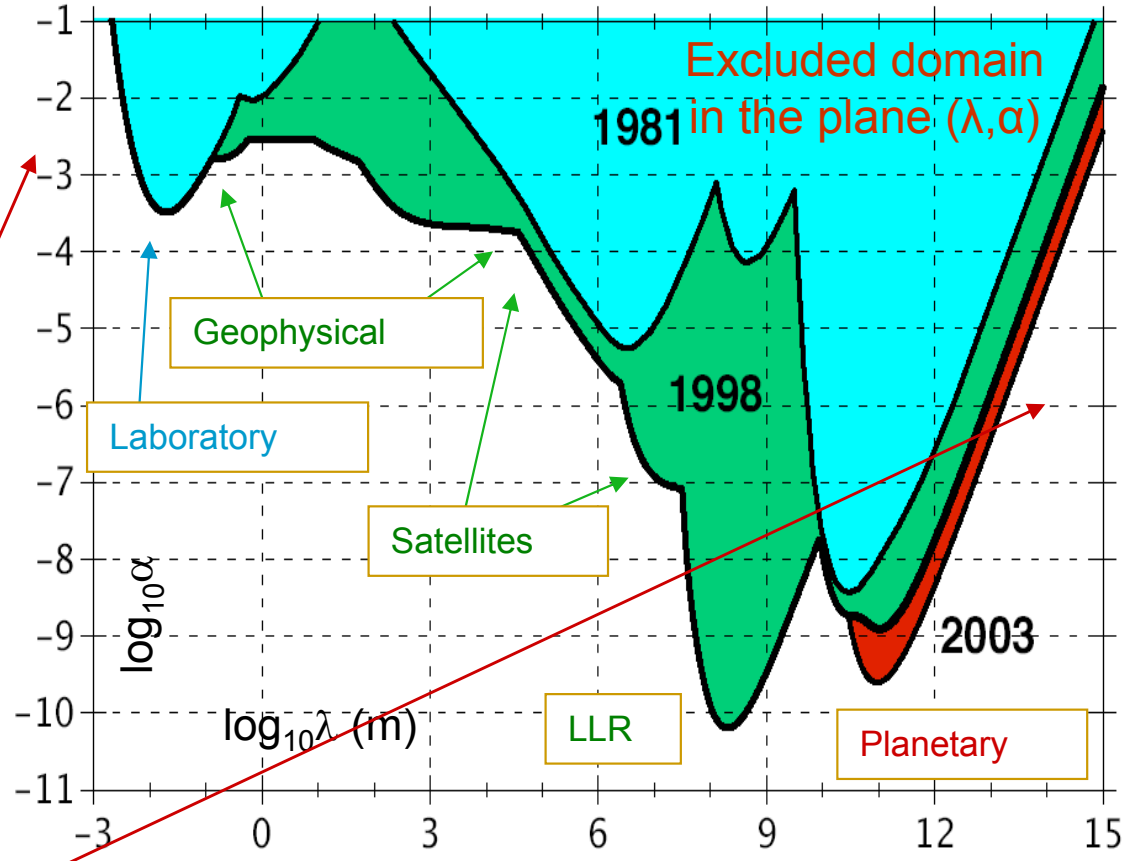
$$V(r) = -\frac{GMm}{r}\left(1 + \alpha e^{-\frac{r}{\lambda}}\right)$$

Windows remain open for deviations at short ranges

$\lambda < 1\,\mathrm{mm}$

or long ranges

$\lambda > 10^{16}\,\mathrm{m}$



Courtesy : J. Coy, E. Fischbach, R. Hellings, C. Talmadge & E. M. Standish (2003) ; see M.T. Jaekel & S. Reynaud IJMP **A20** (2005)

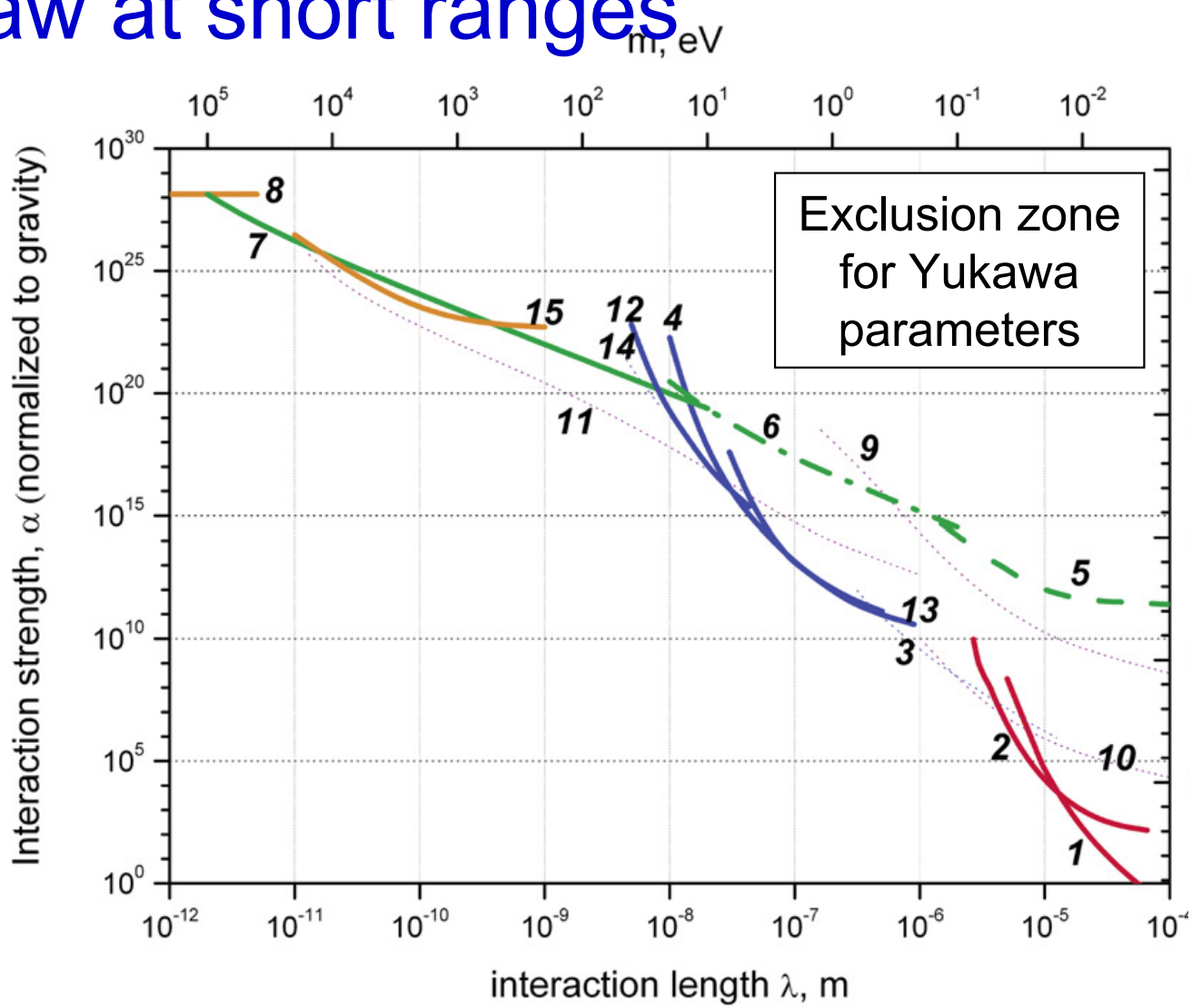
The Search for Non-Newtonian Gravity, E. Fischbach & C. Talmadge (1998)

Testing gravity law at short ranges

- Exclusion plot for an extra Yukawa potential

$$-\frac{GMm}{r}\left(1+\alpha e^{-\frac{r}{\lambda}}\right)$$

- From the mm down to the pm range
  - Torsion-balance measurements
  - Casimir experiments
  - Neutron physics
  - Exotic atoms



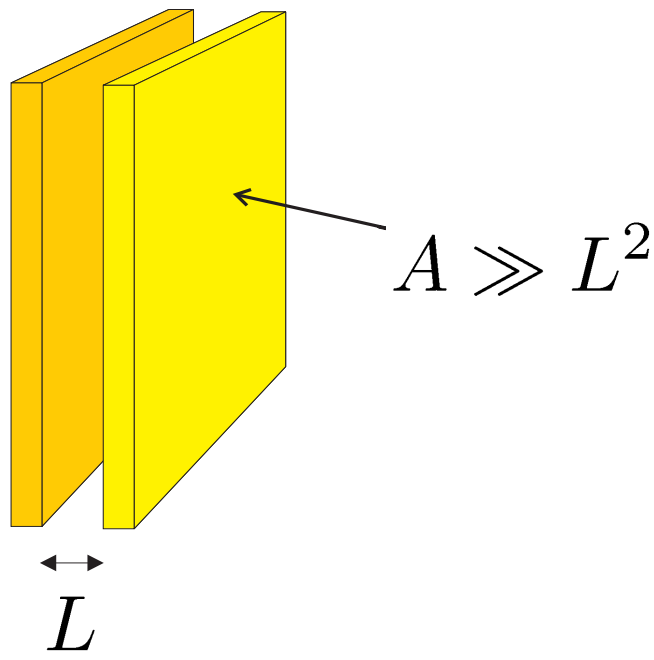
Recent overview : I. Antoniadis, S. Baessler, M. Büchner, V. Fedorov, S. Hoedl, A. Lambrecht, V. Nesvizhevsky, G. Pignol, K. Protasov, S. Reynaud, Yu. Sobolev, *Short-range fundamental forces* C. R. Phys. (2011) doi:10.1016/j.crhy.2011.05.004

E. Adelberger et al, Progress in Particle and Nuclear Physics (2009) **62** 102–134

The Casimir force

Vacuum resists when being confined within walls :
a universal effect depending only on *ħ*, *c*, and geometry

$$F_{\rm Cas} = -\frac{{\rm d}\mathcal{E}_{\rm Cas}}{{\rm d}L}\,, \qquad \mathcal{E}_{\rm Cas} = -\frac{\hbar c \pi^2 A}{720 L^3}$$



- Ideal formula written for
  - Parallel plane mirrors
  - Perfect reflection
  - Null temperature

- Attractive force = negative pressure

$$F_{\rm Cas} = P_{\rm Cas} A\,, \qquad P_{\rm Cas} = -\frac{\hbar c \pi^2}{240 L^4}$$

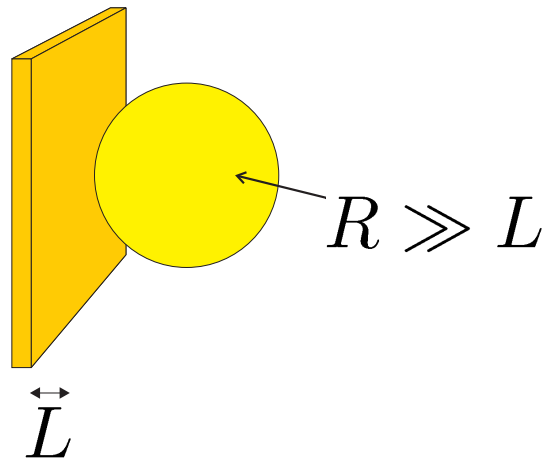
$$|P_{\rm Cas}| \sim 1{\rm mPa}$$
$$\text{at } L = 1\mu{\rm m}$$

H.B.G. Casimir, Proc. K. Ned. Akad. Wet. (Phys.) **51** (1948) 79

The Casimir force between real mirrors

- Real mirrors not perfectly reflecting
  - Force depends on non universal properties of the material plates used in the experiment
- Experiments at room temperature
  - Effect of thermal field fluctuations to be adde to that of vacuum fluctuations
- Effects of geometry and surface physics
  - Plane-sphere geometry used in recent precise experiments
  - Surfaces not ideal : roughness, contamination, electrostatic patches …

M. Jaekel, S. Reynaud,
J. Physique **I-1** (1991) 1395
A. Lambrecht, S. Reynaud
EPJD **8** (2000) 309



A. Lambrecht, P. Maia Neto, S. Reynaud, New J. Physics **8** (2006) 243

Models for metallic mirrors

- Simple models for the (reduced) dielectric function for metals
  - bound electrons (inter-band transitions)
  - conduction electrons
    - determined by (reduced) conductivity σ
  - model for conductivity
    - plasma frequency ω_P
    - Drude relaxation parameter γ

$$\varepsilon[\omega] = \bar{\varepsilon}[\omega] + \frac{\sigma[\omega]}{-i\omega}$$

$$\sigma[\omega] = \frac{\omega_P^2}{\gamma - i\omega}$$

- Drude parameters related to the density of conduction electrons and to the static conductivity
  - finite conductivity σ_0 ⇔ non null γ

$$\omega_P^2 = \frac{nq^2}{\varepsilon_0 m^*}$$

$$\sigma_0 = \frac{\omega_P^2}{\gamma}$$

A. Lambrecht & S. Reynaud Eur. Phys. J. D8 309 (2000)

Pressure between metallic mirrors at T≠0

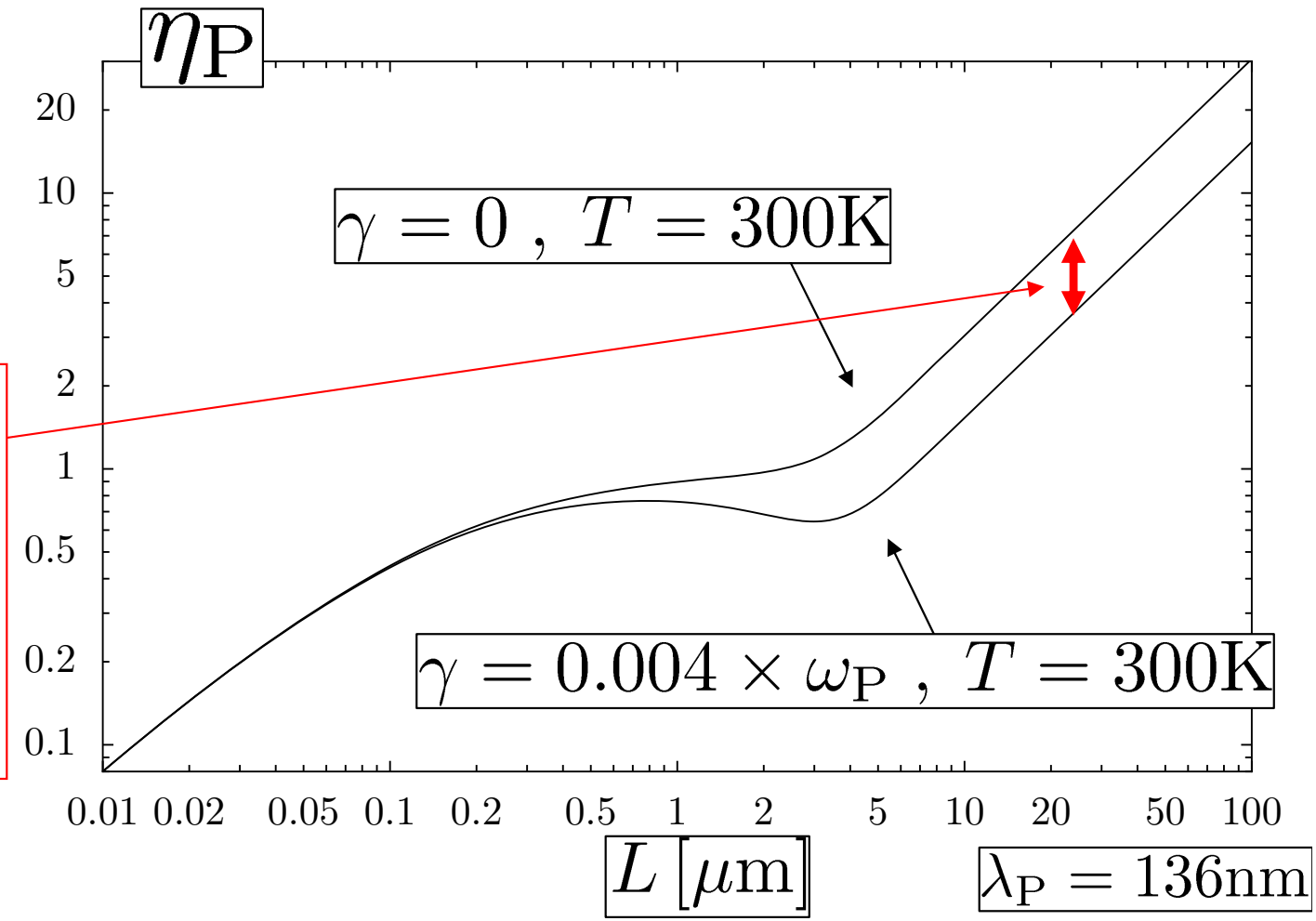
- Pressure divide by ideal Casimir formula

$$\eta_{\mathrm{P}} = \frac{P}{P_{\mathrm{Cas}}}$$

$$P_{\mathrm{Cas}} = -\frac{\hbar c \pi^2}{240 L^4}$$

M. Boström and B.E. Sernelius, Phys. Rev. Lett. **84** (2000) 4757

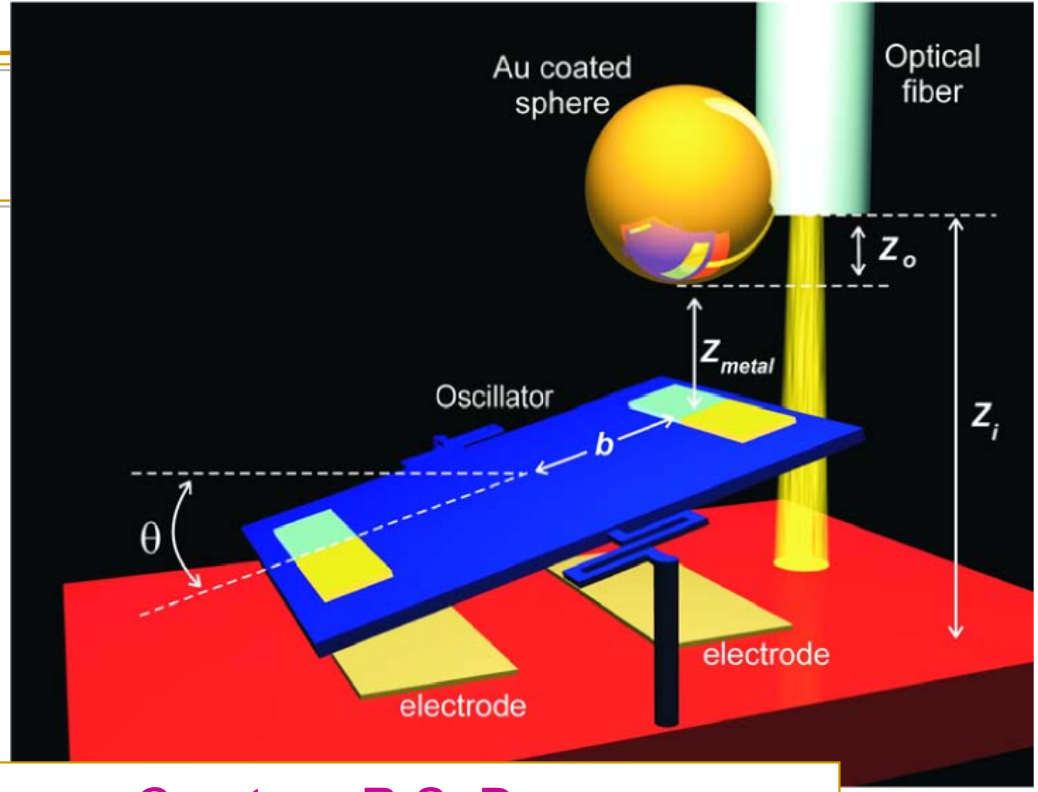
- Effect of small losses tends to a factor 2 at large distance (high *T*)



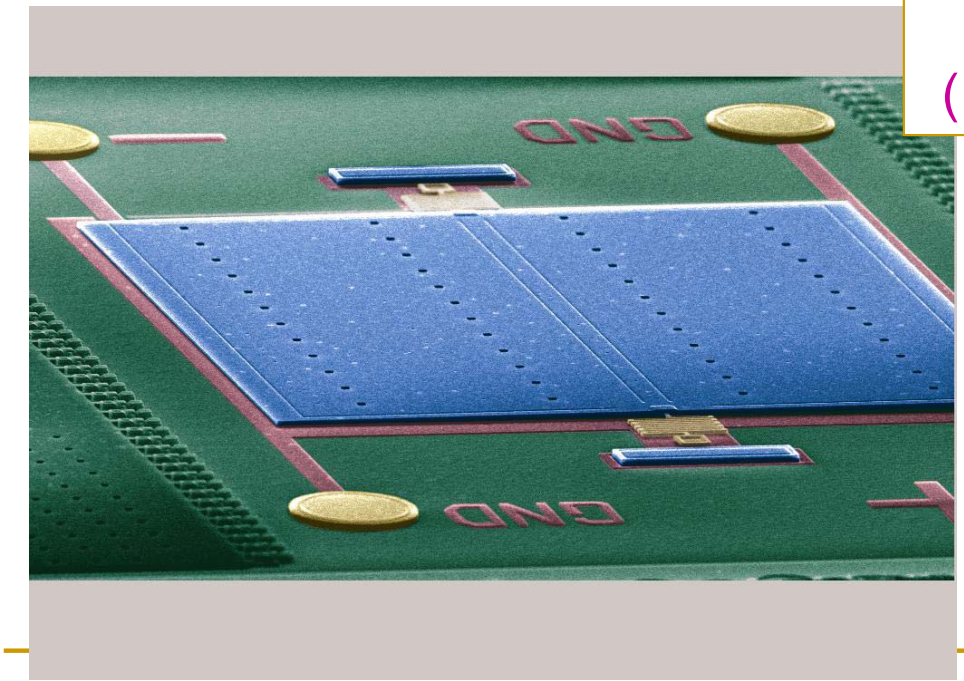
G. Ingold, A. Lambrecht & S. Reynaud, Phys. Rev. **E80** (2009) 041113

Casimir experiments

- Dynamic measurements of the resonance frequency of a microresonator
- Shift of the resonance gives the gradient of Casimir force between a plane and a sphere



Courtesy R.S. Decca
(Indiana U – Purdue U Indianapolis)



Sphere Radius: R = 150 μm

Distances: L = 0.16 - 0.75 μm

In the Proximity Force Approximation (R>>L), the signal is proportional to the pressure $P(L)$ between two planes at distance L

R.S. Decca, D. Lopez, E. Fischbach *et al*, Phys. Rev. **D75** (2007) 077101

Casimir experiments and theory …

Purdue (and Riverside) measurements favor the lossless plasma model and thus deviate from theory with dissipation accounted for

BRIEF REPORTS PHYSICAL REVIEW D 75, 077101 (2007)

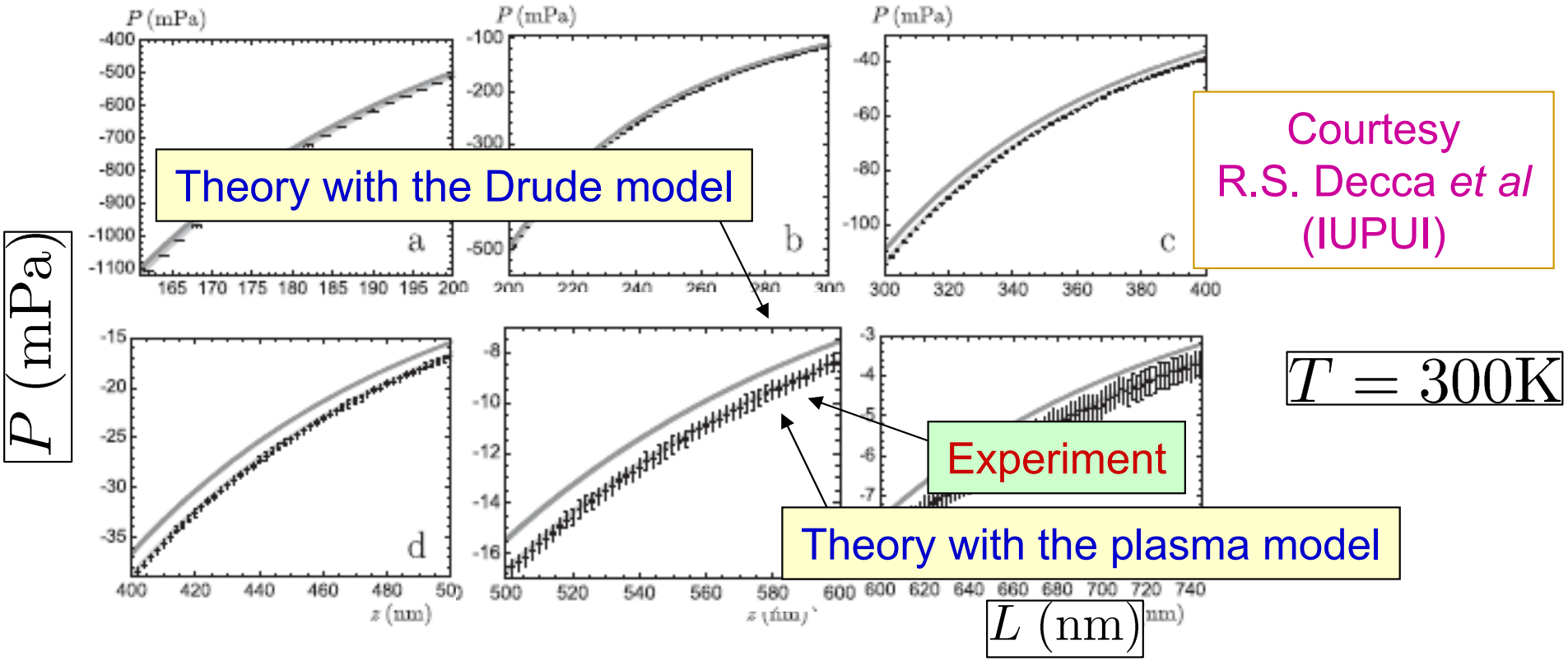


FIG. 1. Experimental data for the Casimir pressure as a function of separation z. Absolute errors are shown by black crosses in different separation regions (a–f). The light- and dark-gray bands represent the theoretical predictions of the impedance and Drude model approaches, respectively. The vertical width of the bands is equal to the theoretical error, and all crosses are shown in true scale.

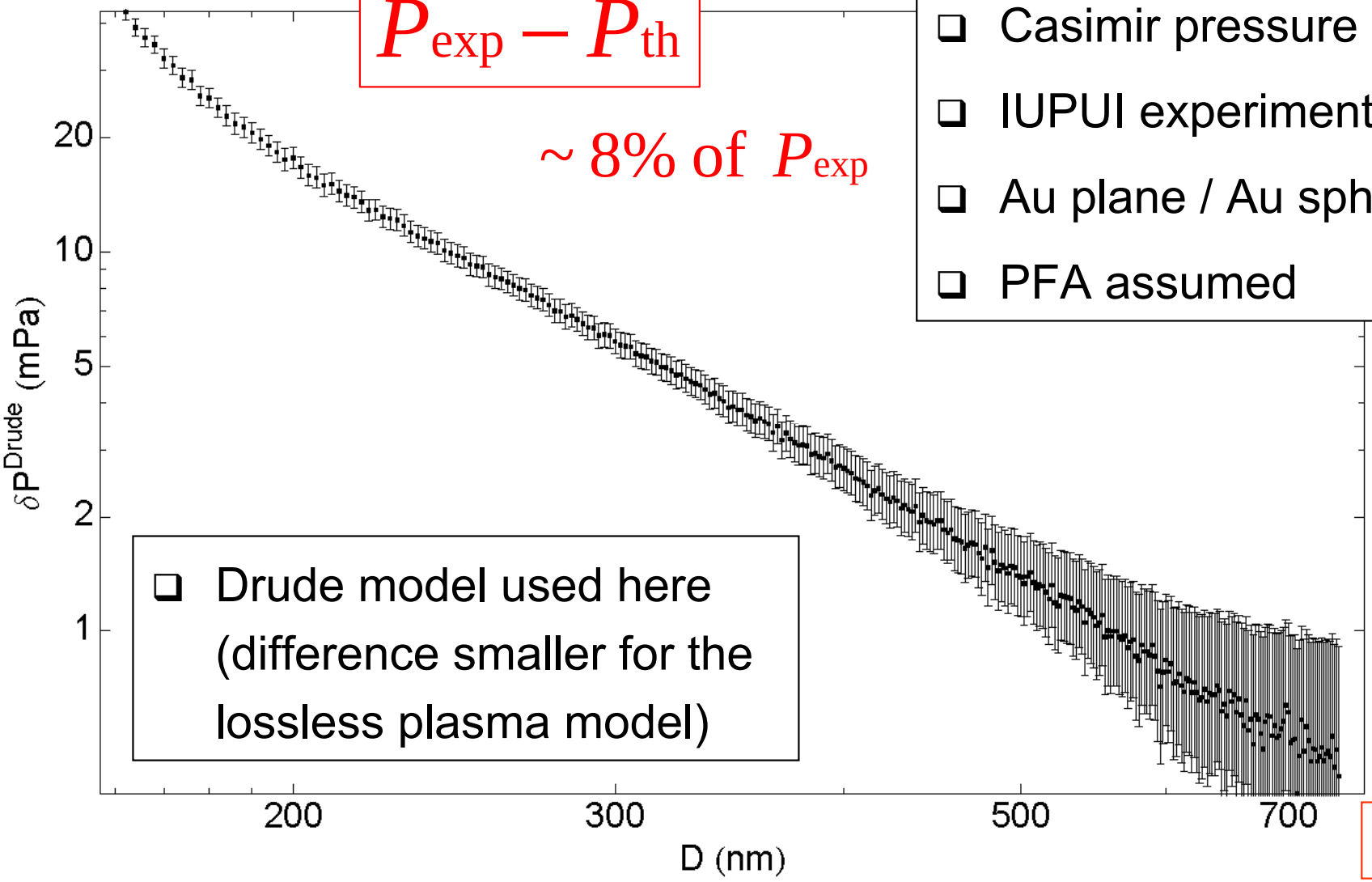
R.S. Decca, D. Lopez, E. Fischbach *et al*, Phys. Rev. **D75** (2007) 077101

Casimir experiments and theory …

$$P_{\text{exp}} - P_{\text{th}}$$

$\sim 8\%$ of P_{exp}

- Casimir pressure
- IUPUI experiment
- Au plane / Au sphere
- PFA assumed



- Drude model used here (difference smaller for the lossless plasma model)

$D \rightarrow L$

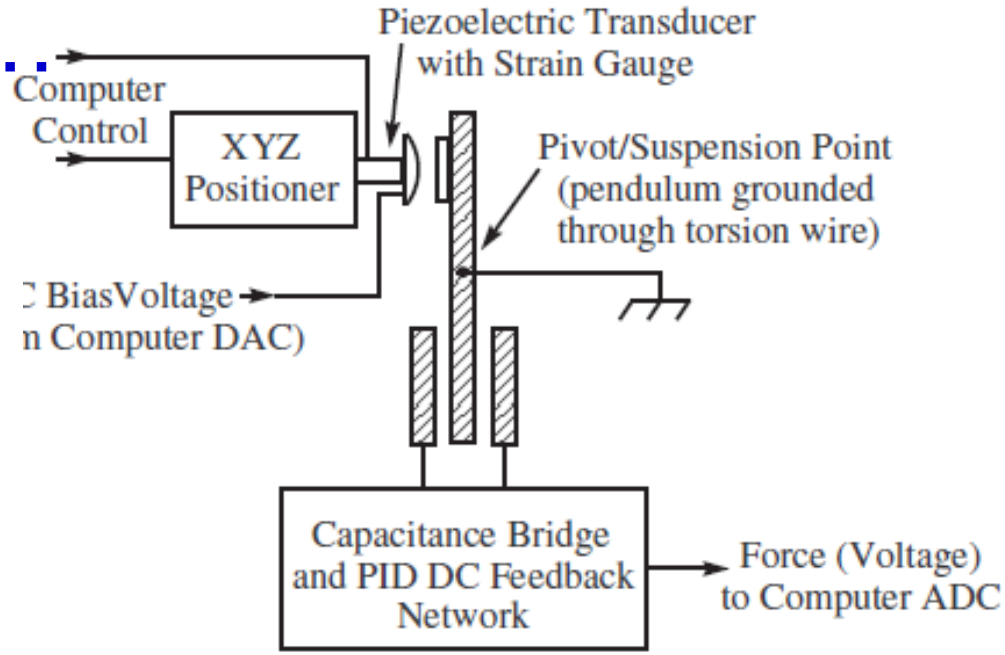
Experimental data kindly provided by R. Decca (IUPUI)

Theoretical pressure calculated by R. Behunin, D. Dalvit, F. Intravaia (LANL)

Deviation looking like a superposition of power laws

Casimir experiments …

- Lamoreaux group @ Yale
  - torsion-pendulum experiment
  - larger radius: R = 156 mm
  - larger distances: L = 0.7 - 7 μm



A.O. Sushkov, W.J. Kim, D.A.R. Dalvit, S.K. Lamoreaux, Nature Phys. (6 Feb 2011)

- Thermal contribution seen at large distances (where it is large)
- Results favor the Drude model after subtraction of a large contribution of the electrostatic patch effect

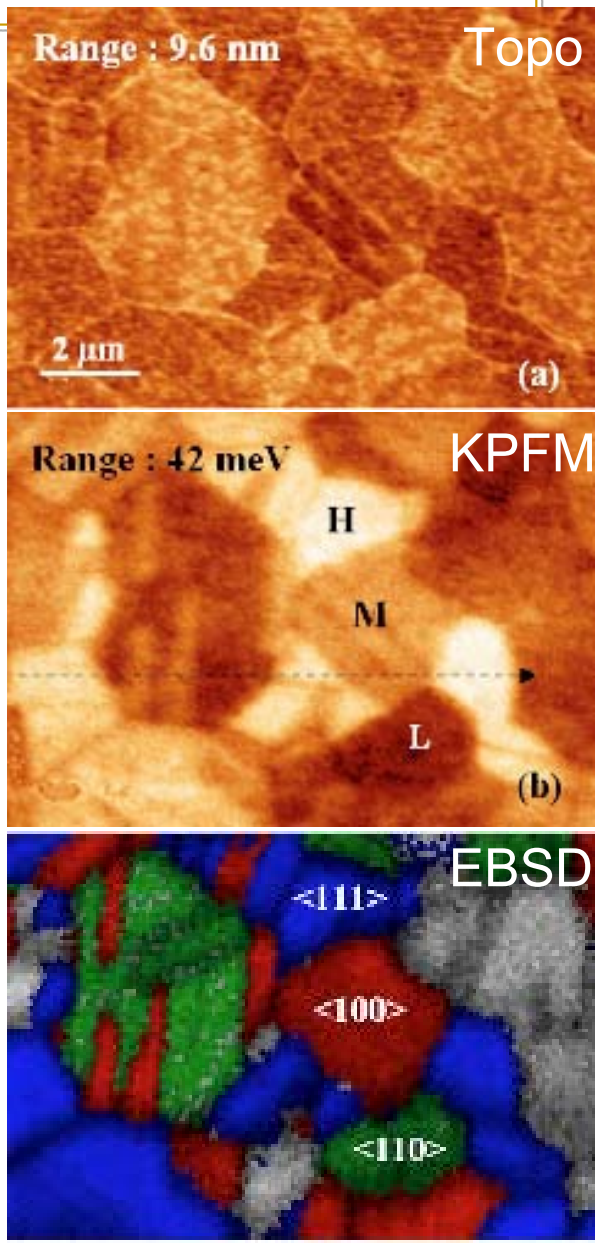
- Results of different experiments point to different models
- Some experiments disagree with the best theoretical model

K. Milton, *News & Views* Nature Physics (6 Feb 2011)

The patch effect

N. Gaillard *et al*, APL **89** (2006) 154101

- Surfaces of metallic plates are not equipotentials
  - Real surfaces are made of crystallites
  - Crystallites correspond to ≠ crystallographic orientations and ≠ work functions
- For ultraclean surfaces →
  (ultra-high vacuum, ultra-low temperature)
  - Patch pattern is related to topography
  - AFM, KPFM, EBSD maps are directly related
- Contaminated surfaces correspond to a different story
- Patch effect has been known for decades to be a limitation for high precision measurements
  - C. W. F. Everitt *et al.*, PRL **106** 221101 (2011)
  - S. Buchman *et al.*, Rev. Sci. Instr. **82** 074502 (2011)

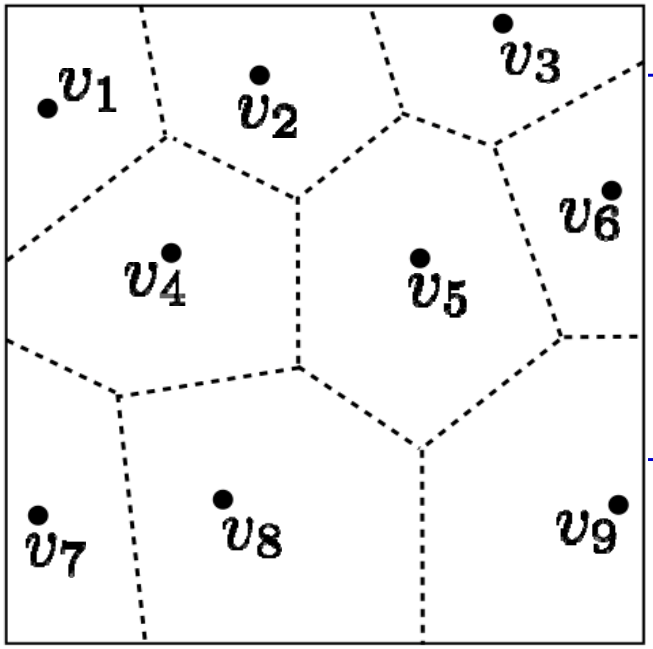


GPB

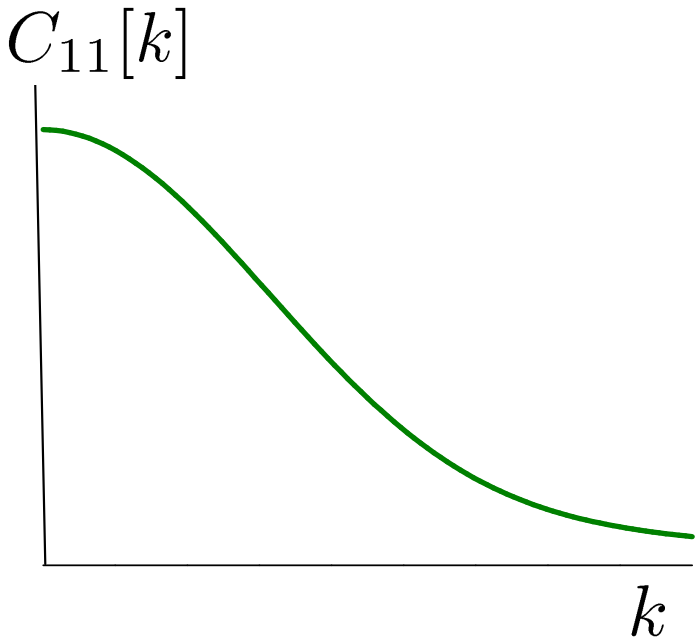
Modeling the patches …

R.O. Behunin, F. Intravaia, D.A.R. Dalvit, P.A. Maia Neto, S. Reynaud, PRA **85** (2012) 012504

- A "quasi-local" representation of patches



tessellation of sample surface and random assignment of the voltage on each patch



- This produces a smooth spectrum (no cutoff)

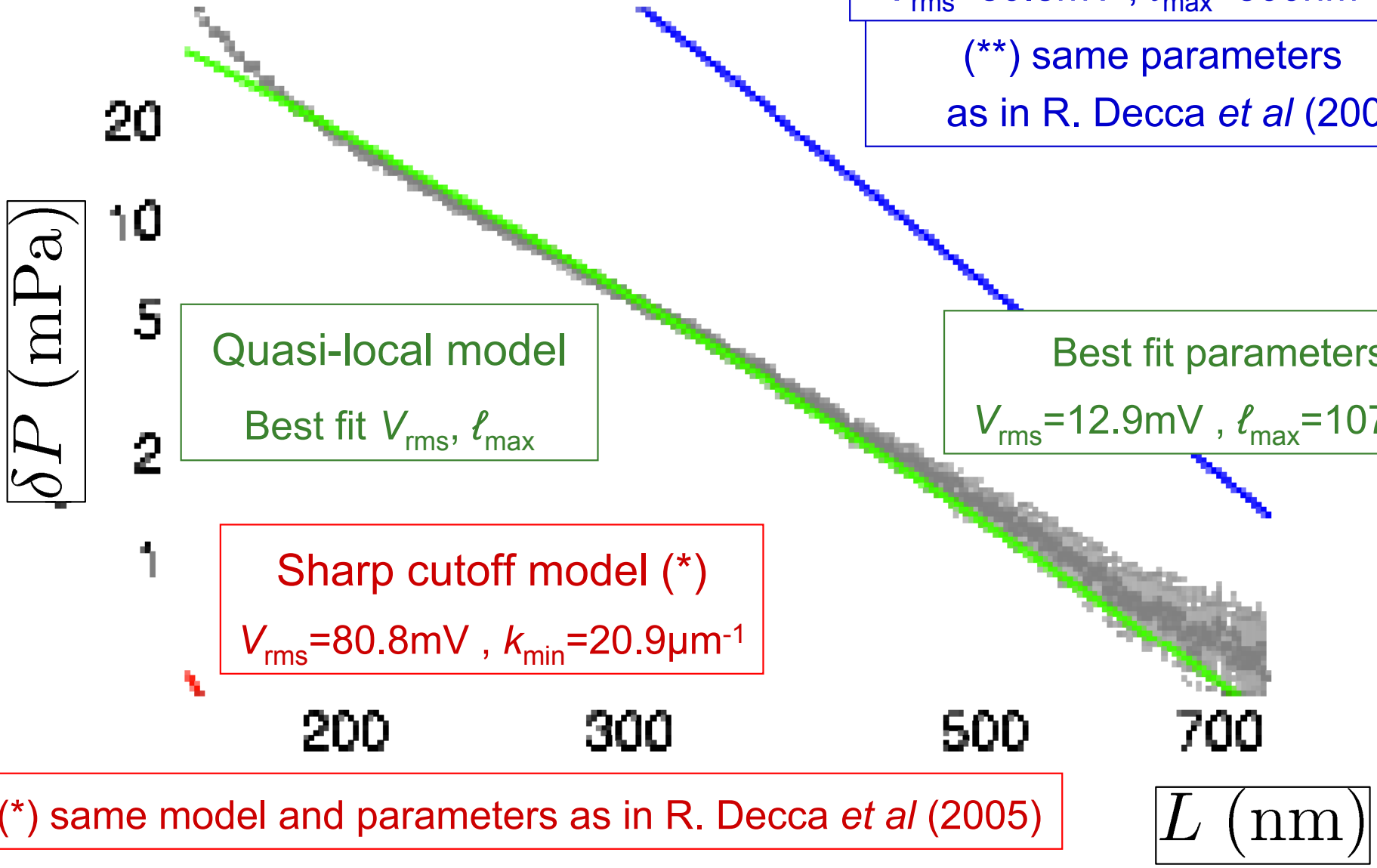
- Similar models used to study the effect of patches in ion traps
  - R. Dubessy, T. Coudreau, L. Guidoni, PRA 80 (2009) 031402
  - D.A. Hite, Y. Colombe, A.C. Wilson et al, PRL 109 (2012) 103001

Modeling the patches …

Quasi-local model (**)

V_{rms}=80.8mV , ℓ_{max}=300nm

(**) same parameters as in R. Decca *et al* (2005)



Quasi-local model

Best fit V_{rms}, ℓ_{max}

Best fit parameters

V_{rms}=12.9mV , ℓ_{max}=1074nm

Sharp cutoff model (*)

V_{rms}=80.8mV , k_{min}=20.9μm^{-1}

(*) same model and parameters as in R. Decca *et al* (2005)

R.O. Behunin, F. Intravaia, D.A.R. Dalvit, P.A. Maia Neto & SR, PRA (2012)

Provisional conclusions

January 2013

- Casimir effect is verified but there is still room for improvement
- Puzzle : some experiments deviate from theory !

- Maybe due to the contribution of electrostatic patches ?
  - differences between IUPUI data and Drude model predictions have been fitted by the quasi-local model for electrostatic patches
    - this is only a fit which has been done within PFA
    - best fit parameters are not compatible with patches identified as crystallites
    - they are compatible with a contamination of the metallic surfaces (contaminants enlarge the patch sizes and spread out the patch voltages)

- Next steps
  - measure real patch voltages with Kelvin Probe Force Microscopy
    - ongoing with ISIS Strasbourg and ISOF Bologna
  - deduce the force in the plane-sphere geometry
    - ongoing with LANL Los Alamos
  - compare with knowledge from other studies

R.O. Behunin *et al*, PRA **86** (2012) 052509