Thermal Casimir force, including applications to graphene

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3. Experiments with dielectrics and semiconductors

4. Casimir-Polder interaction of atoms with graphene

5. Casimir interaction of graphene with material plate

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1. INTRODUCTION

Problems in the Lifshitz theory:

a) Violation of the Nernst heat theorem

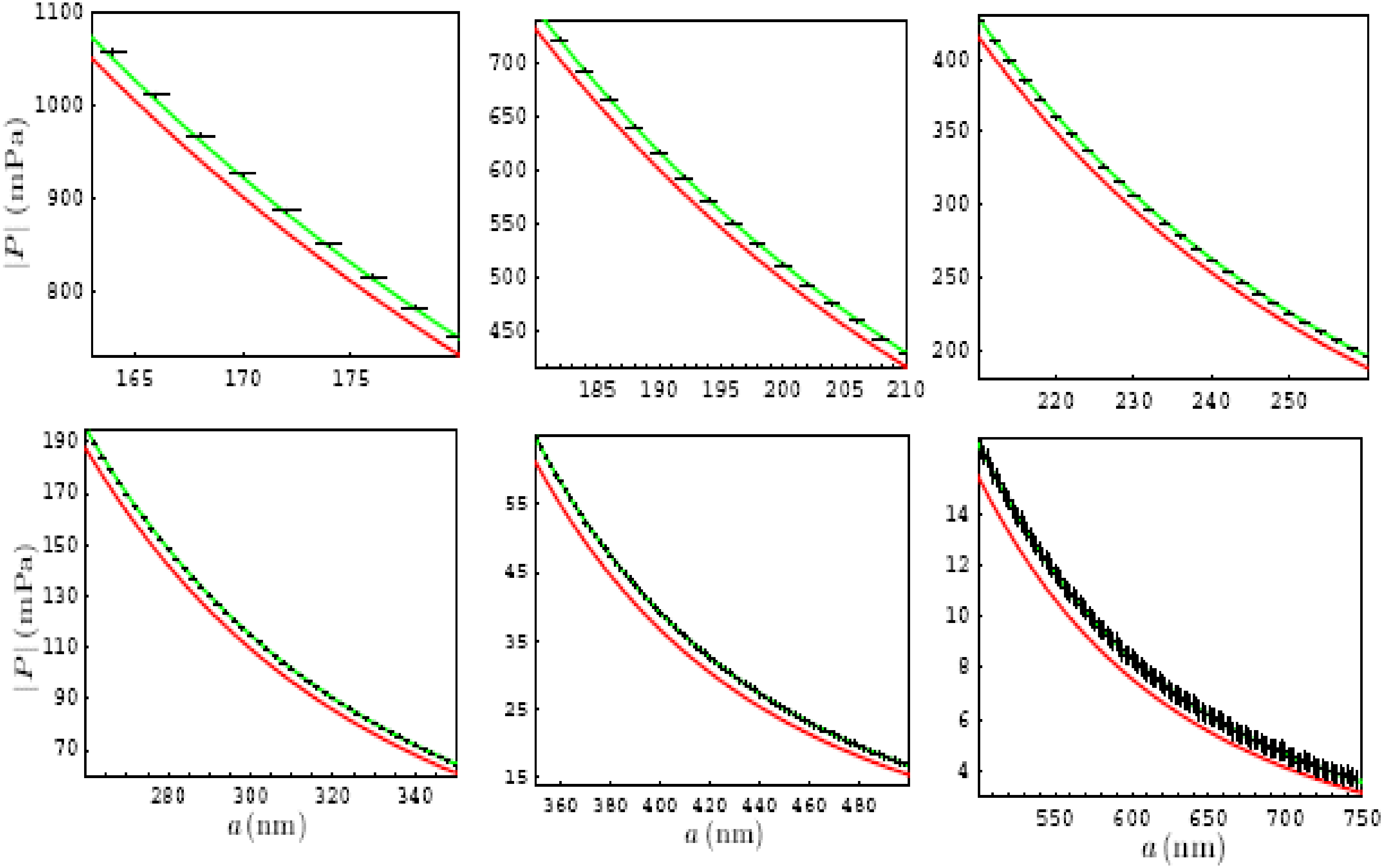
b) Contradiction with the experimental data

2. EXPERIMENTS WITH METALS

2a) Experiments with a micromachined oscillator: Au-coated sphere above Au-coated plate

$$|P(a,T)| = \frac{1}{2\pi R}\frac{\partial F(a,T)}{\partial a}$$

Decca, Lopez, Fischbach, Klimchitskaya, Krause, Mostepanenko, Ann. Phys. 2005; Phys. Rev. D 2007; Eur. Phys. J. C 2007



Experimental crosses are shown at a 95% confidence level.

Red lines show the Drude model approach.

Green lines show the plasma model approach.

Claims against the comparison between experiment and theory:

- influence of surface roughness;

- error in absolute separations;

- errors in the optical data of Au;

- errors in the PFA;

- influence of patch potentials.

Models of patches:

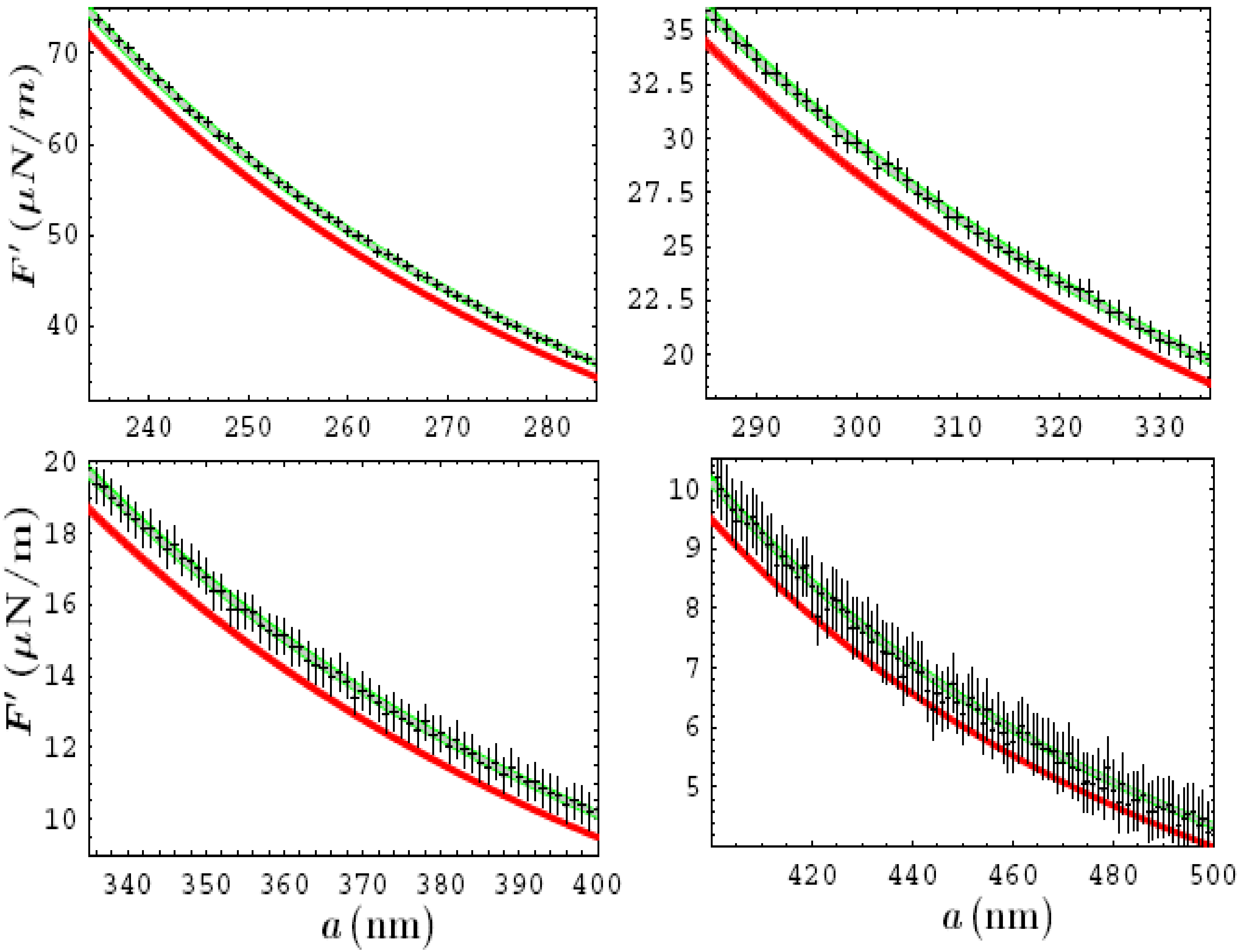
- Speake and Trenkel, Phys. Rev. Lett. 2003
- Behunin, Intravaia, Dalvit, Maia Neto, Reynaud, Phys. Rev. A 2012

Could the patch effect bring the data in agreement with the Drude model approach?

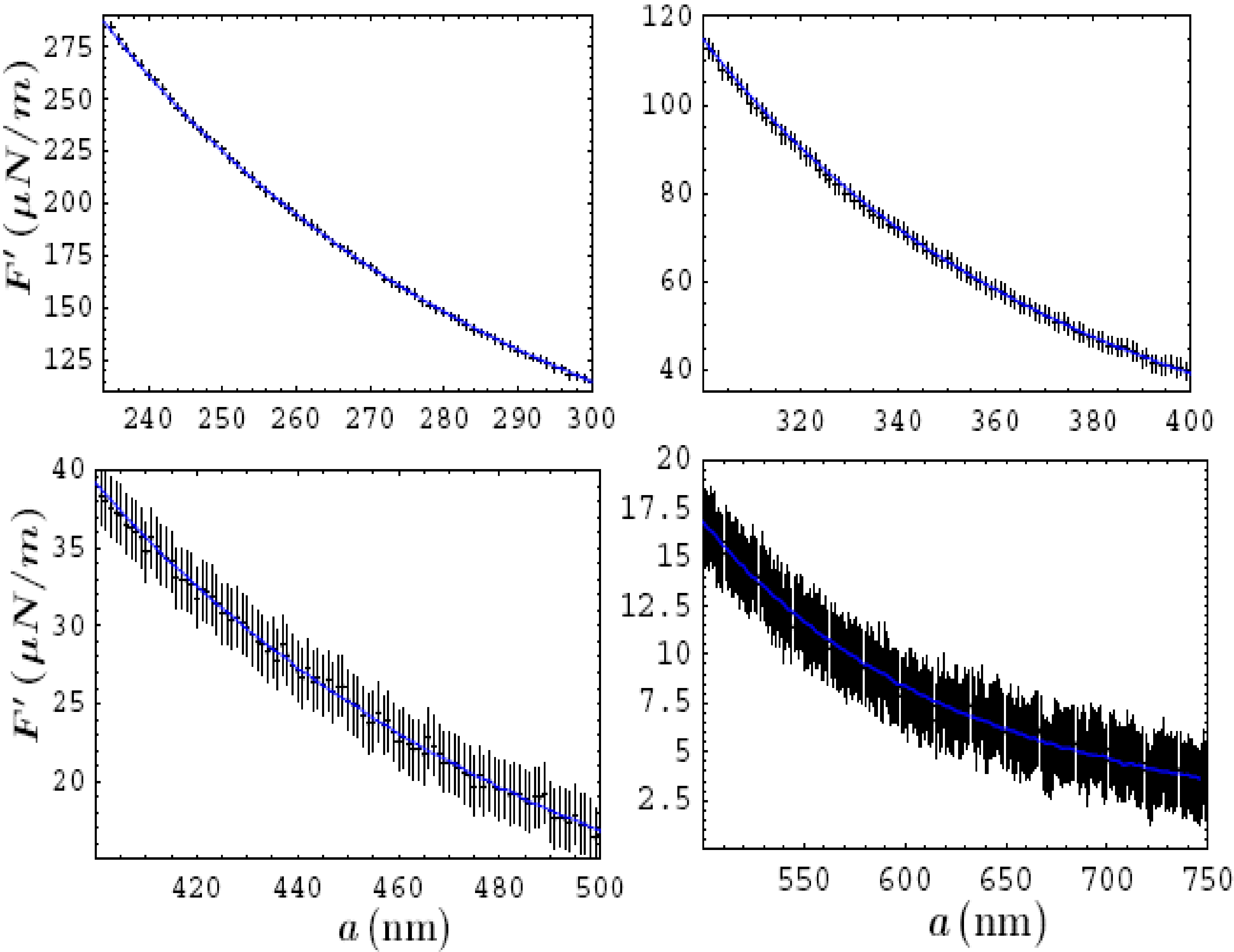
2b) Experiments with a dynamic AFM: Au-coated sphere above Au-coated plate

$$F' \equiv \frac{\partial F(a,T)}{\partial a} = -X'(a,R)(V_i - V_0)^2 - \frac{2k}{\omega_0}\Delta\omega$$

Chang, Banishev, Castillo-Garza, Klimchitskaya, Mostepanenko, Mohideen, Phys. Rev. B 2012; Int. J. Mod. Phys.: Conf. Ser. 2012



Experimental crosses are shown at a 67% confidence level.



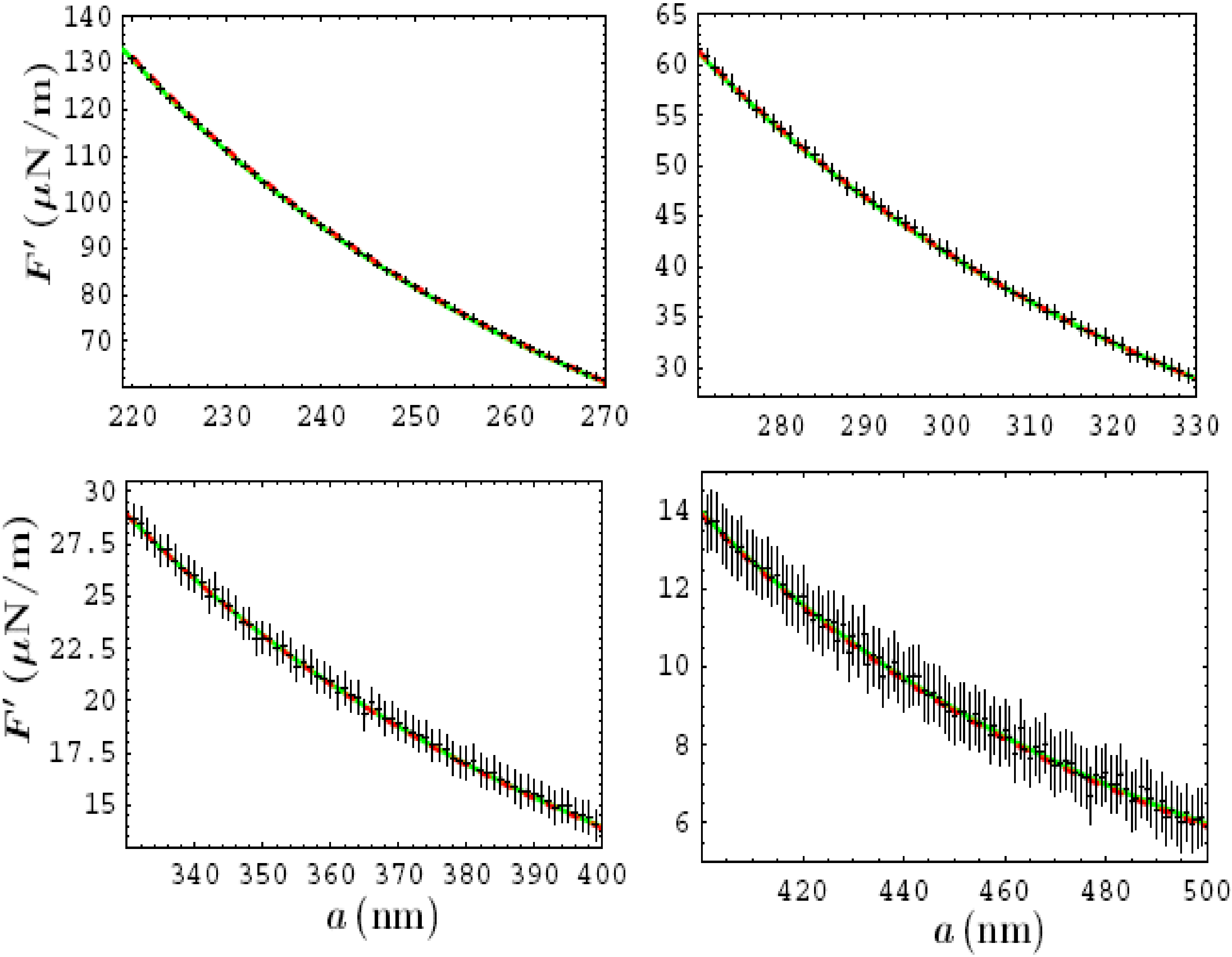
F′ (μN/m)
275
250
225
200
175
150
125
240
250
260
270
280
290
300
120
100
80
60
40
320
340
360
380
400
F′ (μN/m)
40
35
30
25
20
420
440
460
480
500
a (nm)
20
17.5
15
12.5
10
7.5
5
2.5
550
600
650
700
750
a (nm)

2c) Experiments with a dynamic AFM: Au-coated sphere above Ni-coated plate

Magnetic properties influence the Casimir force only through the TE zero-frequency term of the Lifshitz formula.

$$r_{\mathrm{TE,p}}^{(\mathrm{Ni})}(0,k_\perp)=\frac{\mu(0)ck_\perp-\sqrt{c^2k_\perp^2+\mu(0)\omega_p^2}}{\mu(0)ck_\perp+\sqrt{c^2k_\perp^2+\mu(0)\omega_p^2}}$$

Geyer, Klimchitskaya, Mostepanenko, Phys. Rev. B 2010;
Banishev, Chang, Klimchitskaya, Mostepanenko, Mohideen, Phys. Rev. B 2012



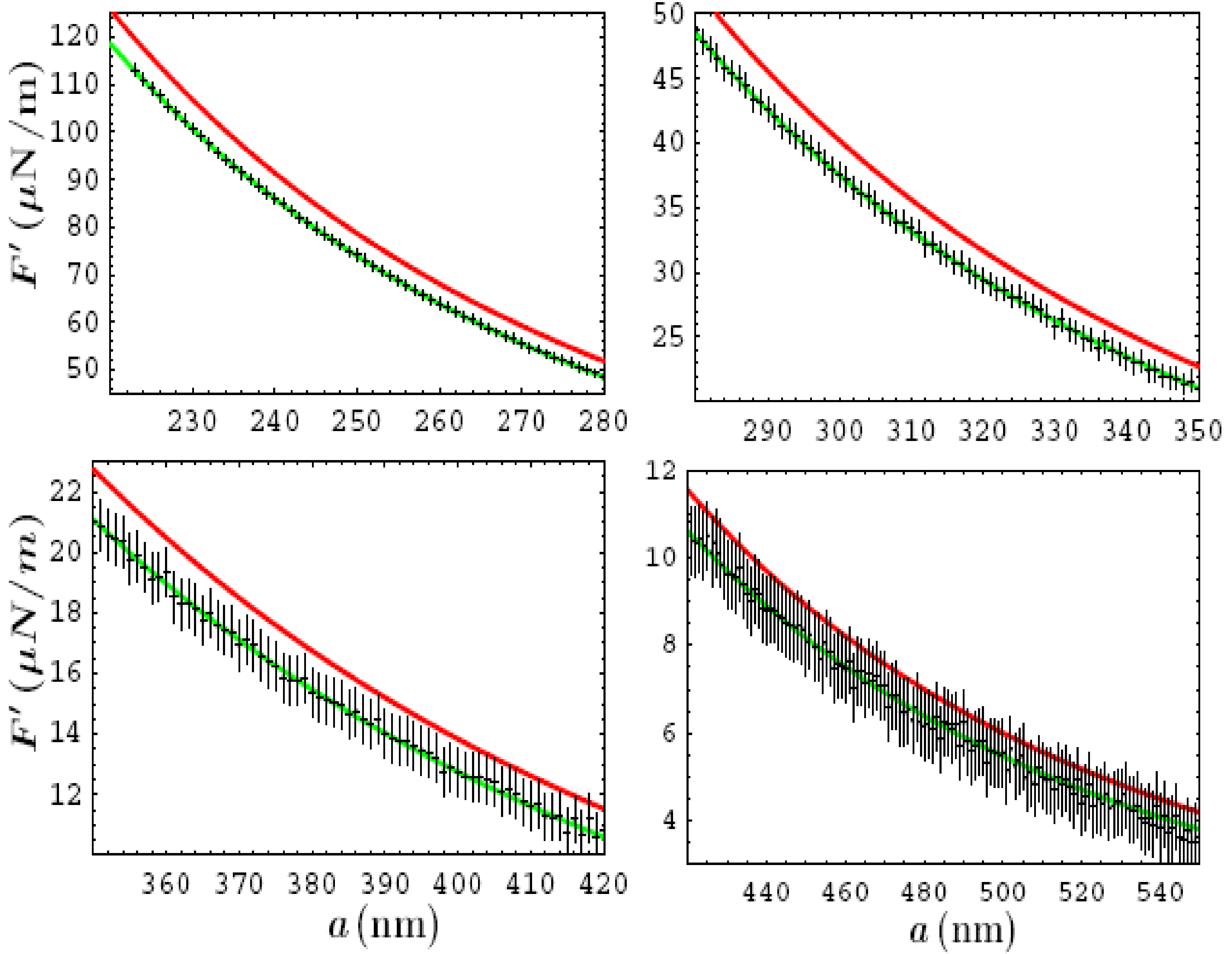
140
130
120
110
100
90
80
70
220
230
240
250
260
270
F' (μN/m)
65
60
55
50
45
40
35
30
280
290
300
310
320
330
30
27.5
25
22.5
20
17.5
15
340
350
360
370
380
390
400
F' (μN/m)
a (nm)
14
12
10
8
6
420
440
460
480
500
a (nm)

2d) Experiments with a dynamic AFM: Ni-coated sphere above Ni-coated plate

Magnetic properties influence the Casimir force when using both the plasma model and the Drude model approaches

$$r_{\mathrm{TE,D}}^{(\mathrm{Ni})}(0, k_\perp) = \frac{\mu(0) - 1}{\mu(0) + 1}$$

Banishev, Klimchitskaya, Mostepanenko, Mohideen, in preparation

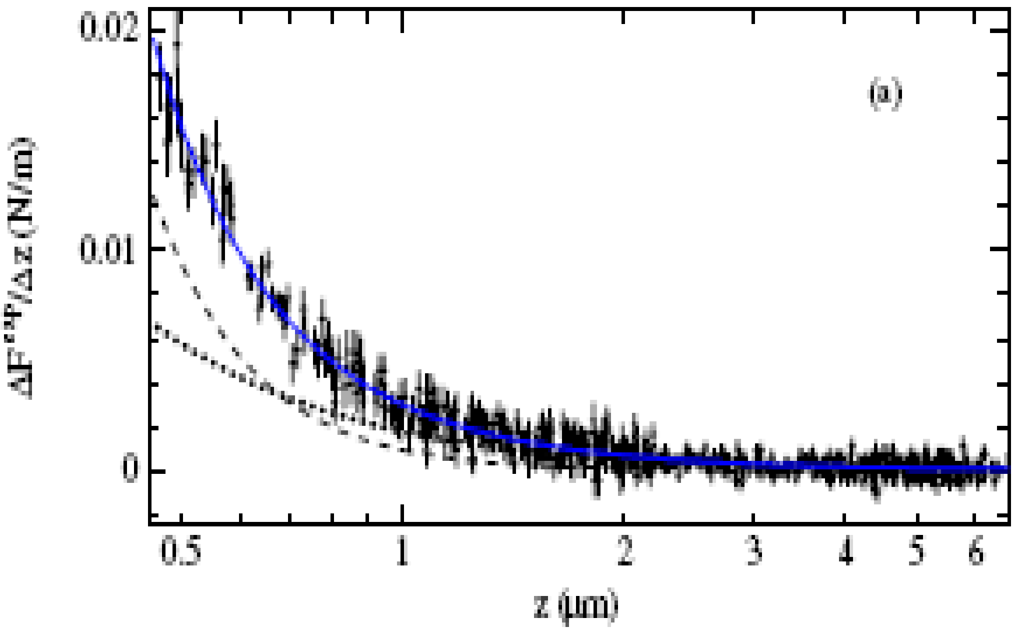


F' (μN/m)
120
110
100
90
80
70
60
50
230
240
250
260
270
280
50
45
40
35
30
25
290
300
310
320
330
340
350
F' (μN/m)
22
20
18
16
14
12
360
370
380
390
400
410
420
a (nm)
12
10
8
6
4
440
460
480
500
520
540
a (nm)

2e) Torsion balance experiments

Confirmation of the thermal correction predicted for ideal metals

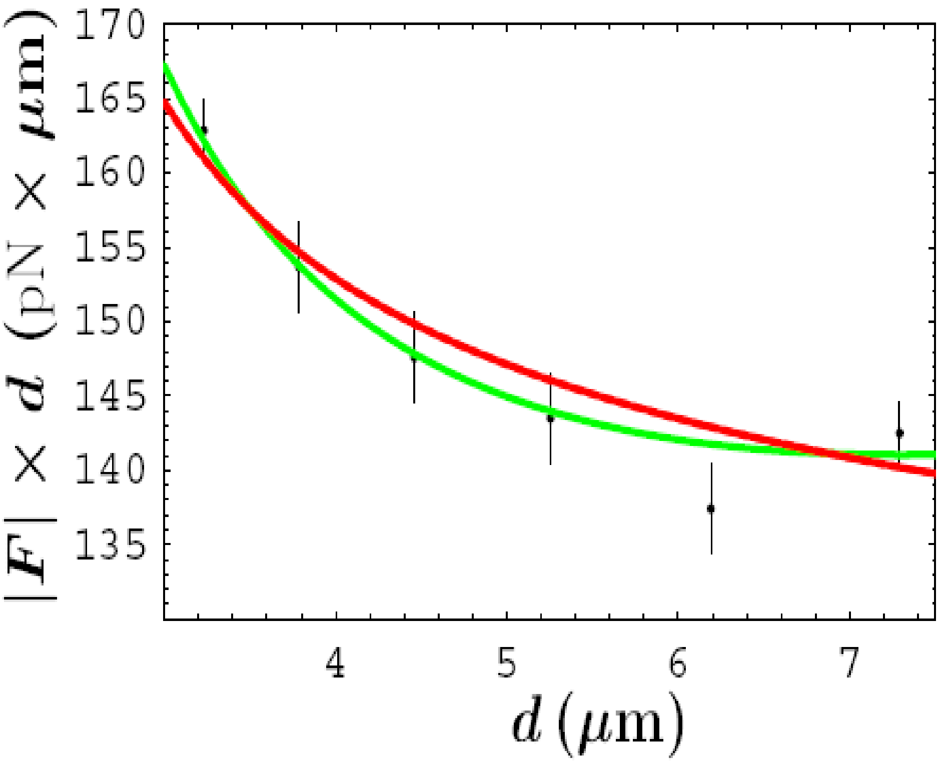
$$R = 20.7\,\text{cm}, \quad 0.48\,\mu\text{m} \le d \le 6.5\mu\text{m}$$



Masuda, Sasaki,
Phys. Rev. Lett. 2009

$$\chi^2_{\min} = 513, \quad f = 558, \quad P(\chi^2 > \chi^2_{\min}) = 0.91$$

Sushkov, Kim, Dalvit, Lamoreaux, Nature Phys. 2011



Klimchitskaya, Bordag. Fischbach, Krause, Mostepanenko, Int. J. Mod. Phys. A 2011; Klimchitskaya, Bordag, Mostepanenko, Int. J. Mod. Phys. A 2012

f=4

Fit using the Drude model:

$$\chi^2_{\rm min} = 19.76, \quad P(\chi^2 > \chi^2_{\rm min}) = 0.16$$

$$V_{\rm rms} = 5.4\,{\rm mV}, \quad a = -3\,{\rm pN}$$

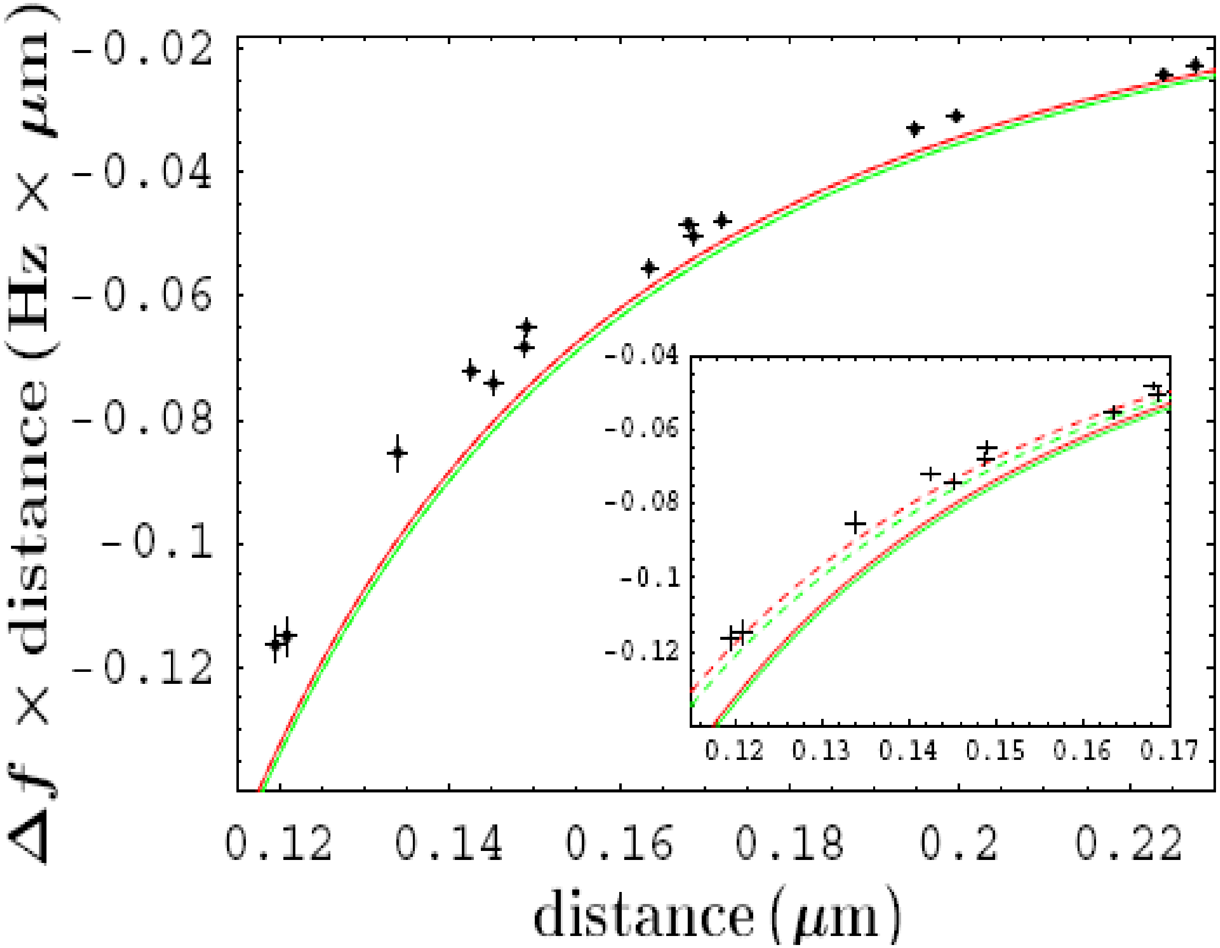
Fit using the plasma model:

$$\chi^2_{\rm min} = 2.76, \quad P(\chi^2 > \chi^2_{\rm min}) = 0.61$$

$$V_{\rm rms} = 4.5\,{\rm mV}, \quad a = 3.6\,{\rm pN}$$

2f) Experiment using a microresonator

Garcia-Sanches, Fong, Bhaskaran, Lamoreaux, Tang, Phys. Rev. Lett. 2012



$\chi_D^2 > 300$

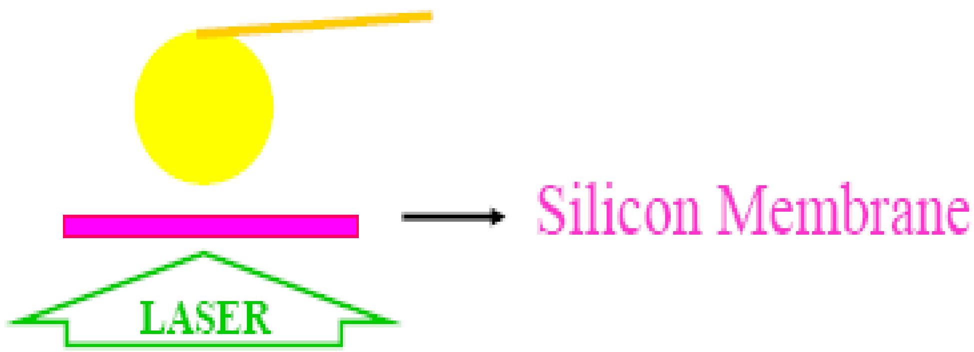
$\chi_p^2 > 419$

$P < 10^{-8}$

Bordag, Klimchitskaya, Mostepanenko, arXiv:1208.1757v1

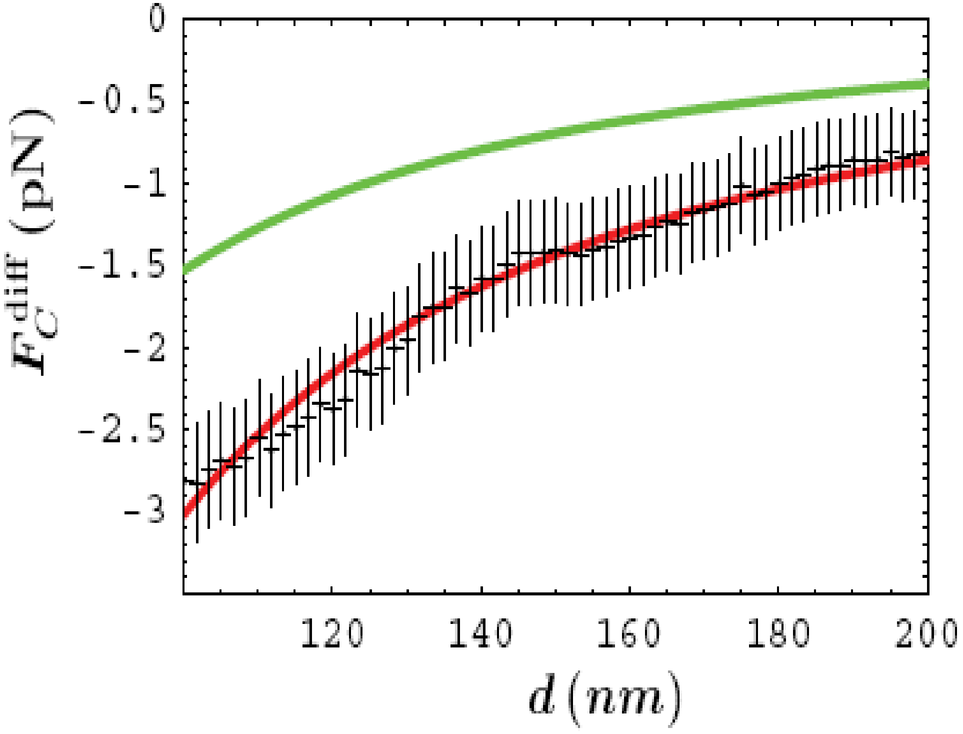
3. EXPERIMENTS WITH DIELECTRICS AND SEMICONDUCTORS

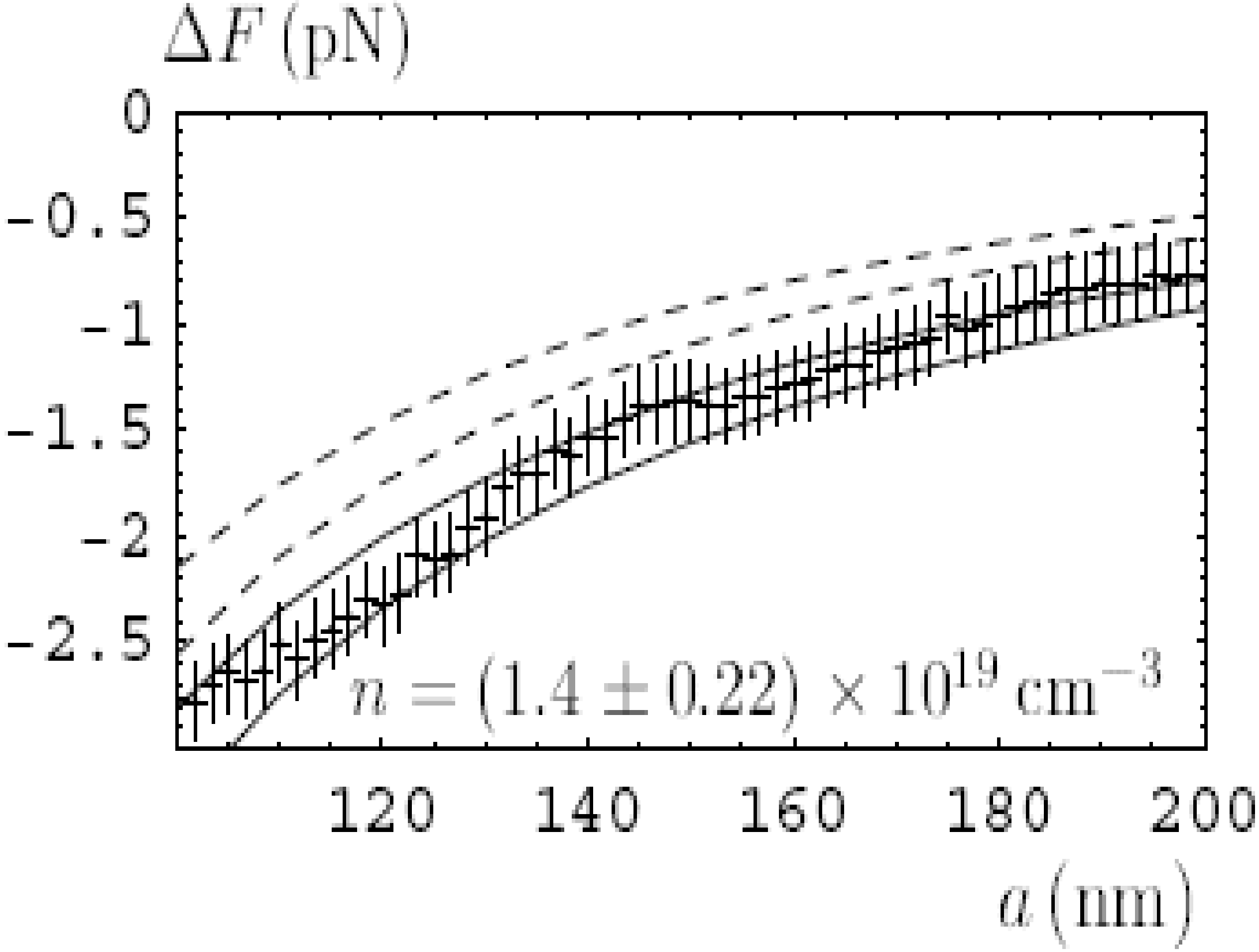
3a) Optical modulation of the Casimir force: Au-coated sphere above Si plate



Chen, Klimchitskaya, Mostepanenko, Mohideen,
Opt. Express 2005; Phys. Rev. B 2007;
Klimchitskaya, Mostepanenko, Mohideen, J. Phys. A 2008

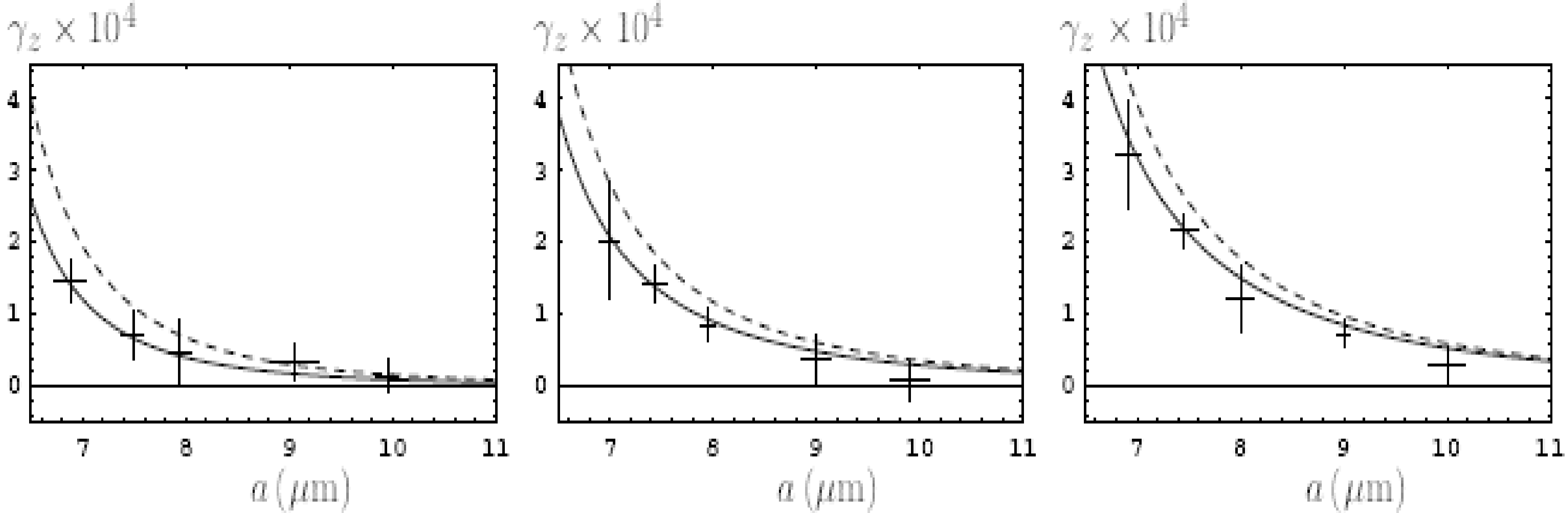
Difference of the Casimir forces in the presence and absence of laser light





Pitaevskii, Phys. Rev. Lett. 2008
Geyer, Klimchitskaya, Mohideen, Mostepanenko, Phys. Rev. Lett. 2009

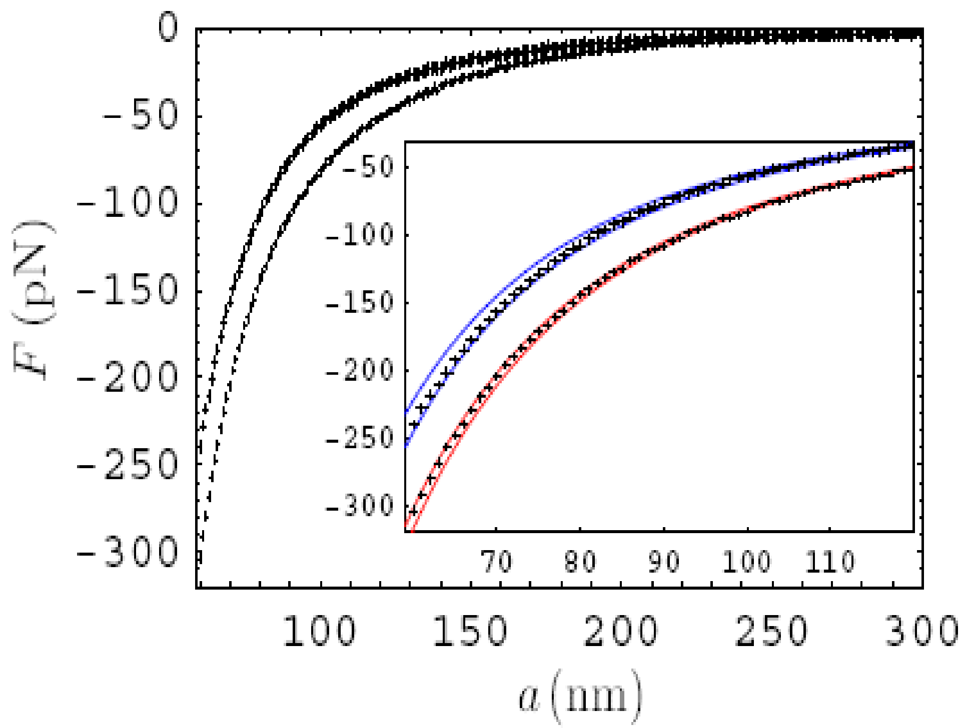
3b) Relative frequency shift of center-of-mass oscillations of Bose-Einstein condensate



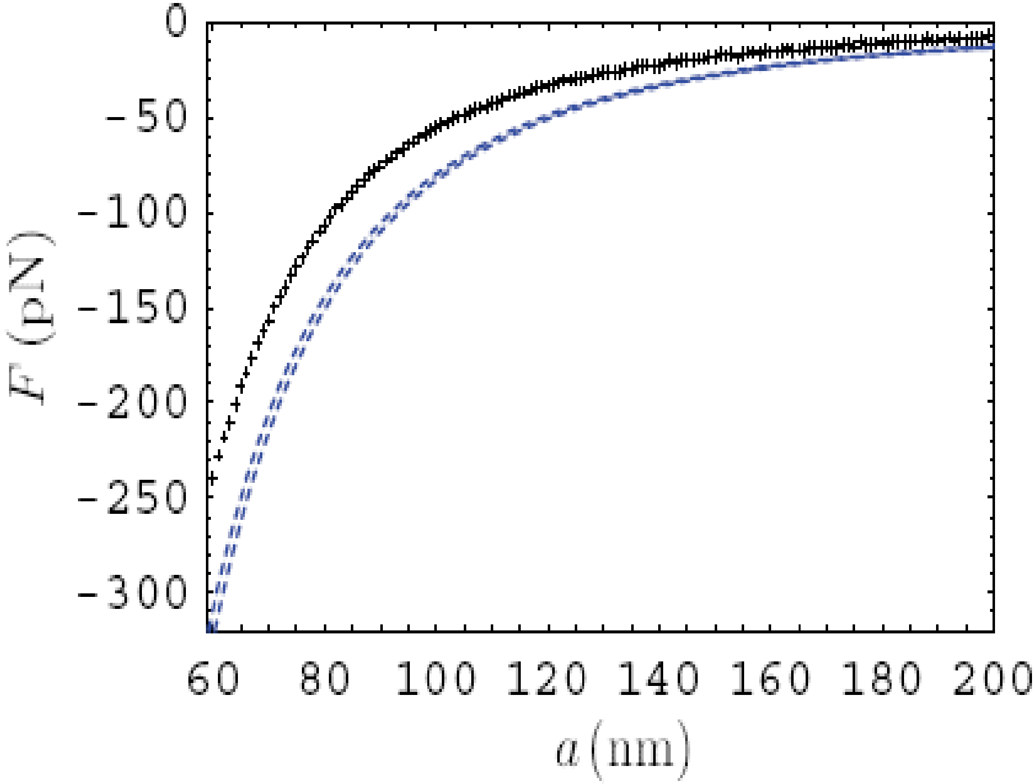
$T_p = T_e = 310\,\mathrm{K}$ $\quad T_p = 479\,\mathrm{K}$ $\quad T_p = 605\,\mathrm{K}$

Obrecht, Wild, Antezza, Pitaevskii, Stringari, Cornell, PRL (2007); Klimchitskaya, Mostepanenko, JPA (2008).

3c) The Casimir force between Au sphere and ITO plate



Chang, Banishev, Klimchitskaya, Mostepanenko, Mohideen, Phys. Rev. Lett. 2011; Banishev, Chang, Castillo-Garza, Klimchitskaya, Mostepanenko, Mohideen, Phys. Rev. B 2012; Int. J. Mod. Phys. A 2012



0
-50
-100
-150
-200
-250
-300
F (pN)
60
80
100
120
140
160
180
200
a (nm)

4. CASIMIR-POLDER INTERACTION OF ATOM WITH GRAPHENE

Dirac model of graphene

$$r_{\rm TM}^{(g)}(i\xi_l, k_\perp) = \frac{q_l \Pi_{00}}{q_l \Pi_{00} + 2\hbar k_\perp^2}$$

$$r_{\rm TE}^{(g)}(i\xi_l, k_\perp) = -\frac{k_\perp^2 \Pi_{\rm tr} - q_l^2 \Pi_{00}}{k_\perp^2 (\Pi_{\rm tr} + 2\hbar q_l) - q_l^2 \Pi_{00}}$$

$$q_l^2 = k_\perp^2 + \frac{\xi_l^2}{c^2}$$

Bordag, Fialkovsky, Gitman, Vassilevich, Phys. Rev. B 2009; Fialkovsky, Marachevsky, Vassilevich, Phys. Rev. B 2011

Hydrodynamic model of graphene

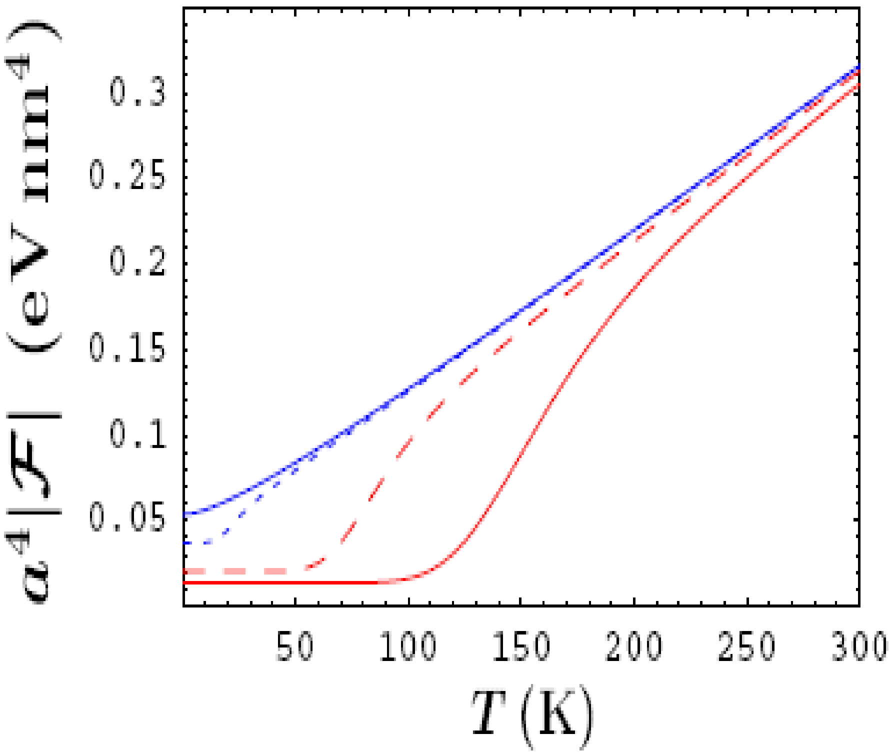
$$r_{\mathrm{TM}}^{(g)}(i\xi_l, k_\perp) = \frac{c^2 q_l K}{c^2 q_l K + \xi_l^2}$$

$$r_{\mathrm{TE}}^{(g)}(i\xi_l, k_\perp) = -\frac{K}{K + q_l}$$

$$K = 2\pi \frac{ne^2}{mc^2} = 6.75 \times 10^5\,\mathrm{m}^{-1}$$

Barton, J. Phys. A 2004, 2005

Metastable He interacting with graphene



Lines from the lowest to the highest are for

$$\Delta = 0.1\,\text{eV}$$

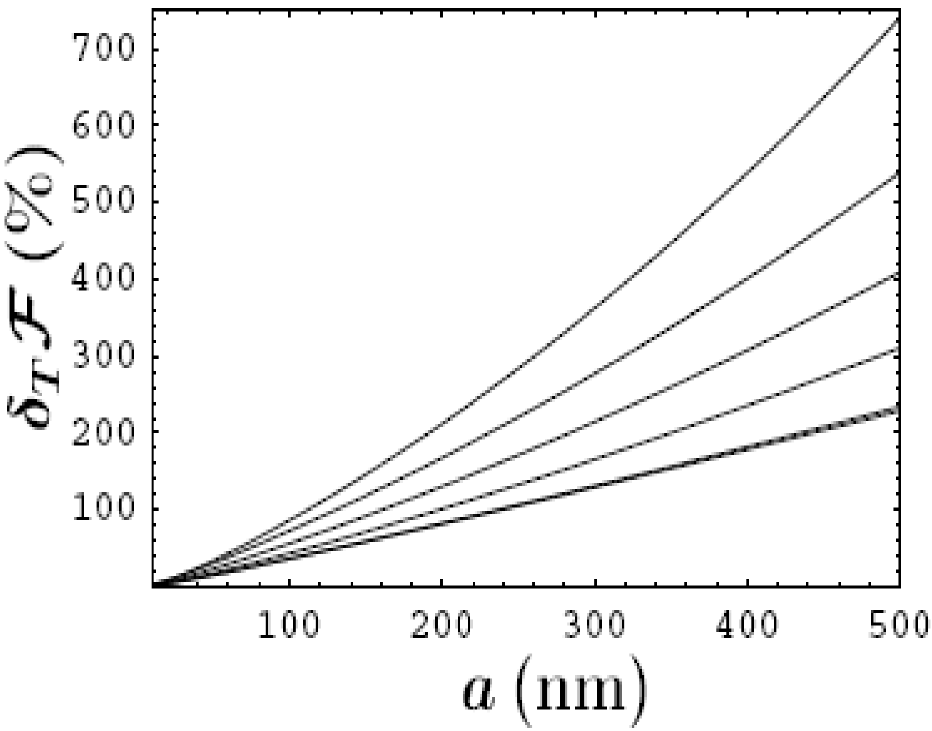
$$\Delta = 0.05\,\text{eV}$$

$$\Delta = 0.01\,\text{eV}$$

$$\Delta = 0\,\text{eV}$$

Chaichian, Klimchitskaya, Mostepanenko, Tureanu, Phys. Rev. A 2012

Relative thermal correction



$T = 300\,\mathrm{K}$

Lines from the highest to the lowest are for

$\Delta = 0.1\,\mathrm{eV}$

$\Delta = 0.05\,\mathrm{eV}$

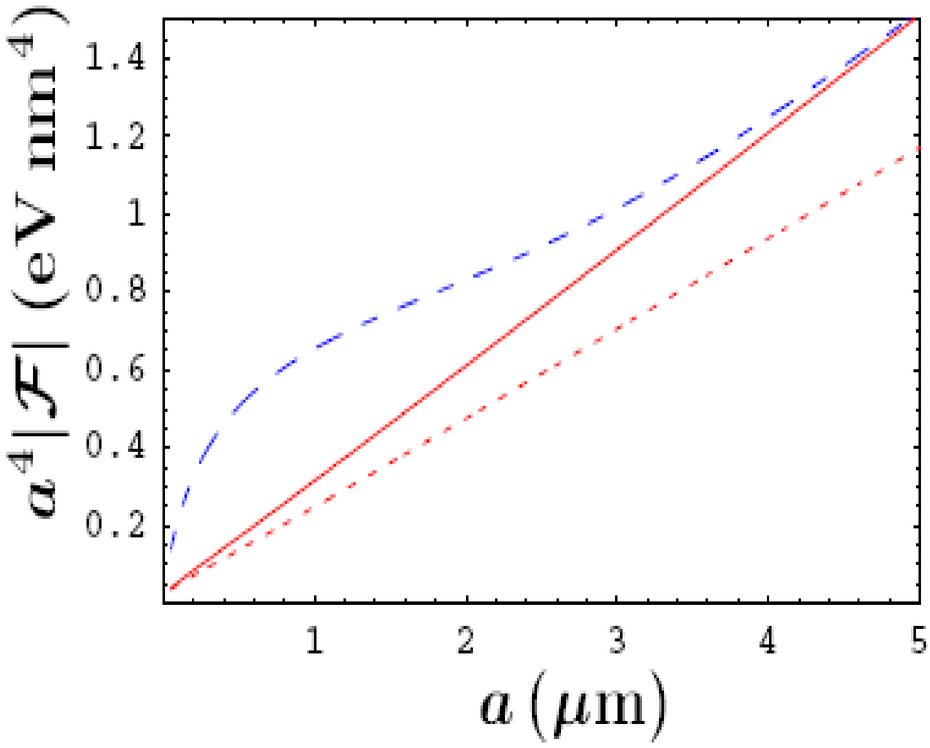
$\Delta = 0.025\,\mathrm{eV}$

$\Delta = 0.01\,\mathrm{eV}$

$\Delta \leq 0.001\,\mathrm{eV}$

Chaichian, Klimchitskaya, Mostepanenko, Tureanu, Phys. Rev. A 2012

Comparison between hydrodynamic (dashed line) and Dirac models

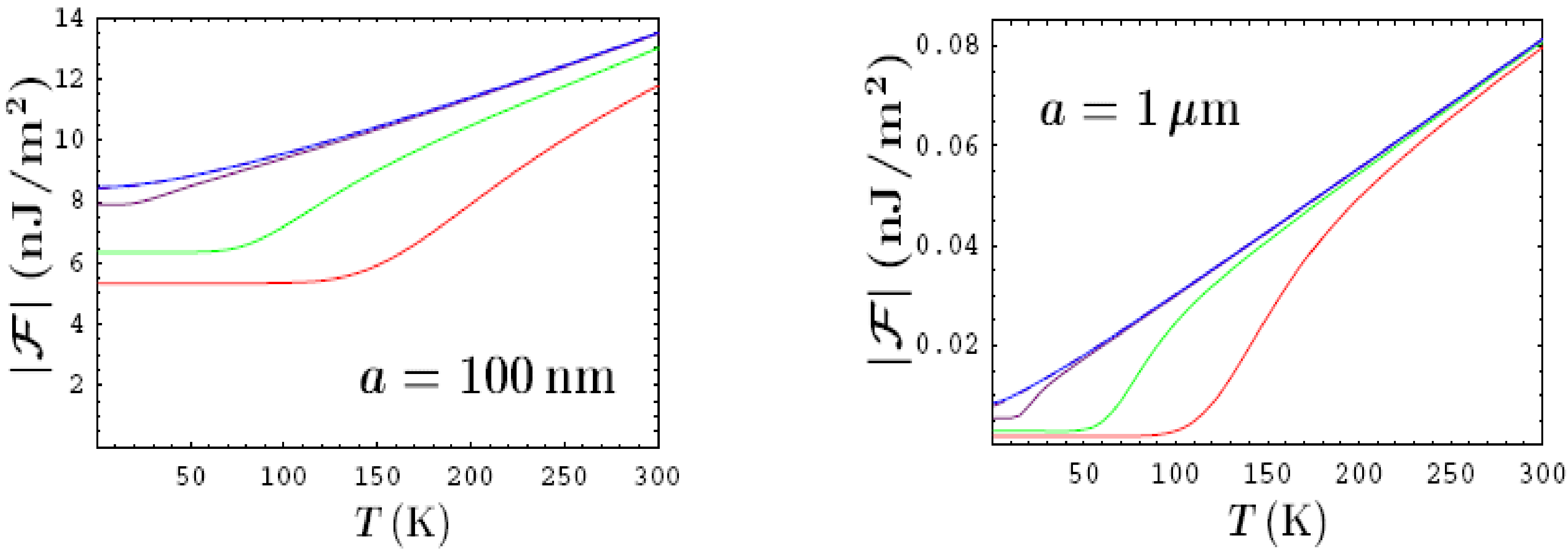


$T = 300\,\mathrm{K}$

Chaichian, Klimchitskaya, Mostepanenko, Tureanu, Phys. Rev. A 2012

5. CASIMIR INTERACTION OF GRAPHENE WITH MATERIAL PLATE

Graphene interacting with Si plate

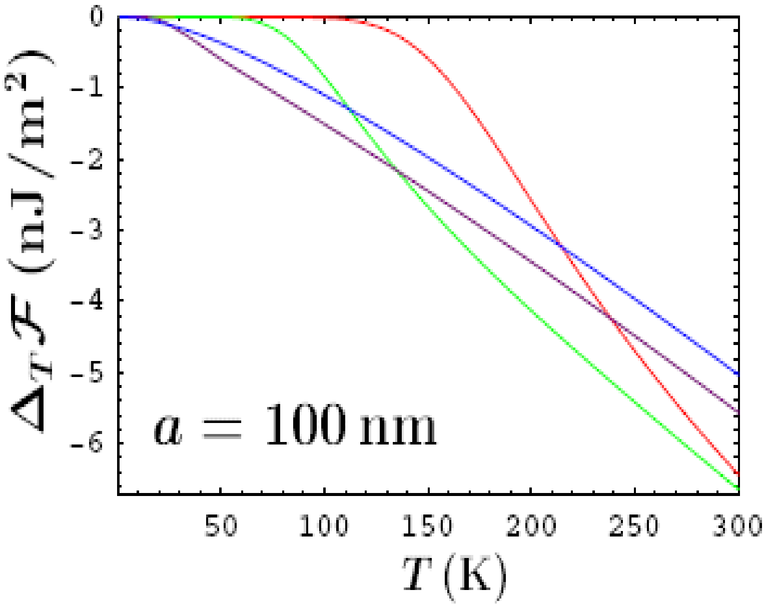


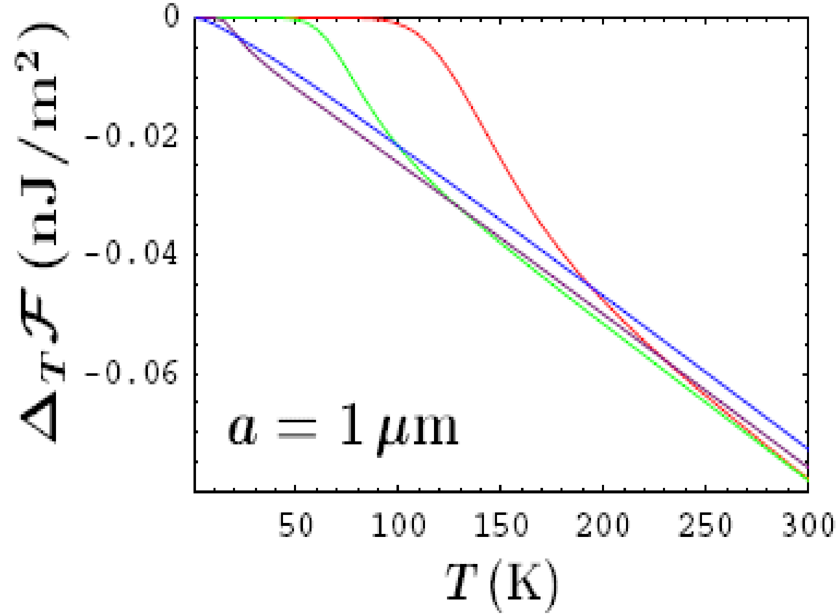
$\Delta = 0.1\,\mathrm{eV}$ (red line) $\Delta = 0.05\,\mathrm{eV}$ (green line)

$\Delta = 0.01\,\mathrm{eV}$ (pink line) $\Delta \leq 0.001\,\mathrm{eV}$ (blue line)

Bordag, Klimchitskaya, Mostepanenko, arXiv:1209.3302v1

Thermal correction to the Casimir energy



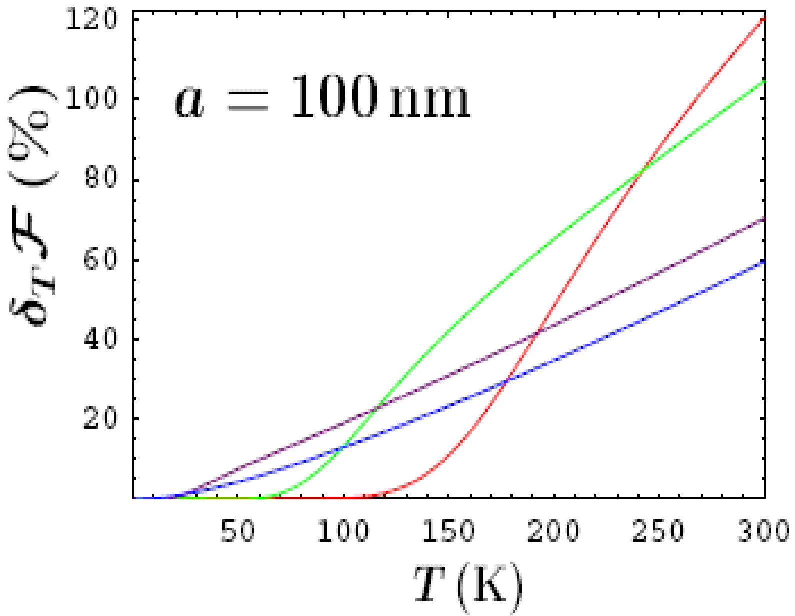


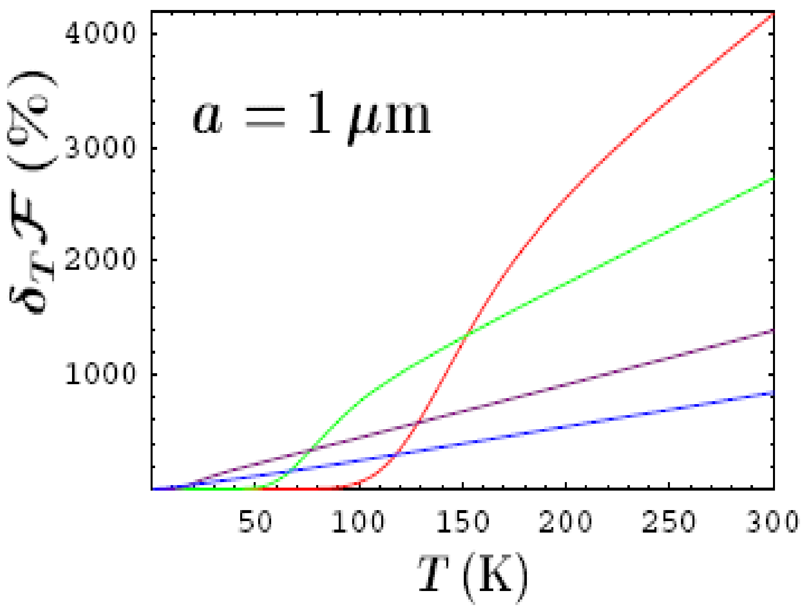
$\Delta = 0.1\,\text{eV}$ (red line) $\Delta = 0.05\,\text{eV}$ (green line)

$\Delta = 0.01\,\text{eV}$ (pink line) $\Delta \leq 0.001\,\text{eV}$ (blue line)

Bordag, Klimchitskaya, Mostepanenko, arXiv:1209.3302v1

Relative thermal correction





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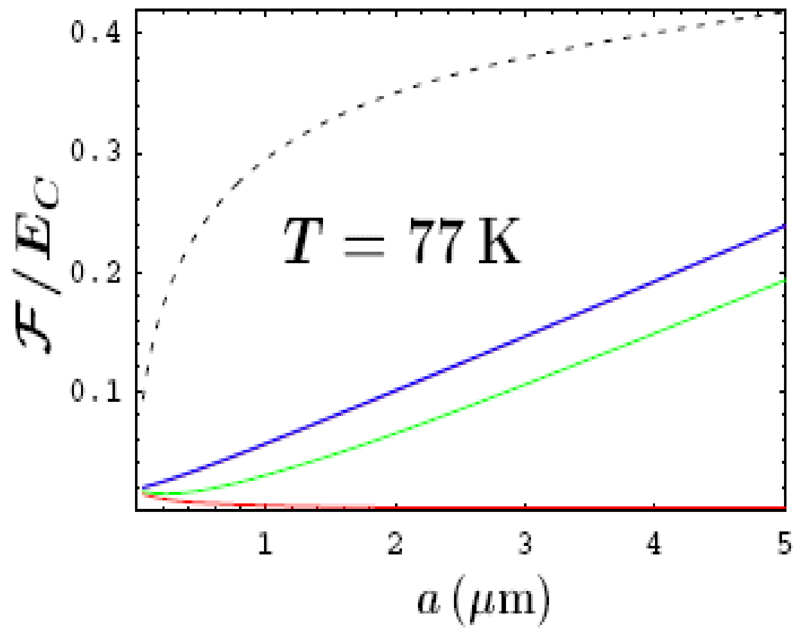
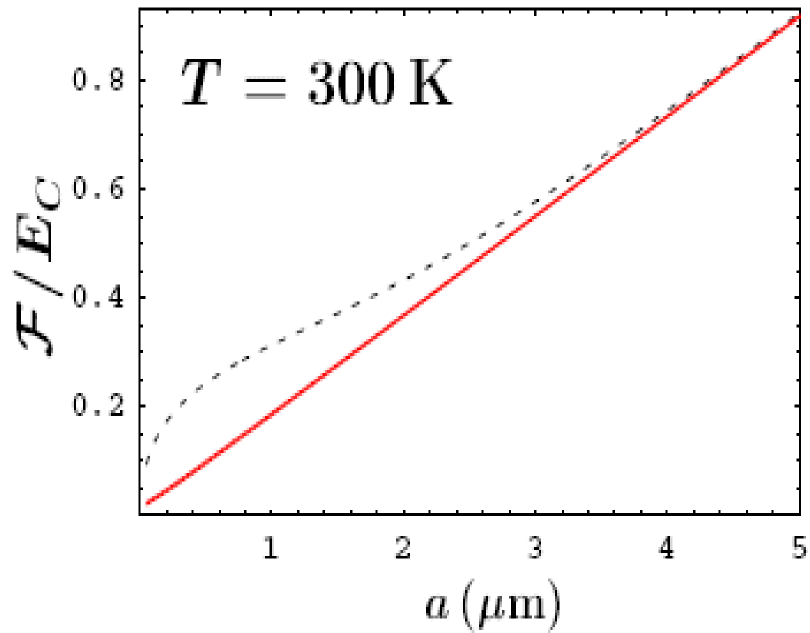
Bordag, Klimchitskaya, Mostepanenko, arXiv:1209.3302v1

Comparison between hydrodynamic (dashed line) and Dirac models





Bordag, Klimchitskaya, Mostepanenko, arXiv:1209.3302v1

6. CONCLUSIONS AND DISCUSSION

a) **Many experiments performed by different experimental groups with metallic, dielectric and semiconductor test bodies demonstrate that the Lifshitz theory using the most realistic models of dielectric permittivity is in deep contradiction with the measurement data for the thermal Casimir force.**

b) The same measurement data are consistent with the Lifshitz theory when the relaxation properties of conduction electrons are omitted for metals and the free charge carriers are disregarded for dielectrics.

c) All kinds of possible weaknesses in these experiments and in their comparison with theory discussed in the literature were carefully analyzed by different authors and shown to have no effect on the conclusions obtained.

d) The two experiments claiming agreement with the Drude model approach for metals are not independent measurements. They are based on the fitting procedures between the data and some model expressions for hypothetical contributions to the force. There are serious specific objections against comparison of the measurement data with theory in these experiments.

e) Measurement of the Casimir-Polder and Casimir interactions of atoms and material bodies with graphene opens new prospective opportunities for investigation of large thermal effects at short separations. There is no direct analogy, however, between theoretical predictions obtained using the Drude model approach for metals and the Dirac model for graphene.