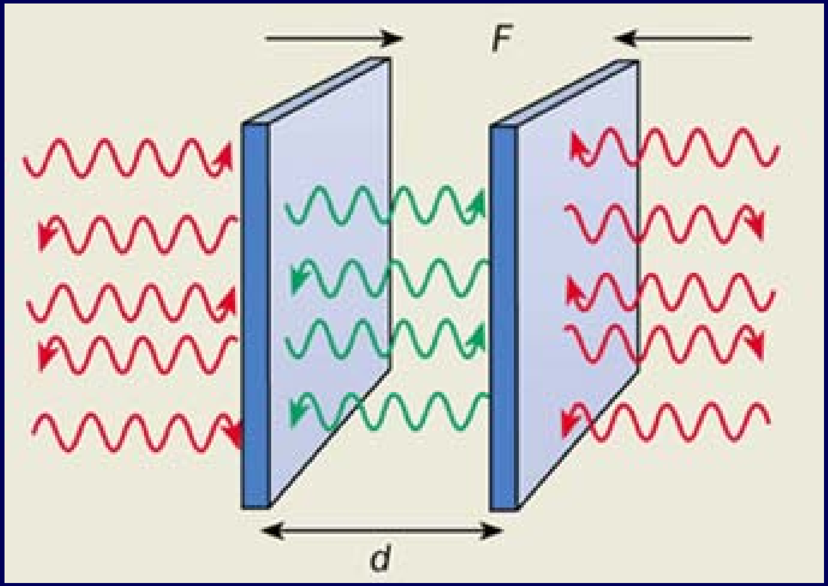
The Casimir Effect: A Force from Nothing

Hendrik Casimir



$$F(d) = -\frac{\pi^2 \hbar c}{240 d^4} A$$

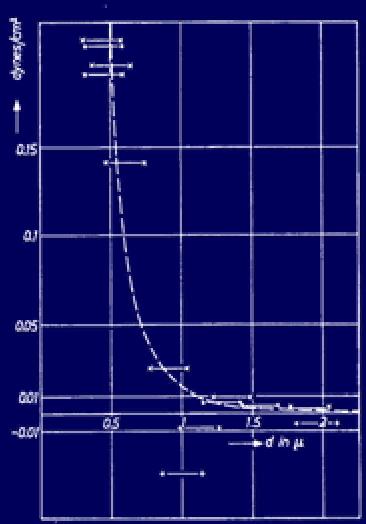
attraction due to confinement of quantum mechanical vacuum fluctuations

*H. B. G. Casimir, Proc. Kon. Nederl. Akad. Wet. B**51,** 793 (1948)*

Experimental Observations

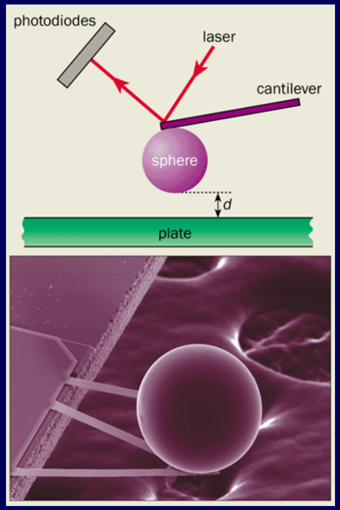
- Mechanical Balance

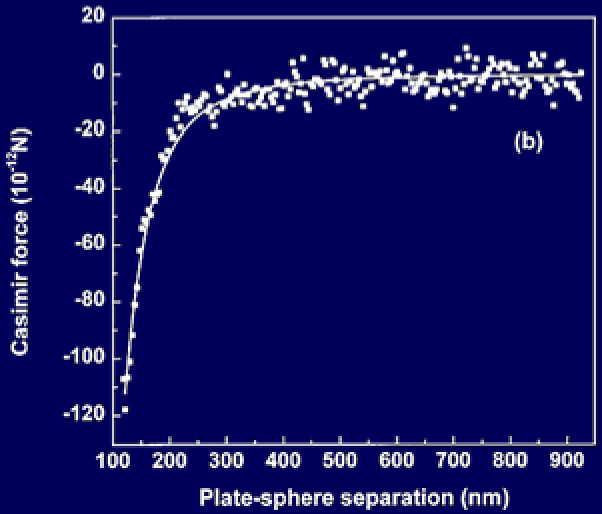
  Sparnaay, Physica ***24****, 751 (1958)*



- AFM

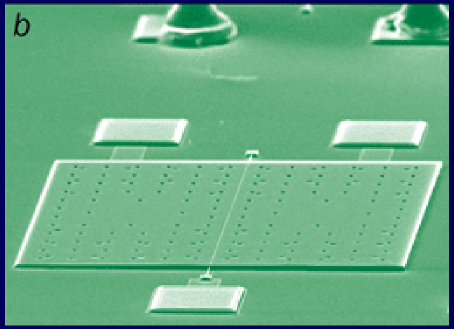
  Mohideen and Roy, PRL ***81,*** *4549-4552 (1998)*

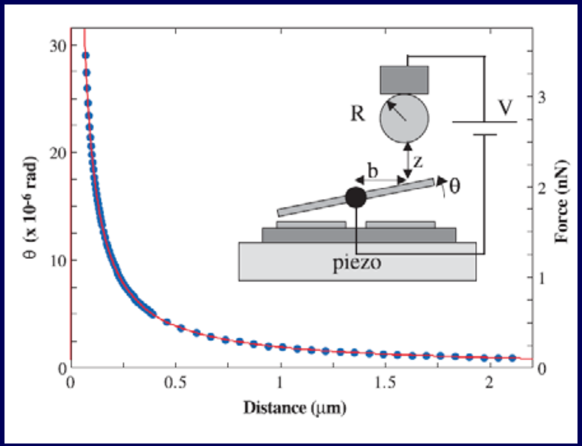




- Actuation of MEMS

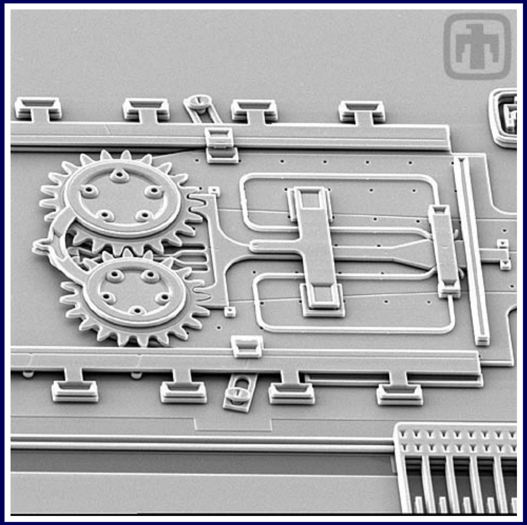
  Chan, Aksyuk, Kleiman, Bishop, Capasso, Science ***291,*** *1941 (2001)*





Failure Mechanisms in MEMS

Casimir forces ⟹ STICTION



Sandia National Laboratory

repulsive Casimir forces:

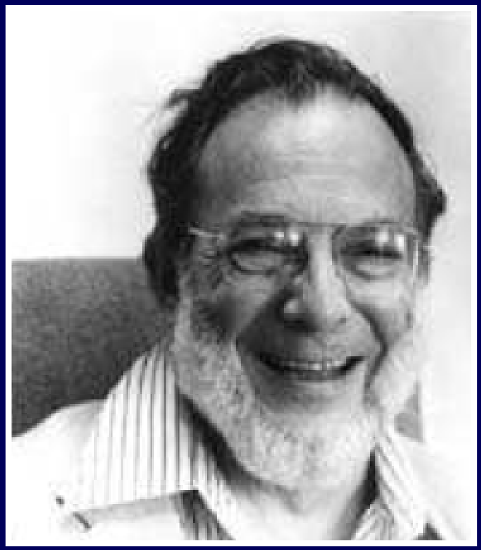
$\mu > \varepsilon$ *Kenneth et al. PRL **89**, 33001 (2002)*

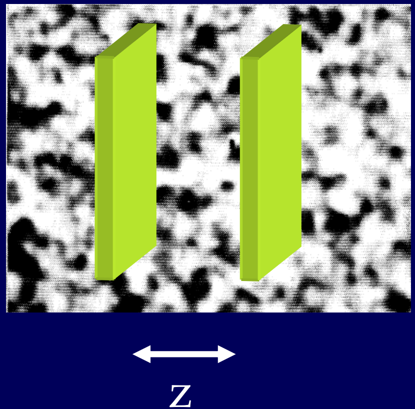
meta-materials *Leonhardt, Philbin, New J. Phys. **9**, 254 (2007)*

The Critical Casimir Effect

„Phenomena at the walls in a critical binary mixture“

M. E. Fisher and P. G. deGennes, C. R. Acad. Sci. Paris ***B287,*** *209 (1978)*





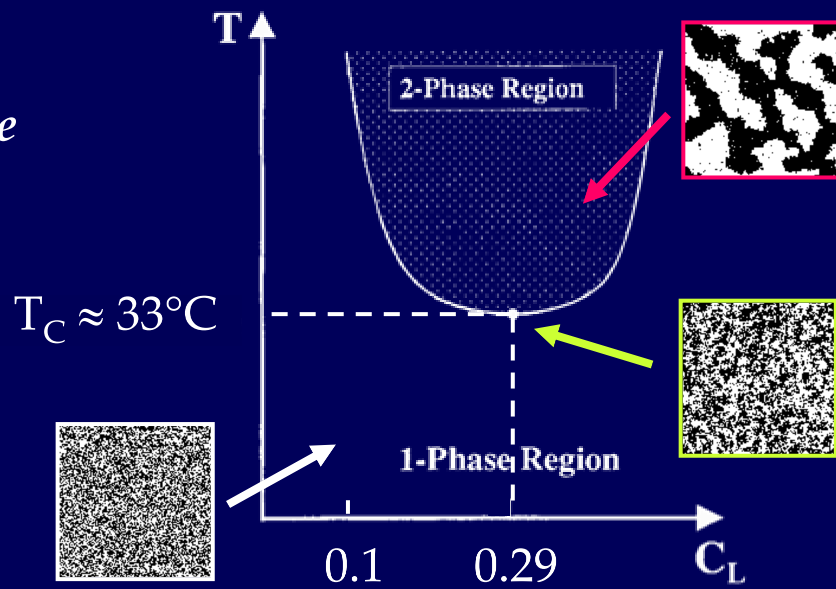
Confinement of order parameter fluctuations close to critical points

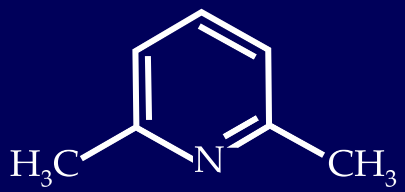
$$F(z) = A\,\frac{k_B T_c}{z^3}\,\vartheta(z/\xi) \qquad \xi = \xi_0 \left|\frac{T}{T_c} - 1\right|^{-\nu}$$

Binary Critical Mixtures

water - lutidine

$m = C - C_C$





36°C

34°C

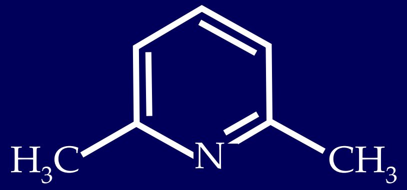
33°C

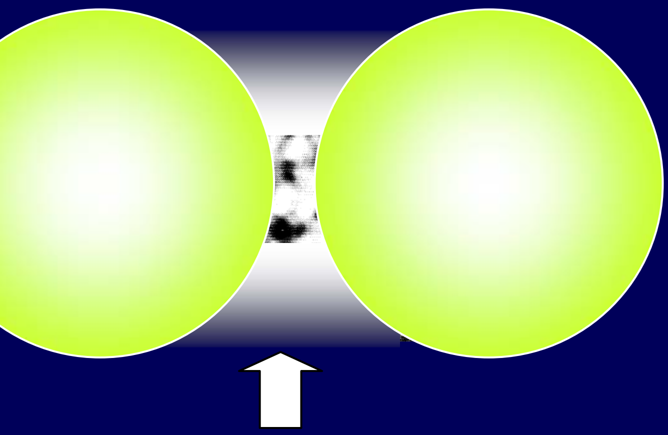
critical opalescence

T < 33°C

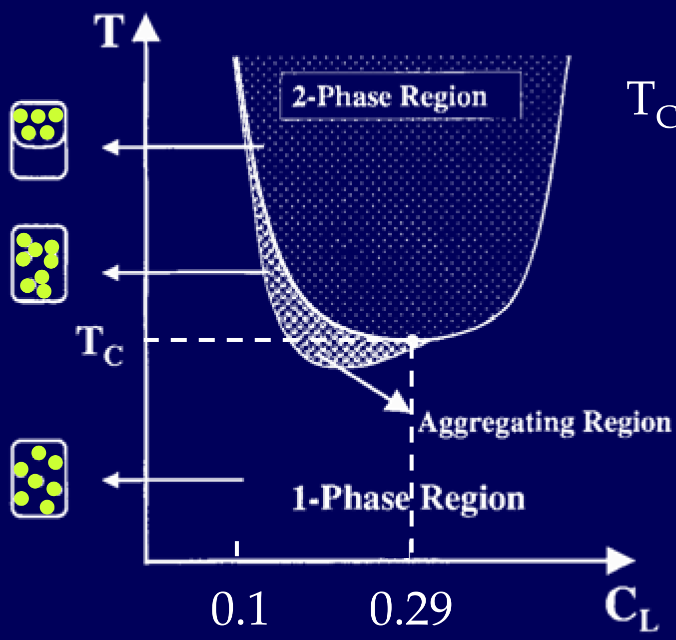
Silica Spheres in Binary Mixtures

- binary mixture of water – 2,6 lutidine
- lower consolute point
- **silica spheres** (2R = 0.16µm)





confinement



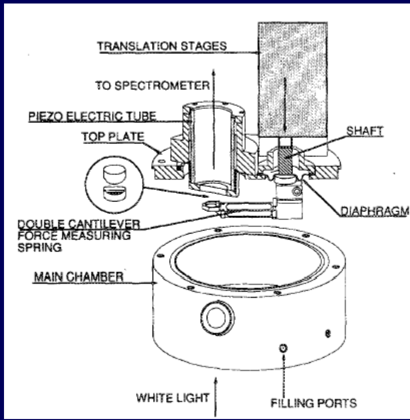
$T_C \approx 33°C$

*Beysens, Estéve, PRL **54,** 2123 (1985)*

Prewetting ? Capillary condensation ?

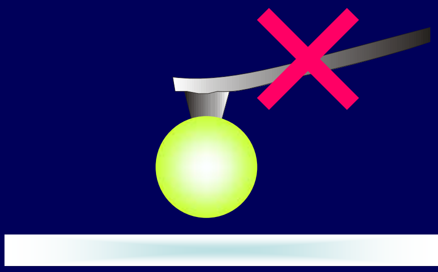
How to Measure Tiny Forces

How to resolve pico … femto Newton



- *Surface Force Apparatus (SFA)*

  J.N. Israelachvili, Intermolecular and surface forces, Academic Press (1991).



- *Atomic Force Microscopy (AFM)*

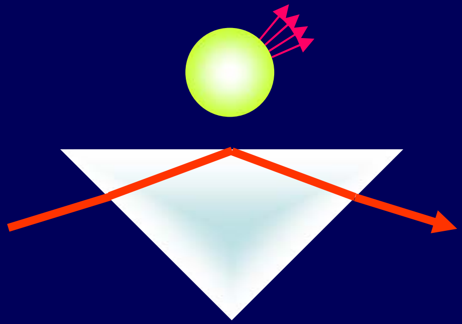
  Ducker, Senden, Pashley, Nature, **353**, 239 (1991).
  Milling,Vincent, J. Chem. Soc., Farady Trans. **93,** 3179 (1997).

resolution limited by spring constant $D \geq 0.01$N/m

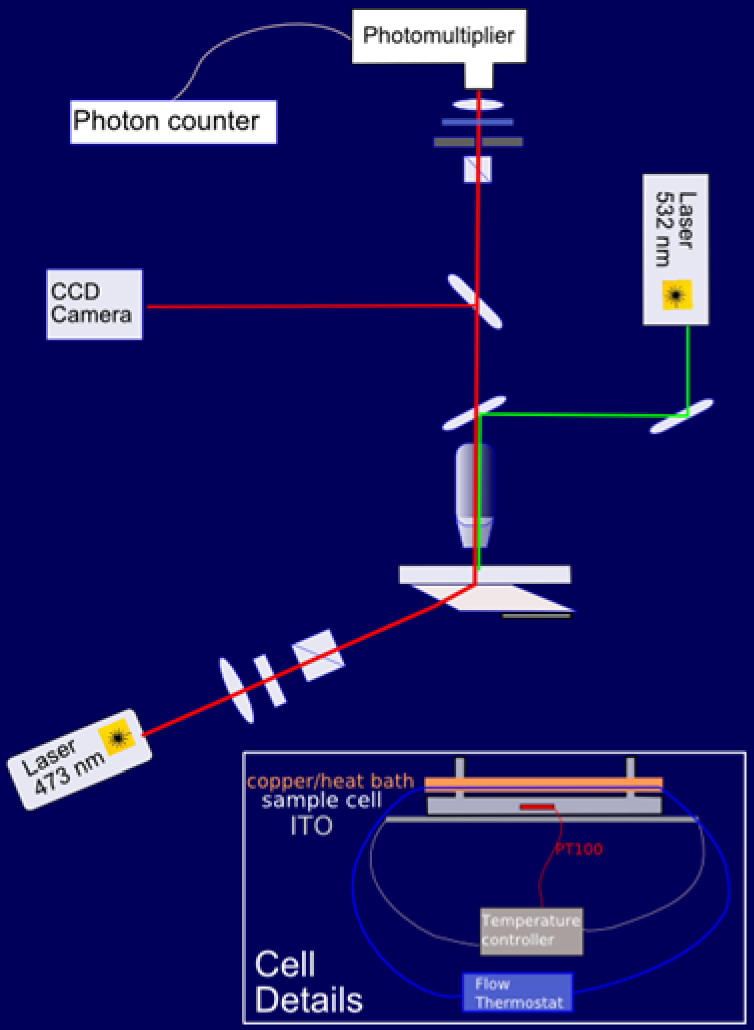
➡ ´freely´ suspended colloidal probe particle

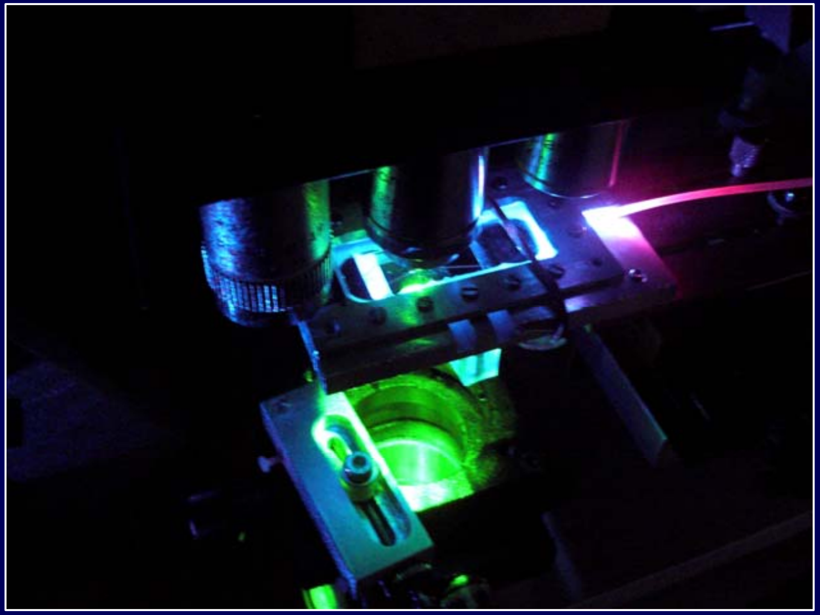
- *Total Internal Reflection Microscopy (TIRM)*

  Walz, Current opinion in colloidal interfaces & science **2,** 600 (1997).
  Prieve, Luo, Lanni, Faraday Discuss. Chem. Soc. **83,** 297 (1987).



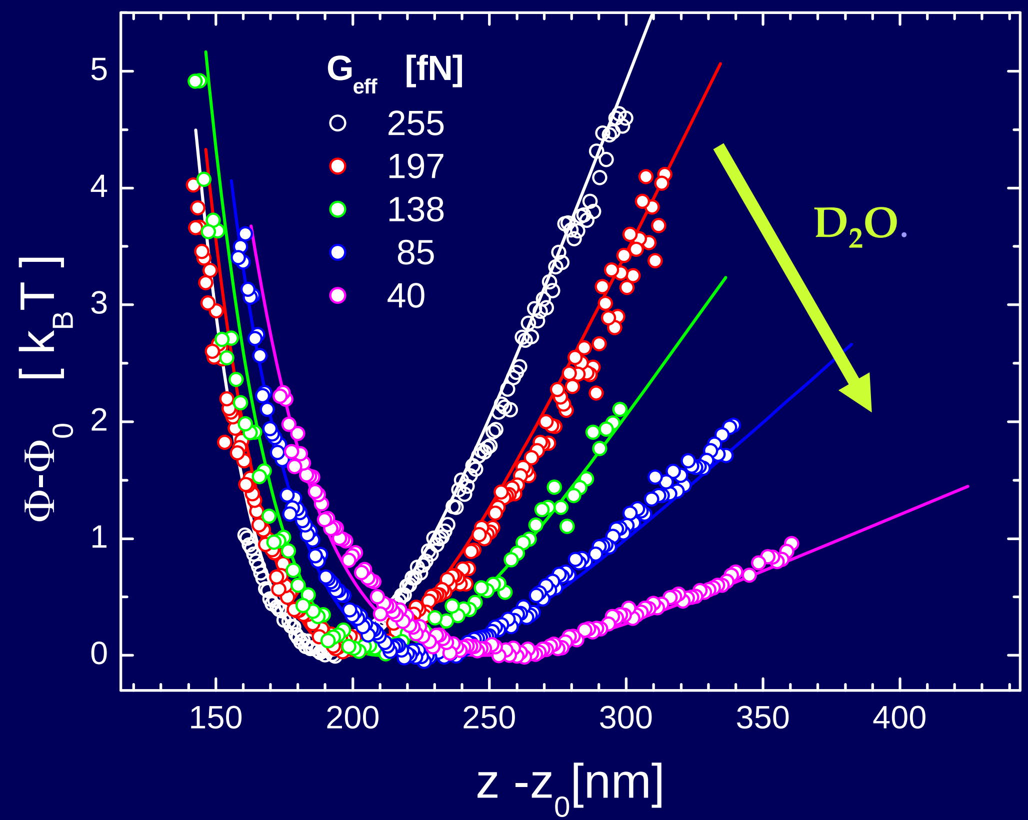
Experimental Setup





$$\Delta T = \pm 0.005°C$$

Sensitivity of TIRM



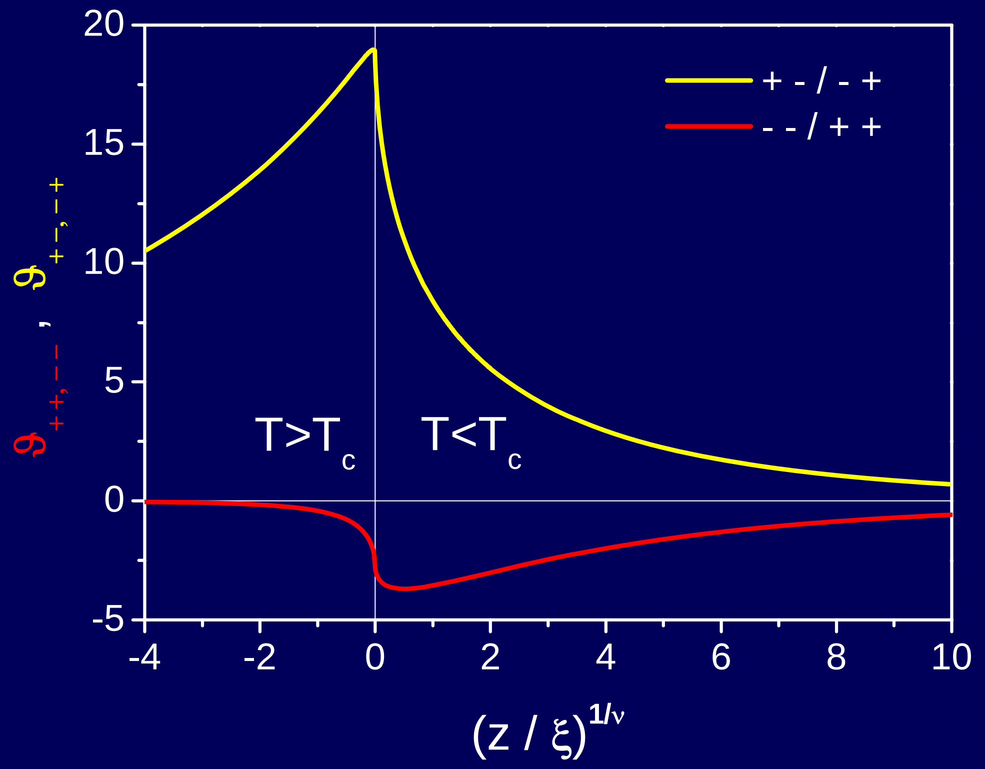
	ρ (g/cm³)
H_2O	1.0
PS	1.05
D_2O	1.1

resolution < 10 fN !

Helden, Roth, Koenderink, Leiderer, Bechinger, PRL ***90,*** *48301 (2003)*

Scaling Function & Boundary Cond.

Sphere-Plate: $$\frac{\Phi}{k_B T} = \frac{R}{z}\vartheta\left(\frac{z}{\xi}\right) \qquad z \le R$$

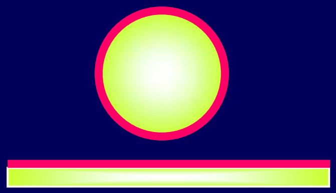


Vasilyev, Gambassi, Maciolek, Dietrich arXiv:0708.2902v1 (2007)

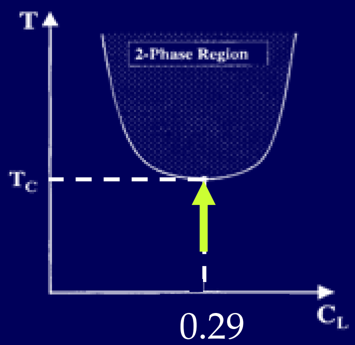
attractive and repulsive critical Casimir forces

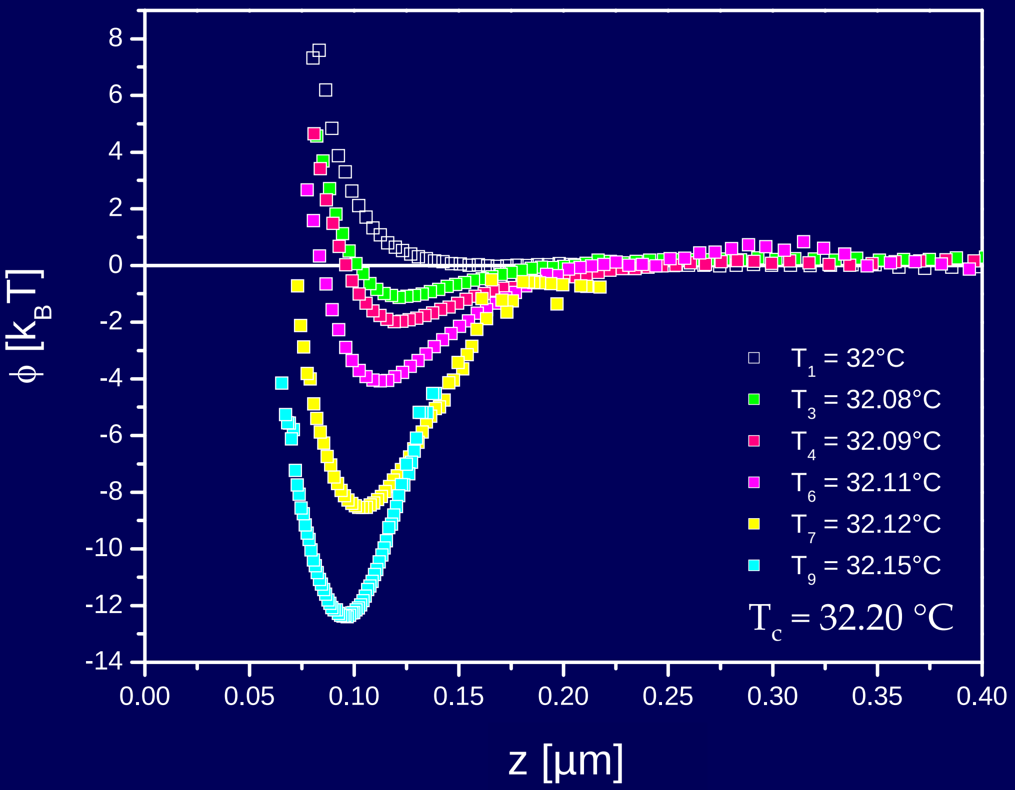
Critical Casimir Forces: + +

++: particle & wall: preferential adsorption of lutidine



PS 3.7μm (x-linked ,weakly charged)
HMDS treated silica wall (hydrophobic)



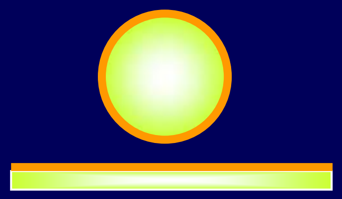


similar results for
$0.25 < c_L < 0.32$

Critical Casimir Forces: --

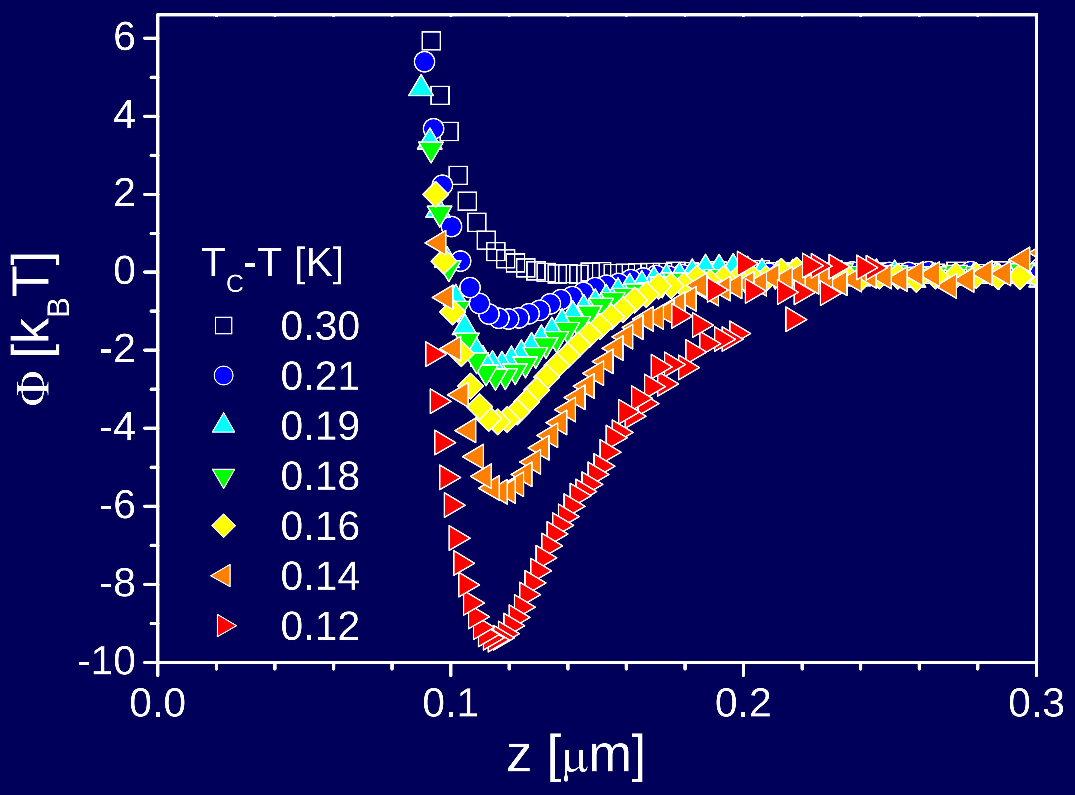
- -: particle & wall: preferential adsorption of water

σ [μC/cm²]	phase
5.70	W
3.85	W
0.38	L



sulfate-terminated PS 2.4μm (10.1μC/cm²)
hydrophilic silica wall

Gallagher et al. Phys. Rev. A ***46,*** *7750 (1992)*



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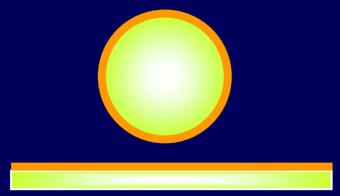

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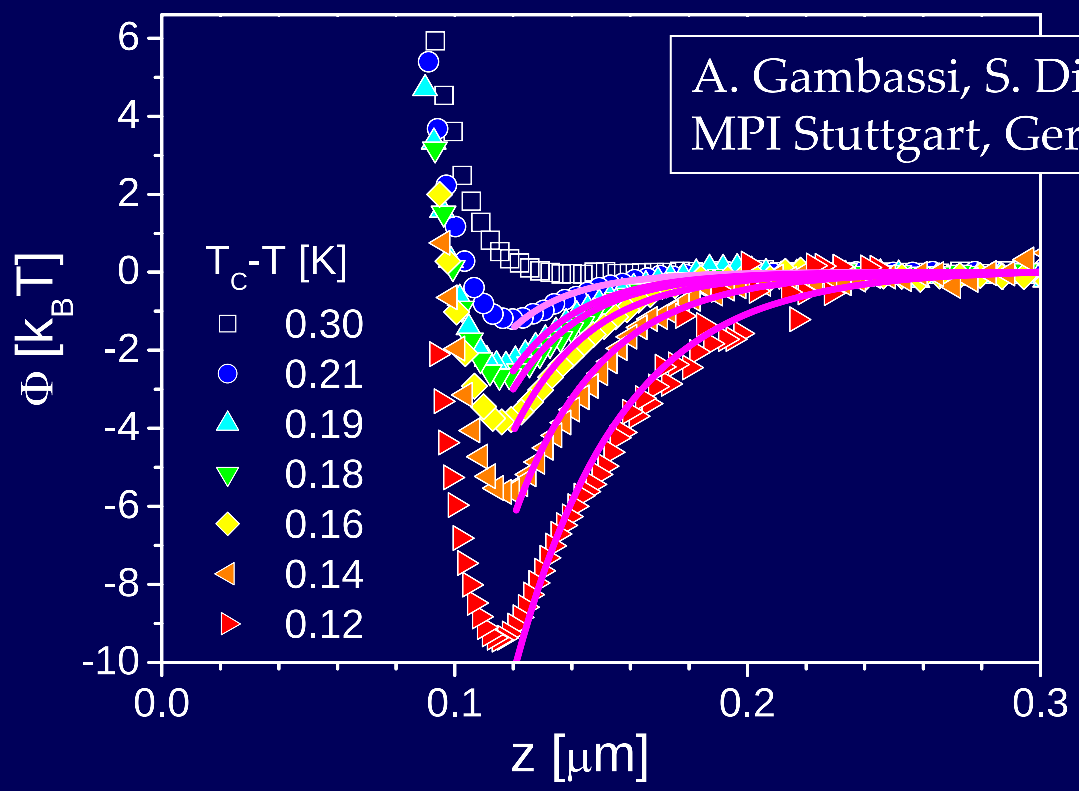
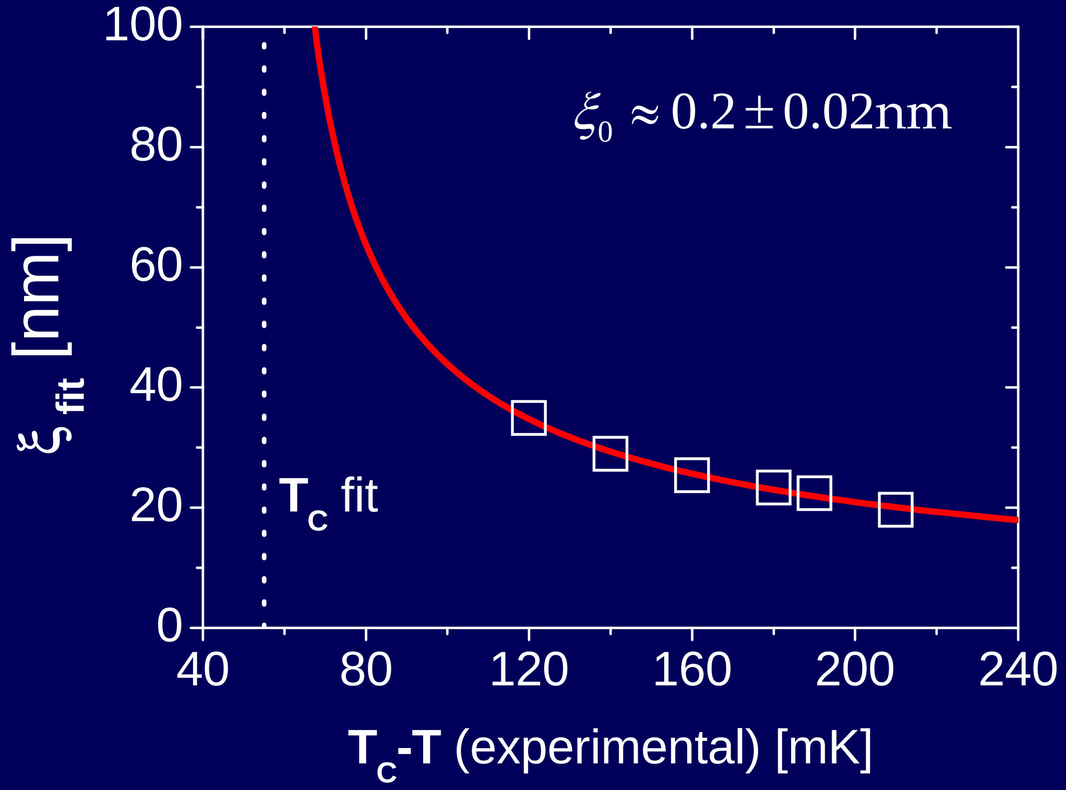


$$\xi(T) = \xi_0 \left| \frac{T}{T_c} - 1 \right|^{-0.63}$$

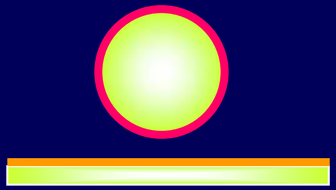
Nature, accepted

Correlation Length

$$\xi(T) = \xi_0 \left| \frac{T}{T_c} - 1 \right|^{-0.63}$$

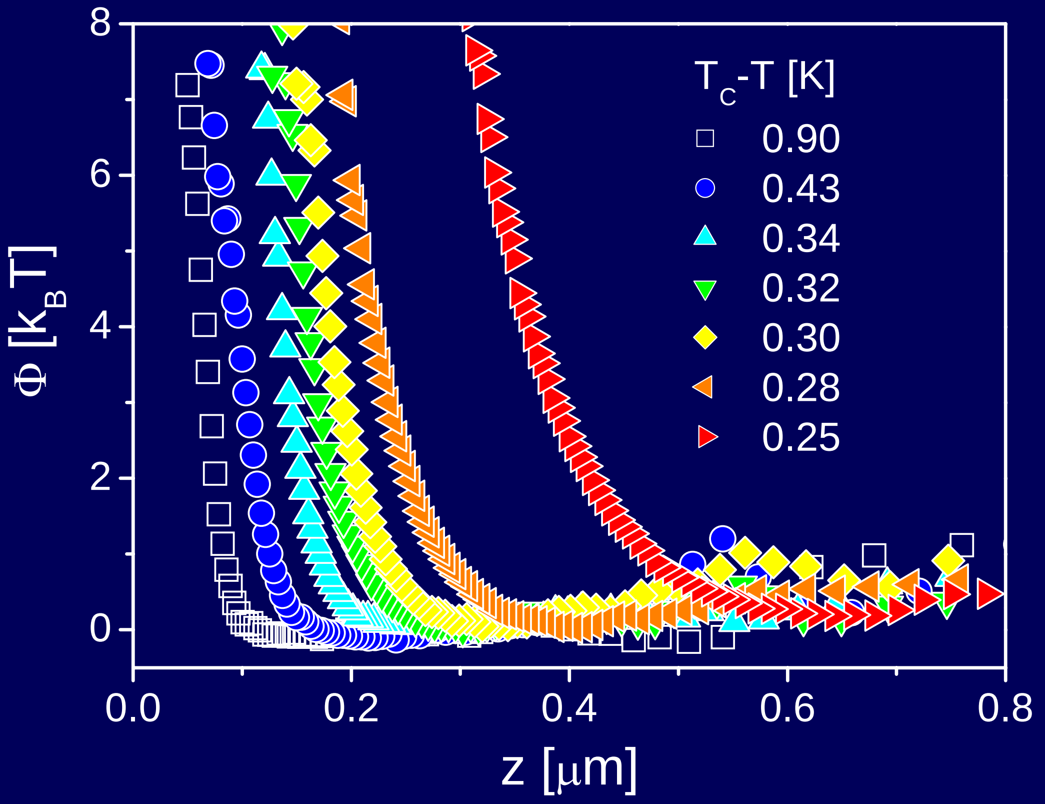


Critical Casimir Forces: + -

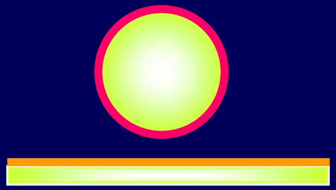


asymetric boundary conditions

→ repulsive critical Casimir force



Critical Casimir Forces: + -



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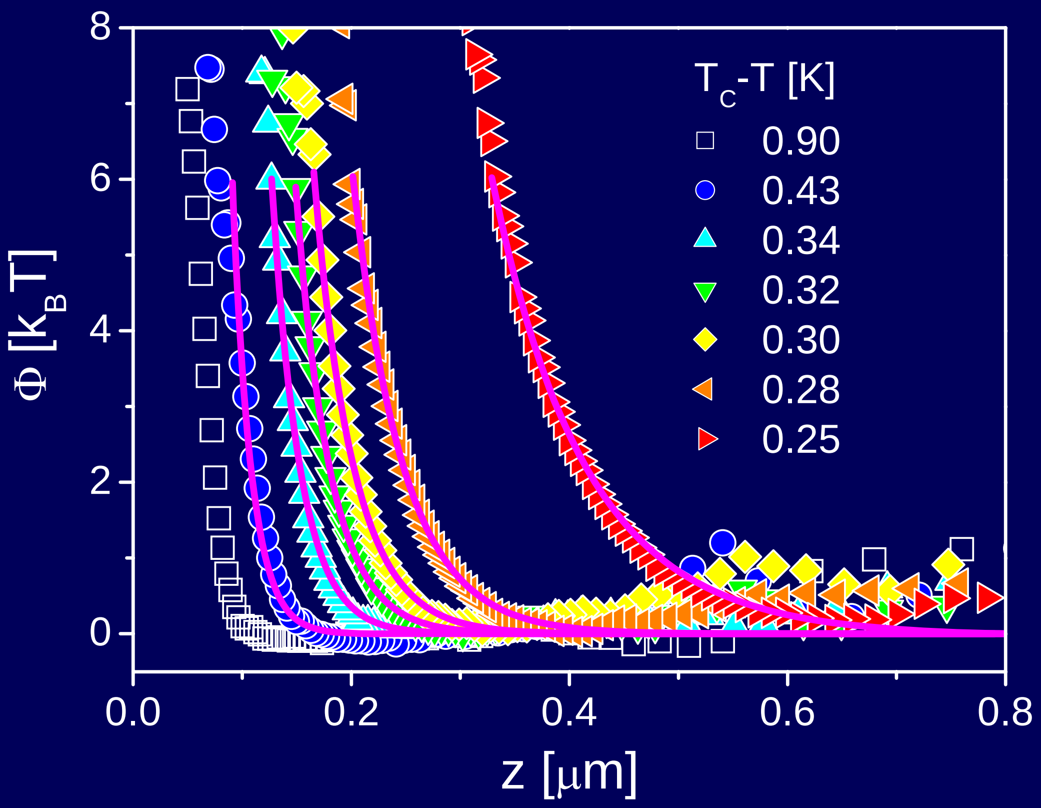

Correlation Length

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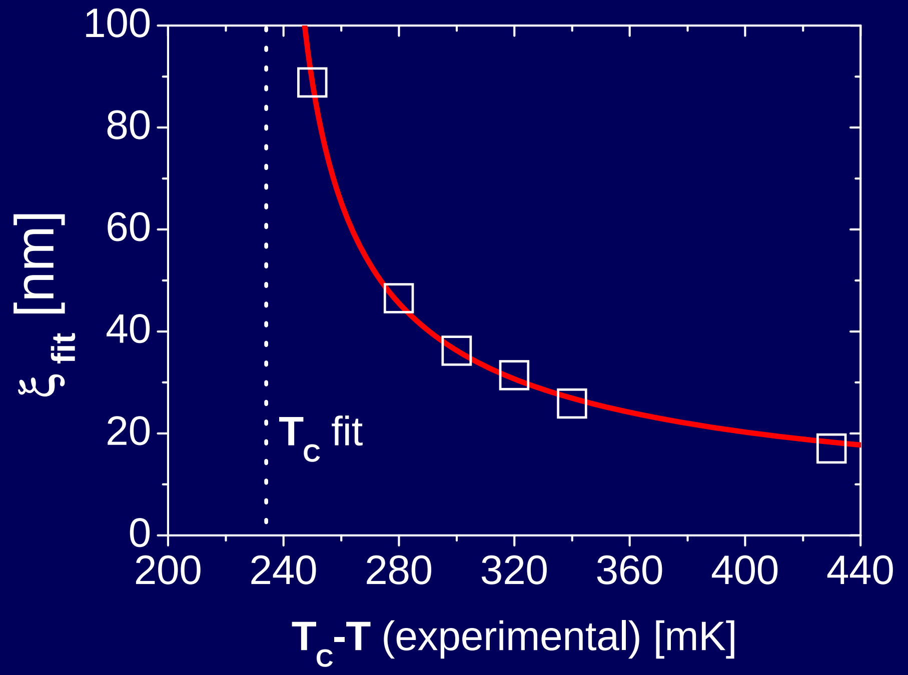
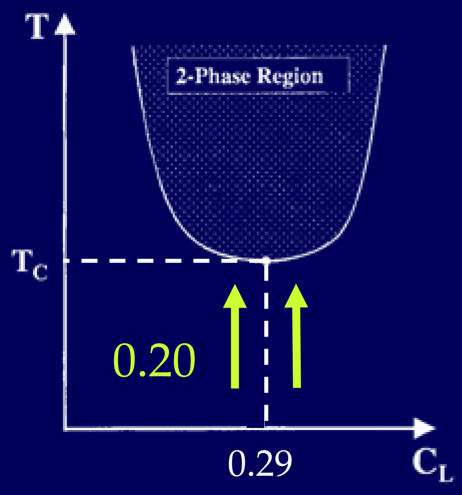
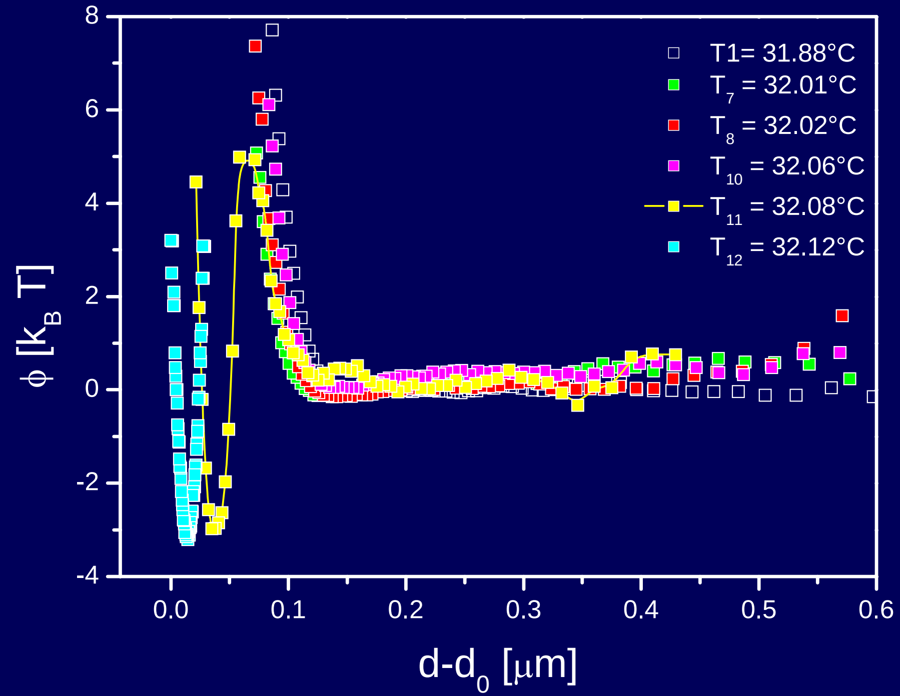
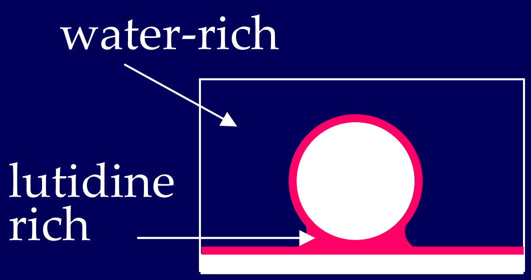


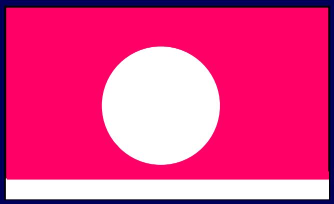
Off-Critical Composition: + +







reduction of surface energy by
BRIDGE FORMATION



No bridge formation for $c_L > c_C$ ✓

Summary & Outlook

- *Direct observation of critical Casimir forces in binary liquids*

  ⇨ attractive and repulsive interactions on the order of many kT

⇨ tunable interaction potential: no salt, no depletion agent, reversible !

- *novel phases (photonic crystals)*
- *colloidal self-assembly on chemically patterned surfaces*
- *anti-stiction coatings for MEMS*