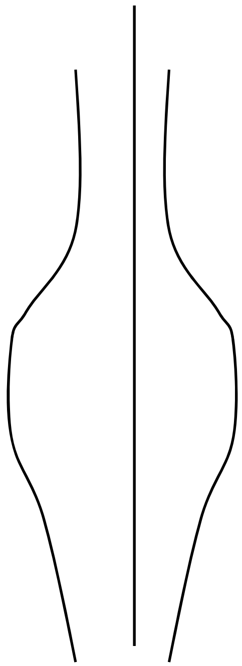
Traps for precision measurement

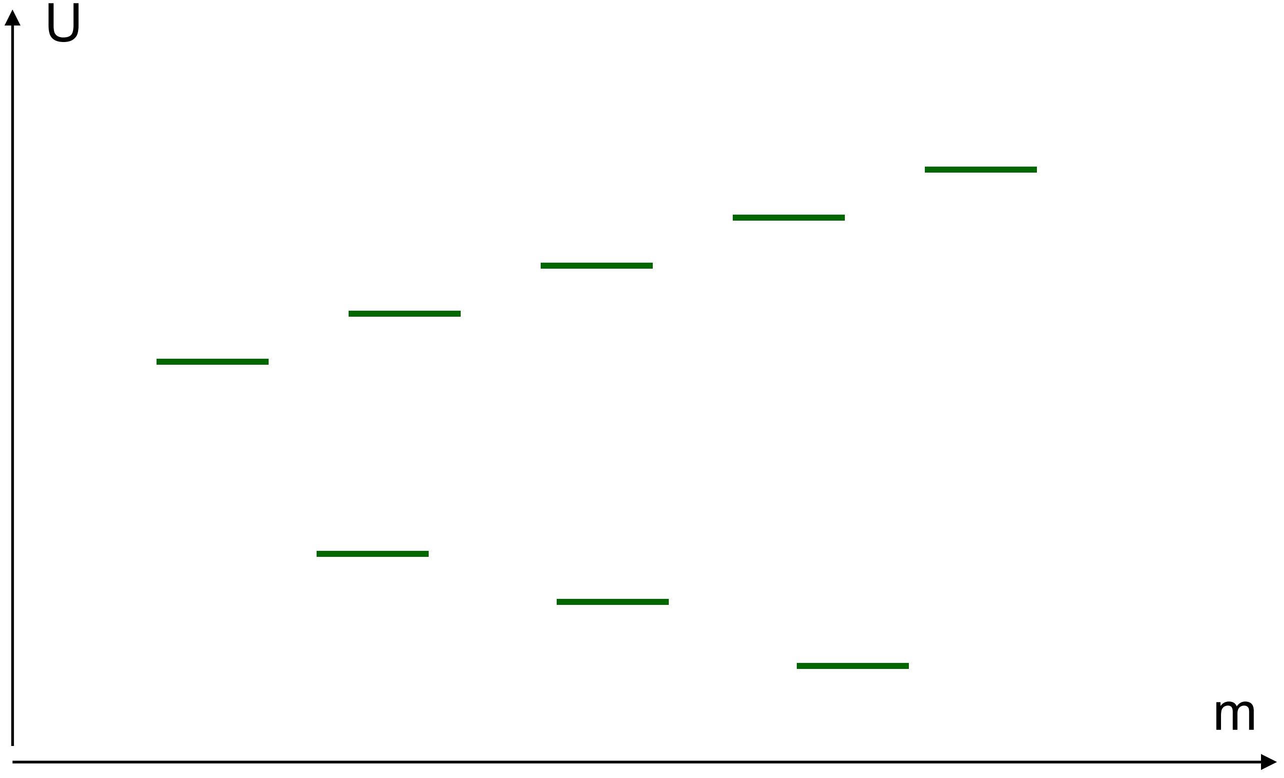
Long coherence times= good.

Traps for precision measurement

Magnetic trap (Ioffe-Pritchard) for neutrals

Force = grad (|B| μ)

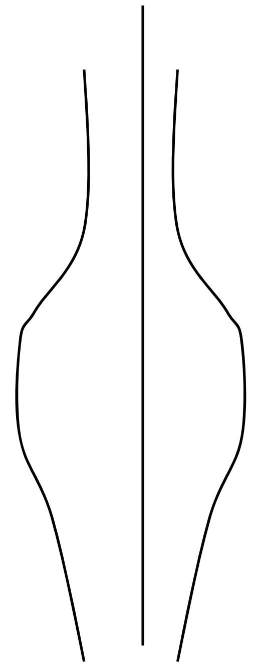


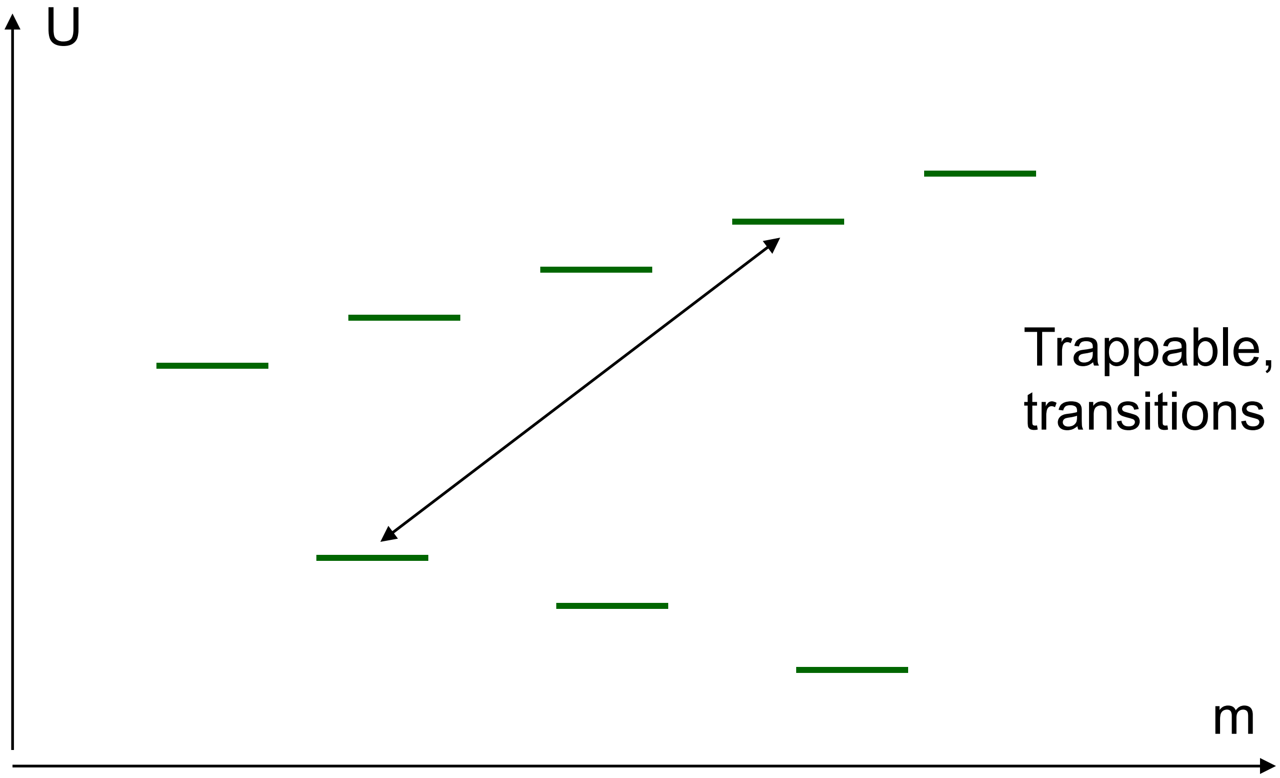


Traps for precision measurement

Magnetic trap (Ioffe-Pritchard) for neutrals

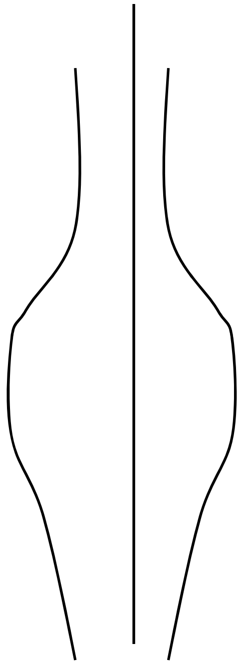
Force = grad (|B| μ)





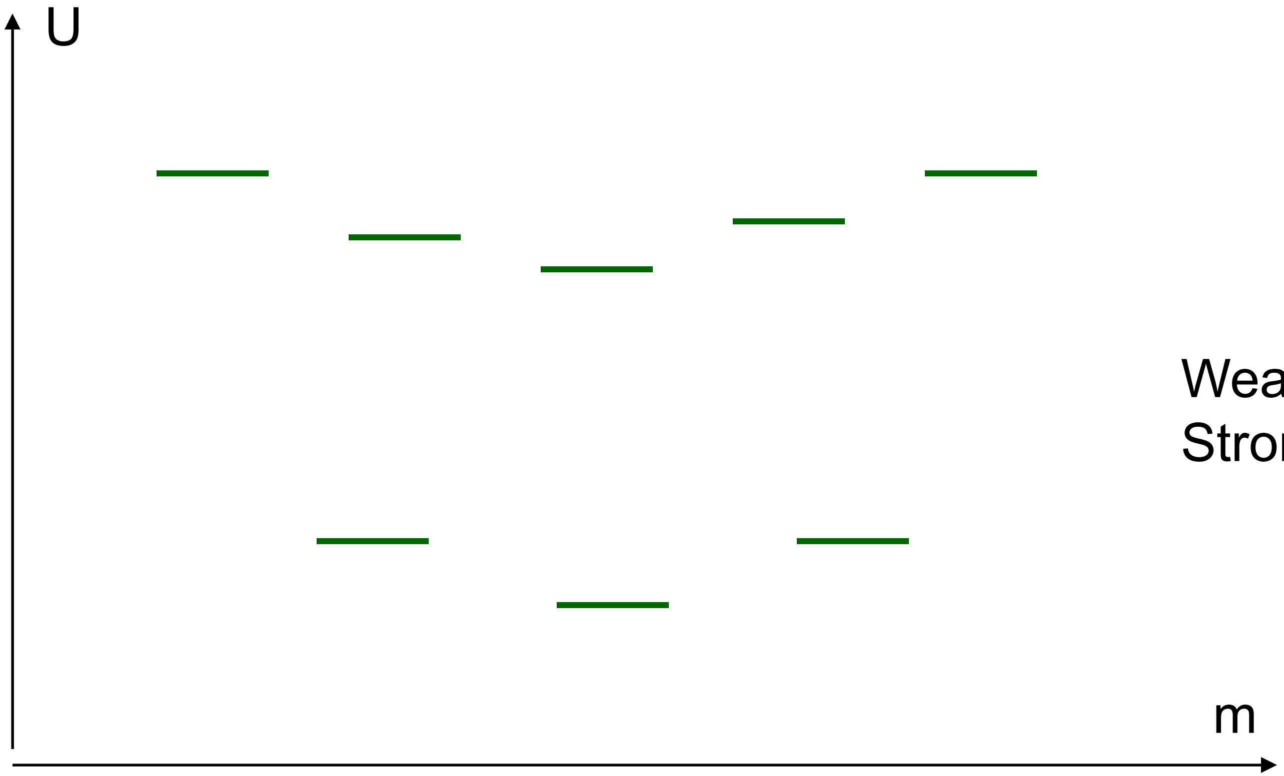
Trappable, B-field insensitive transitions exist, in most species.

Traps for precision measurement



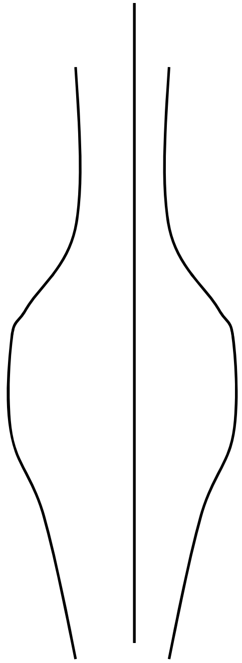
Electrostatic trap (Ioffe-Pritchard) for neutrals

Force = grad (|E| d(E))



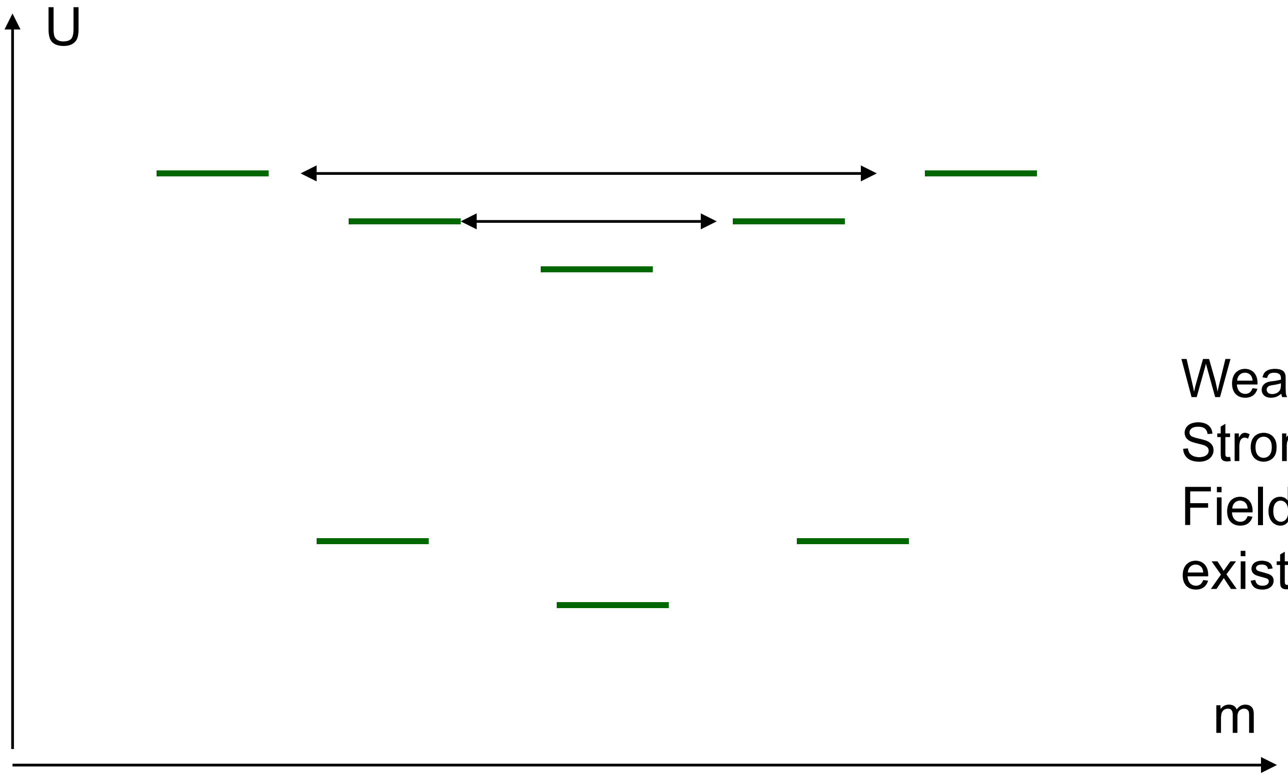
Weak, for atoms.
Strongish, for molecules.

Traps for precision measurement



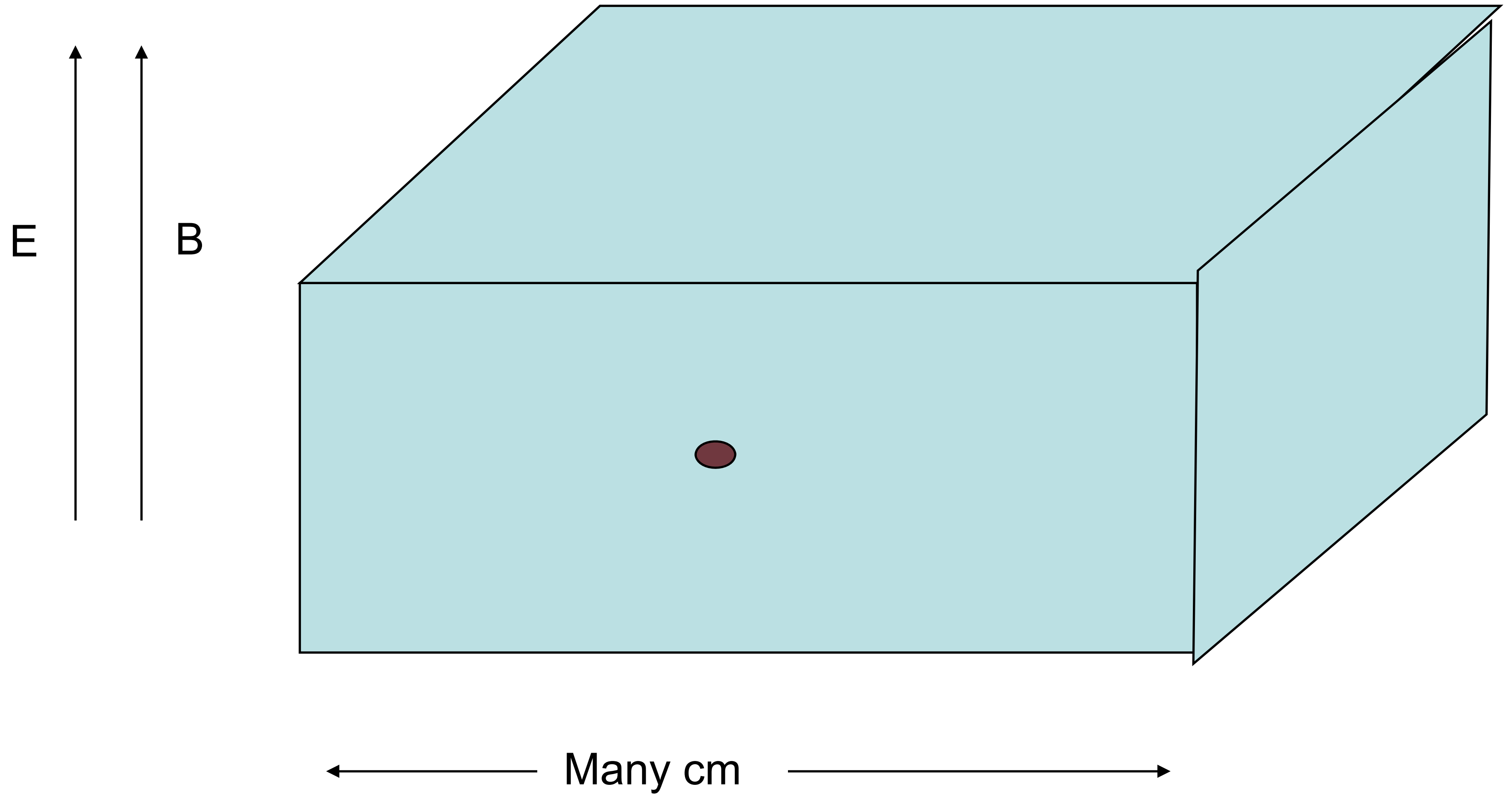
Electrostatic trap (Ioffe-Pritchard) for neutrals

Force = grad (|E| d(E))



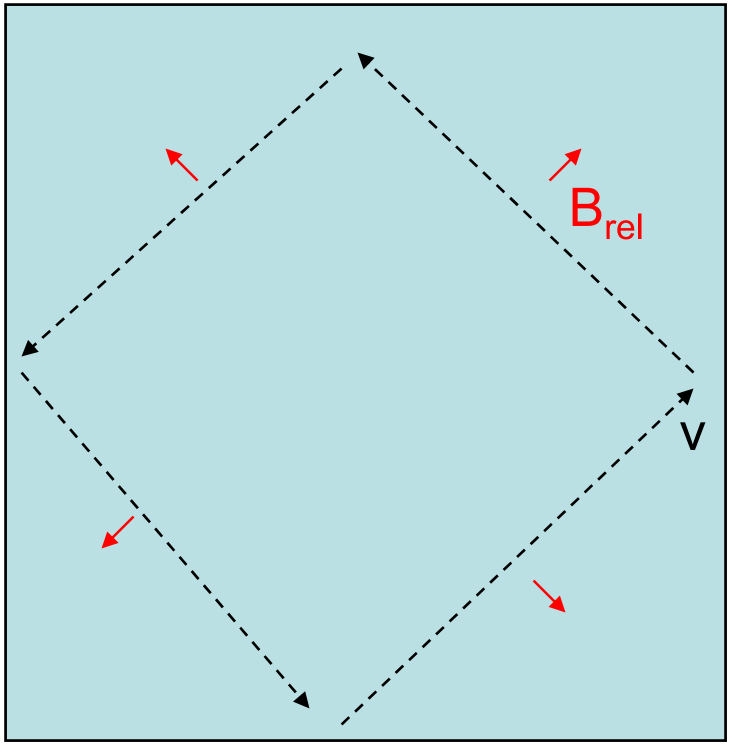
Weak, for atoms.
Strongish, for molecules.
Field insensitive transitions exist.

Neutron-in-a-box (literally)



B_0, E_0, point up out of the screen

Neutron motion partially transforms strong electric field into B-field.

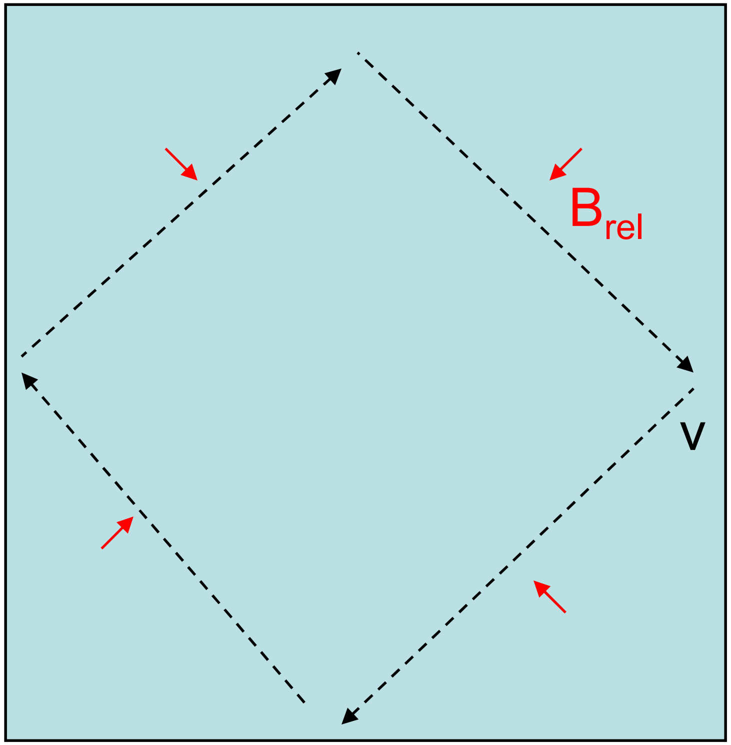


Go back to this case: No dirt (no spatial gradient in B) means no systematic. But, what about dephasing?

Enclosed area of neutron trajectory means enclosed area of B-vector in time. A shift in phase between m=1/2 and m=-1/2 levels!

B_0, E_0, point up out of the screen

Neutron motion partially strong electric field into B-field.



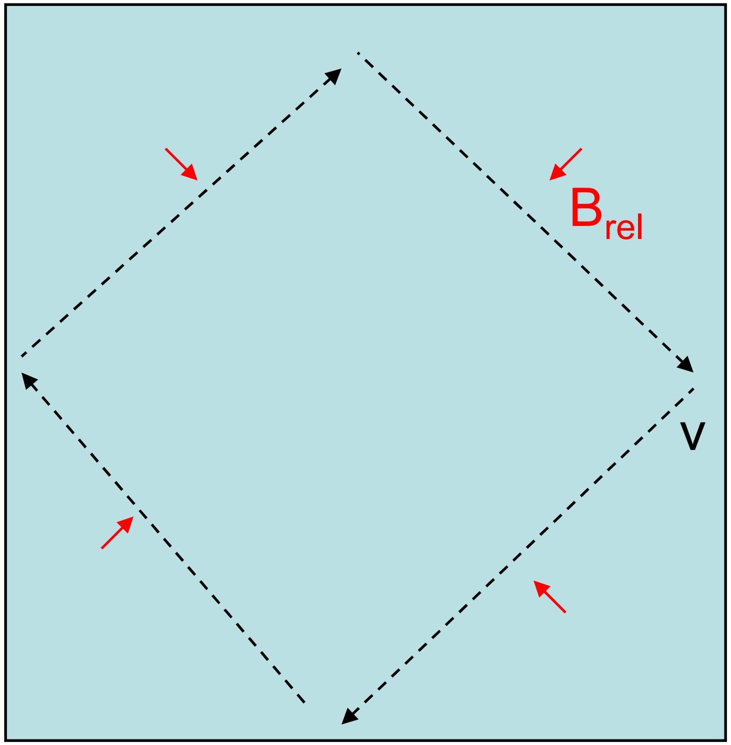
Go back to this case: No dirt (no spatial gradient in B) means no systematic. But, what about dephasing?

Thermal distribution of trajectories means this effect as no net   sign.

Enclosed area of neutron trajectory means
enclosed area of B-vector in time. A shift in phase between
m=1/2 and m=-1/2 levels!

B_0, E_0, point up out of the screen

Neutron motion partially strong electric field into B-field.



Thermal distribution of trajectories means this effect as no net   sign.

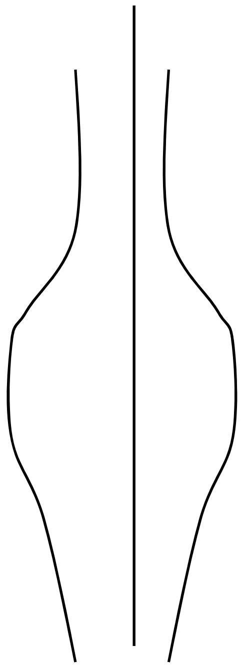
Enclosed area of neutron trajectory means
enclosed area of B-vector in time. A shift in phase between
m=1/2 and m=-1/2 levels!

OK for a box. What about trapped particles!?

Dephasing due Berry’s phase arising from random motion in inhomogenous trapping fields.

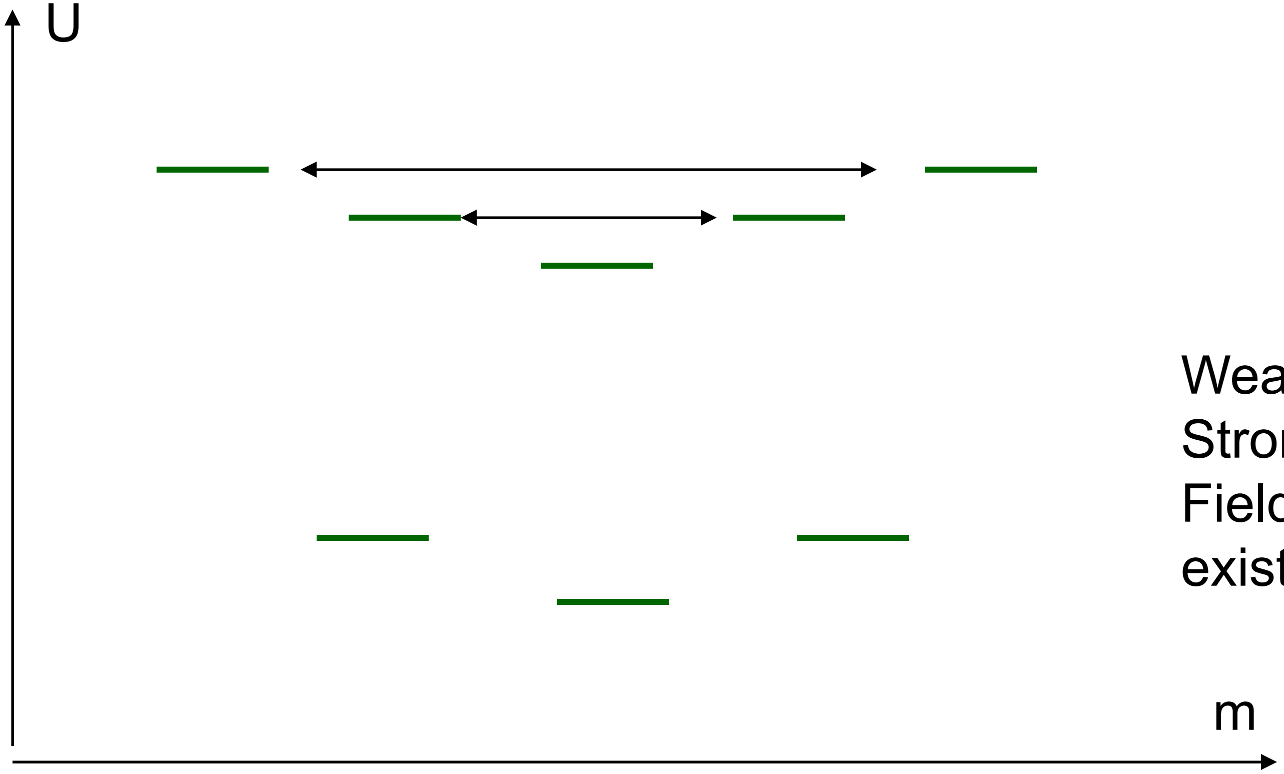
Potentially big problem, except if atoms/molecules are “cold enough”.

Traps for precision measurement



Electrostatic trap (Ioffe-Pritchard) for neutrals

$\text{Force} = \text{grad}\,(|E|\;\; d(E))$

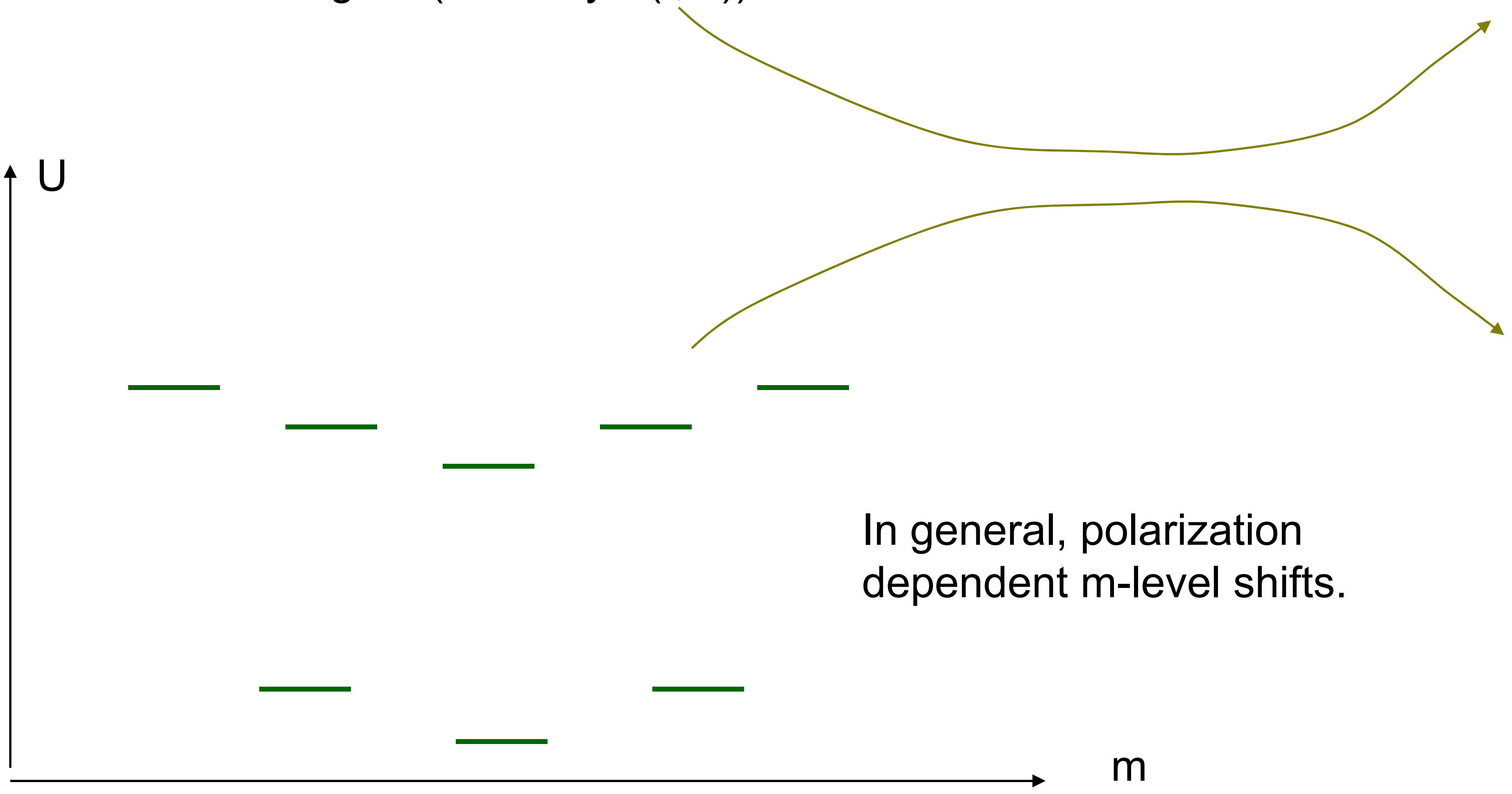


Weak, for atoms.
Strongish, for molecules.
Field insensitive transitions exist.

Traps for precision measurement

Optical dipole traps for neutrals

Force = grad (Intensity P(I, ν))



In general, polarization dependent m-level shifts.

Traps for precision measurement

Paul trap for ions

Force = **E** e (big) Field can be much more spatially homogenous.

At trap center <**E**> = 0

But you can have a rotating bias field.

Symmetry arguments constrain systematics.

Traps for precision measurement

Others: Penning trap. TOP trap. Ioffe-Pritchard trap variants.

Eric's Tips for Better Precision Measurement with Atoms and Molecules (and with other things)

Eric's Tips for Better Precision Measurement with Atoms and Molecules (and other things)

1. In general, frequencies are the easiest thing to measure with precision. From mHz to EHz, you can get clocks stable to 10^{-14} or better, absolute accuracy to 10^{-13}. Take advantage! Try to turn the quantity you want to measure into a frequency.

a. Voltage: Josephson junction oscillation frequency.
b. Magnetic field: Zeeman splitting
c. Electric field: Stark shift.
d. optical intensity: ac Stark shift.
e. mass: cyclotron frequency
f. capacitance: resonance of LC circuit.
g. distance: resonance of a fabry-perot laser cavity.
h. force: ???
i. etc

Eric's Tips for Better Precision Measurement with Atoms and Molecules (and other things)

2. D.C is where precision measurements go to die. Get as far away as you can!

Example. Lens-Thiring effect

Eric's Tips for Better Precision Measurement with Atoms and Molecules (and other things)

3. If you want to measure a very small oscillating field, use heterodyne detection (as e.g. alternative to "photon counters.")

Eric’s Tips for Better Precision Measurement with Atoms and Molecules (and other things)

3. If you want to measure a very small oscillating field, use heterodyne detection (as e.g. alternative to “photon counters.”)

Corollary: for quantum mechanical effects, add an “offset amplitude.”

Eric’s Tips for Better Precision Measurement with Atoms and Molecules (and other things)

4. Experimenters (and numerical experimenters): if you want to understand if some imperfection in your experiment is causing you problems, don’t make it better: make it worse!

Eric’s Tips for Better Precision Measurement with Atoms and Molecules (and other things)

5. You are going to die someday.

Eric's Tips for Better Precision Measurement with Atoms and Molecules (and other things)

5. You are going to die someday.   Stop smoking.

Eric's Tips for Better Precision Measurement with Atoms and Molecules (and other things)

5. You are going to die someday. Stop smoking. Wear a seatbelt.

Eric's Tips for Better Precision Measurement with Atoms and Molecules (and other things)

5. You are going to die someday. Stop smoking. Wear a seatbelt. Most important:

Eric’s Tips for Better Precision Measurement with Atoms and Molecules (and other things)

5. You are going to die someday. Stop smoking. Wear a seatbelt. Most important:
Have a sensible data collection strategy.

Eric's Tips for Better Precision Measurement with Atoms and Molecules (and other things)

5. You are going to die someday. Stop smoking. Wear a seatbelt. Most important:
Have a sensible data collection strategy.
It's like wearing a seatbelt in the lab!

Eric's Tips for Better Precision Measurement with Atoms and Molecules (and with other things)

6. What field provides your quantization axis?

Eric's Tips for Better Precision Measurement with Atoms and Molecules (and with other things)

7. h-bar is a small number. But N_A is a big number!

Is N_A hbar <1?

Is N_A^2 hbar <1?

"The Casimir-Polder Force"
The force experienced by an atom near a surface, arising from spatial patterns in the fluctuations in the E&M field.
With implications for anomalous gravity stuff.

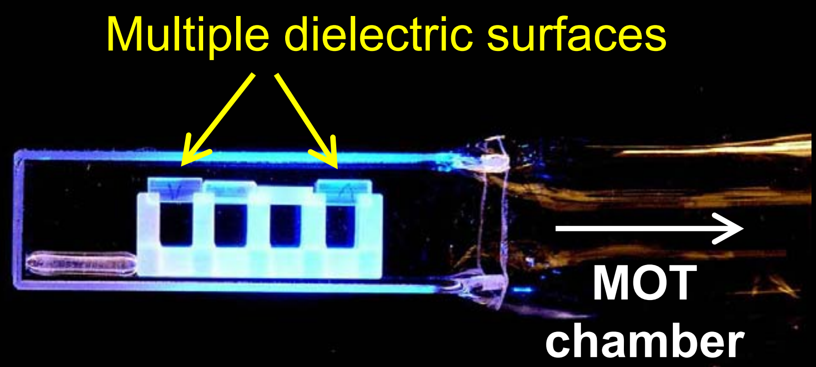
John Obrecht
Rob Wild [Dave Harber]
Thanks, Colleen Gillepsie, Giacomo Roati
NSF, NIST

Other experiments:
Hinds
Westbrook/Aspect
Vuletic, Shimizu, Ketterle...

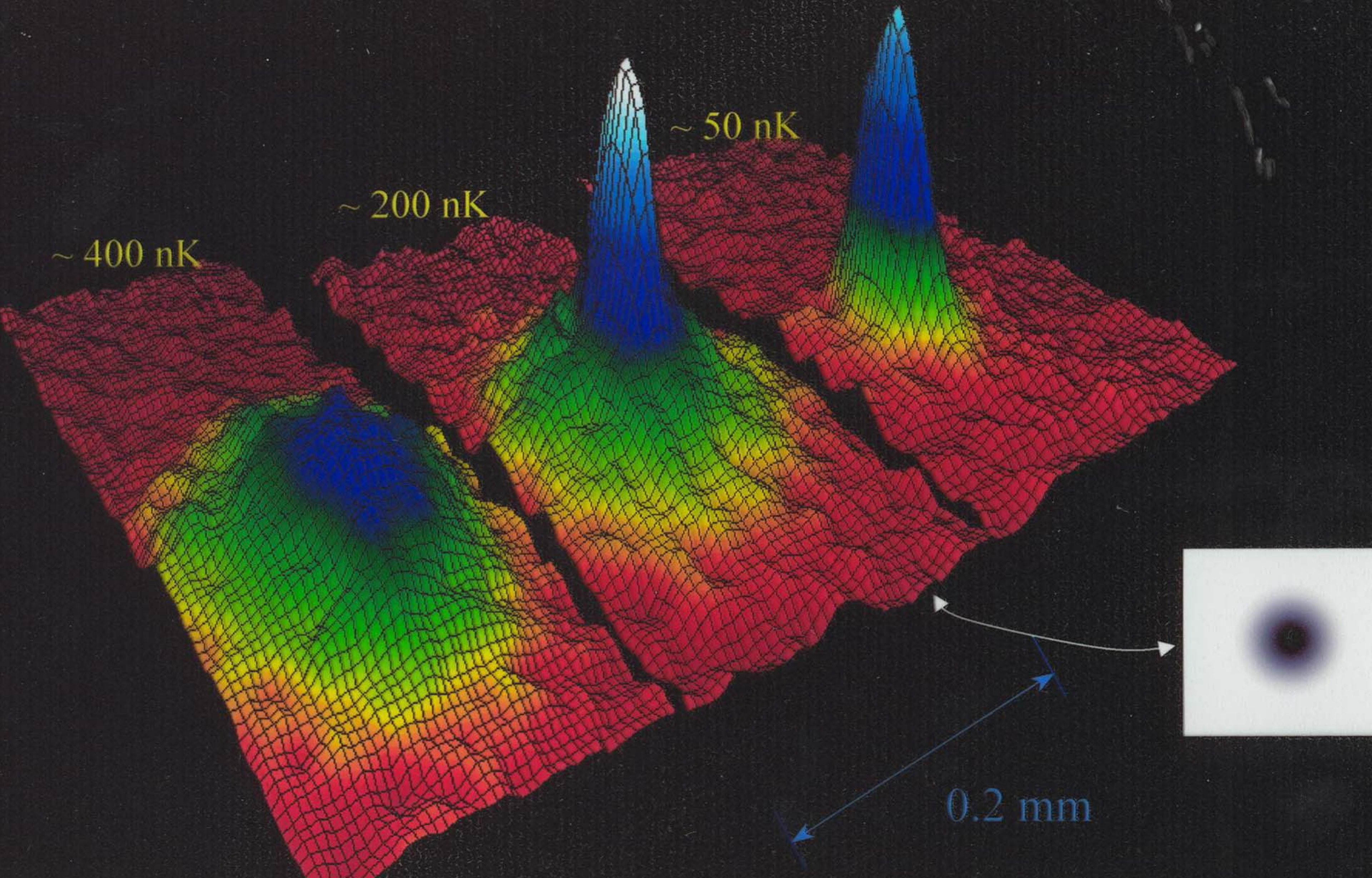
Theory: London, Casimir, Polder, Lifshitz
More recently, Eberlein, Henkel

We acknowledge
"I Tre Trentini":
Mauro Antezza, Lev Pitaevskii and Sandro Stringari

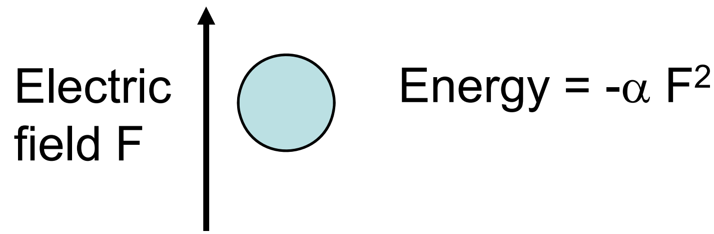
Casimir-Polder force near a dielectric surface

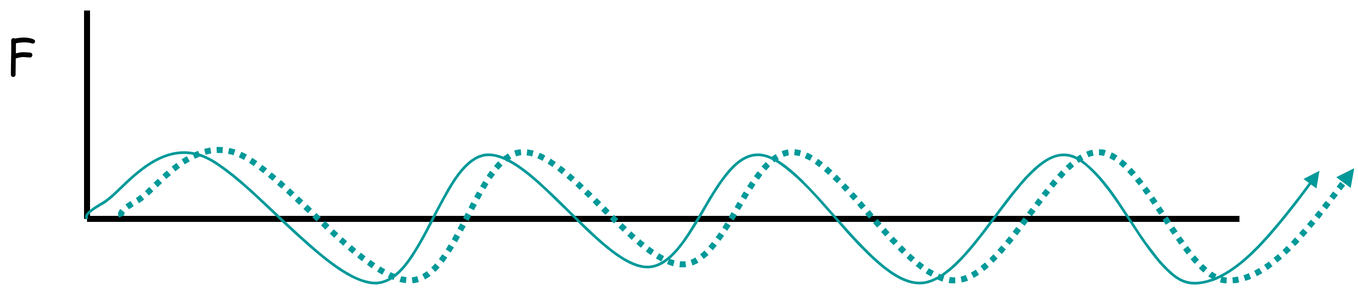


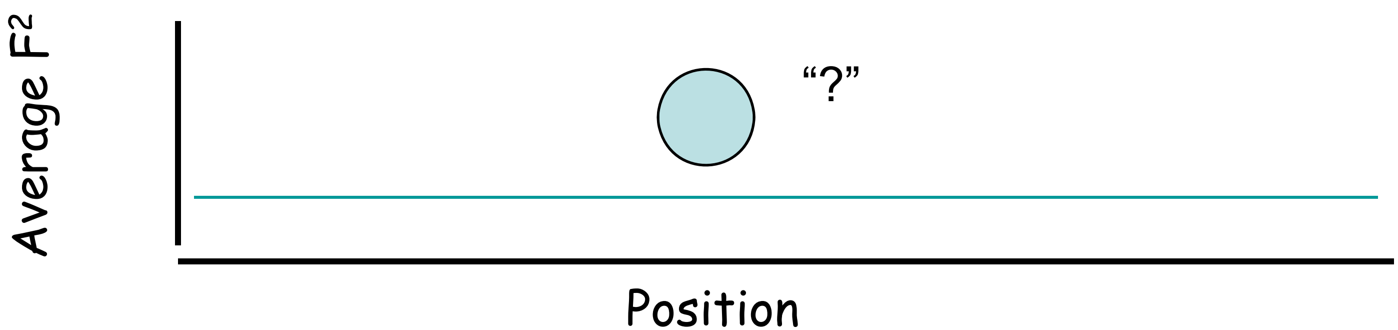
2 D velocity/density distributions



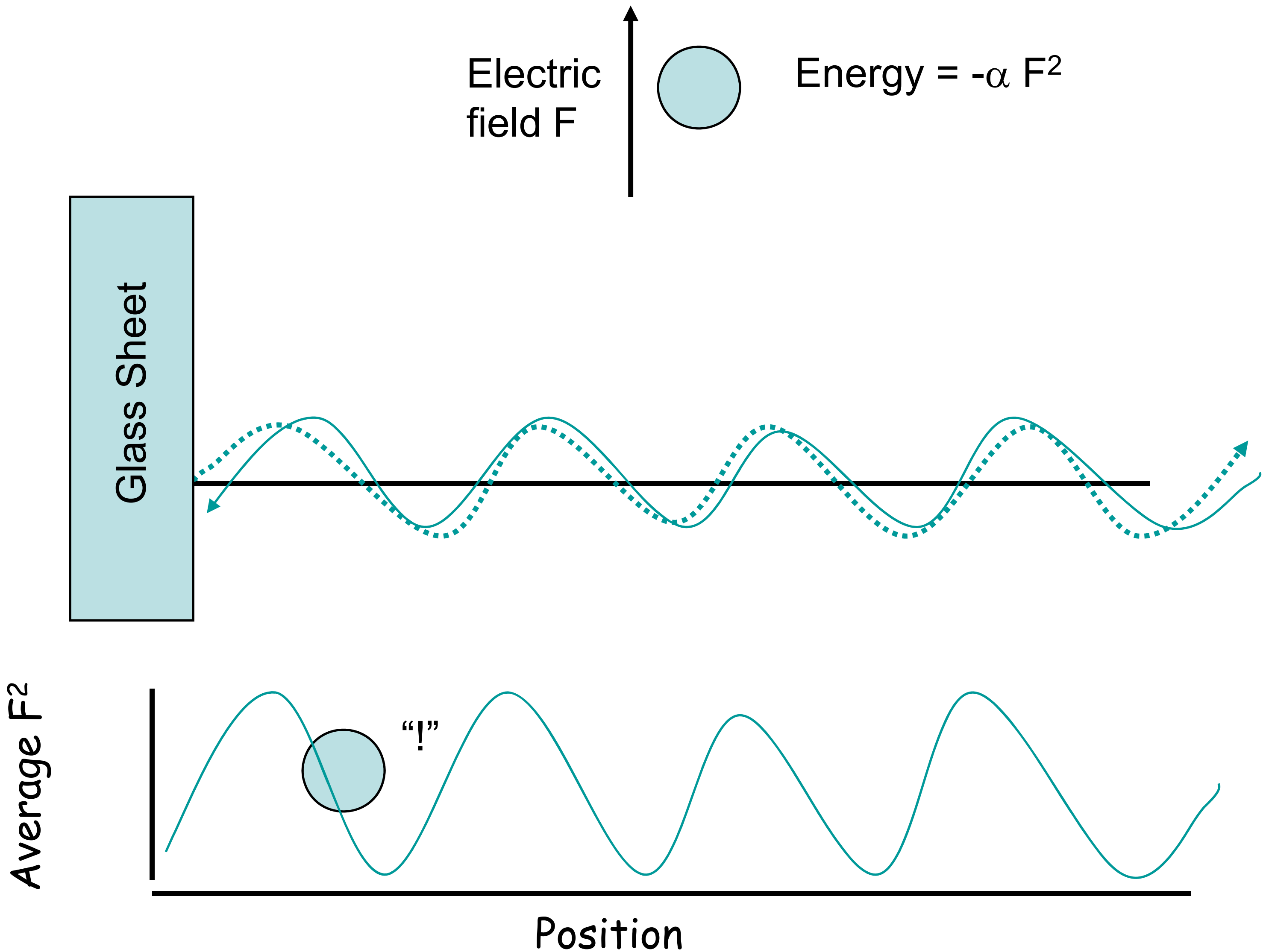
Use an atom.



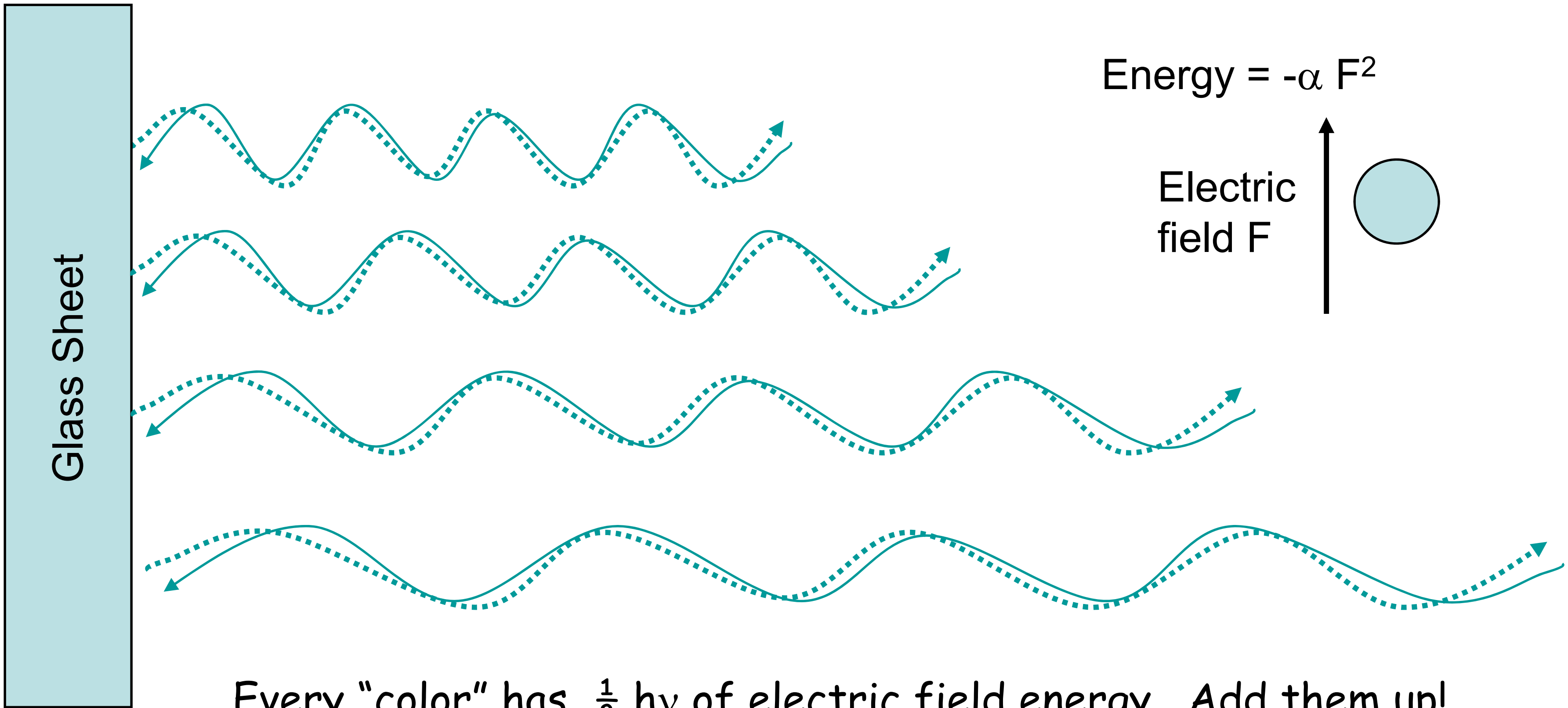




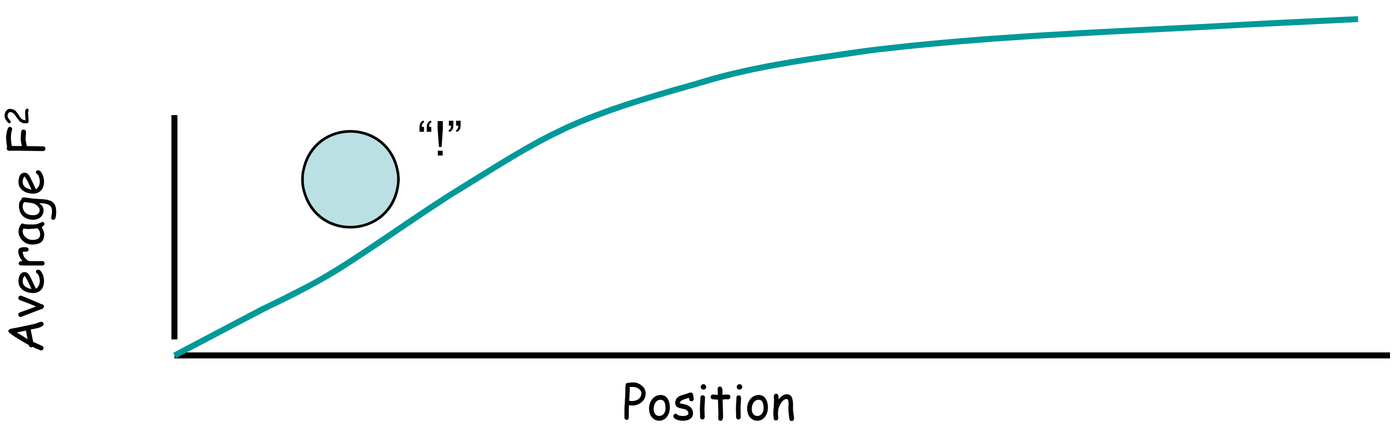
Use an atom.

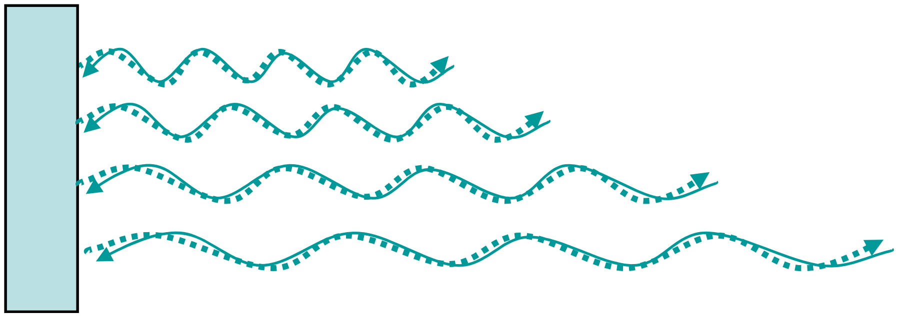


Electric
field F
Energy = -α F2
Glass Sheet
Average F2
"!"
Position

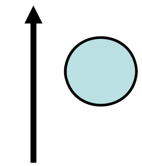


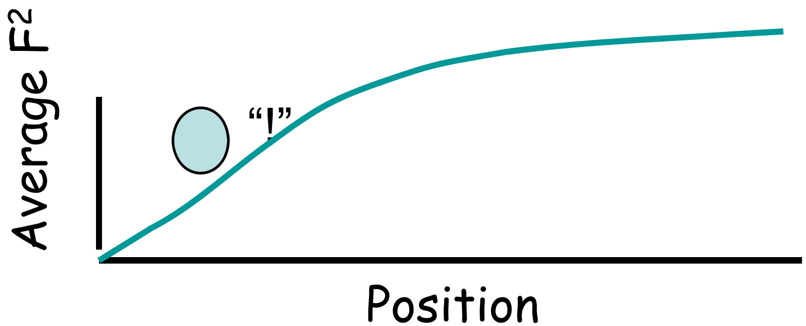
Every "color" has $\frac{1}{2}h\nu$ of electric field energy. Add them up!





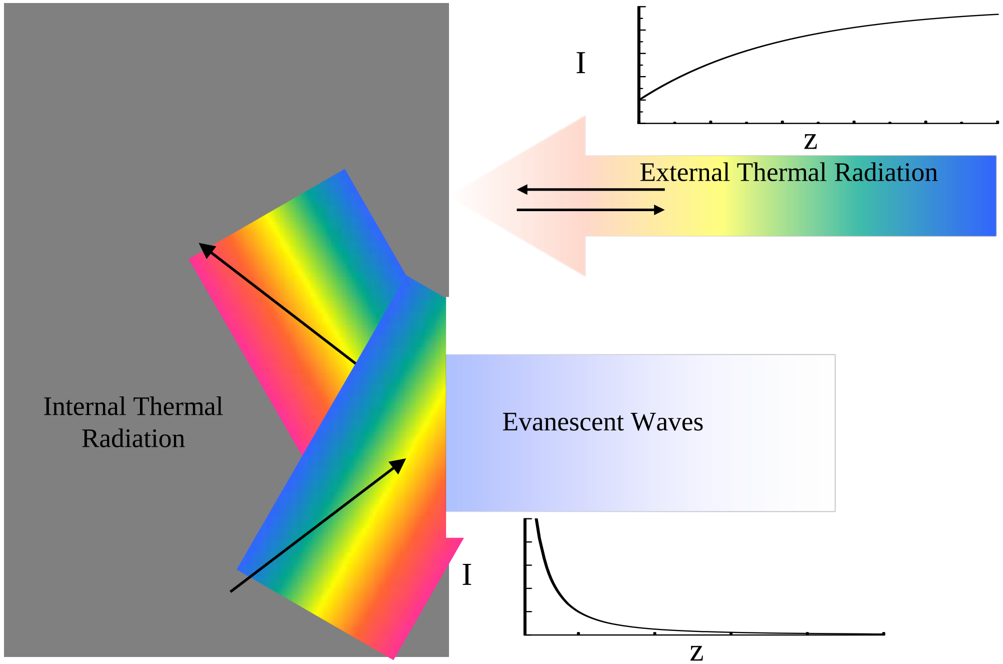
Energy = $-\alpha F^2$





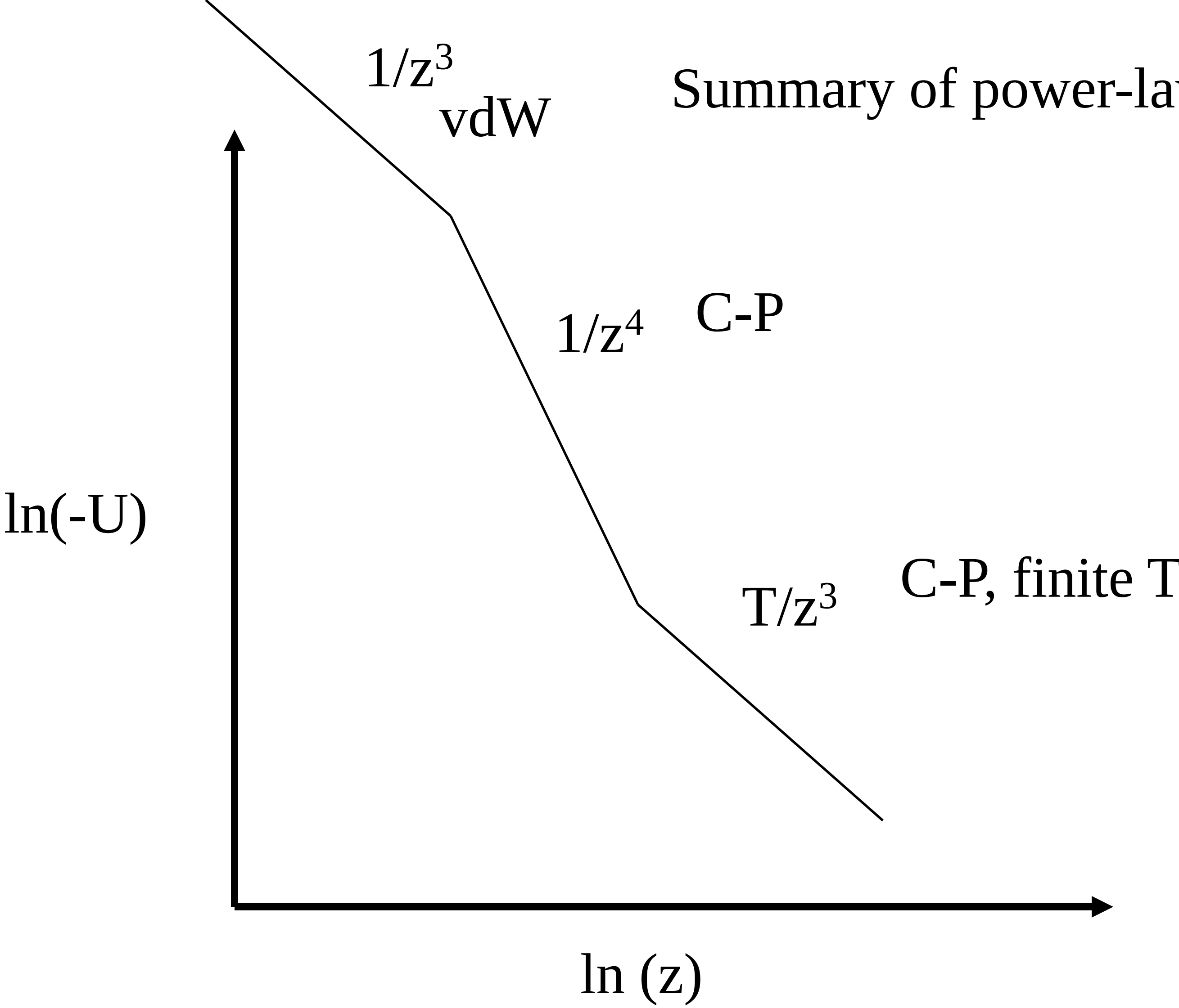
Uh-oh. Experiments say Casimir-Polder force *pulls atom in,* doesn't push atom out!

We have neglected evanescent waves, and incident waves at grazing incidence!

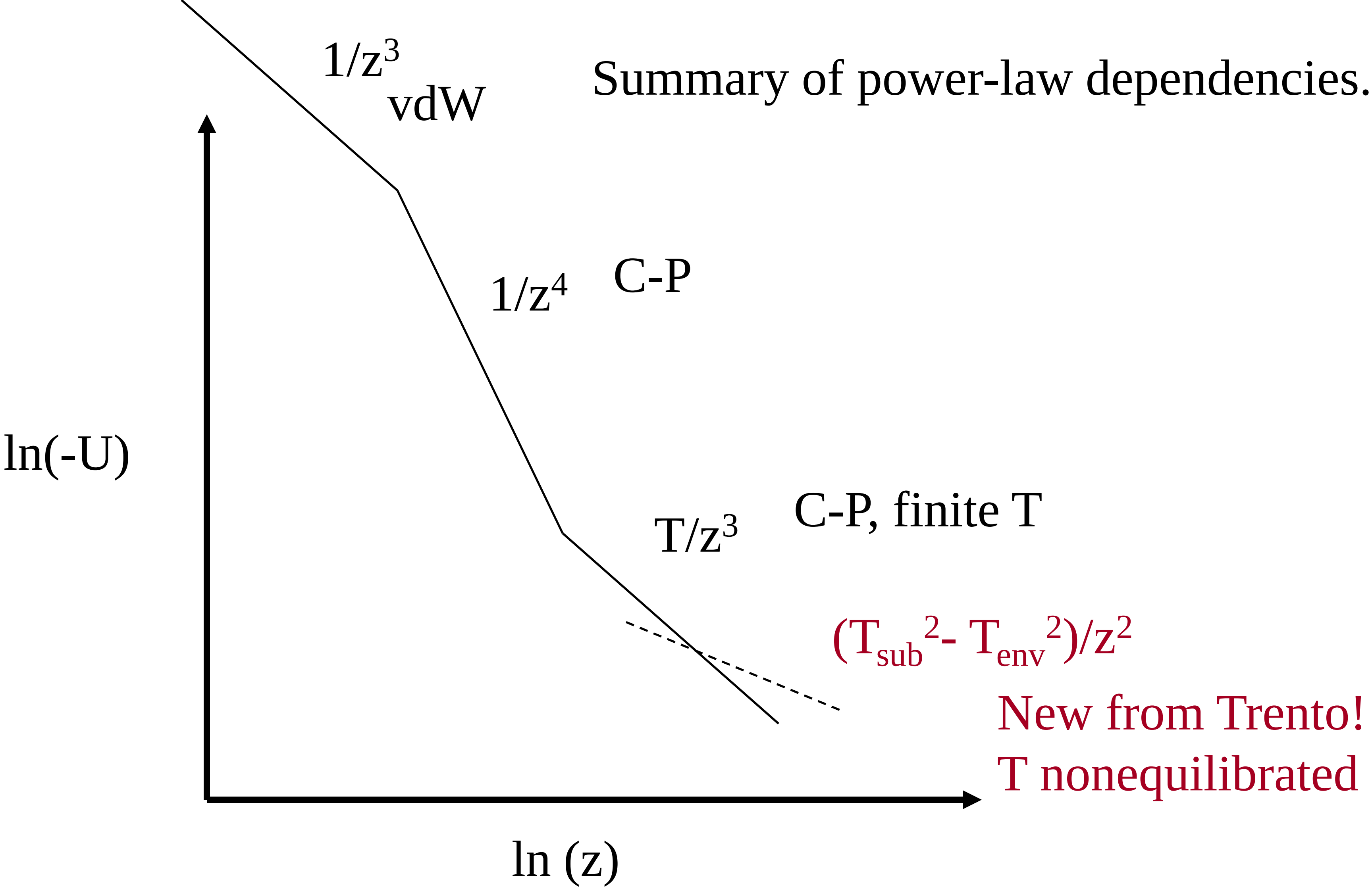


Impinging thermal (and quantum) radiation at normal incidence contributes with opposite sign to force compared to thermal evanescent waves.

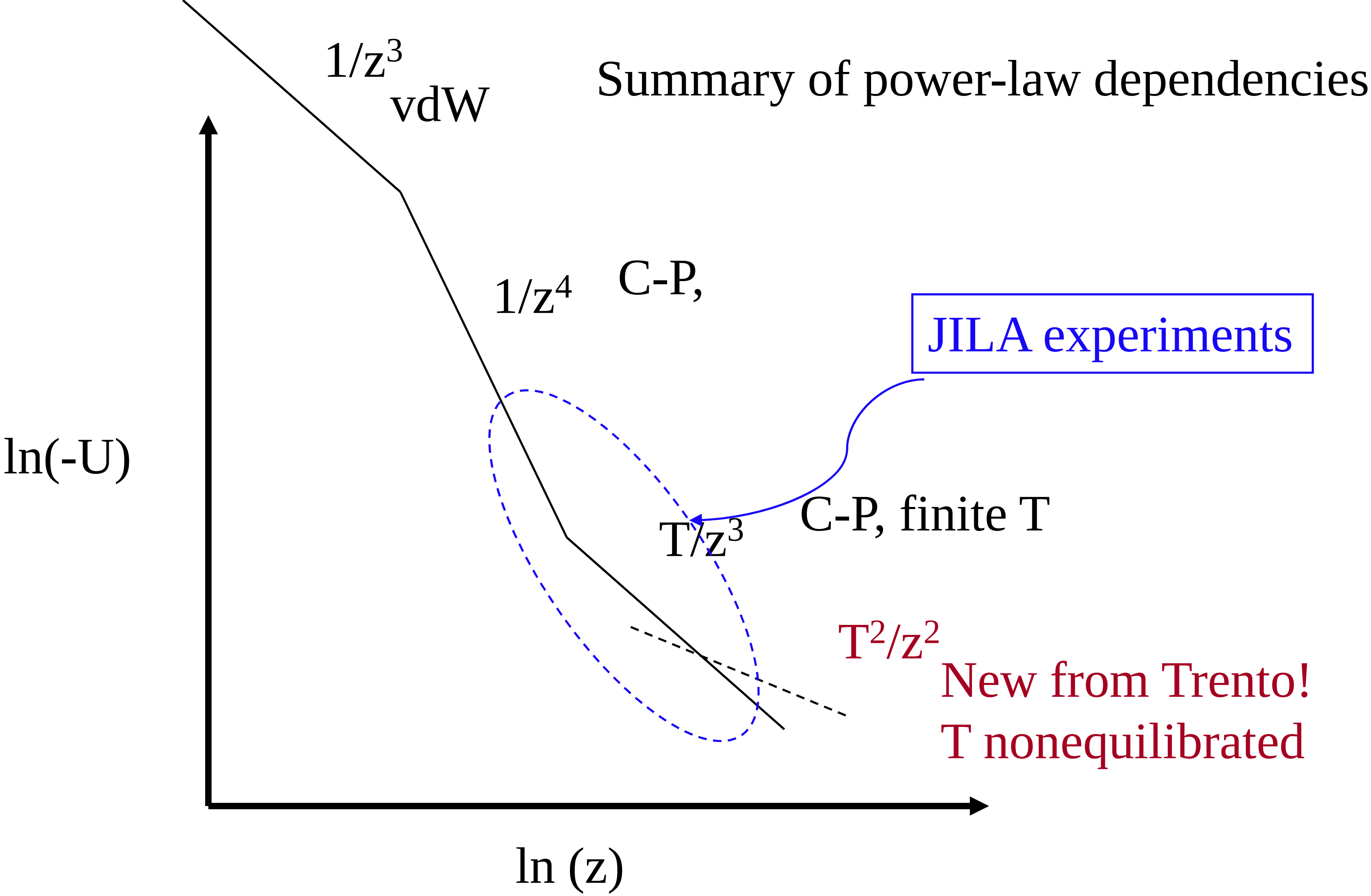
Summary of power-law dependencies.



Summary of power-law dependencies.



Summary of power-law dependencies.



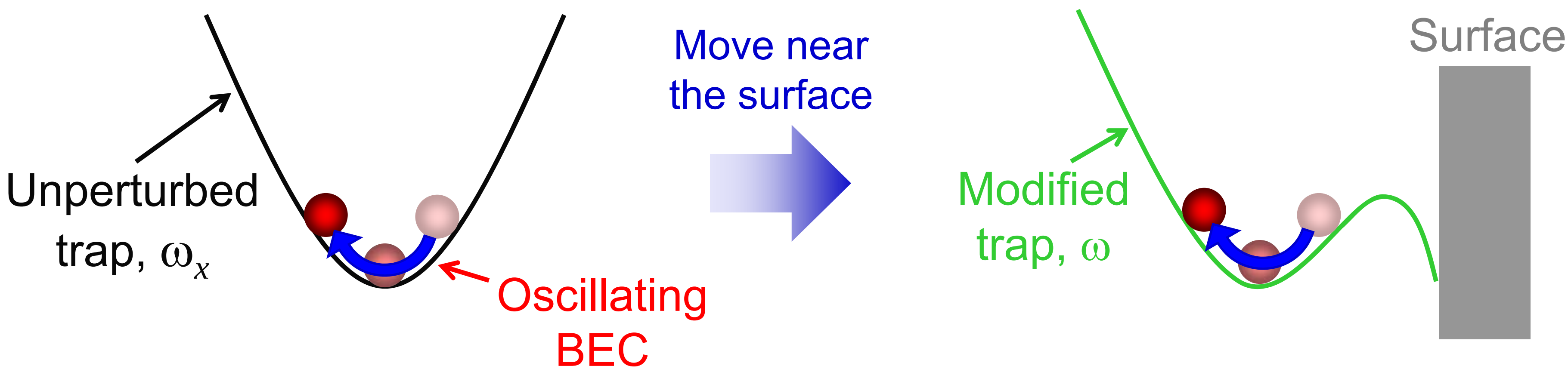
Measuring atom-surface forces

Use trapped BEC as a mechanical oscillator

Measure changes in dipole oscillation frequency

Negative curvature attractive potential

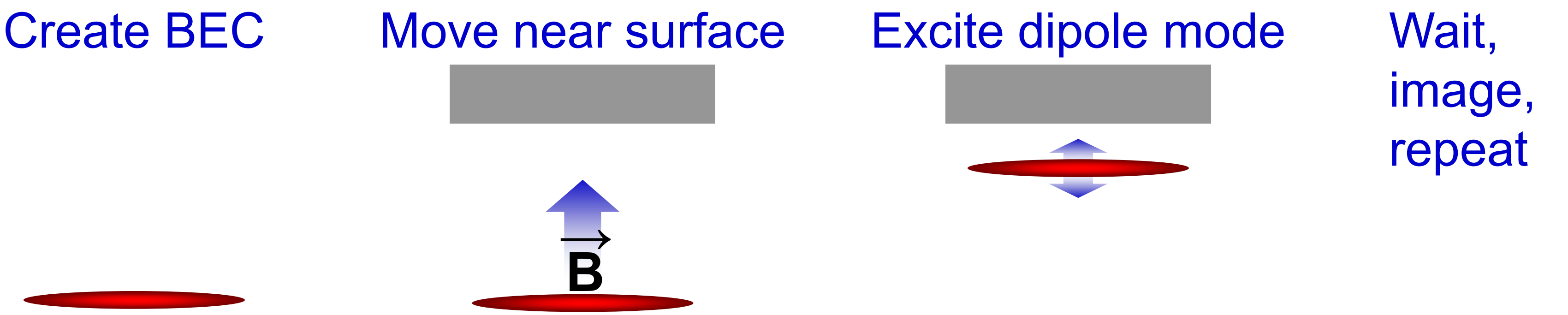
Trap frequency decrease

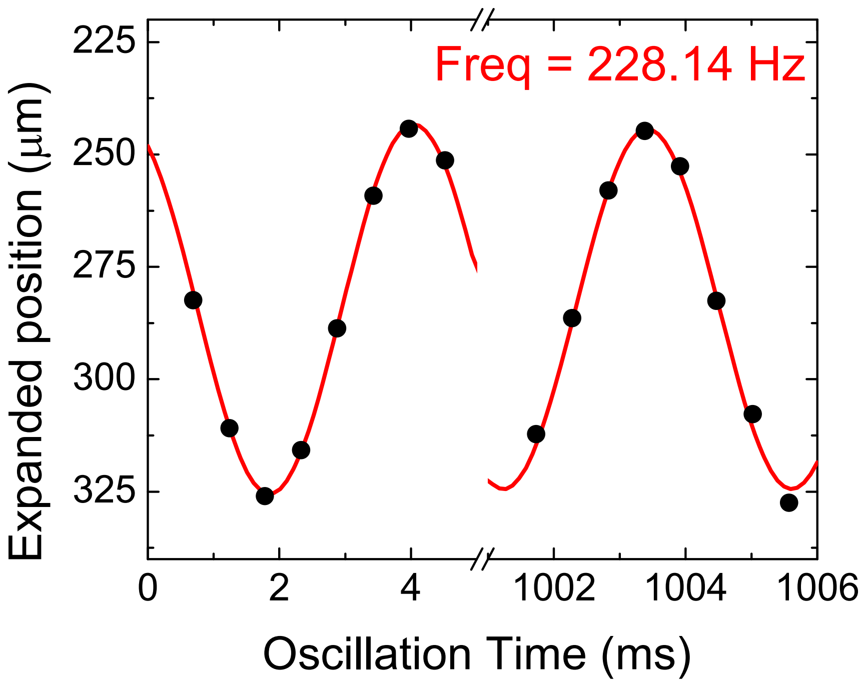


Express trap frequency changes as normalized frequency shifts:

$$\frac{\omega_x - \omega}{\omega_x} \approx -\frac{1}{2\omega_x^2 m}\frac{d^2U}{dx^2}$$

Actual experiment cycle



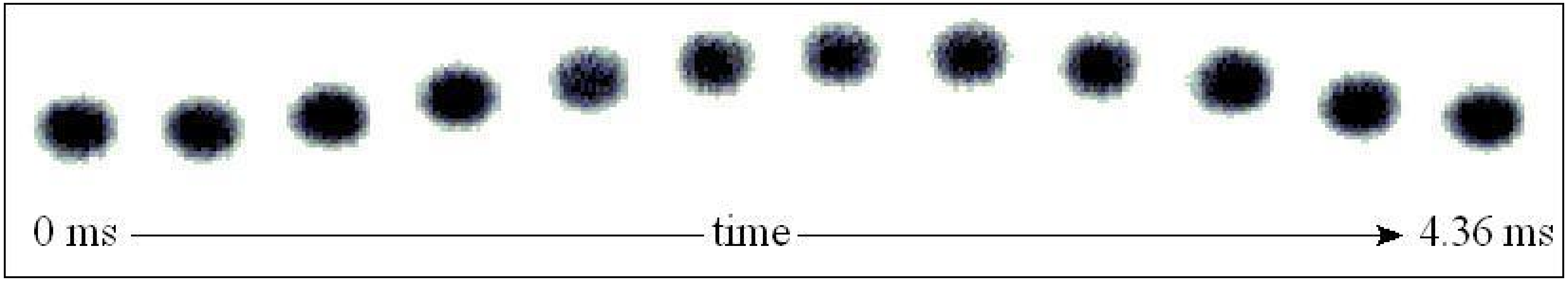


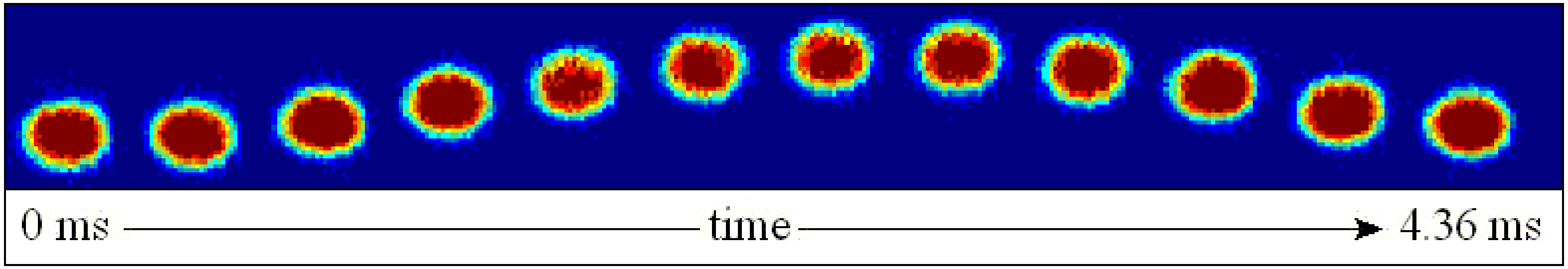
Dipole mode oscillation:

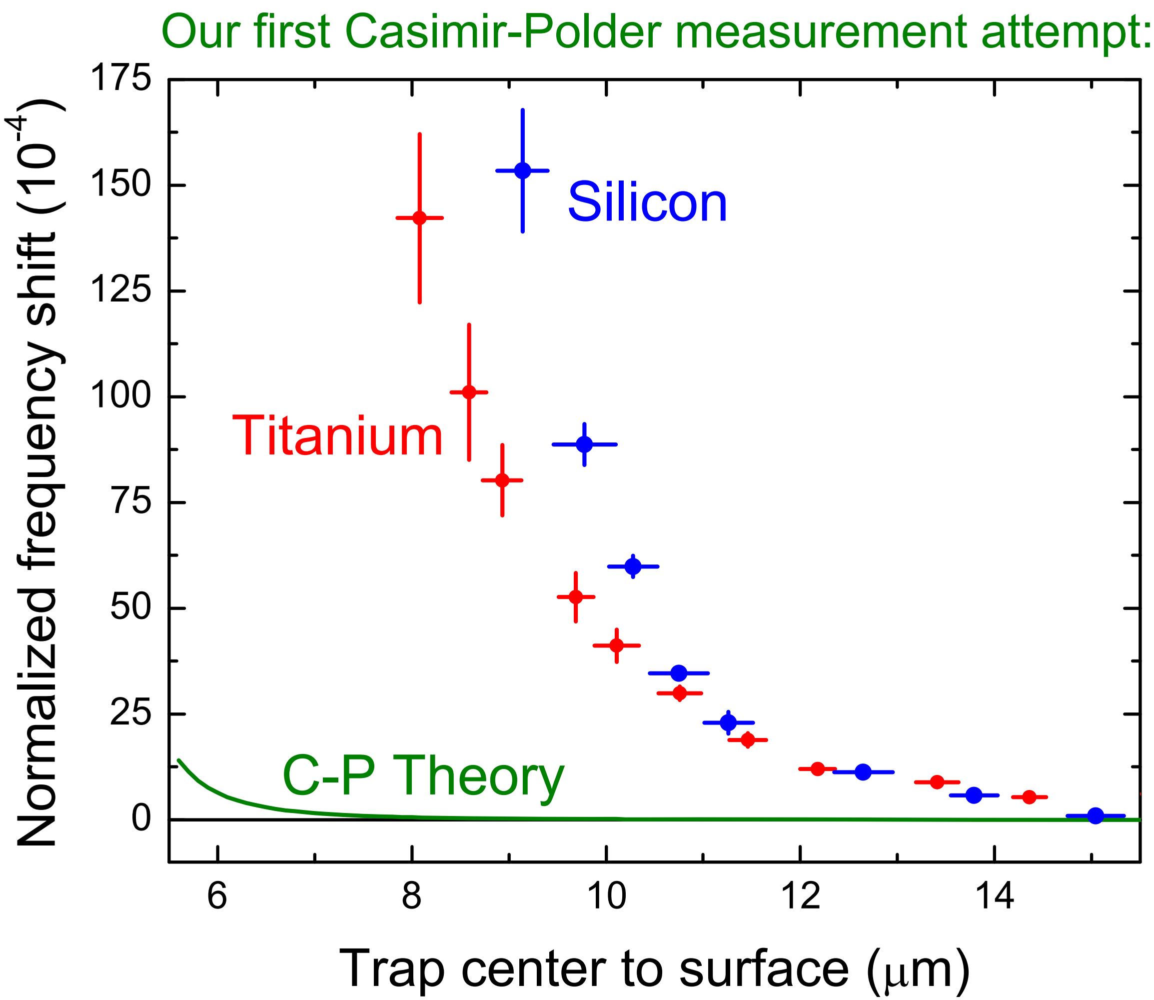
Damping time **~10 seconds**

Frequency resolution **~10 mHz**

Normalized frequency shift resolution **~4 x 10^{-5}**

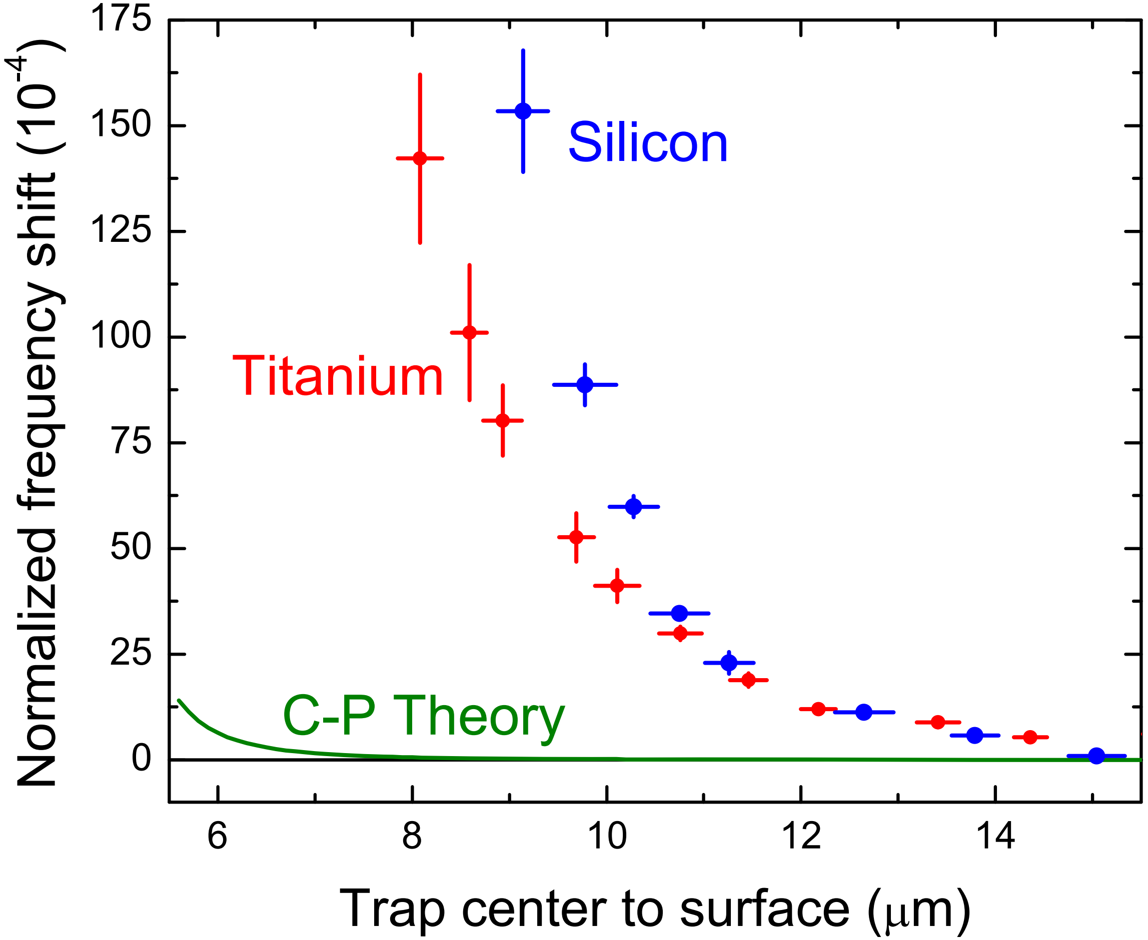

0 ms
time
4.36 ms


0 ms
time
4.36 ms

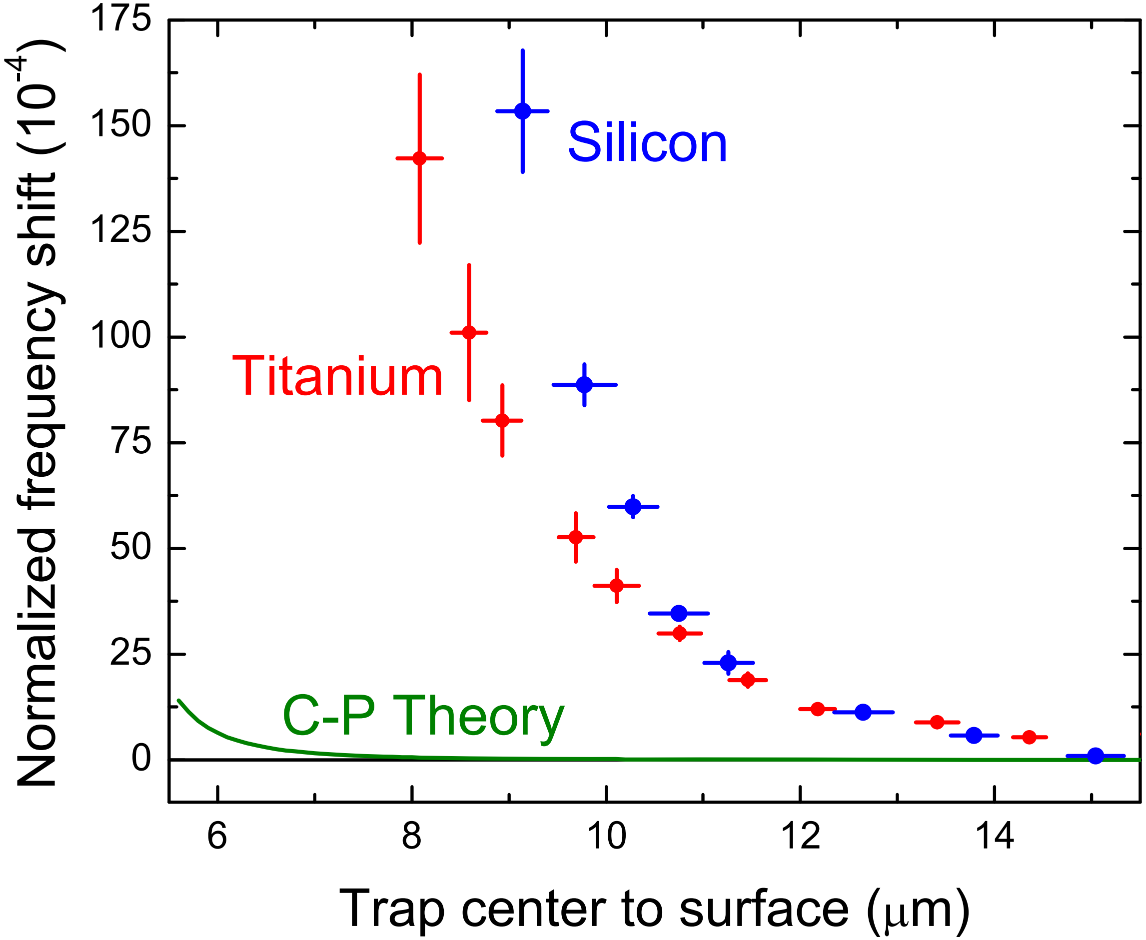


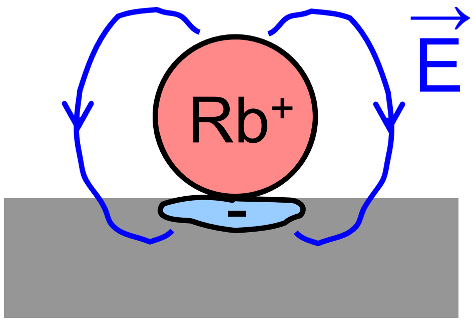
Electric fields from alkali adsorbates

Our first Casimir-Polder measurement attempt:



Our first Casimir-Polder measurement attempt:





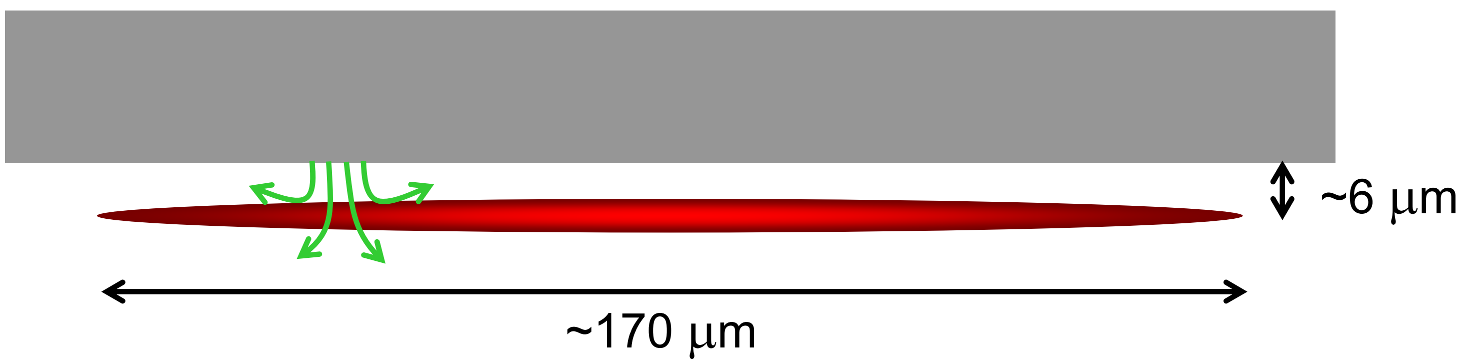
Electric fields from alkali adsorbates

Systematics

How can we put limits on forces from electric and magnetic surface contaminants?

Electric or magnetic surface contaminants are typically localized

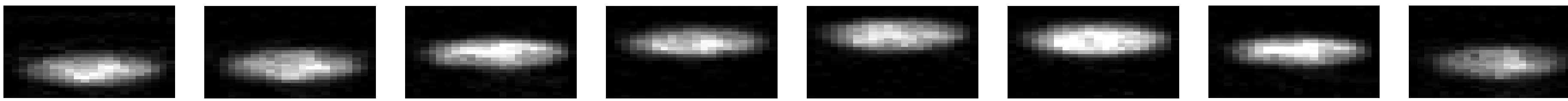
→ affect only part of BEC



Detect spatially inhomogeneous forces by measuring the normalized frequency shift along BEC

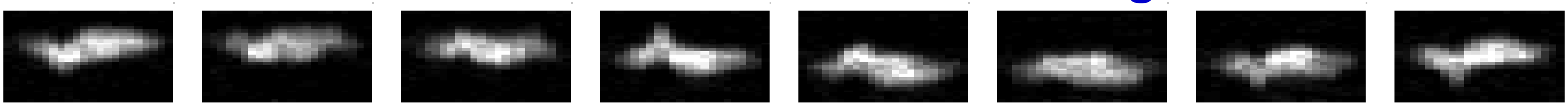
FFS across BEC

Normal BEC oscillation:



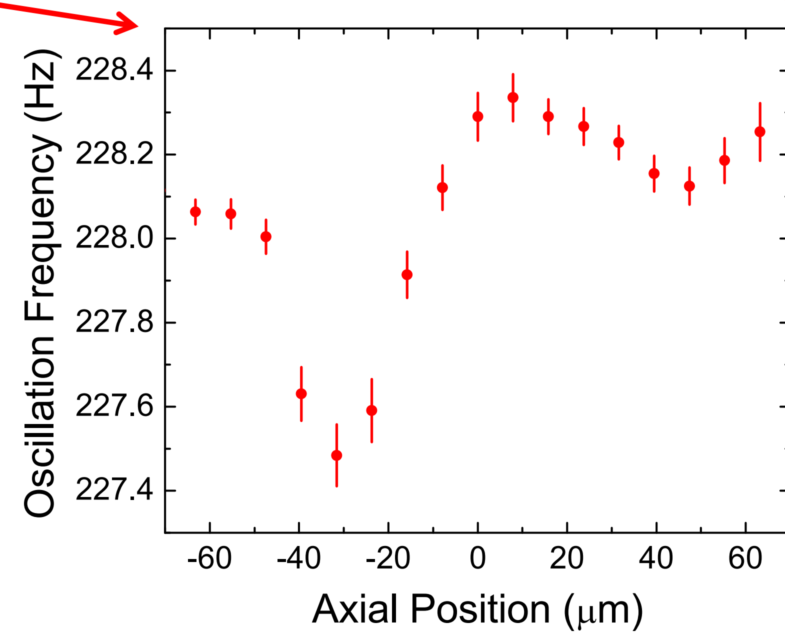
time ⟶

BEC oscillation near "contaminated" surface region:



time ⟶

Analyze the oscillation frequency along the BEC:



If spatial variation > statistical uncertainty

⟶ Significant spatial inhomogeneity

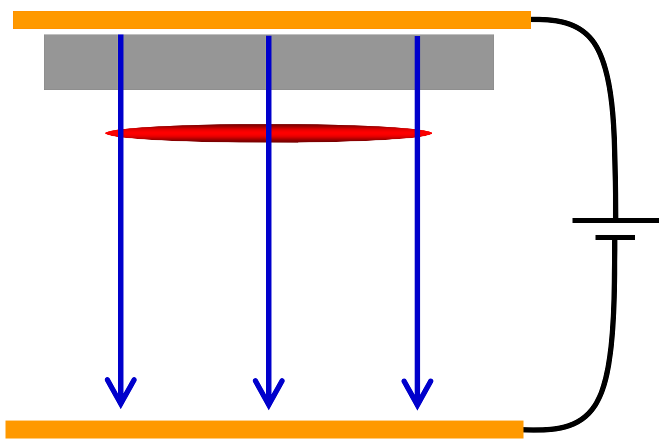
ॐ Spatial variation of the oscillation frequency provides limit on spatially inhomogeneous forces

Uniform fields

What about electric & magnetic fields uniform across BEC?

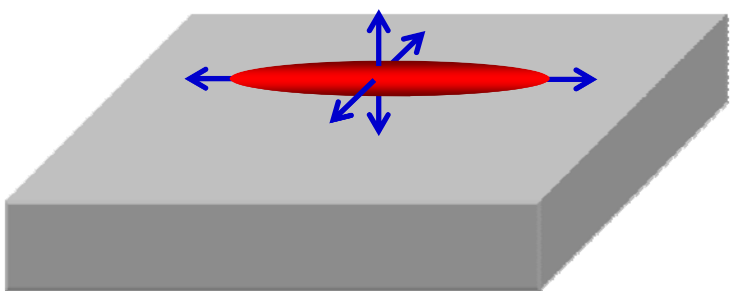
To detect electric fields:

- Use our electric field measurement techniques

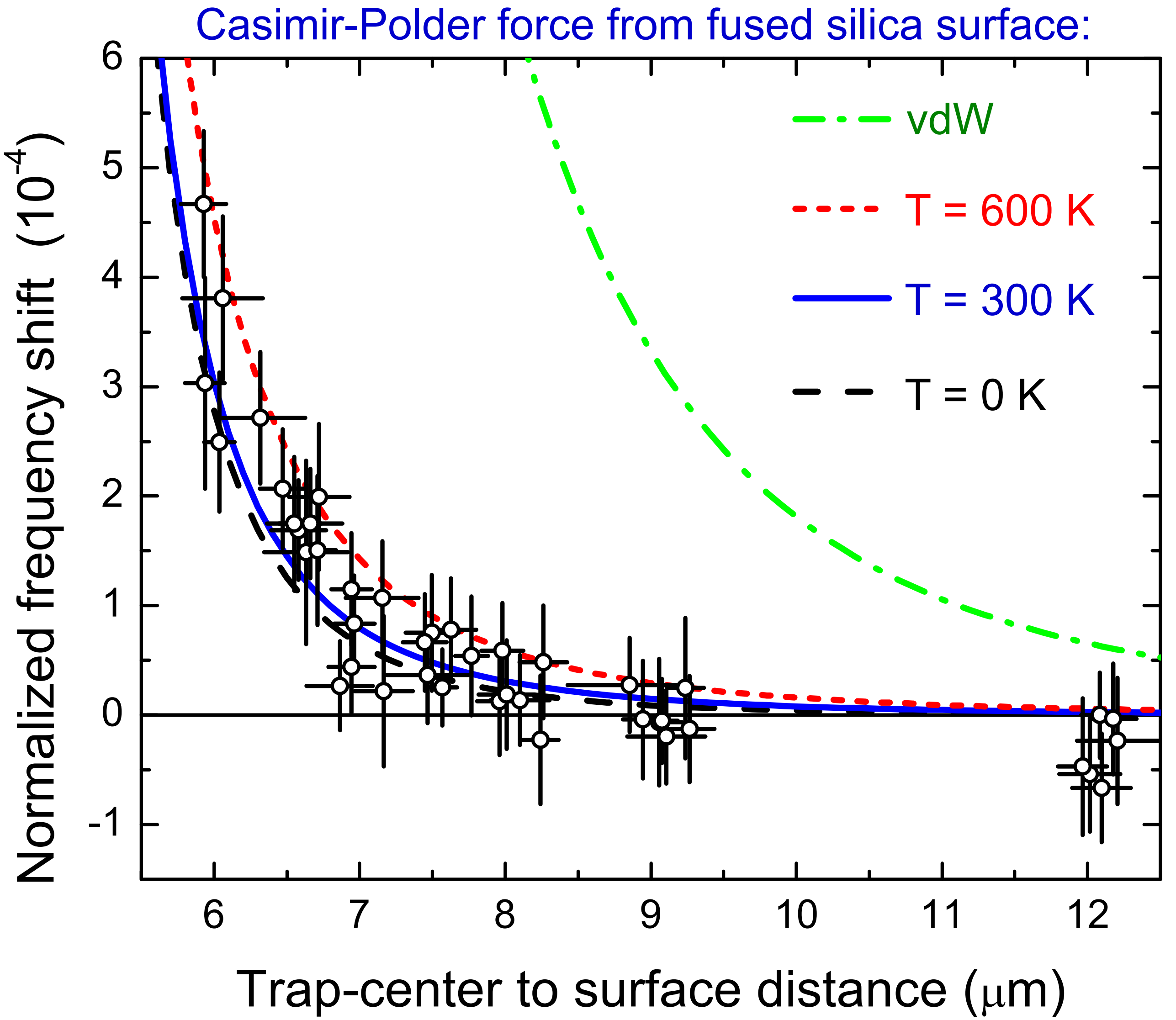


To detect magnetic fields:

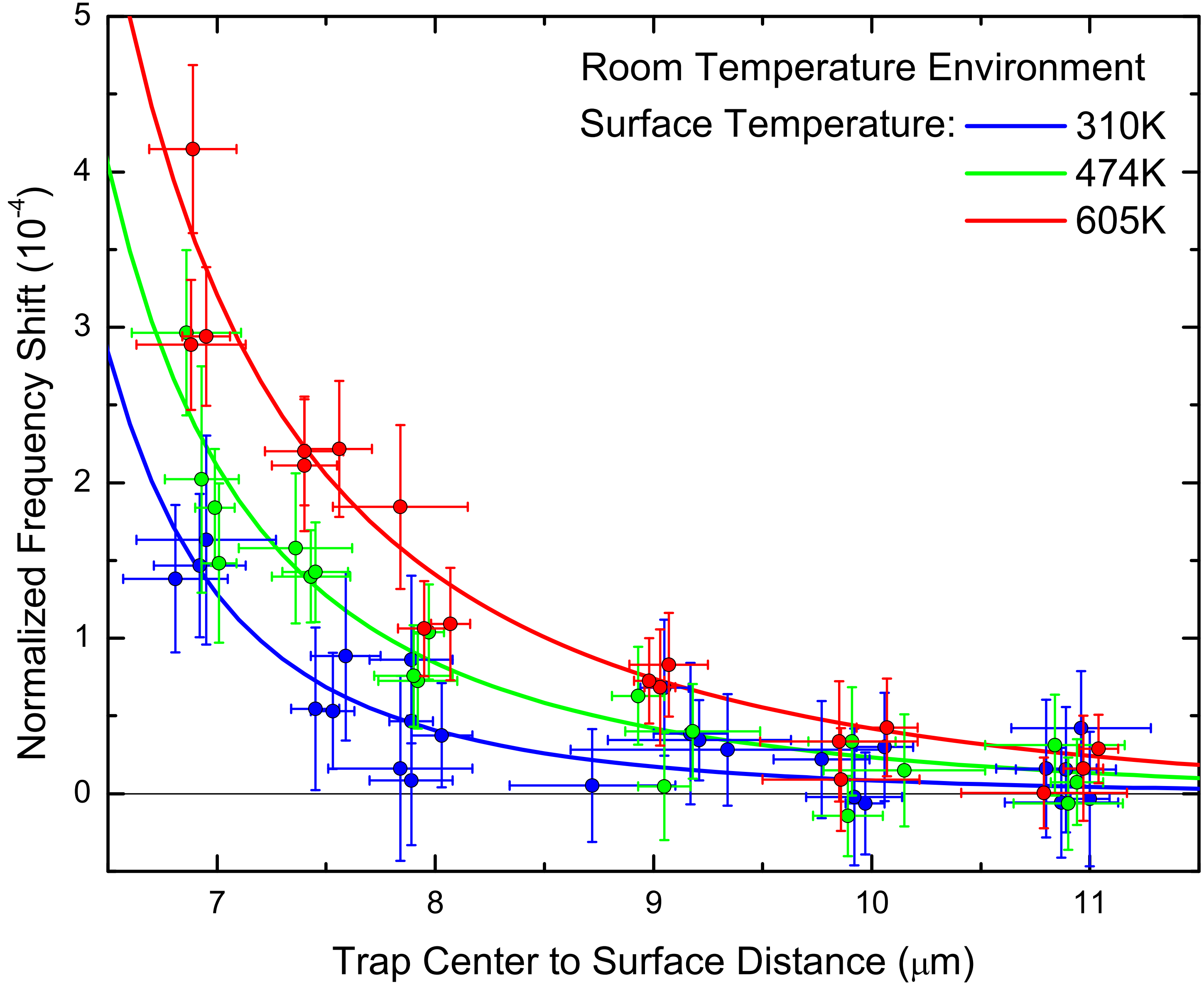
- Magnetic distortions modify the trapping potential in multiple directions
- Measure trap frequencies in directions parallel to surface
- Detect center-of-mass position deviations



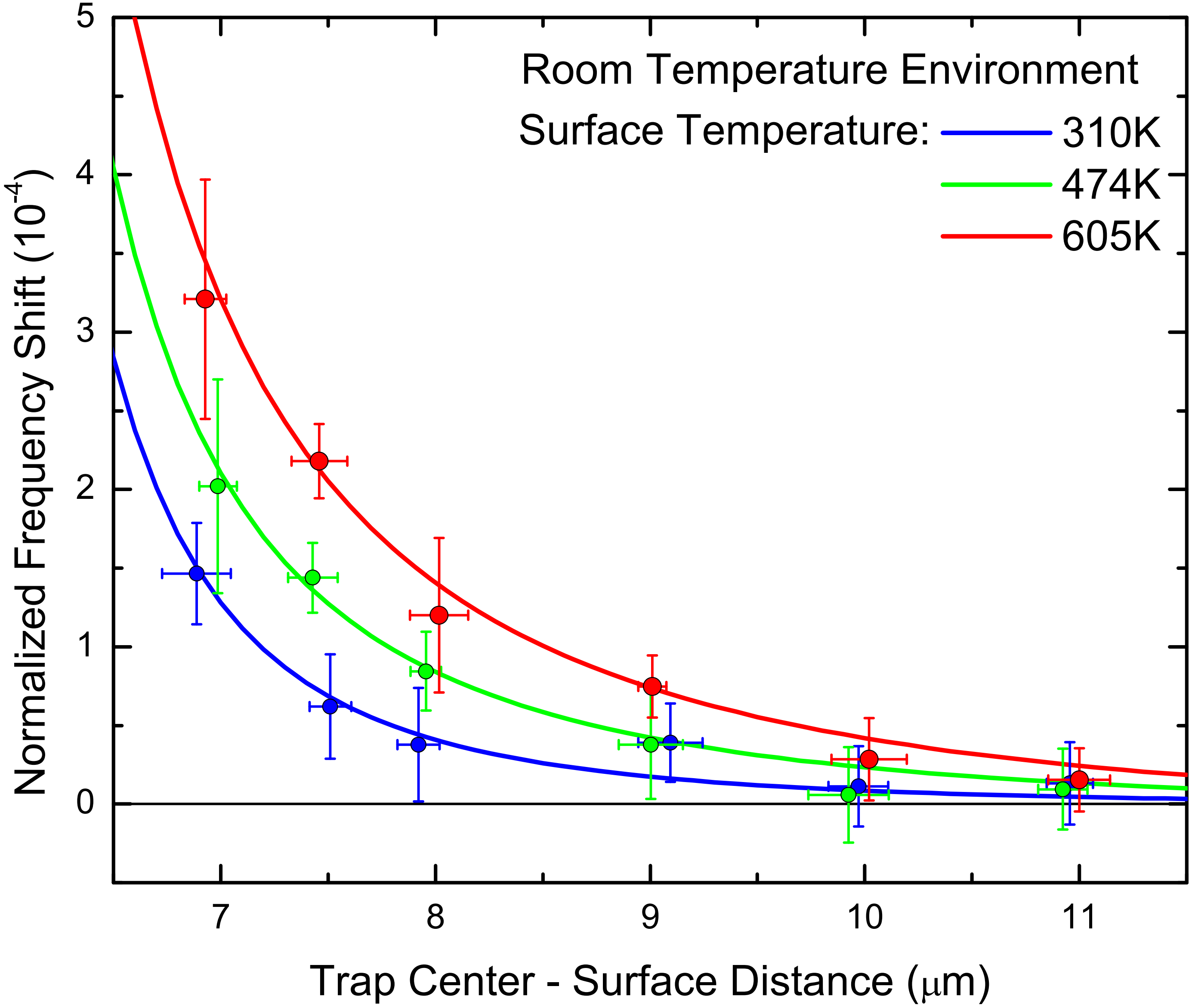
- Data from two different surface locations
- Error bars include statistical and systematic error
- Our data is in agreement with C-P force
- Resolution is not sufficient to discern the temperature correction



Our measurement



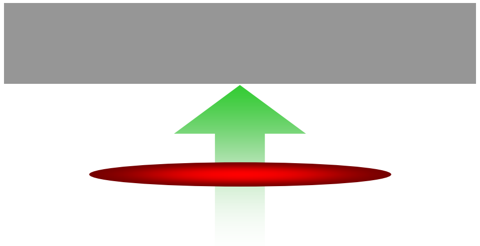
Room Temperature Environment
Surface Temperature:
310K
474K
605K
Normalized Frequency Shift (10^{-4})
Trap Center to Surface Distance (μm)
5
4
3
2
1
0
7
8
9
10
11



Room Temperature Environment
Surface Temperature:
310K
474K
605K
Normalized Frequency Shift (10^{-4})
Trap Center - Surface Distance (μm)
0
1
2
3
4
5
7
8
9
10
11

Yukawa-type forces?:

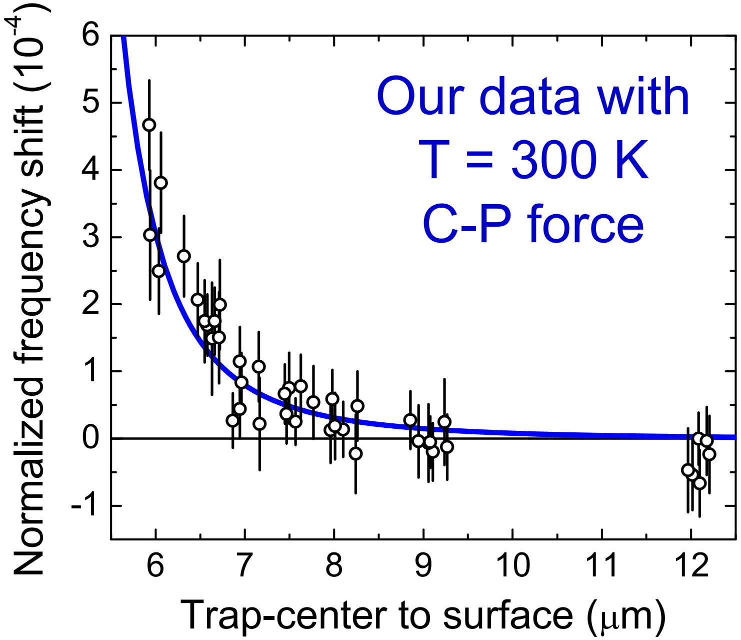
- Exotic force limits from our C-P measurement



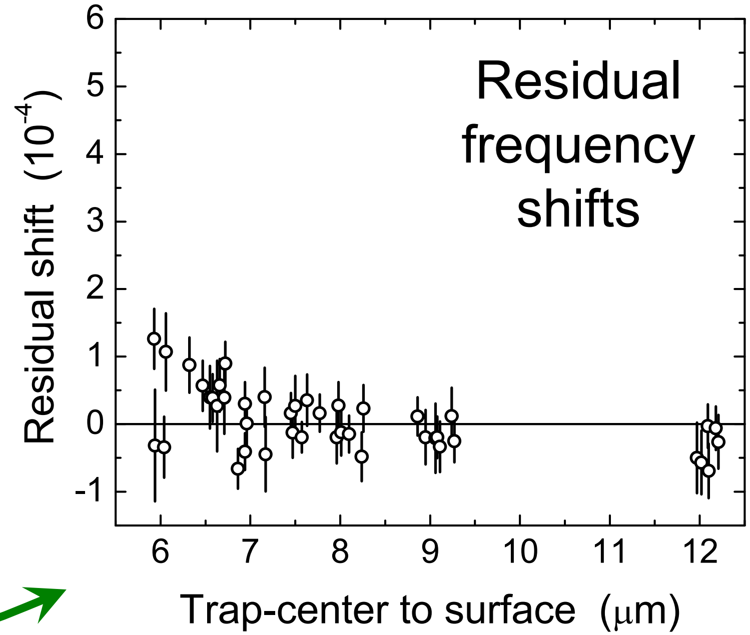
$$U = \int_{\text{Substrate}} \frac{G m_{Rb} \rho_{substrate} \, dV}{r} \left(1 + \alpha e^{-r/\lambda}\right)$$

Residuals to the C-P force

The *absence* of forces in addition to C-P force allows us to obtain limits from our data:

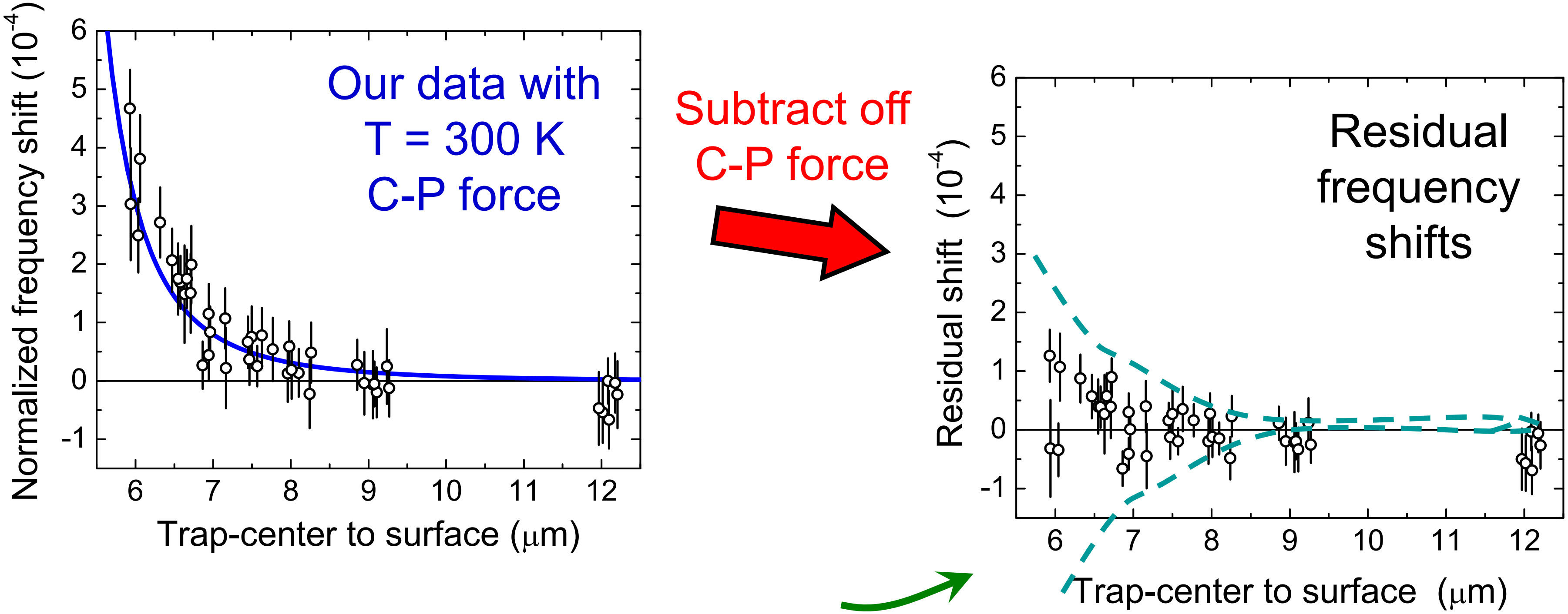


Subtract off
C-P force



Use residuals to obtain a limit on the presence of additional forces

The *absence* of forces in addition to C-P force allows us to obtain limits from our data:

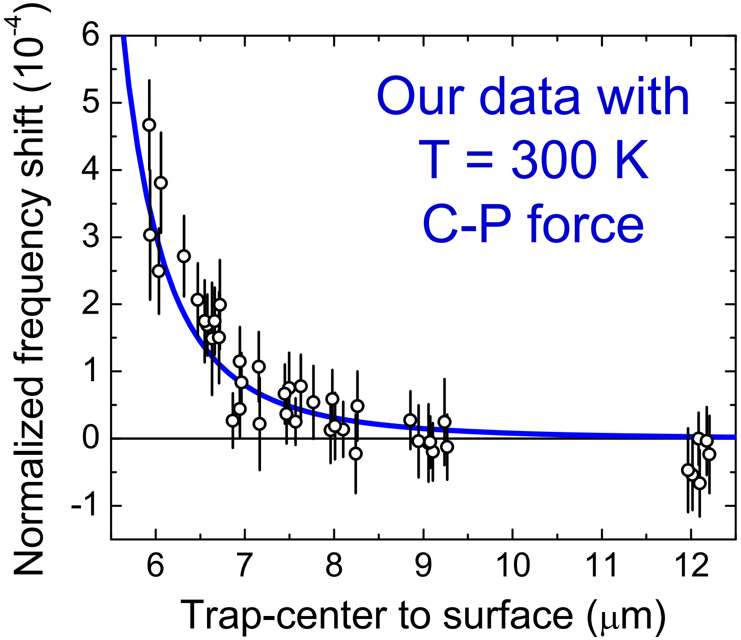


Use residuals to obtain a limit on the presence of additional forces

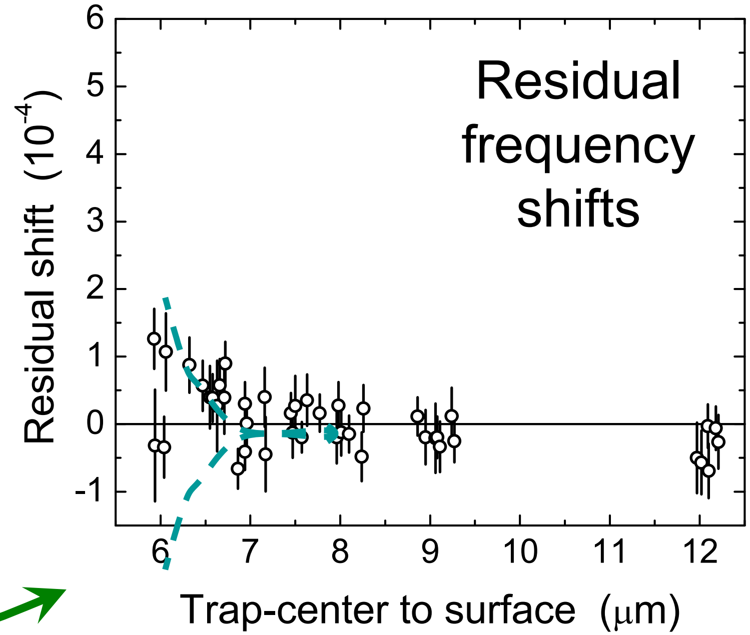
Trial value of λ and α

Residuals to the C-P force

The *absence* of forces in addition to C-P force allows us to obtain limits from our data:



Subtract off C-P force



Use residuals to obtain a limit on the presence of additional forces

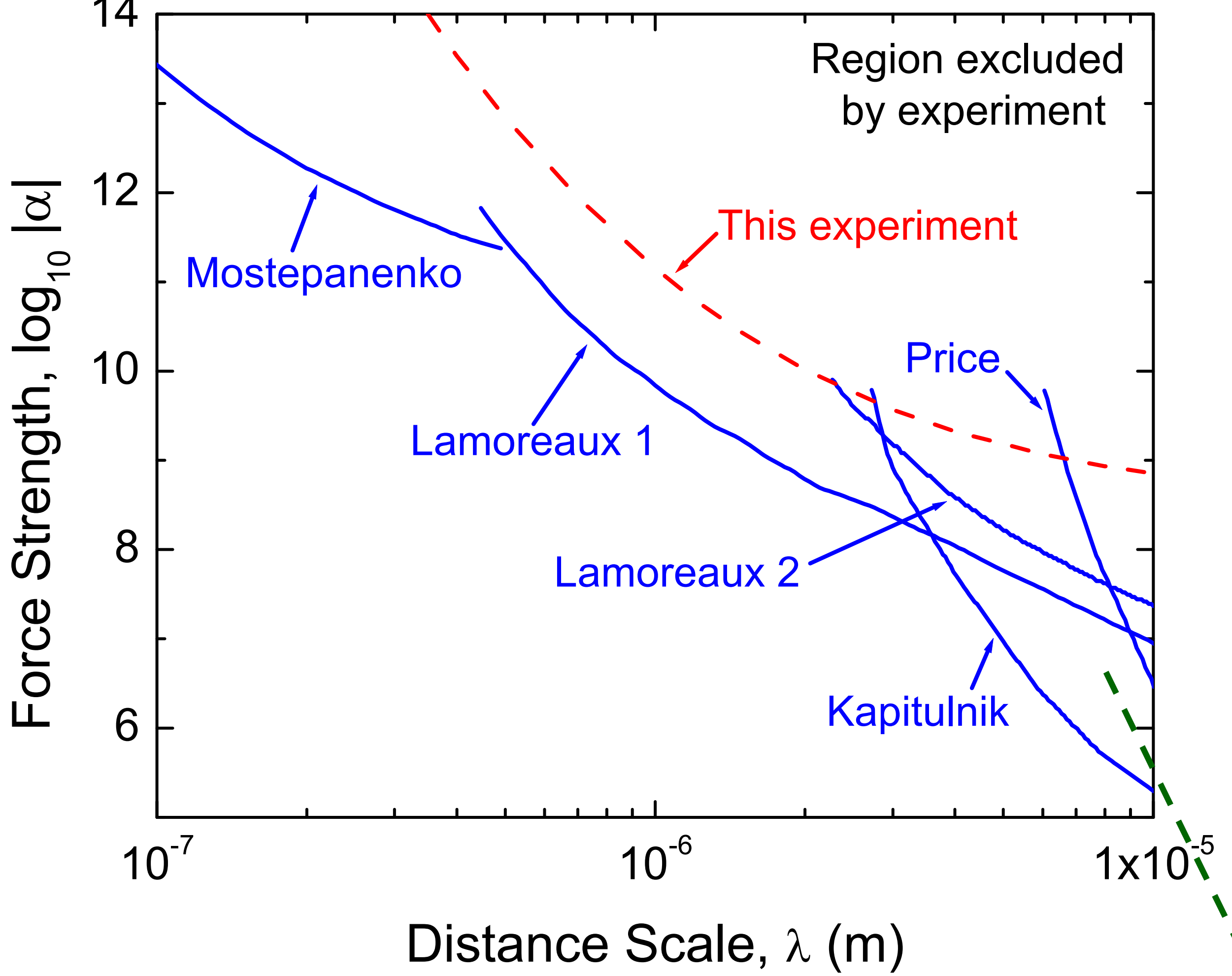
Smaller trial value of λ

Residuals to the C-P force

$$U = \int_V \frac{G m \rho \, dV}{r} \left(1 + \alpha e^{-r/\lambda}\right)$$

- Very different type of measurement (atom-bulk vs. bulk-bulk)
- Our experiment does not* reach the current best limits in 0.3-10 μm range
- Experimental modifications could improve sensitivity by over an order of magnitude

Current limits on forces of this type:



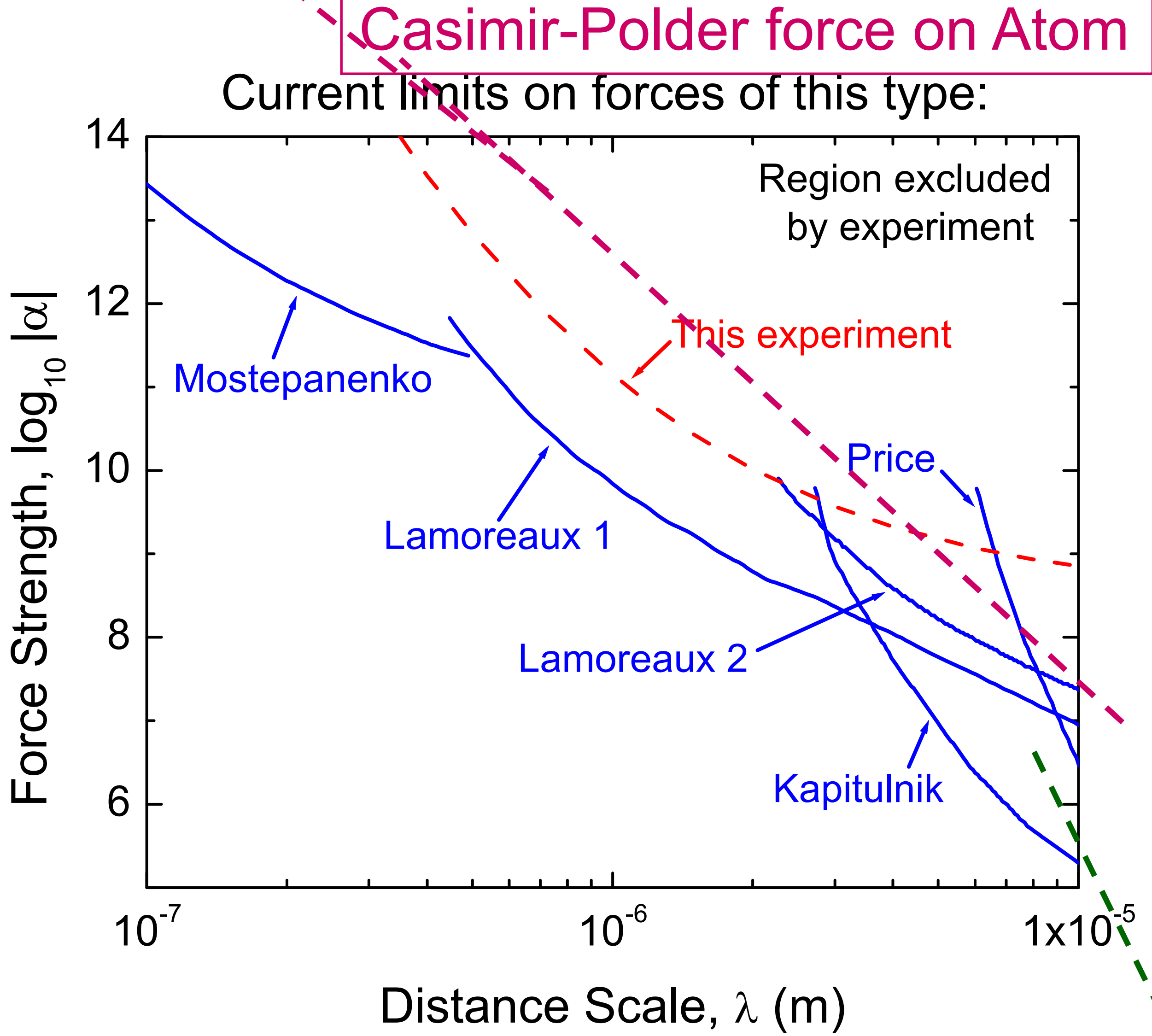
Limits on exotic forces

This way to UW

α=1

$$U = \int_V \frac{Gm\rho \, dV}{r}\left(1+\alpha e^{-r/\lambda}\right)$$

- Very different type of measurement (atom-bulk vs. bulk-bulk)
- Our experiment does not* reach the current best limits in 0.3-10 μm range
- Experimental modifications could improve sensitivity by over an order of magnitude

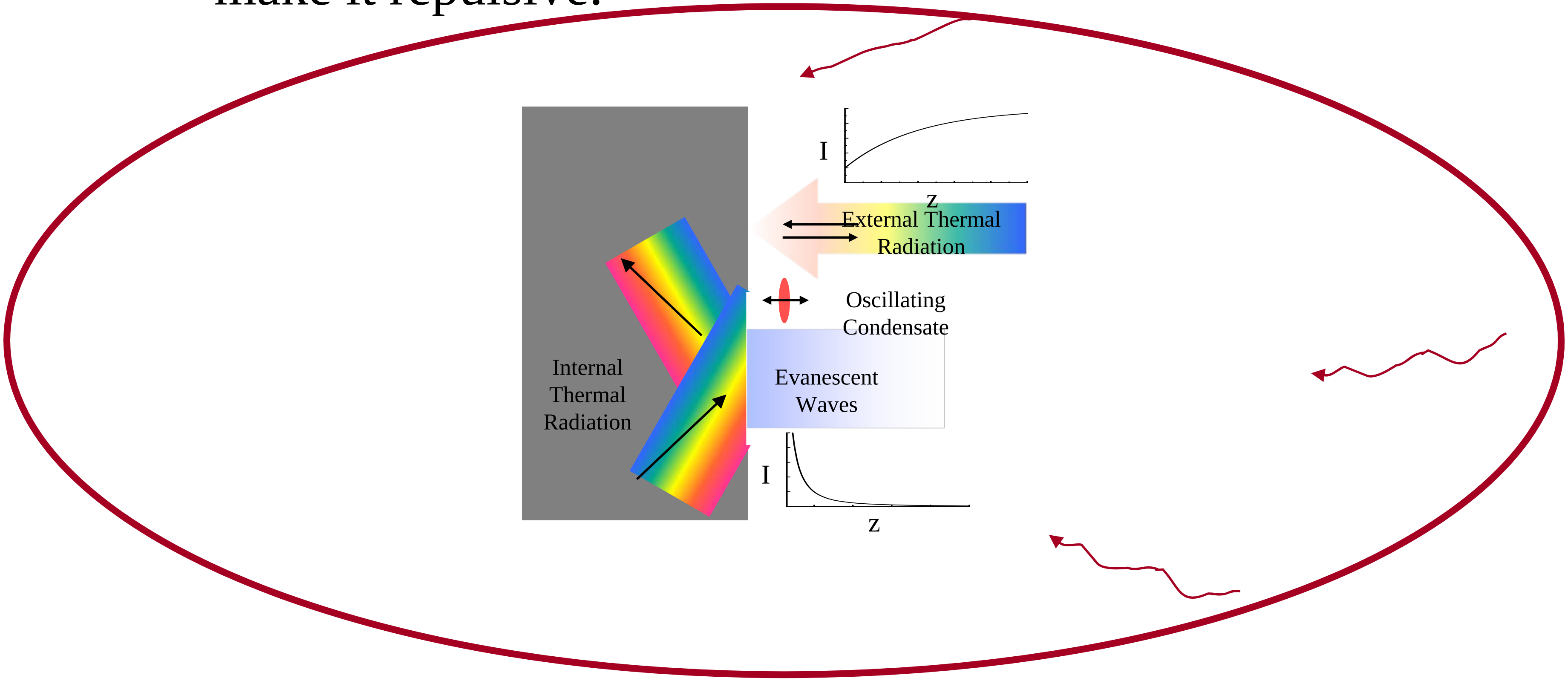


Limits on exotic forces

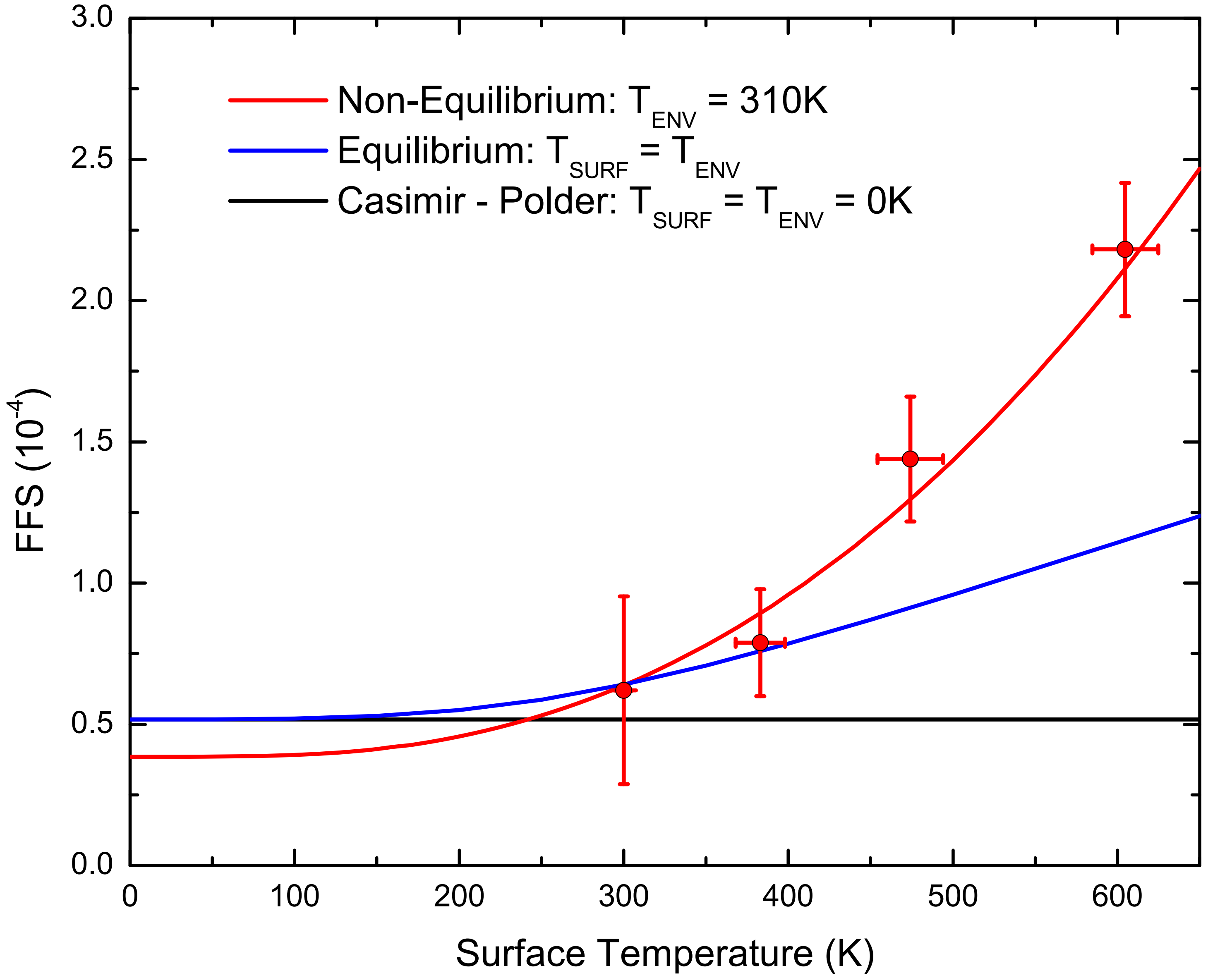
This way to UW

$\alpha=1$

Trento guys say by tinkering with temperature of "far away walls of experiment" relative to temperature of substrate, can change *sign* of total C-P force, make it repulsive.



Fixed distance to substrate, 7.5 microns



Q1:
Why hasn't the gravity from the energy of the zero-point fluctuations of fields imploded the universe?

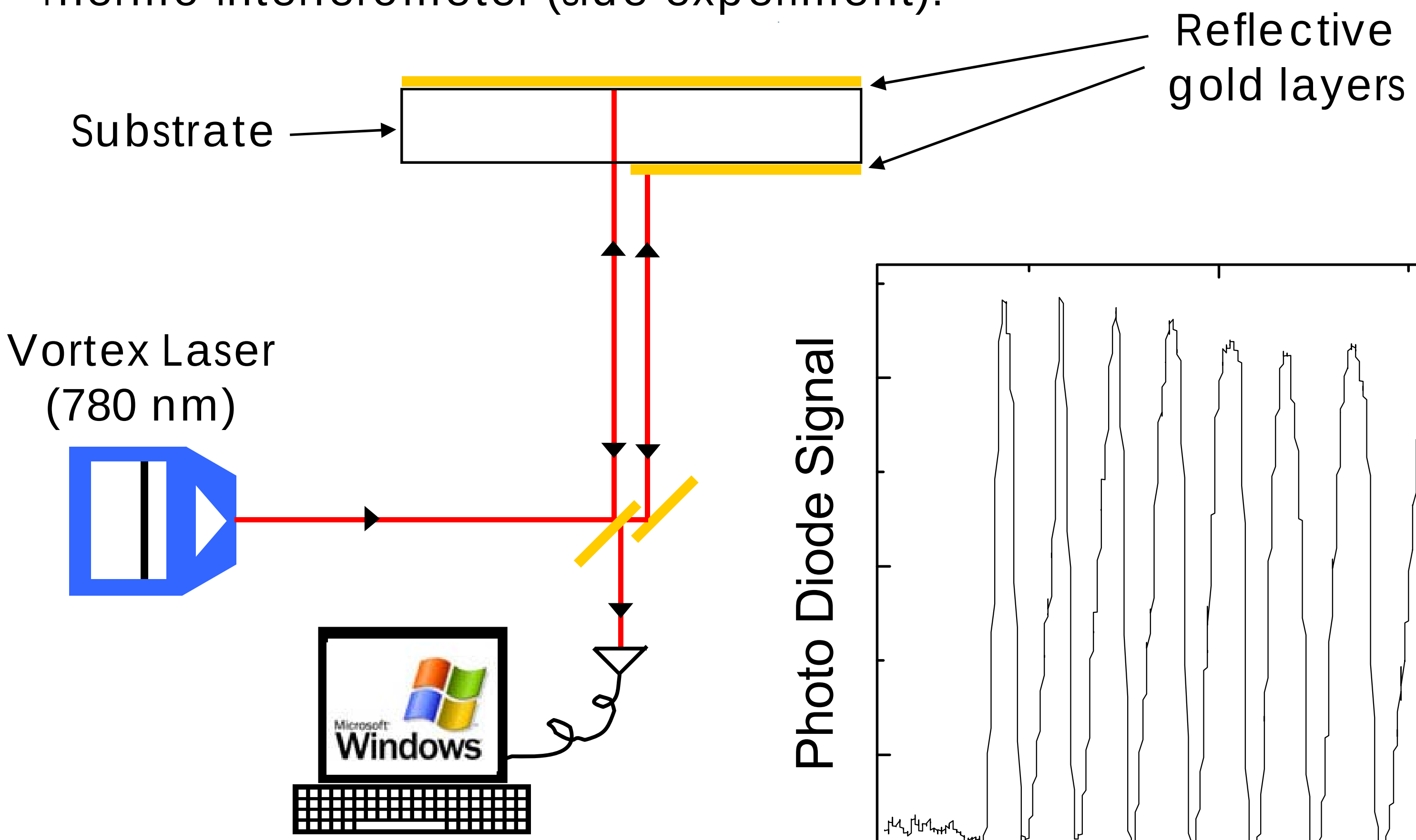
Q2:
And caused us all to die?

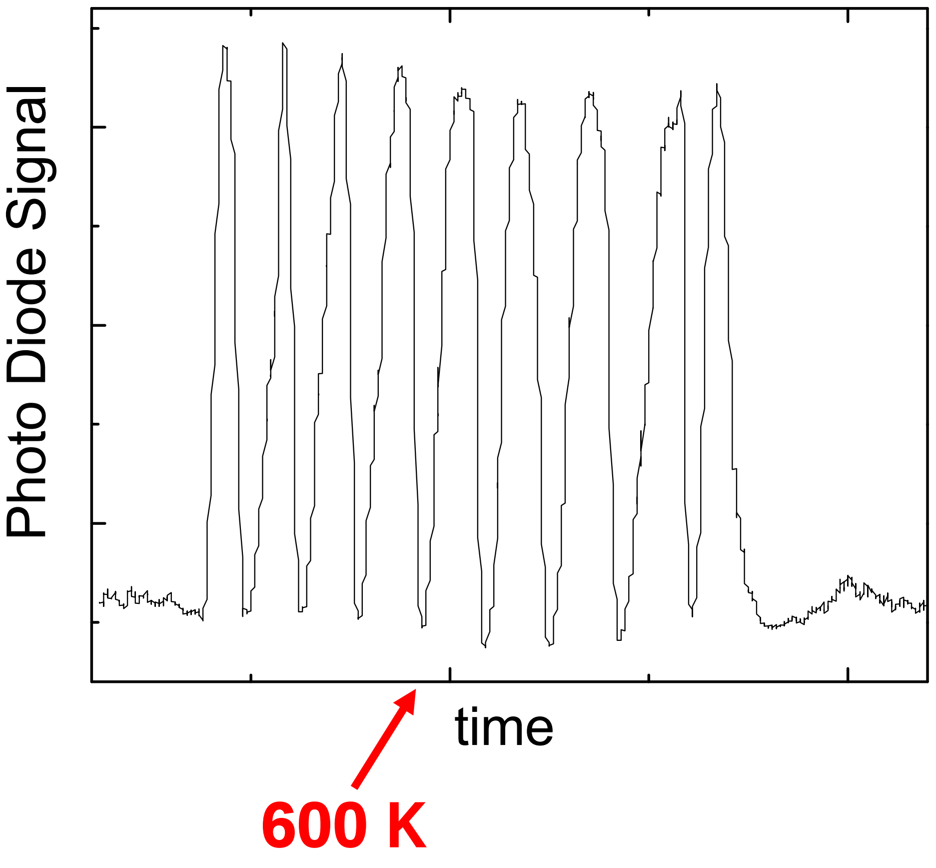
Q3:
Excrutiatingly painful deaths?

A: No clue. But maybe now we understand why the Casimir-Polder force between and atomand a surface is (usually) attractive, not repulsive.

Temperature Measurement

* Thermo-interferometer (side experiment):

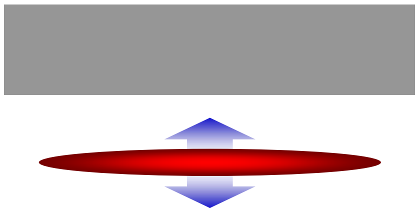




* For 1mm thick fused silica glass:

~30 ^{o}C/fringe

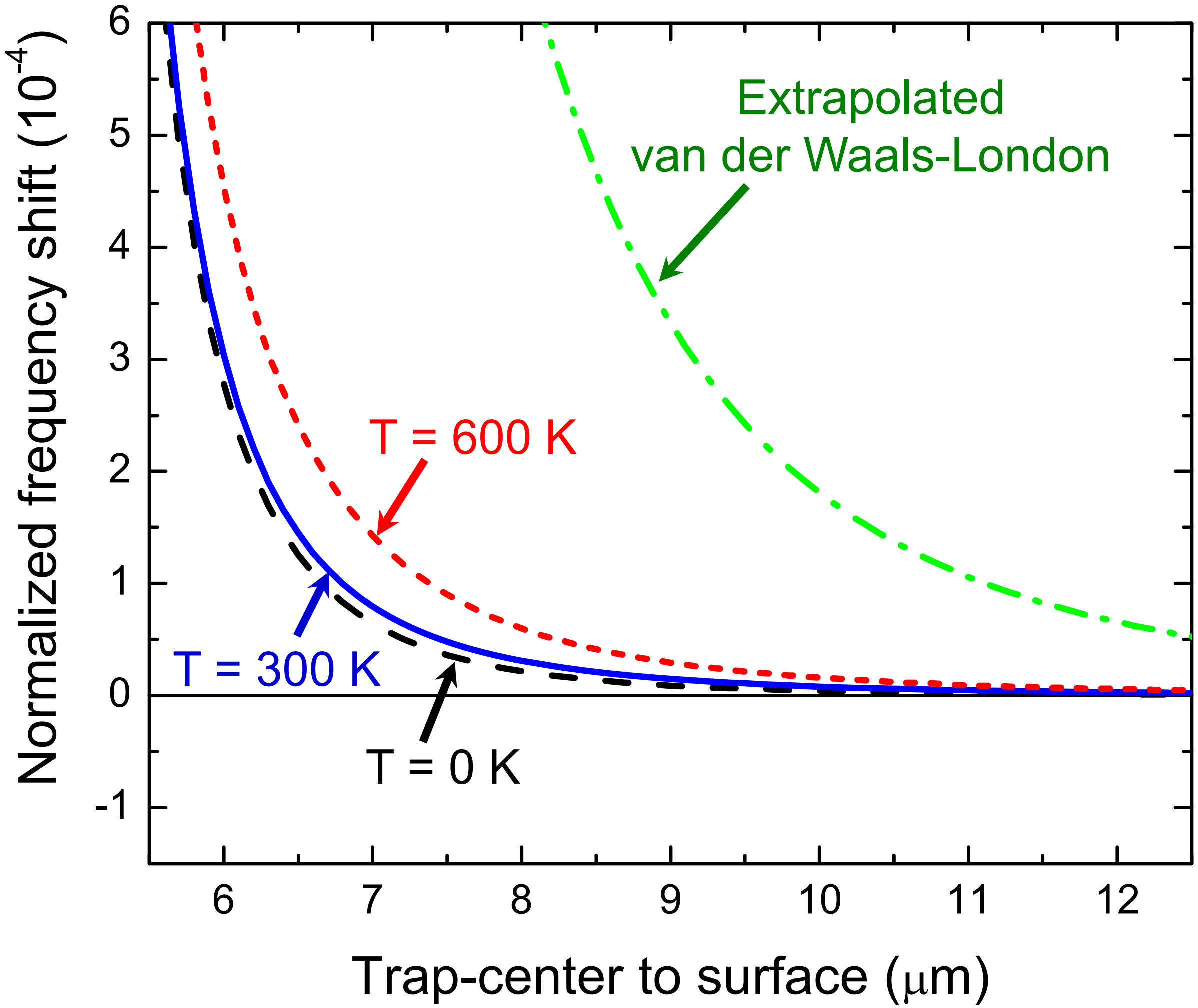
Predicted *FFS* from C-P force



Theory:

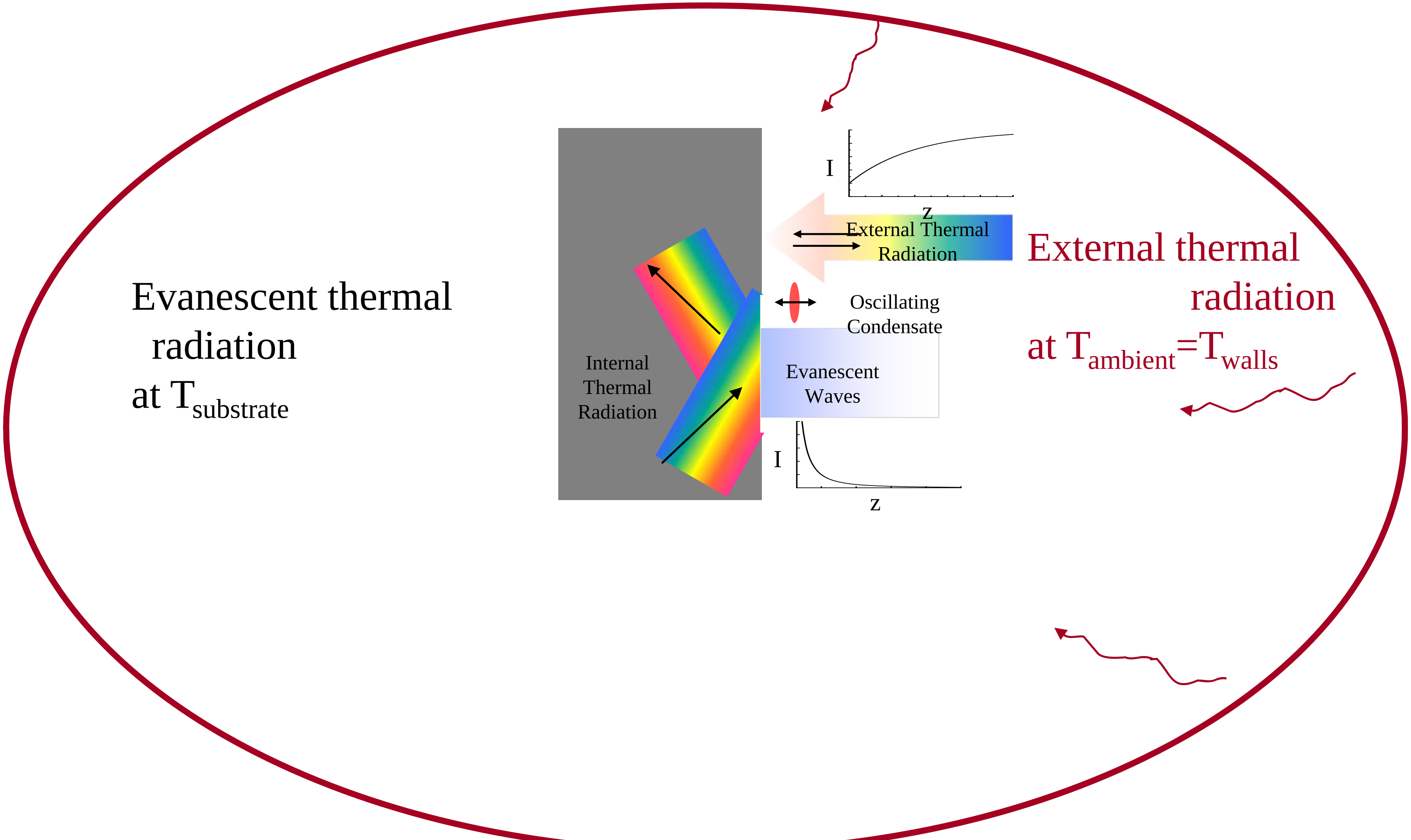
Antezza *et al.*

BEC width and oscillation amplitude accounted for in theory.



M. Antezza, L.P. Pitaevskii, and S. Stringari, Phys. Rev. A **70**, 053619 (2004)

Trento guys say by tinkering with temperature of the substrate relative to the "far away walls of experiment" can remove the cancellation of forces.



Where are we going?

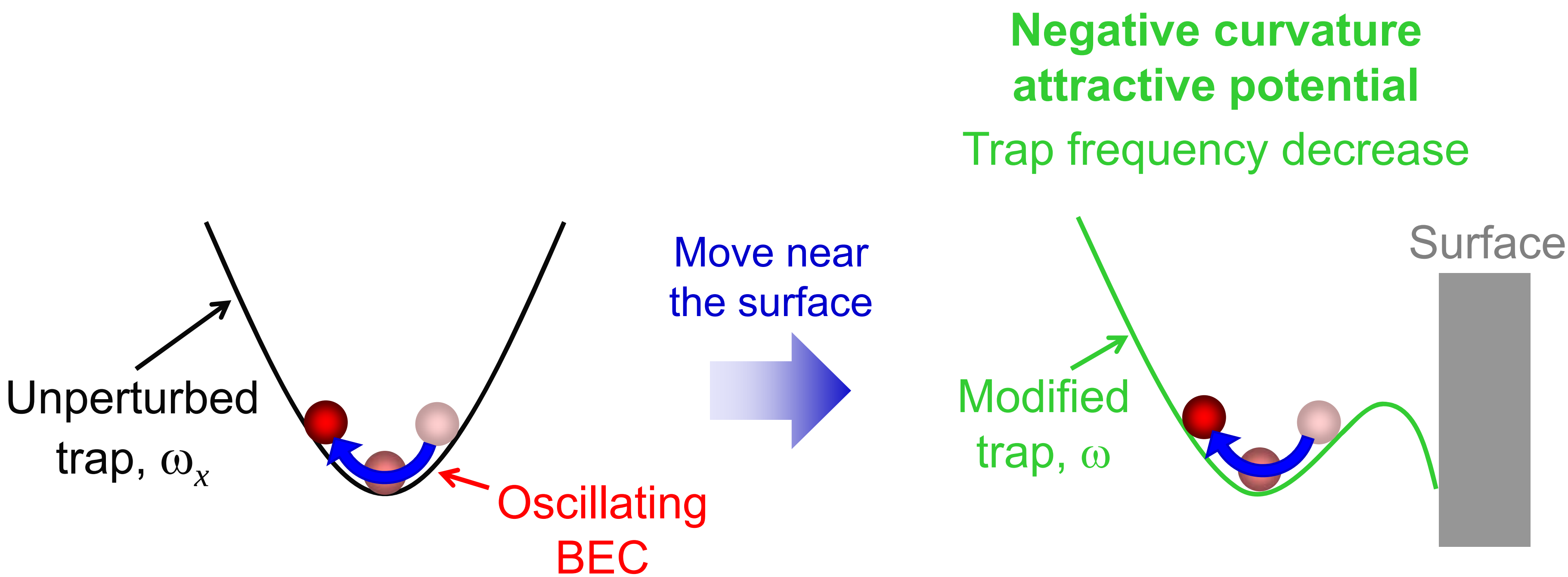
Heat environment, cool substrate, change sign of force?

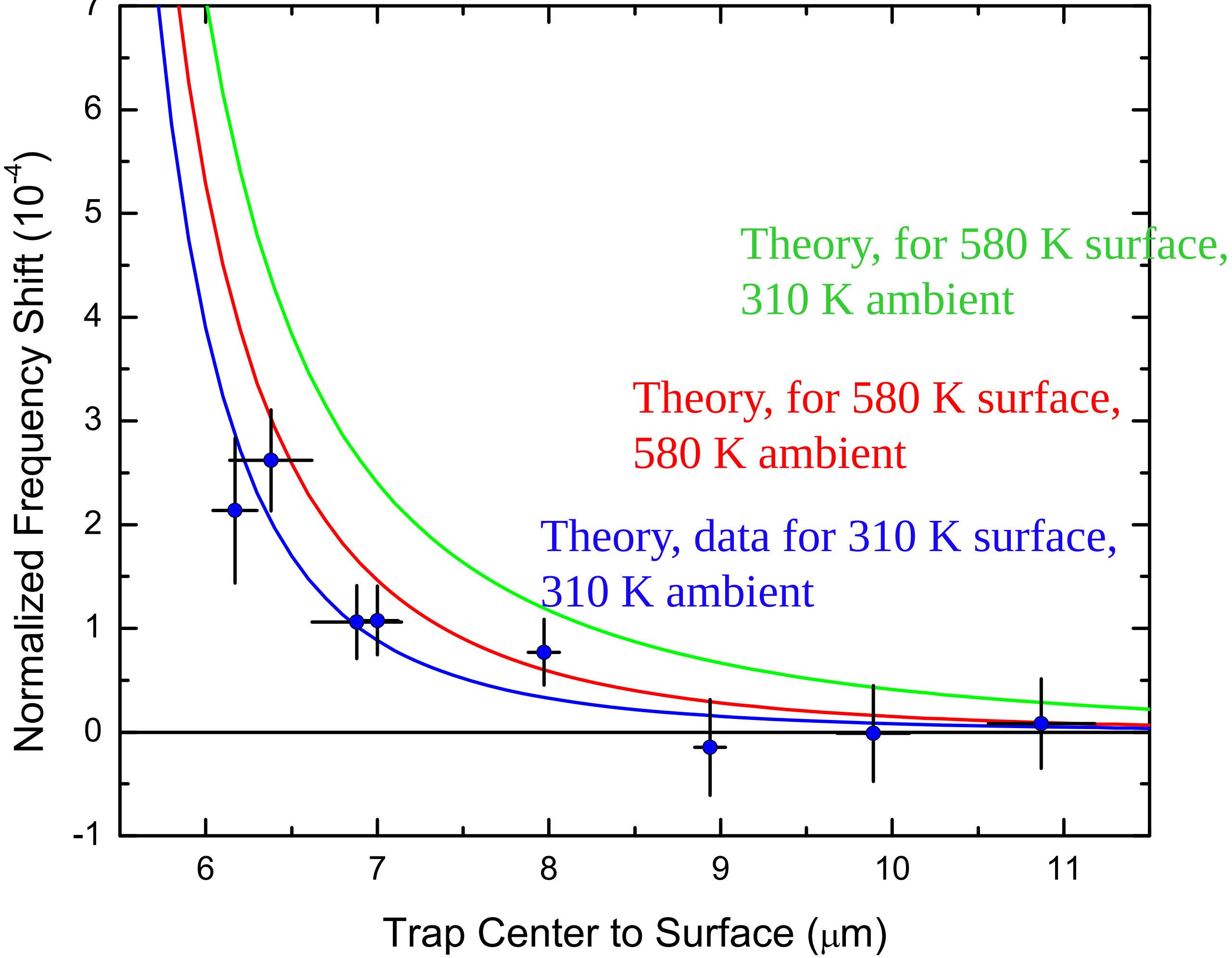
Try substrate with exotic dielectric properties, resonances.

Try spatially textured substrate.

Express trap frequency changes as normalized frequency shifts:

$$\frac{\omega_x - \omega}{\omega_x} \approx -\frac{1}{2\omega_x^2 m}\frac{d^2U}{dx^2}$$





Trento guys say by tinkering with temperature of the substrate relative to the “far away walls of experiment” can remove the cancellation of forces.