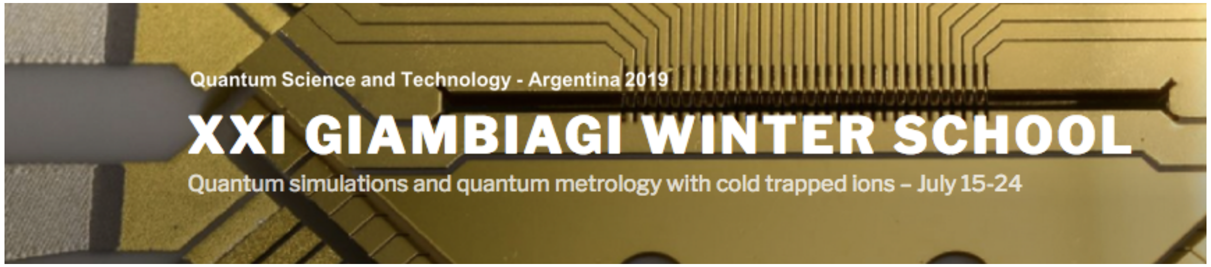

XXI Giambiagi Winter School
July 2019
University of Buenos Aires
Argentina

Quantum Thermodynamics

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University of Exeter, UK

joint work with :
Philipp Kammerlander
Sai Vinjanampathy
Harry Miller
....

UNIVERSITY OF EXETER

Lecture overview

I - Work extraction from quantum coherences (long)

II - Maxwell's demon and his exorcism - experimental evidence (short)

III - Thermodynamics beyond the weak coupling limit (long)

IV - Optional: Non-equilib. temperature of levitated nanospheres (short)

Quantum thermodynamics - Motivation

MICROSCOPIC WORLD

- atoms, electrons, photons

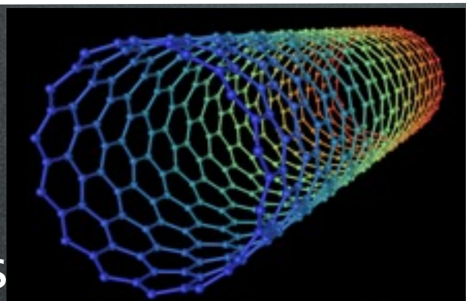
MACROSCOPIC WORLD

- gases, fluids, solids
- pistons and weights

1nm/1amu → 1m/1kg

Quantum Mechanics

- superpositions
- quantum correlations

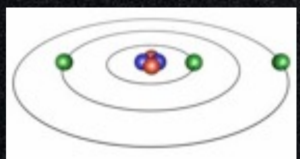


Thermodynamics

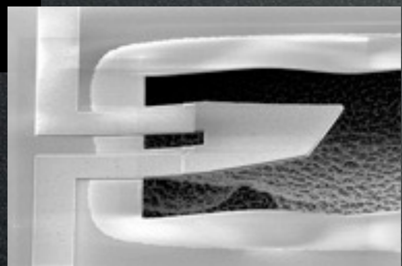
- temperature, work, heat, entropy
- 1st law, 2nd law, 3rd law
- Carnot efficiency, engines

photon

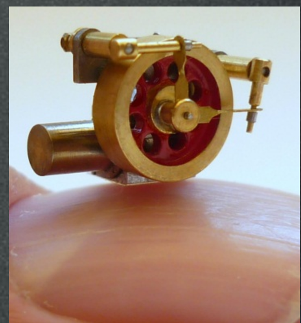
bio-molecule



atom



micro-meter resonator



Outline

- Macroscopic quantum superpositions
- **Non-equilibrium** temperatures of levitated nanospheres

Quantum ground state experiments

How **large** an object can still be in a quantum superposition state?

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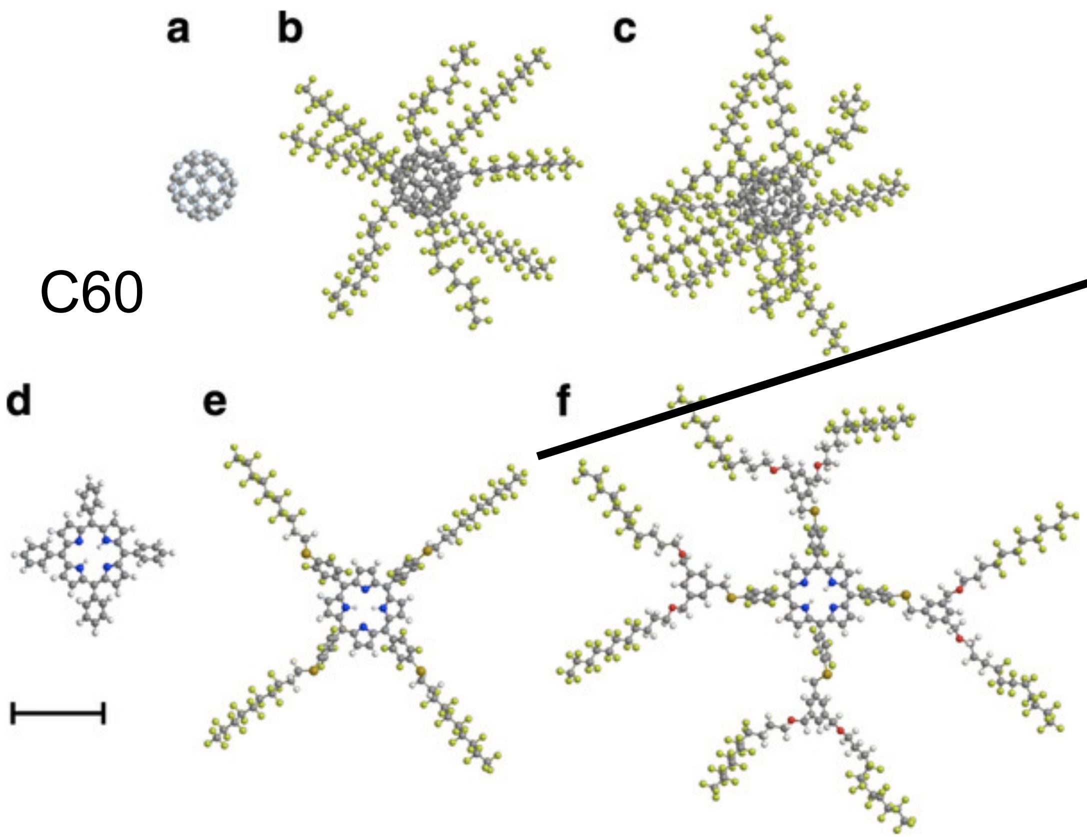
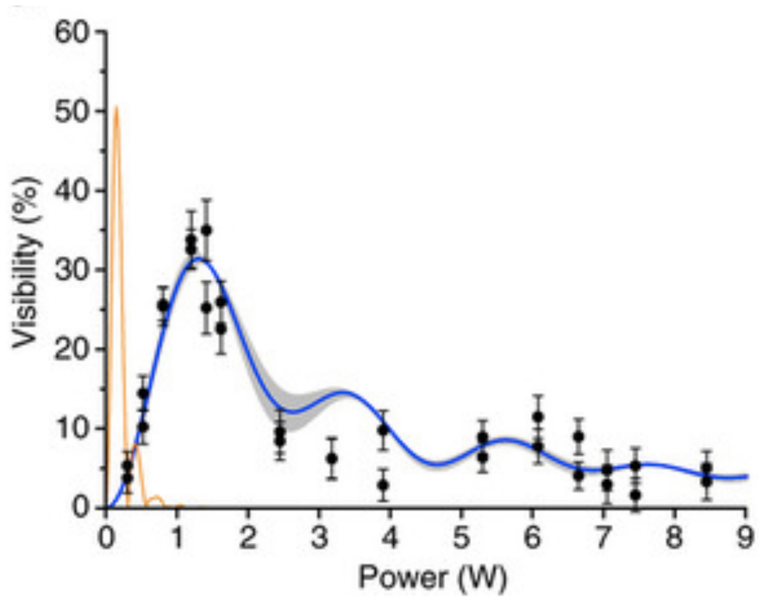
Nature Com 2, 263 (2011)

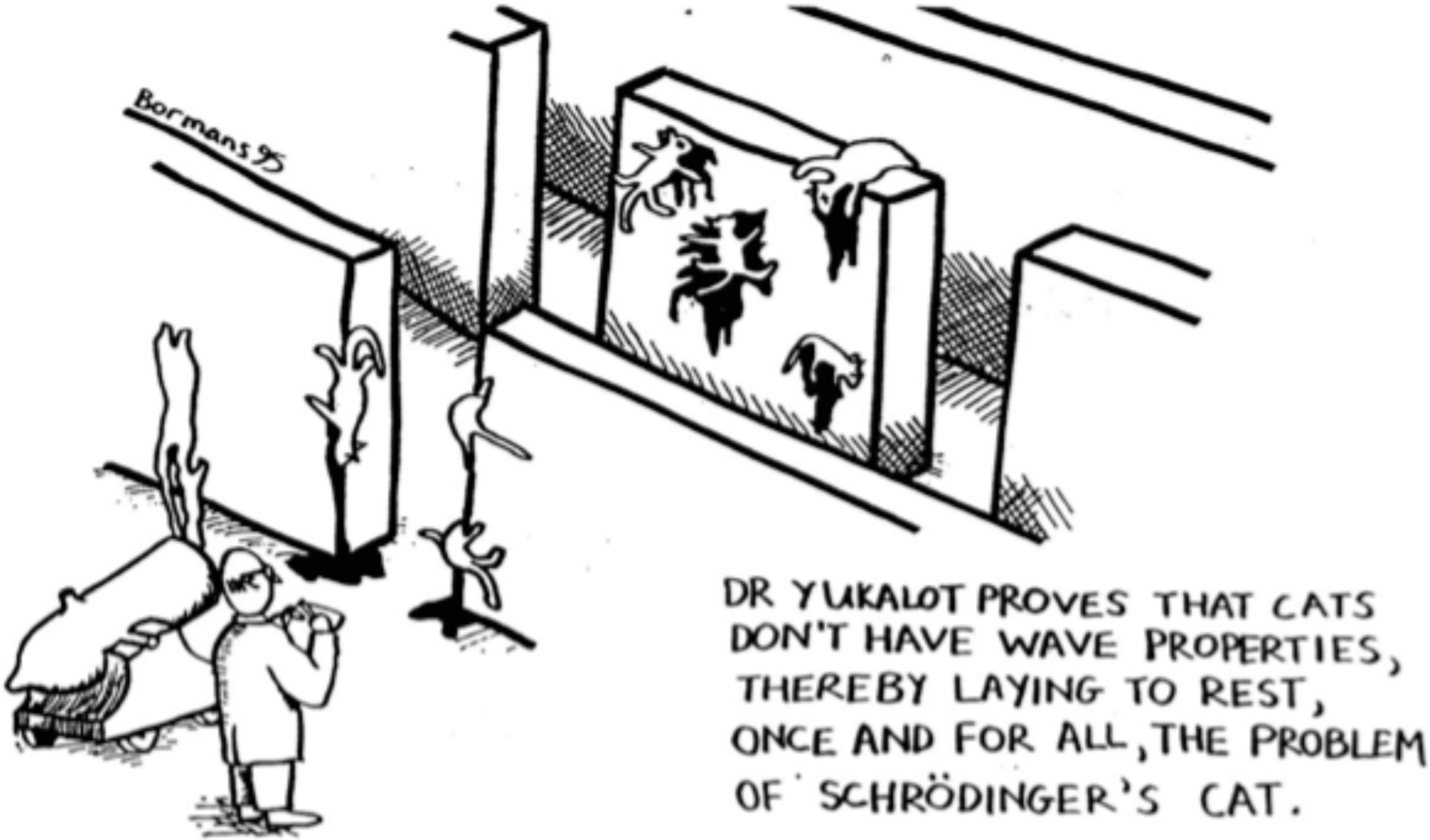


C60



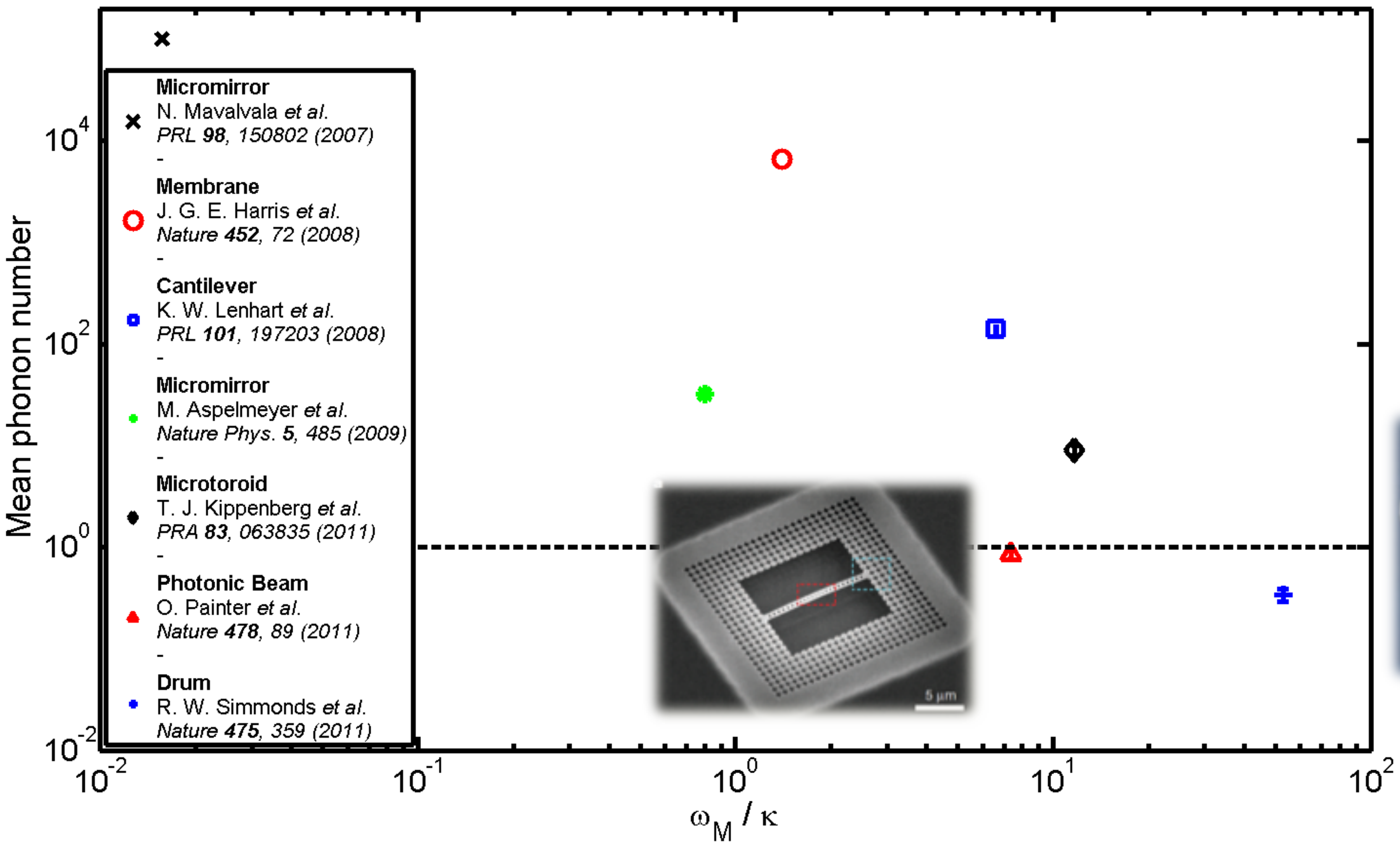
bio-molecules with up to 7k AMU

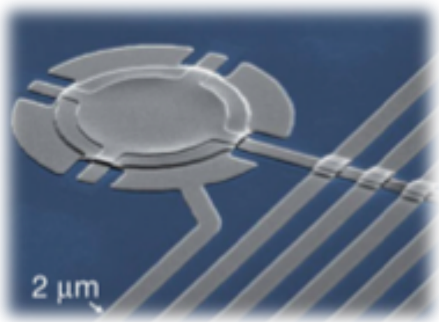
Macroscopic superpositions



Quantum ground state experiments

Optomechanics.
Cool mechanical oscillators through interaction with light, e.g. by feedback and cavity cooling.

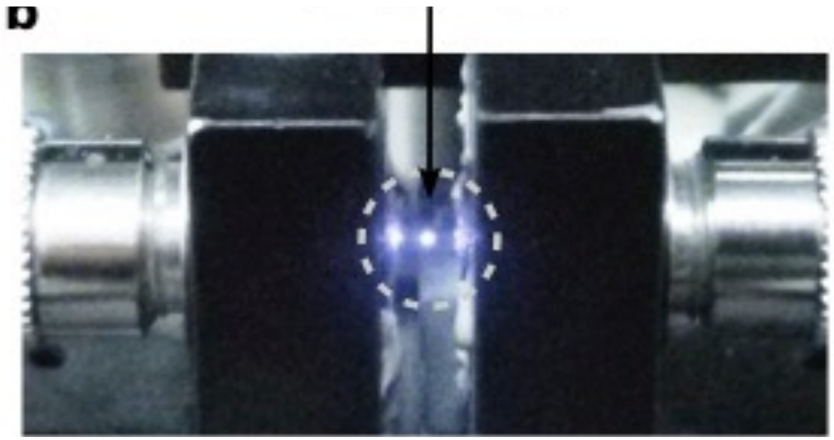




Light-levitated nano-spheres

instead of an oscillator connected to an environment by a bridge

➤ use **nanospheres** that are levitated



silica spheres

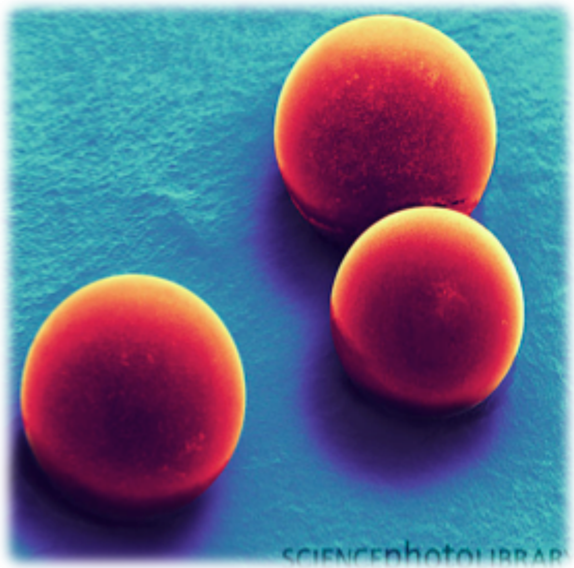
radius R = 100nm - 10mu

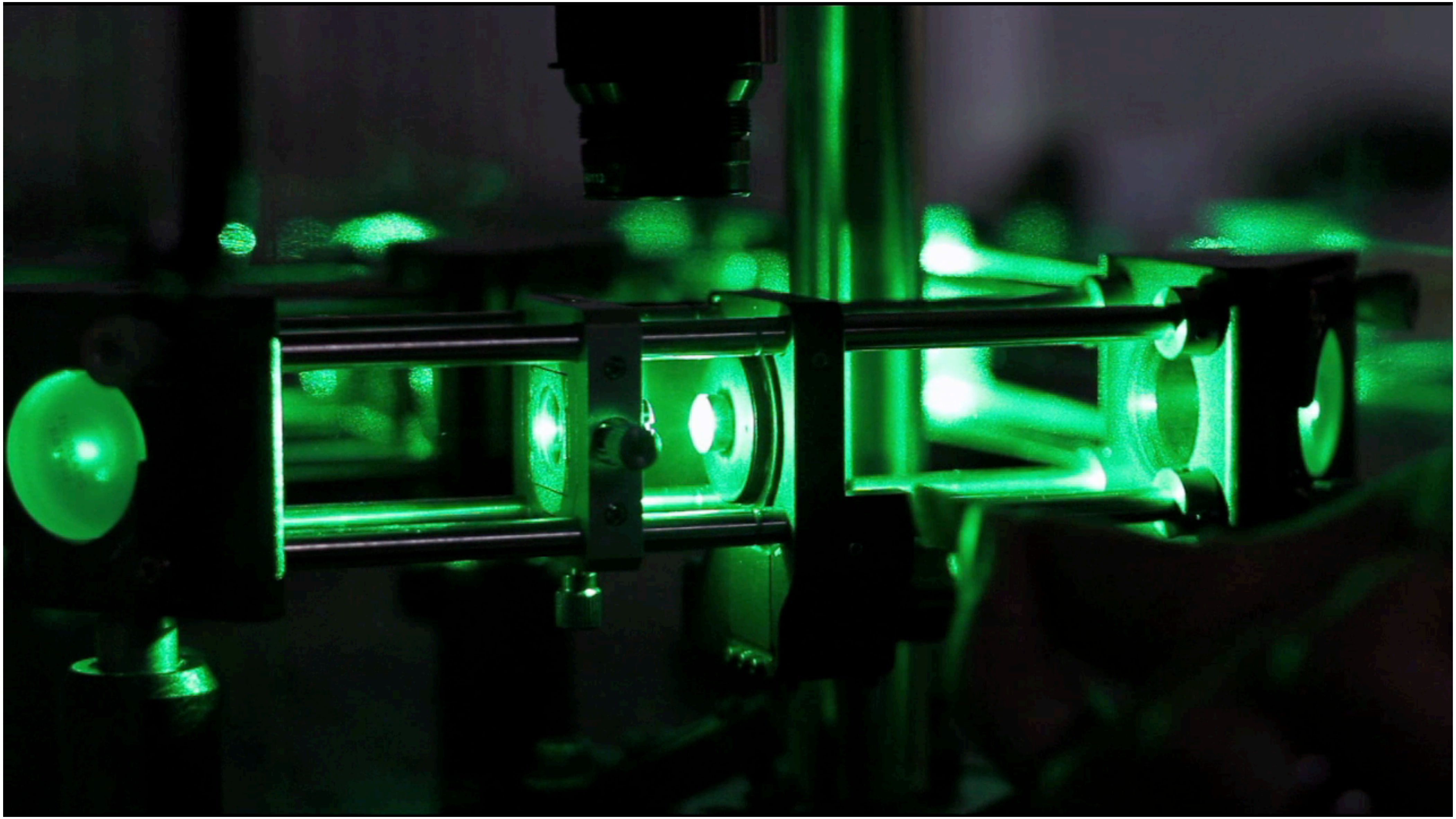
contain 10^8 - 10^{18} atoms

laser creates ➤ trap frequencies of 10kHz

$$k_B T = \hbar\omega$$

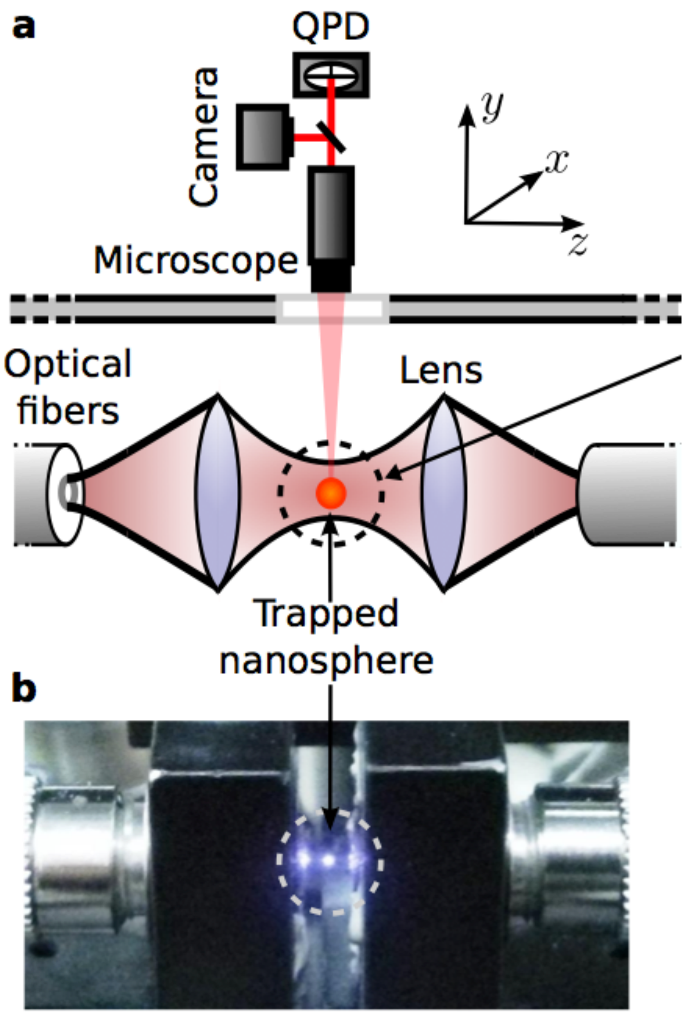
interesting temperature regime: μK





built by Dr J. Millen, recorded by FurnaceTV

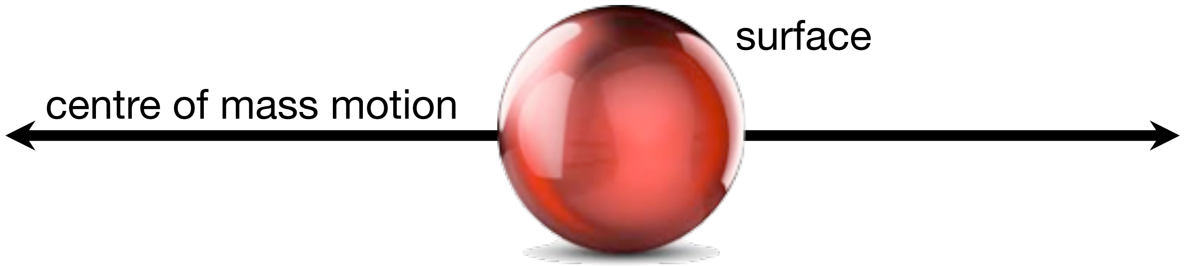
Setup and Question



Aim: cooling to the ground state …

But even without cooling techniques:

How does surface (bulk) temperature of sphere **affect** its CM motion temperature?

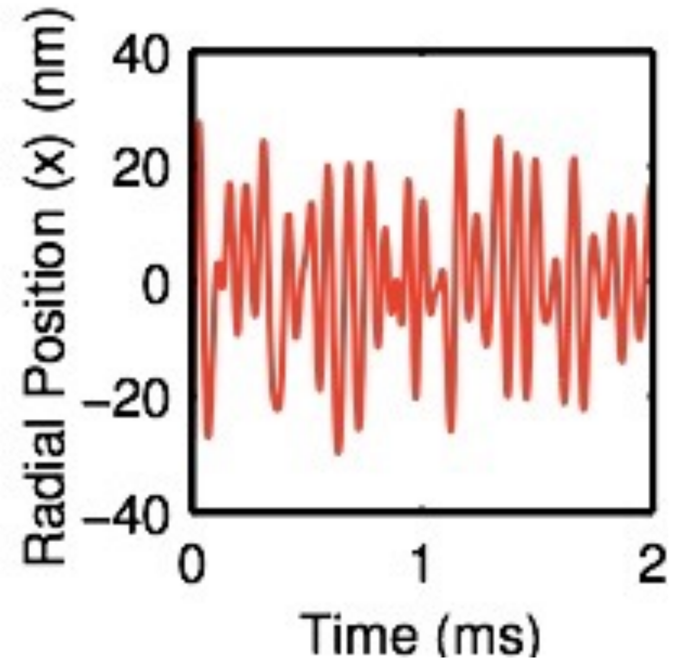


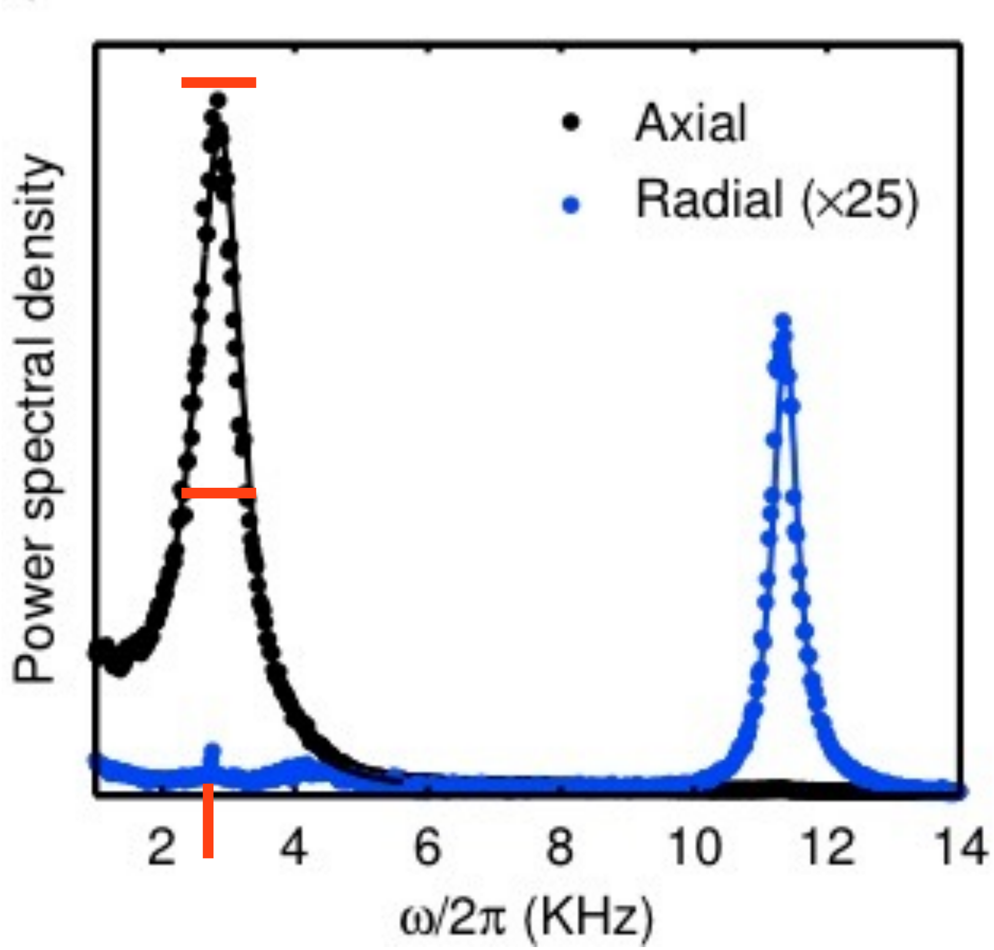
Does the CM motion actually have a temperature?

And how to measure the surface temperature?

Brownian motion position measurements in 2D

QPD tracks movement in 2D in μs





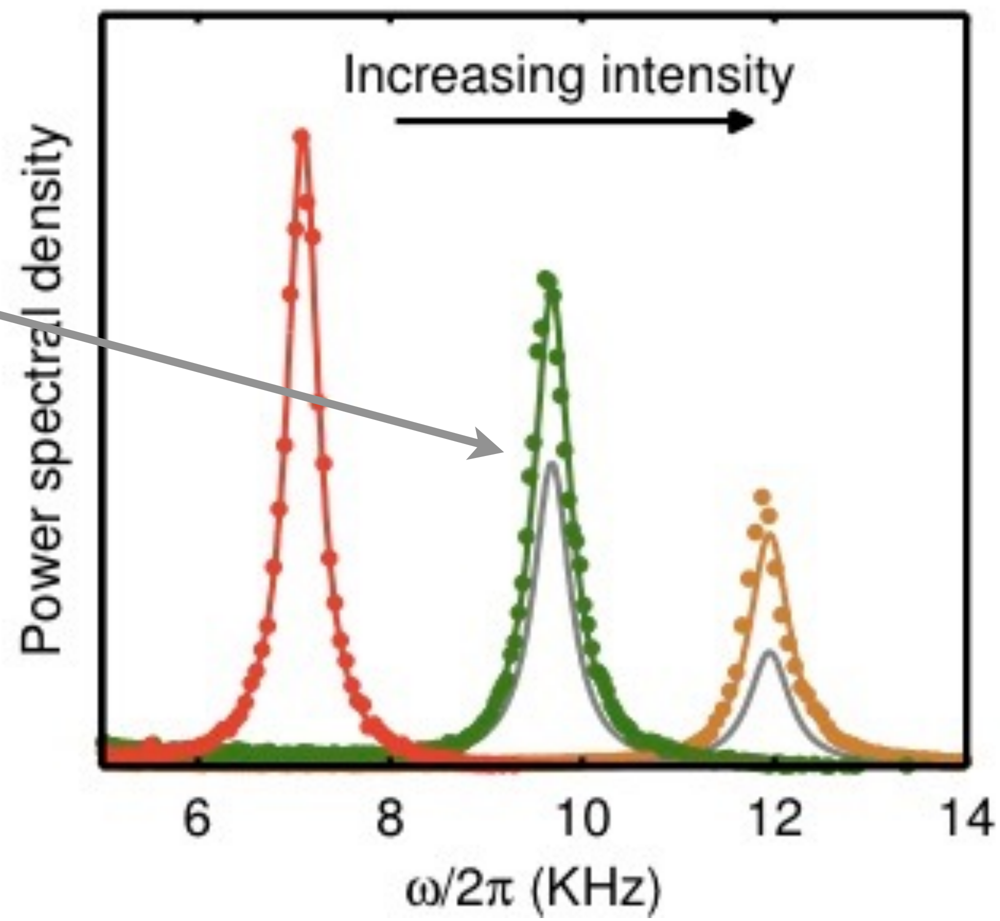
underdamped regime:

if thermal, expect power spectrum $P(\omega) = \frac{2k_B T^{\mathrm{CM}}}{M} \frac{\Gamma^{\mathrm{CM}}}{(\omega_x^2 - \omega^2)^2 + (\omega \Gamma^{\mathrm{CM}})^2}$

Increasing laser intensity

increases trap frequency

expect to find



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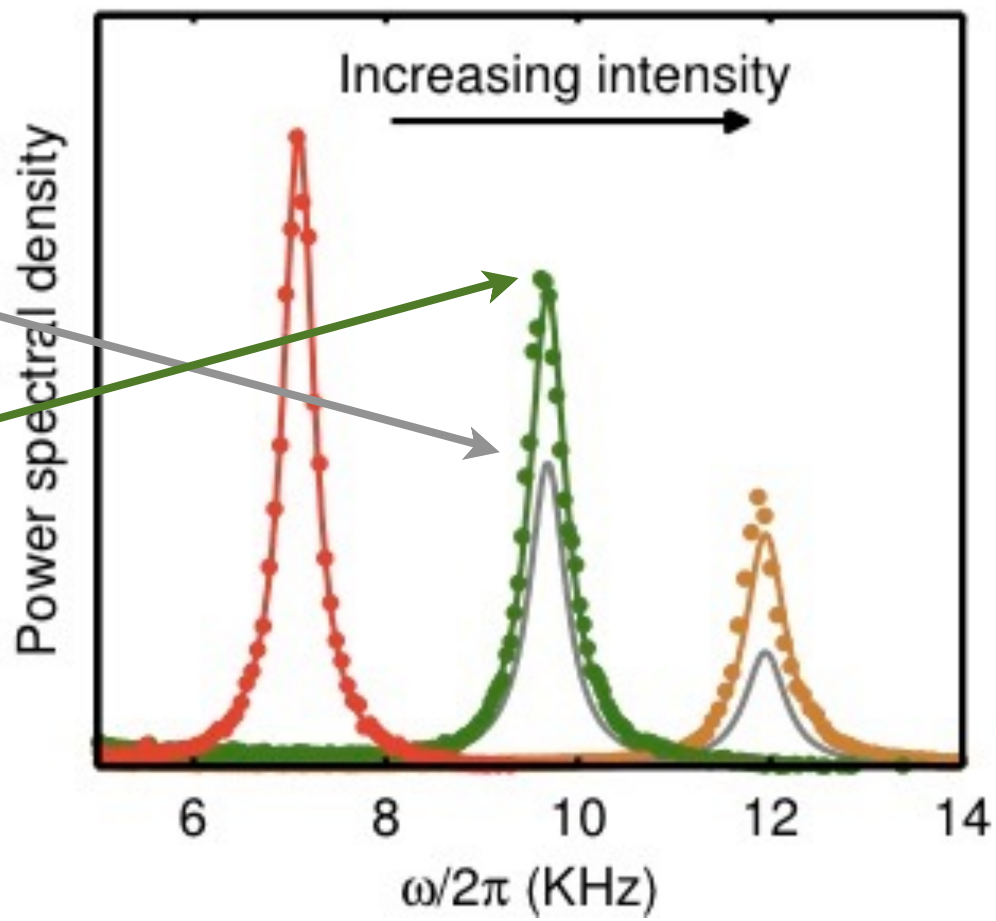
Increasing laser intensity

increases trap frequency

expect to find

find: increased CM temperature



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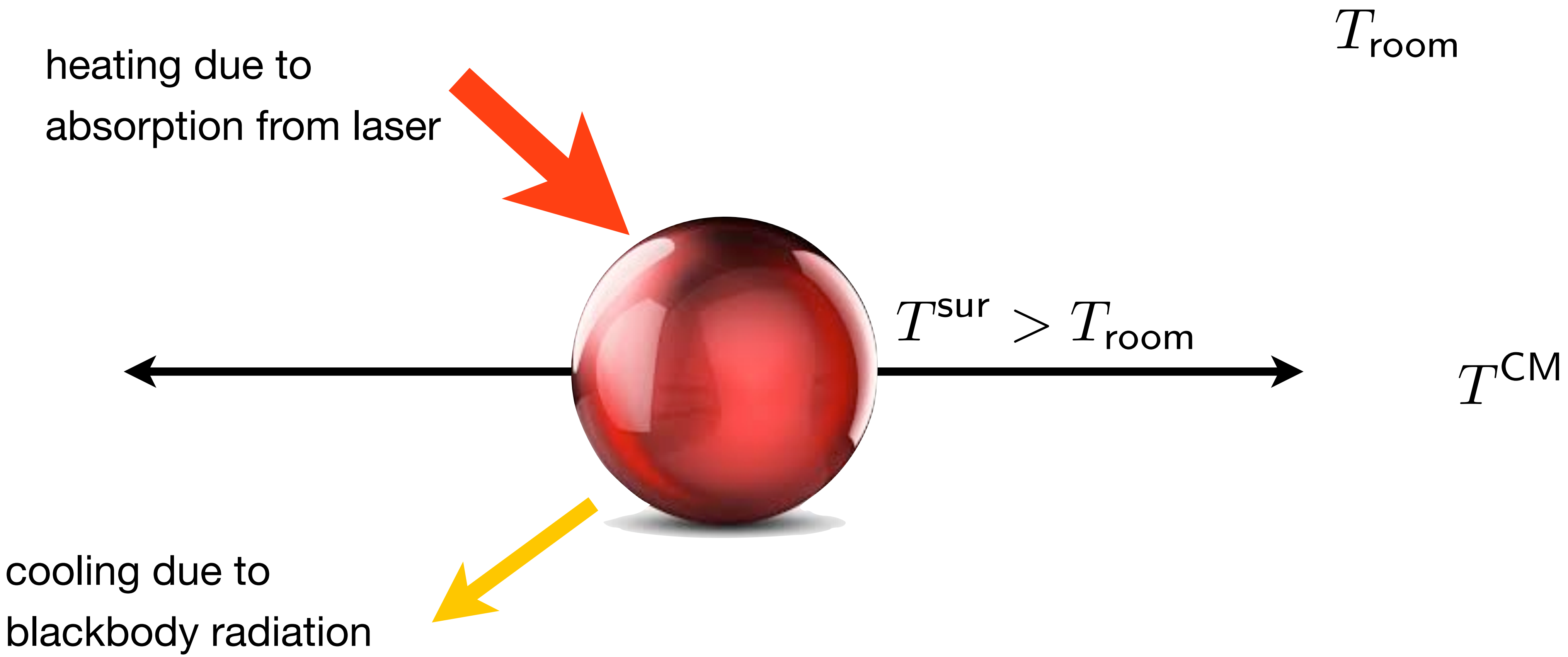
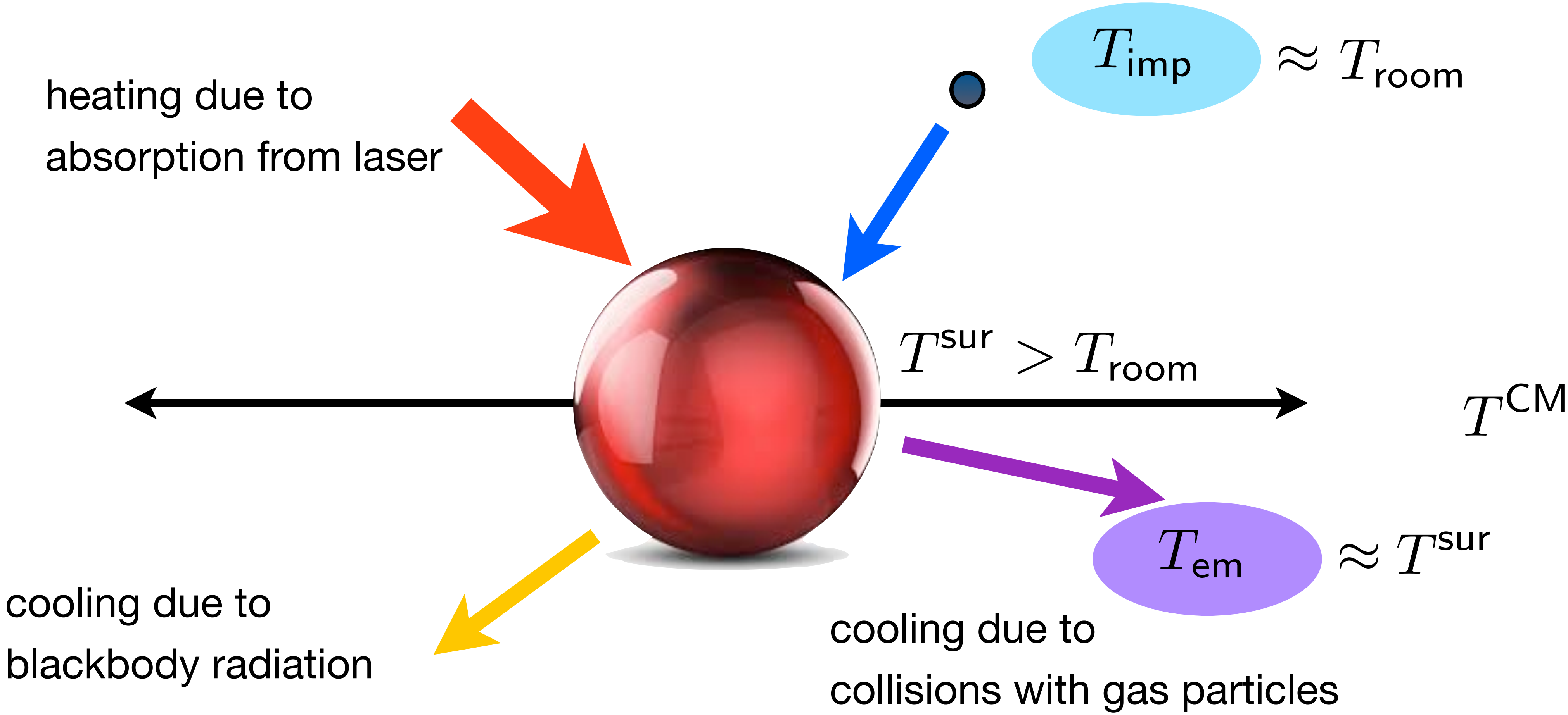
Two temperature model



Two temperature model



Langevin $M\ddot{x}(t) + M(\Gamma^{\text{imp}} + \Gamma_x^{\text{em}})\,\dot{x}(t) + M\omega_x^2\,x(t) = F^{\text{imp}}(t) + F_x^{\text{em}}(t)$

Knudsen number = mean free path/size of object

$\mathrm{Kn} >> 1$ fluid mechanics incorrect, kinetic theory needed

Knudsen regime

Langevin equation for two baths

$$M\ddot{x}(t) + M(\Gamma^{\mathrm{imp}} + \Gamma^{\mathrm{em}}_x)\,\dot{x}(t) + M\omega_x^2\, x(t) = F^{\mathrm{imp}}(t) + F^{\mathrm{em}}_x(t)$$

assuming that the two baths **do not interact** $\langle F^{\mathrm{imp}}(t) F^{\mathrm{em}}_x(t')\rangle = 0$

Power spectrum

$T^{\mathrm{CM}}\,\Gamma_{\mathrm{CM}}$

$$P(\omega) = \frac{2k_B}{M}\,\frac{T^{\mathrm{imp}}\,\Gamma^{\mathrm{imp}} + T^{\mathrm{em}}\,\Gamma^{\mathrm{em}}}{(\omega_x^2 - \omega^2)^2 + \omega^2\,(\Gamma^{\mathrm{imp}} + \Gamma^{\mathrm{em}})^2}.$$

Γ_{CM}

how does damping depend on temperatures?

$\Gamma^{\mathrm{CM}}(T^{\mathrm{imp}}, T^{\mathrm{em}})$

Damping coefficient

1851 Stokes

Stokes' drag force in dense medium $\mathrm{Kn} << 1$

$$F_d = 6\pi\,\mu\,R\,v$$

μ viscosity of liquid

R radius of sphere

1924 Epstein

Epstein damping in very dilute medium $\mathrm{Kn} >> 1$

$$F_d = \frac{8\pi + \pi^2}{6}\,\rho_{gas}\,\bar{v}^{\mathrm{imp}}\,R^2\,v$$

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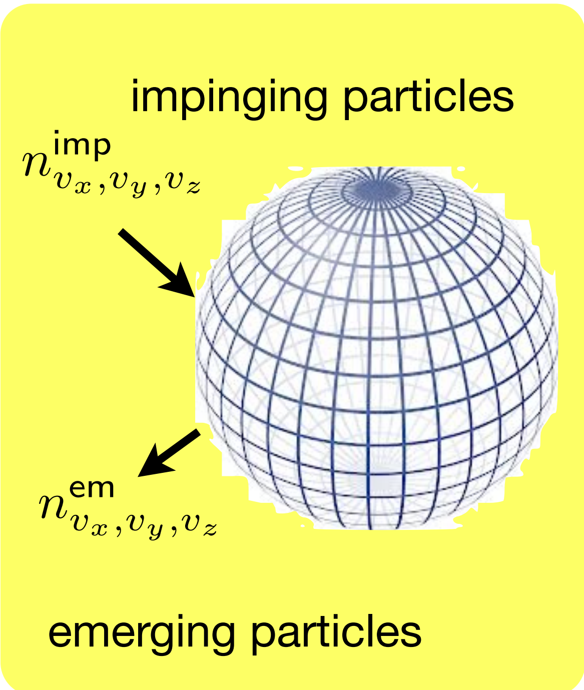
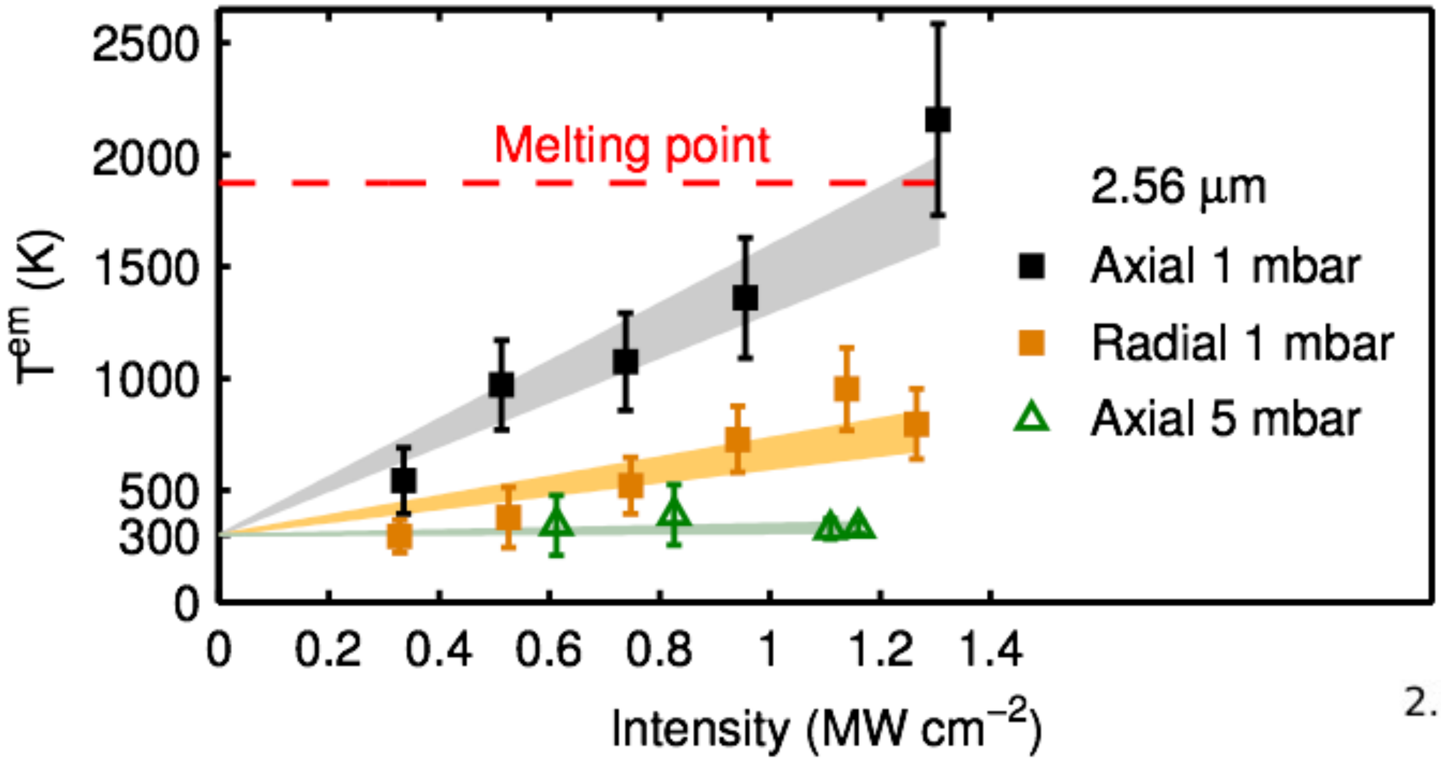


Need to consider the damping of emerging gas at higher temperature

$$\Gamma^{\mathrm{CM}} = \left(1 + \frac{\pi}{8}\sqrt{\frac{T^{\mathrm{em}}}{T^{\mathrm{imp}}}}\right)\Gamma^{\mathrm{imp}}$$

Emerging gas temperature: big spheres



Parameters:

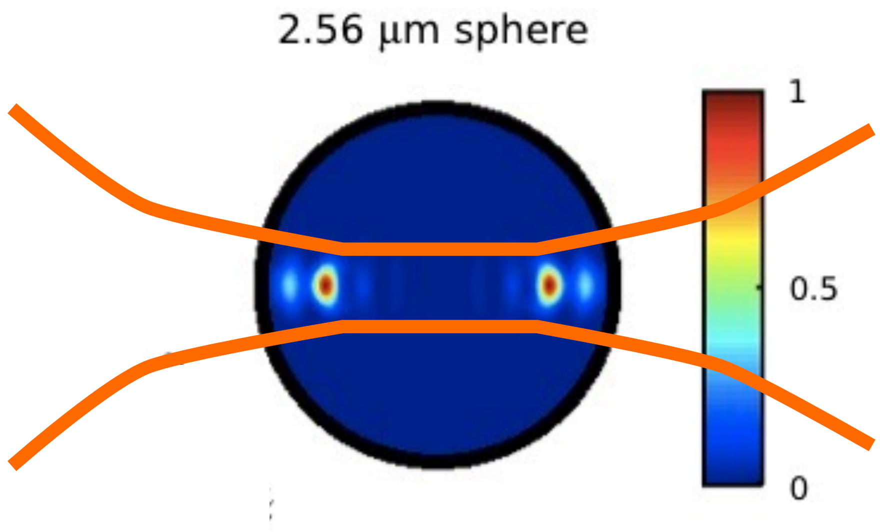
low pressure,

medium laser power,

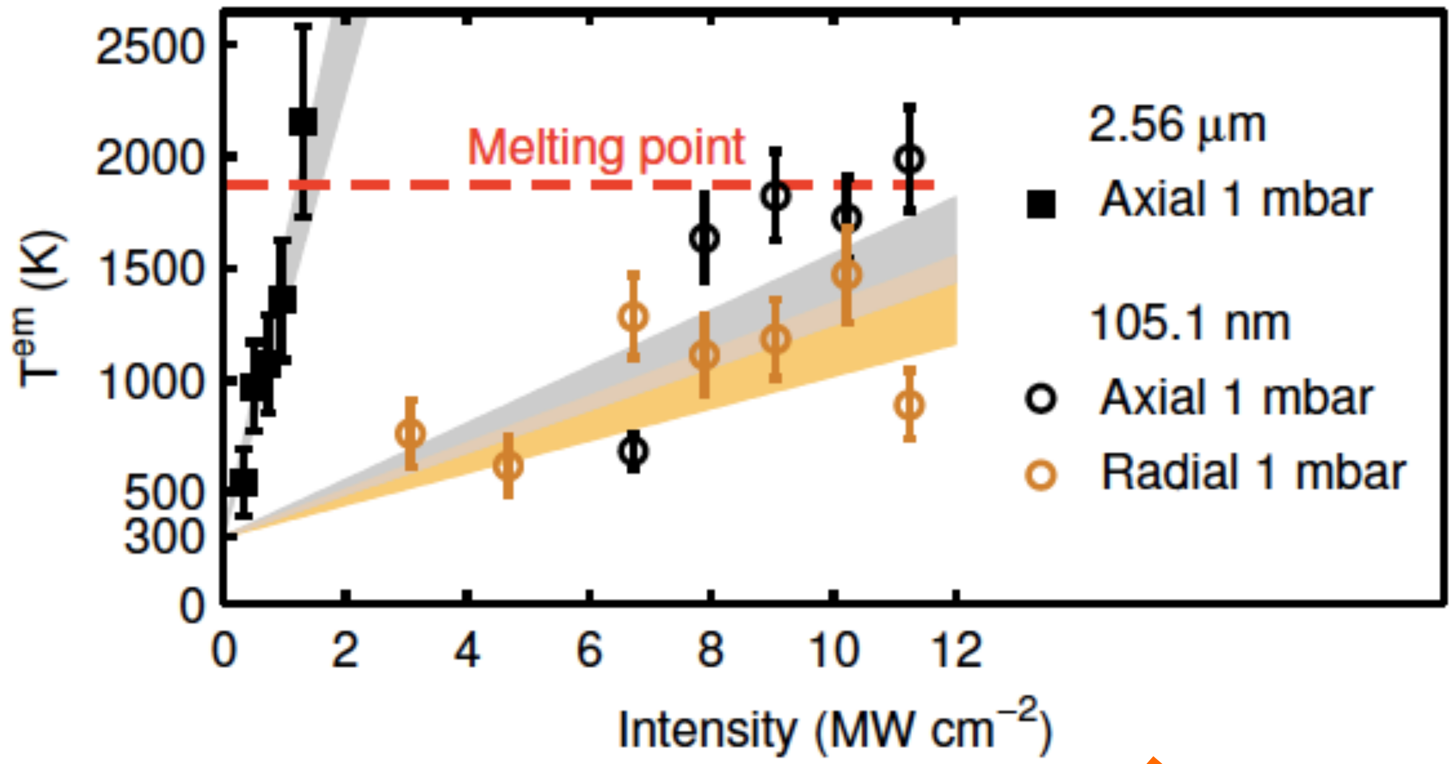
big spheres

➤ very **strong** heating

➤ very large **spatial variation**



Emerging gas temperature: small spheres



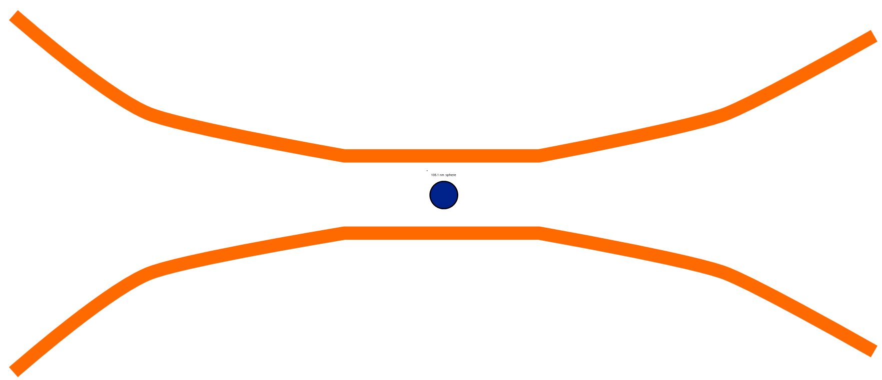
Parameters:

low pressure,

high laser power,

small spheres

- ➤ medium heating
- ➤ no spatial variation



CM damping as function of T^{em}

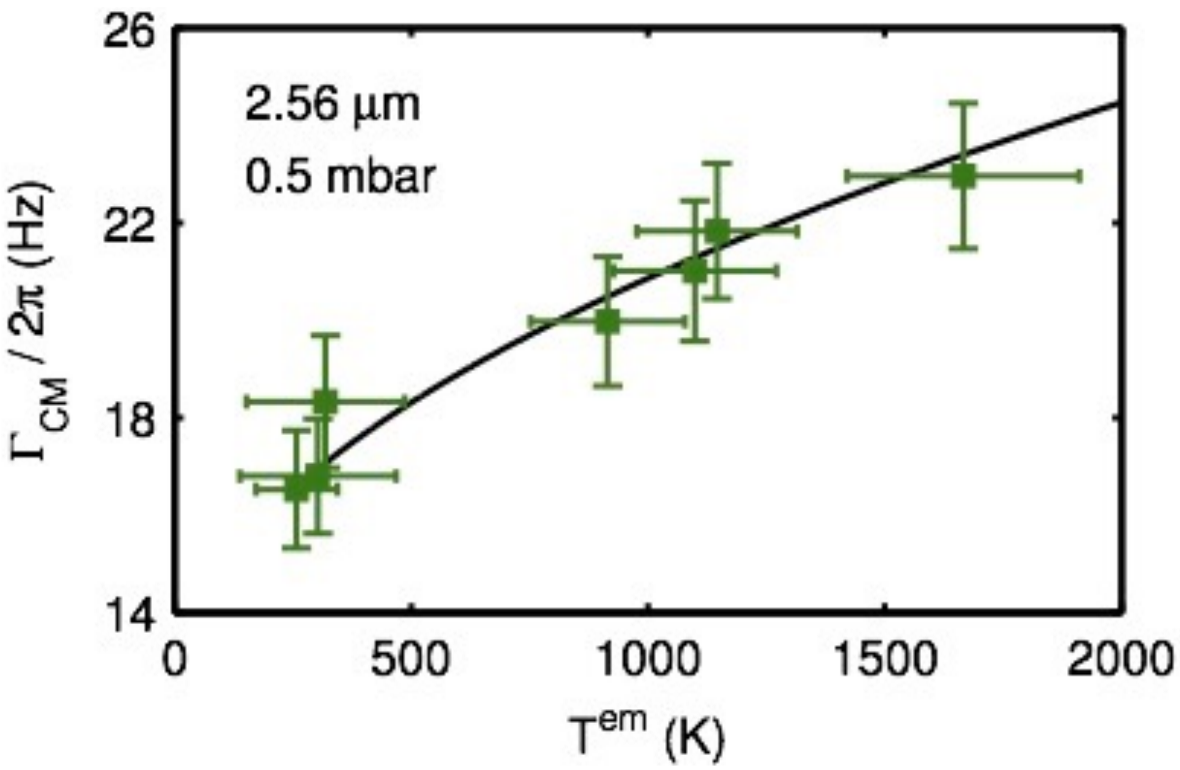
$$\Gamma^{\mathsf{CM}} = \left(1 + \frac{\pi}{8}\sqrt{\frac{T^{\mathsf{em}}}{T^{\mathsf{imp}}}}\right)\Gamma^{\mathsf{imp}}$$

with

$$T^{\mathsf{imp}} = 294\mathrm{K}$$

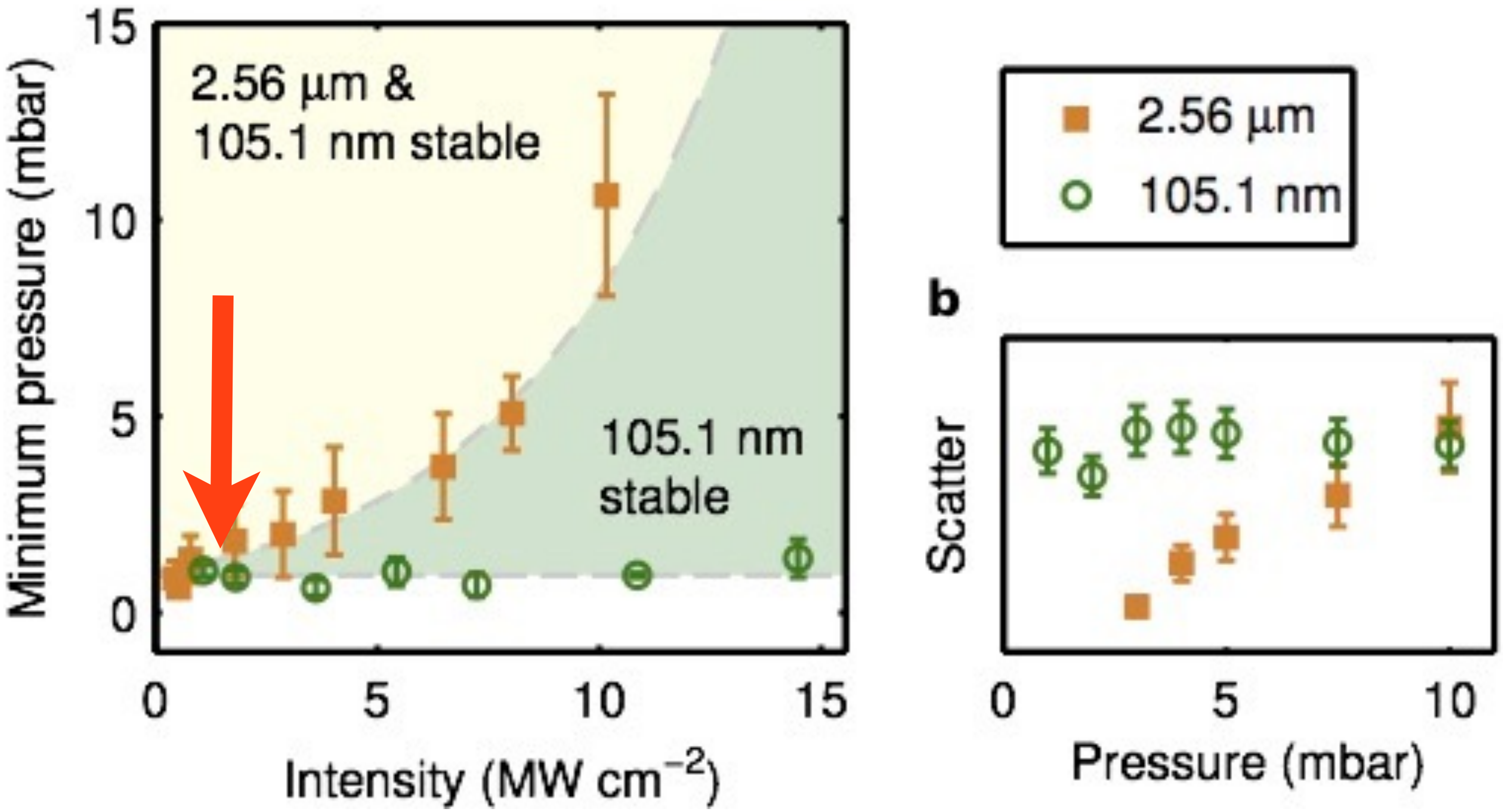
$$\Gamma^{\mathsf{imp}} = \frac{4\pi}{3}\,\rho_{gas}\,\bar{v}^{\mathsf{imp}}\,\frac{R^2}{M}$$

$$= 2\pi \times 12.1\ \mathrm{Hz}$$



➤ fits without any fitting parameter

Leaving from trap



➤ **2.5mu** spheres leave trap because they melt!

➤ **105nm** spheres leave trap due to a **non-temperature** related cause, i.e. noise of apparatus

Summary: Nanosphere temperatures

Nature Nanotechnology
9:425 (2014)

Surface temperature of **nanoscale** objects can be determined by carefully analysing their **non-equilibrium** dynamics.

Nanoscale temperature **gradients** can be observed.

Thank you!


James Millen


Tanapat Deesuwan


Peter Barker

Future: Exploring **underdamped** non-equilibrium dynamics and **quantum thermodynamics**.