Levitating nanoparticles: from new tools to fundamental questions

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Benasque, 21/3/2019

IQI

MARIE CURIE ACTIONS

universität innsbruck

Outline

- Introduction to nanoparticle levitation
- New tools: center of mass cooling
- Fundamental questions: radiative thermalization
- Conclusion and outlook

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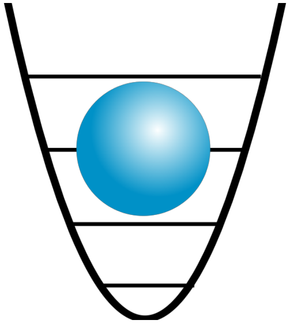

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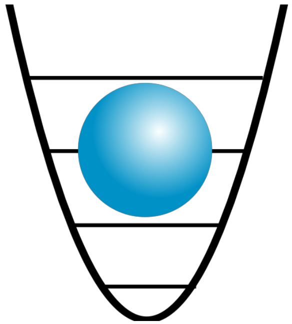

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- Many particle materials and shapes:

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  - Charged metallic particles
  - Nanomagnets
  - Superconducting particles
  - Liquid helium droplets
  - Nanorods, nano-dumbells...

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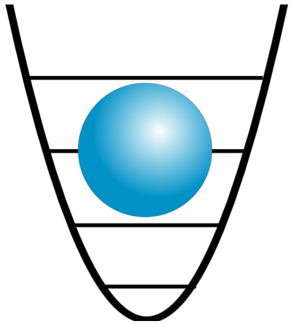

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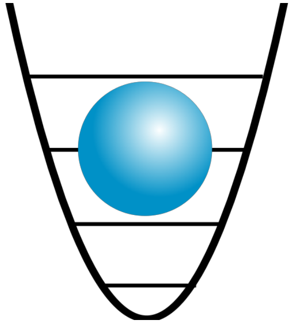

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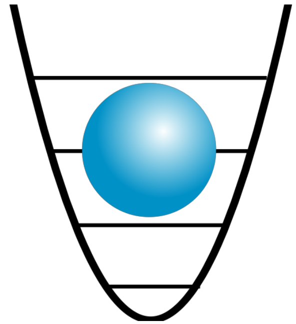

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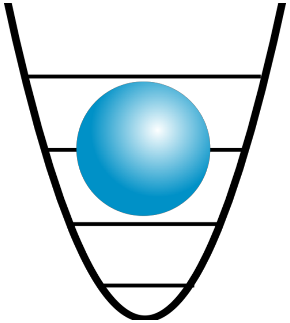

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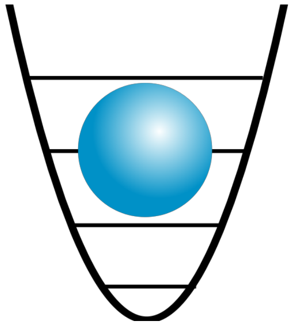

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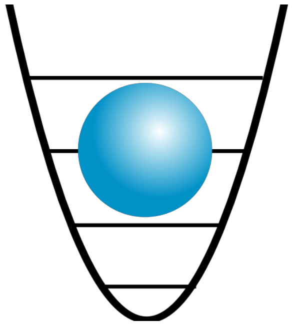

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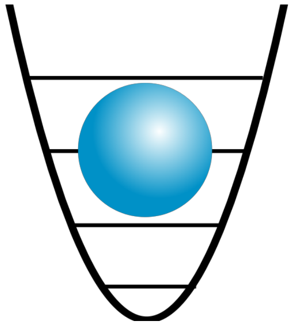

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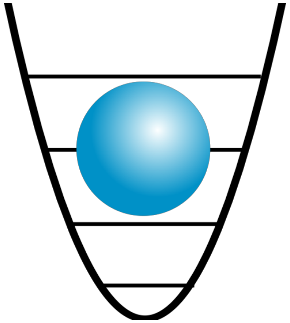

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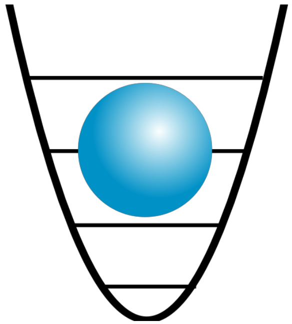

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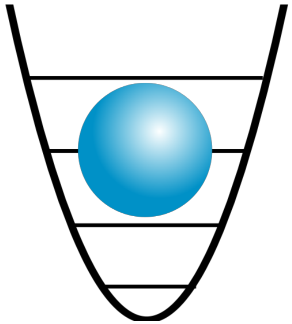

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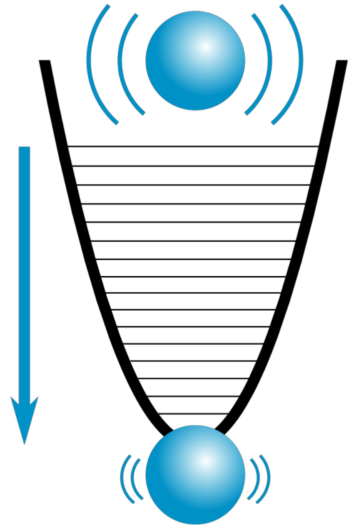
Center-of-mass cooling

- Nanoparticles are levitated at room temperature: $\sim 10^8 - 10^9$ phonons on average

- Reaching the quantum regime requires to bring the particle to its motional ground state, $\langle \hat{n} \rangle < 1$



- Despite initial proposals for cooling using a driven cavity, ground-state cooling still not achieved

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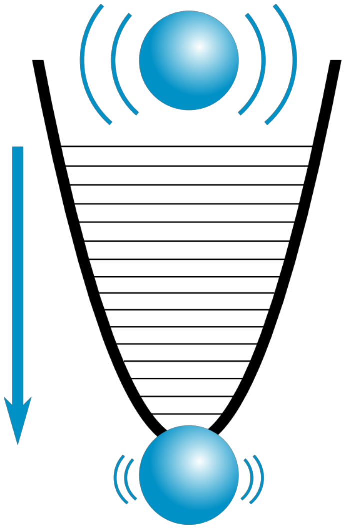

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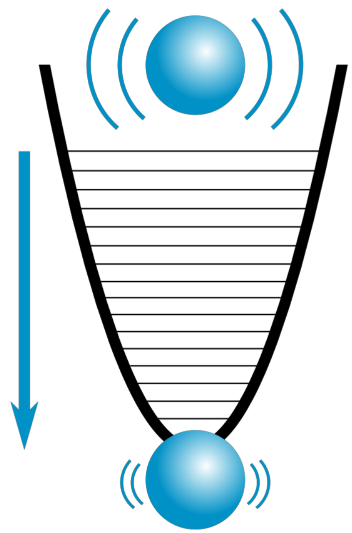

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  - Enhanced controllability
  - Cooling along the three motional axes
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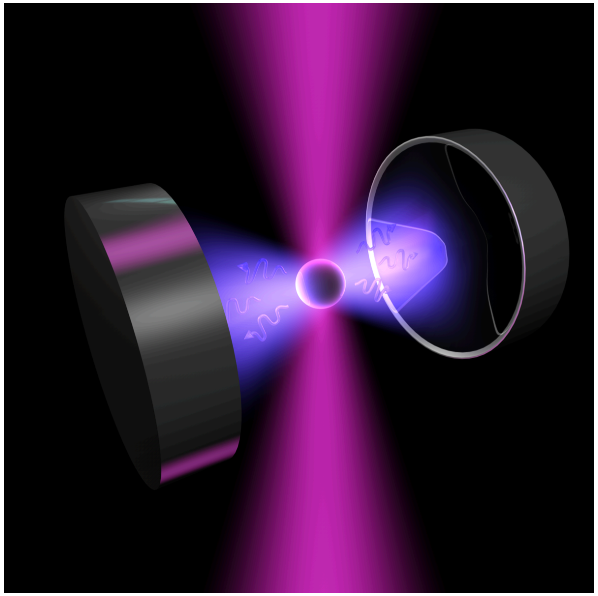

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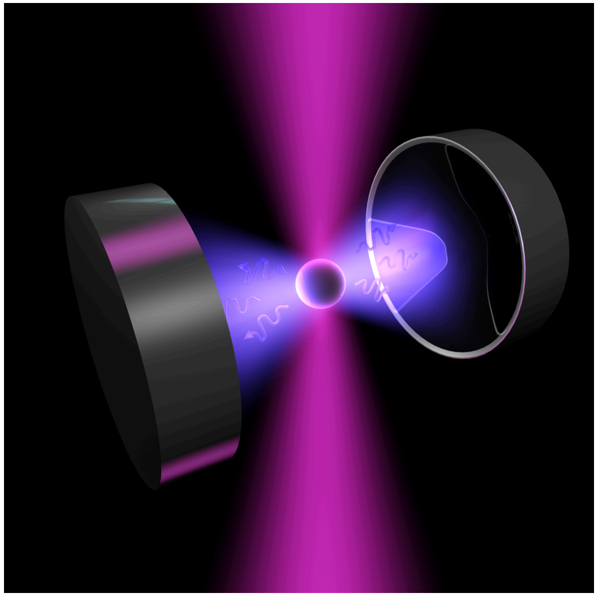

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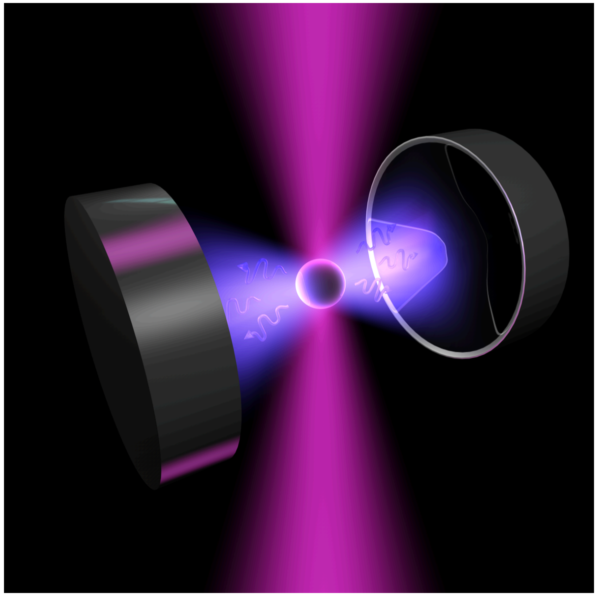

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Theory of center-of-mass cooling in a nutshell

- Interaction Hamiltonian (electric dipole approximation)

$$\hat{H} = \frac{\hat{\mathbf{P}}^2}{2m} + \frac{\varepsilon_0}{2}\int d^3\mathbf{r}\left[\hat{\mathbf{E}}^2(\mathbf{r}) + c^2\hat{\mathbf{B}}^2(\mathbf{r})\right] - \frac{1}{2}\alpha\hat{\mathbf{E}}^2(\hat{\mathbf{R}})$$

- Some approximations:
  - Lamb-Dicke regime
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  - Displaced frame + Linearization
- Trace out free field + exact solution of Master Equation

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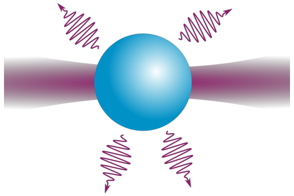

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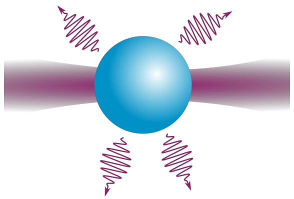

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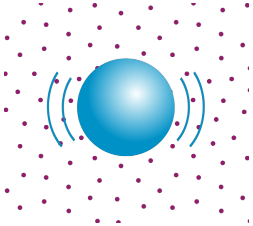

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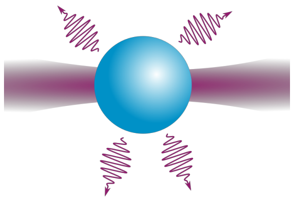

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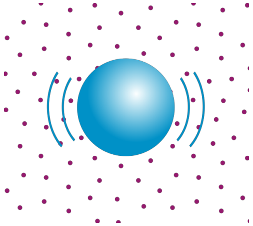

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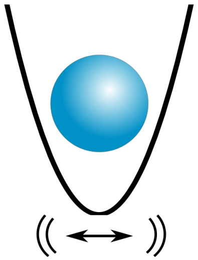

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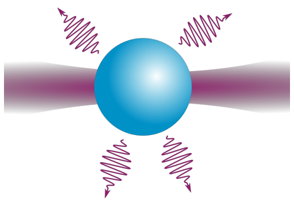

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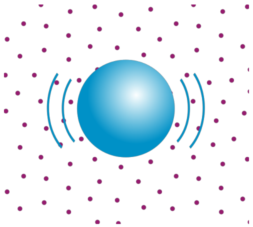

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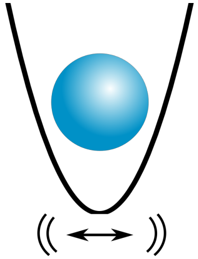
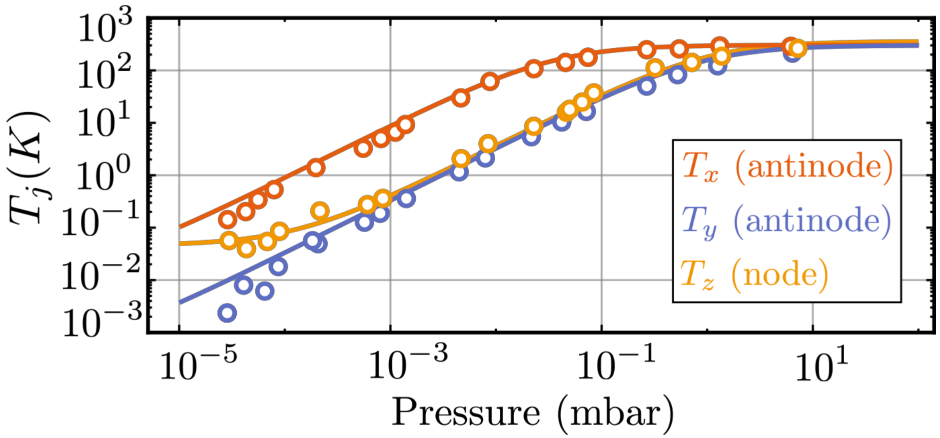


Trap displacement

- Quantitative fitting with experiments:



Center-of-mass cooling: conclusions

- Center of mass cooling via cavity-assisted coherent scattering is currently limited only by trap displacement noise.

- Our theoretical model allows to quantify this decoherence and compute the necessary vibrational isolation for reaching ground-state cooling

- Ground-state cooling is achievable by present experiments

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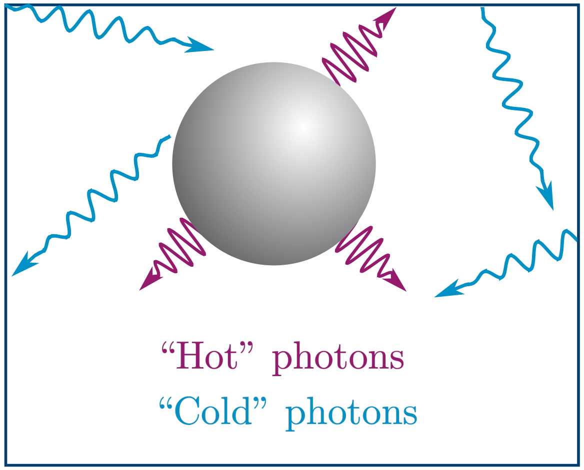

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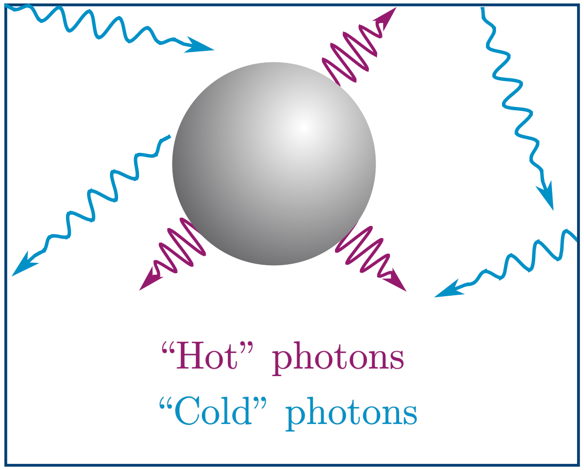

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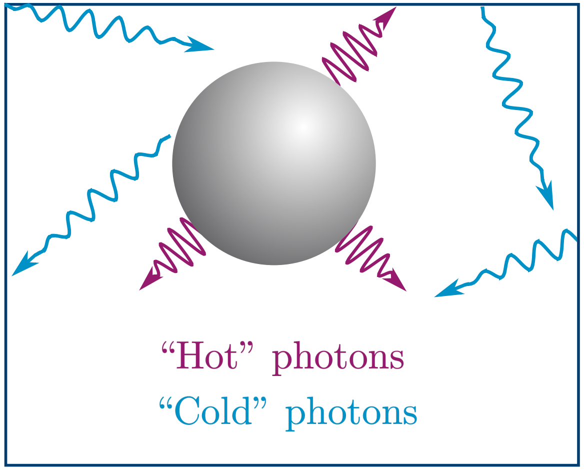

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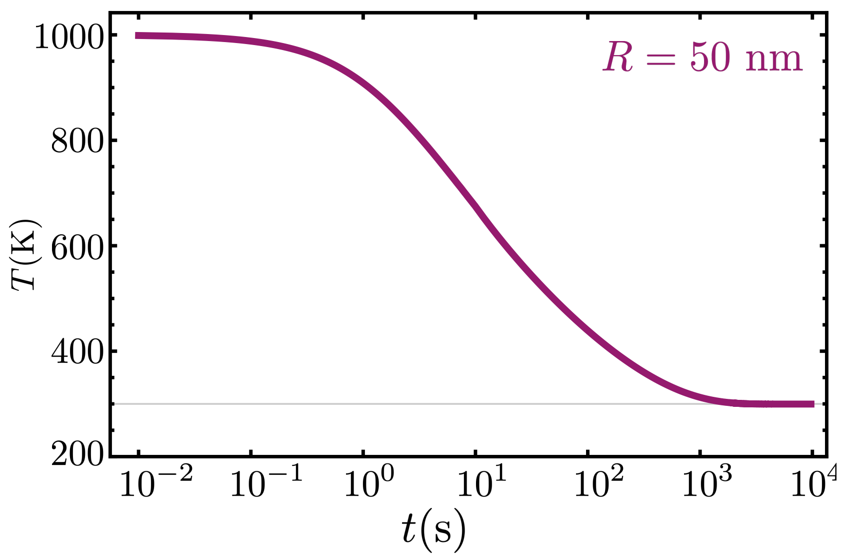

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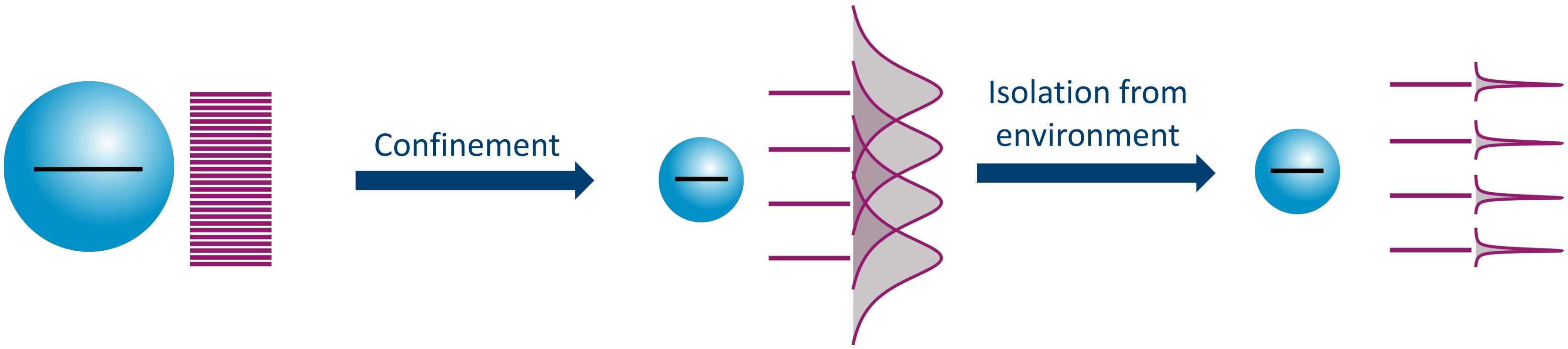

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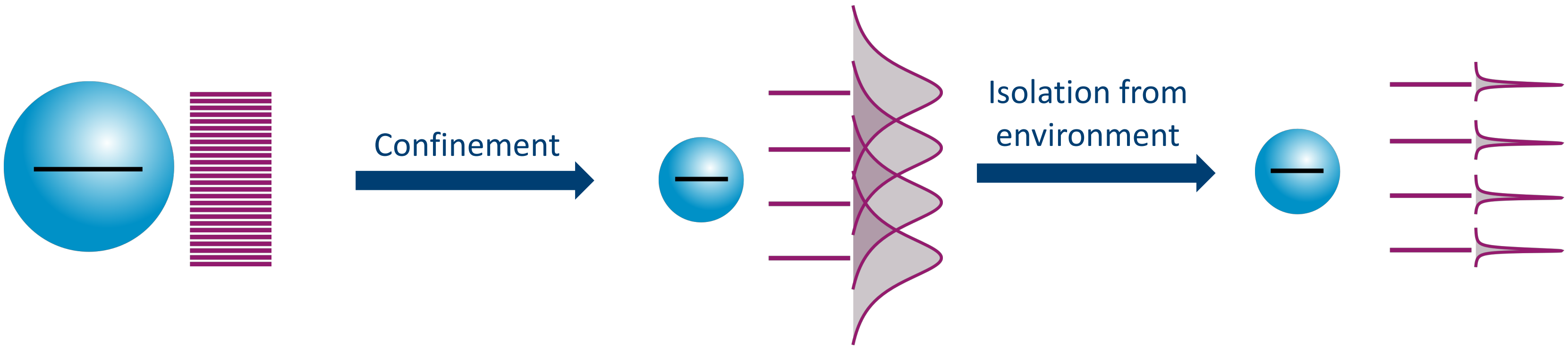

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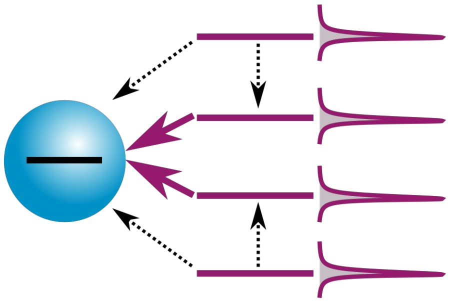

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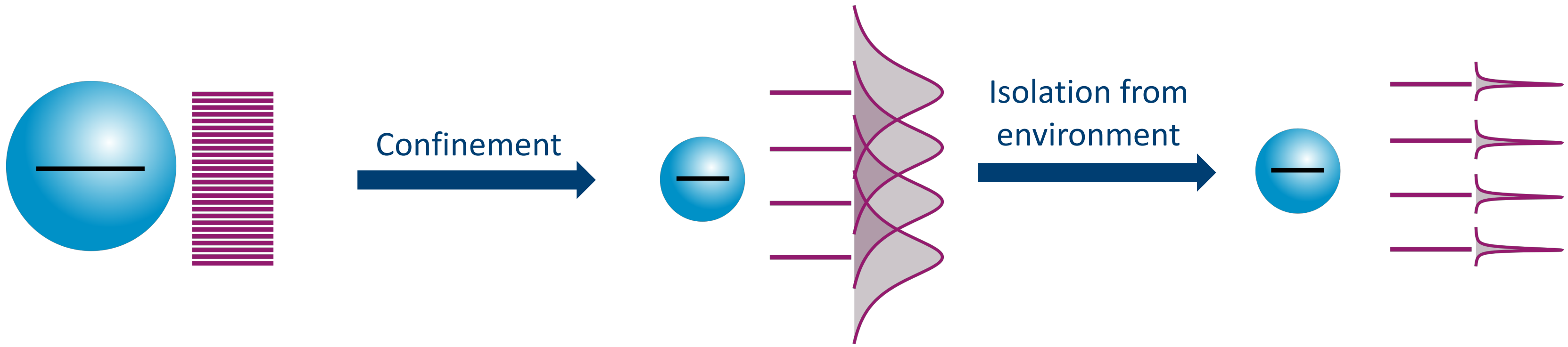

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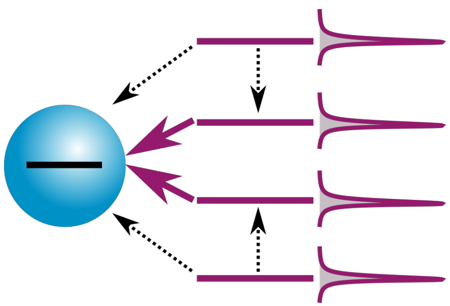

- For a levitated NP in high vacuum, quasi-equilibrium approximation should not hold

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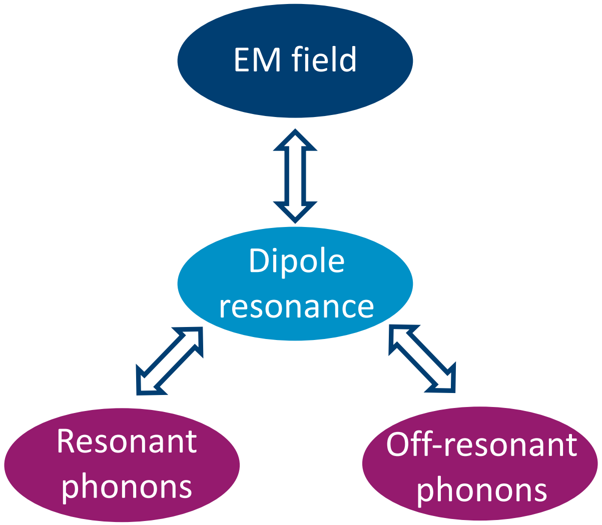
- We build a model based on harmonic oscillators



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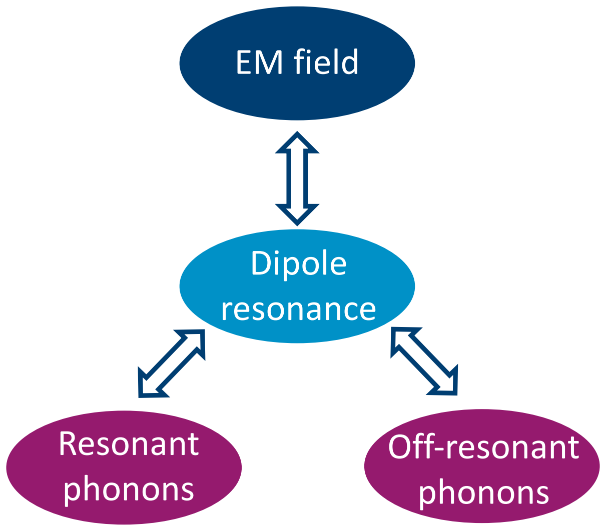

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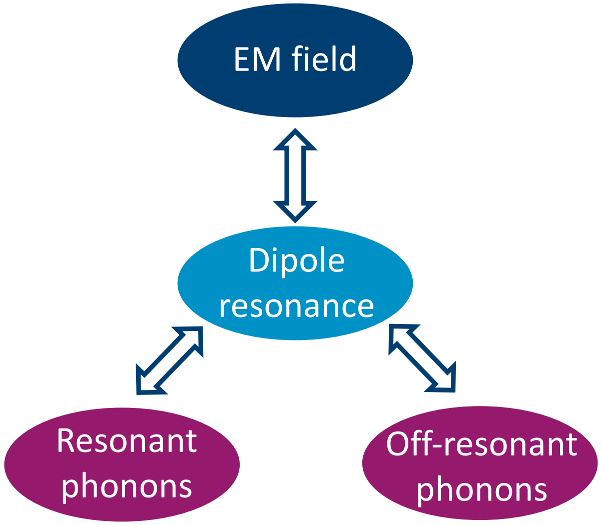
    - Specific heat
    - Thermalization timescale

Rubio-Lopez*, CGB* & Romero-Isart, PRB 98, 155405 (2018)

2. Radiative thermalization

- We build a model based on harmonic oscillators



- Exact solution using the closed-time path integral formalism

- All parameters matched to experimentally measurable quantities:
  - Polarizability
  - Specific heat
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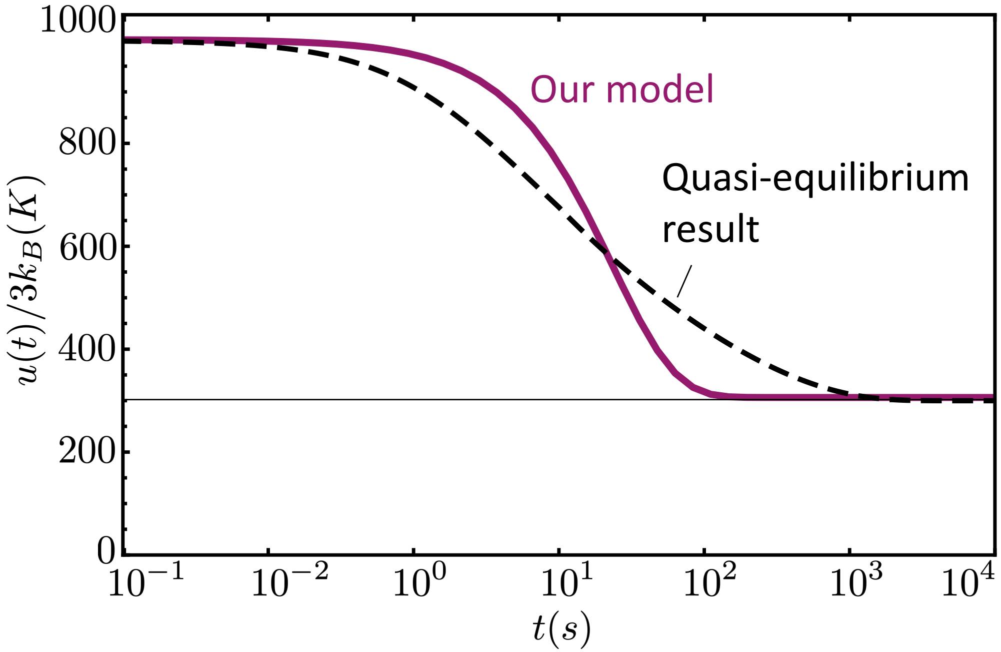
Rubio-Lopez*, CGB* & Romero-Isart, PRB 98, 155405 (2018)

2. Radiative thermalization

- Dynamics of the internal energy $u(t)$



Rubio-Lopez*, CGB* & Romero-Isart, PRB 98, 155405 (2018)

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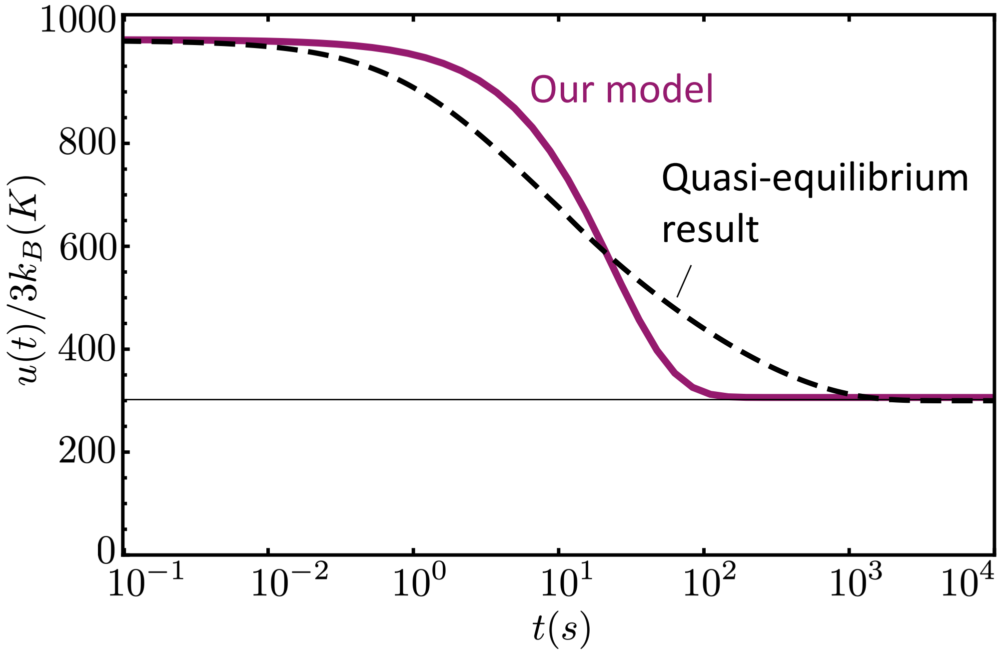

- Fundamentally different dynamics than FED (exponential vs polynomial)

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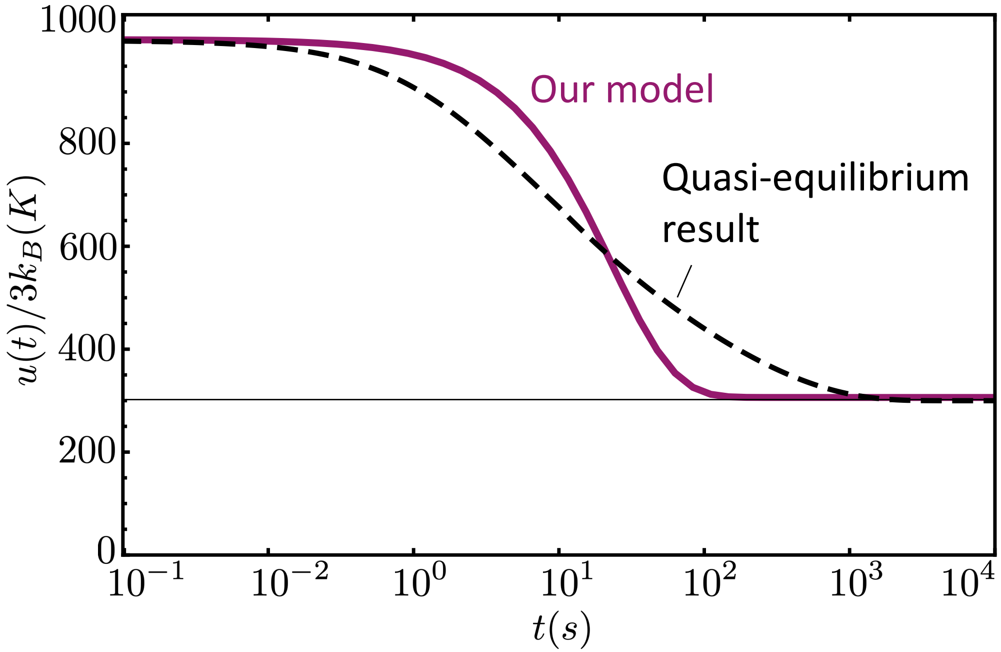

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Rubio-Lopez*, CGB* & Romero-Isart, PRB 98, 155405 (2018)

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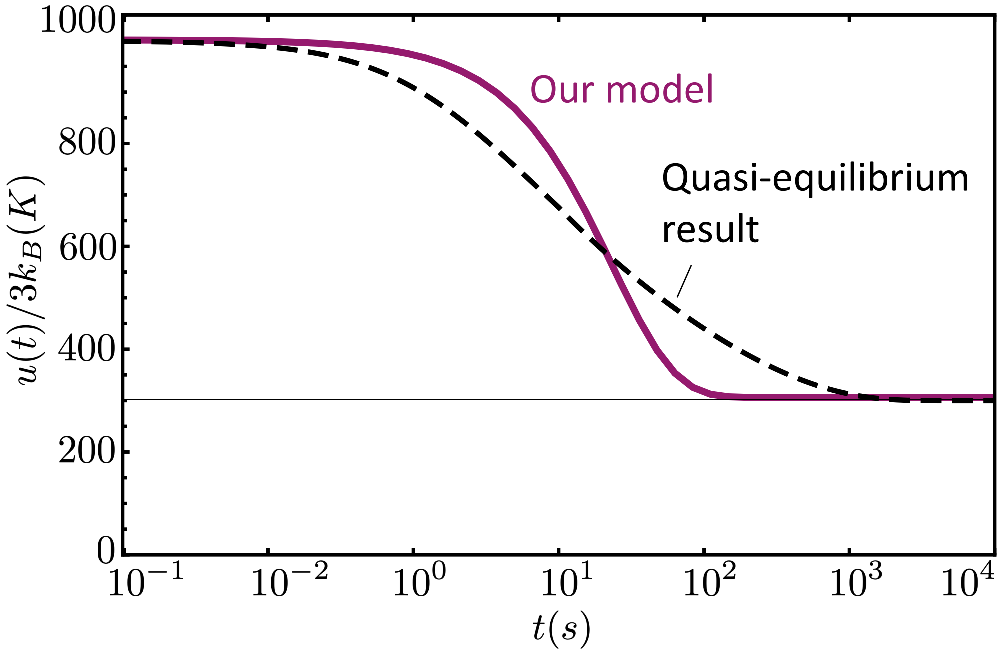


- Fundamentally different dynamics than FED (exponential vs polynomial)
- State of the system is never thermal: out-of-equilibrium thermalization
- Experimentally testable

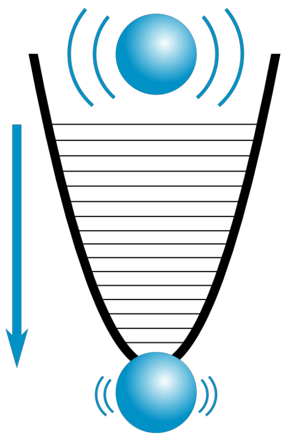
Rubio-Lopez*, CGB* & Romero-Isart, PRB 98, 155405 (2018)

Outline

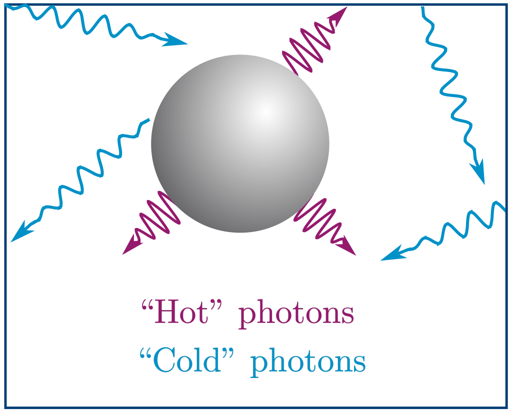
- Introduction to nanoparticle levitation
- New tools: center of mass cooling
- Fundamental questions: radiative thermalization
- Conclusion and outlook

3. Conclusions

1. Center-of-mass cooling



2. Internal dynamics



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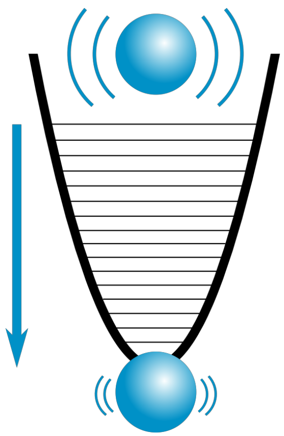

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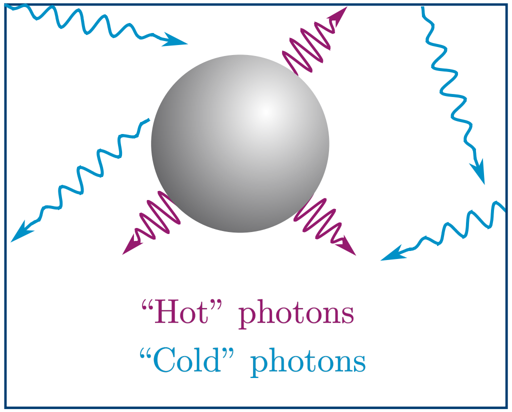

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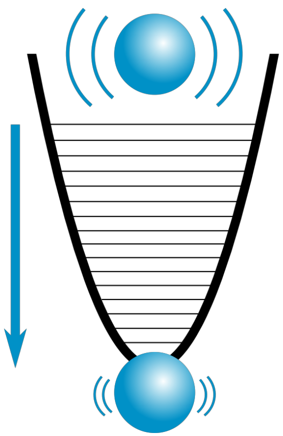

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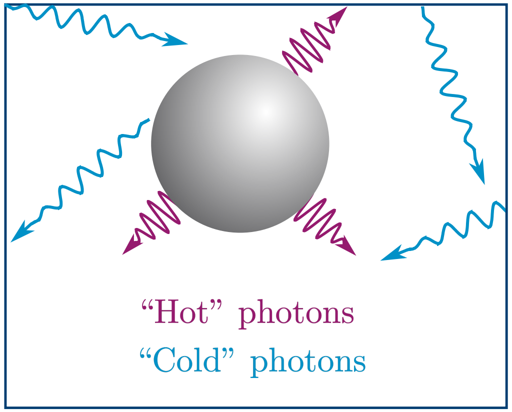

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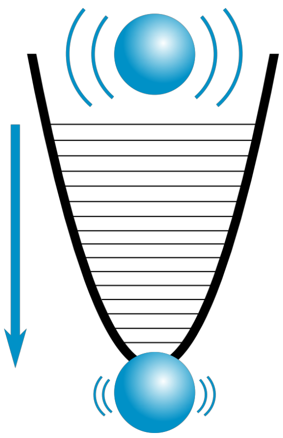

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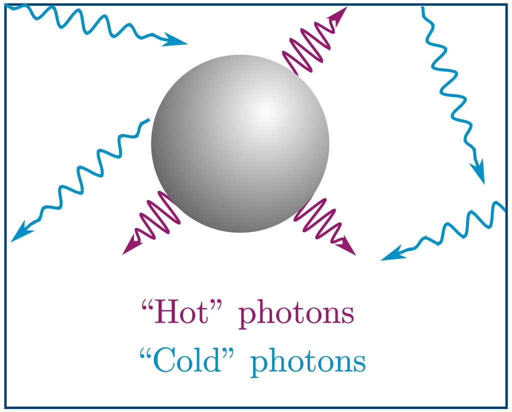

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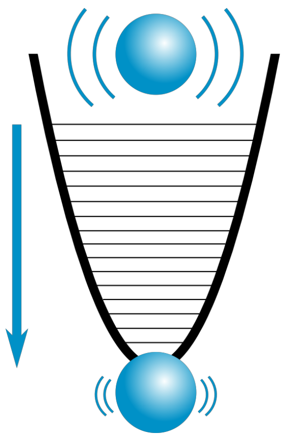

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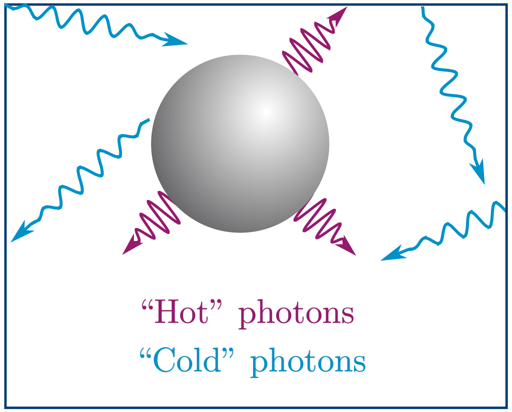


- Radiative thermalization is an out-of-equilibrium process in UHV levitodynamics

- New regime of matter?

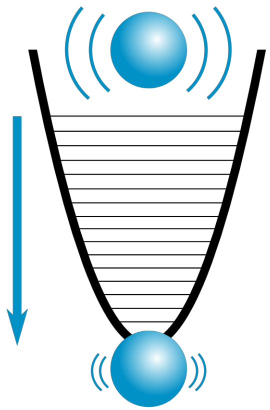
4. Outlook: new regimes of light and matter

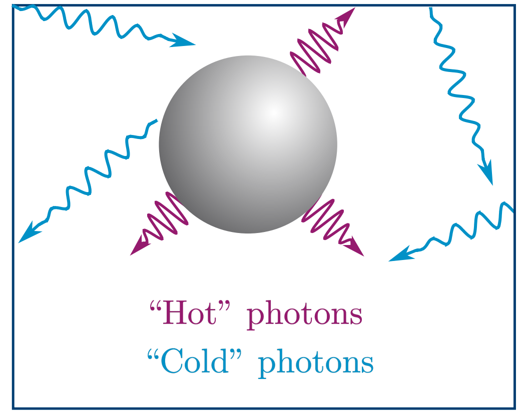
- Brillouin (photon-phonon-photon) scattering for measuring internal dynamics

- Strong magnon-phonon interaction in levitated nanomagnets

- And many more!

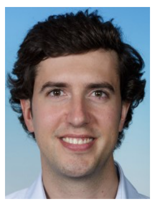
Thank you!






CGB


P. Maurer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Rubio López


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Marie Sklodowska
Curie program