

Entanglement of levitated nanoparticles by wave-packet dispersion

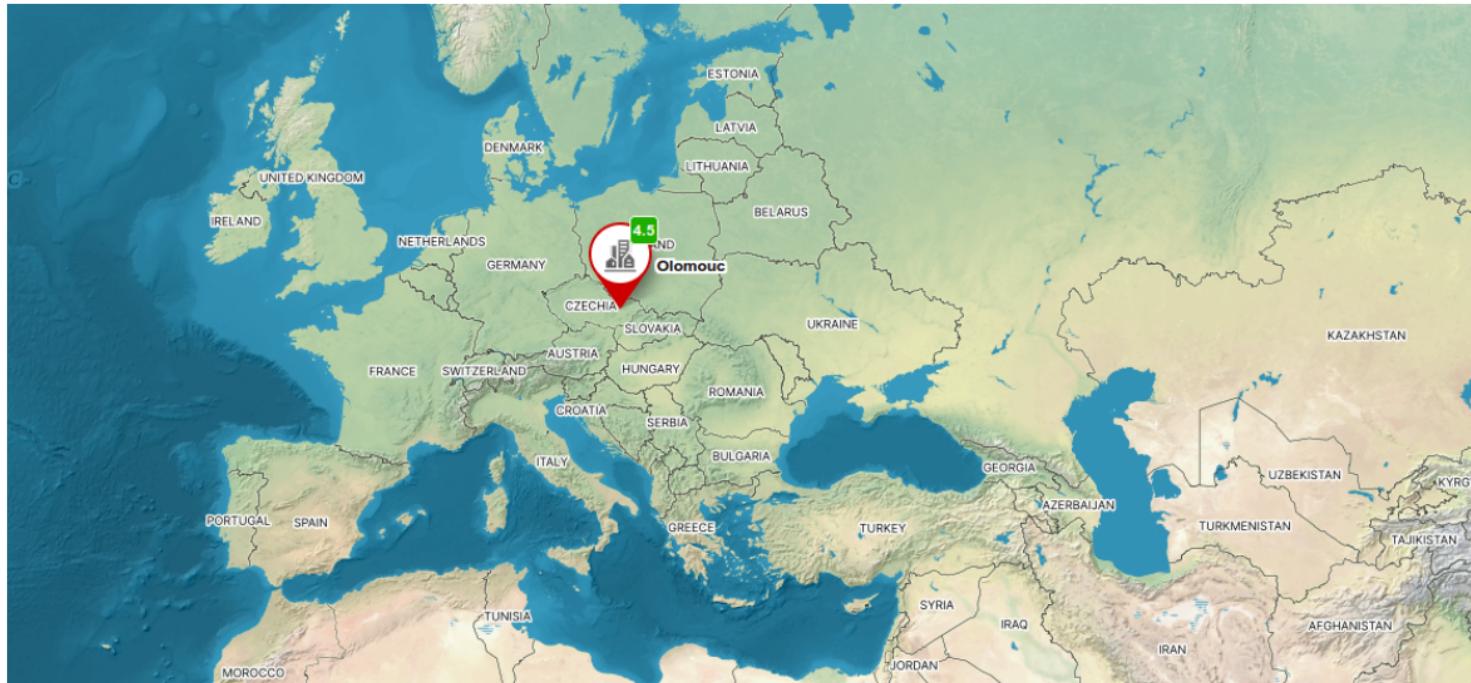
Andrey A. Rakhubovsky, Radim Filip

Department of Optics, Palacký University, Czech Republic

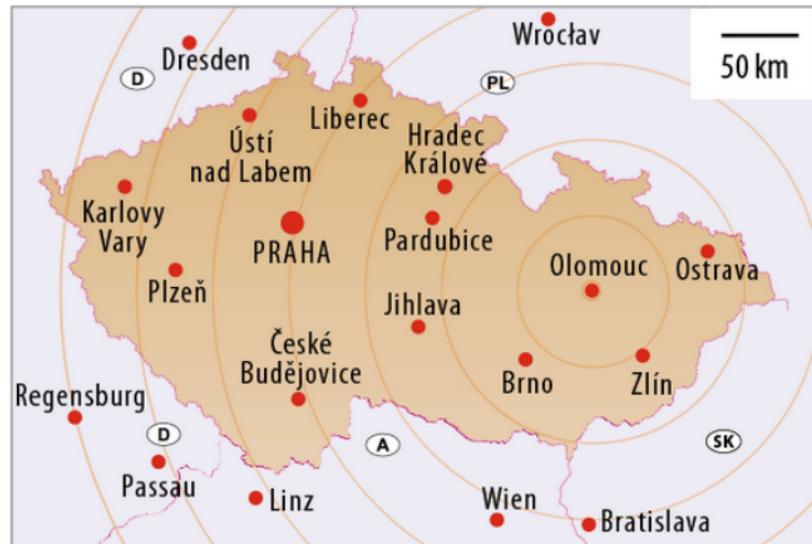
Quantum physics with trapped particles

Monte Verità

October 17, 2024







Radim Filip's Group in Olomouc [from 2022 video]

Radim Filip: Nonclassical and Quantum Non-gaussian States of Light and Matter

Palacký University Olomouc

NONGAUSS: TOPICS AND TEAM



Radim FILIP

Quantum Non-Gaussian States (2002) <u>Lukáš Lachman</u> Luca Innocenti Petr Zapletal Jitendra Verma	Quantum Non-Gaussian Optics (2005) <u>Petr Marek</u> Students: Jan Provazník Vojtěch Kala	Quantum Communication (2010) <u>Vladyslav Usenko</u> Ivan Derkach Students: Olena Kovalenko Akash Oruganti	Quantum Optomechanics (2014) <u>Andrey Rakhubovsky</u> Darren Moore <u>Ondřej Černotík</u> Anil Kumar Foroud Bemani Najme Etehadi Luca Ornigotti	Atoms and Trapped Ions (2015) <u>Alisa Manukhova</u> Darren Moore <u>Kimin Park</u> Pradip Laha Arpita Pal Students: Lukáš Podhora	Quantum Sensing and Estimation (2016) <u>Laszlo Ruppert</u> <u>Atirach Ritboon</u> Payman Mahmoudi Kimin Park Students: Eva Racz
					
					
					
					
					
					
					
					
					
					
					

1:22 / 36:41

The Optomechanics Group in Olomouc [within R. Filip's group]

Radim Filip



Alisa Manukhova



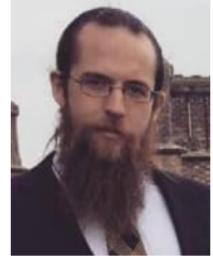
Foroud Bemani



Surabhi Yadav



Darren Moore



Najmeh Etehadi



Shaoni Datta



Lewis Clark



Now @KIT

Ph.D. and Postdoc positions available

Quantum non-Gaussian Everything



Progress in Quantum Electronics

Volume 93, January 2024, 100495



Quantum non-Gaussian optomechanics and electromechanics

Andrey A. Rakhubovsky  Darren W. Moore  Radim Filip  

40 pages, 487 references

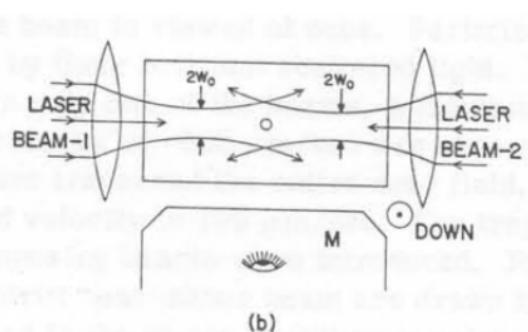
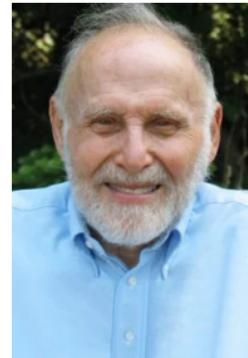
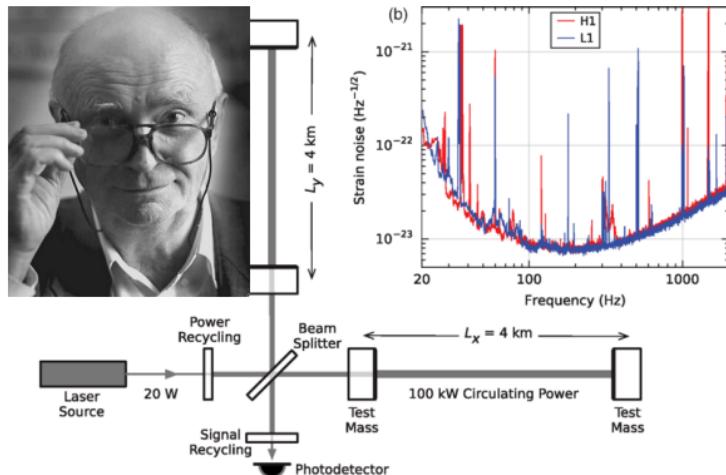
Introduction

Quantum Optomechanics
Levitated Optomechanics

Entanglement of Levitated Nanoparticles



Quantum Optomechanics

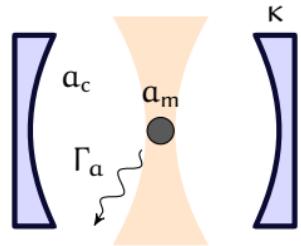


Braginsky & Manukin, Soviet JETP **25**, 653 (1967)
 Right img: B. P. Abbott et al., PRL **116**, 061102 (2016)

A. Ashkin, PRL **24**, 156 (1970)

$$H = \omega_{\text{mech}} a_m^\dagger a_m + \omega_{\text{cav}} a_L^\dagger a_L + g(a_m + a_m^\dagger)(a_L + a_L^\dagger).$$

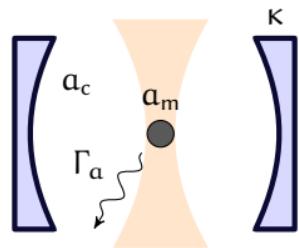
Levitated Optomechanics



The Hamiltonian

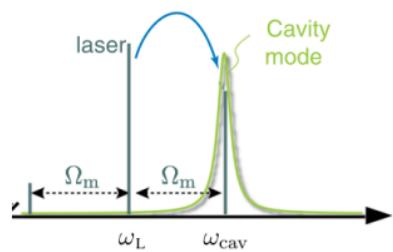
$$H = \frac{p_m^2}{2m} + V(q_m) + \omega_{\text{cav}} a_c^\dagger a_c + g q_m (a_c^\dagger + a_c).$$

Levitated Optomechanics



The Hamiltonian

$$H = \frac{p_m^2}{2m} + V(q_m) + \omega_{cav} a_c^\dagger a_c + g q_m (a_c^\dagger + a_c).$$



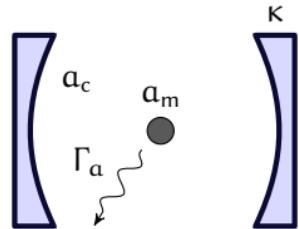
Conventional Interaction (Cooling)

$$H_{int} = g(a_c^\dagger a_m + a_c a_m^\dagger)$$

- ★ Cooling
- ★ Beam-splitter / State swap

M. Aspelmeyer *et al.*, Rev. Mod. Phys. **86**, 1391 (2014)

Levitated Optomechanics



The Hamiltonian

$$H = \frac{p_m^2}{2m} + \omega_{cav} a_c^\dagger a_c .$$

Free Fall

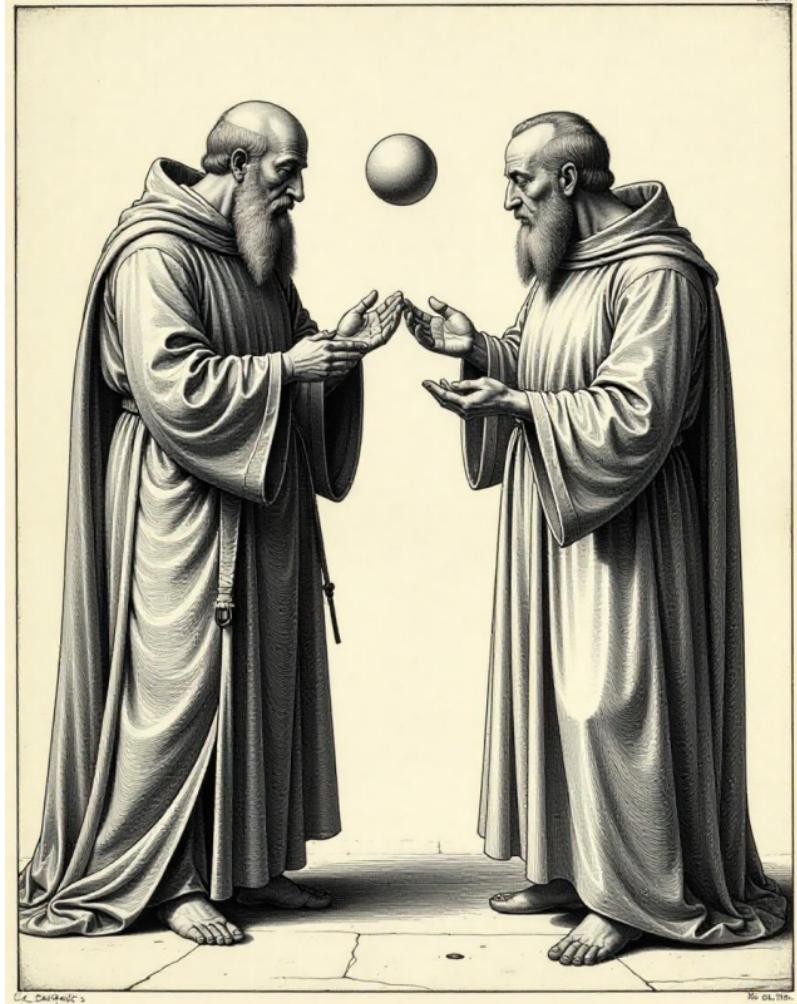
$$\begin{aligned} q &\mapsto q + p\tau, \\ p &\mapsto p. \end{aligned}$$

Squeezing!

Introduction

Quantum Optomechanics
Levitated Optomechanics

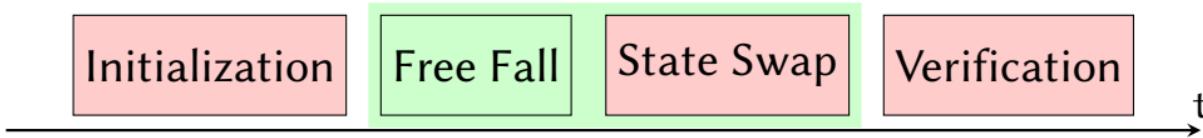
Entanglement of Levitated Nanoparticles



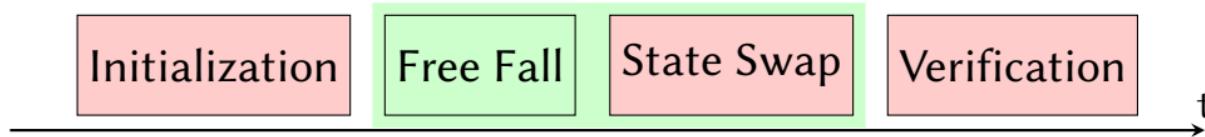
The Protocol



The Protocol

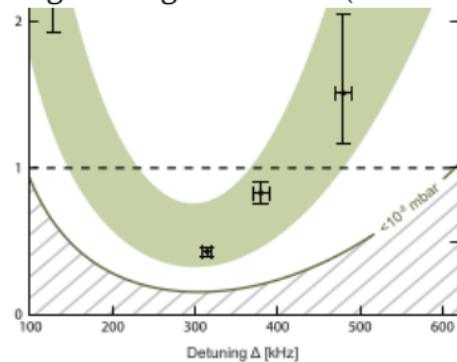


The Protocol



Initialization

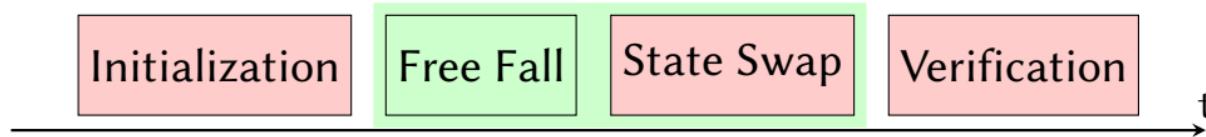
Cooling to the ground state ($\bar{n} = 0.43$)



U. Delić, Science 367, 892 (2020)

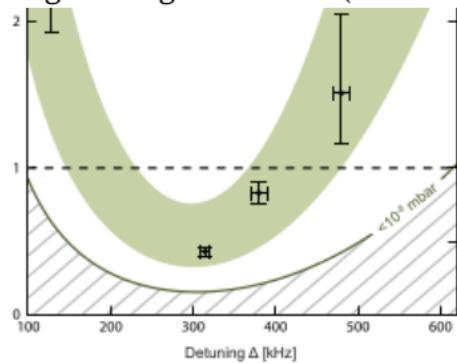
Avoid dark modes

The Protocol



Initialization

Cooling to the ground state ($\bar{n} = 0.43$)



Free Fall

Squeezing

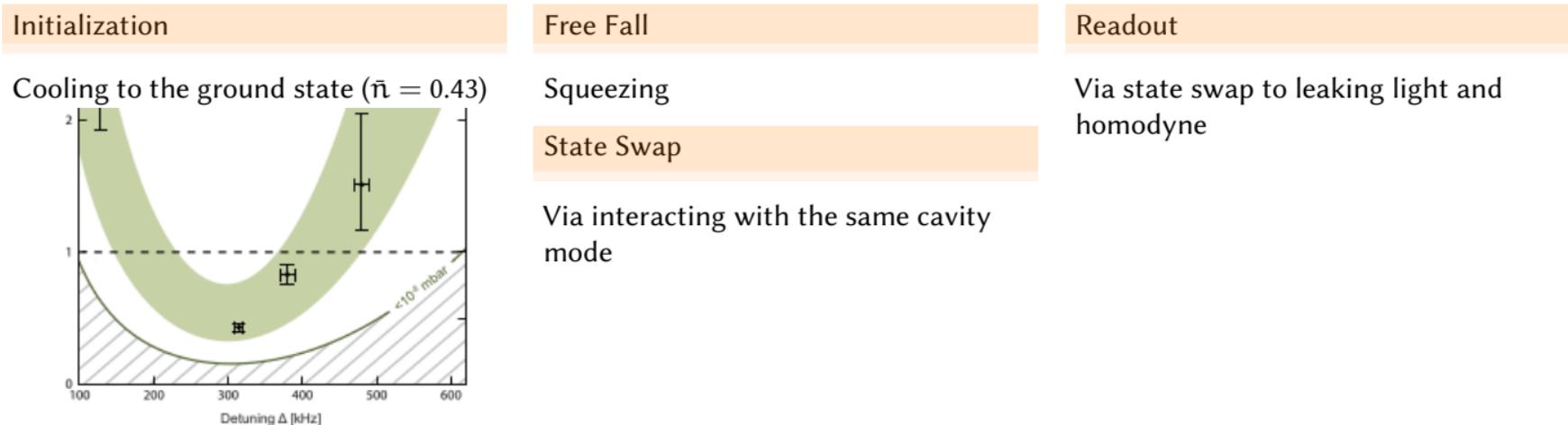
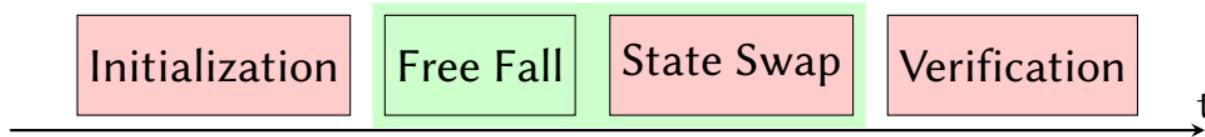
State Swap

Via interacting with the same cavity mode

U. Delić, Science 367, 892 (2020)

Avoid dark modes

The Protocol



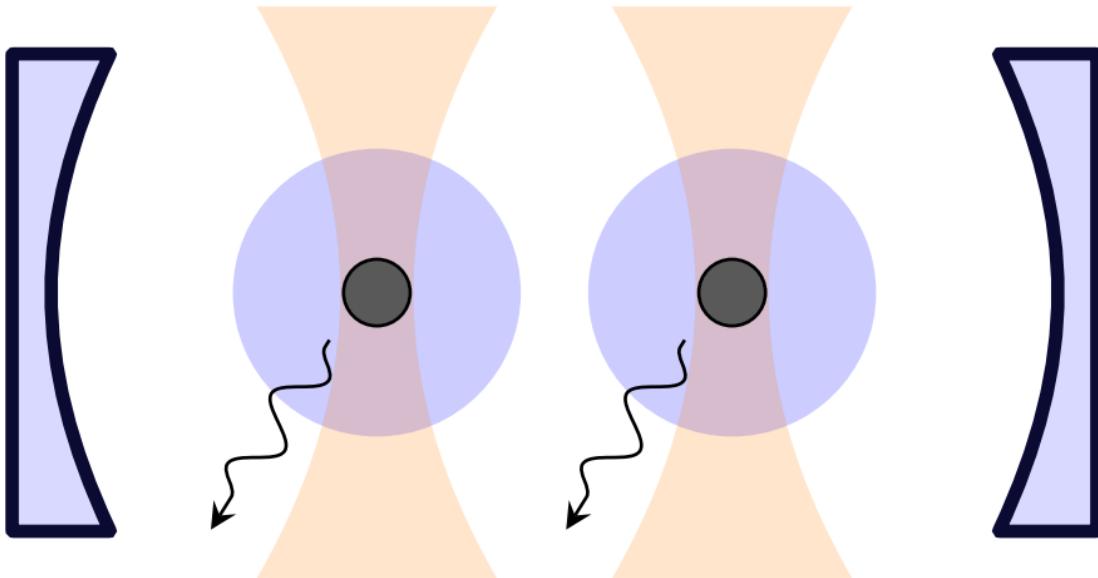
U. Delić, Science 367, 892 (2020)
Avoid dark modes

The Recipe

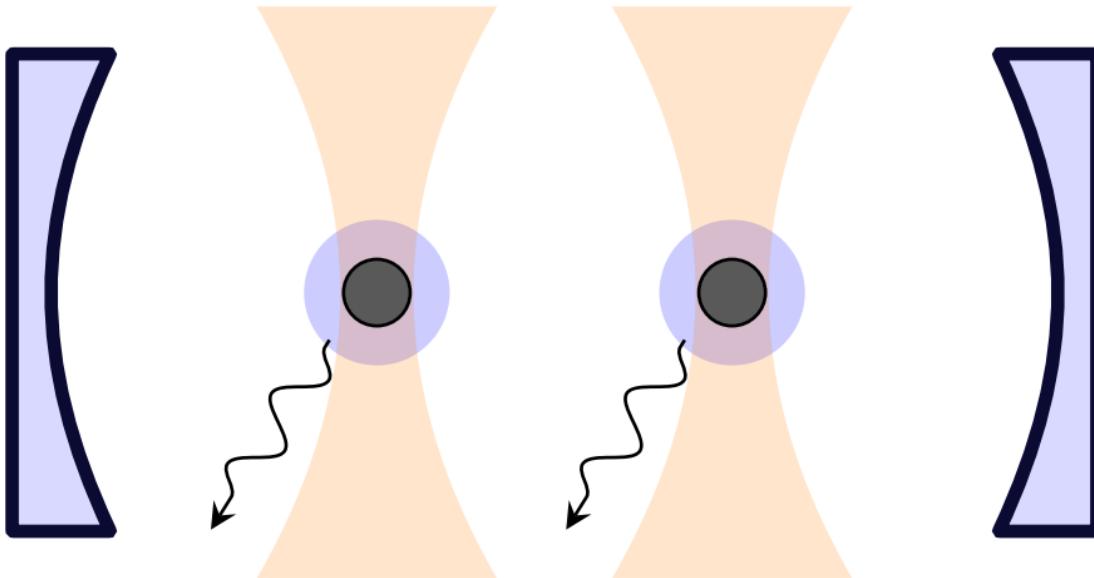


Tapeercarde tfe ainef fier thgitedrof op. 105

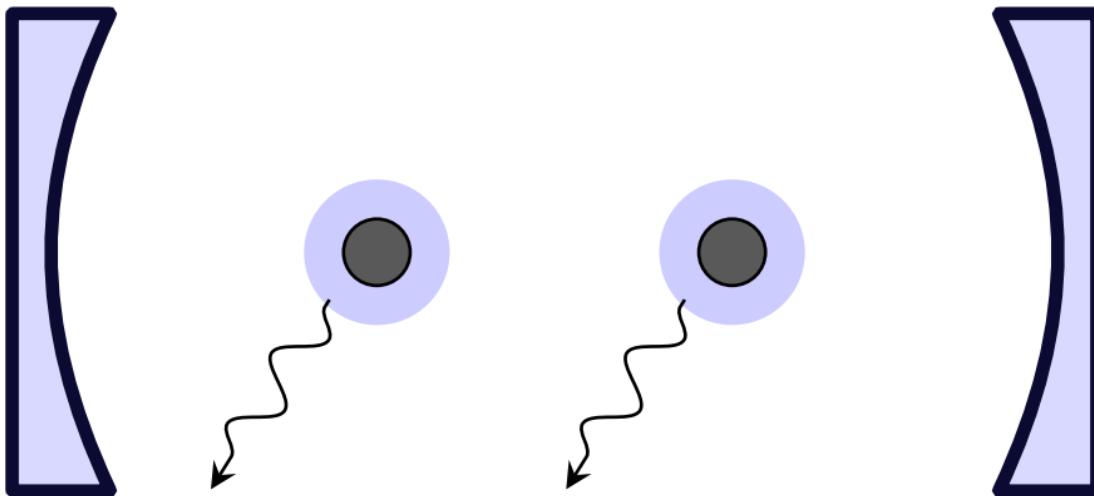
The Protocol



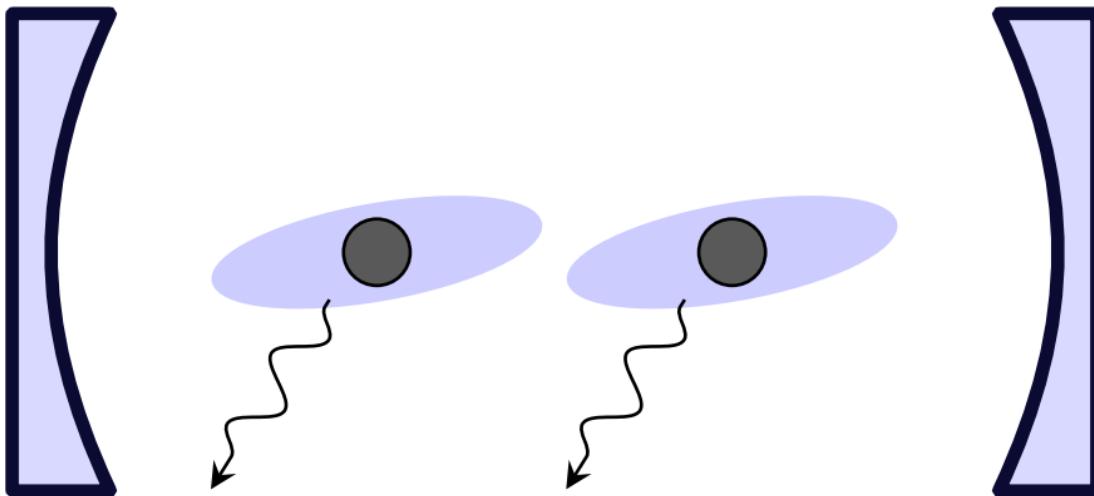
The Protocol



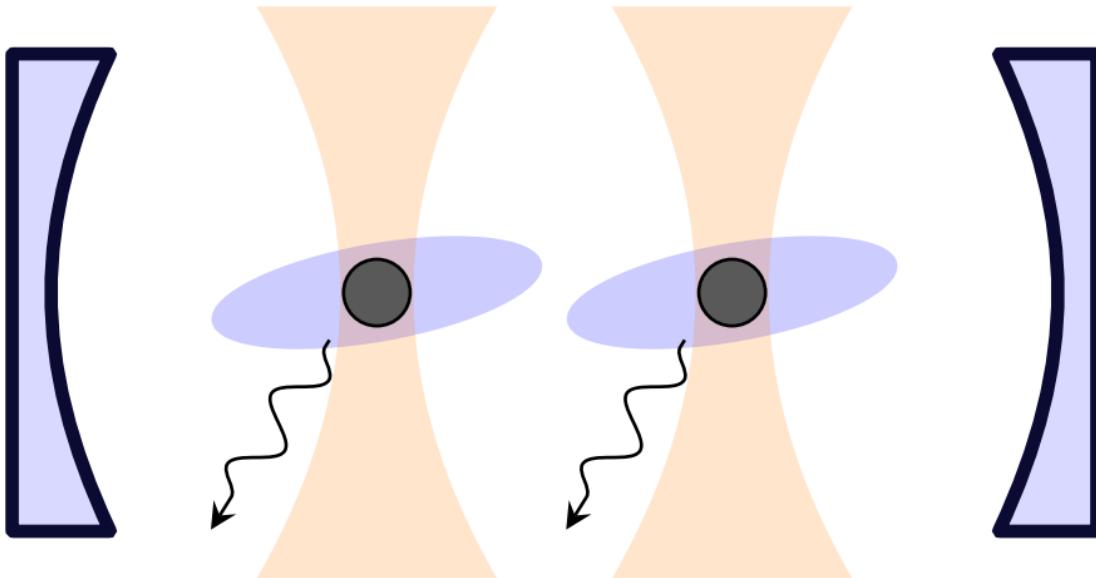
The Protocol



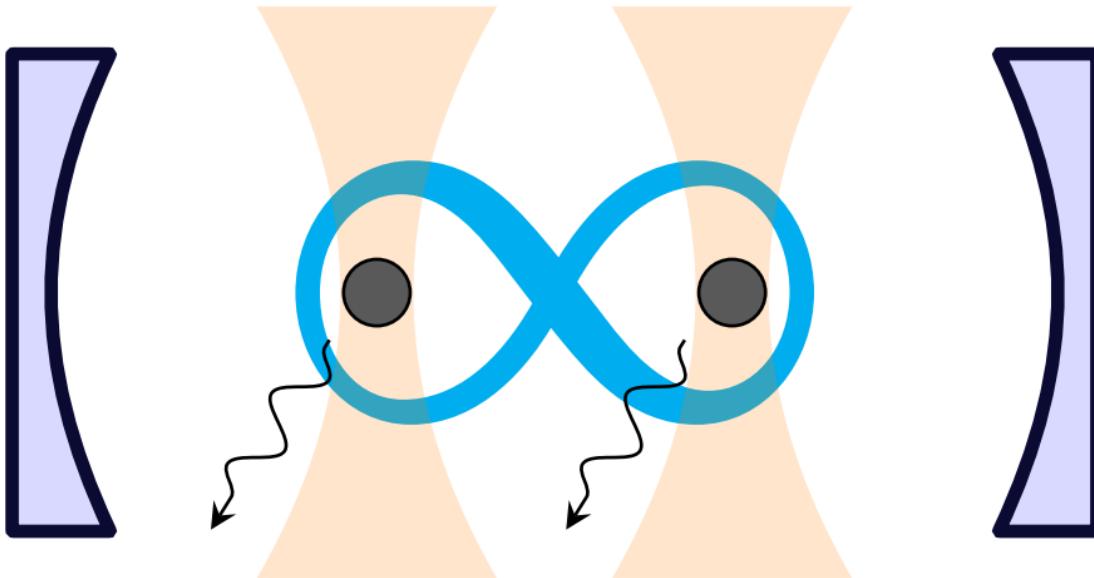
The Protocol



The Protocol



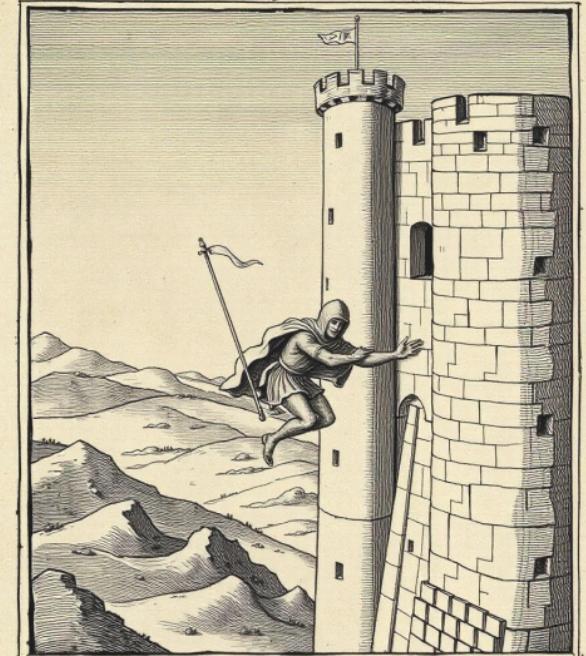
The Protocol



Free Fall

155

Mirce inyler Ducerleas."



Z buel just ten the hilt tile the casle and boddy fiast to pimes to the scare.

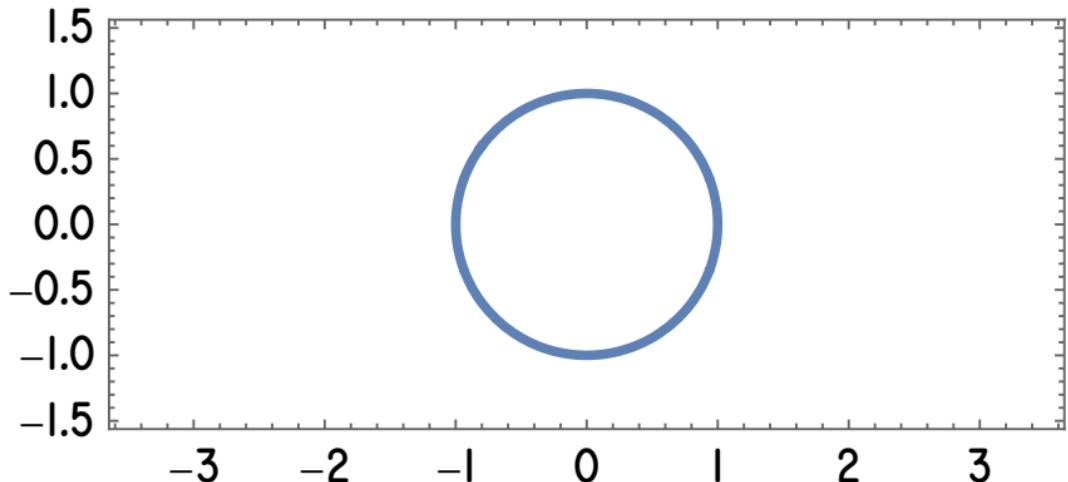
10981

2045

Free fall

$$H = \frac{\omega}{4}(p^2 + x^2) \mapsto \frac{\omega p^2}{4}$$

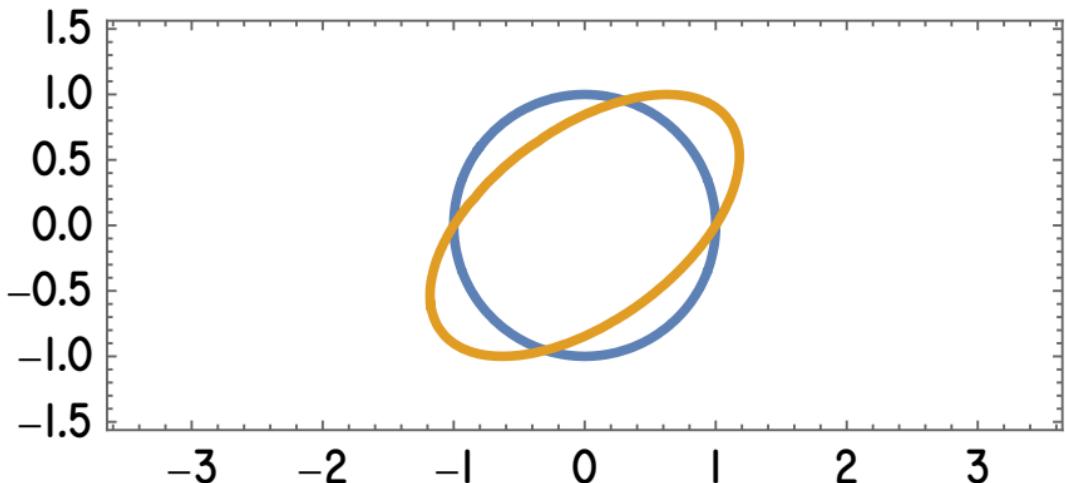
$$\begin{pmatrix} x(\tau) \\ p(\tau) \end{pmatrix} = \begin{pmatrix} x(0) + \omega\tau p(0) \\ p(0) \end{pmatrix}$$



Free fall

$$H = \frac{\omega}{4}(p^2 + x^2) \mapsto \frac{\omega p^2}{4}$$

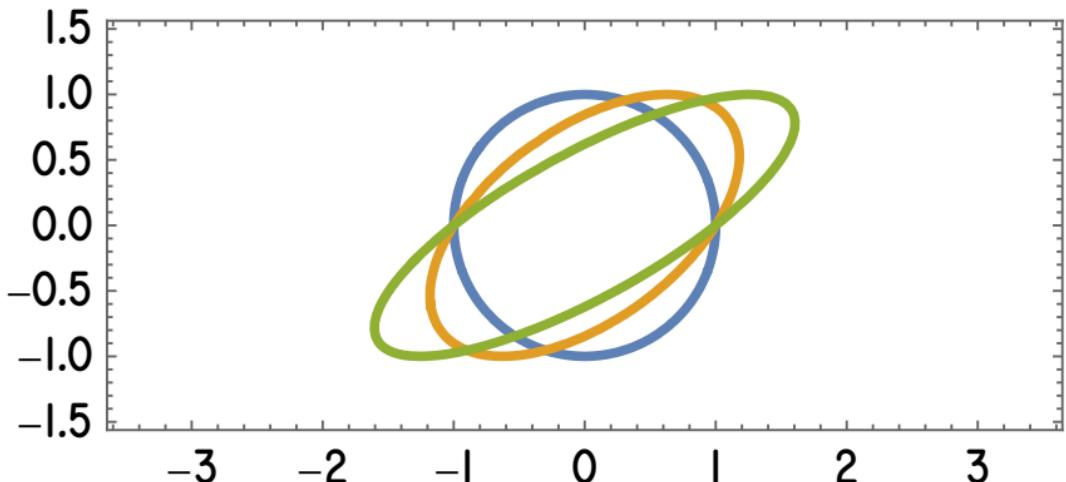
$$\begin{pmatrix} x(\tau) \\ p(\tau) \end{pmatrix} = \begin{pmatrix} x(0) + \omega\tau p(0) \\ p(0) \end{pmatrix}$$



Free fall

$$H = \frac{\omega}{4}(p^2 + x^2) \mapsto \frac{\omega p^2}{4}$$

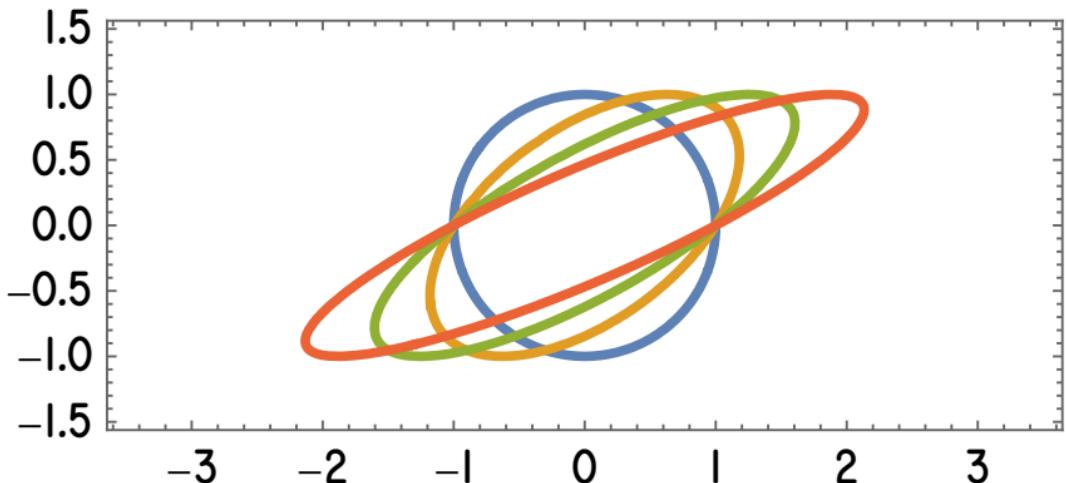
$$\begin{pmatrix} x(\tau) \\ p(\tau) \end{pmatrix} = \begin{pmatrix} x(0) + \omega\tau p(0) \\ p(0) \end{pmatrix}$$



Free fall

$$H = \frac{\omega}{4}(p^2 + x^2) \mapsto \frac{\omega p^2}{4}$$

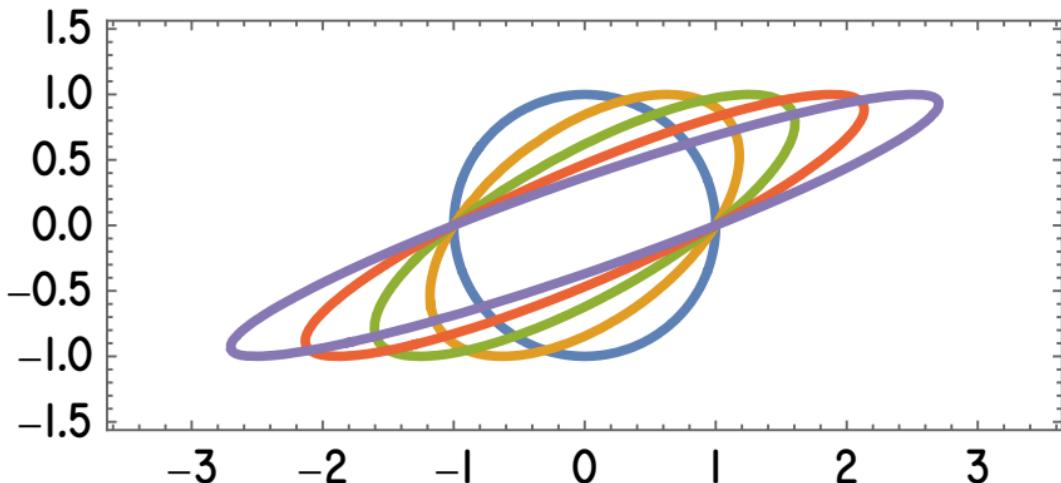
$$\begin{pmatrix} x(\tau) \\ p(\tau) \end{pmatrix} = \begin{pmatrix} x(0) + \omega\tau p(0) \\ p(0) \end{pmatrix}$$



Free fall

$$H = \frac{\omega}{4}(p^2 + x^2) \mapsto \frac{\omega p^2}{4}$$

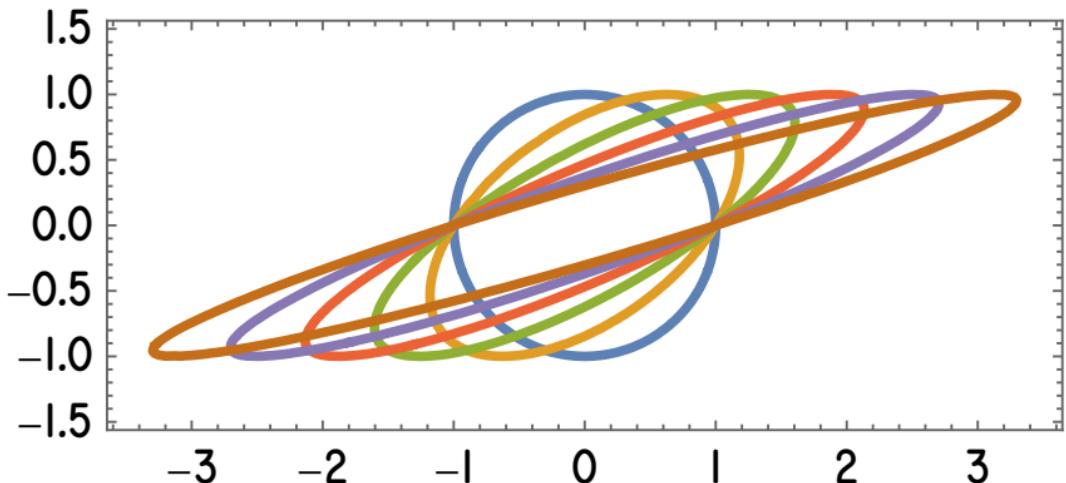
$$\begin{pmatrix} x(\tau) \\ p(\tau) \end{pmatrix} = \begin{pmatrix} x(0) + \omega\tau p(0) \\ p(0) \end{pmatrix}$$



Free fall

$$H = \frac{\omega}{4}(p^2 + x^2) \mapsto \frac{\omega p^2}{4}$$

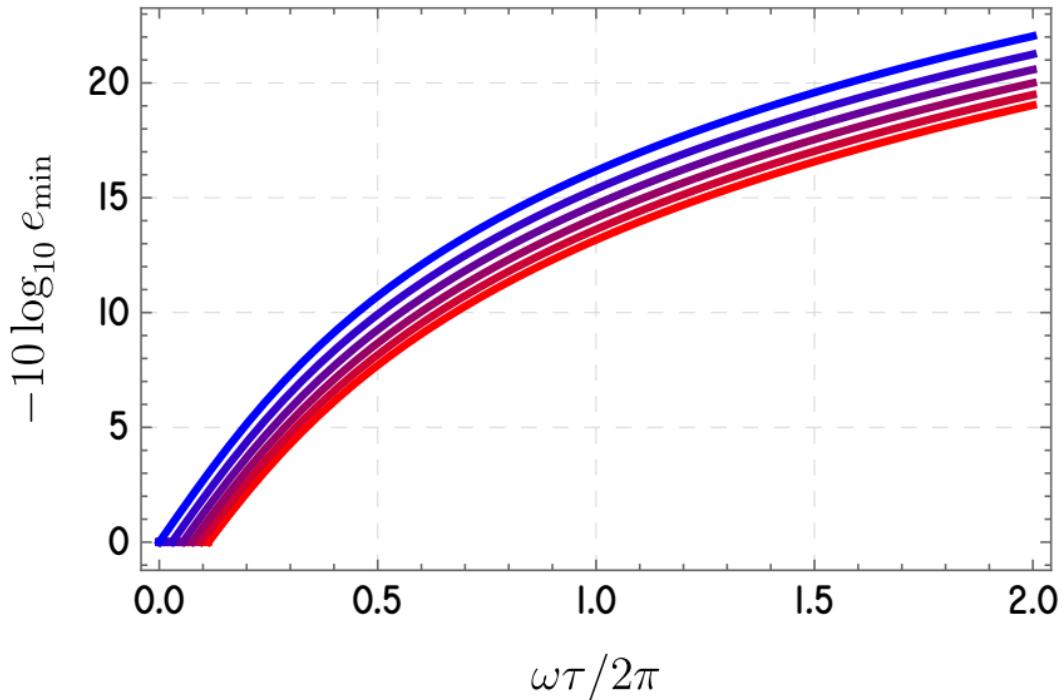
$$\begin{pmatrix} x(\tau) \\ p(\tau) \end{pmatrix} = \begin{pmatrix} x(0) + \omega\tau p(0) \\ p(0) \end{pmatrix}$$



Free fall

$$H = \frac{\omega}{4}(p^2 + x^2) \mapsto \frac{\omega p^2}{4}$$

$$\begin{pmatrix} x(\tau) \\ p(\tau) \end{pmatrix} = \begin{pmatrix} x(0) + \omega\tau p(0) \\ p(0) \end{pmatrix}$$

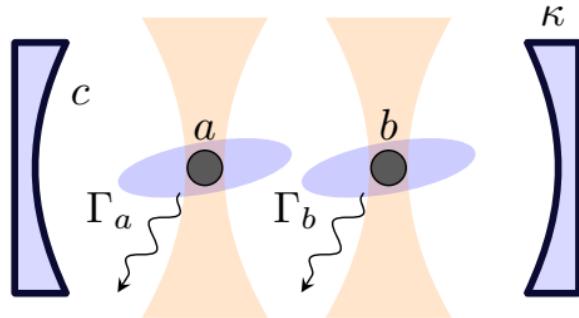


Free Fall



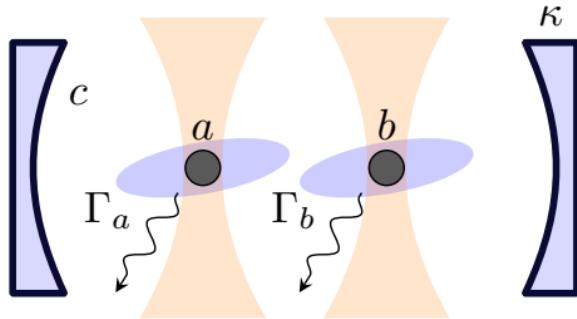
State Swap

$$H = c^\dagger(g_a a + g_b b e^{i\phi}) + \text{h.c.}$$



State Swap

$$H = c^\dagger(g_a a + g_b b e^{i\phi}) + \text{h.c.}$$



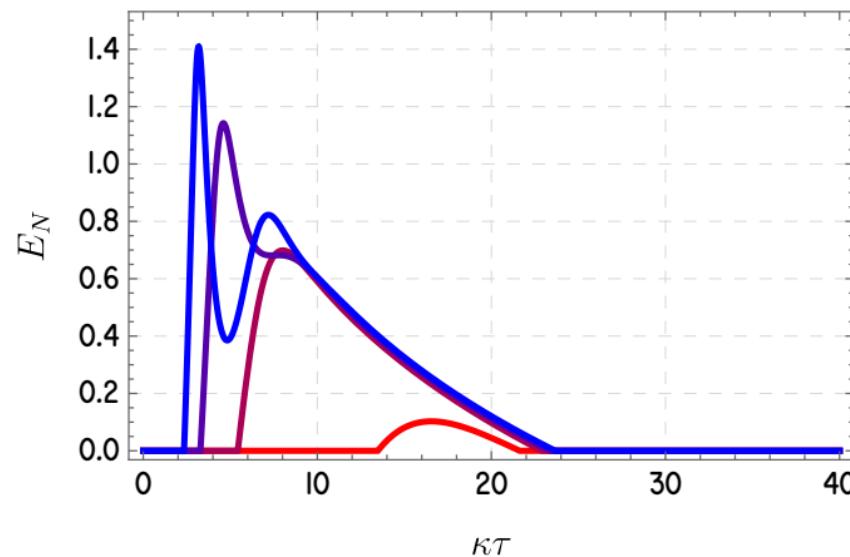
Most parameters from
U. Delić, Science 367, 892 (2020)

There:

- ★ Recoil heating $\Gamma/\kappa = 0.06$
- ★ Cooling to $n_0 = 0.43$
- ★ Linearized coupling $g/\kappa \leq 0.62$

Logarithmic negativity E_N

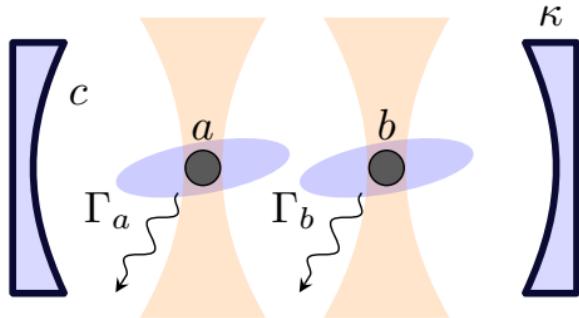
$$\Gamma = 0.02\kappa, n_0 = 0.1, \omega\tau = 4\pi$$



Color: coupling rate $0.3 \leq \frac{g}{\kappa} \leq 0.6$.

State Swap

$$H = c^\dagger(g_a a + g_b b e^{i\phi}) + \text{h.c.}$$



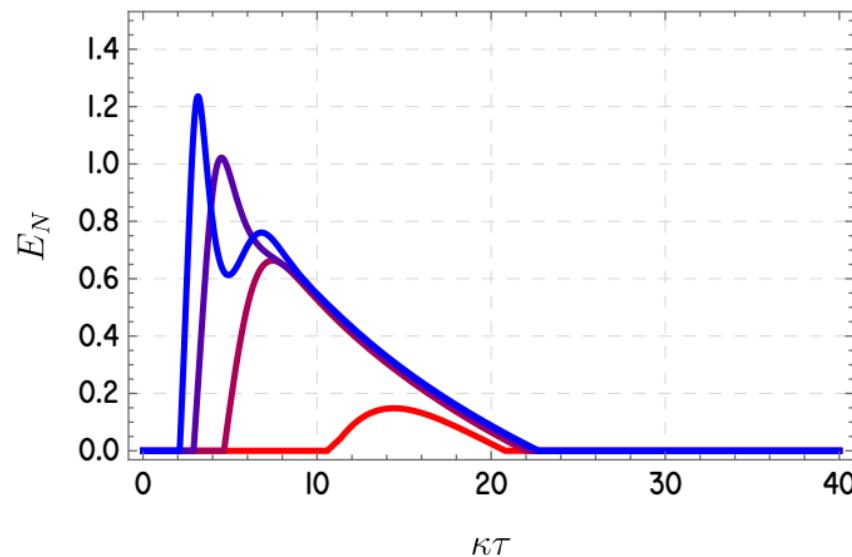
Most parameters from
U. Delić, Science 367, 892 (2020)

There:

- ★ Recoil heating $\Gamma/\kappa = 0.06$
- ★ Cooling to $n_0 = 0.43$
- ★ Linearized coupling $g/\kappa \leq 0.62$

Logarithmic negativity E_N

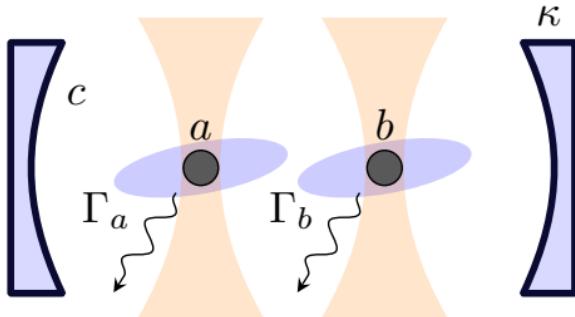
$$\Gamma = 0.02\kappa, n_0 = 0.43, \omega\tau = 2\pi$$



Color: coupling rate $0.3 \leq \frac{g}{\kappa} \leq 0.6$.

State Swap

$$H = c^\dagger(g_a a + g_b b e^{i\phi}) + \text{h.c.}$$

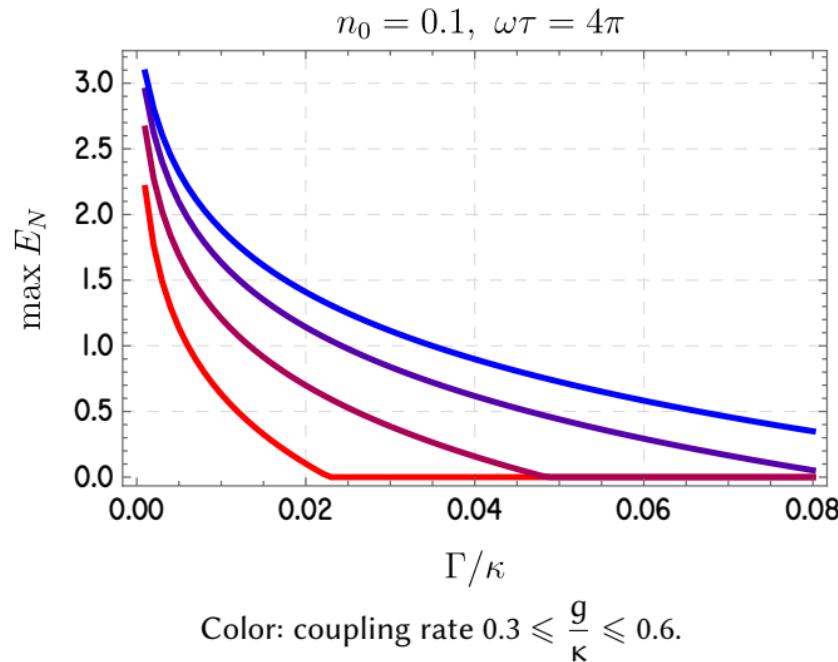


Most parameters from
U. Delić, Science 367, 892 (2020)

There:

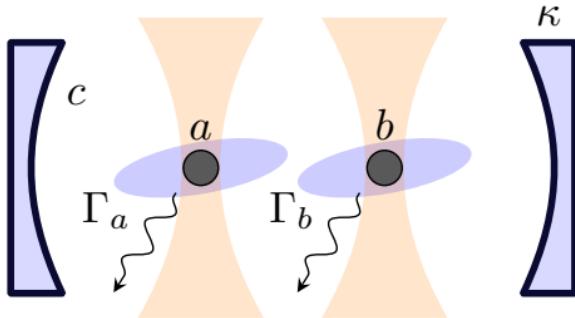
- ★ Recoil heating $\Gamma/\kappa = 0.06$
- ★ Cooling to $n_0 = 0.43$
- ★ Linearized coupling $g/\kappa \leq 0.62$

Logarithmic negativity E_N



State Swap

$$H = c^\dagger(g_a a + g_b b e^{i\phi}) + \text{h.c.}$$

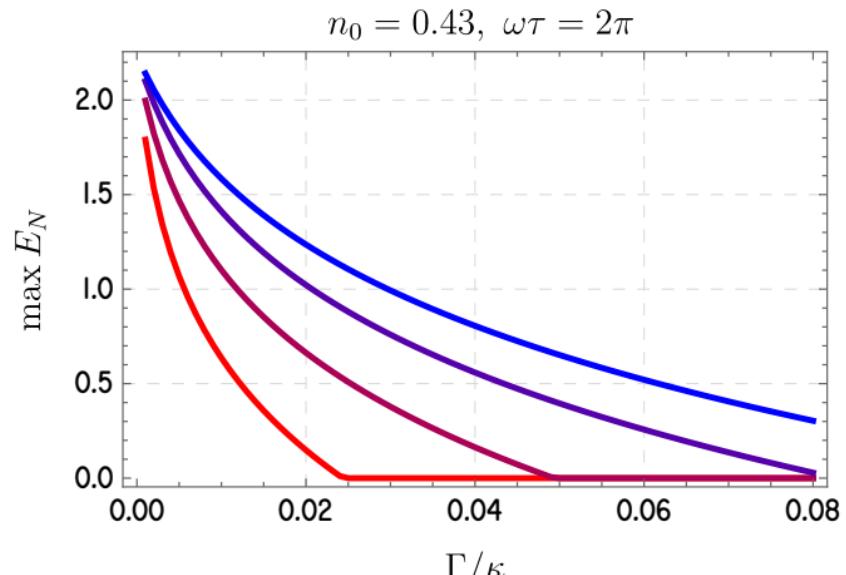


Most parameters from
U. Delić, Science 367, 892 (2020)

There:

- ★ Recoil heating $\Gamma/\kappa = 0.06$
- ★ Cooling to $n_0 = 0.43$
- ★ Linearized coupling $g/\kappa \leq 0.62$

Logarithmic negativity E_N



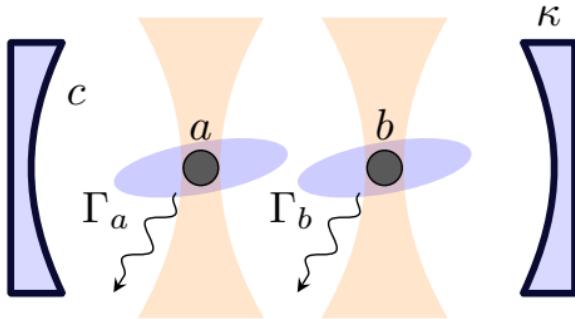
Color: coupling rate $0.3 \leq \frac{g}{\kappa} \leq 0.6$.

Free Fall



Non-identical particles

$$H = c^\dagger(g_a a + g_b b e^{i\phi}) + \text{h.c.}$$

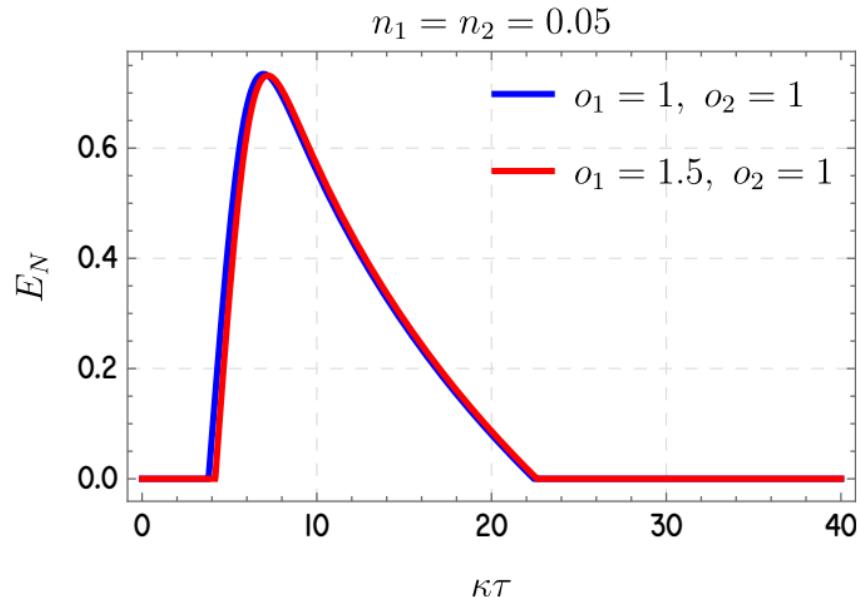


Most parameters from
U. Delić, Science 367, 892 (2020)

There:

- ★ Recoil heating $\Gamma/\kappa = 0.06$
- ★ Cooling to $n_0 = 0.43$
- ★ Linearized coupling $g/\kappa \leq 0.62$

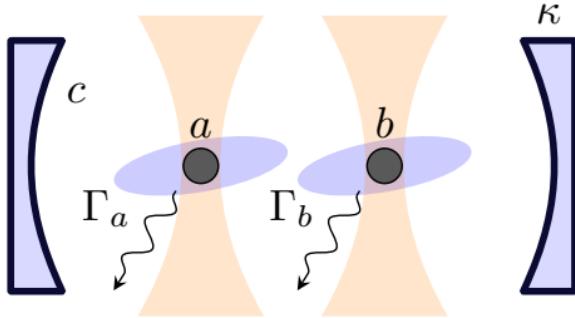
Logarithmic negativity E_N



$$o_i \equiv \frac{\omega_i \tau}{2\pi}$$

Non-identical particles

$$H = c^\dagger(g_a a + g_b b e^{i\phi}) + \text{h.c.}$$

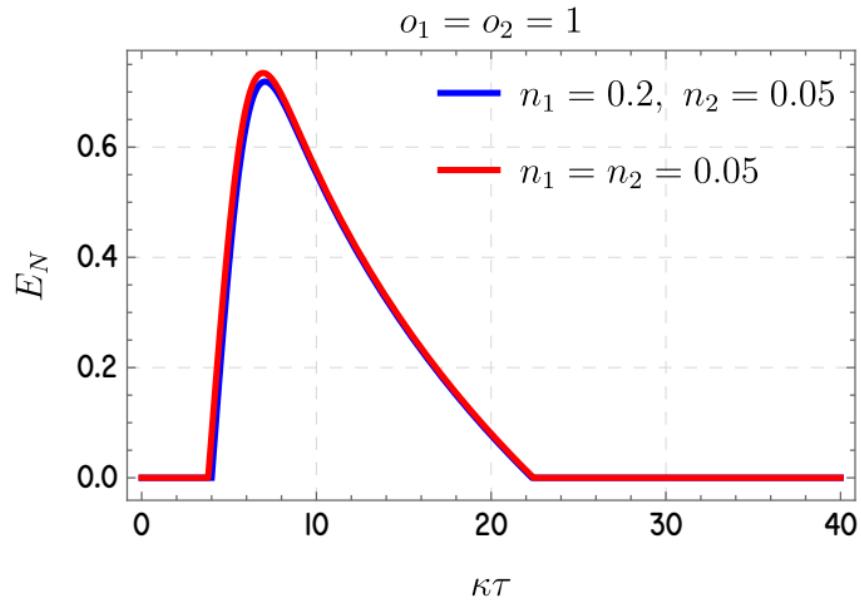


Most parameters from
U. Delić, Science 367, 892 (2020)

There:

- ★ Recoil heating $\Gamma/\kappa = 0.06$
- ★ Cooling to $n_0 = 0.43$
- ★ Linearized coupling $g/\kappa \leq 0.62$

Logarithmic negativity E_N

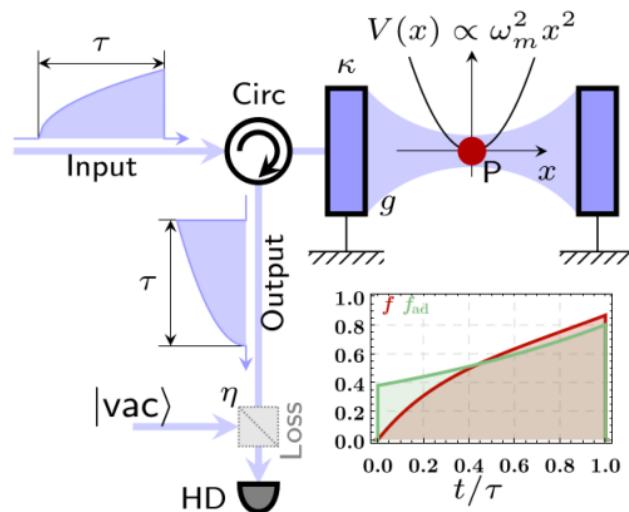


$$o_i \equiv \frac{\omega_i \tau}{2\pi}$$

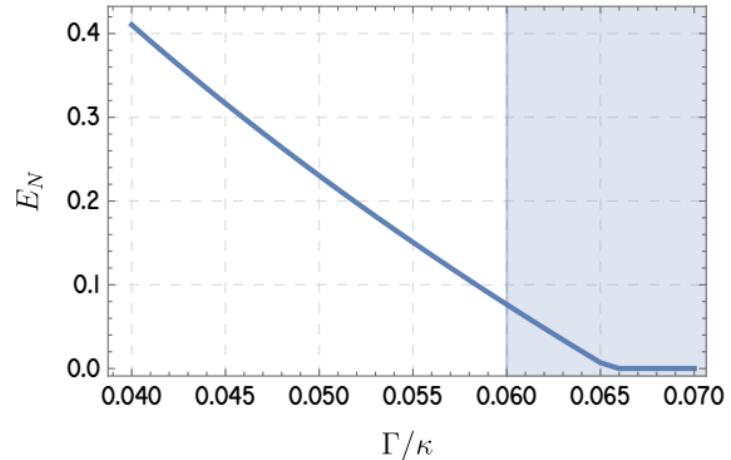
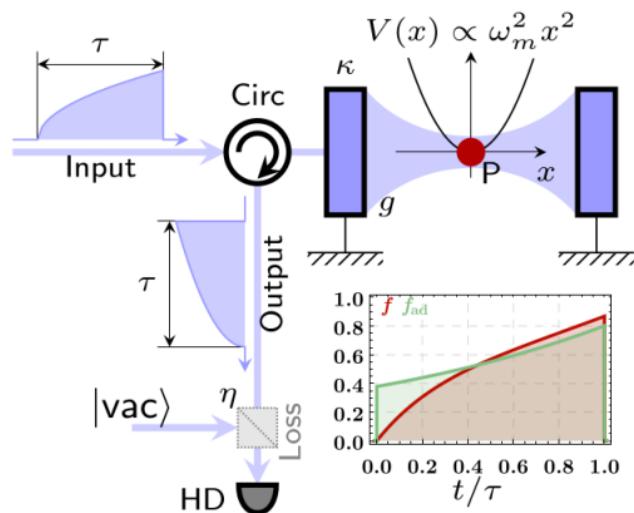
Readout



Readout

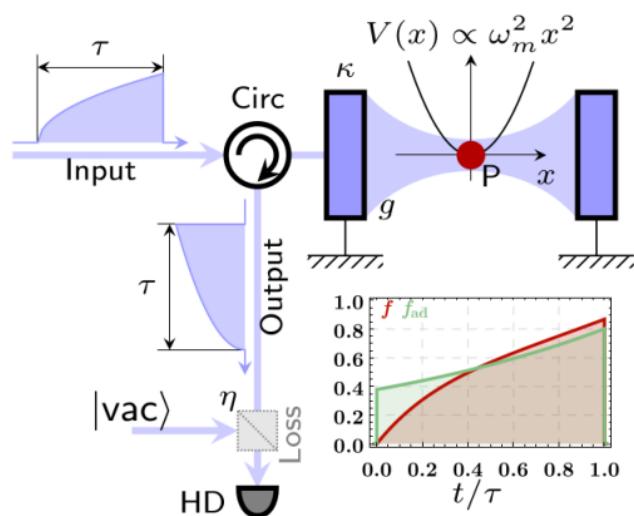


Readout

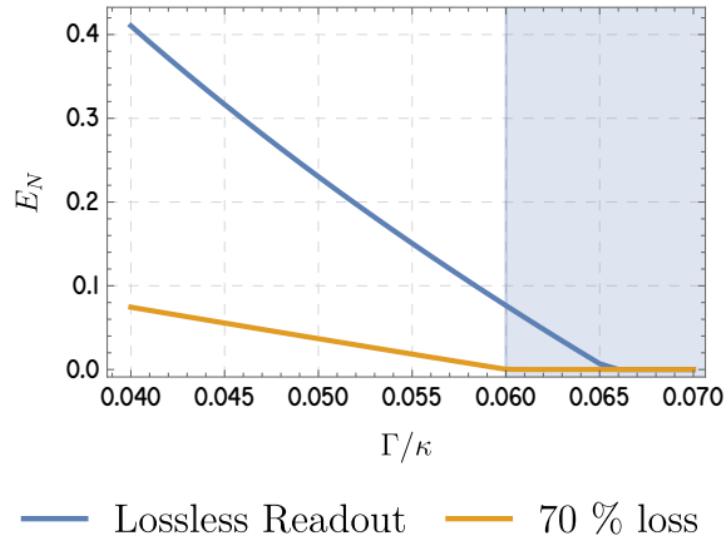


- ★ Coupling rate $g = 0.6\kappa$
- ★ Initial occupation $n_0 = 0.43$

Readout



- ★ Coupling rate $g = 0.6\kappa$
- ★ Initial occupation $n_0 = 0.43$



Thank You!

Ph.D. and postdoc positions available



These slides
<https://bit.ly/andrey-frontiers-2024>



Beware of the appendix slide!

Effective classical simulation

Consider the setup:

- ★ n quantum subsystems
- ★ t operations
- ★ local measurements performed on individual subsystems

The measurement produces one list of outcomes:

$$\mathbf{k} \equiv \{k_1, k_2, \dots, k_n\},$$

one outcome per system.

Probability of the outcomes

$$P(k_1, \dots, k_n) \quad (1)$$

A classical algorithm is said to capable of effective sampling, if it

- ★ is efficient (polynomial) in t and n
- ★ provides outcomes \mathbf{k} draws from the same probability as (1)

The very last frame which is empty