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


ESTONIA
LATVIA
LITHUANIA
DENMARK
UNITED KINGDOM
IRELAND
NETHERLANDS
BELARUS
4.5
Olomouc
GERMANY
CZECHIA
SLOVAKIA
UKRAINE
KAZAKHSTAN
AUSTRIA
FRANCE
SWITZERLAND
HUNGARY
ROMANIA
CROATIA
SERBIA
BULGARIA
ITALY
GEORGIA
UZBEKISTAN
AZERBAIJAN
PORTUGAL
SPAIN
GREECE
TURKEY
TURKMENISTAN
TAJIKISTAN
SYRIA
TUNISIA
IRAQ
AFGHANISTAN
IRAN
JORDAN
MOROCCO

100 km
Amsterdam
NL
Berlin
Warszawa
PL
Bruxelles
D
Luxembourg
L
PRAHA
CZ
UA
SK
Wien
Bratislava
Budapest
Bern
Vaduz
A
CH
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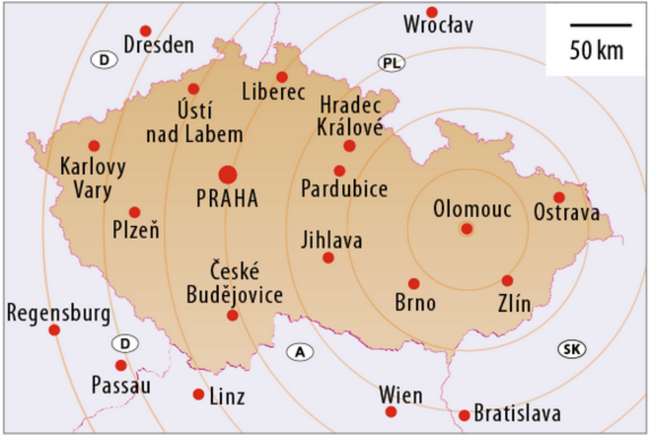
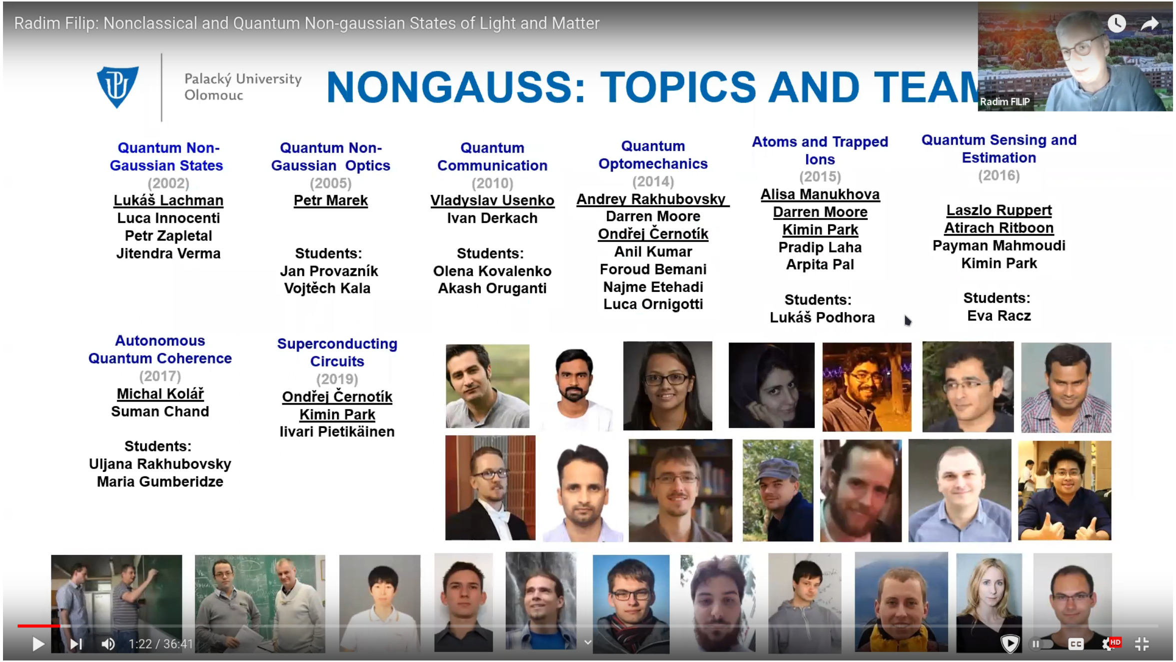
H
RO
Ljubljana
SLO
Zagreb
I
YU
HR
BIH
Beograd



Wrocław
50 km
Dresden
D
PL
Liberec
Ústí nad Labem
Hradec Králové
Karlovy Vary
PRAHA
Pardubice
Olomouc
Ostrava
Plzeň
Jihlava
České Budějovice
Brno
Zlín
Regensburg
D
A
SK
Passau
Linz
Wien
Bratislava

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



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

Radim Filip

Alisa Manukhova

Foroud Bemani

Surabhi Yadav

Darren Moore

Najmeh Etehadi

Now @KIT

Shaoni Datta

Lewis Clark

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

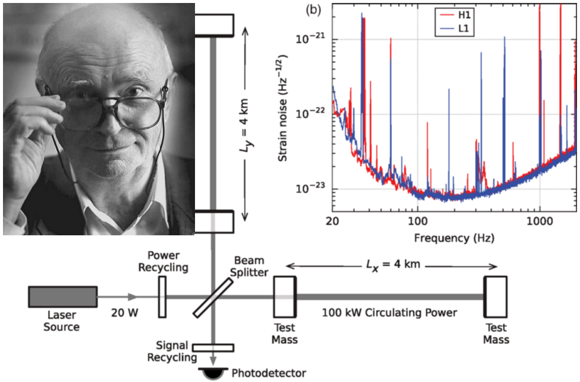
40 pages, 487 references

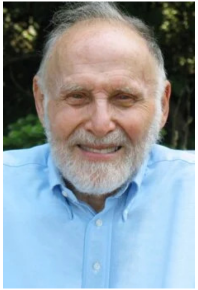
Introduction

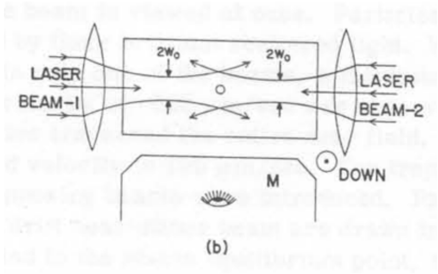
- Quantum Optomechanics
- Levitated Optomechanics

Entanglement of Levitated Nanoparticles

Quantum Optomechanics





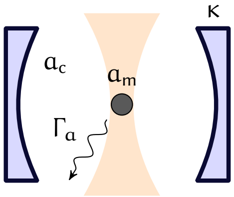


Braginsky & Manukin, Soviet JETP **25**, 653 (1967)
Right img: B. P. Abbott et al., PRL **116**, 061102 (2016)

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

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

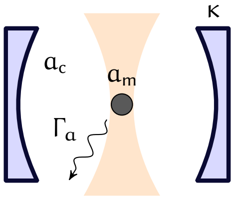
Levitated Optomechanics

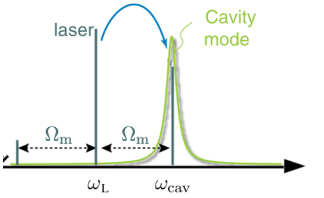


The Hamiltonian

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

Levitated Optomechanics





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

The Hamiltonian

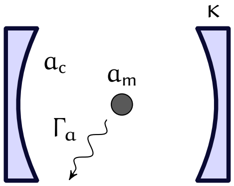
$$H = \frac{p_m^2}{2m} + V(q_m) + \omega_{cav} a_c^\dagger a_c + g q_m (a_c^\dagger + a_c).$$

Conventional Interaction (Cooling)

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

- ★ Cooling
- ★ Beam-splitter / State swap

Levitated Optomechanics



The Hamiltonian

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

Free Fall

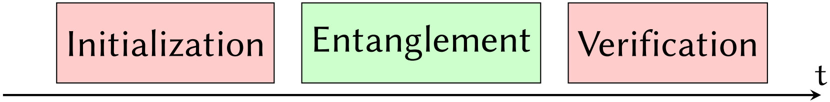
$$q \mapsto q + p\tau,$$
$$p \mapsto p.$$

Squeezing!

Introduction
- Quantum Optomechanics
- Levitated Optomechanics

Entanglement of Levitated Nanoparticles

The Protocol



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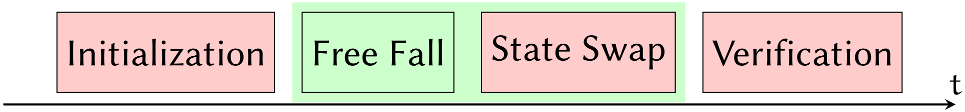
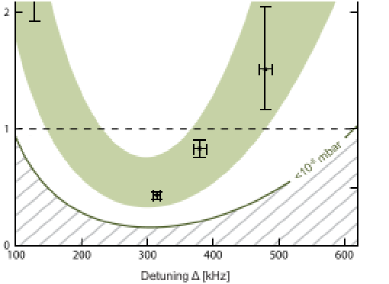


The Protocol

Initialization | Free Fall | State Swap | Verification → t

Initialization

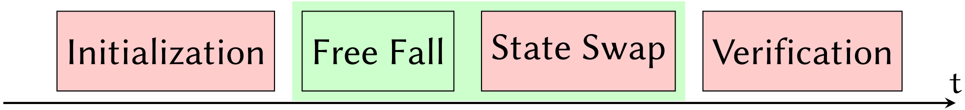
Cooling to the ground state ($\bar{n} = 0.43$)



U. Delić, Science **367**, 892 (2020)

Avoid dark modes

The Protocol



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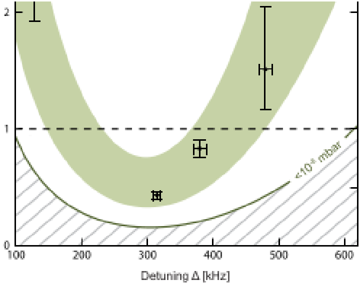


U. Delić, Science **367**, 892 (2020)
Avoid dark modes

Free Fall

Squeezing

State Swap

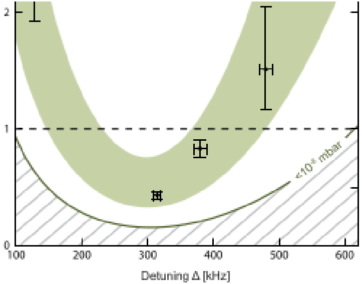
Via interacting with the same cavity mode

The Protocol

Initialization | Free Fall | State Swap | Verification → t

Initialization

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



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

Free Fall

Squeezing

State Swap

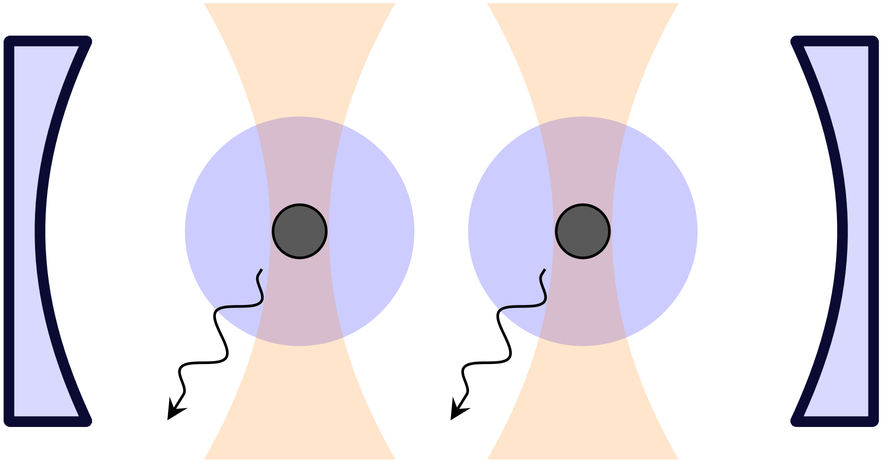
Via interacting with the same cavity mode

Readout

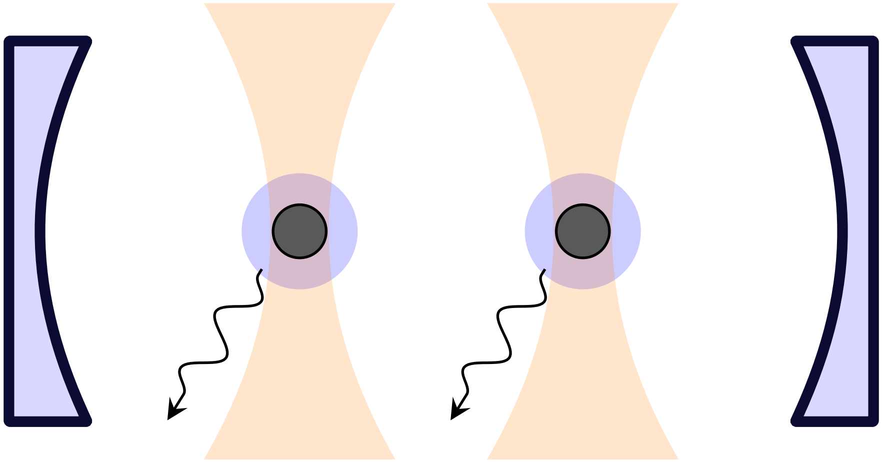
Via state swap to leaking light and homodyne

The Recipe

The Protocol



The Protocol



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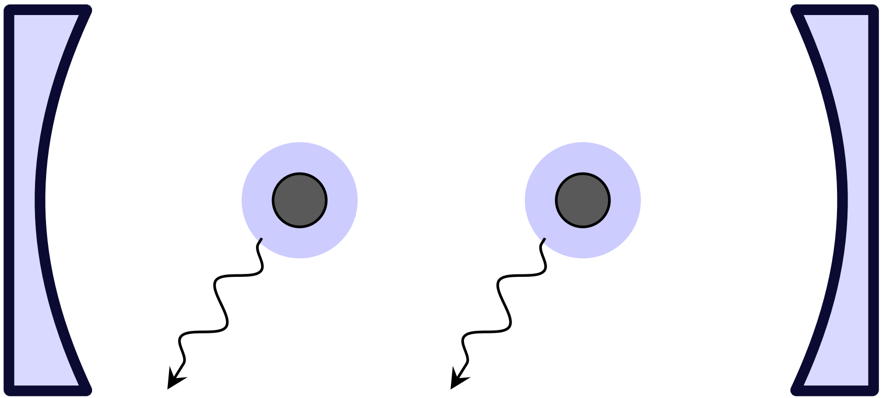

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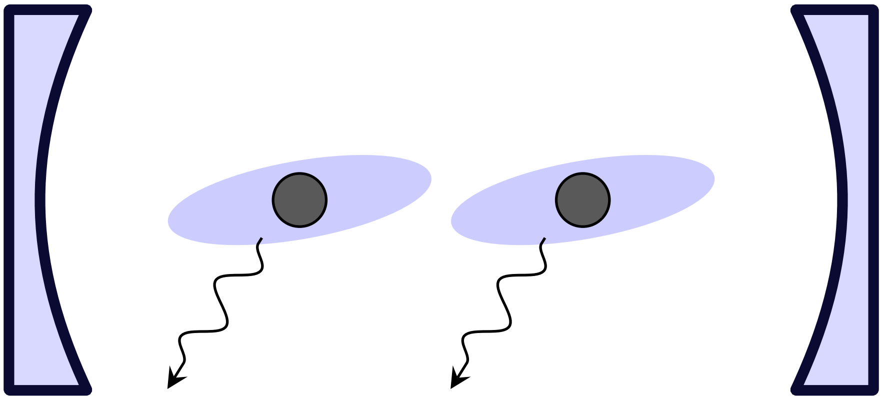

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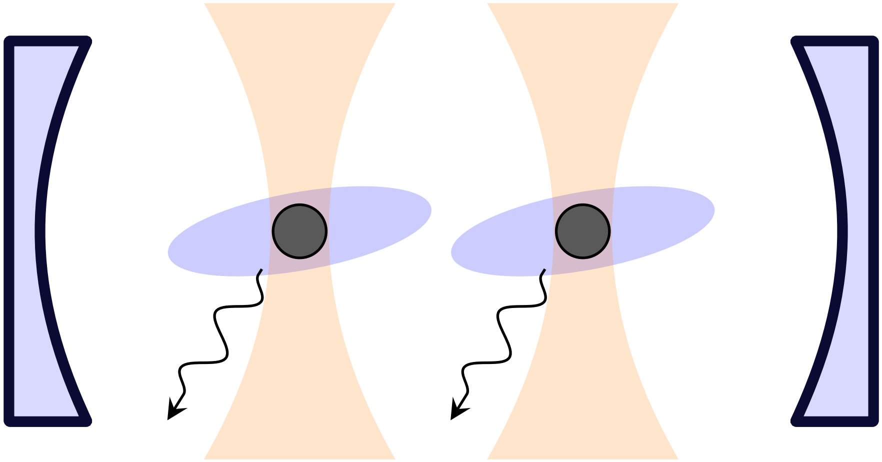
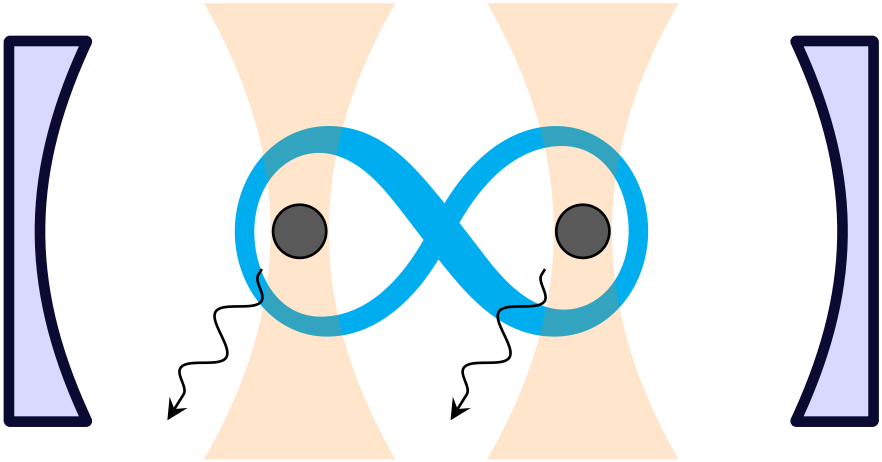
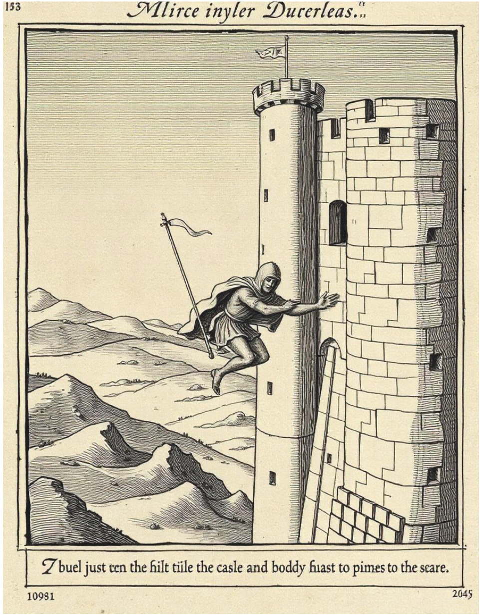


The Protocol



Free Fall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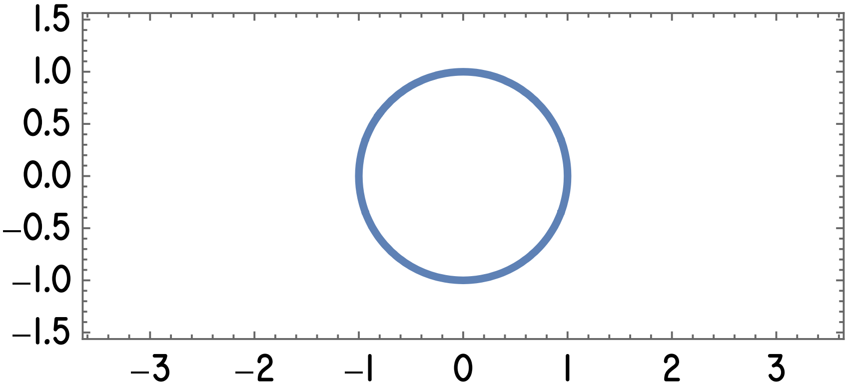
Free fall

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

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



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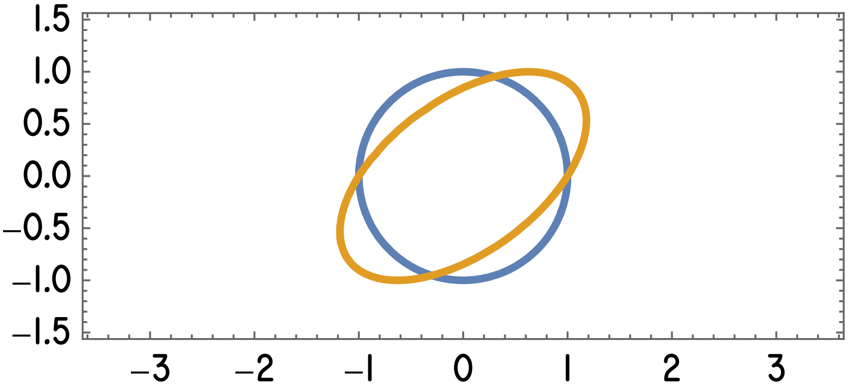

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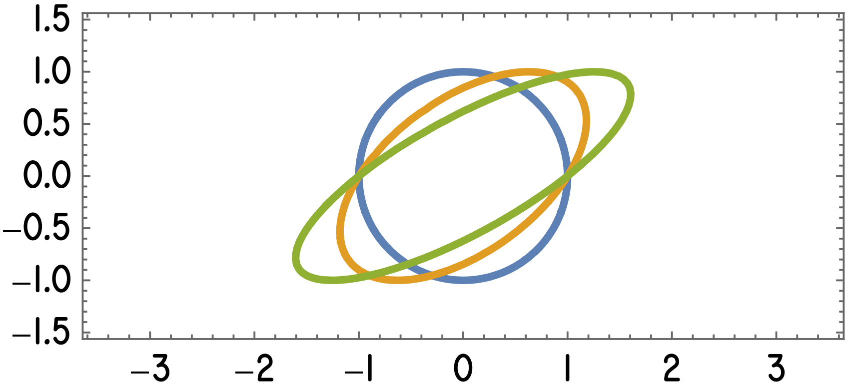

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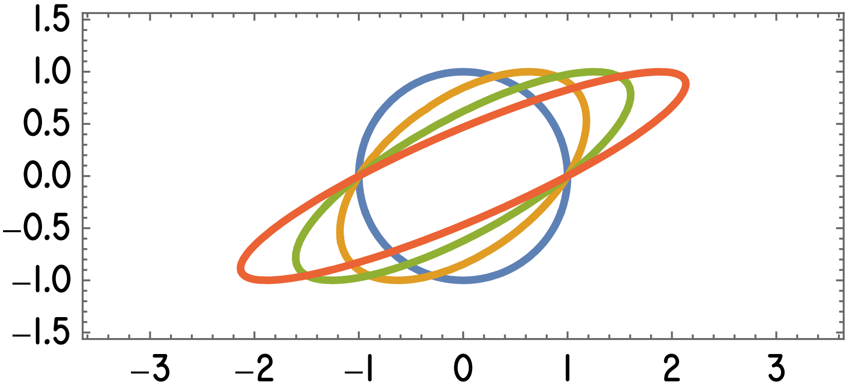

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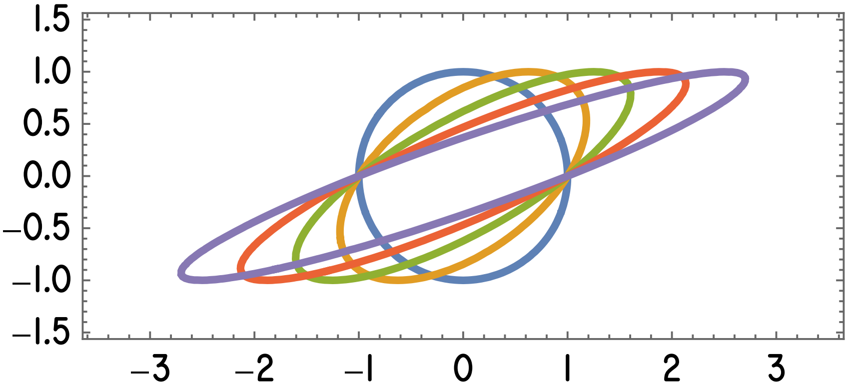

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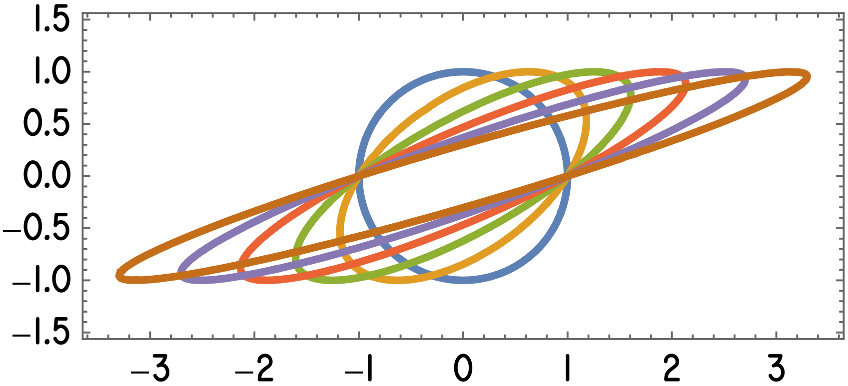

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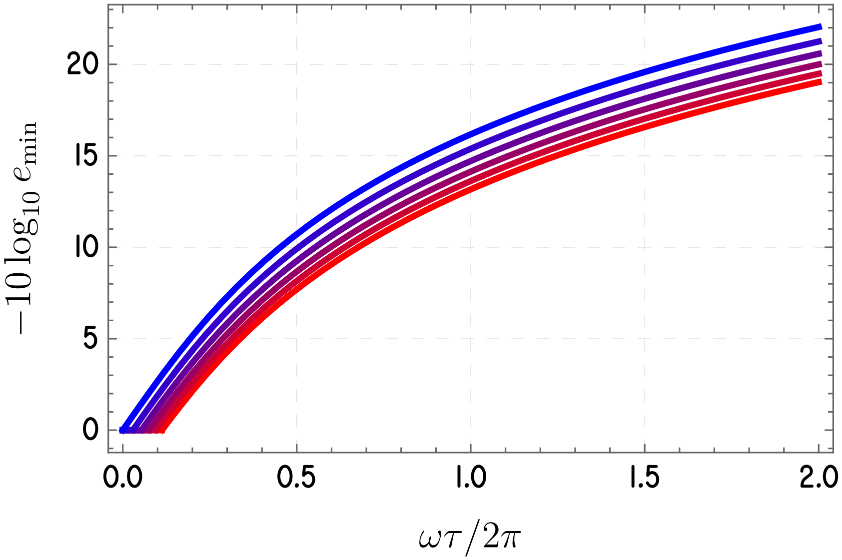
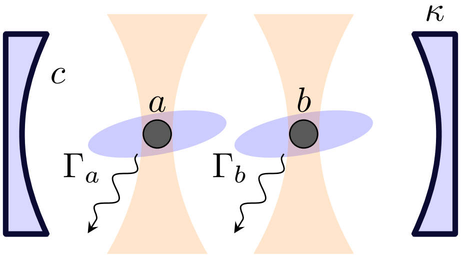


State Swap

State Swap

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



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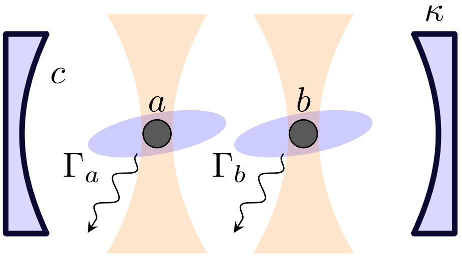
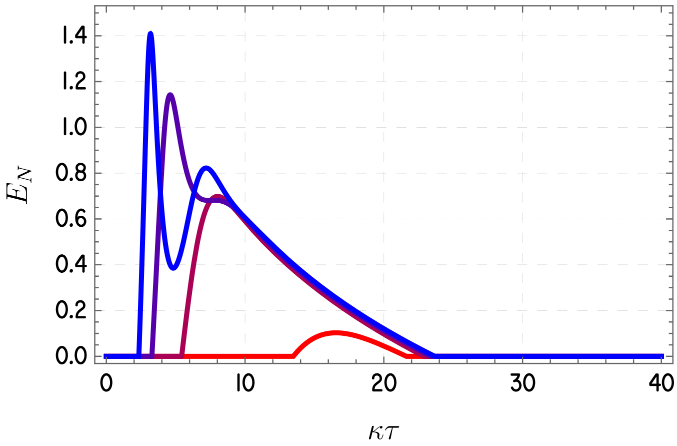


Most parameters from
U. Delić, Science **367**, 892 (2020)
There:

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

Logarithmic negativity E_N

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



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

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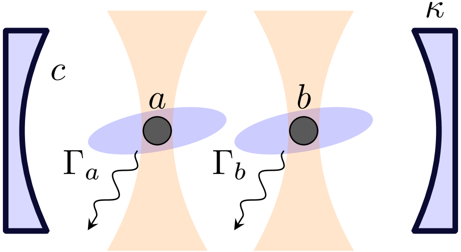

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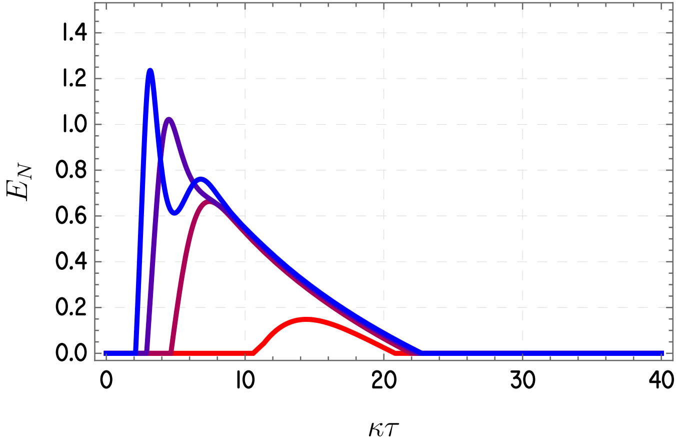

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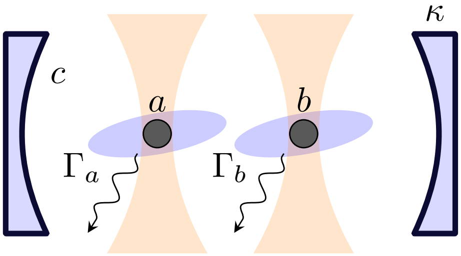

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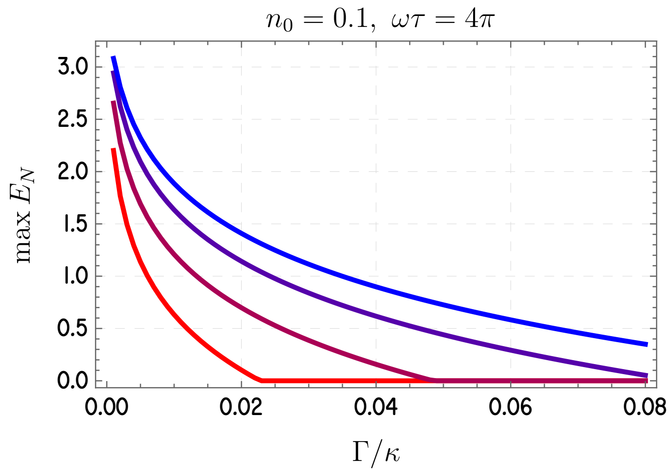

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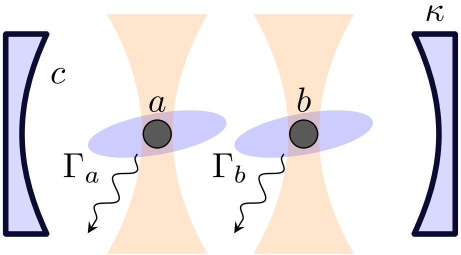

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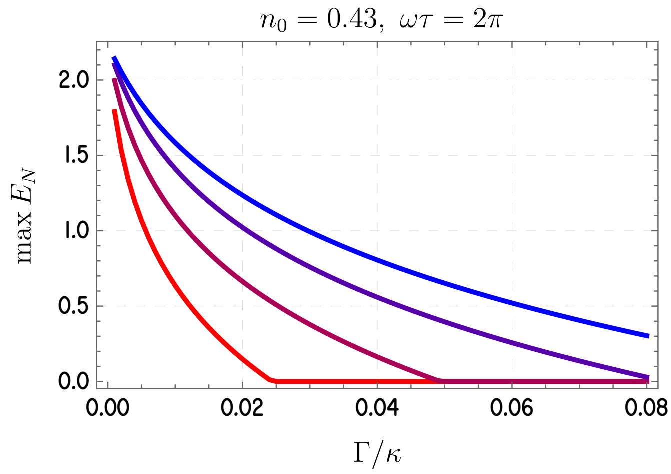
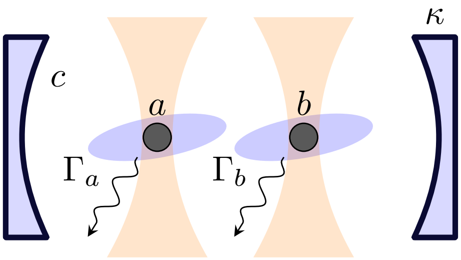


Color: coupling rate $0.3 \leqslant \frac{g}{\kappa} \leqslant 0.6$.

The role of asymmetry

Non-identical particles

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



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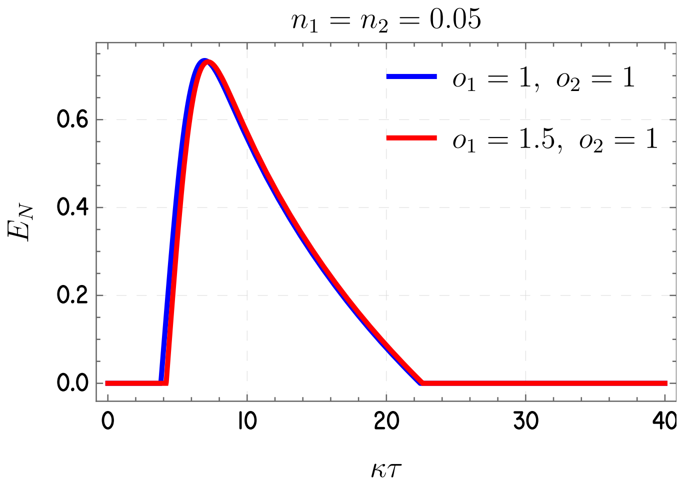

$$o_i \equiv \frac{\omega_i \tau}{2\pi}$$

Non-identical particles

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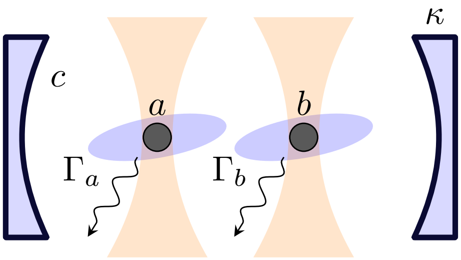

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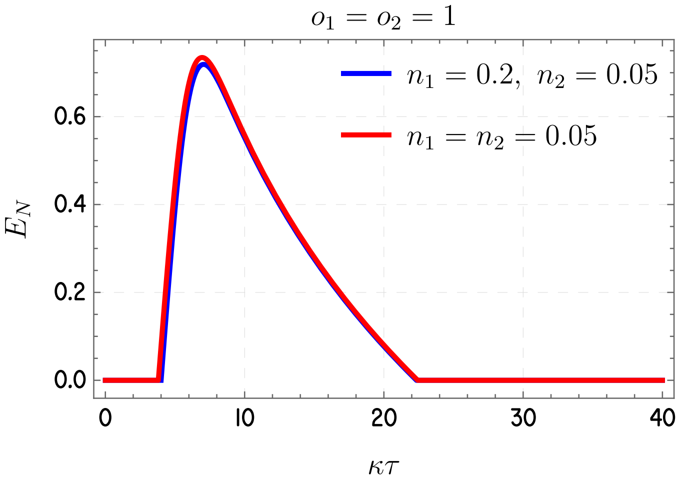

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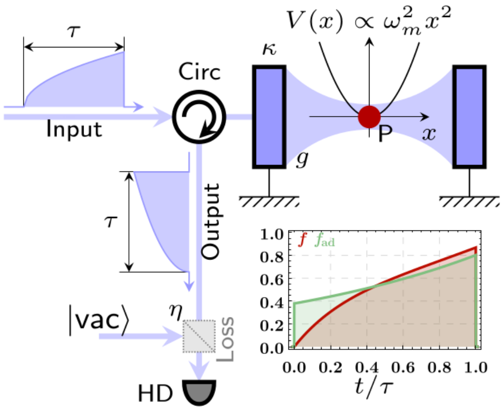
Readout

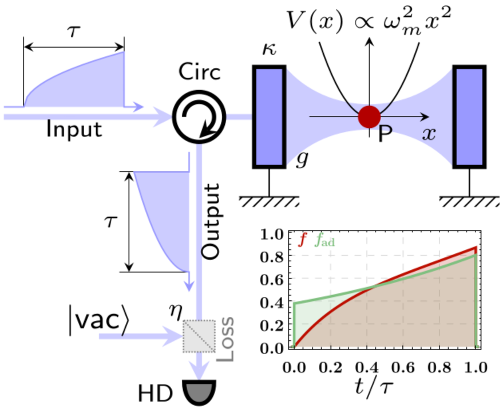
State Examination



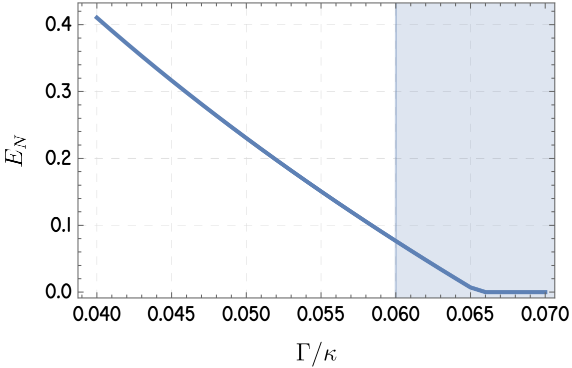
$$X_{\mathrm{out}} = \sqrt{\mathcal{T}}\, X_{\mathrm{mech}} + \sqrt{1-\mathcal{T}}\, X_{\mathrm{Noise}}.$$

$$H = g_a a c_a^\dagger + g_b b c_b^\dagger + \mathrm{h.c.}$$

State Examination



$$X_{out} = \sqrt{\mathcal{T}}\, X_{mech} + \sqrt{1 - \mathcal{T}}\, X_{Noise}.$$

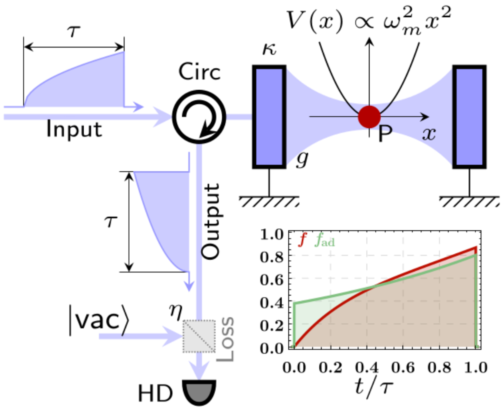


$$H = g_a a c_a^\dagger + g_b b c_b^\dagger + \text{h.c.}$$

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

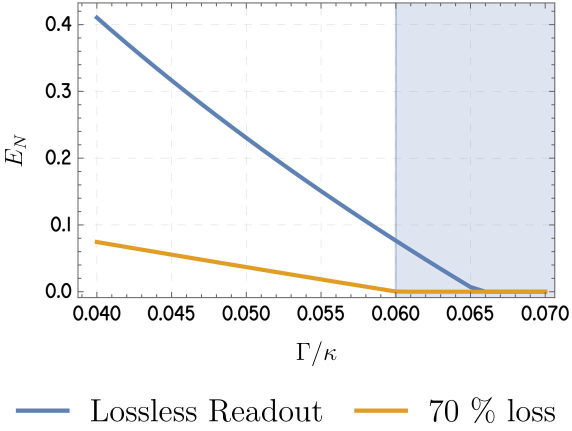
U. Delić, Science **367**, 892 (2020)

State Examination



$$H = g_a a c_a^\dagger + g_b b c_b^\dagger + \text{h.c.}$$

$$X_{\text{out}} = \sqrt{\mathcal{T}}\, X_{\text{mech}} + \sqrt{1-\mathcal{T}}\, X_{\text{Noise}}.$$

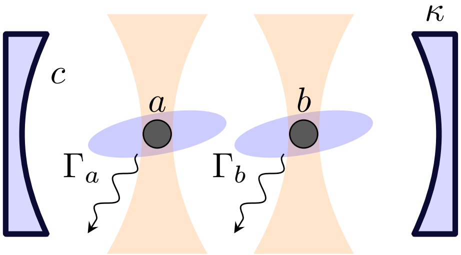


- Coupling rate $g = 0.6\kappa$
- Initial occupation $n_0 = 0.43$

U. Delić, Science **367**, 892 (2020)

Conclusions

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



Requirements for Entanglement

- Beam-splitter interaction
- Free-motion

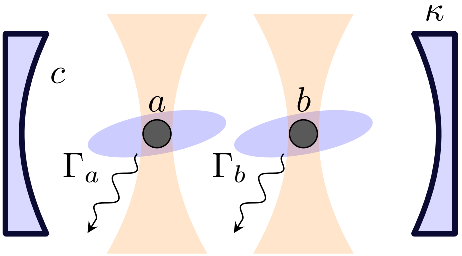
Requirements for Verification

- Beam-splitter
- Individual address

All operations are passive

Conclusions

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



Requirements for Entanglement

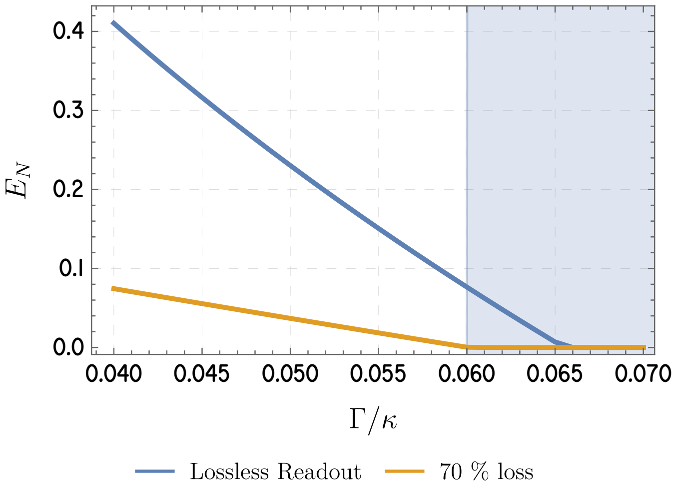
- ★ Beam-splitter interaction
- ★ Free-motion

Requirements for Verification

- ★ Beam-splitter
- ★ Individual address

All operations are passive

- ★ Entanglement is possible
- ★ Can persist recoil heating
- ★ Survives asymmetries
- ★ Does not require initial pure states (but doesn't mind)



Thank You!

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

Phd and Postdoc positions available

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

$$P(k_1, \dots, k_n) \tag{1}$$

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