Levitated Nanoparticles in the Quantum Regime

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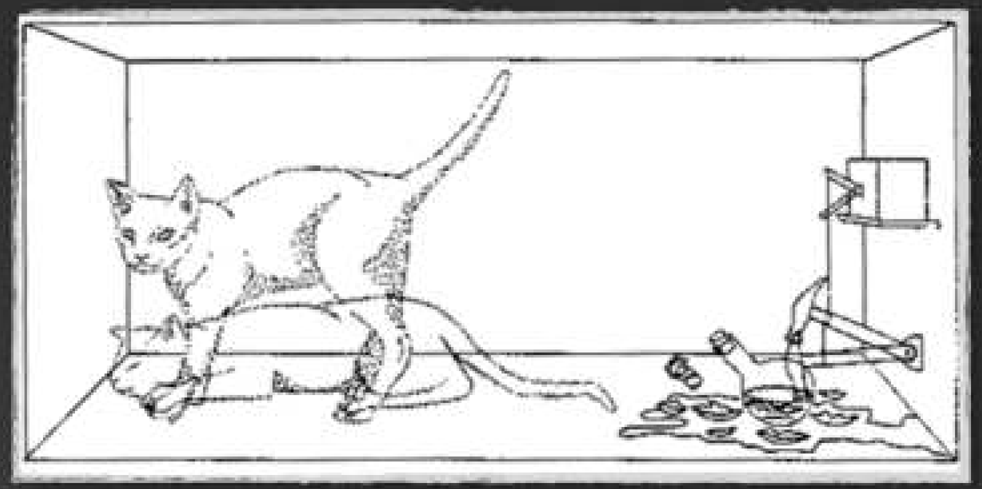
Quantum Science Seminar 26.11.20

Quantum Optics

a success story based on understanding, controlling, and using quantum degrees of freedom in nature

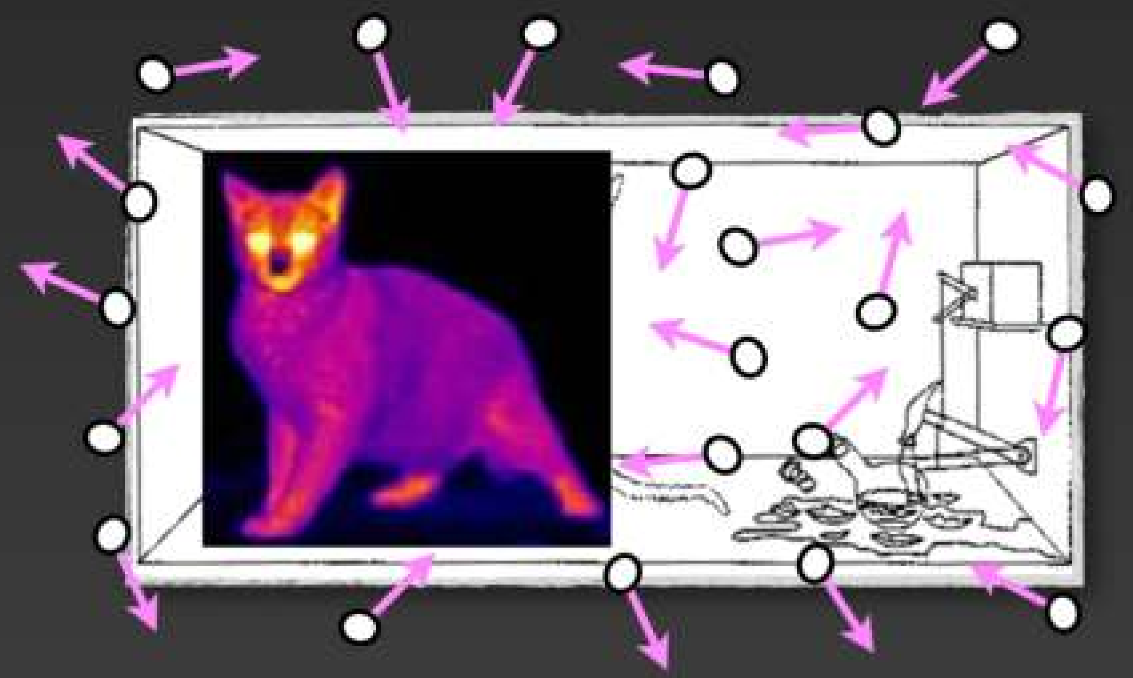
Quantum Optics

quantum phenomena require isolation



Quantum Optics

quantum phenomena require isolation



Quantum Optics

- *Understand*, *control*, *and* *use* *quantum degrees of freedom*
- *Isolation* *is required to prevent decoherence*

In this talk …

Understand / Control / Use
Quantum Degrees of Freedom in a Levitated Object

A top-down approach to quantum physics

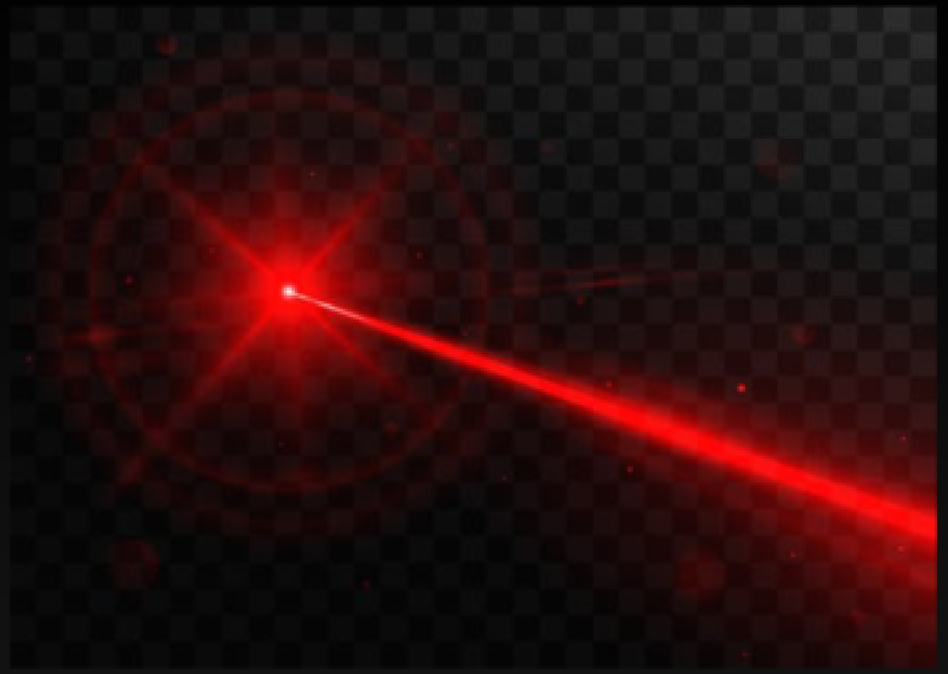
Unique opportunities for applied and fundamental research

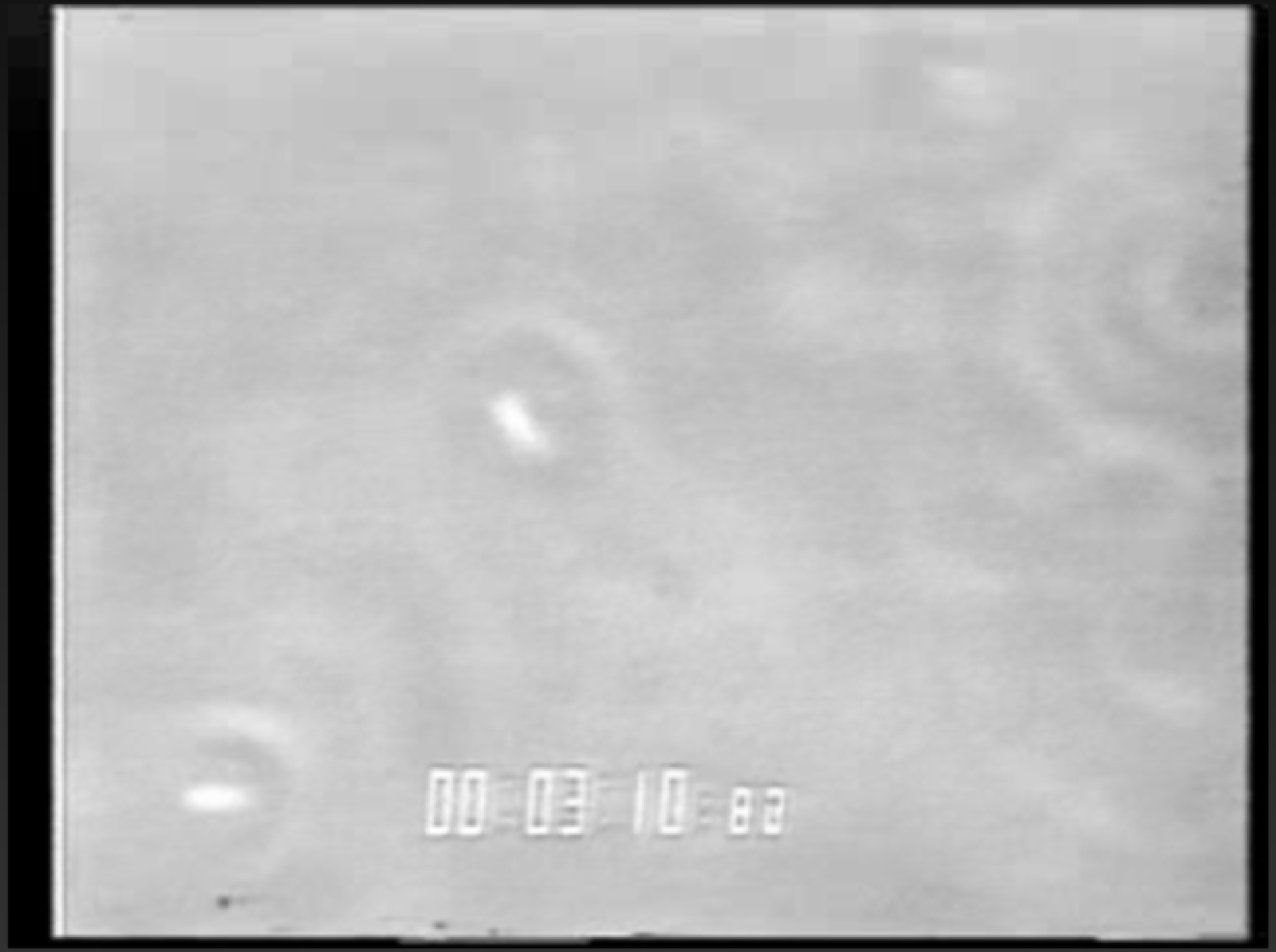
Background

A story that begins in the 1970s …

Arthur Ashkin

Nobel Prize in Physics 2018

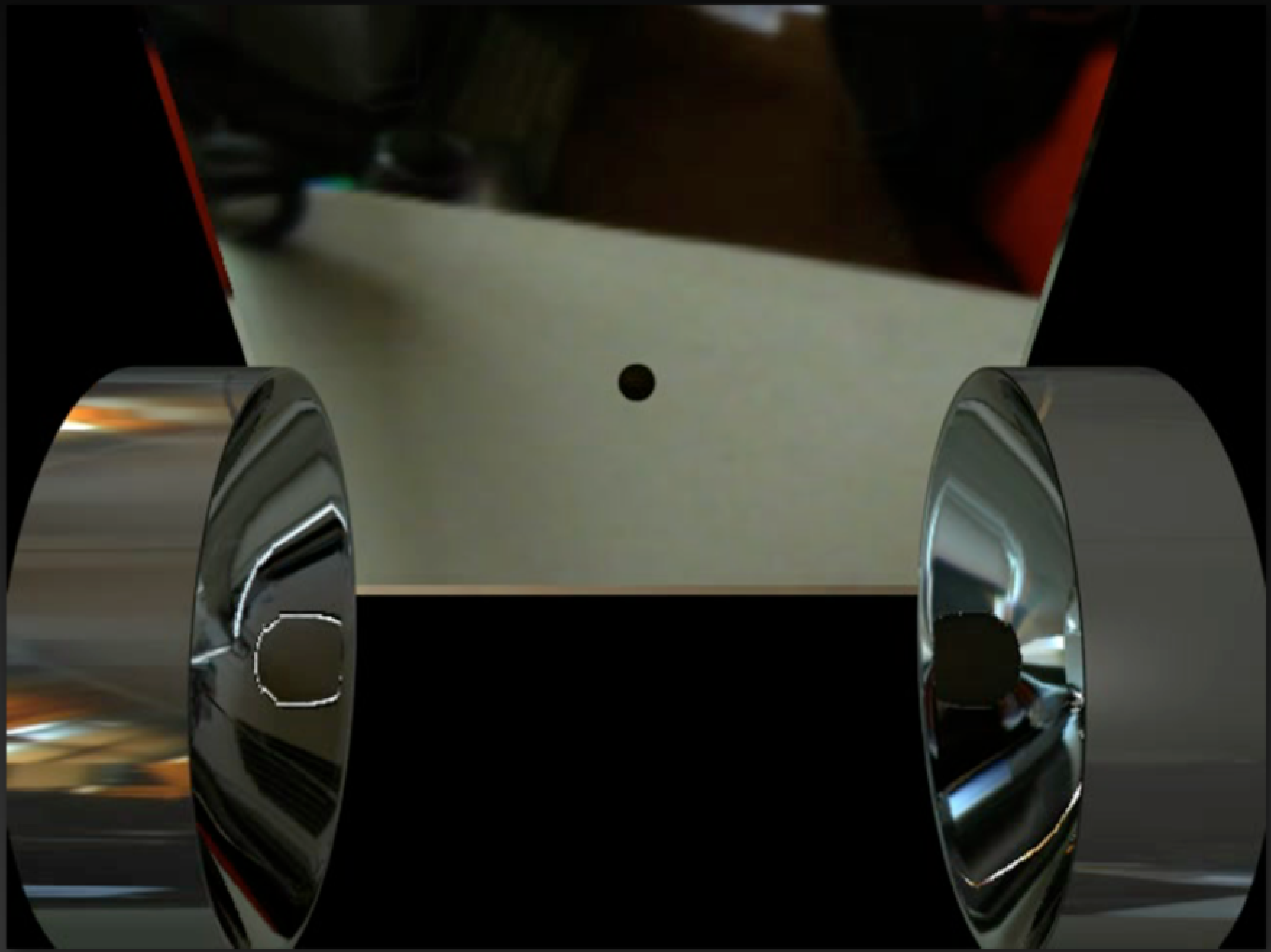




Optical Tweezers

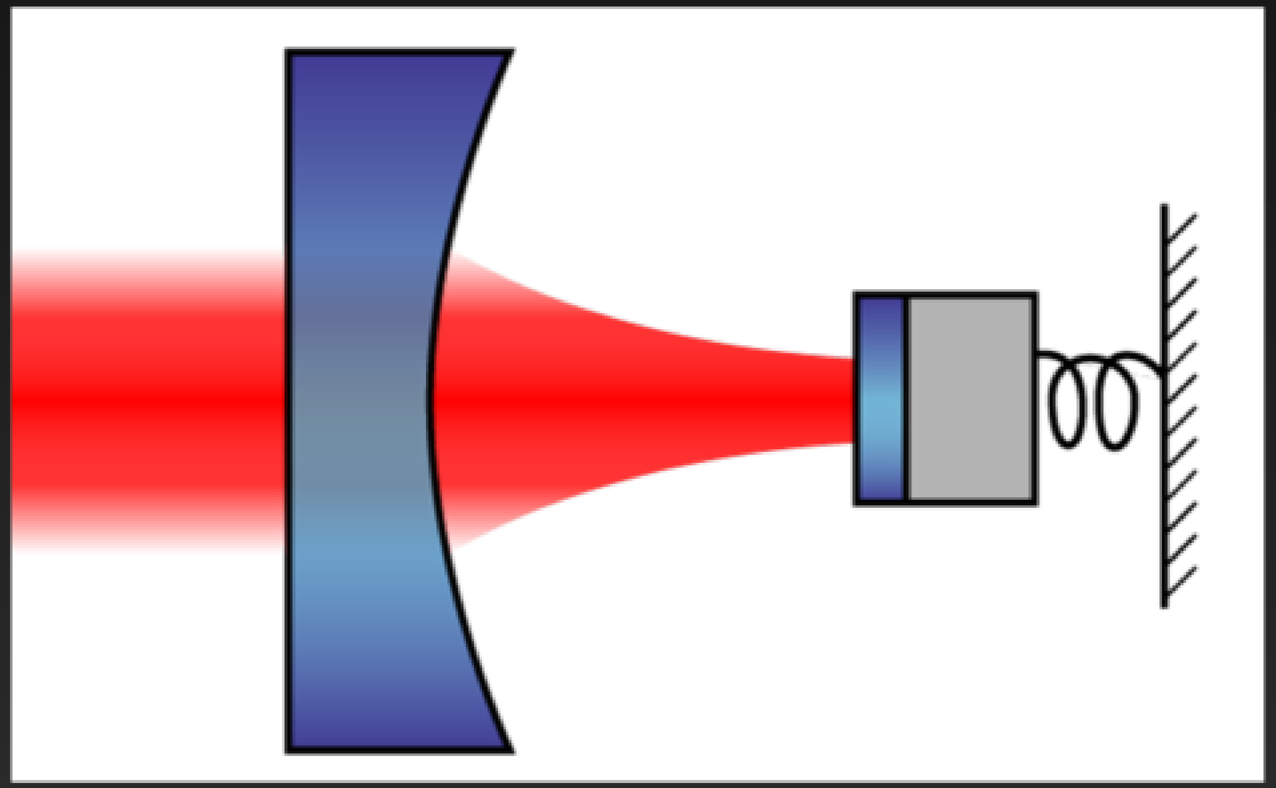
In 2010 …

Cavity Optomechanics with an Optically Levitated Dielectric Nanoparticle



- ORI, M. L. Juan, R. Quidant, J. I. Cirac NJP **12**, 033015 (2010)
- D. E. Chang … H. J. Kimble and P. Zoller PNAS **107**, 1005 (2010)
- P. F. Barker and M. N. Shneider PRA **81**, 023826 (2010)

Like cavity optomechanics



but absence of a mechanical support …

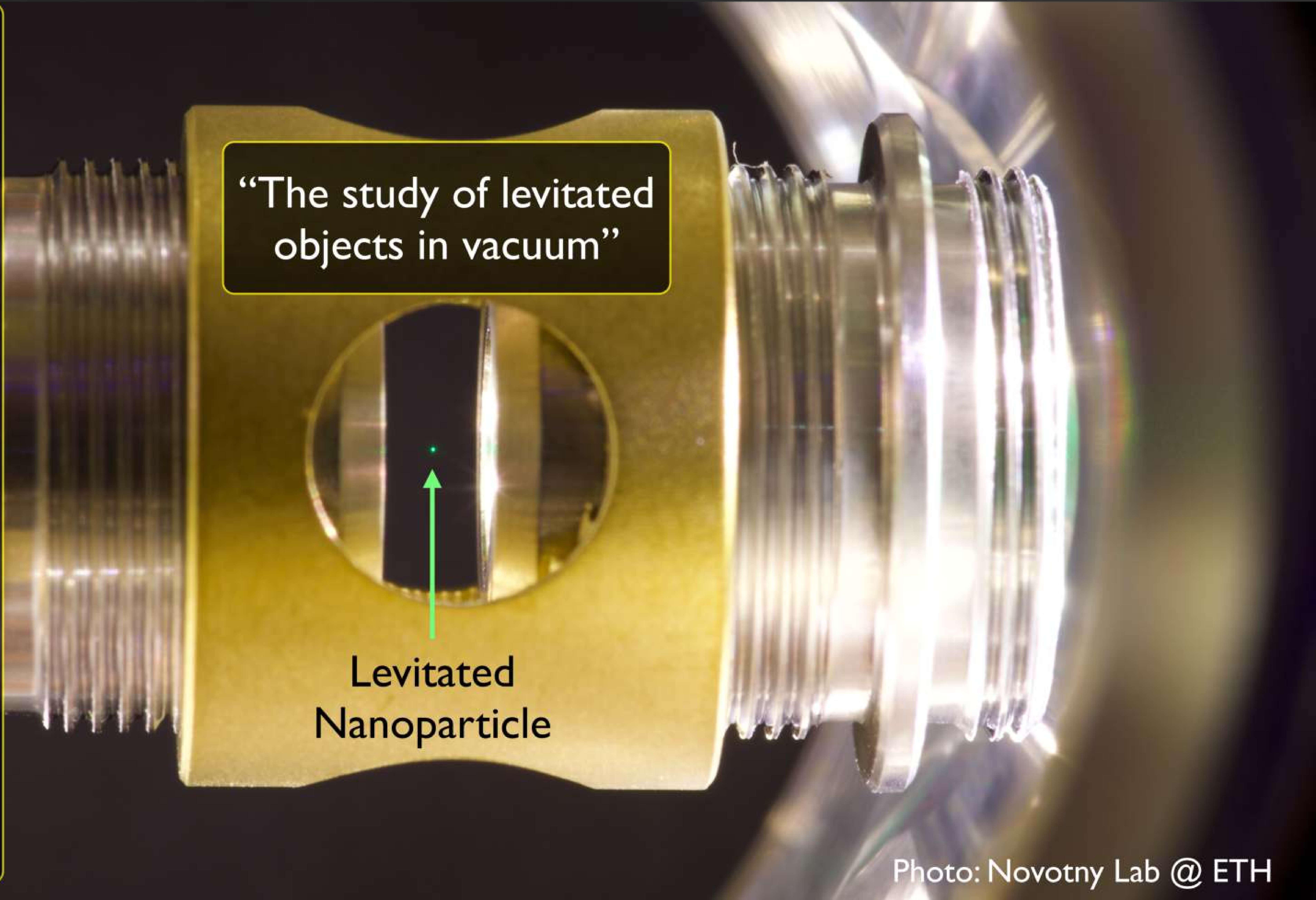
It allows object to be freely translated, rotated and dropped!

In 2020, ten years later …

Levitodynamics

Experimental groups:

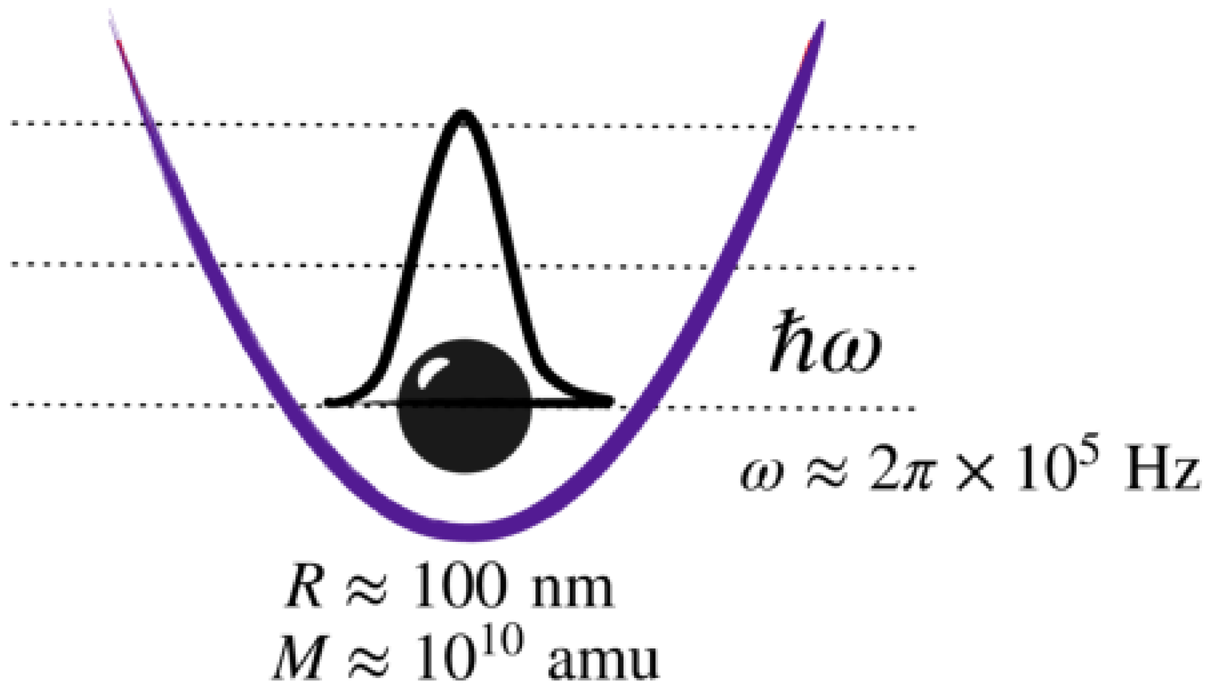
K. Aikawa (Tokyo)
M. Arndt (Vienna)
M. Aspelmeyer (Vienna)
P. Barker (UCL)
D. Budker (Mainz&Berkely)
K. Dholakia (St. Andrews)
B. D'Urso (Montana)
A. Geraci (Northwestern U)
G. Gratta (Stanford)
J. Harris (Yale)
G. Hétet (ENS)
D. F. Jackson Kimball (California State U)
M. L. Juan (Sherbrooke)
B. E. Kane (JQI Maryland)
N. Kiesel (Vienna)
T. Li (Purdue U)
J. Gieseler & M. D. Lukin (Harvard)
J. Millen (King's College)
D. C. Moore (Yale)
A. Nick Vamivakas (Rochester)
T. Northup (Innsbruck)
L. Novotny (ETH)
M. Raizen (Austin)
R. Reimann (TII)
R. A. Rica (Granada)
R. Quidant (ETH)
H. Ulbricht (Southampton)
A. Vinante (Trento)
W. Wieczorek (Chalmers)
… (sorry!)



Advances (experiments)

Cooling to the motional quantum regime

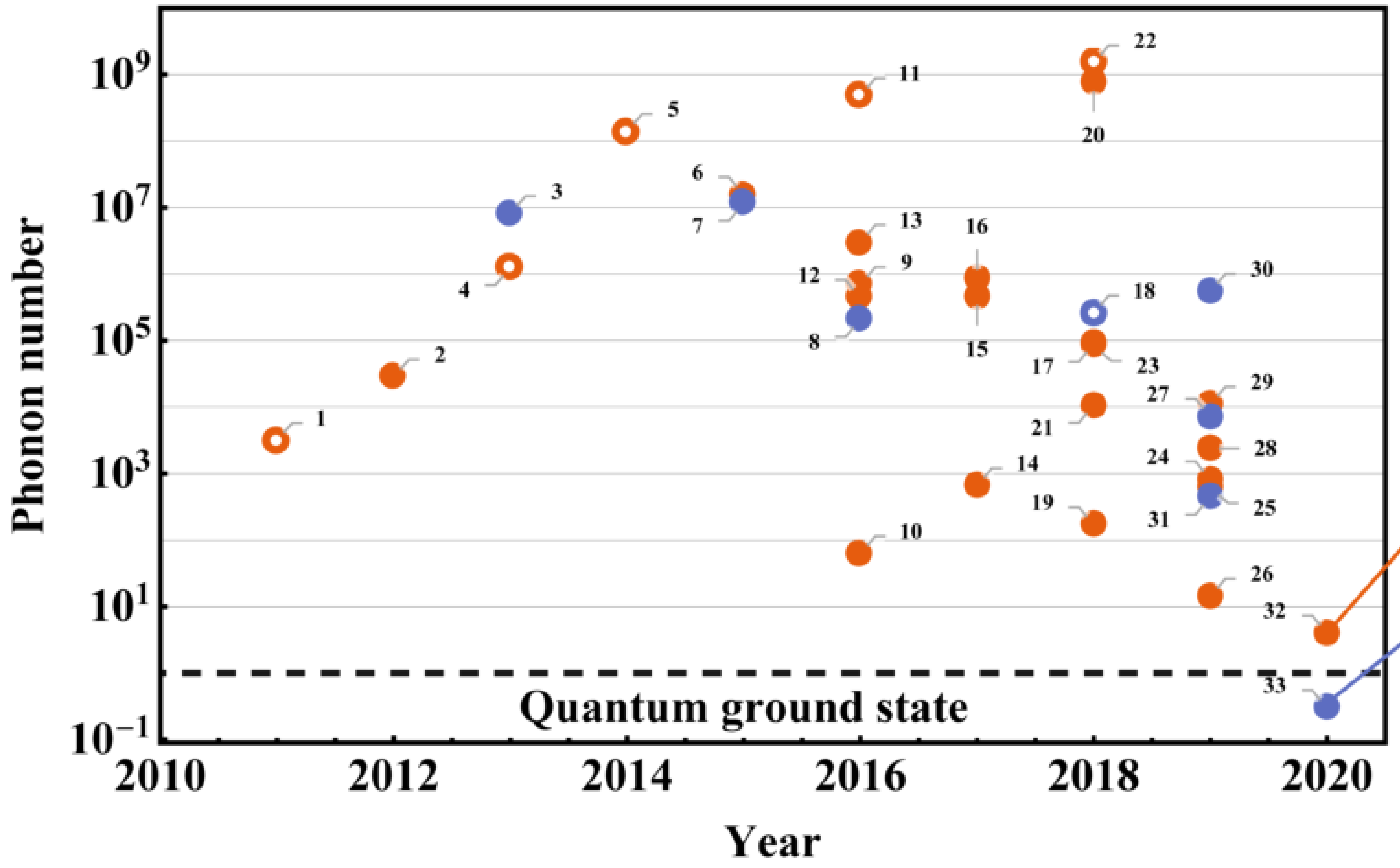
- Quantum ground state



Center-of-mass *quantum* fluctuations

$$\sqrt{\frac{\hbar}{2M\omega}} \sim 10^{-12}\ \mathrm{m} \longrightarrow T \sim 10^{-6}\ \mathrm{K}$$

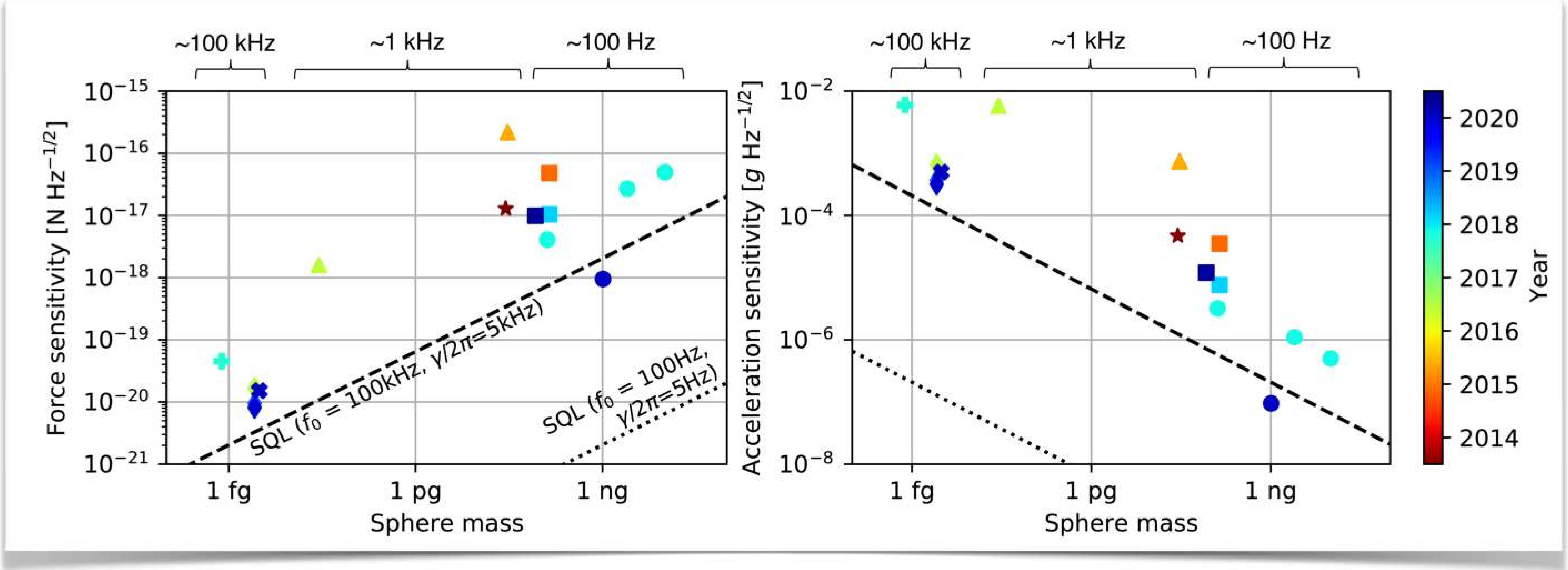
- Two mechanisms: cavity-based and feedback cooling



- Reaching the quantum regime!
  - F. Tebbenjohanns … L. Novotny, PRL **124**, 013603 (2020)
  - U. Delić … M. Aspelmeyer, Science **367**, 892 (2020)
- Theory of cavity cooling via coherent scattering
  - C. Gonzalez-Ballestero … ORI, PRA **100**, 13805 (2019)

High-performance sensing

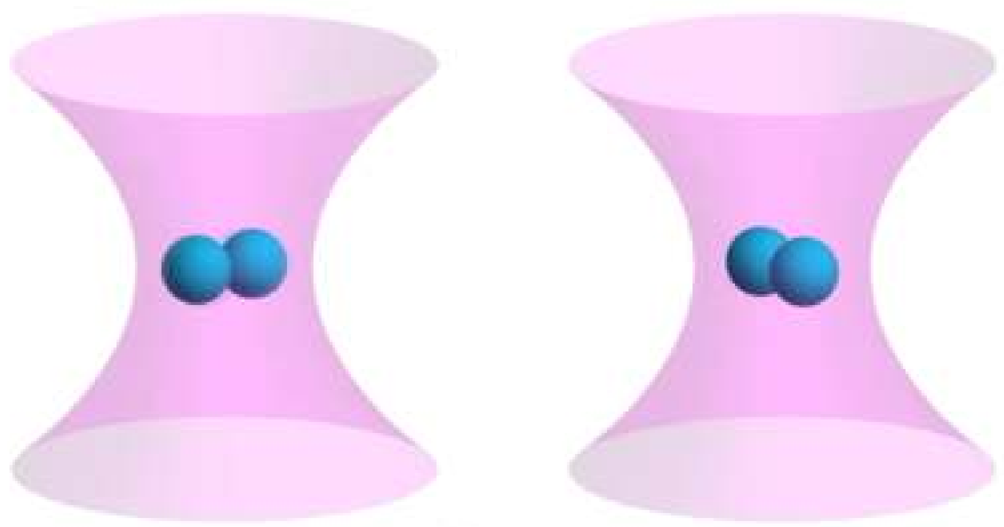
- Inertial and force sensing with levitated nanoparticles



D. C. Moore and A. Geraci, arXiv: 2008.13197

Other degrees of freedom

- Control of rotational degrees of freedom

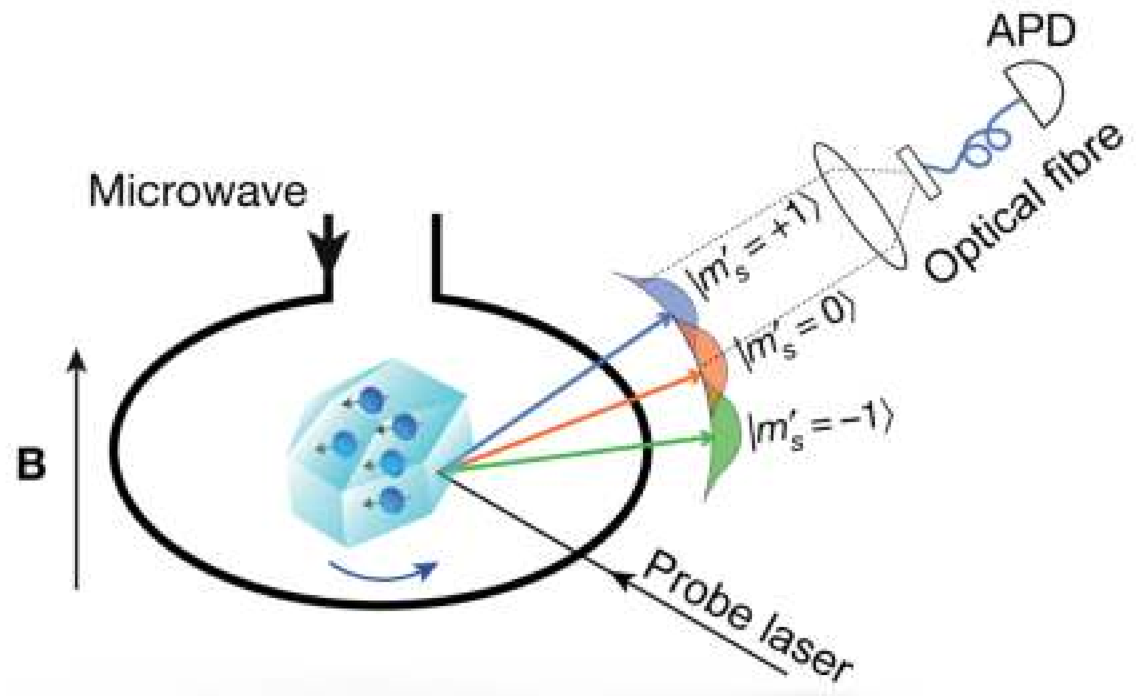


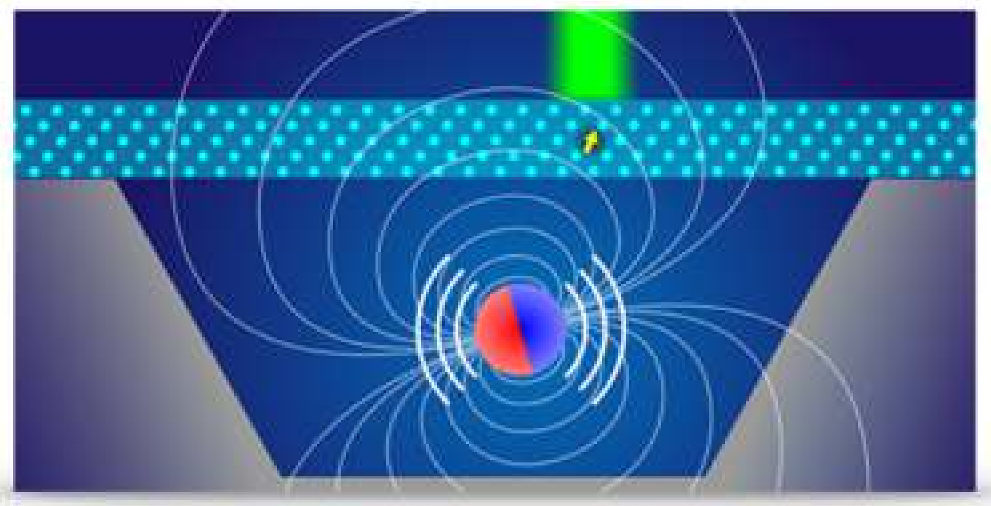
J. Ahn/Purdue Univ.

- Rotation frequency to GHz (limited by material's tensile strength)
- Ultra-stable and sensitive rotors

- S. Kuhn … J. Millen, Nat. Comm. **8**, 1670 (2017)
- R. Reimann … L. Novotny, PRL **121**, 033602 (2018)
- J. Ahn … T. Li, PRL **121**, 033603 (2018)
- J. Ahn … T. Li, Nat. Nanotechnol. **15**, 89 (2020)

- Spin-mechanical coupling





- T. Delord … G. Hétet, Nature **580**, 56 (2020)
- J. Gieseler, … ORI, M. D. Lukin, PRL **124**, 163604 (2020)

Experimental inventory

- Trapping, cooling and measurement implemented:

optically

electrically

magnetically

- Types of particles
  - Dielectric nanoparticles
  - Magnets
  - Metals
  - Diamonds with QEs
  - Superconductors
  - Graphene
  - Superfluid He

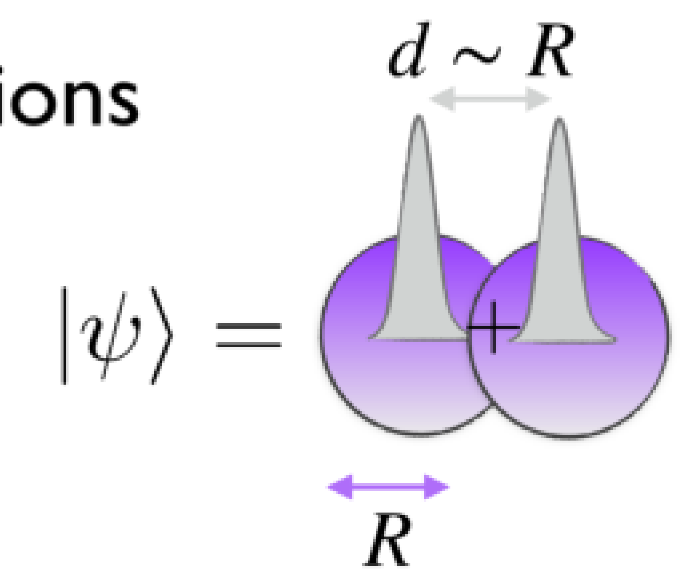
- Complex shapes
  - Spheres
  - Rods
  - Dumbbells
  - Platelets

Applications

Applications

Pushing boundaries of quantum physics

- Macroscopic quantum superpositions
- Classical / quantum transition
- Interplay with gravity



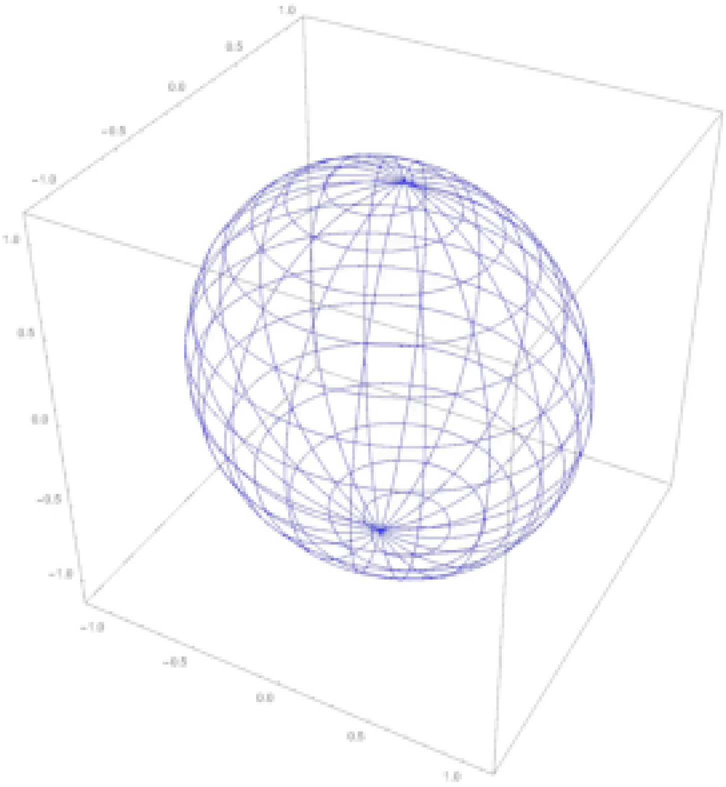
Highly sensitive detectors

- Detecting new physics (high-mass density)
- Technological applications

$$F(r) = \frac{GmM}{r^2}\left(1 + \alpha e^{-r/\lambda}\right)$$

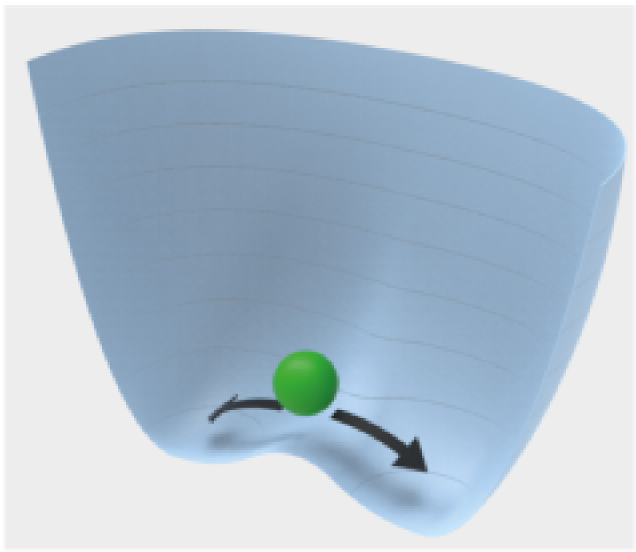
Solid-state objects in extreme conditions

- Internal degrees of freedom
- Extreme stress and isolation
- Phase transitions



Non-equilibrium physics

- Stochastic processes
- Controlled environment
- Many-body dynamics

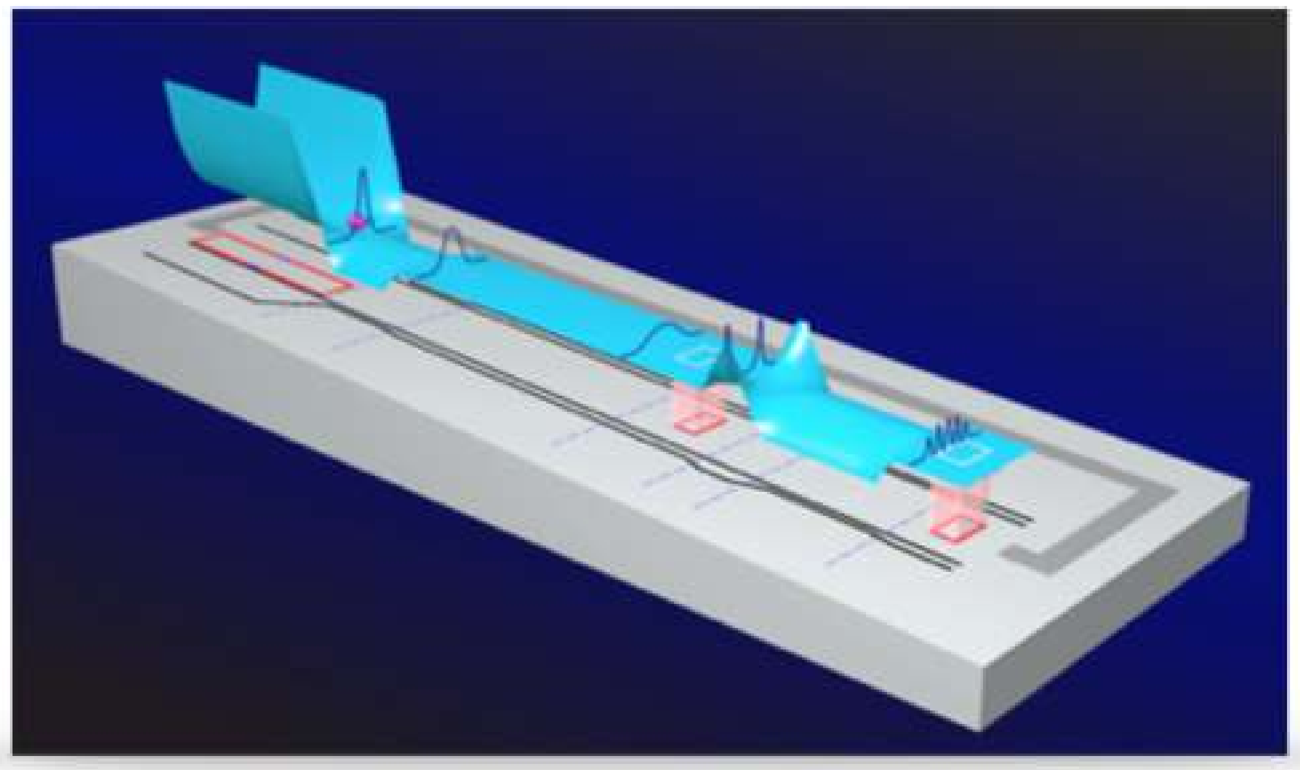


Part II

Our theory group

Theory

Cutting-edge proposals

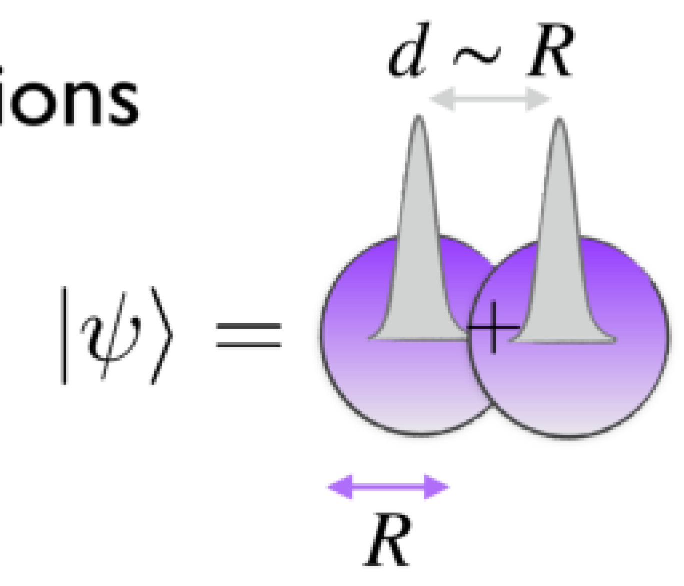


Collaboration with experimentalists

Applications

Pushing boundaries of quantum physics

- Macroscopic quantum superpositions
- Classical / quantum transition
- Interplay with gravity



Highly-sensitive detectors

- Detecting new physics
- Technological applications

$$F(r) = \frac{GmM}{r^2}\left(1 + \alpha e^{-r/\lambda}\right)$$

Solid-state objects in extreme conditions

- Internal degrees of freedom
- Extreme stress and isolation
- Phase transitions

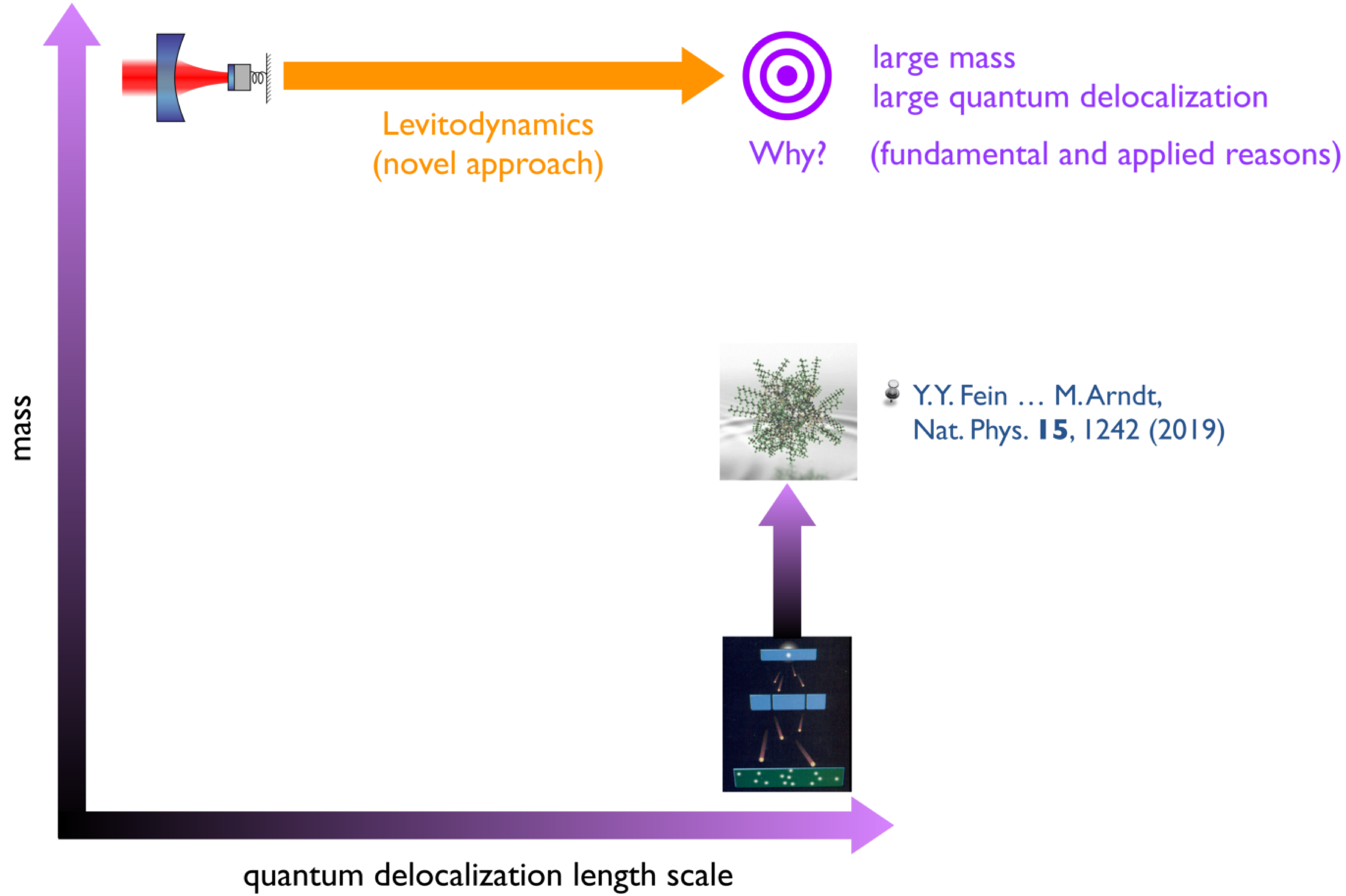
Non-equilibrium physics

- Stochastic processes
- Controlled environment
- Many-body dynamics

Large Quantum Delocalization of a Nanoparticle

- T. Weiss, M. Roda-Llordes, E. Torrontegui, … ORI arXiv: soon

Quantum delocalization of massive objects

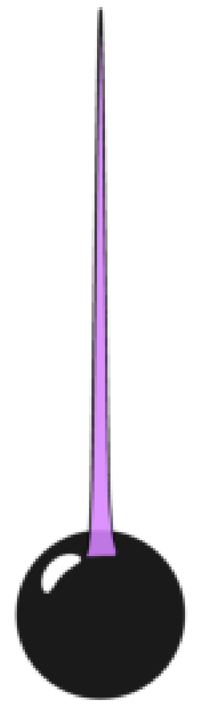


Y.Y. Fein … M. Arndt, Nat. Phys. **15**, 1242 (2019)

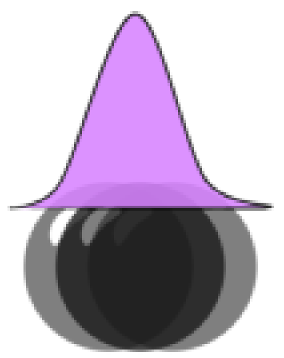
Large quantum delocalization

- Towards large quantum delocalization

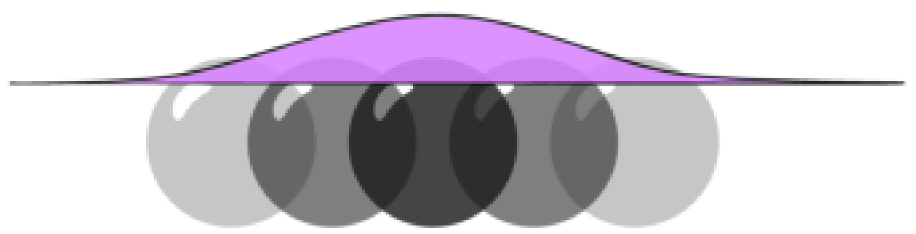
  - NOT a superposition!
  - Quantum pure state



$$\sqrt{\langle \hat{x}^2 \rangle} = x_0 \equiv \sqrt{\frac{\hbar}{2M\omega}} \sim 10^{-12}\ \text{m}$$



$$\sqrt{\langle \hat{x}^2 \rangle} \gg x_0$$



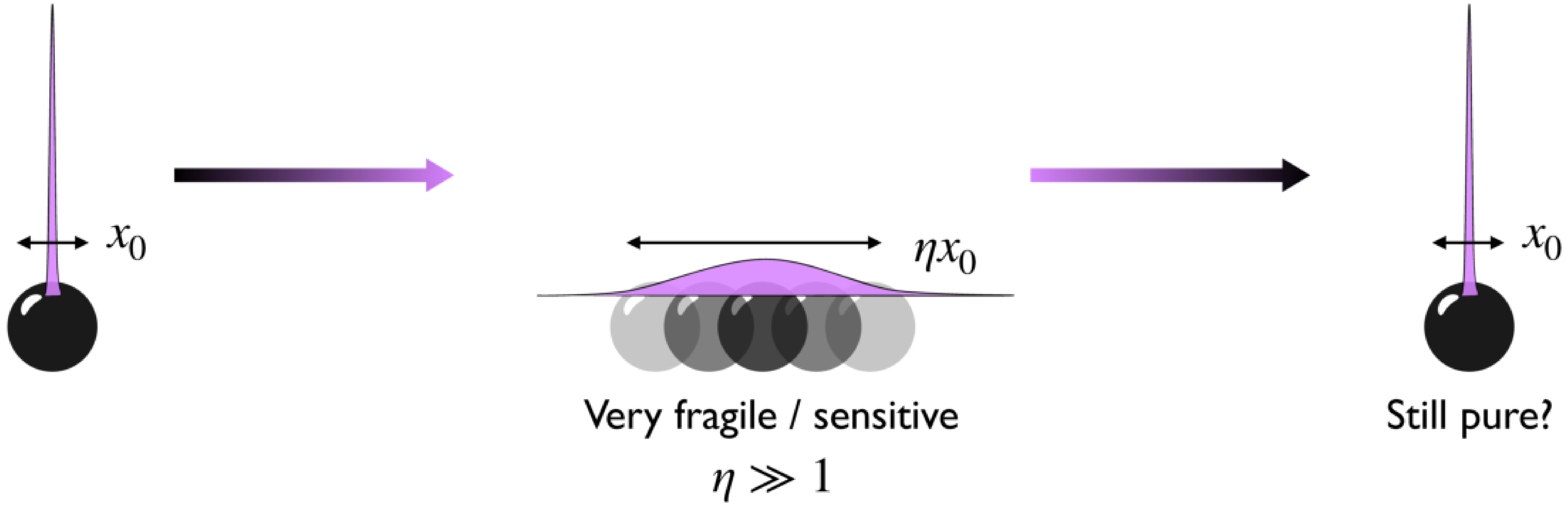
$$\sqrt{\langle \hat{x}^2 \rangle} \gtrsim R \sim 10^{-7}\ \text{m}$$

quantum delocalization length scale

- 3 key ingredients in levitodynamics:
  1. Ground-state cooling
  2. High-degree of isolation (coherence)
  3. Tunable potentials (e.g. inverted)

Optimal loop protocol

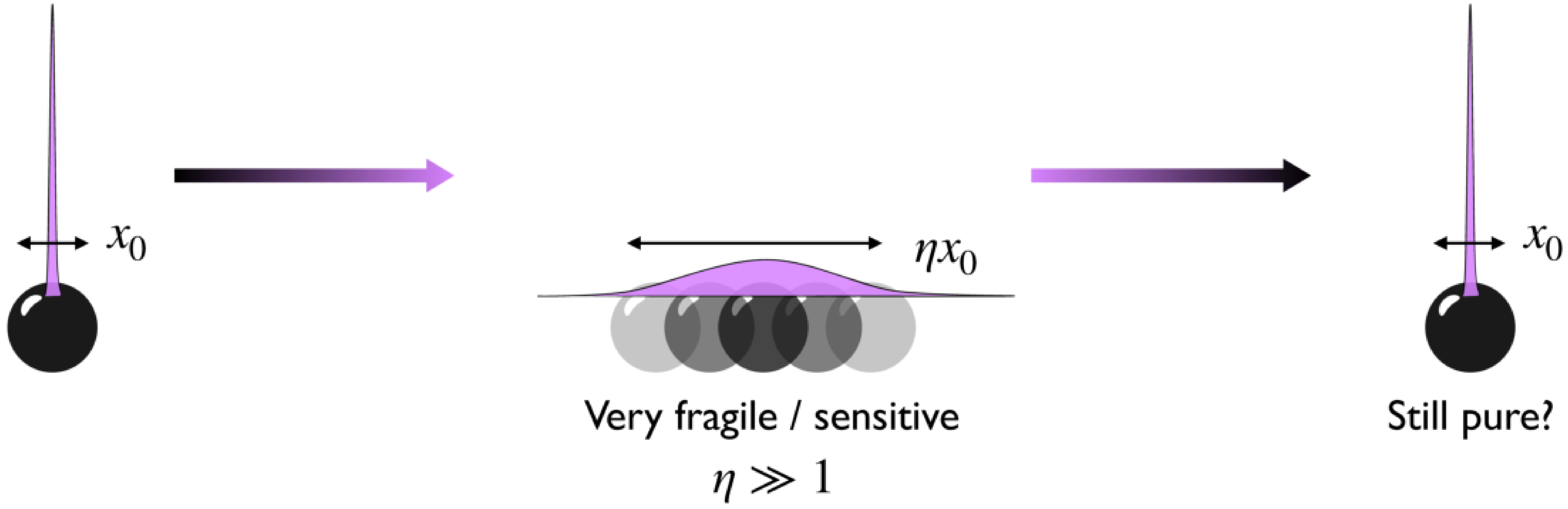
- Loop protocol



- Less decoherence
- More control (repeatability)
- Easier to measure purity

Optimal loop protocol

- Loop protocol

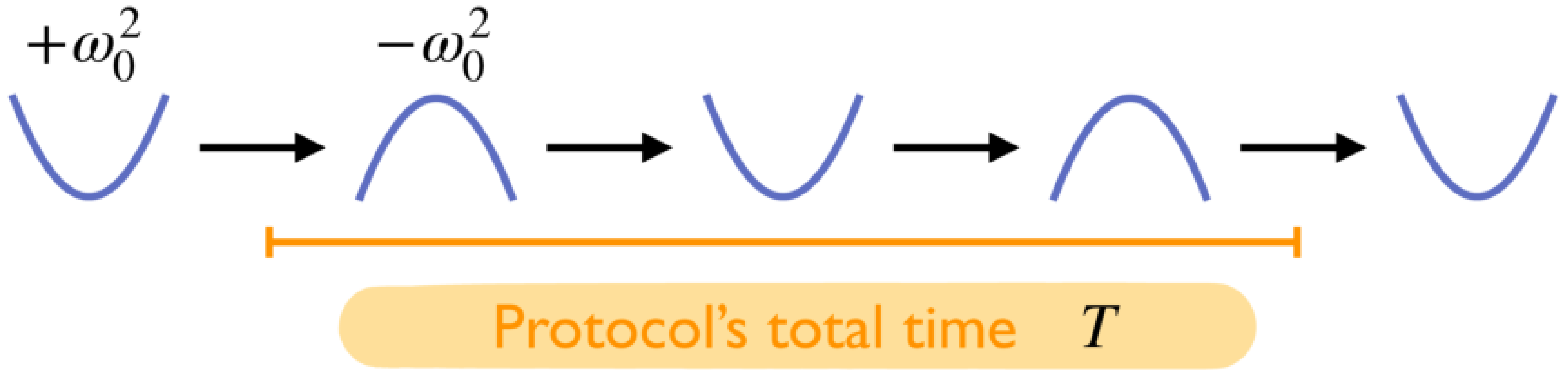


- Control of the harmonic potential

$$\hat{H}(t) = \frac{\hat{p}^2}{2m} + \frac{1}{2} m\omega(t)^2 \hat{x}^2$$

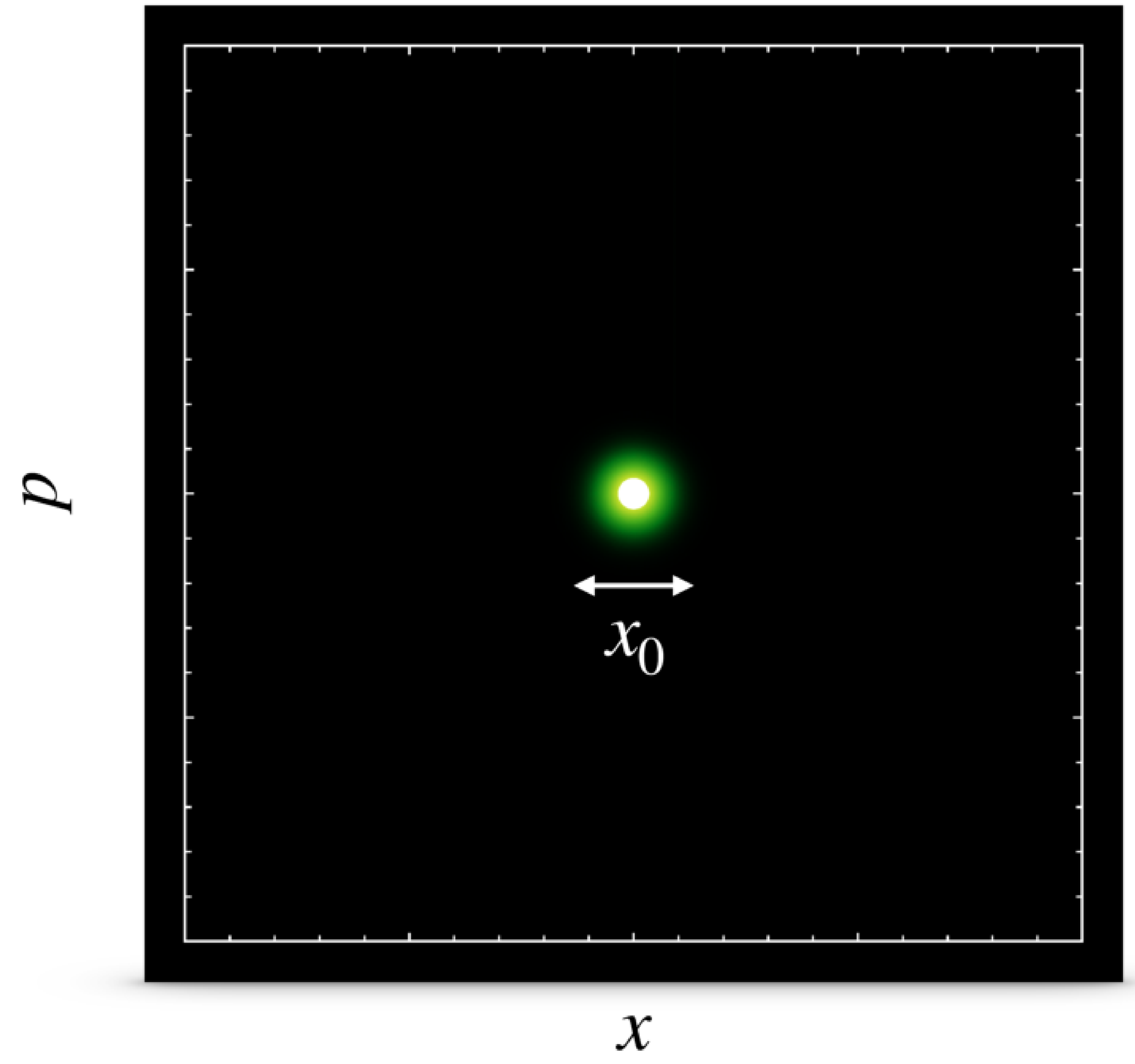
$$-\omega_0^2 \leq \omega^2(t) \leq \omega_0^2$$

- Time-optimal solution (bang-bang)



Optimal loop protocol

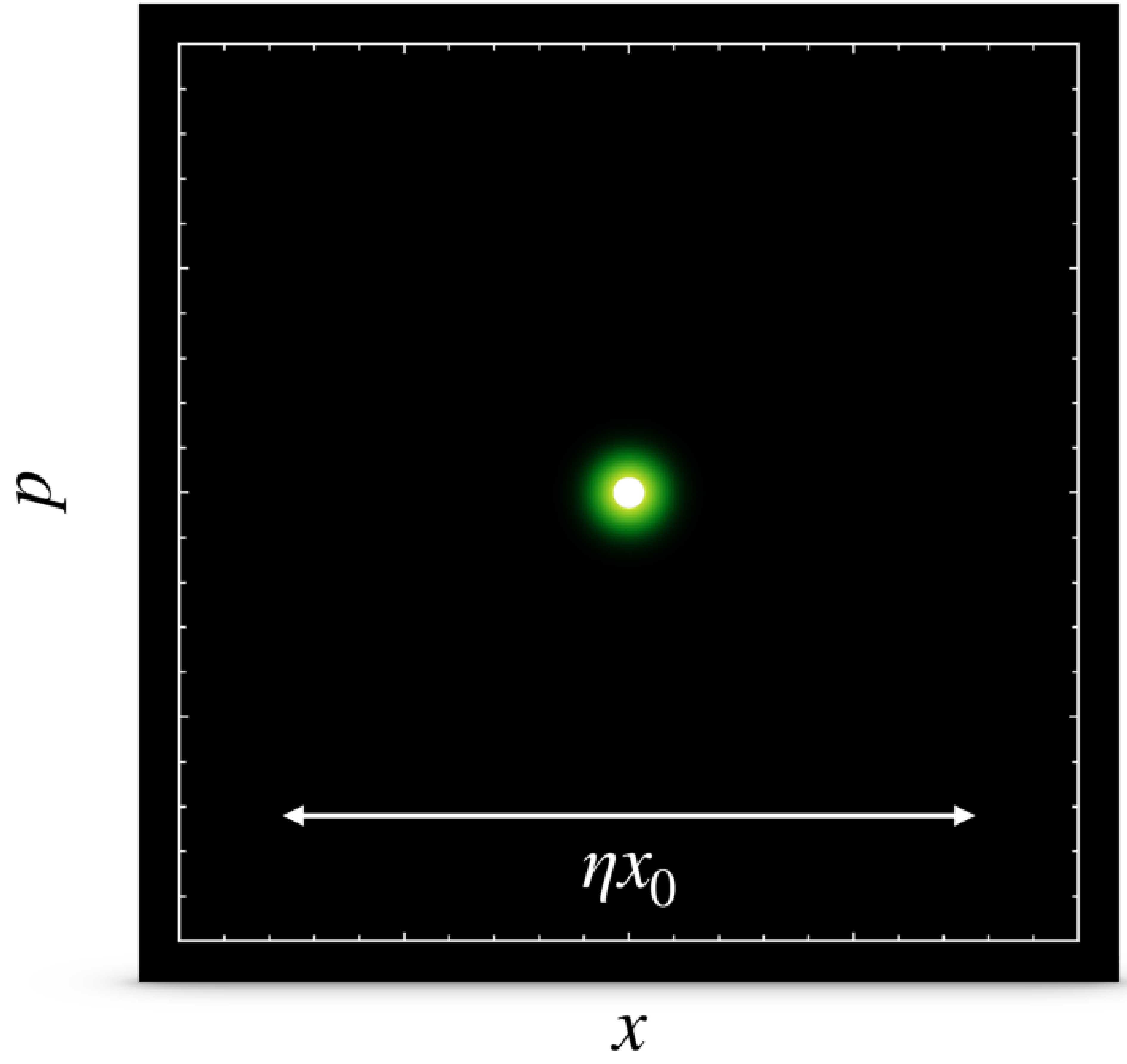
- Loop protocol



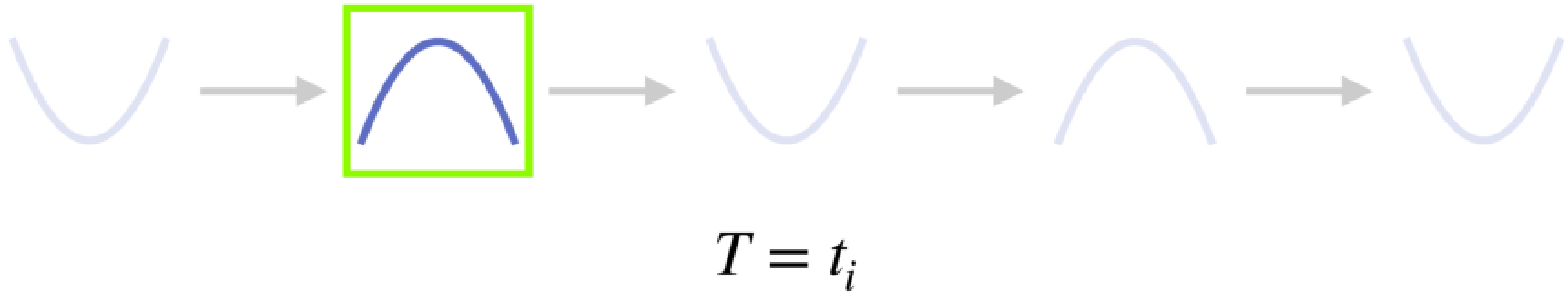
- Motional ground state

Optimal loop protocol

- Loop protocol

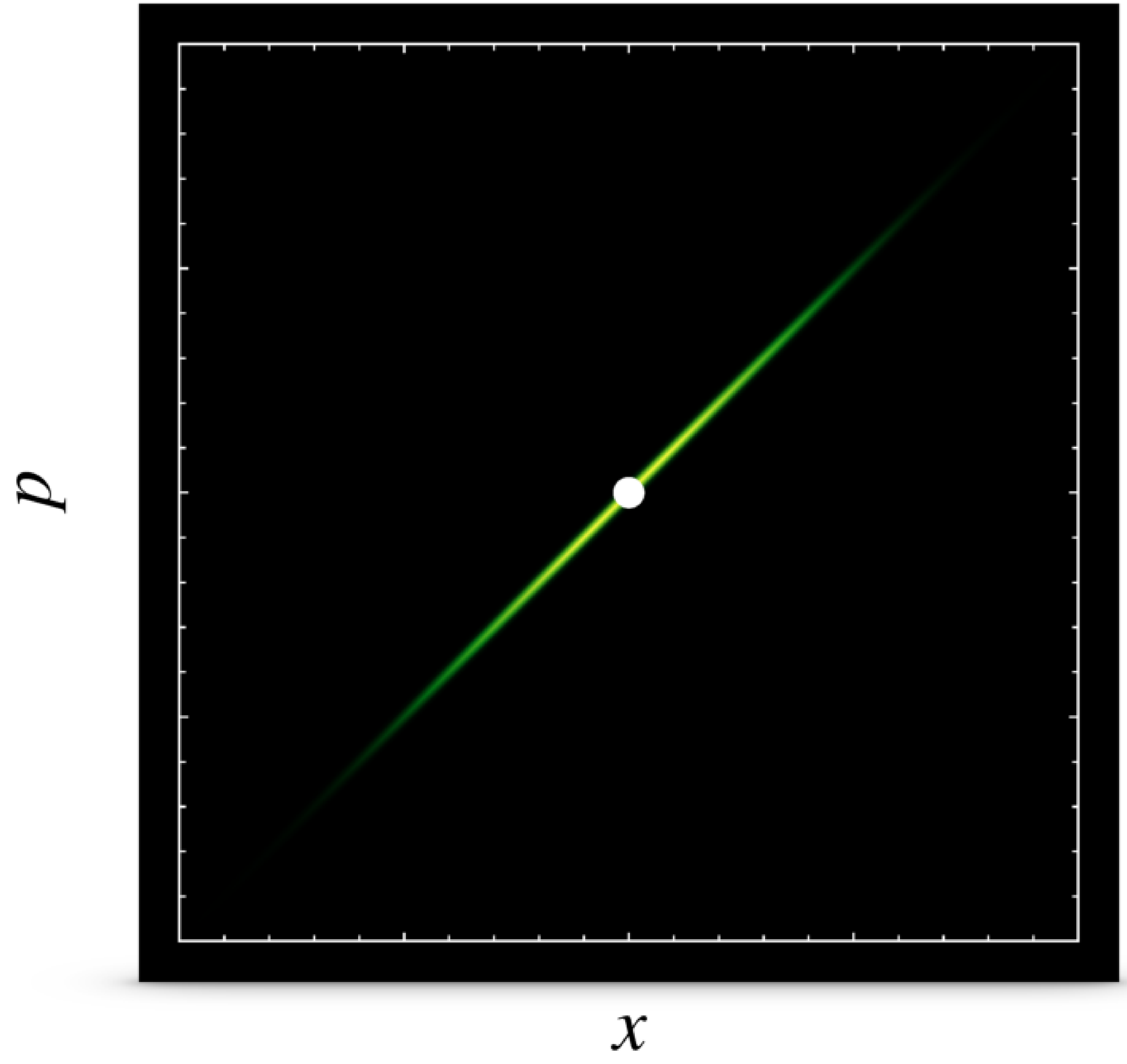


- Coherent expansion
- Exponential growth $\eta = e^{t_i \omega_0}$
- Squeezed state



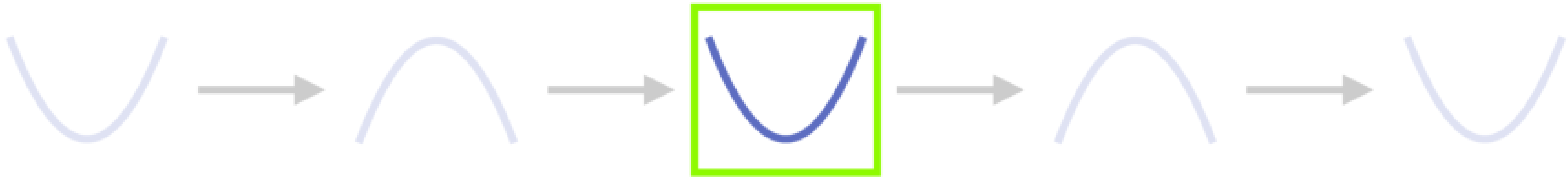
Optimal loop protocol

- Loop protocol



- Rotation

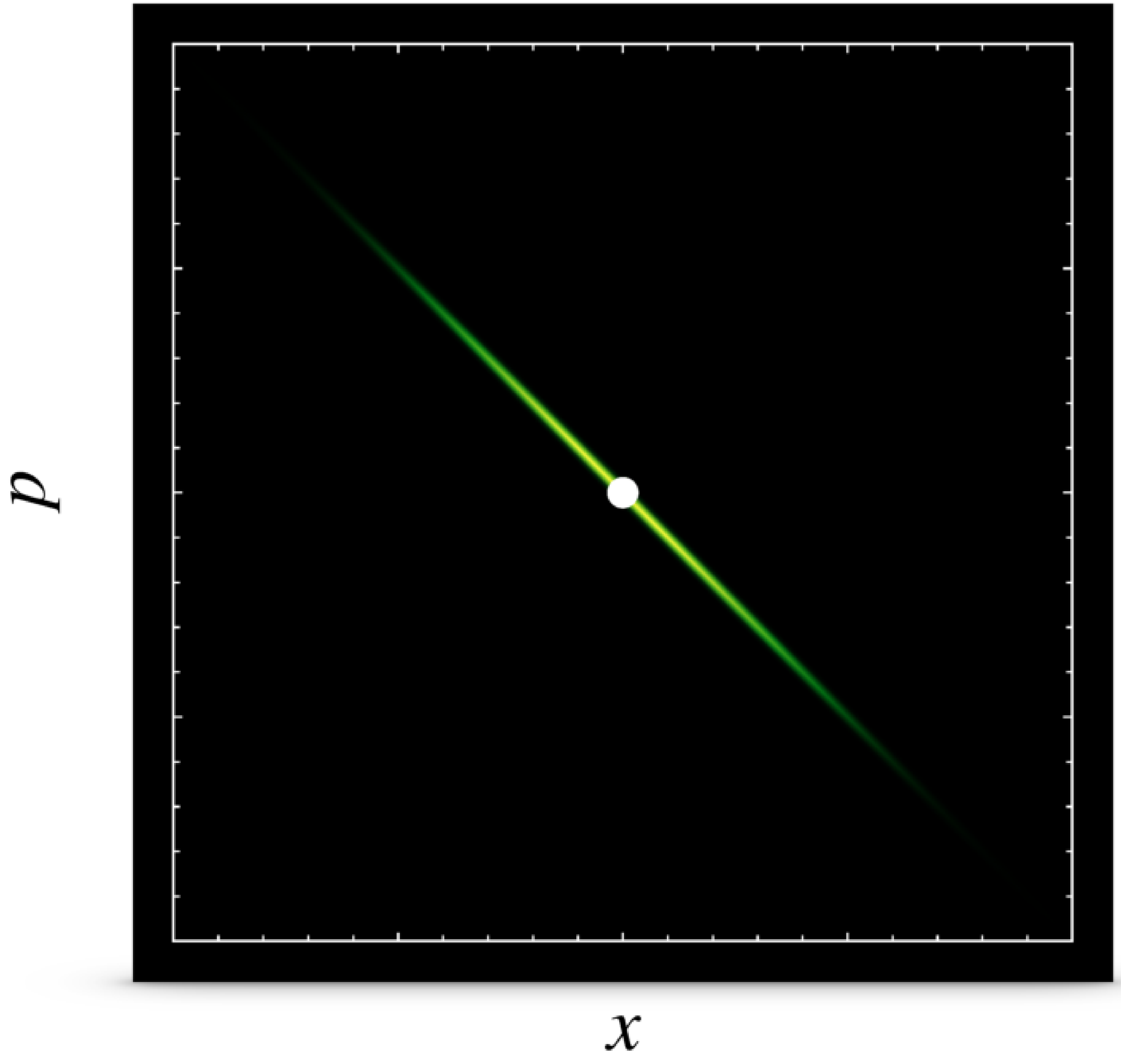
$$t_h\omega_0 = \frac{\pi}{2}$$



$$T = t_i + \frac{\pi}{2\omega_0}$$

Optimal loop protocol

- Loop protocol

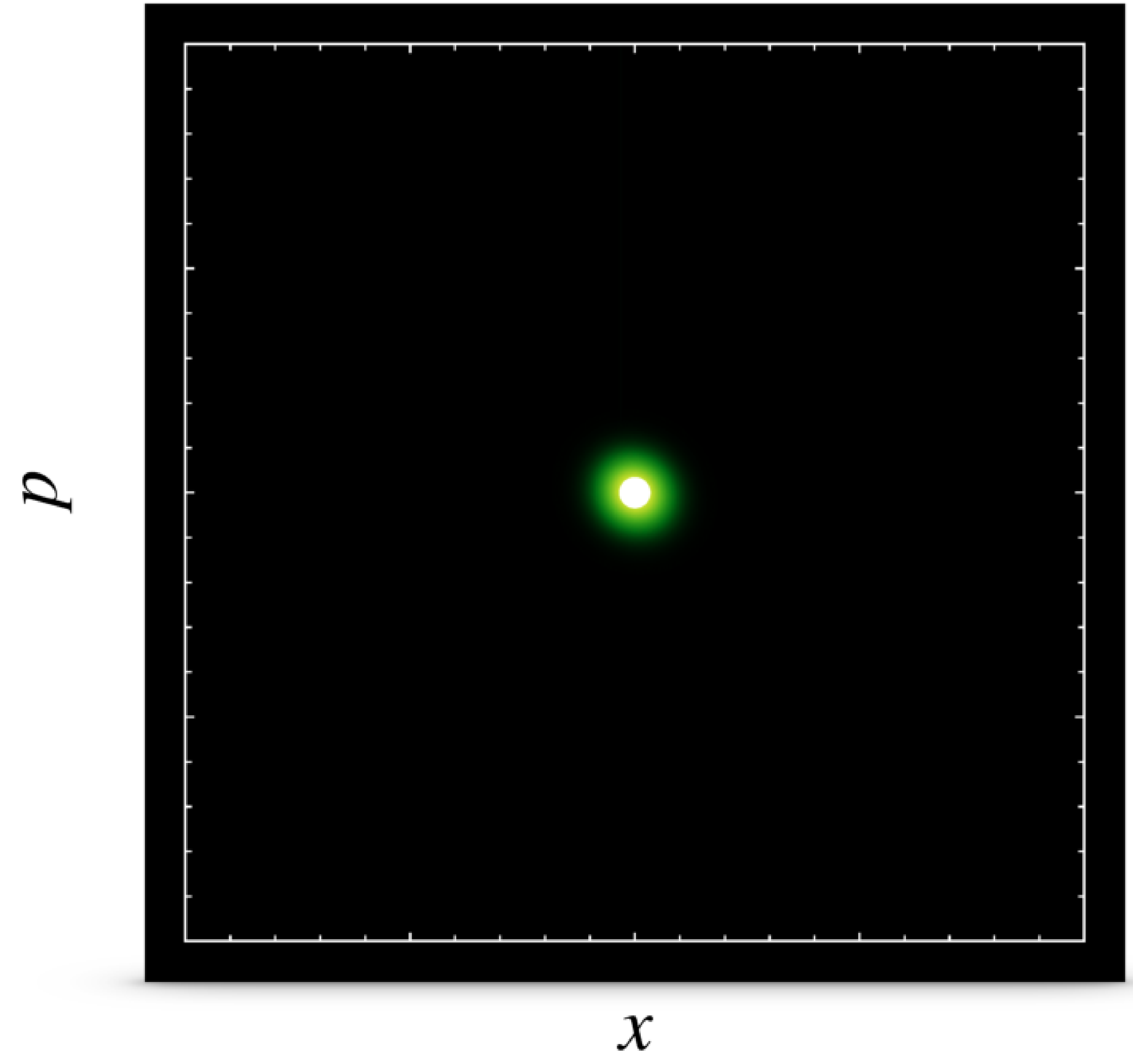


- Contraction
- Recovers initial state

$$T = t_i + \frac{\pi}{2\omega_0} + t_i$$

Optimal loop protocol

- Loop protocol

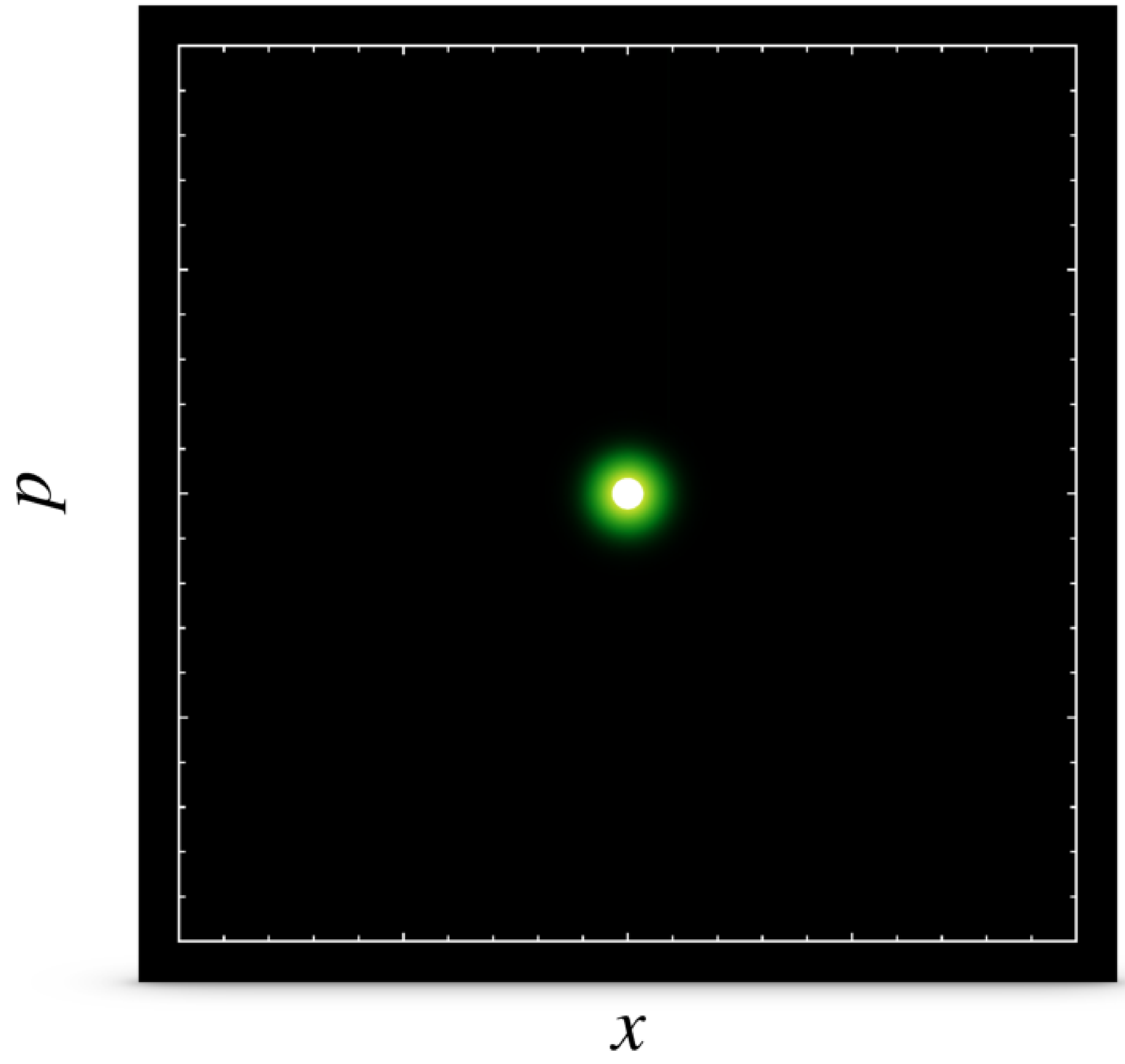


- Protocol finishes

$$T = t_i + \frac{\pi}{2\omega_0} + t_i$$

Optimal loop protocol

- Loop protocol



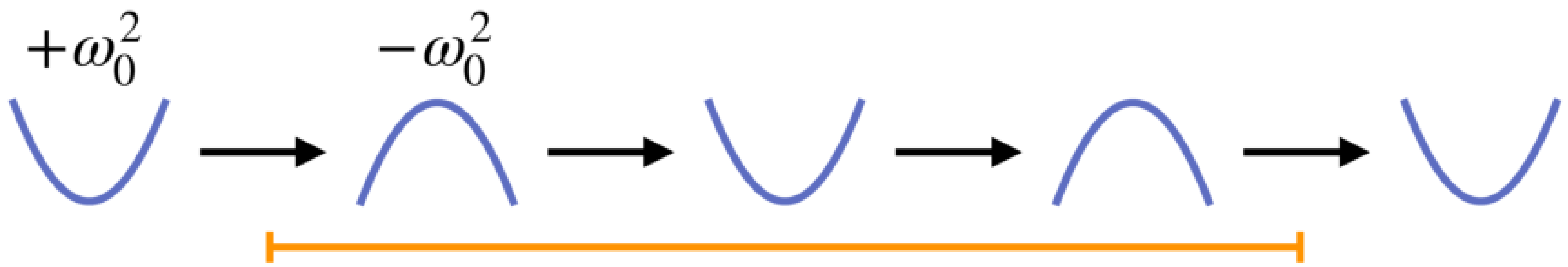
- Exponential growth $\eta = e^{t_i \omega_0}$

- Recovers initial state

$$\hat{U}_{loop} \equiv \hat{U}_i(t_i)\hat{U}_h(\pi/2\omega_0)\hat{U}_i(t_i) = \hat{U}_h(\pi/2\omega_0)$$

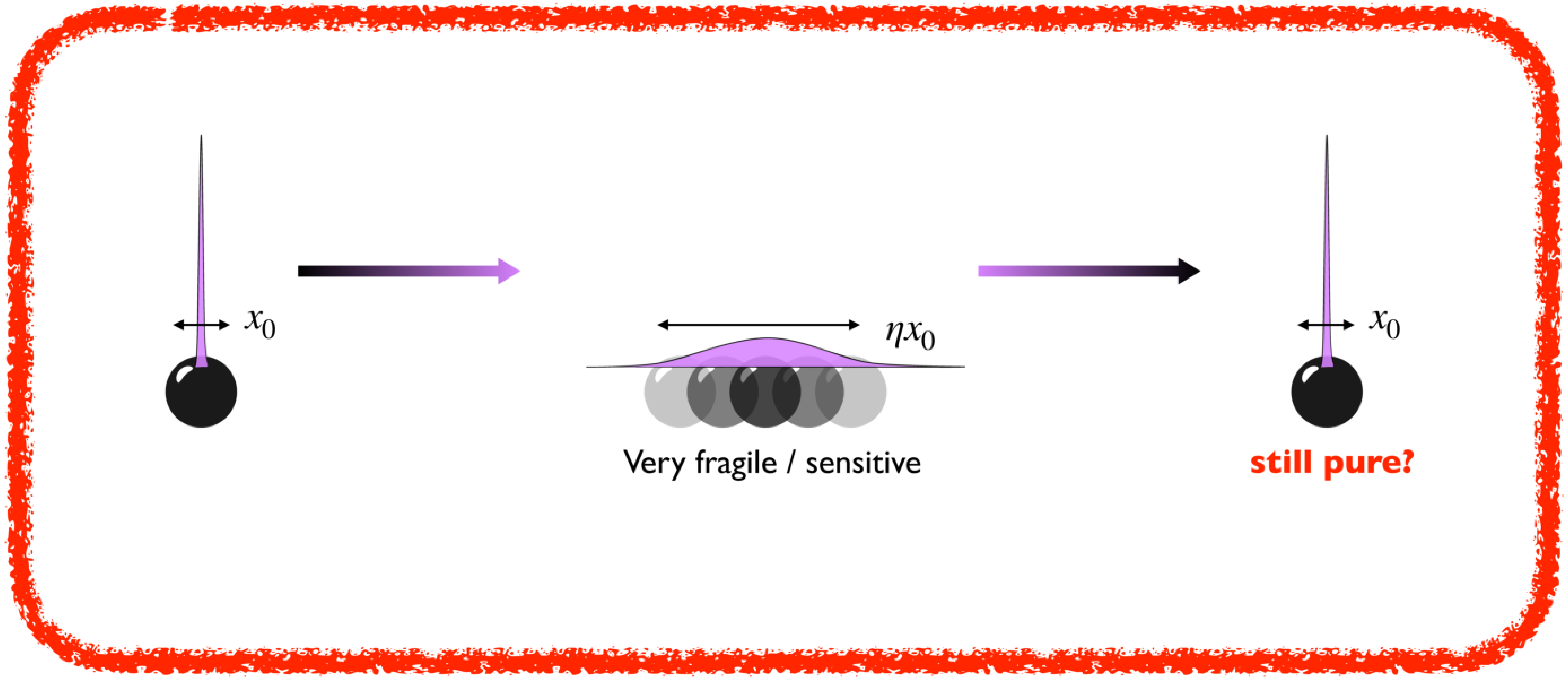
$\hat{U}_{h(i)}(t)$ unitary time evolution operator with harmonic (inverted) potential

- Time-optimal solution (bang-bang)



Protocol's total time $T = 2t_i + \dfrac{\pi}{2\omega_0}$

Decoherence



Environment / Noise

Decoherence

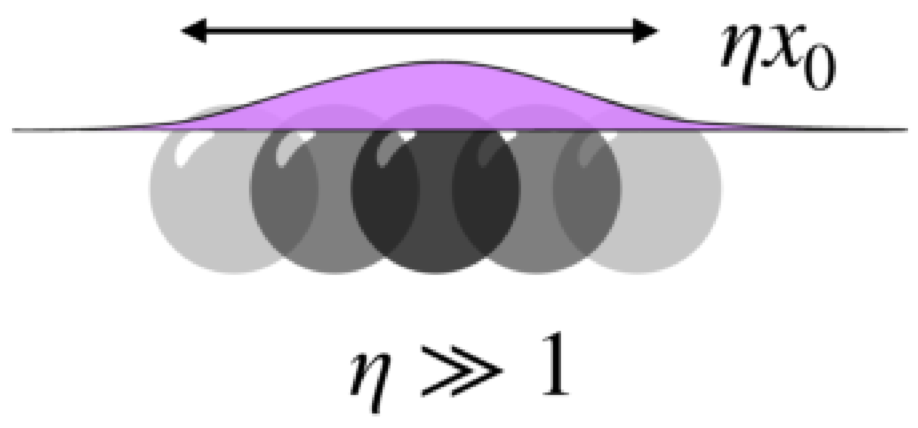
- Scattering of air molecules
  - Loop is faster than a single scattering event

$$\omega_0 T \ll \omega_0/\gamma_{air} \approx 100 \;@\; 10^{-9}\text{mbar}$$

- Displacement noise
  - Recoil heating, vibrations, black-body radiation

$$\dot{\hat{\rho}}(t) = \frac{i}{\hbar}[\hat{\rho}(t), \hat{H}] - \frac{\Gamma_1}{x_0^2}[\hat{x}, [\hat{x}, \hat{\rho}(t)]]$$

Decoherence rate $\sim \Gamma_1 \eta^2$



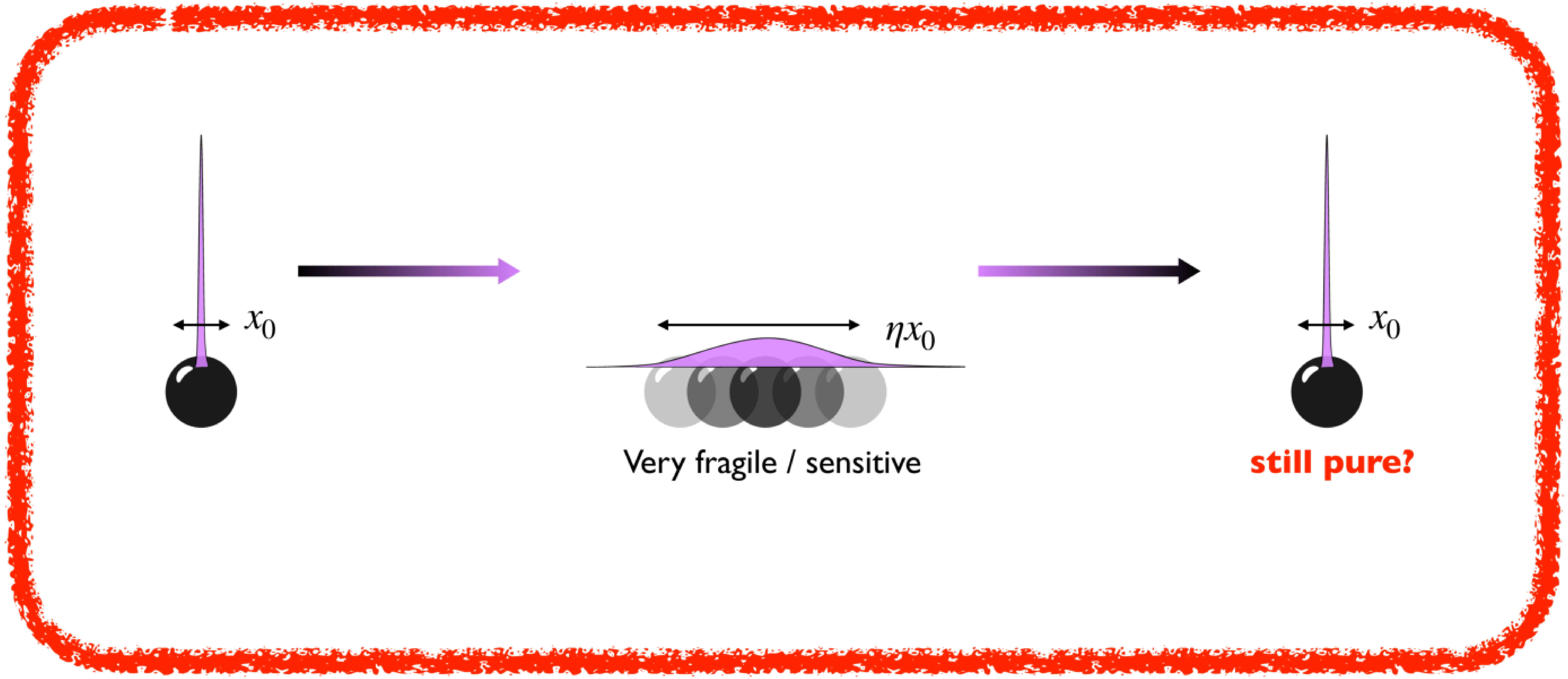
- Frequency noise
  - Relative intensity noise, time switch errors

$$\dot{\hat{\rho}}(t) = \frac{i}{\hbar}[\hat{\rho}(t), \hat{H}] - \frac{\Gamma_2}{x_0^4}[\hat{x}^2, [\hat{x}^2, \hat{\rho}(t)]]$$

Decoherence rate $\sim \Gamma_2 \eta^4$

ORI, PRA **84**, 052121 (2011)

Decoherence

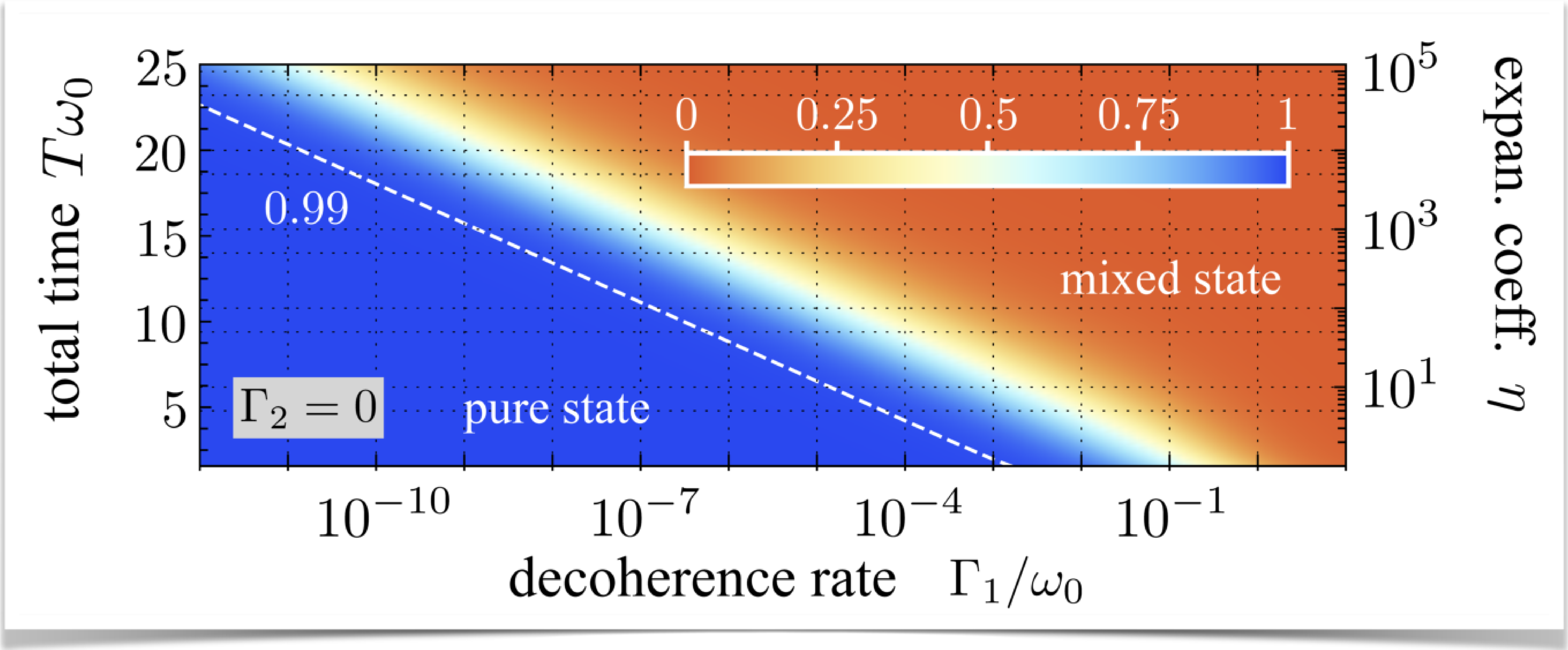


Environment / Noise

Decoherence

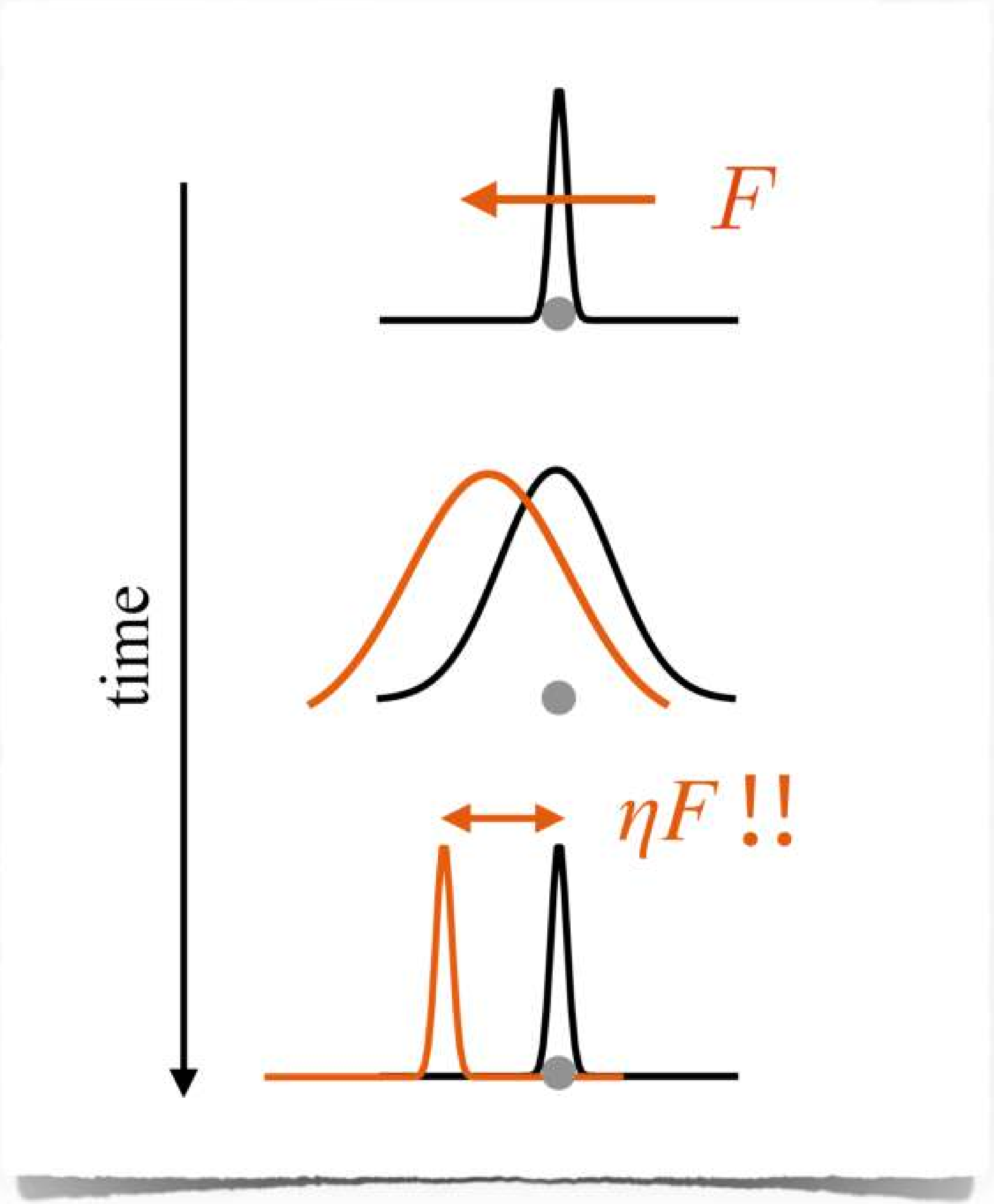
- Final purity in the presence of displacement noise

$$\text{Purity} = \text{tr}\left[\hat{\rho}^2(t = T)\right]$$

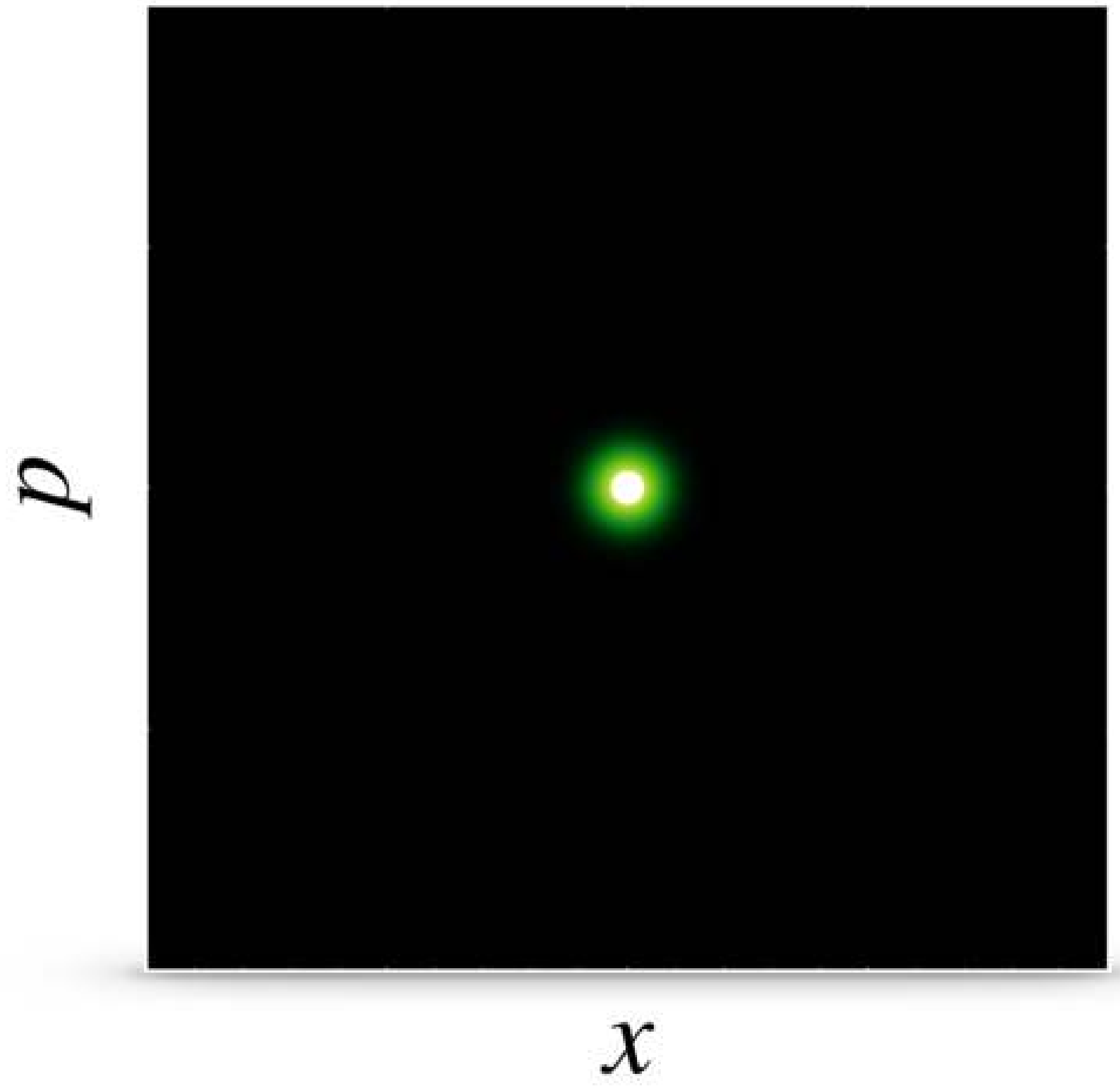


Static force sensing

- Enhanced force sensing



$$\hat{H}^f(t) = \hat{H}(t) + F\hat{x}$$



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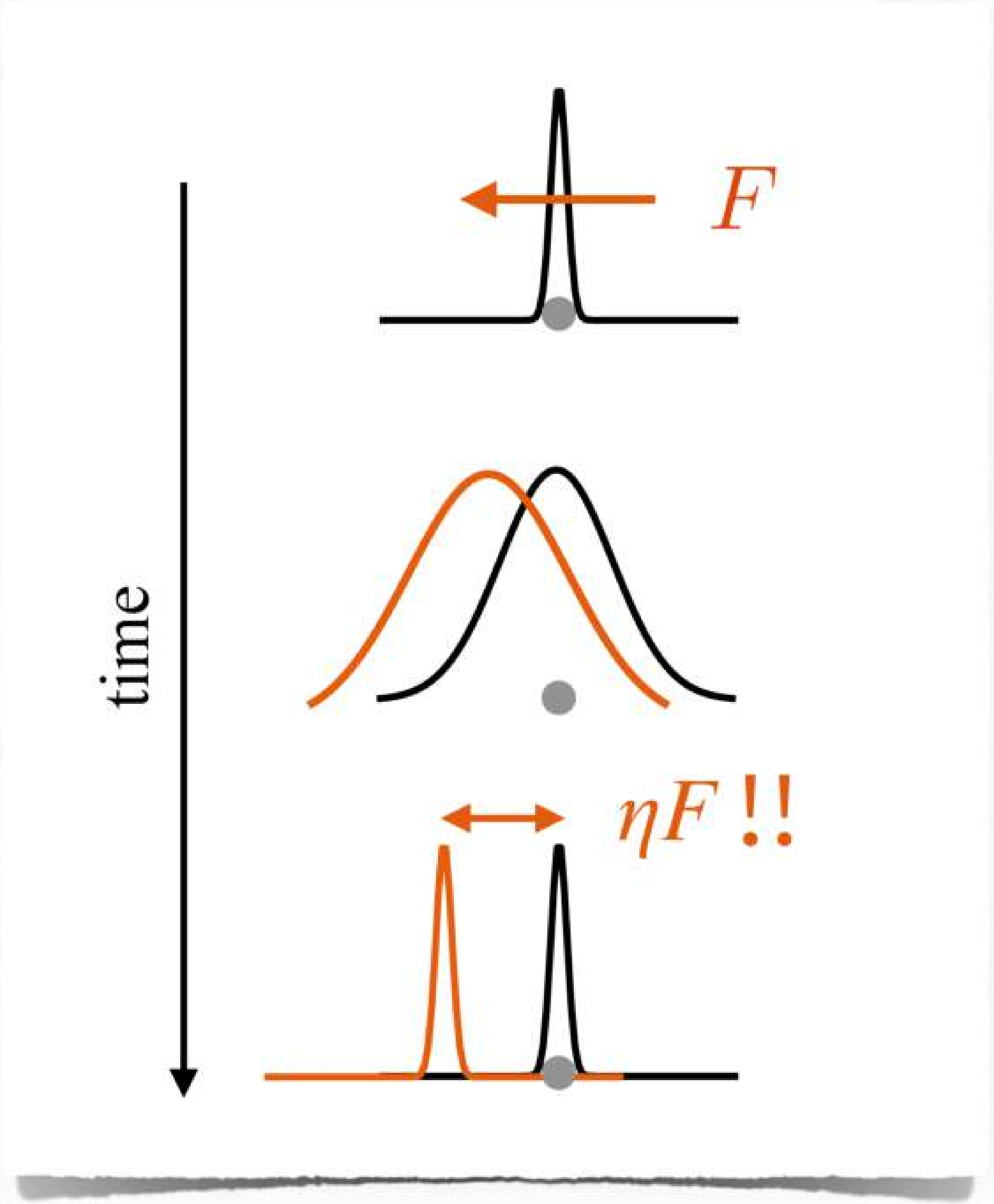
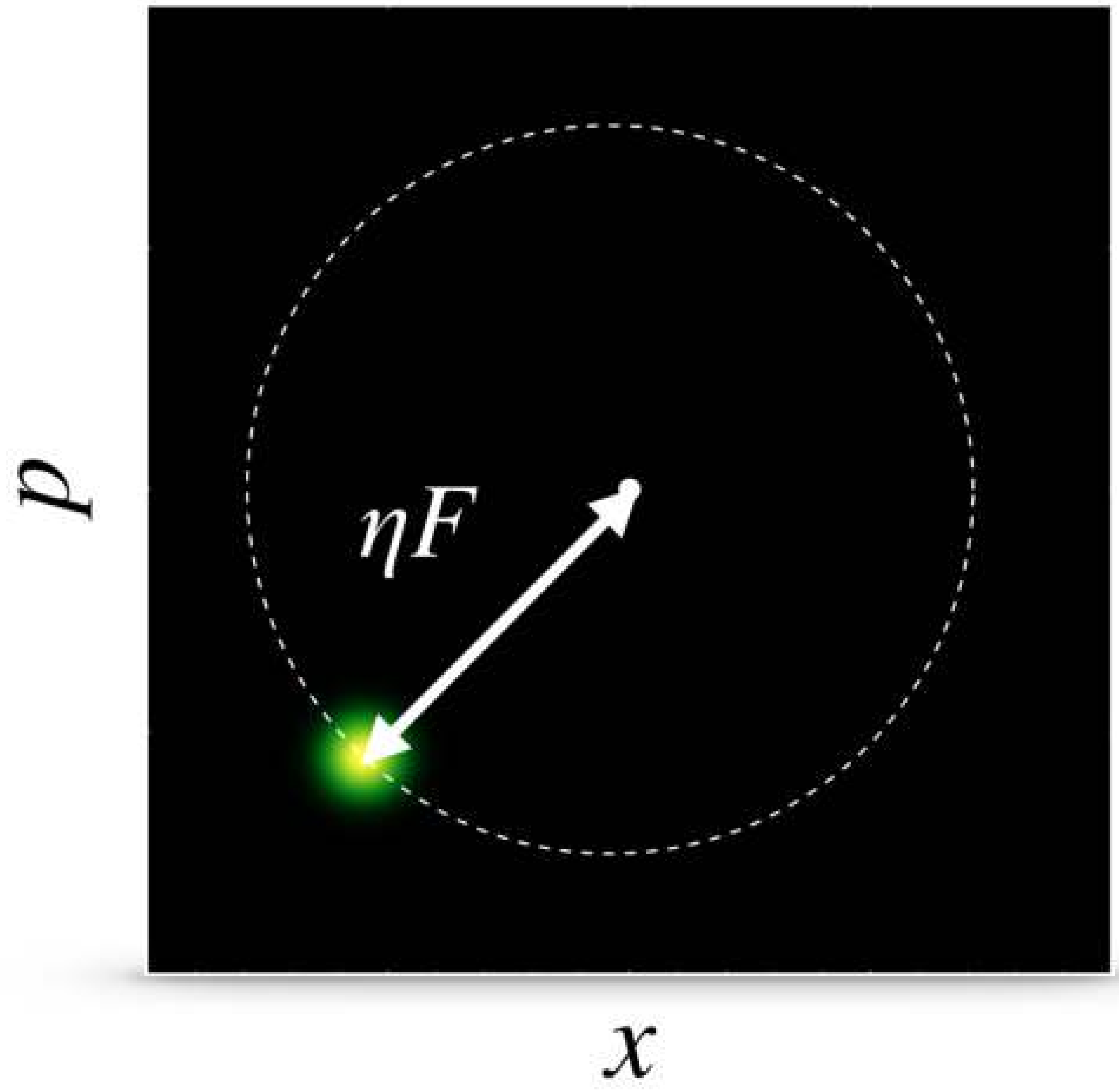


$$\hat{H}^f(t) = \hat{H}(t) + F\hat{x}$$



Static force sensing

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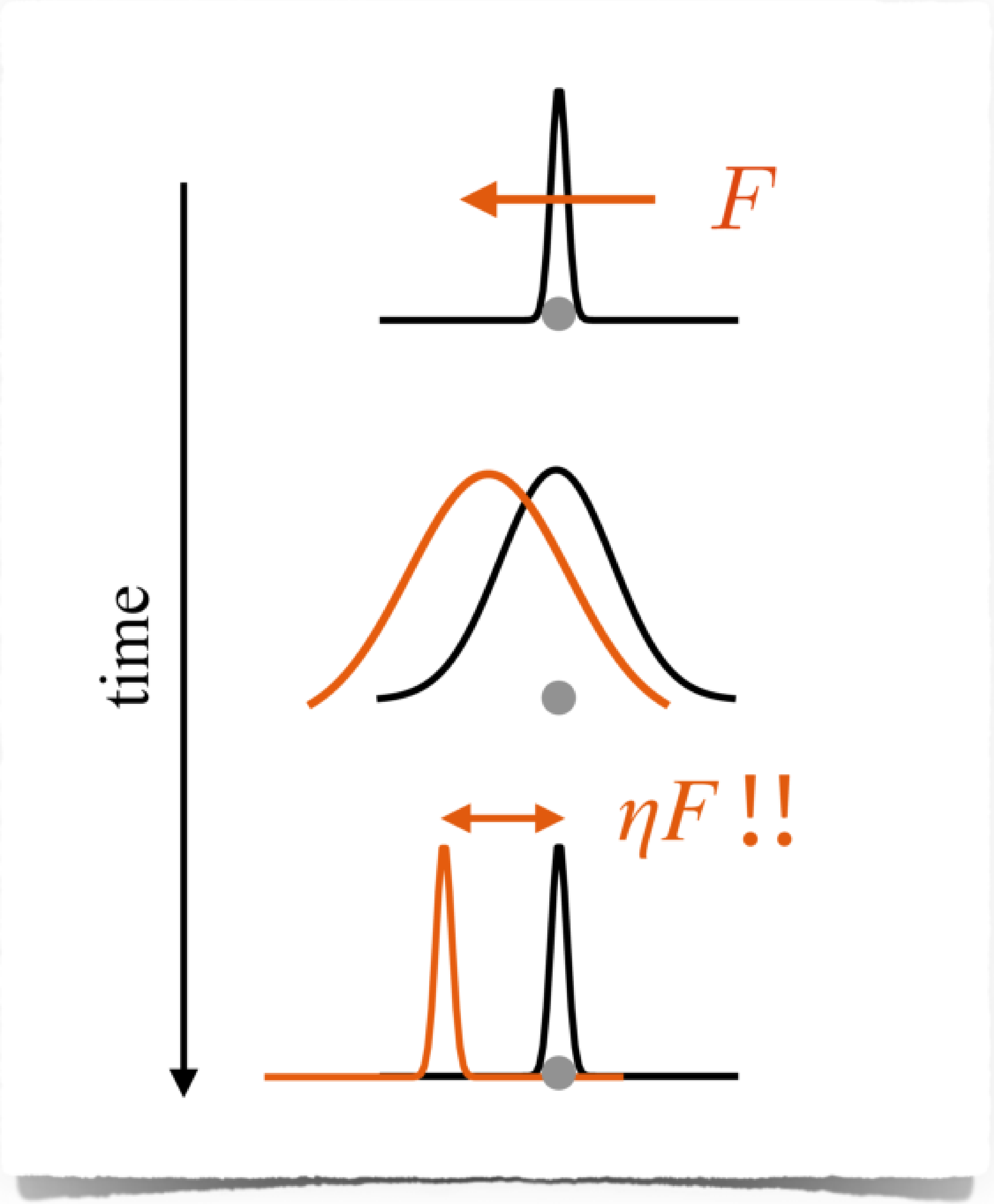
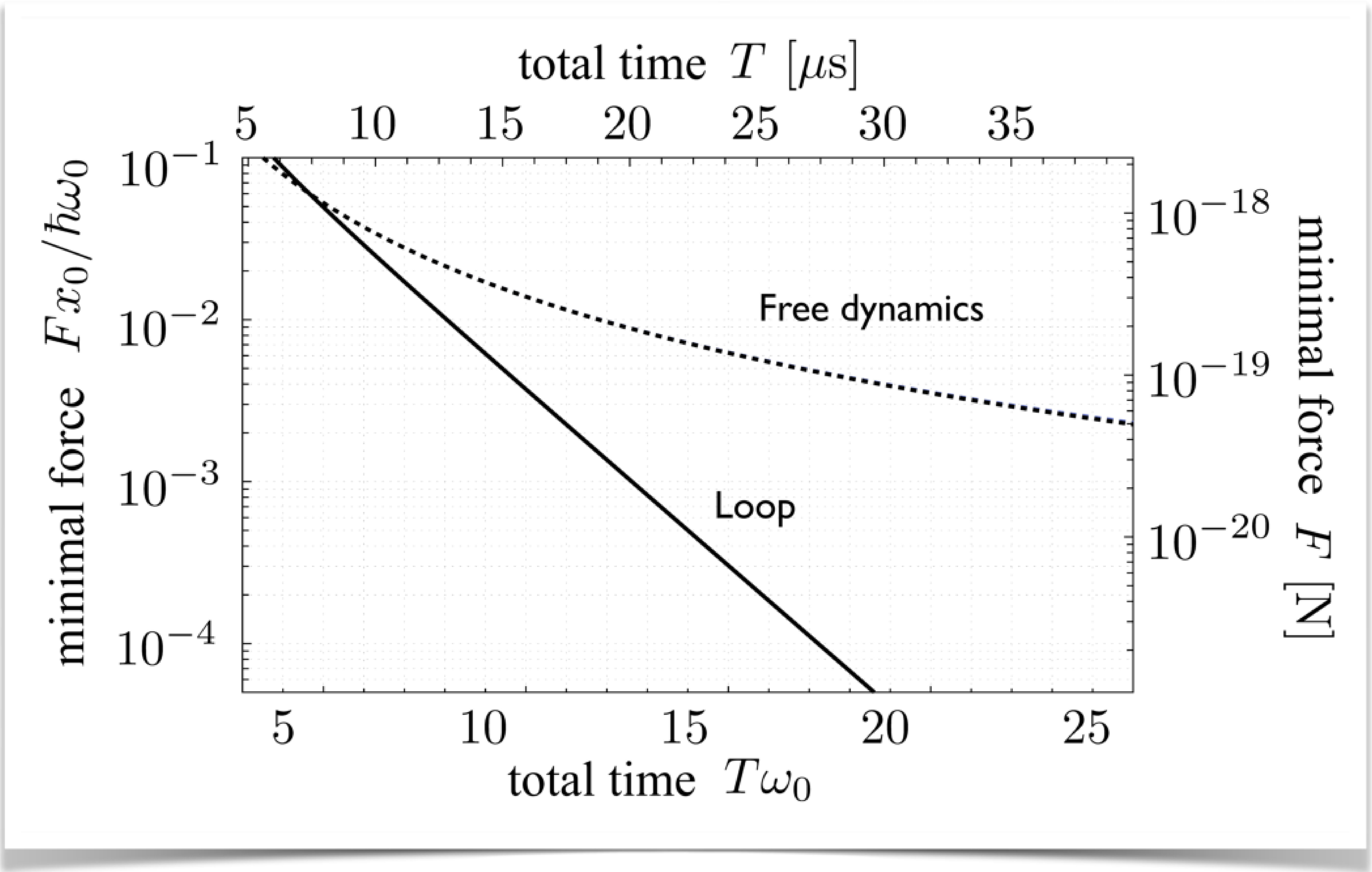


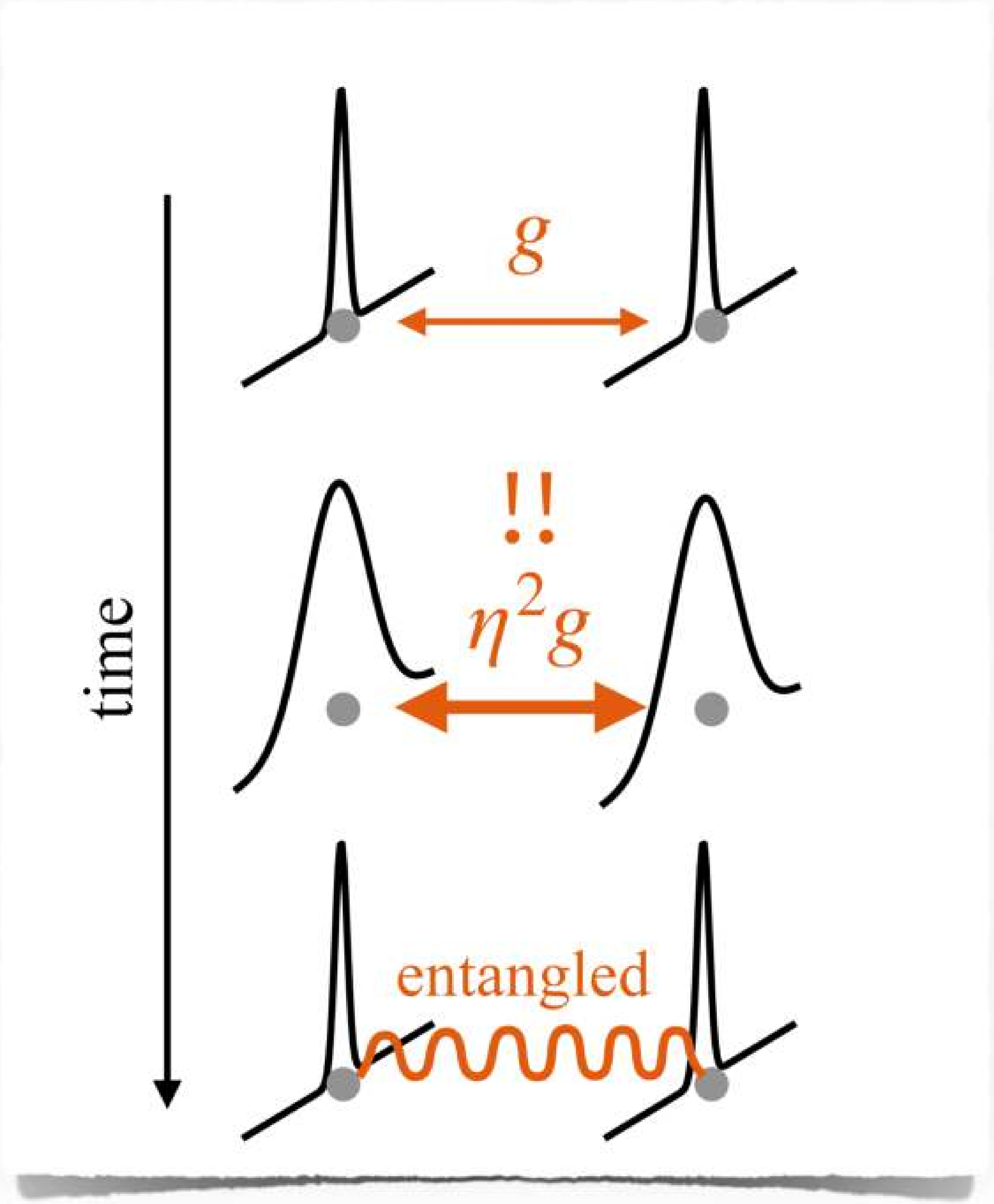
- Quantum Fisher information of the final state $\hat{\rho}(F)$

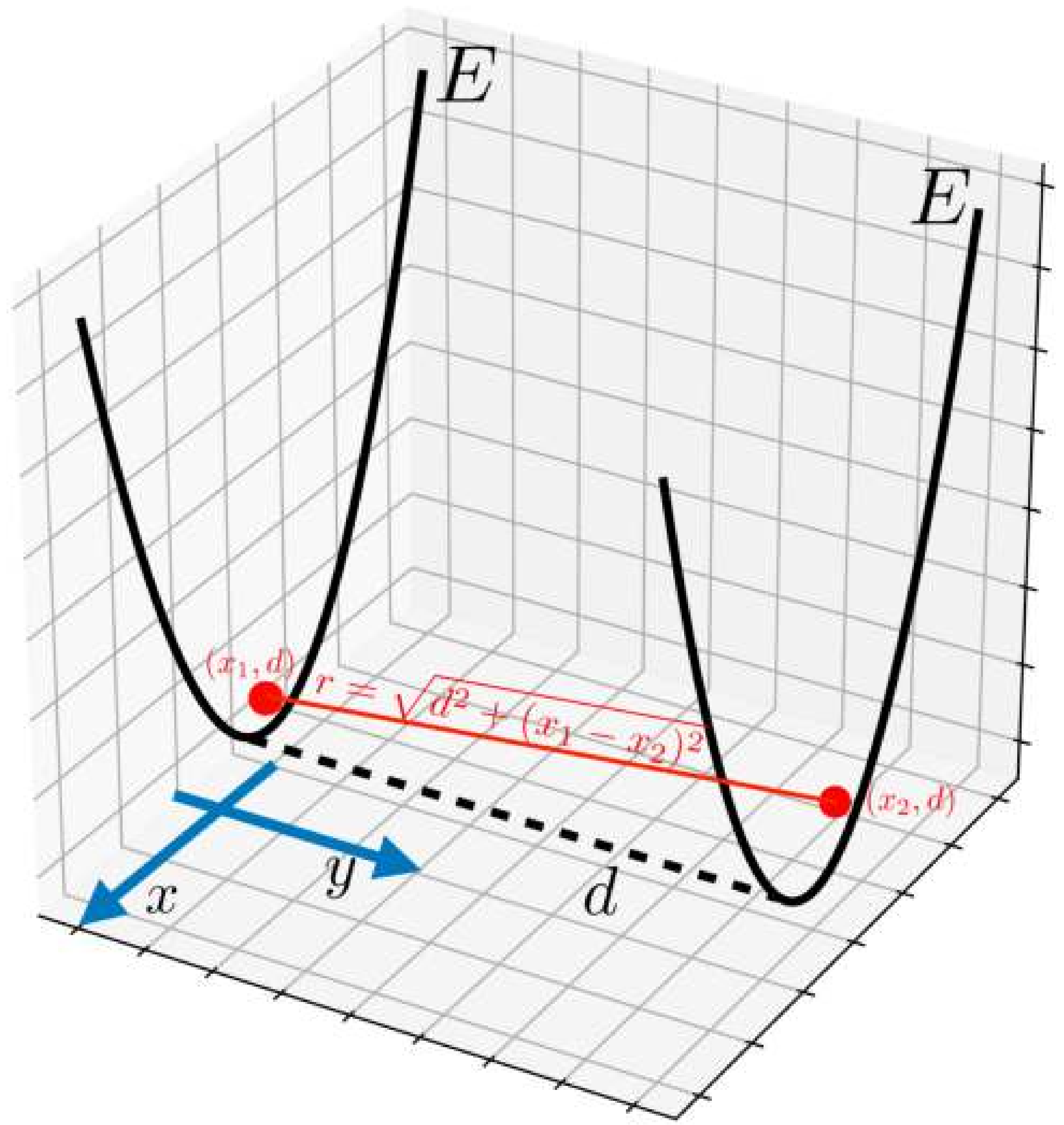


E. Hebestreit … L. Novotny, PRL **121**, 063602 (2018)

Entangling via weak interaction

- Enhanced entangling rate





Interaction:

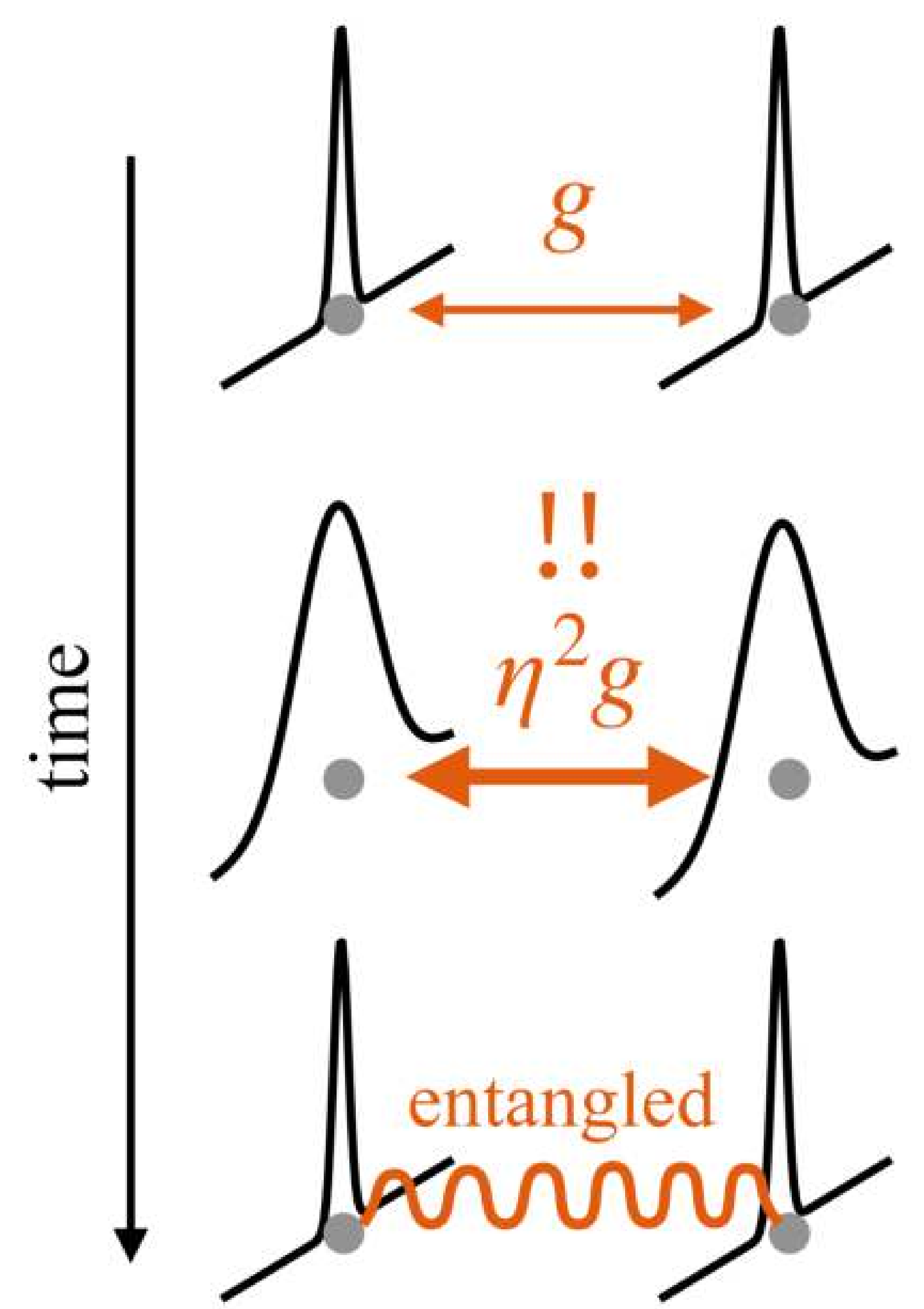
- Electrostatic
- Casimir
- Gravity
- …

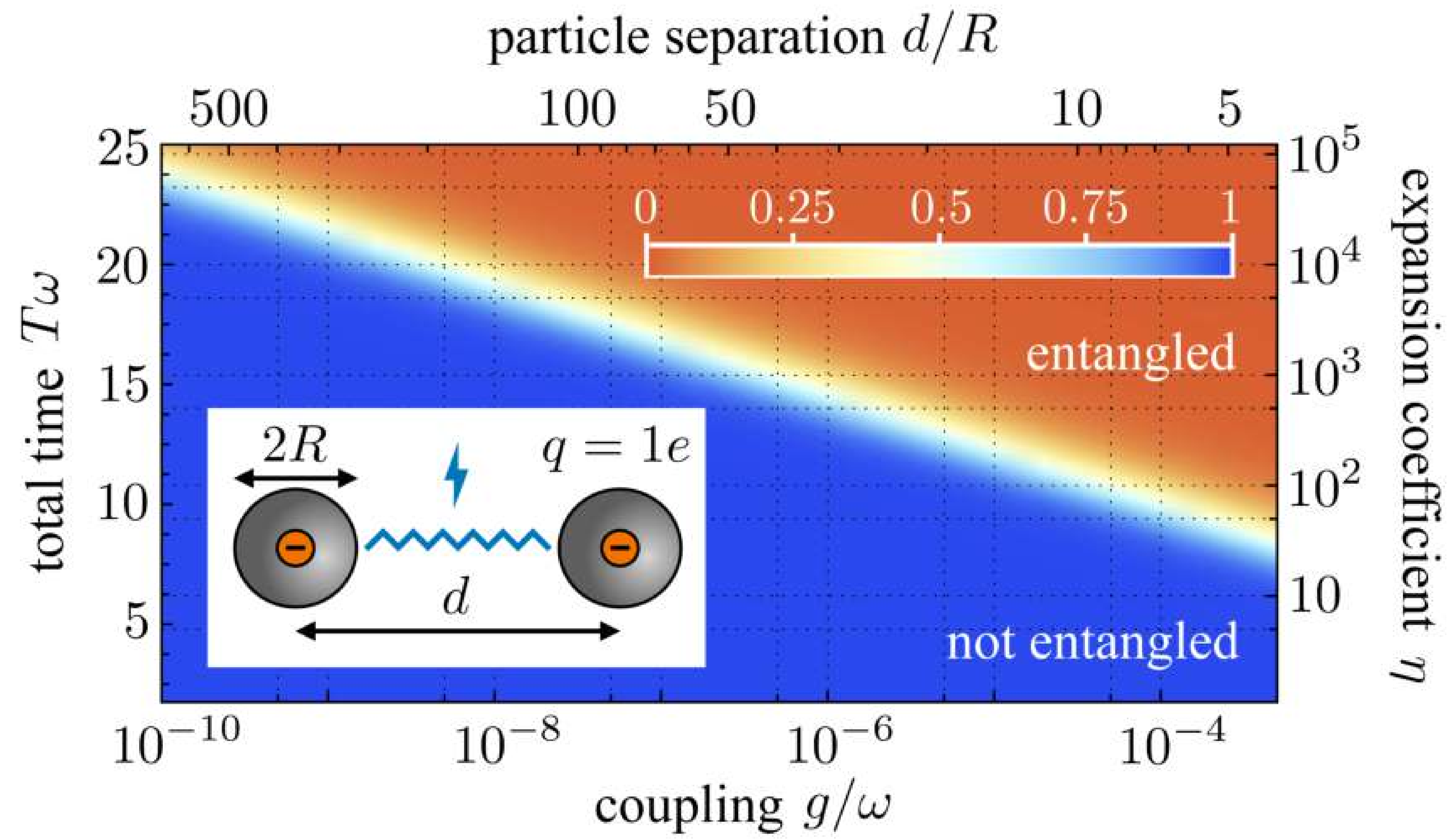
- Weak coupling rate

$$\hat{H}(t) = \sum_{i=1}^{2} \left[\frac{\hat{p}_i^{\,2}}{2m} + \frac{1}{2} m\omega^2(t)\hat{x}_i^{\,2} \right] + \frac{\hbar g}{x_0^2}\hat{x}_1\hat{x}_2$$

Entangling via weak interaction

- Enhanced entangling rate

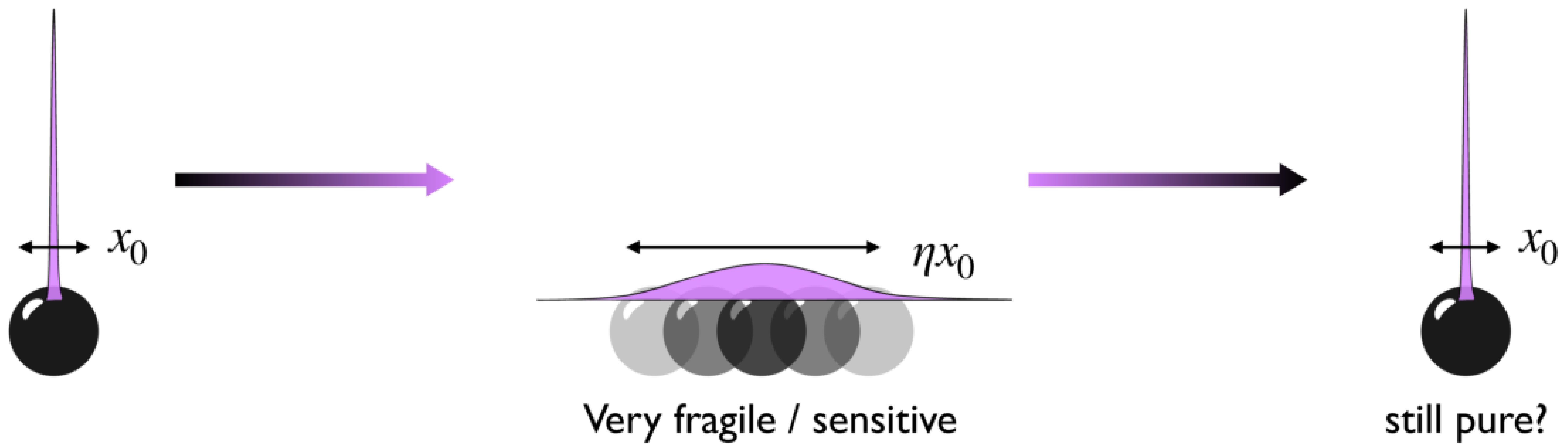




$$\hat{H}(t) = \sum_{i=1}^{2} \left[\frac{\hat{p}_i^{\,2}}{2m} + \frac{1}{2} m\omega^2(t)\hat{x}_i^{\,2} \right] + \frac{\hbar g}{x_0^2}\hat{x}_1\hat{x}_2$$

Conclusions

- Optimal loop protocol (fast and sensitive)



- Large quantum delocalization vs decoherence

- Enhanced force sensing and entanglement via weak forces

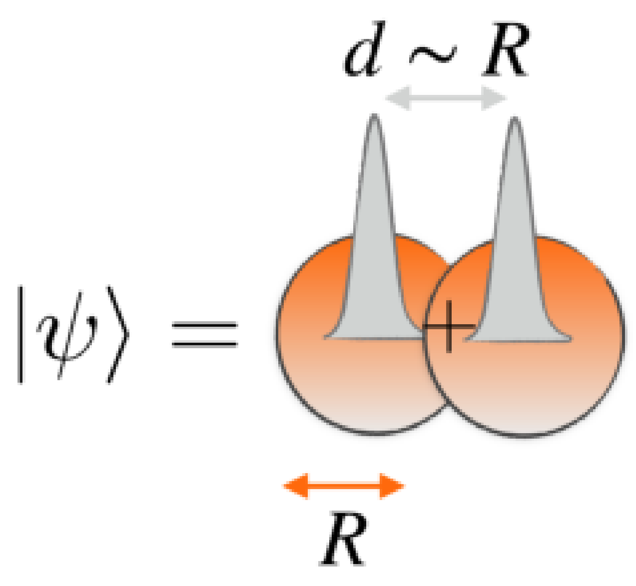
T. Weiss, M. Roda-Llordes, E. Torrontegui, … ORI arXiv: soon

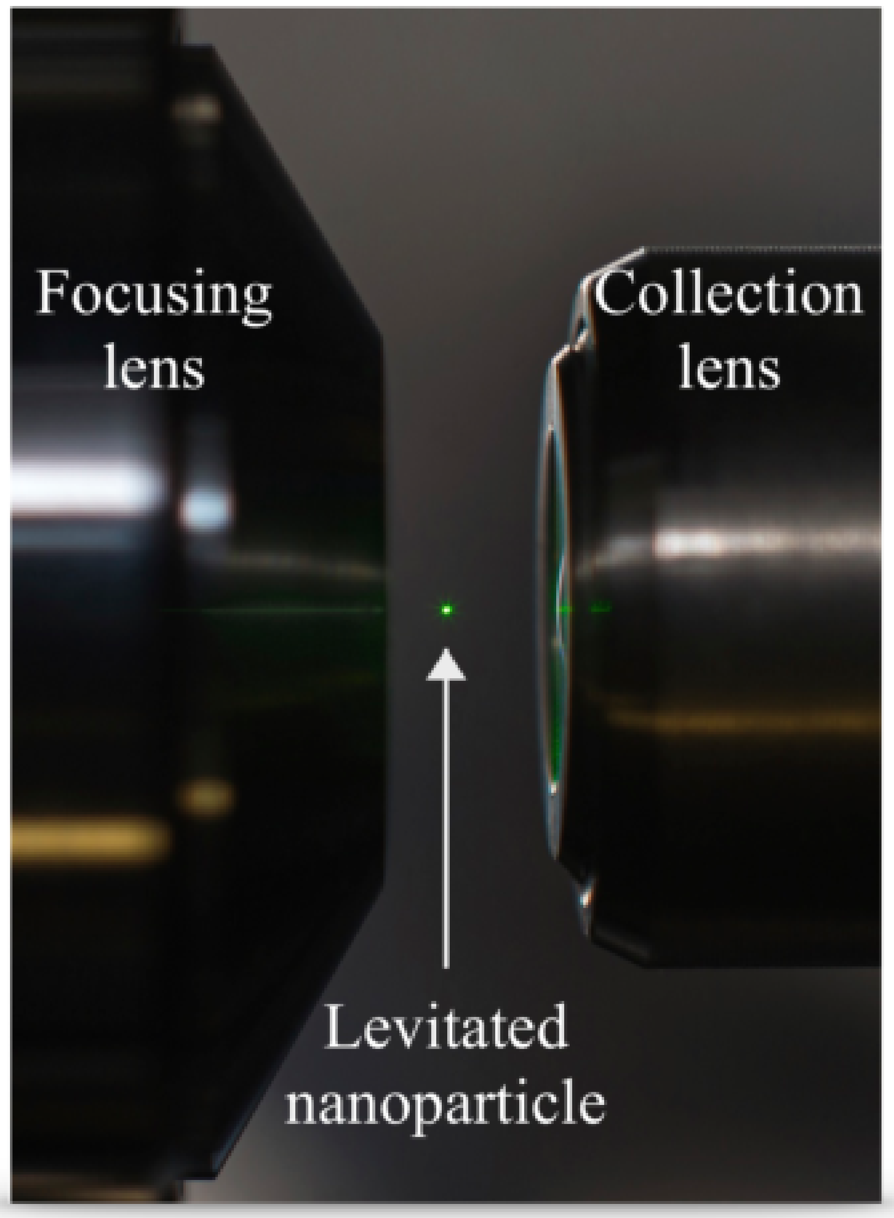
Q-Xtreme

- ERC Synergy Grant: Q-Xtreme (Macroscopic Quantum Superpositions)

European Research Council
Established by the European Commission

- Objective: levitated nanoparticle in large spatial quantum superpositions state





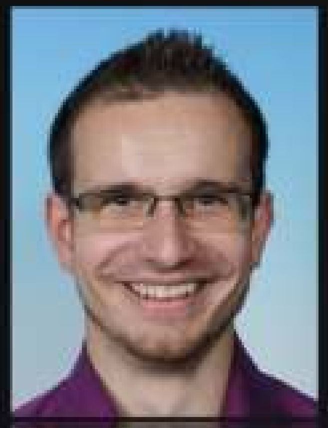
- Synergy Group: M. Aspelmeyer, L. Novotny, R. Quidant, and ORI

- Open positions! (starting on May 2021)

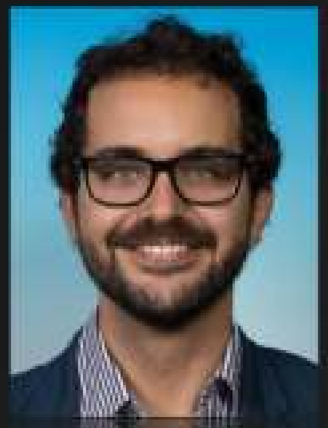
Thank you very much!

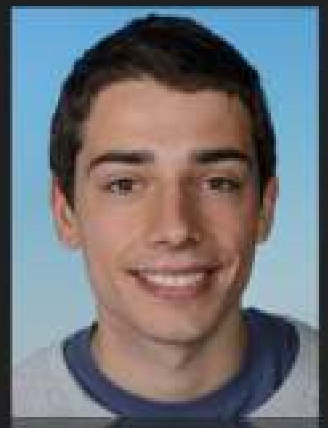
Looking for PhDs and PostDocs!


Patrick Maurer


Daniel Hümmer

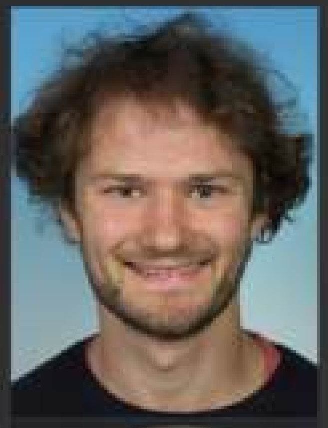

Katja Kustura

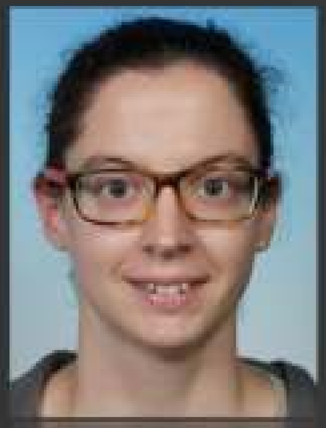

Carlos Gonzalez-Ballestero

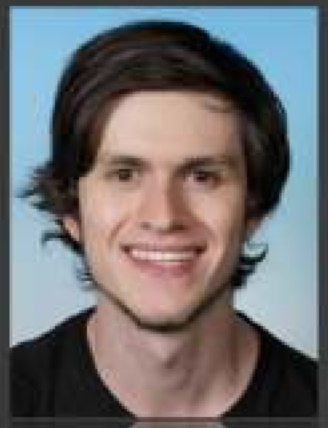

Marc Roda-Llordes


Sílvia Casulleras


Talitha Weiß


Daniele Giannandrea


Valentina Zeni


Callum Carver

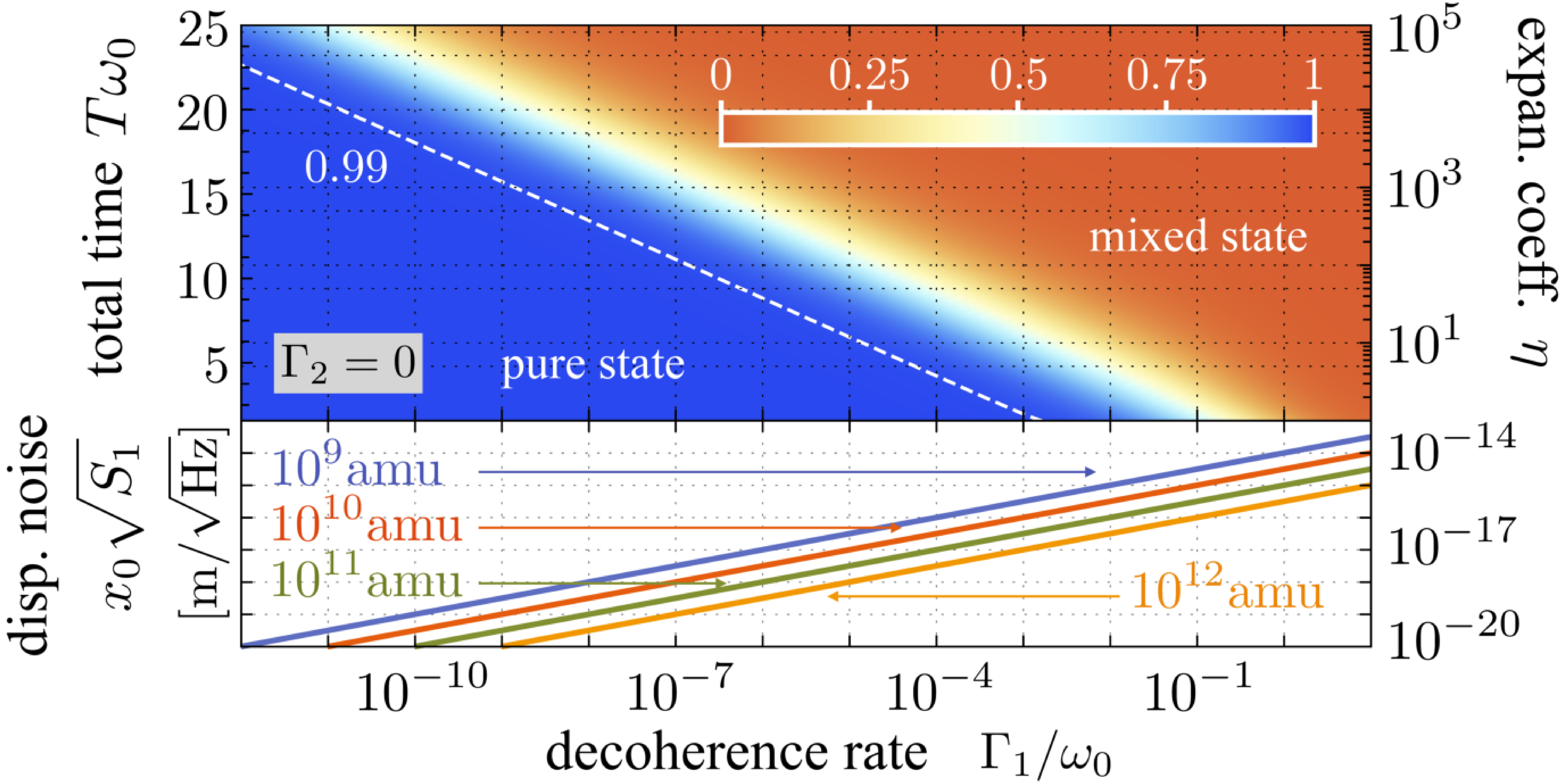
universität innsbruck

IQI

ÖAW AUSTRIAN ACADEMY OF SCIENCES

Decoherence

- Final purity in the presence of displacement noise



Decoherence

- Final purity in the presence of frequency noise