Toward Macroscopic Quantum Superpositions of Levitated Superconducting Microspheres

Oriol Romero-Isart and Hernan Pino

IQOQI - Institute of Quantum Optics and Quantum Information
ITP - Institute of Theoretical Physics, University of Innsbruck
Innsbruck, Austria

Galiano Island, 17th August 2015

Plan of the talk

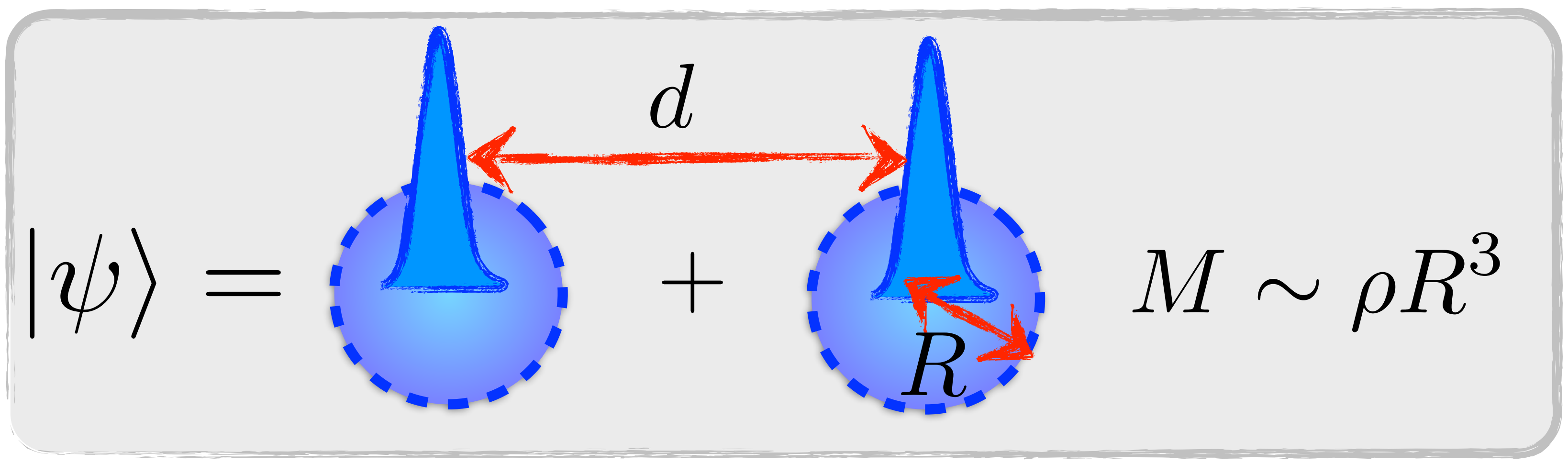
- Motivation: quantum superposition of massive objects
- Decoherence
- Protocol
- Results
- Experimental proposal
- Conclusions

Motivation

Quantum Superposition of a Massive Object

Quantum Superposition of Massive Objects

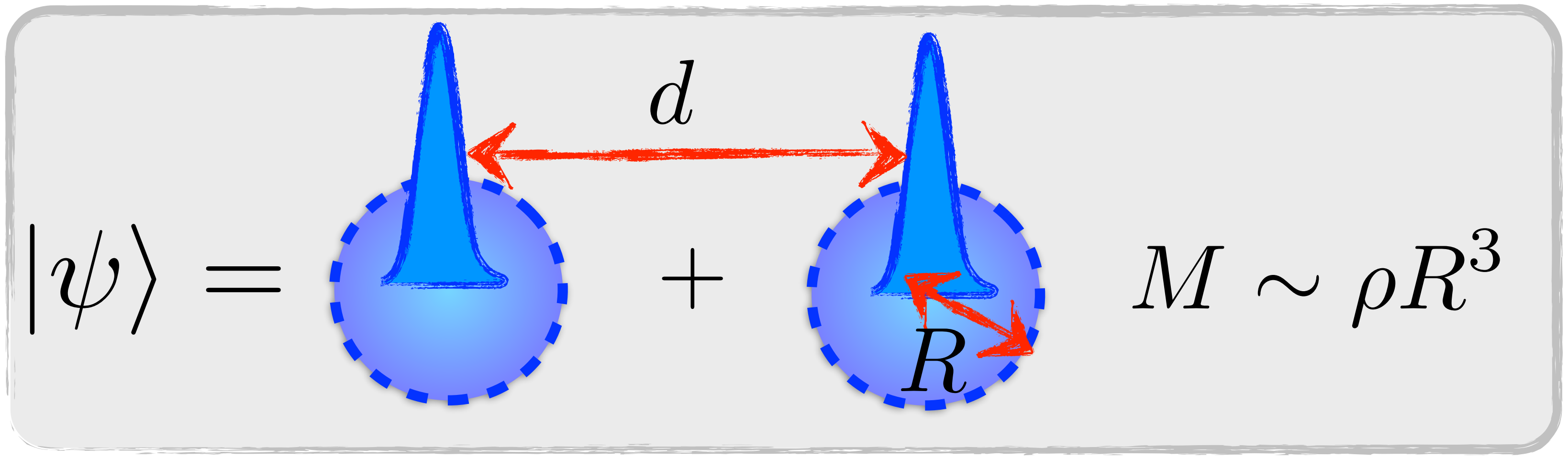
- Spatial superposition of a massive object



- How large can we make **d** and **M**?

Quantum Superposition of Massive Objects

- Spatial superposition of a massive object



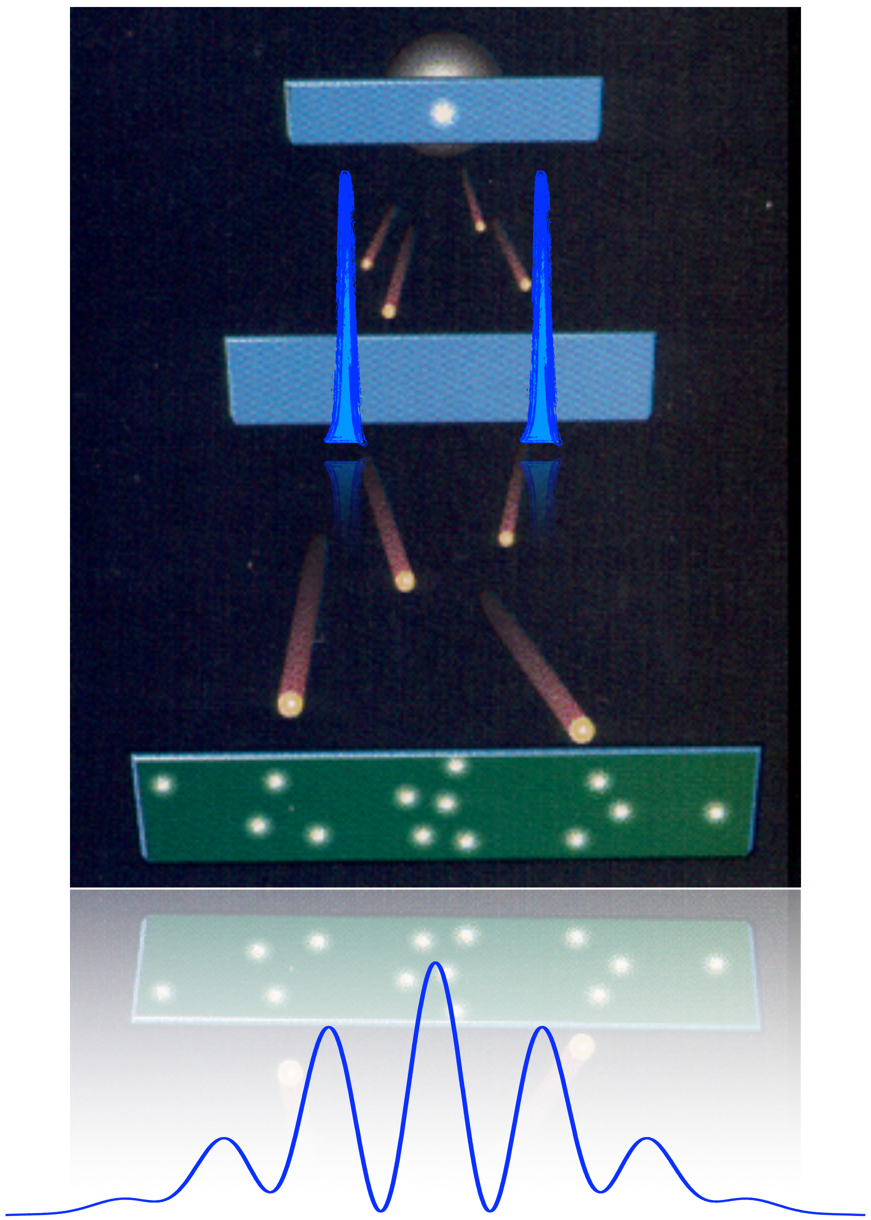
- How large can we make **d** and **M**?

- Why?
  - Fundamental interest: **exploring/testing QM** in new regimes
  - Extremely sensitive to environment: very good **sensor**!
  - Measuring **gravity**?
  - New techniques in **quantum control**
  - **Mesoscopic** physics
  - …

Two strategies

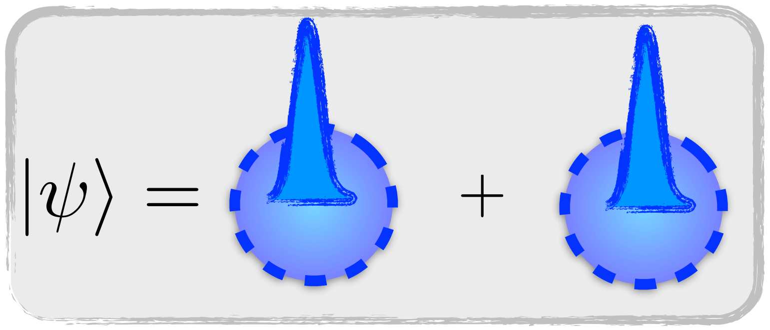
Two strategies

- Matter-wave interferometry

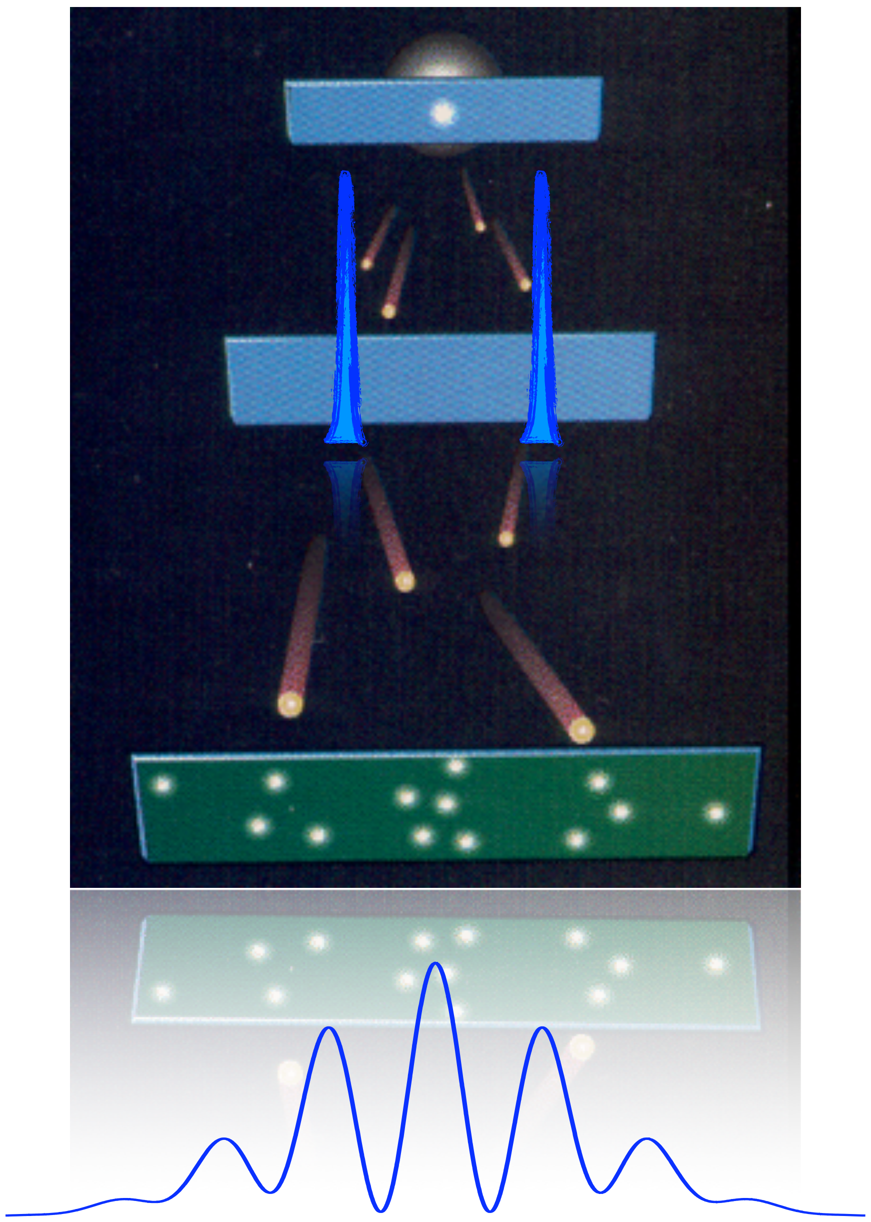


Two strategies

- Matter-wave interferometry

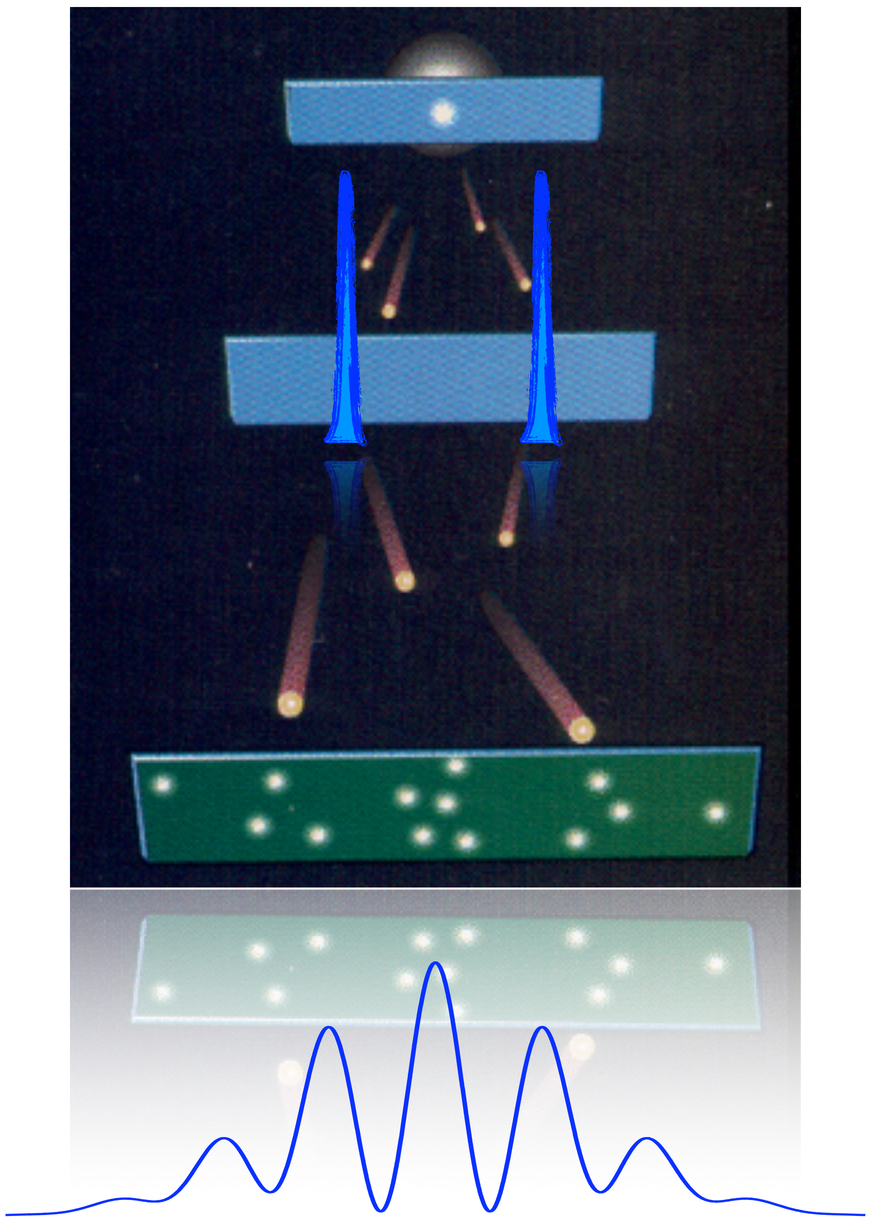


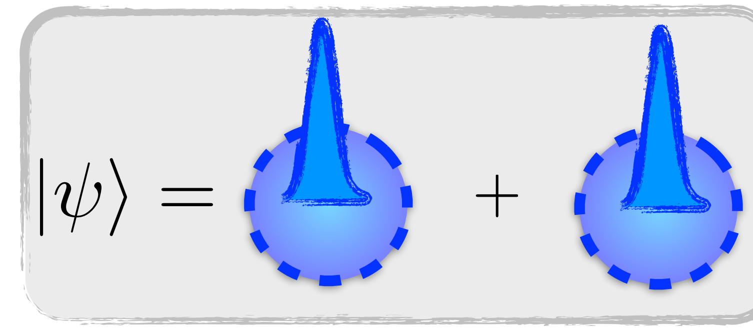
  - Large superpositions
  - Easily probed by the interference pattern
  - Challenge in increasing the mass:



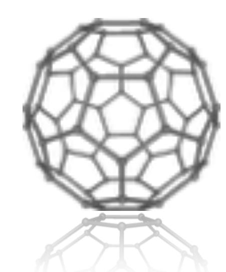
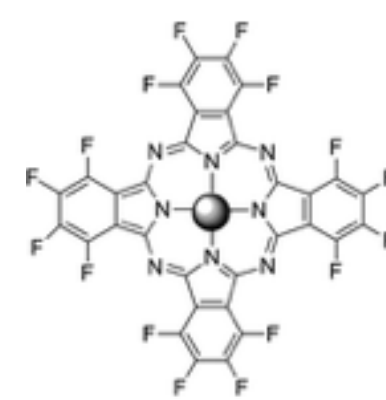
Two strategies

- Matter-wave interferometry





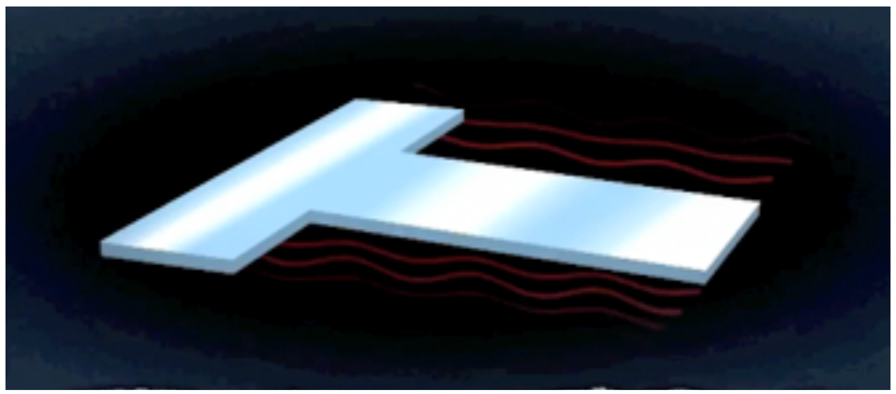
- Large superpositions
- Easily probed by the interference pattern
- Challenge in increasing the mass:

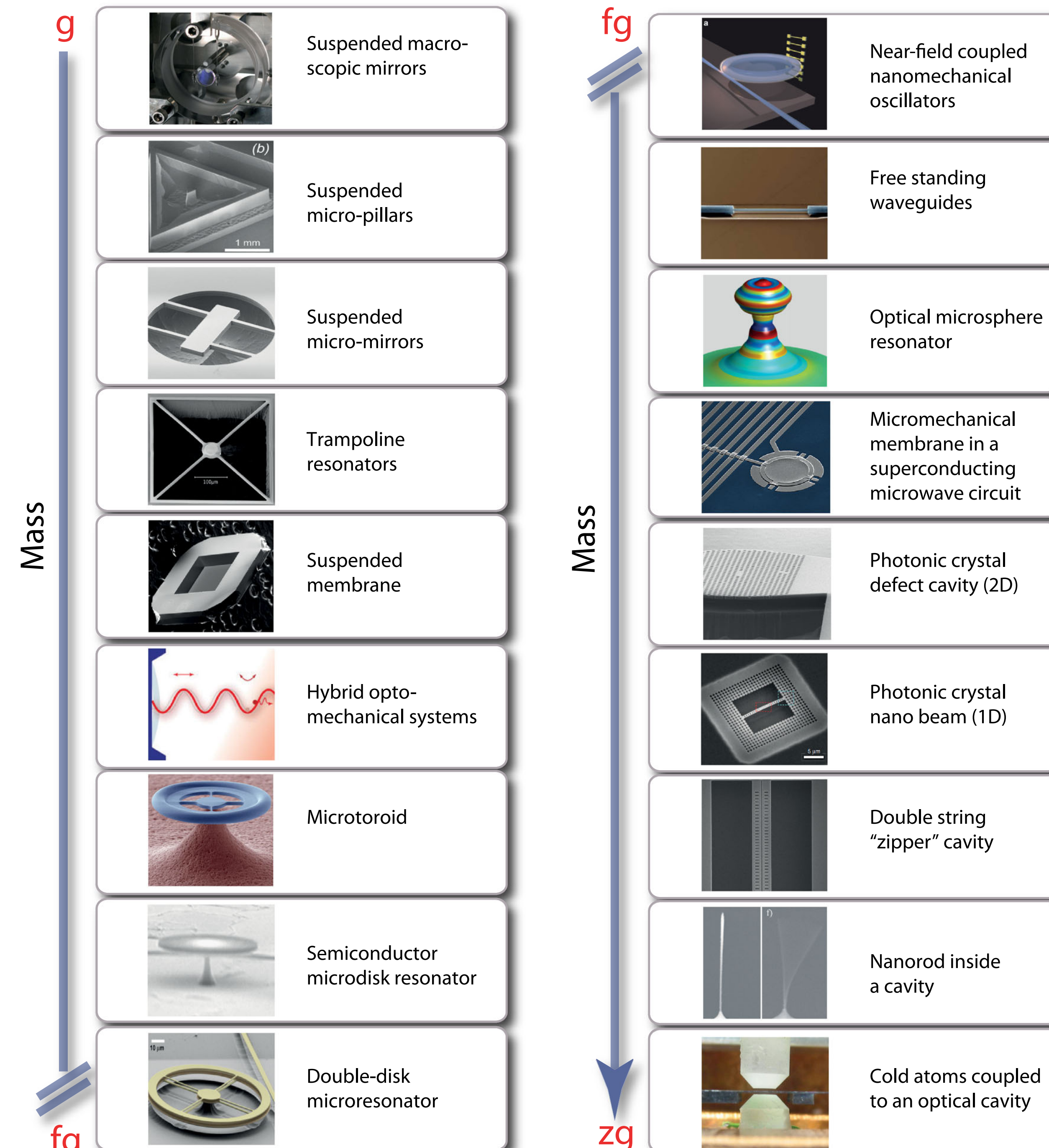
		Mass (AMU):
@ 1930's		~ 1
@ 1999		$\sim 10^2$
@ 2013		$\sim 10^4$

Arndt and Hornberger Nature Phys. **10**, 271 (2014).

Two strategies

- Quantum mechanical resonators



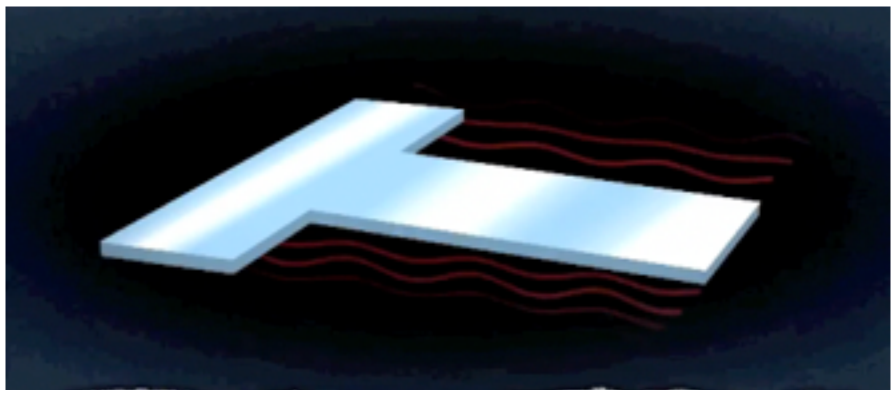


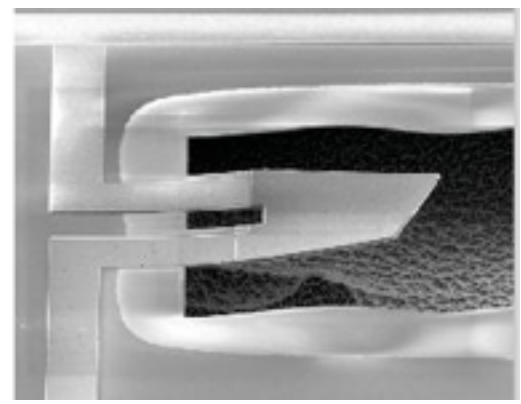
Aspelmeyer, Kippenberg, Marquardt, Rev. Mod. Phys. **86**, 1391 (2014)

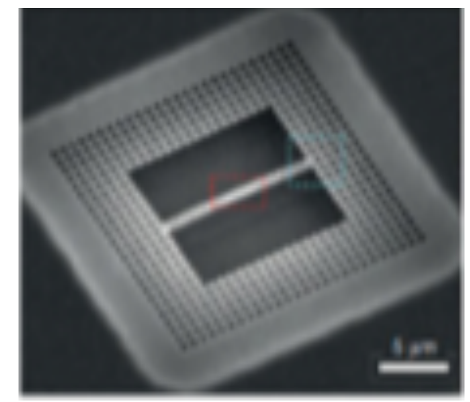
Two strategies

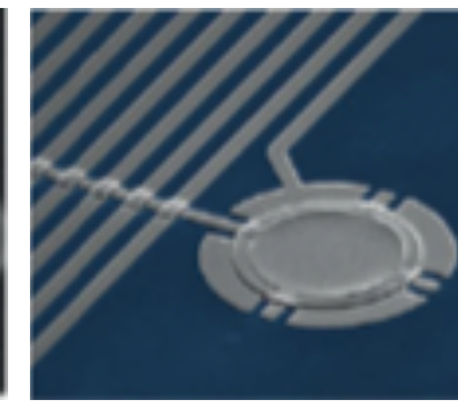
- Quantum mechanical resonators

  - Large mass



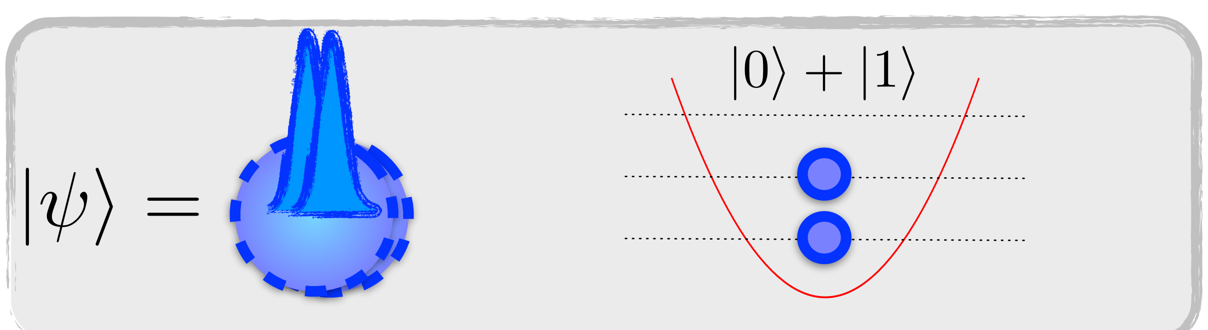






Mass (AMU):	$\sim 10^{13}$	$\sim 10^{11}$	$\sim 10^{13}$
	2010	2011	2011

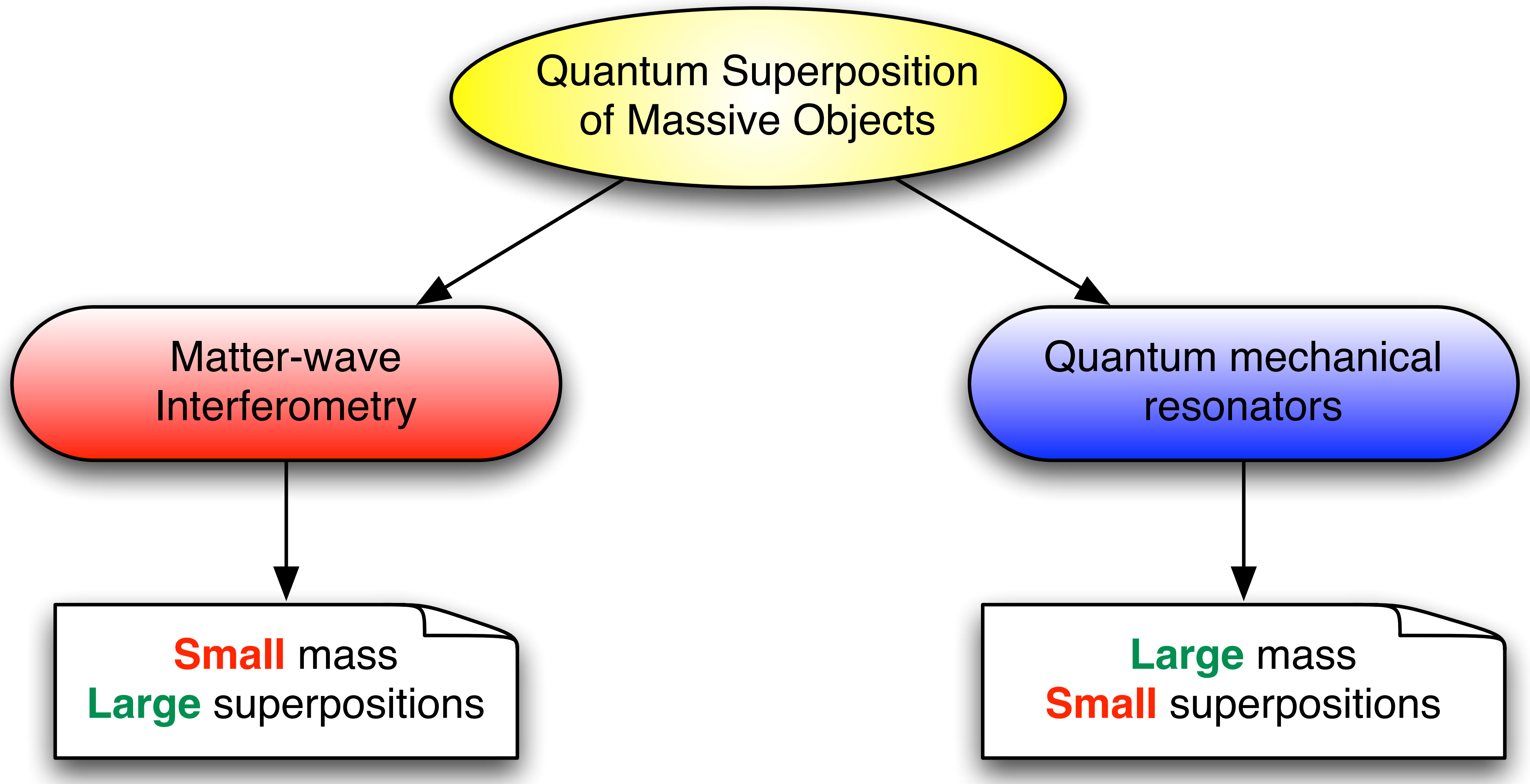
  - Small superpositions:



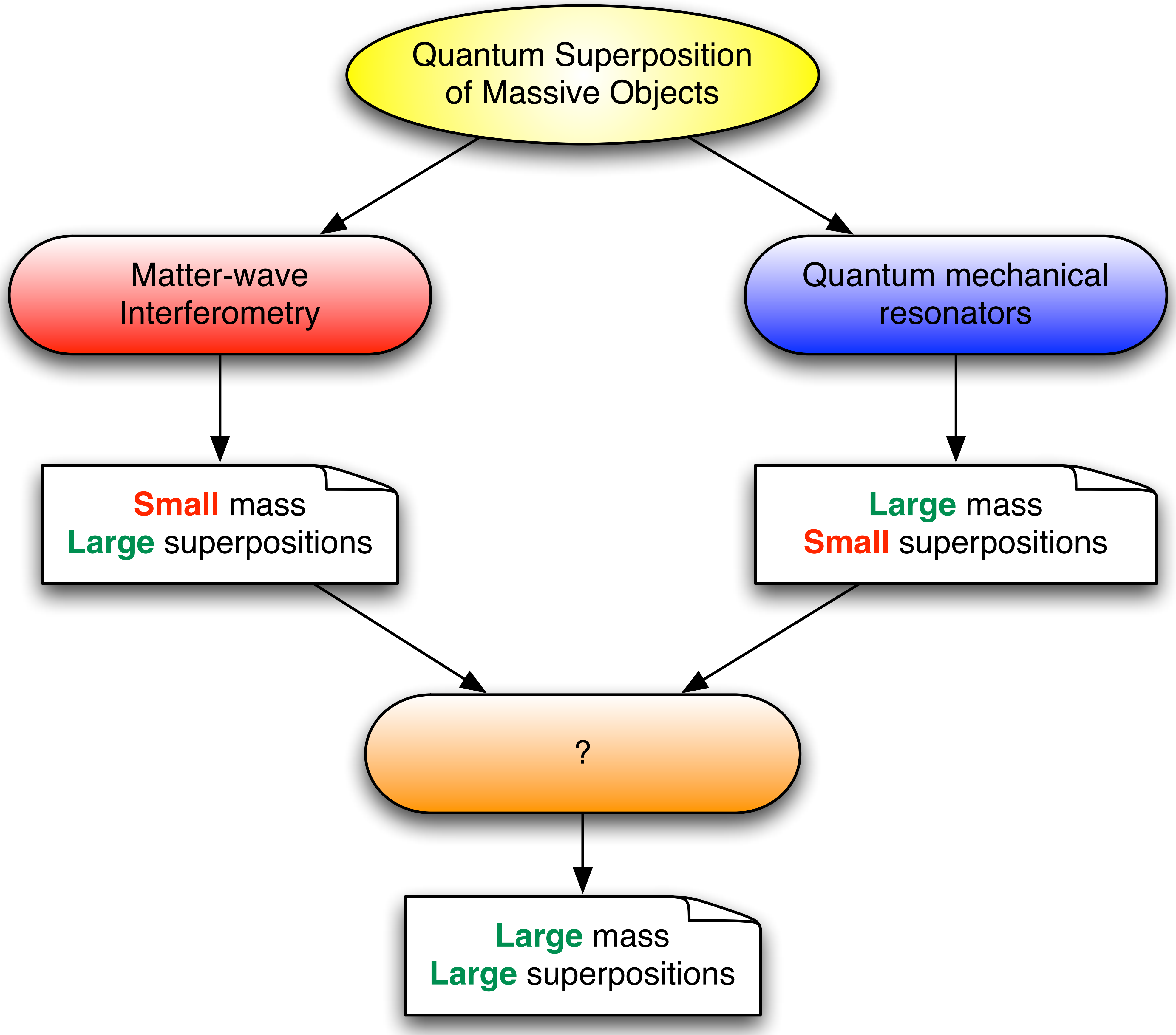
$$x_0 = \sqrt{\frac{\hbar}{2m\omega}} \sim \frac{10^{-7}}{\sqrt{N}}\ \mathrm{m}$$

Aspelmeyer, Kippenberg, Marquardt, Rev. Mod. Phys. **86**, 1391 (2014)

Two strategies



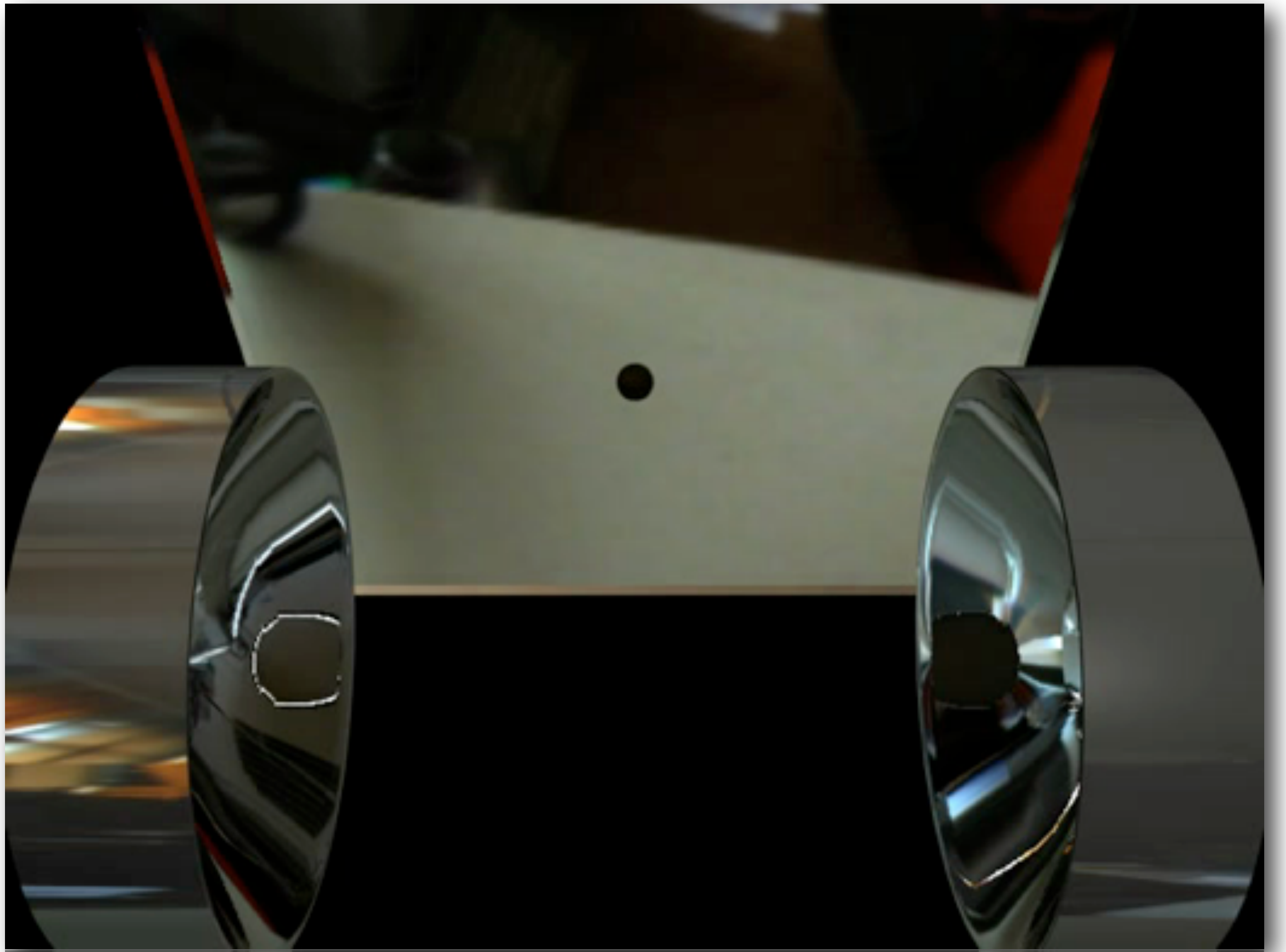
Two strategies



Levitation of nano/micro-spheres

Optical Levitation

- Diameter $\ll \lambda \sim 1\ \mu\mathrm{m}$
- N ~ $10^6 \sim 10^9$

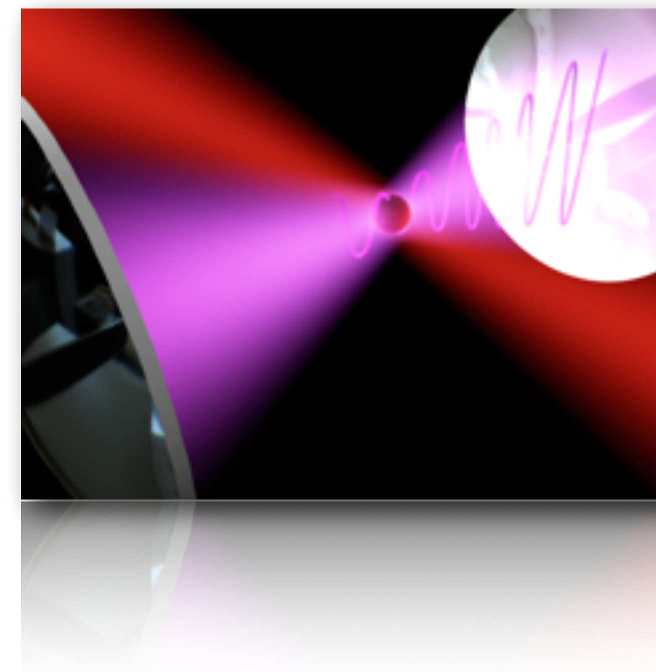


- ORI, M. L. Juan, R. Quidant, J. I. Cirac NJP **12**, 033015 (2010)
- D. E. Chang, *et al.* (Kimble and Zoller) PNAS **107**, 1005 (2010)

Optical levitation of dielectric nanospheres

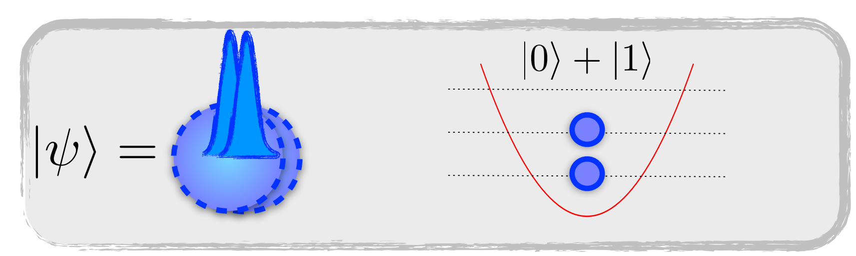
- Theory:
  - Master equation for arbitrary sized dielectrics (all orders in perturbation theory)

$$\dot{\rho}(t) = \mathrm{i}[\rho(t), H] + \dots$$

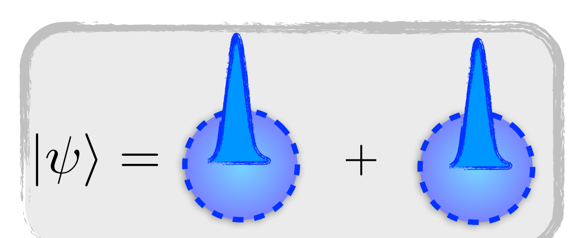


  - Sources of decoherence (gas, black-body, elasticity, ...)
    - ORI, A. C. Pflanzer, *et al.* PRA **83**, 013803 (2011)
    - A. C. Pflanzer, ORI, and J. I. Cirac PRA **86**, 013802 (2012)

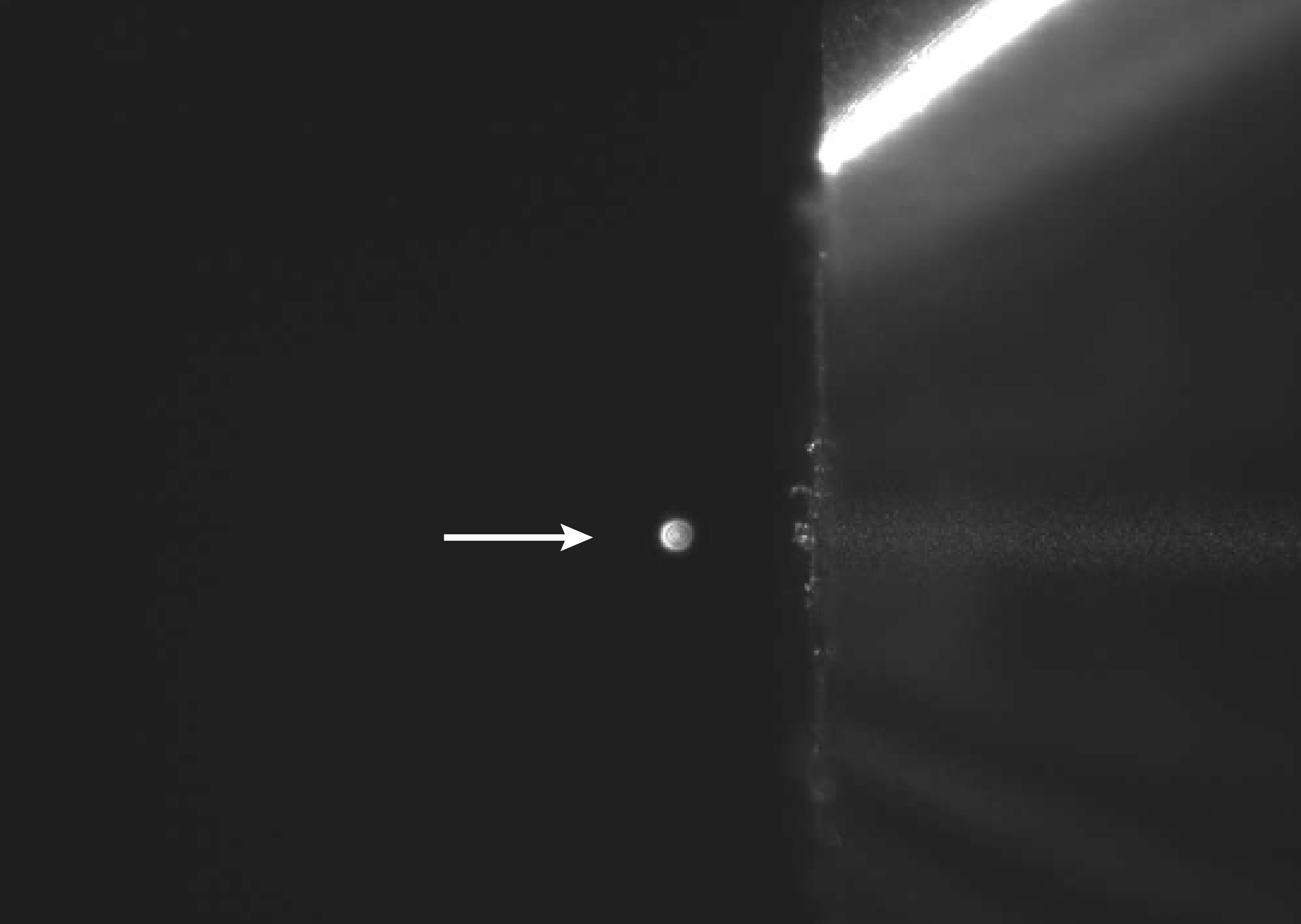
- Protocols:
  - Preparation of "small" quantum superpositions



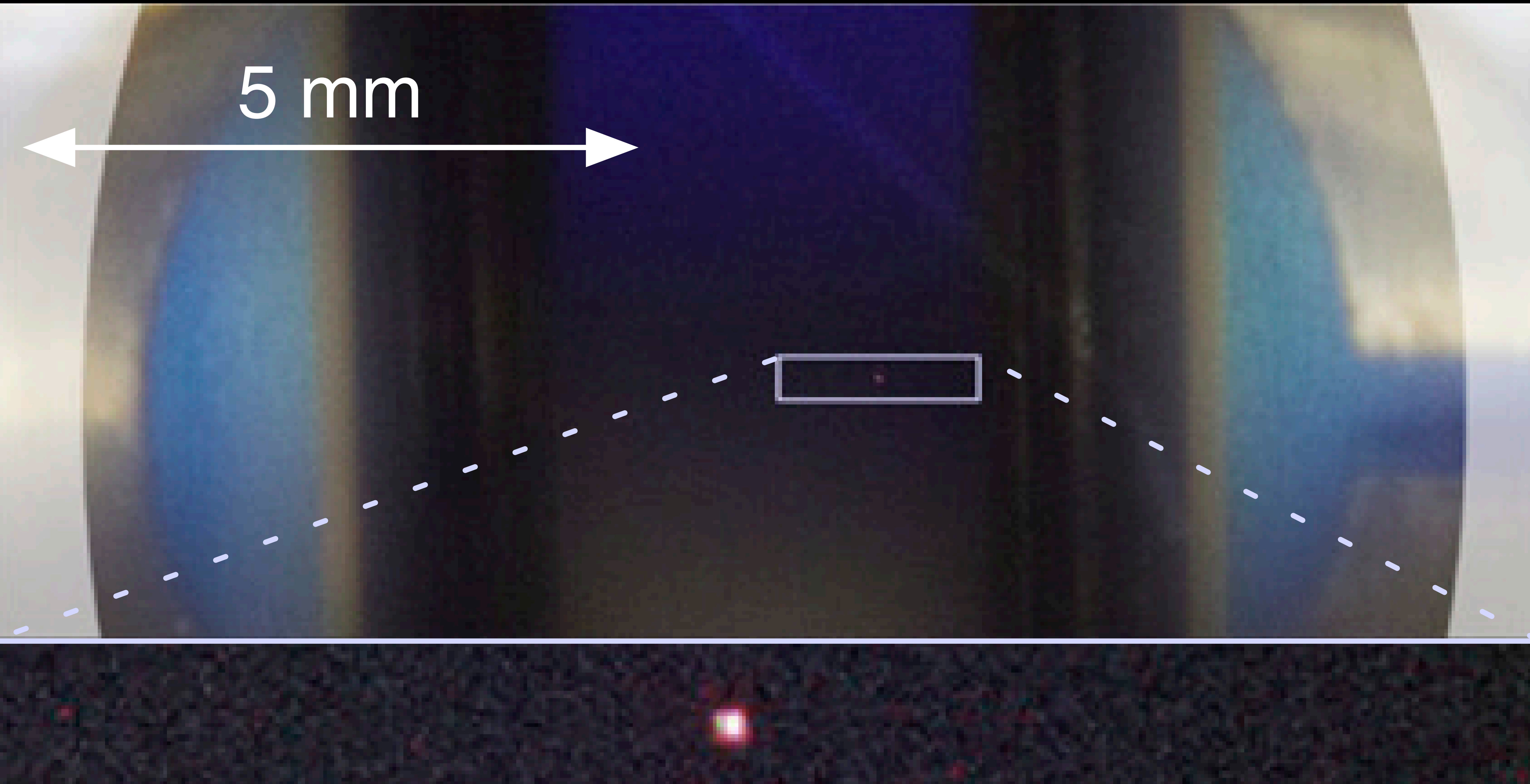
    - ORI, M. L. Juan, R. Quidant, J. I. Cirac NJP **12**, 033015 (2010)
    - ORI, A. C. Pflanzer, *et al.* PRA **83**, 013803 (2011)
    - A. C. Pflanzer, ORI, and J. I. Cirac PRA **88**, 033804 (2013)
  - Preparation of large quantum superpositions



    - ORI, *et al.* PRL **107**, 020405 (2011)
    - ORI PRA **84**, 052121 (2011)

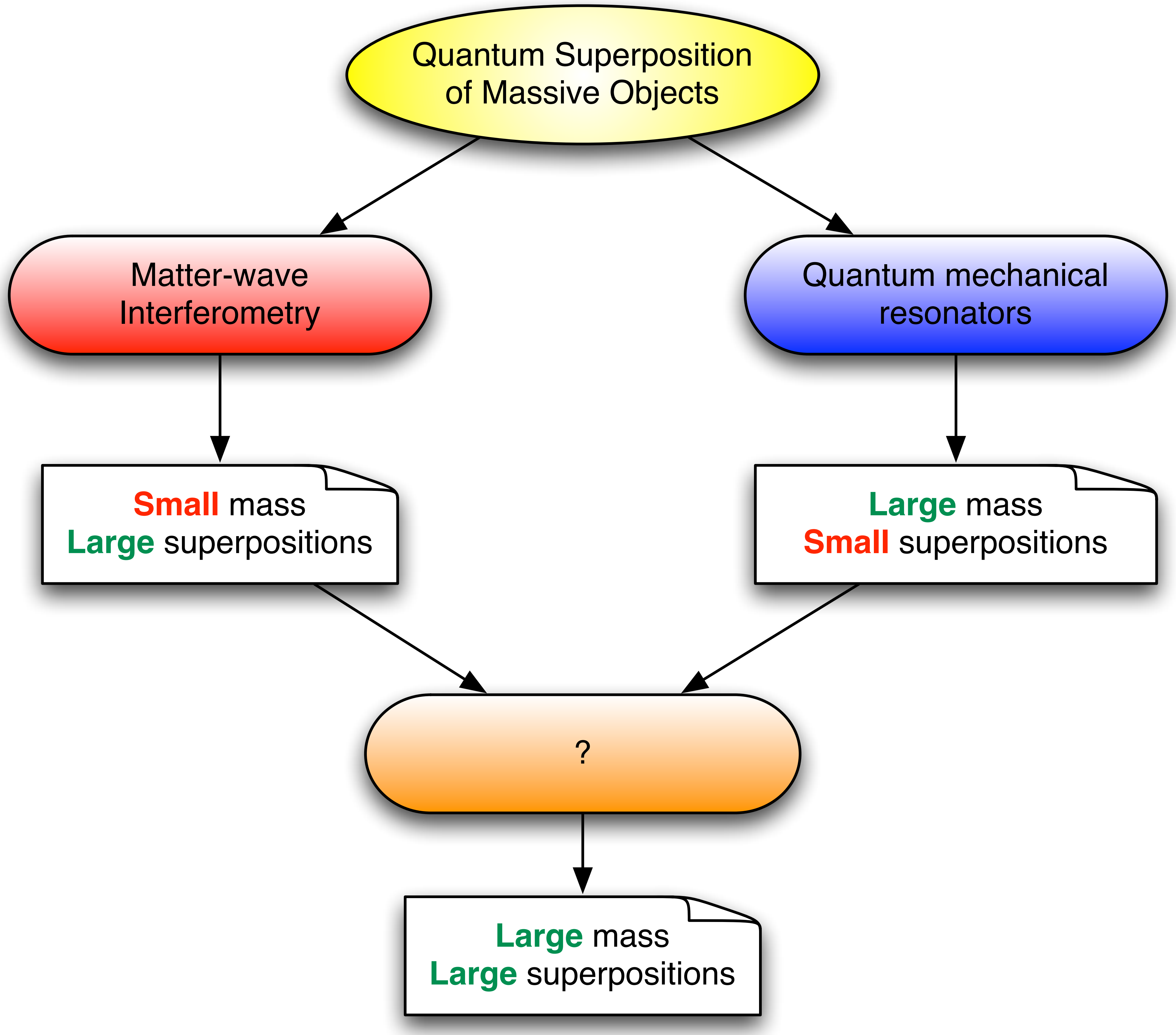


Gieseler, Deutsch, Quidant, Novotny, PRL **109**, 103603 (2012)



Kiesel, Blaser, Delic, Grass, Kaltenbaek, Aspelmeyer, PNAS **110**, 14180 (2013)

Two strategies



Matter-Wave Interference with Levitated Nanospheres

PRL **107,** 020405 (2011) PHYSICAL REVIEW LETTERS week ending 8 JULY 2011

Large Quantum Superpositions and Interference of Massive Nanometer-Sized Objects

O. Romero-Isart,[1] A. C. Pflanzer,[1] F. Blaser,[2] R. Kaltenbaek,[2] N. Kiesel,[2] M. Aspelmeyer,[2] and J. I. Cirac[1]

[1]*Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Strasse 1, D-85748, Garching, Germany*

[2]*Vienna Center for Quantum Science and Technology, Faculty of Physics, University of Vienna, Boltzmanngasse 5, A-1090 Vienna, Austria*

PHYSICAL REVIEW A **84**, 052121 (2011)

Quantum superposition of massive objects and collapse models

Oriol Romero-Isart

Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Str. 1, D-85748 Garching, Germany

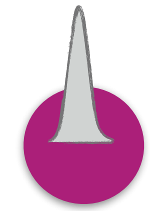
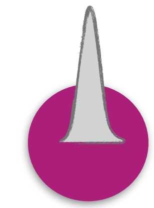
(Received 19 October 2011; published 28 November 2011)

Are they big enough?

“Gravitational Regime” with Quantum Systems

Gravitational Regime

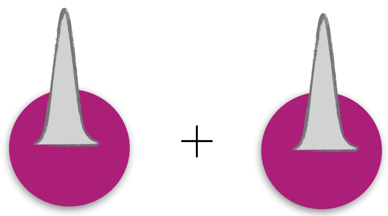
- Macroscopic quantum superpositions

$|\psi\rangle =$  $+$ 

Gravitational Regime

- Macroscopic quantum superpositions

$|\psi\rangle =$



- Entering into the "gravitational regime"

Time scale $\tau = h\frac{2R}{GM^2}$

Gravitational Regime

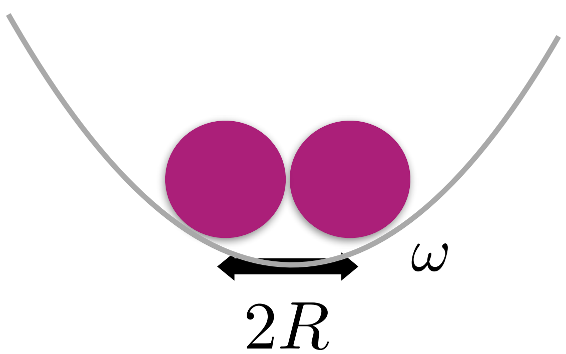
- Macroscopic quantum superpositions

- Entering into the "gravitational regime"

Time scale $\tau = h\frac{2R}{GM^2}$

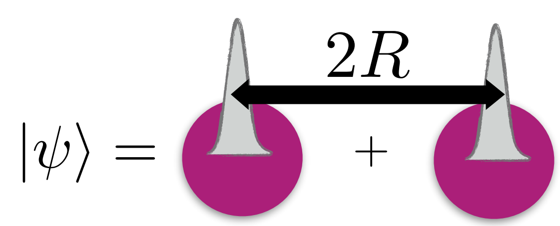
➡ Two interpretations:

Gravitational energy vs kinetic energy of 2 masses



$$G\frac{M^2}{2R} = \hbar\omega \qquad \omega = \frac{2\pi}{\tau}$$

Gravitationall- induced decoherence



Superposition lifetime

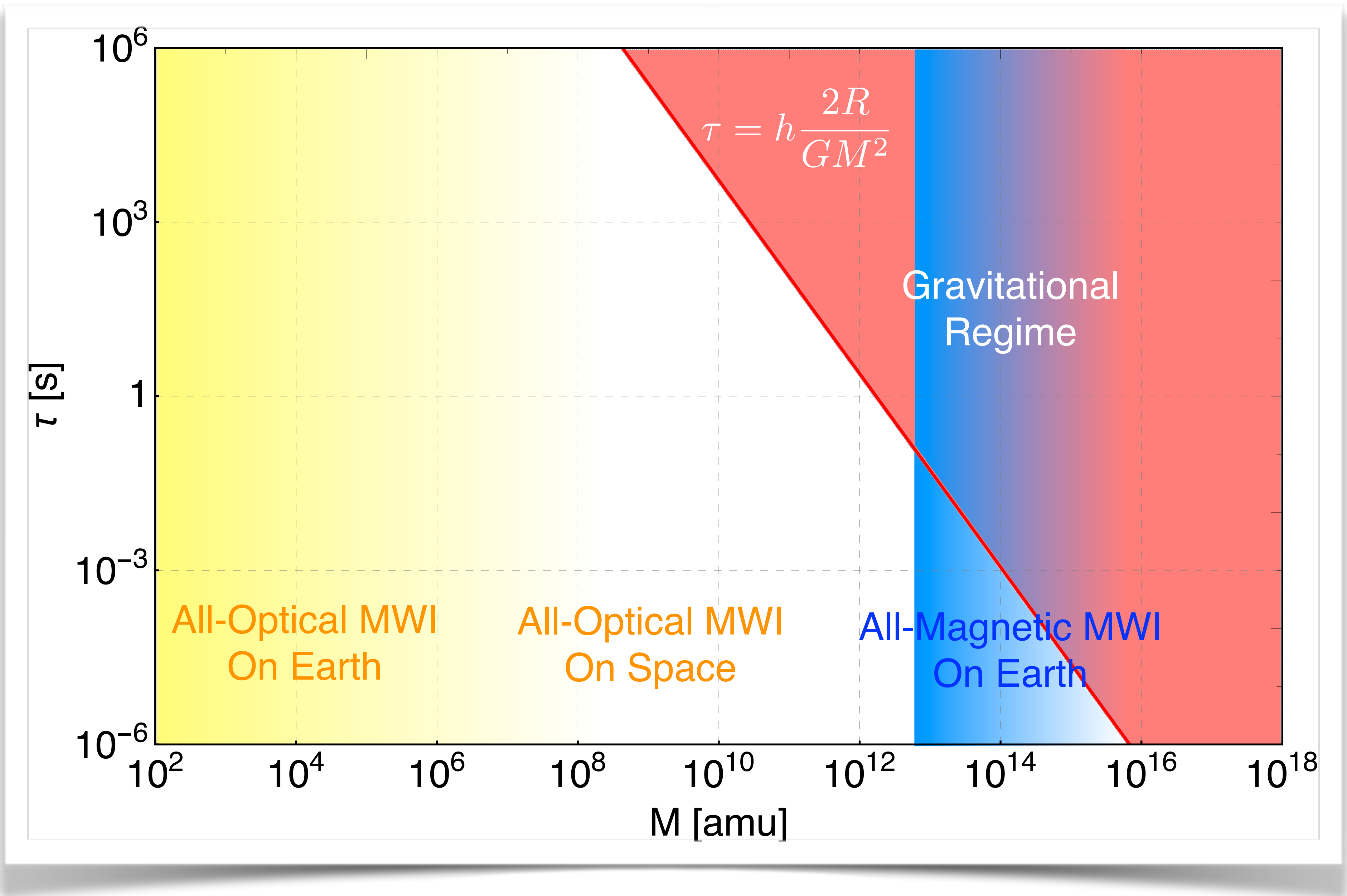
Penrose, Diósi 80's

Gravitational Regime

- Toward macroscopic quantum superpositions $|\psi\rangle =$

- Entering into the "gravitational regime"

Time scale $\tau = h\dfrac{2R}{GM^2}$



Gravitational Regime

- Toward macroscopic quantum superpositions

$|\psi\rangle =$

- Entering into the "gravitational regime"

Time scale $\tau = h\frac{2R}{GM^2}$

- All-magnetic matter-wave interferometer on a chip

Toward Macroscopic Quantum Superpositions of Levitated Superconducting Spheres

Hernan Pino[1,2] and Oriol Romero-Isart[1,2]*
[1] *Institute for Quantum Optics and Quantum Information of the Austrian Academy of Sciences, A-6020 Innsbruck, Austria. and*
[2] *Institute for Theoretical Physics, University of Innsbruck, A-6020 Innsbruck, Austria.*

ArXiv: …

Gravitational Regime

- Toward macroscopic quantum superpositions

$|\psi\rangle =$

- Entering into the "gravitational regime"

Time scale $\tau = h\frac{2R}{GM^2}$

- All-magnetic matter-wave interferometer on a chip

➡ Combination of salient features:

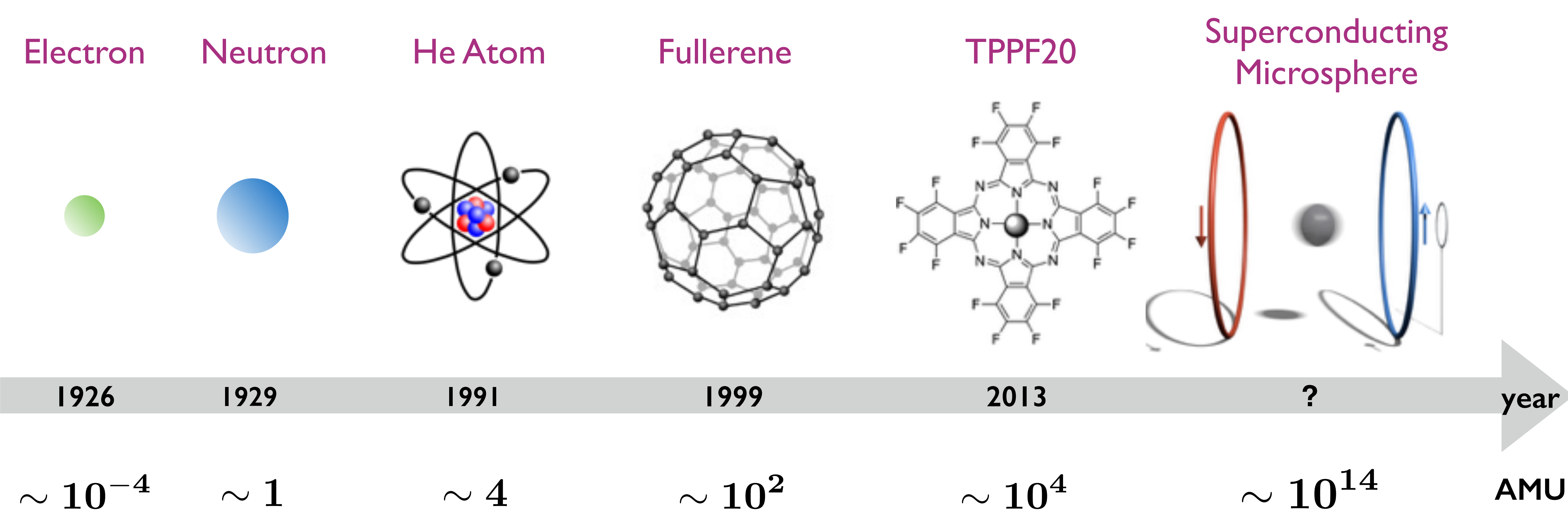
1. Cryogenic temperatures	→	*No black-body decoherence!*
2. Static magnetic potentials	→	*Levitation and exponential speed-up of dynamics (no need for space)!*
3. Coupling to quantum circuits	→	*Purification, quantum double-slit, measurement!*

Gravitational Regime

- Toward macroscopic quantum superpositions $|\psi\rangle =$

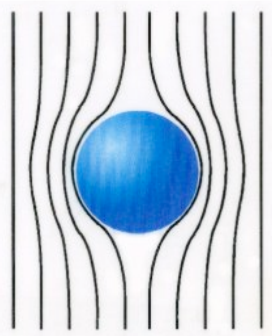
- Entering into the "gravitational regime" **Time scale** $\tau = h\frac{2R}{GM^2}$

- All-magnetic matter-wave interferometer on a chip

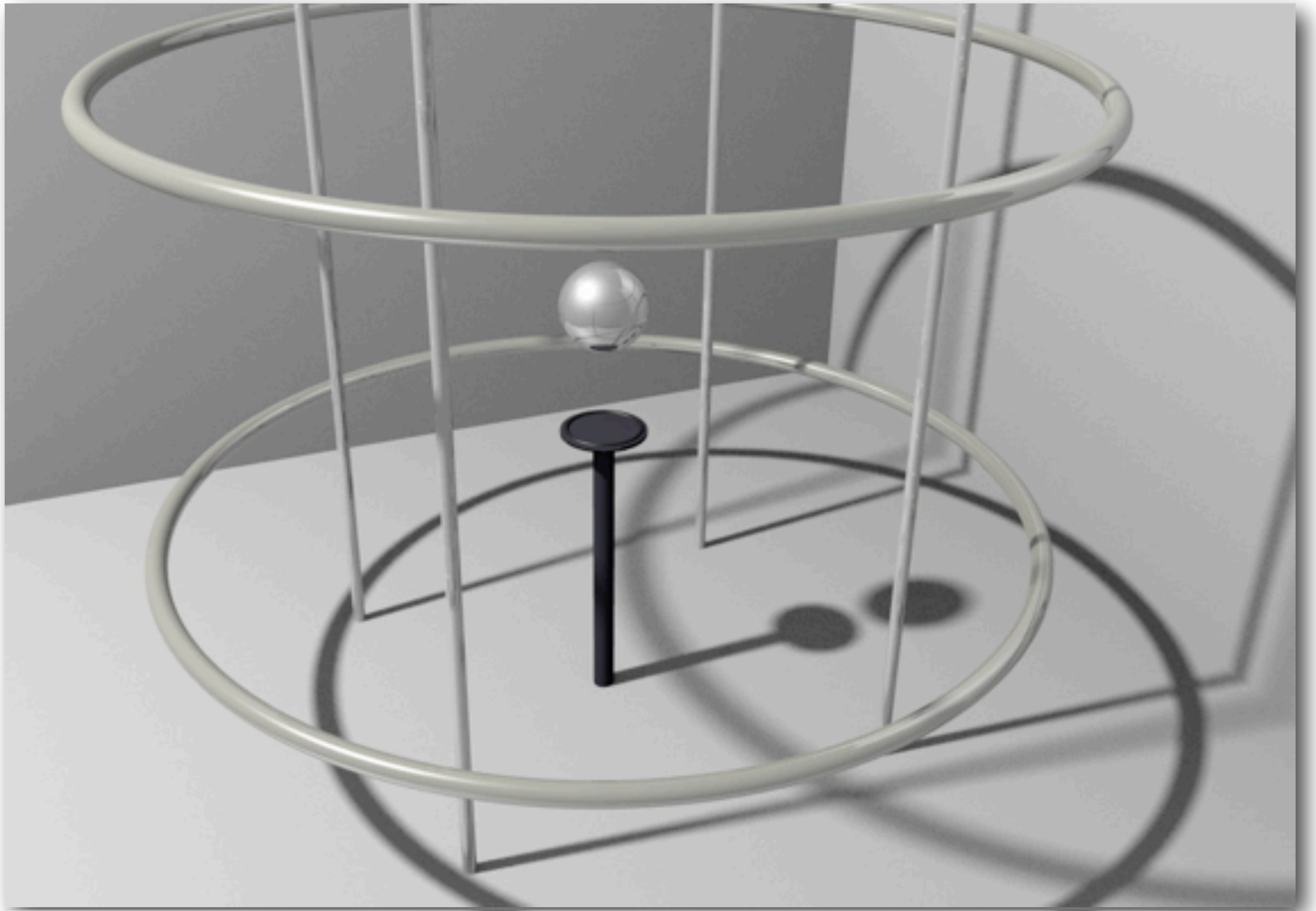


Magnetic levitation

- Magnetic coupling to a quantum circuit



- Diameter $\sim 4\ \mu m$
- N $\sim 10^{14}$

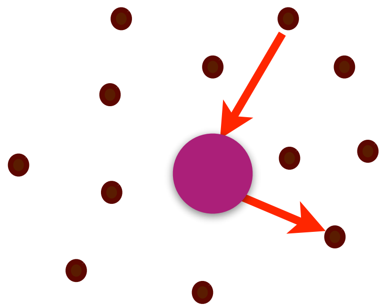


ORI, *et al.* PRL **109** 147205 (2012).

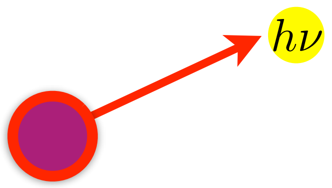
Decoherence

Decoherence

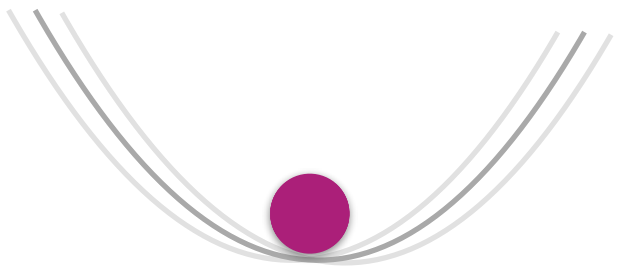
- Scattering of air molecules



- Scattering, emission, and absorption of black-body radiation (or any used light)

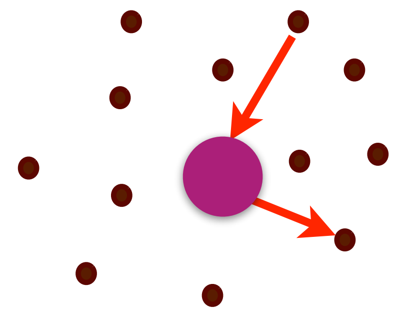


- Fluctuating forces (e.g. due to vibrations)



- Collapse models

Decoherence

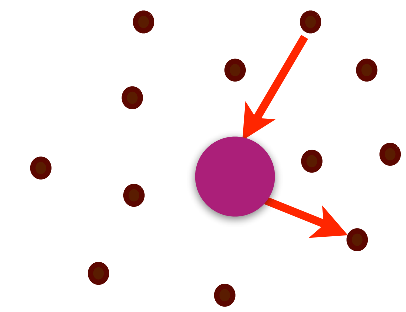


- Decoherence due to scattering of air molecules

$$\langle x|\hat{\rho}(t)|x'\rangle = e^{-\gamma_{\rm air} t}\langle x|\hat{\rho}(0)|x'\rangle$$

$$\gamma_{\rm air} = \frac{16\pi\sqrt{2\pi}}{\sqrt{3}}\frac{PR^2}{\bar{v}m_a}$$

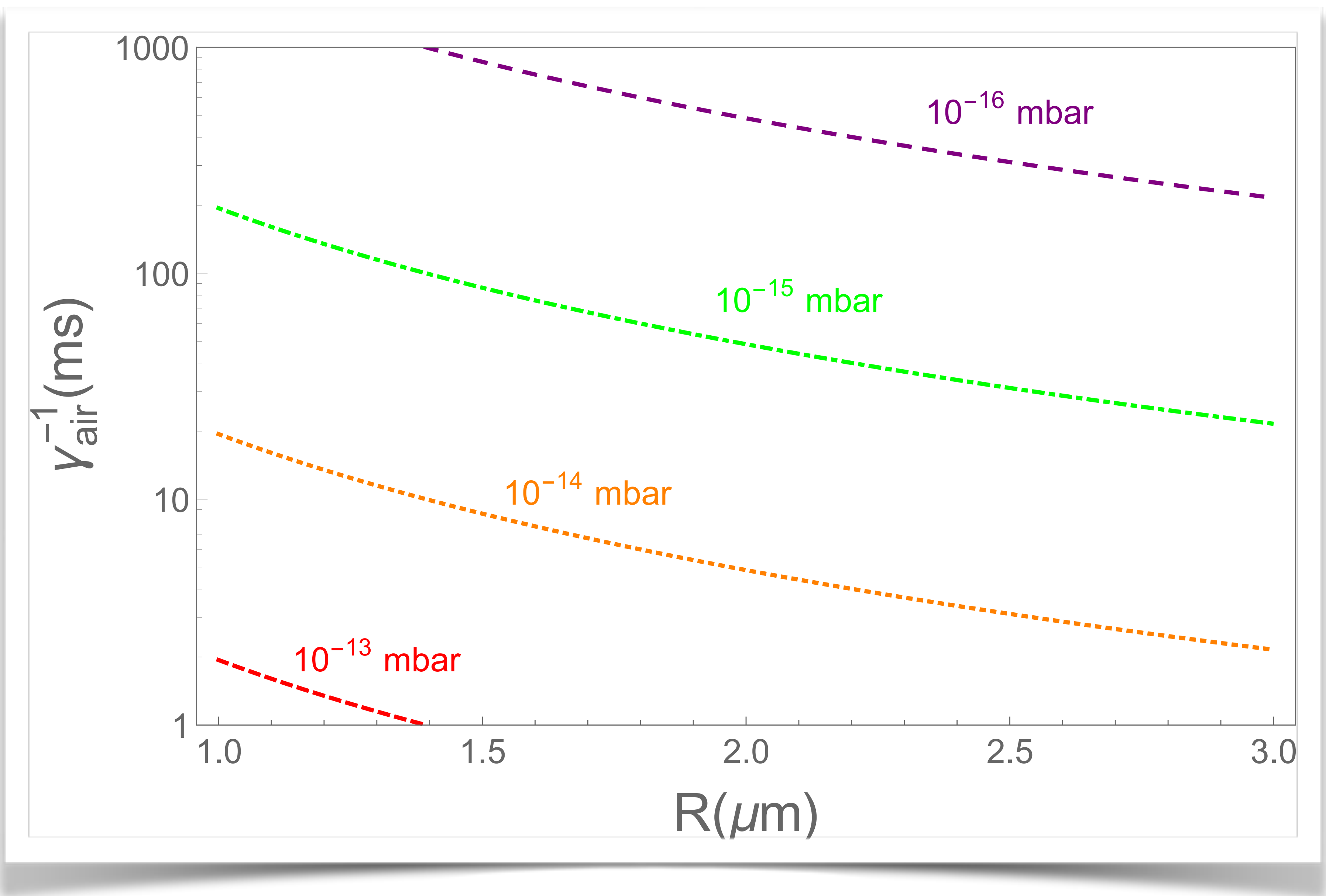
Decoherence



- Decoherence due to scattering of air molecules

$$\langle x|\hat{\rho}(t)|x'\rangle = e^{-\gamma_{\rm air} t}\langle x|\hat{\rho}(0)|x'\rangle$$

$$\gamma_{\rm air} = \frac{16\pi\sqrt{2\pi}}{\sqrt{3}}\frac{PR^2}{\bar{v}m_a}$$

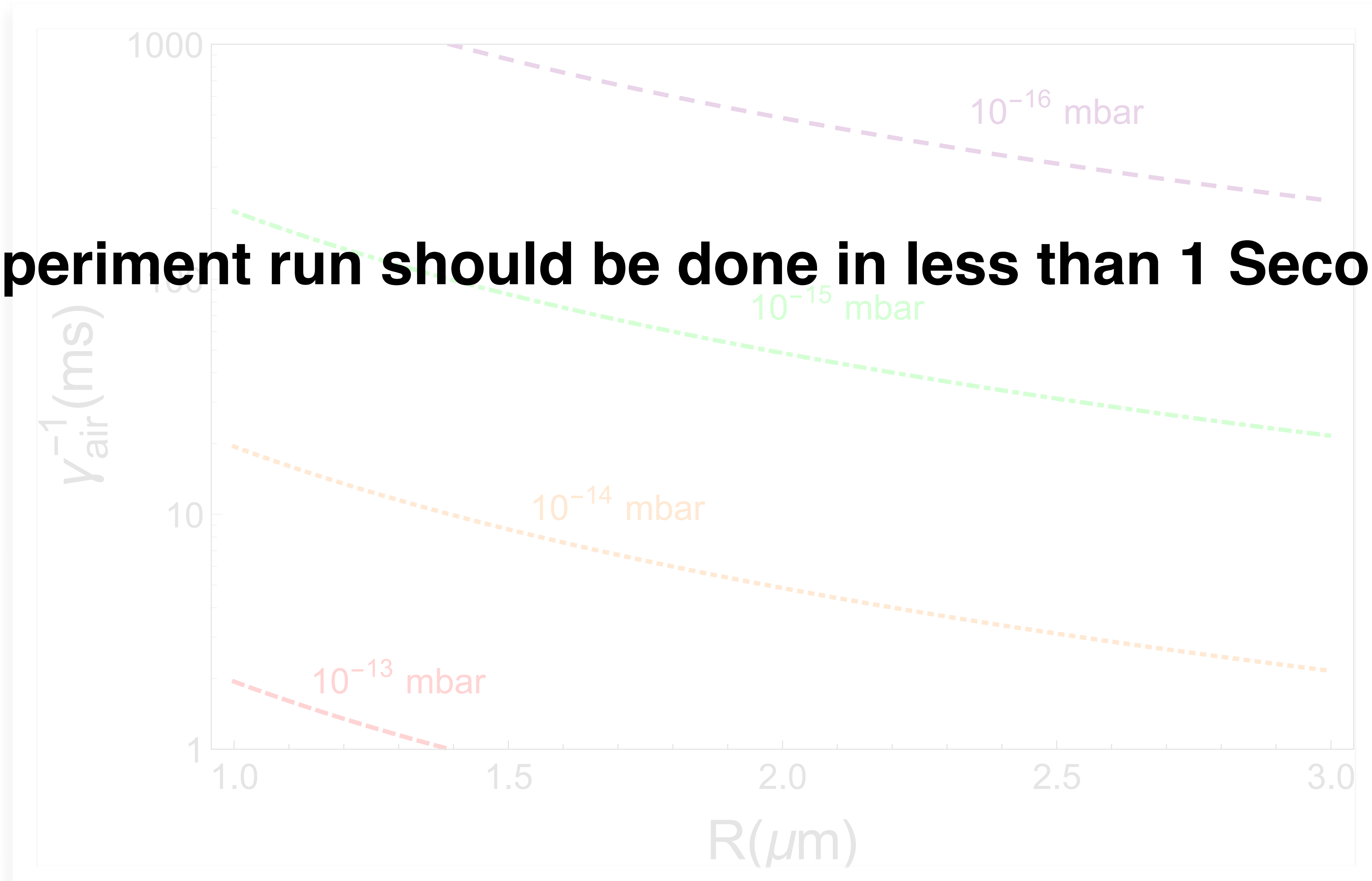


Decoherence

- Decoherence due to scattering of air molecules

$$\langle x|\hat{\rho}(t)|x'\rangle = e^{-\gamma_{\text{air}} t}\langle x|\hat{\rho}(0)|x'\rangle$$

$$\gamma_{\text{air}} = \frac{16\pi\sqrt{2\pi}}{\sqrt{3}}\frac{PR^2}{\bar{v}m_a}$$



Experiment run should be done in less than 1 Second!

Decoherence

- Position localization master equation

$$\dot{\rho} = \frac{1}{\mathrm{i}\hbar}[\hat{H}, \hat{\rho}] - \Lambda[\hat{x}, [\hat{x}, \hat{\rho}]]$$

➡ Describes black-body and fluctuating forces decoherence, and collapse models

$$\langle x|\rho(t)|x'\rangle \sim e^{-\Lambda(x-x')^2}\langle x|\rho(0)|x'\rangle$$

Decoherence

- Position localization master equation

$$\dot{\rho} = \frac{1}{\mathrm{i}\hbar}[\hat{H}, \hat{\rho}] - \Lambda[\hat{x}, [\hat{x}, \hat{\rho}]]$$

- Gravitationally-induced decoherence

$$\Lambda_G = \frac{GM^2}{2\hbar R^3}$$

Decoherence

- Position localization master equation $\dot{\rho} = \frac{1}{i\hbar}[\hat{H}, \hat{\rho}] - \Lambda[\hat{x}, [\hat{x}, \hat{\rho}]]$

- Gravitationally-induced decoherence $\Lambda_G = \frac{GM^2}{2\hbar R^3}$

Very **weak** compared to other collapse models!

But **parameter free**…

G-induced with mass resolution

(Yanbei's talk)

$$\tilde{\Lambda}_G = \Lambda_G \left(\frac{R}{\sigma_{DP}} \right)^3 \sim 10^{18} \Lambda_G$$

CSL Model

(Yanbei's and Angelo's talk)

$$\Lambda_{CSL} \sim \Lambda_G \times 10^6 \times \frac{\gamma^0_{CSL}}{10^{-16}\mathrm{Hz}}$$

Position localization decoherence

- Position localization master equation $\dot{\rho} = \frac{1}{i\hbar}[\hat{H}, \hat{\rho}] - \Lambda[\hat{x}, [\hat{x}, \hat{\rho}]]$

- Gravitationally-induced decoherence $\Lambda_G = \frac{GM^2}{2\hbar R^3}$

Very weak compared to other collapse models!

But parameter free…

Falsifying parameter-free gravitationally-induced decoherence

G-induced with mass resolution

(Yanbei's talk)

$$\tilde{\Lambda}_G = \Lambda_G \left(\frac{R}{\sigma_{DP}}\right)^3 \sim 10^{15} \Lambda_G$$

CSL Model

(Yanbei's and Angelo's talk)

$$\Lambda_{CSL} \sim \Lambda_G \times 10^6 \times \frac{\gamma^0_{CSL}}{10^{-16}\mathrm{Hz}}$$

Position localization decoherence

- Position localization master equation $\dot{\rho} = \frac{1}{i\hbar}[\hat{H}, \hat{\rho}] - \Lambda[\hat{x}, [\hat{x}, \hat{\rho}]]$

- Gravitationally-induced decoherence $\Lambda_G = \frac{GM^2}{2\hbar R^3}$

- Coherence length $\langle x/2|\hat{\rho}|-x/2\rangle = \frac{1}{\sqrt{2\pi V_x}} \exp\left(-\frac{x^2}{\xi^2}\right)$

  ➡ For gaussian states and dynamics $\xi(t) = P(t)\sqrt{8V_x(t)}$

- We require $\Lambda_G \gg \Lambda_{\mathrm{QM}}$

Decoherence

- Position localization master equation

$$\dot{\rho} = \frac{1}{\mathrm{i}\hbar}[\hat{H}, \hat{\rho}] - \Lambda[\hat{x}, [\hat{x}, \hat{\rho}]]$$

- Gravitationally-induced decoherence

$$\Lambda_G = \frac{GM^2}{2\hbar R^3}$$

- Coherence length

$$\langle x/2|\hat{\rho}| - x/2\rangle = \frac{1}{\sqrt{2\pi V_x}} \exp\left(-\frac{x^2}{\xi^2}\right)$$

➡ For gaussian states and dynamics

$$\xi(t) = P(t)\sqrt{8V_x(t)}$$

- We require

$$\Lambda_G \gg \Lambda_{\mathrm{QM}}$$

Protocol

1. Preparing a pure state

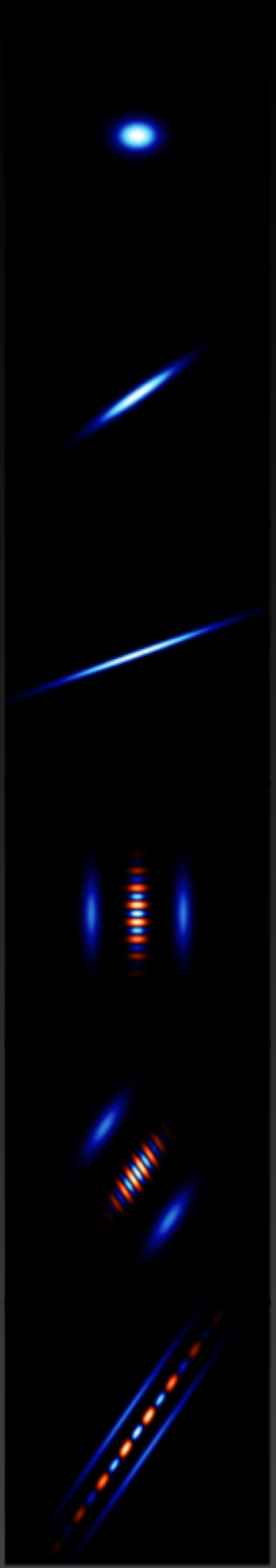
2. Exponential speed-up

3. Free expansion

4. Double slit

5. Rotation

6. Exponential generation of fringes



1. Preparing a pure state

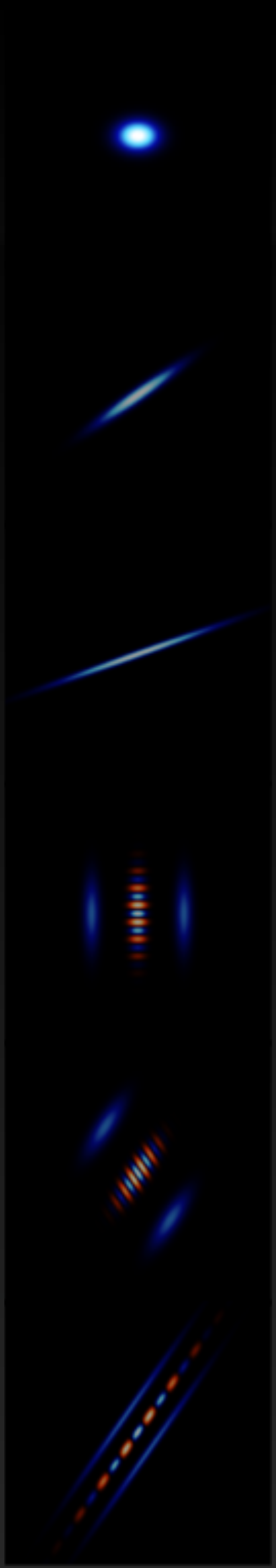
2. Exponential speed-up

3. Free expansion

4. Double slit

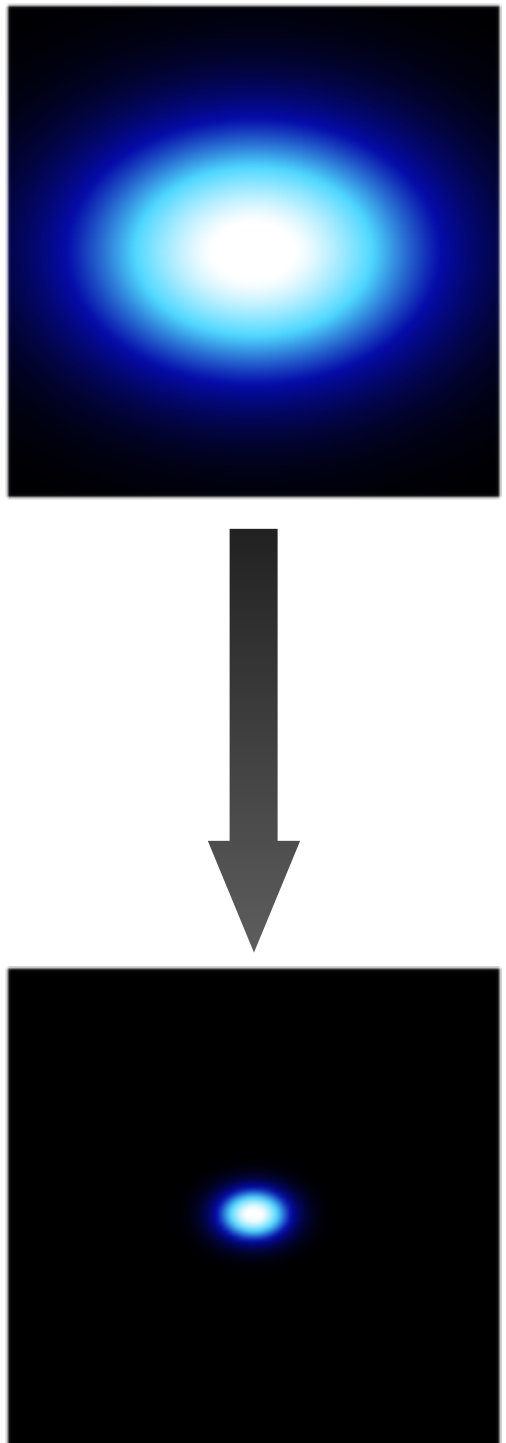
5. Rotation

6. Exponential generation of fringes



Preparing a pure state

- Cooling the center-of-mass motion



Microsphere trapped in an harmonic potential

$$\hat{H} = \frac{\hat{p}^2}{2M} + \frac{1}{2} M \omega_t^2 \hat{x}^2$$

Cooling by coupling to quantum circuit

Density matrix determined by variances

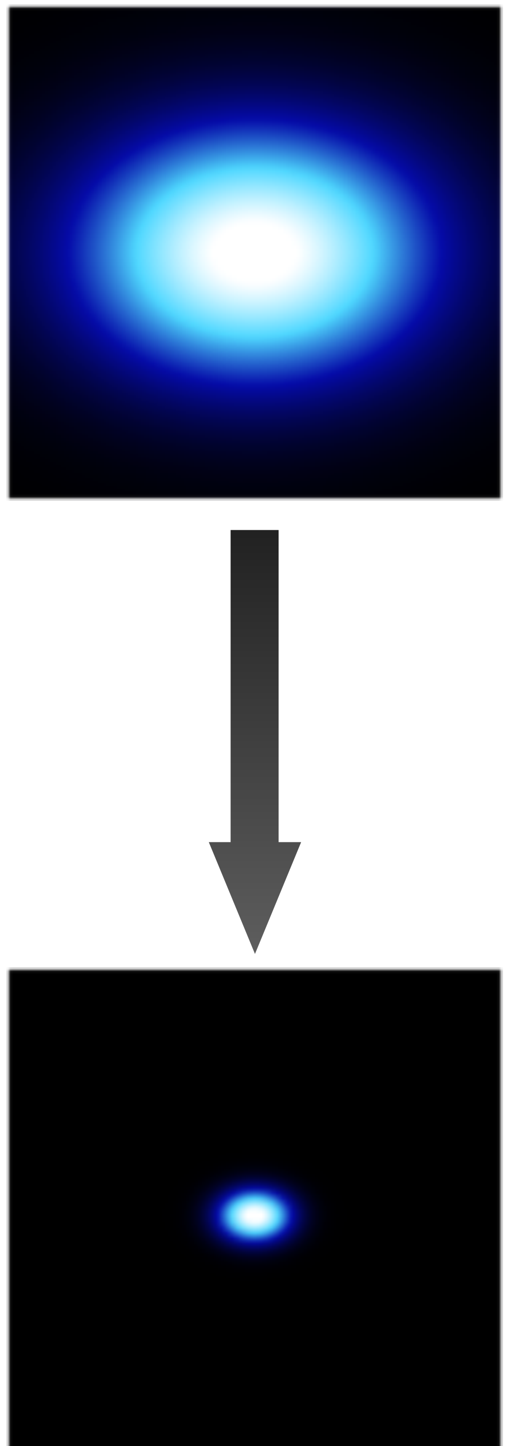
$$V_x = \langle \hat{x}^2 \rangle = \frac{\hbar}{2M\omega_t}(2\bar{n}+1)$$

$$V_p = \langle \hat{p}^2 \rangle = \frac{\hbar M \omega_t}{2}(2\bar{n}+1)$$

$$C = \frac{1}{2}\langle \hat{x}\hat{p} + \hat{p}\hat{x} \rangle = 0$$

Preparing a pure state

- Cooling the center-of-mass motion



Microsphere trapped in an harmonic potential

$$\hat{H} = \frac{\hat{p}^2}{2M} + \frac{1}{2} M \omega_t^2 \hat{x}^2$$

Cooling by coupling to quantum circuit

Density matrix determined by variances

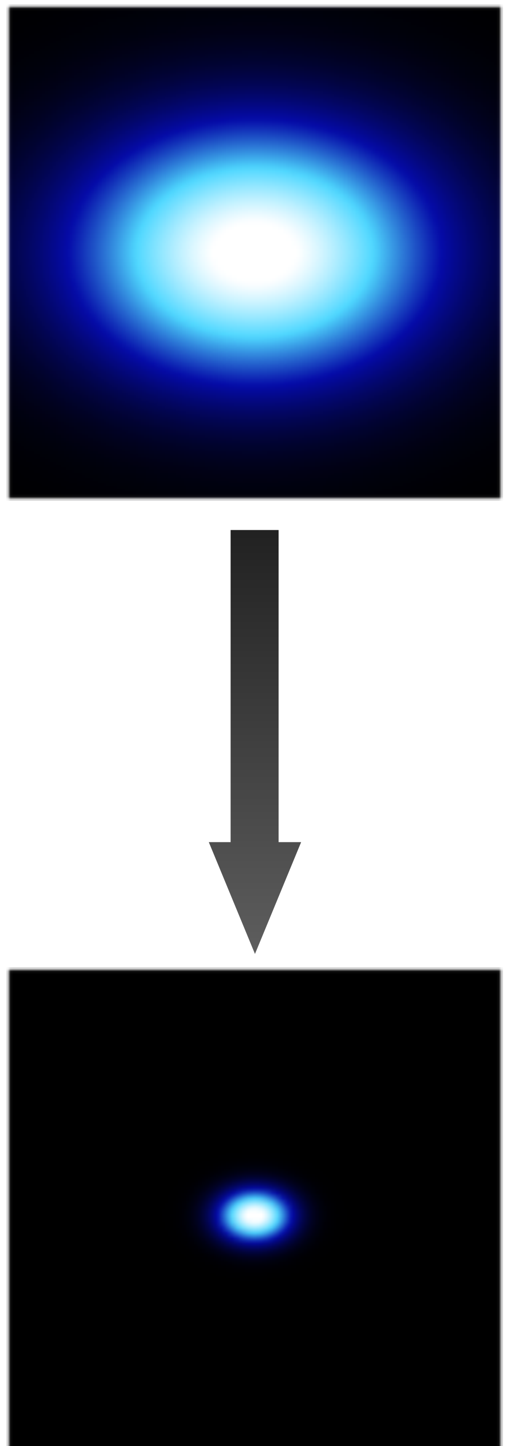
$$V_x = \langle \hat{x}^2 \rangle = \frac{\hbar}{2M\omega_t}(2\bar{n}+1)$$

$$V_p = \langle \hat{p}^2 \rangle = \frac{\hbar M \omega_t}{2}(2\bar{n}+1)$$

$$C = \frac{1}{2}\langle \hat{x}\hat{p} + \hat{p}\hat{x} \rangle = 0$$

Preparing a pure state

- Cooling the center-of-mass motion



Microsphere trapped in an harmonic potential

$$\hat{H} = \frac{\hat{p}^2}{2M} + \frac{1}{2} M \omega_t^2 \hat{x}^2$$

Cooling by coupling to quantum circuit

Density matrix determined by variances

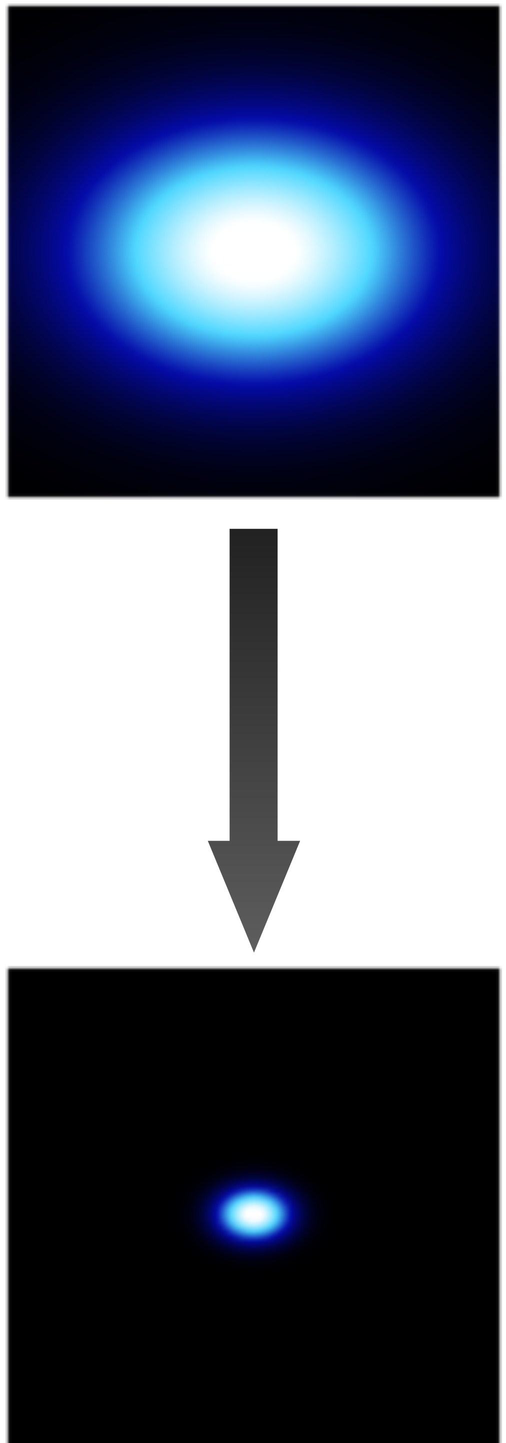
$$V_x = \langle \hat{x}^2 \rangle = \frac{\hbar}{2M\omega_t}(2\bar{n}+1)$$

$$V_p = \langle \hat{p}^2 \rangle = \frac{\hbar M \omega_t}{2}(2\bar{n}+1)$$

$$C = \frac{1}{2}\langle \hat{x}\hat{p} + \hat{p}\hat{x} \rangle = 0$$

Preparing a pure state

- Cooling the center-of-mass motion



Microsphere trapped in an harmonic potential

$$\hat{H} = \frac{\hat{p}^2}{2M} + \frac{1}{2}M\omega_t^2\hat{x}^2$$

Cooling by coupling to quantum circuit

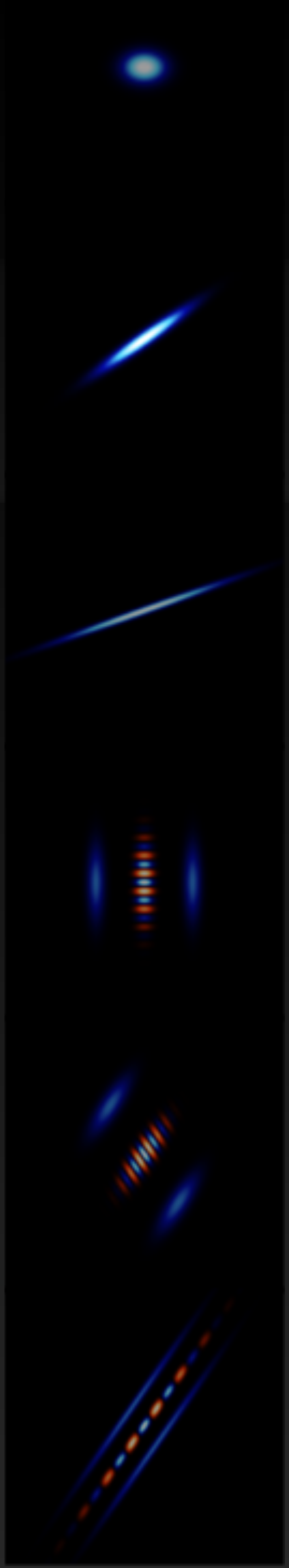
Density matrix determined by variances

$$V_x = \langle \hat{x}^2 \rangle = \frac{\hbar}{2M\omega_t}(2\bar{n}+1)$$

$$V_p = \langle \hat{p}^2 \rangle = \frac{\hbar M\omega_t}{2}(2\bar{n}+1)$$

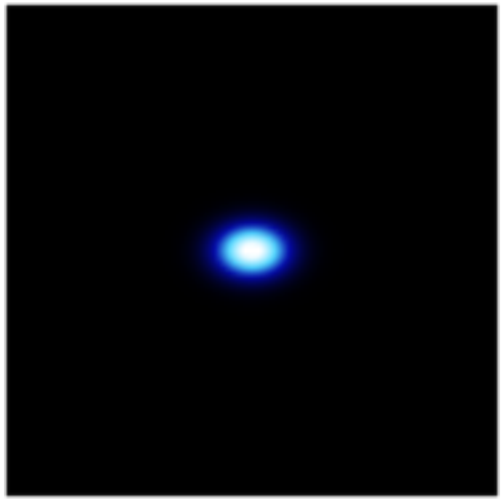
$$C = \frac{1}{2}\langle \hat{x}\hat{p} + \hat{p}\hat{x} \rangle = 0$$

1. Preparing a pure state
2. **Exponential speed-up**
3. Free expansion
4. Double slit
5. Rotation
6. Exponential generation of fringes



Exponential speed-up

- Evolution in a **repulsive** quadratic potential



$$\hat{H} = \frac{\hat{p}^2}{2M} - \frac{1}{2} M \omega_R^2 \hat{x}^2$$

Dynamics can be calculated analytically taking into account decoherence

Momentum (and position) distribution grows exponentially

$$V_p(t) \approx e^{2\omega_R t} V_p(0)$$

Also coherence length

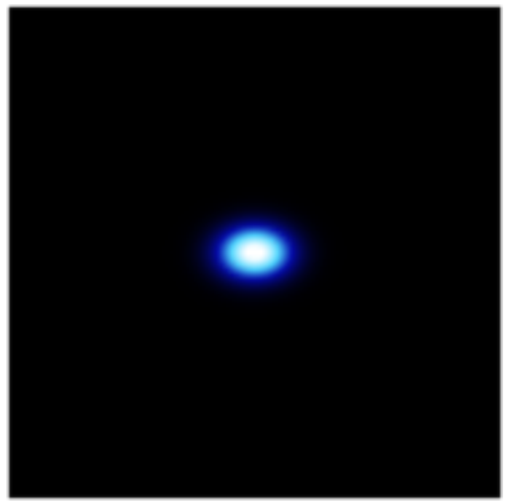
$$\xi(t) = P(t)\sqrt{8V_x(t)}$$

Interesting that for position localization decoherence:

$$\xi(t \to \infty) = \sqrt{\frac{2\omega_r}{\Lambda}}$$

Exponential speed-up

- Evolution in a **repulsive** quadratic potential



$$\hat{H} = \frac{\hat{p}^2}{2M} - \frac{1}{2} M \omega_R^2 \hat{x}^2$$

Dynamics can be **calculated analytically** taking into account decoherence

Momentum (and position) distribution grows **exponentially**

$$V_p(t) \approx e^{2\omega_R t} V_p(0)$$

Also coherence length

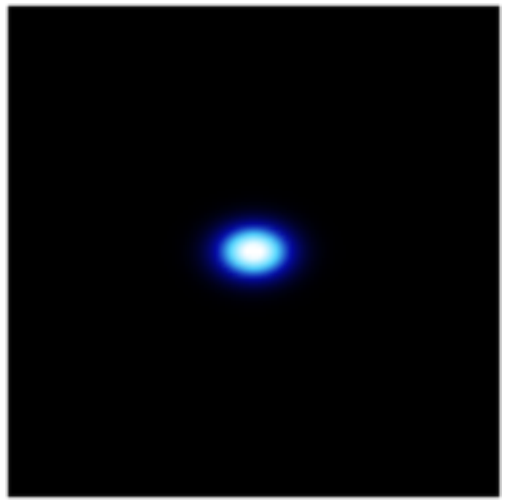
$$\xi(t) = P(t)\sqrt{8V_x(t)}$$

Interesting that for position localization decoherence:

$$\xi(t \to \infty) = \sqrt{\frac{2\omega_r}{\Lambda}}$$

Exponential speed-up

- Evolution in a **repulsive** quadratic potential



$$\hat{H} = \frac{\hat{p}^2}{2M} - \frac{1}{2} M \omega_R^2 \hat{x}^2$$

Dynamics can be **calculated analytically** taking into account decoherence

Momentum (and position) distribution grows **exponentially**

$$V_p(t) \approx e^{2\omega_R t} V_p(0)$$

Also coherence length

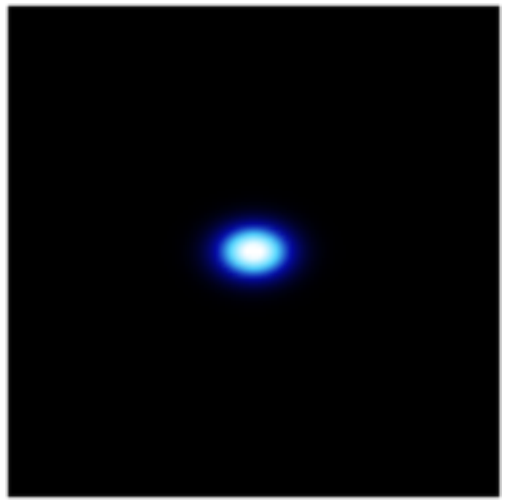
$$\xi(t) = P(t)\sqrt{8V_x(t)}$$

Interesting that for position localization decoherence:

$$\xi(t \to \infty) = \sqrt{\frac{2\omega_r}{\Lambda}}$$

Exponential speed-up

- Evolution in a **repulsive** quadratic potential



$$\hat{H} = \frac{\hat{p}^2}{2M} - \frac{1}{2} M \omega_R^2 \hat{x}^2$$

Dynamics can be **calculated analytically** taking into account decoherence

Momentum (and position) distribution grows **exponentially**

$$V_p(t) \approx e^{2\omega_R t} V_p(0)$$

Also coherence length

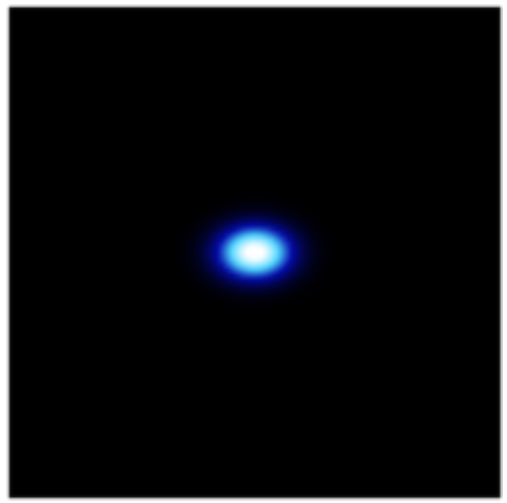
$$\xi(t) = P(t)\sqrt{8V_x(t)}$$

Interesting that for position localization decoherence:

$$\xi(t \to \infty) = \sqrt{\frac{2\omega_r}{\Lambda}}$$

Exponential speed-up

- Evolution in a **repulsive** quadratic potential



$$\hat{H} = \frac{\hat{p}^2}{2M} - \frac{1}{2} M \omega_R^2 \hat{x}^2$$

Dynamics can be **calculated analytically** taking into account decoherence

Momentum (and position) distribution grows **exponentially**

$$V_p(t) \approx e^{2\omega_R t} V_p(0)$$

Also coherence length

$$\xi(t) = P(t)\sqrt{8V_x(t)}$$

Interesting that for position localization decoherence:

$$\xi(t \to \infty) = \sqrt{\frac{2\omega_r}{\Lambda}}$$

1. Preparing a pure state

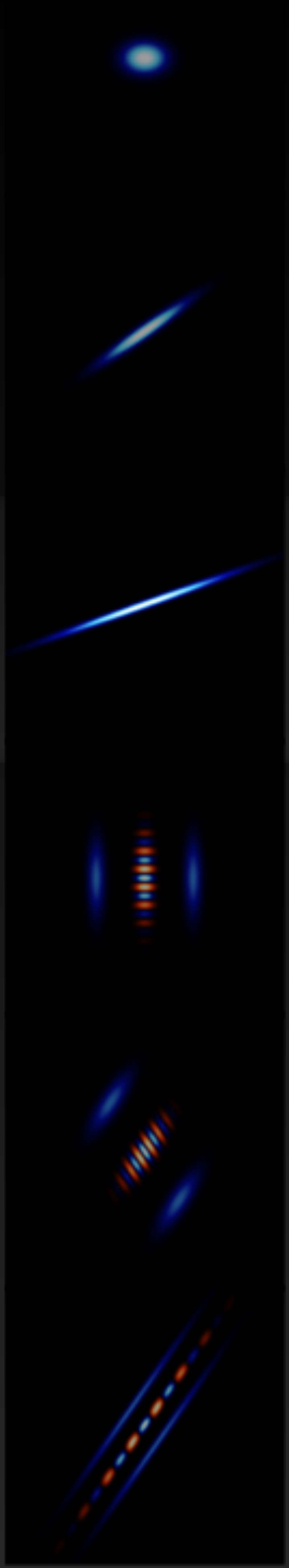
2. Exponential speed-up

3. Free expansion

4. Double slit

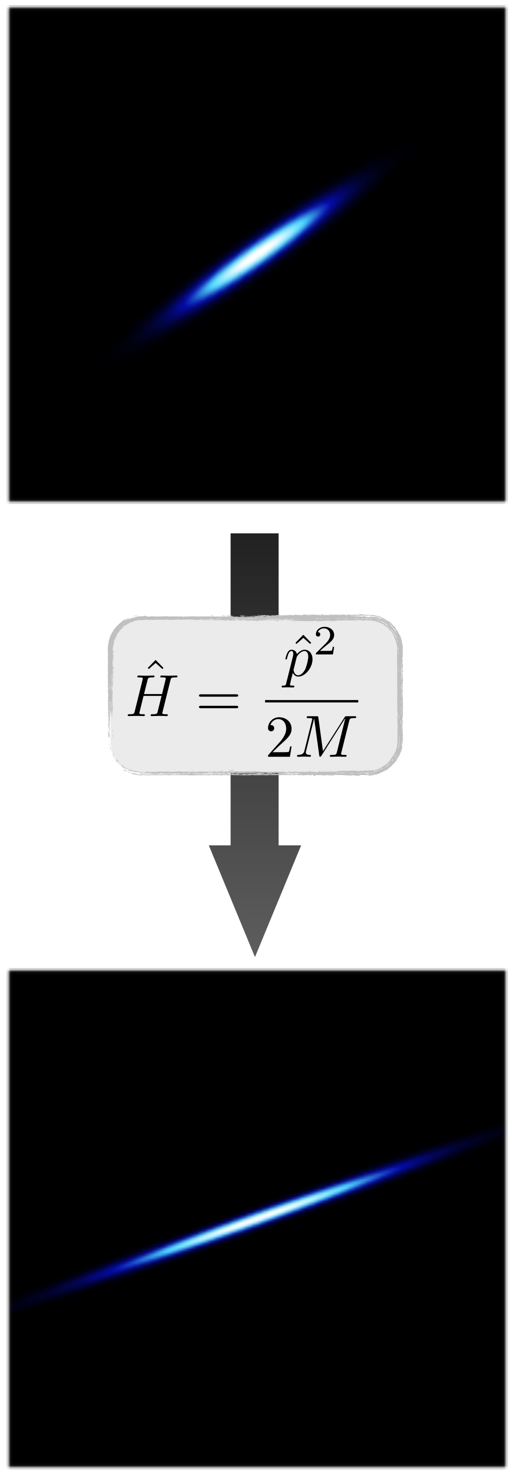
5. Rotation

6. Exponential generation of fringes



Free expansion

- Evolution with free dynamics



Dynamics can be calculated analytically taking into account decoherence

Coherence lengths grows linearly in time at a speed

$$\dot{\xi}_{\mathrm{free}} = \sqrt{\frac{8V_p}{M^2}}$$

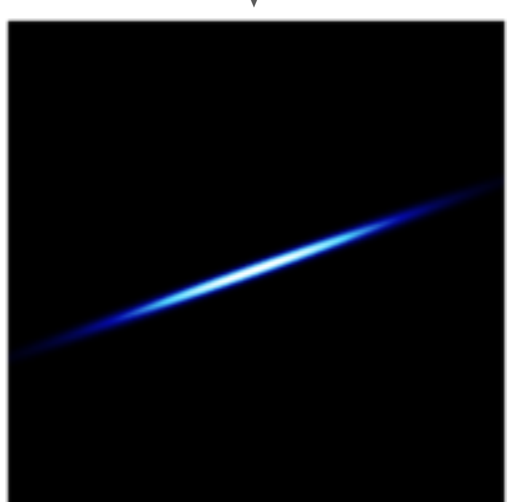
Without momentum speedup the speed is

$$\dot{\xi}_{\mathrm{free}} \approx \frac{10^7}{\sqrt{M[\mathrm{amu}]}} \times 40\ \mathrm{nm/s}$$

Free expansion

- Evolution with free dynamics

$$\hat{H} = \frac{\hat{p}^2}{2M}$$



Dynamics can be calculated analytically taking into account decoherence

Coherence lengths grows linearly in time at a speed

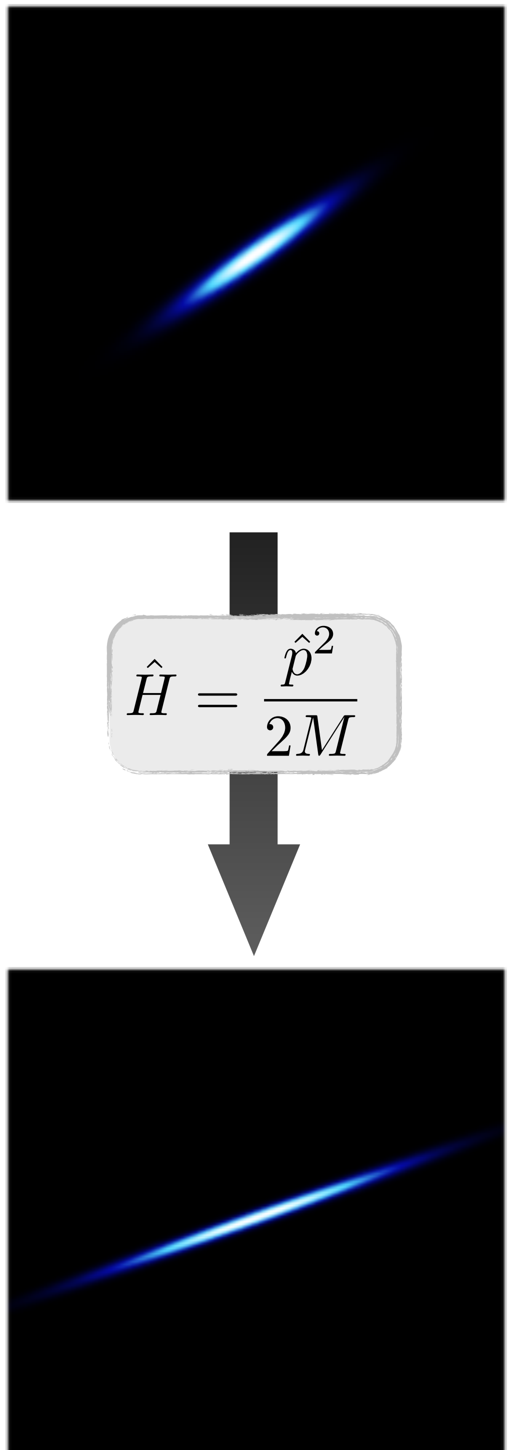
$$\dot{\xi}_{\text{free}} = \sqrt{\frac{8V_p}{M^2}}$$

Without momentum speedup the speed is

$$\dot{\xi}_{\text{free}} \approx \frac{10^7}{\sqrt{M[\text{amu}]}} \times 40 \text{ nm/s}$$

Free expansion

- Evolution with free dynamics



Dynamics can be **calculated analytically** taking into account decoherence

Coherence lengths grows **linearly in time** at a speed

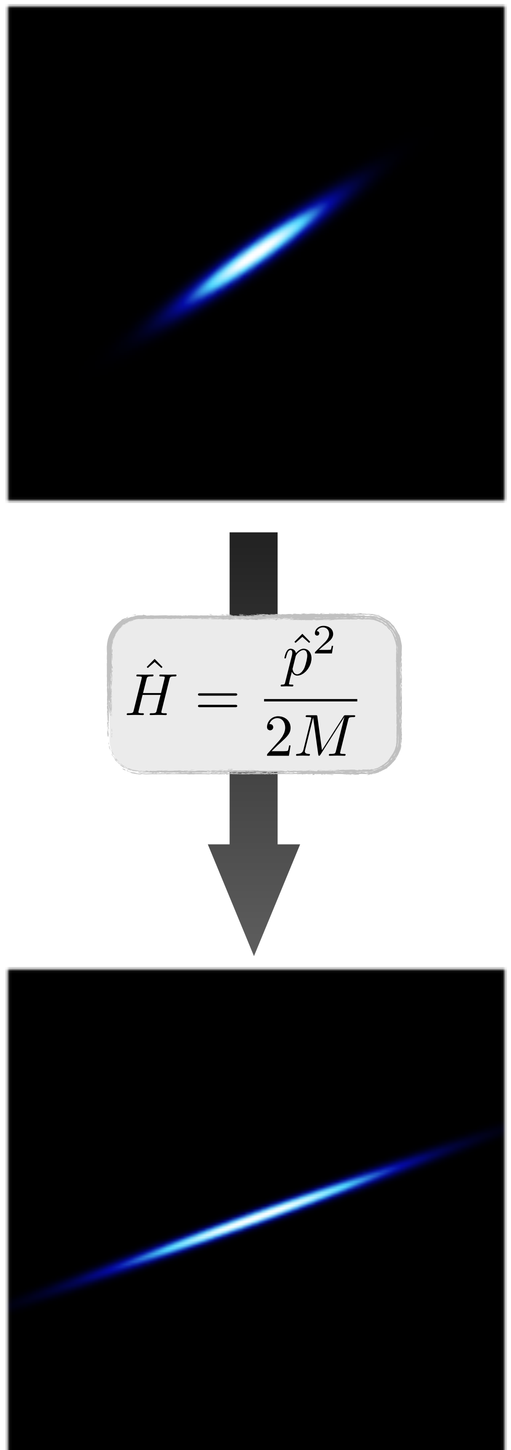
$$\dot{\xi}_{\mathrm{free}} = \sqrt{\frac{8V_p}{M^2}}$$

Without momentum speedup the speed is

$$\dot{\xi}_{\mathrm{free}} \approx \frac{10^7}{\sqrt{M[\mathrm{amu}]}} \times 40\ \mathrm{nm/s}$$

Free expansion

- Evolution with free dynamics



Dynamics can be **calculated analytically** taking into account decoherence

Coherence lengths grows **linearly in time** at a speed

$$\dot{\xi}_{\rm free} = \sqrt{\frac{8V_p}{M^2}}$$

Without momentum **kick** the speed is **very slow**

$$\dot{\xi}_{\rm free} \approx \frac{10^7}{\sqrt{M[\rm amu]}} \times 40 \ {\rm nm/s}$$

1. Preparing a pure state

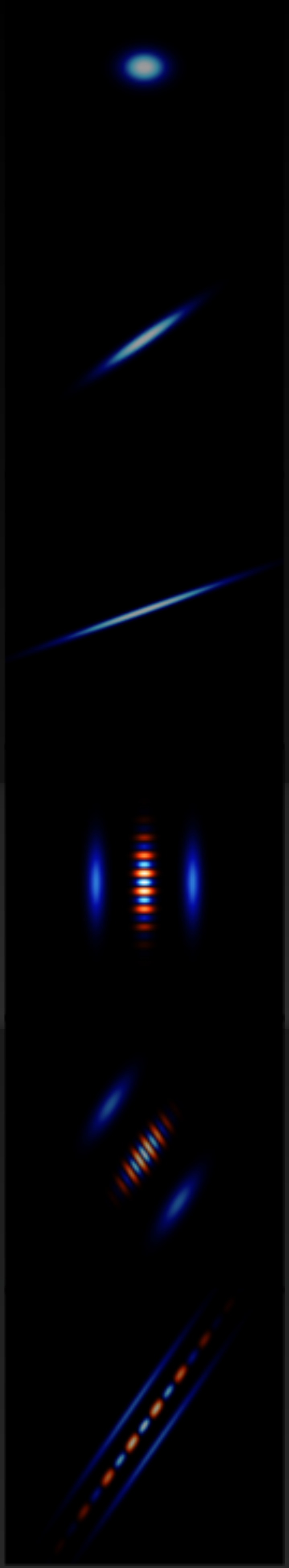
2. Exponential speed-up

3. Free expansion

4. Double slit

5. Rotation

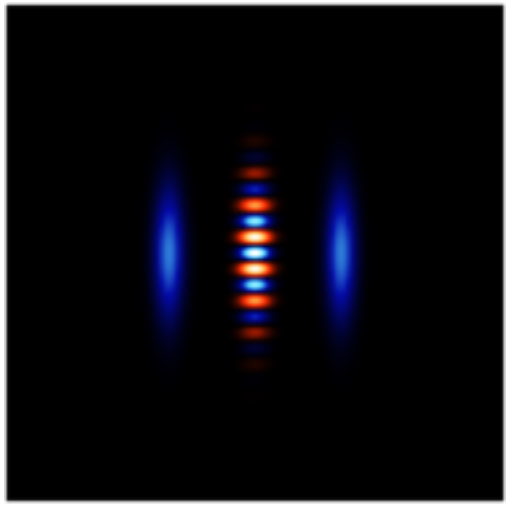
6. Exponential generation of fringes



Double slit

- X squared measurement

$$\hat{\mathcal{M}}_d = e^{\mathrm{i}\phi_{\mathrm{ds}}\left(\frac{\hat{x}}{\sigma}\right)^2}\left\{\exp\left[-\frac{\left(\hat{x}-\frac{d}{2}\right)^2}{4\sigma_d^2}\right]+\exp\left[-\frac{\left(\hat{x}+\frac{d}{2}\right)^2}{4\sigma_d^2}\right]\right\}$$



Interaction with a non-quadratic potential is analytically and numerically very challenging

Coupling to quantum system used to measure X^2

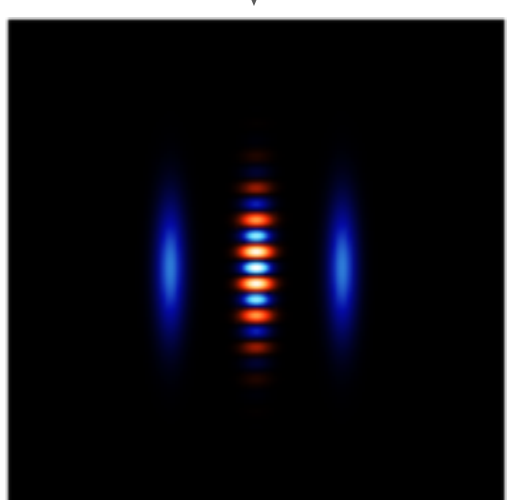
Advantage: double-slit can be smaller than particle size

Disadvantage: slit separation depends on outcome

Double slit

- X squared measurement

$$\hat{\mathcal{M}}_d = e^{\mathrm{i}\phi_{\mathrm{ds}}\left(\frac{\hat{x}}{\sigma}\right)^2}\left\{\exp\left[-\frac{\left(\hat{x}-\frac{d}{2}\right)^2}{4\sigma_d^2}\right]+\exp\left[-\frac{\left(\hat{x}+\frac{d}{2}\right)^2}{4\sigma_d^2}\right]\right\}$$



Interaction with a non-quadratic potential is analytically and numerically very challenging

Coupling to quantum system used to measure X^2

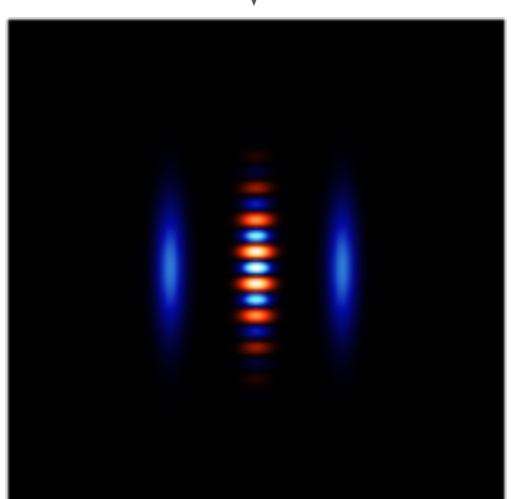
Advantage: double-slit can be smaller than particle size

Disadvantage: slit separation depends on outcome

Double slit

- X squared measurement

$$\hat{\mathcal{M}}_d = e^{\mathrm{i}\phi_{\mathrm{ds}}\left(\frac{\hat{x}}{\sigma}\right)^2}\left\{\exp\left[-\frac{\left(\hat{x}-\frac{d}{2}\right)^2}{4\sigma_d^2}\right]+\exp\left[-\frac{\left(\hat{x}+\frac{d}{2}\right)^2}{4\sigma_d^2}\right]\right\}$$



Interaction with a non-quadratic potential is analytically and numerically very challenging

Coupling to quantum system used to measure X^2

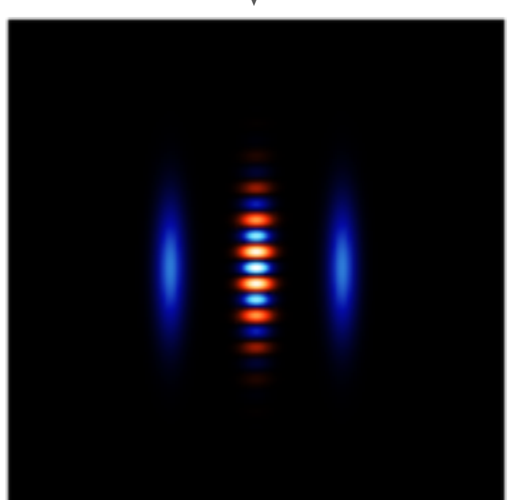
Advantage: double-slit can be smaller than particle size

Disadvantage: slit separation depends on outcome

Double slit

- X squared measurement

$$\hat{\mathcal{M}}_d = e^{\mathrm{i}\phi_{\mathrm{ds}}\left(\frac{\hat{x}}{\sigma}\right)^2} \left\{ \exp\left[-\frac{\left(\hat{x} - \frac{d}{2}\right)^2}{4\sigma_d^2} \right] + \exp\left[-\frac{\left(\hat{x} + \frac{d}{2}\right)^2}{4\sigma_d^2} \right] \right\}$$



Interaction with a non-quadratic potential is analytically and numerically very challenging

Coupling to quantum system used to measure X^2

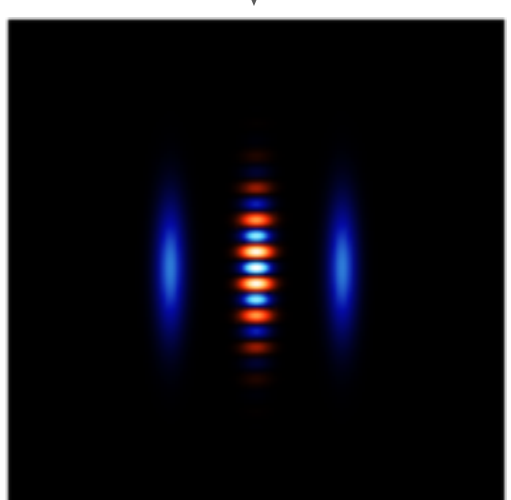
Advantage: double-slit can be smaller than particle size

Disadvantage: slit separation depends on outcome

Double slit

- X squared measurement

$$\hat{\mathcal{M}}_d = e^{\mathrm{i}\phi_{\mathrm{ds}}\left(\frac{\hat{x}}{\sigma}\right)^2}\left\{\exp\left[-\frac{\left(\hat{x}-\frac{d}{2}\right)^2}{4\sigma_d^2}\right]+\exp\left[-\frac{\left(\hat{x}+\frac{d}{2}\right)^2}{4\sigma_d^2}\right]\right\}$$



Interaction with a non-quadratic potential is analytically and numerically very challenging

Coupling to quantum system used to measure X^2

Advantage: double-slit can be smaller than particle size

Disadvantage: slit separation depends on outcome

1. Preparing a pure state

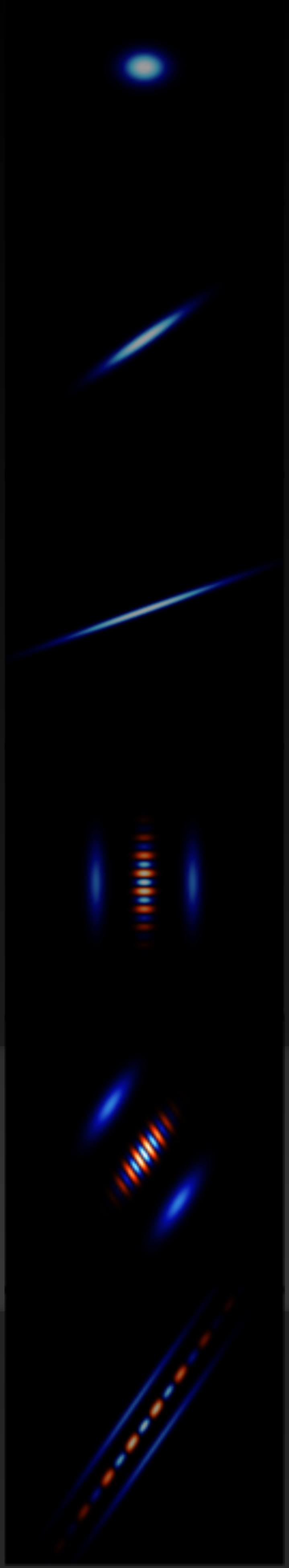
2. Exponential speed-up

3. Free expansion

4. Double slit

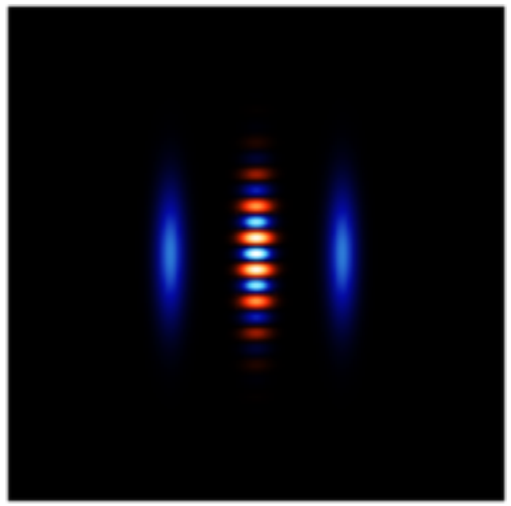
5. Rotation

6. Exponential generation of fringes

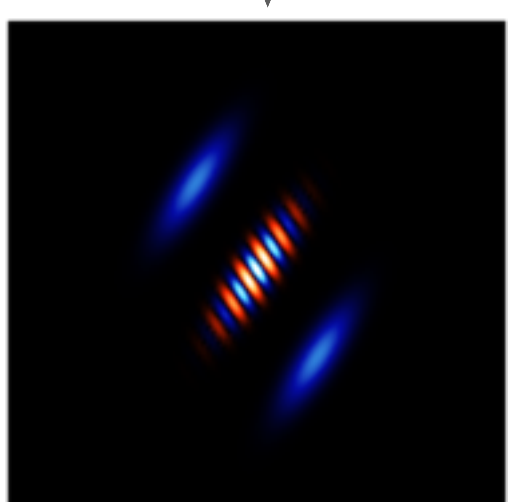


Rotation

- pi/4 rotation



$$\hat{H} = \frac{\hat{p}^2}{2M} + \frac{1}{2} M \omega_R^2 \hat{x}^2$$



We have to prepare state for exponential time-of-flight

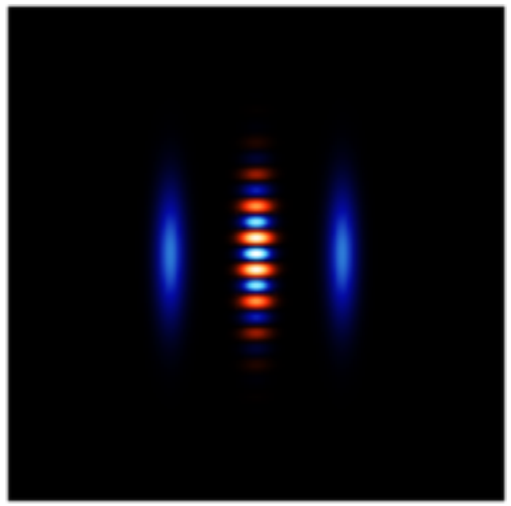
We make a pi/4 rotation

$$\omega_R t = \frac{\pi}{4}$$

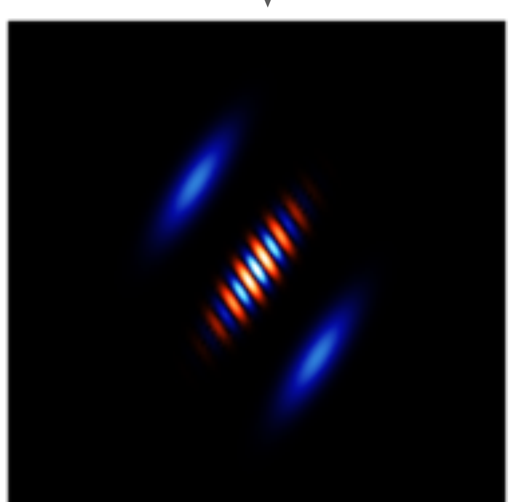
After double slit state is more robust against decoherence

Rotation

- pi/4 rotation



$$\hat{H} = \frac{\hat{p}^2}{2M} + \frac{1}{2} M \omega_R^2 \hat{x}^2$$



We have to **prepare state** for exponential time-of-flight

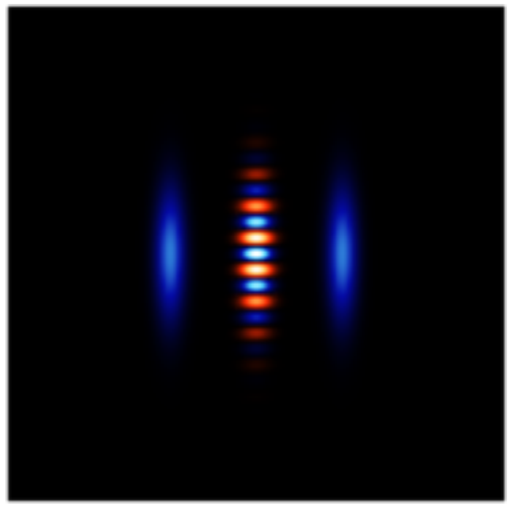
We make a pi/4 rotation

$$\omega_R t = \frac{\pi}{4}$$

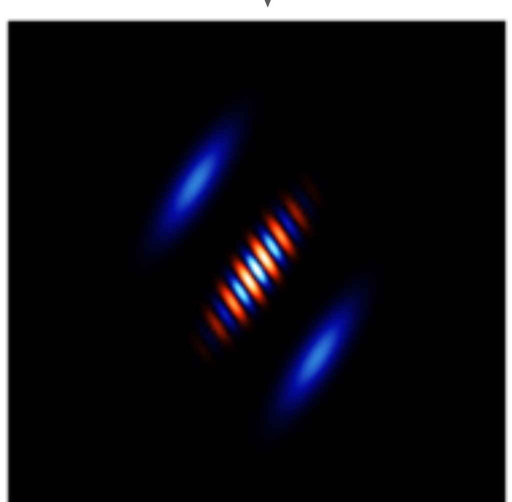
After double slit **state is more robust** against decoherence

Rotation

- pi/4 rotation



$$\hat{H} = \frac{\hat{p}^2}{2M} + \frac{1}{2} M \omega_R^2 \hat{x}^2$$



We have to **prepare state** for exponential time-of-flight

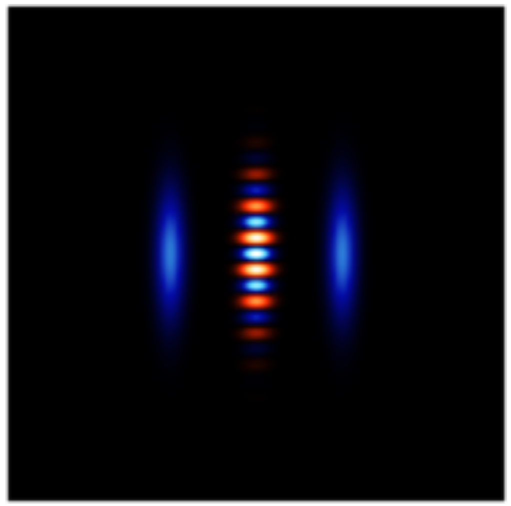
We make a pi/4 rotation

$$\omega_R t = \frac{\pi}{4}$$

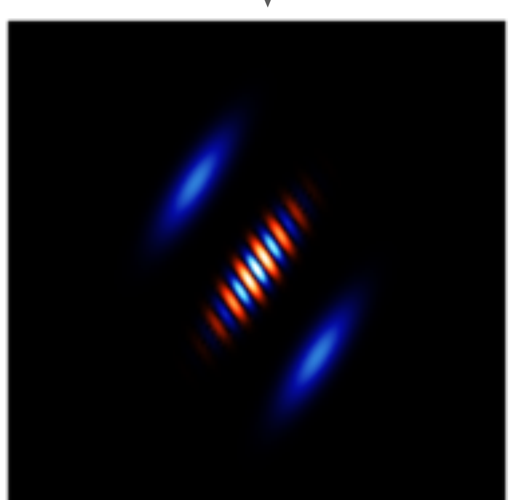
After double slit **state is more robust** against decoherence

Rotation

- pi/4 rotation



$$\hat{H} = \frac{\hat{p}^2}{2M} + \frac{1}{2} M \omega_R^2 \hat{x}^2$$



We have to prepare state for exponential time-of-flight

We make a pi/4 rotation

$$\omega_R t = \frac{\pi}{4}$$

After double slit state is more robust against decoherence

1. Preparing a pure state

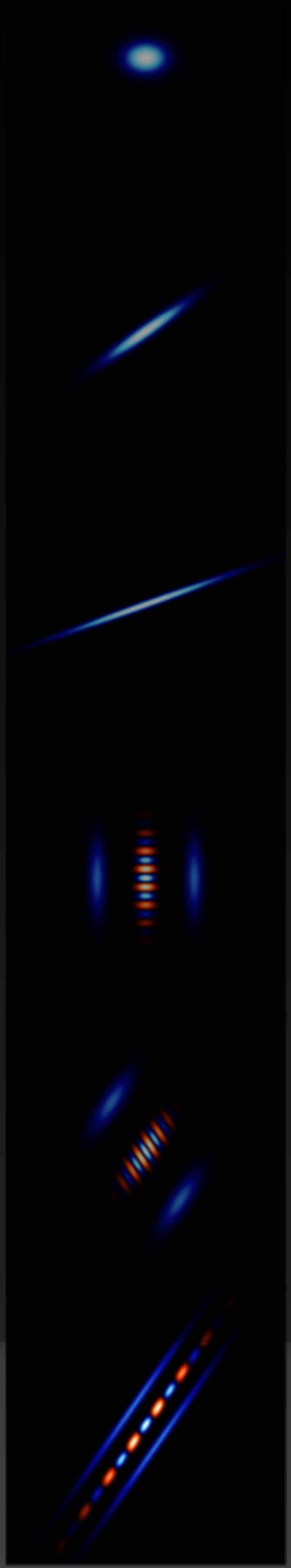
2. Exponential speed-up

3. Free expansion

4. Double slit

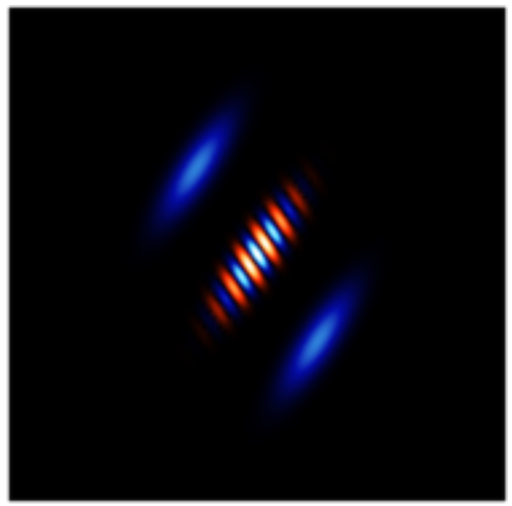
5. Rotation

6. Exponential generation of fringes

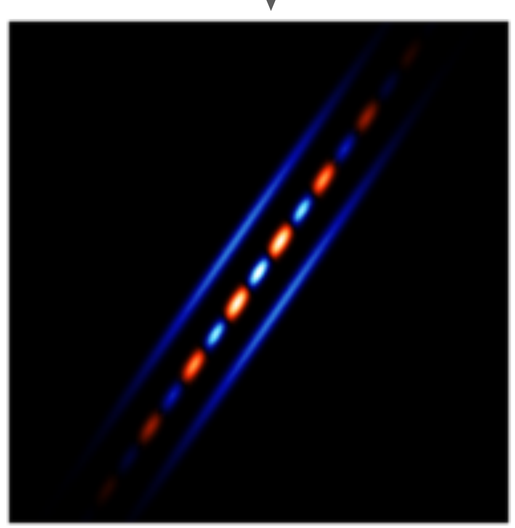


Exponentially generation of fringes

- Evolution in a **repulsive** quadratic potential



$$\hat{H} = \frac{\hat{p}^2}{2M} - \frac{1}{2} M \omega_R^2 \hat{x}^2$$



In **free dynamics** fringes generate **very slowly**

$$x_f = \frac{2\pi\hbar t}{Md}$$

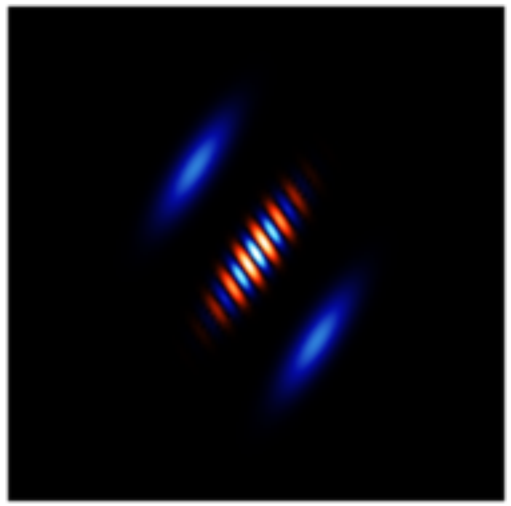
In **repulsive dynamics** fringes generate **exponentially faster**

$$x_f(t) \approx e^{\omega_r t} x_f(0)$$

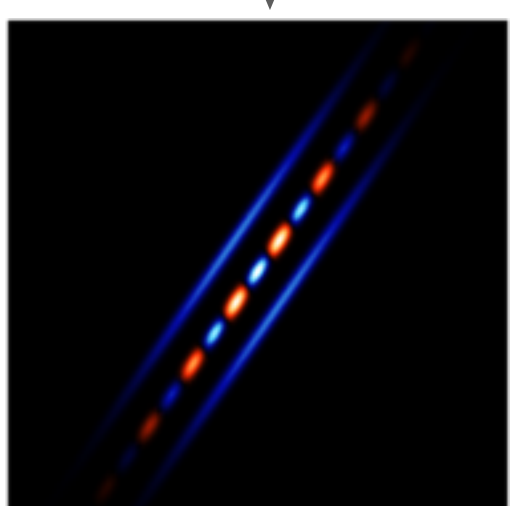
Without previous rotation: no fringes

Exponentially generation of fringes

- Evolution in a **repulsive** quadratic potential



$$\hat{H} = \frac{\hat{p}^2}{2M} - \frac{1}{2} M \omega_R^2 \hat{x}^2$$



In **free dynamics** fringes generate **very slowly**

$$x_f = \frac{2\pi\hbar t}{Md}$$

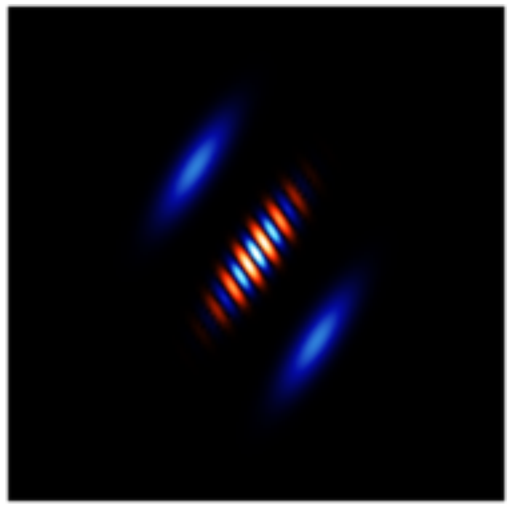
In **repulsive dynamics** fringes generate **exponentially faster**

$$x_f(t) \approx e^{\omega_r t} x_f(0)$$

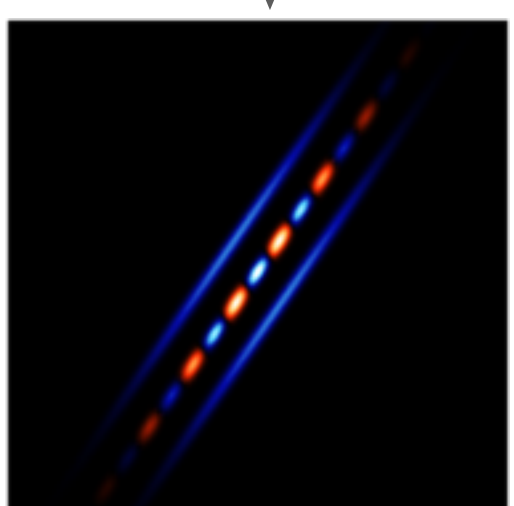
Without previous rotation: no fringes

Exponentially generation of fringes

- Evolution in a **repulsive** quadratic potential



$$\hat{H} = \frac{\hat{p}^2}{2M} - \frac{1}{2} M \omega_R^2 \hat{x}^2$$



In **free dynamics** fringes generate **very slowly**

$$x_f = \frac{2\pi\hbar t}{Md}$$

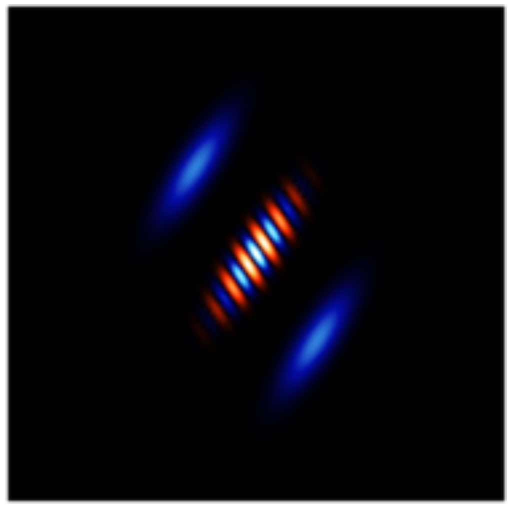
In **repulsive dynamics** fringes generate **exponentially faster**

$$x_f(t) \approx e^{\omega_r t} x_f(0)$$

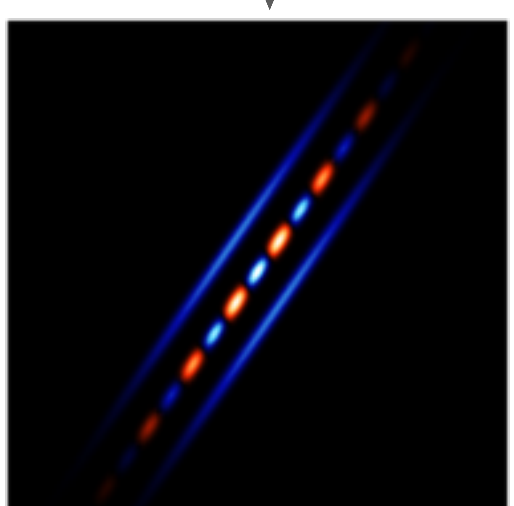
Without previous rotation: no fringes

Exponentially generation of fringes

- Evolution in a **repulsive** quadratic potential



$$\hat{H} = \frac{\hat{p}^2}{2M} - \frac{1}{2}M\omega_R^2\hat{x}^2$$



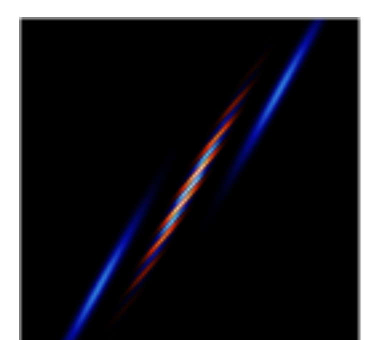
In **free dynamics** fringes generate **very slowly**

$$x_f = \frac{2\pi\hbar t}{Md}$$

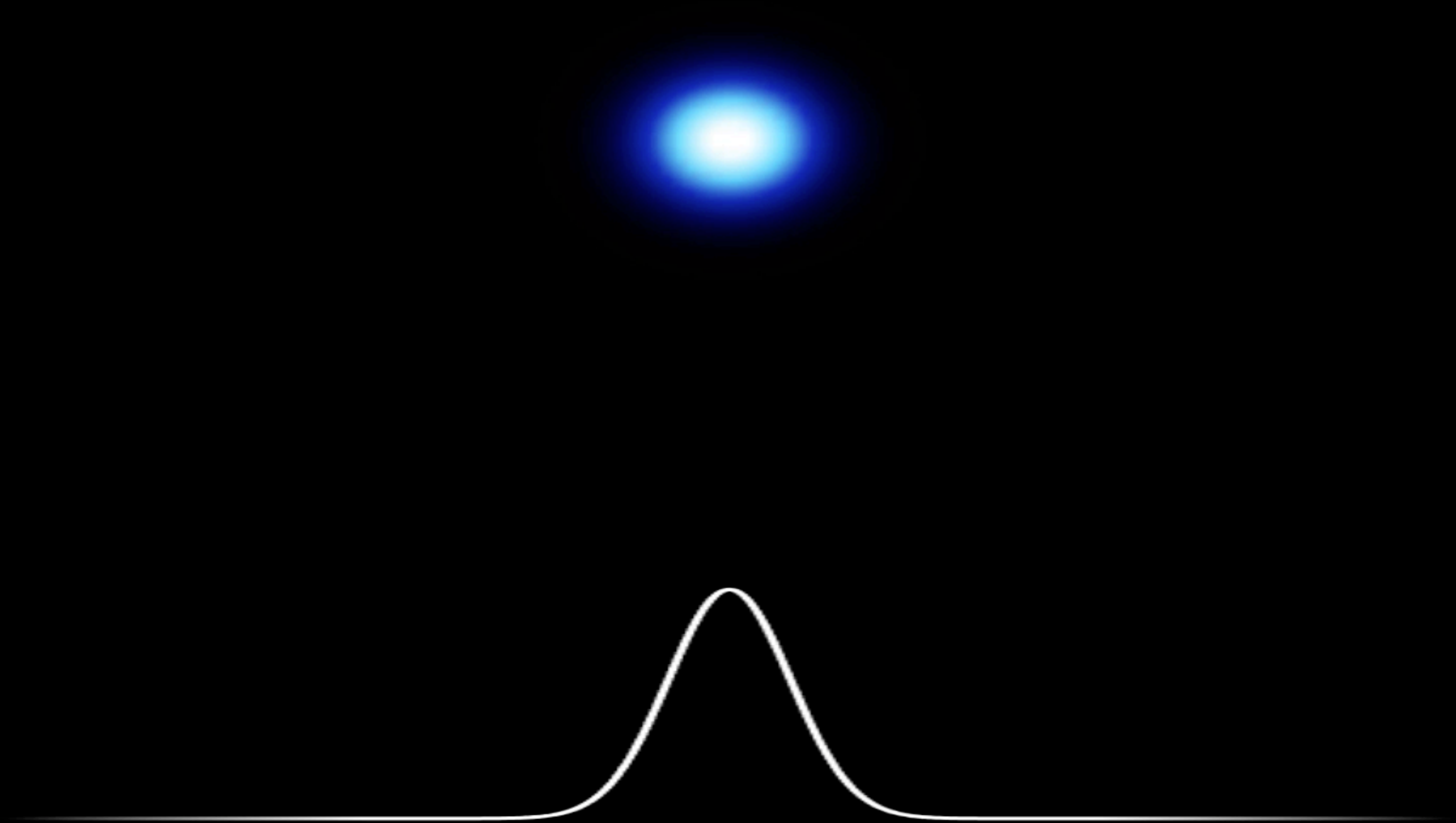
In **repulsive dynamics** fringes generate **exponentially faster**

$$x_f(t) \approx e^{\omega_r t} x_f(0)$$

Without previous rotation: no fringes

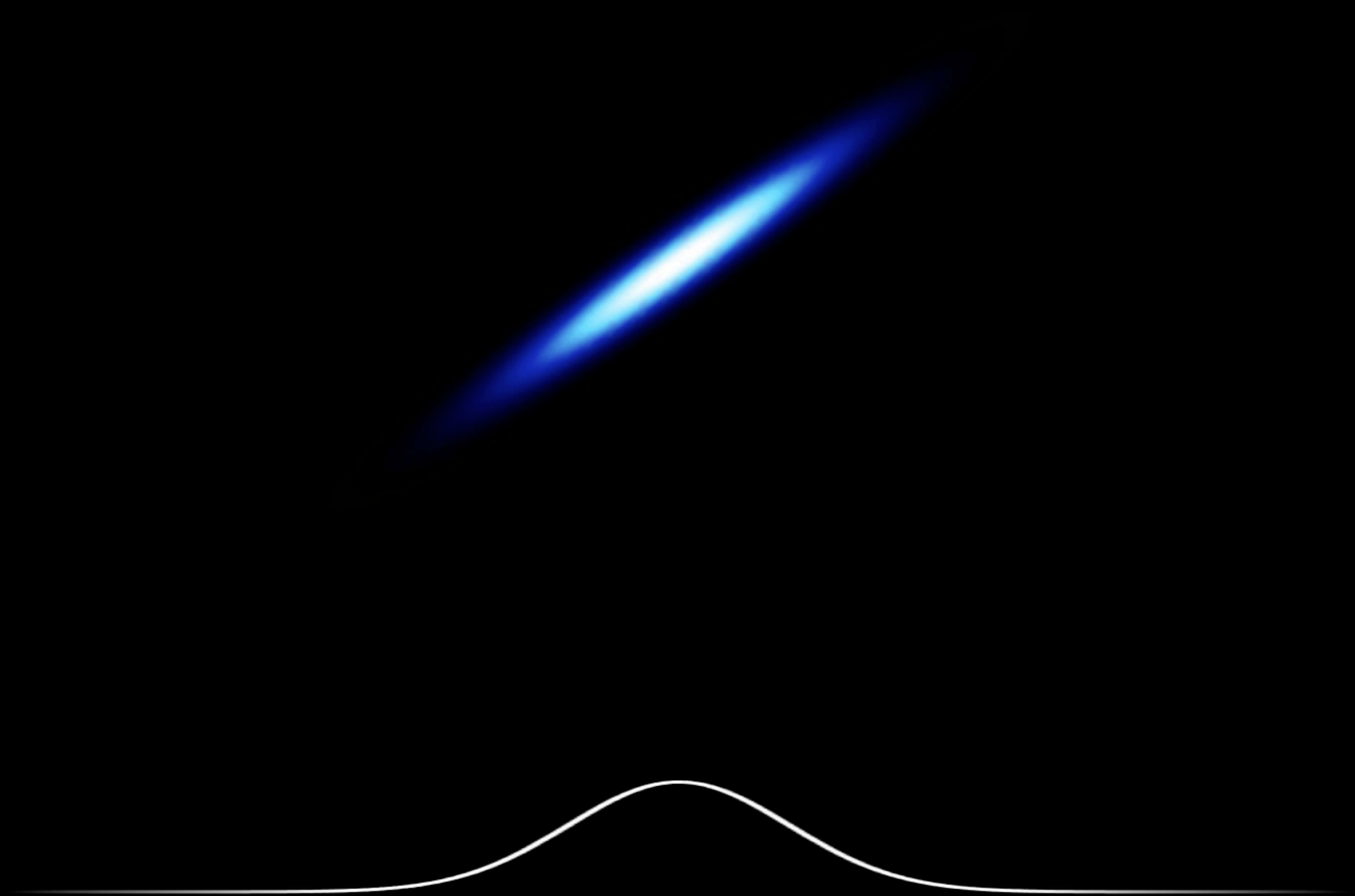


Exponential speed-up:
repulsive potential dynamics



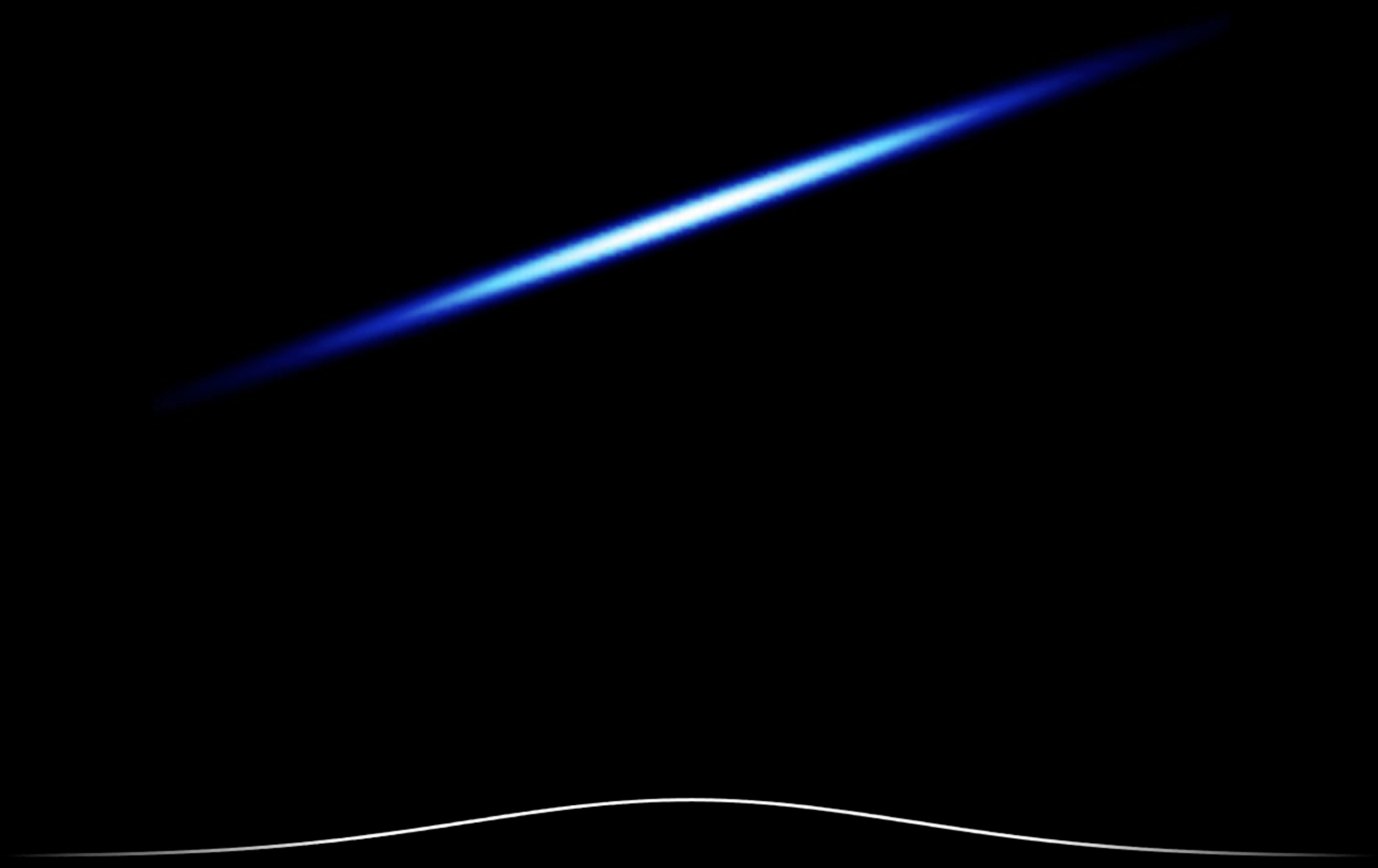
Free expansion:

free dynamics



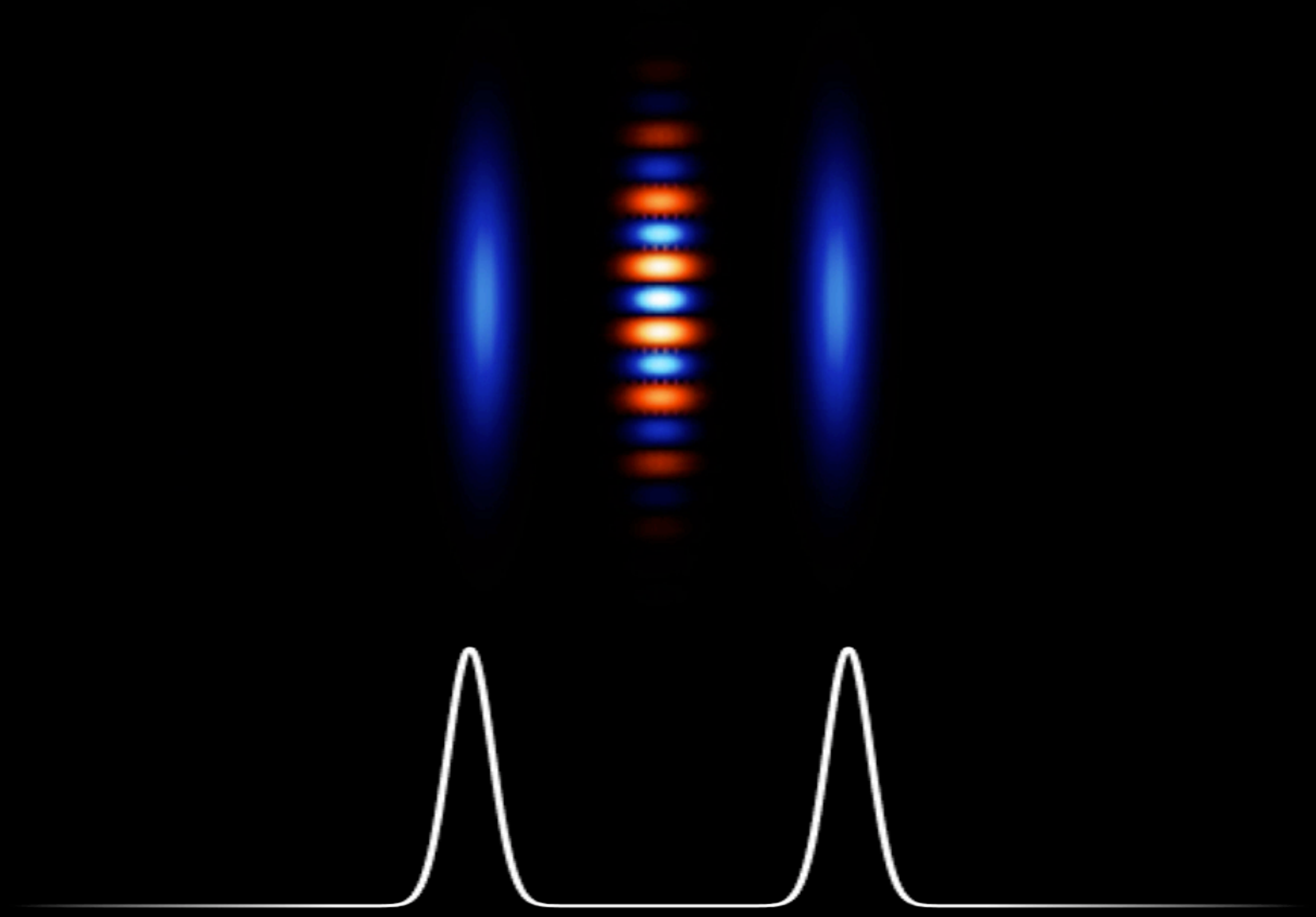
Double-slit:

X-squared measurement

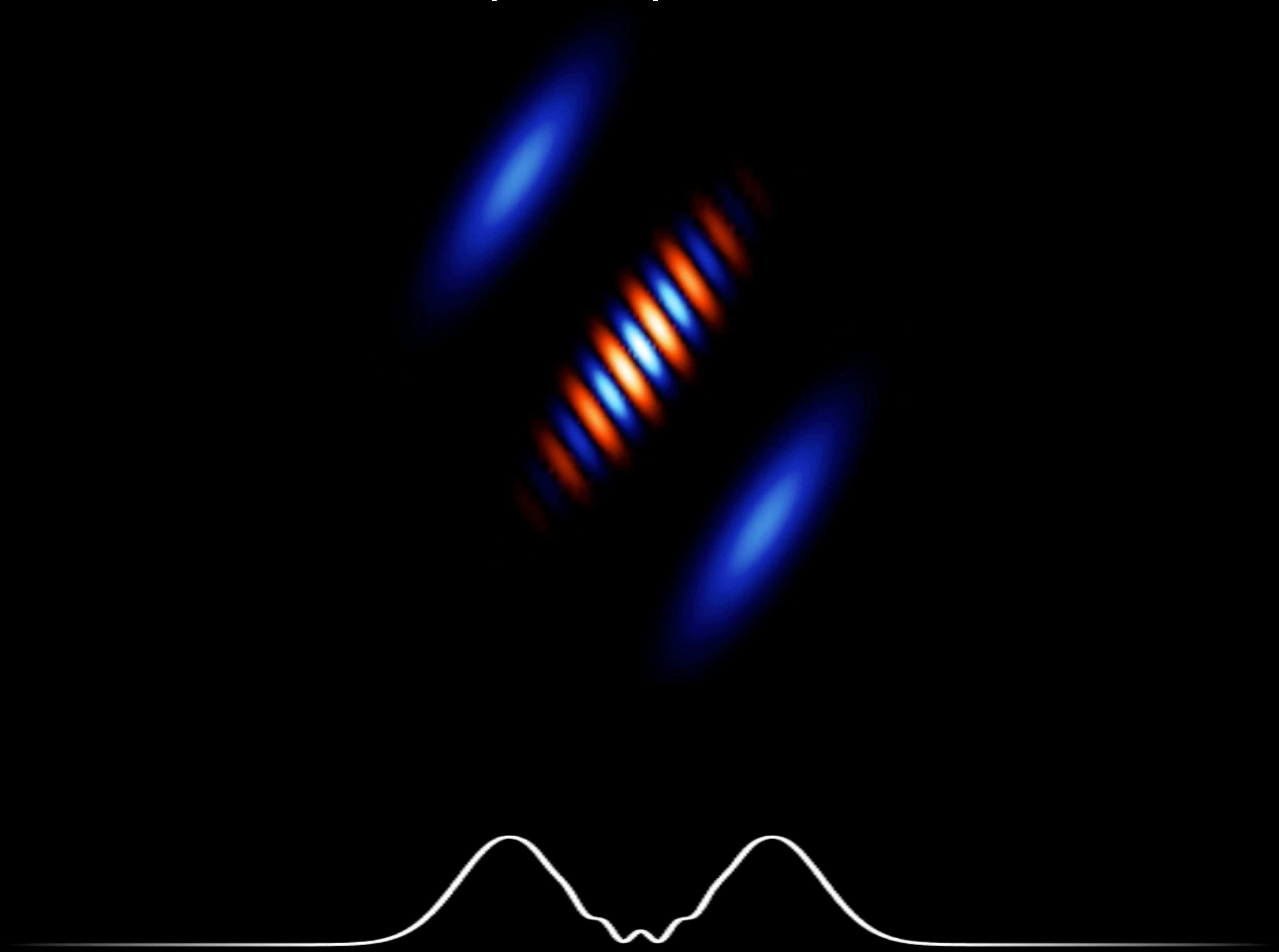


Rotation:

harmonic potential dynamics

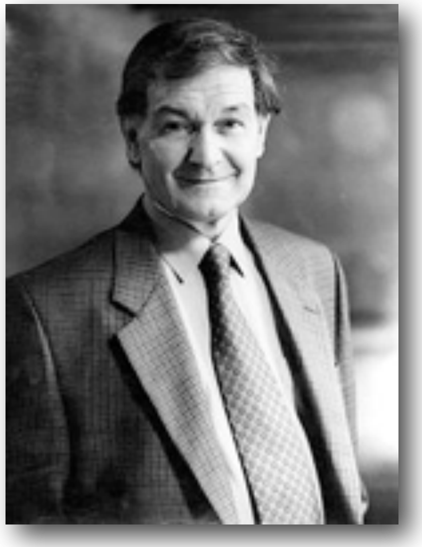


Exponential generation of fringes:
repulsive potential



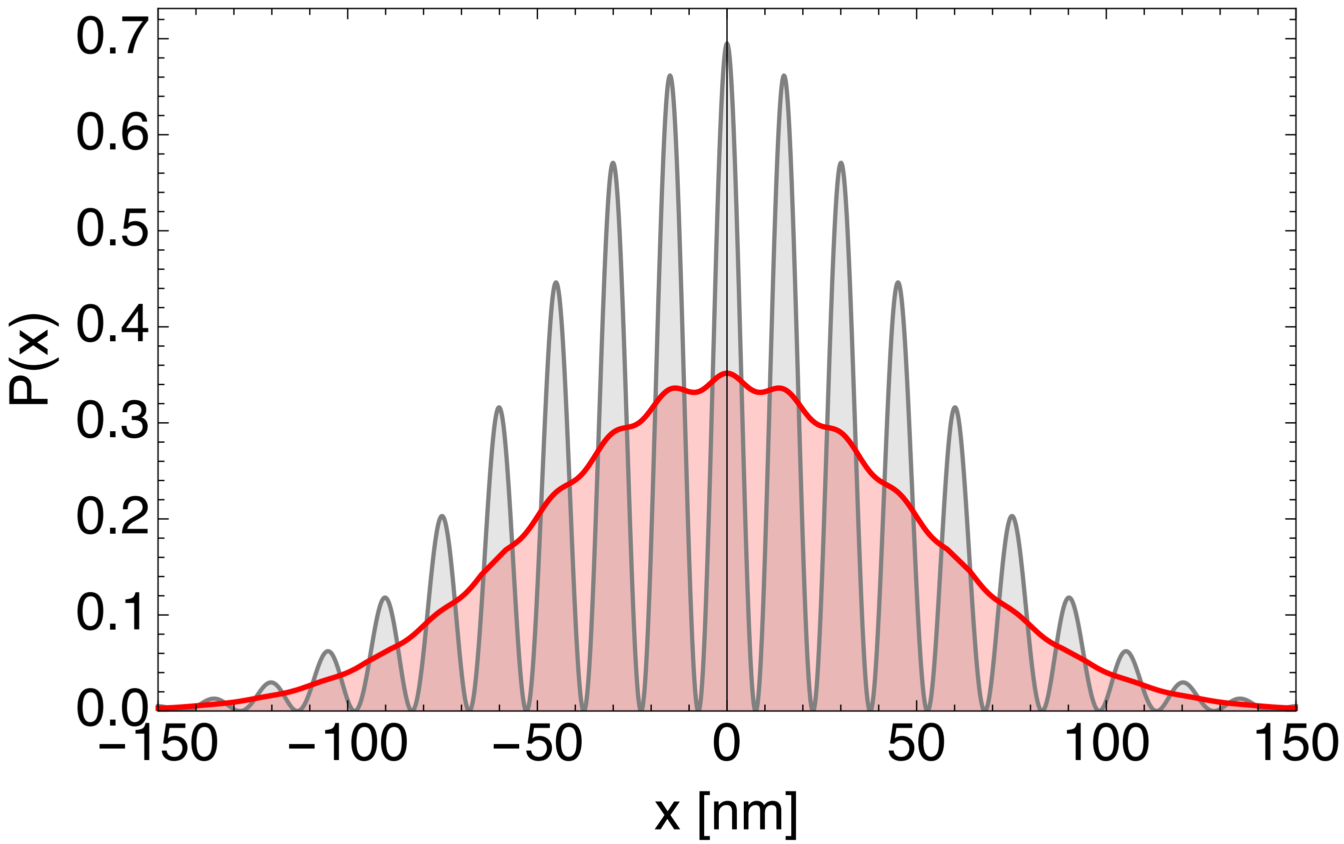
Results

Growing coherence length in repulsive expansion



$$\Lambda_G = \frac{GM^2}{2\hbar R^3}$$

Gravitationally-induced decoherence could be falsified



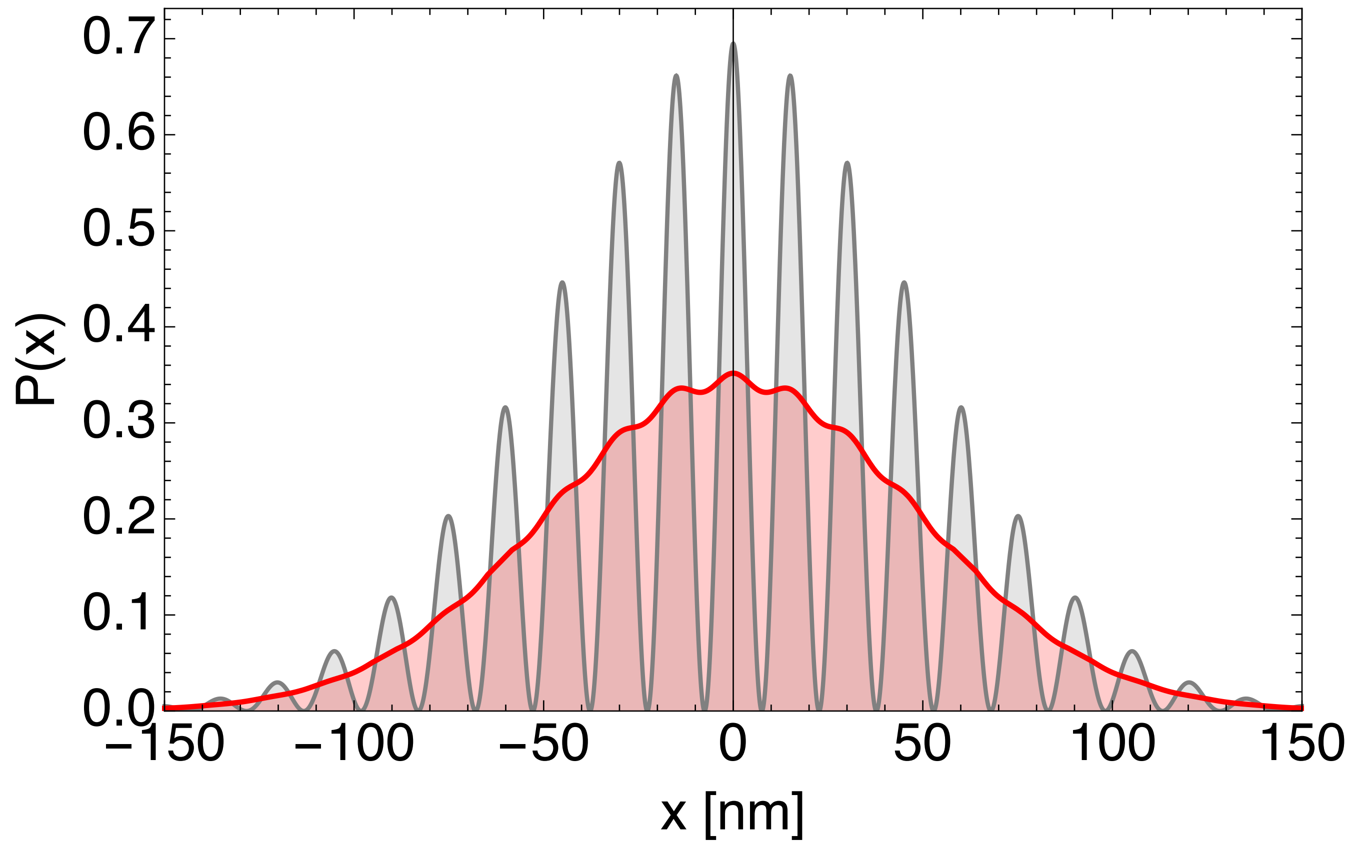
$$\Lambda = \Lambda_G + \Lambda_{QM}$$

$$\Lambda = \Lambda_{QM}$$

Growing coherence length in repulsive expansion

- Sphere (Nb): 4 micrometers

Gravitationally-induced decoherence could be falsified



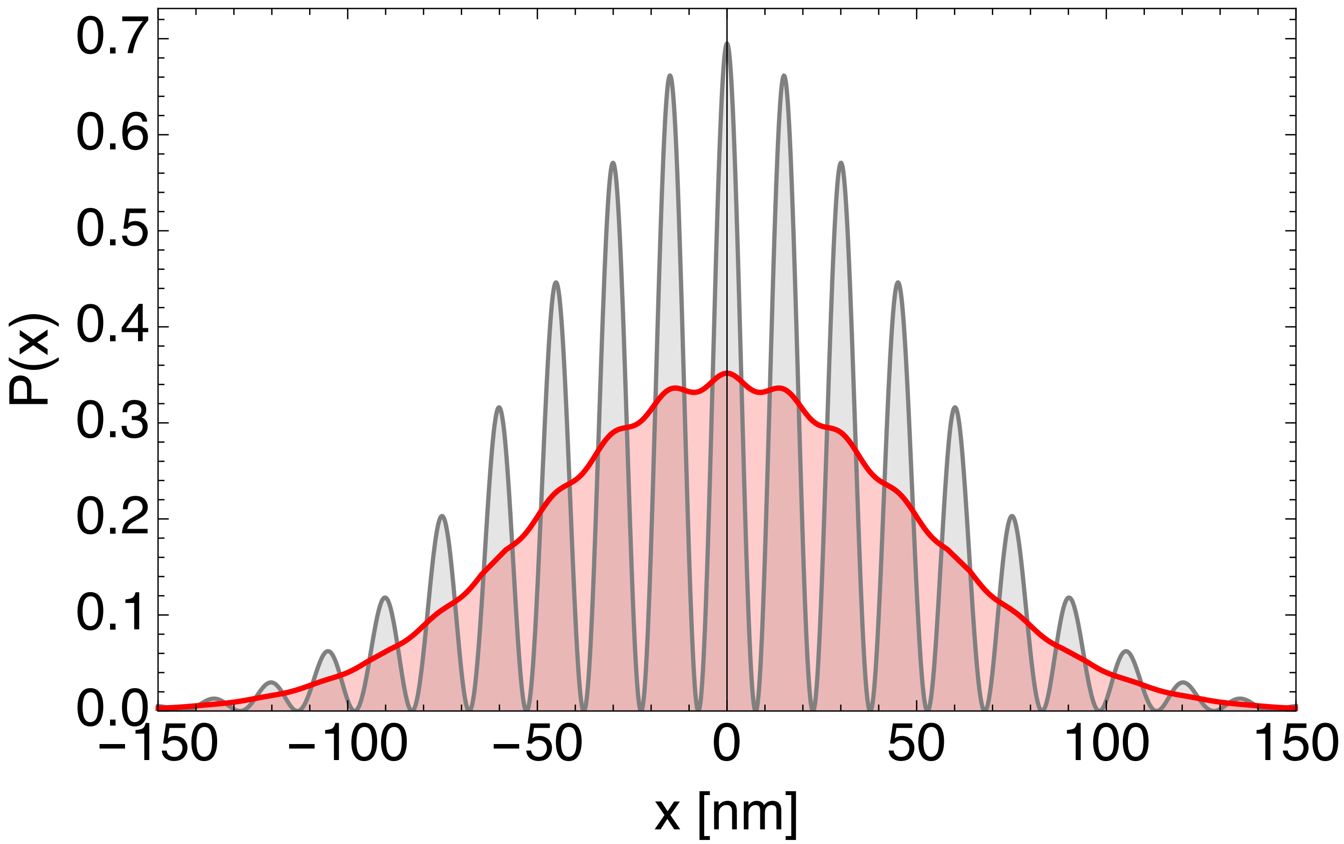
$$\Lambda = \Lambda_G + \Lambda_{QM}$$

$$\Lambda = \Lambda_{QM}$$

Growing coherence length in repulsive expansion

- Sphere (Nb): 4 micrometers
- Total time: 537 ms
  - ➡ Exponential speed-up: 4.8 ms
  - ➡ Free expansion: 500 ms
  - ➡ Rotation: 1.3 ms
  - ➡ Exp generation of fringes: 31.8 ms

Gravitationally-induced decoherence could be falsified



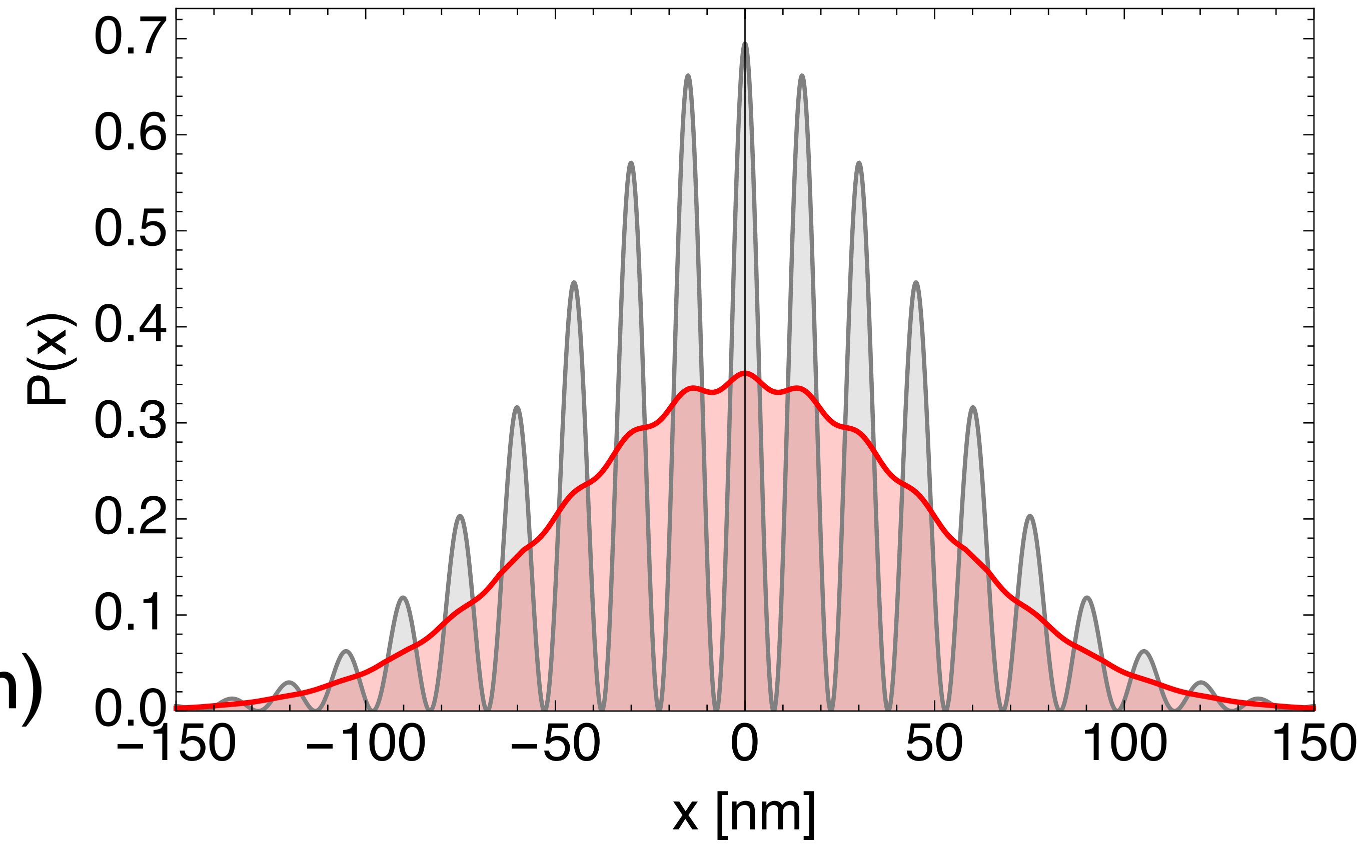
$$\Lambda = \Lambda_G + \Lambda_{QM}$$

$$\Lambda = \Lambda_{QM}$$

Growing coherence length in repulsive expansion

- Sphere (Nb): 4 micrometers
- Total time: 537 ms
  - ➡ Exponential speed-up: 4.8 ms
  - ➡ Free expansion: 500 ms
  - ➡ Rotation: 1.3 ms
  - ➡ Exp generation of fringes: 31.8 ms
- Slit separation: 84 nm (width 4 nm)

Gravitationally-induced decoherence could be falsified



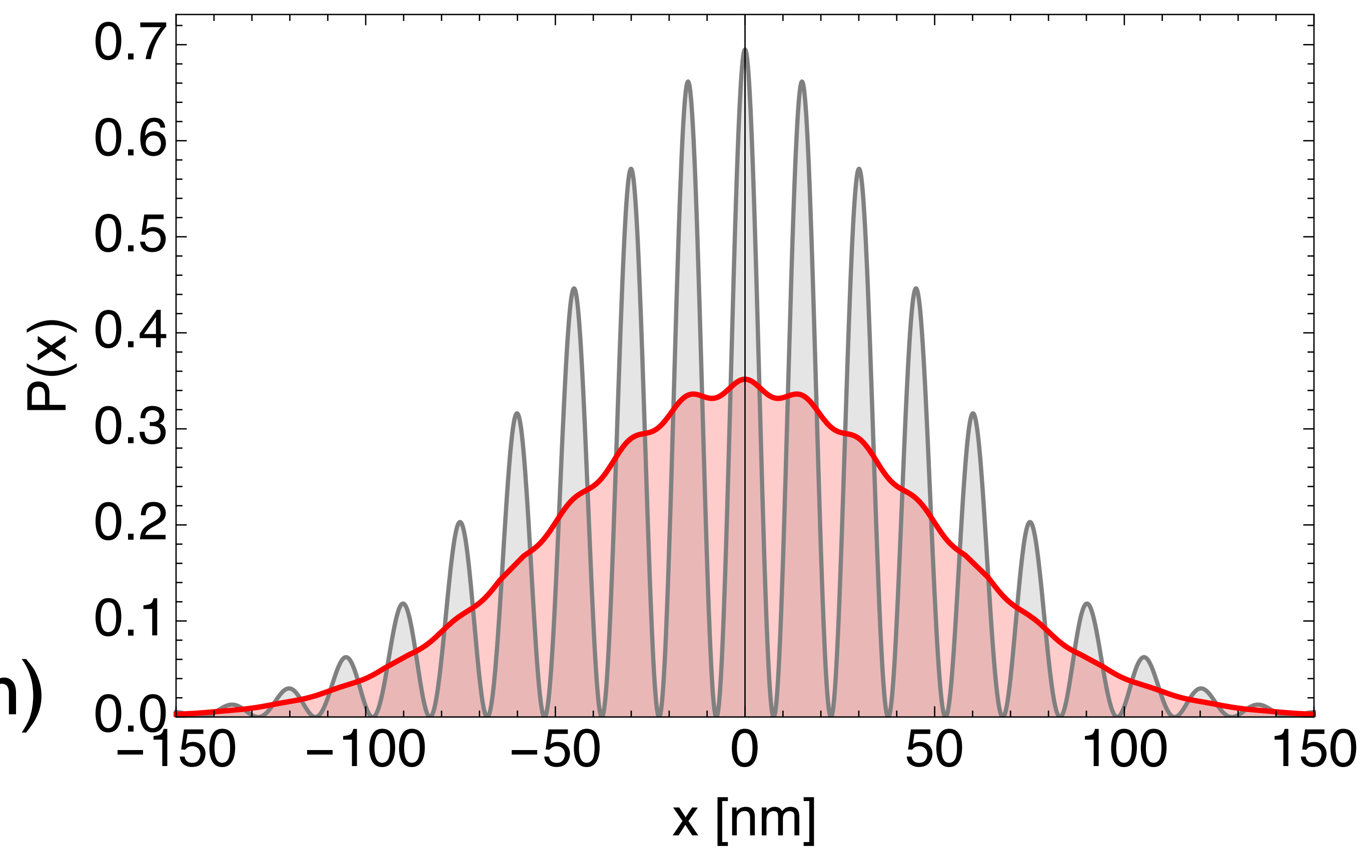
$$\Lambda = \Lambda_G + \Lambda_{QM}$$

$$\Lambda = \Lambda_{QM}$$

Growing coherence length in repulsive expansion

- Sphere (Nb): 4 micrometers
- Total time: 537 ms
  - ➡ Exponential speed-up: 4.8 ms
  - ➡ Free expansion: 500 ms
  - ➡ Rotation: 1.3 ms
  - ➡ Exp generation of fringes: 31.8 ms
- Slit separation: 84 nm (width 4 nm)
- Temperature: < 1K
- Quadratic potentials: 100 Hz

Gravitationally-induced decoherence could be falsified



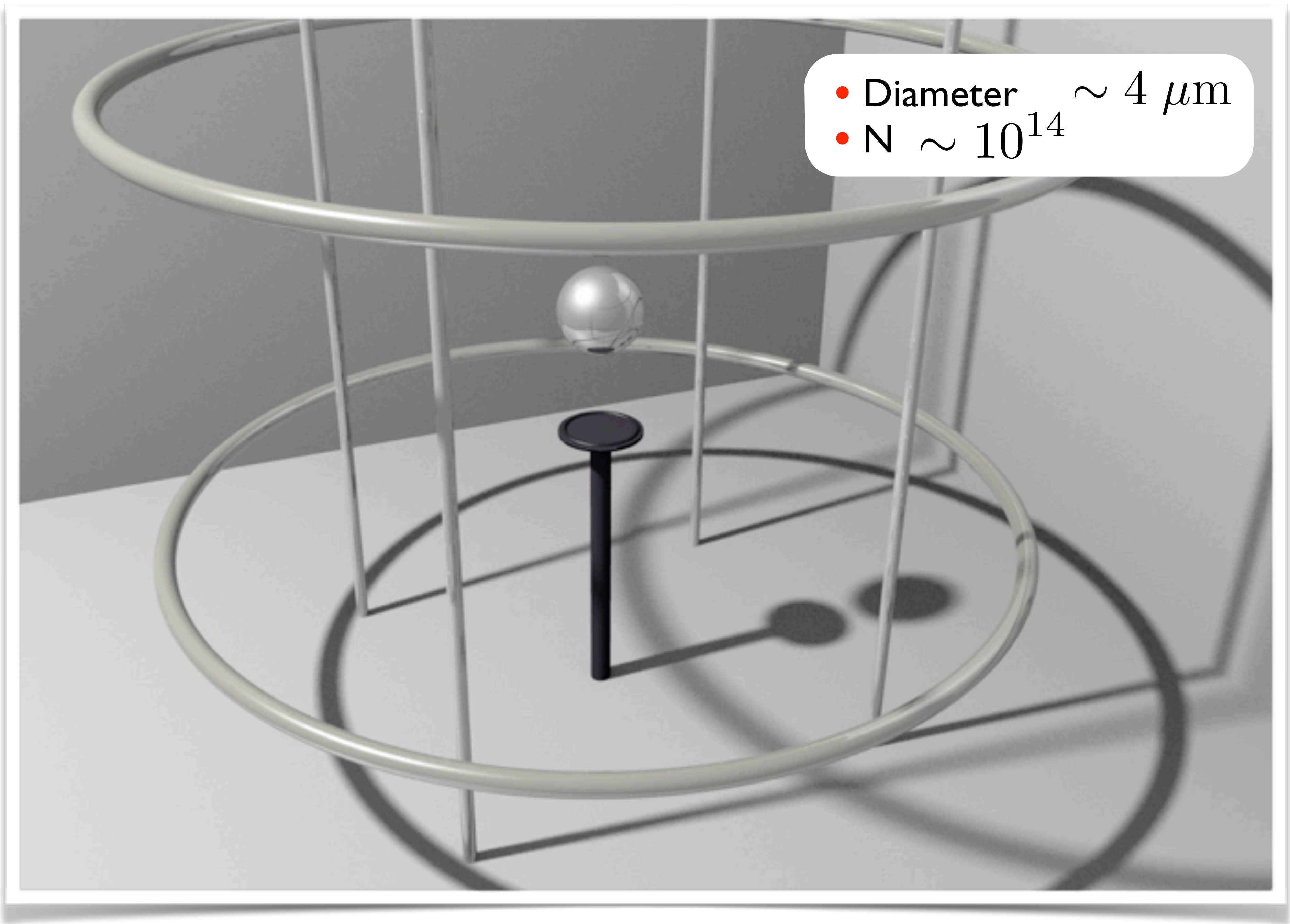
$$\Lambda = \Lambda_G + \Lambda_{QM}$$

$$\Lambda = \Lambda_{QM}$$

Experimental Proposal

Levitating superconducting microspheres

- Quantum magnetomechanics: magnetic coupling to a quantum circuit

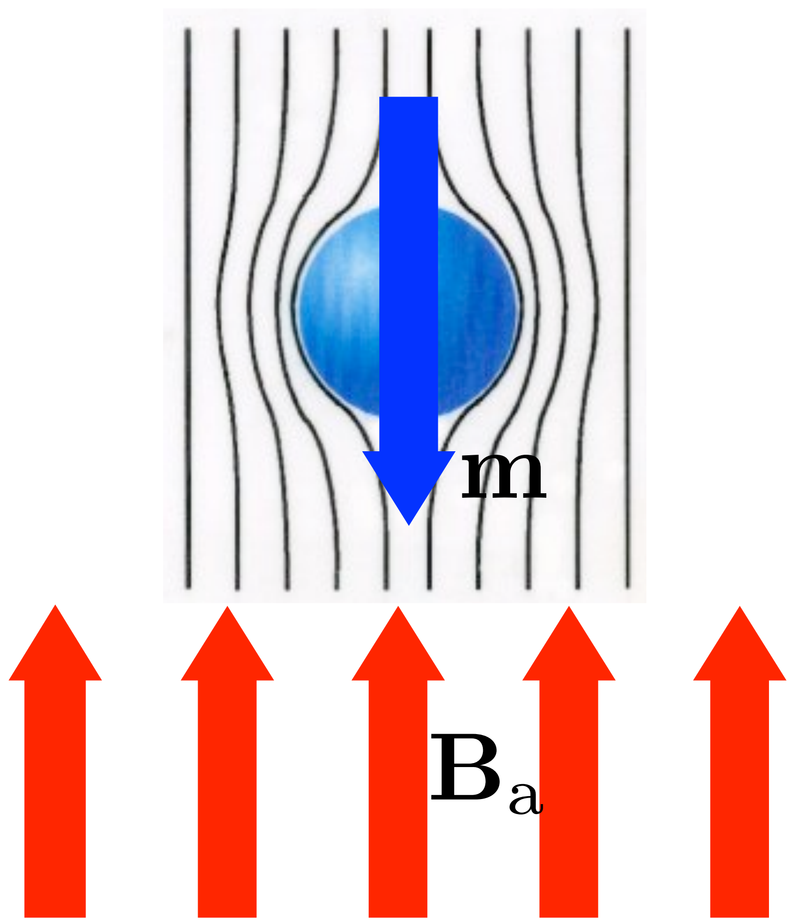


ORI, *et al.* PRL **109** 147205 (2012).

Levitating superconducting microspheres

- Quantum magnetomechanics: magnetic coupling to a quantum circuit

- Sphere behaves as a magnetic dipole



$$\mathbf{m} = -\frac{\mathbf{B}_\mathrm{a}}{\mu_0}\frac{3V}{2}$$

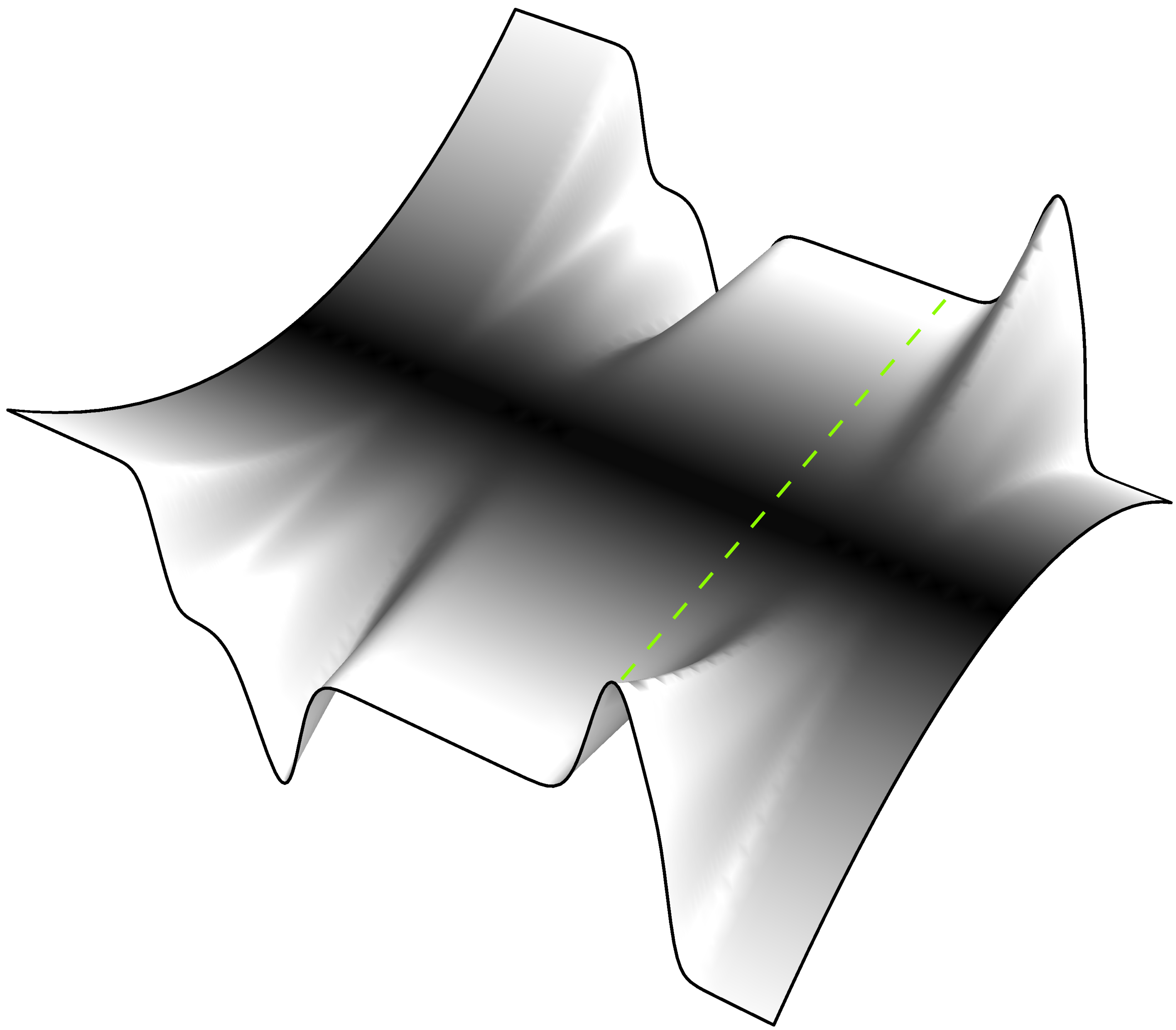
scales with volume!

ORI, *et al.* PRL **109** 147205 (2012).

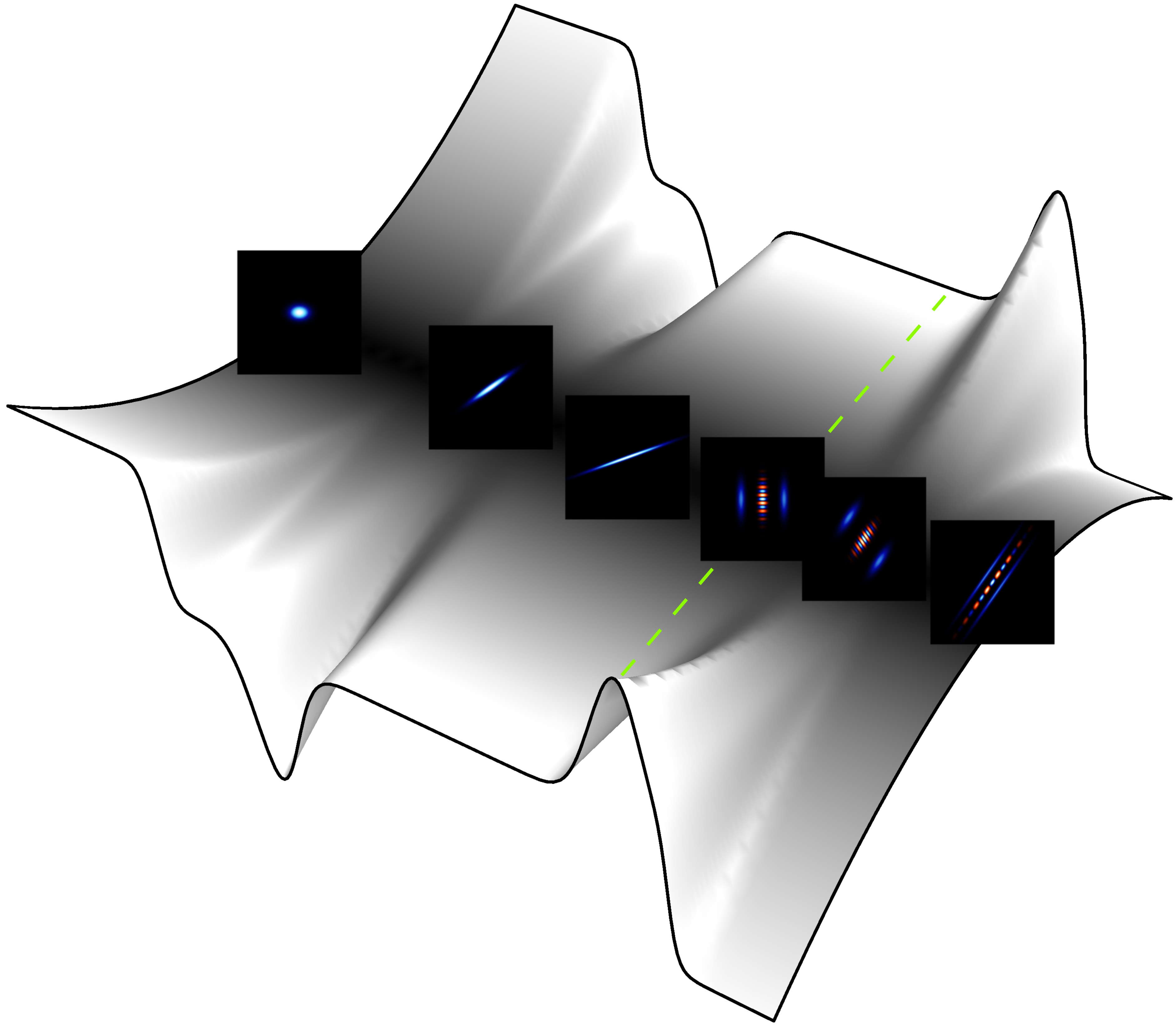
On-chip all-magnetic “skatepark”

for a superconducting microsphere

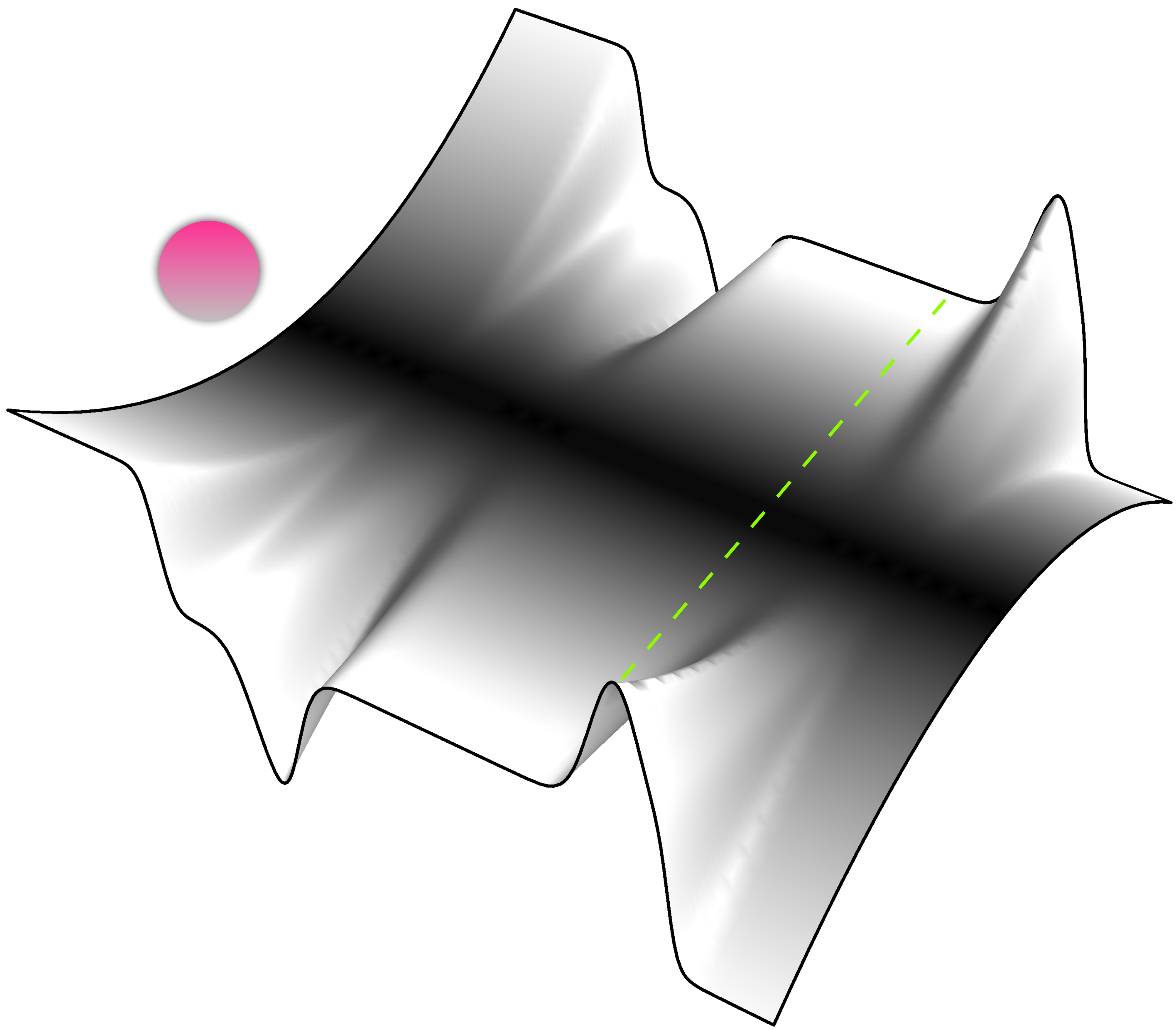
On-chip magnetic “skatepark”



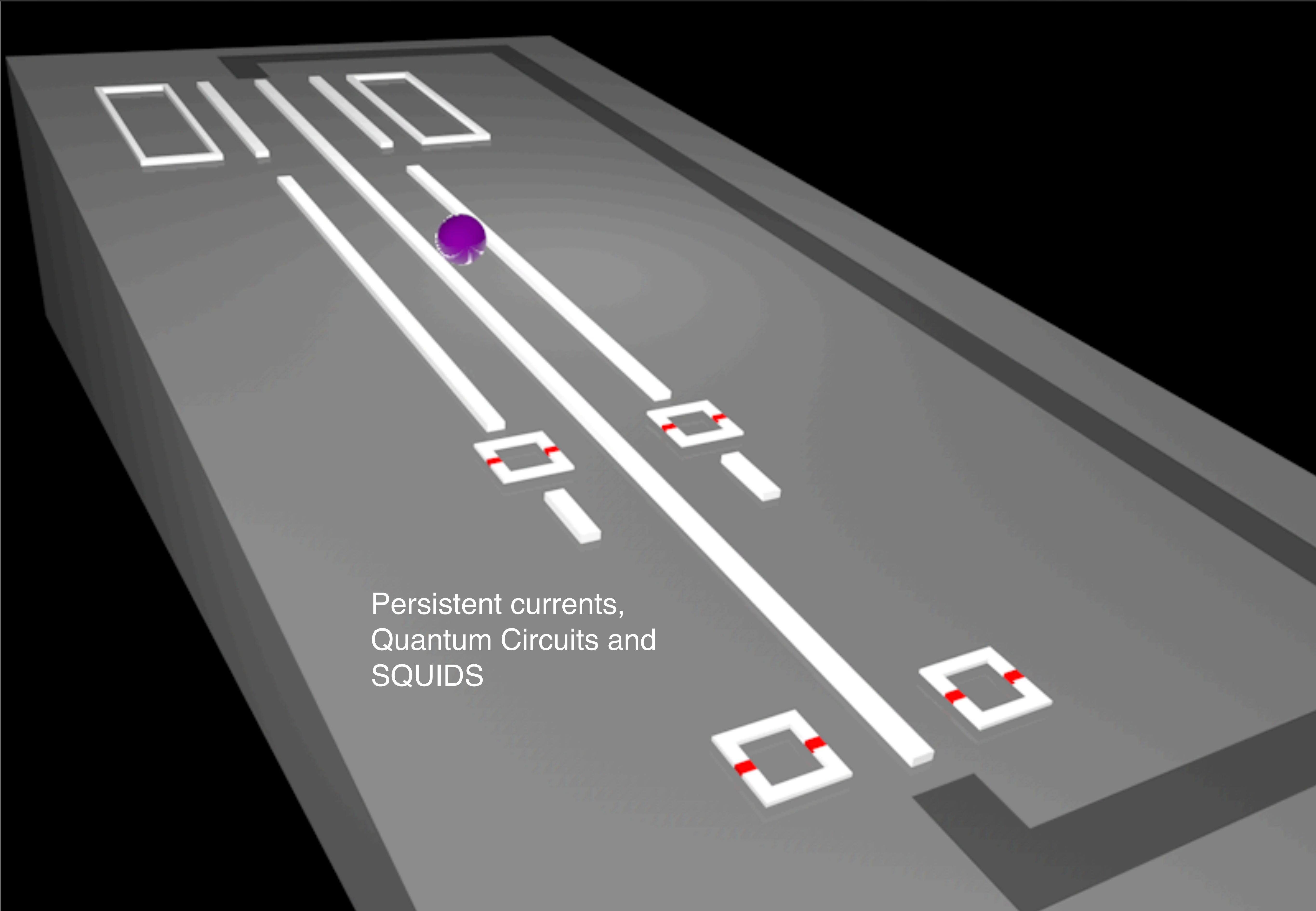
On-chip magnetic “skatepark”



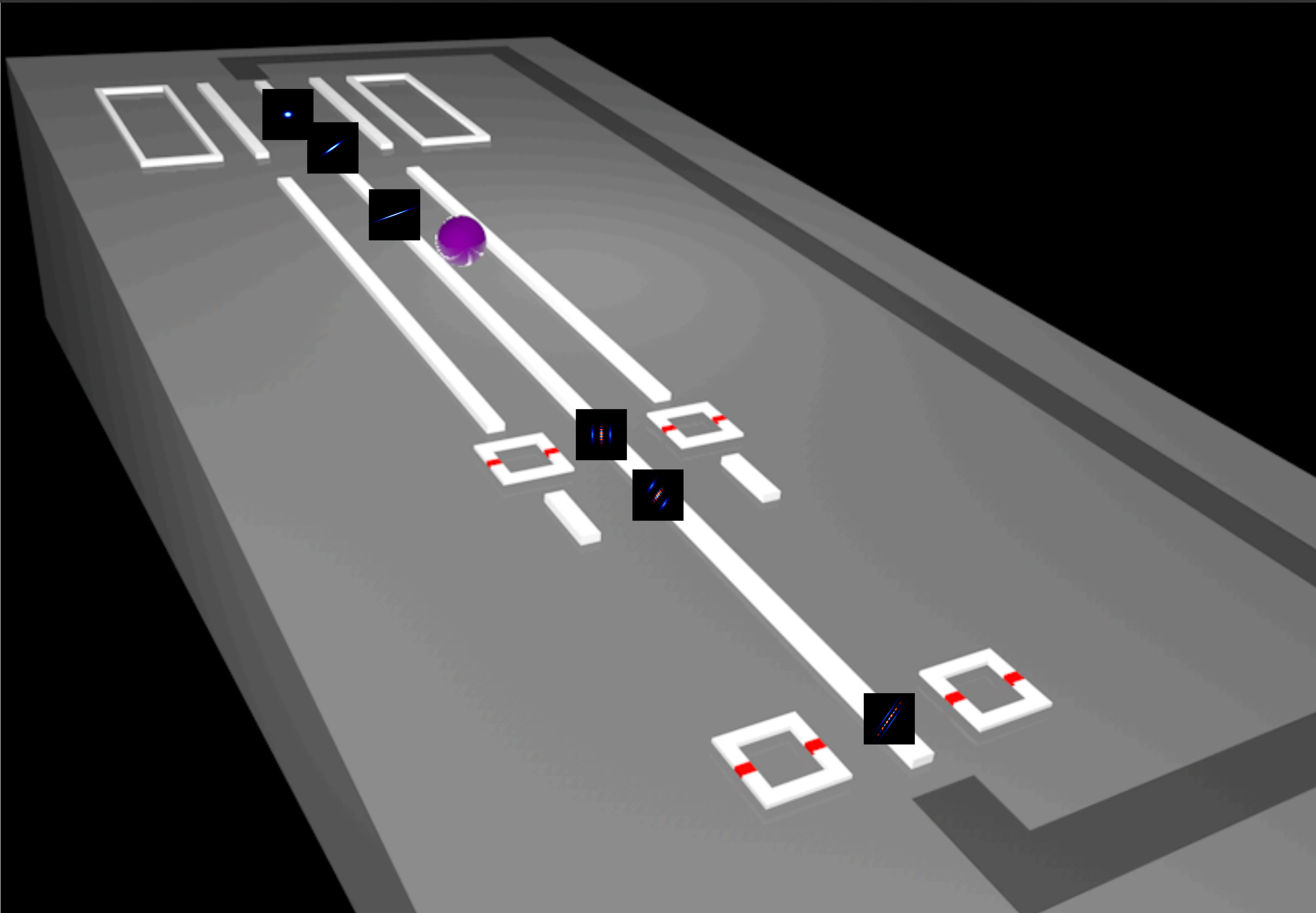
On-chip magnetic “skatepark”



On-chip magnetic “skatepark”



On-chip magnetic “skatepark”



Conclusions

Final remarks

- Gravitationally-induced decoherence? Gravitational regime? $\tau = h\frac{2R}{GM^2}$
- Magnetically levitated superconducting microspheres can falsify it
  - ➡ Mass of 10^14 amu
  - ➡ Cryogenic temperatures
  - ➡ Magnetic levitation
  - ➡ Static potentials
  - ➡ On-chip all-magnetic "skatepark"
- Challenging but put it into context and recall side applications (measuring capital G?)
- This experiment would falsify (by far) all other known collapse models

Final remarks

- Gravitationally-induced decoherence? Gravitational regime? $\tau = h\frac{2R}{GM^2}$

- Magnetically levitated superconducting microspheres can falsify it
  - ➡ Mass of 10^14 amu
  - ➡ Cryogenic temperatures
  - ➡ Magnetic levitation
  - ➡ Static potentials
  - ➡ On-chip all-magnetic "skatepark"

- Challenging but put it into context and recall side applications (measuring capital G?)

- This experiment would falsify (by far) all other known collapse models

Final remarks

- Gravitationally-induced decoherence? Gravitational regime? $\tau = h\frac{2R}{GM^2}$

- Magnetically levitated superconducting microspheres can falsify it
  - ➡ Mass of 10^14 amu
  - ➡ Cryogenic temperatures
  - ➡ Magnetic levitation
  - ➡ Static potentials
  - ➡ On-chip all-magnetic "skatepark"

- Challenging but put it into context and recall side applications (measuring capital G?)

- This experiment would falsify (by far) all other known collapse models

Final remarks

- Gravitationally-induced decoherence? Gravitational regime? $\tau = h\frac{2R}{GM^2}$
- Magnetically levitated superconducting microspheres can falsify it
  - ➡ Mass of 10^14 amu
  - ➡ Cryogenic temperatures
  - ➡ Magnetic levitation
  - ➡ Static potentials
  - ➡ On-chip all-magnetic "skatepark"
- Challenging but put it into context and recall side applications (measuring capital G?)
- This experiment would falsify (by far) all other known collapse models

Thank you very much for your attention