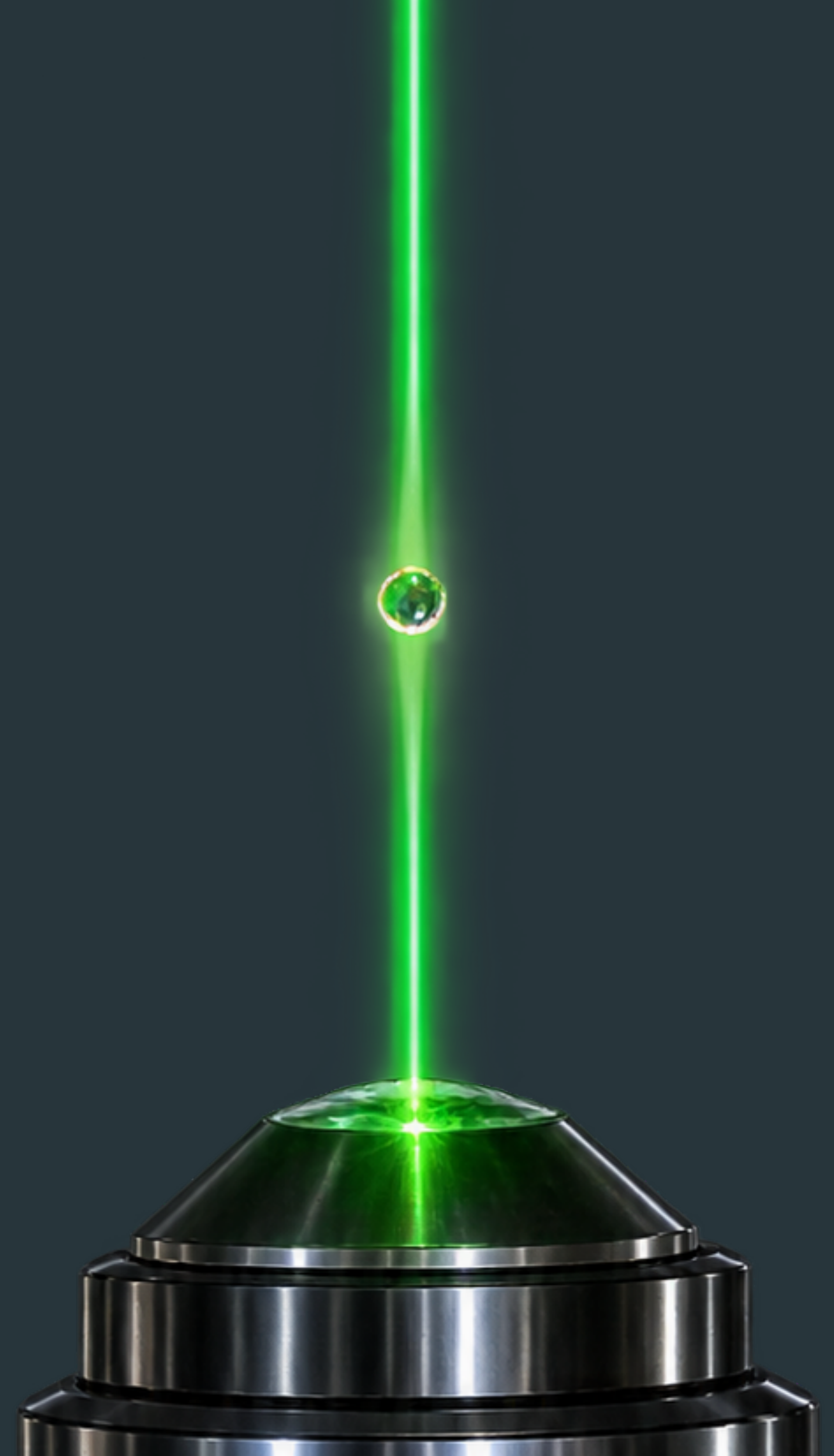


QUANTUM LIMITS SUMMIT

Levitated Quantum Systems for Fundamental Physics

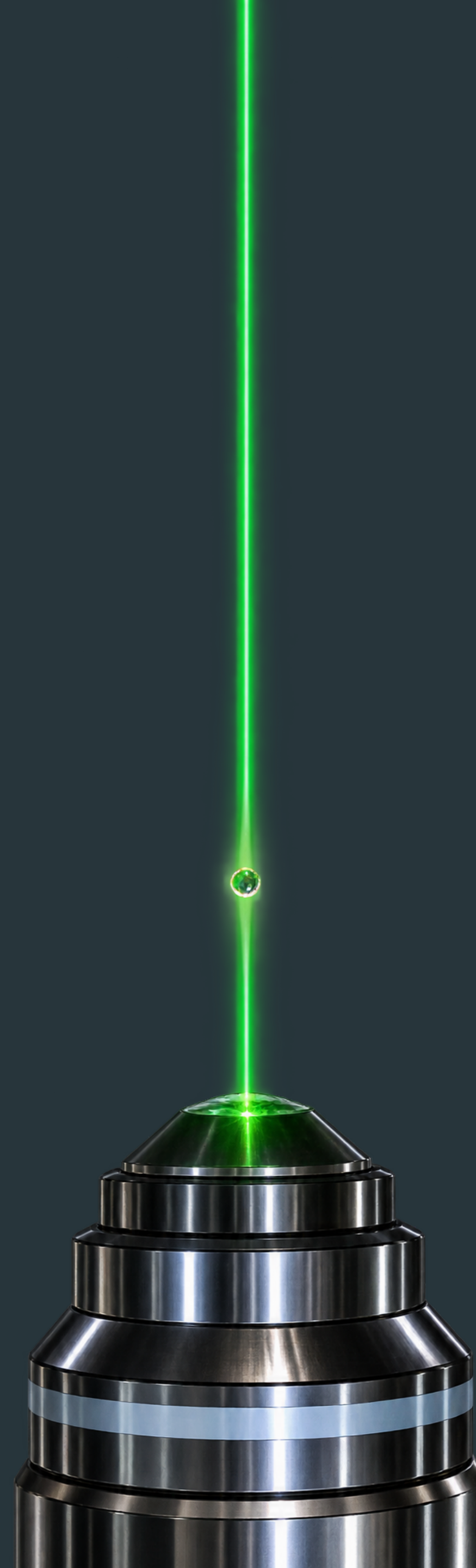
Julen Pedernales

Quantum Nanoscience · **TU Delft**



Why levitated systems?

WHAT WE GAIN



Why levitated systems?

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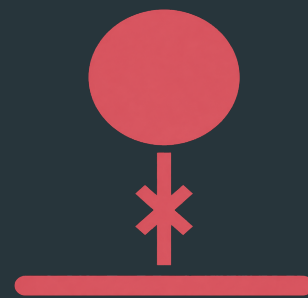
No mechanical support
no clamping loss · no substrate coupling



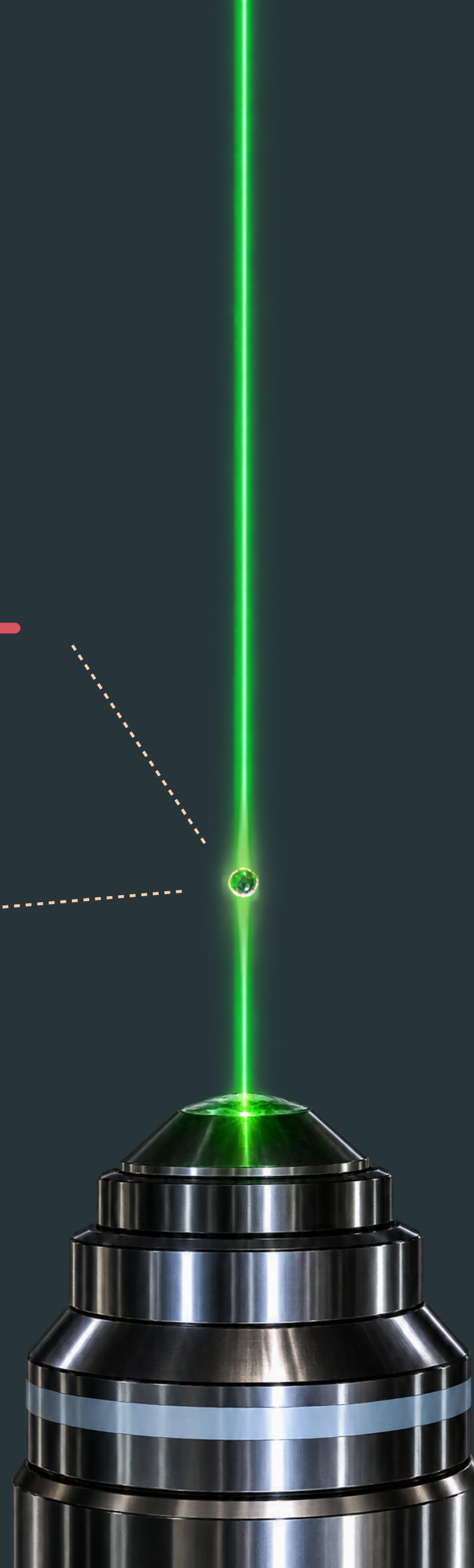
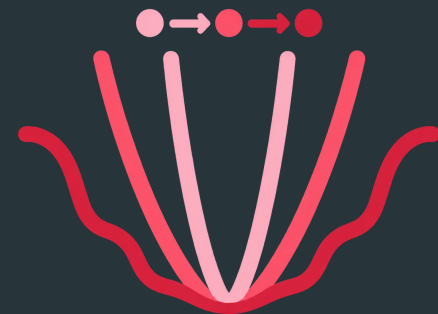
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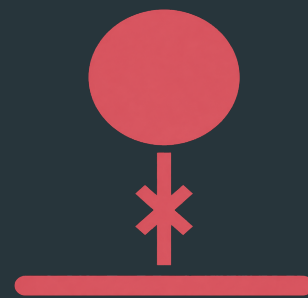
Tunable confinement & release
Trap shaping · release & retrap



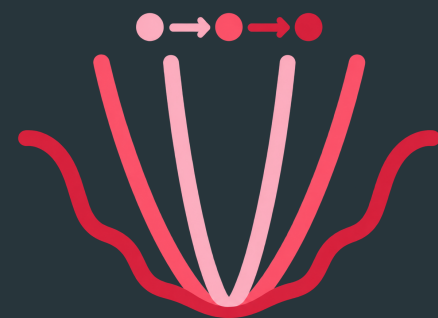
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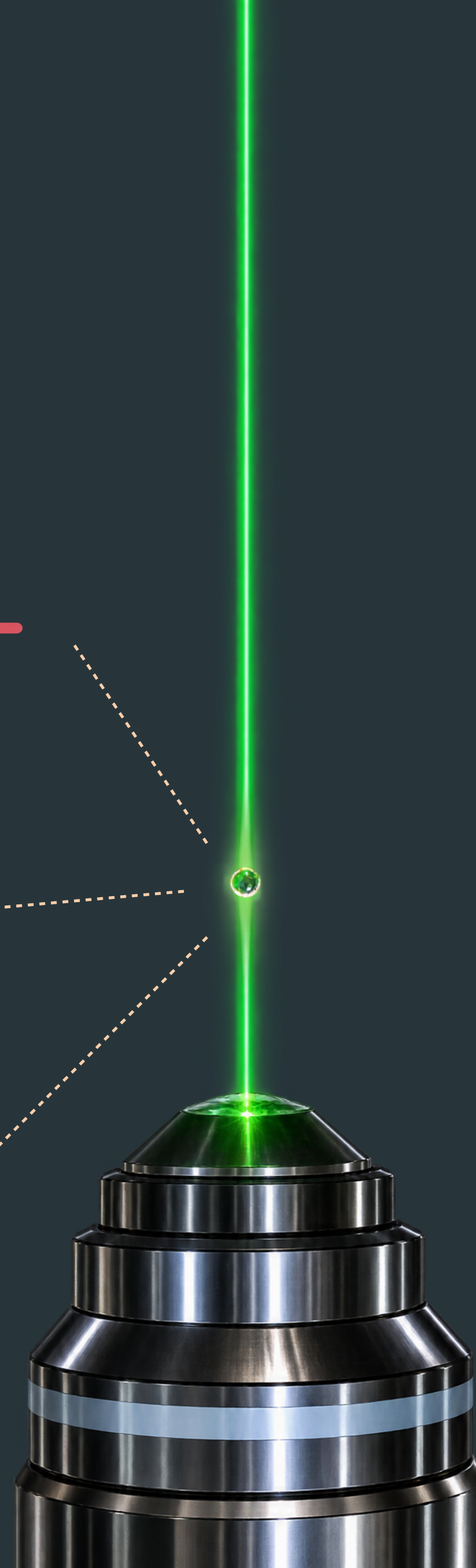
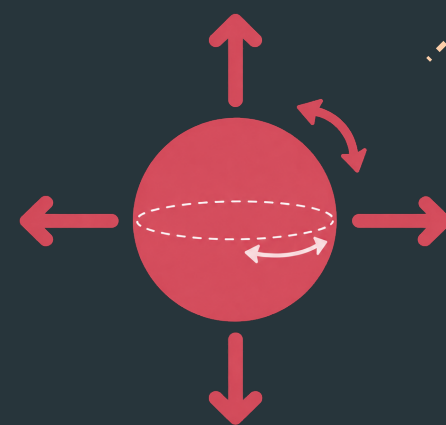
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Full translational & rotational control
3D motion · large excursions
angular momentum

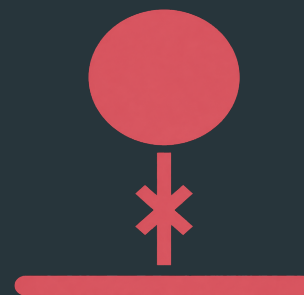


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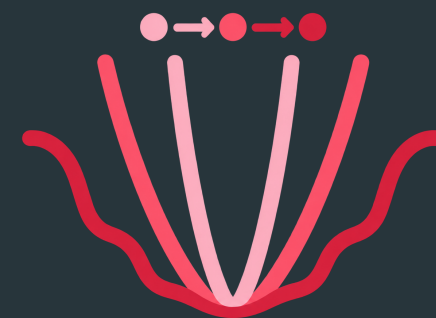
WHAT COMES WITH IT

WHAT WE GAIN

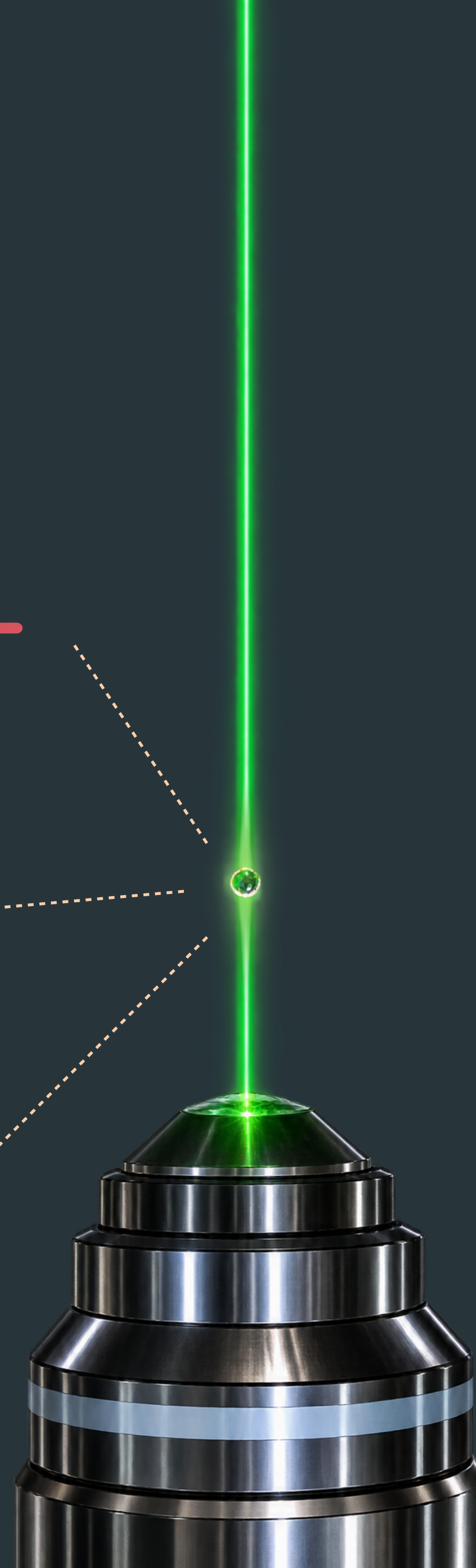
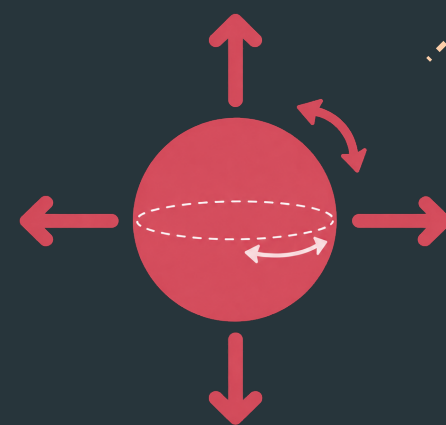
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Levitation does not remove the environment; it creates a different, highly engineerable system–environment interface.



From quantum control to fundamental tests



Three ways to strengthen quantum experiments

1

EXPLOIT THE PLATFORM

· *quantum resources* ·

**What resources can
the physical platform give us?**

Three ways to strengthen quantum experiments

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**What else can destroy
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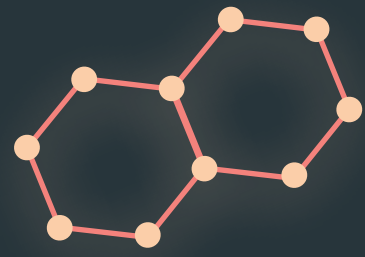
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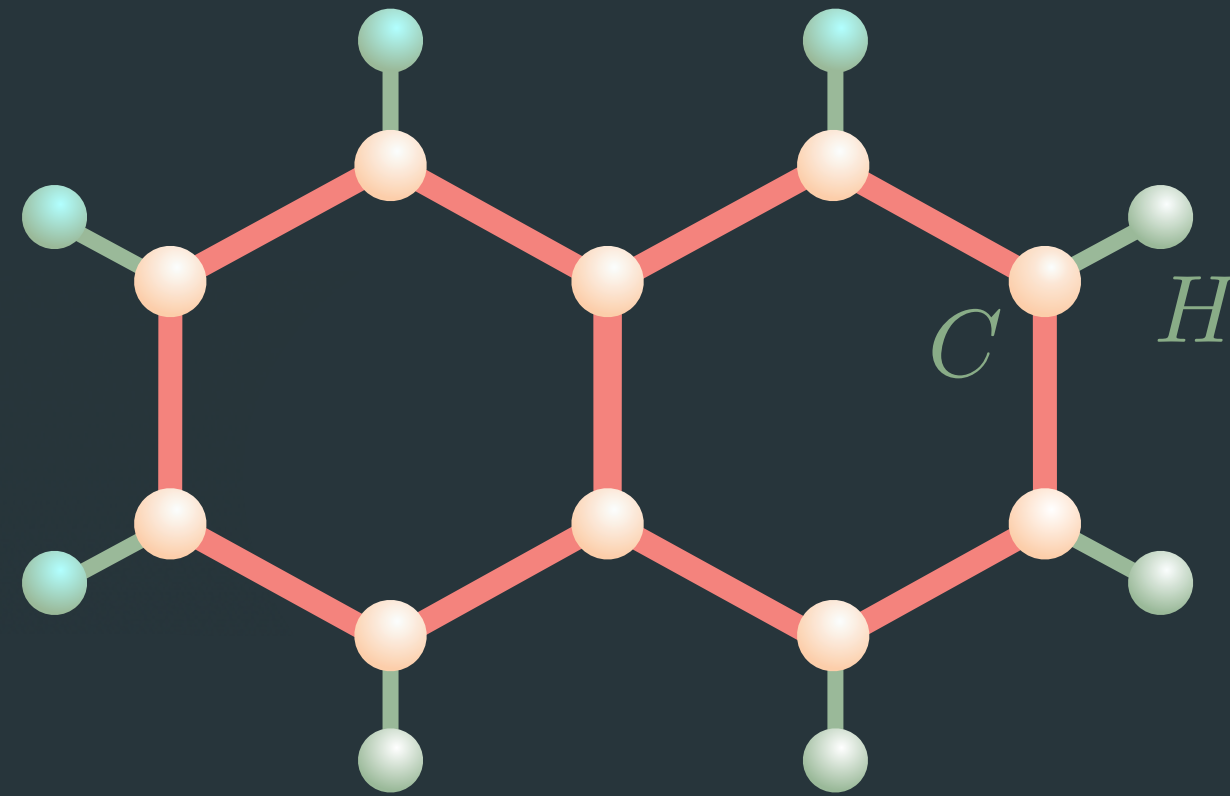
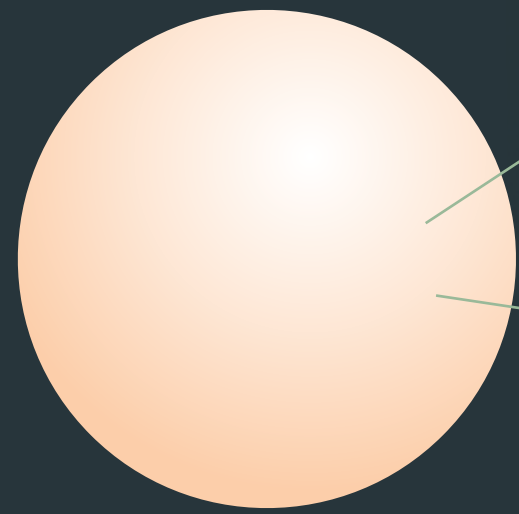
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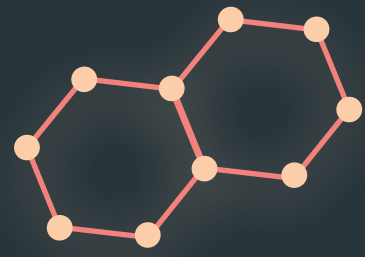
**What else can destroy
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New materials: Pentacene-doped naphthalene

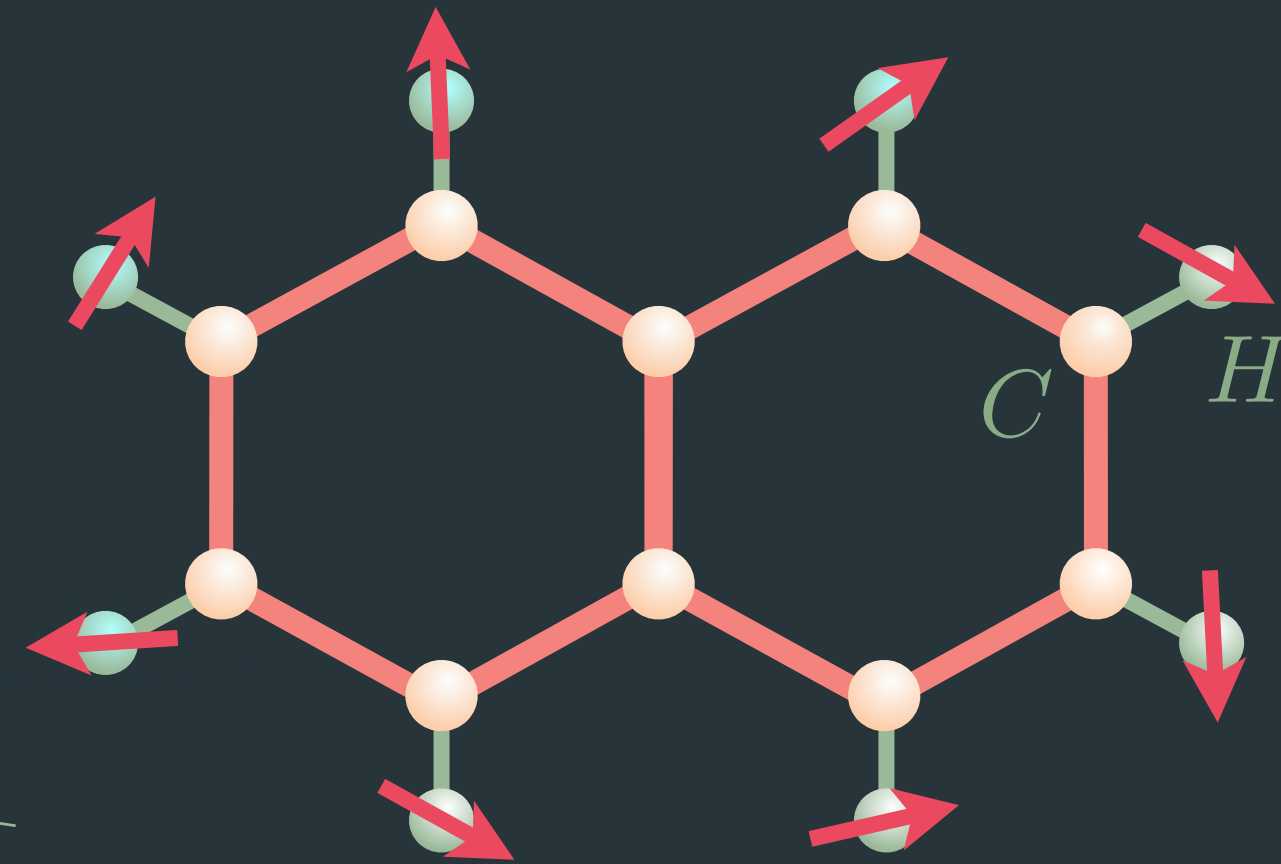
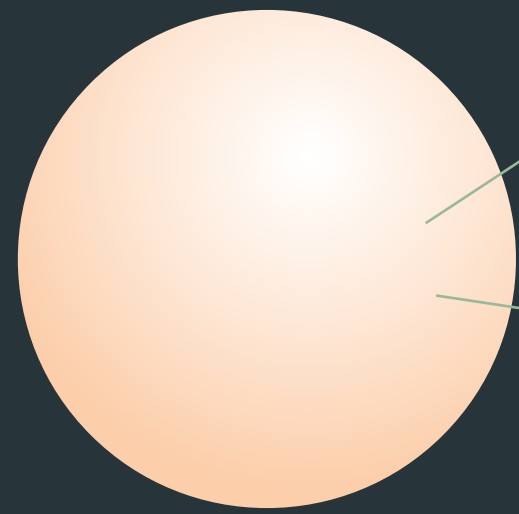
Quantum **9**, 1928 (2025)

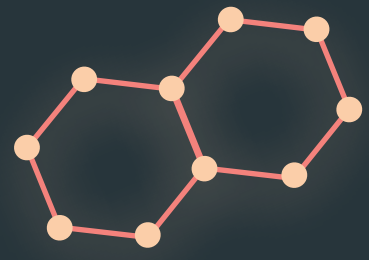




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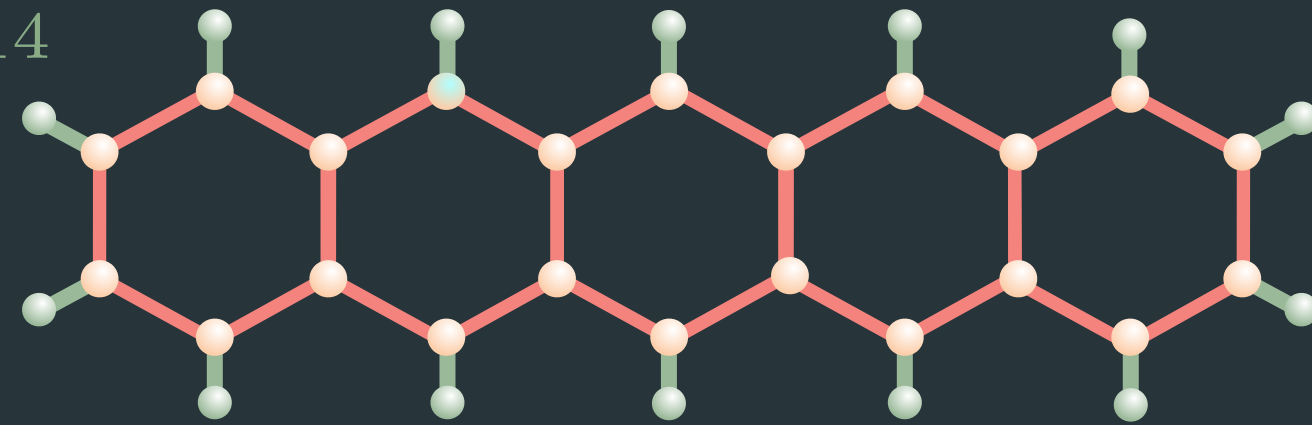
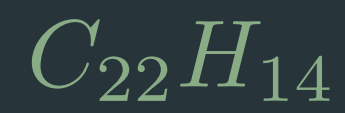
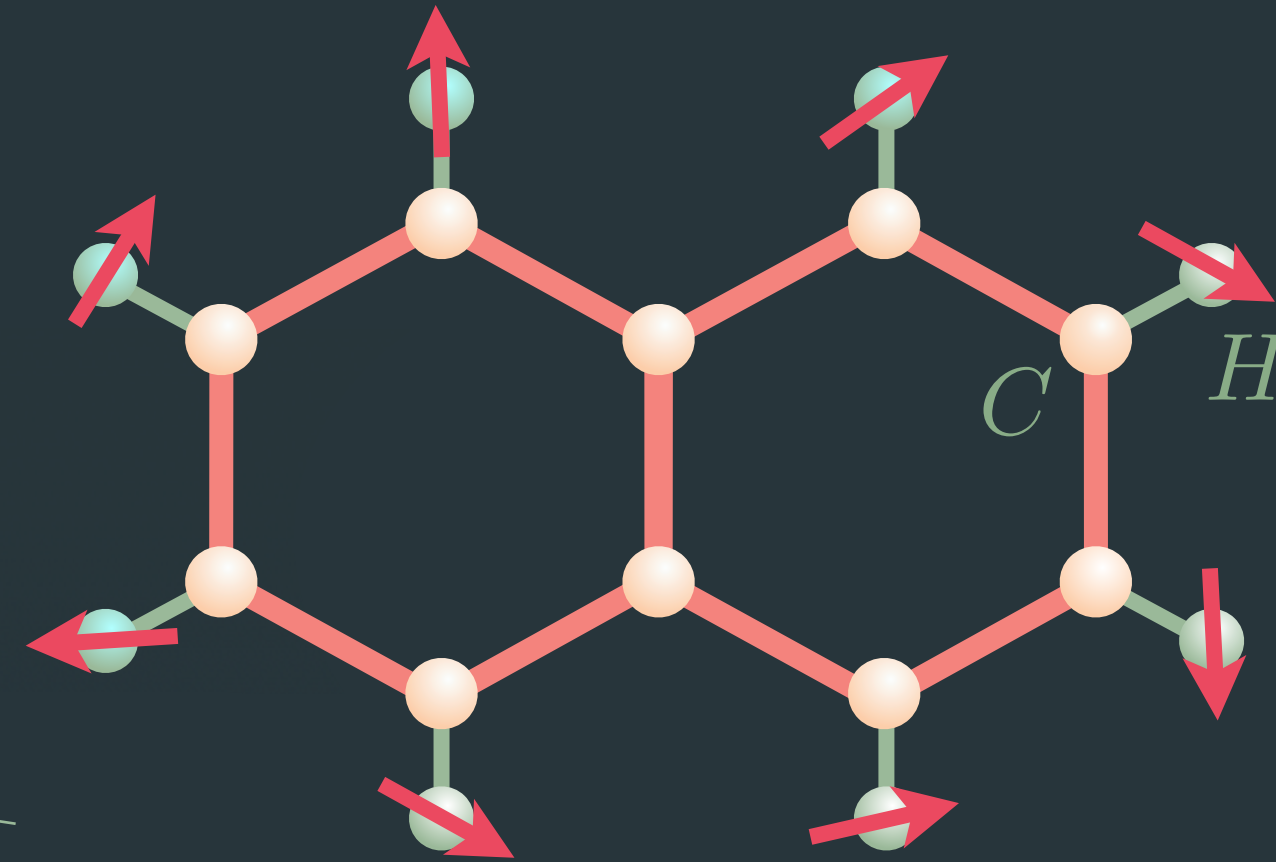
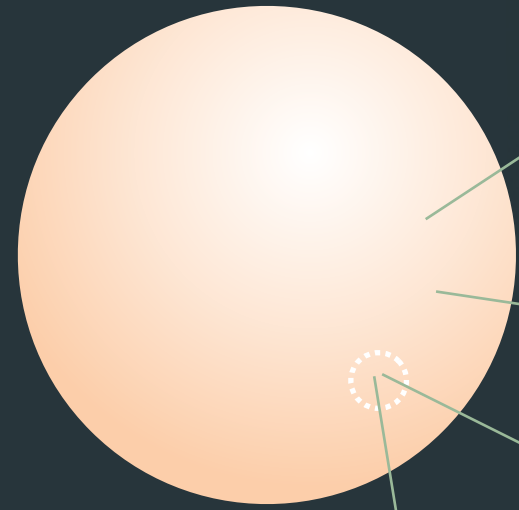
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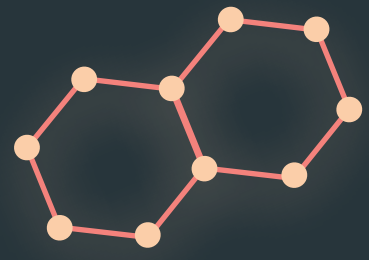
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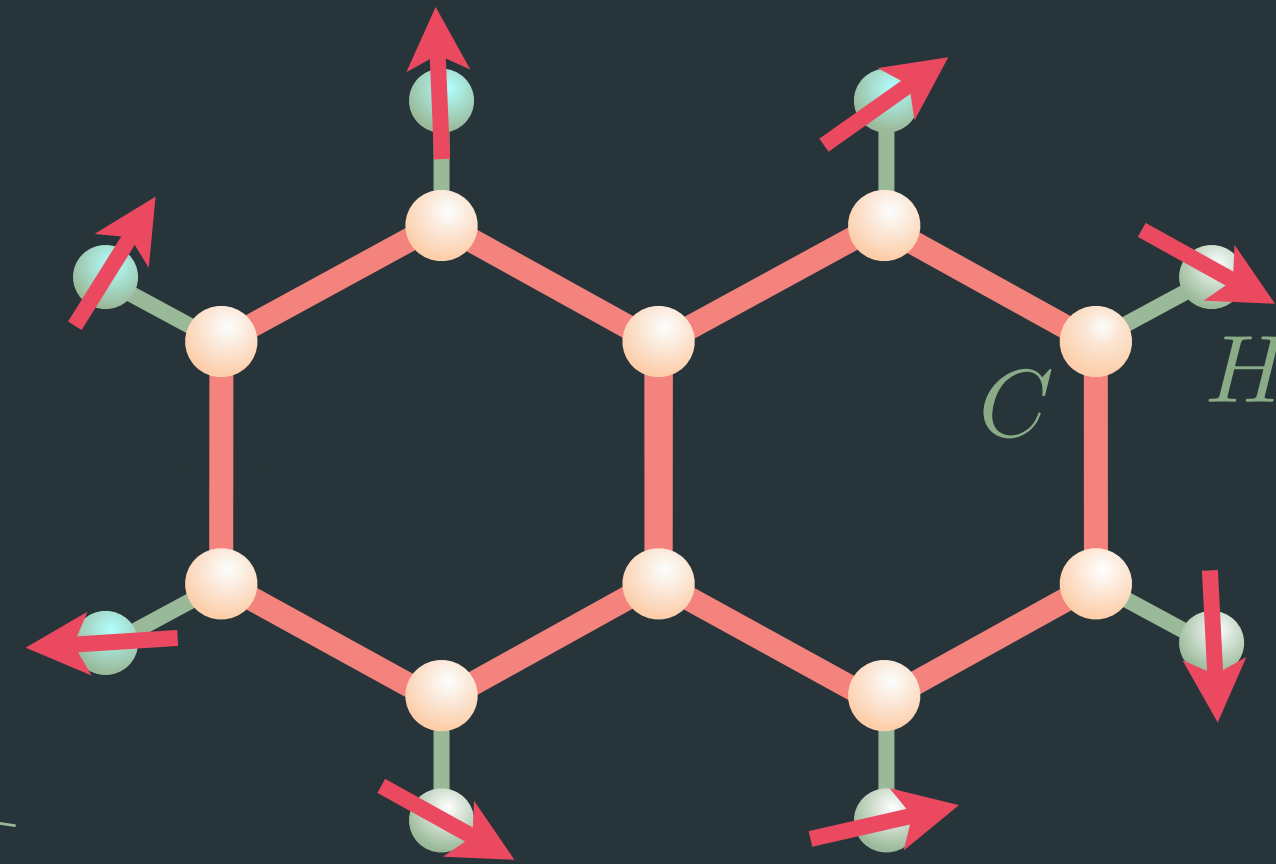
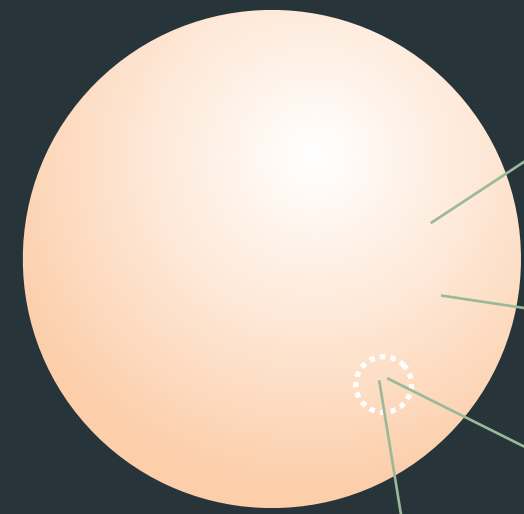
Pentacene contains a short-live electronic triplet state that can be optically excited

Selection rules strongly favor the occupation of one of its three triplet states

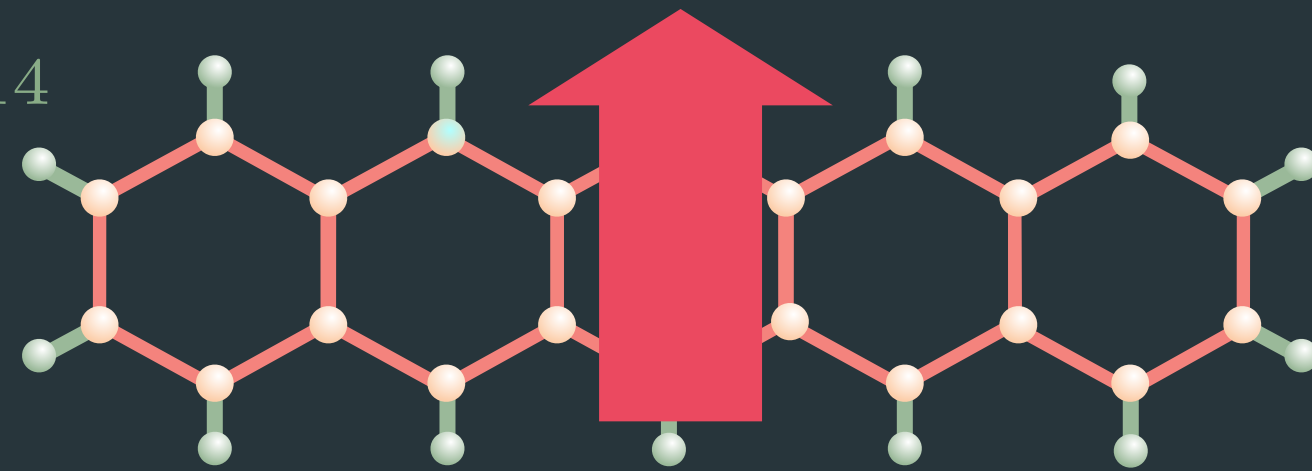


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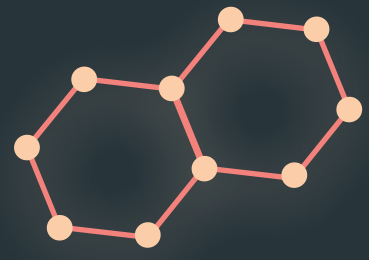
$C_{22}H_{14}$



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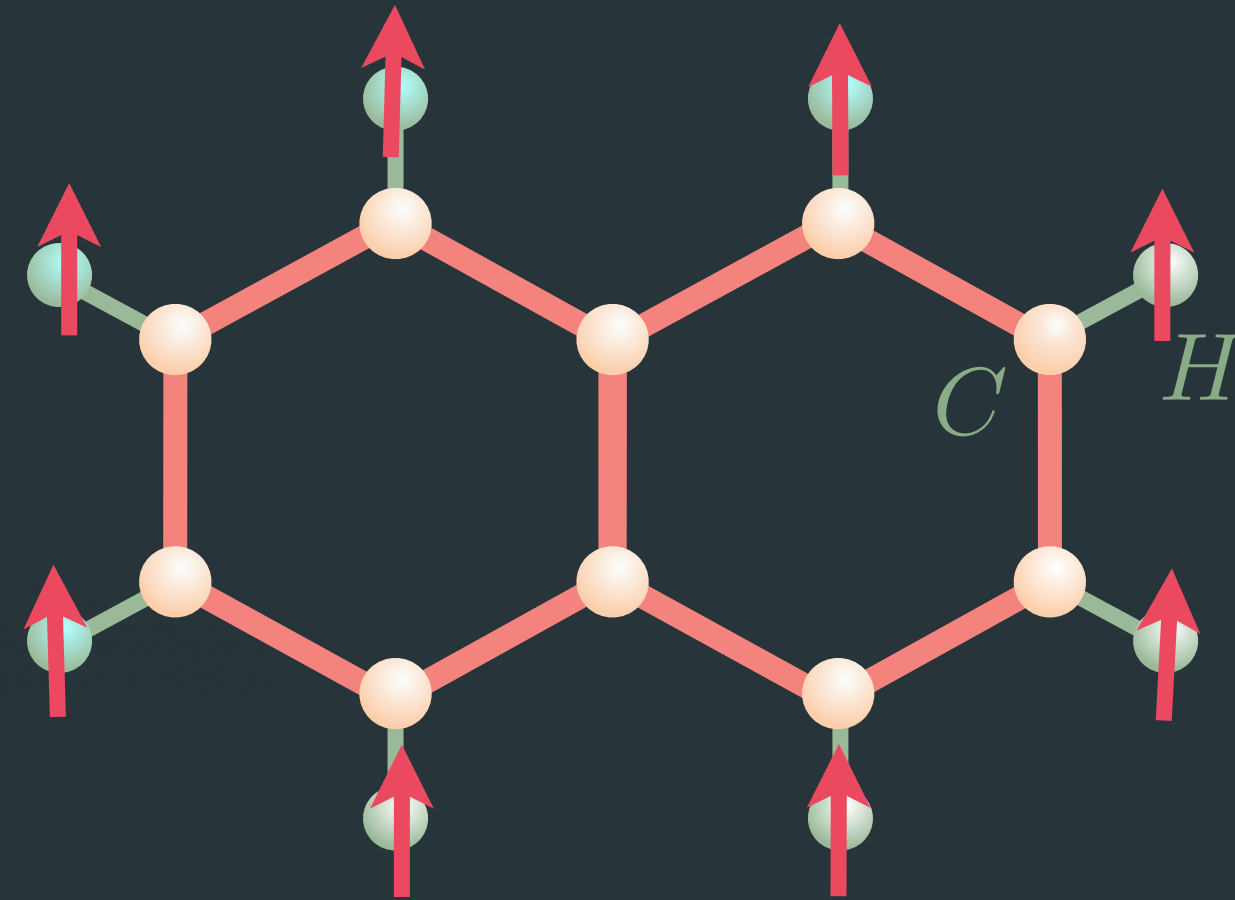
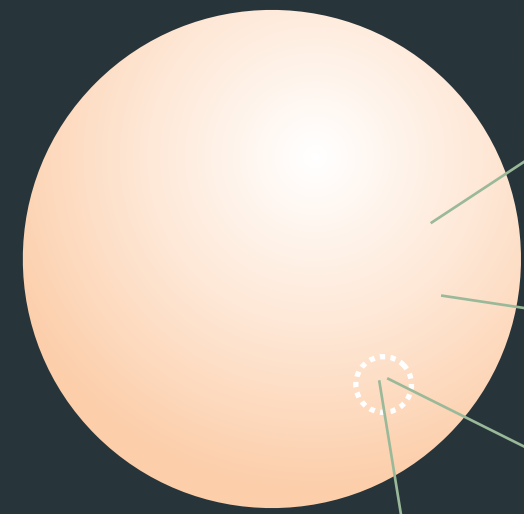
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Through dipole-dipole interactions polarisation
Transfer to the nuclear spin ensemble is possible

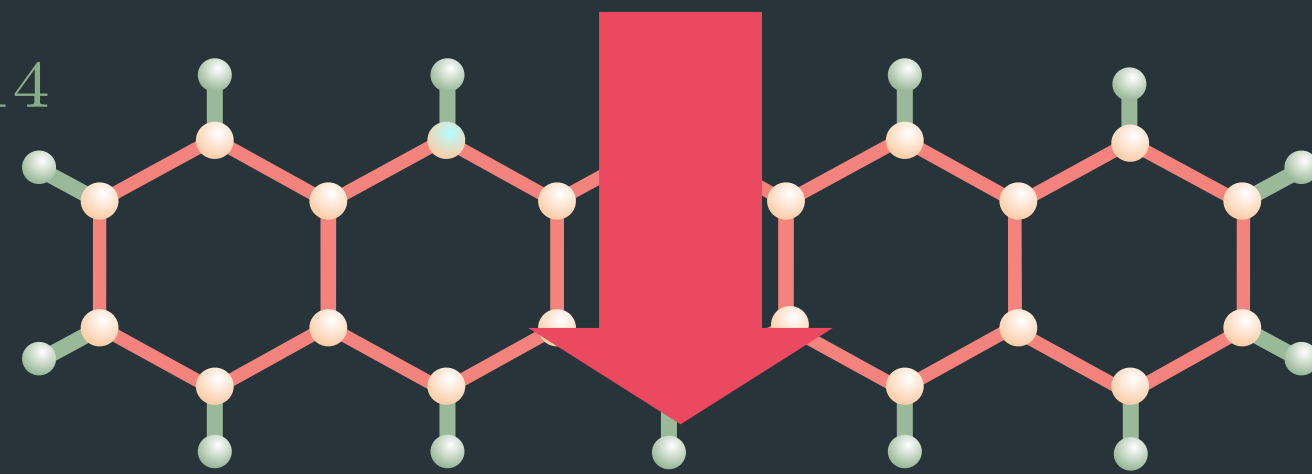


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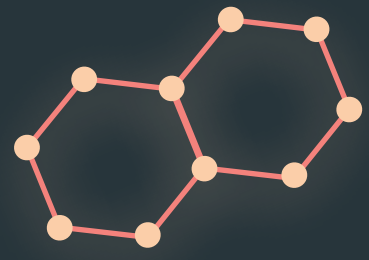
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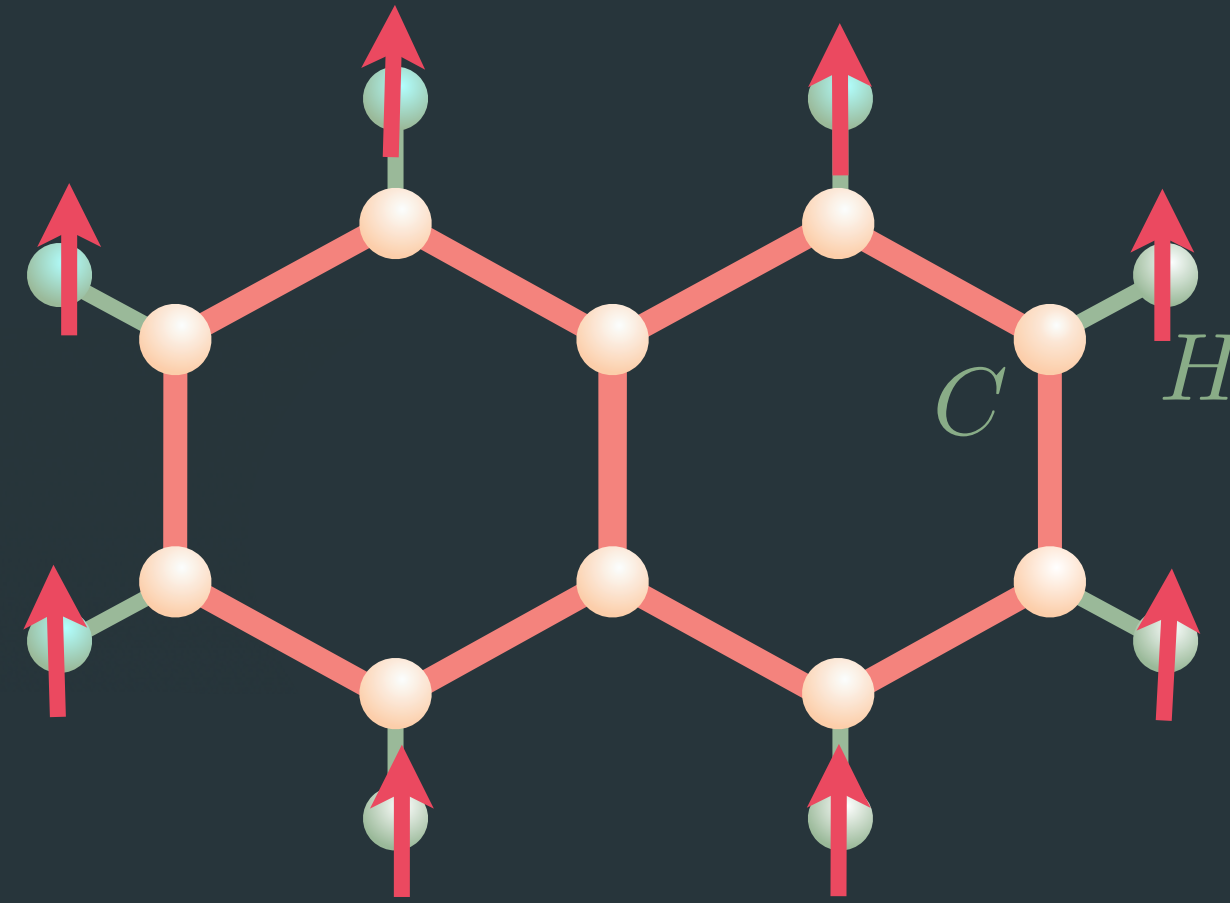
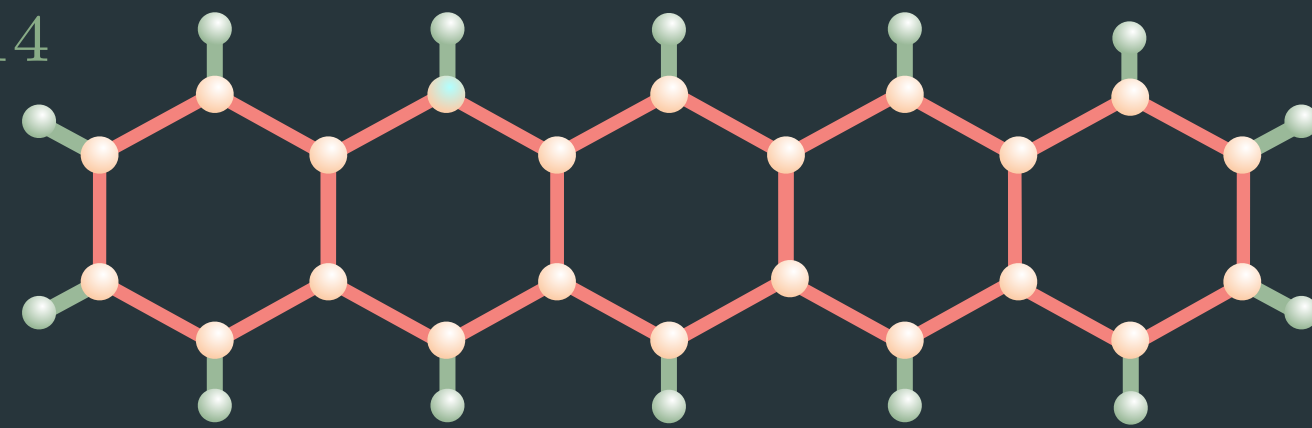
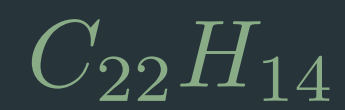
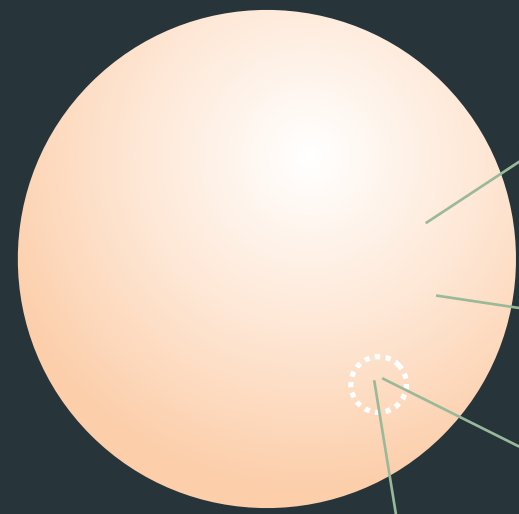
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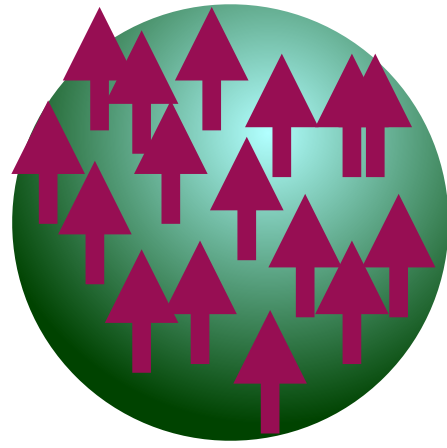
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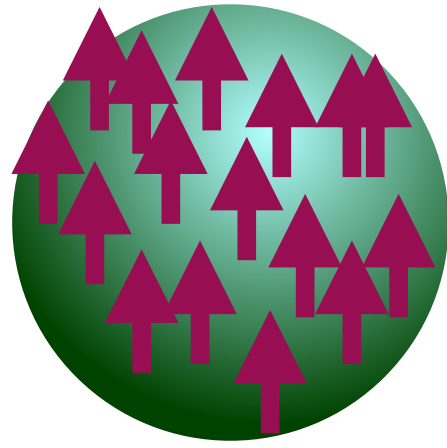
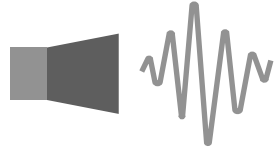
In bulk, **> 80% nuclear spin polarization** has
been demonstrated, with a remarkable **$T_1 > 920$ h**

Multi-spin Stern-Gerlach Interferometry



Multi-spin Stern-Gerlach Interferometry

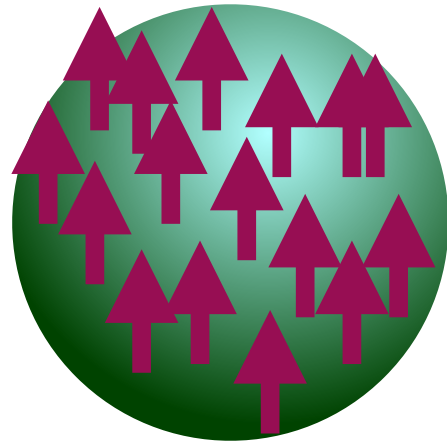
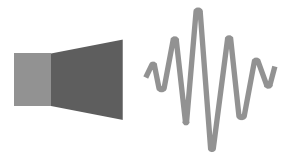
$\pi/2$ pulse



$$|\uparrow\uparrow\uparrow\rangle \rightarrow (|\uparrow\rangle + |\downarrow\rangle) \otimes (|\uparrow\rangle + |\downarrow\rangle) \otimes (|\uparrow\rangle + |\downarrow\rangle)$$

Multi-spin Stern-Gerlach Interferometry

$\pi/2$ pulse



Dicke states

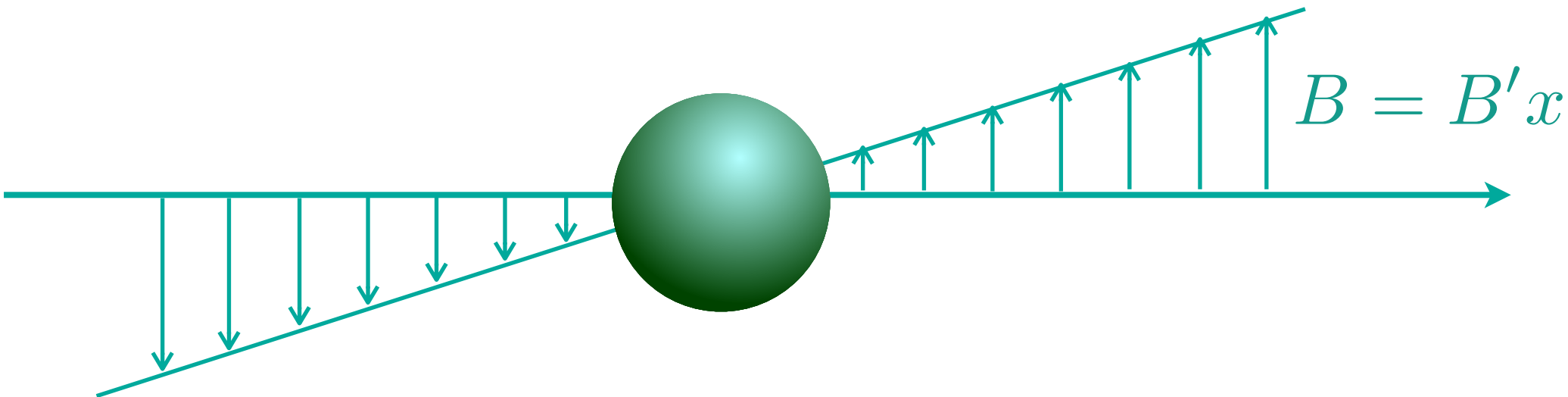
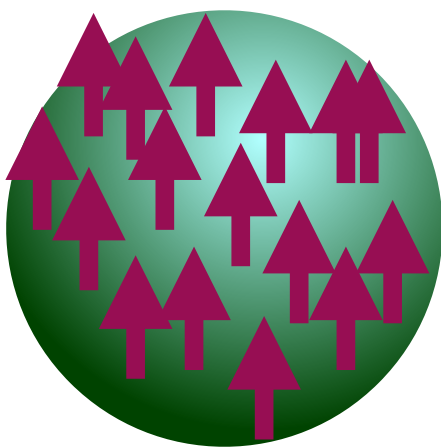
$$|\uparrow\uparrow\uparrow\rangle \rightarrow (|\uparrow\rangle + |\downarrow\rangle) \otimes (|\uparrow\rangle + |\downarrow\rangle) \otimes (|\uparrow\rangle + |\downarrow\rangle) = |0\rangle + |1\rangle + |2\rangle + |3\rangle$$

$\swarrow \qquad \searrow$

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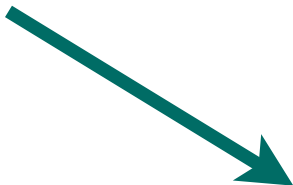


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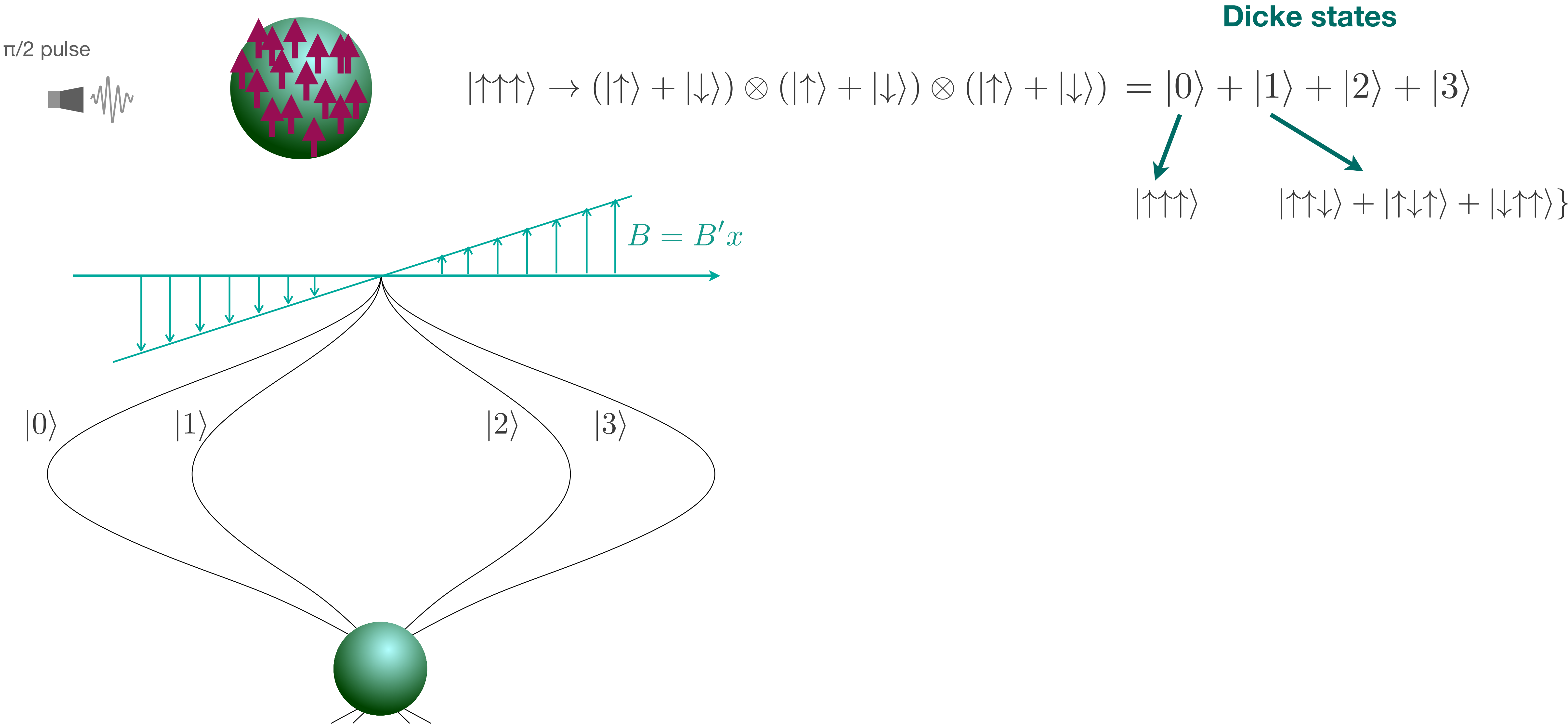


$$|\uparrow\uparrow\uparrow\rangle$$

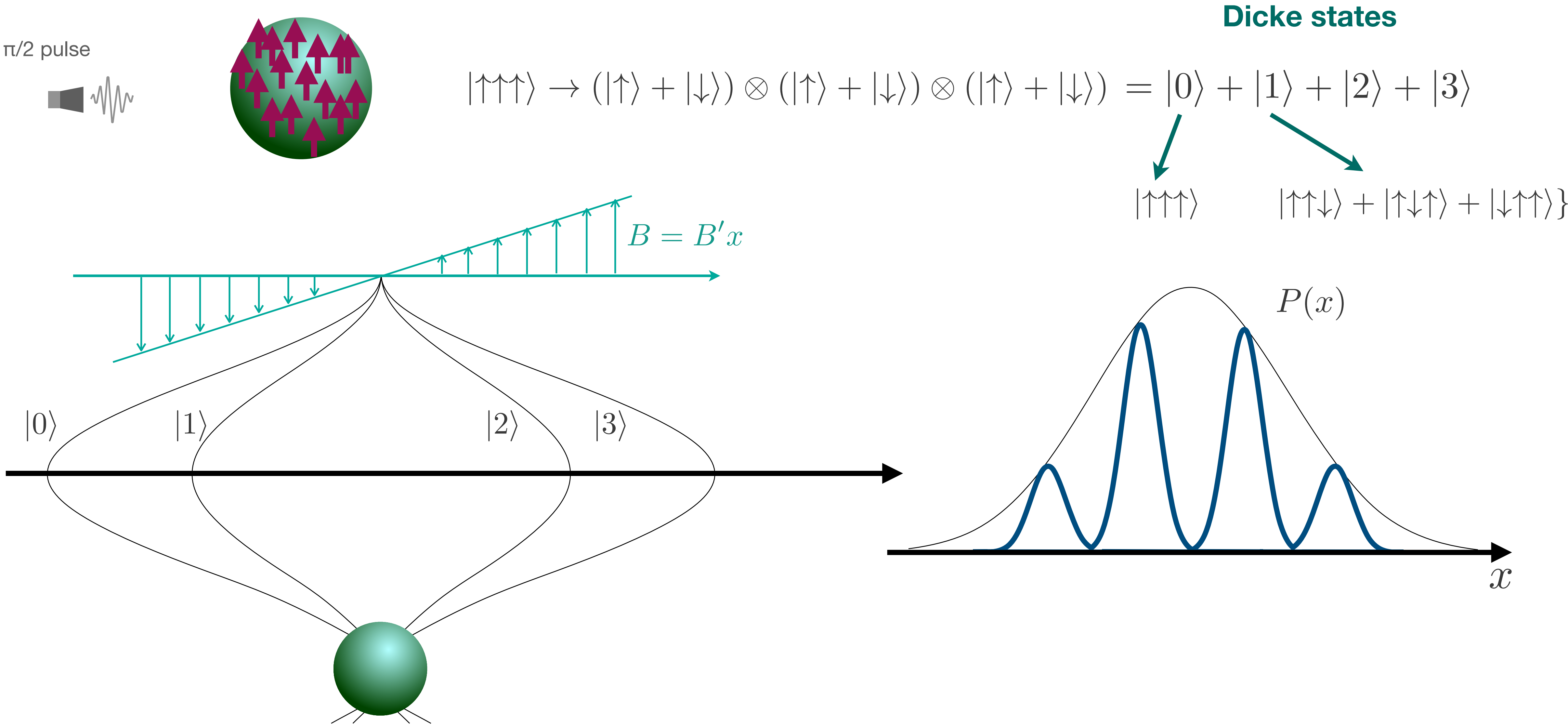


$$|\uparrow\uparrow\downarrow\rangle + |\uparrow\downarrow\uparrow\rangle + |\downarrow\uparrow\uparrow\rangle\}$$

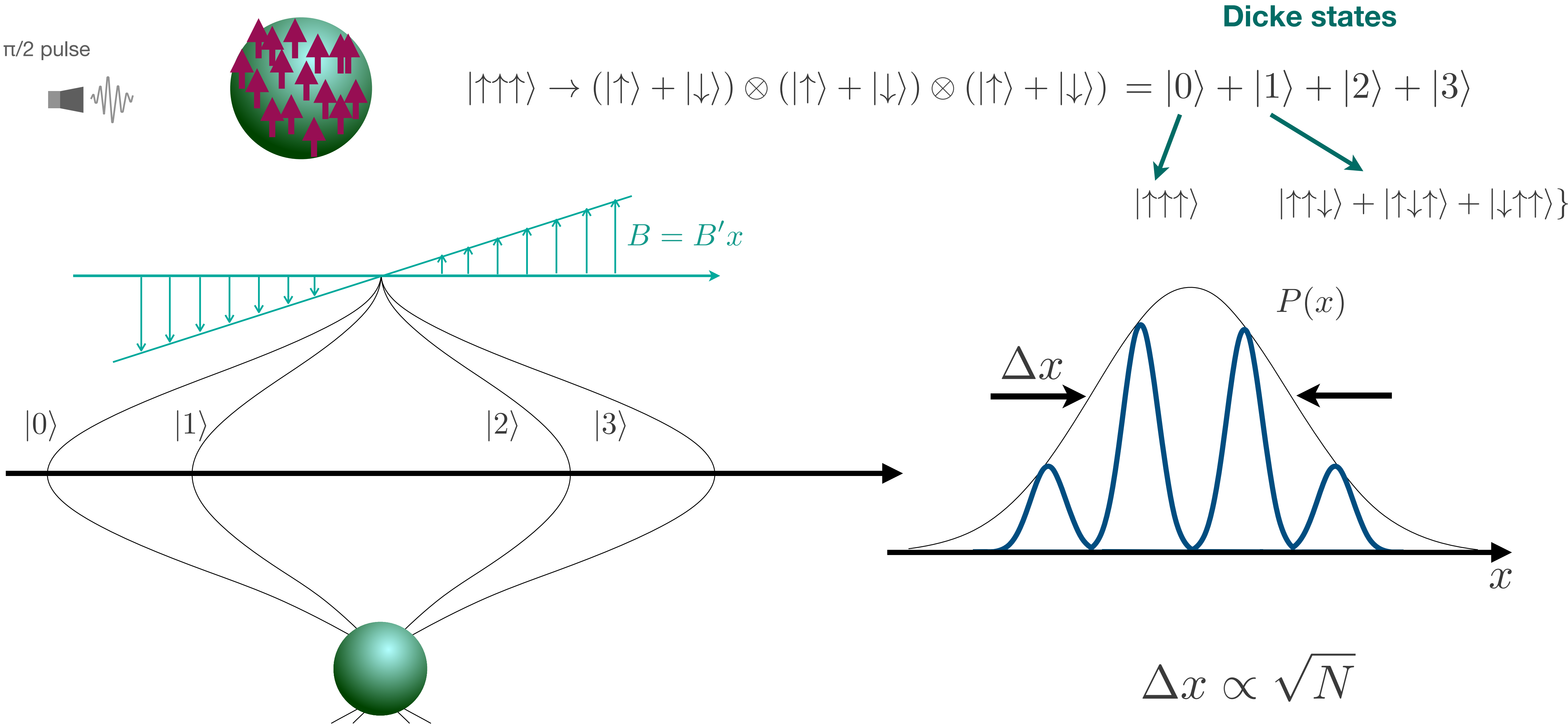
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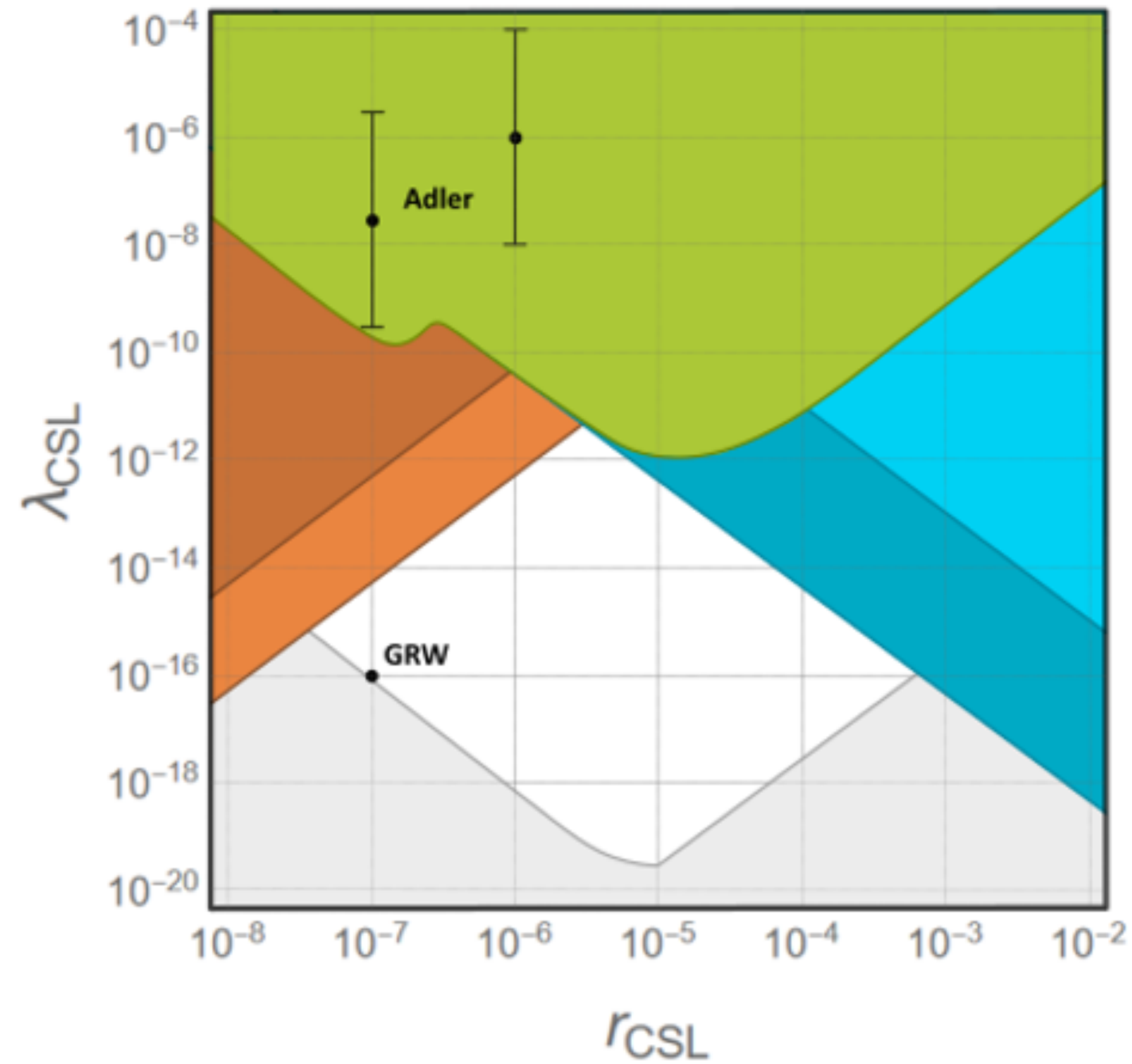


Continuous Spontaneous Localization model

$$\dot{\rho}(x, x') = \frac{i}{\hbar} \langle x | [\hat{H}, \hat{\rho}] | x' \rangle - \xi(\lambda_{csl}, r_{csl}) (1 - e^{-(x-x')^2 / r_{csl}^2}) \rho(x, x')$$

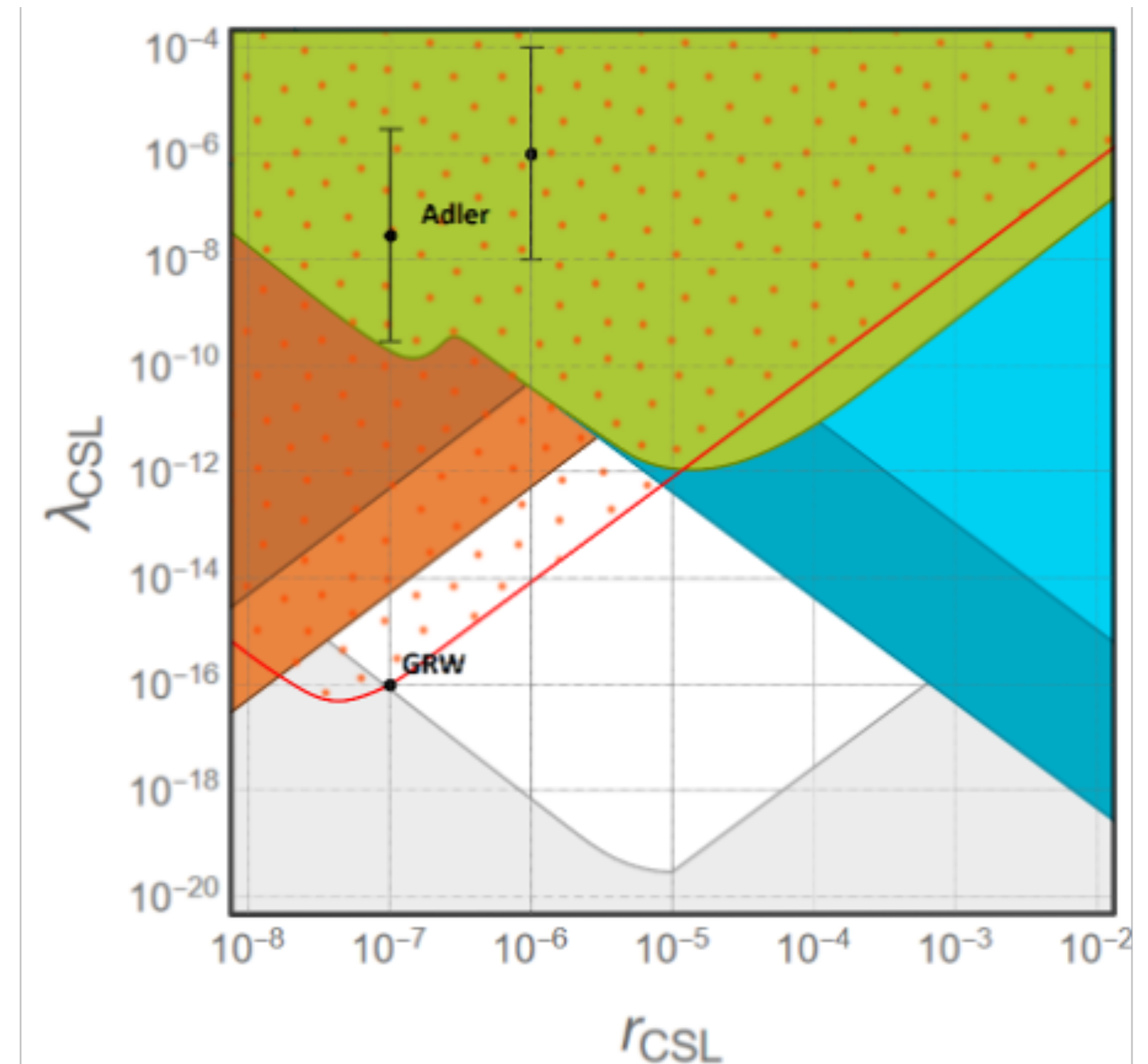
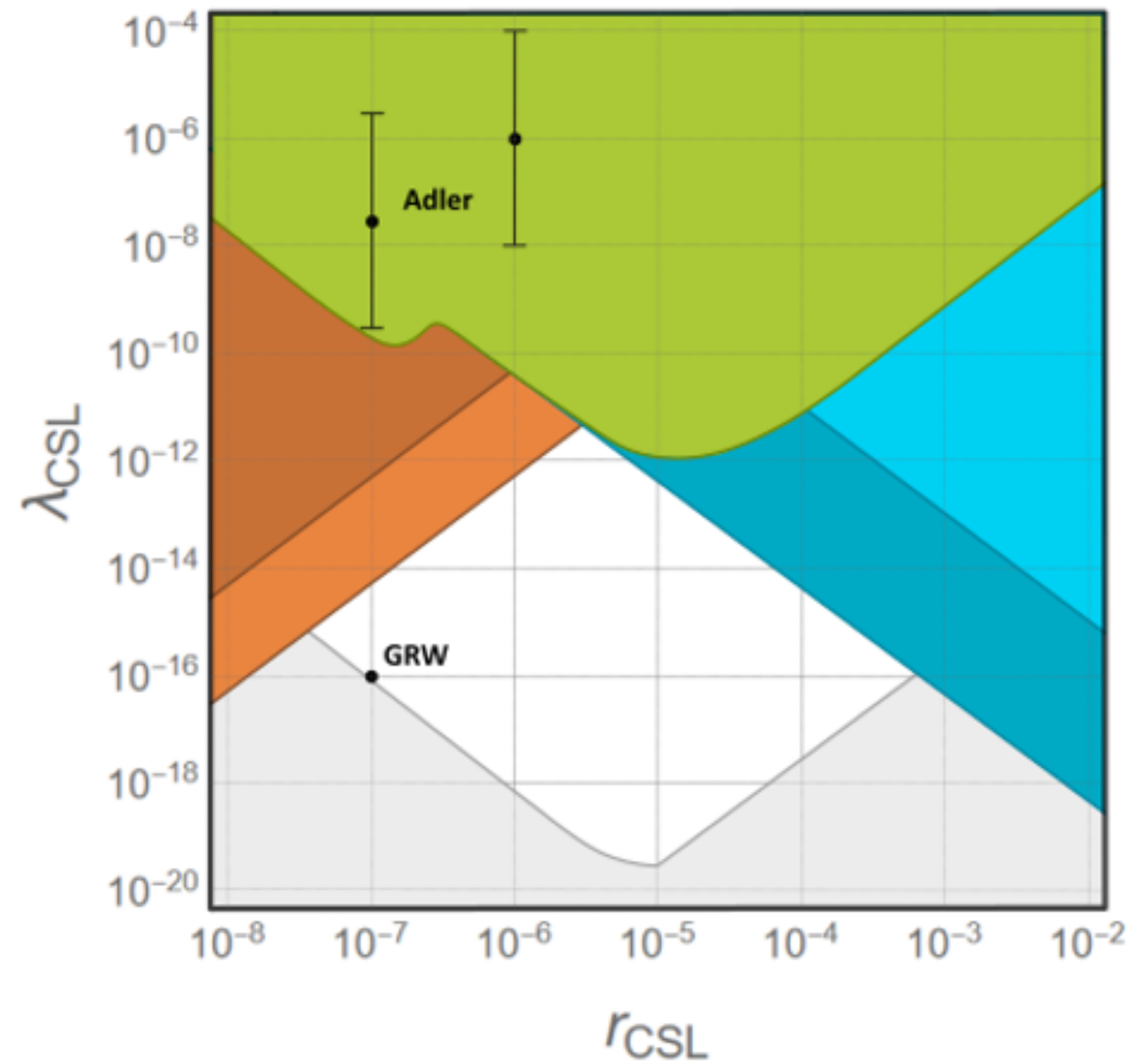
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Three ways to strengthen quantum experiments

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· quantum resources ·

**What resources can
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Feynman thought experiment

1957 Chapel Hill Conference on the role of gravitation in physics

Source mass





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Feynman thought experiment

1957 Chapel Hill Conference on the role of gravitation in physics

Source mass



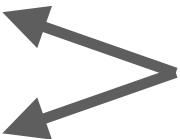
Test mass

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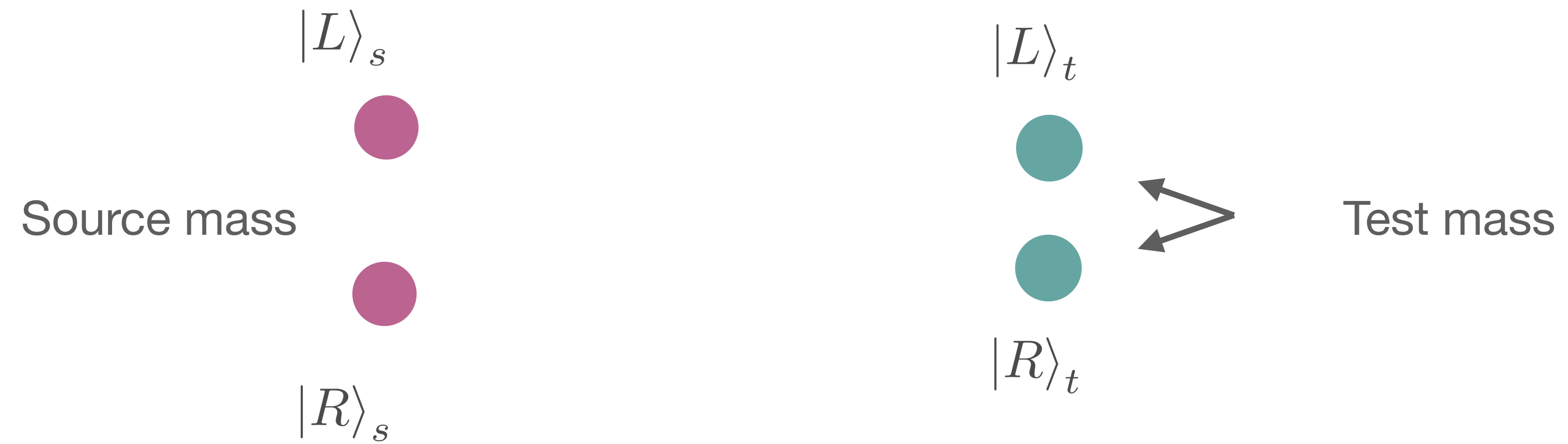


In modern quantum information parlance we call this **entanglement**



Feynman thought experiment

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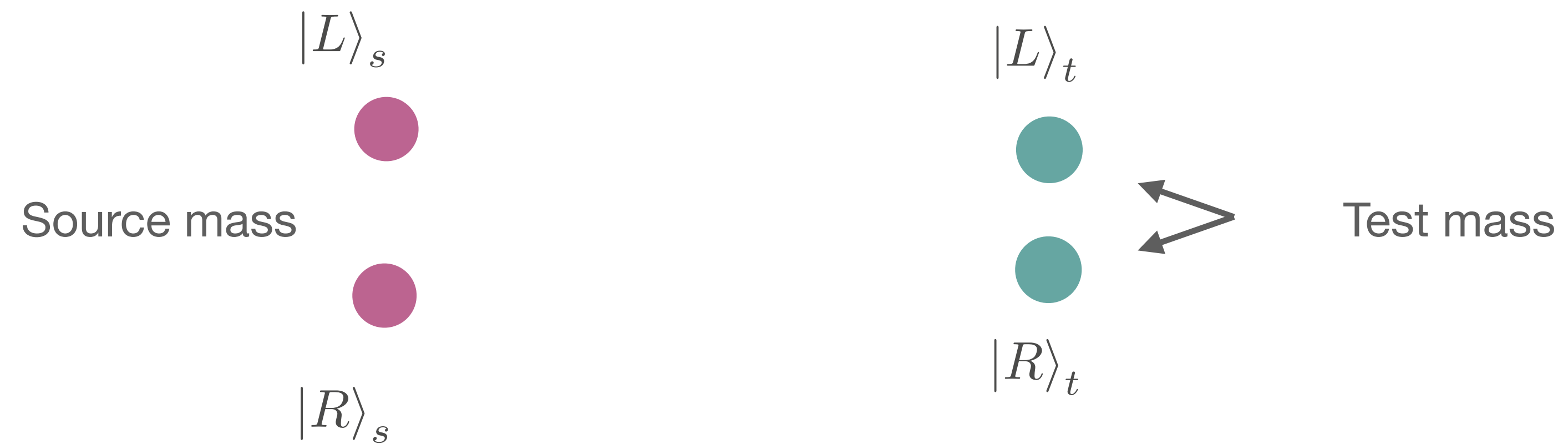
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$$|\psi\rangle_s \otimes |\psi'\rangle_t \rightarrow |L\rangle_s \otimes |L\rangle_t + |R\rangle_s \otimes |R\rangle_t$$



Feynman thought experiment

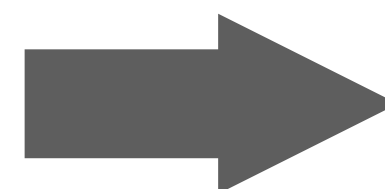
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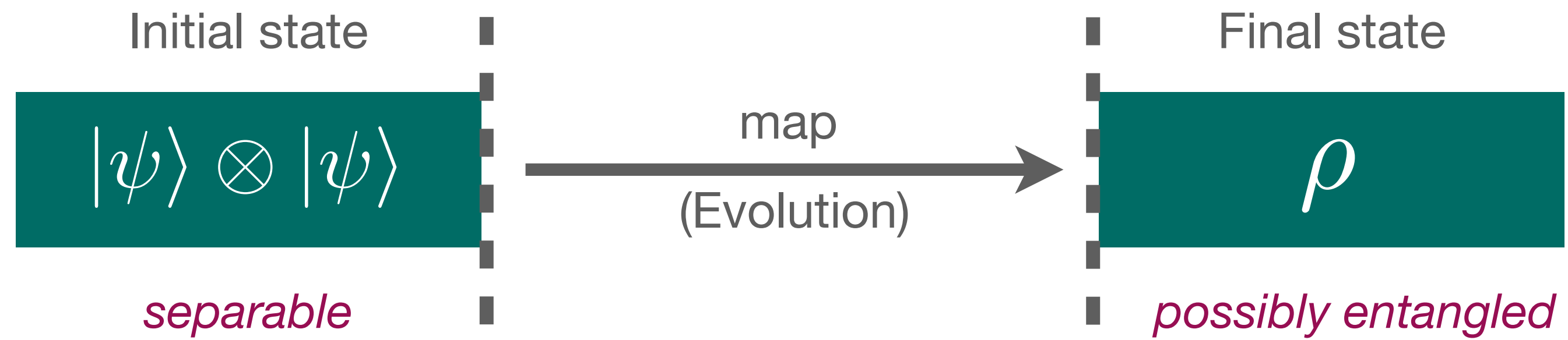
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If there is **entanglement**

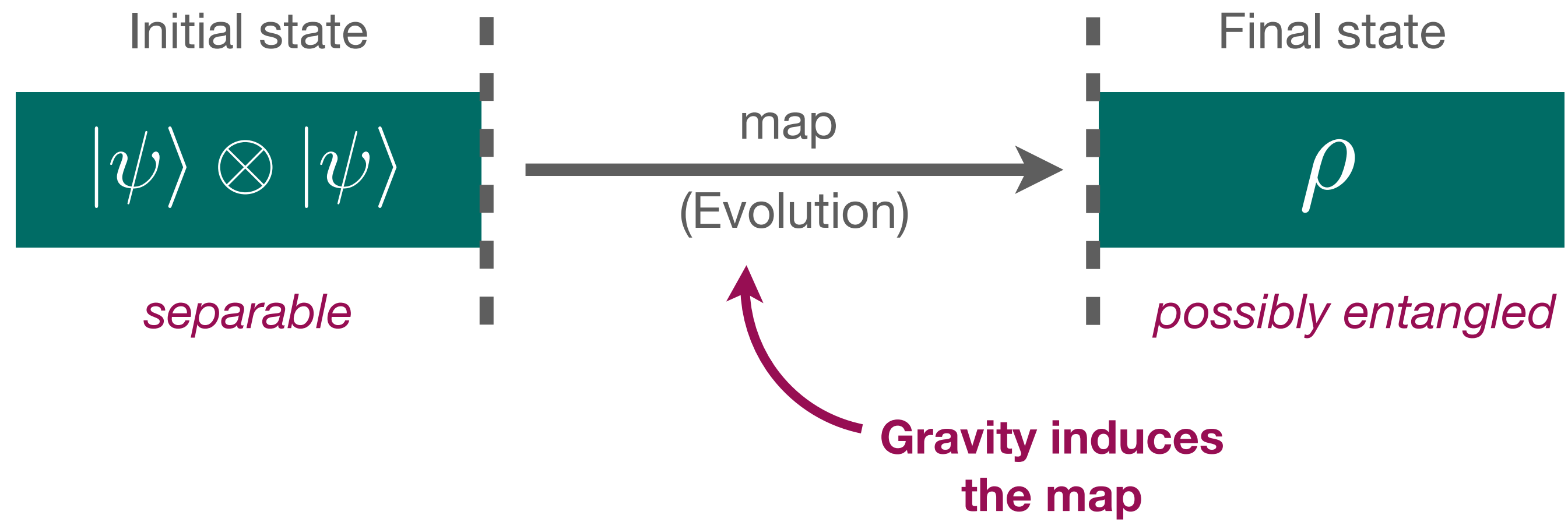


Gravitational evolution is
NOT of **LOCC** form

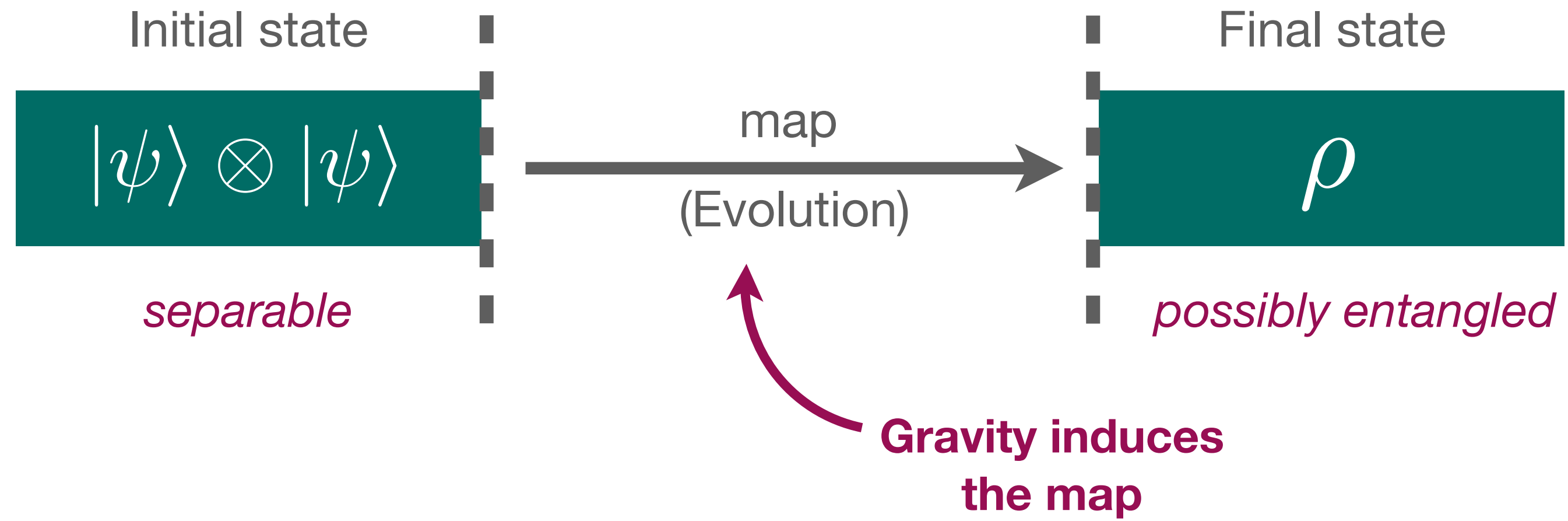
Gravity as a dynamical map



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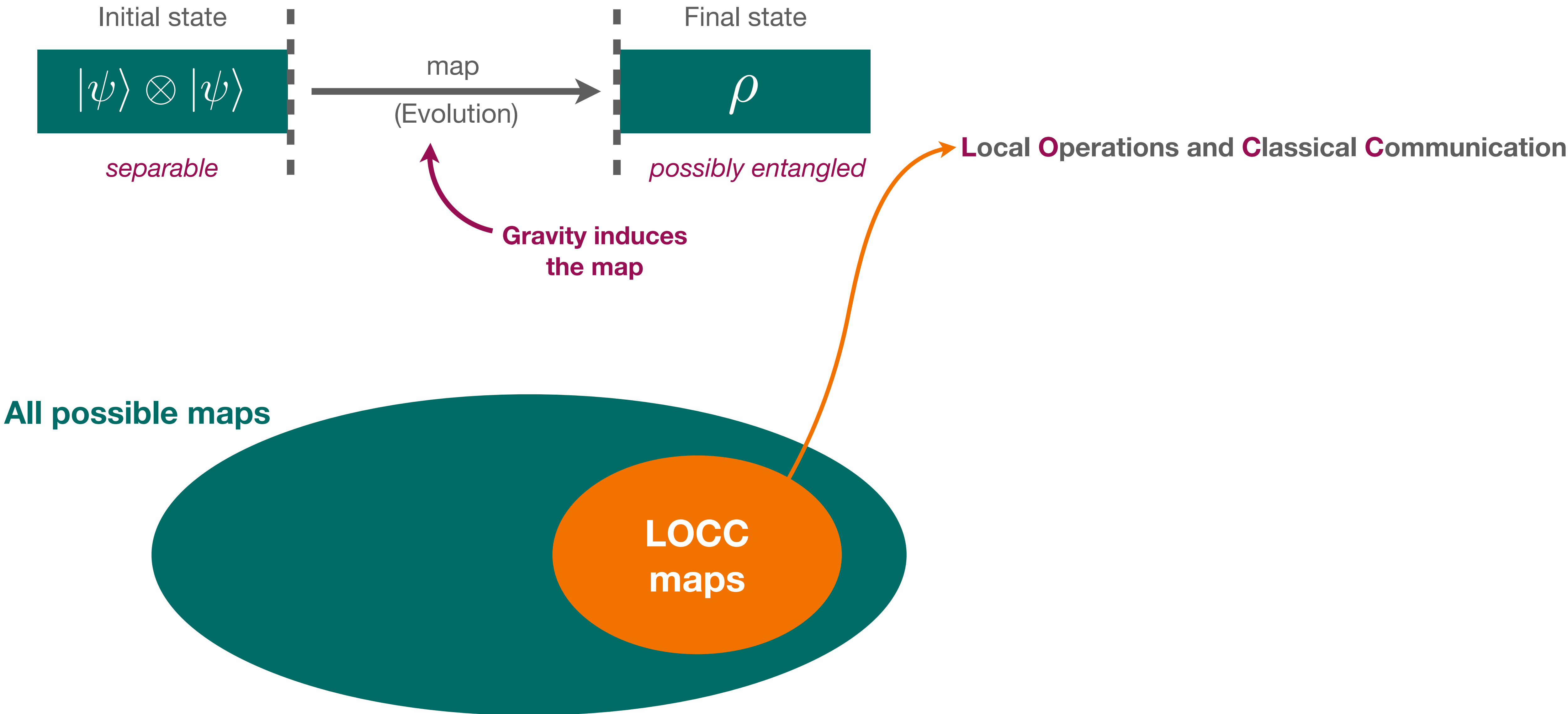
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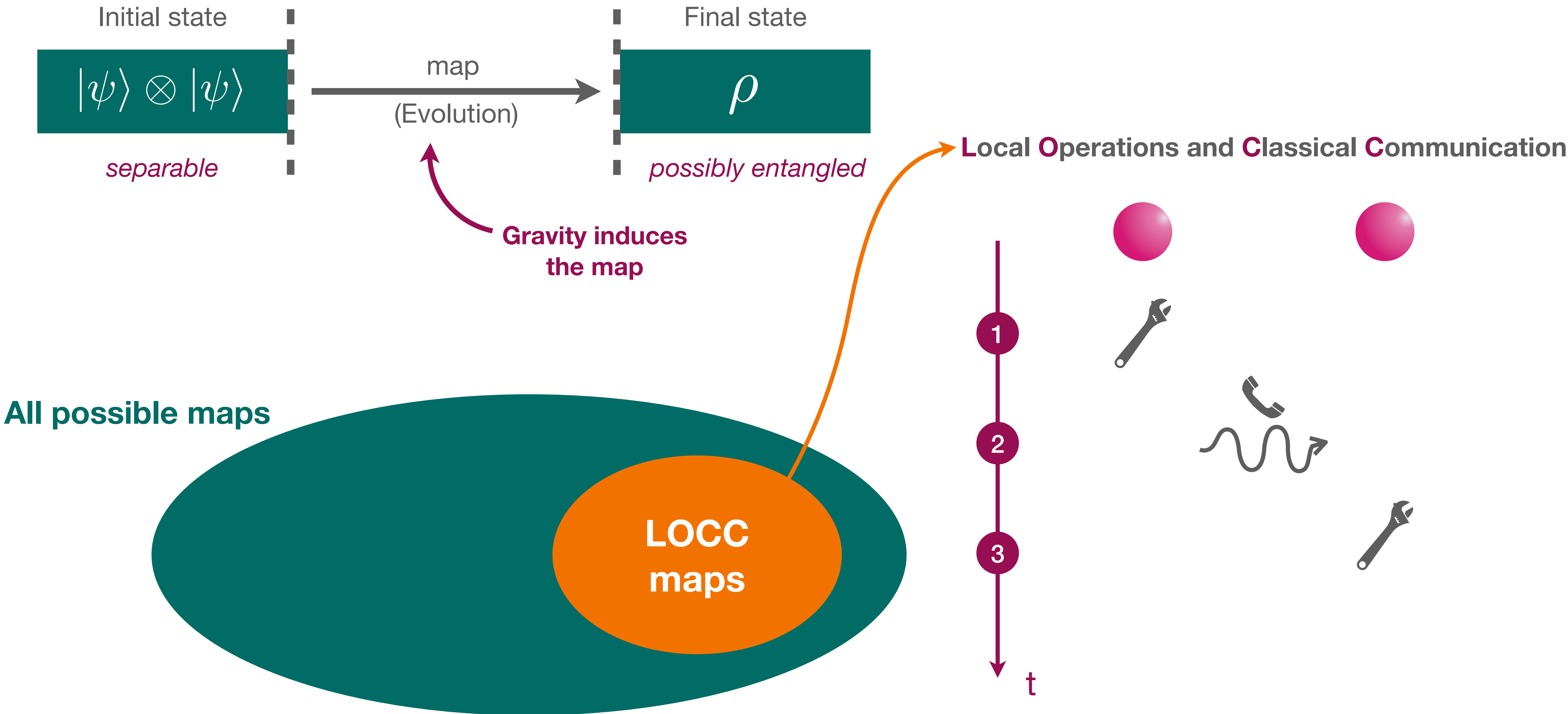
All possible maps



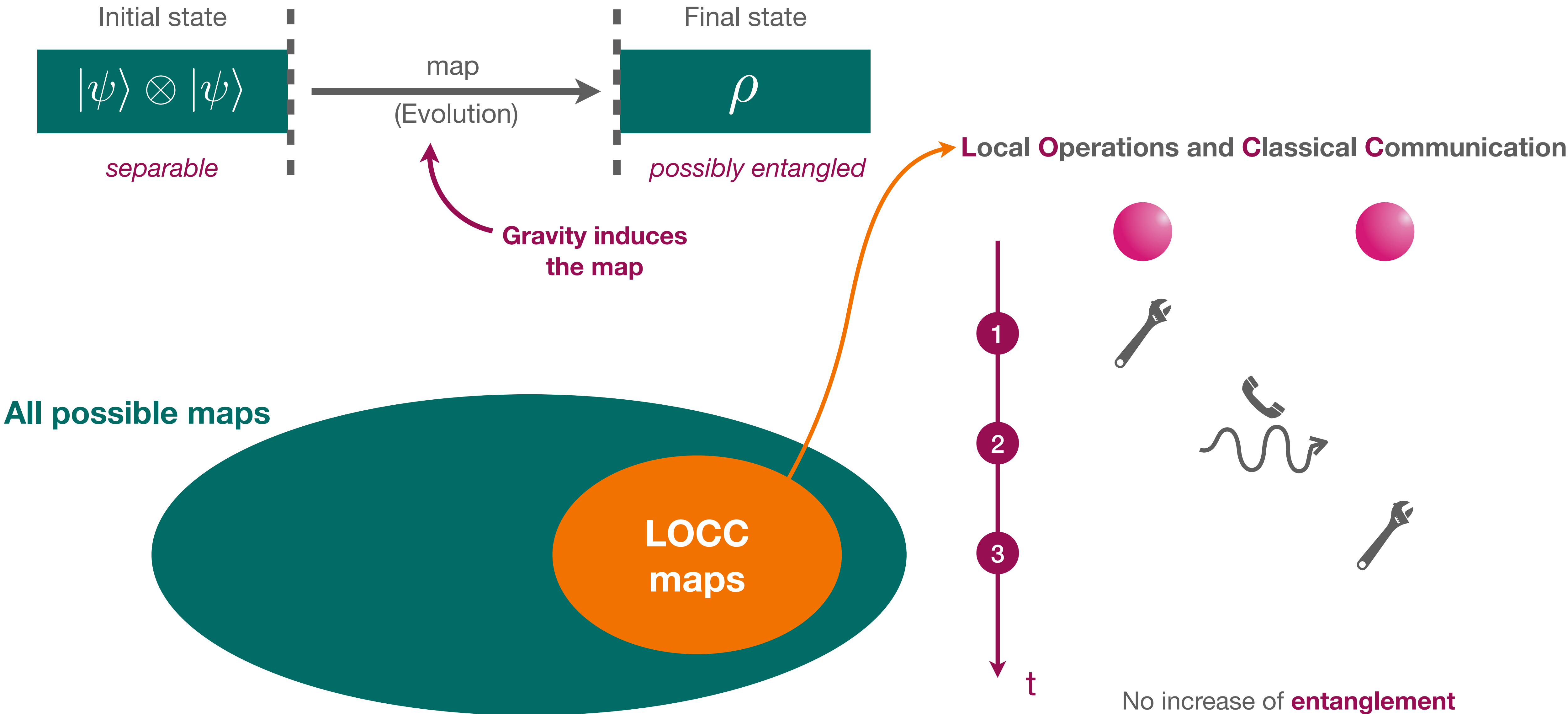
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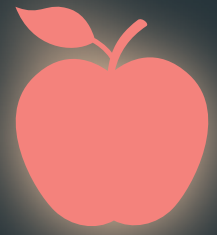


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Gravity as a dynamical map





LOCC simulation fidelity

L. Lami, J. S. Pedernales, and M. B. Plenio, *Phys. Rev. X* **14**, 021022 (2024)

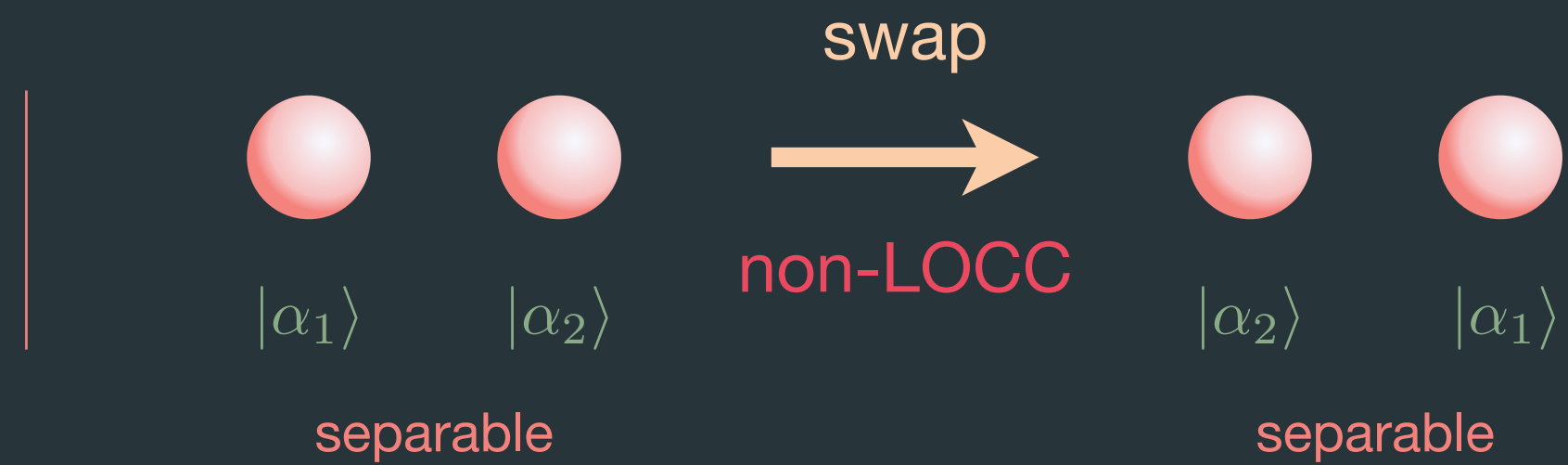
Entanglement is only one
of the limitations of LOCC

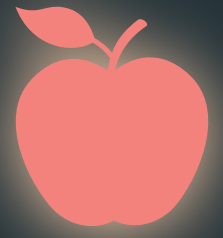


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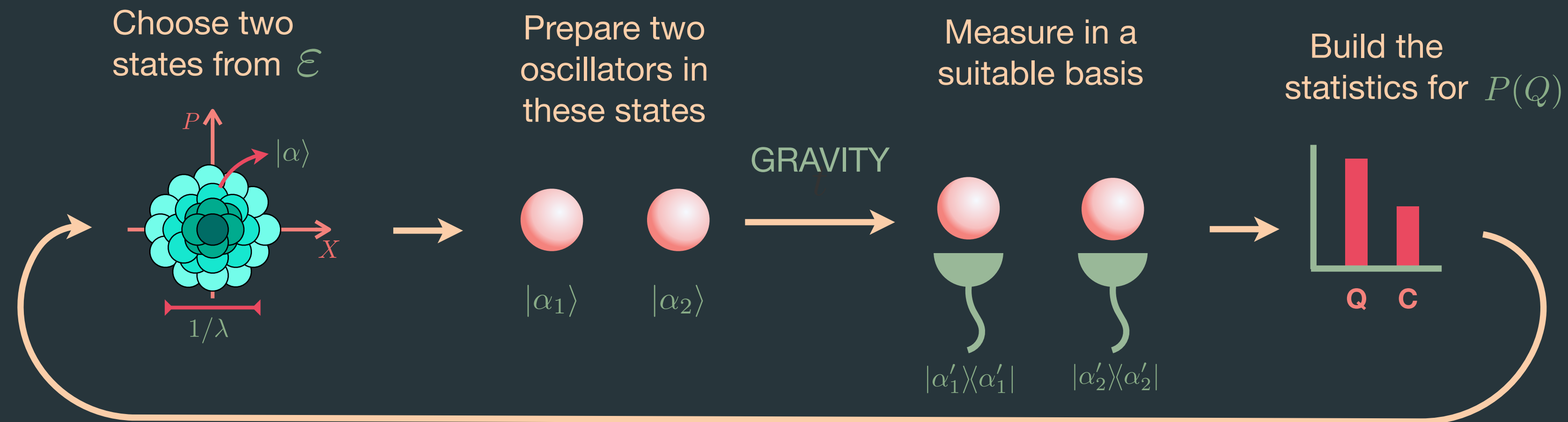
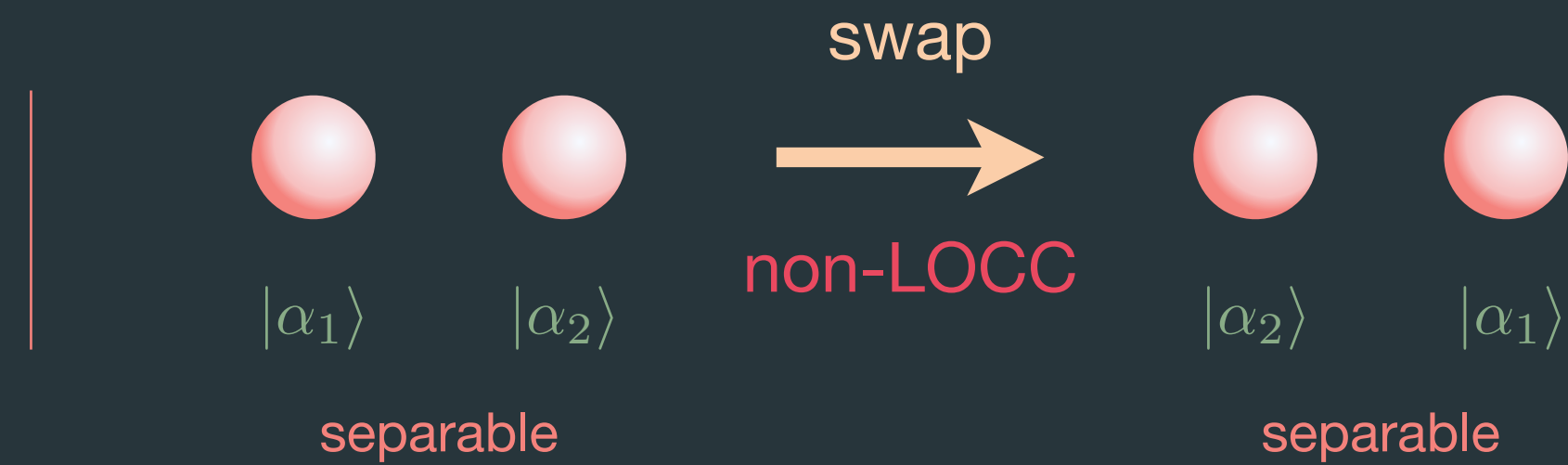


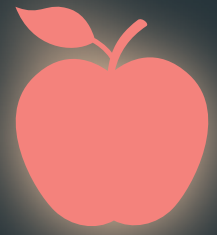


LOCC simulation fidelity

L. Lami, J. S. Pedernales, and M. B. Plenio, *Phys. Rev. X* **14**, 021022 (2024)

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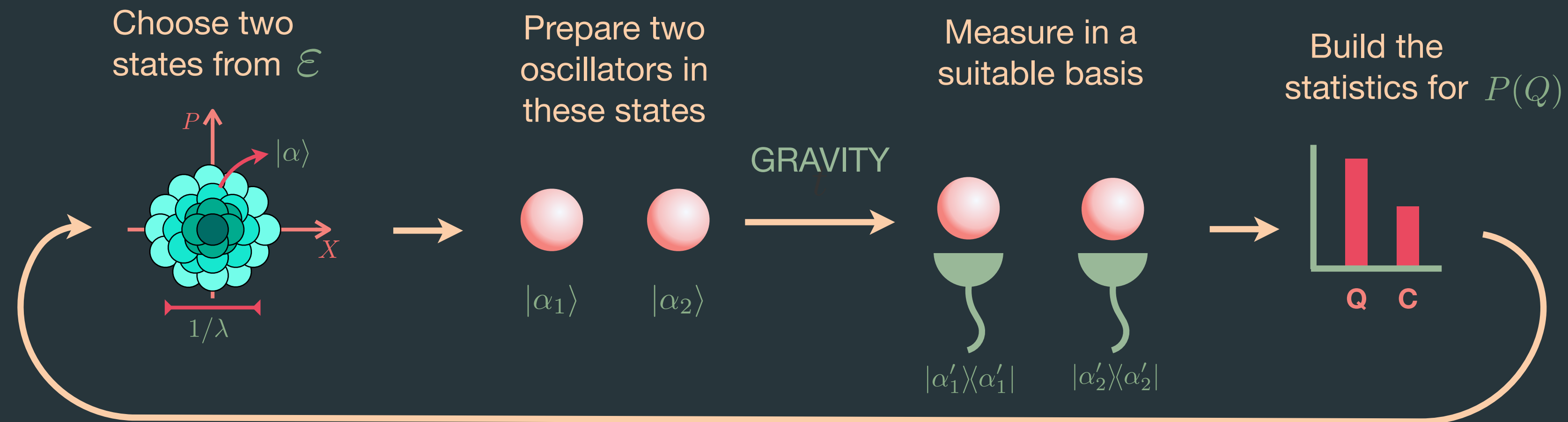
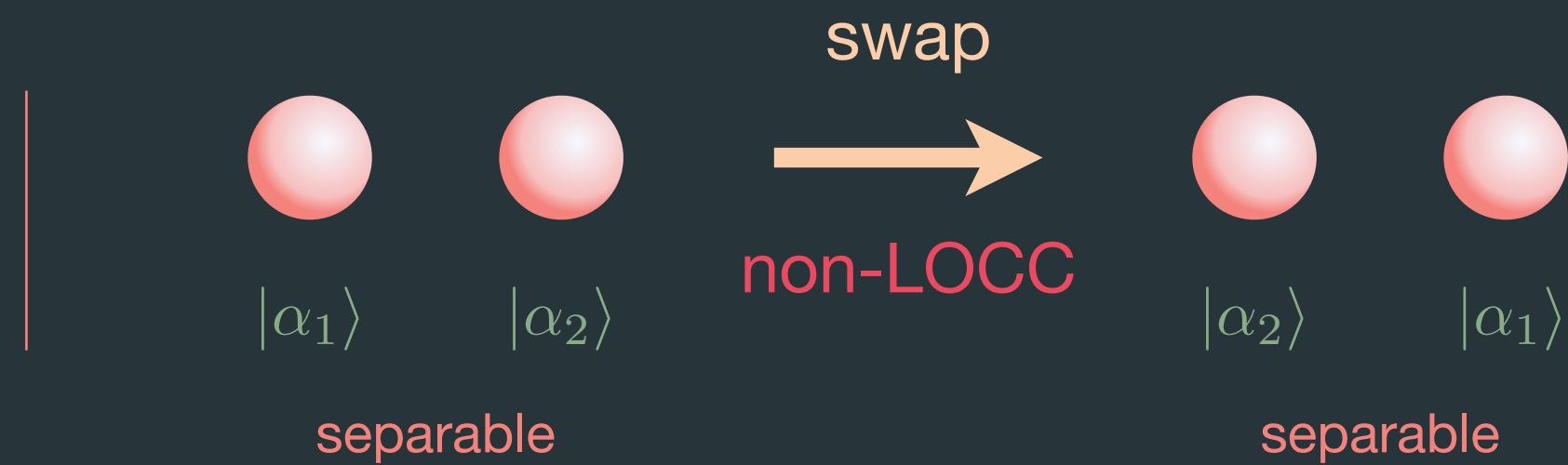




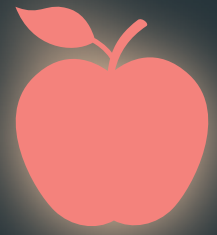
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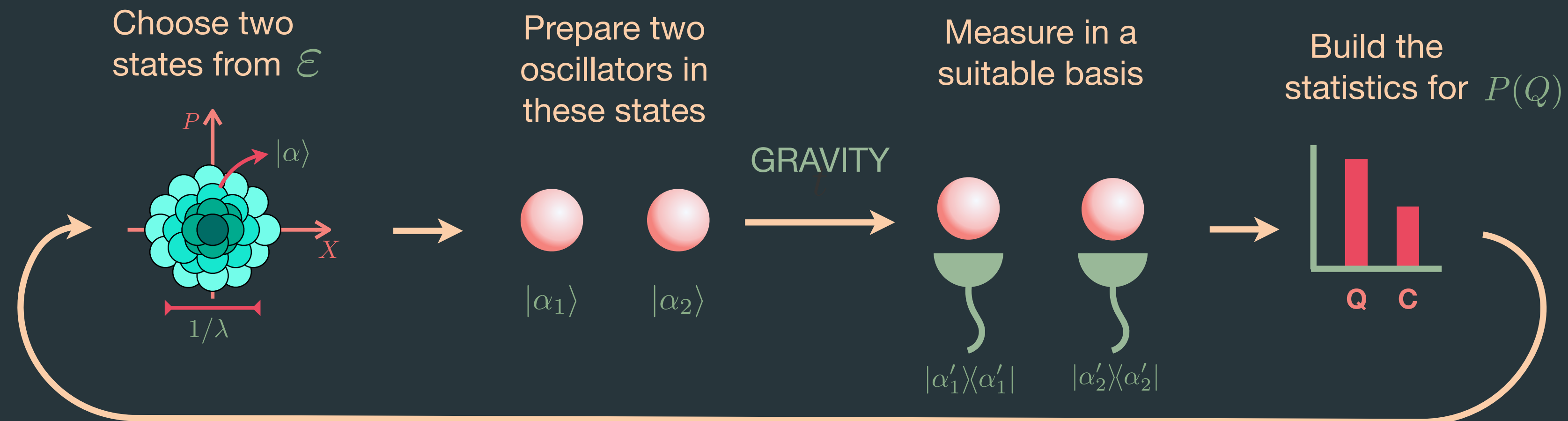
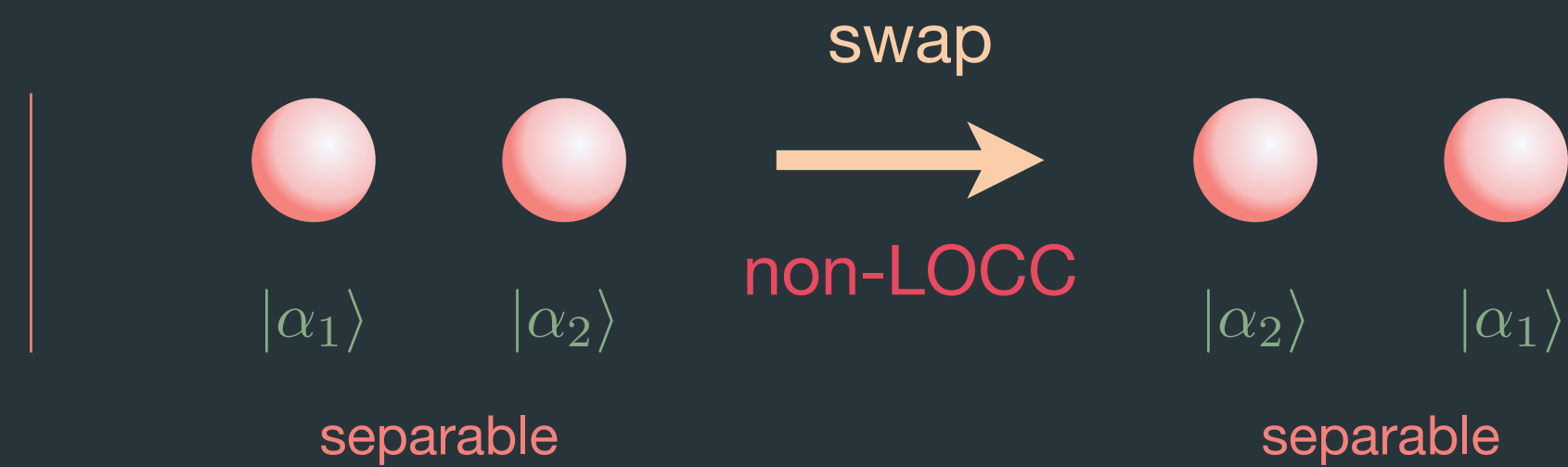
$$P(Q) > \mathcal{F}(\varepsilon, t) \Rightarrow \text{Gravity non-LOCC}$$



LOCC simulation fidelity

L. Lami, J. S. Pedernales, and M. B. Plenio, *Phys. Rev. X* **14**, 021022 (2024)

Entanglement is only **one**
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$P(Q) > \mathcal{F}(\varepsilon, t)$ Gravity **non-LOCC**

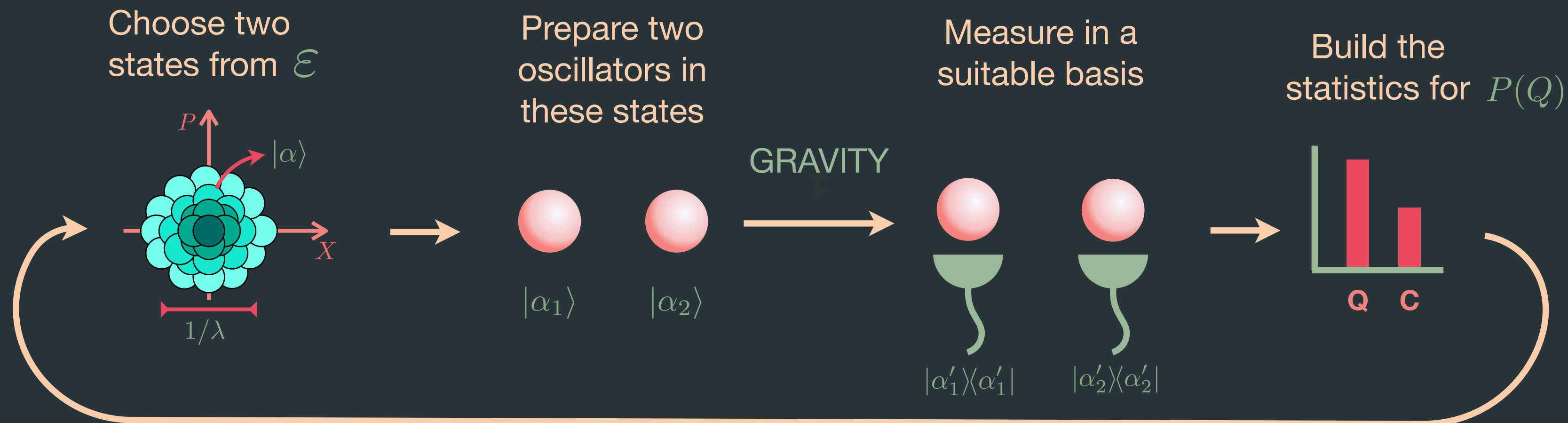
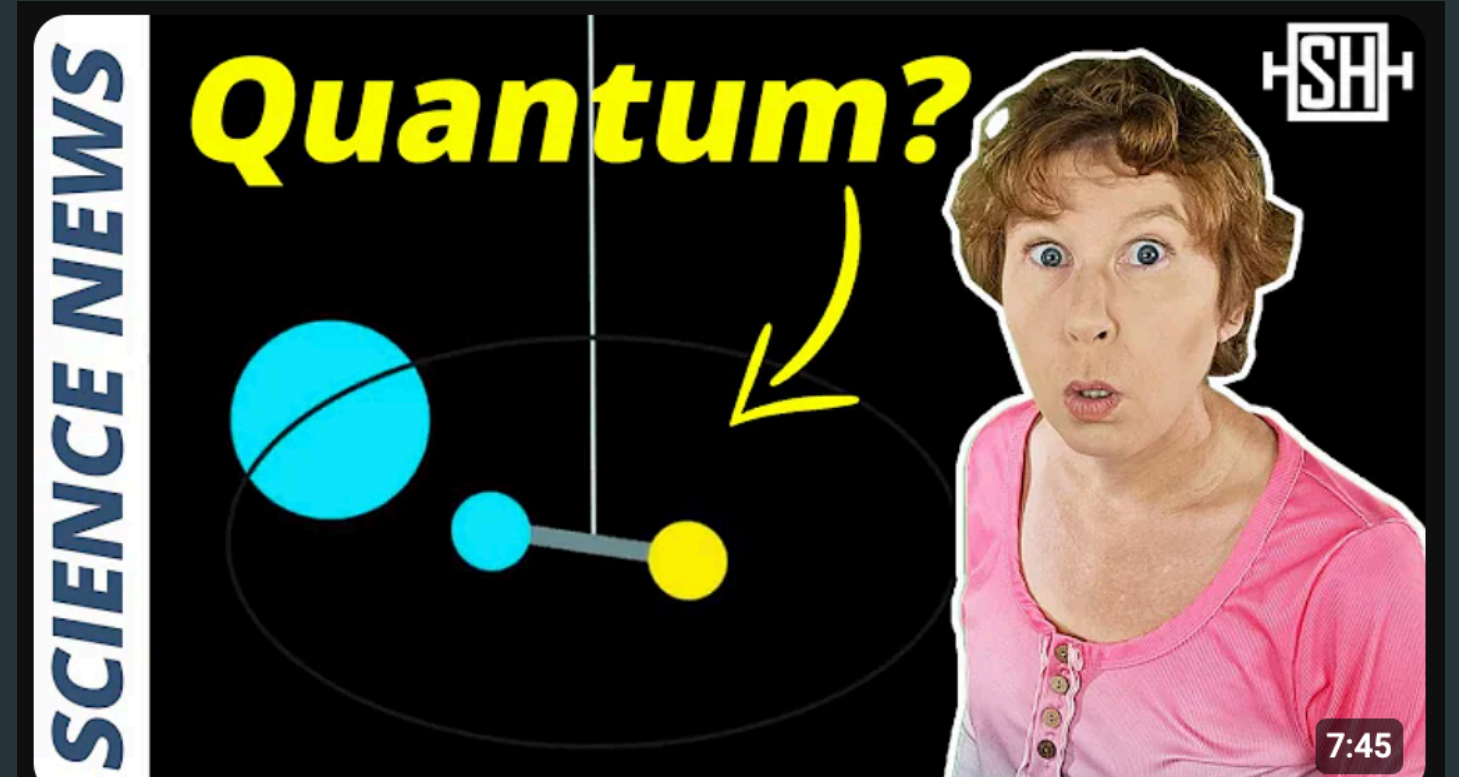
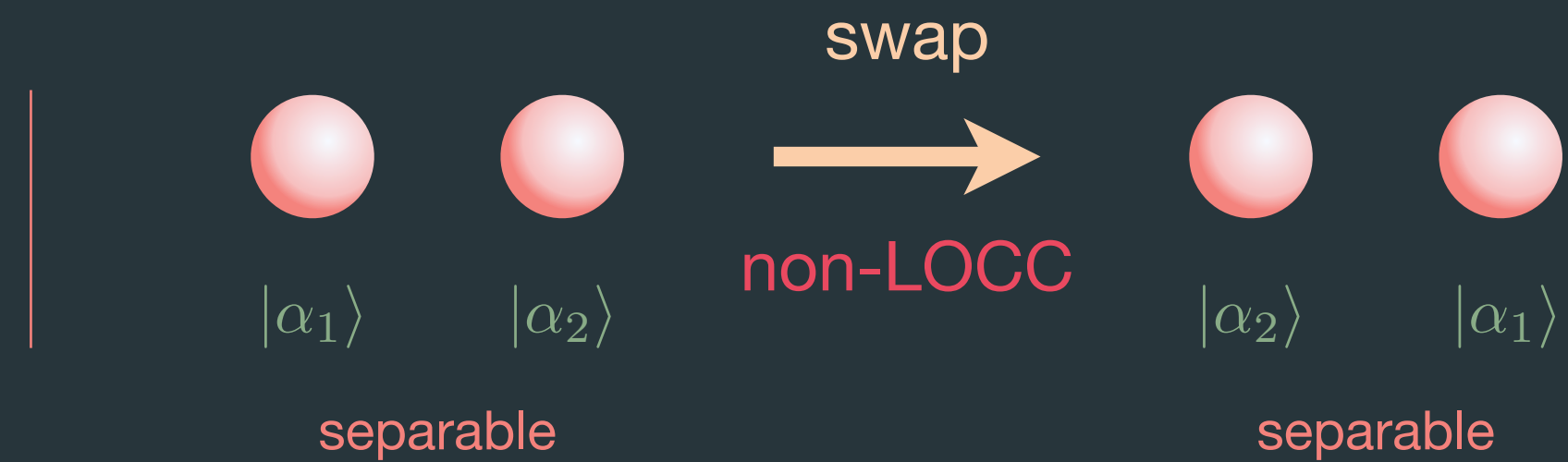
No entanglement required
No large delocalization required



LOCC simulation fidelity

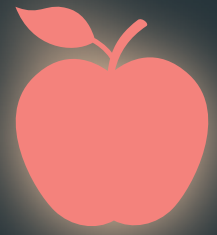
L. Lami, J. S. Pedernales, and M. B. Plenio, *Phys. Rev. X* **14**, 021022 (2024)

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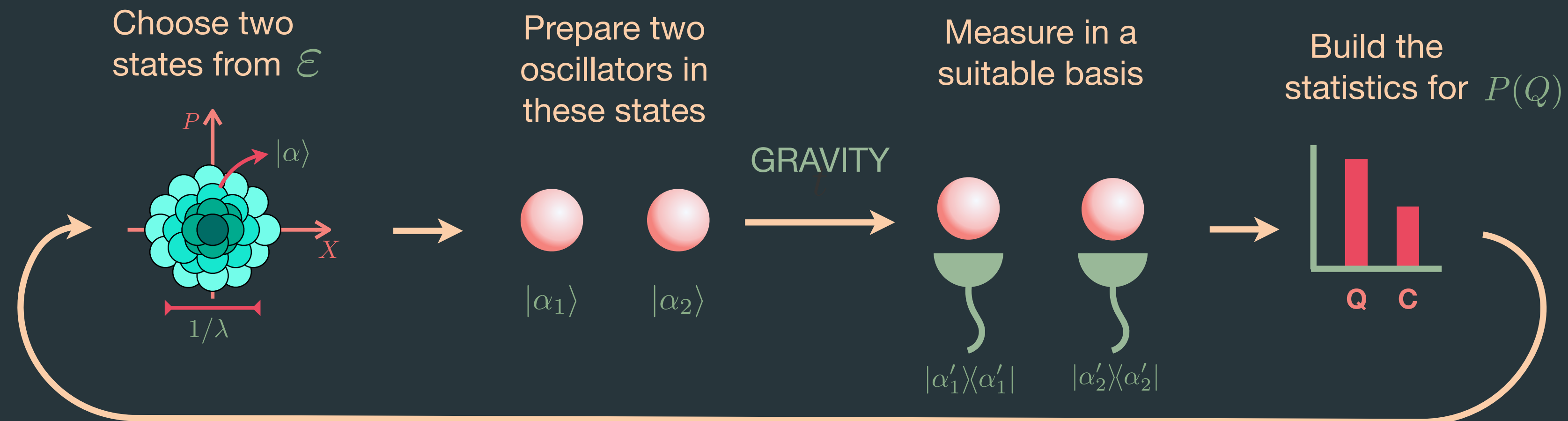
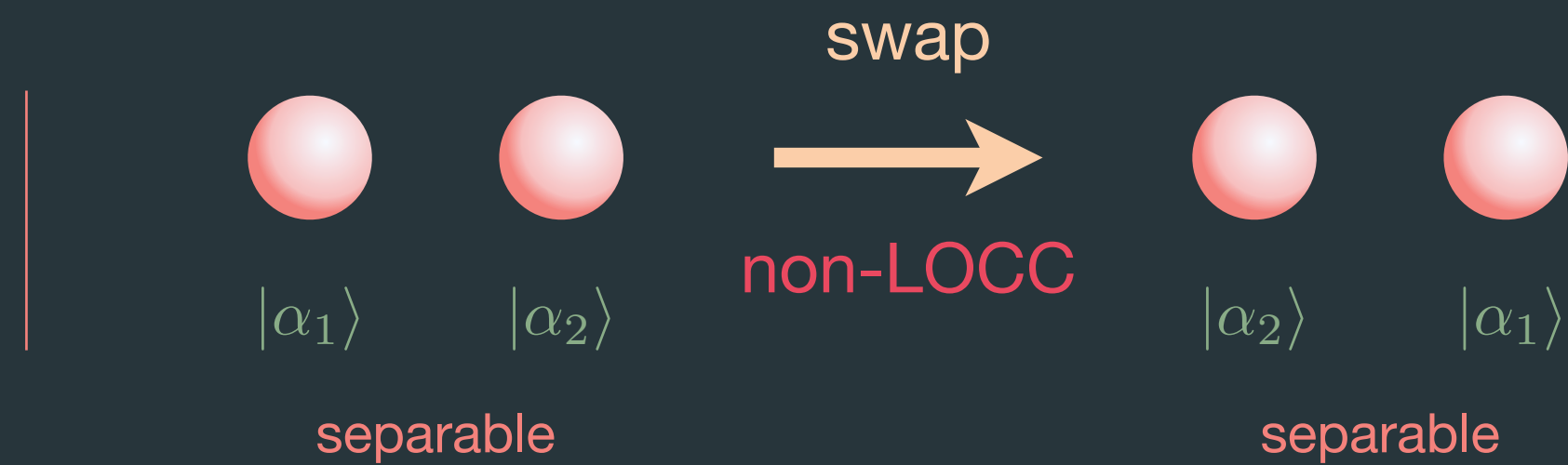
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LOCC simulation fidelity

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Entanglement is only **one**
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No entanglement required
No large delocalization required

Three ways to strengthen quantum experiments

1

EXPLOIT THE PLATFORM

· quantum resources ·

**What resources can
the physical platform give us?**

2

ASK THE RIGHT QUESTION

· operational certification ·

**What does the experiment
really need to demonstrate?**

3

TAKE THE APPARATUS SERIOUSLY

· realistic modeling ·

**What else can destroy
or fake the signal?**

Three ways to strengthen quantum experiments

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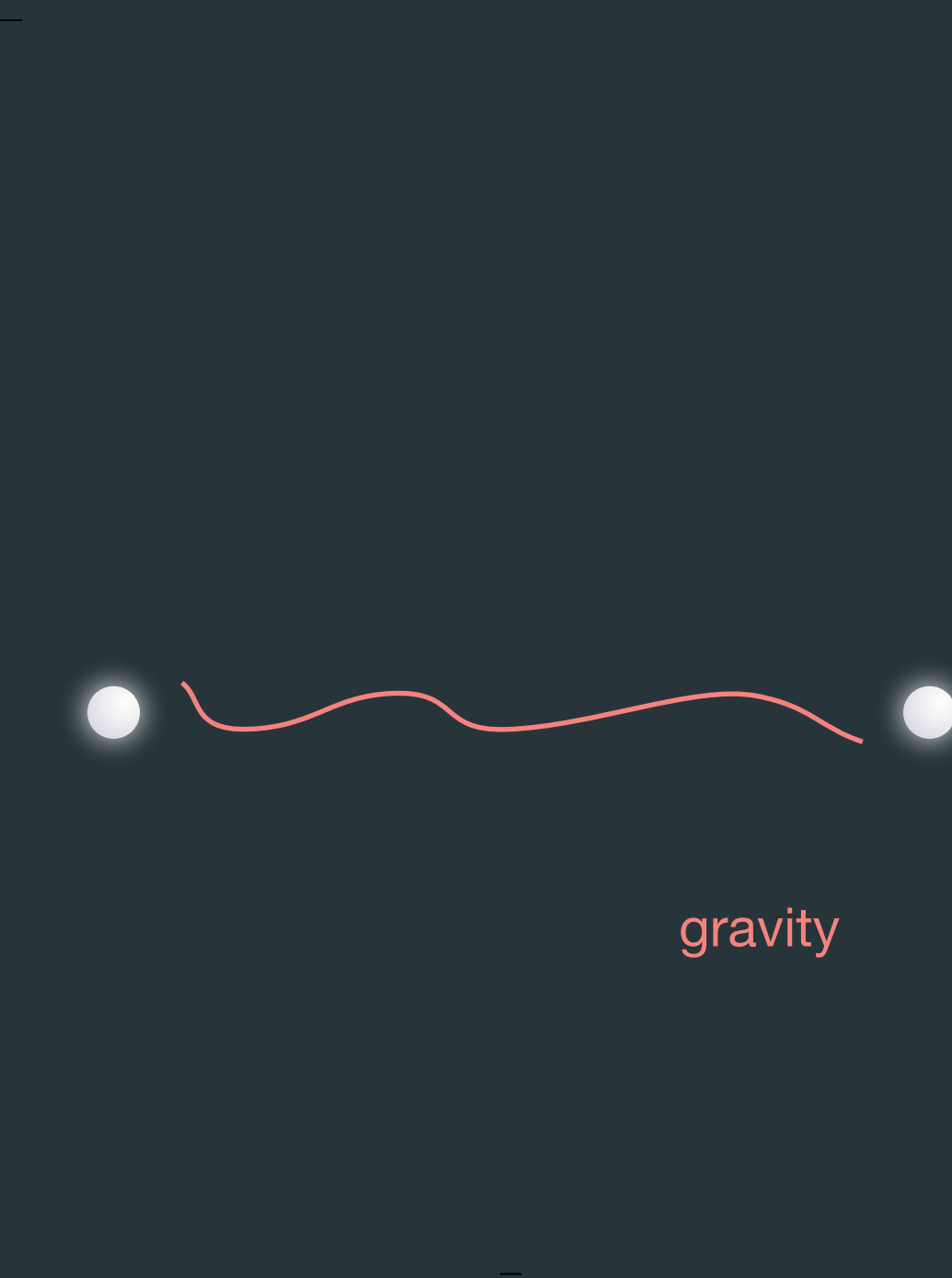
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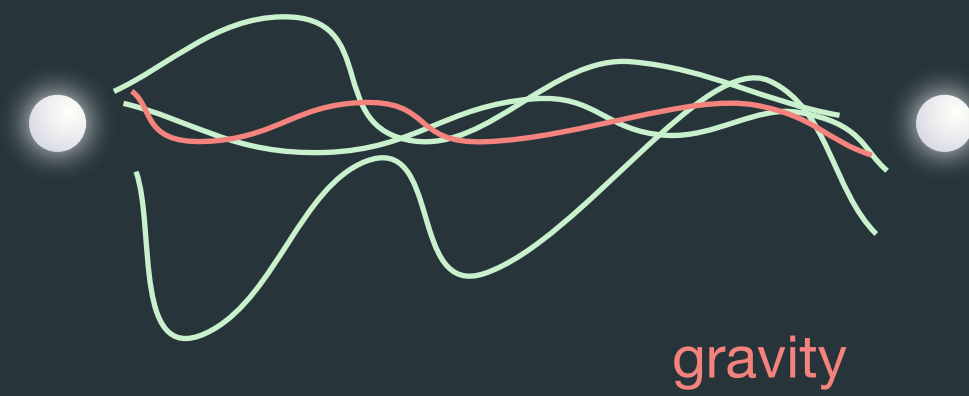
· realistic modeling ·

**What else can destroy
or fake the signal?**

Shielding non-gravitational interactions



Shielding non-gravitational interactions



Casimir interactions

Magnetic interactions

(Magnetic levitation)

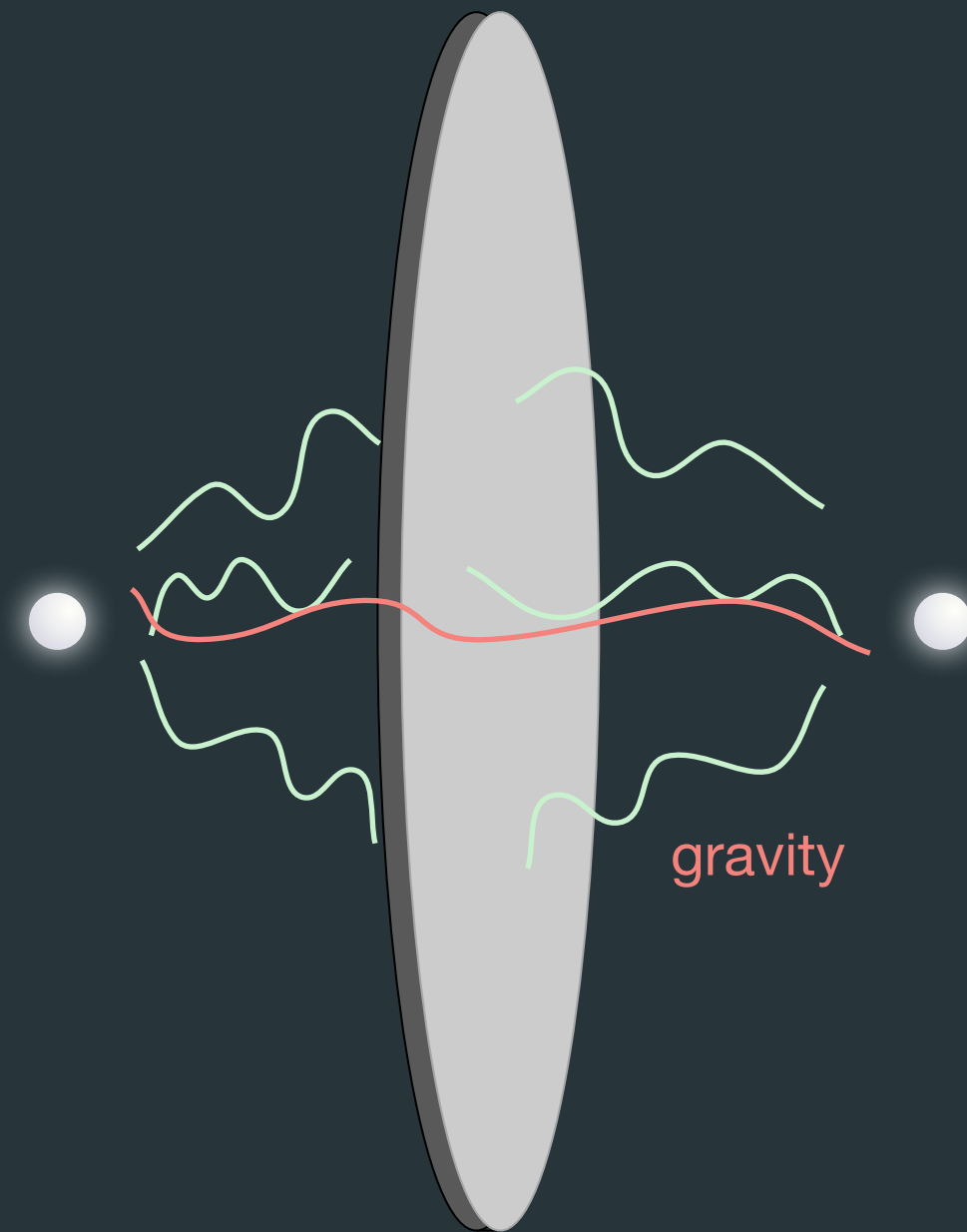
Electric interactions

(Paul trapping)

Optical dipolar interactions

(optical levitation)

Shielding non-gravitational interactions



Casimir interactions

Magnetic interactions

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Electric interactions

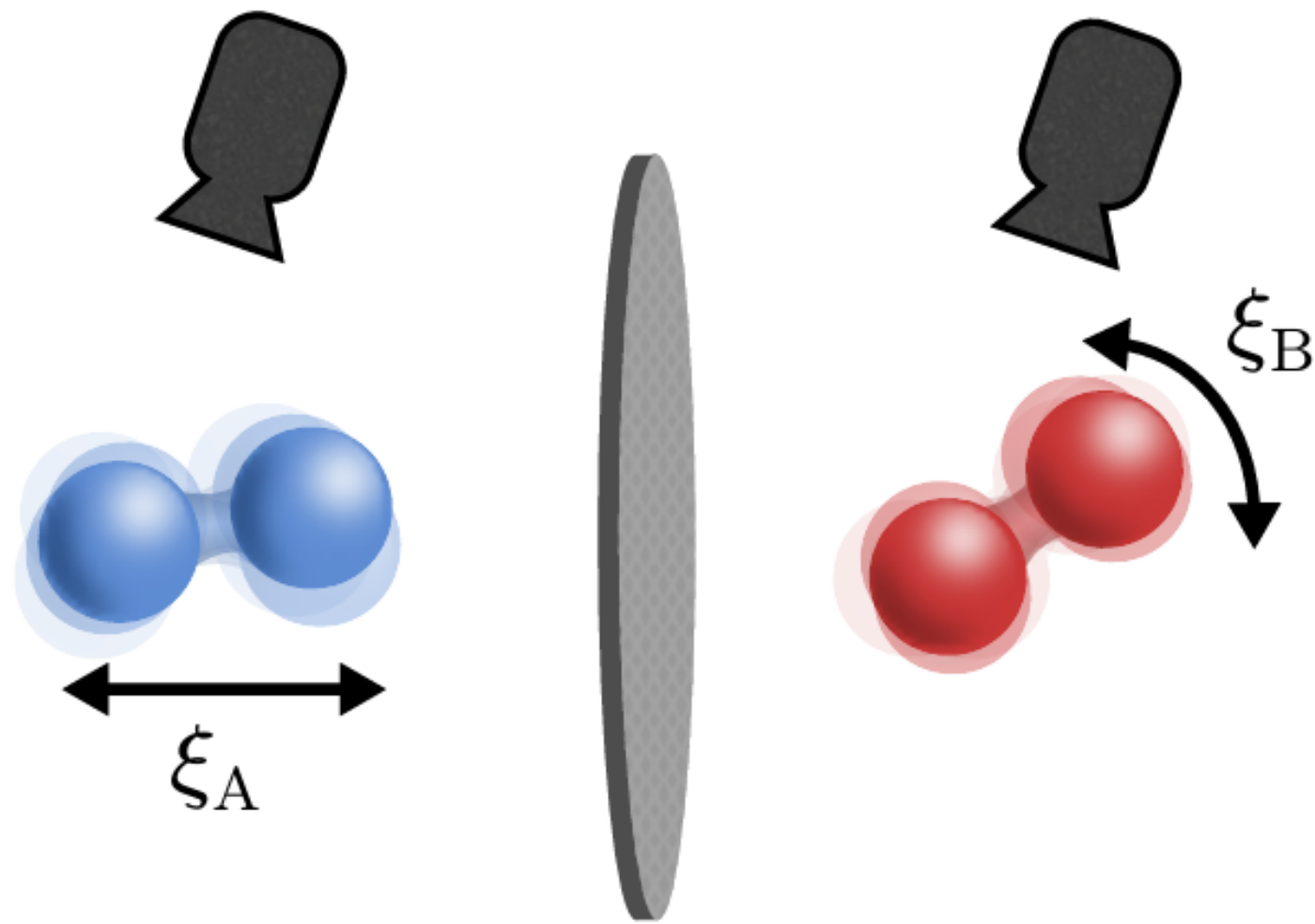
(Paul trapping)

Optical dipolar interactions

(optical levitation)

Stability thresholds

Initially mixed state



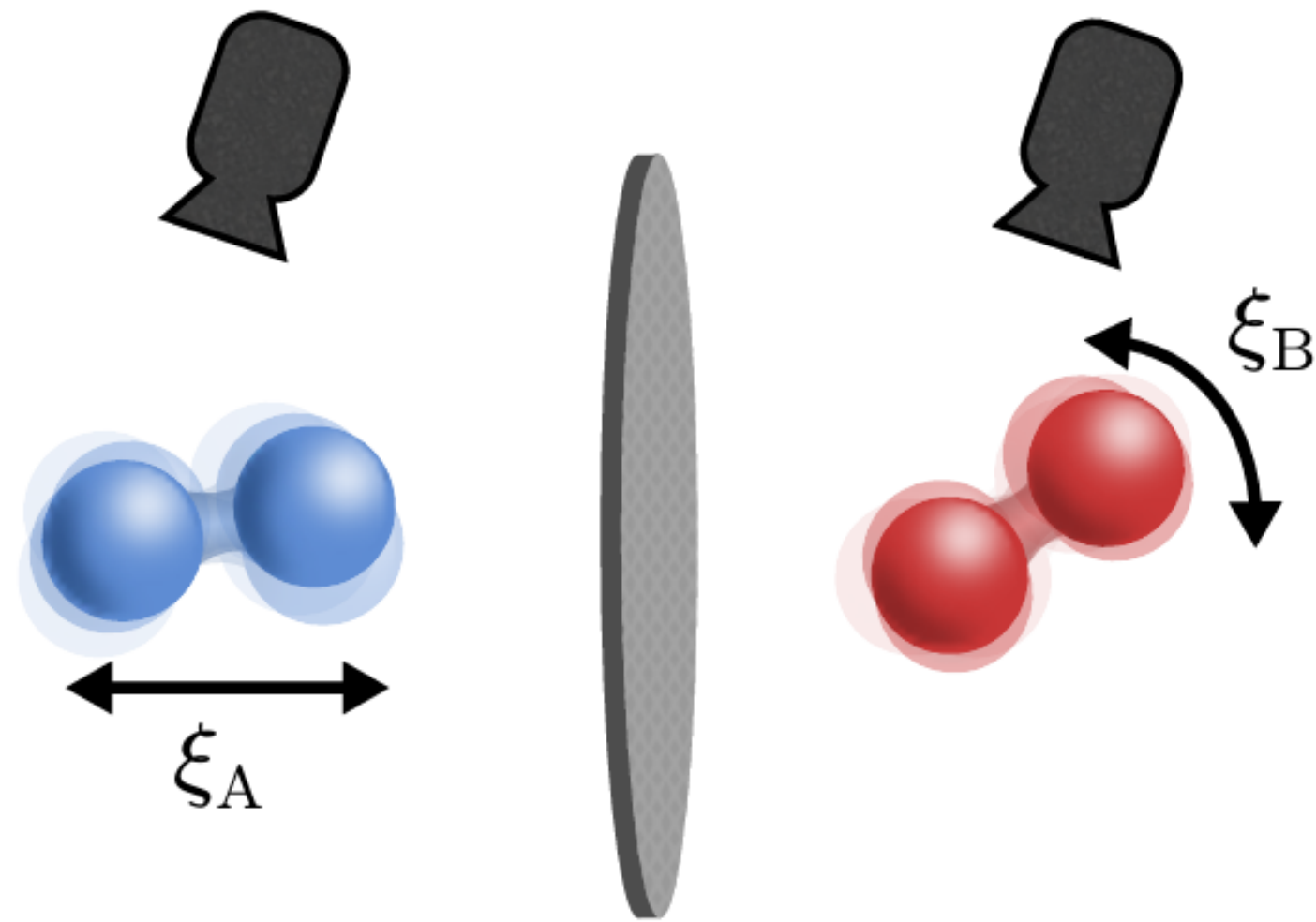
$$\rho(t) = U(t) \left(\underbrace{\int d\xi p(\xi) |\psi(\xi)\rangle \langle \psi(\xi)|}_{\text{Mixed initial State}} \right) U^\dagger(\xi)$$

Mixed initial State

Same Hamiltonian generates evolution
for all realizations

Stability thresholds

Initially mixed state

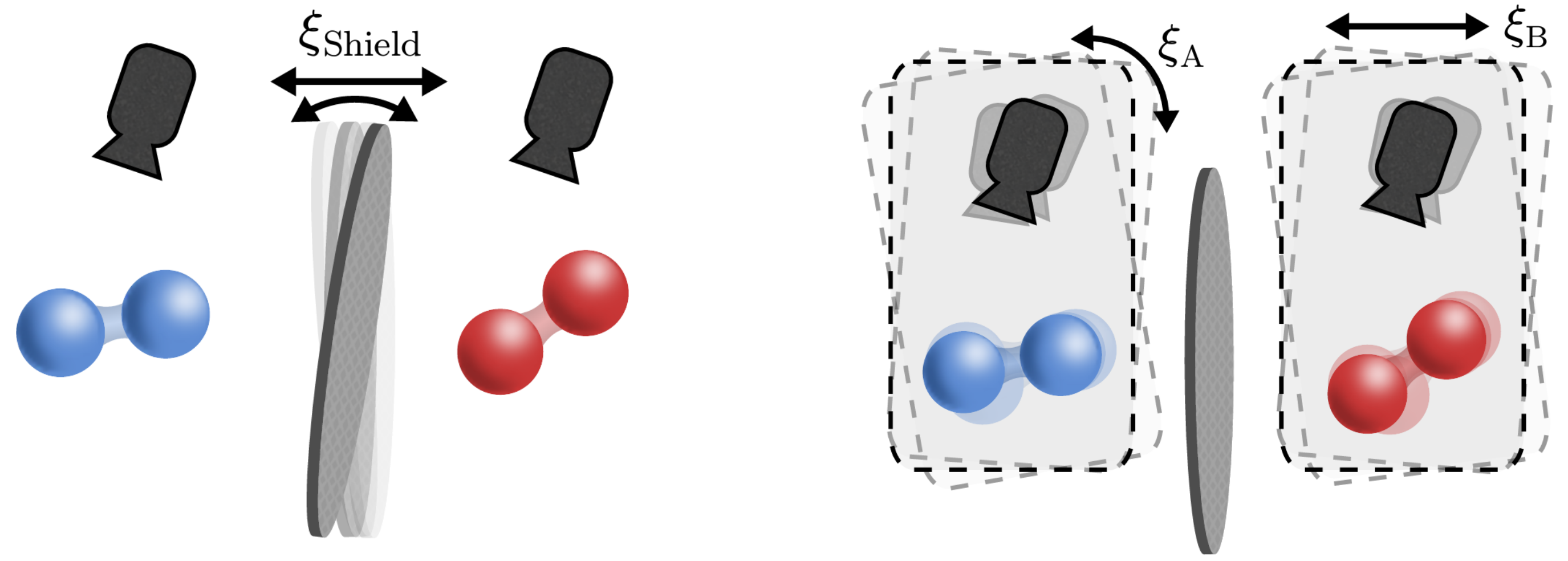


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Mixed initial State

Same Hamiltonian generates evolution for all realizations

Run-to-run variations of the setup geometry

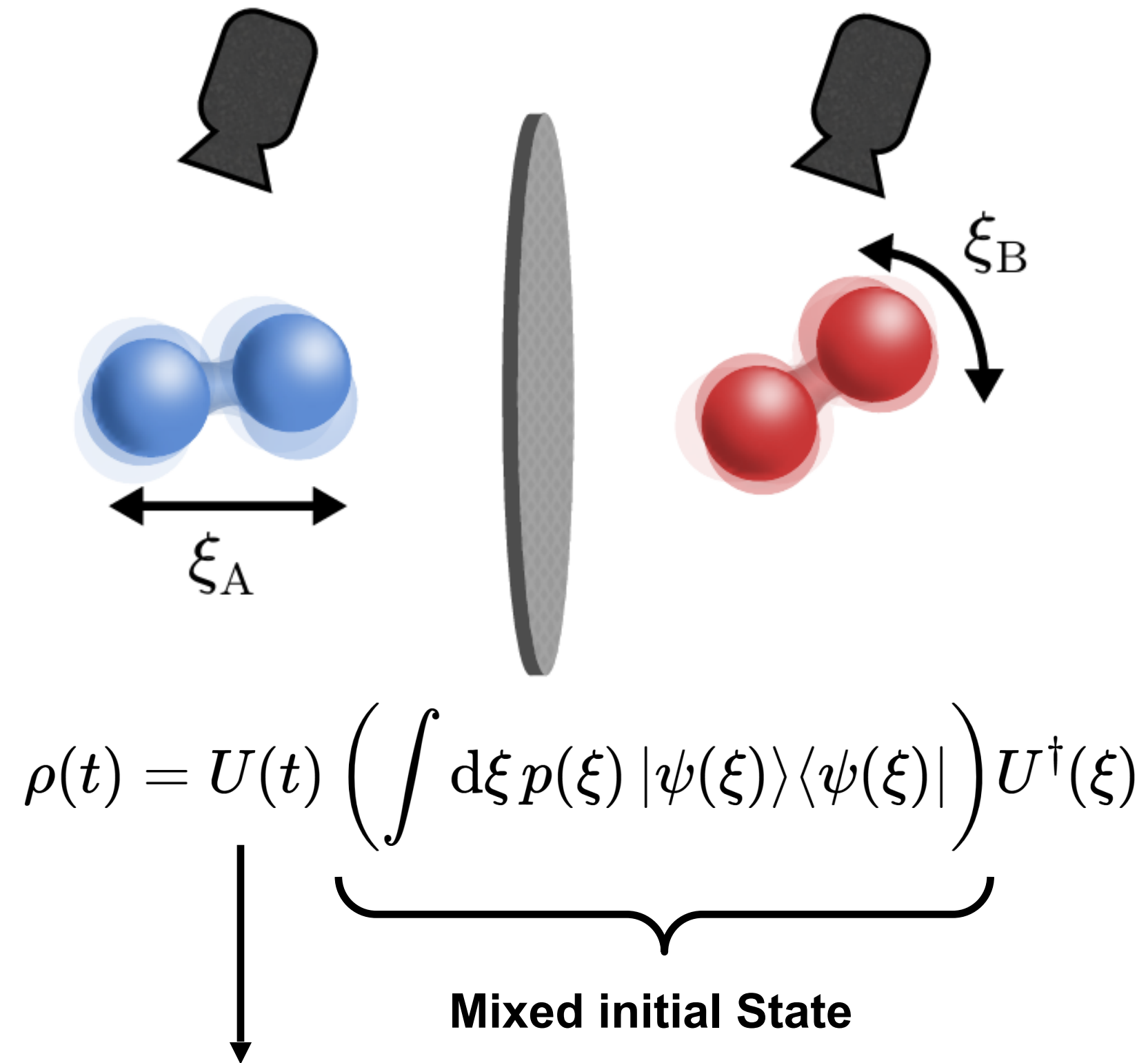


$$\rho(t) = \int d\xi p(\xi) U_\xi(t) \rho_0 U_\xi^\dagger(t) \quad \text{with} \quad U_\xi(t) = \exp\{-i\hat{H}(\xi)t/\hbar\}$$

Pure state

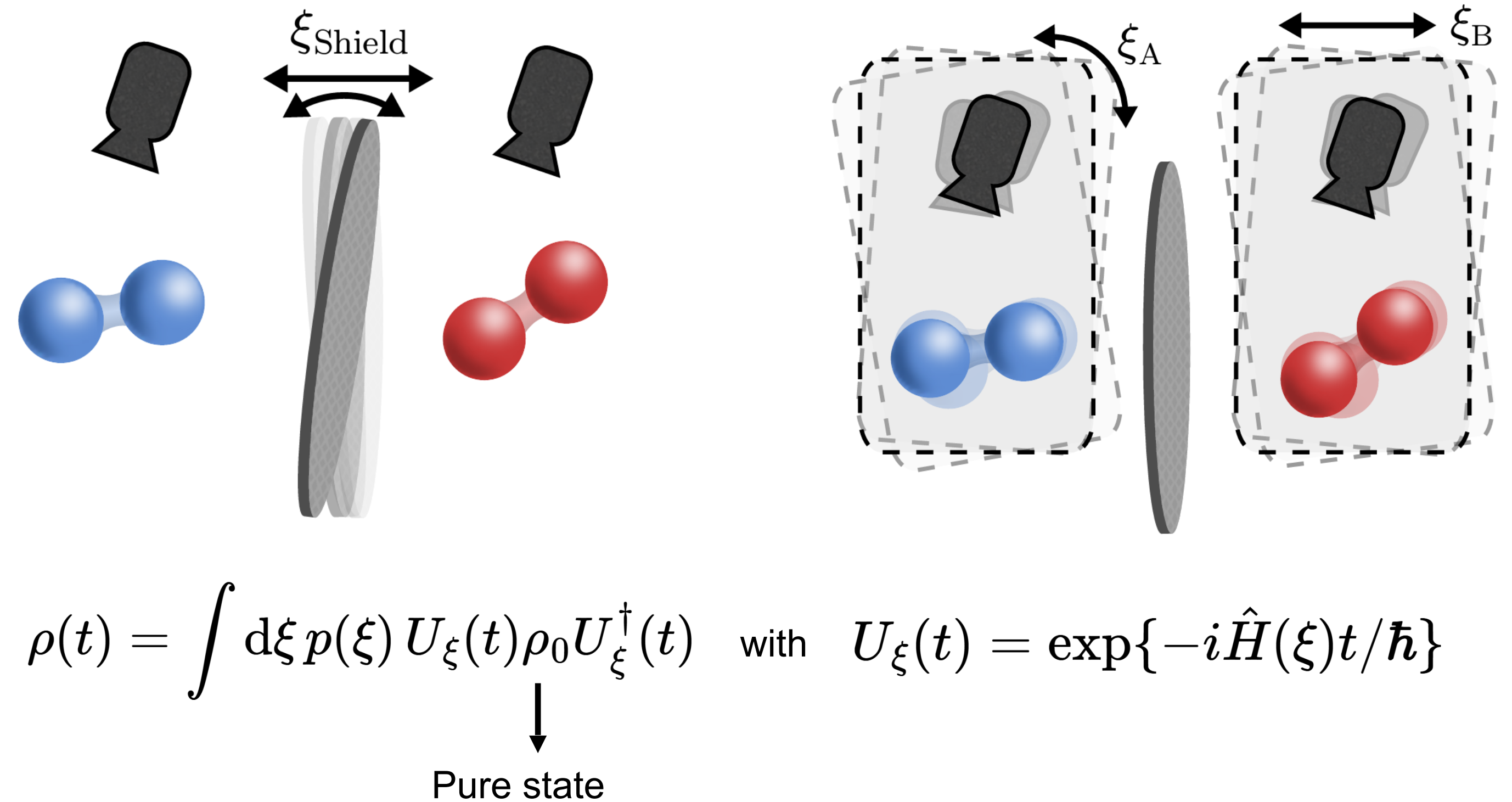
Stability thresholds

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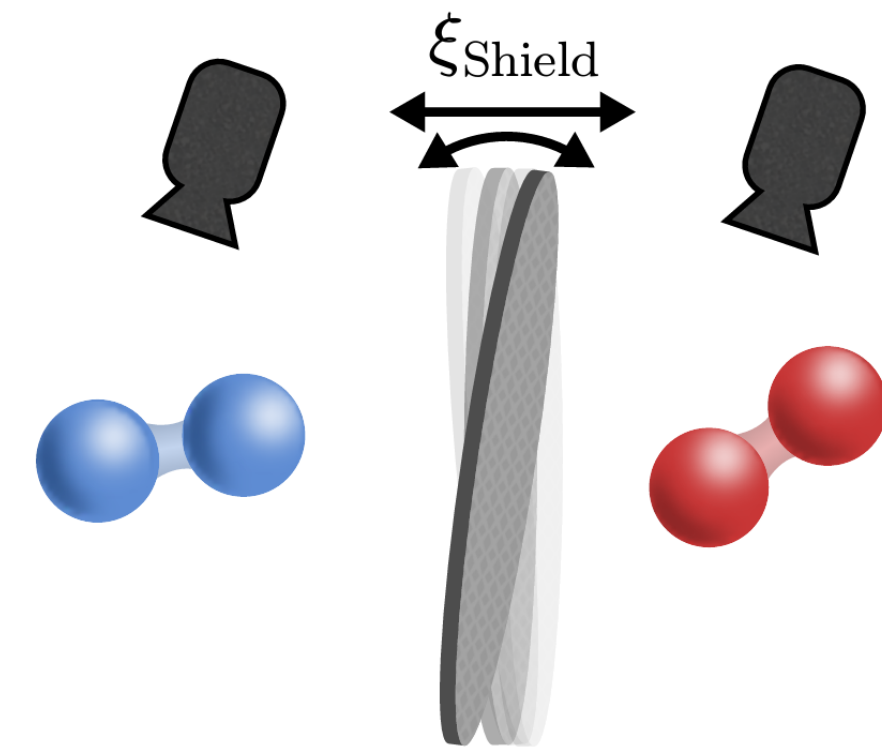
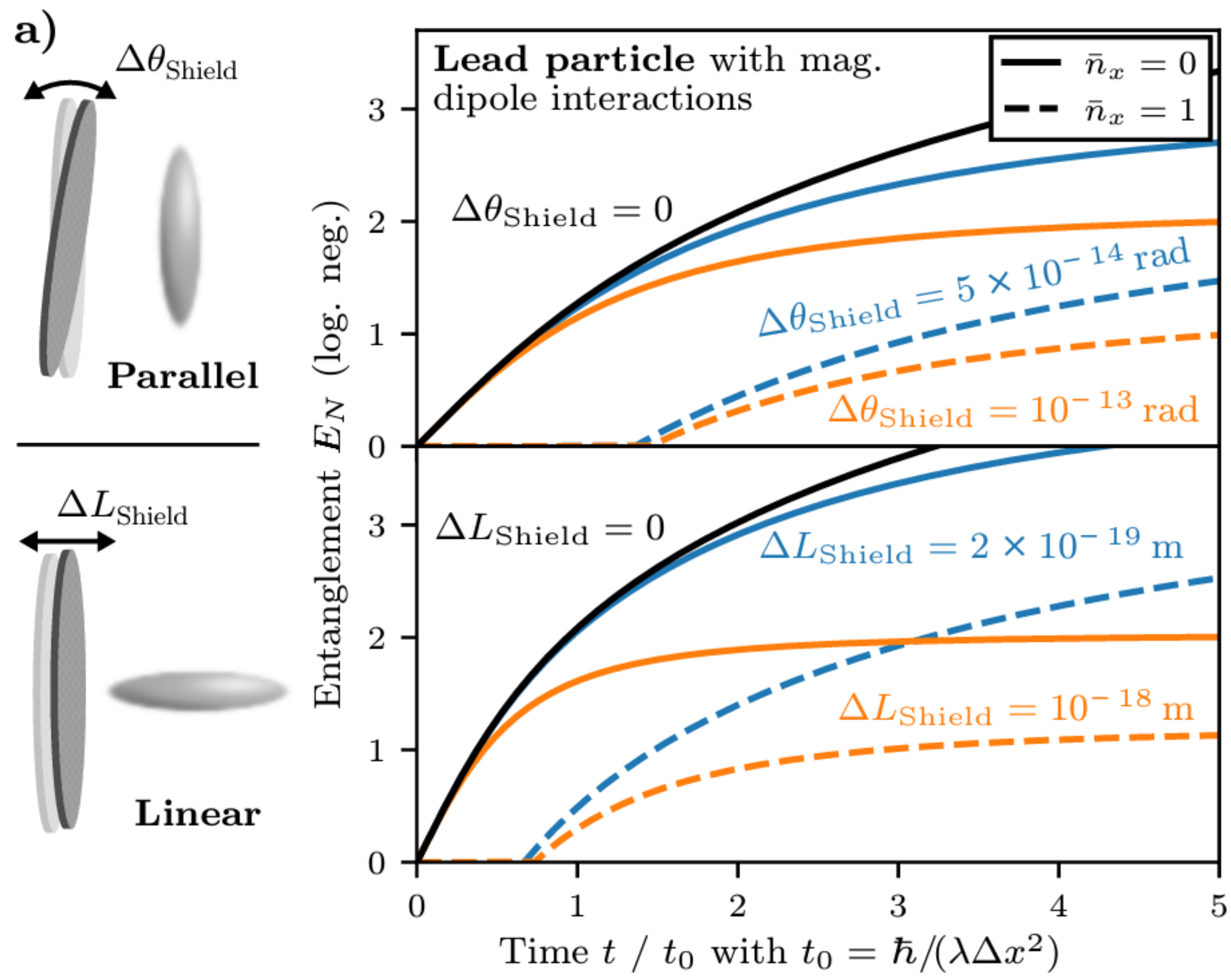


We consider the cases of distance $\xi^{(L)}$ and orientation $\xi^{(\theta)}$ variations

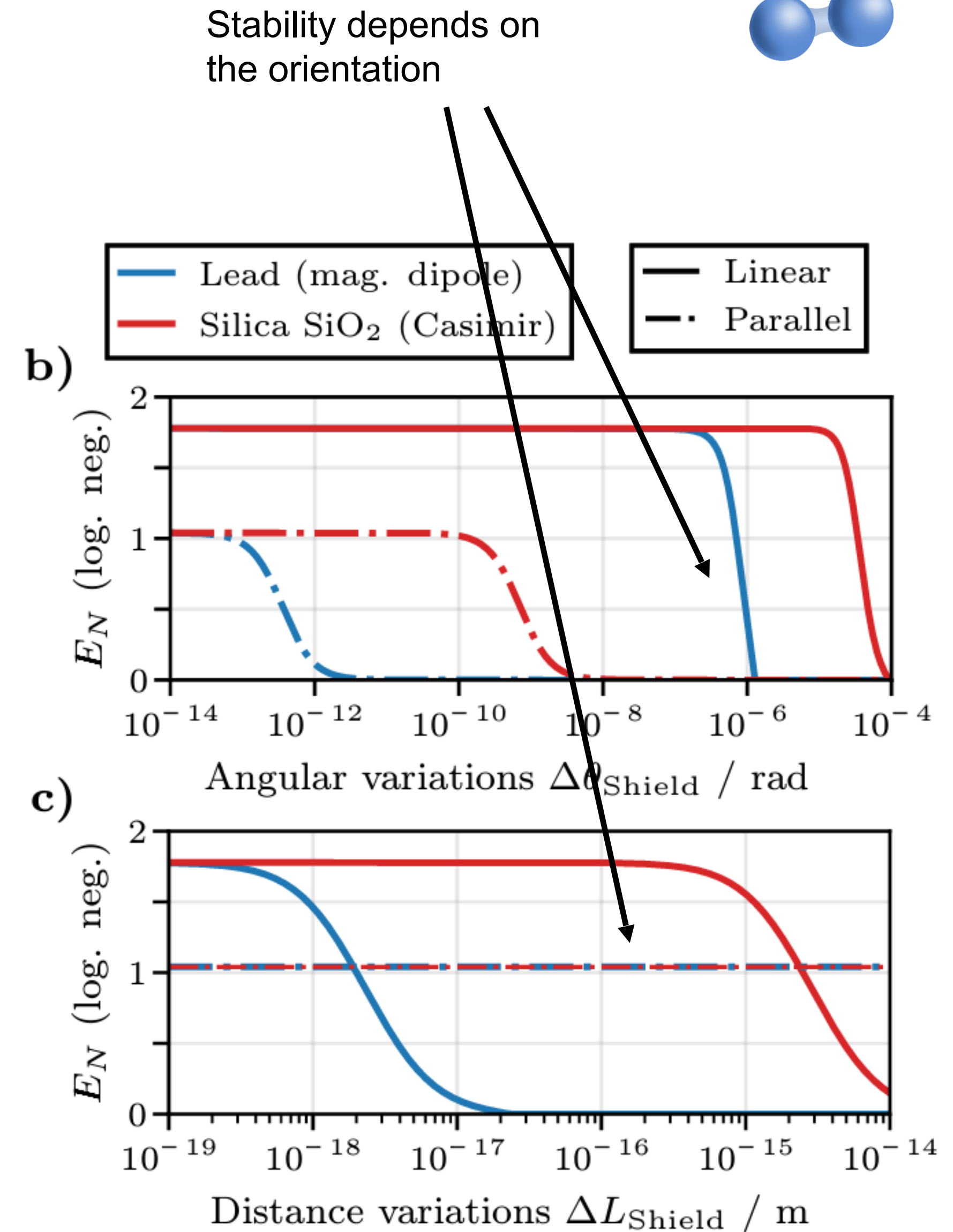
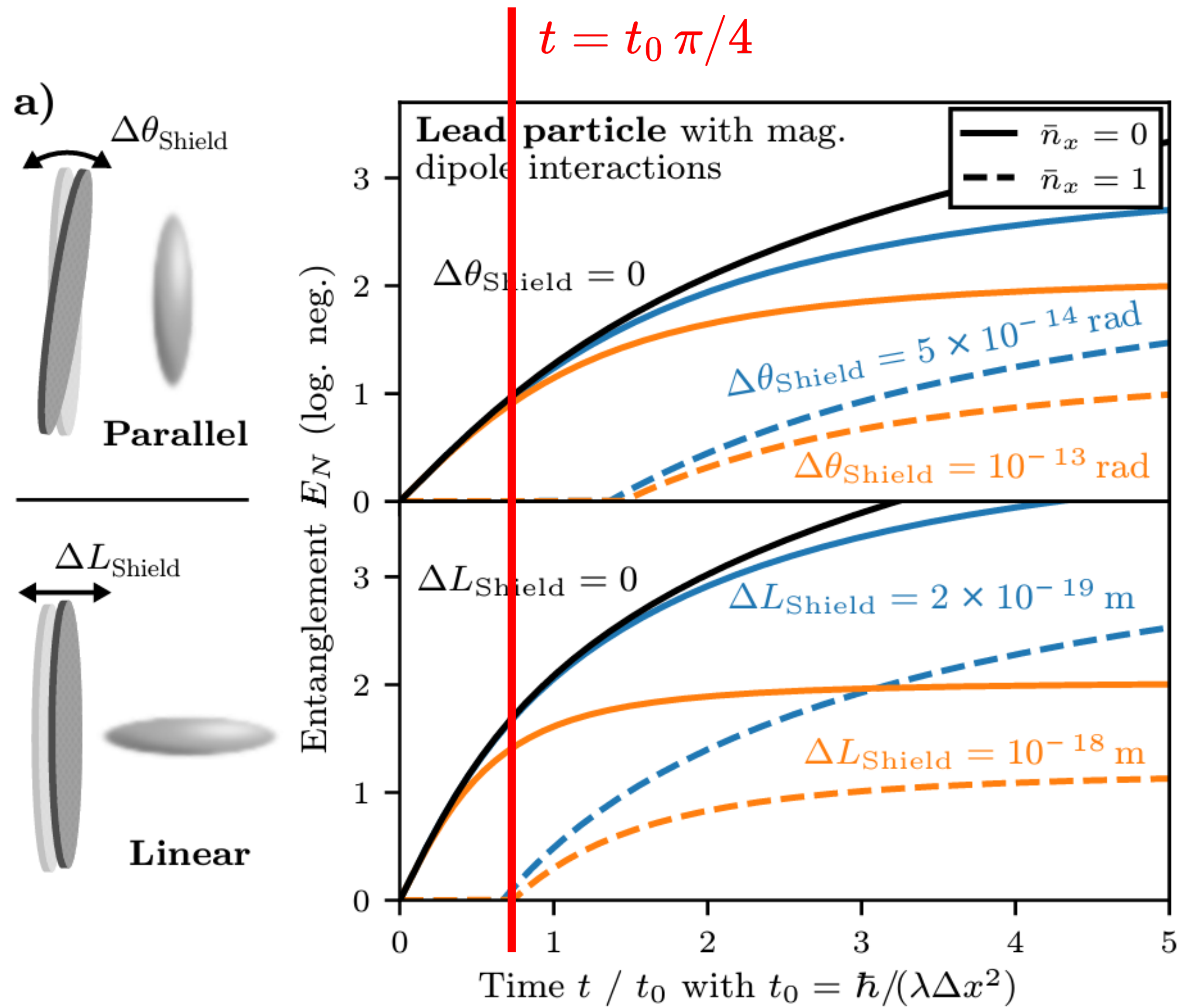
$$\xi_{A/B}^{(L)} \sim \mathcal{N}(0, \Delta L^2)$$

$$\xi_{A/B}^{(\theta)} \sim \mathcal{N}(0, \Delta \theta^2)$$

Shield variations on Gaussian states

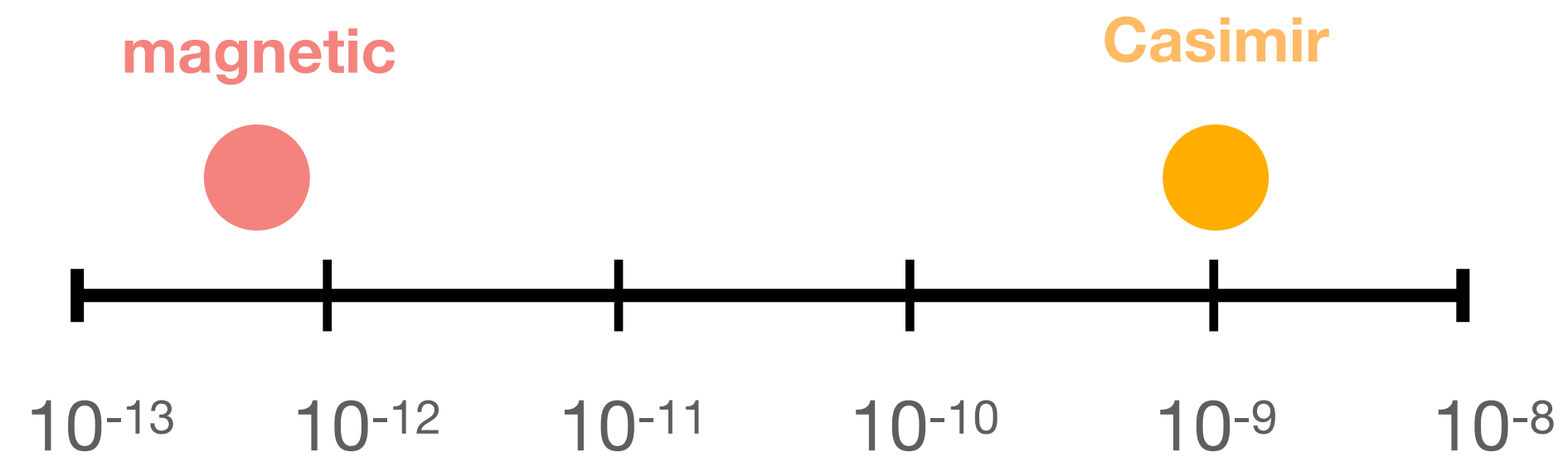


Shield variations on Gaussian states



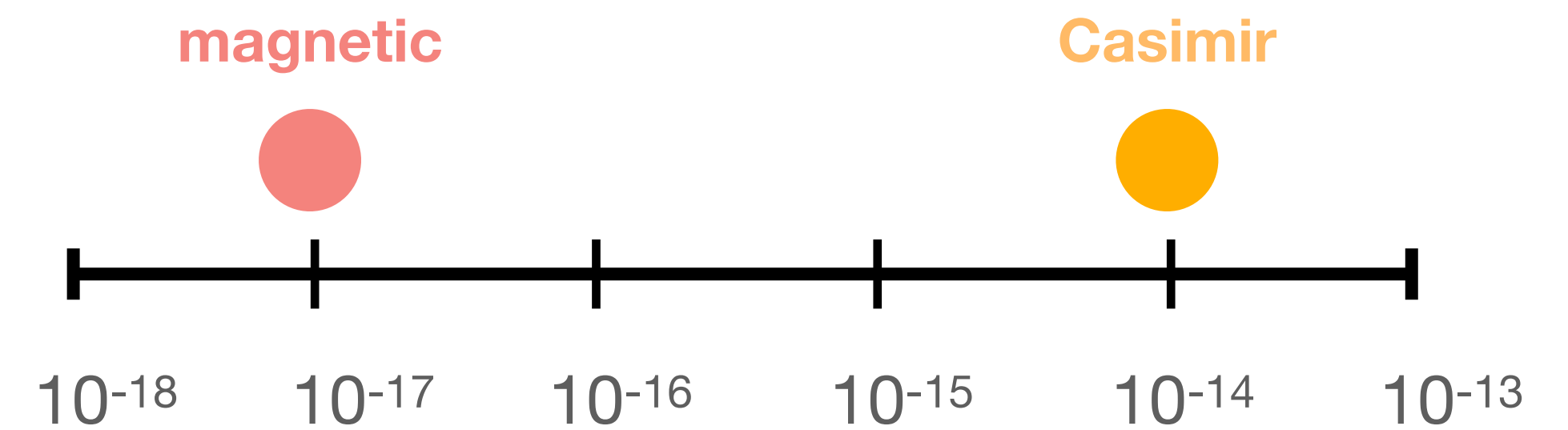
The gravitational signal can demand extreme geometric stability

ANGULAR STABILITY (rad)



←
more stringent

POSITION STABILITY (m)



←
more stringent

Vibrating shield

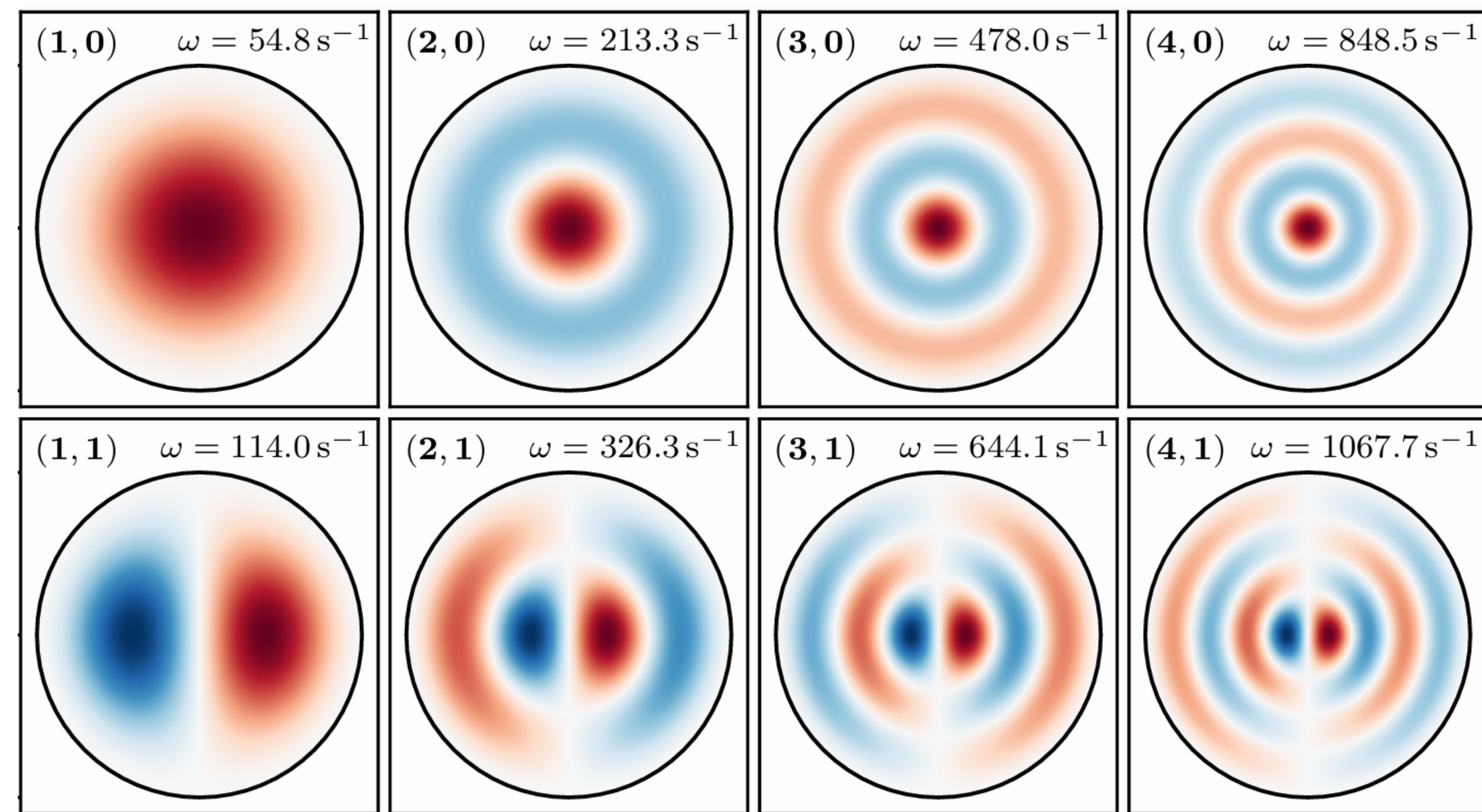
Shape of vibrational eigenmodes, labeled by (k, l) :

$$u_{kl}(r, \vartheta, t) = \left[J_l(\beta_k r) - \frac{J_l(\beta_k r_s)}{I_l(\beta_k r_s)} I_l(\beta_k r) \right] \cos(l\vartheta) \sin(\omega_{kl} t)$$

with

$$\omega_{kl} \sim \frac{d_s}{r_s^2} \sqrt{\frac{E}{12\rho(1-\nu^2)}}$$

~ related to zeros of Bessel functions



Vibrating shield

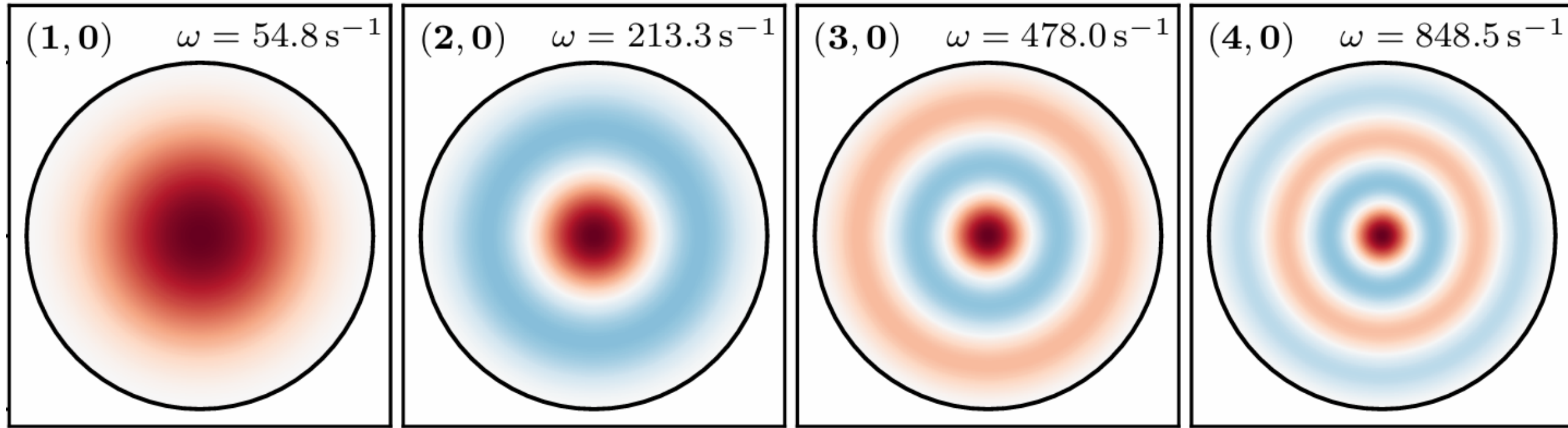
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Initial state

$$\rho_{\text{Shield}} = \bigotimes_{(k,l)} \rho_{\text{th},kl} \quad \text{with}$$

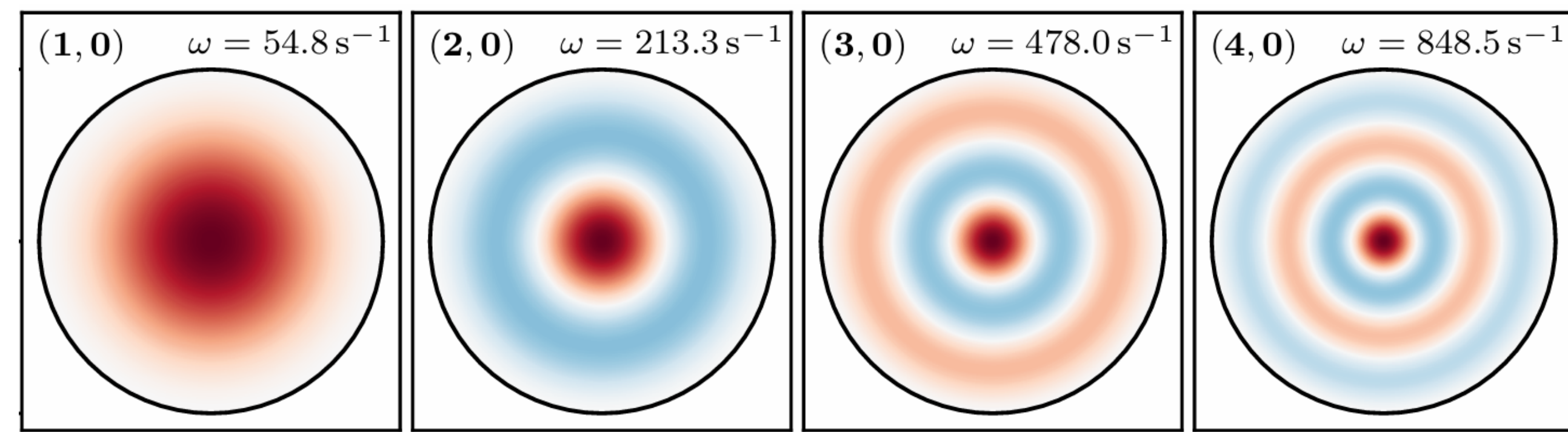
$$(\Delta q_{kl})^2 = \frac{\hbar}{2m\omega_{kl}} \coth\left(\frac{\beta\hbar\omega_{kl}}{2}\right)$$

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$$\bigotimes \rho_{\text{Sys.}}$$

Vibrating shield

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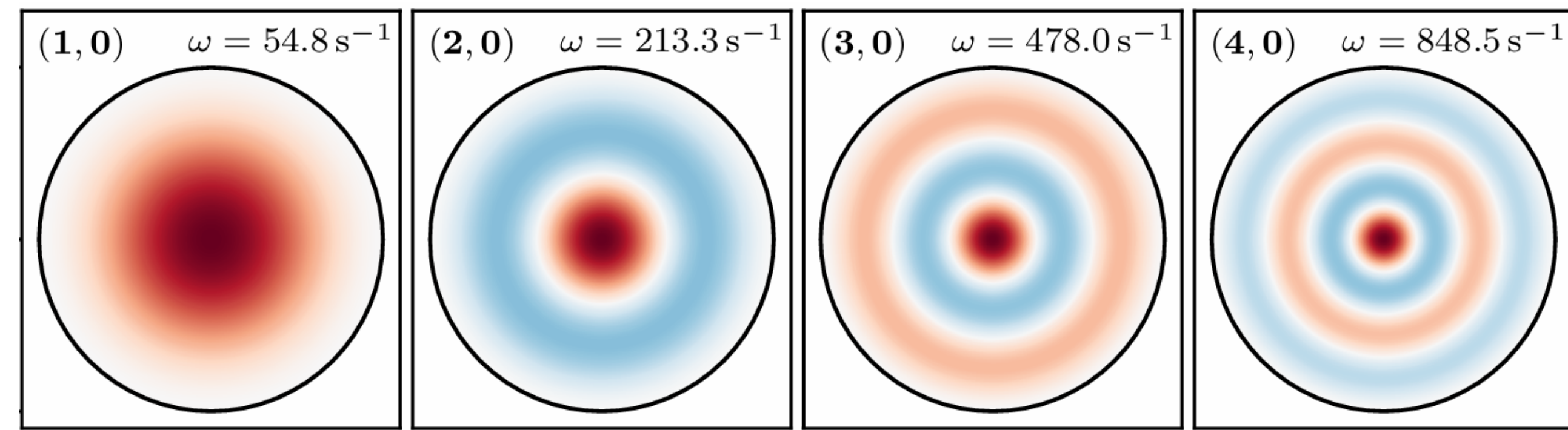
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Hamiltonian evolution

$$\hat{H} = \hat{H}_{\text{Grav.}} + \sum_{(k,l)} \left[\hat{H}_{\text{int},kl} + \hbar\omega_{kl} \left(\hat{a}_{kl}^\dagger \hat{a}_{kl} + \frac{1}{2} \right) \right]$$

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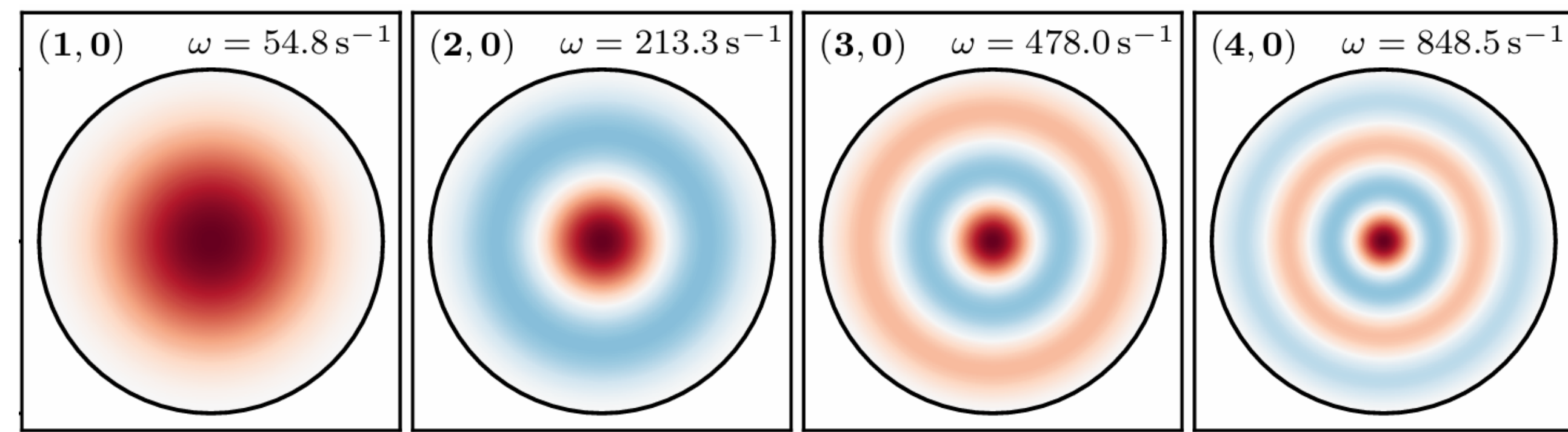
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Tracing out the Shield

$$\rho_{\text{Sys.}}(t) = \text{tr}_{\text{Shield}} \rho(t)$$

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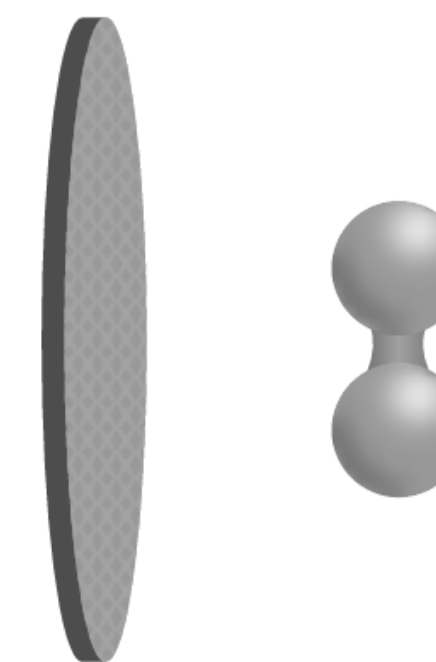
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Entanglement

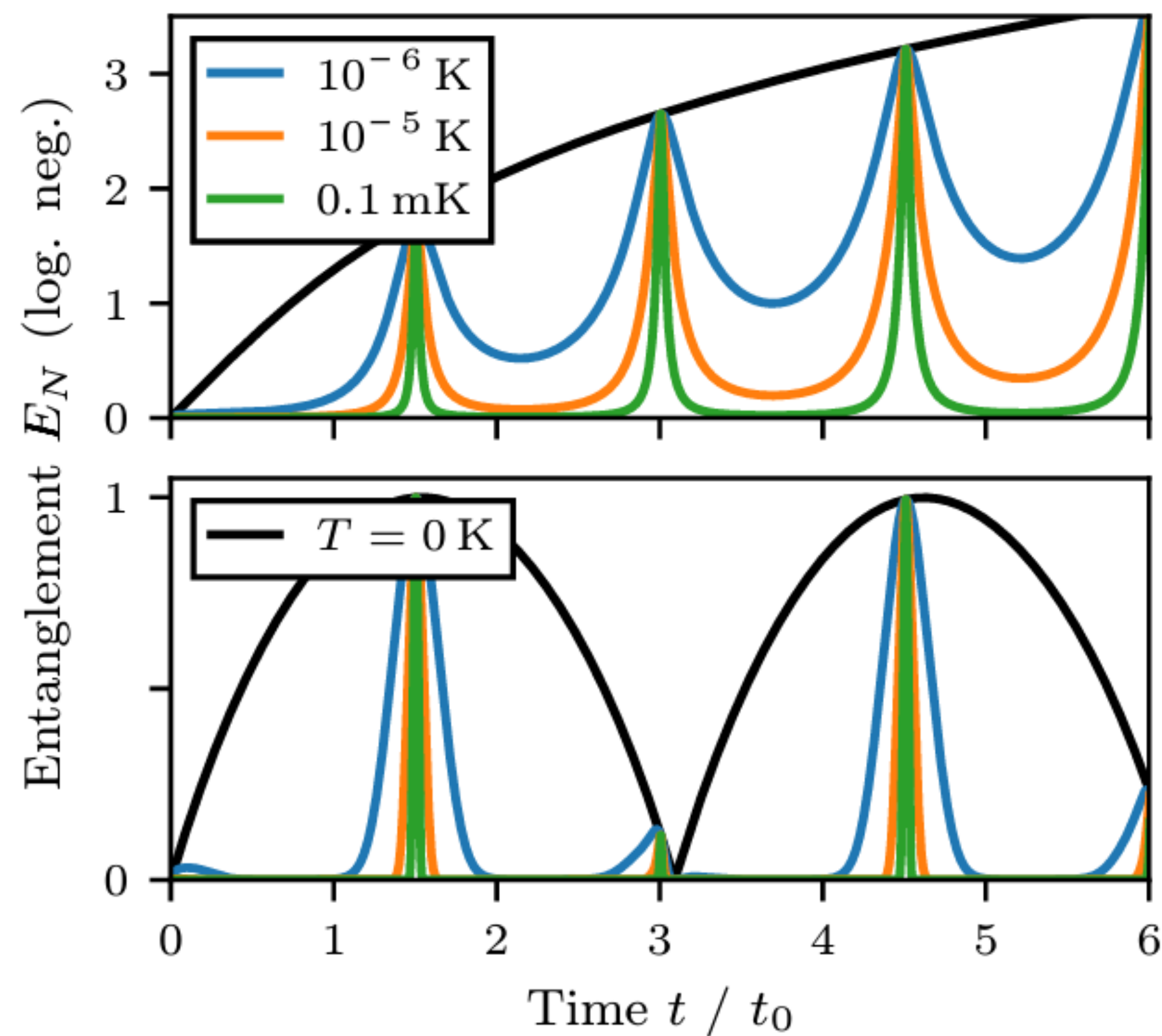
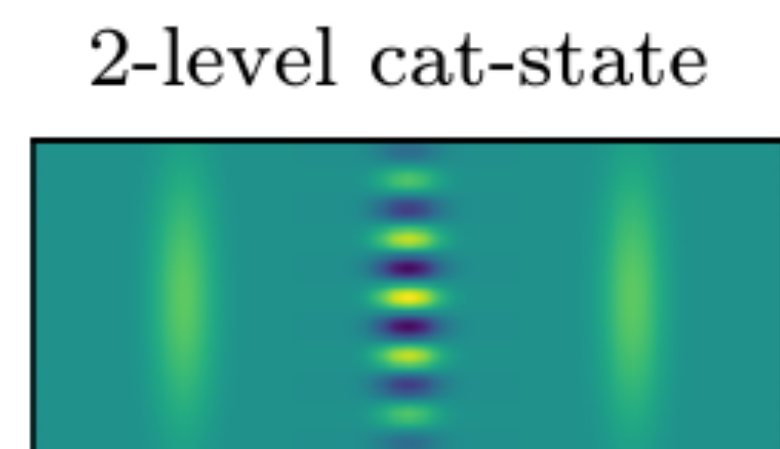
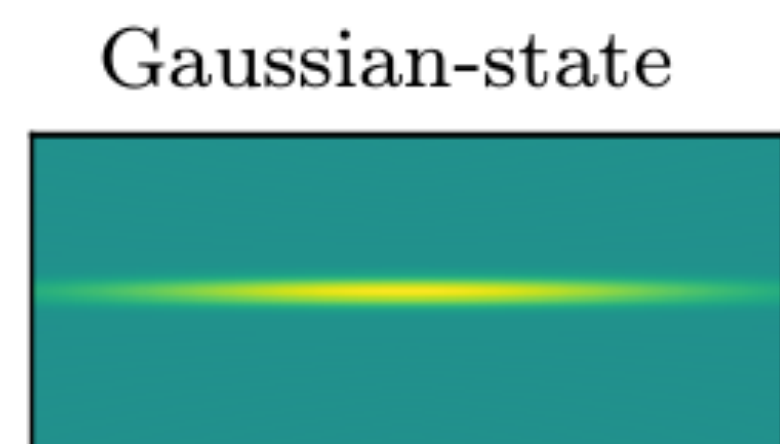
$$E_N = \log_2 \|\rho_{\text{Sys.}}^\Gamma\|_1$$

Entanglement dynamics with a shield

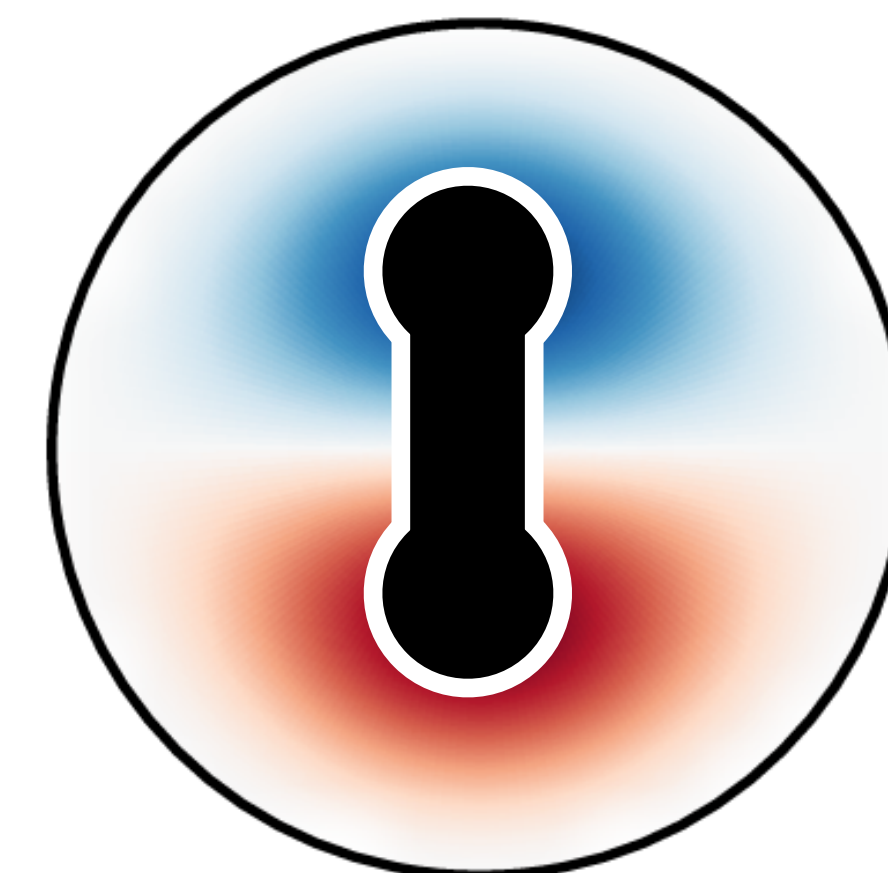
Parallel orientation



a) Single mode (1,1)

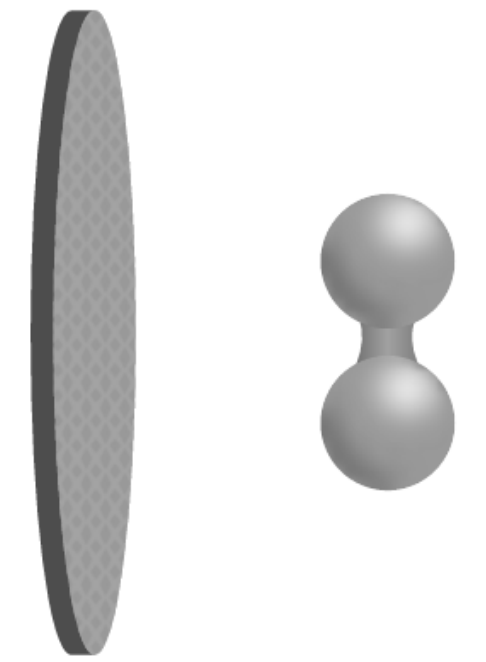


(1,1)

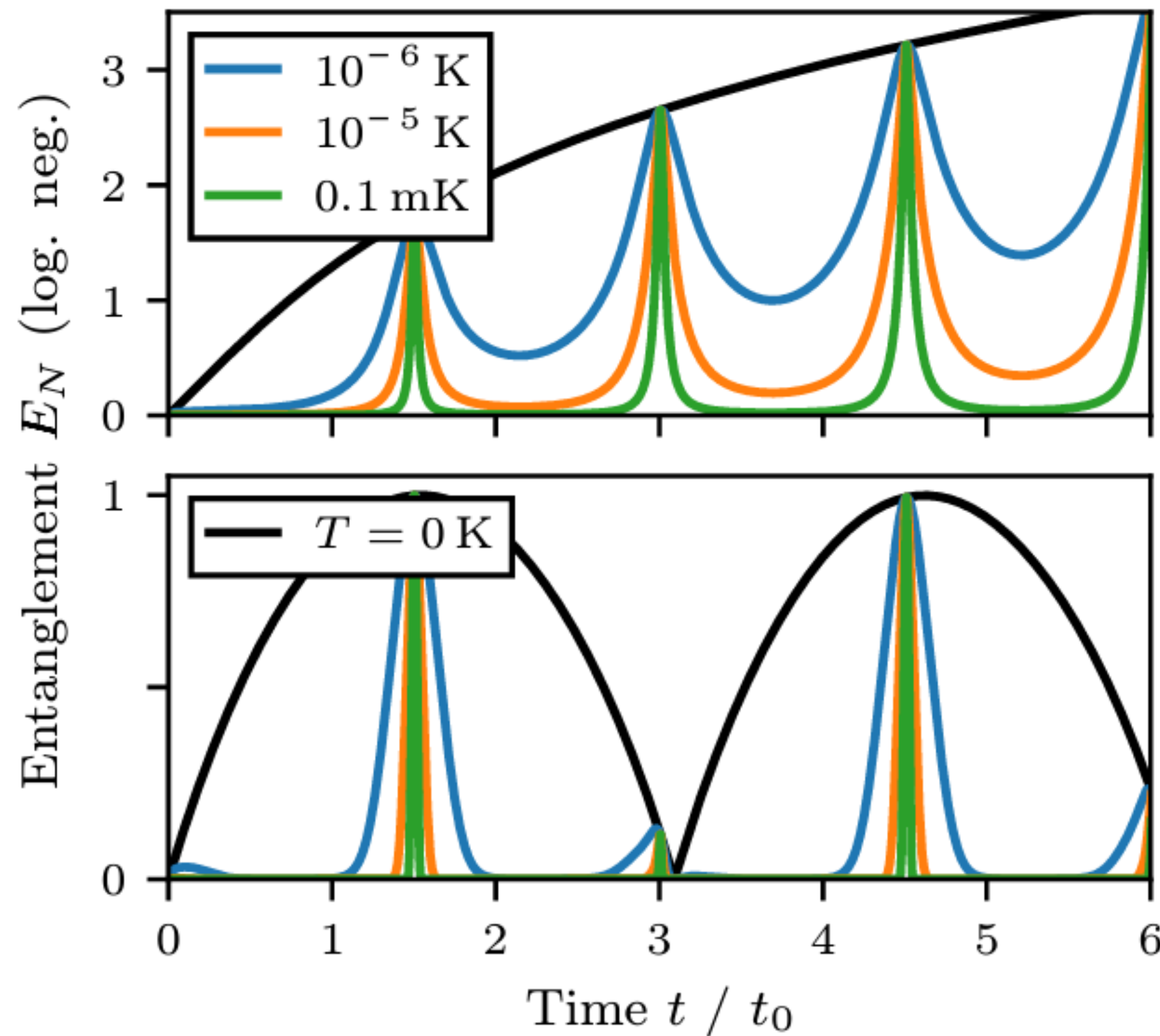


Entanglement dynamics with a shield

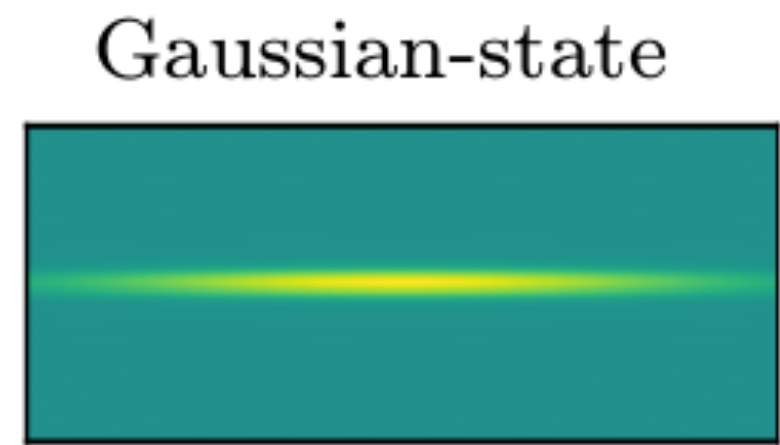
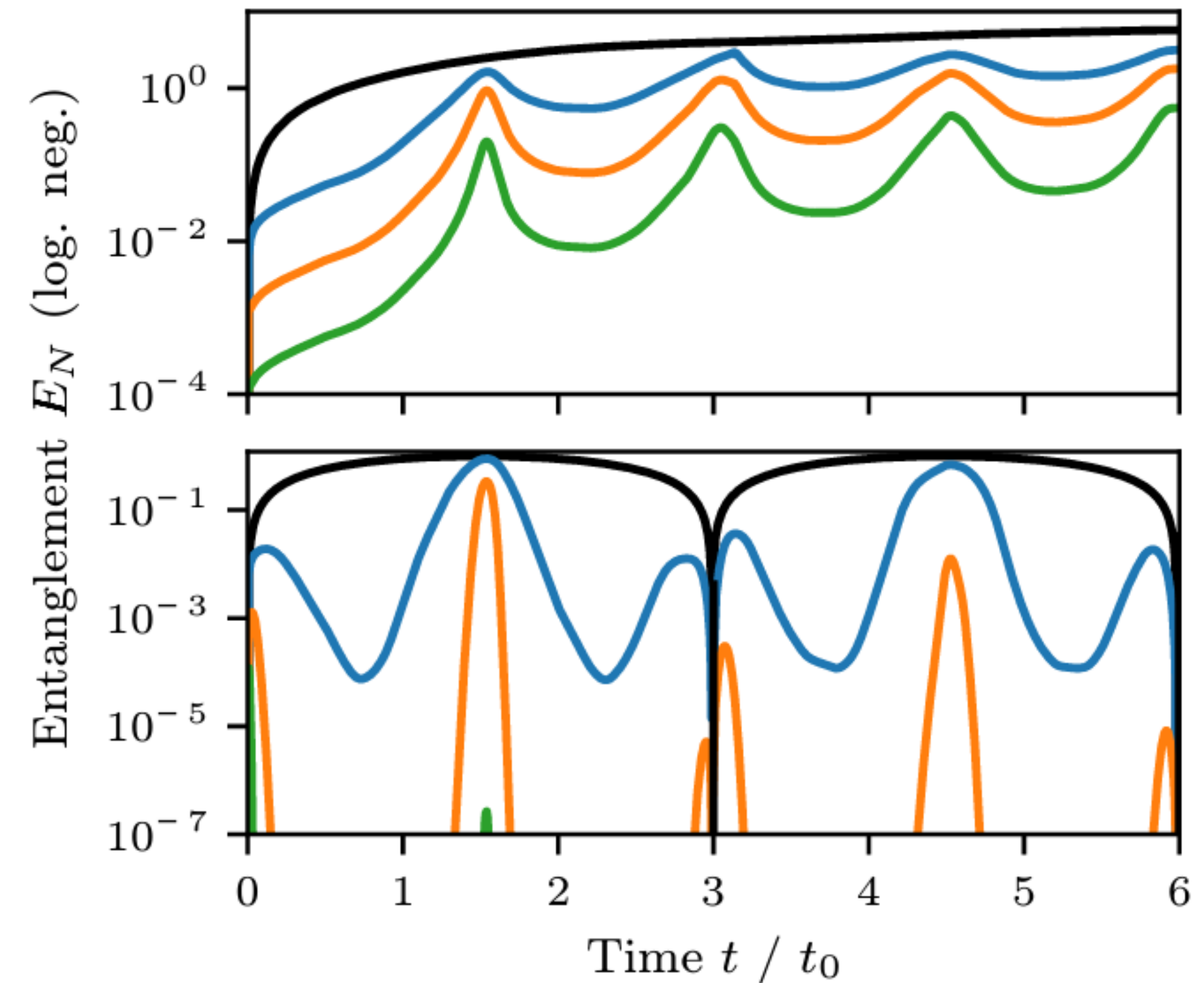
Parallel orientation



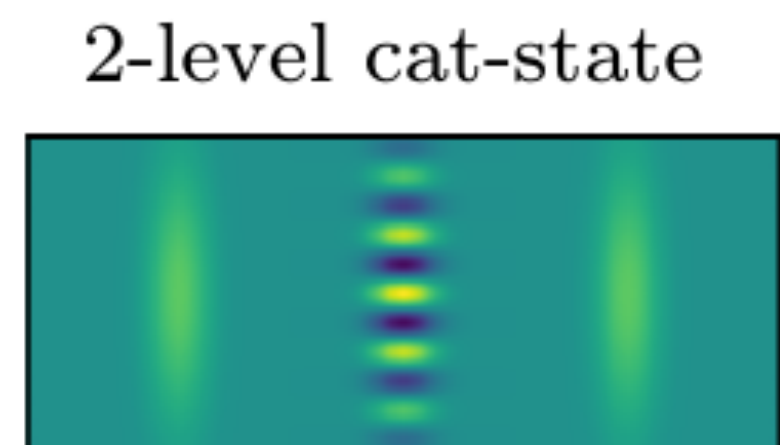
a) Single mode (1,1)



b) Multiple modes



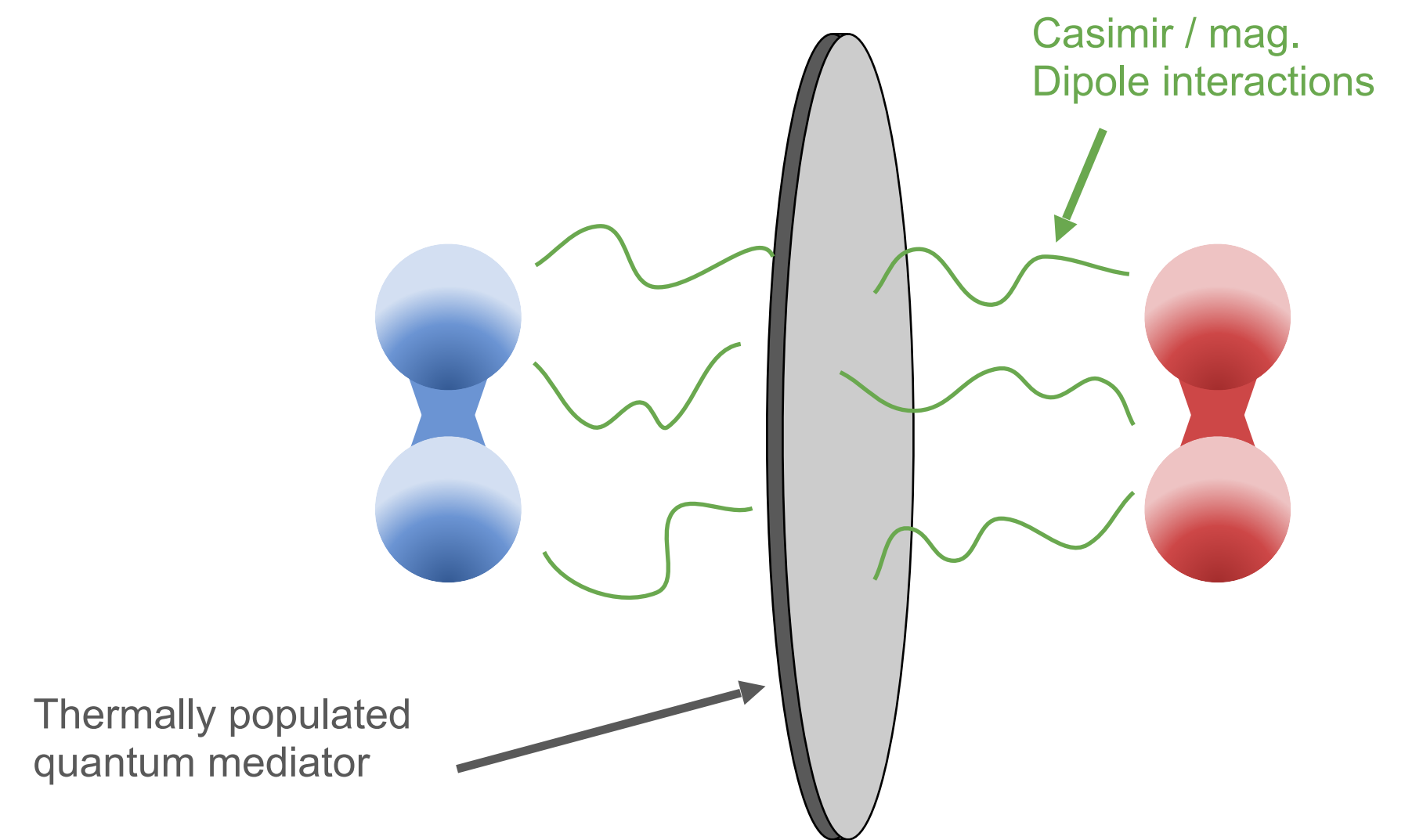
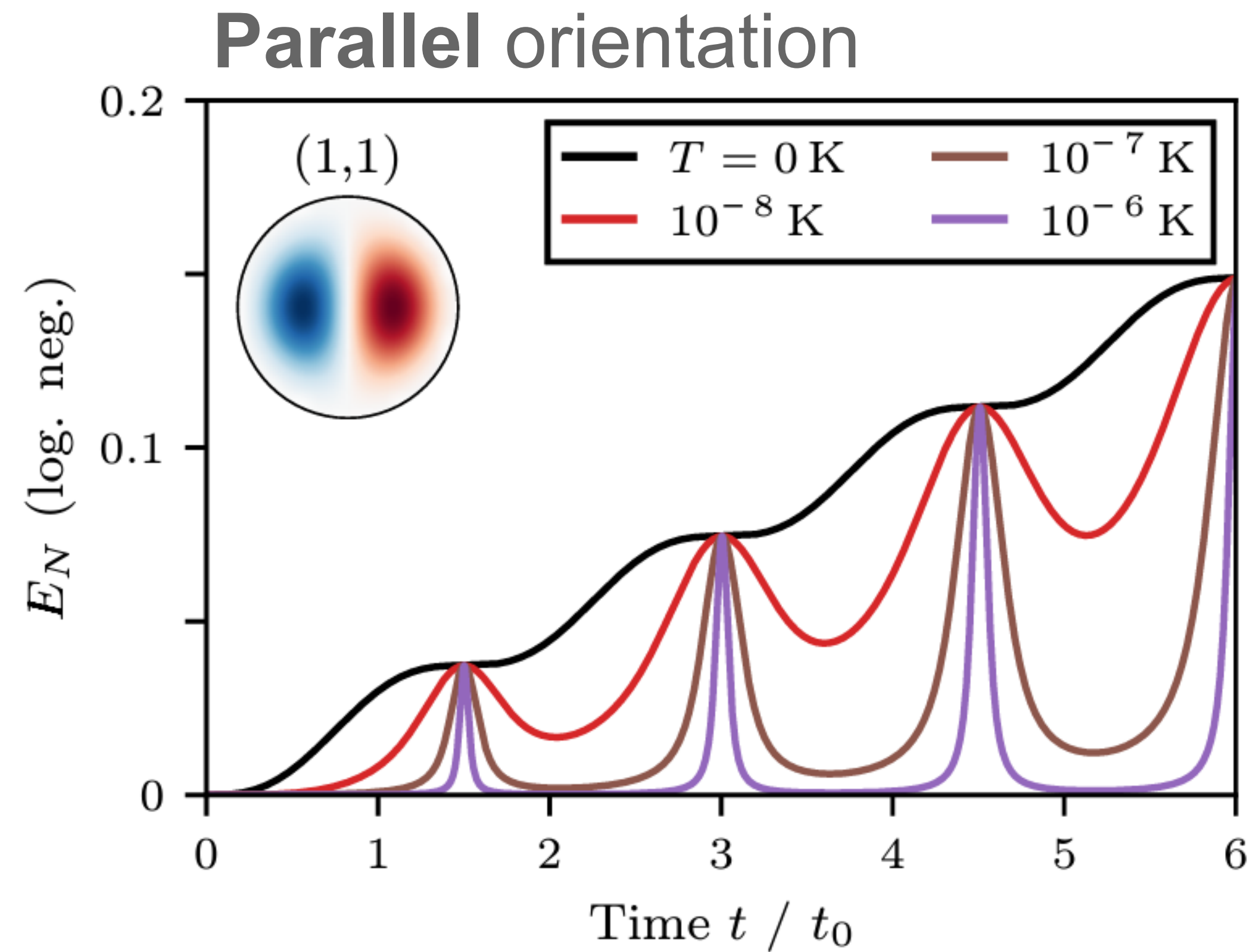
Gaussian-state



2-level cat-state

Non-gravitationally mediated entanglement

Entanglement mediated *through* the shield



Take home message

1

EXPLOIT THE PLATFORM

**Use all available
physical resources**

*Internal degrees of freedom can
enlarge the quantum-control toolbox
and the states we can access.*

2

ASK THE RIGHT QUESTION

**Find the simplest sufficient
operational signature.**

*The witness can be a design
degree of freedom:
e. g., entanglement-free tests of gravity*

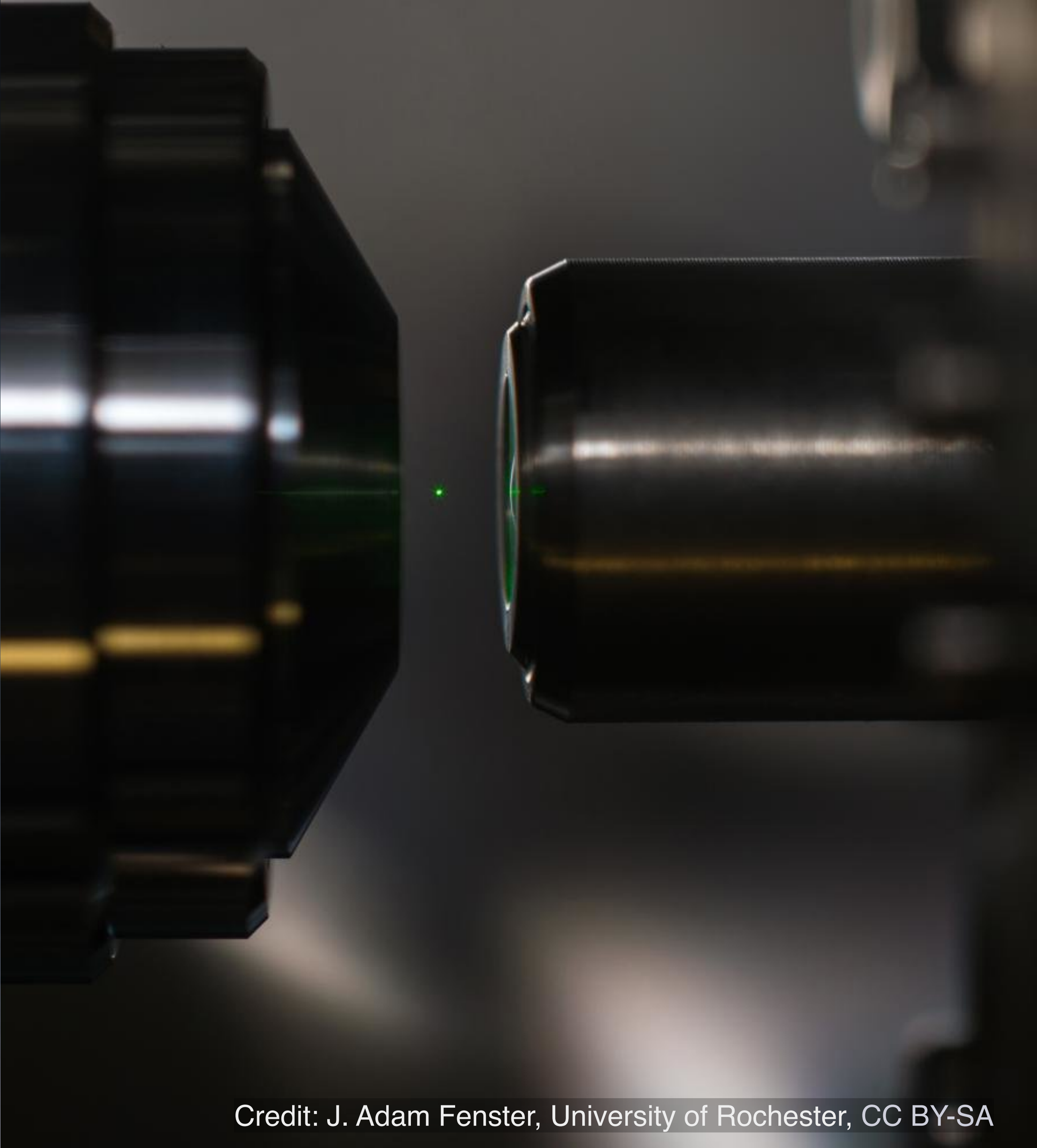
3

TAKE THE APPARATUS SERIOUSLY

**Model enough of the real
experiment to know
what the signal means.**

*Unwanted interactions can suppress
the target signal, or even provide an
alternative mechanism for it.*

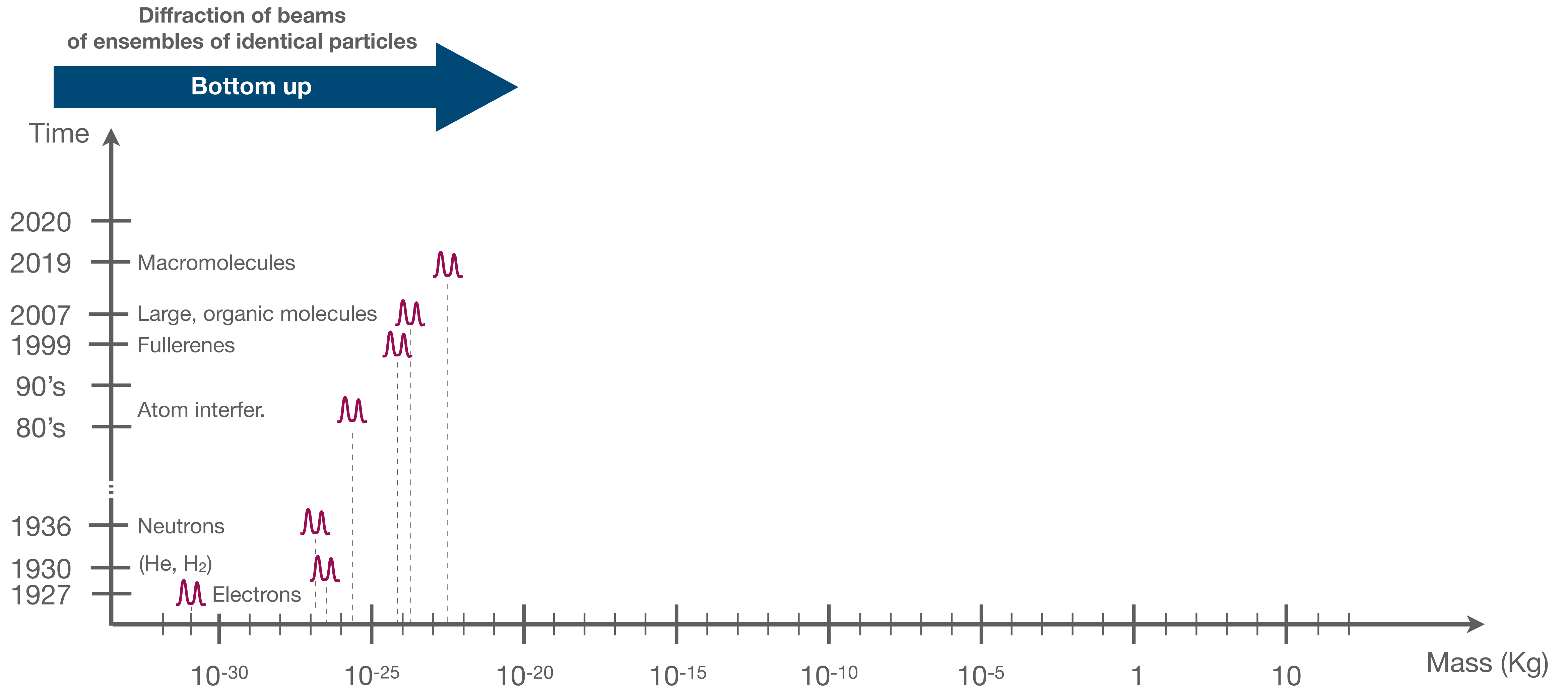
*“...every saint and sinner in the history of our species lived there
-on a mote of dust suspended in a sunbeam.”*
Carl Sagan, *Pale Blue Dot*



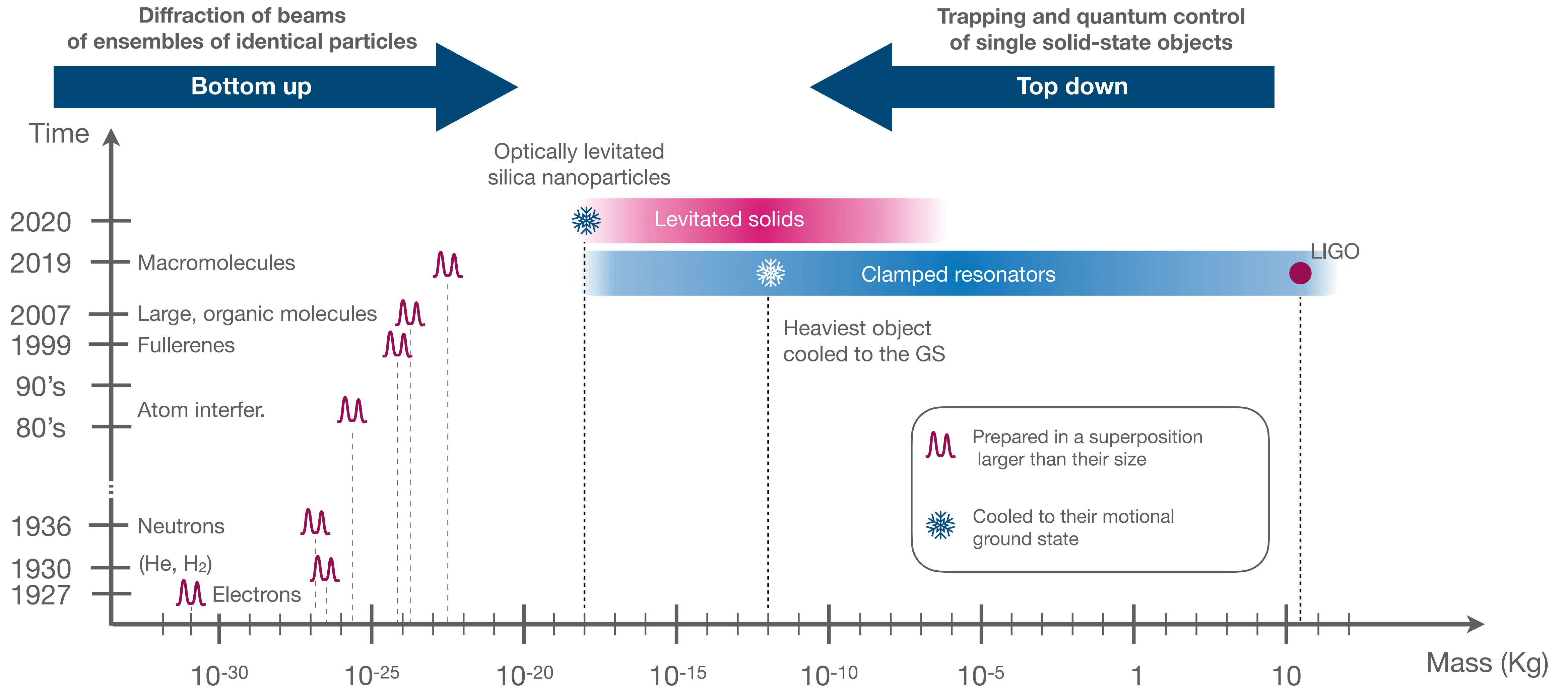
*“...every saint and sinner in the history of our species lived there
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Thank You!

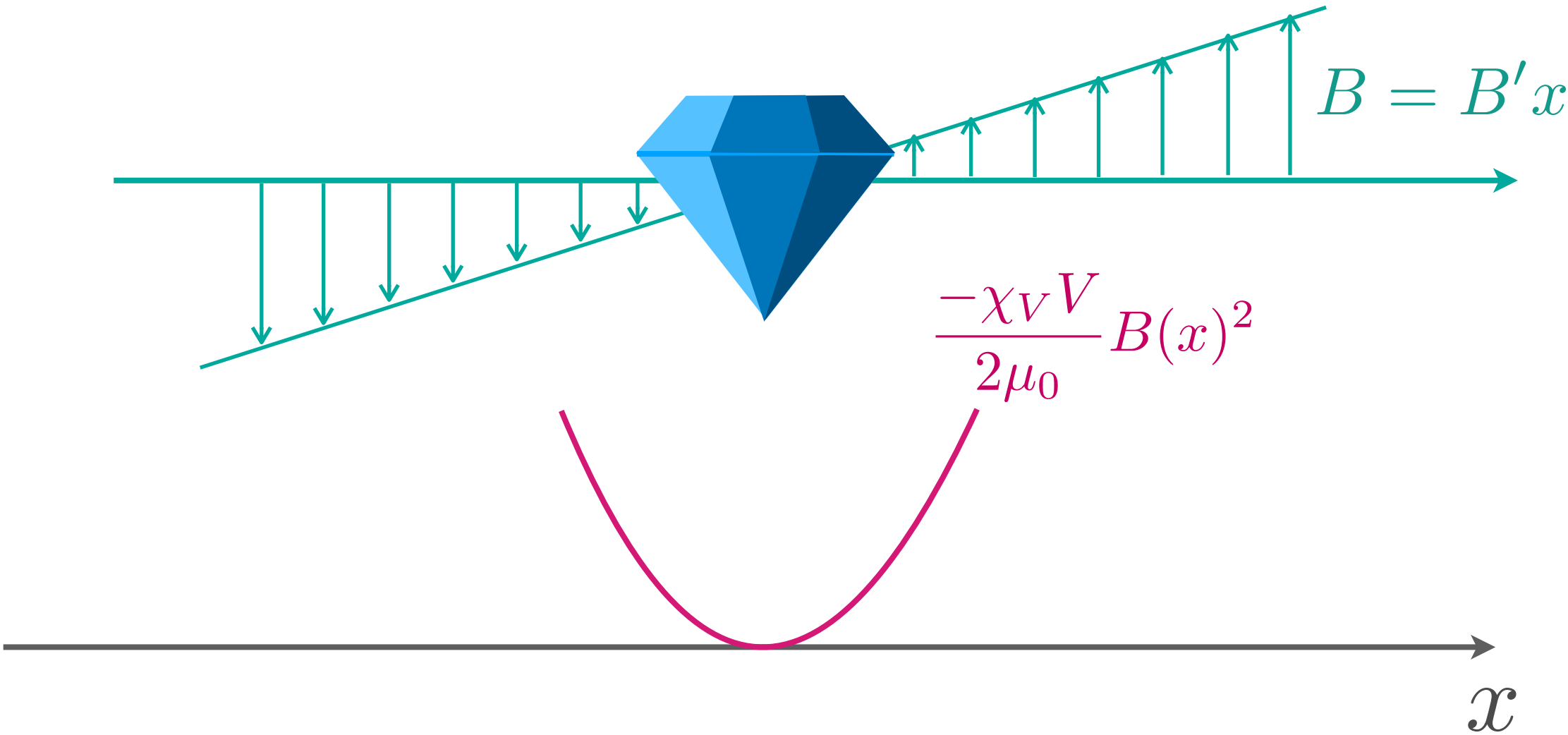
(incomplete) history of matter waves



(incomplete) history of matter waves

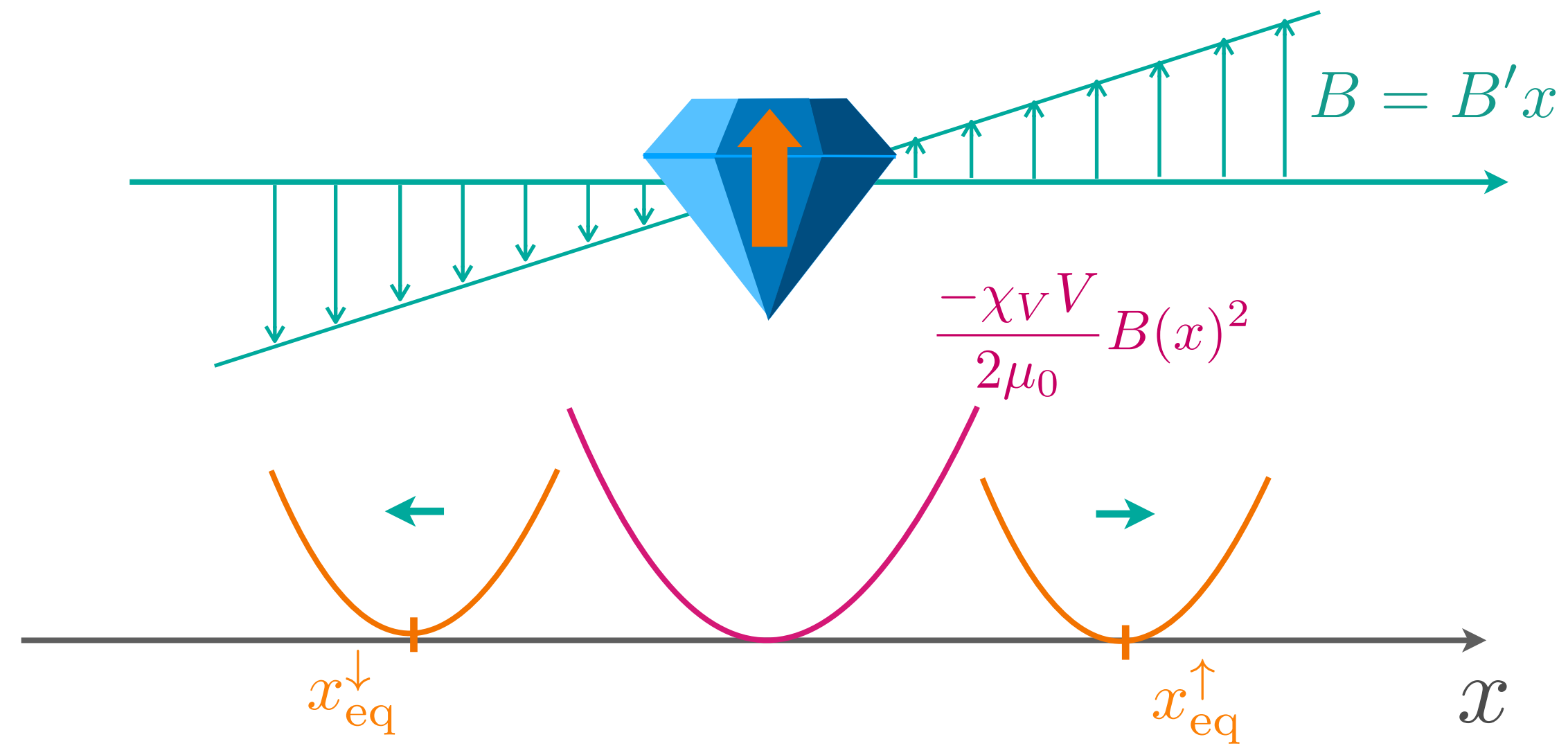


Stern-Gerlach Interferometry with Solids



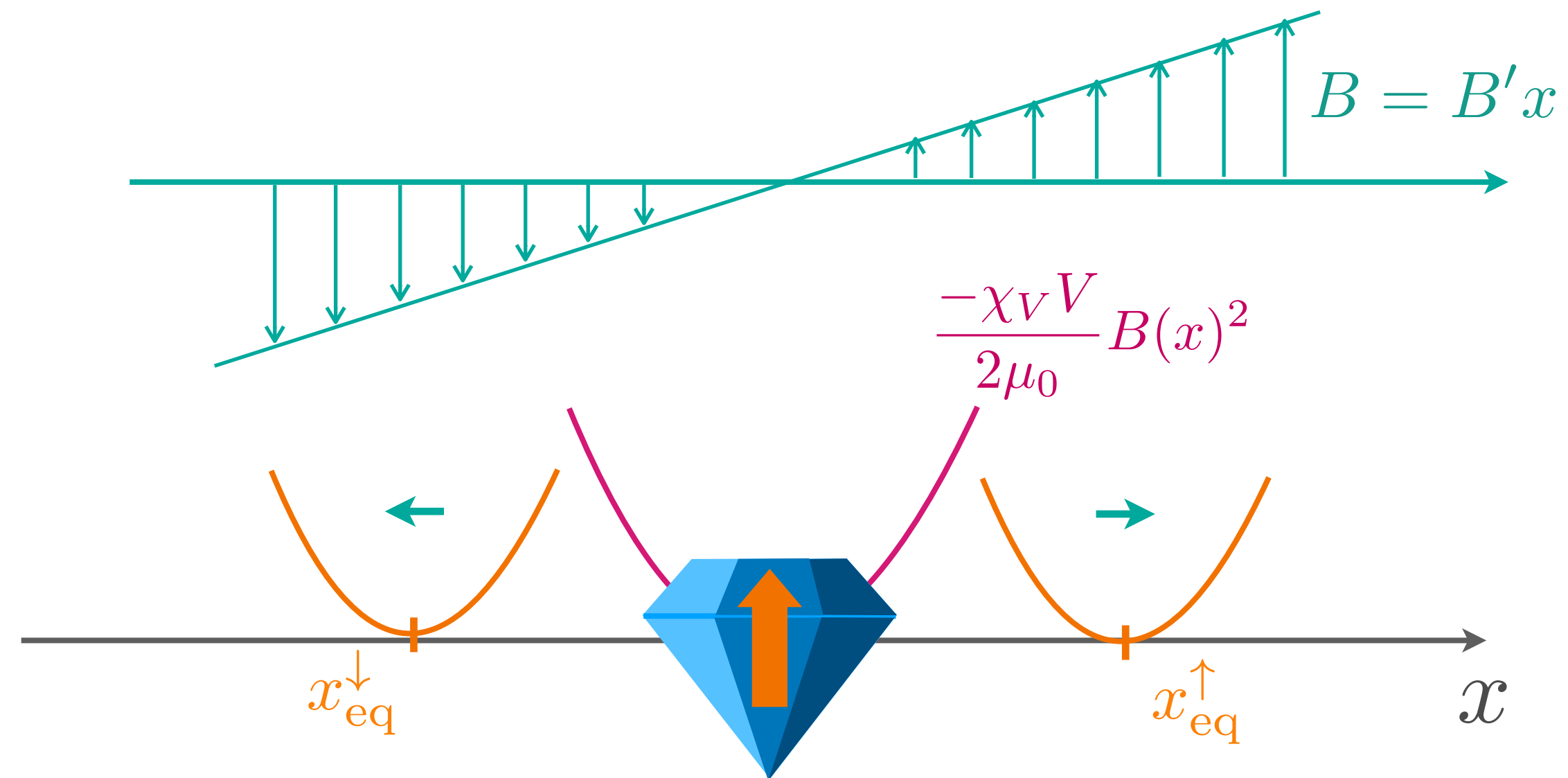
$$\hat{H} = \frac{\hat{p}^2}{2m} - \frac{\chi_V V}{2\mu_0} B'^2 \hat{x}^2$$

Stern-Gerlach Interferometry with Solids



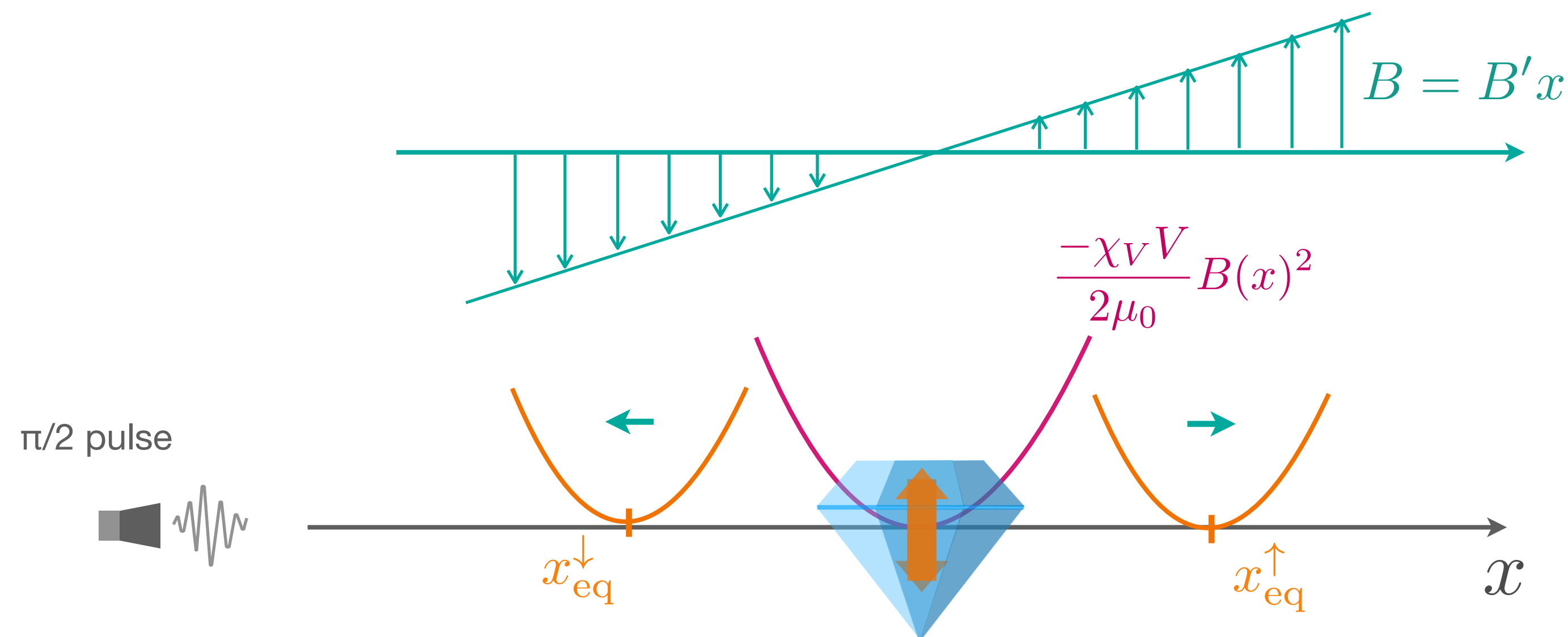
$$\hat{H} = \frac{\hat{p}^2}{2m} - \frac{\chi_V V}{2\mu_0} B'^2 \hat{x}^2 + \hbar \gamma_e \hat{S} B' \hat{x}$$

Stern-Gerlach Interferometry with Solids



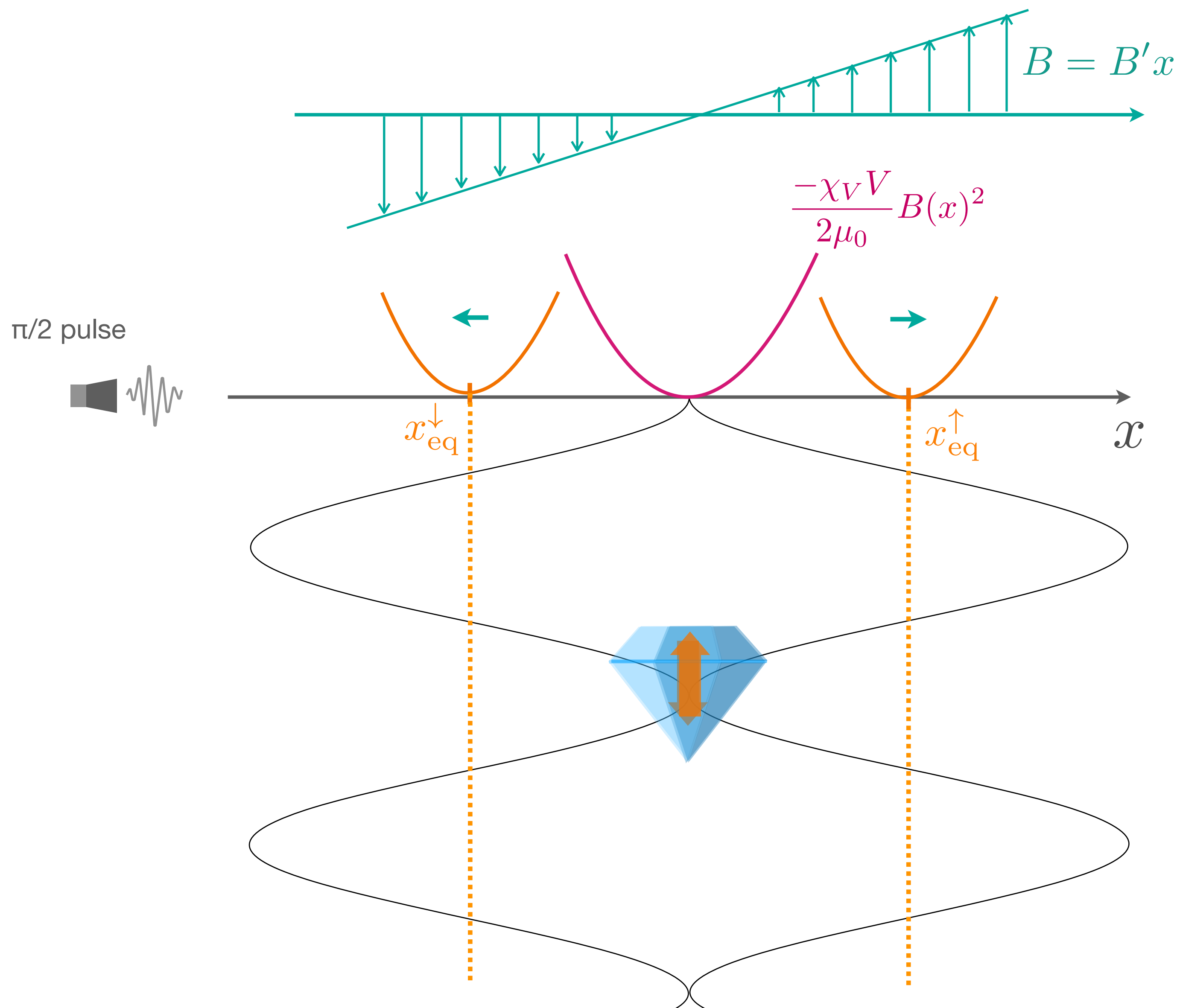
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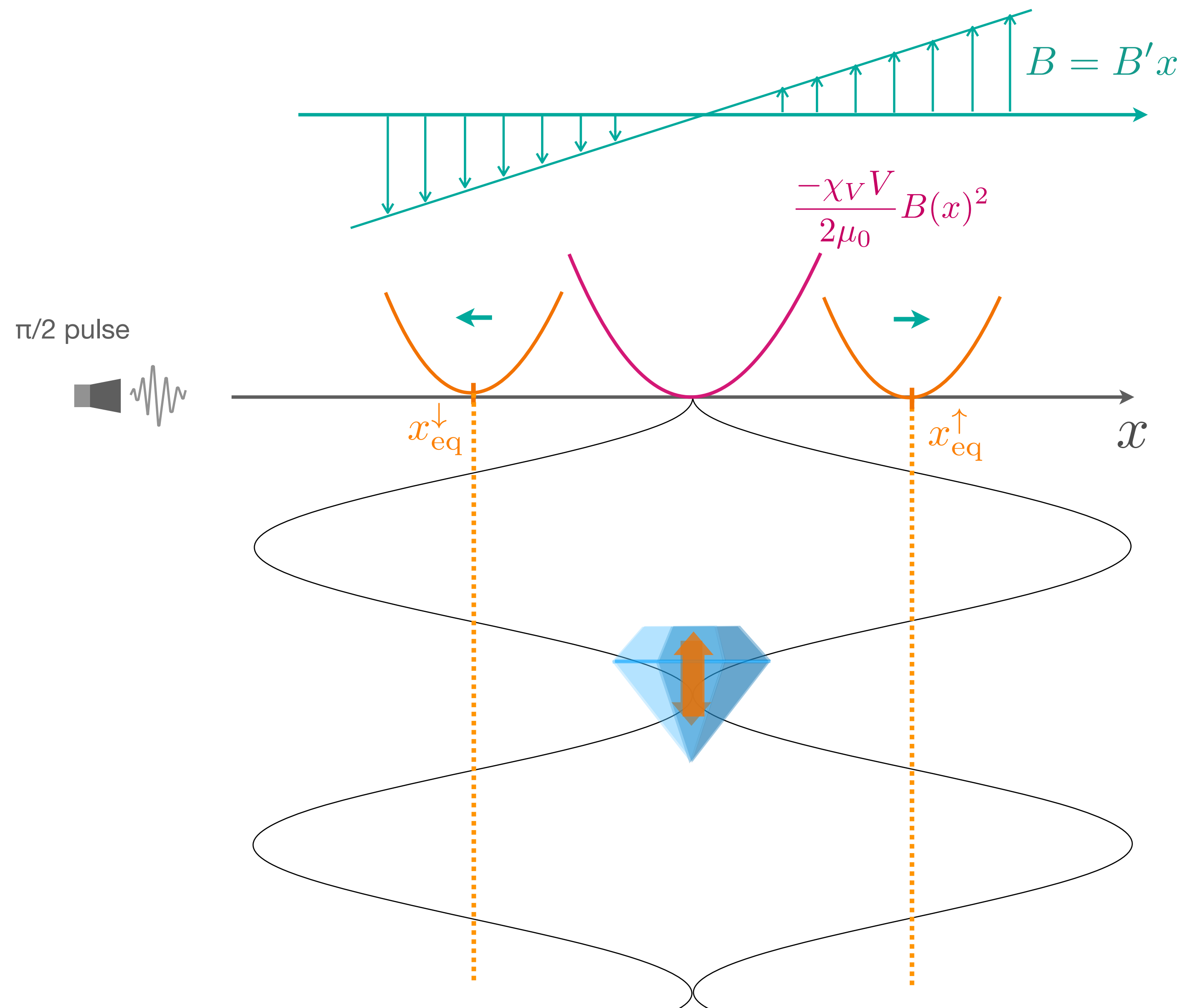
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Stern-Gerlach Interferometry with Solids

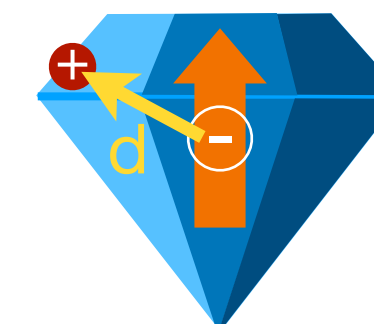


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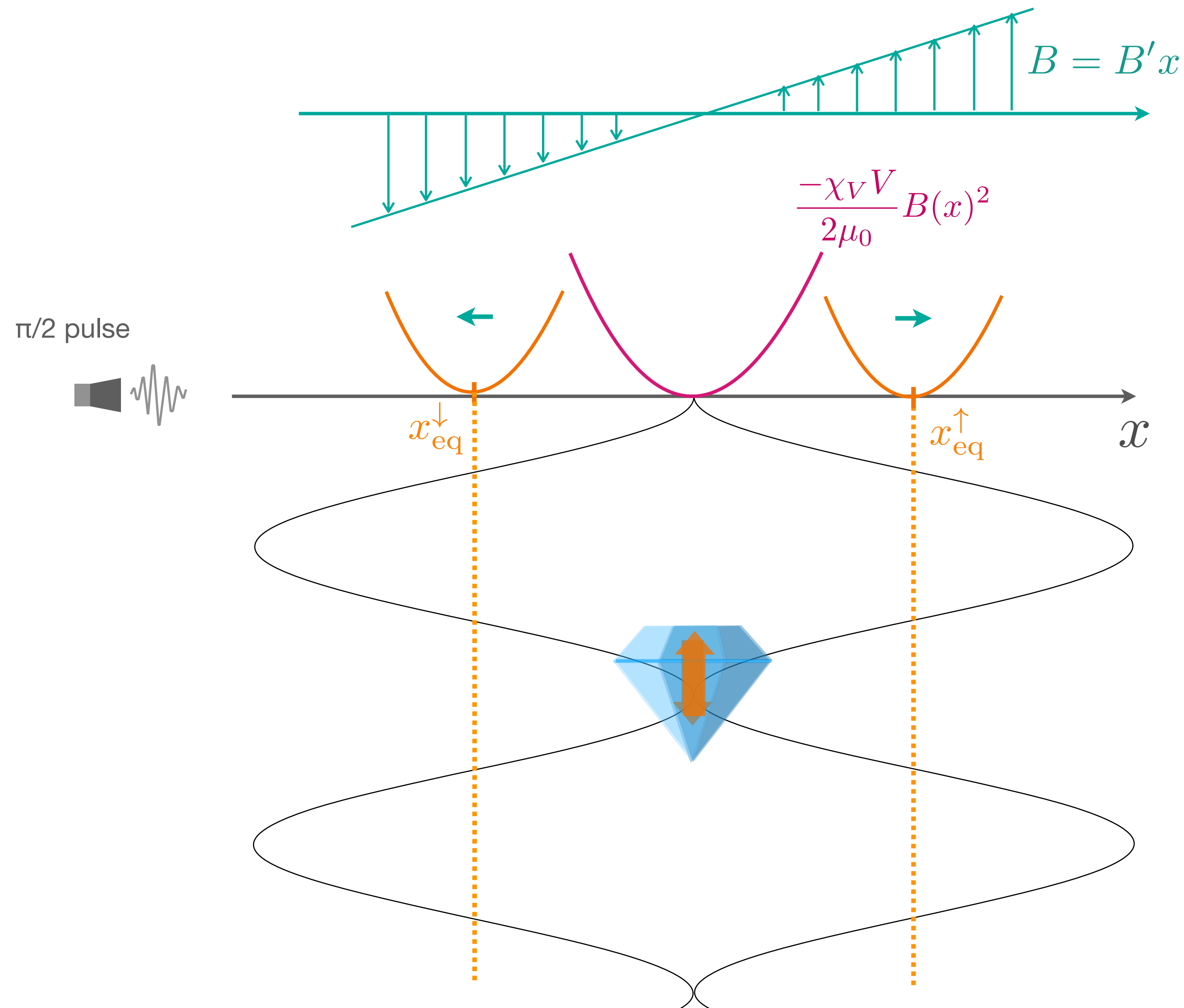
Some sources of noise

Anything that introduces (uncontrolled) relative phases:

- Electronic impurities in diamond (P1 centers, dangling bonds...)
- Dipole moments



Stern-Gerlach Interferometry with Solids

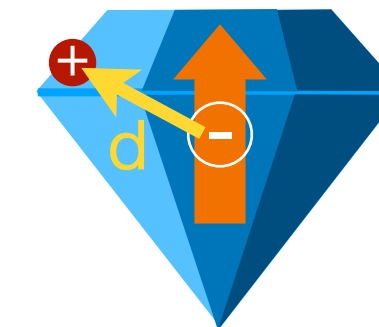


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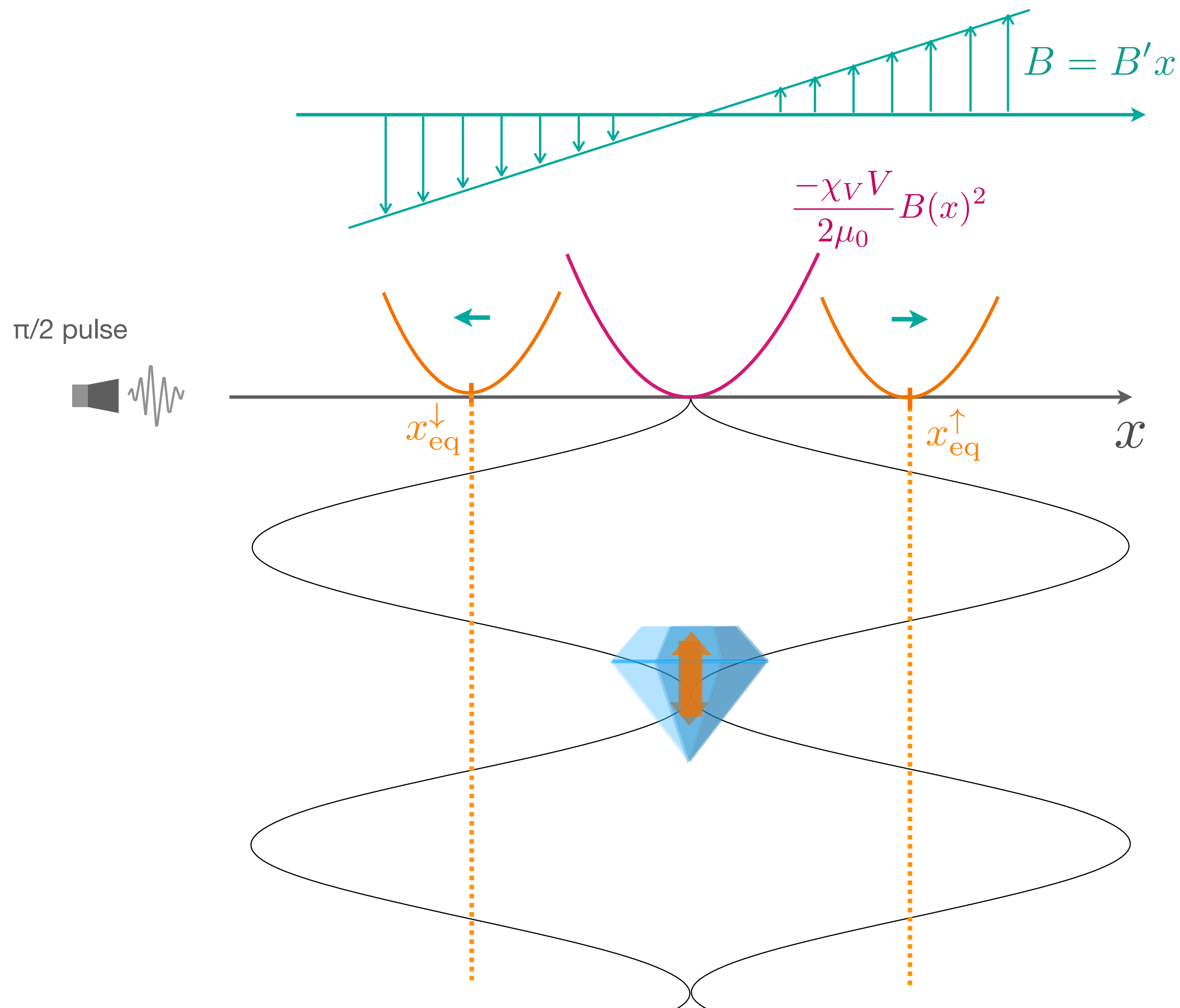
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- Spin-dependent torques

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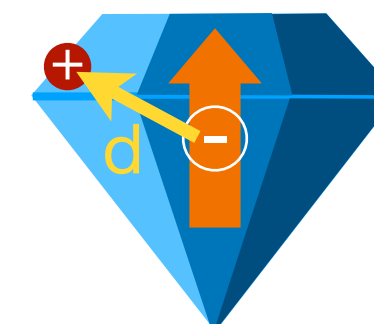


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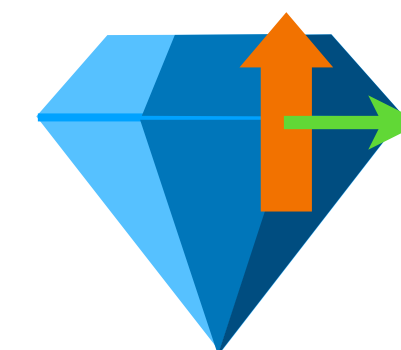
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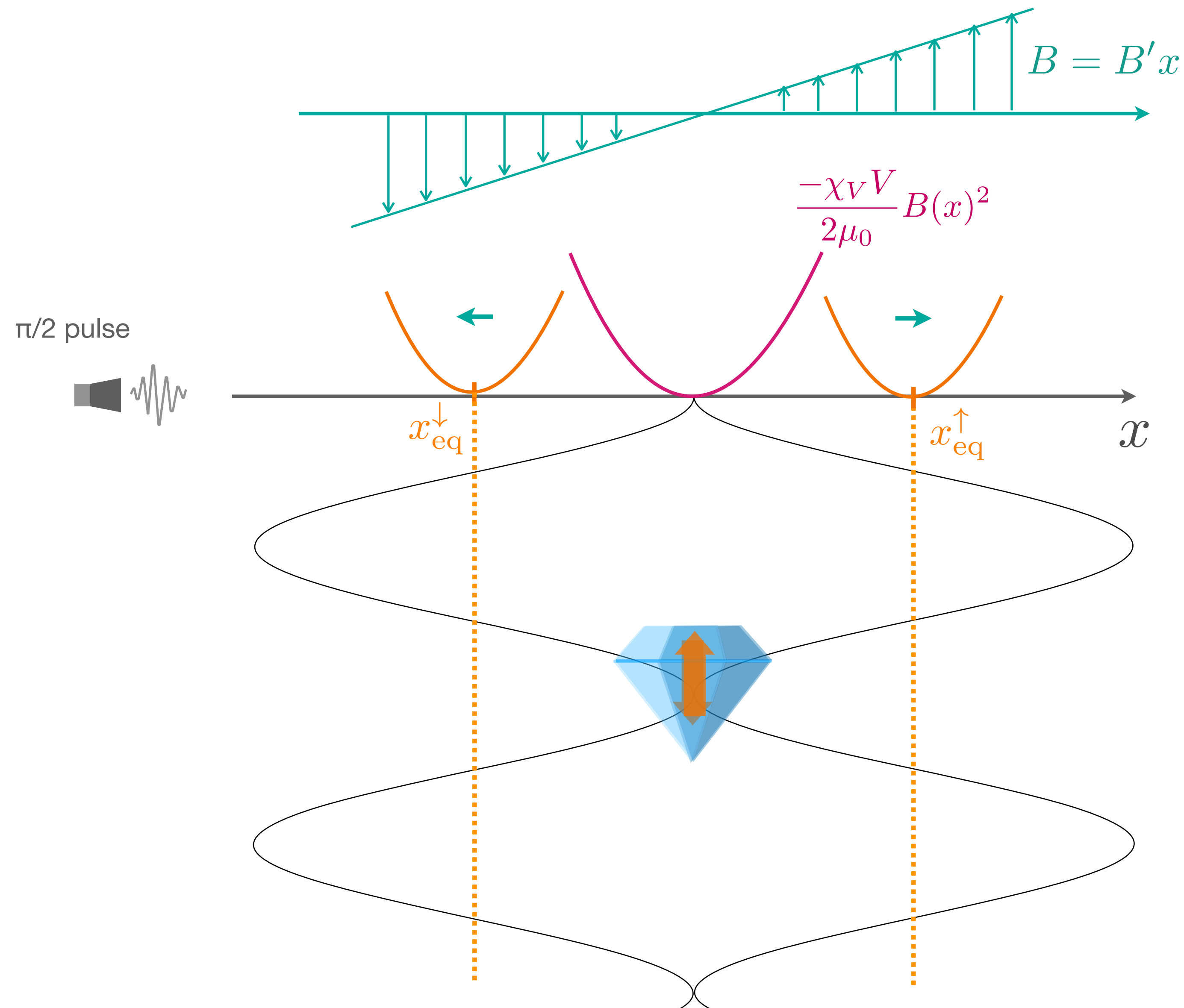
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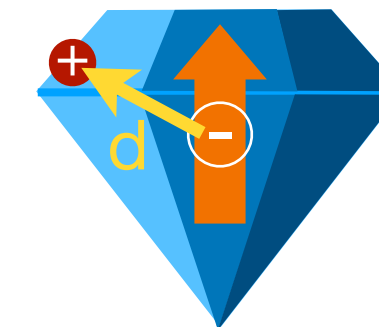


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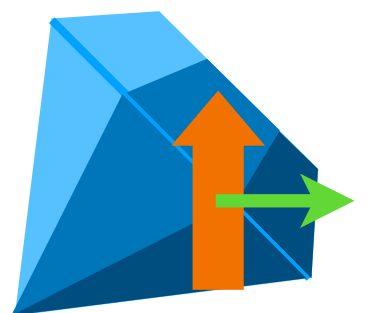
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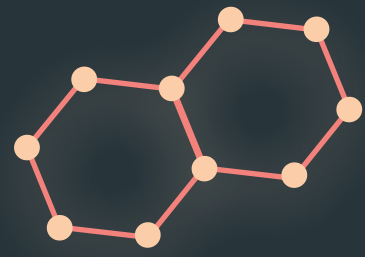


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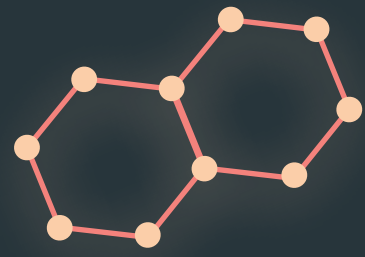




New materials: Pentacene-doped naphthalene

Quantum **9**, 1928 (2025)





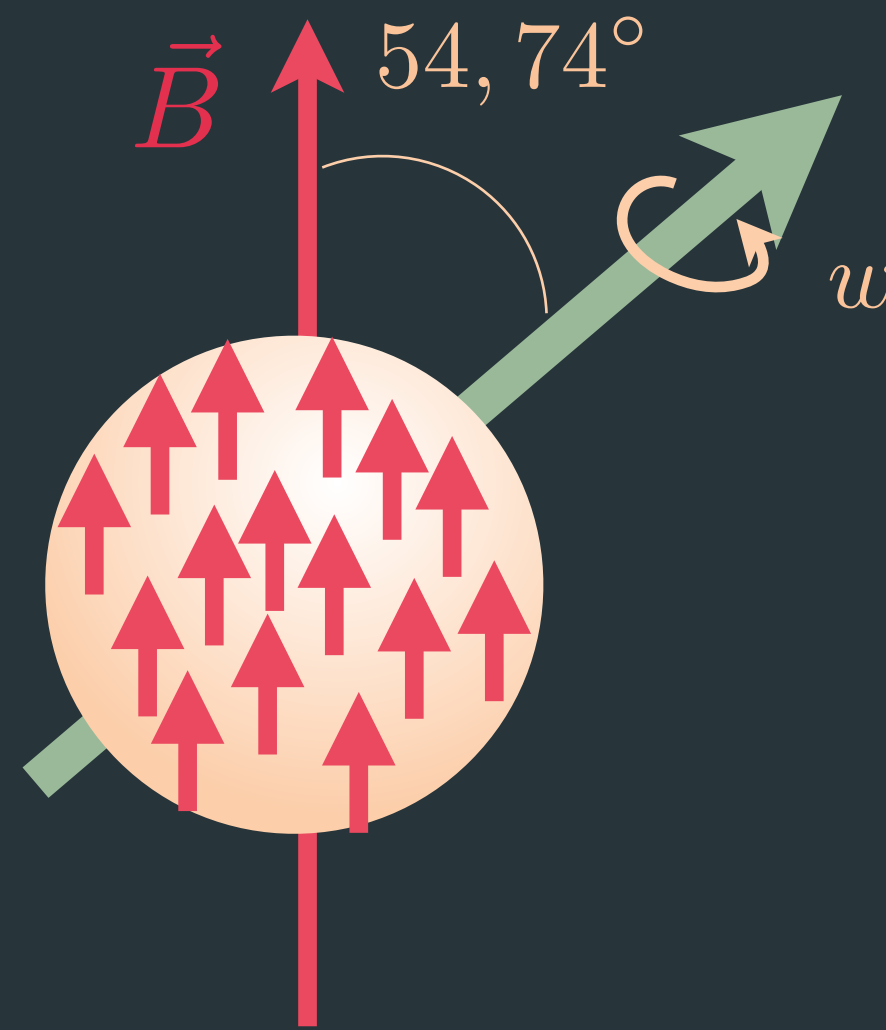
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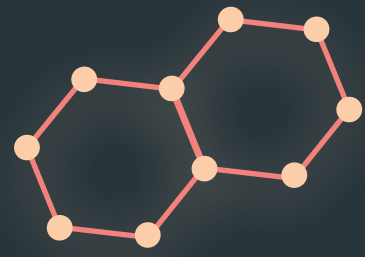
Quantum **9**, 1928 (2025)

Magic-angle spinning

to suppress internuclear interactions

$$T_2 \propto \omega$$





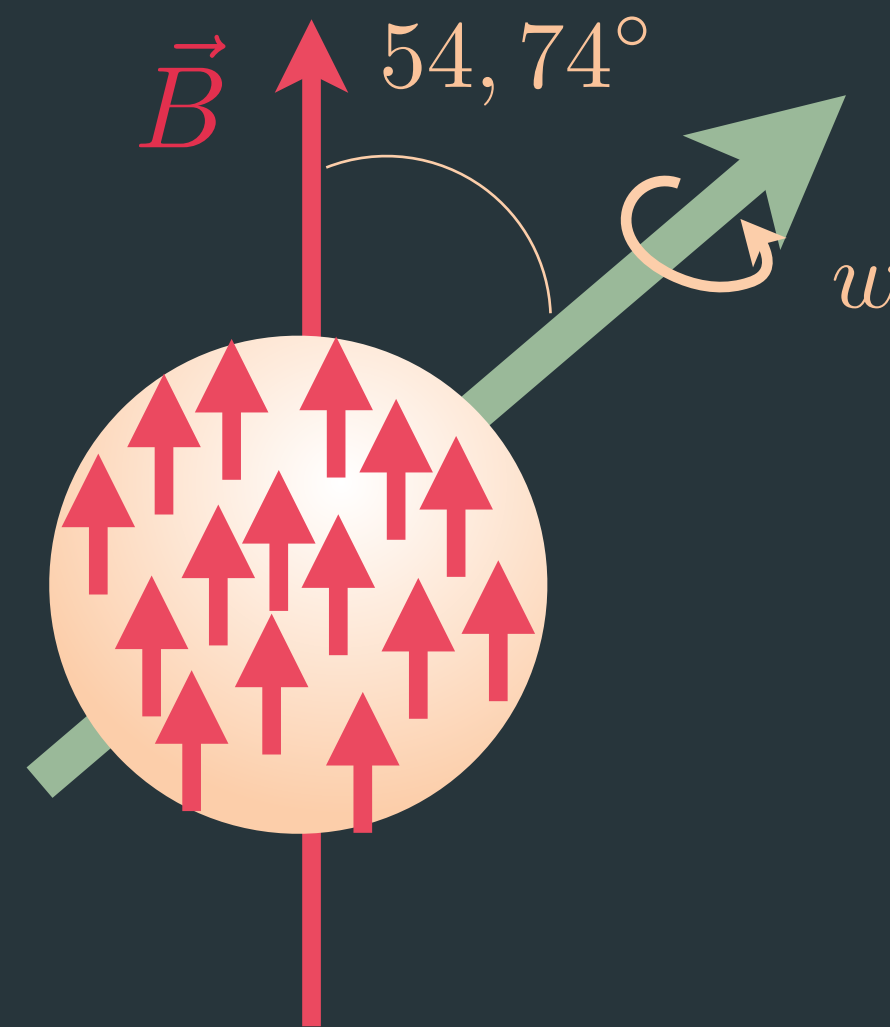
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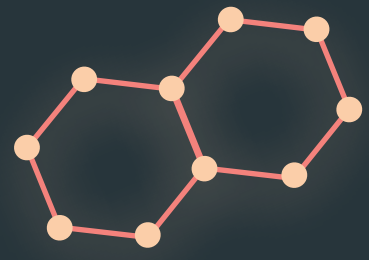
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A levitated arrangement is ideal for rotation

Levitated nanoparticles hold the record for the **fastest rotor** ever made, spinning at frequencies in the **GHz**

$$T_2 \approx 1\text{min}$$

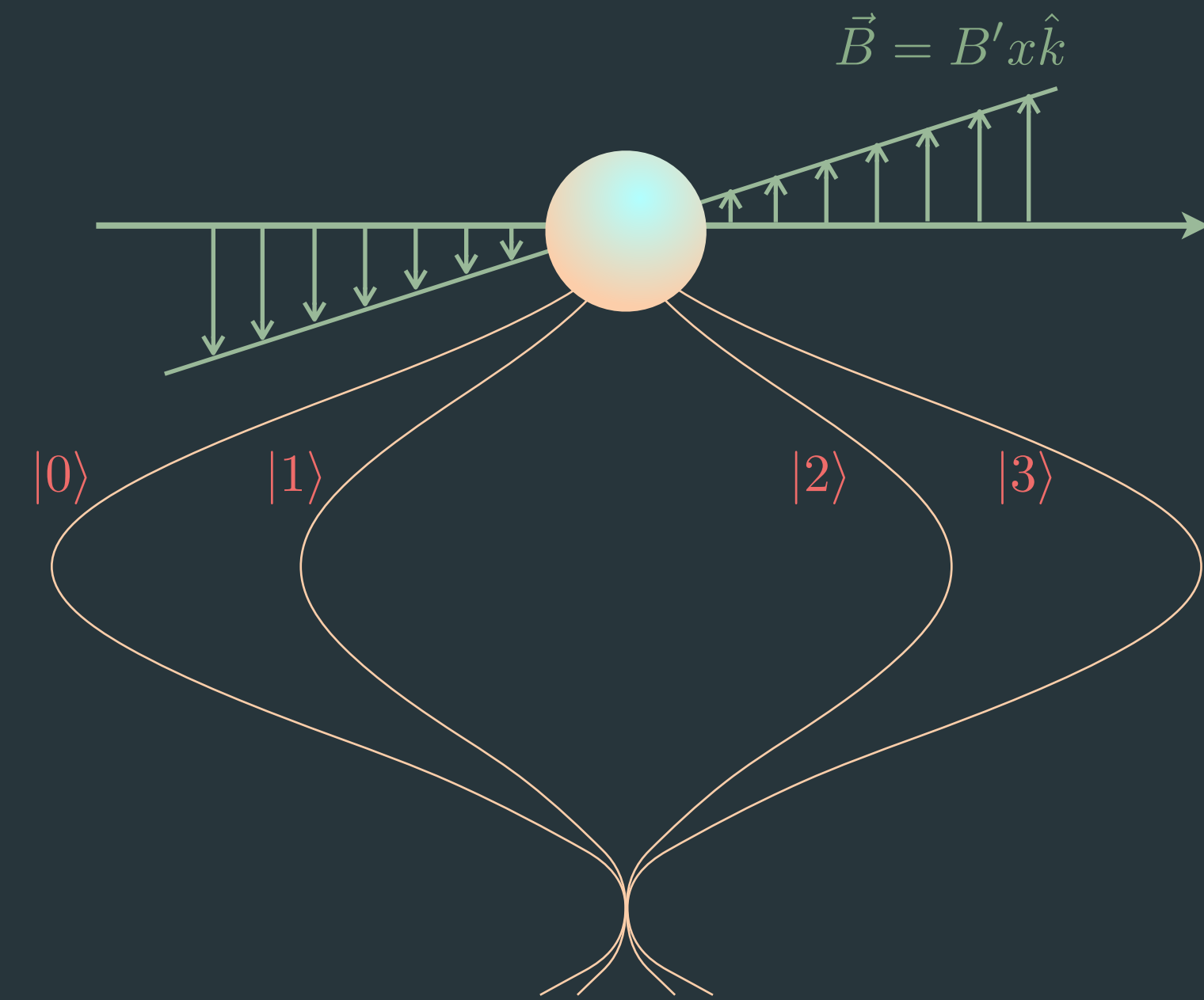
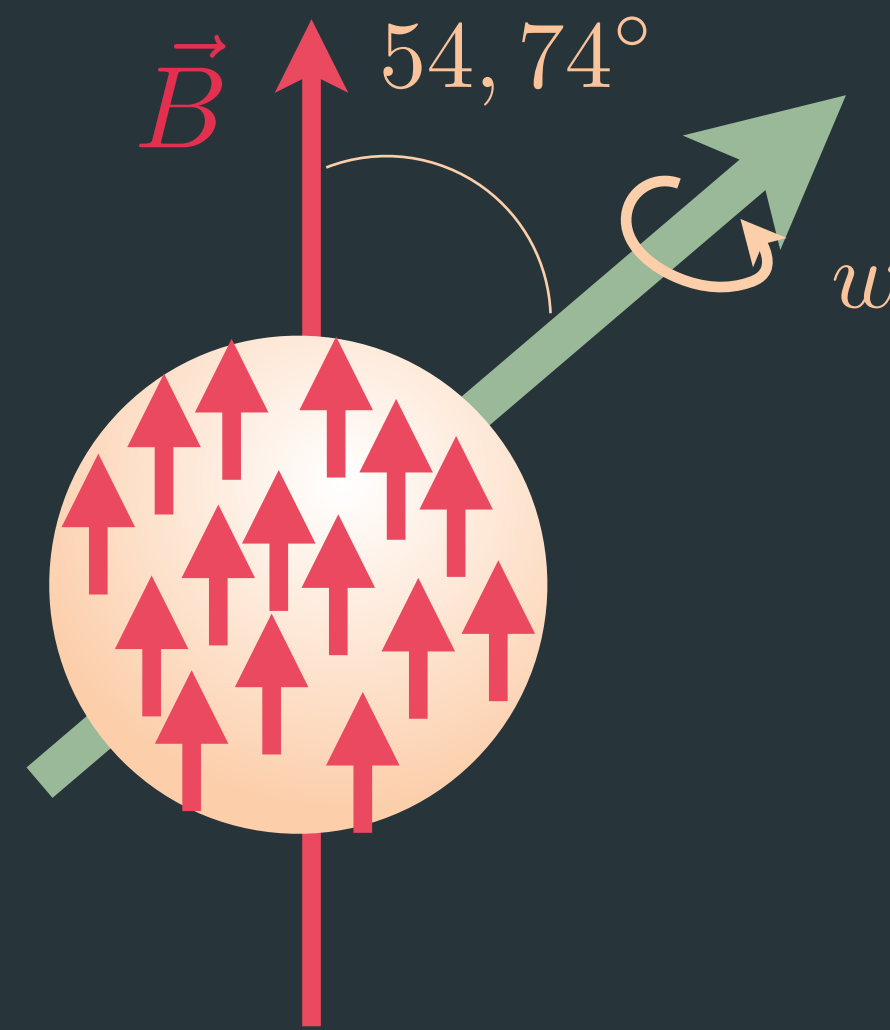


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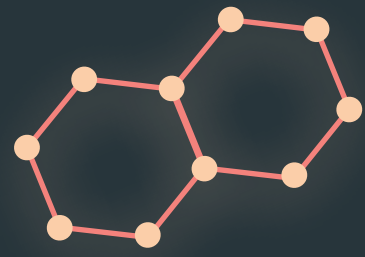
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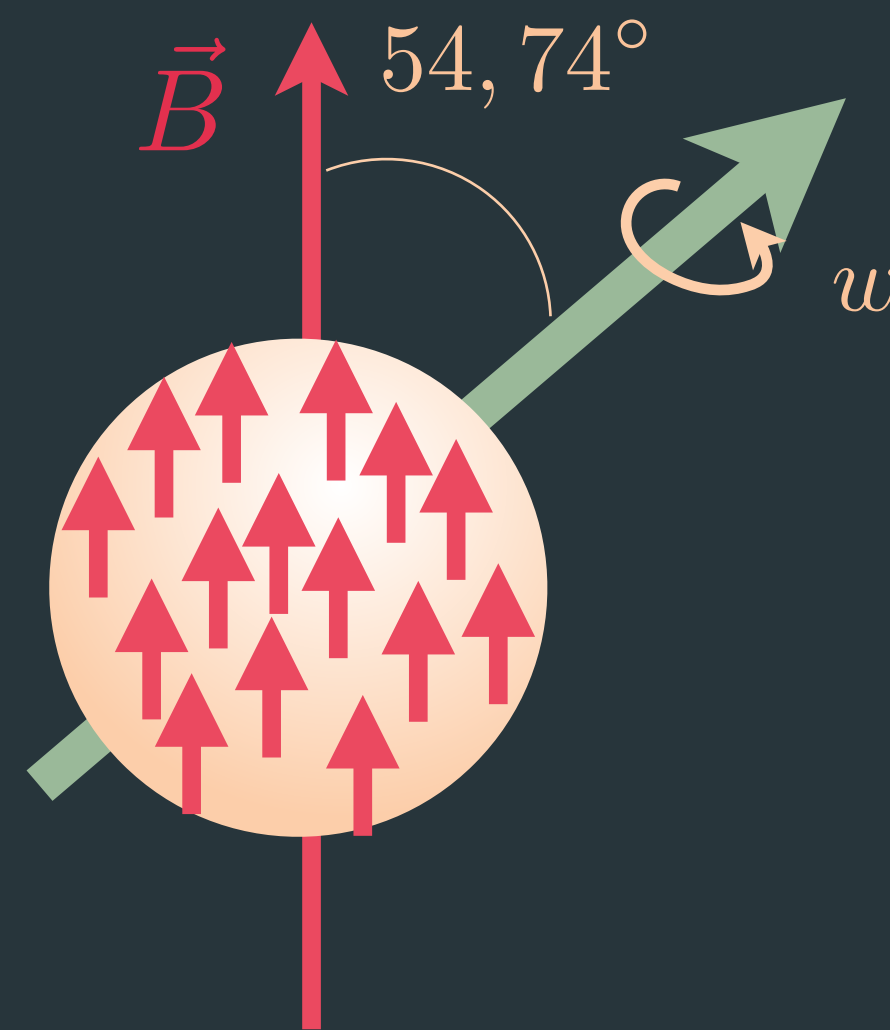
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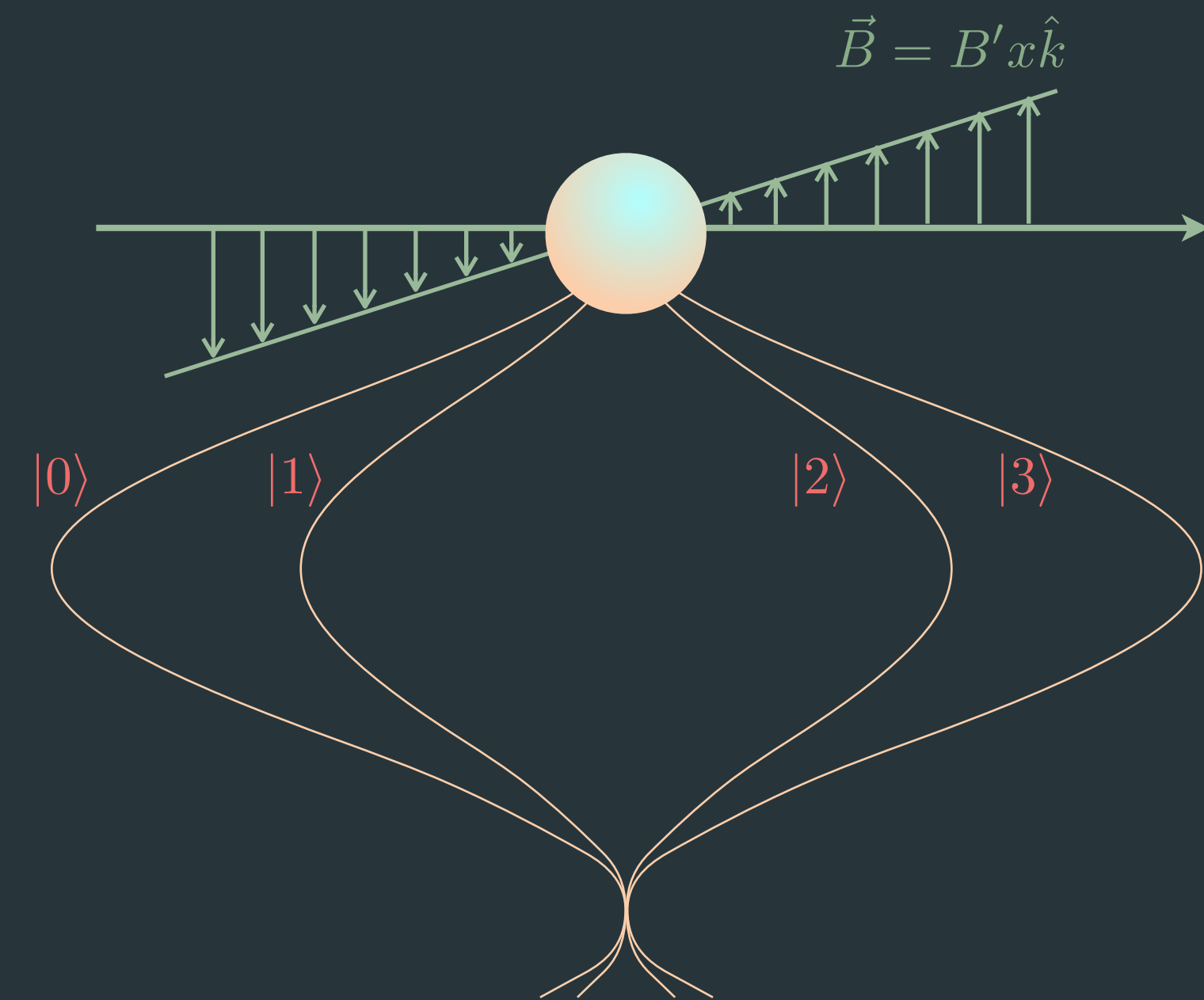
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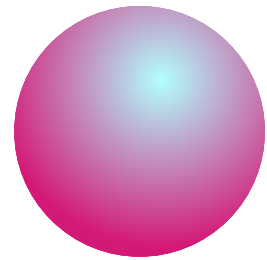
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$$\Delta x \propto \sqrt{N}$$

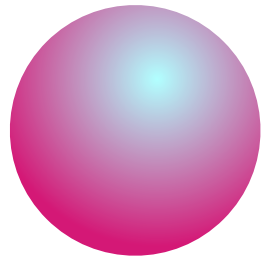
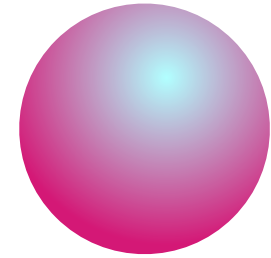
The problem between gravity and quantum mechanics

m

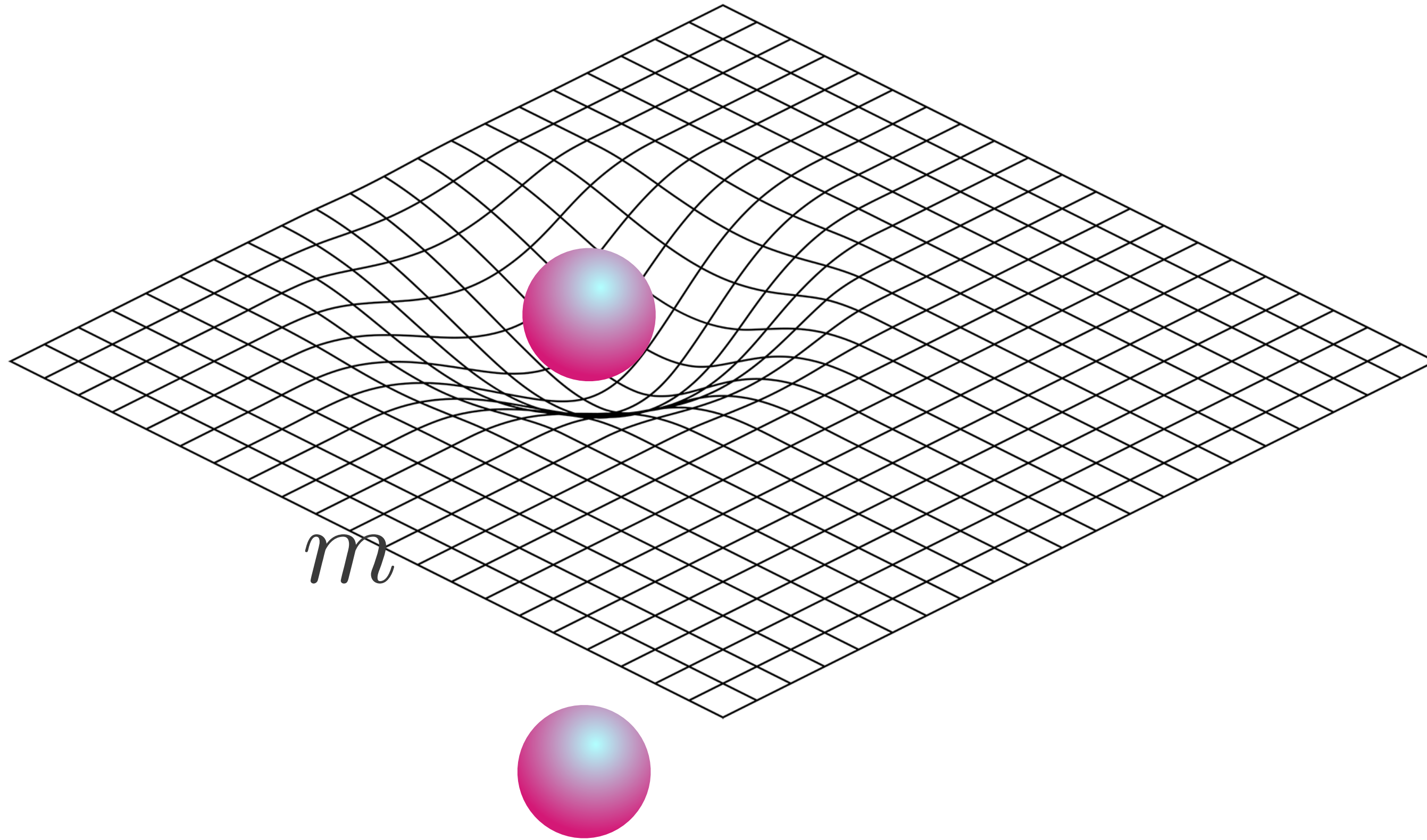


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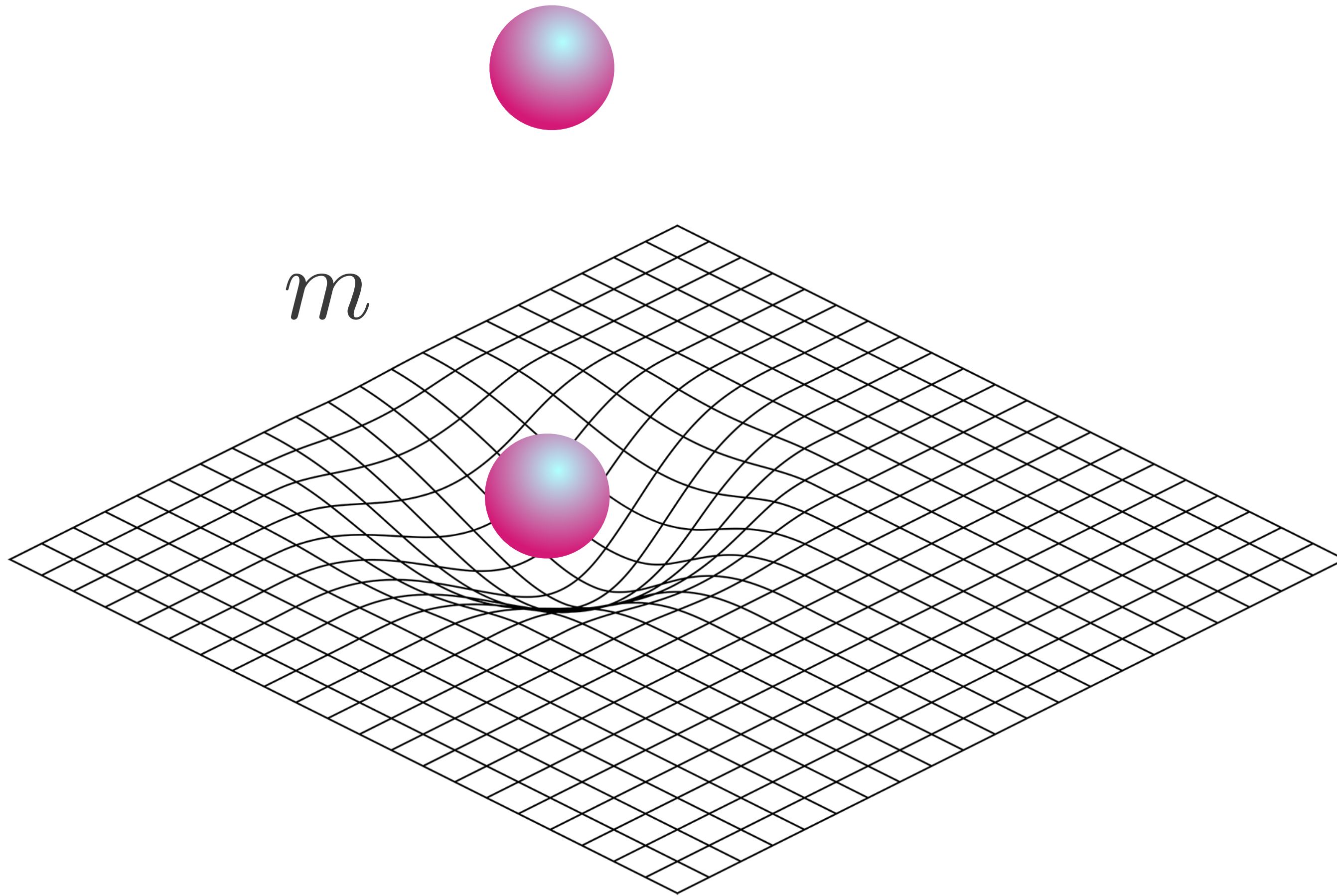
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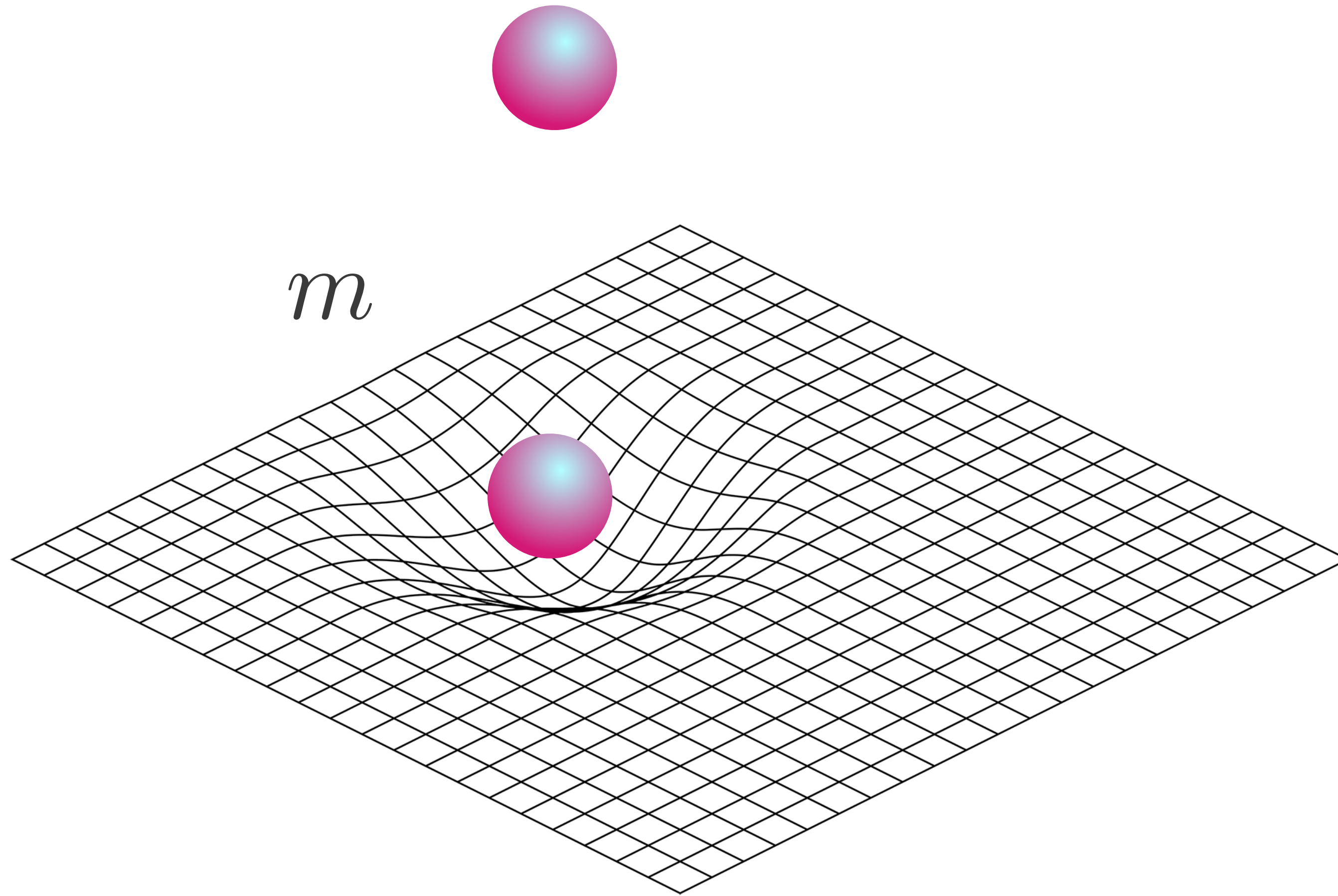
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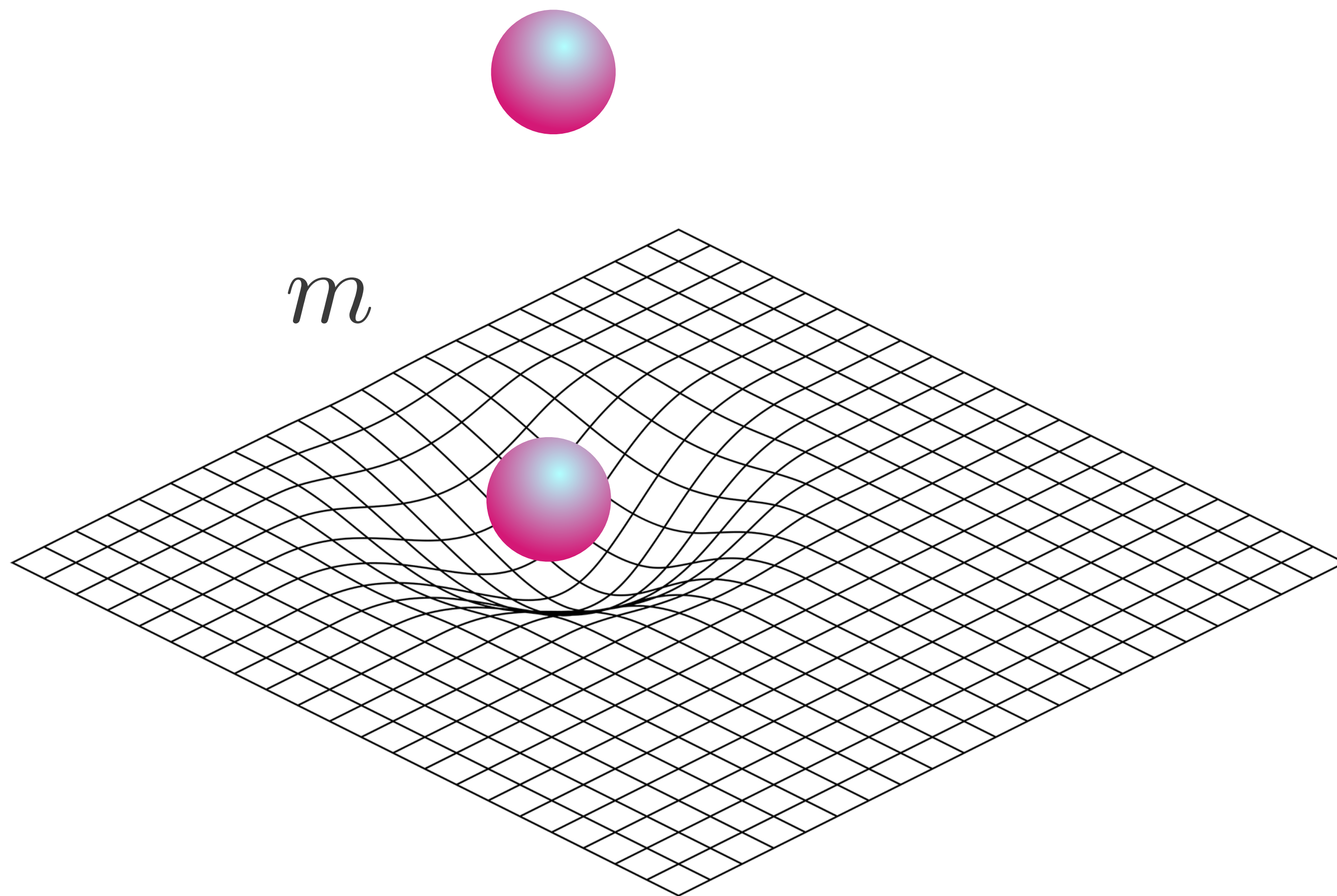


696 Sitzung der physikalisch-mathematischen Klasse vom 22. Juni 1916

Gleichwohl müßten die Atome zufolge der inneratomischen Elektronenbewegung nicht nur elektromagnetische, sondern auch Gravitationsenergie ausstrahlen, wenn auch in winzigem Betrage. Da dies in Wahrheit in der Natur nicht zutreffen dürfte, so scheint es, daß die Quantentheorie nicht nur die MAXWELLSche Elektrodynamik, sondern auch die neue Gravitationstheorie wird modifizieren müssen.

Nachtrag. Das seltsame Ergebnis, daß Gravitationswellen existieren sollen, welche keine Energie transportieren (Typen a, b, c), klärt sich in einfacher Weise auf. Es handelt sich nämlich dabei nicht um »reale« Wellen, sondern um »scheinbare« Wellen, die darauf beruhen, daß als Bezugssystem ein wellenartig zitterndes Koordinatensystem benutzt wird. Dies sieht man bequem in folgender Weise ein

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Semi-classical theories

Diosi-Penrose
Oppenheim
....

Quantum theories

Loop Quantum Gravity
String Theory
....



Feynman thought experiment

1957 Chapel Hill Conference on the role of gravitation in physics

Source mass





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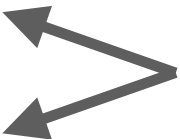
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In modern quantum information parlance we call this **entanglement**



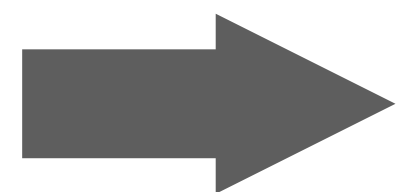
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Gravitational interaction is
NOT of **LOCC** form

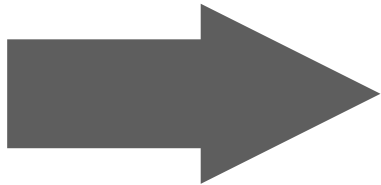


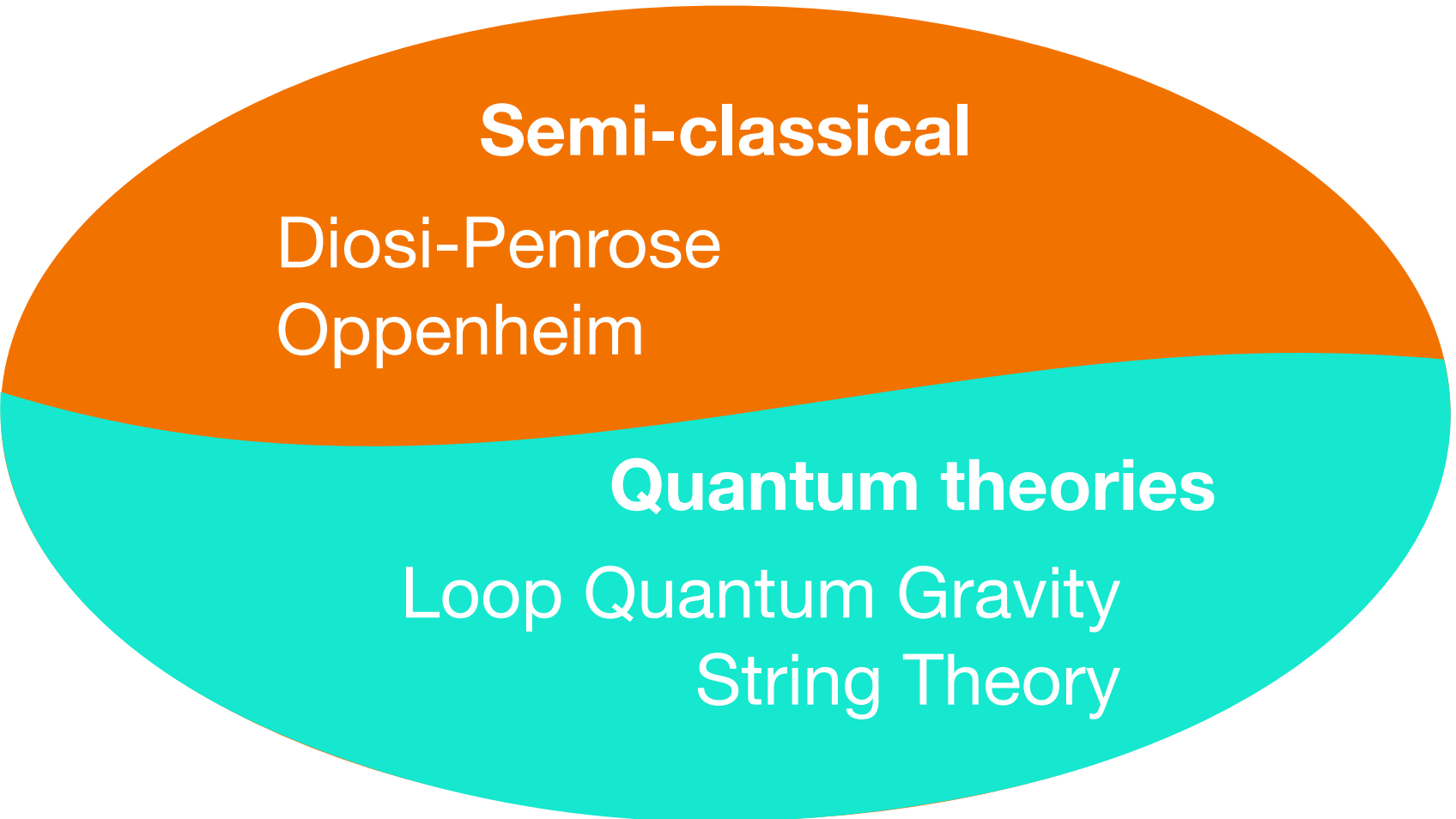
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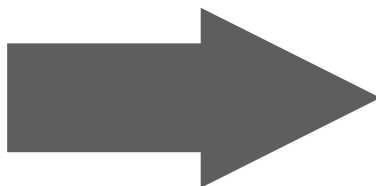
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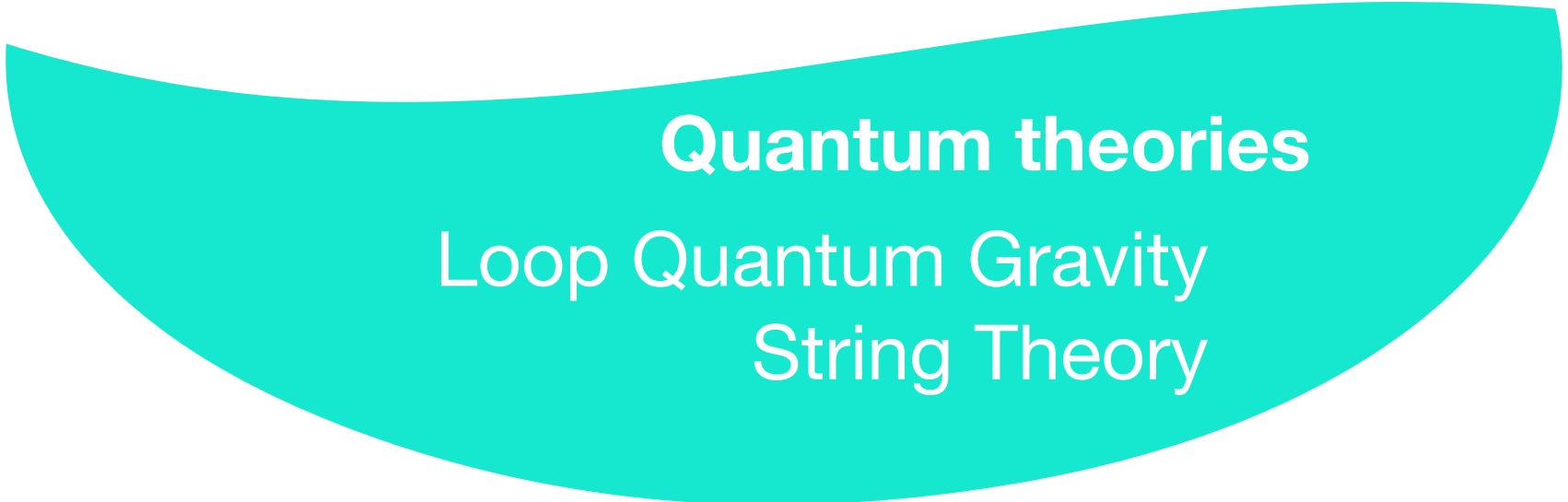


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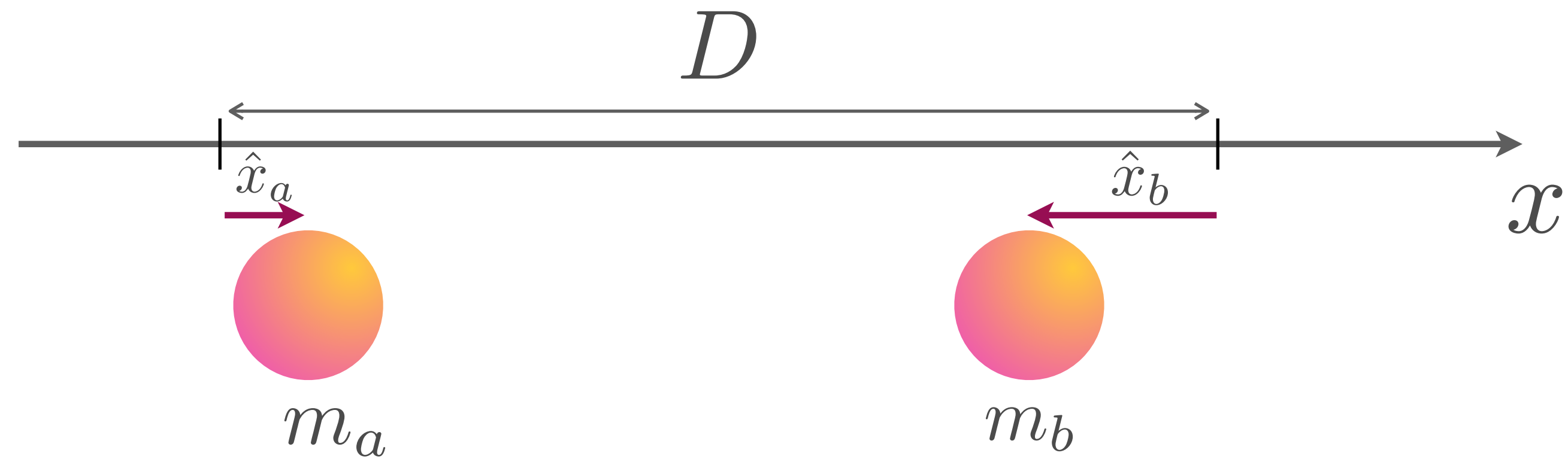


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Gravitational entanglement

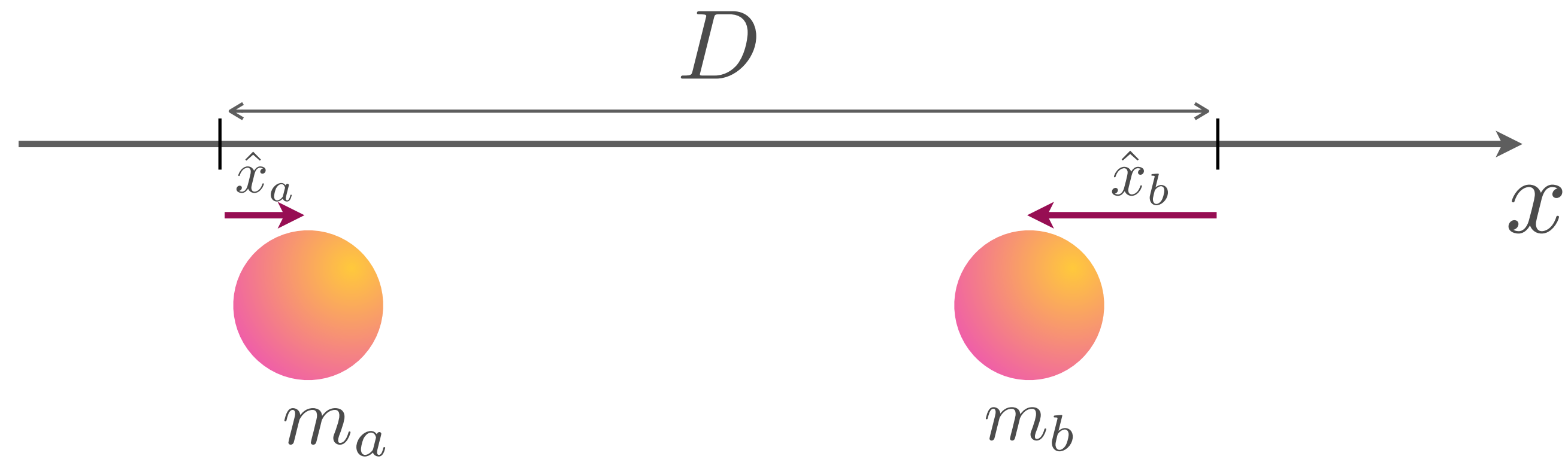
J. S. Pedernales and M. B. Plenio, Contemporary Physics, **64**:2, 147–163 (2023)



$$V_{\text{int}}(\hat{x}_a, \hat{x}_b) = \frac{Gm_a m_b}{|D + \hat{x}_a - \hat{x}_b|}$$

Gravitational entanglement

J. S. Pedernales and M. B. Plenio, Contemporary Physics, **64**:2, 147–163 (2023)



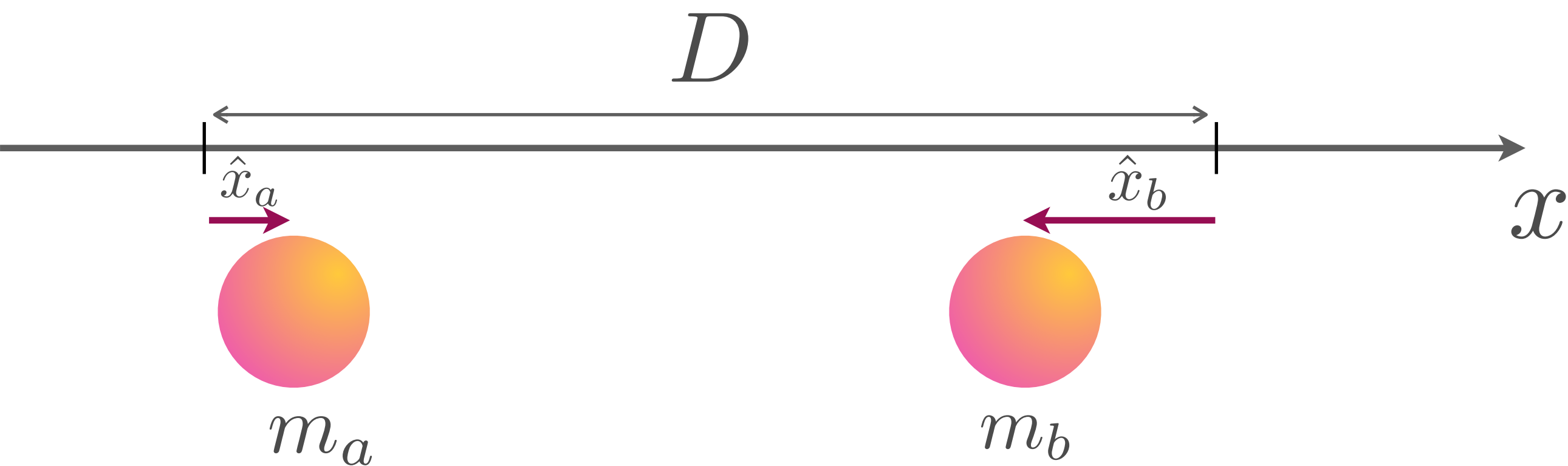
$$V_{\text{int}}(\hat{x}_a, \hat{x}_b) = \frac{Gm_a m_b}{|D + \hat{x}_a - \hat{x}_b|} = \dots + \lambda \hat{x}_a \hat{x}_b + \dots$$

■ $\lambda = \frac{2Gm_a m_b}{D^3}$

■ $D^2 \gg \langle (\hat{x}_a - \hat{x}_b)^2 \rangle$

Gravitational entanglement

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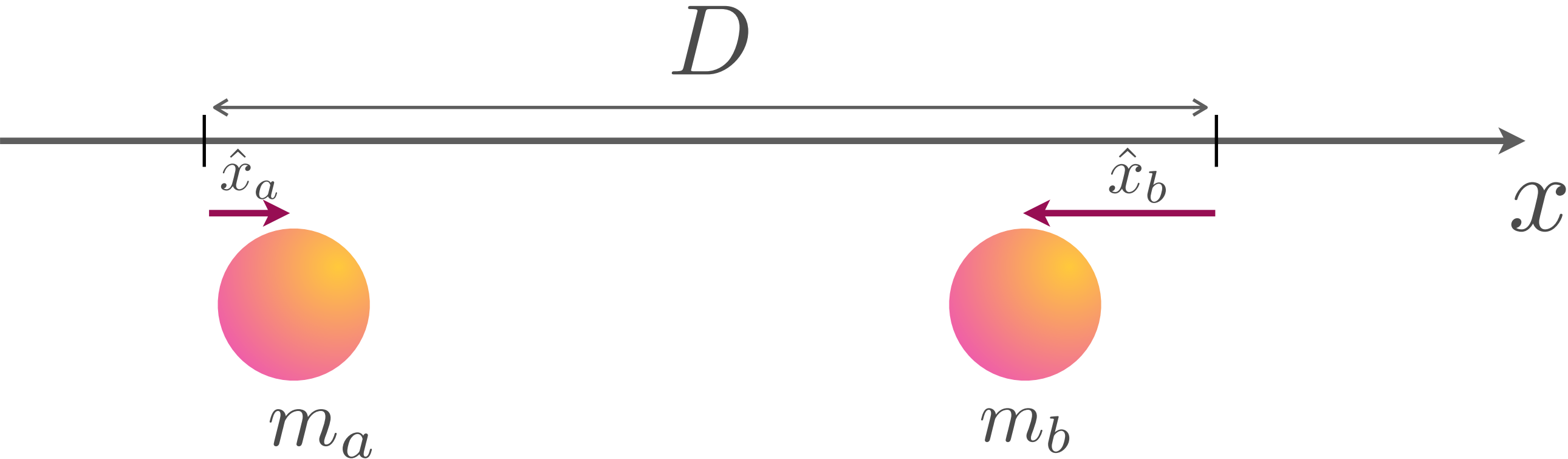
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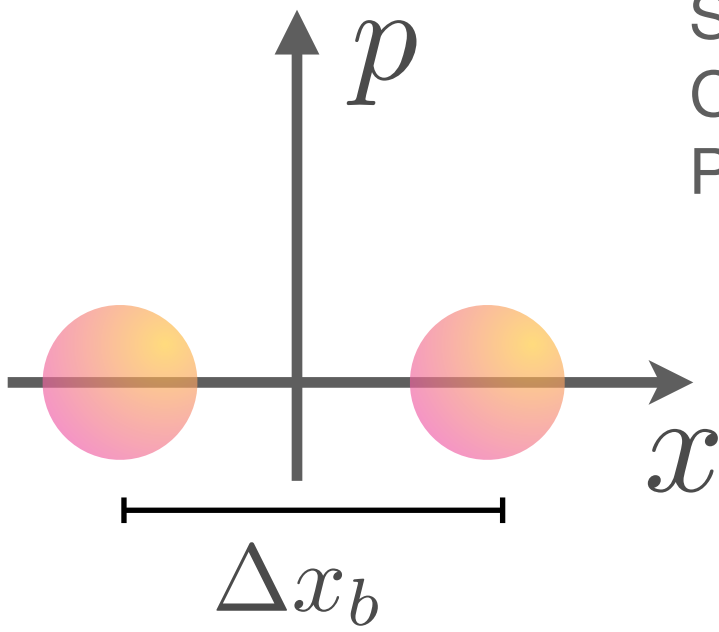
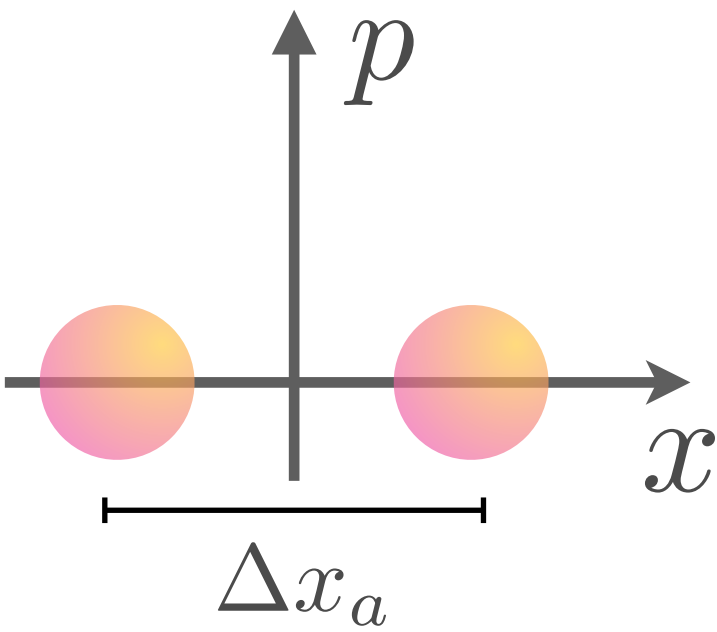
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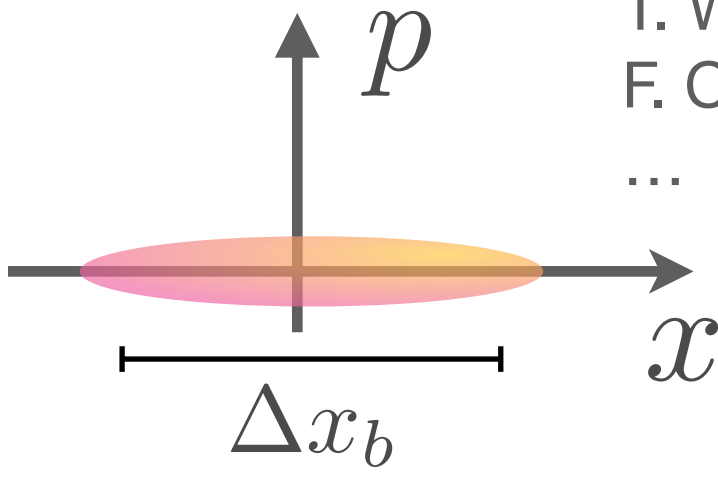
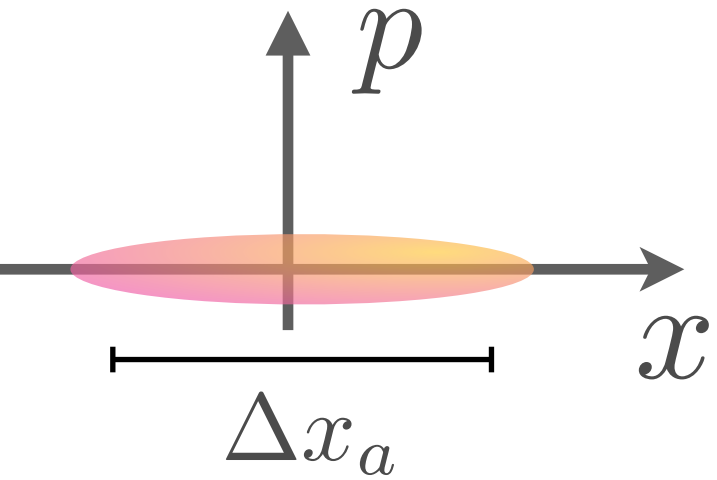
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S. Bose et al. PRL **119**, 240401 (2017)
C. Marletto and V. Vedral,
PRL **119**, 240401 (2017), ...



T. Krisnanda et al., npj Quant. Inf. **6**, 12 (2020),
T. Weiss et al., PRL **127**, 023601 (2021),
F. Cosco et al., PRA **103**, 061501 (2021),
...

Maximize $m \Delta x$

Can I run the experiment with initial coherent states?

$$H = \omega_a a^\dagger a + \omega_b b^\dagger b + \eta(a + a^\dagger)(b + b^\dagger) = \omega_a a^\dagger a + \omega_b b^\dagger b + \underbrace{\eta(ab^\dagger + a^\dagger b)}_{\text{Beam-splitter}} + \underbrace{\eta(ab + a^\dagger b^\dagger)}_{\text{Two-mode Squeezing}}$$

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Beam-splitter

Two-mode
Squeezing

↓
resonant

↓
non-resonant

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RWA $\longrightarrow H_{\text{bs}} \approx \omega_a a^\dagger a + \omega_b b^\dagger b + \eta(ab^\dagger + a^\dagger b)$

resonant non-resonant

Initial coherent states
do not get entangled!!

$$|\alpha_A\rangle \otimes |\alpha_B\rangle \xrightarrow{e^{-iH_{\text{bs}}t/\hbar}} |(\cos(\eta t)\alpha_A - i\sin(\eta t)\alpha_B)\rangle \otimes |(\cos(\eta t)\alpha_B - i\sin(\eta t)\alpha_A)\rangle$$

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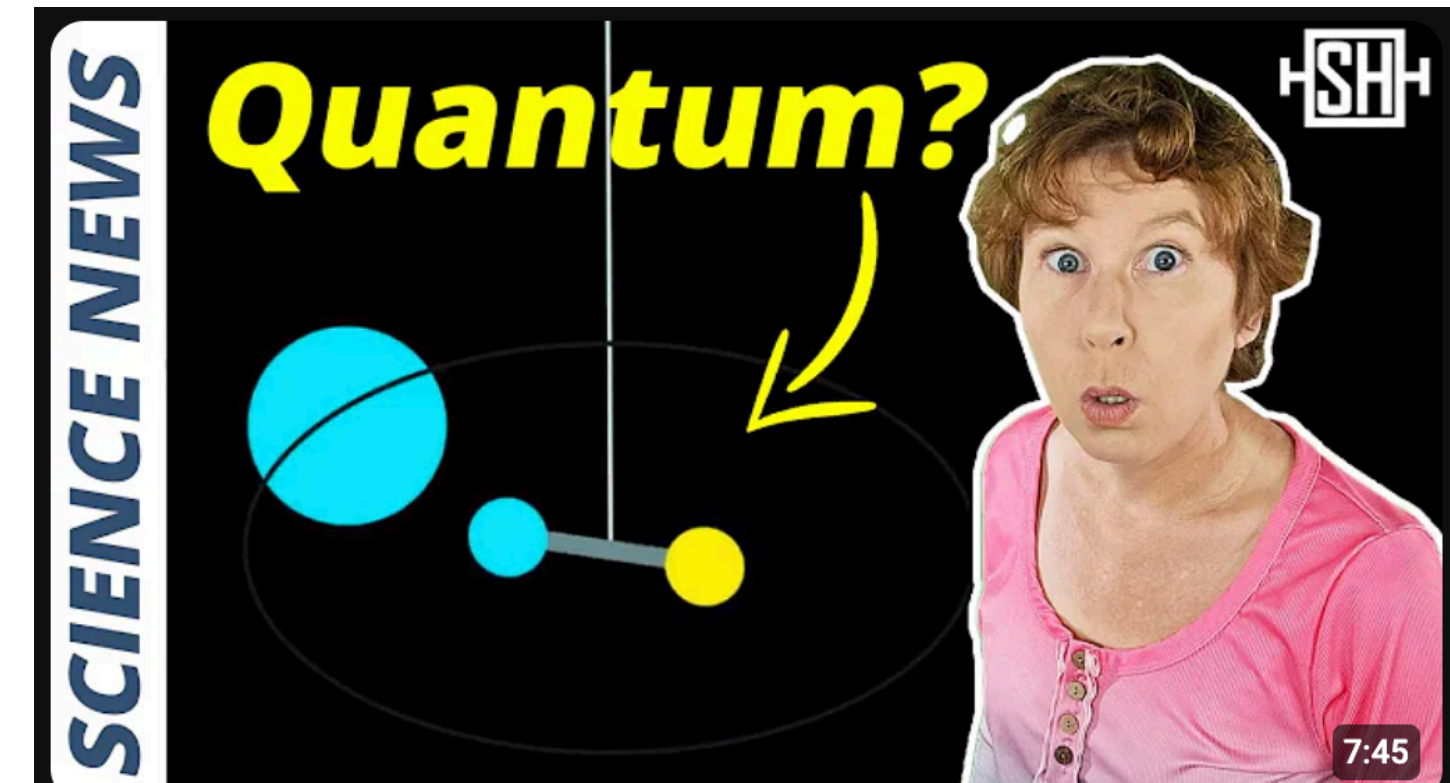
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Can I determine the LOCC character in the absence of entanglement?

An operational way of setting the problem

Ludovico Lami, Julen Pedernales, and Martin Plenio, PRX **14**, 021022 (2024)



An operational way of setting the problem

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My guess is that gravity is U_{grav}

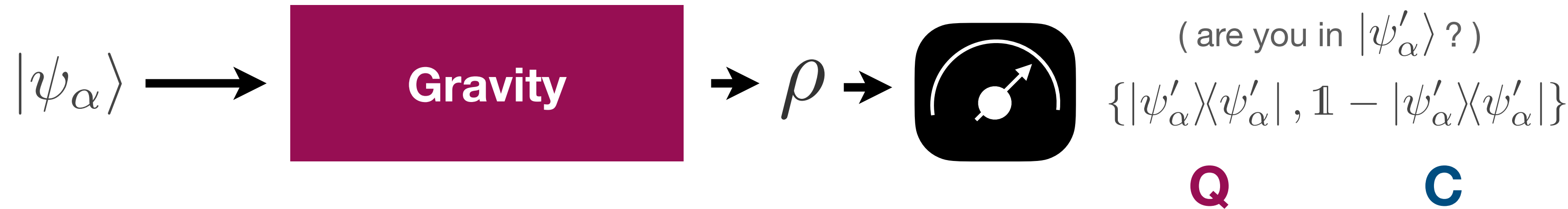
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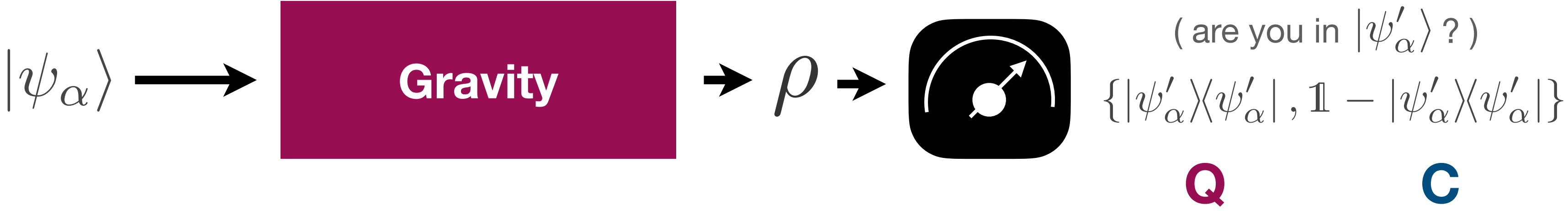
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$$P(Q|LOCC) = \sum_\alpha p_\alpha \text{Tr} [|\psi'_\alpha\rangle\langle\psi'_\alpha| \Lambda_{\text{LOCC}}(|\psi_\alpha\rangle\langle\psi_\alpha|)] \leq \mathcal{F}(\mathcal{E}, U_{\text{grav}})$$

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Ludovico Lami, Julen Pedernales, and Martin Plenio, PRX **14**, 021022 (2024)

My guess is that gravity is U_{grav}

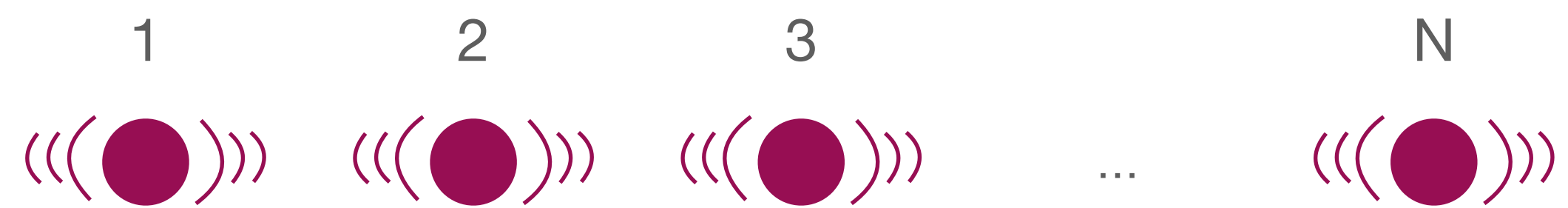


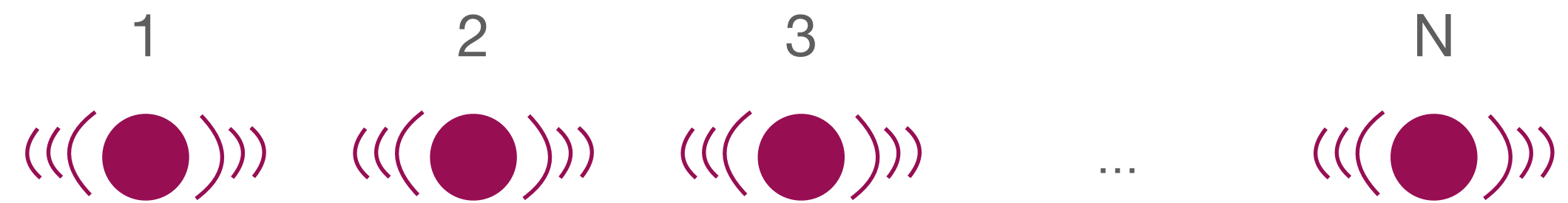
$$P(Q|U_{\text{grav}}) = \sum_\alpha p_\alpha \text{Tr} [|\psi'_\alpha\rangle\langle\psi'_\alpha| U_{\text{grav}} |\psi_\alpha\rangle\langle\psi_\alpha| U_{\text{grav}}^\dagger] = 1$$

$$P(Q|LOCC) = \sum_\alpha p_\alpha \text{Tr} [|\psi'_\alpha\rangle\langle\psi'_\alpha| \Lambda_{\text{LOCC}}(|\psi_\alpha\rangle\langle\psi_\alpha|)] \leq \mathcal{F}(\mathcal{E}, U_{\text{grav}})$$

Simulation fidelity

$$\mathcal{F}(\mathcal{E}, U_{\text{grav}}) = \sup_{\Lambda \in \text{LOCC}} \sum_\alpha p_\alpha \text{Tr} [|\psi'_\alpha\rangle\langle\psi'_\alpha| \Lambda_{\text{LOCC}}(|\psi_\alpha\rangle\langle\psi_\alpha|)]$$



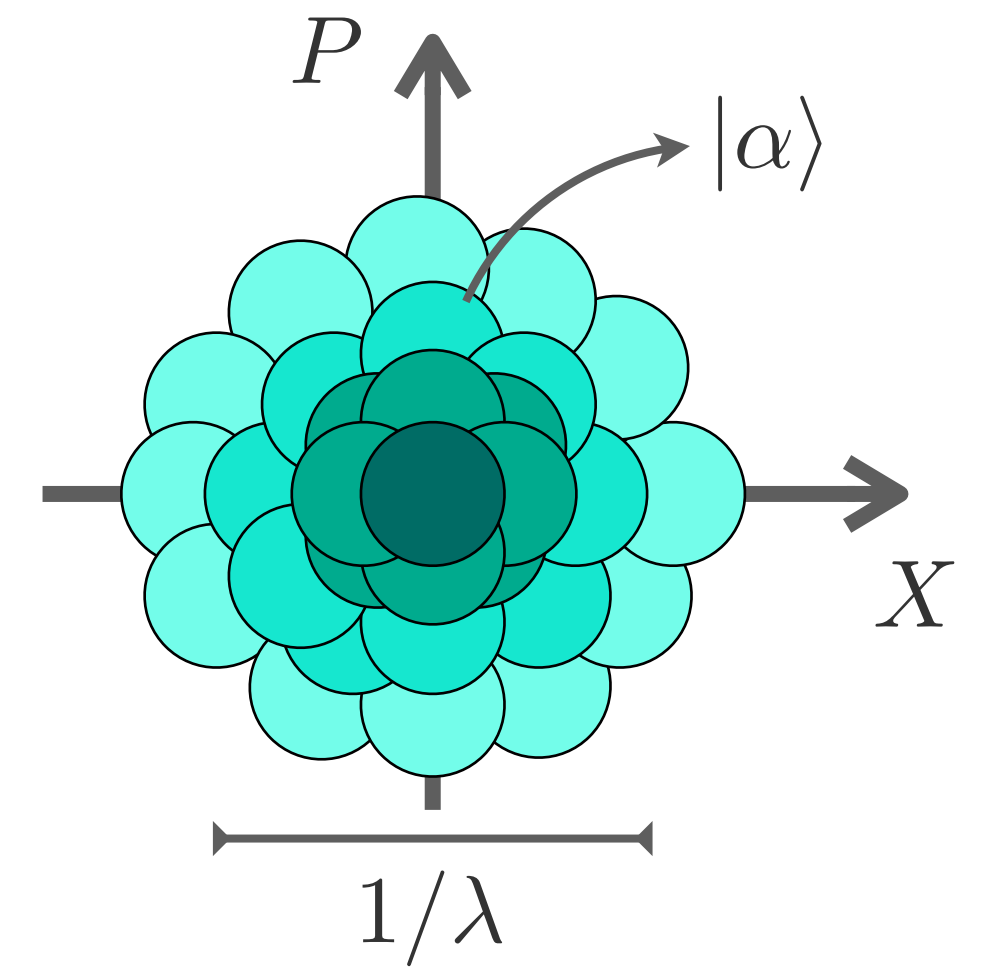


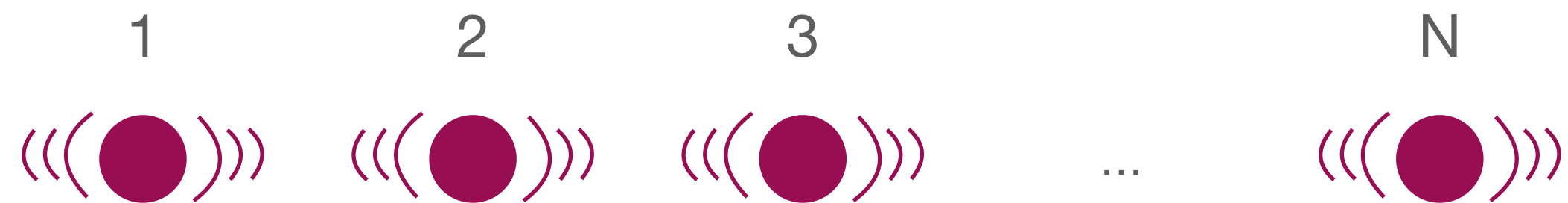
Initial coherent state ensamble

$$\mathcal{E} = \{p_\lambda(\alpha), |\alpha\rangle\langle\alpha|\} \quad \text{with} \quad p_\lambda(\alpha) = \frac{\lambda}{\pi} e^{-\lambda|\alpha|^2}$$

Beam-splitter type of evolution

$$H = \sum_{i < j} \eta_{ij} (a_i a_j^\dagger + a_i^\dagger a_j) \longrightarrow U_{\text{bm}}$$



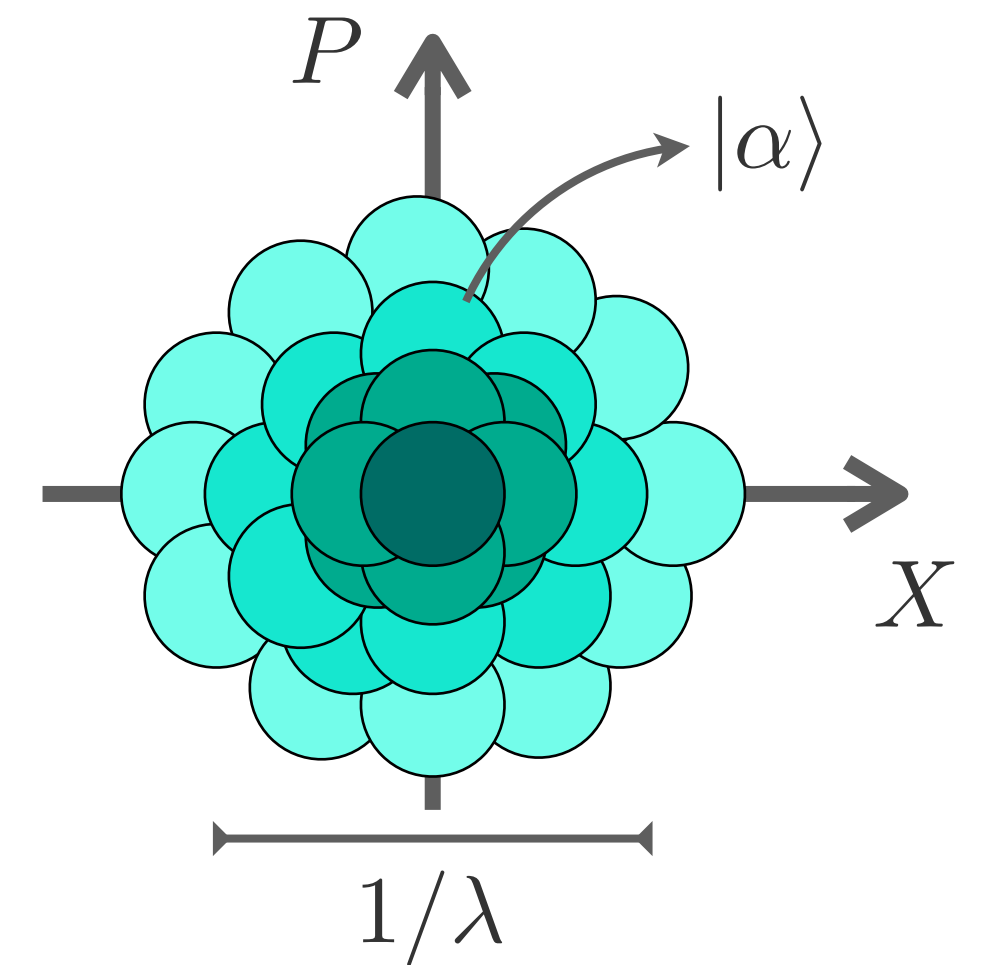


Initial coherent
state ensemble

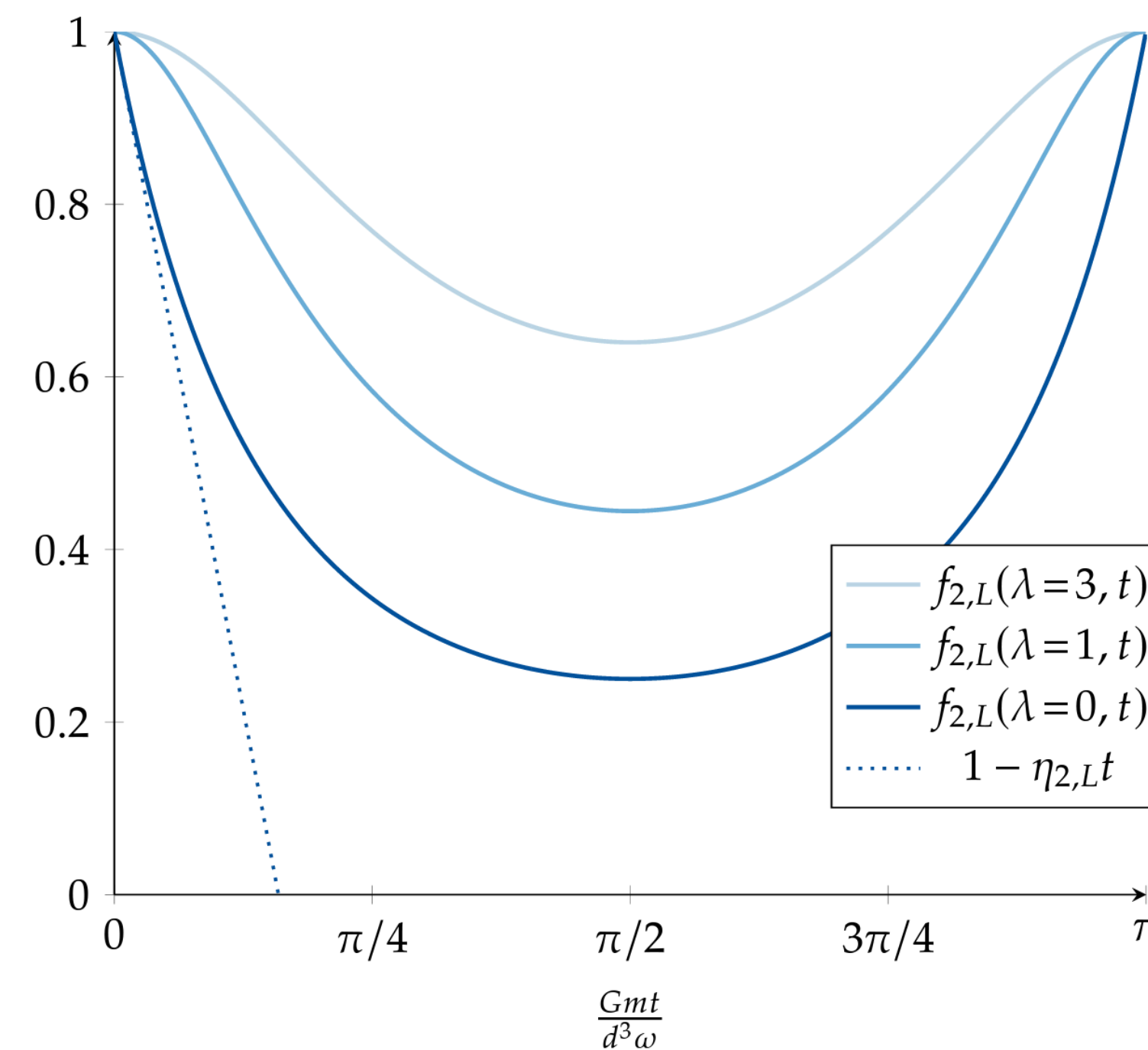
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$$H = \sum_{i<j} \eta_{ij} (a_i a_j^\dagger + a_i^\dagger a_j) \quad \longrightarrow \quad U_{\text{bm}}$$

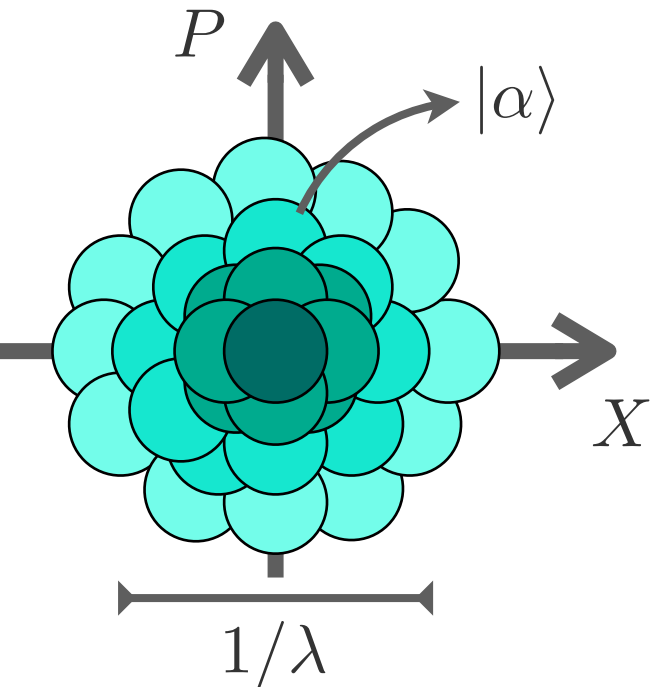


$\longrightarrow \mathcal{F}(\mathcal{E}, U_{\text{bm}},) \leq f_n(\lambda, t)$



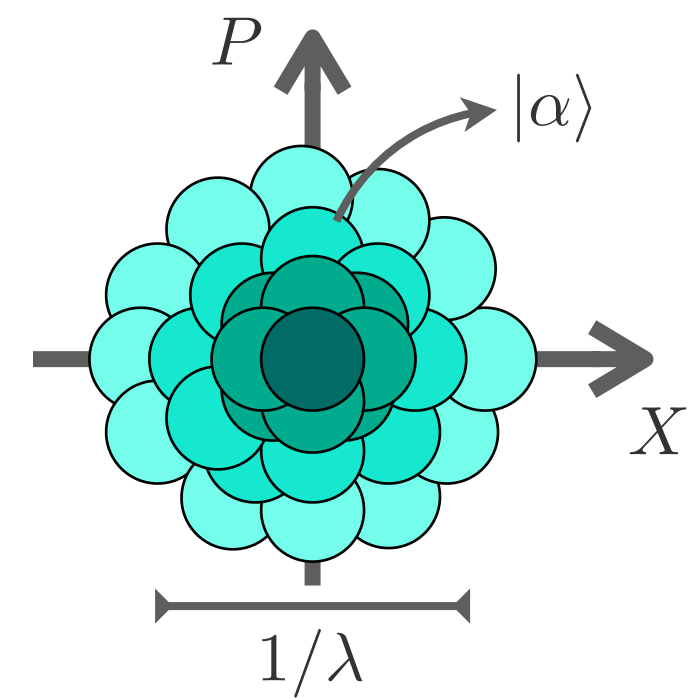
Entanglement-free test with 2 levitated nanoparticles

Choose two states
from $\mathcal{E}$

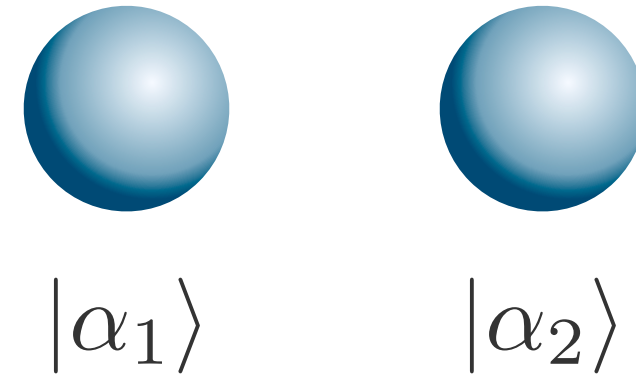


Entanglement-free test with 2 levitated nanoparticles

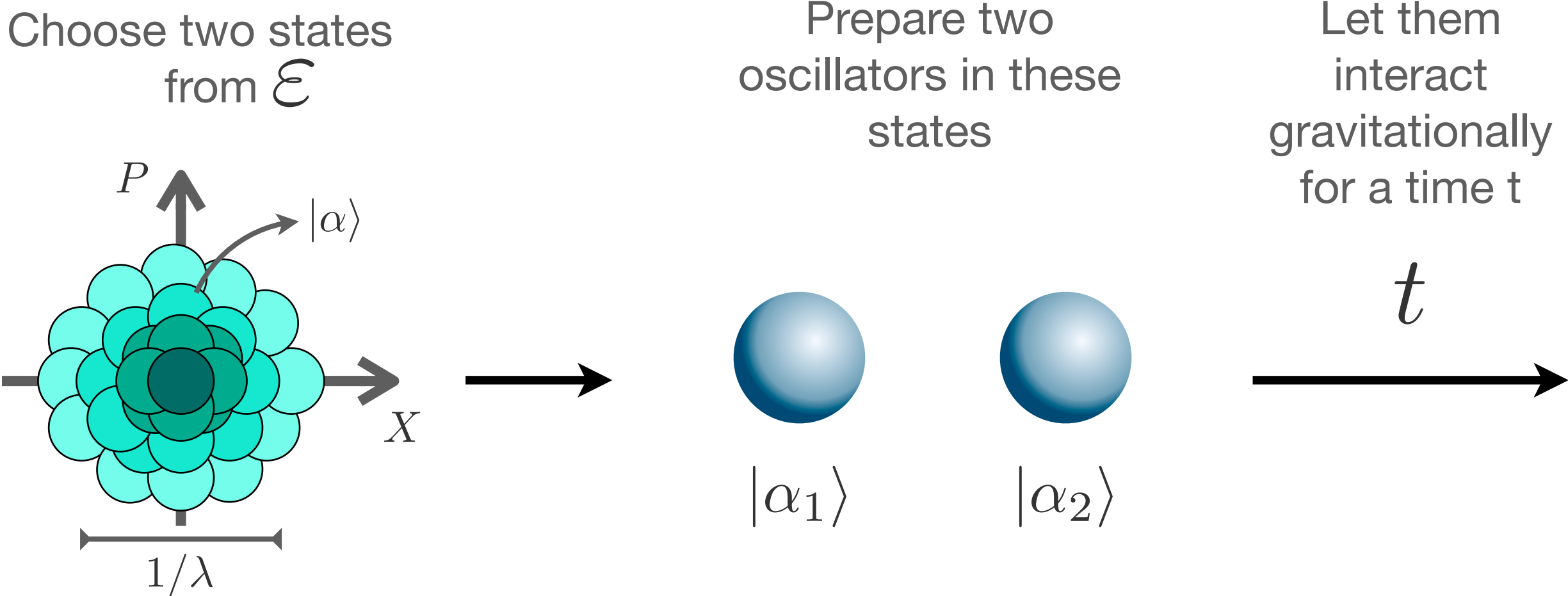
Choose two states
from $\mathcal{E}$



Prepare two
oscillators in these
states

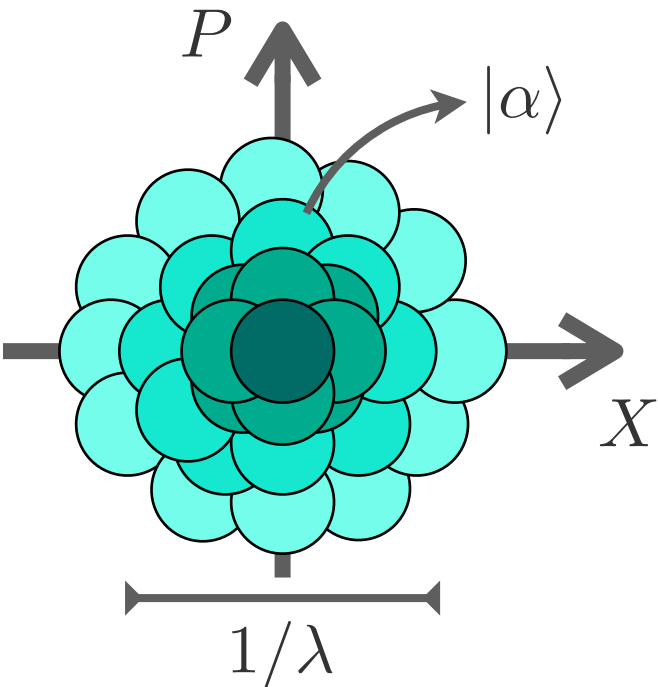


Entanglement-free test with 2 levitated nanoparticles

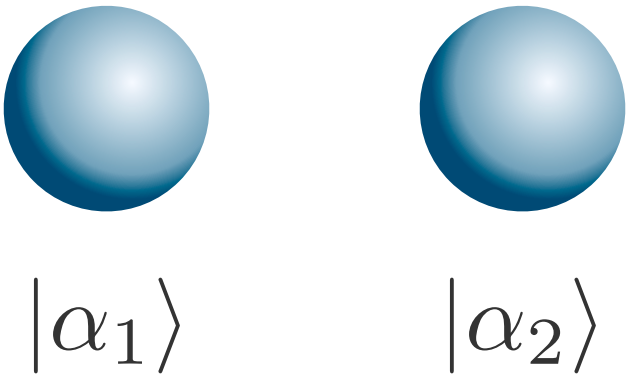


Entanglement-free test with 2 levitated nanoparticles

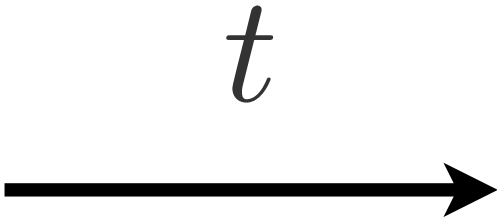
Choose two states
from $\mathcal{E}$



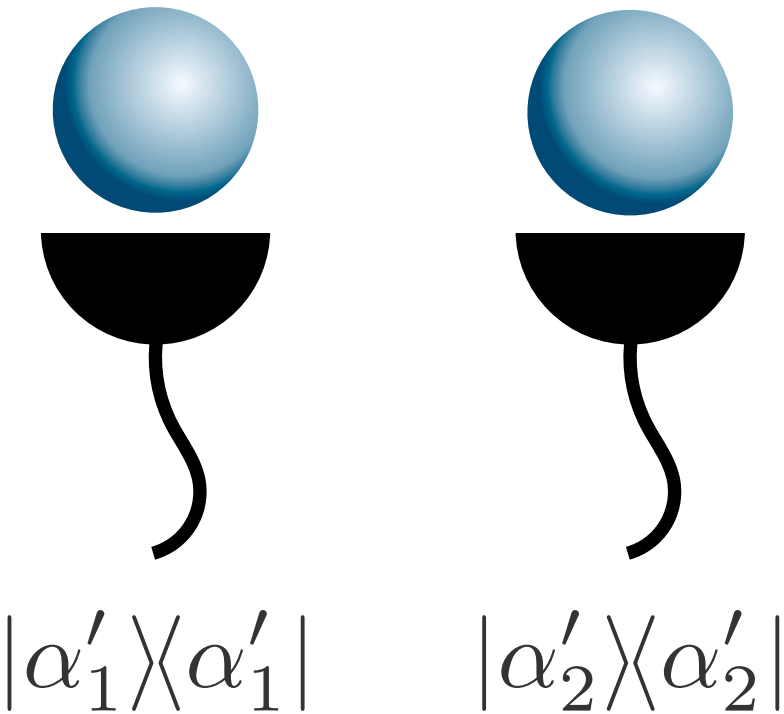
Prepare two
oscillators in these
states



Let them
interact
gravitationally
for a time t

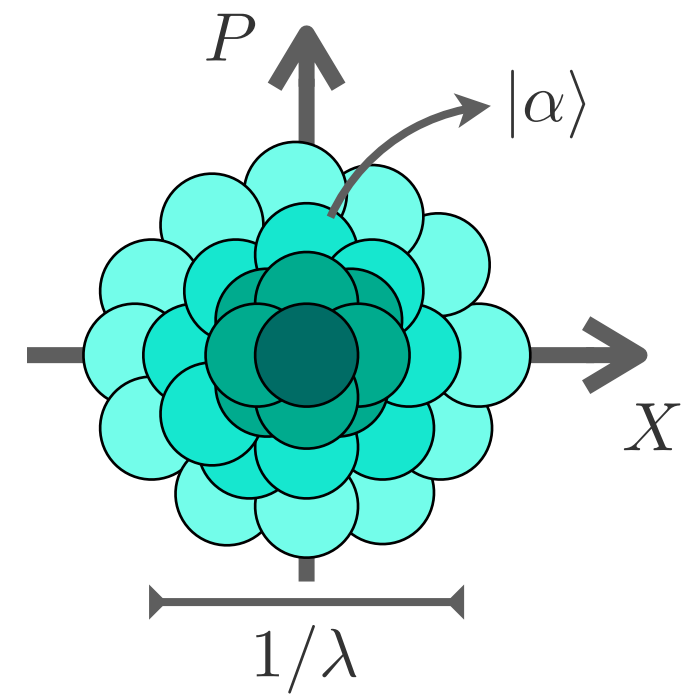


Measure in a
suitable basis

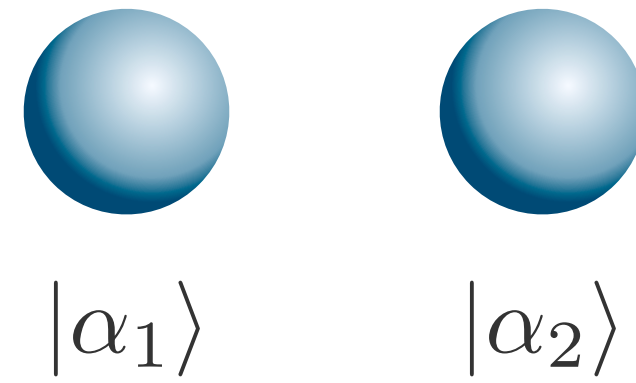


Entanglement-free test with 2 levitated nanoparticles

Choose two states
from $\mathcal{E}$



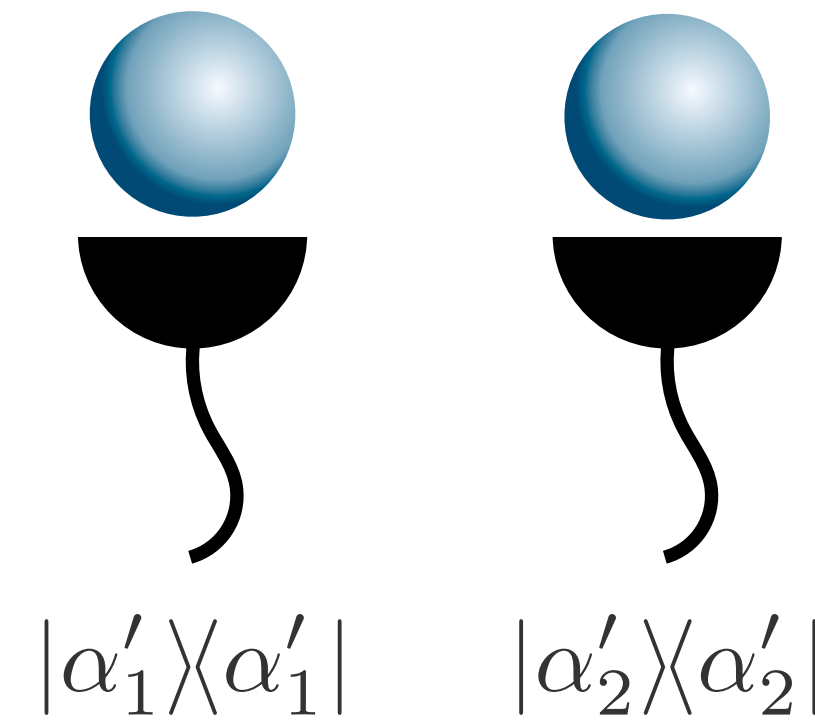
Prepare two
oscillators in these
states



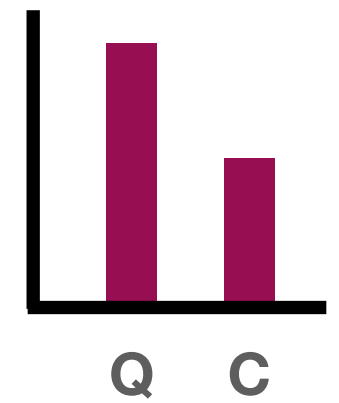
Let them
interact
gravitationally
for a time t



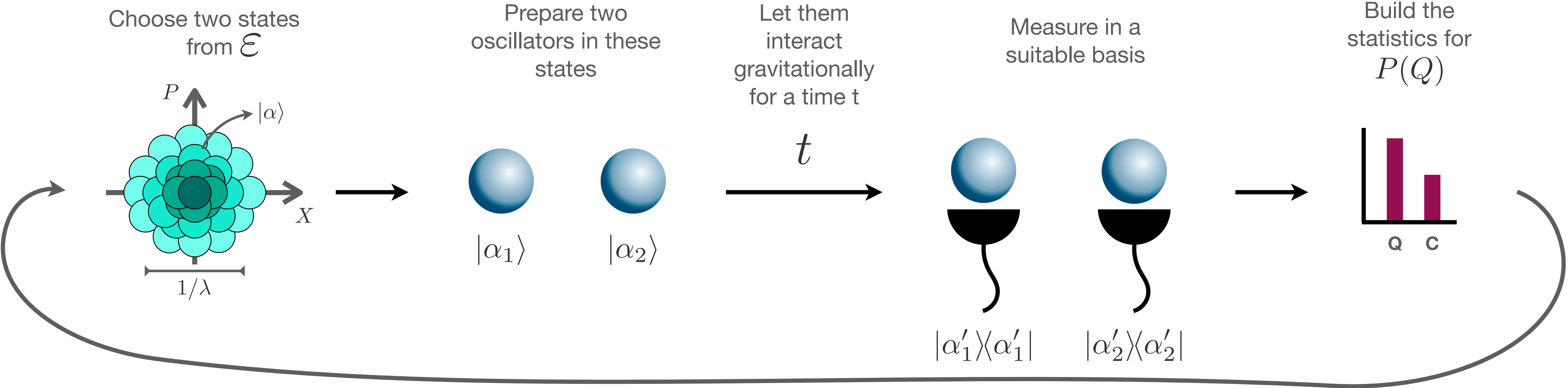
Measure in a
suitable basis



Build the
statistics for
 $P(Q)$

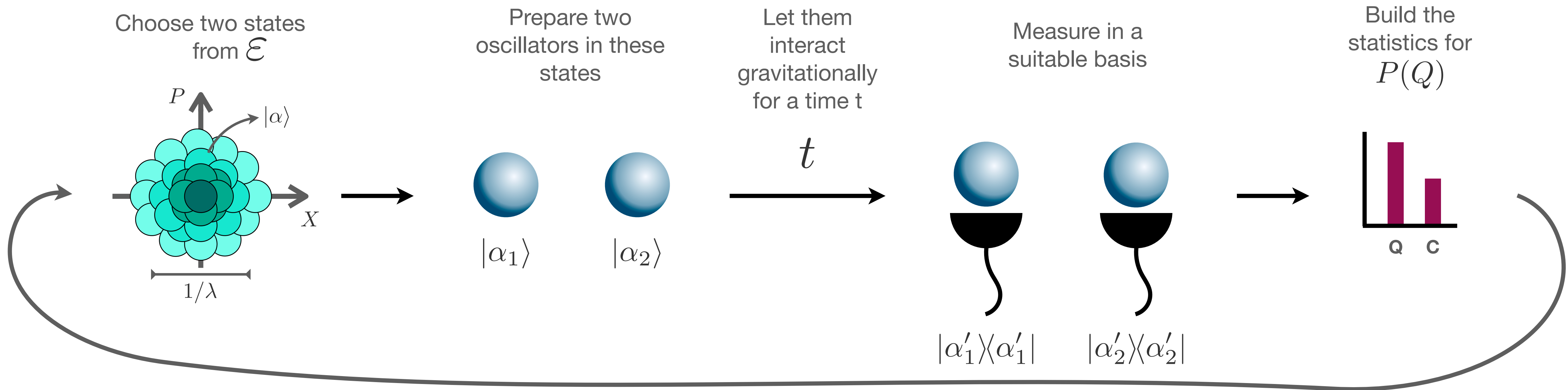


Entanglement-free test with 2 levitated nanoparticles



If $P(Q) > \mathcal{F}(\varepsilon, t)$ gravity non-LOCC

Entanglement-free test with 2 levitated nanoparticles

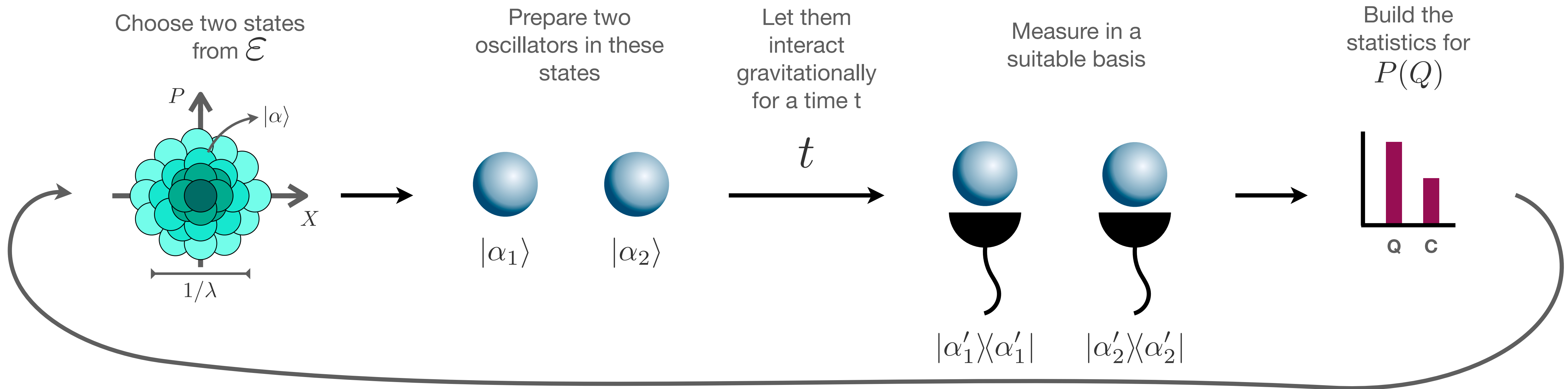


If $P(Q) > \mathcal{F}(\varepsilon, t)$ gravity non-LOCC

No large delocalisations required

No entanglement required

Entanglement-free test with 2 levitated nanoparticles



If $P(Q) > \mathcal{F}(\varepsilon, t)$ gravity non-LOCC

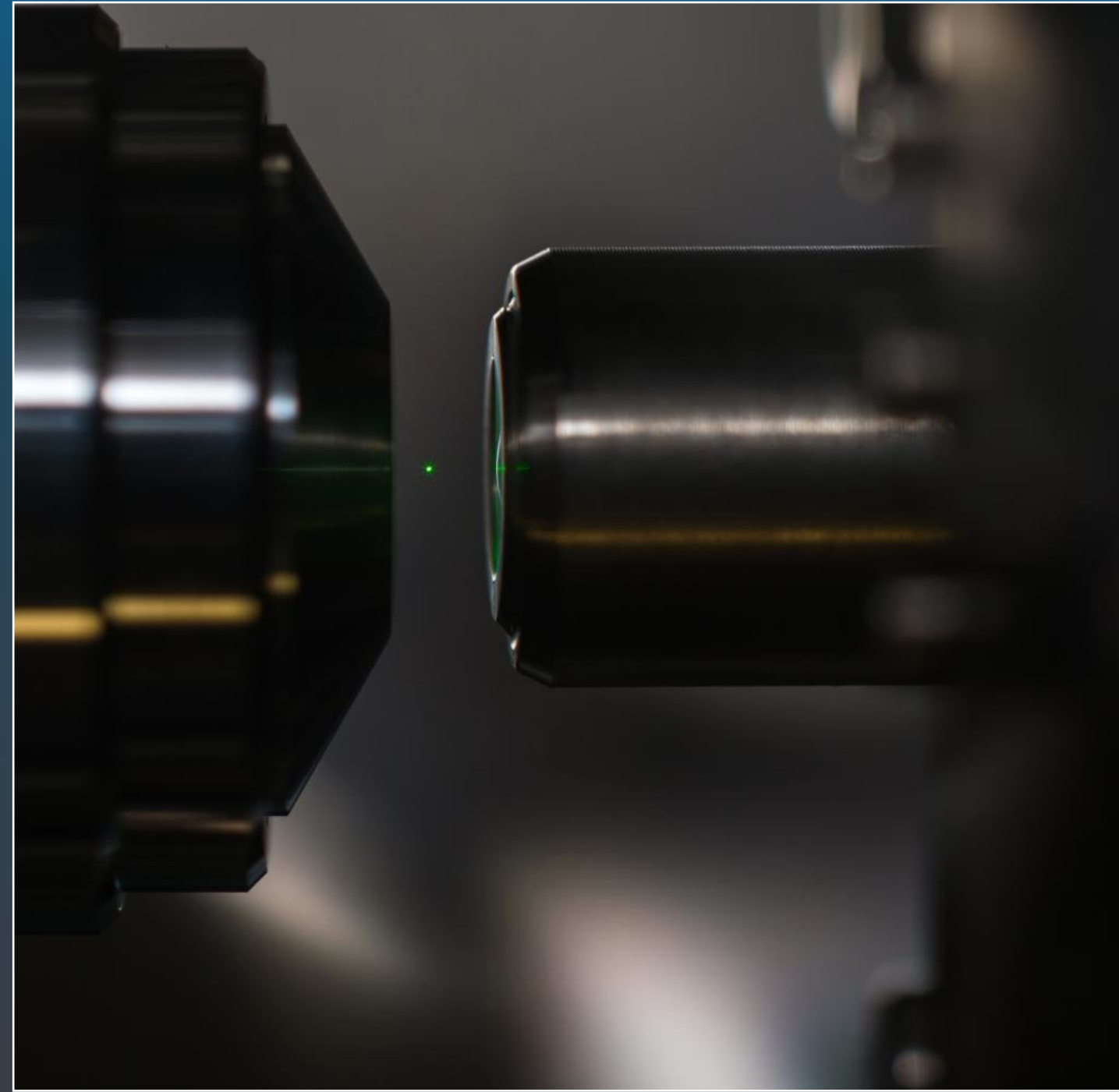
No large delocalisations required

No entanglement required

Prepare and detect coherent states with sufficient precision

Long coherence times required

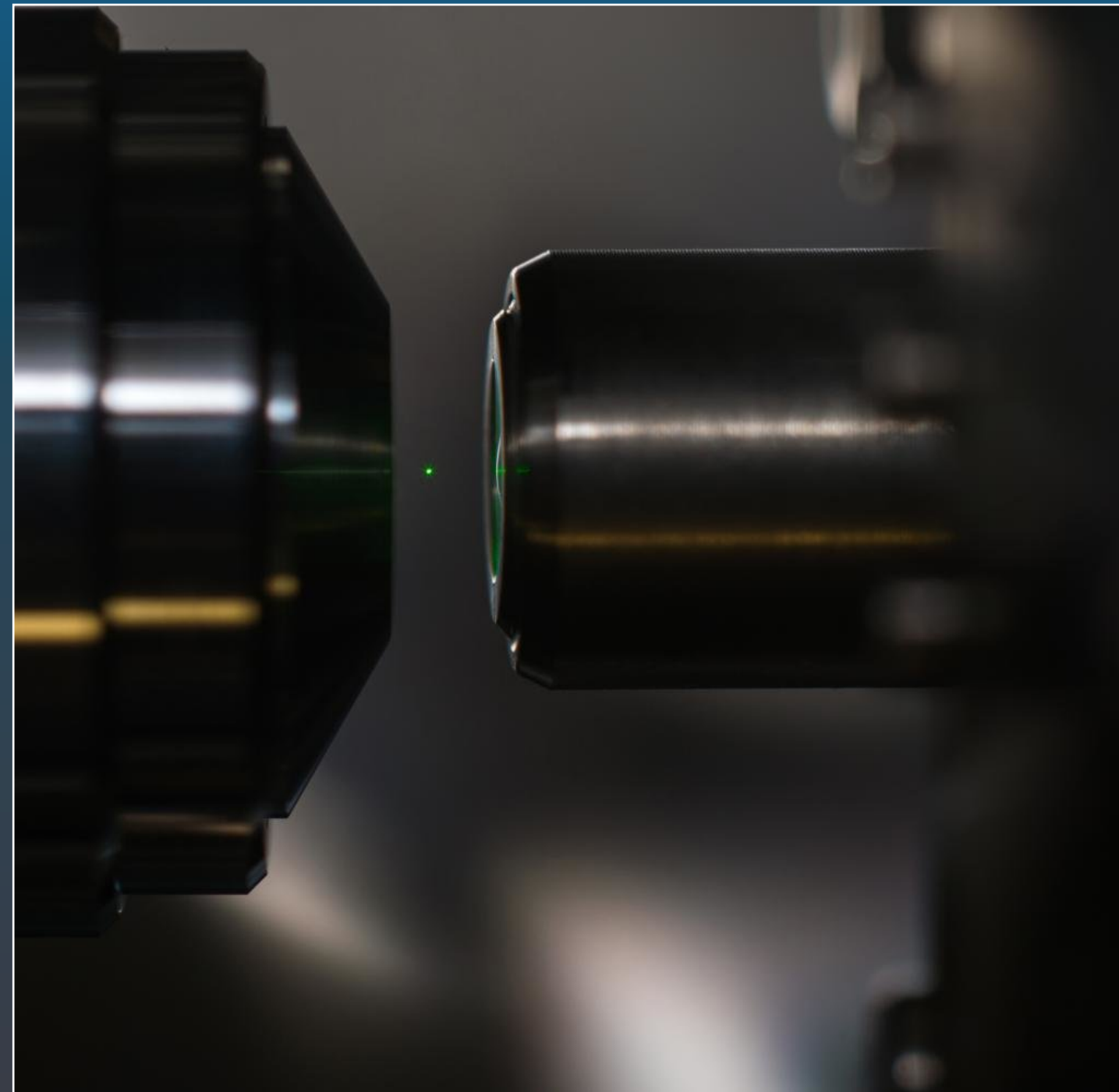
Take home message



New
Physics?

Levitated optomechanics is a new tool to explore the **large-mass** regime of quantum mechanics

Take home message

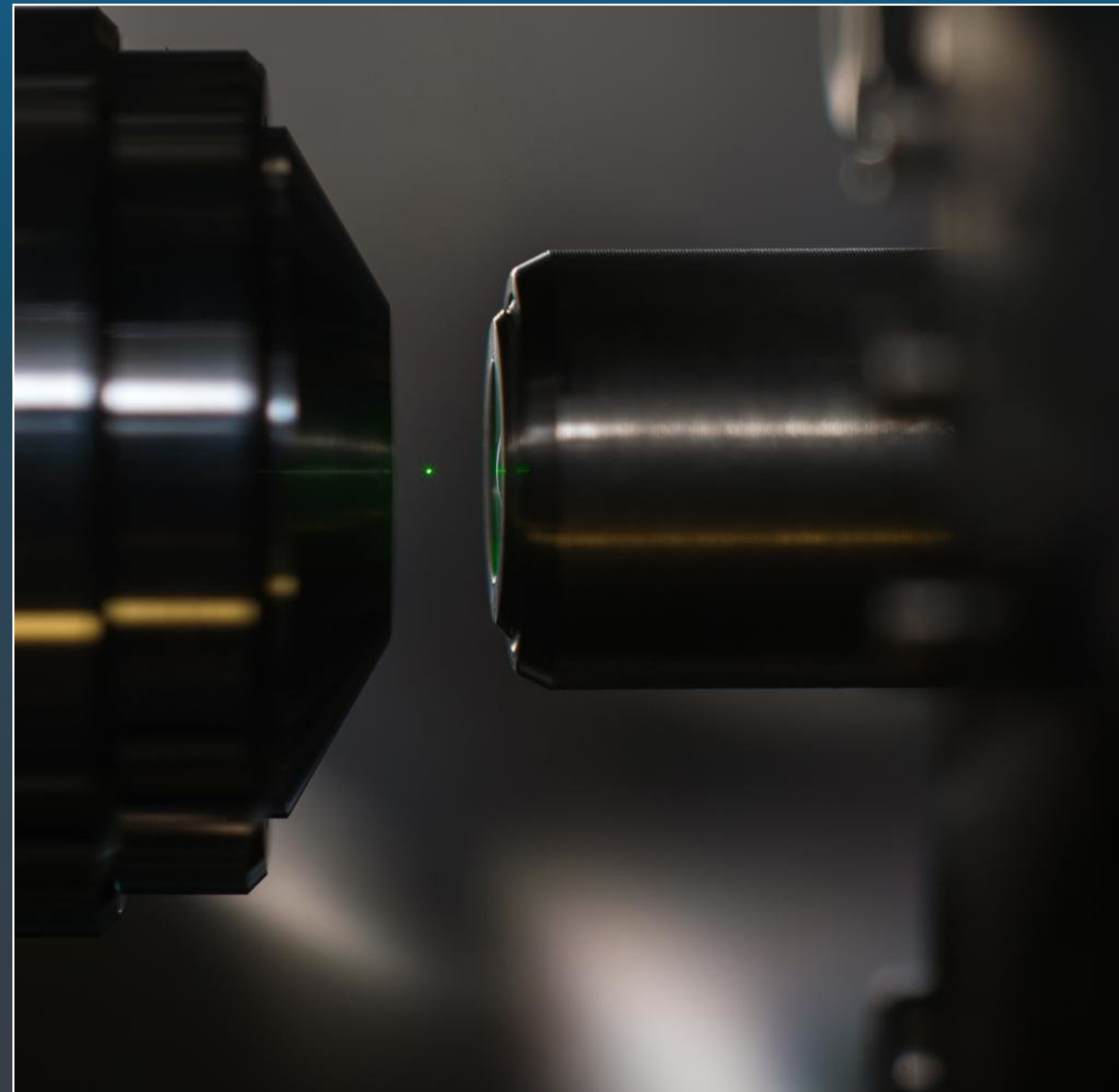


New
Physics?

Levitated optomechanics is a new tool to explore the **large-mass** regime of quantum mechanics

Thank you!

Take home message



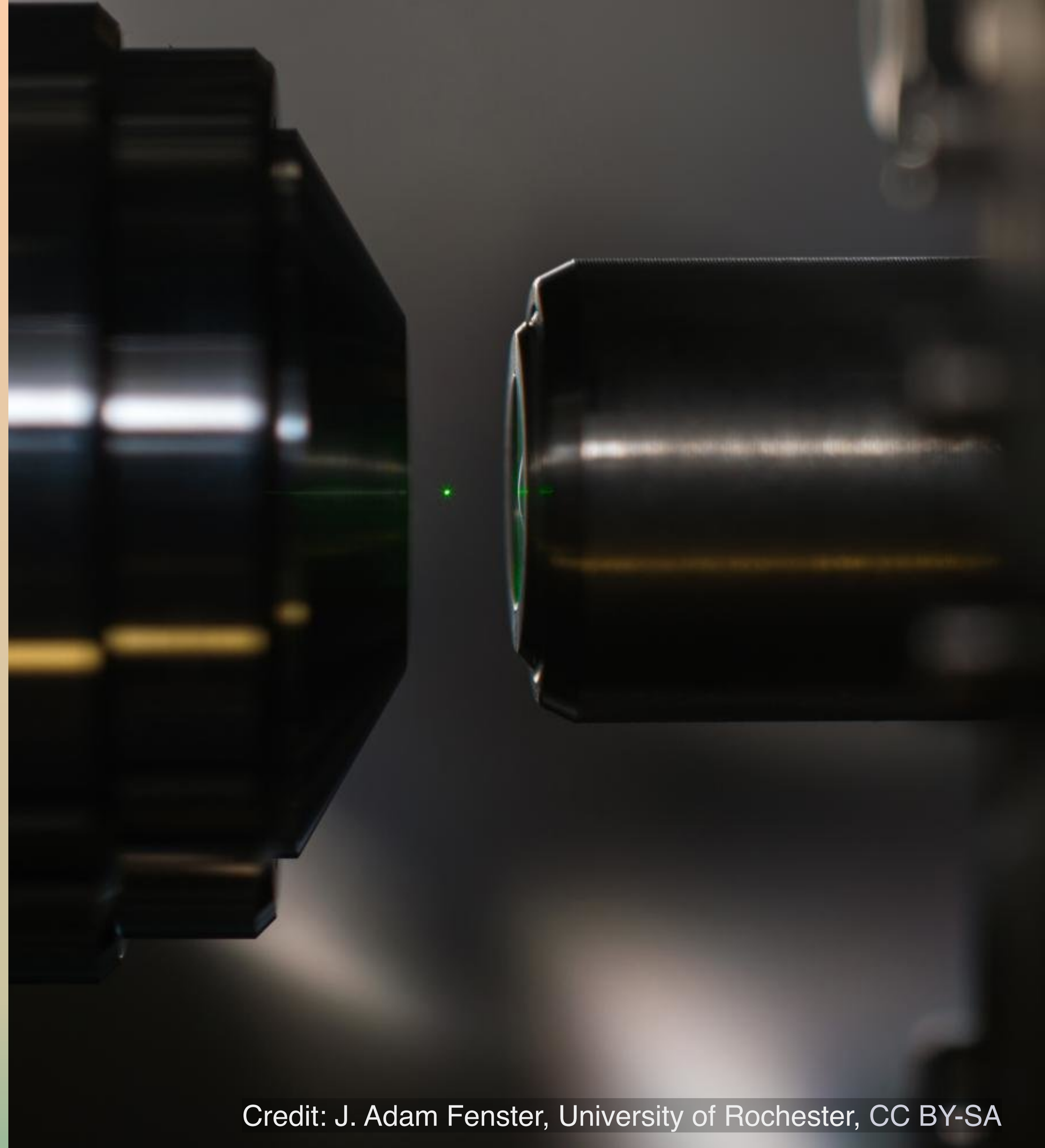
New
Physics?

Levitated optomechanics is a new tool to explore the **large-mass** regime of quantum mechanics

Thank you!

Levitodynamics

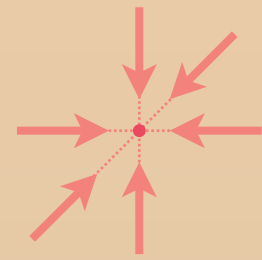
Quantum control of the **mechanical degrees of freedom** of nano- and micro-scale particles **suspended in a vacuum**



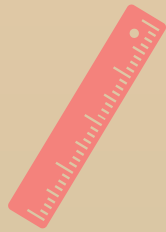
Credit: J. Adam Fenster, University of Rochester, CC BY-SA

Levitodynamics

Quantum control of the **mechanical degrees of freedom** of nano- and micro-scale particles **suspended in a vacuum**



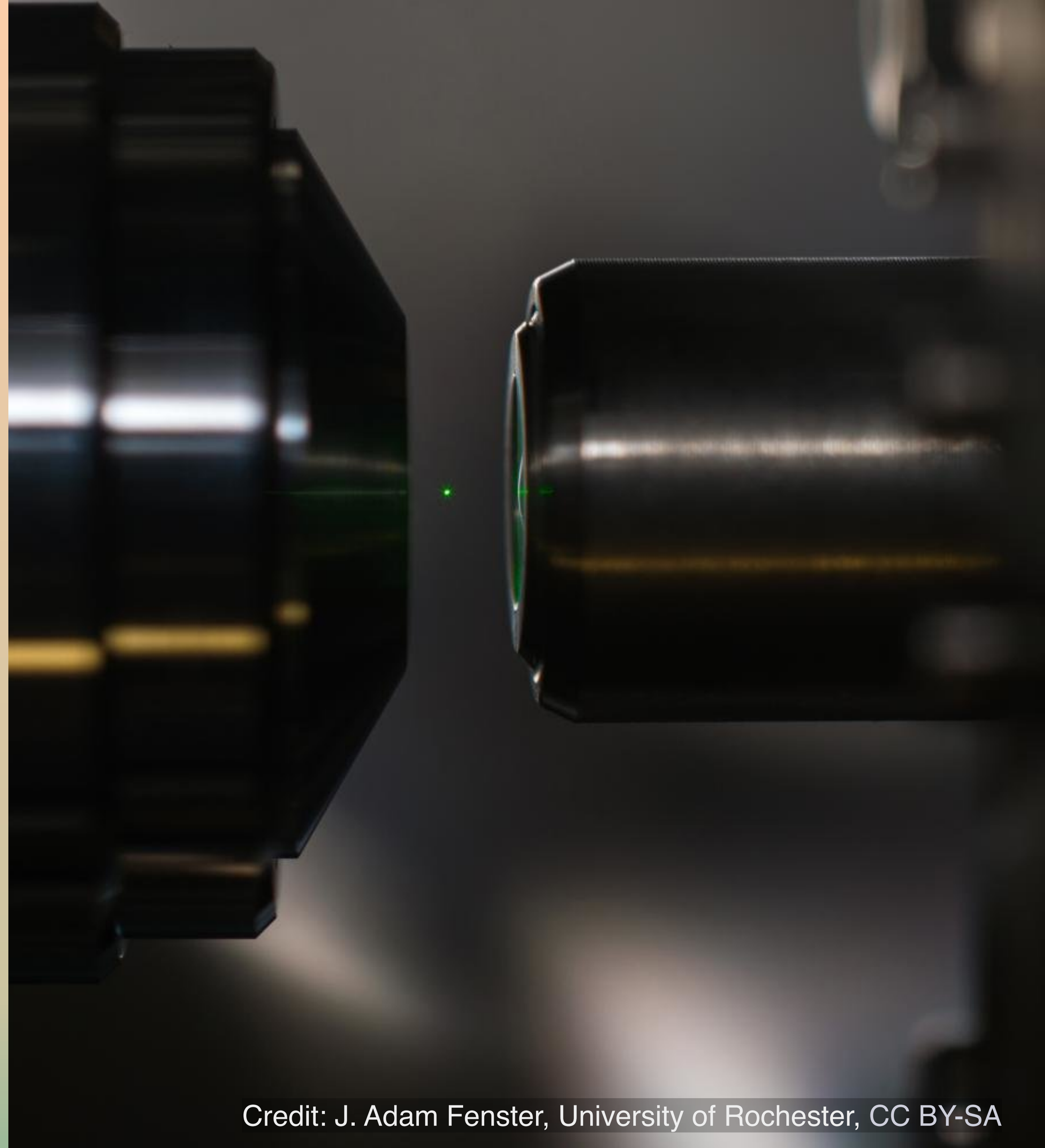
Optical tweezers, Paul traps,
magneto-gravitational ...



$\sim [10^{-7} - 10^{-5}] \text{ m}$
 $\sim [10^{-17} - 10^{-11}] \text{ Kg}$
 $\sim [10^8 - 10^{14}] \text{ \# atoms}$



silica, diamond,



(some) sources of noise

- | Collisions with surrounding gas molecules
- | Fluctuations of the trapping potentials
- | Vibrational noise
- | Internal heating
- | Black-body radiation
- | Magnetic defects, dipole moments...
- | Surface noise
- | Gravitational noise

