Challenges to Quantum Gravity in the Laboratory

Towards Robust Interference with Massive Particles

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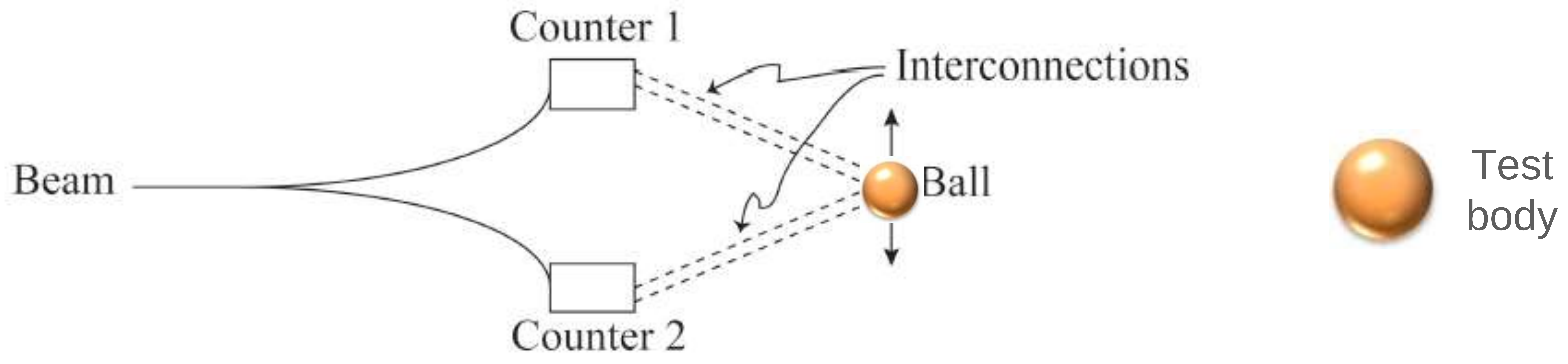
Ulm University

Challenges to Quantum Gravity in the Laboratory

Feynman’s Thought Experiment



R.P. Feynman, in a discussion at „The role of Gravitation in Physics“, 1957 Chapel Hill Conference (DeWitt and Rickles eds.)

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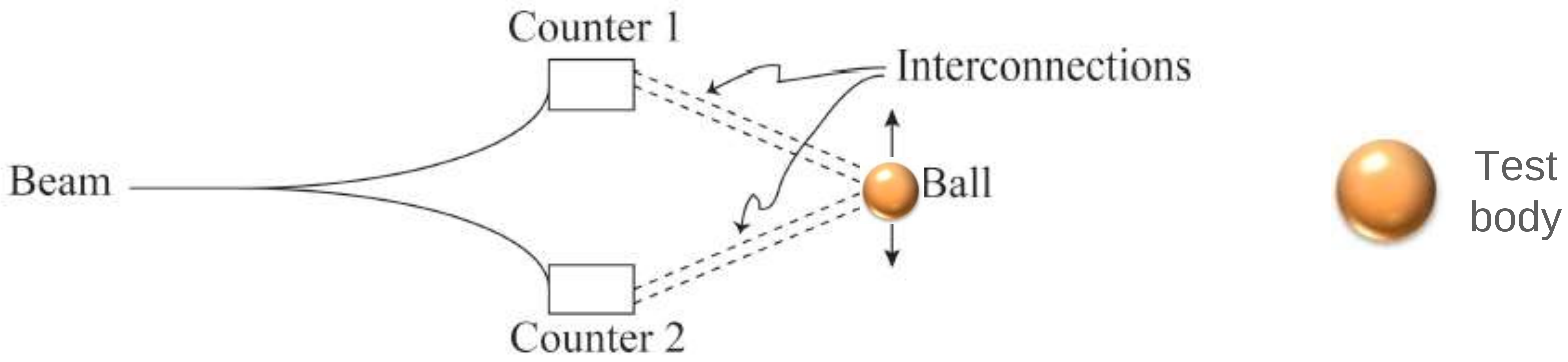
Feynman's Thought Experiment



$$|z_B\rangle_B |z_T\rangle_T + |-z_B\rangle_B |-z_T\rangle_T$$

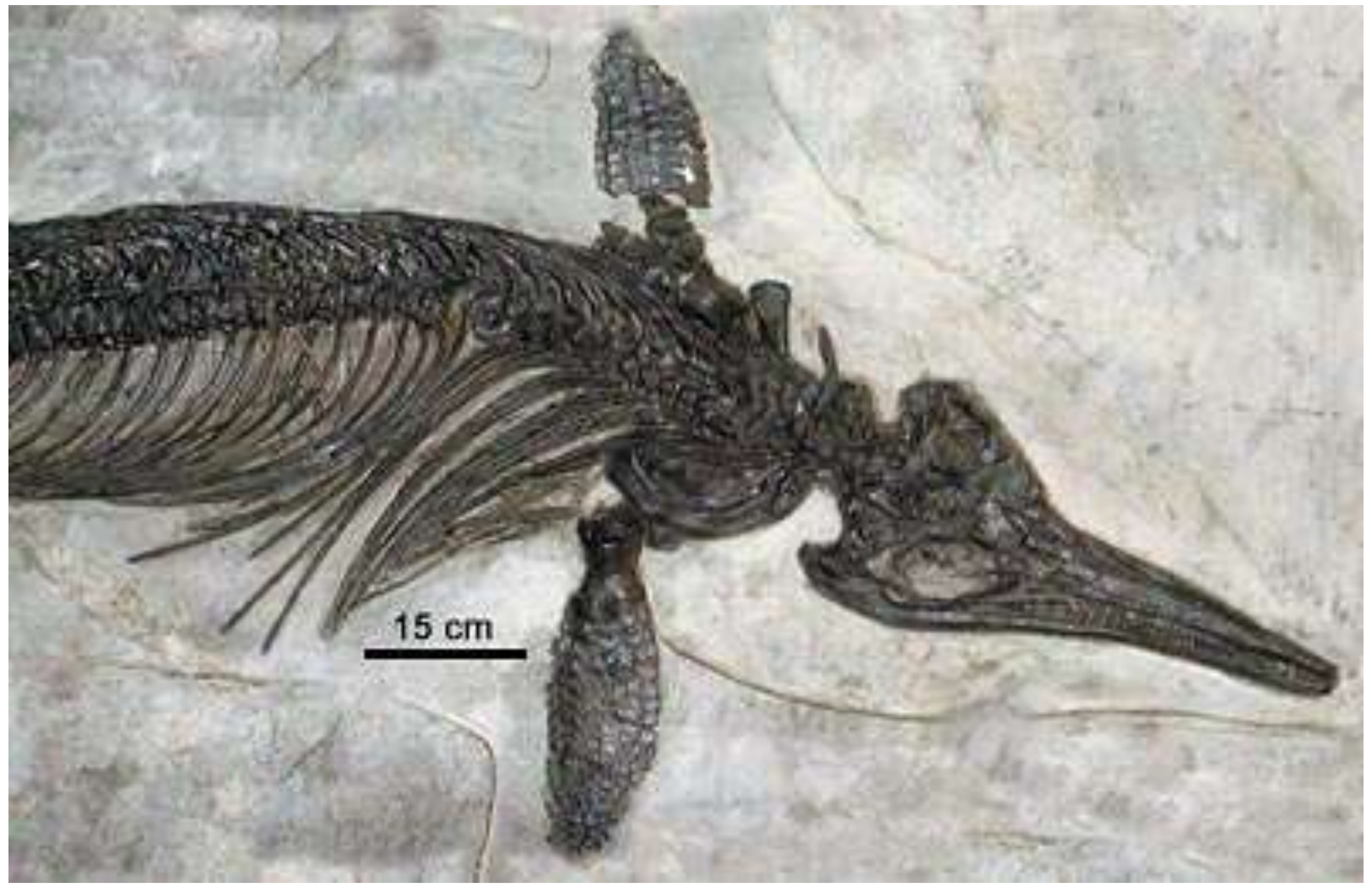
But, gravitational interaction yield tiny displacements,
so the experiment is really really hard.

R.P. Feynman, in a discussion at „The role of Gravitation in Physics", 1957 Chapel Hill Conference (DeWitt and Rickles eds.)

1952

Schrödinger in 1952

> "... whenever experiment with just one electron or atom or (small) molecule. In thought experiments, we sometimes assume that we do; this invariably entails ridiculous consequences ... we are not experimenting with single [quantum] particles, any more than we can raise Ichthyosauria in the zoo."



E. Schrödinger, "Are There Quantum Jumps." British Journal for the Philosophy of Science 3, 233 (1952)

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2021

Schrödinger in 1952

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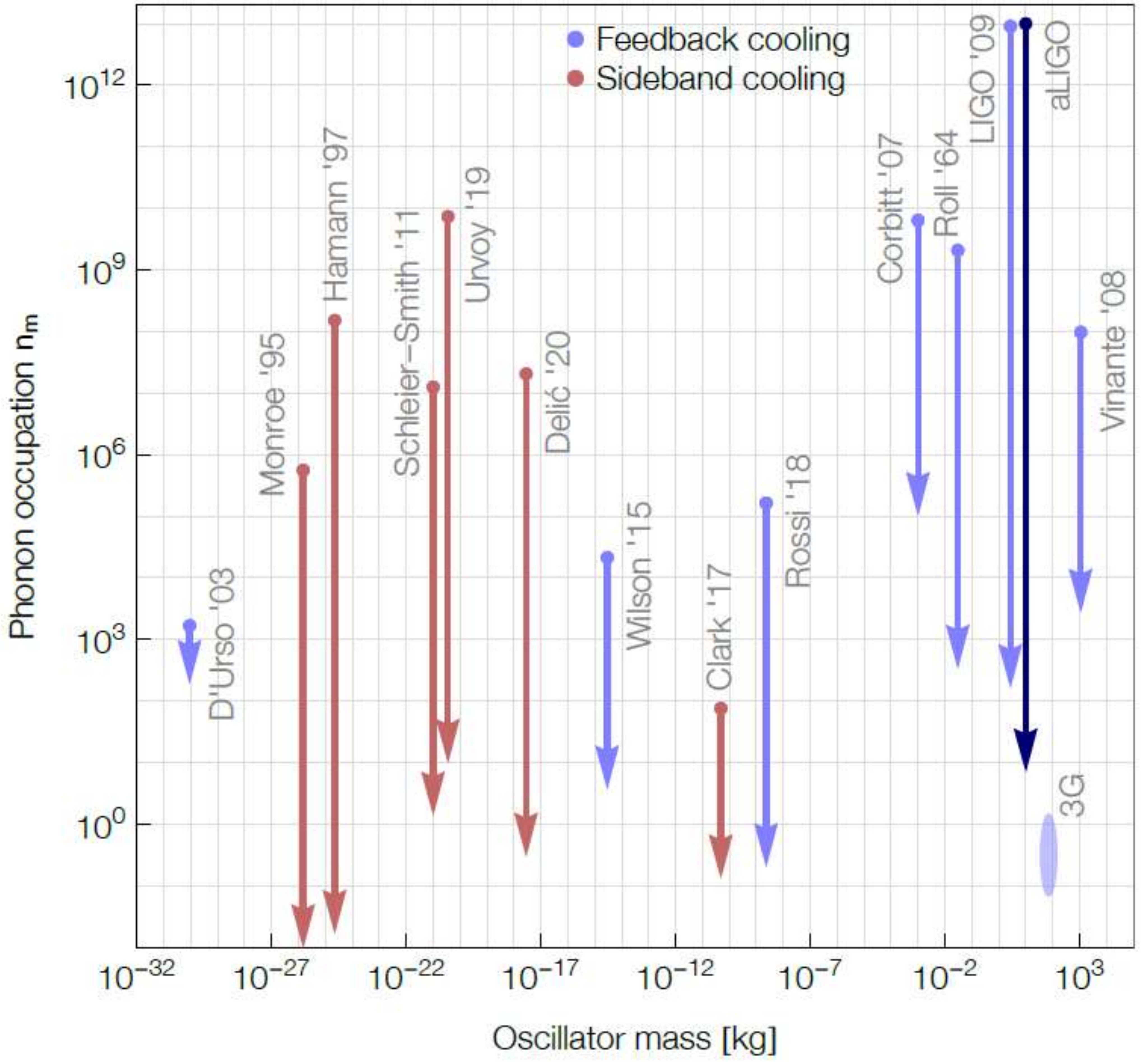

Lindner & Peres, PRA 2005
Pikovski, Vanner, Aspelmeyer, Kim, Brukner, Nat Phys 2012
Kafri & Taylor, arXiv: 1311.4558
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Albrecht, Retzker, Plenio, PRA 2014
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Krisnanda, Zuppardo, Paternostro, Paterek, arXiv:1607.01140
Schmöle, Dragoists, Hepach, Aspelmeyer, Class. Q. Grav. 2016
Bose, Mazumdar, Morley, Ulbricht, Toros, Paternostro, Geraci, Barker, Kim, Milburn, PRL 2017
Carlesso, Bassi, Paternostro, Ulbricht, NJP 2019
Pedernales, Morley, Plenio, arXiv:1906.00835
Miao, Martony, Yang, Datta, PRA 2020
Krisnanda, Tham, Paternostro, Pateerk, npj QI 2020
Pedernales, Cosco, Plenio, PRL 2020
Cosco, Pedernales, Plenio, arXiv:2012.07815
Weiss, Road, Torrontegui, Aspelmeyer, Romero-Isart, arXiv: 2012.12260
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Taken from Whittle et al, “Approaching the motional ground state of a 10 Kg object”, arXiv:2102.12665

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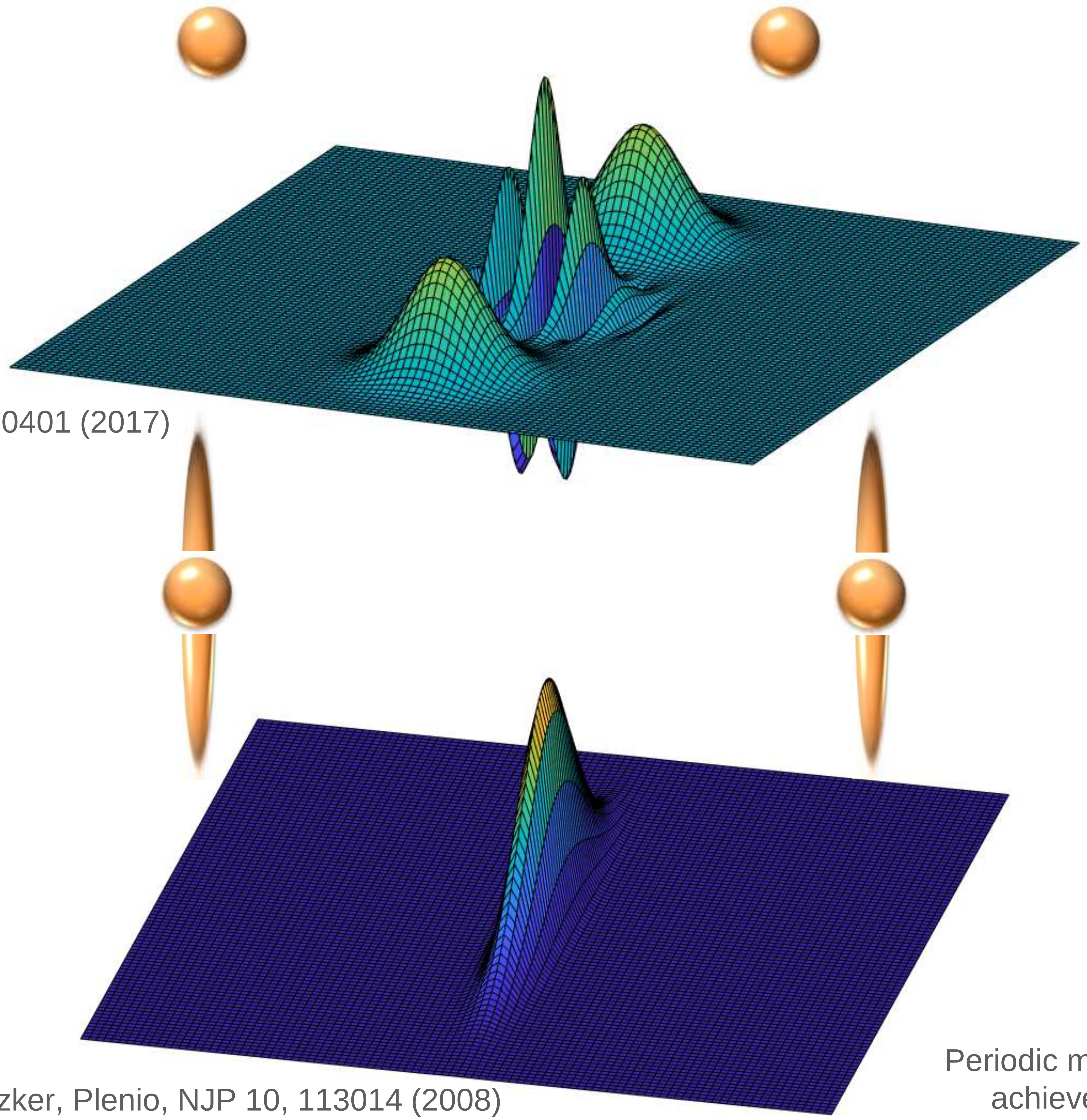
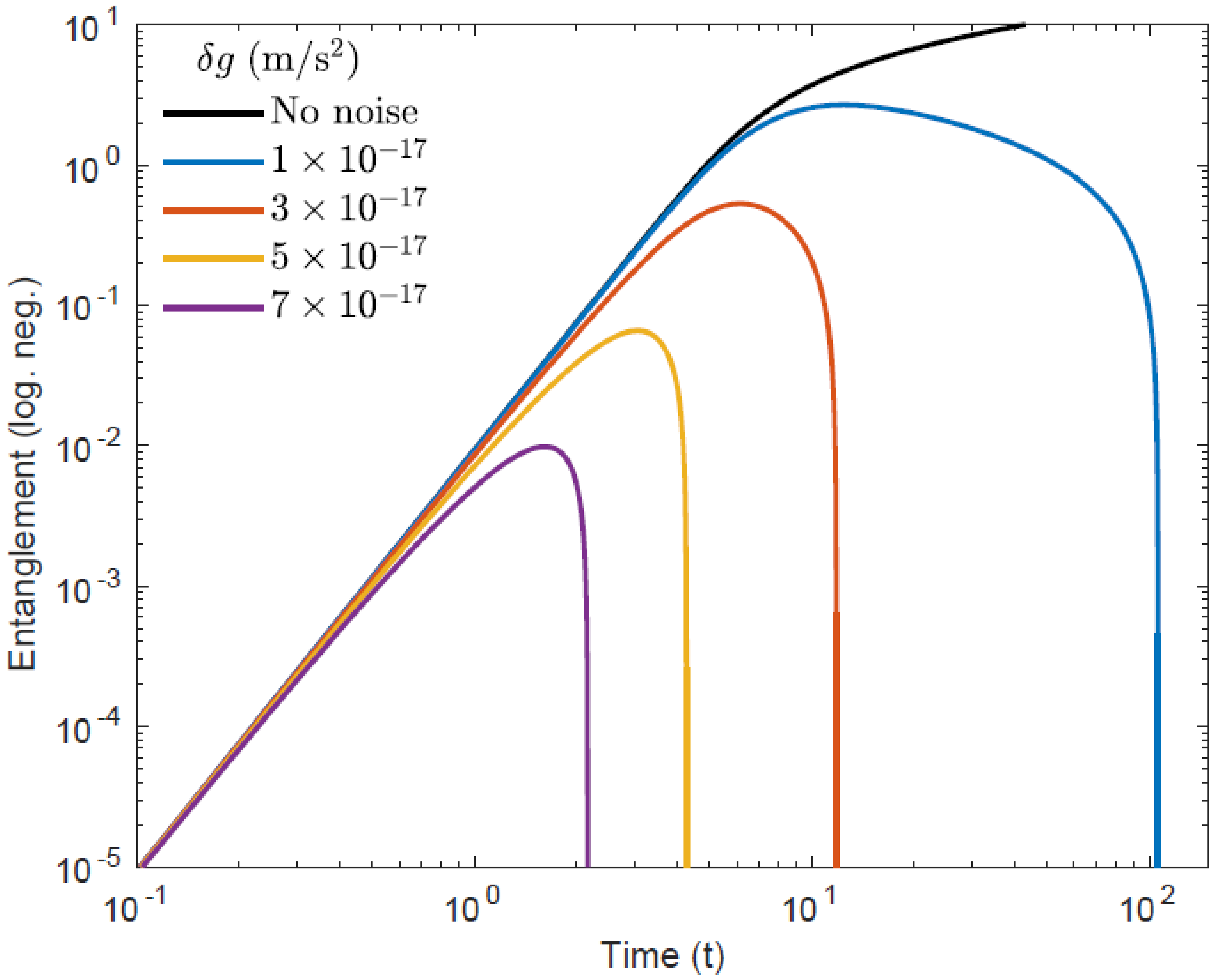
Challenges



PRL 119, 240401 (2017)



Mendez-Veiga, Pedernales, Plenio

Periodic modulation of potential achieves rapid squeezing

Serafini, Retzker, Plenio, NJP 10, 113014 (2008)
Krisnanda, Tham, Paternostro, Paterek, Npj QI 6, 12 (2020)
Cosco, Pedernales, Plenio, arXiv:2012.07815 & Weiss, Road, Torrontegui, Aspelmeyer, Romero-Isart, arXiv:2012.11235

Challenges to Gravity in the Laboratory

Challenges

Gravity: M = 1 Kg @ L = 1000 m $\longrightarrow$ $\delta g = 6.67 \cdot 10^{-17} \frac{m}{s^2}$

Electric: M = 1e^- @ L = 10cm from 1μm body with static dipole moment due to 1e^-e^+ $\longrightarrow$ $\delta g = 4.62 \cdot 10^{-17} \frac{m}{s^2}$

Magnetic: Diamagnetic particle in B = 0.1T & random gradient 10^{-12} T/m $\longrightarrow$ $\delta g = 7.96 \cdot 10^{-17} \frac{m}{s^2}$

Temperature, collisions, spin flips, …

⇩

Clean up experimental environment as much as possible

Need to develop strategies for measurement protocols that are robust to noise.

Pedernales, Morley, Plenio, arXiv:1906.00835

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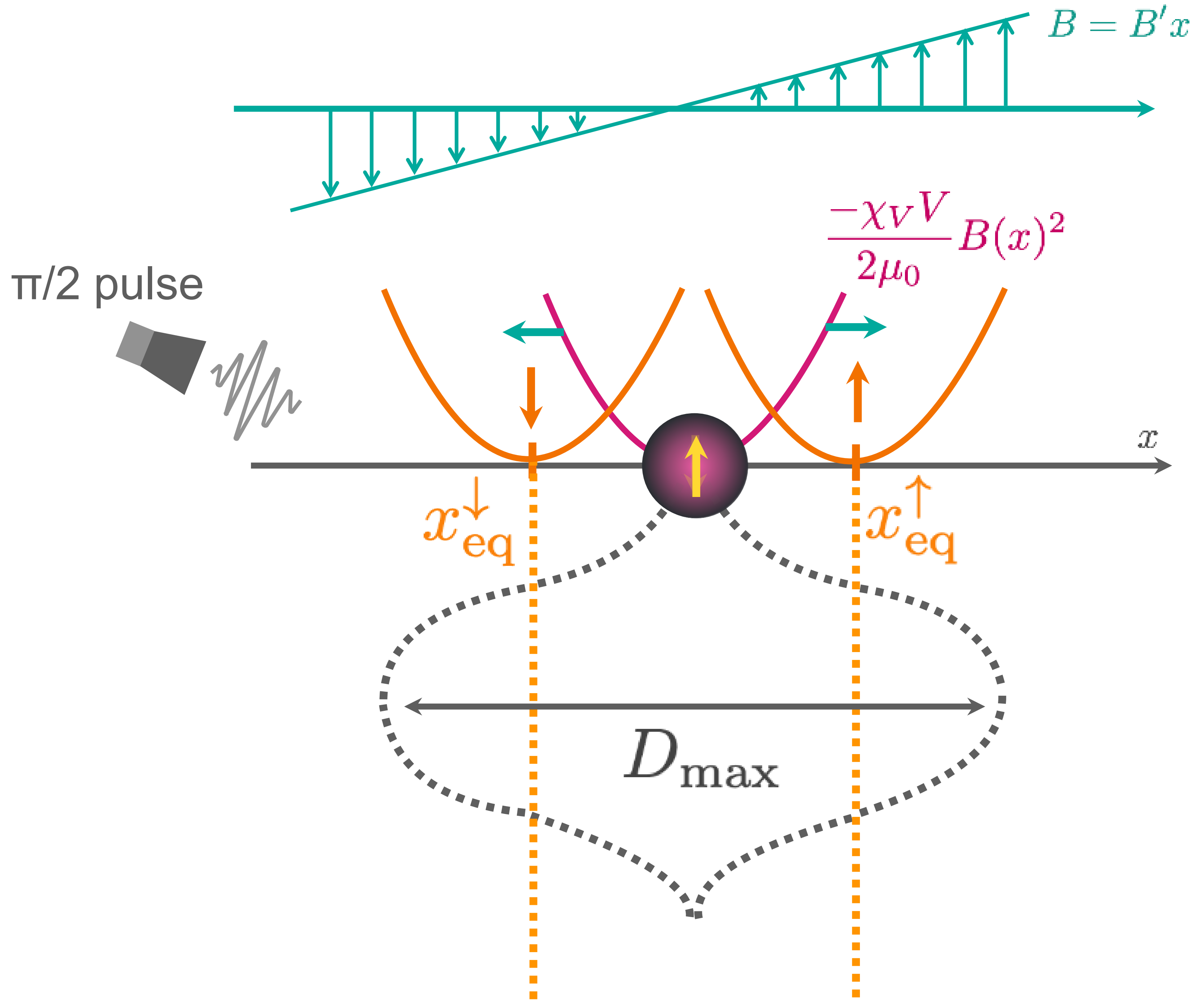
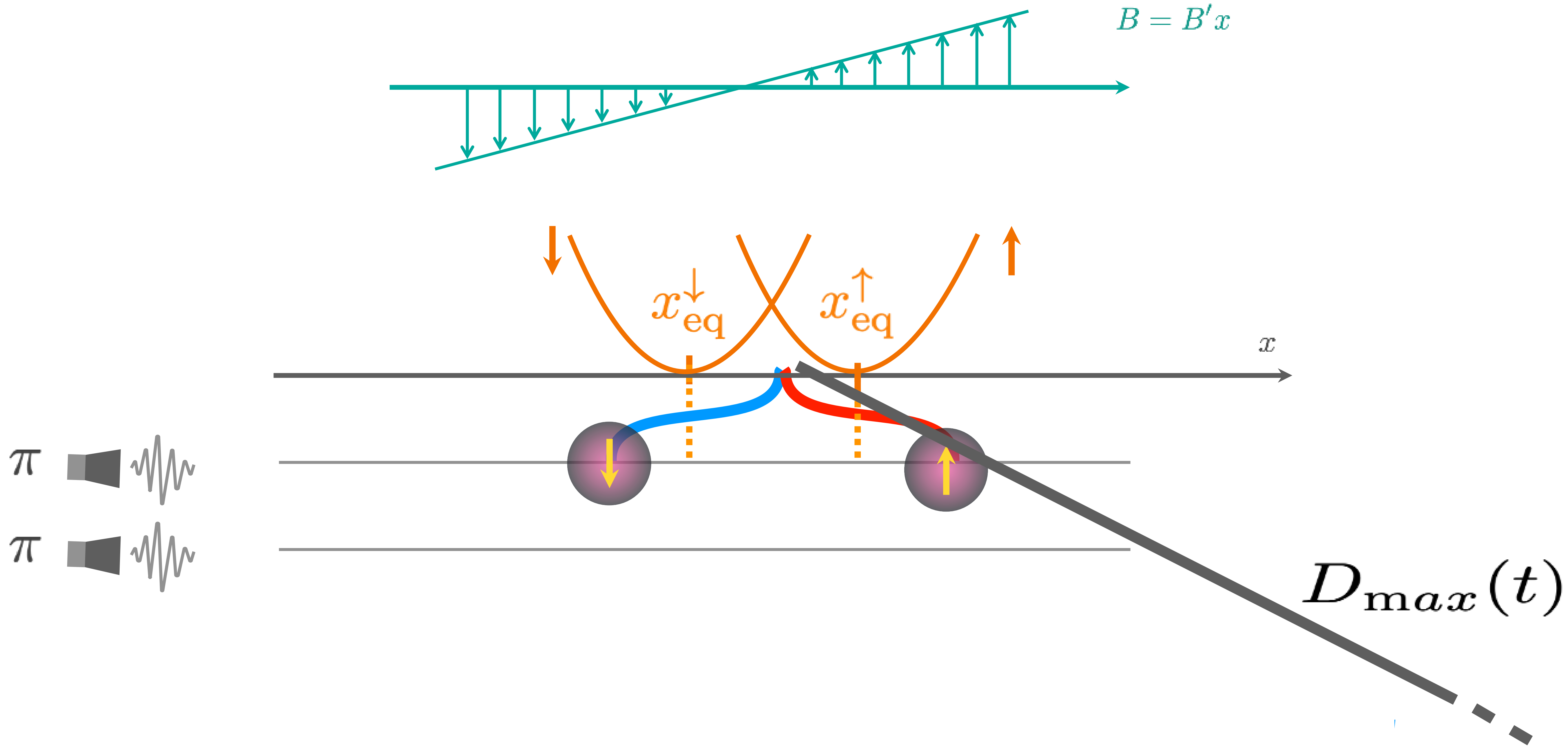
Curing Slow Noise by Symmetrisation





$$D_{\max} = \frac{4\hbar\gamma_e\mu_0}{-\chi_V}\frac{1}{VB'}$$

$$D_{\max} = \frac{4\hbar\gamma_e}{\pi V}\sqrt{\frac{\mu_0}{-\chi_V \rho_D}}\,t$$

Symmetrisation of path averages slow random forces

Pedernales, Morley, Plenio, Phys. Rev. Lett. 125, 023602 (2020)

Slide by J. Pedernales

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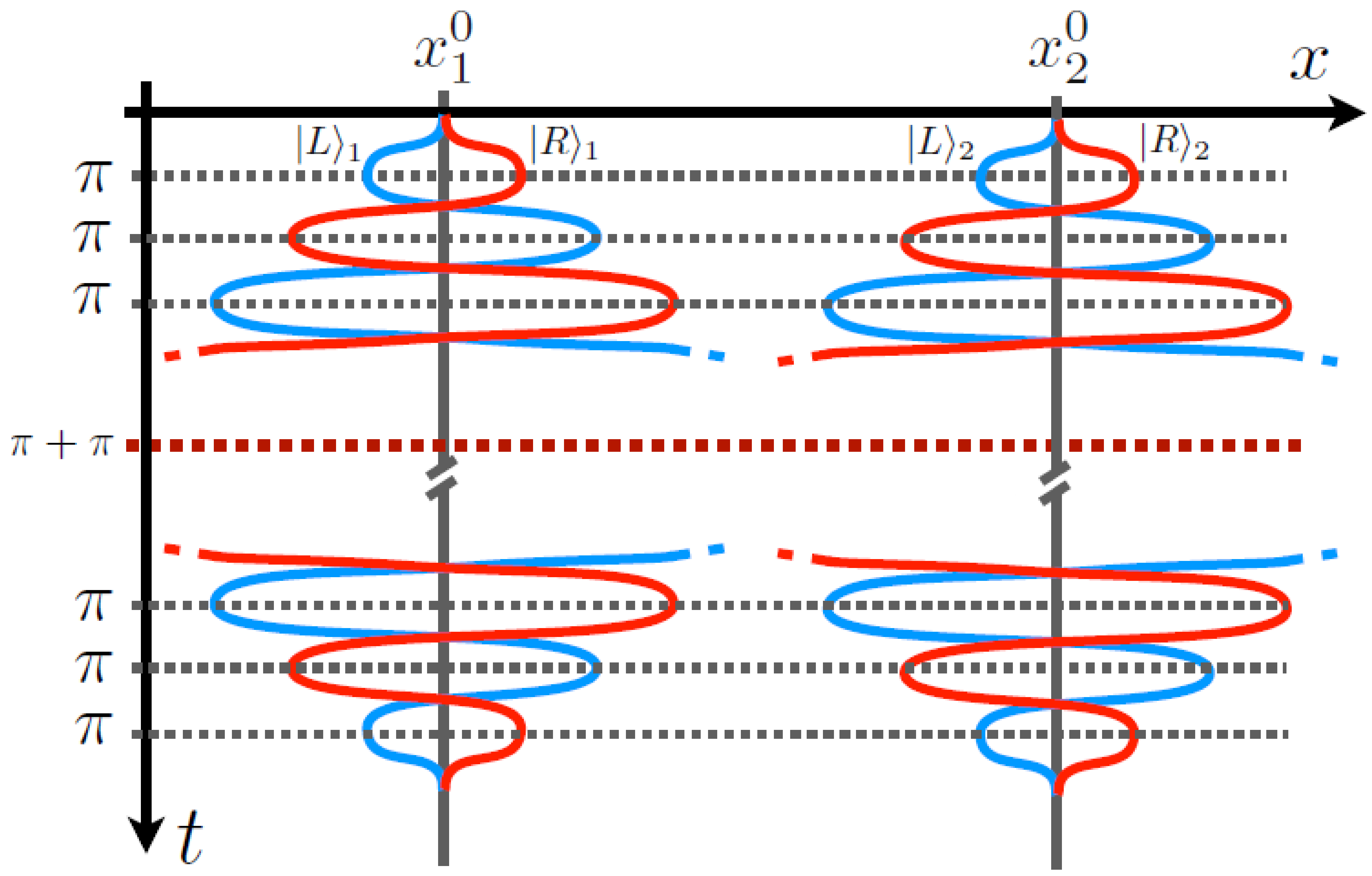
Curing Slow Noise by Symmetrisation



Force gradients are not averaged, hence short distance interaction between particles is preserved

Signal to noise ratio is improved

Pedernales, Morley, Plenio, Phys. Rev. Lett. 125, 023602 (2020)

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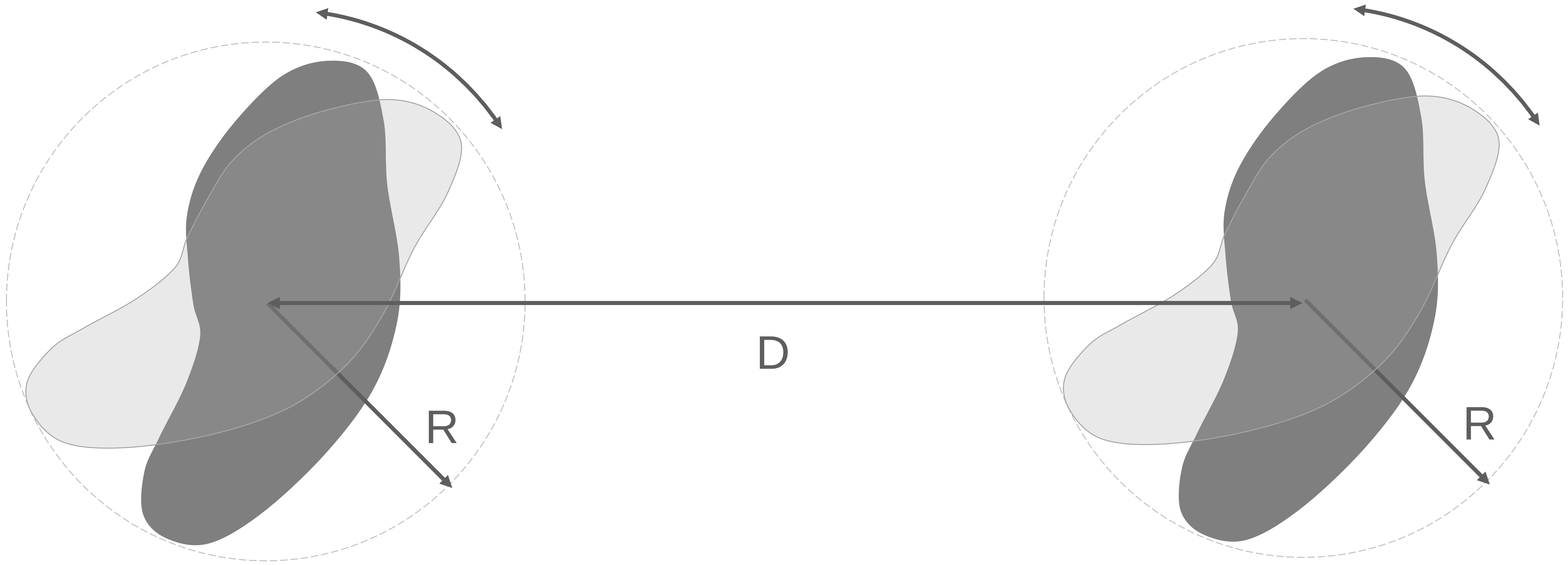
Curing Noise from Distant Sources Part I



Interaction of masses in
superposition of orientations

Pedernales, Cosco, Plenio, Phys. Rev. Lett. 125, 0905021 (2020)

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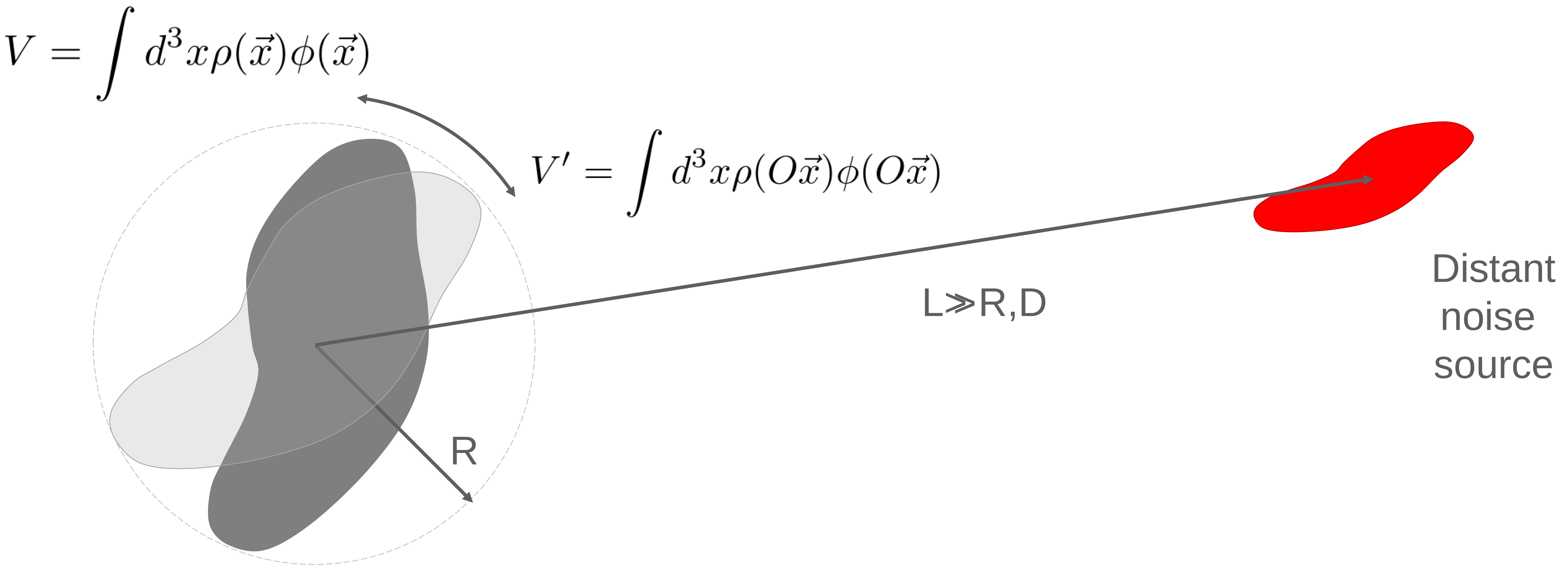
Curing Noise from Distant Sources Part I



Mass in superposition of orientations

Presence of distant noise source leads to fluctuation in energy of different orientations of test mass.

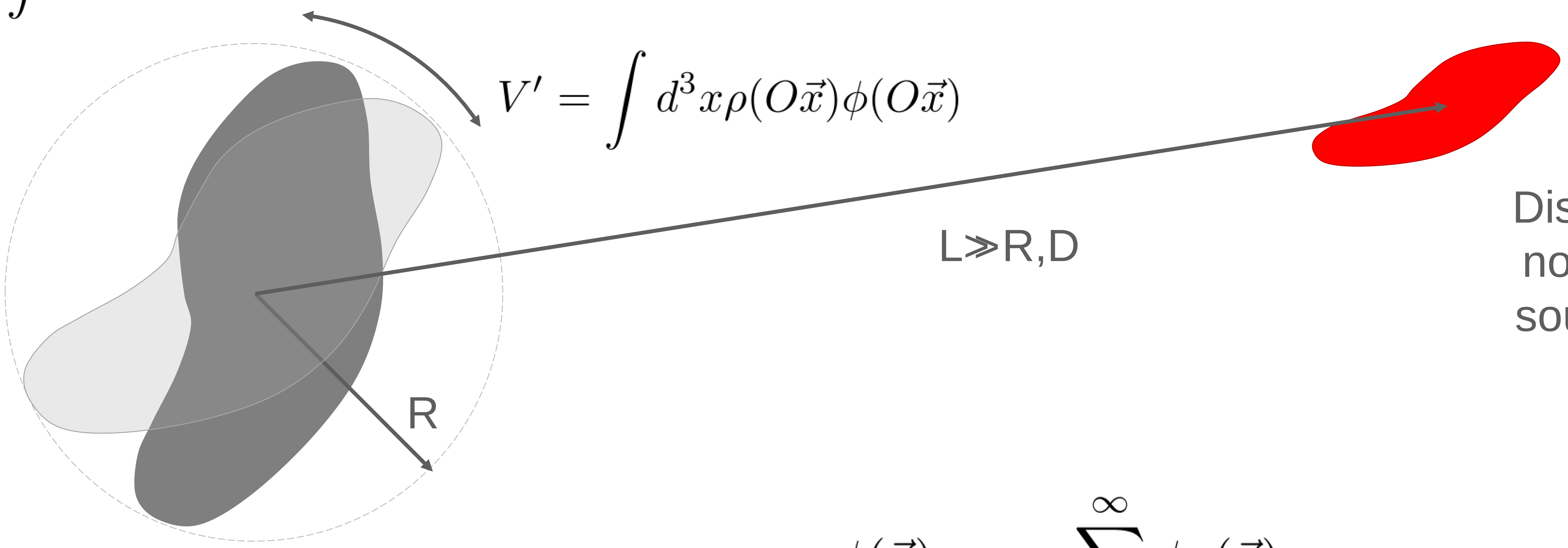
Pedernales, Cosco, Plenio, Phys. Rev. Lett. 125, 0905021 (2020)

Challenges to Gravity in the Laboratory

Curing Noise from Distant Sources Part I

$$V = \int d^3x \rho(\vec{x})\phi(\vec{x})$$

$$V' = \int d^3x \rho(O\vec{x})\phi(O\vec{x})$$



Mass in superposition of orientations

$$\begin{aligned}\phi(\vec{x}) &= \sum_{n=0}^{\infty} \phi_n(\vec{x}) \\ &= \sum_{n=0}^{\infty} \sum_{i_1,\ldots,i_N=1}^{3} M_{i_1,\ldots,i_N} \underbrace{\vec{x}_{i_1} \cdot \ldots \cdot \vec{x}_{i_N}}\end{aligned}$$

$M_{i_1,\ldots,i_N} \sim \left(\frac{1}{L}\right)^N$, $\quad \vec{x}_{i_1} \cdot \ldots \cdot \vec{x}_{i_N} \sim R^N$

Pedernales, Cosco, Plenio, Phys. Rev. Lett. 125, 0905021 (2020)

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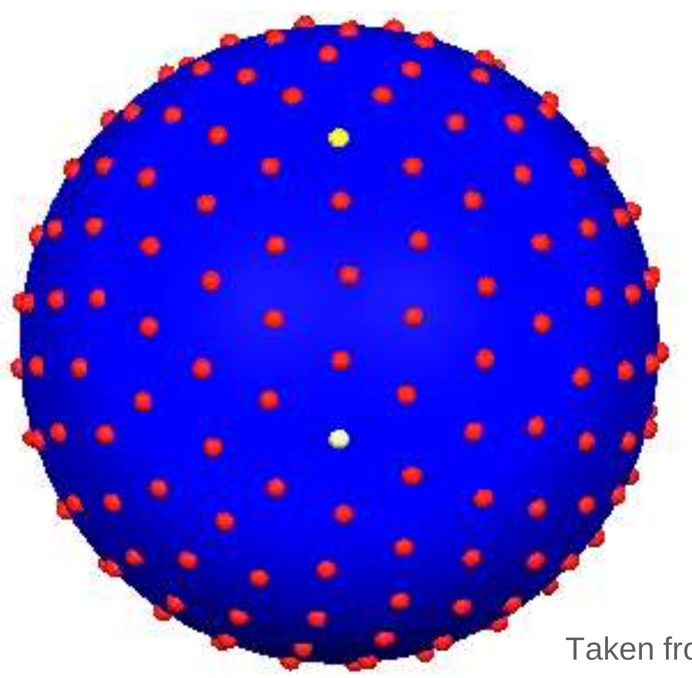
Curing Noise from Distant Sources Part I

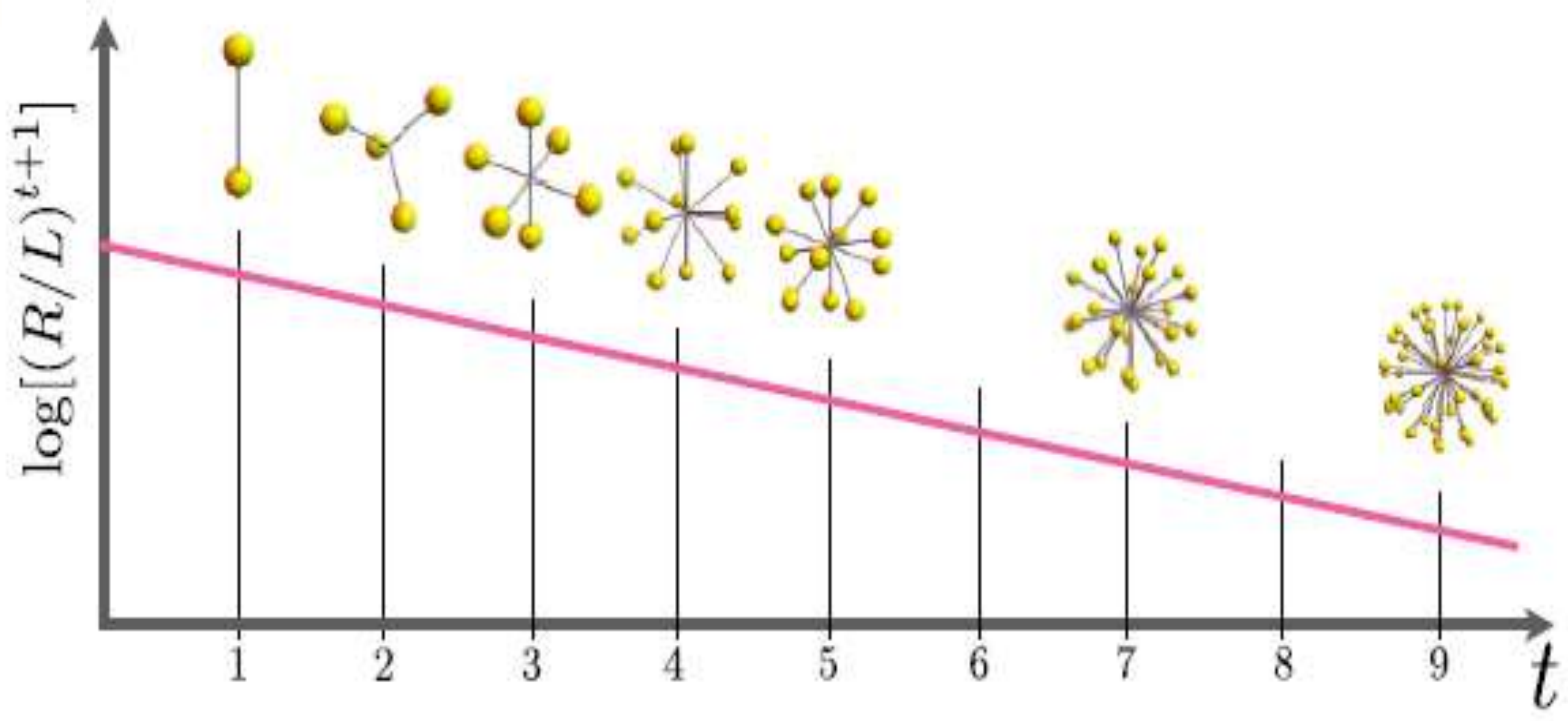
Spherical t-design: Any set of points $\vec{x}_i$ such that

$$\int_{S^2} f(\vec{x}) d\mu(\vec{x}) = \frac{1}{N} \sum_{i=1}^{N} f(\vec{x}_i)$$

for any polynomial of order t.



Taken from An & Chen, arXiv1611.02785



Noise $\sim \left(\frac{R}{L}\right)^N$

Interaction $\sim \left(\frac{R}{D}\right)^N$

SNR $\sim \left(\frac{L}{D}\right)^N \to \infty$

Pedernales, Cosco, Plenio, Phys. Rev. Lett. 125, 0905021 (2020)

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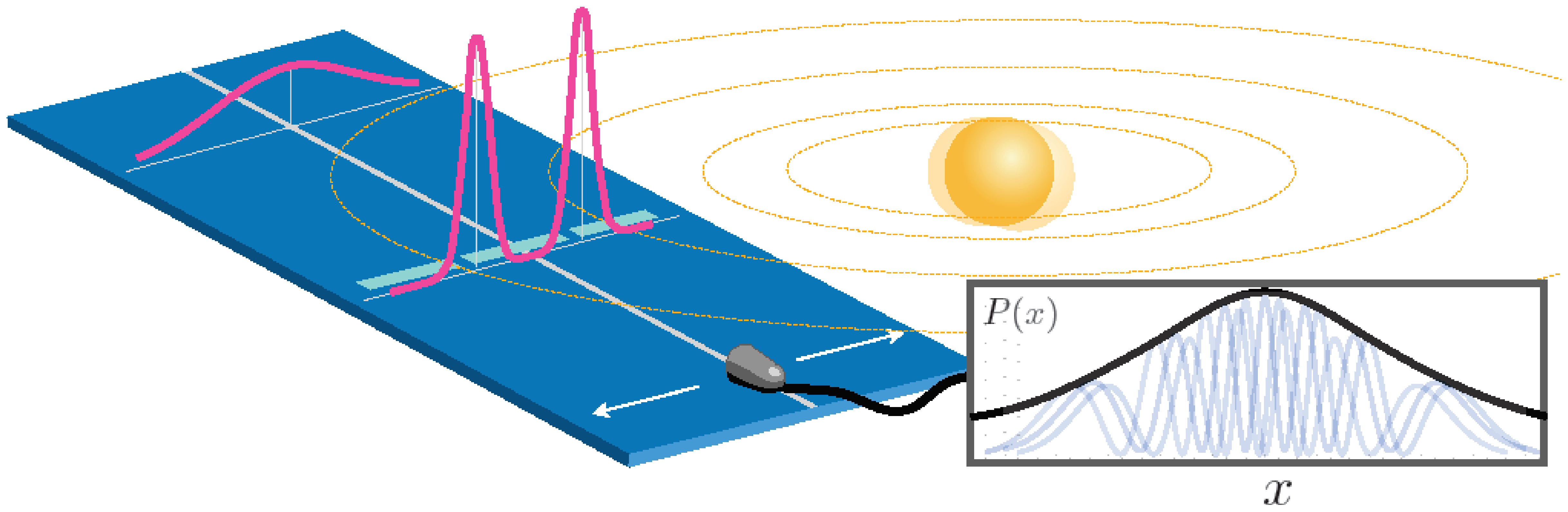
Curing Noise from Distant Sources Part II



$$P(x, t_k) = \frac{4}{\mathbb{N}_{t_k}} e^{-\frac{[x - x_\gamma(t_k)]^2}{2\sigma_{t_k}^2}} \cos^2[k_{t_k}/2(x - x_\gamma(t_k))]$$

$$\bar{P}(x) = \frac{e^{-\frac{x^2}{2(\sigma_{t_k}^2+\sigma_\gamma^2)}}}{\bar{\mathbb{N}}} \left[1 + e^{-k^2 \frac{\sigma_{t_k}^2 \sigma_\gamma^2}{2(\sigma_{t_k}^2+\sigma_\gamma^2)}} \cos\left[k \frac{\sigma_{t_k}^2}{\sigma_\gamma^2+\sigma_{t_k}^2} x\right]\right]$$

Coordinate $x_- = \frac{x_1 - x_2}{2}$ is insensitive to fluctuations

but do the setups have to be identical?

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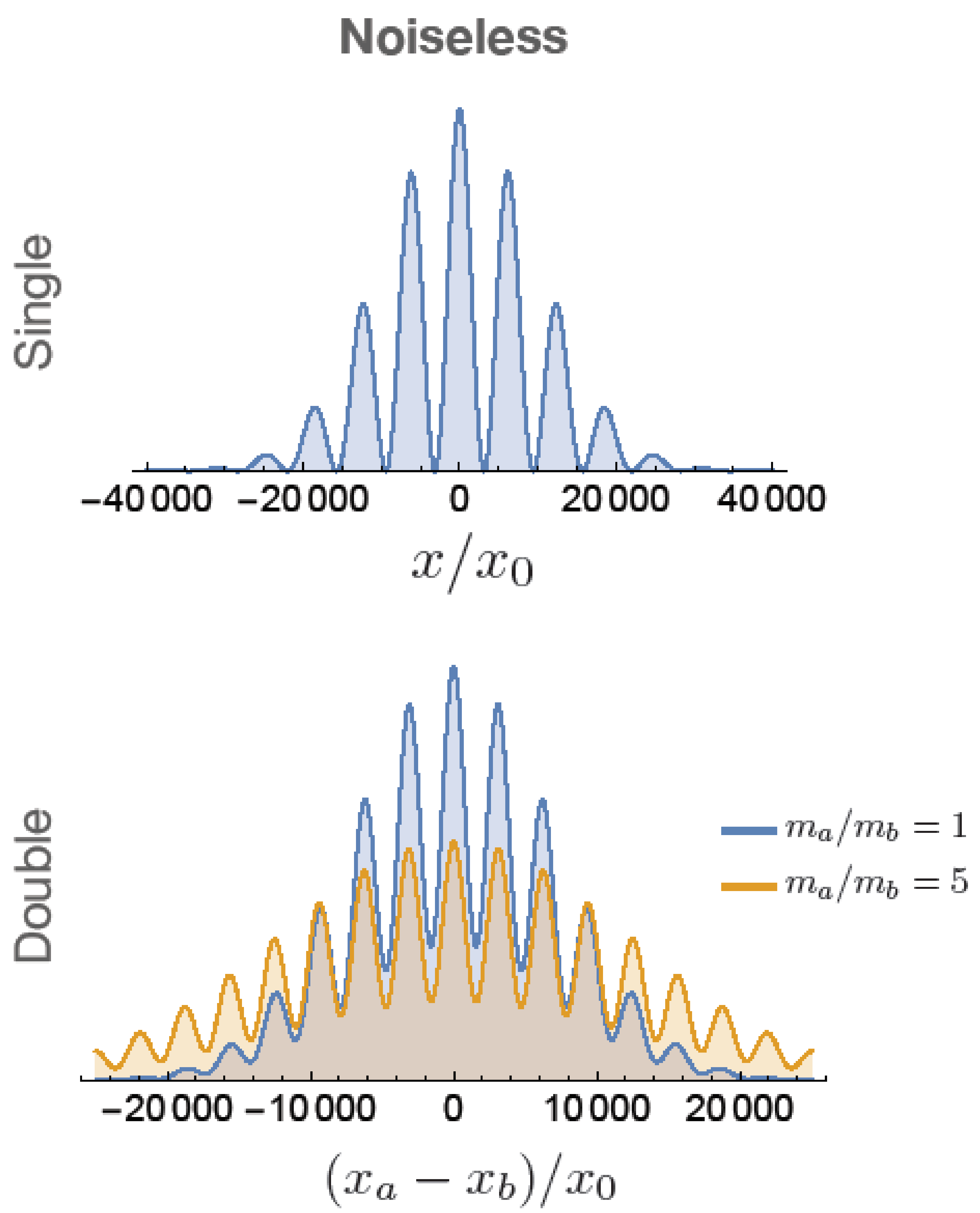
Curing Noise from Distant Sources Part II



Can be generalised to

- arbitrary masses between experiments
- Use n setups to eliminate nth order gradient perturbations

  …

Pedernales & Plenio, arXiv: this week

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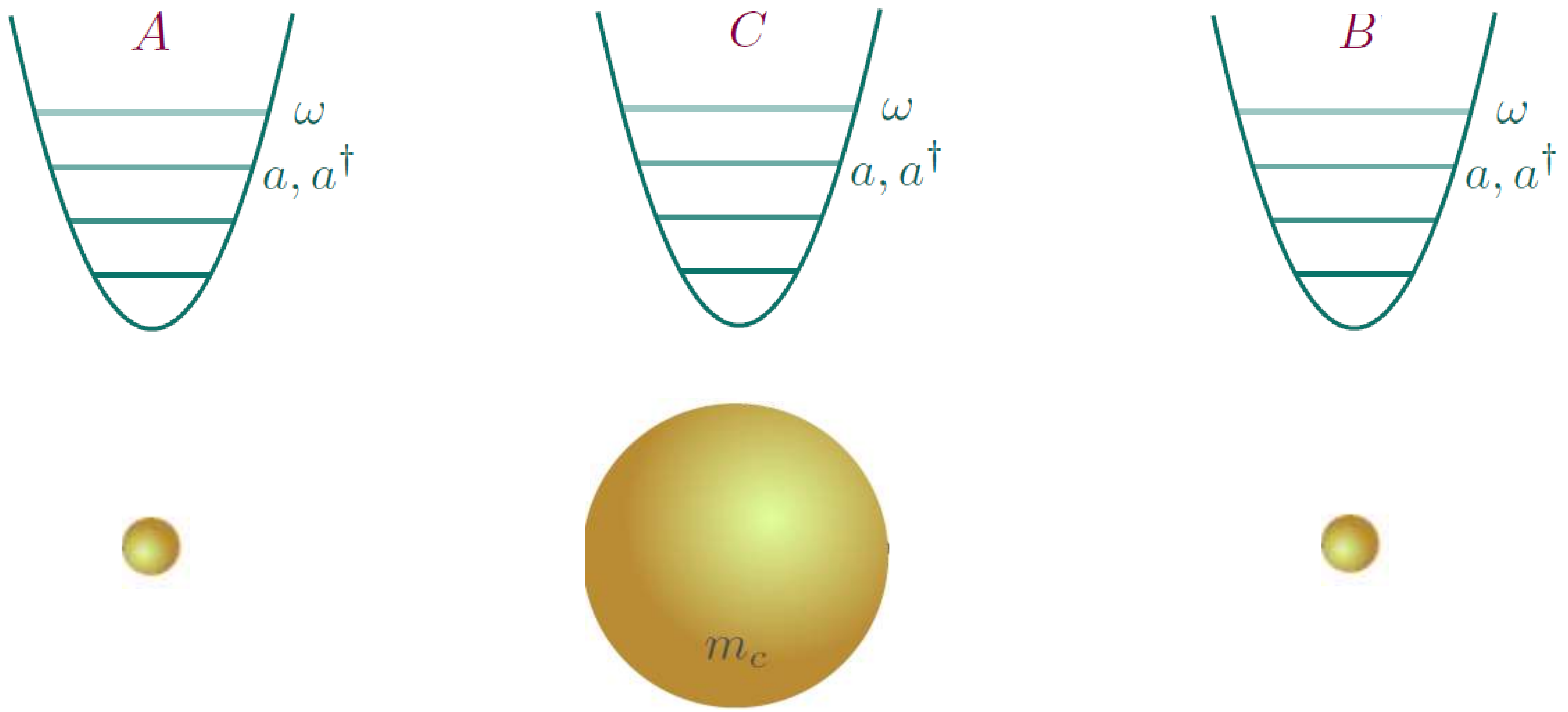
Speeding up Protocols



Pedernales, Streltsov, Plenio, arXiv:2104.14524

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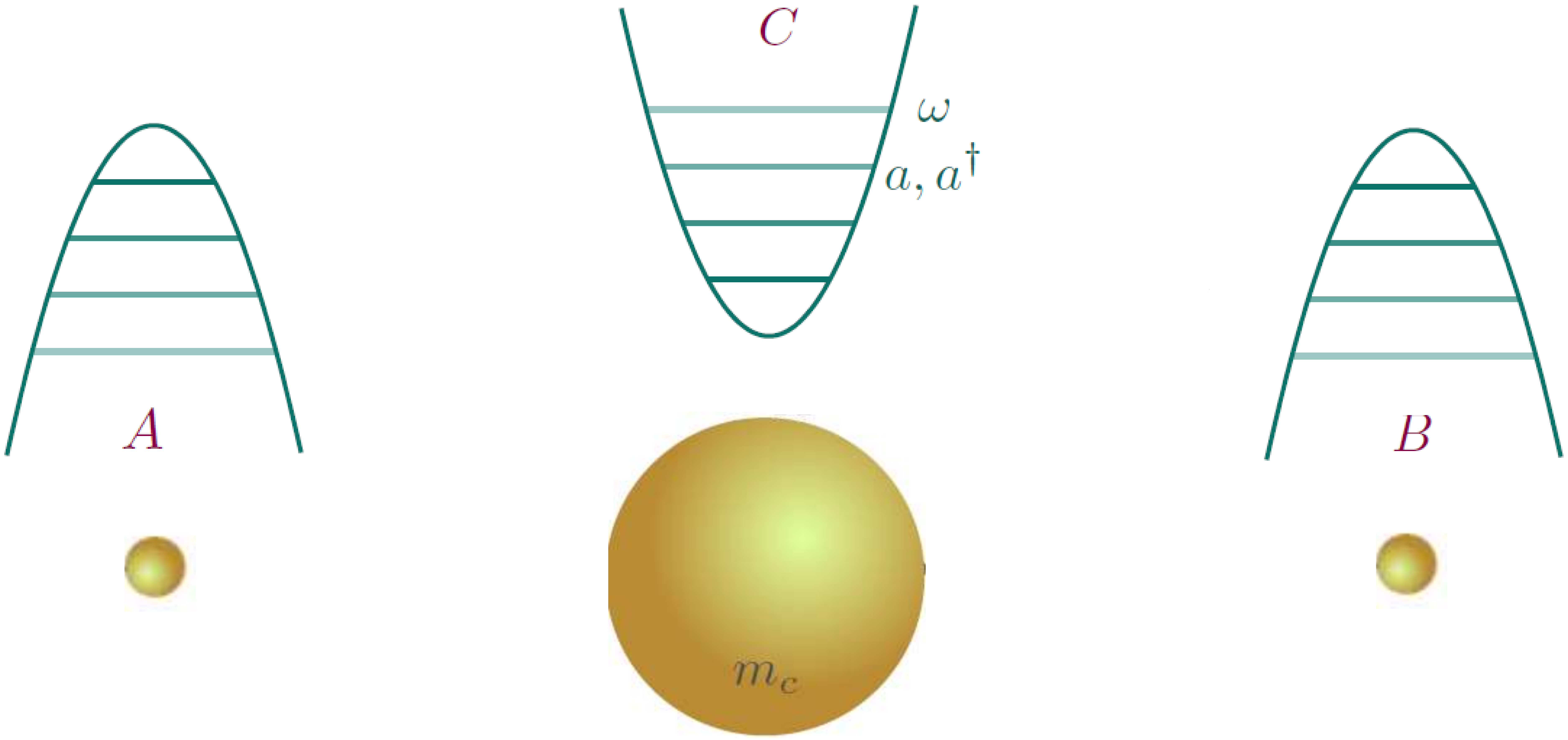
Speeding up Protocols



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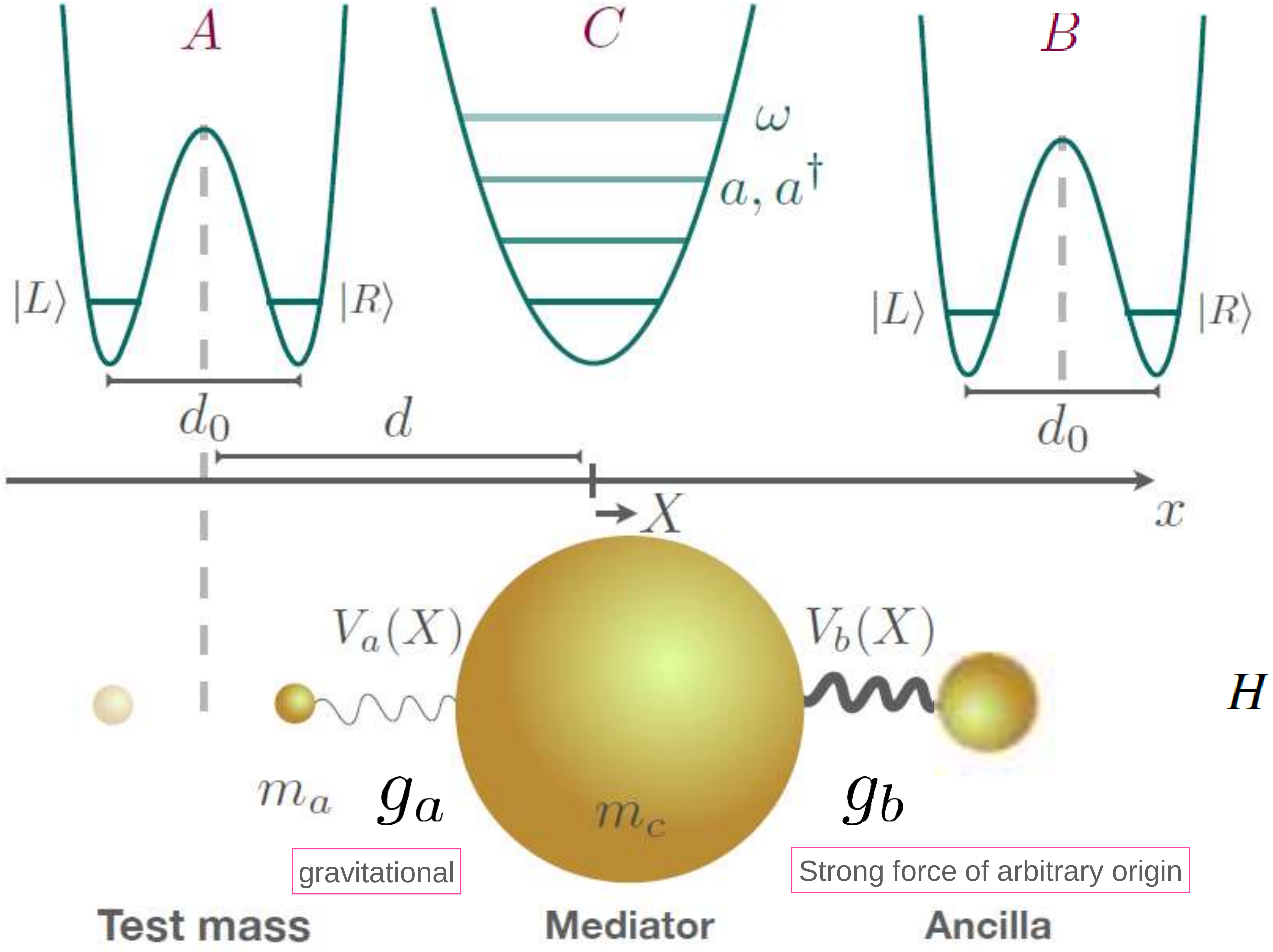
Speeding up Protocols



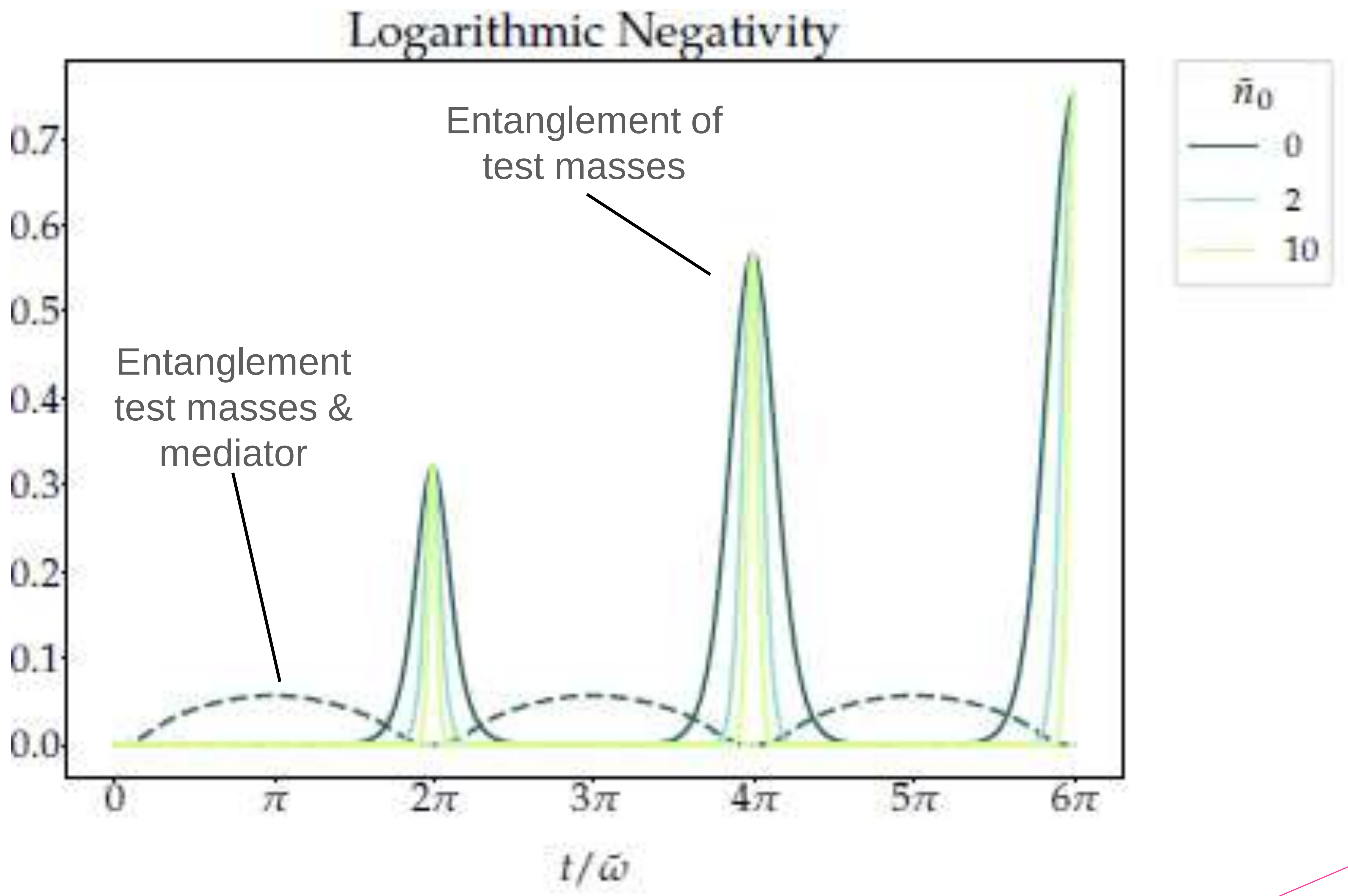
$$H = \hbar\omega_a \sigma_a^z + \hbar\omega_b \sigma_b^z + \hbar\tilde{\omega} a^\dagger a + \hbar(g_a \sigma_z^a + g_b \sigma_z^b)(a + a^\dagger)$$

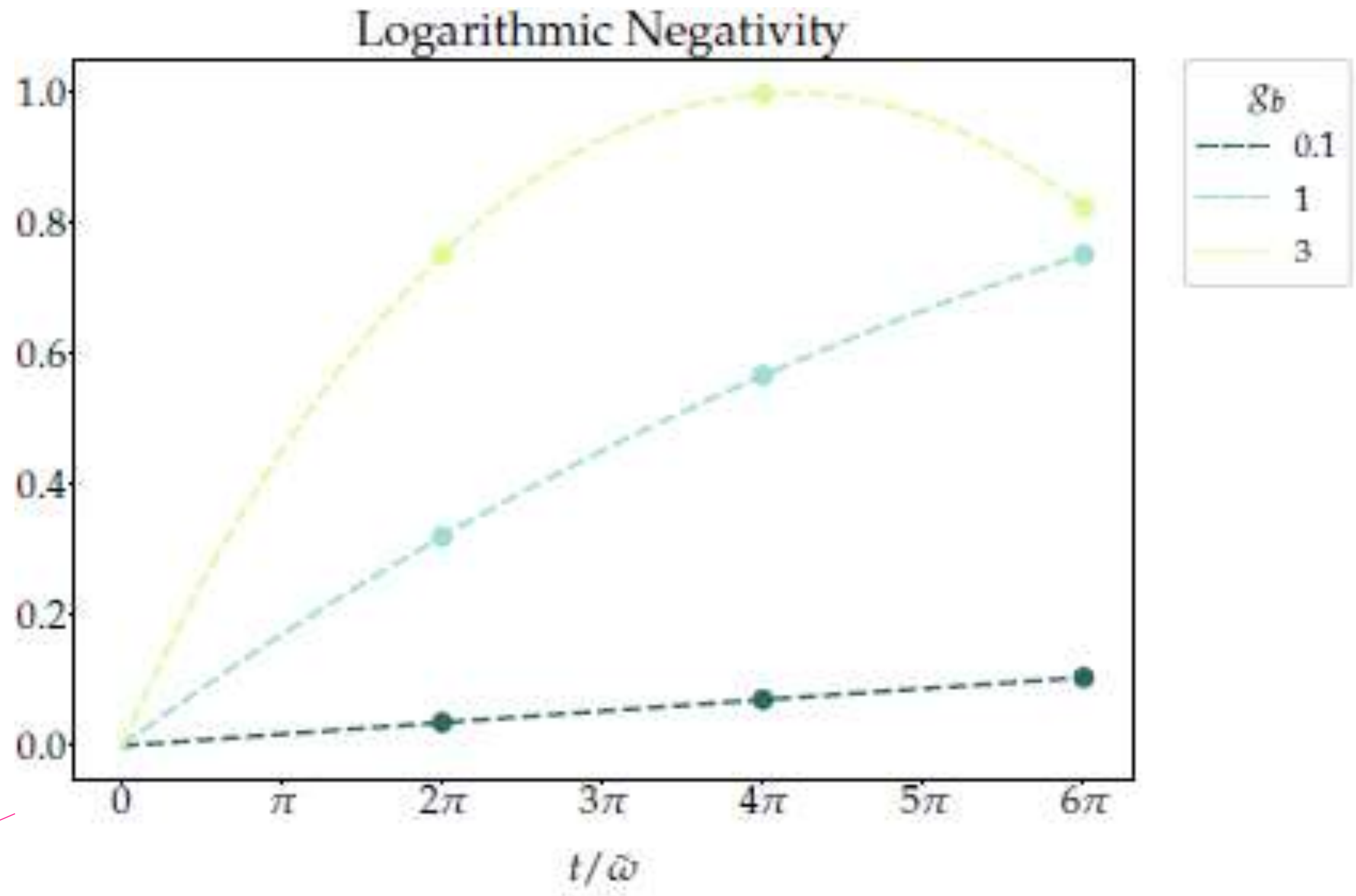
$$g_b \gg g_a$$

Pedernales, Streltsov, Plenio, arXiv:2104.14524

Challenges to Gravity in the Laboratory

Speeding up Protocols





$$U(t) = \qquad e^{-i\frac{2g_a g_b}{\tilde{\omega}}\sigma_z^a \sigma_z^b (t - \frac{\sin\tilde{\omega}t}{\tilde{\omega}})}$$

$$\alpha_t = \frac{e^{-i\omega t} - 1}{\omega}$$

Pedernales, Streltsov, Plenio, arXiv:2104.14524

Challenges to Gravity in the Laboratory

Speeding up Protocols

Origin of enhancement is mass and amplitude of mediator

Limit: Amplitude comparable to distance of test masses

Ratio of achievable entanglement for the same time t →

$$\frac{\phi_m}{\phi_d} = \frac{1}{\sqrt{2}}\frac{m_c}{m_a}\frac{\Delta_c}{d_0} \leq \frac{1}{\sqrt{2}}\frac{m_c}{m_a}\frac{d}{d_0}$$

Independent of temperature of mediator !

Conclusion: With the investment of sufficiently much thought to increase experimental perfection, material properties etc and, at the same time, an effort to design robust protocols, Feynman's thought experiment may well become a reality before the 100th birthday of its original proposal.

Pedernales, Streltsov, Plenio, arXiv:2104.14524

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