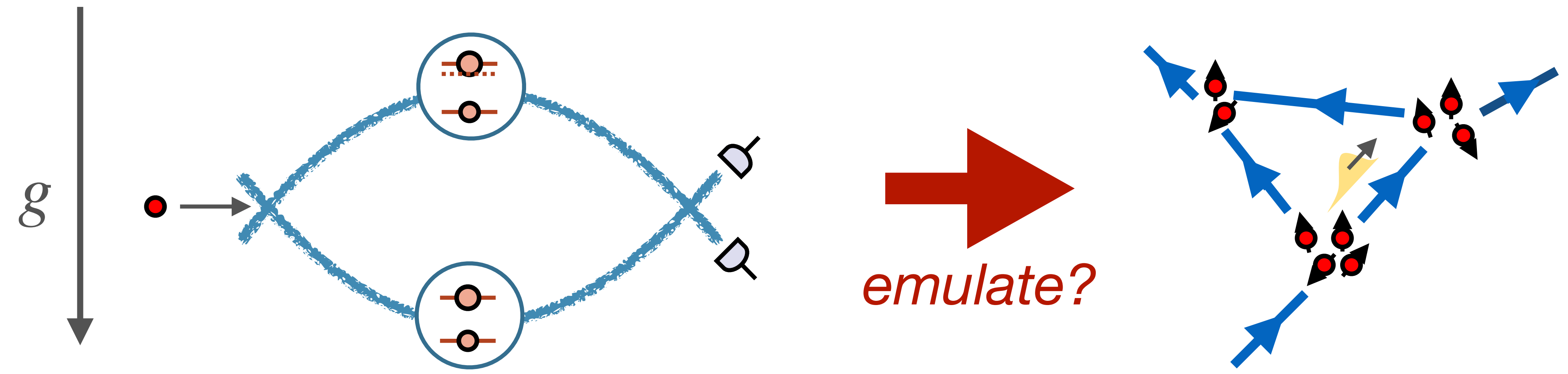
Non-local mass superpositions in atomic ensemble quantum networks

Charles Fromonteil

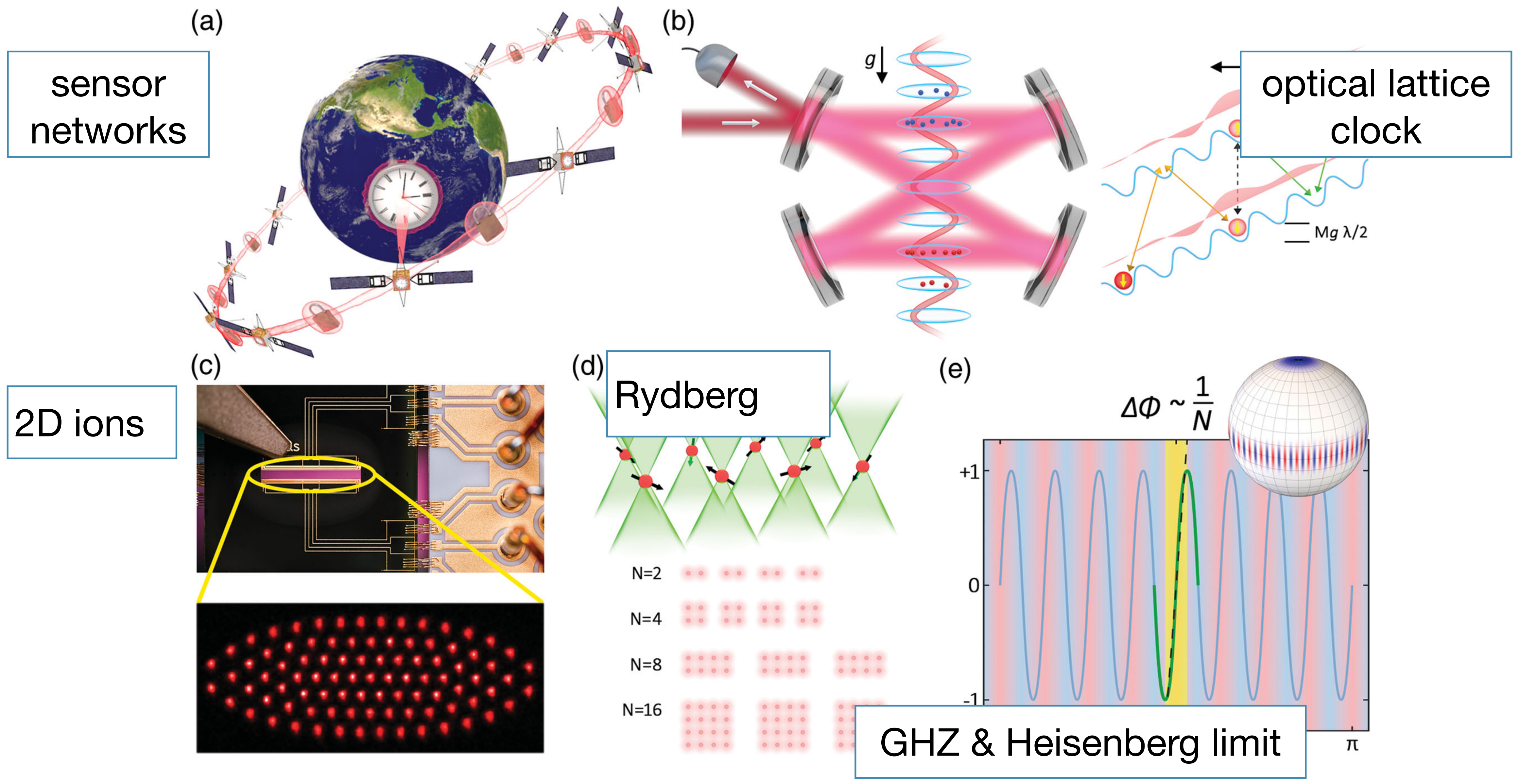
Atomic clock interferometer **Non-local Ramsey interferometer**



C. Fromonteil et al., arXiv 2509.19501

see also: J. P. Covey et al., arXiv 2502.12954

Quantum information for quantum metrology



J. Ye and P. Zoller, Phys. Rev. Lett. ***132****, 190001 (2024)*

Connections and application to fundamental symmetry & gravity:

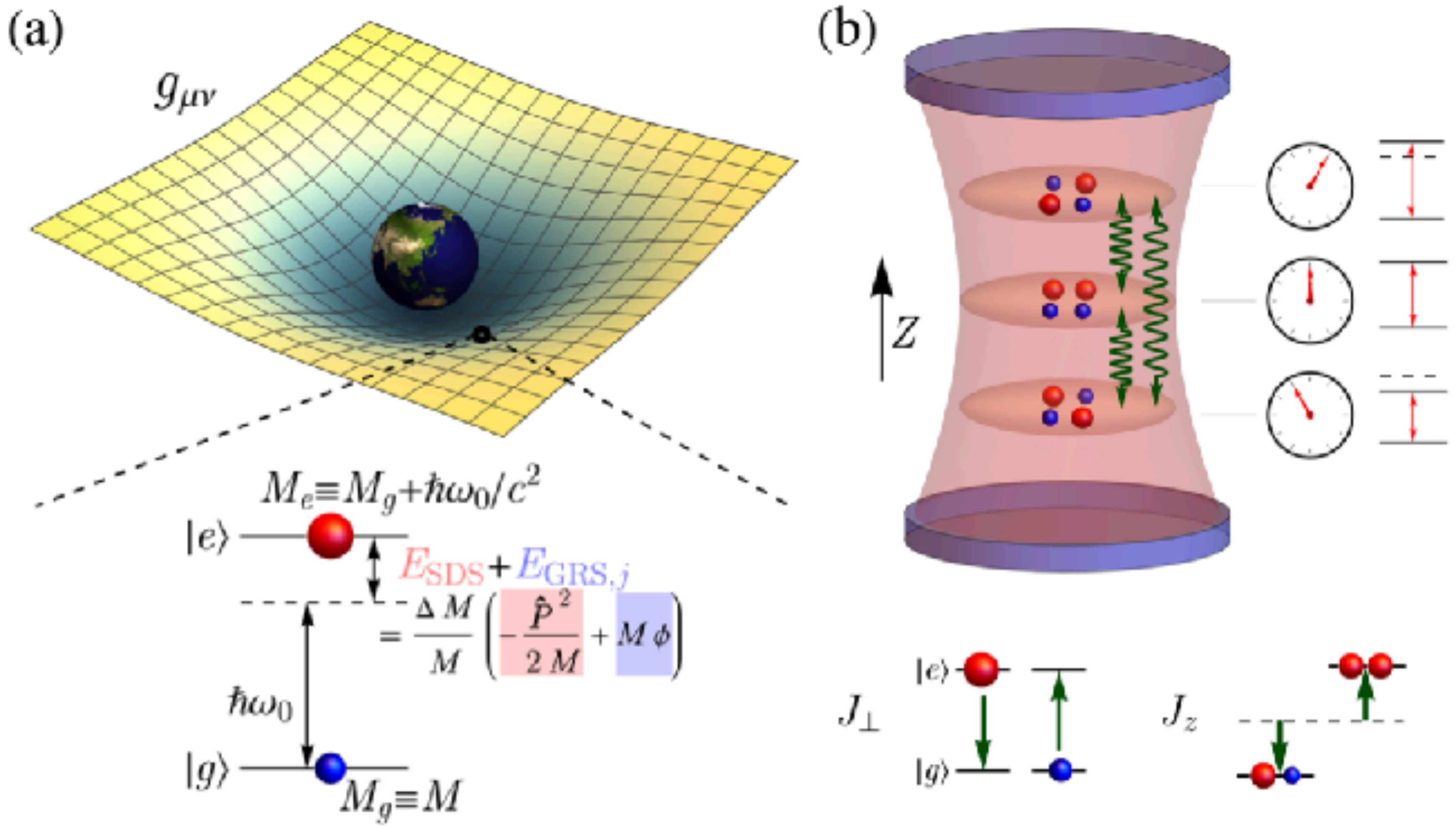
- atomic clocks ~ 1×10^{-21}
- dark matter
- EDM (ACME, JILA)
- biological and chemical physics

In this Essay, we argue that a compelling long-term vision for fundamental physics and novel applications is to harness the rapid development of quantum information science to define and advance the frontiers of measurement physics, with strong potential for fundamental discoveries.

Use programmable many-body systems as quantum sensors → Harness *local* and *non-local* entanglement

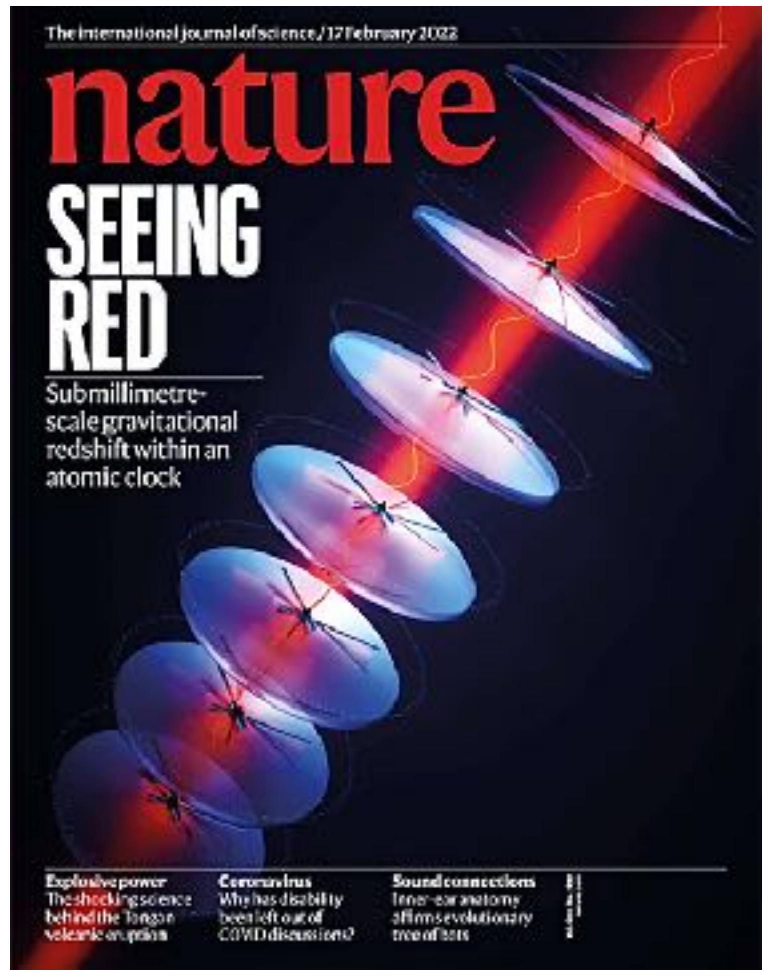
Gravity-Quantum interface in Optical Atomic Clocks

Probe interplay of redshift and entangling interactions



A. Chu et al., Phys. Rev. Lett. ***134****, 093201 (2025)*

Redshift measurement on lattice spacing scale



~mm redshift

see also: *X. Zheng et al., Nat. Commun.* ***14****, 4886 (2023)*

T. Bothwell et al., Nature ***602****, 420-424 (2022)*

Gravity-quantum interplay at small distances

Large masses and large distances

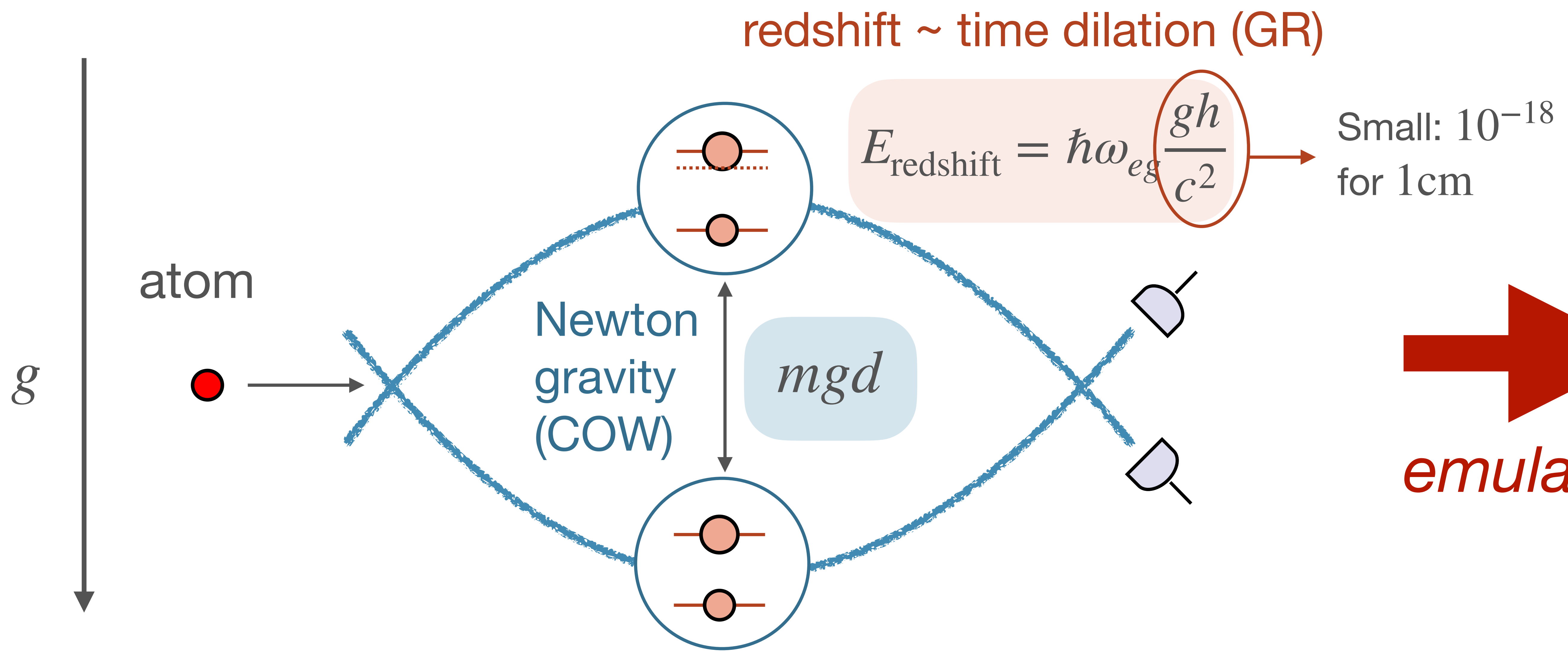
Probe non-local superposition states

Challenge!

Emulating atom-clock interferometers

Emulating atom-clock interferometers with quantum networks

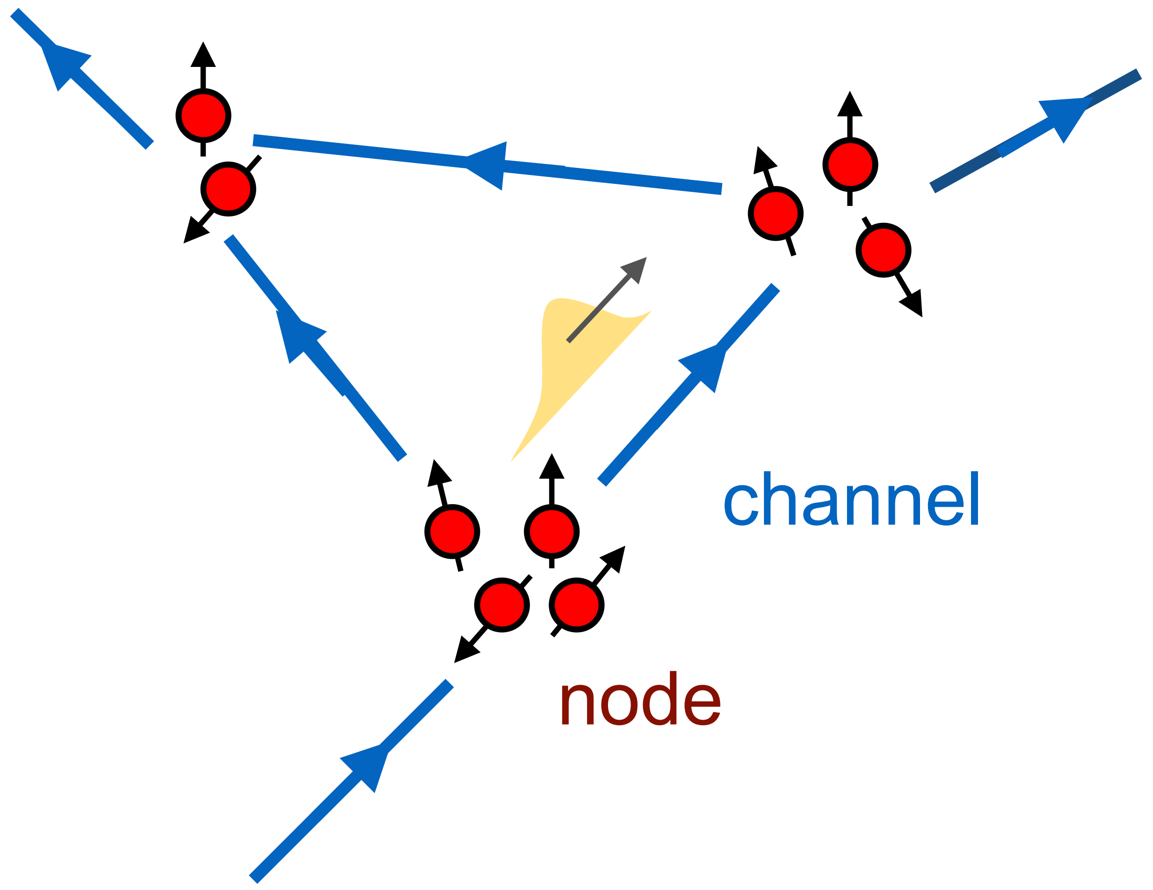
Atom-clock interferometer (ACI)



Single particle; superpositions in external and internal degrees of freedom

emulate!

Large-distance quantum networks



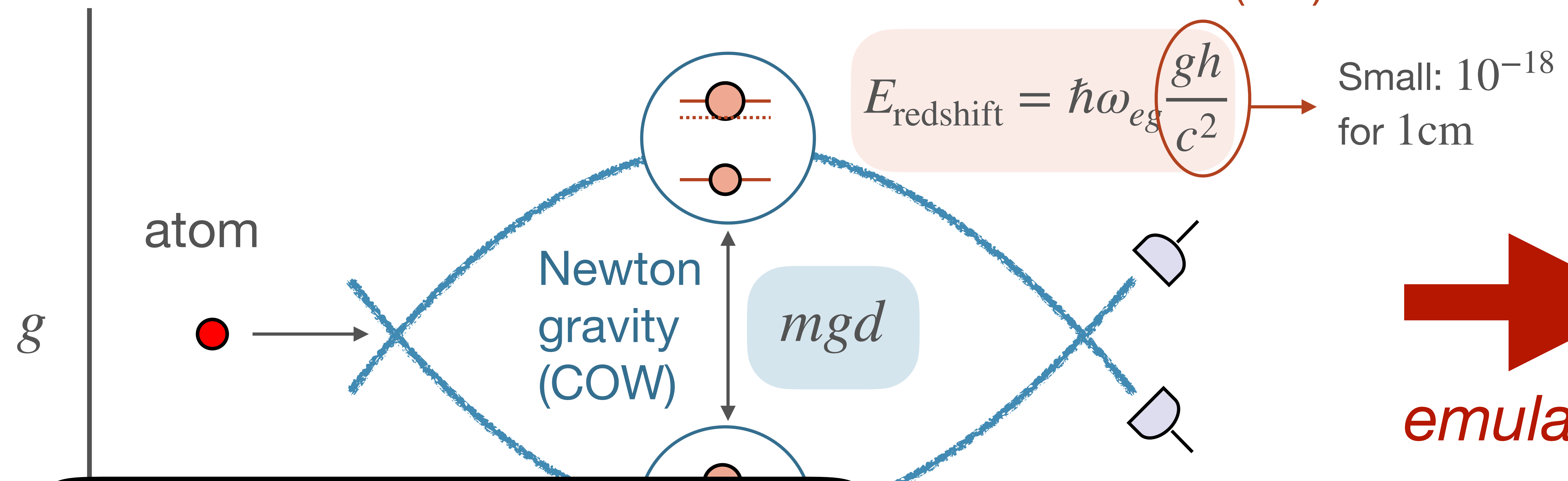
Many particles; non-local superpositions with entanglement

see also: J. P. Covey, I. Pikovski, J. Borregaard, *Probing curved spacetime with a distributed atomic processor clock, PRX Quantum* ***6****, 030310* (2025).

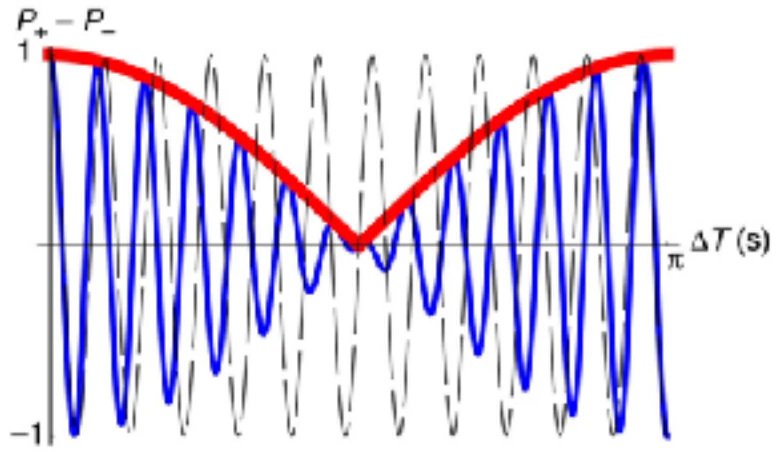
Emulating atom-clock interferometers with quantum networks

Atom-clock interferometer (ACI)

redshift ~ time dilation (GR)



Beating: loss of interference visibility



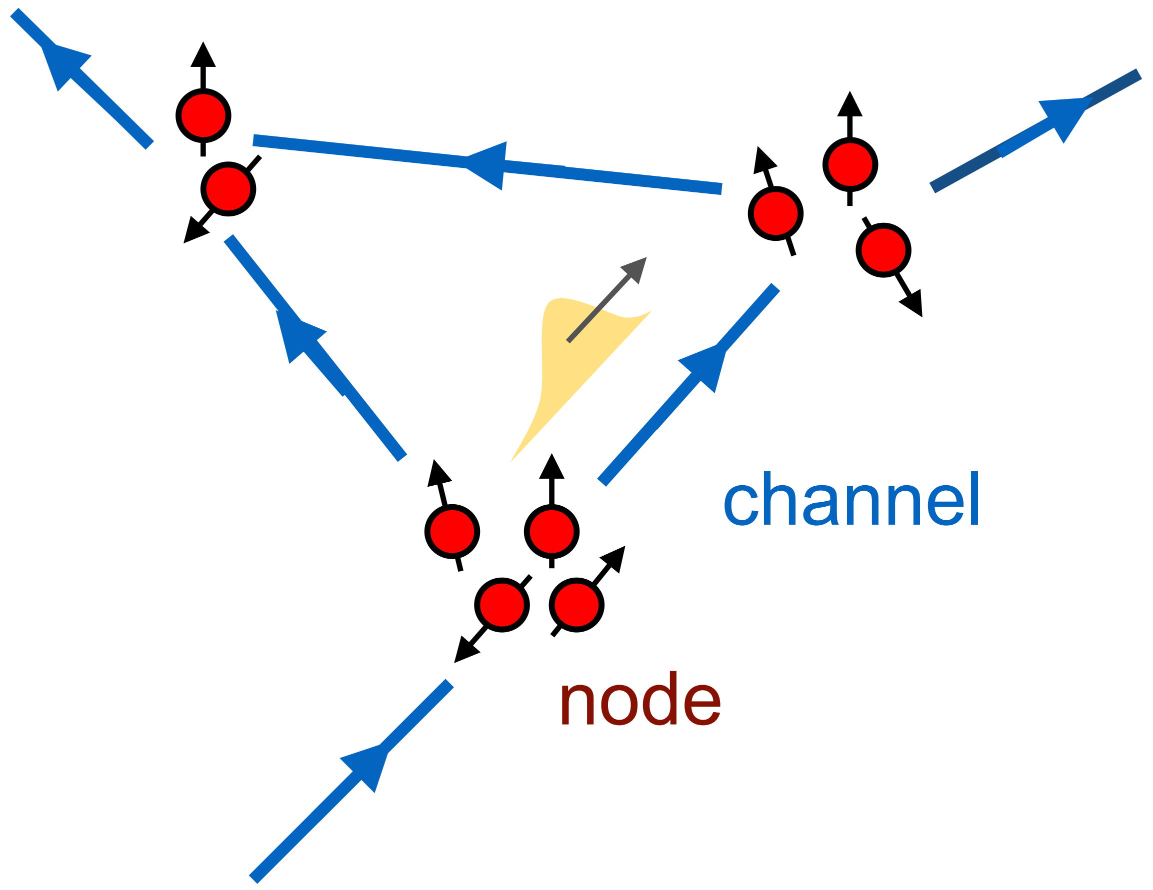
Decay - Revival

M. Zych et al., Nat. Commun. ***2****, 505 (2011)*

ons in external
f freedom

emulate!

Large-distance quantum networks



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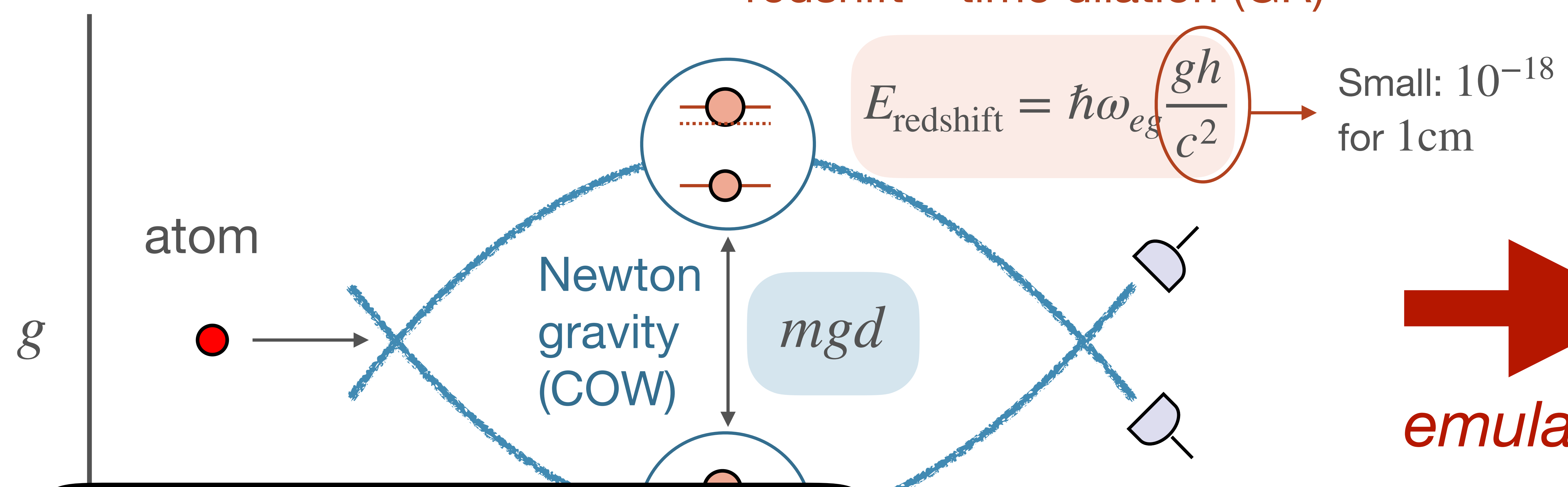

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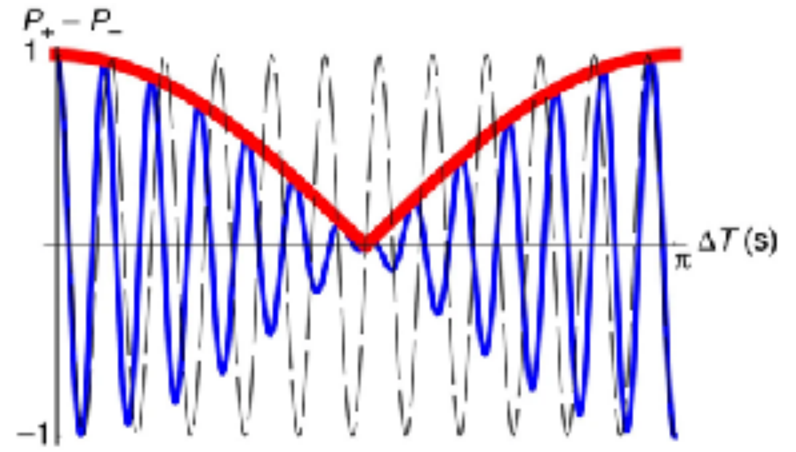


Decay - Revival

M. Zych et al., Nat. Commun. ***2****, 505 (2011)*

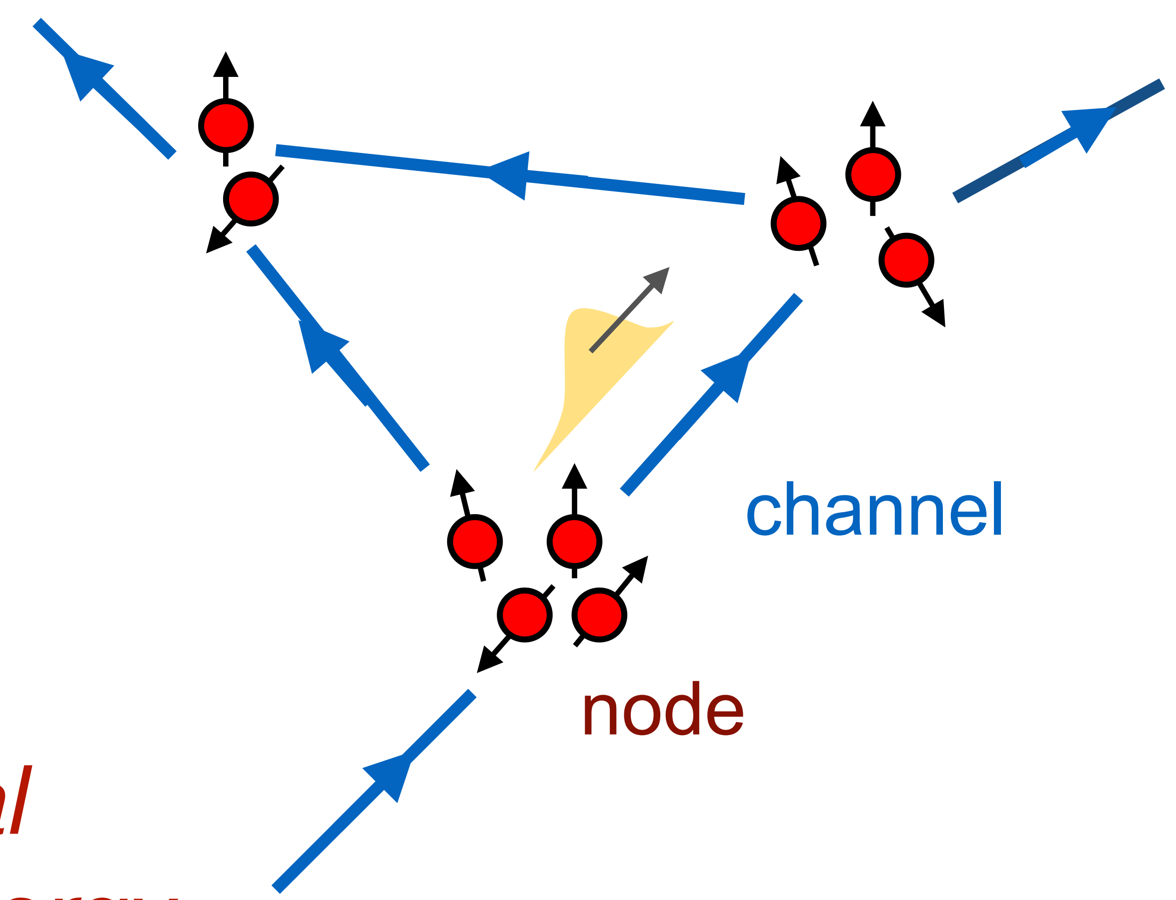
Earth

ons in external
f freedom

emulate!

Both settings: non-local superpositions of mass/energy

Large-distance quantum networks



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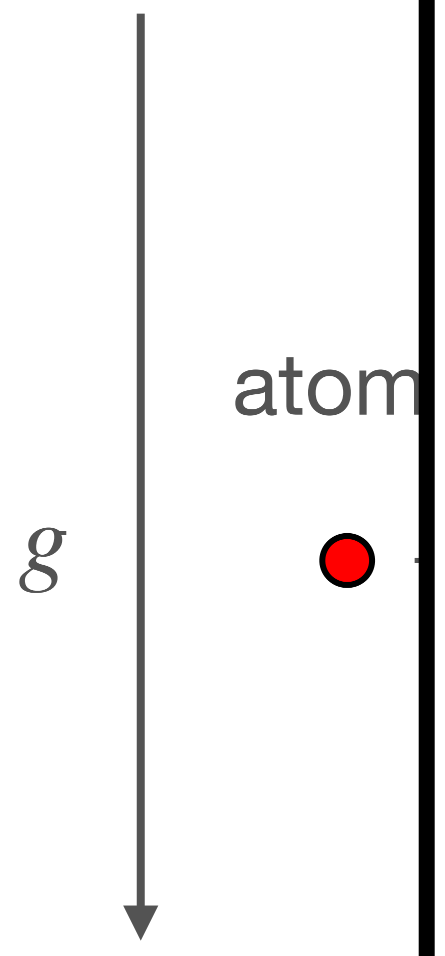
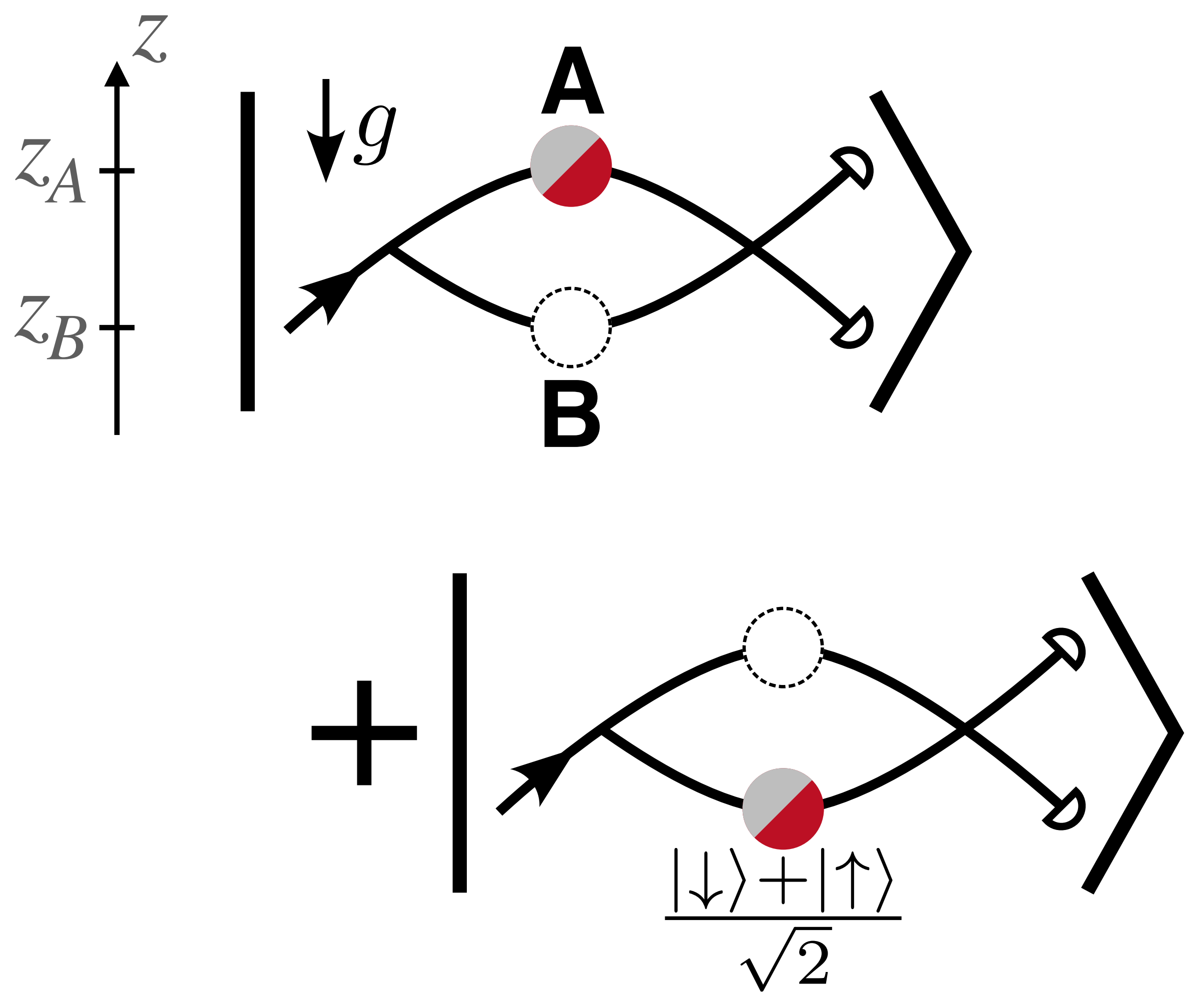
Emulating atom-clock interferometers with quantum networks



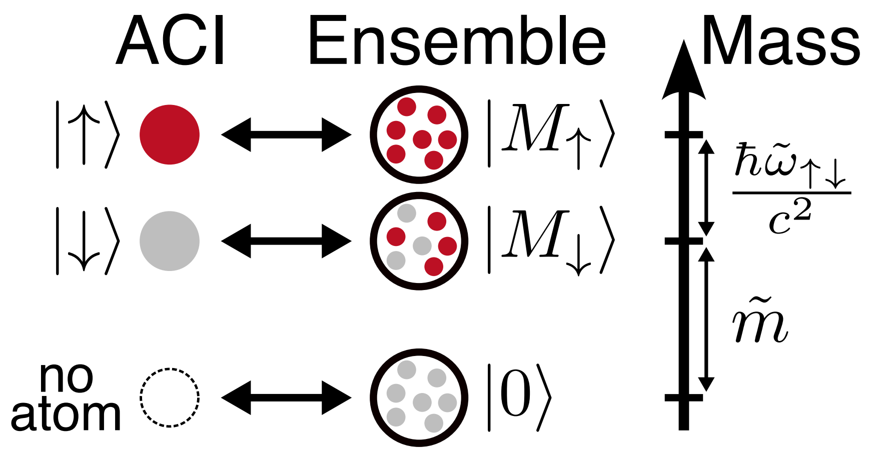
Non-local mass superpositions

Atom-clock interferometer



Atomic mass m (large)

Excitation mass $m_{\uparrow\downarrow} = \hbar\omega_{\uparrow\downarrow}/c^2$ (small)



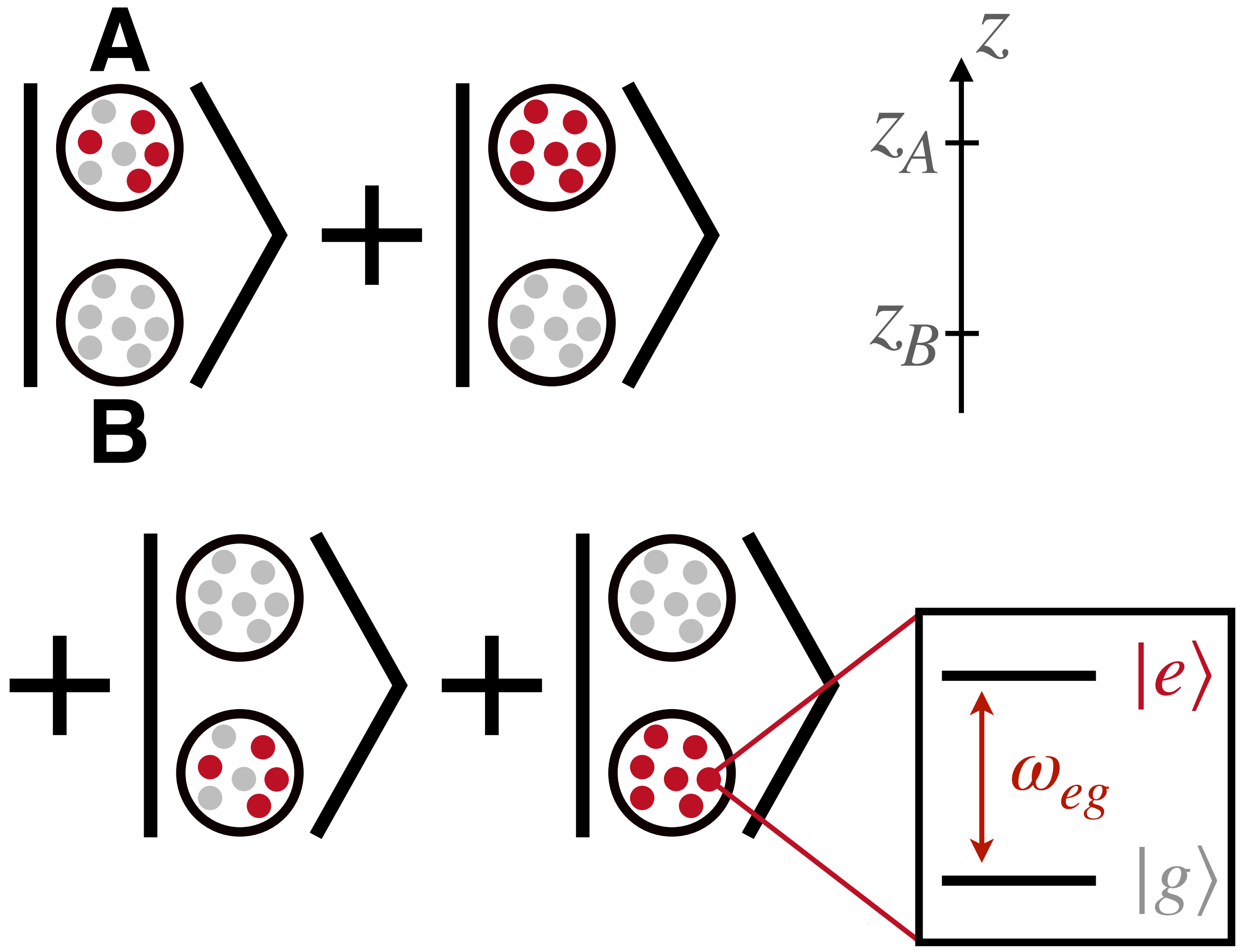
Mass defect

$$m \to \hat{m} = m + \hat{H}_I/c^2$$

Couples to gravity: redshift

$$\hat{H} = \sum_{A/B} \hat{M}_{A/B}\,\phi(z_{A/B})$$

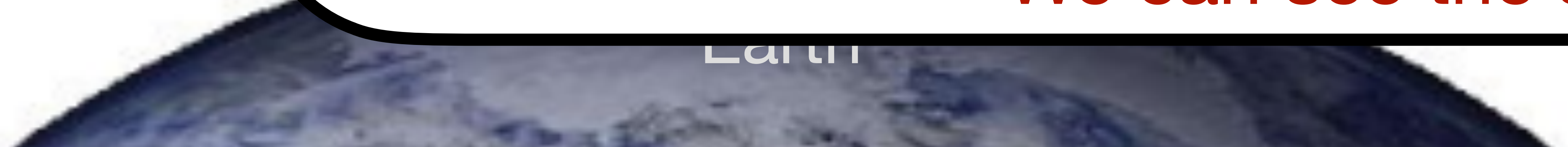
Atomic-ensemble quantum networks



Excitation mass $m_{eg} = \hbar\omega_{eg}/c^2$ (small)

Internal (node) masses $M_\sigma = \ell_\sigma m_{eg}$

We can see the same physics in both settings

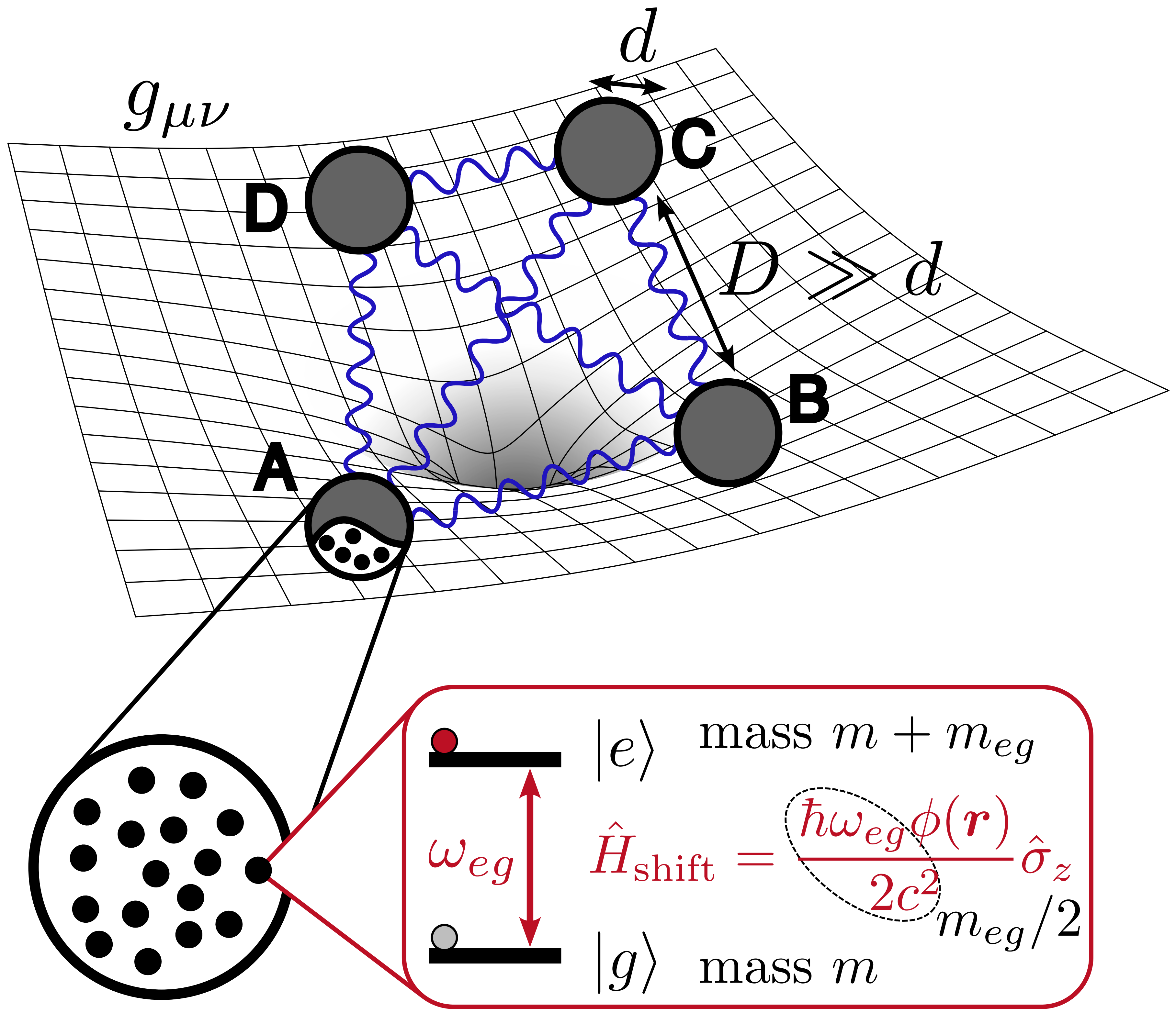


…ard, …ed atomic processor clock, *PRX Quantum* **6**, 030310 (2025).

Non-local mass superpositions

Setup - quantum sensor network

Large-distance sensor network with atomic ensemble nodes



Node: N-atom ensemble

More atoms → larger masses

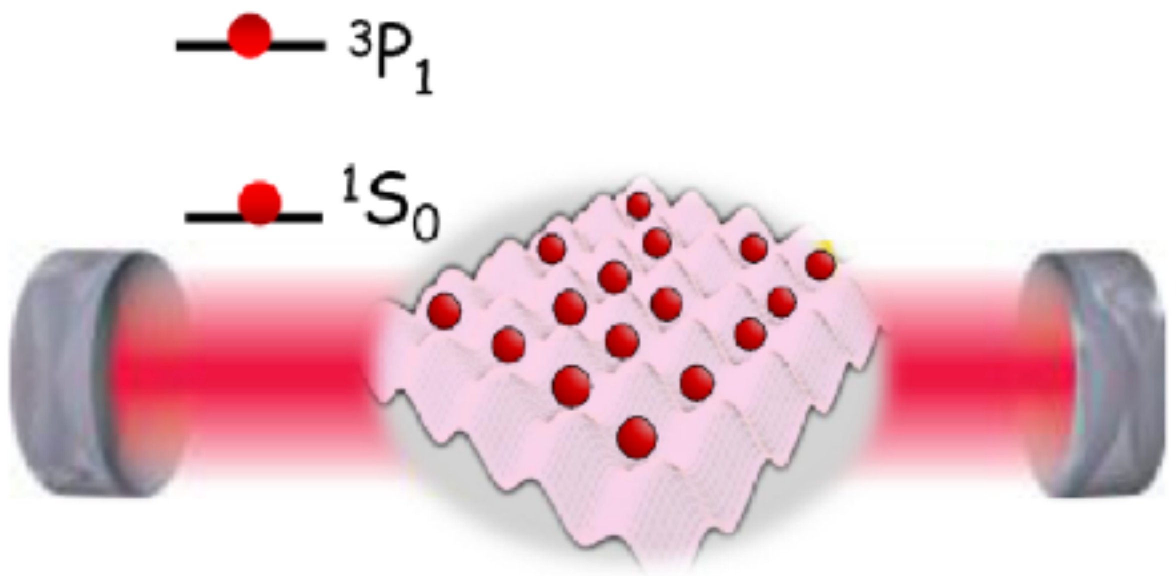
Build **quantum superpositions** of non-local mass distributions:

General state:

$$|\Psi\rangle = \sum_{\boldsymbol{M}} \Psi_{\boldsymbol{M}} |M\rangle_A \otimes |M'\rangle_B \otimes |M''\rangle_C \otimes \dots$$

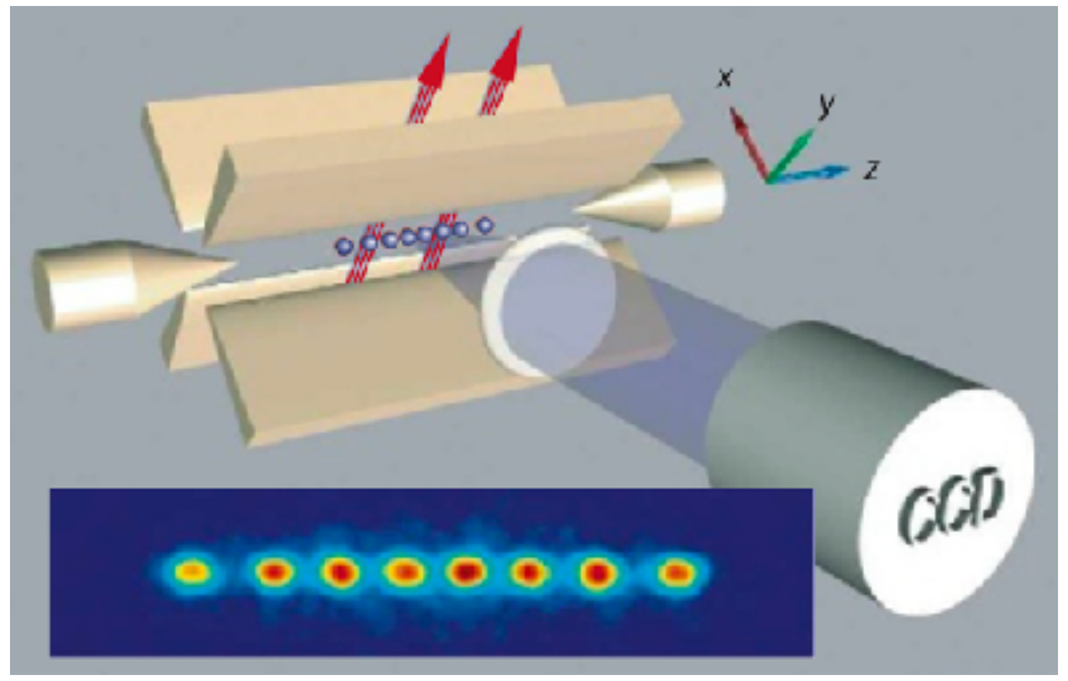
Alternative implementations (depending on platform)

Atomic ensembles



E. S. Polzik and J. Ye, Phys. Rev. A ***93****, 021404 (2016)*

Trapped ions



R. Blatt and D. Wineland, Nature ***453****, 1008-1015 (2008)*

GR-corrected Hamiltonian

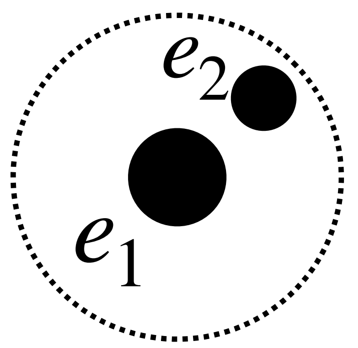
Generally: QFT in curved spacetime. We restrict to **weakly curved spacetime** ($|g_{\mu\nu} - \eta_{\mu\nu}| \ll 1$) to treat GR corrections perturbatively, to **leading order** in c^{-2}.

Post-Newtonian metric

$$g_{\mu\nu} = \begin{pmatrix} -1 - 2\frac{\phi(z)}{c^2} - 2\frac{\phi(z)^2}{c^4} + O\left(c^{-6}\right) & O\left(c^{-5}\right) \\ O\left(c^{-5}\right) & \left(1 - 2\frac{\phi(z)}{c^2}\right) \mathrm{Id} + \mathrm{O}\left(\mathrm{c}^{-4}\right) \end{pmatrix}$$

Expansion in terms of **gravitational potential** $\phi(z) \ll c^2$

Atom: composite particle



External (center-of-mass) and **internal** (relative) degrees of freedom

Lagrangian with corrections → composite particle description

See:

*P. K. Schwartz and D. Giulini, PRA **100**, 052116 (2019)*

*M. Werner et al., PRD **109**, 022008 (2024)*

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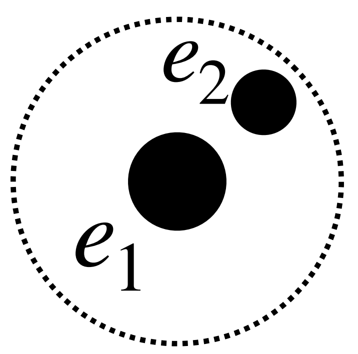

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Hamiltonian: $$\hat{H} = \underbrace{\hat{H}_M}_{\text{Motional}} + \underbrace{\hat{H}_I}_{\text{Internal}} + \underbrace{\hat{H}_{M-I}}_{\text{Relativistic coupling}} + \underbrace{\hat{H}_{A-L}}_{\text{Interaction with light}} + O\left(c^{-4}\right)$$

Focus on internal d.o.f

Absorb $\hat{H}_I$ corrections in definition of $|g\rangle$ and $|e\rangle$

Localized and cold atomic ensembles

Free evolution : no electromagnetic field

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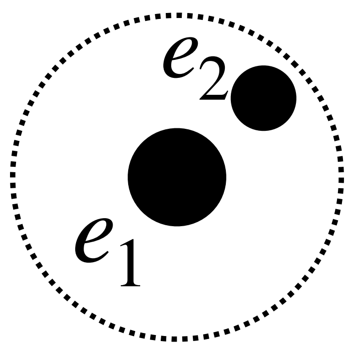

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Result:

$$\hat{H} = \sum_{\substack{n \\ i\in n}} \left[mc^2 + m\phi(\boldsymbol{r}_n) + \frac{\hbar\omega_{eg}}{c^2}\left(c^2 + \phi(\boldsymbol{r}_n)\right)\frac{\hat{\sigma}_z^{(i)} + 1}{2} \right]$$

$$= \sum_n \left(\hat{M}_n c^2 + \hat{M}_n \phi(\boldsymbol{r}_n) \right)$$

$$\boxed{\hat{M}_n = Nm + (m_{eg}/2)\sum_{i\in n}(\hat{\sigma}_z^{(i)} + 1)}$$

See:

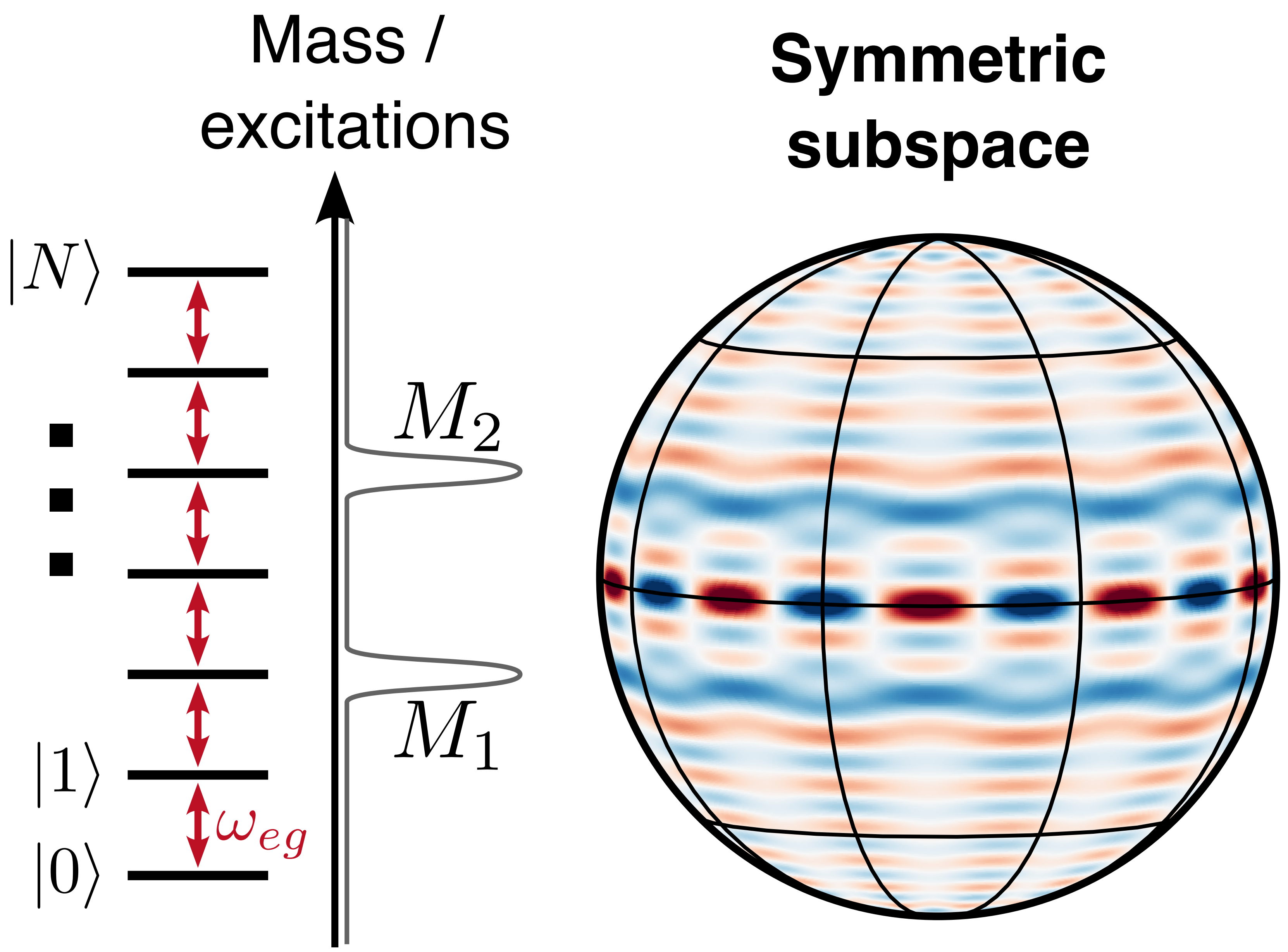
P. K. Schwartz and D. Giulini, PRA ***100****, 052116 (2019)*

M. Werner et al., PRD ***109****, 022008 (2024)*

Local and non-local superpositions

Local mass superpositions (within a node)

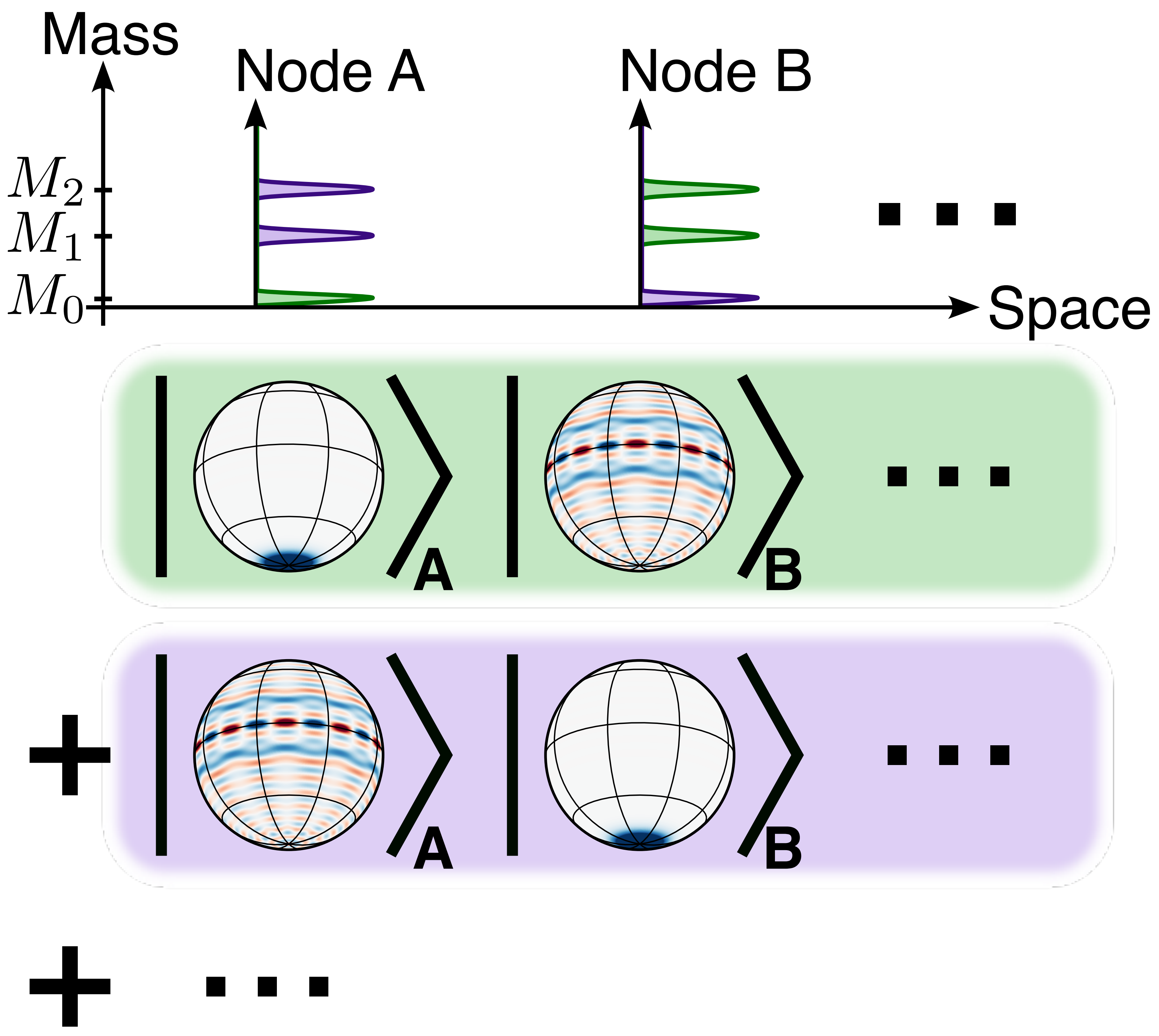
Local Hilbert space spanned by ladder of Dicke states



Platform-dependent choice: Natural with global addressing

Manipulation: global driving

Non-local mass superpositions (entanglement)



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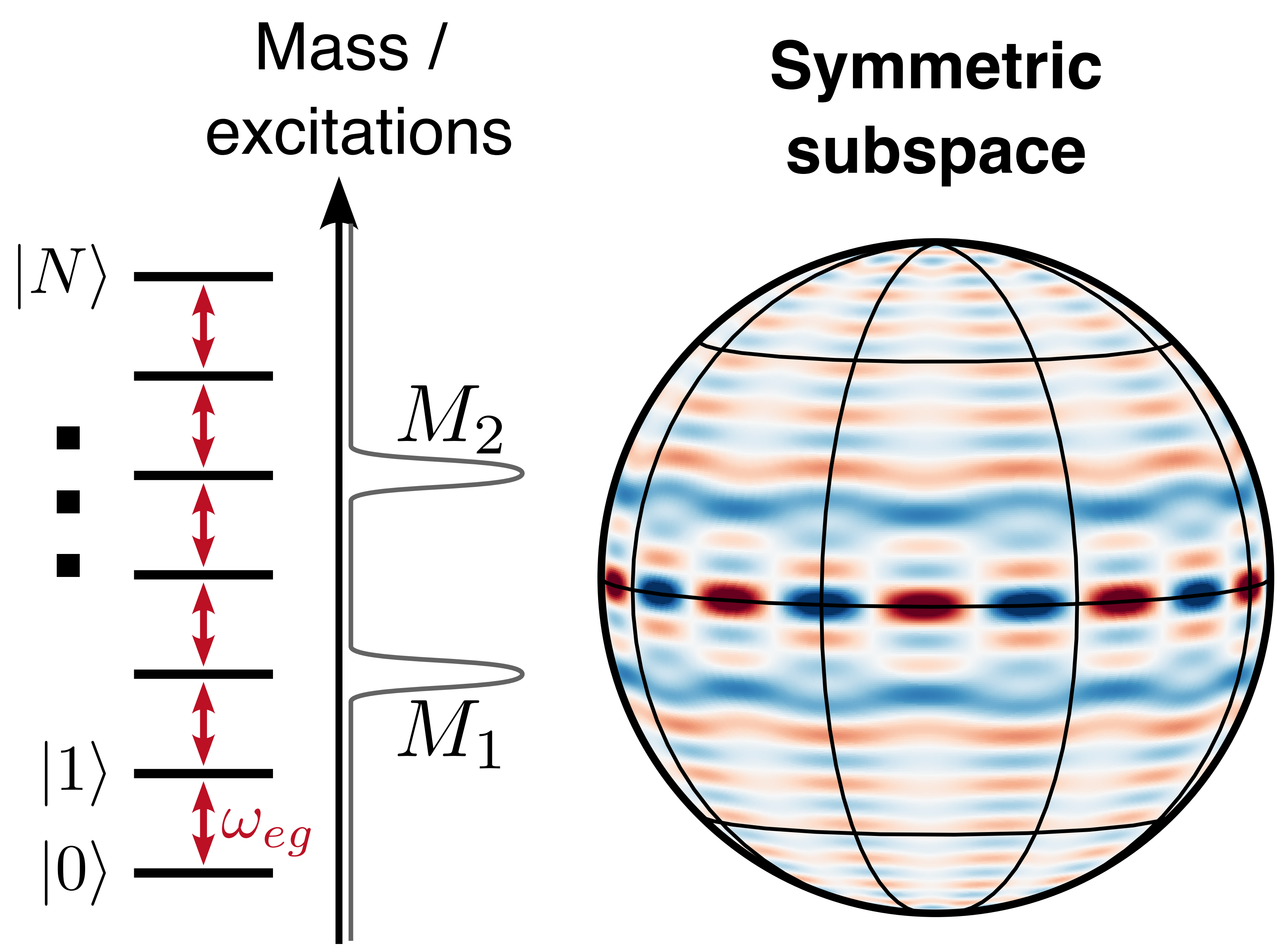

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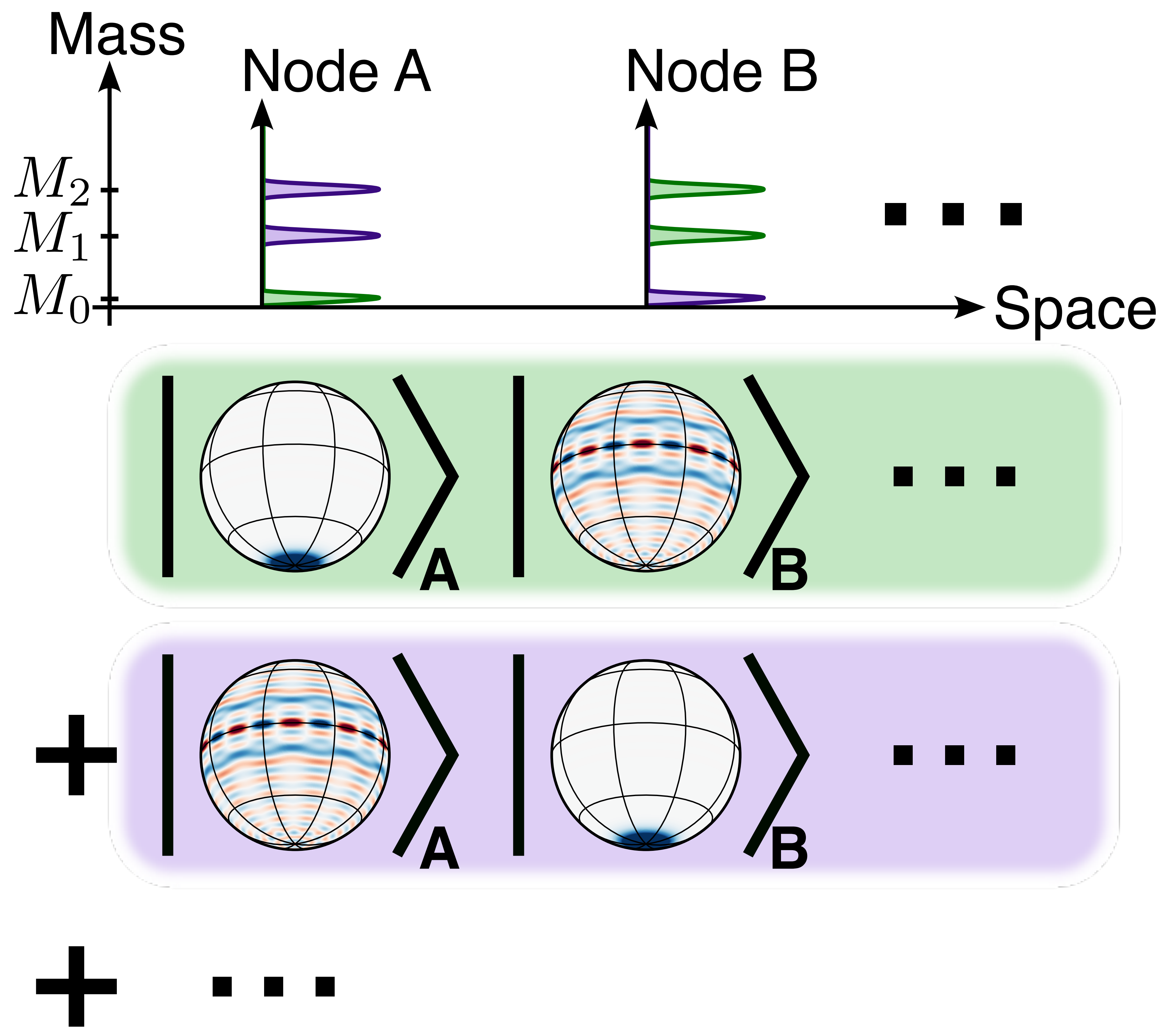
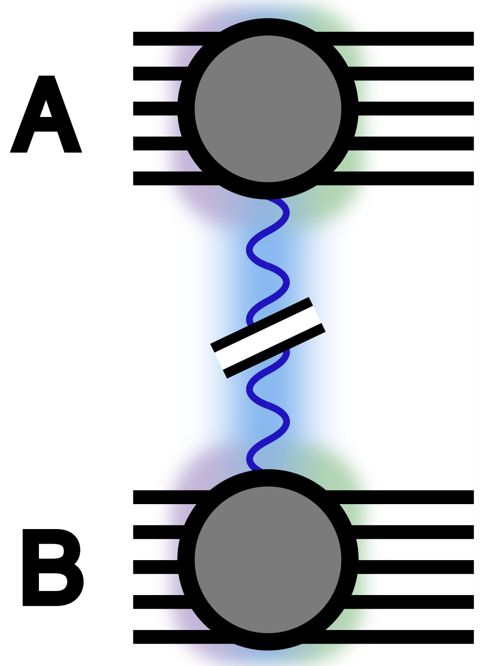


Ability to **generate arbitrary superpositions:**
"Gravity-Quantum lab"

Preparing mass superpositions

Preparing mass superpositions

Generate delocalized **single excitation** (Bell pair)



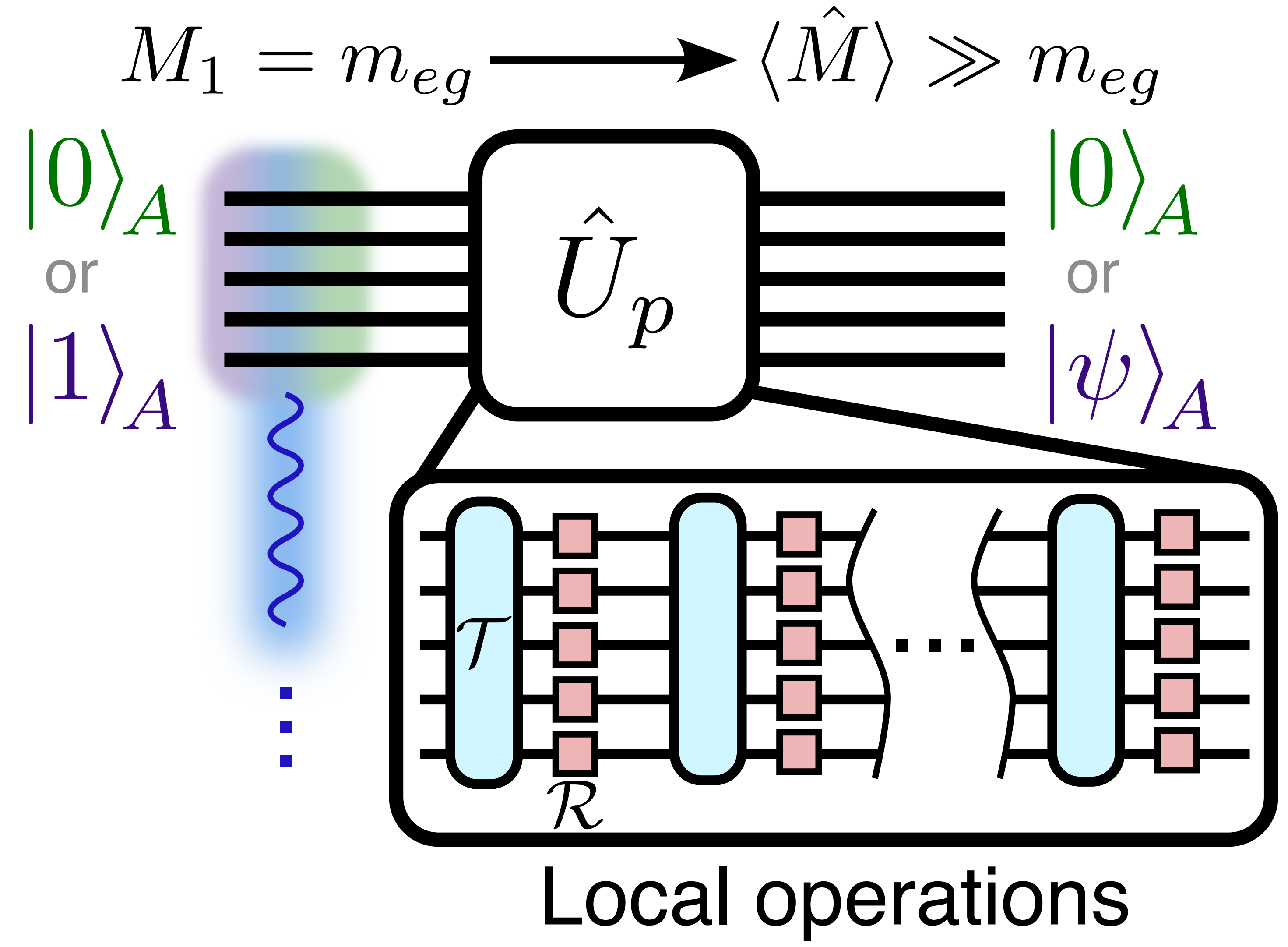
Seed state:

$$|0\rangle_A \otimes |1\rangle_B + |1\rangle_A \otimes |0\rangle_B$$

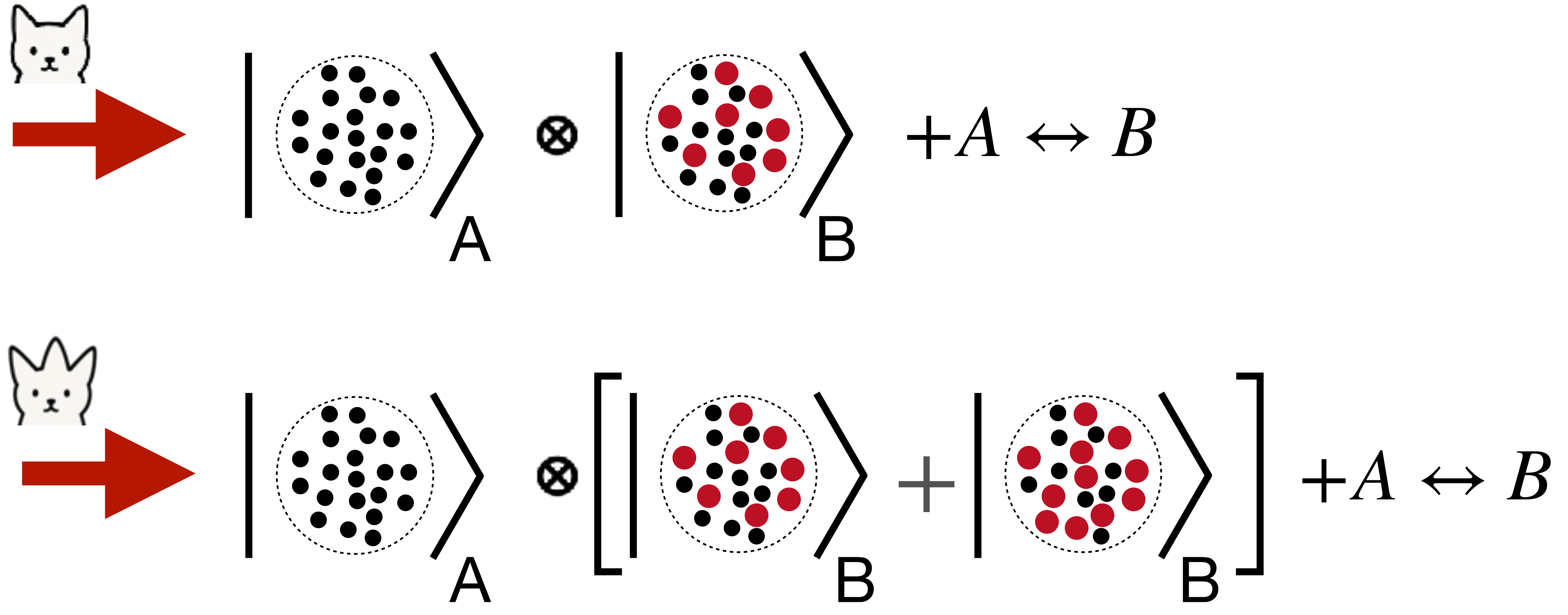
Single excitation

$M_1 = m_{eg}$

Apply **local** preparation unitary



Non-local Schrödinger cat states:

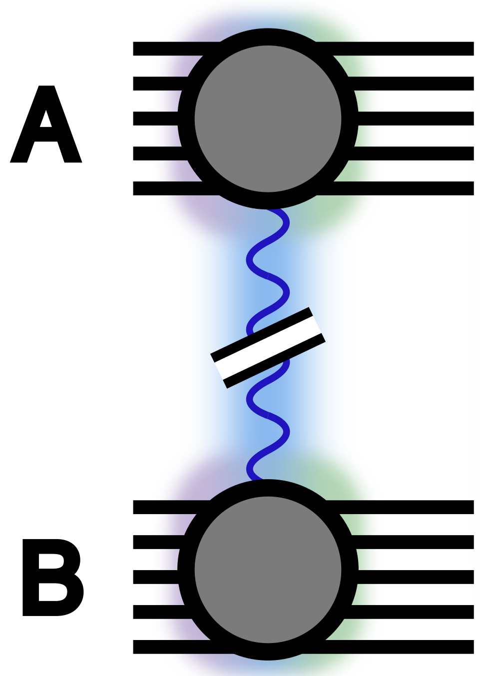


Variational optimization to find the right circuit:

$$\hat{U}_p = \underbrace{\hat{\mathscr{R}}_{\mathbf{n_p}}(\theta_p)}_{\text{Rotations}} \underbrace{\hat{\mathscr{T}}_{\mathbf{n_{p-1}}}(\chi_{p-1}) \ldots \hat{\mathscr{T}}_{\mathbf{n_1}}(\chi_1)}_{\text{One-axis twisting}}$$

Entanglement distribution

Generate delocalized **single excitation** (Bell pair)



Seed state:

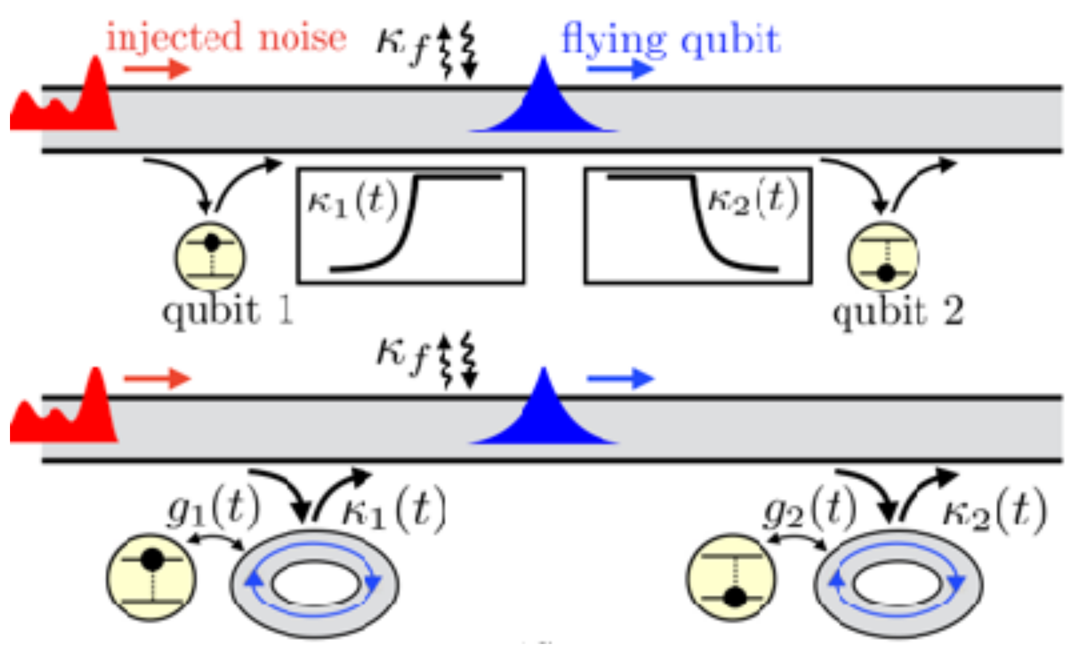
$$|0\rangle_A \otimes |1\rangle_B + |1\rangle_A \otimes |0\rangle_B$$

Single excitation

$$M_1 = m_{eg}$$

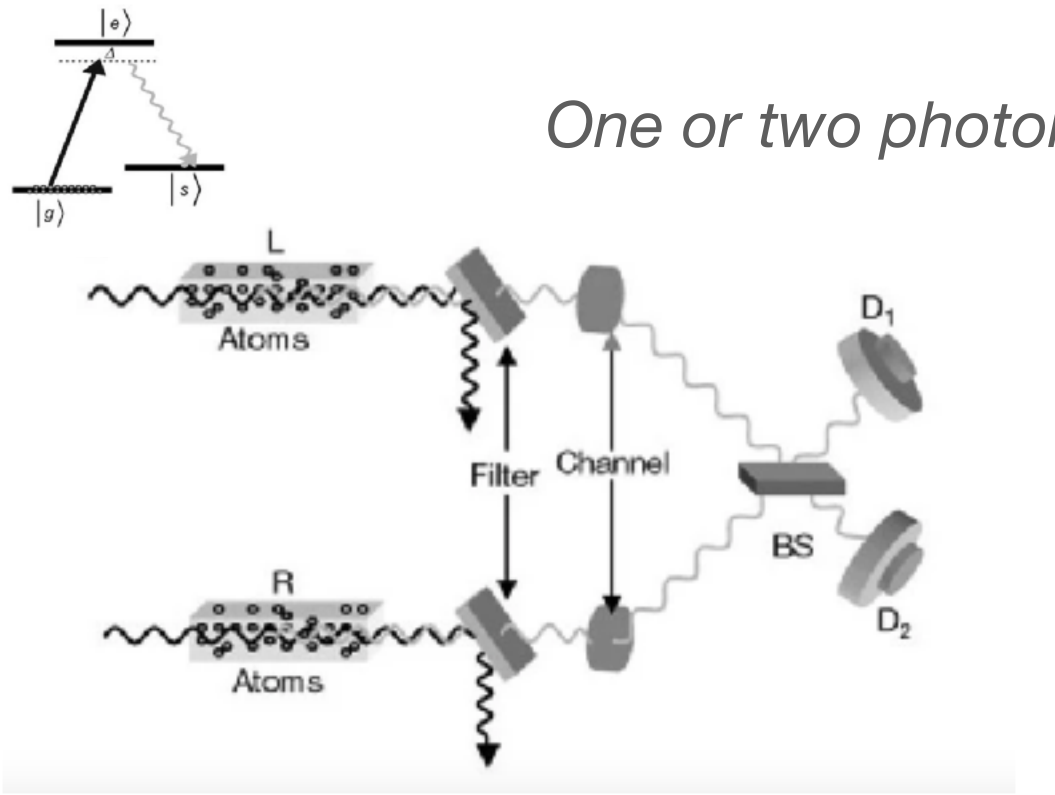
Quantum communication schemes: deterministic or probabilistic

Quantum state transfer



Quantum repeater protocol

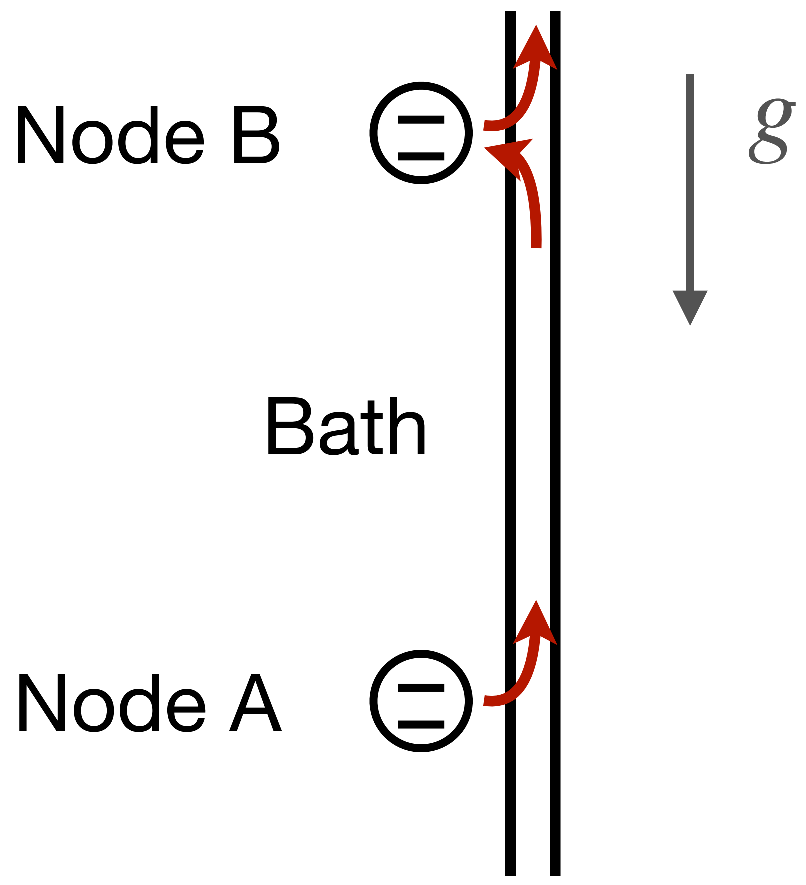
One or two photons



B. Vermersch et al., Phys. Rev. Lett. ***118****, 133601 (2017)*

L.-M. Duan et al., Nature ***414****, 413-418 (2001)*

Do relativistic corrections change the picture?



Quantum Optics model including GR corrections

- Redshift → detuning of atomic transition frequencies
- Phase-corrected mode functions

$$\boldsymbol{A}_{k,\sigma}(\vec{x},t) = \vec{\alpha}_\sigma e^{i[-kct+k(z-\frac{gz^2}{c^2})]}$$

- Delay time correction

➡ **Small systematic shifts**

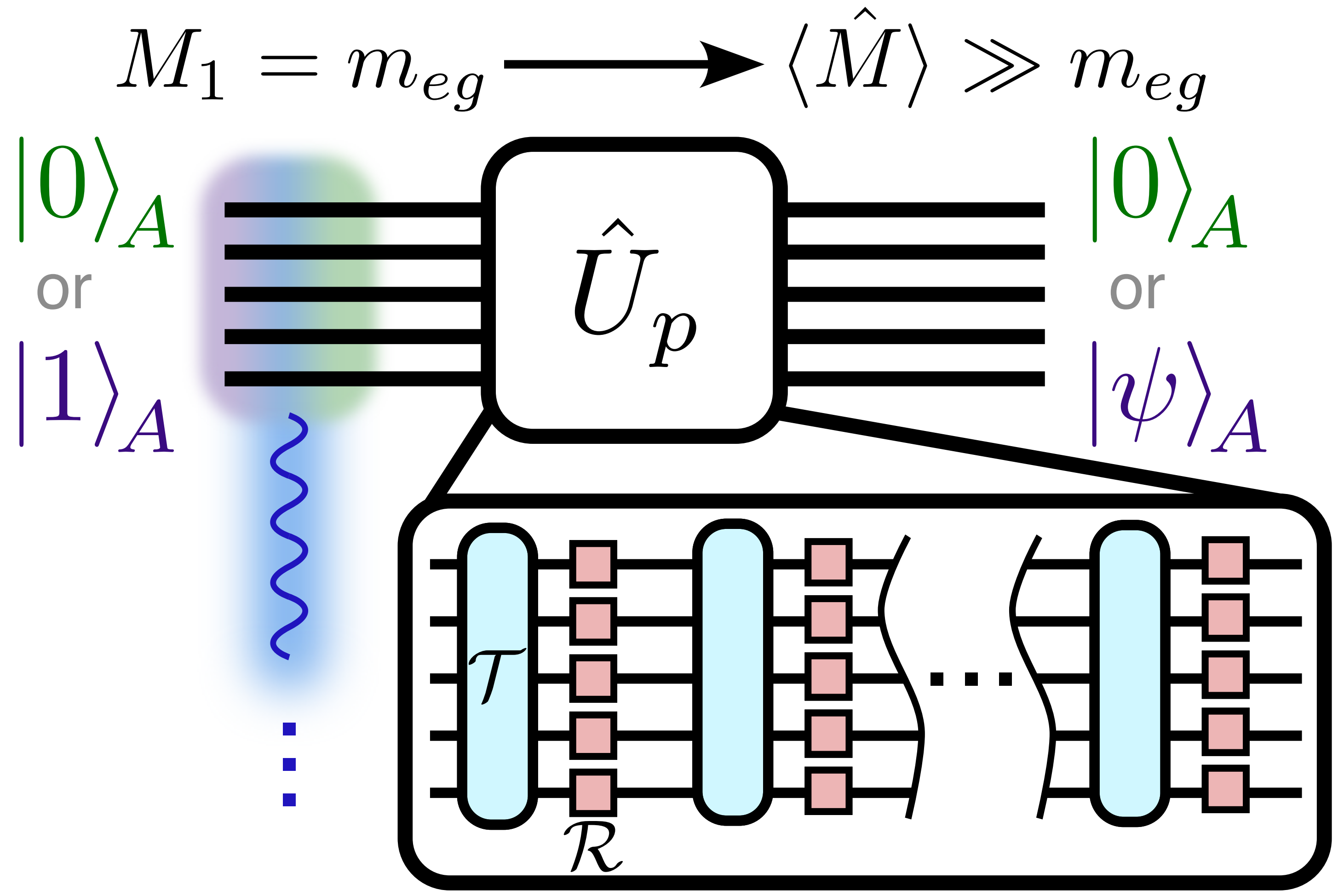
Variational state preparation

Goal: “**growing Schrödinger cats**”

$|0\rangle \to |0\rangle$ ⟶ *Constraint: keep vacuum unchanged*

$|1\rangle \to |\psi\rangle$ ⟶ Large average mass; Superposition of several levels

Target



Optimize the circuit (classically or on-device)

Resources: one-axis-twisting and global rotations

$$\hat{U}_p = \hat{\mathscr{R}}_{\mathbf{n_p}}(\theta_p)\,\hat{\mathscr{T}}_{\mathbf{n_{p-1}}}(\chi_{p-1})\,\dots\,\hat{\mathscr{T}}_{\mathbf{n_1}}(\chi_1)$$

Reposition states on the Bloch sphere — *Separate vacuum and excitation*

Cost functions

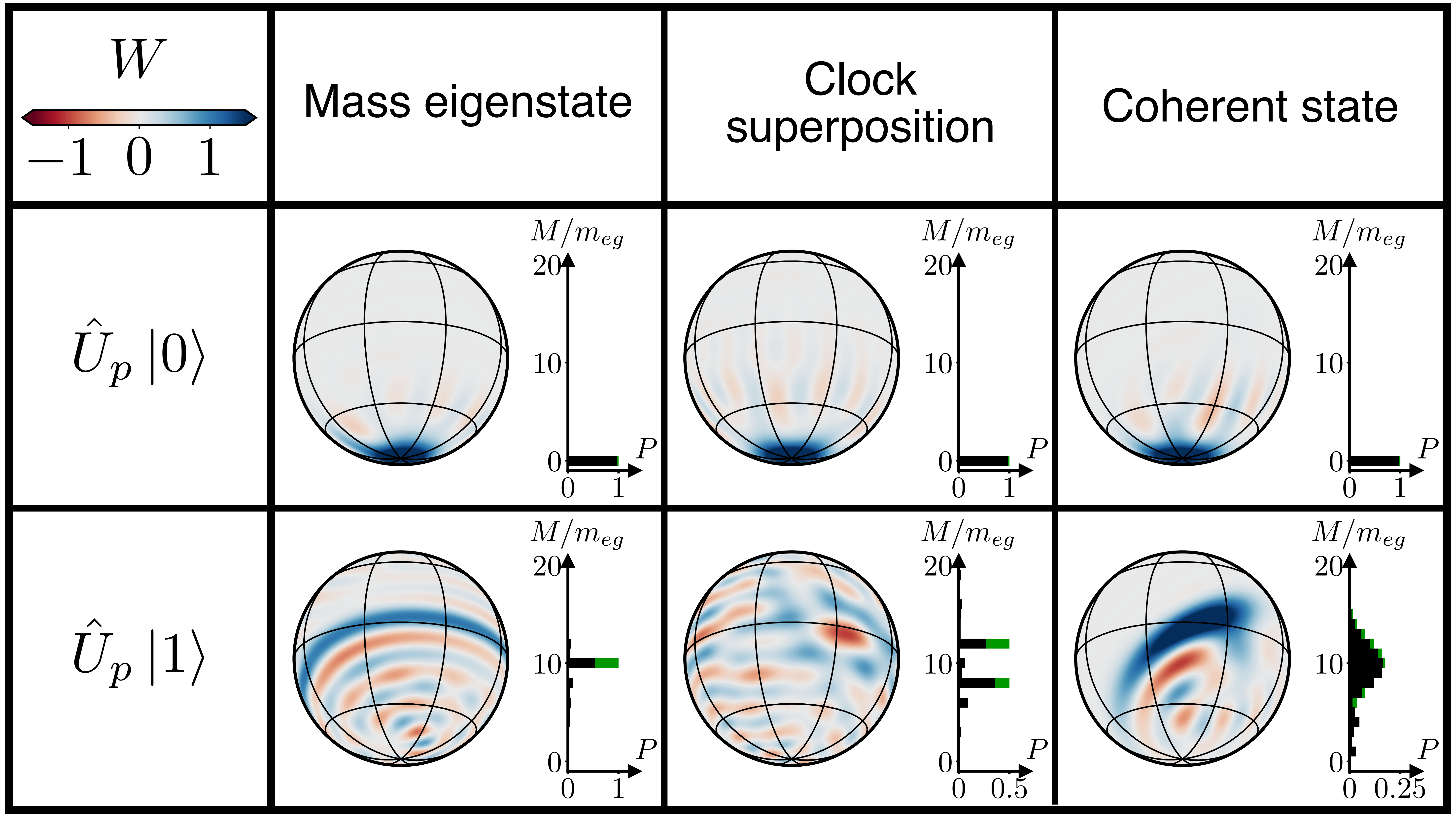
Only probability distribution impacts interference pattern

- Fidelity of $|0\rangle$ state result.
- Target state probability distribution overlap

See also:

*R. Kaubruegger et al., Phys. Rev. X **11**, 041045 (2021)*
*C. D. Marciniak et al., Nature **603**, 604 (2022)*

Resulting states



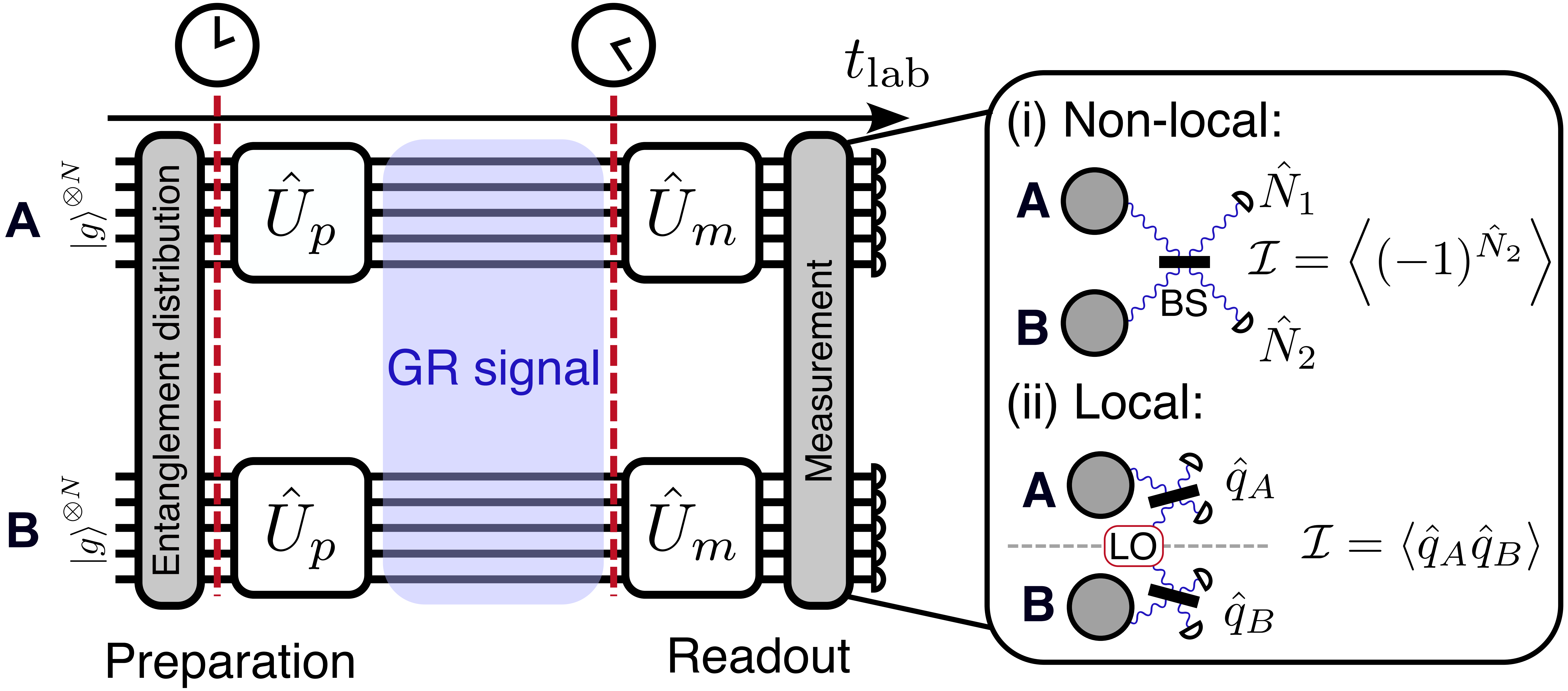
Three example target states:

- Single mass eigenstate $|M\rangle$ (analog: COW scheme)
- Superposition of two mass eigenstates $(|M_1\rangle + |M_2\rangle)/\sqrt{2}$ (analog: atom-clock interferometer)
- Coherent state of mass excitations $\hat{\mathscr{R}}_y(\pi/2)|0\rangle$ (analog: macroscopic particle in superposition)

$N = 20$: **3-5 layers of OAT**

Non-local Ramsey interferometer

Non-local Ramsey interferometer



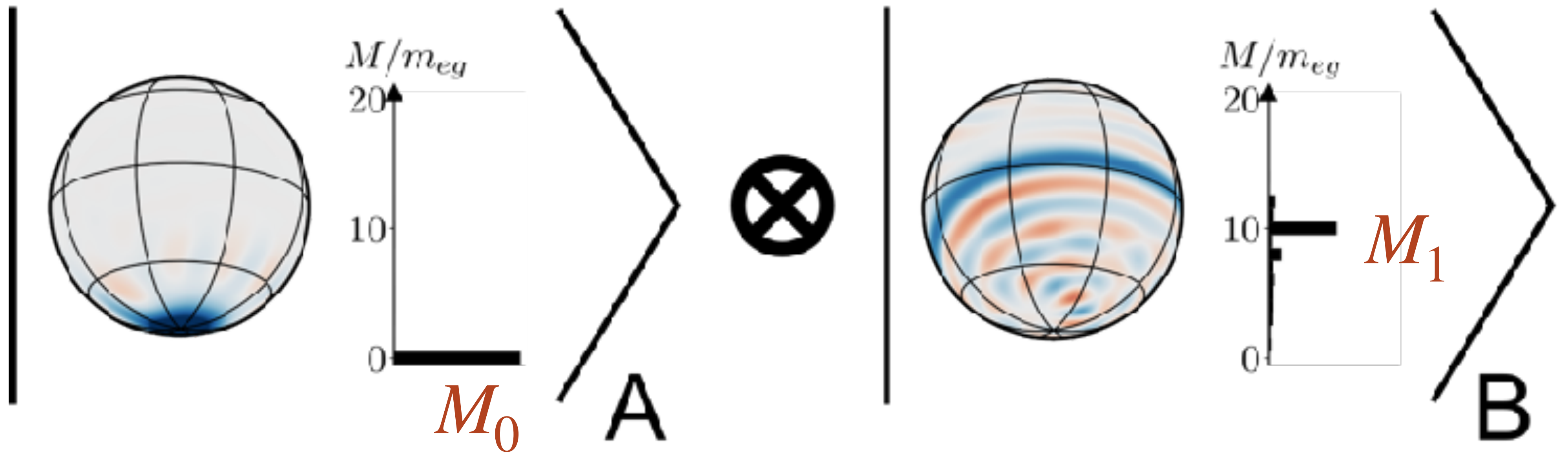
1. Prepare superposition state (previous part)
2. Accumulate phases under GR Hamiltonian
3. Decoding (if needed) and measurement (local or non-local)

$$|\Psi_i\rangle = \sum_{\ell \geq 1} \psi_\ell \frac{|0\rangle_A \otimes |\ell\rangle_B + |\ell\rangle_A \otimes |0\rangle_B}{\sqrt{2}} \;\Rightarrow\; |\Psi_f\rangle = \sum_{\ell \geq 1} \psi_\ell \frac{e^{-i\varphi_{\ell,B}}|0\rangle_A \otimes |\ell\rangle_B + e^{-i\varphi_{\ell,A}}|\ell\rangle_A \otimes |0\rangle_B}{\sqrt{2}}$$

Interference pattern is a **weighted sum** of oscillations, with different **frequencies** corresponding to different **mass/energies**

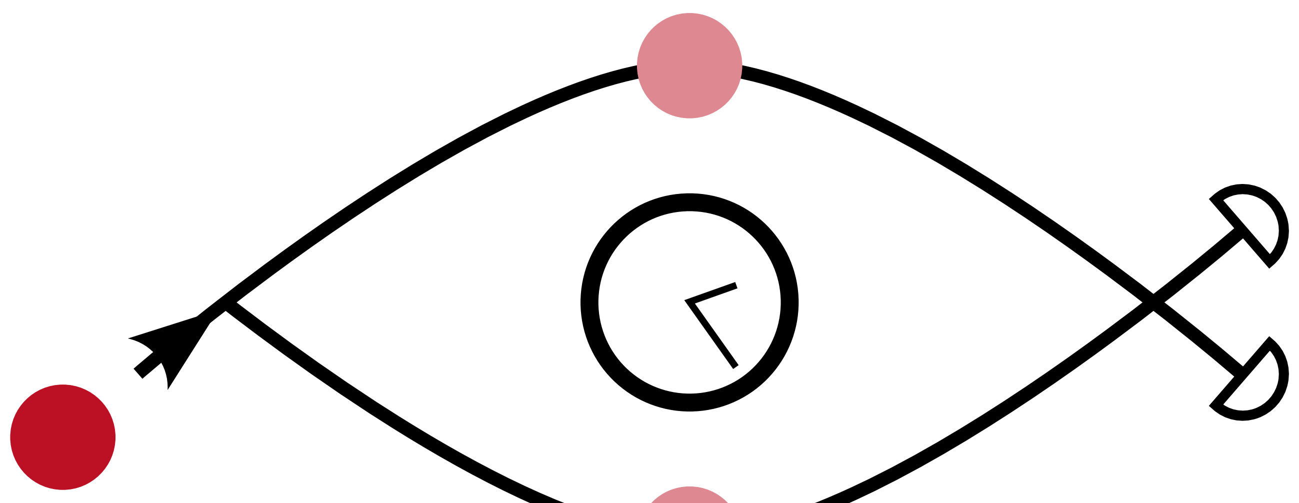
Expected interference patterns

Mass eigenstate



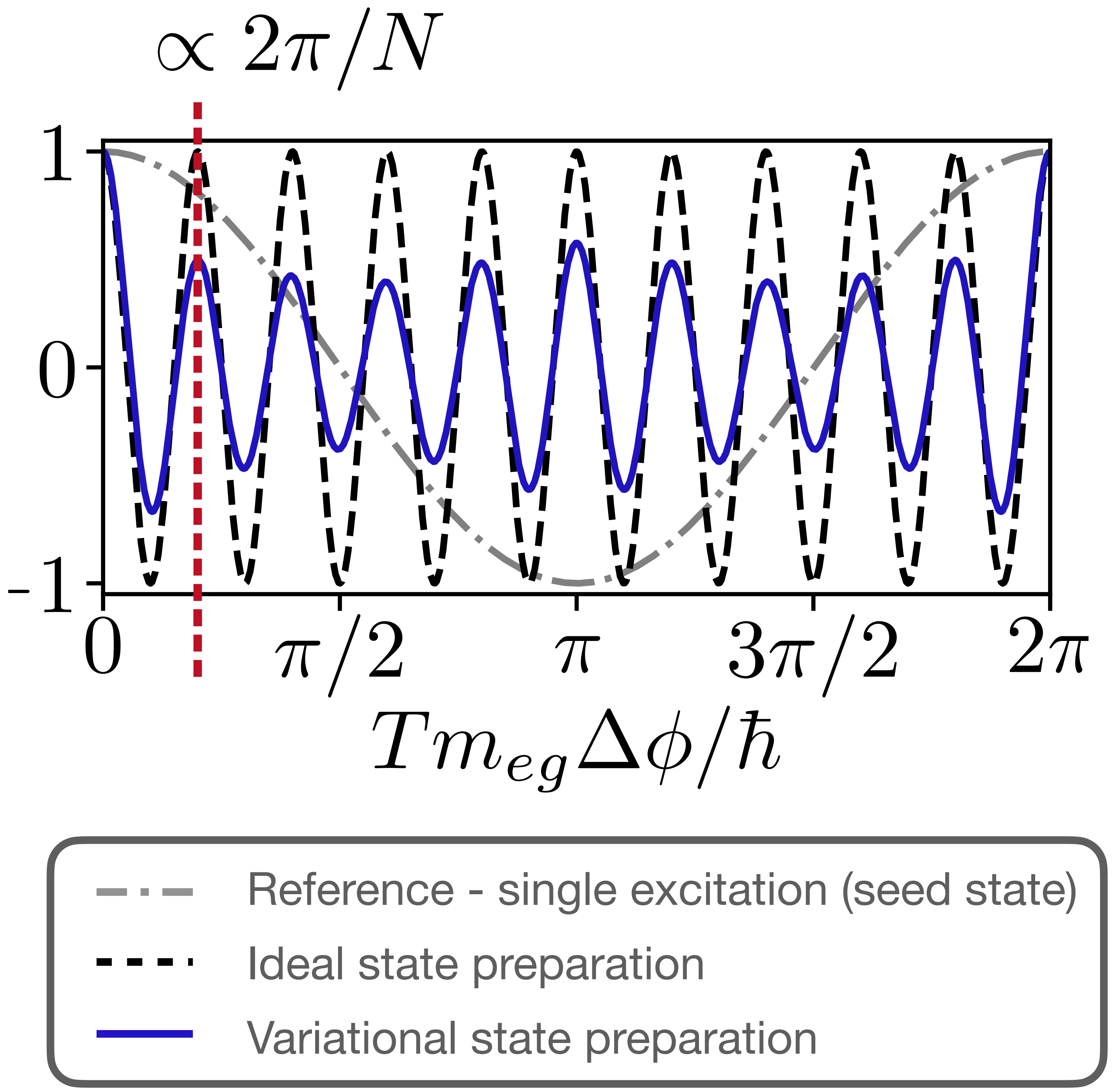
$$+A \leftrightarrow B$$

Equivalent:
COW experiment



One frequency

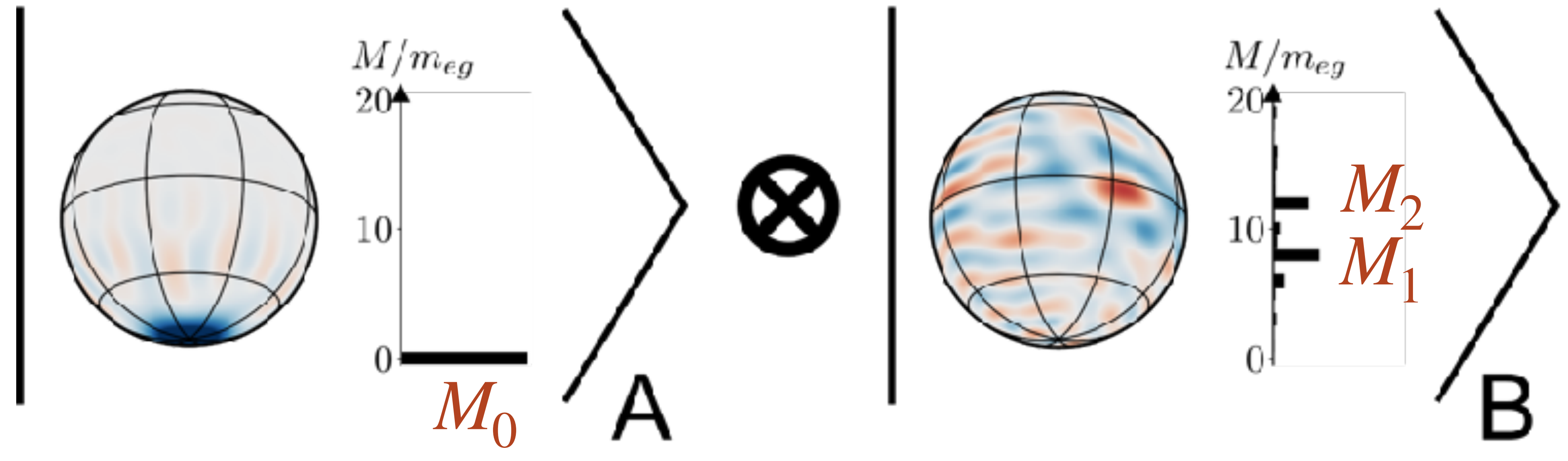
Interference pattern:



Single-frequency oscillation
Fast decay of noisy amplitudes —
signal oscillation with lower visibility

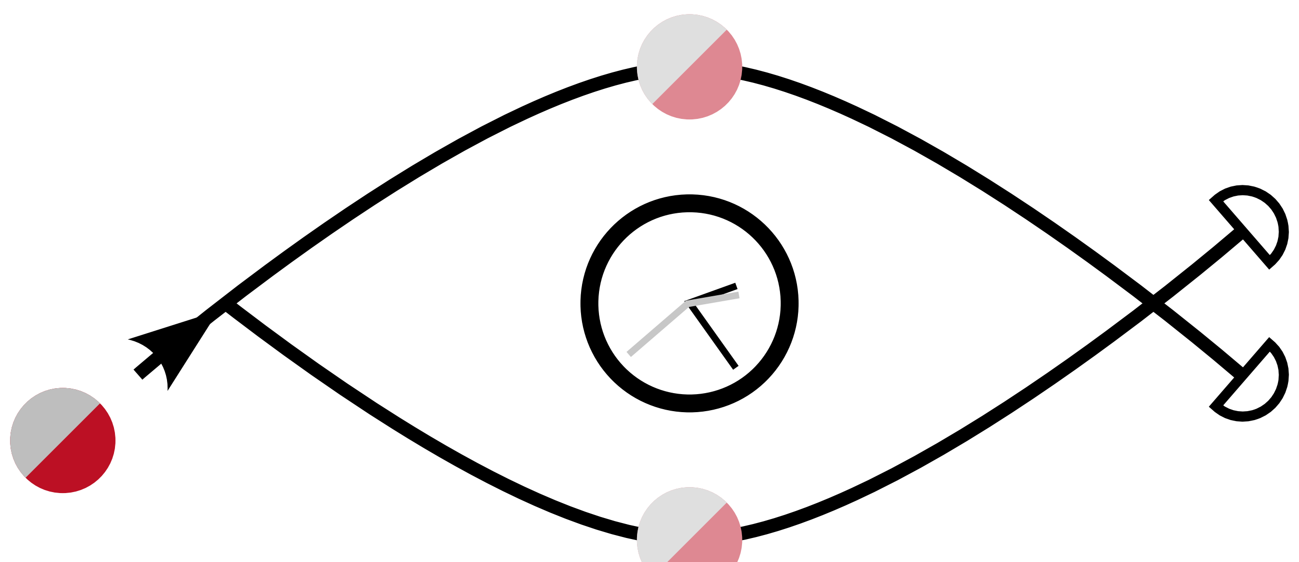
Expected interference patterns

Superposition of two mass eigenstates



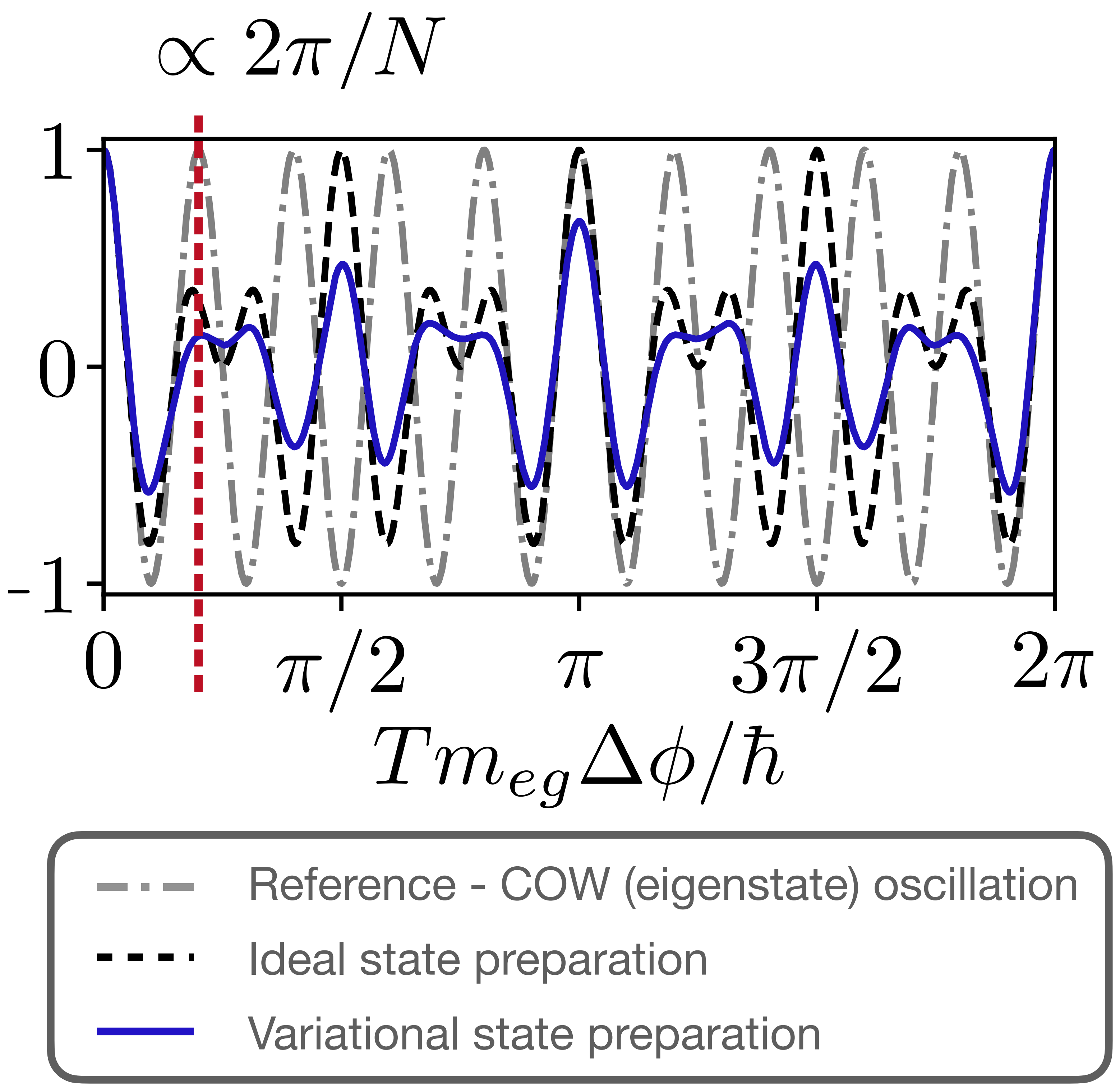
$$+A \leftrightarrow B$$

Equivalent: two-level atom (clock) interferometer



Two frequencies

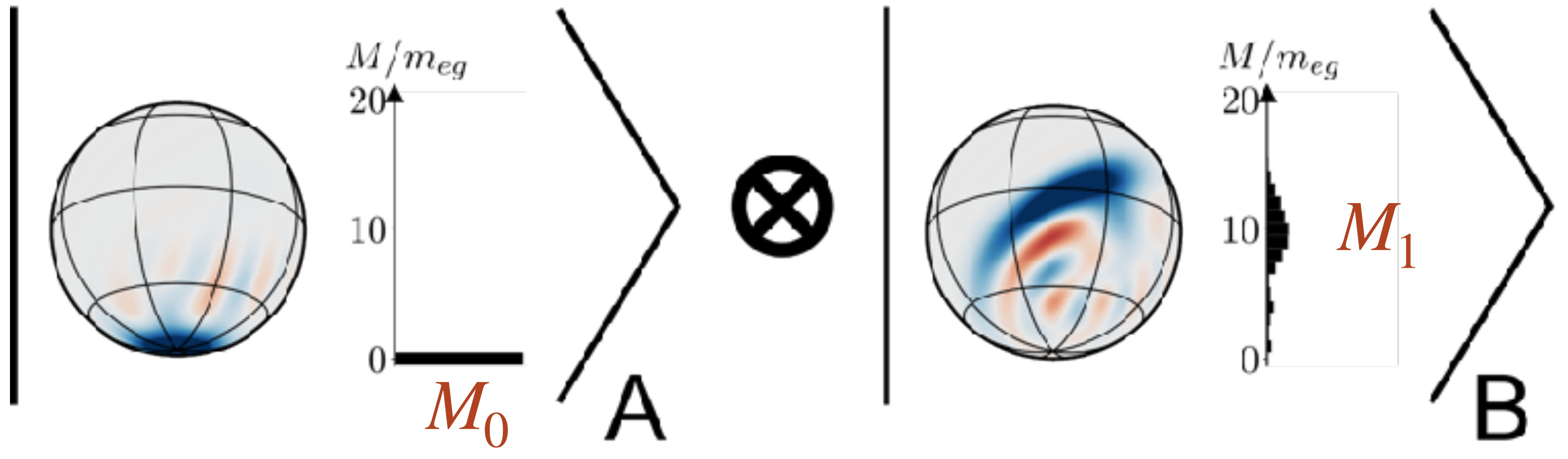
Interference pattern:



Visible beating between M_1 and M_2 frequencies

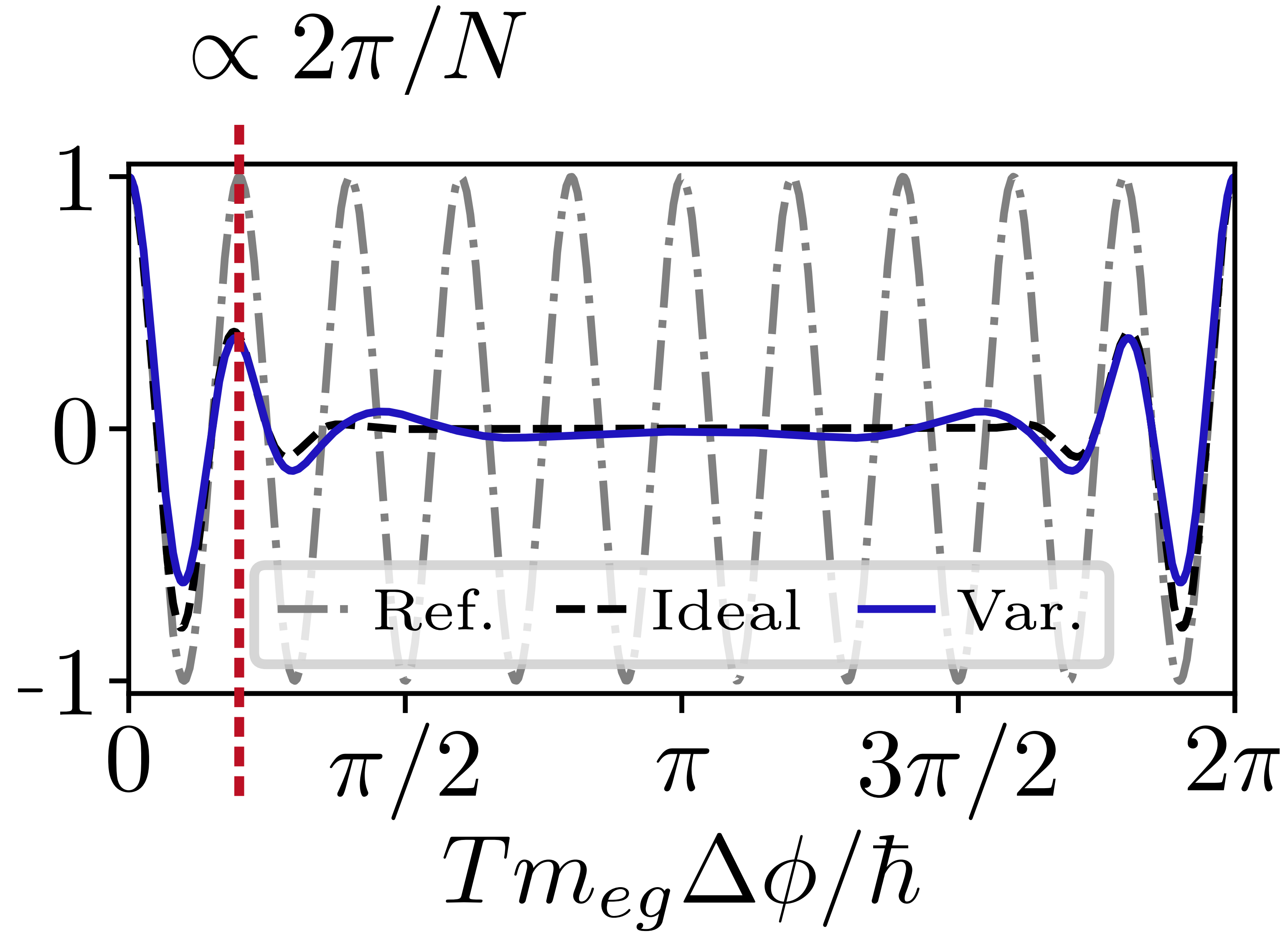
Expected interference patterns

Coherent state of mass excitations



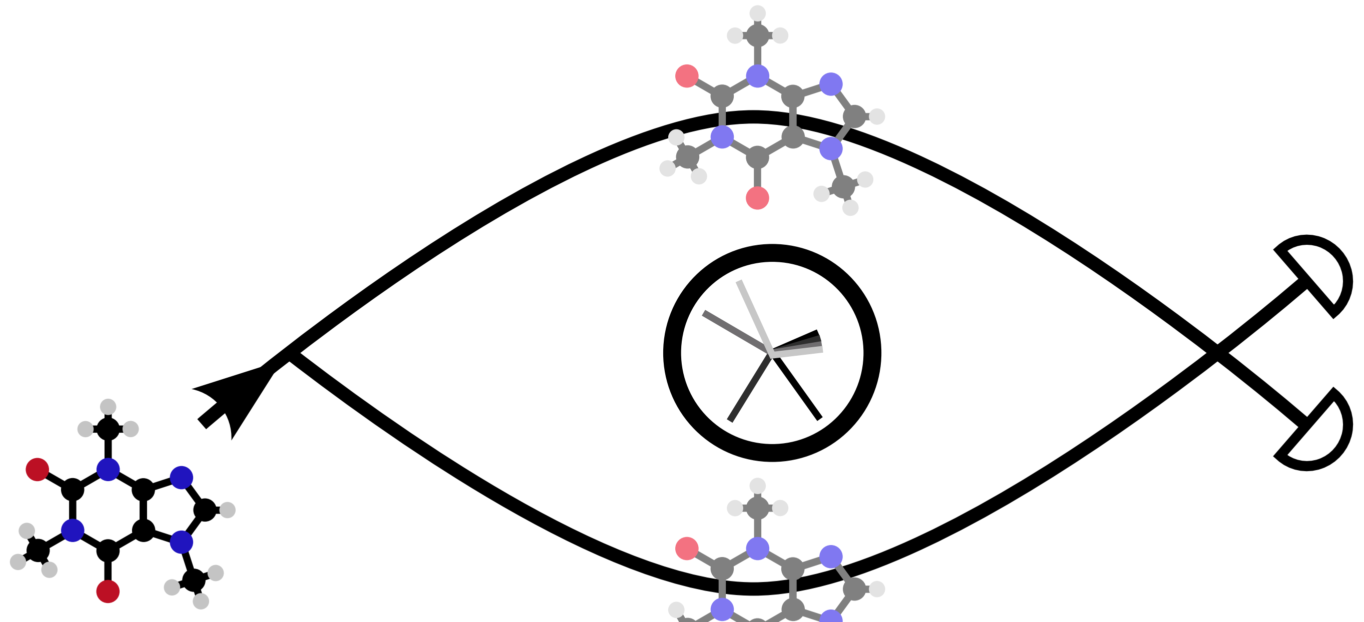
$$+A \leftrightarrow B$$

Interference pattern:



Reference - COW (eigenstate) oscillation
Ideal state preparation
Variational state preparation

Equivalent: complex particle (gravitational decoherence)



Many frequencies

Signal oscillation with frequency given by average mass
Fast loss of visibility — Gravitational "decoherence"

Outlook

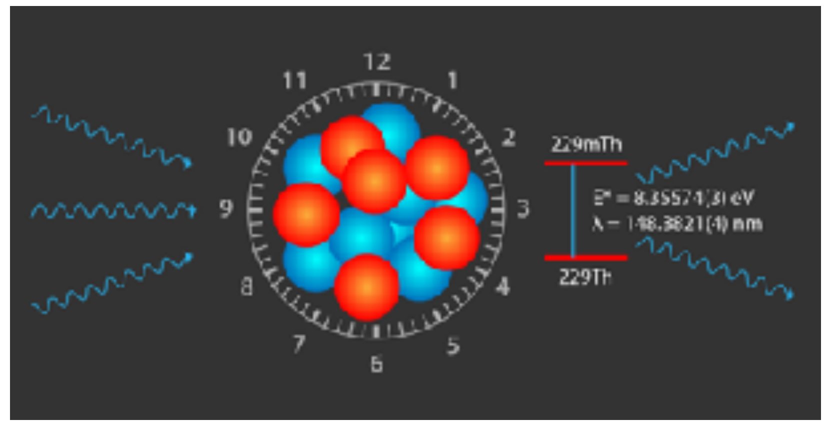
- Possible experiment in Innsbruck

J Bate

B Lanyon

*V. Krutyanskiy et al., Phys. Rev. Lett. **130**, 050803 (2023)*

- Enhance mass/energy scales: nuclear transitions?

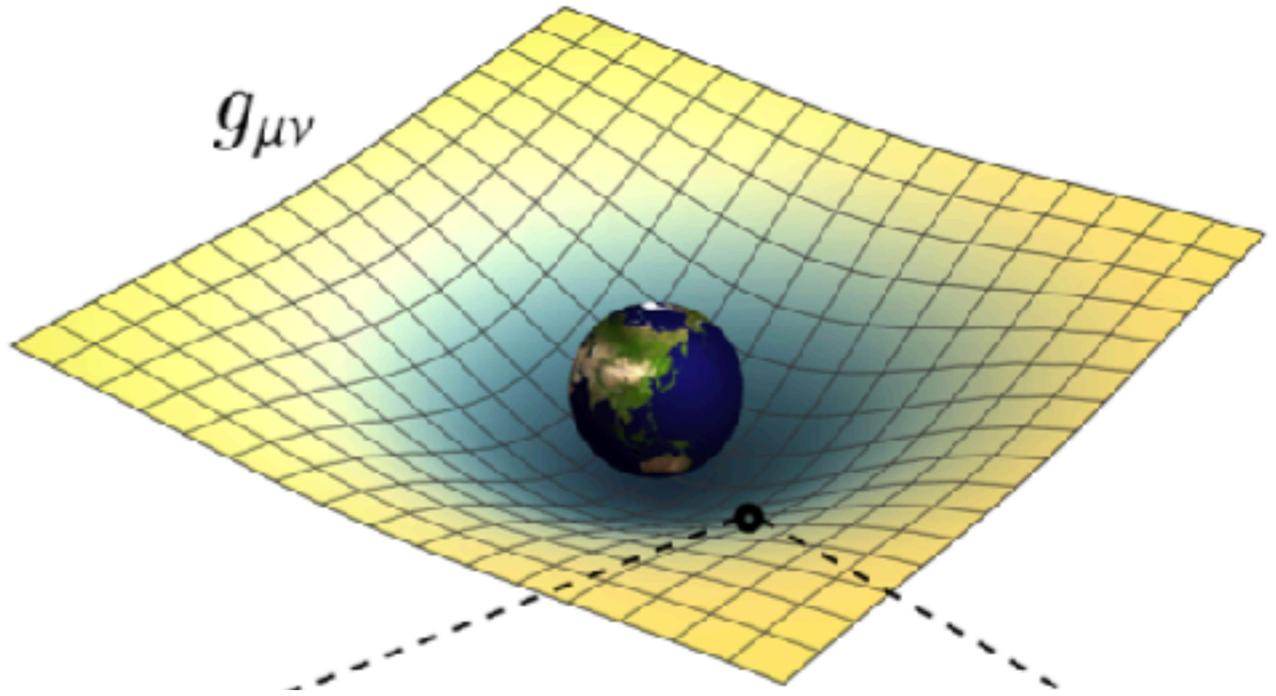


*P. Thirolf, Physics **17**, 71 (2024)*

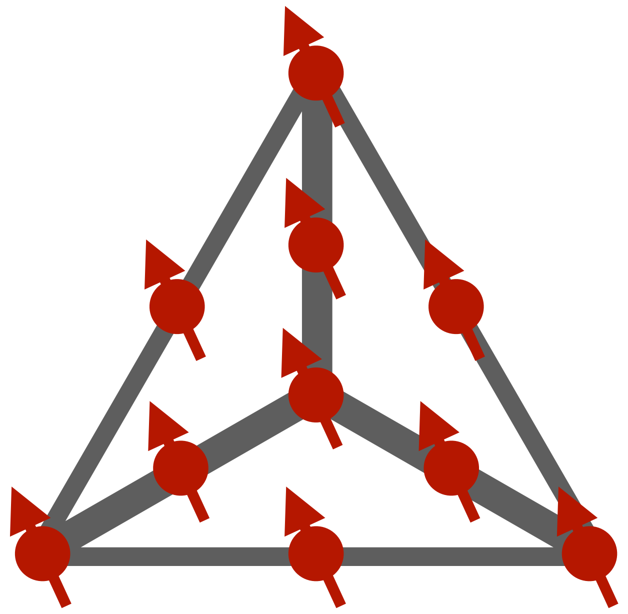
See:
*J. Tiedau et al., Phys. Rev. Lett. **132**, 182501 (2024)*
*R. Elwell et al., Phys. Rev. Lett. **133**, 013201 (2024)*
*C. Zhang et al., Nature **633**, 63-70 (2024)*

- New/interesting physics not accessible in atom interferometer experiments?

Curvature:
Riemann tensor ${R^a}_{bcd}$



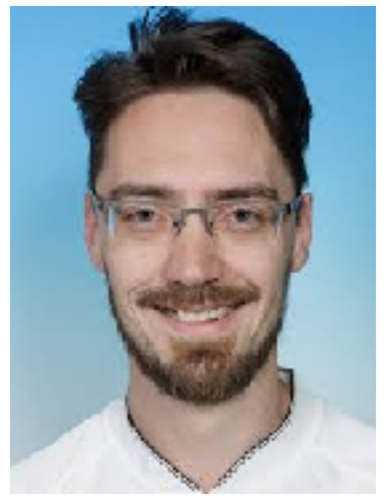
➡ Kretschmann scalar $K \approx \sum_{ij} \kappa_{ij} \left(\partial_i \partial_j \phi(\vec{r}) \right)^2$



$K = f(\phi_1, \ldots, \phi_{10})$

Distributed quantum sensing task!

Collaborators:

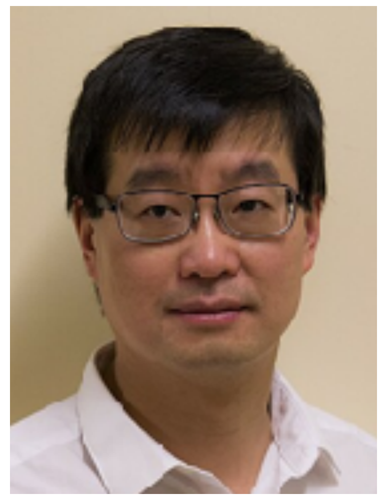


D Vasilyev

T Zache

K Hammerer

AM Rey



J Ye

H Pichler

P Zoller

Thank you for listening!

https://arxiv.org/abs/2509.19501