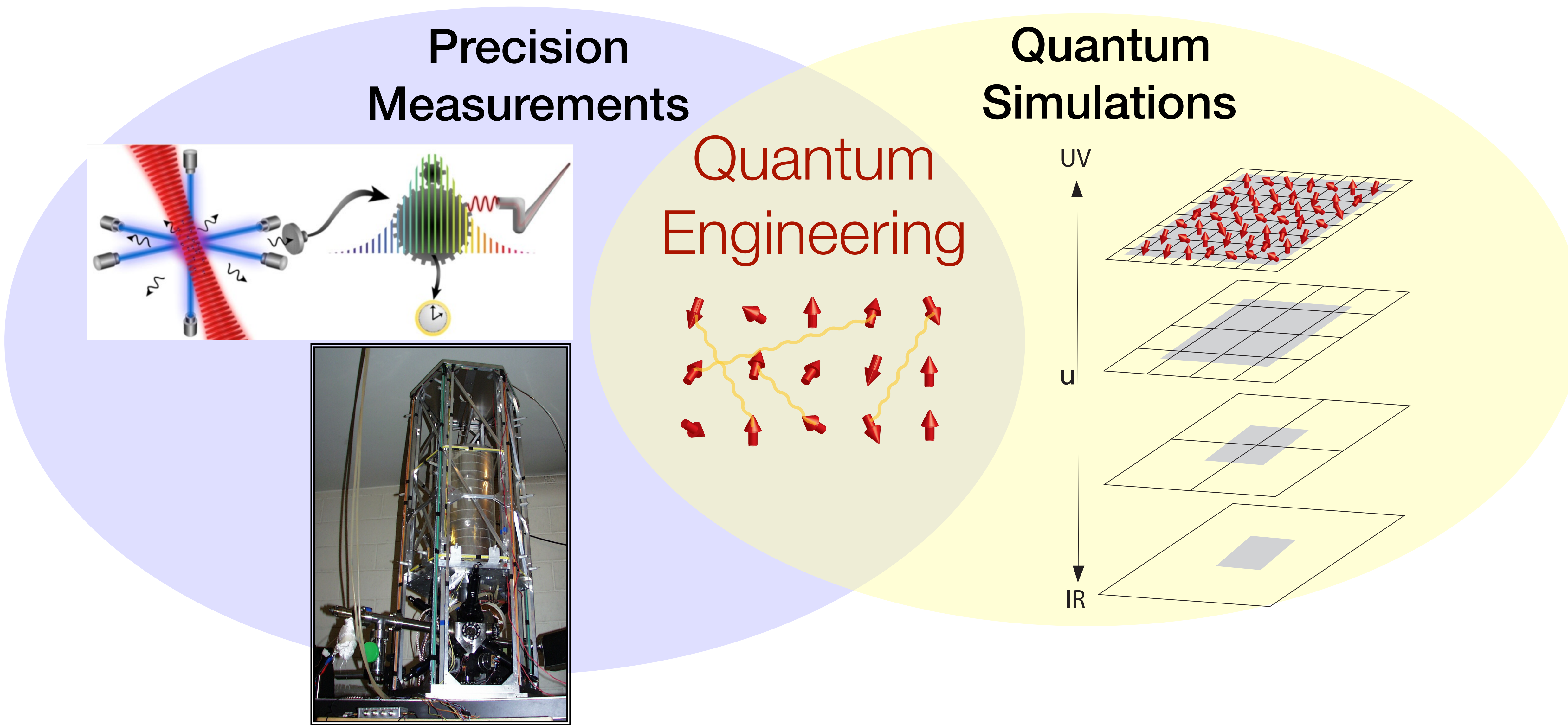
Quantum Engineering with Cold Atoms and Light

Monika Schleier-Smith

December 13, 2017

Stanford University

Quantum Engineering for Fundamental Physics

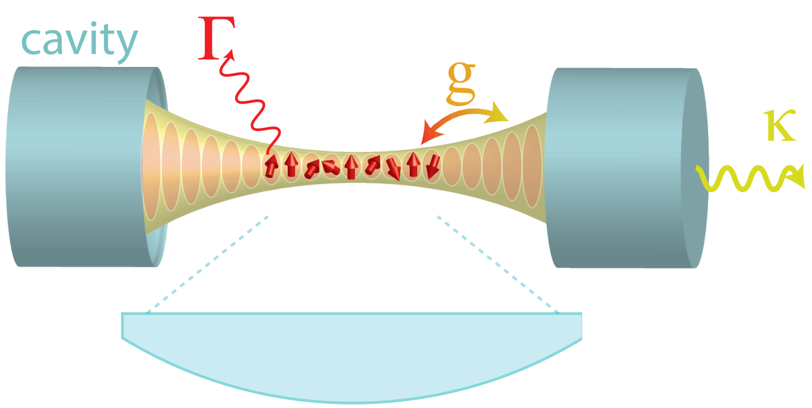


Outline

Motivation and Background

Quantum metrology

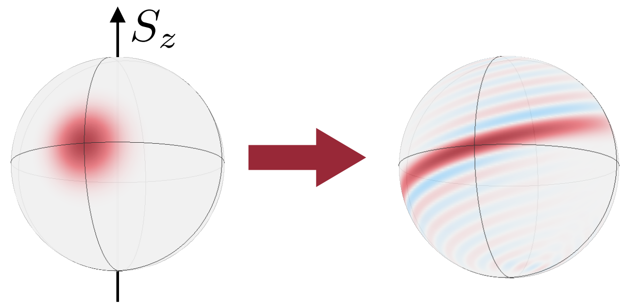
Entangling atoms with photons



Seeking the Heisenberg Limit

Engineering entanglement in a dissipative world

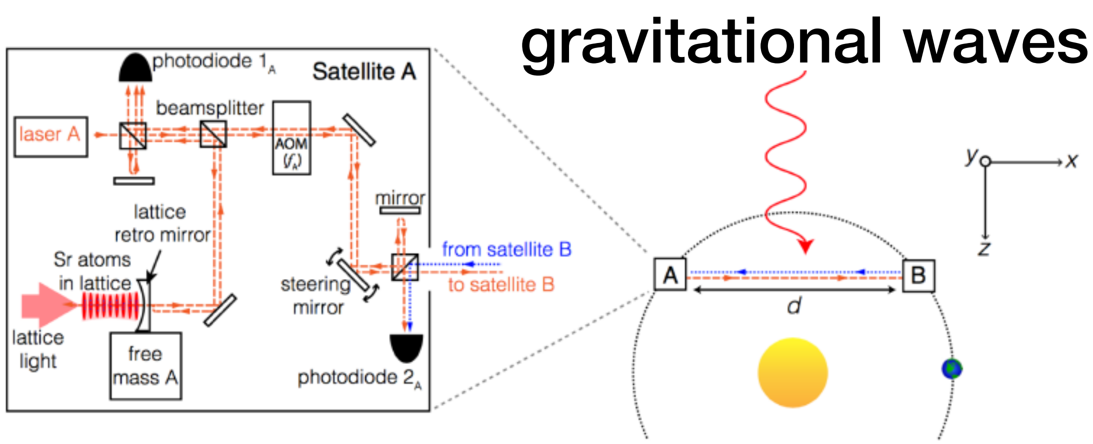
Harnessing entanglement in a noisy world



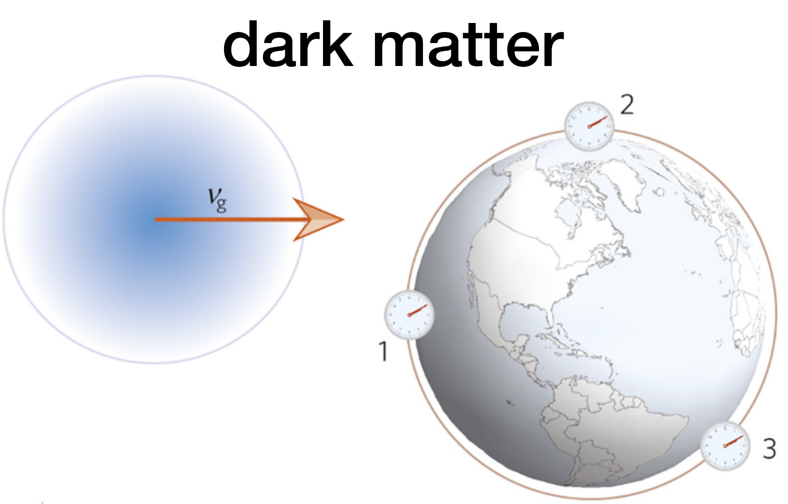
Summary & Outlook

Quantum Metrology: Motivation

Ultra-stable clocks as sensors



Kolkowitz, … & Ye, *Phys. Rev. D* (2016).

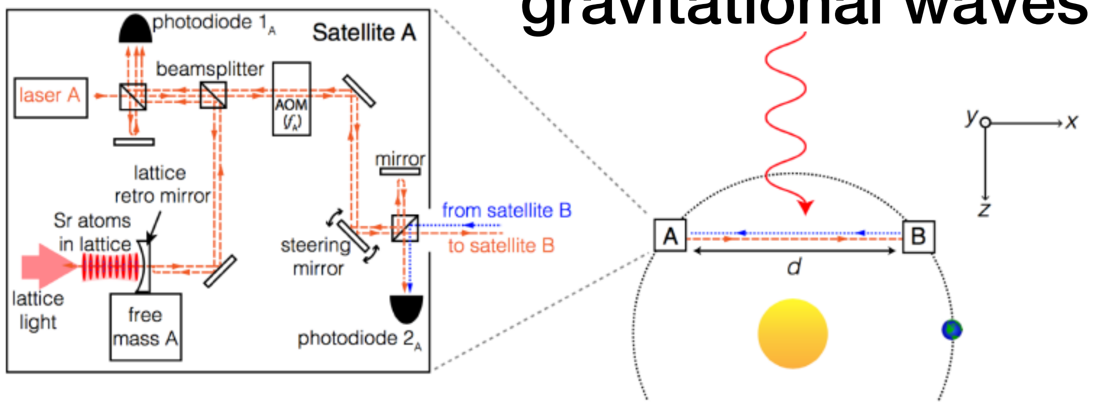


Derevianko & Pospelov, *Nat. Phys.* (2014).
Arvanitaki, Huang, & Van Tilburg, *PRD* (2015).

Quantum Metrology: Motivation

Ultra-stable clocks as sensors

gravitational waves



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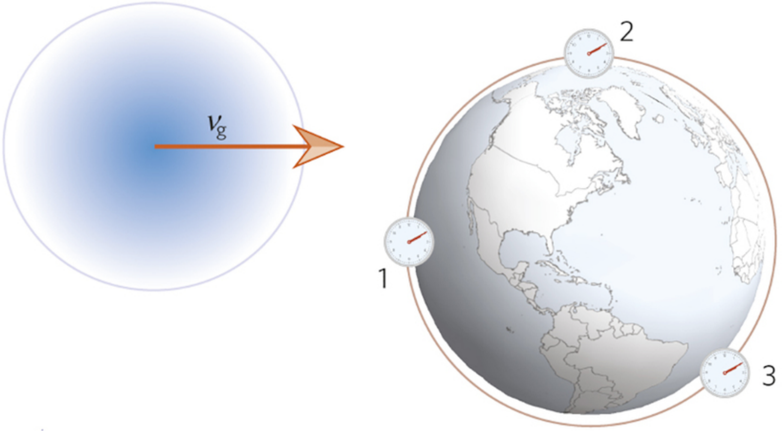
dark matter



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Entanglement can enable…

→ higher precision in fixed time with finite atom number *N*

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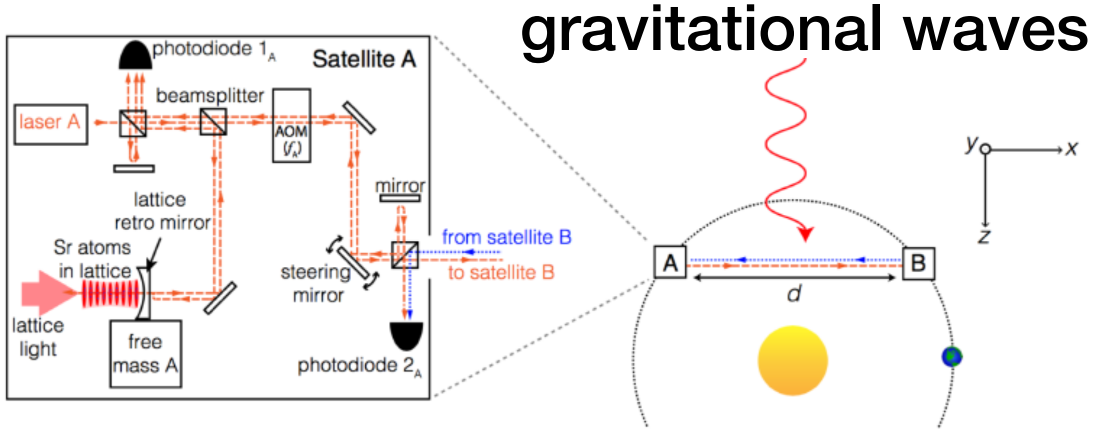

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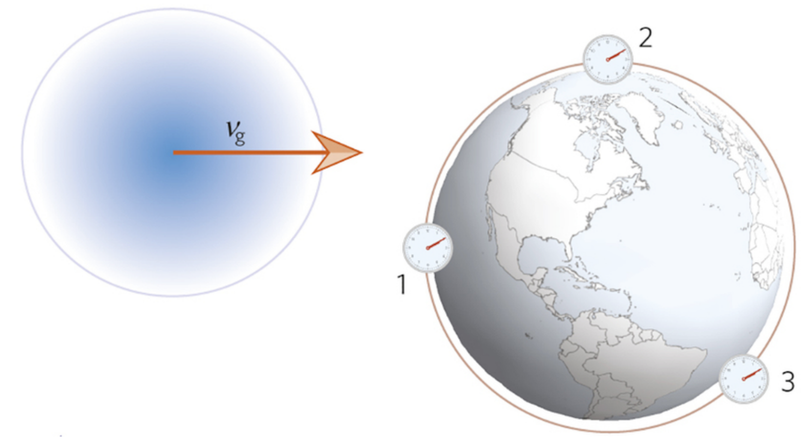

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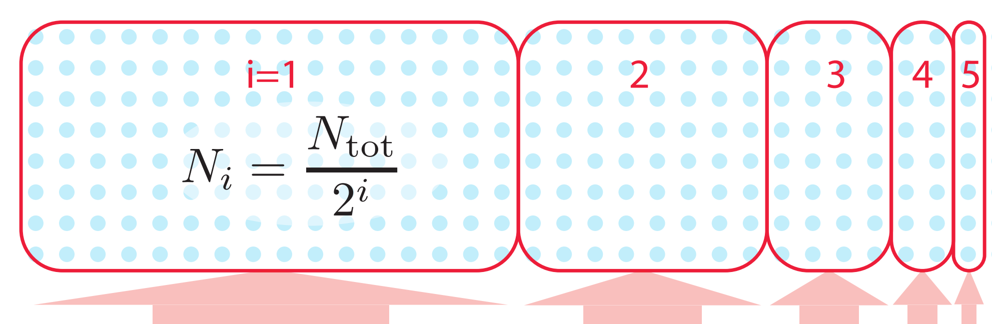
Entanglement can enable…

→ higher precision in fixed time with finite atom number N

→ distribution of resources for enhanced bandwidth or dynamic range



Inspiration: Kessler, …, Sorensen, Ye, Lukin, PRL (2014).

Quantum Metrology: Motivation

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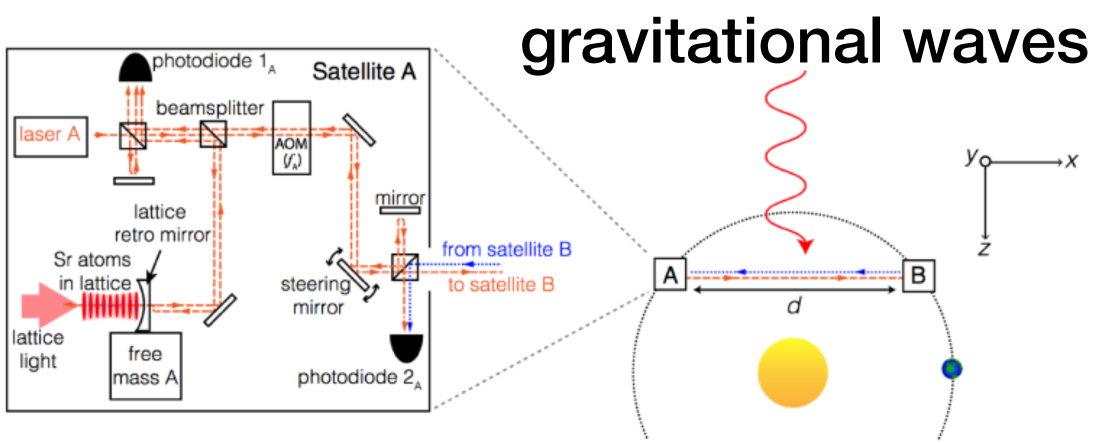

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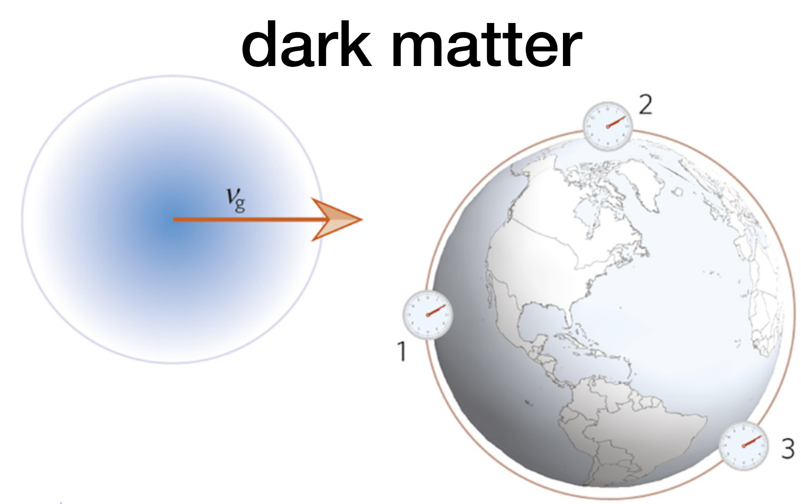
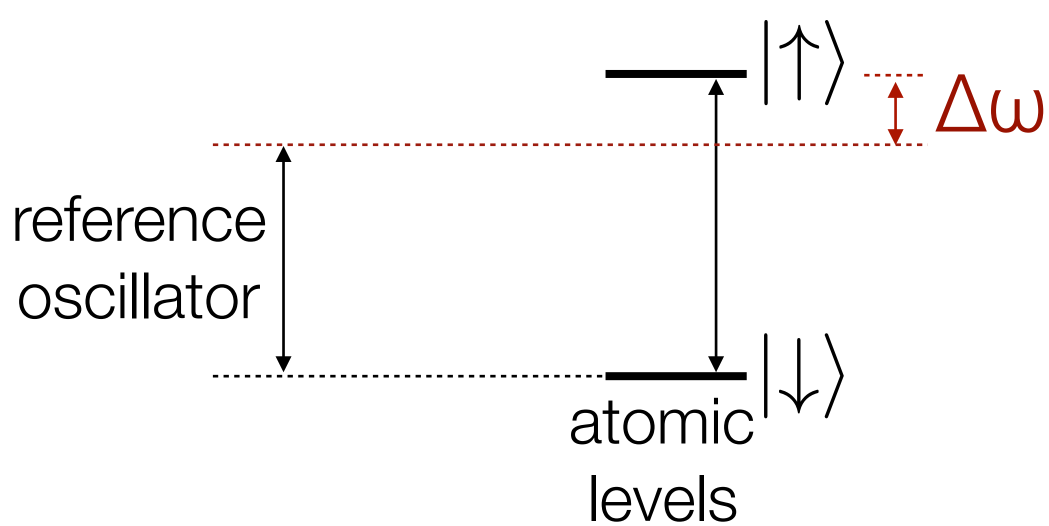


Derevianko & Pospelov, *Nat. Phys.* (2014).

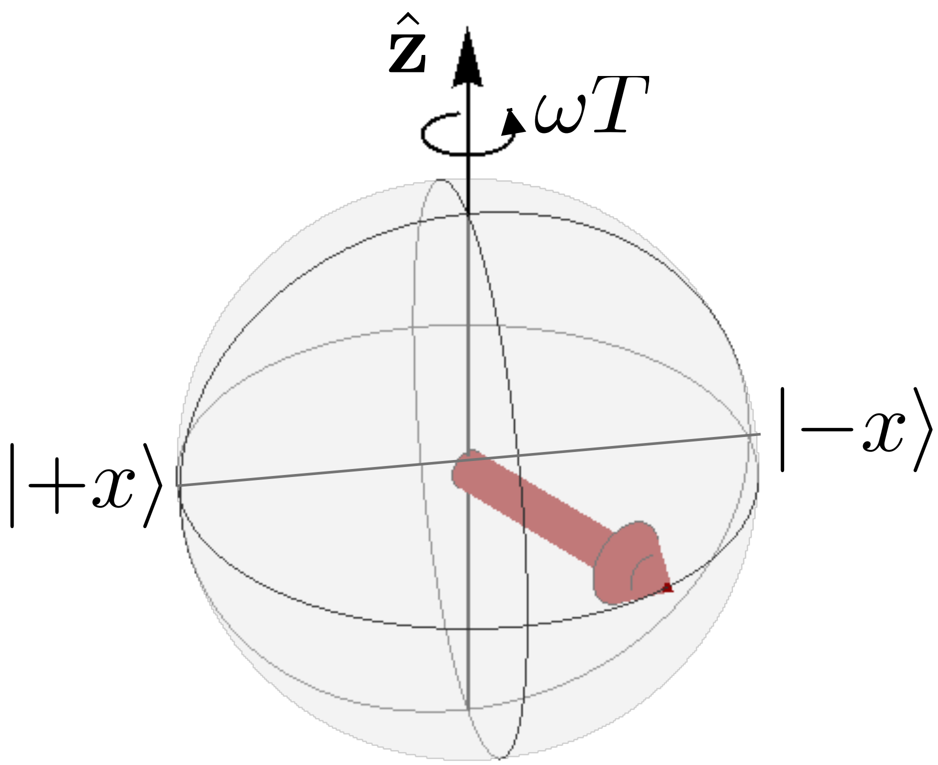
How fast can an atomic sensor detect a perturbation?



Speed Limits in Quantum Sensing

Time *T* for perturbation Δω to appreciably change the quantum state

Single spin: $|\uparrow\rangle + e^{i\omega T}|\downarrow\rangle$



$$\Delta\omega T \sim 1$$

Speed Limits in Quantum Sensing

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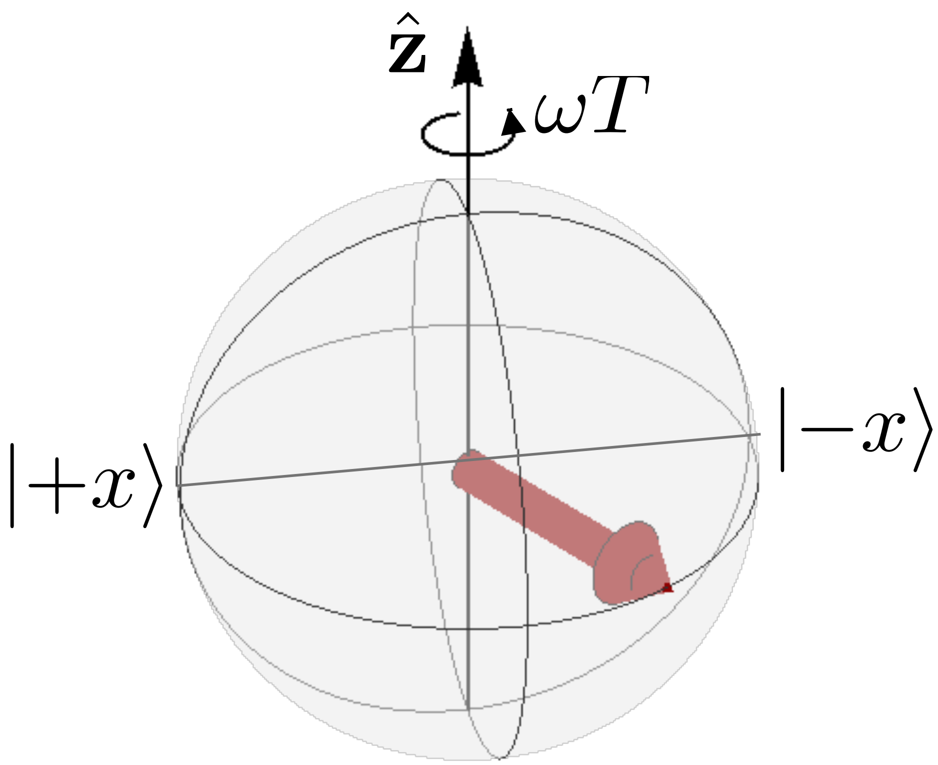

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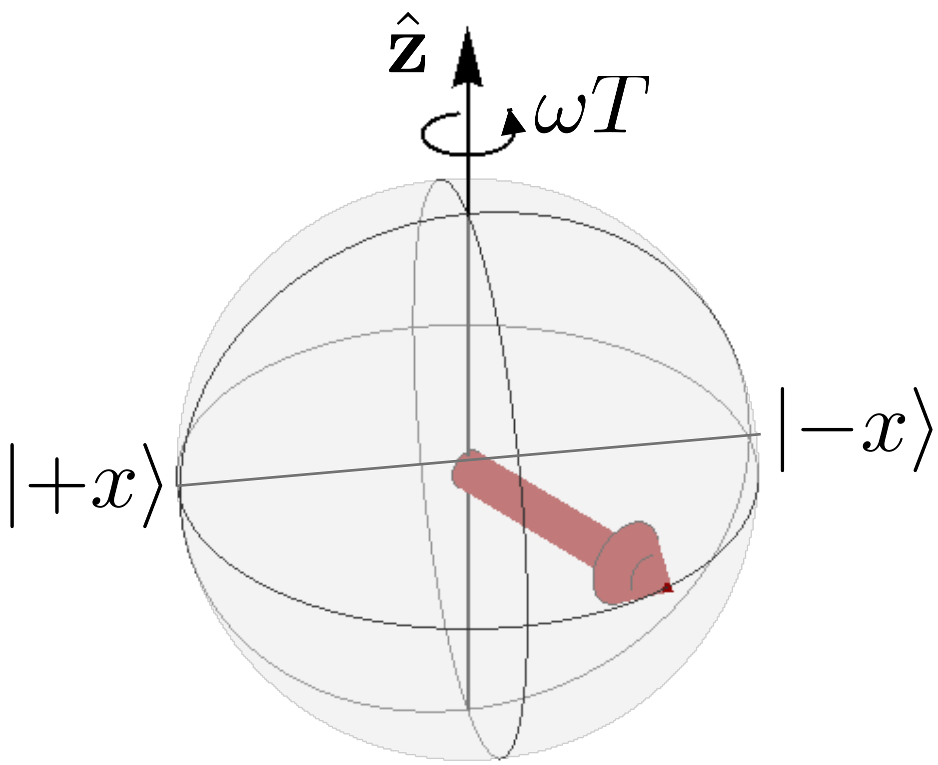

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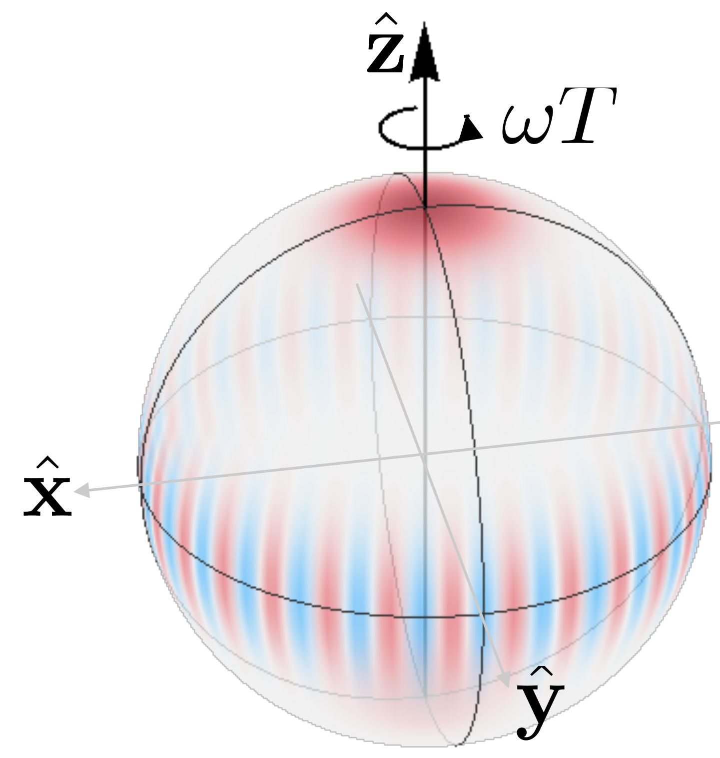

$\Delta\omega T \sim 1/N$

Heisenberg Limit

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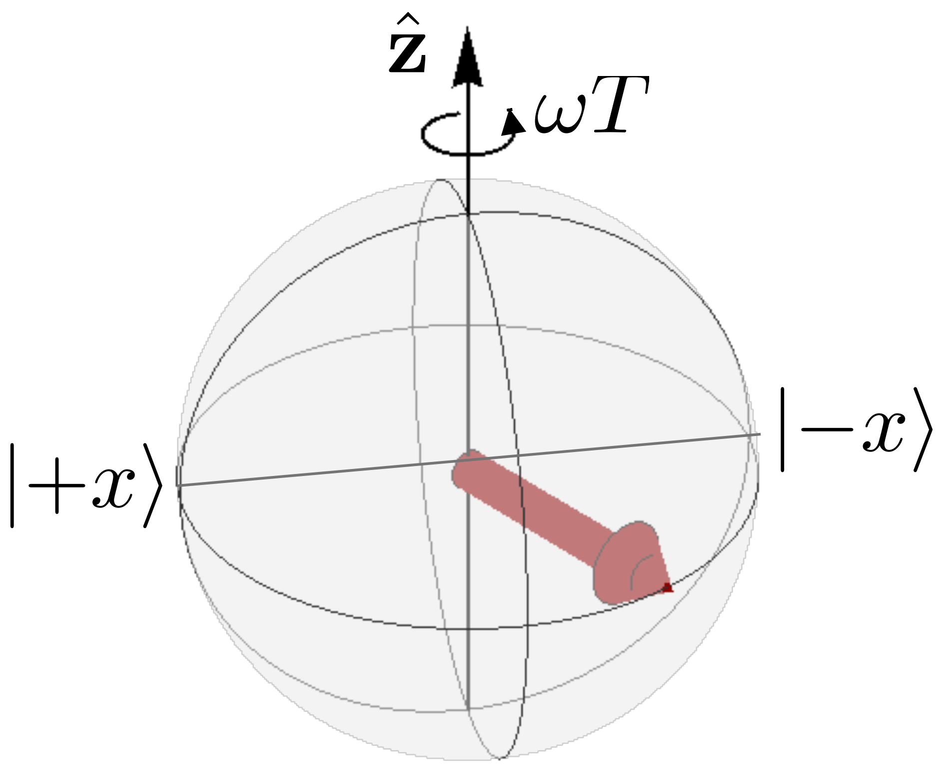

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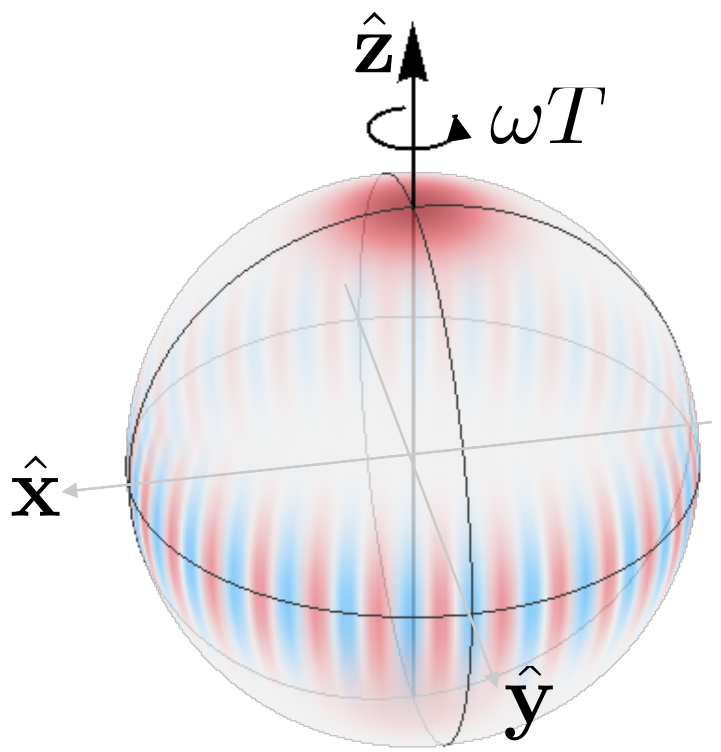


$$\Delta\omega T \sim 1/N$$

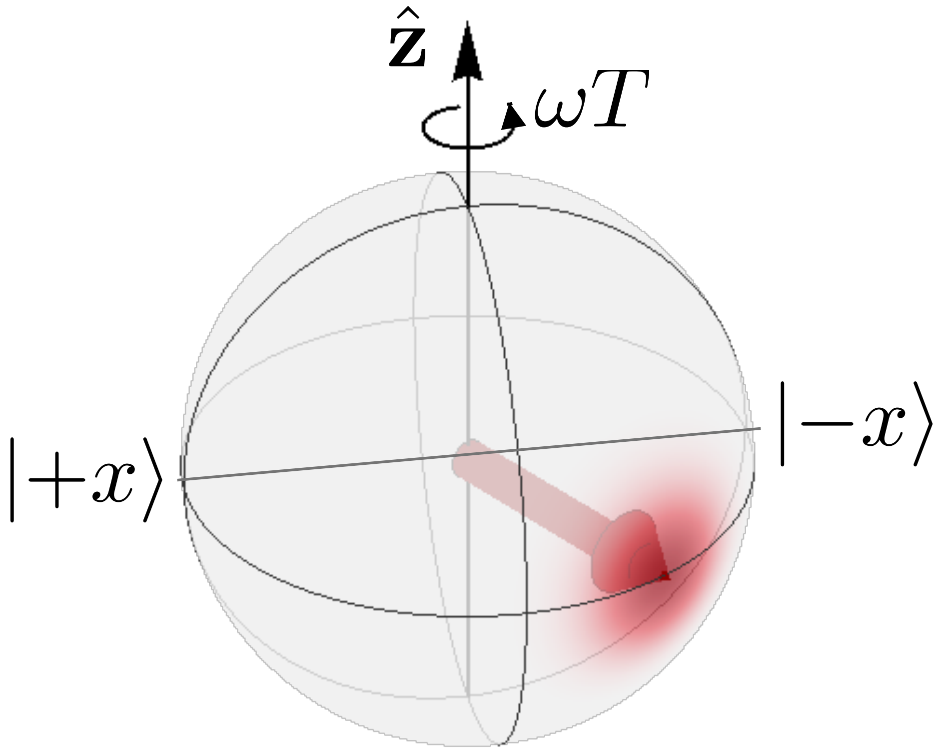
Heisenberg Limit

requires *N*-particle entanglement

Speed Limits in Quantum Sensing

Time T for perturbation $\Delta\omega$ to appreciably change the quantum state

N spins: $\left(|\uparrow\rangle + e^{i\omega T}|\downarrow\rangle\right)^{\otimes N}$



$$\Delta\omega T = 1/\sqrt{N}$$

Standard Quantum Limit
for uncorrelated atoms

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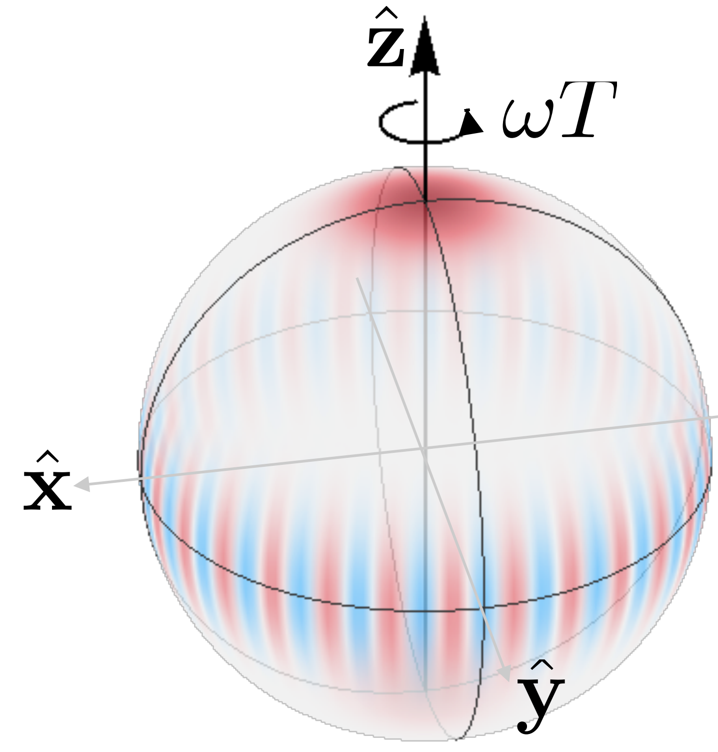

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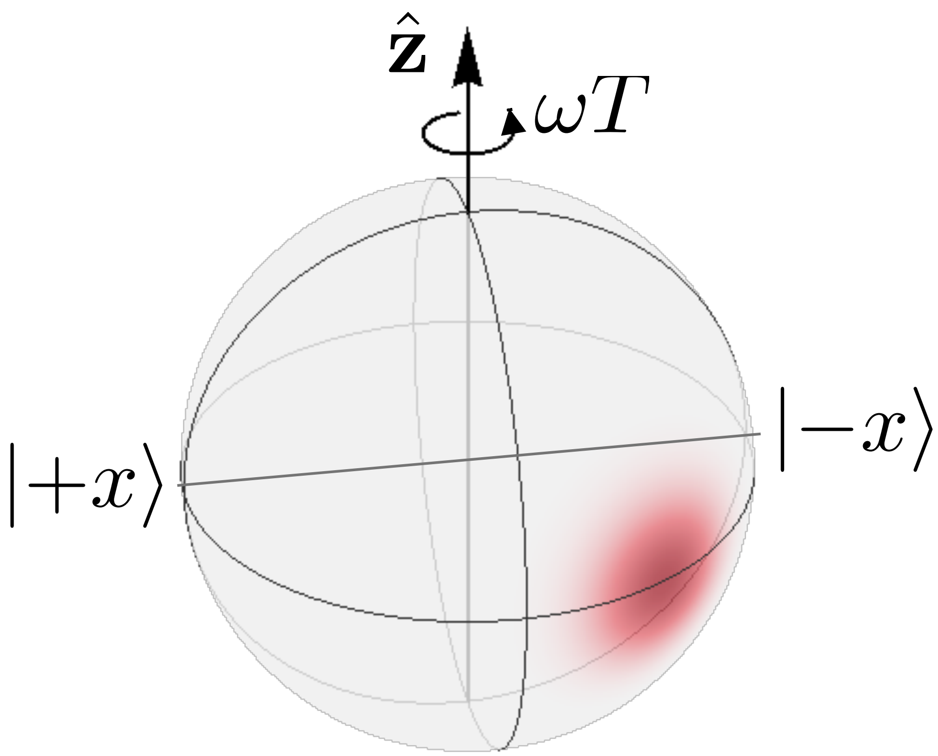

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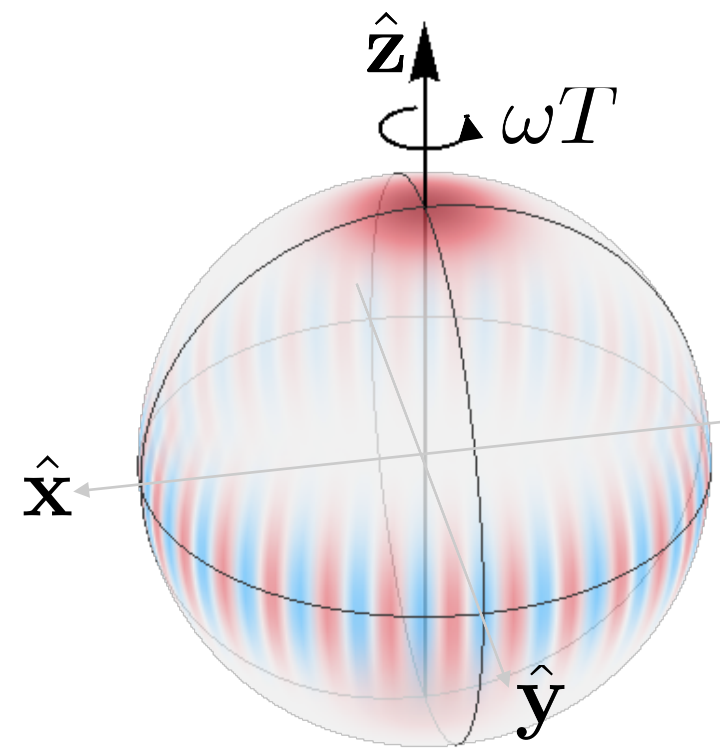

$$\Delta\omega T = 1/N$$

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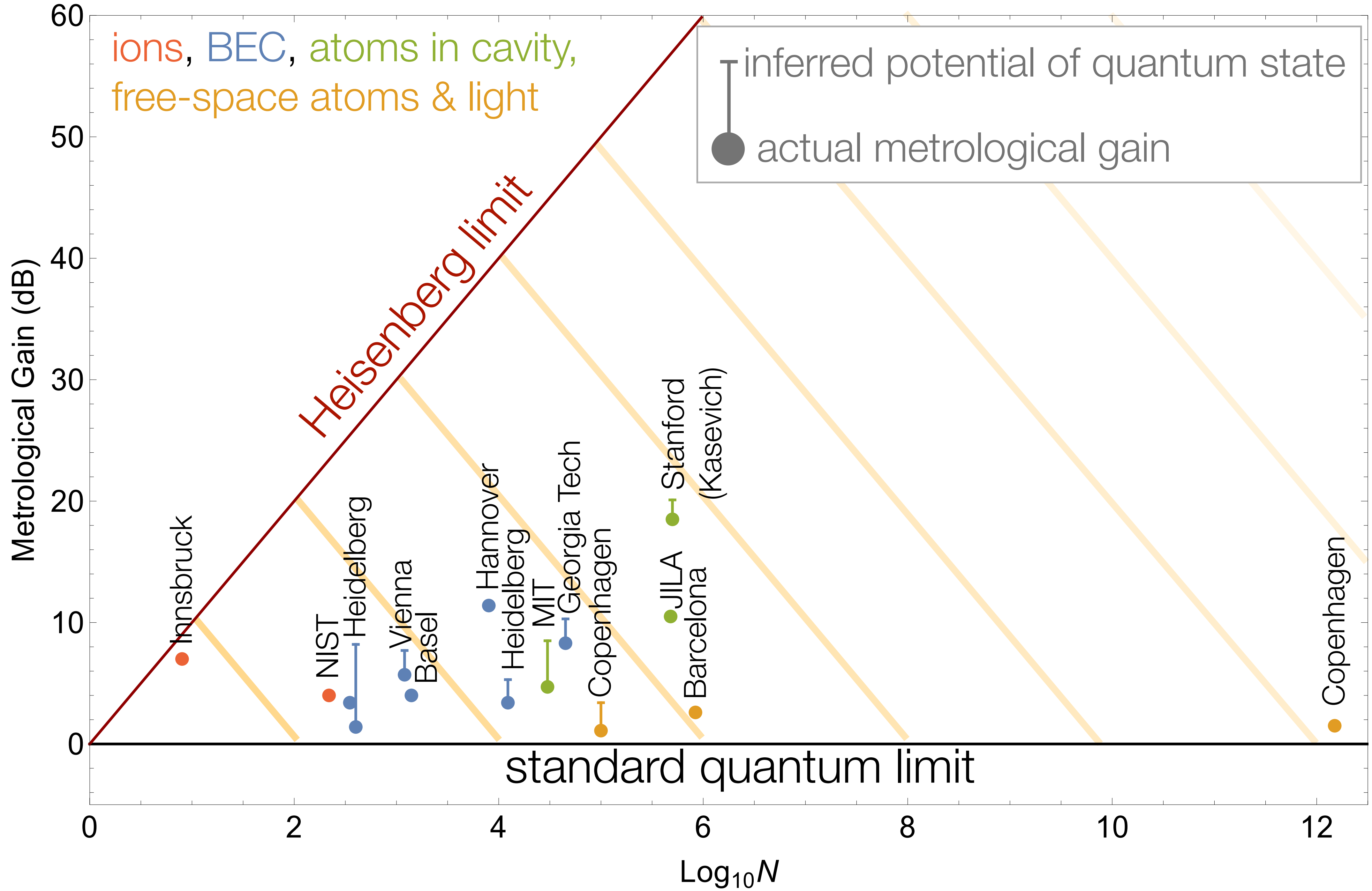
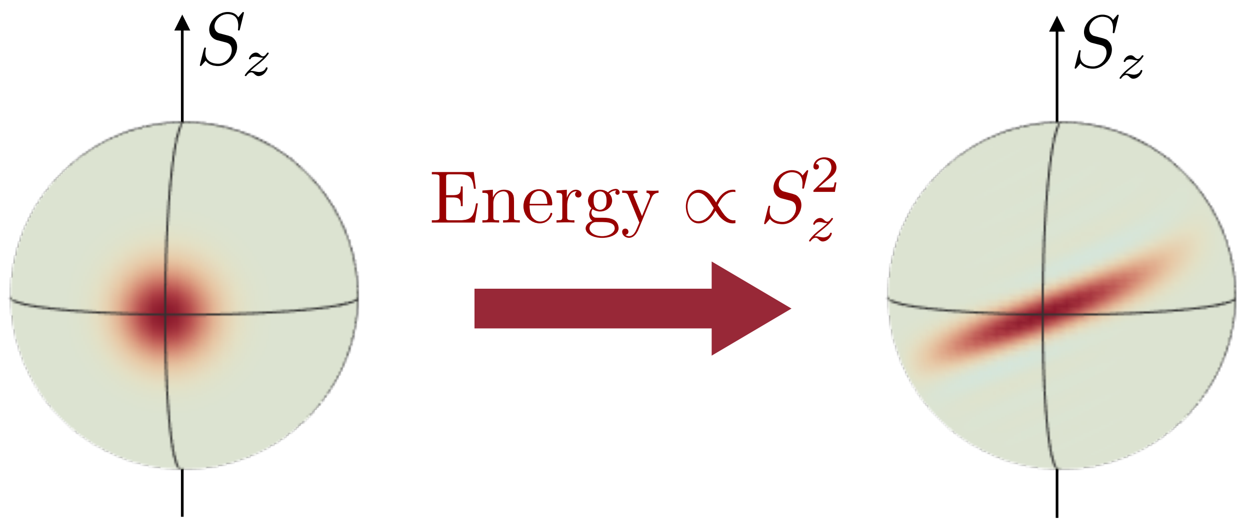
Entanglement-Enhanced Measurements



Generating Entanglement

…by spin-spin interactions

One-axis twisting [Kitagawa & Ueda, *PRA* 1993]



Collective spin

$$\mathbf{S} = \sum_{i=1}^{N} \mathbf{s}_i$$

Generating Entanglement

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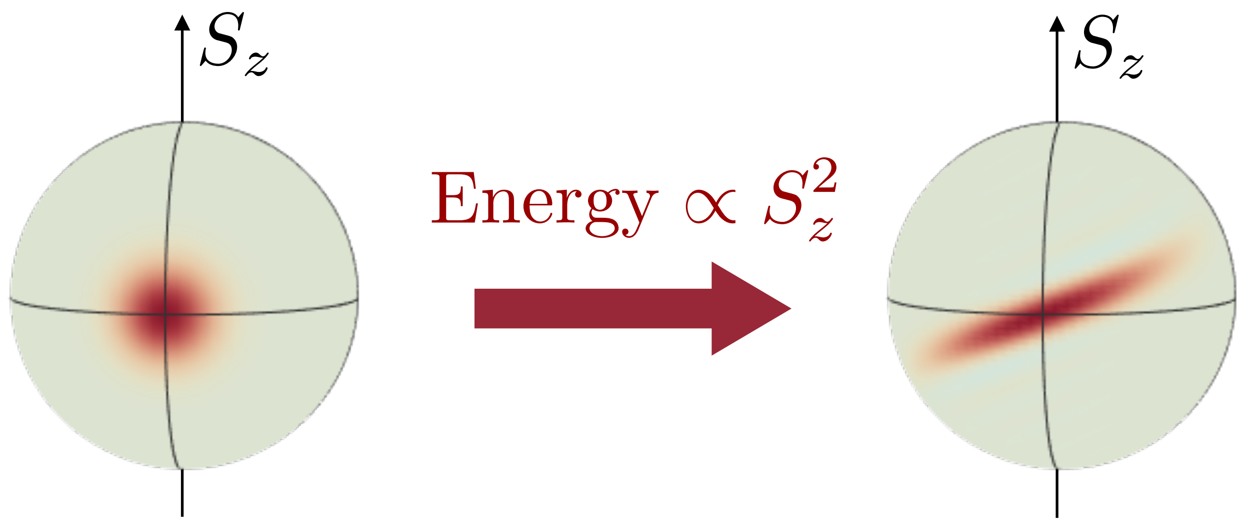


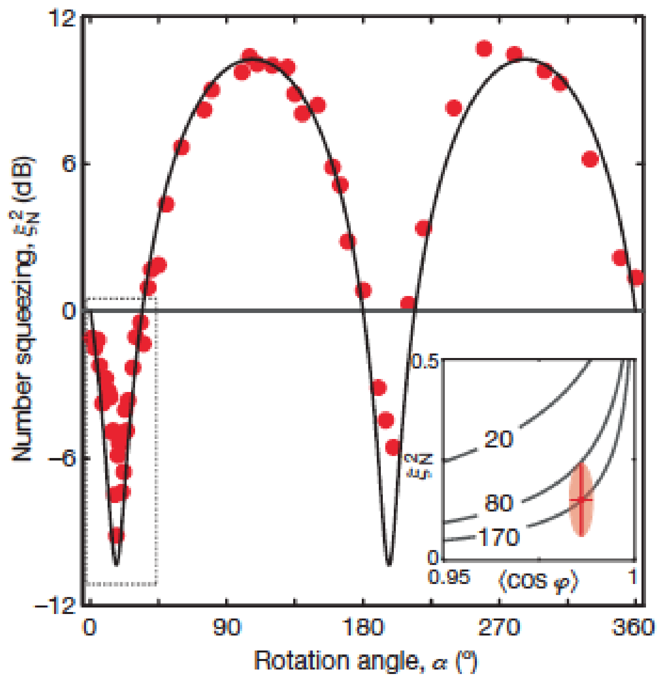
Collective spin

$$\mathbf{S} = \sum_{i=1}^{N} \mathbf{s}_i$$

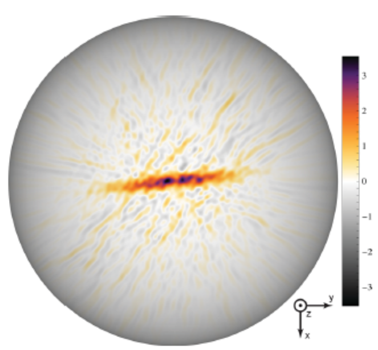
The one-axis twisting Hamiltonian corresponds to the energy propotional to the square of the population difference. The two-axis twisting Hamiltonian corresponds to the simultaneous excitation-deexcitation of two atoms. Although realistic physical schemes are yet to be found, these nonlinear Hamiltonians will provide some clues in the search for squeezed atomic states [21].

One-Axis Twisting: Implementations

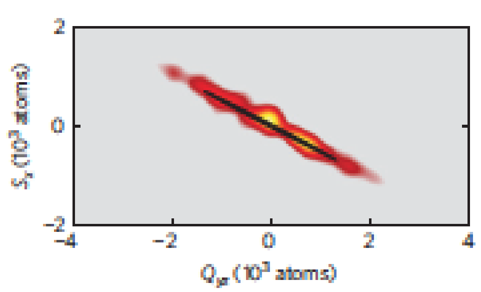
BECs



Gross, . . . & Oberthaler, *Nature* (2010).

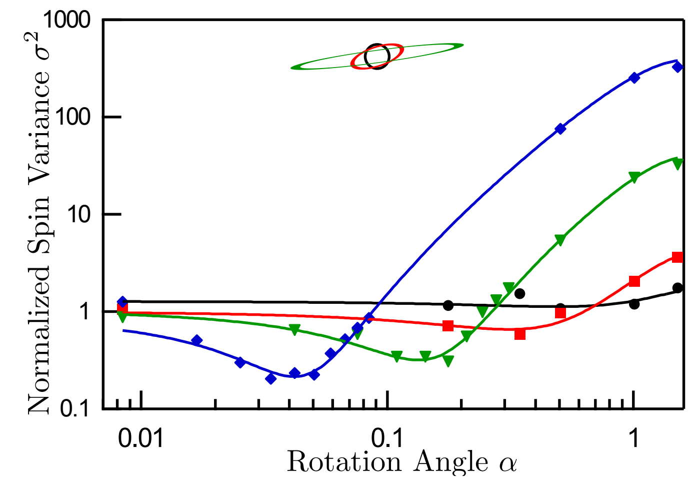


Riedl, . . . & Treutlein, *Nature* (2010).



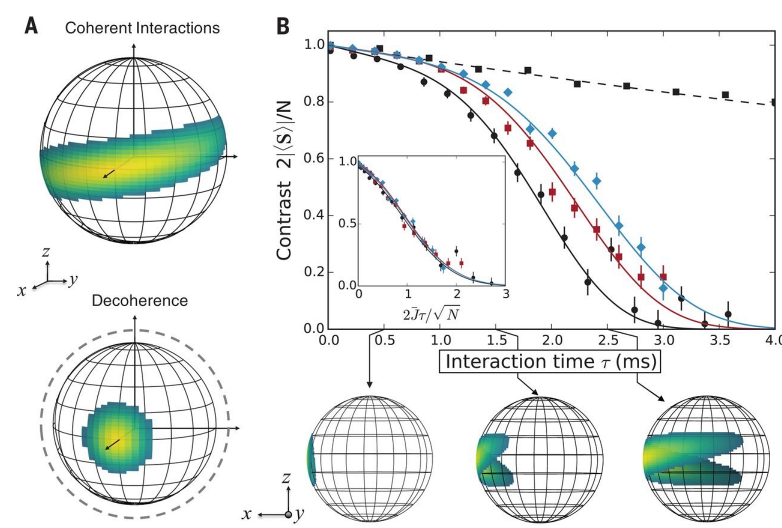
Hamley, . . . & Chapman, *Nature Physics* (2011).

Cavity QED



Leroux, MS-S & Vuletic, *PRL* (2010).
Hosten, … & Kasevich, *Science* (2016).

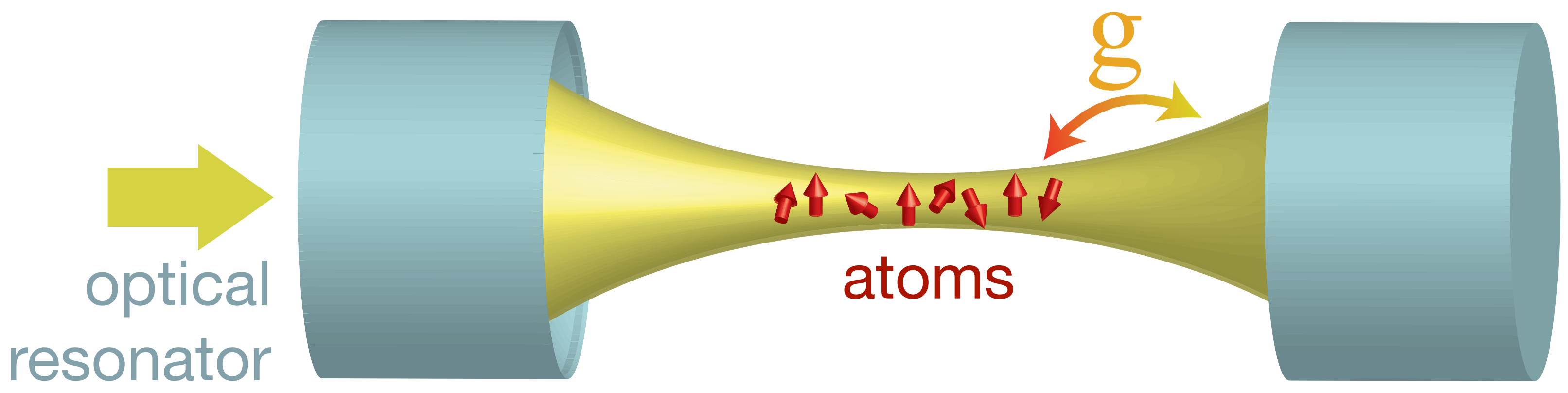
Ion traps



Bohnet, … & Bollinger, *Science* (2016).
14-ion cat states: Monz, … & Blatt *PRL* (2011).

Photon-Mediated Interactions

Atoms “talk” to each other via **single mode of light** in an *optical resonator*



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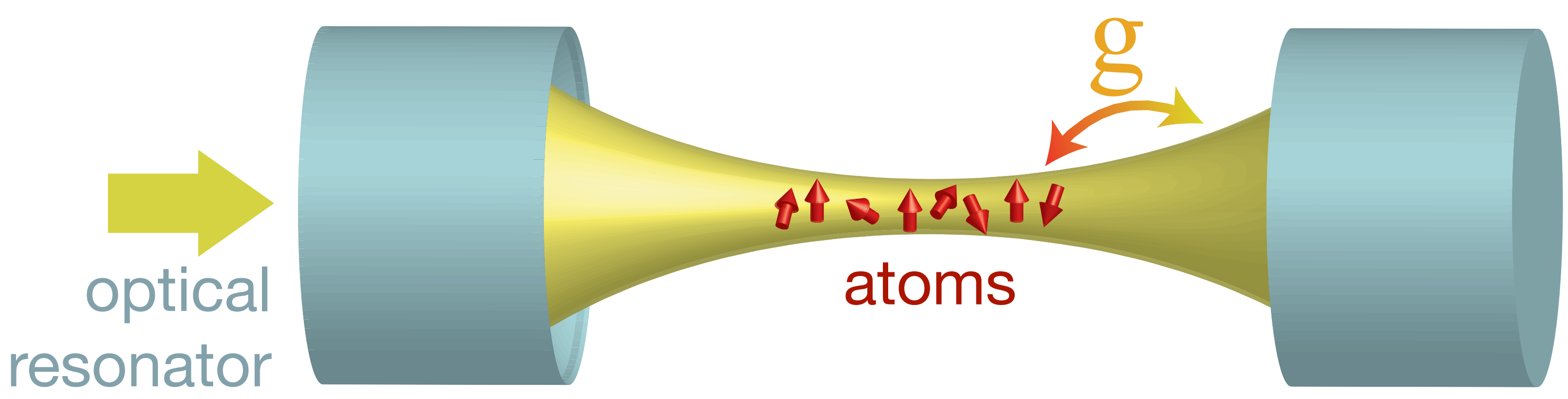

- **Non-local →** entangling atoms even in a dilute system

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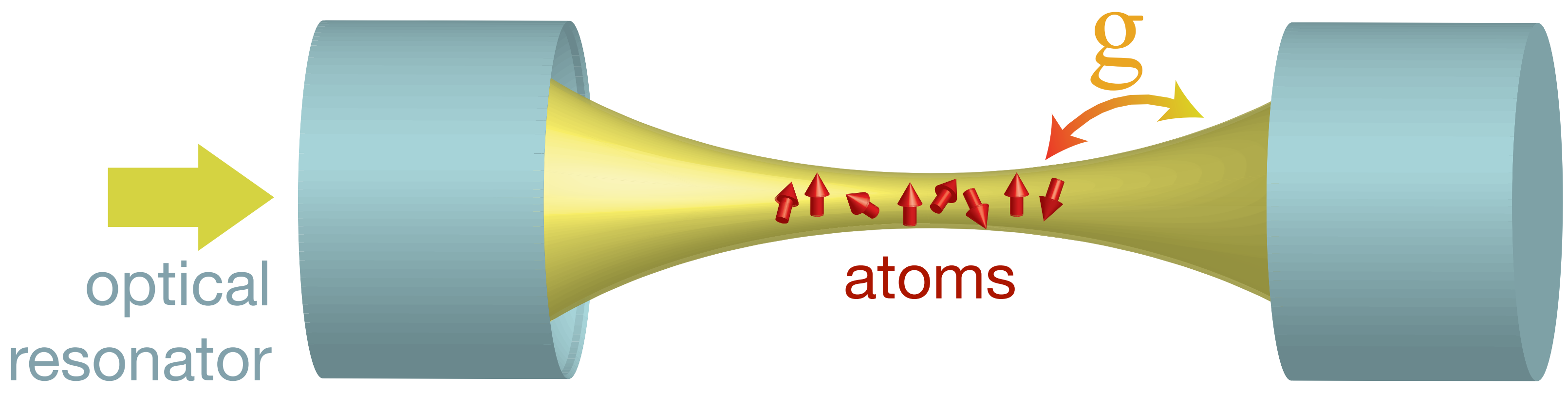

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- Easy to switch on/off for precision measurement

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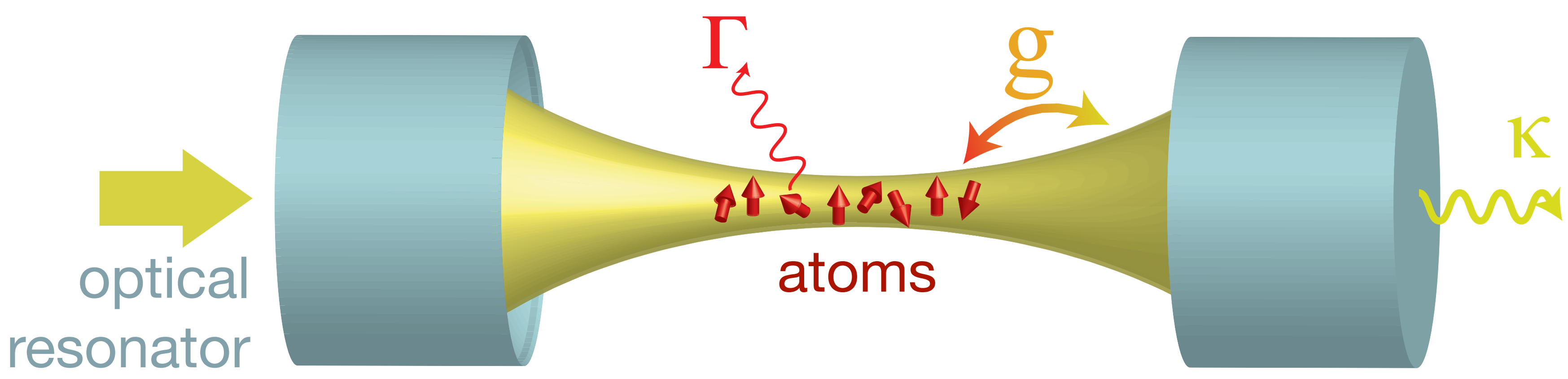

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- *Dissipation?*

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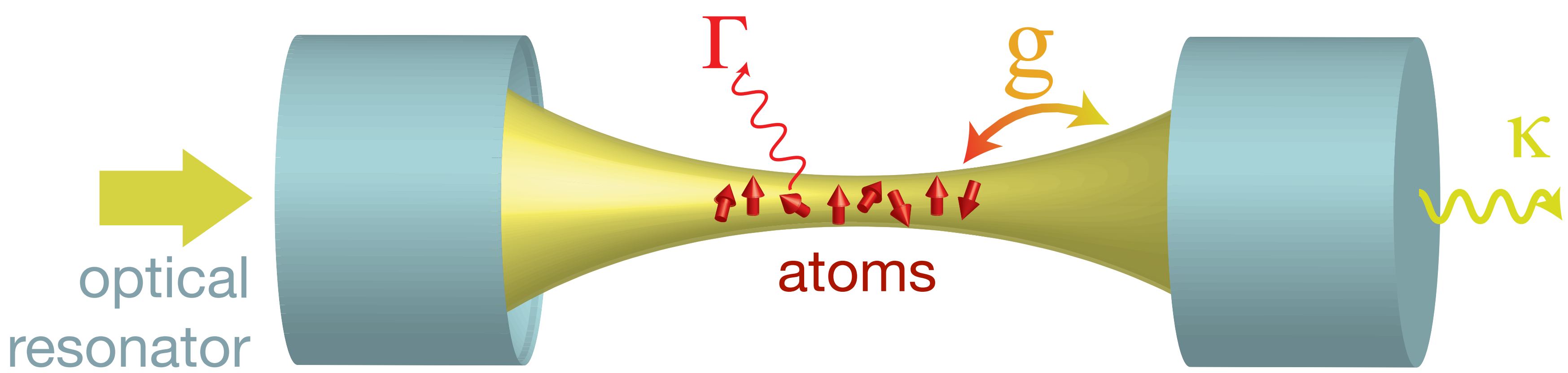

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  - Interactions can be coherent for strong coupling $\eta \equiv 4g^2/(\kappa\Gamma) \gg 1$

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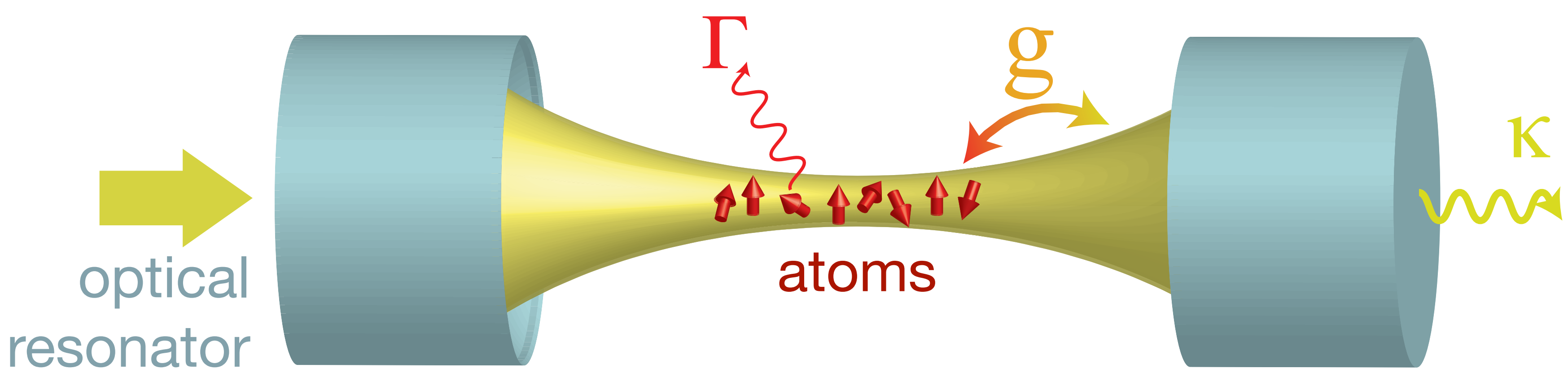
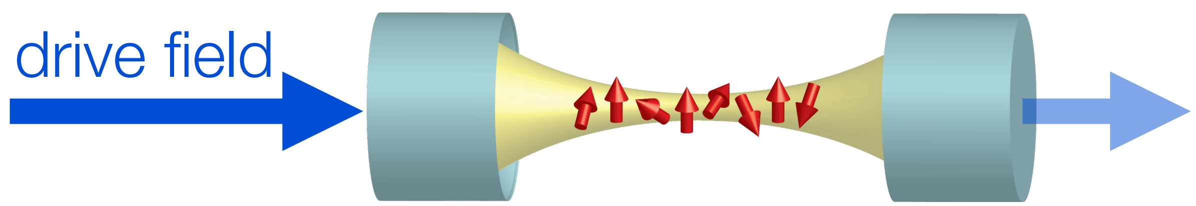
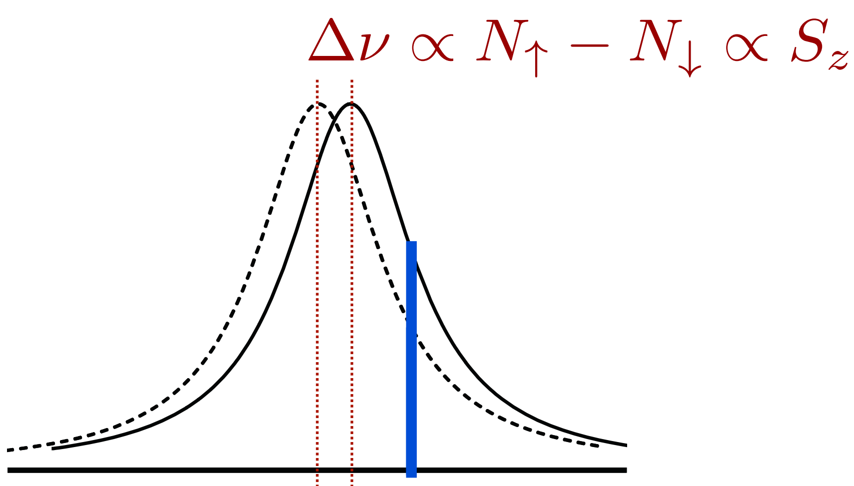


- **Non-local** → entangling atoms even in a dilute system
- Easy to switch on/off for precision measurement
- *Dissipation?*
  - Interactions can be coherent for strong coupling $\eta \equiv 4g^2/(\kappa\Gamma) \gg 1$
  - Or maximize info. in exiting light & entangle atoms by measurement

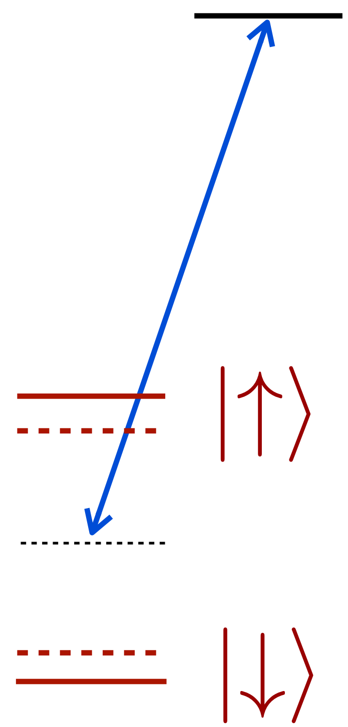
Photon-Mediated Ising Interactions

MS-S, ID Leroux & V Vuletic, *PRA* **81**, 021804*(R)* (2010).

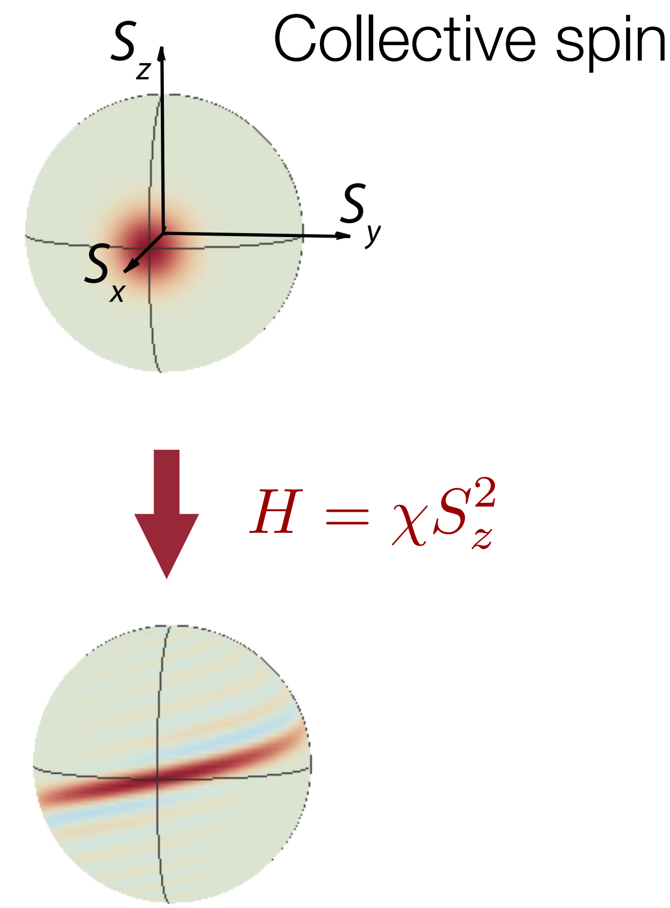




cavity resonance
is shifted by atoms



atomic levels
are shifted by light



effective interaction
mediated by light

“one-axis twisting”

[Kitagawa & Ueda, PRA, 1993.]

Spin Squeezing

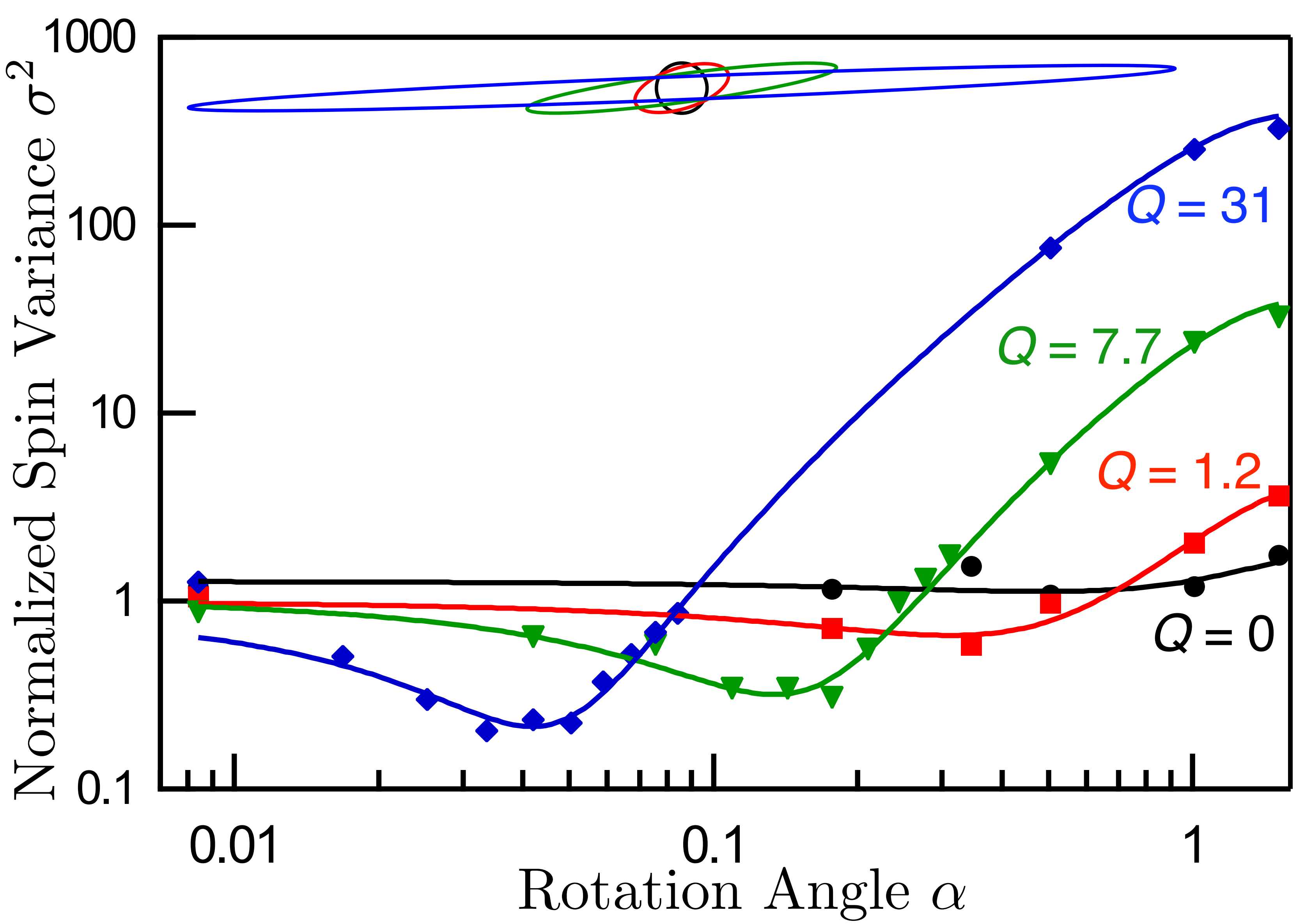
ID Leroux, MS-S & V Vuletic,
PRL **104**, 073602 (2010).

Twisting strength $Q = N\chi t = \begin{pmatrix}\text{\# of photons scattered} \\ \text{into cavity per atom}\end{pmatrix}$

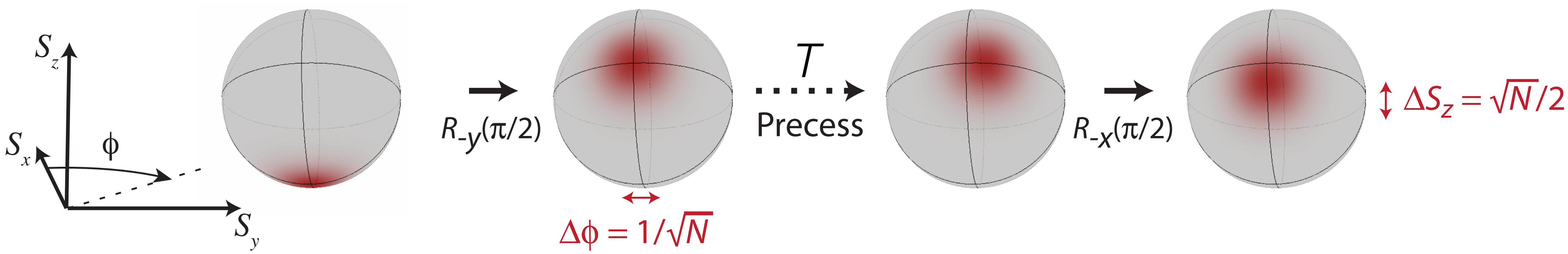
$N = 4\times10^4$ atoms

$\eta = 0.1$, $\delta=\kappa/2$

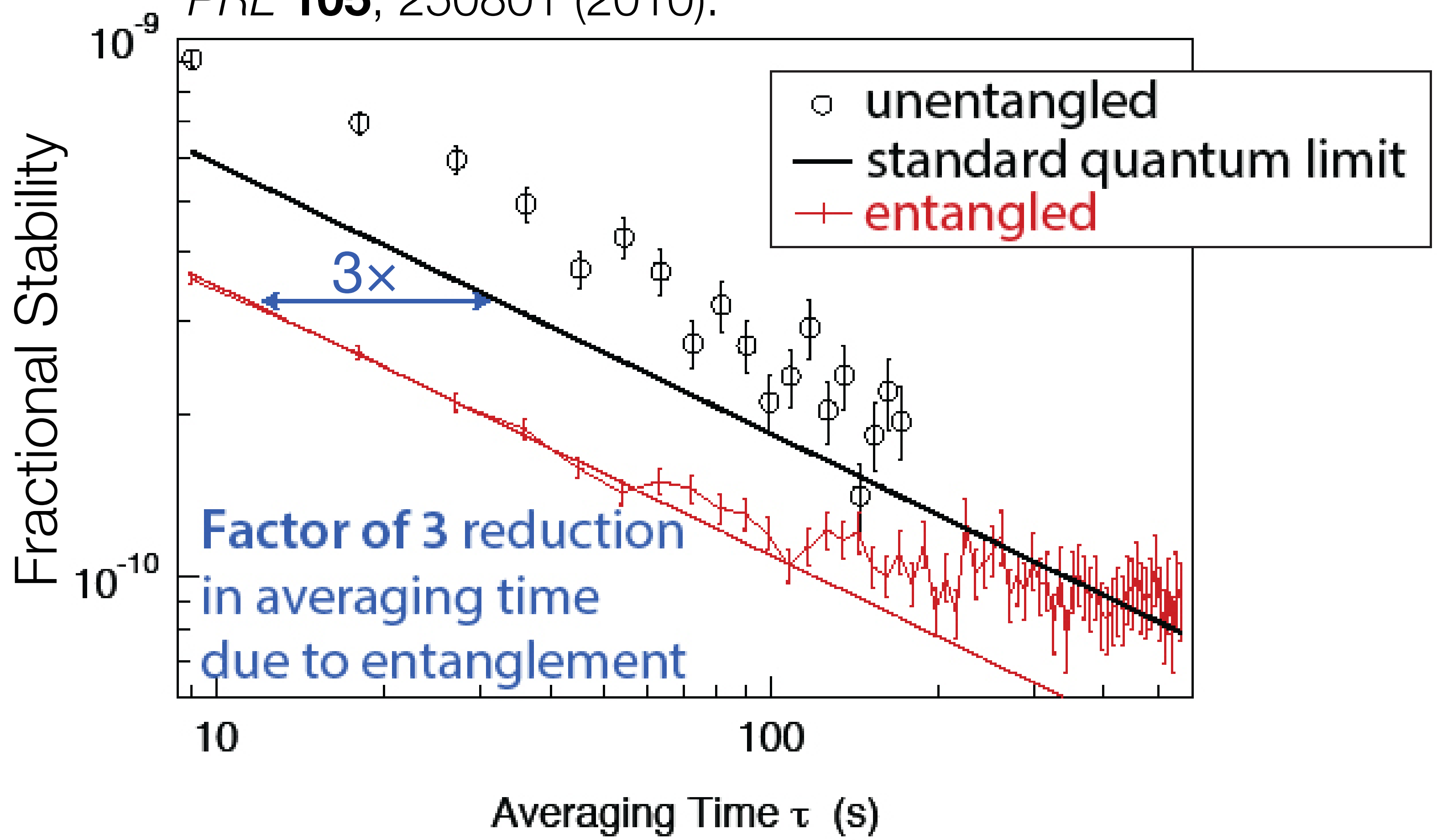
$\Rightarrow N\eta \gg 1$



Enhanced Atomic Clocks



ID Leroux, MS-S & V Vuletic,
PRL **105**, 250801 (2010).



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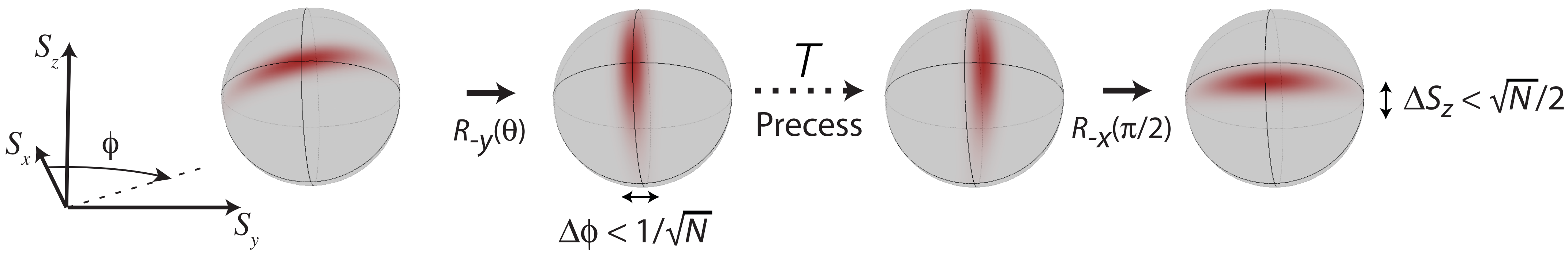

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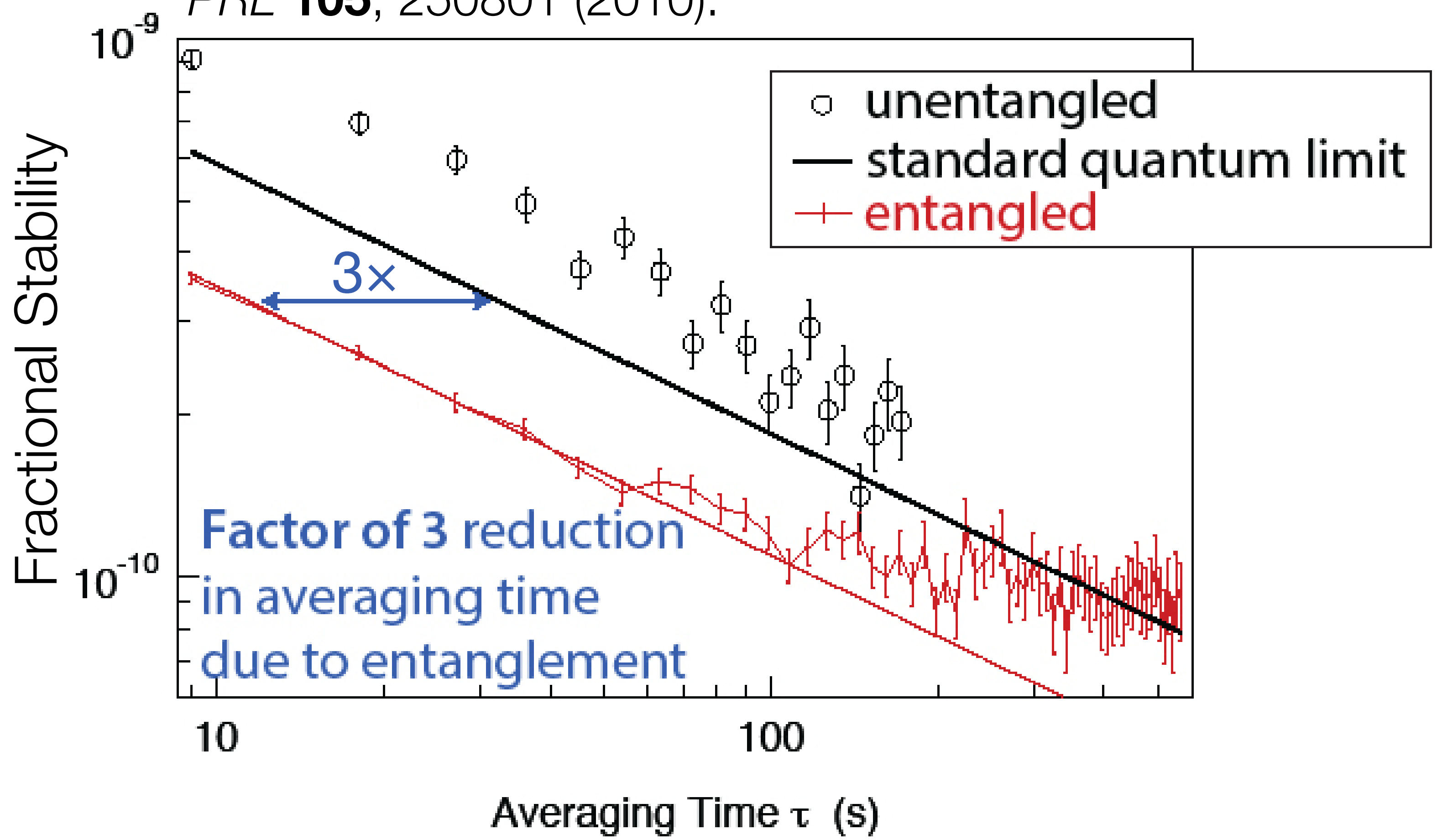

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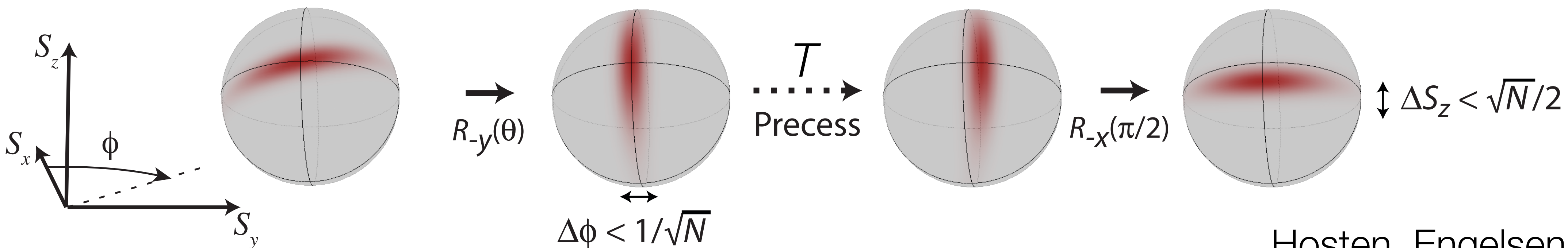
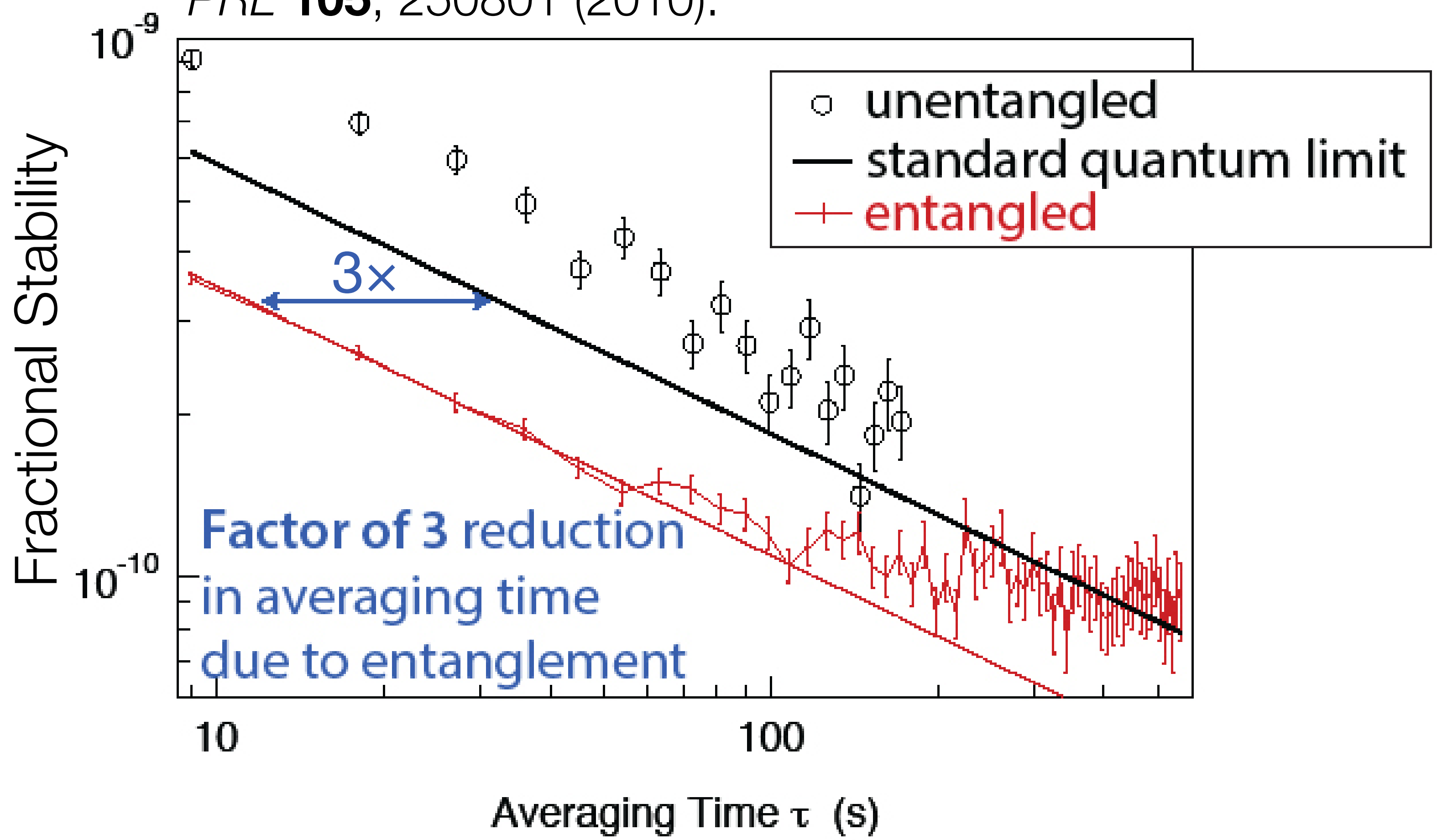
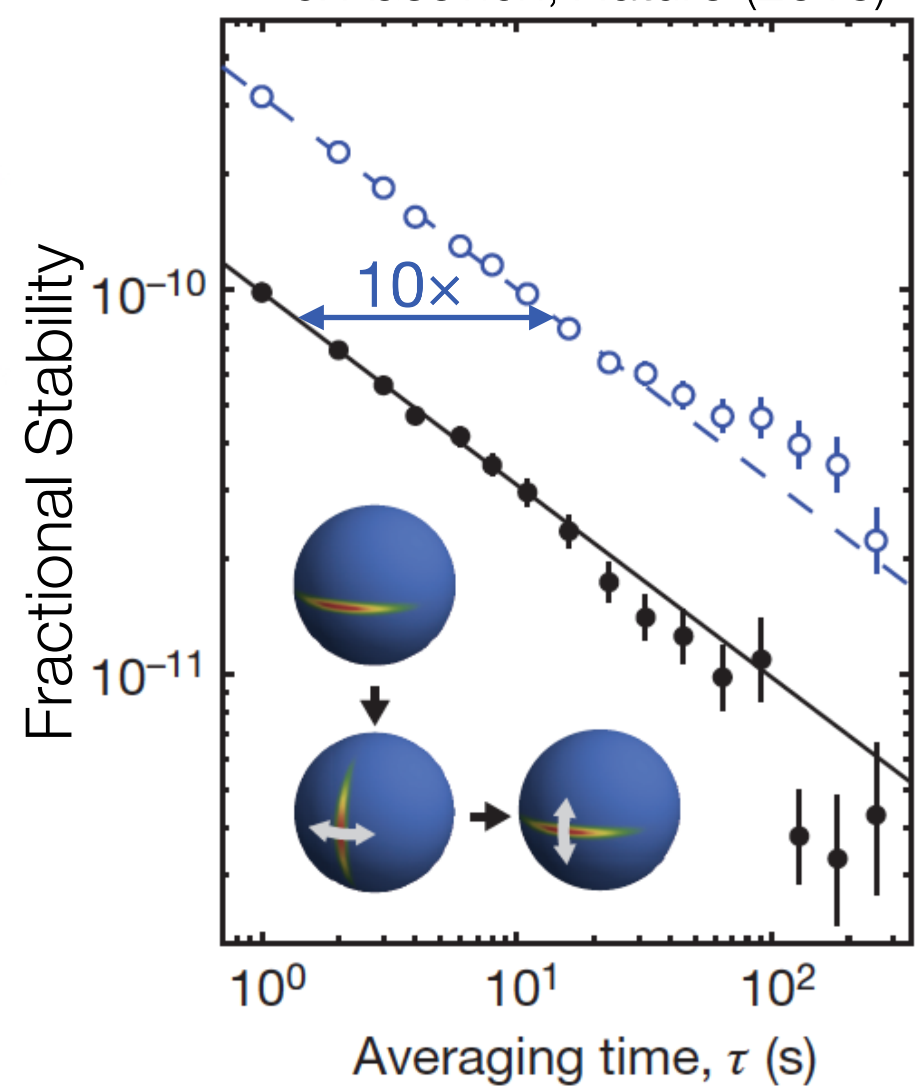


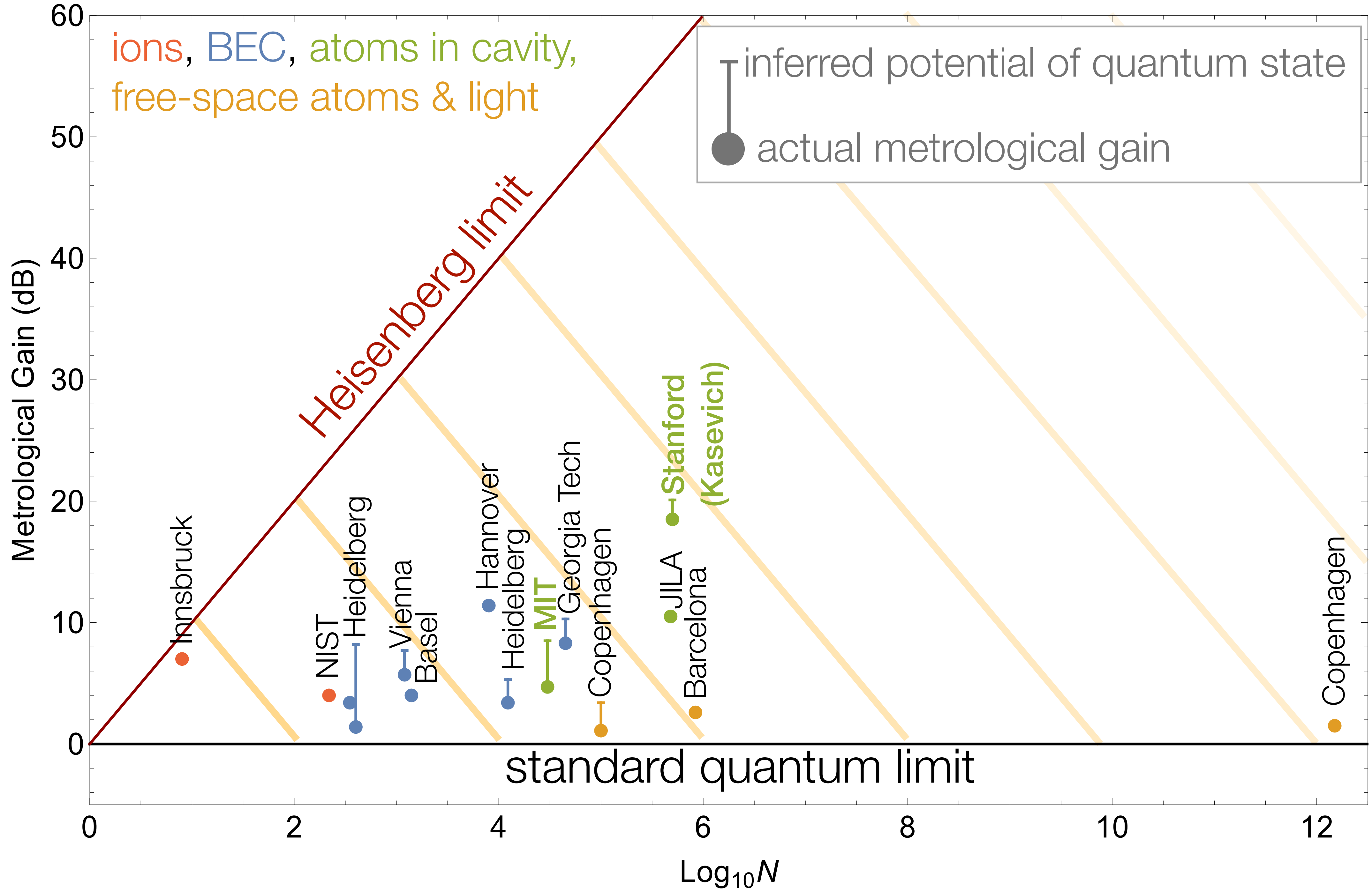
Hosten, Engelsen, Krishnakumar & Kasevich, *Nature* (2016).

ID Leroux, MS-S & V Vuletic, *PRL* **105**, 250801 (2010).

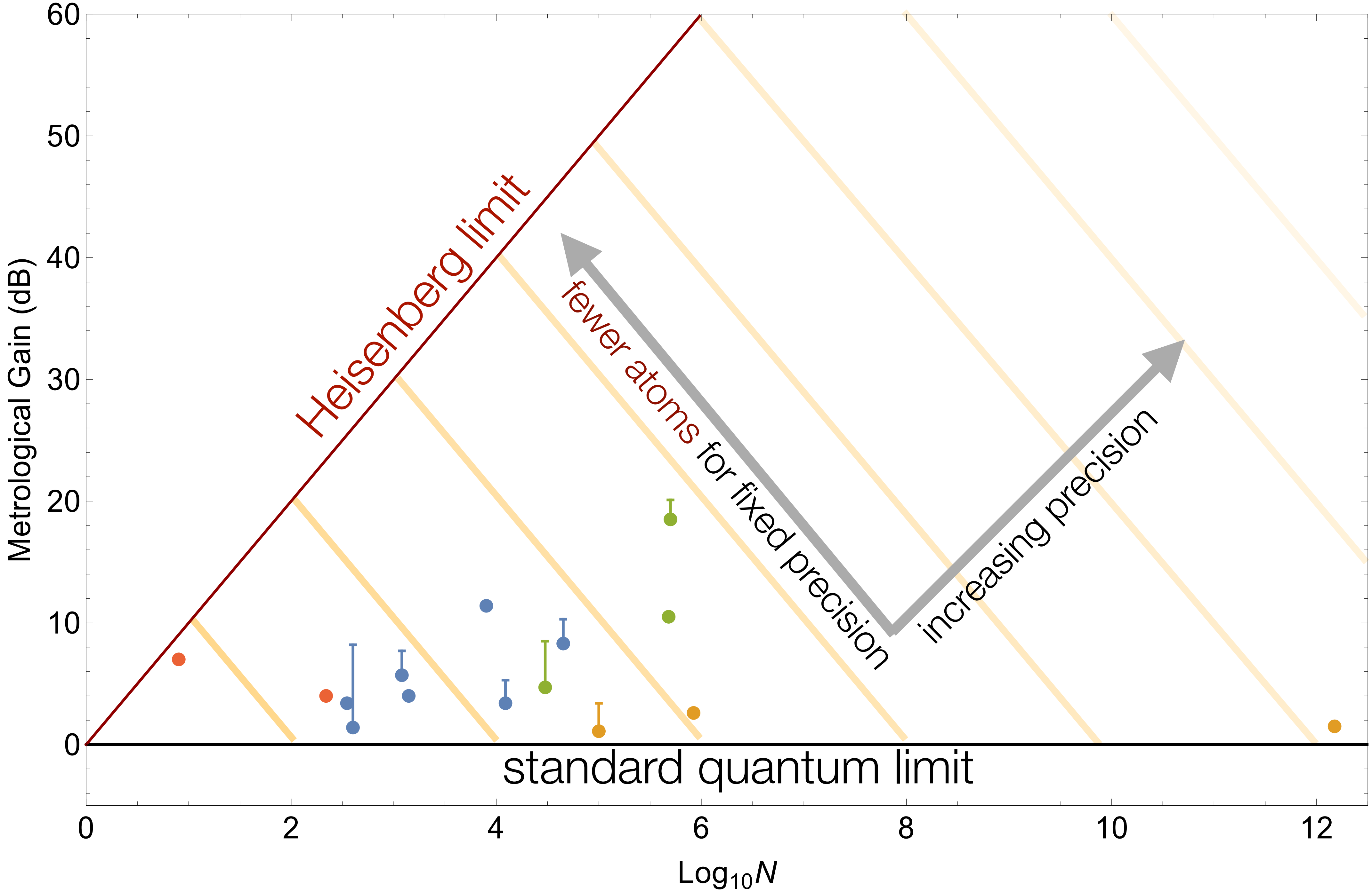




Entanglement-Enhanced Measurements



Approaching the Heisenberg Limit?



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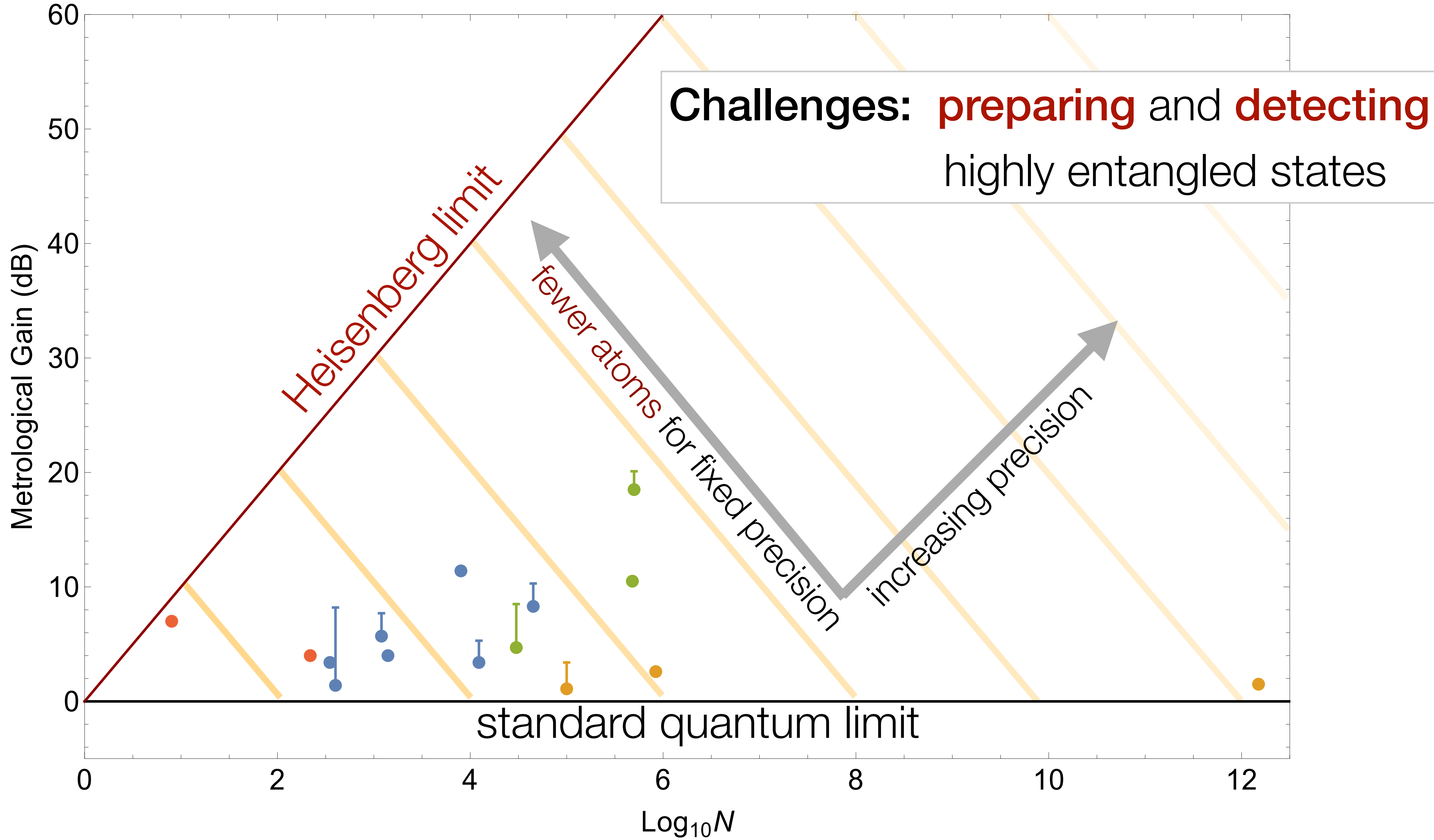
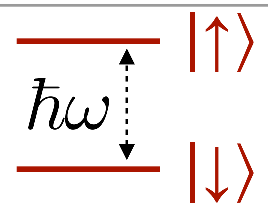


Towards the Heisenberg Limit?



Fundamental limit set by Heisenberg Uncertainty Principle $\Delta E \Delta T \geq \hbar/2$

$$\Delta E \leq \frac{N}{2}\hbar\omega \;\Rightarrow\; \Delta(\omega T) \geq \frac{1}{N}$$

Heisenberg Limit

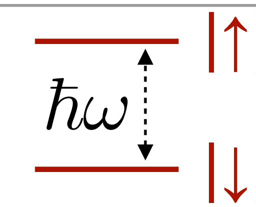
Reaching the Heisenberg Limit requires a state with *maximum uncertainty* in energy

Alive   Dead

$$|\psi\rangle_{\text{cat}} = \frac{|\uparrow\uparrow\uparrow\ldots\uparrow\rangle + |\downarrow\downarrow\downarrow\ldots\downarrow\rangle}{\sqrt{2}}$$

GHZ (“cat”) state

Towards the Heisenberg Limit?



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Heisenberg Limit

Reaching the Heisenberg Limit requires a state with *maximum uncertainty* in energy

Alive, Dead

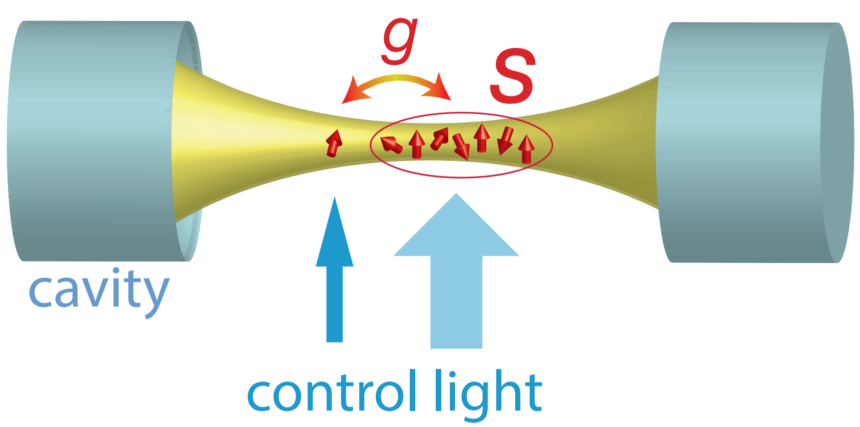
$$|\psi\rangle_{\text{cat}} = \frac{|\uparrow\uparrow\uparrow\ldots\uparrow\rangle + |\downarrow\downarrow\downarrow\ldots\downarrow\rangle}{\sqrt{2}}$$

GHZ (“cat”) state

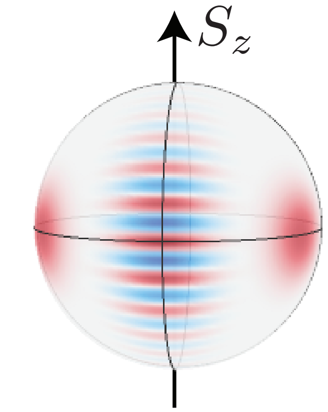
- ***Making and detecting these states at large N?***
- ***Easier alternatives?***

Routes to Cat States?

Qubit-Ensemble Interface



$$\frac{|\uparrow\rangle + |\downarrow\rangle}{\sqrt{2}} \rightarrow \frac{|0\rangle + |1\rangle}{\sqrt{2}} \rightarrow$$



Schrödinger's cat

Routes to Cat States?

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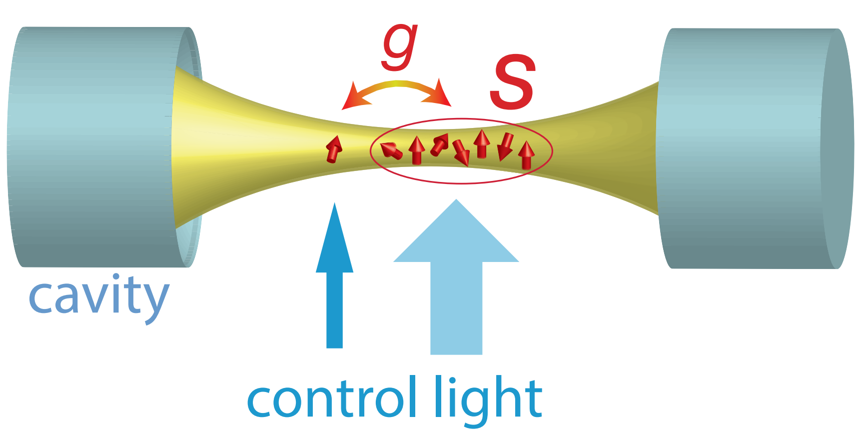

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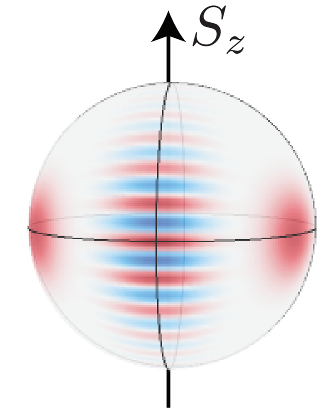
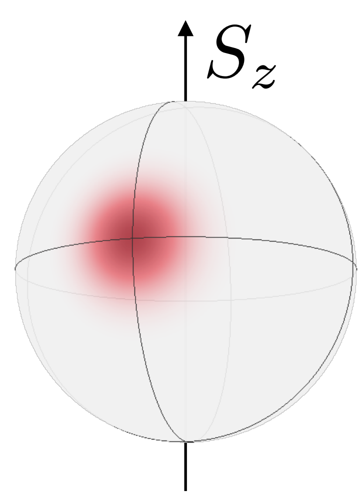


Schrödinger's cat

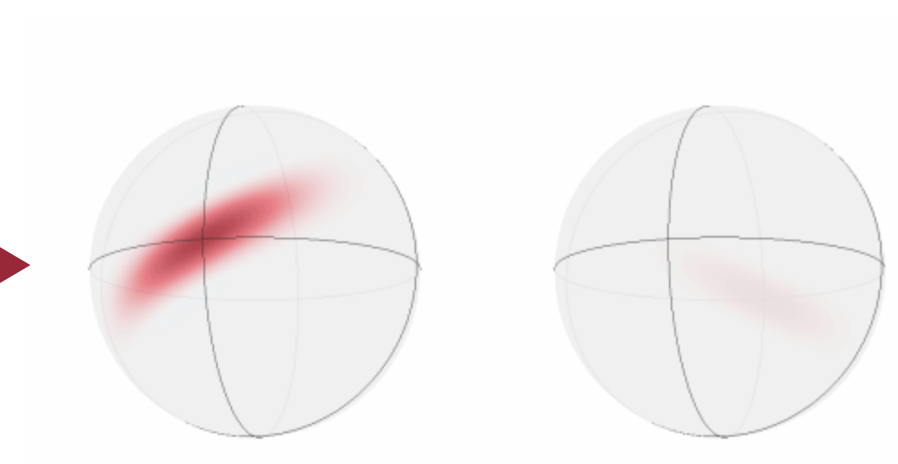
Collective Interactions

collective spin $\mathbf{S} = \sum_{i=1}^{N} \mathbf{s}_i$



$H = \chi S_z^2$

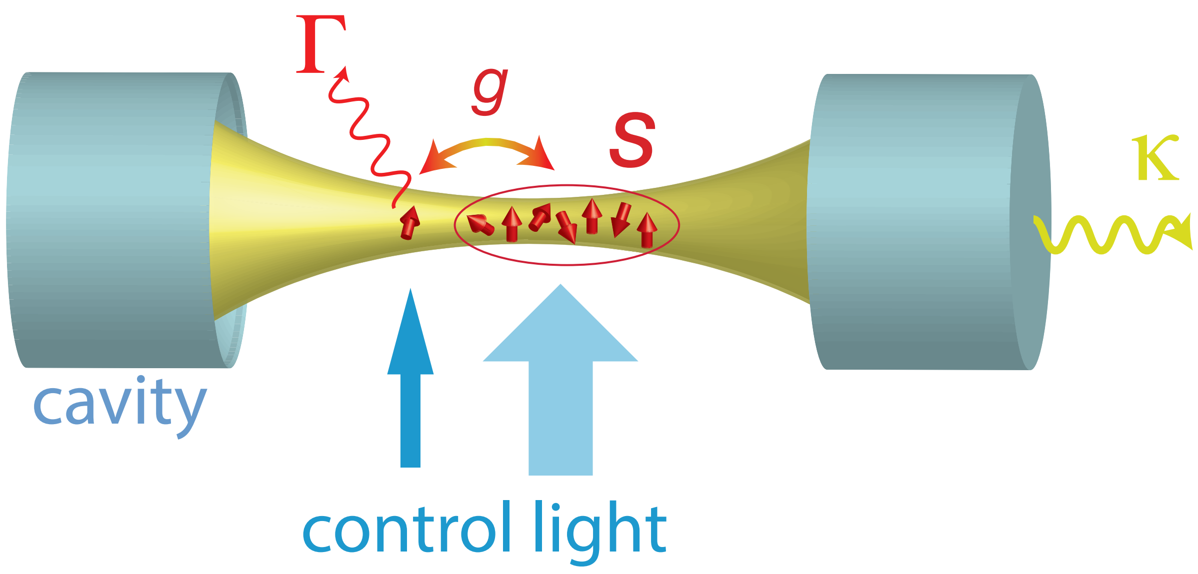
twist



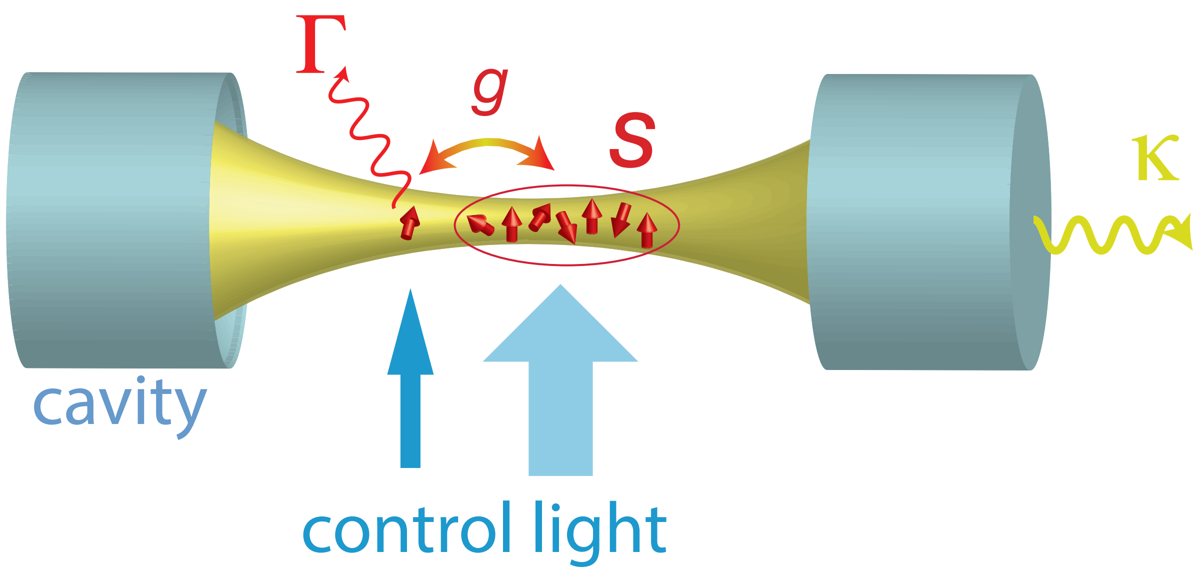
front view

back view

Challenge: Dissipation



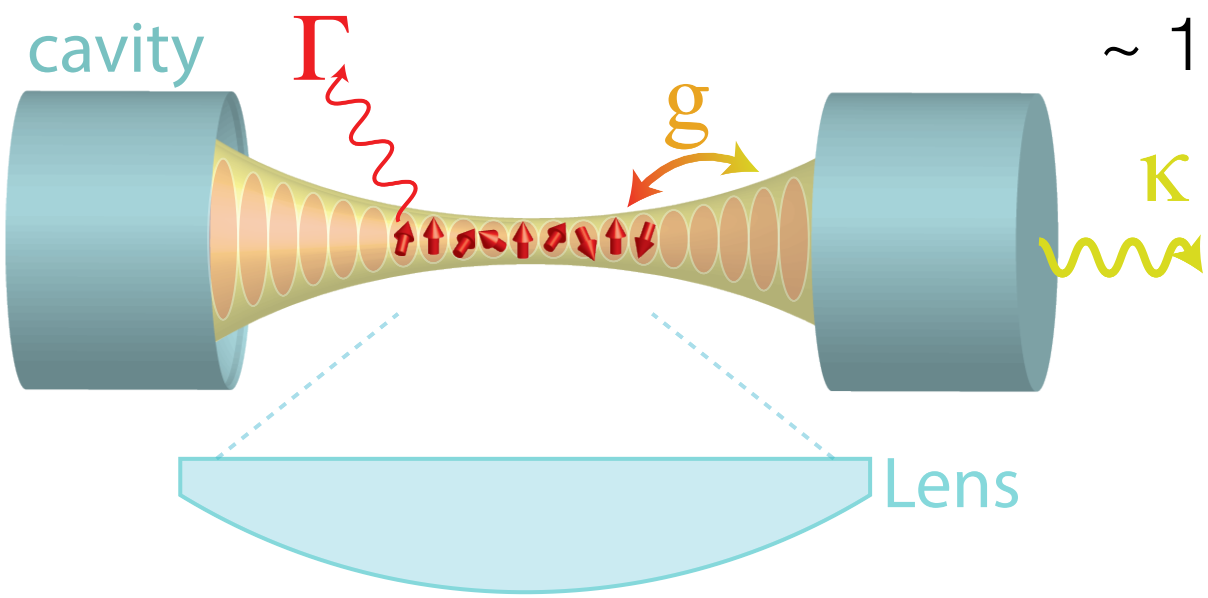
Challenge: Dissipation



Two-fold approach

- **Maximize interaction-to-decay ratio**
- Devise entanglement schemes that are robust to photon loss

Experiment Design



~ 10^1 - 10^3 atoms

- Strong coupling: $\eta \equiv \frac{4g^2}{\kappa\Gamma} \sim \frac{F\lambda^2}{w^2} \gg 1$
- Optical access for imaging & addressing

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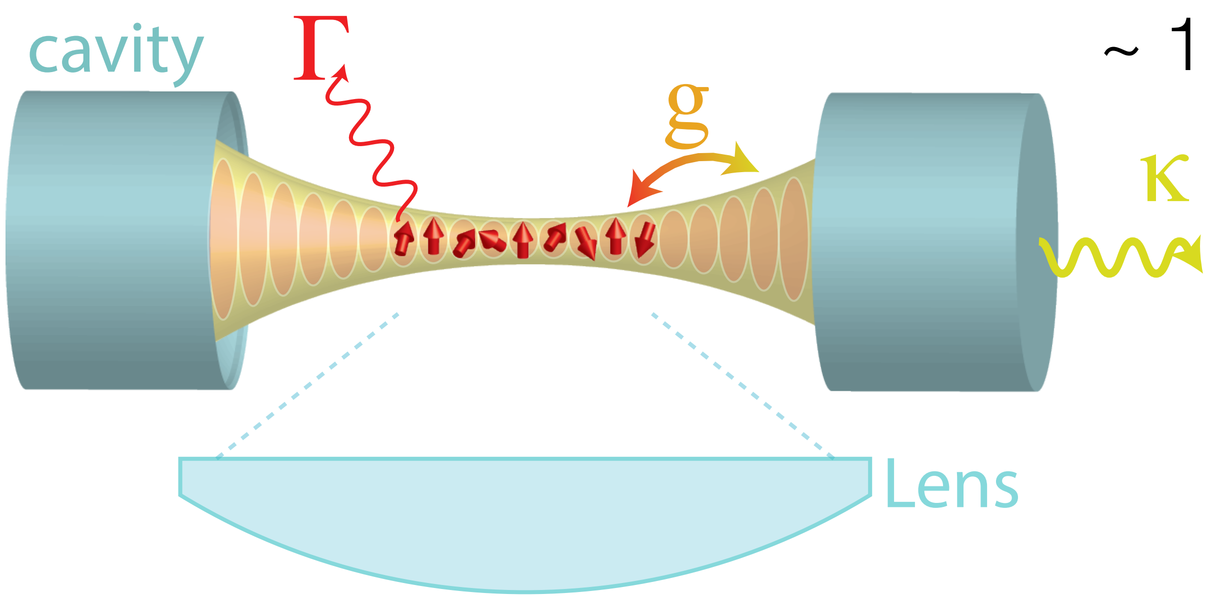

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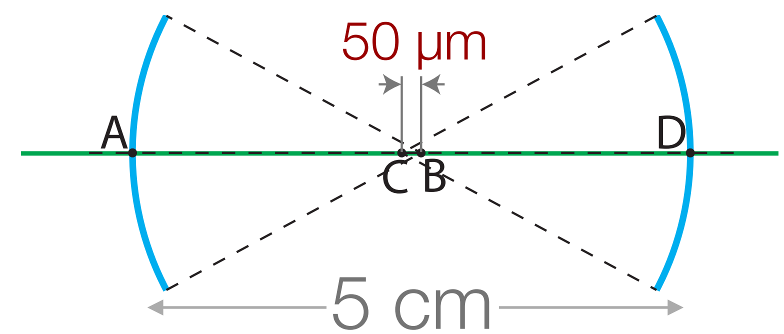


- Strong coupling: $\eta \equiv \frac{4g^2}{\kappa\Gamma} \sim \frac{F\lambda^2}{w^2} \gg 1$
- Optical access for imaging & addressing

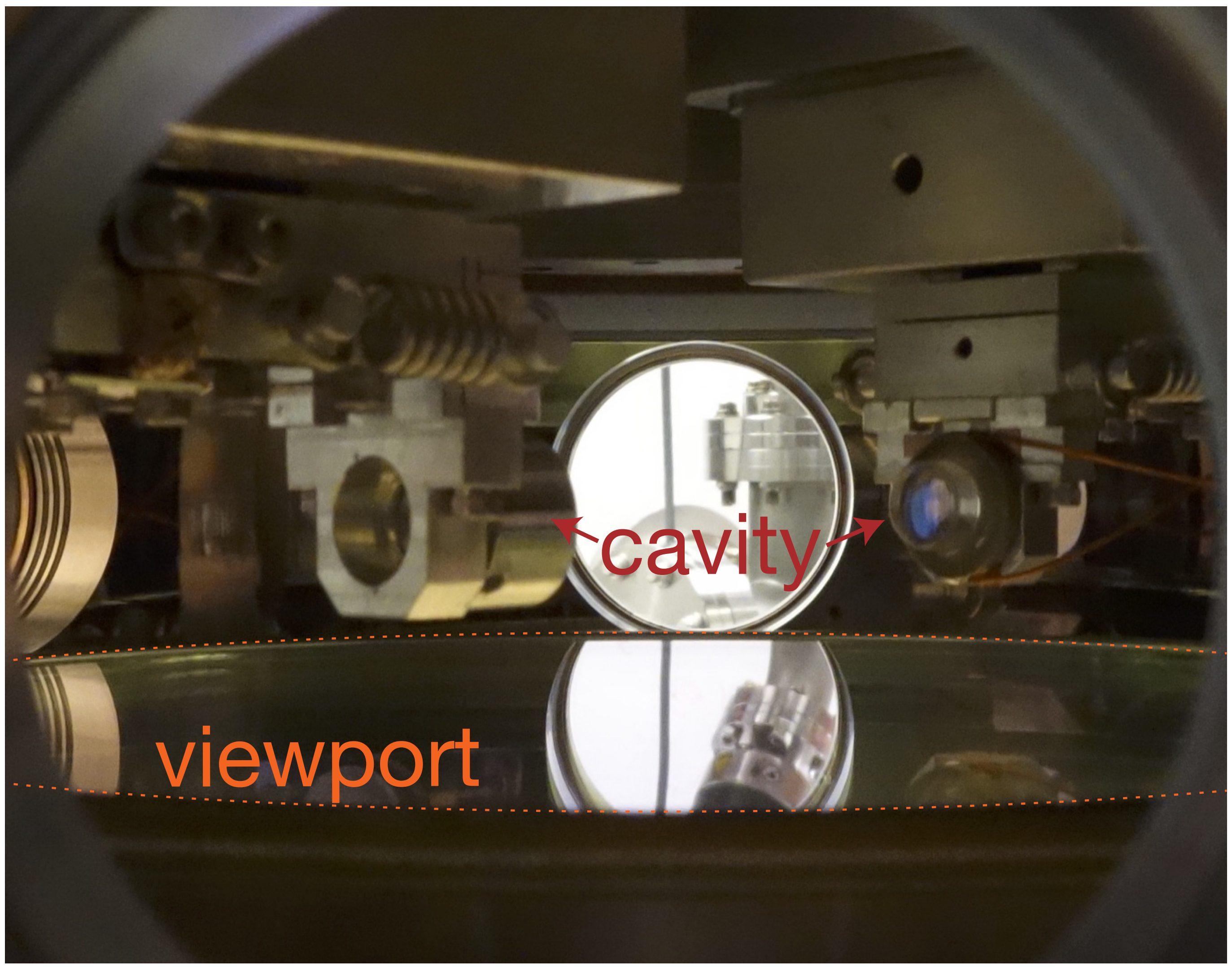
$\Rightarrow$ Near-concentric resonator

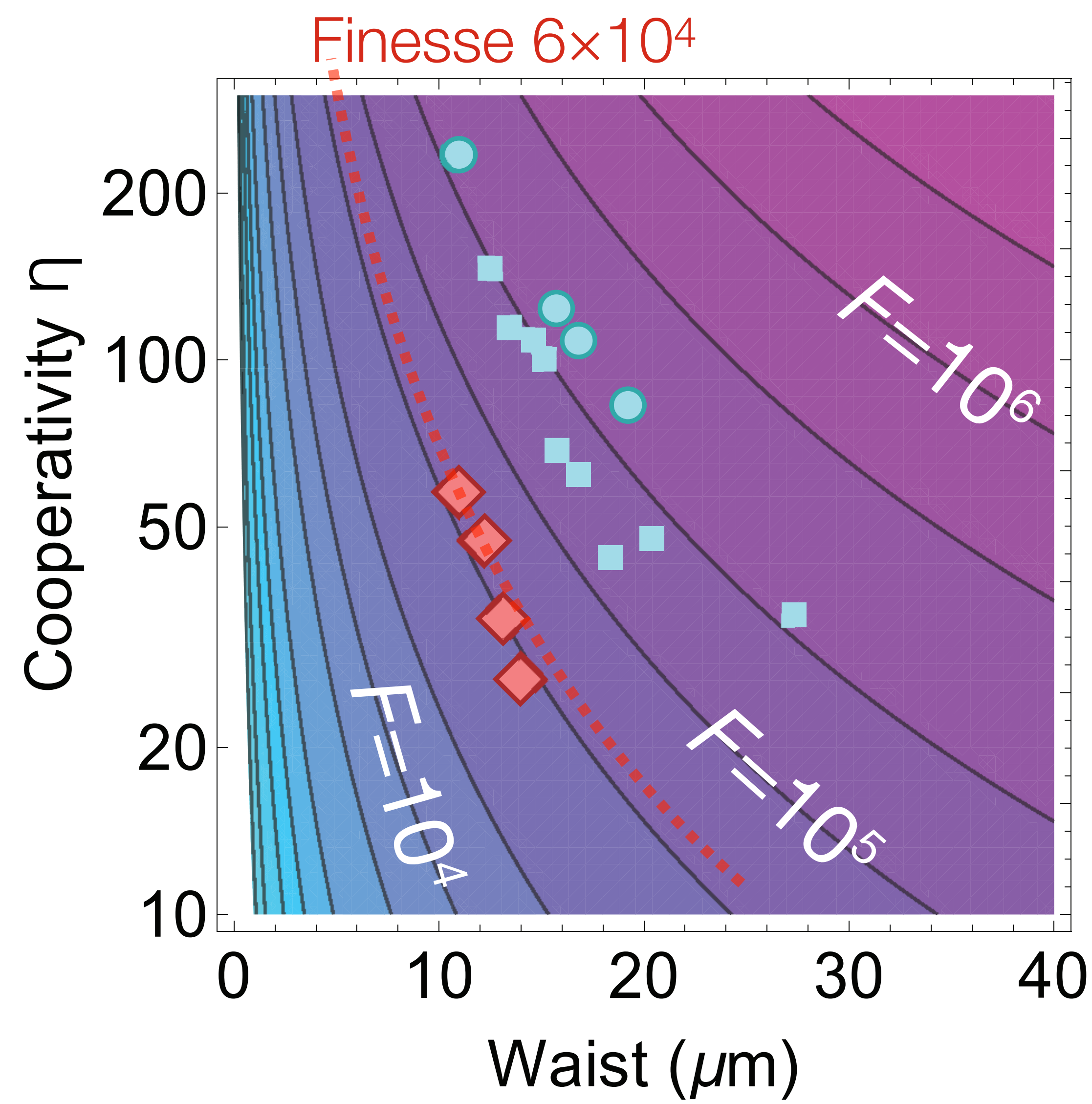
Waist w ~ 12 μm

Finesse F ~ 10^5

Non-degenerate modes

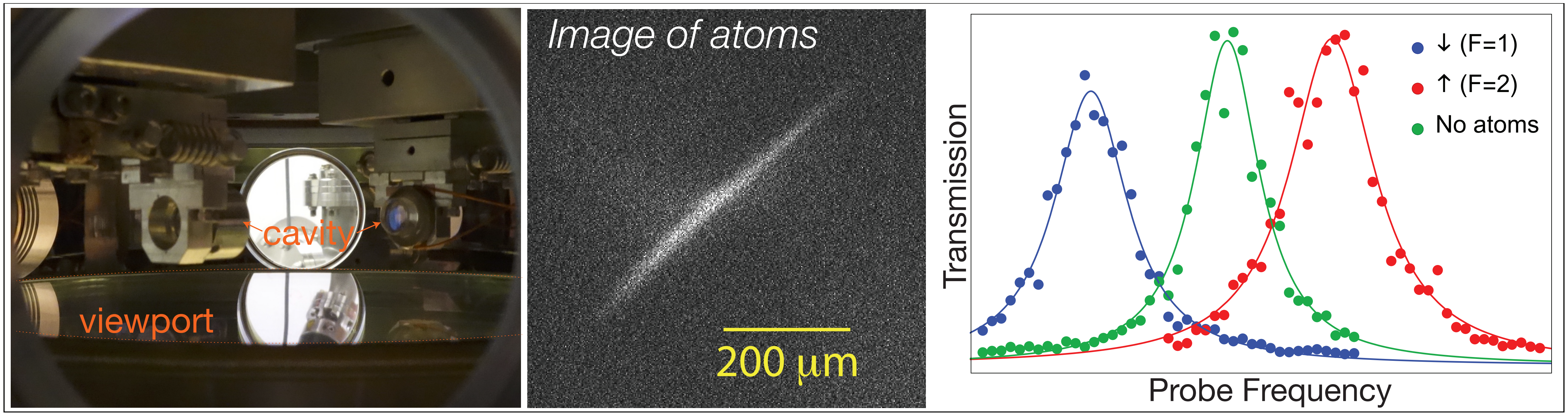
Strong Coupling with Optical Access

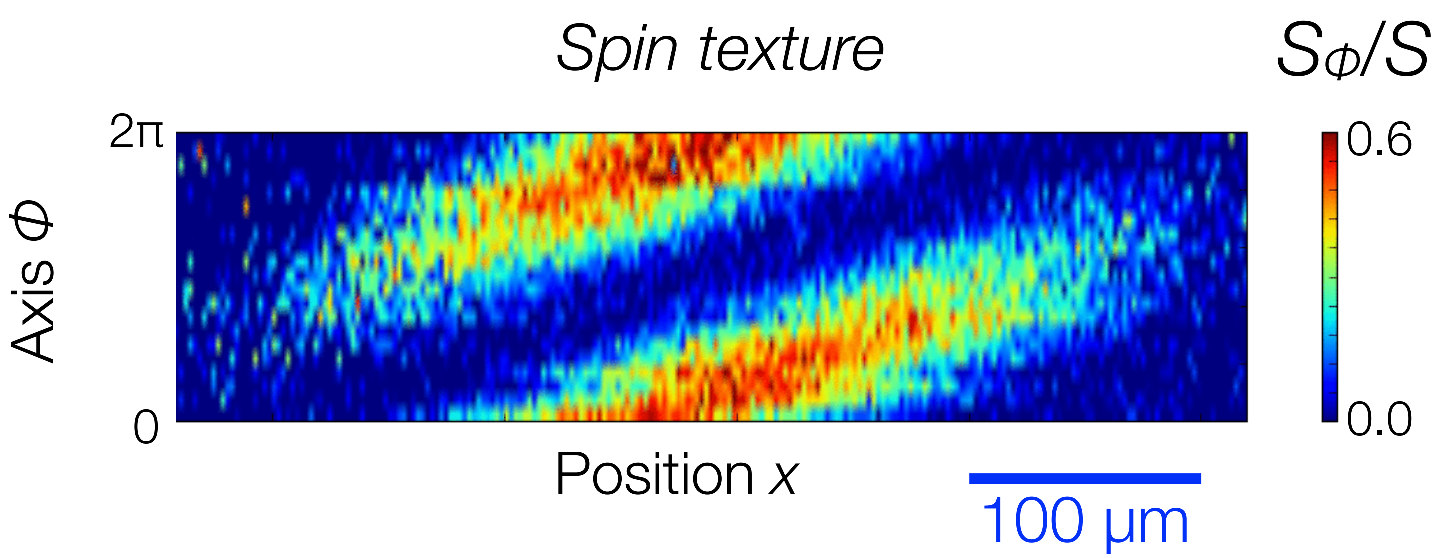




Single-atom cooperativity η ~ 50

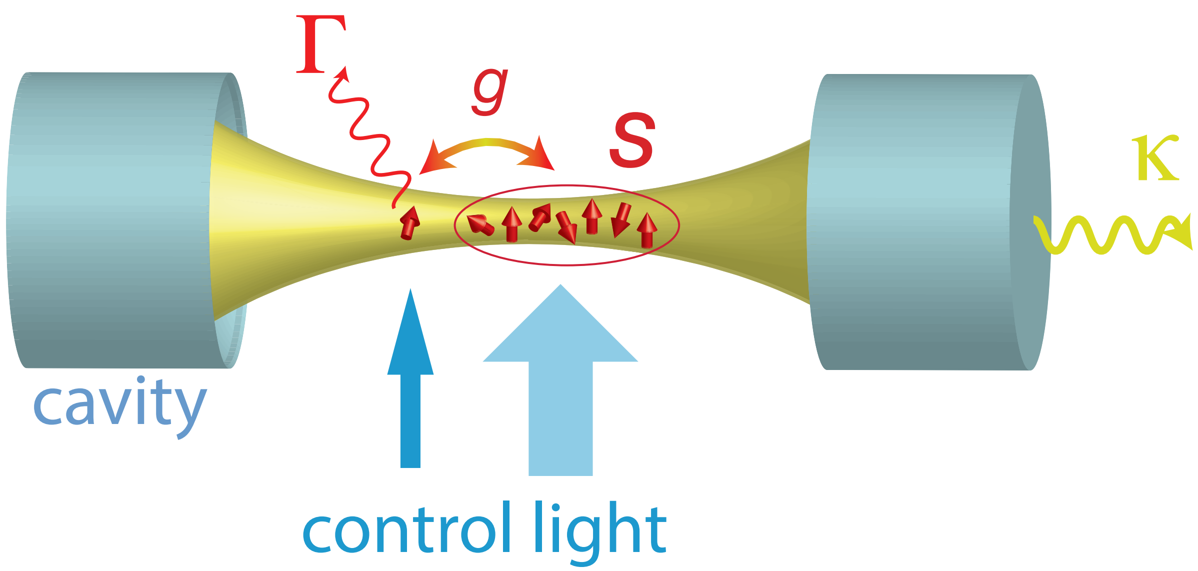
Experimental Toolbox





State-sensitive imaging

Photon-Mediated Entanglement



Two-fold approach

✔ **Maximize interaction-to-decay ratio**

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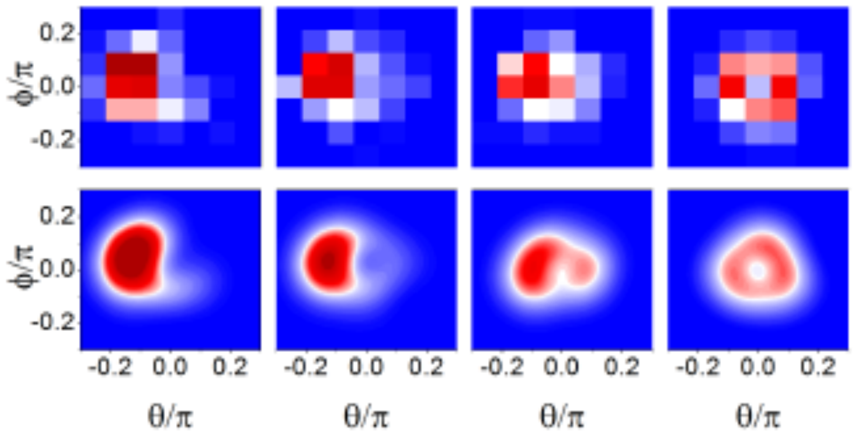
Approaches to Entanglement

E.g., collective spin excitation

Strong coupling: η ~ 100, deterministic



Barontini, Hohmann, Haas, Esteve & Reichel, *Science* (2016).
Haas, Reichel, Volz, Gehr & Esteve, *Science* (2016).

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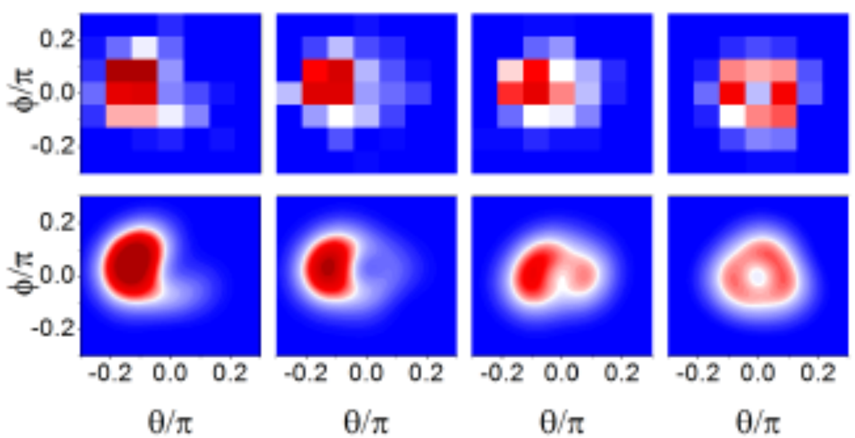

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Weak coupling,
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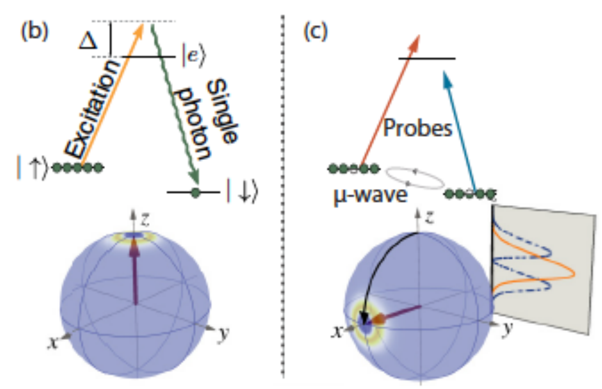
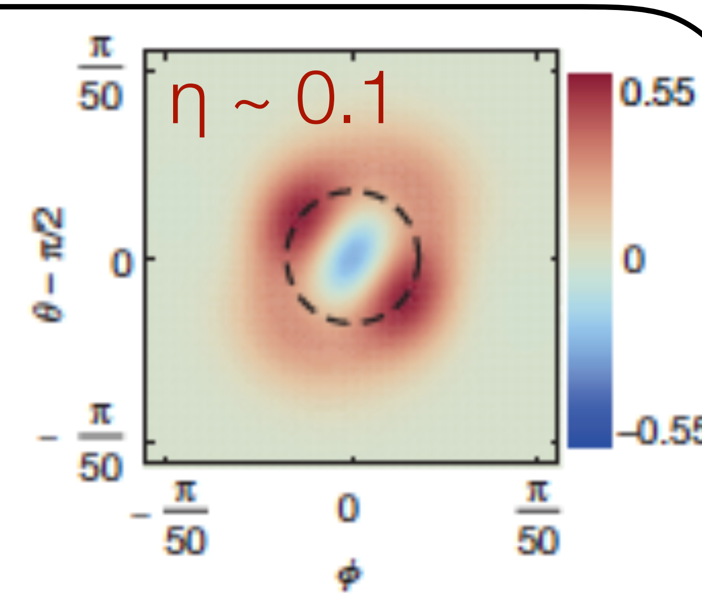


Christensen, … & Polzik, *PRA* (2014).



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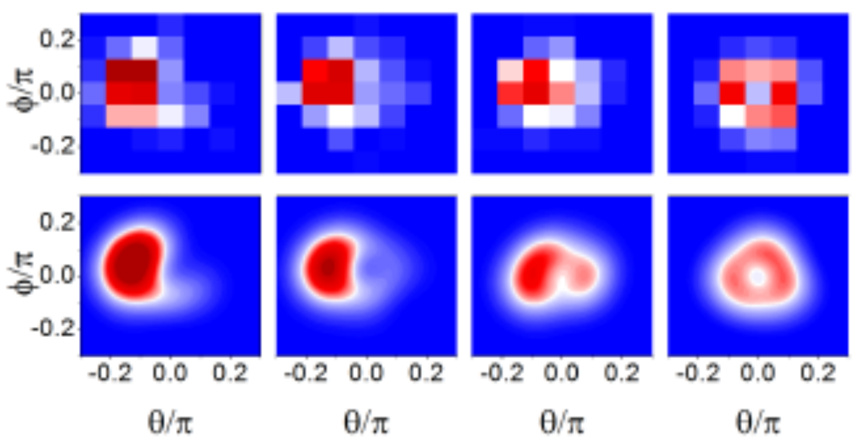

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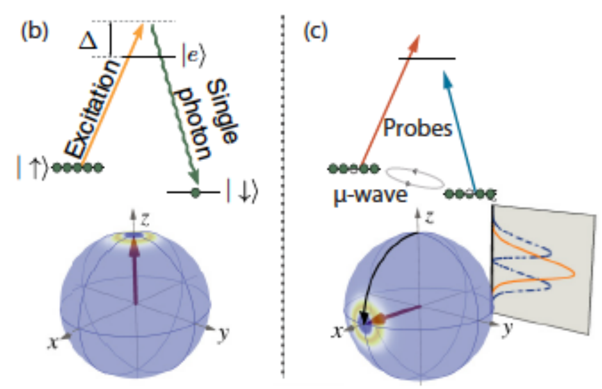

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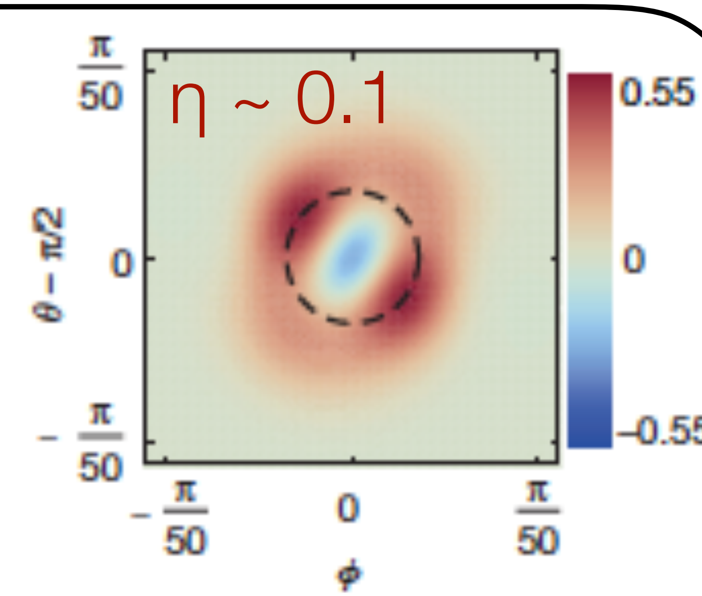

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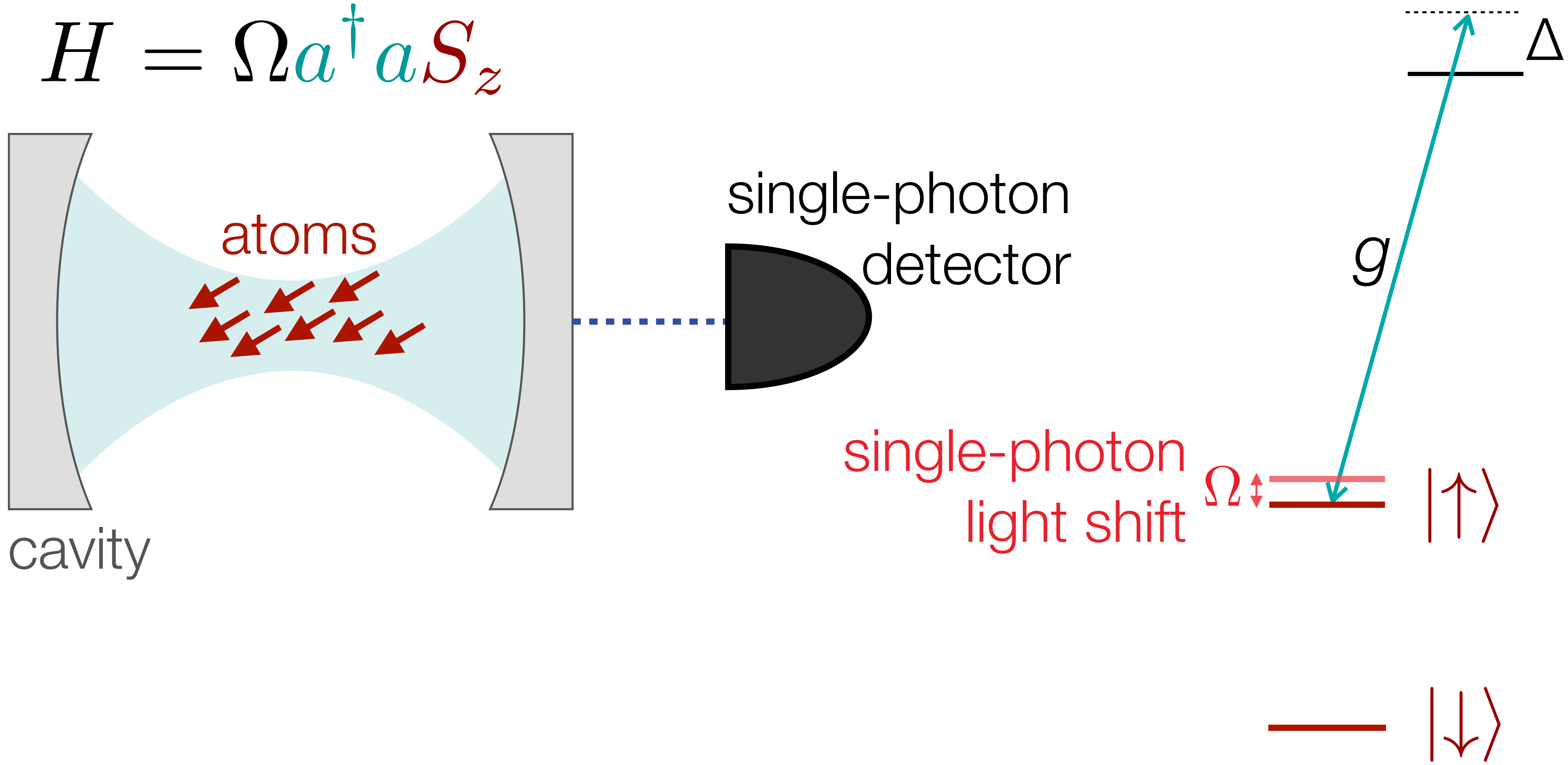
Heralding + strong coupling → *Schrödinger's cat states?*

More versatile quantum control?

Dispersive Atom-Light Interaction

$$H = \Omega a^\dagger a S_z$$



Dispersive Atom-Light Interaction

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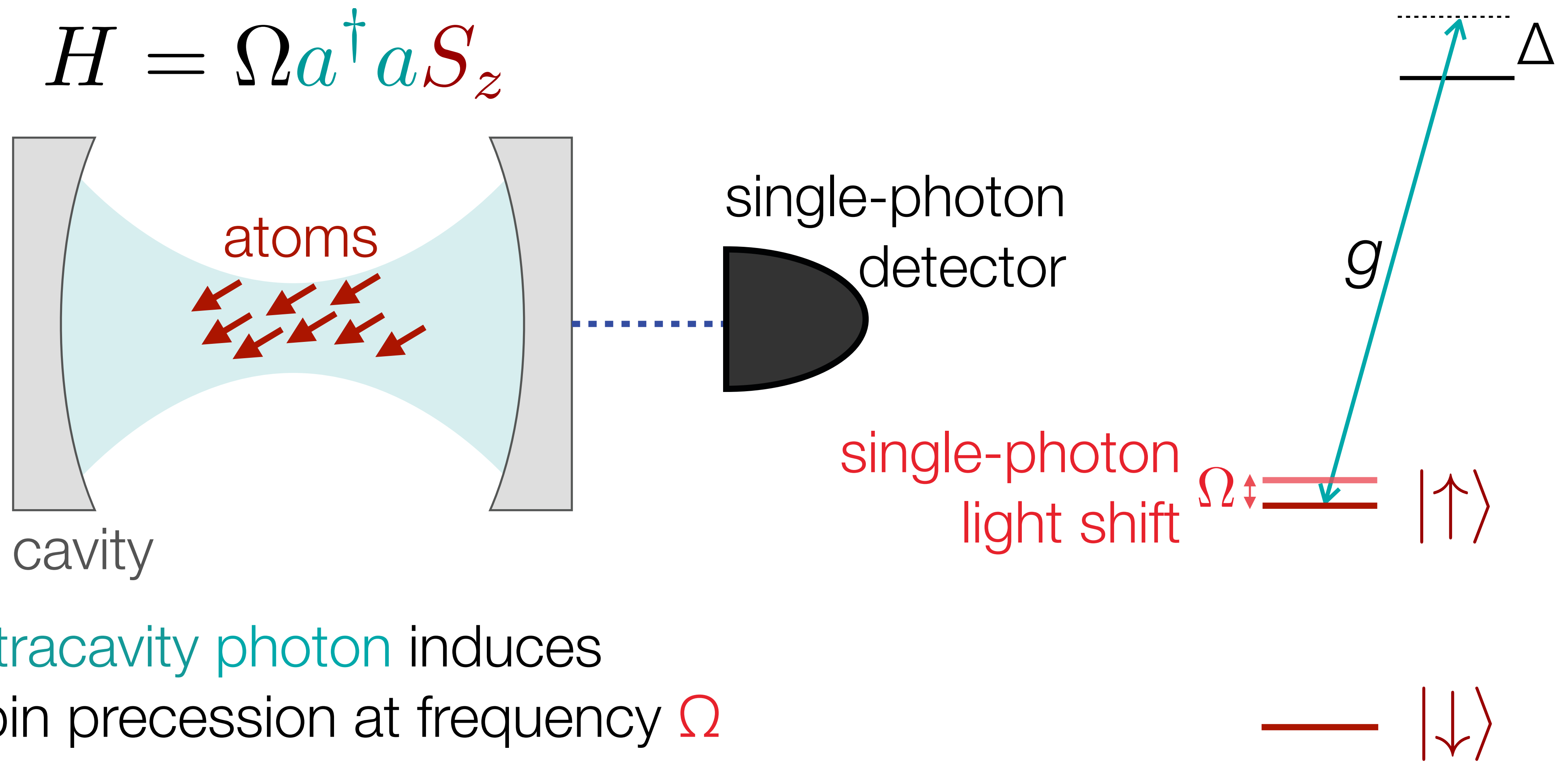

Intracavity photon induces spin precession at frequency Ω

Dispersive Atom-Light Interaction

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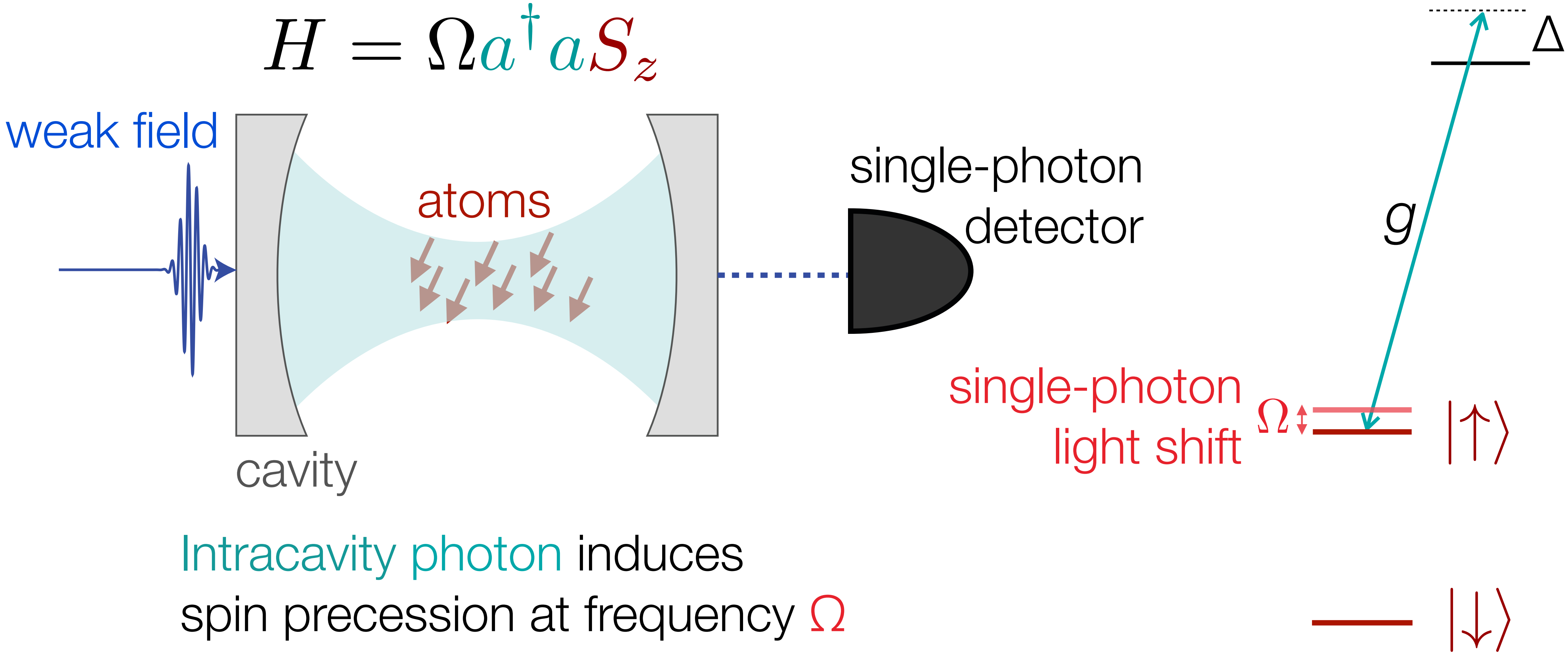
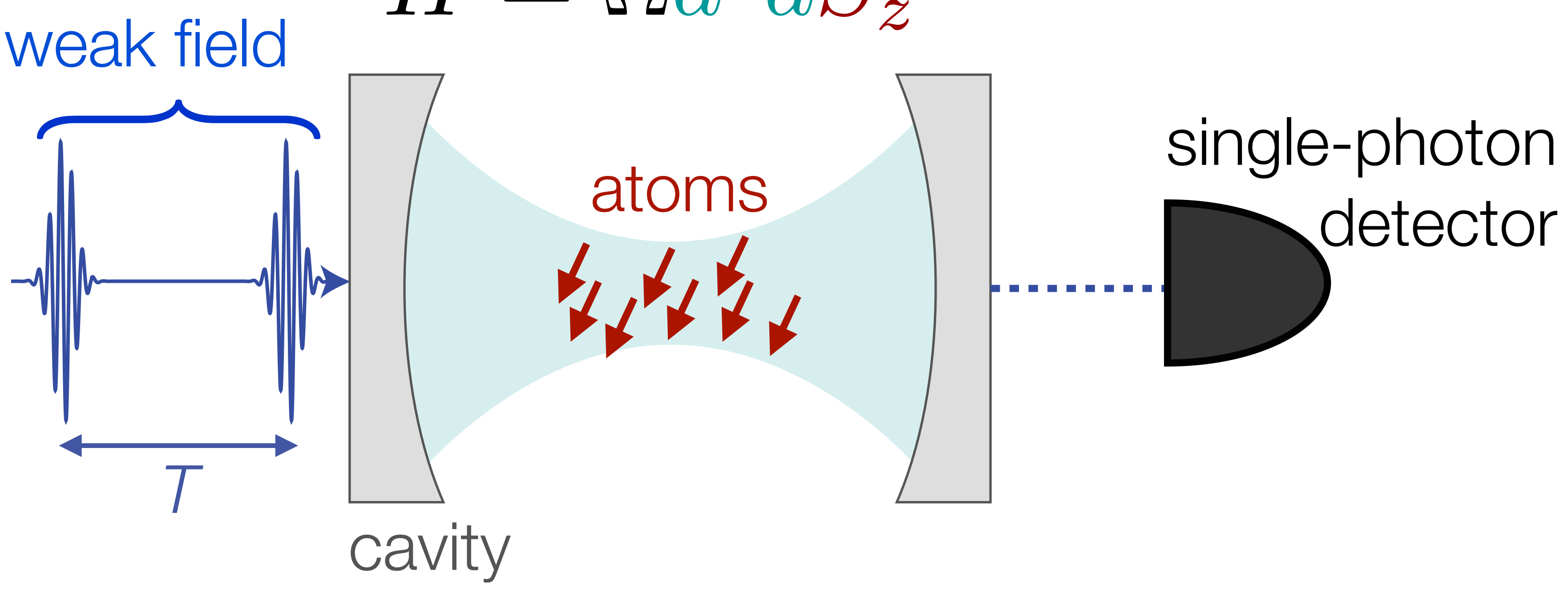


Intracavity photon induces spin precession at frequency Ω

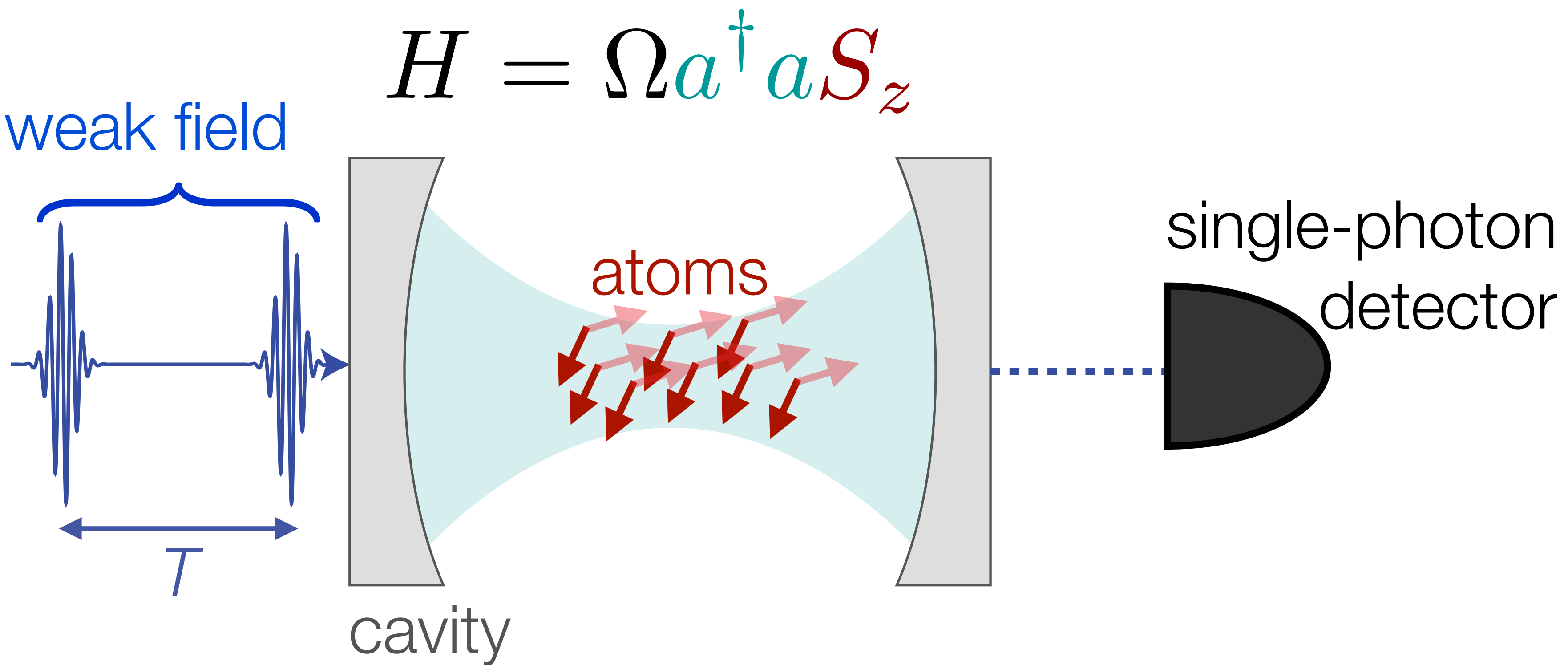
Short input pulse + detection a time t later
⇒ spins precessed by Ωt

Heralded Cat States

$$H = \Omega a^\dagger a S_z$$



Heralded Cat States



If we detect a photon *after* the second pulse,
how much time did it spend in the cavity?

Heralded Cat States

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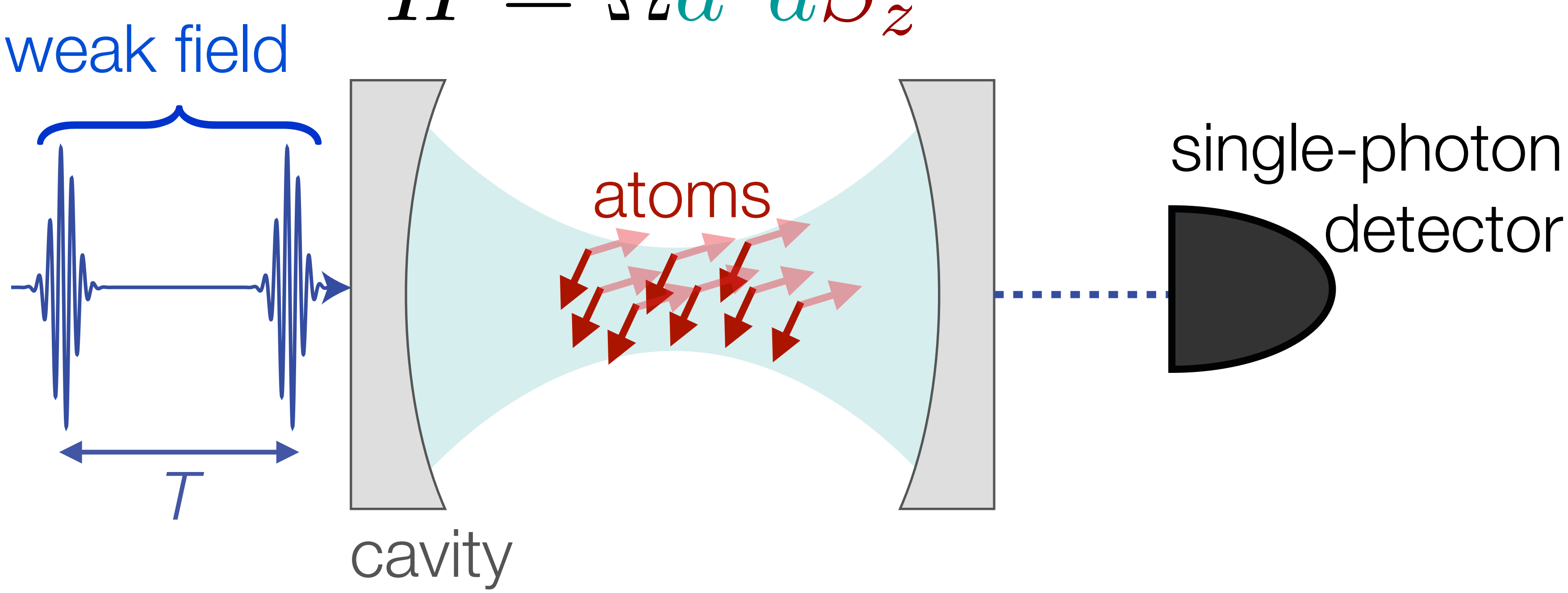

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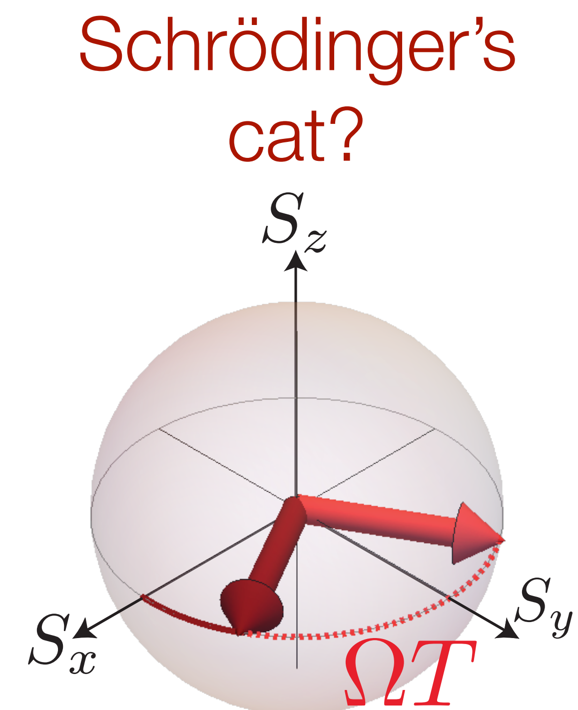

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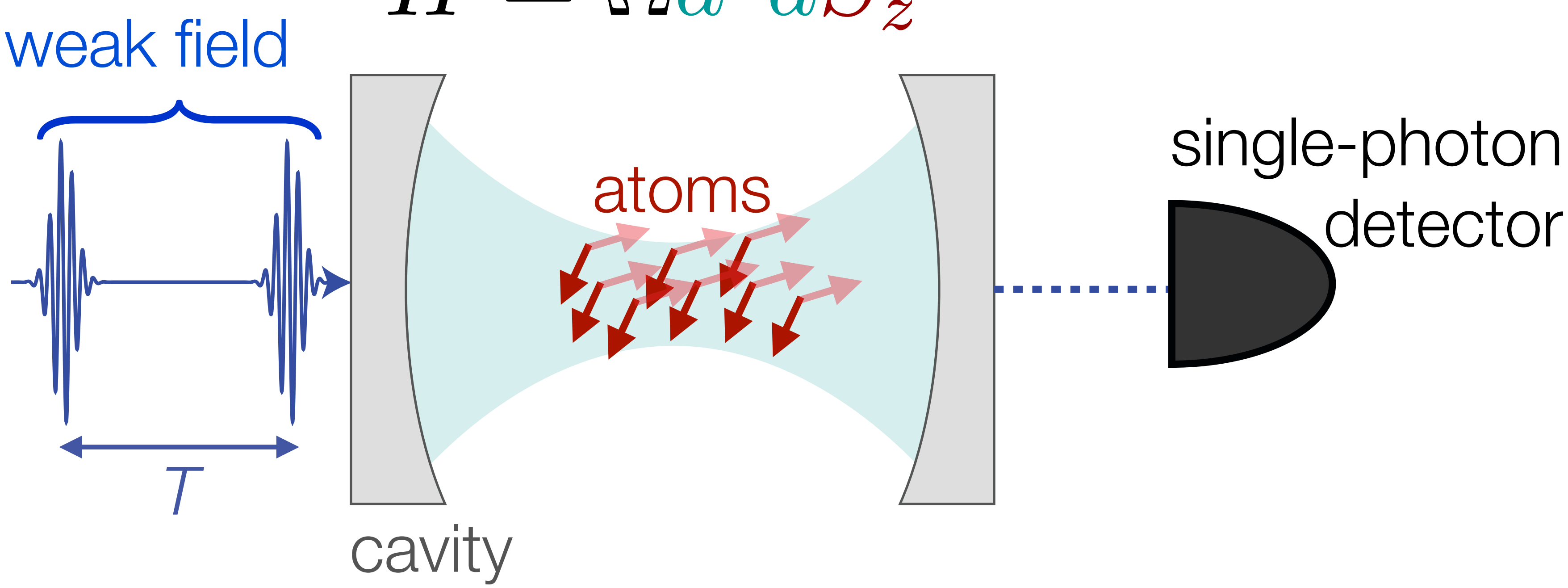
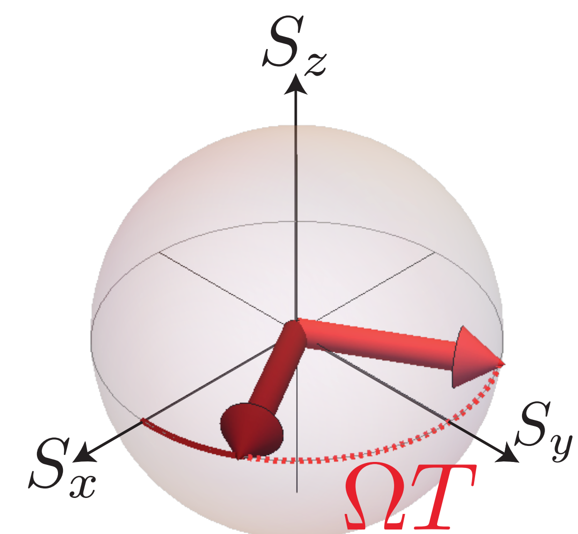


Schrödinger's cat?



If we detect a photon *after* the second pulse, how much time did it spend in the cavity?

What if T is longer than the cavity lifetime 1/κ ?

Heralded Cat States

E. Davis, Z. Wang, G. Bentsen, T. Li,
A. Safavi-Naeini & MS-S (in prep).

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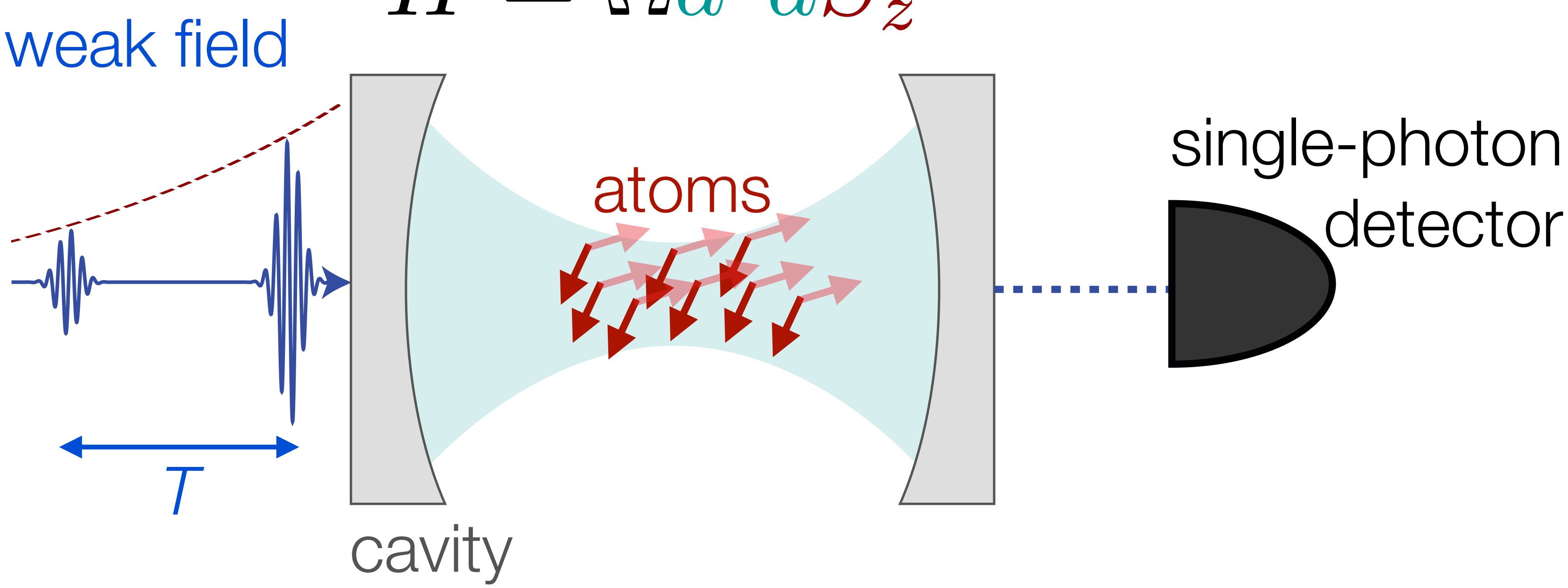
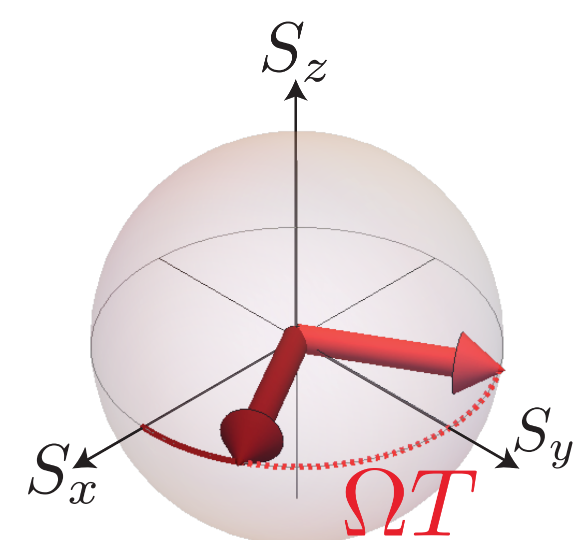


Schrödinger's cat



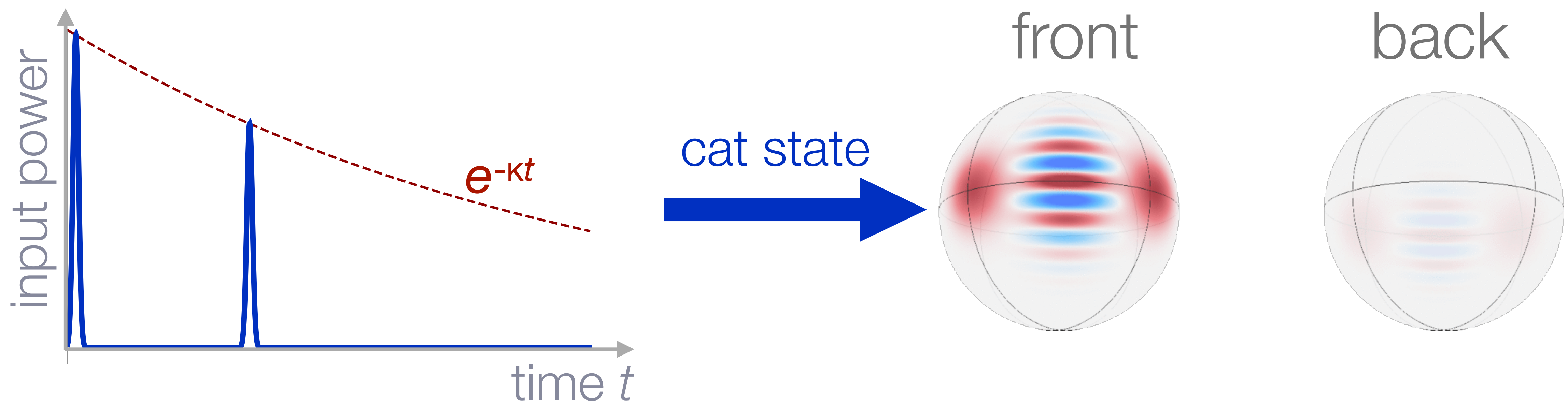
If we detect a photon after the second pulse, was it in the cavity for a time t or t-T?

For *equal superposition* even at finite cavity lifetime 1/κ:
Make second pulse weaker than first by $e^{-\kappa T}$

Single Photon as a Paintbrush

E. Davis, Z. Wang, G. Bentsen, T. Li,
A. Safavi-Naeini & MS-S (in prep).

…for versatile quantum control:



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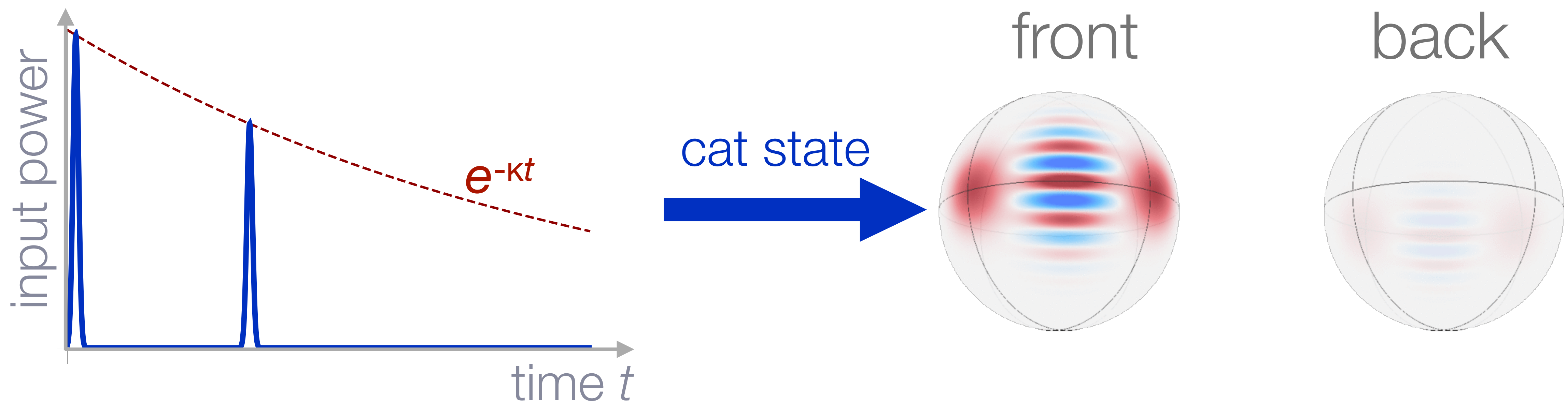

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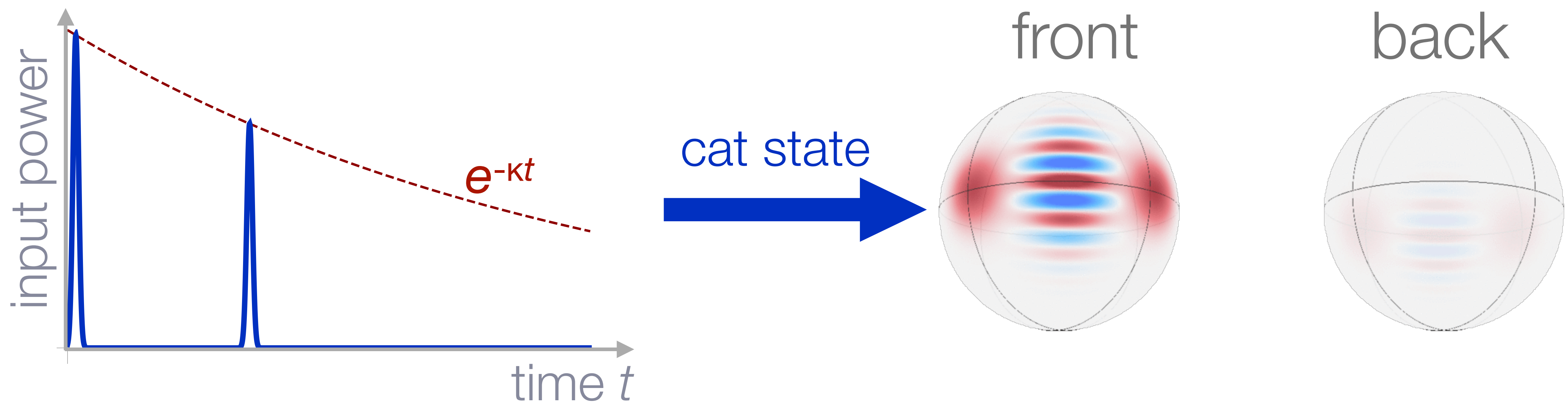

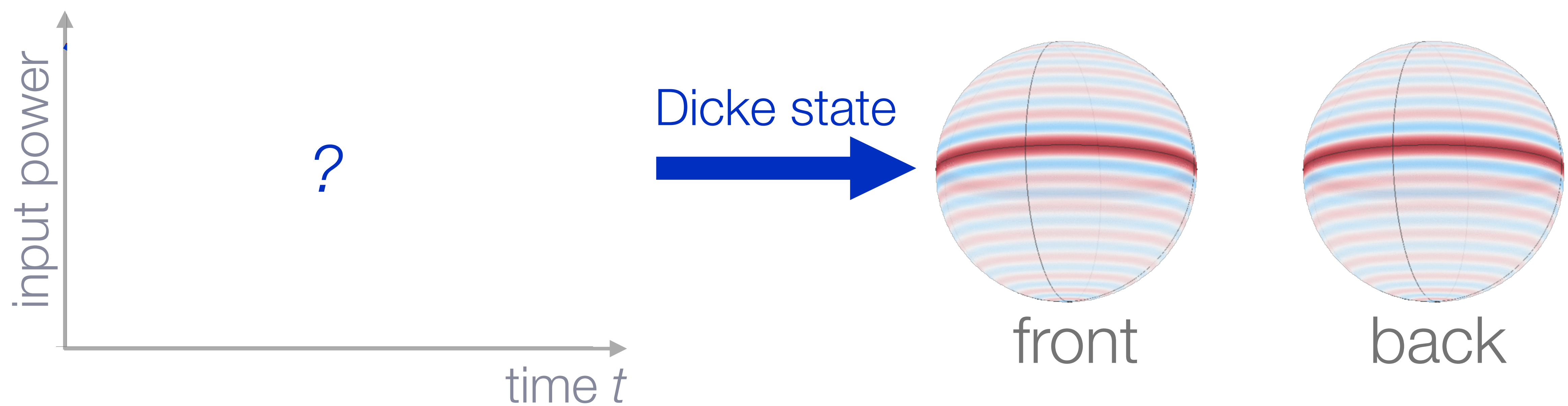

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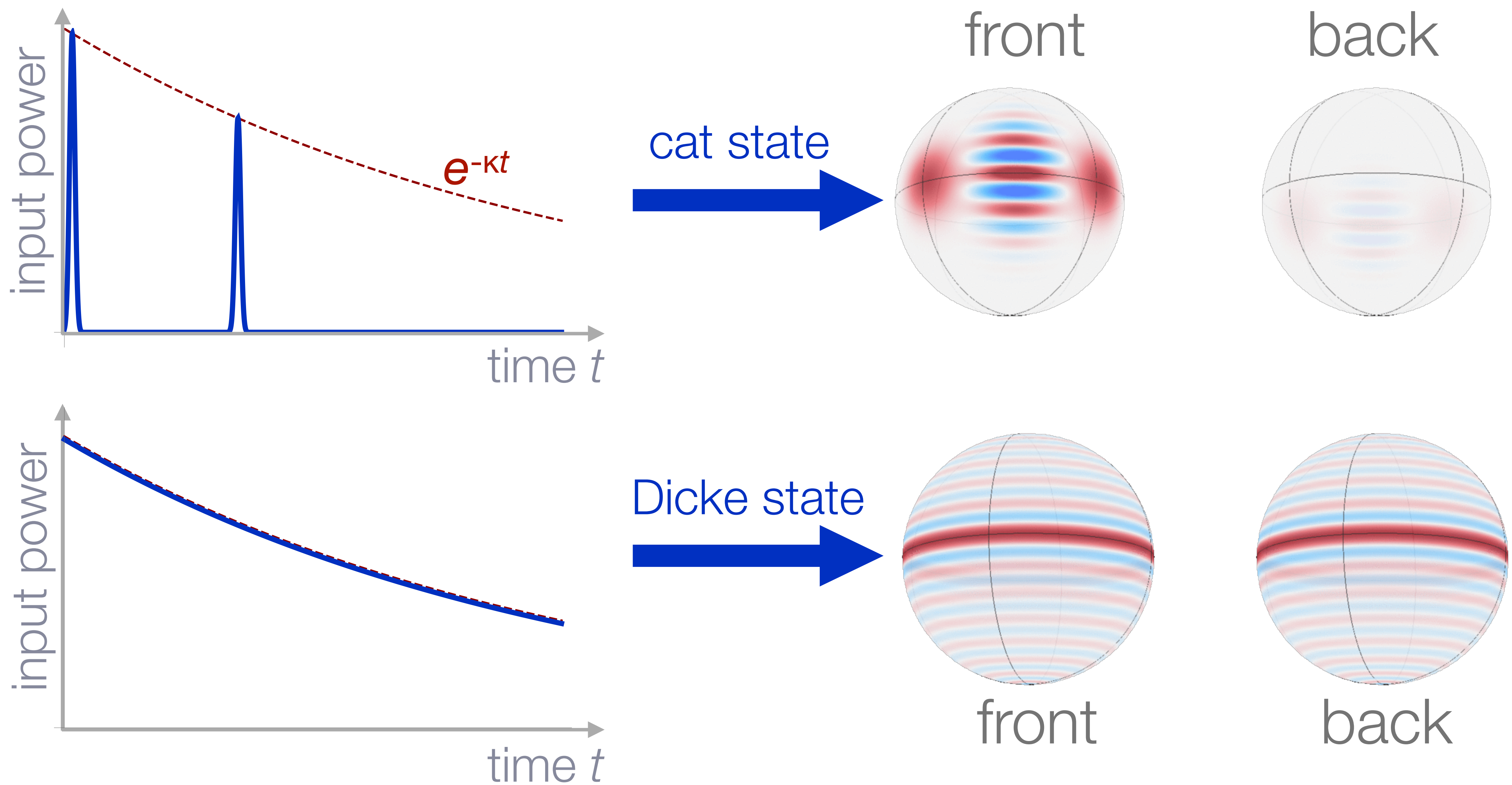

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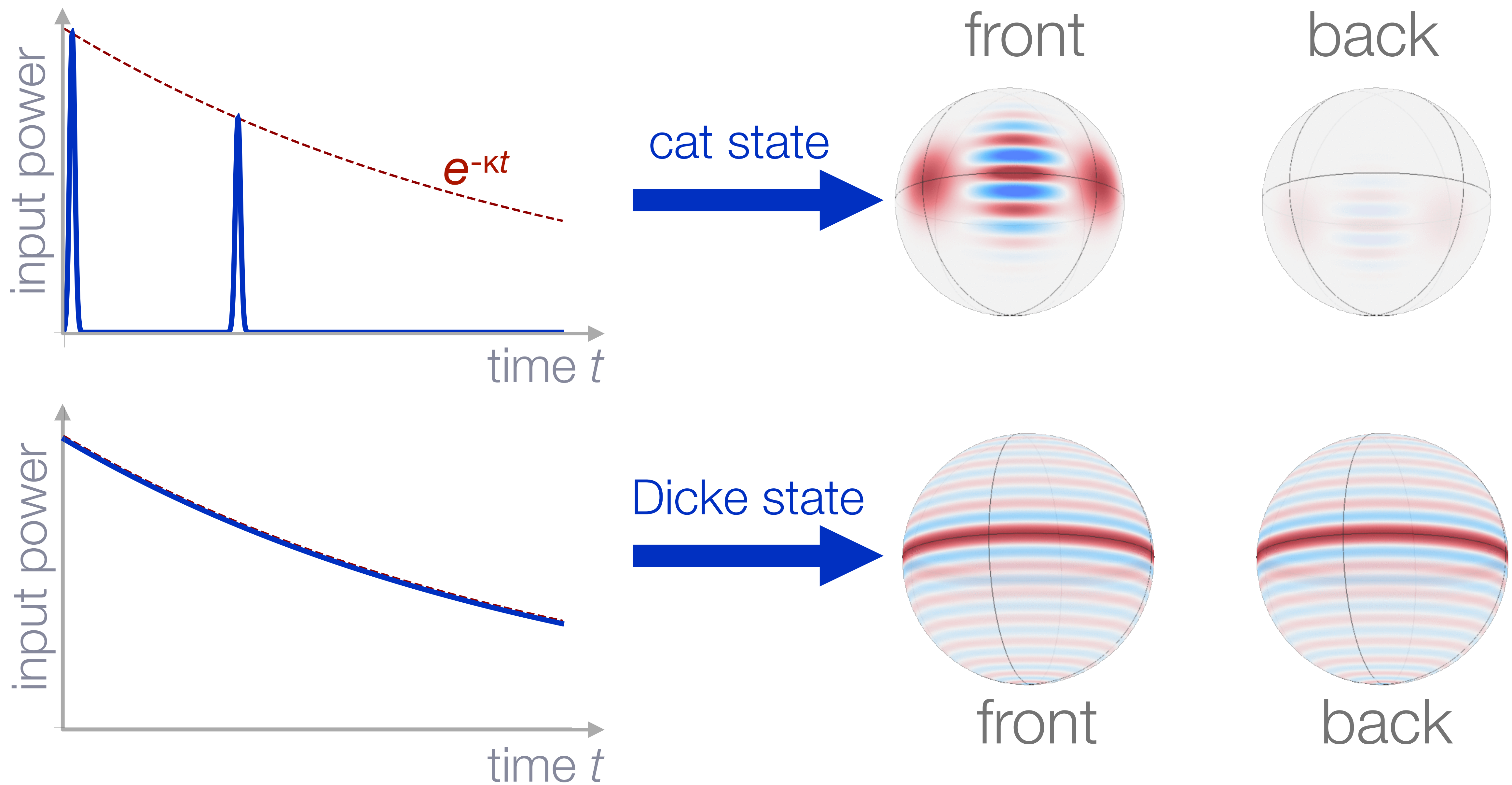
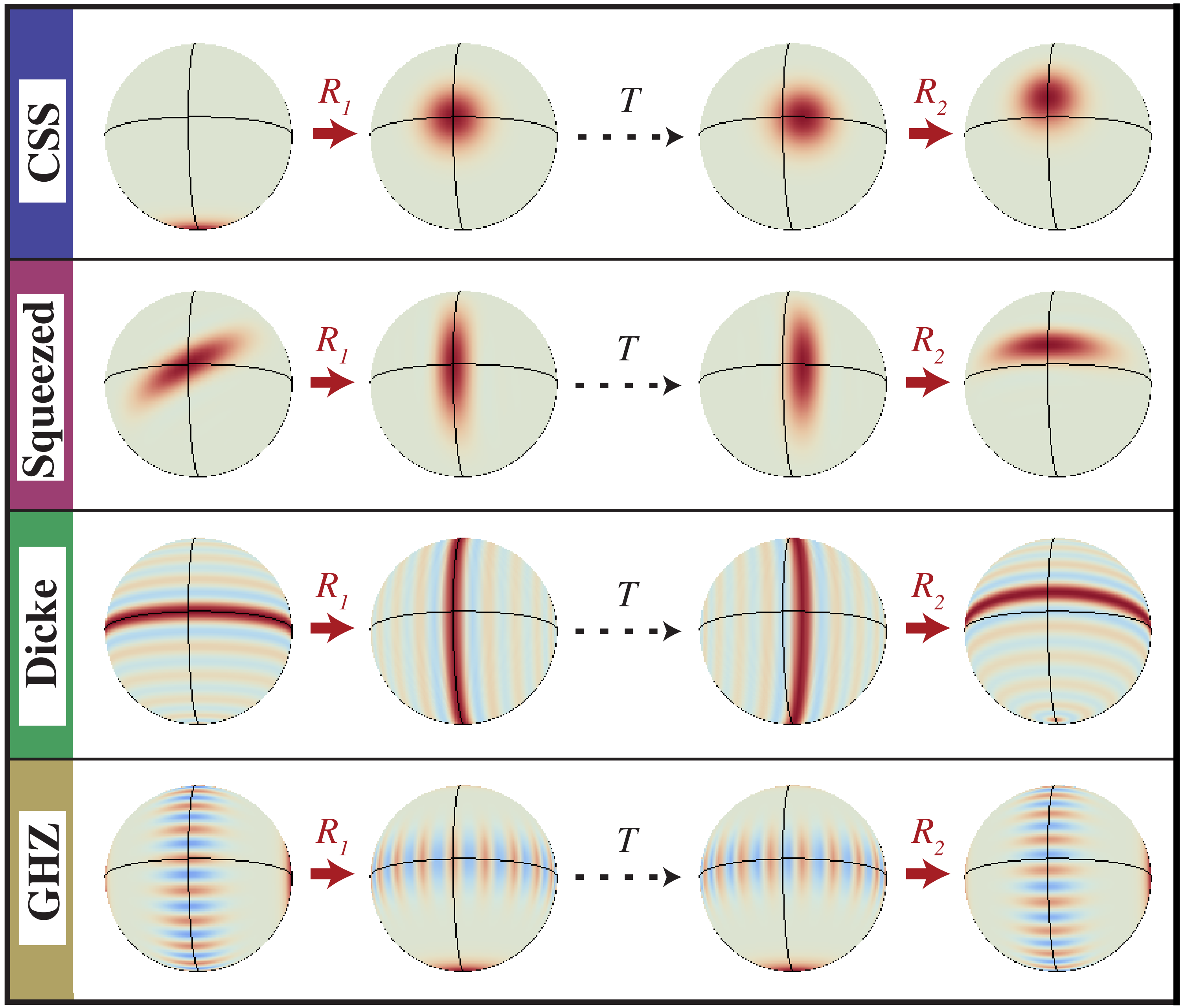


*vs. chisel (“carving”): Chen, Hu, Dong, Braverman, Zhang & Vuletic, *PRL* (2015).

Generalized Ramsey Spectroscopy



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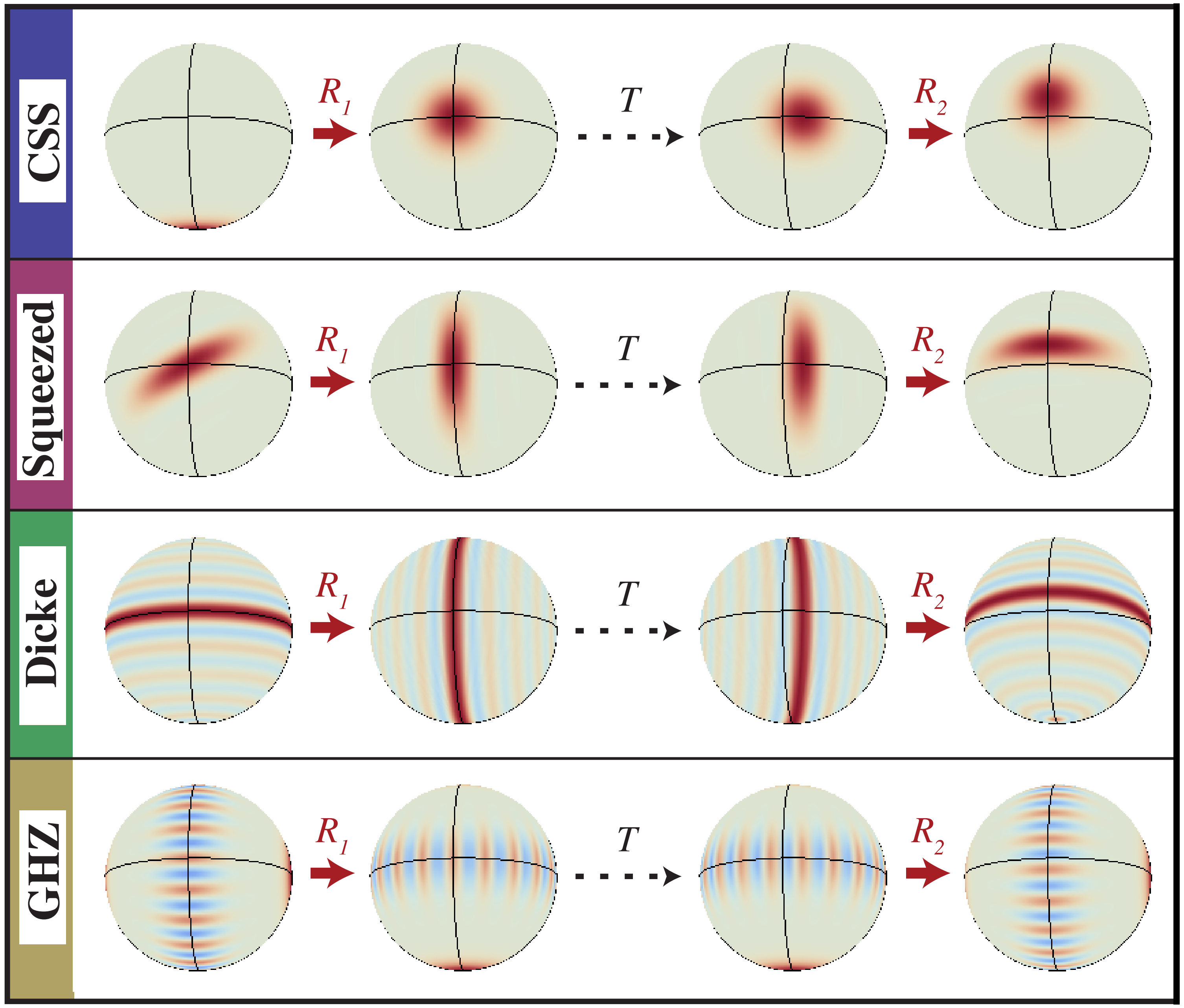

If we could make any state, which would we choose?

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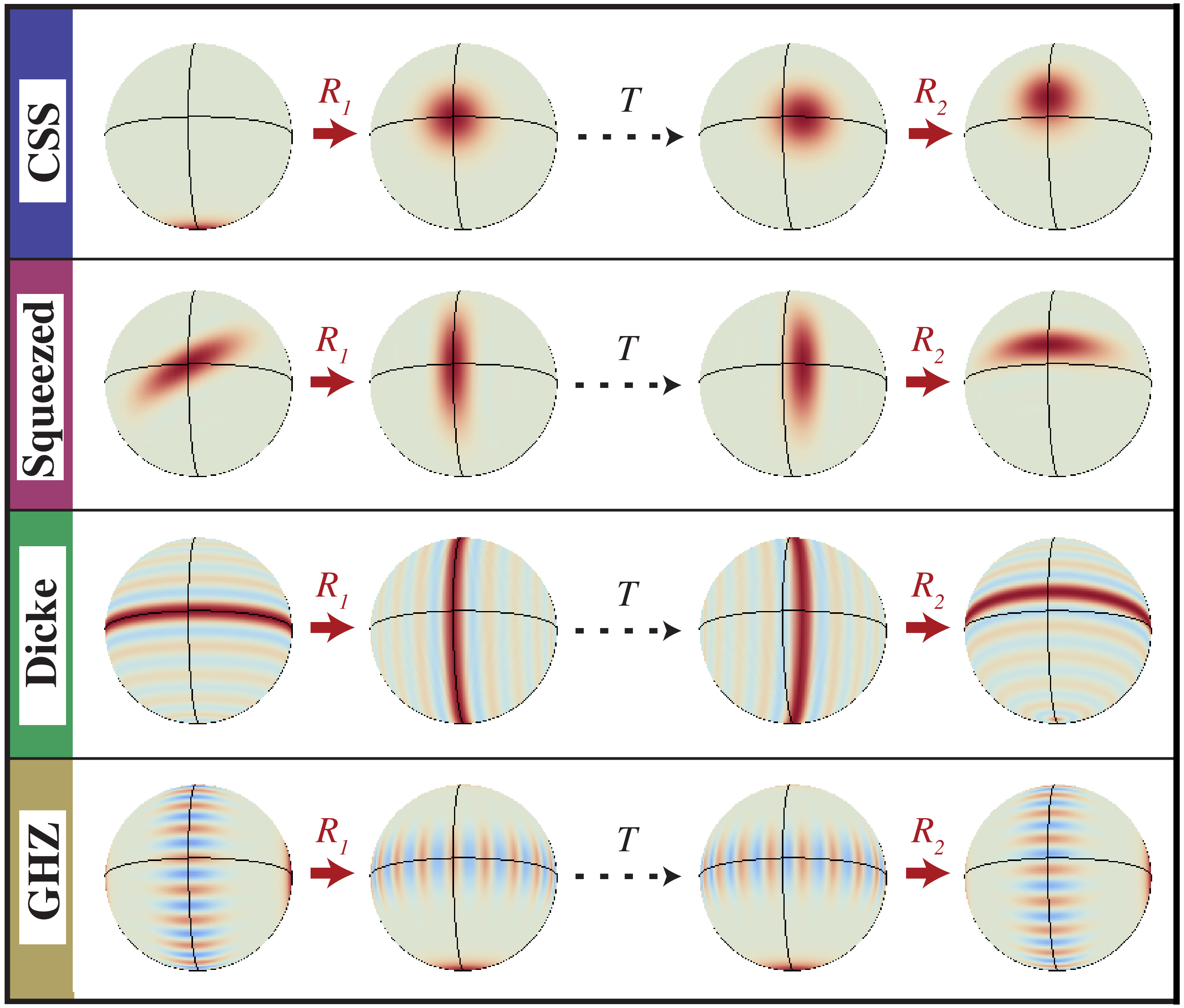
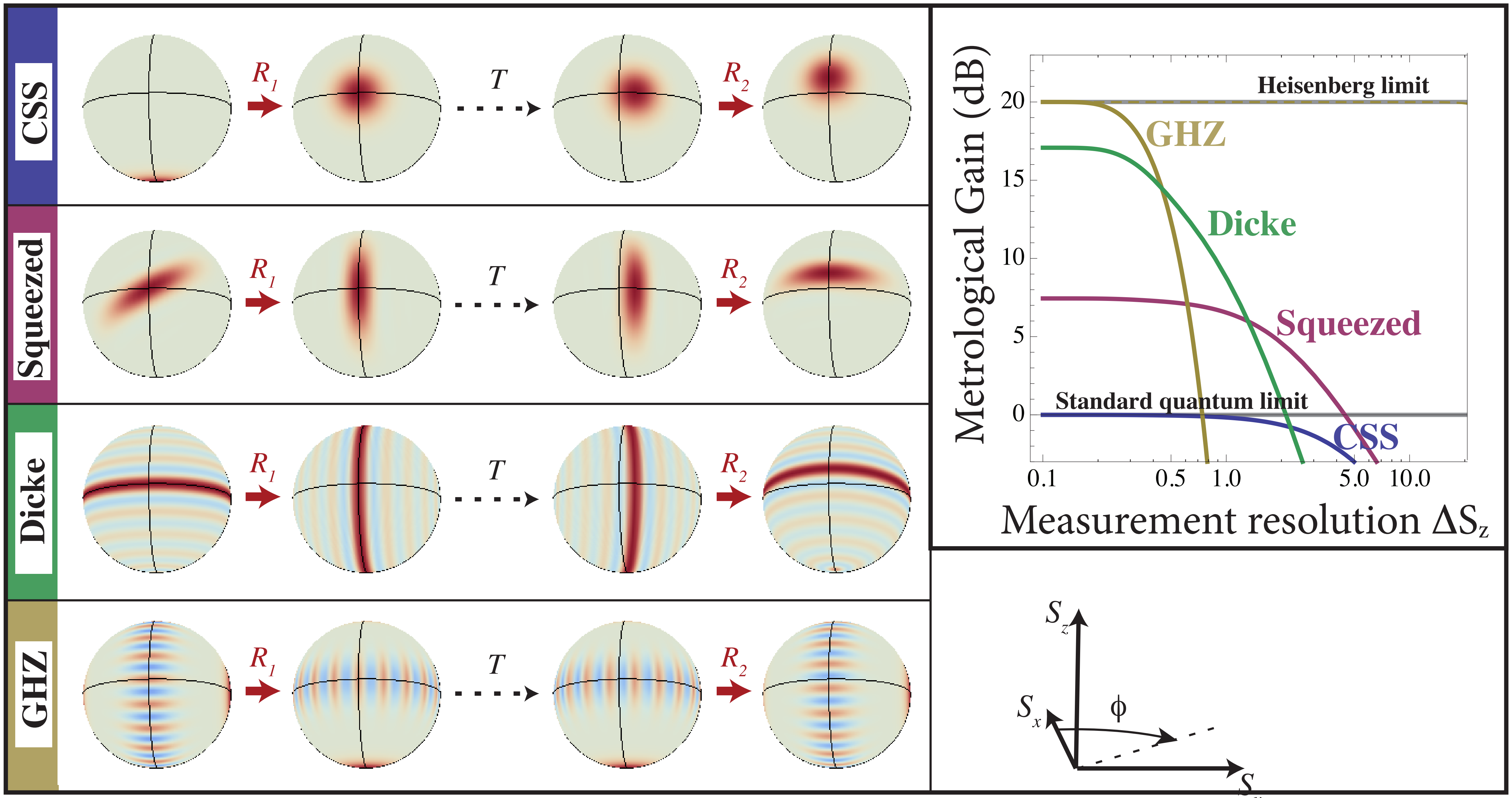


If we could make any state, which would we choose?

It depends.

Metrological Gain *vs.* Detection Noise

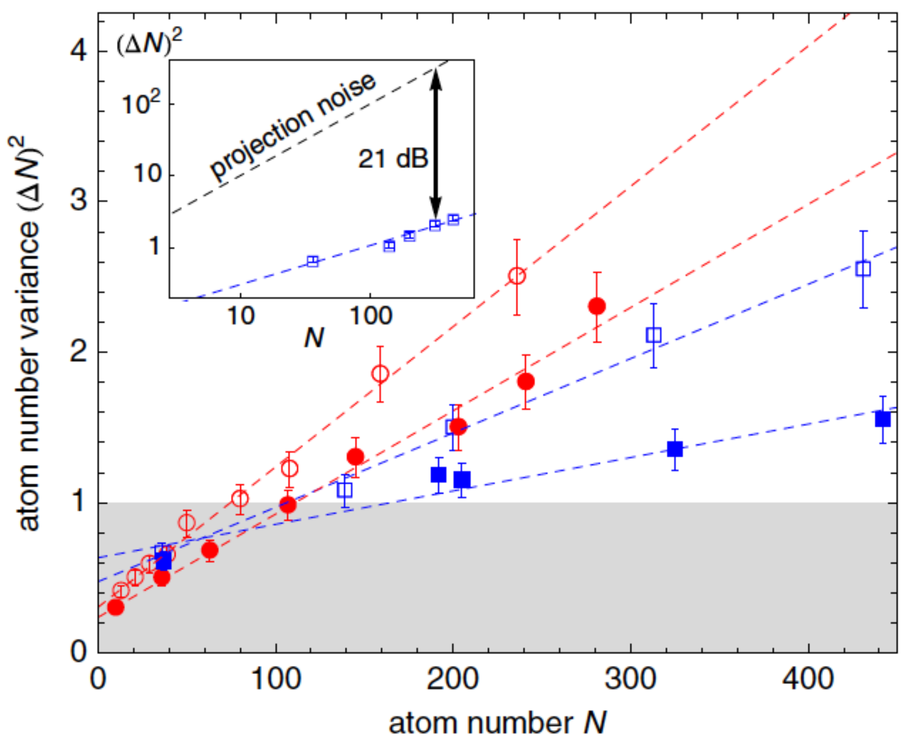


Reaping the Full Benefit of Entanglement

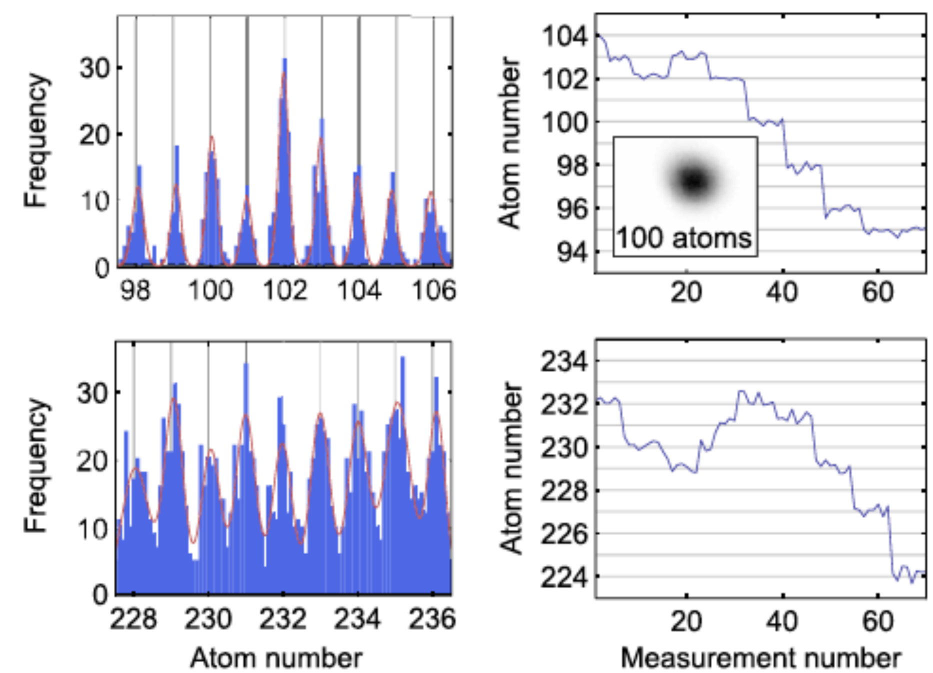
Approaches:

- Perfecting state detection

  Cavity-aided state-sensitive single-atom resolution:
  H. Zhang *et al.*, *PRL* **109**, 133603 (2012).

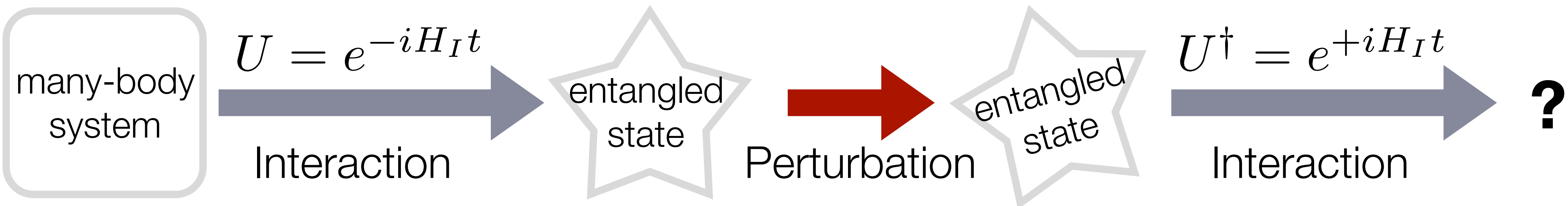


  Free-space detection by MOT recapture:
  Hume *et al.*, *PRL* (2013).



- *Circumventing the need to directly detect the entangled state?*

Echo Spectroscopy



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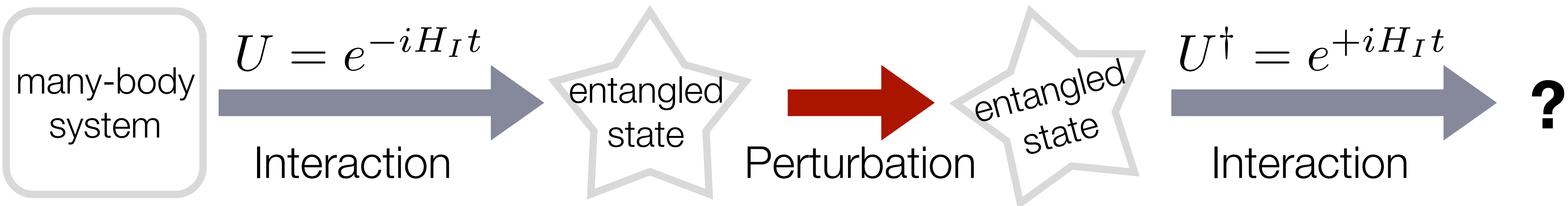
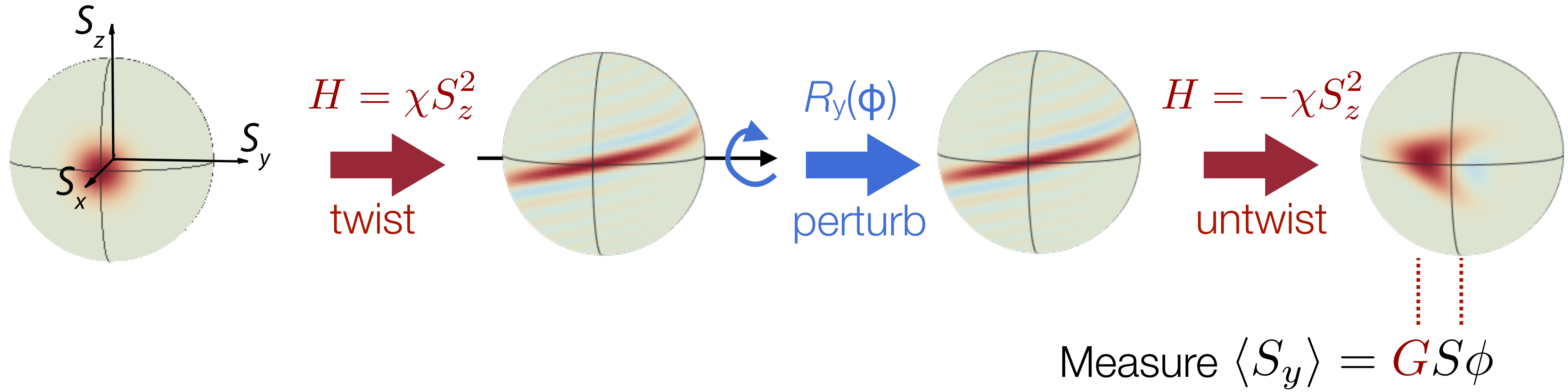


Detect perturbation by measuring whether system returns to *initial state*, rather than directly detecting the entangled state

Inspiration: Loschmidt echo (diagnostic of chaos)

One-Axis Twisting Echo

E. Davis, G. Bentsen, & MS-S,
PRL **116**, 053601 (2016).



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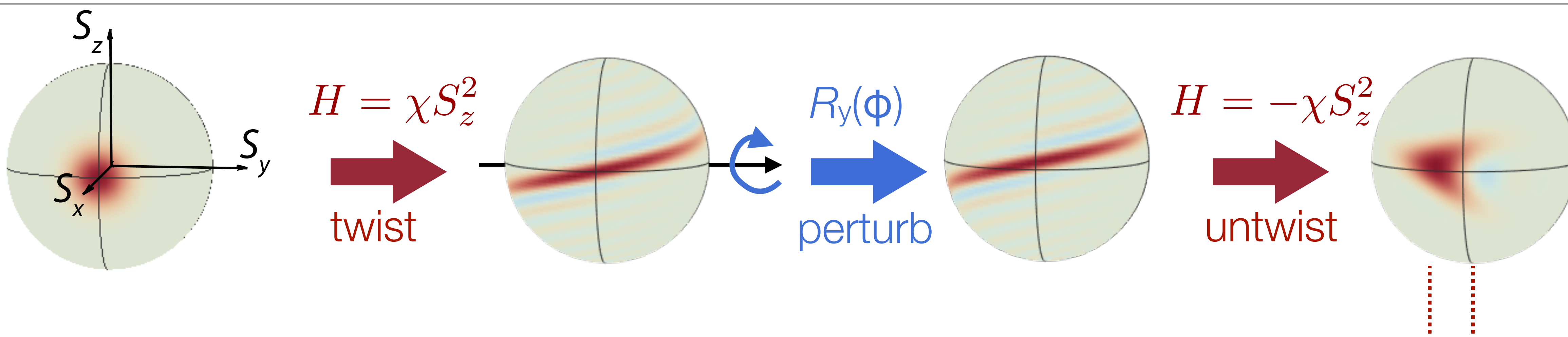

Measure $\langle S_y \rangle = GS\phi$

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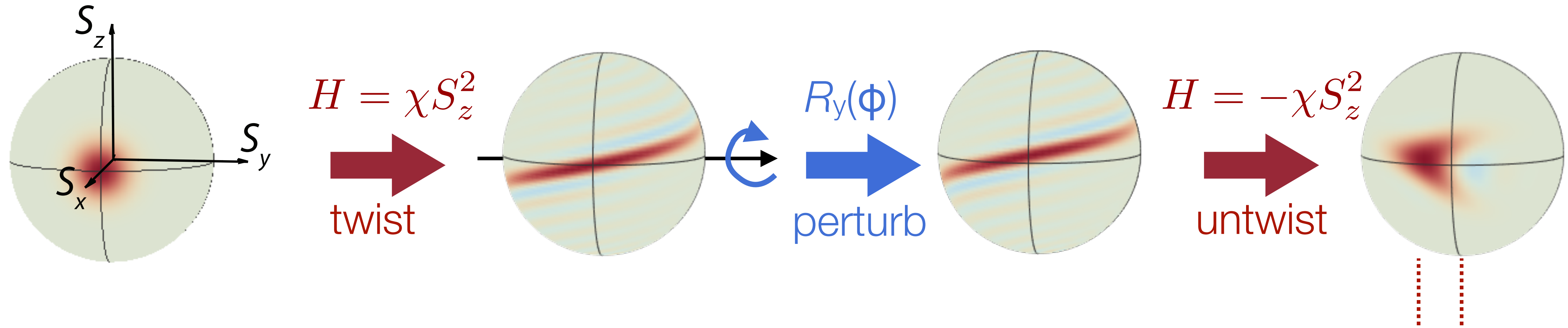

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Signal amplified by factor G
Quantum noise is that of the *initial* state

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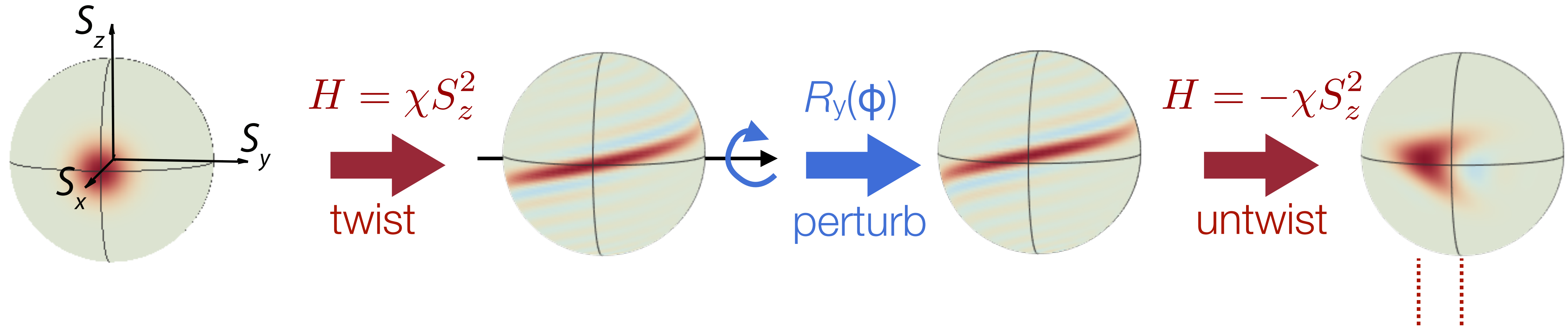

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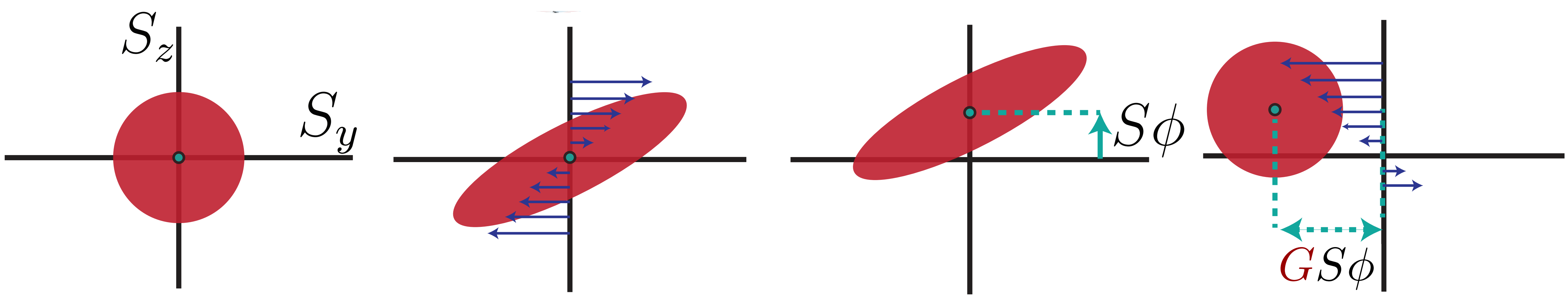

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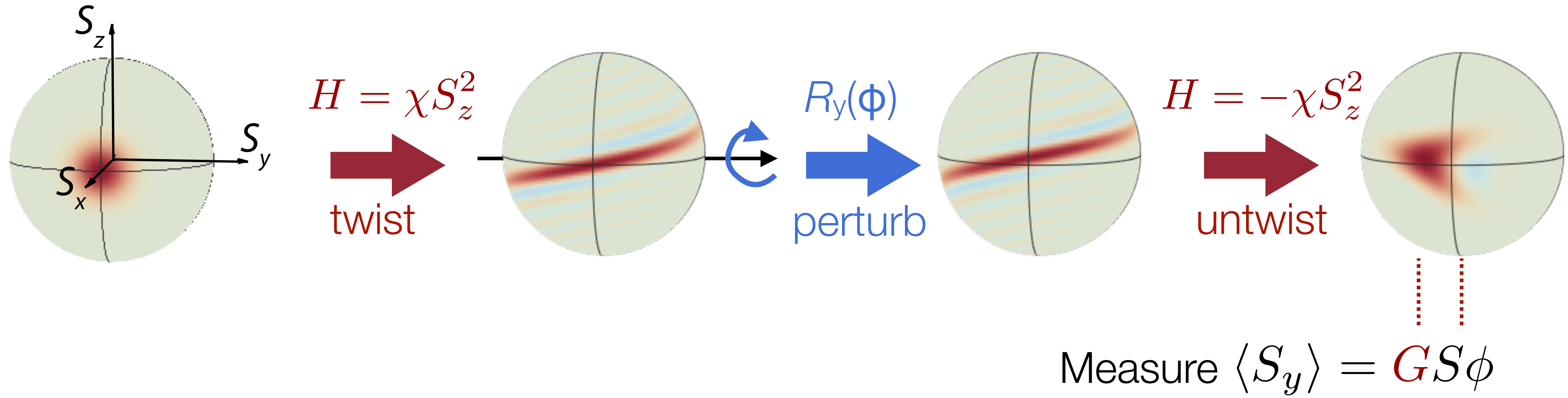

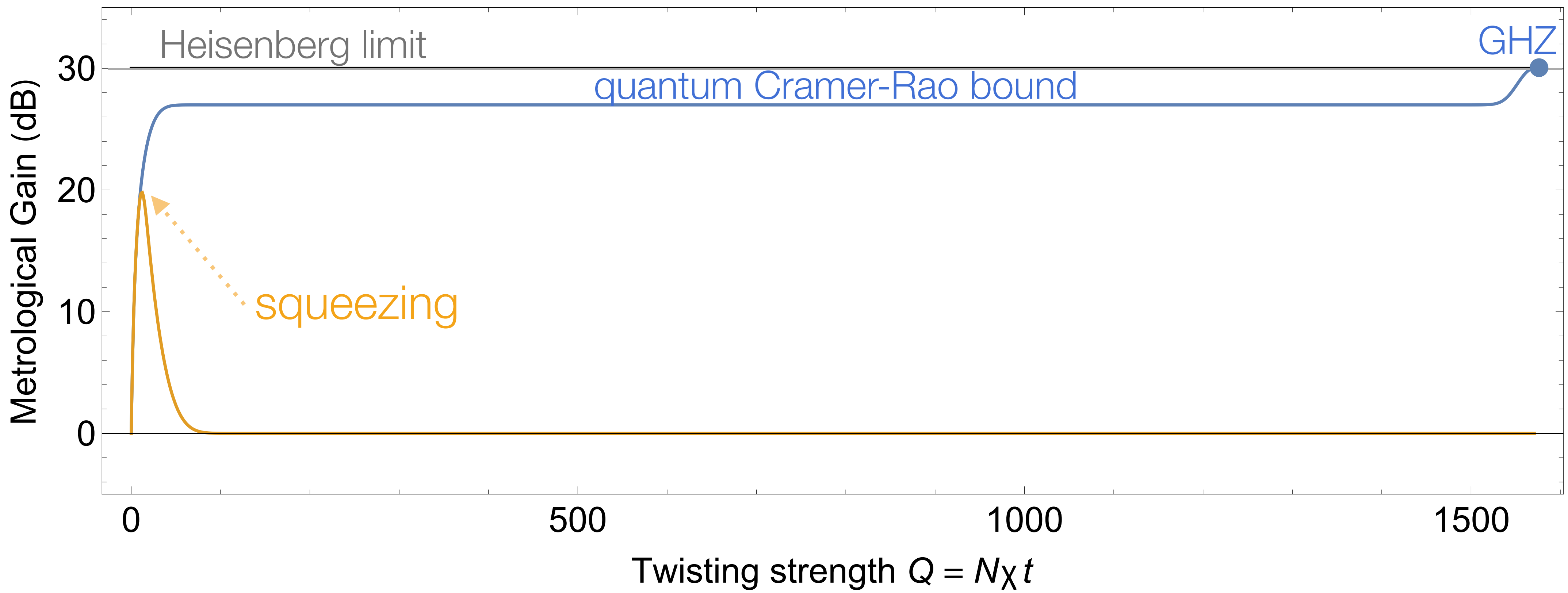

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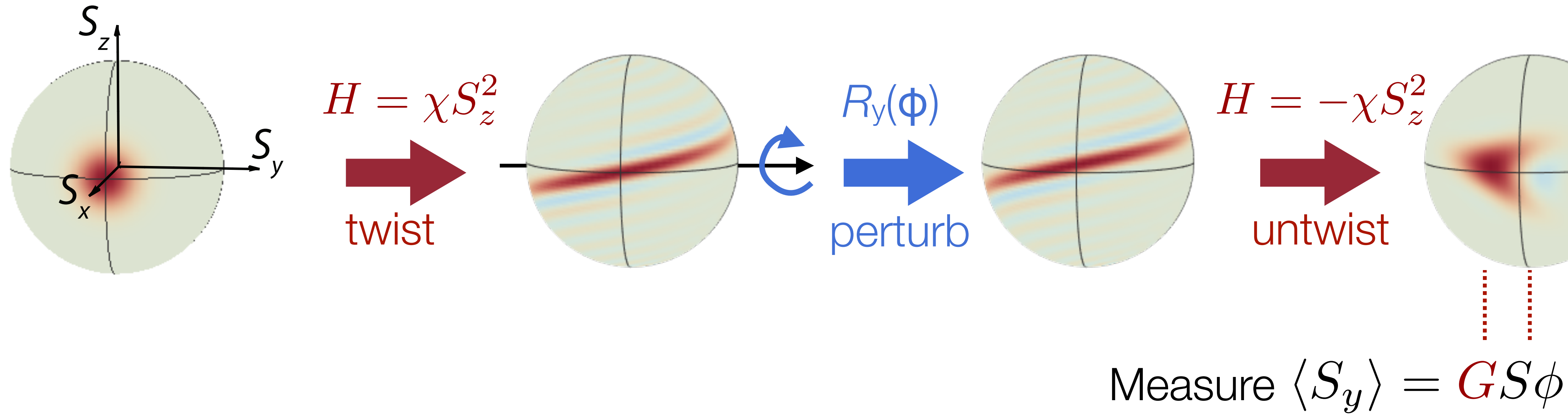
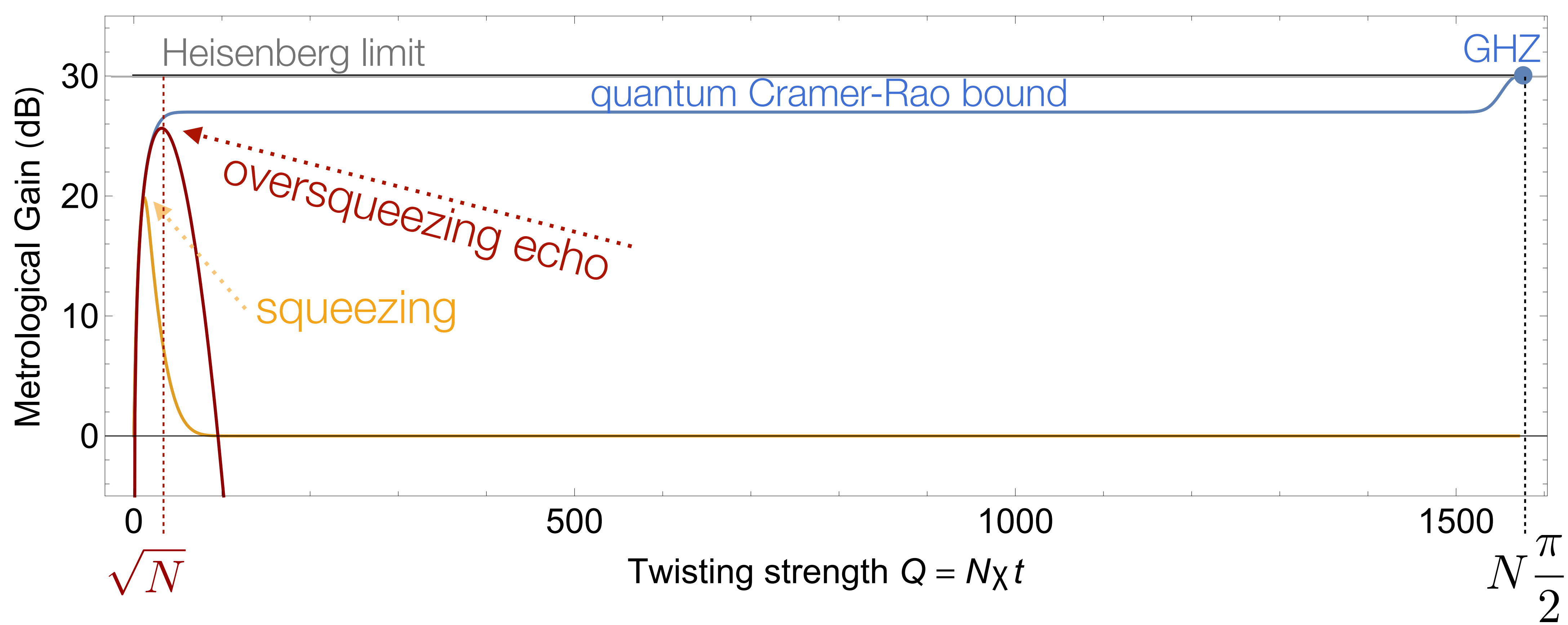
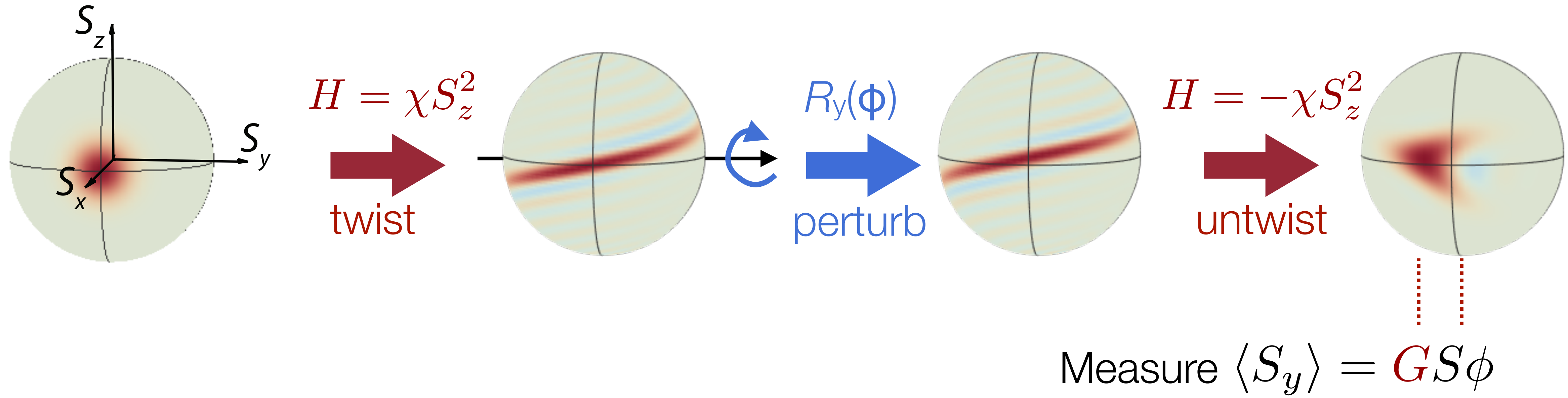
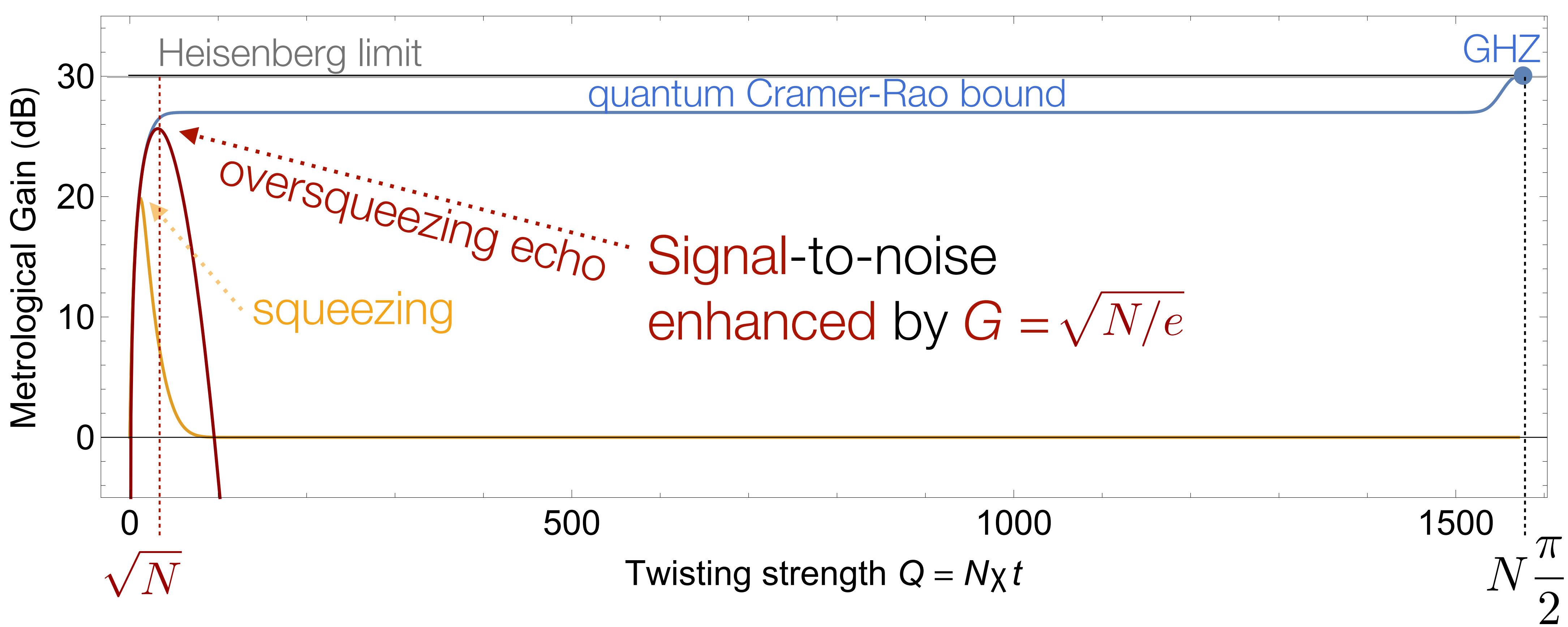




One-Axis Twisting Echo

E. Davis, G. Bentsen, & MS-S,
PRL **116**, 053601 (2016).





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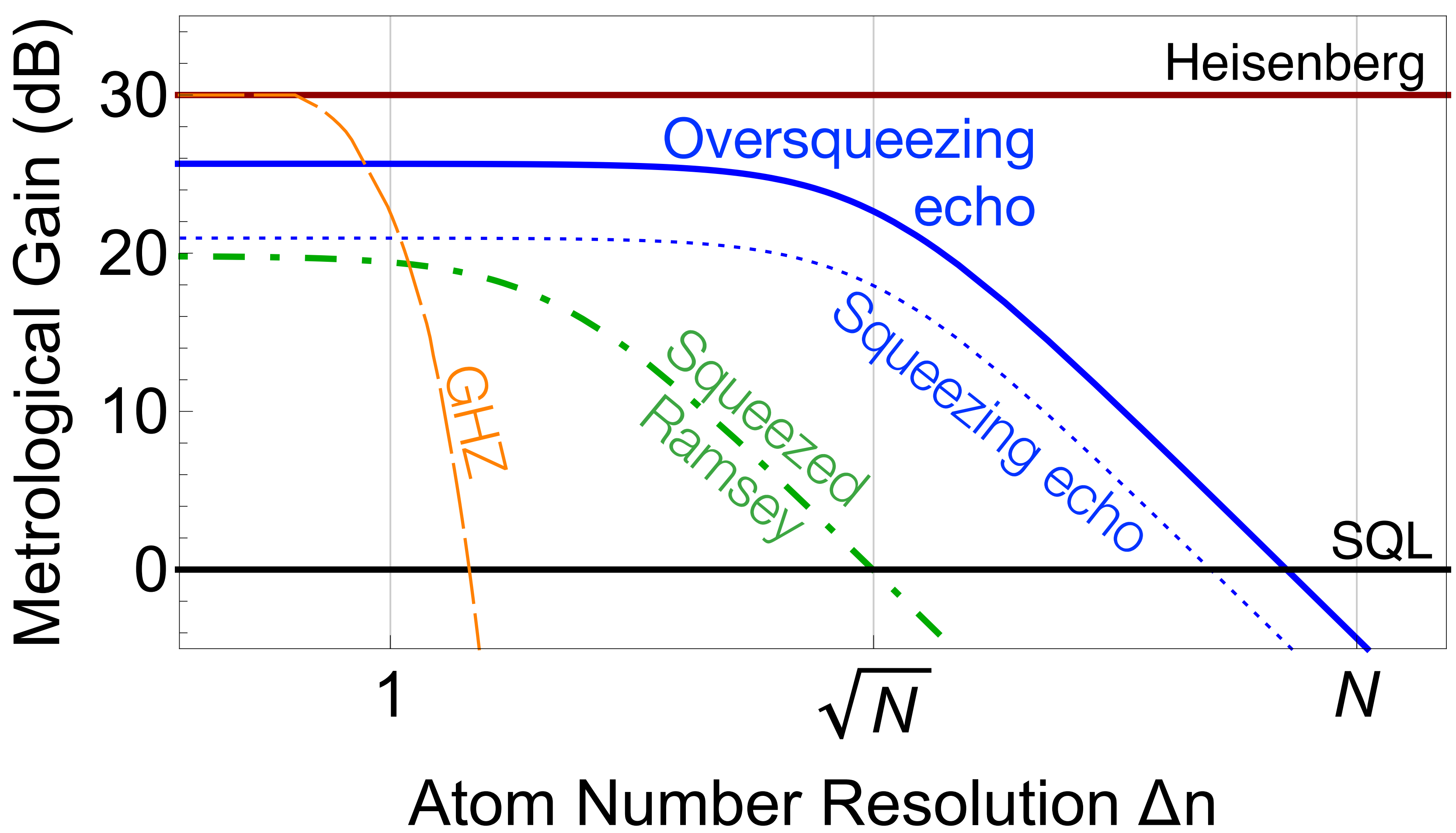
- Heisenberg scaling $\Delta\phi = \sqrt{e}/N$ reached after short twisting time
- Measurement resolution $\Delta S_{\mathrm{meas}} \lesssim \sqrt{N}/2$ suffices!



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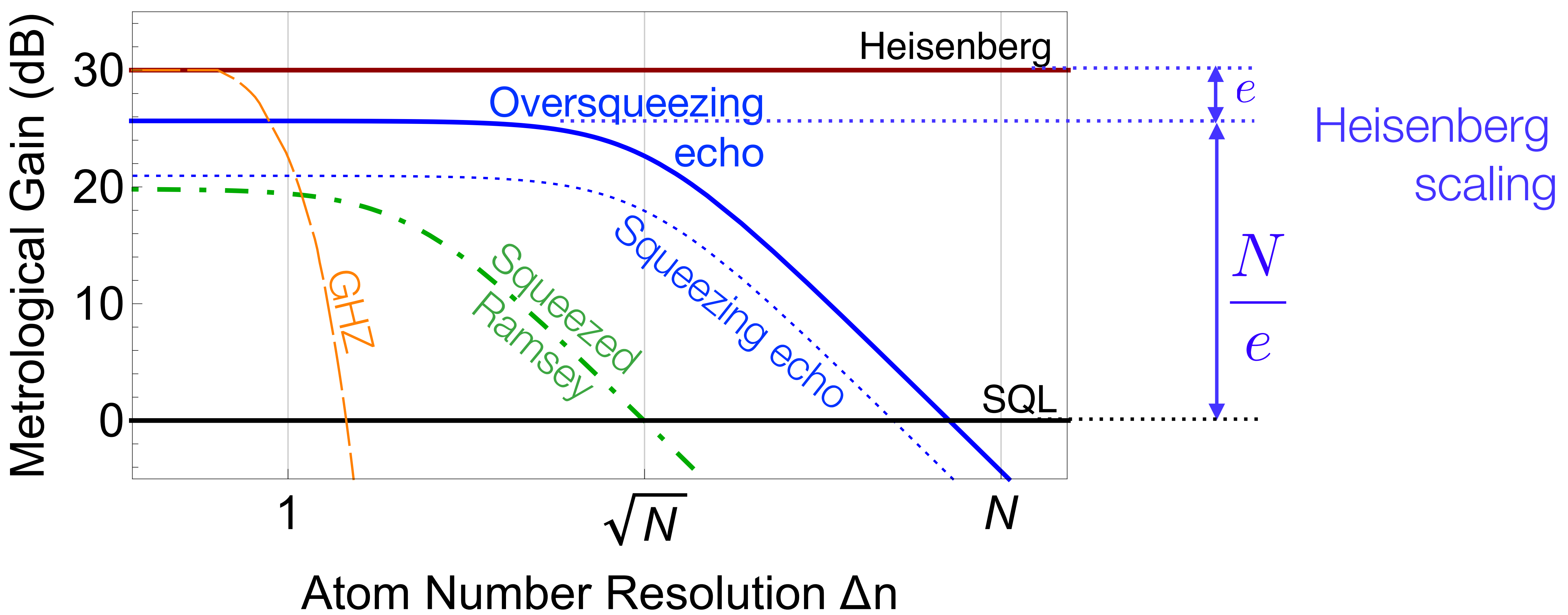
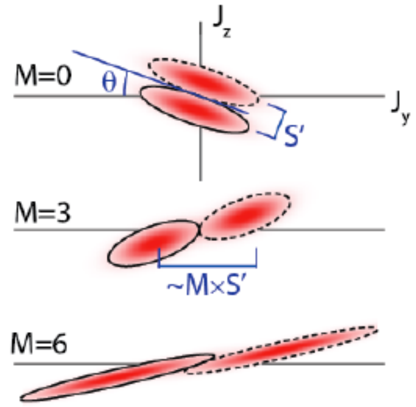
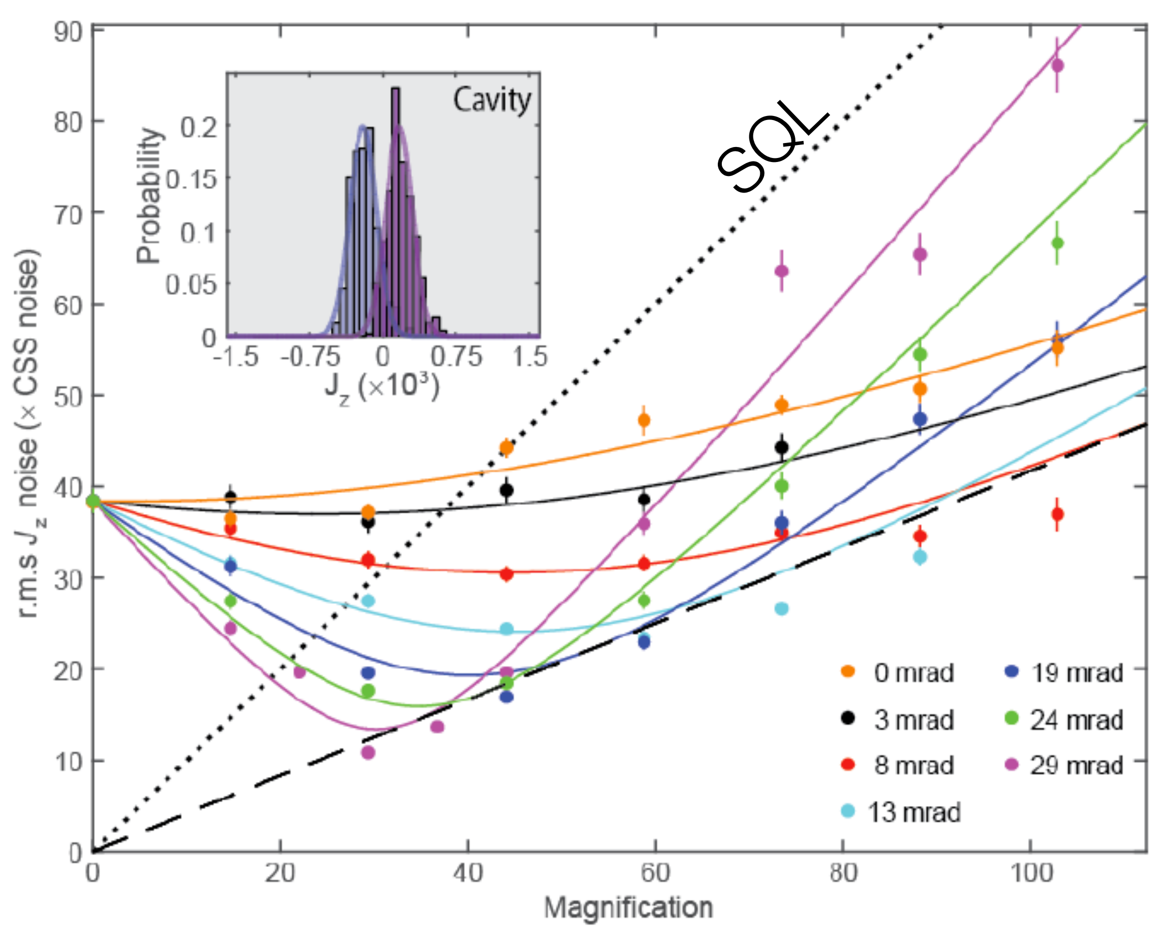


Interaction-Based Readout: Demonstrations

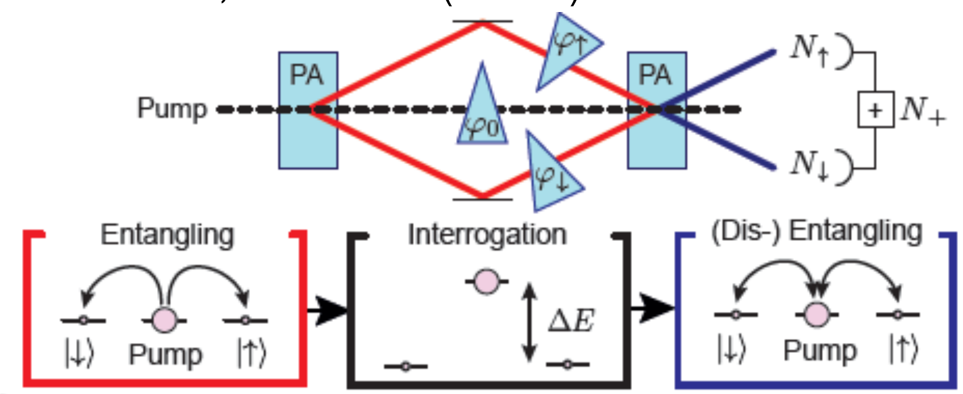
Hosten, Krishnakumar, Engelson & Kasevich, *Science* (2016).

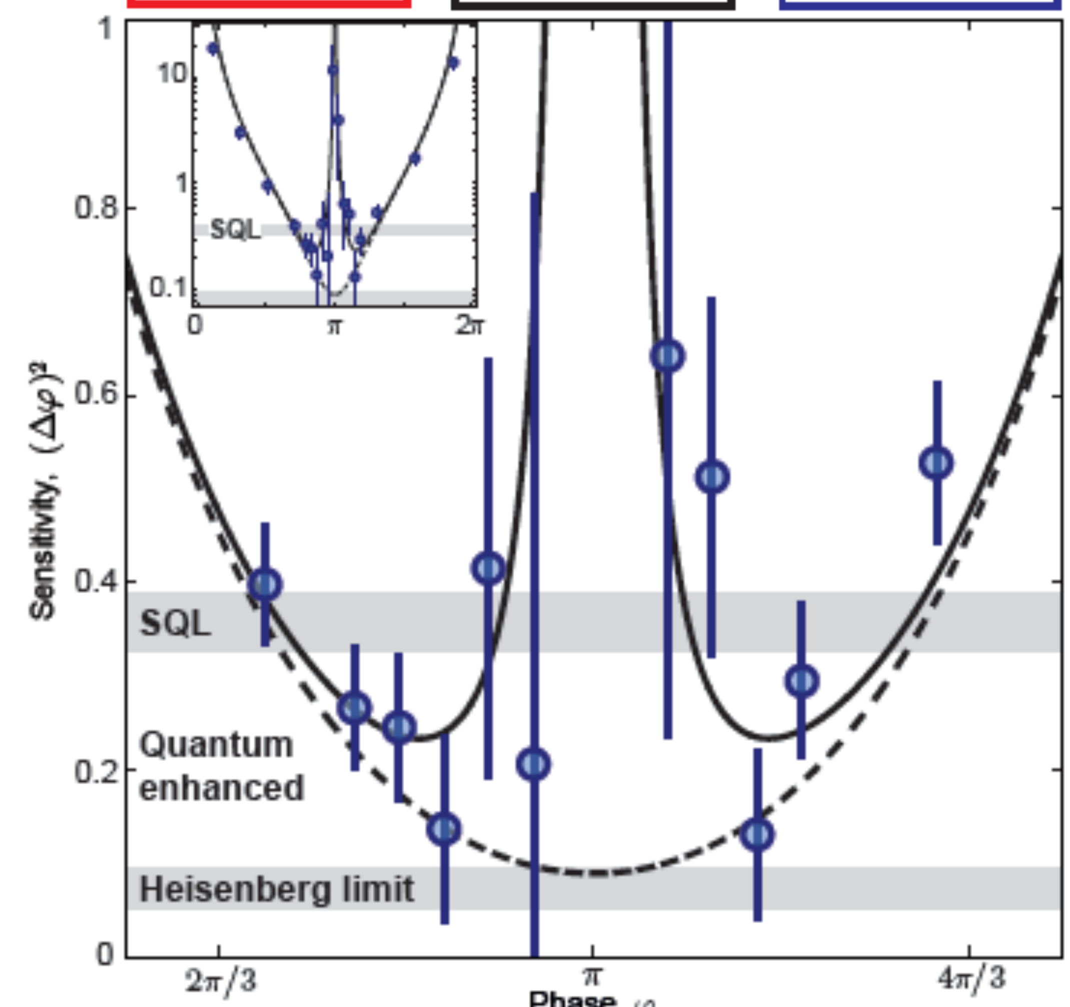
8 dB squeezing detected with low-resolution fluorescence imaging





Linnemann, Strobel, Muessel, Schulz, Lewis-Swan, Kheruntsyan, & Oberthaler, *PRL* 117, 013001 (2016).



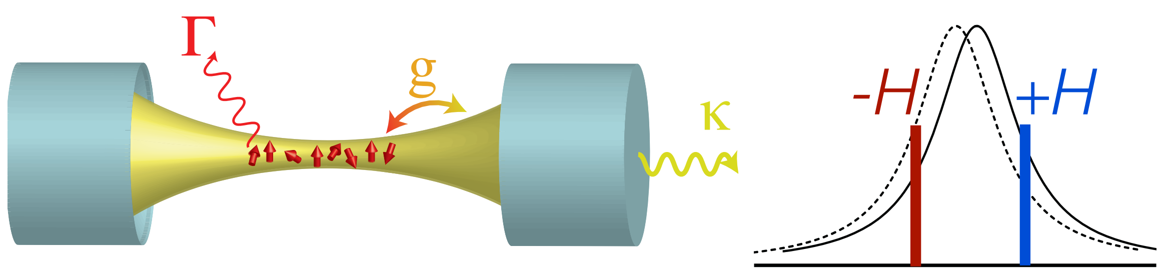


Oversqueezing Echo: Implementations?

Requirement: coherent interactions of switchable sign

Ion Penning trap

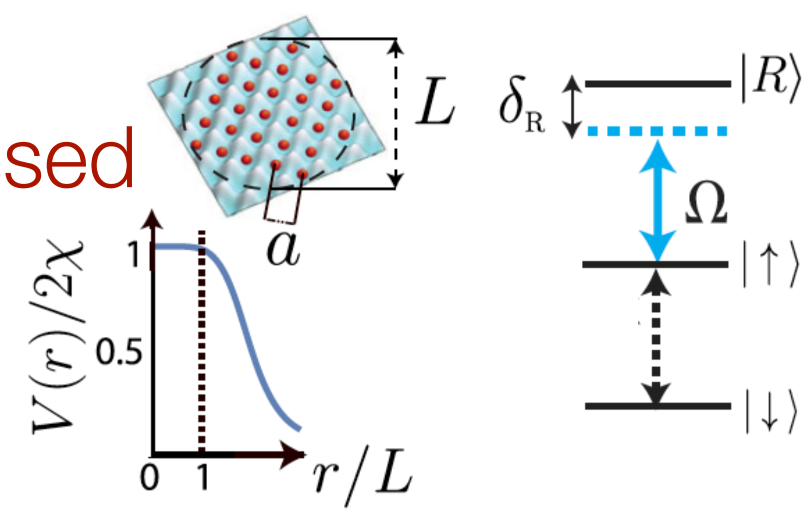
Gärttner, Bohnet, Safavi-Naini, Wall, Bollinger, & Rey, *Nat. Phys.* (2017).



Atoms in strong-coupling cavity

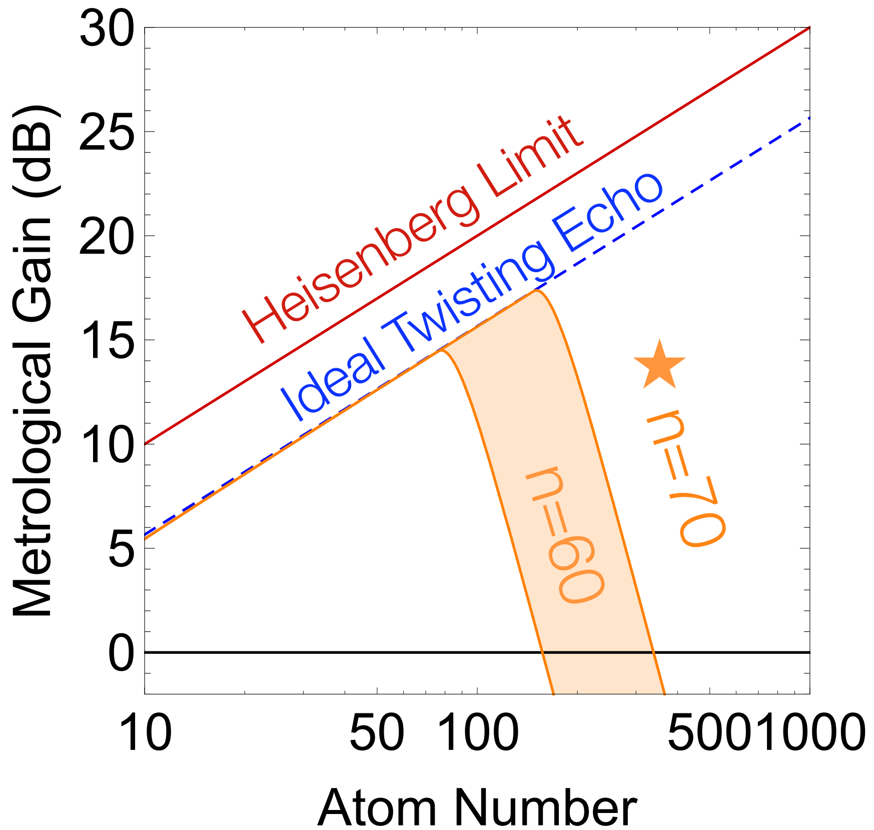
Photon-mediated interactions

Rydberg-dressed atoms



Prospects for Quantum Metrology

…by Rydberg dressing



★ 200 entangled atoms with sensitivity matching ~10^4 unentangled atoms

Inspiration: "Spin squeezing in a Rydberg lattice clock," Gil, Mukherjee, Bridge, Jones & Pohl, *PRL* (2014).

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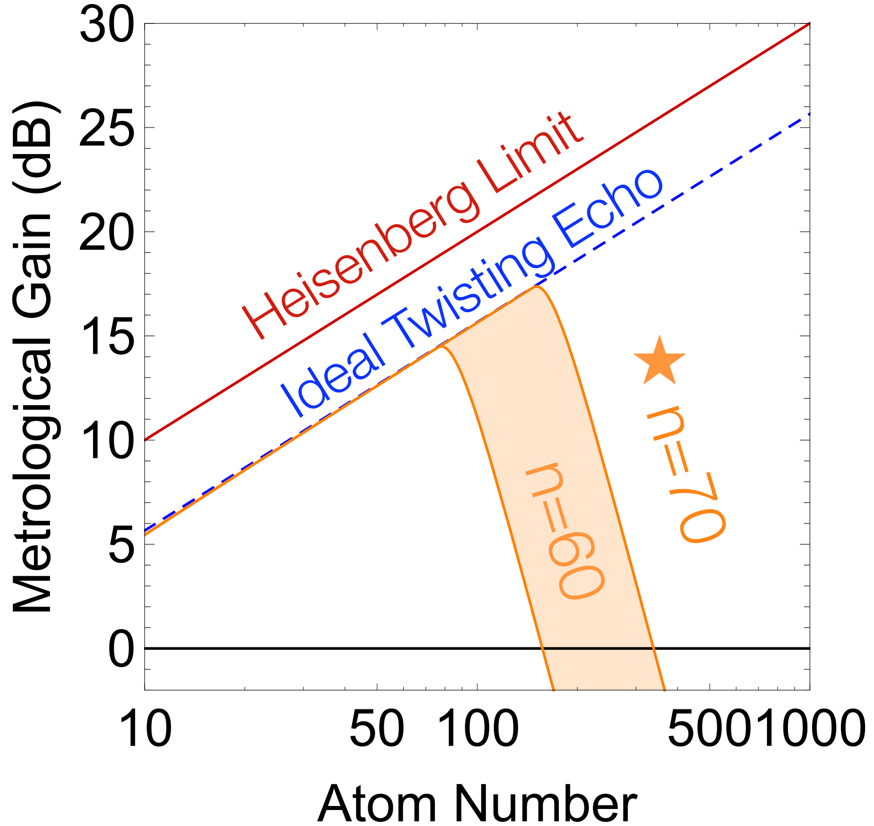

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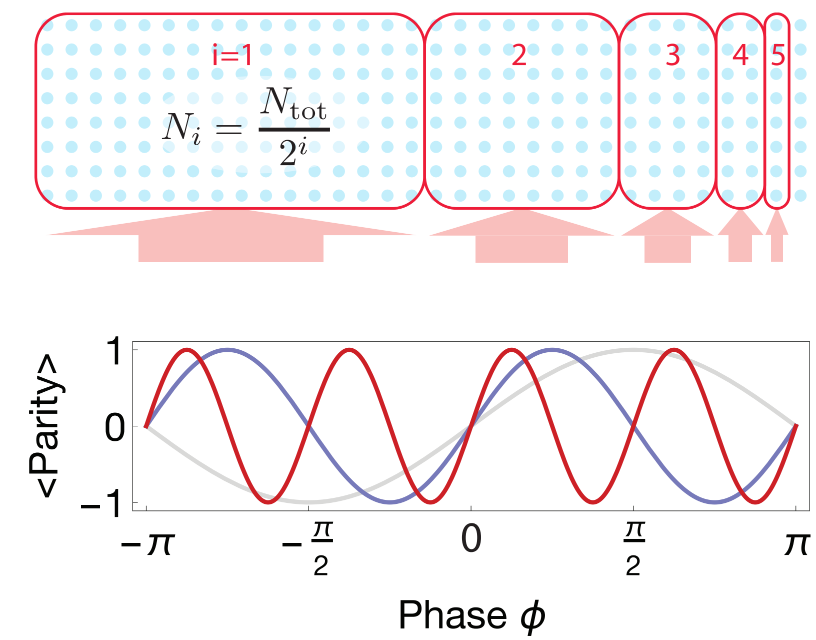
Arrays of entangled ensembles?

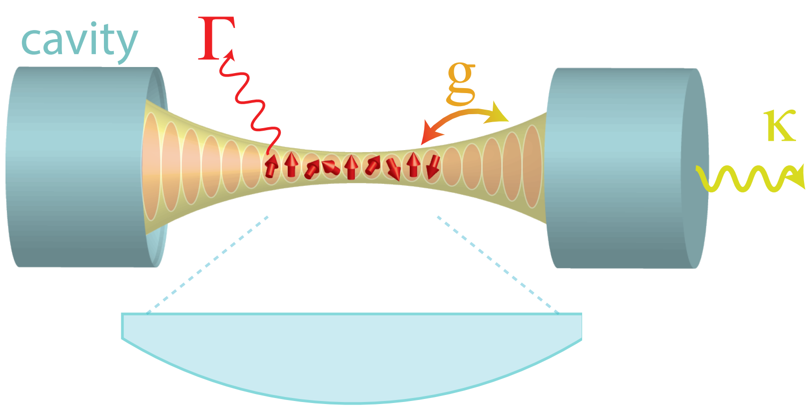


- tracking local oscillator phase in clock
  Kessler, …, Sorensen, Ye, Lukin, PRL (2014).
- broadband sensing
- spatially resolved sensing

Outline

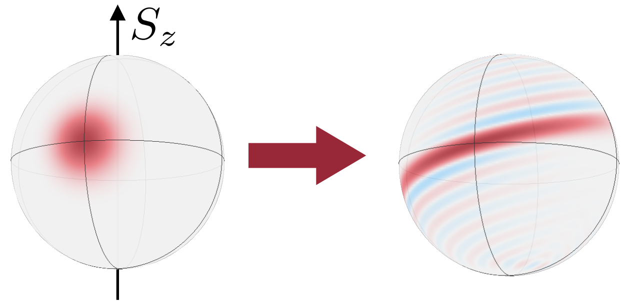
✔Motivation and Background

- Quantum metrology
- Entangling atoms with photons



✔Seeking the Heisenberg Limit

- Engineering entanglement in a dissipative world
- Harnessing entanglement in a noisy world

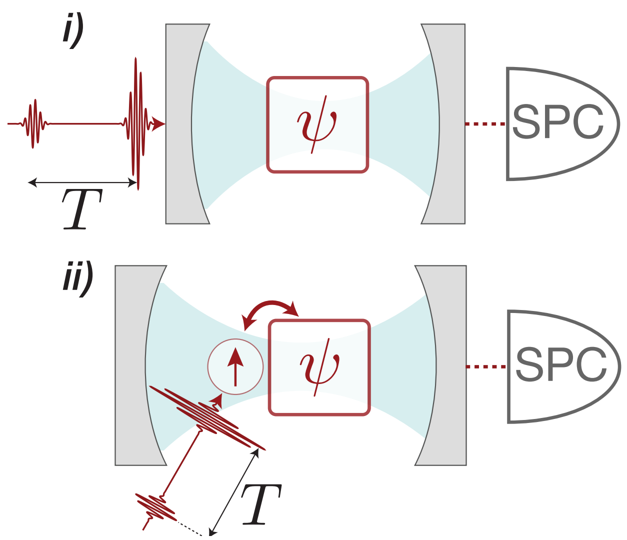


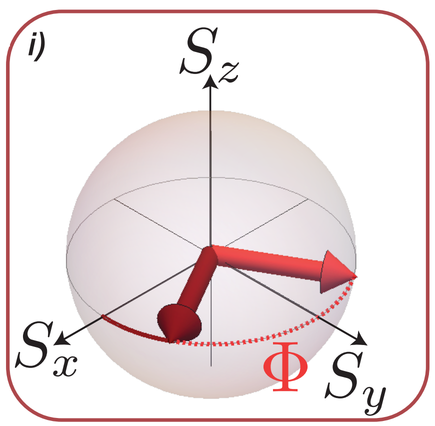
Summary & Outlook

Quantum Engineering in an Imperfect World

Harnessing entangled states in spite of detection noise:
Echo spectroscopy with over-squeezed, non-Gaussian states

Engineering entangled states in spite of dissipation:
Single-photon paintbrush with robustness to photon loss





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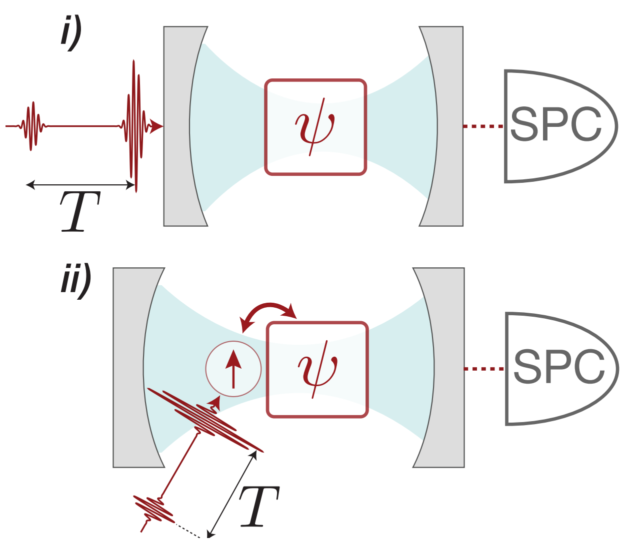
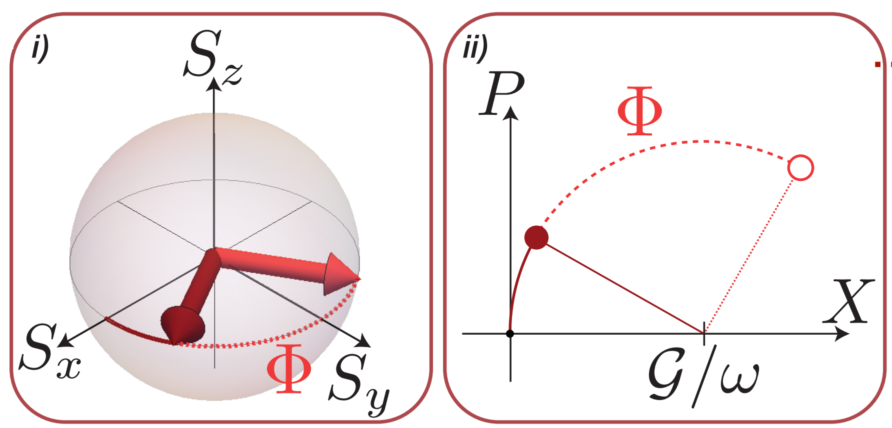


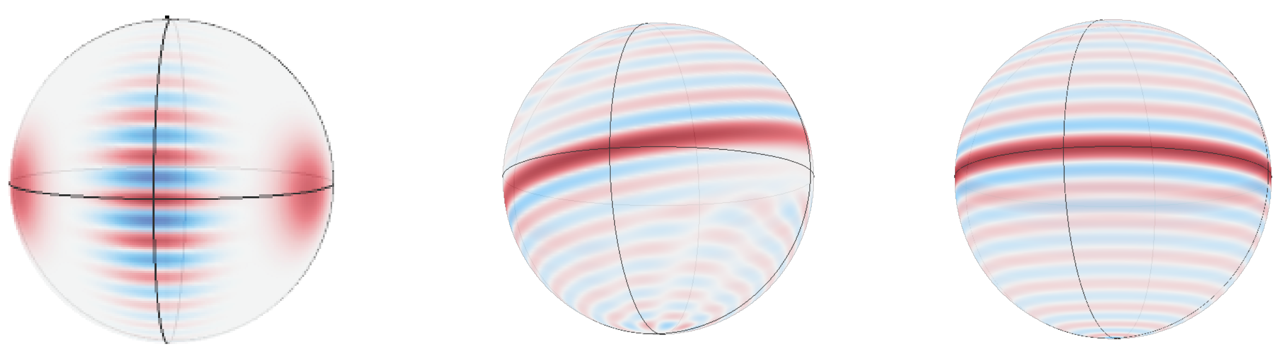


Alternative application:
non-classical states of
mechanical oscillators

Summary

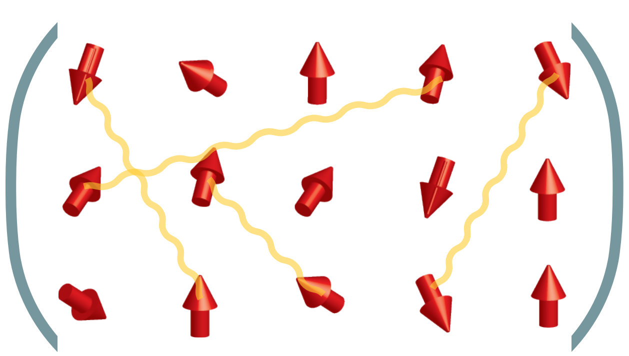
Atomic clocks and sensors have surpassed the Standard Quantum Limit, but still are far from the Heisenberg Limit

Which entangled states to use, how to generate, how best to detect?
Many open questions, but we are making progress!



Atom-light interactions provide a versatile toolbox

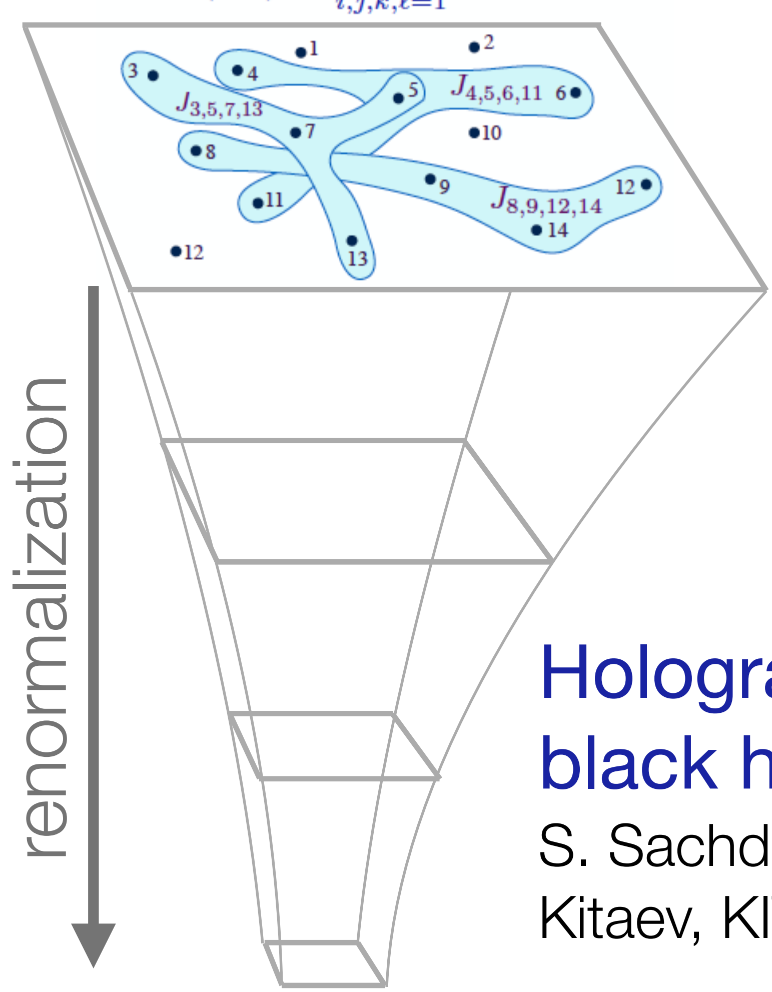
- near-term applications in atomic clocks
- advancing control & understanding of entanglement



Outlook: Quantum Simulation

Fermions
with non-local hopping

$$H = \frac{1}{(2N)^{3/2}} \sum_{i,j,k,\ell=1}^{N} J_{ij;k\ell}\, c_i^\dagger c_j^\dagger c_k c_\ell$$

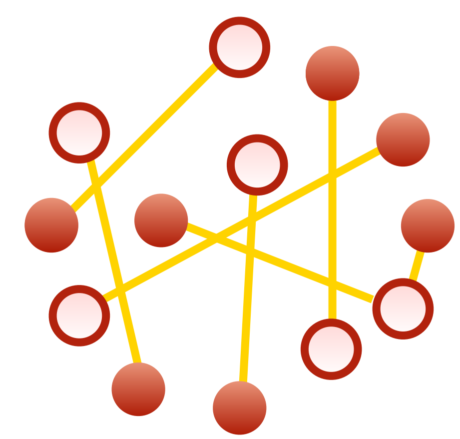


Holographic dual:
black hole

S. Sachdev, *PRX* (2015).
Kitaev, KITP (2015).

Hard-core bosons
with non-local hopping?

$$H \propto \sum_{i,j} J_{ij} \sigma_+^i \sigma_-^j$$



Natural approach:
bosons = spin excitations,
hopping mediated by light

Acknowledgements

Research Group

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Lukas Homeier

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Zhaoyou Wang

Past visitors

Anna Wang
Thomas Reimann
Sebastian Scherg

Extras

Fidelity of Single-Photon Paintbrush

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For weak input pulse, conditioned on detecting a single photon:
perfect fidelity even in presence of cavity losses & atomic scattering

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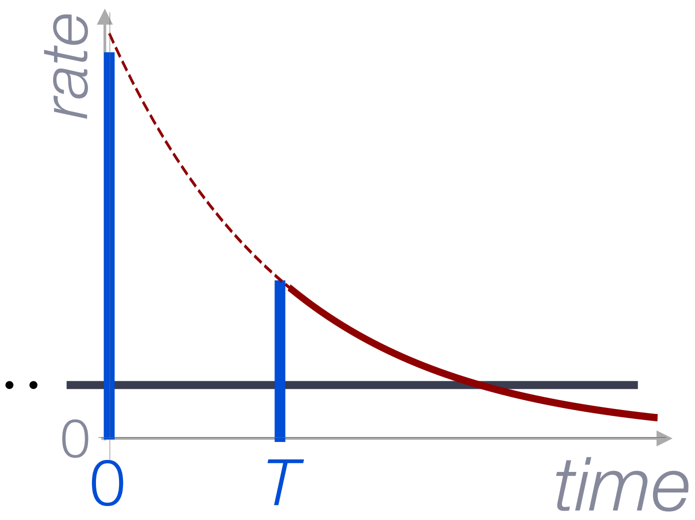
Real-world limitations:

- Precession time *T* limited by competition between heralding rate and **dark counts of detector**



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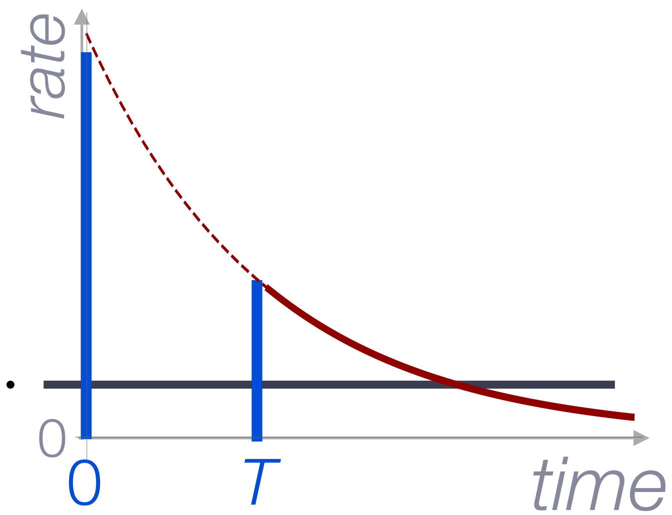

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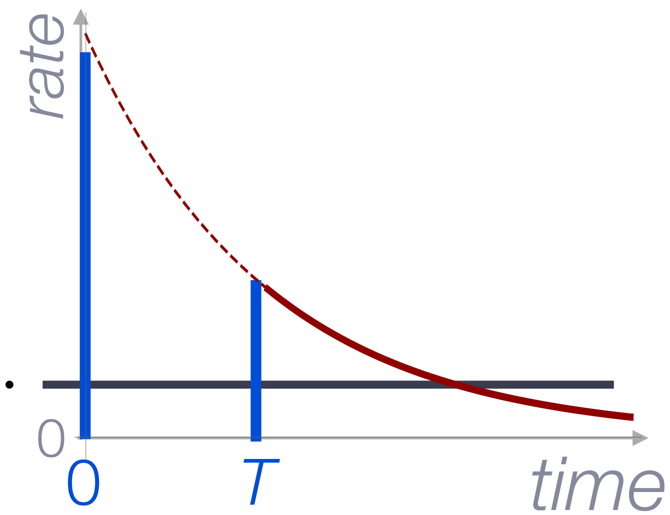
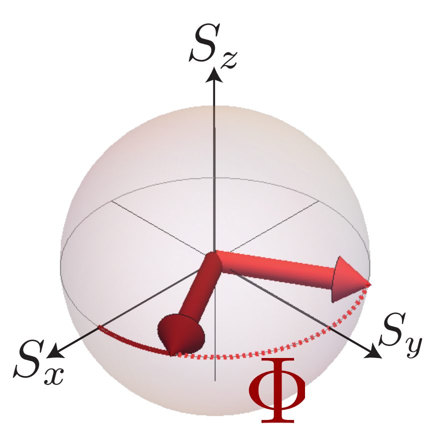
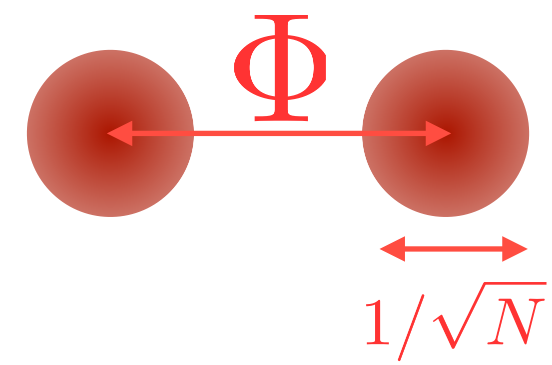


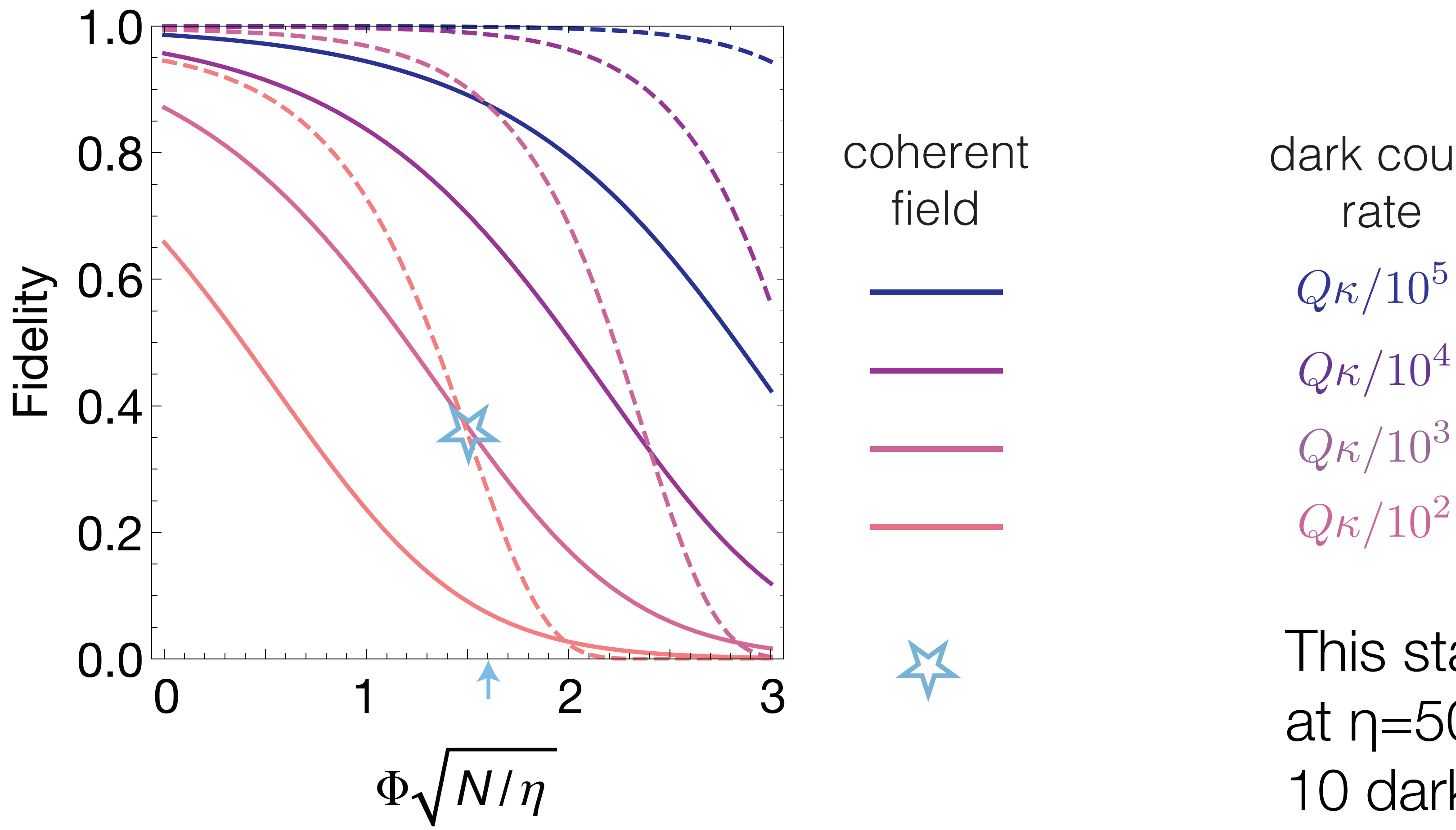
Cooperativity *η* sets practical limit to phase $\Phi \equiv \Omega T$



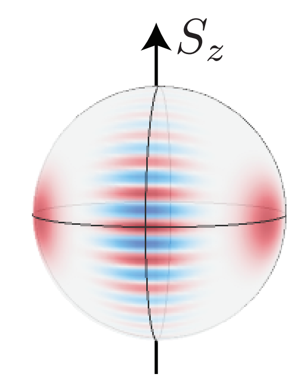
Cat Size vs. Cooperativity

"Size" of the cat quantified by $\Phi\sqrt{N}$





This state at η=50, Qκ = 10⁴/s, 10 dark counts /s



N=30, Φ=2π/3

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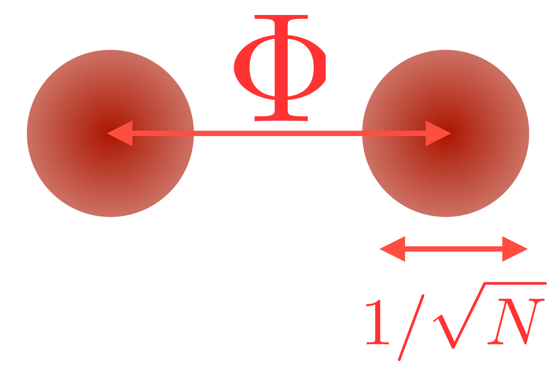
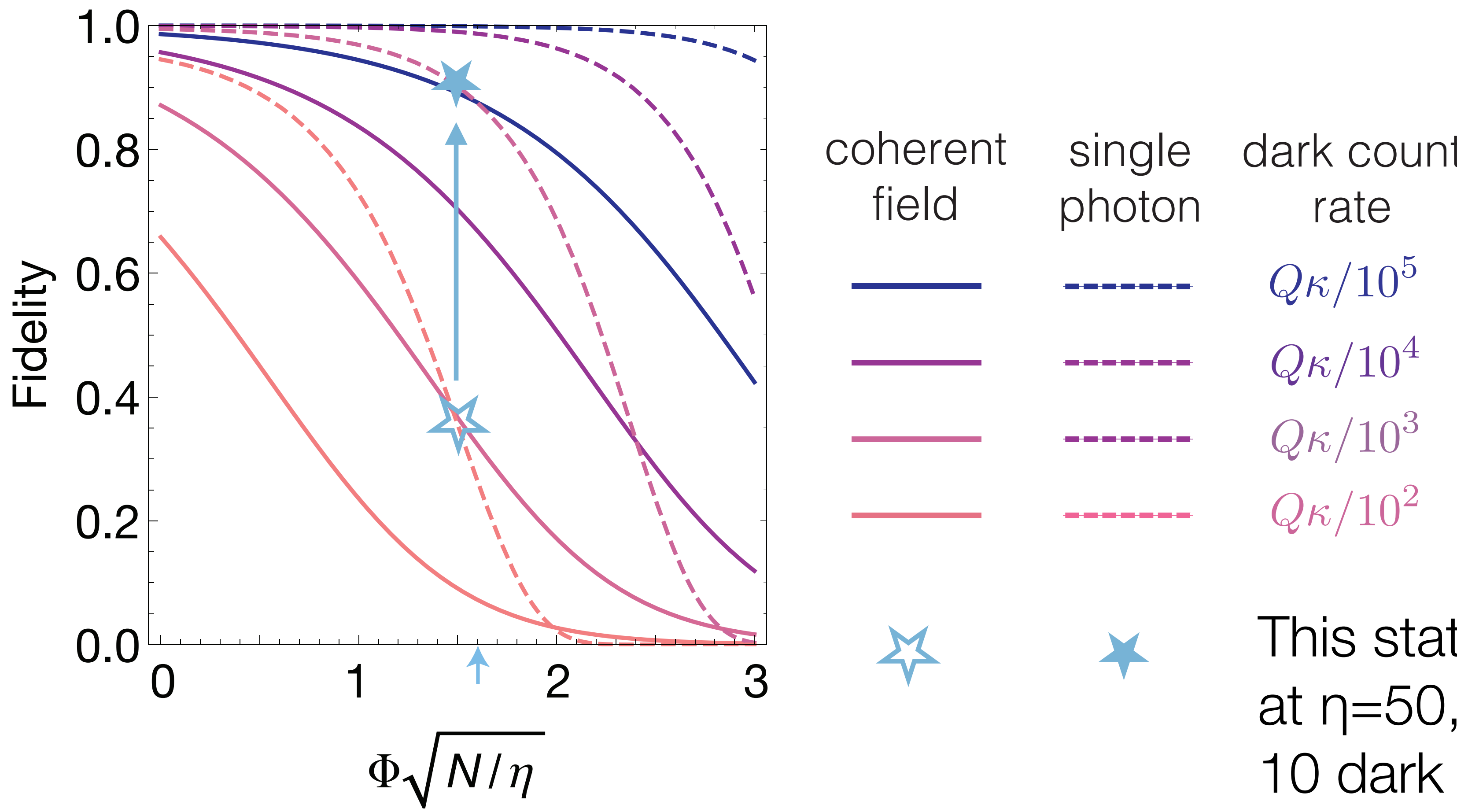
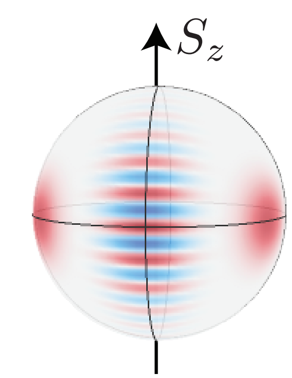




This state at η=50, Qκ = 10^4/s, 10 dark counts /s



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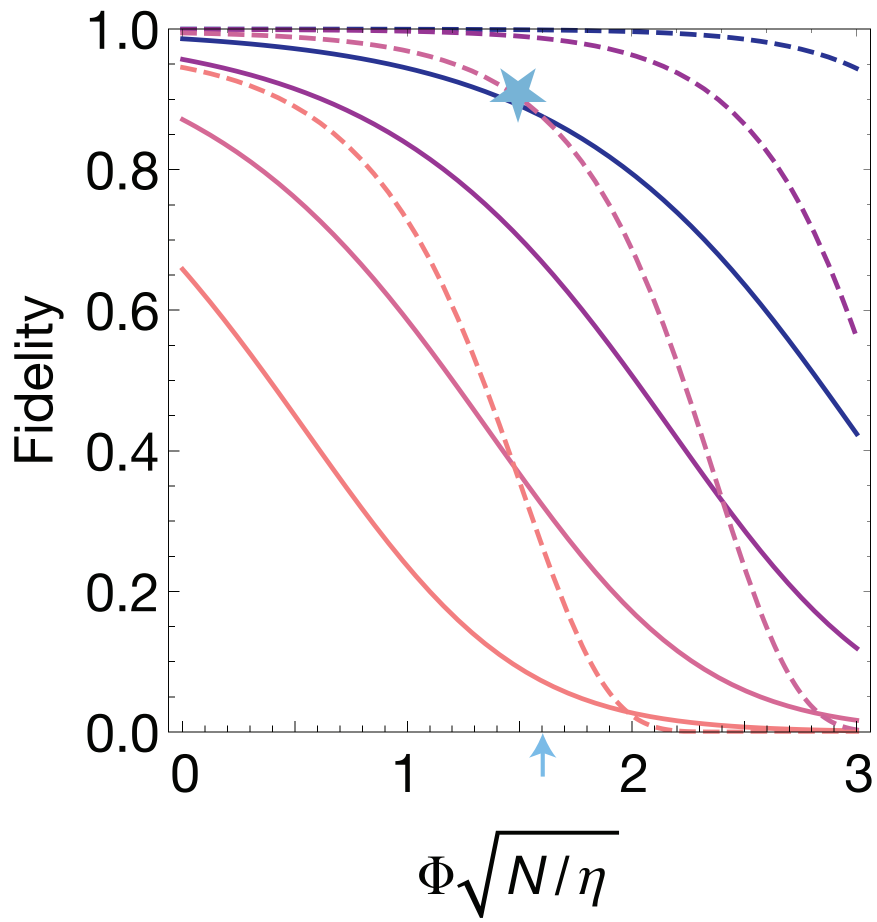

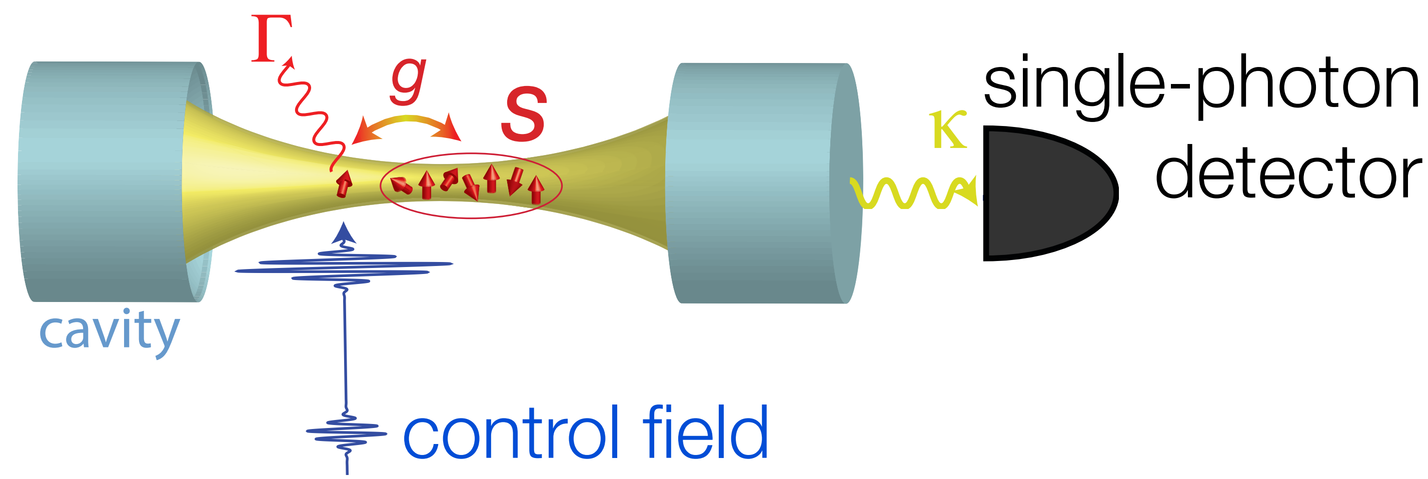

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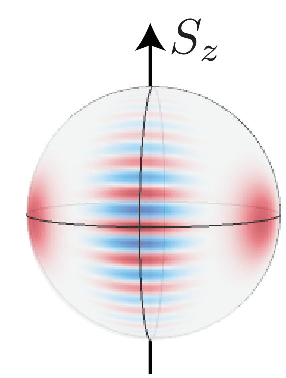

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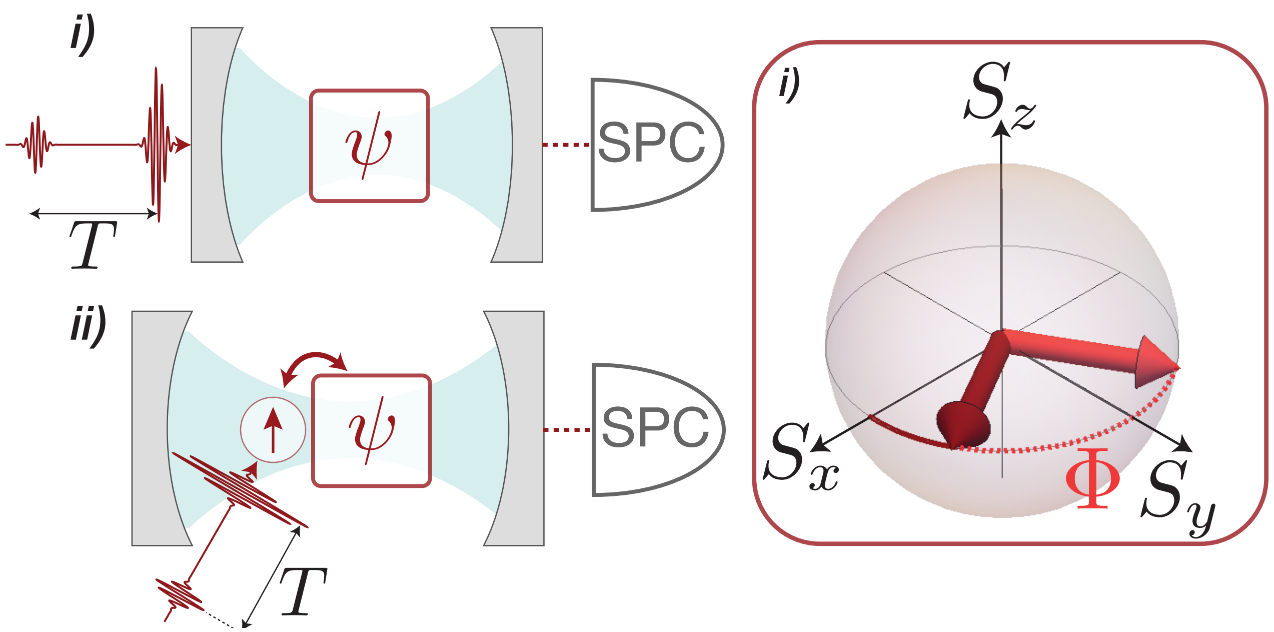
Painting Summary & Outlook



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- Time-shaped photon "paints" the target state, heralded by detection
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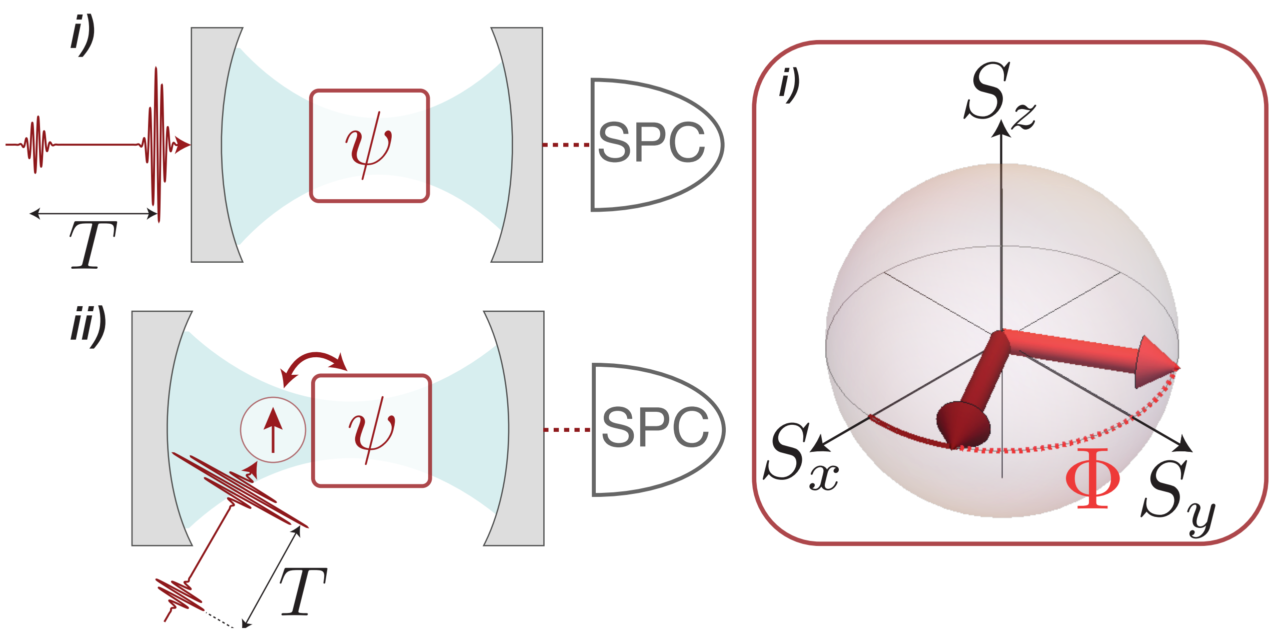

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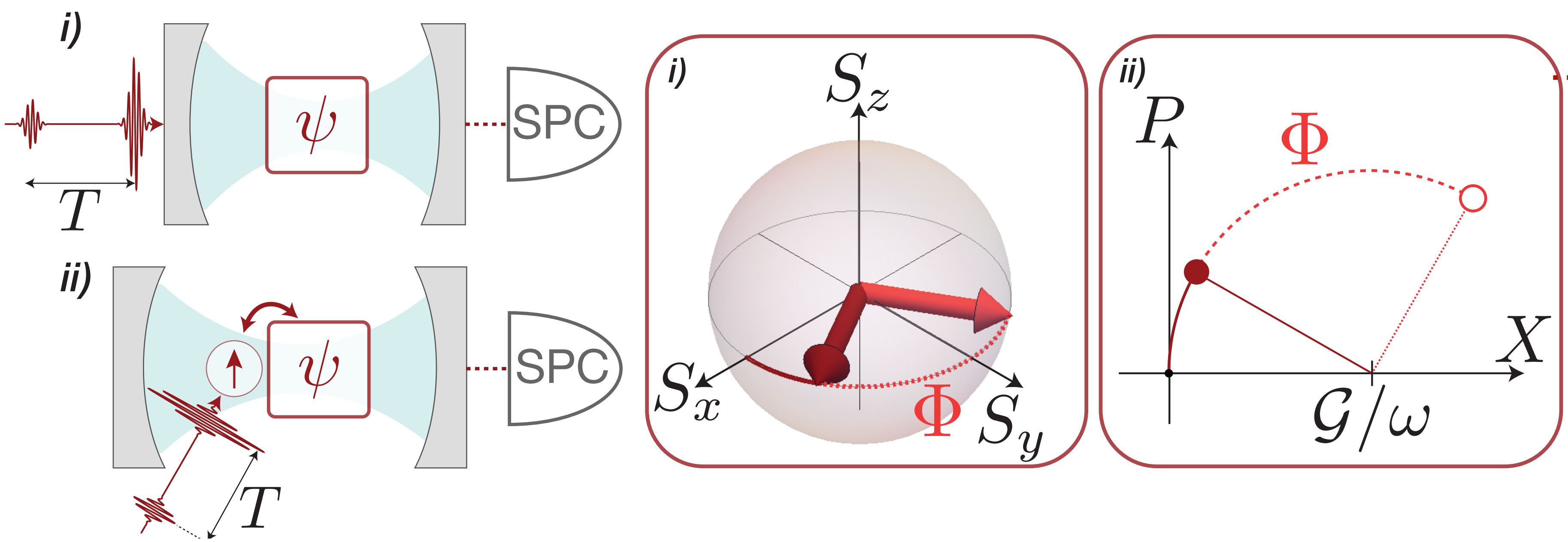

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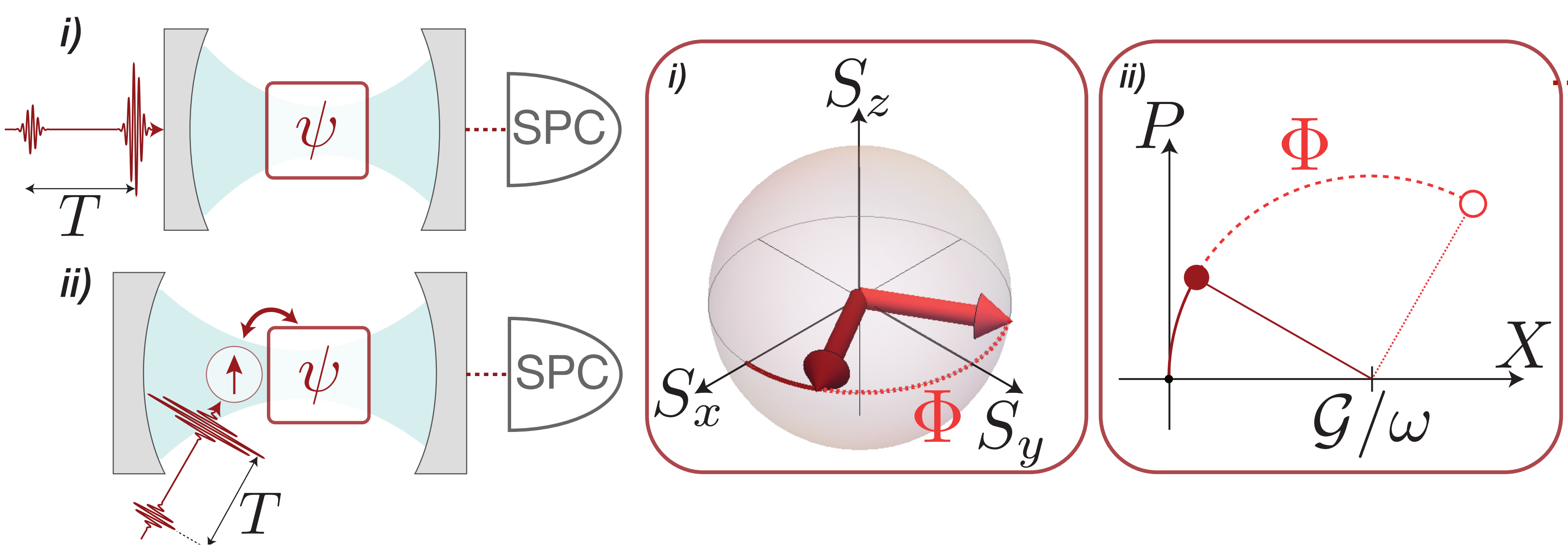

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Outlook: *simulating novel interactions conditioned on photodetection?*