# Quantum Engineering and Quantum Simulation with Light-Mediated Interactions

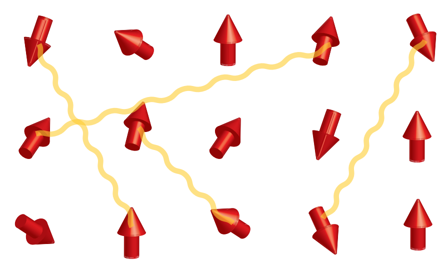
Monika Schleier-Smith
Emily Davis Greg Bentsen

October 9, 2015

Stanford University

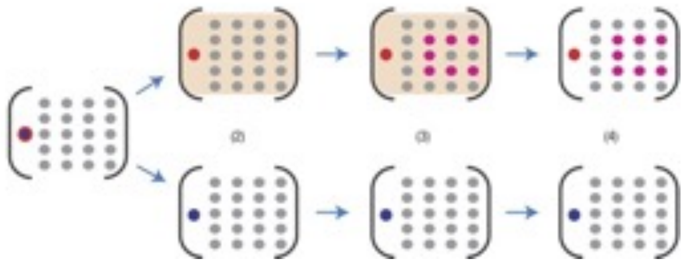
# Motivation

Most interactions in nature are local.



Non-local interactions offer new opportunities:

- Many-particle entanglement for quantum metrology
- Topological encoding of quantum information



L. Jiang *et al.*, *Nature Physics* (2008).

- Quantum simulations:
  - Spin glass models ↔ NP hard optimization problems
    [Gopalakrishnan, Lev, Sachdev, Diehl, …]
  - Quantum gravity? High-energy physics?

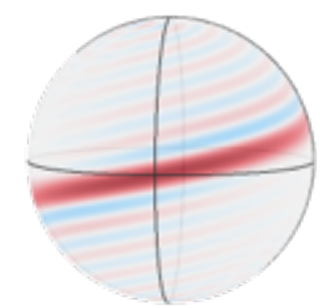
# Outline

Engineering light-mediated spin-spin interactions

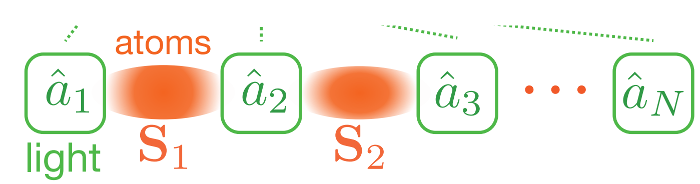
- **Objective:** coherent non-local interactions

- **Past experiments:** dissipative spin squeezing

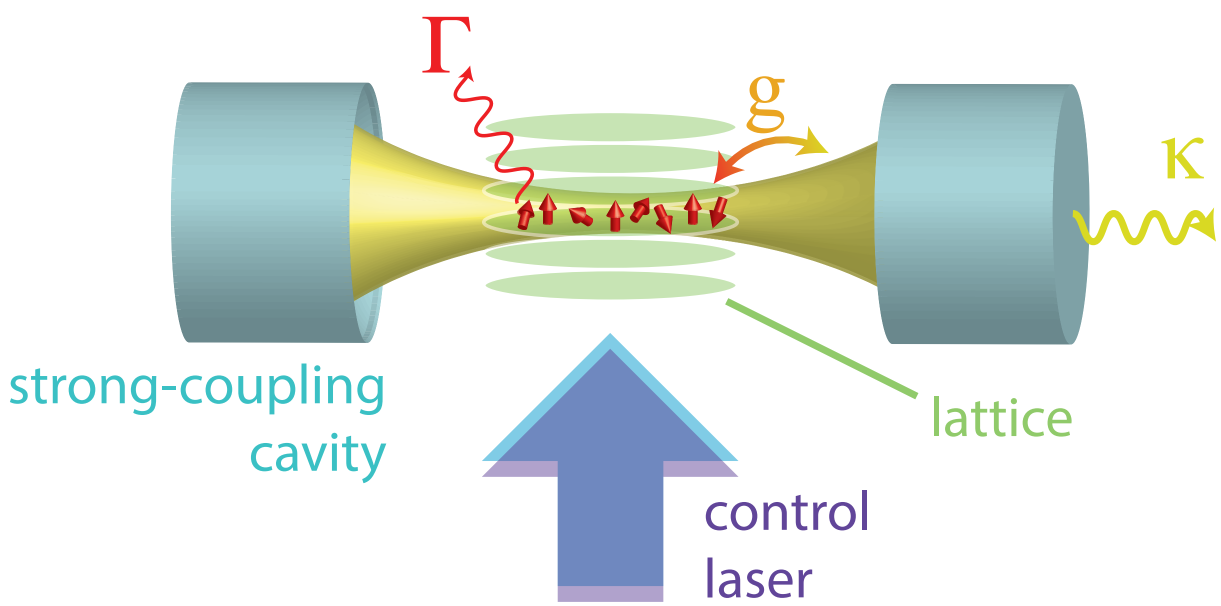
## Prospects

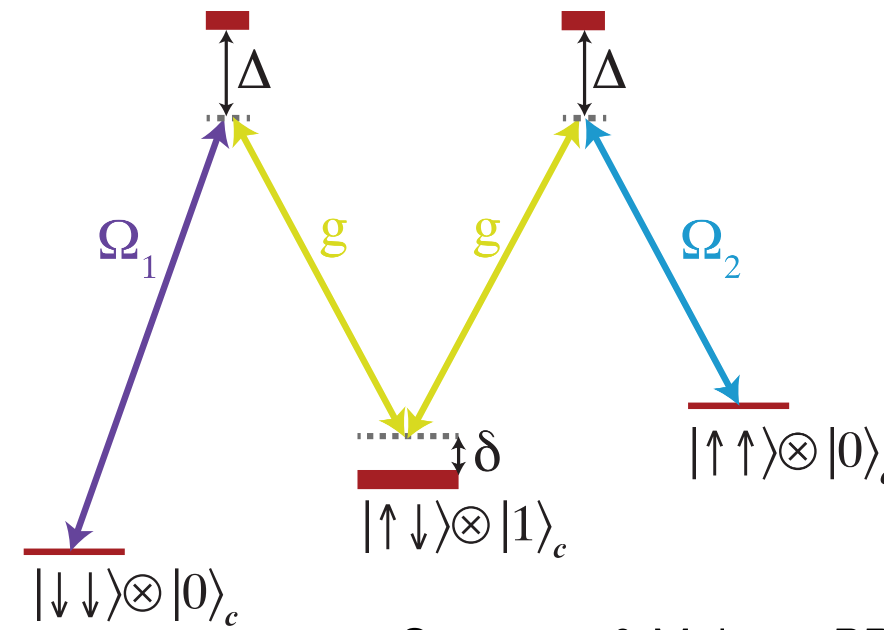


- Quantum metrology
- Quantum scrambling: chaos & black holes
- Photonic lattices & dynamical gauge fields



# Photon-Mediated Spin Interactions

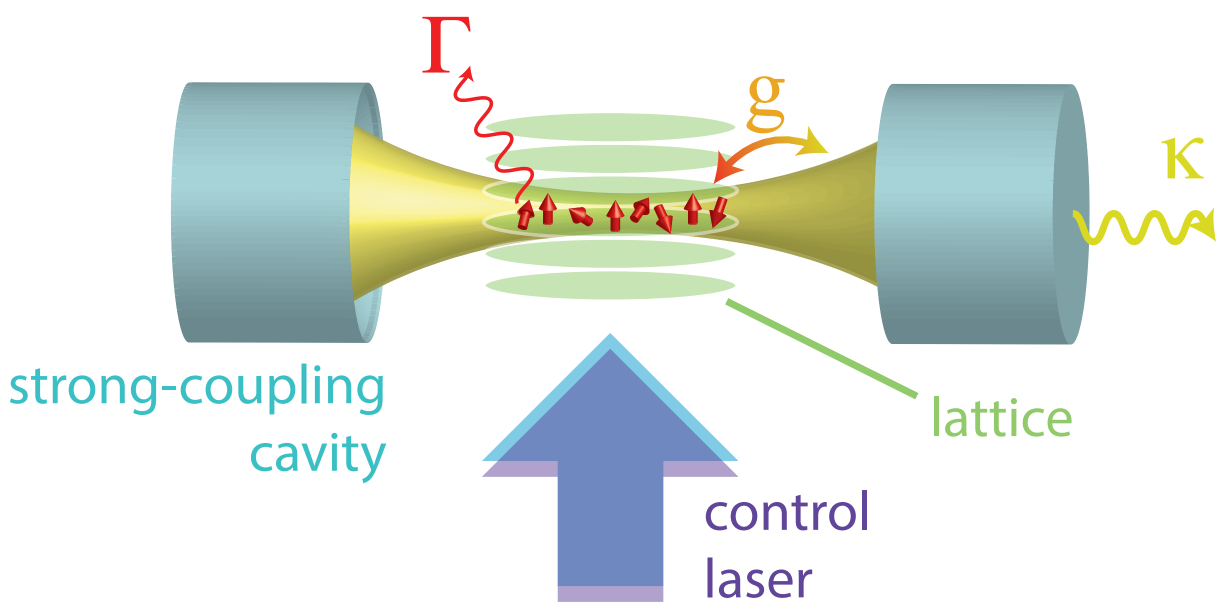


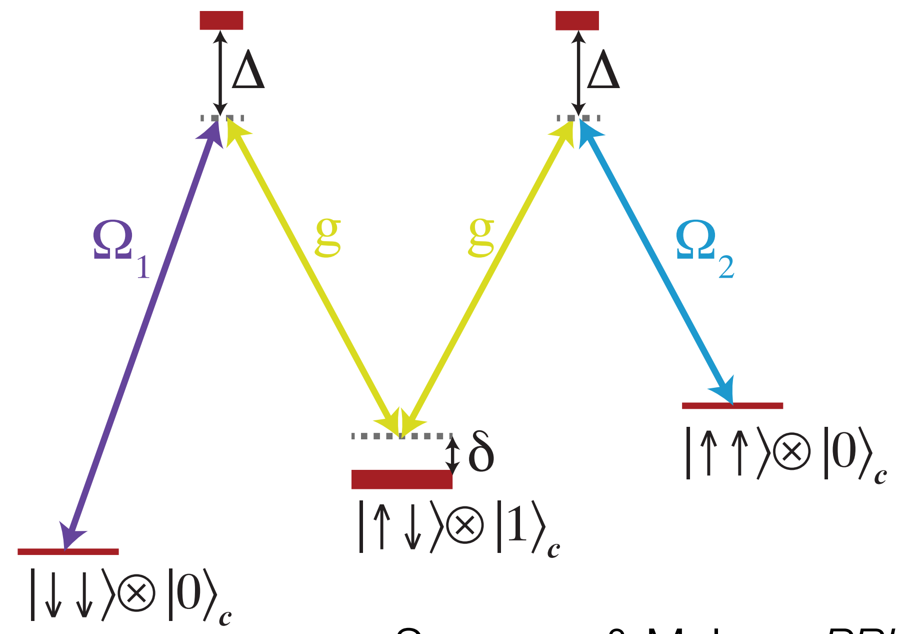




Sørensen & Mølmer, *PRL* (2002).

Pairwise correlated spin flips: $$H \propto \sum_{i,j} (s_+^i + s_-^i)(s_+^j + s_-^j) \propto \sum_{i,j} s_x^i s_x^j$$

# Photon-Mediated Spin Interactions



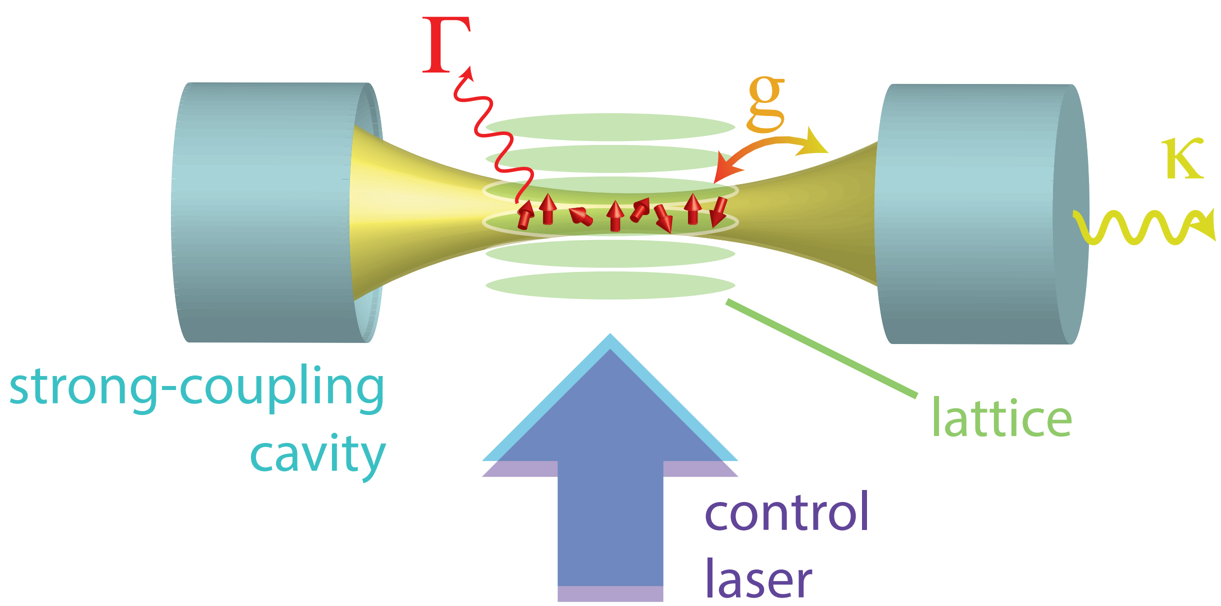



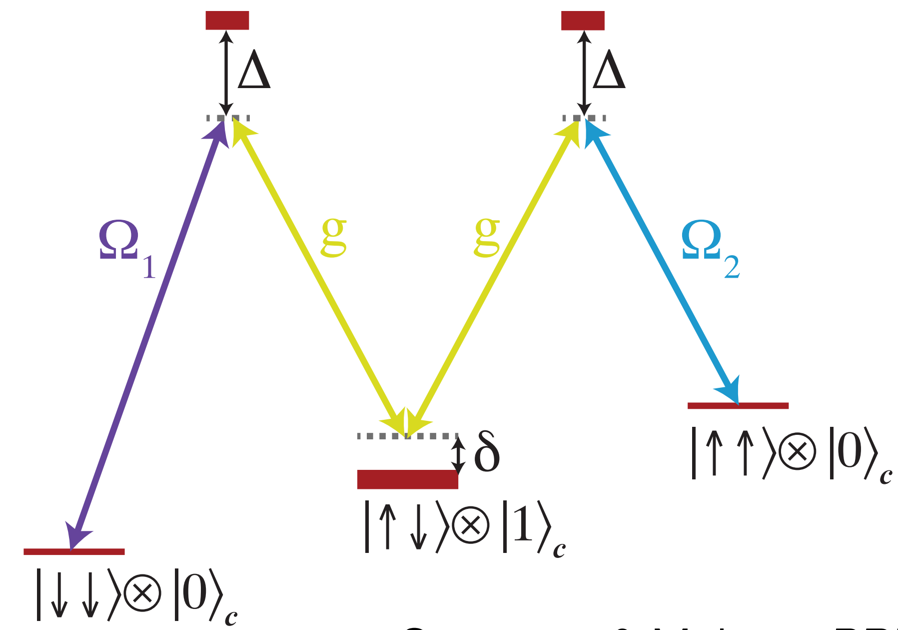

Sørensen & Mølmer, *PRL* (2002).

Pairwise correlated spin flips: $H \propto \sum_{i,j} (s_+^i + s_-^i)(s_+^j + s_-^j) \propto \sum_{i,j} s_x^i s_x^j$

- Spatial addressing enables controlled interactions between arbitrary pairs

# Photon-Mediated Spin Interactions



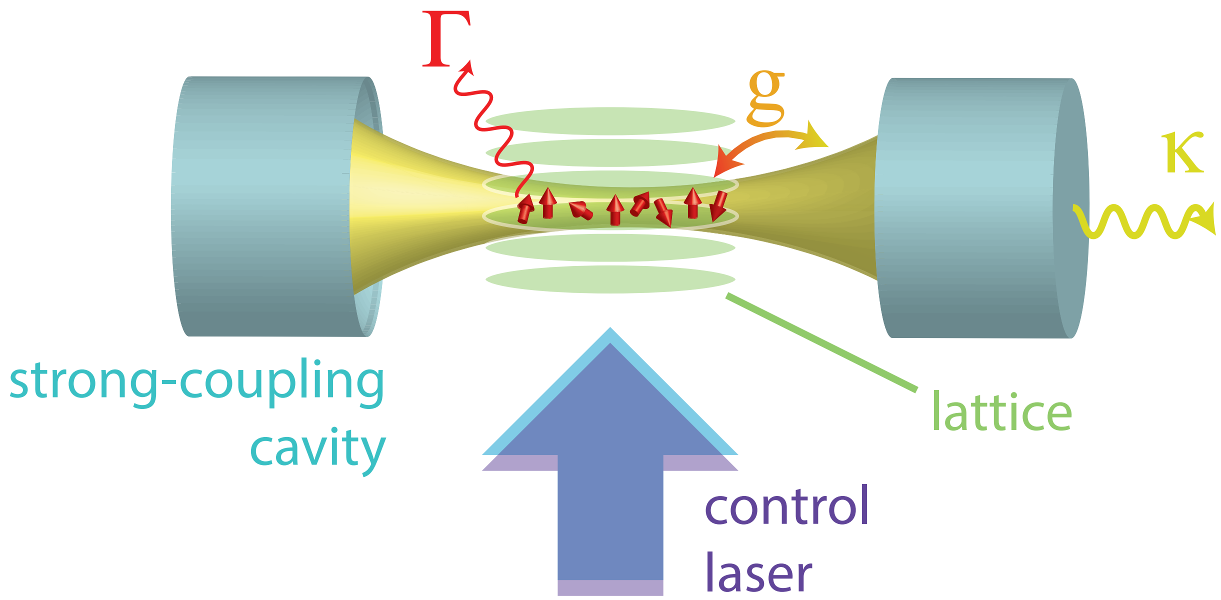




Sørensen & Mølmer, *PRL* (2002).

Pairwise correlated spin flips: $H \propto \sum_{i,j} (s_+^i + s_-^i)(s_+^j + s_-^j) \propto \sum_{i,j} s_x^i s_x^j$

- Spatial addressing enables controlled interactions between arbitrary pairs
- Coherent interactions for $\delta \gg \kappa$ and strong coupling $\eta \equiv 4g^2/(\kappa\Gamma) \gg 1$

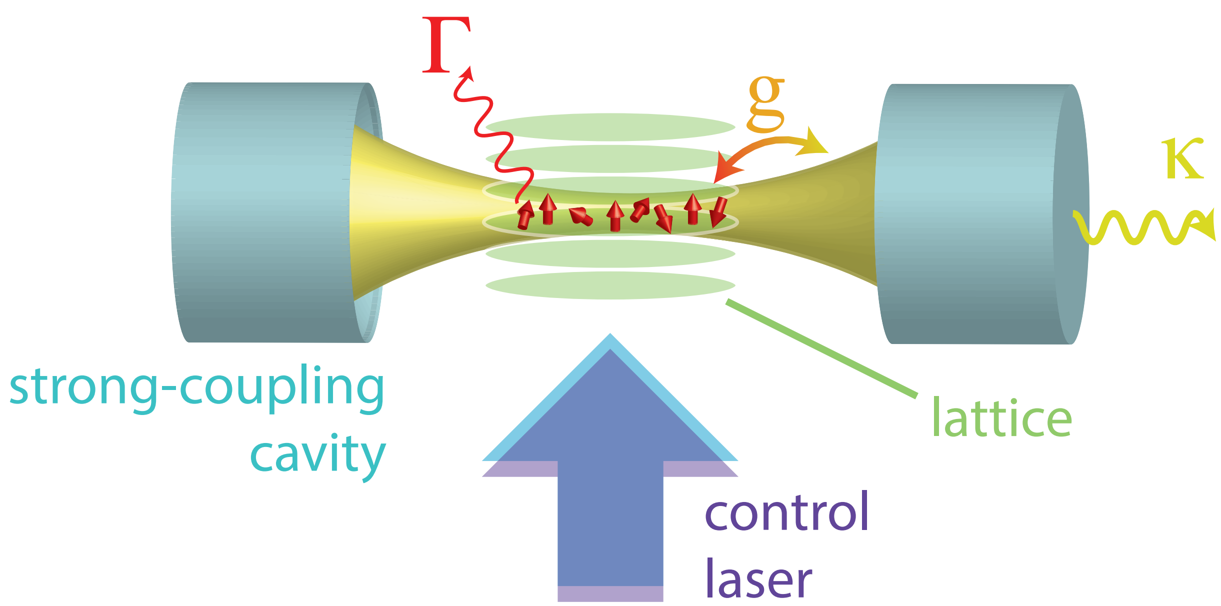
# Experiment Design




~ $10^1$ - $10^3$ atoms

- Strong coupling: $\eta \equiv \frac{4g^2}{\kappa\Gamma} \sim \frac{F\lambda^2}{w^2} \gg 1$
- Optical access for addressing from side
- Confinement in transverse lattice

# 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 addressing from side
- Confinement in transverse lattice

$\Rightarrow$ Near-concentric resonator

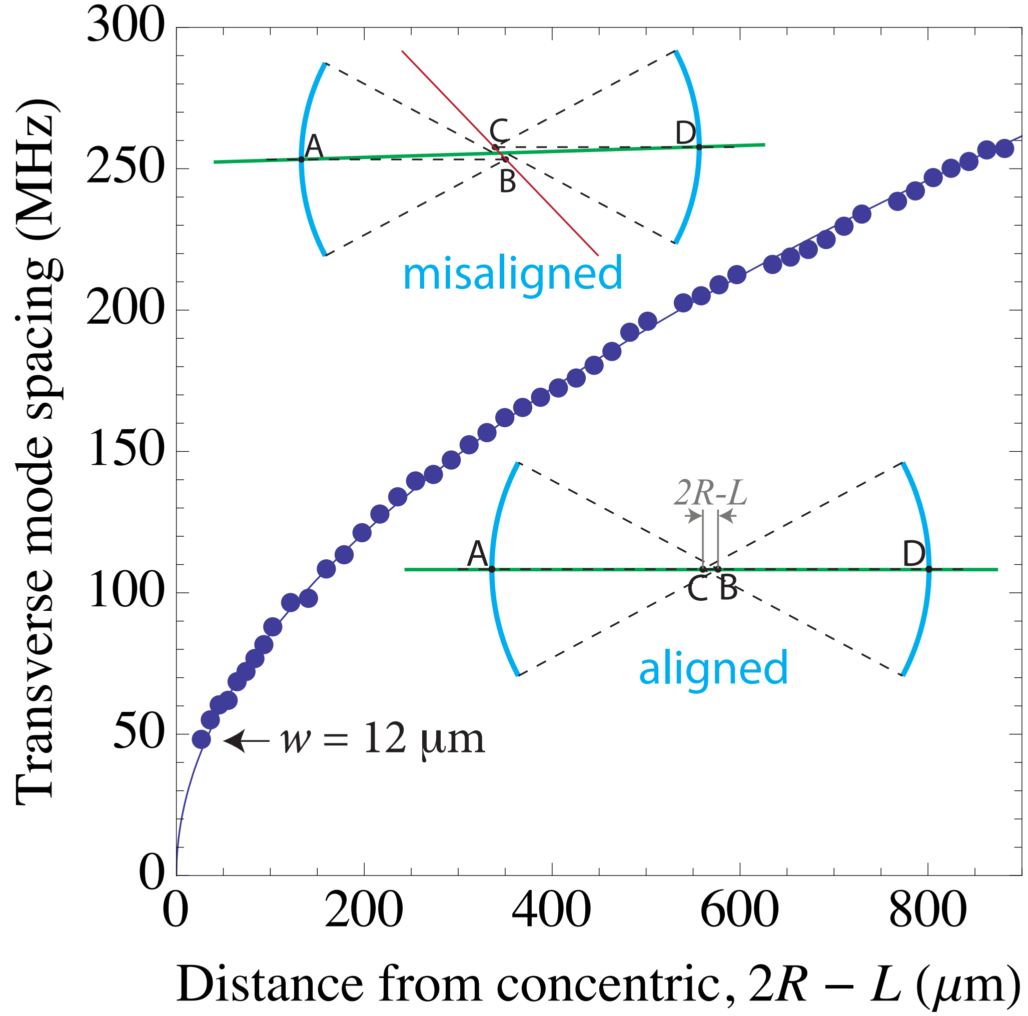
Length $L$ ~ 5 cm

Waist $w$ ~ 12 μm

Non-degenerate modes

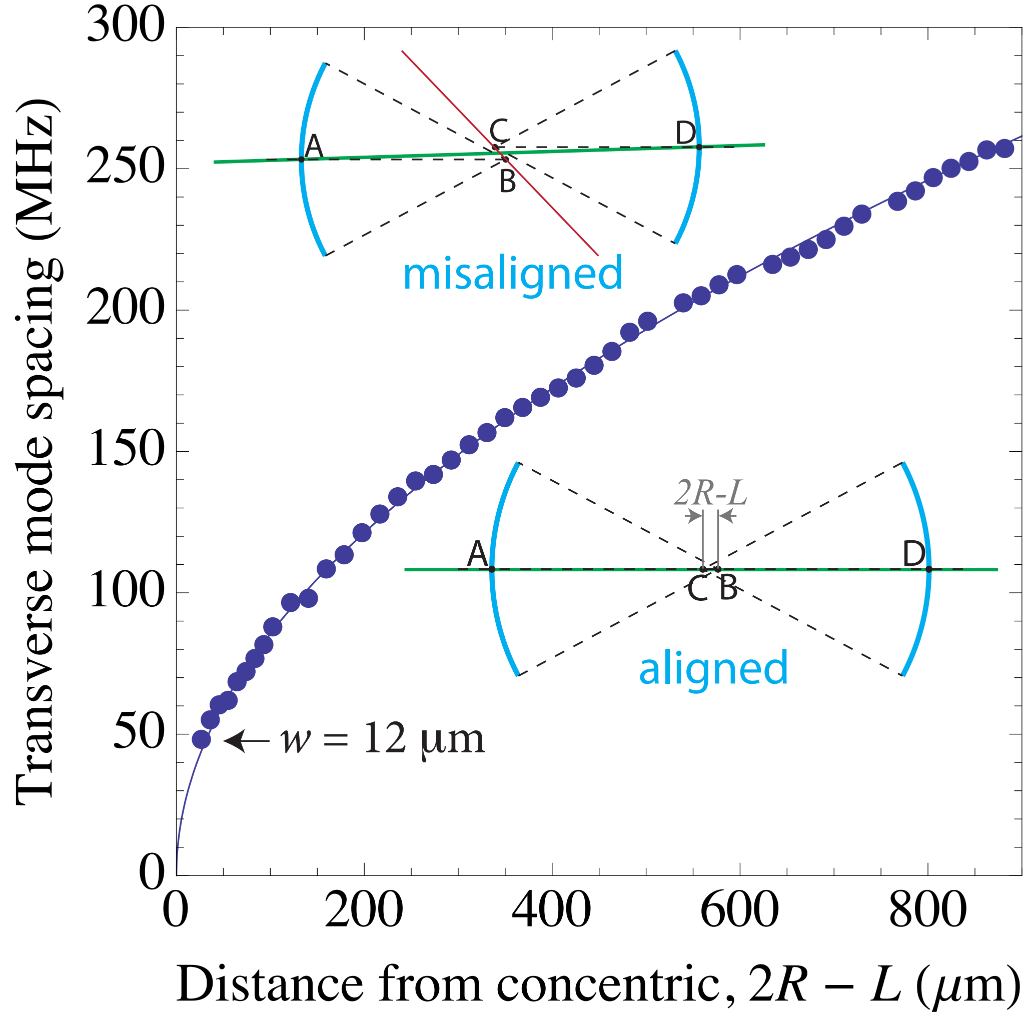
# Near-Concentric Resonator

## Challenging alignment

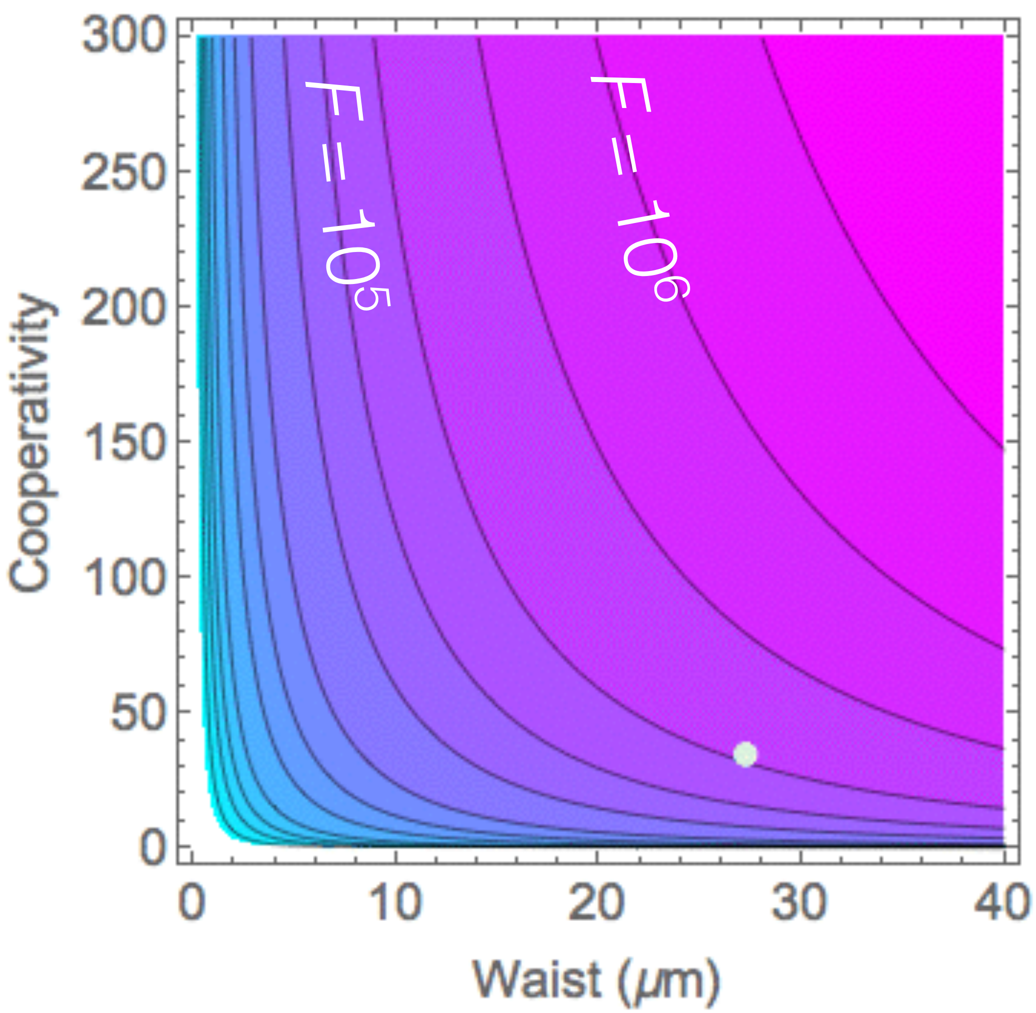


# Near-Concentric Resonator

## Challenging alignment

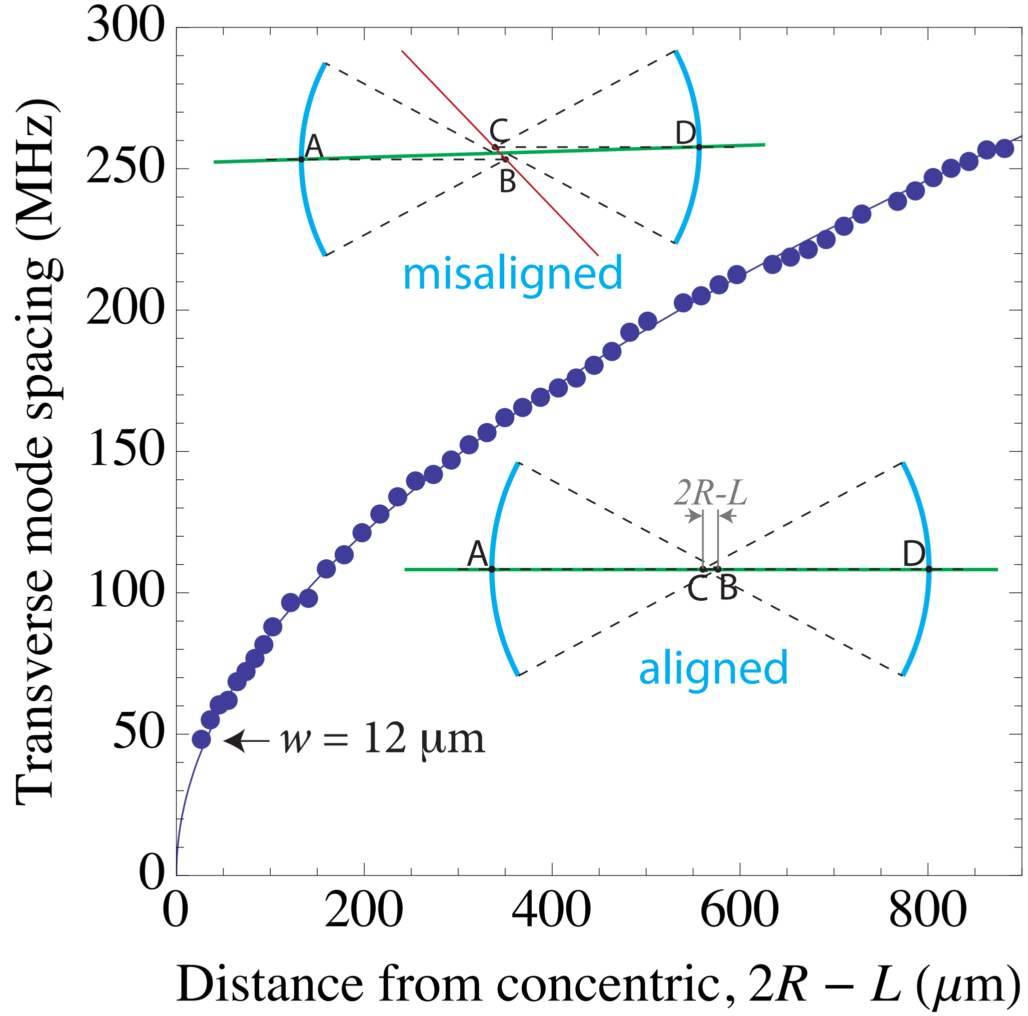



## Maintaining finesse?

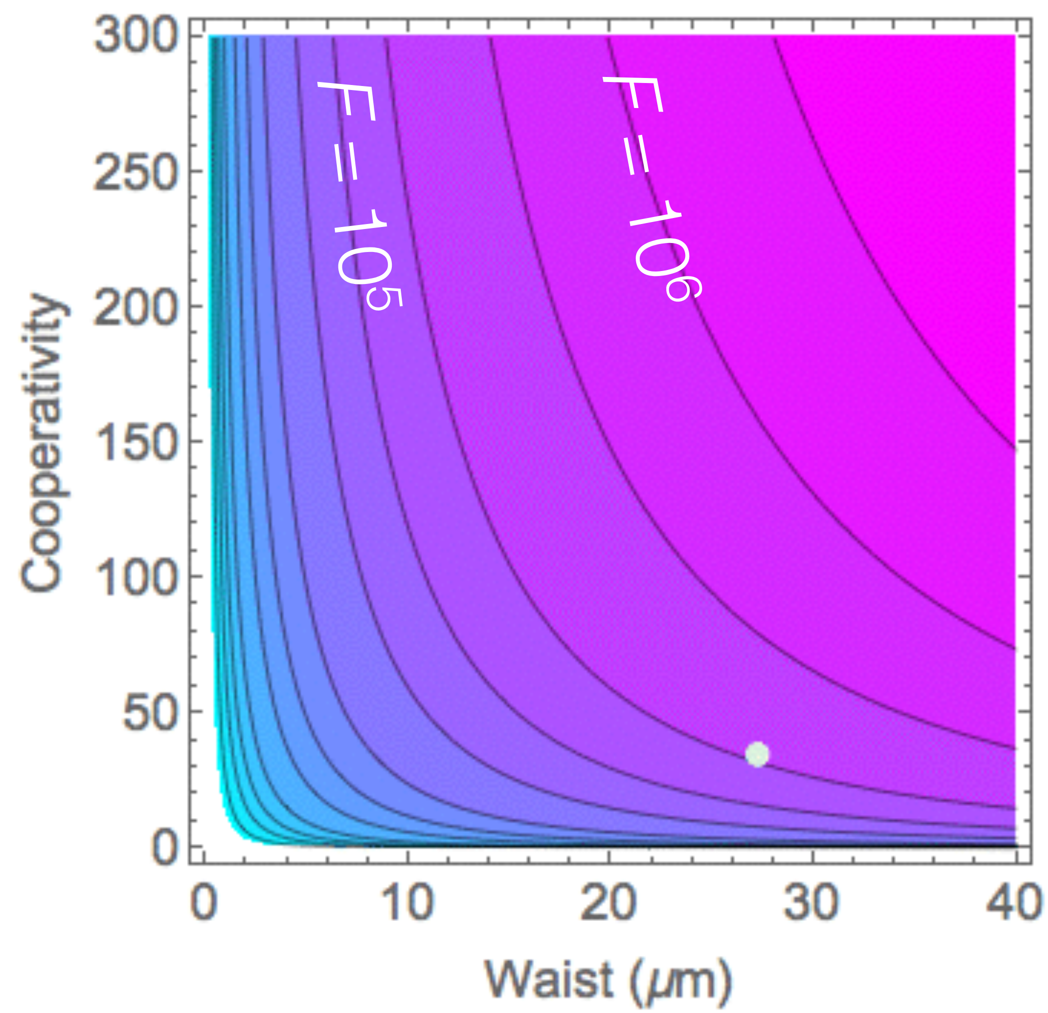


# Near-Concentric Resonator

## Challenging alignment

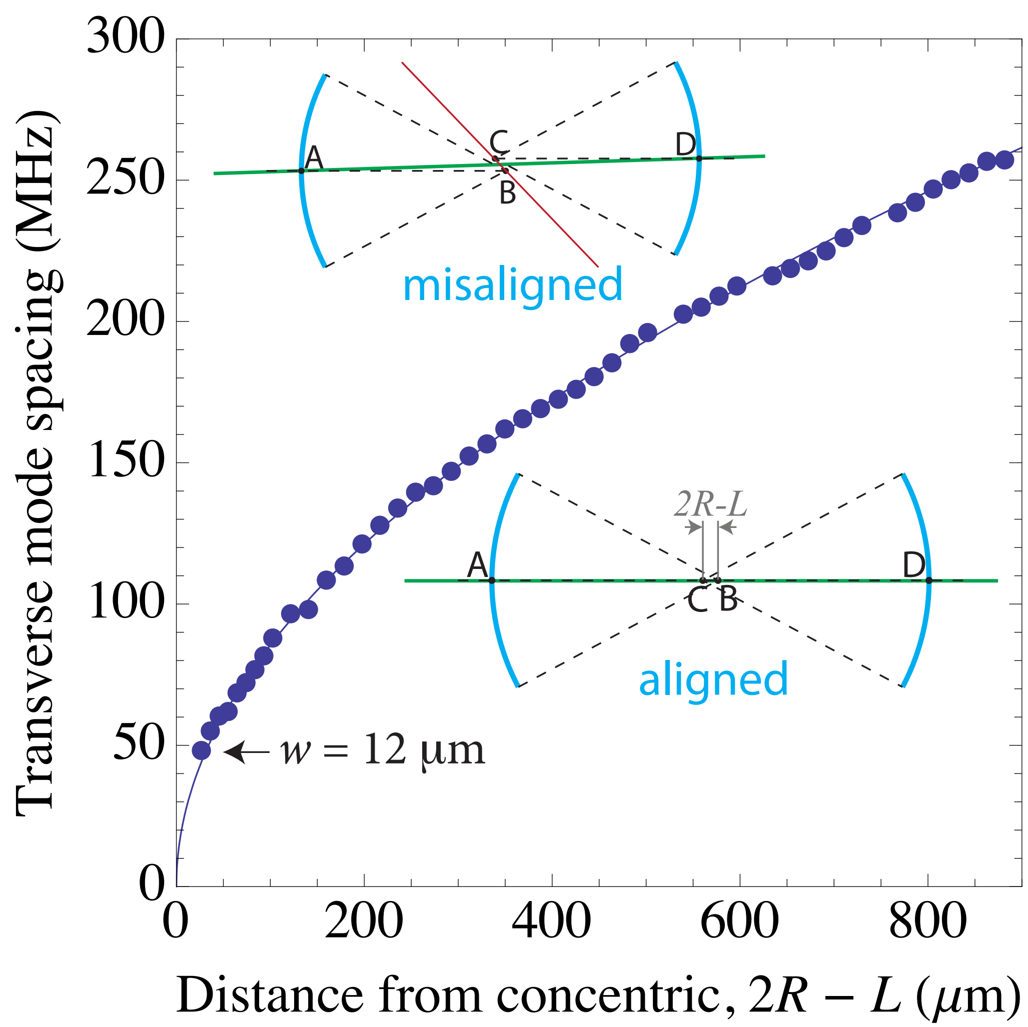



## Maintaining finesse?

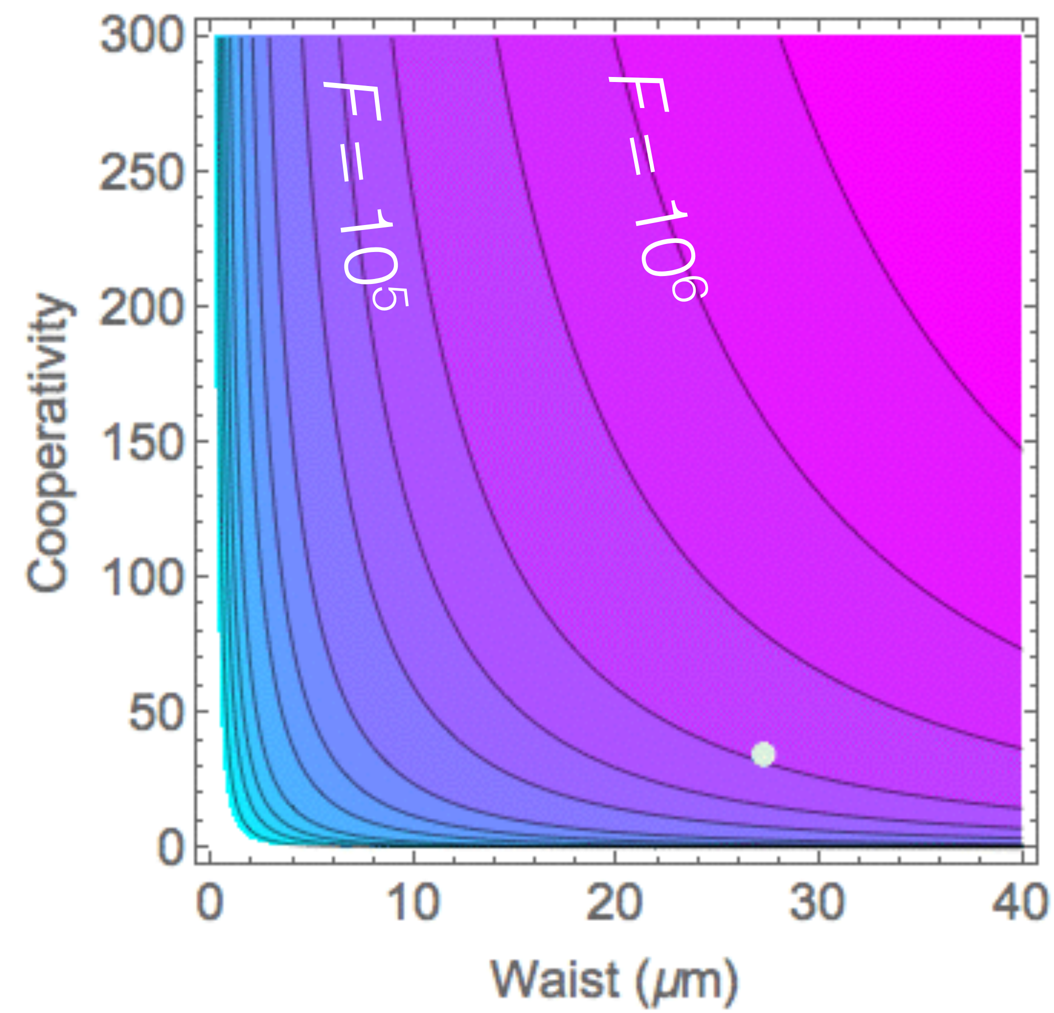


# Near-Concentric Resonator

## Challenging alignment

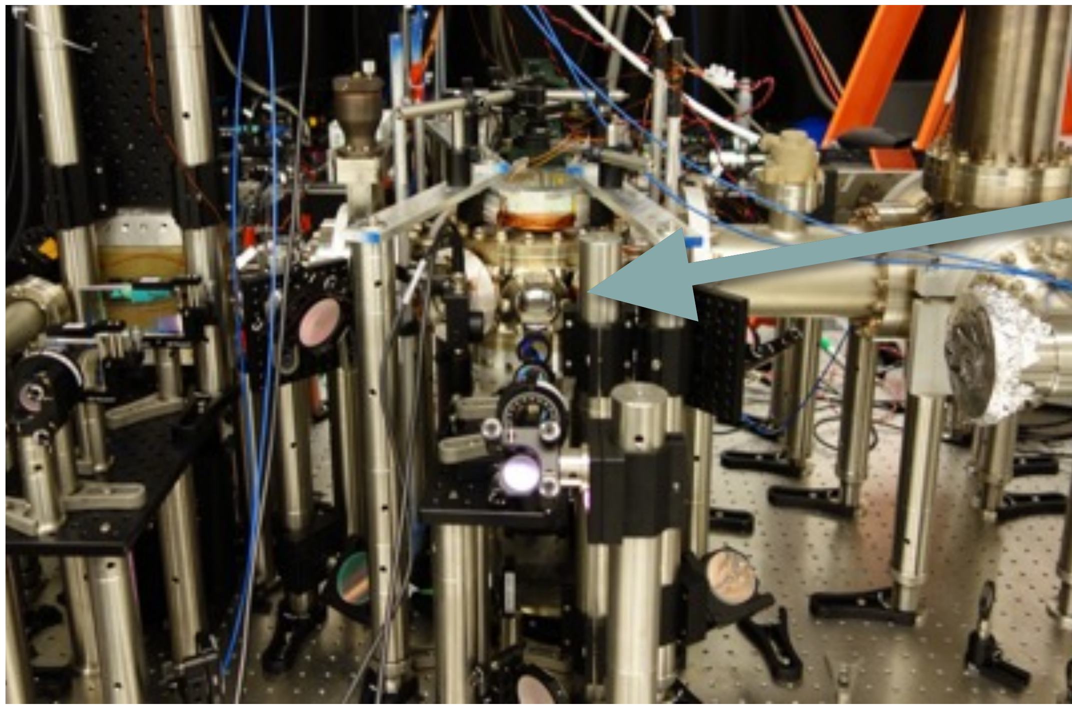


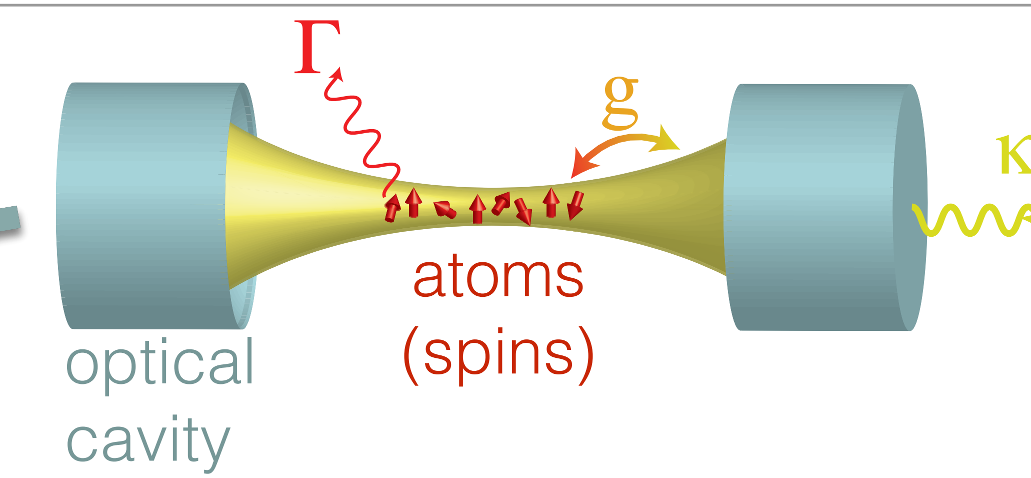

## Maintaining finesse?

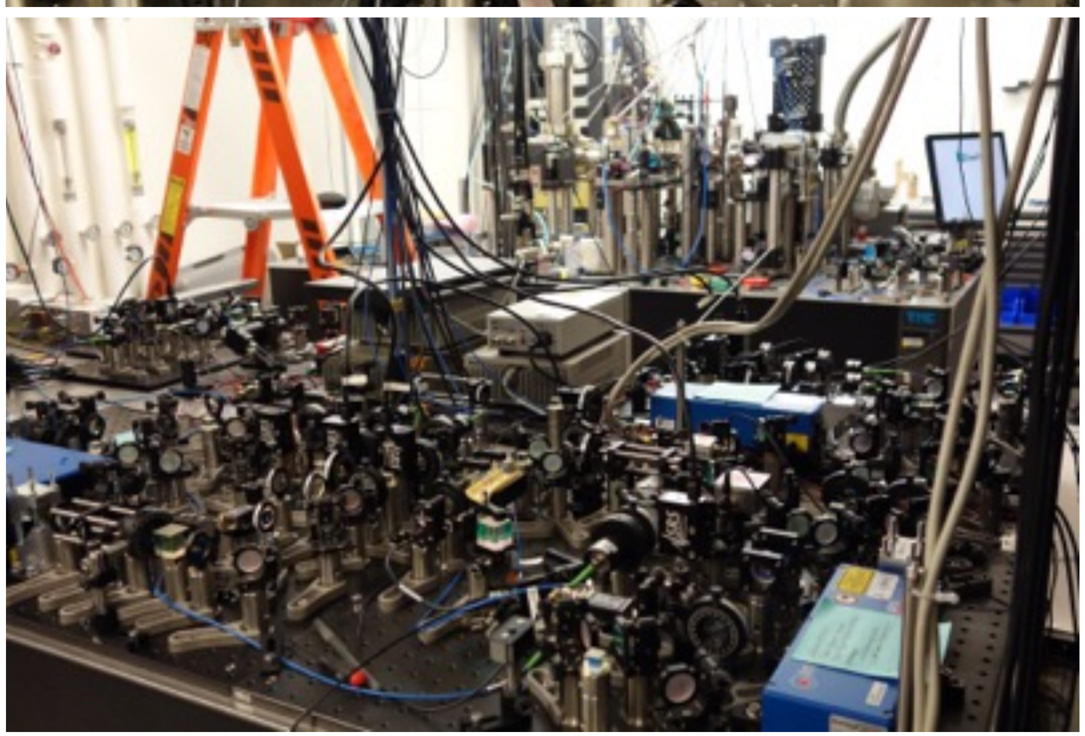


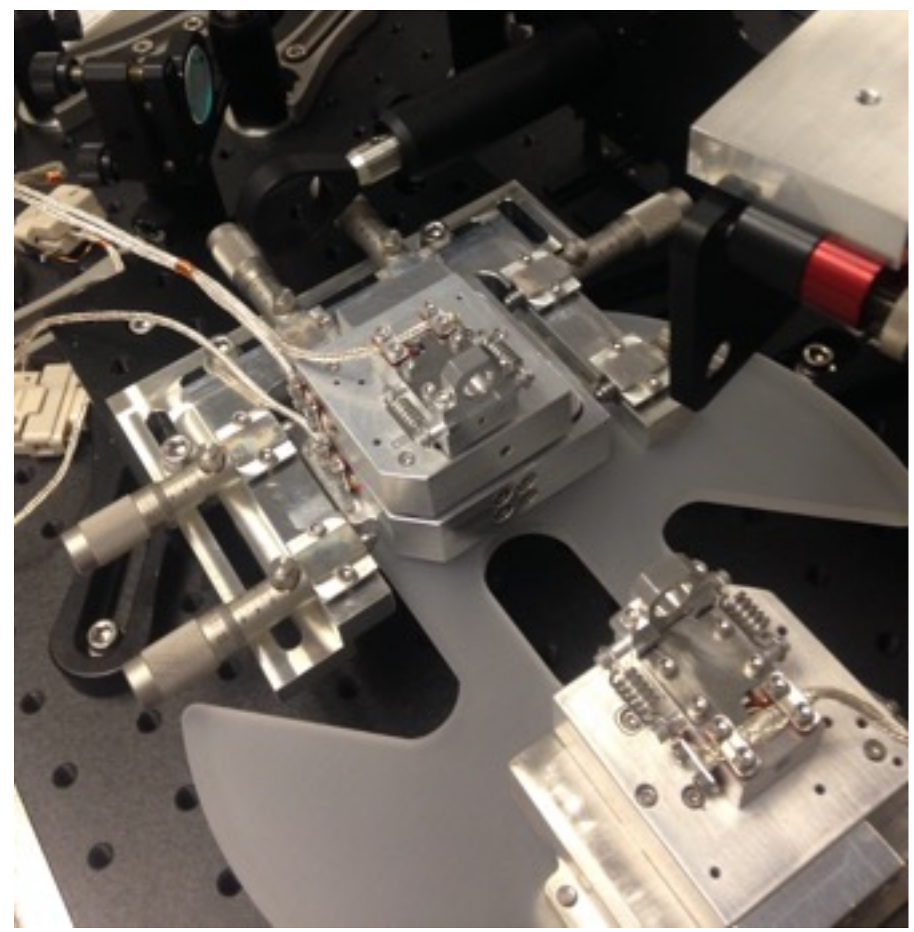

⇒ Single-atom cooperativity $\eta \sim 200$ + excellent optical access

# Progress in the Lab





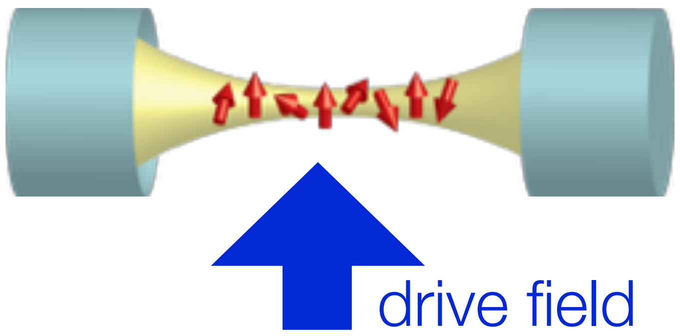


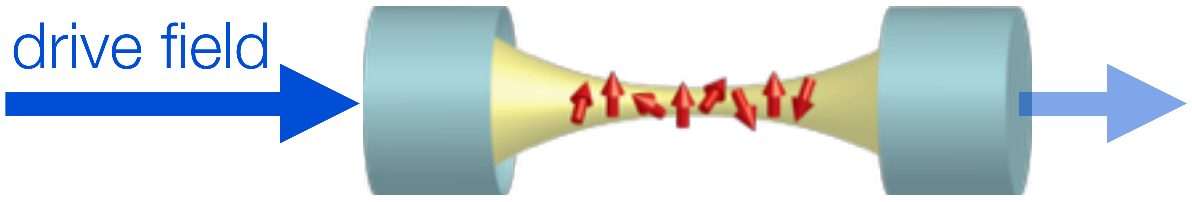
UHV-compatible
alignment stage

# Two Approaches

…to generating spin-spin interactions

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



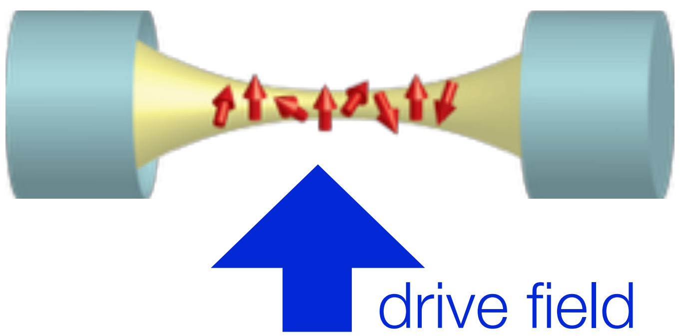

Interaction : $H = \chi S_x^2$

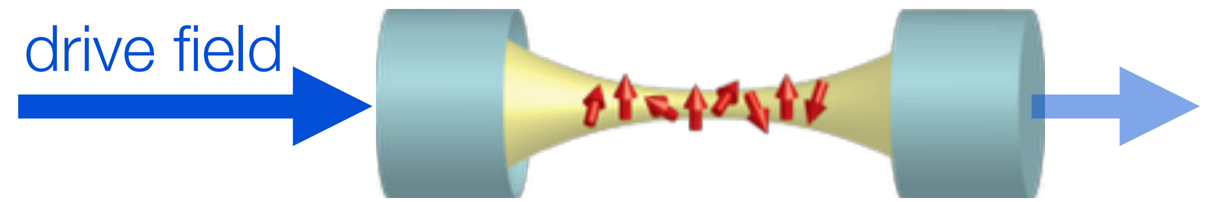
Interaction : $H = \chi S_z^2$

# Two Approaches

…to generating spin-spin interactions

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




$$\text{Interaction}: \; H = \chi S_x^2$$

$$\text{Interaction}: \; H = \chi S_z^2$$

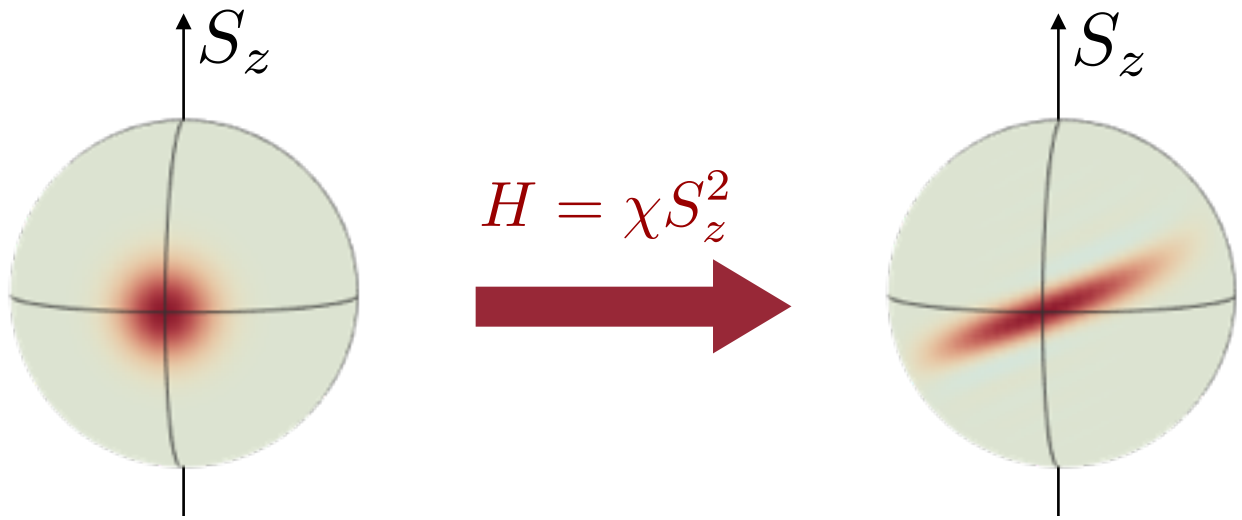
- *Versatile control of interactions*
- *Technically demanding*

- *Global interactions only*
- *Simpler: already demonstrated!*

# Global interactions for quantum metrology

## Generating entanglement by spin-spin interactions

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



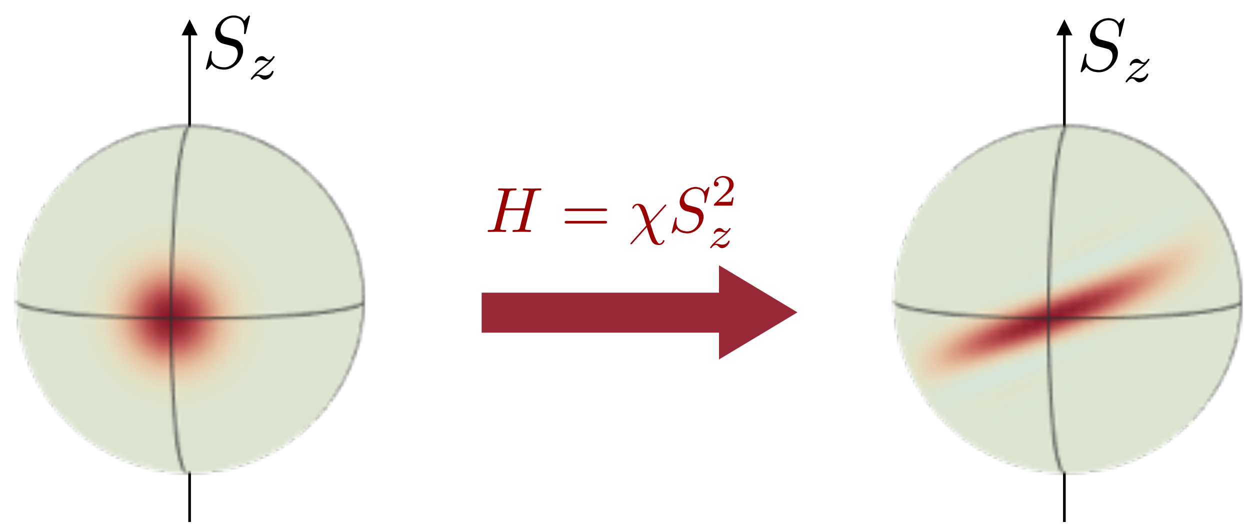

Collective spin

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

# Global interactions for quantum metrology

## Generating entanglement by spin-spin interactions

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

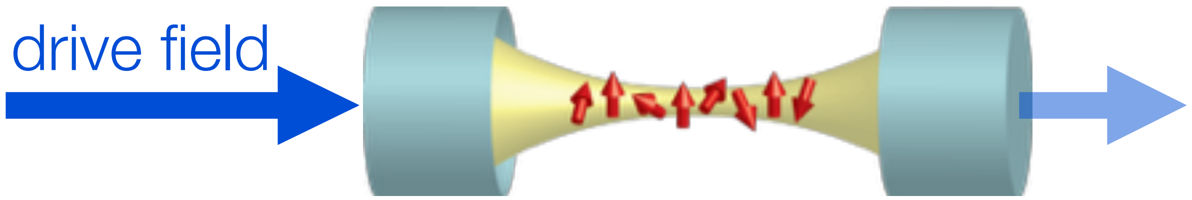


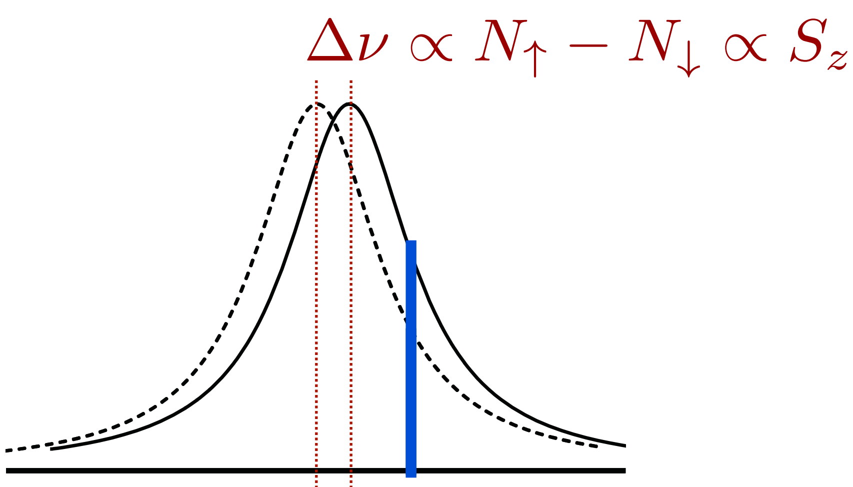

Collective spin

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

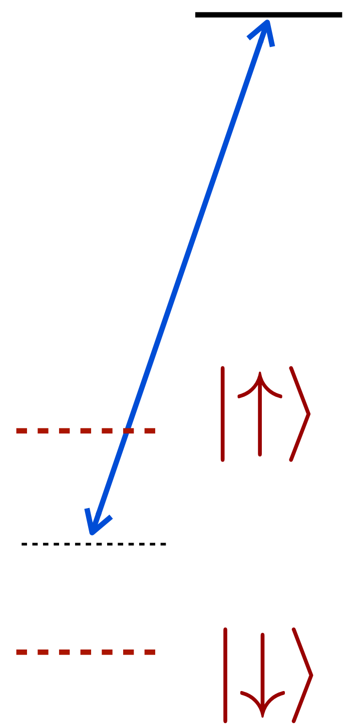
The one-axis twisting Hamiltonian corresponds to the energy propotional to the square of the population difference. The two-axis twisting Hamiltonian corresponds to the simultaneous excitation-deexcitation of two atoms. Although realistic physical schemes are yet to be found, these nonlinear Hamiltonians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

# Cavity Feedback Squeezing



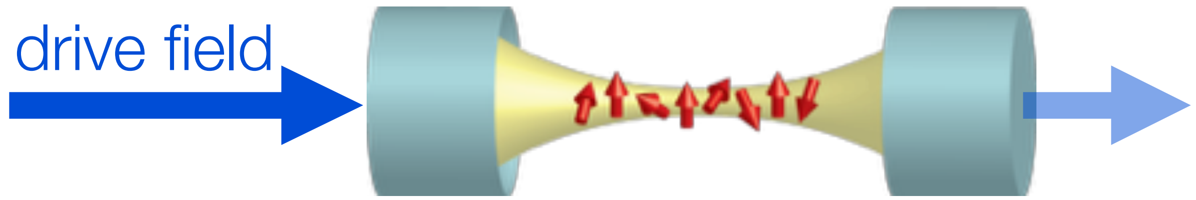

cavity resonance
is shifted by atoms

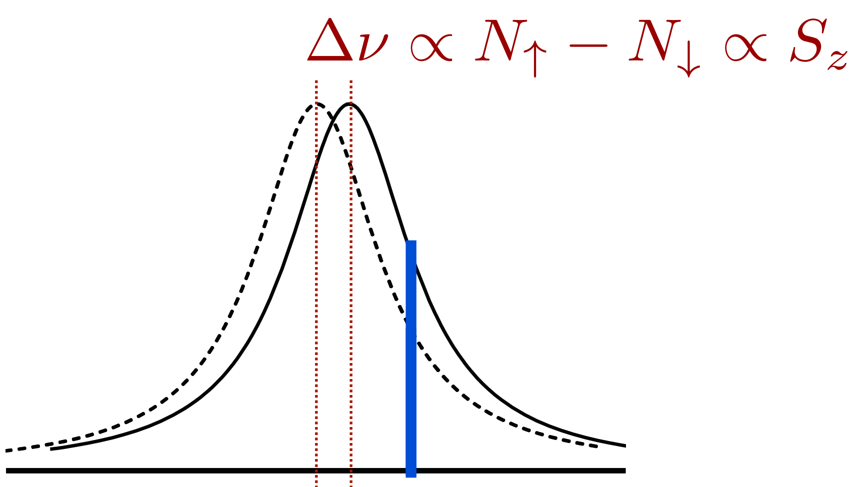



atomic levels

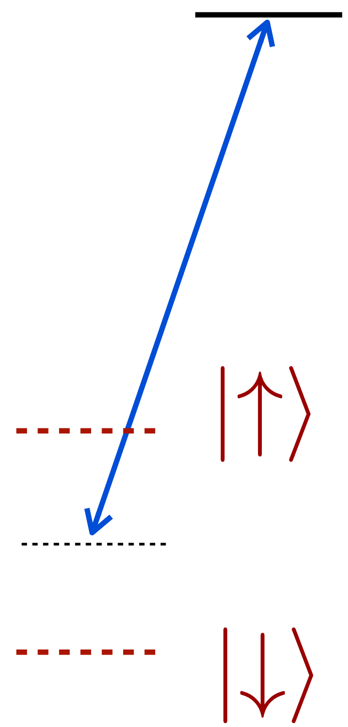
# Cavity Feedback Squeezing

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



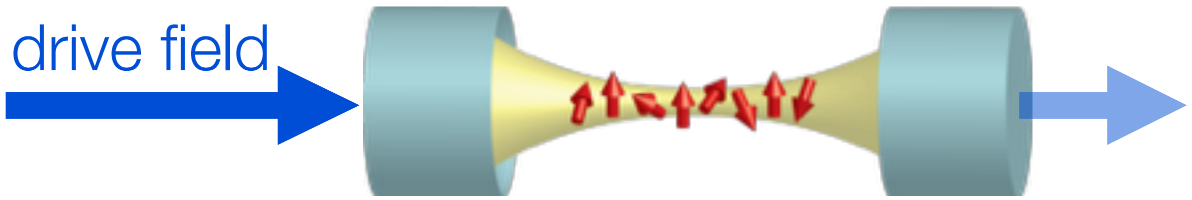

cavity resonance
is shifted by atoms



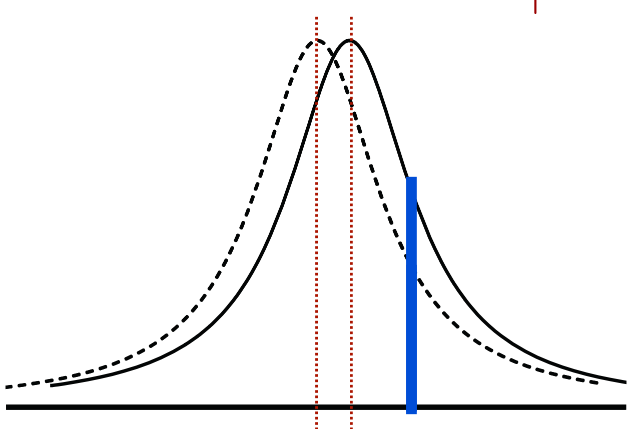

atomic levels

# Cavity Feedback Squeezing

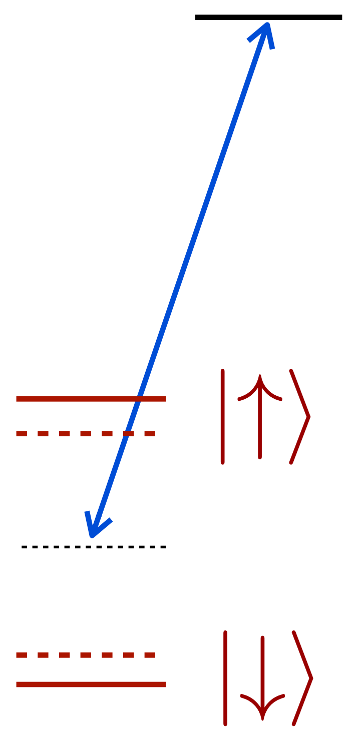
MS-S, ID Leroux & V Vuletic,
*PRA* **81**, 021804*(R)* (2010).




$$\Delta\nu \propto N_\uparrow - N_\downarrow \propto S_z$$



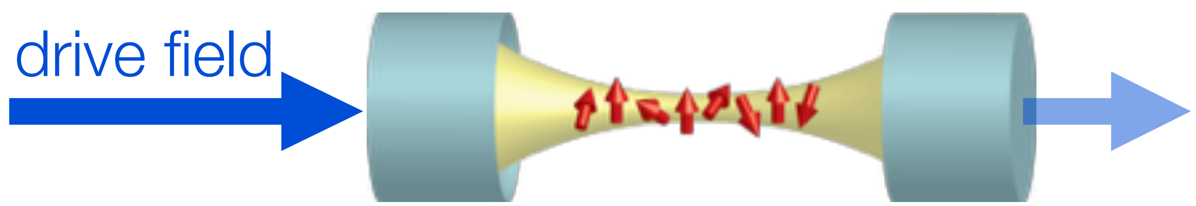
cavity resonance
is shifted by atoms



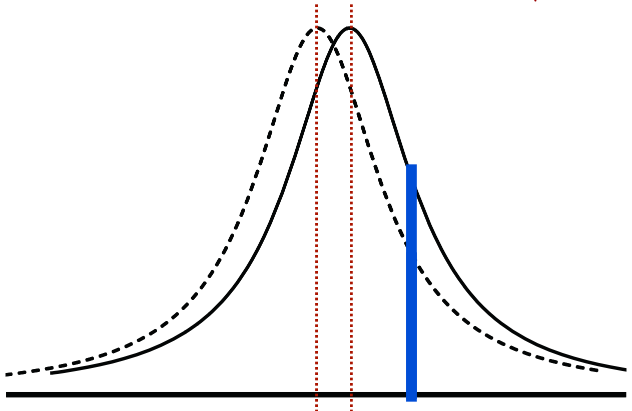

atomic levels
are shifted by light

# Cavity Feedback Squeezing

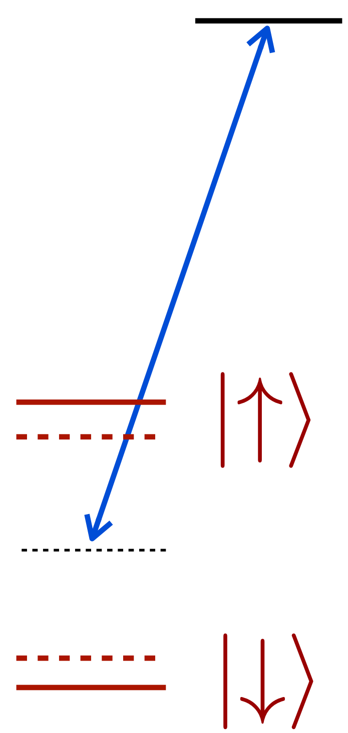
MS-S, ID Leroux & V Vuletic,
*PRA* **81**, 021804*(R)* (2010).




$\Delta\nu \propto N_\uparrow - N_\downarrow \propto S_z$

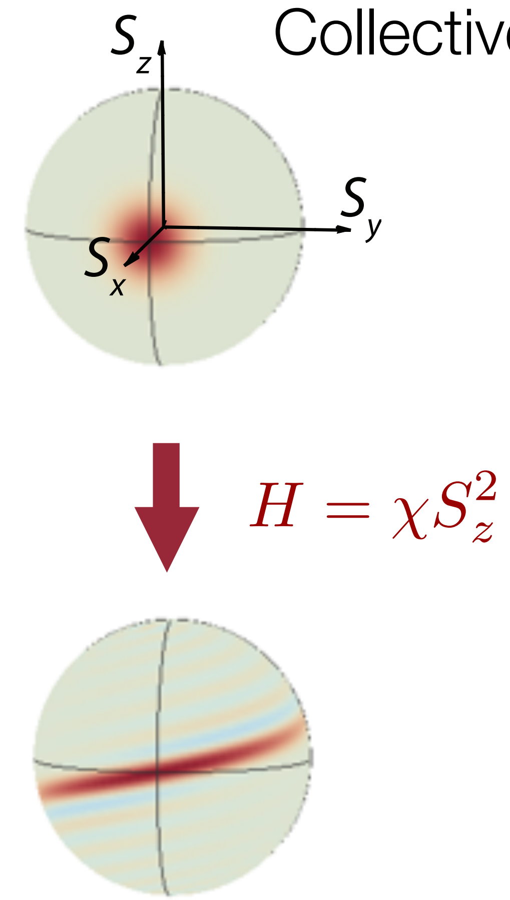


cavity resonance
is shifted by atoms




atomic levels
are shifted by light

Collective spin




effective interaction
mediated by light

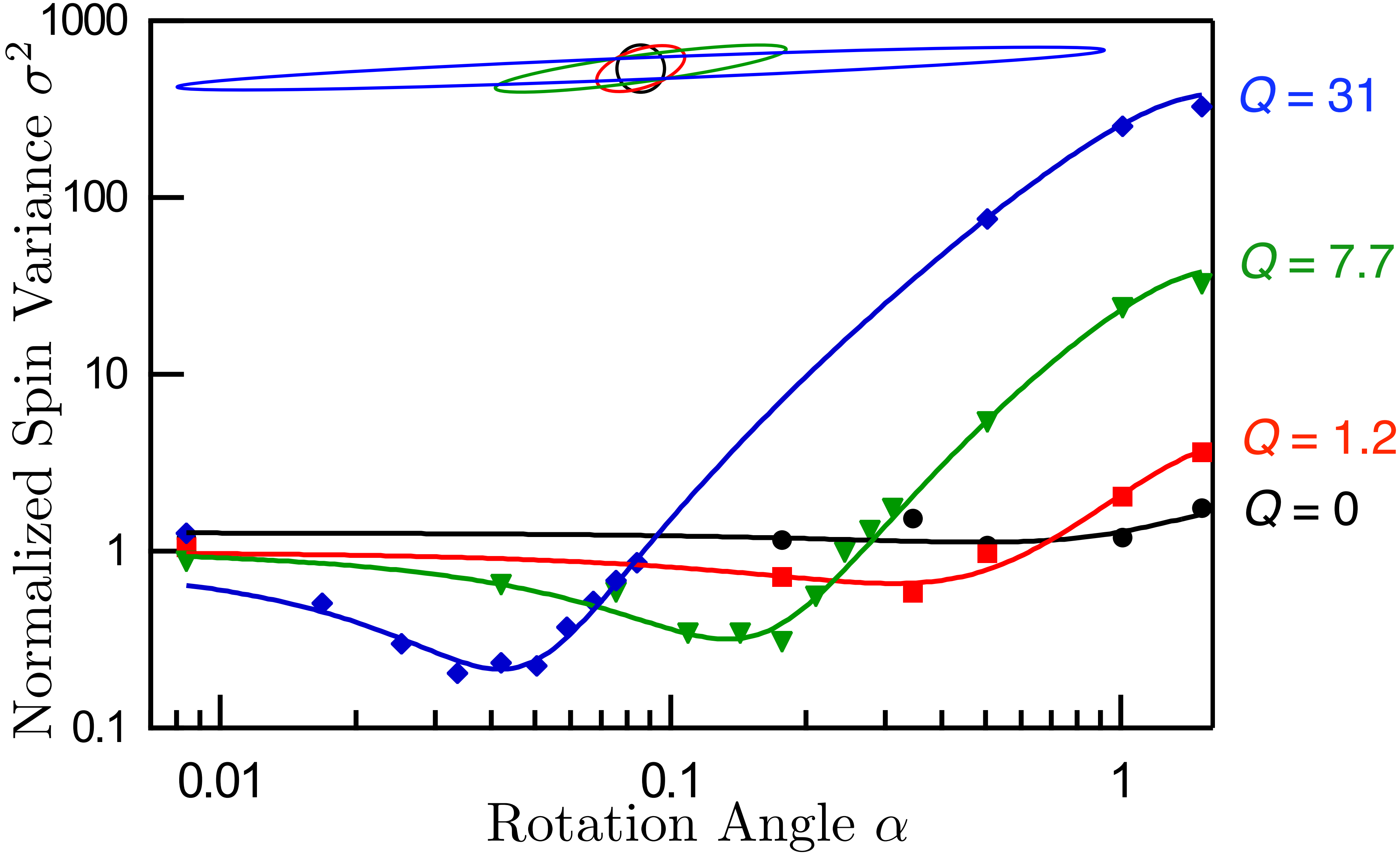
“one-axis twisting”
[Kitagawa & Ueda, PRA, 1993.]

# 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
$\eta = 4g^2/(\kappa\Gamma) = 0.1$

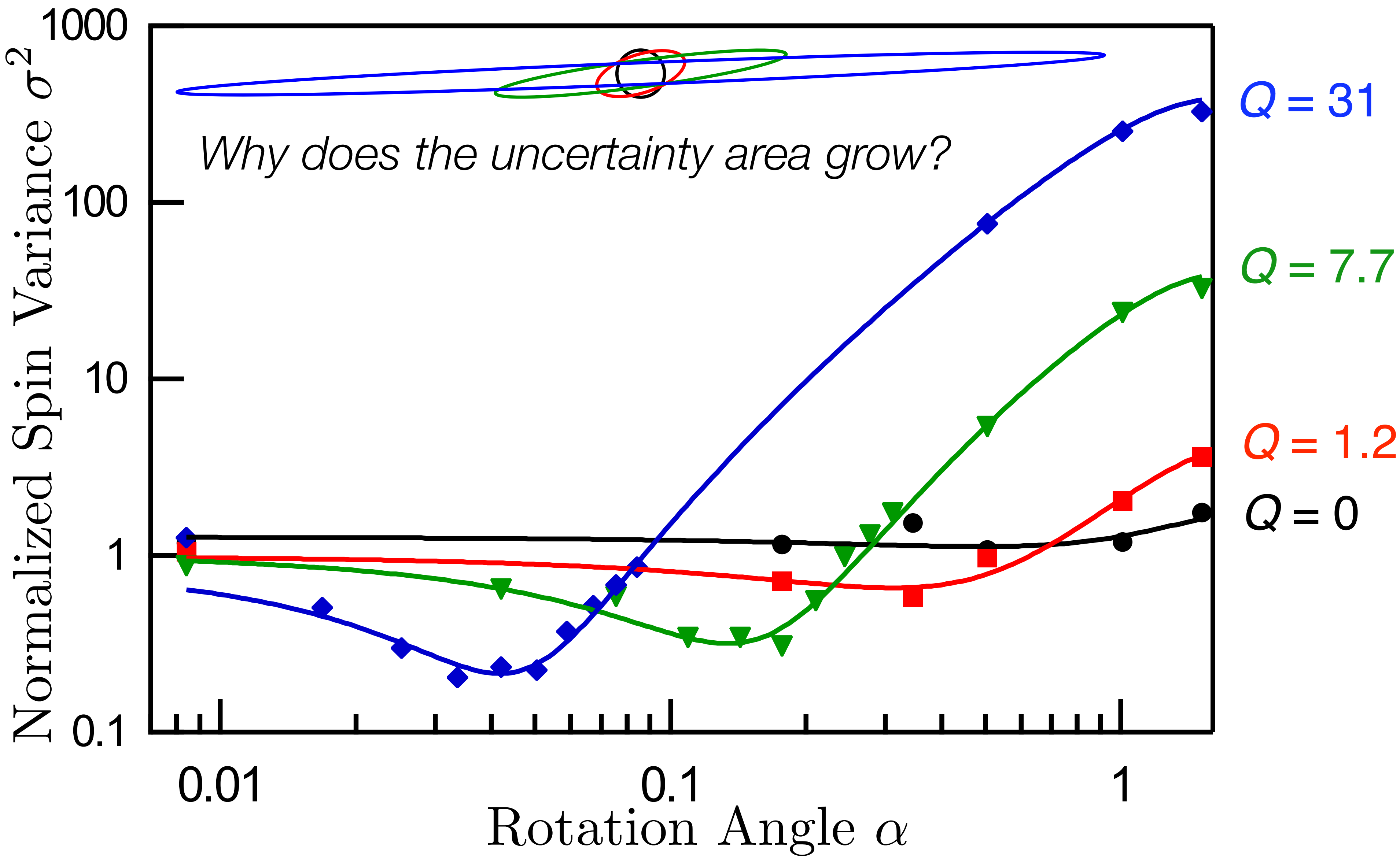


# Spin Squeezing

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

Twisting strength $Q = N\chi t = \left(\begin{array}{c}\text{\# of photons scattered} \\ \text{into cavity per atom}\end{array}\right)$

$N = 4\times10^4$ atoms
$\eta = 4g^2/(\kappa\Gamma) = 0.1$

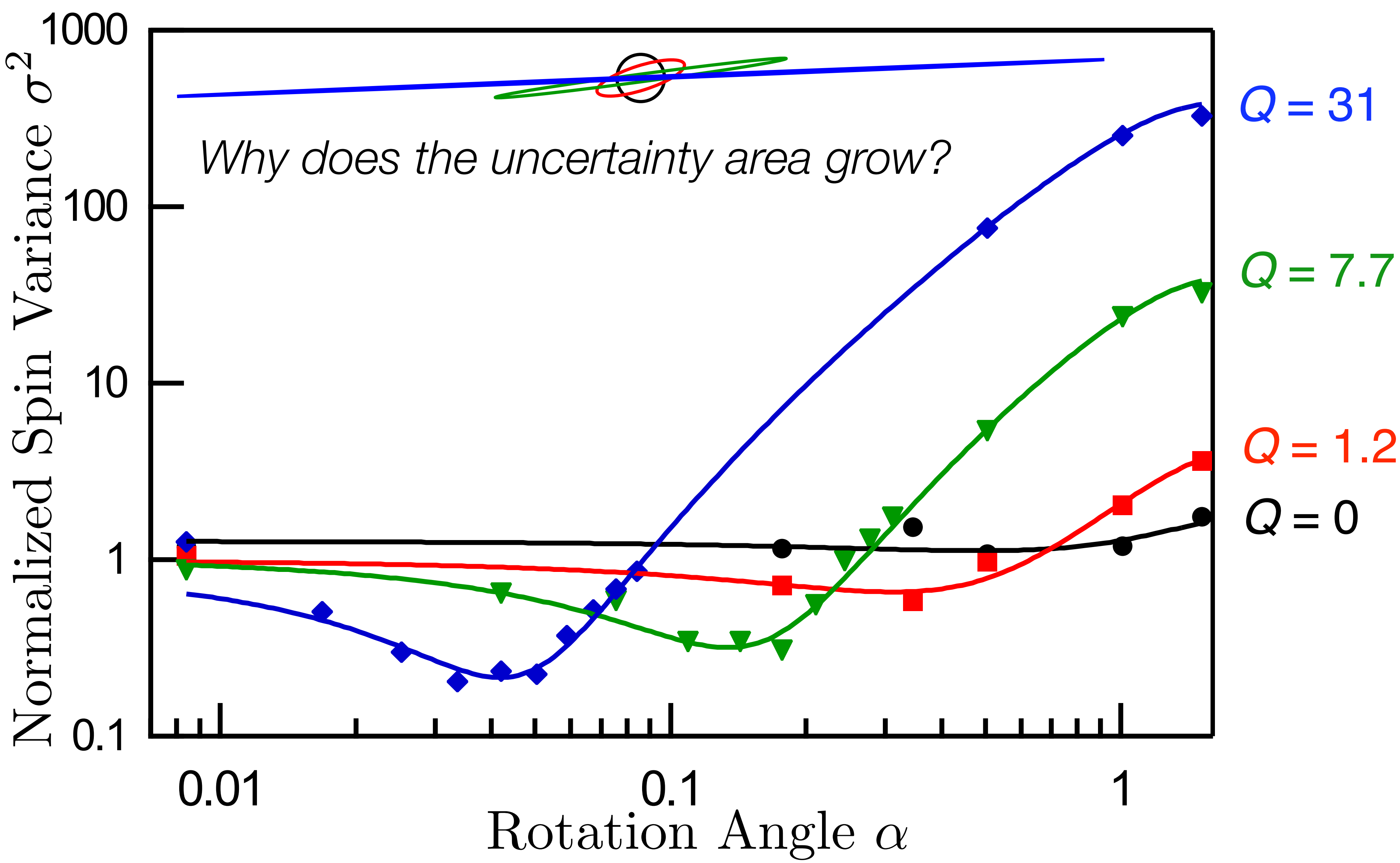


# Spin Squeezing

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

Twisting strength $Q = N\chi t = \left(\begin{array}{c}\text{\# of photons scattered} \\ \text{into cavity per atom}\end{array}\right)$

$N = 4\times10^4$ atoms
$\eta = 4g^2/(\kappa\Gamma) = 0.1$

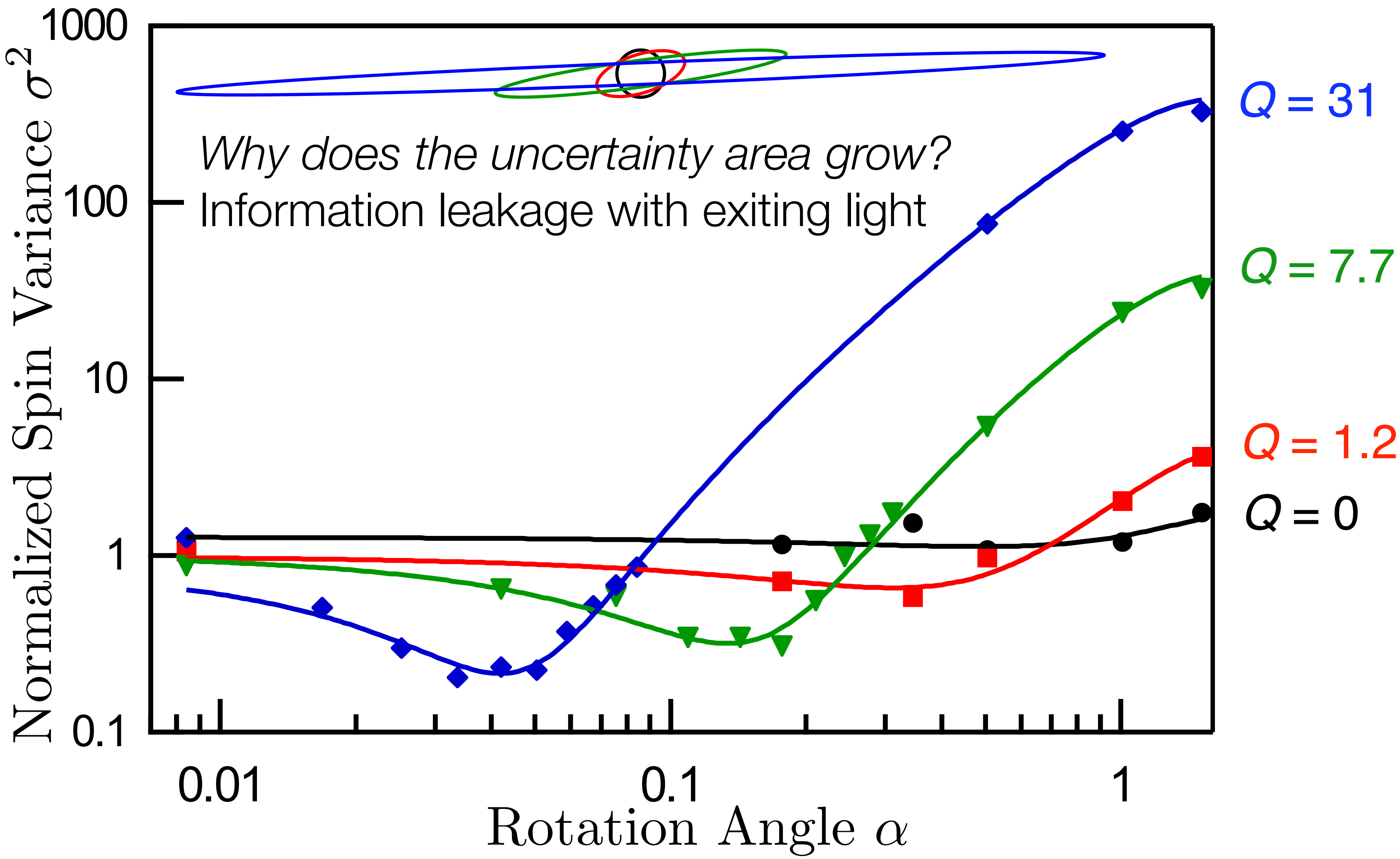


# Spin Squeezing

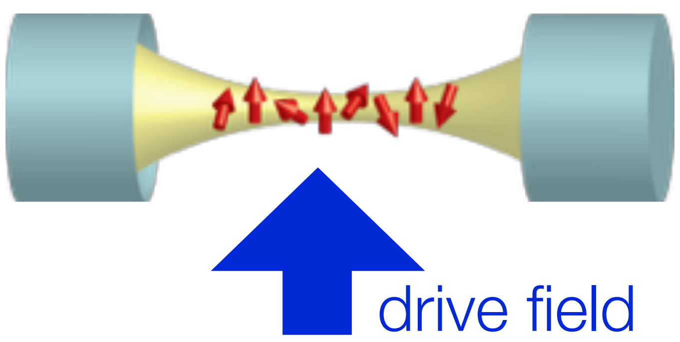
ID Leroux, MS-S & V Vuletic,
*PRL* **104**, 073602 (2010).

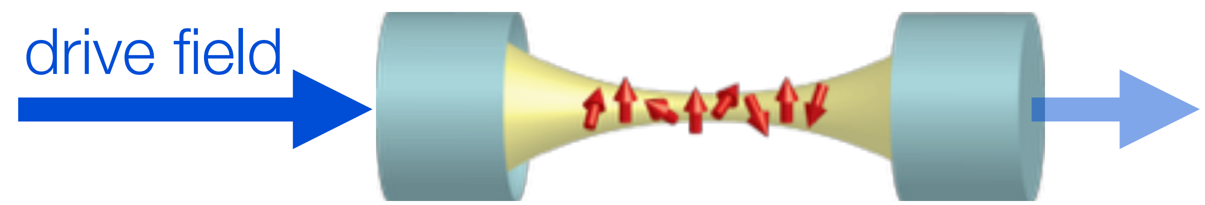
Twisting strength $Q = N\chi t = \left(\begin{array}{c}\text{\# of photons scattered} \\ \text{into cavity per atom}\end{array}\right)$

$N = 4\times10^4$ atoms
$\eta = 4g^2/(\kappa\Gamma) = 0.1$



# Dissipation




Interaction : $H = \chi S_x^2$

Dissipation : $L = \sqrt{\frac{\kappa}{\delta}}\chi S_x$

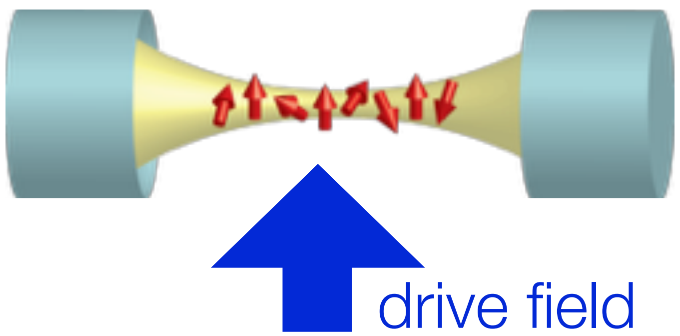
Interaction : $H = \chi S_z^2$

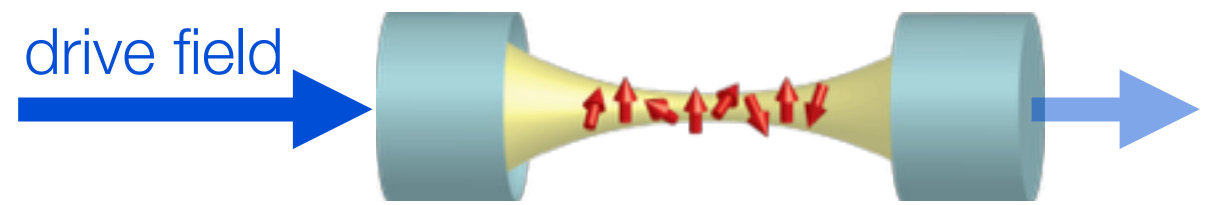
Dissipation : $L = \sqrt{\frac{\kappa}{\delta}}\chi S_z$

detuning from cavity resonance

# Dissipation

…accompanying light-mediated interactions




Interaction : $H = \chi S_x^2$

Dissipation : $L = \sqrt{\frac{\kappa}{\delta}}\chi S_x$

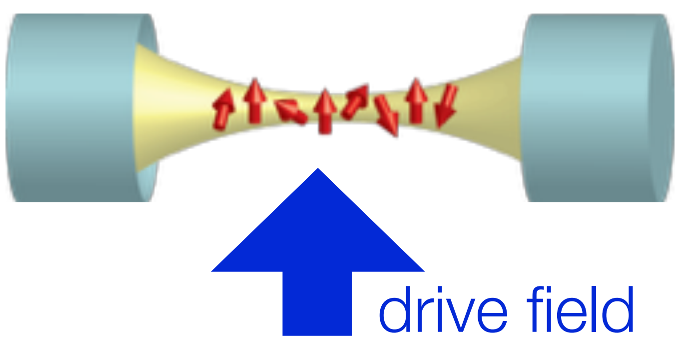
Interaction : $H = \chi S_z^2$

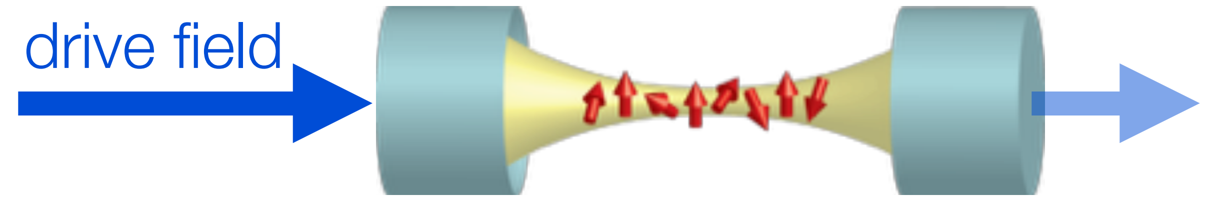
Dissipation : $L = \sqrt{\frac{\kappa}{\delta}}\chi S_z$

detuning from cavity resonance

# Dissipation

…accompanying light-mediated interactions




$$\text{Interaction}: \; H = \chi S_x^2 \qquad\qquad \text{Interaction}: \; H = \chi S_z^2$$

$$\text{Dissipation}: \; L = \sqrt{\frac{\kappa}{\delta}}\chi S_x \qquad\qquad \text{Dissipation}: \; L = \sqrt{\frac{\kappa}{\delta}}\chi S_z$$

detuning from cavity resonance

**Spontaneous emission:** $\Gamma_{\mathrm{sc}} \approx \dfrac{\chi\delta}{\eta\kappa}$

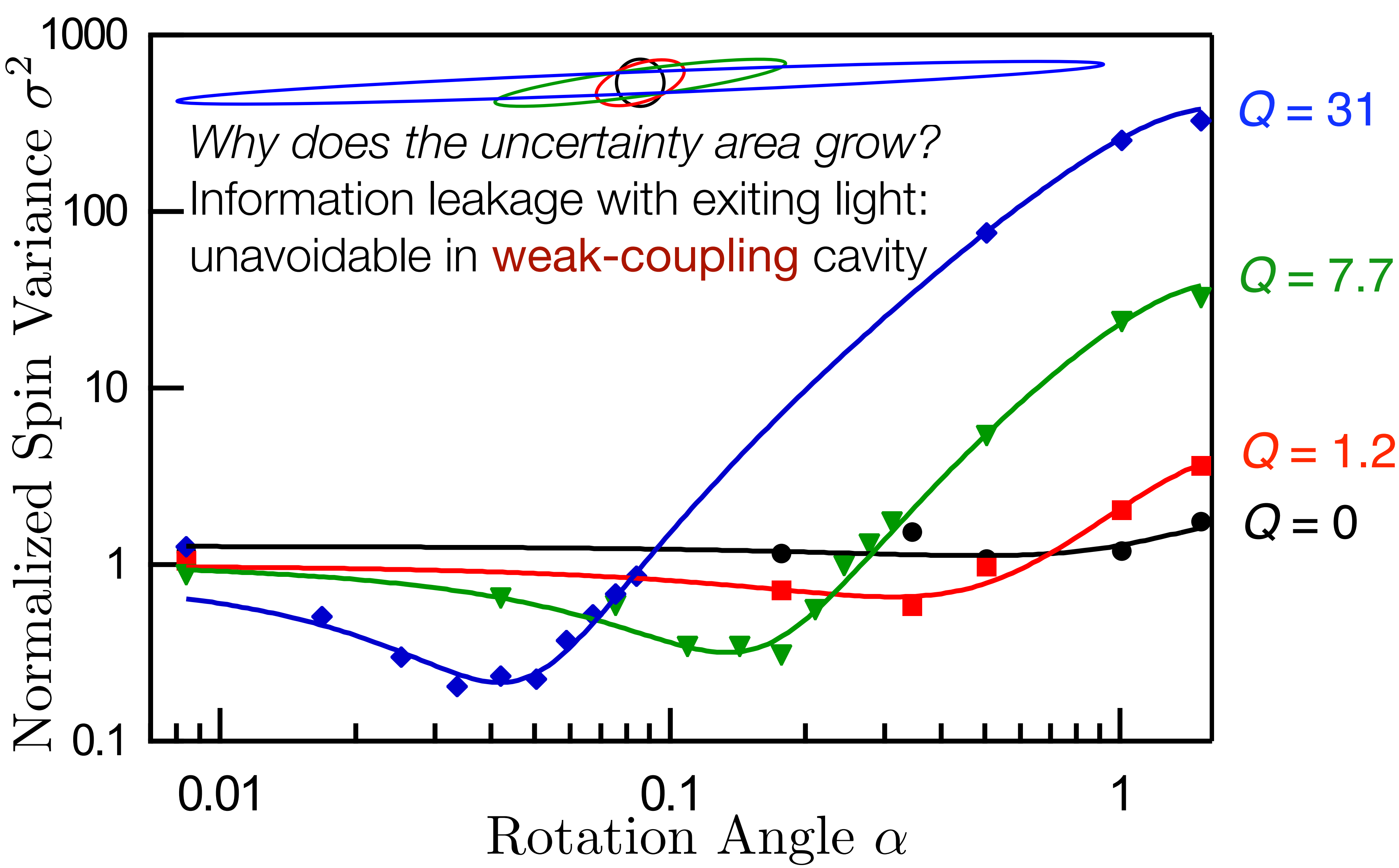
Coherent interactions require large detuning δ + strong coupling

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

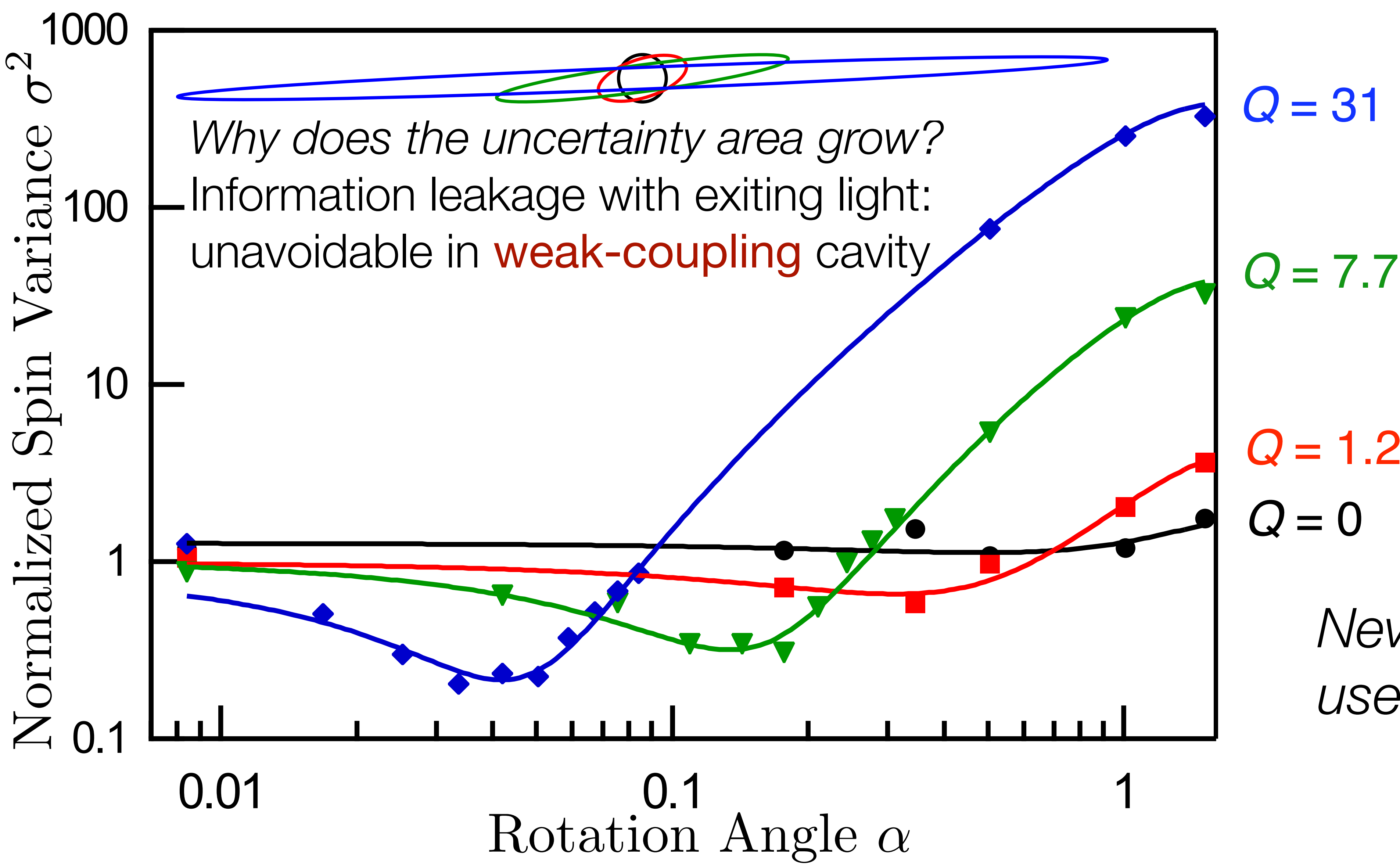


# Spin Squeezing

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

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

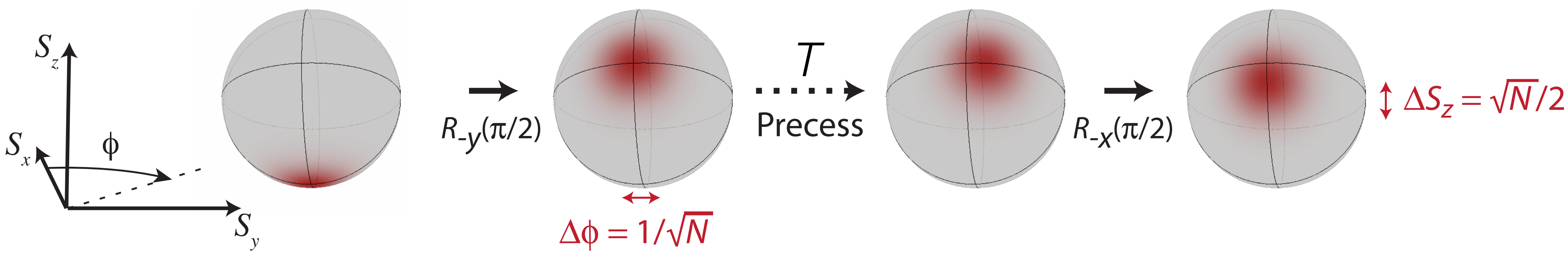
$N = 4\times10^4$ atoms
$\eta = 0.1$, $\delta=\kappa/2$

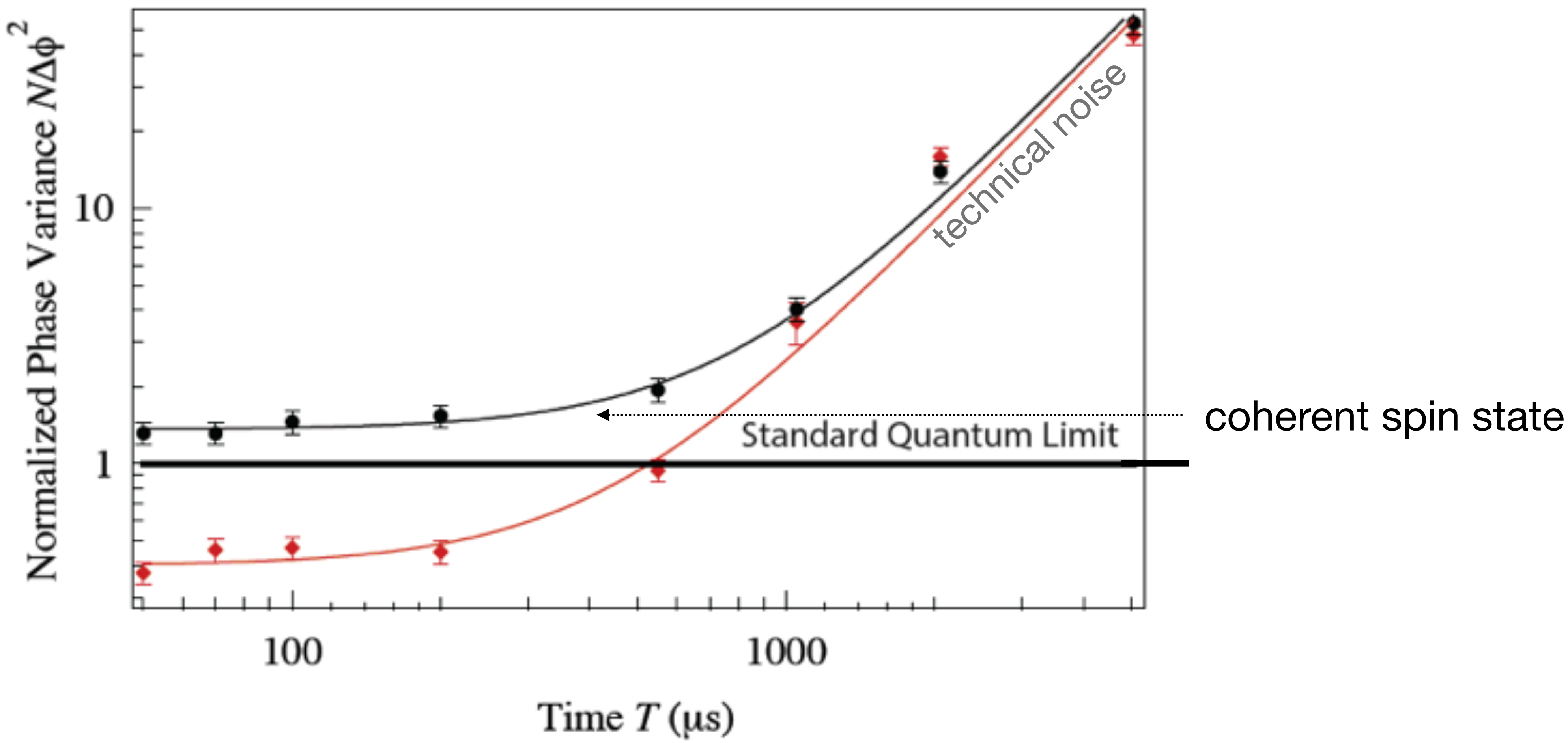



*Nevertheless:*
*useful entanglement!*

# Ramsey Spectroscopy

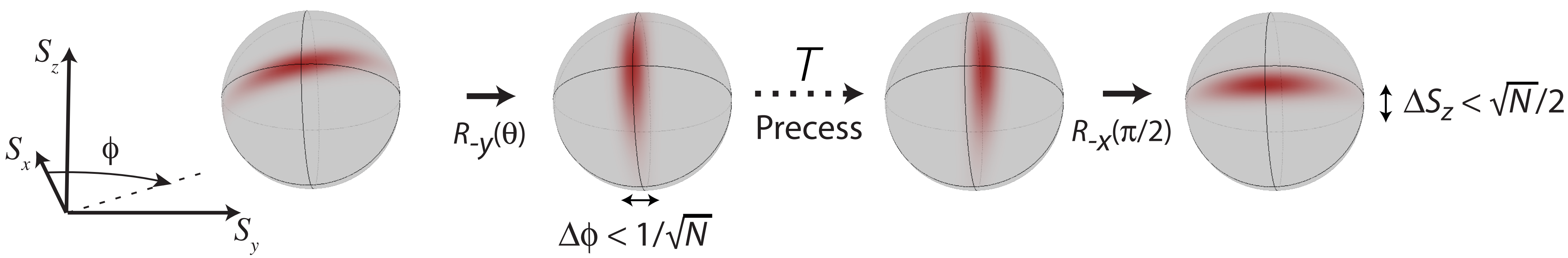
ID Leroux, MS-S & V Vuletic,
*PRL* **105**, 250801 (2010).

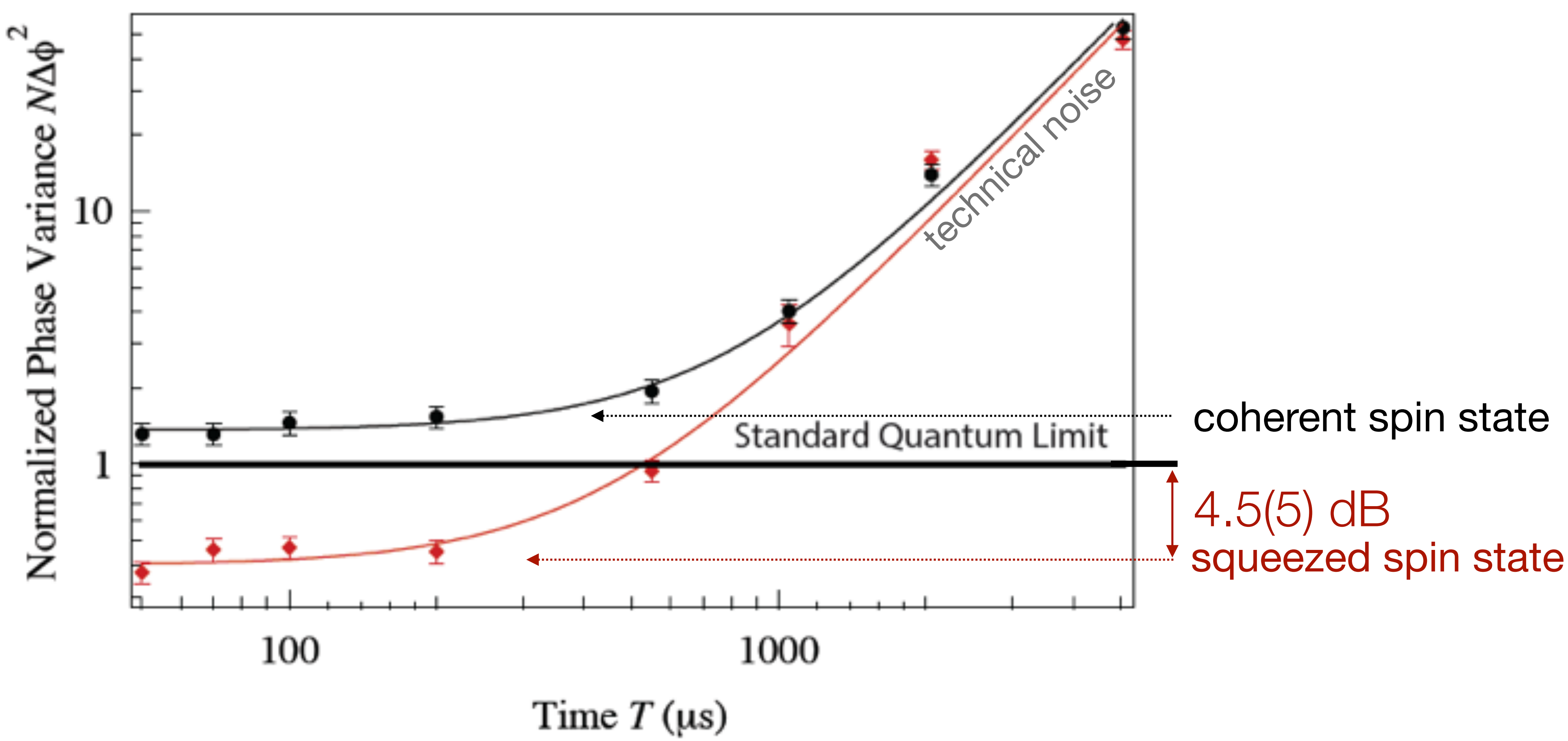


# Ramsey Spectroscopy

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

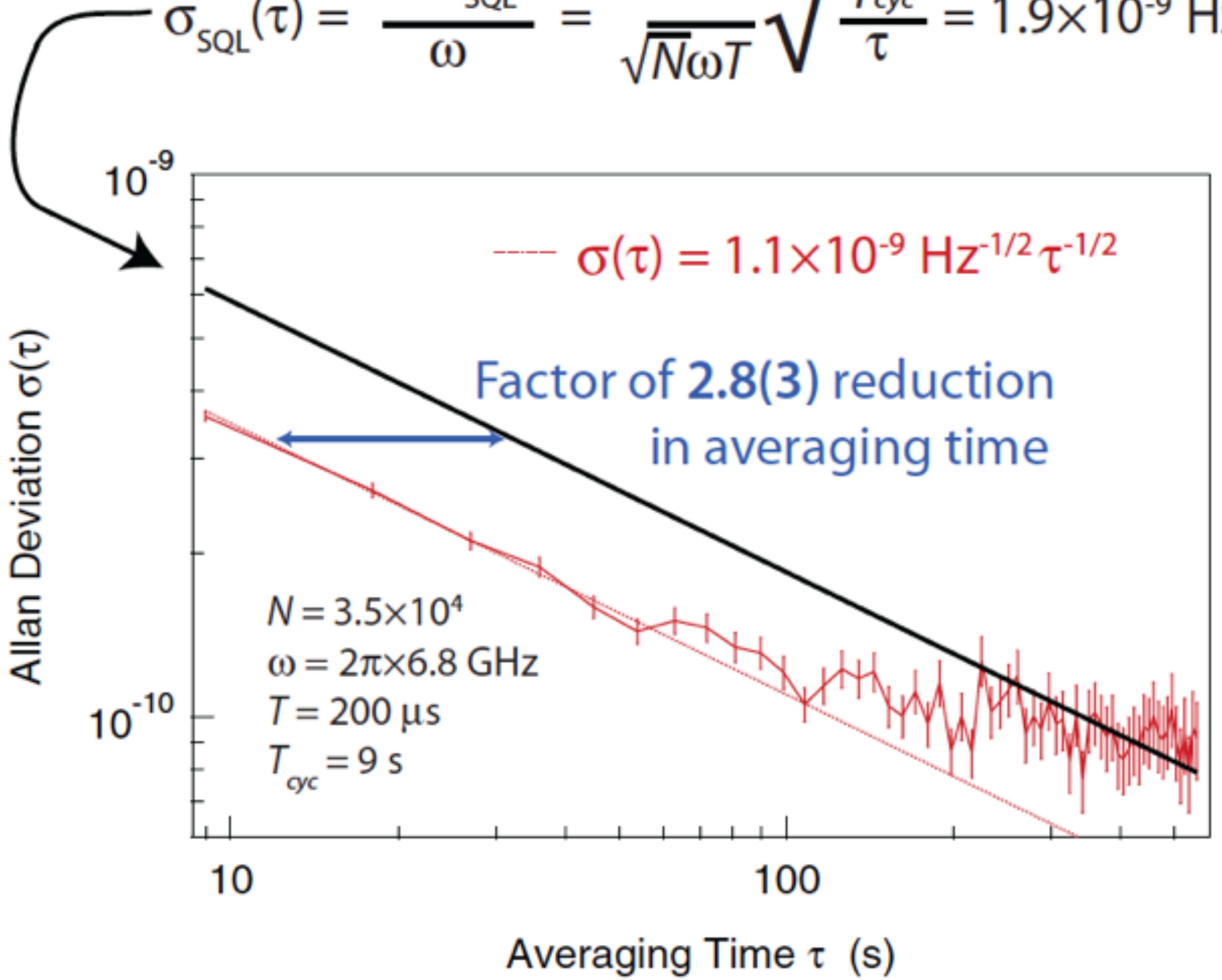


# Squeezed Atomic Clock

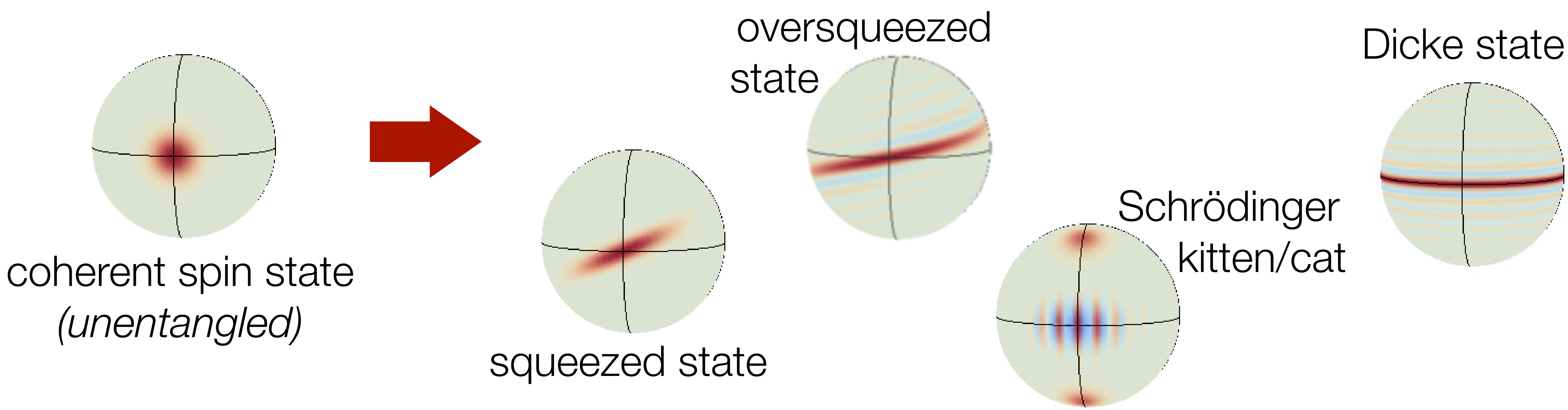
ID Leroux, MS-S & V Vuletic,
*PRL* **105**, 250801 (2010).

$$\sigma_{SQL}(\tau) = \frac{\Delta\omega_{SQL}}{\omega} = \frac{1}{\sqrt{N}\omega T}\sqrt{\frac{T_{cyc}}{\tau}} = 1.9\times10^{-9}\ \mathrm{Hz}^{-1/2}\tau^{-1/2}$$



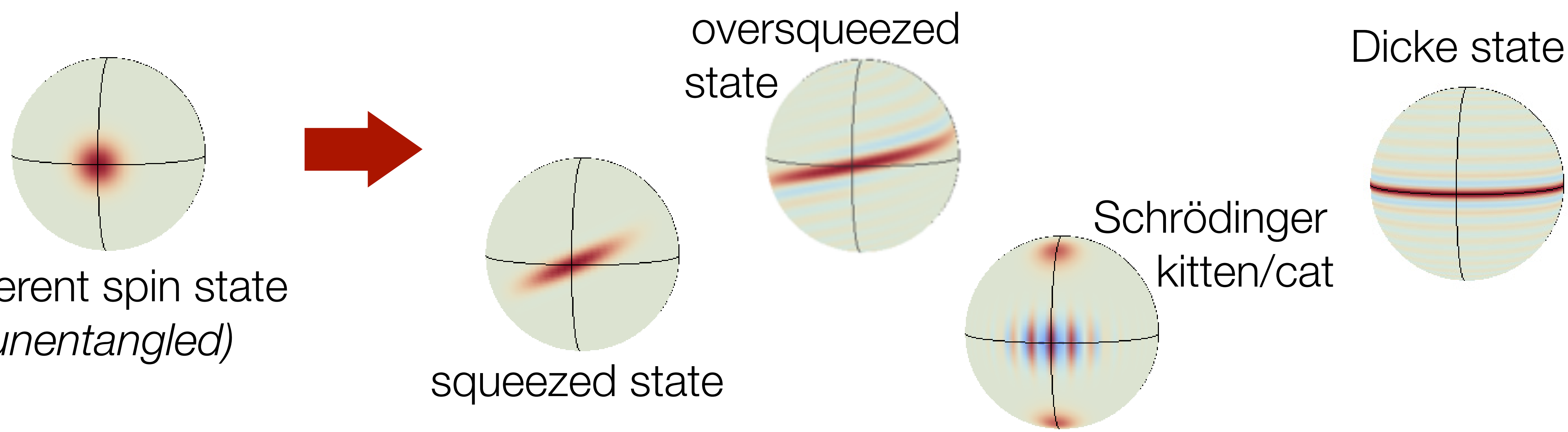

*Recent advances:*
*Kasevich group*

# Quantum Engineering for Metrology



# Quantum Engineering for Metrology

Resources: (Copenhagen, Heidelberg, Basel, MIT, JILA, Hannover, Georgia Tech, Barcelona, Kyoto, Paris, Vienna, Innsbruck…)

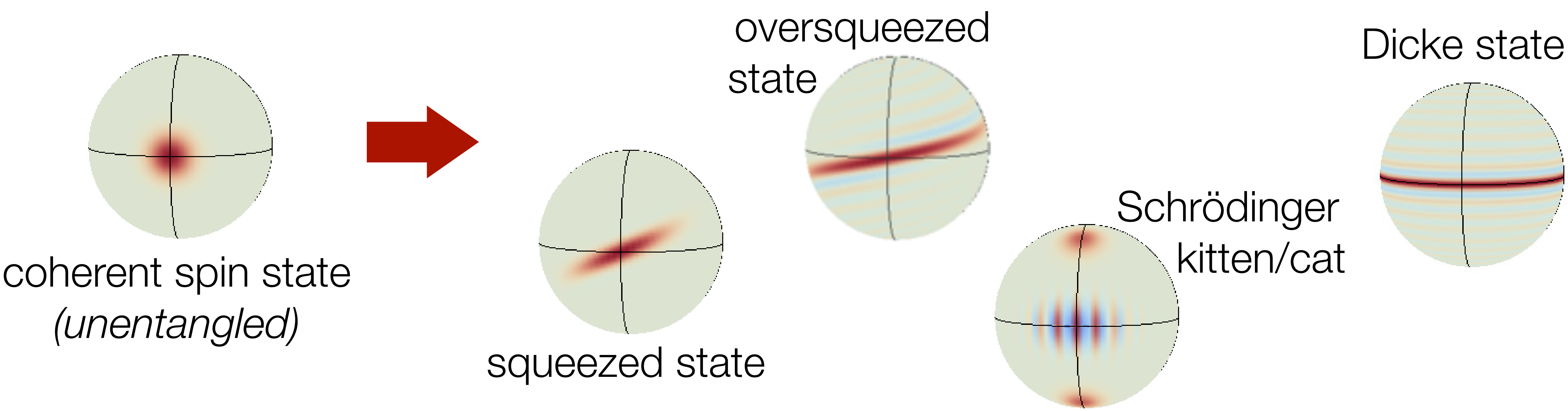



*Which state is best for a given task?*

*How should we design measurement protocols to reap the benefits of entanglement?*

# Quantum Engineering for Metrology

Resources: (Copenhagen, Heidelberg, Basel, MIT, JILA, Hannover, Georgia Tech, Barcelona, Kyoto, Paris, Vienna, Innsbruck…)




*Which state is best for a given task?*

*How should we design measurement protocols to reap the benefits of entanglement?*

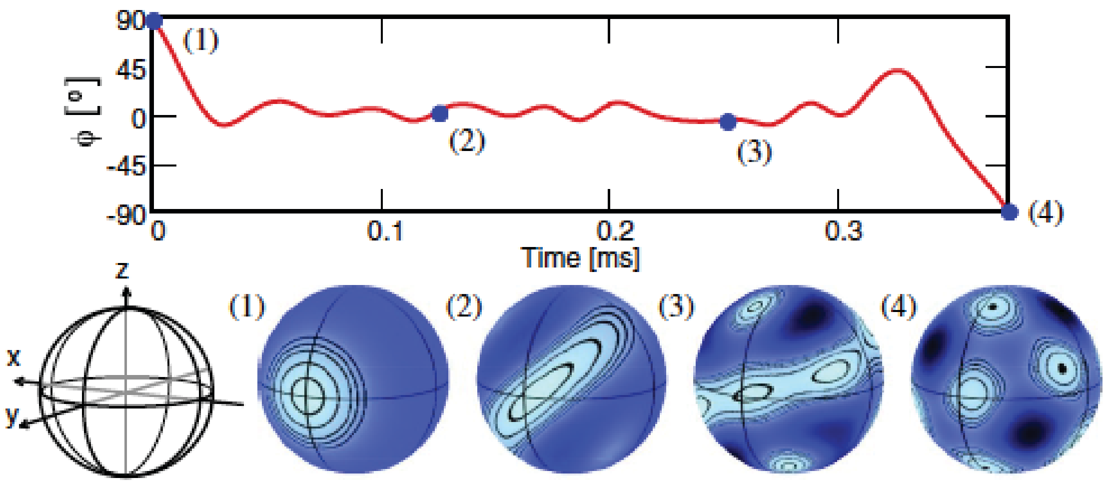
**Vision:** versatile experimental platform for exploring these questions

# Prospect

## Quantum control Hamiltonian

$$H = \alpha(t) S_z^2 + \mathbf{\Omega}(t) \cdot \mathbf{S}$$

…in principle allows full control over spin-$S$ Bloch sphere



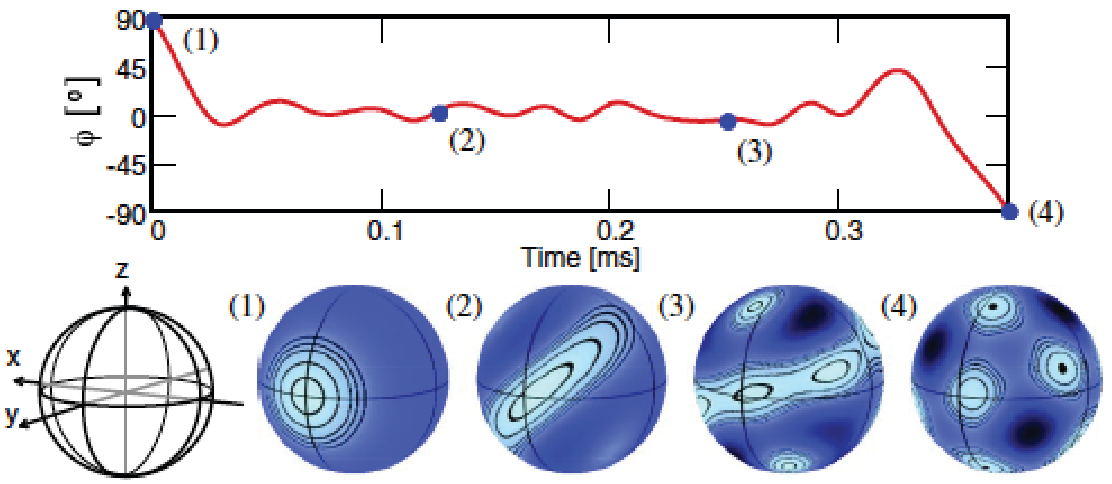

S. Chaudhury, … I. Deutsch & P. Jessen, *PRL* (2007).

# Prospect

## Quantum control Hamiltonian

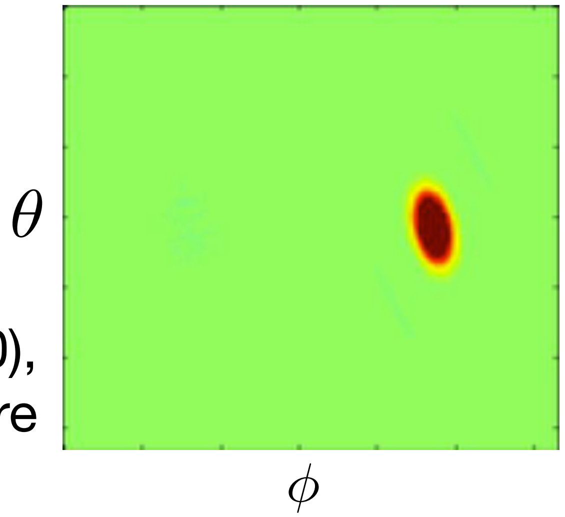
$$H = \alpha(t) S_z^2 + \boldsymbol{\Omega}(t) \cdot \mathbf{S}$$

…in principle allows full control over spin-$S$ Bloch sphere




S. Chaudhury, … I. Deutsch & P. Jessen, *PRL* (2007).

Realizable for **collective spin** by cavity-mediated interactions



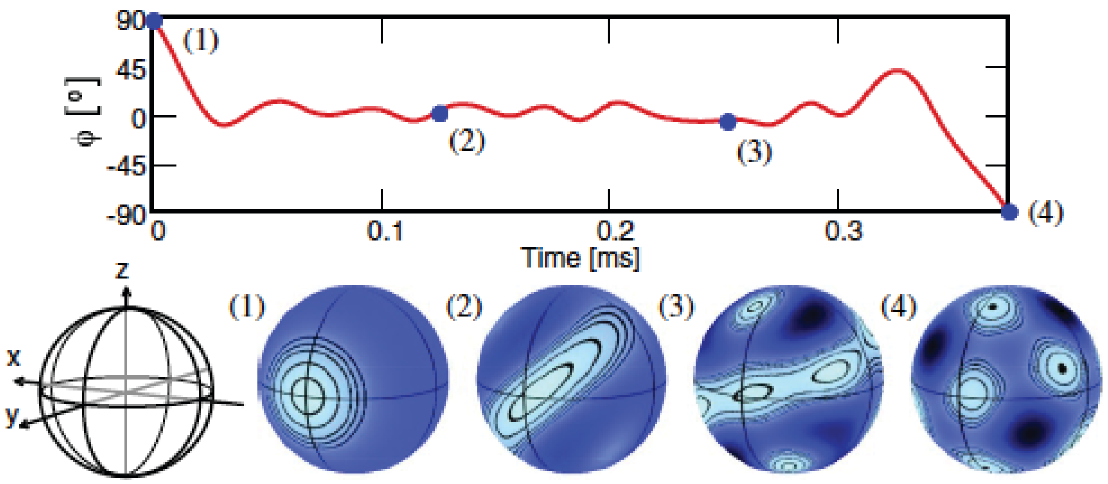

Simulated dynamics ($N$=60, η~100), showing interference on Bloch sphere

# Prospect

## Quantum control Hamiltonian

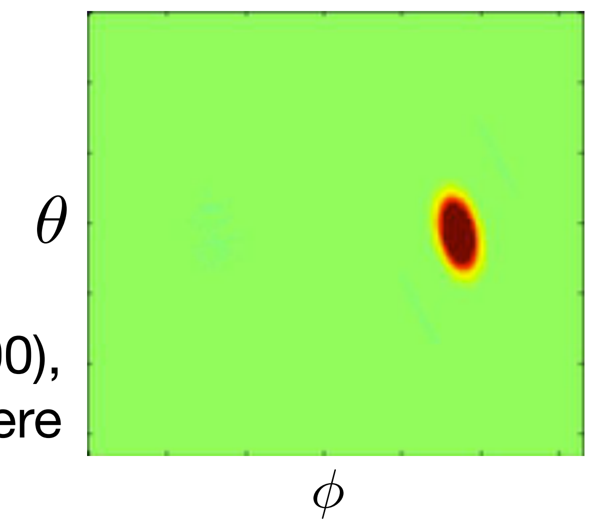
$$H = \alpha(t) S_z^2 + \mathbf{\Omega}(t) \cdot \mathbf{S}$$

…in principle allows full control over spin-$S$ Bloch sphere




S. Chaudhury, … I. Deutsch & P. Jessen, *PRL* (2007).

Realizable for **collective spin** by cavity-mediated interactions




Simulated dynamics ($N$=60, η~100), showing interference on Bloch sphere

# Approaching the Heisenberg Limit?

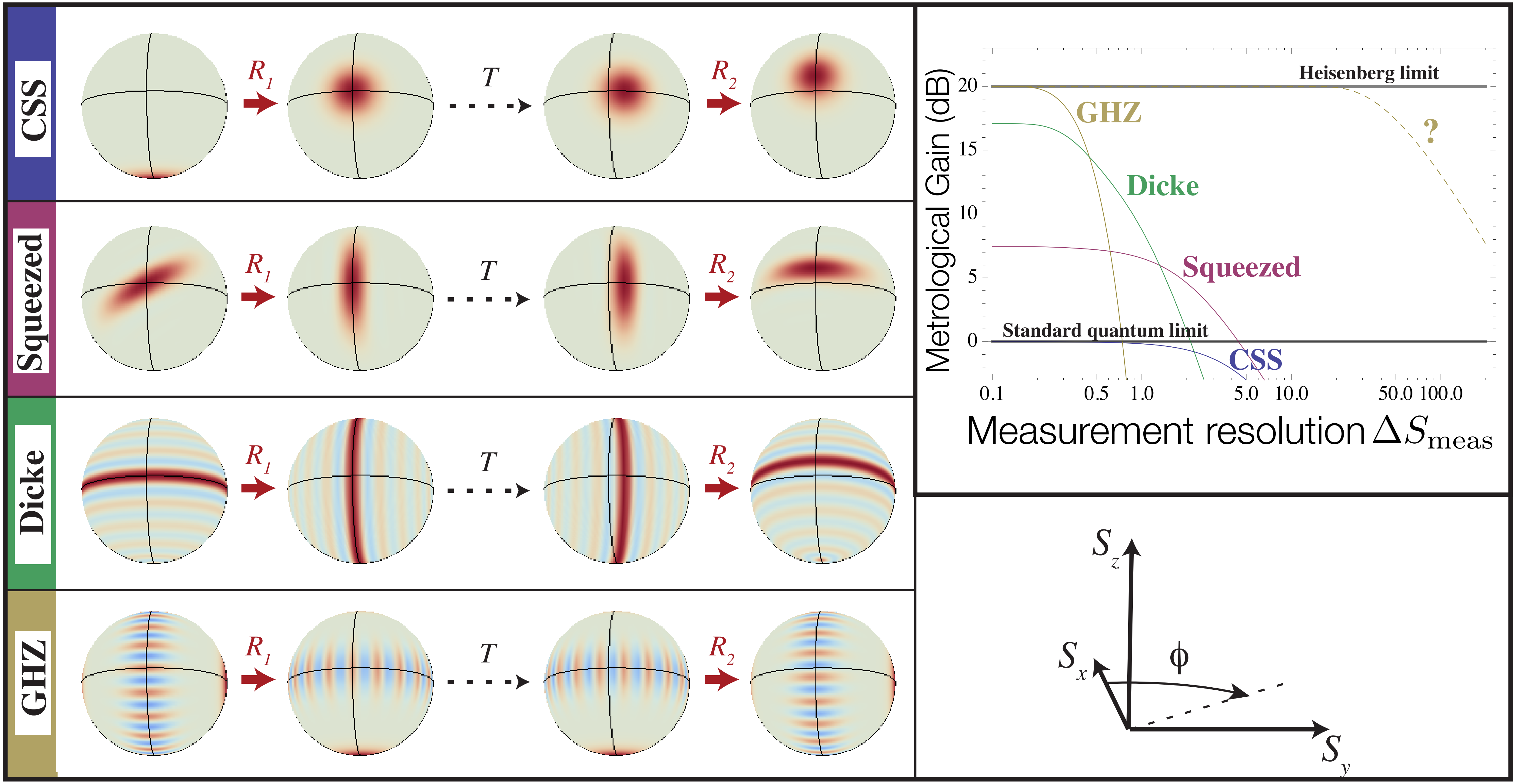
$$\Delta E \Delta T \geq \hbar/2\,, \quad \Delta E \leq \frac{N}{2}\hbar\omega \;\Rightarrow\; \Delta(\omega T) \geq \frac{1}{N}$$

⇒ Reaching the Heisenberg limit requires state with *maximum* uncertainty in energy

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

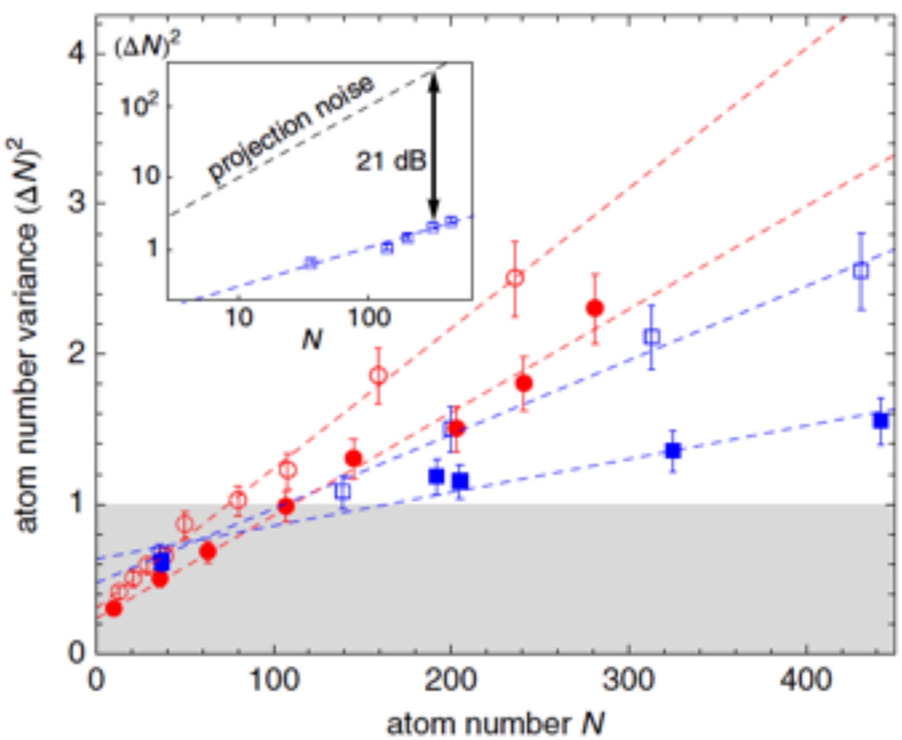
- Useless after loss of a *single* particle
- Preparation via $H = \chi S_z^2$ requires *fixed* time $\chi t = \pi/2$ ⇒ twisting strength $Q \propto N$
- Detection requires resolution $\Delta S_z \ll 1$

# Metrological Gain *vs.* Measurement Resolution

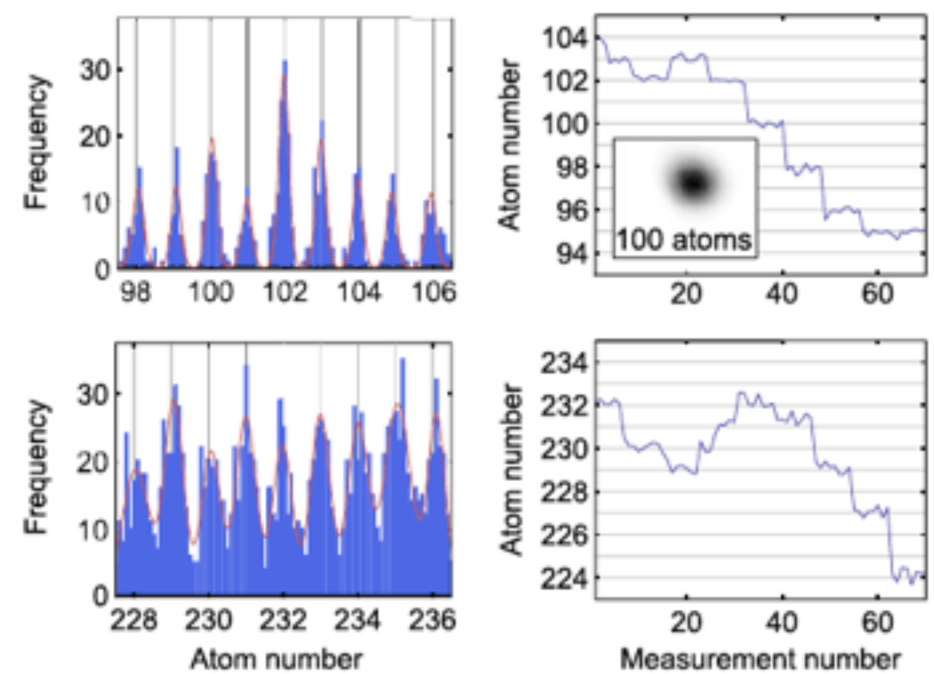


# Reaping the Full Benefit of Entanglement

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).

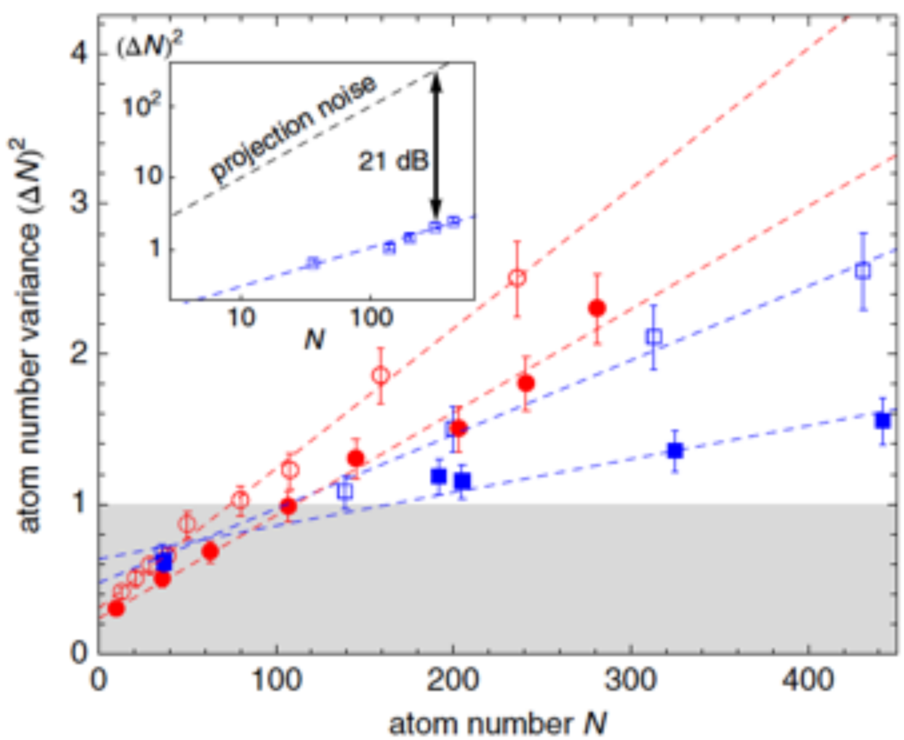


# Reaping the Full Benefit of Entanglement

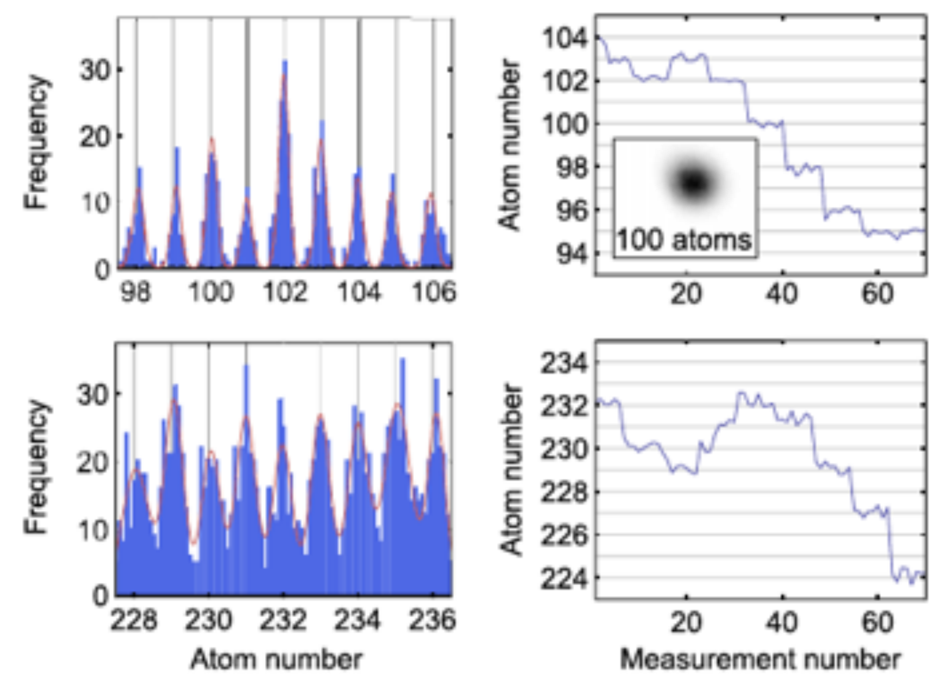
## Approaches:

- 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).

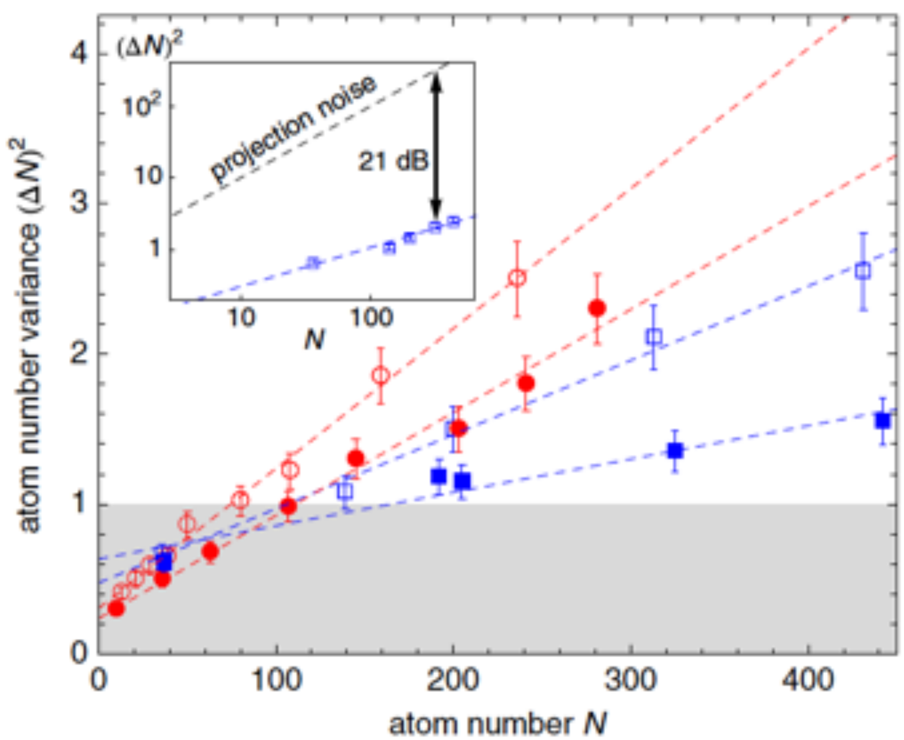


# Reaping the Full Benefit of Entanglement

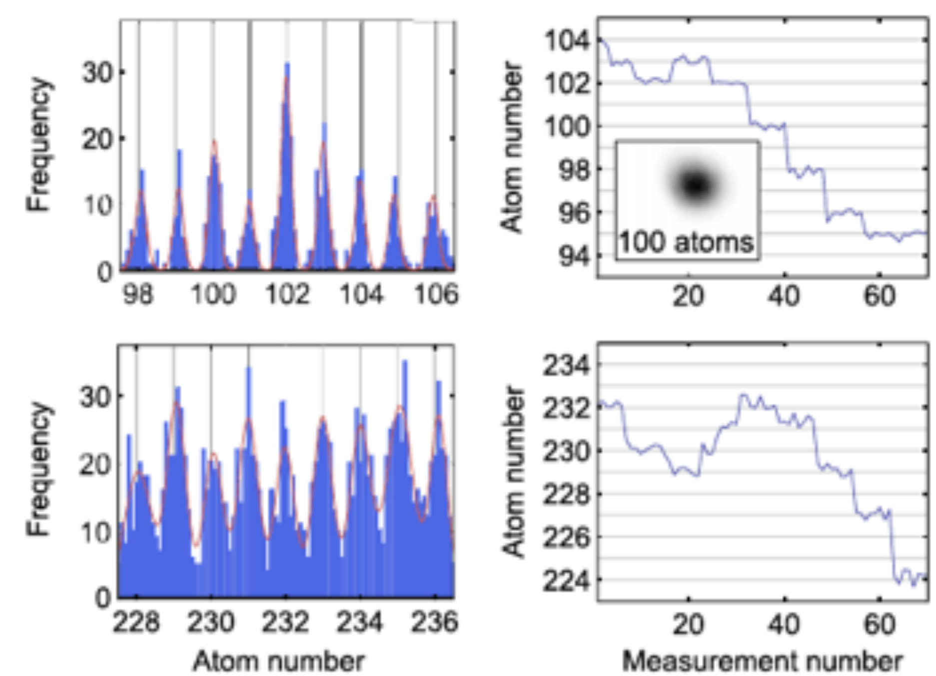
## Approaches:

- Perfecting state detection

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

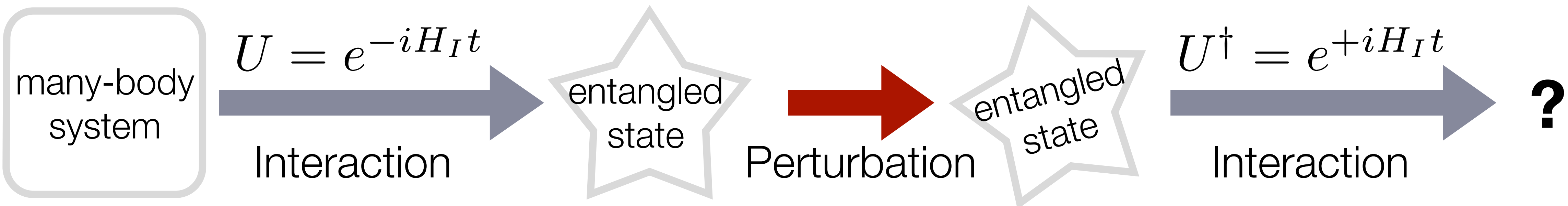



  Free-space detection by MOT recapture:
  Hume *et al.*, *PRL* (2013).




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

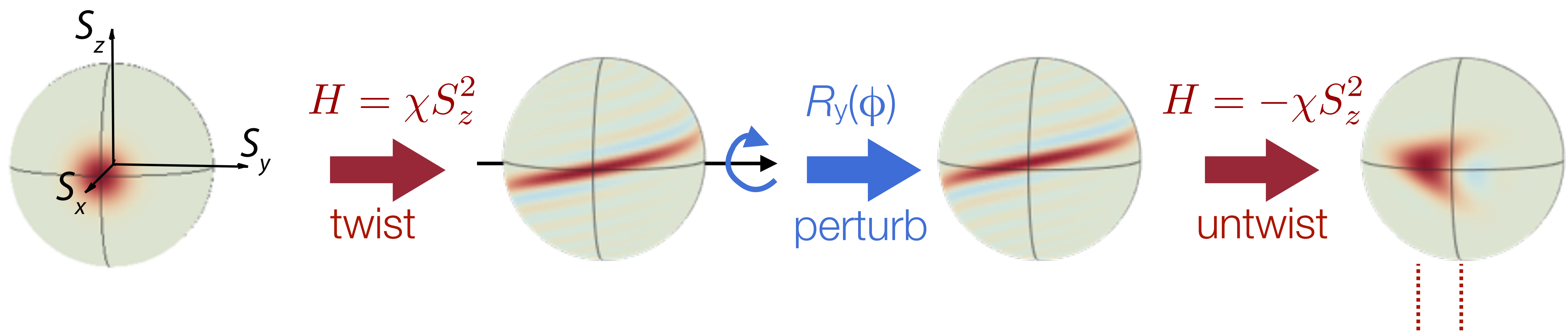
# Echo Spectroscopy




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

# One-Axis Twisting Echo (ideal)

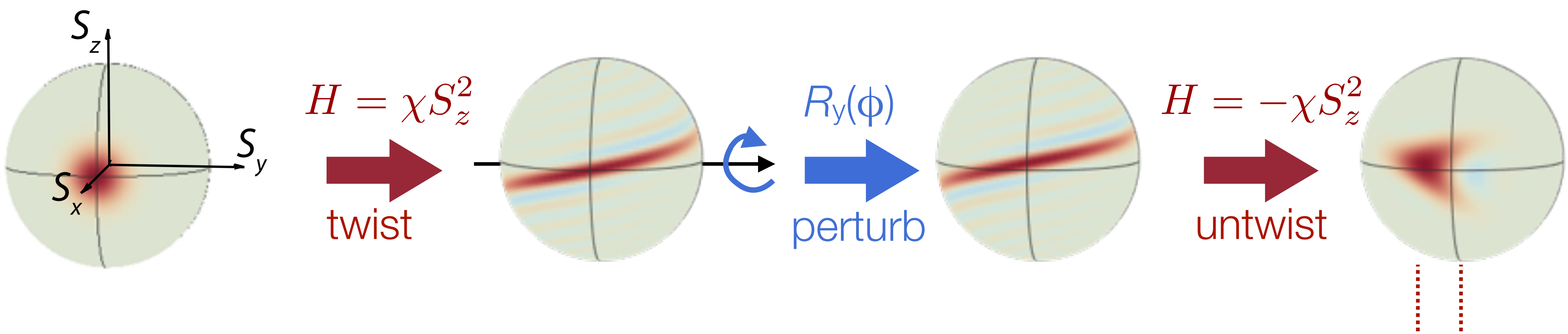
E. Davis, G. Bentsen, & MS-S,
*arXiv*:1508.04110[quant-ph].




Measure $\langle S_y \rangle \approx Q e^{-Q^2/(4S)} S\phi$

# One-Axis Twisting Echo (ideal)

E. Davis, G. Bentsen, & MS-S, *arXiv*:1508.04110[quant-ph].

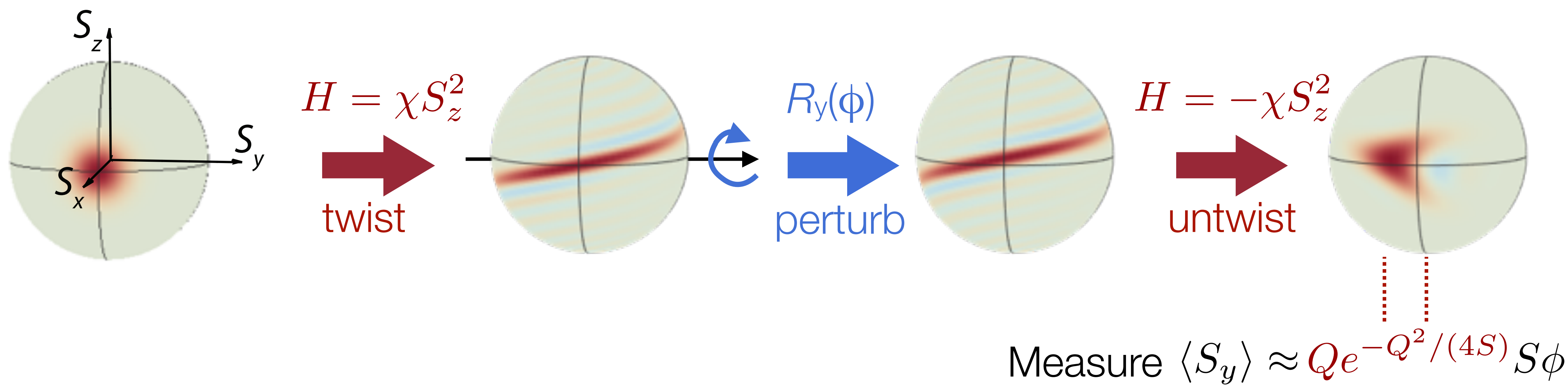


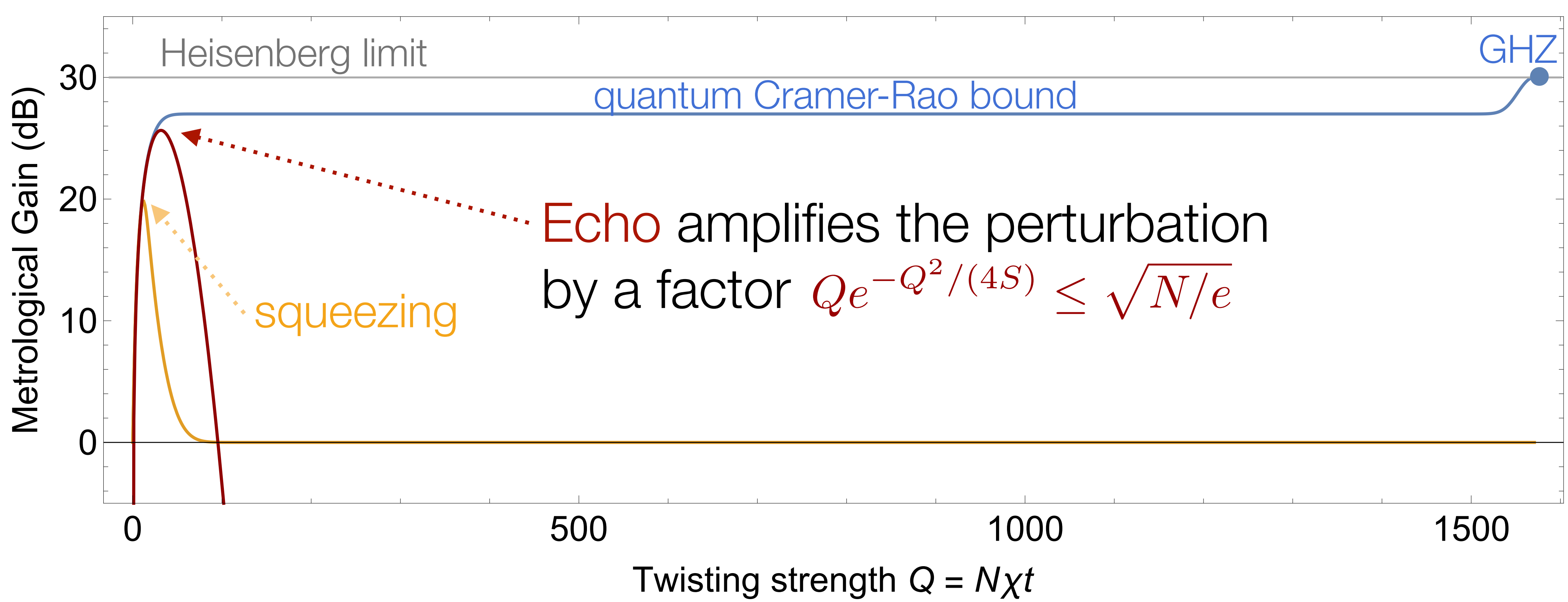

Measure $\langle S_y \rangle \approx Qe^{-Q^2/(4S)} S\phi$

Echo amplifies the perturbation
by a factor $Qe^{-Q^2/(4S)} \leq \sqrt{N/e}$

# One-Axis Twisting Echo (ideal)

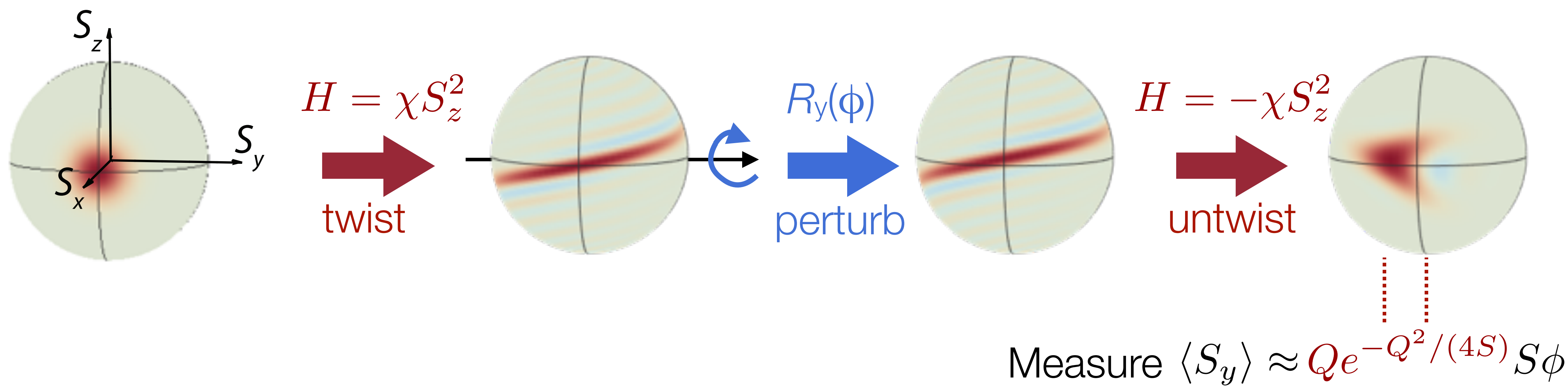
E. Davis, G. Bentsen, & MS-S,
*arXiv*:1508.04110[quant-ph].

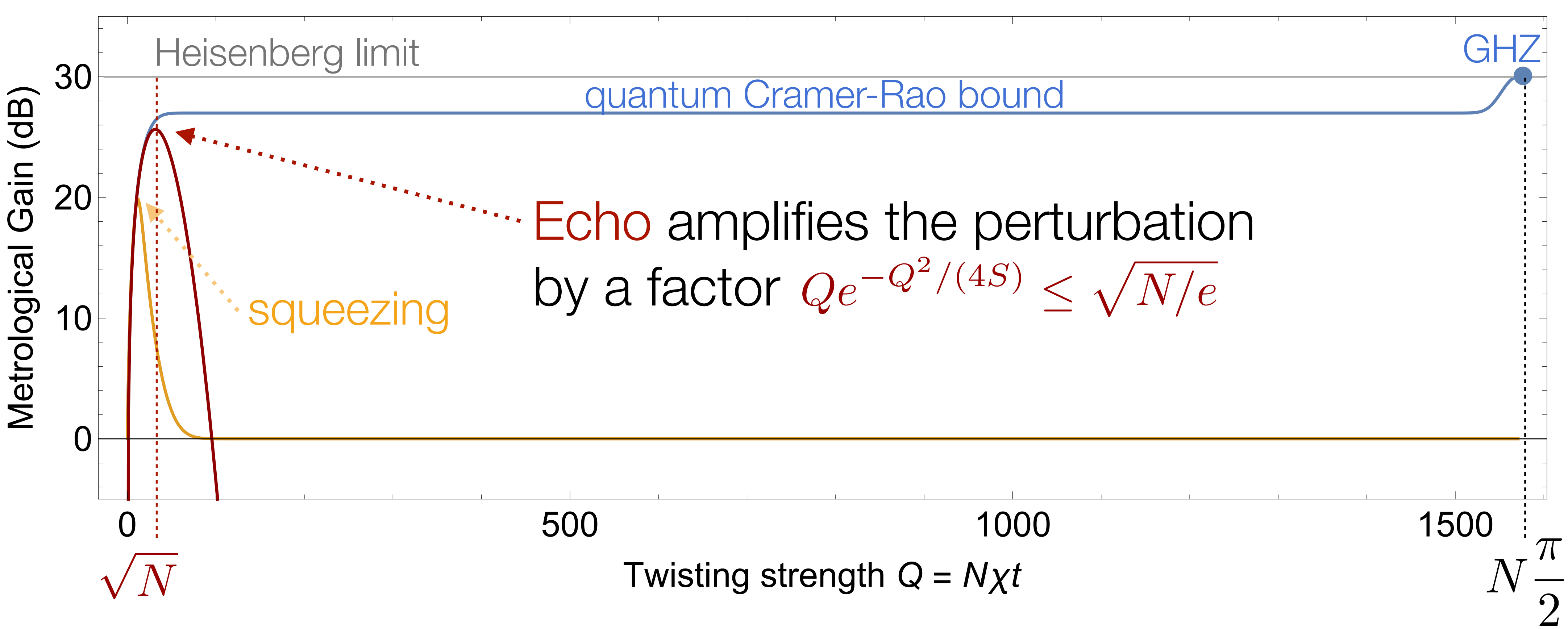


# One-Axis Twisting Echo (ideal)

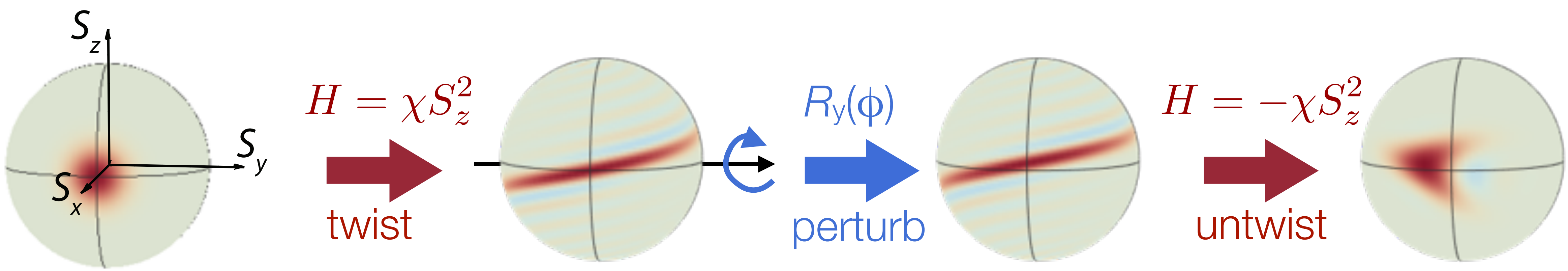
E. Davis, G. Bentsen, & MS-S,
*arXiv*:1508.04110[quant-ph].



# One-Axis Twisting Echo (ideal)

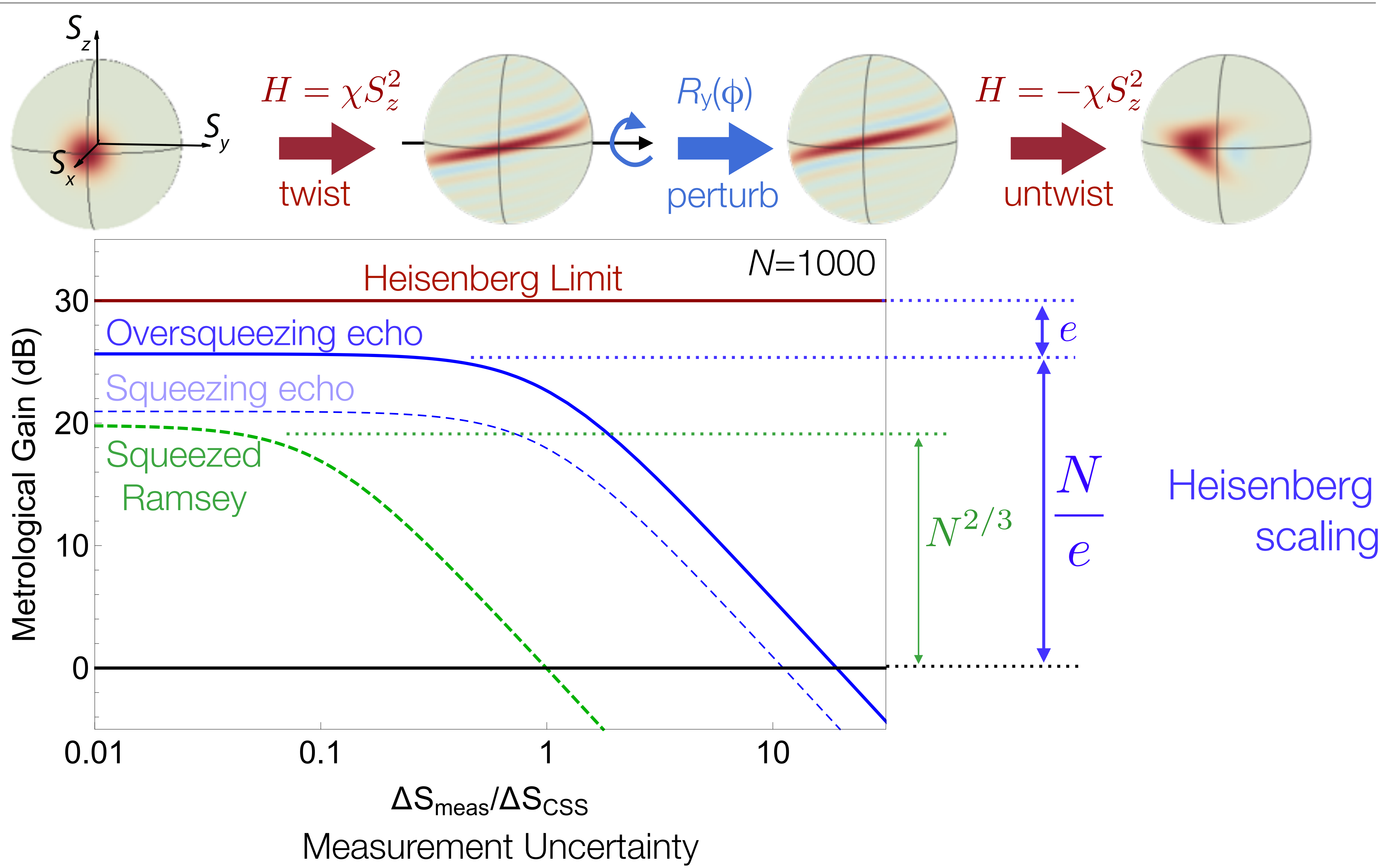
E. Davis, G. Bentsen, & MS-S,
*arXiv*:1508.04110[quant-ph].




Measurement Uncertainty

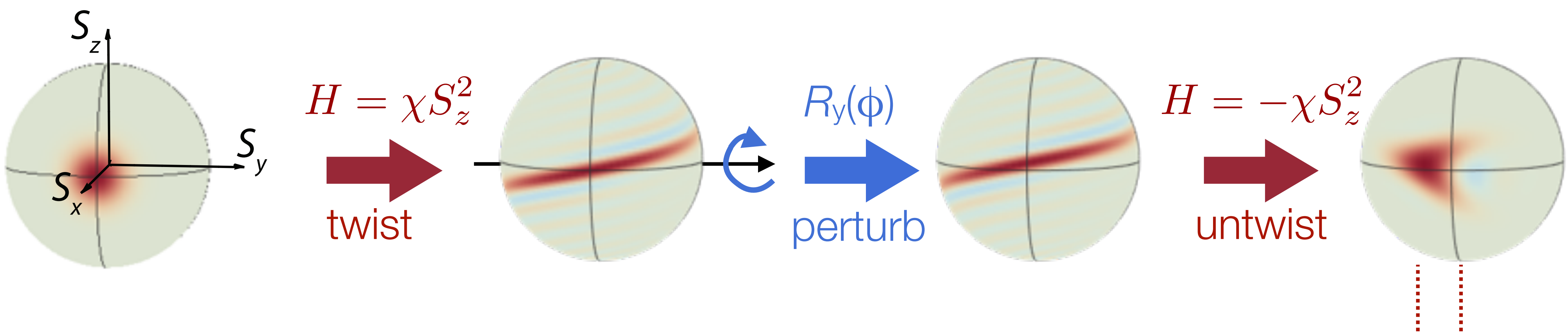
# One-Axis Twisting Echo (ideal)

E. Davis, G. Bentsen, & MS-S,
*arXiv*:1508.04110[quant-ph].



# One-Axis Twisting Echo (ideal)

E. Davis, G. Bentsen, & MS-S, *arXiv*:1508.04110[quant-ph].

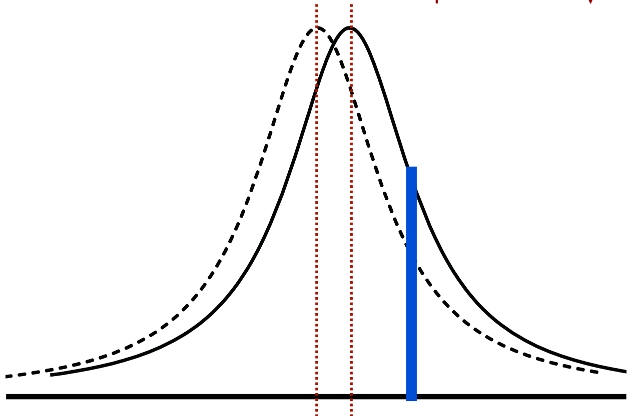



Measure $S_y = QS\phi$

- Heisenberg scaling $\Delta\phi = \sqrt{e}/N$ reached at $\chi t = 1/\sqrt{N}$
- Measurement resolution $\Delta S_{\mathrm{meas}} \lesssim \sqrt{N}/2$ suffices!

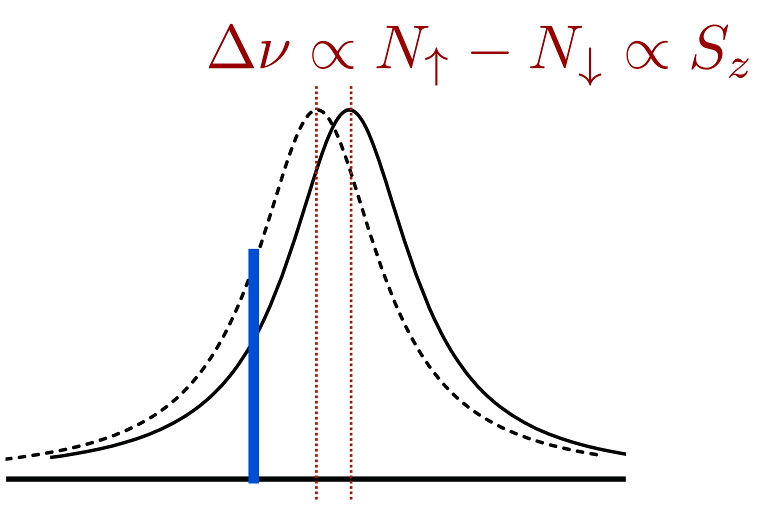
# One-Axis Twisting Echo: Implementation?

| $H = \mu S_z^2$ | Switchable sign | Coherence | Atom # |
|---|---|---|---|
| Cavity-mediated interactions | ✔ | (✔) | $10^1$-$10^6$ |
| BEC: collisional interactions | ? | ? | $10^2$-$10^4$ |
| Ion traps: phonon-mediated interactions | ✔ | ✔ | $10^0$-$10^2$ |
| Rydberg dressing (in optical clock) | ✔ | (✔) | $10^0$-$10^{3+}$ |



# One-Axis Twisting Echo: Implementation?

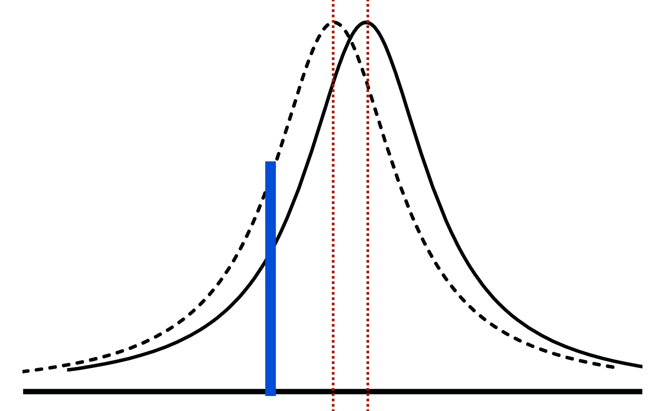
| $H = \mu S_z^2$ | Switchable sign | Coherence | Atom # |
|---|---|---|---|
| Cavity-mediated interactions | ✔ | (✔) | $10^1$-$10^6$ |
| BEC: collisional interactions | ? | ? | $10^2$-$10^4$ |
| Ion traps: phonon-mediated interactions | ✔ | ✔ | $10^0$-$10^2$ |
| Rydberg dressing (in optical clock) | ✔ | (✔) | $10^0$-$10^{3+}$ |

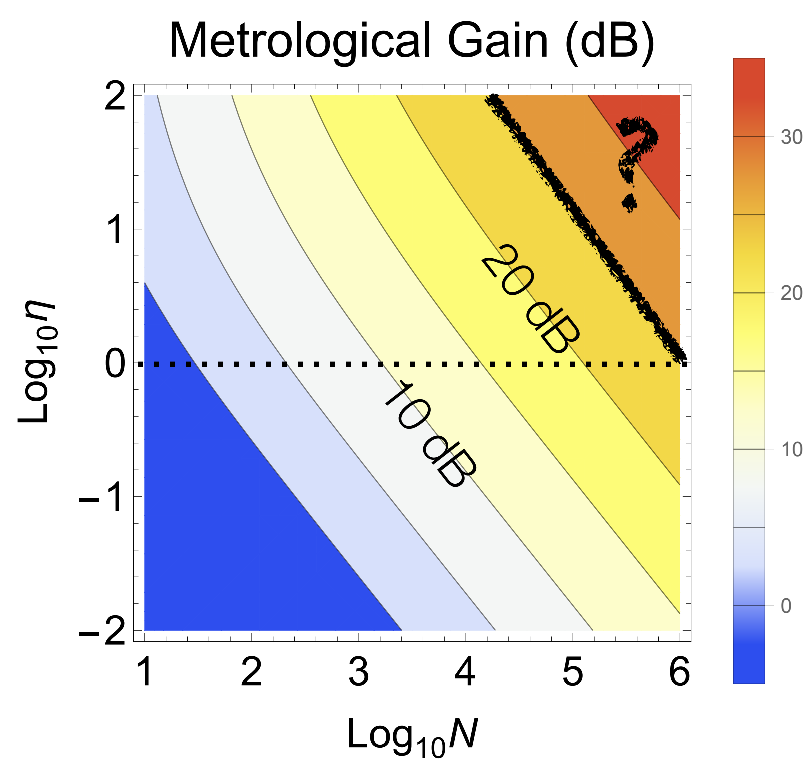


# One-Axis Twisting Echo: Implementation?

| $H = \mu S_z^2$ | Switchable sign | Coherence | Atom # |
|---|---|---|---|
| Cavity-mediated interactions | ✔ | (✔) | $10^1$-$10^6$ |
| BEC: collisional interactions | ? | ? | $10^2$-$10^4$ |
| Ion traps: phonon-mediated interactions | ✔ | ✔ | $10^0$-$10^2$ |
| Rydberg dressing (in optical clock) | ✔ | (✔) | $10^0$-$10^{3+}$ |

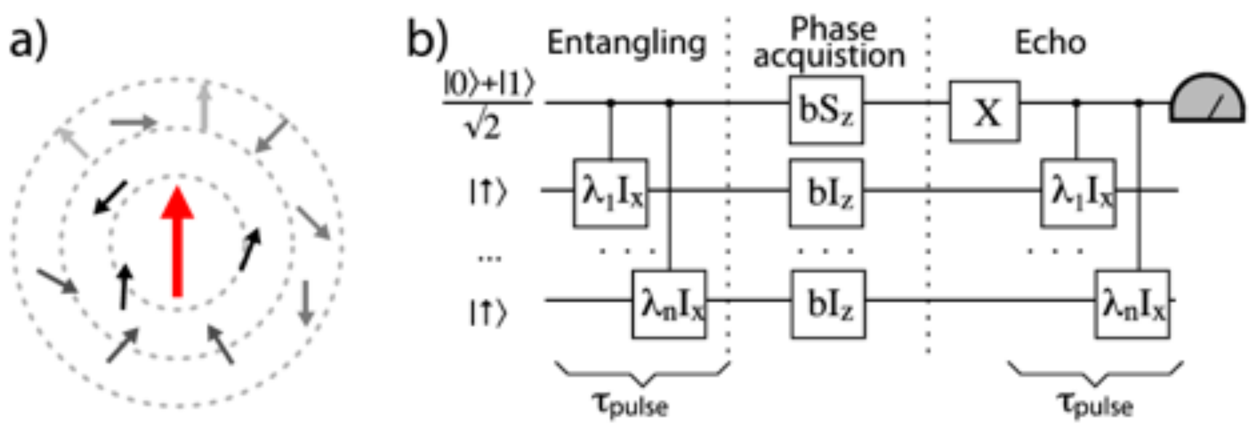
$\Delta\nu \propto N_\uparrow - N_\downarrow \propto S_z$



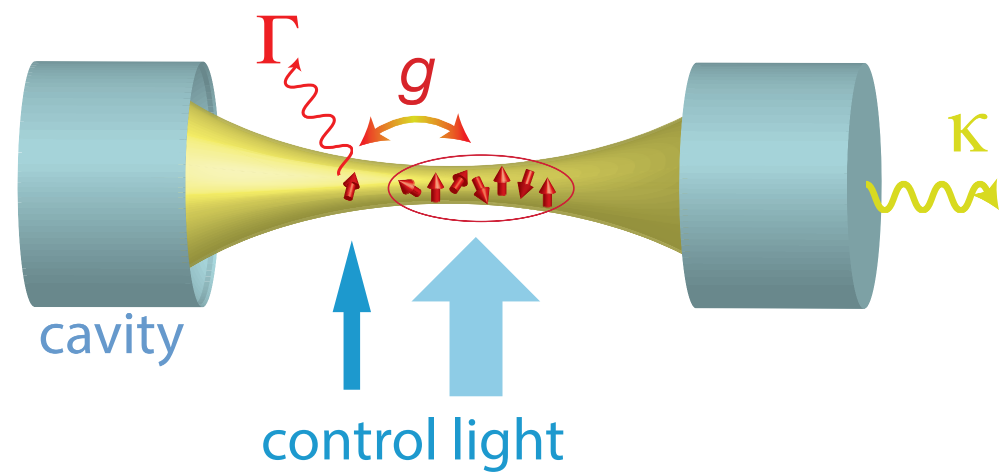


# Echoes: Further Outlook

### Environment-assisted precision measurement



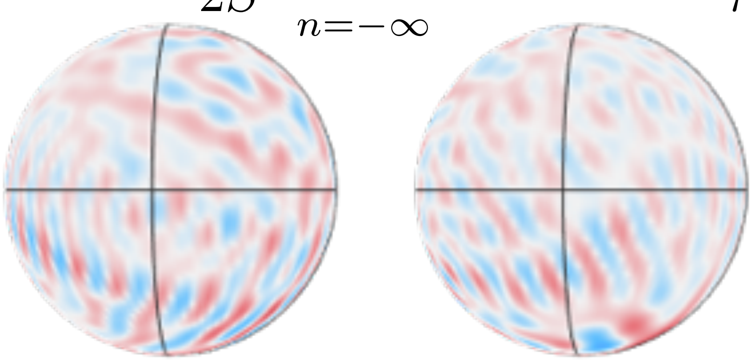

Goldstein, Cappellaro, Maze, Hodges, Jiang, Sørensen, & Lukin, PRL (2011).




### Loschmidt echo in a chaotic system

- Rapid generation of many-particle entanglement?
- Harnessing sensitivity to perturbations for metrological gain?
- Sub-planck features on Bloch sphere?

$$H = \frac{QS_z^2}{2S}\sum_{n=-\infty}^{\infty}\delta(t-n\tau) + \frac{p}{\tau}S_y$$



Quantum kicked top

Haake, *Z. Phys. B*, 1987.
Chaudhury *et al.*, *Nature* (2009).

# Measuring Fast Scrambling

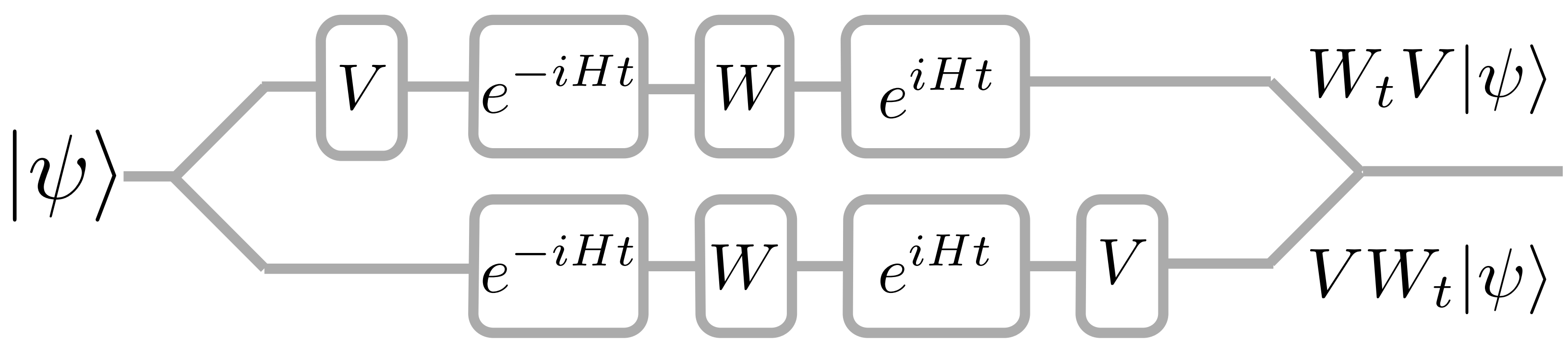
with Brian Swingle & Patrick Hayden

Scrambling: when all degrees of freedom become entangled with one another

[Hayden, Preskill, Susskind, Shenker, Stanford, …]

- Fundamental bound on scrambling speed saturated by black holes
- Mapping between black holes and chaotic spin models

Quantified by decay of out-of-time-order correlation functions $F = \langle\psi|W_t^\dagger V^\dagger W_t V|\psi\rangle$




Measuring $F$ requires:

- "Reversing time" ($H \to -H$)
- Qubit-controlled operation on many-particle system

# Measuring Fast Scrambling

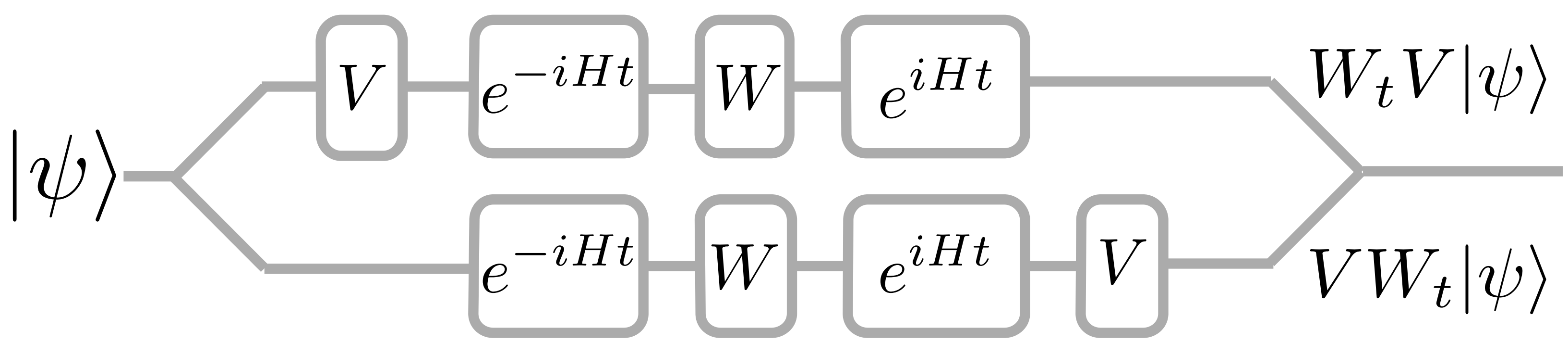
with Brian Swingle & Patrick Hayden

Scrambling: when all degrees of freedom become entangled with one another

[Hayden, Preskill, Susskind, Shenker, Stanford, …]

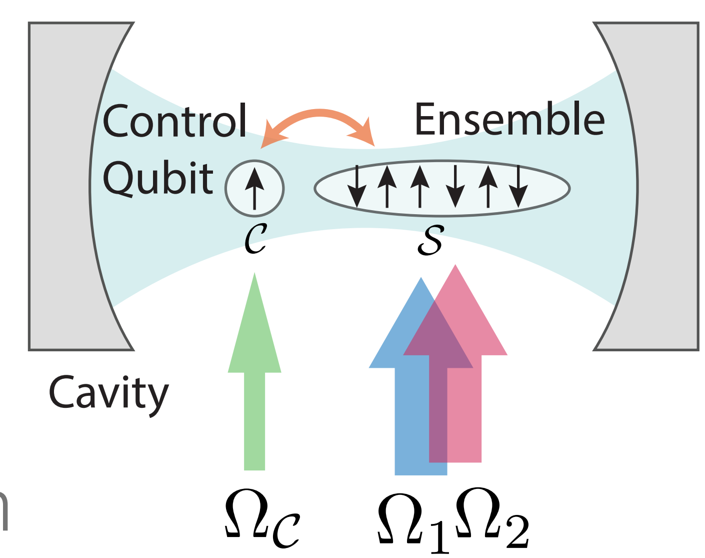
- Fundamental bound on scrambling speed saturated by black holes
- Mapping between black holes and chaotic spin models

Quantified by decay of out-of-time-order correlation functions $F = \langle\psi|W_t^\dagger V^\dagger W_t V|\psi\rangle$




Measuring $F$ requires:

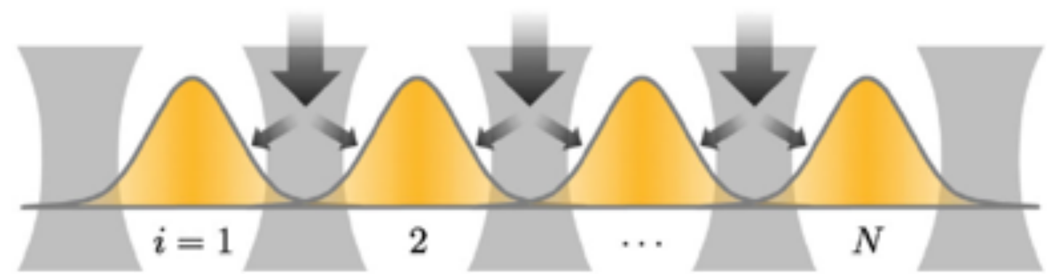
- “Reversing time” ($H \to -H$)
- Qubit-controlled operation on many-particle system



# Prospect: Photonic Lattices

## Motivation: many-body physics in coupled cavity arrays

- Driven-dissipative Hubbard models
- Majorana-like modes of light
- Gauge fields for photons



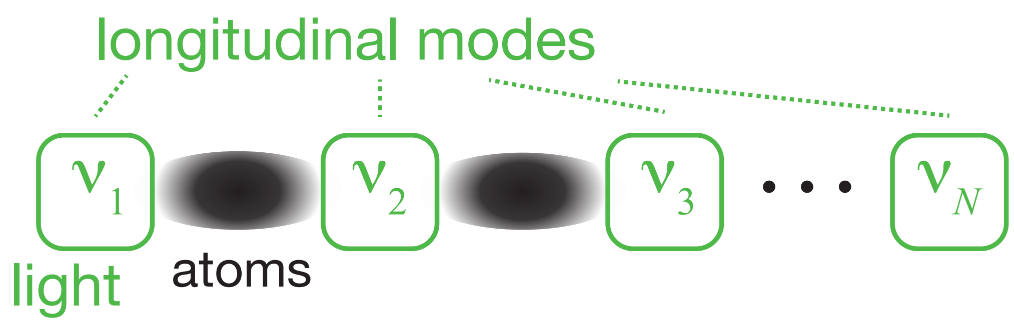

Bardyn & Imamoglu, PRL (2012).

## Approach:

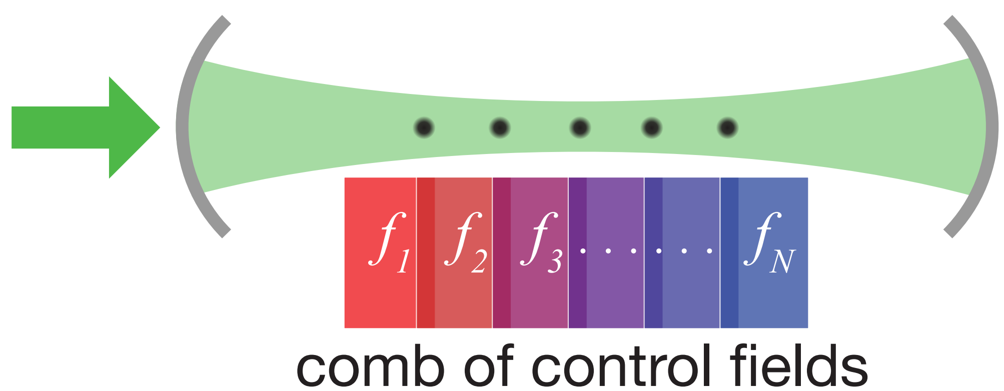
- Lattice in synthetic dimension: frequency space
- Hopping mediated by atoms

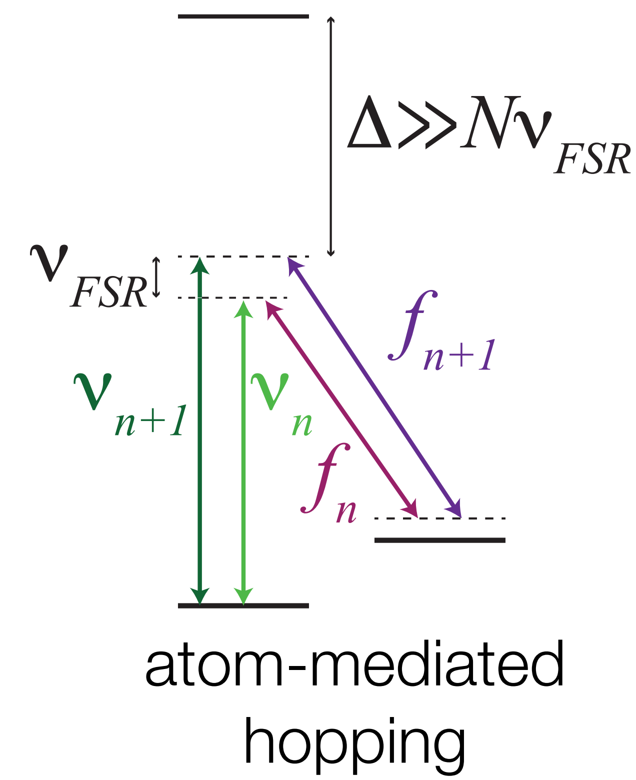
# Photonic Lattice in Synthetic Dimensions

Concept:




Implementation:




- Atoms also mediate interactions between photons in each mode
- Extension to 2 polarization modes ⇒ ladder (+ magnetic flux)

# Prospect: Dynamical Gauge Field

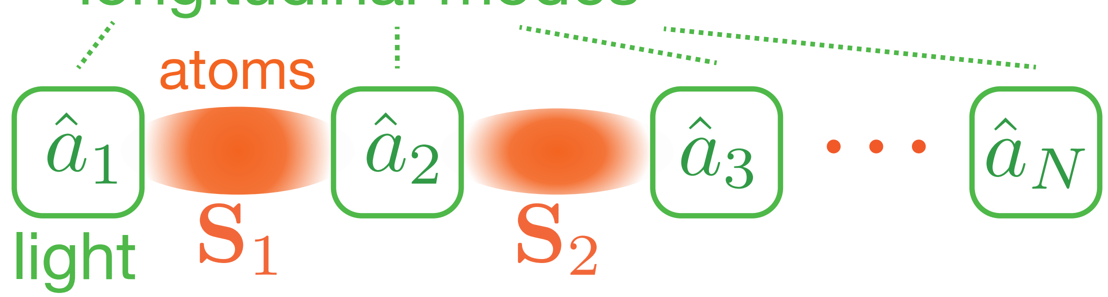
E.g., Schwinger model: $$H = \sum_\ell \left[ m\hat{\psi}_\ell^\dagger (-1)^\ell \hat{\psi}_\ell + g(S_\ell^z)^2 - J\hat{\psi}_{\ell+1}^\dagger S_\ell^+ \hat{\psi}_\ell + h.c. \right]$$

fermions    gauge field    hopping

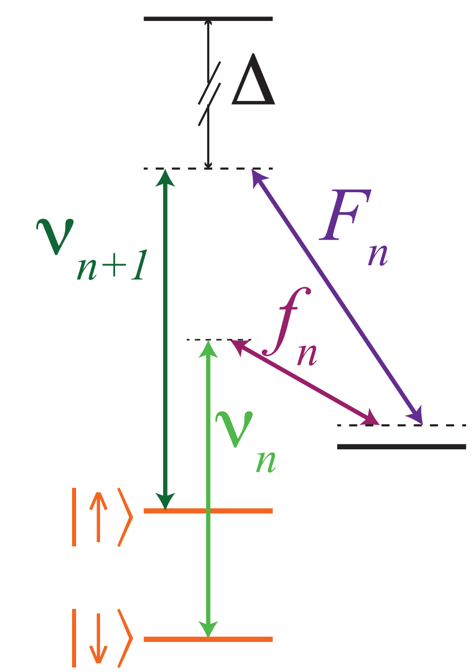
Proposed implementations:

- optical lattices [Zohar & Resnik, *PRL* (2011); D. Banerjee, Dalmonte, Müller, … & Zoller, *PRL* (2013).]
- superconducting circuits [Marcos, Rabl, Rico & Zoller, *PRL* (2013).]

Cold atoms +
optical photons?




$$H = \sum_\ell \left[ g(S_\ell^z)^2 - J\hat{a}_{\ell+1}^\dagger S_\ell^+ \hat{a}_\ell + h.c. + U\hat{a}_\ell^\dagger \hat{a}_\ell^\dagger \hat{a}_\ell \hat{a}_\ell \right]$$




spin-flip-mediated
hopping

# Acknowledgements


## Current group

Emily Davis

Gregory Bentsen

Tori Borish

Ognjen Markovic

Sebastian Scherg

## Collaborators

Brian Swingle

Patrick Hayden

## Past visitors

Anna Wang (→ HRL Labs)

Thomas Reimann (→ ENS)


Stanford University