Measuring OTOCs with Trapped-Ions

Arghavan Safavi-Naini

Collaborators

Ana Maria Rey

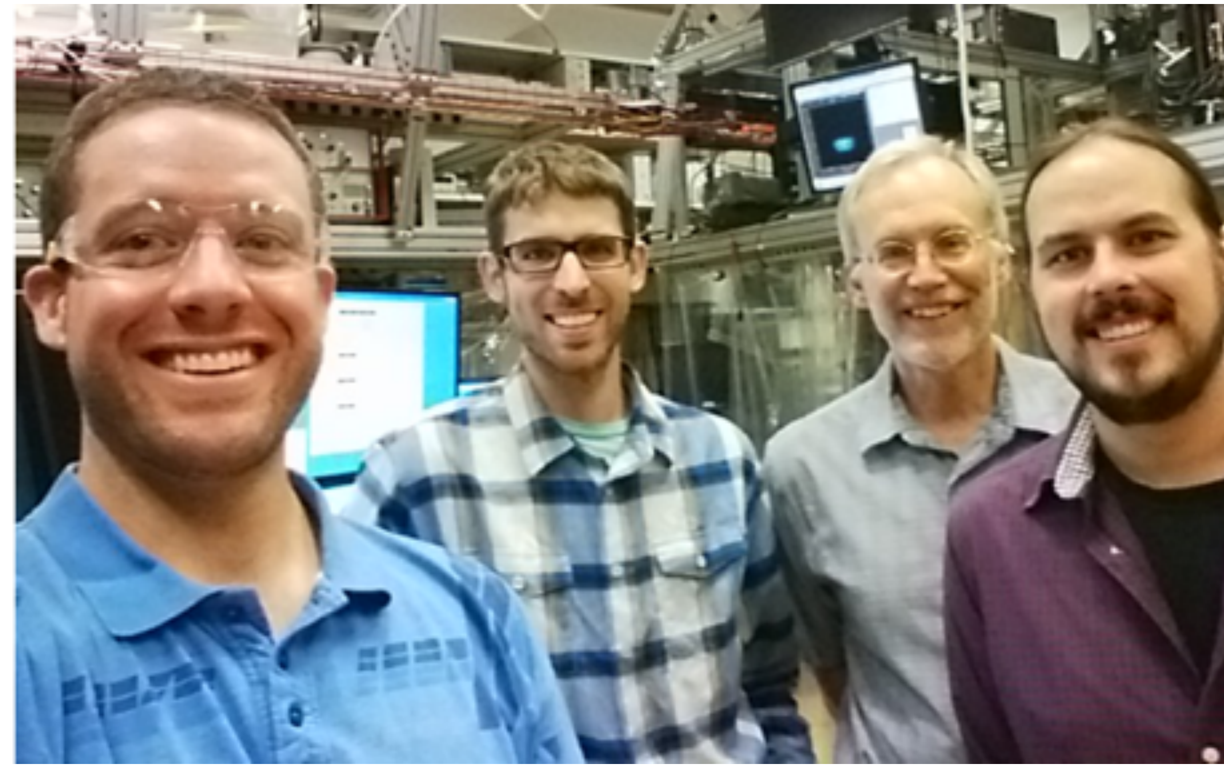
Michael Wall

Martin Garttner

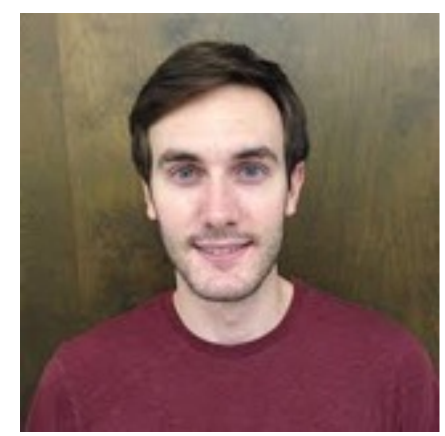
Robert Lewis-Swan

Experiments

John Bollinger



Joe Britton Justin Bohnet Brian Sawyer



Kevin Gilmore

Elena Jordan

References

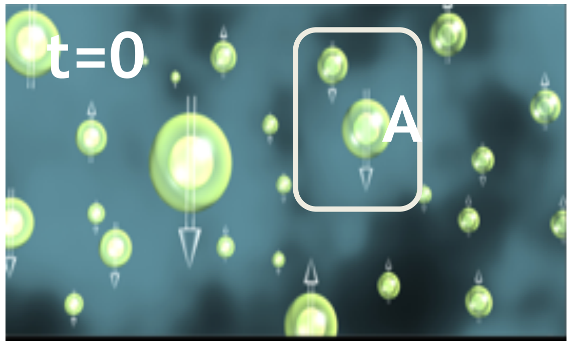
- Garttner, Bohnet, **ASN,** Wall, Gilmore, Bollinger, Rey '17
- Wall, **ASN,** Rey, '16, '17
- Garttner, Hauke, Rey '17
- **ASN,** Lewis-Swann, Garttner, Gilmore, Jordan, Rey, Bollinger, In preparation.

Quantum Simulation

→ Quantum many-body problems intractable for classical computers.
→ Use well-controlled quantum system to simulate (an idealized version of) another quantum system

Quantum Simulation

→ Quantum many-body problems intractable for classical computers.
→ Use well-controlled system of fully characterized quantum components to simulate another quantum system

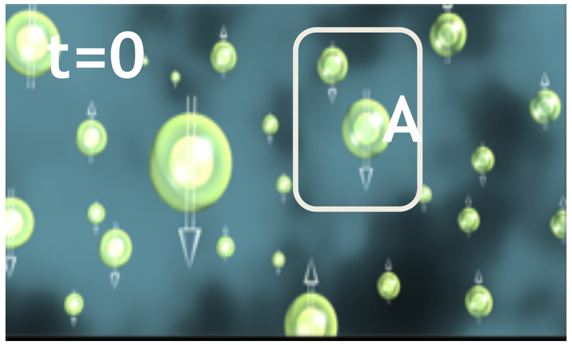


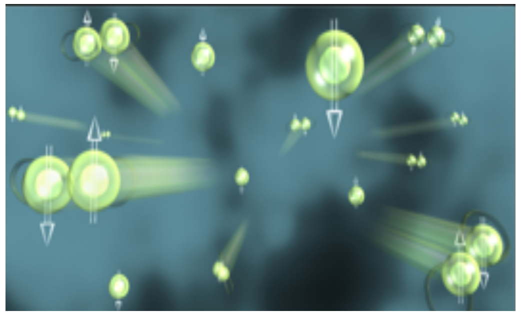
$$|\psi_{\mathrm{in}}\rangle$$

Can prepare easily
separable

Quantum Simulation

→ Quantum many-body problems intractable for classical computers.
→ Use well-controlled system of fully characterized quantum components to simulate another quantum system





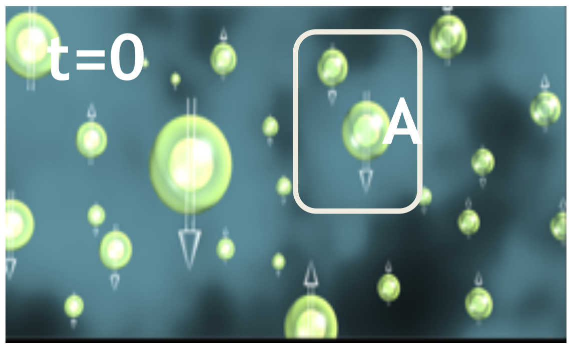
$|\psi_{\text{in}}\rangle$ → $\mathcal{H}$

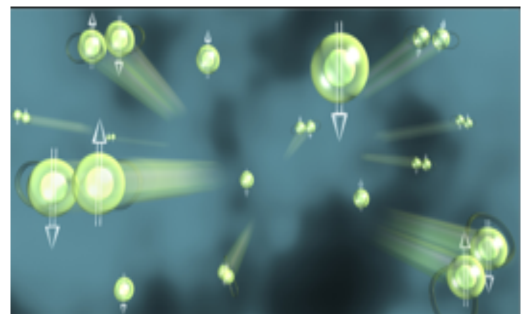
Can prepare easily
separable

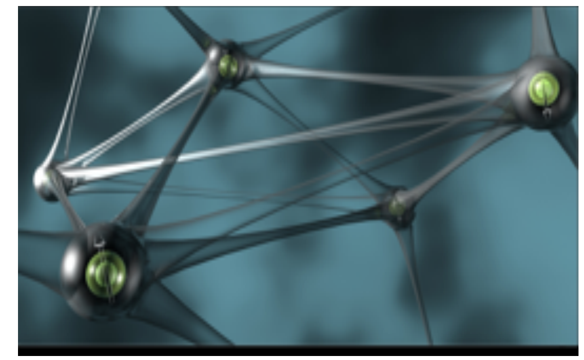
Evolve

Quantum Simulation

→ Quantum many-body problems intractable for classical computers.
→ Use well-controlled quantum system to simulate (an idealized version of) another quantum system







$|\psi_{\mathrm{in}}\rangle$ → $\mathcal{H}$ → $|\psi_{\mathrm{out}}\rangle$

Can prepare easily
separable

Evolve

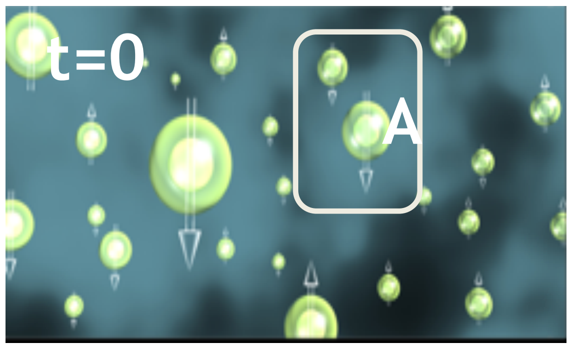
Useful state
entangled

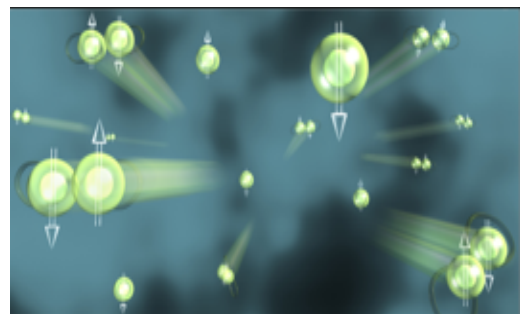
→ Hard to characterize the state fully
- Full-state tomography scales badly
- Often limited to global observables in large systems

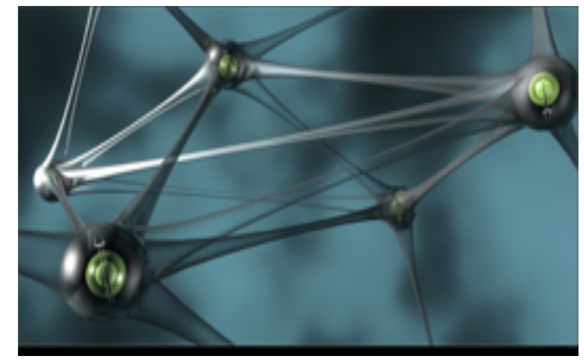
→ Verifiable implementations
- Choose Hamiltonians that can be benchmarked
- Develop measures that are experimentally and theoretically viable

Quantum Simulation

→ Quantum many-body problems intractable for classical computers.
→ Use well-controlled quantum system to simulate (an idealized version of) another quantum system







$|\psi_{\text{in}}\rangle$ → $\mathcal{H}$ → $|\psi_{\text{out}}\rangle$

Can prepare easily
separable

Evolve

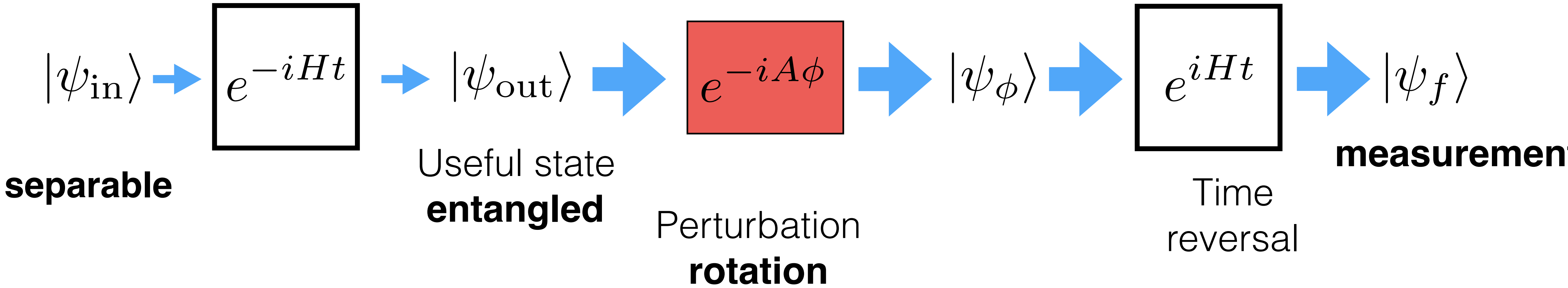
Useful state
entangled

→ Hard to characterize the state fully
- Full-state tomography scales badly
- **Often limited to global observables in large systems**

What is the best we can do with these limitations?

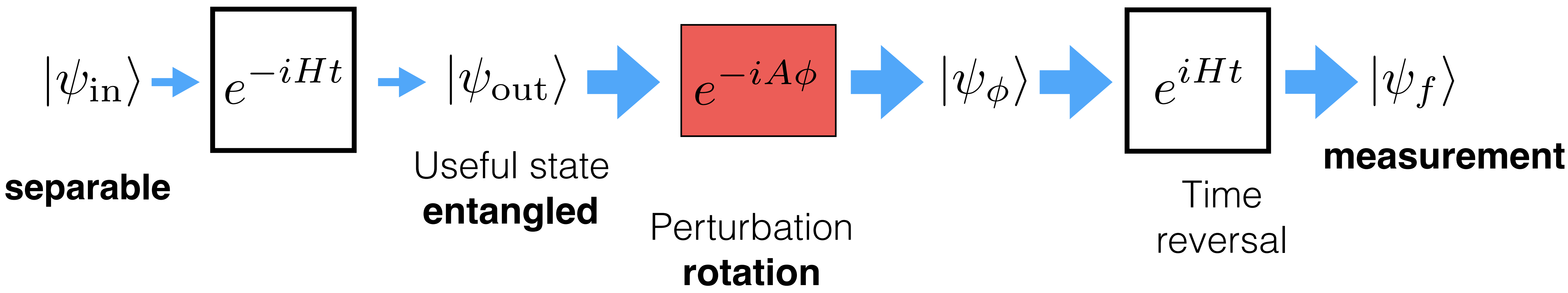
→ Verifiable implementations
- Choose Hamiltonians that can be benchmarked
- Develop measures that are experimentally and theoretically viable

Time-reversal to the Rescue



Time reversal allows to extract **more information** about the state using only **global observables** $\langle\psi_f|\hat{A}|\psi_f\rangle$

Time-reversal to the Rescue

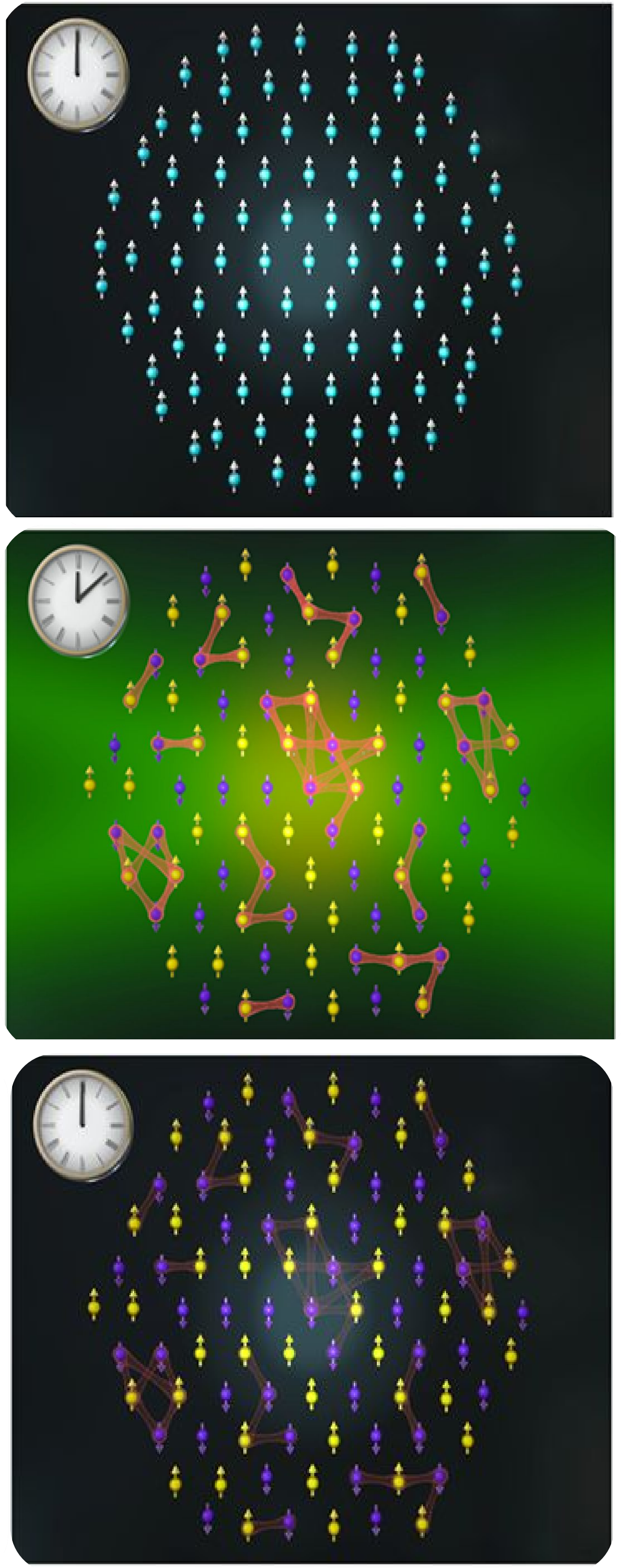


Time reversal allows to extract **more information** about the state using only **global observables** $\langle\psi_f|\hat{A}|\psi_f\rangle$

Out of time order correlator

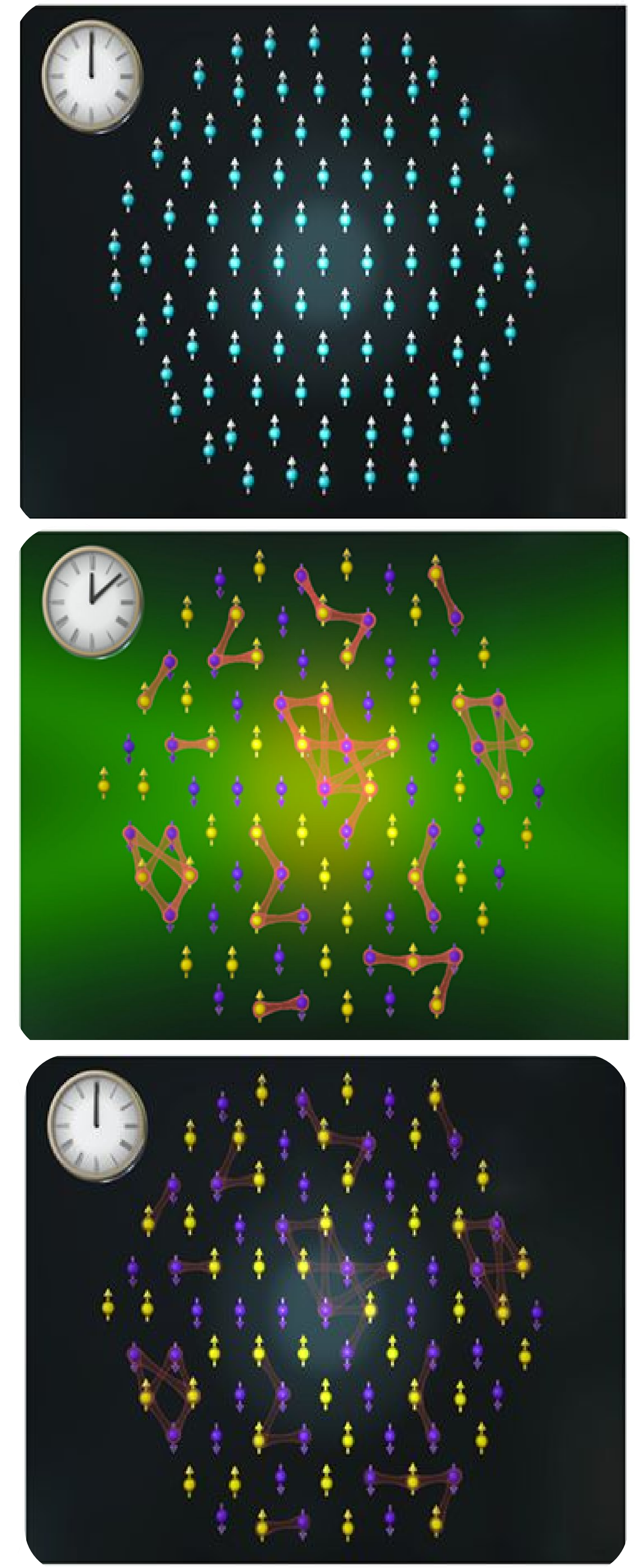
Overview

- Trapped ion quantum simulator of **Ising dynamics**



Overview

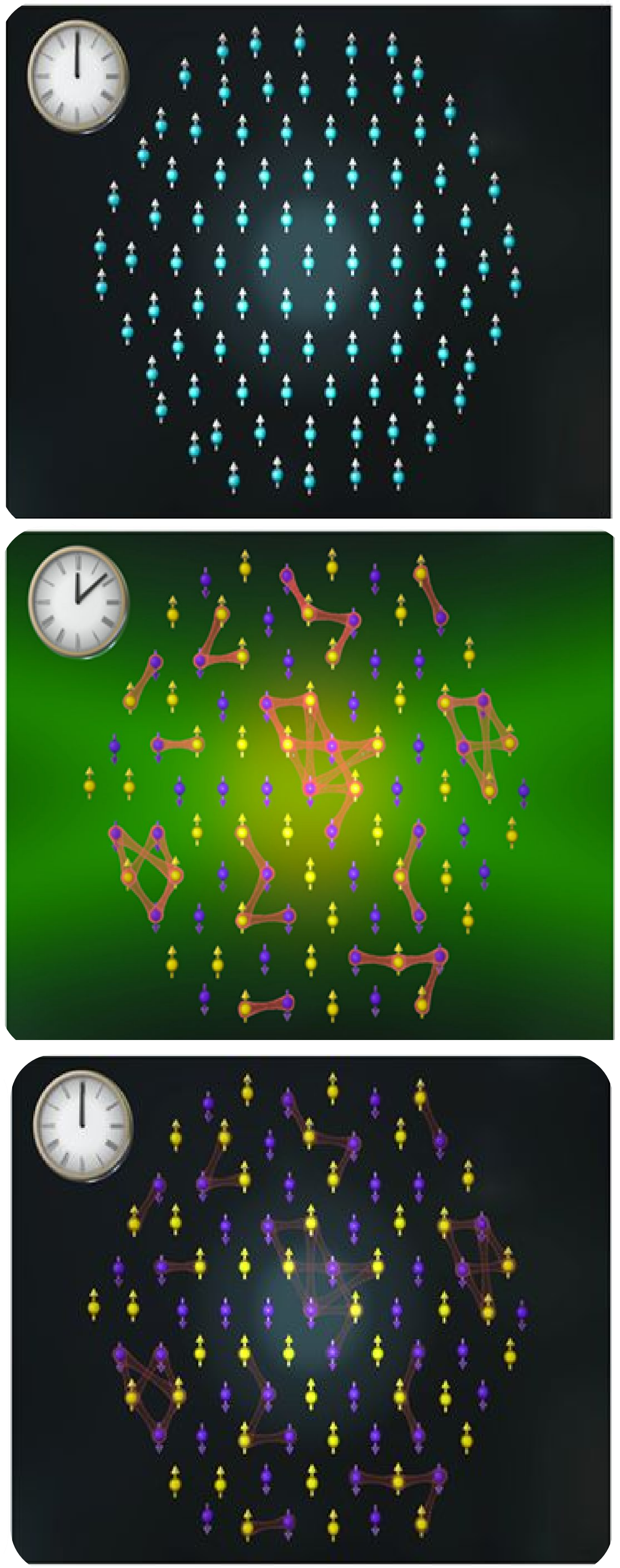
- Trapped ion quantum simulator of **Ising dynamics**
- **Fidelity** measurement
  - → Multiple quantum coherences
  - → Loschmidt echo
  - → Quantum Fisher information
- **Magnetization** measurement
  - → Buildup of correlations



Overview

- Trapped ion quantum simulator of **Ising dynamics**
- **Fidelity** measurement
  - → Multiple quantum coherences
  - → Loschmidt echo
  - → Quantum Fisher information
- **Magnetization** measurement
  - → Buildup of correlations

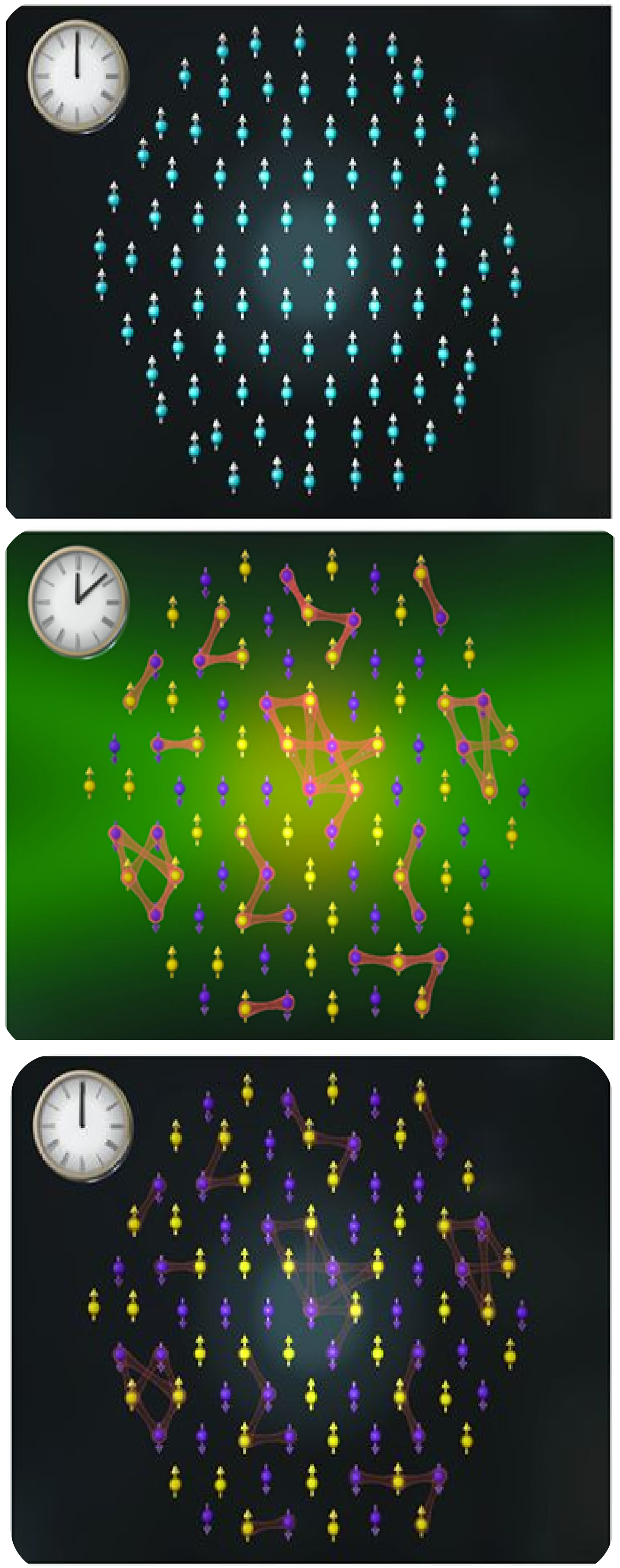
OTOCs



Overview

- Trapped ion quantum simulator of **Ising dynamics**
- **Fidelity** measurement
  - → Multiple quantum coherences
  - → Loschmidt echo
  - → Quantum Fisher information
- **Magnetization** measurement
  - → Buildup of correlations
- Adding complexity: **Dicke model**

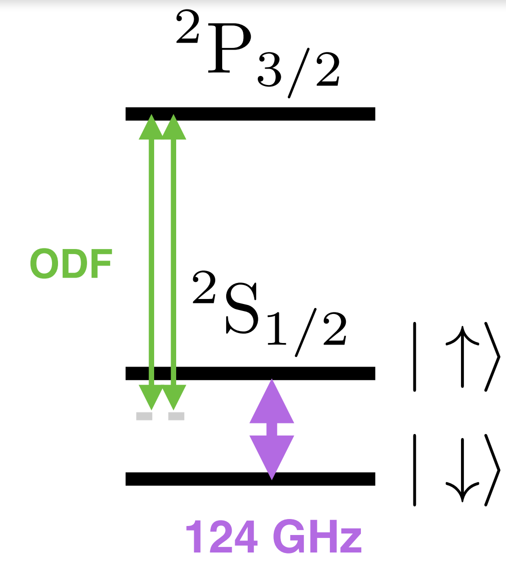
OTOCs

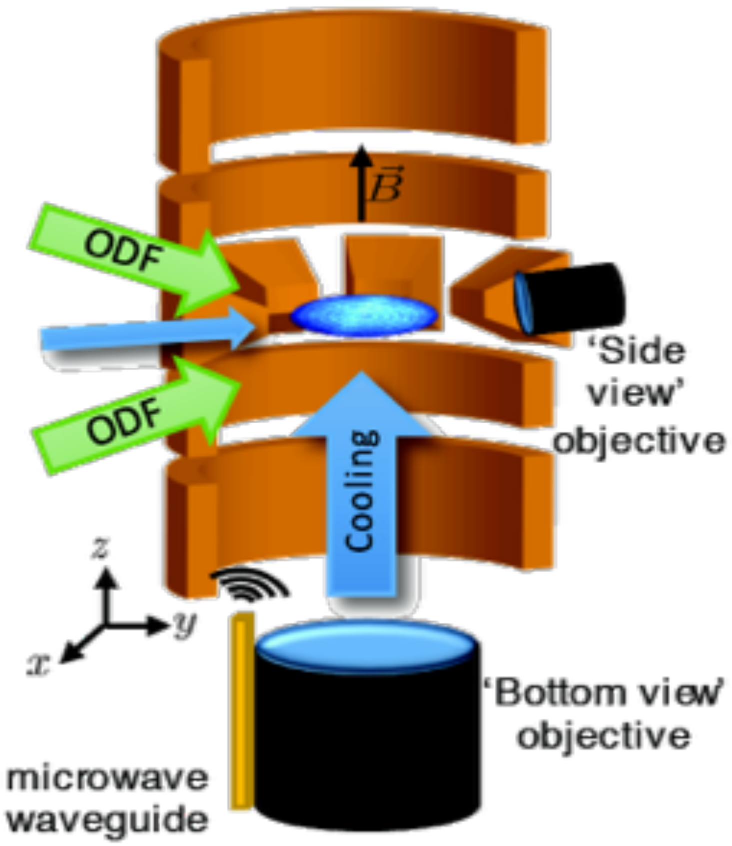


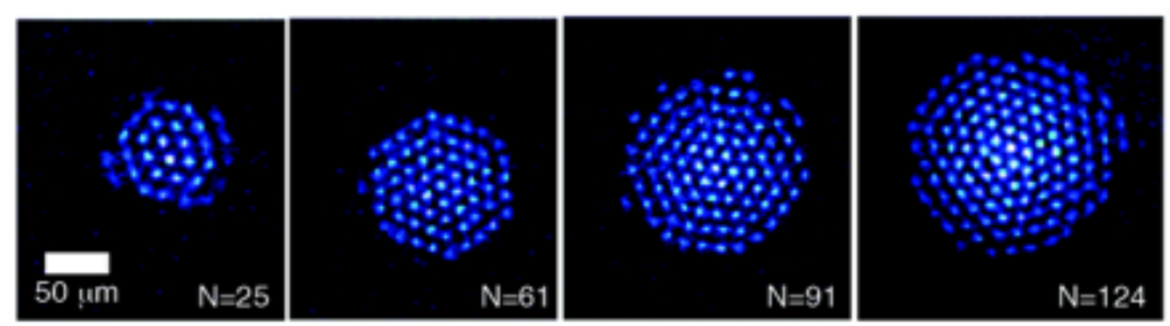
System

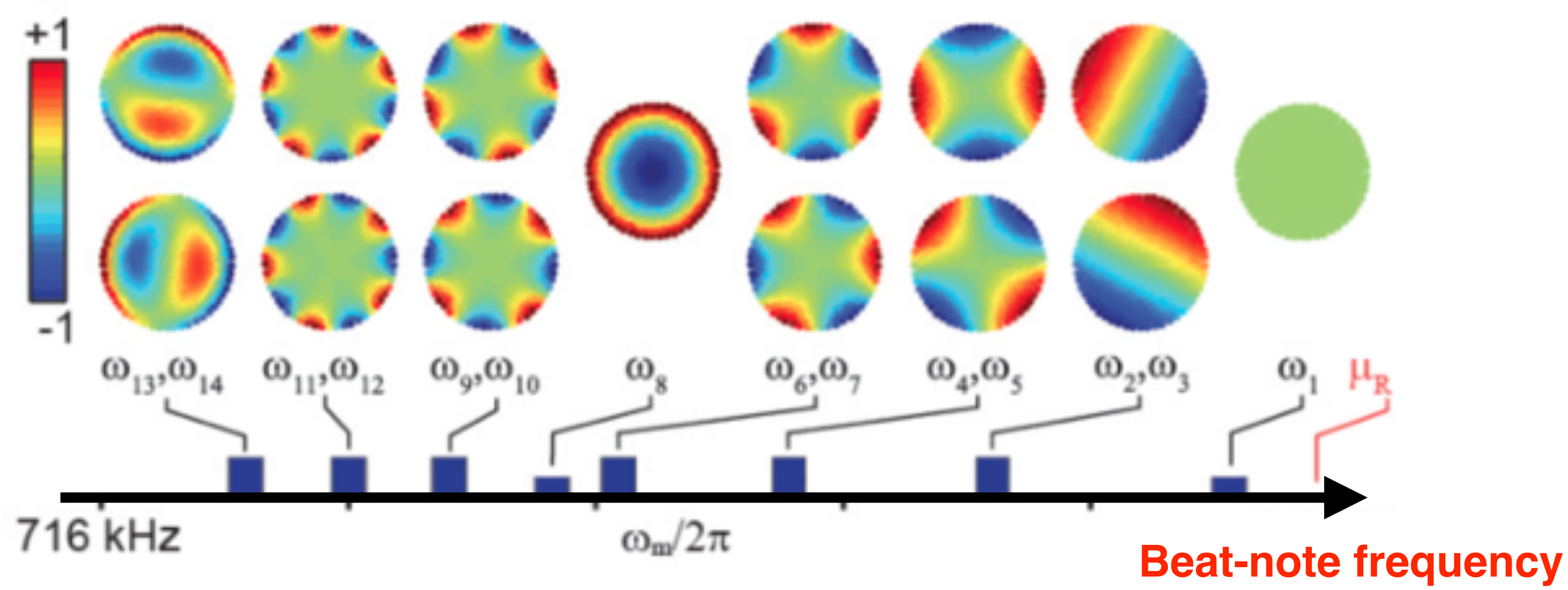
Our system:

- Triangular crystal of Be^{+} ions
  - Stabilized due to the **Coulomb repulsion** between the ions and **external trapping**
- Use two hyperfine states of the ion to form the **spin**
- Couple the spin to the transverse modes of the crystal (**phonons**)









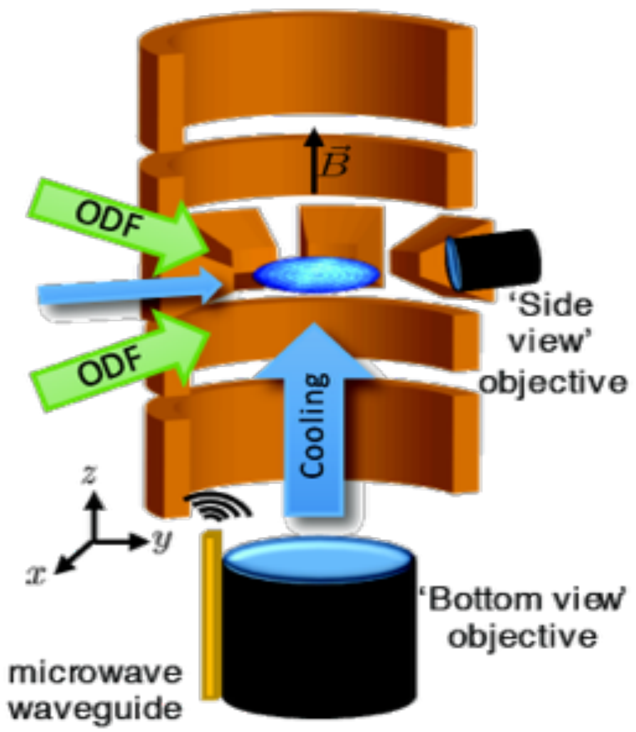
Frequency of the vibrational modes

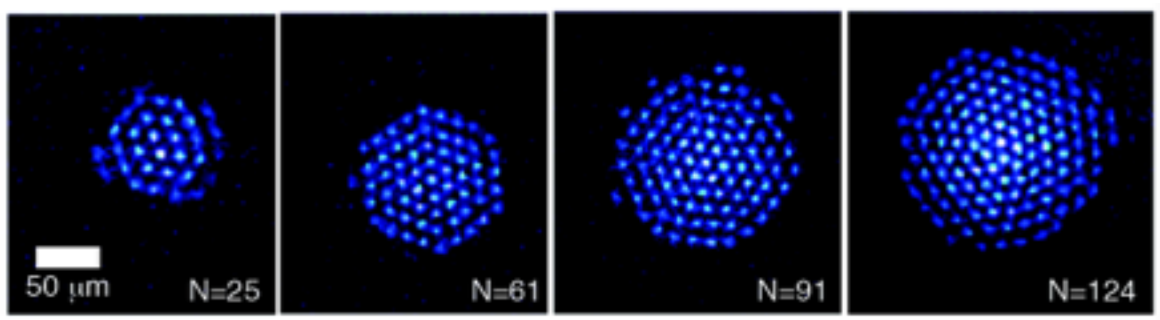
Britton et al. Nature 2012
Bohnet et al. Science 2015

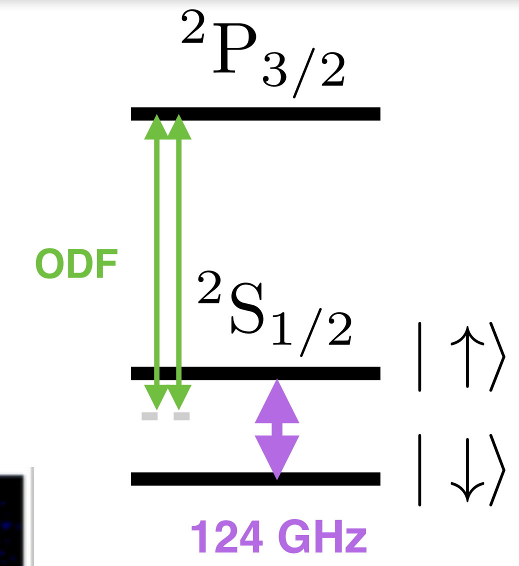
System

Our system:

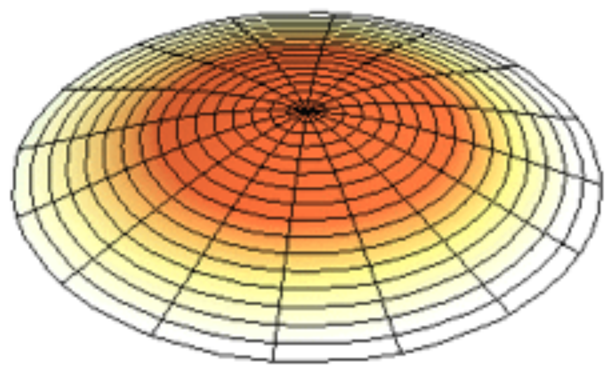
- Triangular crystal of Be^+ ions
  - Stabilized due to the **Coulomb repulsion** between the ions and **external trapping**
- Use two hyperfine states of the ion to form the **spin**
- Couple the spin to the transverse modes of the crystal (**phonons**)







ONLY couple to COM



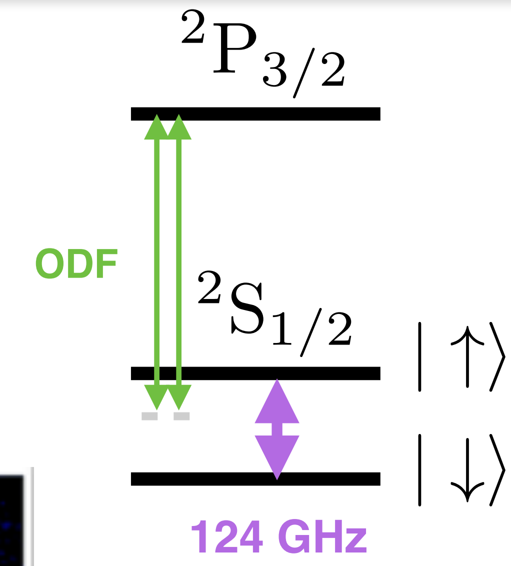
COM

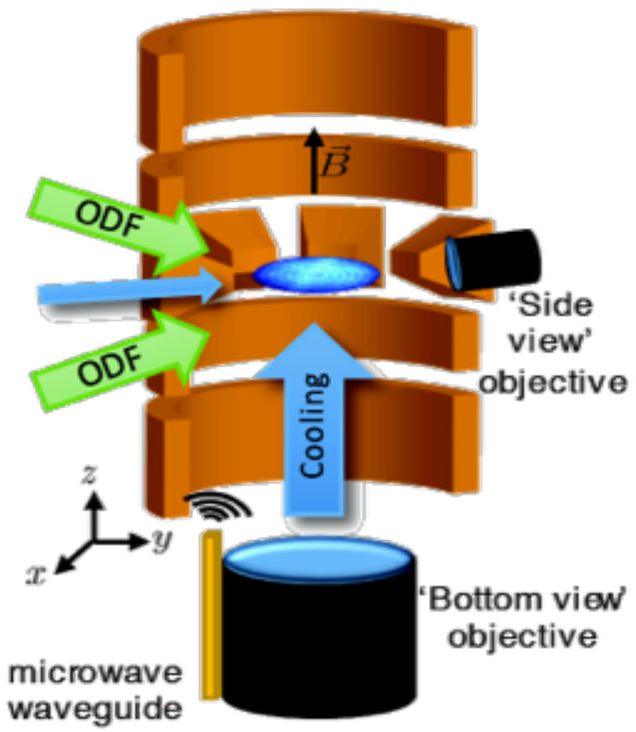
Britton et al. Nature 2012
Bohnet et al. Science 2015

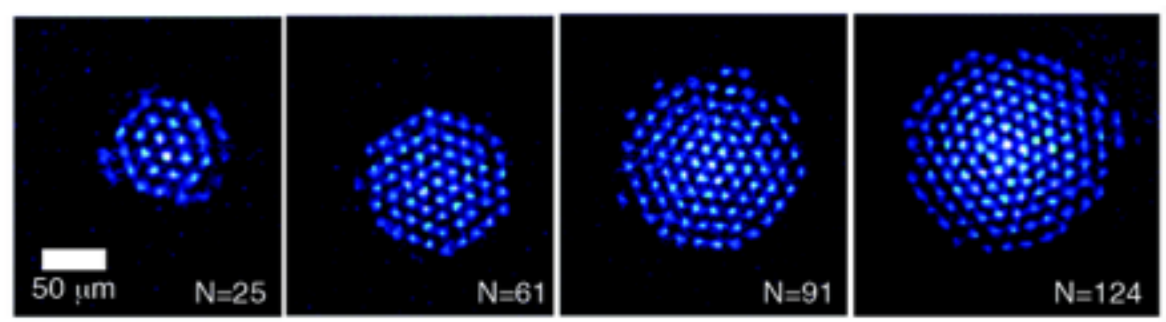
System

Our system:

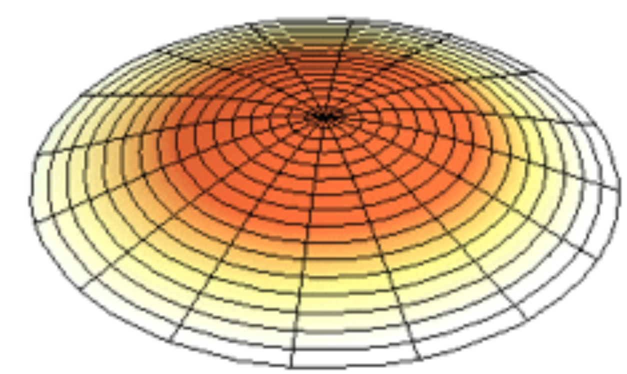
- Triangular crystal of Be^+ ions
  - Stabilized due to the **Coulomb repulsion** between the ions and **external trapping**
- Use two hyperfine states of the ion to form the **spin**
- Couple the spin to the transverse modes of the crystal (**phonons**)







ONLY couple to COM



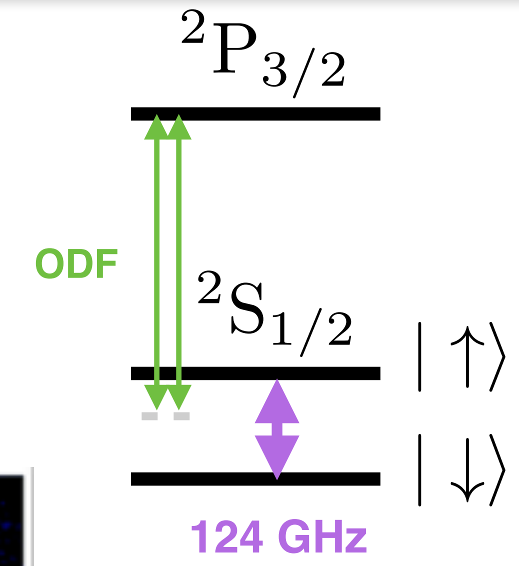
COM

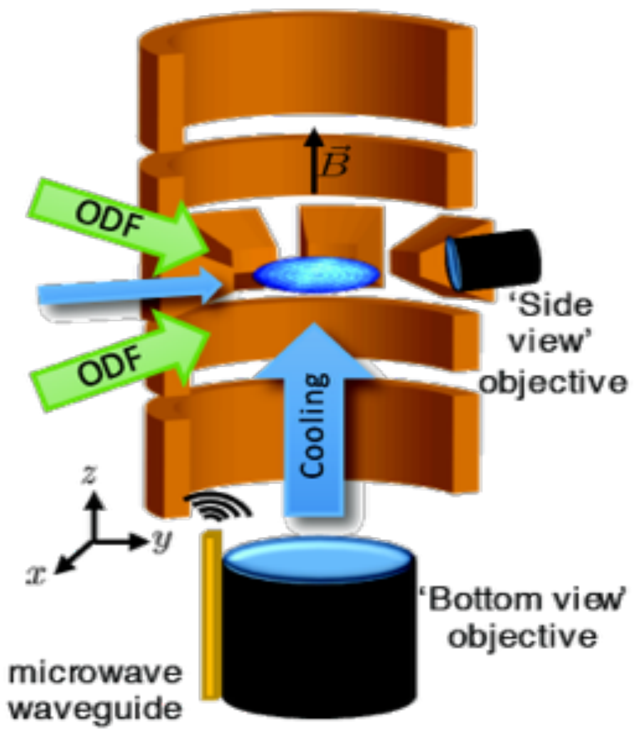
Britton et al. Nature 2012
Bohnet et al. Science 2015

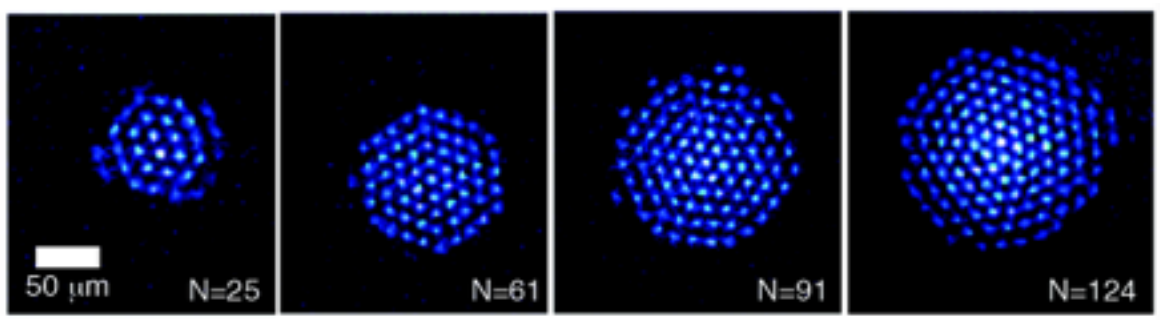
System

Our system:

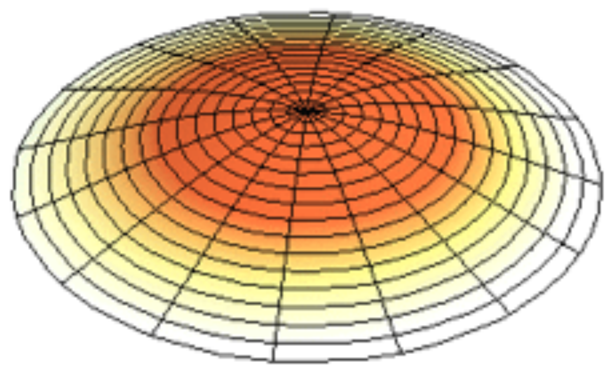
- Triangular crystal of Be^+ ions
  - Stabilized due to the **Coulomb repulsion** between the ions and **external trapping**
- Use two hyperfine states of the ion to form the **spin**
- Couple the spin to the transverse modes of the crystal (**phonons**)







ONLY couple to COM



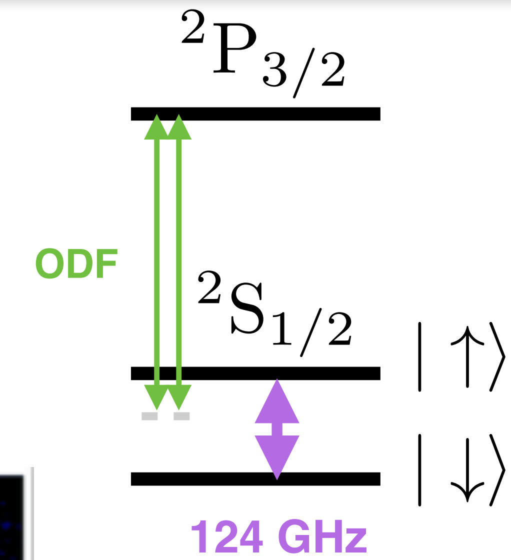
COM

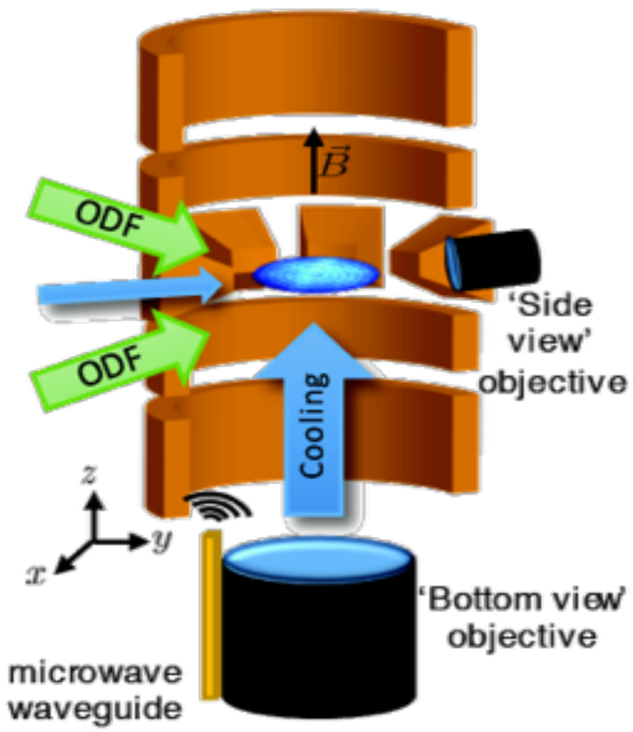
Britton et al. Nature 2012
Bohnet et al. Science 2015

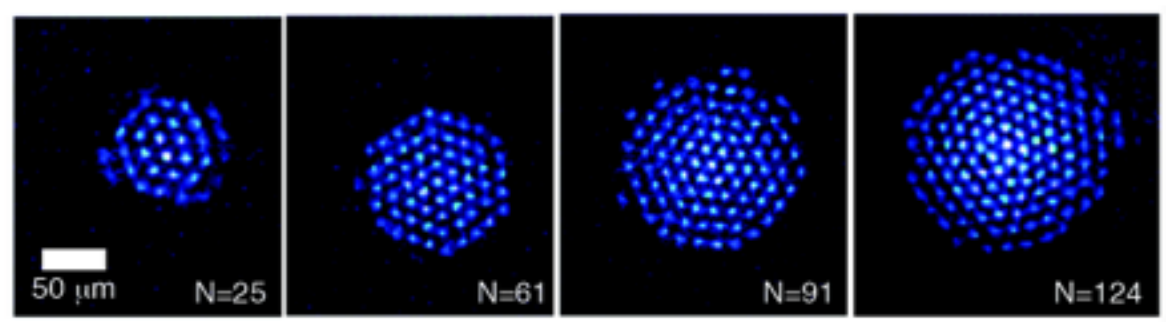
System

Our system:

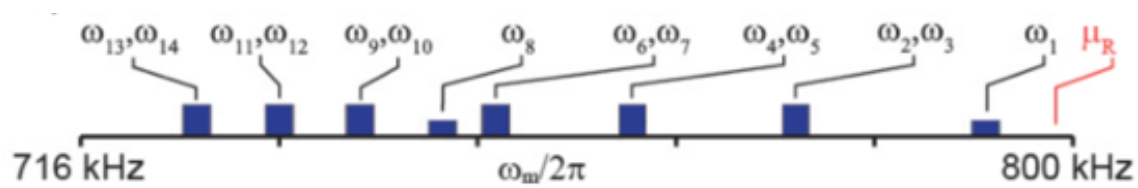
- Triangular crystal of Be^+ ions
  - Stabilized due to the **Coulomb repulsion** between the ions and **external trapping**
- Use two hyperfine states of the ion to form the **spin**
- Couple the spin to the transverse modes of the crystal (**phonons**)

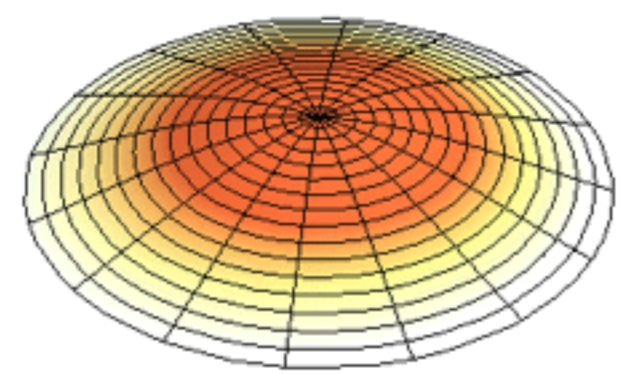






ONLY couple to COM





COM

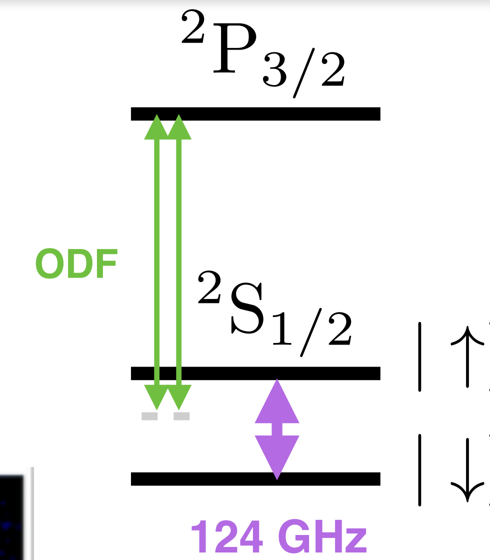
$$H(t) = -g(\mu_R, t)\hat{z}\hat{S}_z + \omega_0 n$$

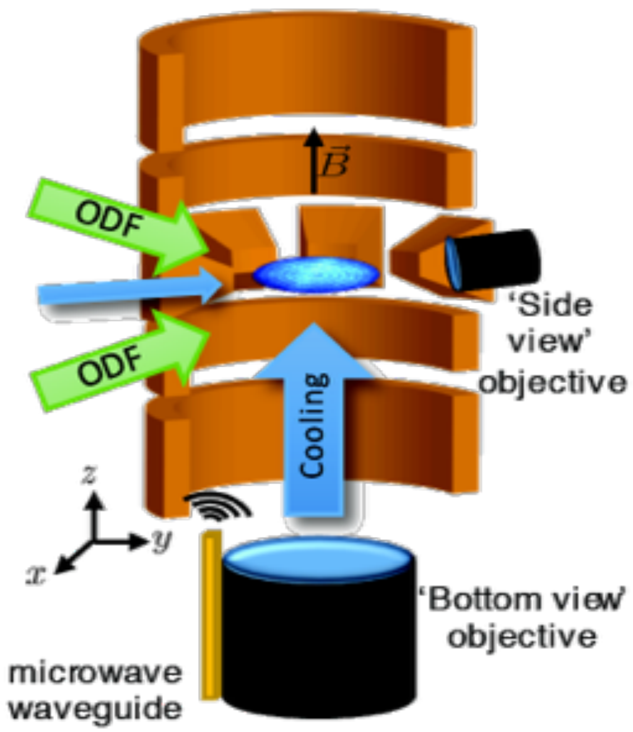
Britton et al. Nature 2012
Bohnet et al. Science 2015

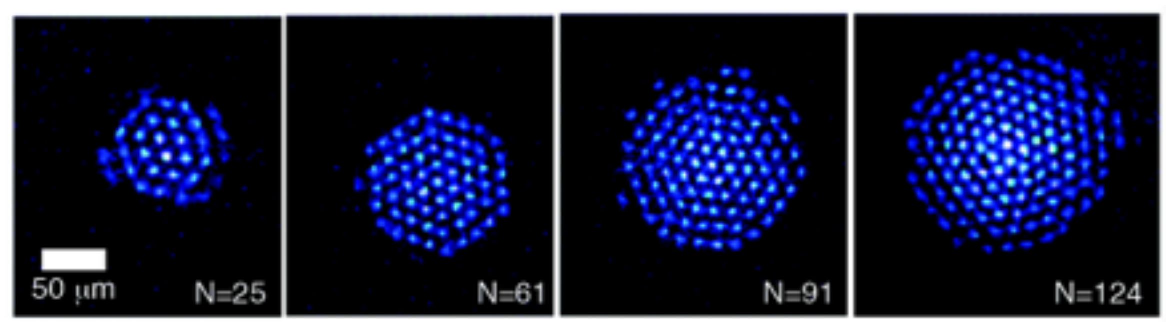
System

Our system:

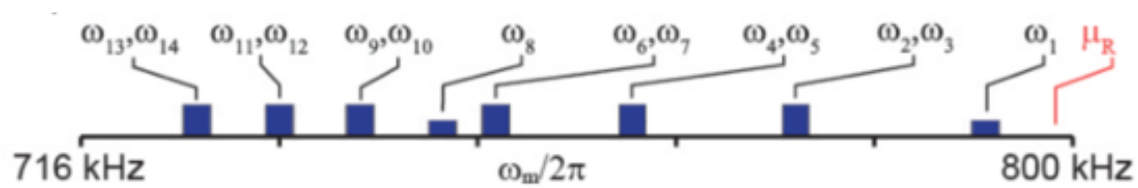
- Triangular crystal of Be^+ ions
    - Stabilized due to the **Coulomb repulsion** between the ions and **external trapping**
- Use two hyperfine states of the ion to form the **spin**
- Couple the spin to the transverse modes of the crystal (**phonons**)

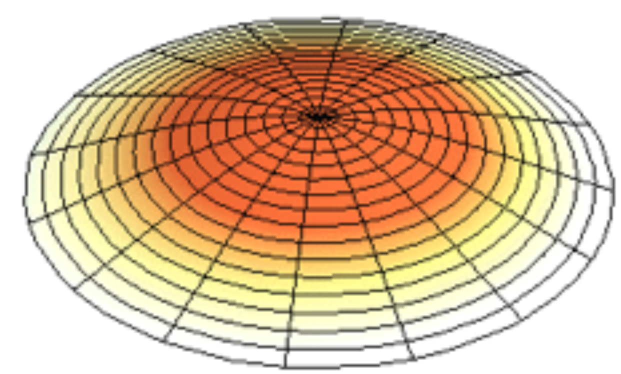






ONLY couple to COM





COM

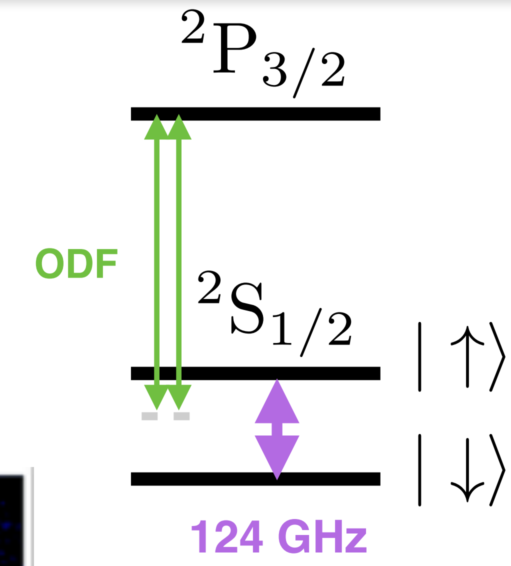
$$H(t) = -g(\mu_R, t)\hat{z}\hat{S}_z + \omega_0 n$$

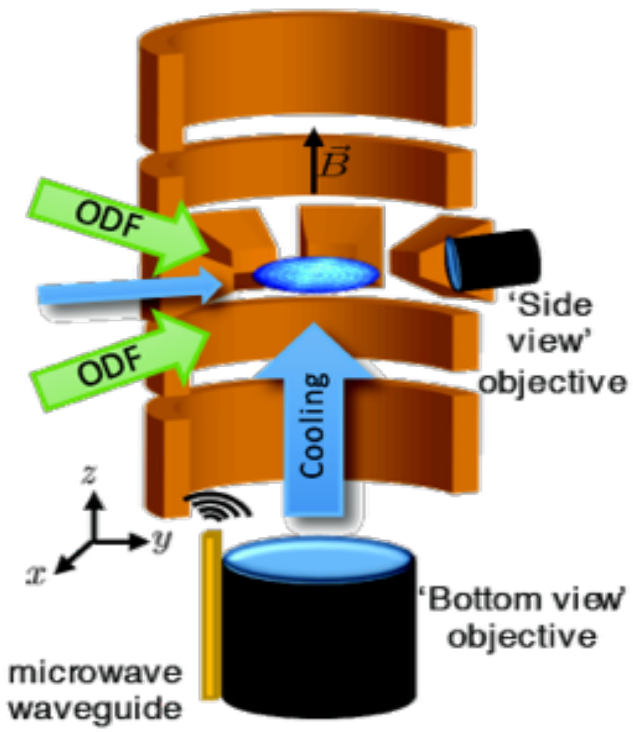
Britton et al. Nature 2012
Bohnet et al. Science 2015

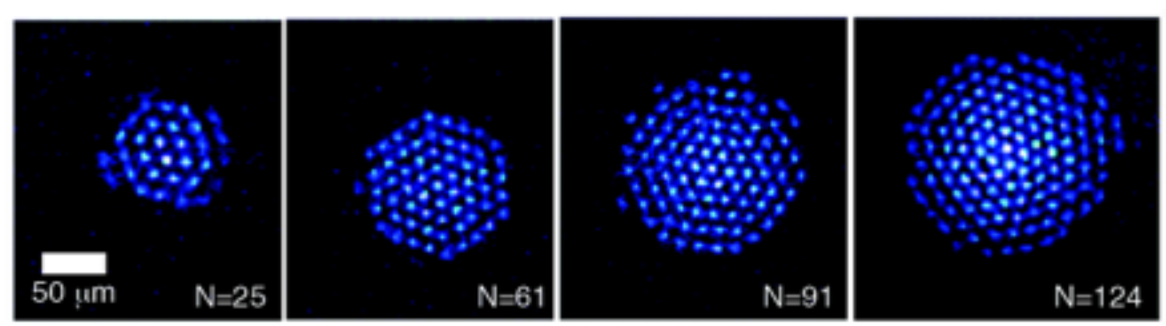
System

Our system:

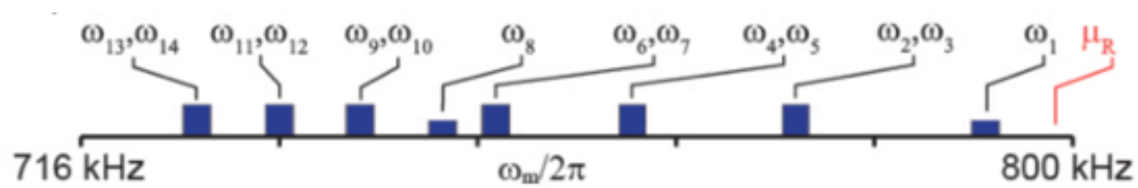
- Triangular crystal of Be^{+} ions
  - Stabilized due to the **Coulomb repulsion** between the ions and **external trapping**
- Use two hyperfine states of the ion to form the **spin**
- Couple the spin to the transverse modes of the crystal (**phonons**)

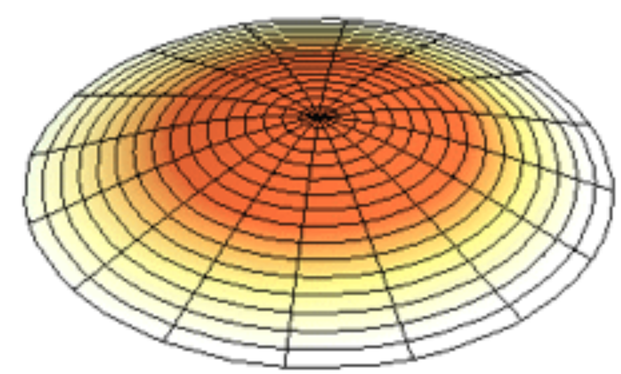






ONLY couple to COM





COM

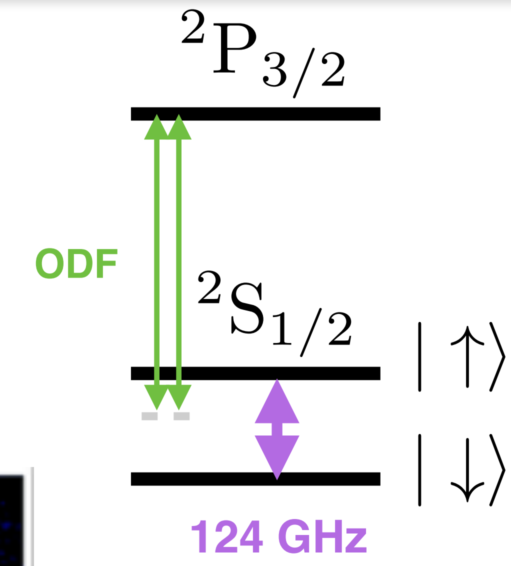
$$H(t) = -g(\mu_R, t)\hat{z}\hat{S}_z + \omega_0 n$$

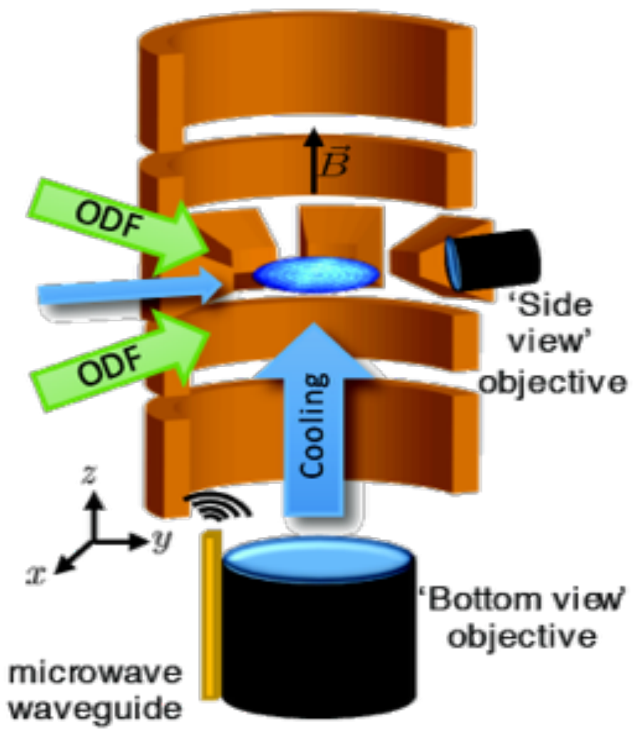
Britton et al. Nature 2012
Bohnet et al. Science 2015

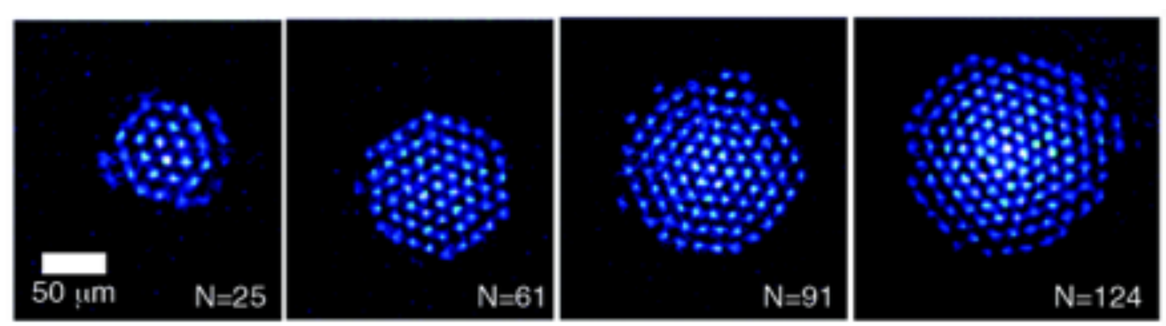
System

Our system:

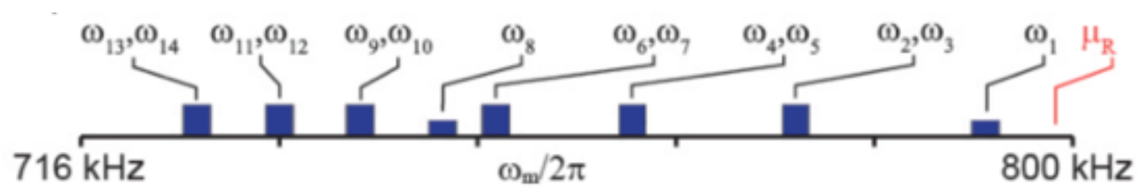
- Triangular crystal of Be^+ ions
  - Stabilized due to the **Coulomb repulsion** between the ions and **external trapping**
- Use two hyperfine states of the ion to form the **spin**
- Couple the spin to the transverse modes of the crystal (**phonons**)

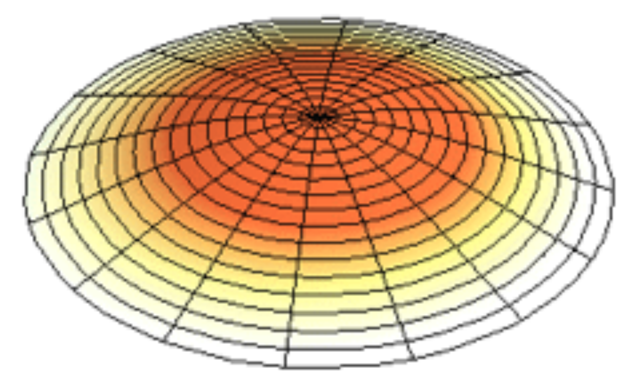






ONLY couple to COM





COM

$$H(t) = -g(\mu_R, t)\hat{z}\hat{S}_z + \omega_0 n$$

$$U(t) = U_{\text{SP}}(t)U_{\text{SS}}(t)$$

spin-phonon **spin-spin**

$$\hat{H}_{\text{SS}} = \frac{J}{N}\hat{S}_z^2$$

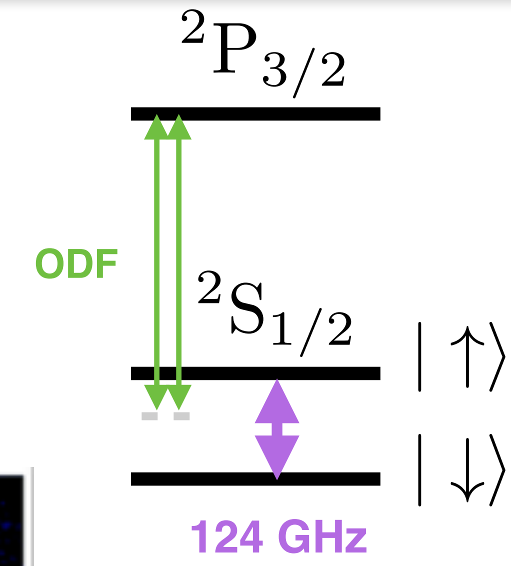
$$J \propto \frac{g^2}{\delta}$$

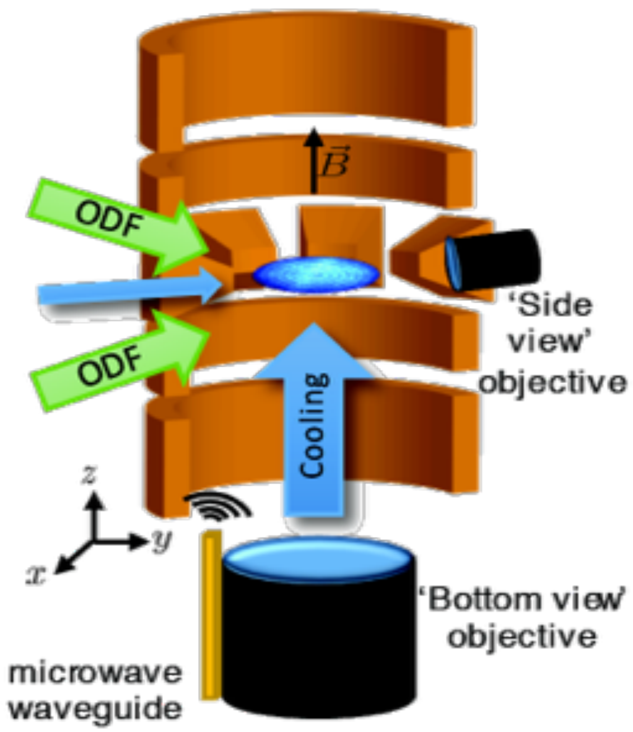
Britton et al. Nature 2012
Bohnet et al. Science 2015
Wall, ASN, Rey, '16 '17

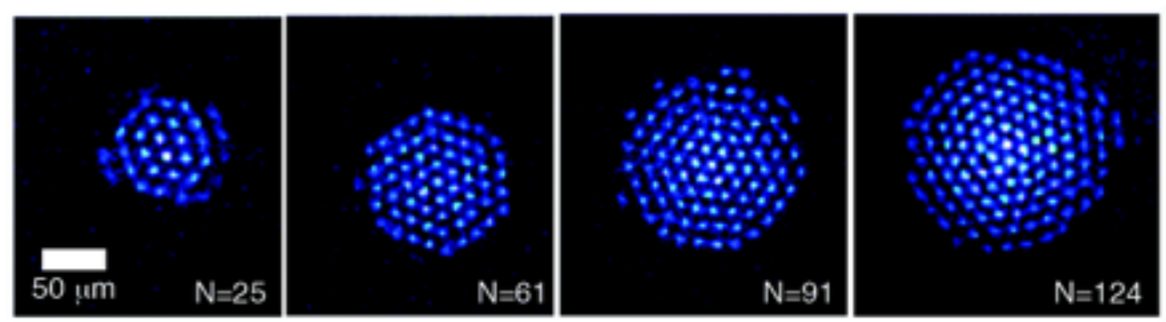
System

Our system:

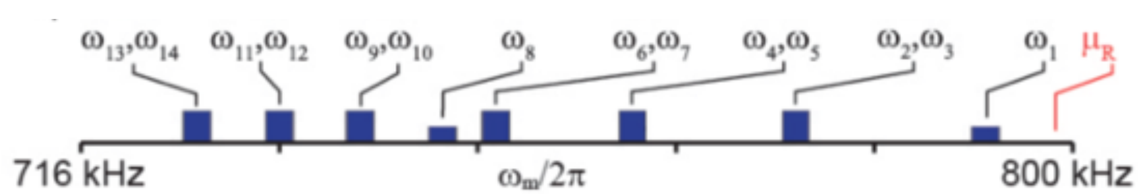
- Triangular crystal of Be^+ ions
  - Stabilized due to the **Coulomb repulsion** between the ions and **external trapping**
- Use two hyperfine states of the ion to form the **spin**
- Couple the spin to the transverse modes of the crystal (**phonons**)

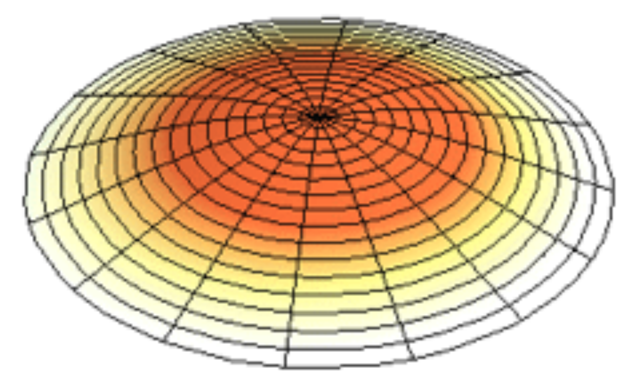






ONLY couple to COM





COM

$$H(t) = -g(\mu_R, t)\hat{z}\hat{S}_z + \omega_0 n$$

$$U(t) = U_{\text{SP}}(t)U_{\text{SS}}(t)$$

spin-phonon **spin-spin**

$$\hat{H}_{\text{SS}} = \frac{J}{N}\hat{S}_z^2$$

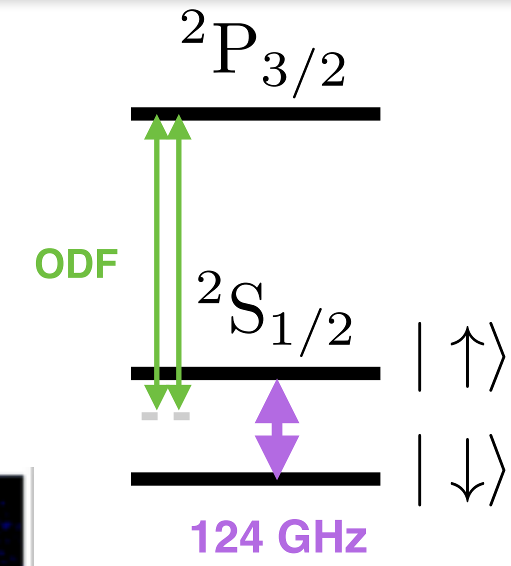
$$J \propto \frac{g^2}{\delta}$$

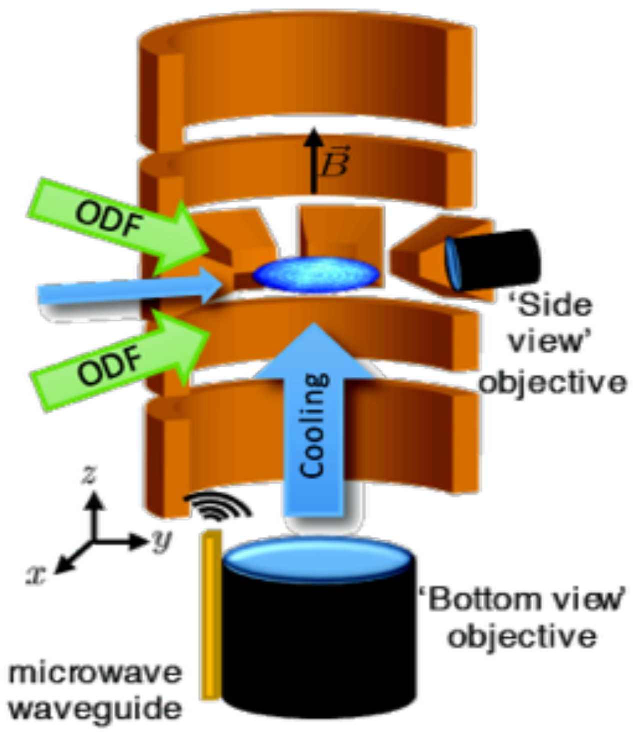
Britton et al. Nature 2012
Bohnet et al. Science 2015
Wall, ASN, Rey, '16 '17

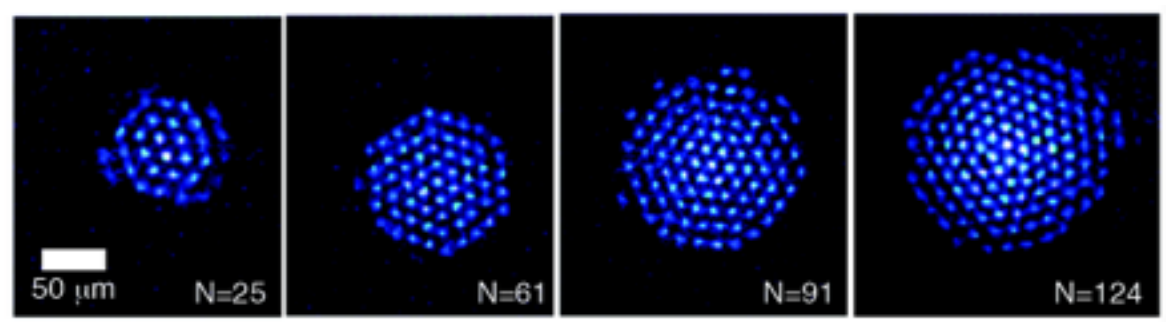
System

Our system:

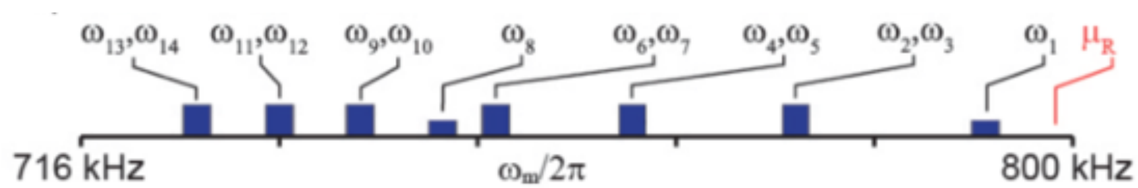
- Triangular crystal of Be^+ ions
  - Stabilized due to the **Coulomb repulsion** between the ions and **external trapping**
- Use two hyperfine states of the ion to form the **spin**
- Couple the spin to the transverse modes of the crystal (**phonons**)

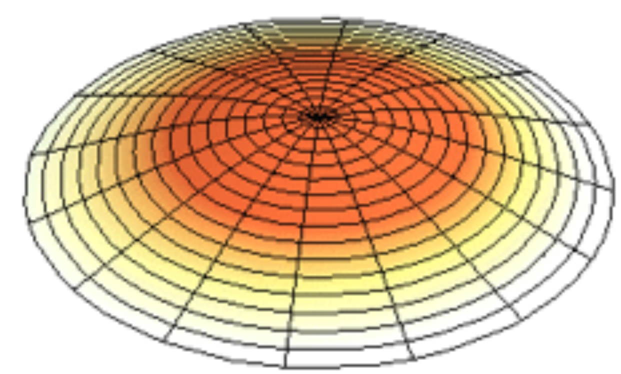






ONLY couple to COM





COM

$$H(t) = -g(\mu_R, t)\hat{z}\hat{S}_z + \omega_0 n$$

$$U(t) = U_{\mathrm{SP}}(t)U_{\mathrm{SS}}(t)$$

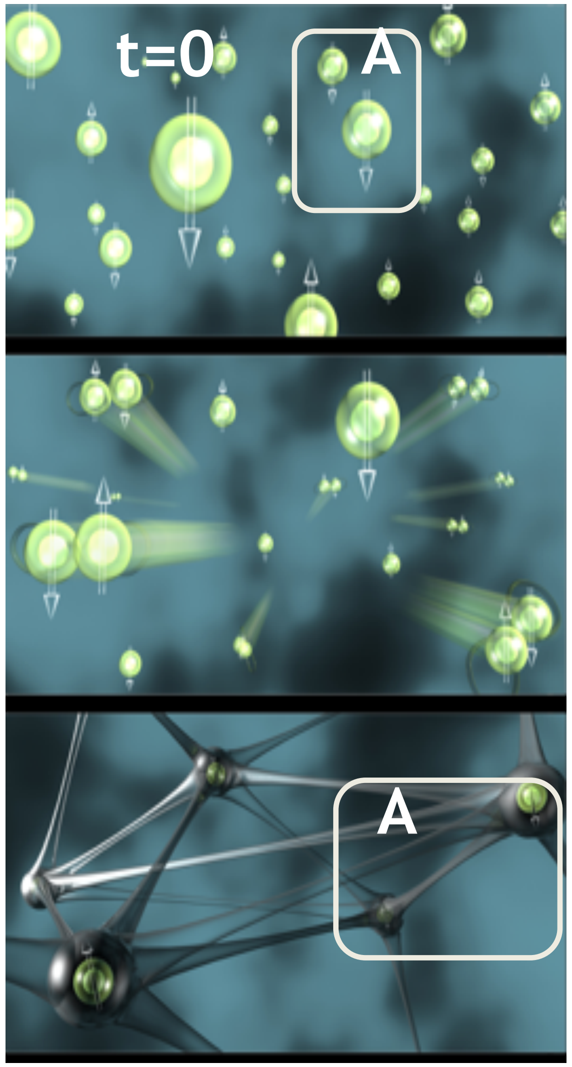
spin-phonon **spin-spin**

$$\hat{H}_{\mathrm{SS}} = \frac{J}{N}\hat{S}_z^2$$

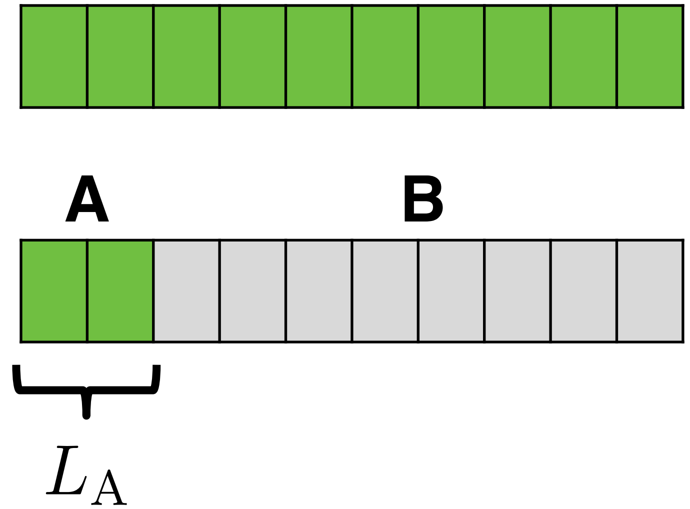
$$J \propto \frac{g^2}{\delta}$$

Britton et al. Nature 2012
Bohnet et al. Science 2015
Wall, ASN, Rey, '16 '17

Entanglement Entropy



Global Unitary dynamics



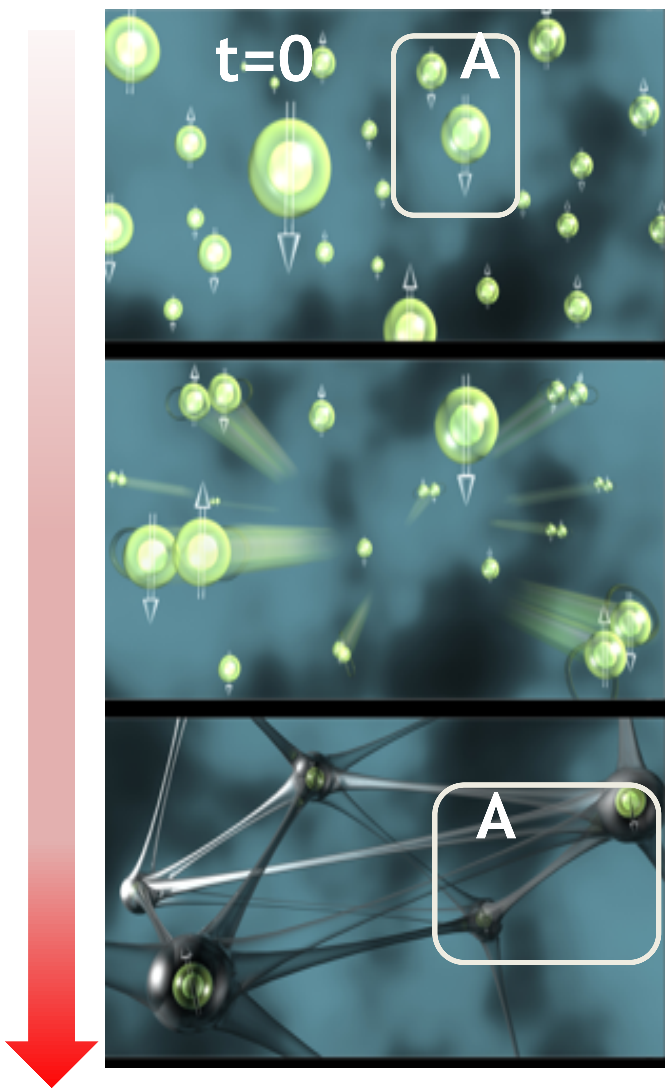
$\hat{\rho}$ $\qquad \ln\left[\mathrm{Tr}(\hat{\rho}^2)\right] = 0$

$\hat{\rho}_{\mathrm{A}} = \mathrm{Tr}_{\mathrm{B}}\hat{\rho}$ Reduced density matrix of A

Renyi entropy: Purity of the A subsystem

$$S_{\mathrm{A}} = -\ln\left[\mathrm{Tr}(\hat{\rho}_{\mathrm{A}}^2)\right]$$

Entanglement Entropy



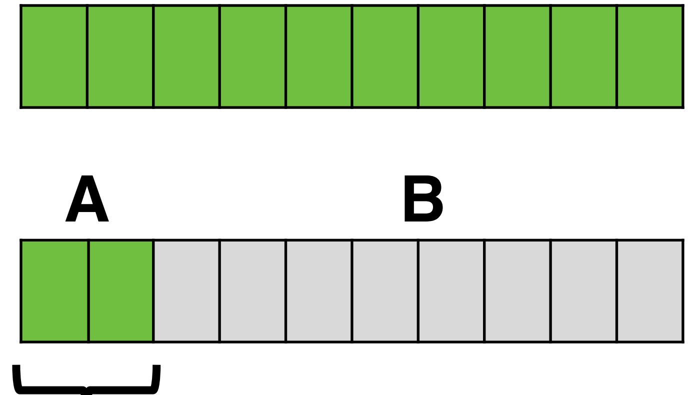
$S_A = 0$

Product state

Global Unitary dynamics

$S_A \rightarrow L_A$

Highly entangled



$\hat{\rho}$ $\quad \ln\left[\mathrm{Tr}(\hat{\rho}^2)\right] = 0$

$\hat{\rho}_\mathrm{A} = \mathrm{Tr}_\mathrm{B}\hat{\rho}$ Reduced density matrix of A

L_A

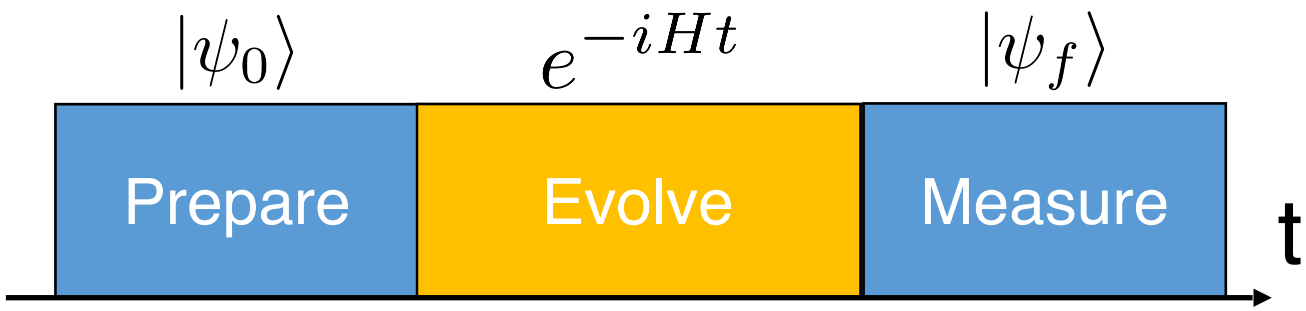
Renyi entropy: Purity of the A subsystem

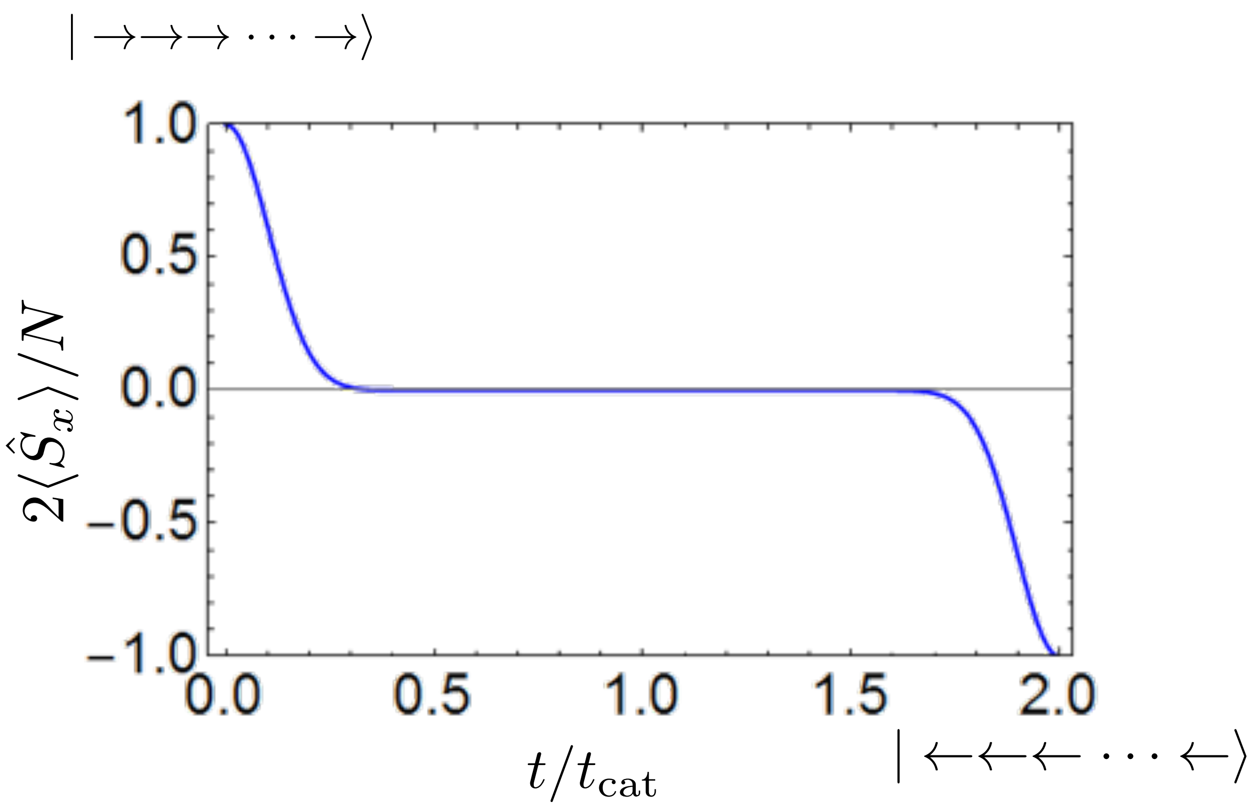
$$S_\mathrm{A} = -\ln\left[\mathrm{Tr}(\hat{\rho}_\mathrm{A}^2)\right]$$

Product state $\quad \hat{\rho} = \otimes \hat{\rho}_i$

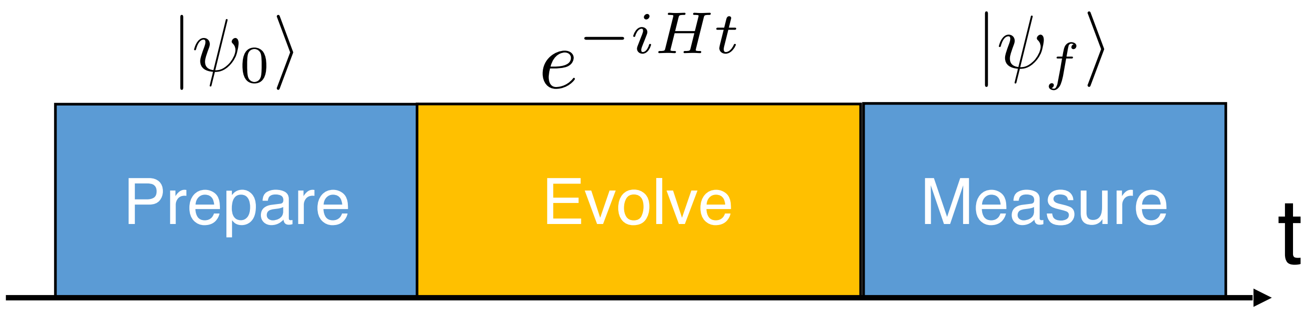
Entangled state $\quad S_\mathrm{A} > 0$

All-to-All Ising Model: One-body Observables

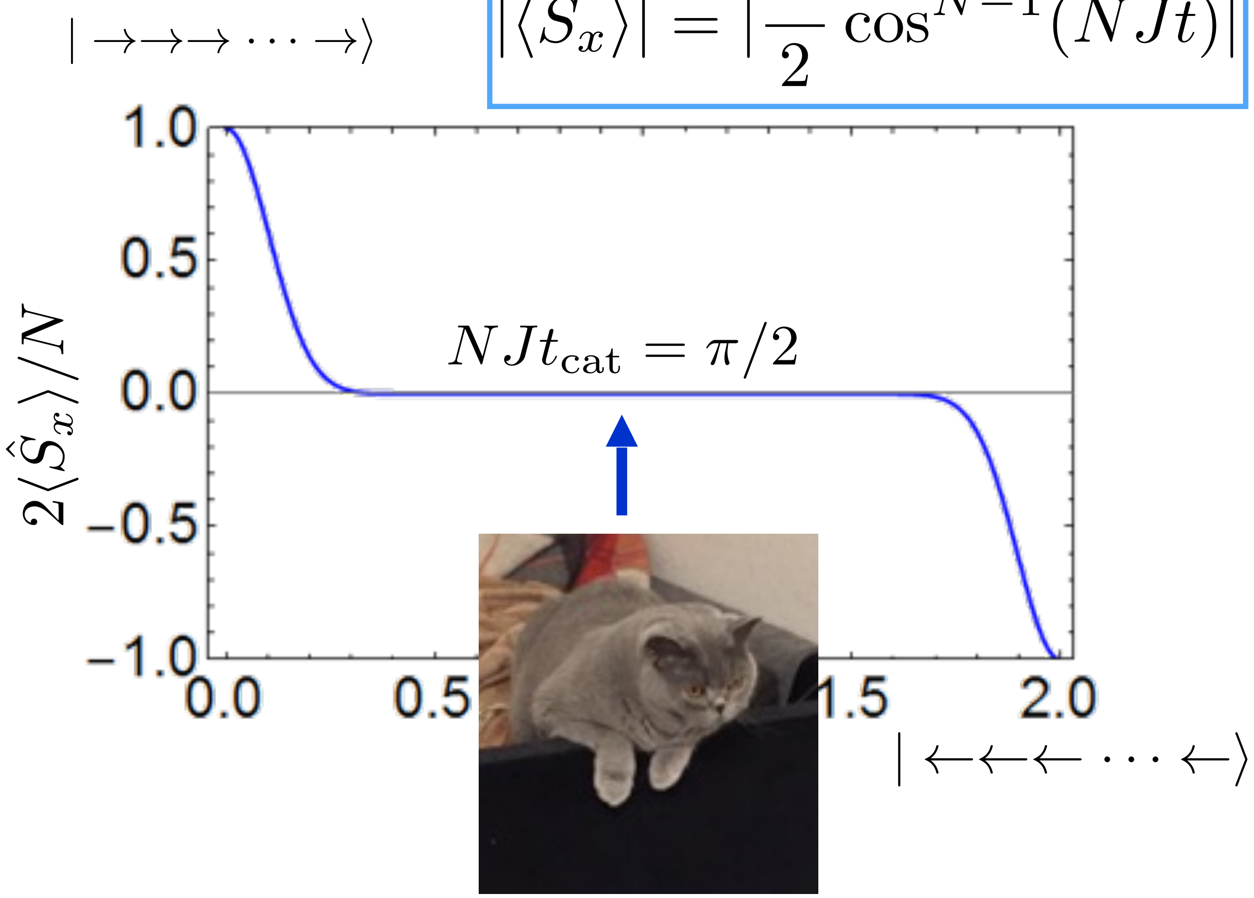




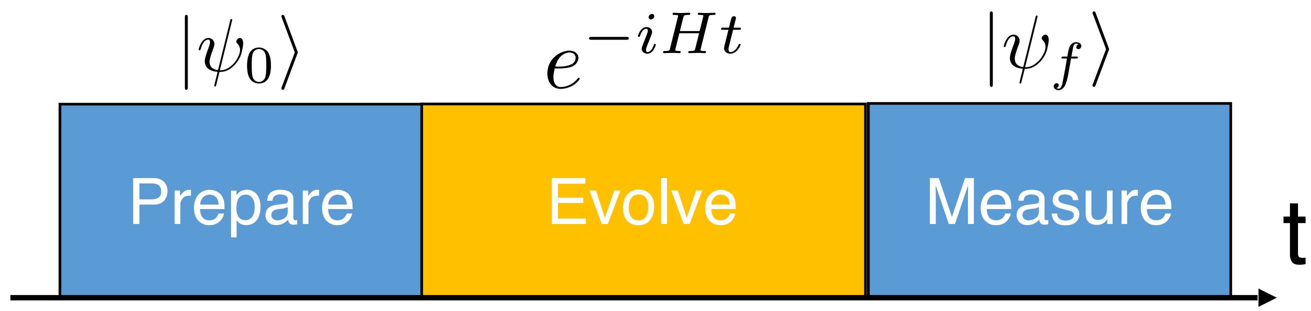
All-to-All Ising Model: One-body Observables



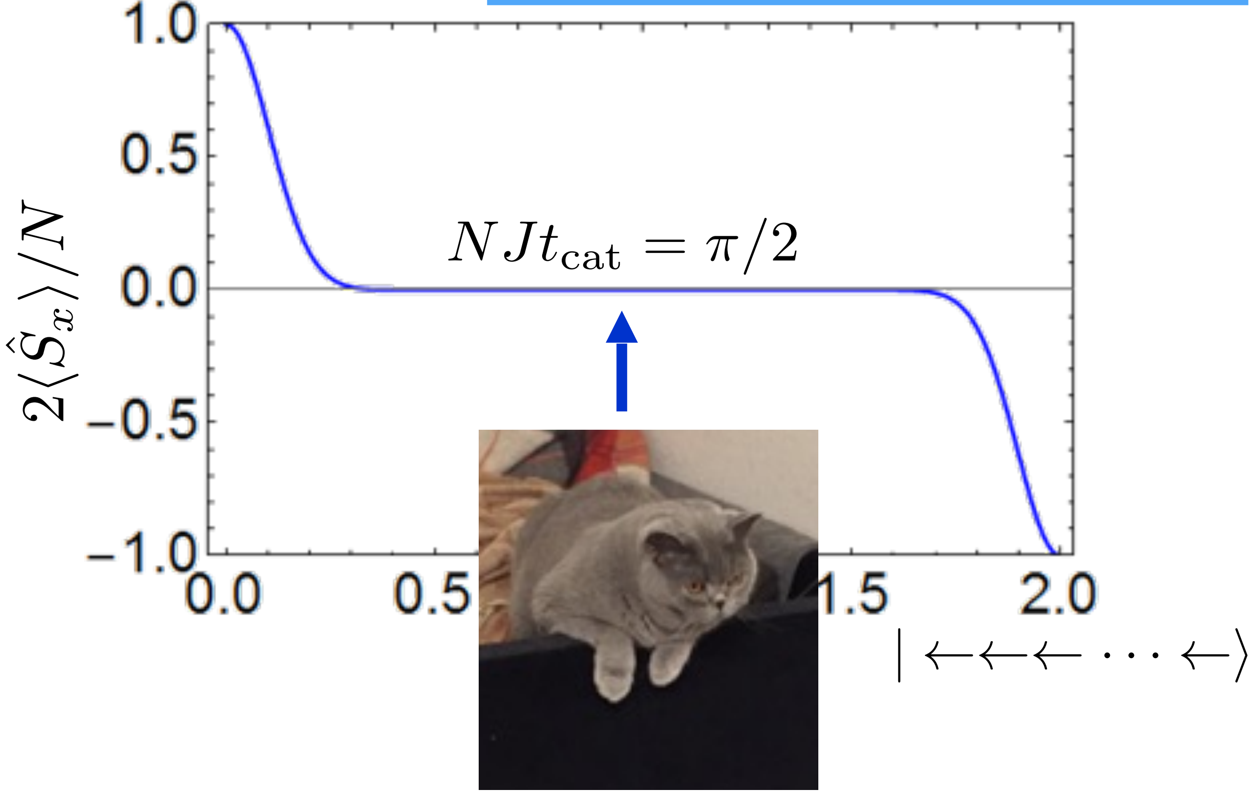
$$|\langle \hat{S}_x \rangle| = |\frac{N}{2}\cos^{N-1}(NJt)|$$



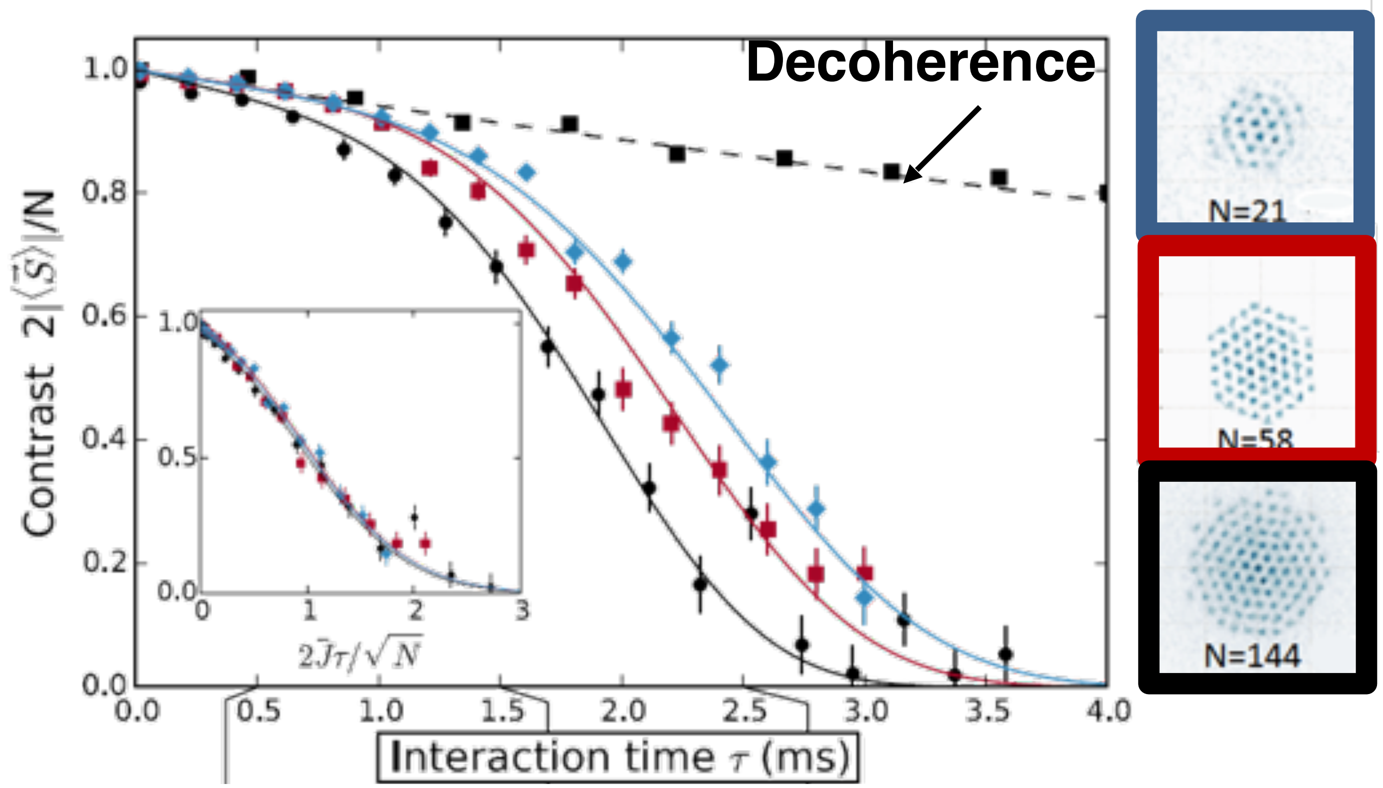
All-to-All Ising Model: One-body Observables



$$|\langle \hat{S}_x \rangle| = |\frac{N}{2}\cos^{N-1}(NJt)|$$

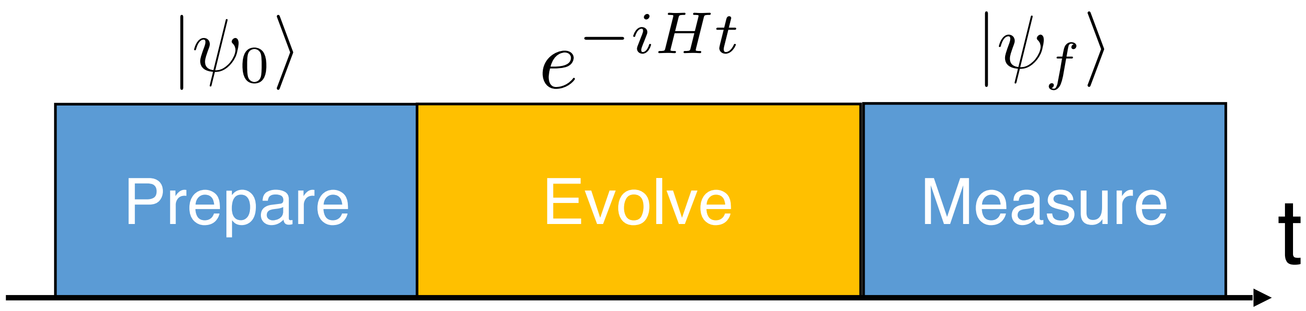


Coherent spin demagnetization observed experimentally: collapse of rescaled data



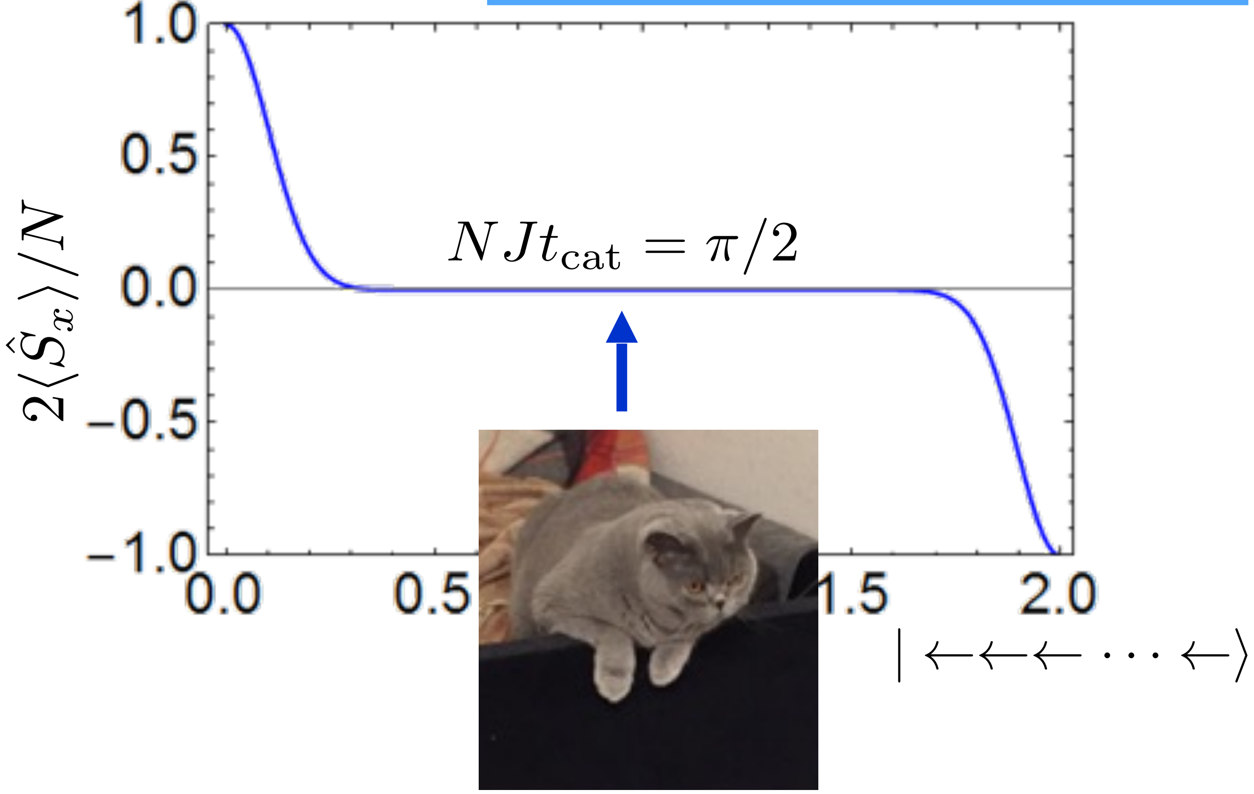
Bohnet *et al.*, Science 352, 1297(2016)

All-to-All Ising Model: One-body Observables

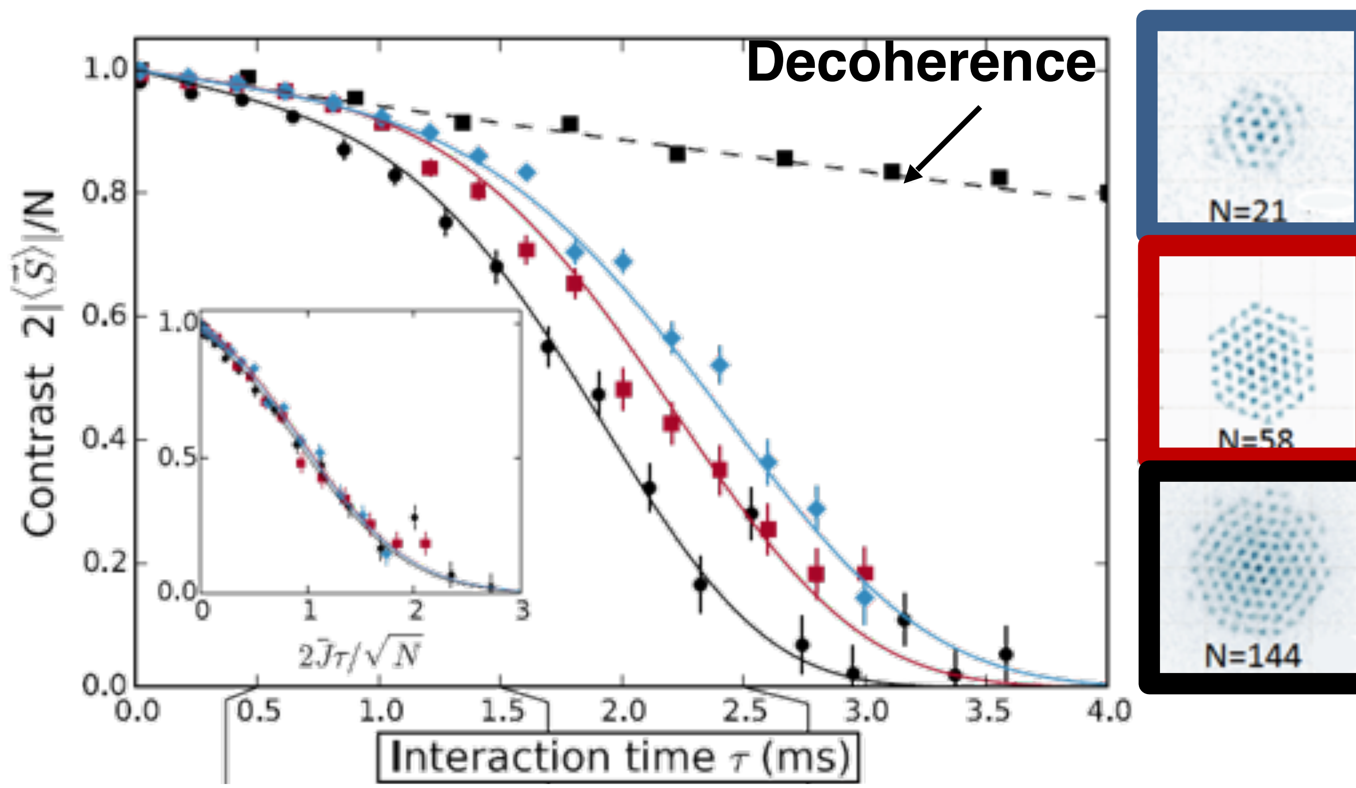


$$|\langle \hat{S}_x \rangle| = |\frac{N}{2}\cos^{N-1}(NJt)|$$

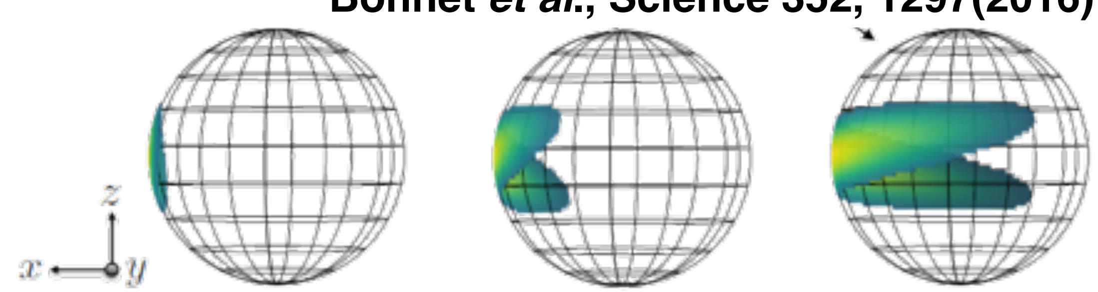
$|\rightarrow\rightarrow\rightarrow\cdots\rightarrow\rangle$



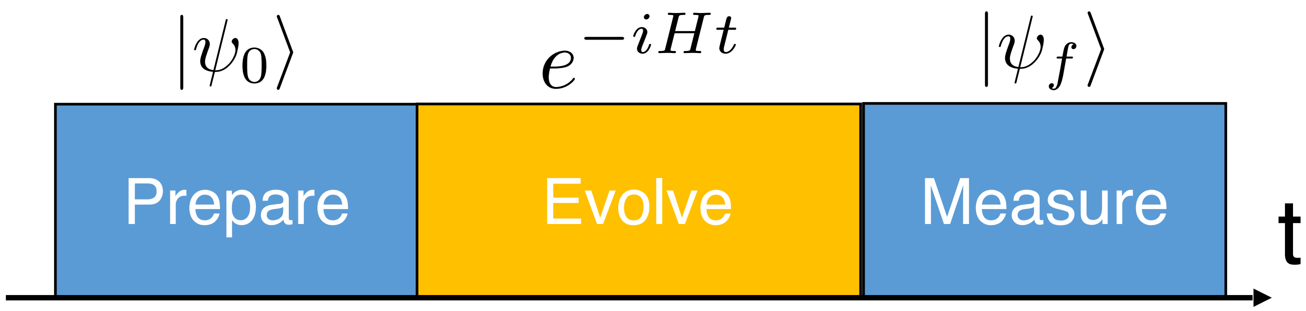
Coherent spin demagnetization observed experimentally: collapse of rescaled data

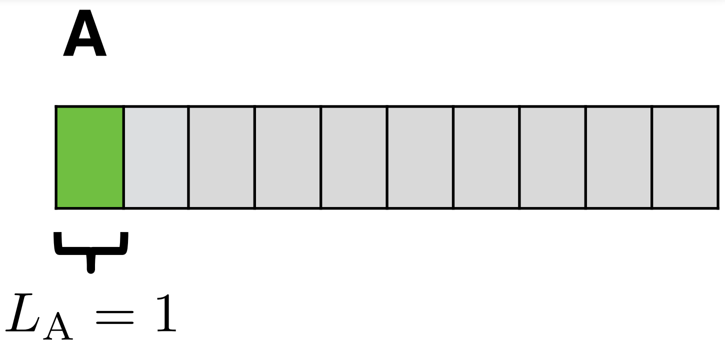


Bohnet *et al.*, Science 352, 1297(2016)



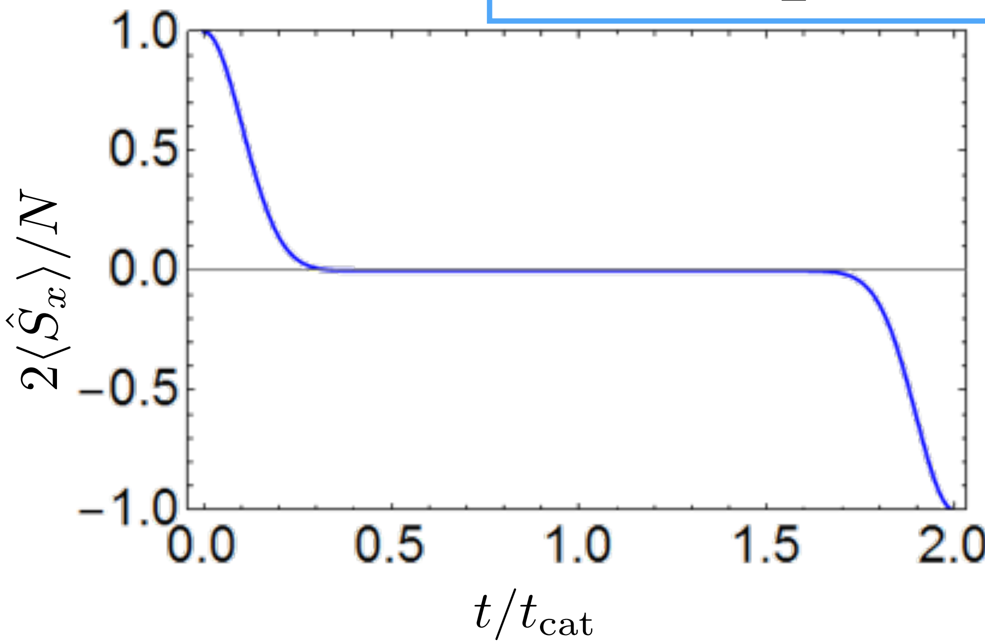
All-to-All Ising Model: One-body Observables



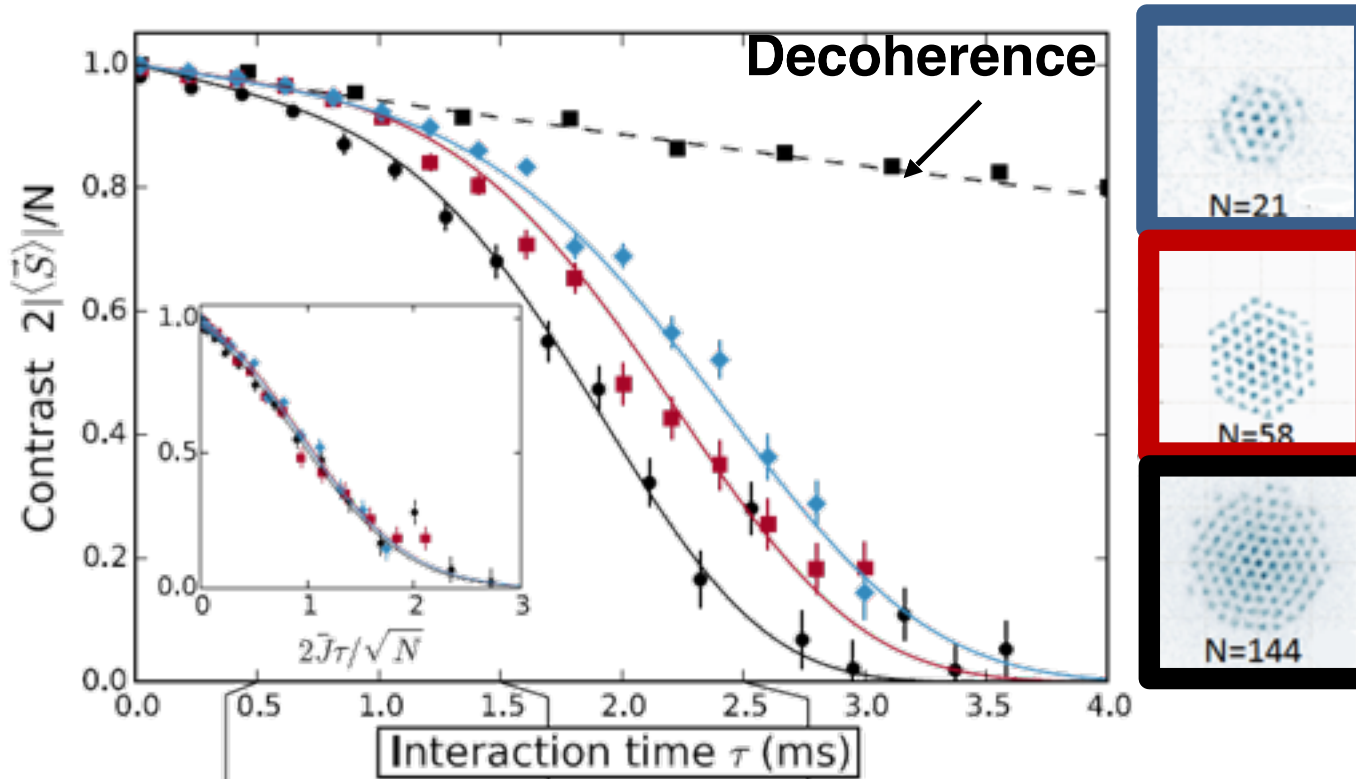


$|\rightarrow\rightarrow\rightarrow\cdots\rightarrow\rangle$

$$|\langle\hat{S}_x\rangle| = |\frac{N}{2}\cos^{N-1}(NJt)|$$

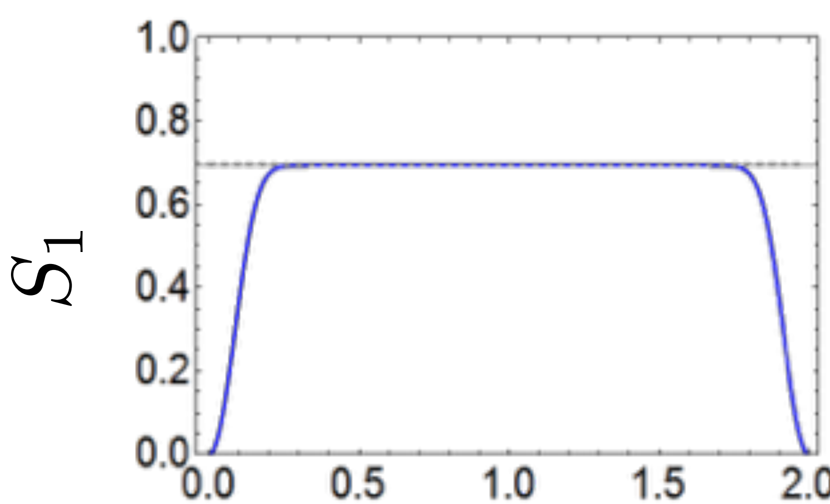


Coherent spin demagnetization observed experimentally: collapse of rescaled data



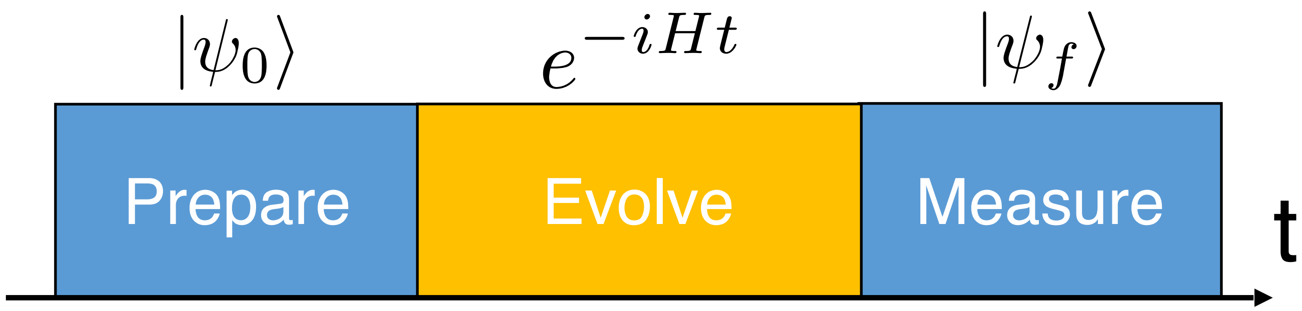
Bohnet *et al.*, Science 352, 1297(2016)

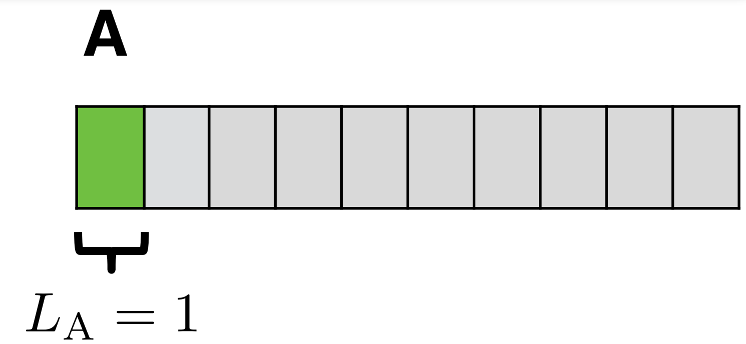
Connection to Renyi entropy of partition of length 1?



$$S_1 = -\ln\left[\frac{1}{2}\left(1+\left(\frac{2}{N}\langle\hat{S}_x\rangle\right)^2\right)\right]$$

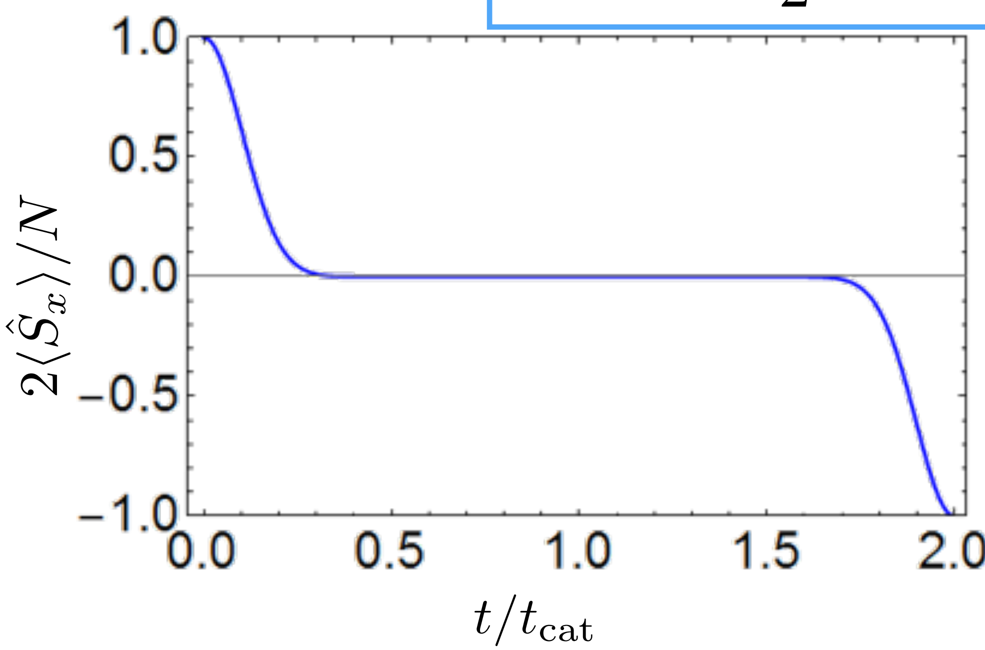
All-to-All Ising Model: One-body Observables



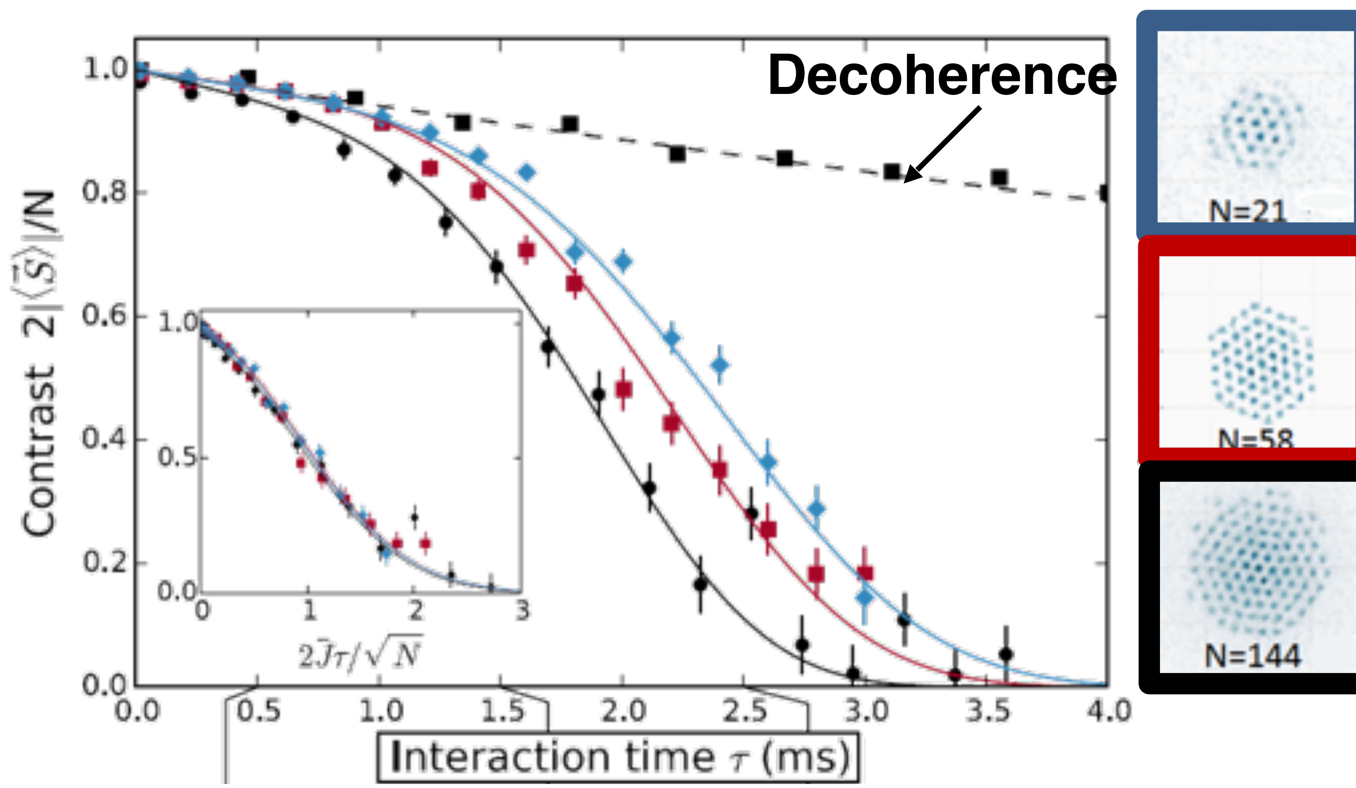


$$|\langle \hat{S}_x \rangle| = |\frac{N}{2}\cos^{N-1}(NJt)|$$

$|\rightarrow\rightarrow\rightarrow\cdots\rightarrow\rangle$

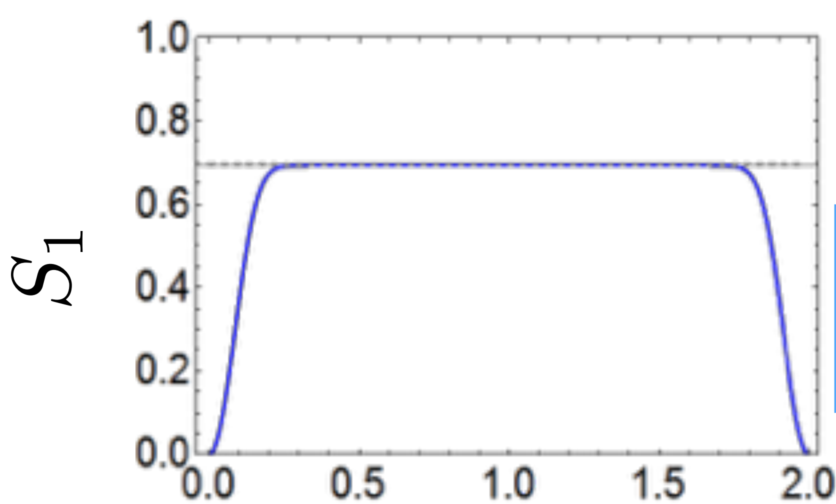


Coherent spin demagnetization observed experimentally: collapse of rescaled data



Bohnet *et al.*, Science 352, 1297(2016)

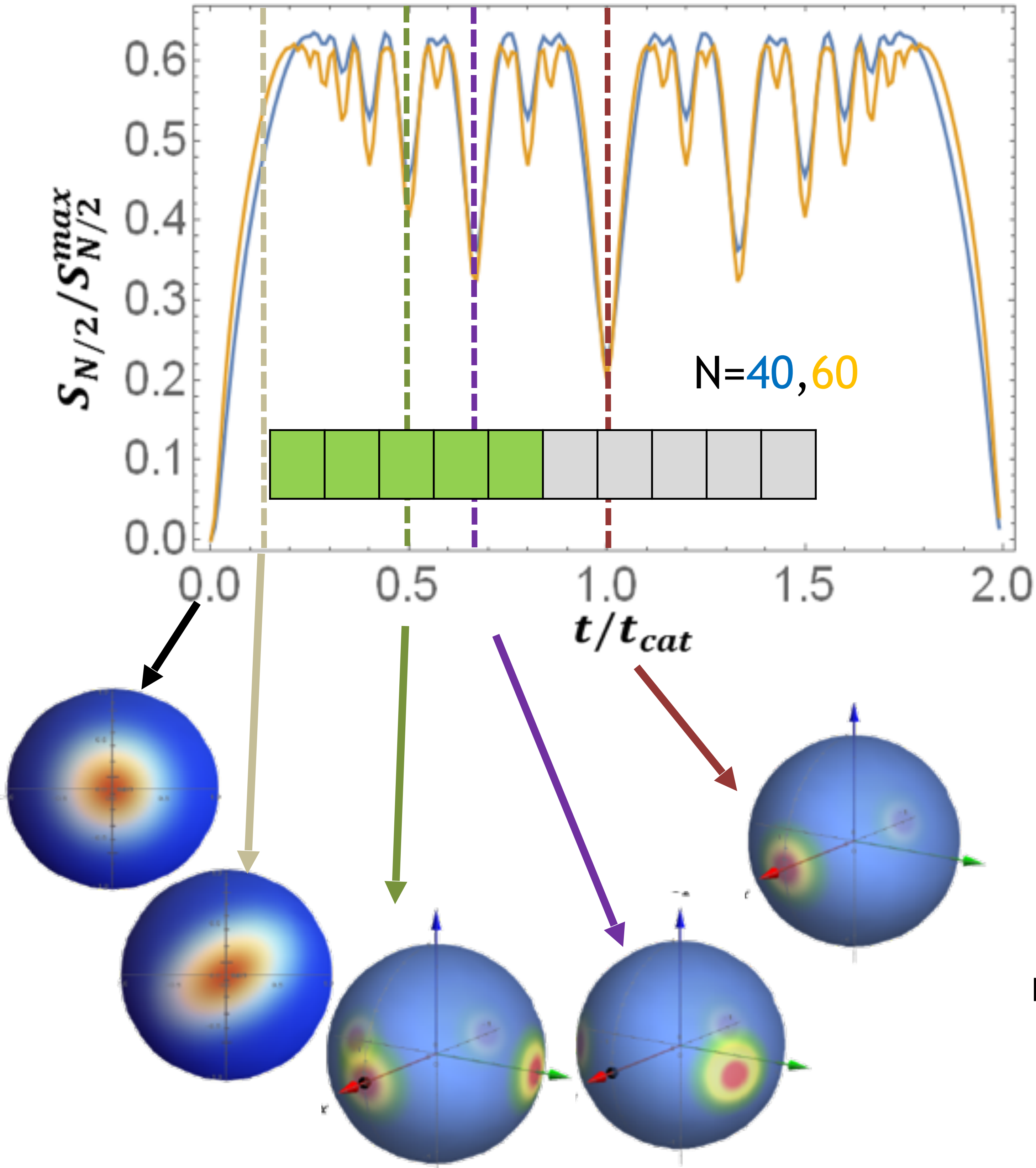
Connection to Renyi entropy of partition of length 1?



$$S_1 = -\ln\left[\frac{1}{2}\left(1 + \left(\frac{2}{N}\langle \hat{S}_x \rangle\right)^2\right)\right]$$

Can we understand what the system is doing in more detail with global measurements?

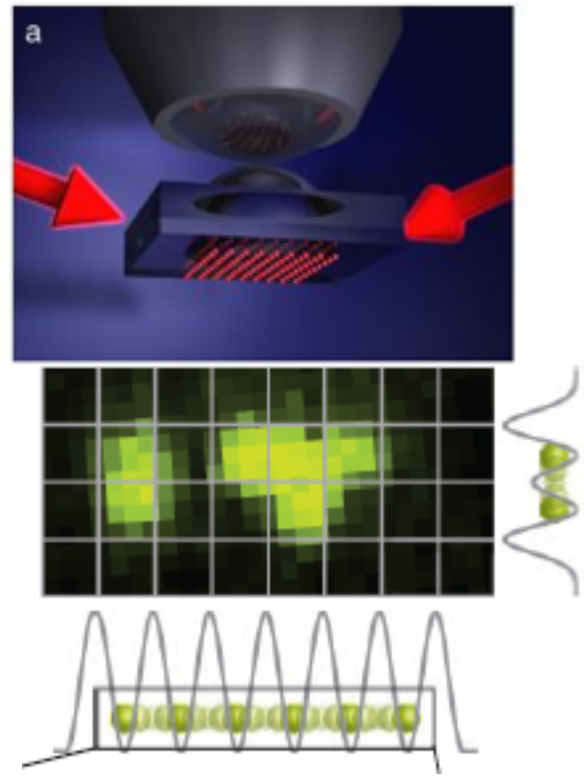
All-to-All Ising Model: Entanglement



Entanglement entropy for the half-chain: features instead of the plateau

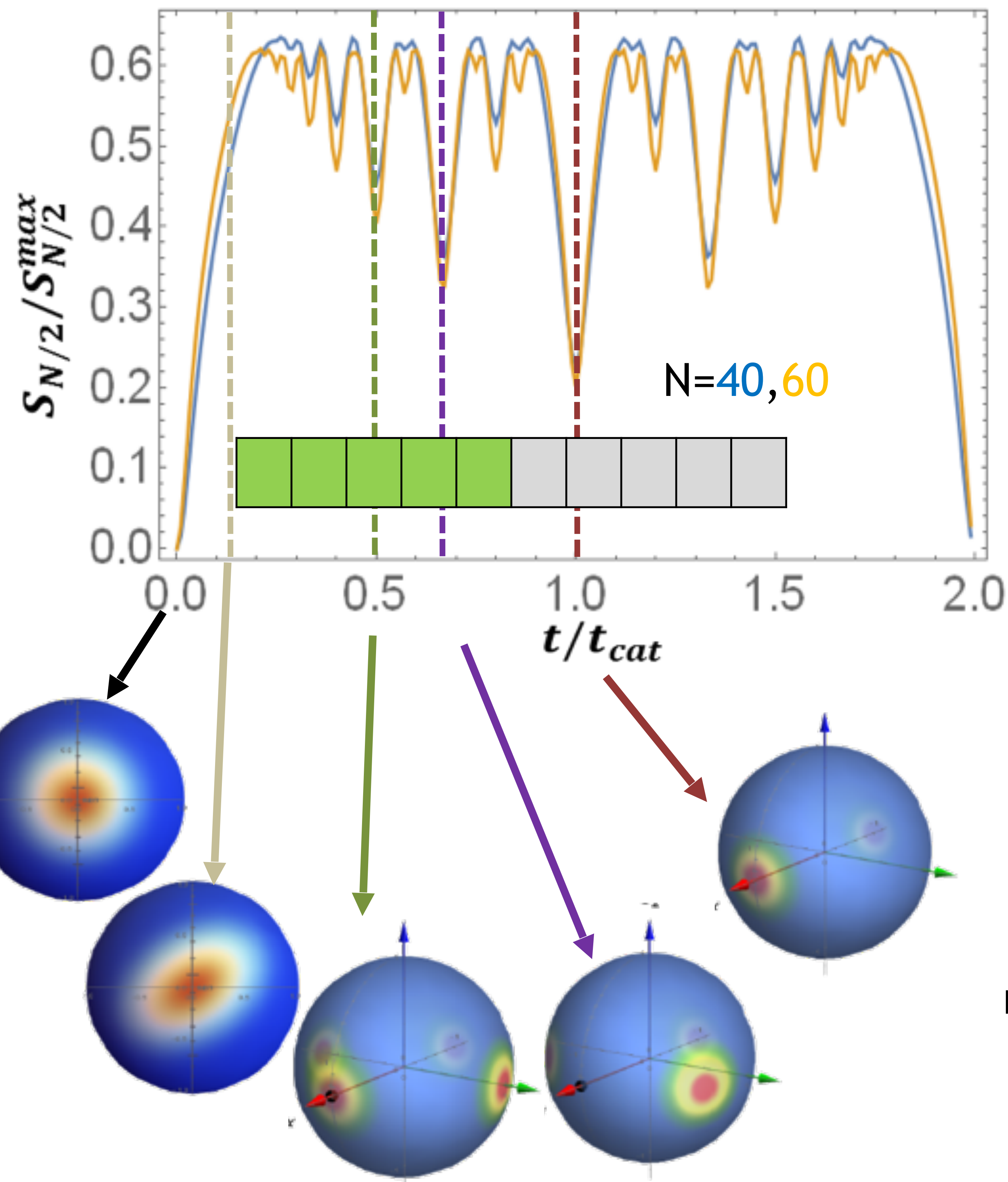
Caveats:

- Single site resolution (quantum gas microscope)
  - Limited to ~10 ions
- Intractable for large systems



Experiments: A. Kaufman *et al* Science 353, 794 (2016)

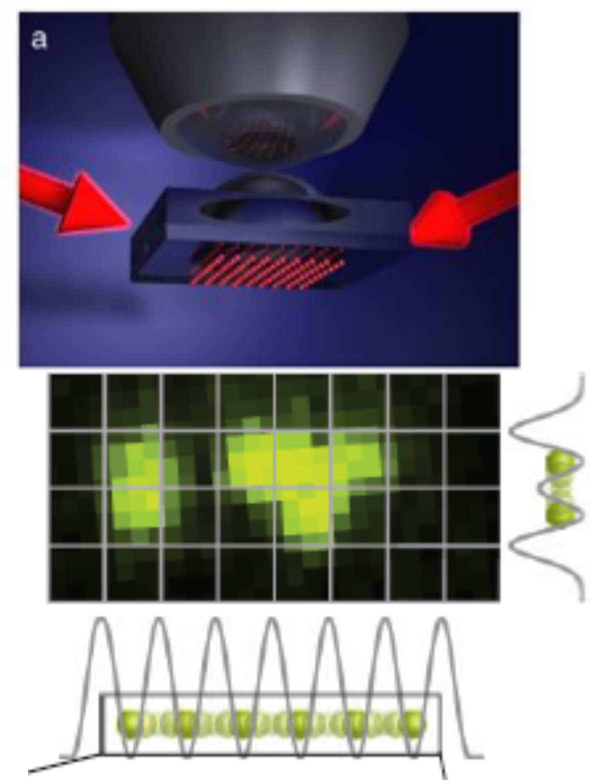
All-to-All Ising Model: Entanglement



Entanglement entropy for the half-chain: features instead of the plateau

Caveats:

- Single site resolution (quantum gas microscope)
  - Limited to ~10 ions
- Intractable for large systems



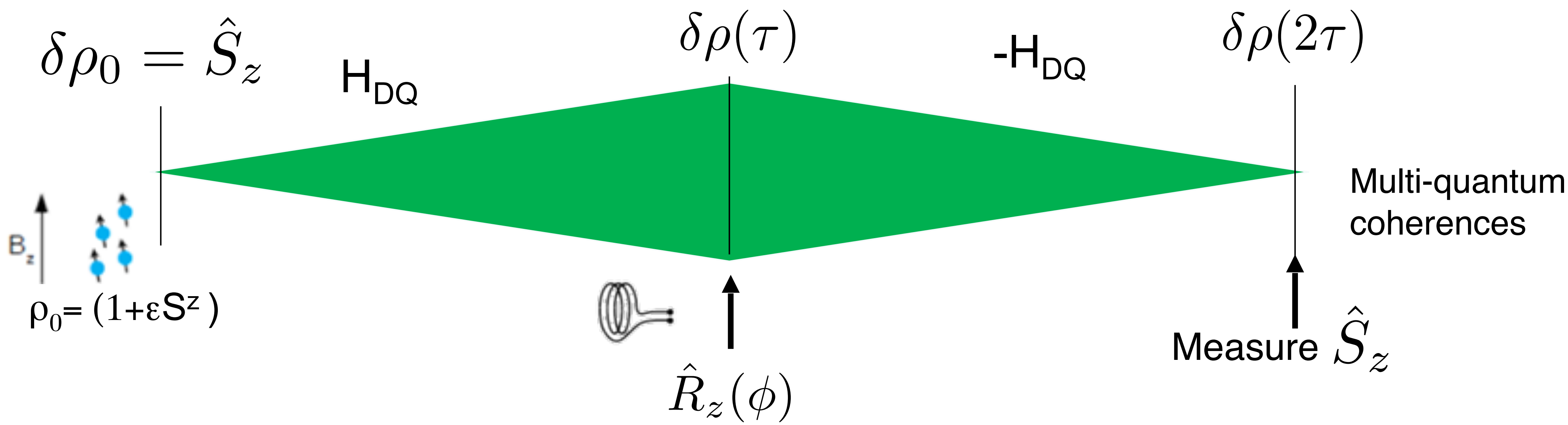
Experiments: A. Kaufman *et al* Science 353, 794 (2016)

Large system + absence of single site resolution?

Multiple Quantum Coherence (MQC) Spectrum

Multi-Quantum coherence spectrum (NMR)

$$H_{\mathrm{DQ}} \propto \sum_{ij} J_{ij}(\hat{\sigma}_i^+ \hat{\sigma}_j^+ + \hat{\sigma}_i^- \hat{\sigma}_j^-)$$

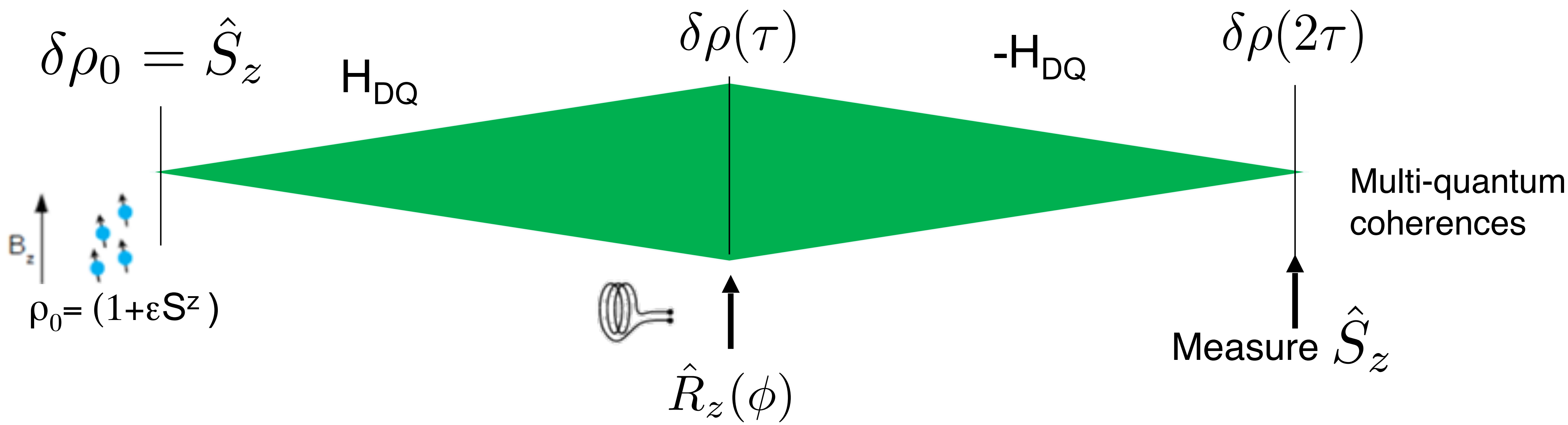


1. Start with a highly mixed state
2. Evolve
3. Rotate
4. Time-reverse
5. Measure magnetization: here fully characterizes the state

M. Munowitz and M. Mehring , Sol. St. Com., 64, 605 (1987)

Multiple Quantum Coherence (MQC) Spectrum

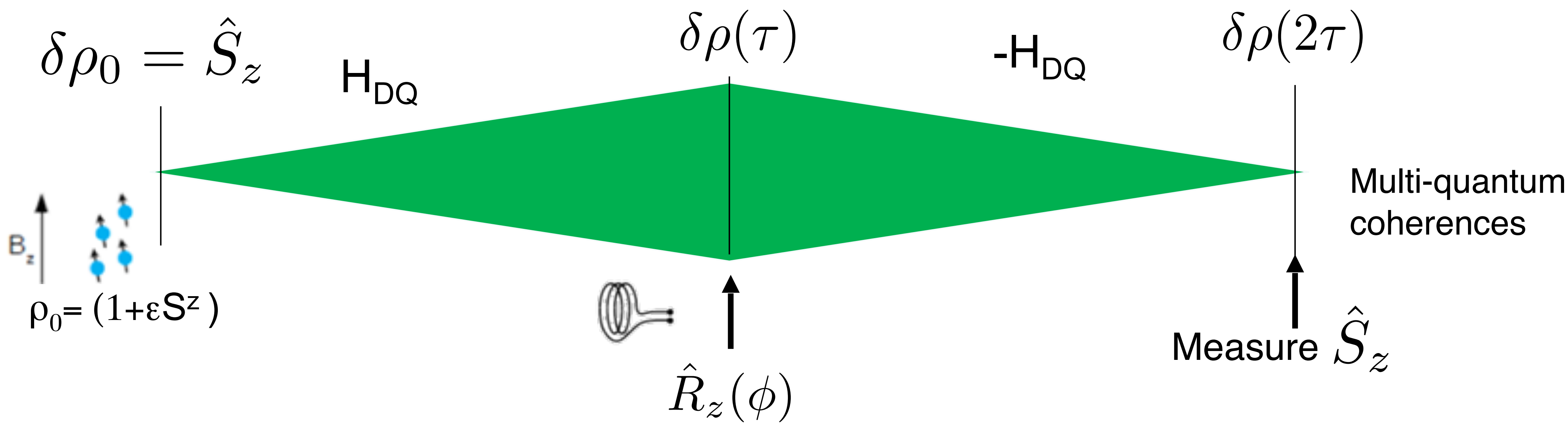
$$\langle \hat{S}_z \rangle = \mathrm{Tr}\left[\delta\rho_0 \delta\rho(2\tau)\right] = \mathrm{Tr}\left[\delta\rho_0 e^{itH_{\mathrm{DQ}}} e^{-i\phi \hat{S}_z} e^{-itH_{\mathrm{DQ}}} \rho_0 e^{-itH_{\mathrm{DQ}}} e^{i\phi \hat{S}_z} e^{itH_{\mathrm{DQ}}}\right]$$



1. Start with a highly mixed state
2. Evolve
3. Rotate
4. Time-reverse
5. Measure magnetization: here fully characterizes the state

Multiple Quantum Coherence (MQC) Spectrum

$$\langle \hat{S}_z \rangle = \mathrm{Tr}\left[\delta\rho_0 \delta\rho(2\tau)\right] = \mathrm{Tr}\left[\underbrace{\delta\rho_0}_{V^\dagger(0)} \underbrace{e^{itH_{\mathrm{DQ}}} e^{-i\phi \hat{S}_z} e^{-itH_{\mathrm{DQ}}}}_{W^\dagger(t)} \underbrace{\rho_0}_{V(0)} \underbrace{e^{-itH_{\mathrm{DQ}}} e^{i\phi \hat{S}_z} e^{itH_{\mathrm{DQ}}}}_{W(t)}\right]$$

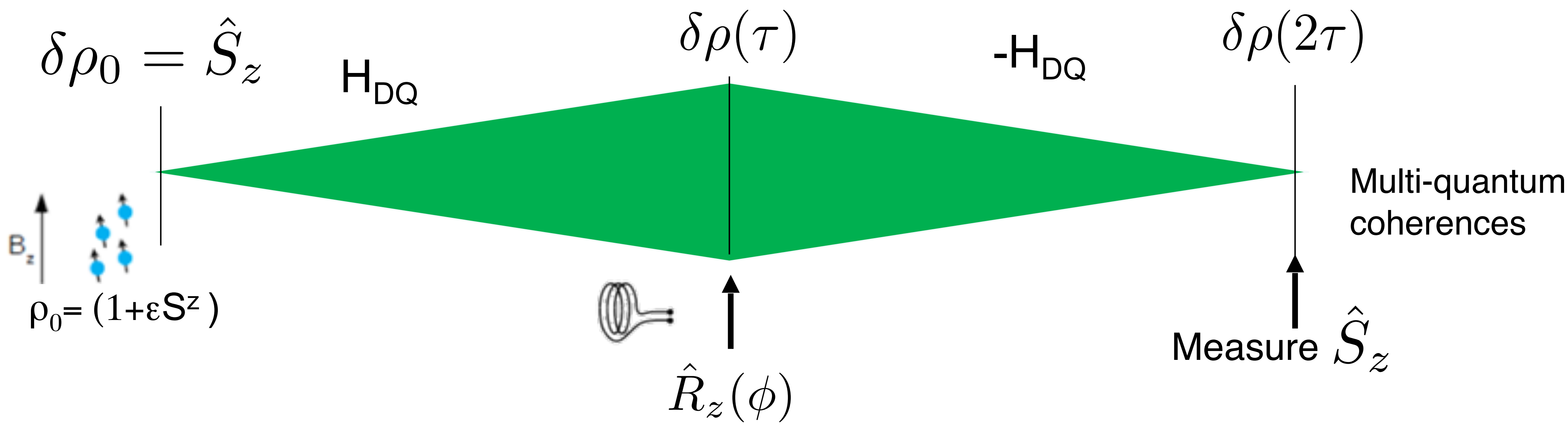


1. Start with a highly mixed state
2. Evolve
3. Rotate
4. Time-reverse
5. Measure magnetization: here fully characterizes the state

Multiple Quantum Coherence (MQC) Spectrum

$$\langle \hat{S}_z \rangle = \mathrm{Tr}\left[\delta\rho_0 \delta\rho(2\tau)\right] = \mathrm{Tr}\left[\underbrace{\delta\rho_0}_{V^\dagger(0)} \underbrace{e^{itH_{\mathrm{DQ}}} e^{-i\phi \hat{S}_z} e^{-itH_{\mathrm{DQ}}}}_{W^\dagger(t)} \underbrace{\rho_0}_{V(0)} \underbrace{e^{-itH_{\mathrm{DQ}}} e^{i\phi \hat{S}_z} e^{itH_{\mathrm{DQ}}}}_{W(t)}\right]$$

$$F(t) = \langle W^\dagger(t) V^\dagger(0) W(t) V(0) \rangle$$



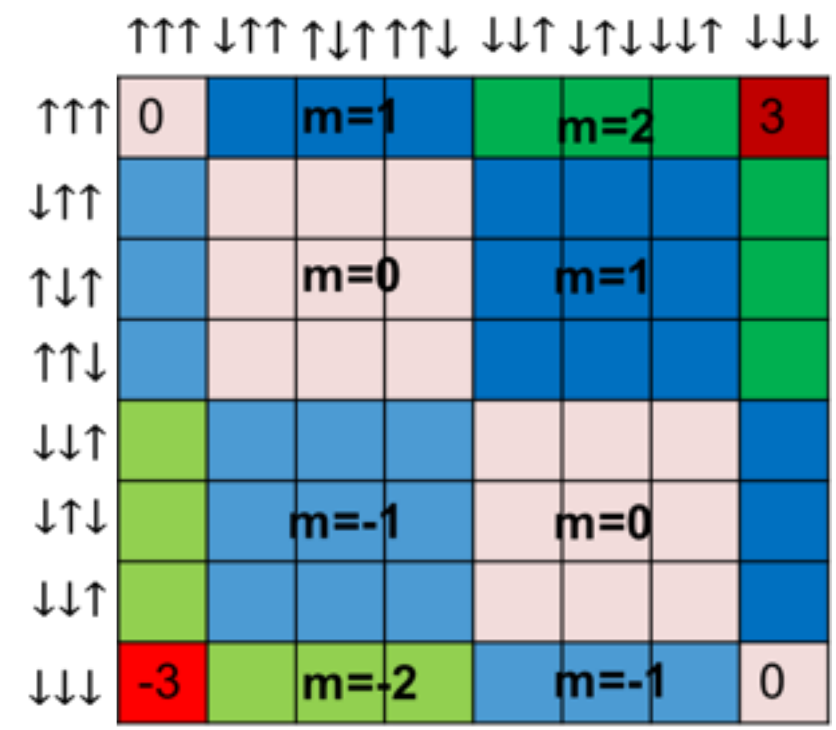
1. Start with a highly mixed state
2. Evolve
3. Rotate
4. Time-reverse
5. Measure magnetization: here fully characterizes the state

Multi-quantum Coherences

How do we generalize coherences from **one** particle to **many**?

$$\hat{\rho} = \begin{bmatrix} \rho_{\uparrow\uparrow} & \rho_{\uparrow\downarrow} \\ \rho_{\downarrow\uparrow} & \rho_{\downarrow\downarrow} \end{bmatrix}$$

N=3

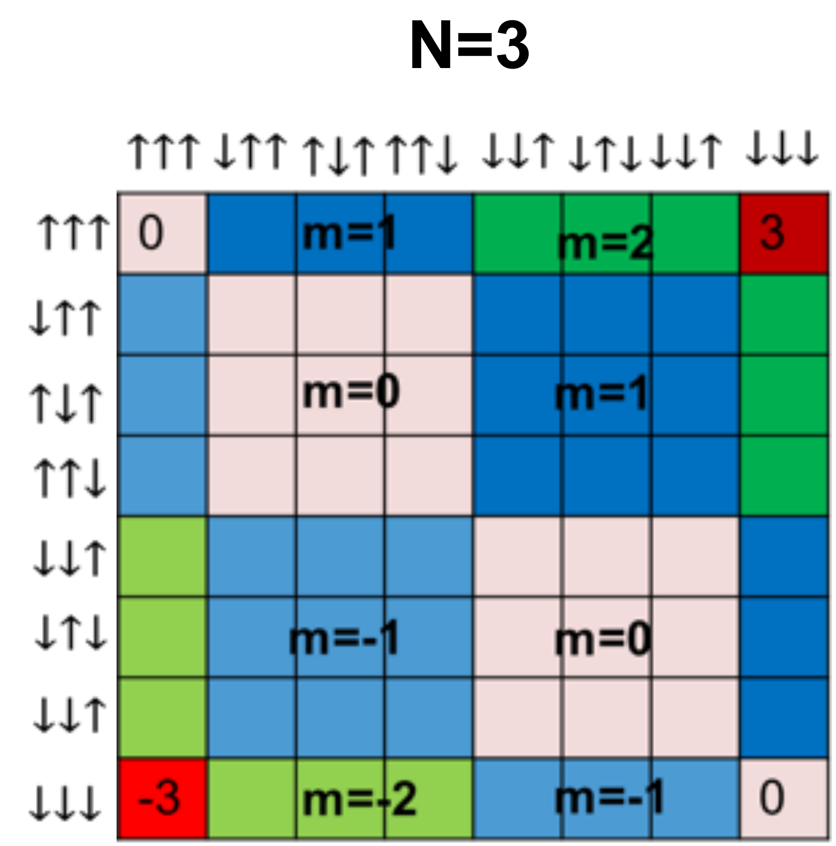


$$\hat{\rho} = \sum_m \hat{\rho}_m$$

Multi-quantum Coherences

How do we generalize coherences from **one** particle to **many**?

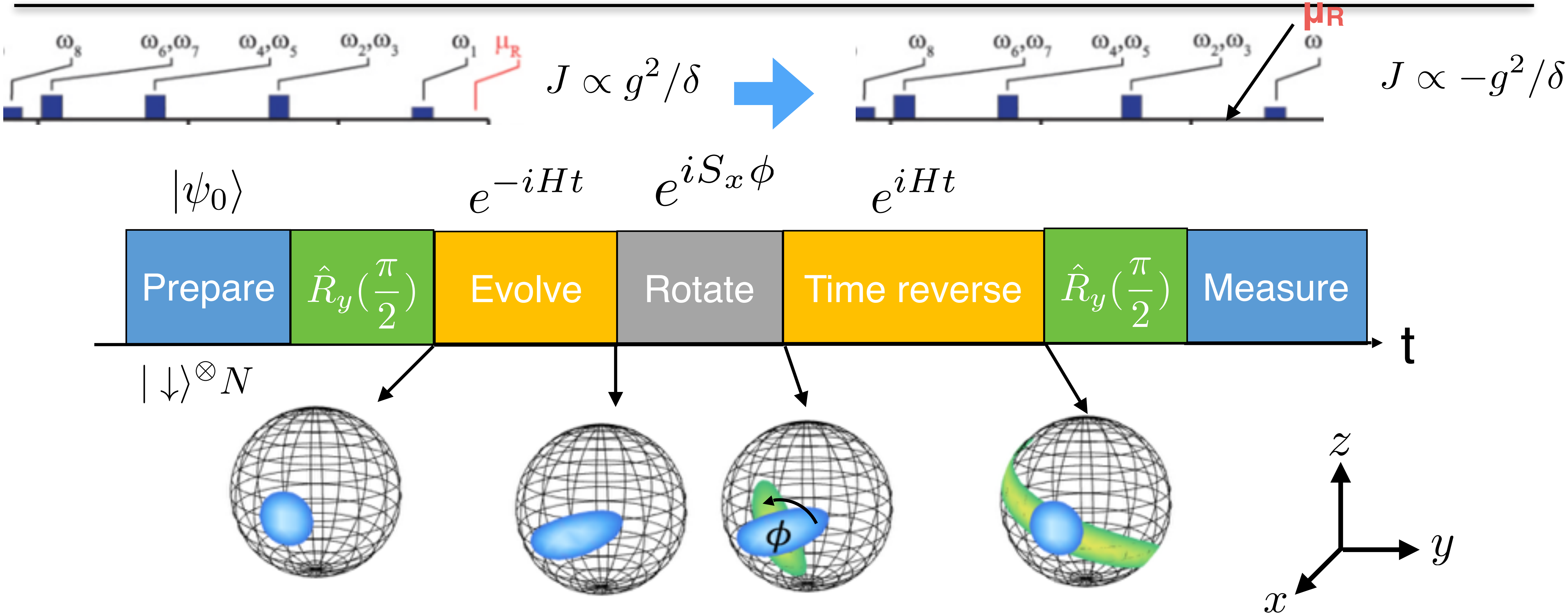
$$\hat{\rho} = \begin{bmatrix} \rho_{\uparrow\uparrow} & \rho_{\uparrow\downarrow} \\ \rho_{\downarrow\uparrow} & \rho_{\downarrow\downarrow} \end{bmatrix}$$



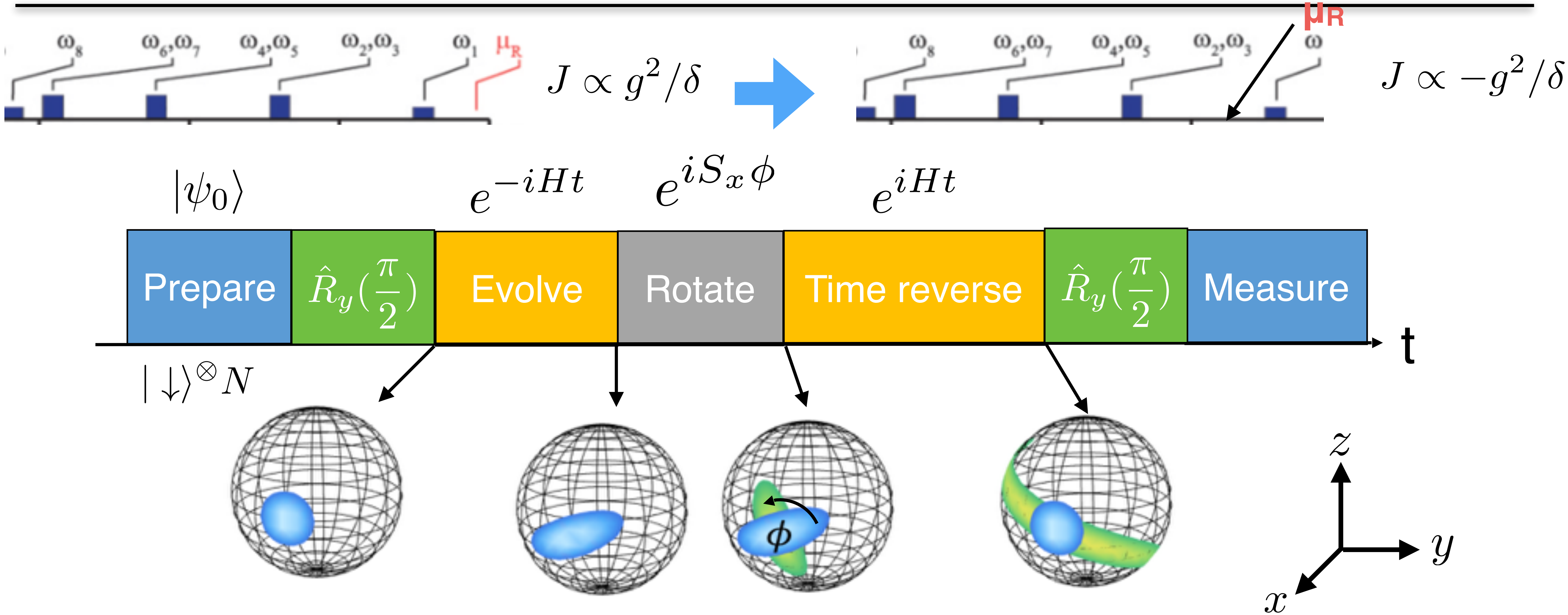
$$\hat{\rho} = \sum_m \hat{\rho}_m$$

$$\hat{\rho}_m = \langle \{(n-m)\downarrow\} | \hat{\rho} | \{n\downarrow\} \rangle \neq 0$$

Reversing Time with Ions

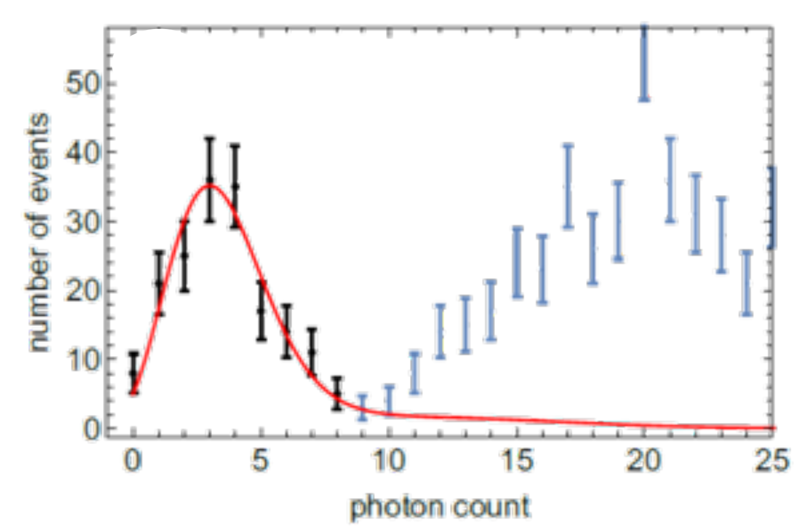


Reversing Time with Ions

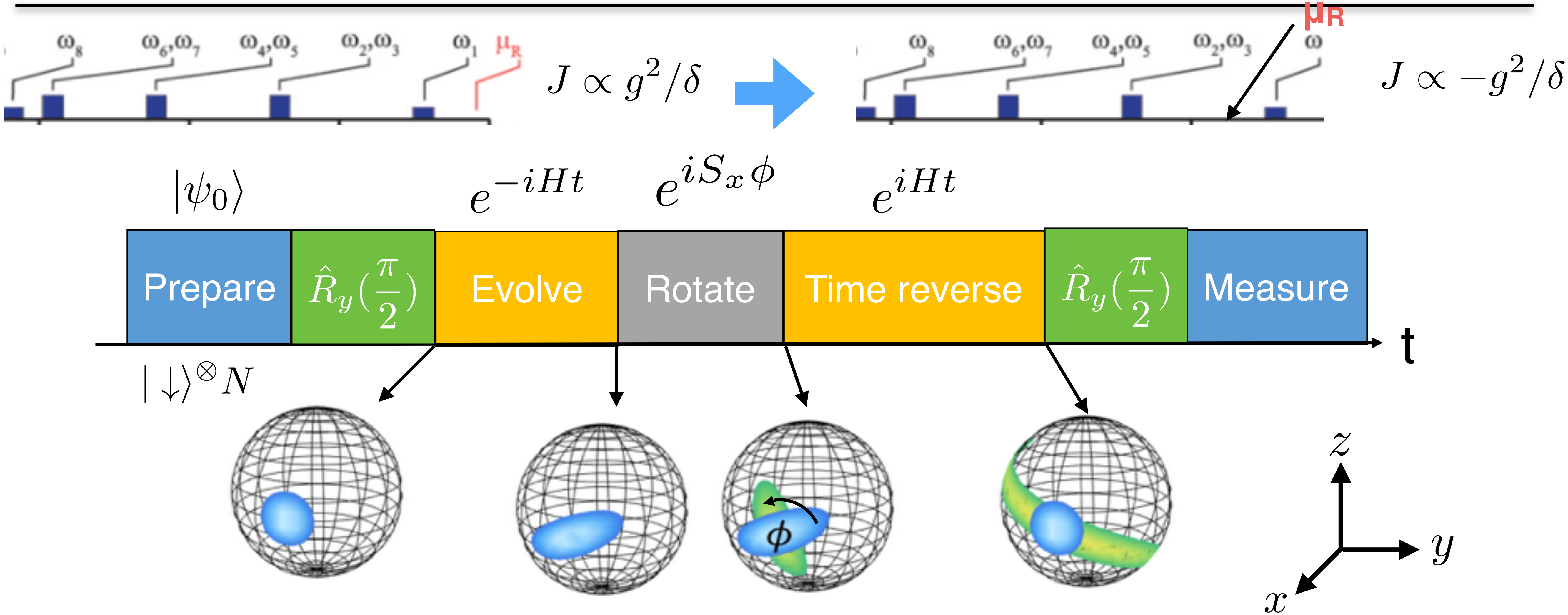


Pure initial state -> Measure Fidelity

Probability of all down



Reversing Time with Ions



Many-body Loschmidt echo

$$\langle\rho_0\rangle = Tr[\rho_0\rho_f] = Tr[\rho_0\, e^{itH} e^{-i\phi\hat{S}_x}\, e^{-itH} \rho_0\, e^{itH}\, e^{i\phi\hat{S}_x}\, e^{-itH}]$$

$$= \sum_{m=-N}^{N} \underbrace{Tr[\rho_m\rho_m^\dagger]}_{I_m}\, e^{im\phi}$$

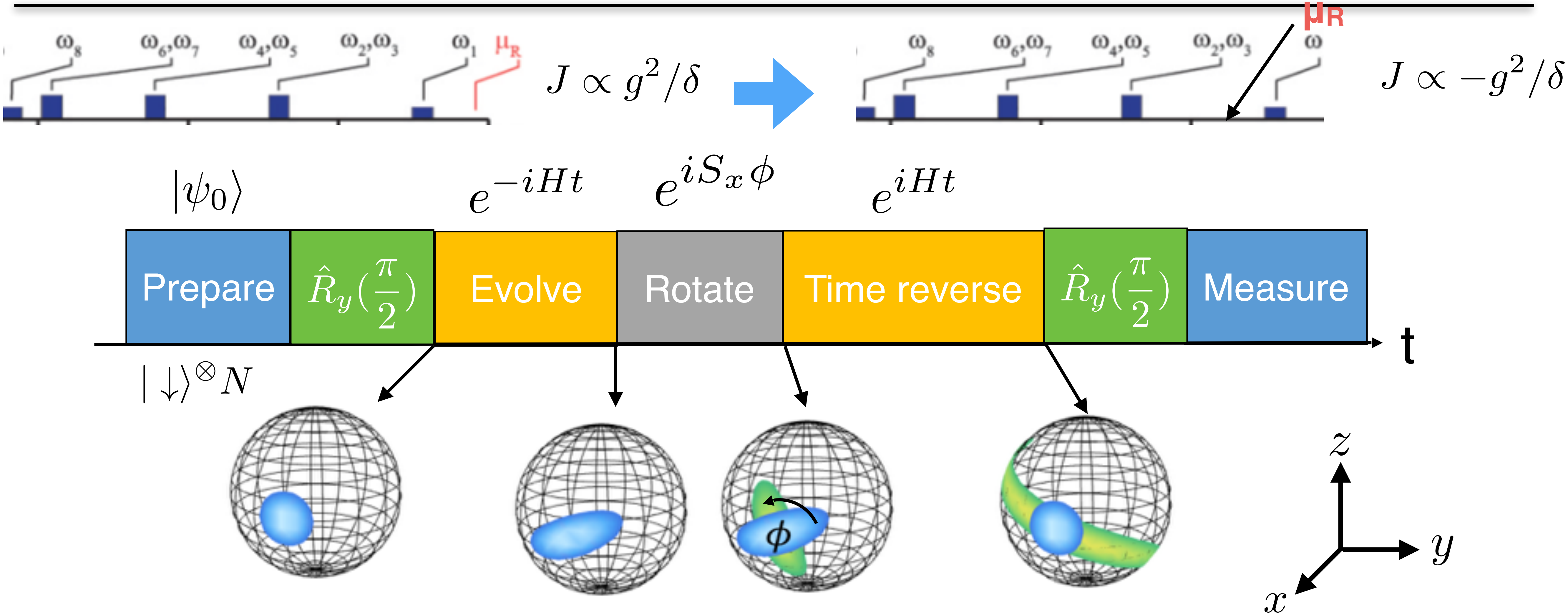
I_m=Multi-quantum coherences

$$I_m = \mathrm{Tr}\,[\underbrace{\rho_{-m}(t)\rho_m(t)}_{\text{Type of purity}}]$$

$$I_0 = \mathrm{Tr}\left[\rho_0^2(t)\right]$$

Fourier transform: ϕ gives the Multi-Quantum spectrum.

Reversing Time with Ions



Many-body Loschmidt echo

$$\langle \rho_0 \rangle = Tr[\rho_0 \rho_f] = Tr[\rho_0\, e^{itH} e^{-i\phi \hat{S}_x}\, e^{-itH} \rho_0\, e^{itH}\, e^{i\phi \hat{S}_x}\, e^{-itH}]$$

$$= \sum_{m=-N}^{N} \underbrace{Tr[\rho_m \rho_m^{\dagger}]}_{I_m} e^{im\phi}$$

I_m=Multi-quantum coherences

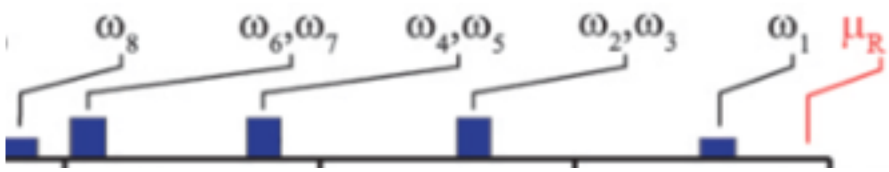
$$I_m = \mathrm{Tr}\left[\underbrace{\rho_{-m}(t)\rho_m(t)}_{\text{Type of purity}}\right]$$

$$I_0 = \mathrm{Tr}\left[\rho_0^2(t)\right]$$

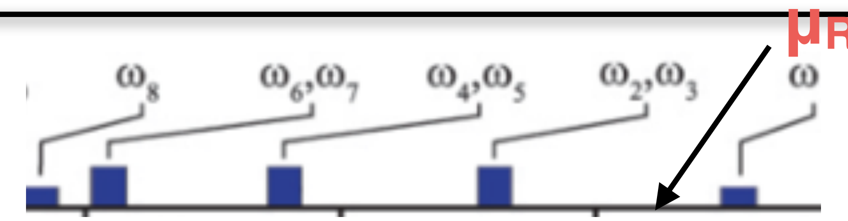
Fourier transform: ϕ gives the Multi-Quantum spectrum.

Connection to Renyi entropy?

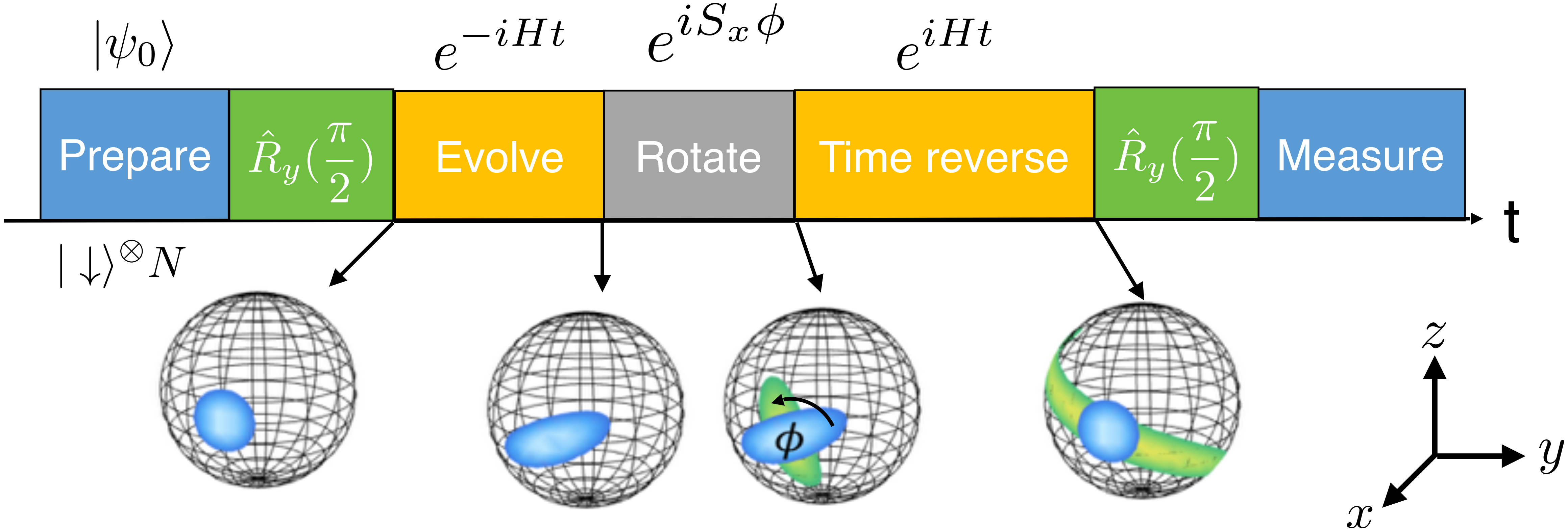
Reversing Time with Ions



$J \propto g^2/\delta$



$J \propto -g^2/\delta$



Many-body Loschmidt echo

$$\langle\rho_0\rangle = Tr[\rho_0\rho_f] = Tr[\rho_0\, e^{itH} e^{-i\phi\hat{S}_x} e^{-itH} \rho_0\, e^{itH} e^{i\phi\hat{S}_x} e^{-itH}] = \sum_{m=-N}^{N} Tr[\rho_m \rho_m^\dagger]\, e^{im\phi}$$

$V^\dagger(0)$ $W^\dagger(t)$ $V(0)$ $W(t)$

Fidelity OTOC

$$I_m = \mathrm{Tr}\left[\rho_{-m}(t)\rho_m(t)\right]$$

Type of purity

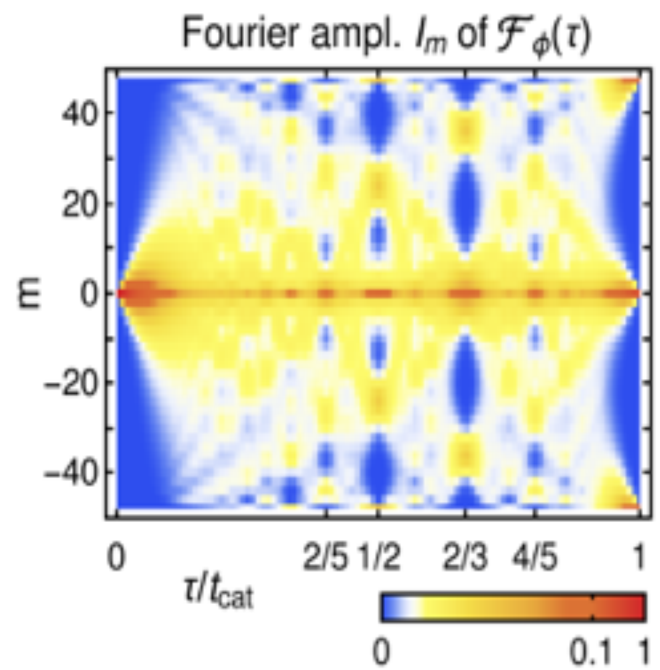
$$I_0 = \mathrm{Tr}\left[\rho_0^2(t)\right]$$

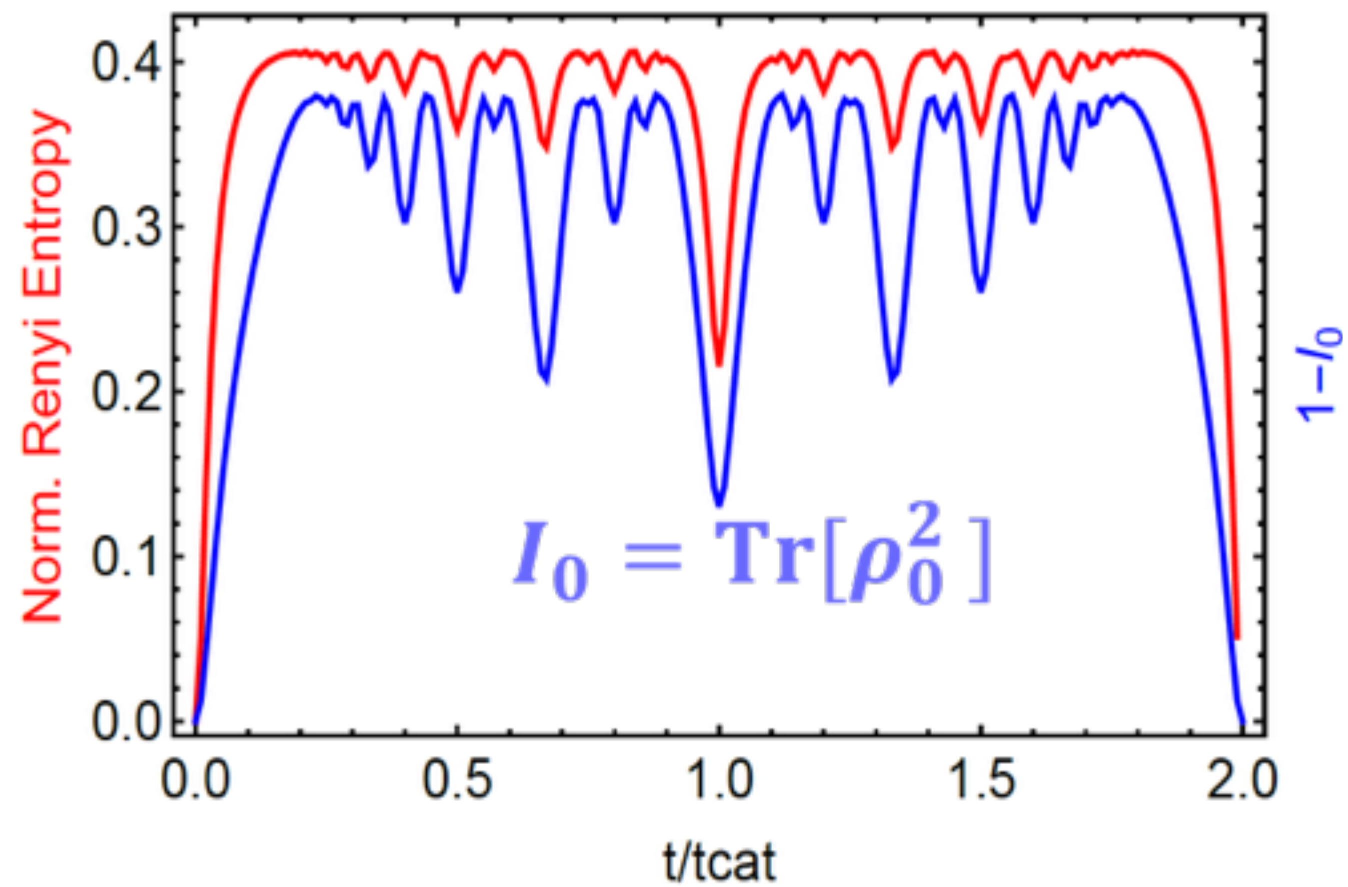
Fourier transform: ϕ gives the Multi-Quantum spectrum.

Connection to Renyi entropy?

MQC in All-to-all Ising Model

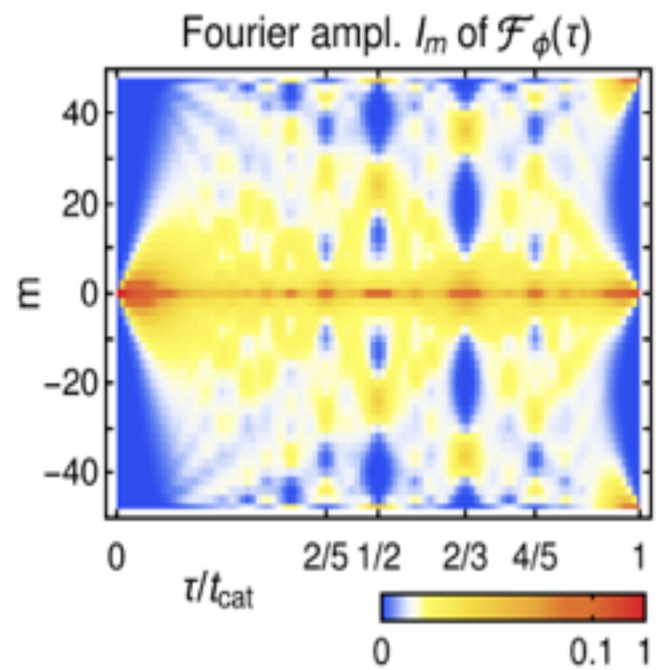
Information stored in the initial (local) state is distributed , through the interactions, over many-body degrees of freedom of the system.

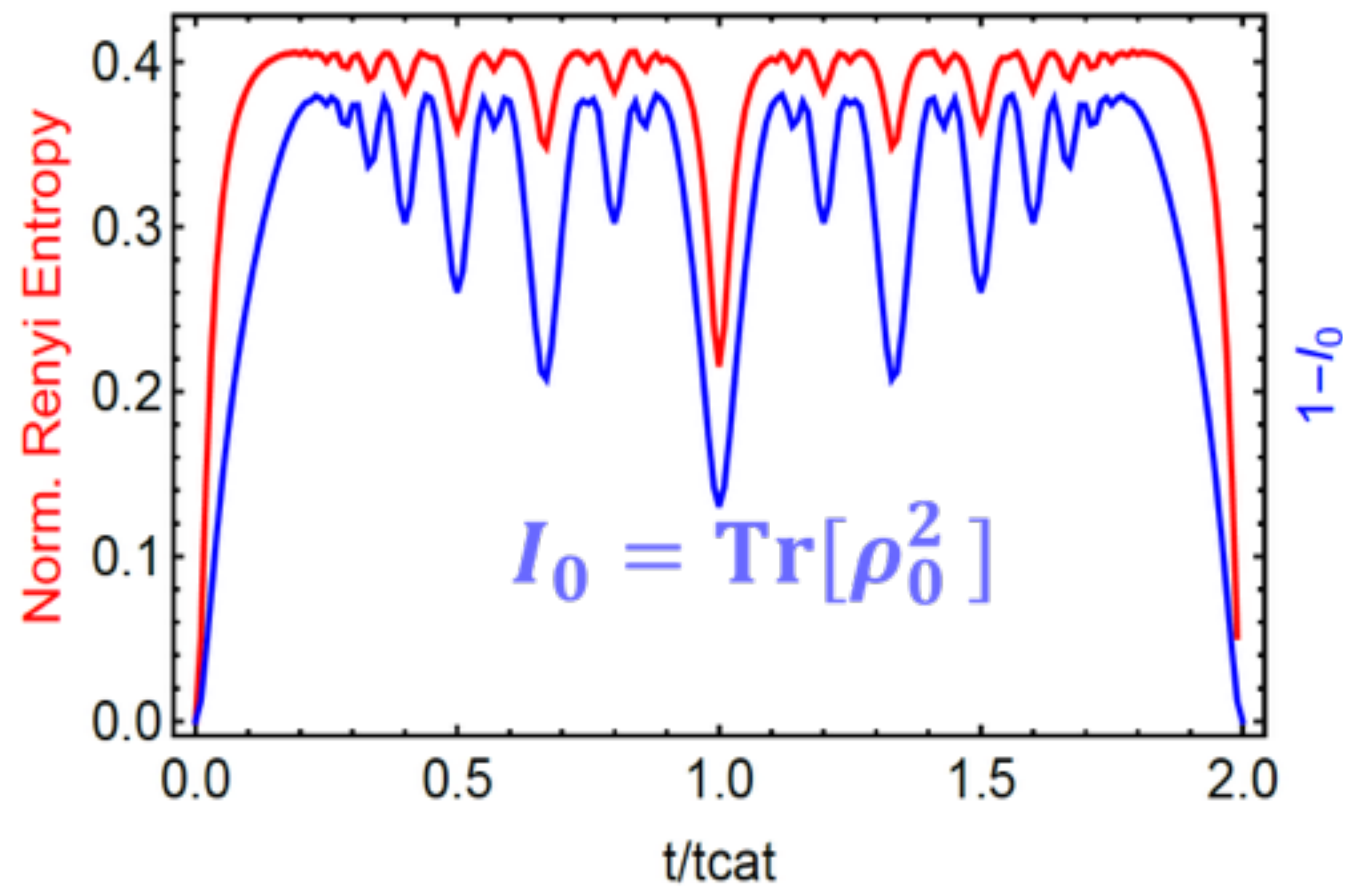




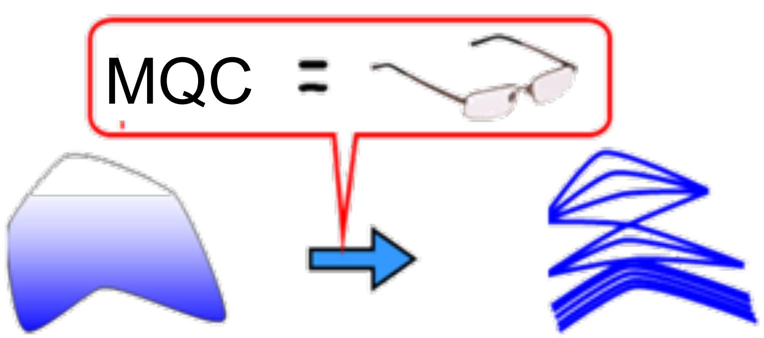
MQC in All-to-all Ising Model

Information stored in the initial (local) state is distributed , through the interactions, over many-body degrees of freedom of the system.

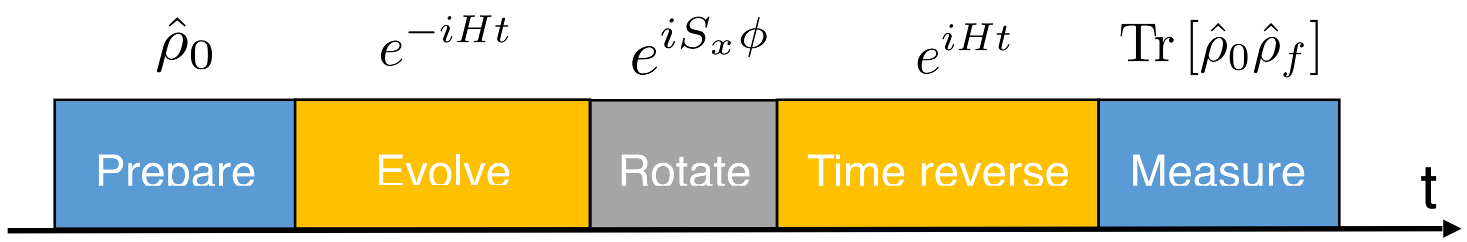


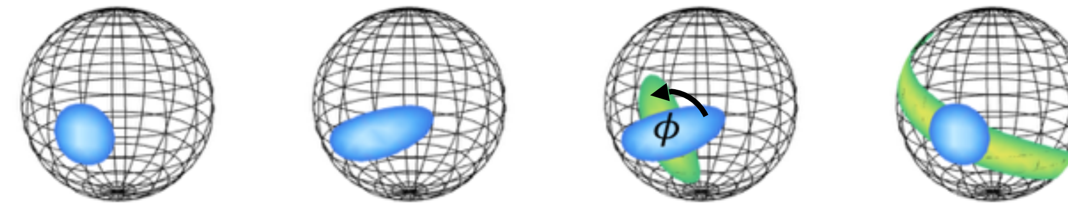


Detailed structure of the state without single-site resolution



Fidelity Measurement





Many-body Loschmidt echo

$$\langle \rho_0 \rangle = Tr[\rho_0 \rho_f] = Tr[\rho_0\, e^{itH} e^{-i\phi \hat{S}_x}\, e^{-itH} \rho_0\, e^{itH}\, e^{i\phi \hat{S}_x}\, e^{-itH}]$$

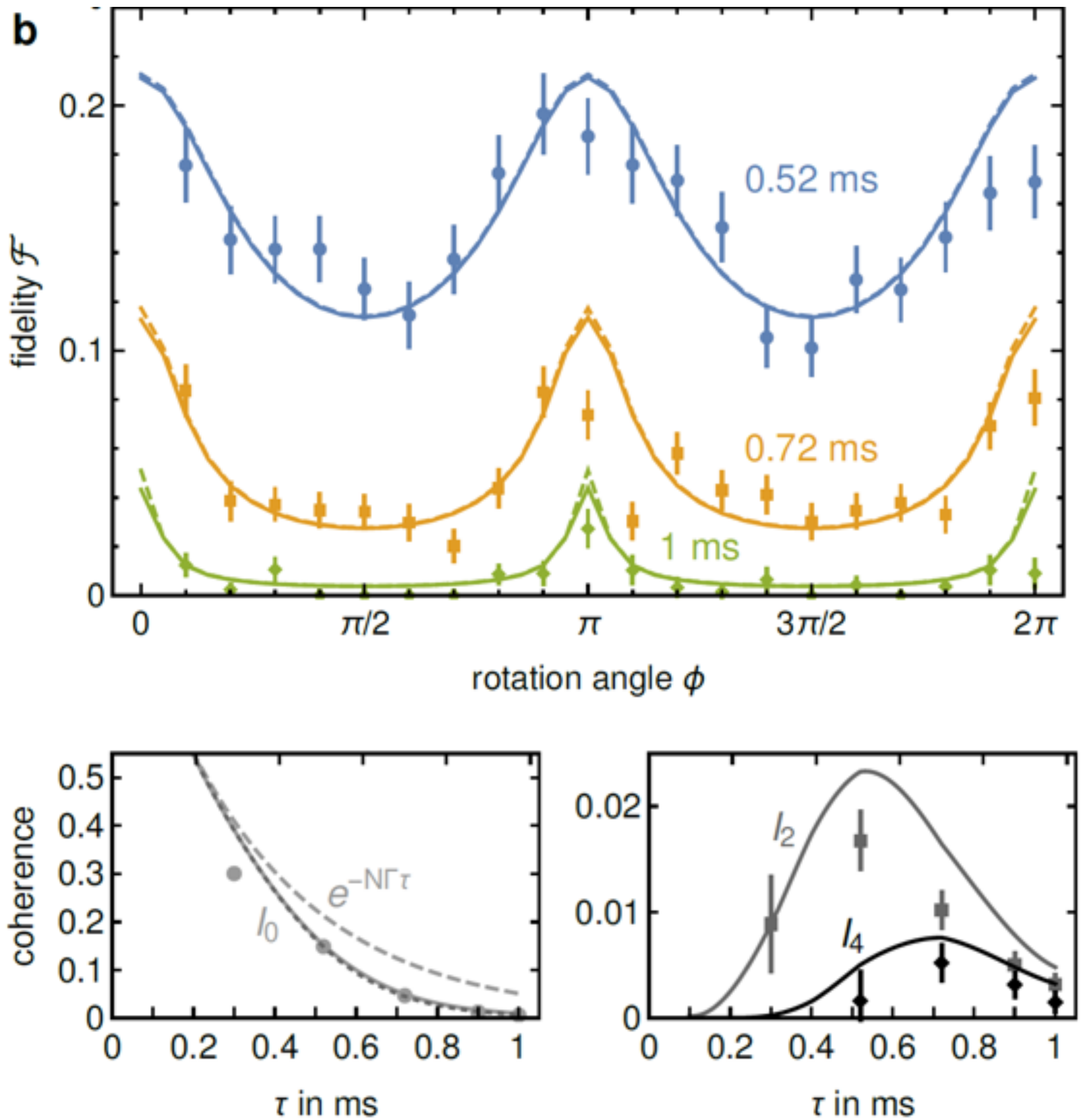
$$= \sum_{m=-N}^{N} \underbrace{Tr[\rho_m \rho_m^\dagger]}_{I_m}\, e^{im\phi}$$

OTOC measurement but also connected to a **multi-partite entanglement witness:**

Quantum Fisher Information (QFI)

- How much that state changes with respect to a rotation
- Can show $F_Q(\rho, A) \geq -2\frac{d^2}{d\phi^2}\mathrm{Tr}[\hat{\rho}_0\hat{\rho}_f]|_{\phi=0}$
- MQC has even more information since not limited to small angles

Fidelity Measurement: Experimental Result



→ OTOC witnesses multi-particle entanglement!

→ Experimentally measured the OTOC

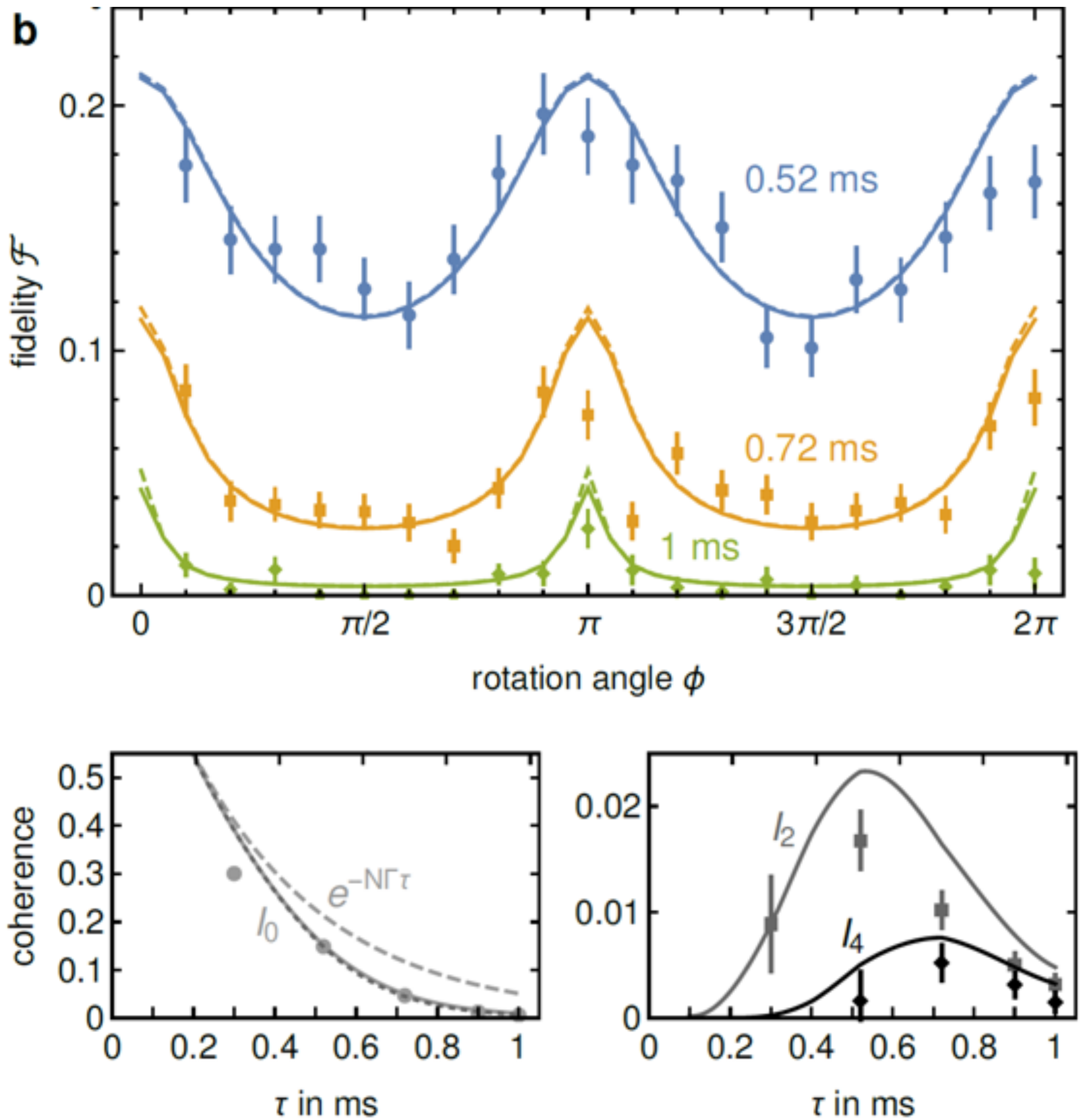
→ Fully benchmarked experimental system: **spins + phonons + decoherence**

$$I_0^{pure}(\tau) = (1 + J^2\tau^2)^{-1}$$

Not a fast scrambler

Gärttner, Bohnet, ASN, Wall, Rey, Bollinger, Nature Physics 2017

Fidelity Measurement: Experimental Result



→ OTOC witnesses multi-particle entanglement!

→ Experimentally measured the OTOC

→ Fully benchmarked experimental system: **spins + phonons + decoherence**

$$I_0^{pure}(\tau) = (1 + J^2\tau^2)^{-1}$$

Not a fast scrambler

Obstacle:

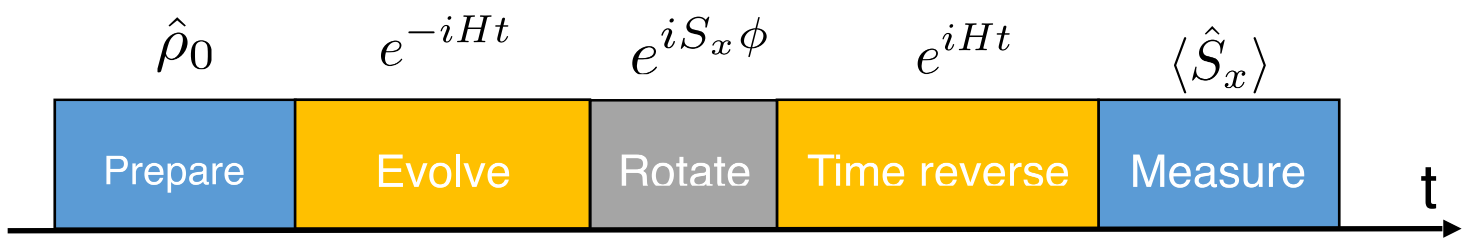
Light scattering

$$I_0(\tau) = e^{-\Gamma N\tau} I_0^{pure}$$

limited to 6.5% cat time

Gärttner, Bohnet, ASN, Wall, Rey, Bollinger, Nature Physics 2017

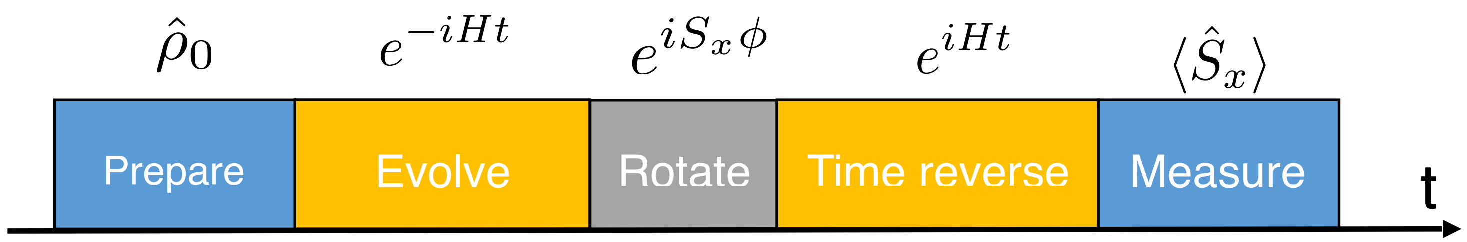
Magnetization



$$\langle S_x \rangle = \langle \Psi_0 | \, e^{itH} \, e^{i\phi S_x} \, e^{-itH} S_x \, e^{itH} \, e^{-i\phi S_x} \, e^{-itH} | \Psi_0 \rangle$$

$$= \frac{2}{N} \langle \Psi_0 | \, \underbrace{e^{itH} \, W^\dagger \, e^{-itH}}_{W^\dagger(t)} \, \underbrace{V^\dagger}_{V^\dagger(0)} \, \underbrace{e^{itH} \, W \, e^{-itH}}_{W(t)} \, \underbrace{V}_{V(0)} | \Psi_0 \rangle$$

Magnetization



$$\langle S_x \rangle = \langle \Psi_0 | \, e^{itH} \, e^{i\phi S_x} \, e^{-itH} S_x \, e^{itH} \, e^{-i\phi S_x} \, e^{-itH} | \Psi_0 \rangle$$

$$= \sum_m \langle \Psi | C_m | \Psi \rangle \, e^{i\phi m}$$

$$C_m = \sum \underbrace{\sigma_1^z \sigma_4^y \ldots \sigma_k^z}_{\text{At least m terms}}$$

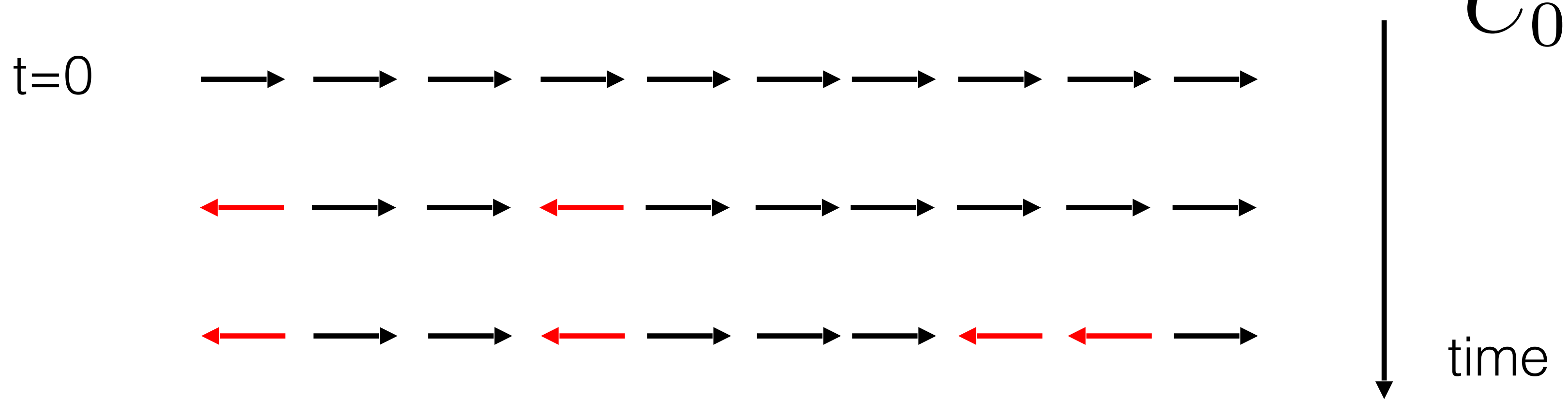
Fourier components of magnetization OTOC

- **Signals the buildup of at least m-body correlations**
- **Far less sensitive to decoherence**

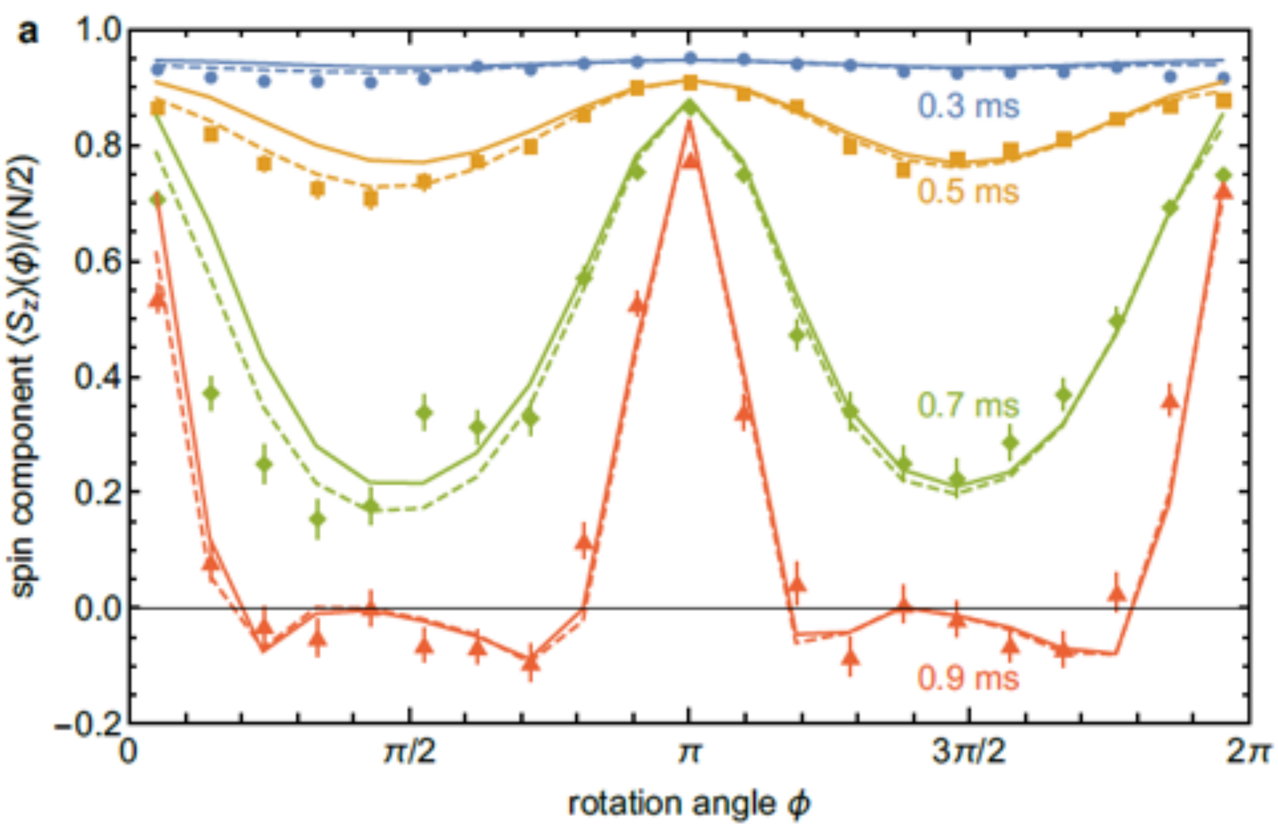
$$C_0(\tau) \sim e^{-\Gamma\tau} C_0^{\text{pure}}$$

How do the correlations propagate?

$$\sigma_i^z \sigma_j^z = \sigma_i^+ \sigma_j^+ + \sigma_i^- \sigma_j^- + \sigma_i^- \sigma_j^+ + \sigma_i^+ \sigma_j^-$$

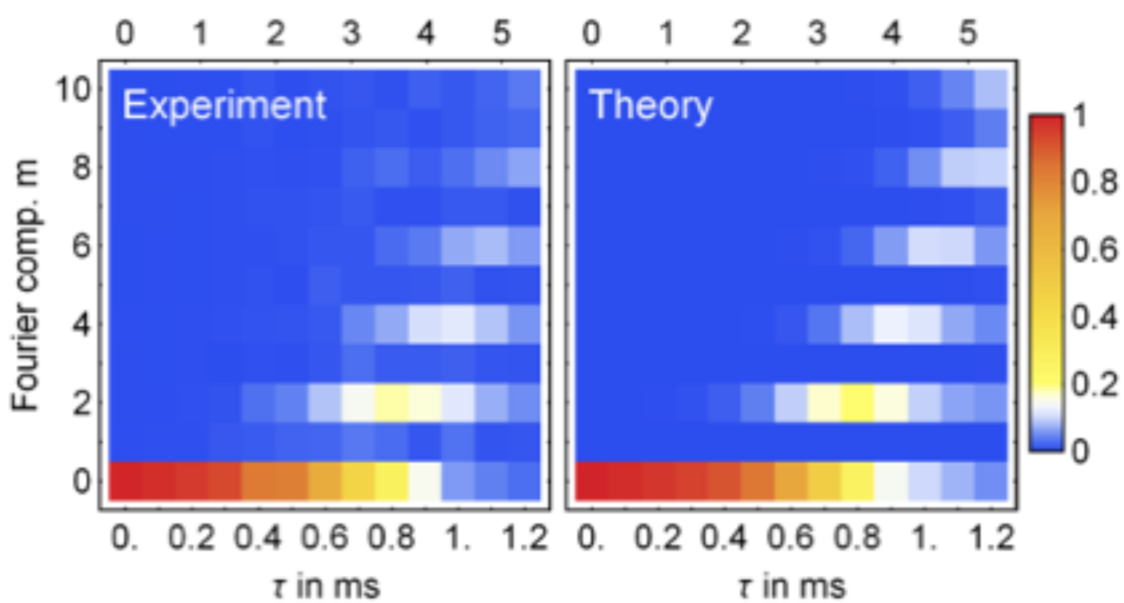


Magnetization OTOC: Experimental Results



$$H_{\mathrm{SS}} = \frac{J}{N}\hat{S}_z^2$$

$$J \sim 5\mathrm{kHz}$$
$$N = 111$$
$$\Gamma = 93\mathrm{Hz}$$



Global measurements + **Time reversal**

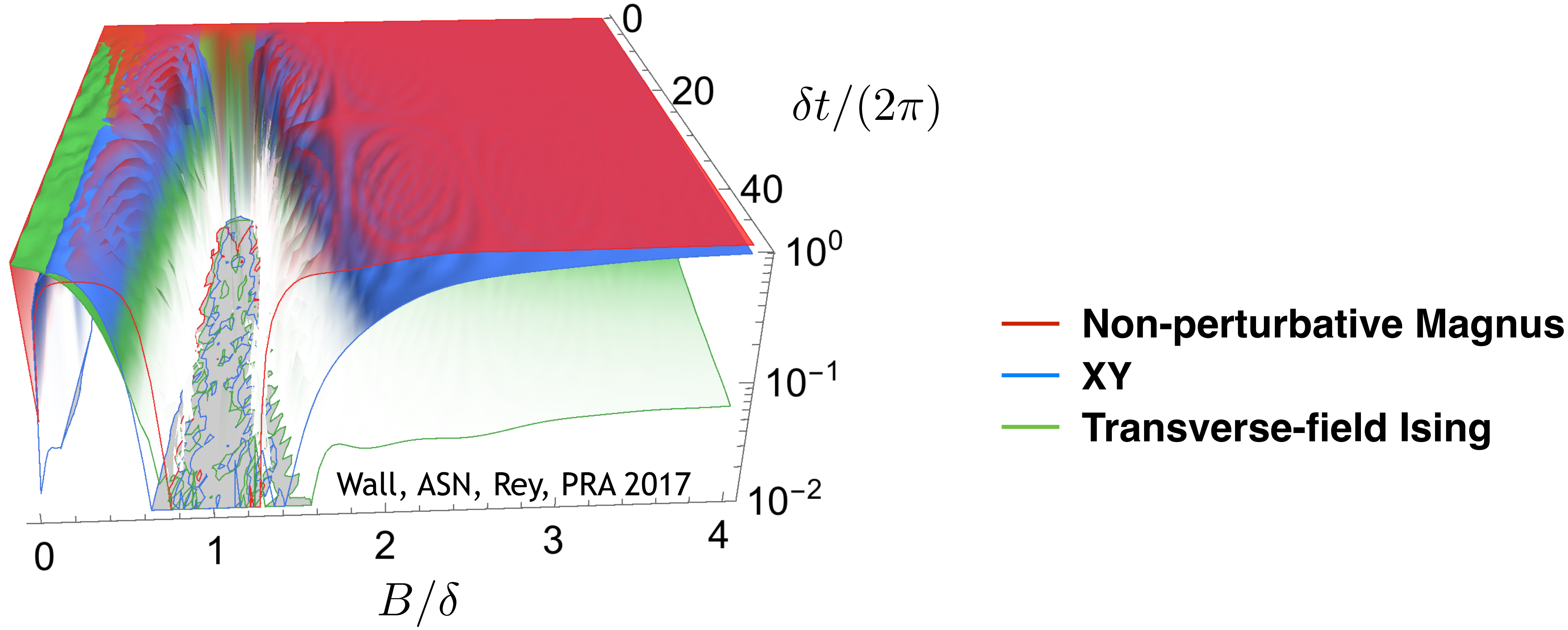
- OTOC
- Benchmark the simulator
  - Decoherence and Hamiltonian
  - Characterization of the final state
- Dynamics of correlations

Gärttner, Bohnet, ASN, Wall, Rey, Bollinger, Nature Physics 2017

Transverse Magnetic Field

- The most straight-forward next step experimentally:
  - Add a transverse field: non-commuting term

$$\hat{H} = -\delta \hat{a}^\dagger \hat{a} - g(\hat{a} + \hat{a}^\dagger)\hat{S}_z + B(t)\hat{S}_x$$

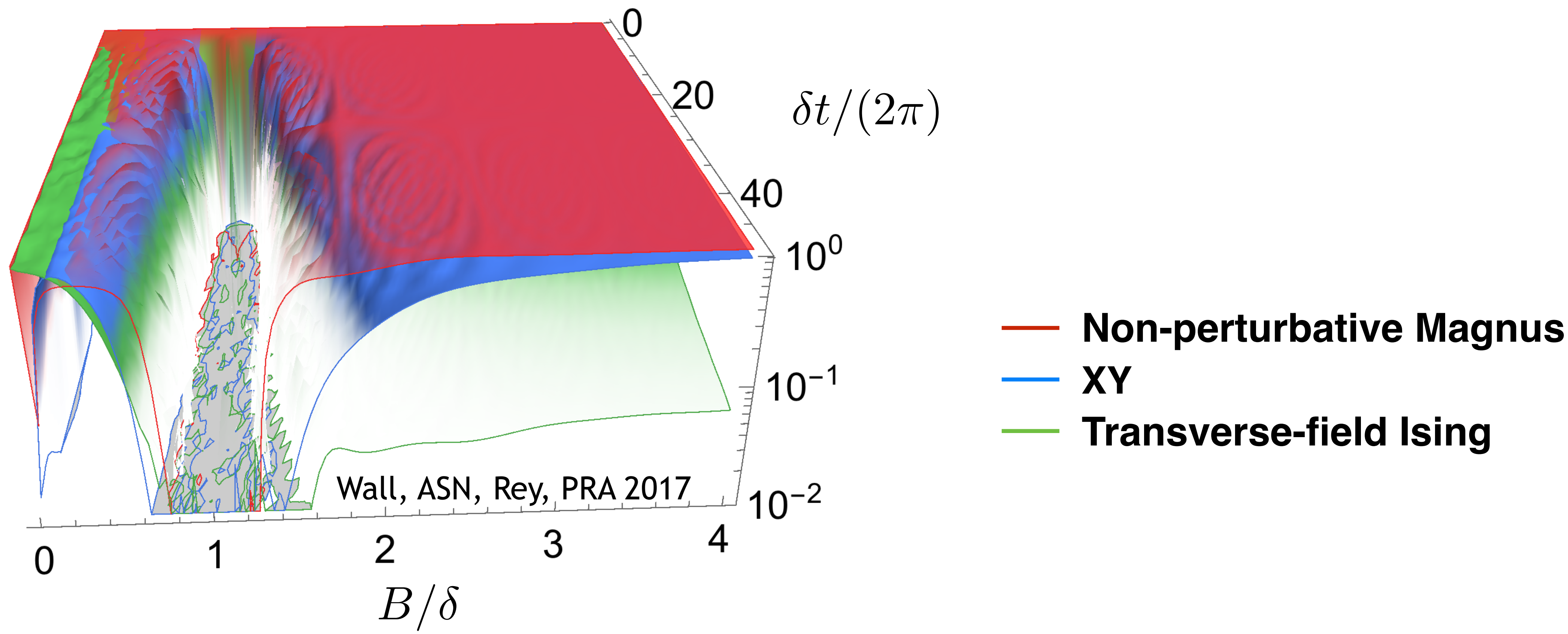


Transverse Magnetic Field

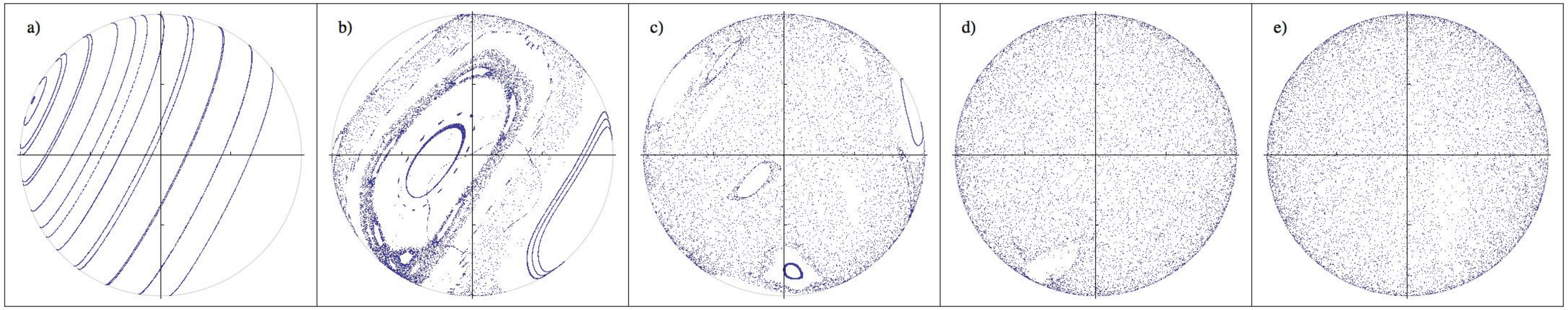
- The most straight-forward next step experimentally:
  - Add a transverse field: non-commuting term

$$\hat{H} = -\delta \hat{a}^\dagger \hat{a} - g(\hat{a} + \hat{a}^\dagger)\hat{S}_z + B(t)\hat{S}_x$$

Dicke model



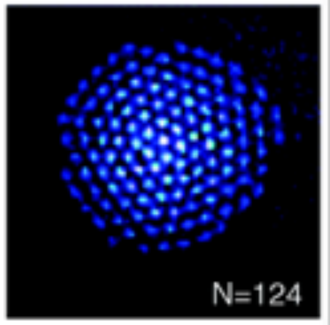
classical chaos with increasing g



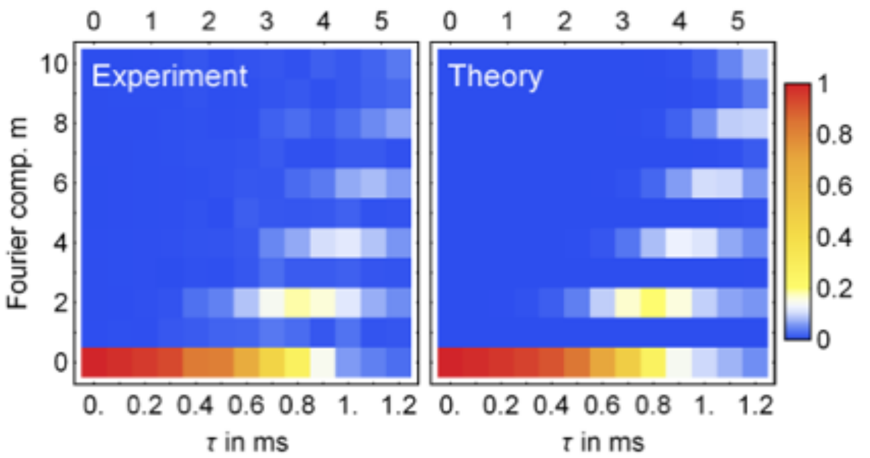
Altland, Haake '11 '13

Conclusions and Outlook

Benchmarking of a trapped-ion simulator of **Ising** and **Dicke** models of ~100 ions



Observation of the dynamics of quantum coherences and correlations



But what about our relatively simple model?

- Fine grain information about the state only from global measurements
- Characterize spread of coherences (Fidelity) and correlations (Magnetization)
- Connection to entanglement witnesses (Fidelity)

Future Directions:

- Scrambling in the Dicke model
- States outside of the symmetric manifold
- Dynamical phase transition in the Dicke model
- Preparation of the spin-phonon cat state

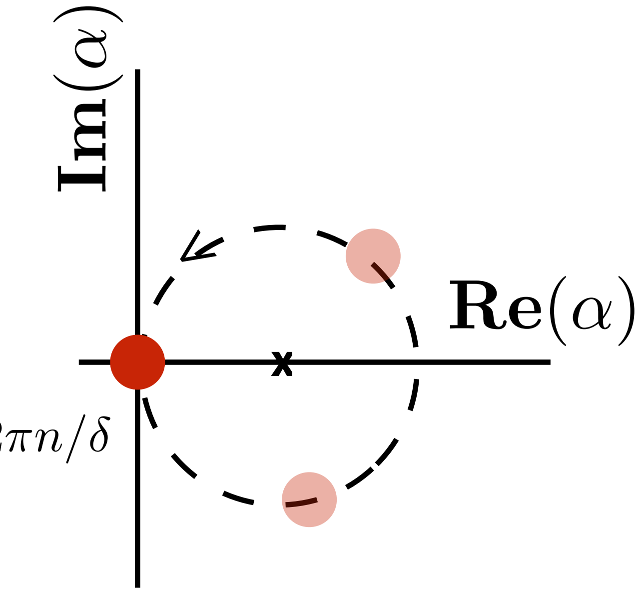
References

- Garttner, Bohnet, **ASN,** Wall, Gilmore, Bollinger, Rey '17
- Wall, **ASN,** Rey, '16, '17
- Garttner, Hauke, Rey '17
- **ASN,** Lewis-Swann, Garttner, Gilmore, Jordan, Rey, Bollinger, In preparation.

Stroboscopic Spin Dynamics

Dynamics generated by: $U(t) = U_{\text{SP}}(t) U_{\text{SS}}(t)$

$H_{\text{SP}} = \hat{D}(\alpha \hat{S}_z)$ spin-dependent displacement of phonons



- Spin and motion decouple at specific times $t = 2\pi n/\delta$

$$U_{\text{SP}}(t_n) = I$$

Stroboscopically measure the same dynamics as the Ising model:

$$H_{\text{SS}} = \frac{J}{N} \hat{S}_z^2 \qquad J \sim 1/\delta$$

Uniform couplings when coupled only to the COM