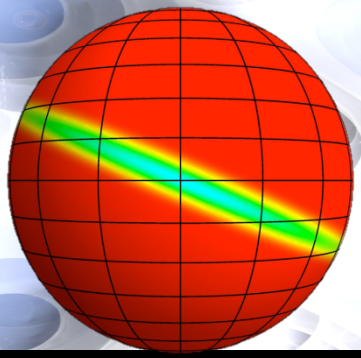

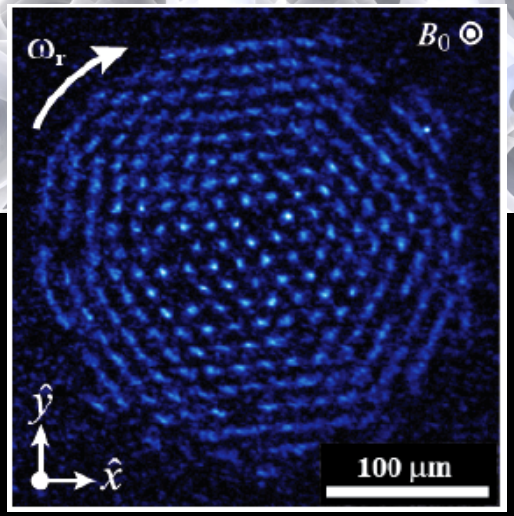

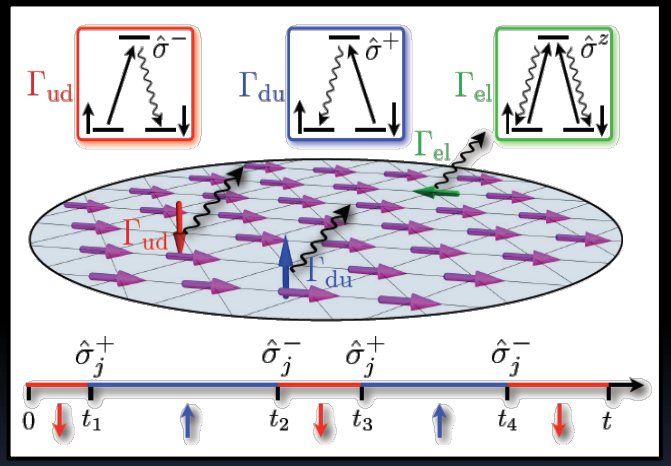

Kaden Hazzard
Rice University

Louisiana State University
Quantum Krispy Kreme seminar
Mar 27, 2015

NO DEMOCRACY FOR ENTANGLEMEN

not all entanglements are created equal

Collaborators

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NIST-Boulder

Also: Salvatore Manmana (Goettingen), Mauritz van den Worm, Michael Kastner (Stellenbosch), Tilman Pfau (Stuttgart), Emanuele Dalla Torre (Bar Ilan), JILA molecule group (Jun Ye, Debbie Jin, …)

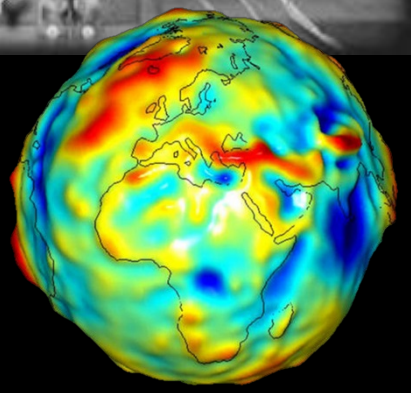
QUANTUM

Quantum metrology: magnetic fields, rotation, gravity

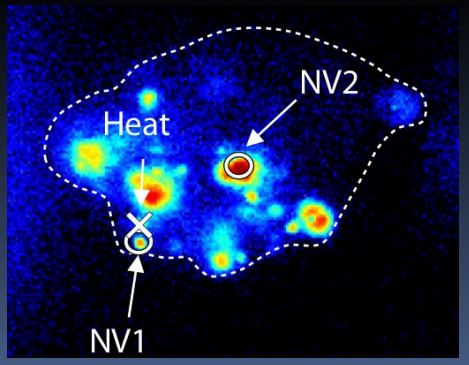
Quantum communication

Quantum computation

Advanced materials



gravitational field



thermometry in a cell

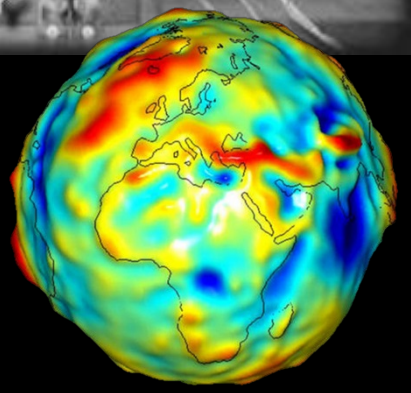
QUANTUM

Quantum metrology: magnetic fields, rotation, gravity

Quantum communication

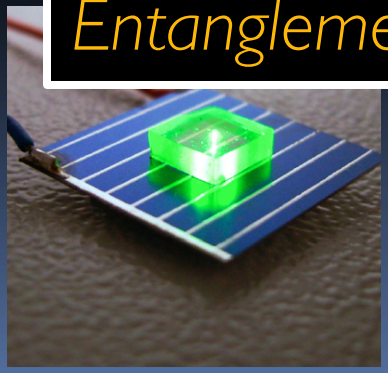
Quantum computation

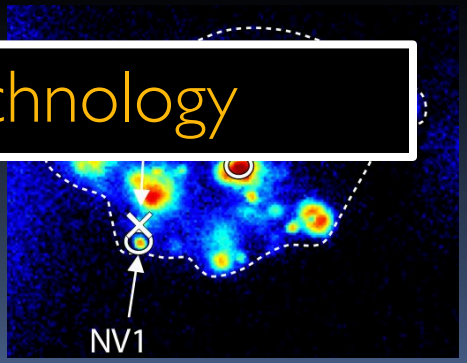
Advanced materials



gravitational field

Entanglement is necessary for all quantum technology





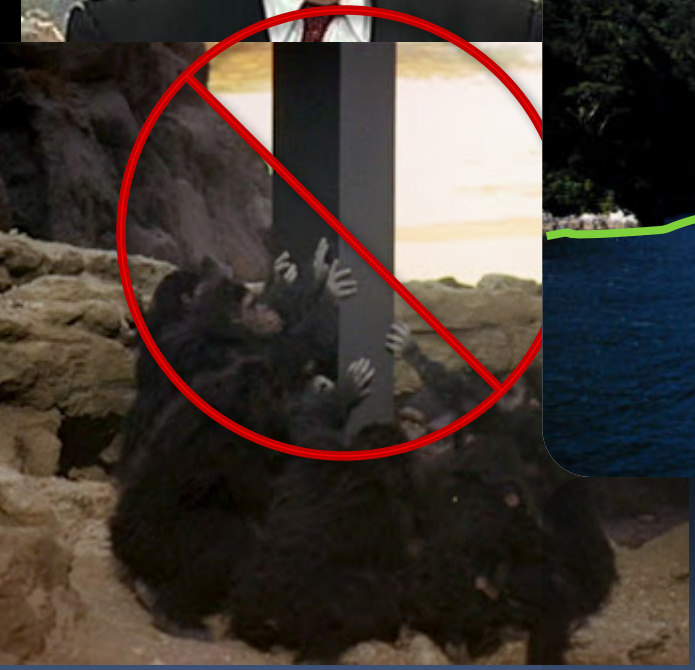
thermometry in a cell

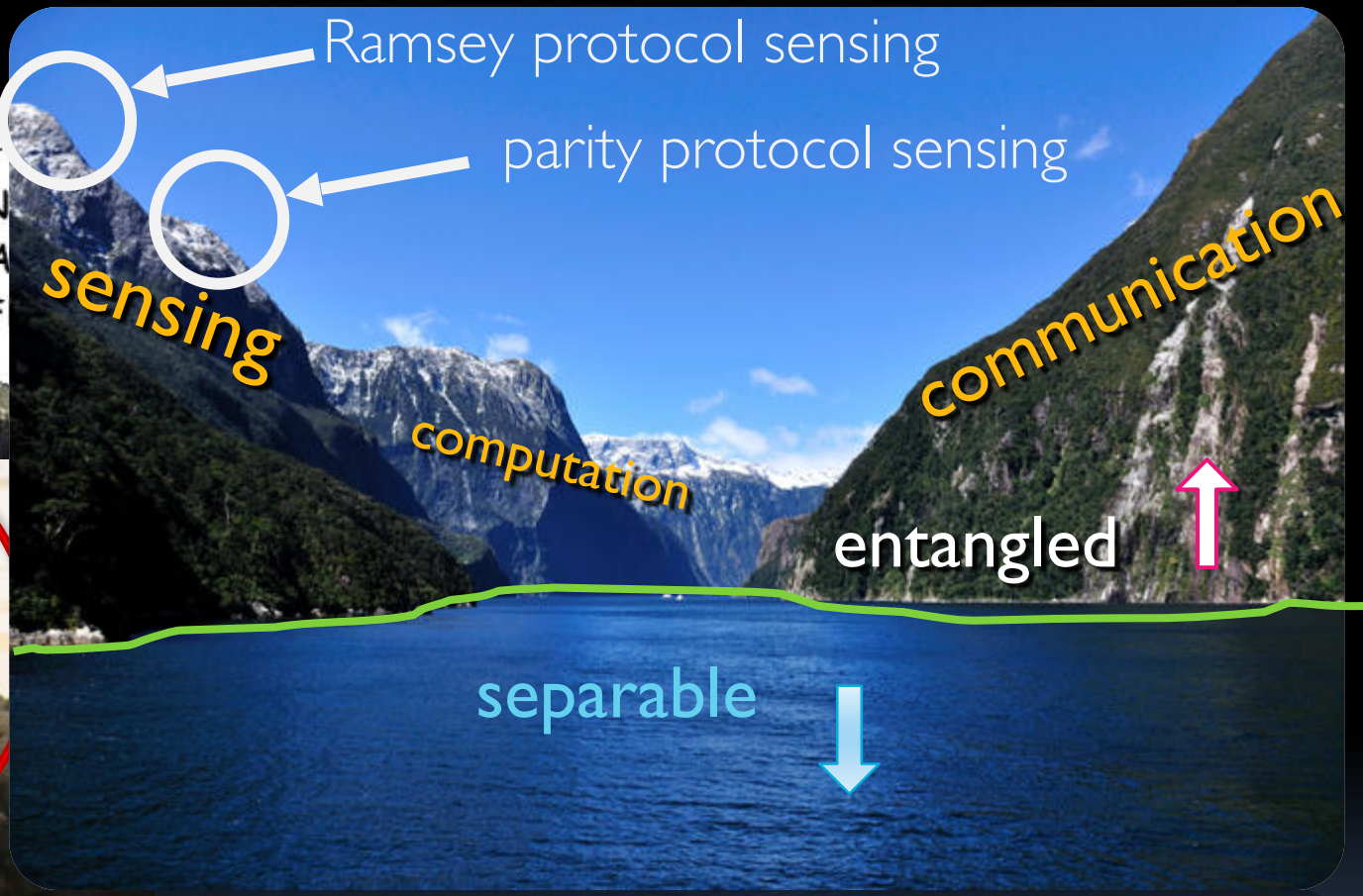
So all that's left is…

make more entanglement, please?

So all that's left is…

make more entanglement, please?

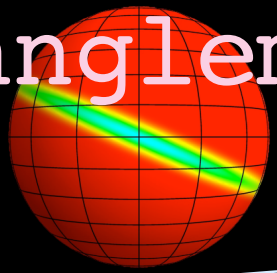




- Entanglement isn't monolithic : each quantum technology requires a *different kind* of entanglement
- Decoherence is a fundamental challenge

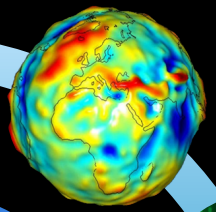
Task

Type of entanglement



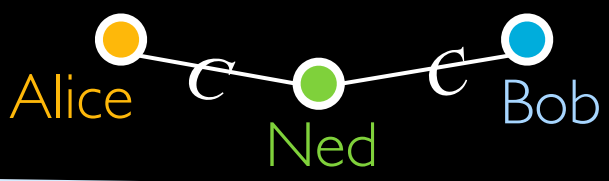
squeezing, GHZ-ness

- metrology

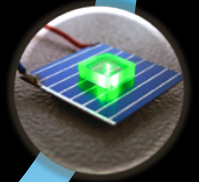


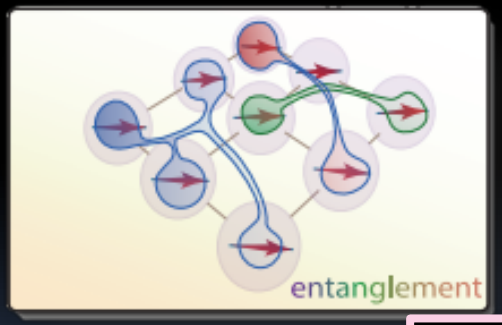
- communication

concurrence



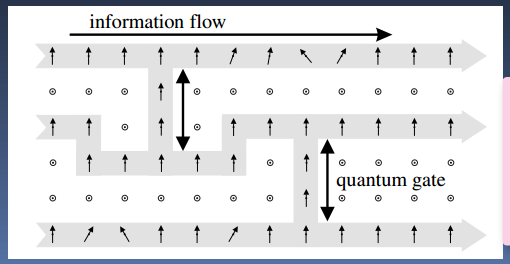
- classical intractability





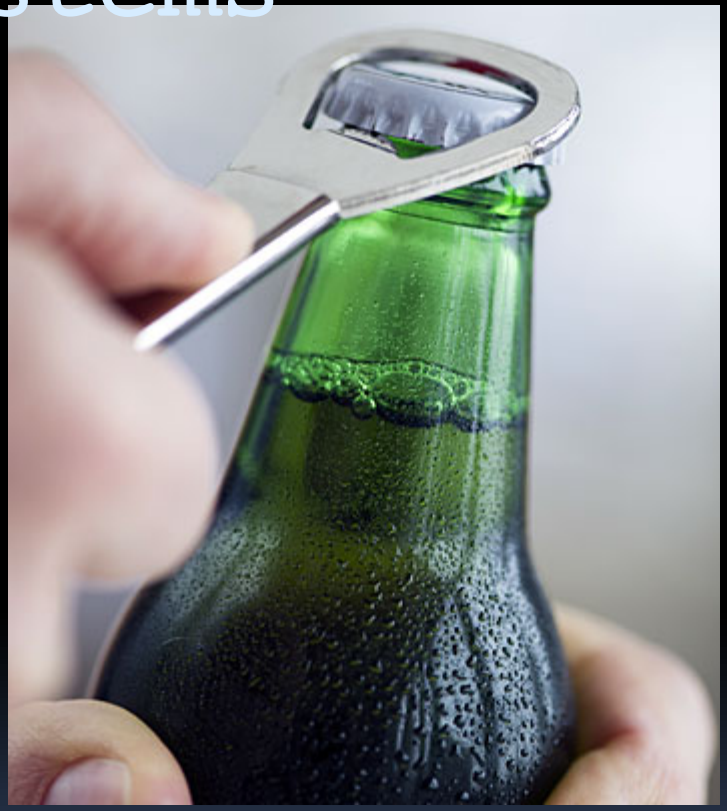
entropy

- computation



cluster states

decoherence: open quantum systems

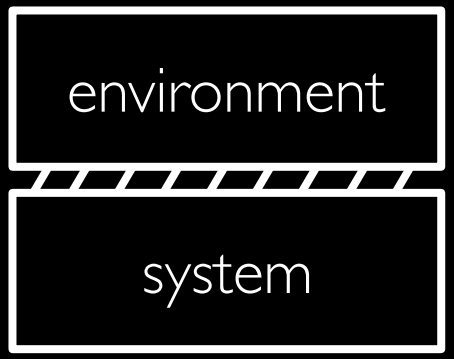


closed

open

Modeling open systems

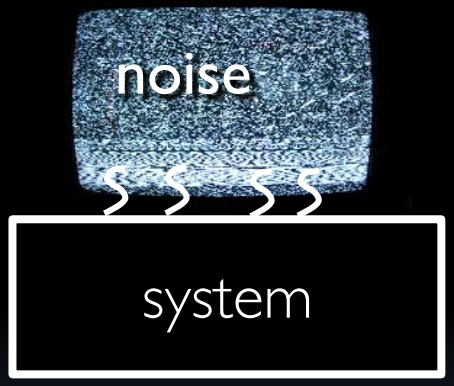
- system + environment



$$H = H_s + H_{env} + H_{s-e}$$

$$i\partial_t |\psi\rangle = H|\psi\rangle$$

- system + noise



$$H = H_s + \eta(t) H_{noise}$$

$$i\partial_t |\psi\rangle = H|\psi\rangle$$

- system probability distr. **(master eqn)**

$$i\partial_t \rho = [H_s, \rho] + L[\rho]$$

with the "jump operator"

Modeling open systems

church of the smaller Hilbert space

Many approaches; each has advantages and disadvantages
Here we use master equation
Pros: No need to double system size, reduces extraneous details
Cons: assumes Markovian (accurate for many systems)
only gives averages (can't condition on measurement record)

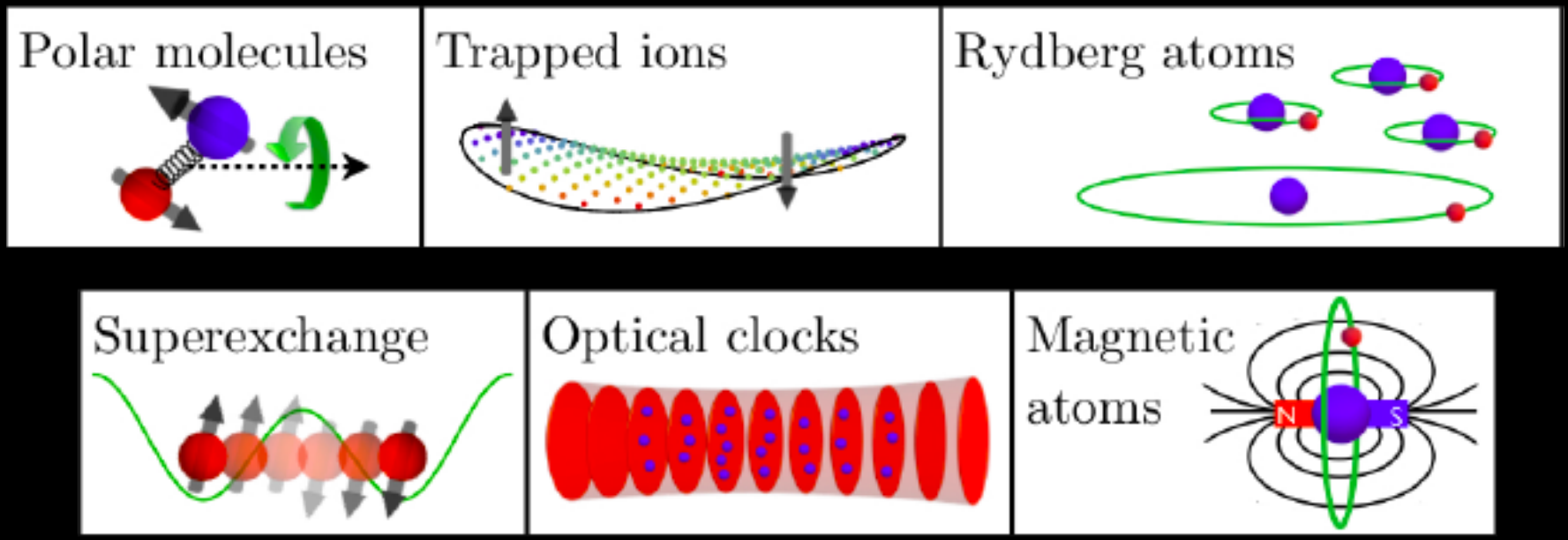
- system probability distr. **(master eqn)**

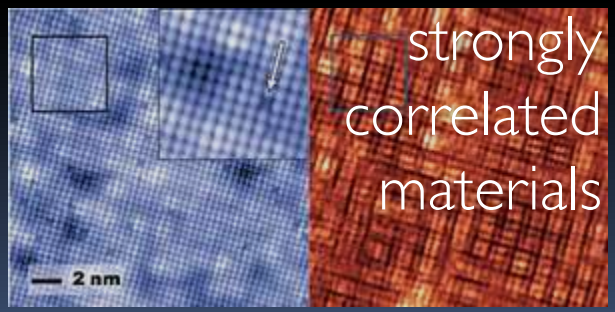
mixed system

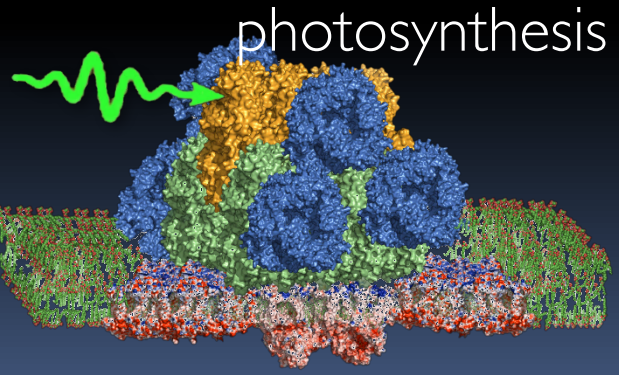
$$i\partial_t \rho = [H_s, \rho] + L[\rho]$$

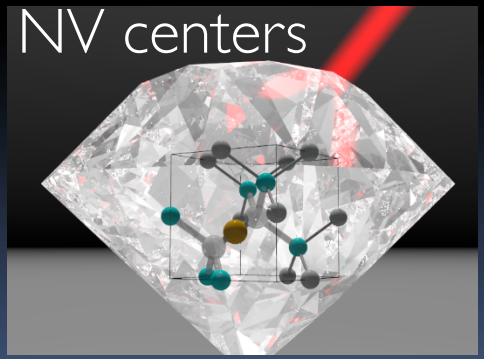
with the "jump operator"

entanglement matters for matter









All unified by the XXZ model

XXZ model is everywhere

Systems have $$H = \sum_{ij} [J^z_{ij} S^z_i S^z_j + \frac{J^\perp_{ij}}{2}\left(S^+_i S^-_j + h.c. \right)]$$

A zoo!

Without special engineering:

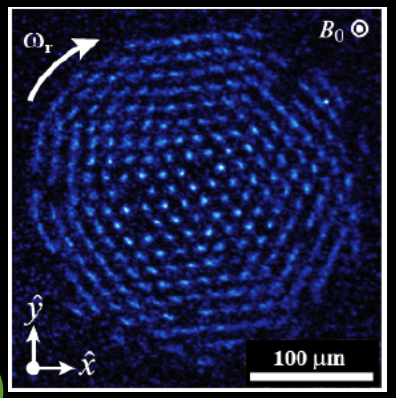
Molecules (yesterday):

Ions: with

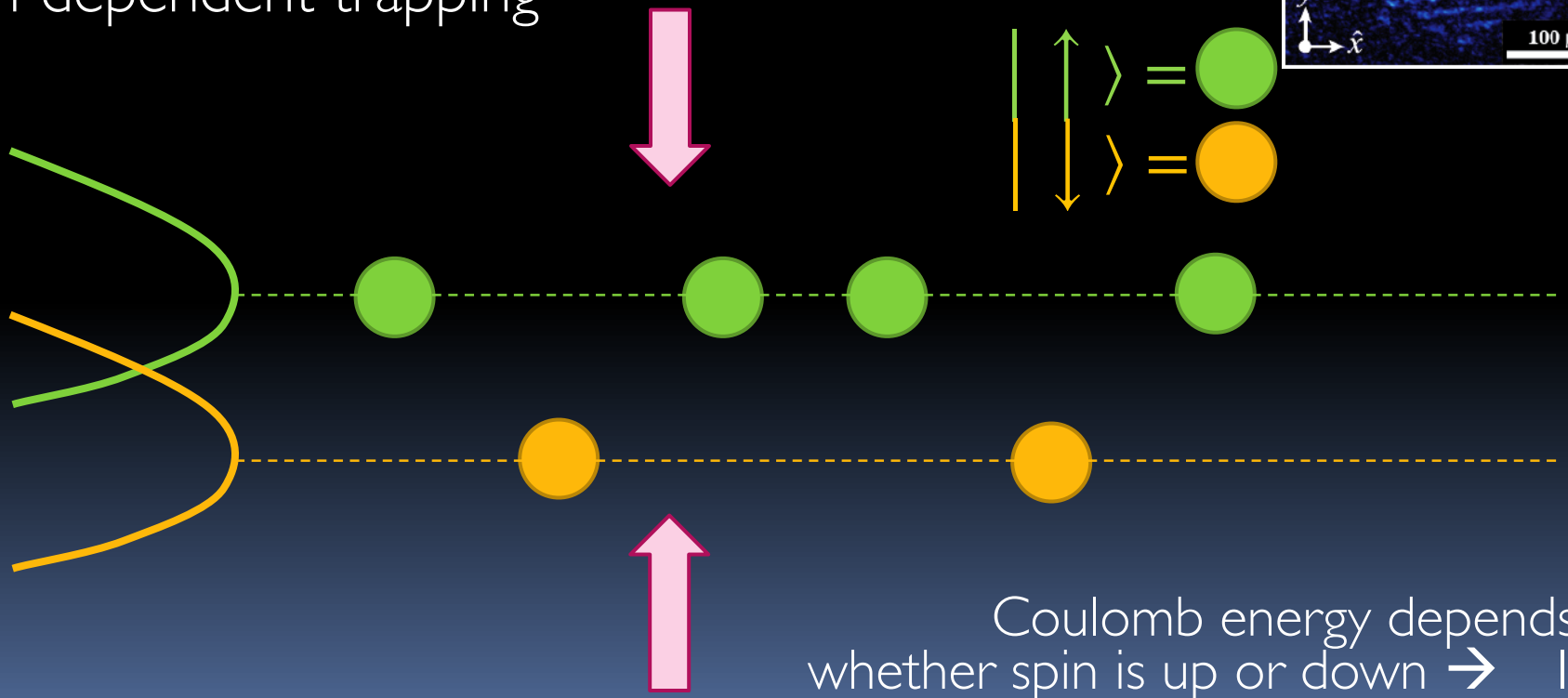
Rydbergs:

Ion interactions

$$H = \sum_{ij} J_{ij}^{z} S_i^z S_j^z ,$$



Spin-dependent trapping



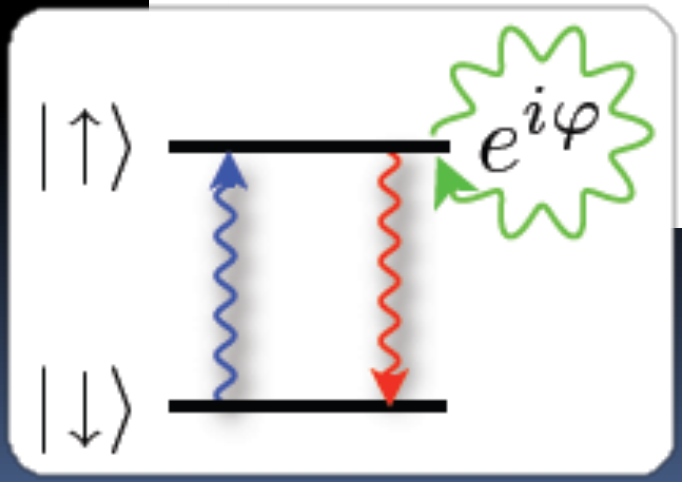
Coulomb energy depends on whether spin is up or down → Ising

decoherence in trapped ions

illustrative; form is the same for many systems

Uys et al., *PRL* **105**, *200401 (2010)*

$$\dot{\rho} = -i\left[\frac{J}{\mathcal{N}}\sum_{i>j}\hat{\sigma}_i^z\hat{\sigma}_j^z, \rho\right] + \frac{\Gamma_{\mathrm{ud}}}{2}\sum_j\left(2\hat{\sigma}_j^-\rho\,\hat{\sigma}_j^+ - \rho\hat{\sigma}_j^+\hat{\sigma}_j^- - \hat{\sigma}_j^+\hat{\sigma}_j^-\rho\right)$$
$$+ \frac{\Gamma_{\mathrm{du}}}{2}\sum_j\left(2\hat{\sigma}_j^+\rho\,\hat{\sigma}_j^- - \rho\hat{\sigma}_j^-\hat{\sigma}_j^+ - \hat{\sigma}_j^-\hat{\sigma}_j^+\rho\right)$$
$$+ \frac{\Gamma_{\mathrm{el}}}{8}\sum_j\left(2\hat{\sigma}_j^z\rho\,\hat{\sigma}_j^z - \rho\hat{\sigma}_j^z\hat{\sigma}_j^z - \hat{\sigma}_j^z\hat{\sigma}_j^z\rho\right)$$



Markovian master equation is basically exact

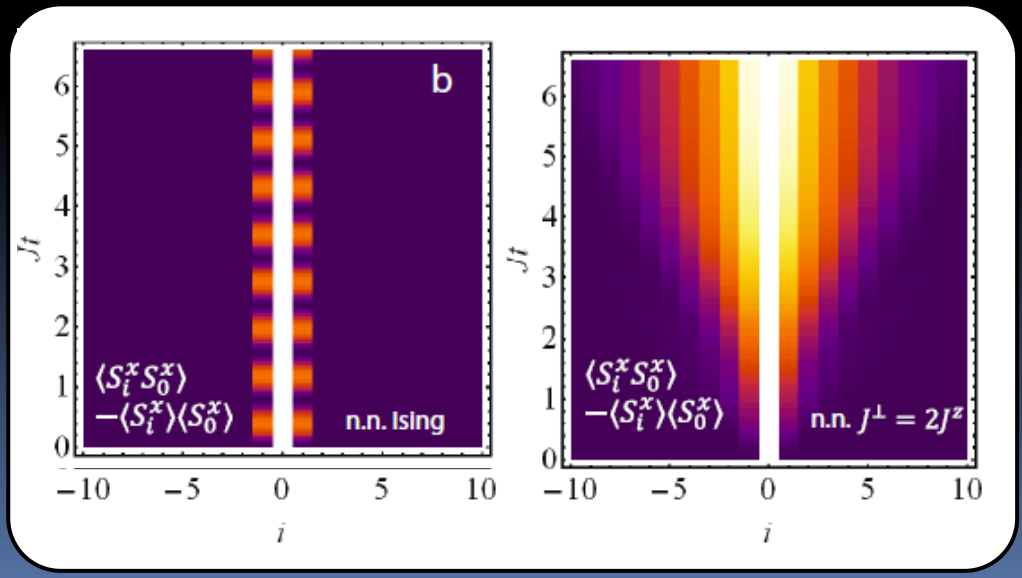
intermission: outline of results

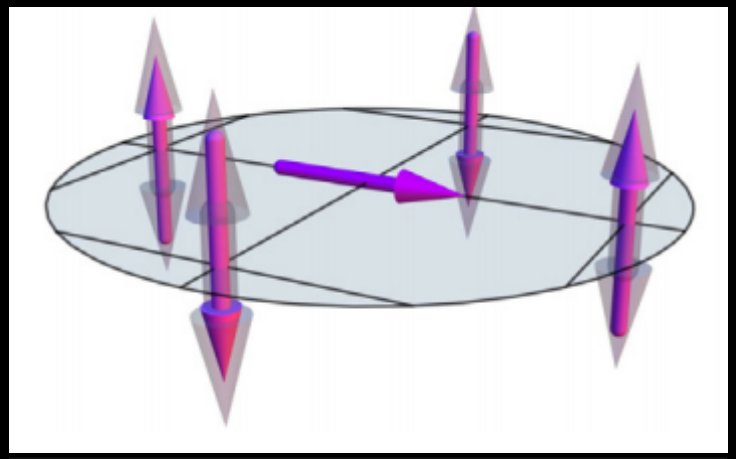
So far: motivation & set up

Up next: results

1. Ising + decoherence: correlations

2. Comparative entanglement (no decoherence)

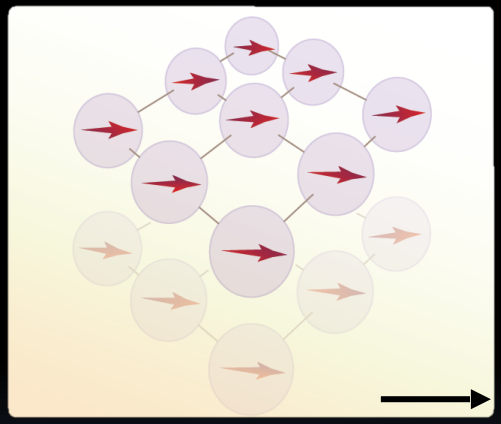




Effects of decoherence (Ising model)

Quench dynamics

Same as yesterday's Ramsey/quantum quench:

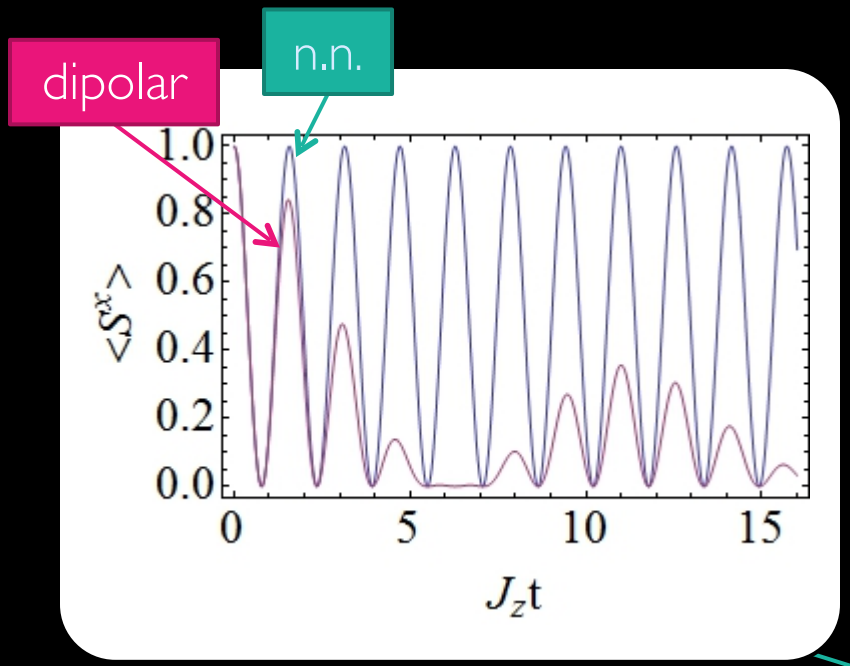


Measure , , …

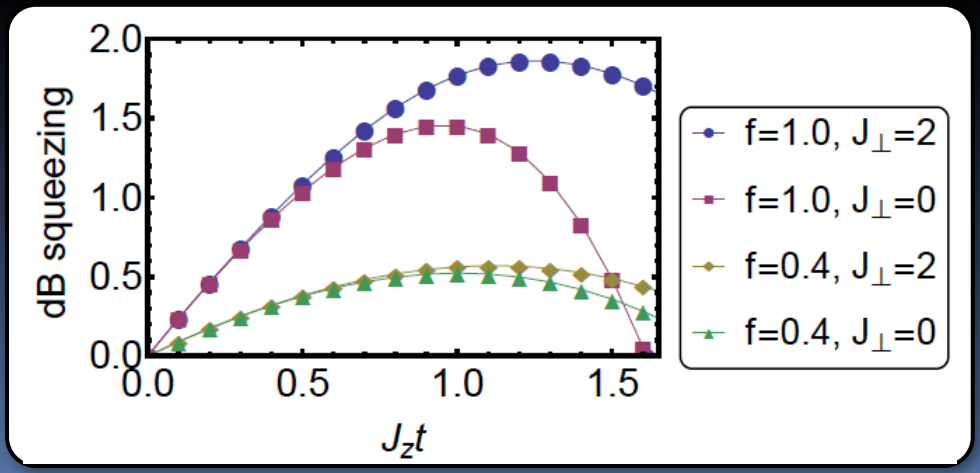
except will also look at other initial spin angles
and final measurements

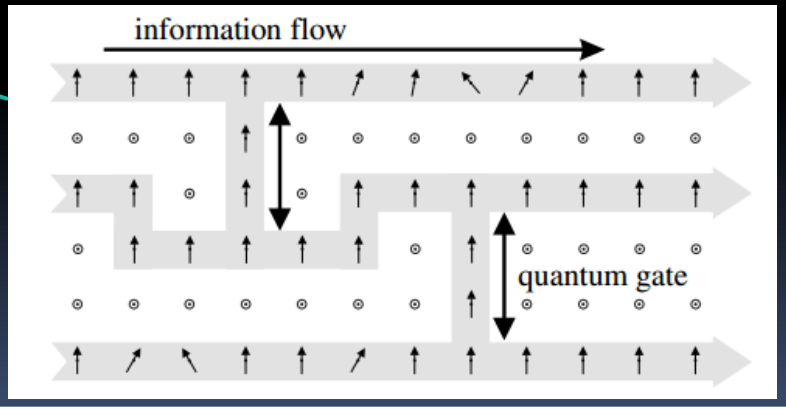
$$H = \sum_{ij} J_{ij}^z S_i^z S_j^z$$

Ising isn't classical!



- N.N → cluster state: one-way quantum computation
- all-to-all → GHZ state: Schroedinger cats, Heisenberg
- general → squeezing





Raussendorf & Briegel, PRL **86,** 5188 (2001)

Solution: Ising correlations

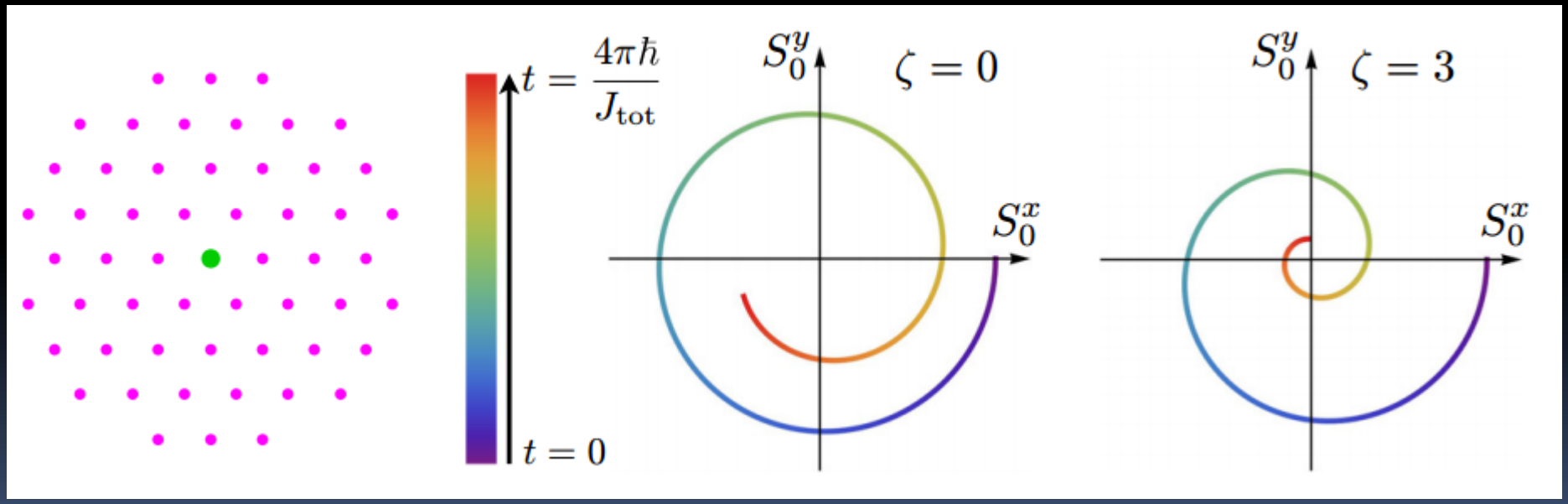
$$\mathrm{H} = \sum_{i \neq j} \frac{J_{ij}}{2} S_i^z S_j^z$$

Example of solution for correlation ()

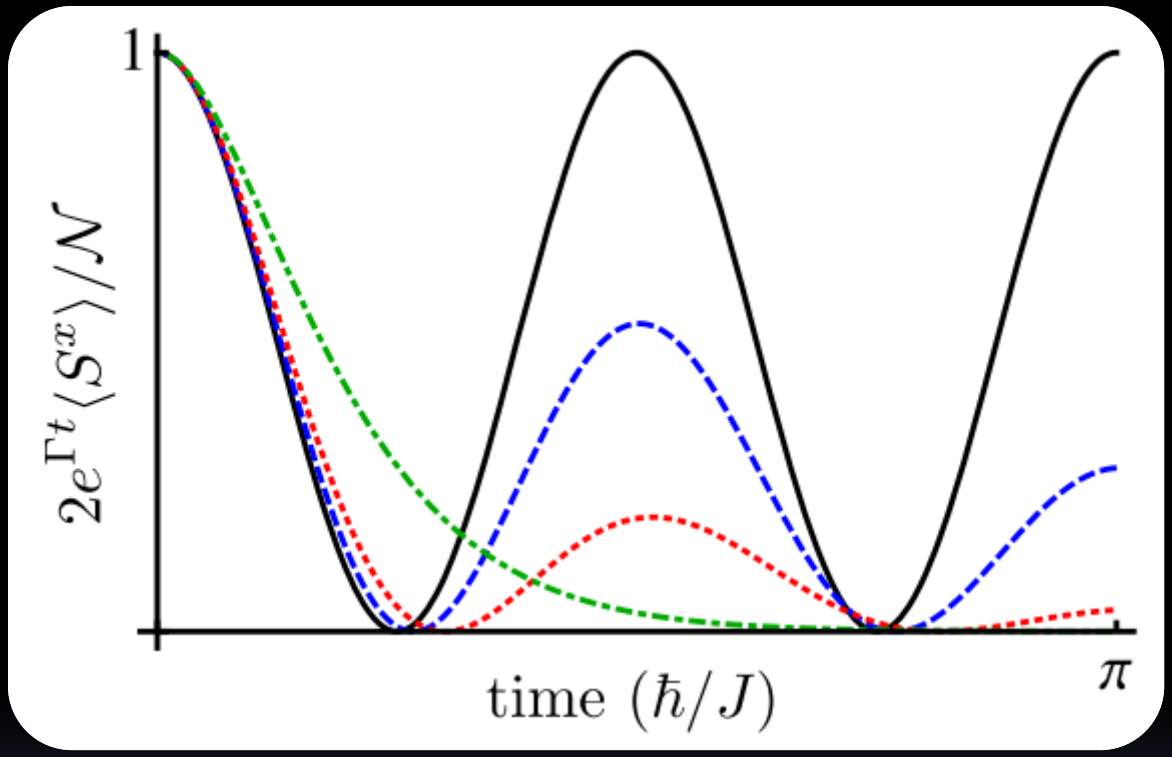
$$s_J = i(\Gamma_{ud} - \Gamma_{du})/2 + 2J/N$$

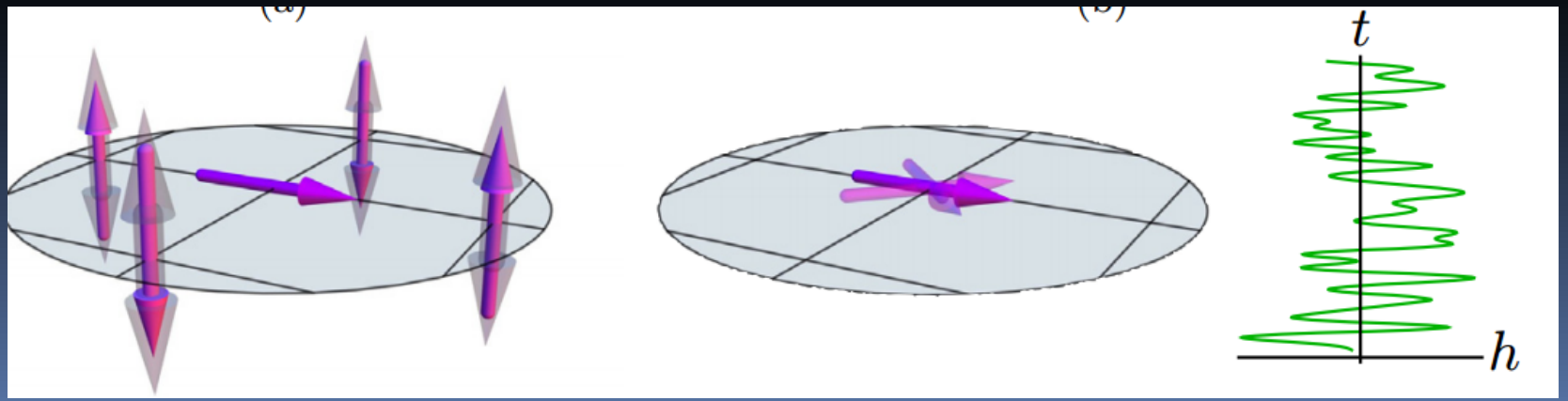
Ising: Bloch vector

0

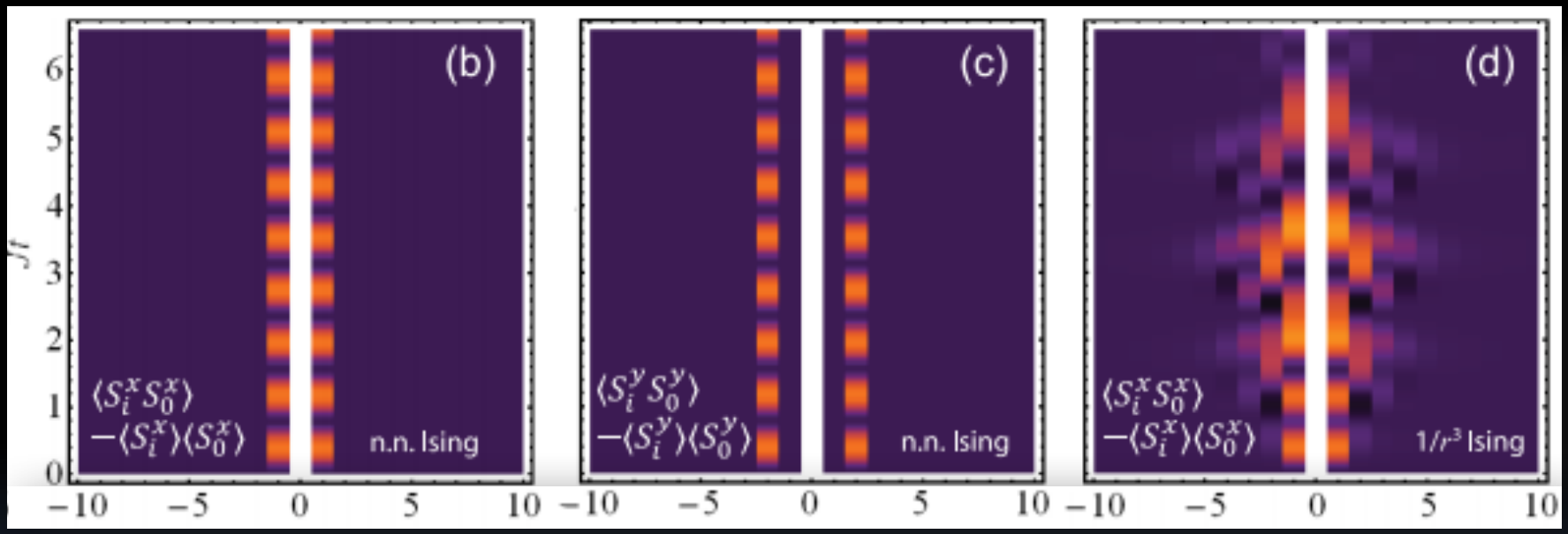


Ising decoherence: Bloch vector





Ising decoherence: spin correlations

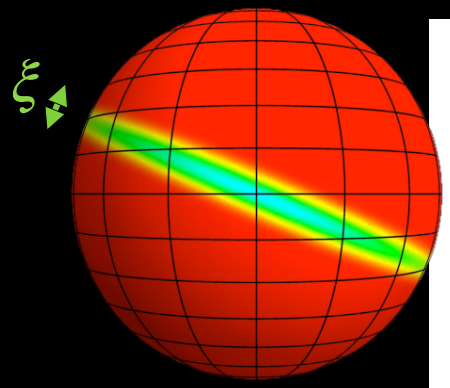


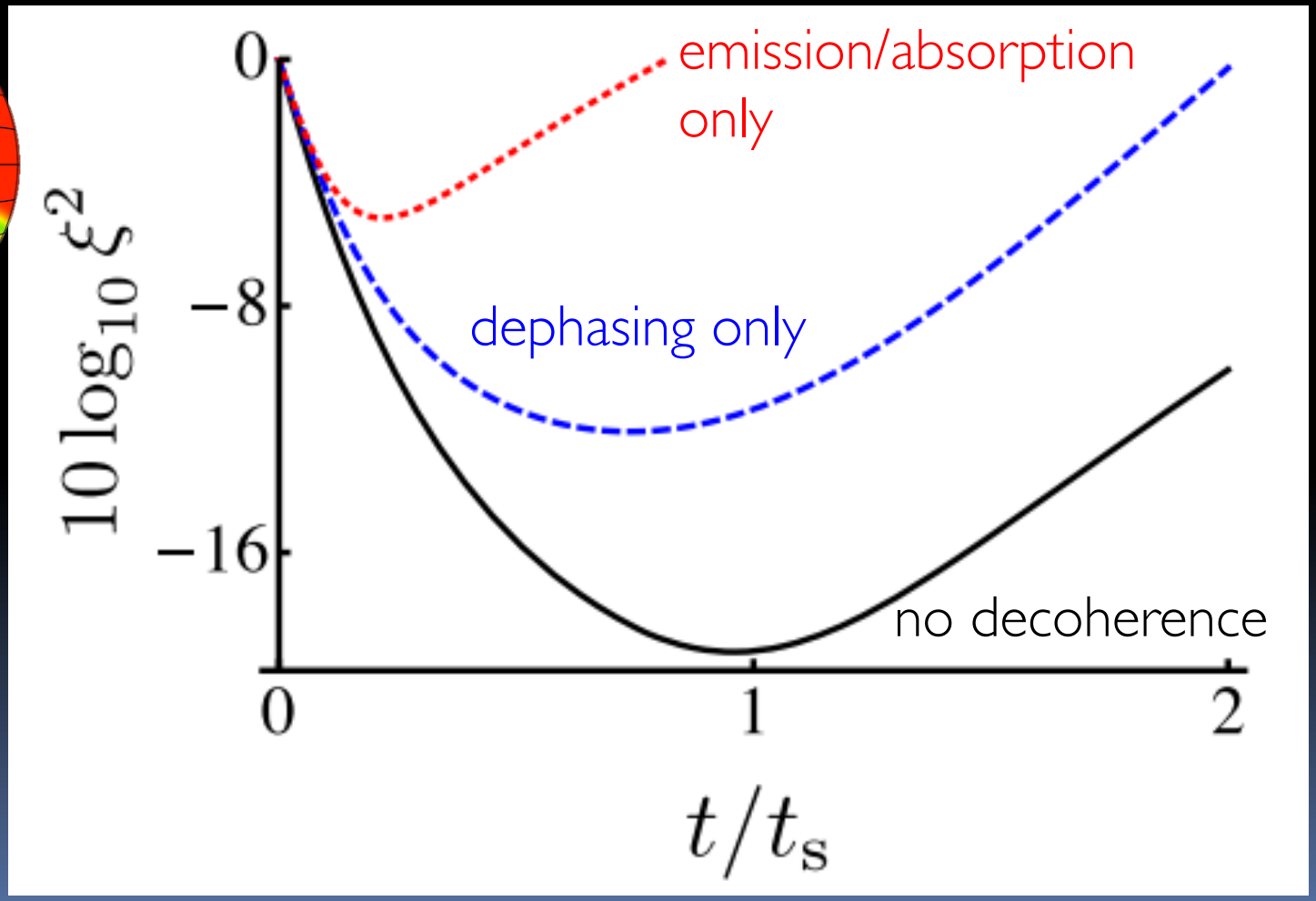
$\Gamma = 0$

Turning on decoherence, correlations damp in time

Ising decoherence: squeezing

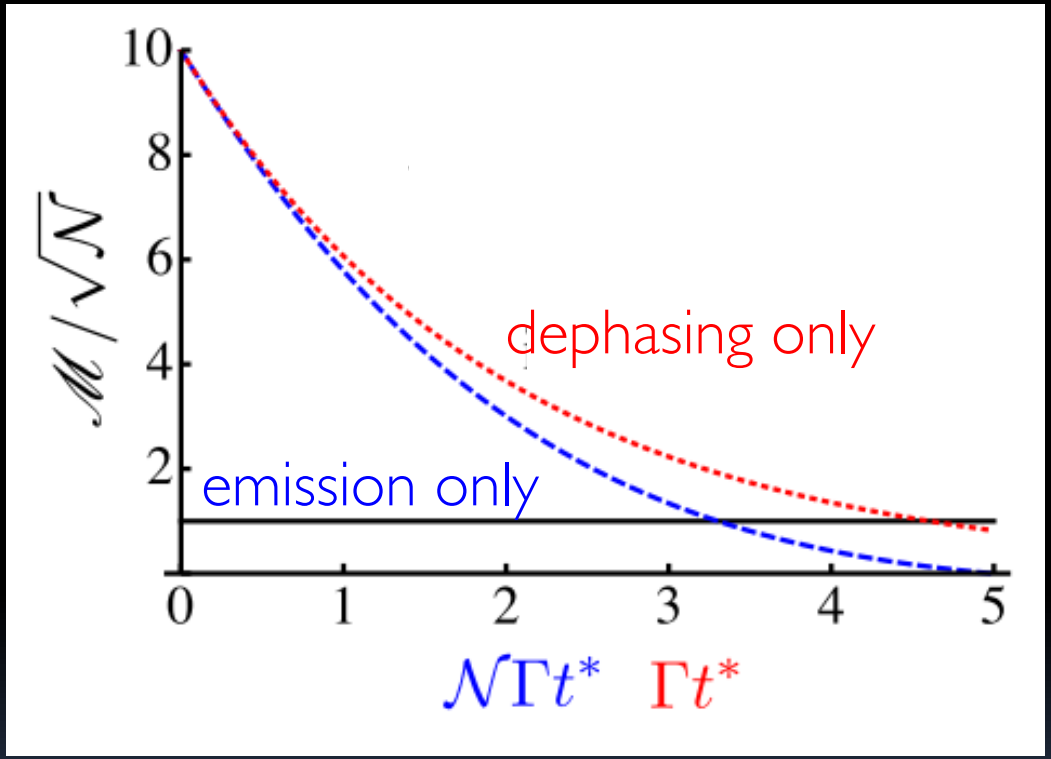
all-to-all or one-axis-twisting





Ising decoherence: GHZ-nes

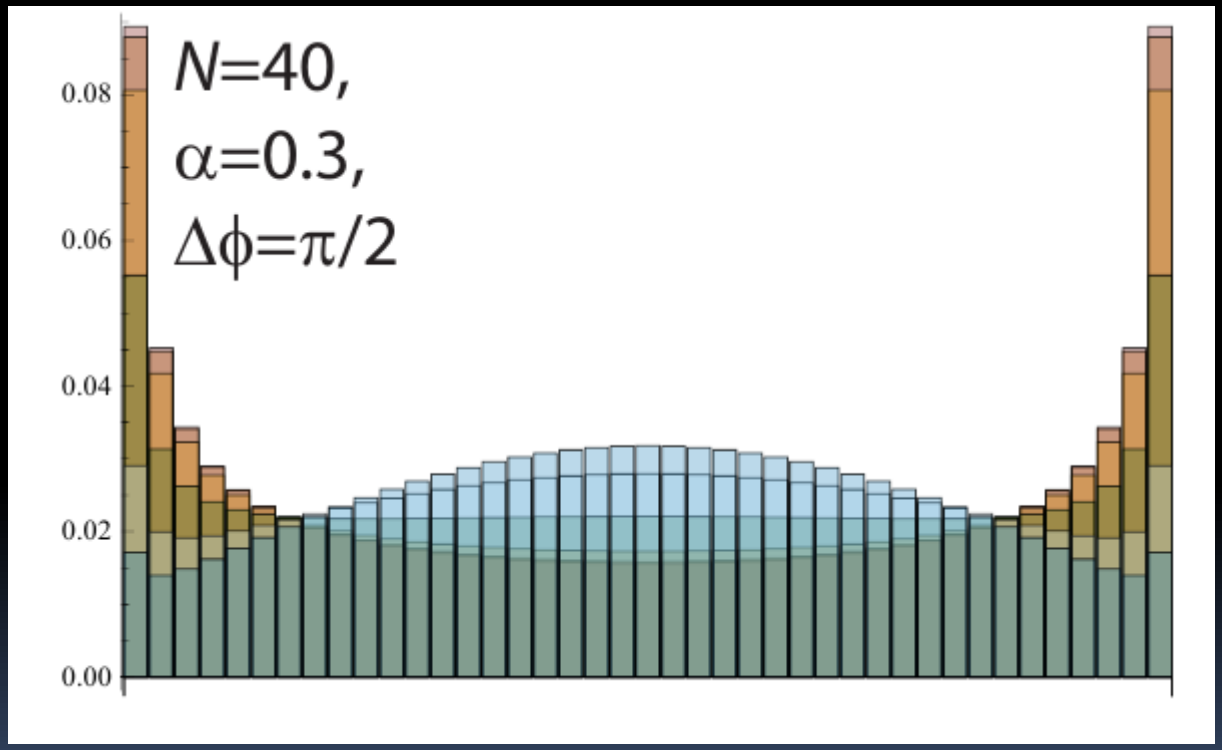
Metrological gain via GHZ-like protocol (Ramsey with parity measurement)



Emission (blue) is *much* worse than dephasing!
(note different scales)

Ising (+more) decoherence: full counting statistics

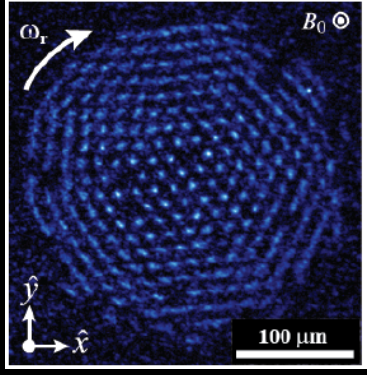
P(



S^x

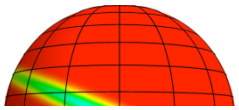
Ion experiment

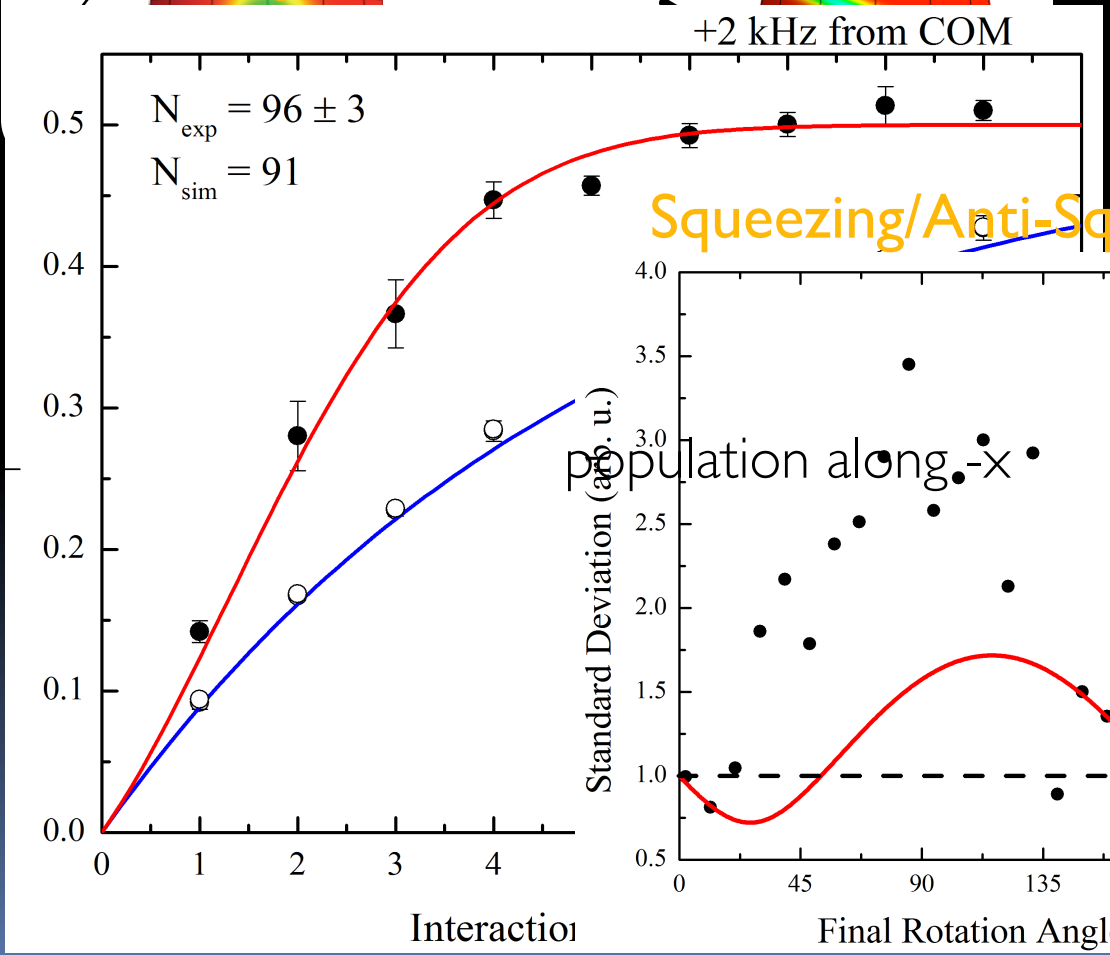
Warning: preliminary, cherry-picked, …



Bollinger group, unpublished

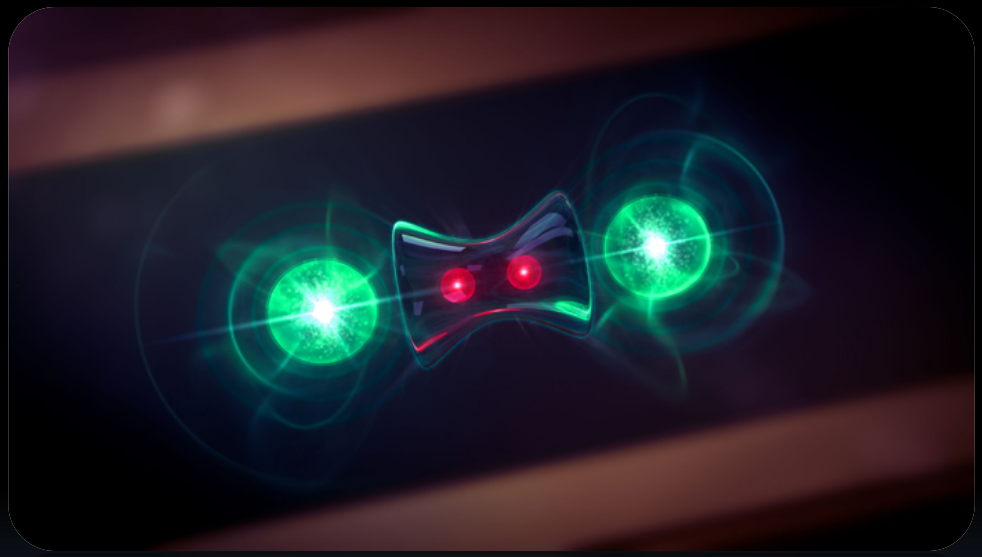
Depolarization:





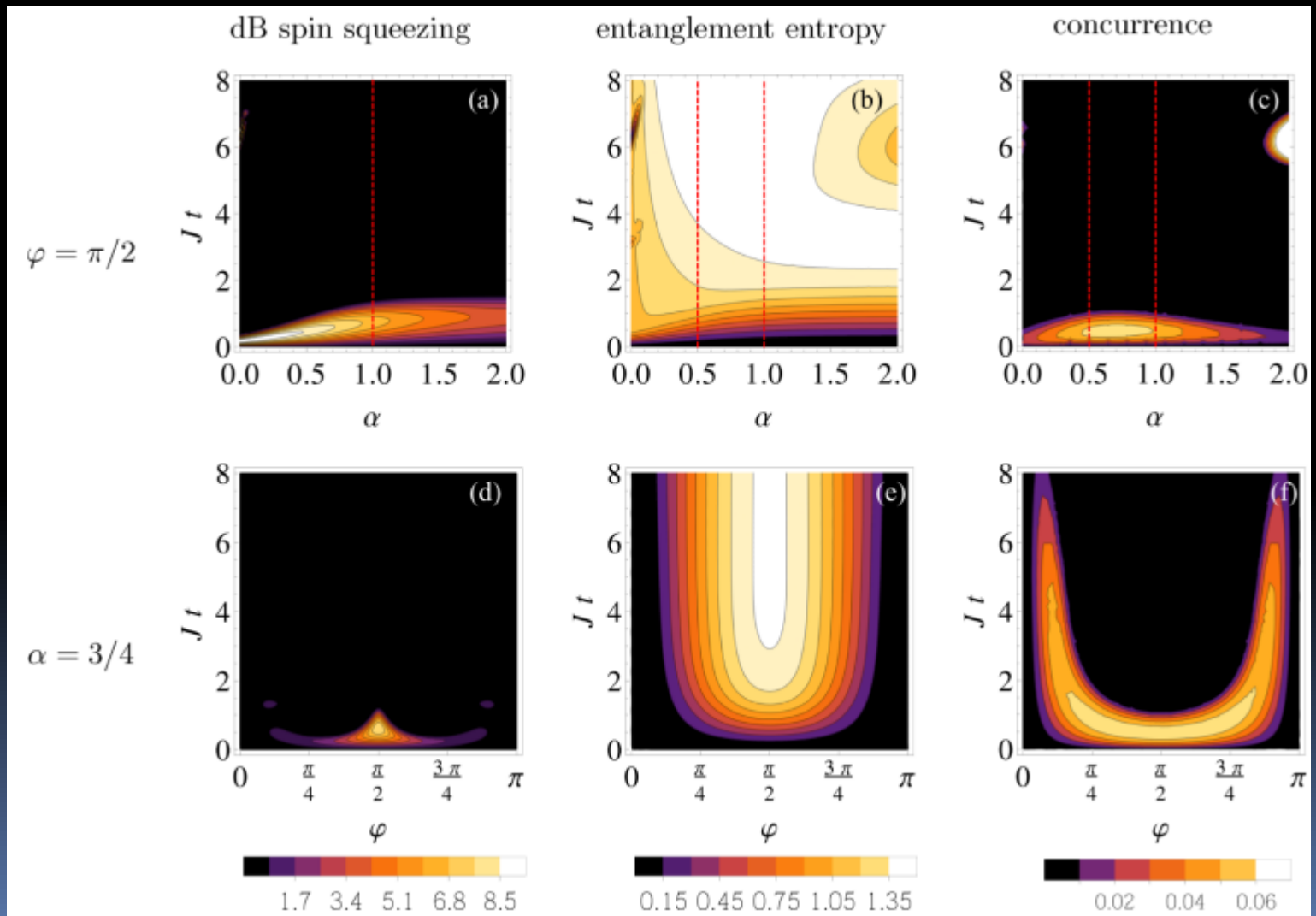
Squeezing/Anti-Squeezing

population along -x

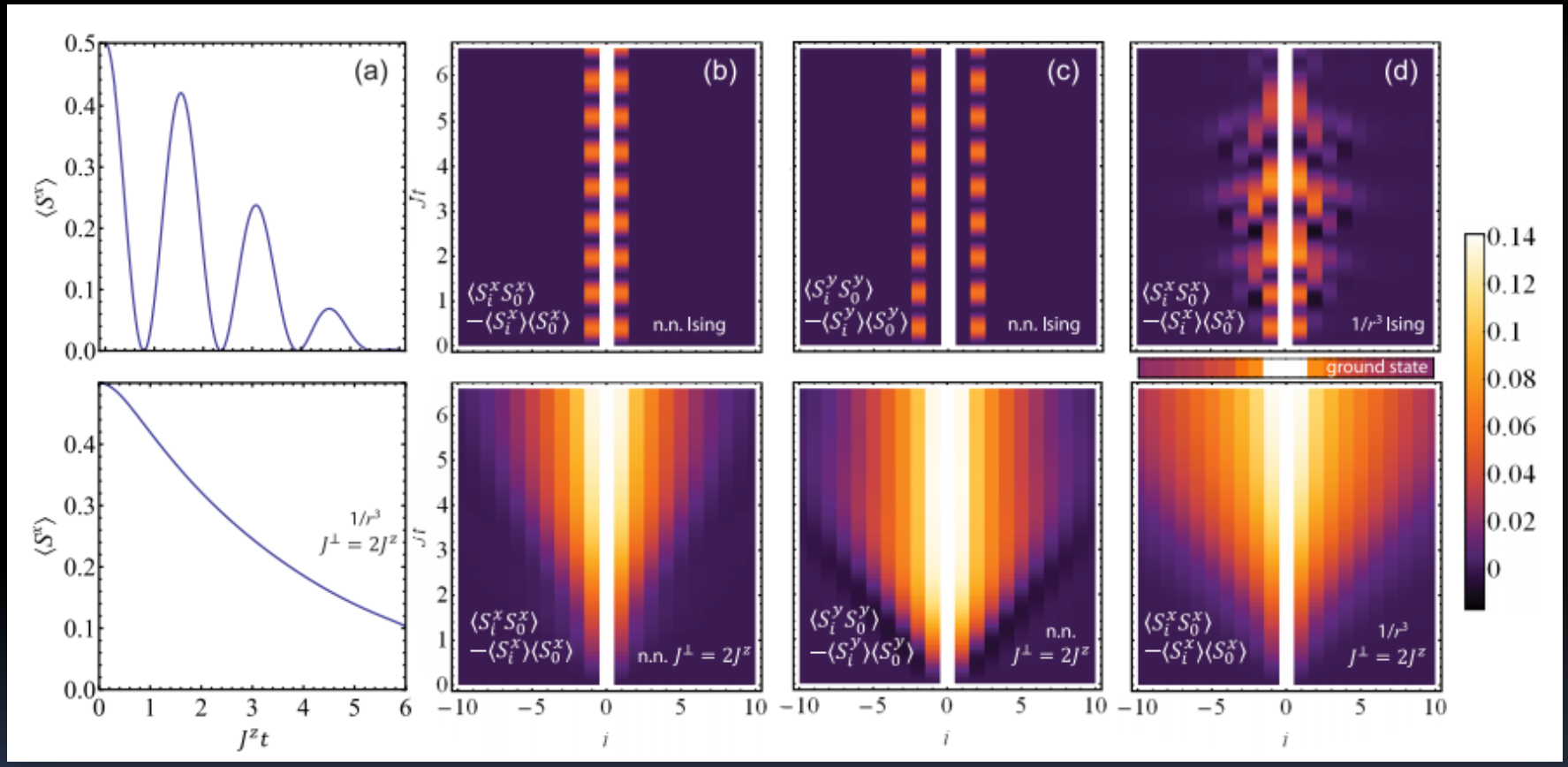


Comparative entanglement

Ising: no decoherence, entanglement measures



Beyond Ising: XXZ, no decoherence

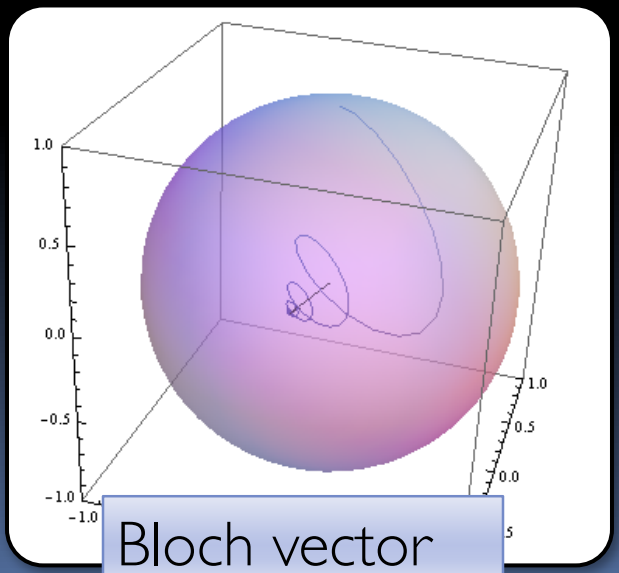


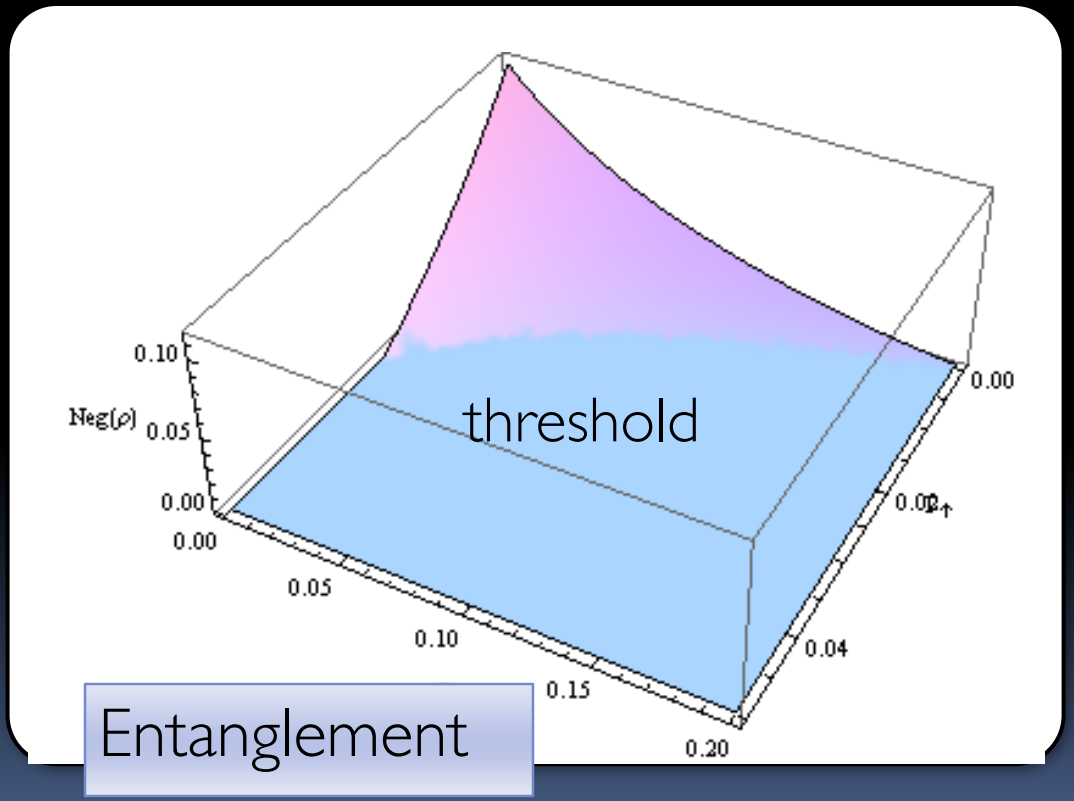
Ising has similar *growth* of correlations, but different *propagation*

Ising + transverse field. Steady states with decoherence?

- Steady state has
  - coherence
  - correlations
  - entanglement!

  (but threshold!)

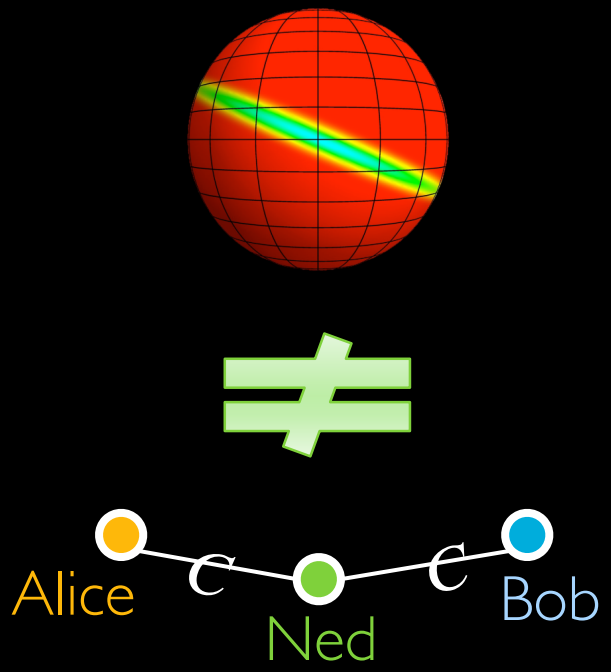




Charlex Xu, Hazzard --- 2 spins

Conclusions

- XXZ describes many experimental systems
- Exactly solved dissipative quantum many-body dynamics
  - Ising, but not classical
- Comparative study of entanglement
  - different resources grow differently!



- Ising solution with decoherence:
  - Foss-Feig, Hazzard, Bollinger, & Rey, PRA 87, 042101 (2013)
  - Foss-Feig, Hazzard, Bollinger, Rey, & Clark, New Journal of Physics 15, 113008 (2013)
  - van den Worm and Kastner have solved without decoherence for special tipping angles
- Comparative entanglement, experimental realizations:
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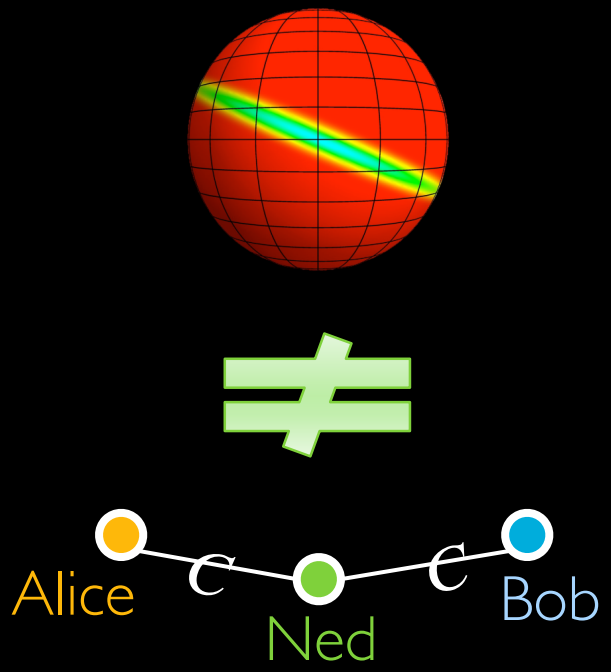
Conclusions

- XXZ describes many experimental systems
- Exactly solved dissipative quantum many-body dynamics
  - Ising, but not classical
- Comparative study of entanglement
  - different resources grow differently!



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