Kaden R. A. Hazzard
JILA, NIST, CU-Boulder Dept. of Physics
KITP: Feb 2, 2013

MANY-BODY PHYSICS IN CURRENT MOLECULE EXPERIMENTS: NONEQUILIBRIUM

Collaborators

Ana Maria Rey
JILA

Michael Foss-Feig
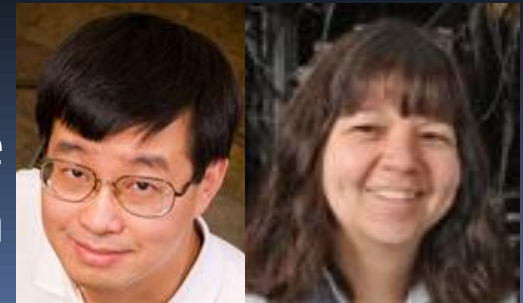*JILA, NIST-Maryland*

Salvatore Manmana
JILA, Goettingen

Alexey Gorshkov
Caltech, JQI

Joe Britton,
John Bollinger,
Brian Sawyer
NIST-Boulder

Jun Ye,
Debbie Jin
JILA

Punchline

- Ultracold molecules in lattices → interesting, useful phases of matter

- New ideas: many-body physics in *current* experiments

  - sparse lattices

  - high $T \sim 300$nK. Few μK, mK useful?

Precision metrology & sensing

Ultracold many body physics

Emulate condensed matter

- Molecules: Hazzard, Manmana, Foss-Feig, Rey, arxiv:1209.4076, PRL (to appear)
- Exact Ising + decoherence: Foss-Feig, Hazzard, Bollinger, Rey, arxiv:1209.5795
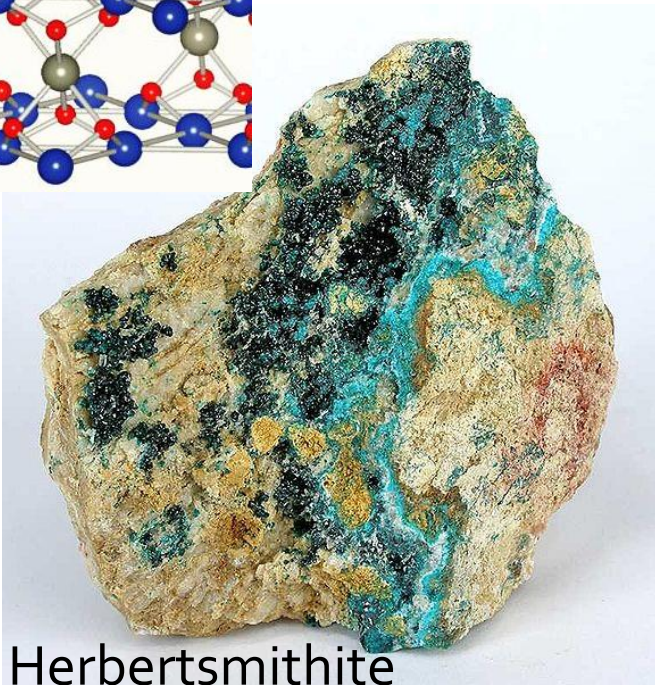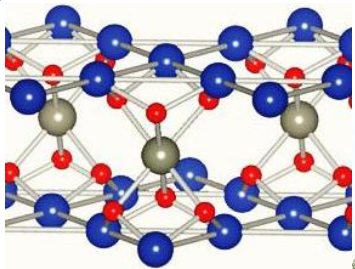- Related -
- Rabi molecules: Hazzard, Gorshkov, Rey, PRA **84**, 033608 (2011)
- Equilibrium model engineering:
  - Manmana, Stoudenmire, Hazzard, Rey, Gorshkov arxiv:1210.5518, PRB (to appear);
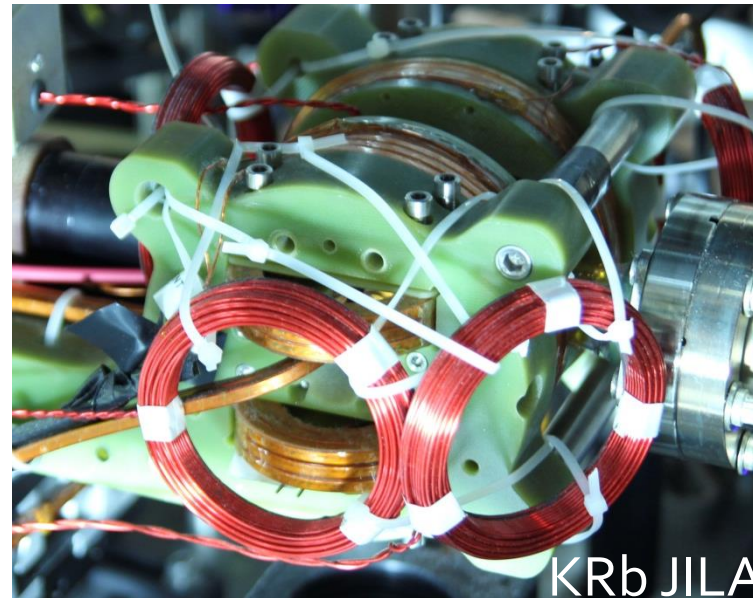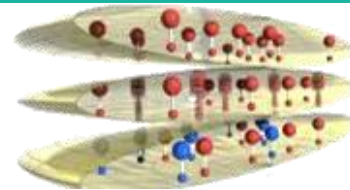 - Gorshkov, Hazzard, Rey arxiv:1301.5636

The vision; the dream

Herbertsmithite

KRb JILA

Quantum emulation

Interlude: why we dream

Excellent reasons to care about exotic phases

Fascination: fractionalized excitations

Applications: robust to perturbations, quantum computation

Applications: superpositions robust to classes of noise

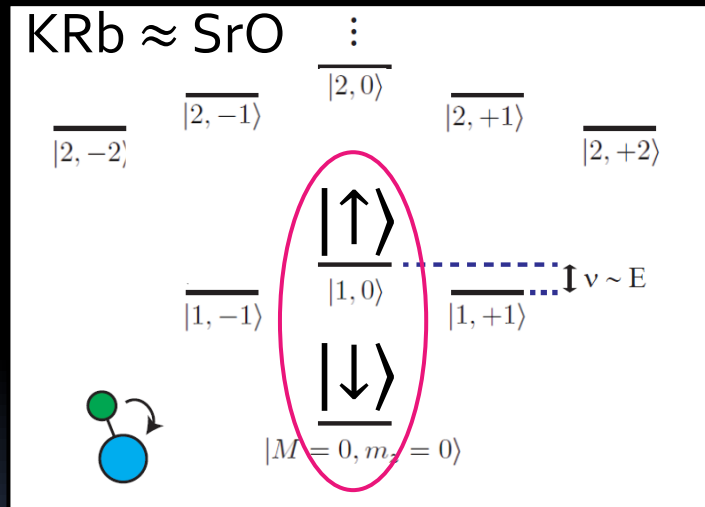Applications: each new phase = qualitatively new response to fields (E, B, …)

can be much more specific

A proposal

Molecules in 2D lattice too deep for tunneling, $E \perp$ lattice

XXZ model: $H = \sum_{ij} \frac{1}{r_{ij}^3} [J_z S_i^z S_j^z + \frac{J_\perp}{2} (S_i^+ S_j^- + h.c.)]$

Gorshkov et al. PRL **107**, 115301 (2011). Barnett et al '06, Micheli et al '06, Schachenmeyer et al '10, Wall, Carr '10

KRb $\approx$ SrO

$\overline{|2,-2\rangle}$ $\quad$ $\overline{|2,-1\rangle}$ $\quad$ $\overline{|2,0\rangle}$ $\quad$ $\overline{|2,+1\rangle}$ $\quad$ $\overline{|2,+2\rangle}$

$|\uparrow\rangle$
$\overline{|1,0\rangle}$

$\overline{|1,-1\rangle}$ $\quad$ $\overline{|1,+1\rangle}$ $\quad$ $\updownarrow \nu \sim E$

$|\downarrow\rangle$

$|M=0, m_z = 0\rangle$

Microwave dressing $\rightarrow$ tune anisotropies of J_z and $J_\perp$

Enormously rich family of models, topological phases ("SPT", Kitaev, ...)

Manmana, Stoudenmire, Hazzard, Rey, Gorshkov arxiv:1210.5518, PRB (to appear)
Gorshkov, Hazzard, Rey arxiv:1301.5636

Dream or hallucination?
visions meet reality…

Experiment – where theory comes to die
~ Sid Nagel

Dream or hallucination?

visions meet reality…

Vision (usual proposals)	Reality
Lattice	in JILA KRb
Unit filling, $T \sim 100\text{nK}$	0.1/site, 300nK (to 10^7nK)
Prepare interacting ground states in ~sec lifetime (or ms decoherence time?)	$\lvert \cdots \downarrow\downarrow\downarrow \cdots \rangle$
Detection: spectra, complicated manipulations	rotational populations

Plus (sometimes) hopefully straightforward dressing, …

Dream or hallucination?

visions meet reality...

Vision (usual proposals)	Reality
Lattice	
Unit filling (low-T, high-n ... e)	
Prepare interacting grou... states in ~sec lifetime (o... decoherence time?)	
Detection: spectra, complicated manipulatio...	...ions

Plus (sometimes) hopefu... g, ...

... these proposals hold long time promise, but until then...

Meet in the middle…

Theory

~~Stress~~ thermometer
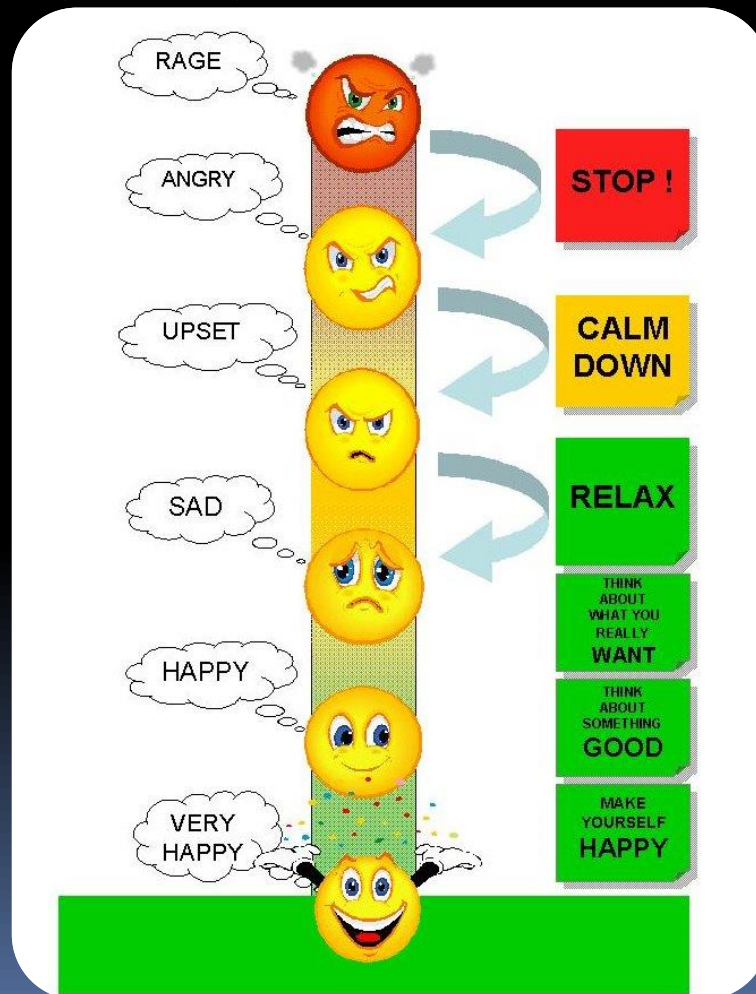
experiment

today's talk!

100 nK

most theory proposals

Idea: dynamics
(other KITPers: "sub-optimal control")

Ramsey spectroscopy

1. Initially $|\downarrow\downarrow\downarrow\rangle$

2. Rotate spins by θ

3. Wait time τ

4. Read ϕ component
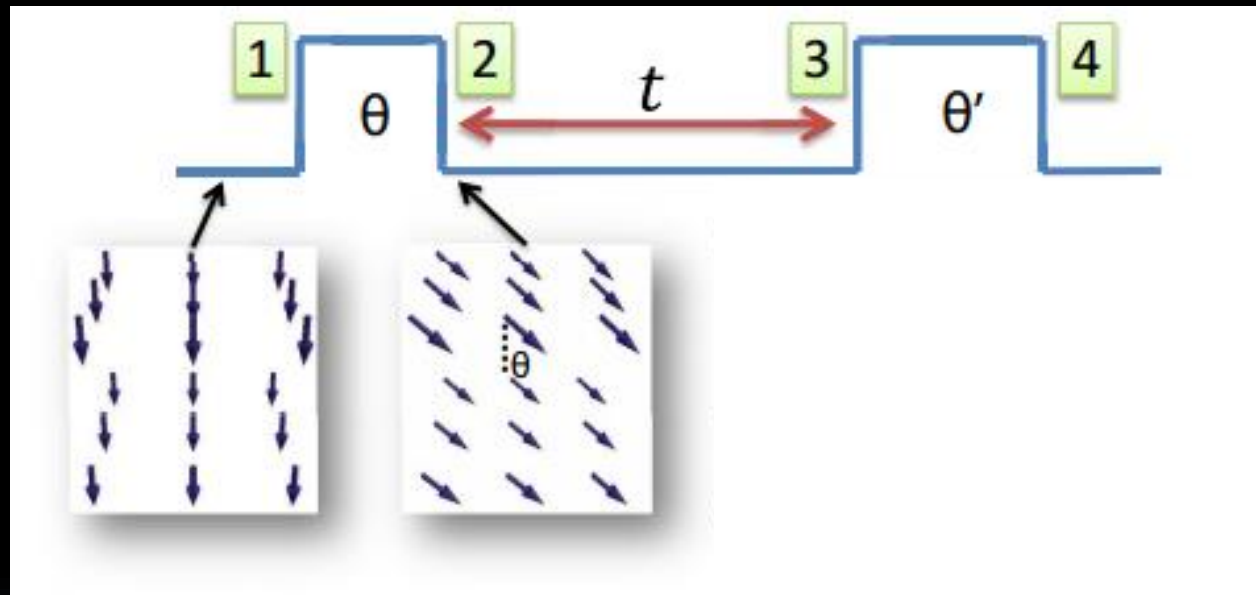
Hazzard, Manmana, Foss-Feig, Rey, arxiv:1209.4076, PRL (to appear)

Quench

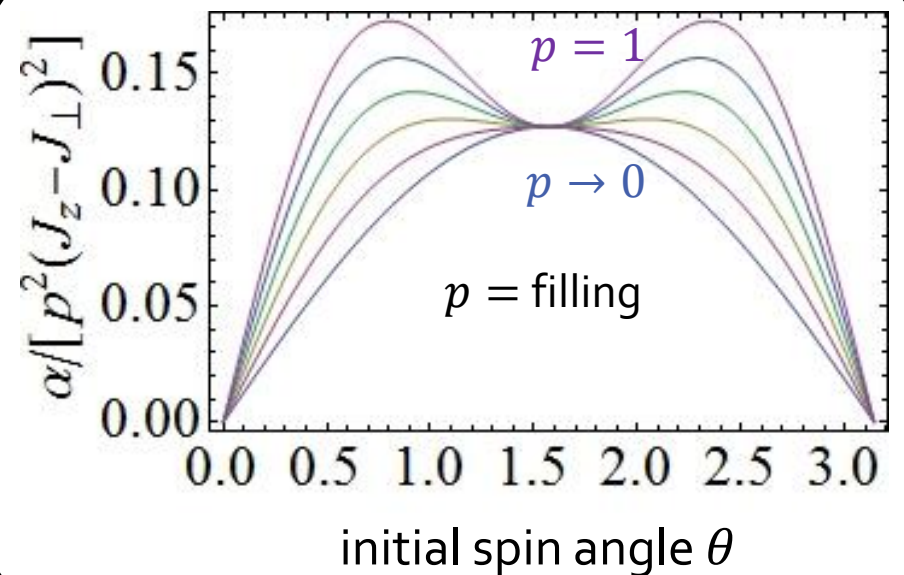$h_\theta = \infty$ ground state

Evolve with $h_\theta = 0$

Global "phase diagram"
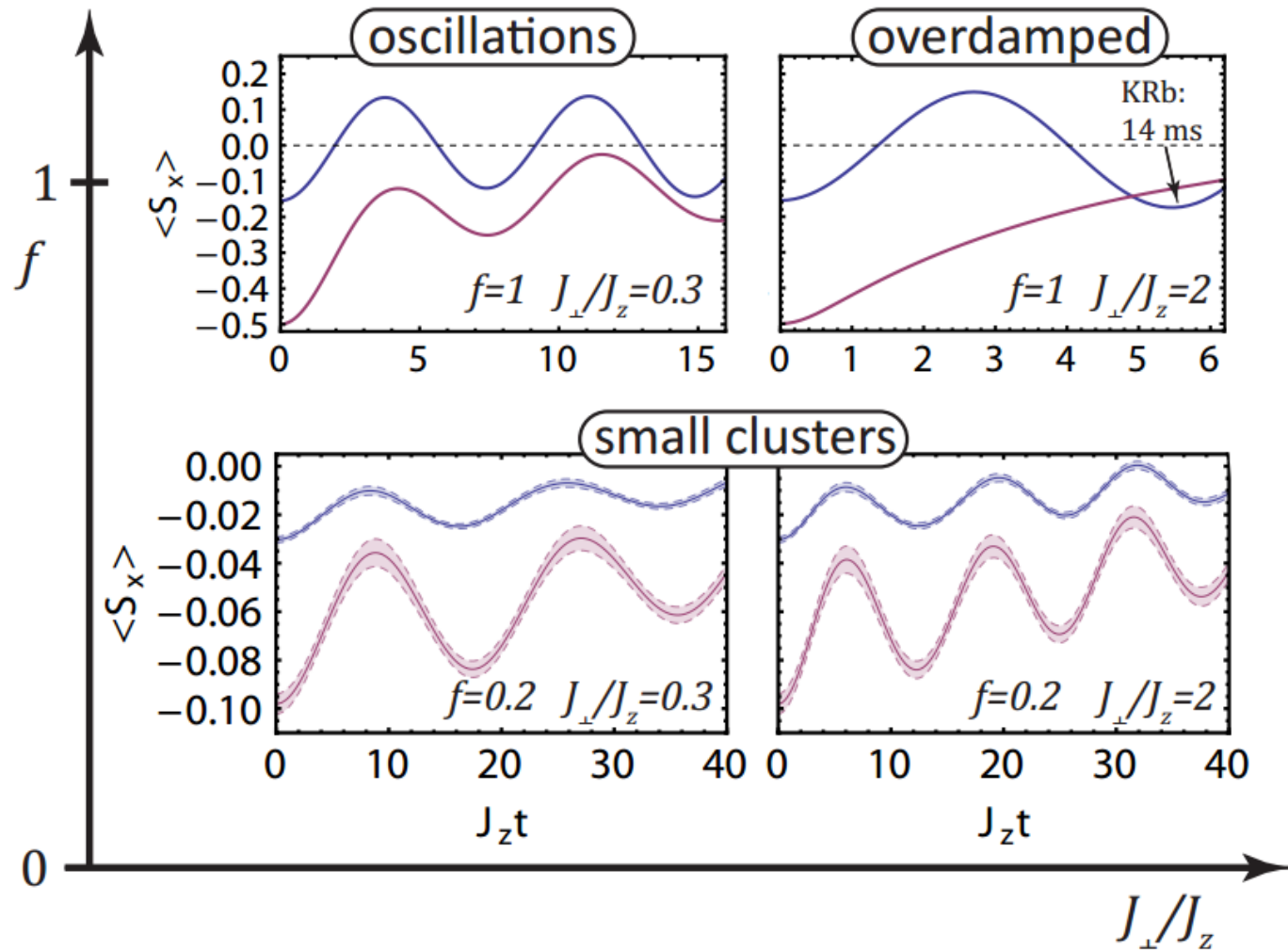
Short times → verify model

Find $\langle S^x(t)\rangle = \langle S^x(0)\rangle - \alpha t^2 + O(t^4)$,

$\alpha = \dfrac{(J_z - J_\perp)^2 \sin\theta}{8}\{2\zeta(6)\sin^2\theta + 4\zeta(3)^2\cos^2\theta\}$

(Example is d=1)

- θ-dependence can confirm XXZ model (cross-check: $\langle S^y\rangle$, etc.)
- E-field dependence checks expected couplings $J_\perp, J_z$

$p = 1$

$p \to 0$

$p = $ filling

initial spin angle θ

Later times → interesting states

dipolar

n.n.

$\theta = \pi/2$

$\langle S^x \rangle$

$J_z t$
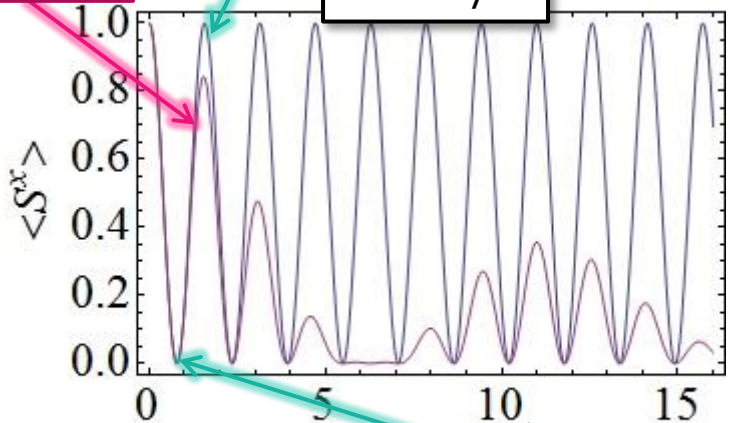
$f = 1, d = 1,$
Ising: $J_\perp = 0$

cluster state

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

dB squeezing

$J_z t$

- f=1.0, $J_\perp$=2
- f=1.0, $J_\perp$=0
- f=0.4, $J_\perp$=2
- f=0.4, $J_\perp$=0

information flow

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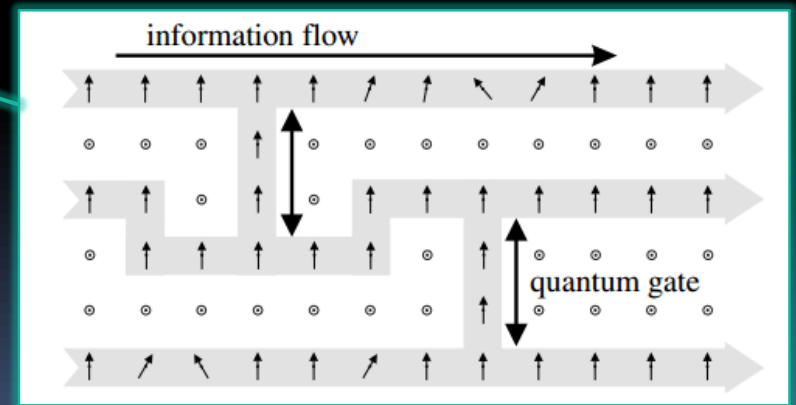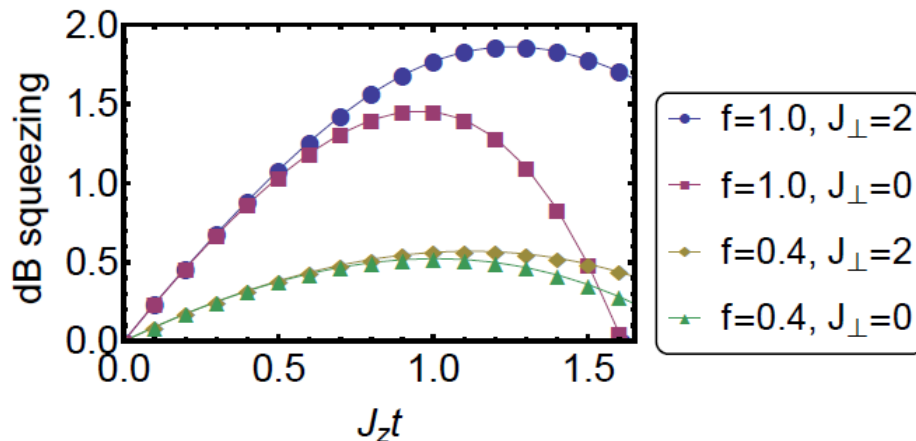
Raussendorf & Briegel, PRL **86,** 5188 (2001)

Correlations & entanglement

$\sum_a \langle S_a^x S_{a+i}^x \rangle$, 1D
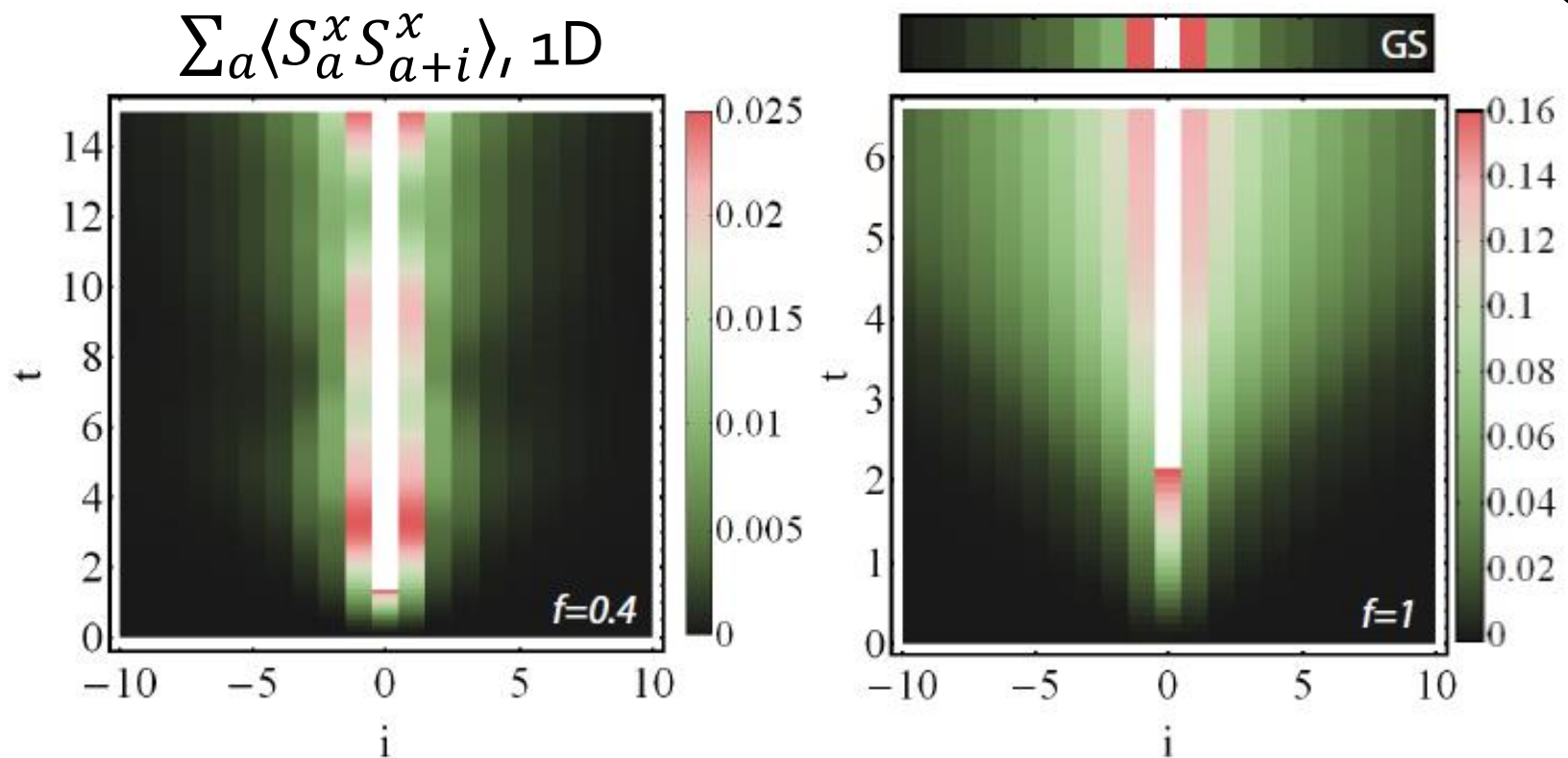
correlations, squeezing, persist with disorder

Overview

Theoretically tractable limit	How relates to goals
Short times: $\{J_z, J_\perp\}t \ll 1$	Verify/benchmark XXZ
Near-Heisenberg: $J_z \approx J_\perp$ Ising: $J_\perp = 0$	Make interesting states ("cat", cluster, squeezed, …)
d=1 (DMRG)	& entangled/correlated ones.

Other exact calculations omitted:
- Small-filling expansion
- Near-SU(2) 1D thermodynamic limit
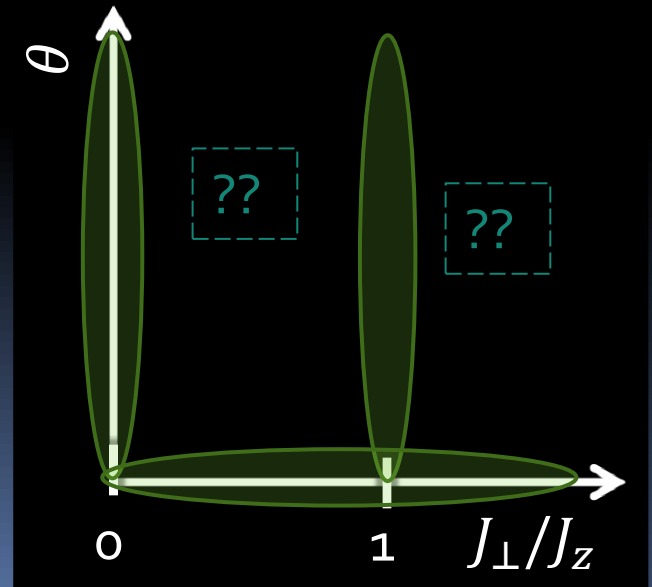
Universal nonequilibrium dynamics
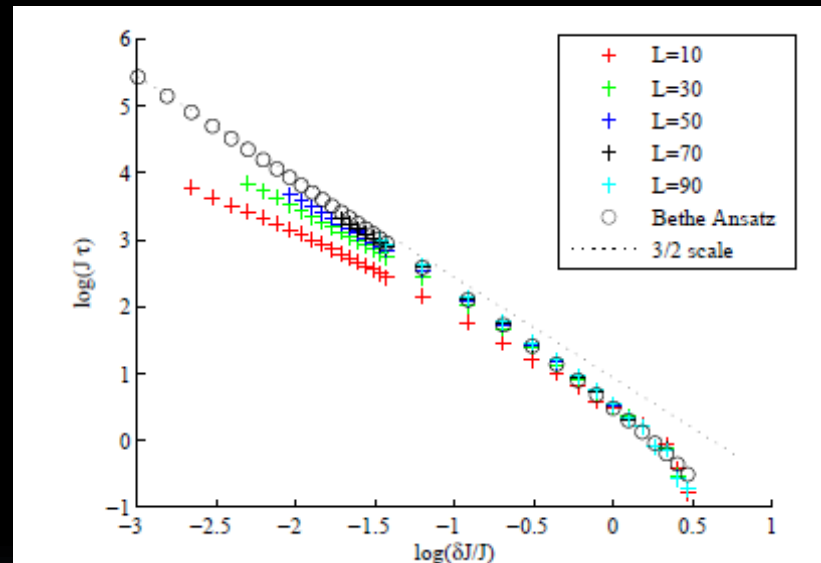
- One dimension (Idea: Emanuele Dalla Torre)
  - Near-SU(2): interaction quench
    out of Luttinger liquid ground state

Decoherence in experiment?
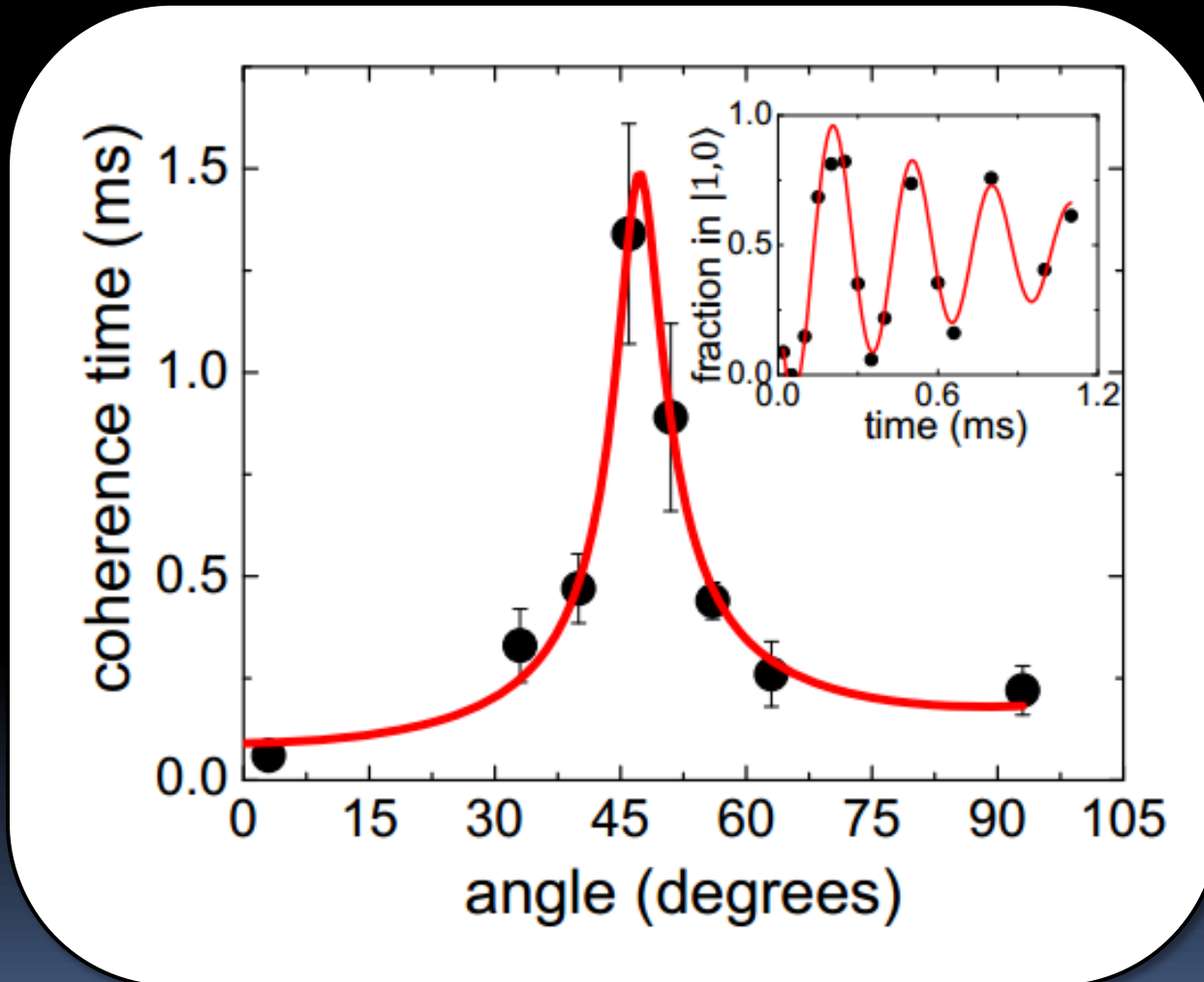
… or many body interactions?

Decoherence (`molecule-relevant?`)

Physics (single spin decoherence)
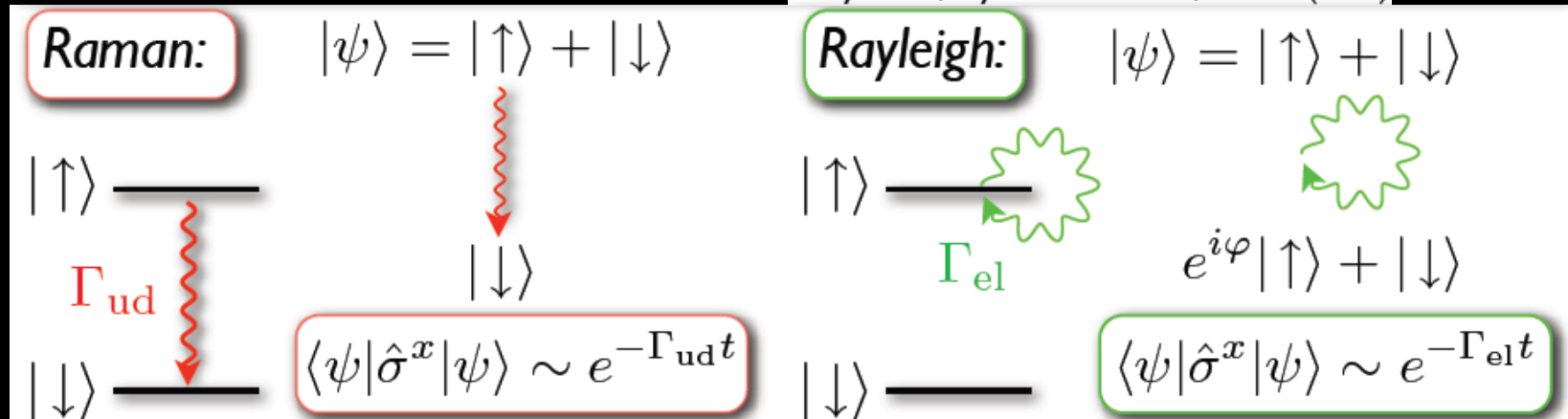
Math

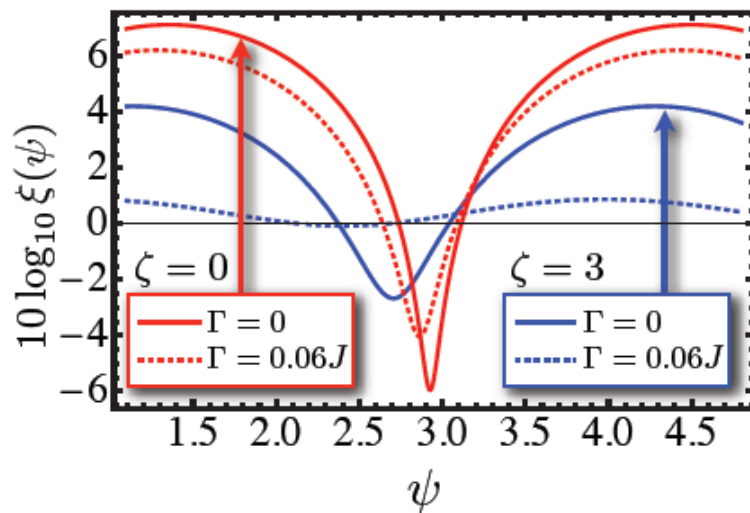# Exact Ising solution: decoherence in a many body system

"Exact solutions are rare, precious jewels in physics." ~Bretislav Friedrich

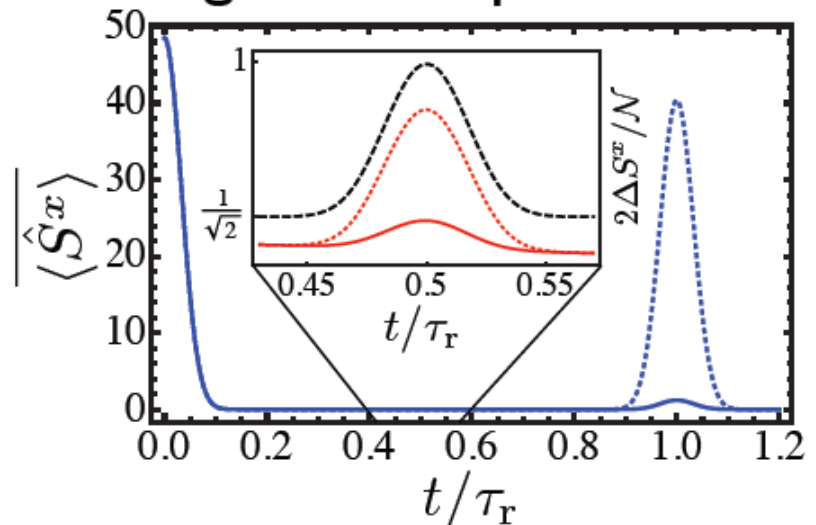Averages, correlations: $\mathrm{Tr}\left[\sigma_j^+ \sigma_k^- \rho\right] \sim \prod_{l \neq j,k} \Phi([J_{jl} - J_{kl}]t)$

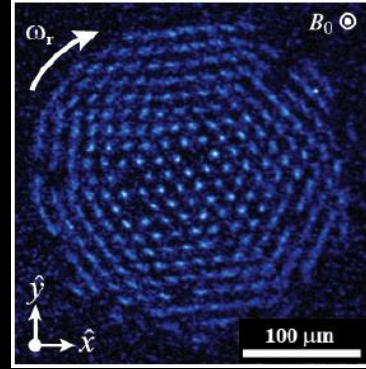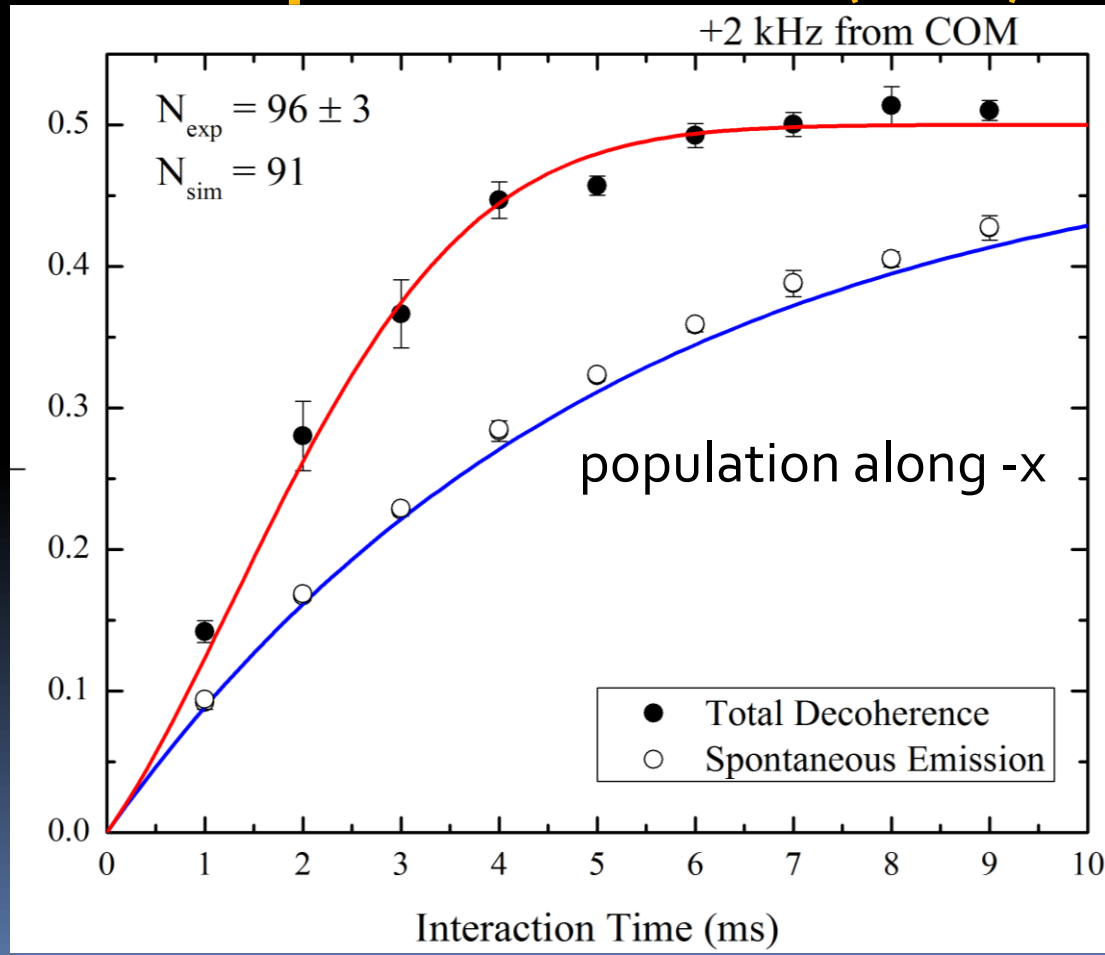Foss-Feig, Hazzard, Bollinger, Rey, arxiv:1209.5795

Example application:

Ion experiment comparison

Depolarization: $\langle S^x \rangle$

Bollinger group, unpublished

+2 kHz from COM

$N_{exp} = 96 \pm 3$

$N_{sim} = 91$

population along -x

● Total Decoherence
○ Spontaneous Emission

Interaction Time (ms)

Ion experiment comparison

Pic: *Britton et al.*, Nature **484,** 489 (2012)

Bollinger group, unpublished

Depolarization: $\langle S^x \rangle$
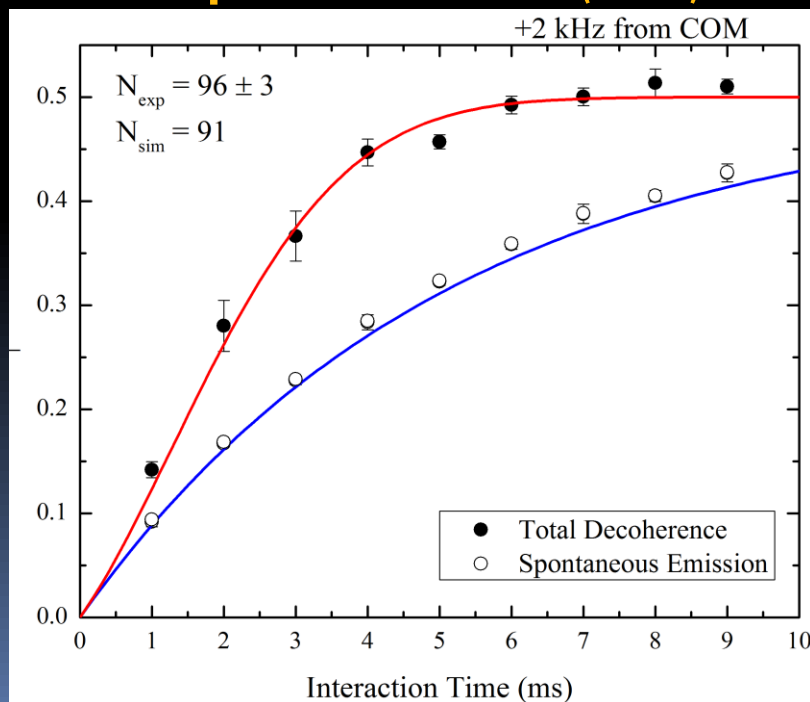
Squeezing/Anti-Squeezing

$N_{exp} = 96 \pm 3$
$N_{sim} = 91$

+2 kHz from COM

- ● Total Decoherence
- ○ Spontaneous Emission

Interaction Time (ms)

population along -x

- ● Experiment
- — Theory

Standard Deviation (arb. u.)

Final Rotation Angle (degrees)
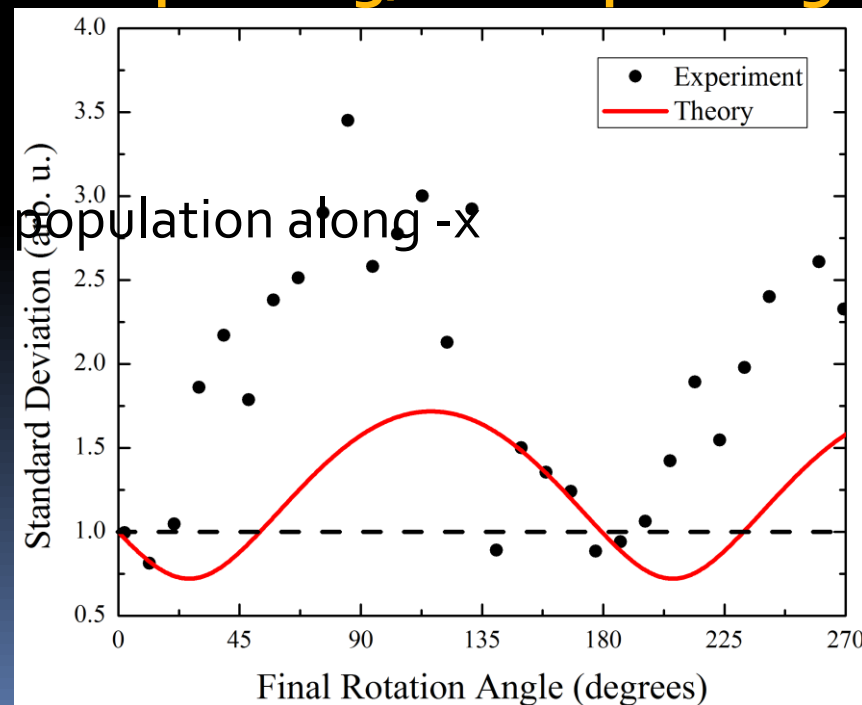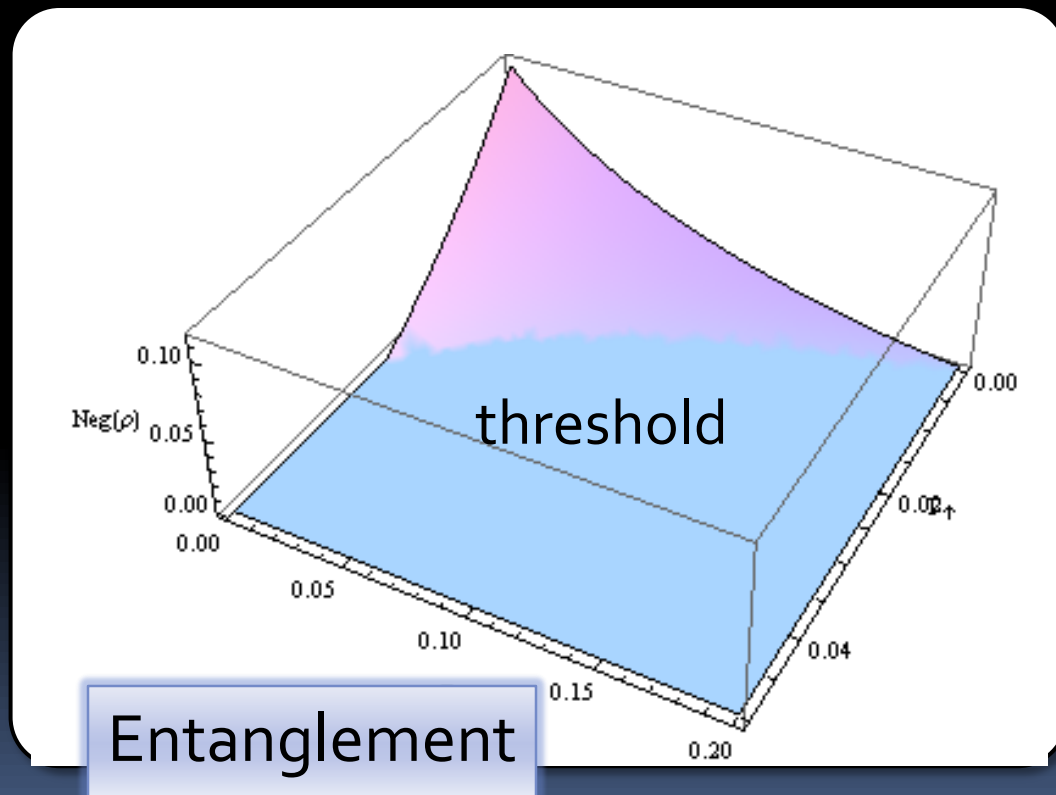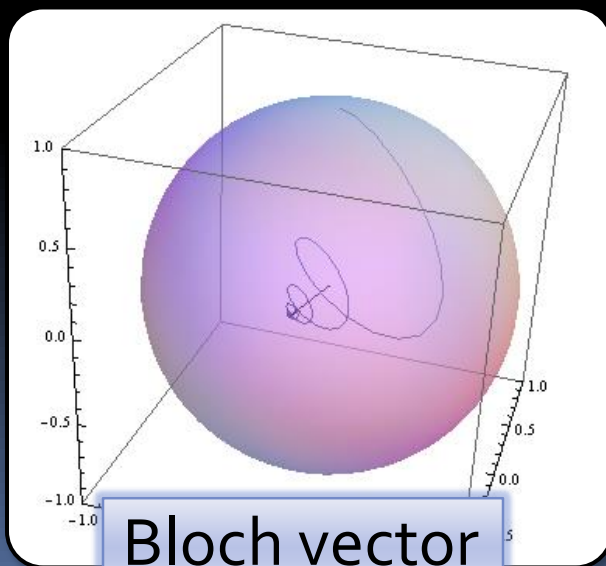
Steady state correlation despite decoherence

- Steady state solution with decoherence has

  - superpositions

  - correlations

  - entanglement!

threshold

Entanglement

Bloch vector

Even warmer gases??

- **Precedent: clocks**

Just a sampling of *experiments*
Swallows et al., Science **331**, 1043 - 1046 (2011); Bishof et al., PRA **84**, 052716 (2011); Ludlow et al., PR A **84**, 052724 (2011); Lemke et al., PRL. **107**, 103902 (2011); Bishof et al., PRL. **106**, 250801 (2011)
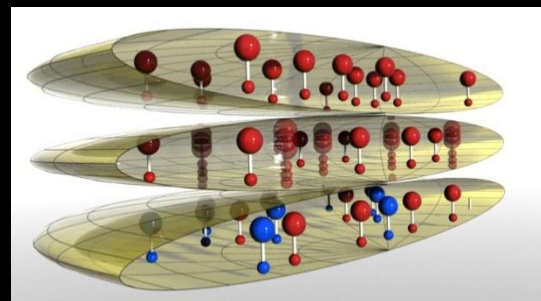
- **Fast motion averages position, uncouples from spin**

Martin et al., arXiv:1212.6291

- Issues with molecules:
  - reactions?
    uberresonances! (Mayle, Ruzic, Bohn arXiv:1203.6868)
  - but JILA OH experiments!
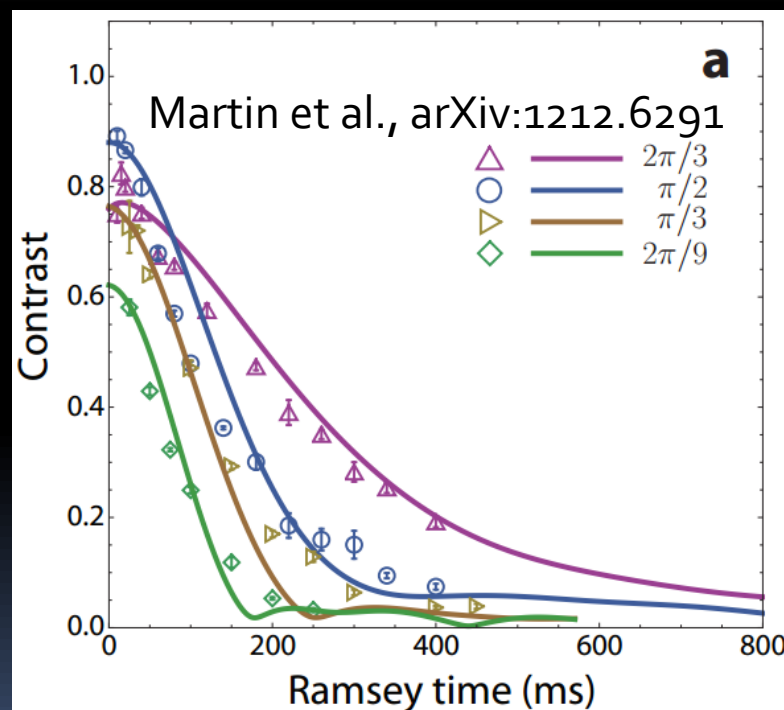
Summary/future
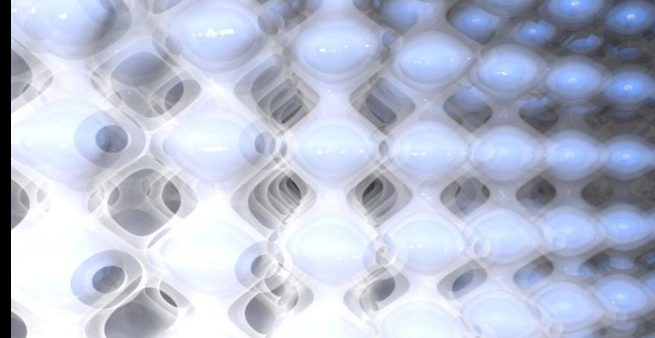
- Ultracold molecules in lattices
  → interesting, useful phases of matter

- New ideas: many-body physics in
  current KRb experiments

- Future:

  - warm gases. "spin waves"

  - closer comparison to JILA KRb

- Molecules: Hazzard, Manmana, Foss-Feig, Rey, arxiv:1209.4076, PRL (to appear)
- Exact Ising + decoherence: Foss-Feig, Hazzard, Bollinger, Rey, arxiv:1209.5795
- Related -
- Rabi molecules: Hazzard, Gorshkov, Rey, PRA **84**, 033608 (2011)
- Equilibrium model engineering:
  - Manmana, Stoudenmire, Hazzard, Rey, Gorshkov arxiv:1210.5518, PRB (to appear).
  - Gorshkov, Hazzard, Rey arxiv:1301.5636