Title: Engineering Programmable Spin Interactions in a Near-Concentric Cavity

Speakers: Emily Davis

Collection: Machine Learning for Quantum Design

Date: July 08, 2019 - 3:30 PM

URL: http://pirsa.org/19070018

Engineering Programmable Spin Interactions with Atoms and Photons

Emily Davis

Gregory Bentsen, Avikar Periwal, Eric Cooper, Monika Schleier-Smith

Machine Learning for Quantum Design
Perimeter Institute
July 8, 2019

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PI
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As quantum data generation increases…

As quantum data generation increases…

Computing

IBM Q

XANADU

Google AI

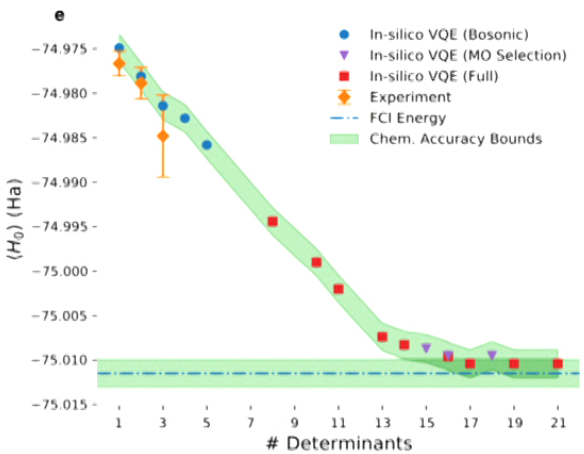
D-Wave
The Quantum Computing Company

Honeywell

rigetti

ATOM COMPUTING

IONQ



Ground-state energy estimation of the water molecule on a trapped ion quantum computer.
Y. Nam, et al. arXiv:1902.10171 (2019)

As quantum data generation increases…

Computing

IBM Q

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D:wave

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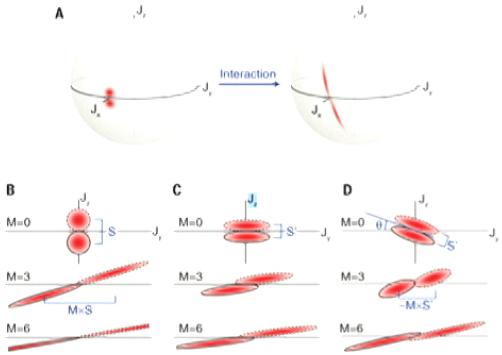
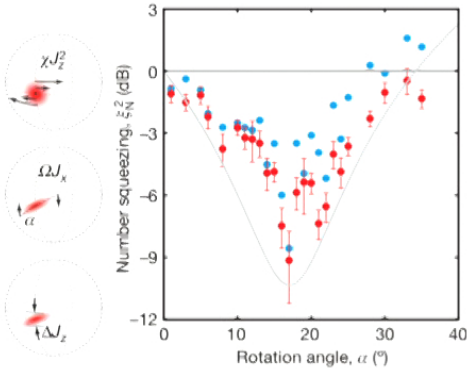
ATOM COMPUTING

Metrology



Quantum phase magnification
O. Hosten, et al.
Science **24** (2016)

Nonlinear atom interferometer surpasses classical precision limit
C. Gross, et al.
Nature **464** (2010)



Spin Models

As quantum data generation increases…

Computing

IBM Q

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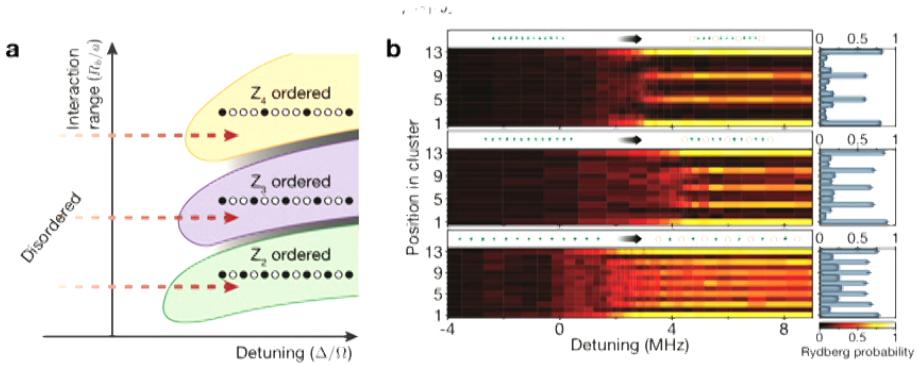
ATOM COMPUTING

Metrology

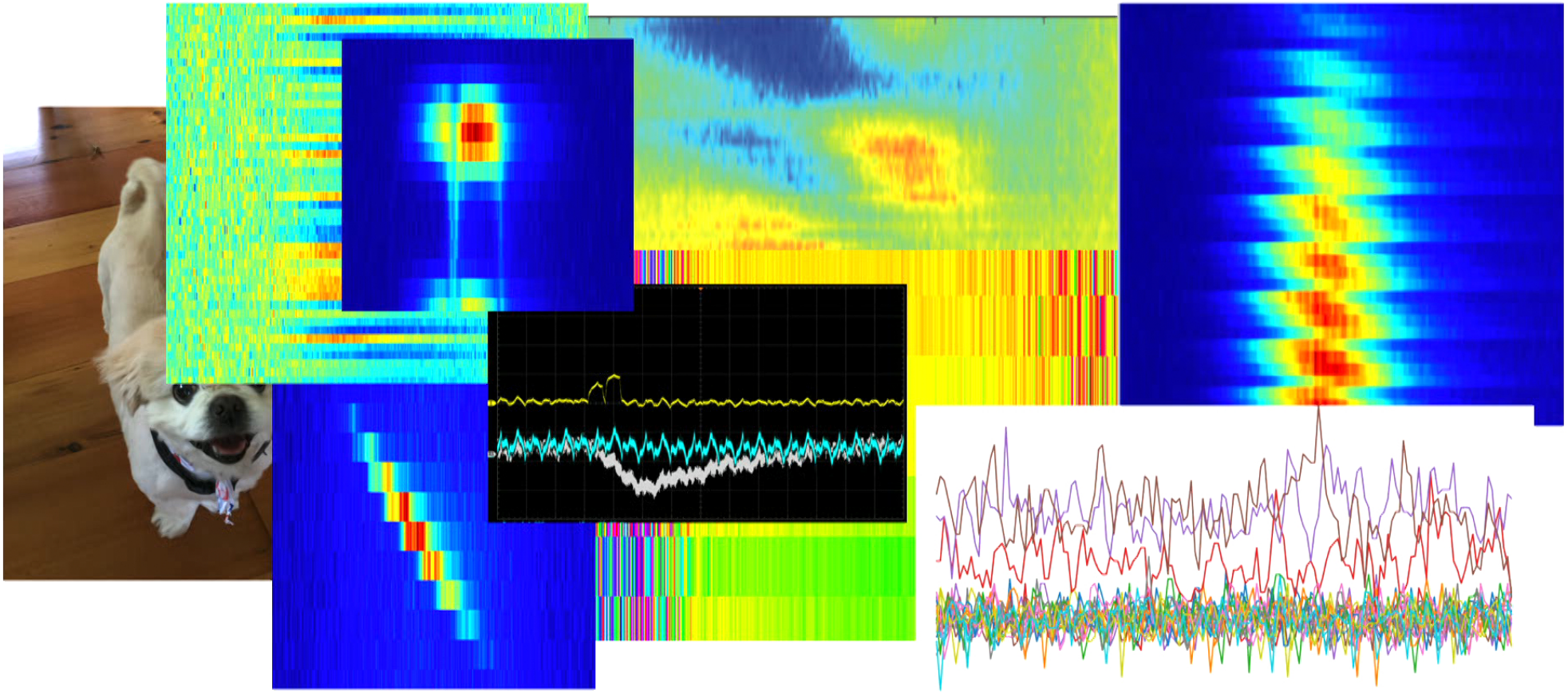
Quantum Simulation

$$\frac{\mathcal{H}}{\hbar} = \sum_i \frac{\Omega_i}{2}\sigma_x^i - \sum_i \Delta_i n_i + \sum_{i<j} V_{ij} n_i n_j,$$

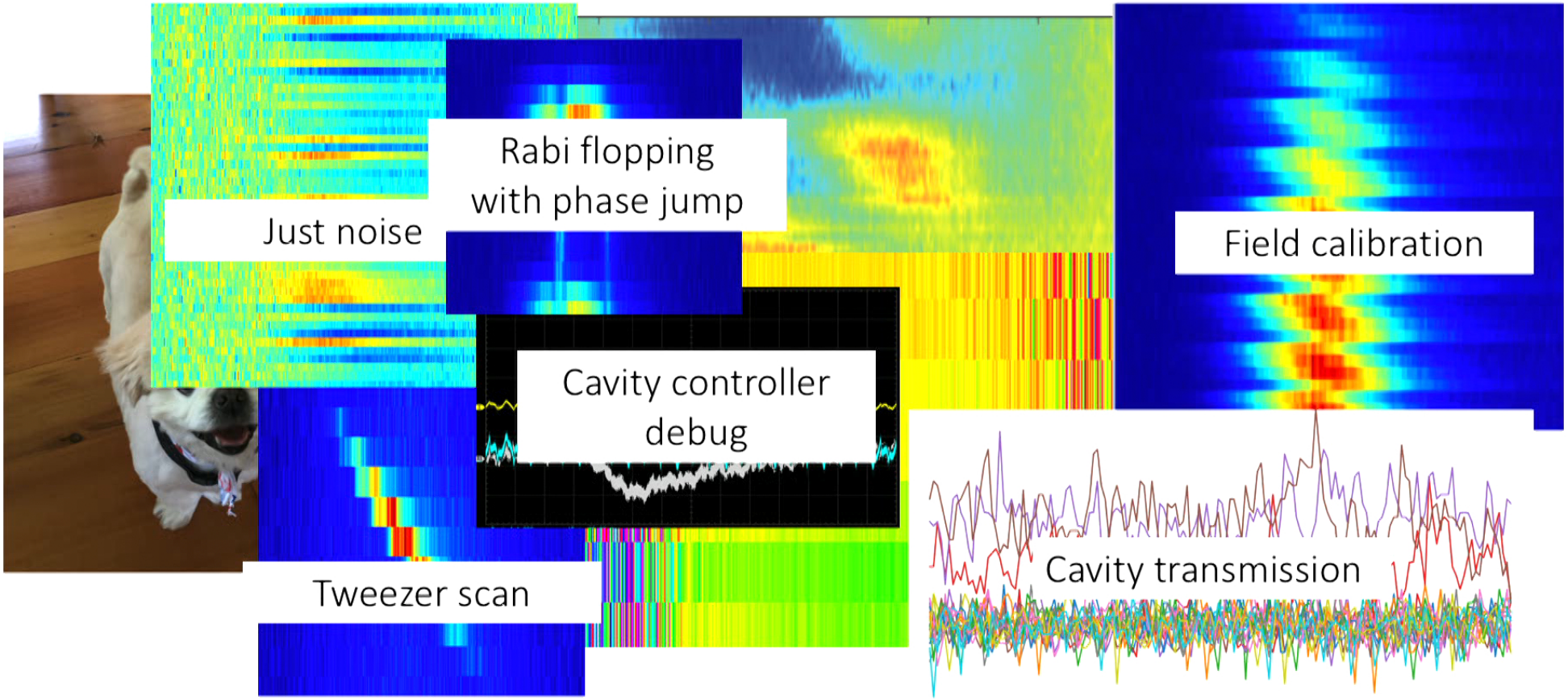


Probing many-body dynamics
on a 51-atom quantum simulator
H. Bernien, et al. Nature **551** (2017)

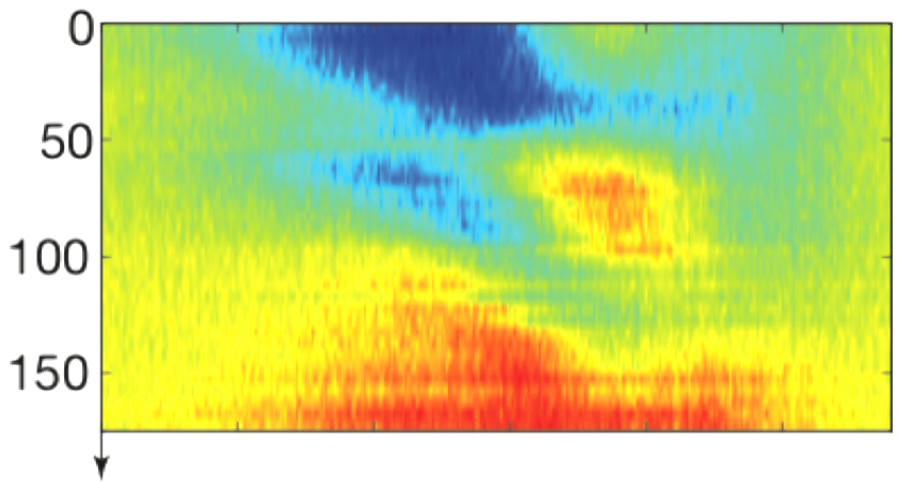
As quantum data generation increases…



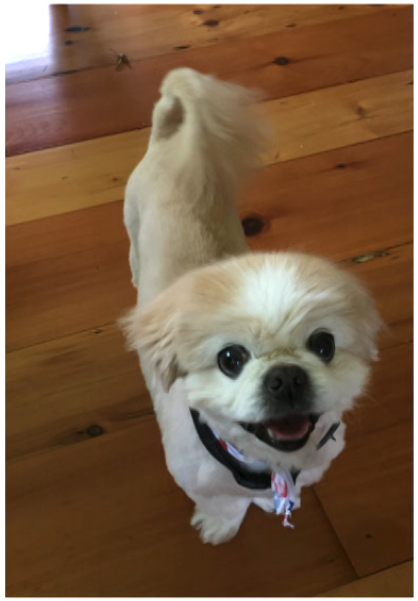
As quantum data generation increases…



As quantum data generation increases…



Result: This is publishable!

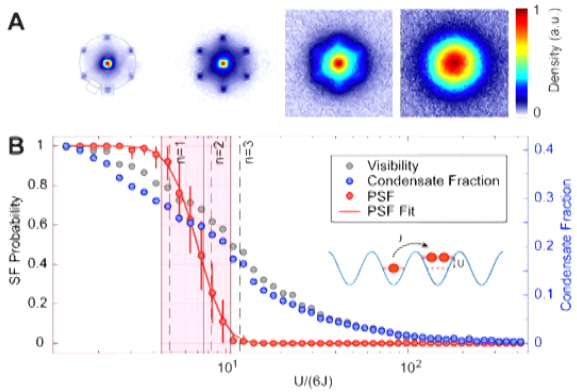


Result: Emily, your dog pictures do not belong on the Lab Wiki.

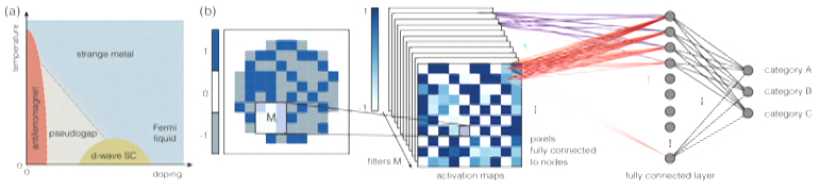
...how can machine learning help?

By providing physical insight:

Recognizing and classifying order



Identifying Quantum Phase Transitions using Artificial Neural Networks on Experimental Data
B. Rem, et al.
Nature Physics (2019)



Classifying Snapshots of the Doped Hubbard Model with Machine Learning
A. Bohrdt, et al.
arXiv:1811.12425 (2018)

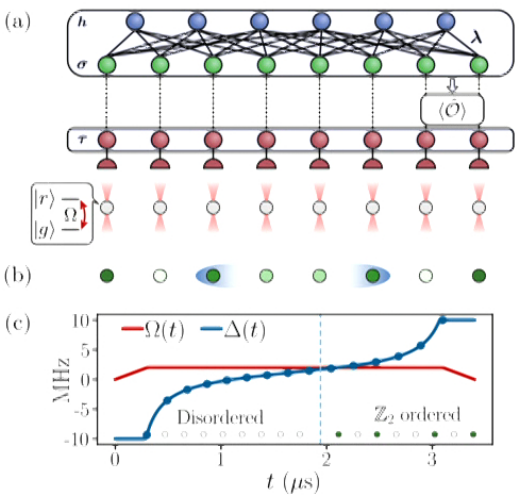
...how can machine learning help?

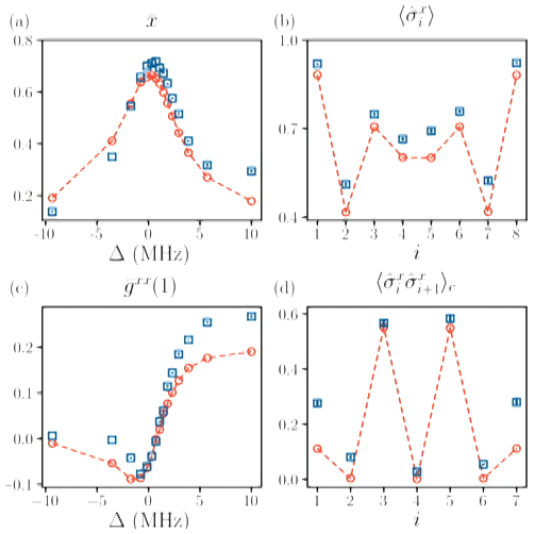
By providing physical insight:

Recognizing and classifying order

Performing state tomography

Reconstruction of off-diagonal observables





Integrating Neural Networks with a Quantum Simulator for State Reconstruction
G. Torlai, B. Timar, E. van Nieuwenburg, ..., R. Melko, M. Endres
arXiv:1904.08441 (2019)

Neural-Network Quantum State Tomography
G. Torlai, G. Mazzola, J. Carrasquilla, M. Troyer, R. Melko, G. Carleo
Nature Physics 14 (2018)

...how can machine learning help?

By improving experimental control:

Parameter optimization and optimal control

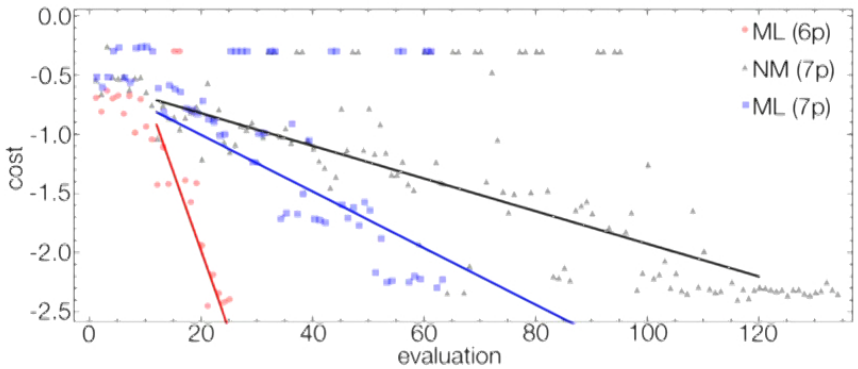
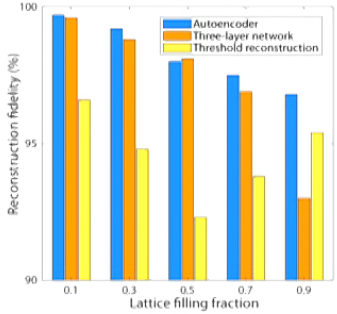


Figure 3. Optimization of evaporation curves to produce a BEC.

Fast machine-learning online optimization of ultra-cold-atom experiments
P. B. Wigley, et al. Nature Scientific Reports **6** (2016)

Readout Fidelity

Deep Learning-Assisted Classification of Site-Resolved Quantum Gas Microscope Images
L.R.B. Picard, et al.
arXiv:1904.08074 (2019)



Machine learning assisted readout of trapped-ion qubits
A. Seif, et al. J. Phys. B **51** (2018)

Tunable Nonlocal Heisenberg Model

$$H = \sum_{i,j} J_i J_j (f_i^x f_j^x + f_i^y f_j^y + \alpha f_i^z f_j^z)$$

Tunable Nonlocal Heisenberg Model

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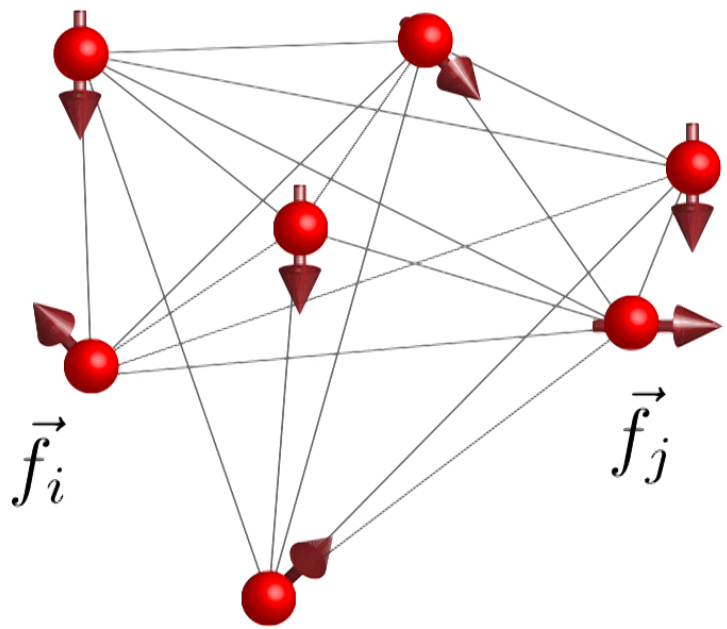

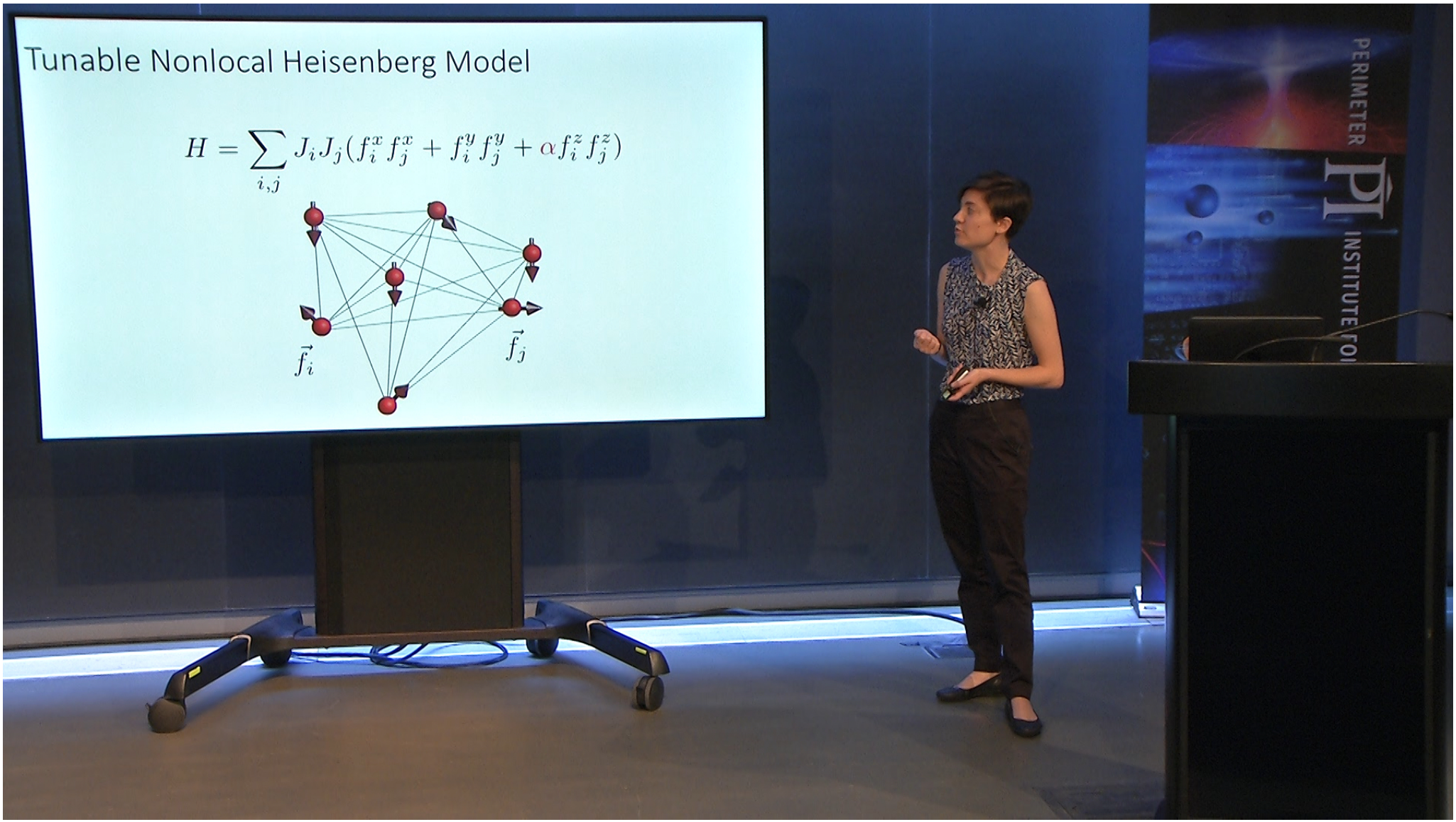
Tunable Nonlocal Heisenberg Model
$H = \sum_{i,j} J_i J_j (f_i^x f_j^x + f_i^y f_j^y + \alpha f_i^z f_j^z)$
$\vec{f}_i$
$\vec{f}_j$
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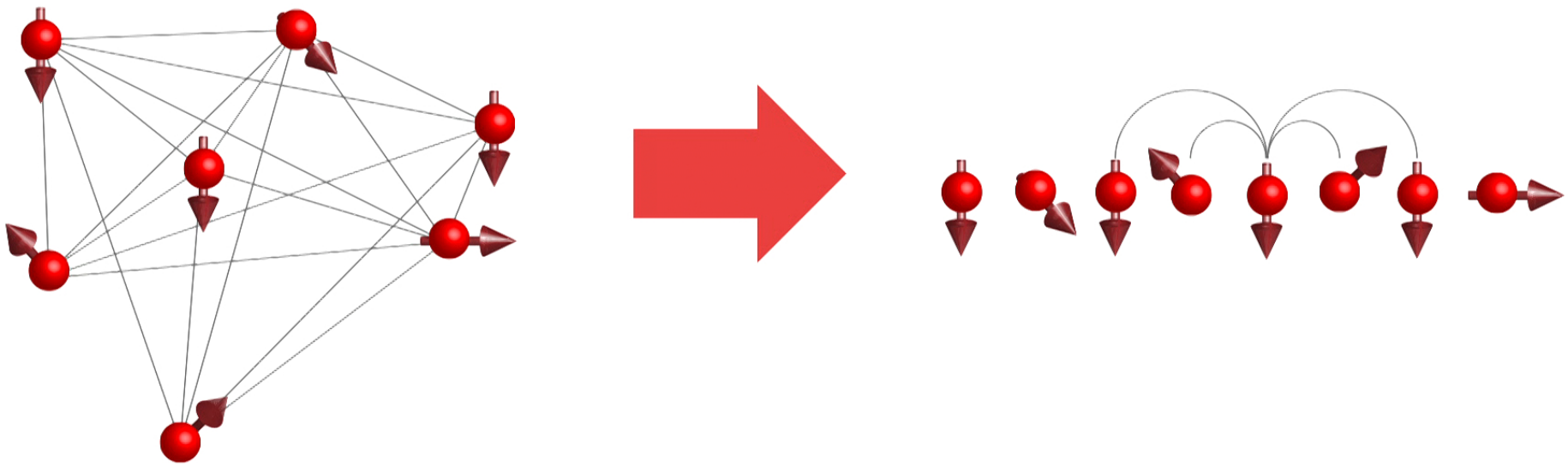
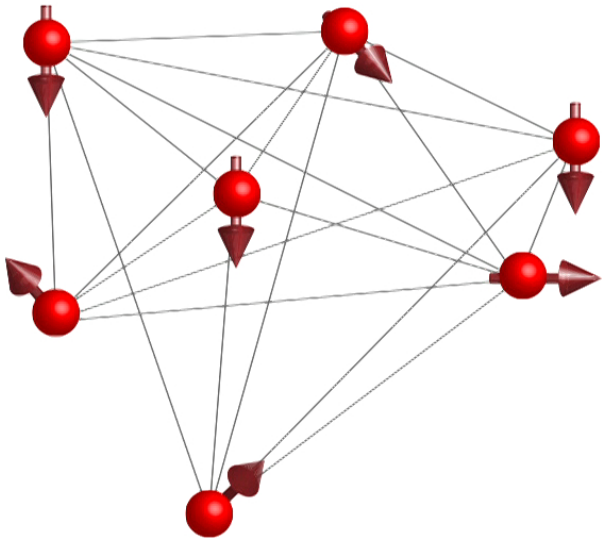
Tunable Nonlocal Heisenberg Model

$$H = \sum_{i,j} J_i J_j (f_i^x f_j^x + f_i^y f_j^y + \alpha f_i^z f_j^z)$$



Photon-Mediated Interactions



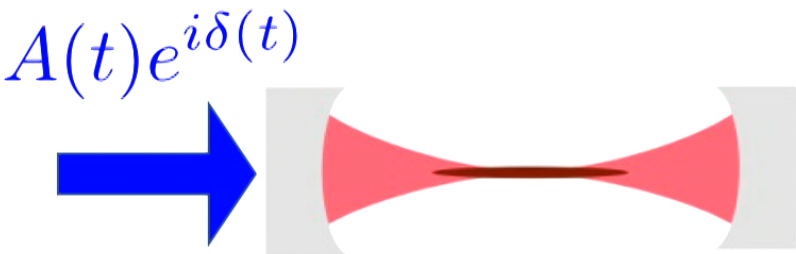
Nonlocal interactions

All-to-all coupling

Dynamically controllable

strength and sign

Switch ON/OFF

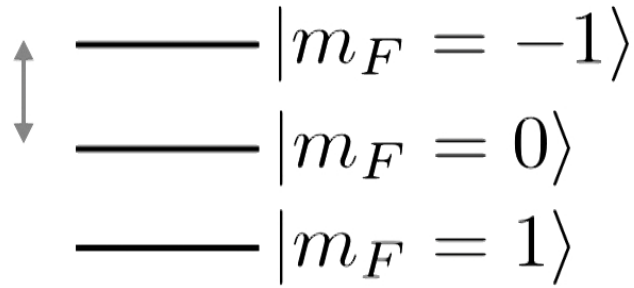


PLATFORM:
COLD ATOMS IN A CAVITY

Atomic Level Structure

Spin $F = 1$ system formed
by Zeeman levels:

ω_Z = 700 kHz/G

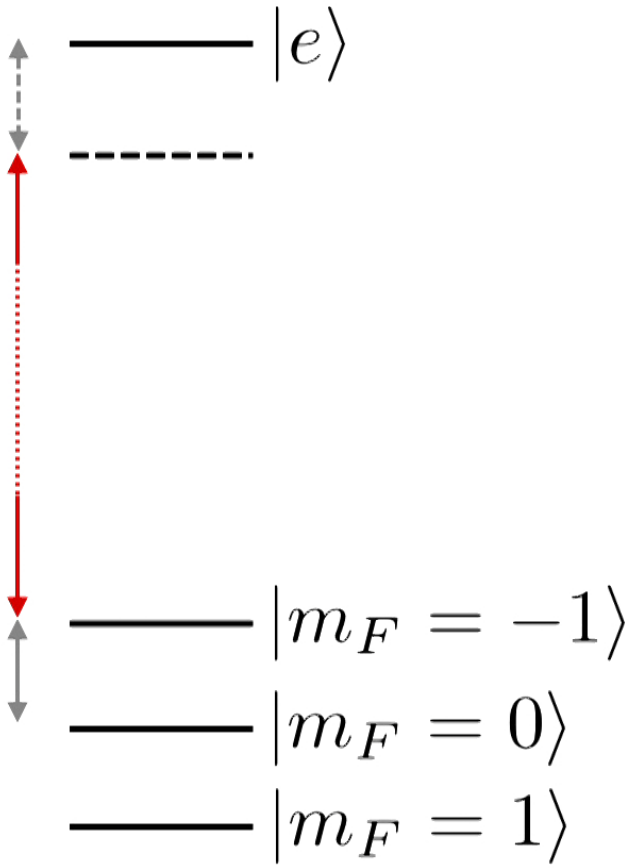


Atomic Level Structure

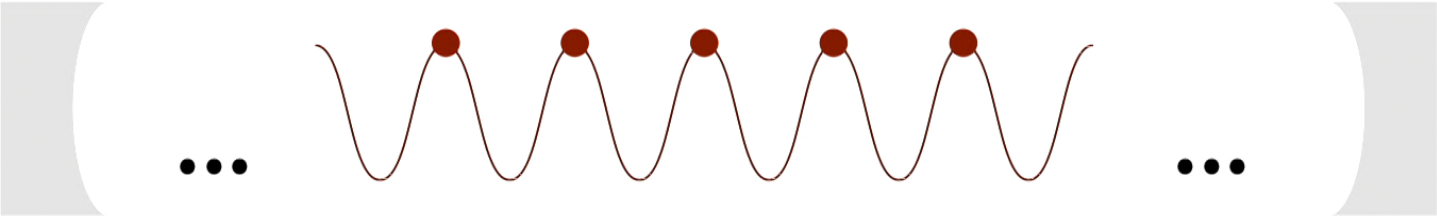
Δ 10 GHz

Optical transition
780nm, 384 THz

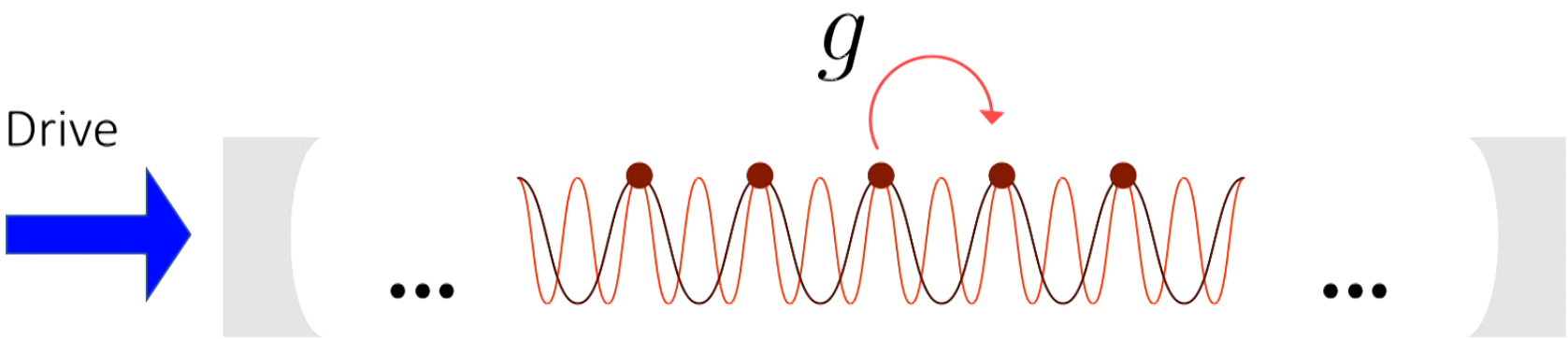
ω_Z 700 kHz/G



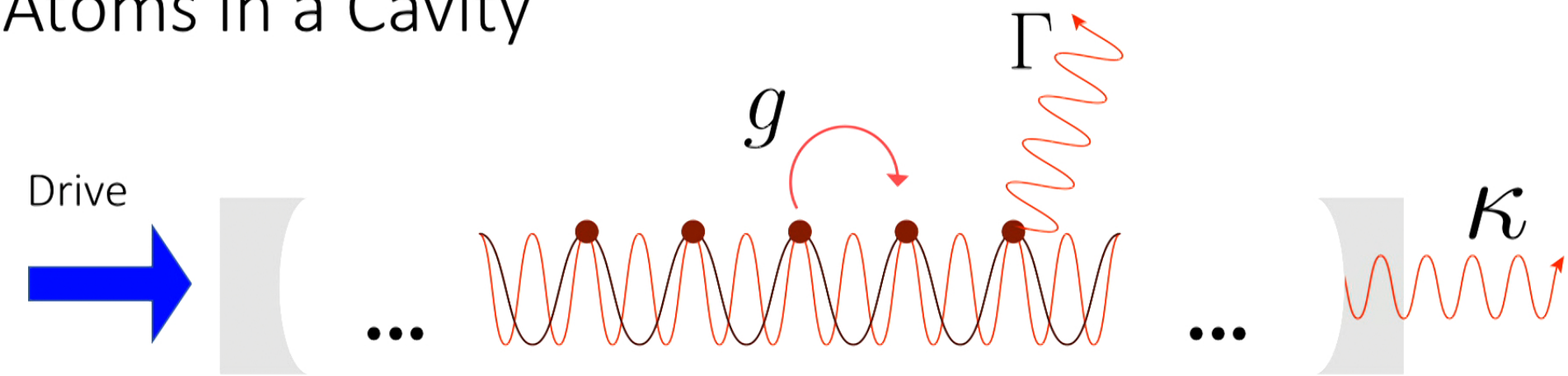
Atoms in a Cavity



Photon-Mediated Interactions



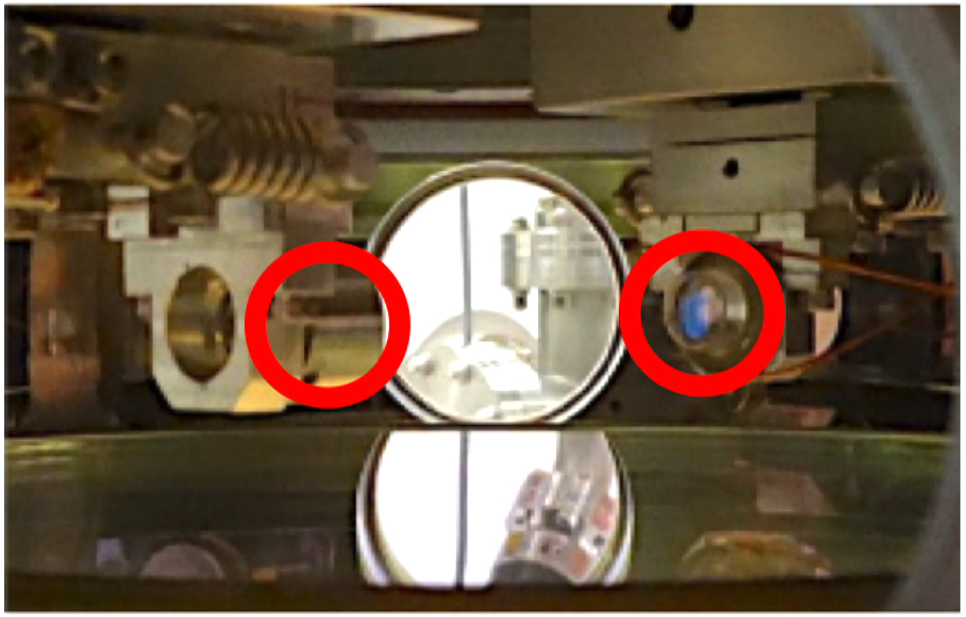
Atoms in a Cavity



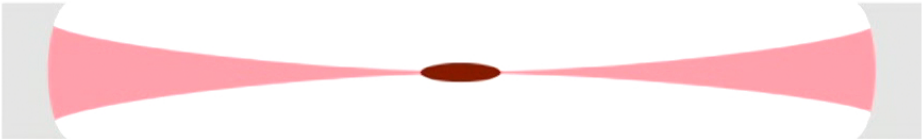
Single-atom cooperativity $\eta = \dfrac{4g^2}{\Gamma\kappa}$

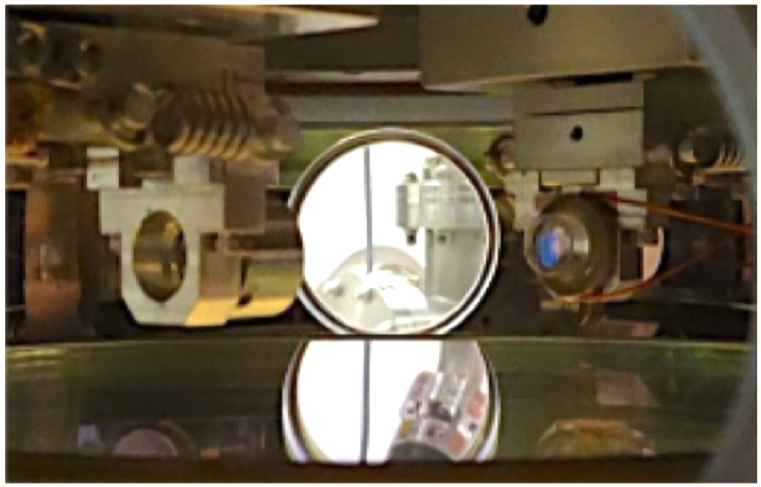
Strong coupling regime $\eta > 1$

Apparatus

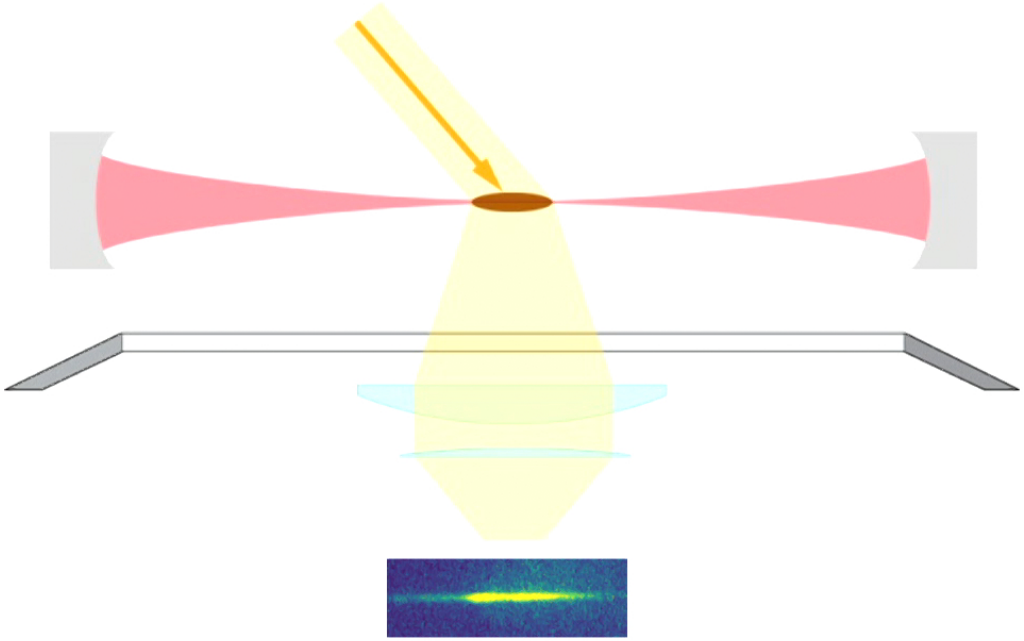


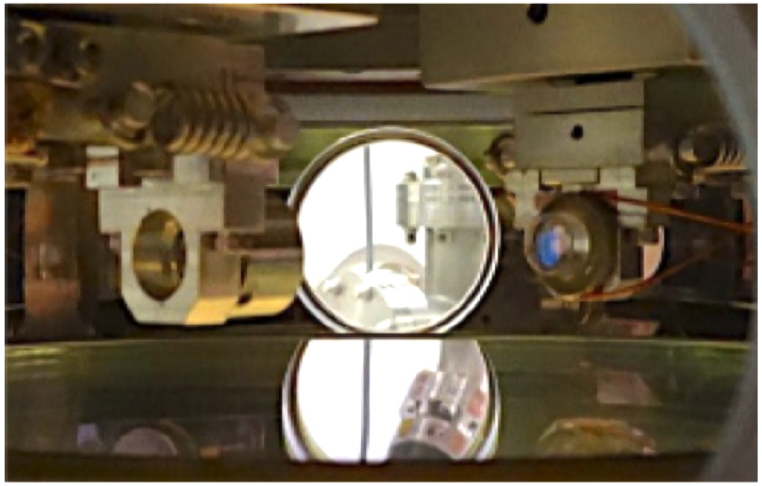
Apparatus



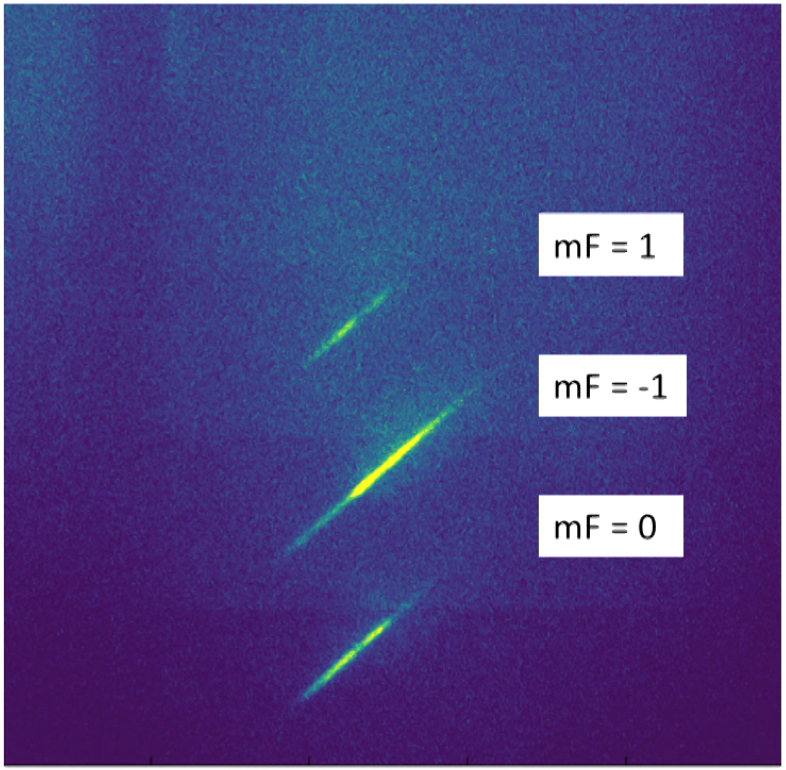


Fluorescence Imaging



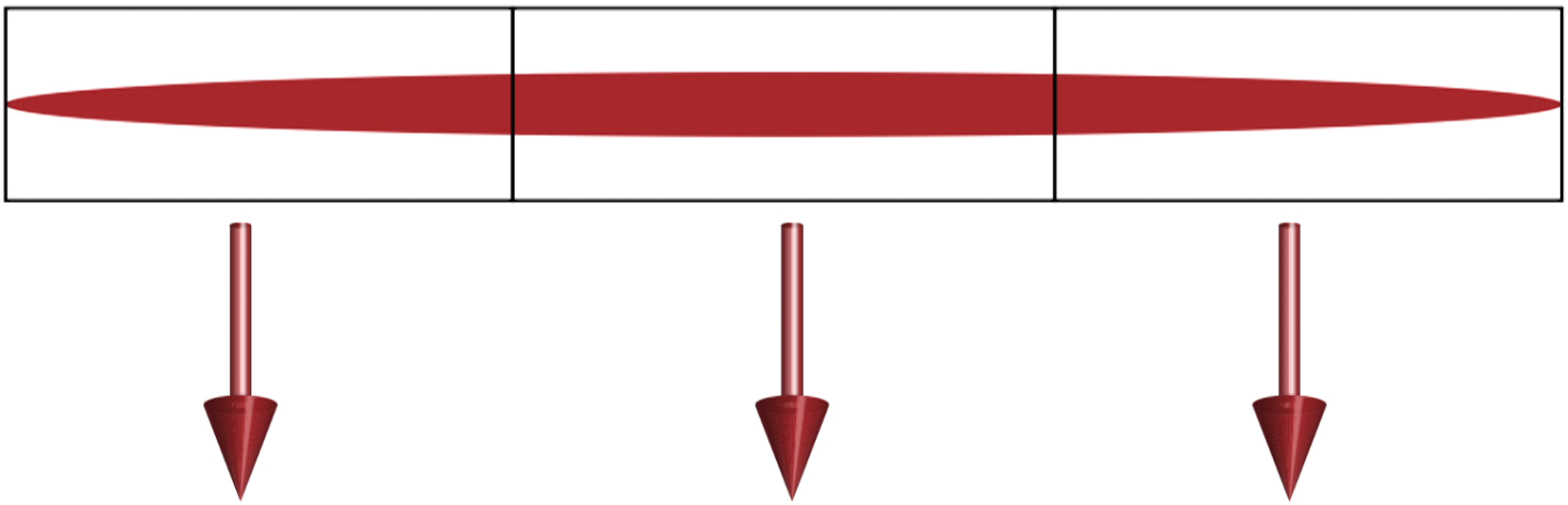


Three State Imaging

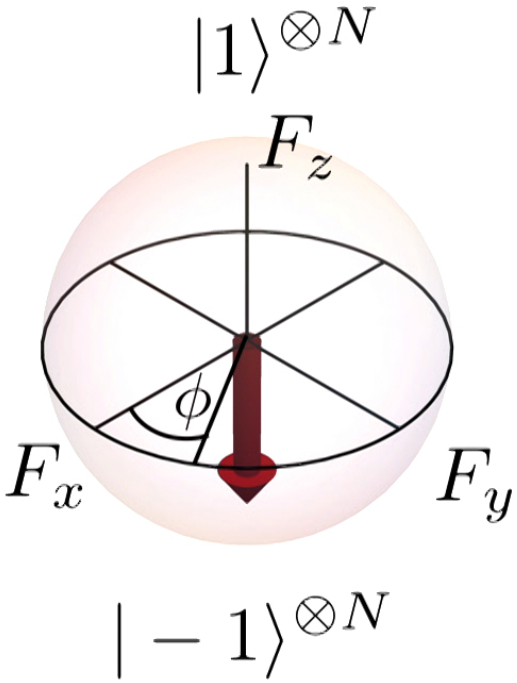


From Atoms to Large Collective Spins: $\vec{F} = \sum_i \vec{f}_i$

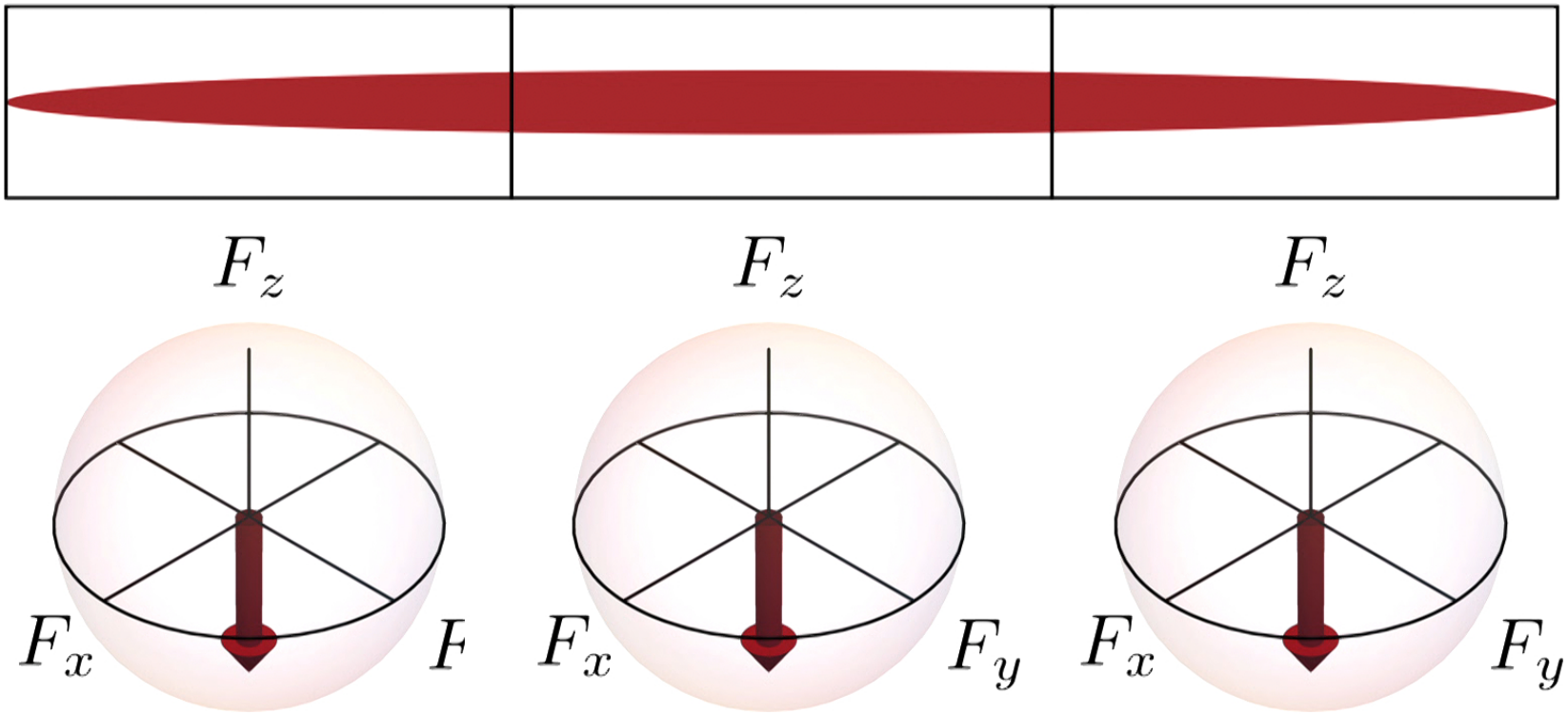
Atom cloud



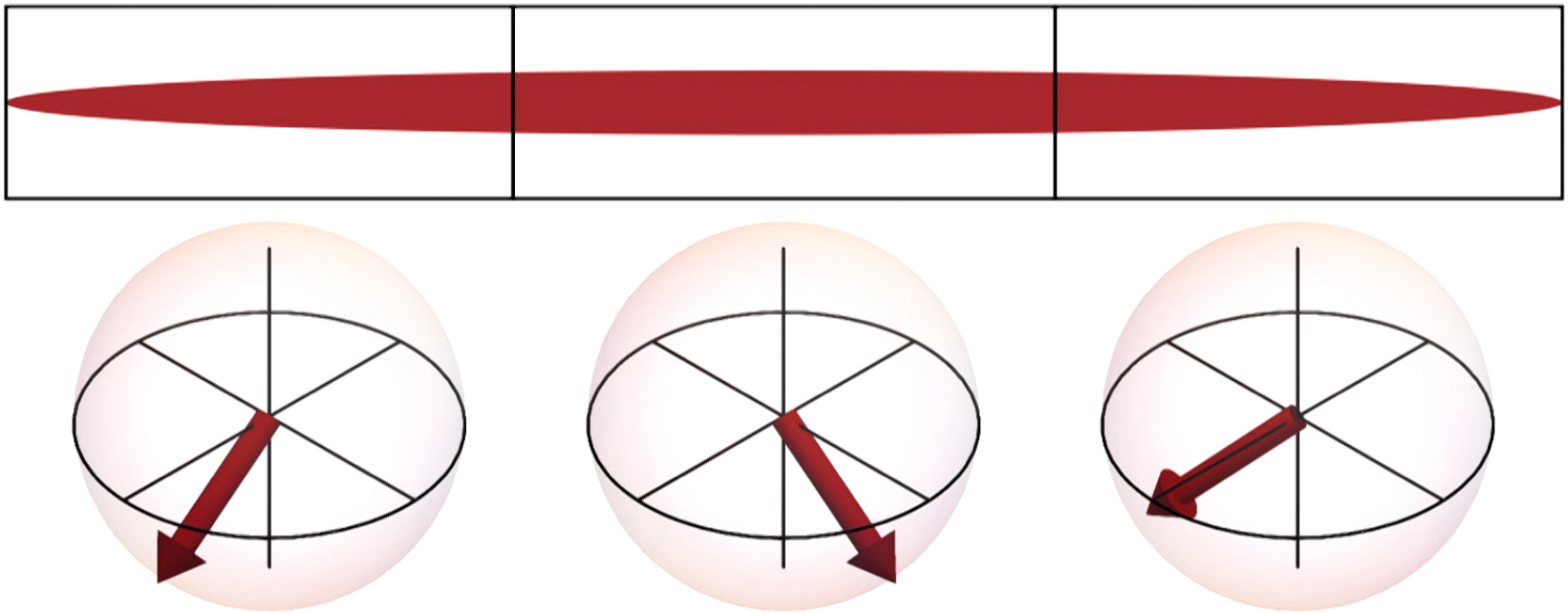
Spin-F Bloch Sphere



State Preparation

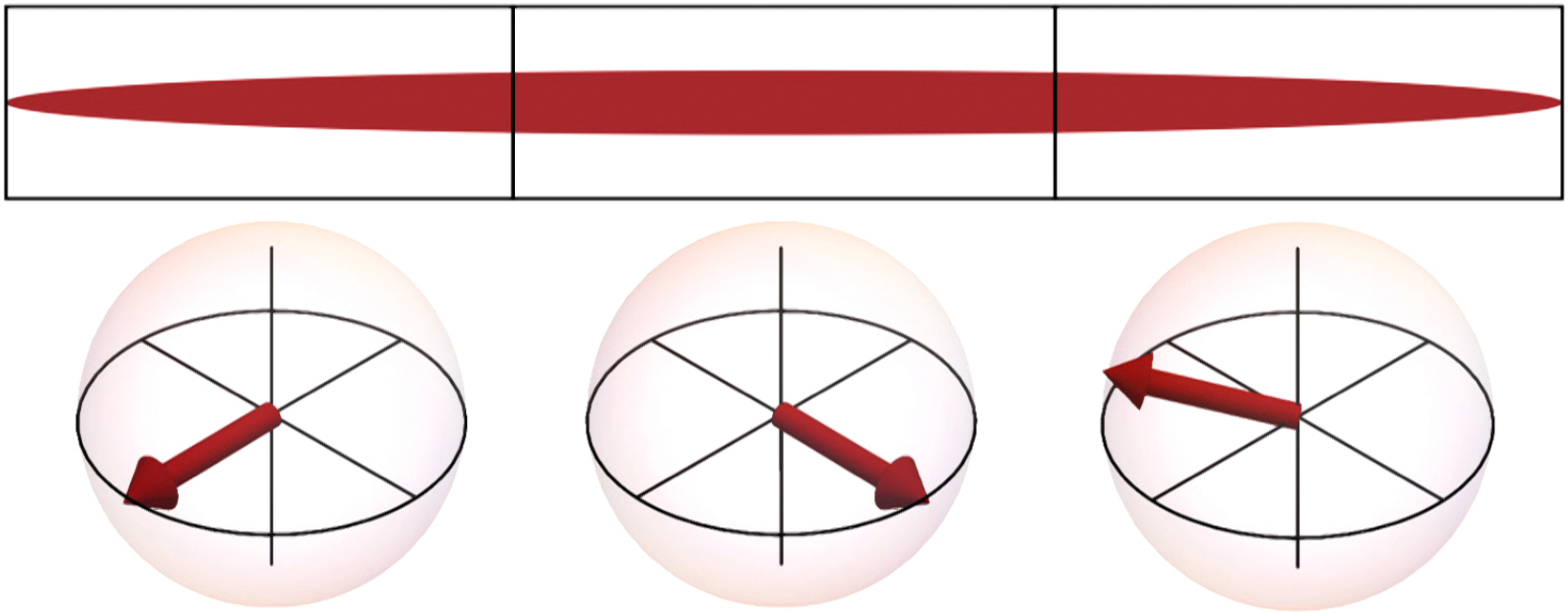


Arbitrary Local Raman Rotations



$$H \sim -F_y \qquad H \sim F_x \qquad H \sim -F_x - F_y$$

Arbitrary Local Raman Rotations



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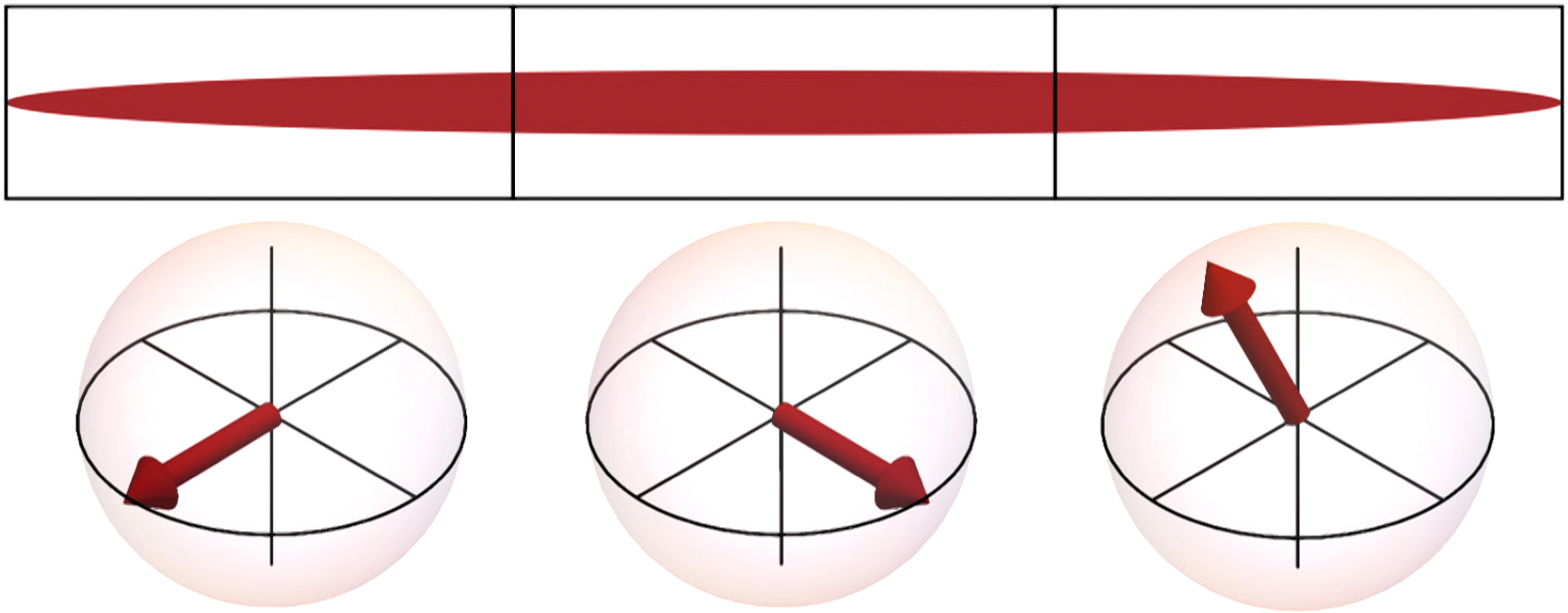
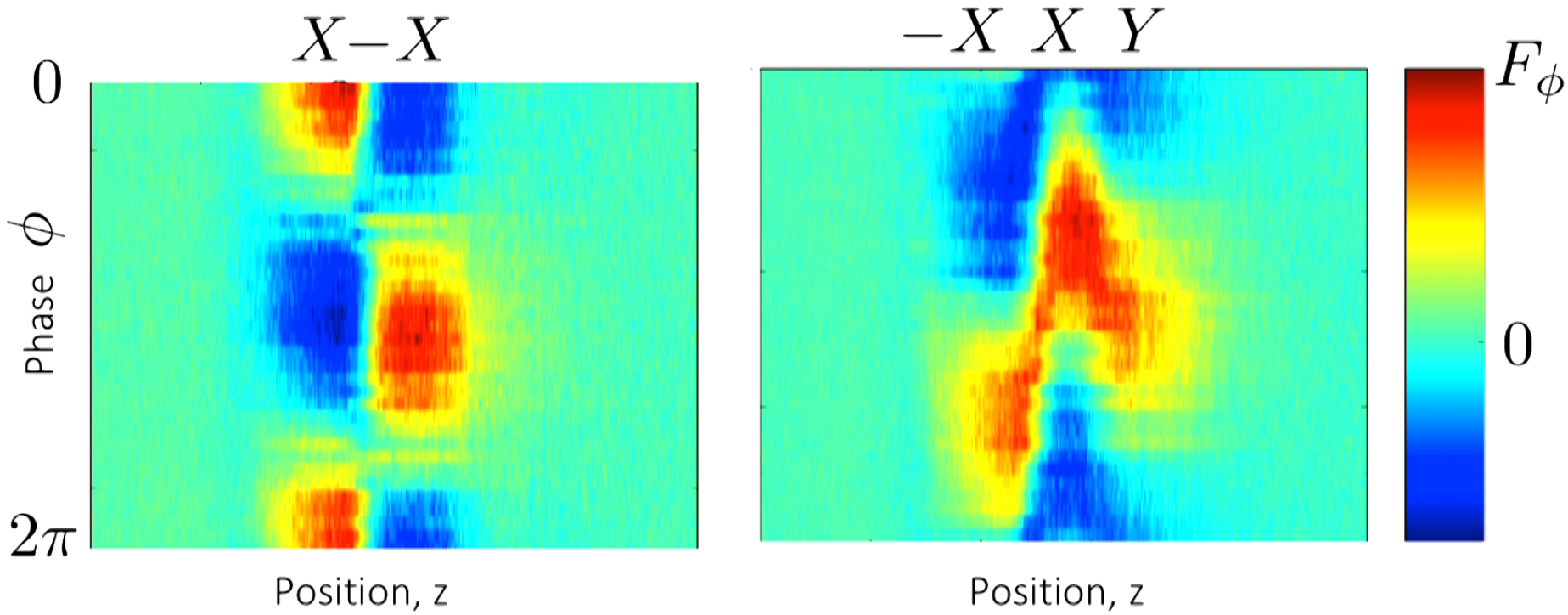
Arbitrary Local Raman Rotations



$$H \sim -F_y \qquad H \sim F_x \qquad H \sim -F_x - F_y$$

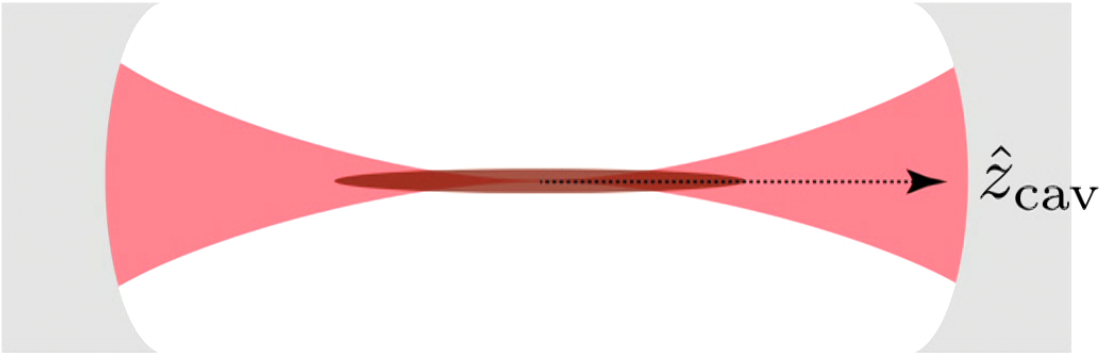
Spin Texture Verification



HAMILTONIAN IMPLEMENTATION

$$H = \sum_{i,j} J_i J_j (f_i^x f_j^x + f_i^y f_j^y + \alpha f_i^z f_j^z)$$

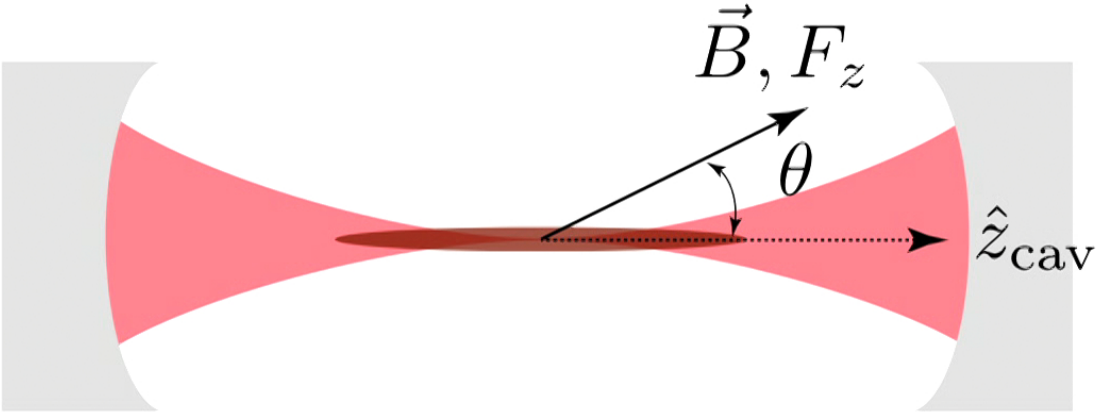
Faraday Effect



$$H_I \propto (a_+^\dagger a_+ - a_-^\dagger a_-)\vec{F} \cdot \hat{z}_{\mathrm{cav}}$$

$a_{+/-}$ annihilates a $\sigma_{+/-}$ photon in cavity mode

Faraday Effect

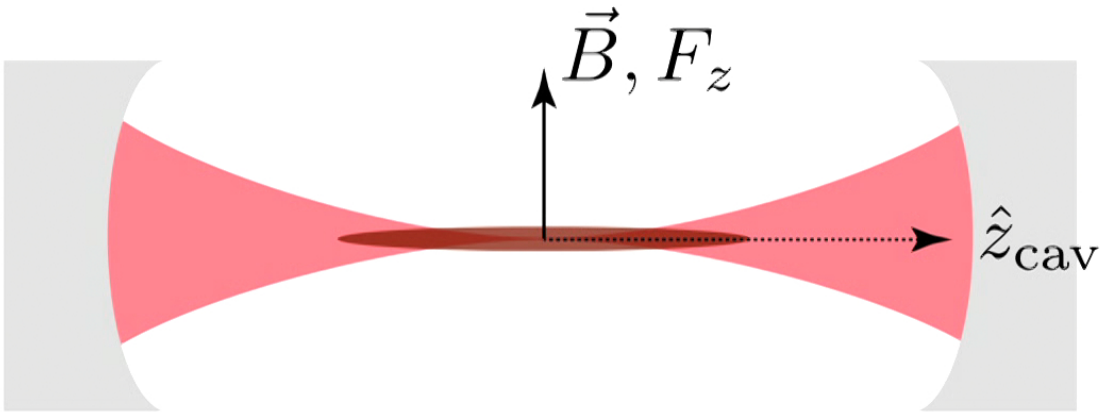


$$H_I \propto (a_+^\dagger a_+ - a_-^\dagger a_-)\vec{F} \cdot \hat{z}_{\mathrm{cav}}$$

Quantization axis for spin $\vec{F}$ defined by applied field $\vec{B}$

Pure Spin-Exchange Interactions

$$\mathcal{H} = \frac{1}{\sqrt{2}}(a_+ + a_-)$$

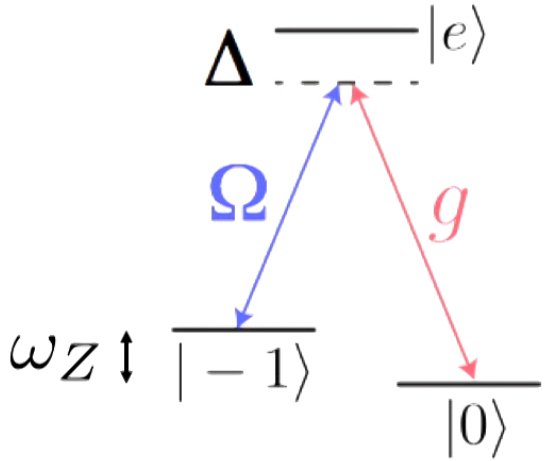


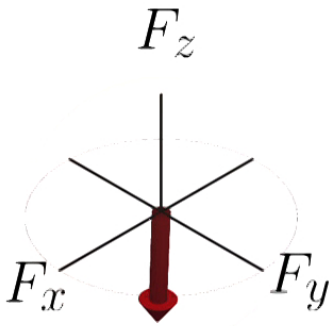
$$H_I \propto (a_+^\dagger a_+ - a_-^\dagger a_-) F_x$$

$$H \propto (\mathcal{V}^\dagger \mathcal{H} - \mathcal{H}^\dagger \mathcal{V})(F_+ + F_-)$$

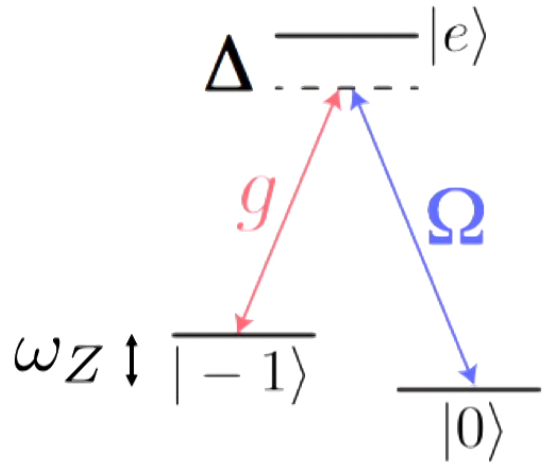
Single Spin Raman Processes

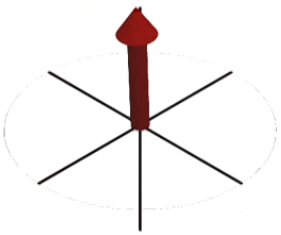
$\mathcal{H}\mathcal{V}^\dagger F_+$





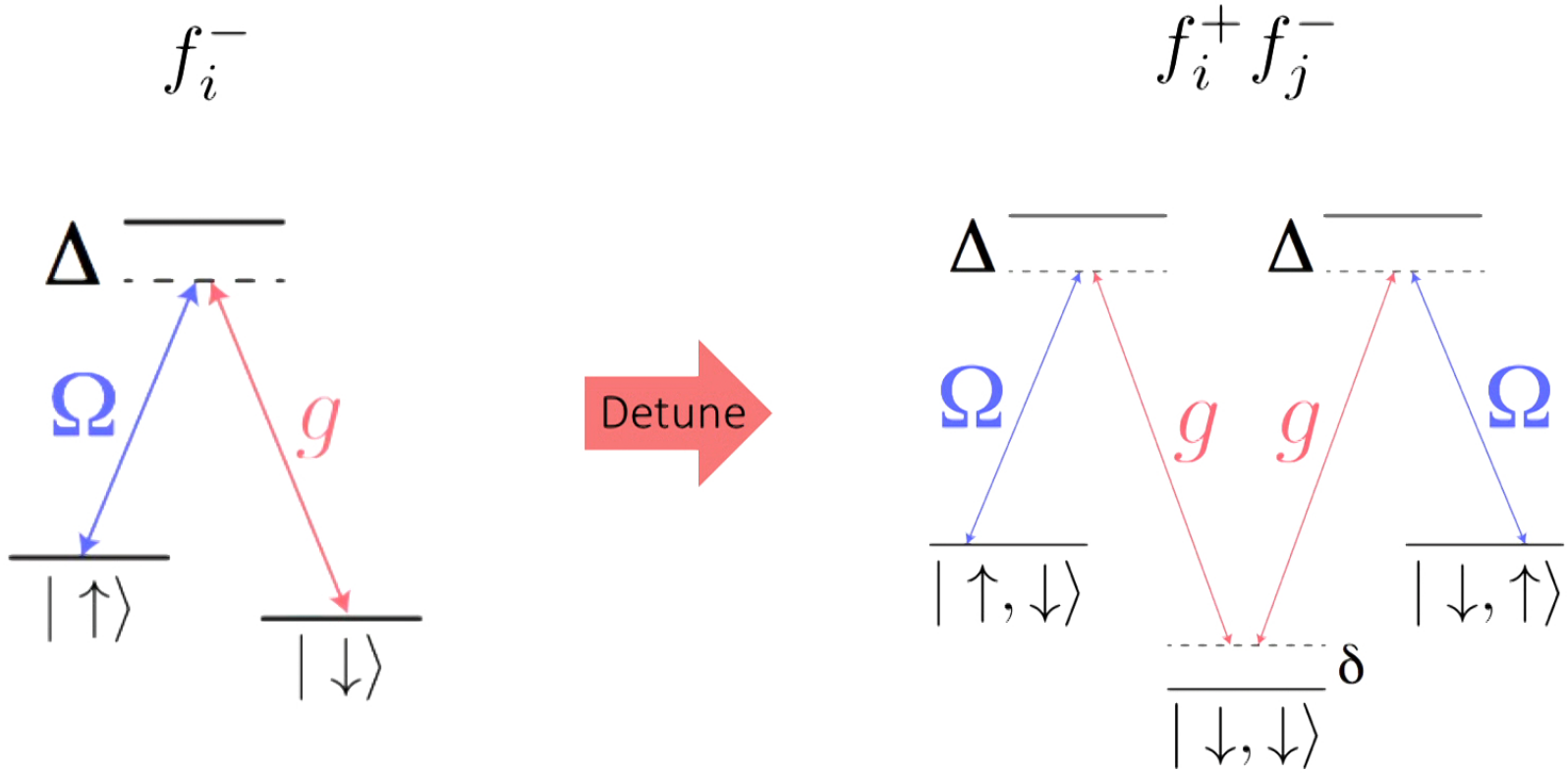
$\mathcal{H}\mathcal{V}^\dagger F_-$



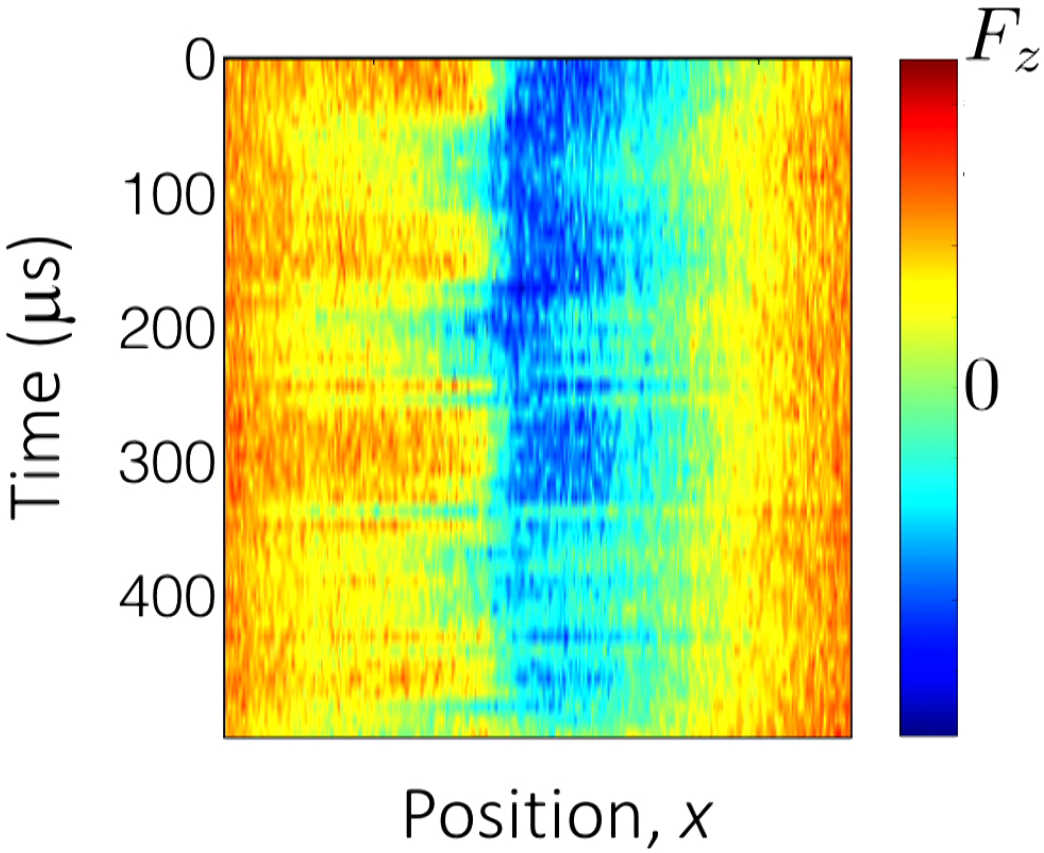


Kohler, Spethmann, Schreppler, and Stamper-Kurn. PRL **118** (2017)

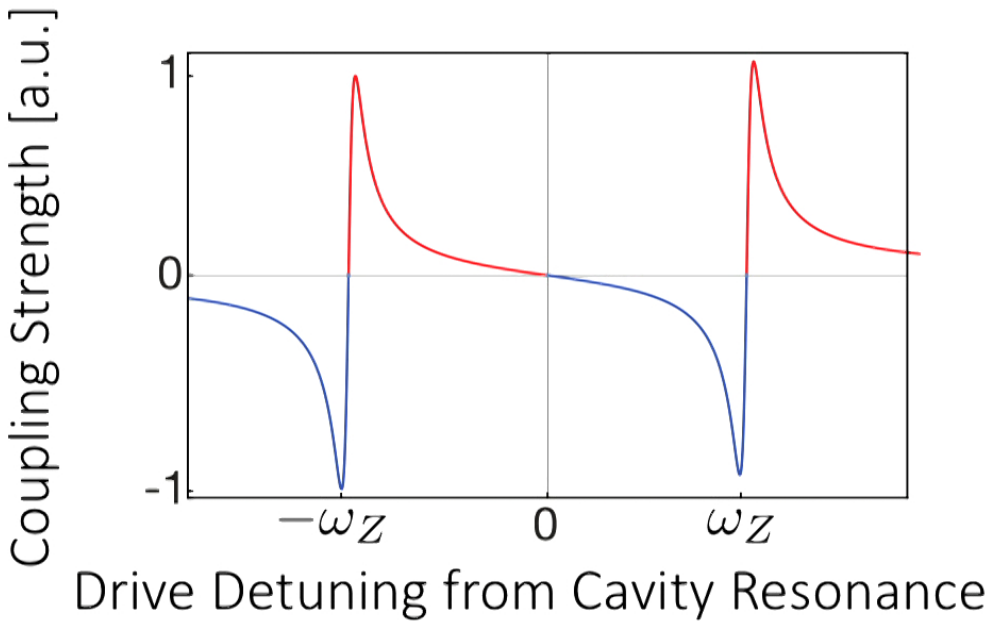
Pure Spin-Exchange Interactions



Spin-Exchange Data



Spin-Exchange Coupling



Can we use local Raman addressing to prepare a state that evolves in a simple way and allows us to extract $\chi_{SE}(\delta)$?

Measuring Spin-Exchange Couplings

$$H = \sum_{i,j} \chi_{SE}(f_i^x f_j^x + f_i^y f_j^y)$$

Mean field: $H \sim \vec{B} \cdot \vec{F}_j$

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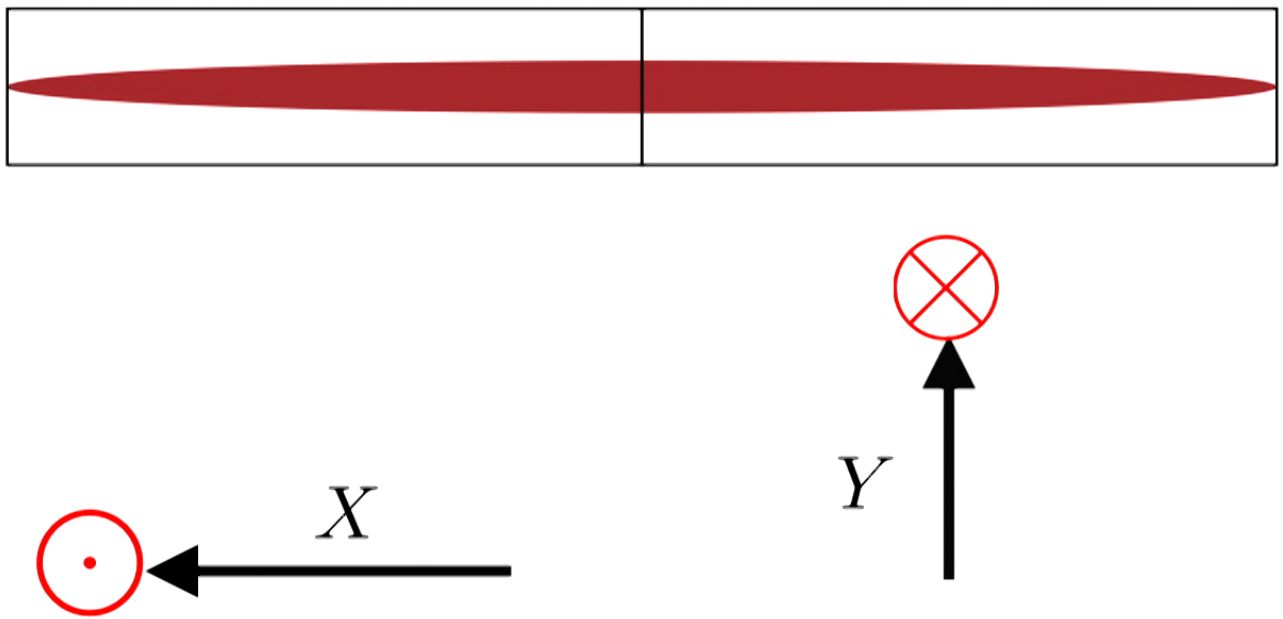

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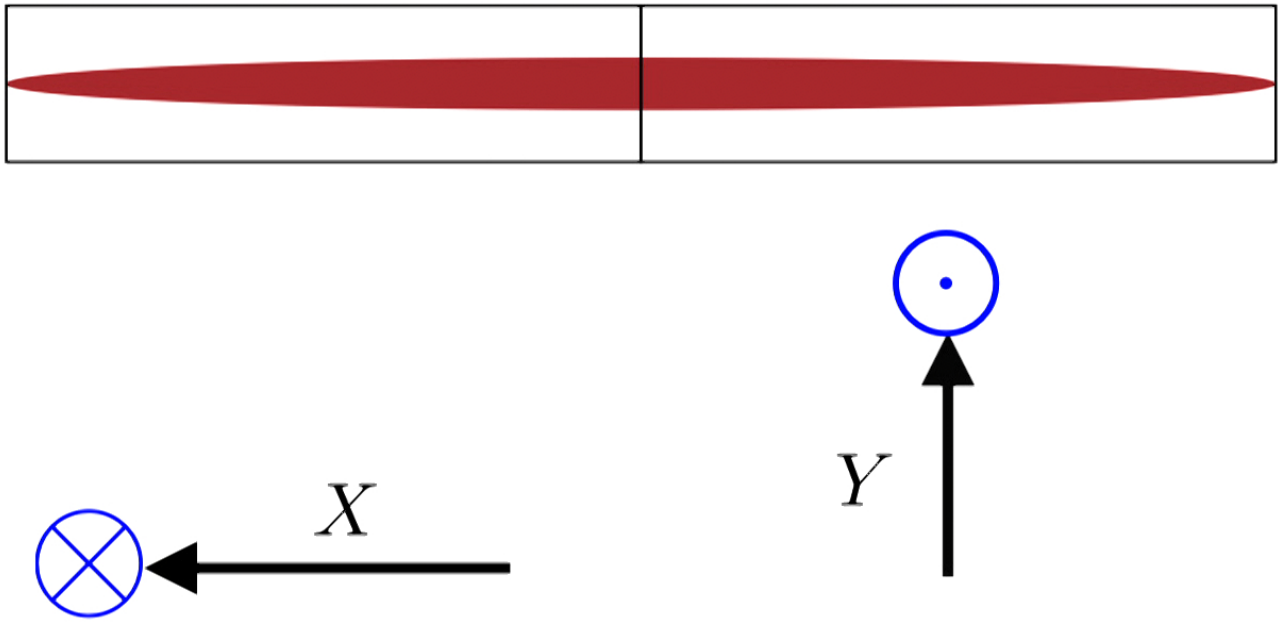
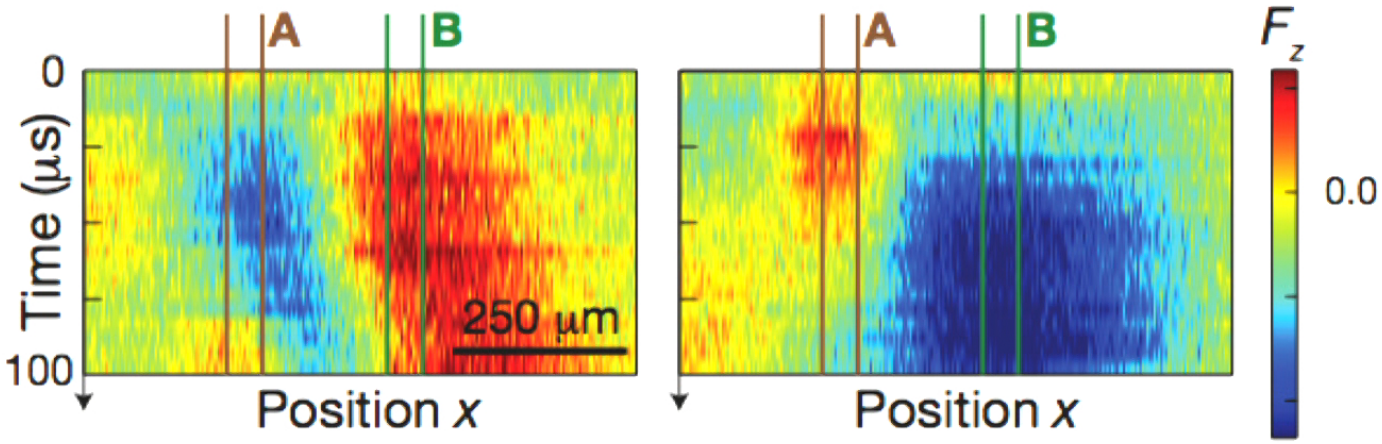
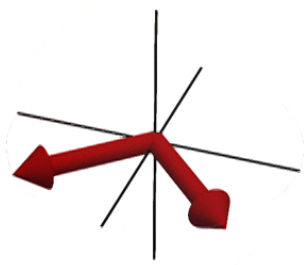
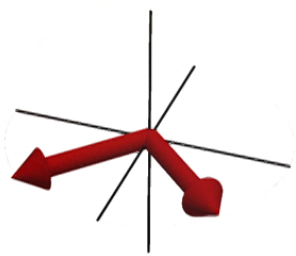


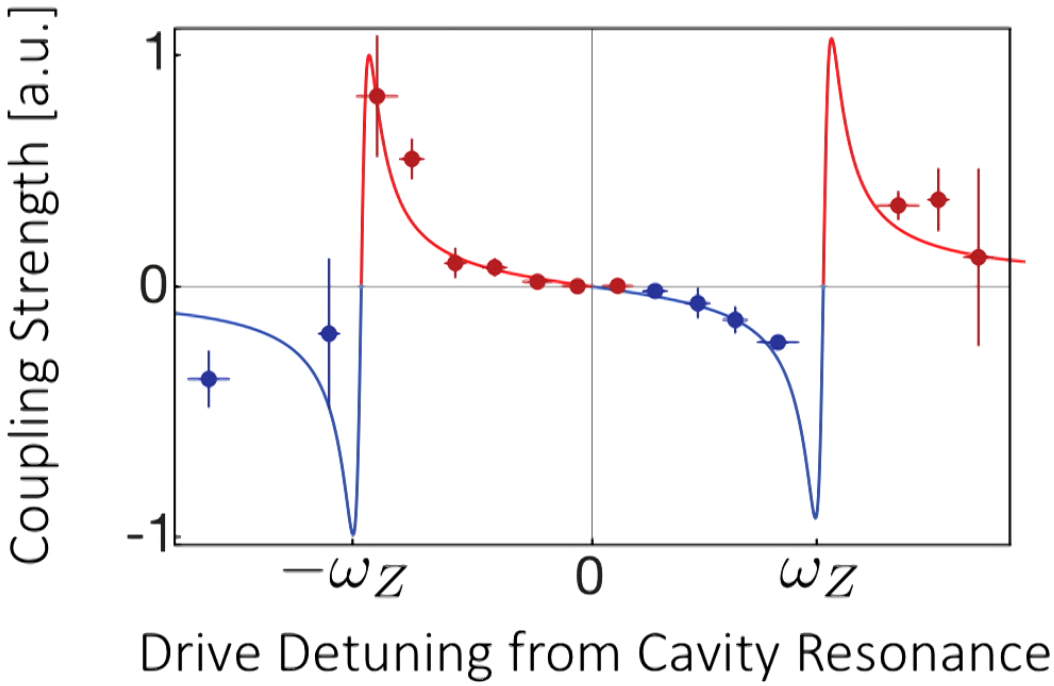
Magnetization Data







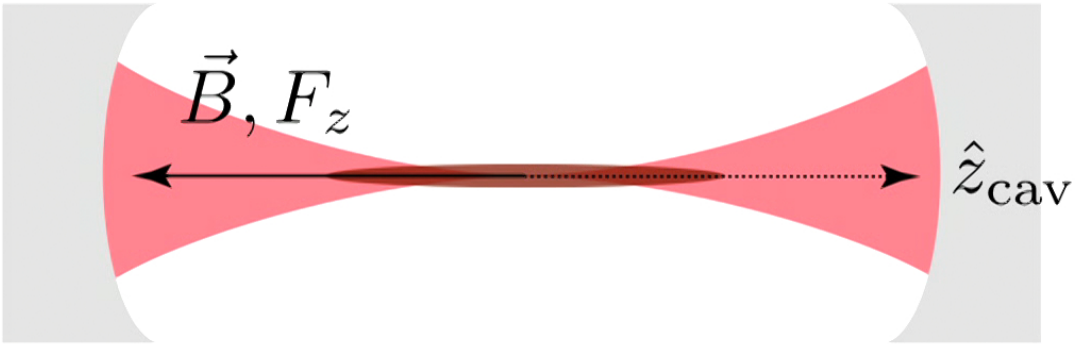
Spin-Exchange Coupling vs Detuning



Photon-Mediated Spin-Exchange Dynamics of Spin-1 Atoms
E.J. Davis, G. Bentsen, L. Homeier, T. Li, M.H. Schleier-Smith PRL **122** (2019)

Pure Ising Interactions

$$\mathcal{H} = \frac{1}{\sqrt{2}}(a_+ + a_-)$$

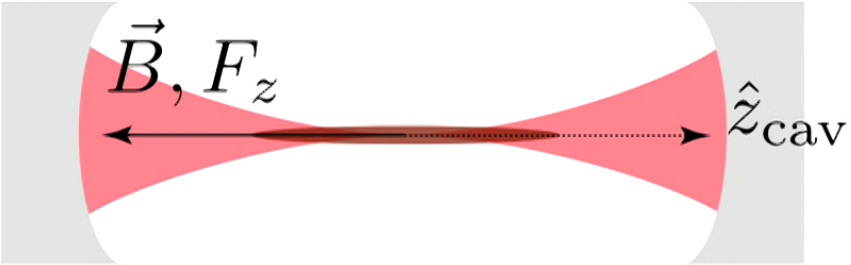


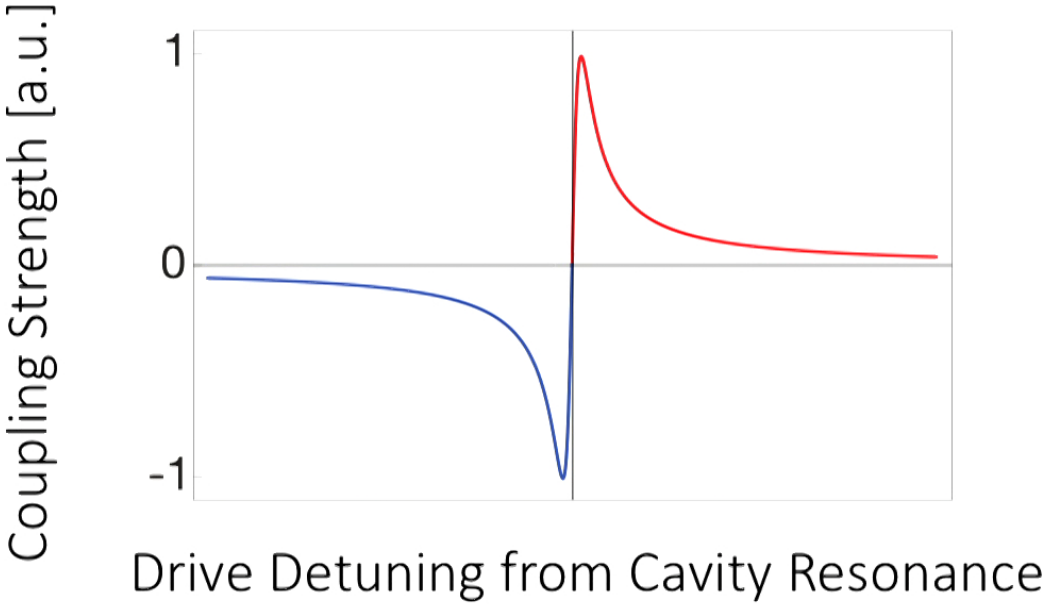
$$H_I \propto (a_+^\dagger a_+ - a_-^\dagger a_-) F_z$$

$$H \propto F_z^2$$

Pure Ising Interactions

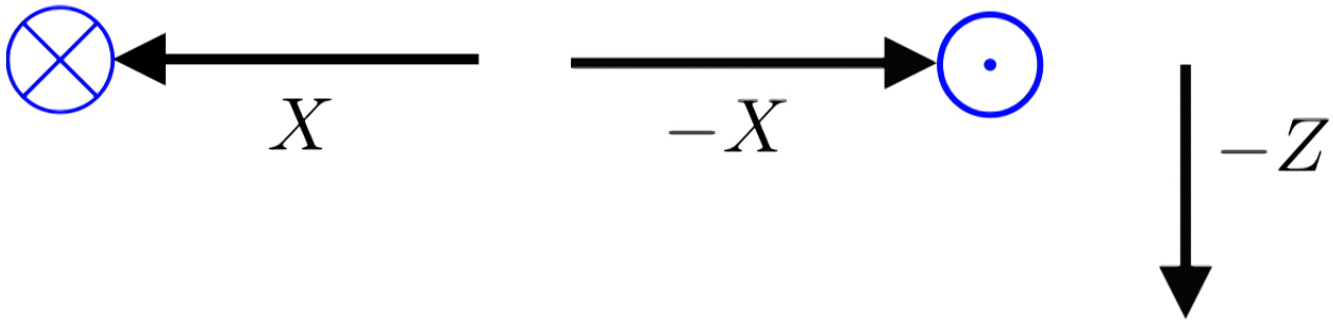
$$H \propto F_z^2$$



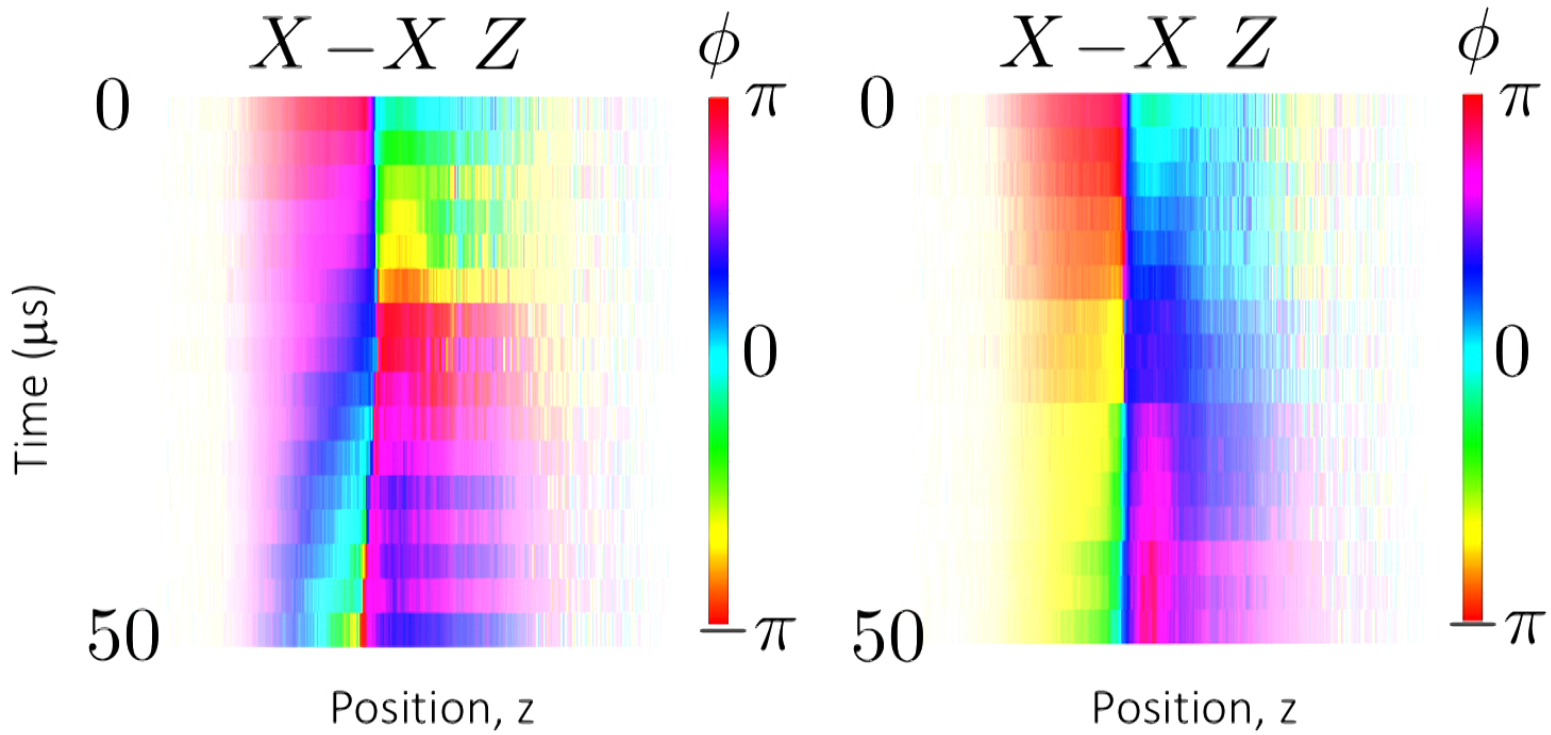


Measure Ising Couplings

$$H = \sum_{i,j} \chi_{SE}(f_i^x f_j^x + f_i^y f_j^y) + \chi_Z f_i^z f_j^z \qquad H \sim \vec{B} \cdot \vec{F}_j$$

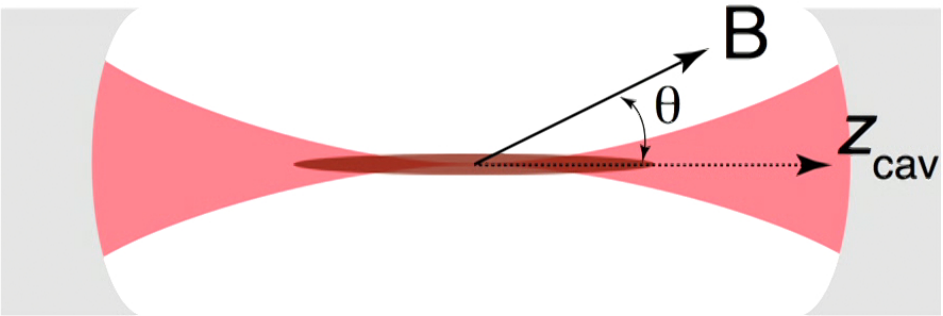


Phase Data


$X-X\ Z$
ϕ
π
0
$-\pi$
0
50
Time (μs)
Position, z
$X-X\ Z$
ϕ
π
0
$-\pi$
0
50
Position, z

Tune Alpha by Rotating B

$$H = \sum_{i,j} J_i J_j (f_i^x f_j^x + f_i^y f_j^y + \alpha f_i^z f_j^z)$$

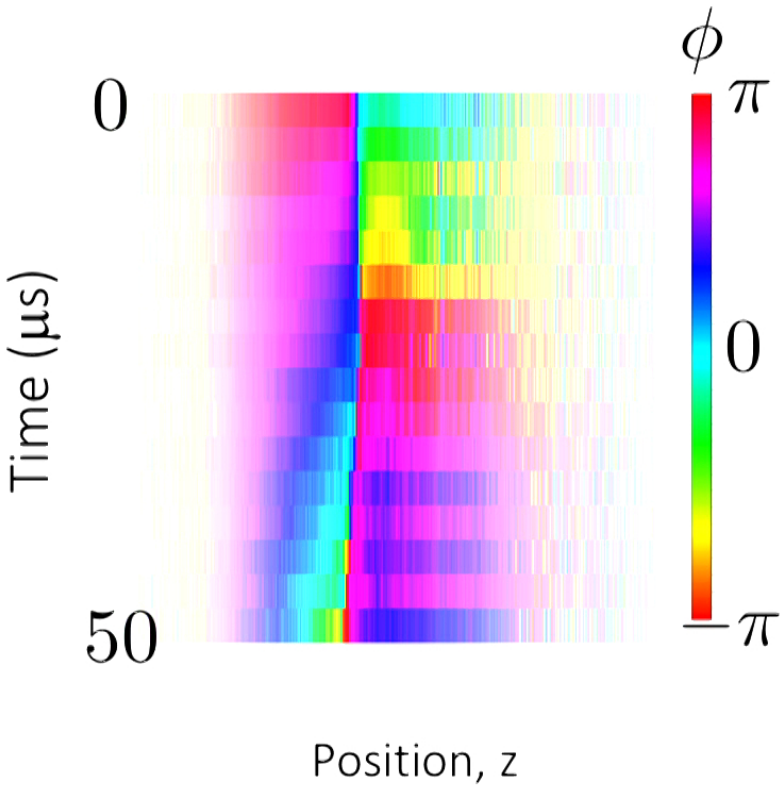


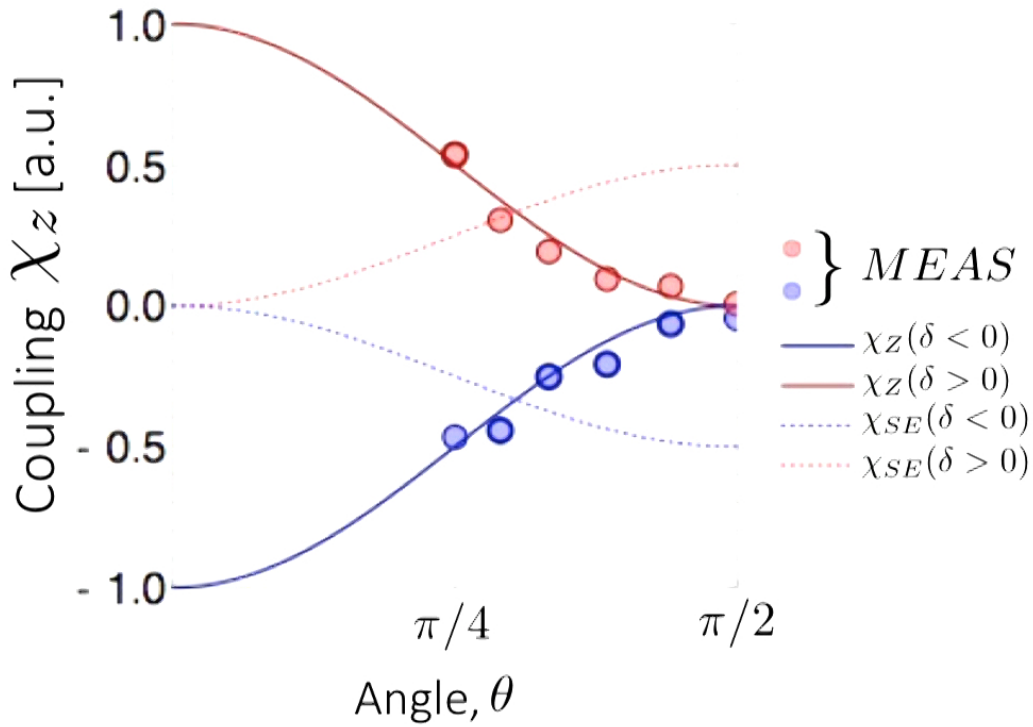
$$\alpha = 2\cot^2(\theta)$$

$$\chi_Z = \cos^2(\theta)$$

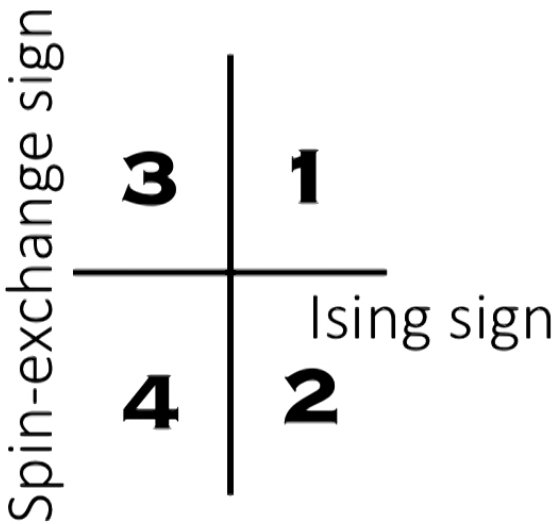
$$\chi_{SE} = \frac{1}{2}\sin^2(\theta)$$

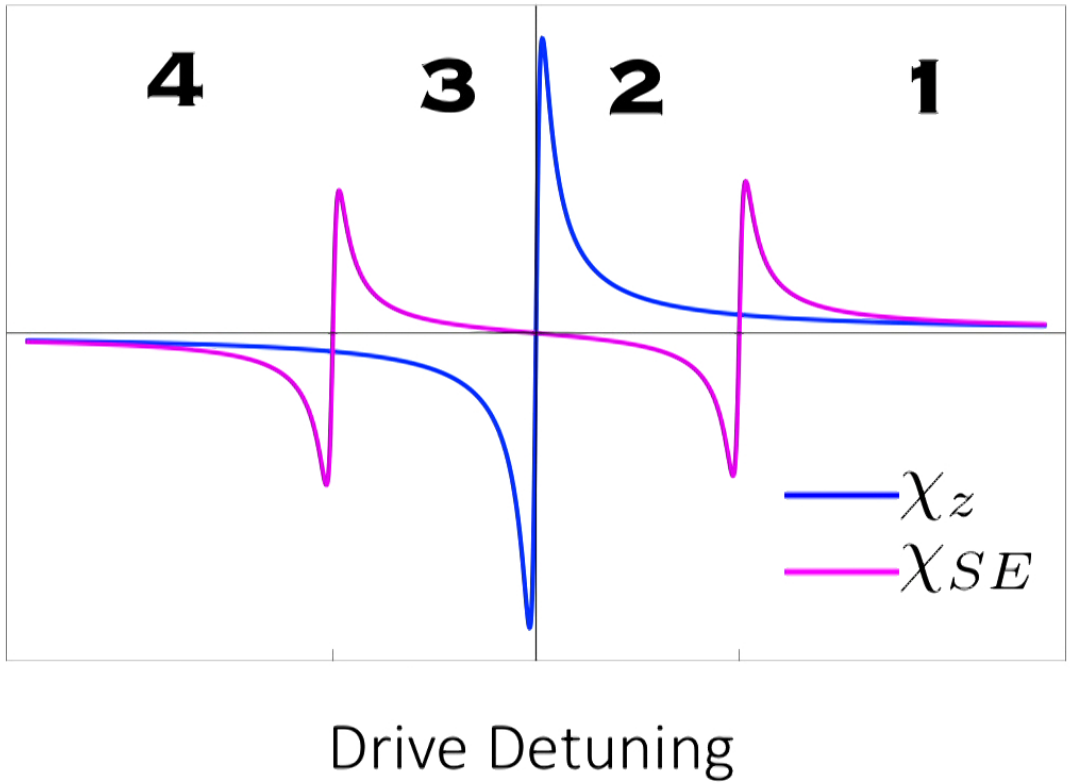
Preliminary Data: Ising Coupling vs Theta





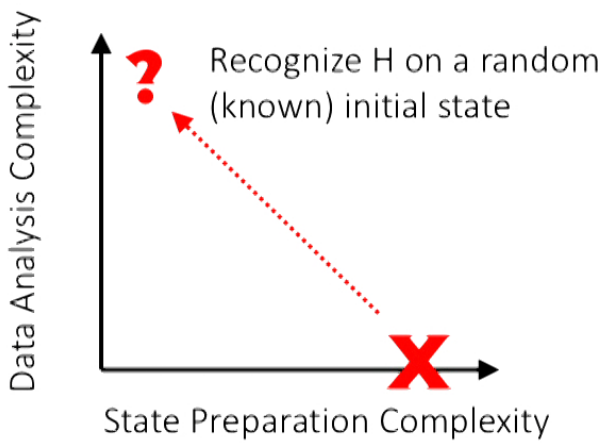
Relative Strength and Sign

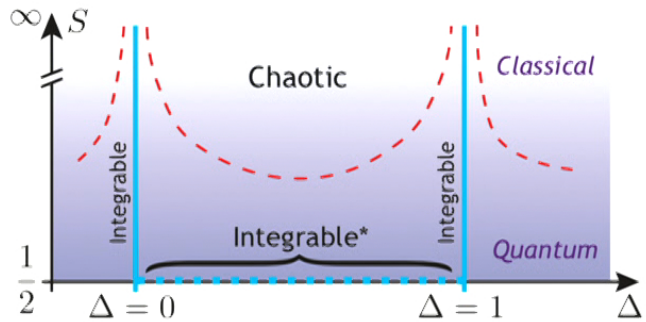




Possibilities for ML

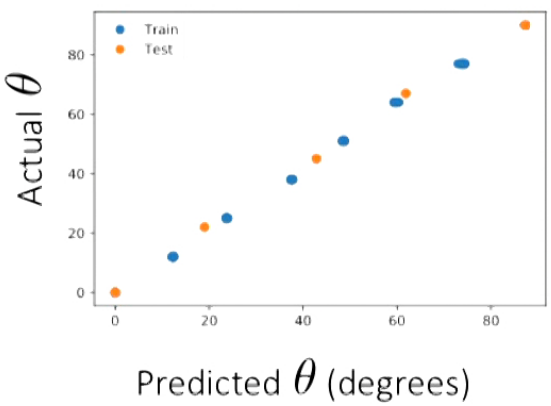
Hamiltonian Tomography





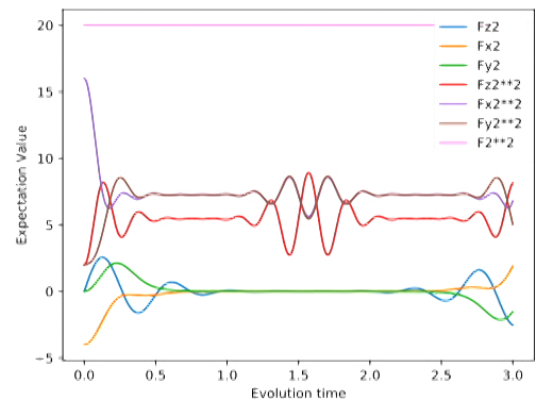
G. Bentsen et al. arXiv:1904.10966

Beyond Mean Field: autodetection of correlations from data



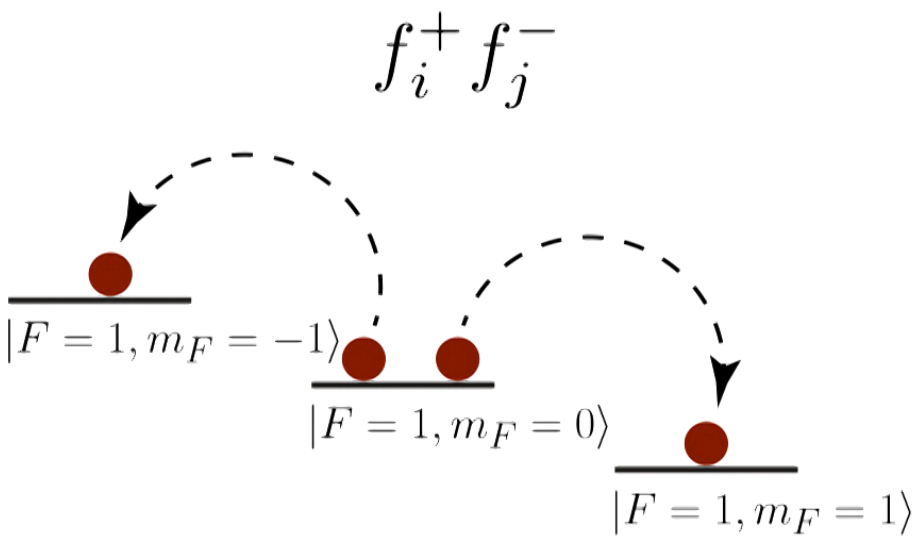
Classification of integrable vs chaotic dynamics

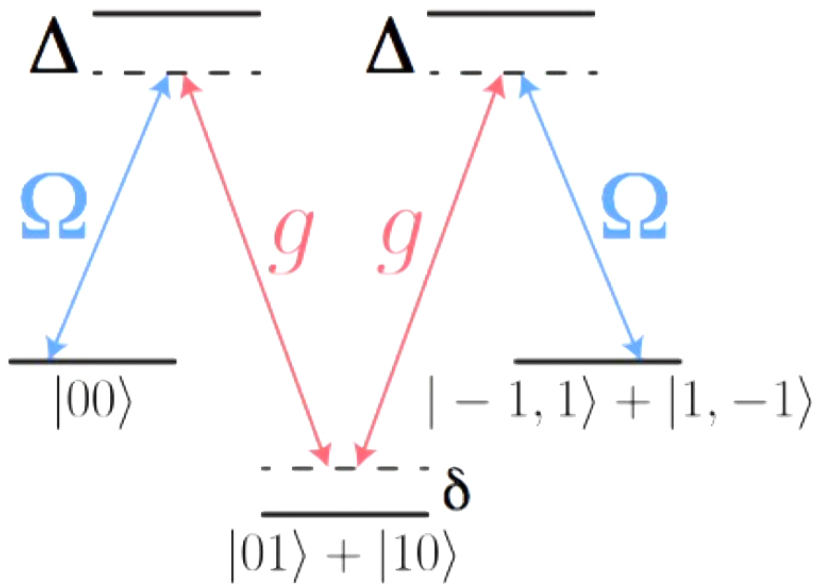
Extraction of conserved quantities from data



ACCESSING A HIGHLY ENTANGLED STATE VIA SPIN-MIXING DYNAMICS

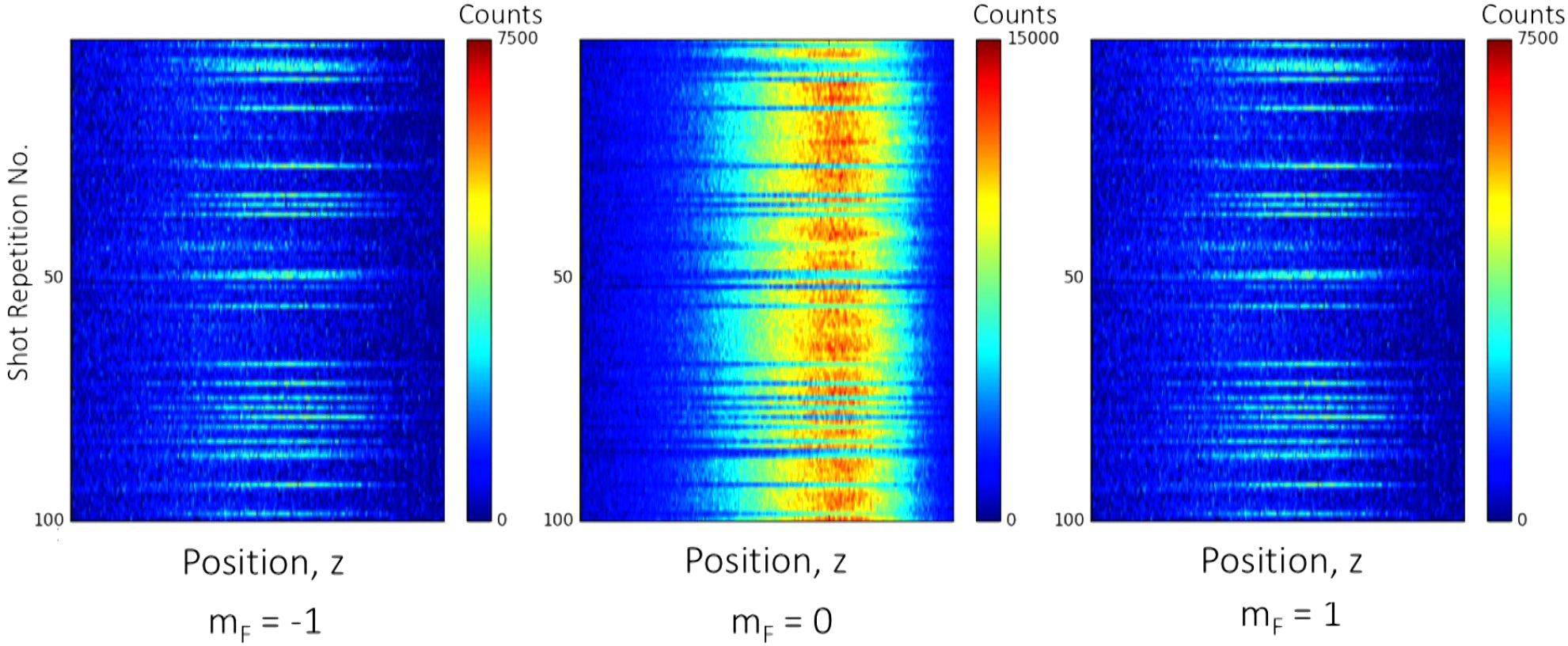
Spin-Mixing with Spin-1 Atoms



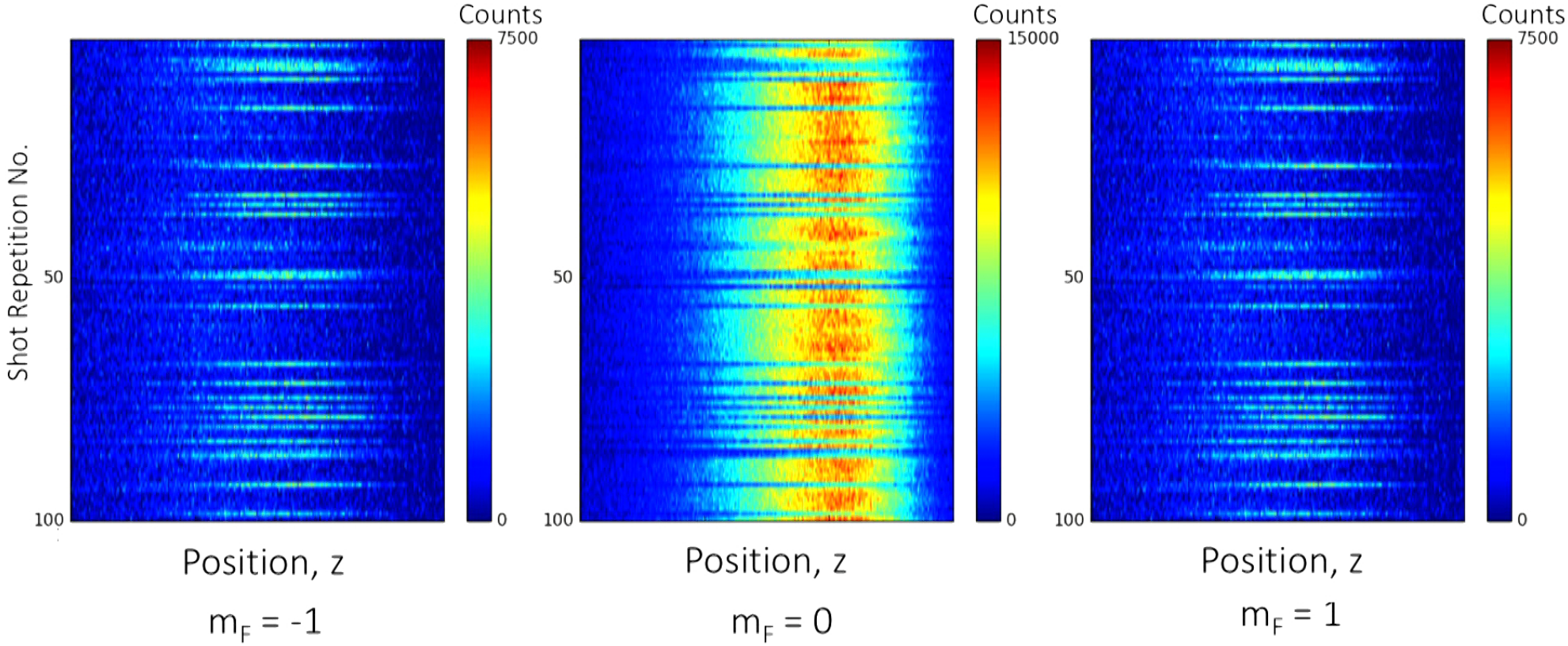


C. D. Hamley, C. S. Gerving, T. M. Hoang, E. M. Bookjans, and M. S. Chapman Nature Physics (2012)
X. Luo, Y. Zou, L. Wu, Q. Liu, M. Han, M. Tey, and L. You Science (2017)
D. Linnemann, H. Strobel, W. Muessel, J. Schulz, R.J. Lewis-Swan, K.V. Kheruntsyan, and M.K. Oberthaler PRL (2016)

Spin-Mixing with Spin-1 Atoms



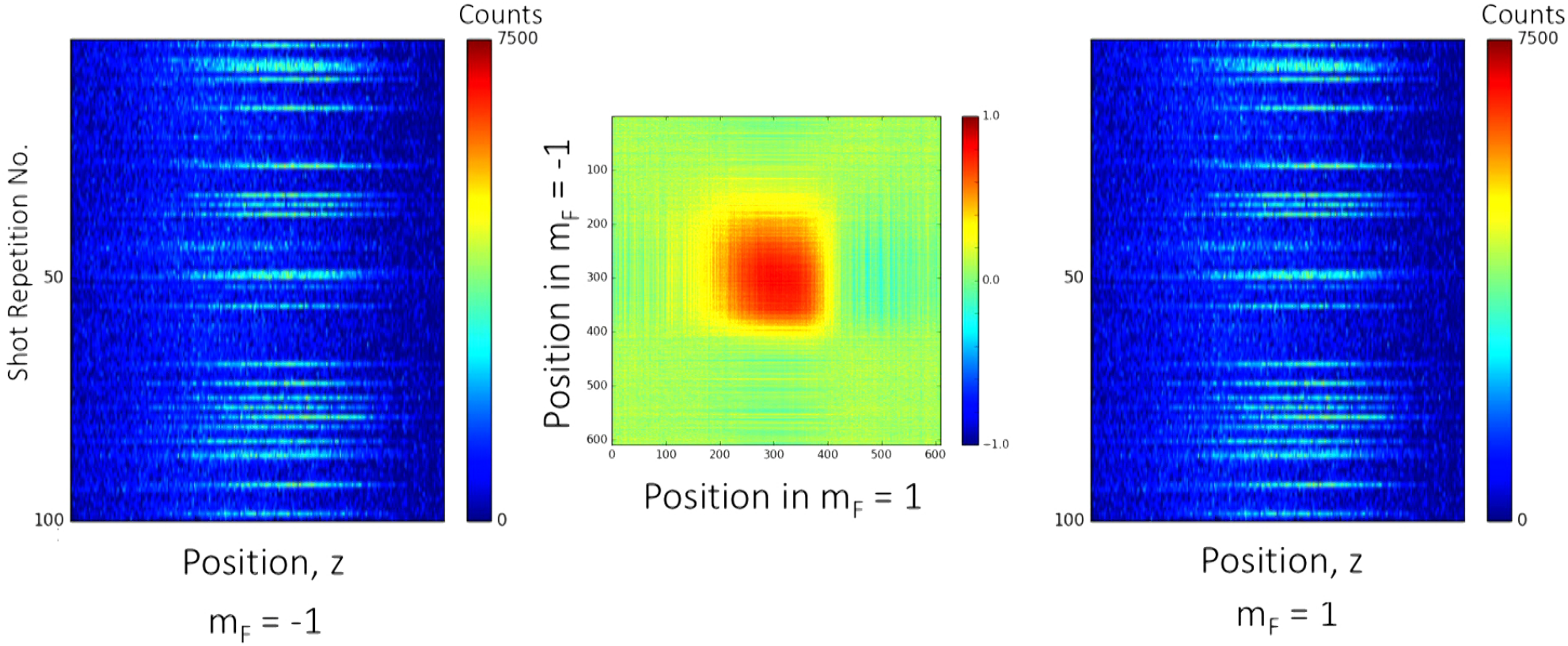
Spin-Mixing with Spin-1 Atoms



Pair-creation state characterization: metrologically useful entanglement?

$$|\psi_{TF}\rangle = \frac{1}{\sqrt{6}}(|\uparrow\uparrow\downarrow\downarrow\rangle + |\downarrow\uparrow\uparrow\downarrow\rangle + |\downarrow\downarrow\uparrow\uparrow\rangle + |\uparrow\downarrow\downarrow\uparrow\rangle + |\uparrow\downarrow\uparrow\downarrow\rangle + |\downarrow\uparrow\downarrow\uparrow\rangle)$$

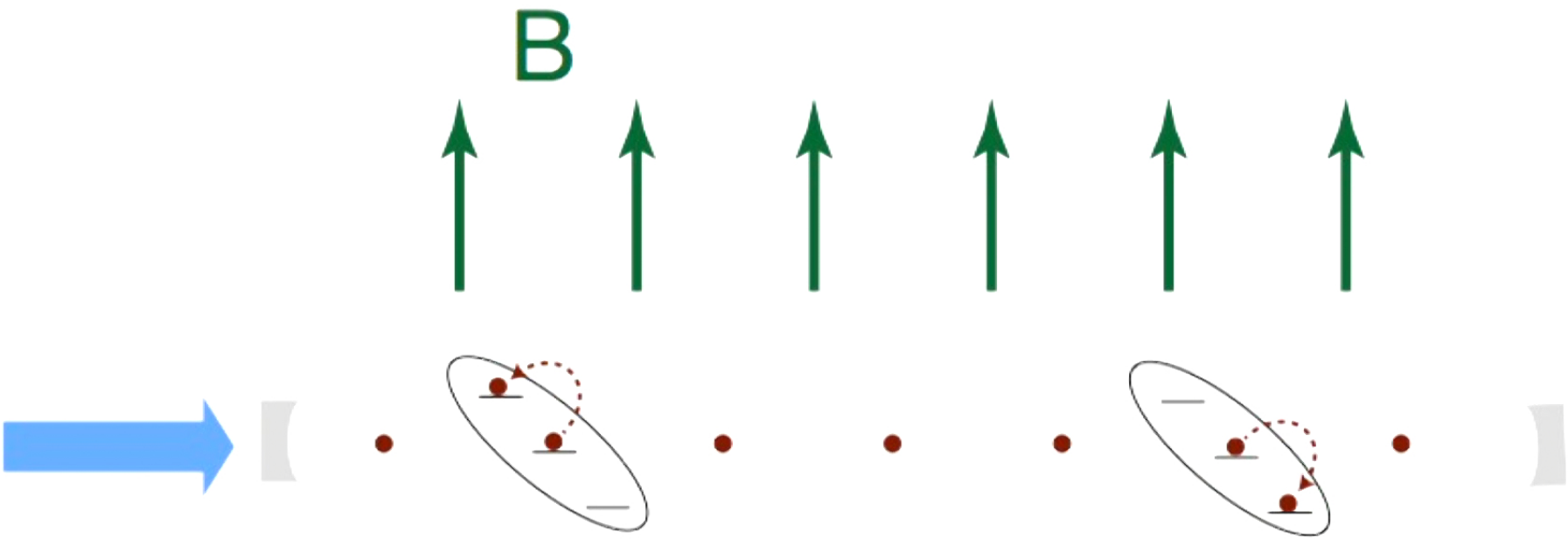
Spatial Correlations between Side Modes



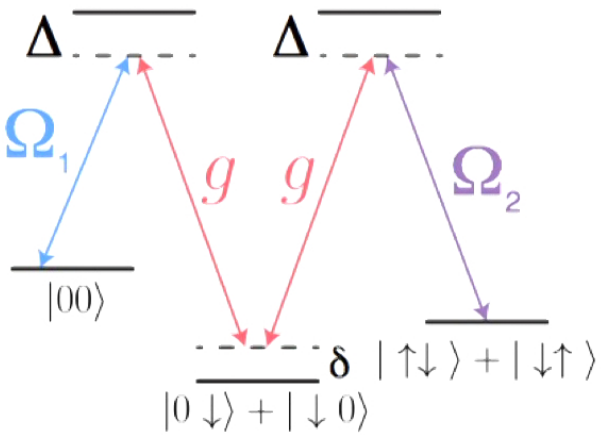
PROGRAMMING DISTANCE-DEPENDENT INTERACTIONS

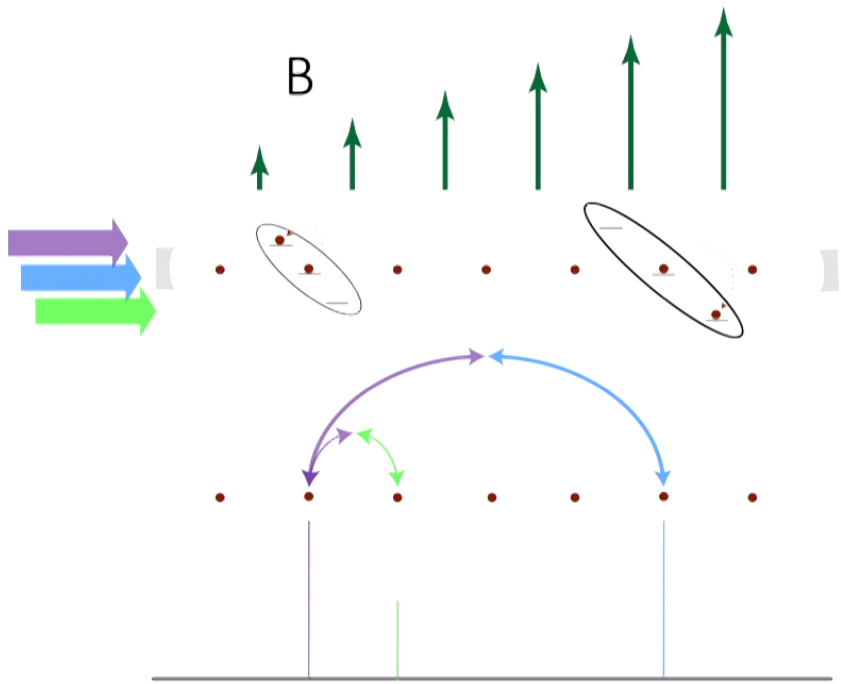
$$H = \sum_{i,j} J_i J_j (F_i^x F_j^x + F_i^y F_j^y)$$

Spin-Mixing in a Uniform Field



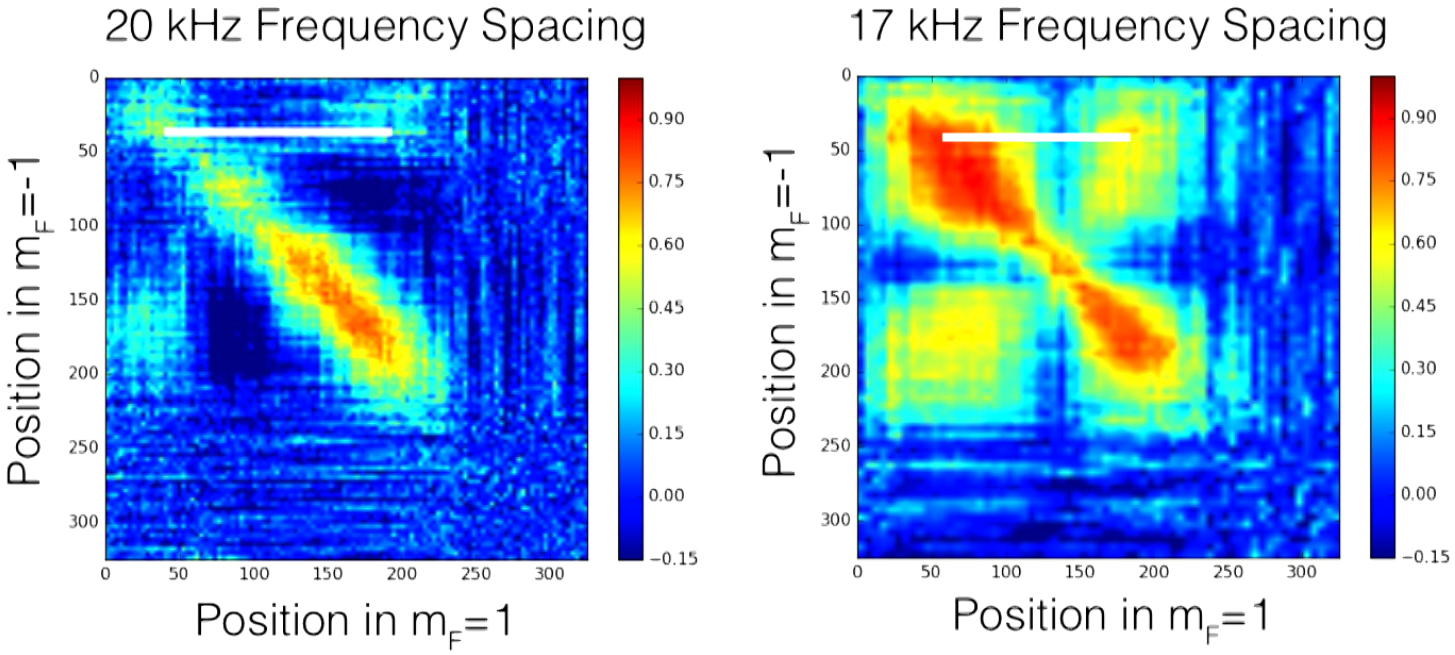
Spin-Mixing in a Magnetic Field Gradient





C.-L. Hung, A. González-Tudela, J.I. Cirac, and H. J. Kimble PNAS (2016)

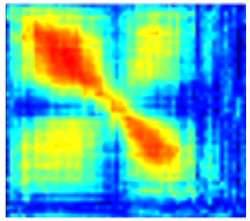
Spatial Correlations between Side Modes



Magnetic Field Gradient: 50 kHz/200 pixels

Possibilities for ML

Automatically extract interesting features in the spatial-dependence and time-dependence of correlation structure



State tomography with noisier data

- Target observables of interest without single atom resolution
- Use extra information from cavity light
- Use local Raman readout for more local measurement combinations

Distinguish quantum correlations from classical noise

Possibilities for ML

Extract spatial and time dependence of correlation structure
State tomography with noisier data
Distinguish quantum correlations from classical noise

Hamiltonian tomography
Beyond mean field: autodetection of correlations from data
Classification of integrable vs chaotic dynamics
Extraction of conserved quantities from data

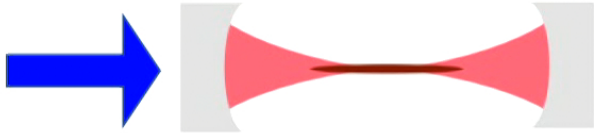
Possibilities for ML

Extract spatial and time dependence of entanglement structure
State tomography with noisier data
Distinguish quantum correlations from classical noise

Hamiltonian tomography
Beyond mean field: autodetection of correlations from data
Classification of integrable vs chaotic dynamics
Extraction of conserved quantities from data

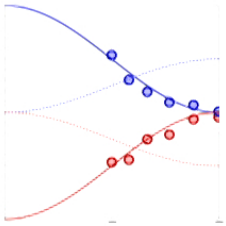
Quantum machine learning [QCNNs I. Cong, S. Choi , M. Lukin arXiv:1810.03787 (2018)]
Integrating ML on data collection into measurement feedback loops

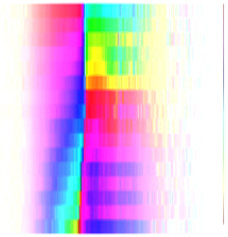
Summary



Platform

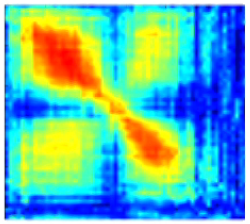
- Nonlocal, tunable, switchable interactions
- Cavity with local Raman addressing, imaging





Tunable Heisenberg Hamiltonians

- Characterized tunable strength and sign
- First observation of photon-mediated spin-mixing
- Preliminary demonstration of distance-dependent interactions



Possibilities for ML!

Thanks!

PI: Monika Schleier-Smith

Group members:

Cavity lab: Gregory Bentsen, Avikar Periwal, Eric Cooper

Rydberg lab: Tori Borish, Ognjen Markovic, Jacob Hines

Former group members:

Tracy Li, Lukas Homeier, Simon Evered, Katherine van Kirk

Poster with Zhaoyou Wang:

Calculating Renyi Entropies using Neural Autoregressive Quantum States