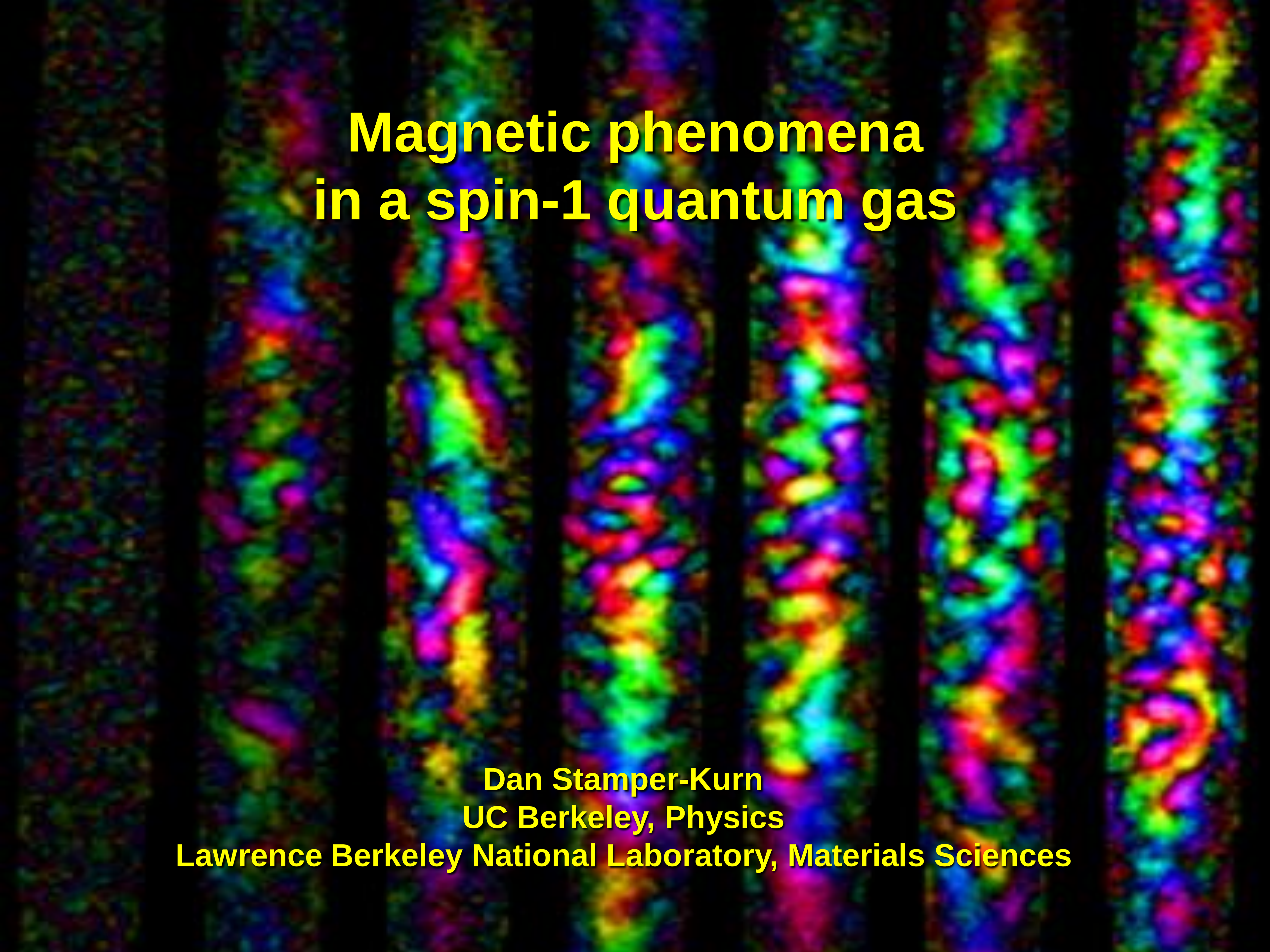
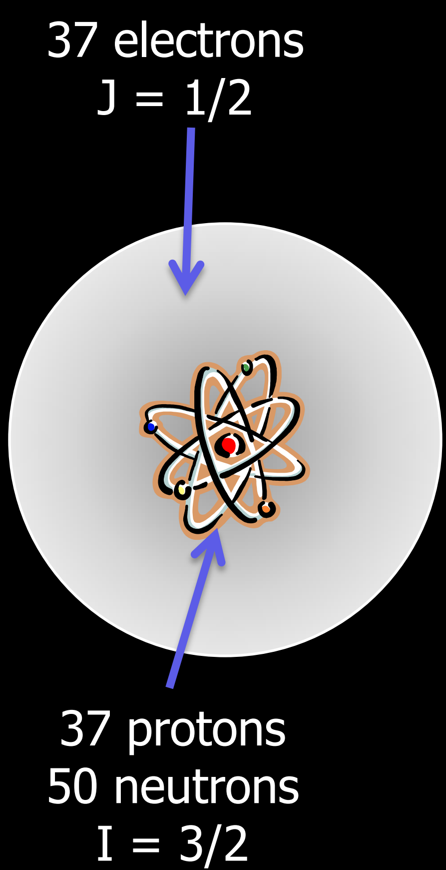


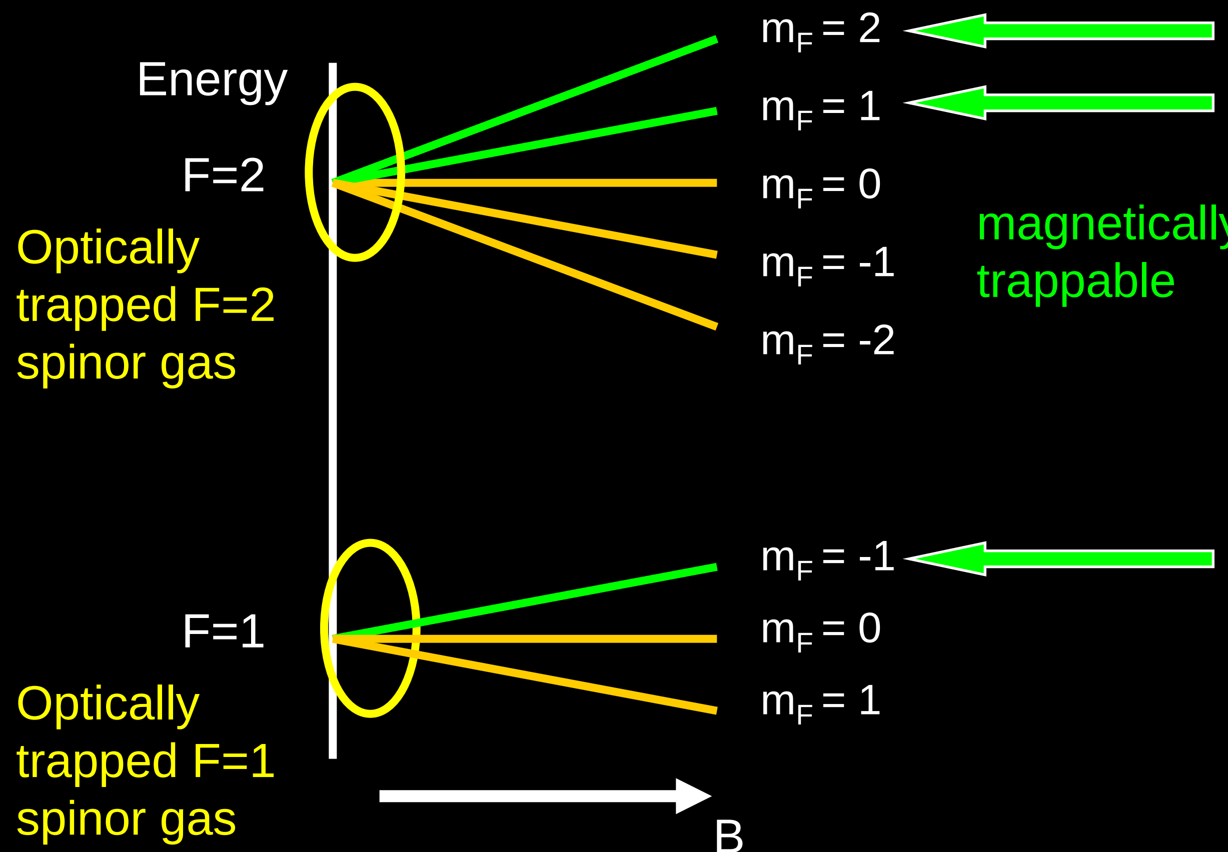
Magnetic phenomena in a spin-1 quantum gas

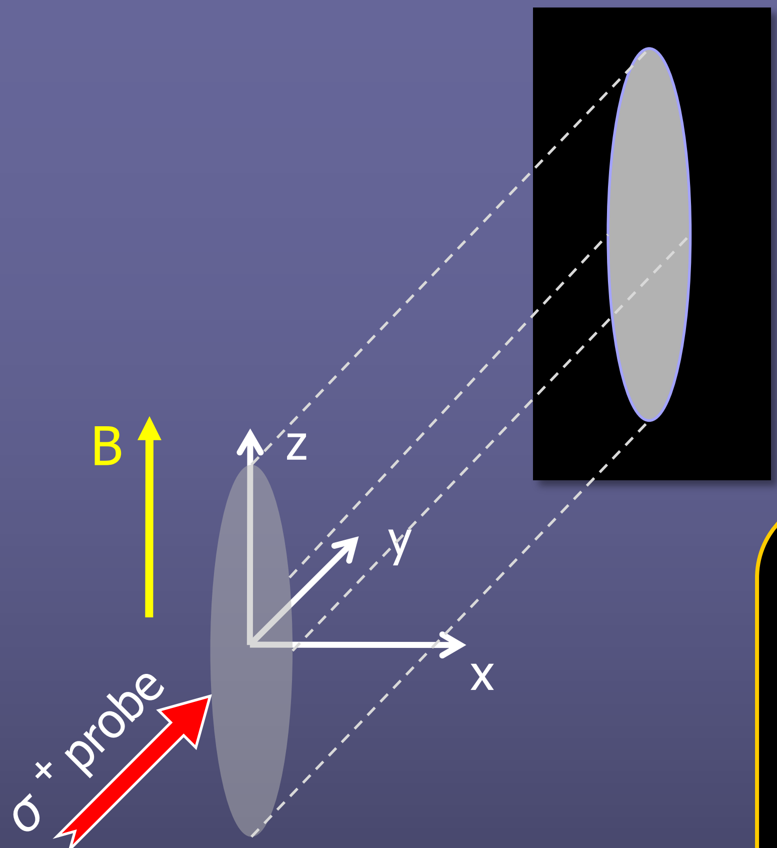
Dan Stamper-Kurn
UC Berkeley, Physics
Lawrence Berkeley National Laboratory, Materials Sciences

Spinor gases

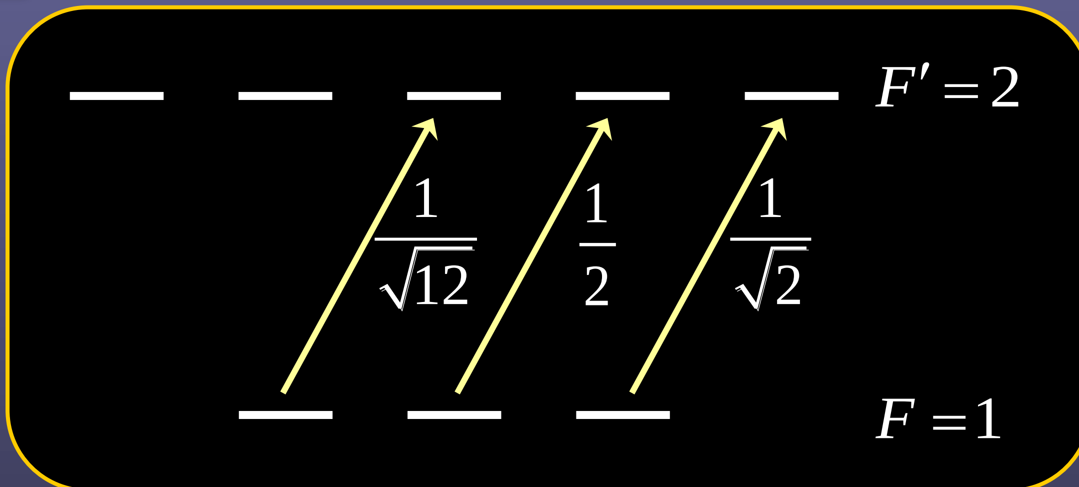


$$\vec{F} = \vec{I} + \vec{J}$$





phase-contrast image;
dispersive (minimally destructive)



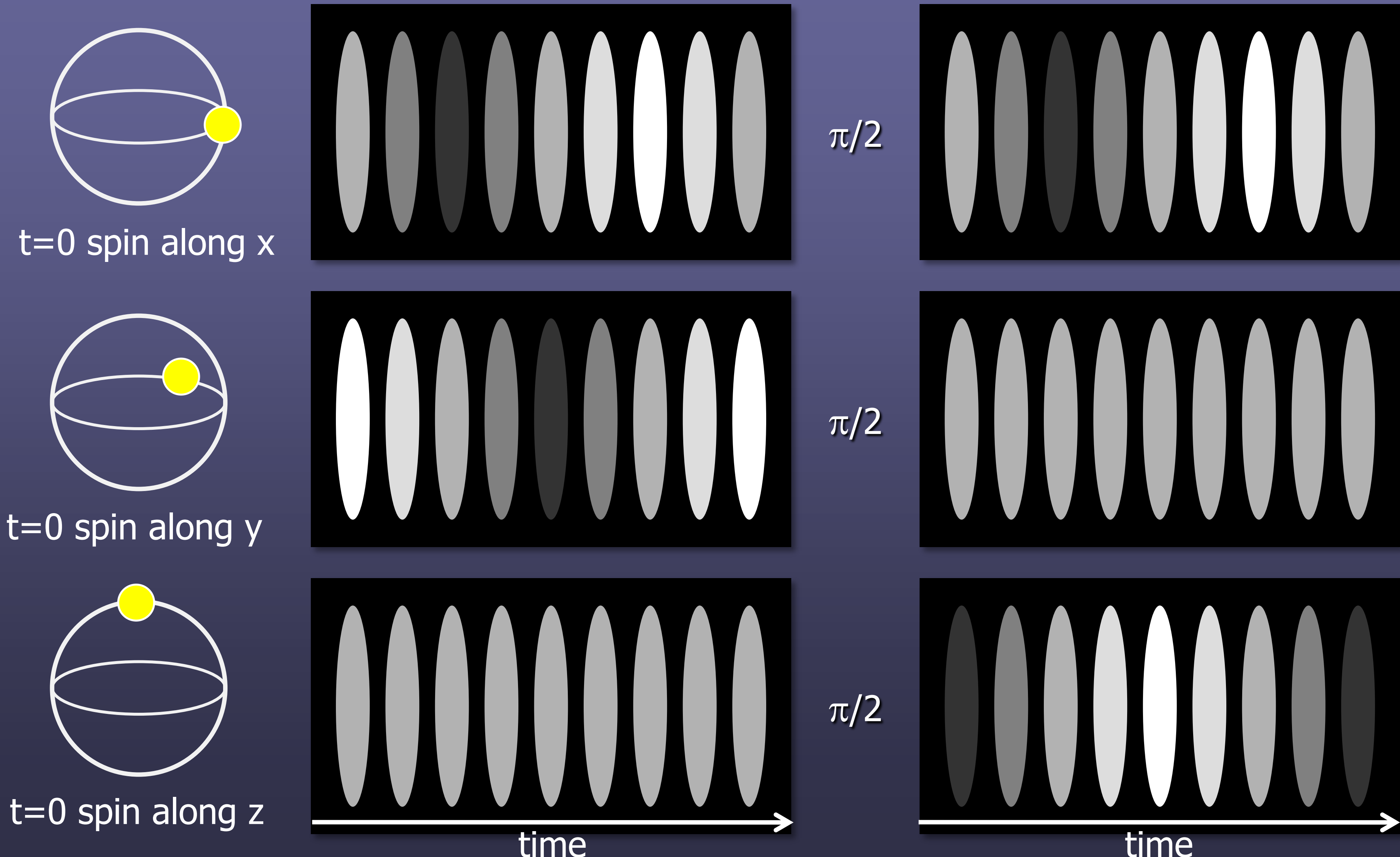
small

signal
(normalized # photons/pixel)

$$S \propto 1 + \frac{\gamma}{\Delta}\sigma_0\left[s_0 n_{2D} + s_1 n_{2D}\left\langle F_y \right\rangle + \ldots \right]$$

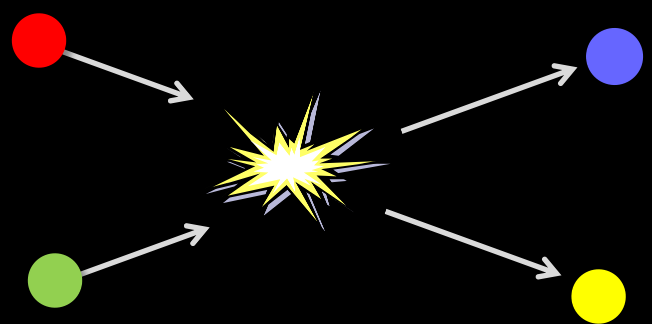
Measuring the vector spin

- Larmor precession: continuous spin rotation about z-axis
- resonant RF pulses: a $\pi/2$ spin rotation about x-axis

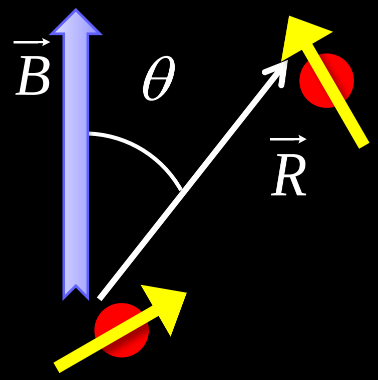


Interatomic interactions

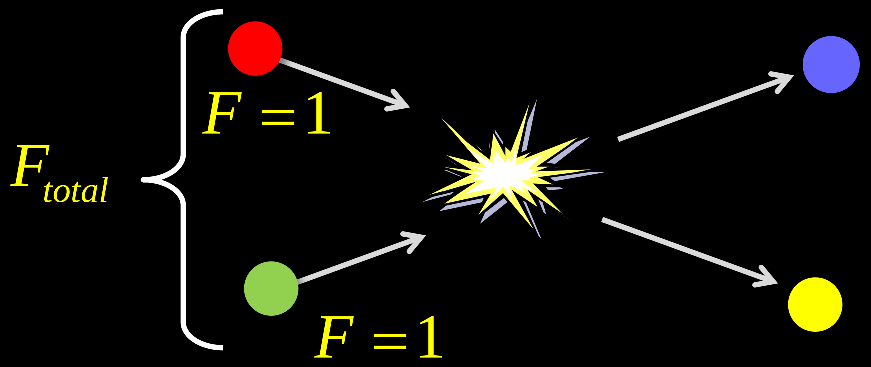
contact interactions



magnetic dipolar interactions



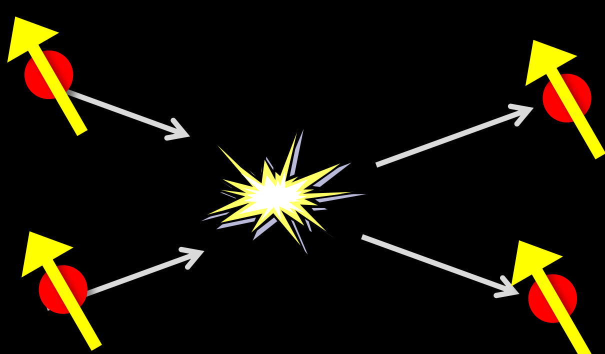
Interatomic interactions



- Low energy
  - only s-wave collisions occur
  - interactions characterized by scattering length
- Rotational symmetry: interactions depend on total spin, not its orientation

	$F_{total} = 0$	$F_{total} = 2$
^{87}Rb:	a_0 = 5.39 nm	a_2 = 5.31 nm

interactions are repulsive



slightly less repulsive
"ferromagnetic"

Energy scales in a spinor Bose-Einstein condensate

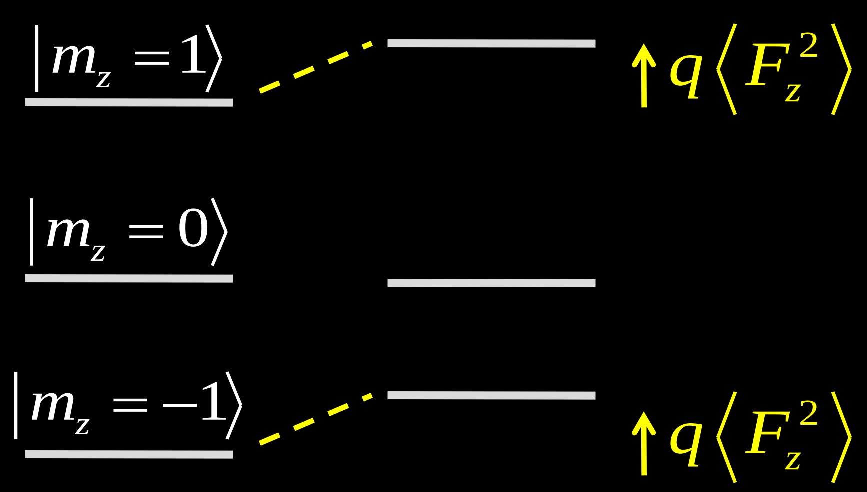
- spin-independent contact interactions

$$\mu = c_0 n \qquad \approx 2000 \text{ Hz, or } 100 \text{ nK}$$

- spin-dependent contact interactions

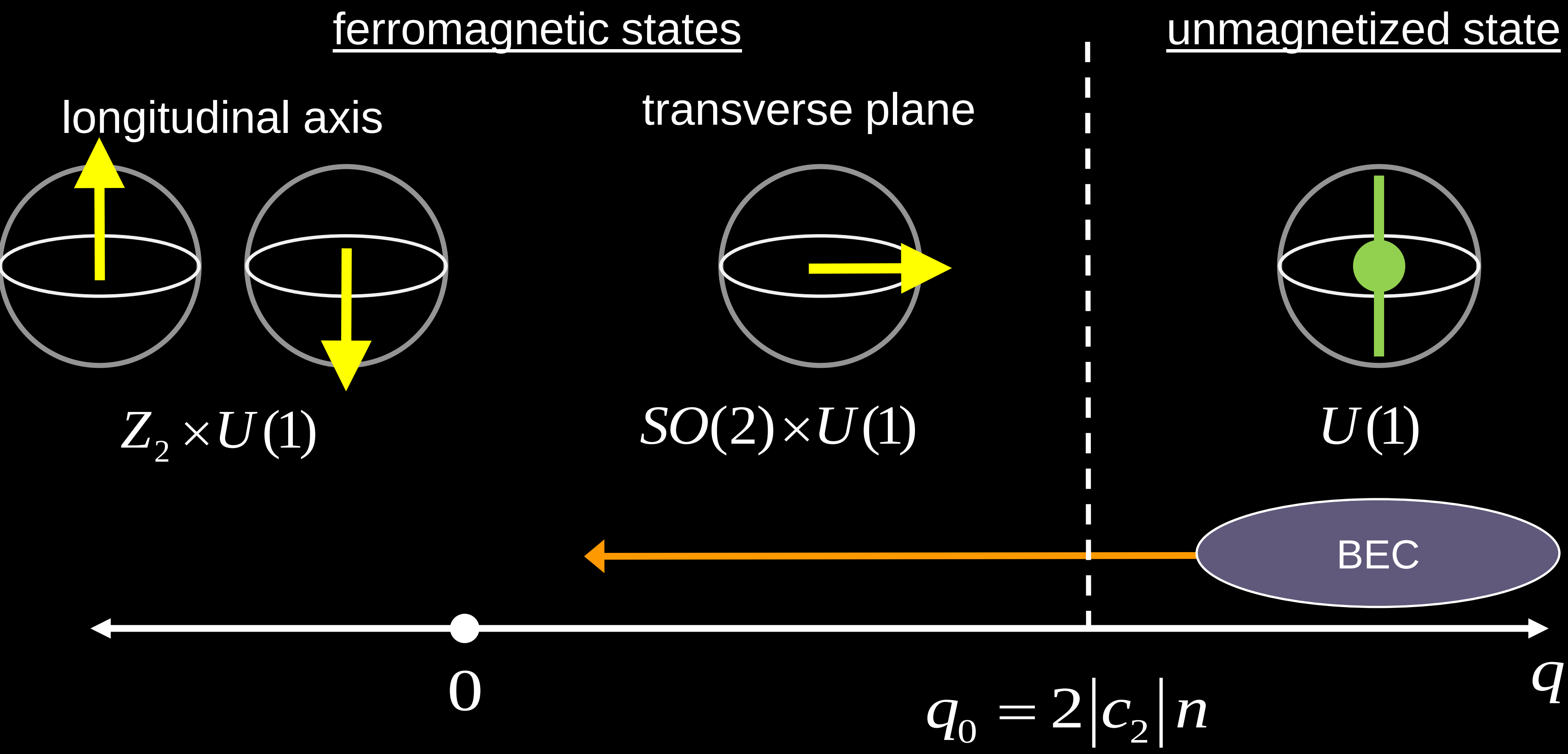
$$\Delta\mu = -|c_2| n \langle \vec{F} \rangle^2 \qquad \approx 10 \text{ Hz, or } 0.5 \text{ nK}$$

- quadratic Zeeman shift

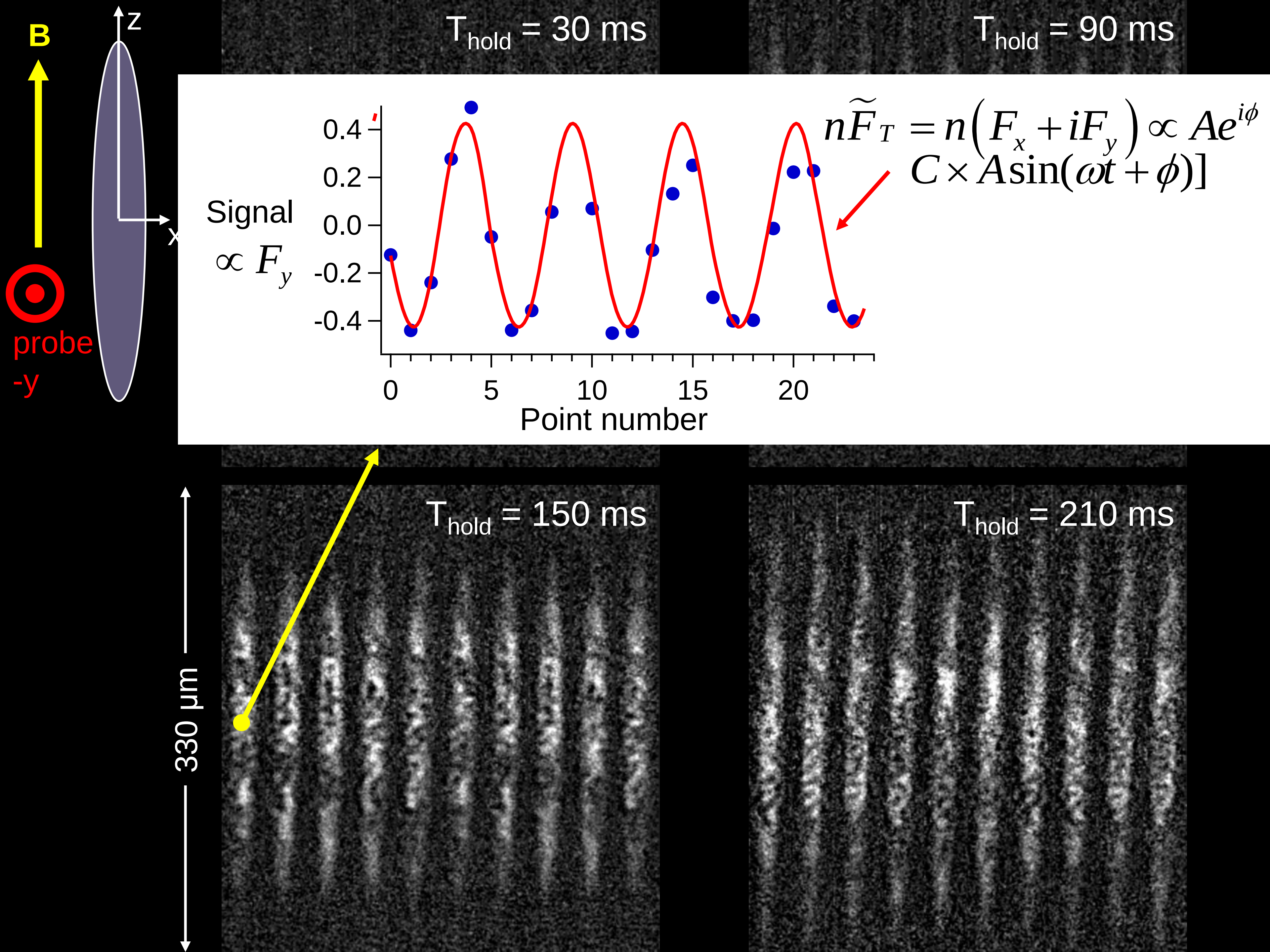


Phases and symmetries

$$E = -|c_2| n \langle \vec{F} \rangle^2 + q \langle F_z^2 \rangle$$



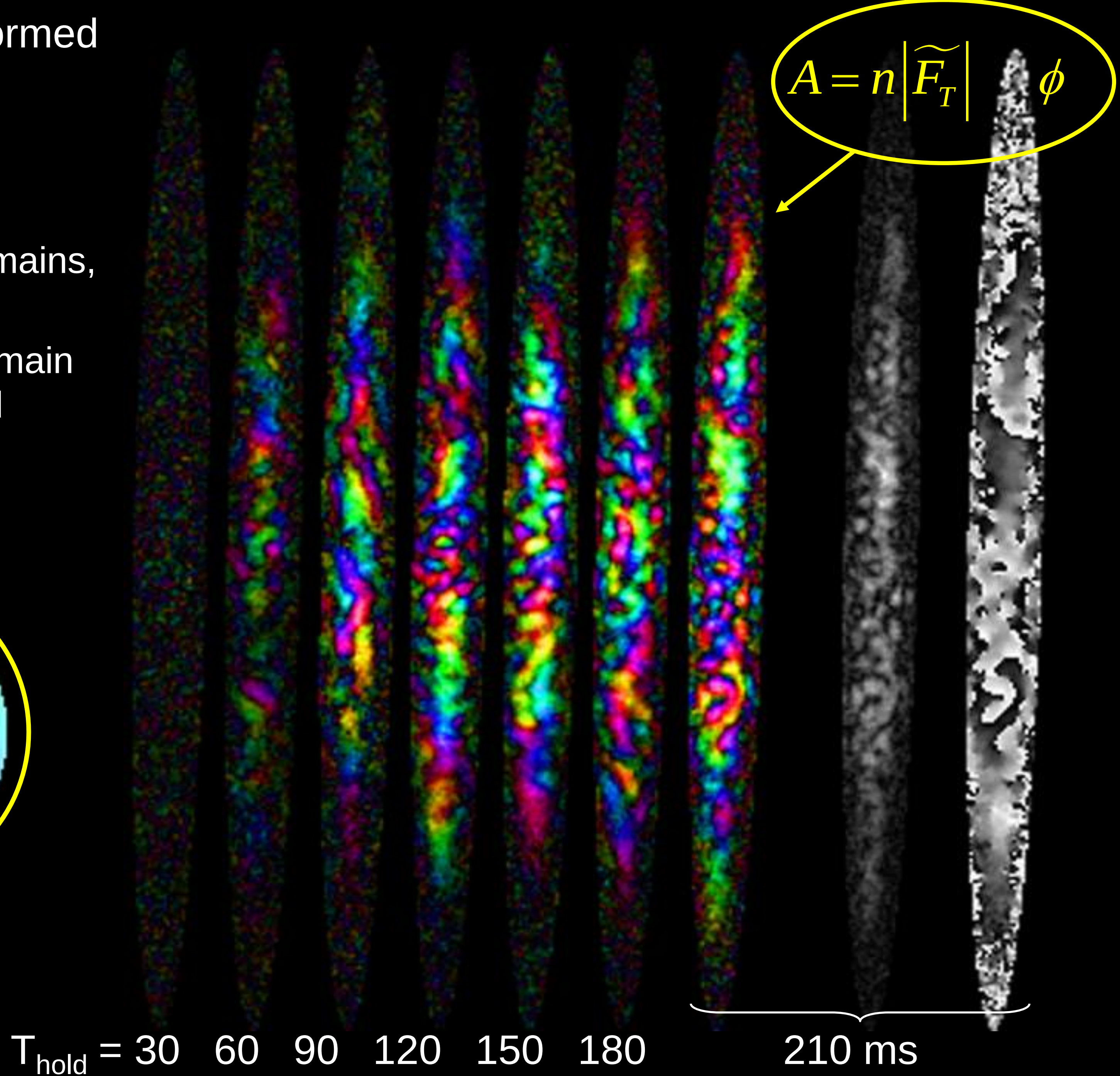
Non-equilibrium (quantum) dynamics at a (quantum) phase transition



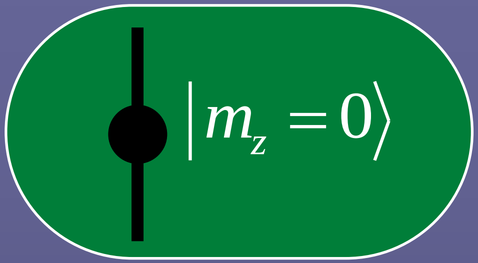
B
z
x
probe
-y
T_hold = 30 ms
T_hold = 90 ms
T_hold = 150 ms
T_hold = 210 ms
330 μm
Signal
∝ F_y
0.4
0.2
0.0
-0.2
-0.4
0
5
10
15
20
Point number
$n\widetilde{F}_T = n(F_x + iF_y) \propto Ae^{i\phi}$
$C \times A\sin(\omega t + \phi)]$

Spontaneously formed ferromagnetism

- inhomogeneously broken symmetry
- ferromagnetic domains, large and small
- unmagnetized domain walls marking rapid reorientation



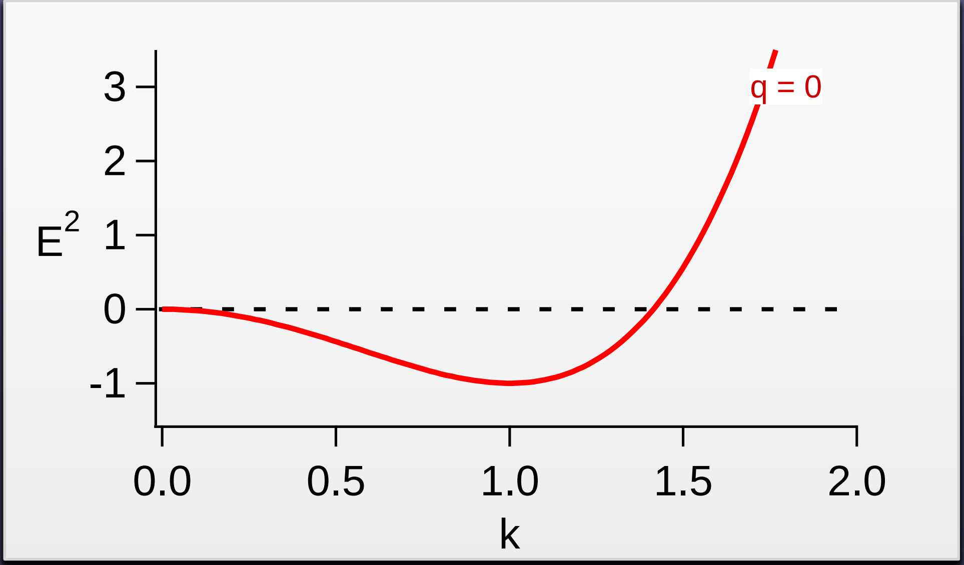
Spectrum of stable and unstable modes



- Bogoliubov spectrum
  - Gapless phonon (m=0 phase/density excitation)
  - Spin excitations

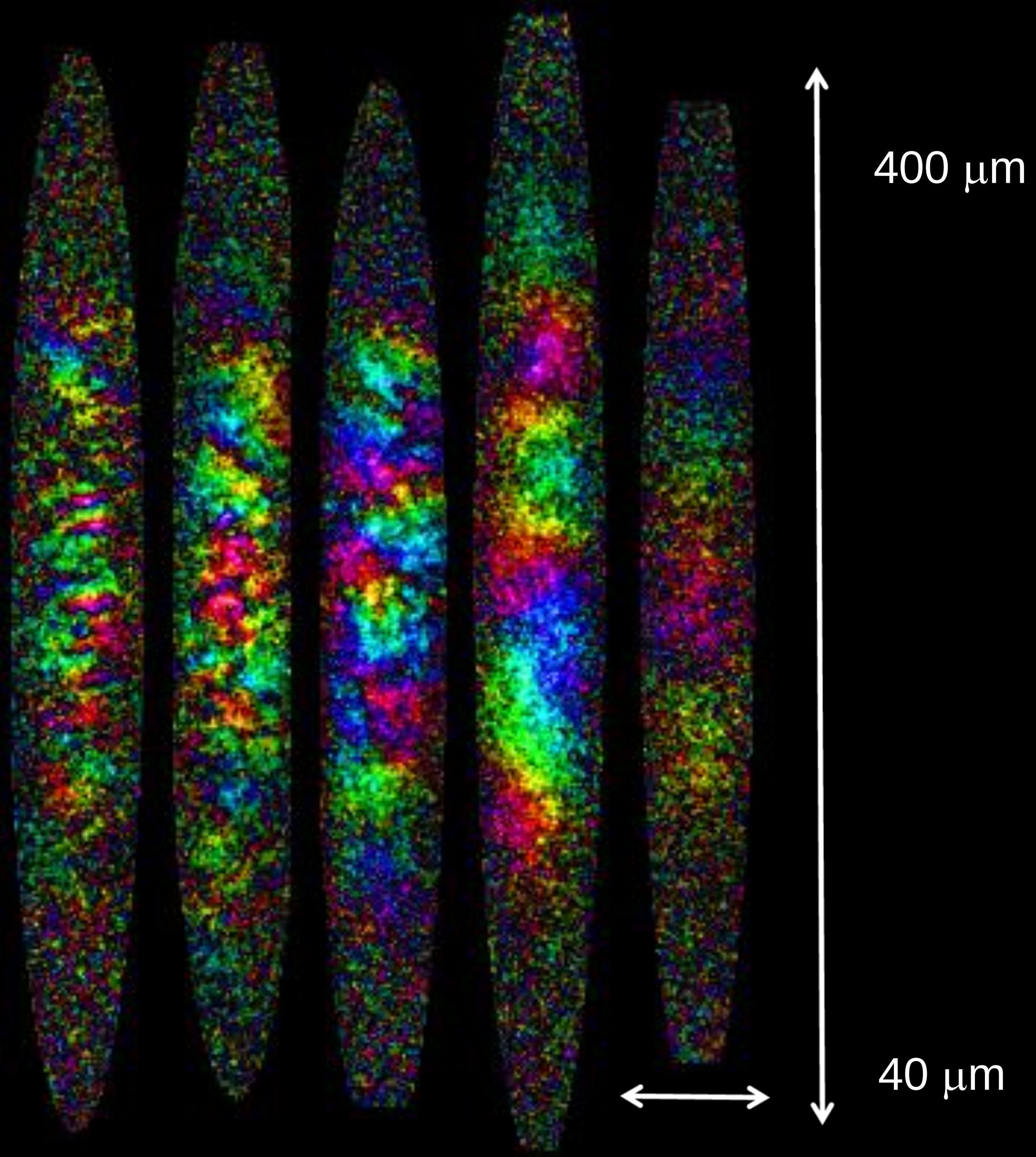
$$E_S^2 = (k^2 + q)(k^2 + q - 2)$$

Energies scaled by $c_2 n$



q>2:	spin excitations are gapped by $\sqrt{q(q-2)}$
1>q>2:	broad, "white" instability
0>q>1:	broad, "colored" instability
q<0:	sharp instability at specific q≠0

Tuning the amplifier

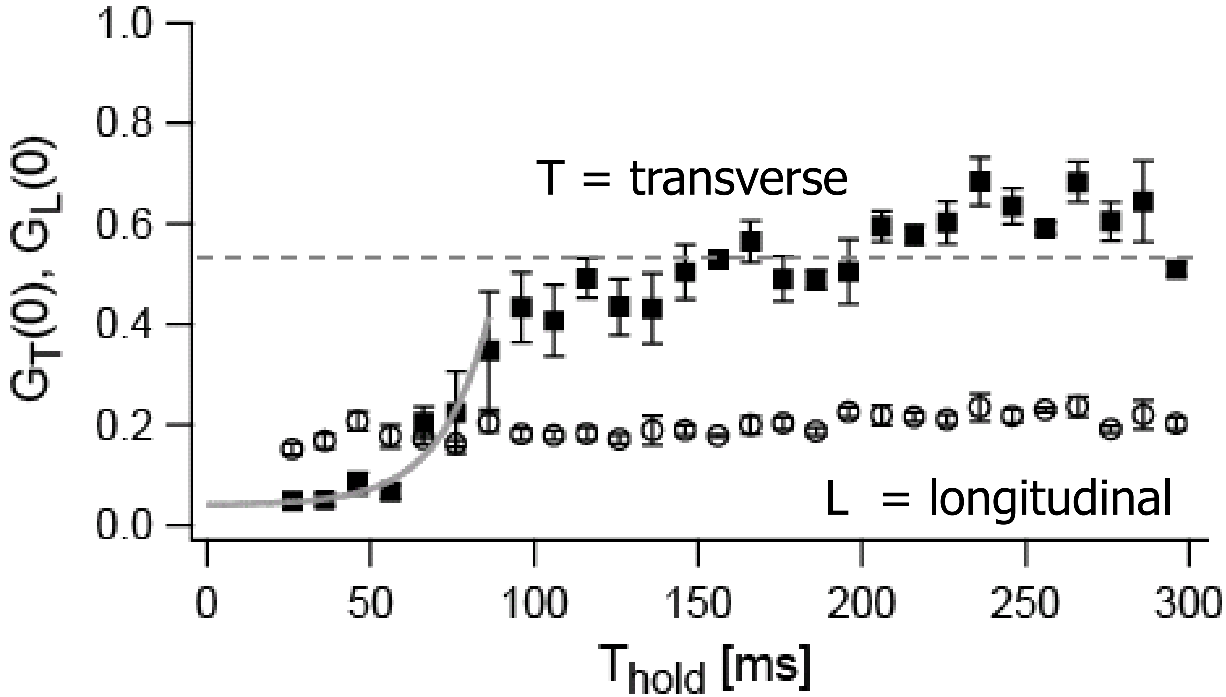


Hold time= 170 ms

Quench end point q = -2 Hz 0Hz 2 Hz 5 Hz 10 Hz

$$G(\delta r) = \frac{\sum_r n\vec{F}(r+\delta r) \bullet n\vec{F} n(r)}{\sum_r n(r+\delta r) n(r)}$$

spin-spin correlation function

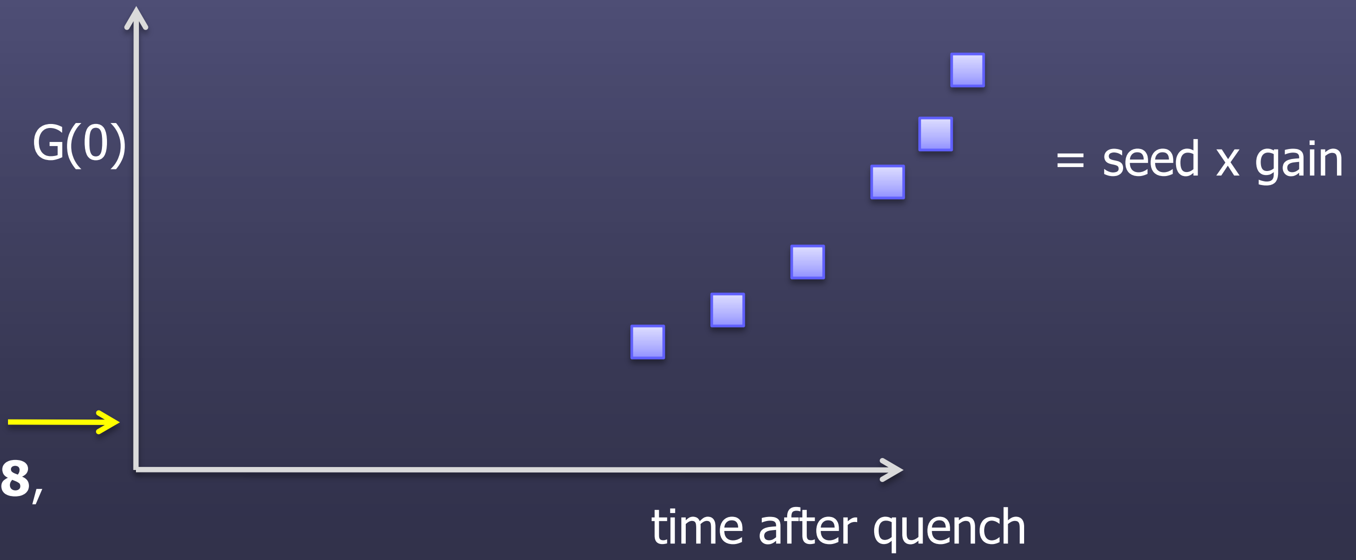


measure of area of domain walls

“Spontaneous symmetry breaking in a quenched ferromagnetic spinor BEC,” Nature 443,312 (2006)

Quantum aspects of spontaneous magnetization

- mean-field theory
  - atomic gas treated as a classical field (like classical E+B fields)
  - predicts dynamical instability – non-zero magnetization will grow
  - does not explain symmetry breaking – whence non-zero magnetization?
- quantum-field theory
  - includes quantum fluctuations
  - fluctuations provide symmetry-breaking seed

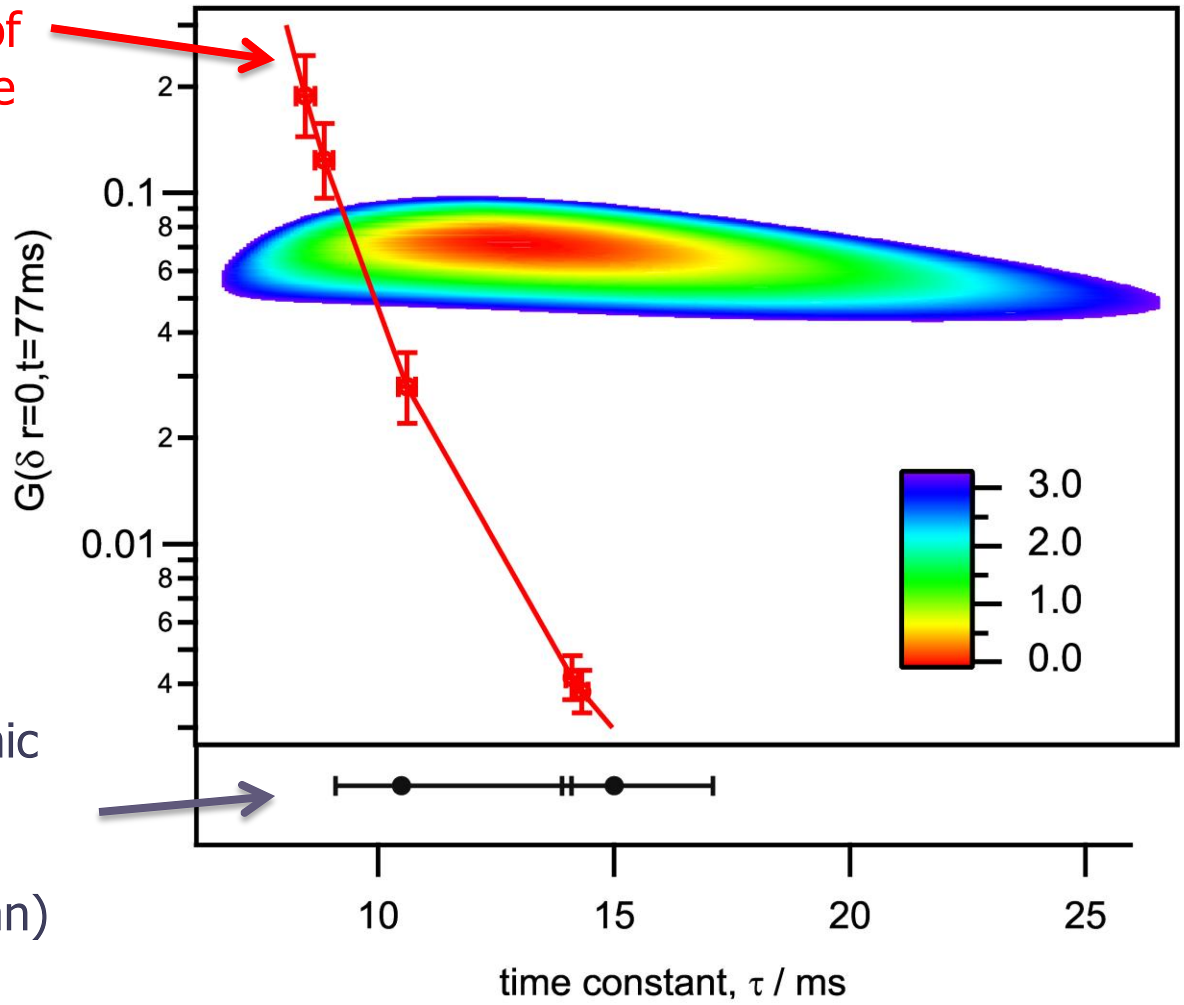


quantify seed by extrapolation

Lamacraft, PRL **98**, 160404 (2007)

Amplification of spin fluctuations

calculated amplification of quantum noise

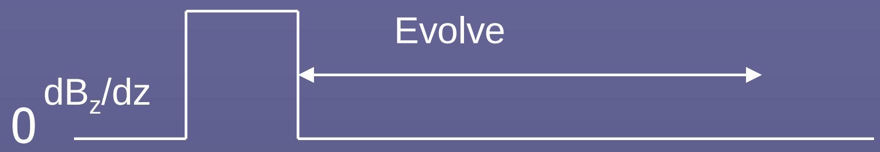


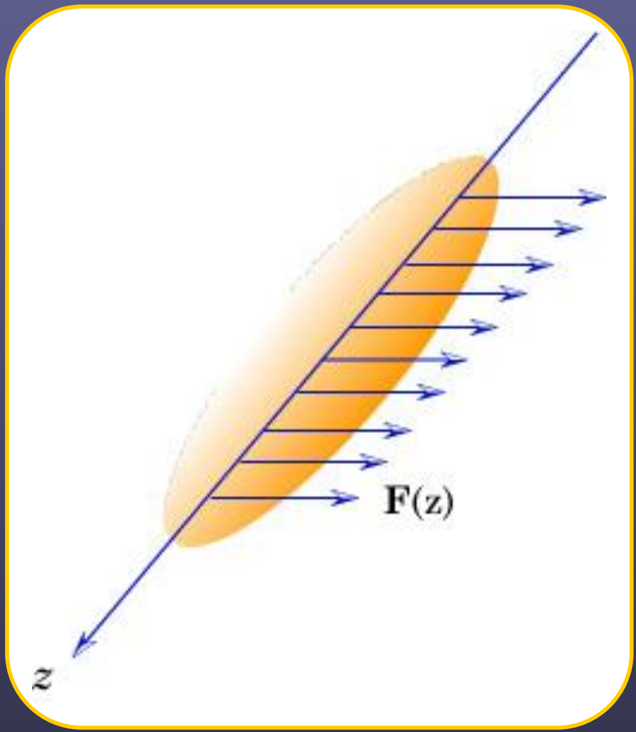
related to atomic scattering properties (Bloch, Chapman)

noise is (nearly) quantum noise
amplifier is (nearly) quantum-limited (@30dB gain)

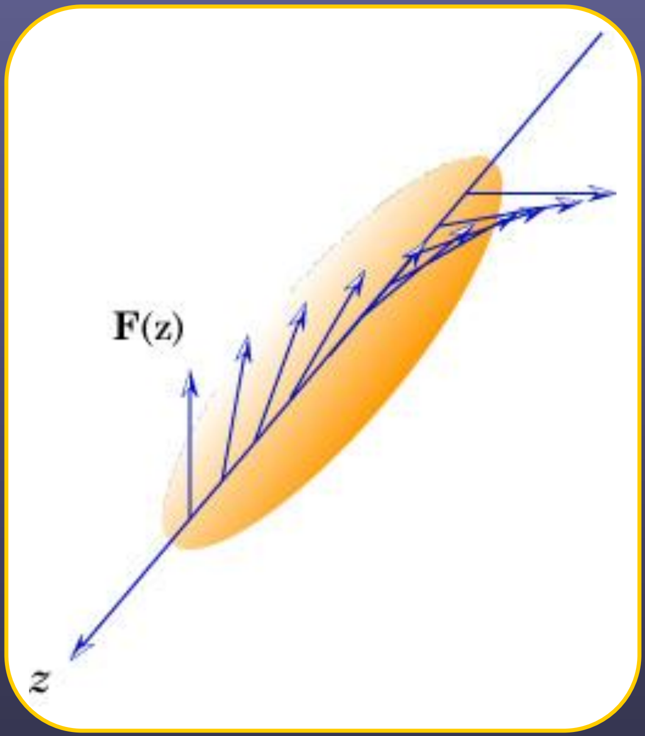
Ferromagnetic spin textures

- generate helical spin pattern (uniform spin current) using inhomogeneous field





w/o gradient
zero-wavevector helix



with gradient
non-zero-wavevector helix

Ferromagnetic spin textures

energy budget:

- spin-dependent contact interaction:

$$-|c_2| n \left| \langle \vec{F} \rangle \right|^2$$

~ - 0.5 nK, minimized

- quadratic Zeeman shift:

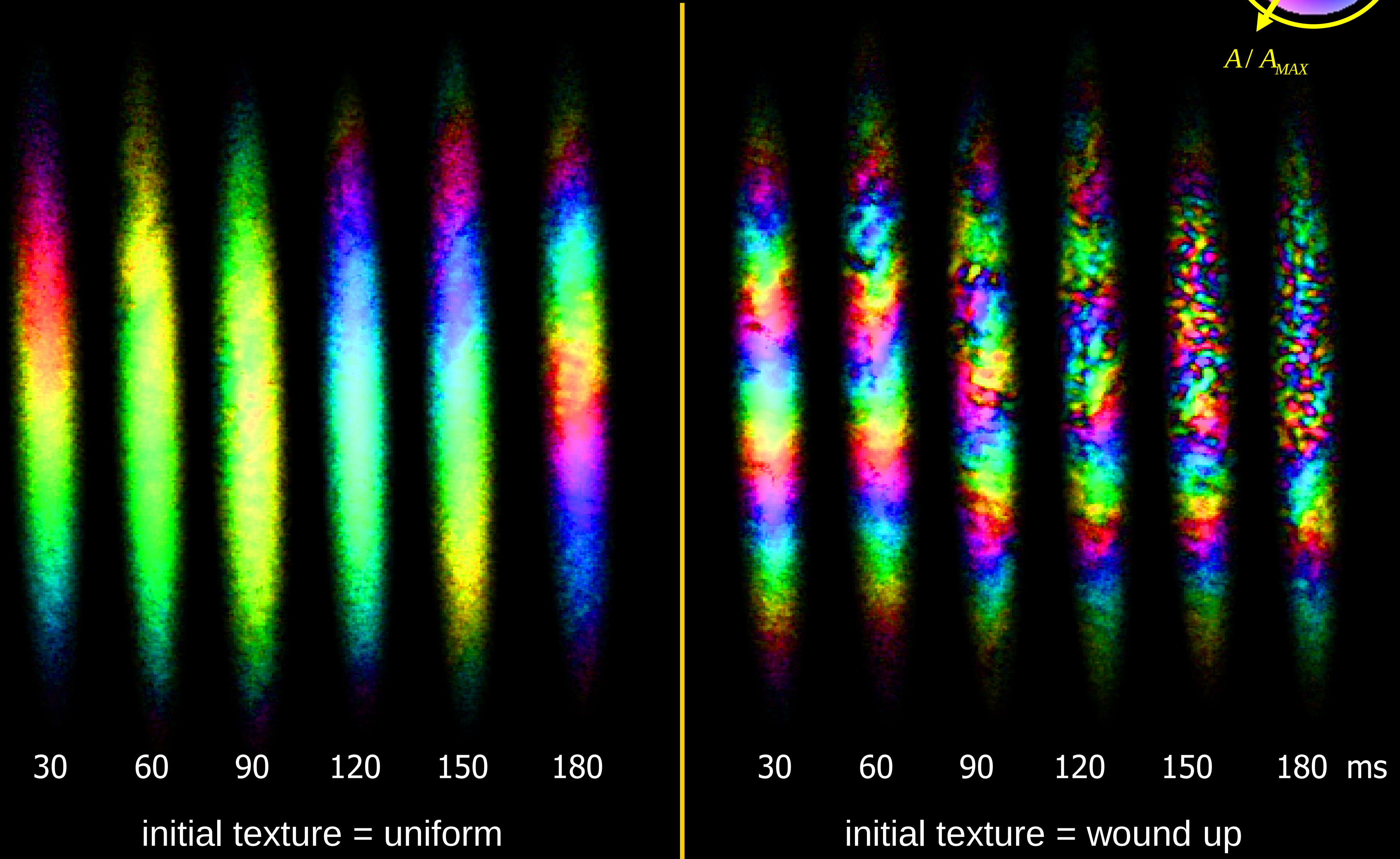
$$q F_z^2 = \frac{q}{2}$$

excess ~ 30 pK; λ = 60 μm

- spin current kinetic energy

λ ≥ 50 μm   ν ≤ 1 Hz

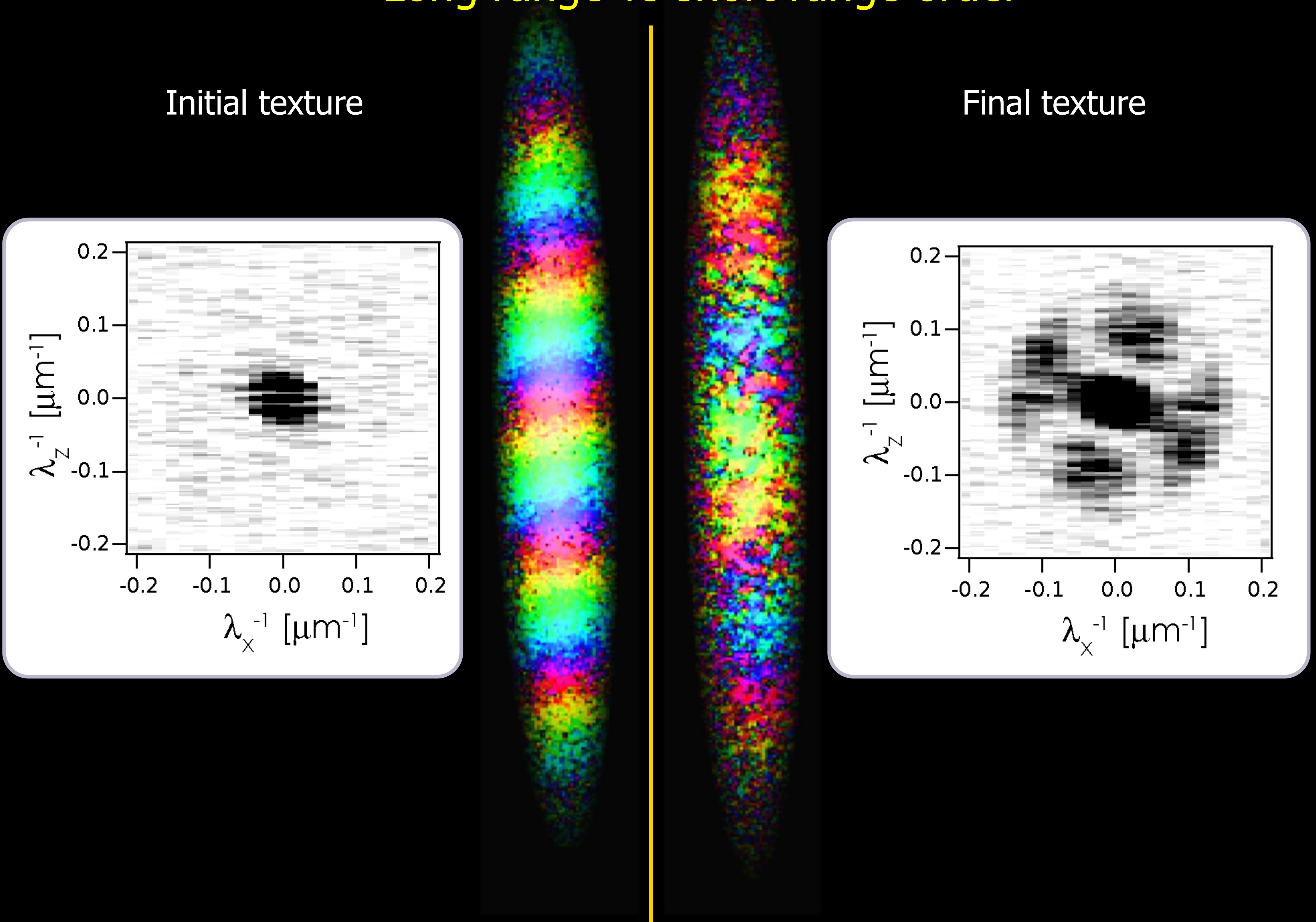
Dissolving spin textures



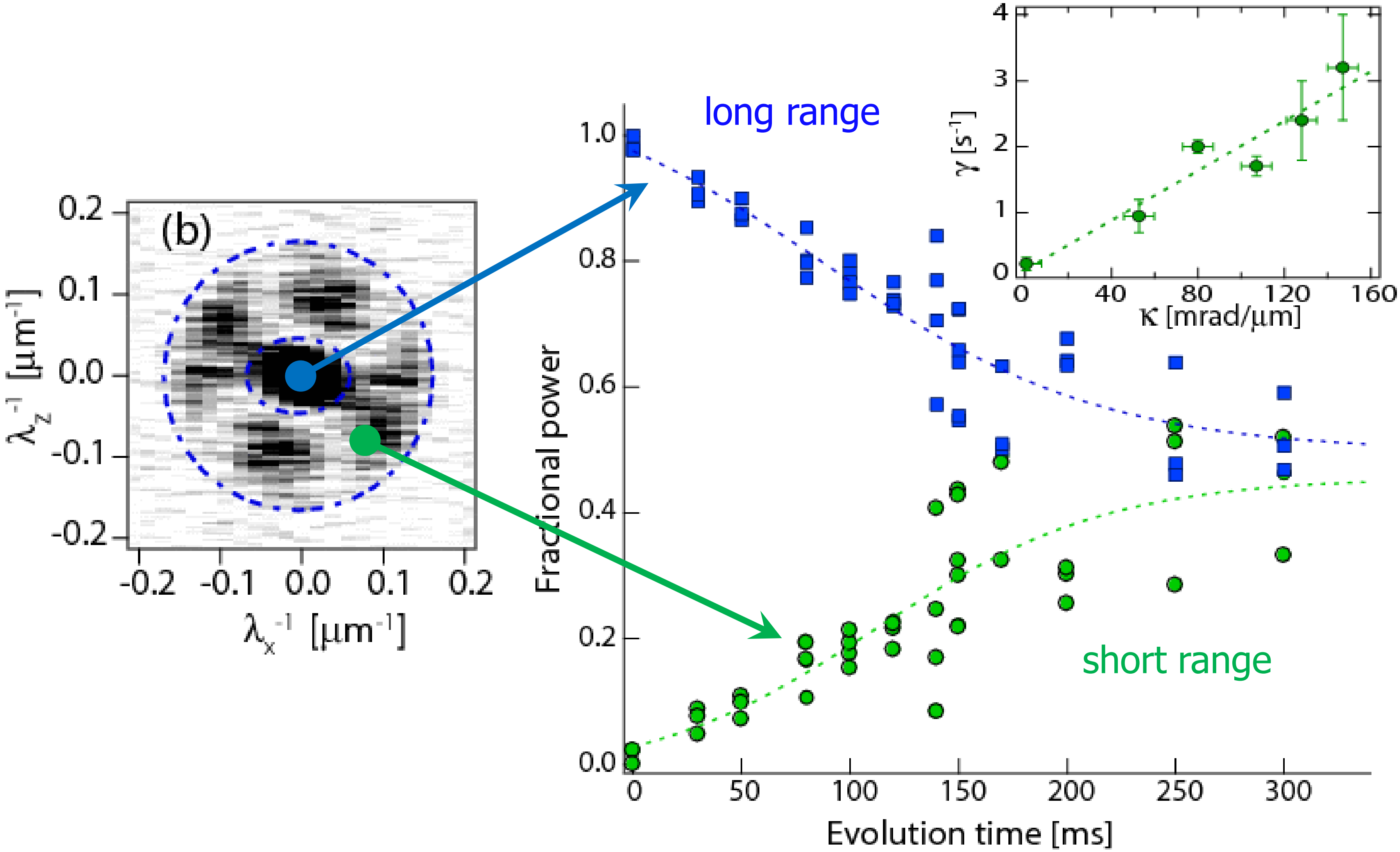
Long range vs short range order

Initial texture

Final texture



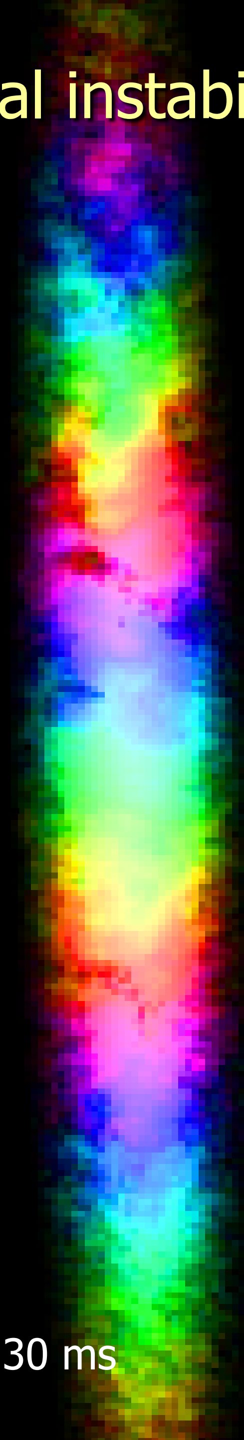
Long range vs short range order



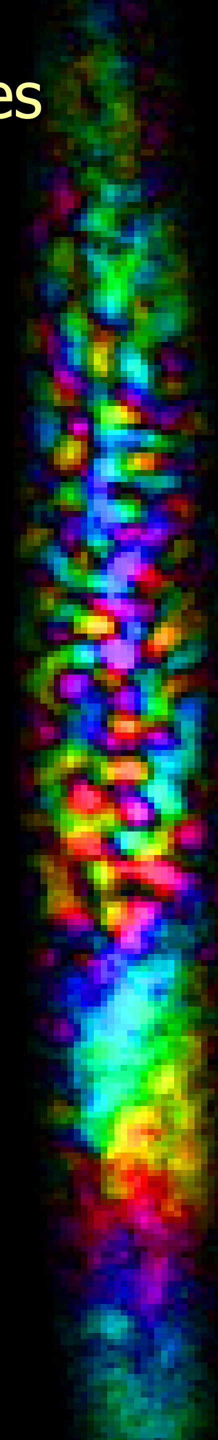
Possible role of dynamical instabilities

- Lamacraft, Demler et al.:
  (arXiv:0710.1848, arXiv:0710.2499)
  - spiral state is dynamically unstable

- But, where did the energy come from?

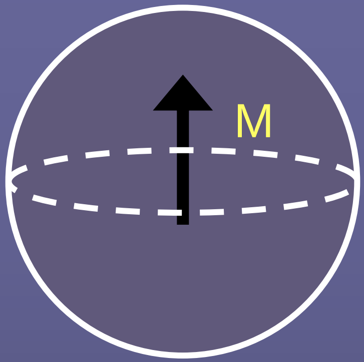


30 ms



180 ms

Dipolar interactions: magnetism in a quantum fluid



		@ 3 10^{14} cm^{-3}
self-field:	$B \approx \mu_0 M = (\mu_0 g_F \mu_B) n$	17 μG
energy per particle:	$U_d = (\mu_0 g_F^2 \mu_B^2) n$	h x 12 Hz

- Comparison to other energy scales:
  - total interaction energy: μ ~ h x 2000 Hz

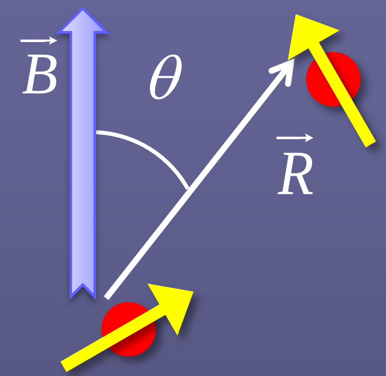
$\Rightarrow$ Pfau, Santos, Lewenstein, others: ^{52}Cr (6 μ_B), polar molecules (>137 μ_B)

  - spin-dependent interaction energy: μ ~ h x 12 Hz

$\Rightarrow$ Yi and Pu, PRL 97, 020401 (2006); Kawaguchi, Saito, Ueda PRL 97, 130404 (2006)

$\Rightarrow$ ^{87}Rb is an essentially dipolar spinor quantum fluid

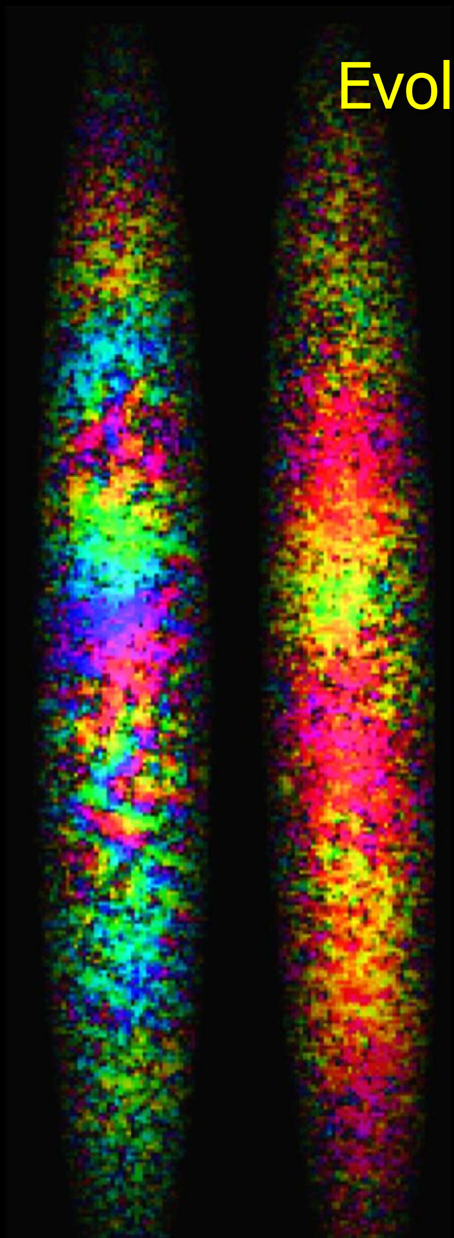
tempering dipolar interactions

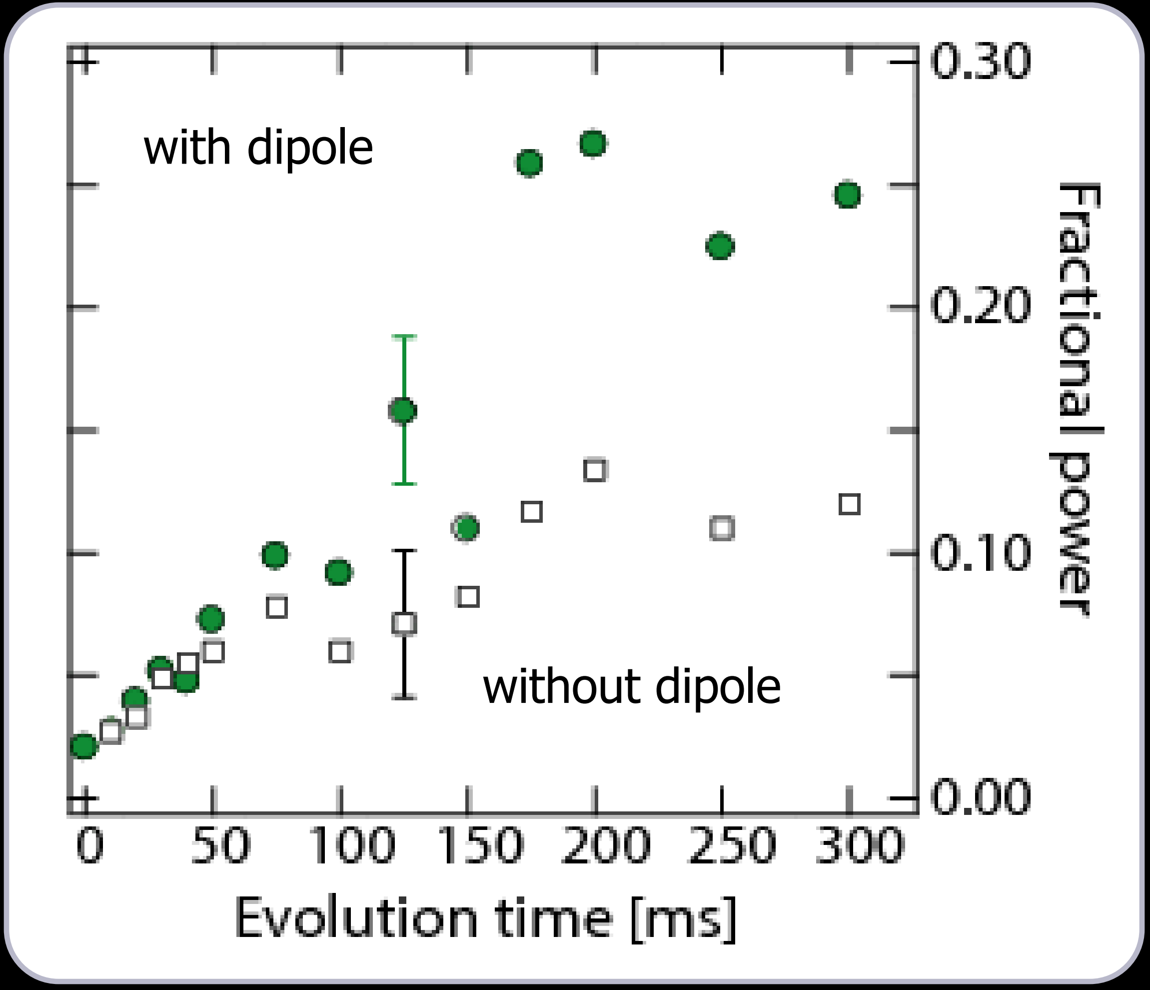


$$U = -J\left(\frac{3}{2}\cos^2\theta - \frac{1}{2}\right)\left[F_{1,z}F_{2,z} - \frac{1}{2}\left(F_{1,x}F_{2,x} + F_{1,y}F_{2,y}\right)\right]$$

- Magic angle spinning (hard for us)
- Stochastic spin-flip narrowing: repeated RF ($\pi/2$) pulses with random phase (easy for us)

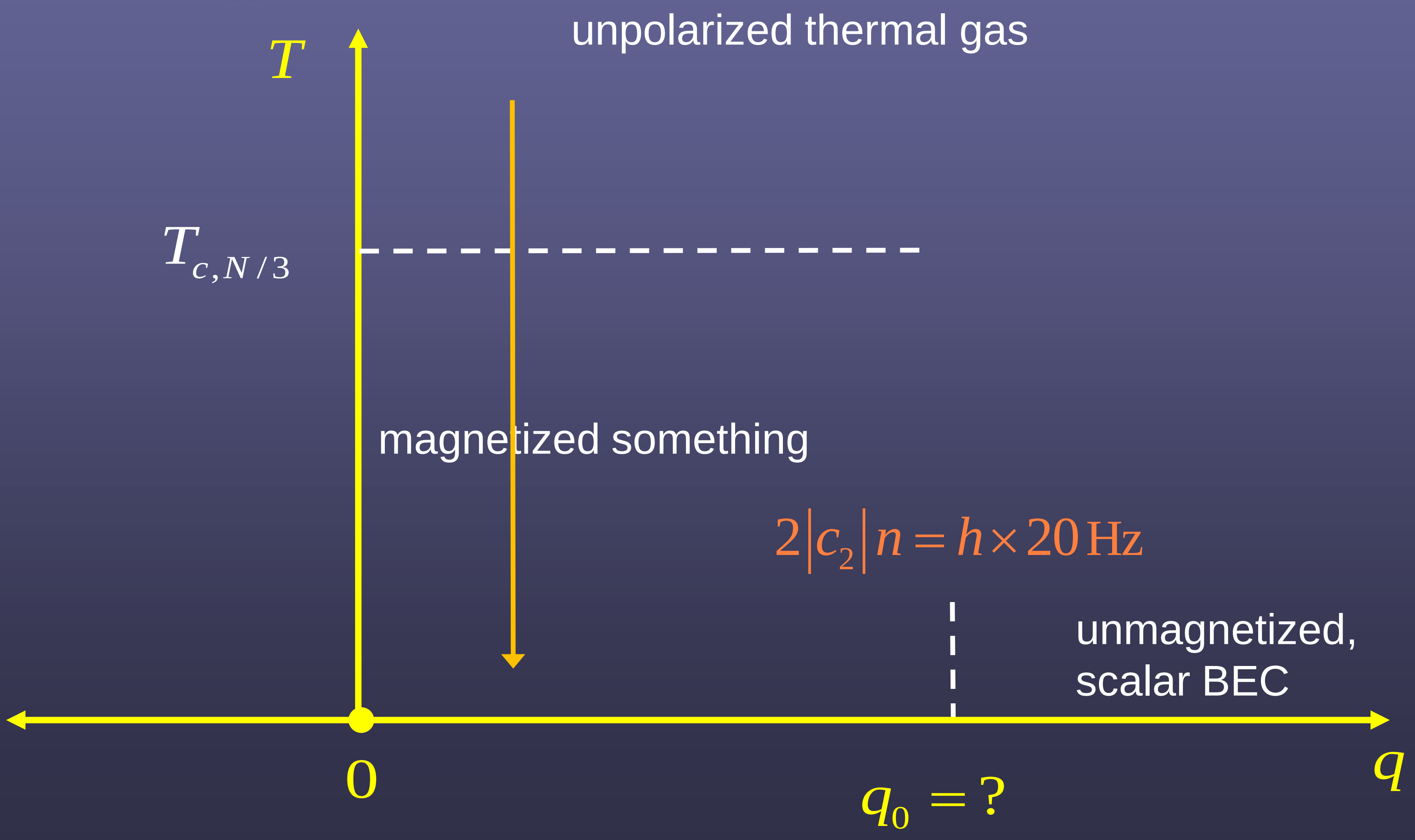
Evolution with/without dipolar interactions



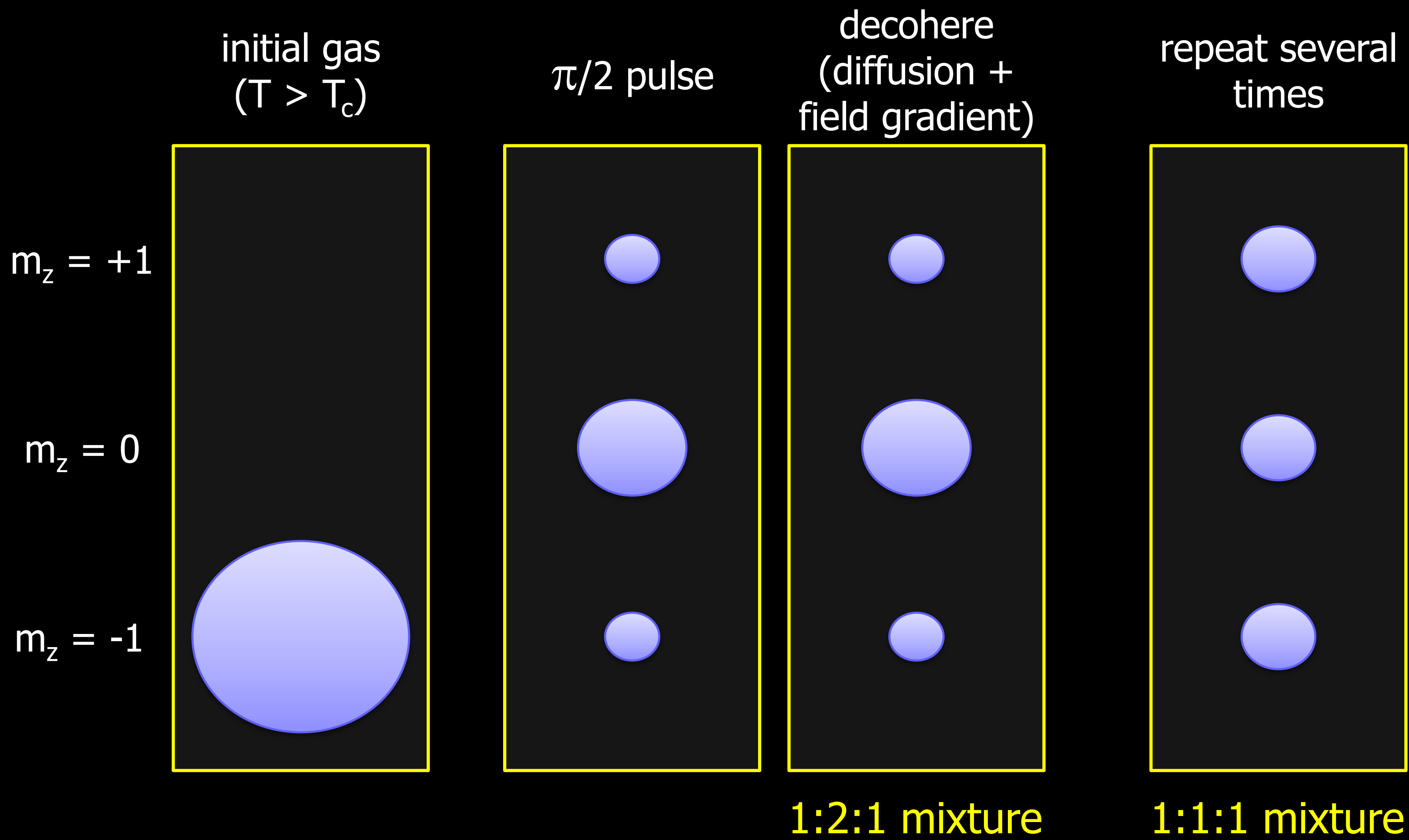


F=1 ^{87}Rb gas at thermal equilibrium

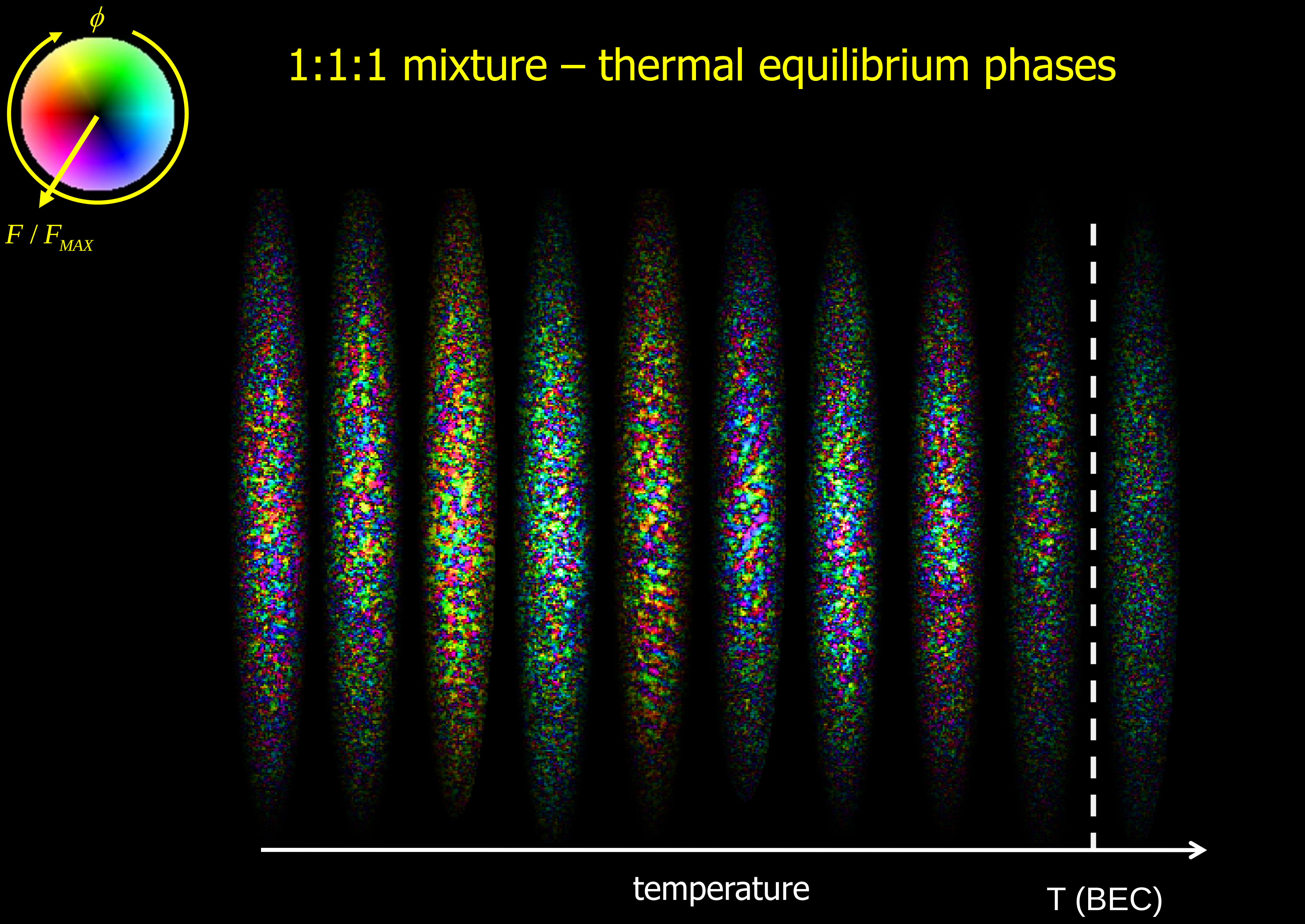
- prepare fully depolarized thermal gas in uniform magnetic field
- lower temperature
- what happens?



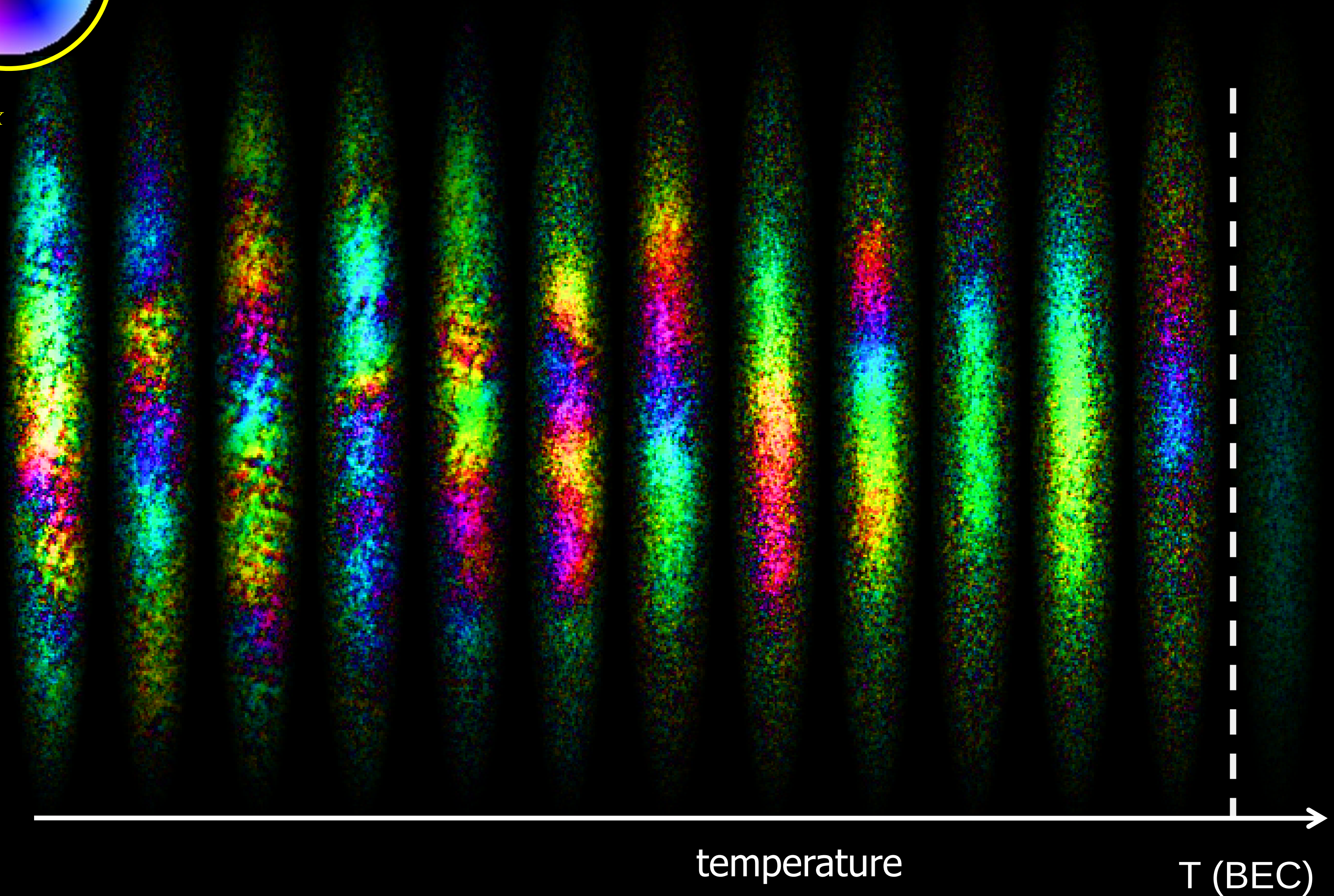
preparing unmagnetized gases



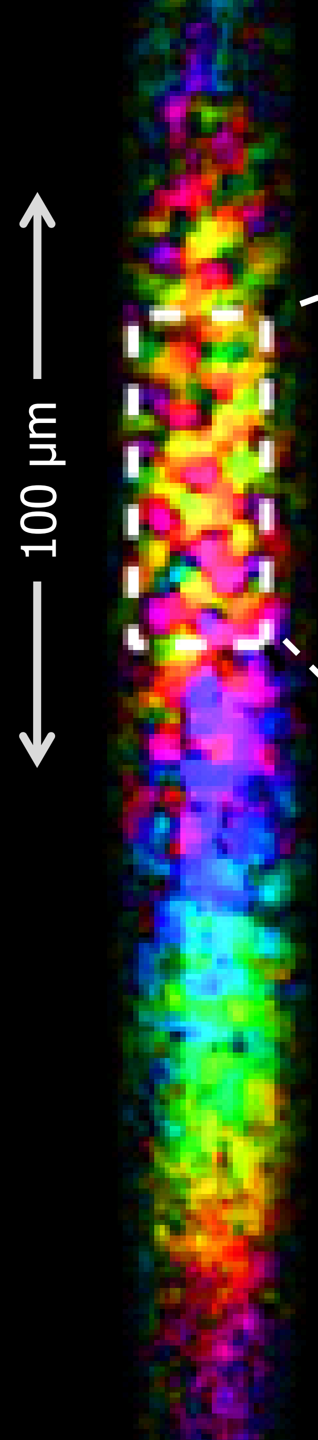
1:1:1 mixture – thermal equilibrium phases

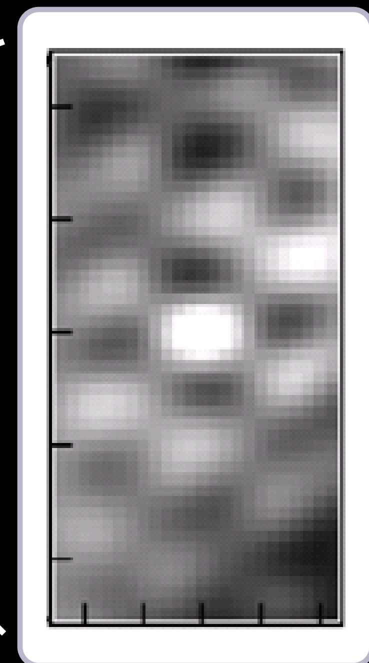


1:2:1 mixture – thermal equilibrium phases



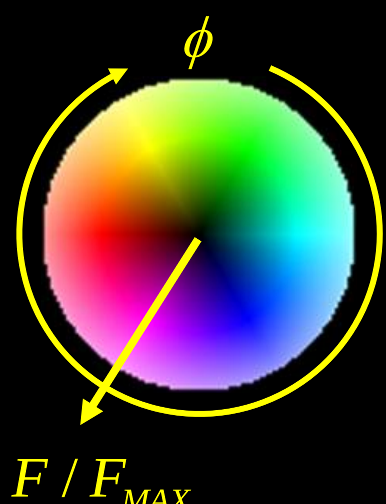
Low temperature phase of F=1 ^{87}Rb: spatial correlations





spin-spin correlation

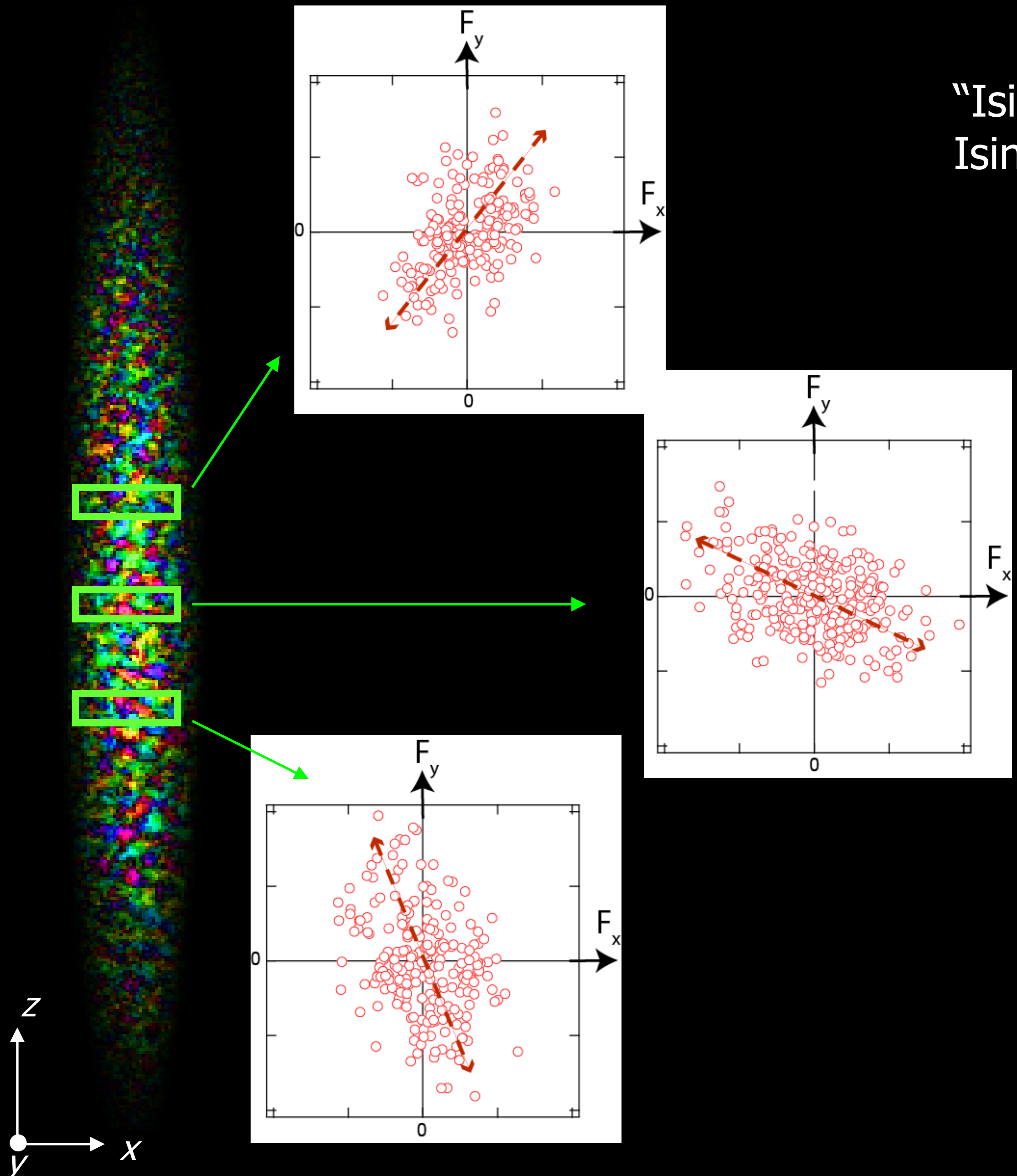
$$G_{tot}(\delta r) = \frac{\sum_r n\vec{F}(r+\delta r) \bullet n\vec{F}(r)}{\sum_r n(r+\delta r)\, n(r)}$$

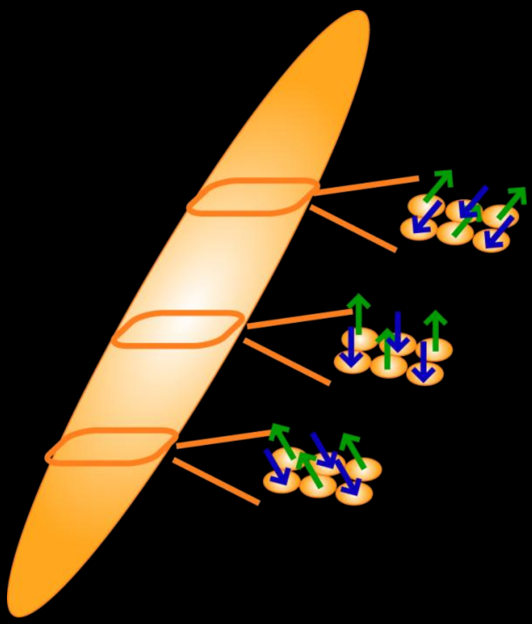


Crystalline order!?

theory ideas from Joel Moore, Dung-Hai Lee, Ashvin Vishwanath, Jason Ho

"Ising-like" lattice
Ising axis varies across cloud





E1: Spinor BEC
Jennie Guzman
Sabrina Leslie
Christopher Smallwood
Mukund Vengalattore
(James Higbie)
(Lorraine Sadler)

E2,E3: Cavity QED
Thierry Botter
Daniel Brooks
Joseph Lowney
Zhao-Yuan Ma
Kater Murch
Tom Purdy
(Kevin Moore)
(Subhadeep Gupta)

E4: Ring-trap interferometry
Joanne Daniels
Ed Marti
Ryan Olf
Tony Oettl
Enrico Vogt
Tiger Wu

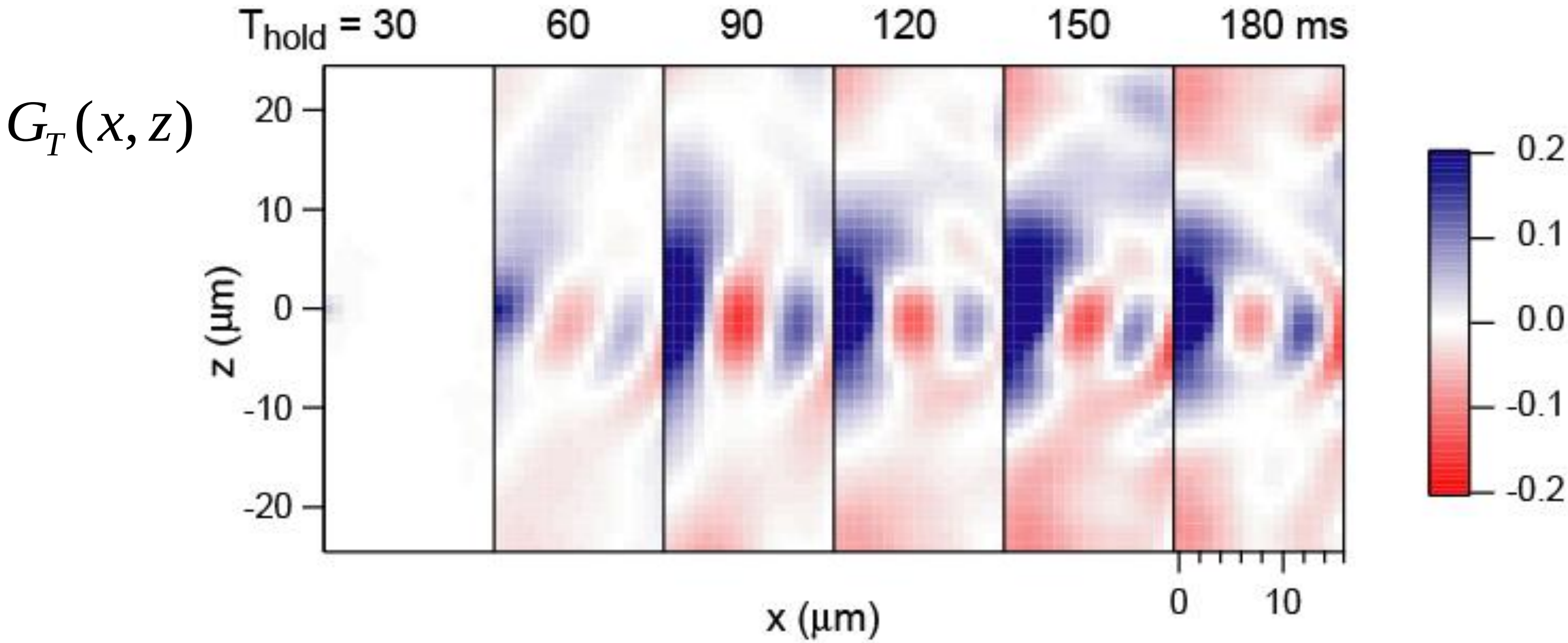
gBECi
Guided BEC Interferometry

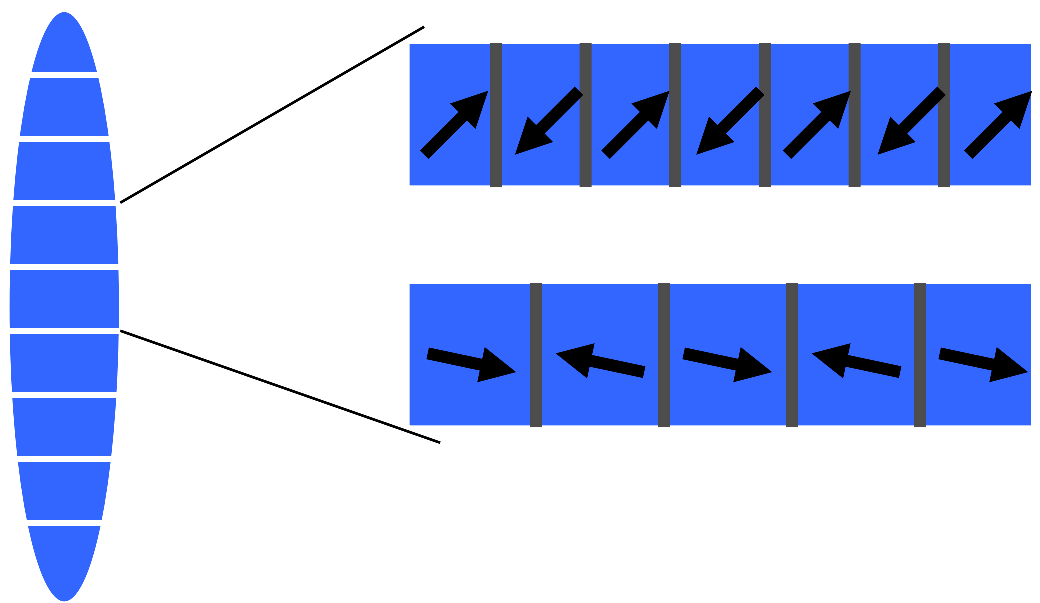
OPTICAL LATTICE EMULATOR OLE

BERKELEY LAB

Open questions – future directions

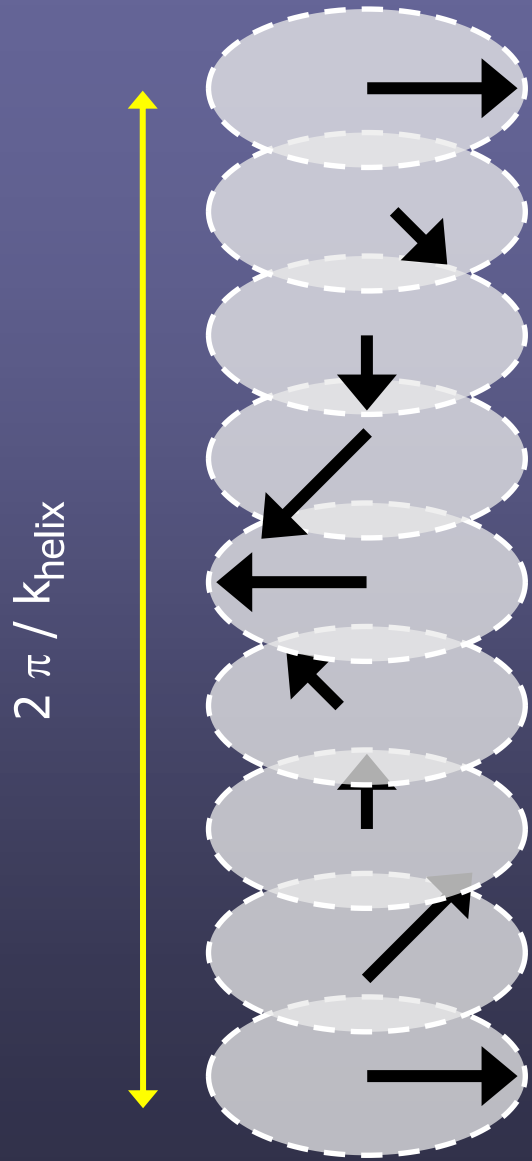
- Complete phase diagram of ^{87}Rb spin-1 gas
  - q, T, magnetization (F_z), dimensionality
- Spin lattice
  - better characterization of structure, domain boundaries, vortices?
  - superfluid?
- Phase transitions, quantum and thermal
  - quantum atom optics
  - critical phenomena
- Spinor gas magnetometry
  - surpass atomic shot noise; spatially resolved spin squeezing
- Strongly correlated systems: quantum magnetism in optical lattices
  - collaboration w/Moore, Vishwanath + others

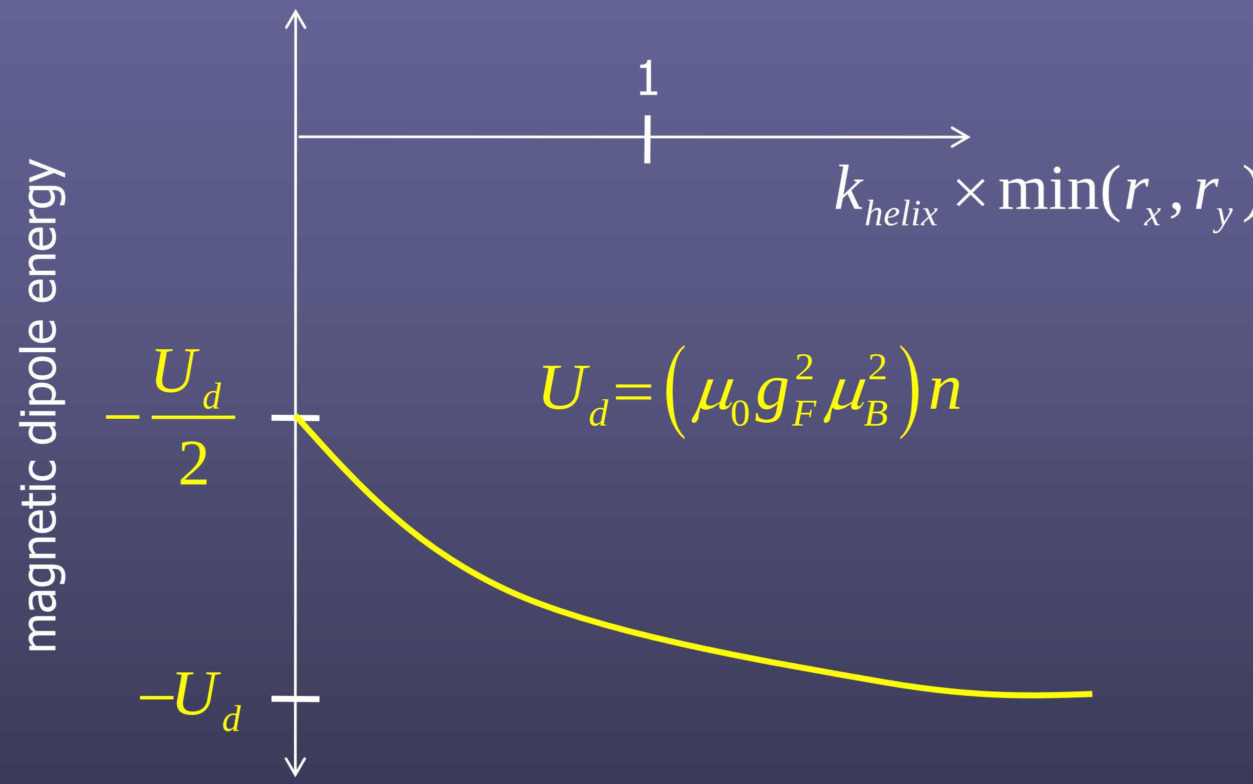


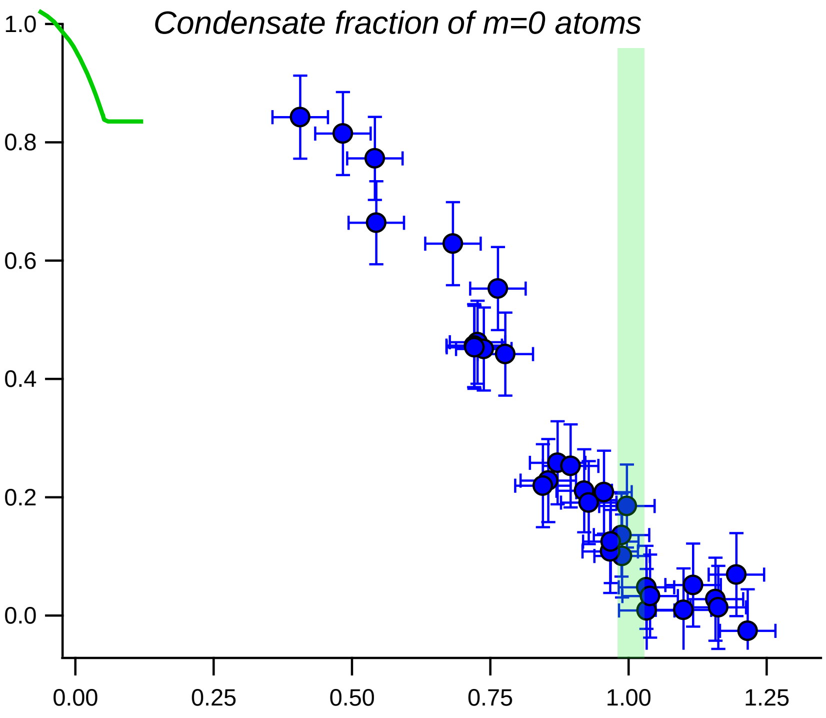


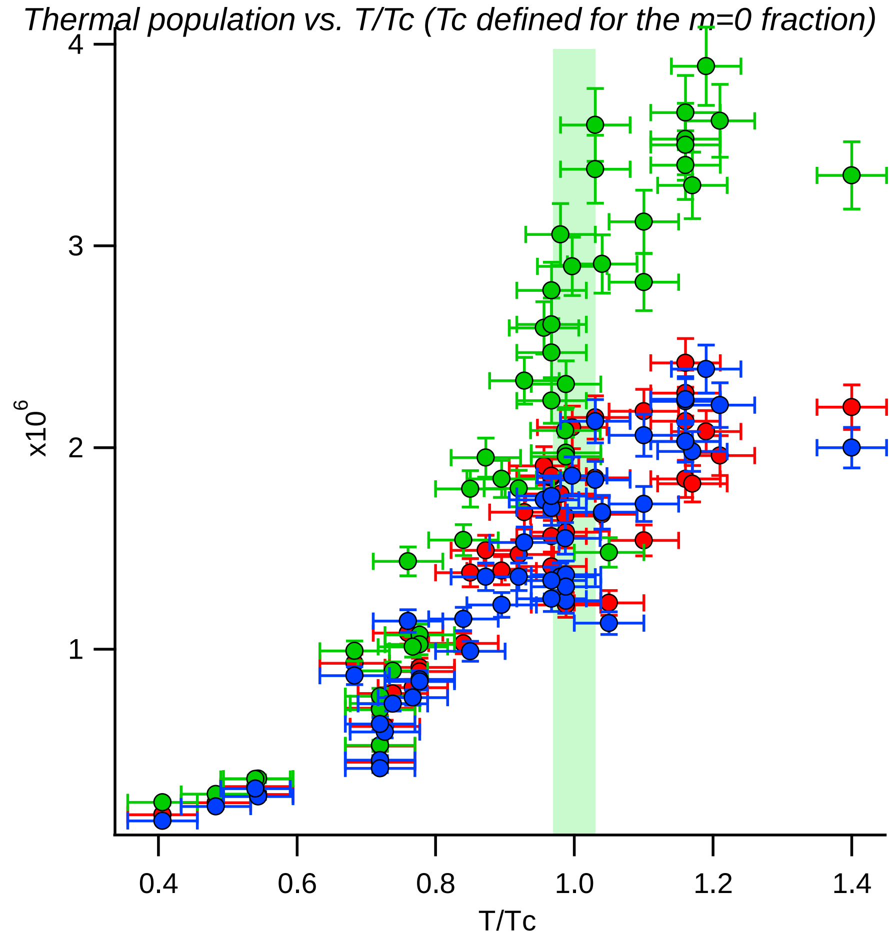
phase separation
occurs/symmetry broken
spontaneously
in disconnected radial
bands

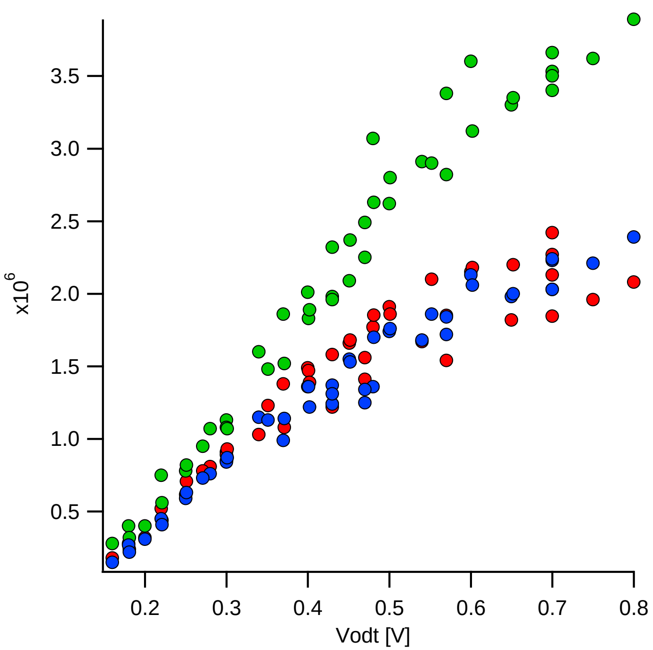
Dipolar interactions in the spin helix



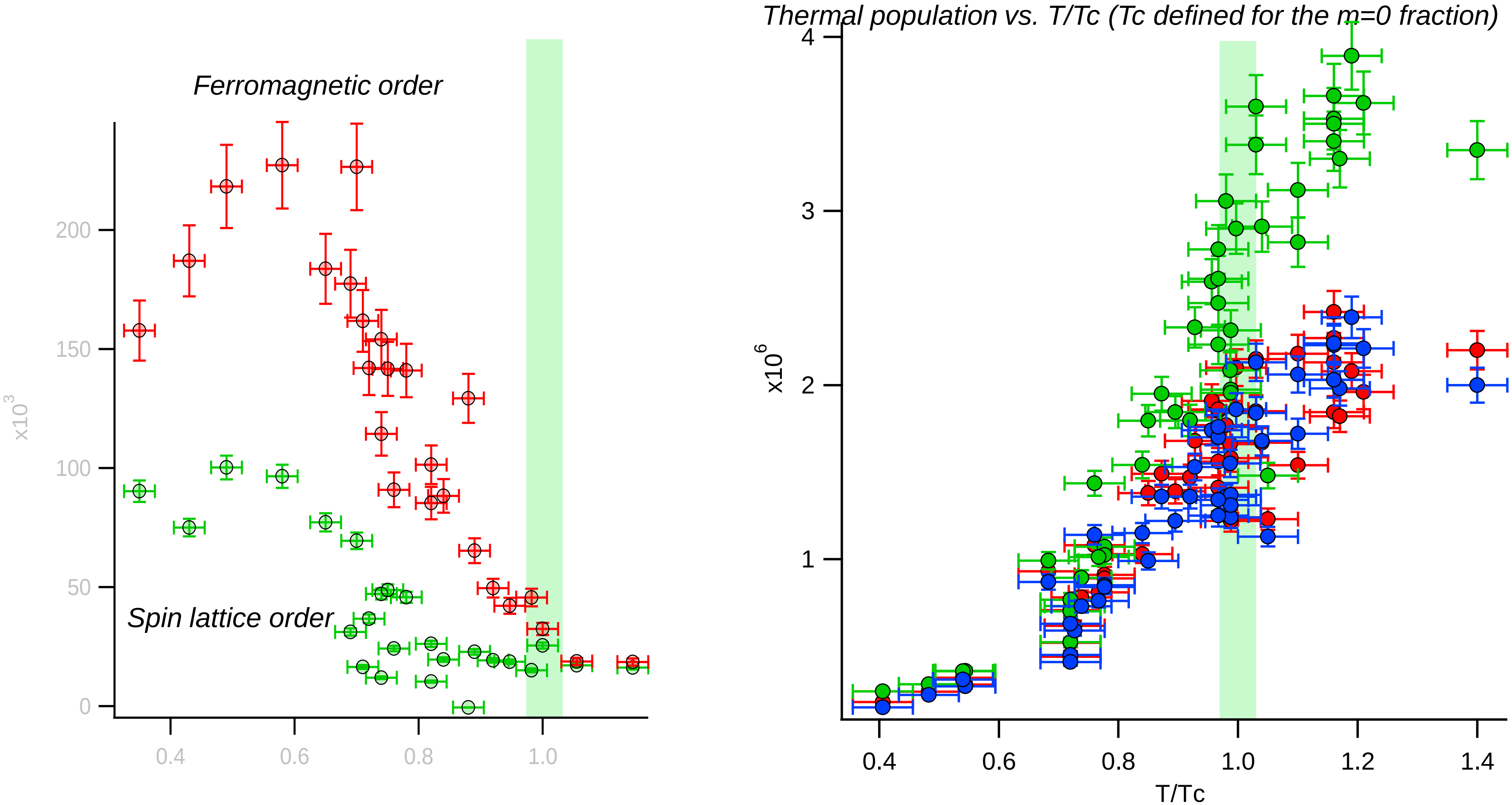








Thermal populations vs Vodt



Order parameters for the (1,2,1) mixtures and corresponding thermal fractions in the three components (RGB = +1, 0, -1)