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2030-20

Conference on Research Frontiers in Ultra-Cold Atoms

4 - 8 May 2009

Evidence for supersolid behavior in a spin-1 Rubidium gas

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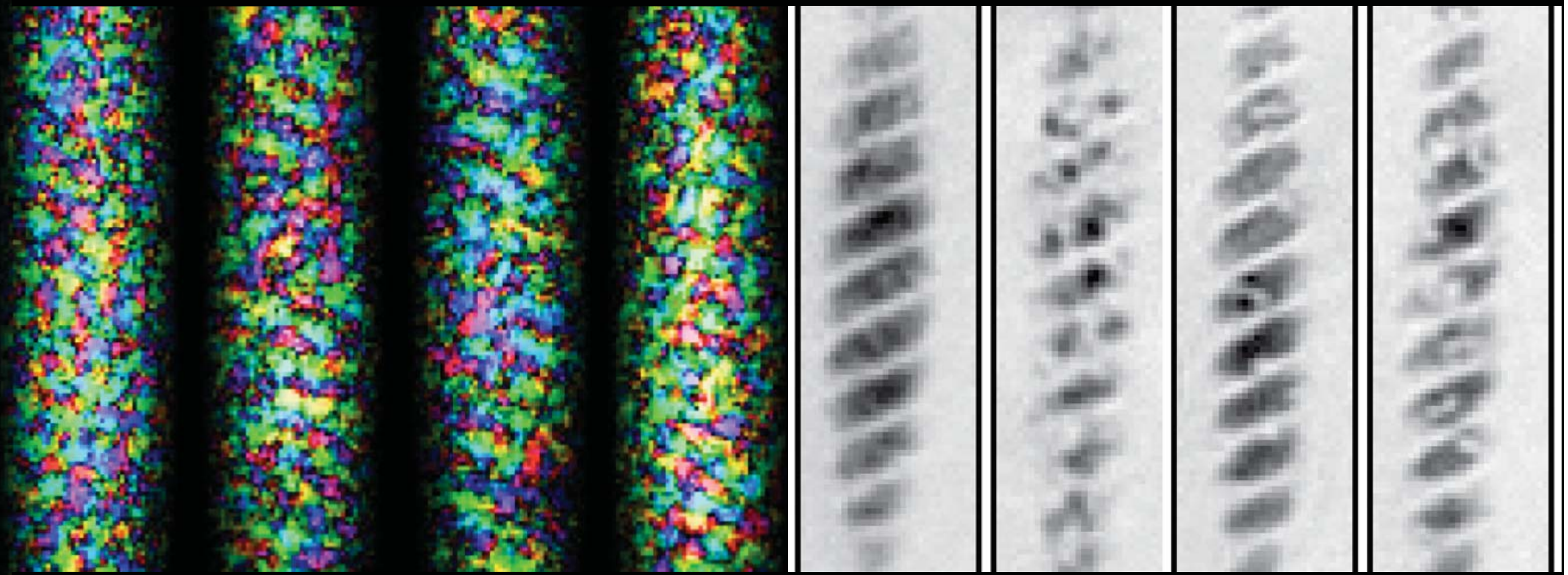
Evidence for supersolid behavior in a spin-1 rubidium gas



Kater Murch
UC Berkeley

Conference on Research Frontiers in Ultra-Cold Atoms
ICTP May 2009

Outline

- To read
  - Chan specific heat measurement 2007
  - ⇒ Yi and Pu, PRL 97, 020401 (2006); Kawaguchi, Saito, Ueda PRL 97, 130404 (2006)
  - ⇒ Pfau, Santos, Lewenstein, others: ^{52}Cr (6 μ_B)
    ⇒ Jin, Ye (JILA): polar molecules (>137 μ_B)
  - Barnett, Turner, Demler [PRL **97**, 180412 (2007)]
- Lamacraft, PRA 77, 062622 (2008), Cherng, et al., PRL 100, 180404 (2008)

Outline

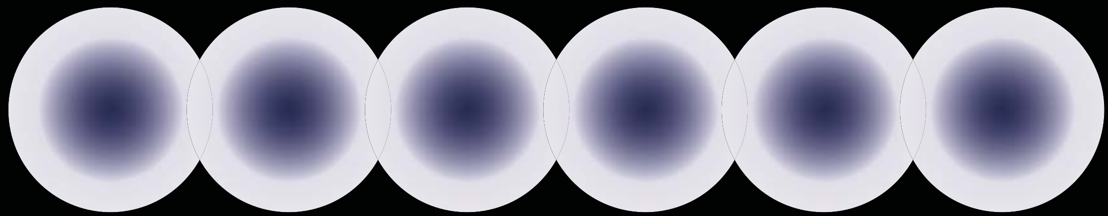
- Rb F=1 phase diagram (slides leading up to it)
- How to image magnitization (experimental interlude)
- 3 experiments
  - Wind up experiment (following experimental observation)
  - Evaporation; “121”
  - Evaporation “111”
- Probing coherence of these gases:
  - Looks like a BEC in TOF: furthermore if you look closely we see phase fluctuations and vorticies; phase defects show up in TOF.
  - From original interference experiment to Heterodyne AI
  - Heterodyne Atom interferometry
  - Applying this probe to scalar system; Imaging Resolution limits measurement
  - Mean field chirp
  - Short distance measurements, interpretation.
- Current work; experimental upgrade, longer equilibration time, different geometries, better quantification of crystal, cancel expansion of gas.

Supersolid?

particles “localized” at lattice sites

$\Rightarrow$ translational symmetry breaking

real-space regular structure (density, magnetization, ...)



but particles may be simultaneously “delocalized”: superposition of locations

$$\Psi = \left(|\text{site } 1\rangle + |\text{site } 2\rangle + |\text{site } 3\rangle + \ldots\right)^N$$

delocalization may lead to superfluidity

$\Rightarrow$ long-range phase coherence

“off-diagonal long-range order”

some number uncertainty per site $\Rightarrow$ phase certainty at each site

First suggestions: [Andreev & Lifshitz, Reatto, Chester, Leggett] ~1970

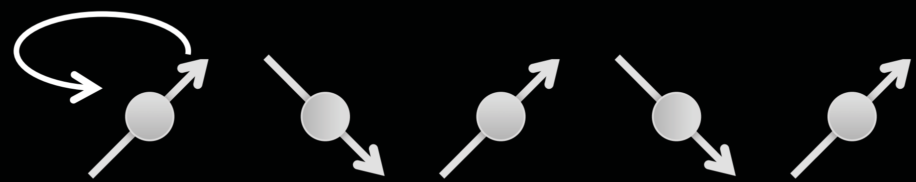
theory:
ingredients, characteristics, variants, candidates

experiments:
solid ^4He
2D helium films
solid H_2

"Quantum crystals"

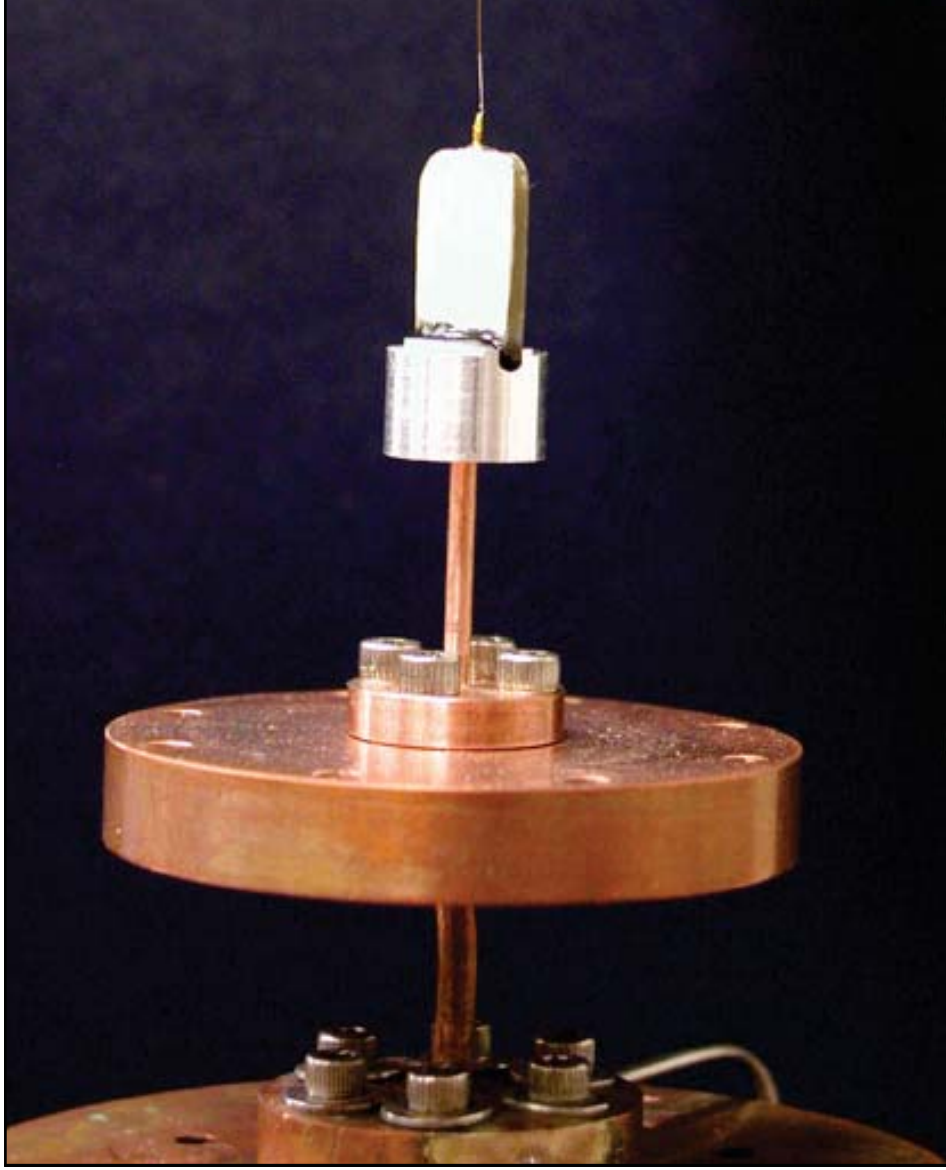
- Bosons with long-range interactions
  - Pomeau & Rica (1994): start from fluid and increase interactions, see rotons and instability (cf Cherng & Demler)
- "Lattice supersolids": Bosons on lattice
  - Liu & Fisher (1972) [also Bruder, Fazio, Schon; van Otterlo, Wagenblast; Batrouni, Scalettar; …]
  - Bose-Hubbard models, related to JJ arrays, cold atoms
- "Spin supersolids": Quantum magnets
  - Fisher & Nelson (1974) + lots of work 90's onwards: "spinflop" = "boson"

XY: SF phase

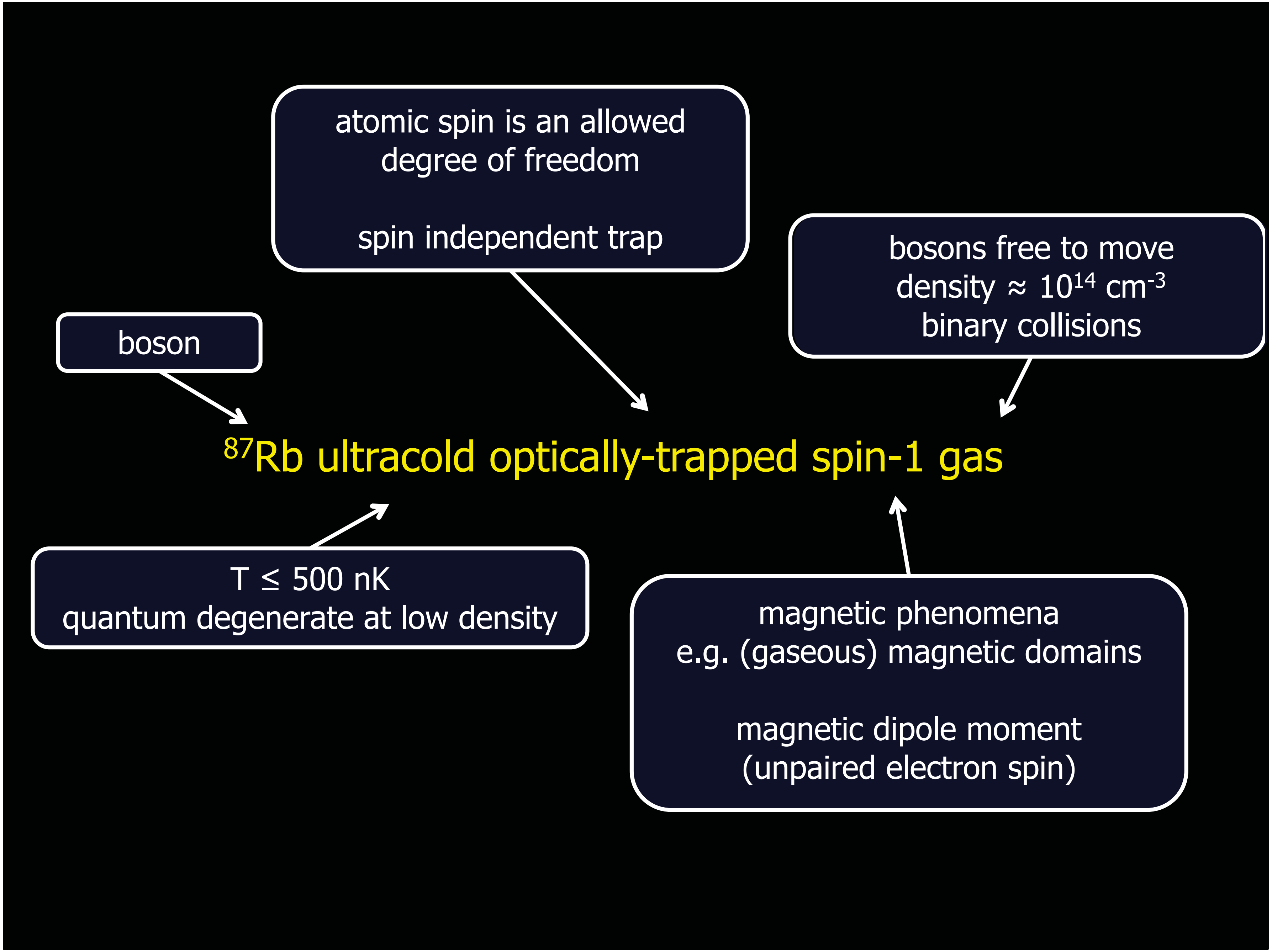


Z: solid

Experiments: Torsional oscillators, vycor, dislocations, impurities...



- Kim & Chan (2004 + on)
  - non-classical rotational inertia – superfluid decouples from motion
  - strongly affected by annealing… (Rittner & Reppy, Chan, …)
- Anomalous shear modulus
  - role of dislocations... (Day & Beamish 2007)
- Δ specific heat (Lin, Clark & Chan 2007)
- “Unusual mass transport” in solid (Ray & Hallock 2008)

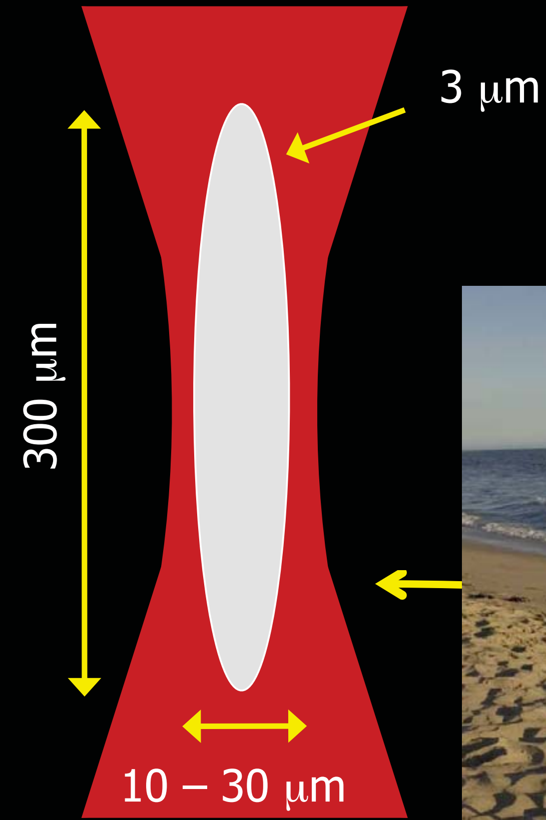


atomic spin is an allowed degree of freedom
spin independent trap
bosons free to move
density ≈ 10^{14} cm^{-3}
binary collisions
boson
^{87}Rb ultracold optically-trapped spin-1 gas
T ≤ 500 nK
quantum degenerate at low density
magnetic phenomena
e.g. (gaseous) magnetic domains
magnetic dipole moment
(unpaired electron spin)

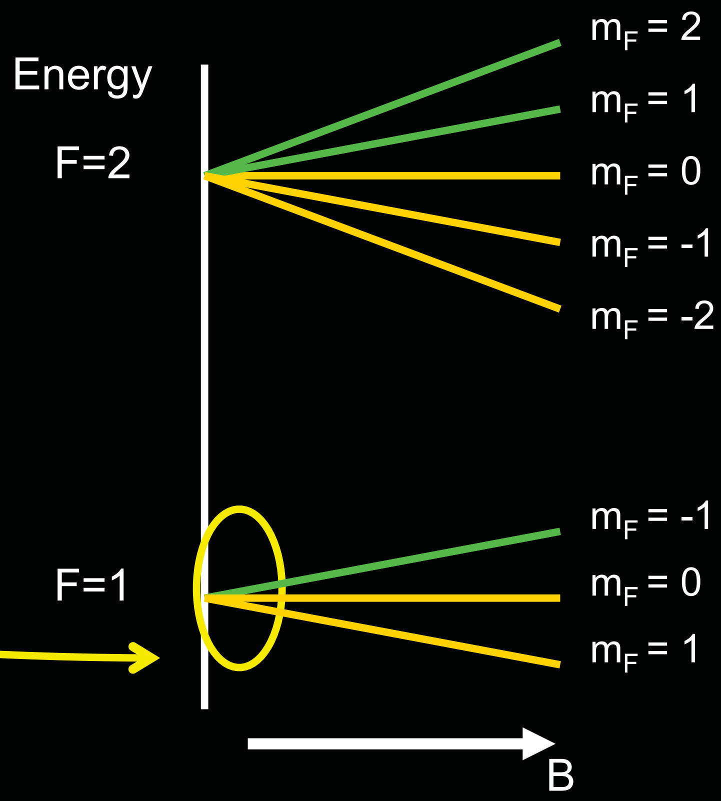
Optically trapped spin-1 gas

N ≥ 2 x 10^6 atoms

T ≥ 50 nK



geometry ≈ surfboard



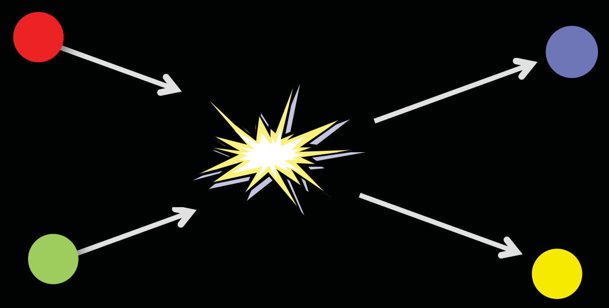
$$\sqrt{8\pi\bar{a}n_0} < r_y < \sqrt{8\pi|\delta a|n_0}$$

2D spin dynamics

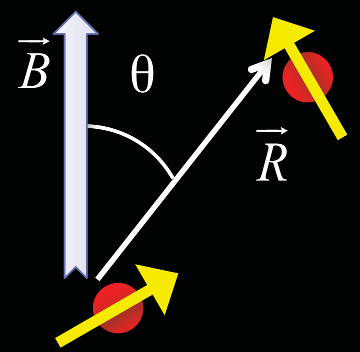
3D condensate

Interatomic interactions

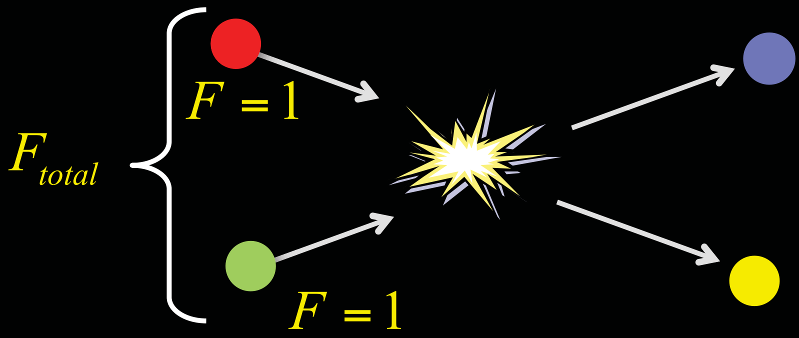
contact interactions



magnetic dipolar interactions



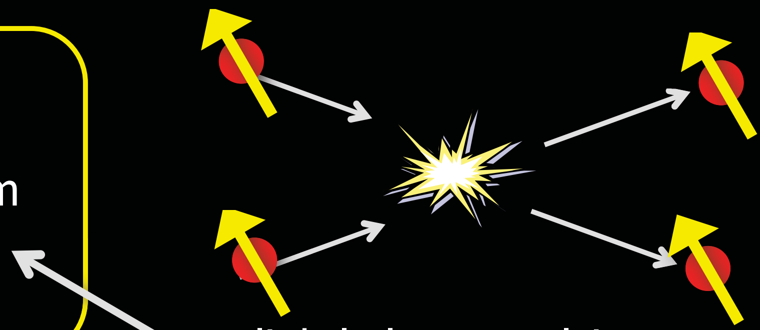
Interatomic interactions



- Low energy
  - only s-wave collisions occur; 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



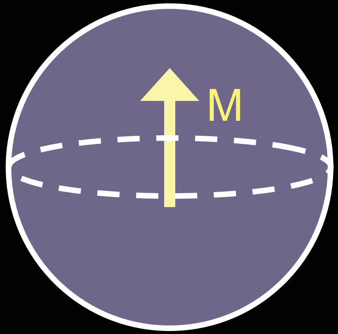
slightly less repulsive
prefers magnetic states

in dense BEC:

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

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

Dipolar interactions: magnetism in a quantum fluid
"Quantum ferrofluids"



		@ $3\ 10^{14}$ 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
    - ⇒ Pfau, Santos, Lewenstein, others: ^{52}Cr (6 μ_B)
    - ⇒ Jin, Ye (JILA): polar molecules (>137 μ_B)
  - spin-dependent interaction energy: μ ~ h x 12 Hz

⇒ Yi and Pu, PRL 97, 020401 (2006); Kawaguchi, Saito, Ueda PRL 97, 130404 (2006)

⇒ ^{87}Rb is an essentially dipolar spinor quantum fluid

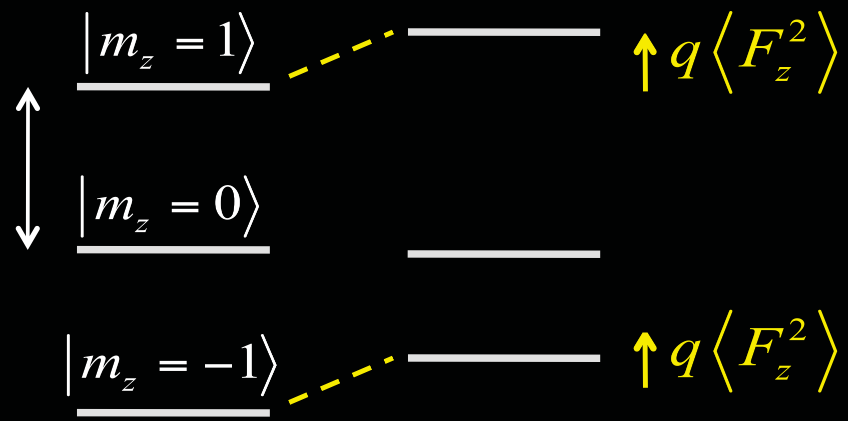
Effects of magnetic field

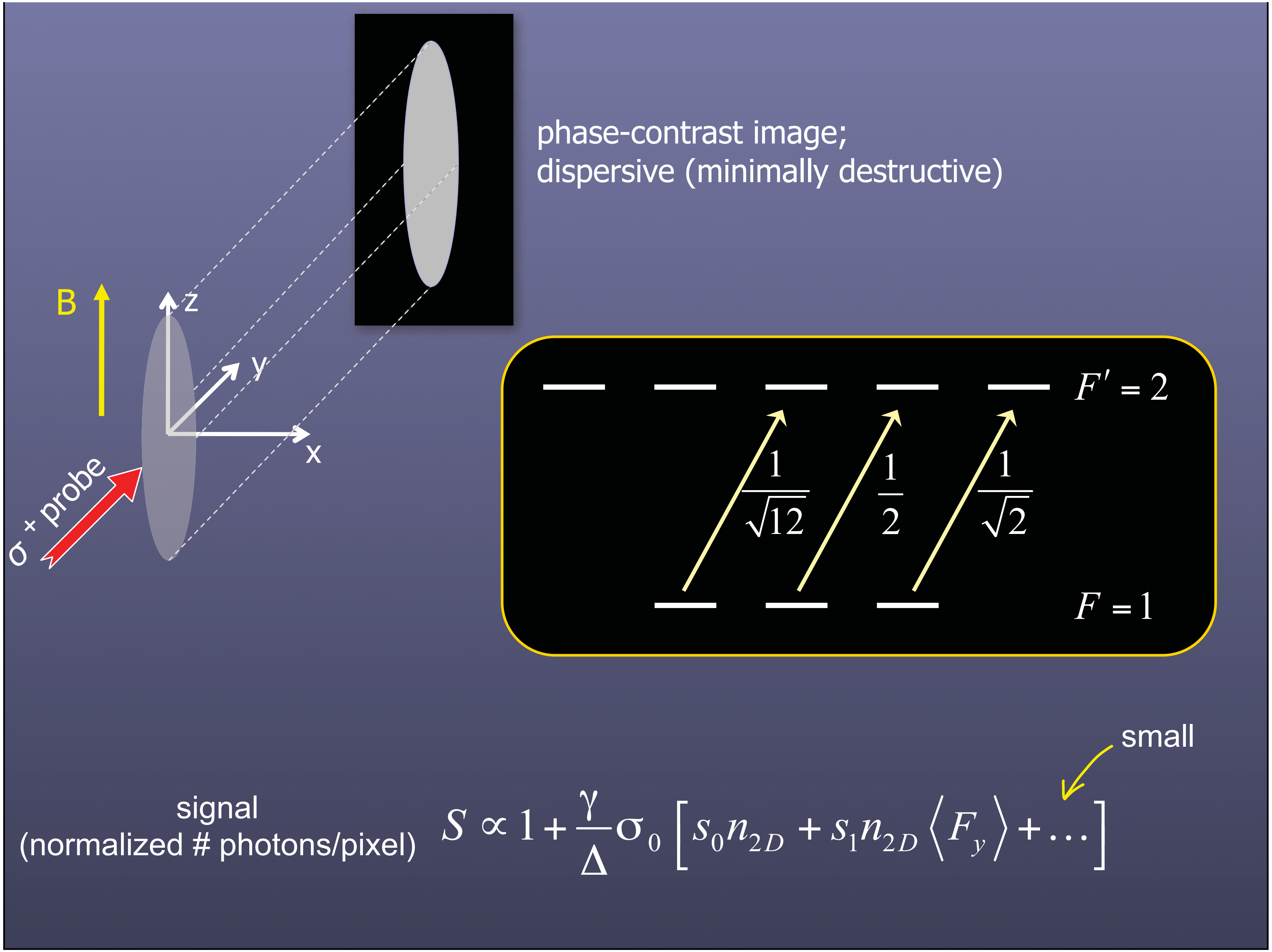
- linear Zeeman shift
  - Transverse coherences rapidly precess

- quadratic Zeeman shift: q
  - m=0 condensate favored at high q

$$E_z = g_F \mu_B B$$

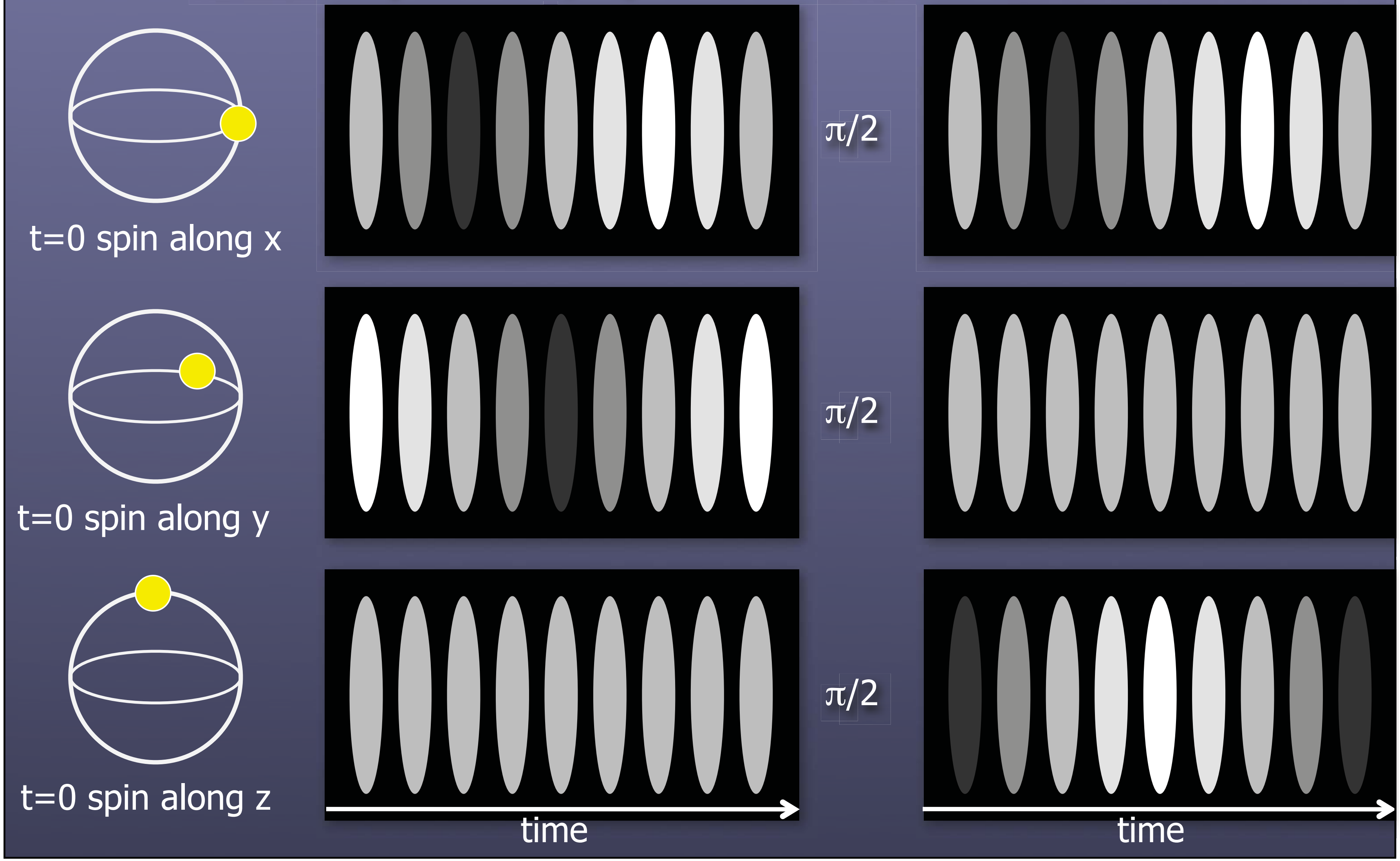
≈ 100 kHz, or 5 μK



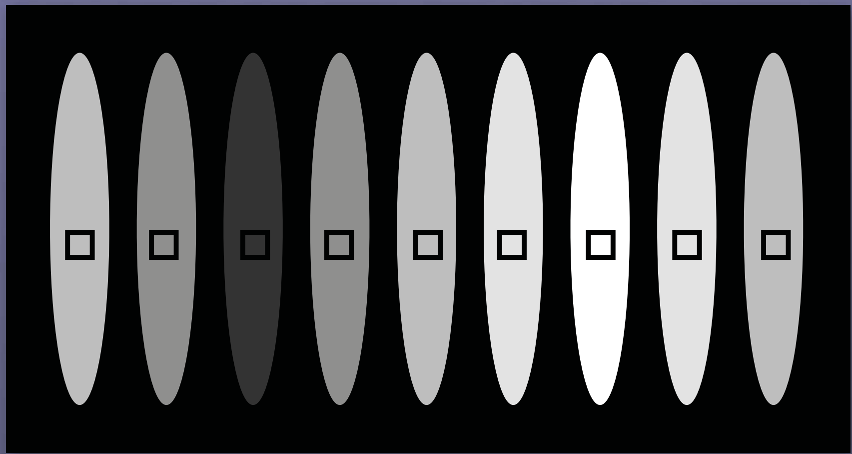

phase-contrast image;
dispersive (minimally destructive)
B
z
y
x
σ + probe
$F' = 2$
$\frac{1}{\sqrt{12}}$
$\frac{1}{2}$
$\frac{1}{\sqrt{2}}$
$F = 1$
small
signal
(normalized # photons/pixel)
$S \propto 1 + \frac{\gamma}{\Delta}\sigma_0 \left[s_0 n_{2D} + s_1 n_{2D} \langle F_y \rangle + \ldots \right]$

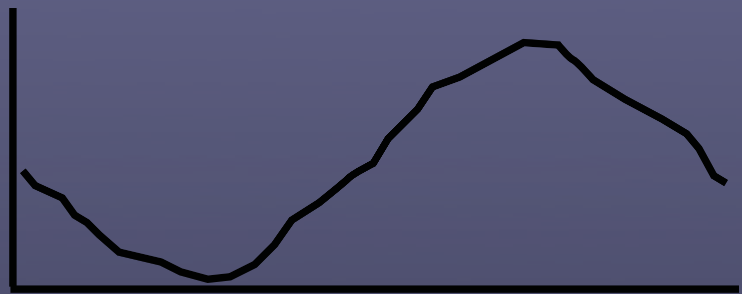
Measuring the vector spin

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



Displaying the vector spin

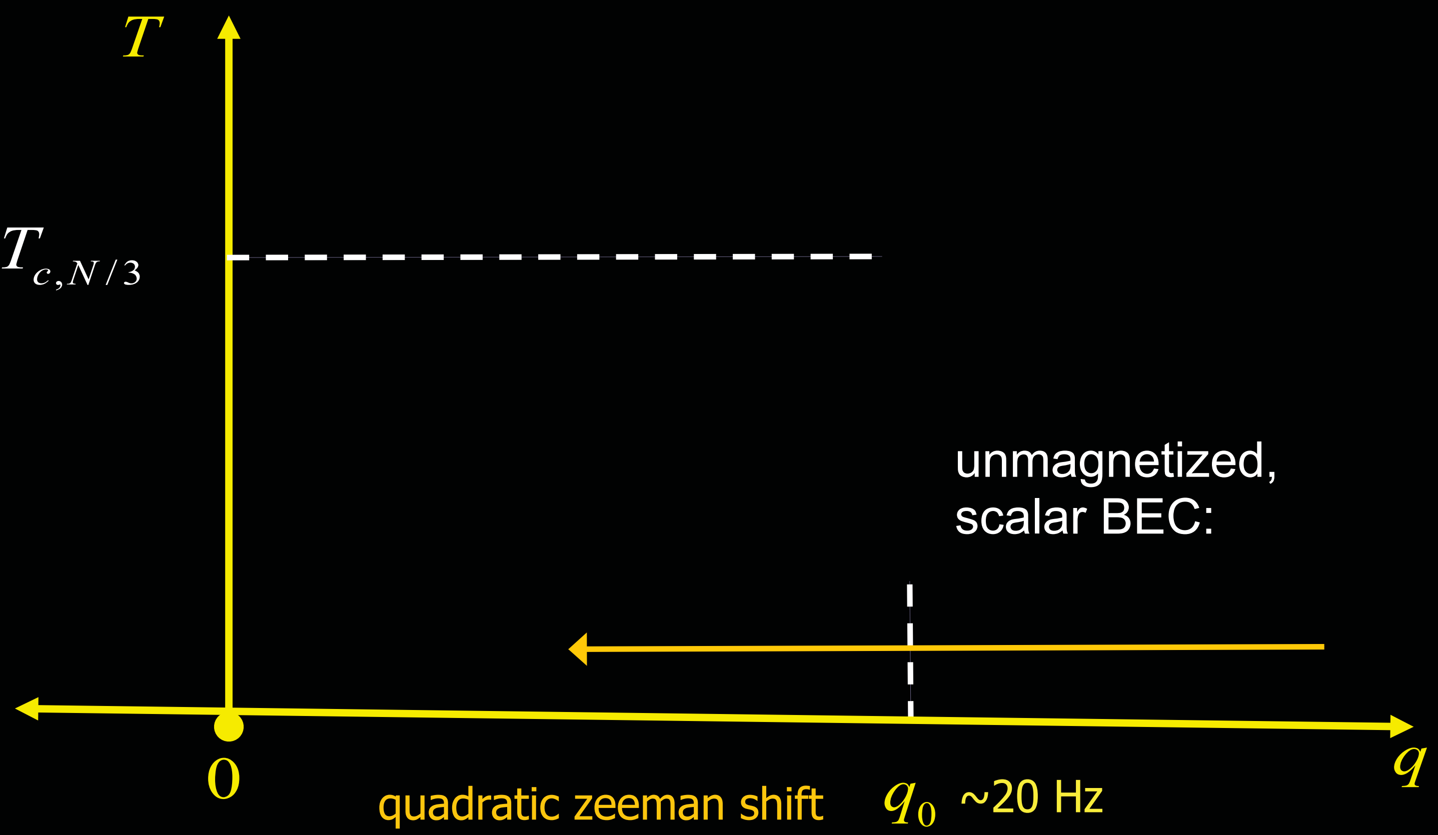


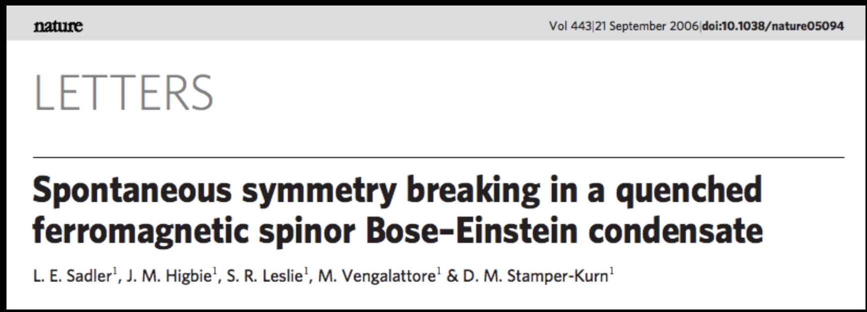


Least squares estimate of phase and amplitude which obtains the CR bound

Phase-Amplitude map

F=1 ^{87}Rb gas phase diagram: overview





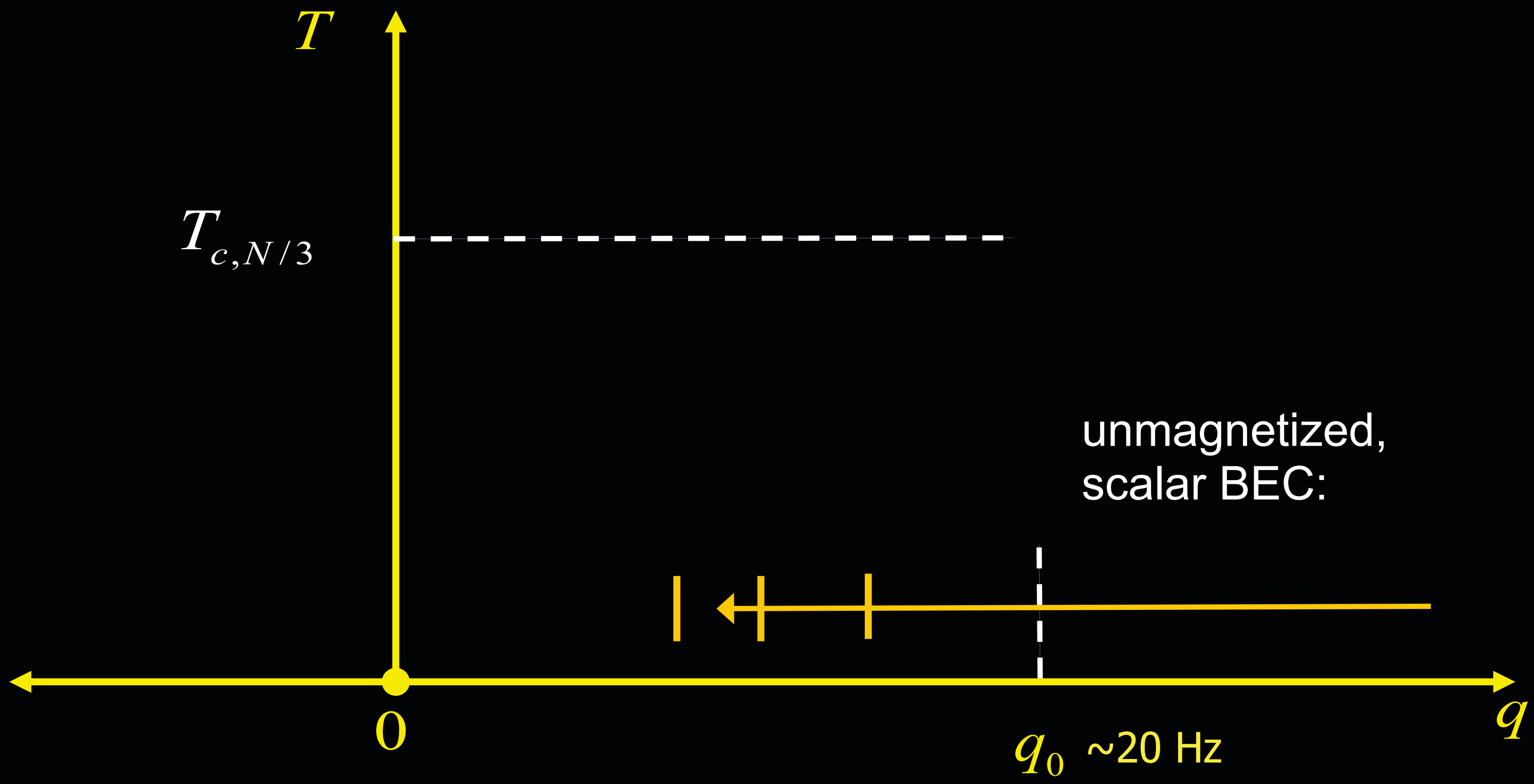
nature
Vol 443|21 September 2006|doi:10.1038/nature05094

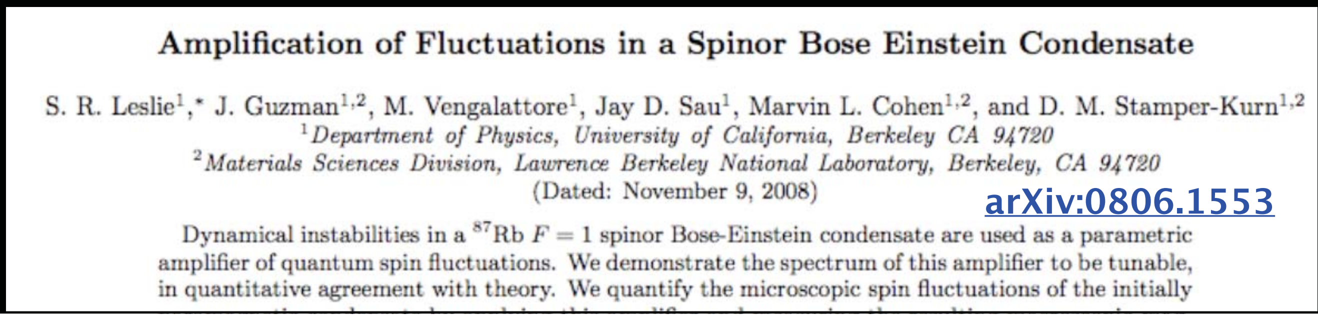
LETTERS

Spontaneous symmetry breaking in a quenched ferromagnetic spinor Bose–Einstein condensate

L. E. Sadler[1], J. M. Higbie[1], S. R. Leslie[1], M. Vengalattore[1] & D. M. Stamper-Kurn[1]

F=1 ^{87}Rb gas phase diagram: overview





Amplification of Fluctuations in a Spinor Bose Einstein Condensate

S. R. Leslie[1],* J. Guzman[1,2], M. Vengalattore[1], Jay D. Sau[1], Marvin L. Cohen[1,2], and D. M. Stamper-Kurn[1,2]
[1] *Department of Physics, University of California, Berkeley CA 94720*
[2] *Materials Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720*
(Dated: November 9, 2008)

Dynamical instabilities in a ^{87}Rb $F = 1$ spinor Bose-Einstein condensate are used as a parametric amplifier of quantum spin fluctuations. We demonstrate the spectrum of this amplifier to be tunable, in quantitative agreement with theory. We quantify the microscopic spin fluctuations of the initially

arXiv:0806.1553

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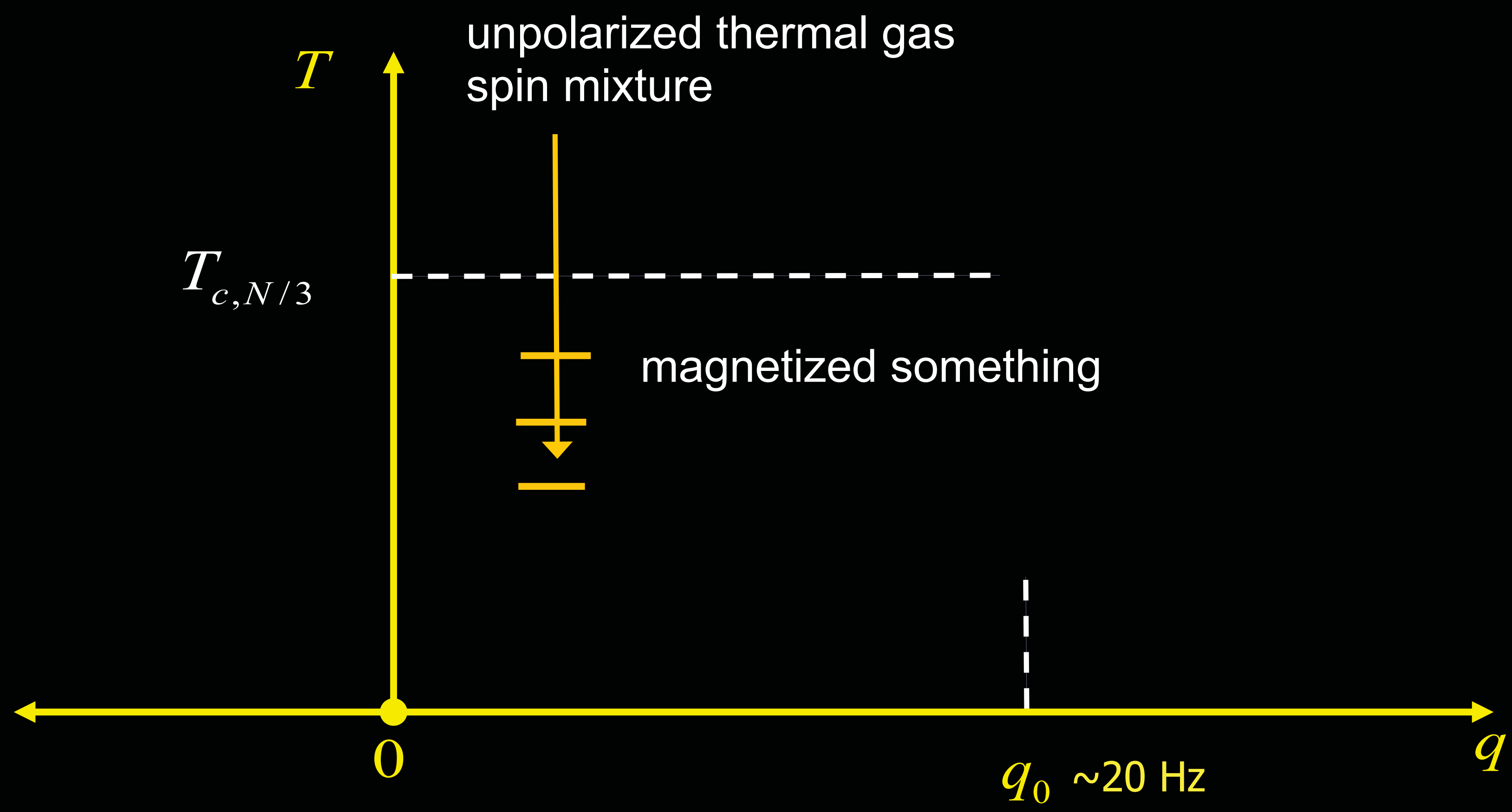
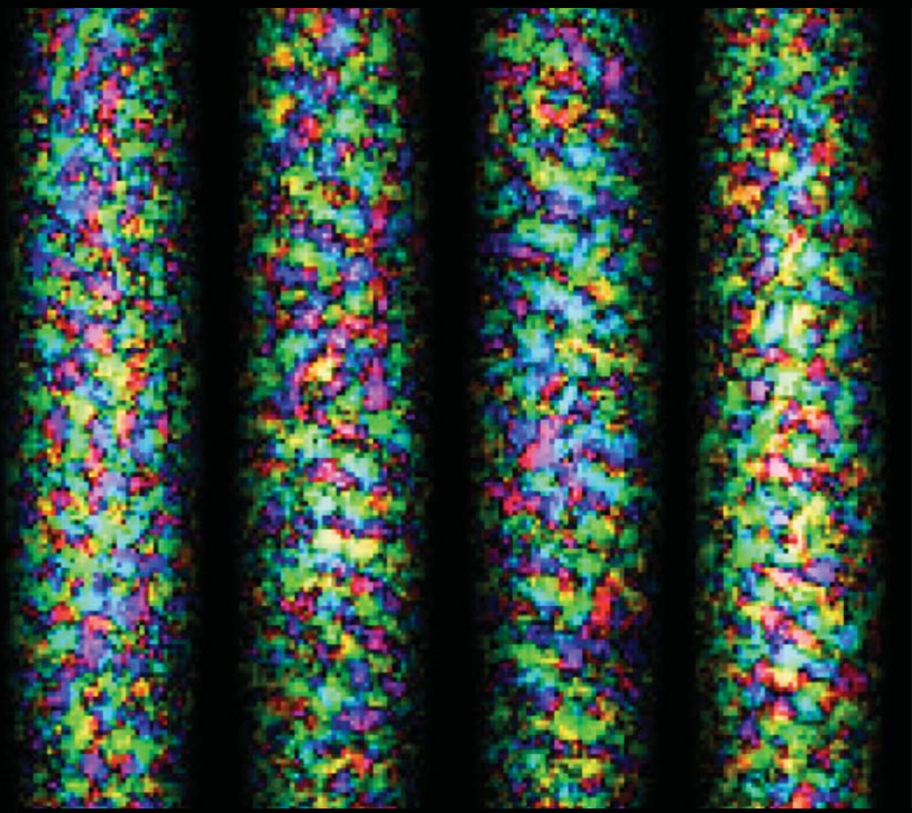
Experiment: F=1 ^{87}Rb gas at thermal equilibrium

- prepare fully depolarized thermal gas in uniform magnetic field
- lower temperature
- take pictures



"Crystalline magnetic order in a dipolar spinor quantum gas," arXiv:0901.3800 (2009)

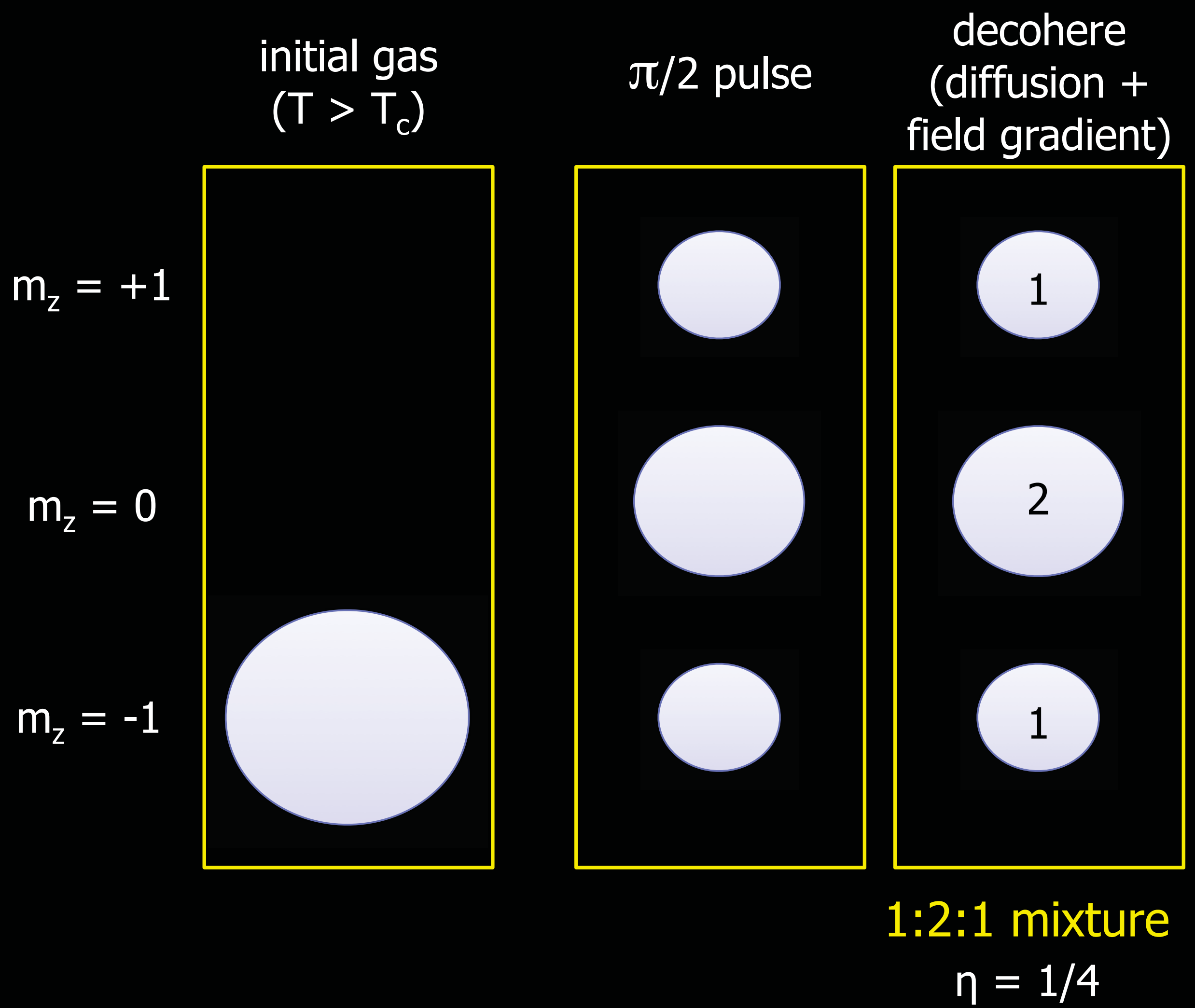


Observation #1

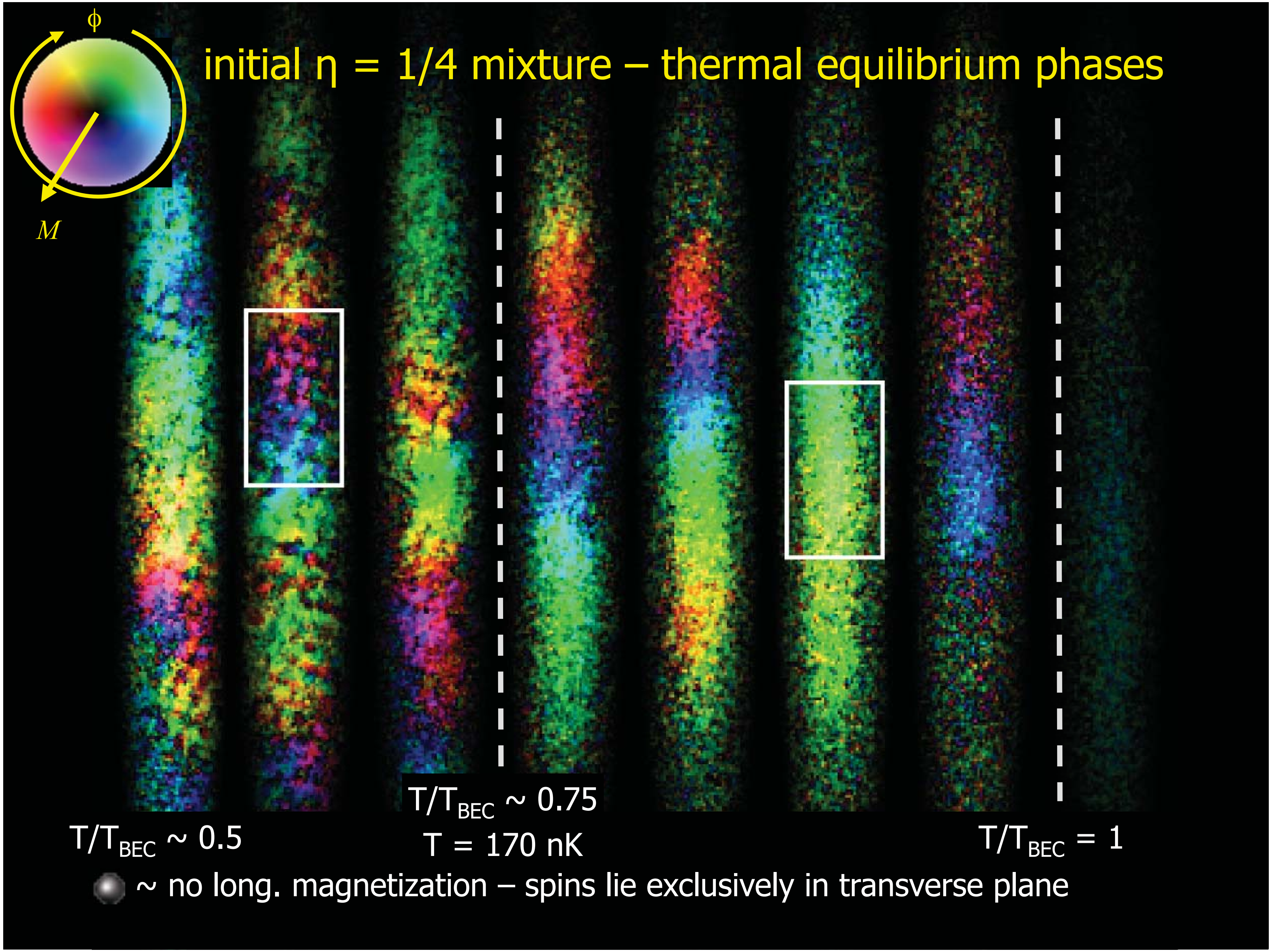
direct imaging of low-temperature spatially patterned magnetization in gas produced by slow evaporative cooling

Spontaneous breaking of translational symmetry

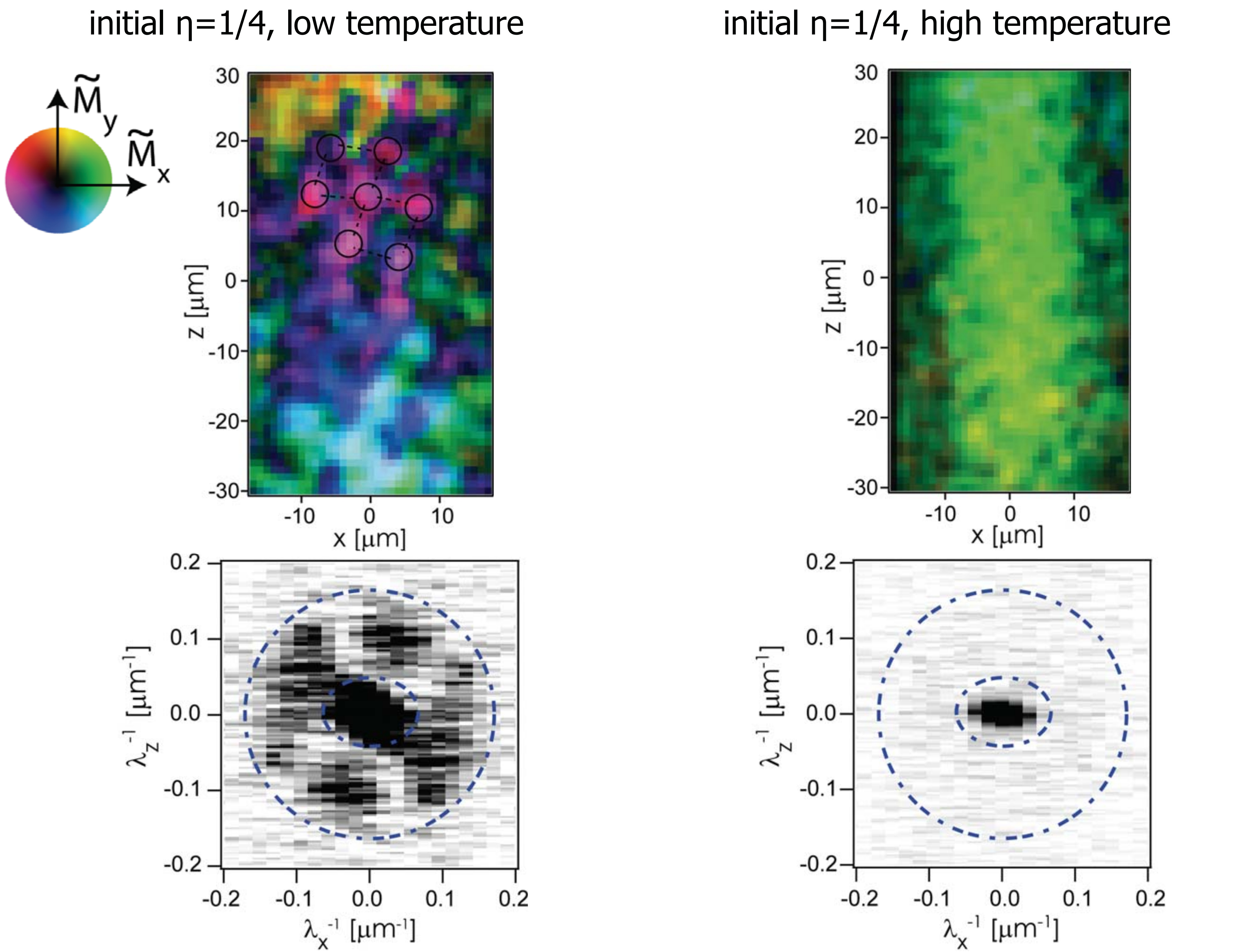
preparing unmagnetized gases



Quadrupole moment (nematicity): related to η = [m=0] – [m=1]



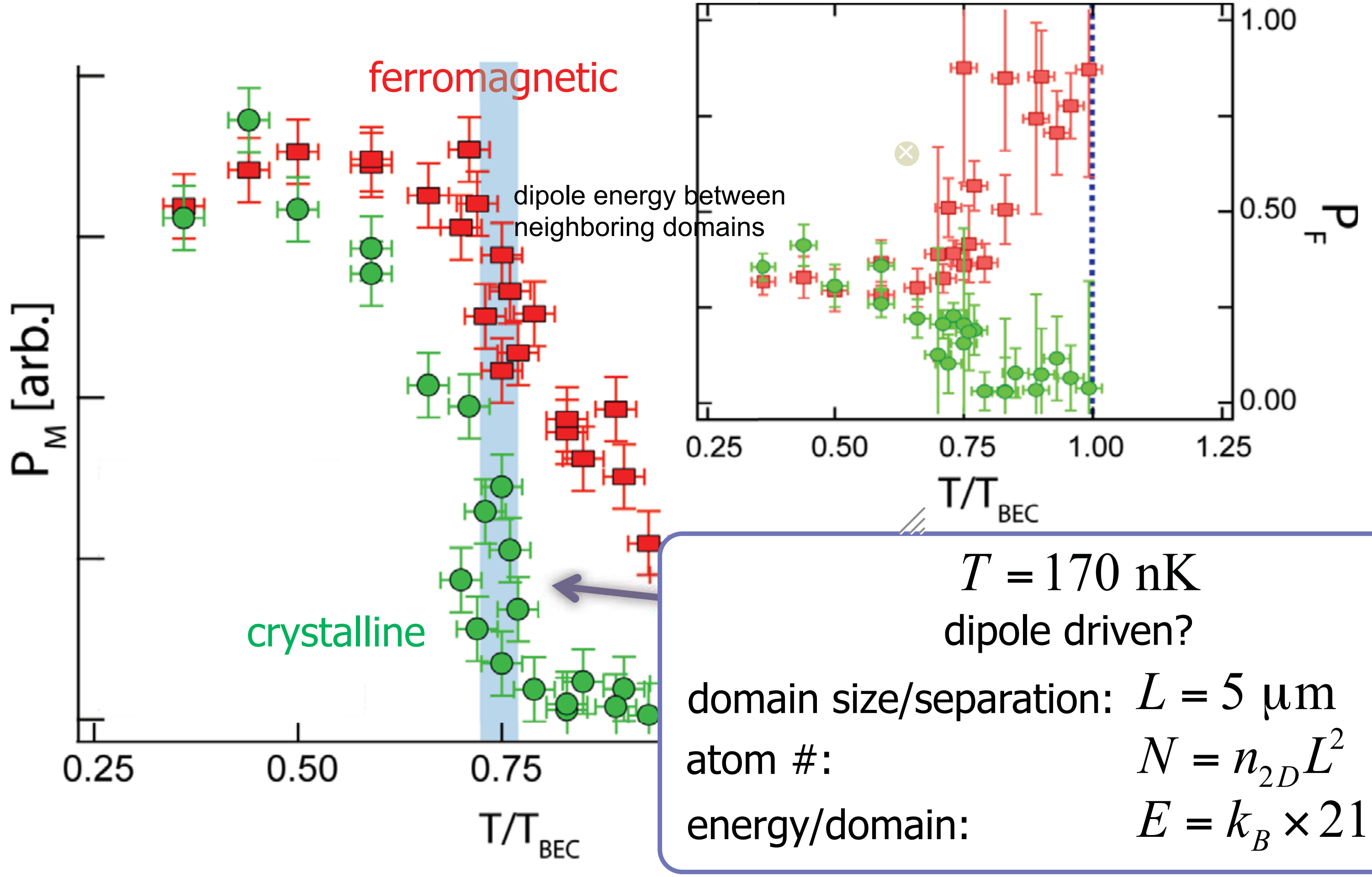
ϕ
M
initial η = 1/4 mixture – thermal equilibrium phases
T/T_BEC ~ 0.5
T/T_BEC ~ 0.75
T = 170 nK
T/T_BEC = 1
~ no long. magnetization – spins lie exclusively in transverse plane



initial η=1/4, low temperature
initial η=1/4, high temperature
$\tilde{M}_y$
$\tilde{M}_x$
z [μm]
x [μm]
λ_z^{-1} [μm^{-1}]
λ_x^{-1} [μm^{-1}]

Ferromagnetic and crystalline order parameters

initial η = 1/4 mixture



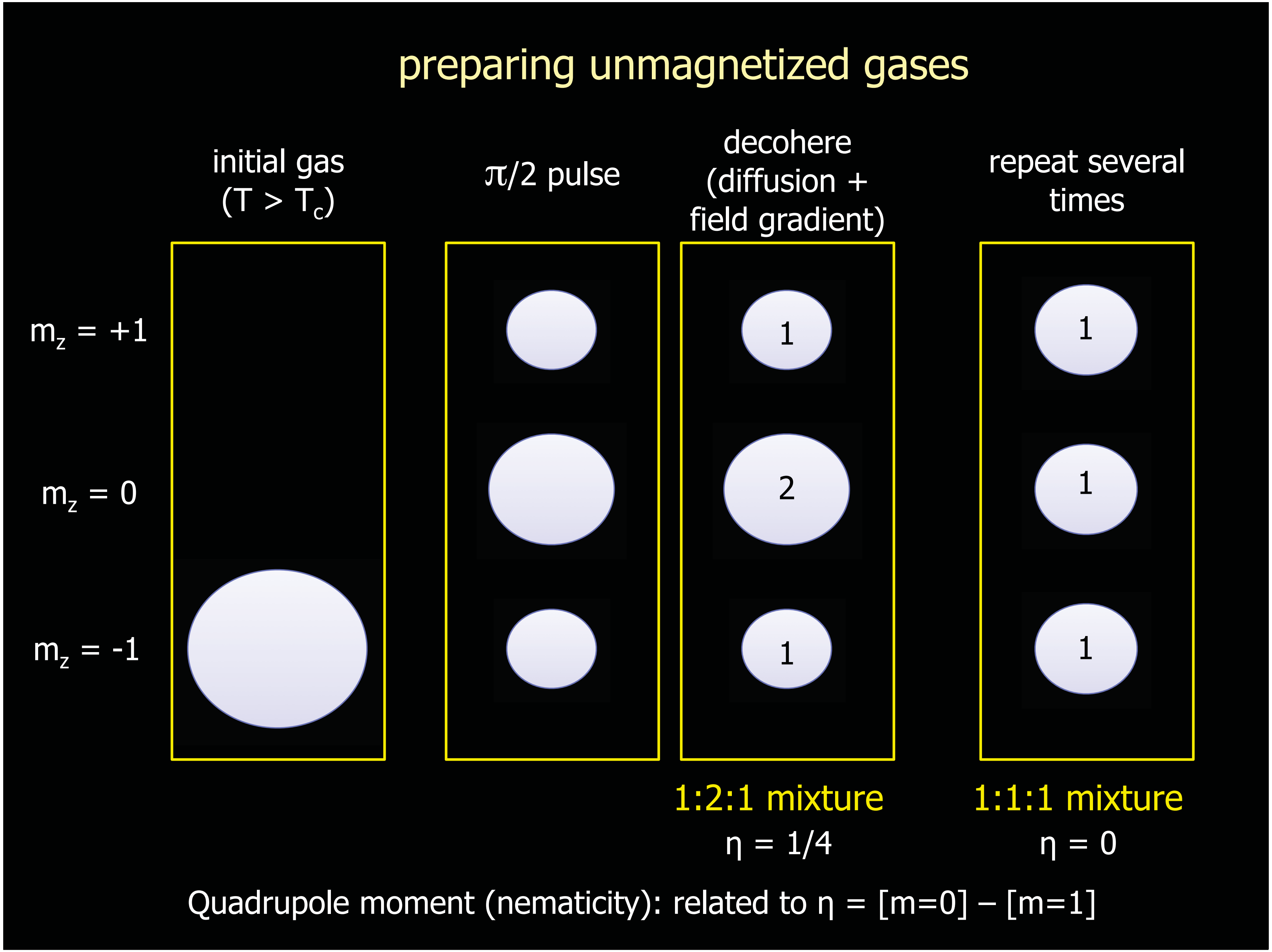
$T = 170$ nK

dipole driven?

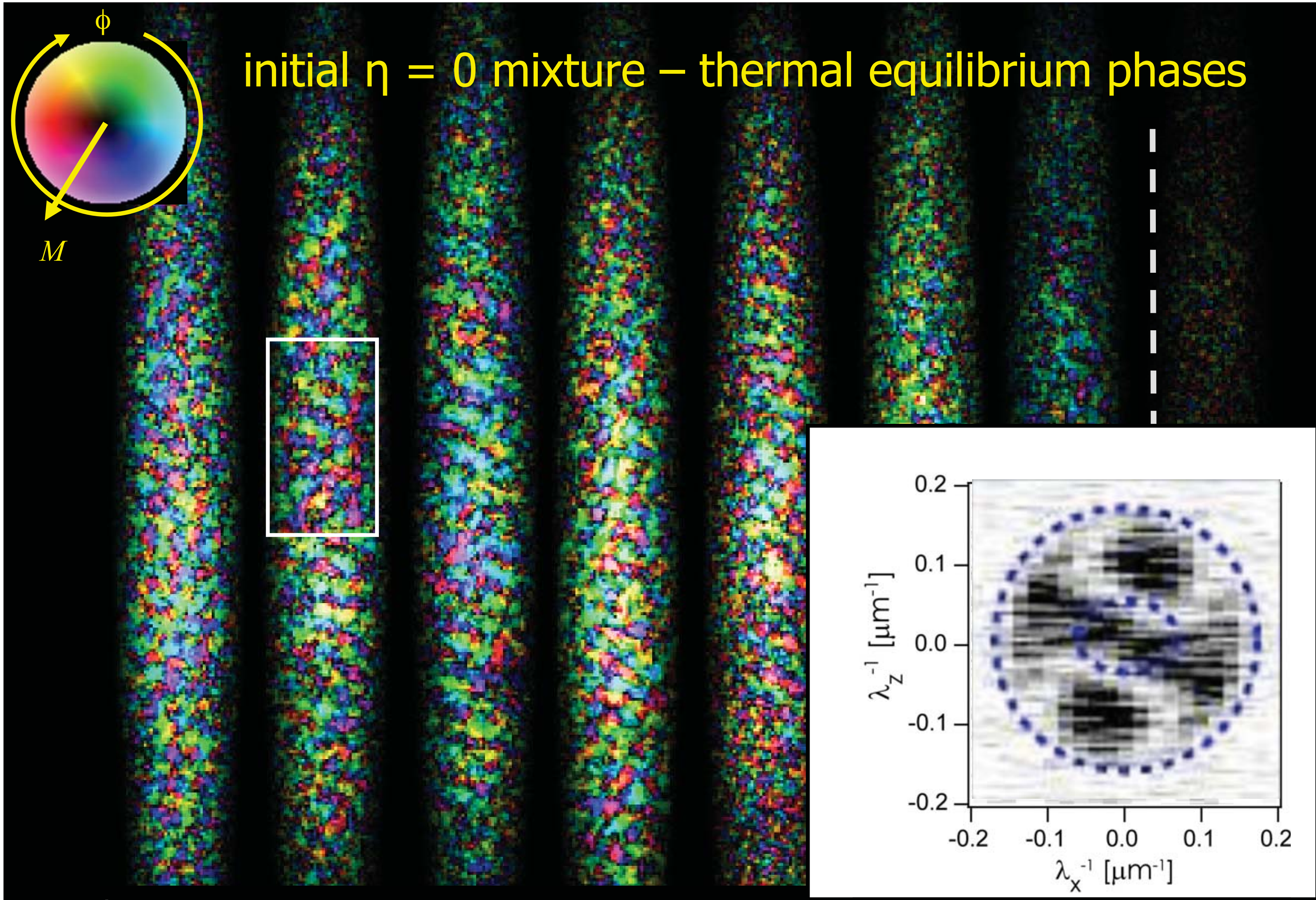
domain size/separation: $L = 5\ \mu\text{m}$

atom #: $N = n_{2D}L^2$

energy/domain: $E = k_B \times 210$ nK


preparing unmagnetized gases
initial gas
(T > T$_c$)
π/2 pulse
decohere
(diffusion +
field gradient)
repeat several
times
m$_z$ = +1
m$_z$ = 0
m$_z$ = -1
1
2
1
1
1
1
1:2:1 mixture
η = 1/4
1:1:1 mixture
η = 0
Quadrupole moment (nematicity): related to η = [m=0] – [m=1]

initial η = 0 mixture – thermal equilibrium phases

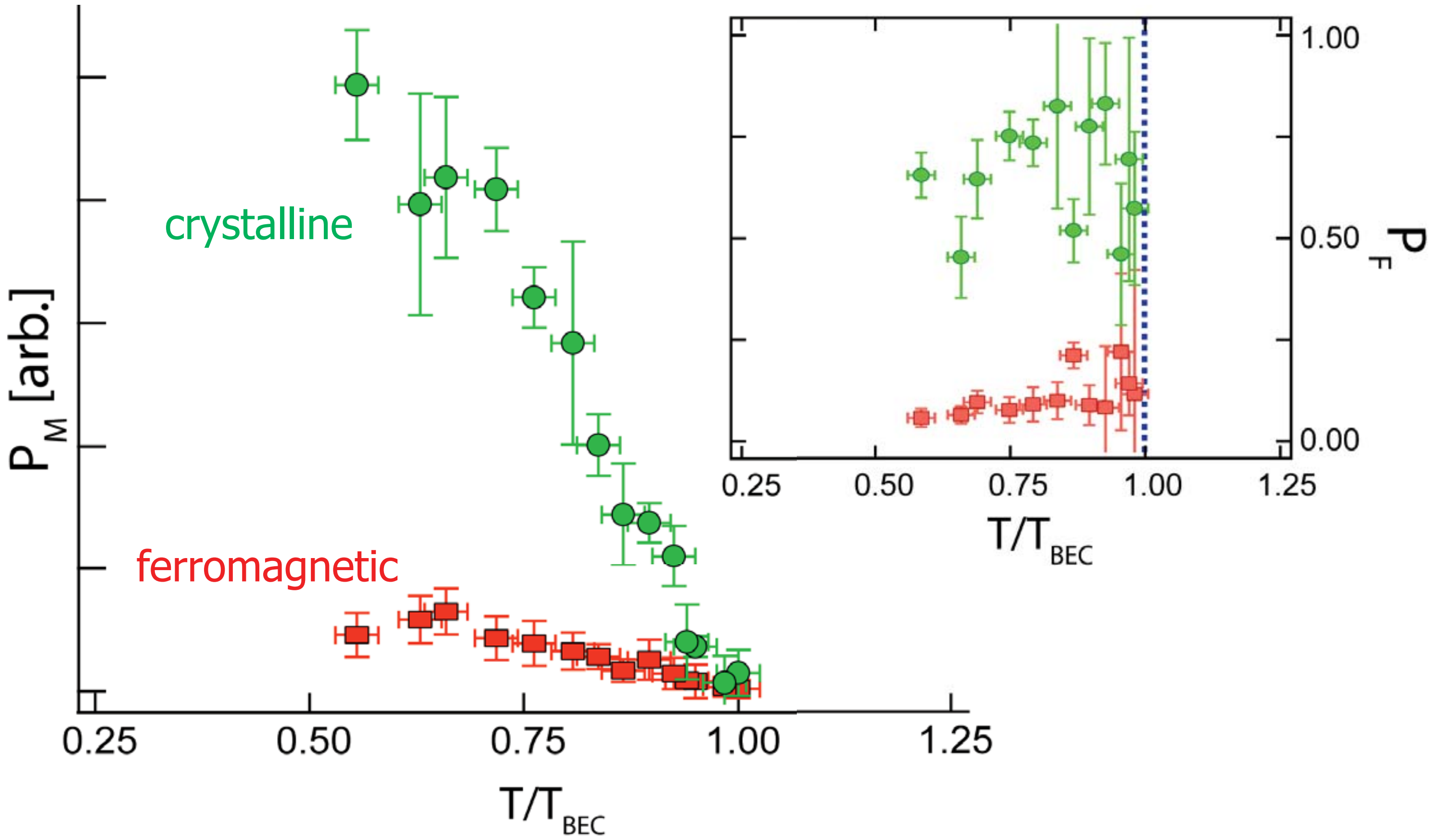


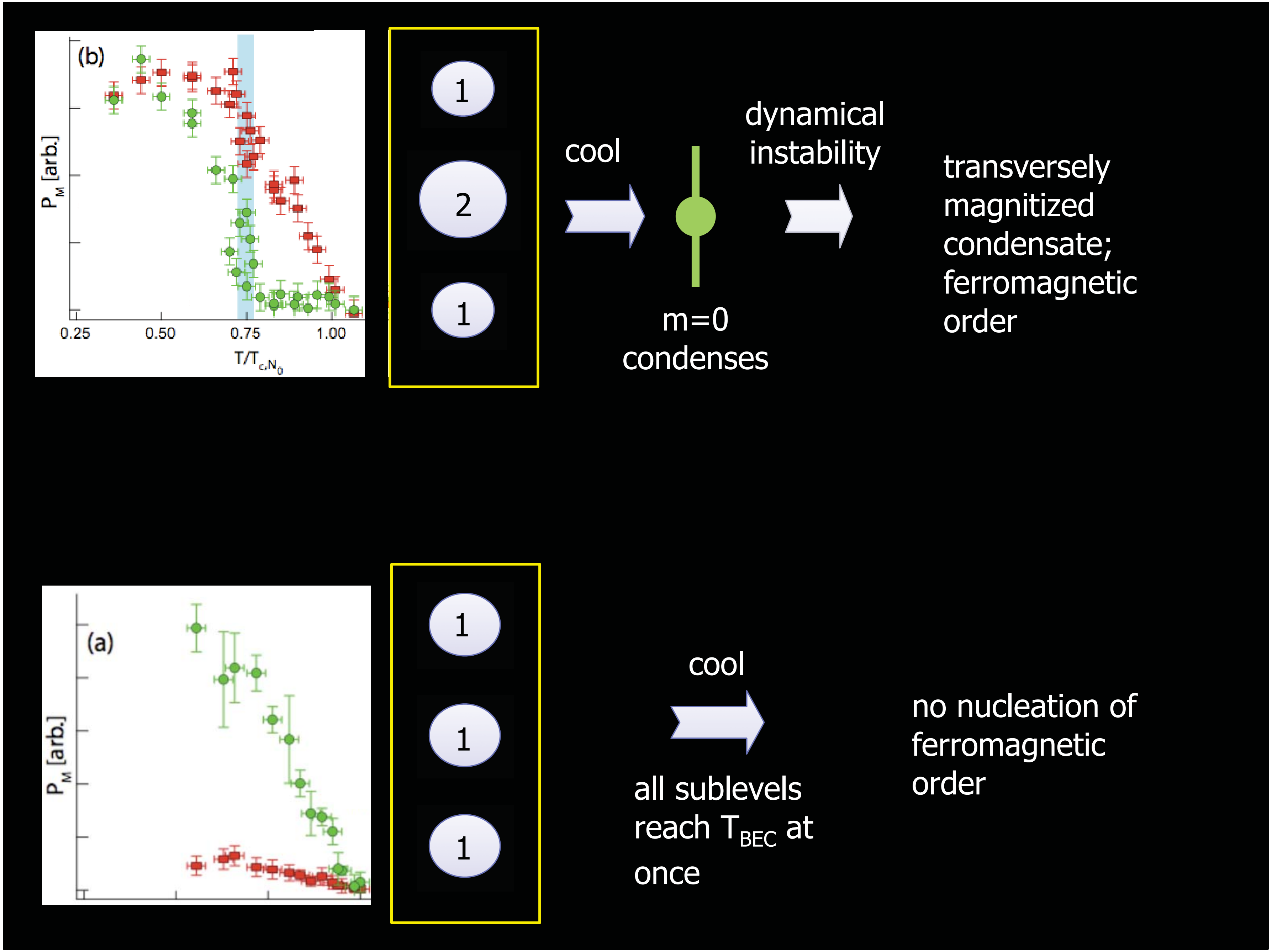
$T/T_{BEC} = 0.55$ $T/T_{BEC} = 1$

- similar spatial variation in long. magnetization – no globally preferred spin direction

Ferromagnetic and crystalline order parameters

initial η = 0 mixture

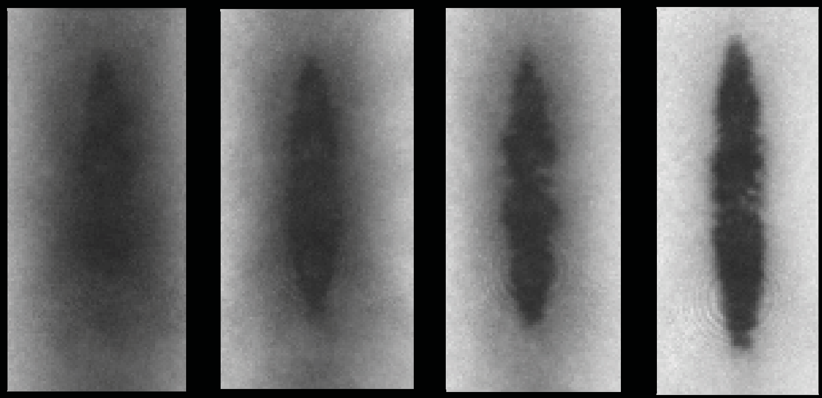




(b)
P_M [arb.]
0.25
0.50
0.75
1.00
T/T_c,N_0
1
2
1
cool
dynamical instability
m=0 condenses
transversely magnitized condensate; ferromagnetic order
(a)
P_M [arb.]
1
1
1
cool
all sublevels reach T_BEC at once
no nucleation of ferromagnetic order

Both spinors (η=0 and 1/4) exhibit hallmarks of Bose condensation

- Looks like a BEC in TOF:



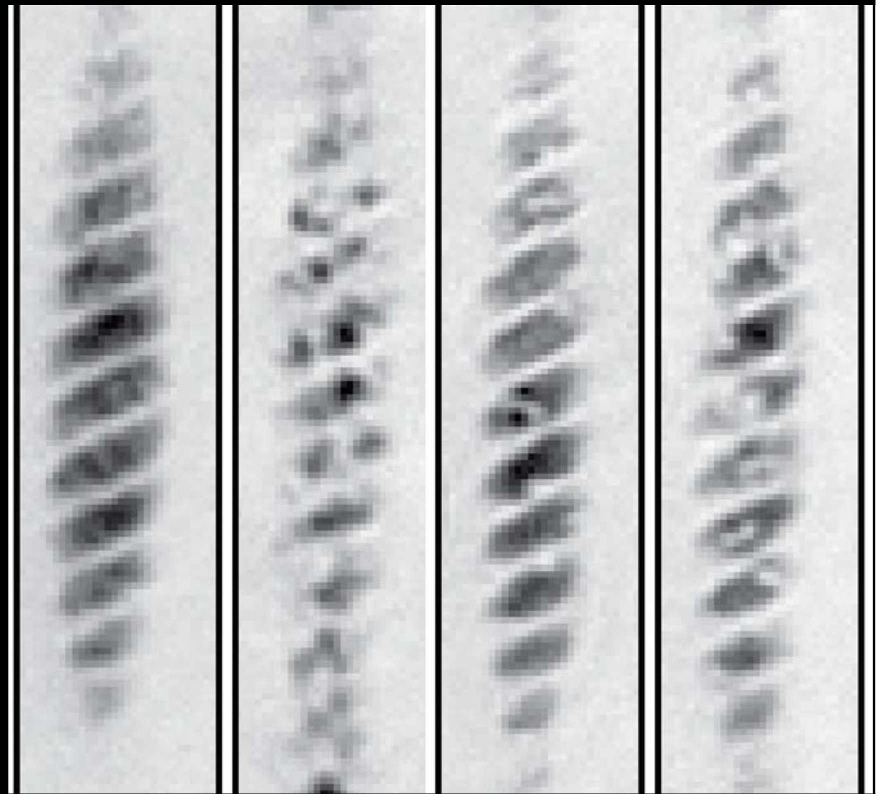
m=0 component
of η=1/4 spinor

Is it a superfluid?
(long range off-diagonal order)

Observation #2

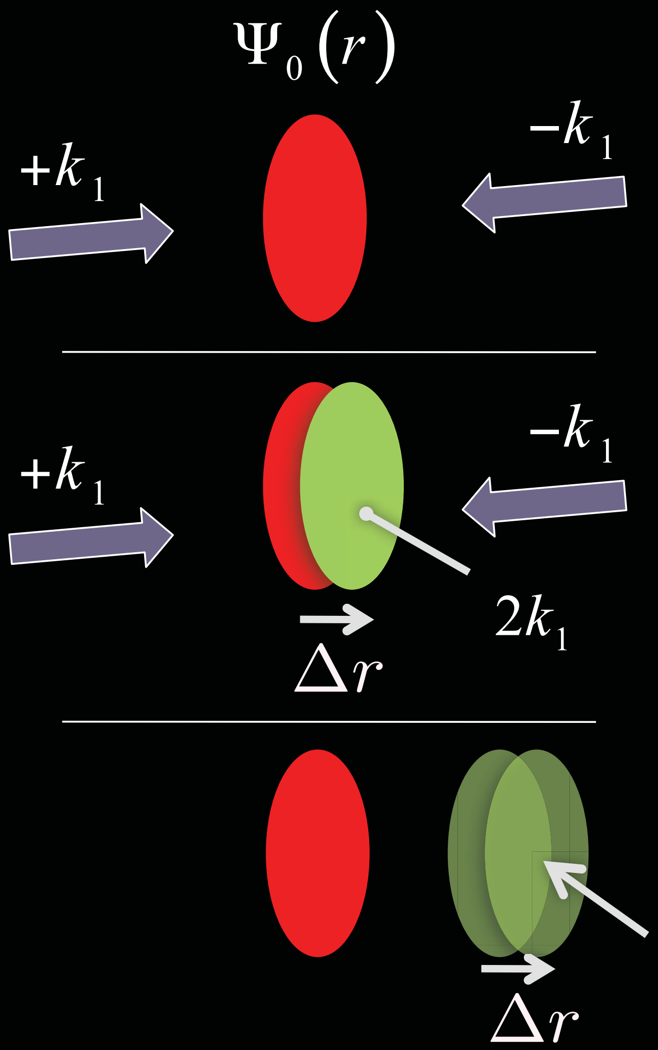
off-diagonal density operator, i.e. first-order correlation function, measured by atom interferometry

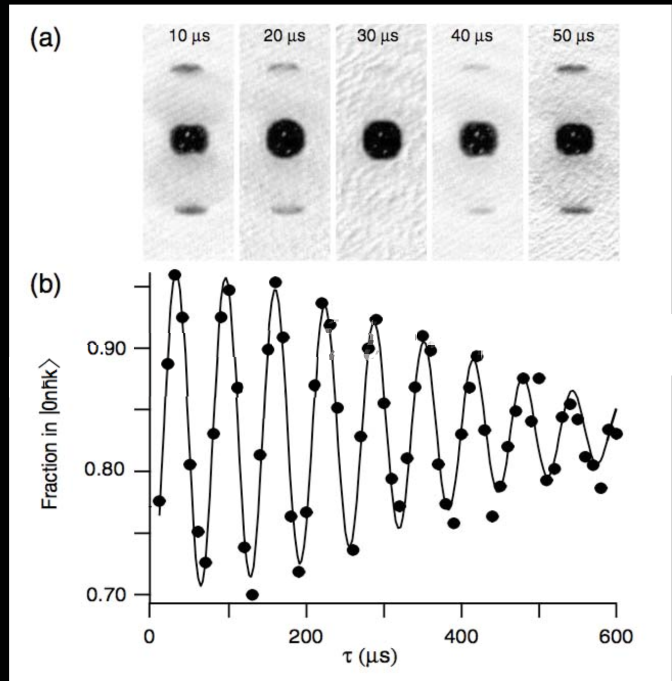
Spontaneous establishment of off-diagonal long-range order



Measuring coherence via atom interferometry

Ramsey-type (two pulse) Bragg scattering:





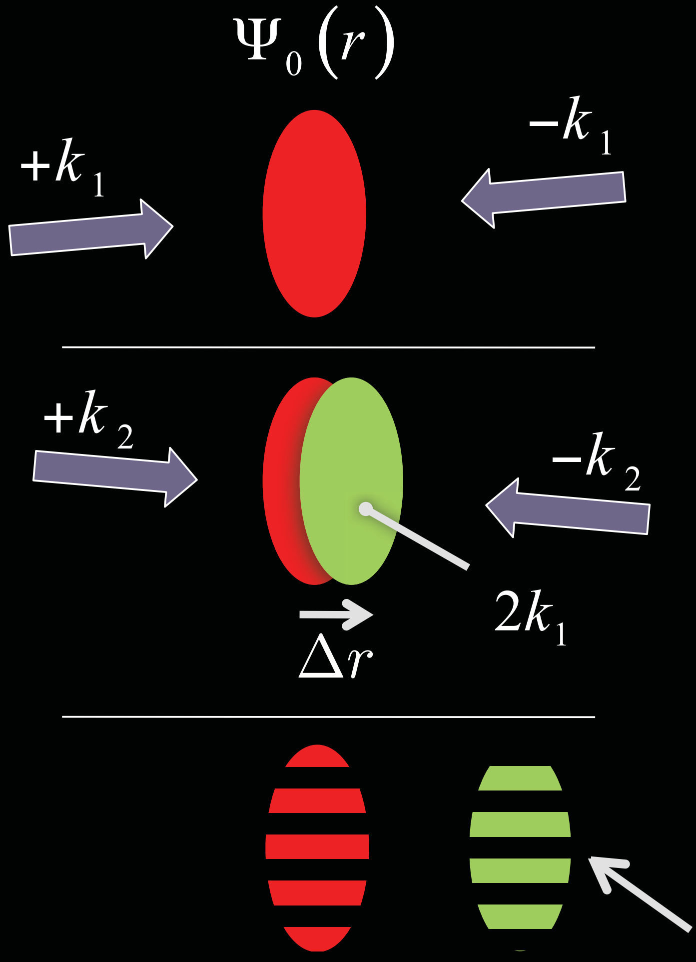
Campbell 2005

$$|\Psi_0(r) + e^{i\phi}\Psi_0(r+\Delta r)|^2$$

Spatial heterodyne atom interferometry

Ramsey-type (two pulse) Bragg scattering with 2 different wavevectors:

see Cladé et al, arXiv:0805.3519



$$\sim a_1 \Psi_0(r) e^{i2k_1 \cdot r}$$

$$\sim a_2 \Psi_0(r + \Delta r) e^{i2k_2 \cdot r}$$

$$|a_1 \Psi_0(r) e^{i2k_1 \cdot r} + a_2 \Psi_0(r + \Delta r) e^{i2k_2 \cdot r}|^2$$

$$|a_1\Psi_0(r)e^{i2k_1\cdot r} + a_2\Psi_0(r+\Delta r)e^{i2k_2\cdot r}|^2$$

$$a_1^2\Psi_0^*(r)\Psi_0(r) + a_2^2\Psi_0^*(r+\Delta r)\Psi_0(r+\Delta r) + \left(a_1a_2\Psi_0^*(r)\Psi_0(r+\Delta r)e^{i\Delta k\cdot r} + c.c.\right)$$

Density from first pulse

Density from second pulse

Interesting quantity

$$F(\Delta k) = \int dr \left[(\cancel{n_1} + \cancel{n_2})e^{-i\Delta k\cdot r} + a_1a_2\Psi_0^*(r)\Psi_0(r+\Delta r) + \cancel{c r}.t\right]$$

"good heterodyne" approximation

$$F(\Delta k) \sim \langle\Psi_0^*(r)\Psi_0(r+\Delta r)\rangle$$

"First order correlation function":

$$\tilde{g}^{(1)} = \frac{F(\Delta k) + F(-\Delta k)}{N_1 + N_2} = g^{(1)} \times f(\Delta r)$$

test run: scalar BEC

Kapitza-Dirac pulses in Raman-Nath regime

absorption image after time of flight

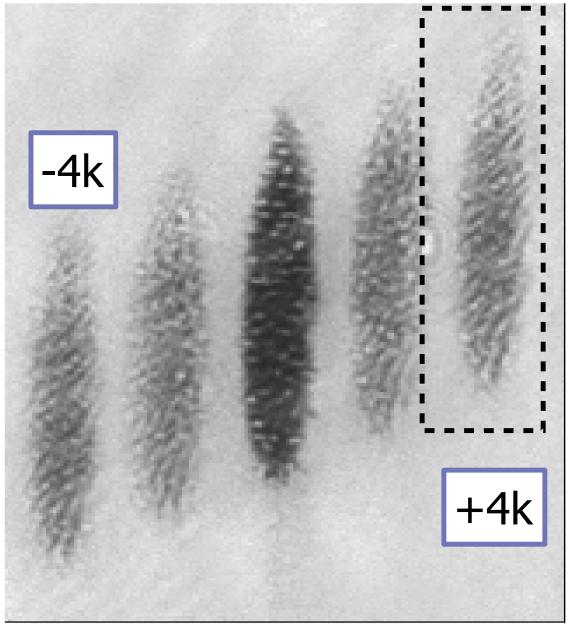
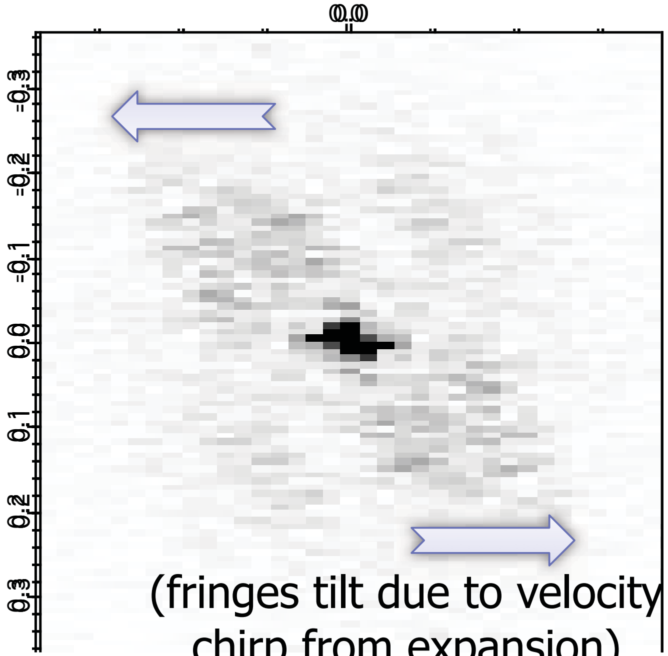
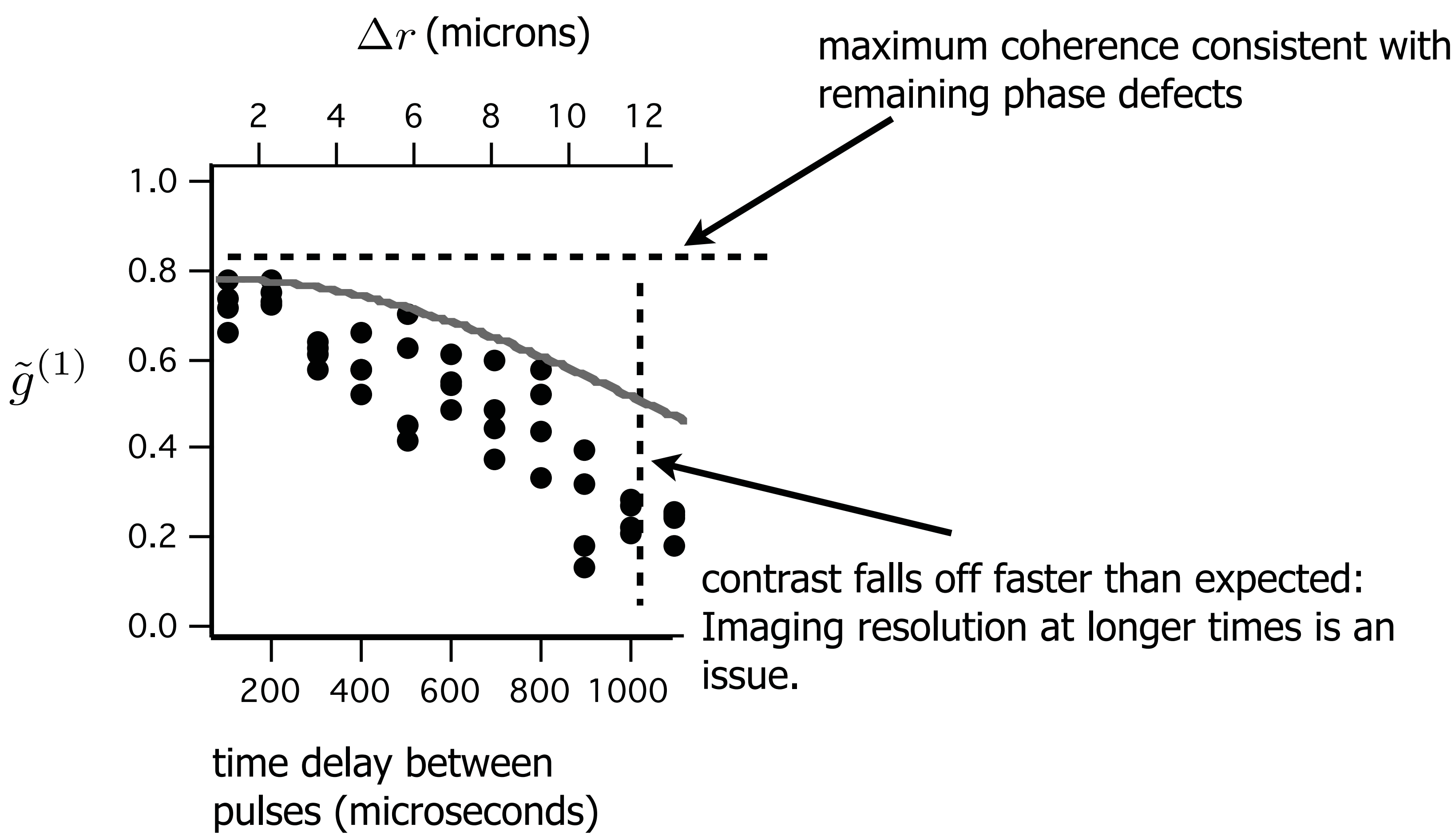


image Fourier transform



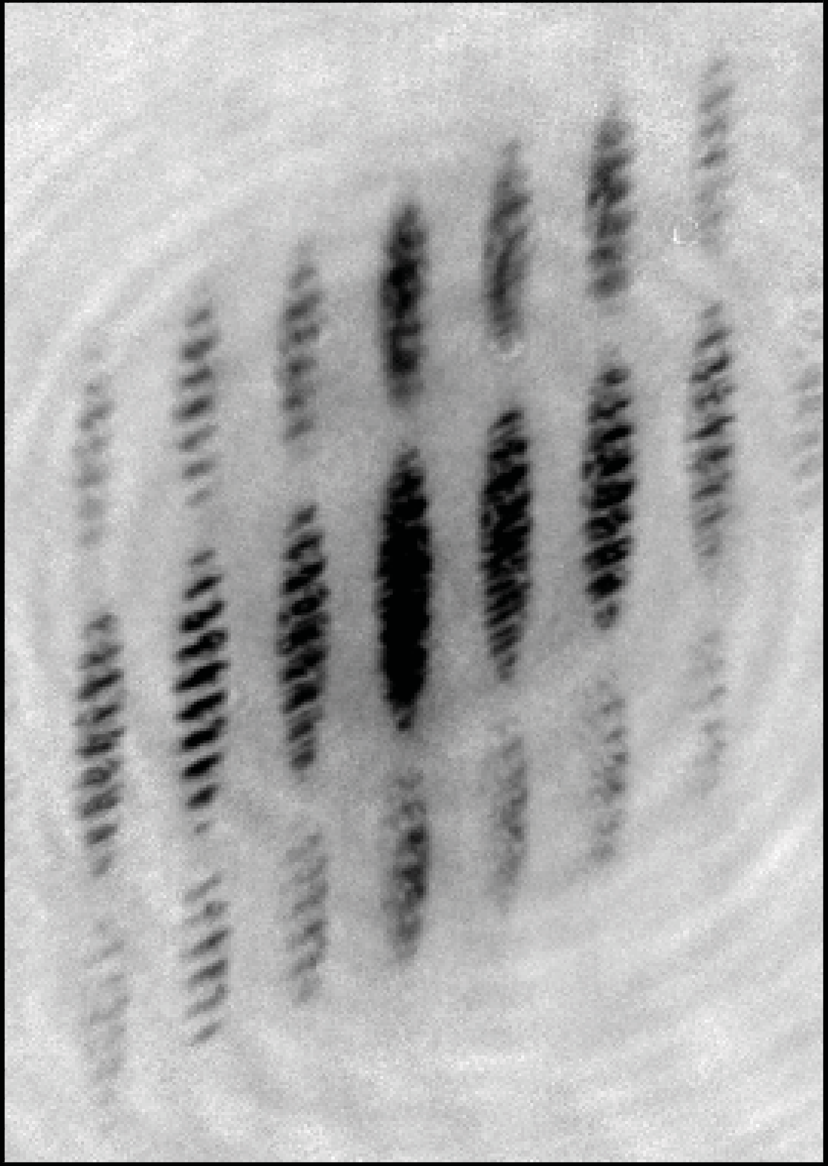
(fringes tilt due to velocity chirp from expansion)

test run: scalar BEC



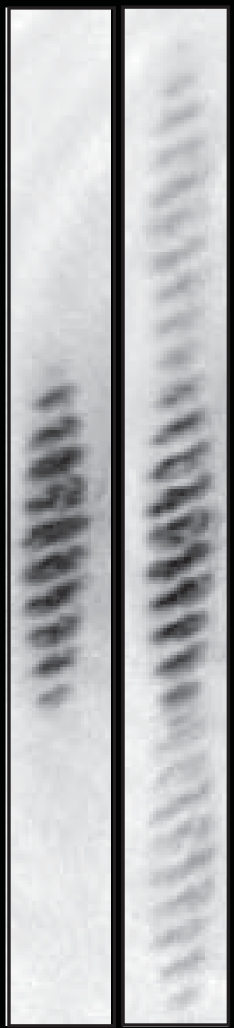
Atom interferometry: with spinors

- Stern-Gerlach separation
- Many orders diffracted
- Challenge to keep everything in focus
- Very cool!



Spinor gases in crystalline phase

without Stern-Gerlach spin separation



with Stern-Gerlach spin separation

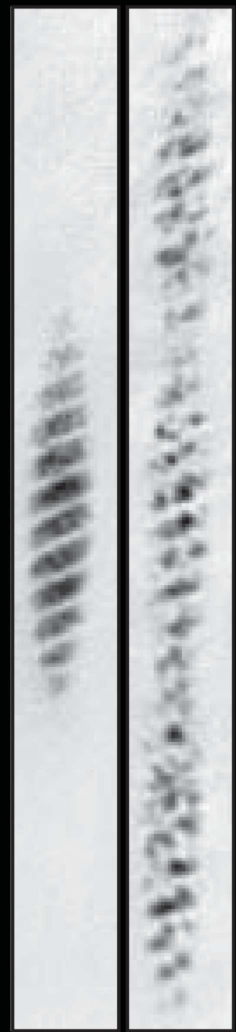
m_z=+1

m_z=0

m_z=-1

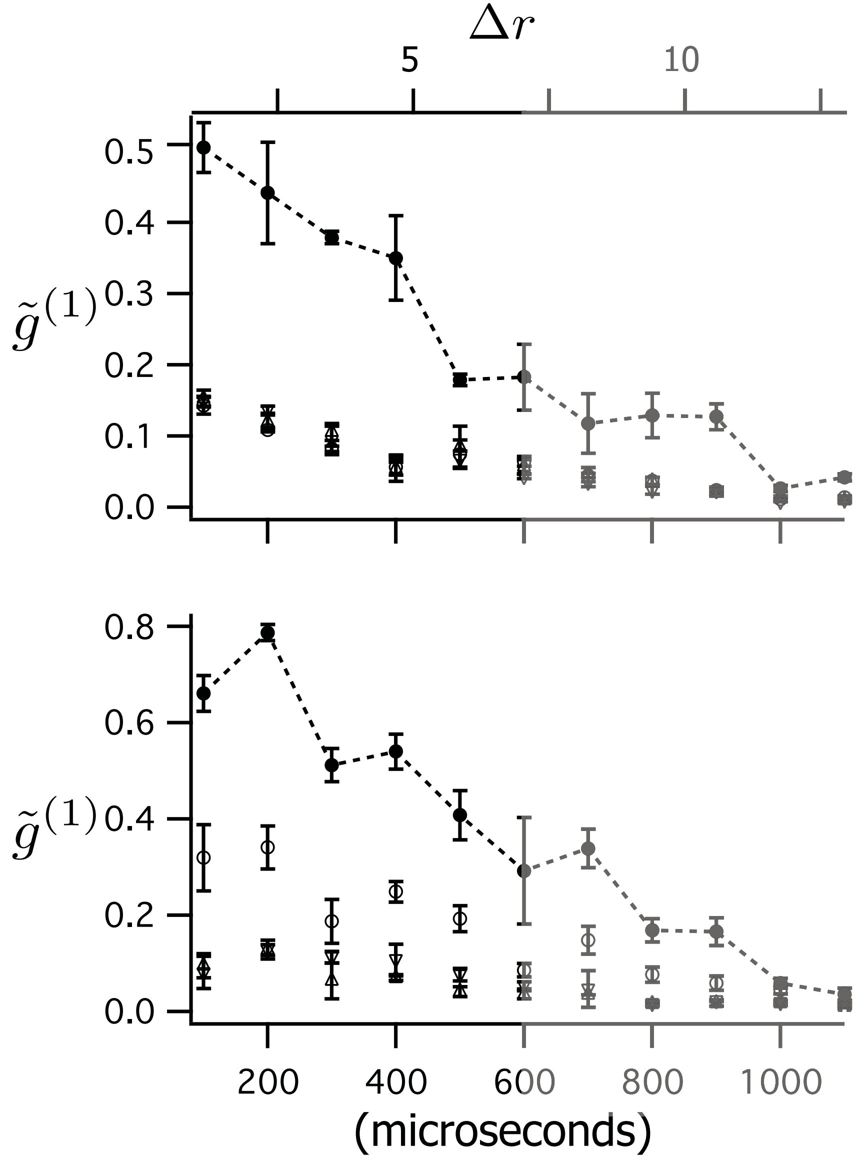
Transversely magnitized
no crystal

η=1/4



η=0

Spinor gases in crystalline phase



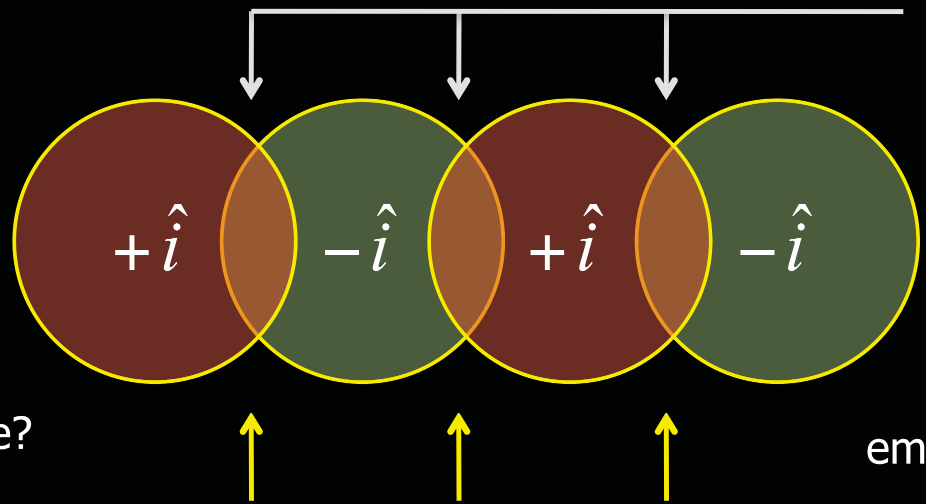
η=0: coherence is shared equally between three components

η=1/4: m=0 component has majority of coherence (also majority of atoms)

Generally: we see long range coherence for crystalline phase

Possible coherence in the crystalline phase

Observed checkerboard lattice:



unmagnetized domain walls

emergent spin axis

$\pm\hat{i}$

Phase coherence?

emergent nematic axis

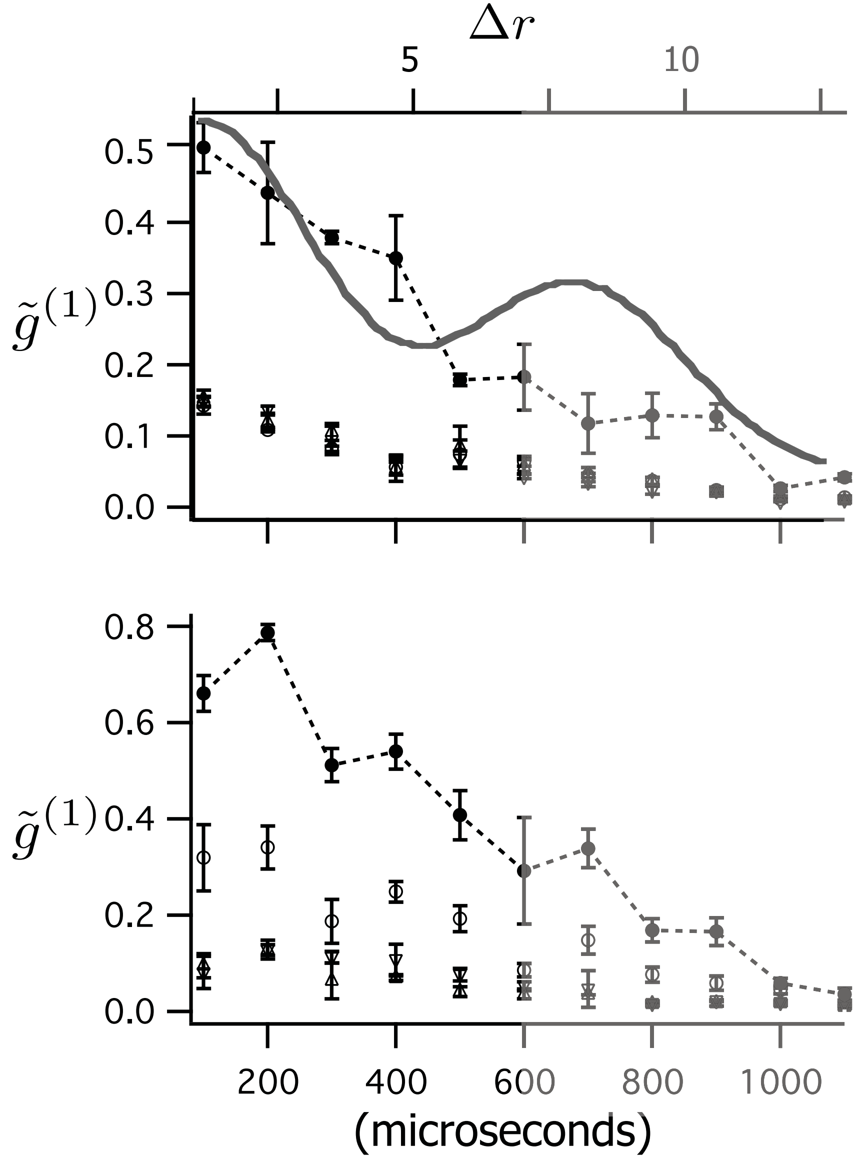
$\pm\hat{j}$

$$\Psi(\text{wall}) = \frac{1}{\sqrt{2}}\left(\left|+\hat{i}\right\rangle + e^{i\phi}\left|-\hat{i}\right\rangle\right) = \left|m_{\hat{j}} = 0\right\rangle$$

1. Latent long-range magnetic order: a second nematic axis

2. Long-range off-diagonal order of nematic background

Spinor gases in crystalline phase



about half of the m=+/-1 atoms contribute to the crystal

λ = 2π (10μm) crystal

Summary

- Is ^{87}Rb F=1 spinor gas a supersolid at low temperature?
  - Not certain…
- Ingredients: mobile bosons (exchange) + long-range interactions (dipolar)
- Evidence for crystalline ordering from direct imaging
  - thermal equilibrium?
  - initial state dependence: hysteresis? metastability?
  - small system size (~6 domains wide). "quasi-long-range?" hexatic?
  - other properties of a solid not yet probed.
  - crystal not observed in interferometry experiment.
- Evidence for superfluidity from atom interferometry
  - measured across 30 micron dimension
  - other properties of superfluid not yet probed

Current status

- Is ^{87}Rb F=1 spinor gas a <u>supersolid</u> at low temperature?
- Not certain…
- thermal equilibrium?
- small system size (~6 domains wide). "quasi-long-range?" hexatic?
- other properties of a solid not yet probed

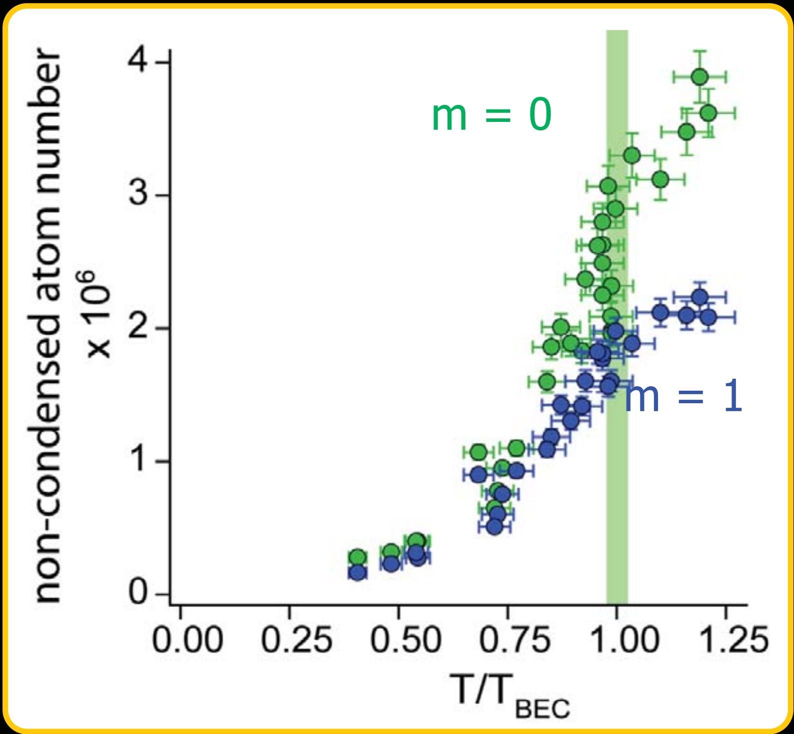
Constructed a new experimental apparatus:
Longer equilibration times,
Faster duty cycle
Better magnetic field control
Better optical access
Cancel mean-field expansion


E1: Spinor BEC
Jennie Guzman
(Sabrina Leslie)
Kater Murch
(Friedhelm Serwane)
(Mukund Vengalattore)
E2,E3: Cavity QED
Thierry Botter
Nathan Brahams
Daniel Brooks
Gee-Na Kim
Zhao-Yuan Ma
Guil Miranda
Tom Purdy
E4: Ring-trap interferometry
Ed Marti
Ryan Olf
Tony Oettl
Enrico Vogt

DARPA

non-equilibrium? metastable? extrinsic?

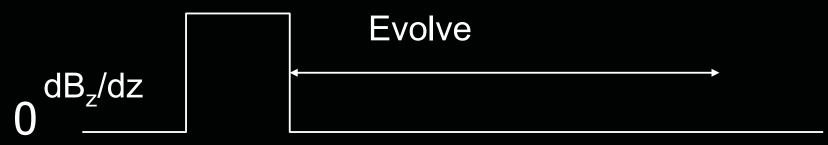
- non-equilibrium thermal spin mixture persists only above T_{BEC}

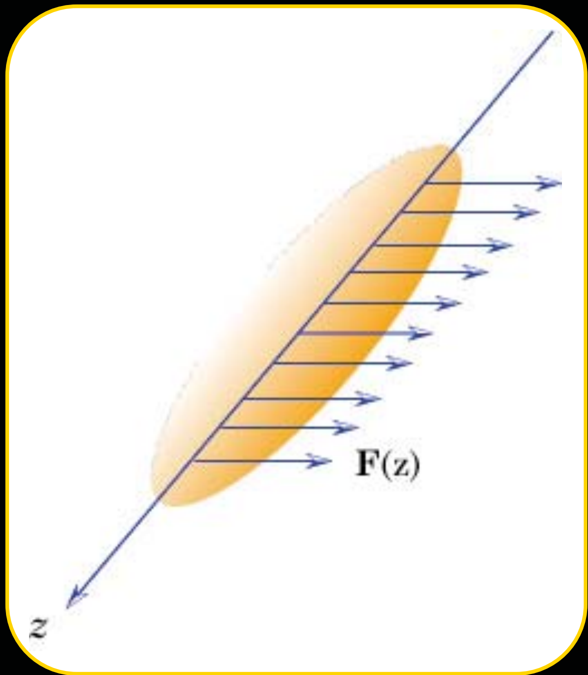


- no variation with cooling time, equilibration time
- crystalline pattern seen in relaxation from other states (quench, helix)
- low-temperature, small atom-number gases are crystalline

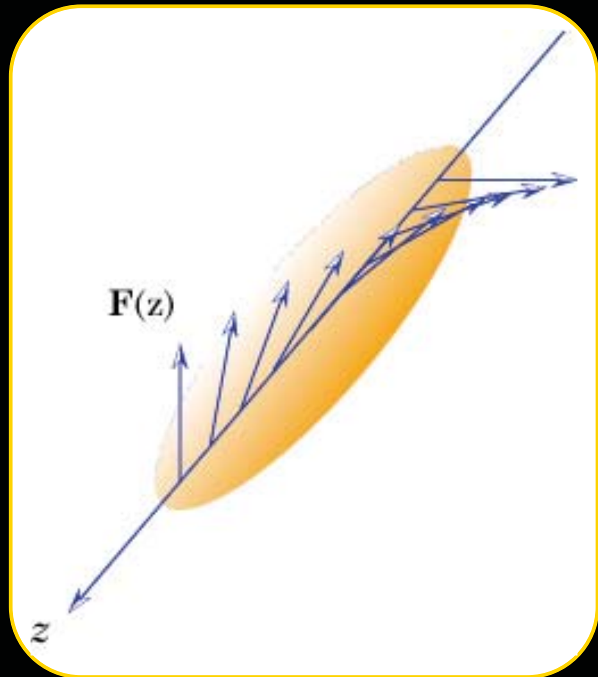
Experiment 1: Dissolution of ferromagnetic spin textures

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

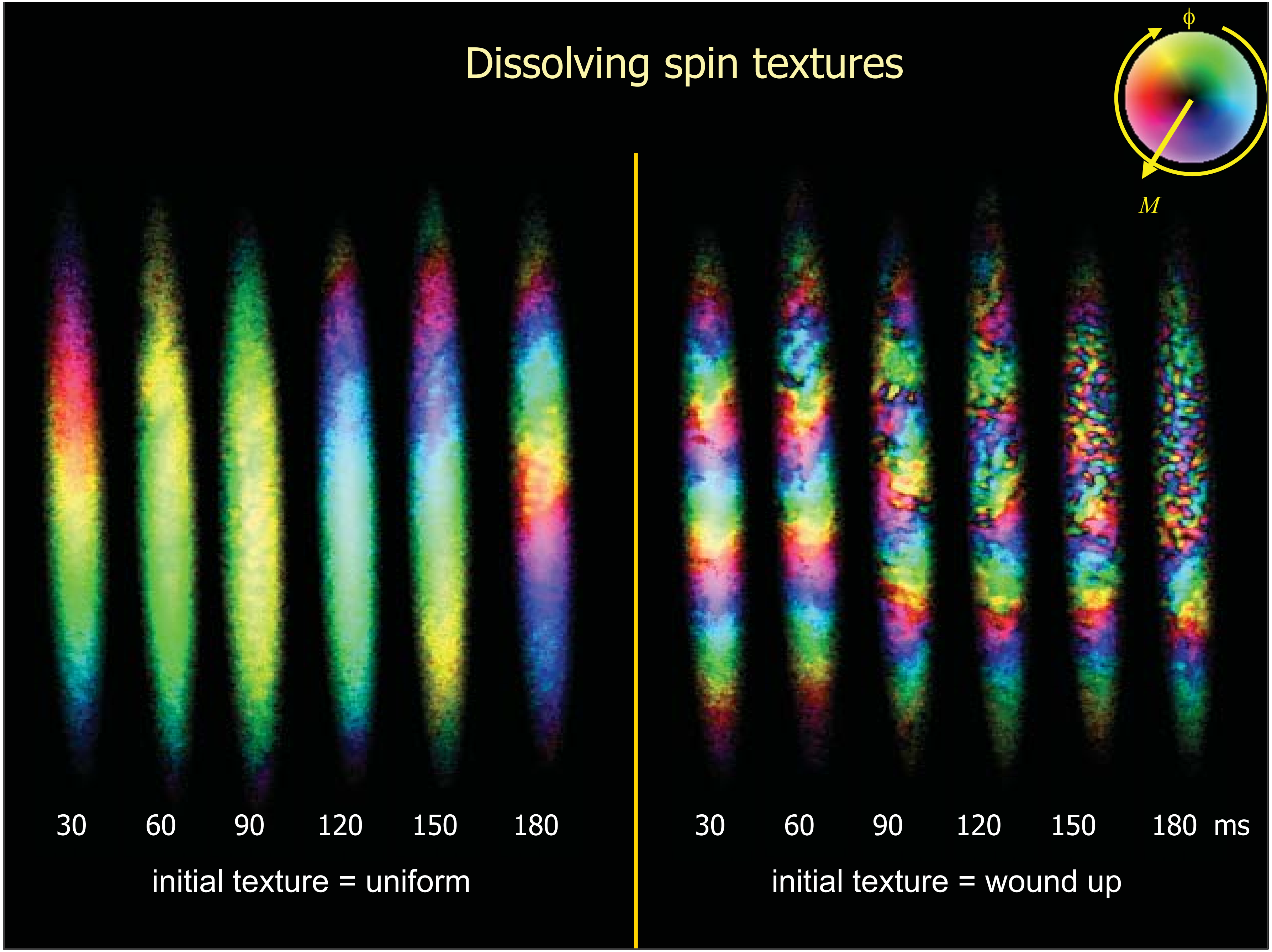


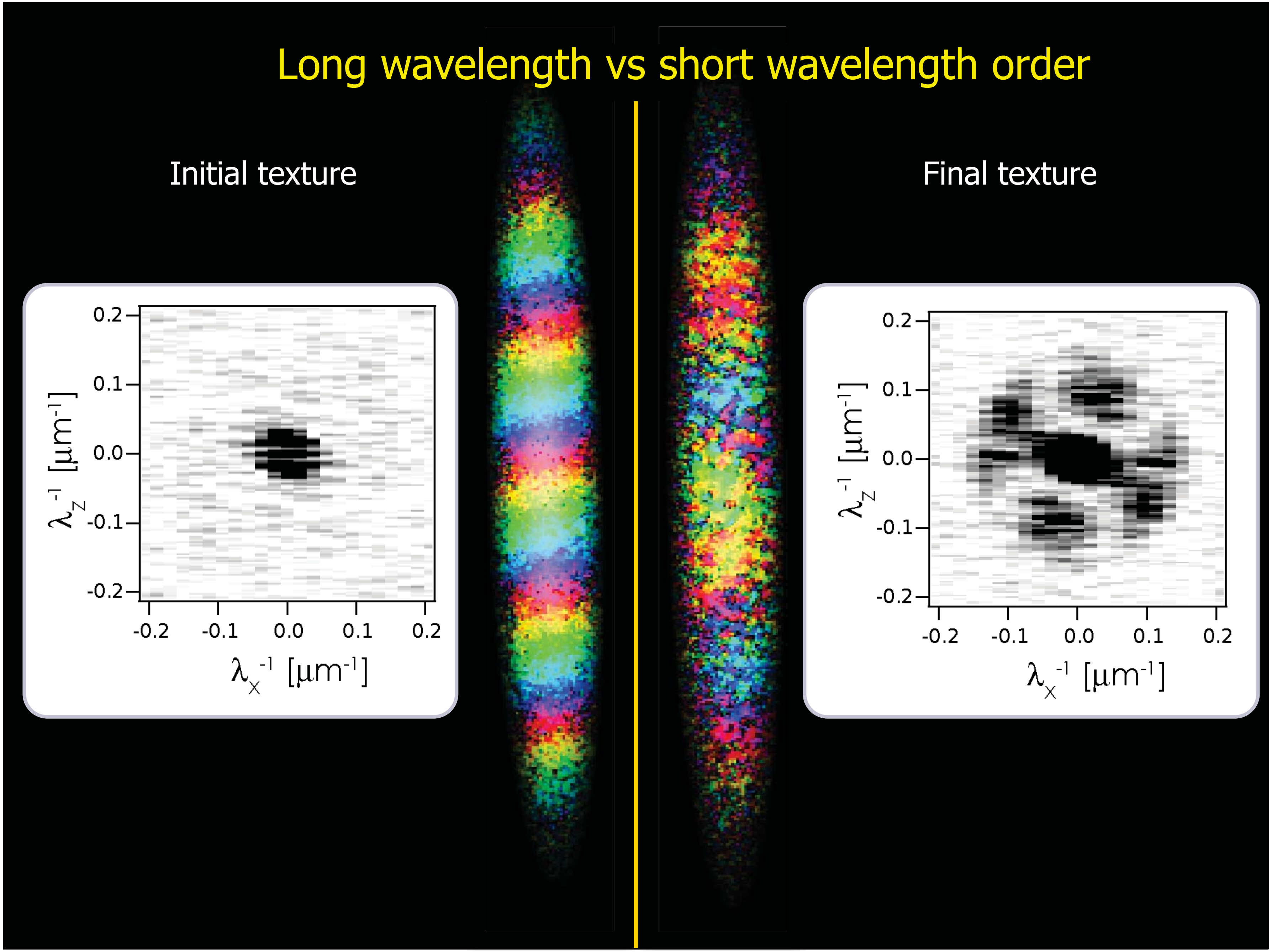


w/o gradient
zero-wavevector helix

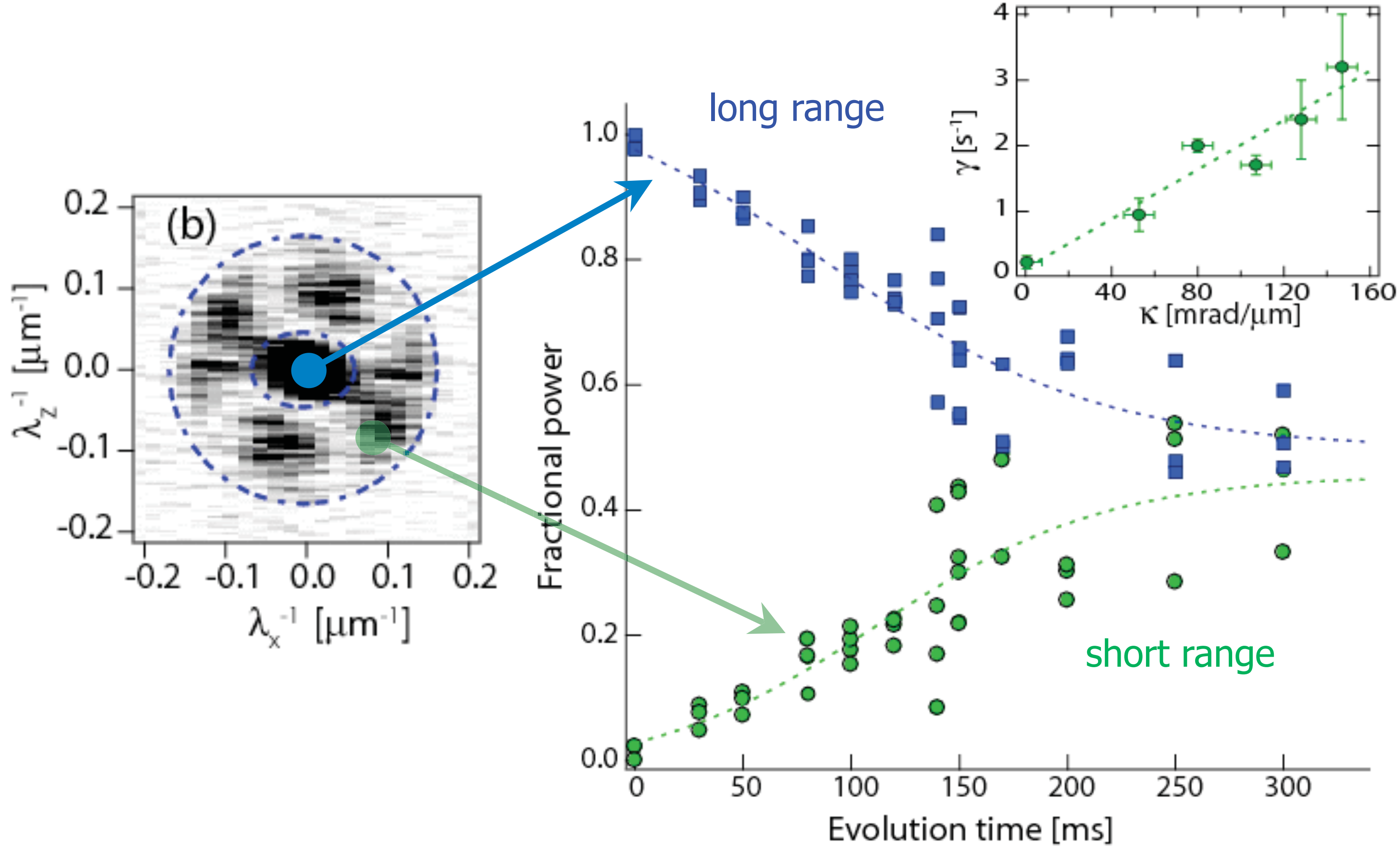


with gradient
non-zero-wavevector helix

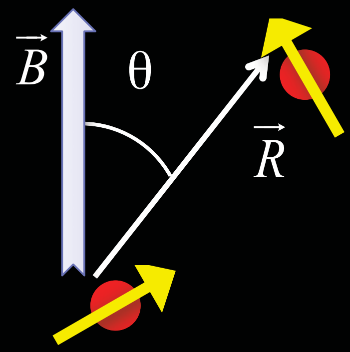

Dissolving spin textures
ϕ
M
30 60 90 120 150 180
initial texture = uniform
30 60 90 120 150 180 ms
initial texture = wound up


Long wavelength vs short wavelength order
Initial texture
Final texture
0.2
0.1
0.0
-0.1
-0.2
-0.2
-0.1
0.0
0.1
0.2
λ_z^{-1} [µm^{-1}]
λ_x^{-1} [µm^{-1}]
0.2
0.1
0.0
-0.1
-0.2
-0.2
-0.1
0.0
0.1
0.2
λ_z^{-1} [µm^{-1}]
λ_x^{-1} [µm^{-1}]

Long wavelength vs short wavelength order



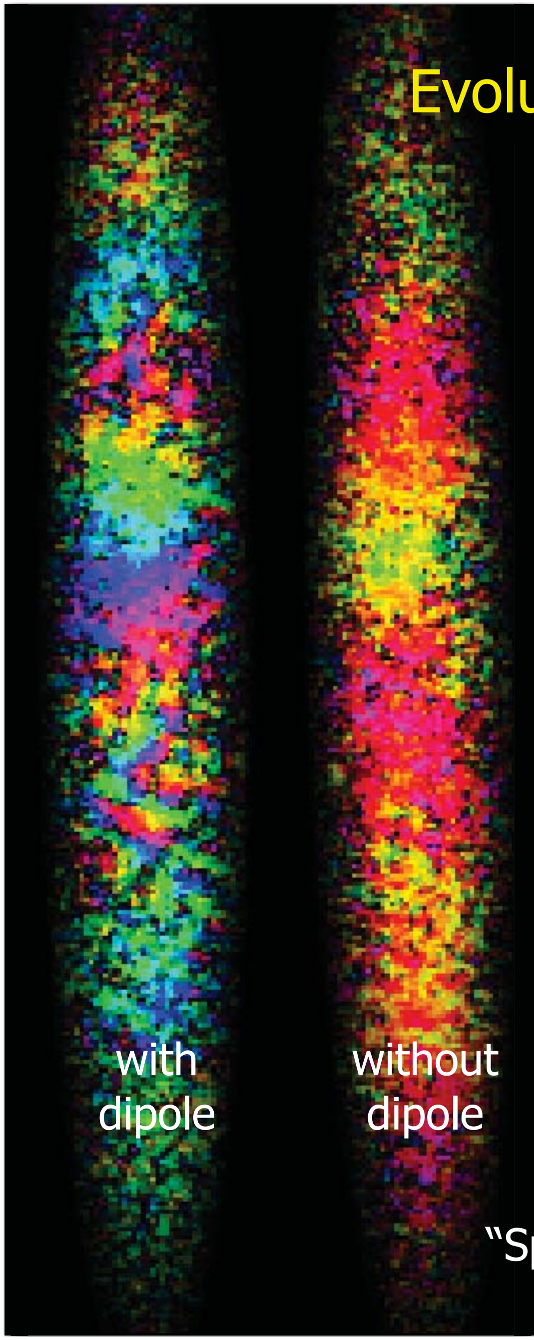
tempering dipolar interactions

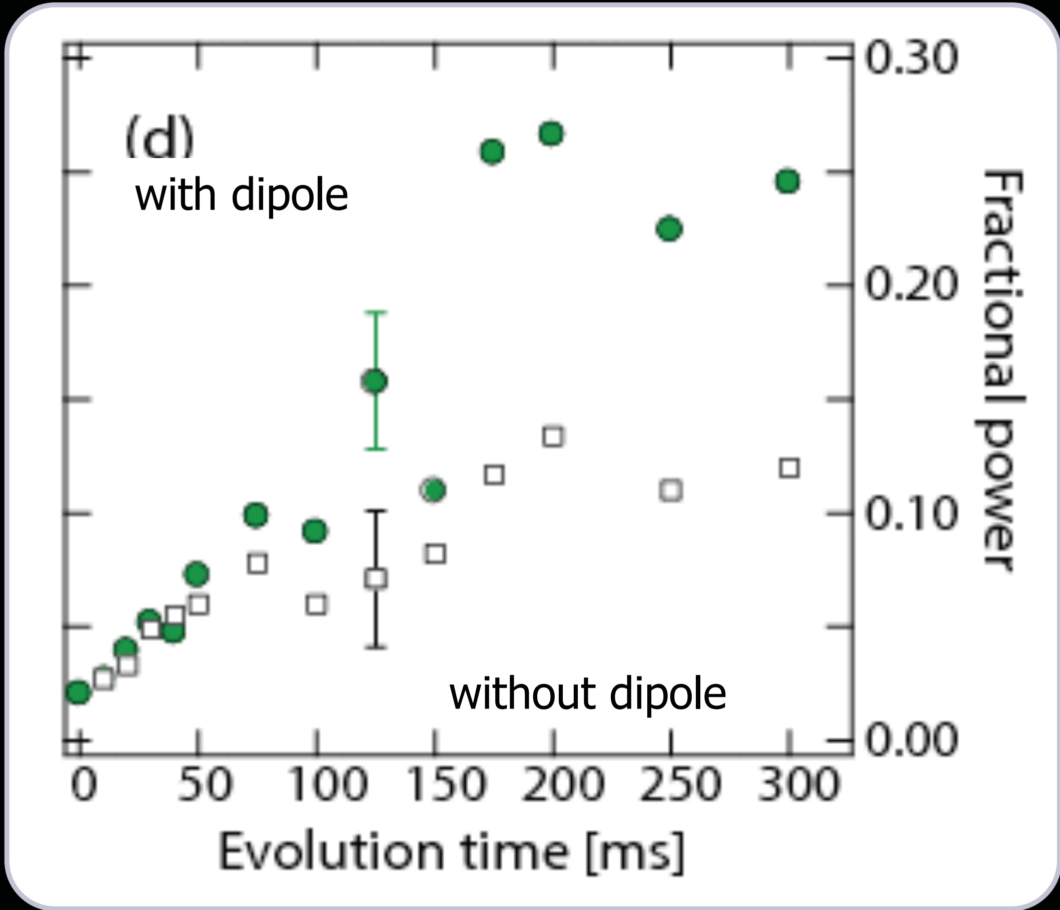


$$U = -J\left(\frac{3}{2}\cos^2\theta - \frac{1}{2}\right)\left[F_{1,z}F_{2,z} - \frac{1}{2}\left(F_{1,x}F_{2,x} + F_{1,y}F_{2,y}\right)\right]$$

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

Evolution with/without dipolar interactions





Strength of short lengthscale modulation

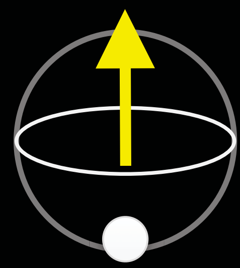
"Spontaneously modulated spin textures in a dipolar spinor BEC,"
PRL **100**, 170403 (2008)

Quantum states of an F=1 atom

Examples:

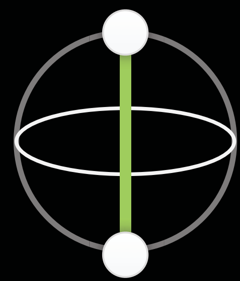
"magnetic"
"oriented"

$$\Psi = \hat{R}\left| m_z = 1 \right\rangle$$



"non-magnetic"
"nematic"
"aligned"

$$\Psi = \hat{R}\left| m_z = 0 \right\rangle$$



Barnett, Turner, Demler
[PRL **97**, 180401 (2007)]

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:

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

excess ~ 30 pK; λ = 60 μm

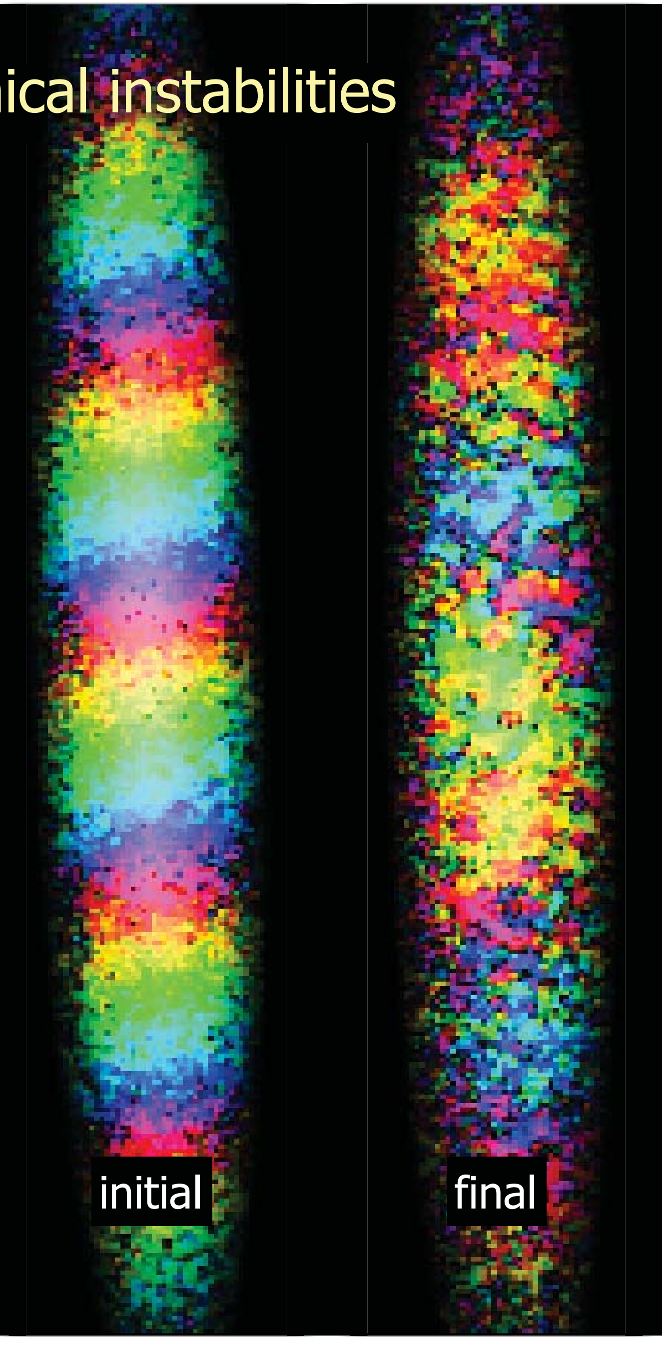
- spin current kinetic energy

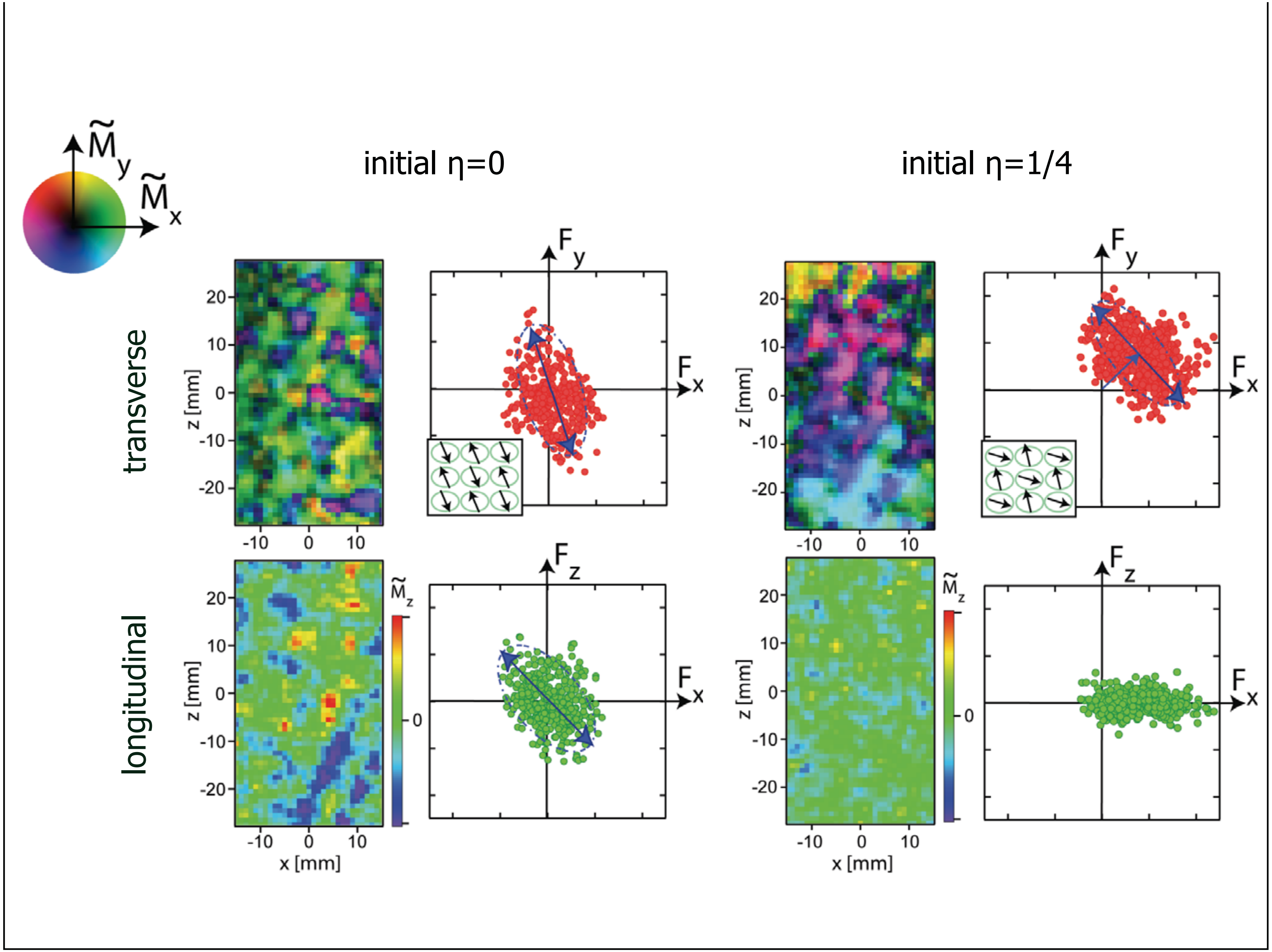
λ ≥ 50 μm   ν ≤ 1 Hz

Possible role of dynamical instabilities

- Lamacraft, PRA 77, 062622 (2008), Cherng, et al., PRL 100, 180404 (2008)
  - spiral state is dynamically unstable

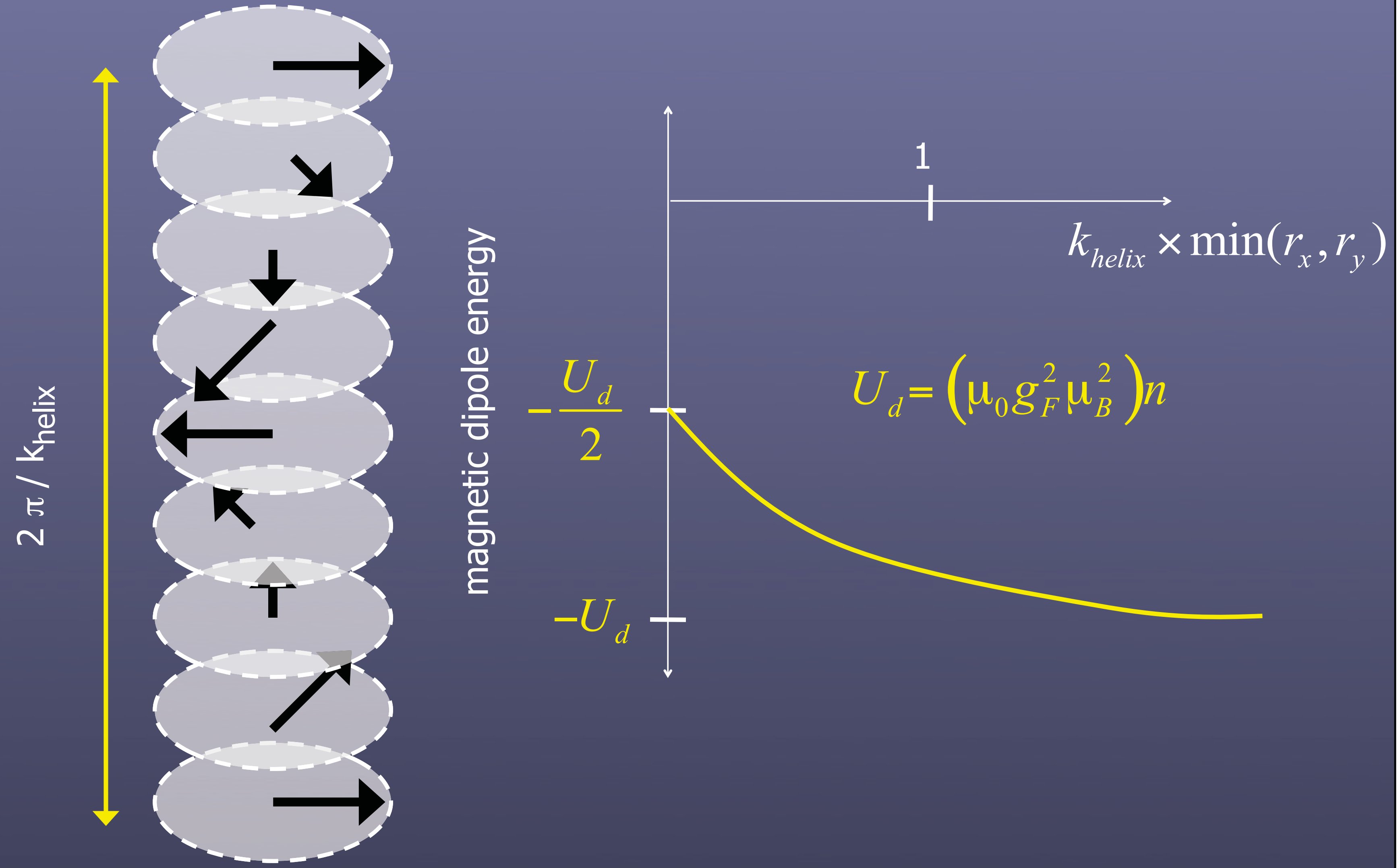
But whence the energy?

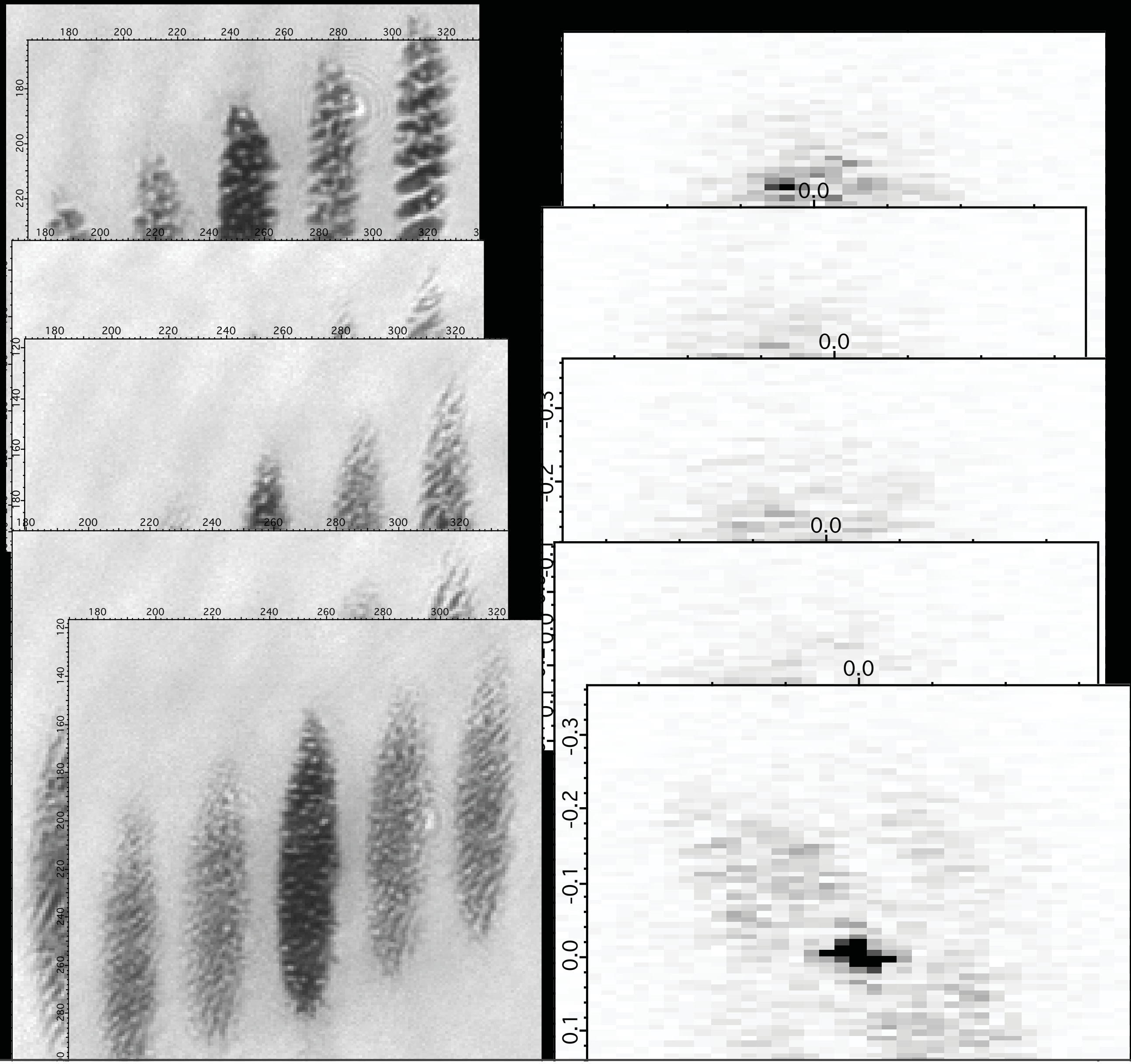




initial η=0
initial η=1/4
transverse
longitudinal
z [mm]
x [mm]
F_y
F_x
F_z
M̃_x
M̃_y
M̃_z
20
10
0
-10
-20

Dipolar interactions in the spin helix




0.0
-0.3
-0.2
-0.1
0.0
0.1

Supersolid = superfluid + solid?

"stiff" – shear modulus
spatially ordered
constituents "localized"

"flows"
not ordered
constituents "delocalized"

- Does quantum mechanics blur the distinction between these at T=0?