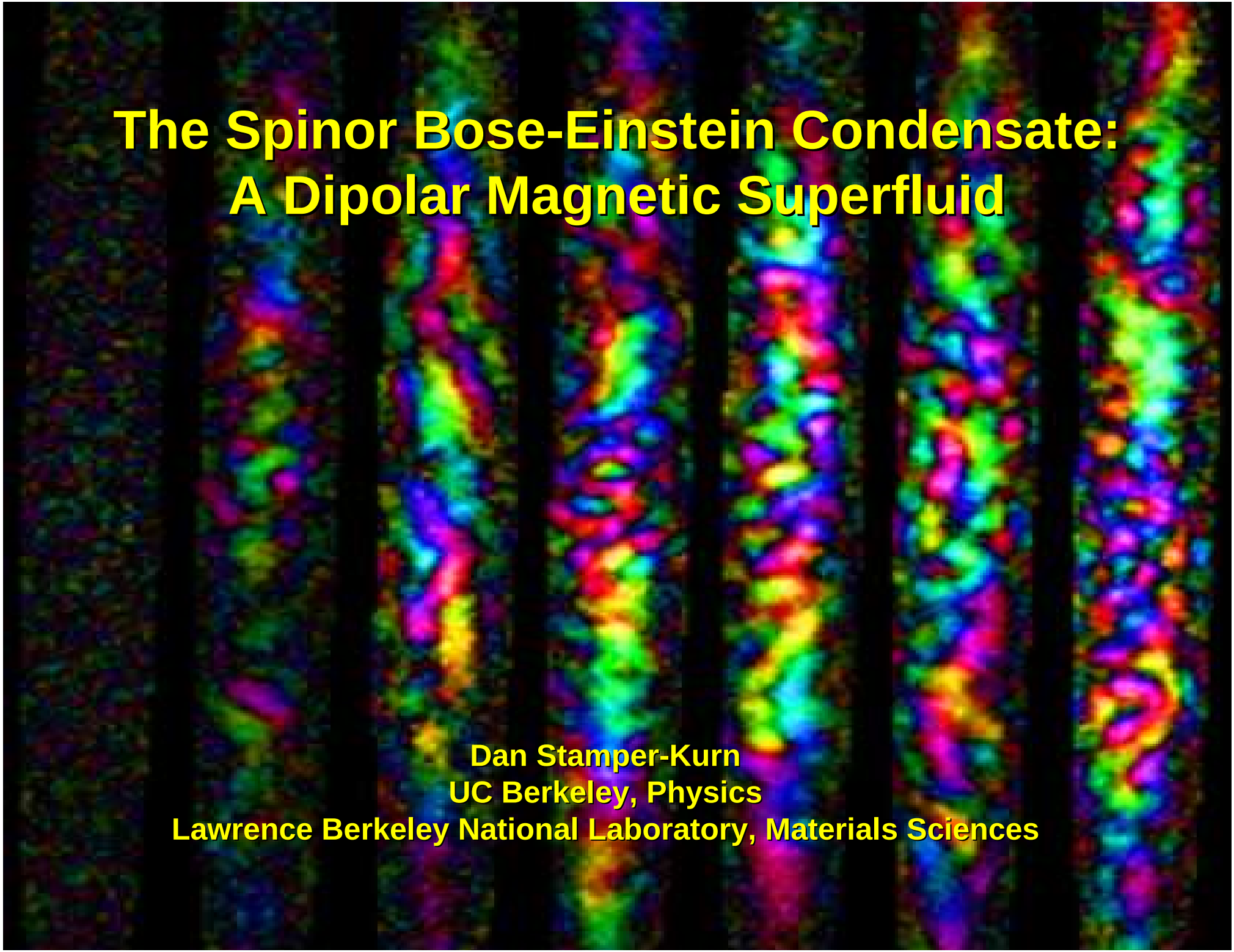
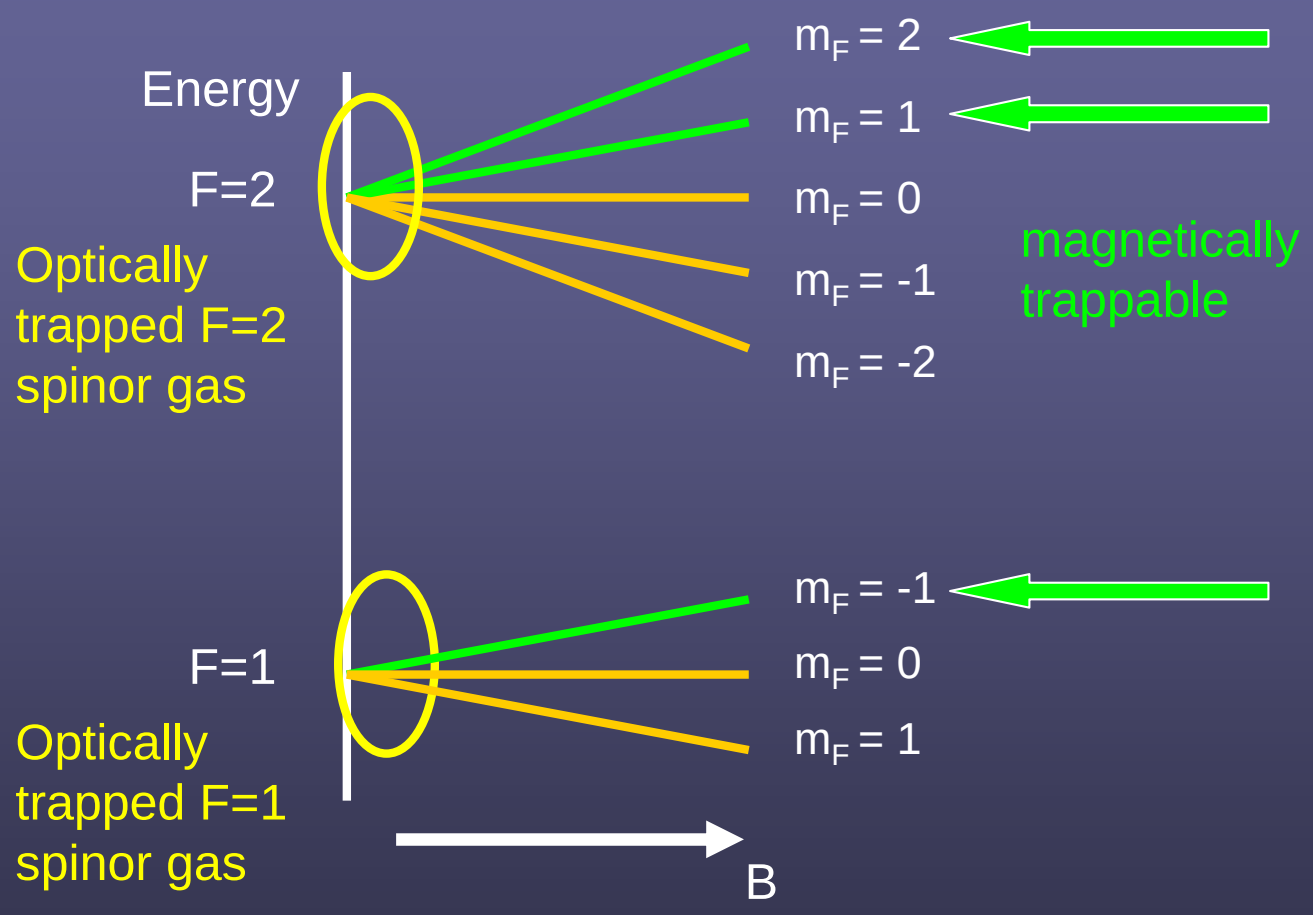


The Spinor Bose-Einstein Condensate: A Dipolar Magnetic Superfluid

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

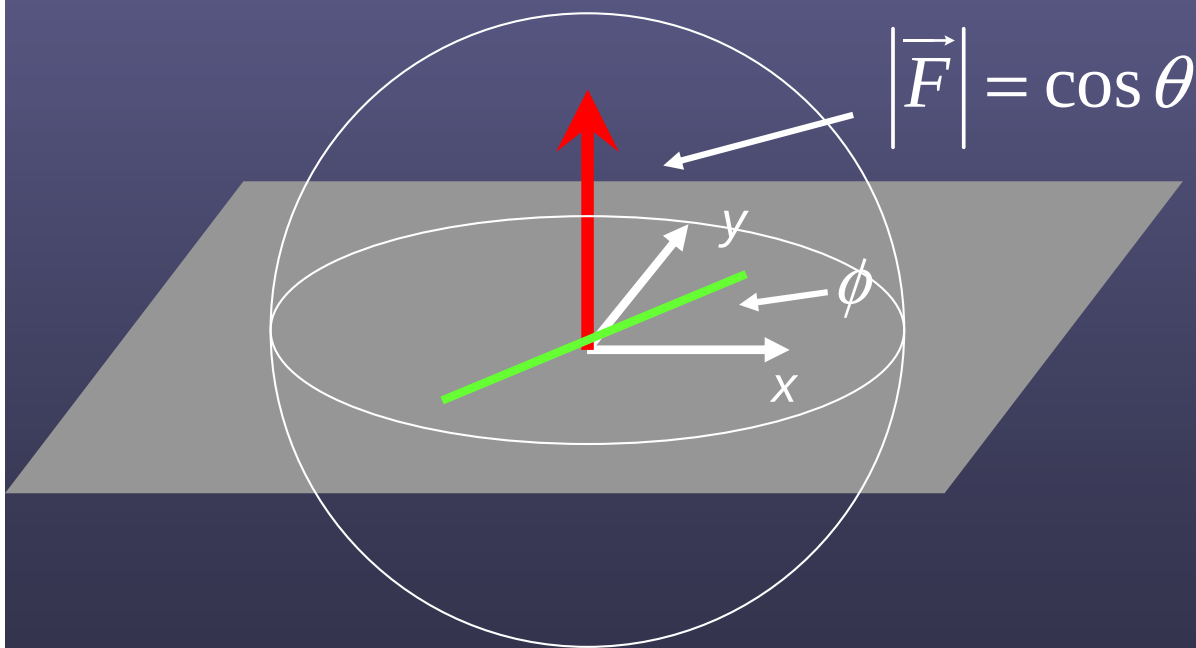
Spinor gases



What do we want to know?

$$\rho = \begin{pmatrix} \rho_{+1,+1} & \rho_{+1,0} & \rho_{+1,-1} \\ \rho_{0,+1} & \rho_{0,0} & \rho_{0,-1} \\ \rho_{-1,+1} & \rho_{-1,0} & \rho_{-1,-1} \end{pmatrix}$$

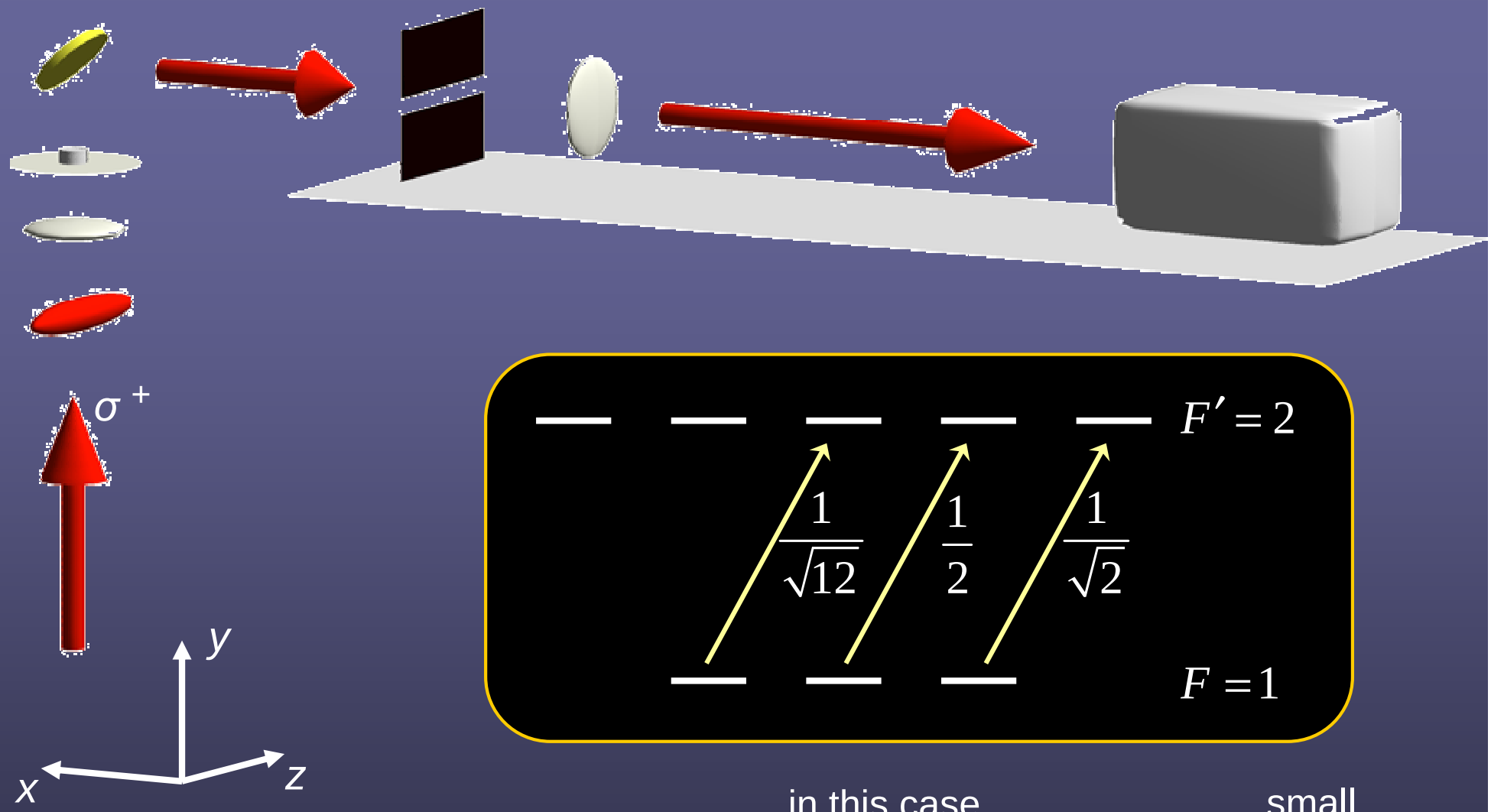
$$\chi = \begin{pmatrix} \chi_{\sigma^+,\sigma^+} & \chi_{\sigma^+,\pi} & \chi_{\sigma^+,\sigma^-} \\ \chi_{\pi,\sigma^+} & \chi_{\pi,\pi} & \chi_{\pi,\sigma^-} \\ \chi_{\sigma^-,\sigma^+} & \chi_{\sigma^-,\pi} & \chi_{\sigma^-,\sigma^-} \end{pmatrix}$$



spin F
Δm=1 coherences
“orientation”

nematicity N
Δm=2 coherences
“alignment”

$$R\left(e^{i\phi}\cos\frac{\theta}{2}\left|m=1\right\rangle - e^{-i\phi}\sin\frac{\theta}{2}\left|m=-1\right\rangle \right)$$



signal
(# photons/pixel)

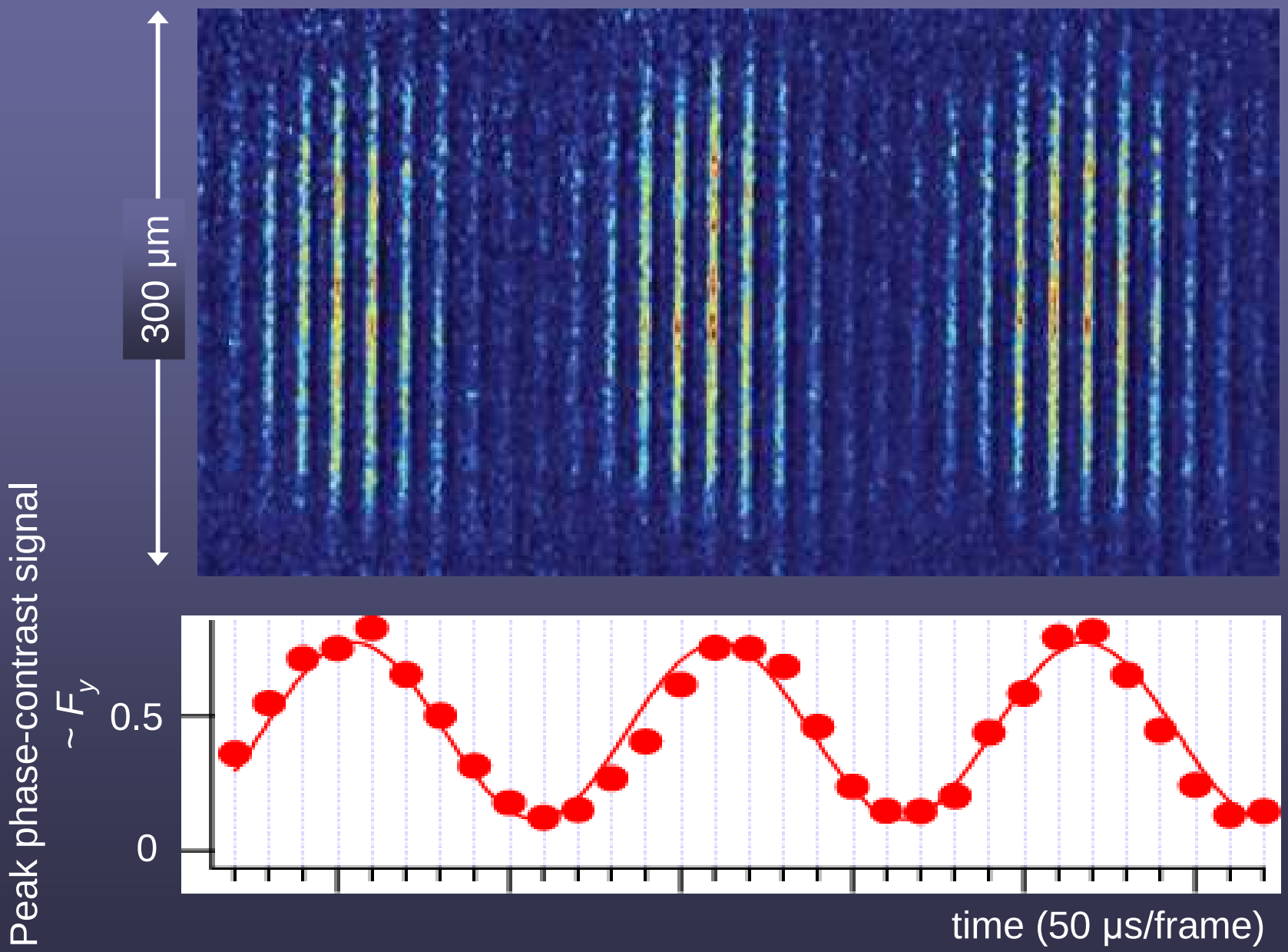
in this case

small

$$S = N_\gamma \left[1 + A\left((\square\, 1) + \langle F_y \rangle + \varepsilon \langle F_y^2 \rangle \right) \right]$$

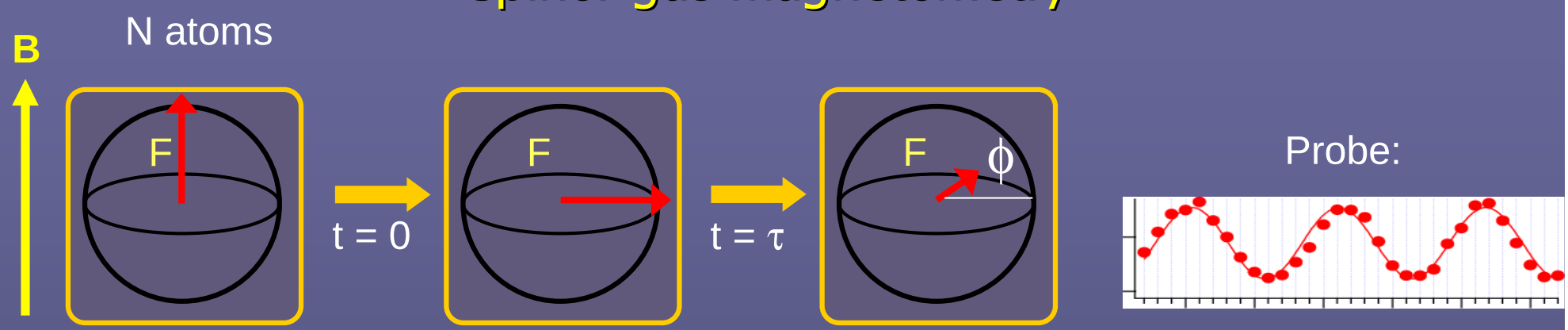
$\propto n_{2D}$

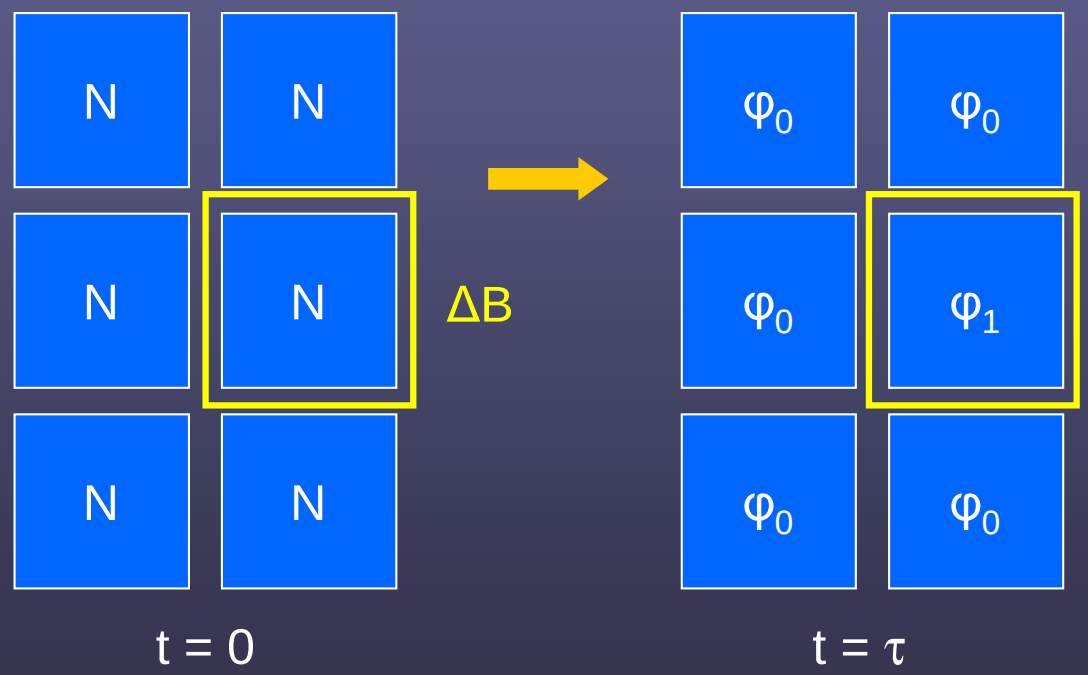
Direct imaging of Larmor precession



Aliased sampling: 2 x 20 kHz – Observed rate = 38.097(15) kHz

Spinor gas magnetometry



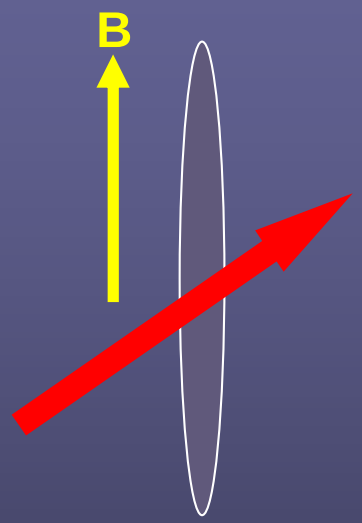


Area-resolving: $$\Delta B = \left(\frac{\hbar}{g \mu_B} \frac{1}{\sqrt{D T_{coh} n_{2D}}} \right) \times \frac{1}{\sqrt{T_{total} A}} = S_A \times \frac{1}{\sqrt{T_{total} A}}$$

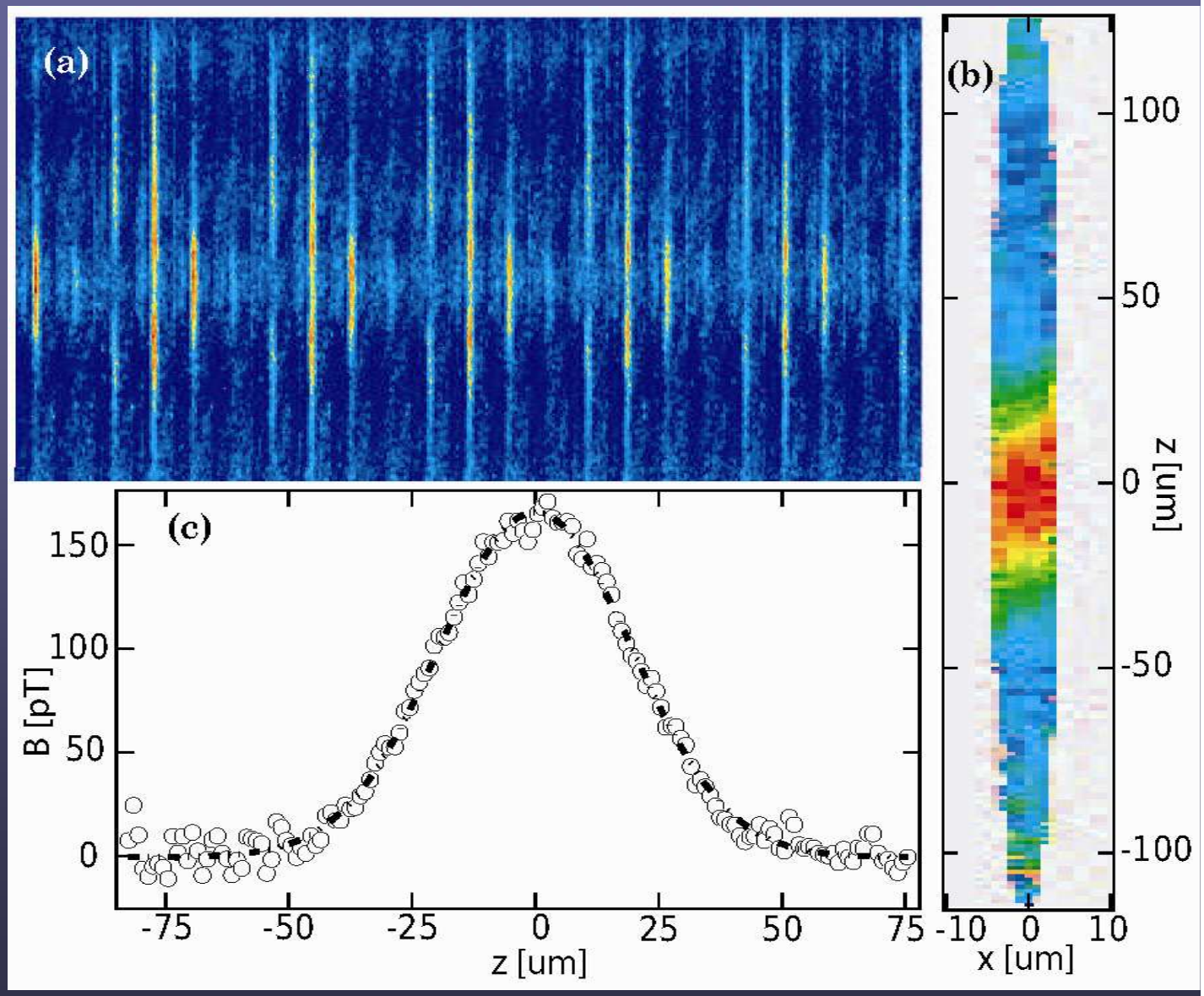
Experimental demonstration

- Clarify fundamental and technical limits on precision
  - single-particle and collective light scattering, experimental tricks
  - unbiased phase estimation methods
- Measure background noise
  - confirm areal and temporal scaling of sensitivity
- Measure localized magnetic field
  - quantum-mechanical diffusion of magnetization
  - limits to dynamic range

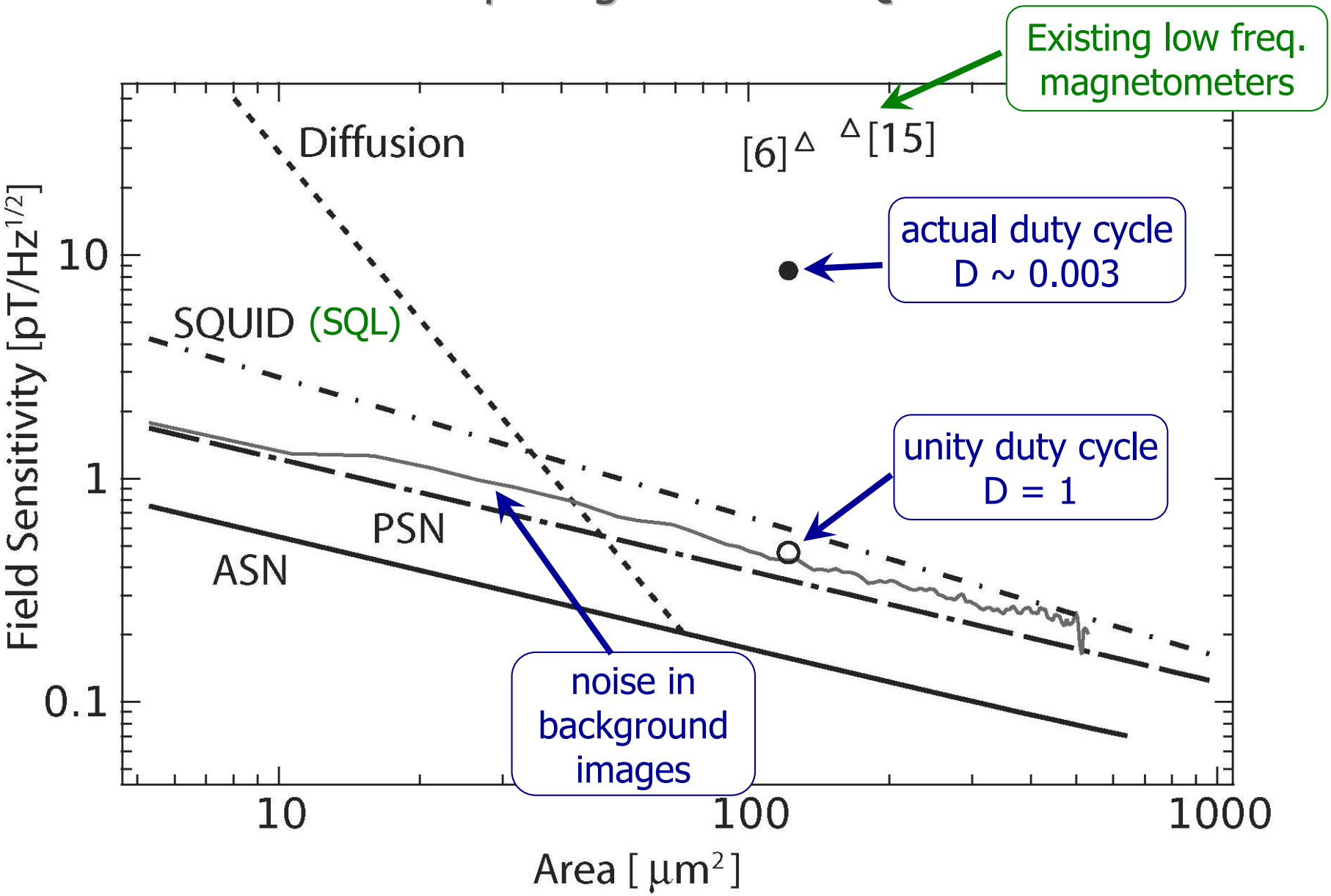
“Field” measurements



AC Stark shift = “Fictitious” magnetic field

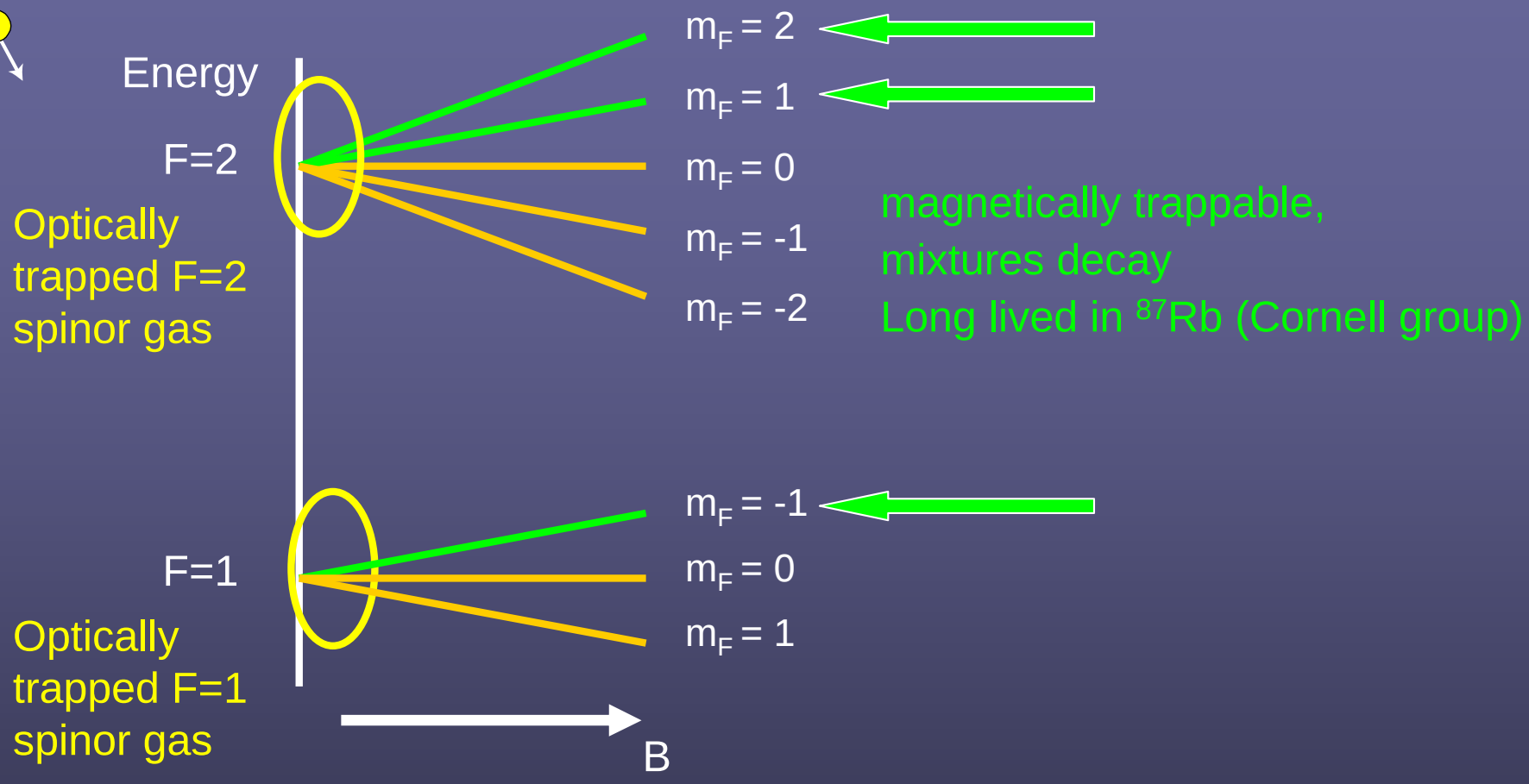


Comparing atoms & SQUIDs



"High resolution magnetometry with a spinor BEC," arXiv:cond-mat/0612685

Bose-Einstein condensates with spin



Quantum fluids are described by vector order parameter (somewhat similar to ^{3}He)

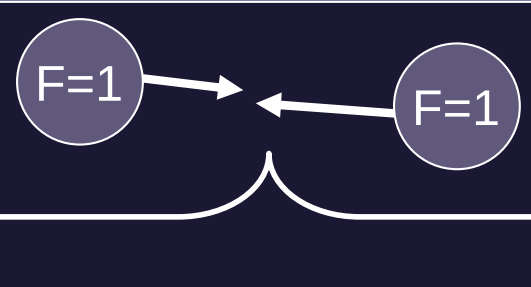
$$\Psi(x) \Longrightarrow \vec{\Psi}(x)$$

so what?

- Symmetries of order parameter
  - broken symmetries + excitations, phase transitions, topologies

- Symmetries in interactions

e.g. F=1 spinor, low B



	$F_{tot} = 0$	$F_{tot} = 1$	$F_{tot} = 2$
ultracold gas (s-wave)	a_0	no interactions leads to spin waves	a_2
single spatial mode (e.g. BEC)	a_0	not allowed	a_2

Energy Scales in a Spinor Condensate (circa 2006)

- Spin dependent interaction energy

$$E_{spin} = c_2\, n \left| \left\langle \vec{F} \right\rangle \right|^2$$

≈ 8 Hz, or 400 picokelvin!

$\propto \Delta a$ Klausen, Bohn, Greene, PRA 64, 053602 (2001)

- Non-linear (quadratic) Zeeman shift

$$E_{quad} = q F_z^2$$

$$q = (72\ \mathrm{Hz}/\mathrm{G}^2) h \times B^2$$

-1 + +1 → 0 + 0

isotropic
interaction energy dominates

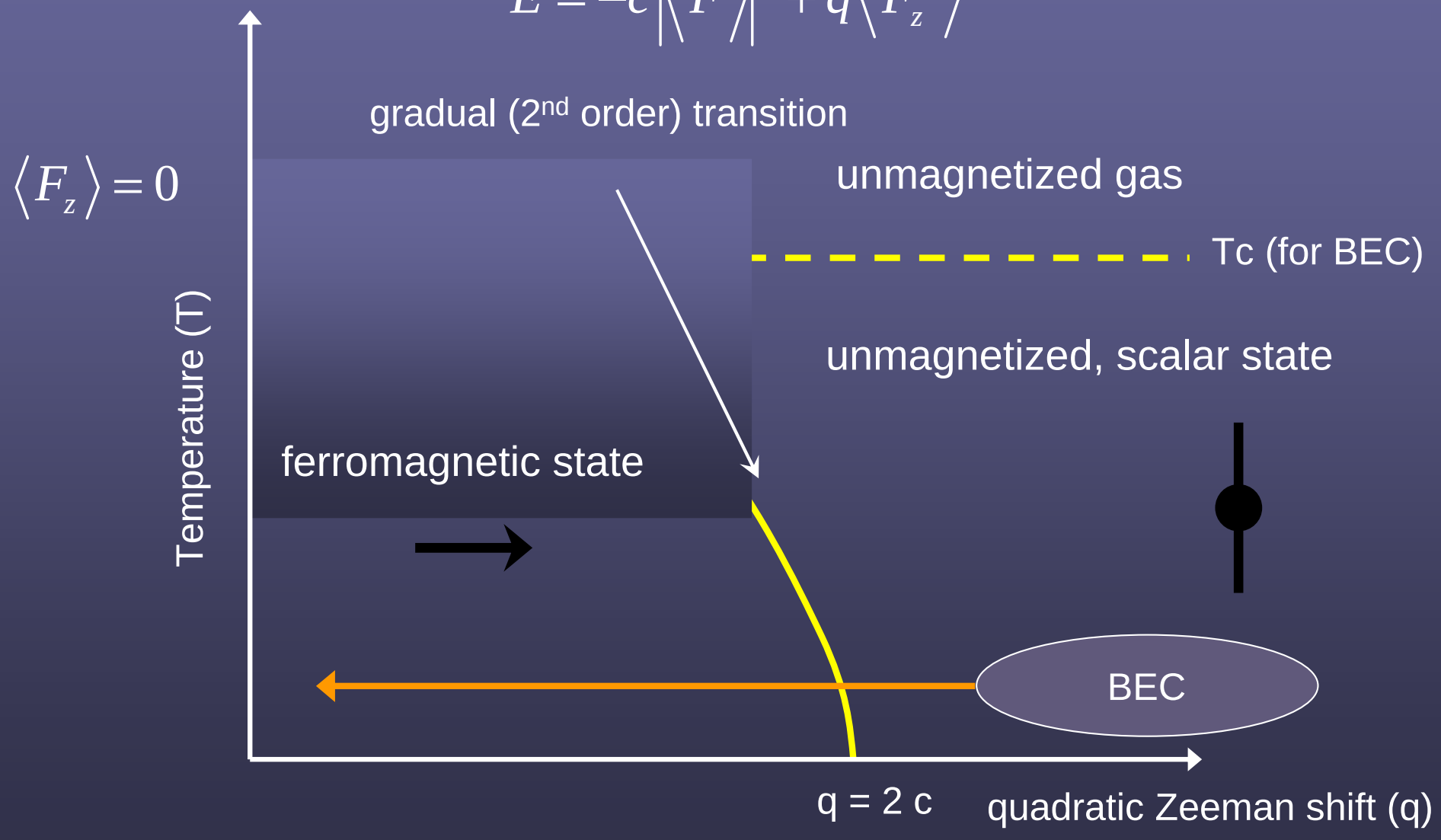
anisotropic
quadratic term dominates

0 $\quad q = 2|c_2|n \quad q\,(\propto B^2)$

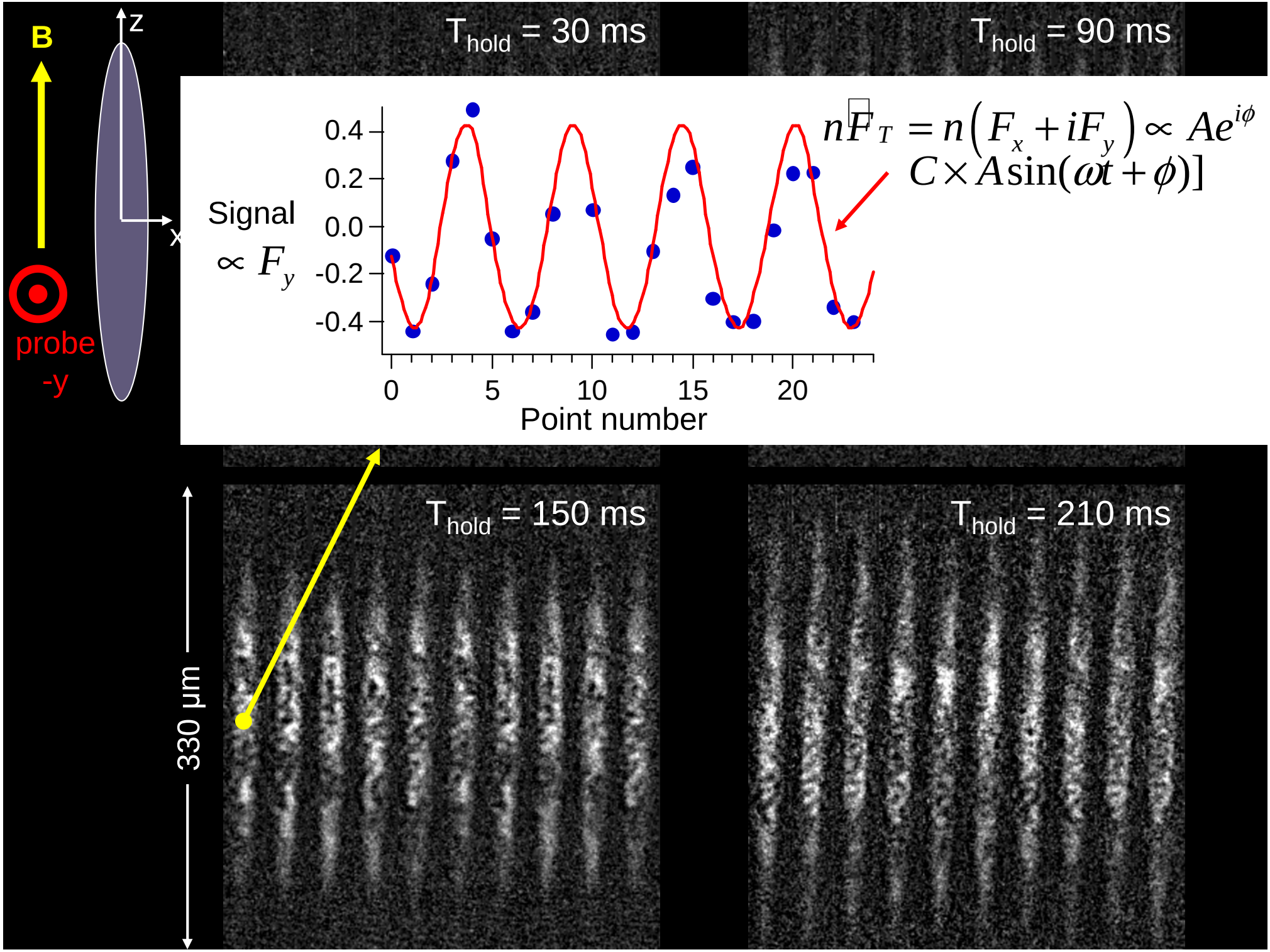
Quenching across a symmetry-breaking transition

James Higbie, Sabrina Leslie, Lorraine Sadler, Mukund Vengalattore

$$E = -c\left|\left\langle \vec{F} \right\rangle\right|^2 + q\left\langle F_z^2 \right\rangle$$

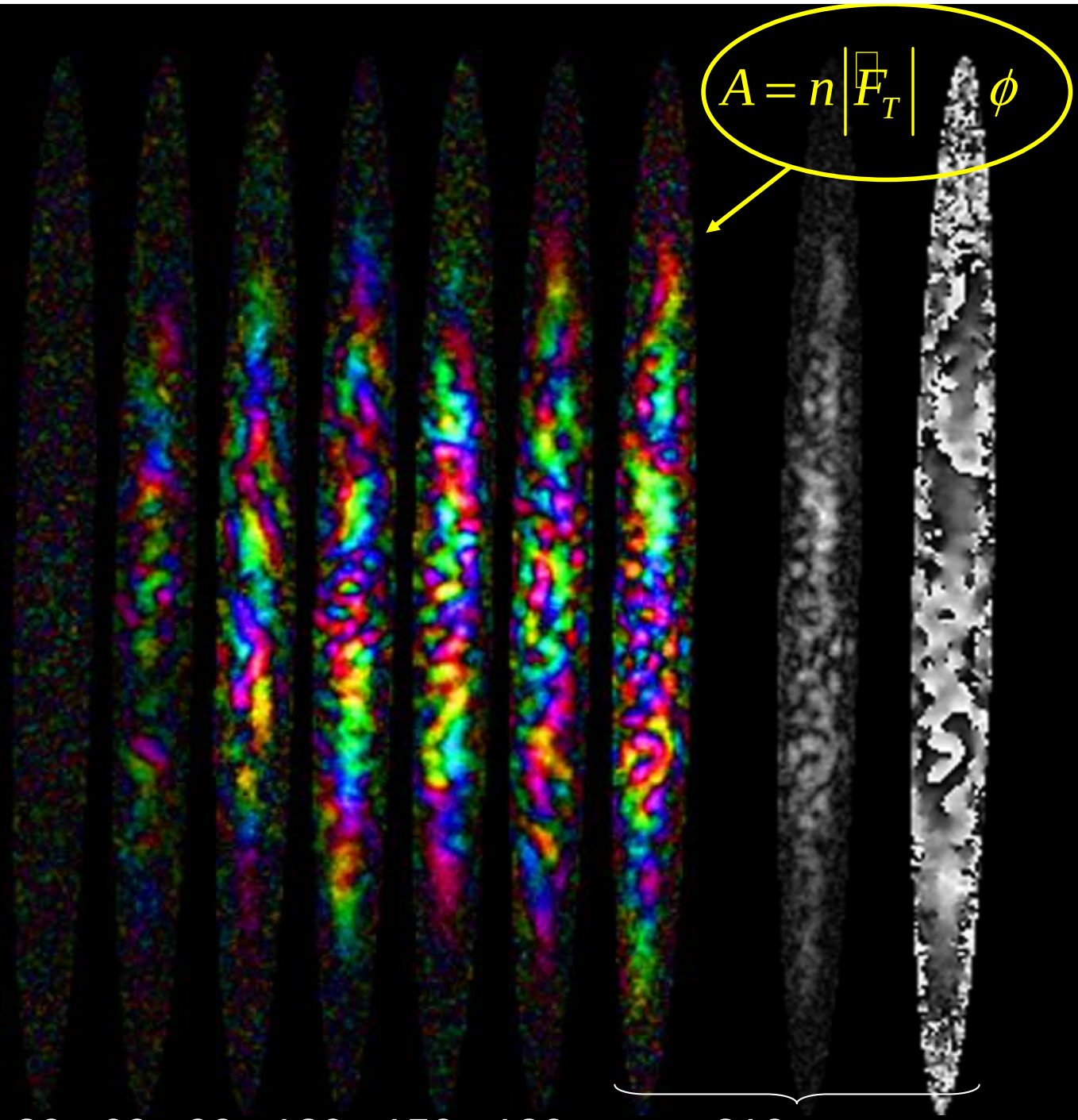


Quench dynamics; phase-ordering kinetics


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

Spontaneously formed ferromagnetism

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



Spontaneously formed ferromagnetism

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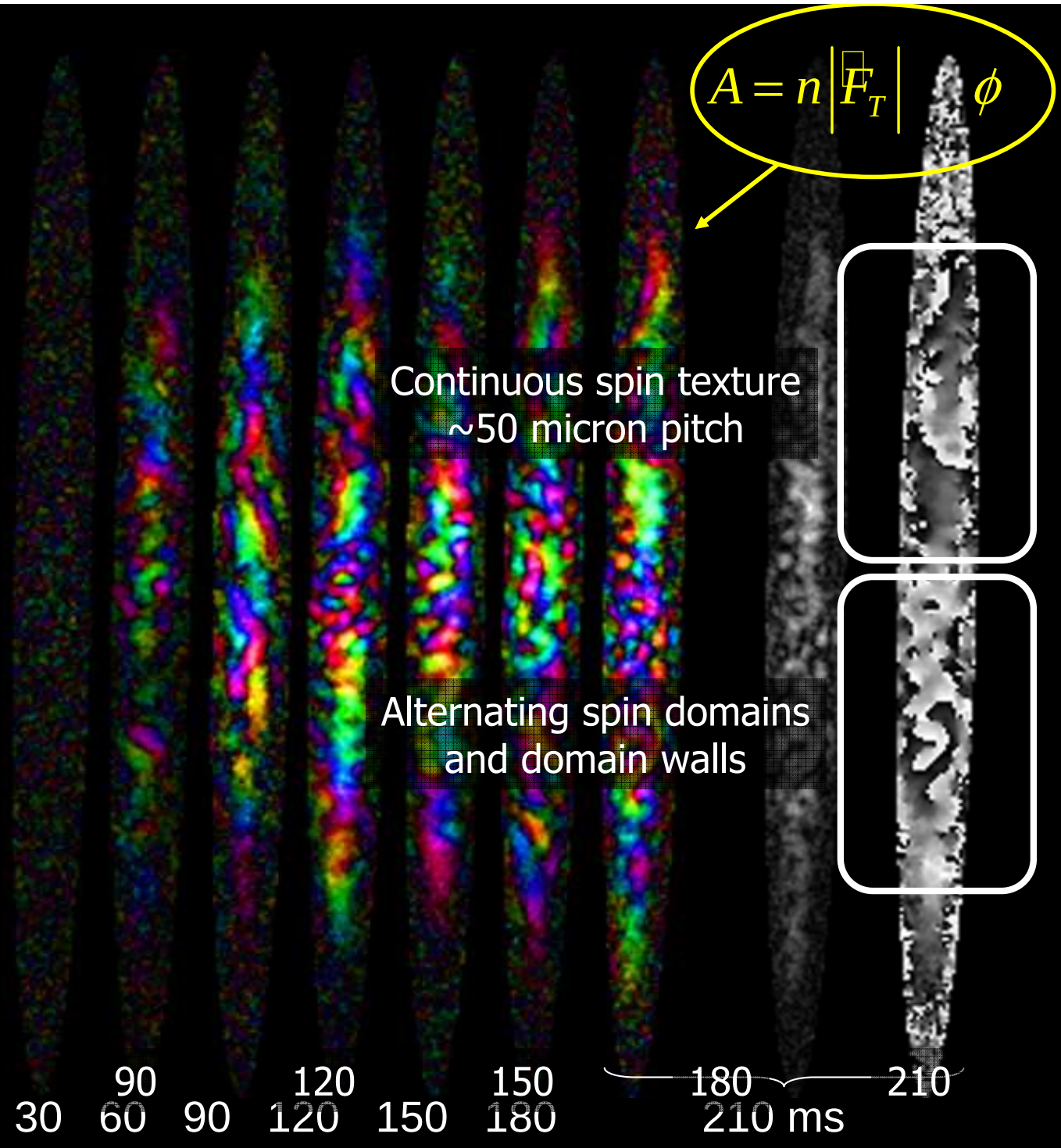
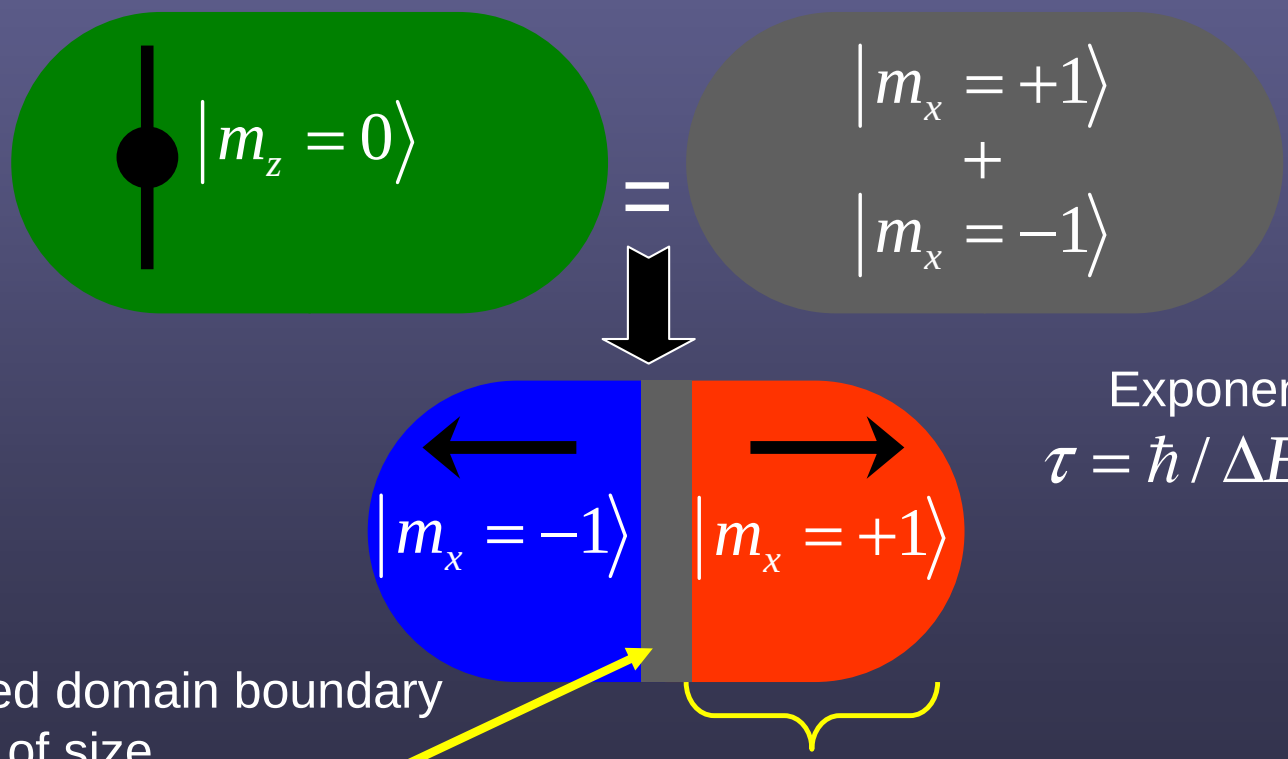


Ferromagnetism via spinodal decomposition

	$\lvert m=0\rangle+\lvert m=\pm1\rangle$	$\lvert m=1\rangle+\lvert m=-1\rangle$	
Polar (Na)	Separate	Mix	MIT
Ferro (Rb)	Mix	Separate	G-Tech



Exponential timescale

$$\tau=\hbar/\Delta E_S=13.7(3)\text{ms}$$

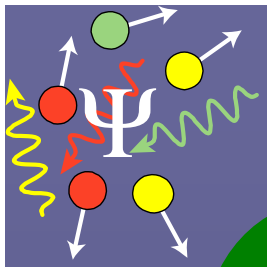
Unmagnetized domain boundary of size

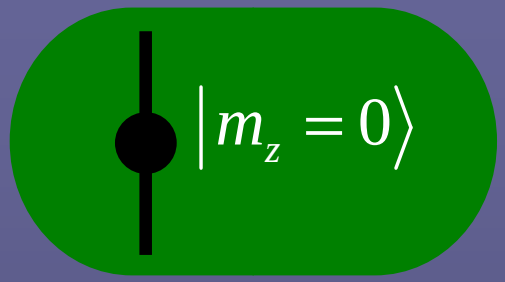
$$b\cong\xi_S=2.6\mu m$$

Ferromagnetic domain of size $\pi\xi_S=8.3\mu m$

Timmermans, PRL **81**, 5718 (1998); Saito and Ueda, PRA **72**, 023610 (2005)

Spectrum of stable and unstable modes

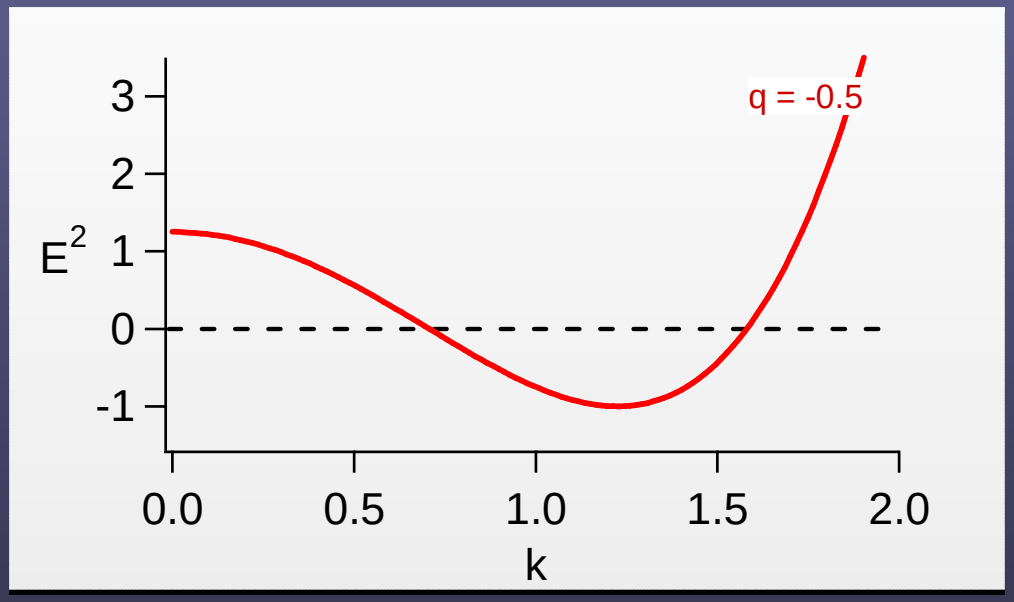




- Bogoliubov spectrum
  - Gapless phonon (m=0 phase/density excitation)
  - Spin excitations

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

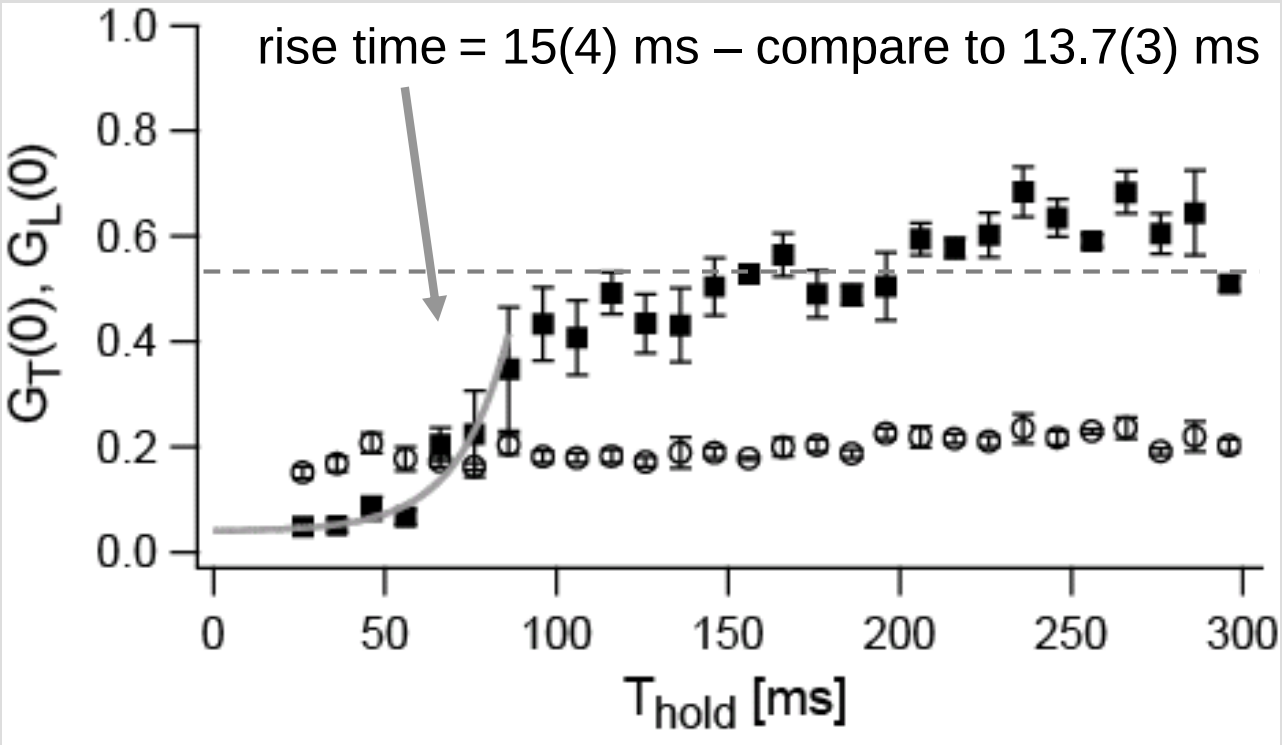
Energies scaled by $c_2 n$



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

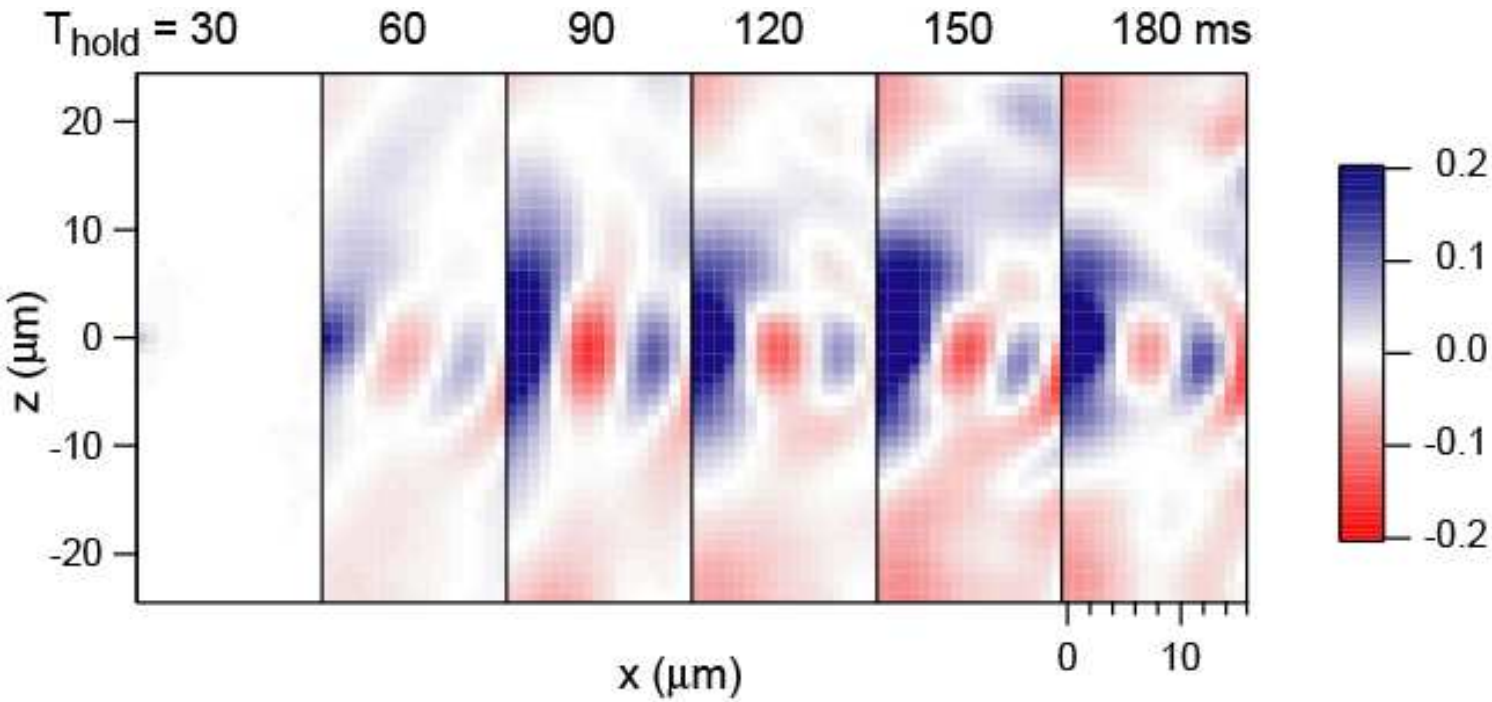
$$G_{T,L}(\delta r) = \mathrm{Re}\left[\frac{\sum_r F^*_{T,L}(r+\delta r)\, n(r+\delta r)\, F_{T,L}(r)\, n(r)}{\sum_r n(r+\delta r)\, n(r)}\right]$$

spin-spin correlation function

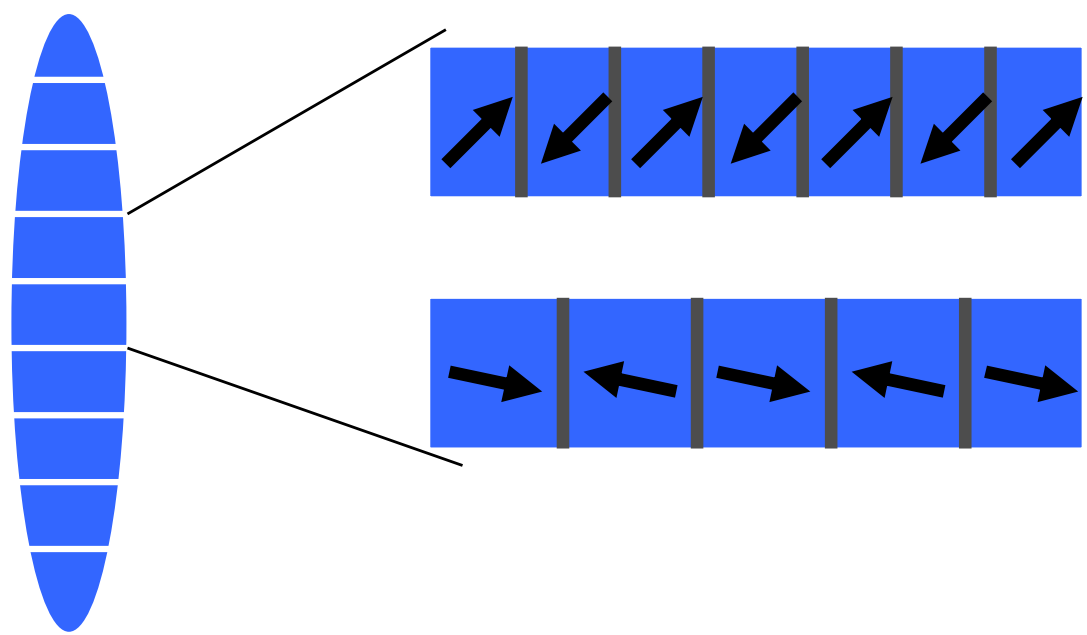


measure of area of domain walls

$G_T(x,z)$

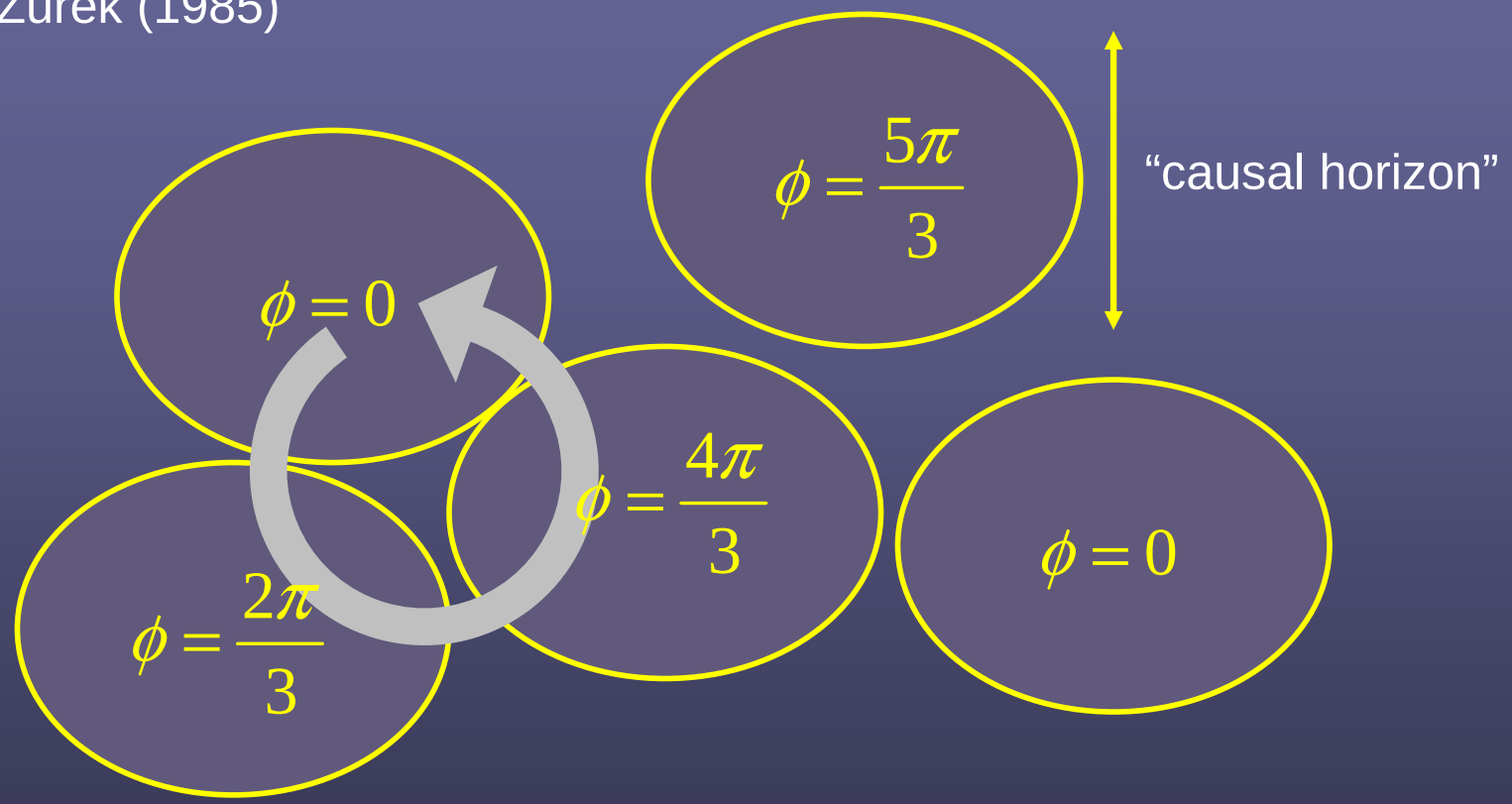


phase separation occurs/symmetry broken spontaneously in disconnected radial bands



Topological defect formation across a symmetry-breaking phase transition

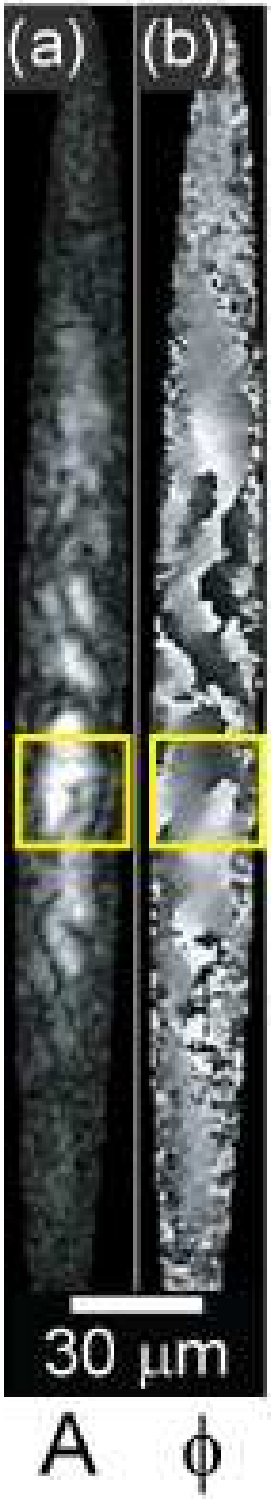
Kibble (1976), Zurek (1985)

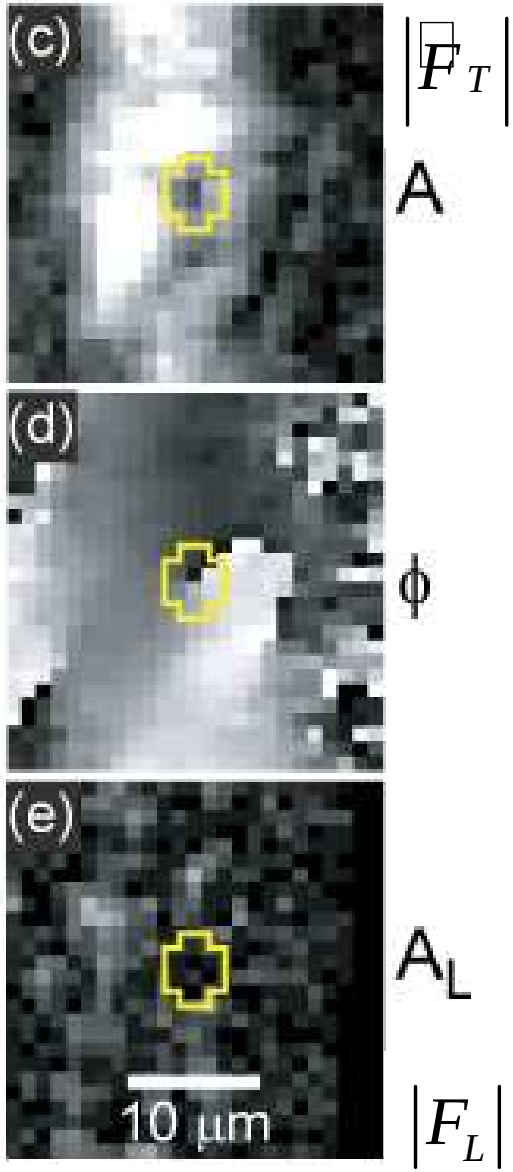


"Cosmology in the laboratory"

Liquid crystals	[Chuang et al, Science 251, 1336 (1991)]
Superfluid helium	[Hendry et al., Nature 368, 315 (1994)]

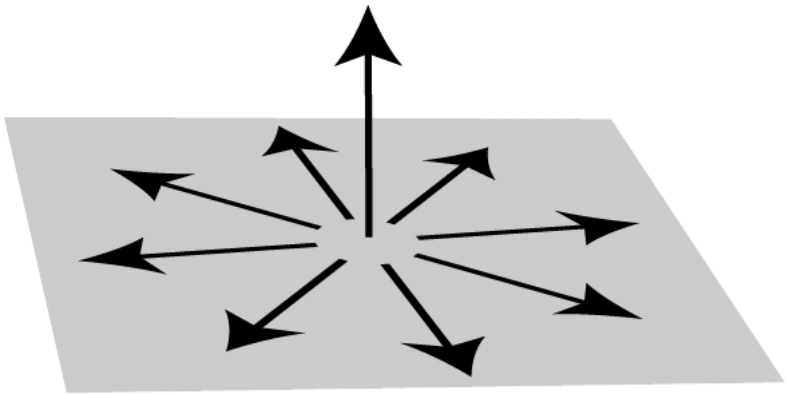
Spontaneously formed spin vortices



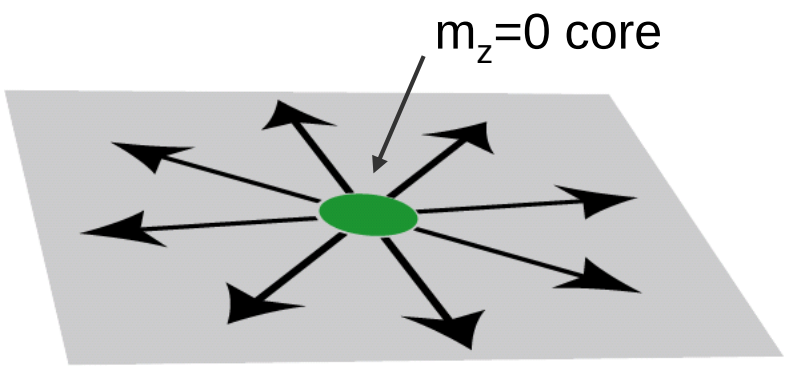


T_{hold} = 150 ms

candidates:



Mermin-Ho vortex (meron)



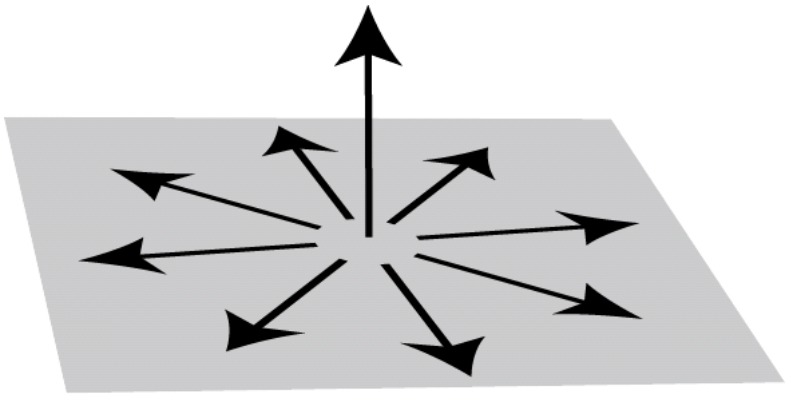
“Polar core” spin vortex

Nature 443, 312 (2006)

Spontaneously formed spin vortices

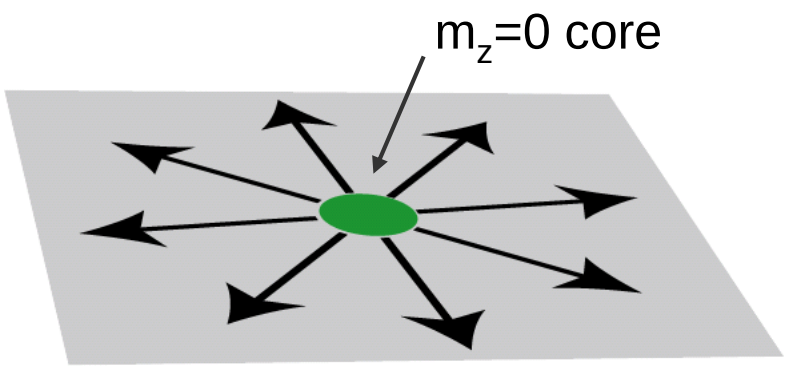
candidates:

$$\vec{\Psi} = \begin{pmatrix} a(r) & \times & 1 \\ b(r) & \times & e^{-i\phi} \\ c(r) & \times & e^{-2i\phi} \end{pmatrix}$$



Mermin-Ho vortex (meron)

$$\vec{\Psi} = \begin{pmatrix} a(r) & \times & e^{i\phi} \\ b(r) & \times & 1 \\ c(r) & \times & e^{-i\phi} \end{pmatrix}$$

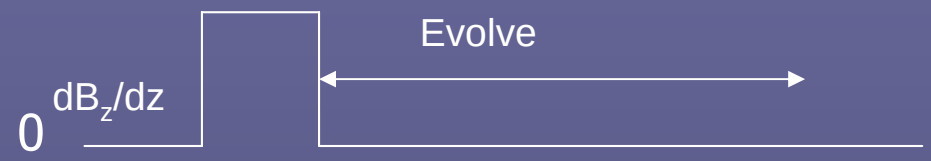


“Polar core” spin vortex

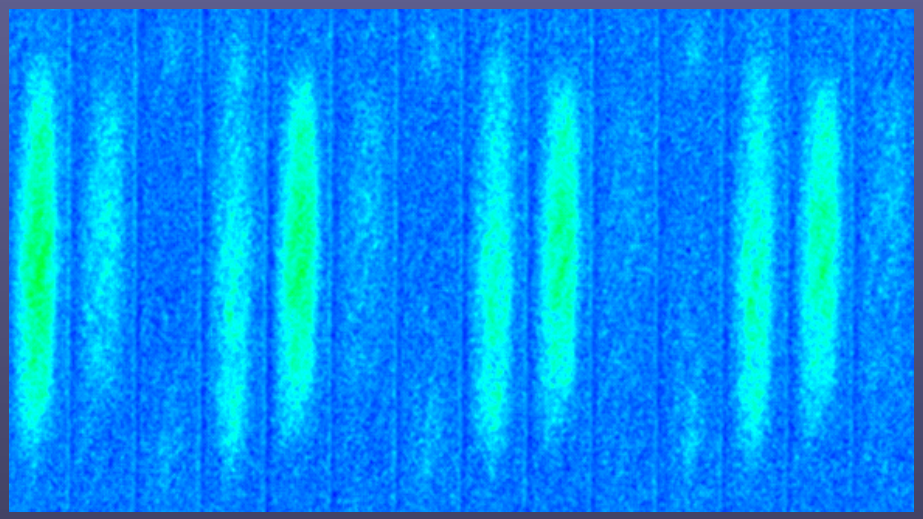
Broken chiral symmetry;
Saito, Kawaguchi, Ueda, PRL **96**, 065302 (2006)

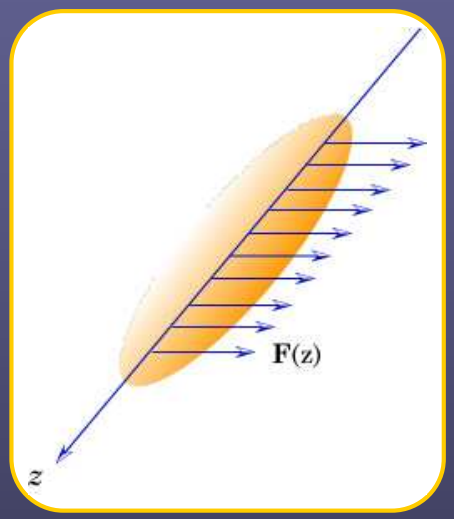
Ferromagnetic spin textures

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

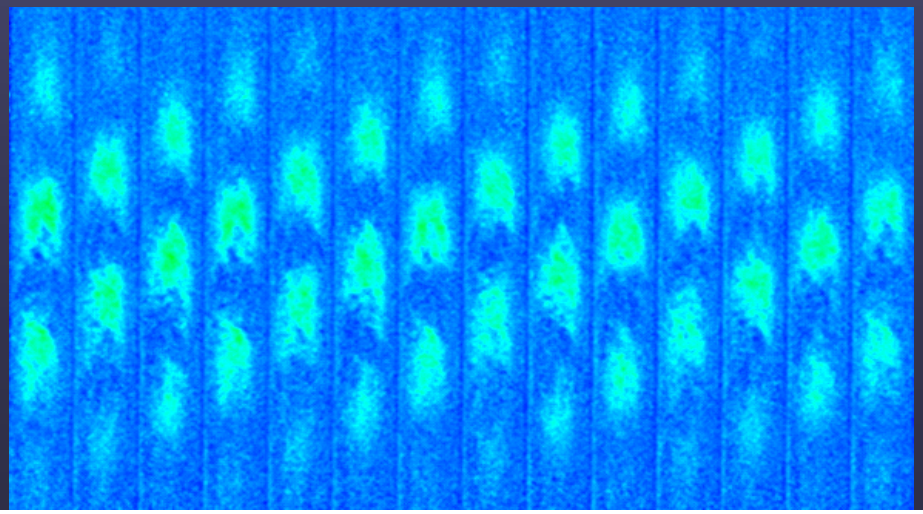


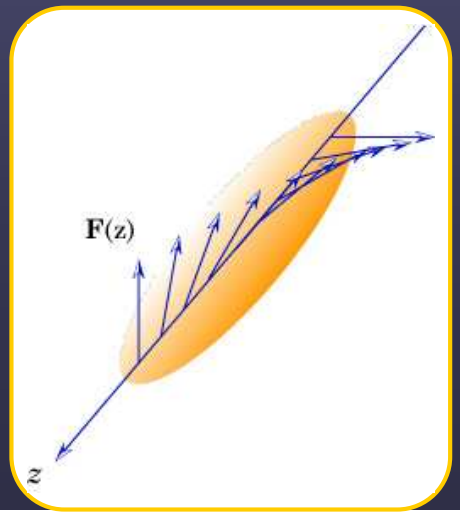
w/o gradient





with gradient





Ferromagnetic spin textures

clean starting point for studying dynamics

energy budget:

- spin-dependent contact interaction:

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

~ - 0.5 nK, minimized

- quadratic Zeeman shift:

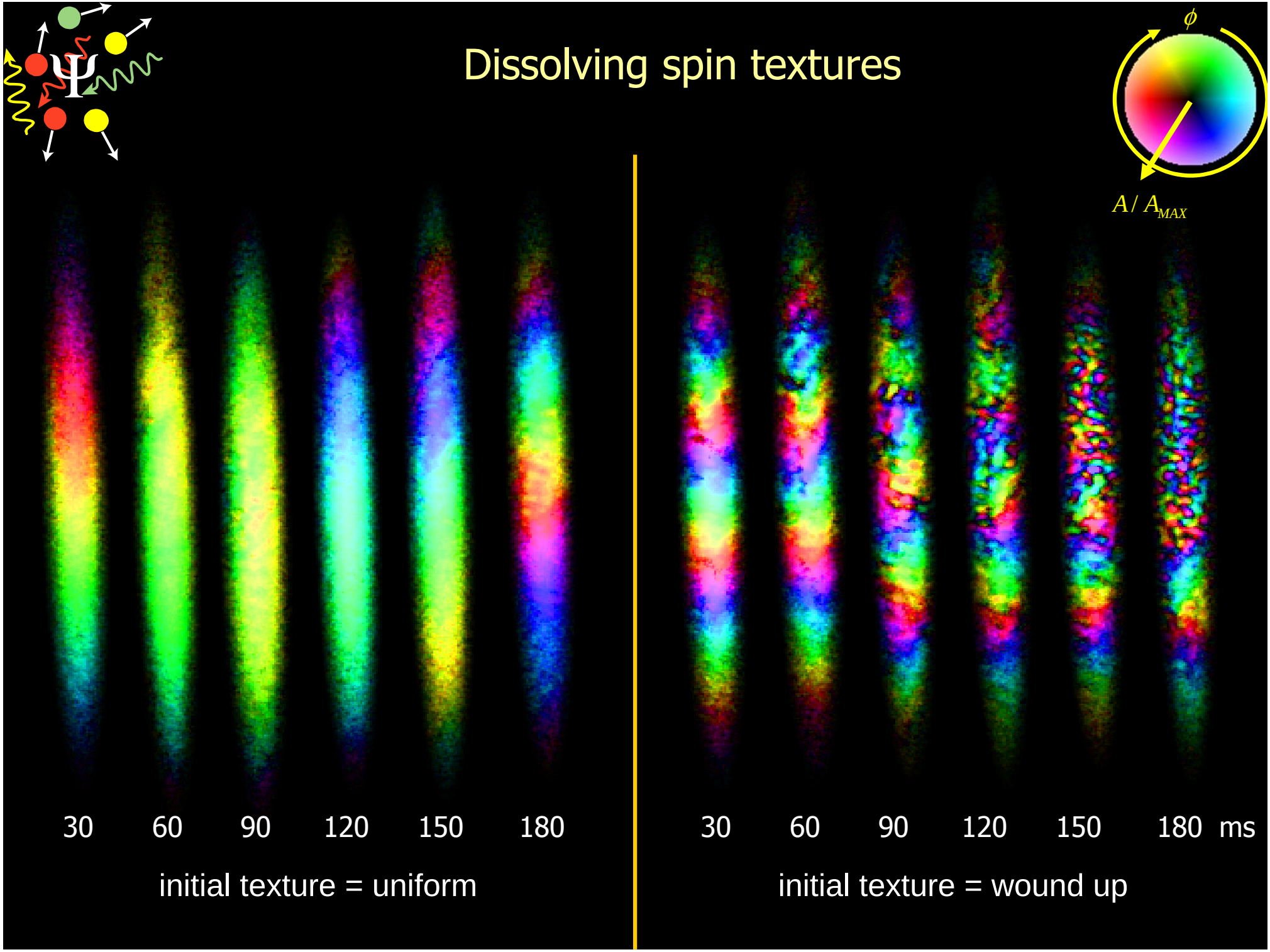
$$qF_z^2 = \frac{q}{2}$$

excess ~ 30 pK; λ = 60 μm

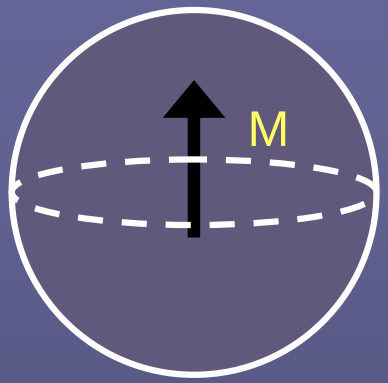
- spin current kinetic energy

λ ≥ 50 μm ν ≤ 1 Hz

Dissolving spin textures



Dipolar interactions: magnetism in a quantum fluid



		@ 4 10^{14} cm^{-3}
self-field:	$B \approx \mu_0 M = (\mu_0 g_F \mu_B) n$	23 μG
energy per particle:	$E = (\mu_0 g_F^2 \mu_B^2) n$	k_B x 0.8 nK

- Comparison to other energy scales:
  - total interaction energy: μ ~ k_B x 200 nK

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

  - spin-dependent interaction energy: μ ~ k_B x 0.8 nK

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

  - ferromagnetic spin texture: K.E. < k_B x 30 pK

Present/future directions/speculation

- Equilibrium phase diagram of spinor BEC vs. q, T, …
  - effects of long-range, anisotropic interactions
  - effects of dimensionality
- Phase transitions, quantum and thermal
  - ascertain role of quantum vs thermal fluctuations: 2 temperatures
  - quantum atom optics: is it still a BEC?
  - critical exponents
- Phenomenology of spinor BEC dynamics
  - domain walls, various spin vortices, interactions b/w them
- Spinor gas magnetometry
  - surpass atomic shot noise; spatially resolved spin squeezing
  - applications to …?

Daniel Brooks, Jennie Guzman, Sabrina Leslie, Kevin Moore, Kater Murch, Tom Purdy, Lorraine Sadler, Ed Marti, Ryan Olf, Subhadeep Gupta, Mukund Vengalattore

Looking for great students and postdocs

http://physics.berkeley.edu/research/ultracold

gBECi Guided BEC Interferometry

The David and Lucile Packard Foundation

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