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# Quantum Control with Spinor Bose-Einstein Condensates

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# Quantum Control with Spinor Bose-Einstein Condensates

HILARY M. HURST

OPEN QUANTUM FRONTIER INSTITUTE WORKSHOP

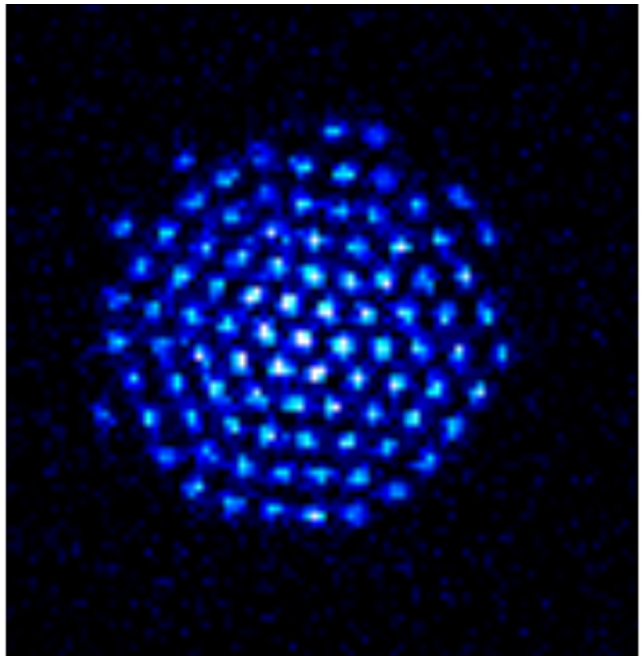
COLORADO SCHOOL OF MINES

FEBRUARY 21, 2020

# Quantum Simulation: Engineering the Quantum World

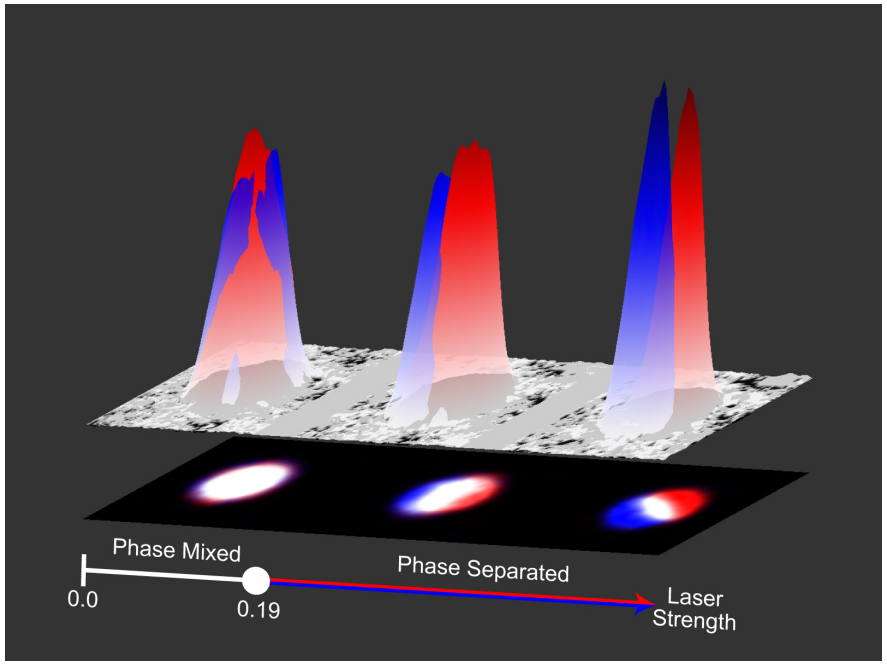
*"...if you want to make a simulation of nature, you'd better make it quantum mechanical."*
*- Richard Feynman*

'bottom up' approach:
- designer quantum building blocks
- i.e. 'perfect' crystals trapped ions:



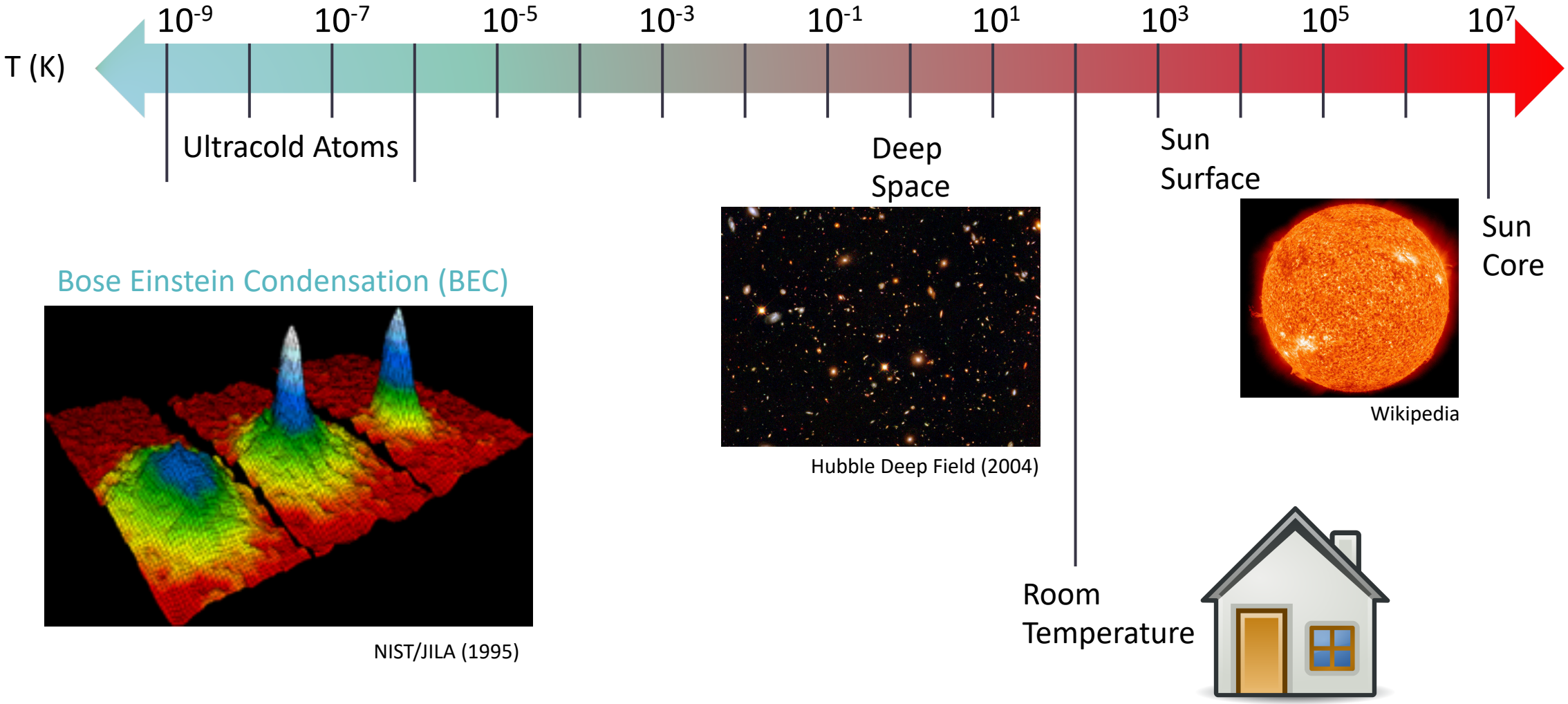
J. Bollinger, NIST

'top down' approach:
- engineering new dynamics via external fields
- i.e. coupling motional and spin states in quantum gases:



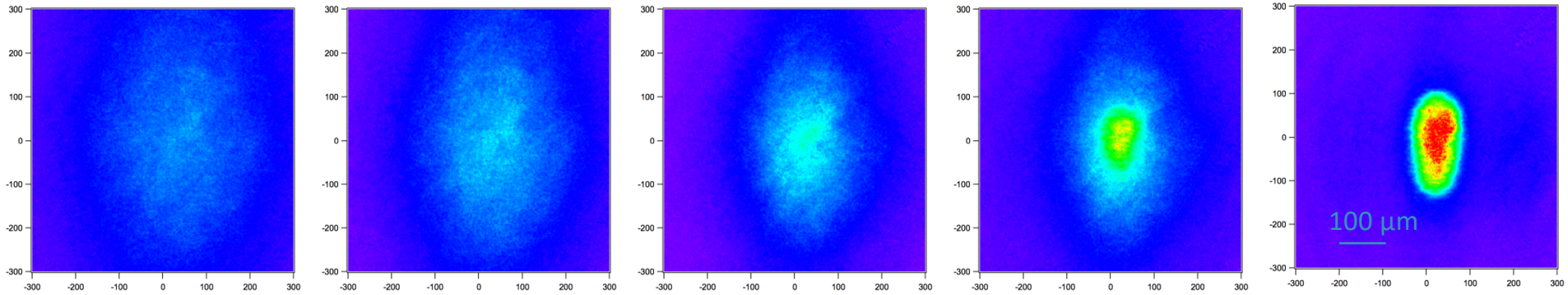

I. B. Spielman, NIST

# Our Platform: Ultracold Atoms (They are Really, Really Cold)



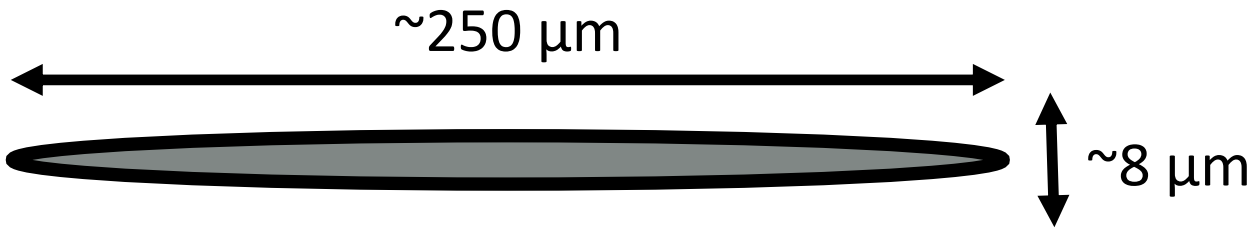
# Our Platform II: Bose-Einstein Condensates

BEC 'Wavefunction' : $\psi(x,t)$




Images: L. M. Aycock, Spielman Lab

Evaporative cooling

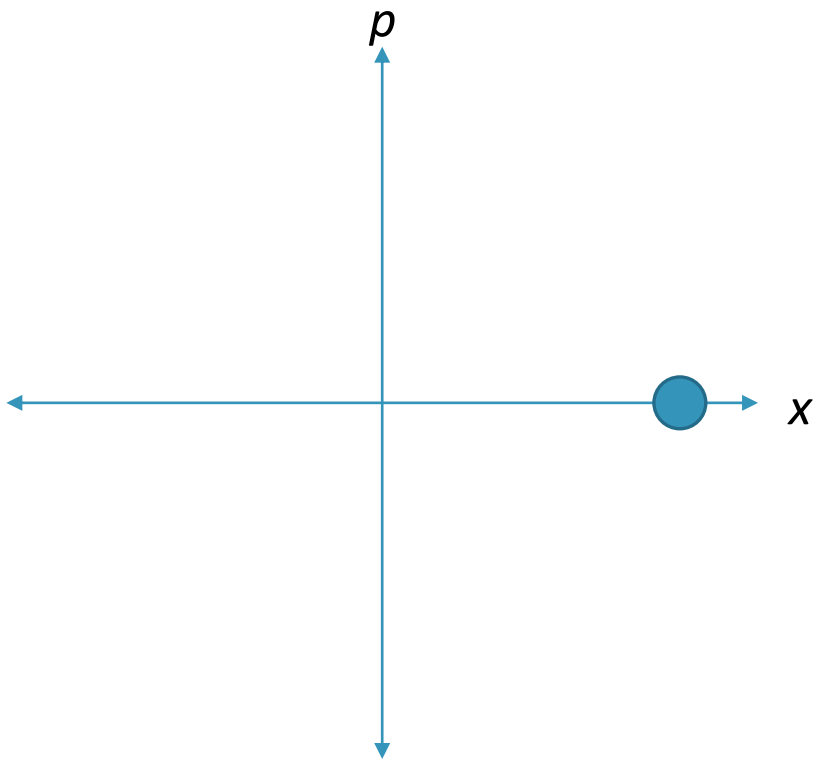


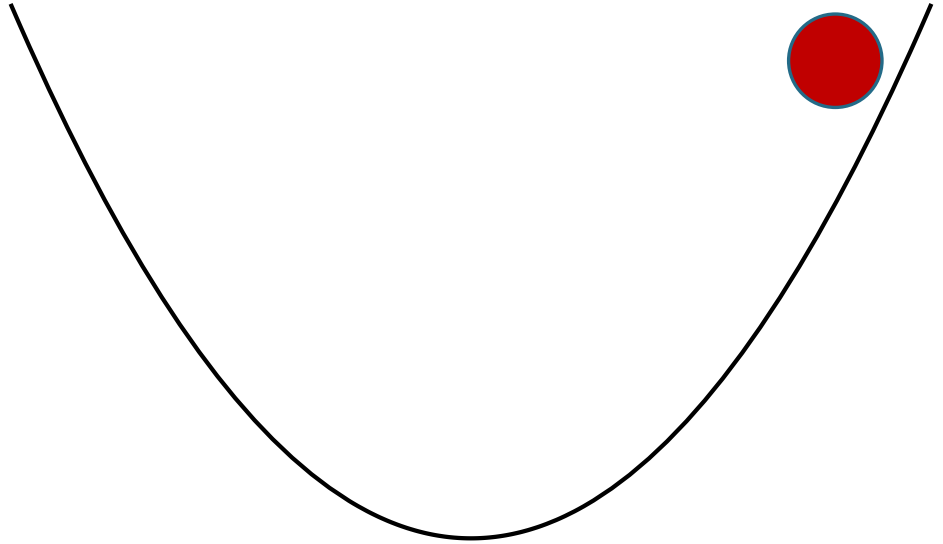

$$i\hbar\frac{\partial\psi}{\partial t} = \underbrace{\left[-\frac{\hbar^2}{2m}\frac{\partial^2}{\partial x^2} + V(x) + g|\psi|^2 - \mu\right]}_{\mathcal{H}}\psi$$

Elongated condensates

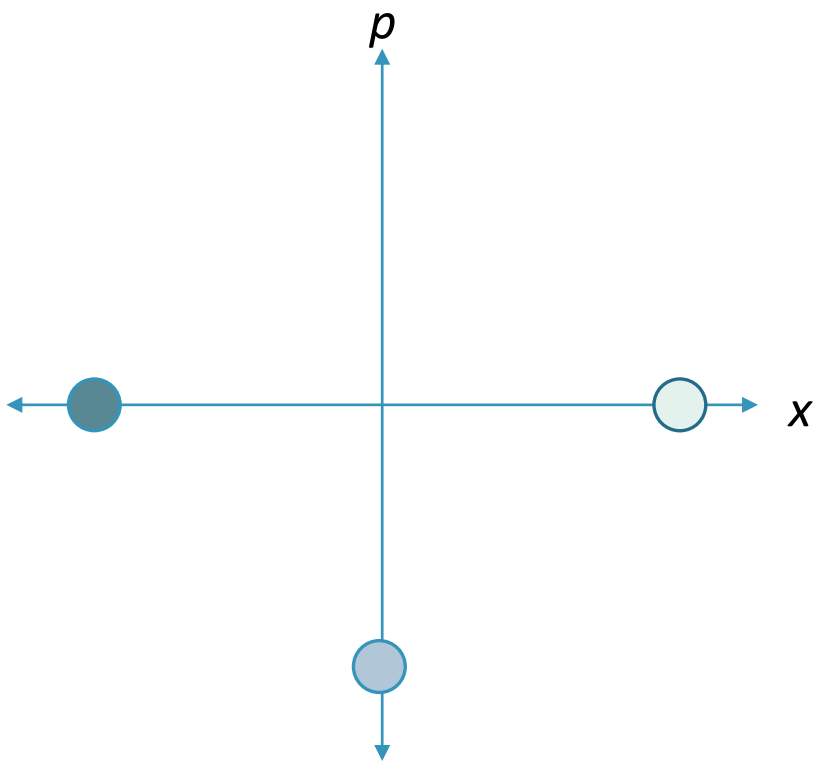
T ~ 10 nK

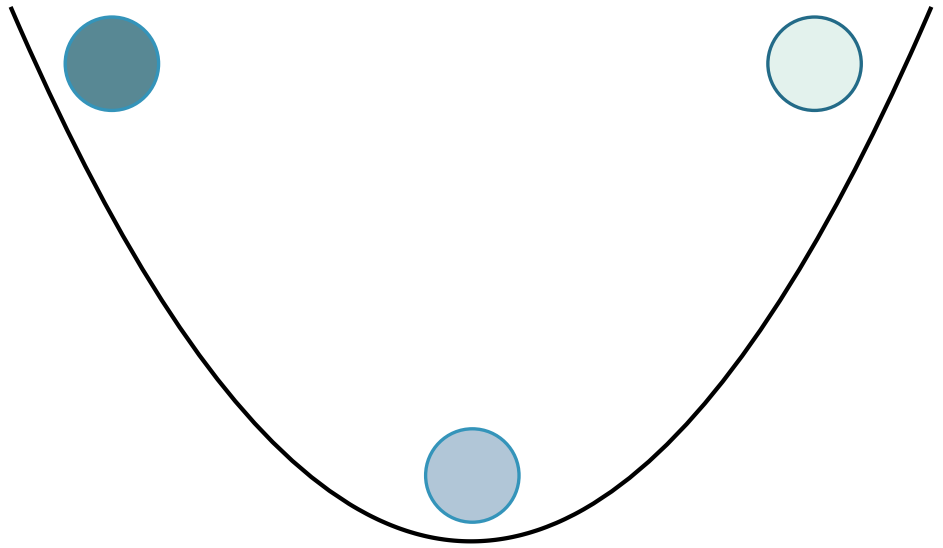
# Measuring Quantum Objects: Phase Space



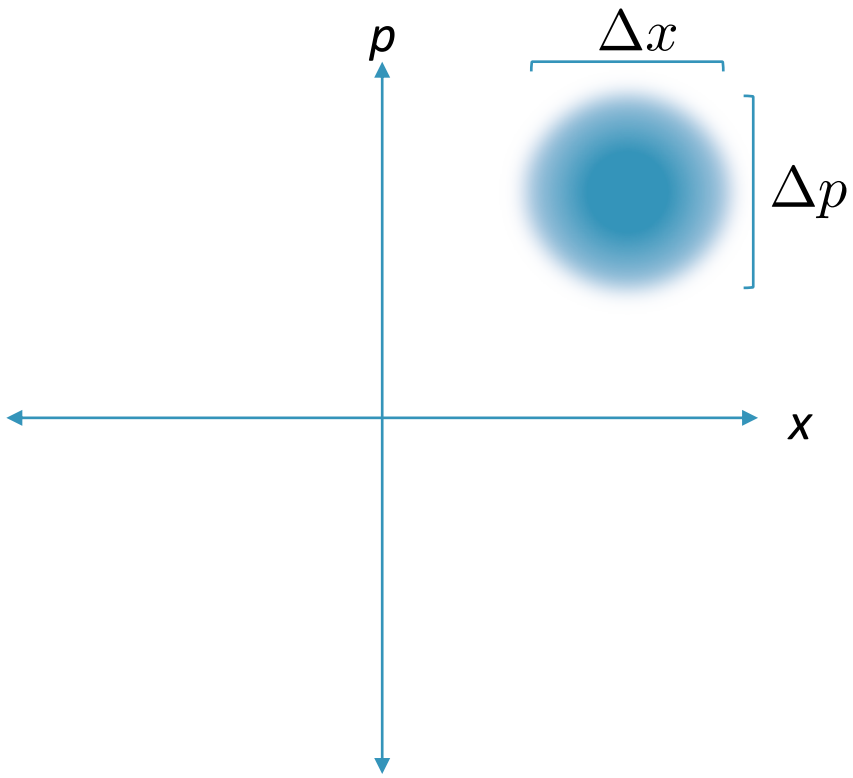



# Measuring Quantum Objects: Phase Space



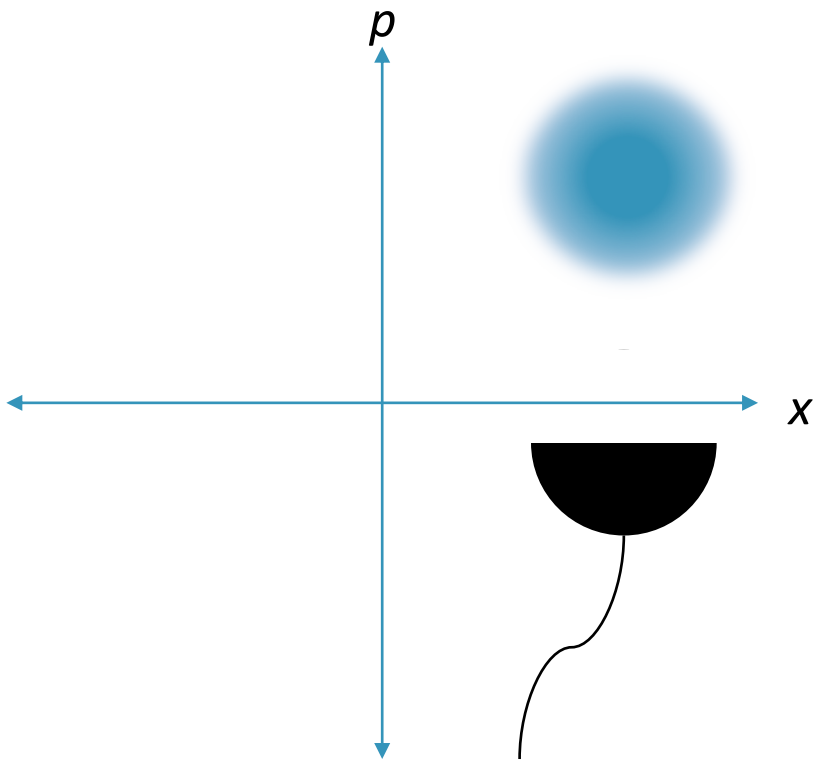
# Weak Measurement: An Outline




$$\Delta x \Delta p \geq \frac{\hbar}{2}$$

$$|\psi\rangle = \sum_x c_x |x\rangle$$

# Projective Measurement

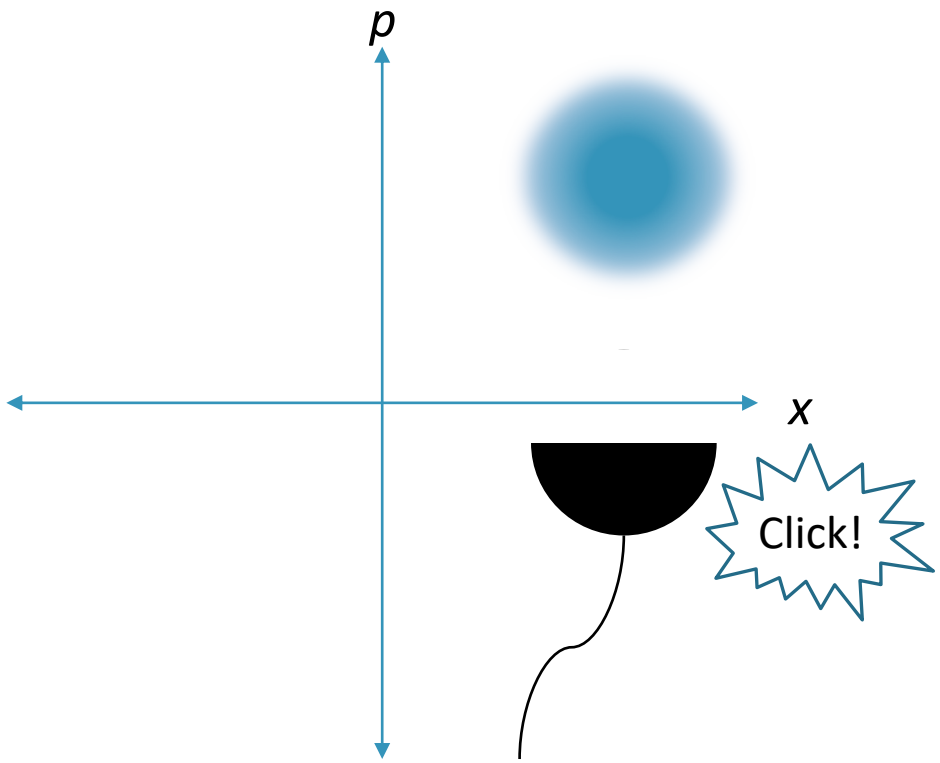



Classical Meter

Before Measurement:

$$|\psi\rangle = \sum_x c_x |x\rangle$$

# Projective Measurement



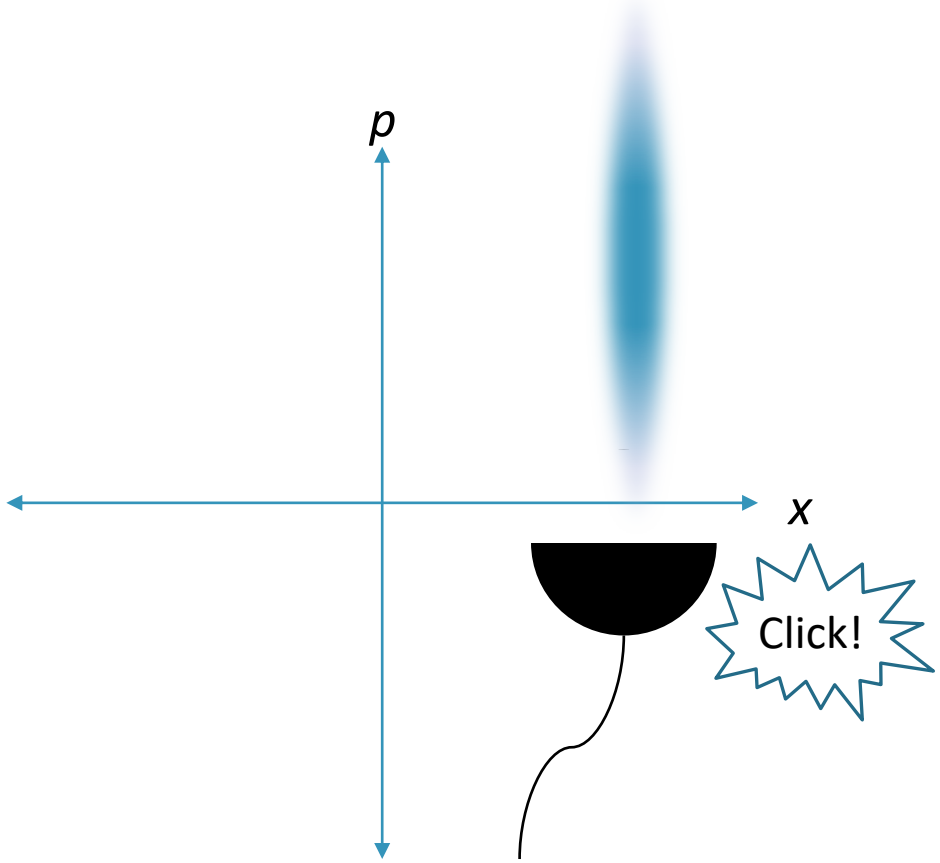

Before Measurement:

$$|\psi\rangle = \sum_x c_x |x\rangle$$

Measure Position:

$$\mathcal{M}_{|x} = \langle\psi|\hat{x}|\psi\rangle$$

# Projective Measurement




Before Measurement:

$$|\psi\rangle = \sum_x c_x |x\rangle$$

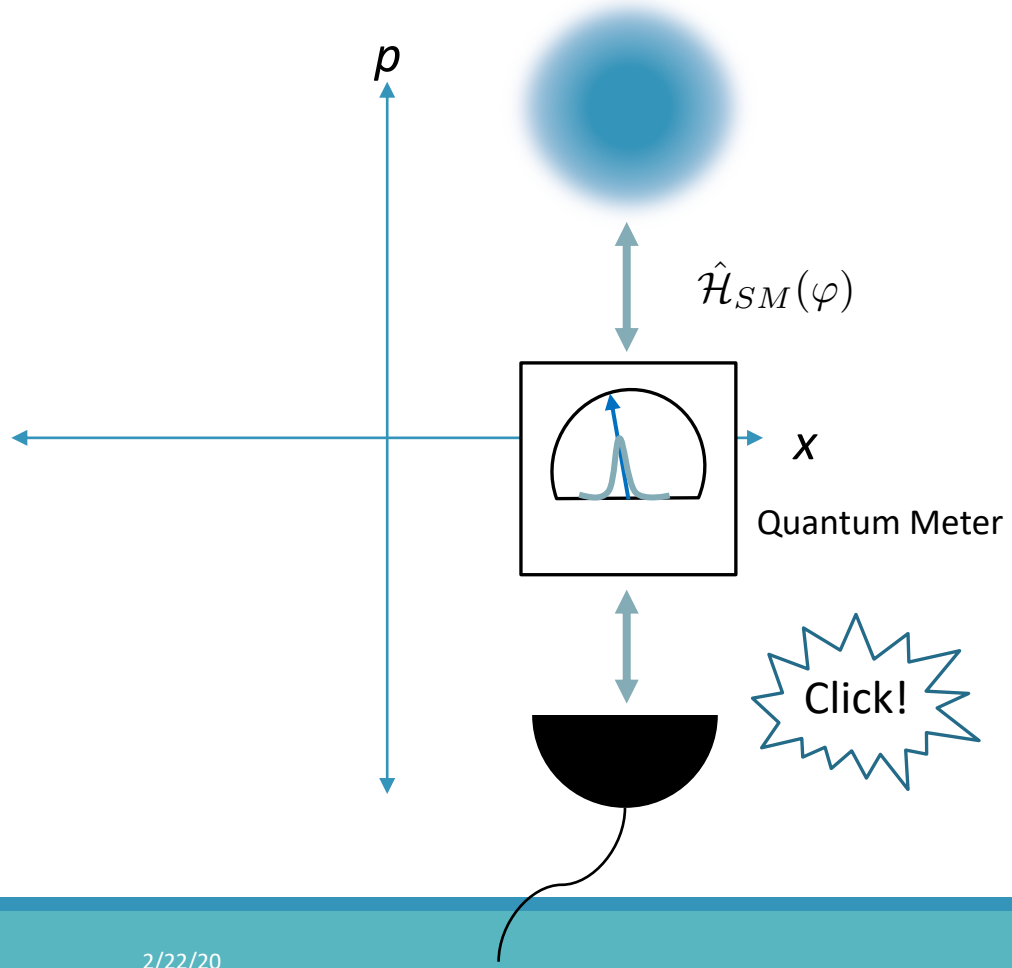
Measure Position:

$$\mathcal{M}_{|x} = \langle\psi|\hat{x}|\psi\rangle$$

After Measurement:

$$|\psi_{|x}\rangle = c_x|x\rangle \rightarrow |x\rangle$$

# Weak Measurement




Before Measurement:

$$|\psi\rangle = \sum_x c_x |x\rangle$$

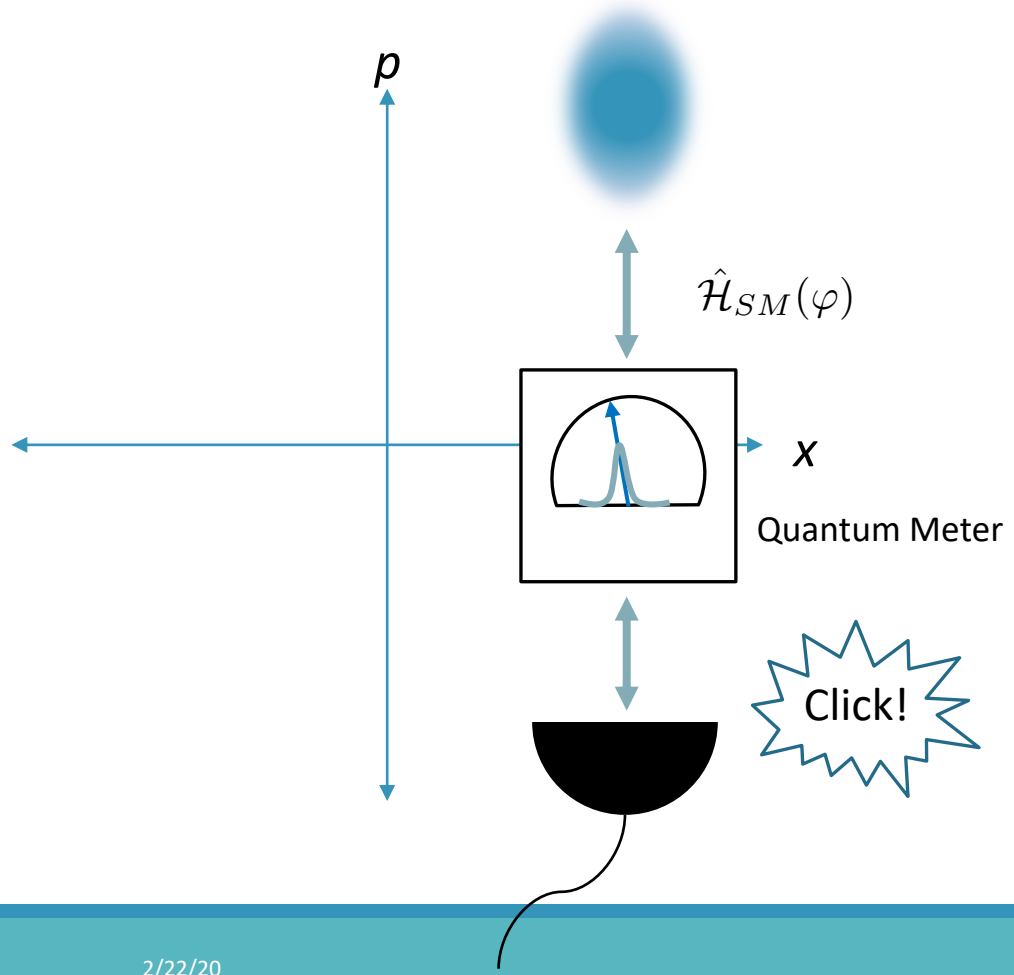
Measure Position:

Random noise

$$\mathcal{M}_{|x} = \langle\psi|\hat{x}|\psi\rangle + \frac{m}{\varphi}$$

'measurement strength'
<1

# Weak Measurement




Before Measurement:

$$|\psi\rangle = \sum_x c_x |x\rangle$$

Measure Position:

Random noise

$$\mathcal{M}_{|x} = \langle\psi|\hat{x}|\psi\rangle + \frac{m}{\varphi}$$

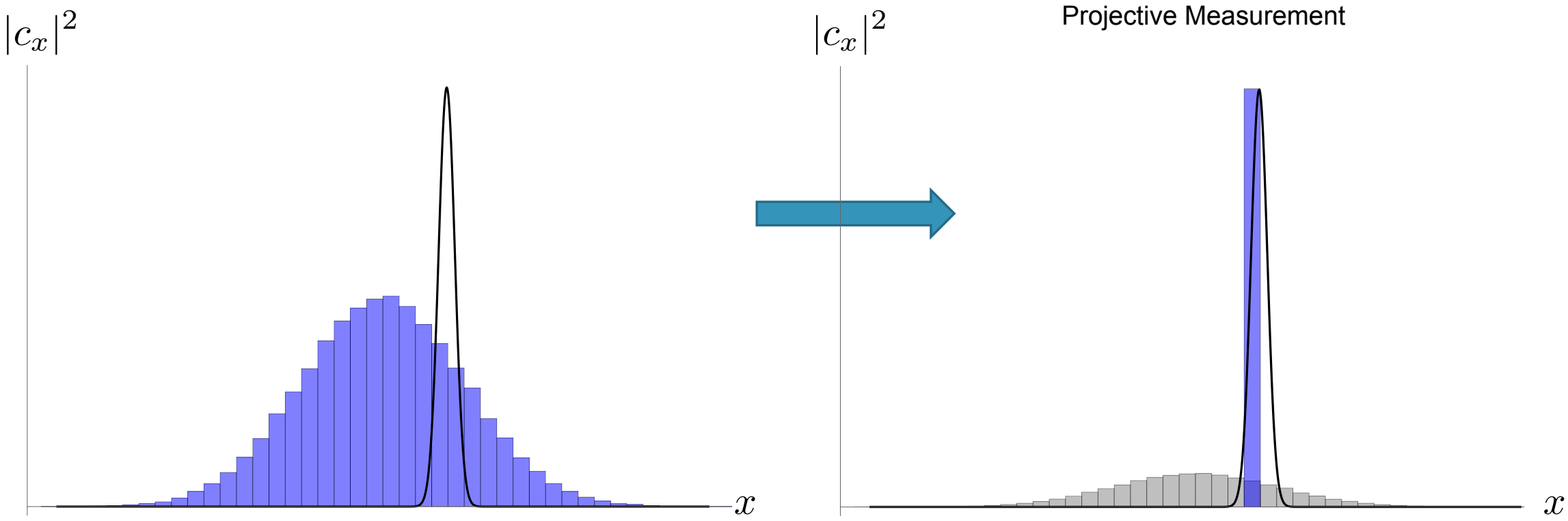
After Measurement:

$$|\psi_{|x}\rangle = \sum_x \tilde{c}_x |x\rangle$$

'measurement strength' < 1

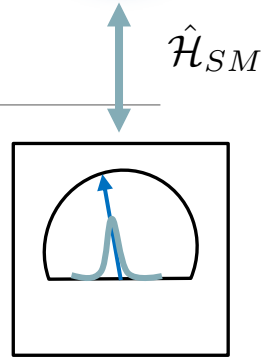
# Quantum Backaction

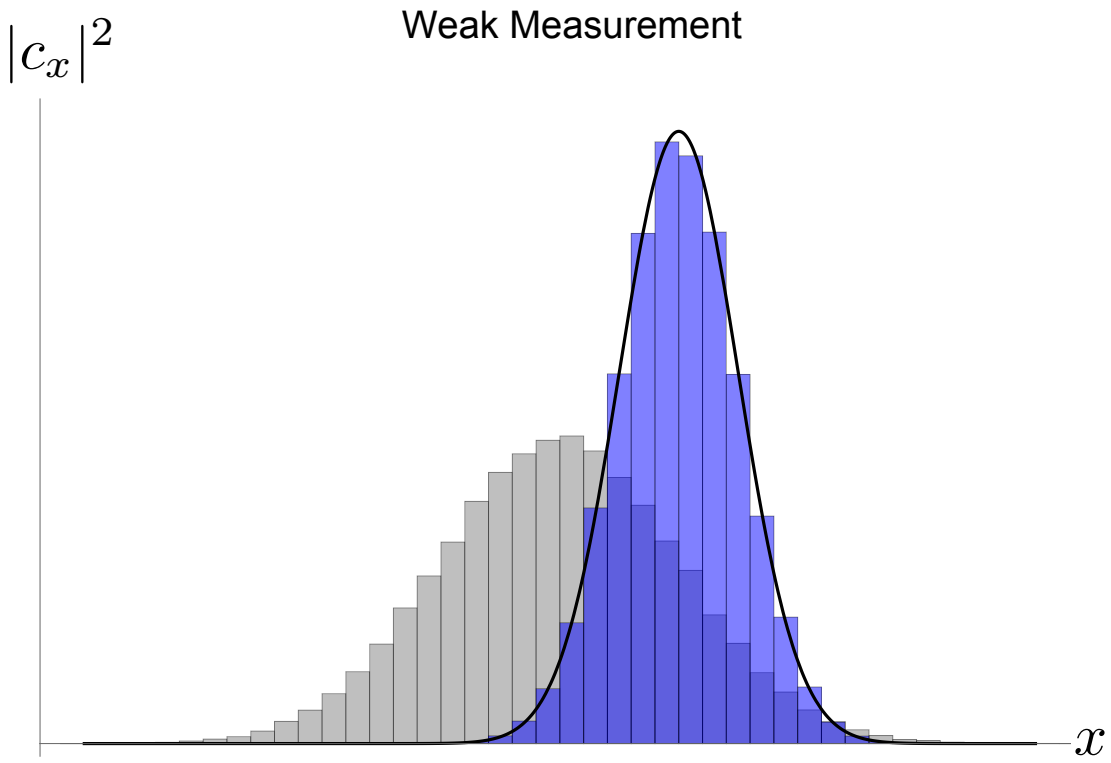
$$|\psi\rangle = \sum_x c_x |x\rangle$$

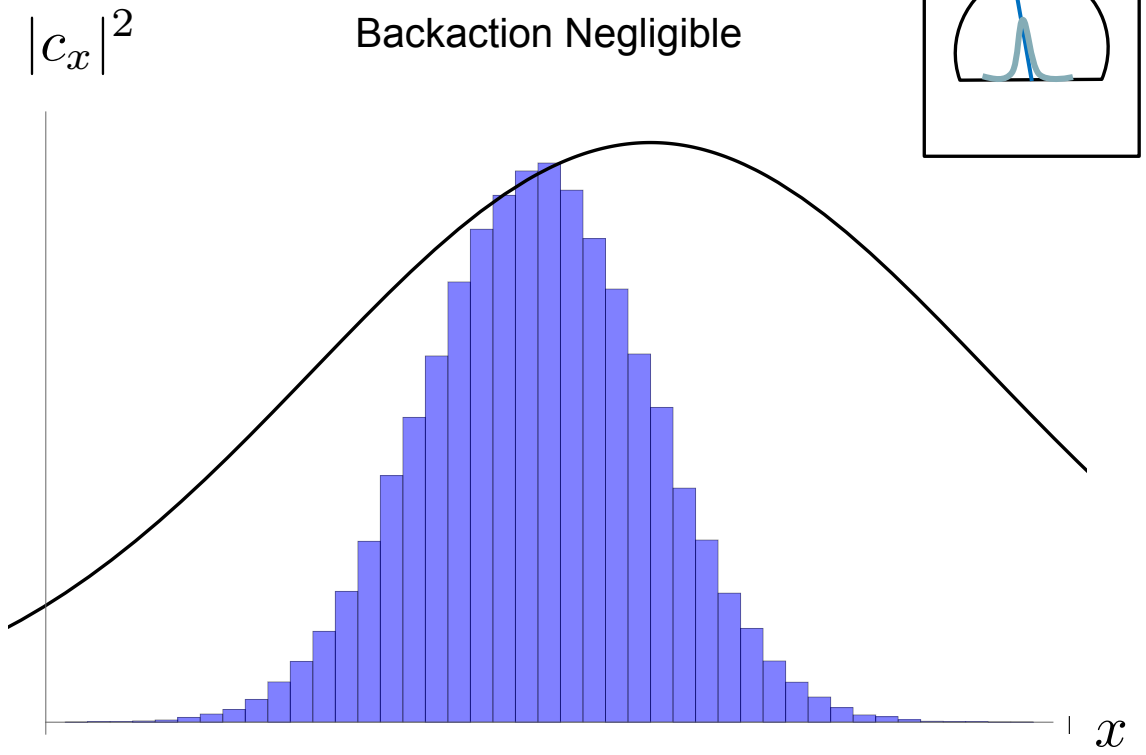


# Quantum Backaction

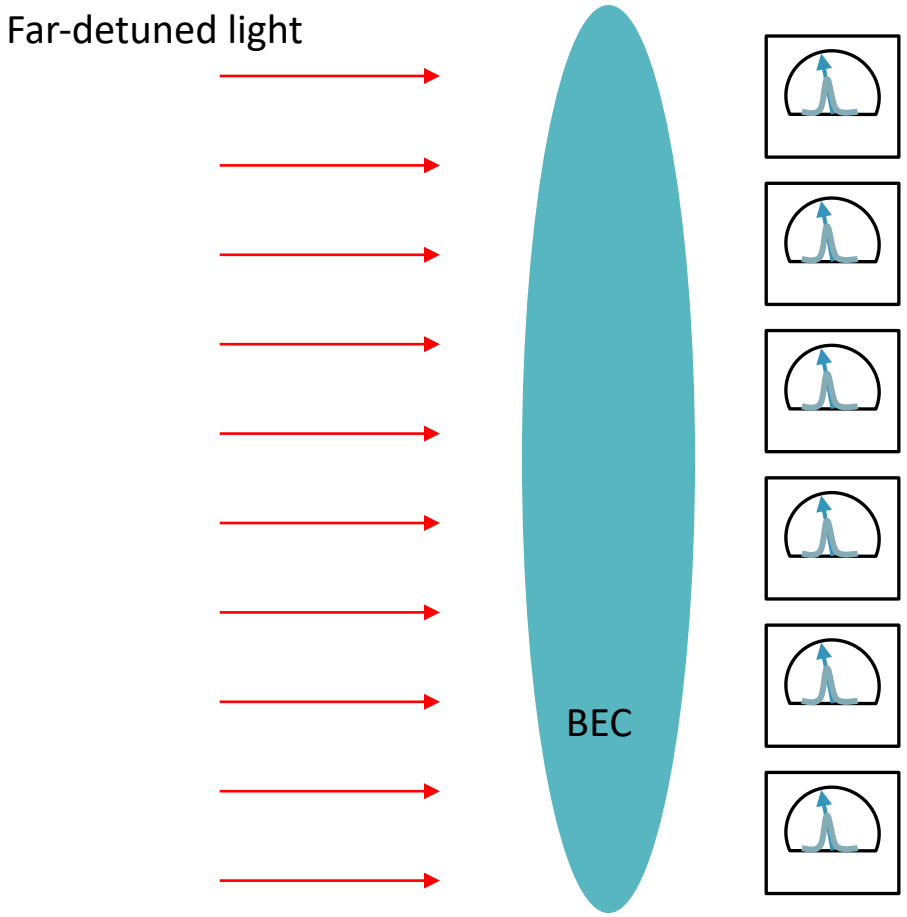
$$|\psi\rangle = \sum_x c_x |x\rangle$$



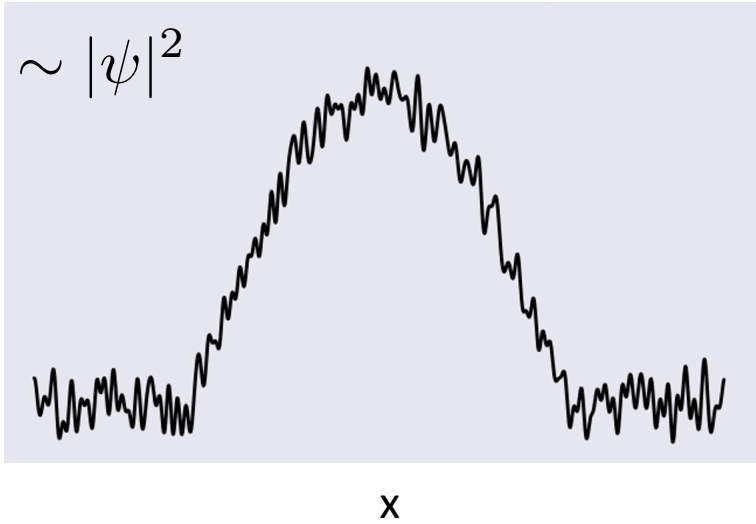
# Weak Measurement For BEC: Phase-Contrast Imaging




Homodyne Detection

System-meter coupling for phase contrast imaging

$$\hat{\mathcal{H}}_{SM} \approx \varphi\ \hat{n}_{BEC} \otimes \hat{n}_{ph}$$



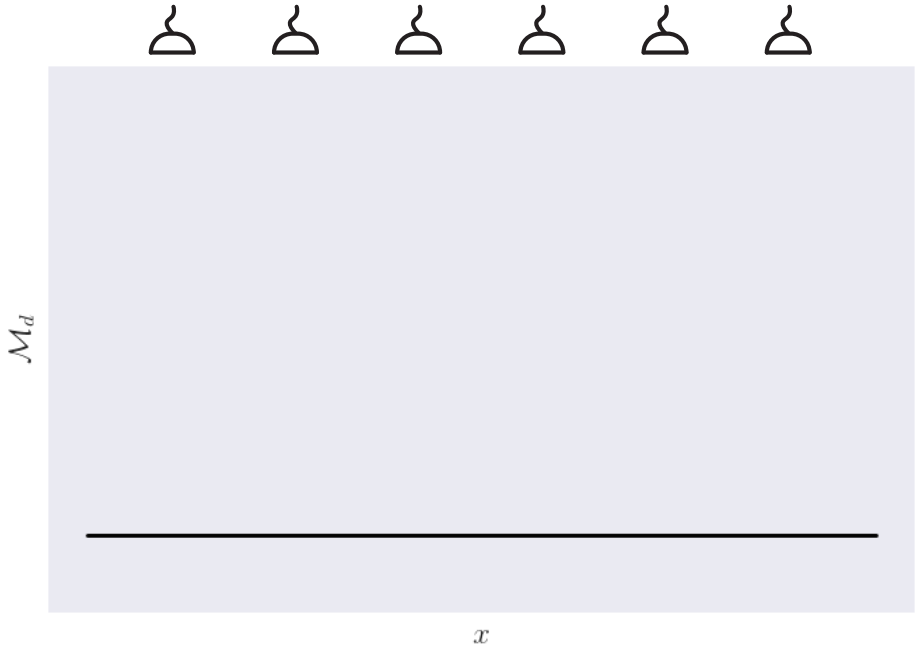
# Example: Measuring BEC Density

$$d\psi_H = -i\left[\mathcal{H} - \mu\right]\psi dt$$

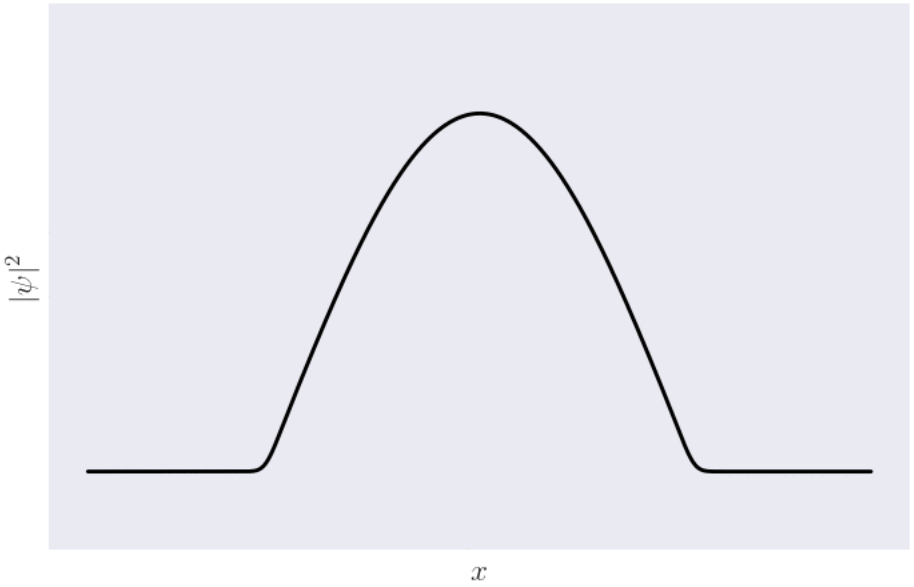
$$d\psi_M = \left[-\frac{\varphi^2}{4}dt + \varphi m(x)\sqrt{dt}\right]\psi$$

Stochastic Evolution Equation
(@ mean-field level)

Observer




System Evolution

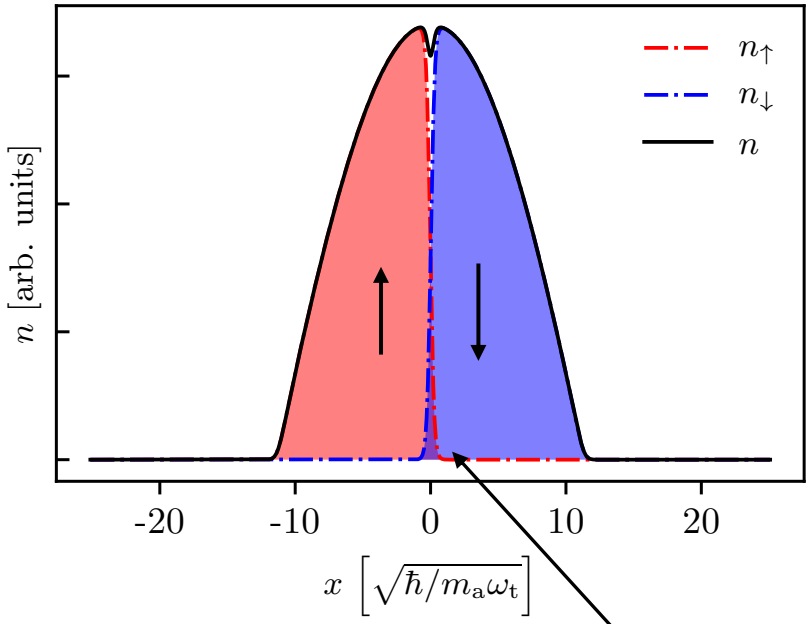


# Spin-1/2 BECs

$$E_{\text{int}} \sim u_2 \int dx\ [n_\uparrow(x) - n_\downarrow(x)]^2 = u_2 \int dx\ S_z^2(x)$$

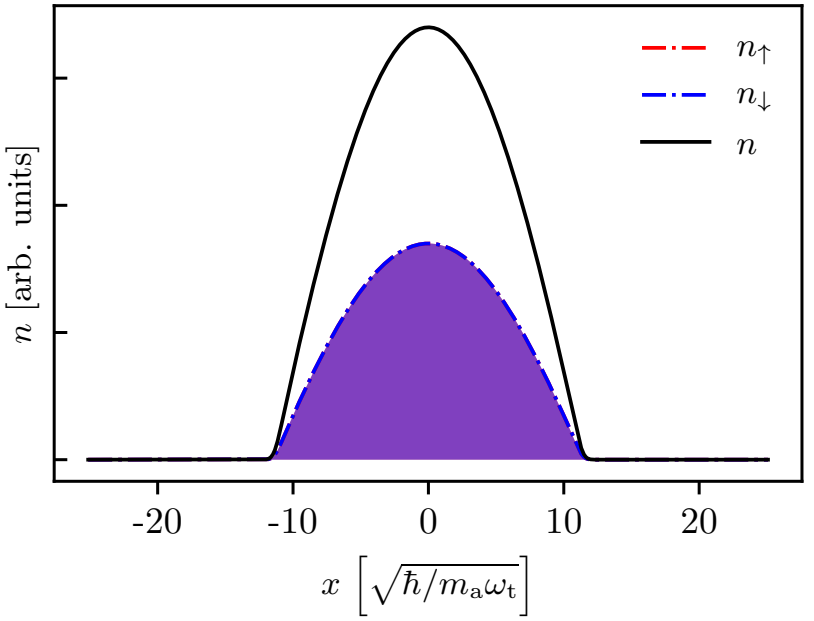
Spinor Bose-Einstein condensates: multiple internal states

$u_2 < 0$




Domain Wall

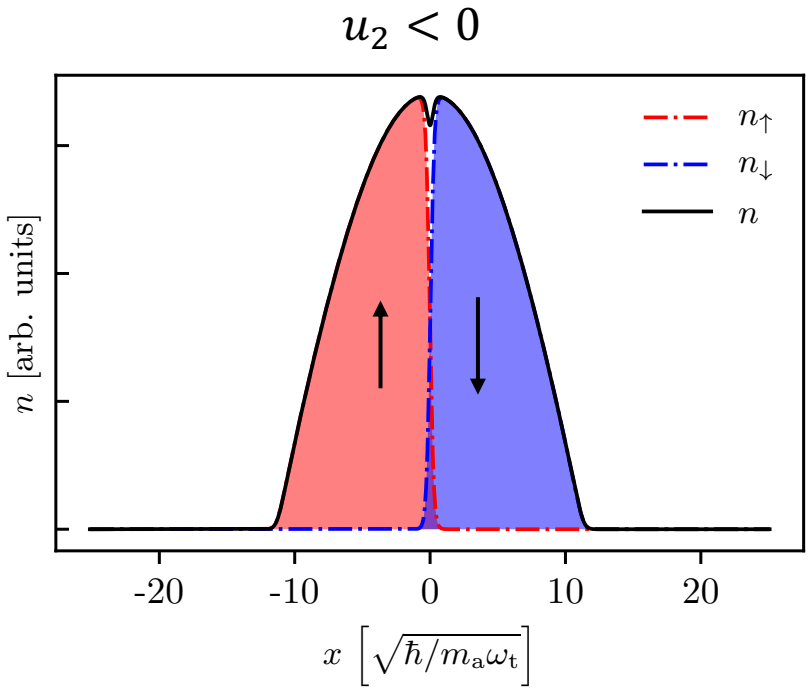
$u_2 > 0$

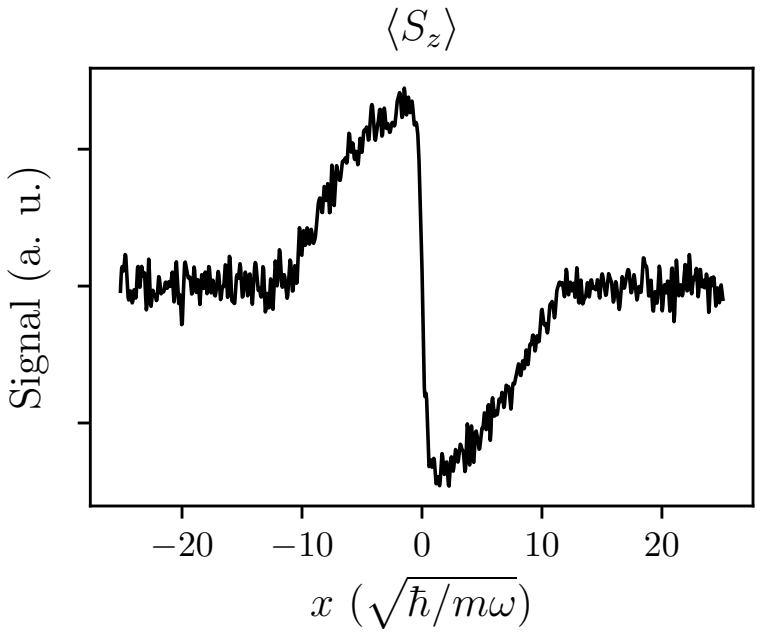



$$\mathcal{H}_{\uparrow(\downarrow)} = \frac{\hat{p}^2}{2m} + u_0 n(x) \pm u_2 S_z(x)$$

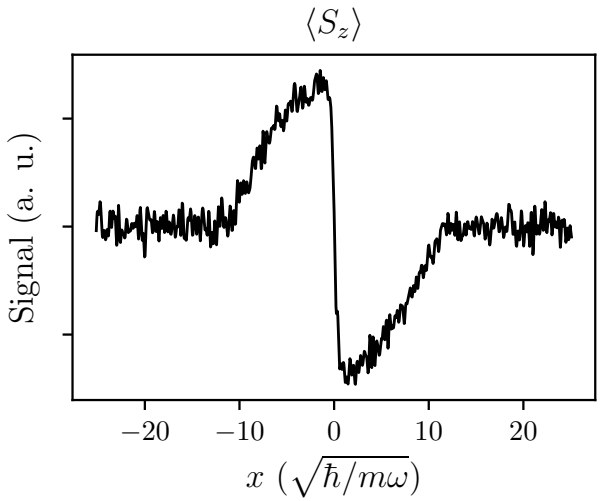
# Weak Measurement For Domain Walls

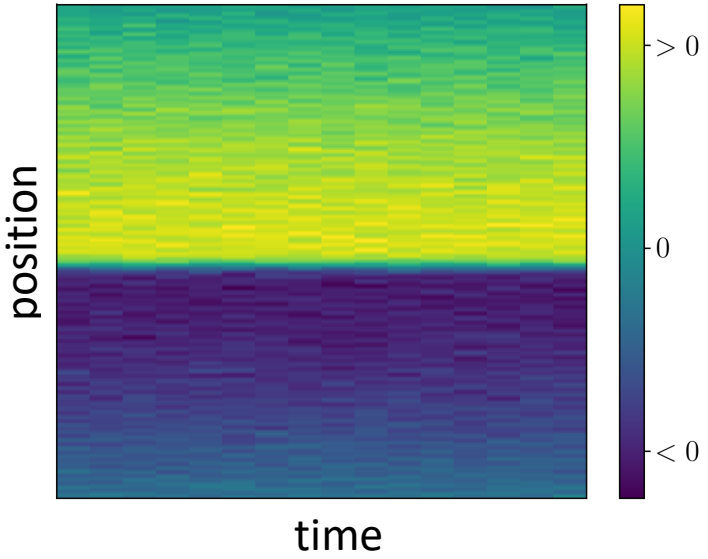
$$\mathcal{M}_z(x) = \langle \hat{S}_z(x) \rangle + \frac{m(x)}{\varphi}$$

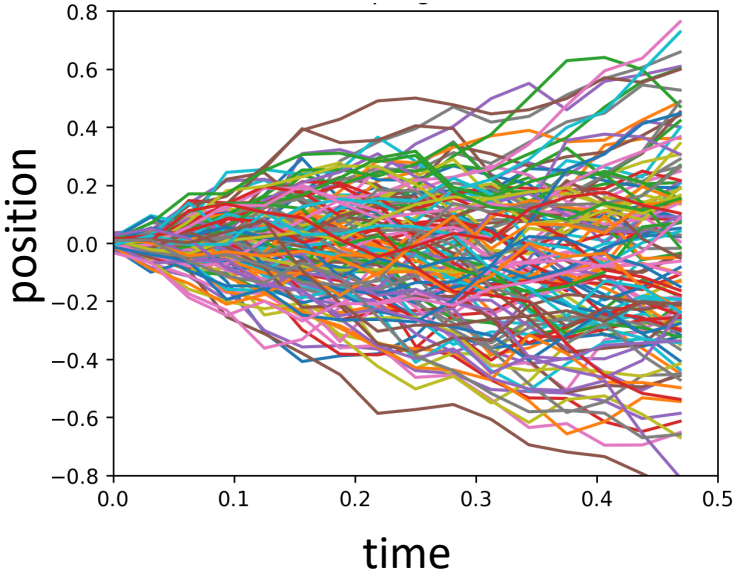


# Real-Time Picture of Domain Wall Dynamics

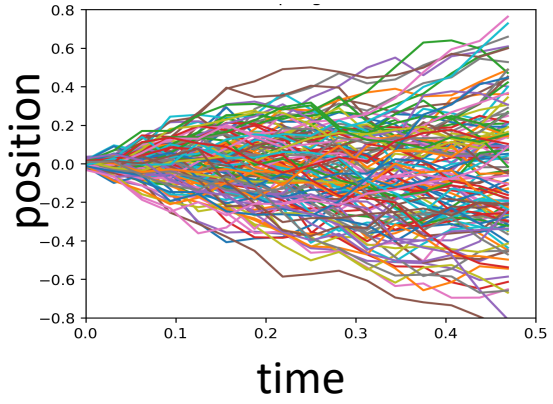


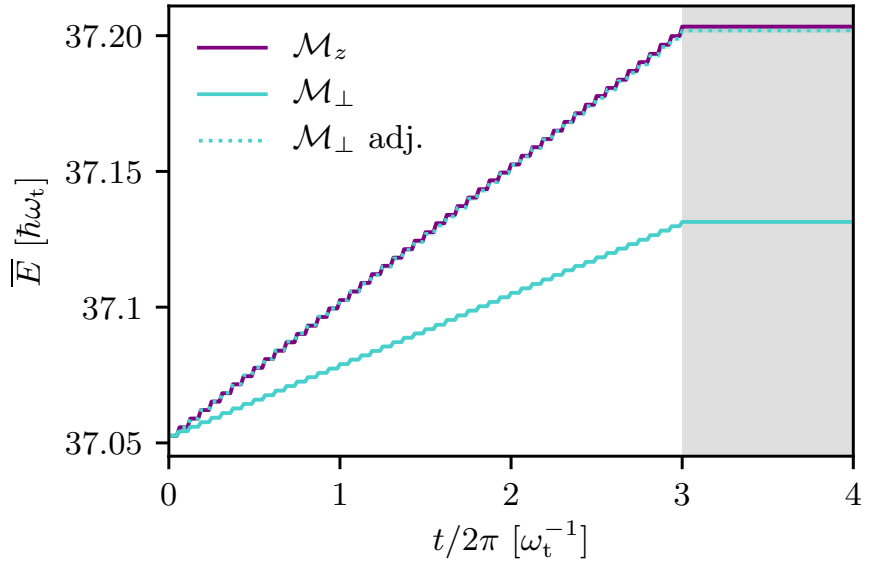
# Quantifying Measurement Backaction

## Domain Wall Diffusion




## Heating

- Measurement backaction adds energy to the system
- Measurement observable affects heating



# Feedback for Hamiltonian Engineering

My Claim: Using feedback signals derived from weak measurement, we can alter the effective Hamiltonian for the system dynamics

$$\mathcal{H} = \frac{\hat{p}^2}{2m} + u_0 n(x) + u_2 S_z(x)\hat{\tau}^z + V[\mathcal{M}(x)]$$

$$d\psi_{H'} = -i\left[\mathcal{H}_{\text{eff}} - \mu\right]\psi dt$$

$$d\psi_{M'} = \left[-\frac{\varphi^2}{4}dt + \varphi w(x,\varphi)\sqrt{dt}\right]\psi$$

$$V[\mathcal{M}(x)] = g_2 \mathcal{M}_z(x)\hat{\tau}^z$$

$$\mathcal{M}_z(x) = \langle \hat{S}_z(x)\rangle + \frac{m(x)}{\varphi}$$

$$\mathcal{H}_{\text{eff}} \approx \frac{\hat{p}^2}{2m} + u_0 n(x) + (u_2 + g_2) S_z(x)\hat{\tau}^z$$

u2 and g2 both affect the steady-state condensate phase

# Time-Dependent Feedback

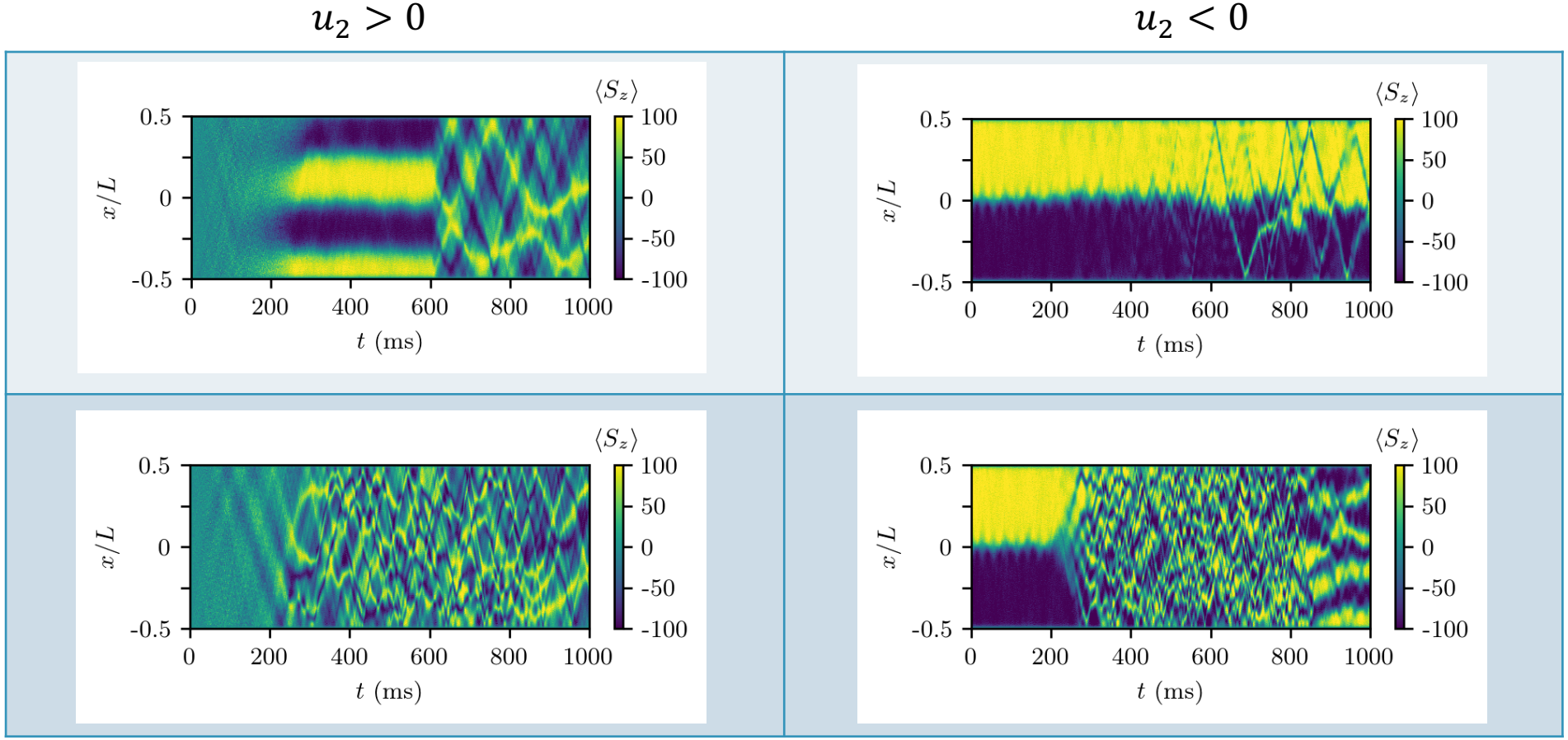
$$\mathcal{H}_{\text{eff}} \approx \frac{\hat{p}^2}{2m} + u_0 n(x) + (u_2 + g_2) S_z(x) \hat{\tau}^z$$

Protocol 1:

- g2 < 0 on from 200 to 600 ms

Protocol 2:

- g2 > 0 on from 200 to 600 ms

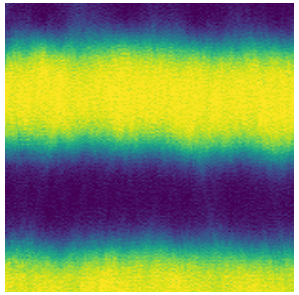


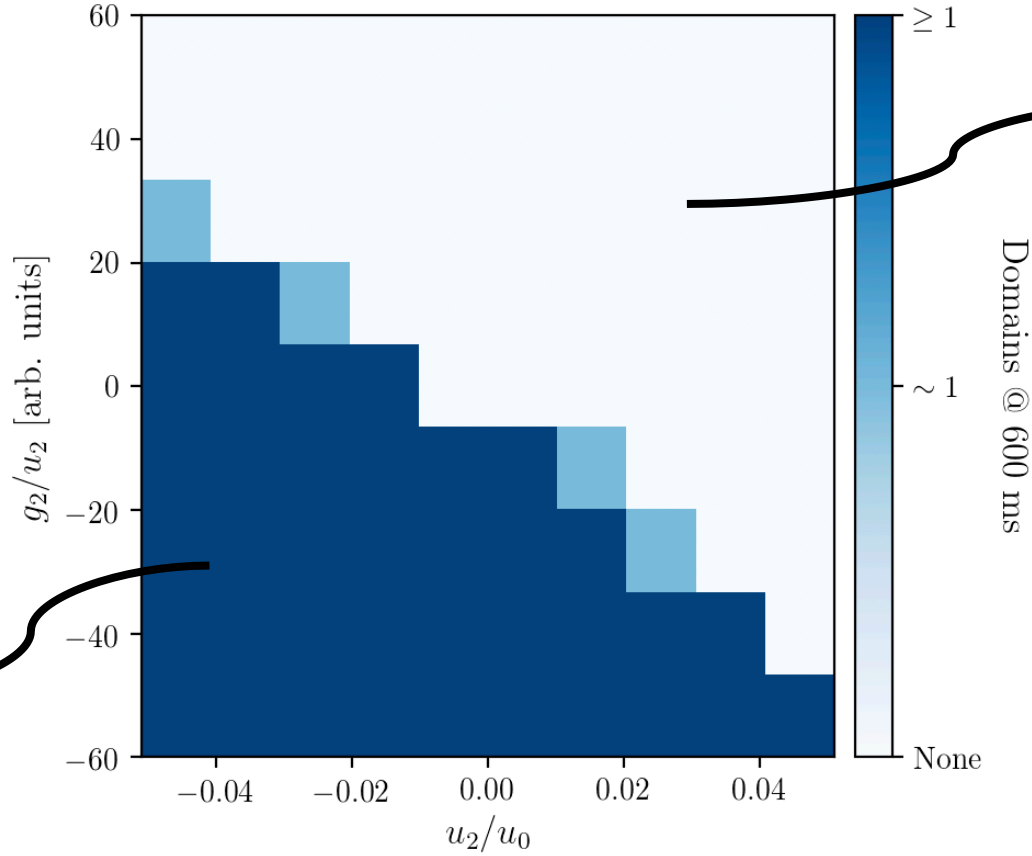
# Steady-State Phase Diagram

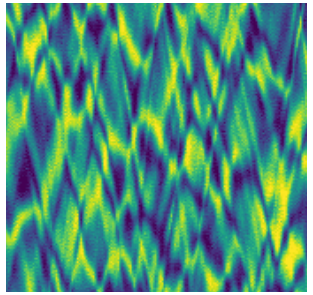
$$\mathcal{H}_{\text{eff}} \approx \frac{\hat{p}^2}{2m} + u_0 n(x) + (u_2 + g_2) S_z(x) \hat{\tau}^z$$

Preliminary

Ordered phase with single spin domains



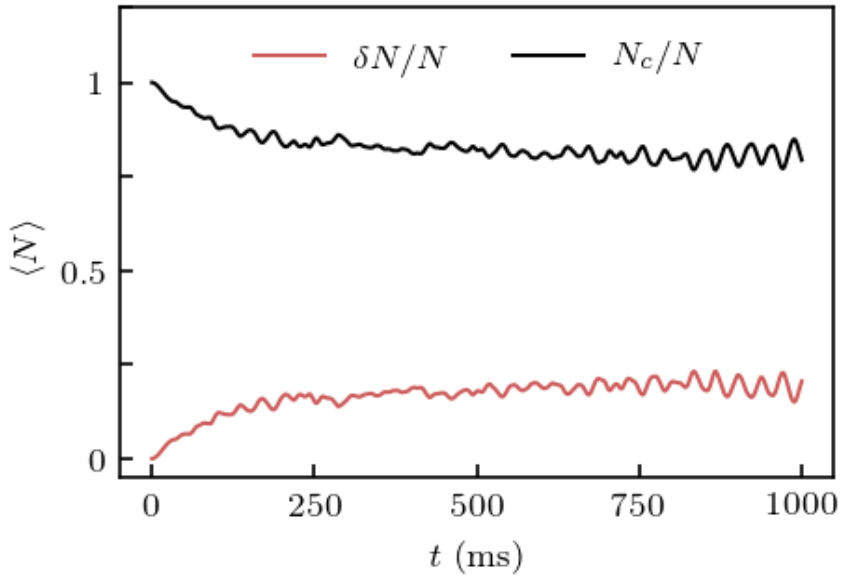


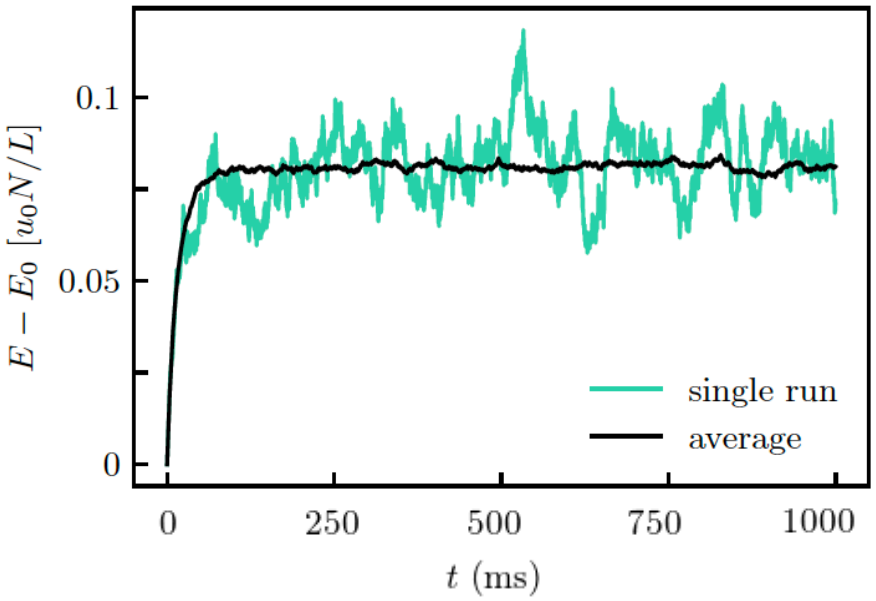
'Quenched' Phase with disordered spin orientation

# Feedback Cooling

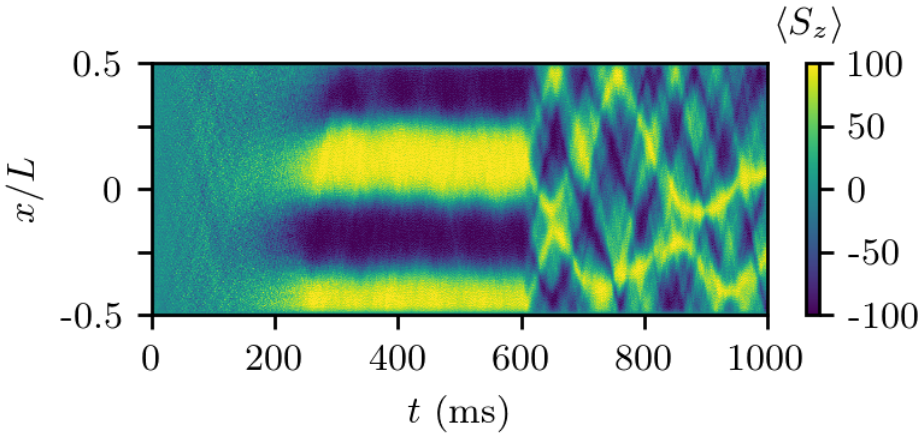
Condensate Fraction Stabilizes over ~ 200 ms




Energy Stabilizes over ~50 ms

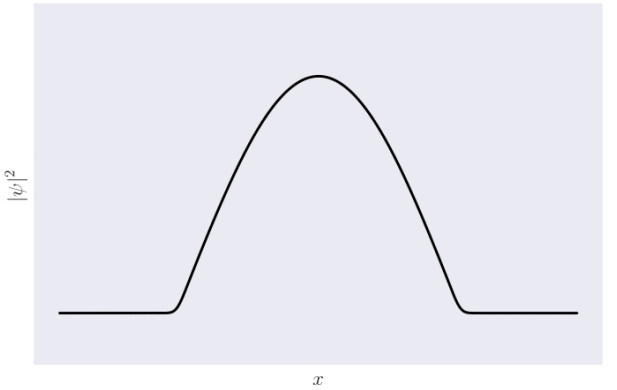


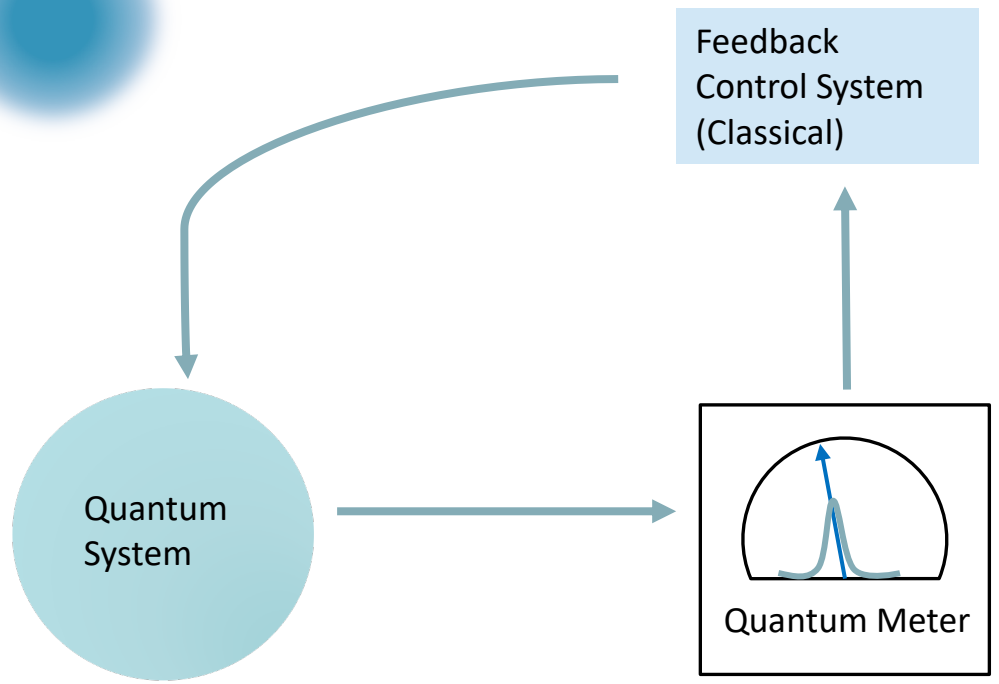
# A Pathway to Quantum Control




Weak Measurement for Domain Walls
*Physical Review A **99**, 053612 (2019)*

Feedback-Induced Phase Transitions in Spinor BEC
- posting soon!



# Thanks to...

PHYSICS FRONTIER CENTER
JOINT QUANTUM INSTITUTE

Questions?

Ian Spielman (PI)
UMD, JQI/NIST