Detecting coherence and quantum fluctuations

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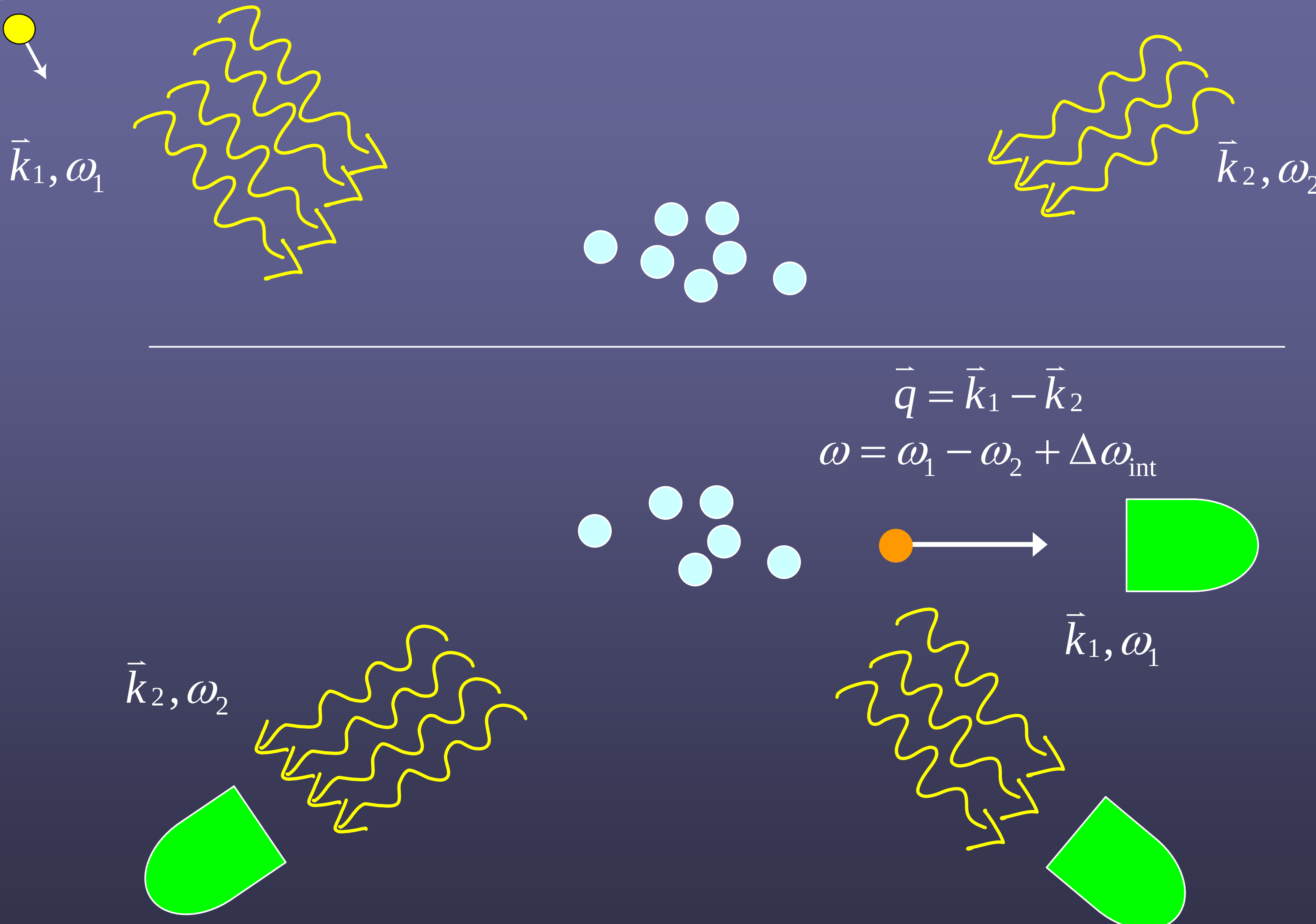
Outline

- Probing atomic systems with Bragg and Raman scattering
- Coherence-enhanced imaging
  - Spatial mapping of the coherent portion of an inhomogeneous gas
  - Spatial features in extended-sample superradiance
  - Coherence time of a propagating spin grating
- Bichromatic superradiant pump-probe spectroscopy (bSPPS)
  - Tomographic method
  - Application to atom beam circulating in storage ring

- Ultracold atoms trapped in a high-finesse optical resonator
  - System description
  - Cavity-enhanced heating of atomic motion

- Direct imaging of magnetization

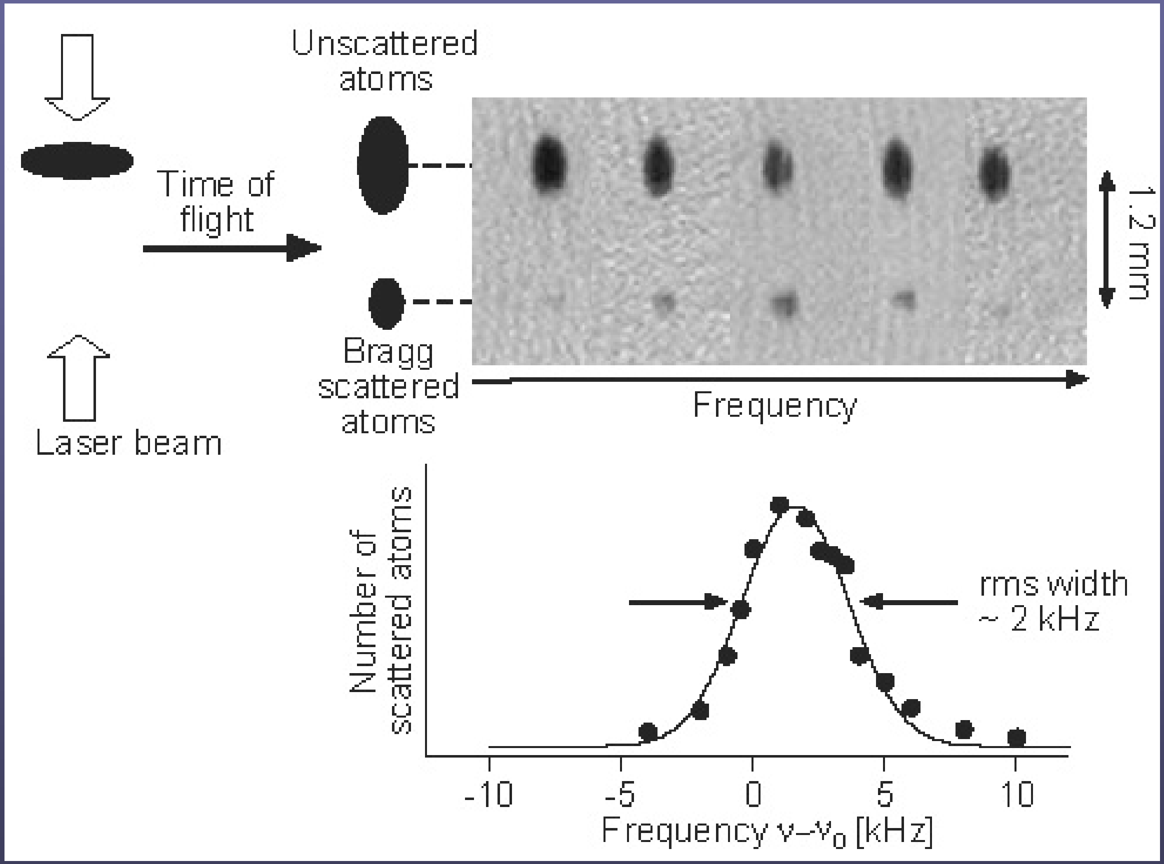
Bragg and Raman scattering



akin to neutron scattering of condensed materials

response measures dynamic structure factor, properties of the sample

Bragg scattering spectrum



Bragg spectroscopy of a BEC, Stenger et al, PRL 82, 4569 (1999)

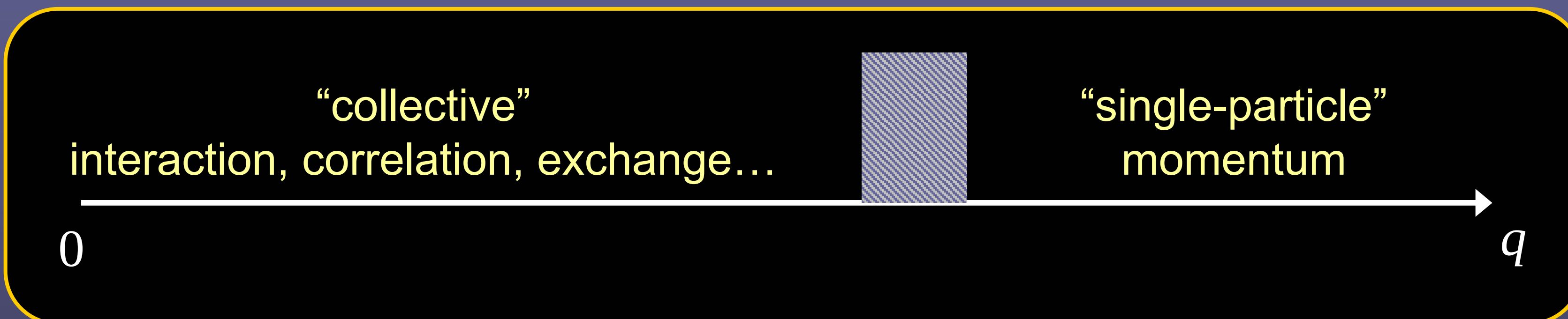
- Phillips, Ketterle: coherence, structure factor, interaction effects
- Davidson: Bogoliubov spectrum, effects of confinement
- Aspect: limited coherence in 1 D
- Heinzen: lattice-trapped gases

Bragg/Raman spectra: coherence, interactions, structure

- Bragg/Raman response related to (spin) structure factor

$$S(q,\omega)=\frac{1}{Z}\sum e^{-\hbar\omega/k_BT}\left|\langle m|\hat{\sigma}\rho_q|n\rangle\right|\delta(\omega-\omega_m+\omega_n)$$

information depends on physical reqime probed



e.g. in weakly interacting Bose gas

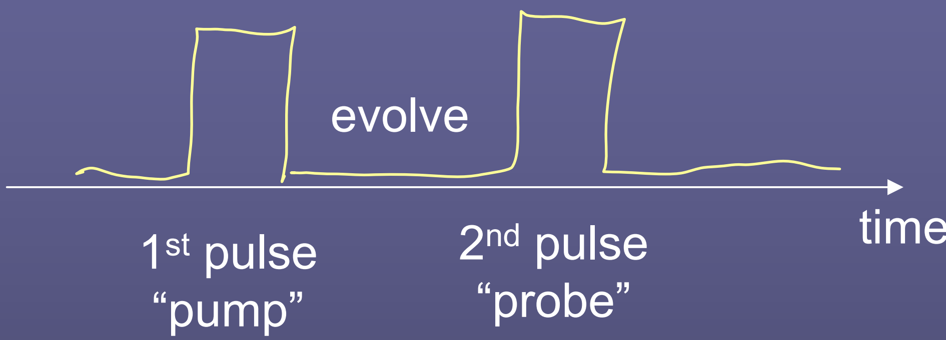
rms line width $(\Delta\omega)^2 \simeq (\Delta\omega_{\text{int},LDA})^2+(\Delta\omega_{Doppler})^2$

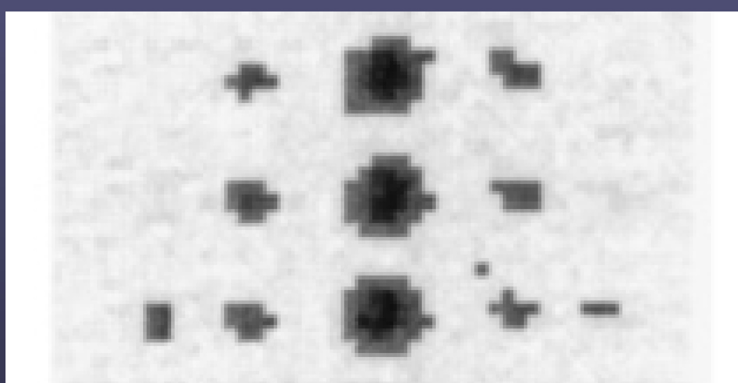
Bragg: exchange
Raman: differences in scattering

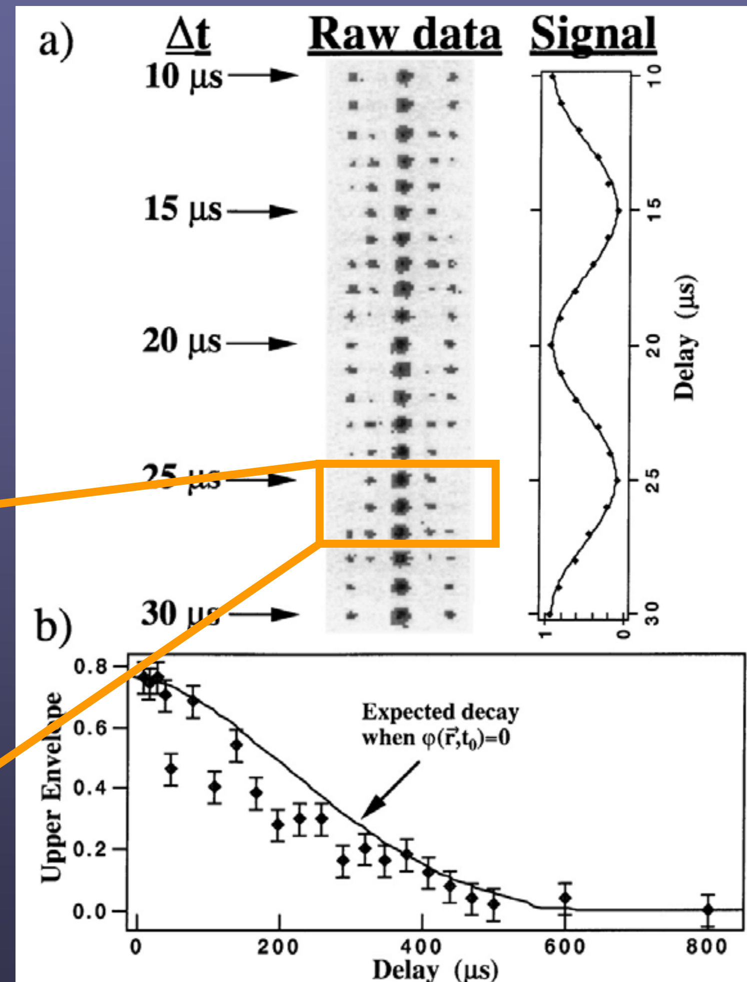
$$\Delta\omega_{Doppler}\approx O(1)\times\frac{\hbar q}{m}\frac{1}{\lambda_{coh}}$$

Zambelli et al, PRA 61, 063608 (2000)

Ramsey/interferometric method

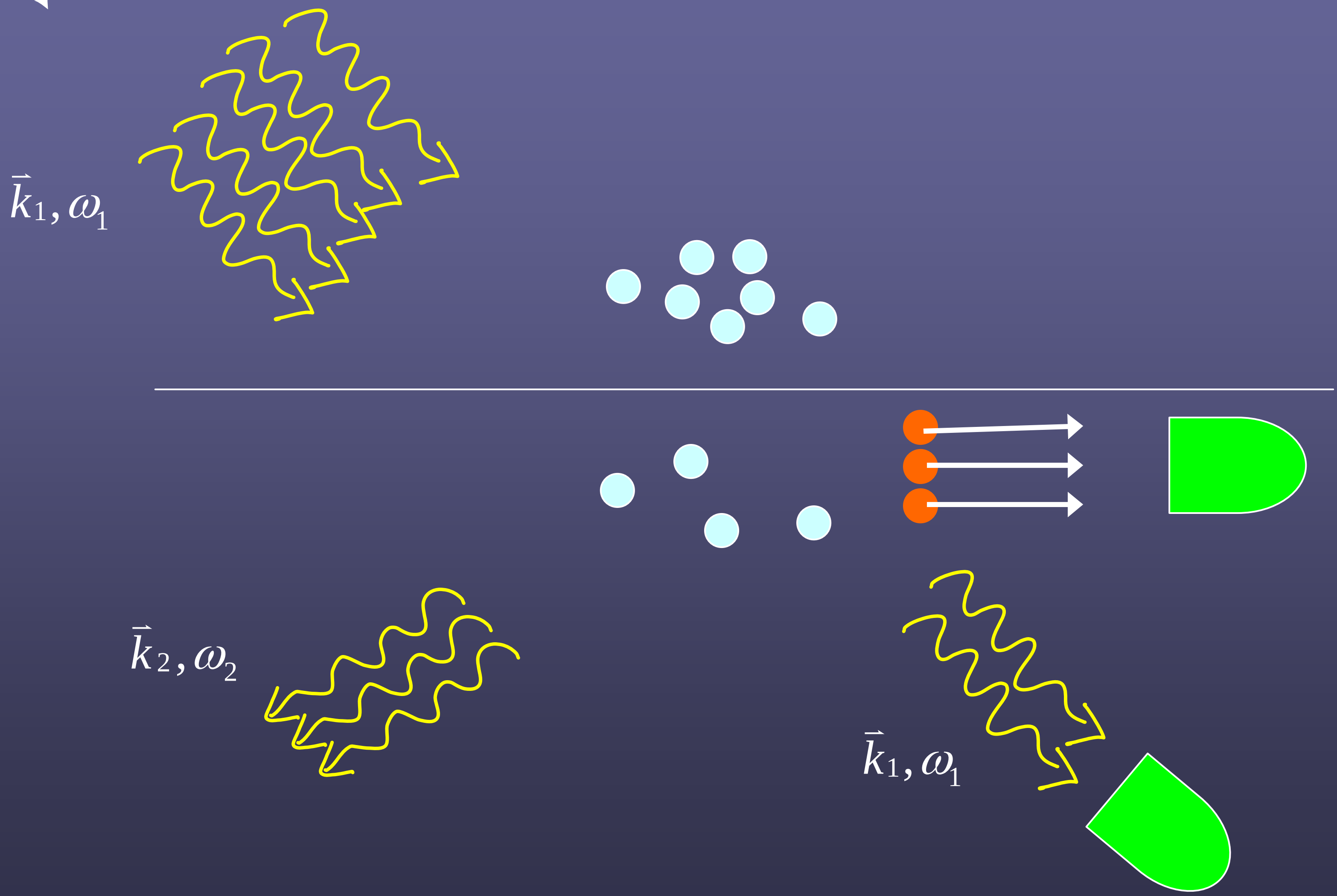


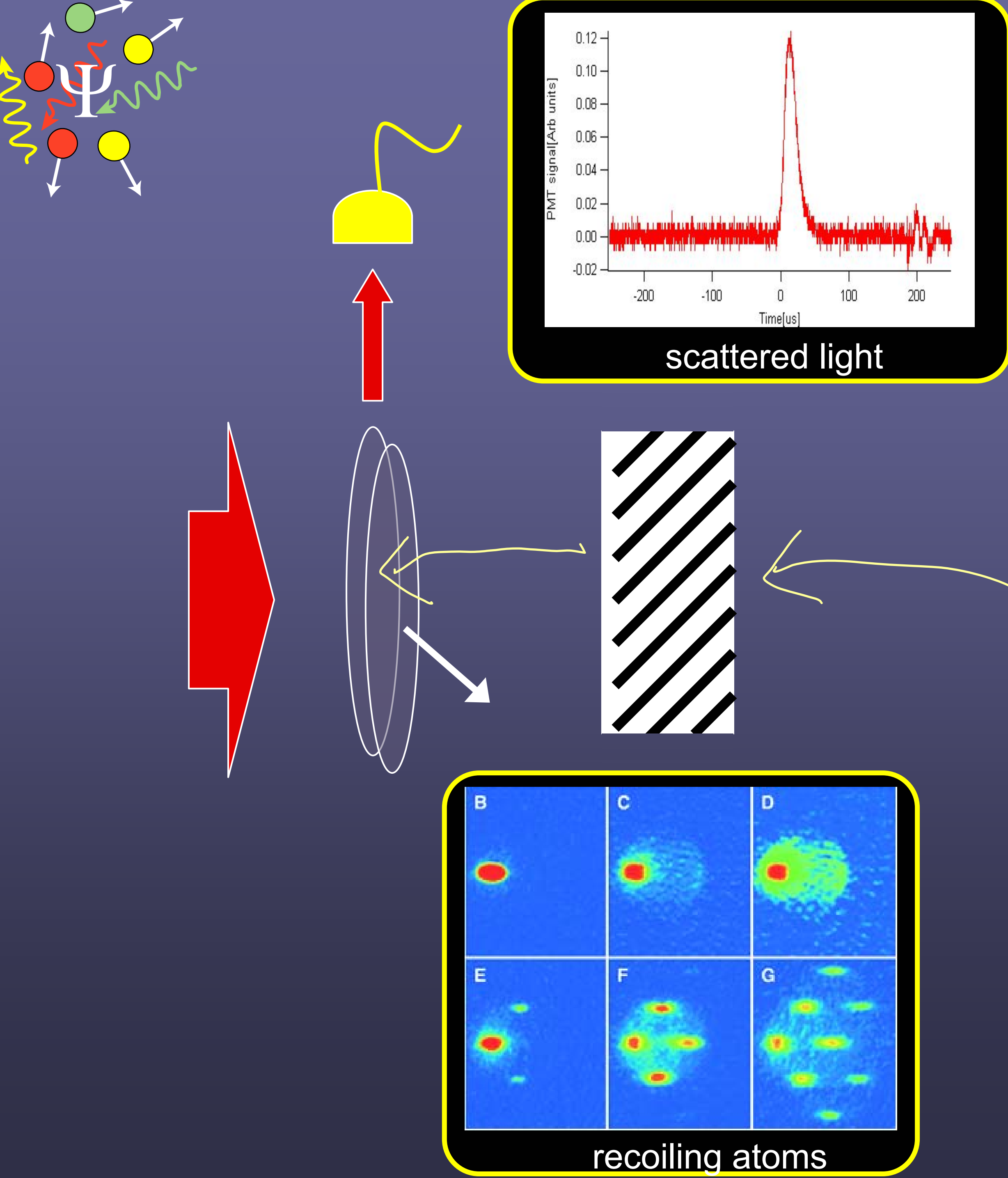




Hagley et al, PRL 83, 3112 (1999)

Superradiance: Self-stimulated scattering



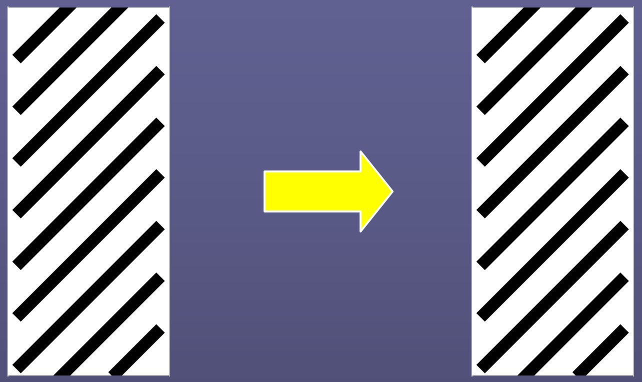


Superradiance establishes a polarization grating which collectively scatters light

Mechanisms for dephasing and decay

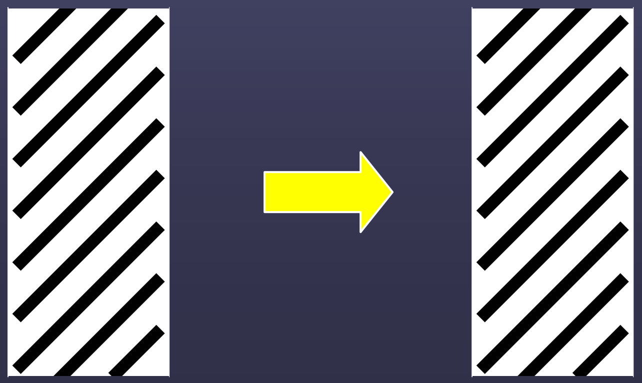
Dephasing

- mean-field interactions
  (inhomogeneous mean-field collision width)
- position/momentum correlations
  (inhomogeneous Doppler width)
- Raman: Zeeman shifts
  (inhomogeneous Zeeman width)

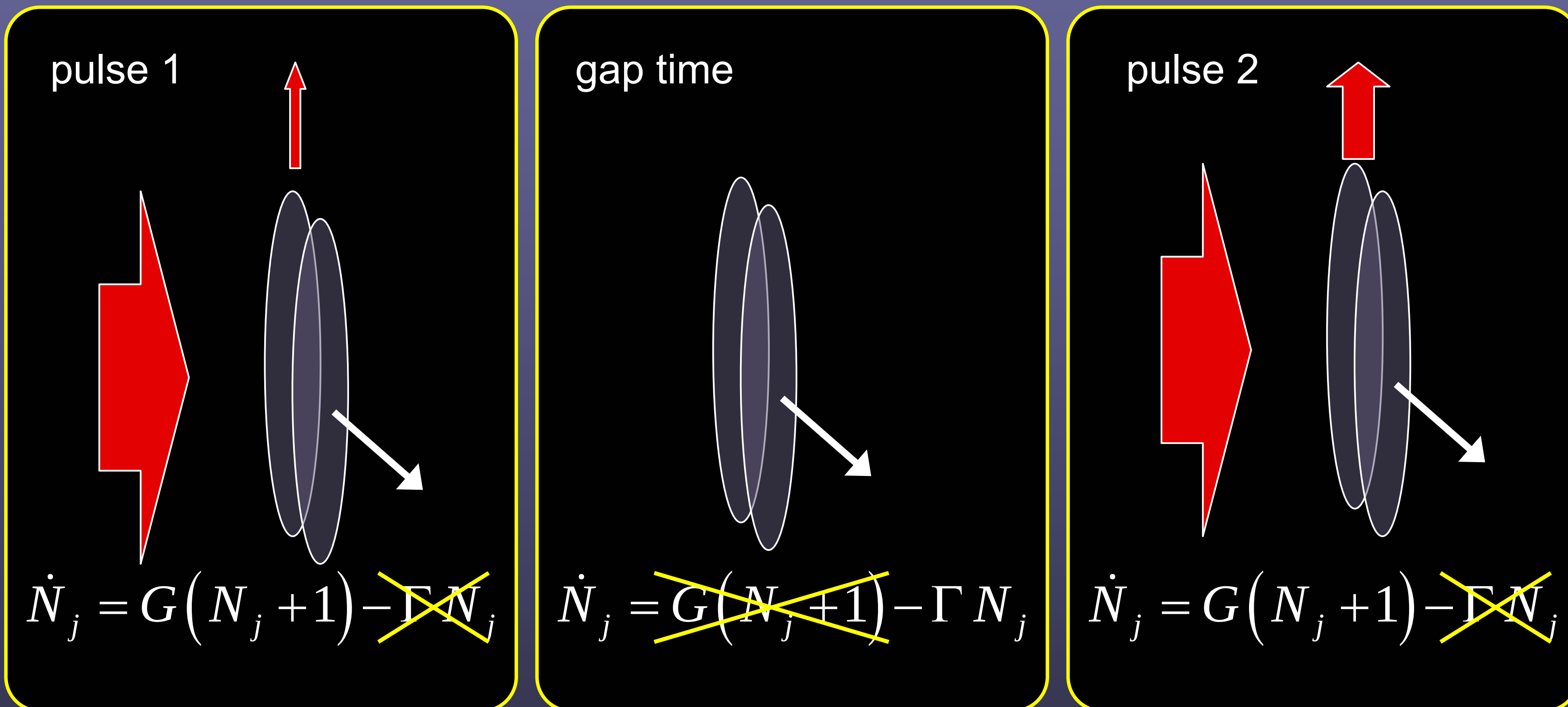


Decay

- collisions
  (homogeneous collision width)
- non-zero temperature
  (homogeneous Doppler width)
- Raman: spin decay/decoherence
  (homogeneous Zeeman width)

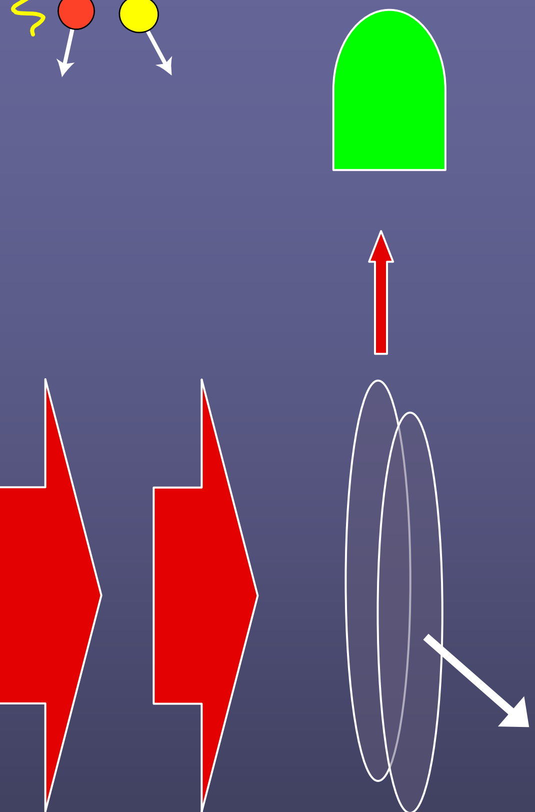


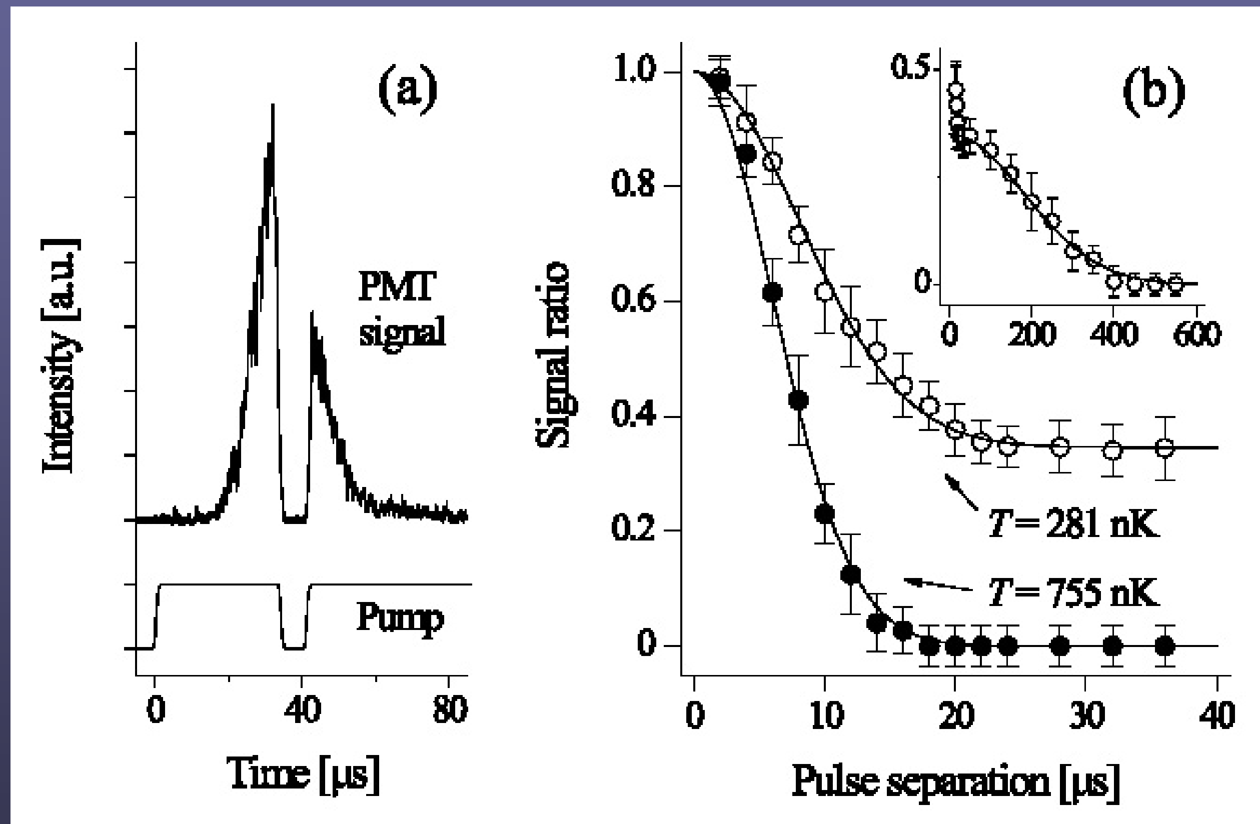
Superradiant pump-probe spectroscopy (SPPS)



Rayleigh: Inouye *et al.* (98)
Raman: Schneble *et al.*, Yoshikawa *et al.* (03)
Thermal vapors: Yoshikawa *et al.* (05)
Coherence-enhanced imaging: Sadler *et al.* (06)

Superradiant pump-probe spectroscopy (SPPS)

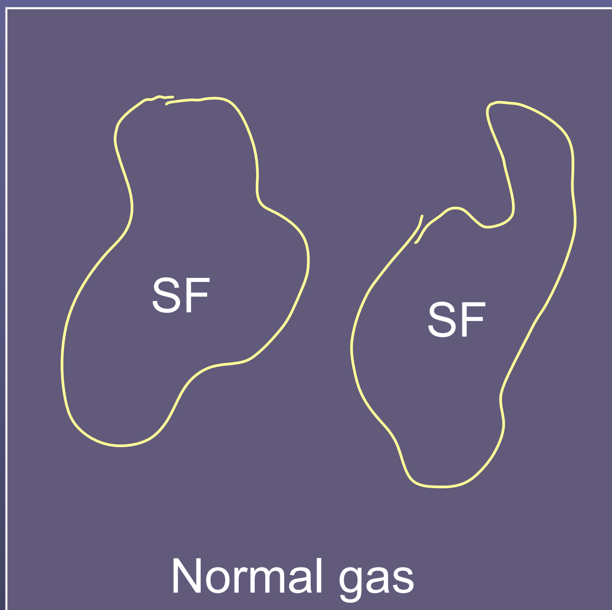




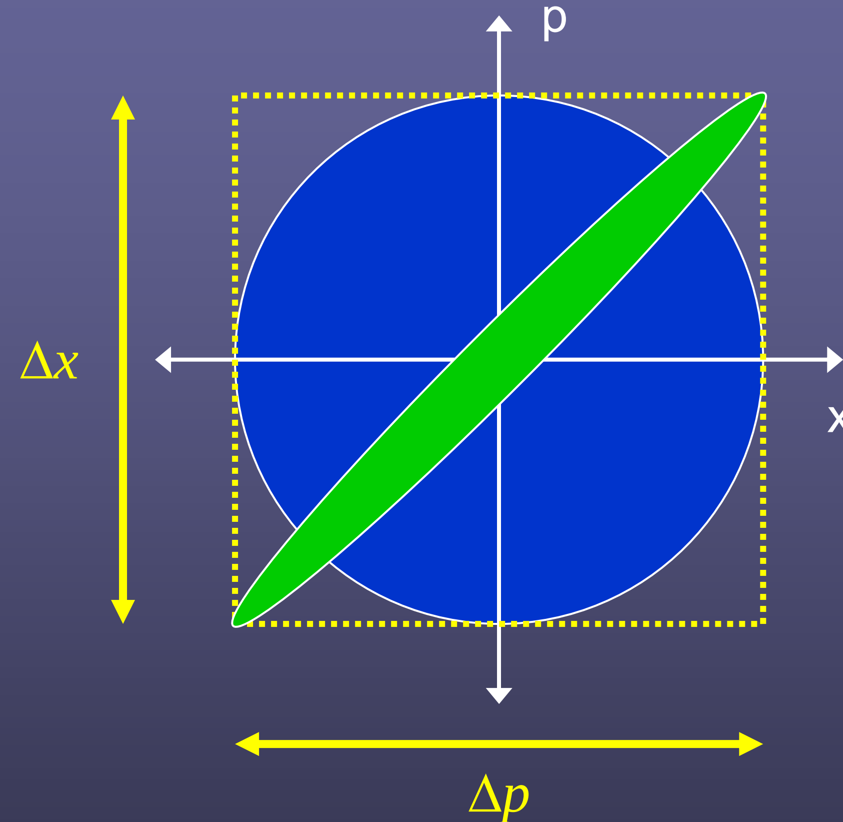
Yoshikawa, Torii, Kuga, PRL 94, 083602 (2005)

Limitations / Opportunities

- Inhomogeneous gases

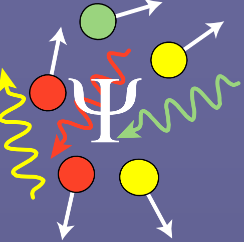


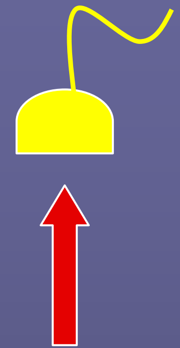
e.g. non-equilibrium from quenching, first order transition, inhomogeneous confinement

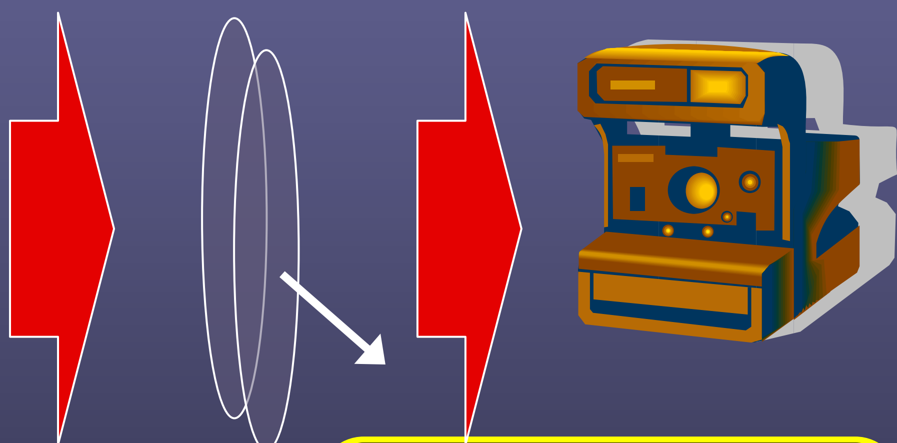


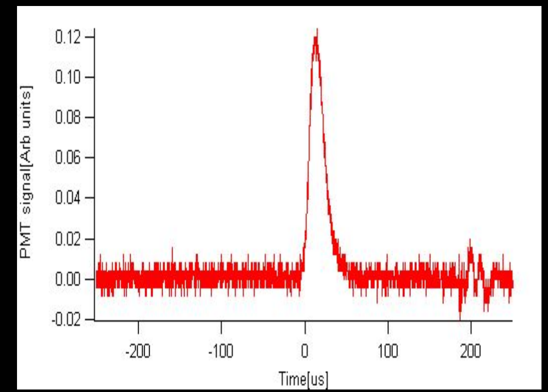
e.g. atomic beams

Coherence-enhanced imaging

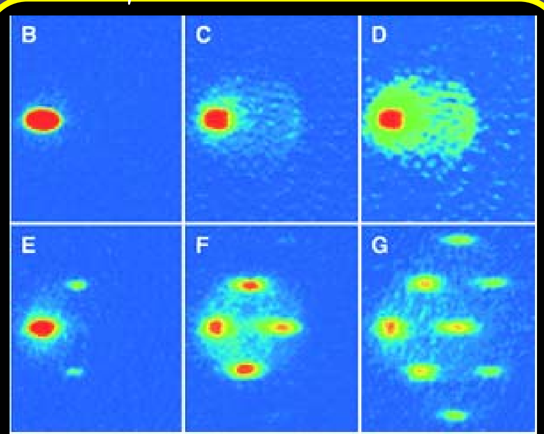




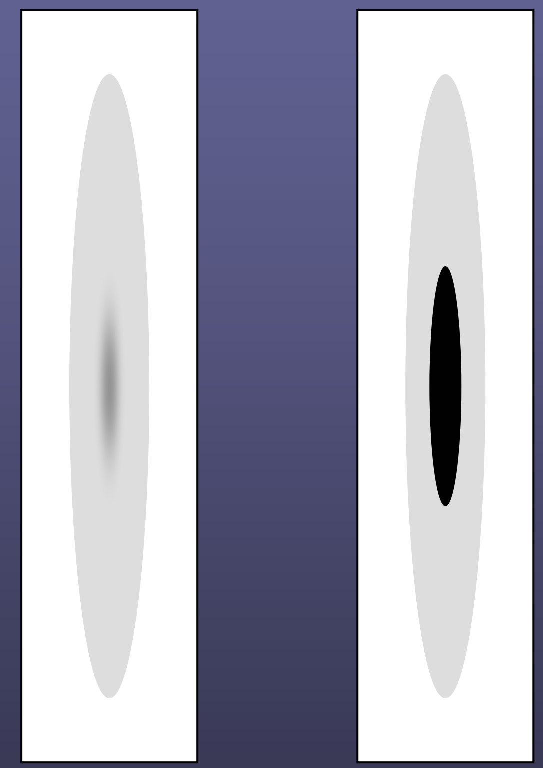




scattered light



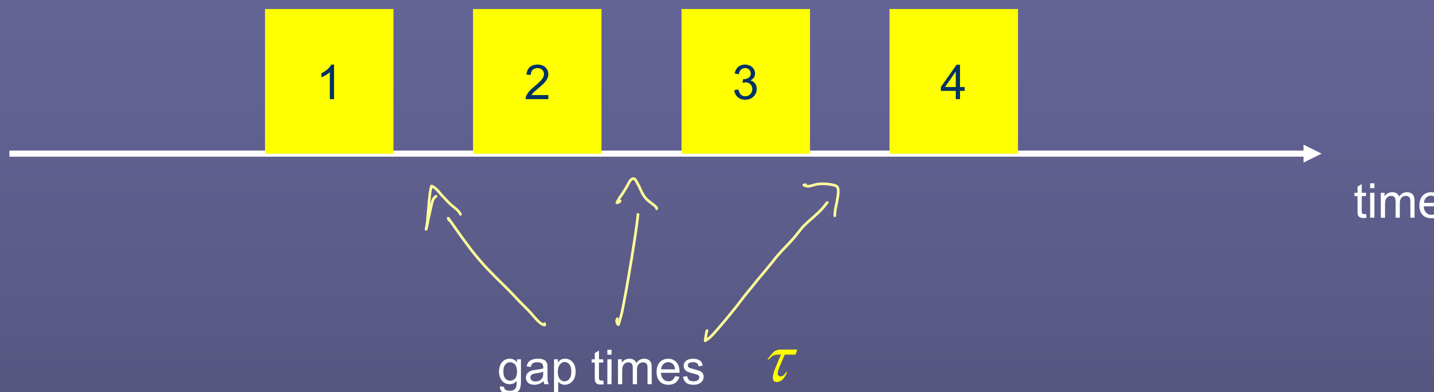
recoiling atoms



normal (linear) in-situ image

enhanced (non-linear) in-situ image

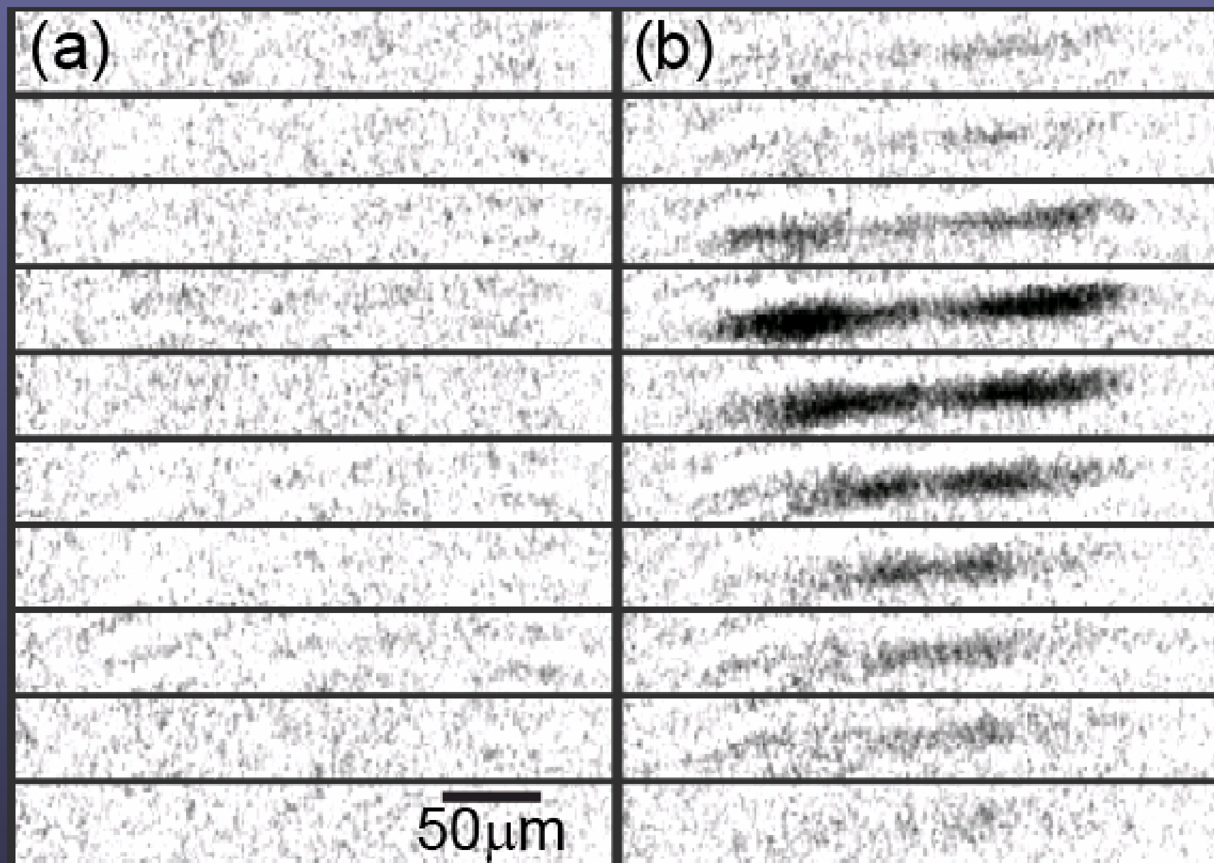
Selective imaging of coherent matter



choose gap time such that

$$\tau > \frac{m}{\hbar q} \lambda_{dB}$$

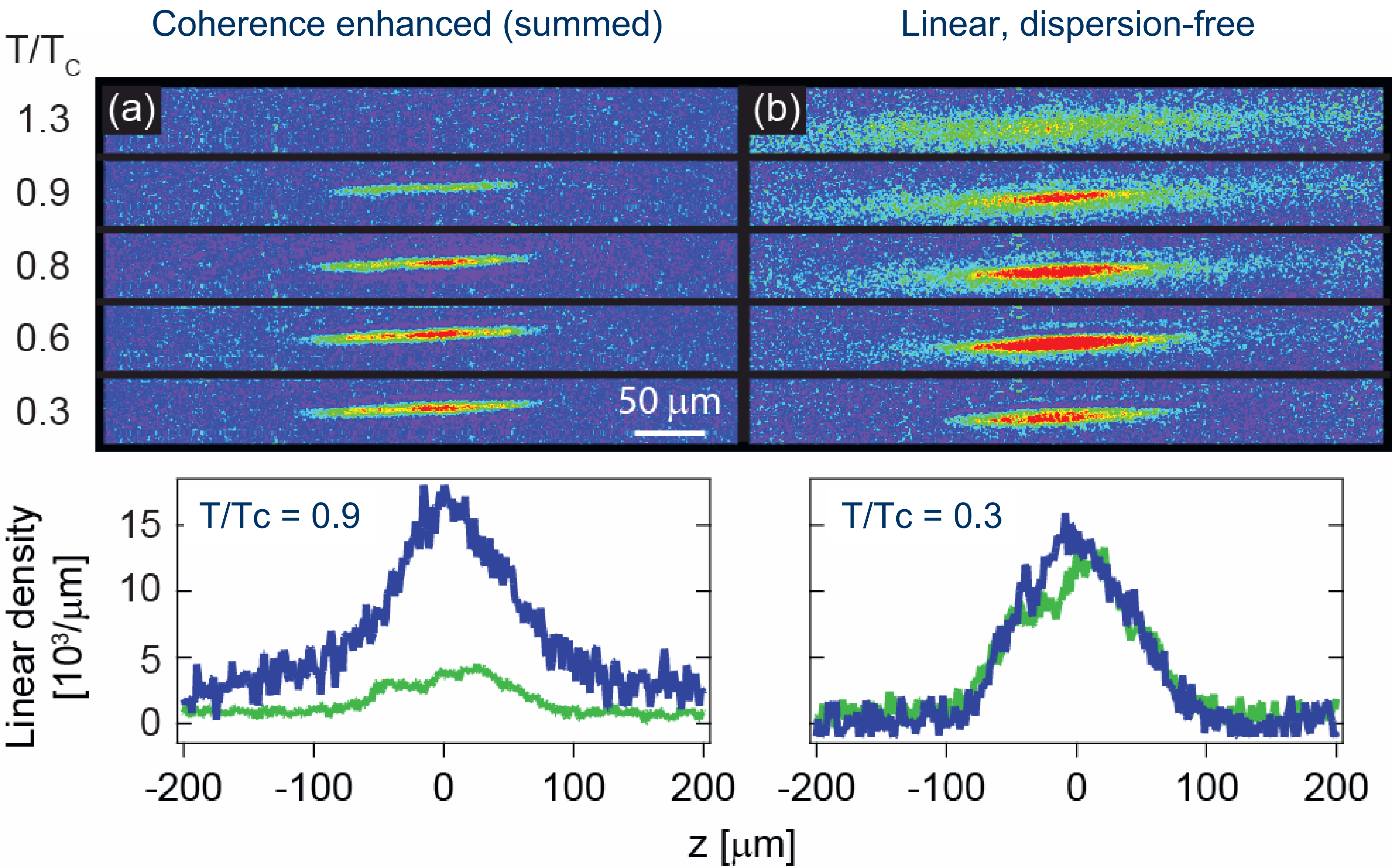
Selective imaging of coherent matter



Normal gas (T > Tc)　　Degenerate gas (T << Tc)

see: Uys and Meystre, “Theory of coherent Raman superradiance imaging of condensed Bose gases,” arXiv:cond-mat/0602343

Linear vs non-linear imaging

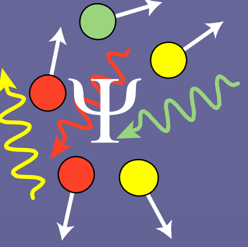


“Coherence-enhanced imaging of a degenerate Bose gas,” PRL (in press)

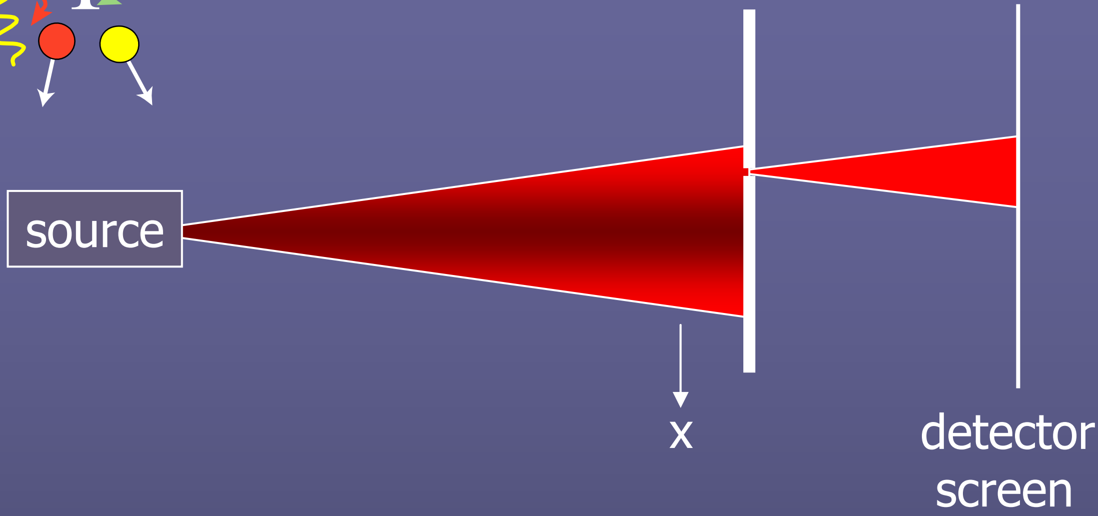
Probing the quantum state of a guided atom laser pulse

Is coherence of guided atom-laser pulse degraded during operation of an interferometer, e.g. due to

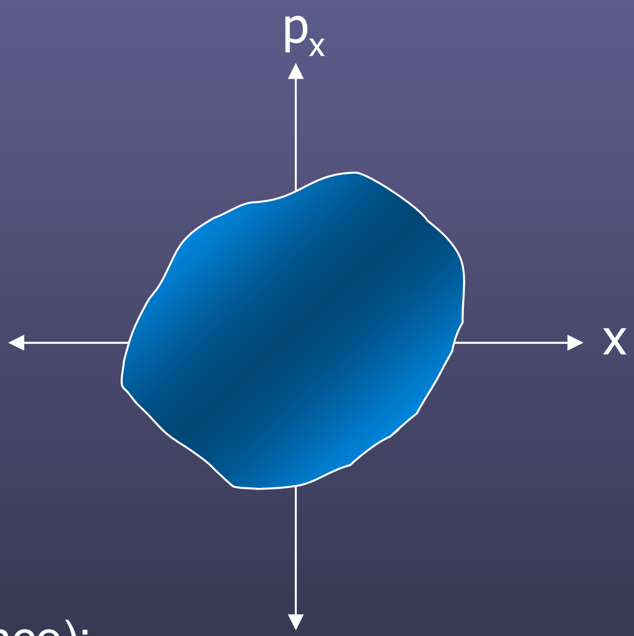
- injection into waveguide
- expansion and propagation in guide? [Anderson, Olshanii, …]
- coupling of energetic longitudinal motion to internal degrees of freedom [various, betatron oscillations, …]
- rethermalization / onset of one-dimensional effects [Sengstock, Porto/Phillips, Weiss, …]



Diagnosing a particle beam



"Pepper pot"



classical only:

phase-space distribution $f(x,p)$

quantum also (accounts for partial coherence):

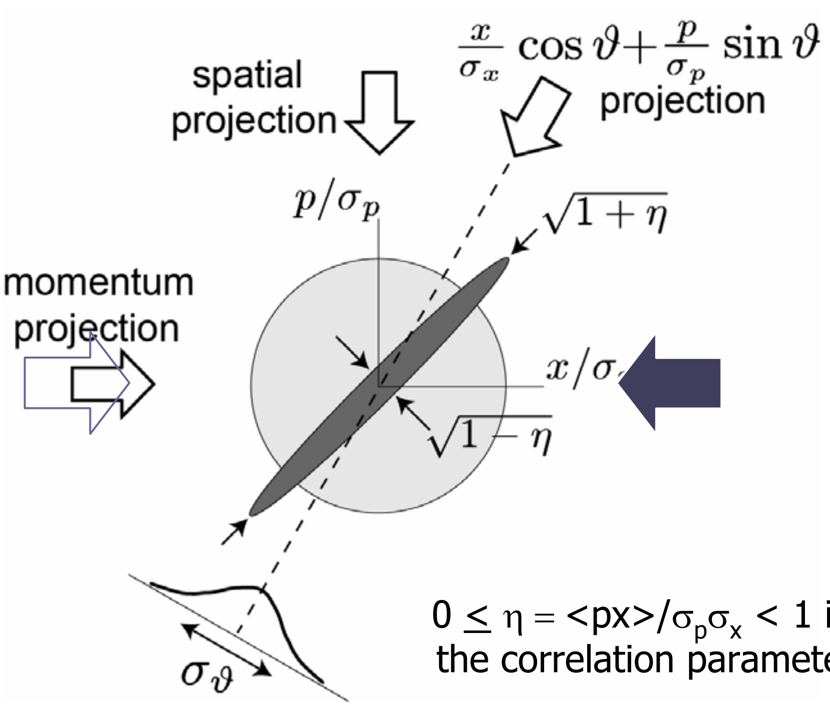
Wigner function

$$W(x,p)=\frac{1}{2\pi}\int e^{-ipy/\hbar}\left\langle x-\frac{y}{2}\right|\hat{\rho}\left|x+\frac{y}{2}\right\rangle dy$$

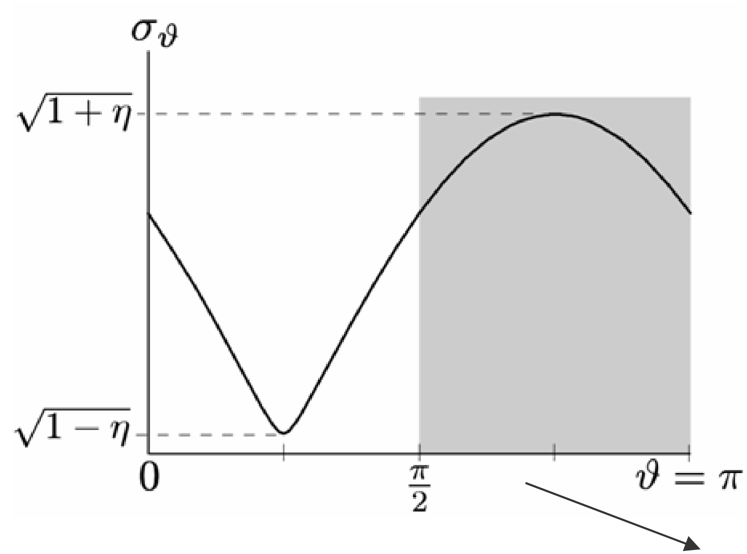
Diagnosing a particle beam

The quantum "pepper pot"
Quantum-state tomography:

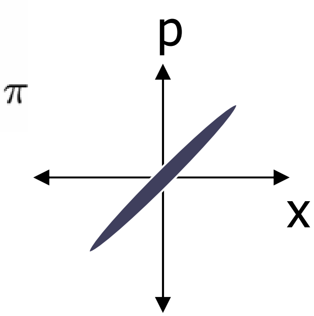
Observe all projections of the Wigner function



$0 \leq \eta = \langle px \rangle / \sigma_p \sigma_x < 1$ is the correlation parameter



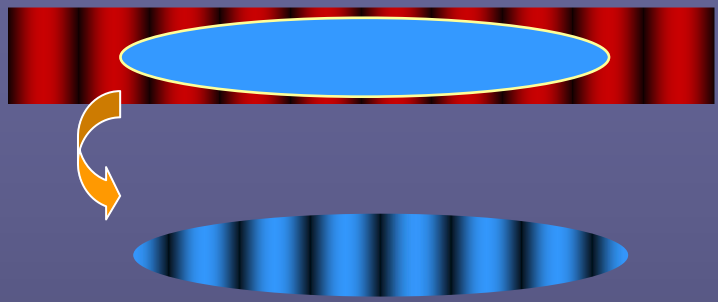
"backprojection" yields original distribution



Bichromatic superradiant pump-probe spectroscopy (bSPPS)

$k_{\text{in}}^{(1)}$

$k_{\text{out}}^{(1)}$



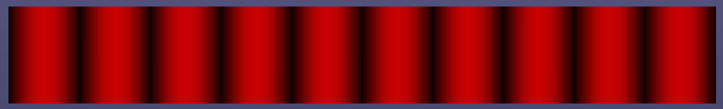
$q_1 = k_{\text{out}}^{(1)} - k_{\text{in}}^{(1)}$

wait:

monochromatic SPPS:

$k_{\text{in}}^{(2)}$

$k_{\text{out}}^{(2)}$



$q_2 = q_1$

phase matching misfit

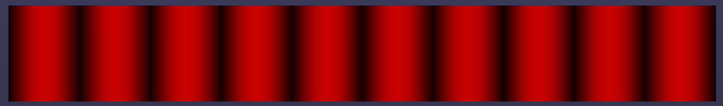
decay of Γ vs. time reflects momentum distribution

$\theta = 0$ projection of $W(x, p)$

bichromatic SPPS:

$k_{\text{in}}^{(2)}$

$k_{\text{out}}^{(2)}$

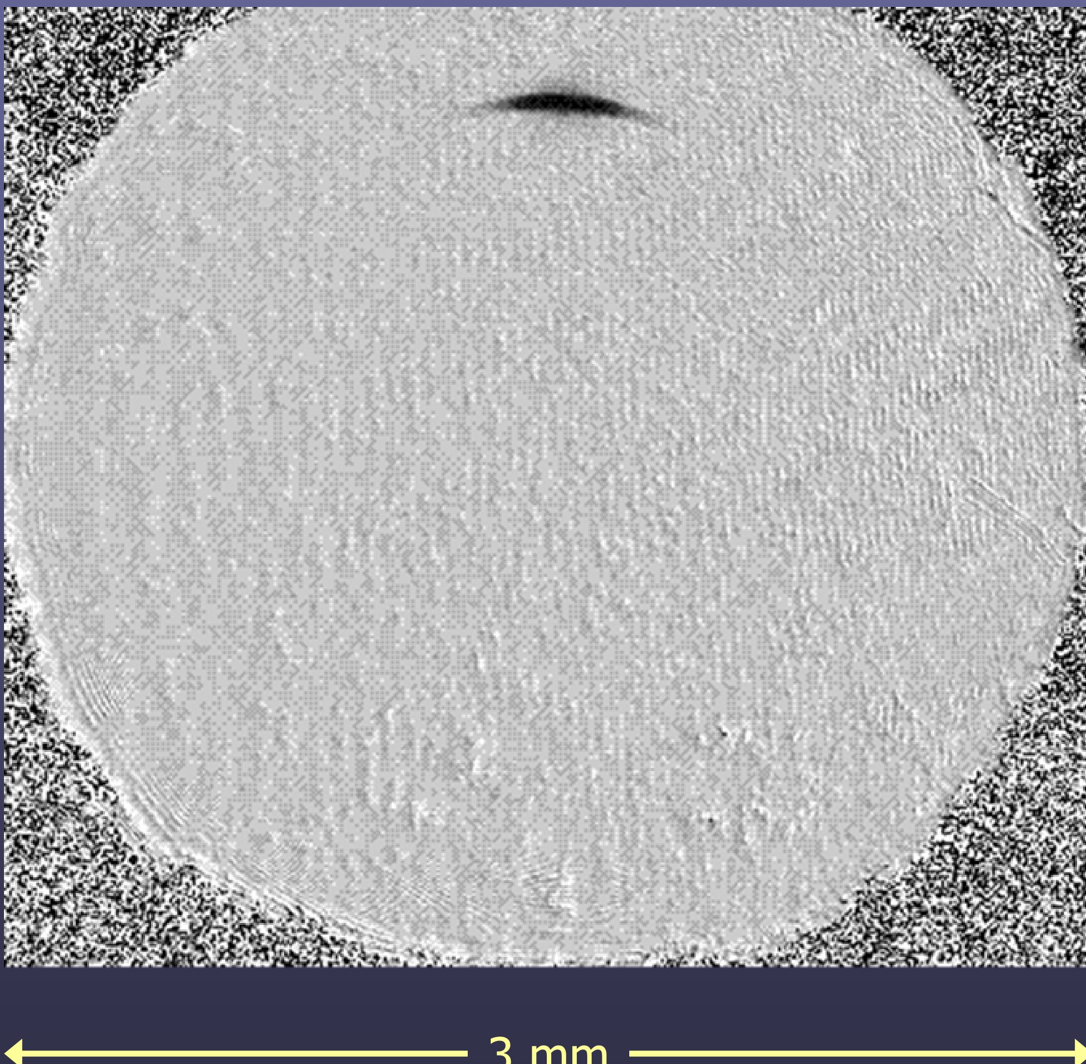


$q_2 \neq q_1$

$\tan\theta = \frac{-\Delta q m}{q_1 \tau} \frac{\sigma_x}{\sigma_p}$ projection of $W(x, p)$

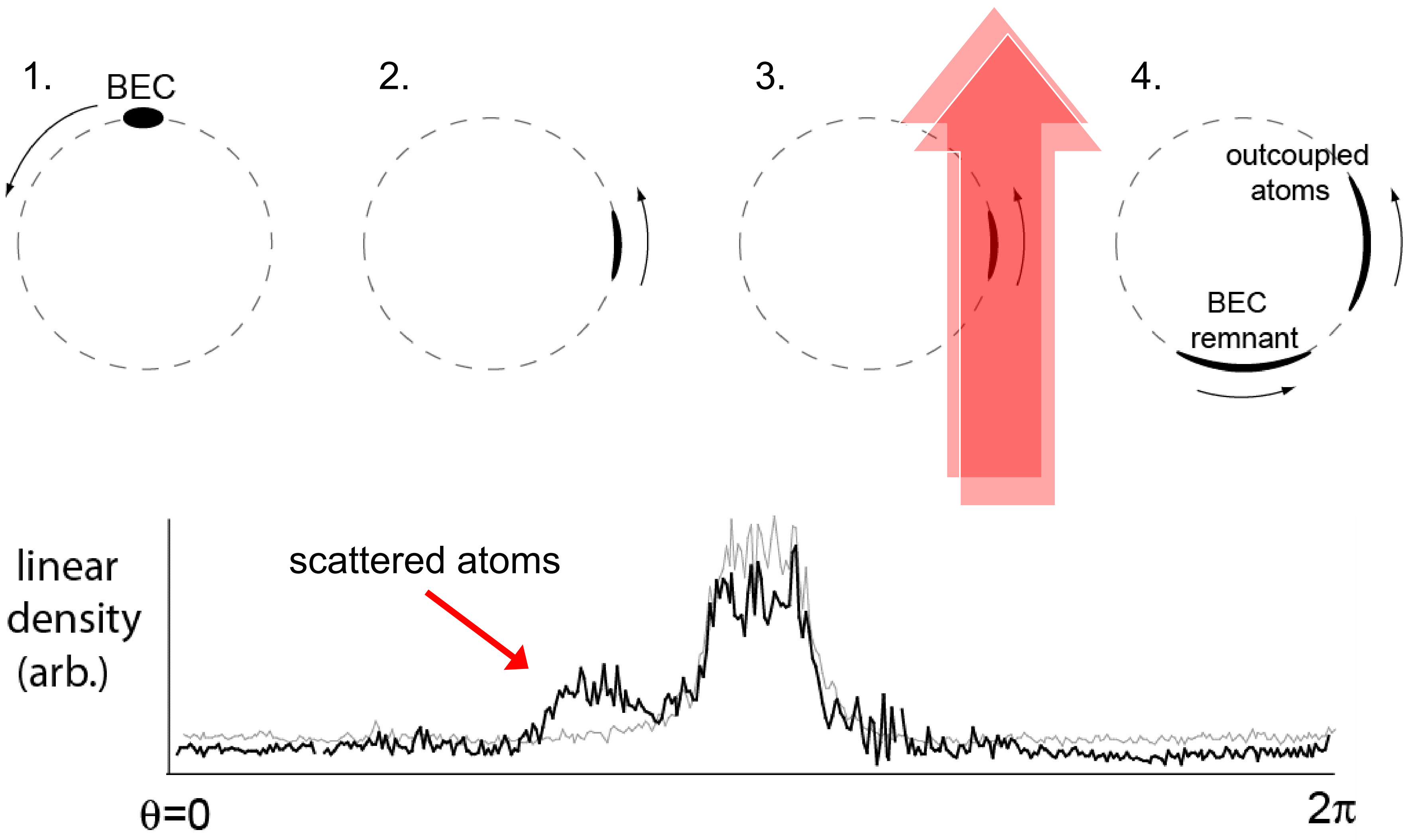
offers potential for full tomography of the Wigner function

Experimental testbed: ultracold-atom storage ring



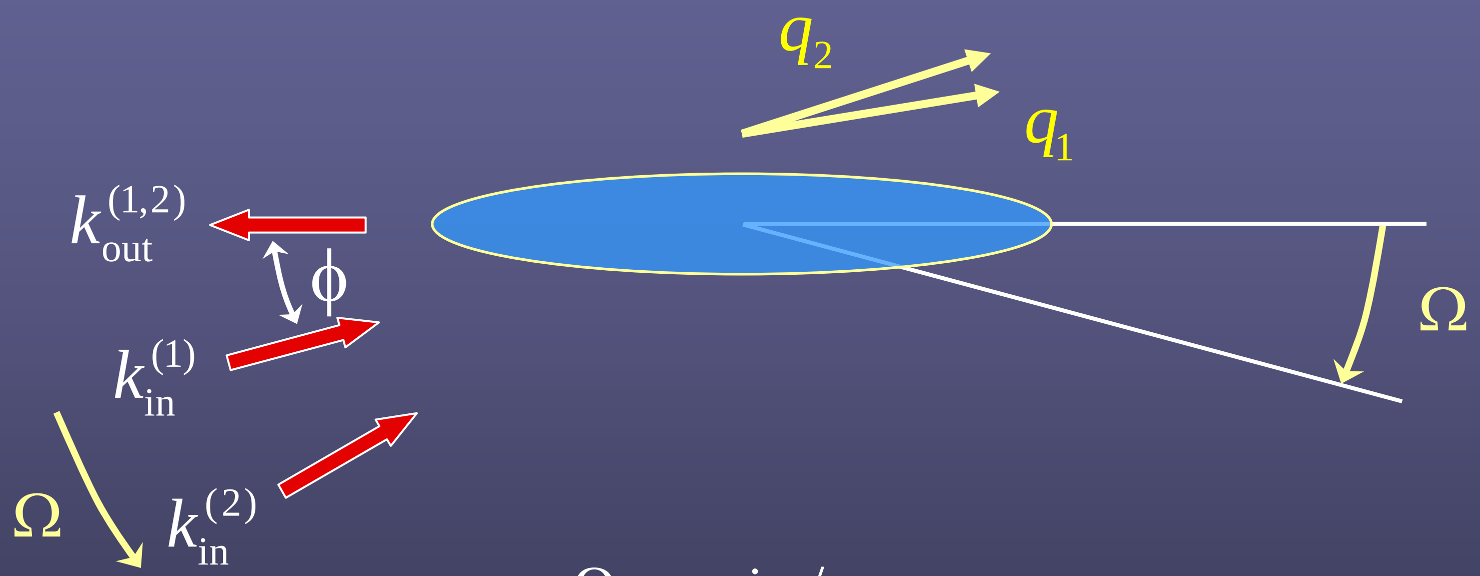
- ^{87}Rb BEC of 300,000 atoms
- TORT-based storage ring
  - r = 1.25 mm
  - 85 Hz transverse trap freq.
- launched into circular motion
  - 8.4 revolutions/second
  - linear velocity = 83 mm/s
- longitudinal momentum spread measured by guided time-of-flight
  - σ_v = 1.8 mm/s
  - consistent with coherent launch sequence

Gupta *et al.*, PRL **95**, 143201 (2005); Murch *et al.*, PRL **96**, 013202 (2006)



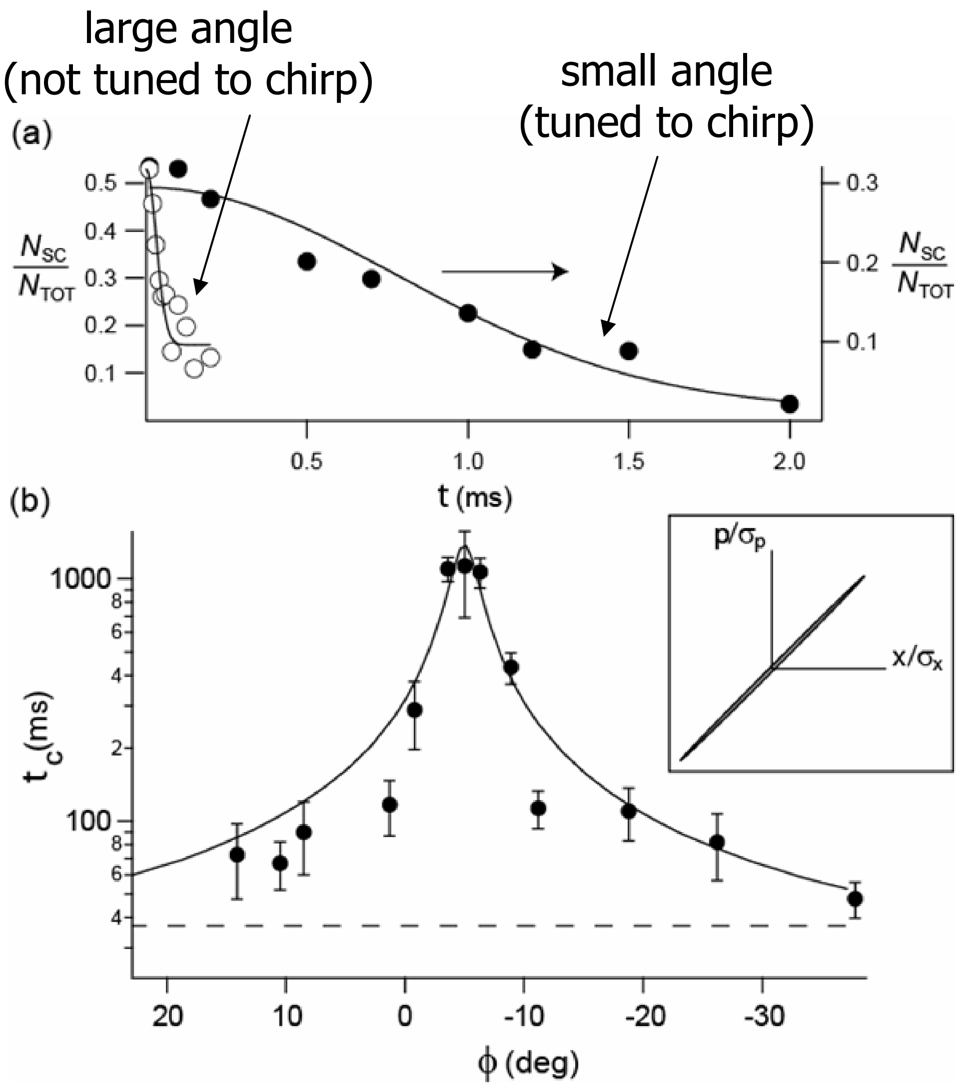
1.
BEC
2.
3.
4.
outcoupled atoms
BEC remnant
linear density (arb.)
scattered atoms
θ=0
2π

bSPPS in a curved waveguide



$$\tan\theta = \frac{m\Omega\sigma_x}{\sigma_p}\frac{\sin\phi}{1+\cos\phi}$$ projection of $W(x,p)$

Spatial coherence in a chirped atomic beam

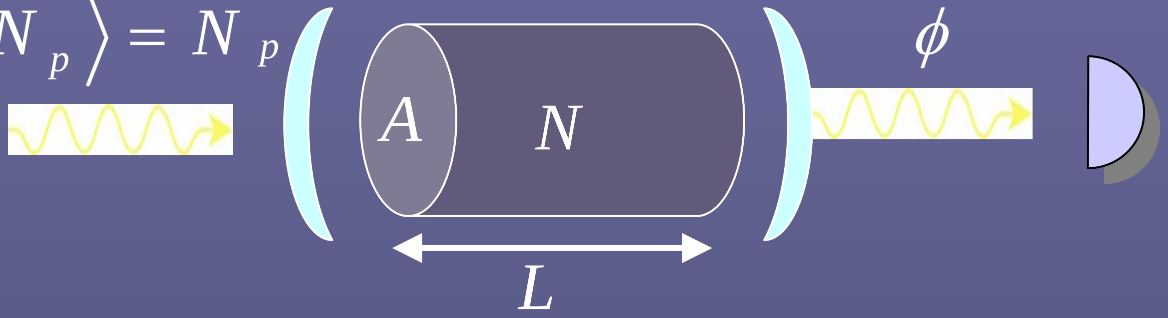


- long coherence times observed after 3 full revolutions in the guide:
  - travel distance = 23.6 mm
  - travel time = 360 ms
  - enclosed area = 14.7 mm^2
- radial single-mode propagation
- lower limit on coherence length measured in chirped beam
  - L > 13 mm
  - phase space area < 9 hbar

K. Moore et al., PRL 97, 180410 (2006)

Neutral atom counting/spin squeezing: Limits to non-destructive measurement

$$\langle N_p \rangle = \overline{N}_p$$



e.g. homodyne or polarization detection

- photon shot noise limits precision (want more light)
- photon scattering changes populations indeterminately (want less light)

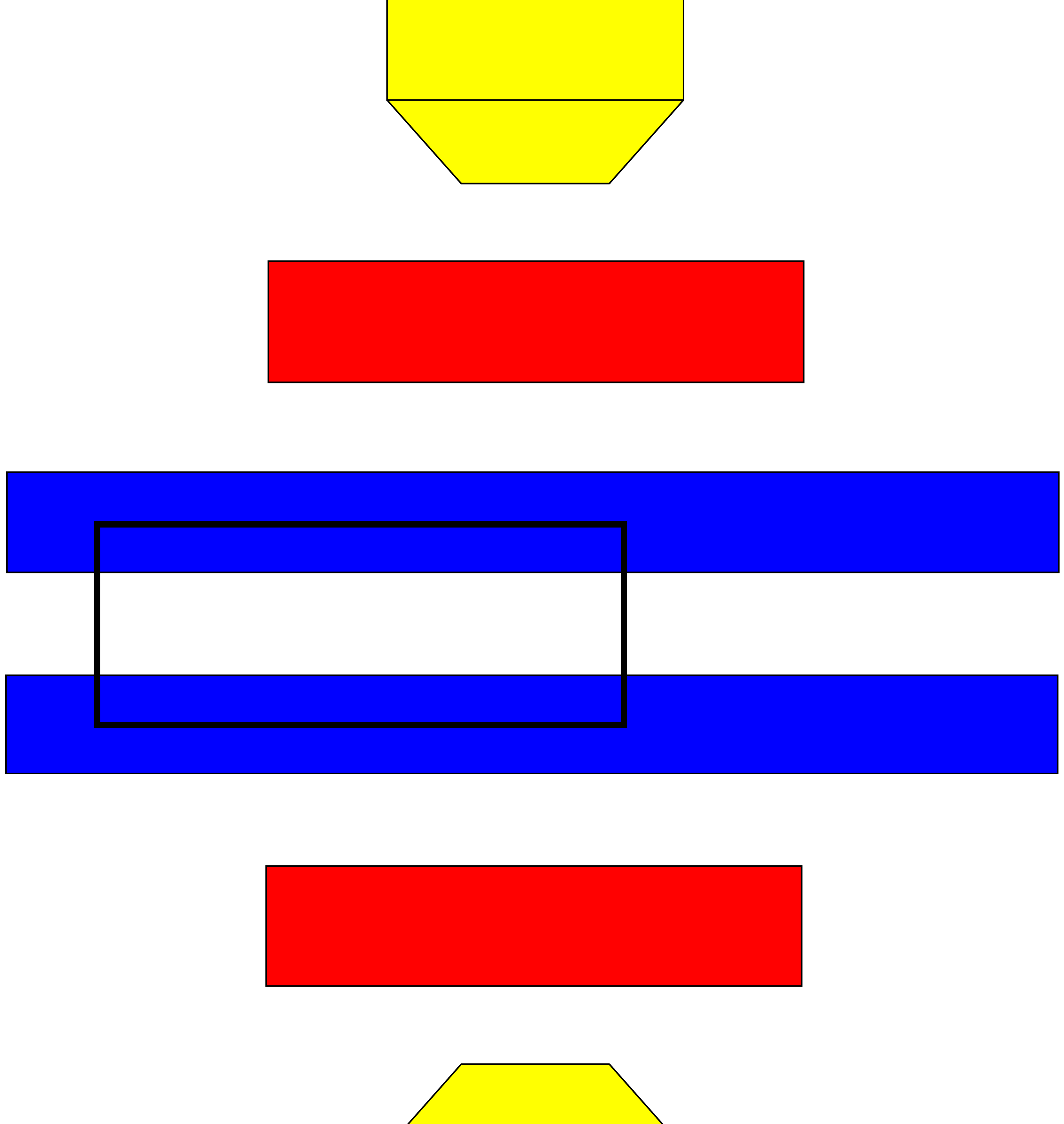
$$\Delta N_{meas} = \left(\frac{A}{N\sigma}\right)^{1/4}\sqrt{N}$$

- Add a cavity:

$$\Delta N_{meas} = \left(\frac{A}{FN\sigma}\right)^{1/4}\sqrt{N}$$

$$\left(\frac{1}{CN}\right)^{1/4}$$

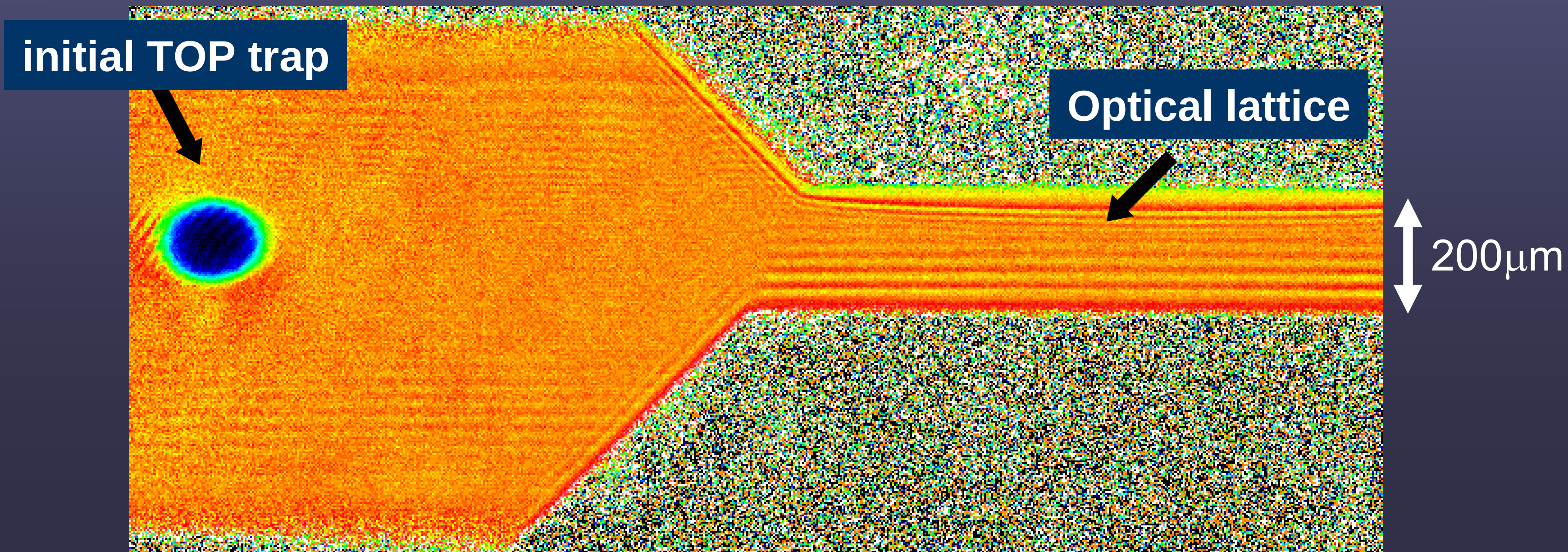
single-atom counting up to ~ 100 atoms (cooperativity)

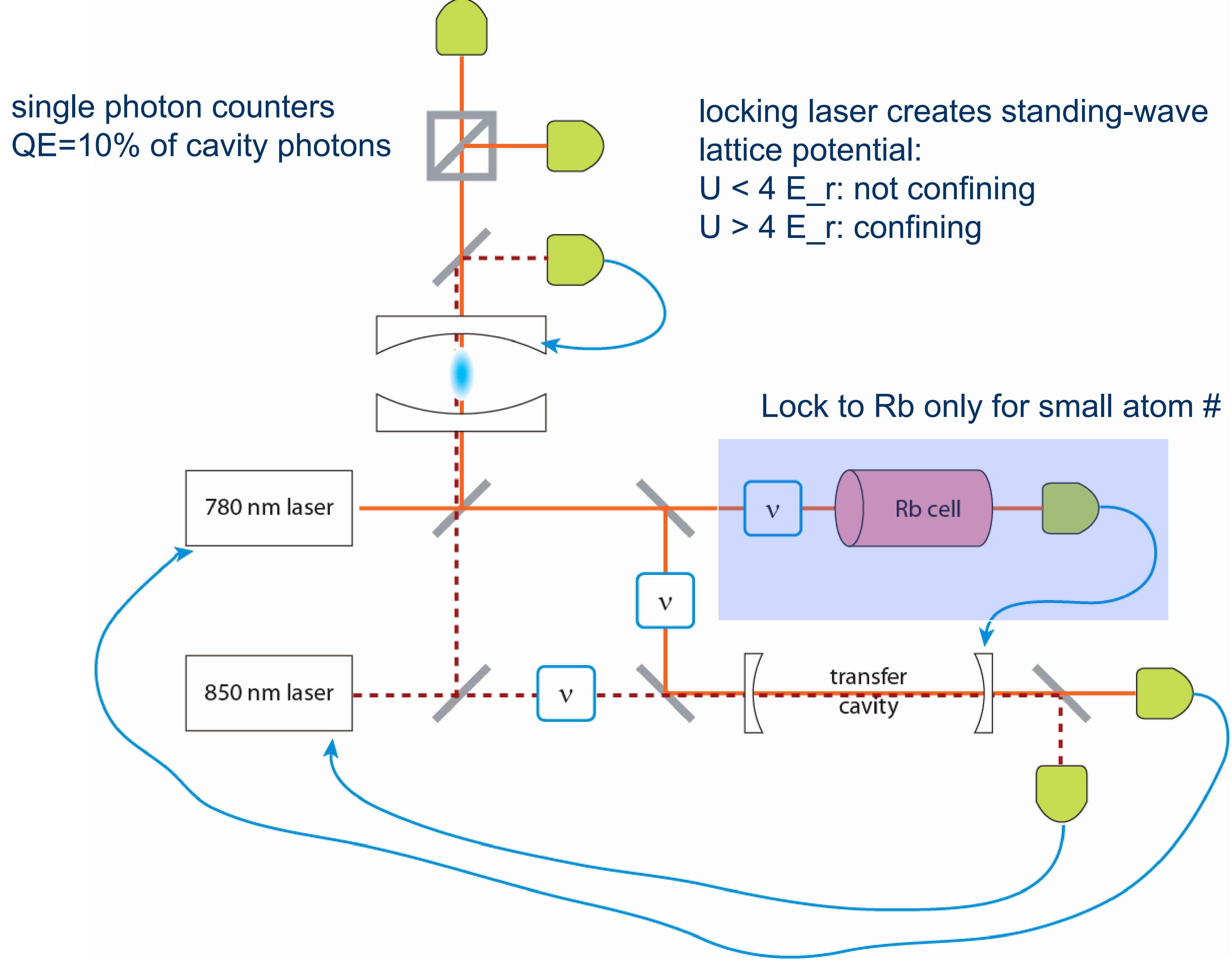


Cavity loading procedure

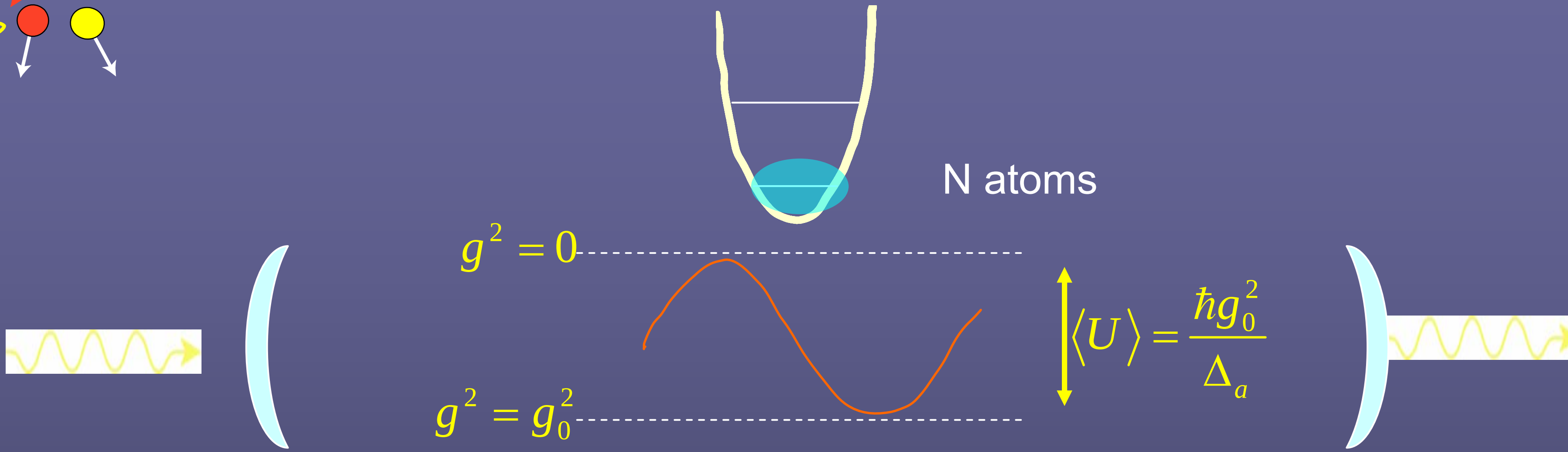
- Magnetic trapping outside cavity (TOP trap)
- Evaporative cooling
- Translation of the magnetic trap to within the cavity mode
- Transfer to 1D optical lattice inside cavity + turn off magnetic trap

Result: ~50,000 atoms trapped in ~200 sites of the in-cavity standing wave trap, at T ~ 1 μK (20 kHz)




single photon counters
QE=10% of cavity photons
locking laser creates standing-wave
lattice potential:
U < 4 E_r: not confining
U > 4 E_r: confining
Lock to Rb only for small atom #
780 nm laser
850 nm laser
ν
ν
ν
ν
Rb cell
transfer
cavity

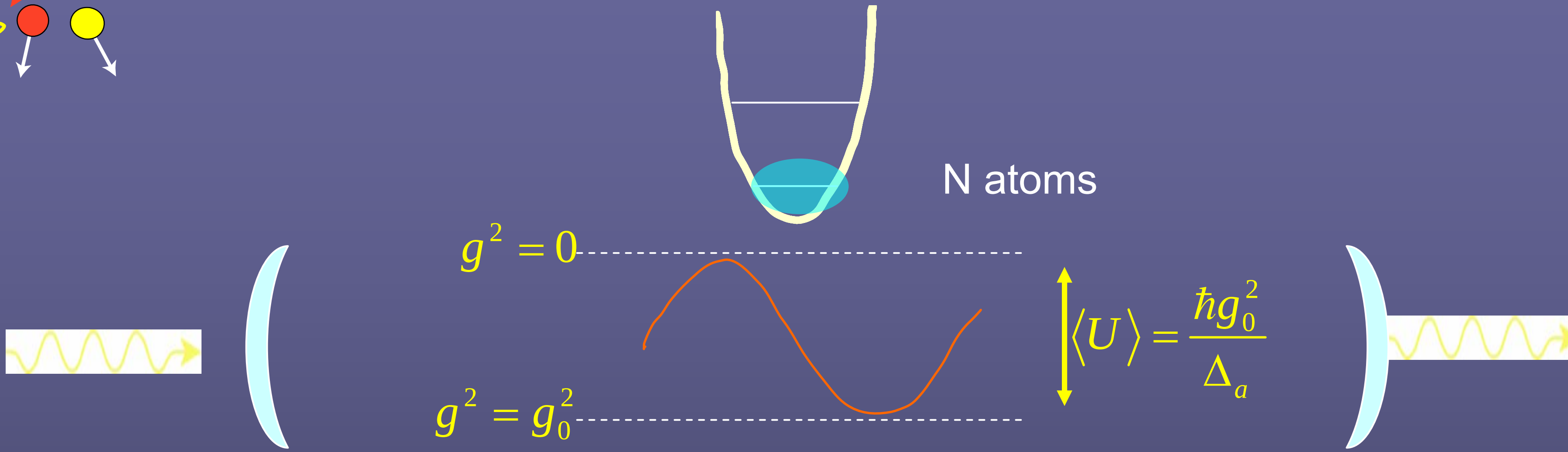
Cavity quantum electrodynamics with cold trapped atoms



- "Coherent" effect: Optical forces in the cavity will displace the trapped atoms

Leads to non-linear optics at <n> ~ 0.01 photons in the cavity
Leads to bistability (akin to "Bifurcation Amplifier" in SQUIDs)

Cavity quantum electrodynamics with cold trapped atoms



- "Incoherent" effect: Fluctuations in intra-cavity intensity will cause heating

$$\frac{dE}{dt} = \frac{1}{m}\int d\tau \left(\langle F(t+\tau) F(t) \rangle - \langle F(t+\tau) \rangle \langle F(t) \rangle \right) \cos \omega_T \tau$$

$$F = -\nabla \left(\frac{\hbar g_0^2 \cos^2(kx)}{\Delta_a} \right) \hat{n}_{ph}(t)$$

Cavity-induced heating

Three sources of heating:

1. recoil heating from spontaneous emission
2. dipole force fluctuation from spontaneous emission

3. dipole force fluctuation from photon field

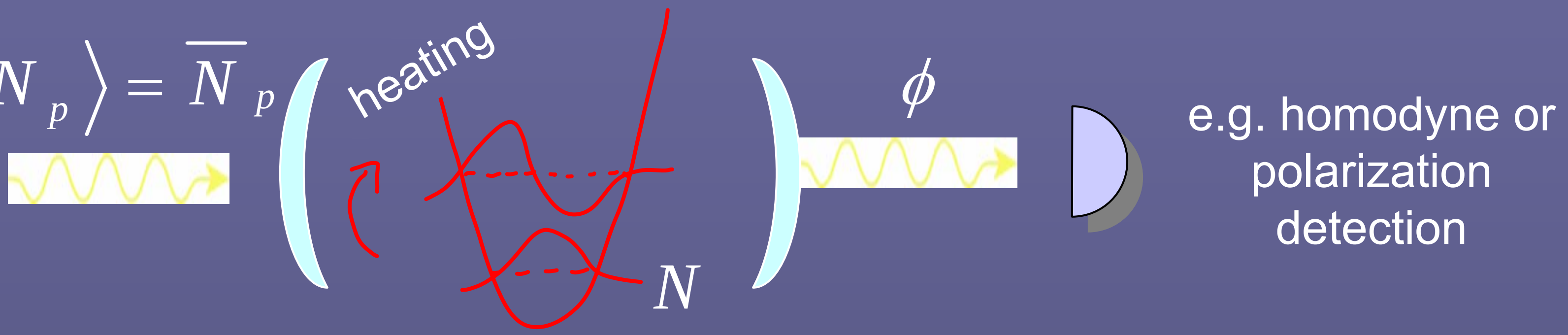
$$\frac{dE}{dt} \approx \frac{\hbar^2 k^2}{2m} g_0^2 n_{ph} \frac{\Gamma}{\Delta_a^2} \left(1 + \frac{8C \sin^2(2kx)}{1 + \left(\Delta_c / \kappa \right)^2} \right)$$

For our system, on resonance:
cavity accentuates heating by O(100)

see discussion by Ritsch, Rempe, others

Implications for non-destructive measurement

$$\langle N_p \rangle = \overline{N}_p$$

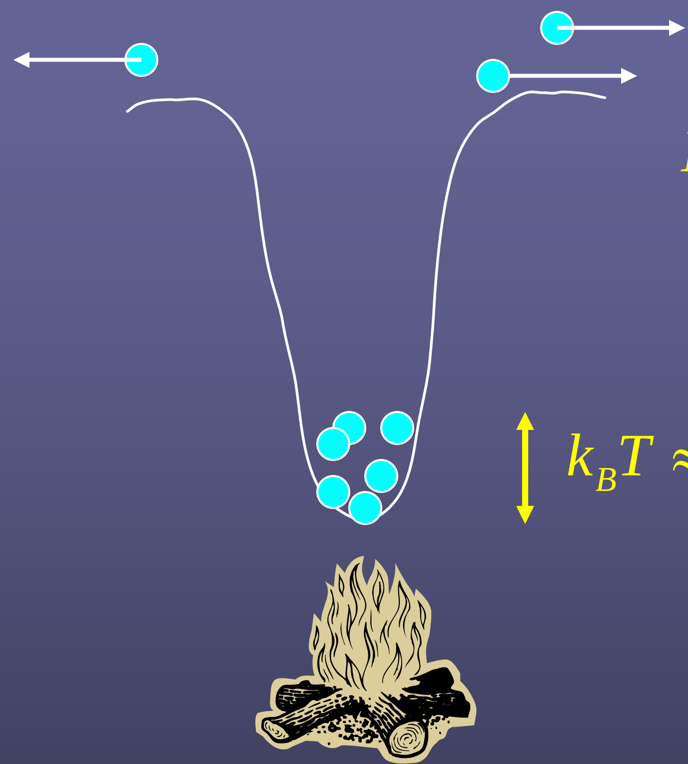


- photon shot noise limits precision (want more light)
- photon scattering and dipole fluctuations changes populations of trap states (i.e. cause heating) indeterminately (want less light)

- Add a cavity:

$$\Delta N_{meas} = \left(\frac{1}{CN\cos^2(kz)} \right)^{1/4} \times \sqrt{\frac{E_{recoil}}{E_{trap}} \left(1 + 8C\sin^2(kz)\right)}$$

Cavity-induced heating: measured by atom loss

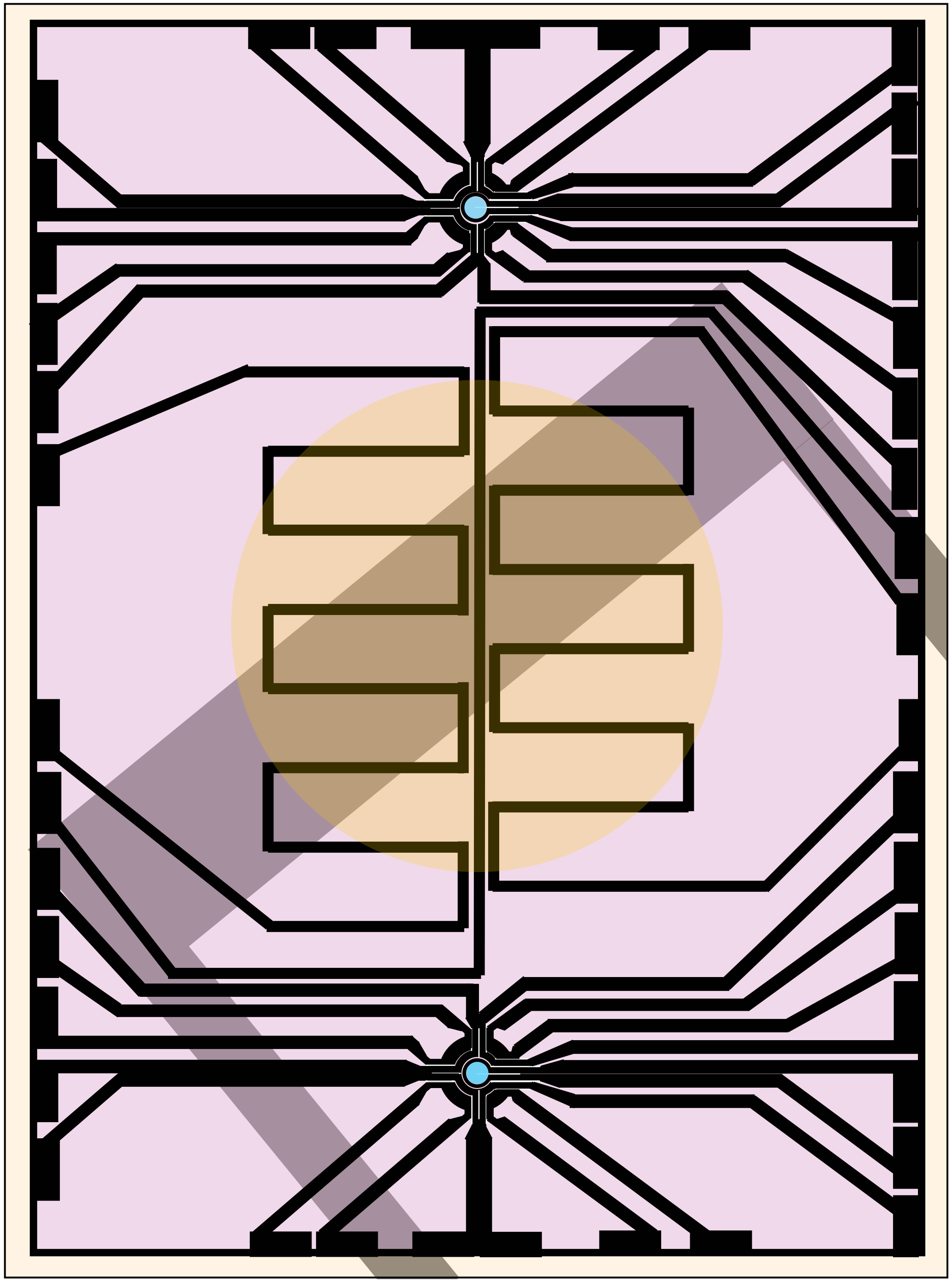


$$N\frac{dE}{dt} = (U - k_B T)\frac{-dN}{dt}$$

$$k_B T \approx \frac{1}{10} U$$

Progress:

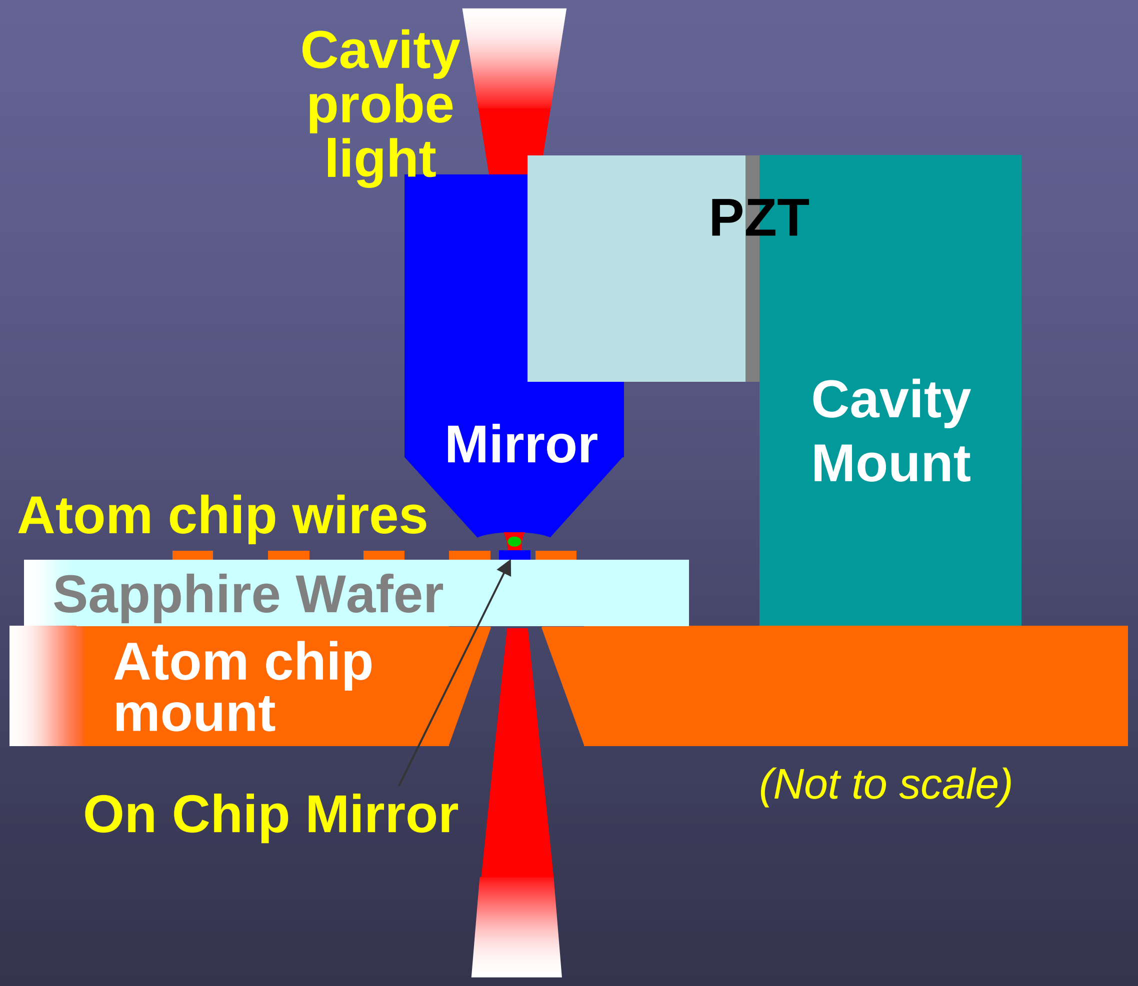
- Confirmed temperature remains ~ constant
- Confirmed scaling with detuning from atomic resonance, trap depth
- Observe cavity enhancement of heating by ~x 100



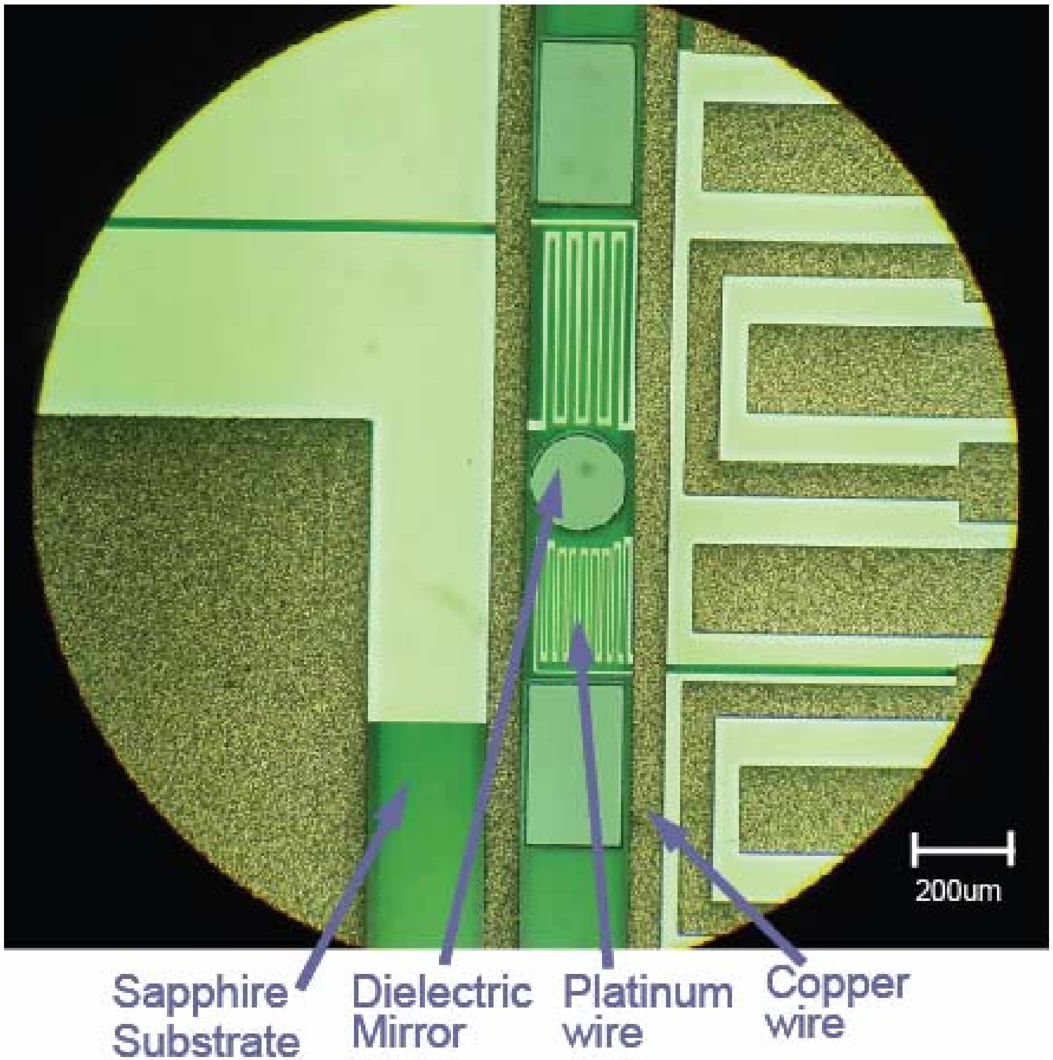
Experiment Stage	Temp	Size
Mirror U-MOT	300μK	~10^4μm
Polarization-Gradient Cooling	20μK	~10^4μm
Transfer to on Chip trap	100μK	~10^2μm
Evaporative Cooling	<1μK	~10μm
Magnetic Conveyer Belt to cavity	<1μK	~10μm
Cavity QED with tightly confined atoms	<1μK	<1μm

- Weinstein,Libbrecht, PRA 52, 4004 (1995)
- W. Hansel, et al., PRL 86, 608 (2001)
- Wildermuth et al., PRA 69, 030901 (2004)

Sapphire-substrate: on-chip mirrors

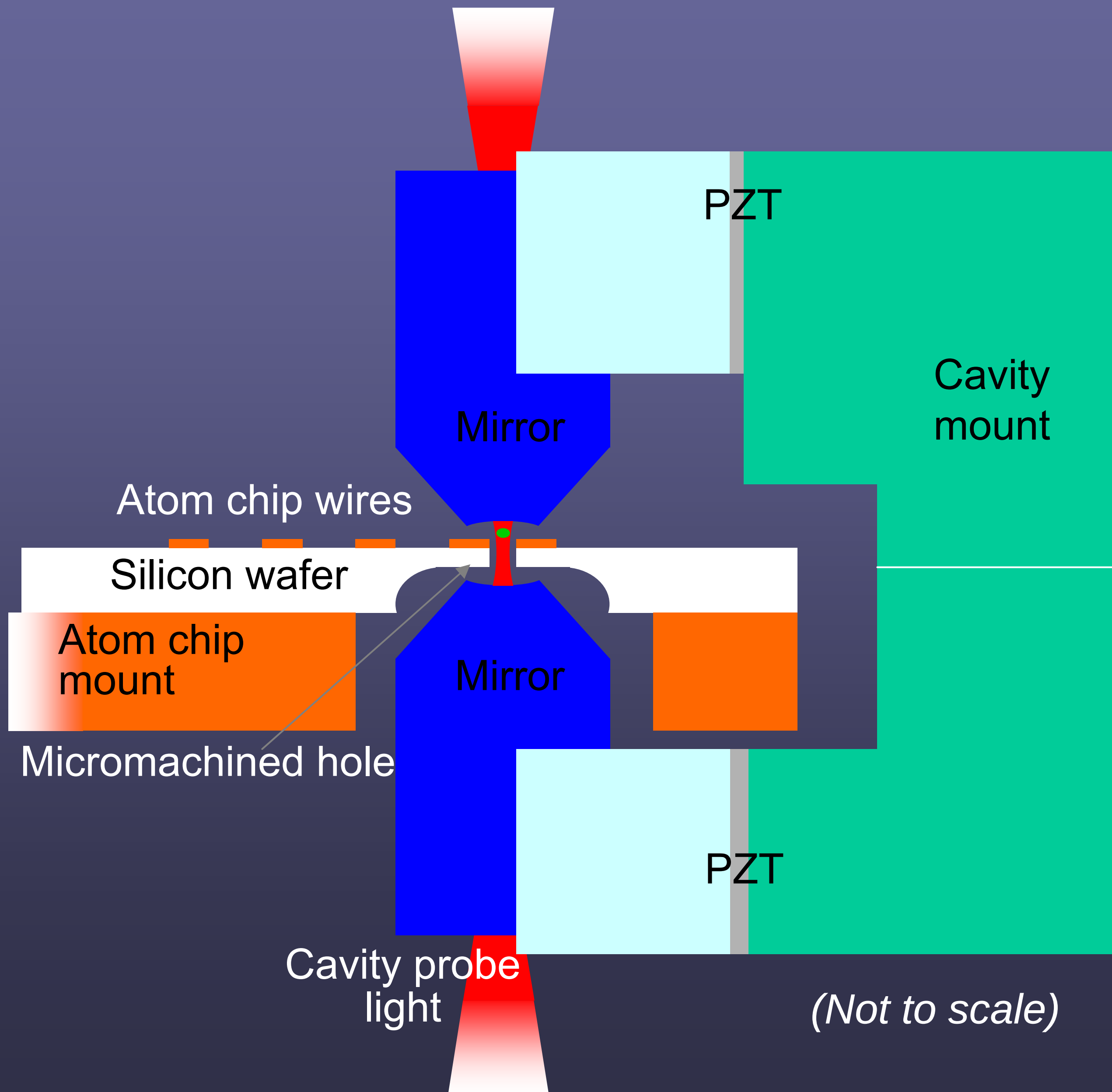


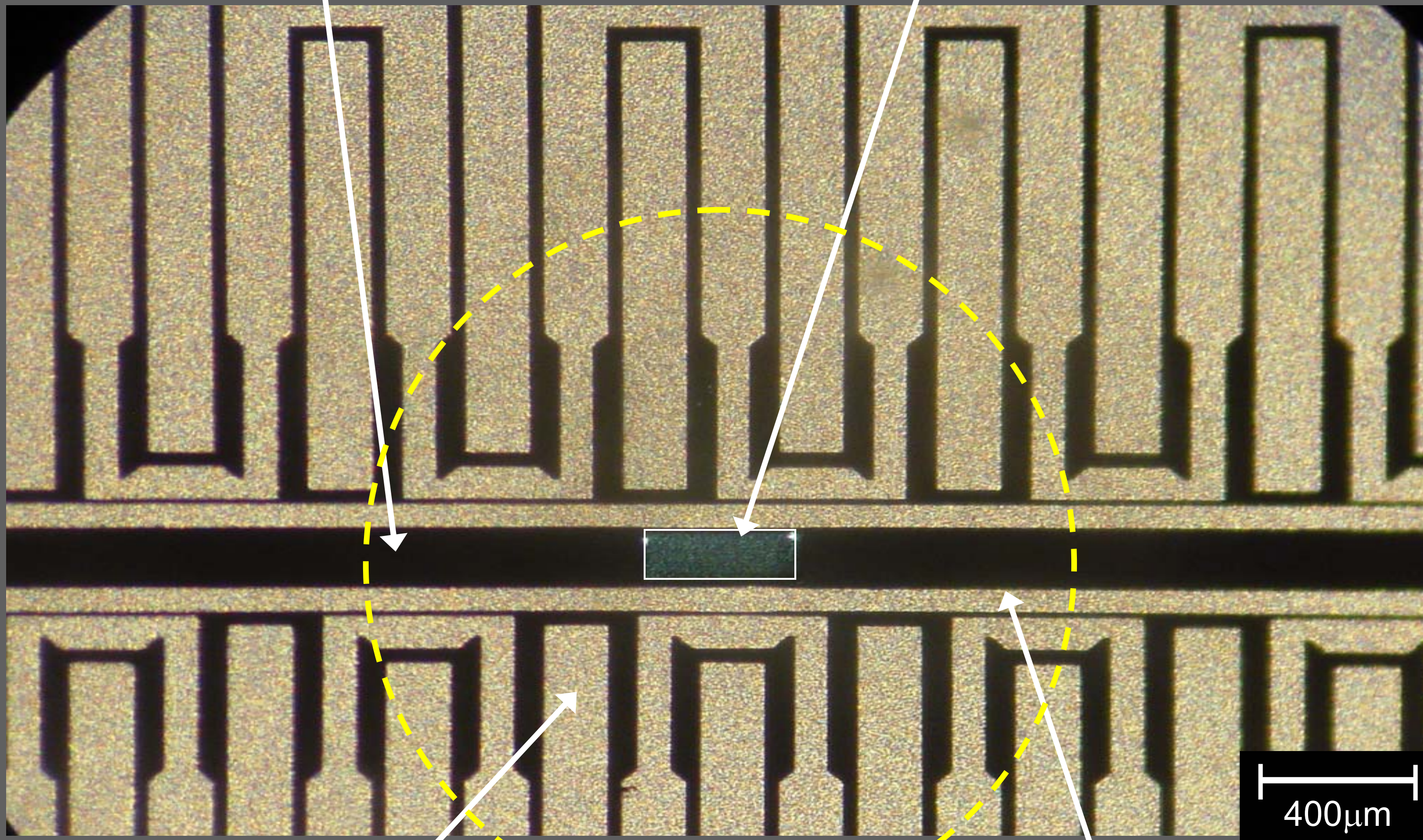
CQED atom chip test device



- Operated simulating experimental conditions:
  - Feedback unity gain at ~200 kHz !?

Silicon chip design: isolating cavity from chip

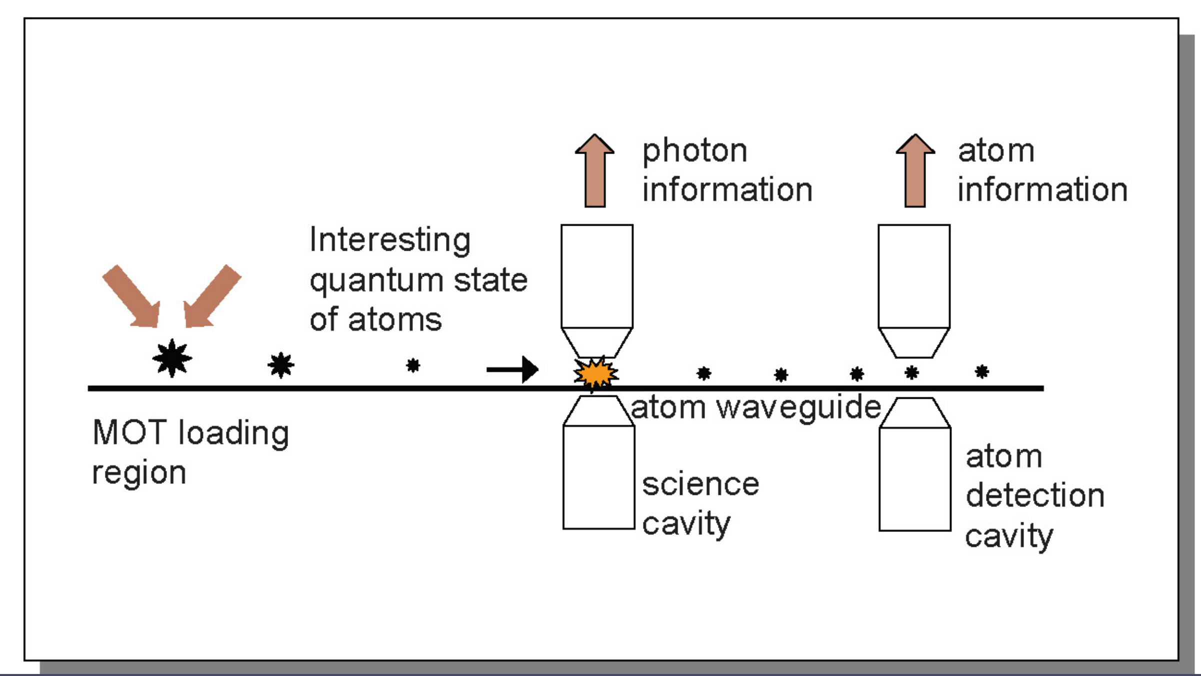




by Tom Purdy @ Berkeley microfab facility

CQED/Atom chip: quantum atom optics and transport

Daniel Brooks, Tom Purdy



- Can we detect single field quanta non-destructively (QND)?
  - Measure arrival statistics (etc) in first cavity + repeat in second cavity
- Deliberate engineering of quantum atom optical state / quantum transport
  - Modify beam (actively or passively) in first cavity + diagnose in second
- Entangle distant (3.5 mm) atoms or atomic ensembles
  - trap (optically, magnetically) in each cavity + perform joint measurements

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

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