The Squeezed Atom Laser

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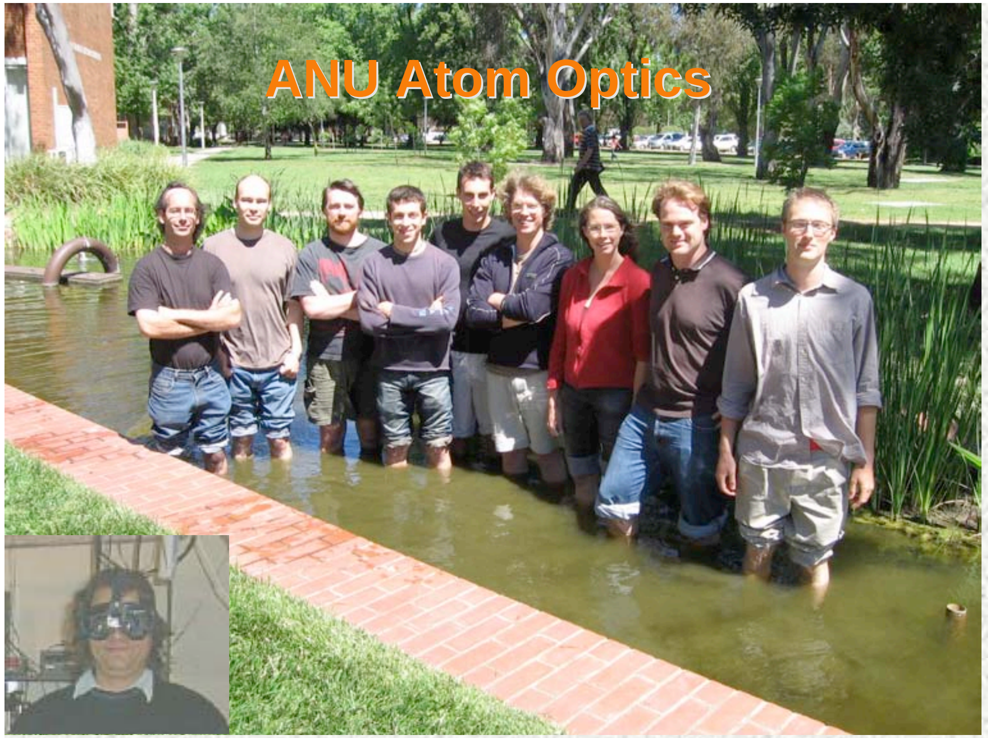
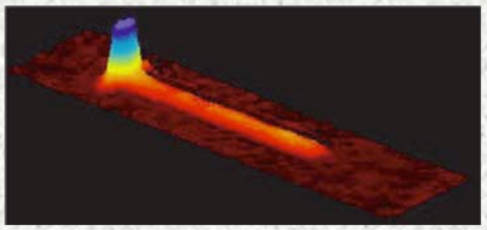
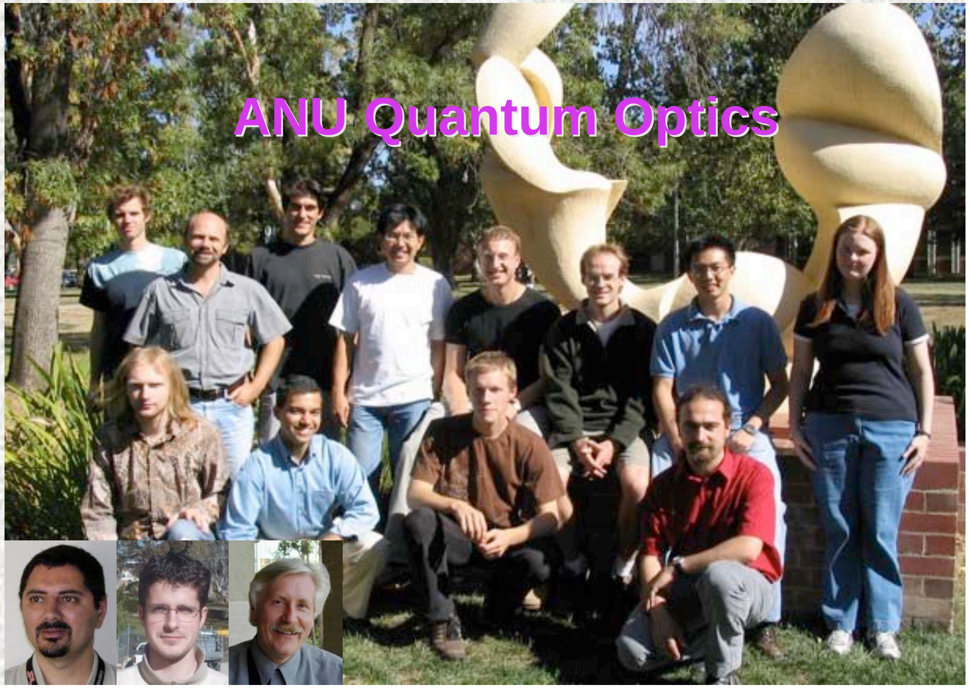


Theory:
Joe Hope, Mattias Johnsson, Simon Haine
Sebastian Wuester, Craig Savage

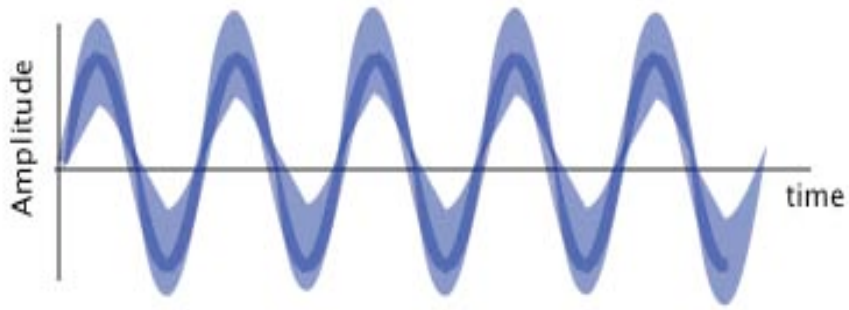
Atom Laser Experiment:
Nick Robins, Cristina Figl, Matthew Jeppesen,
Julien Dugue, John Close

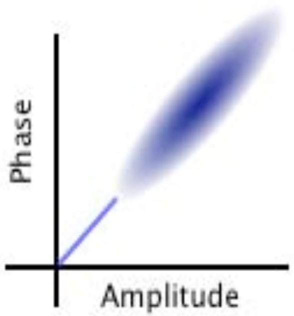


Squeezing at Rubidium Wavelengths Experiment:
Katie Pilypas, Magnus Hsu, Gabriel Hetet, Oliver
Glockl, Charles Harb, Pingkoy Lam, Hans Bachor



Squeezing





$$V(\hat{X}^{+}) > 1$$

$$V(\hat{X}^{-}) < 1$$

Amplitude and Phase are conjugate observables

$$[\hat{X}^{+},\ \hat{X}^{-}] = -2i$$

$$V(\hat{X}^{+})V(\hat{X}^{-}) \geq 1$$

Can't have a state with perfectly well defined amplitude **and** phase

Motivation:

Precision measurement:

- Atom lasers useful for precision measurement.

- Atomic shot noise will limit the sensitivity of any measurement.

- Squeezing will reduce shot noise.

Fundamental:

- Tests of entanglement with massive particles.

Why atom laser?

- Can use amplitude and phase quadratures as conjugate observables.

How to get squeezing:

Two choices:

Use atomic nonlinearity somehow

$$H = U\hat{\psi}^{+}\hat{\psi}^{+}\hat{\psi}\hat{\psi}$$

Kerr squeezing, 4-wave mixing

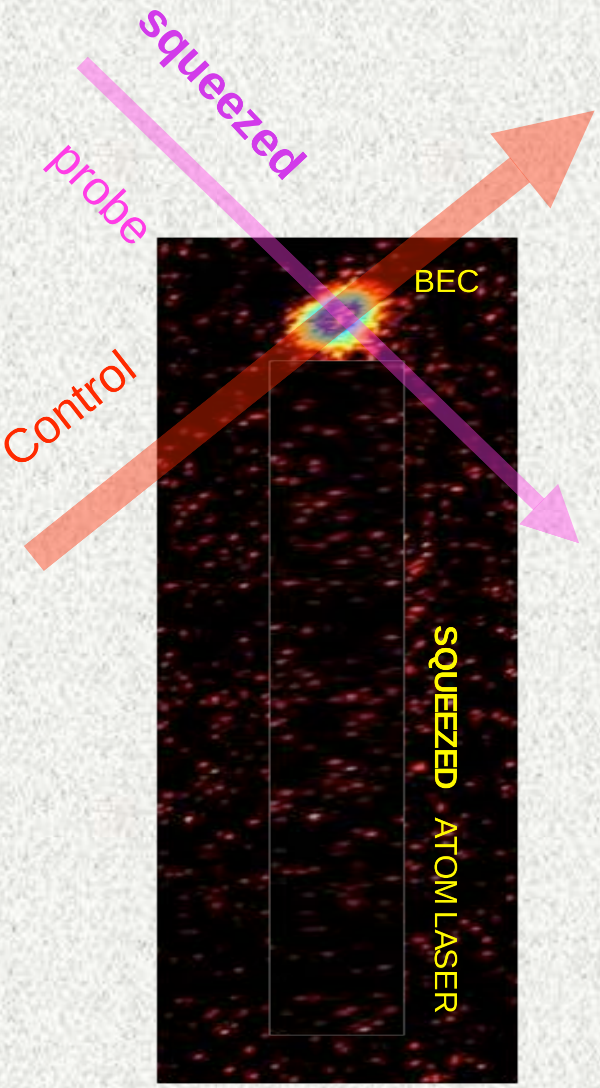
$$H = \chi(\hat{\psi}_m^{+}\hat{\psi}_a\hat{\psi}_a + \hat{\psi}_a^{+}\hat{\psi}_a^{+}\hat{\psi}_m)$$

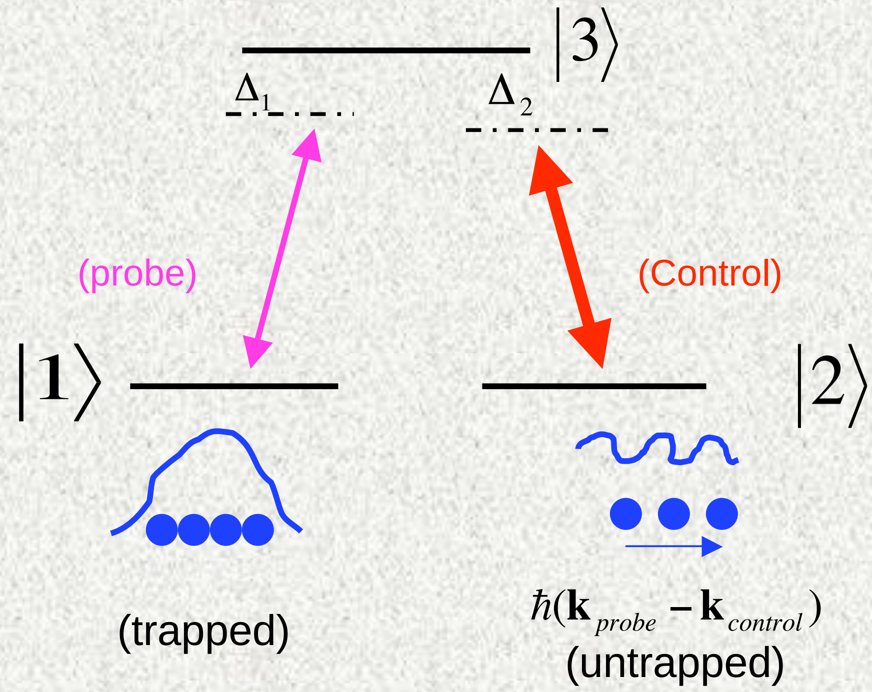
Molecular dissociation

Use squeezed light

Squeezed light (almost) on tap at ANU

Raman Atom Laser

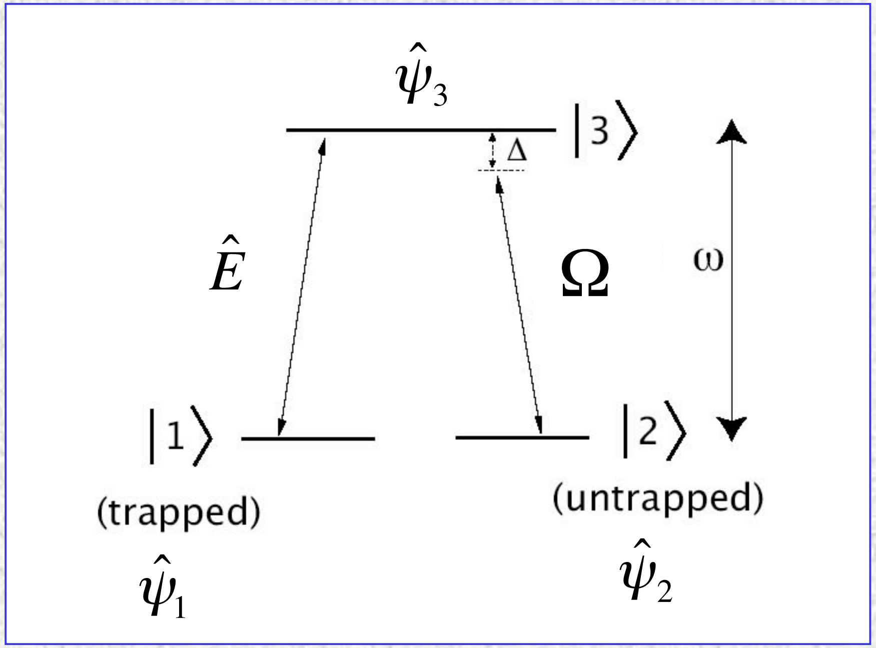




- Each outcoupled atom receives a momentum kick of $\hbar(\mathbf{k}_{probe} - \mathbf{k}_{control})$

- In certain regimes, each photon for the probe beam gives you one outcoupled atom.

Single mode model



- Adiabatically eliminate excited state $(\hat{\psi}_3)$

- Assume control field Ω and condensate field $\hat{\psi}_1$ are large and coherent (semiclassical approximation)

$$i\dot{\hat{\psi}}_2 = \omega_2 \hat{\psi}_2 - \Omega_C \hat{E}$$

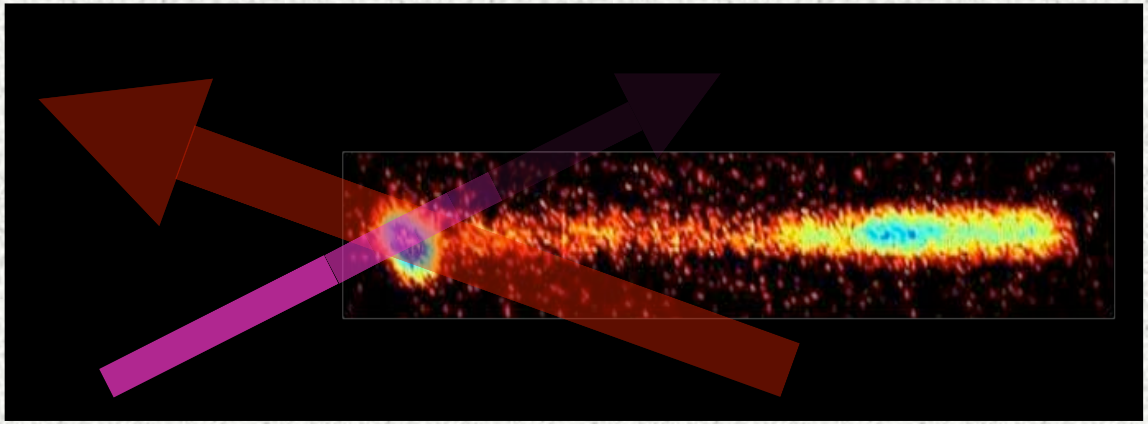
$$i\dot{\hat{E}} = \omega_0 \hat{E} - \Omega_C^* \hat{\psi}_2$$

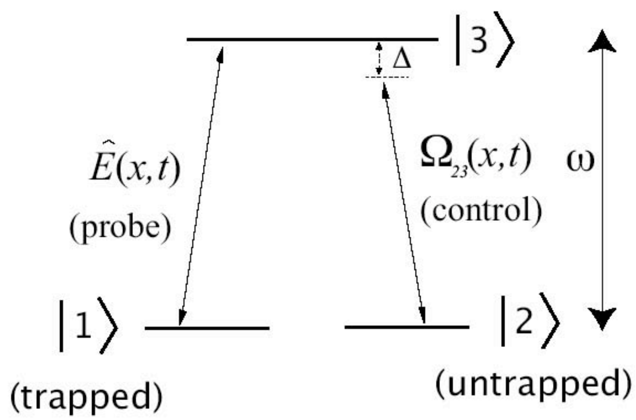
Rabi flopping

$$\hat{\psi}_2(t) = \cos(\Omega_C t)\hat{\psi}_2(0) - i\sin(\Omega_C t)\hat{E}(0)$$

$$\hat{E}(t) = \cos(\Omega_C t)\hat{E}(0) - i\sin(\Omega_C t)\hat{\psi}_2(0)$$

Hui Jing *et al.* PRA 63, 015601, (2000).





$$\hat{\psi} \rightarrow \hat{\psi}(x) \qquad \hat{E} \rightarrow \hat{E}(x) \qquad \text{etc.}$$

Need to consider the multimode dynamics of the probe beam and the atom laser beam

$$\mathcal{H} = \mathcal{H}_{\text{atom}} + \mathcal{H}_{\text{int}} + \mathcal{H}_{\text{light}}$$

$$= \int \hat{\psi}_1^\dagger(x) H_1 \hat{\psi}_1(x) dx + \int \hat{\psi}_2^\dagger(x)(-\frac{\hbar^2}{2m}\nabla^2)\hat{\psi}_2(x) dx + \int \hat{\psi}_3^\dagger(x)(-\frac{\hbar^2}{2m}\nabla^2 + \hbar\omega_0)\hat{\psi}_3(x) dx$$

$$+ \hbar \int (\hat{\psi}_2(x)\hat{\psi}_3^\dagger(x)\Omega(x,t) + h.c.) dx + \hbar g_{13} \int (\hat{E}(x)\hat{\psi}_1(x)\hat{\psi}_3^\dagger + h.c.) dx + \mathcal{H}_{\text{light}}$$

approximations…

- Far detuned - ignore spontaneous emission
- Condensate and control field remain in coherent state.

Heisenberg Equations of Motion:

$$i\dot{\hat{\psi}}_2(x) = (-\frac{\hbar}{2m}\frac{\partial^2}{\partial x^2} - \frac{|\Omega_{23}|^2}{\Delta})\hat{\psi}_2(x) - \Omega_C \tilde{E}(x)$$

Outcoupled atoms

$$i\dot{\tilde{E}}(x) = (-ic\frac{\partial}{\partial x} - (\omega_0 - \Delta))\tilde{E} - \Omega_C^* \hat{\psi}_2(x)$$

Optical probe field

$$\Omega_C = \frac{g_{13}\Omega_{23}}{\Delta} e^{-ik_0 x}\phi_1(x) \qquad \phi_1(x,t) = \langle \hat{\psi}_1(x) \rangle$$

$$i\dot{\phi}_1(x) = (-\frac{\hbar}{2m}\frac{\partial^2}{\partial x^2} + V_{trap}(x) - \frac{g_{13}^2}{\Delta}\langle \tilde{E}^\dagger(x)\tilde{E}(x)\rangle)\phi_1(x) - \Omega_C \langle \tilde{E}^\dagger(x)\hat{\psi}_2(x)\rangle$$

Trapped atoms

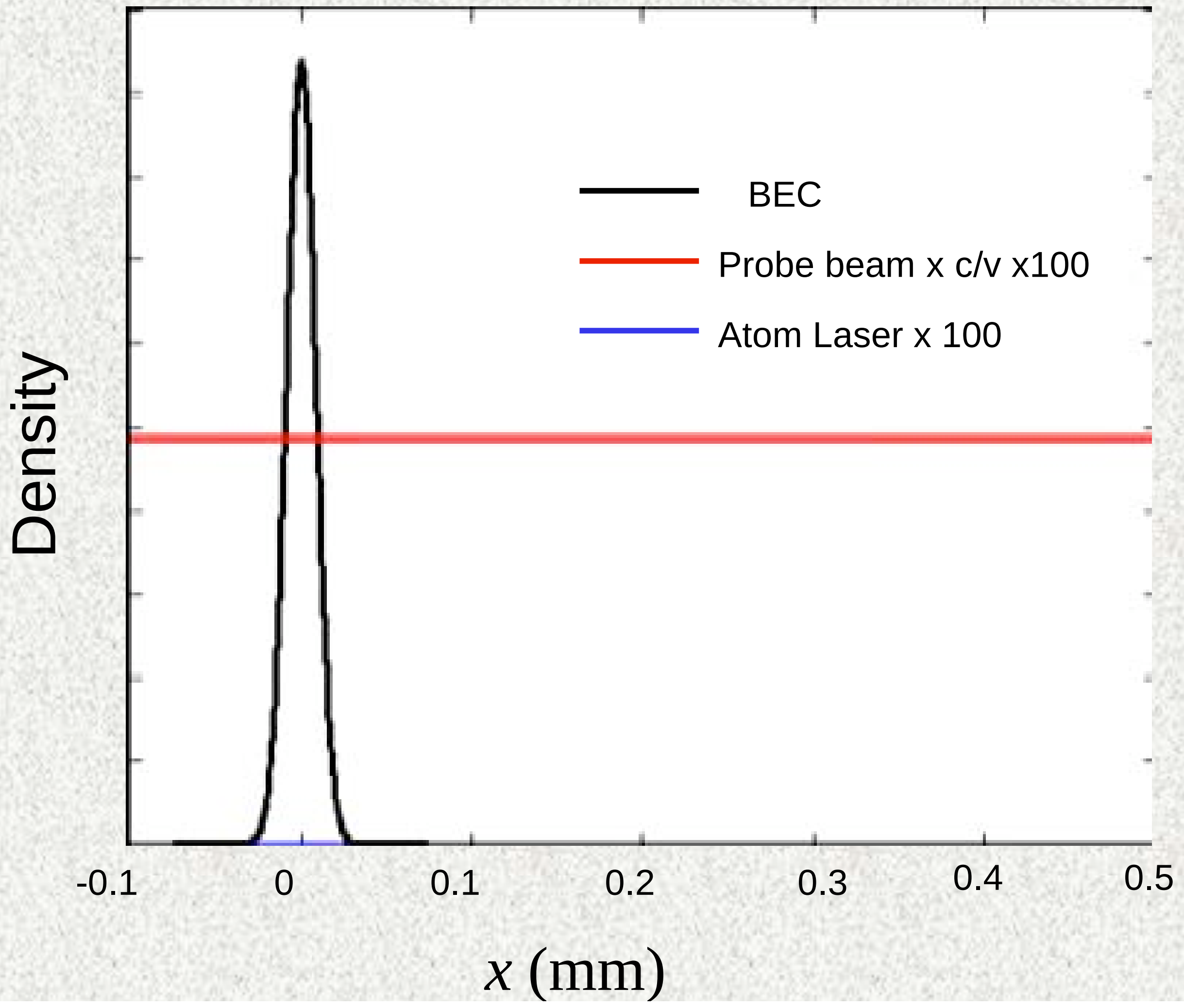
Solution:

$$\hat{\psi}_2(x,t) = \sum_i f_i(x,t)\hat{a}_i + \sum_i g_i(x,t)\hat{b}_i$$

$$\tilde{E}(x,t) = \sum_i p_i(x,t)\hat{b}_i + \sum_i q_i(x,t)\hat{a}_i$$

$$i\dot{f}_i(x) = H_a f_i(x) - \tilde{\Omega}_C q_i(x)$$
$$i\dot{g}_i(x) = H_a g_i(x) - \tilde{\Omega}_C p_i(x)$$
$$i\dot{p}_i(x) = H_b p_i(x) - \tilde{\Omega}_C^* g_i(x)$$
$$i\dot{q}_i(x) = H_b q_i(x) - \tilde{\Omega}_C^* f_i(x)$$

- Qauntum efficiency of outcoupling (atoms/photon) ~1
  - (Vacuum Rabi frequency ~1/T_{leave})
- Probe beam weak ($N_{probe} << N_{condensate}$)
- Appropriate two-photon detuning

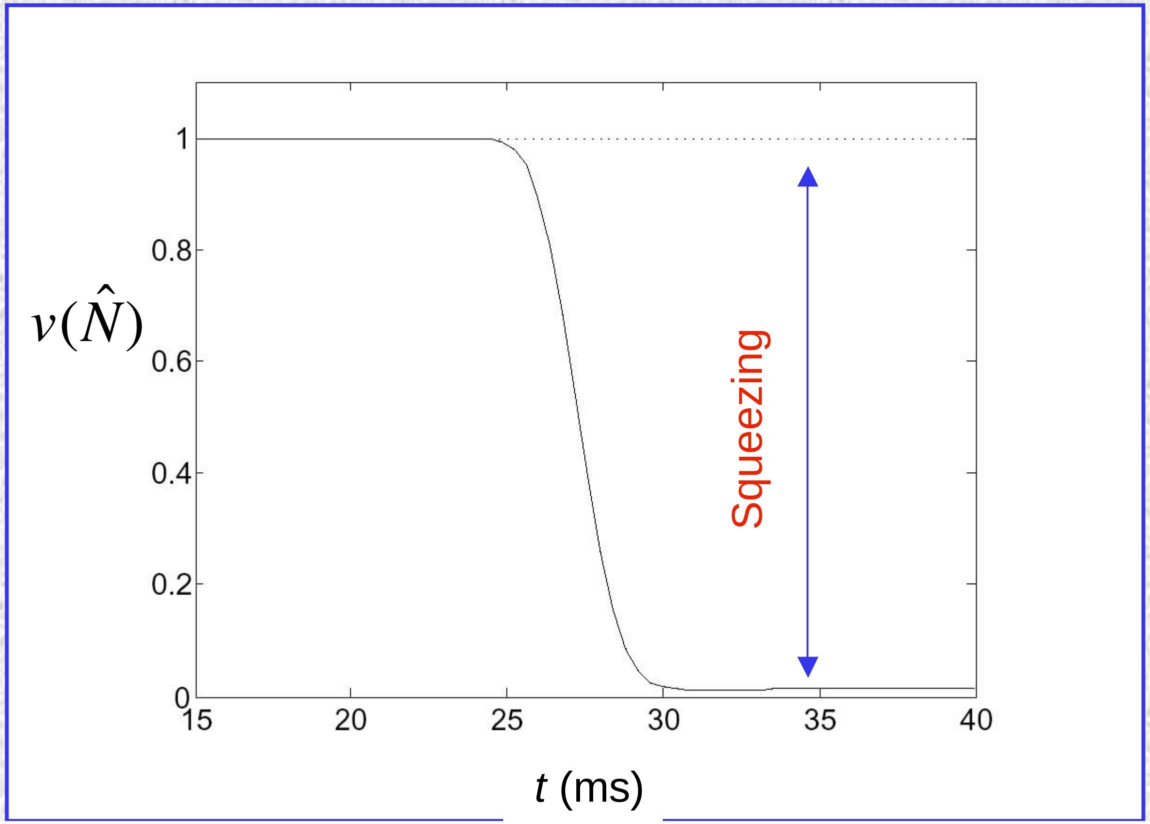


Quantum Fluctuations

$$v(\hat{N}) = \frac{\langle \hat{N}^2 \rangle - \langle \hat{N} \rangle^2}{\langle \hat{N} \rangle}$$

Perfect squeezing $v(\hat{N}) = 0$

No squeezing $v(\hat{N}) = 1$



S. A. Haine and J. J. Hope
Las. Phys. Lett. **2** 597 (2005)

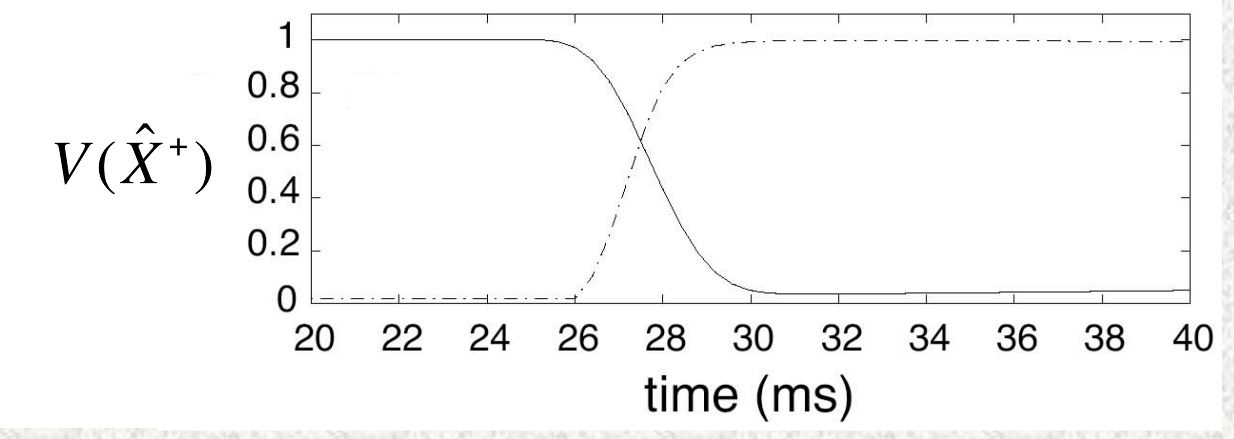
Quadrature Squeezing

$$\hat{X}^{+} = \int_{x_1}^{x_2} L_{\psi}^{*}(x,t)\hat{\psi}(x,t) + L_{\psi}(x,t)\hat{\psi}^{\dagger}(x,t)dx$$

$$\hat{X}^{-} = i\int_{x_1}^{x_2} L_{\psi}^{*}(x,t)\hat{\psi}(x,t) - L_{\psi}(x,t)\hat{\psi}^{\dagger}(x,t)dx$$

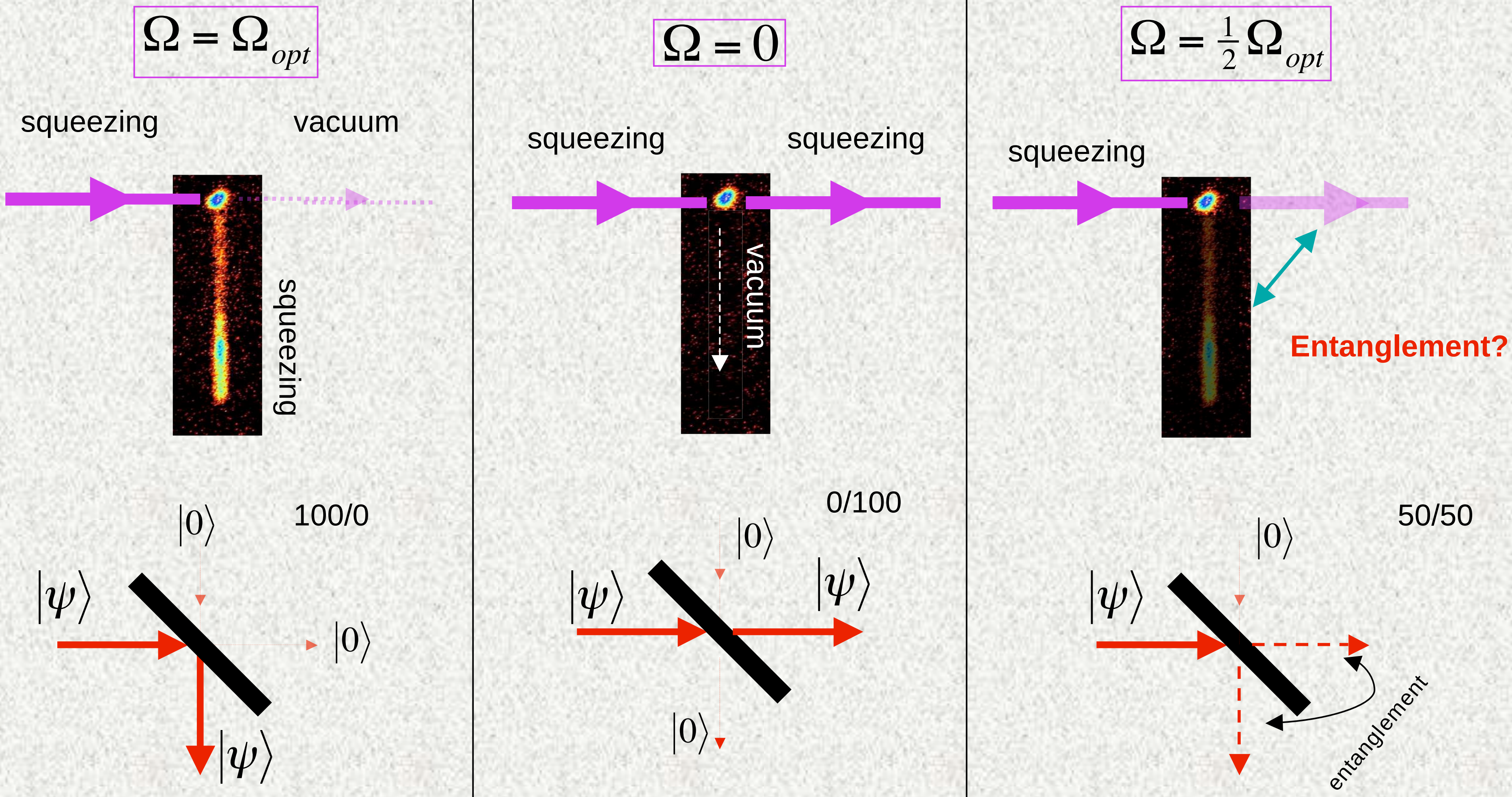
Commutation relations give:

$$V(\hat{X}^{+})V(\hat{X}^{-}) \geq 1$$

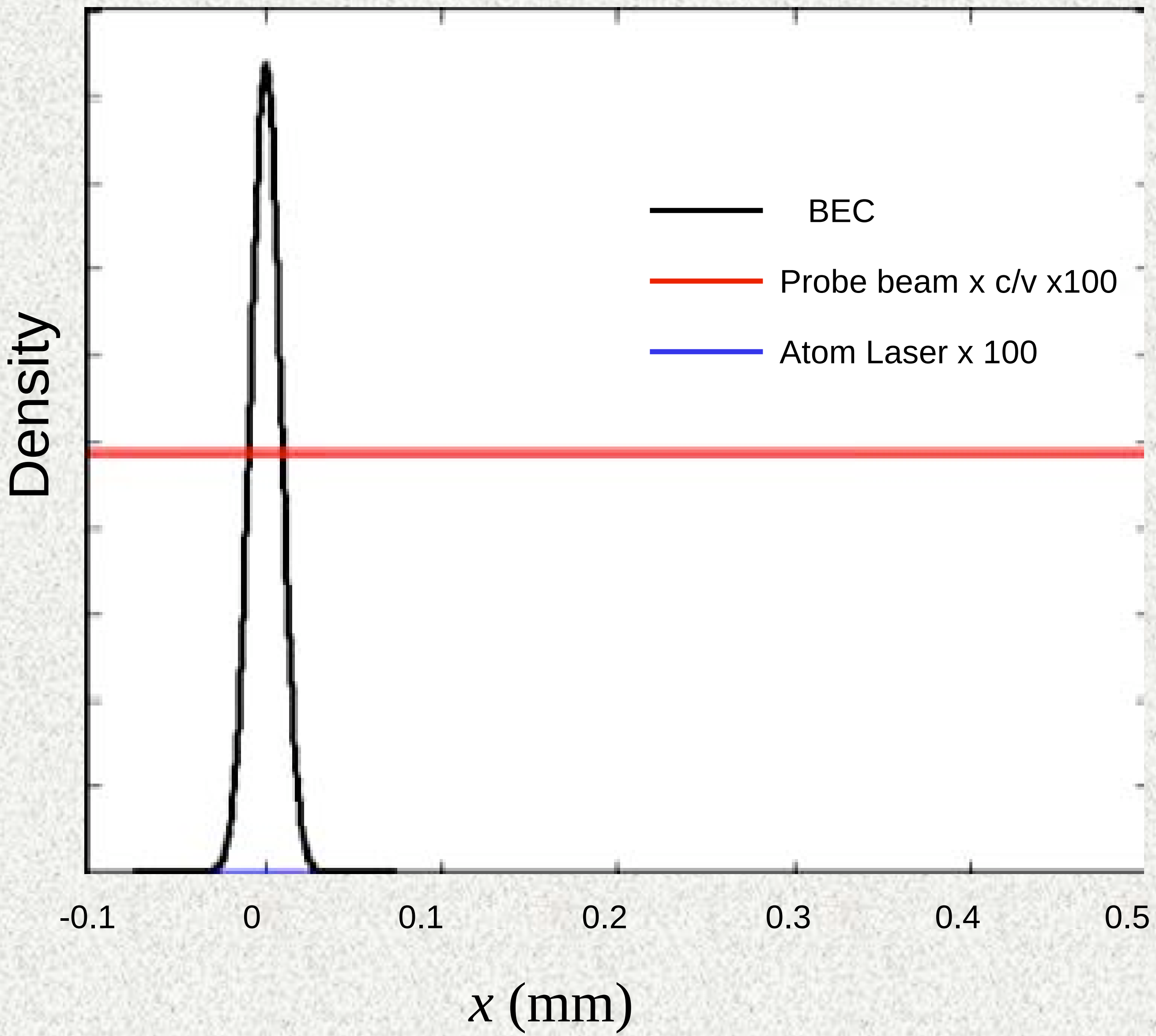


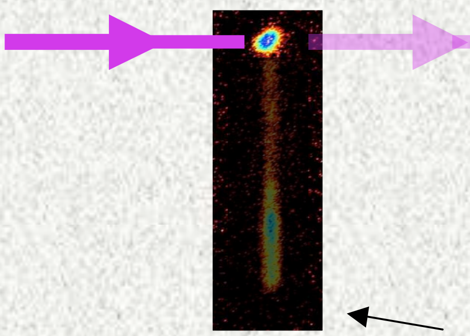
- Homodyne detector required to measure quadratures.
  - could use bright atom laser from same BEC as local oscillator.

Atom-Light Entanglement



Atom-Light Entanglement



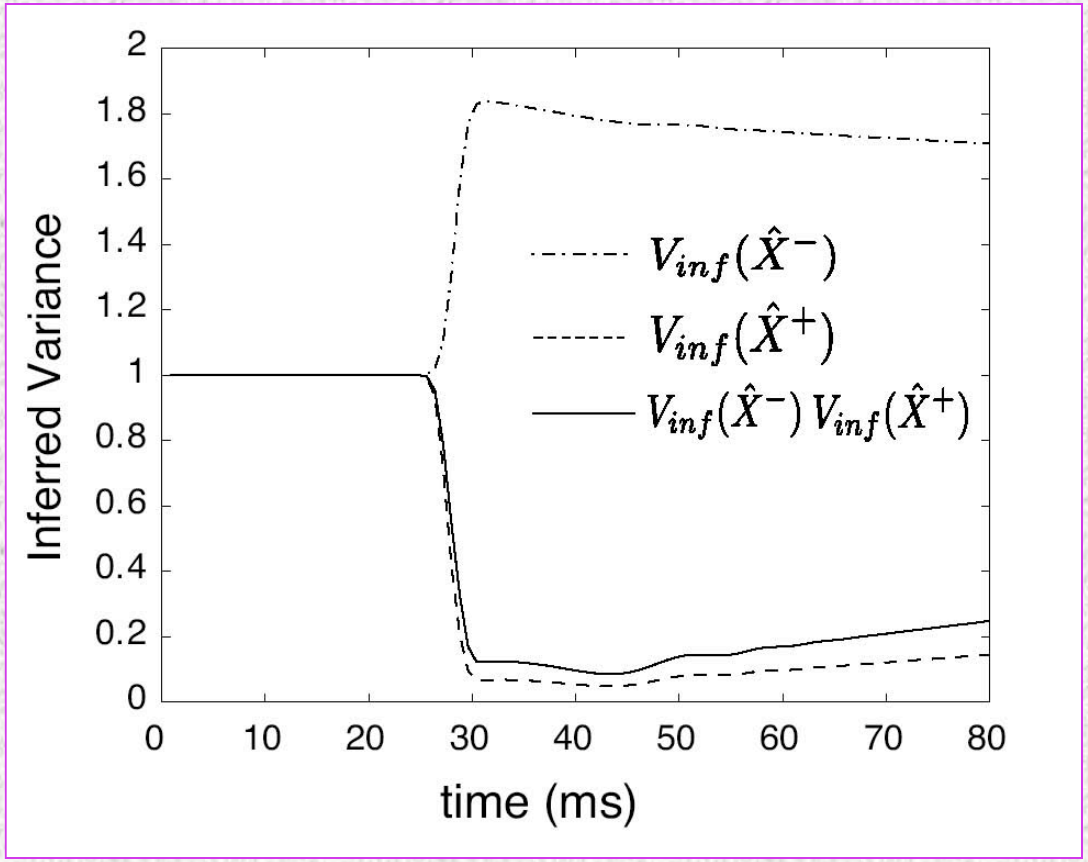


Measure quadratures
of the light beam

Infer results of measurements on the atomic beam

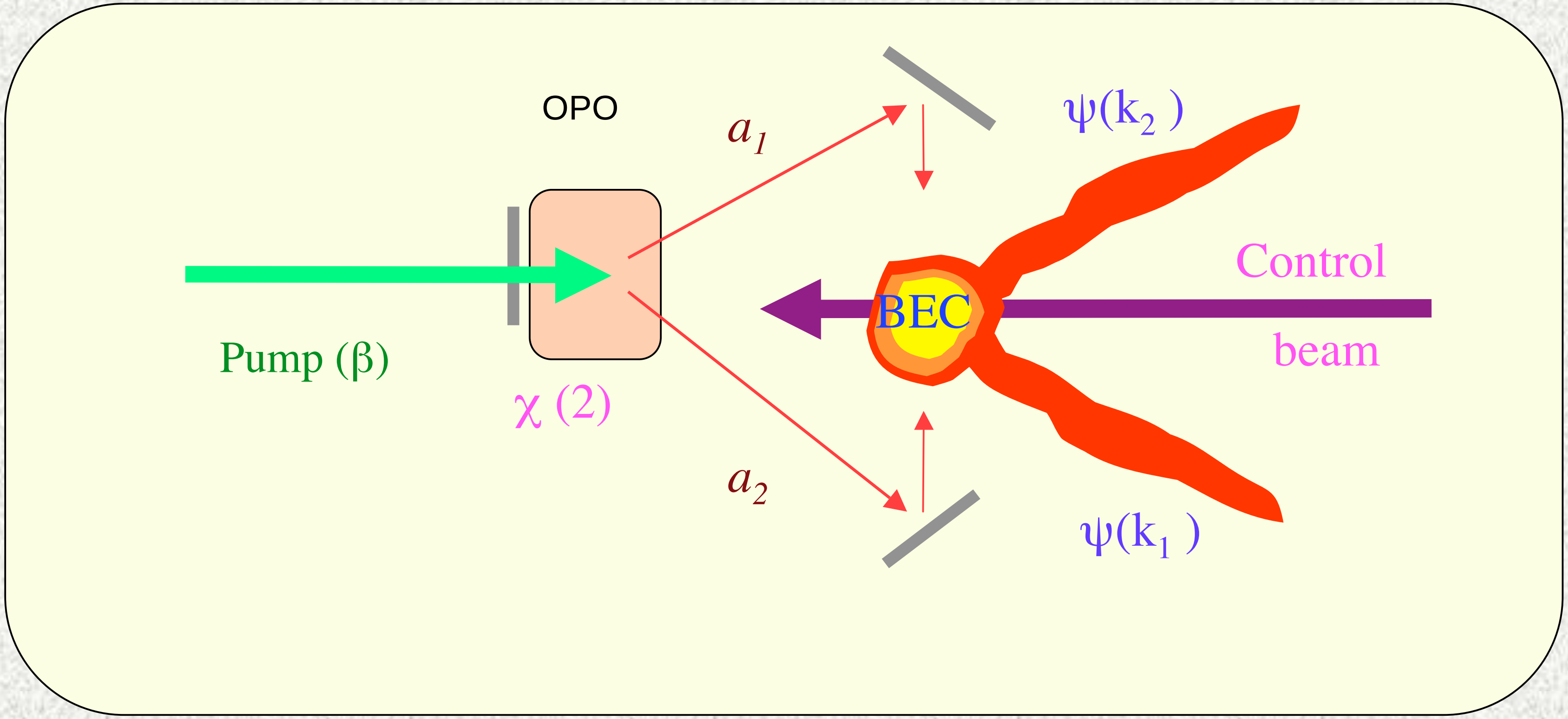
Entangled if:

$$V^{\inf}(\hat{X}^{+})V^{\inf}(\hat{X}^{-}) < 1$$



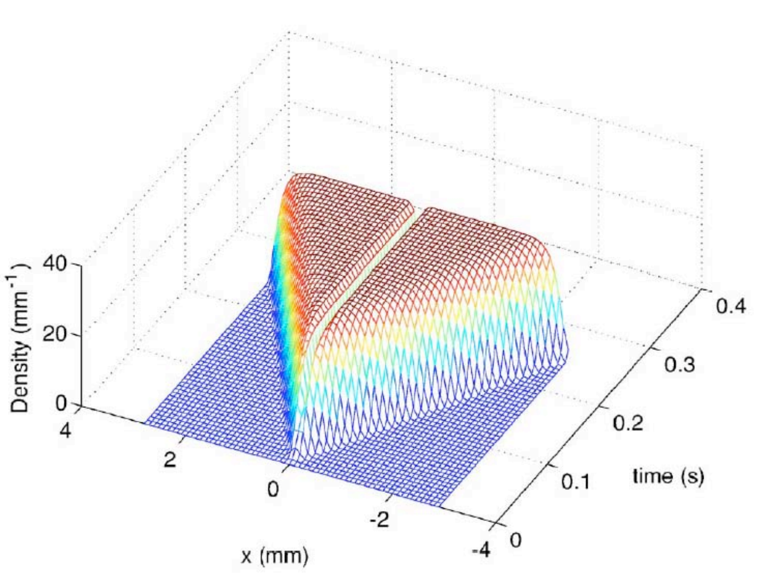
S. A. Haine, M. K. Olsen, J. J. Hope, quant-ph/0601029 (2005).

Entangled atom laser beams

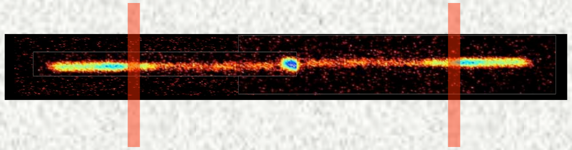


- By making measurements on one beam, can infer results of measurements on the other beam to better than the uncertainty principle.
- Fundamental tests of entanglement with massive particles.
- Practical applications: Precision measurement below the quantum limit, teleportation.

Flux Squeezing

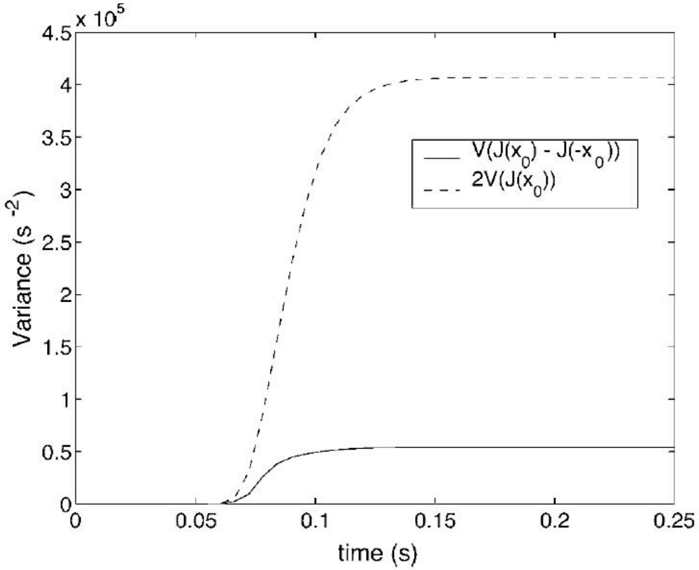


Flux difference



$\hat{J}_1$ $\hat{J}_2$

$V(\hat{J}_1 - \hat{J}_2)$



EPR Criterion

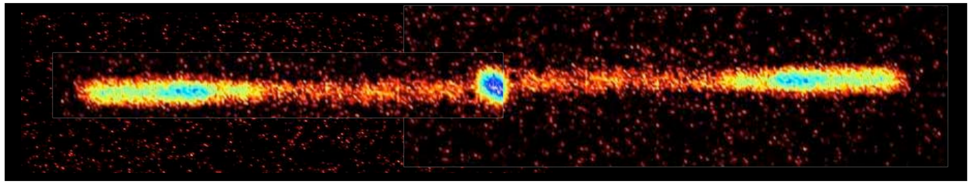
Amplitude and phase quadratures:

$$\hat{X}^+ = \int (L^*(x,t)\hat{\psi}(x) + L(x,t)\hat{\psi}^\dagger(x))dx$$

$$\hat{X}^- = i\int (L^*(x,t)\hat{\psi}(x) - L(x,t)\hat{\psi}^\dagger(x))dx$$

Commutation relations give:

$$V(\hat{X}^+)V(\hat{X}^-) \geq 1$$



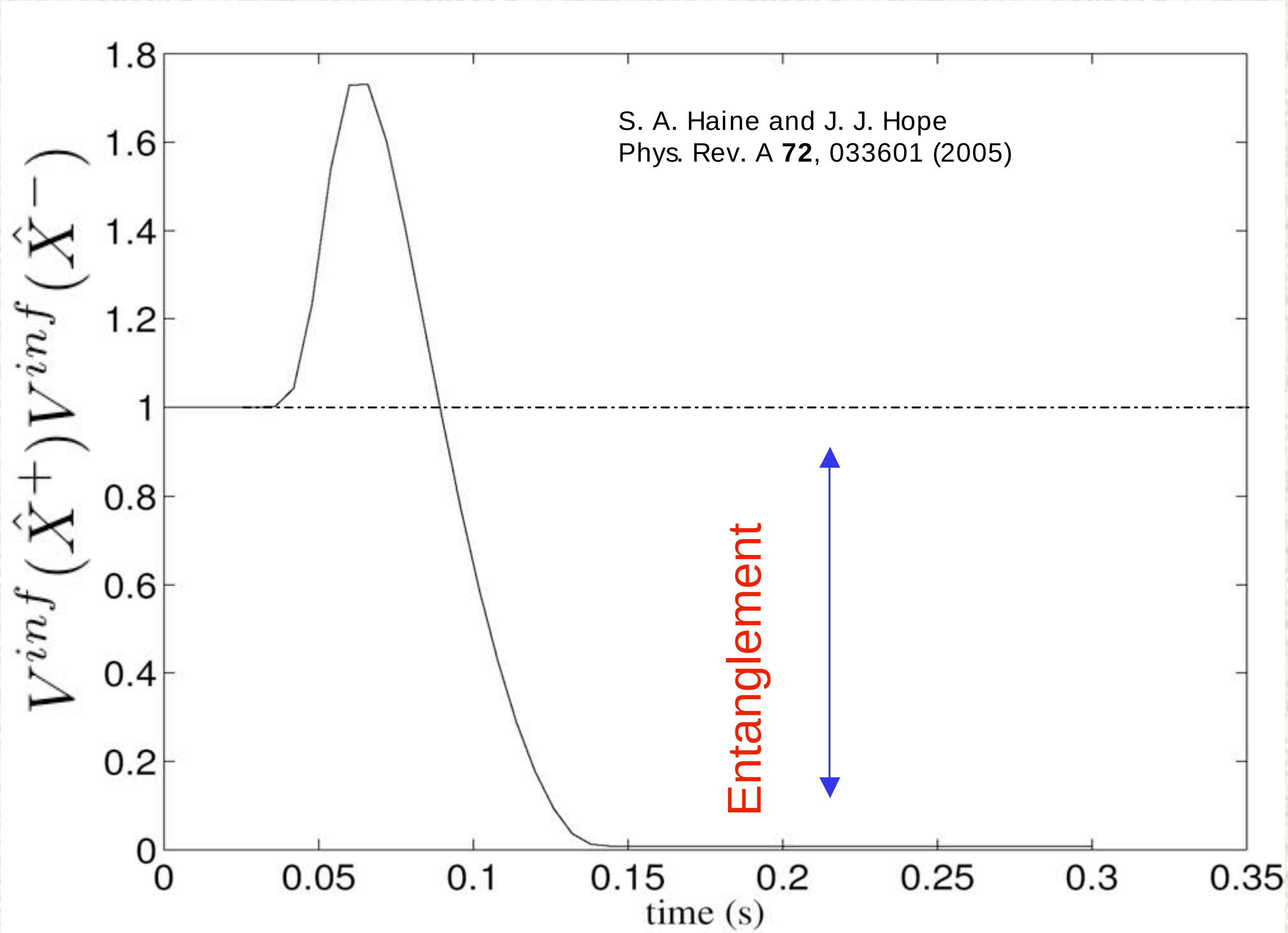
Measure left beam → Infer results of measurements on the right beam

To demonstrate the EPR criterion:

$$V^{\inf}(\hat{X}^+)V^{\inf}(\hat{X}^-) < 1$$

To demonstrate the EPR criterion:

$$V^{\inf}(\hat{X}^{+})V^{\inf}(\hat{X}^{-}) < 1$$



How hard is this experiment?

<u>Things we need:</u>

- Raman atom laser. ✓

- Squeezed light at atom optics frequencies
  - on the way

- Atom detection with high quantum efficiency.
  - hard, but has been done before

- Homodyne detector for quadrature squeezing.
  - we have some ideas.

Summary:

- Can use squeezed light to generate a squeezed atom laser.
- Can generate entangled atom laser beams, and entanglement between atomic beam and optical beam.
- Should be possible with realistic parameters.

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Thank you