Squeezing an atom laser the easy way

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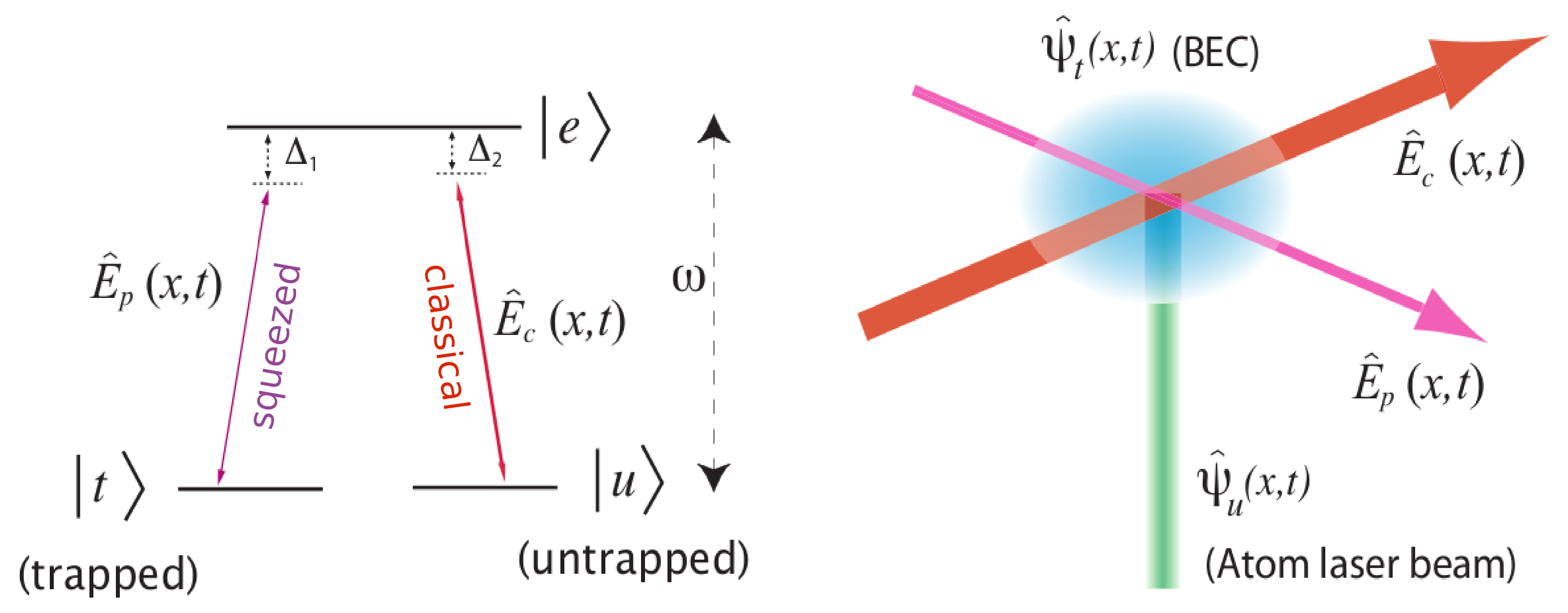
Using squeezed light



- Outcoupling atoms with squeezed light can generate a squeezed atom laser beam
- Requires squeezed light at the right frequencies

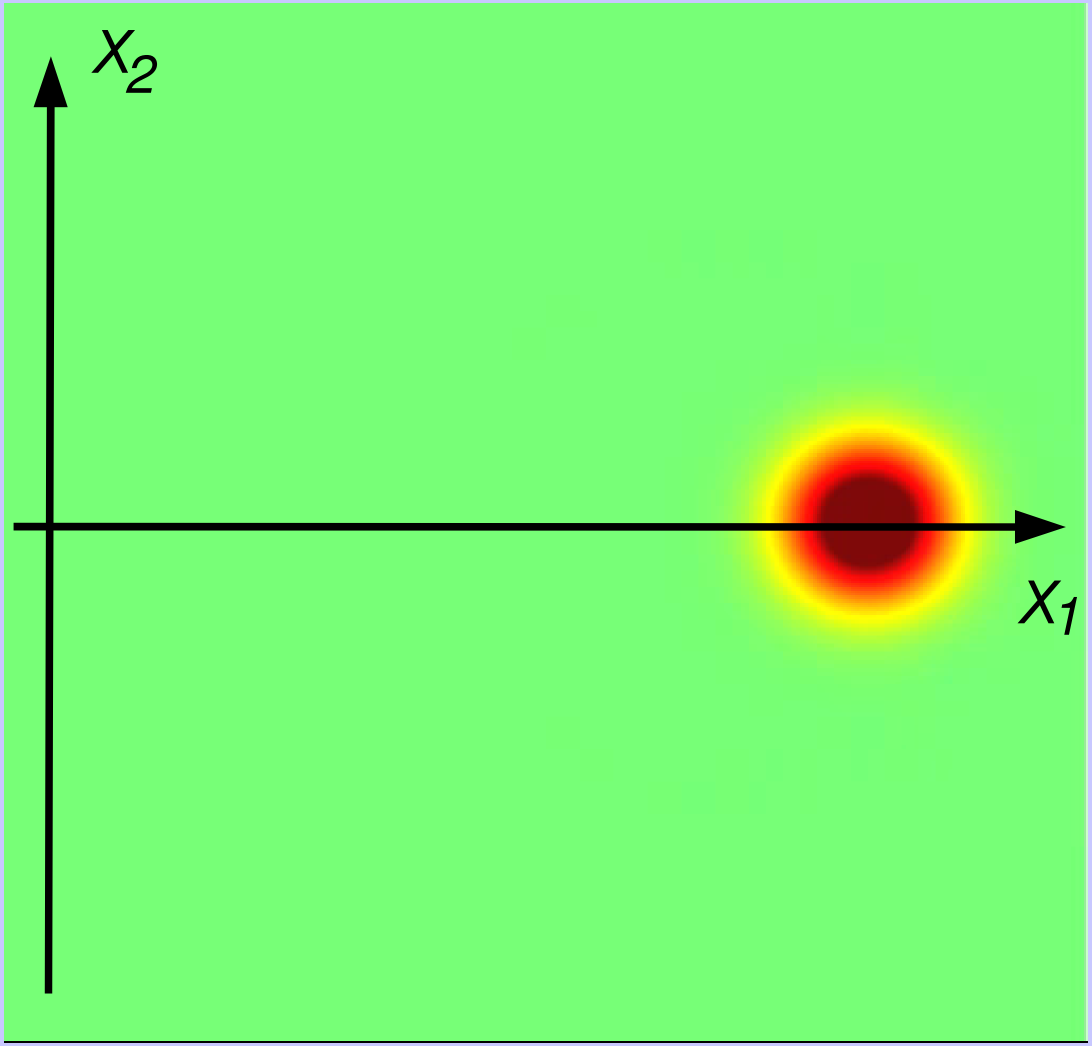
Kerr squeezing

The Kerr Hamiltonian is given by

$$\hat{H} = \hbar\omega\hat{a}^\dagger\hat{a} + \frac{\chi}{2}\hat{a}^\dagger\hat{a}^\dagger\hat{a}\hat{a}$$

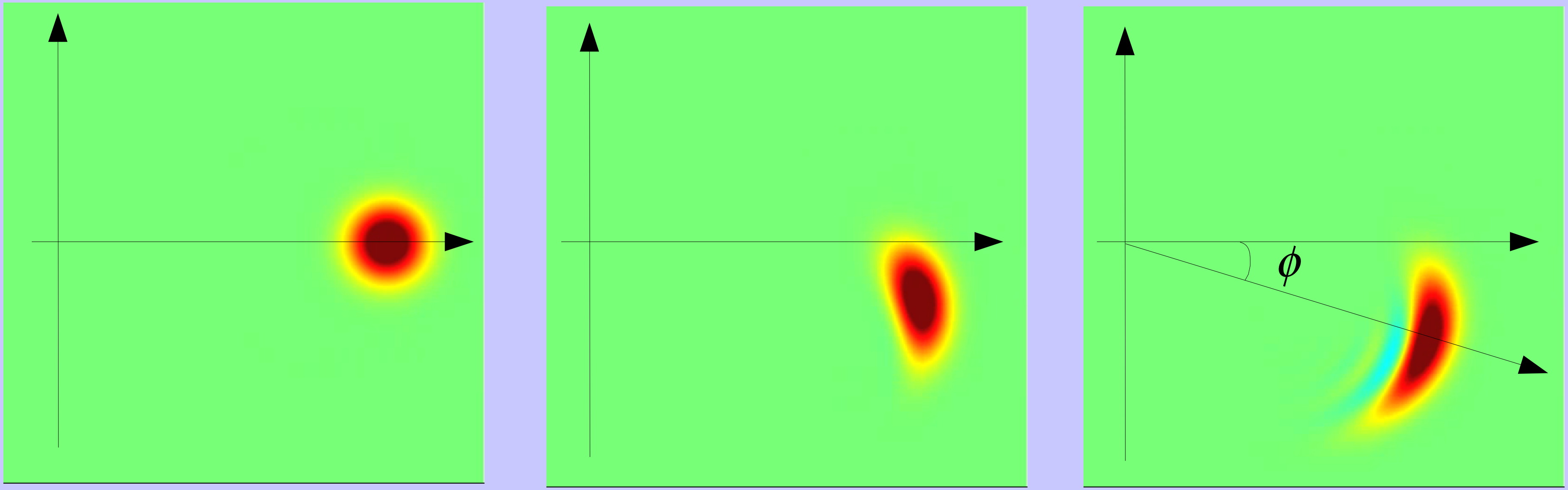
- Well studied in nonlinear and quantum optics
- Observed in systems like doped optical fibres
- Gives rise to quadrature squeezing

Kerr squeezing - Wigner picture



Coherent State: $\mathrm{var}(X_1) = \mathrm{var}(X_2) = 1$

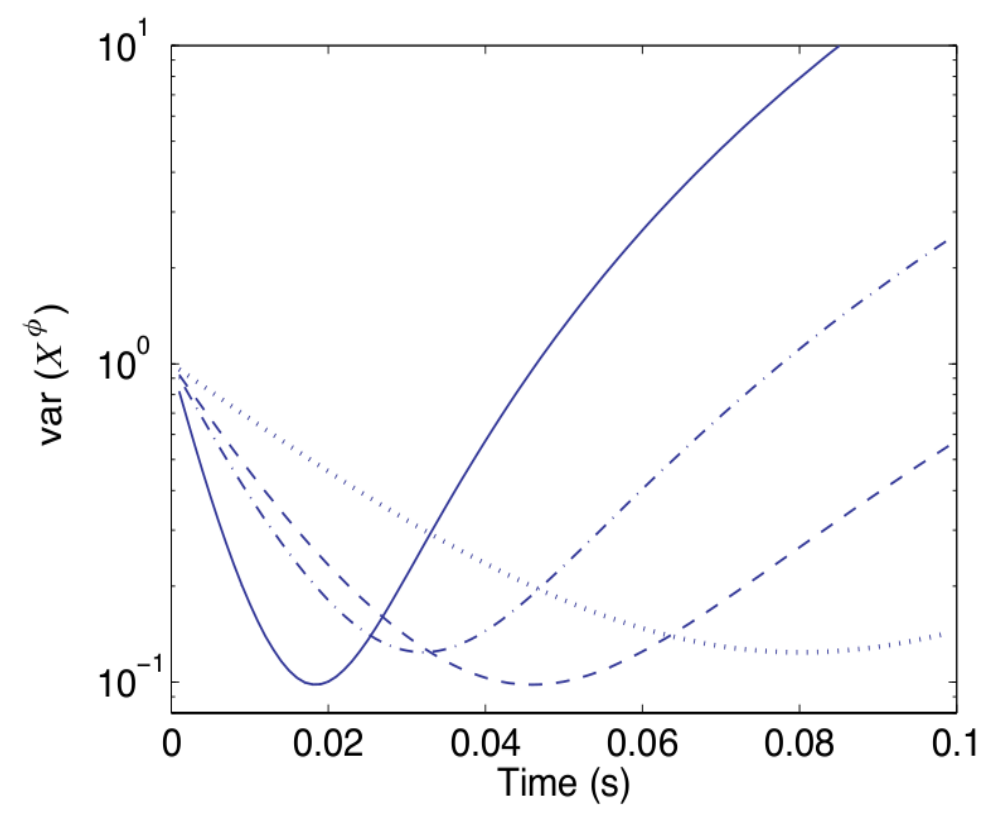
Kerr squeezing - Wigner picture



The nonlinearity causes a shearing effect

$\mathrm{Var}(X^{\phi}) < 1$ indicating quadrature squeezing

Kerr squeezing – analytic solutions



$$\hat{H} = \hbar\omega\hat{a}^\dagger\hat{a} + \frac{\chi}{2}\hat{a}^\dagger\hat{a}^\dagger\hat{a}\hat{a}$$

Solid: $\chi = 0.1\hbar$, $N = 1000$

Dashed: $\chi = 0.4\hbar$, $N = 1000$

Dot-dash: $\chi = 0.1\hbar$, $N = 500$

Dotted: $\chi = 0.04\hbar$, $N = 500$

- Squeezing reaches a maximum, then decreases
- Amount of squeezing depends on the nonlinearity

The Kerr effect and atom lasers

$$
\begin{aligned}
\hat{H} \quad = \quad & \hat{\Psi}_t^\dagger(\hat{T}+\hat{V}_{\text{trap}})\hat{\Psi}_t + \frac{U}{2}\hat{\Psi}_t^\dagger\hat{\Psi}_t^\dagger\hat{\Psi}_t\hat{\Psi}_t && \leftarrow \text{BEC} \\
& +\Omega\hat{\Psi}_t^\dagger\hat{\Psi}_u + \Omega^*\hat{\Psi}_u^\dagger\hat{\Psi}_t && \leftarrow \text{Coupling} \\
& +\hat{\Psi}_u^\dagger(\hat{T}+\hat{V}_{\text{grav}})\hat{\Psi}_u + \frac{U}{2}\hat{\Psi}_u^\dagger\hat{\Psi}_u^\dagger\hat{\Psi}_u\hat{\Psi}_u && \leftarrow \text{Beam}
\end{aligned}
$$

- The beam Hamiltonian looks just like the Kerr Hamiltonian
- Nonlinearity now dependent on *U* and beam density
- The further the beam falls, the more it squeezes
- After some distance, squeezing effect turns off

Simulating the system

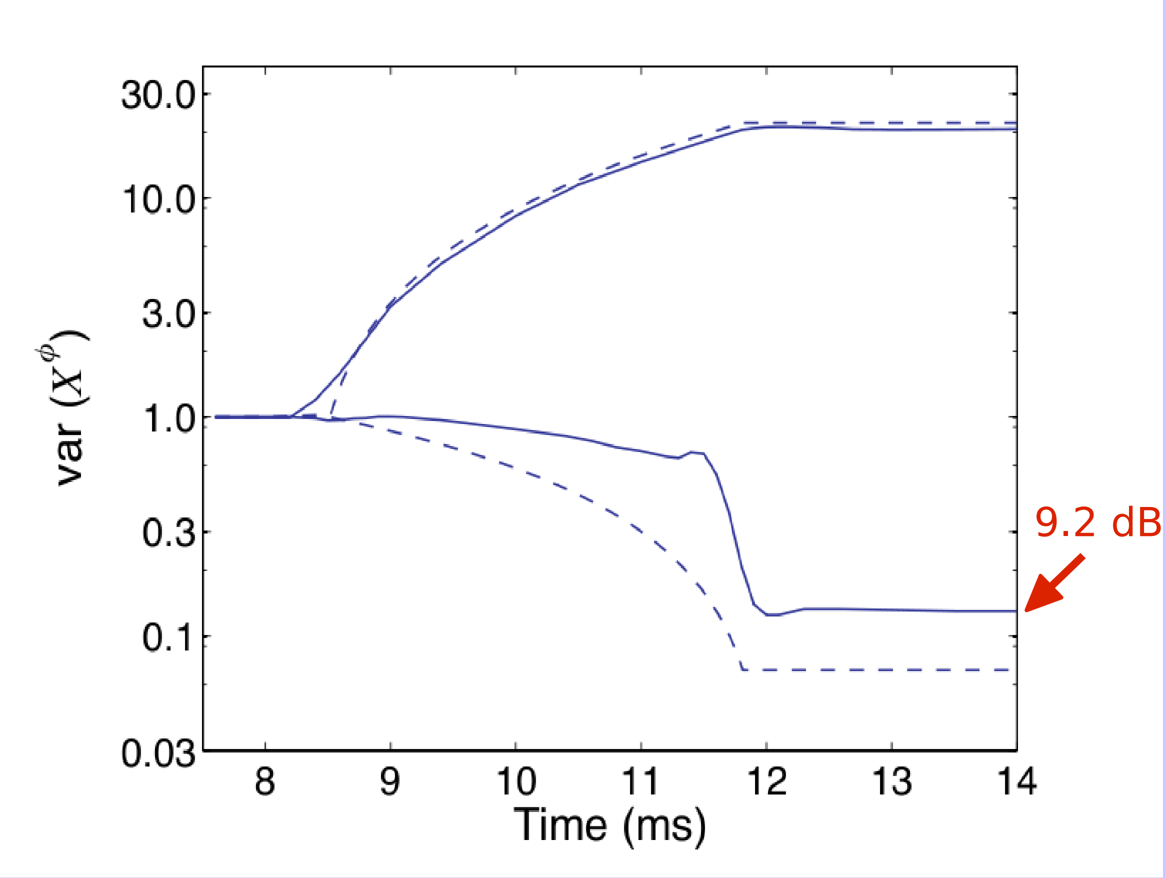
- GPE is not good enough, so use stochastic methods

- Want to make this realistic
  - simulation should be multimode
  - include back action on the BEC
  - should include spatial effects

- Need a mode-matched local oscillator. Then

$$\hat{X}^{\phi} = \hat{b} + \hat{b}^{\dagger}, \quad \text{where} \quad \hat{b} = \int_{z_1}^{z_2} L(z) e^{i\phi} \hat{\Psi}_u(z) dz$$

where *L(z)* is the mode function of the local oscillator



9.2 dB

Dashed line – single mode analytic solutions

Solid line – multimode stochastic simulation

Upper lines – max antisqueezing

Lower lines – max squeezing

Plots of measured squeezing and antisqueezing in a region 20 µm long, well below the BEC.

Beam wavefront reaches region 8ms after outcoupling starts; steady state reached after 12ms.

Realistic numbers... and problem

- Let's take some realistic numbers
  - Rb Raman atom laser, region 1cm below BEC
  - Choose mode matching region 25 μm long
  - $\omega = 2\pi$(60x600x600)
  - N = 500,000
  - Outcoupling frequency Ω = 500 rad/s

- Obtain best squeezing of var(X^{ϕ}) = 0.14 = 8.5dB

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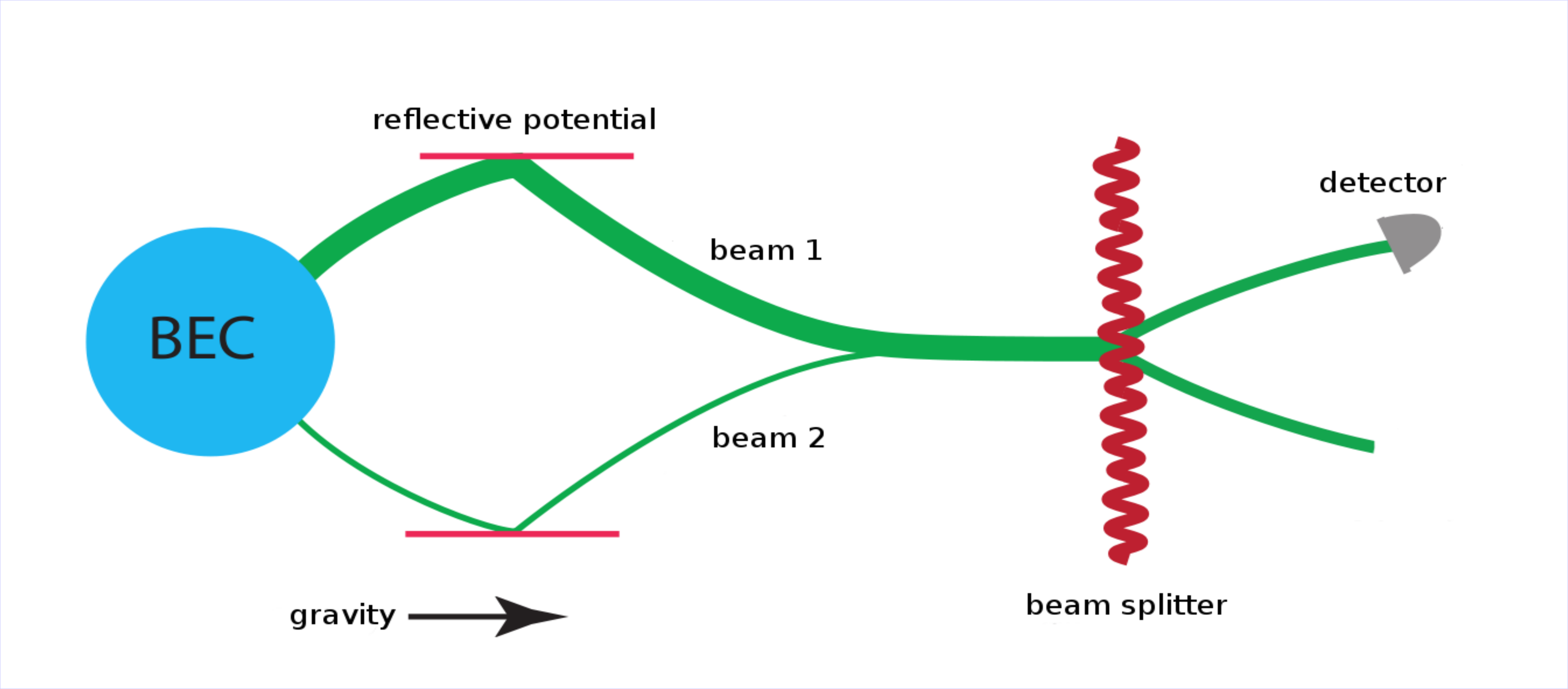
Problem: The local oscillator is assumed to be a strong coherent state. It will Kerr squeeze too!



What happens if we combine two Kerr-squeezed beams on a beam splitter? We get number squeezing!

For two equal-strength beams, and same parameters as before, we get intensity noise of 0.17 = 7.7dB

Intensity noise suppression is robust to relative beam strength.

Conclusions

- Scheme is highly tunable
- Need high, but achievable, beam densities
- Can get quadrature squeezing, but getting a local oscillator could be tricky
- Scheme can also generate a number squeezed beam