Superradiance-like phenomena observed in atomic four-wave mixing

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<u>*Experiment:*</u>

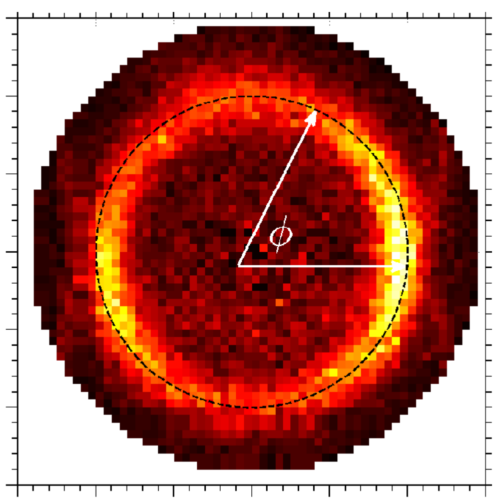
Christoph Westbrook, Denis Boiron,
Jean-Christophe Jaskula, Valentina Krachmalnicoff, Marie Bonneau

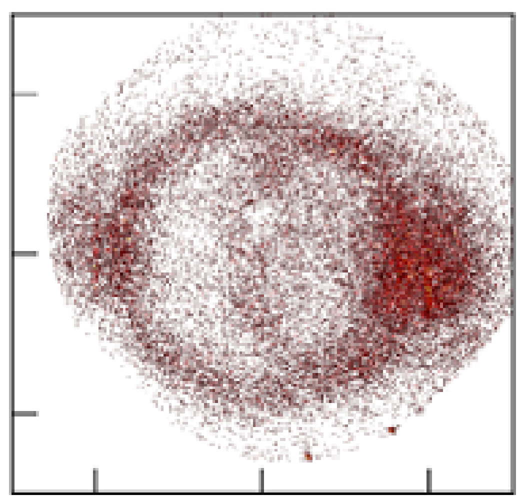
Institut d'Optique, Palaiseau, France

<u>*(more) Theory:*</u>

Karen Kheruntsyan

University of Queensland, Brisbane, Australia



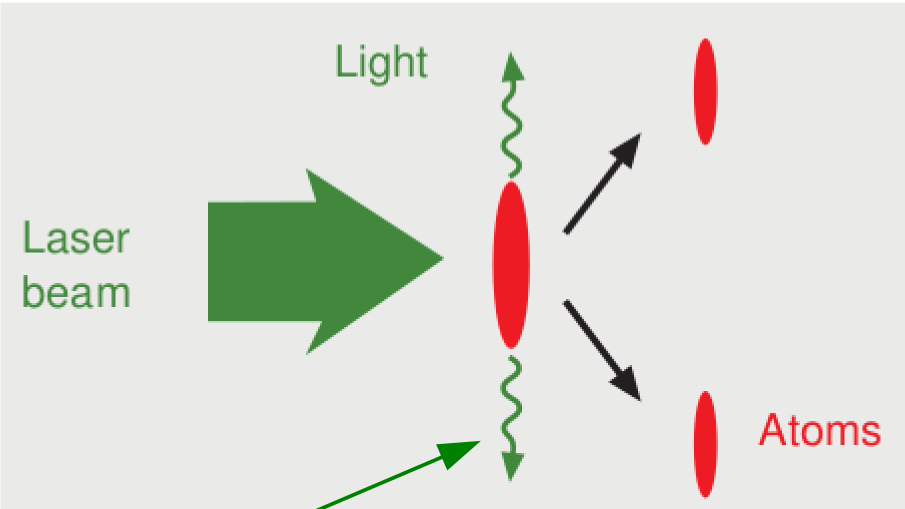


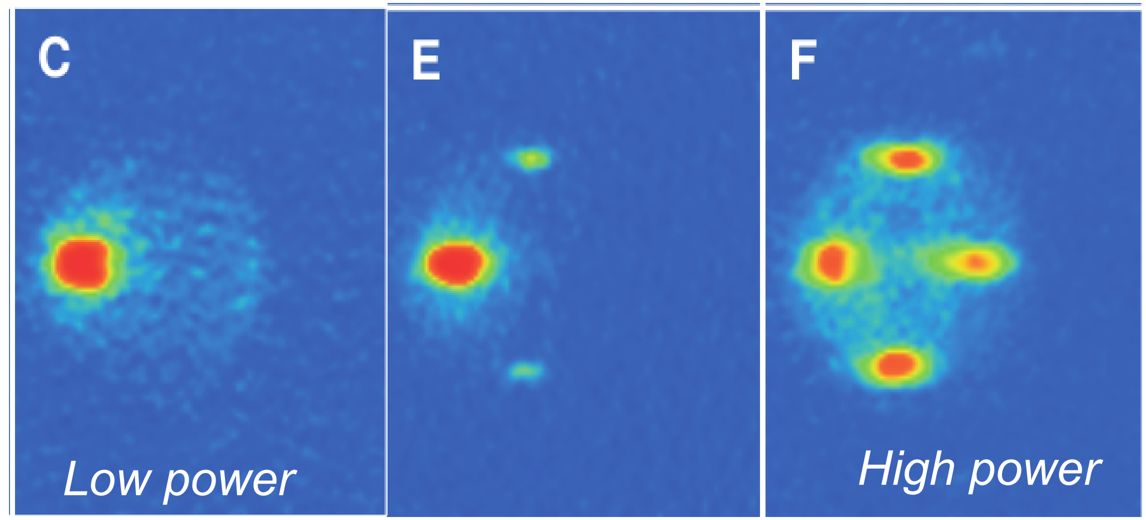
arXiv:1406.1327

Optical superradiance & its atomic analogue

OPTICAL SUPERRADIANCE

Inouye, Chikkatur, Stamper-Kurn, Stenger, Pritchard, Ketterle, Science **285**, 571 (1999)





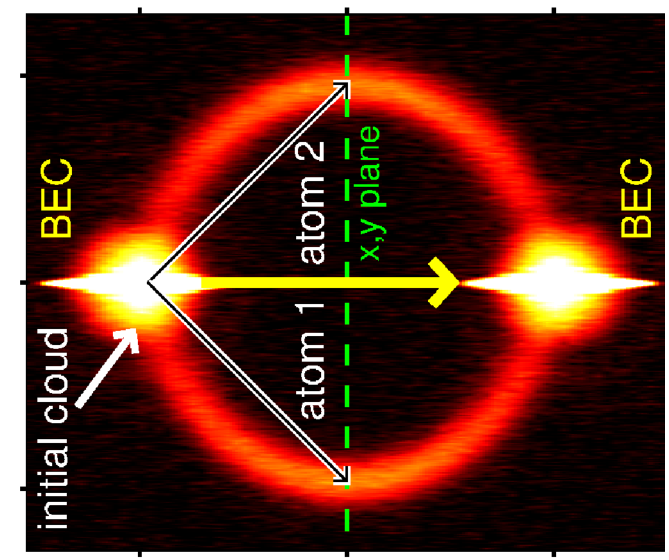
1. *photons are scattered*
2. *scattering rate ~ (1+n)* *(<u>Bose enhancement</u>)*
3. *those scattered along the long axis of cloud preferentially stimulate more scattering*
4. *photons build up in the "end-fire" modes*

<u>GAIN</u>

$$\mathcal{G} \approx g n_{\max}/\hbar$$

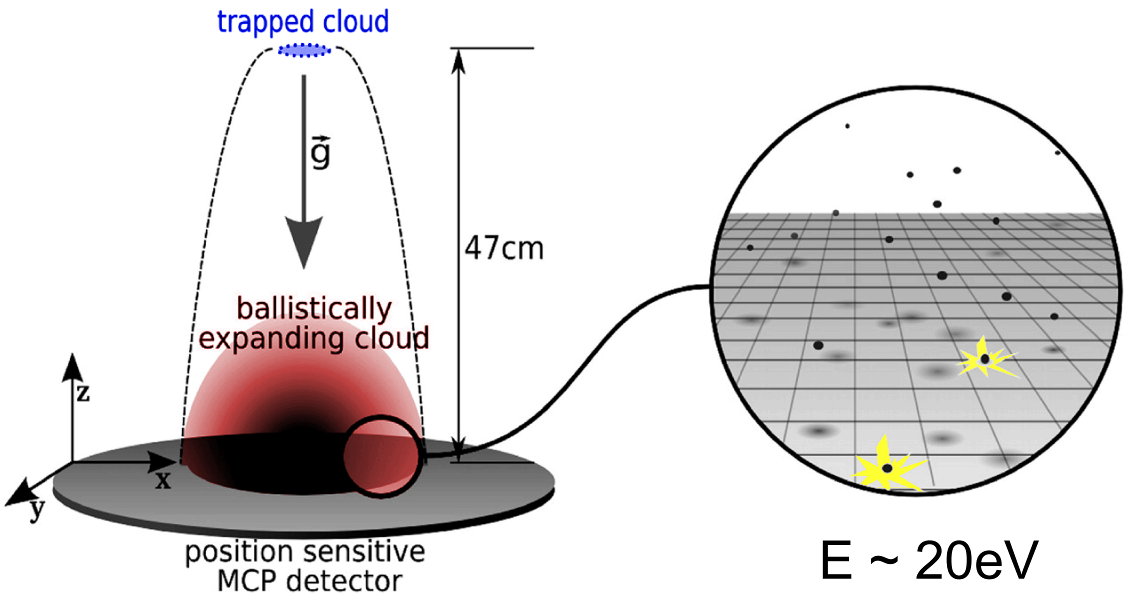
$$n(k,t)_{\max} \sim \sinh^2[\mathcal{G}t]$$

ATOM-ONLY ANALOGUE



PD, Jaskula, Bonneau, Krachmalnicoff, Boiron, Westbrook, Kheruntsyan, arXiv:1406.1327

BEC collision – Palaiseau experiment



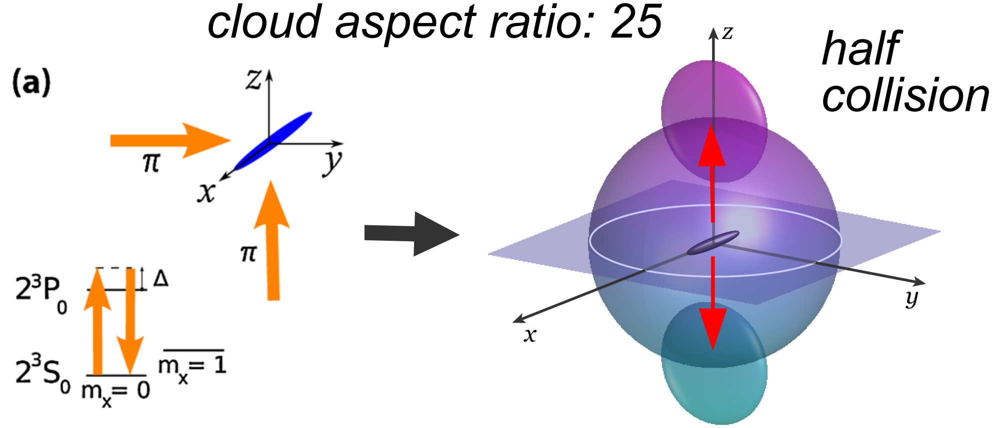
E ~ 20eV

^{4}He in metastable state

Single atom detection efficiency η ~ 12%

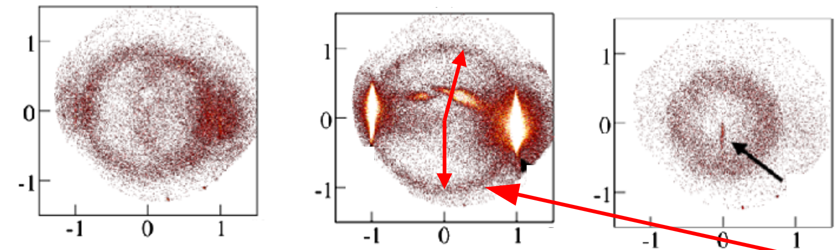
cloud aspect ratio: 25

half collision



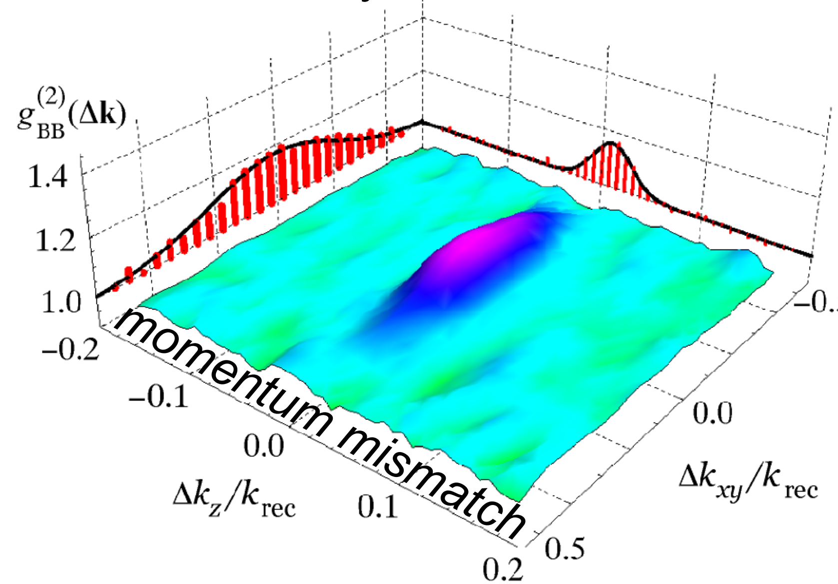
t=0 Bragg pulse   t=0.3 s expansion

Single-atom tomography of momentum distribution



Perrin, Chang, Krachmalnicoff, Schellekens, Boiron, Aspect, Westbrook, PRL **99**, 150405 (2007)

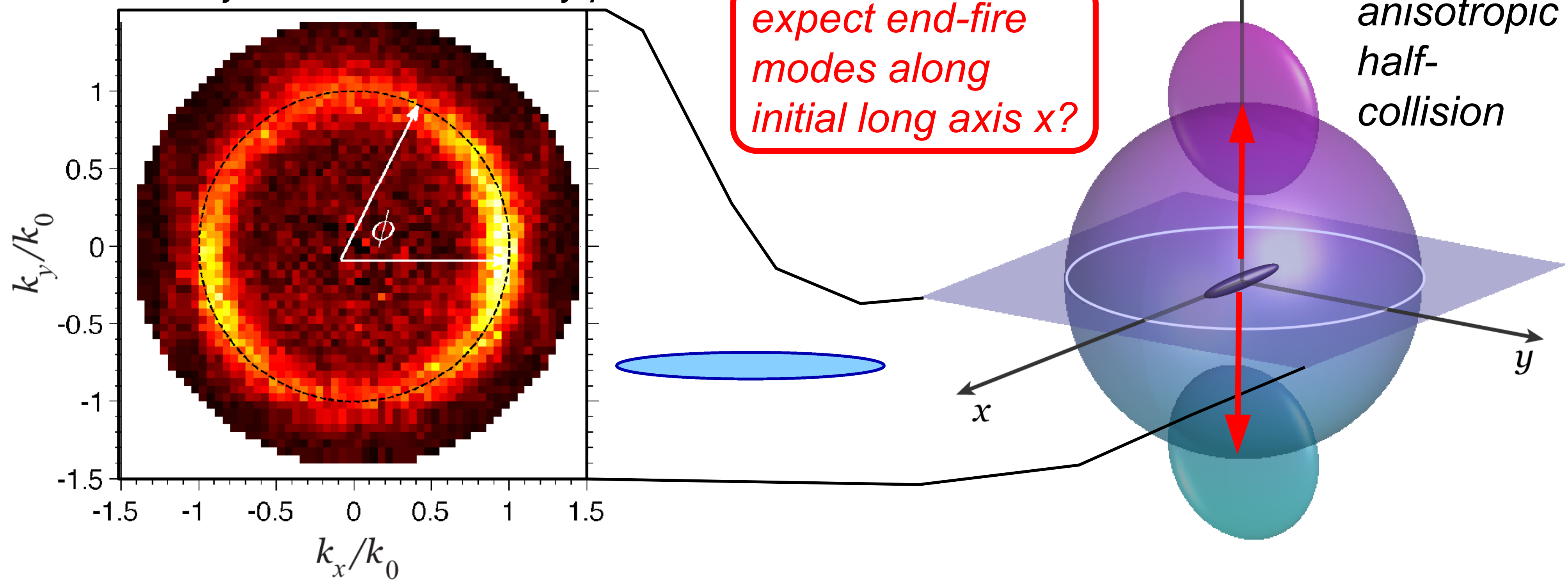
Counter-propagating pairs: density correlations

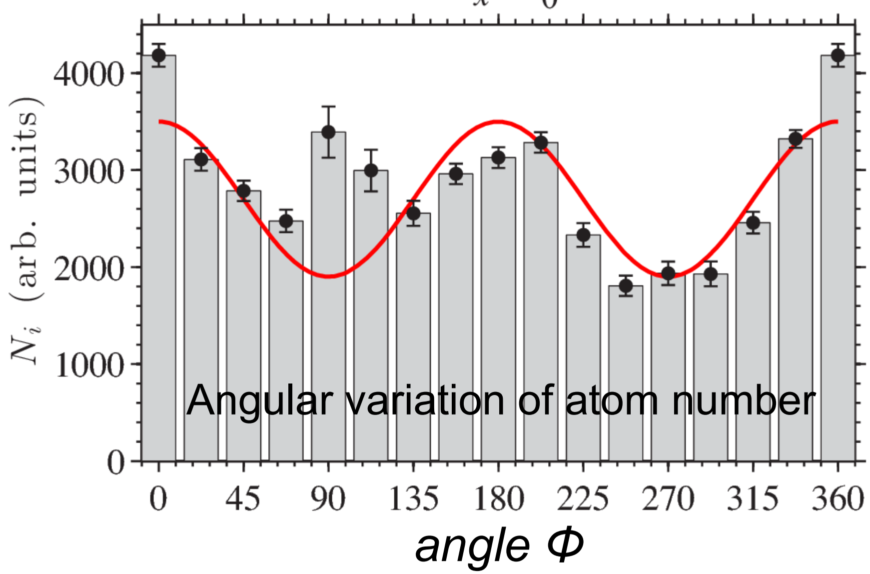


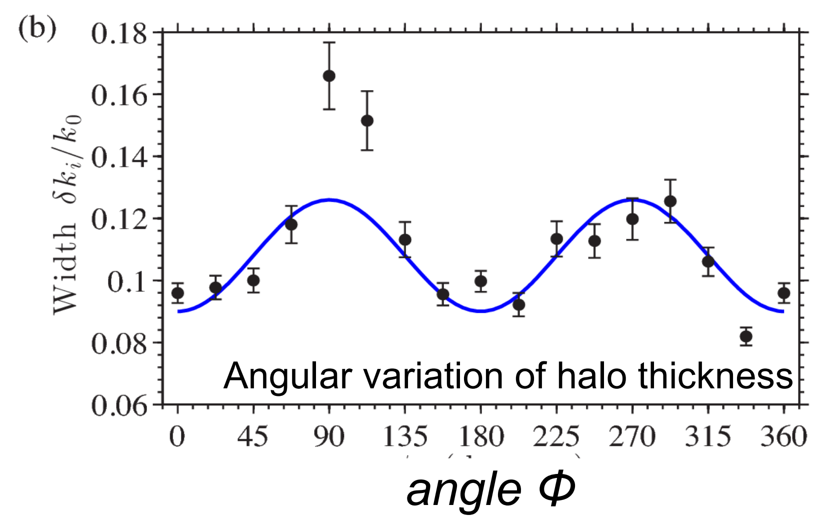
Kheruntsyan, Jaskula, PD, Bonneau, Partridge, Ruaudel, Boiron, Lopes, Westbrook, PRL **108**, 260401 (2012)

Experimental data

Atom density measured in the x-y plane







NARODOWE CENTRUM NAUKI

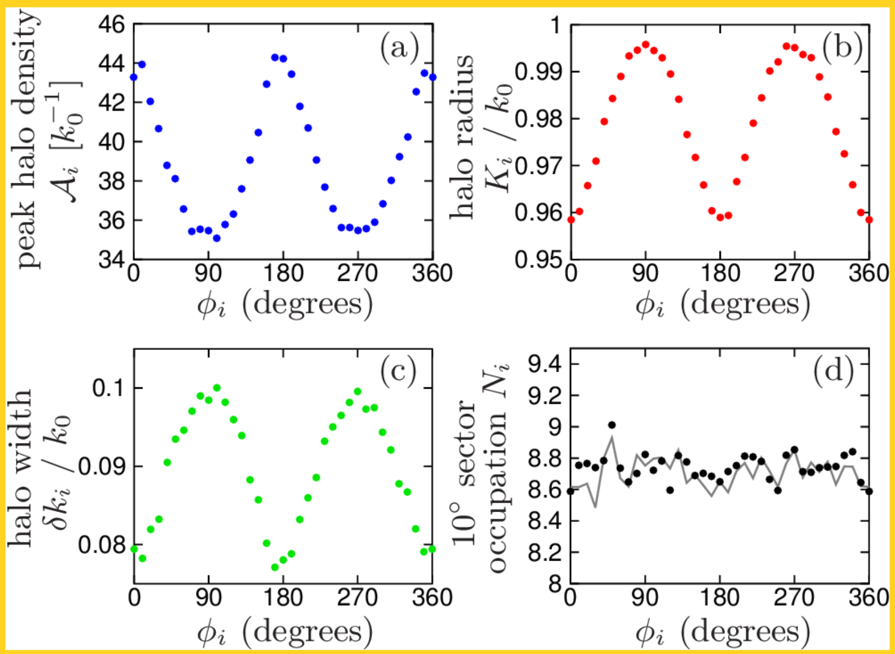
Simulation – stochastic Bogoliubov

PD, Chwedeńczuk, Ziń, Trippenbach, PRA **83,** 063625 (2011)

Bogoliubov:

$$\widehat{\Psi}(\mathbf{x},t) = \phi(\mathbf{x},t) + \widehat{\delta}(\mathbf{x},t)$$

condensate fluctuations



GPE

$$i\hbar\frac{d\phi(x)}{dt} = \left[H_0(x) + g|\phi(x)|^2\right]\phi(x)$$

Bogoliubov de Gennes

$$i\hbar\,\partial_t\hat{\delta}(\mathbf{x},t) = \left[-\frac{\hbar^2}{2m}\nabla^2 + 2g|\phi(\mathbf{x},t)|^2\right]\hat{\delta}(\mathbf{x},t) + g\phi^2(\mathbf{x},t)\hat{\delta}^\dagger(\mathbf{x},t)$$

The Bogoliubov fluctuation field $\widehat{\delta}(\mathbf{x},t)$ is treated using the positive-P representation

$$i\hbar\frac{d\psi(x)}{dt} = \left\{H_0(x) + 2g|\phi(x)|^2\right\}\psi(x) + g\phi(x)^2\widetilde{\psi}(x)^* + \sqrt{i\hbar g}\,\phi(x)\xi(x,t)$$

noise

$$i\hbar\frac{d\widetilde{\psi}(x)}{dt} = \left\{H_0(x) + 2g|\phi(x)|^2\right\}\widetilde{\psi}(x) + g\phi(x)^2\psi(x)^* + \sqrt{i\hbar g}\,\phi(x)\widetilde{\xi}(x,t)$$

Can now use plane wave basis ---> no diagonalizing of 10^7 X 10^7 matrices :)

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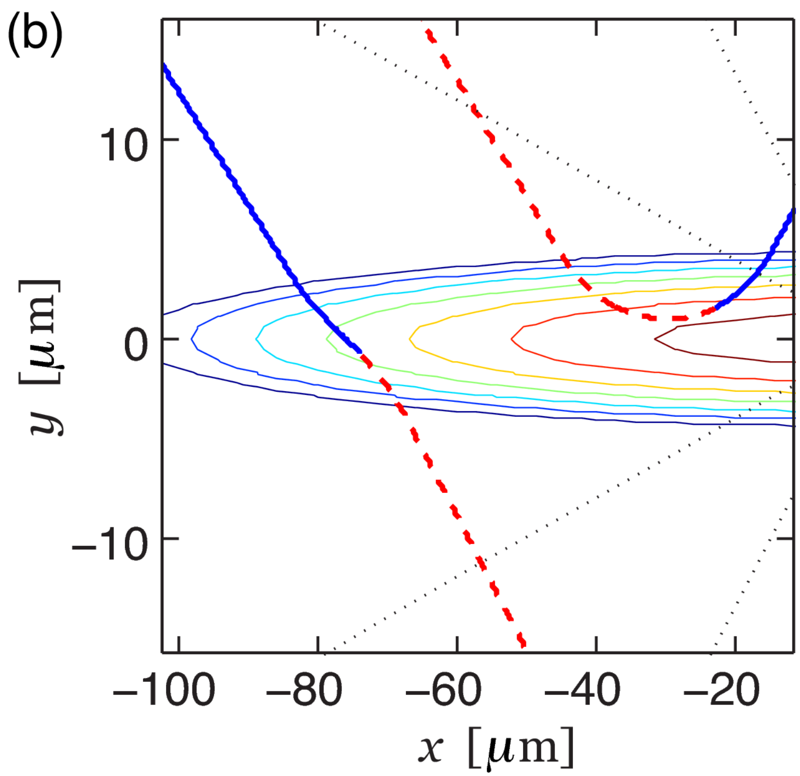
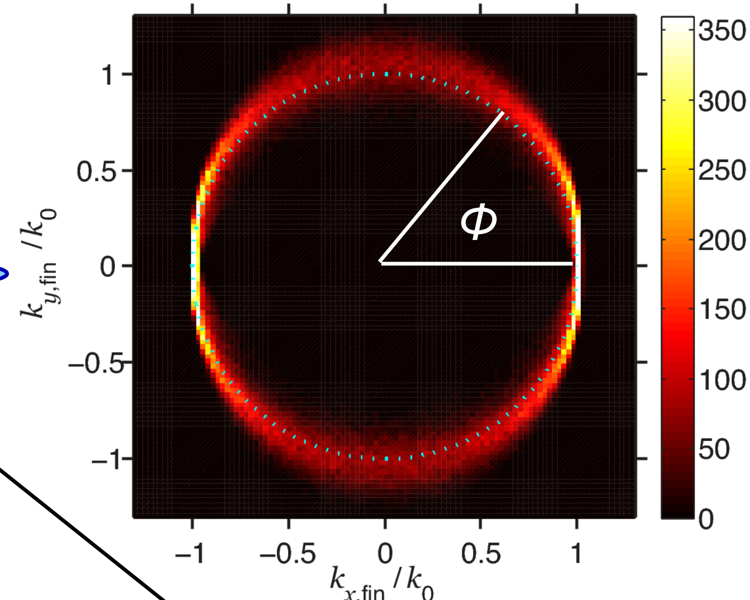
“Skier” effect

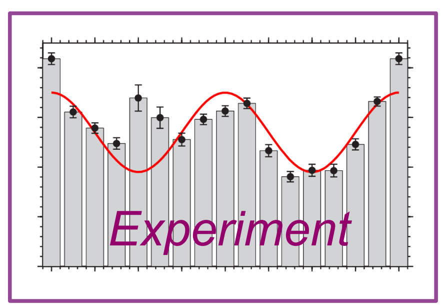
Classical trajectory deflections due to the mean field of the condensate

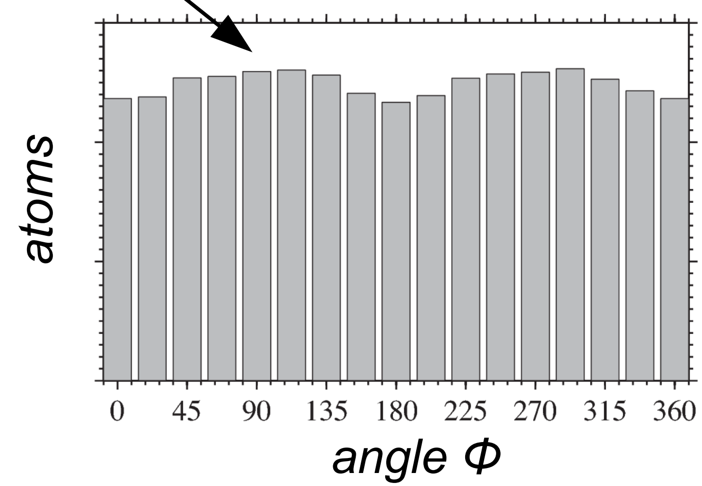
- Change halo's density profile
- But in the opposite sense to that observed



Simple test particle simulation

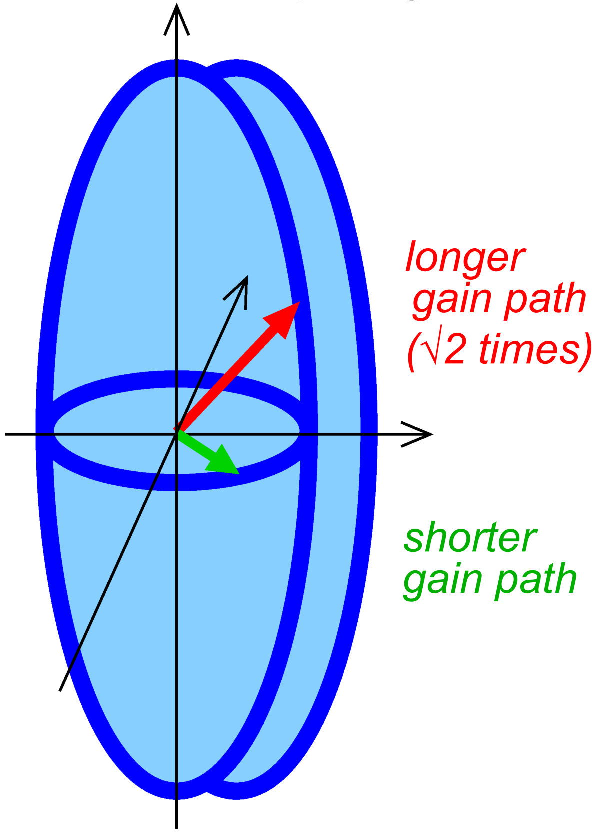






Anisotropic gain, tradeoff

Anisotropic gain

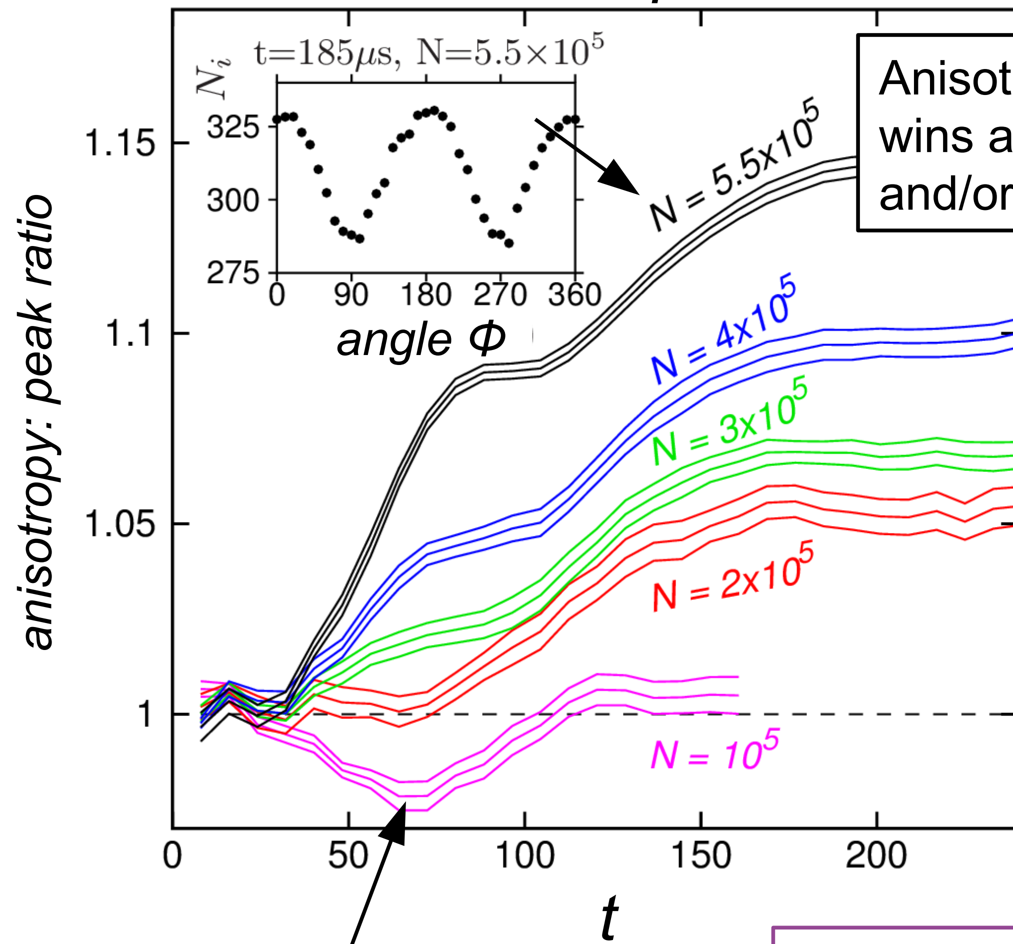


GAIN

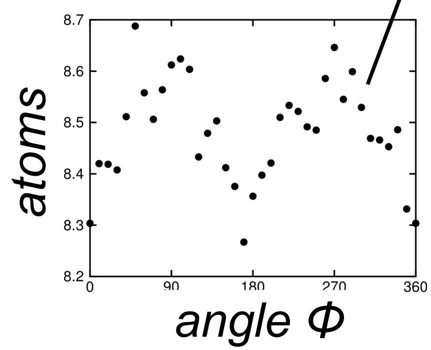
$$n(k,t)_{\max} \sim \sinh^2[\mathcal{G}t]$$

$$\mathcal{G} \approx g n_{\max}/\hbar$$

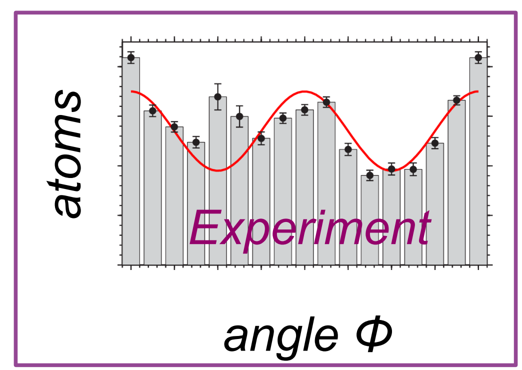
simulations: peak ratio



Anisotropic gain wins at long times and/or large N



Skier effect At short times



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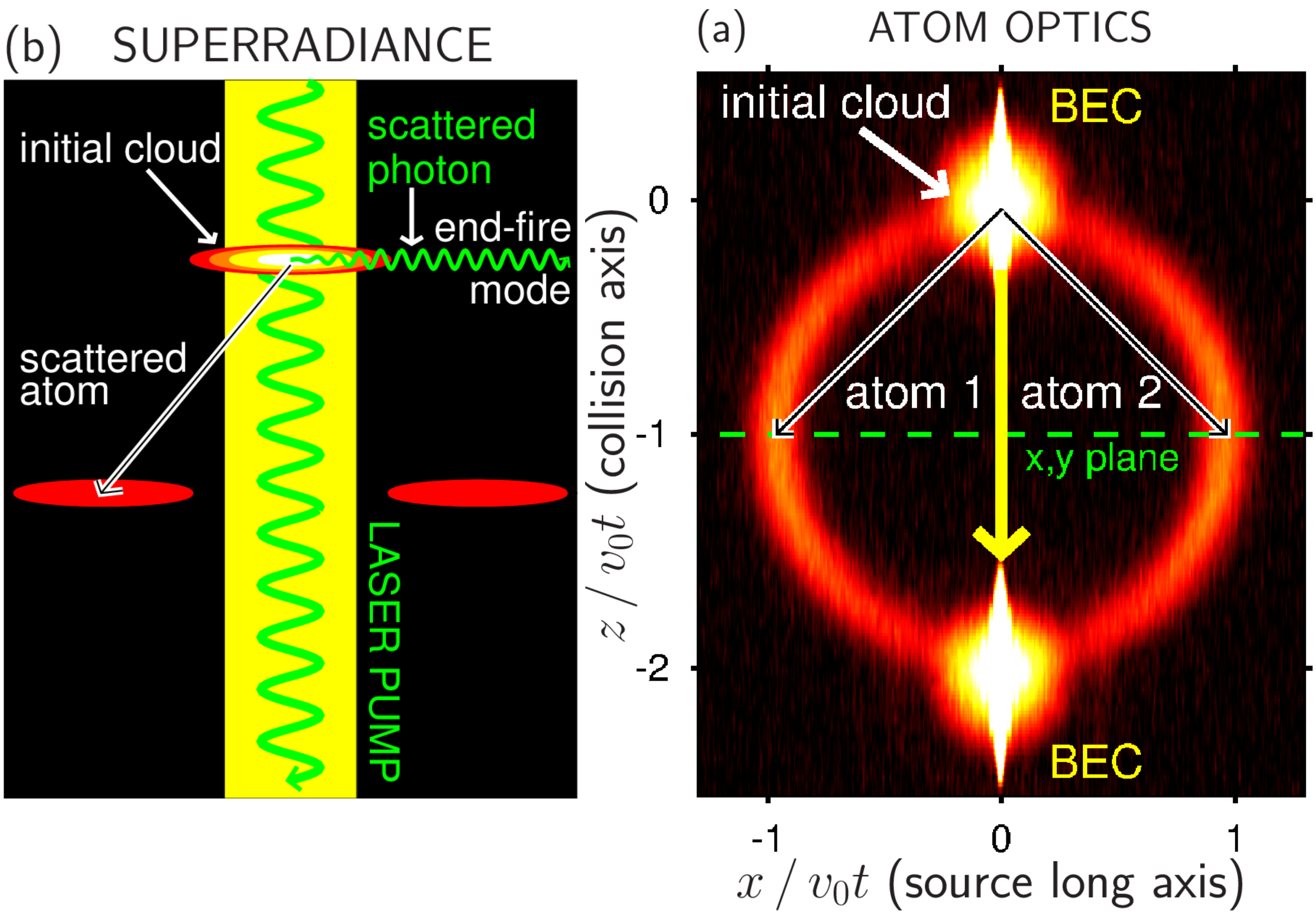
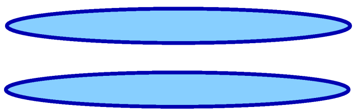
Atomic and optical superradiance: comparison





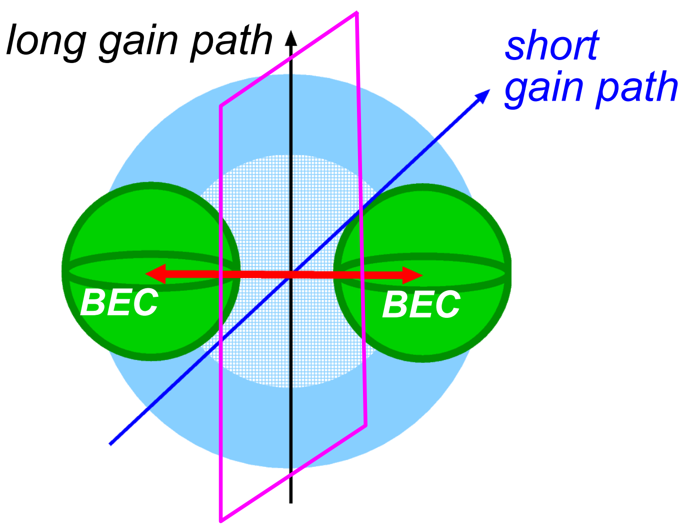
Primary differences:

(1) duration

(2) energy/momentum conservation laws

Conclusions + outlook

- Superradiance analogue seen in all-atom collisions
- Qualitative differences: Evidence of a tradeoff between
  - Anisotropic gain
  - Skier effect on BEC mean field.
- Observed a fairly weak effect due to:
  - Different conditions in all-atomic experiments:
    - Equal mases of colliding particles
    - Short "illumination" time
  - → Moderate difference in path lengths through cloud



Better geometry: pancake BEC colllision