Analogue of dynamical Casimir effect with matter waves

He* Experiment

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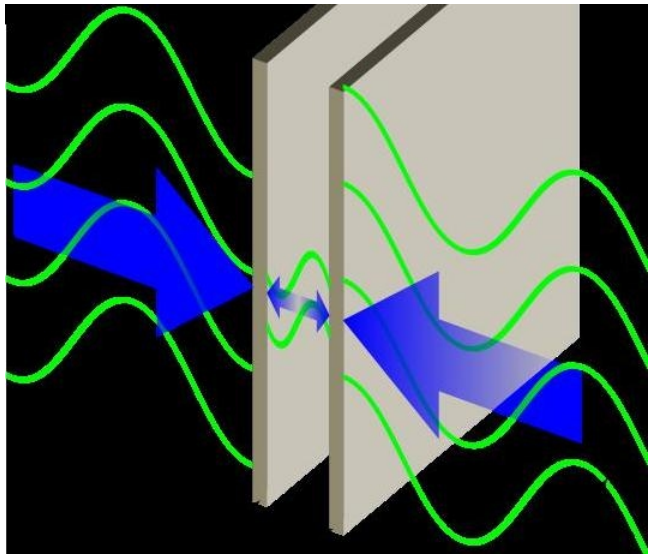
05/04/2013

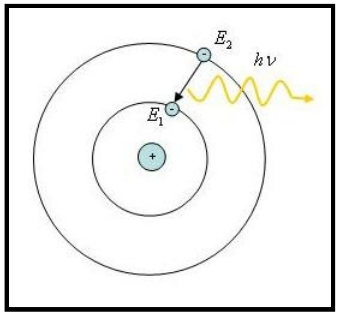
Different well known effects due to vacuum fluctuations

Quantum optics and classical optics are quite different when the number of photons are decreasing. But when we reduce the number of photons to zero, then the classical point of view is no longer valid.



Static Casimir effect:

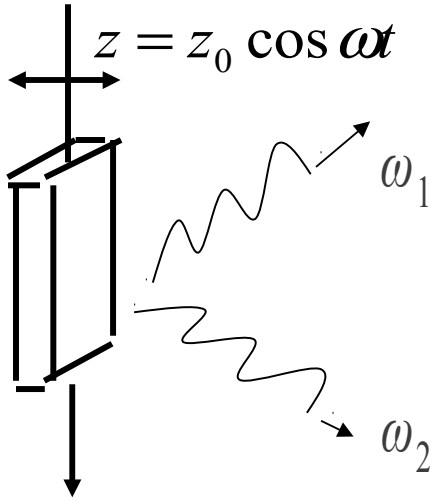
Spontaneous emission



Boundaries conditions impose a quantization of the vacuum. Less modes inside the cavity can induce a “pressure force”.

Dynamical effects due to vacuum fluctuations:

The dynamical Casimir effect DCE



The boundary conditions are modified at a velocity close to the speed of light.
In this conditions the ground state of the system at a given time t becomes an excited state at time t+dt.

This excited state can be written as pairs of photons satisfying:

$$\omega = \omega_1 + \omega_2$$

G.T. Moore, *J. Math. Phys*. **11**, 2679 (1970)

S.A. Fulling, P.C.W. Davies, *Proc. R. Soc. London Ser. A* **348**, 393 (1976)

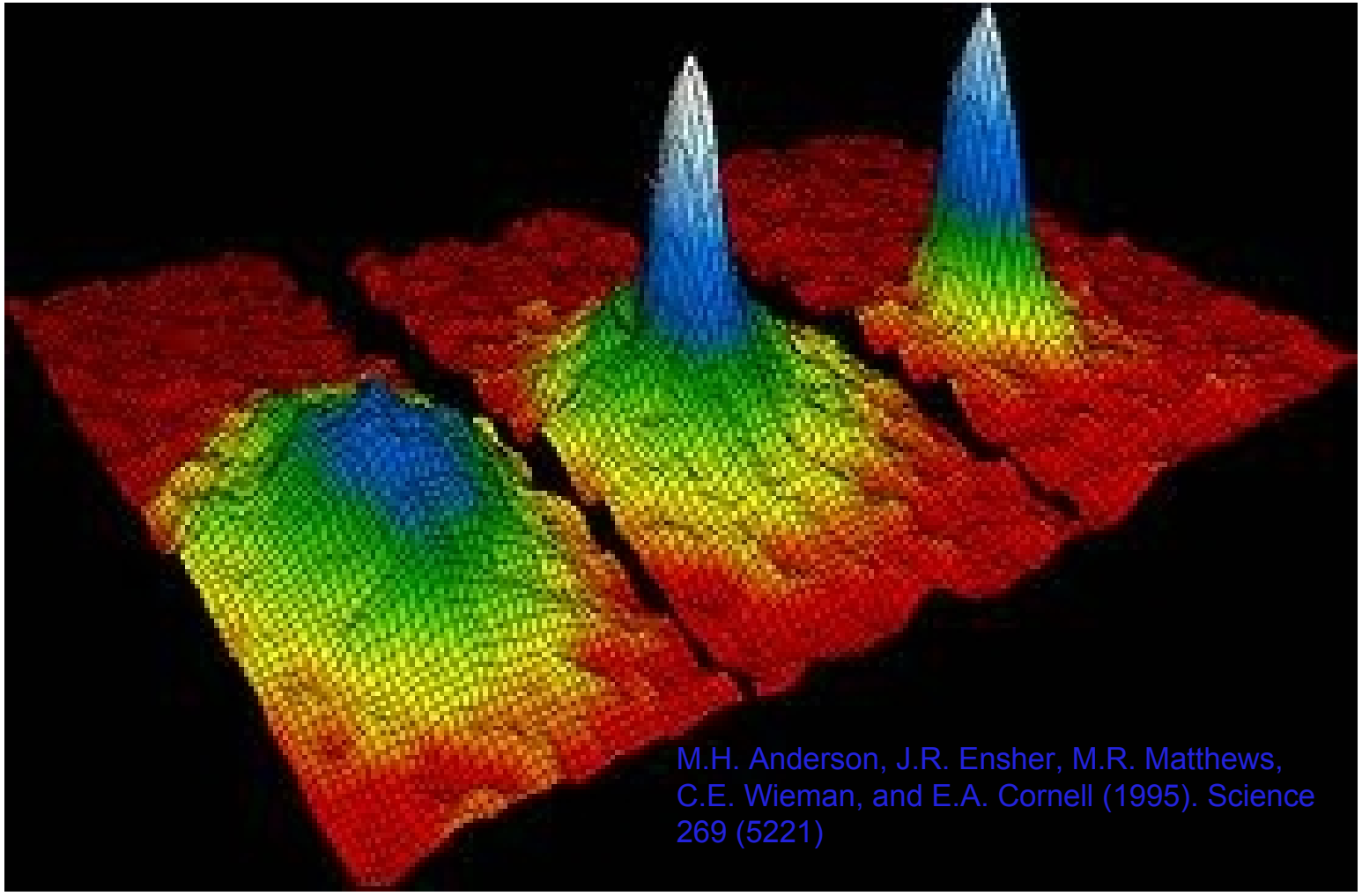
A. Lambrecht, M.-T. Jaekel, S. Reynaud, *Phys. Rev. Lett.* **77**, 615 (1996)

P. Nation, J. Johansson, B. Bloncowe, F. Nori, *Rev. Mod. Phys.* **84**, 1 (2012)

Wilson & al. ***Nature*** **479**, 376 (2011)

System:

Bose-Einstein condensate



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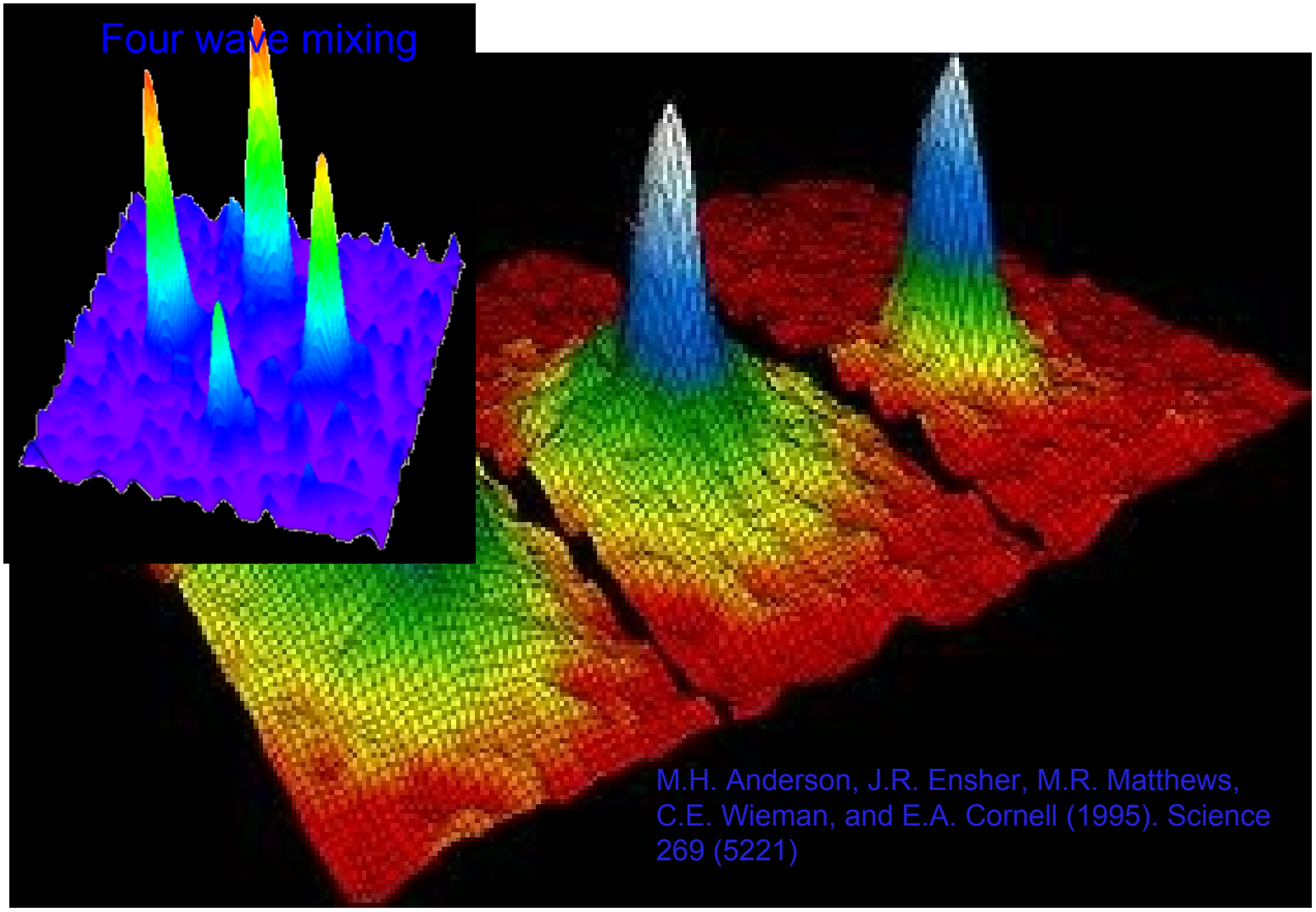

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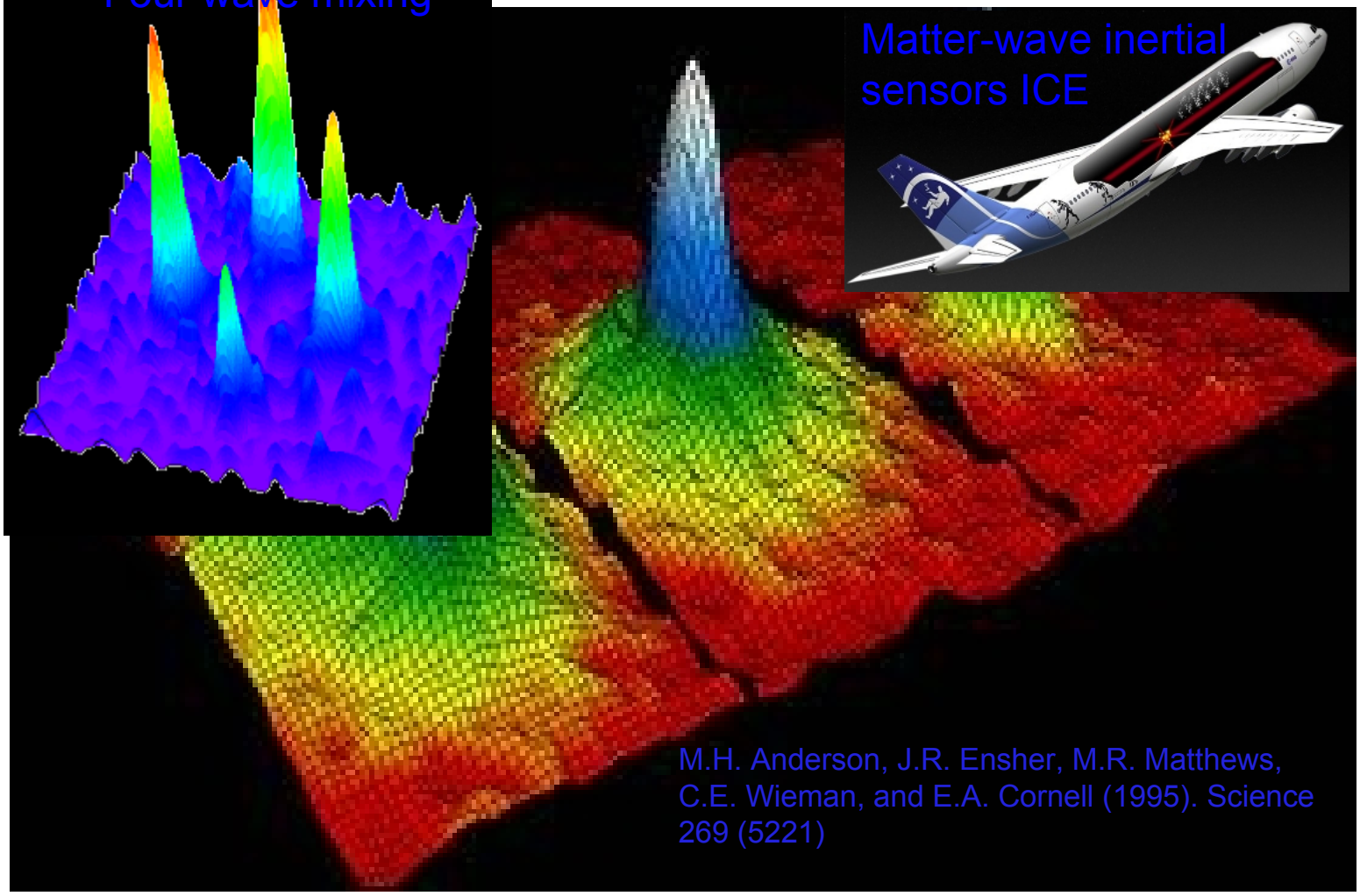

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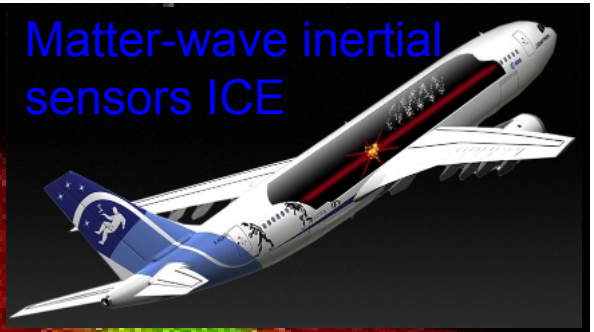

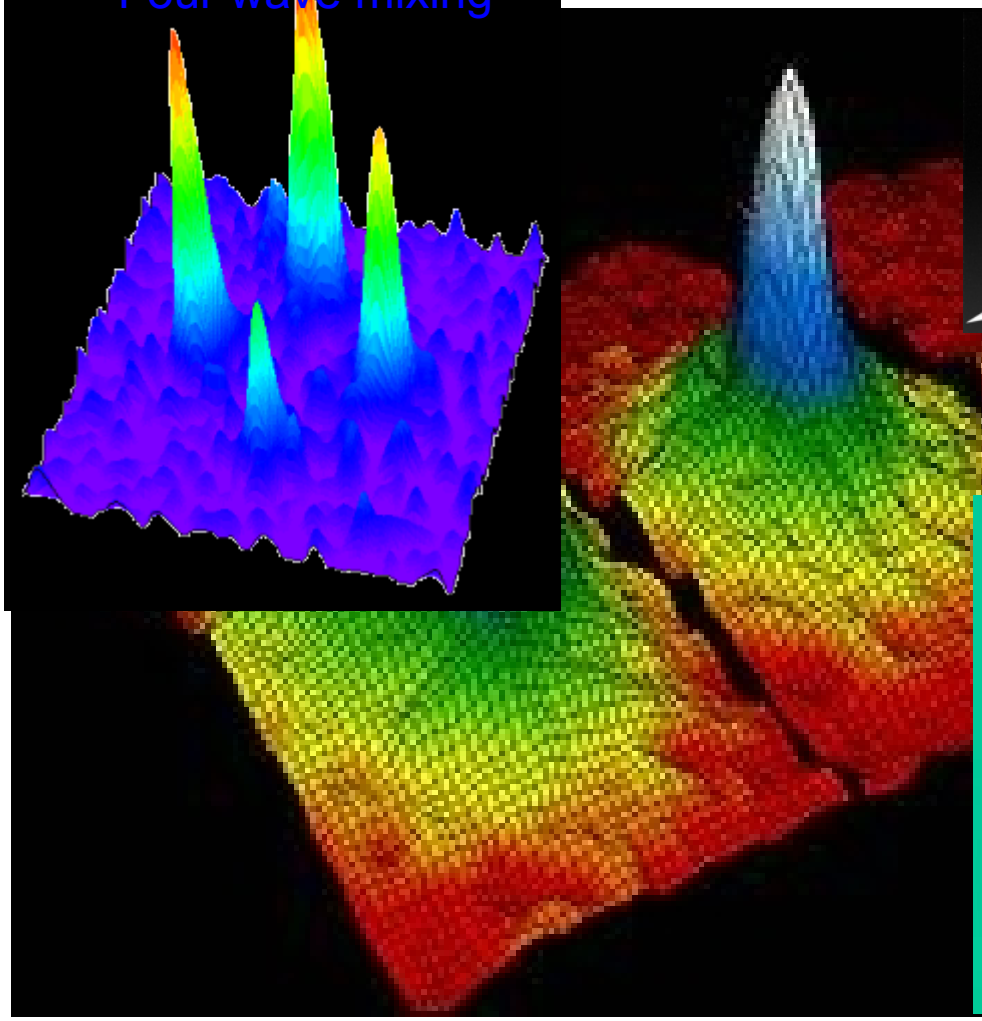

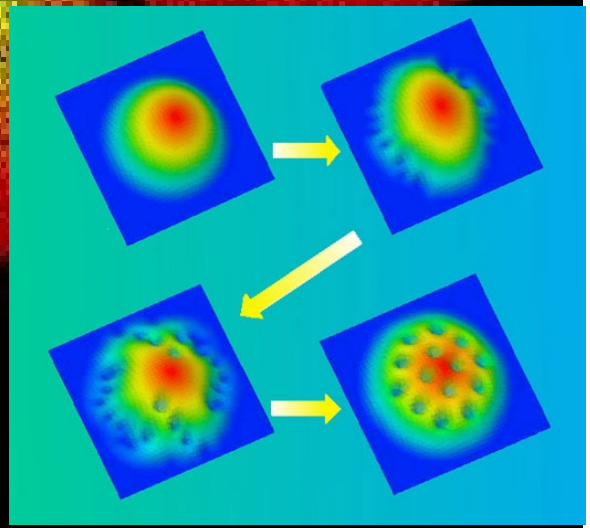

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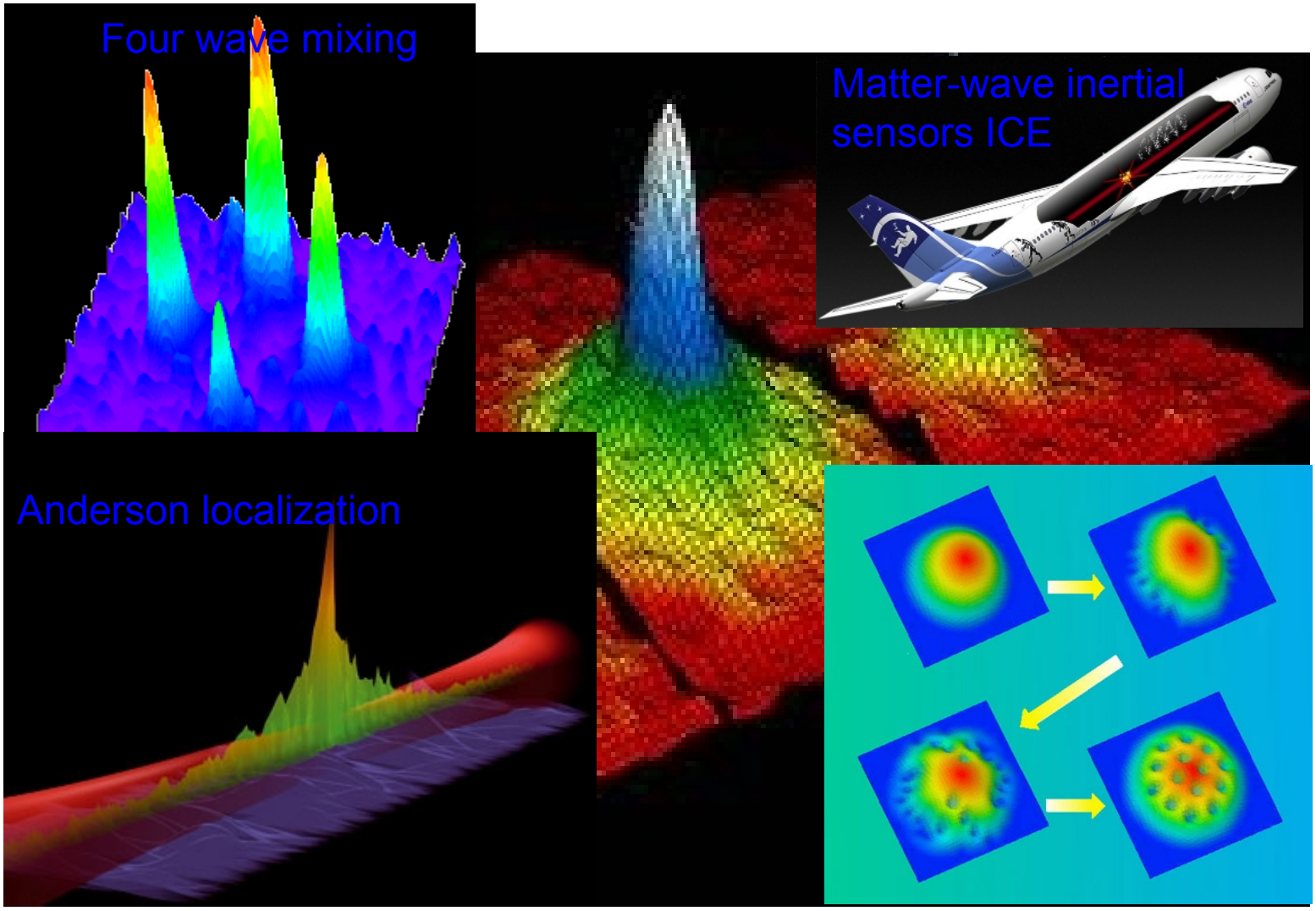

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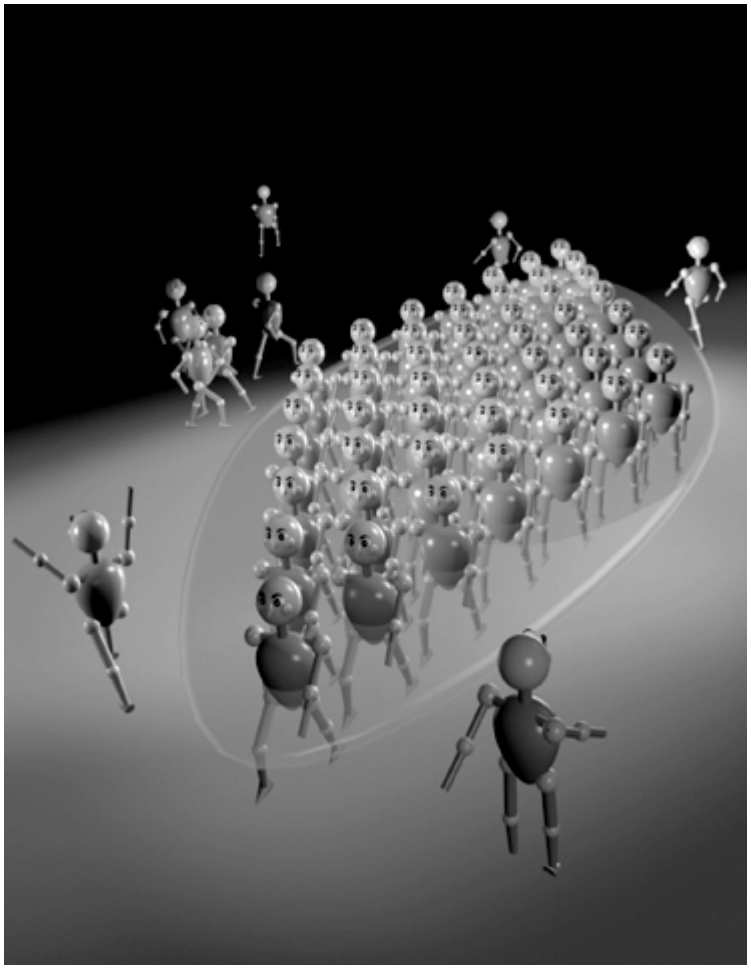


System:

Bose-Einstein condensate and Bogoliubov excitations

All atoms in the same state → The vacuum of Bogoliubov excitations.

At t=0 $$H = \sum_k \hbar \omega_k b_k^\dagger b_k$$

with,

$$\omega_k = \sqrt{\frac{\hbar k^2}{2m}\left(\frac{\hbar k^2}{2m} + 2\mu\right)}$$

$$\mu = mc^2$$

↓

Speed of sound in the condensate

System:

Bose-Einstein condensate and Bogoliubov excitations

Chemical potential modulation → optical index of refraction in a cavity

Analogy to the modulation of an

$$\mu(t) = \mu_0 + \delta\mu(t)$$

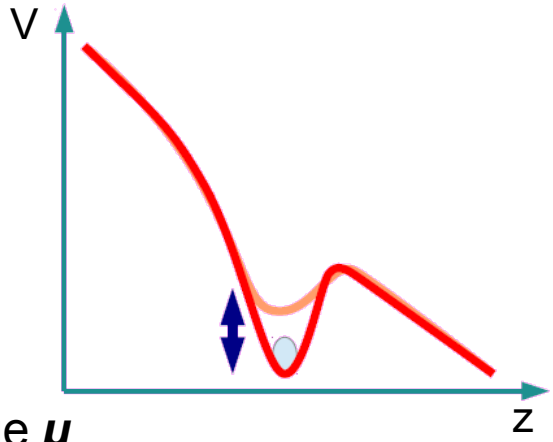
$$H = H_0 + \frac{\delta\mu(t)}{2} \sum \left(u_k + v_k\right)^2 \times \left(b_k^\dagger + b_{-k}\right)\left(b_k + b_{-k}^\dagger\right)$$

Production of pairs of phonons

Carusotto et al. *EPJD* **56**, 391 (2010)

Realization of the experiment:

How do we change μ?



$$\mu(t) = \frac{4\pi\hbar^2 a}{m} n(t)$$

By changing the density of our cloud we can change μ

A change in the power of the optical dipole trap (ODP), can change the density

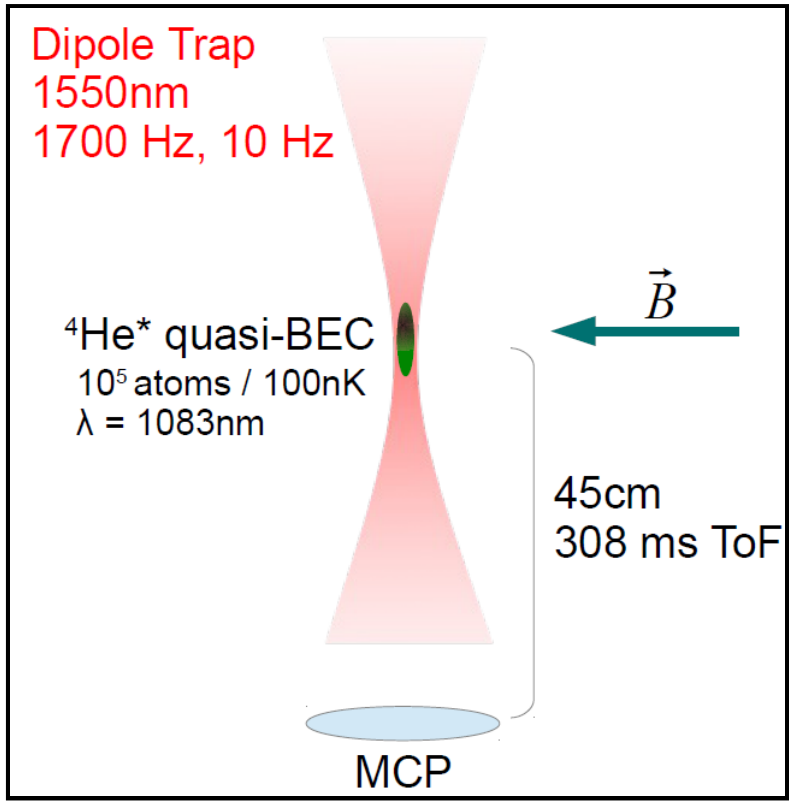
Sudden re-compression of the trap

Modulation of the trap

Experimental Setup

Red detuned light → Attractive force to the maximum of intensity → Increase of the density

Evaporative cooling → We lose atoms with higher energy



Experimental Setup:

The detection & Micro Channel Plate (MCP)

^{4}He* -> internal energy of **20 eV**

Single particle detection:

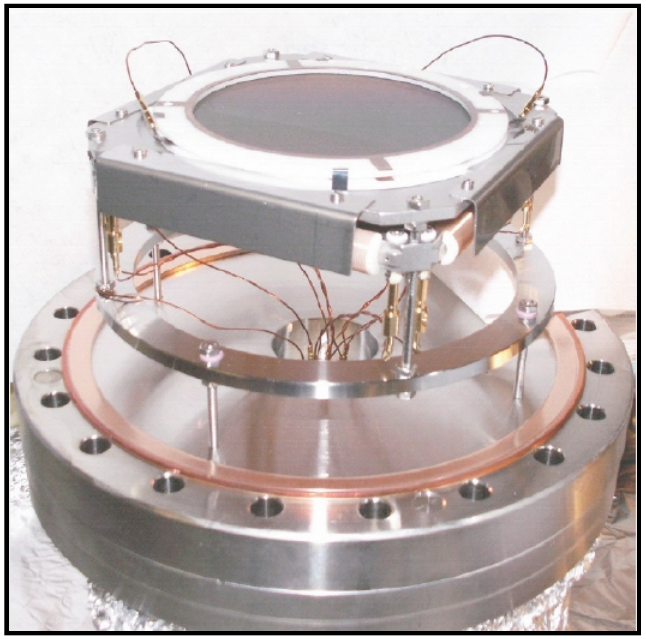
Low noise

Quantum efficiency ~12 %

3D reconstruction:

300 μm resolution on horizontal plane

20 ns (~60 nm) resolution on the vertical axis.



MCP and delay line

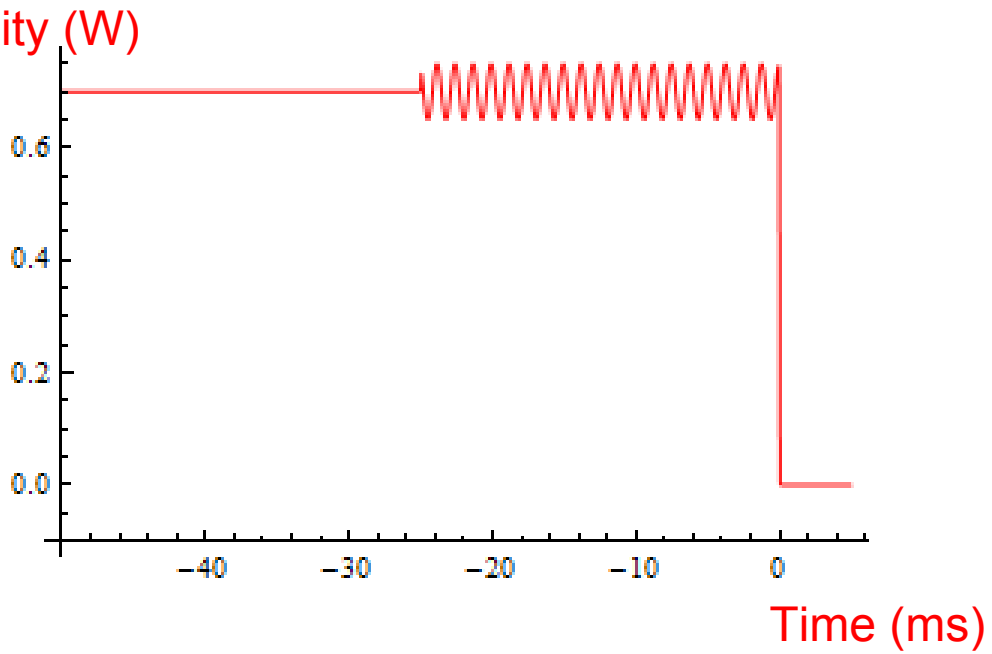
Realization of the experiment:

Modulation of the trap

Modulation of the laser intensity of about 15 % for ~ 20 ms.

$\omega_{mod} \approx 2\pi \times 0.9 - 5$ kHz

In our process, momentum must be conserved -> $k_2 = -k_1$.



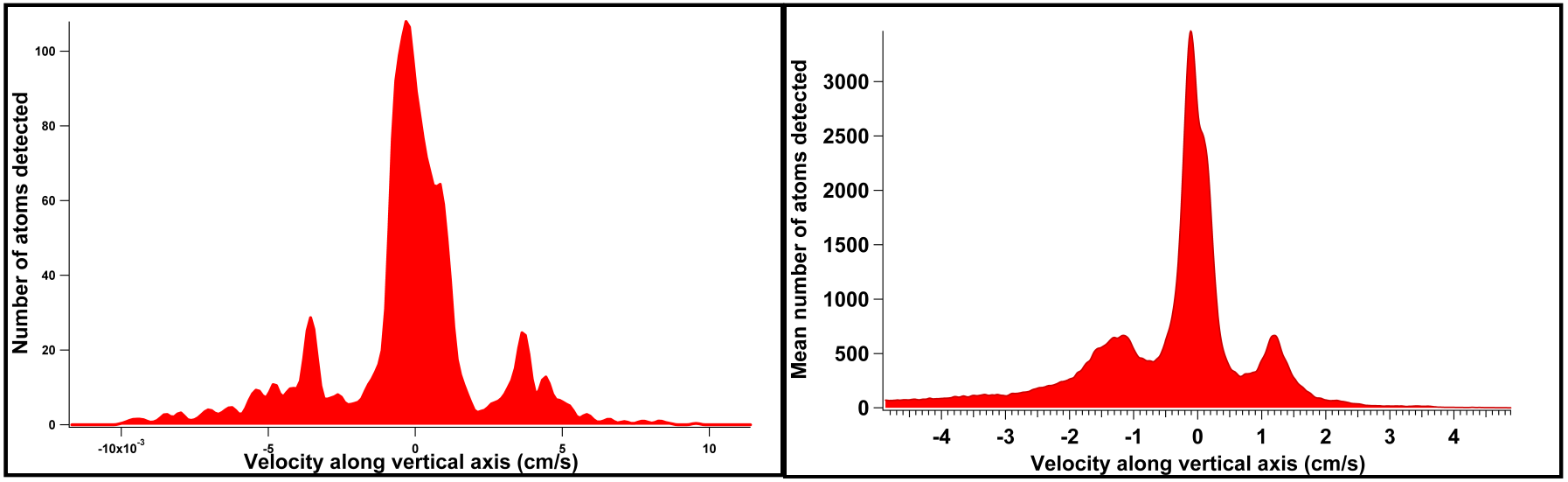
Engels, P. & Atherton, C. *Phys.Rev.Lett.* **98**, 095301 (2007)

Realization of the experiment:

Modulation of the trap

Example of data after TOF for ω_{mod} = 2.5 kHz

Averaged over ~2000 shots

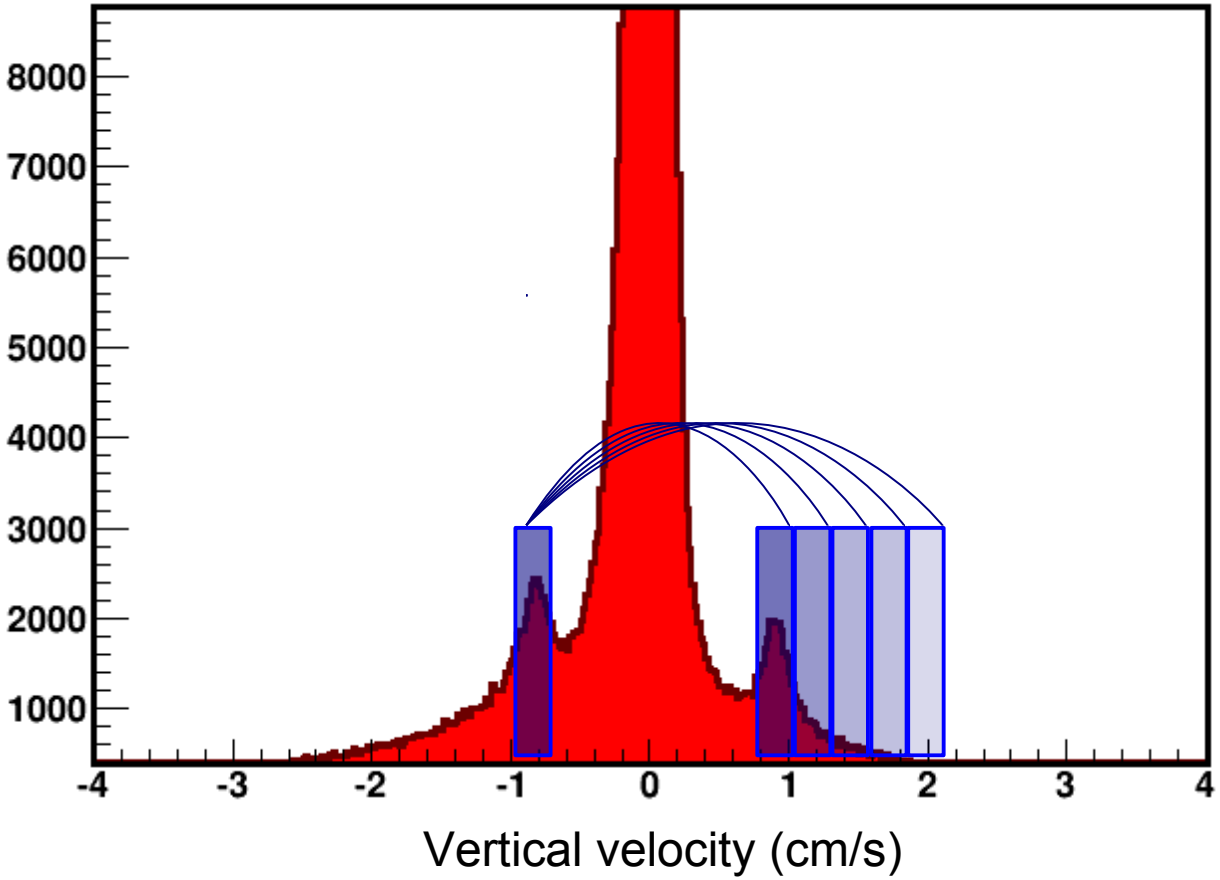


J-C. Jaskula et al. Phys. Rev. Lett. 109, 220401 (2012)

Realization of the experiment:

Modulation of the trap

two-body correlation function

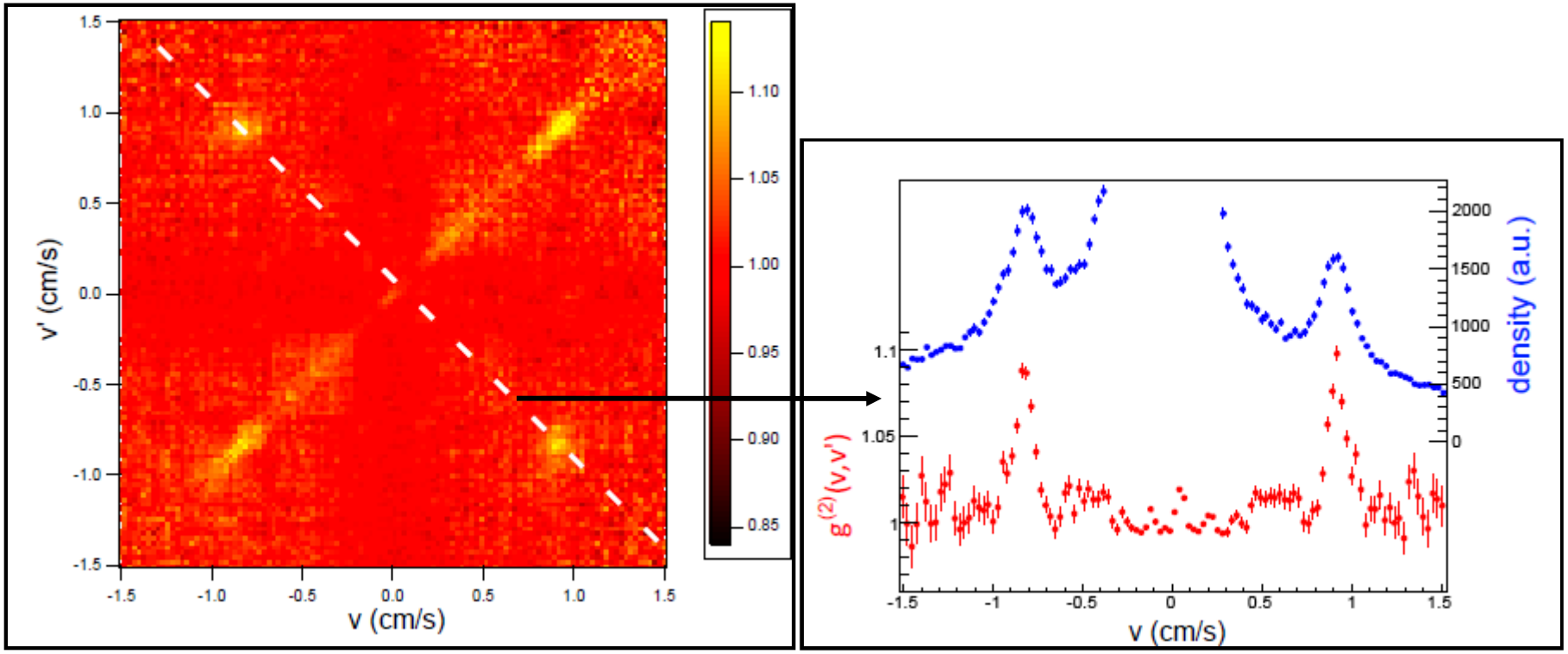


$$g^{(2)}(v,v') = \frac{\langle n_v n_{v'} \rangle}{\langle n_v \rangle \langle n_{v'} \rangle}$$

Realization of the experiment:

Modulation of the trap

two-body correlation function



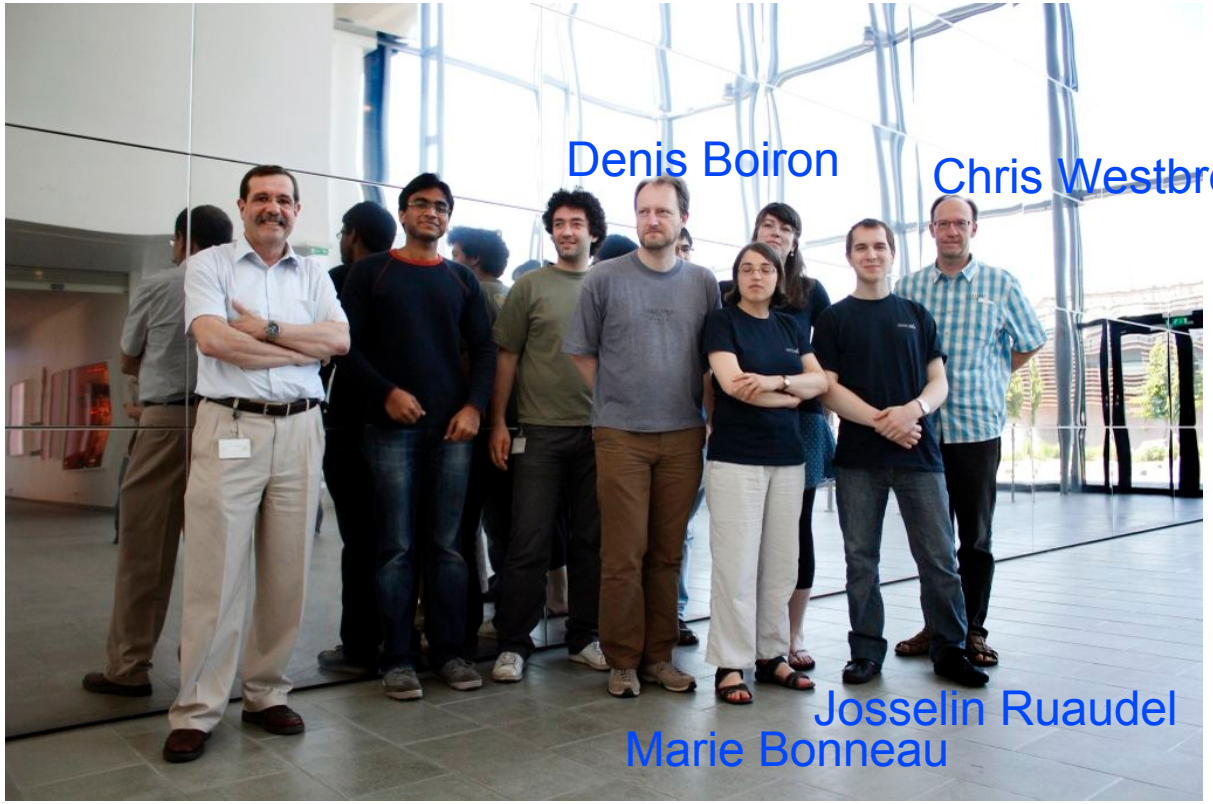
J-C. Jaskula et al. Phys. Rev. Lett. 109, 220401 (2012)

Conclusions

- We demonstrated creation of pairs of phonon but not really from vacuum, since (T>0K);

- Next step: Sub-Poissonian distribution for the difference atomic population between the two peaks will prove the quantum nature of the process. We modified the experiment and expect to have new results soon.

Thank you for your attention

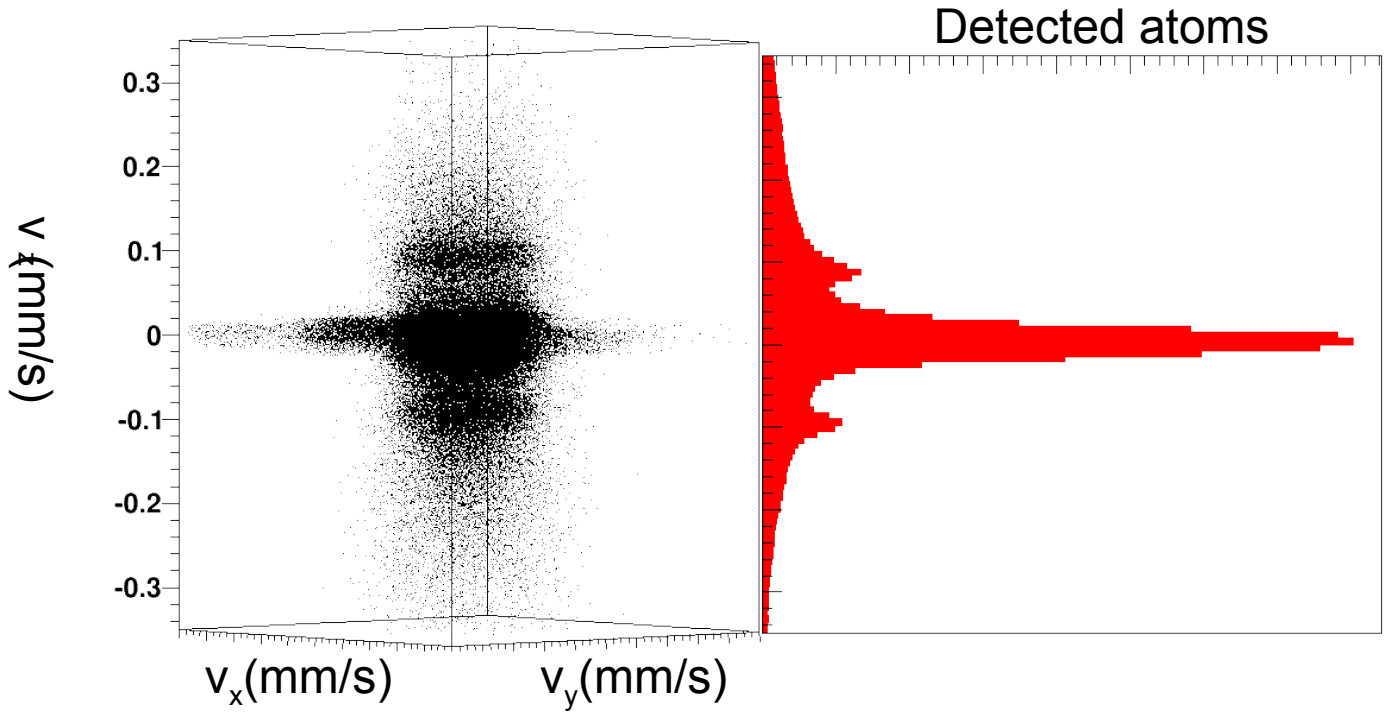


J-C Jaskula

G. Partridge

Realization of the experiment:

Modulation of the trap

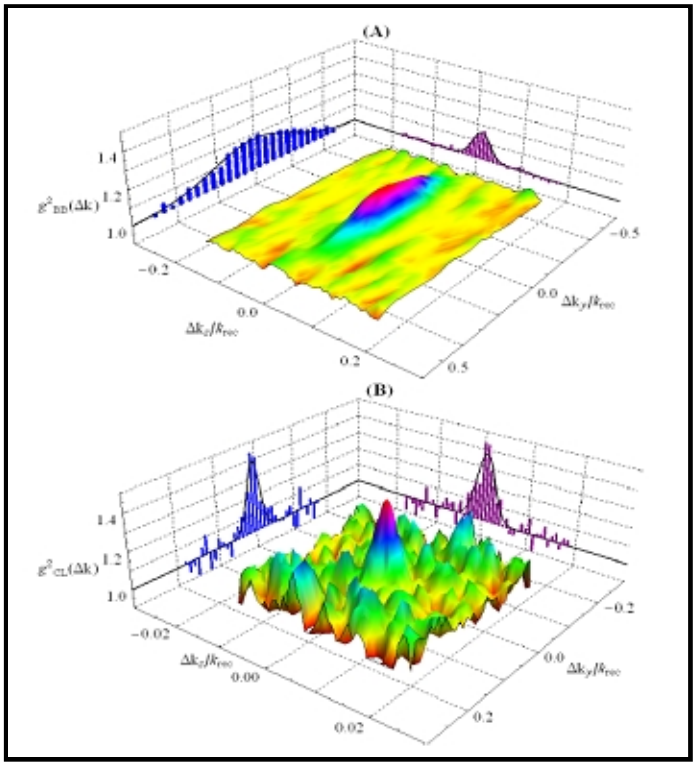


Experimental Setup:

The detection & Micro Channel Plate (MCP)

This detection gives us nice images but also the possibility to study second order correlations

$$g^{(2)}(v,v') = \frac{\langle n_v n_{v'} \rangle}{\langle n_v \rangle \langle n_{v'} \rangle}$$



K.V. Kherunstyan Phys. Rev. Lett. 108, 260401 (2012)

Analogy to DCE with matter waves:

Theory in this context, Bogoliubov excitations

To take into account quantum fluctuations about the state in which all the atoms are condensed in a single quantum state one can write:

$$\hat{\psi}(\vec{r}) = \psi(\vec{r}) + \delta$$

$$\psi(\vec{r}) = \sqrt{N_0} V^{-1/2}$$

Describe the ground state of the system and treated as a classical field

The Hamiltonian can than be written in terms of single particle operators

$$\mu = \frac{4\pi\hbar^2 a}{m} n(\vec{r}=0)$$

Chemical potential

General idea of the experimental realization

Shake shake shake

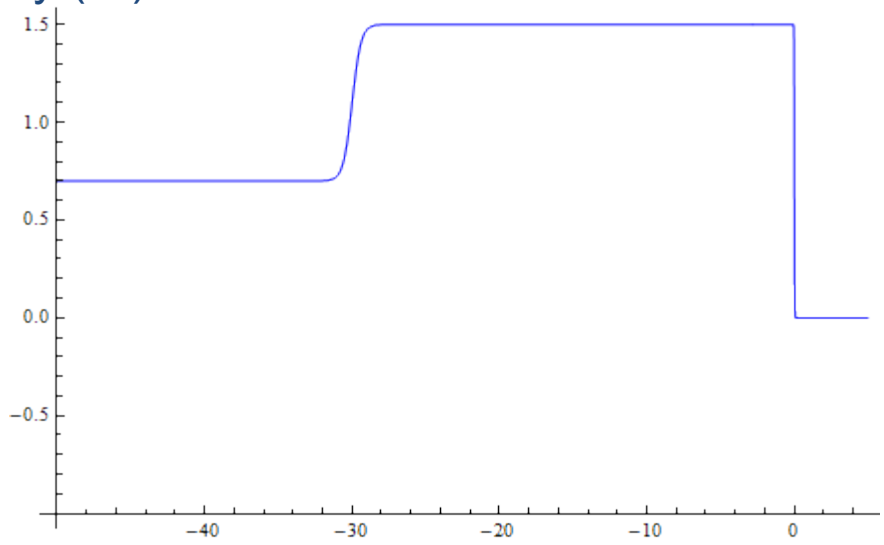
A.V. Dodonov Phys. Scr. 87, 038103 (2013)

Realization of the experiment:

Sudden re-compression

Sudden increase (factor 2) of the power of the ODP in ~ 30 μs and hold for ~30 ms

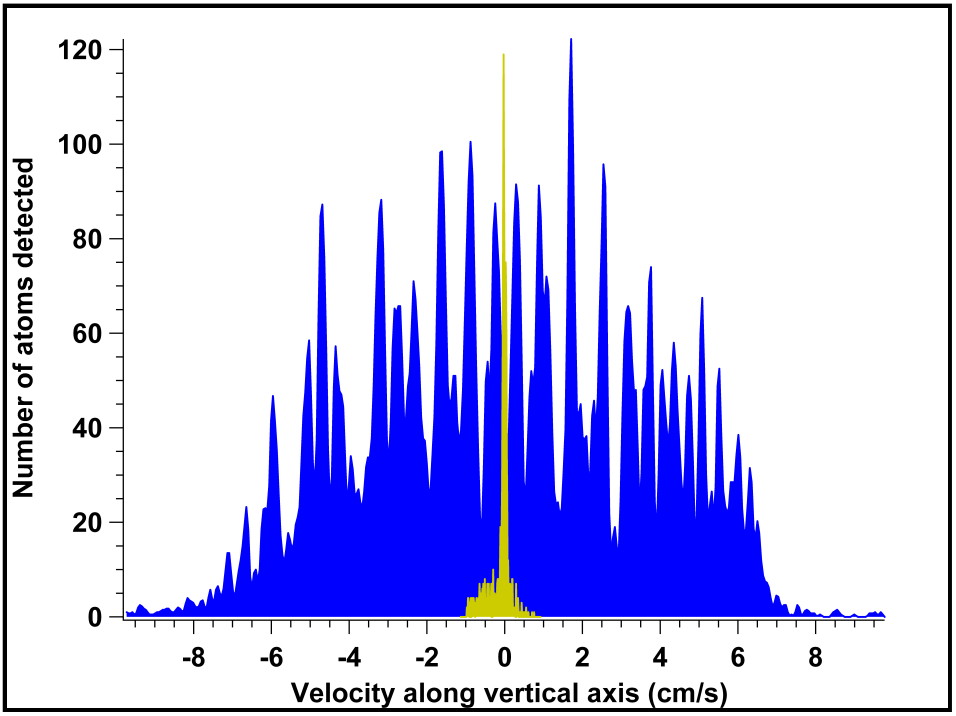
Laser intensity (W)

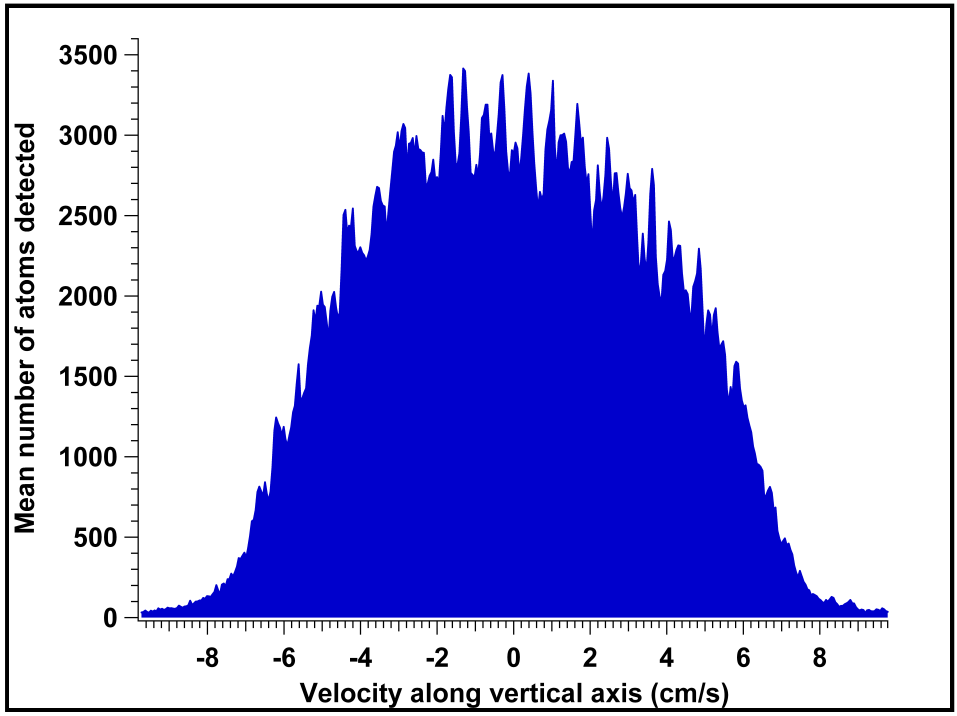


Time (ms)

Realization of the experiment:

Sudden re-compression

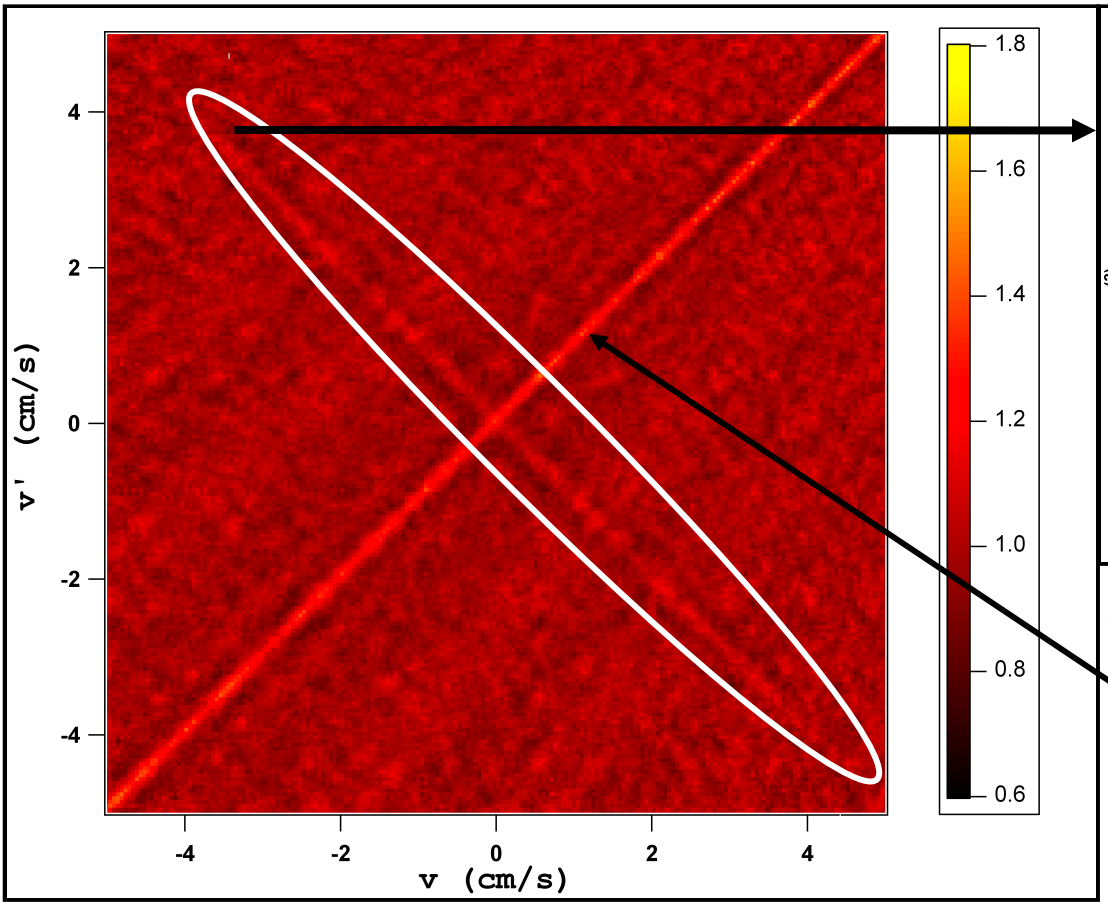


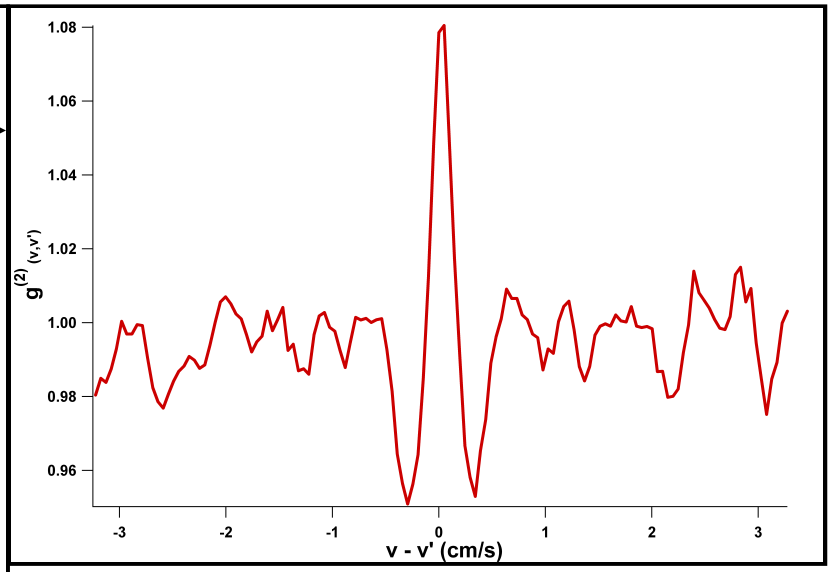


Realization of the experiment:

Sudden re-compression

2nd order correlation function





J-C. Jaskula et al. Phys. Rev. Lett. 109, 220401 (2012)

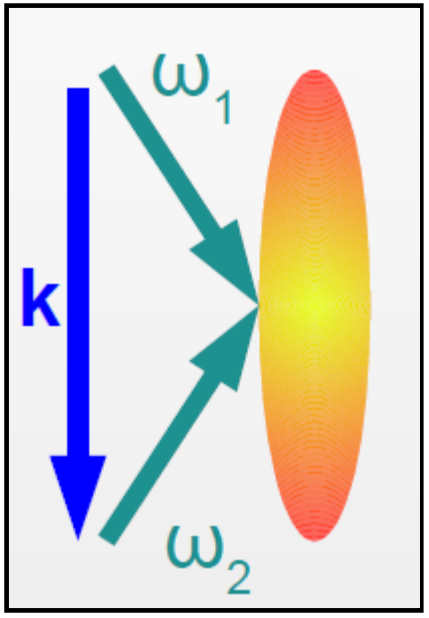
Hambury Brown and Twiss effect

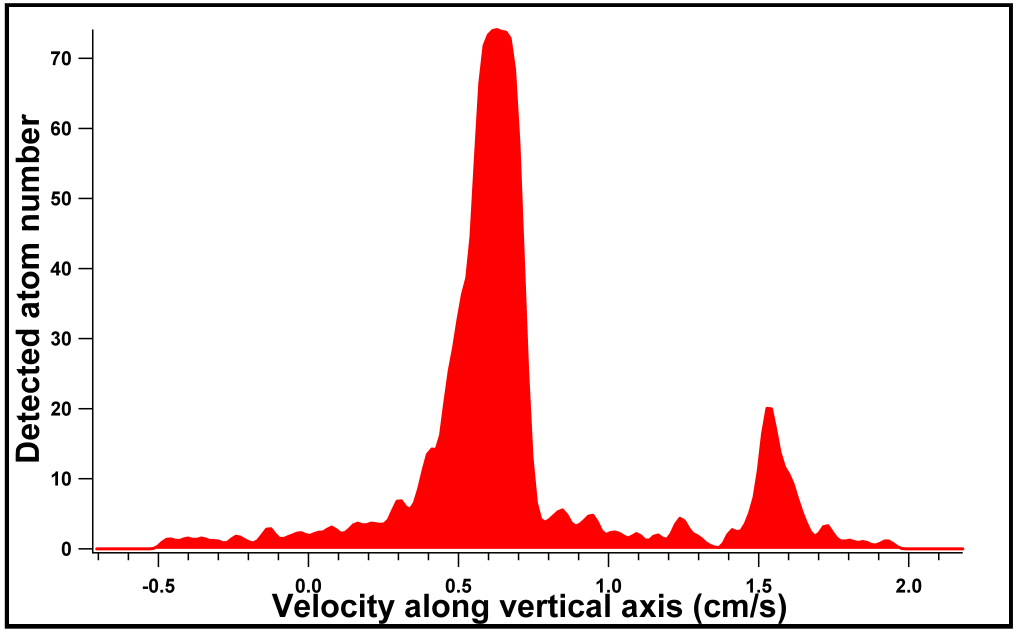
M.Schellekens et al., Science 310 (2005)

Realization of the experiment:

Modulation of the trap

Bragg spectroscopy





J. Steinhaueur & al., *Phys. Rev. Lett.* 88, 120407 (2002)

Realization of the experiment:

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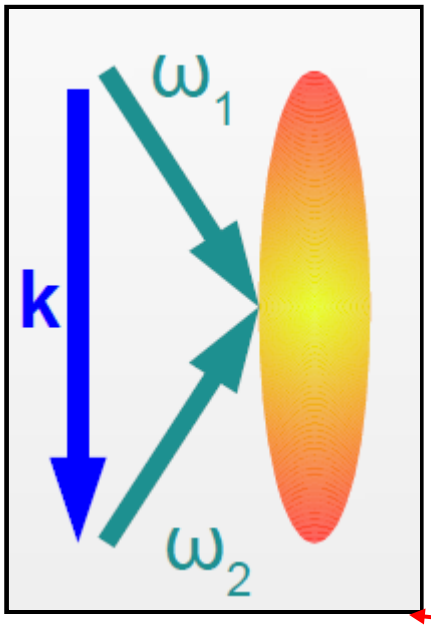
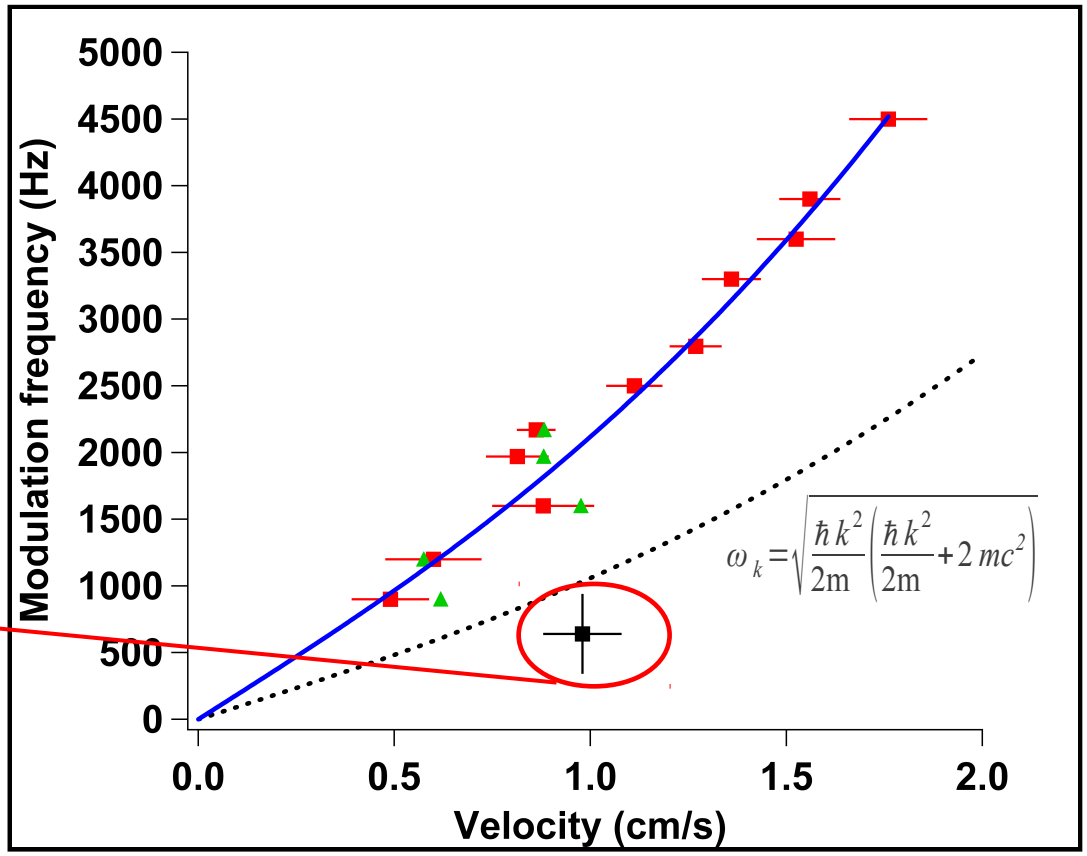


Value obtained by
Bragg spectroscopy

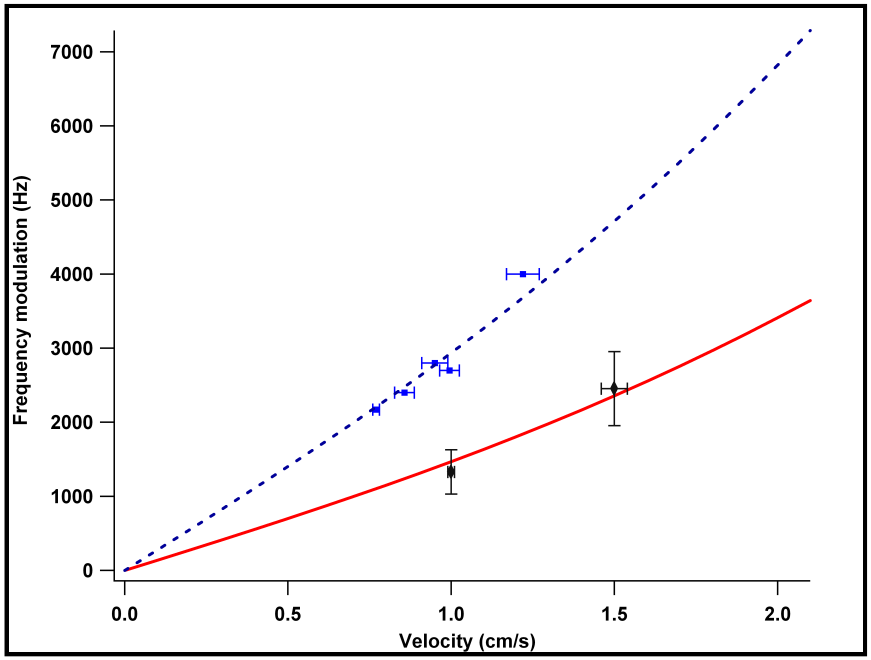


Realization of the experiment:

Modulation of the trap

Dispersion relation

For a different density we obtain by Bragg spectroscopy c=0.75 cm/s and α = 2,02+/- 0.1



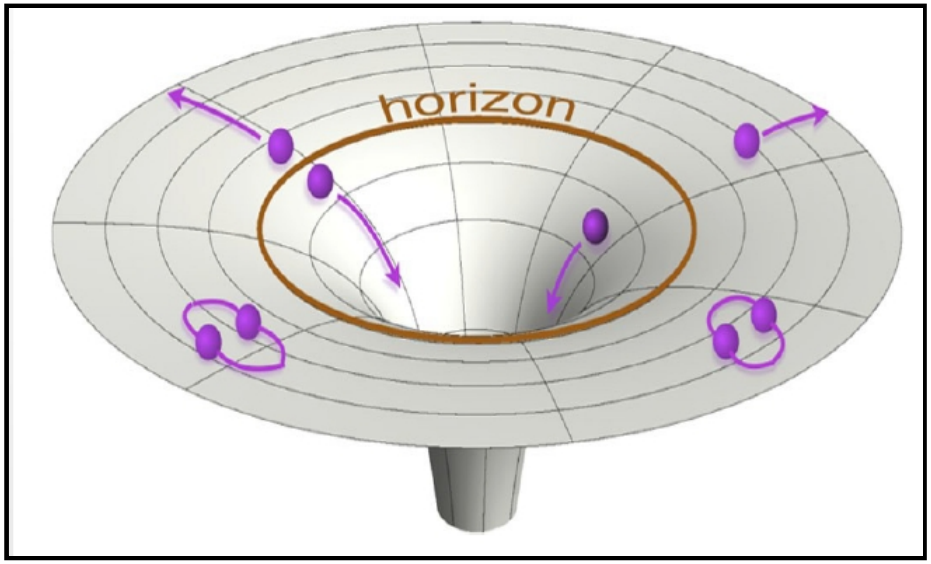
New way to determine the sound velocity of a condensate

Perspectives

Hawking radiation

Near the horizon of a black hole:

The particle of negative energy “falls” in the black hole. For an external observer the black hole seems to radiate particles, photons.



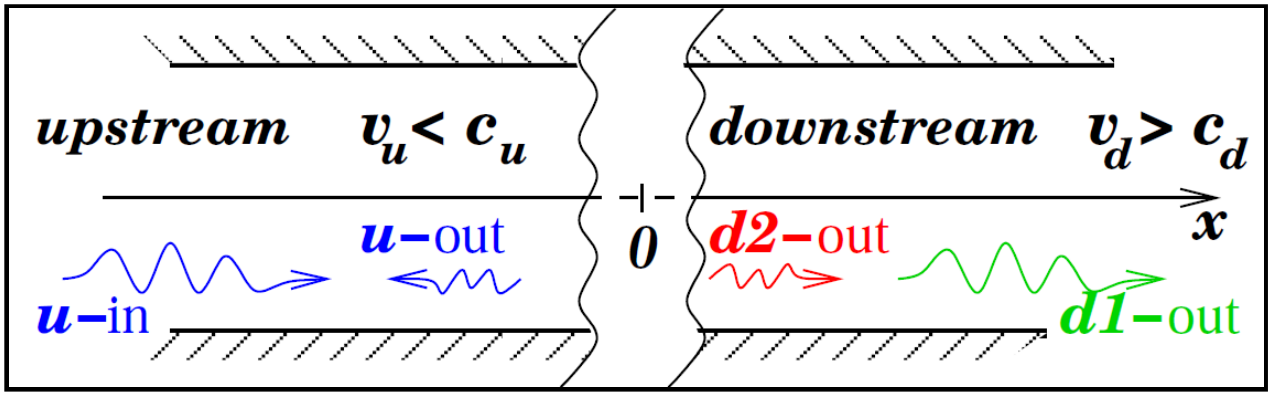
P. Nation & al. *Rev. Mod. Phys.* **84**, 1 (2012)

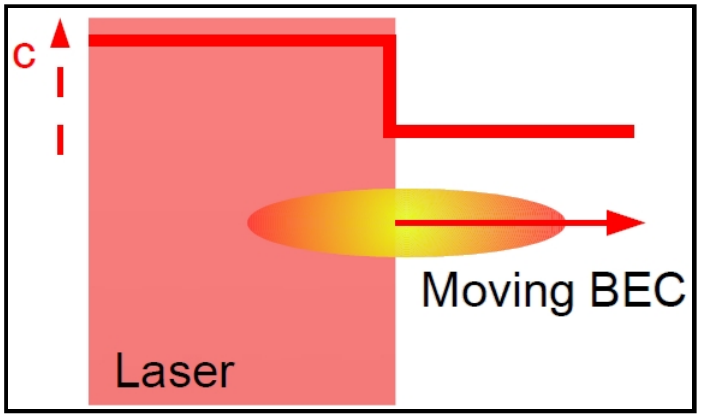
Hawking, S. W. *Nature*, **248** (5443):30 (1974)

Perspectives

Hawking radiation

An analog model: dumb hole





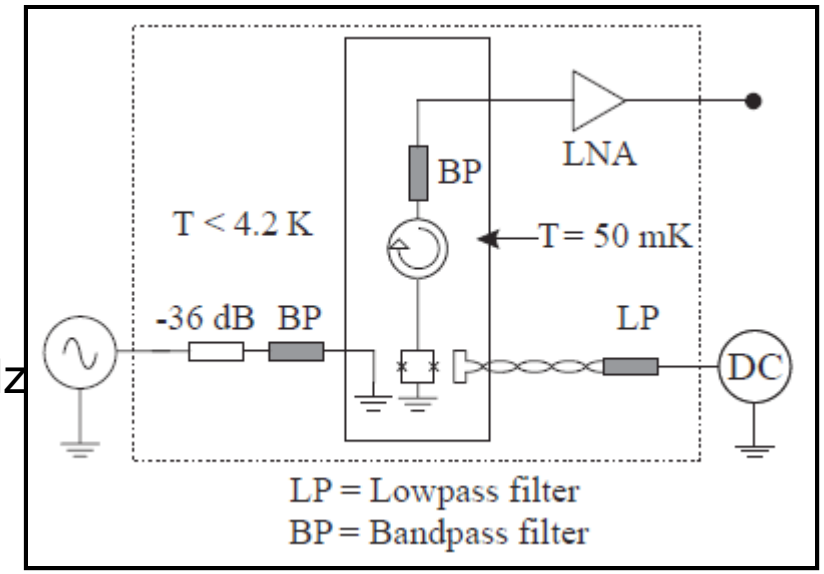
Recati & al. *Phys.Rev. A.*, **80**, 043603 (2009)

Lahav & al. *Phys. Rev. Lett.*, **105**, 240401 (2010)

Dynamical effects due to vacuum fluctuations:

The dynamical Casimir effect

DCE



Drive :

$\omega = 2\pi \times 10$ GHz

Output analysed at

$\omega_1 = \omega + \Delta$

$\omega_2 = \omega - \Delta$

2 Josephson junctions at 50 mK

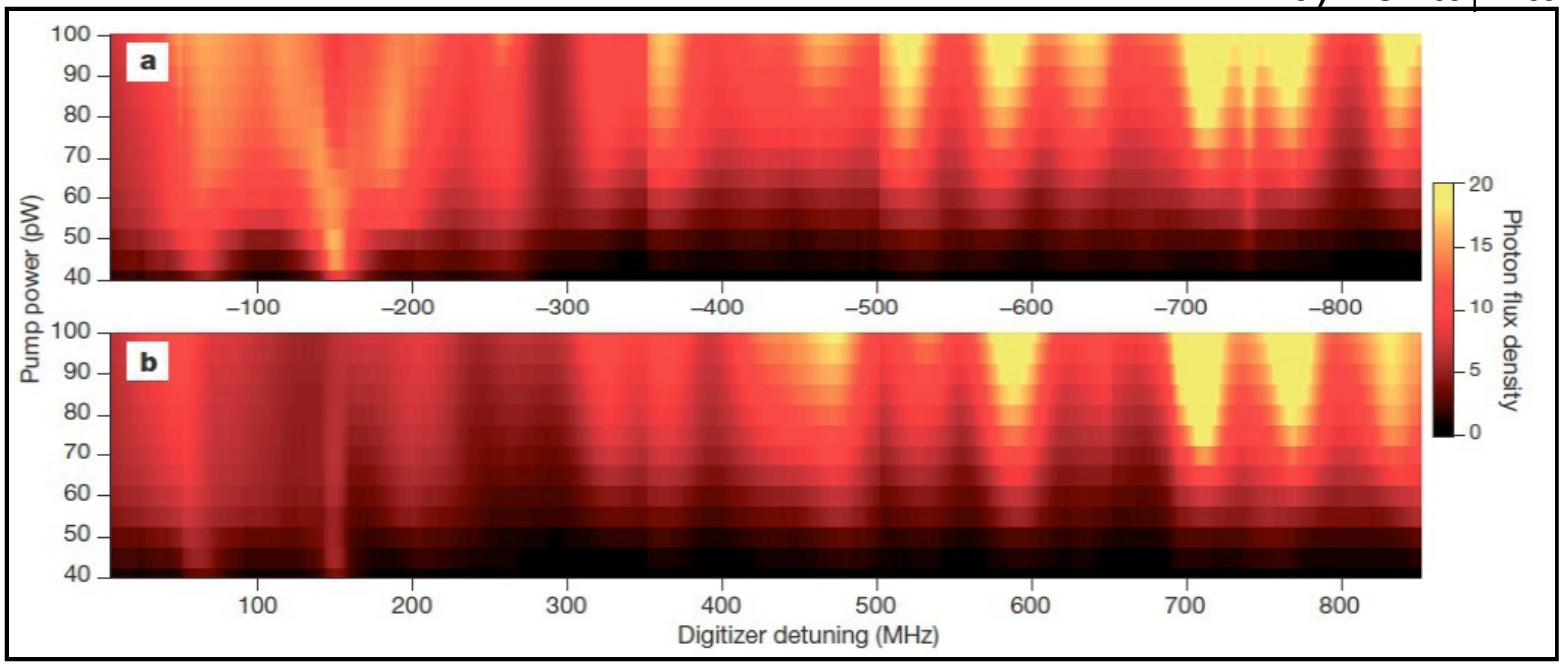
Wilson & al. ***Nature* 479**, 376 (2011)

Dynamical effects due to vacuum fluctuations:

The dynamical Casimir effect DCE

a) For $\omega_2 = \omega - \Delta$

b) For $\omega_1 = \omega + \Delta$

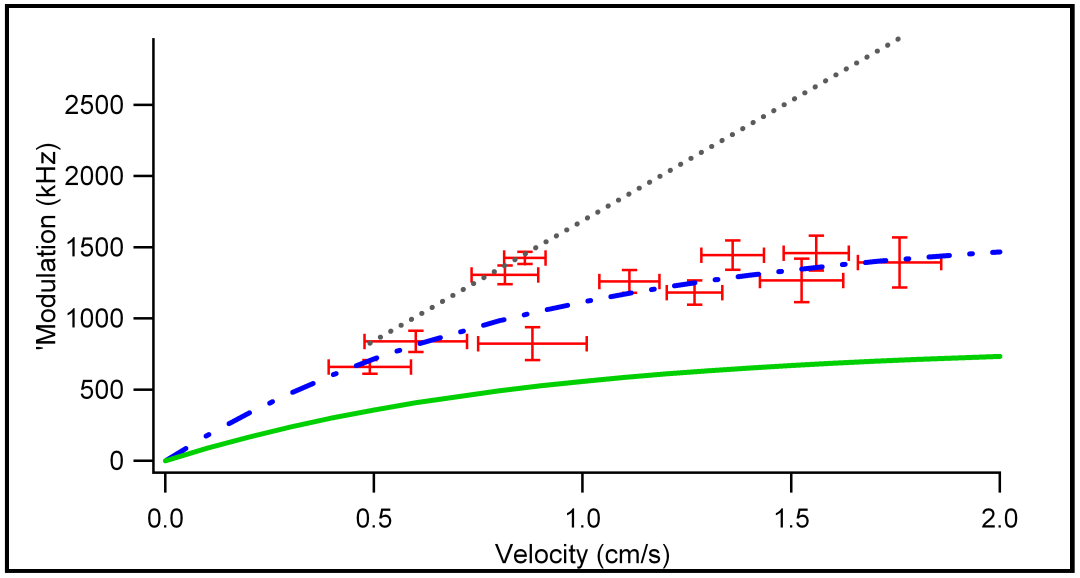


Realization of the experiment:

Modulation of the trap

Dispersion relation

$$\omega_k * \alpha \sqrt{\frac{\hbar k^2}{2m}\left(\frac{\hbar k^2}{2m} + 2mc^2\right)} - \alpha \frac{\hbar k^2}{2m}$$



Realization of the experiment:

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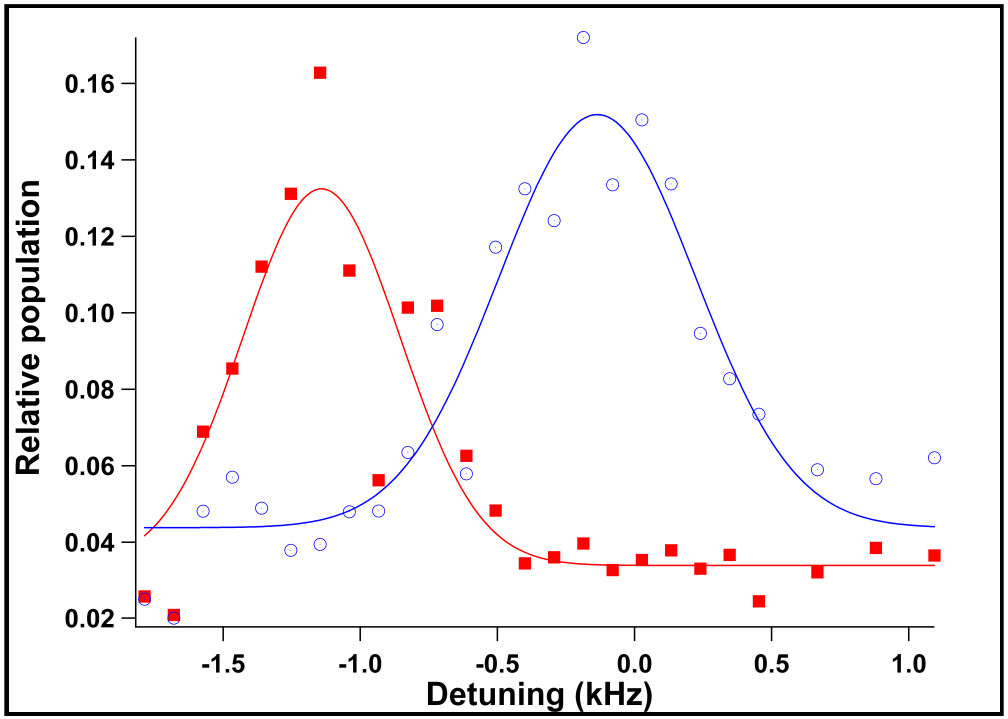

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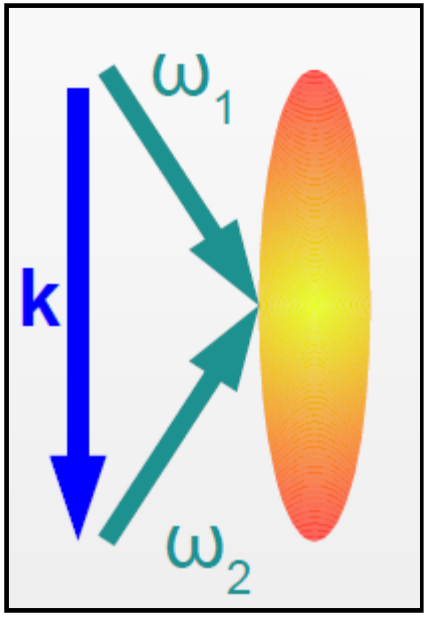

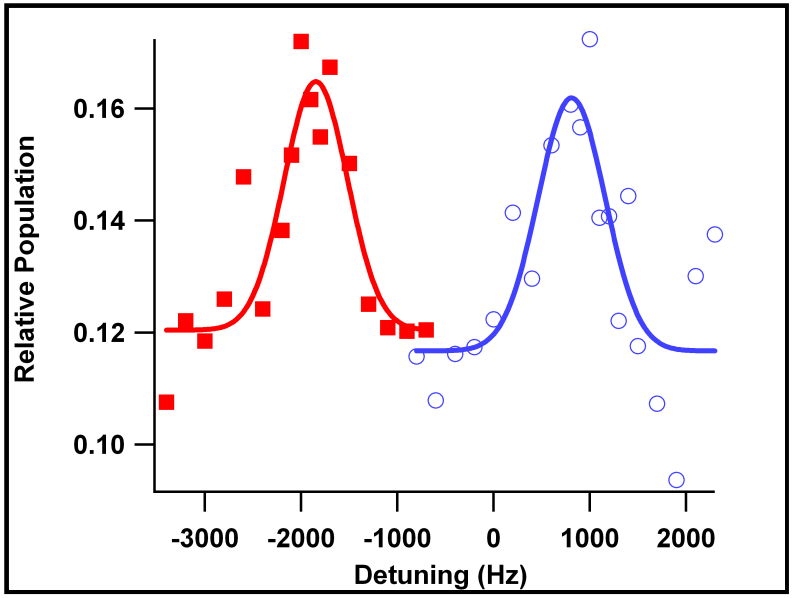

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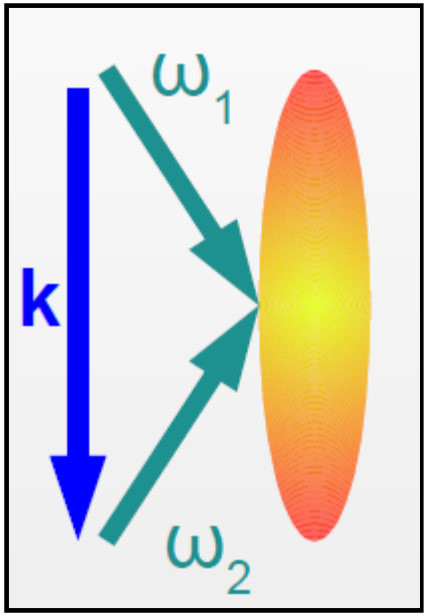
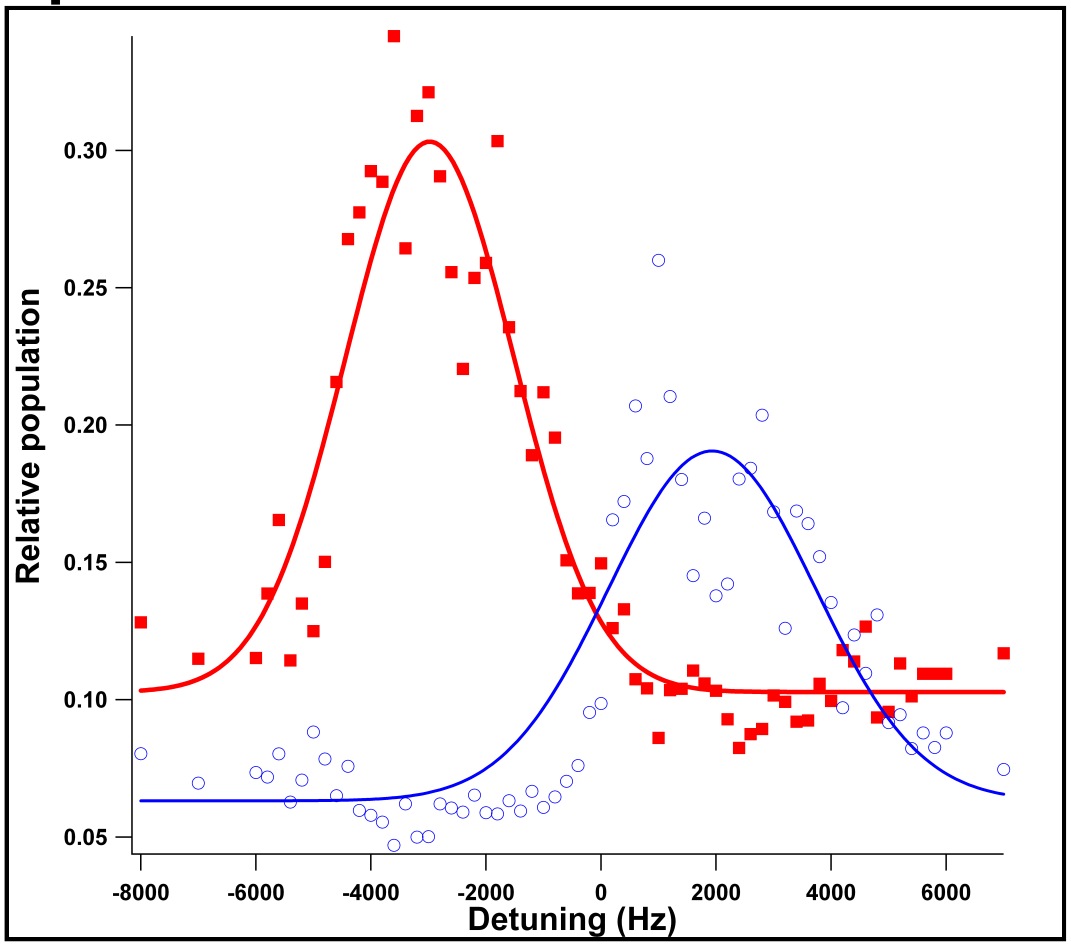
Dispersion relation

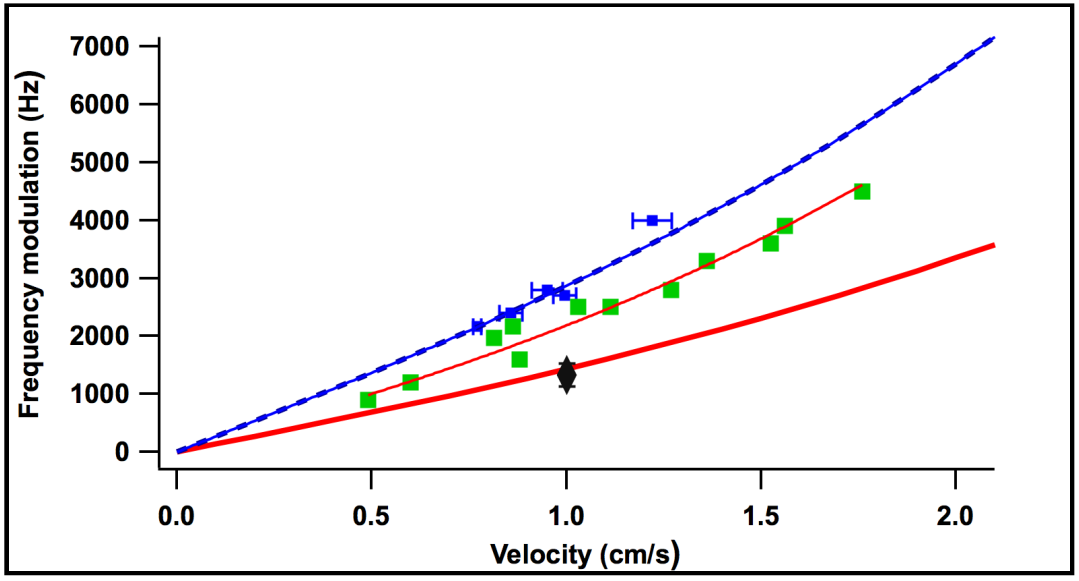
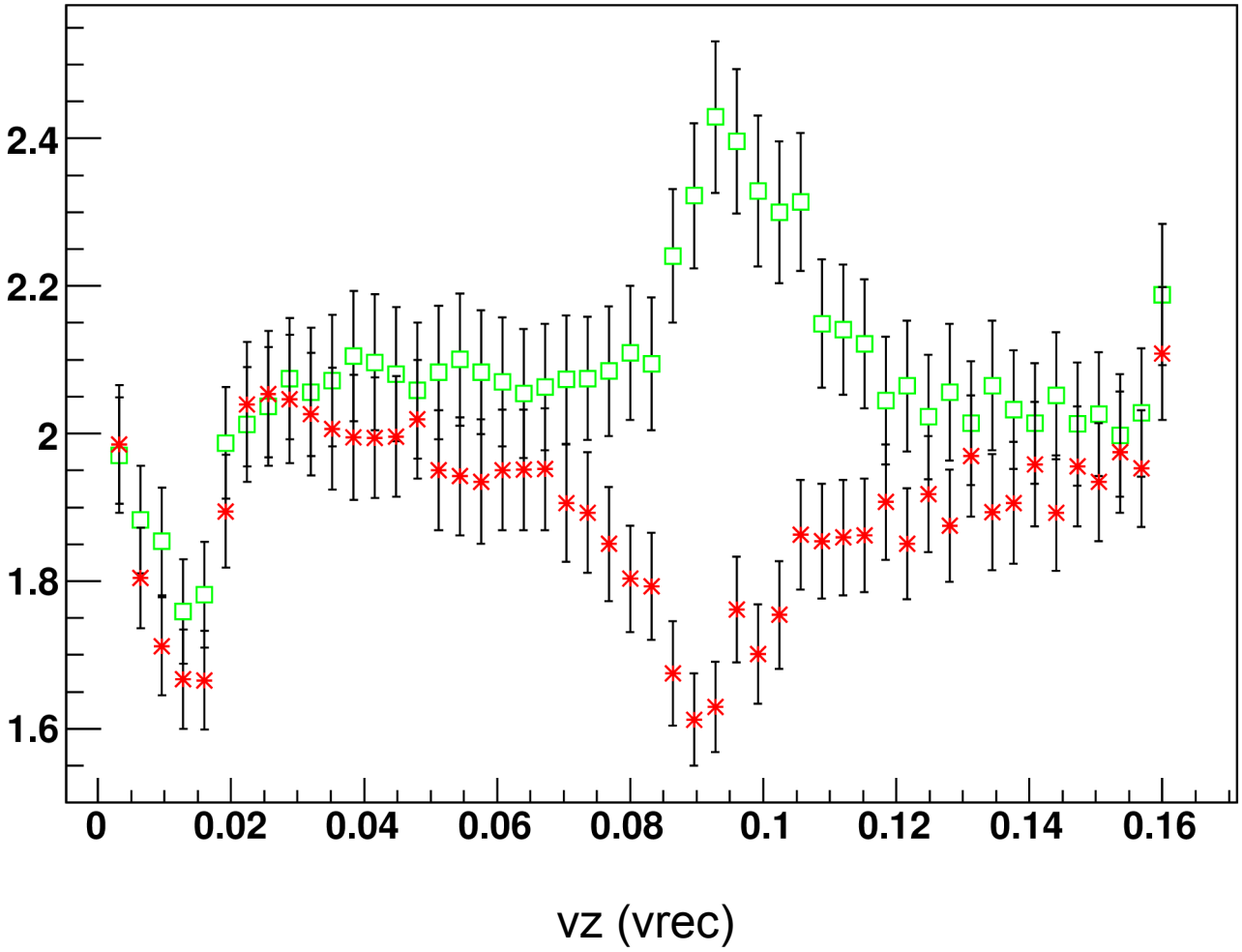




Realization of the experiment:

Modulation of the trap

Dispersion relation



Squeezing for k_1=0.85 v_{rec}