The dynamical Casimir effect in a BEC
or
Parametric downconversion of phonons
or
Cosmological particle production in the lab

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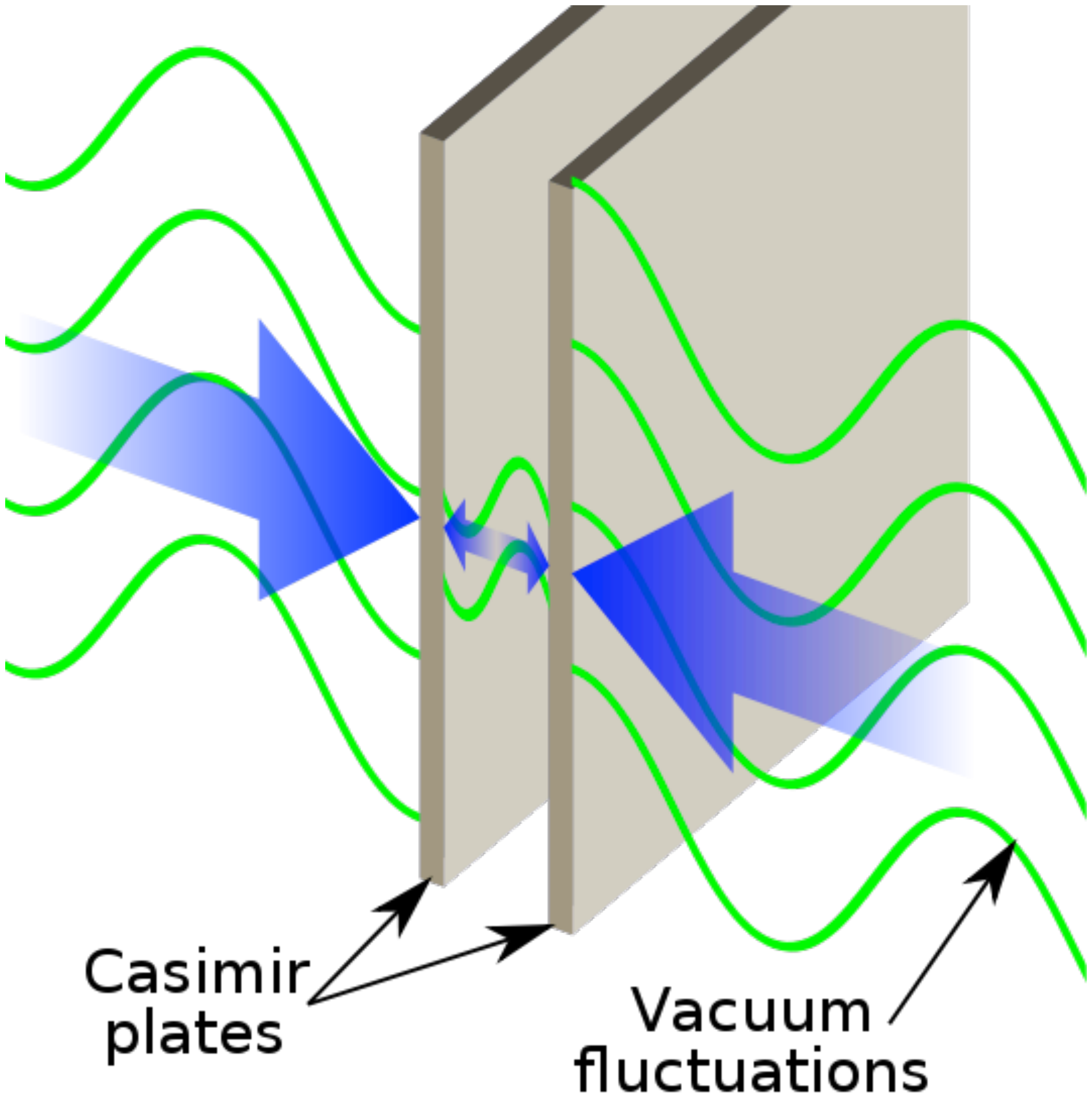
12 september 2012

What to say?

- Electrodynamics
  - The Casimir effect
  - What is “dynamical”?
- Acoustic analogs
  - Black holes in water
  - **BEC**
- Black holes and BEC

Jaskula et al. arXiv:1207.1338

The Casimir effect



An attractive force between two conducting plates:

$$F_{\mathrm{Cas}} = \frac{\hbar c \pi^2 A}{240 L^4}$$

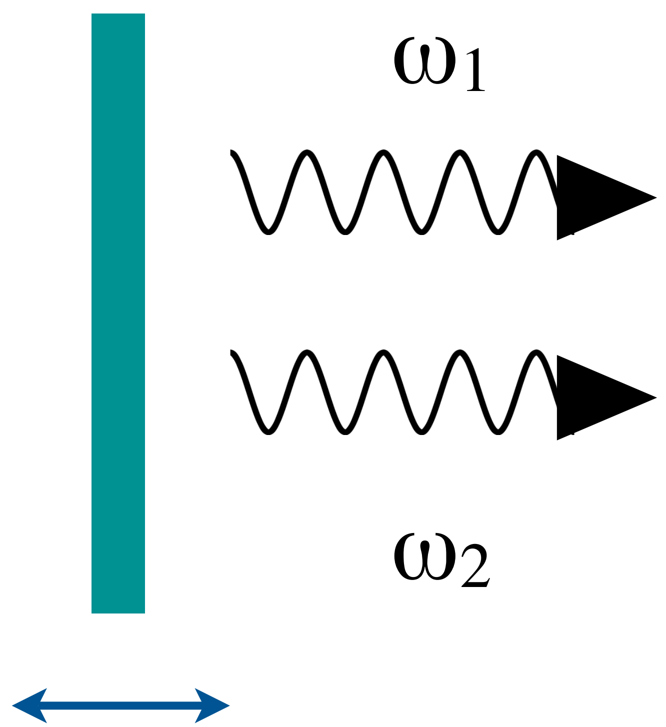
Can be thought of as originating from vacuum fluctuations.

(Almost) macroscopic effect containing $\hbar$ and c

H.B.G. Casimir, Proc. K. Ned. Akad. Wet. 51 (1948) 793.
A. Lambrecht, “A force from nothing”, Physics World 15, 29 (2002).

The "Dynamical" Casimir effect

Radiation of an accelerated mirror:



$v = v_0 \cos \omega t$

real photon pairs with

$\omega_1 + \omega_2 = \omega$

also looks like parametric down conversion

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)

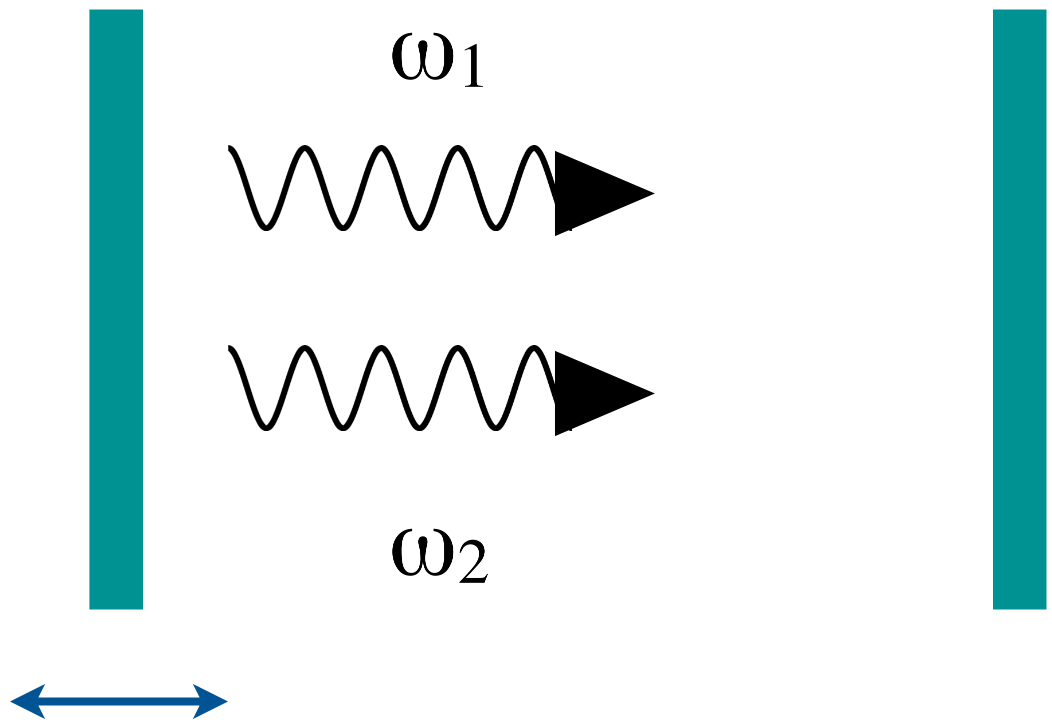
...

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

Understanding the effect

1. Friction of the vacuum. An accelerated mirror experiences a damping force when interacting with vacuum fluctuations. The energy is radiated as photons - in pairs
Kardar and Golestanian, Rev Mod Phys 71 1233 (1999)

2. Particle production accompanies any sudden modification of the boundary conditions of a quantum field.



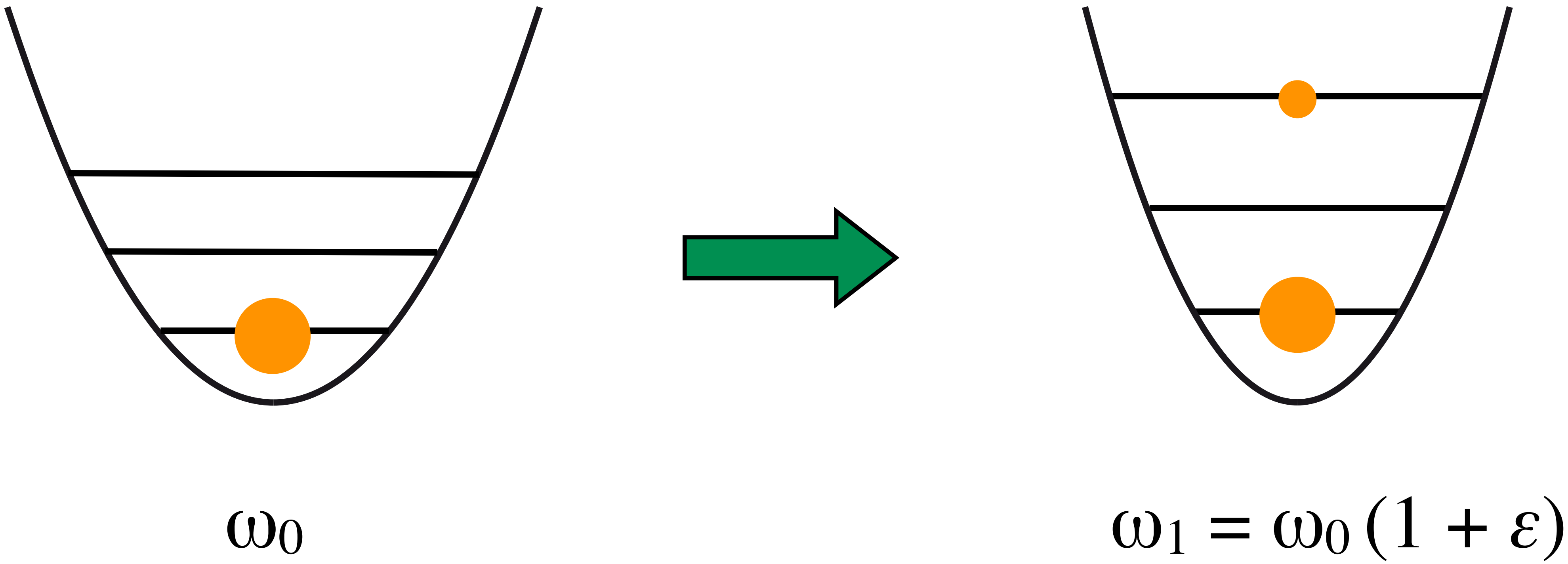
$v = v_0 \cos \omega t$

$$N_{\text{photons}} \sim \omega\tau \left(\frac{v}{c}\right)^2 \frac{1}{T}$$

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

Toy model: single mode

Parametrically driven quantum harmonic oscillator



A sudden change in stiffness projects the ground state onto a superposition of $n = 0$ and $n = 2$ (+ higher order even modes) → pairs (squeezed vacuum)

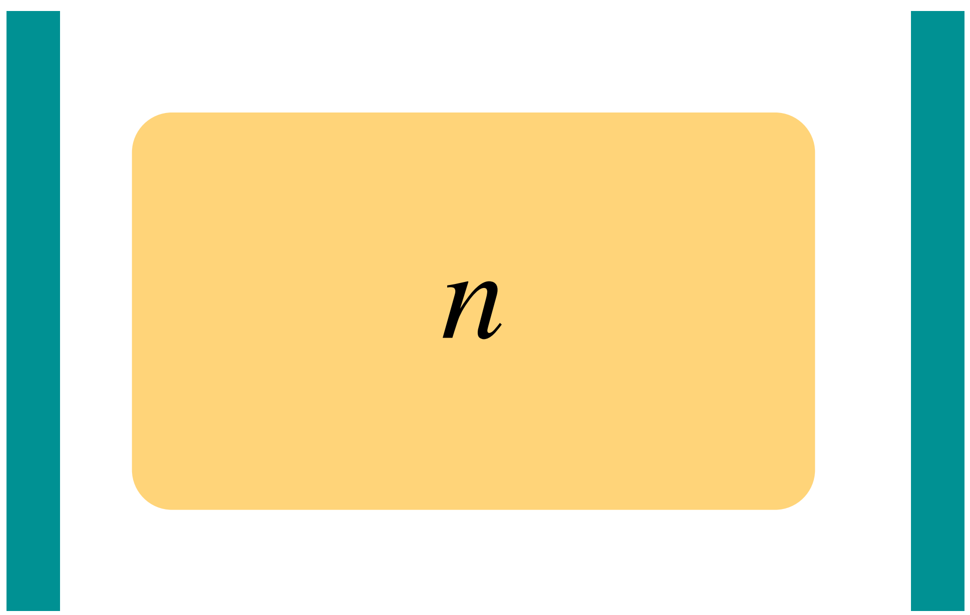
$$H \sim a_0 a_1^\dagger a_2^\dagger + h.c.$$

Without motion: changing the speed of light

VOLUME 62, NUMBER 15 PHYSICAL REVIEW LETTERS 10 APRIL 1989

Accelerating Reference Frame for Electromagnetic Waves in a Rapidly Growing Plasma: Unruh-Davies-Fulling-DeWitt Radiation and the Nonadiabatic Casimir Effect

E. Yablonovitch
Bell Communications Research, Navesink Research Center, Red Bank, New Jersey 07701-7040
(Received 6 July 1988)

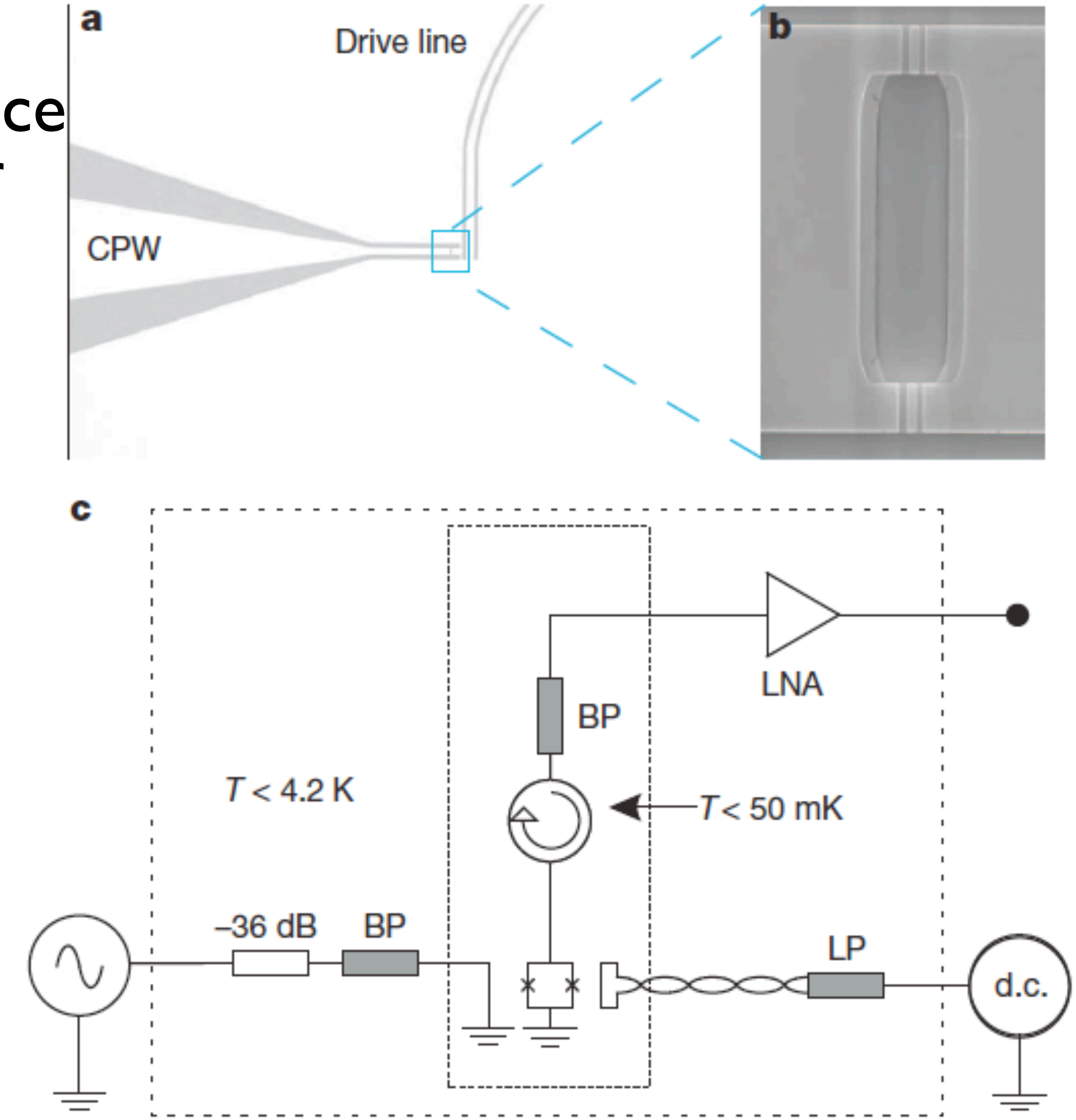


$$n(t)^2 = 1 + (\omega_p(t)/\omega)^2$$

1. Change plasma frequency Yablonovitch PRL 1989
2. Change skin depth in a semiconductor Braggio et al EPL 2005
3. Use a laser induced Kerr effect Dezael, Lambrecht EPL 2010

Experimental observation (Wilson et al. Nature 479, 376 (2011))

Change in B flux changes inductance and the length of transmission line (CPW)



2 Josephson junctions 50 mK

Output analysed at

$\omega_1 = \omega/2 + \Delta$

$\omega_2 = \omega/2 - \Delta$

Drive:

$\omega/2\pi = 10$ GHz

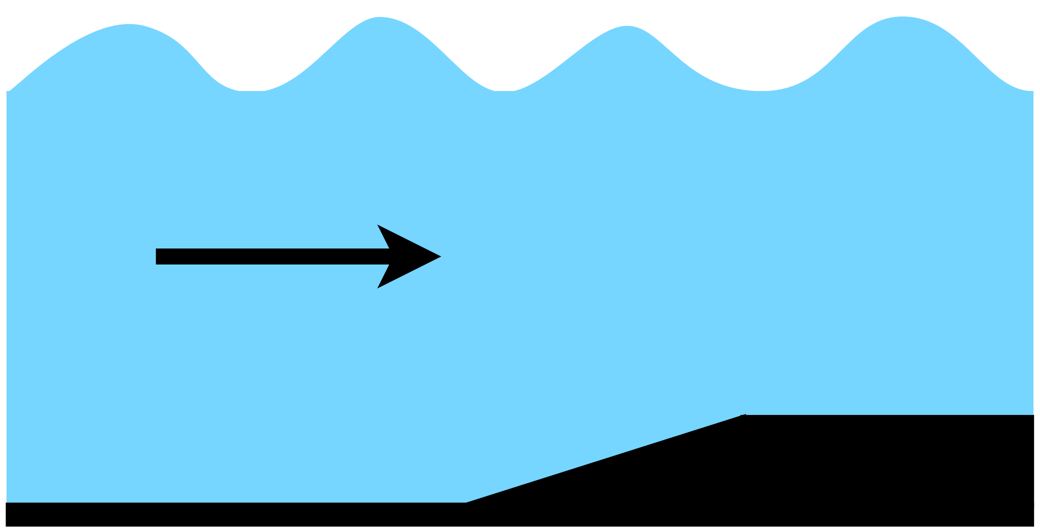
see also Lahteenmaki et al. arXiv:1111.5608

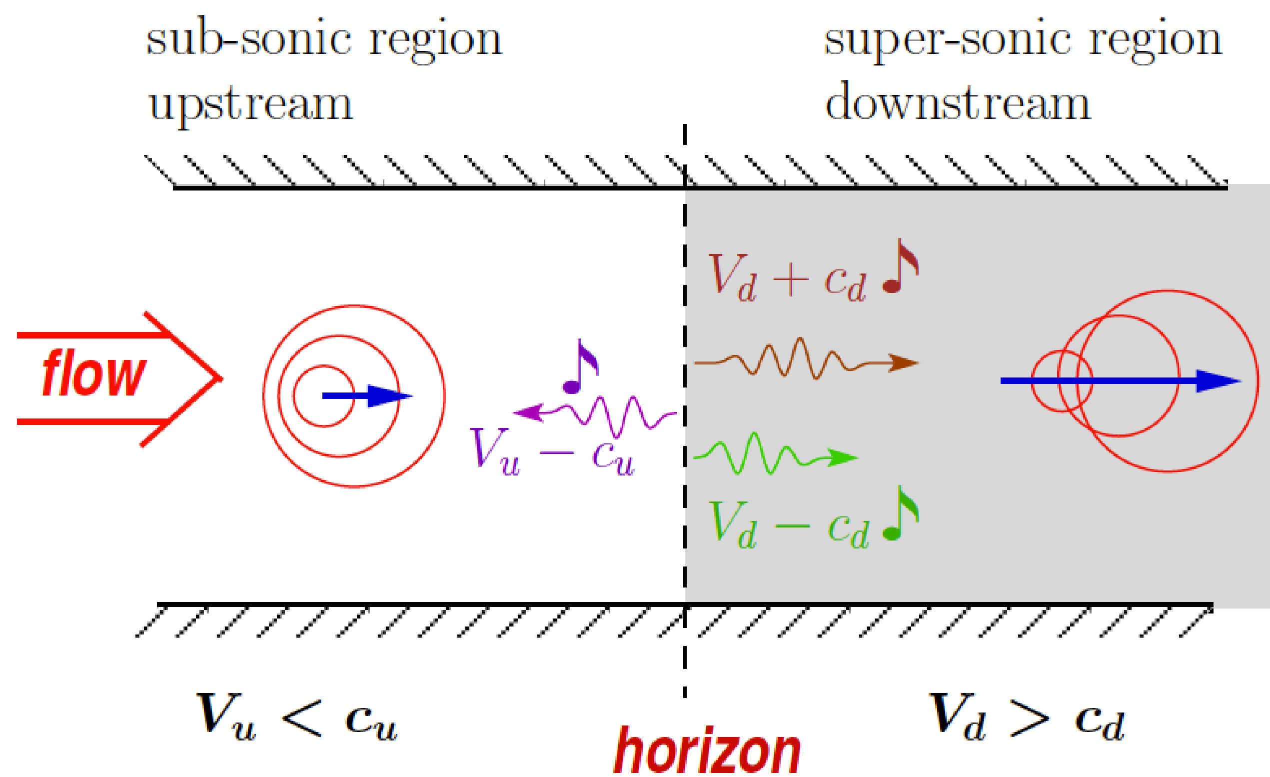
Sonic analog: change the speed of sound (PRL 1981)

Experimental Black-Hole Evaporation?

W. G. Unruh
Department of Physics, University of British Columbia, Vancouver, British Columbia V6T 2A6, Canada
(Received 8 December 1980)

It is shown that the same arguments which lead to black-hole evaporation also predict that a thermal spectrum of sound waves should be given out from the sonic horizon in transsonic fluid flow.





Speed of surface waves relative to flow in a water tank changes. Unruh suggested one could realize a sonic horizon and observe “classical” Hawking radiation Weinfurtner et al. PRL 2011

Dynamical Casimir Gedankeneffekt in water

Suddenly change the depth of the water. Look for spontaneous creation of waves (in pairs). Faraday waves ...

In a BEC, $c^2 \sim \mu/m \sim f\,(N, m, a, \omega)$

Sonic Analog to the Dynamical Casimir Effect

A sudden modification of the boundary conditions for a quantum field can also lead to the spontaneous emission of correlated pairs ...

So,
Modulate the scattering length a,
in a homogenous BEC:

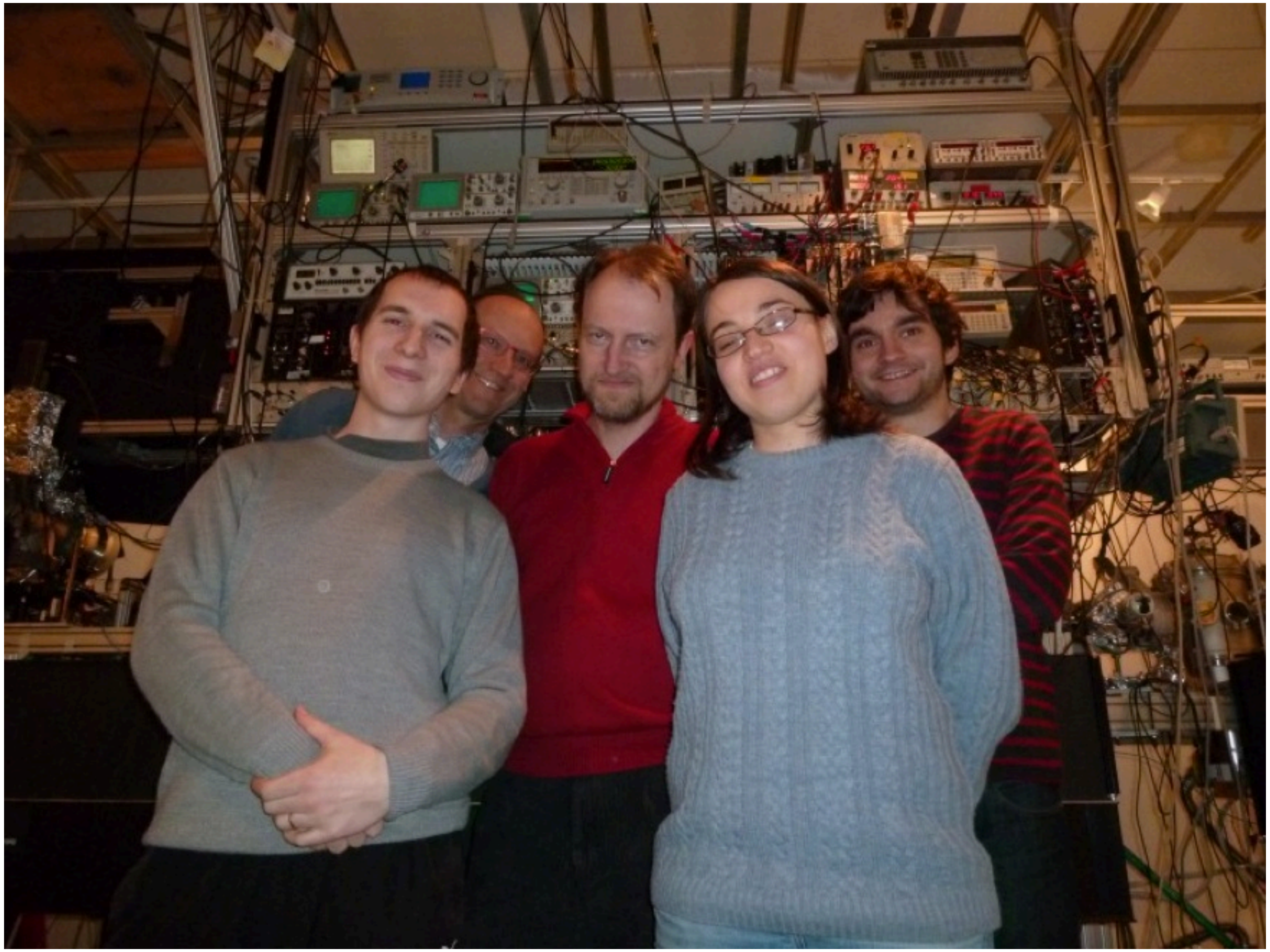
$$a(t) = a_0 + \delta a(t)$$

$$\mathcal{H} = \mathcal{H}_0 + \frac{2\pi\hbar^2 n}{m}\,\delta a(t) \sum_{\mathbf{k}} (u_{\mathbf{k}} + v_{\mathbf{k}})^2 \times \boxed{\left(b_k^\dagger + b_{-k}\right)\left(b_k + b_{-k}^\dagger\right)} \quad (9)$$

Pair creation

Carusotto, Balbinot, Fabbri, Recati, "Density correlations and analog dynamical Casimir emission of Bogoliubov phonons in a modulated atomic BEC", EPJD 56, 391 (2010)

The team (... is looking for a post doc)



Guthrie Partridge

C I W

Denis Boiron

Rafael Lopes

Josselin Ruadel

Marie Bonneau

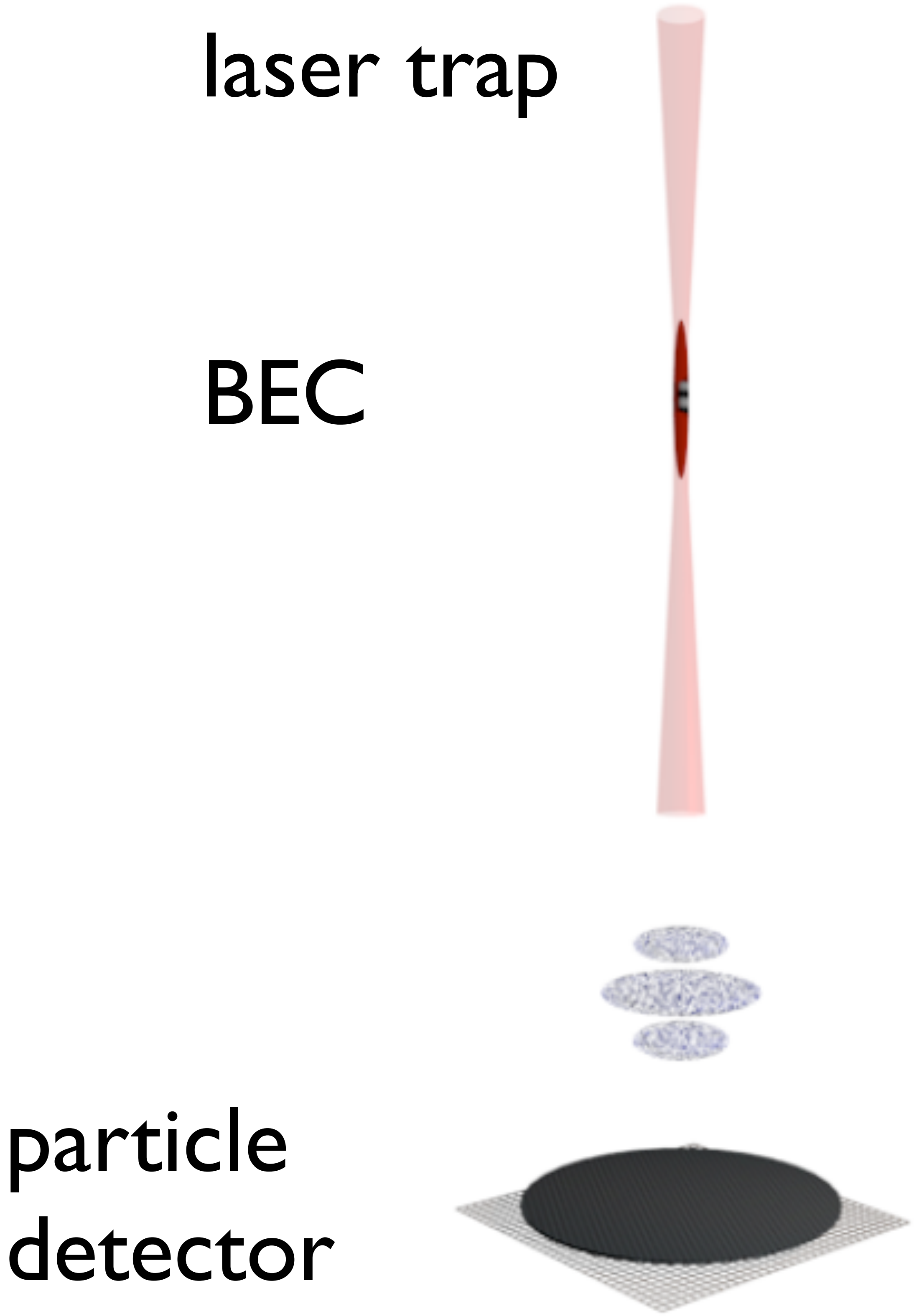
Jean-Christophe Jaskula

Apparatus

Detect atoms in excited cloud of He* in momentum space. Time of flight 307 ms

He*: the 2^3S_1 state
20 eV

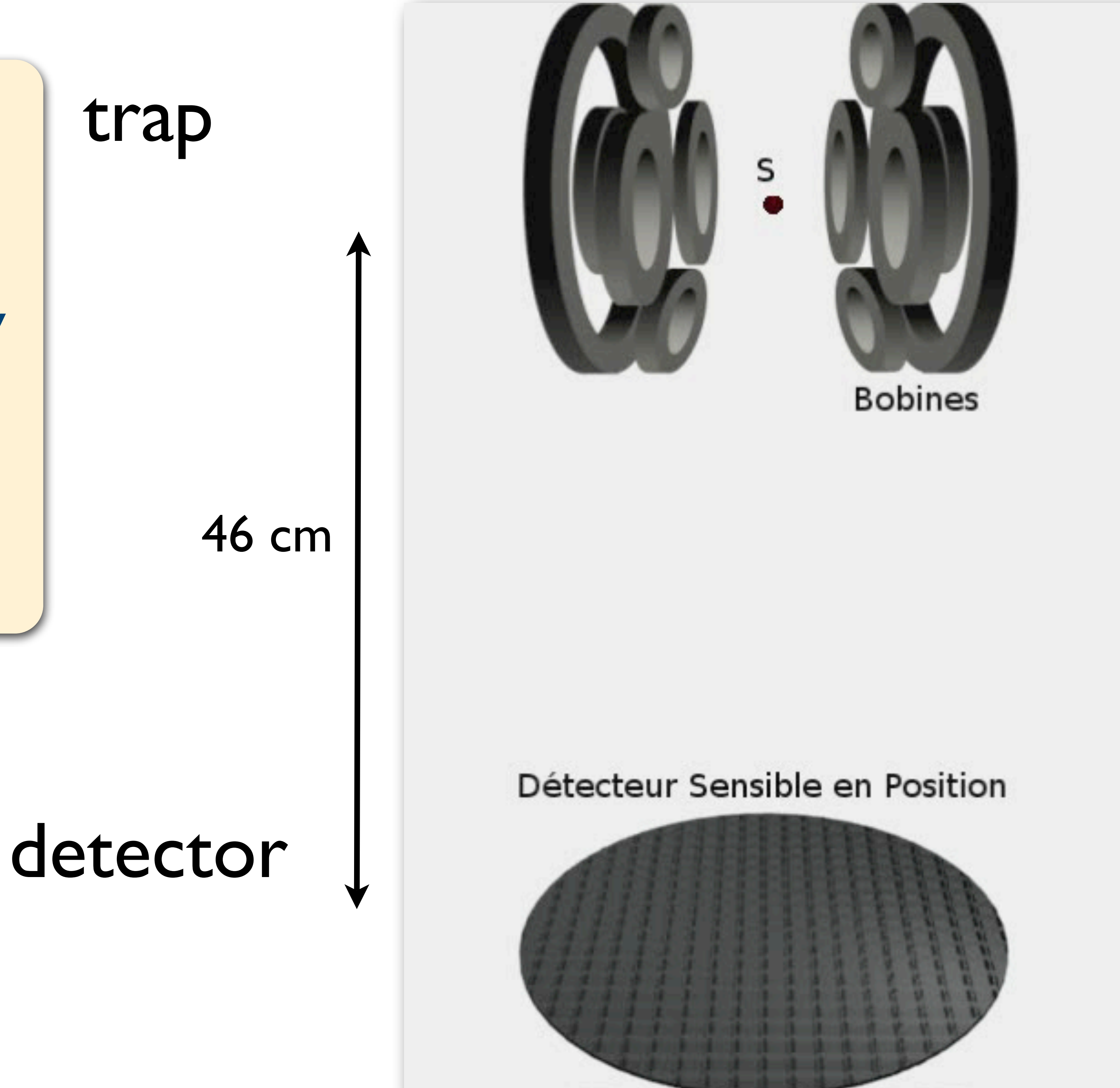
modulate trap laser intensity



"Time of flight" observation

typically 10^5 atoms
time of flight ~ 300 ms
width of TOF ~ 10 ms
We record *x,y,t* for every detected atom.

Get velocity distribution and correlation function.



quasi-condensate
$\omega_\varrho = 1.5$ kHz, $\omega_z = 7$ Hz
$l_z \sim 1$ mm
$\mu \sim 3$ kHz

Analog to the dynamical Casimir effect

inspired by Carusotto et al EPJD 2010

Generate excitations:

$\omega_k = \omega_{mod}/2$

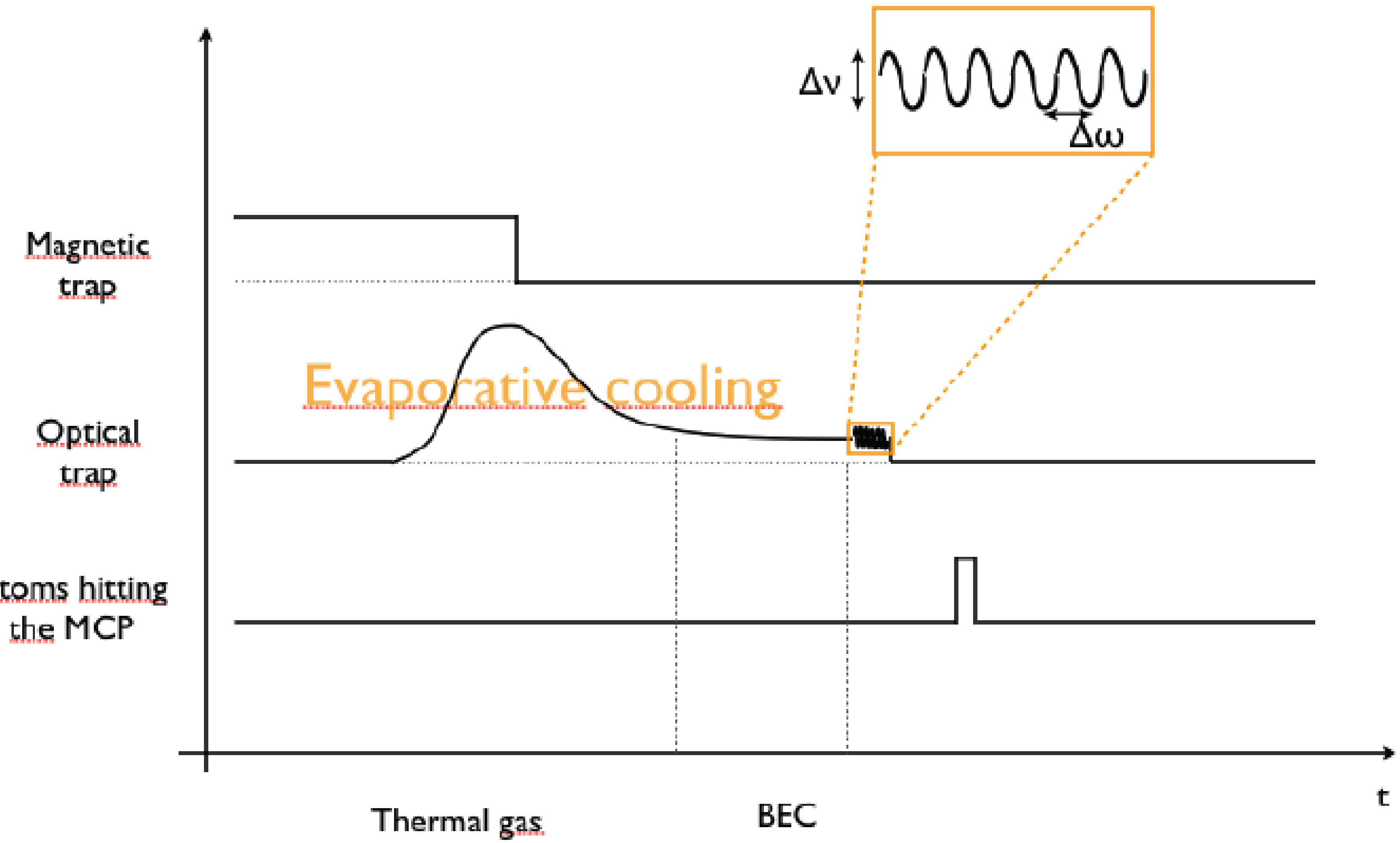
as should be the case for a parametric oscillator

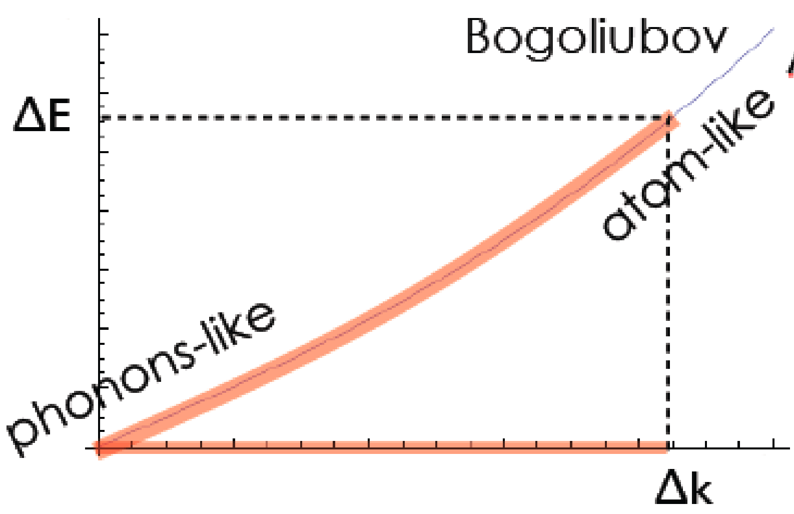
$H \sim b_k^\dagger\, b_{-k}^\dagger + h.c.$

modulation: $\Delta t = 30$ ms

$\Delta\nu = 0.1\ \nu_{trap}$

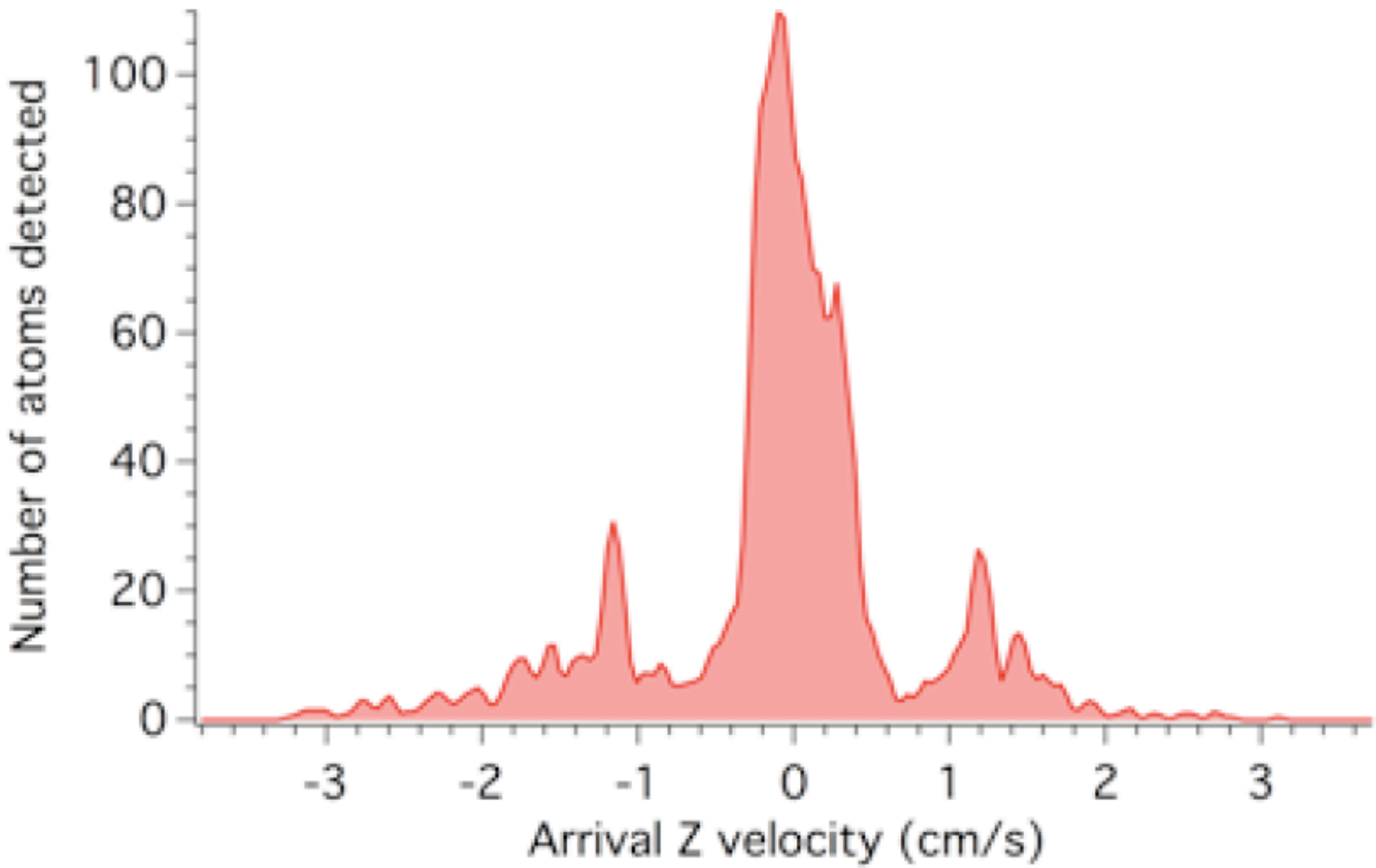
$\omega_{mod}/2\pi = 0.5$ - 5 kHz

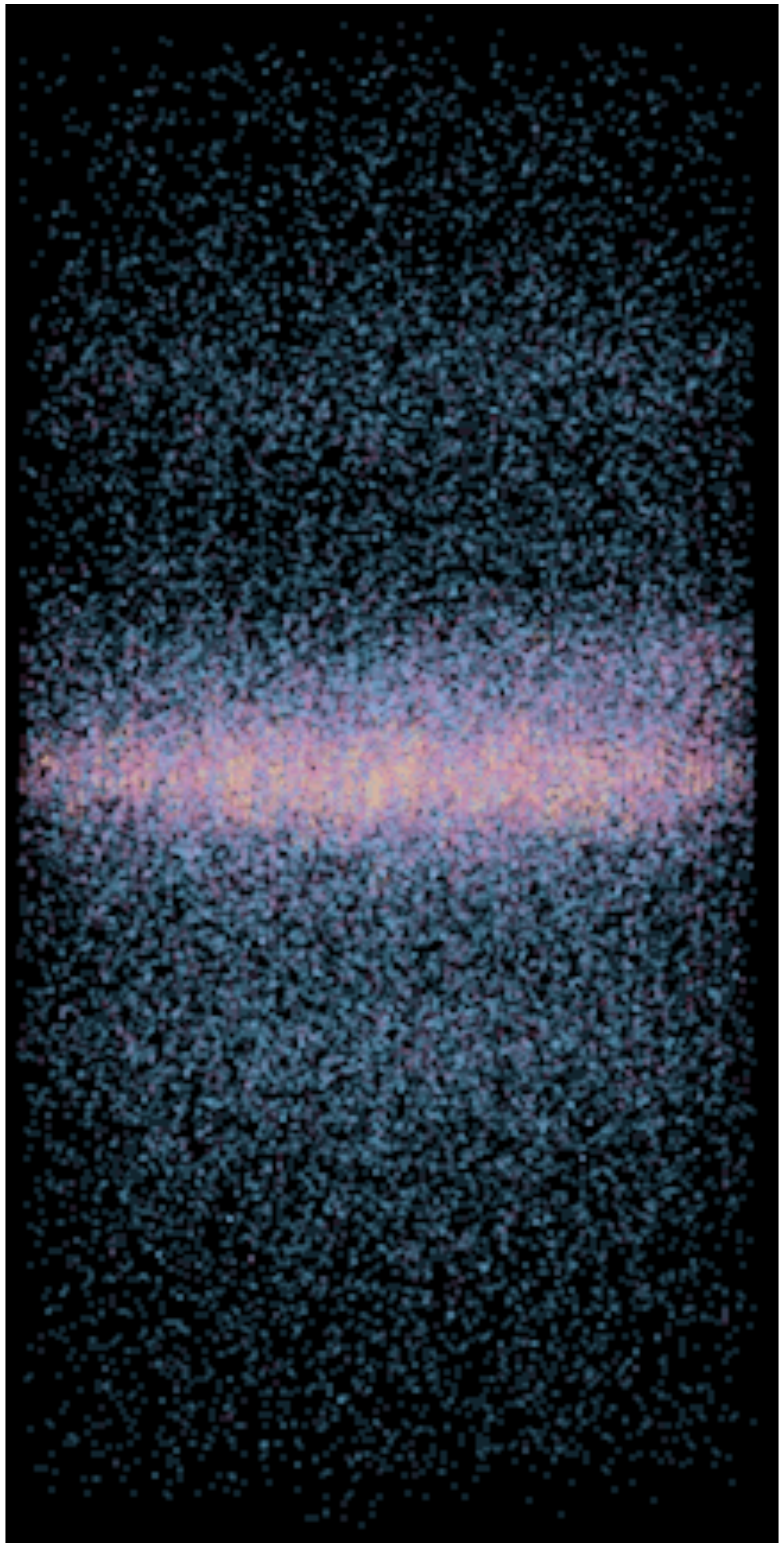




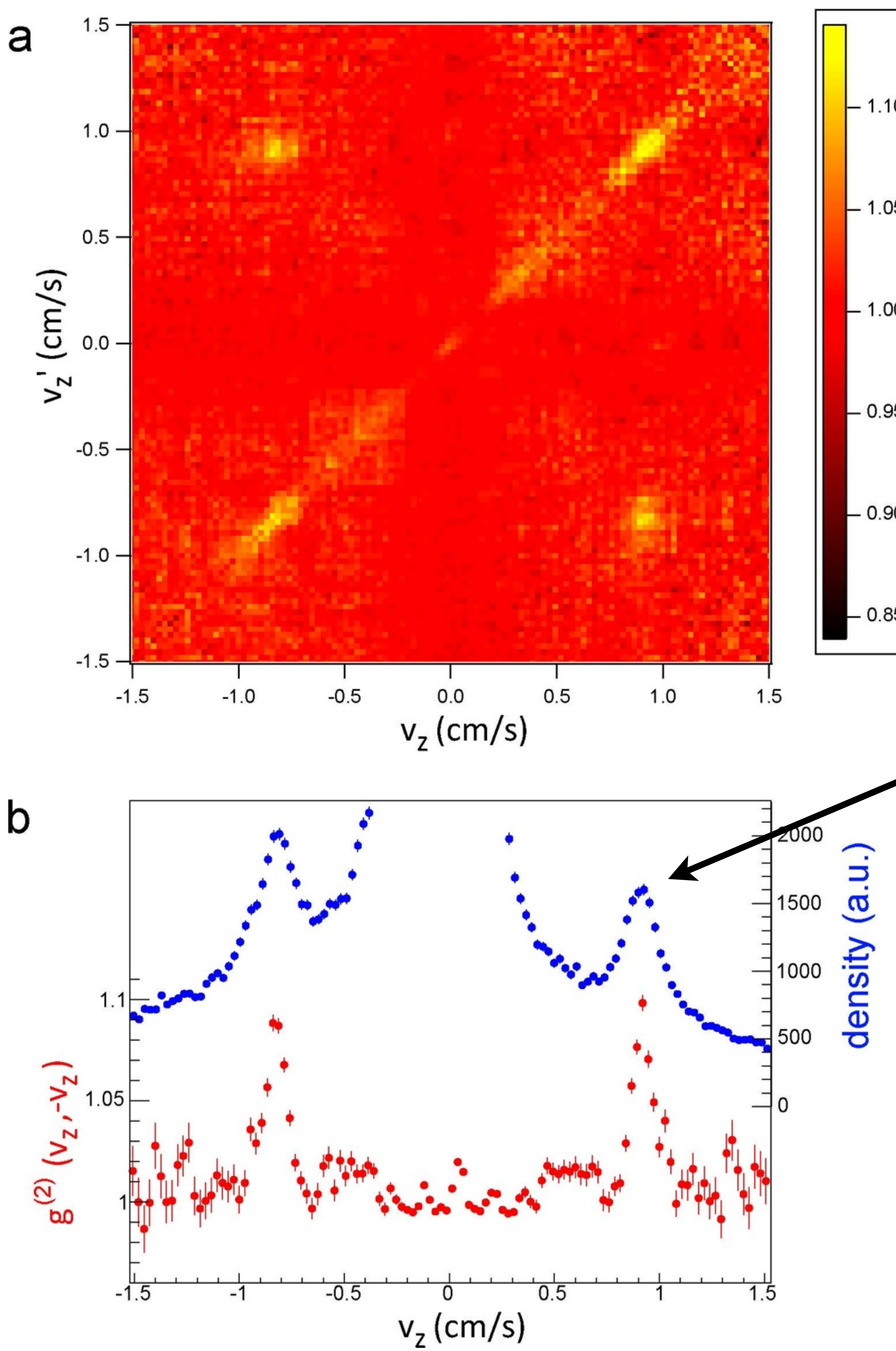
sinusoidal modulation (velocity scale)

$n(v)$





Correlation function



$$g^{(2)}(v,v') = \frac{\text{pair histogram of single shots}}{\text{histogram of different shots}}$$

what is the energy of this excitation?

$n(v)$ $\quad\quad$ $v=\hbar k/m$

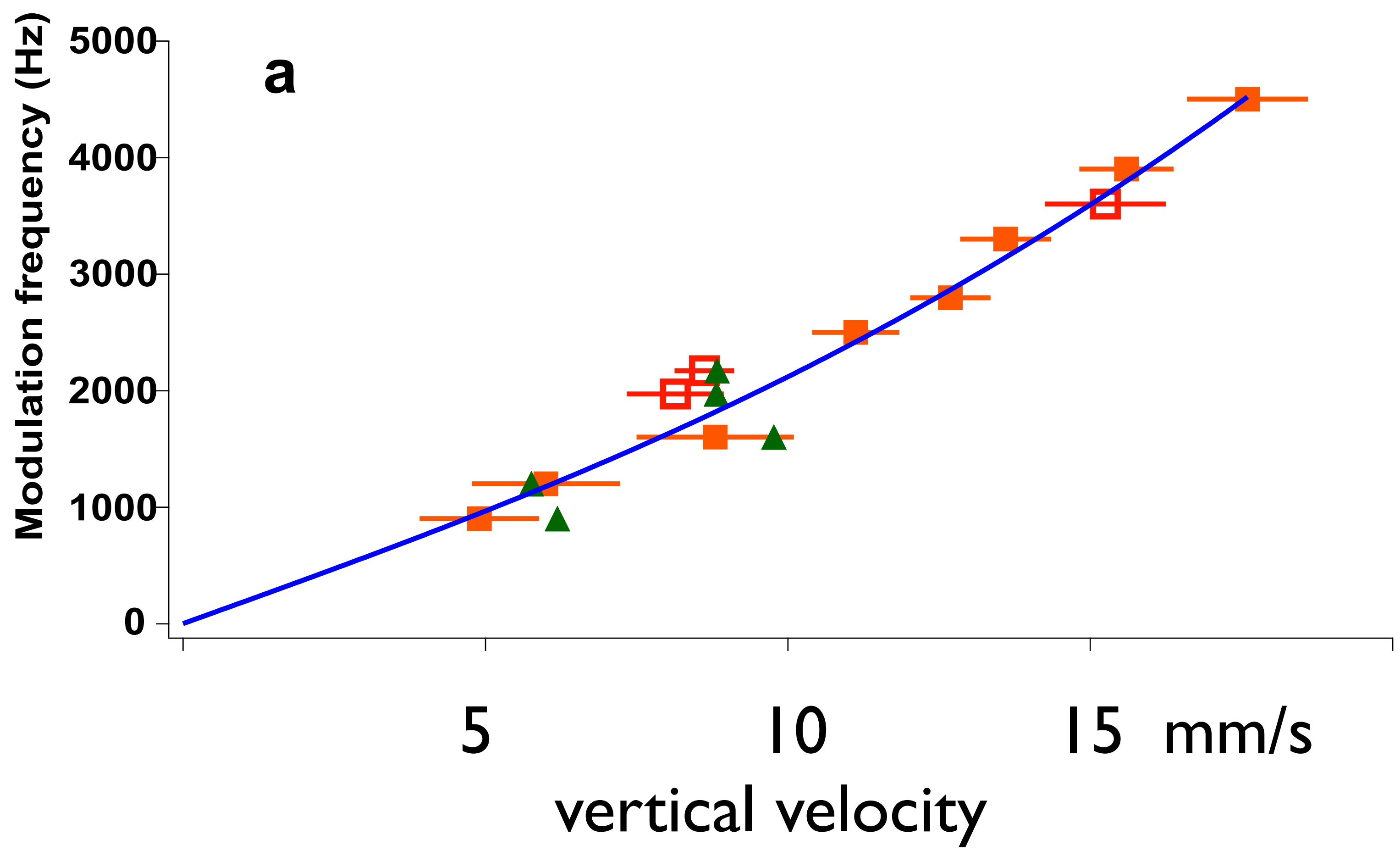
$g^{(2)}(v,v'=-v)$

How to show $\omega_{mod} = \omega_k + \omega_{-k}$

$$\omega_{\text{mod}} = 2\omega_k$$

fit: $\alpha = 2.2$

$c = 8$ mm/s

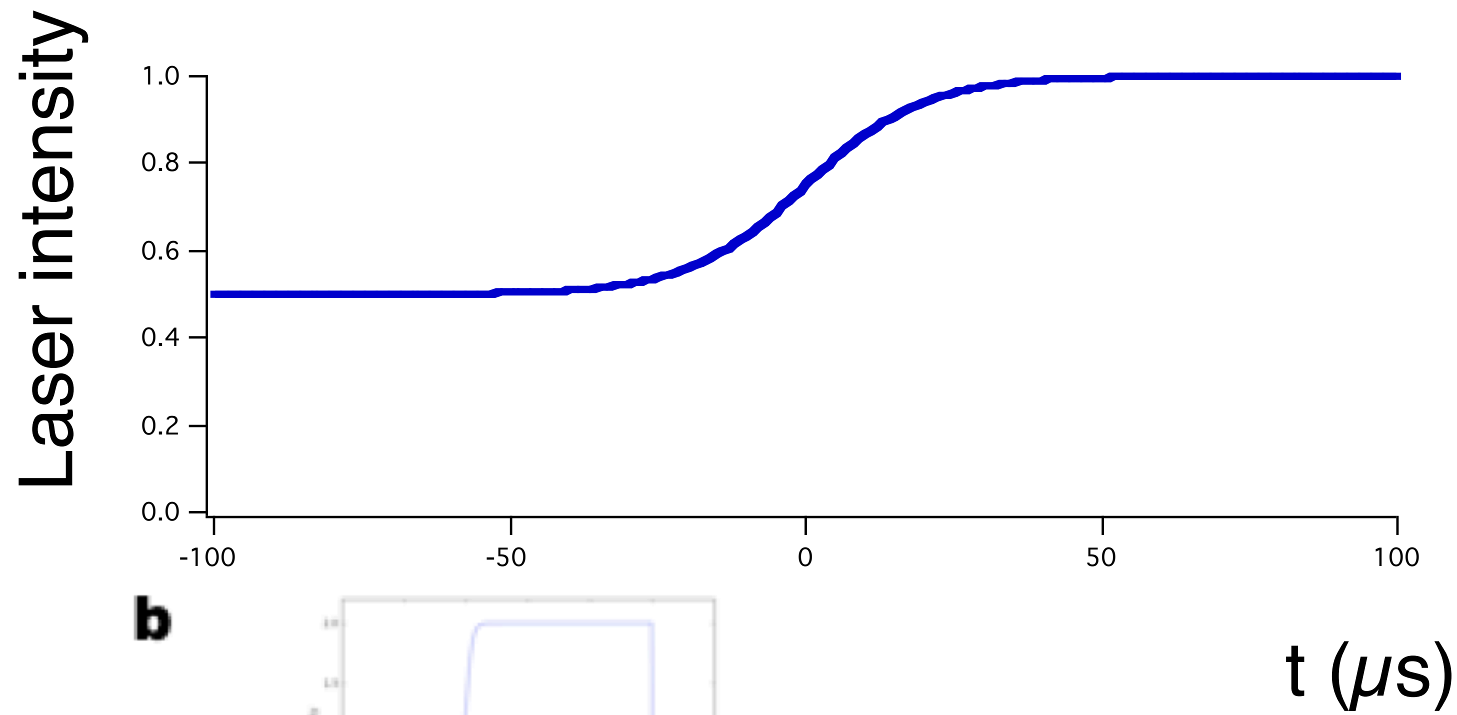


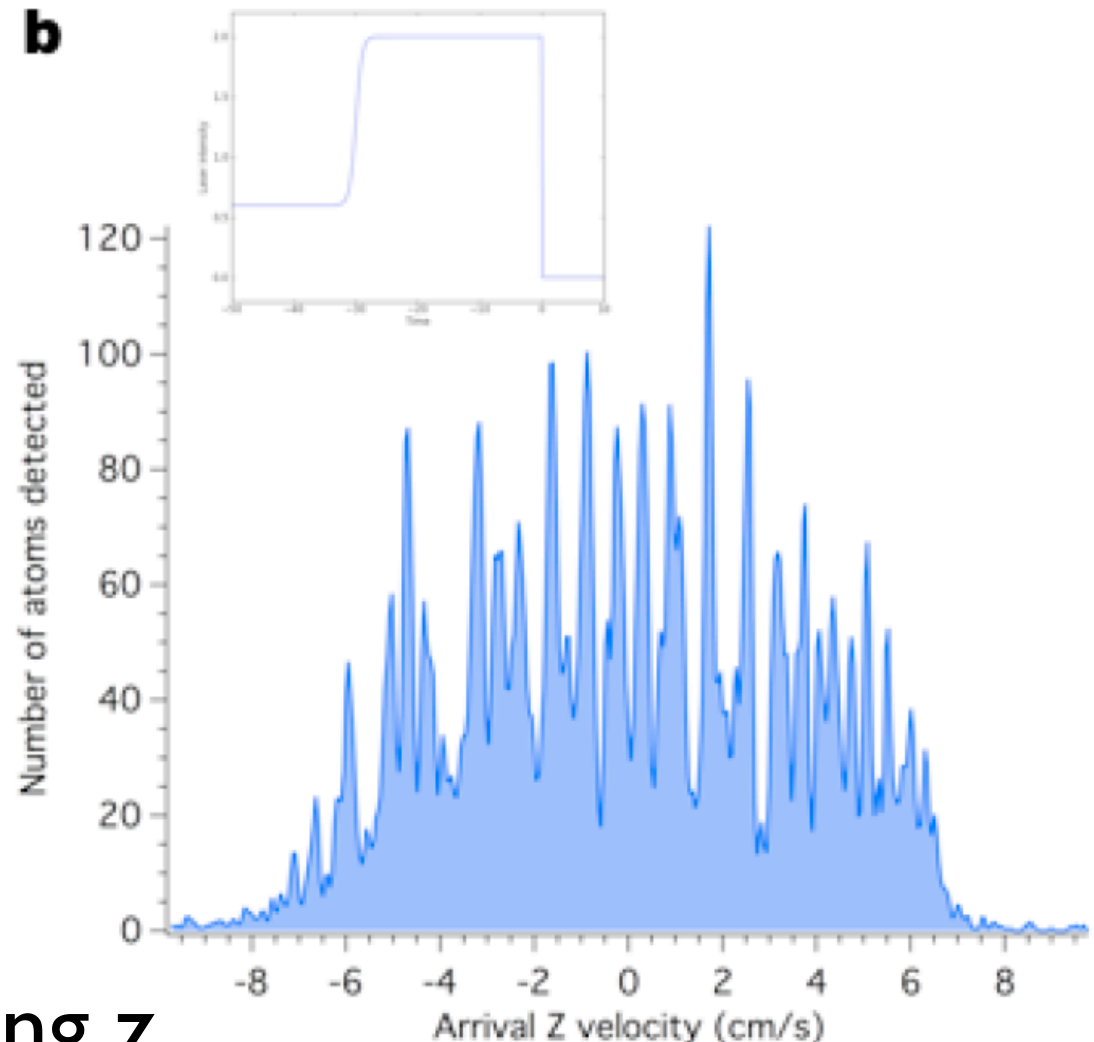
- ■ from density
- ▲ from correlation function

we can verify $\alpha = 2$ using Bragg scattering

Sudden compression of a BEC

Increase trap laser intensity by factor of 2 in ~ 30 μs ($\Delta\omega$ = 5 kHz)
hold ~ 30 ms

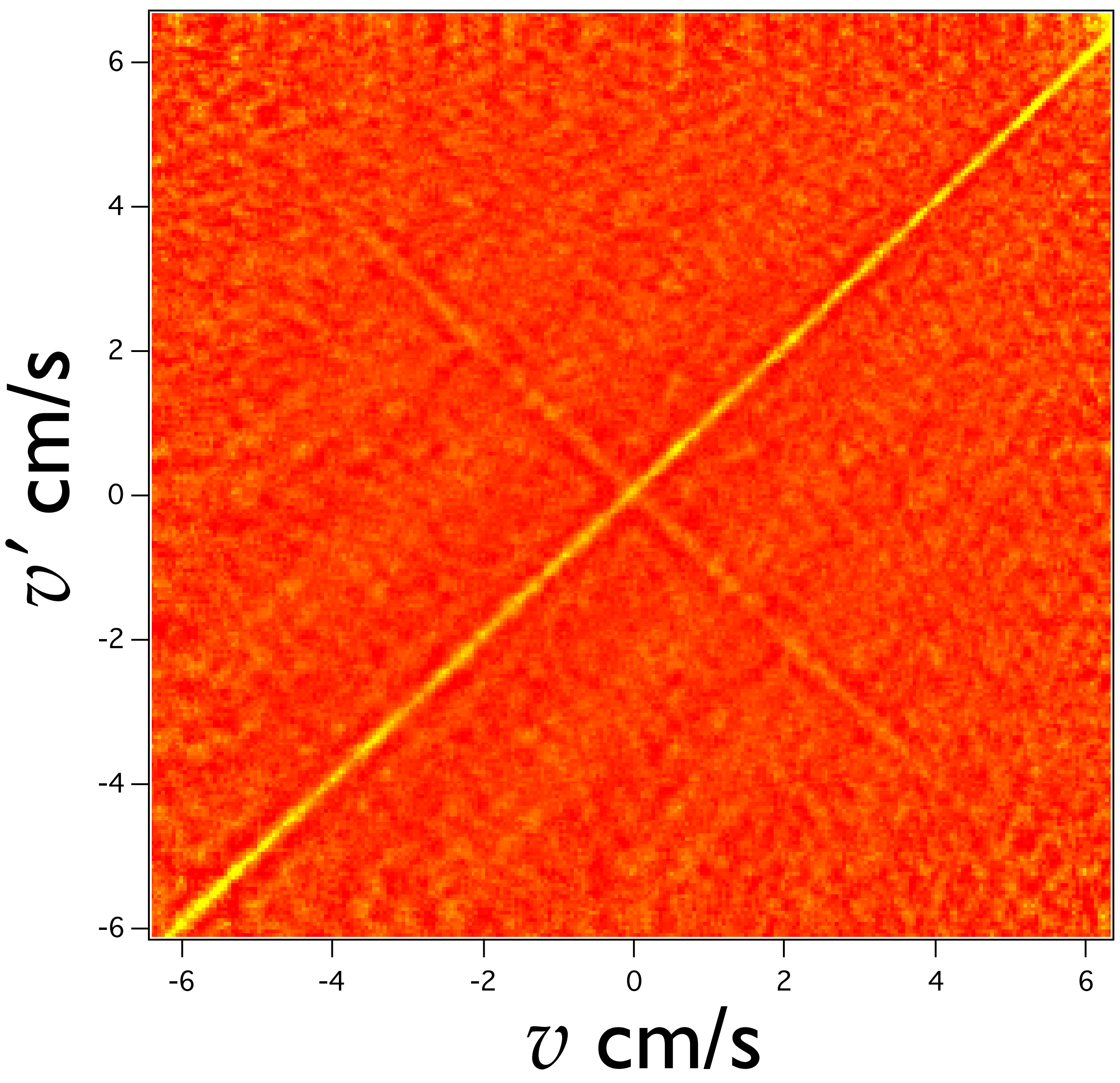


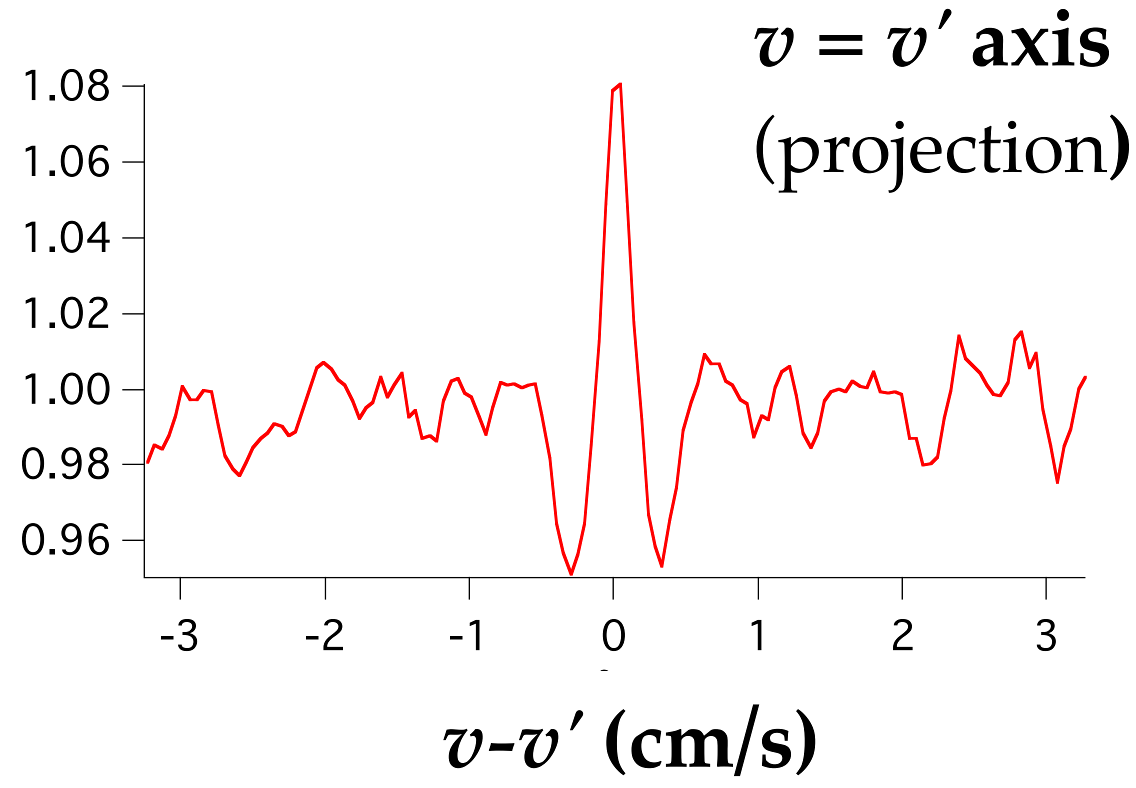


(quasi-)condensate parameters:
l_z = 0.5 mm
ω_ϱ = 1.5 kHz, ω_z = 7 Hz
Highly elongated
μ ~ 3 kHz
c ~ 1 cm/s
ξ = 500 nm

Distribution along z

Correlations in the v - v′ plane





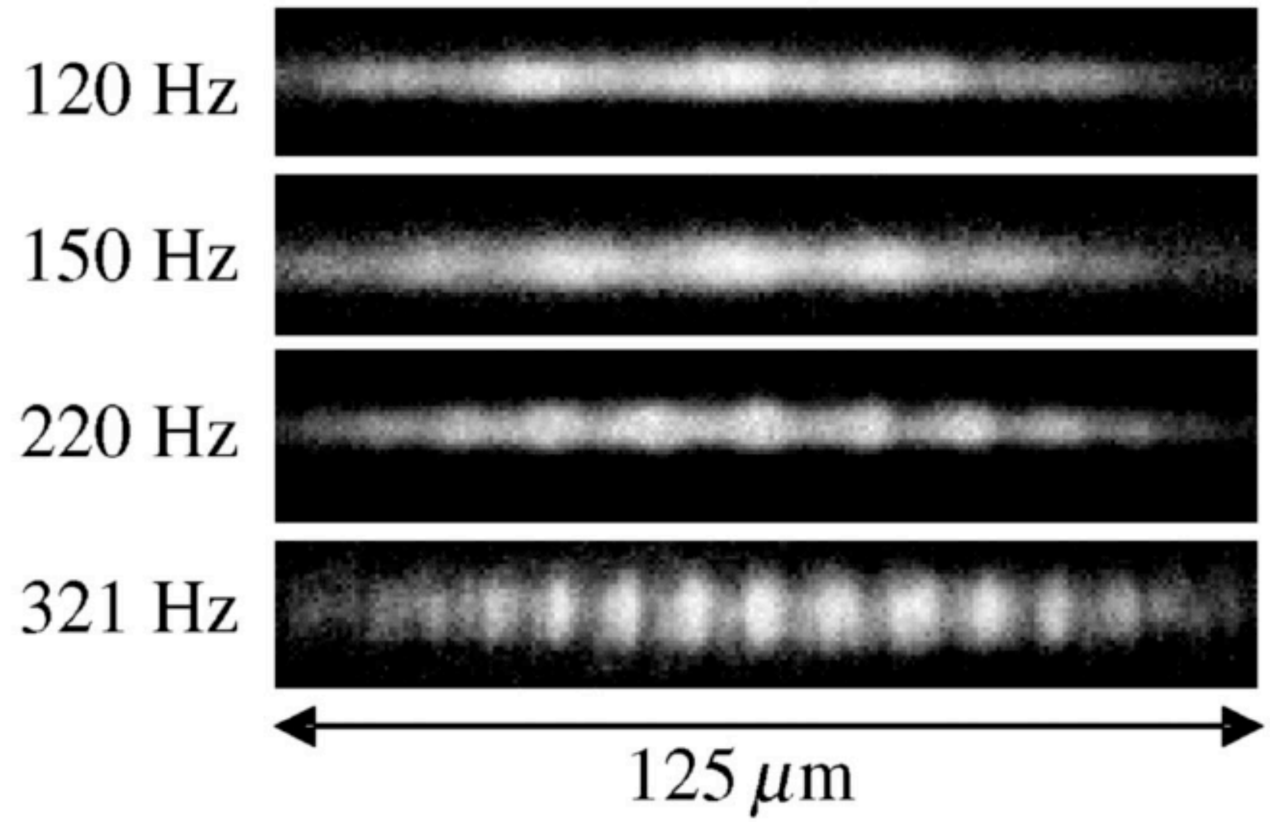
$$g^{(2)}(v,v') = \frac{\text{pair histogram of single shots}}{\text{histogram of different shots}}$$

HBT effect

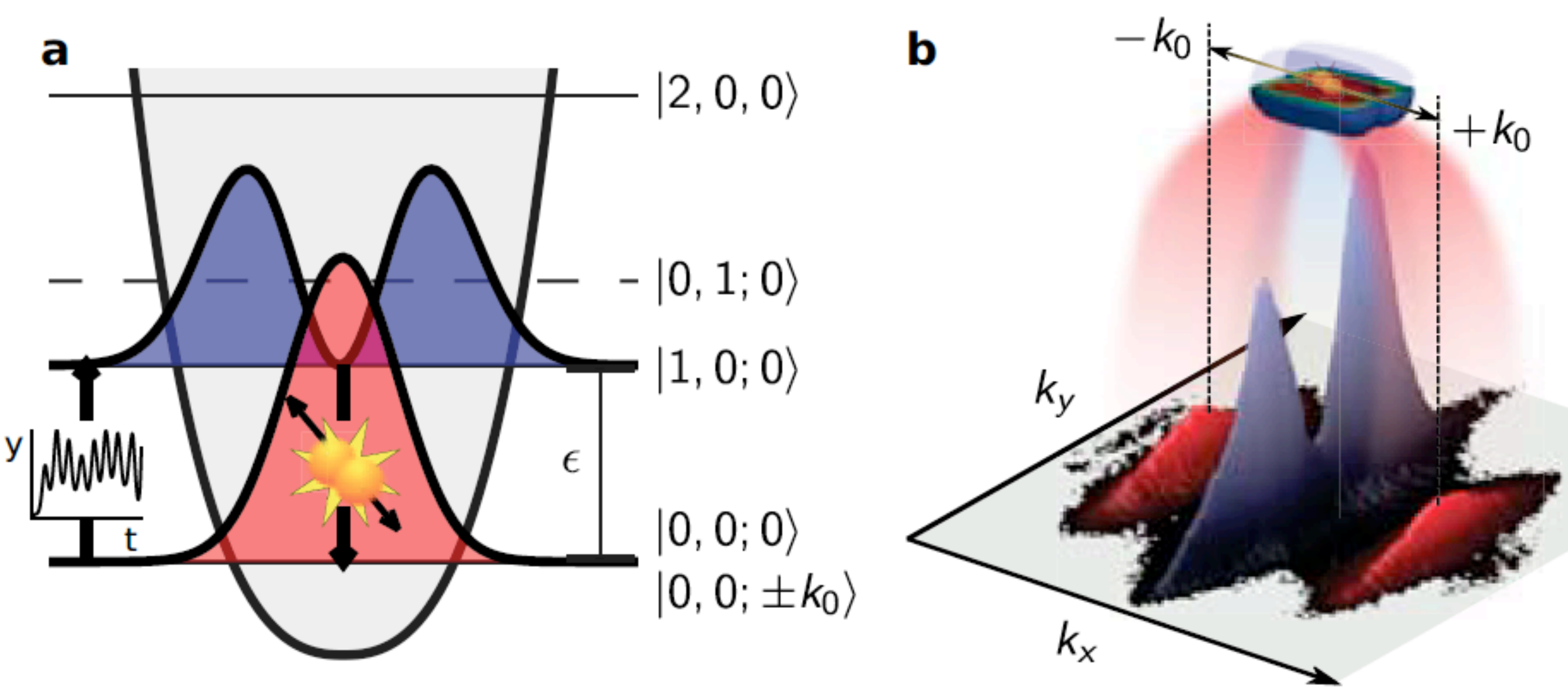
$v,-v$ correlation

Related observations

“Faraday waves ...”
Engels et al.
PRL 98 095301 (2007)
In a mag. trap, modulate transverse confinement,
in situ images.
Spatial period corresponds to $\omega/2$

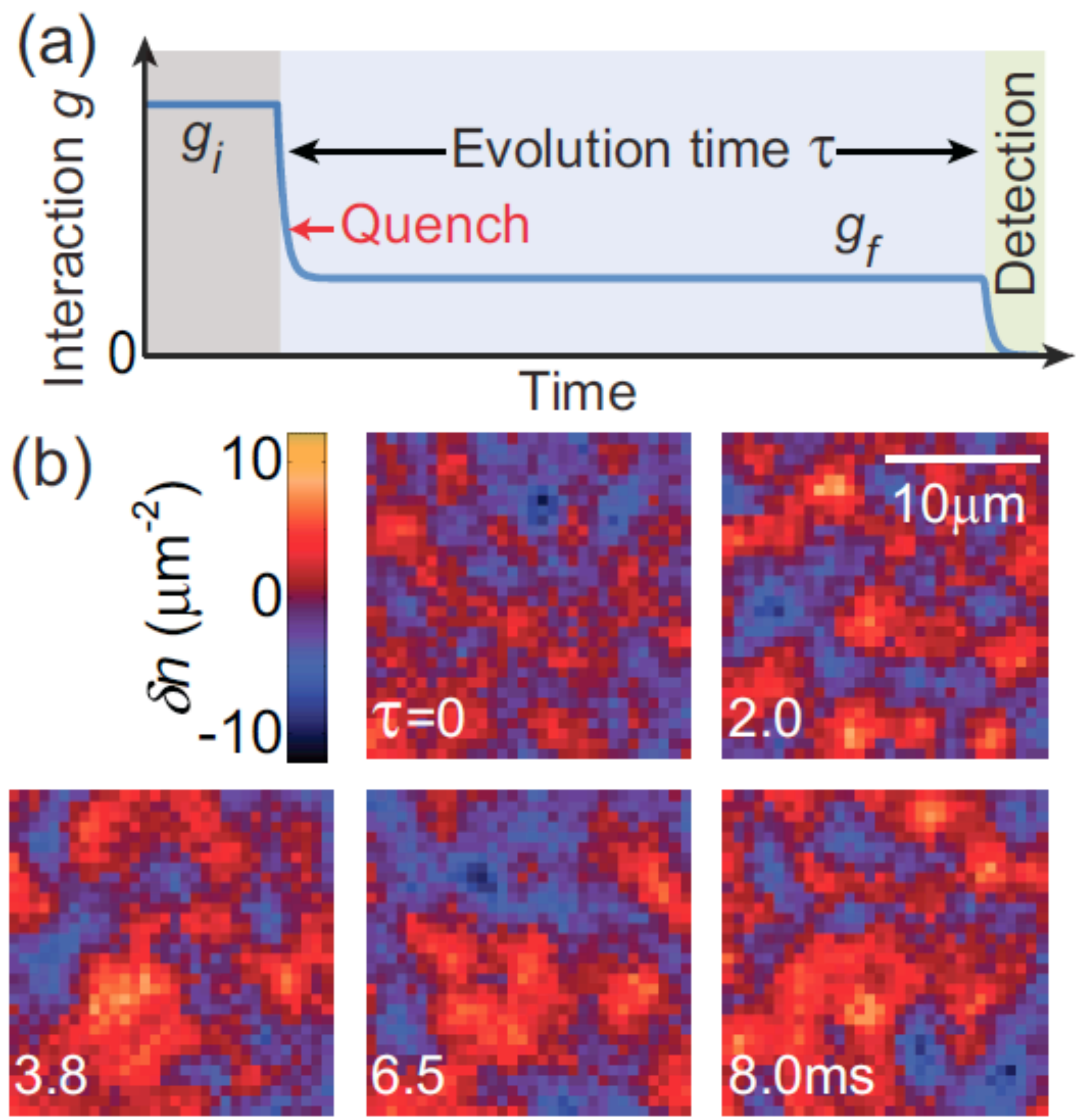


“Twin atom beams”
Bücker et al.
Nat. Phys. 7, 608 (2011)
Modulate trap centre to excite transverse mode
collisions produce longitudinally moving atoms.
Subpoissonian difference
$\Delta N^2 \sim 0.37$ (or 0.11)



More related observations

"Cosmology to cold atoms: observation of Sakharov oscillations ..."
Hung, Gurarie and Chin
arXiv:.1209.0011
Suddenly change the scattering length; in situ images show expanding and propagating density fluctuations.



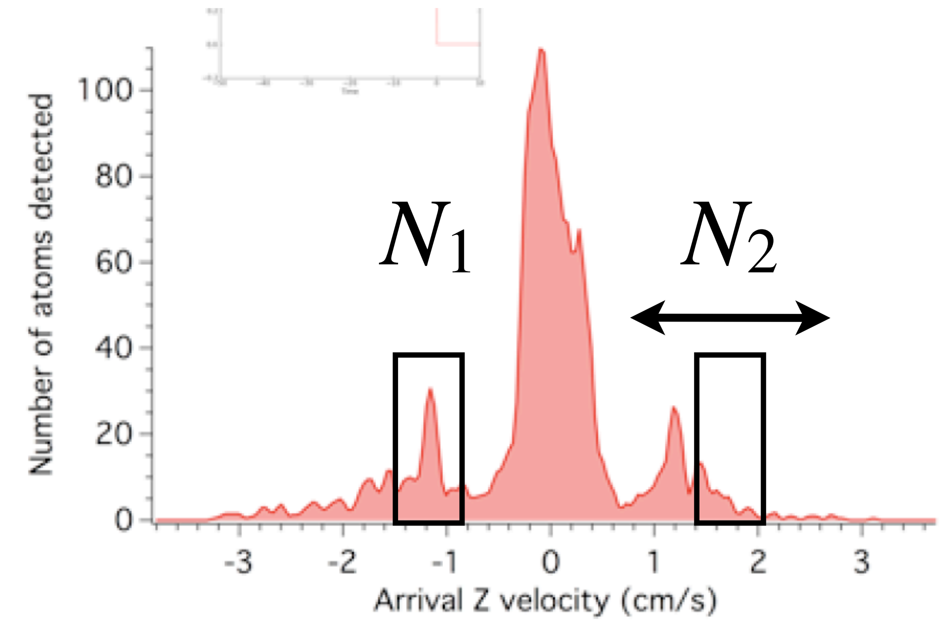
Recalls theoretical proposals by
Fedichev and Fischer PRA 2004
Jain, Weinfurtner, Visser and Gardiner, PRA 2007

So far so good, but...

Nonzero temperature:

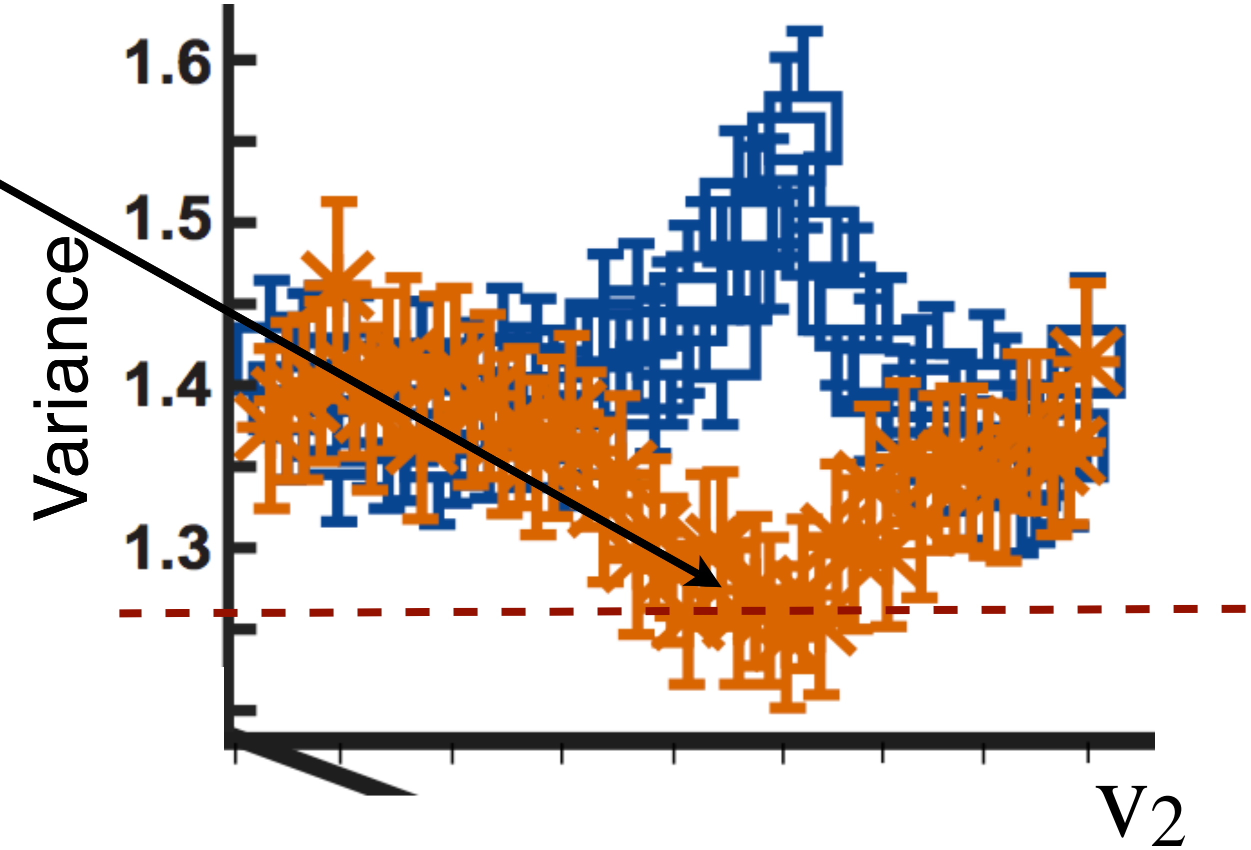
$k_B T/h = 4$ kHz (200 nK)

thermally stimulated



Lack of sub-Poissonian statistics:

$\Delta(N_1 - N_2)^2 / (N_1 + N_2) > 1$



No violation of Cauchy-Schwarz inequality (see P. Deuar)

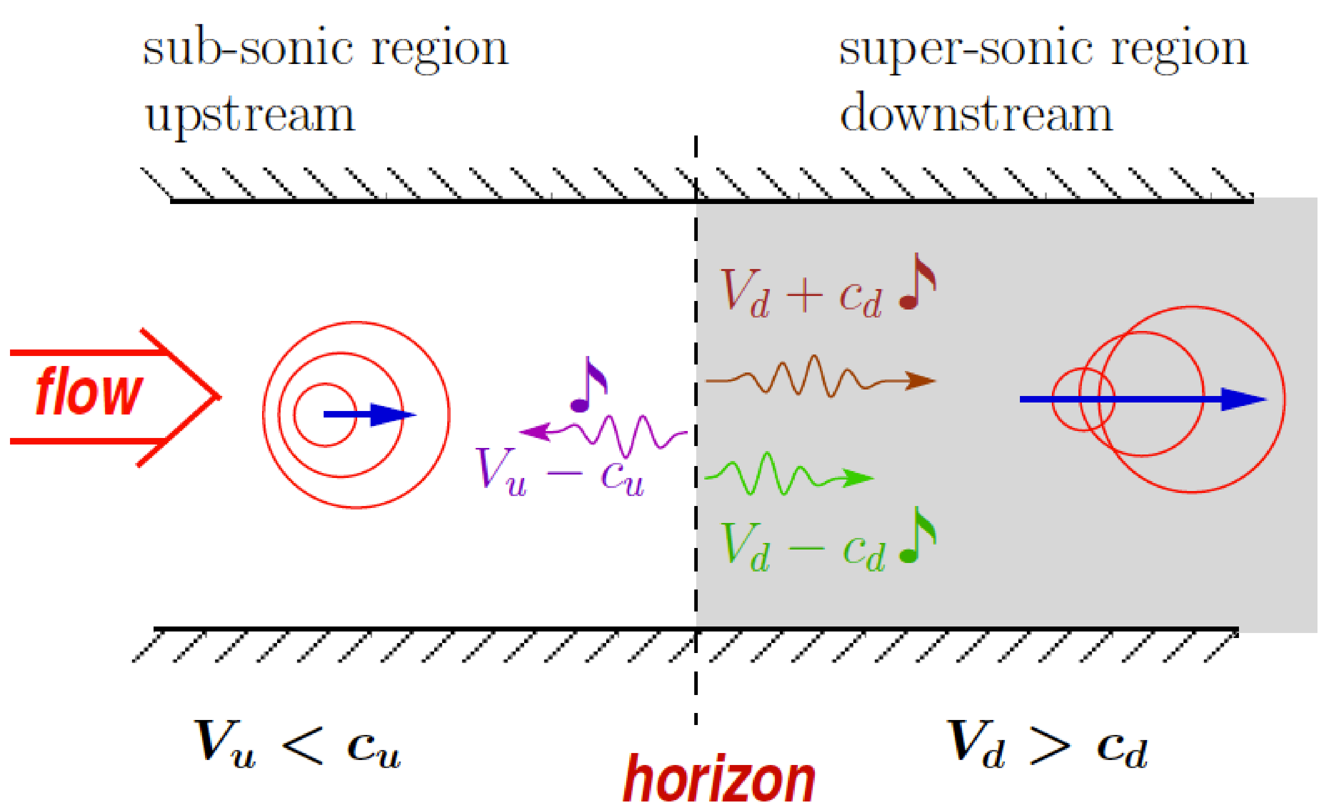
Due to $T \neq 0$?

A sub-Poissonian variance would demonstrate that the result cannot be due to fluctuations of classical waves.

Sonic Hawking radiation in BEC

A black hole produces correlated particles is very appealing to quantum opticians - looks like a parametric oscillator

$$H \sim a_0 a_1^\dagger a_2^\dagger + h.c.$$

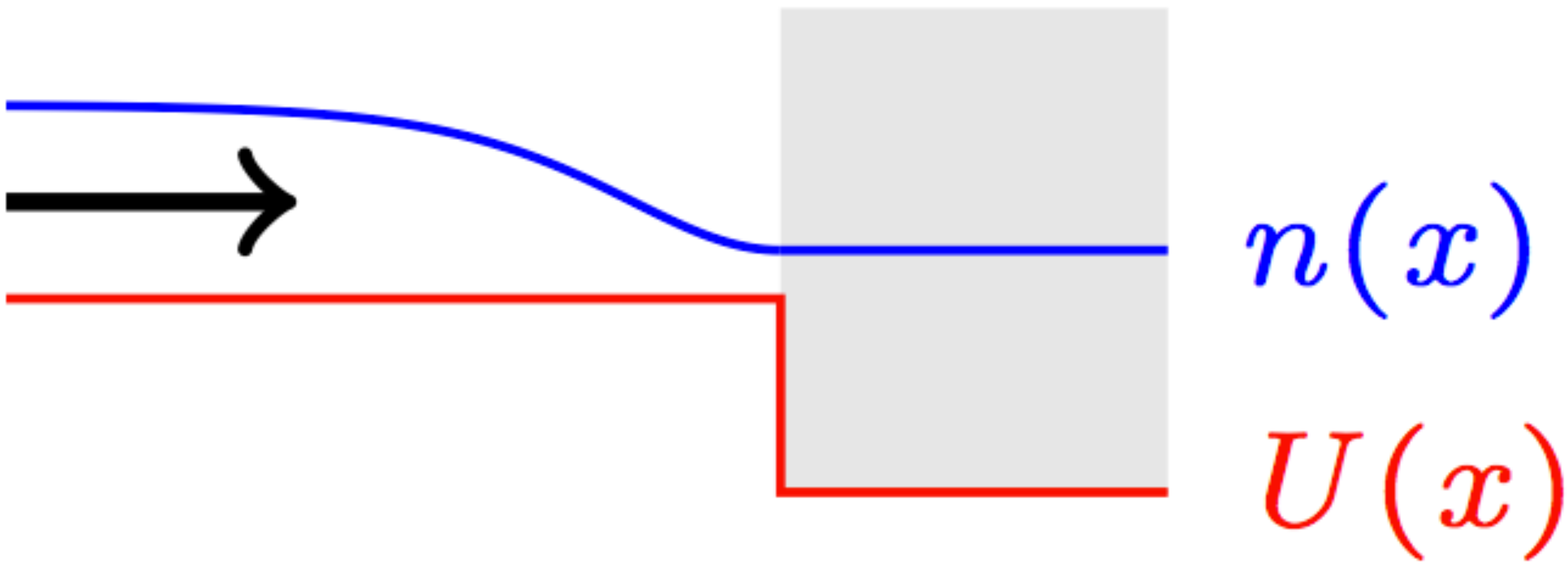


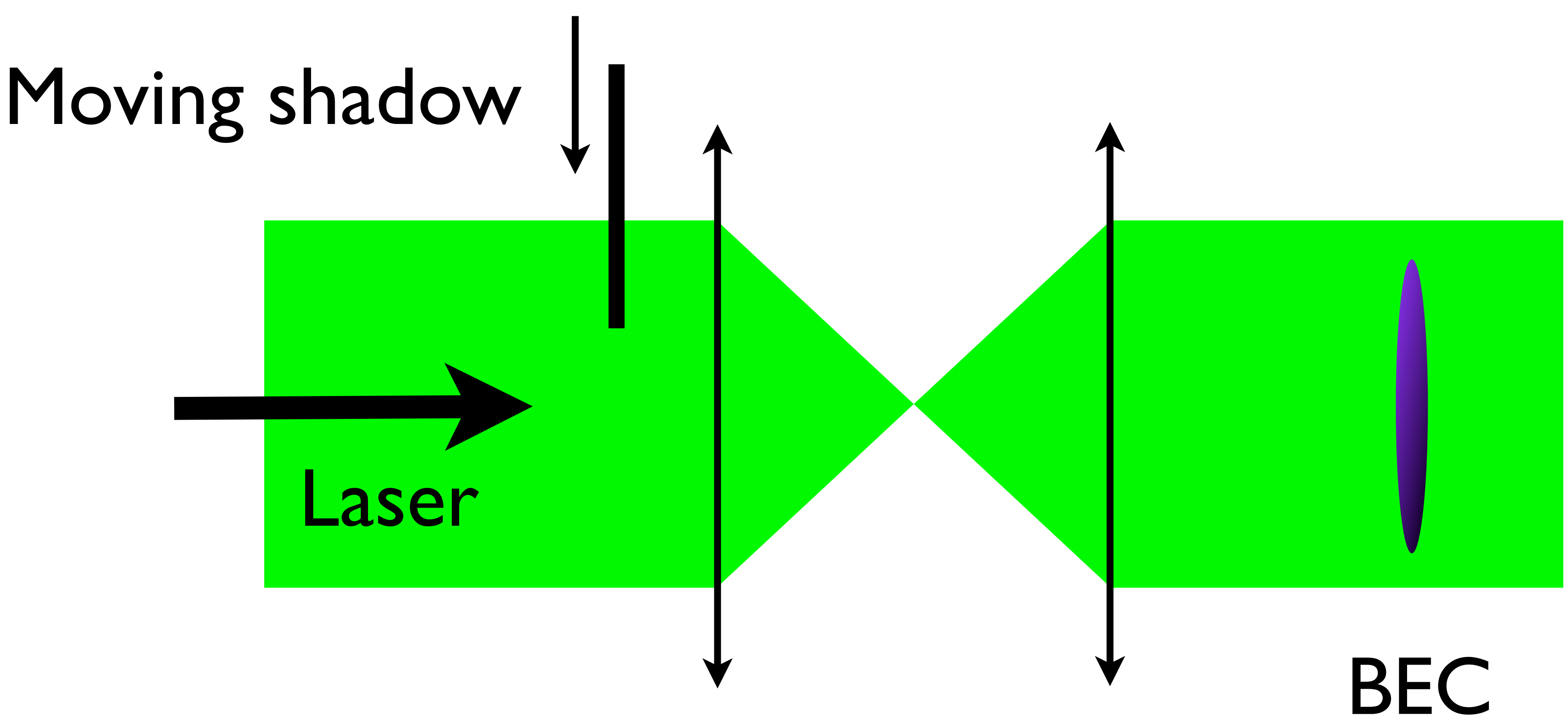
Garay, Anglin, Cirac, Zoller, PRA 63, 023611 (2001), “Sonic black holes in dilute BECs”

Balbinot et al PRA 78 021603 (2008), “Nonlocal density correlations as a signature of Hawking radiation from acoustic black holes”

Lahav et al. PRL 105, 240401 (2010), “Realization of a sonic black hole analog in a BEC”.

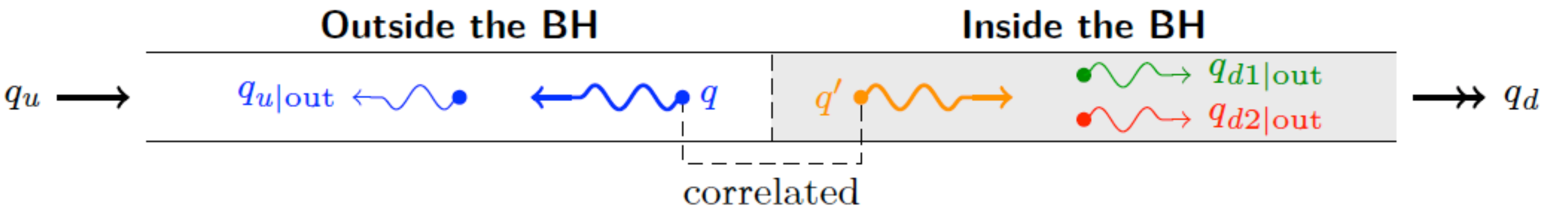
Experimental realization of a horizon

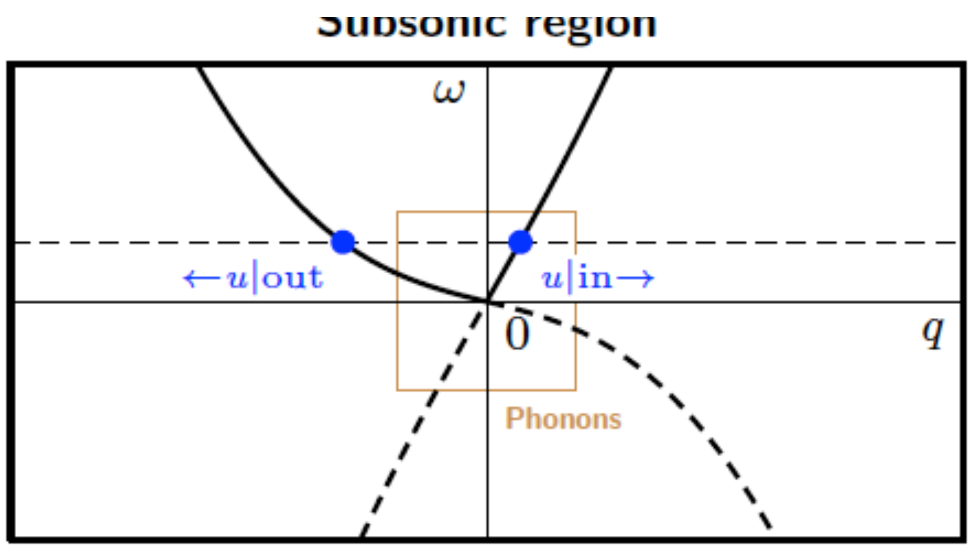




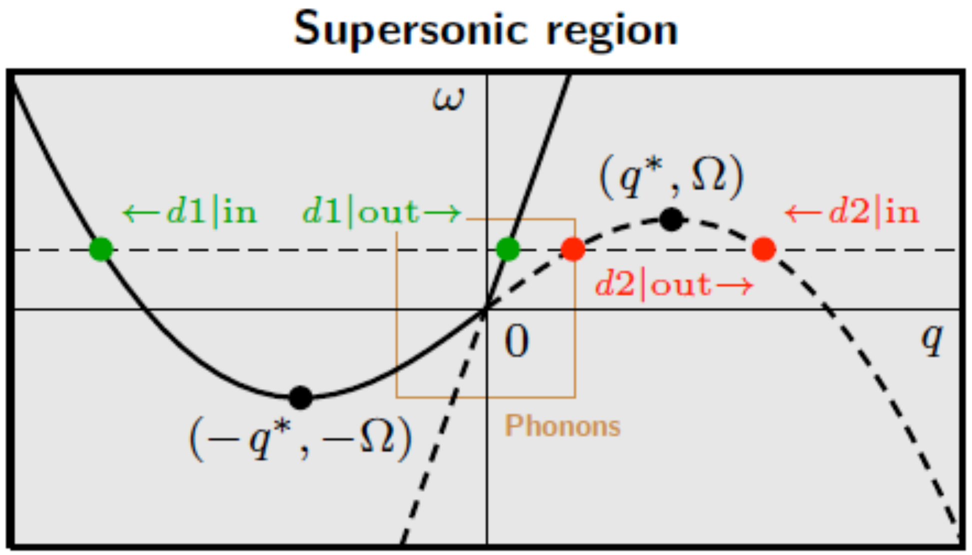
$v \sim 1$ cm/s
$d \sim 1$mm
$t \sim 100$ ms

Signature of Hawking radiation in p-space



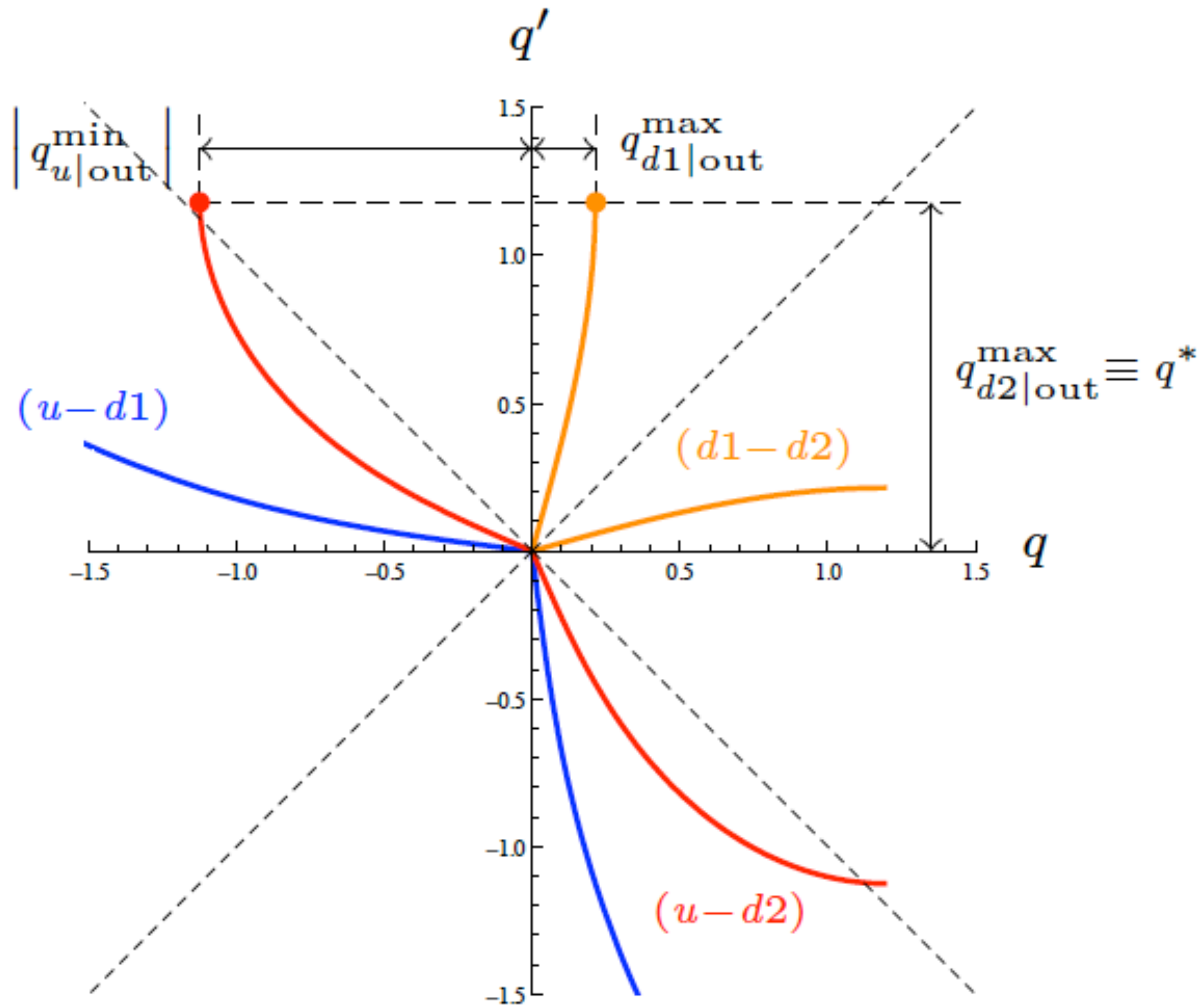


$\ell \in \{u|\mathrm{in}, u|\mathrm{out}, u|\mathrm{eva}\}, \forall \omega > 0$



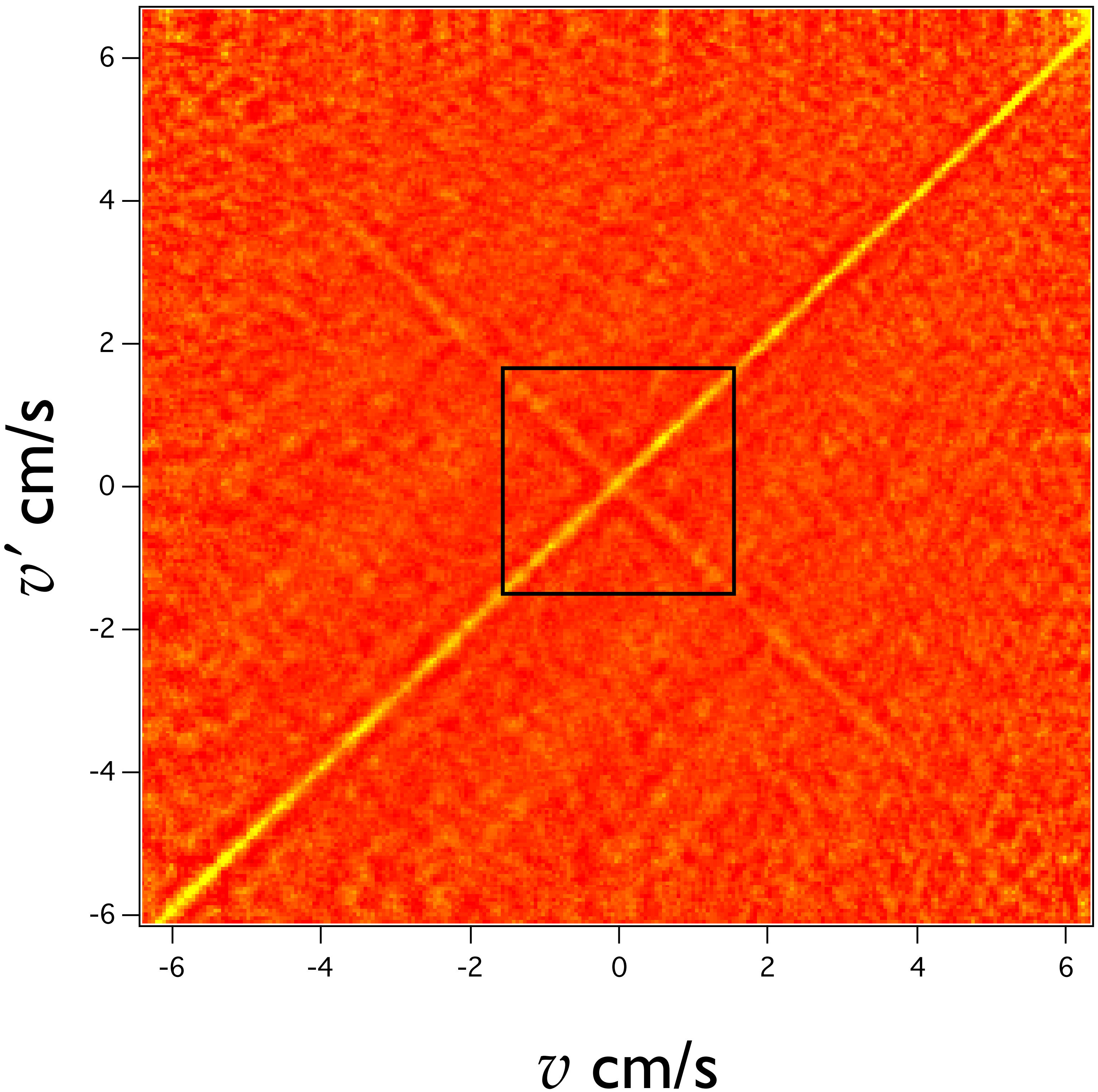
$\ell \in \{d1|\mathrm{in}, d1|\mathrm{out}, d2|\mathrm{in}, d2|\mathrm{out}\}, \forall \omega < \Omega$

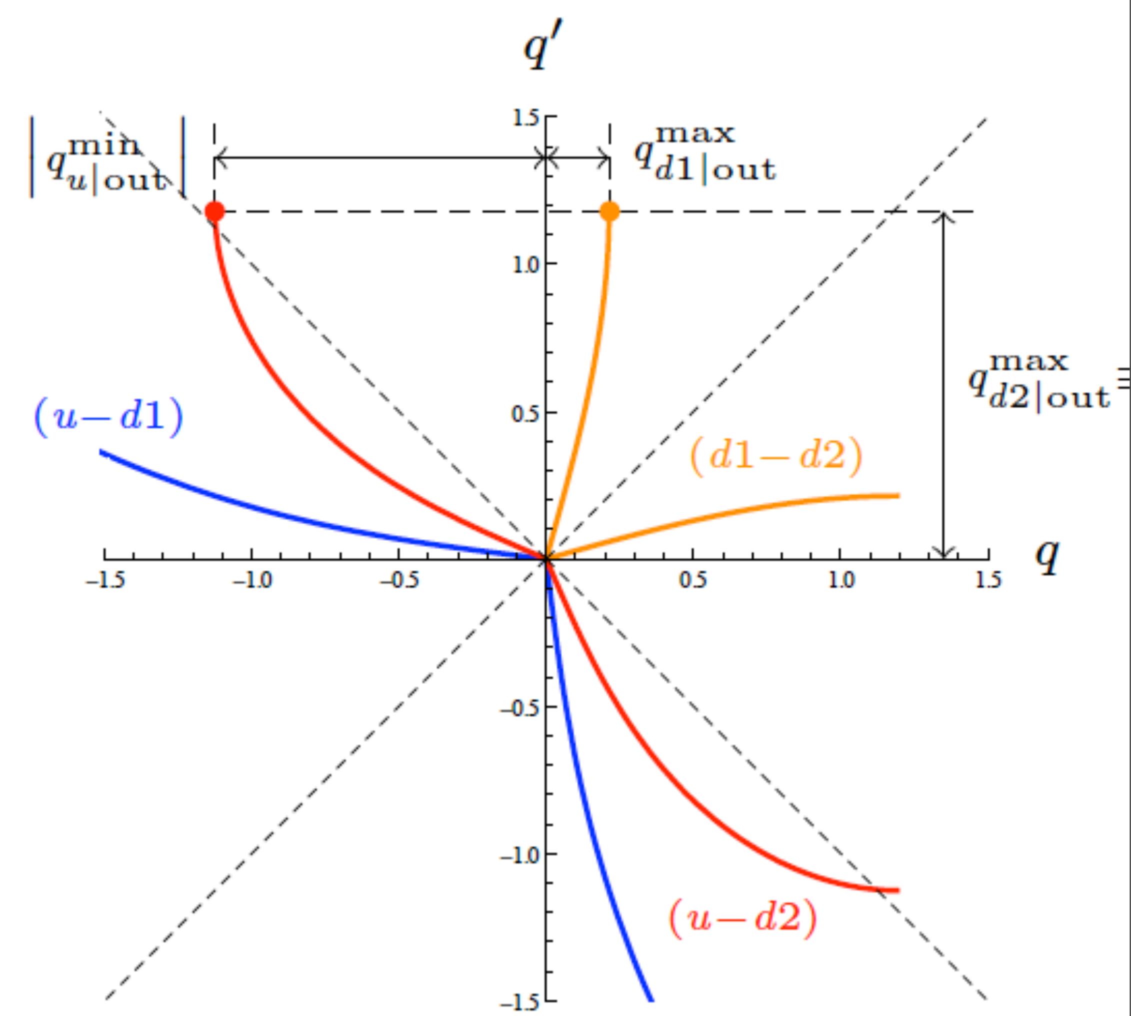
$\ell \in \{d1|\mathrm{in}, d1|\mathrm{out}, d|\mathrm{eva}\}, \forall \omega > \Omega$



P.-E. Larré, N. Pavloff

Correlations in momentum space





Amplitude of correlations?

Conclusions and outlook

- Trap modulation certainly produces correlated excitations obeying $\omega_{\text{mod}} = \omega_k + \omega_{-k}$
- Here $kT/h \sim 4$ kHz. Excitations not from vacuum.
- No sub-Poissonian number difference (yet)
- Simulation of particle production the expansion of the early universe? (Jain, Weinfurtner, Visser, Gardiner, PRA 2007, Fedichev, Fischer PRA 2004)
- Other aspects of quantum transport?

Thanks