Phonons and other quantum fields in the lab

Chris Westbrook
Laboratoire Charles Fabry, Palaiseau

Itzykson Meeting, Saclay
8 june 2017

Non-linear QED

Light by light scattering

Magnetic vacuum birefringence

...

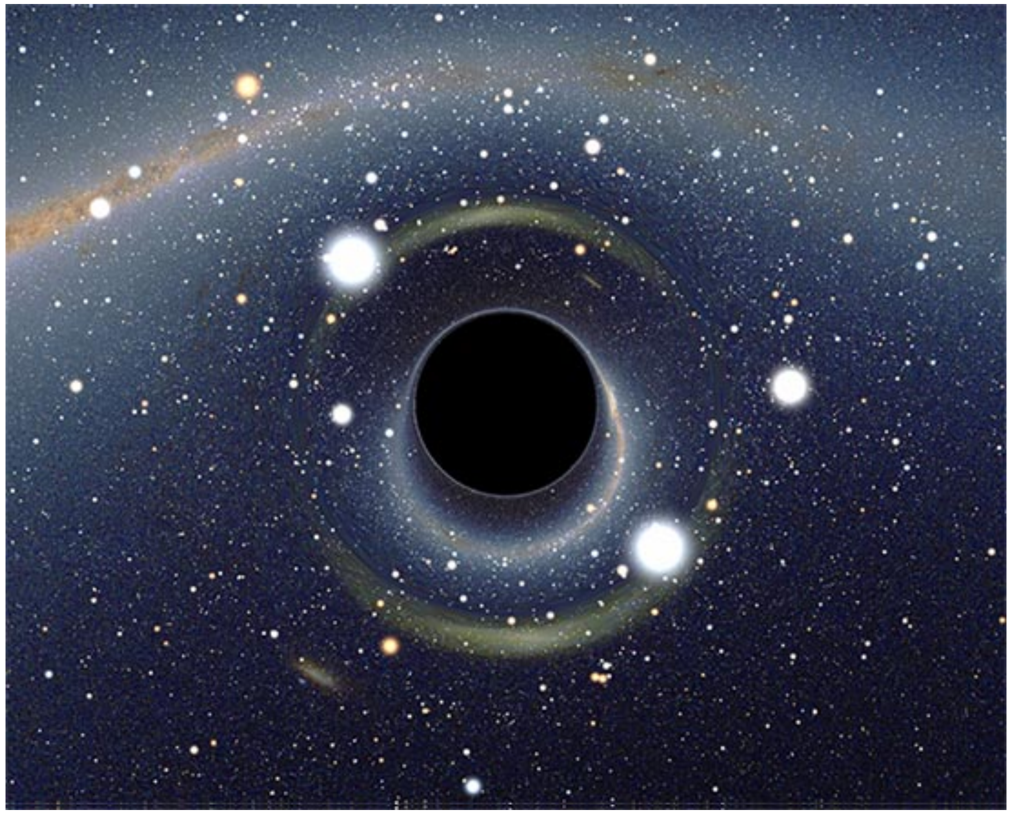
Hawking radiation

Acoustic analogs

Dynamical Casimir effect

Entanglement (but not of photons)

Black holes



S. Hawking, Nature (1974)
"Black hole explosions"

Bogoliubov transformation relating incoming and outgoing fields:

$$b_i = \sum_j \{\bar{\alpha}_{ij} a_j - \bar{\beta}_{ij} a_j^{+}\}$$

In a parametric oscillator pairs of particles are entangled.
What about in a black hole?

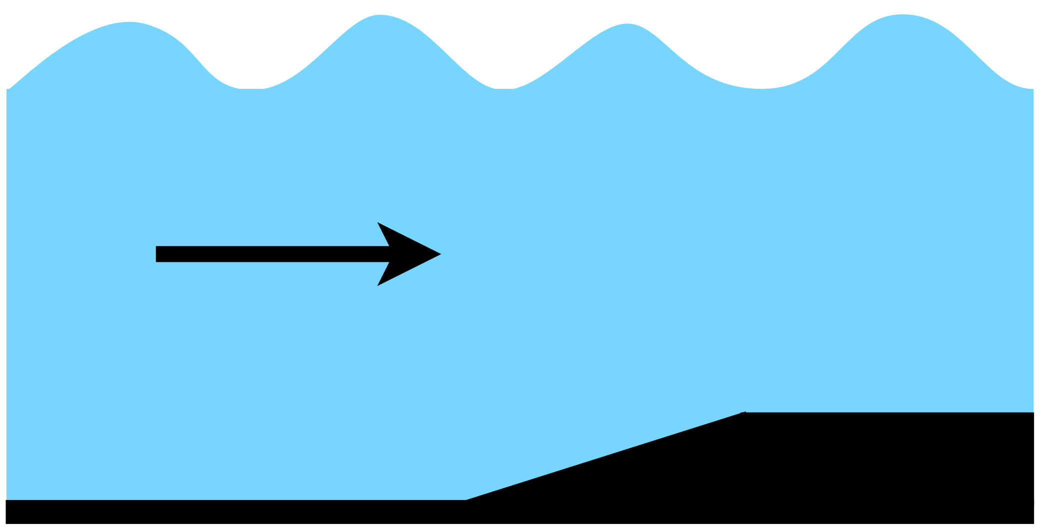
Sonic analog: change the speed of sound (PRL 1981)

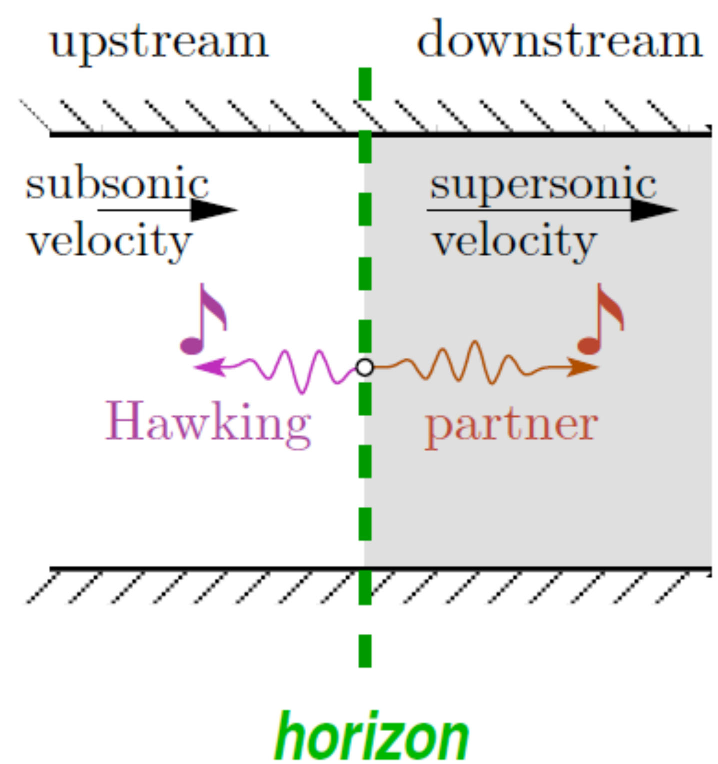
Experimental Black-Hole Evaporation?

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 (stimulated) Hawking radiation

Weinfurtner et al. PRL 2011 (Vancouver), Euvé et al. PRL 2016 (Poitiers)

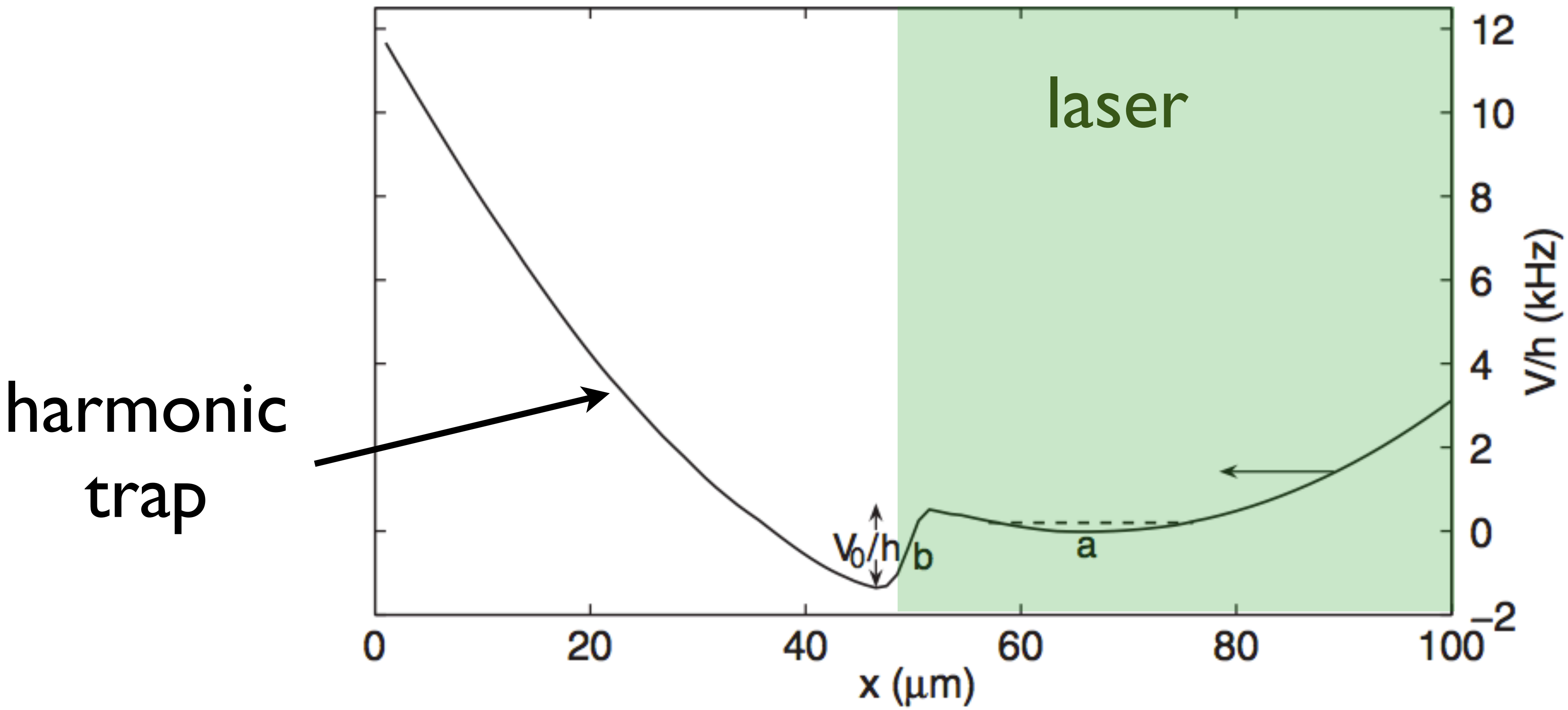
Black holes in BEC's

Low temperature: quantum Hawking radiation?

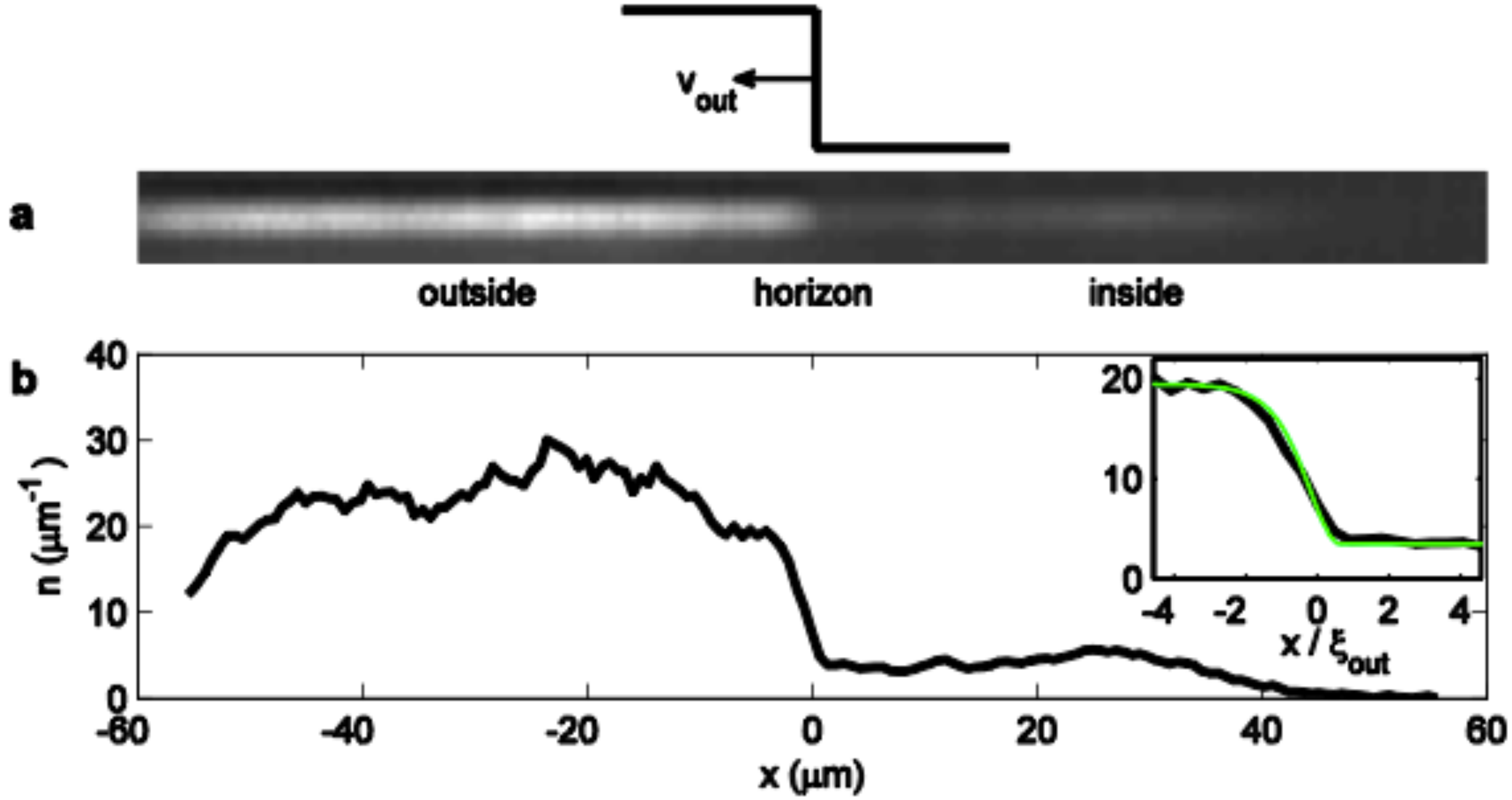
$T_{Hawking}$ ~1 nk

Speed of sound in a BEC $c_s^2 = (4\pi\,\hbar^2)\, a\, \varrho/m^2$

Lahav et al. PRL 2010, "Realization of a sonic black hole":



Data: density profiles



and their correlations ...

Progress (?) since 2010

2014 "Observation of self amplifying Hawking radiation in a black hole laser", Nat. Phys, 10, 864

2016 "Observation of quantum Hawking radiation and its entanglement in an analogue black hole", Nat Phys. 12, 959

But:

2016 "Questioning the recent observation of quantum Hawking radiation" arXiv:1609.03803

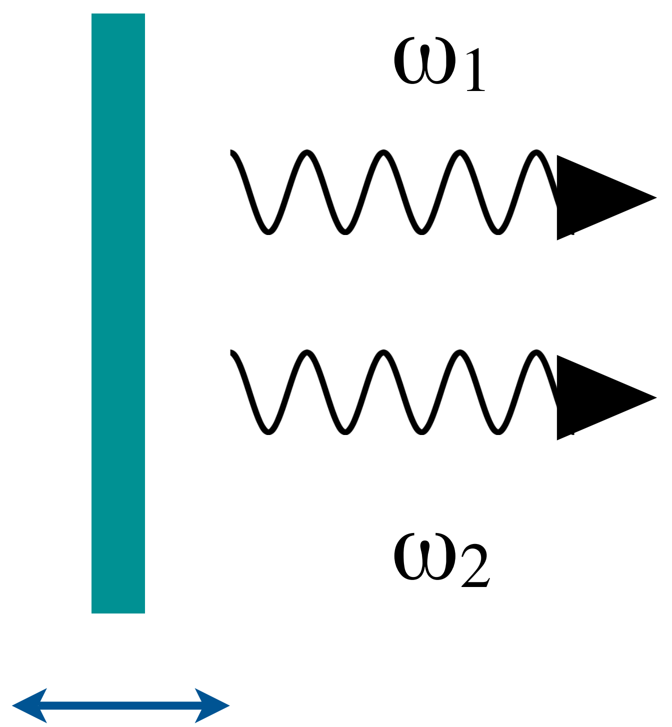
2016 "Mechanism of stimulated Hawking radiation in a laboratory Bose-Einstein condensate", arXiv:1605.01027

2017 "Induced density correlations in a sonic black hole condensate" arXiv:1705.01907

Will this ever impact quantum gravity?

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

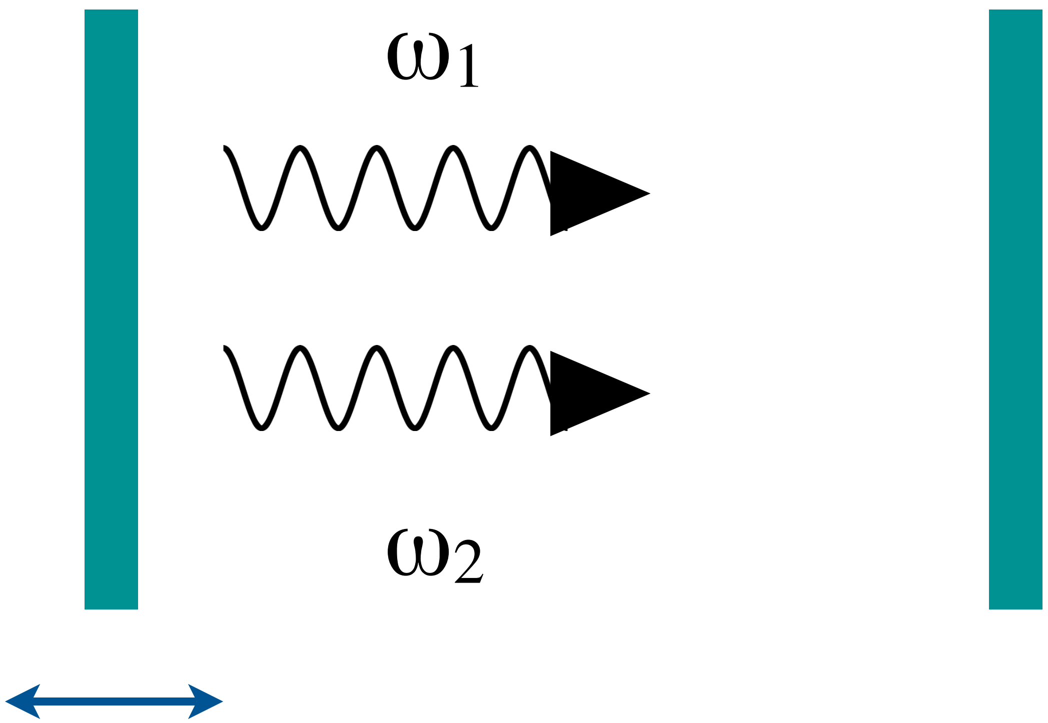
G.T. Moore, J. Math. Phys. 11, 2679 (1970)
S.A. Fulling, P.C.W. Davies, Proc. R. Soc. London Ser. A 348, 393 (1976)
A. Lambrecht, M.-T. Jaekel, S. Reynaud, Phys. Rev. Lett. 77, 615 (1996)
...
P. Nation, J. Johansson, M. Bloncowe, F Nori, Rev. Mod. Phys. 84, 1 (2012)

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.



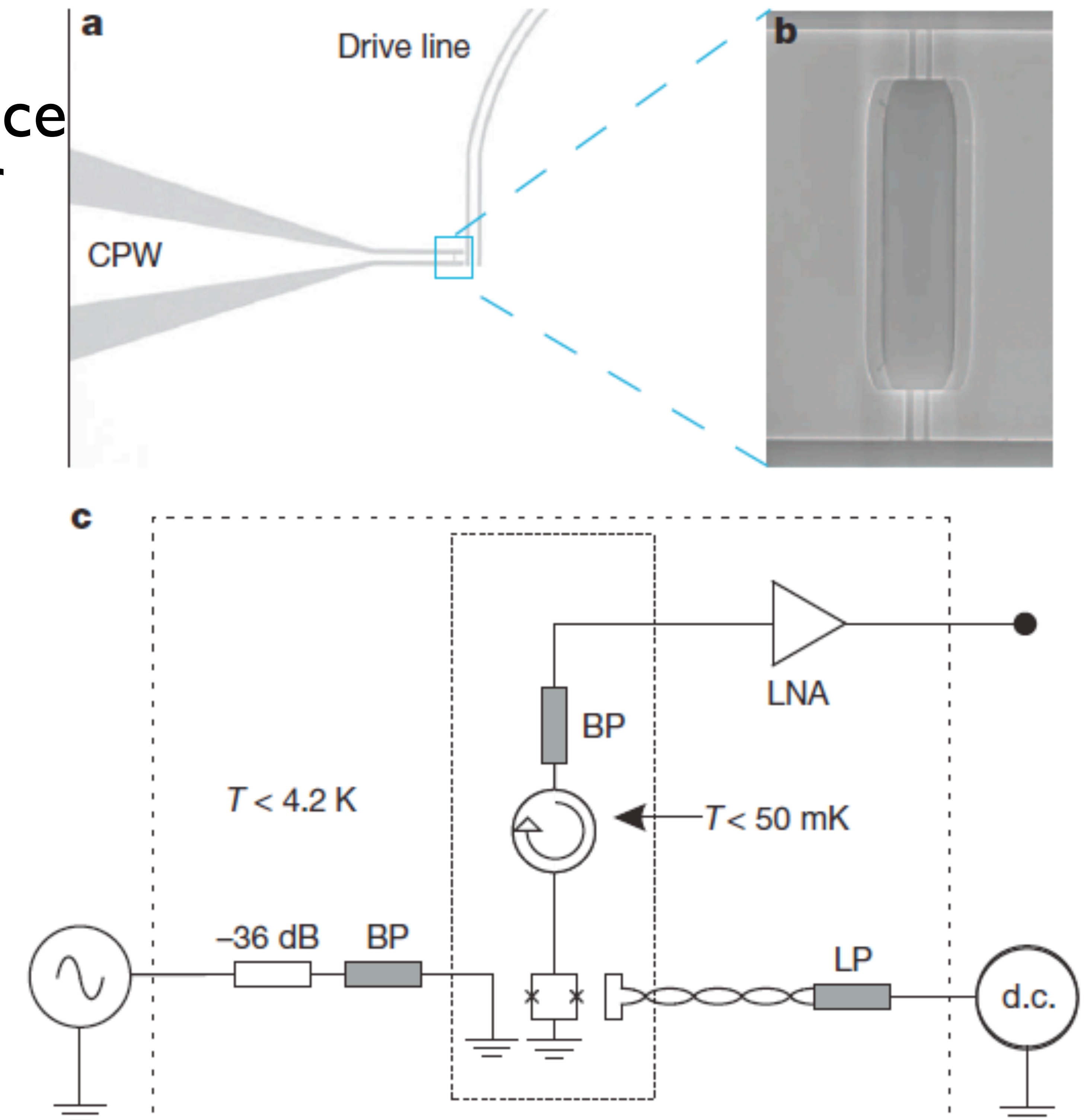
$$v = v_0 \cos \omega t$$

$$N_{\mathrm{photons}} \sim \omega\tau \left(\frac{v}{c}\right)^2 F$$

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

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. PNAS (2013)

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:

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

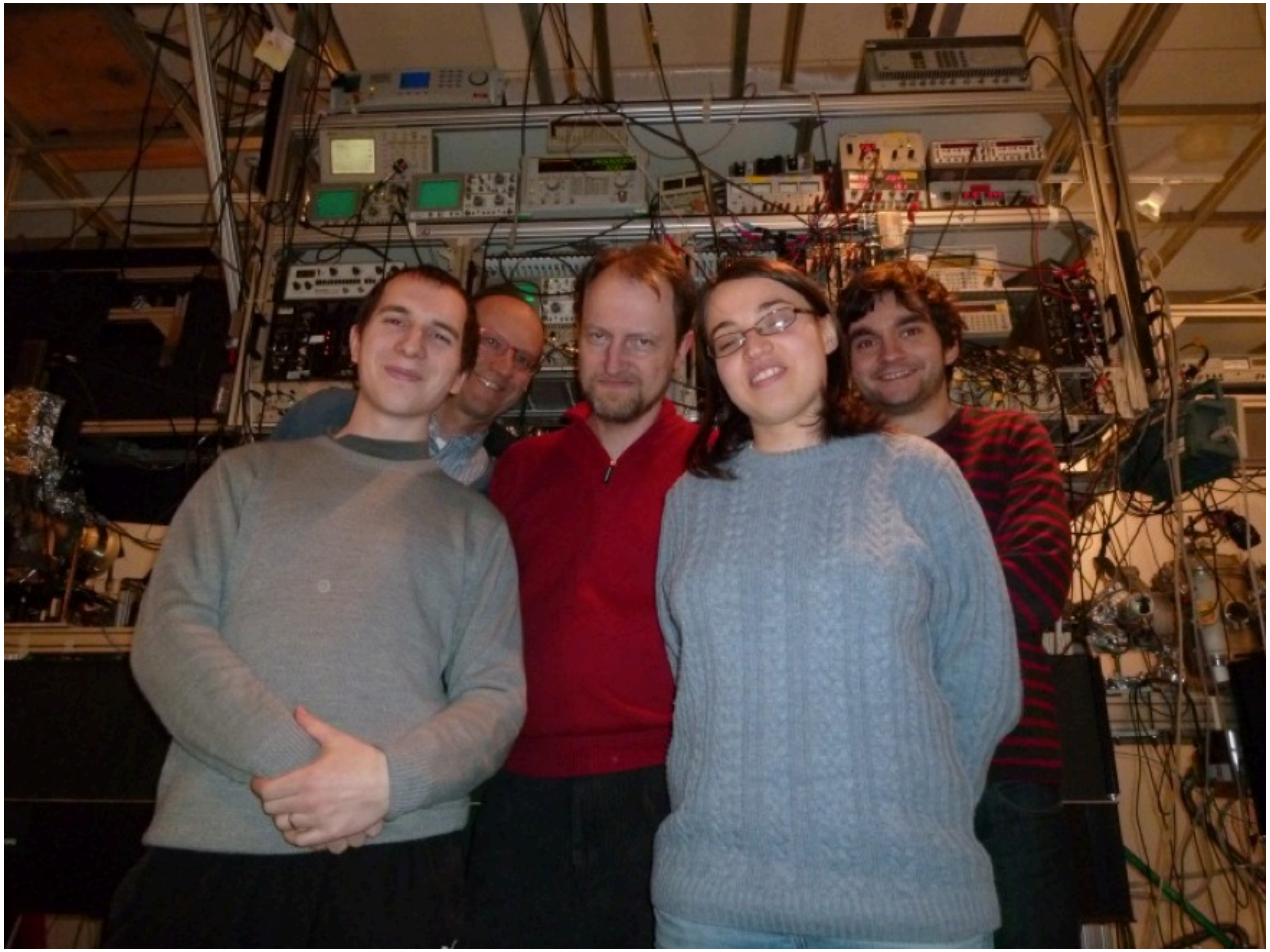
$$\mathcal{H} = \mathcal{H}_0 + \frac{2\pi\hbar^2 n}{m}\,\delta a(t) \sum_{\mathbf{k}} (u_{\mathbf{k}} + v_{\mathbf{k}})^2 \times \boxed{\left(b_k^\dagger + b_{-k}\right)\left(b_k + b_{-k}^\dagger\right)} \quad (9)$$

Pair creation

Or modulate something else: $c_s^2 = (4\pi\,\hbar^2)\; a\; \varrho/m^2$

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

Jean-Christophe
Jaskula

C I W Denis Boiron Rafael Lopes

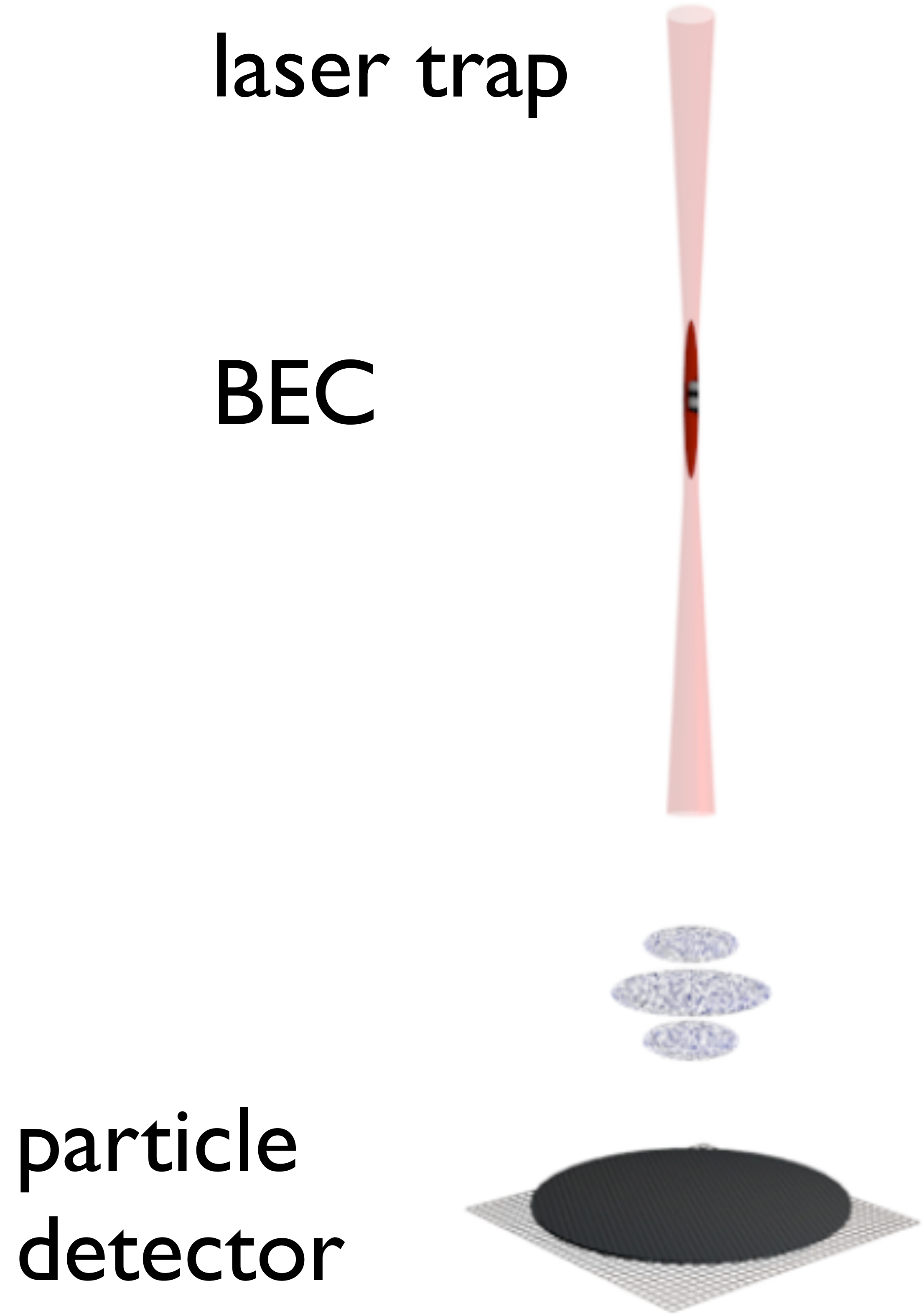
Josselin Ruaudel Marie Bonneau

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.

trap

46 cm

detector

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

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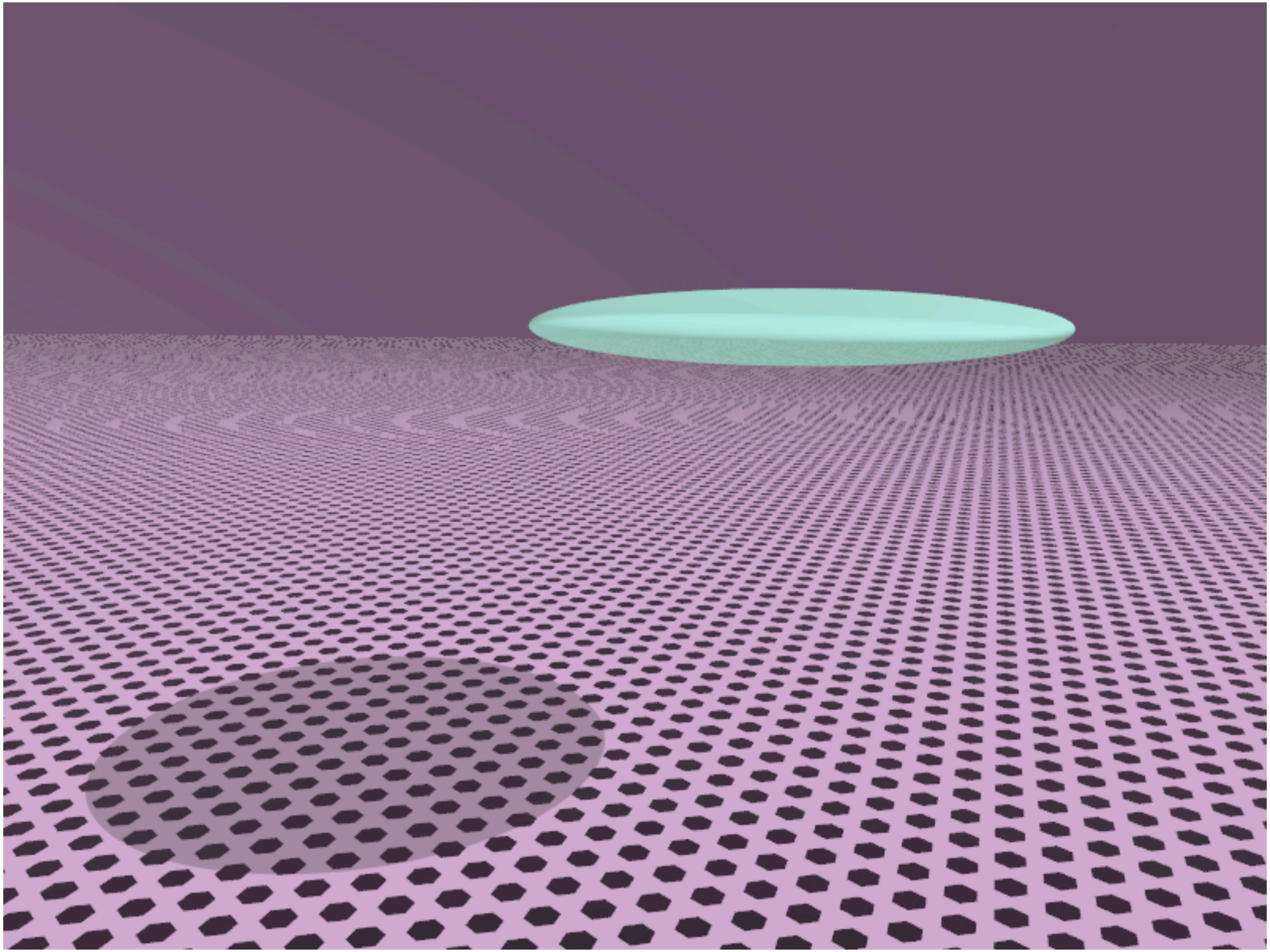
detector

Close-up of MCP (not to scale)

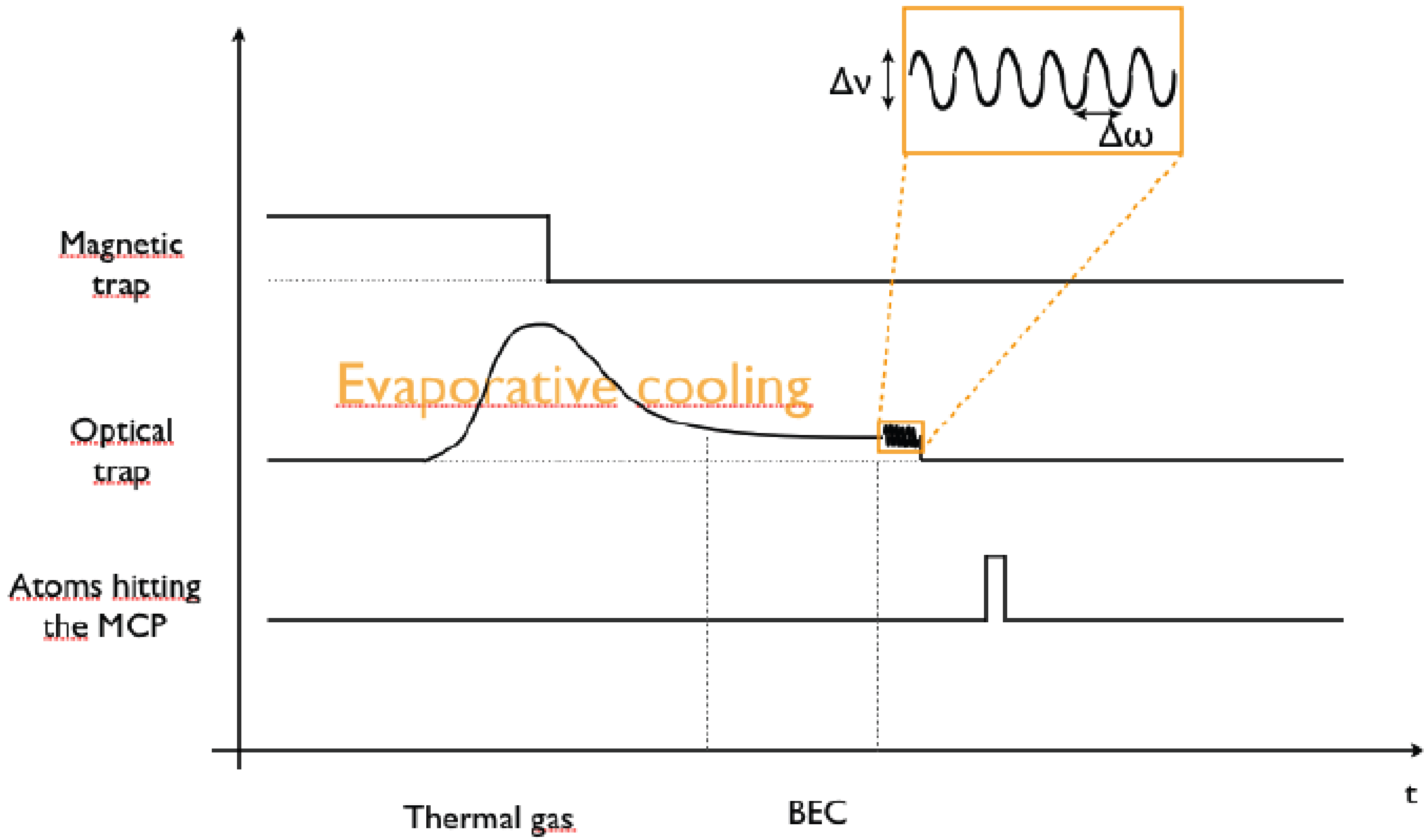


hole separation: 24 μm   transverse BEC size: ~ 3 cm   q. e. 25%

Analog to the dynamical Casimir effect

inspired by Carusotto et al EPJD 2010

modulation: $\Delta t = 30$ ms
$\Delta\nu = 0.1\ \nu_{trap}$
$\Delta\omega_{mod}/2\pi = 0.5$ - 5 kHz



Analog to the dynamical Casimir effect

inspired by Carusotto et al EPJD 2010

Generate excitations:

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

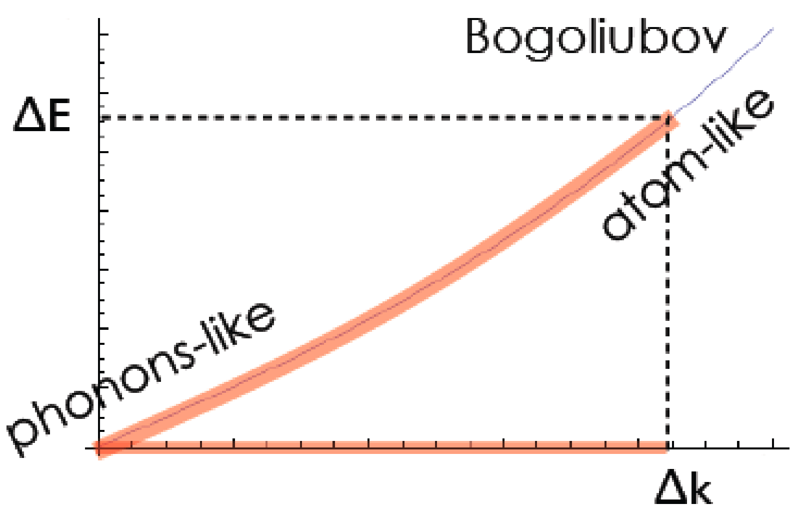
as should be the case for a parametric oscillator

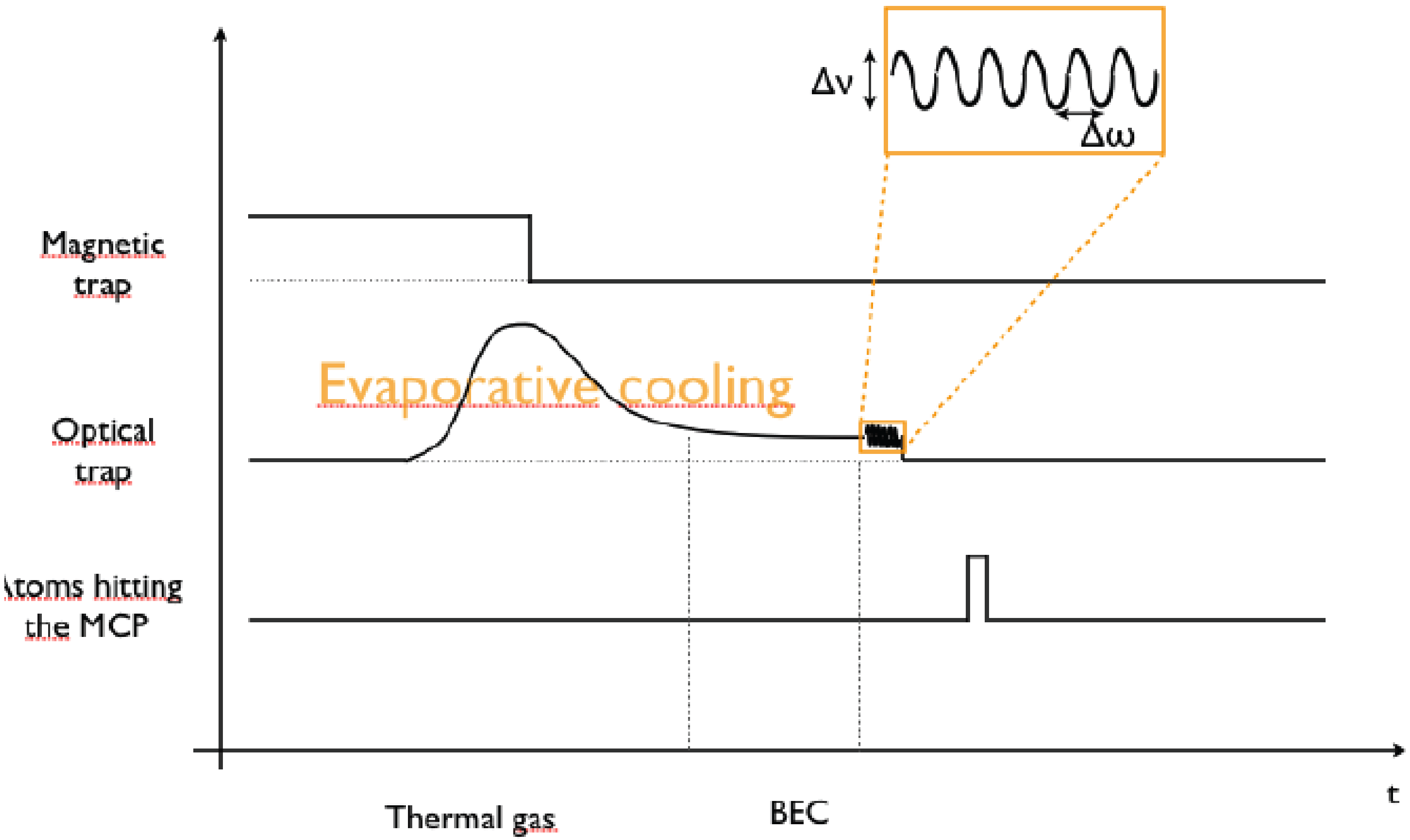
$H \sim b_k^\dagger\, b_{-k}^\dagger + h.c.$

modulation: $\Delta t = 30$ ms

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

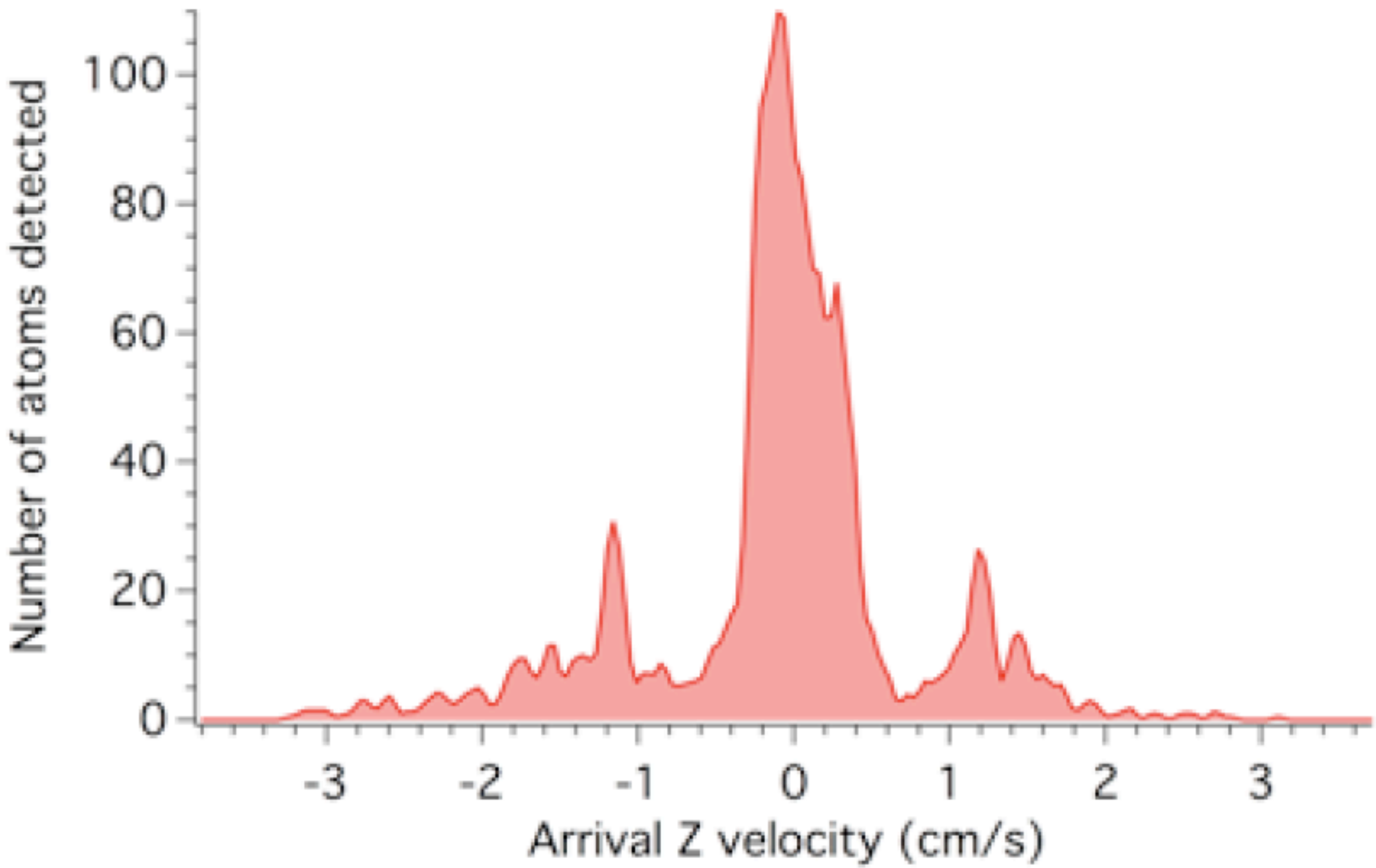
$\Delta\omega_{mod}/2\pi = 0.5$ - 5 kHz





sinusoidal modulation (velocity scale)

$n(v)$



sinusoidal modulation (velocity scale)

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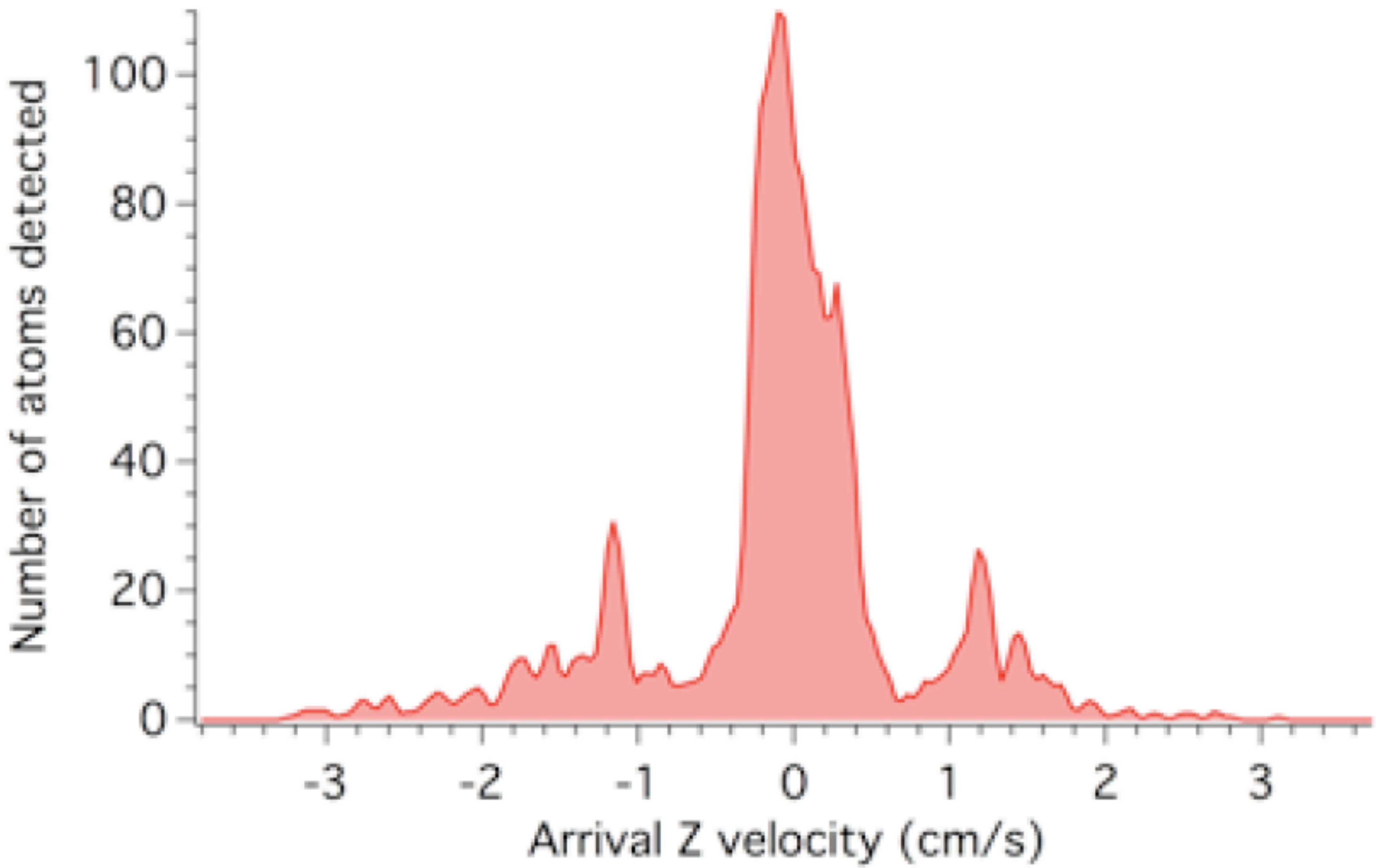
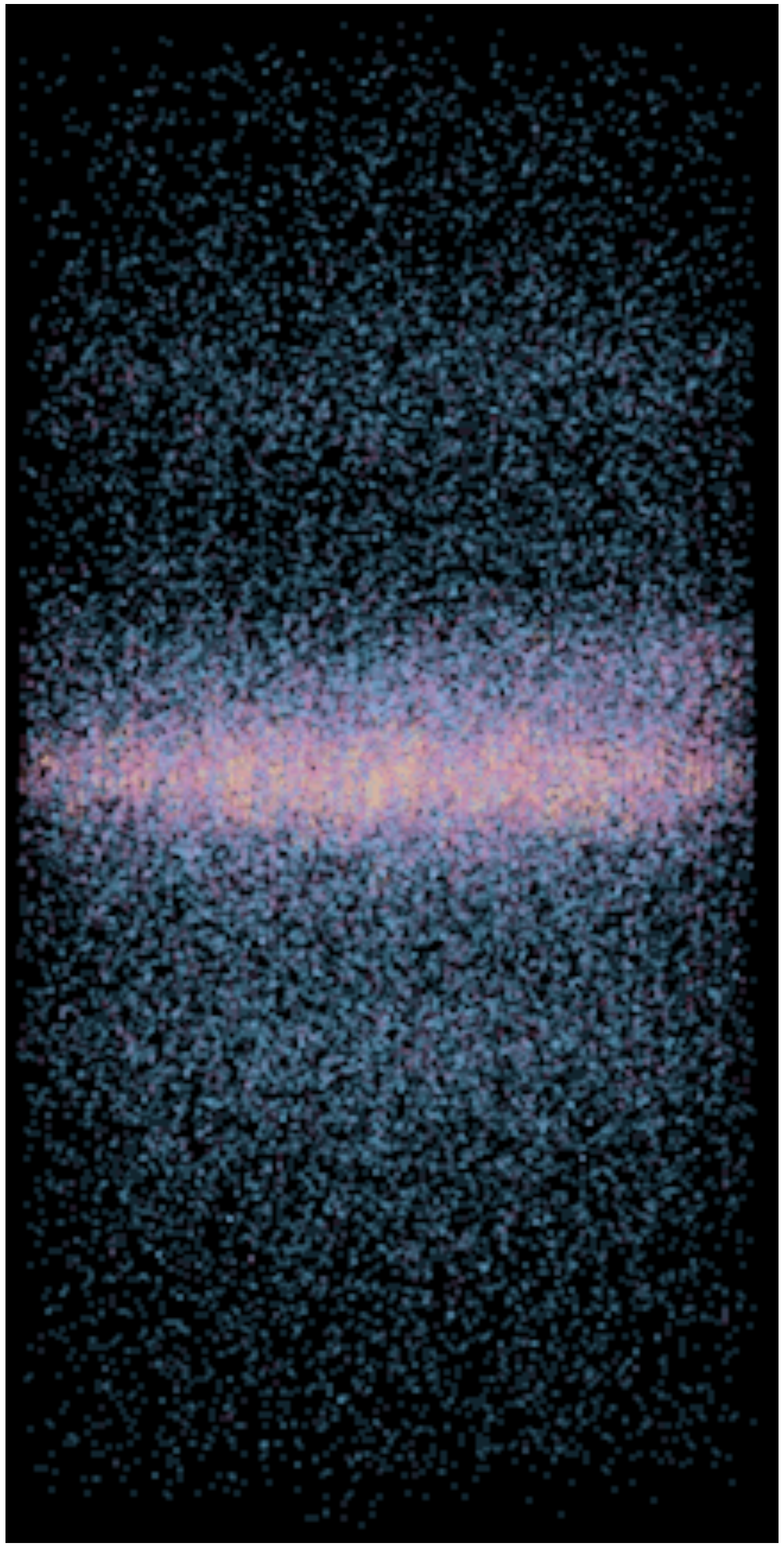
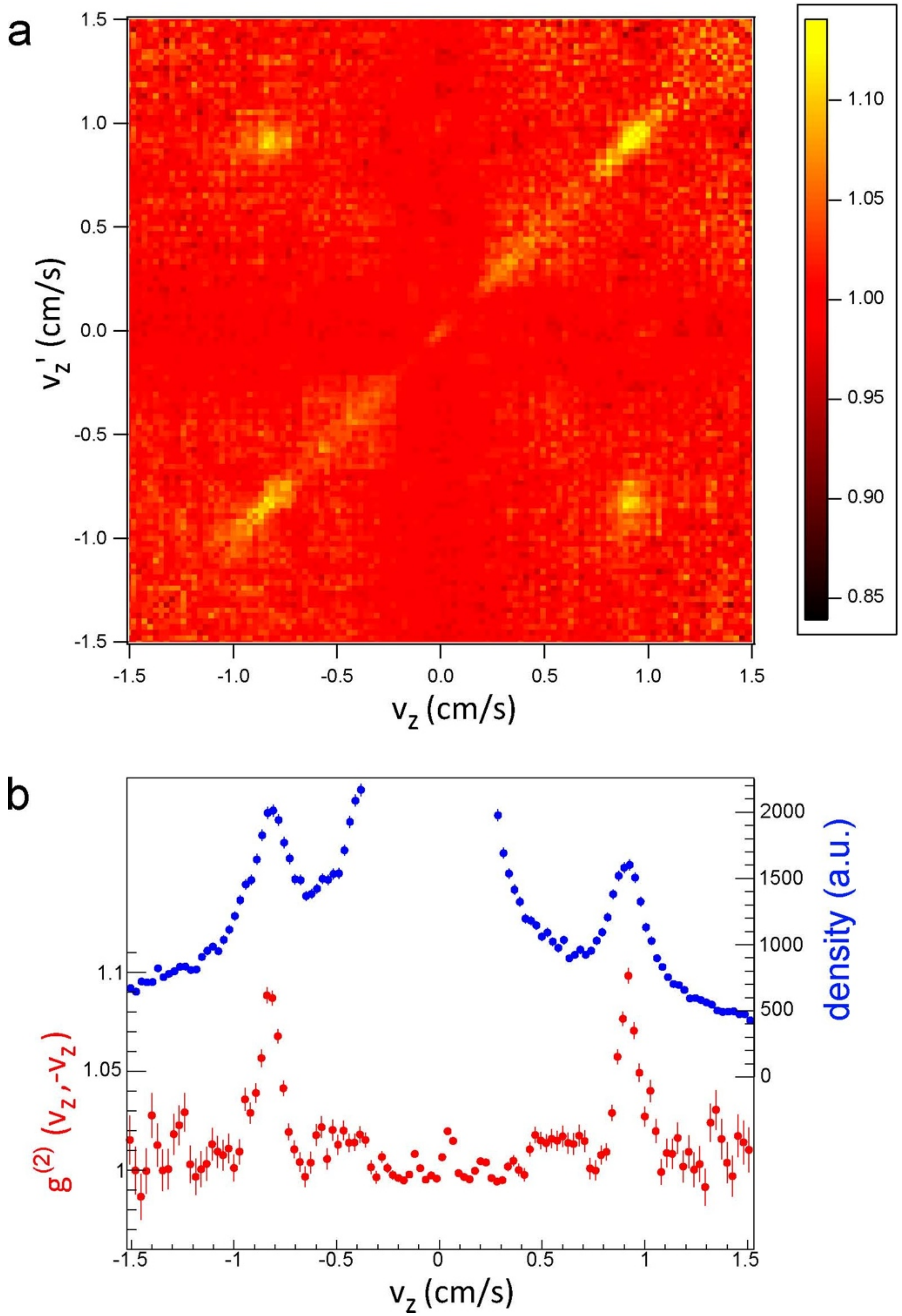




Correlation function

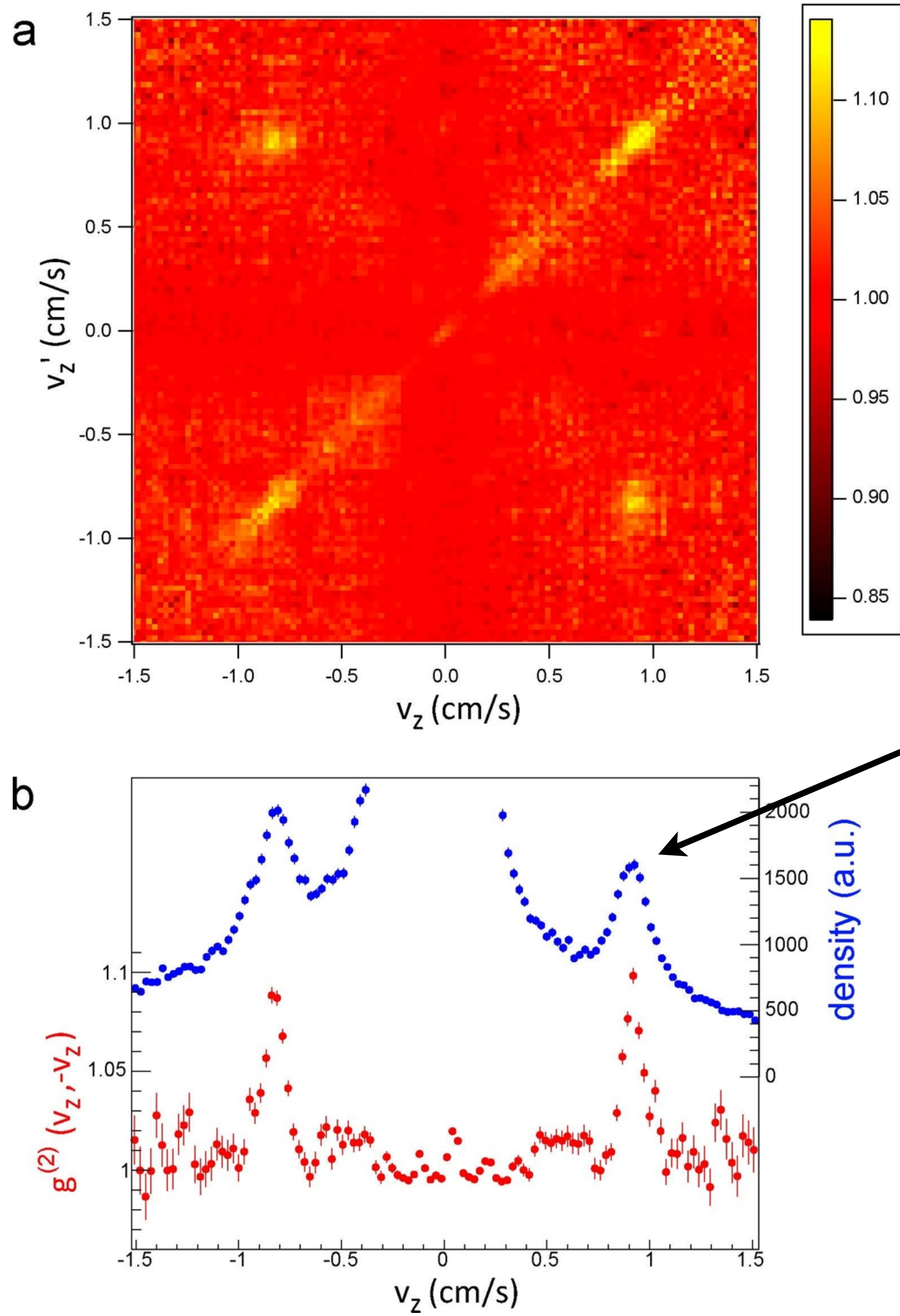


$$g^{(2)}(v,v') = \frac{\text{pair histogram of single shots}}{\text{histogram of different shots}}$$

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

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

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?

$n(v)$

$v = \hbar k / m$

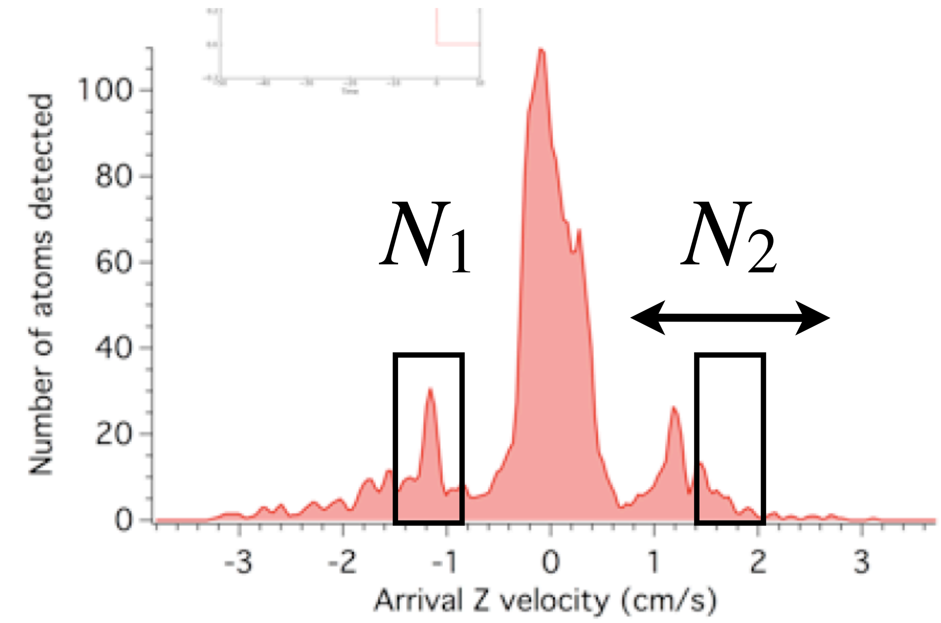
$g^{(2)}(v, v' = -v)$

So far so good, but...

Nonzero temperature:

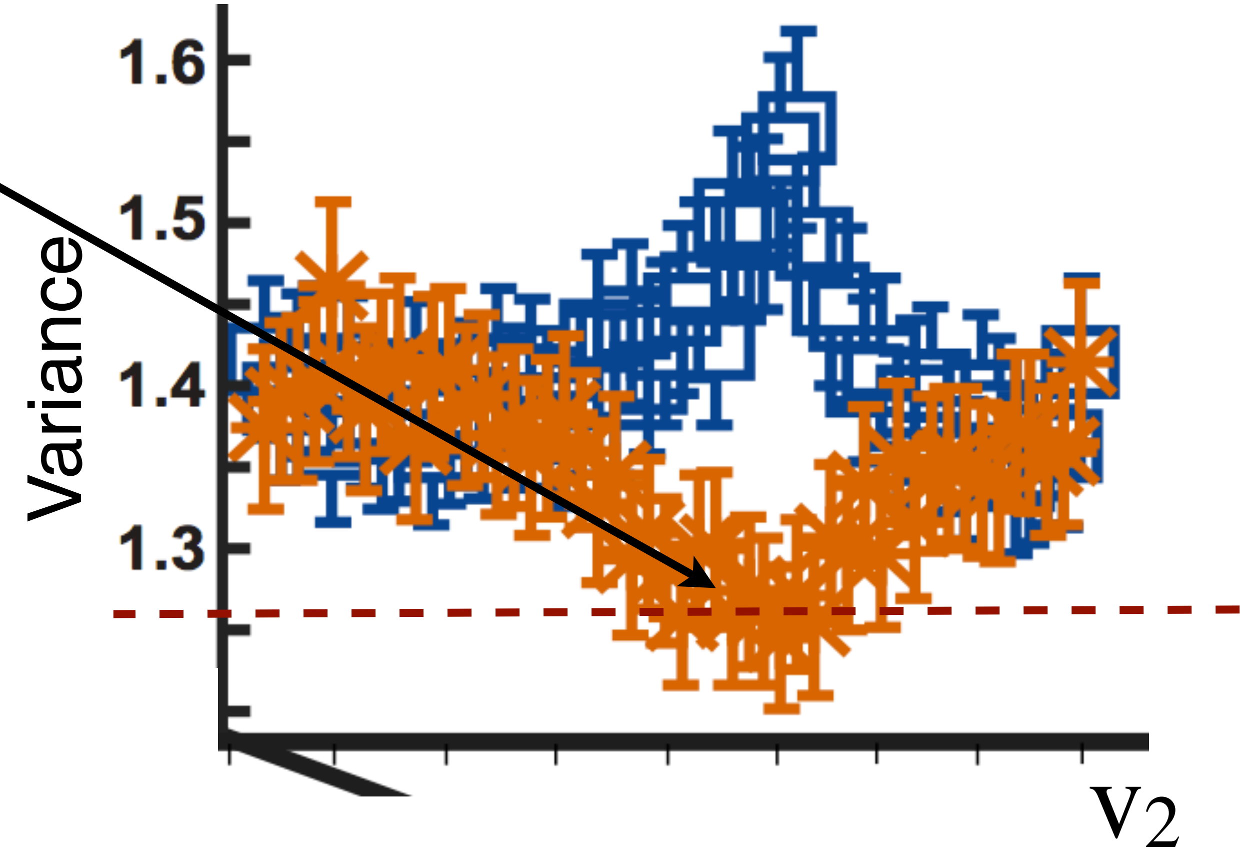
$k_B T/h = 4$ kHz (200 nK)

thermally stimulated



Lack of sub-Poissonian statistics:

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

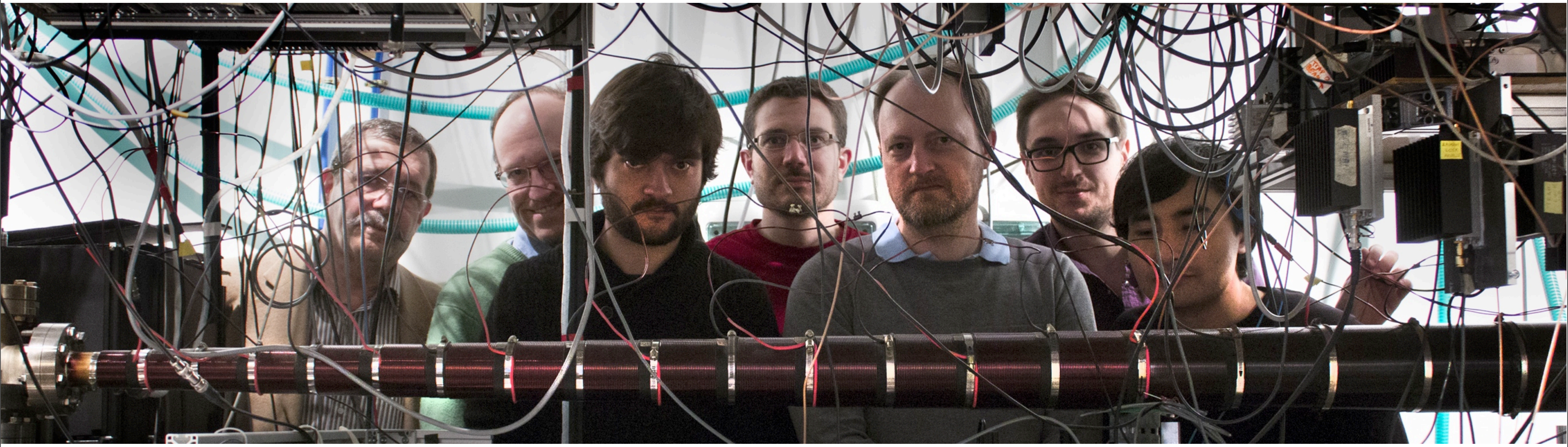


No violation of Cauchy-Schwarz inequality

Due to $T \neq 0$?

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

Atom Entanglement team



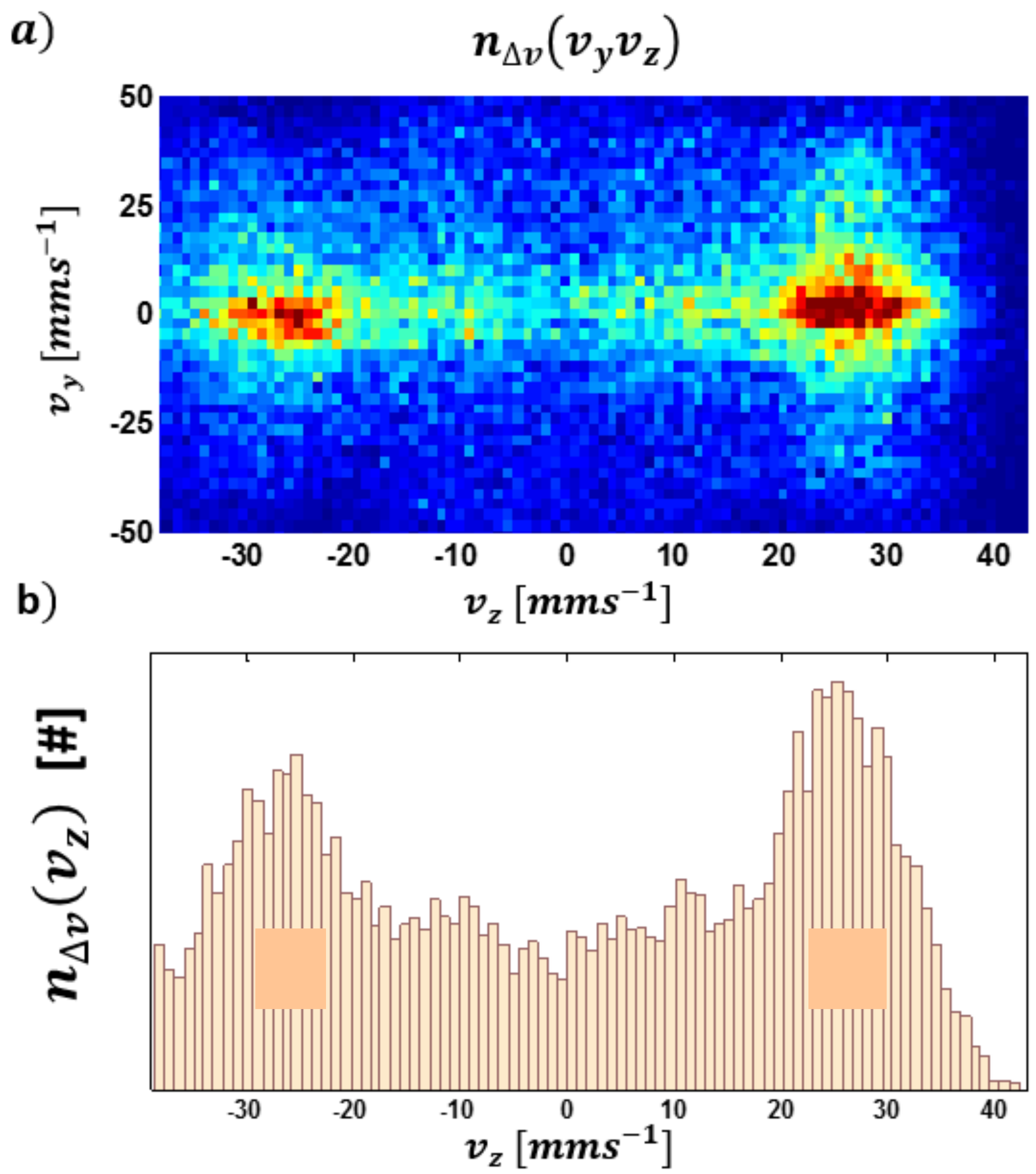
Maxime Perrier | Alain Aspect | C I W | Marc Cheneau | Pierre Dussarat | Ziad Amodjee

Raphael Lopes | Denis Boiron | Almazbek Imanaliev

We haven't done it for phonons, but we can also look at higher energy excitations: individual atoms.

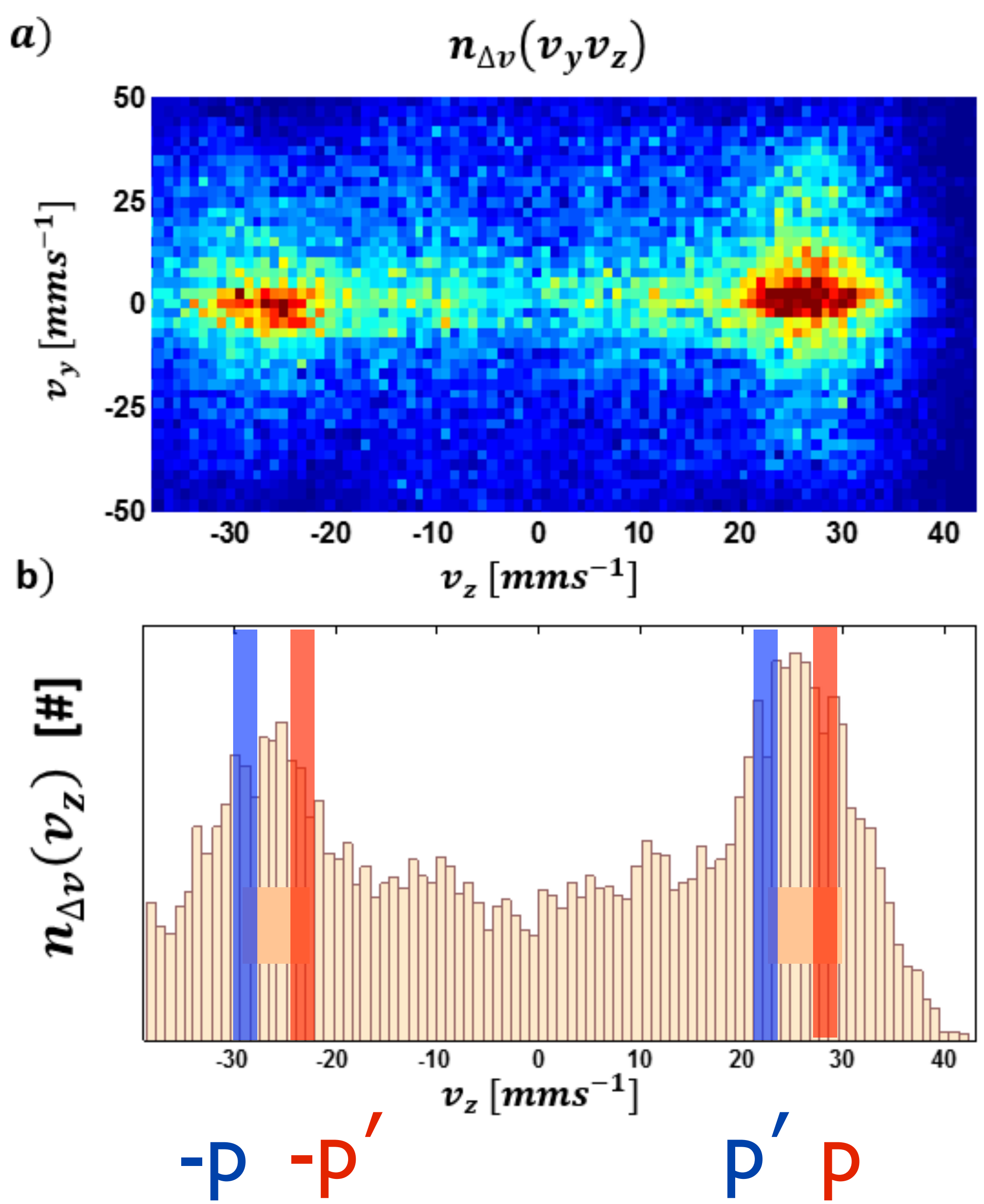
Entanglement of atoms in 2017

A different source of pairs (atomic collisions)



Entanglement of atoms in 2017

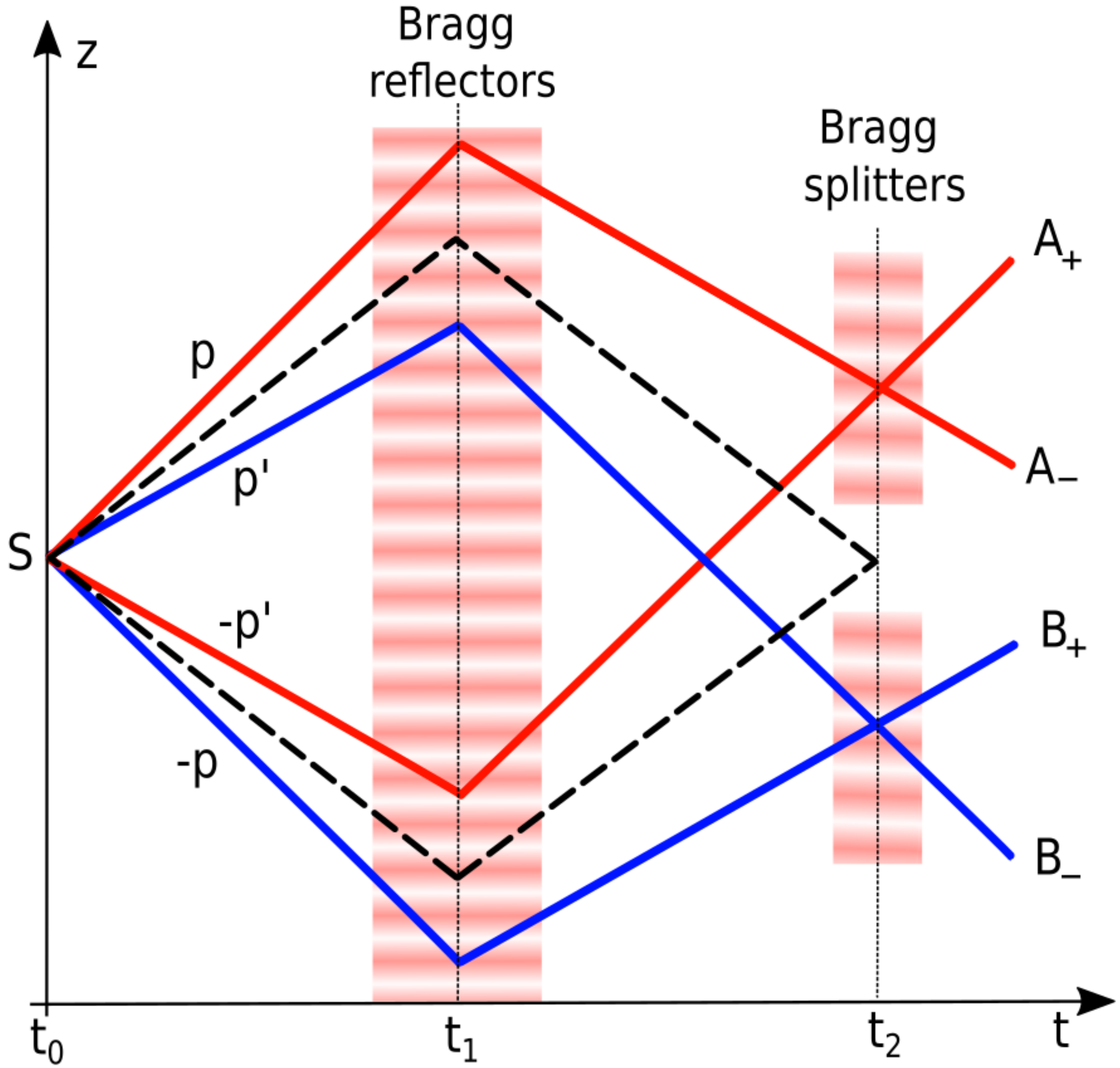
A different source of pairs (atomic collisions)



p and -p are correlated
p′ and -p′ are correlated
A pair can be in a superposition of both:

$$|\psi\rangle = 1/\sqrt{2}\left(|p, p'\rangle + |-p, -p'\rangle\right)$$

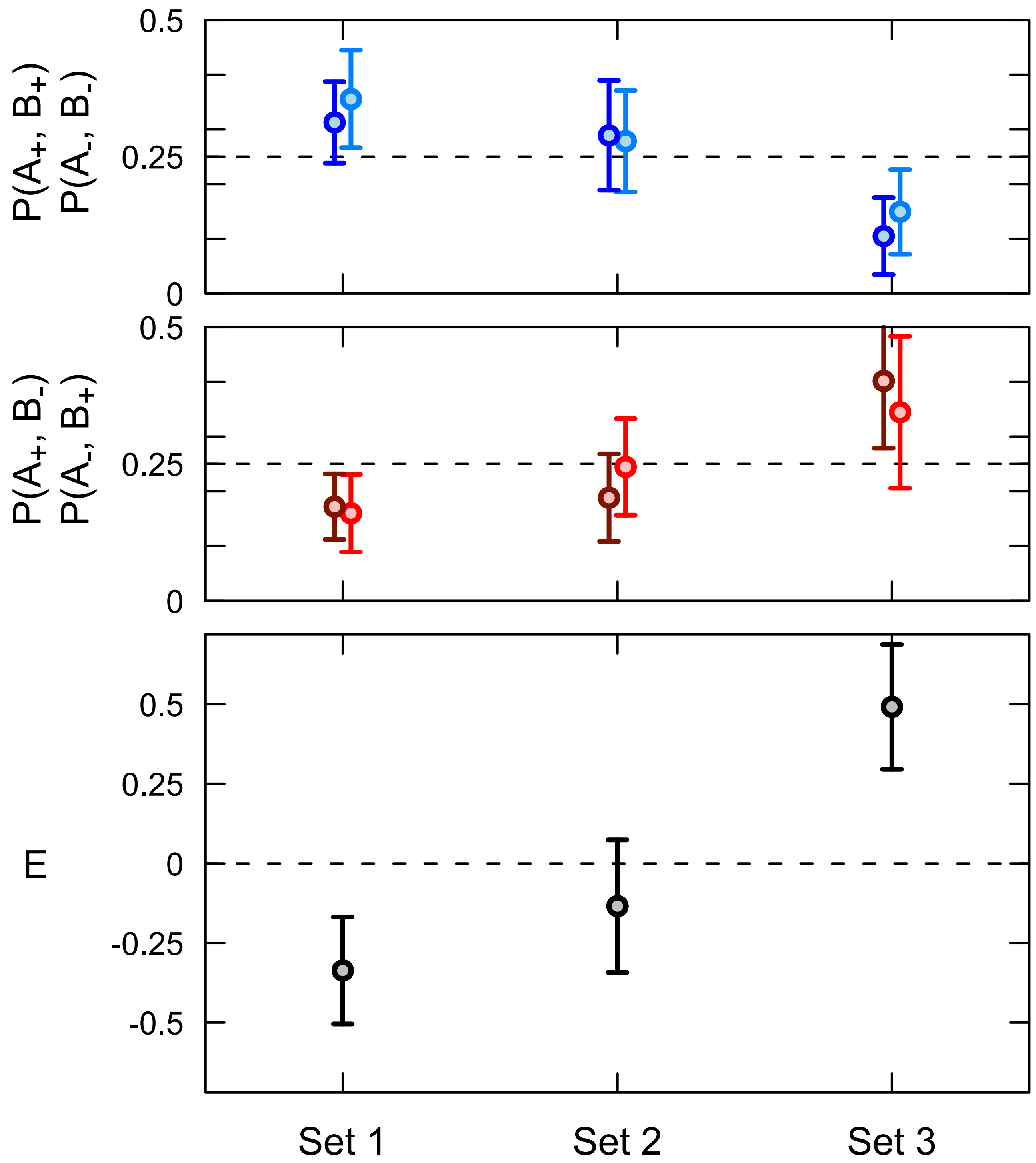
2 particle interferometer



Singles rates $A_\pm$, $B_\pm$ are all equal

$$E = \mathcal{P}(A_+, B_+) + \mathcal{P}(A_-, B_-) - \mathcal{P}(A_+, B_-) - \mathcal{P}(A_-, B_+)$$

Data



$$
\begin{aligned}
E &= \mathcal{P}(A_+, B_+) + \mathcal{P}(A_-, B_-) \\
&\quad - \mathcal{P}(A_+, B_-) - \mathcal{P}(A_-, B_+) \\
&= V \cos(\phi_A - \phi_B) \ .
\end{aligned}
$$

Data consistent with an entangled state

No Bell violation (yet)

Future

Demonstrate phase dependence in interferometer → entanglement

Violate Bell's inequality with freely falling atoms

Observe sub-Poissonian effect for dynamical Casimir effect

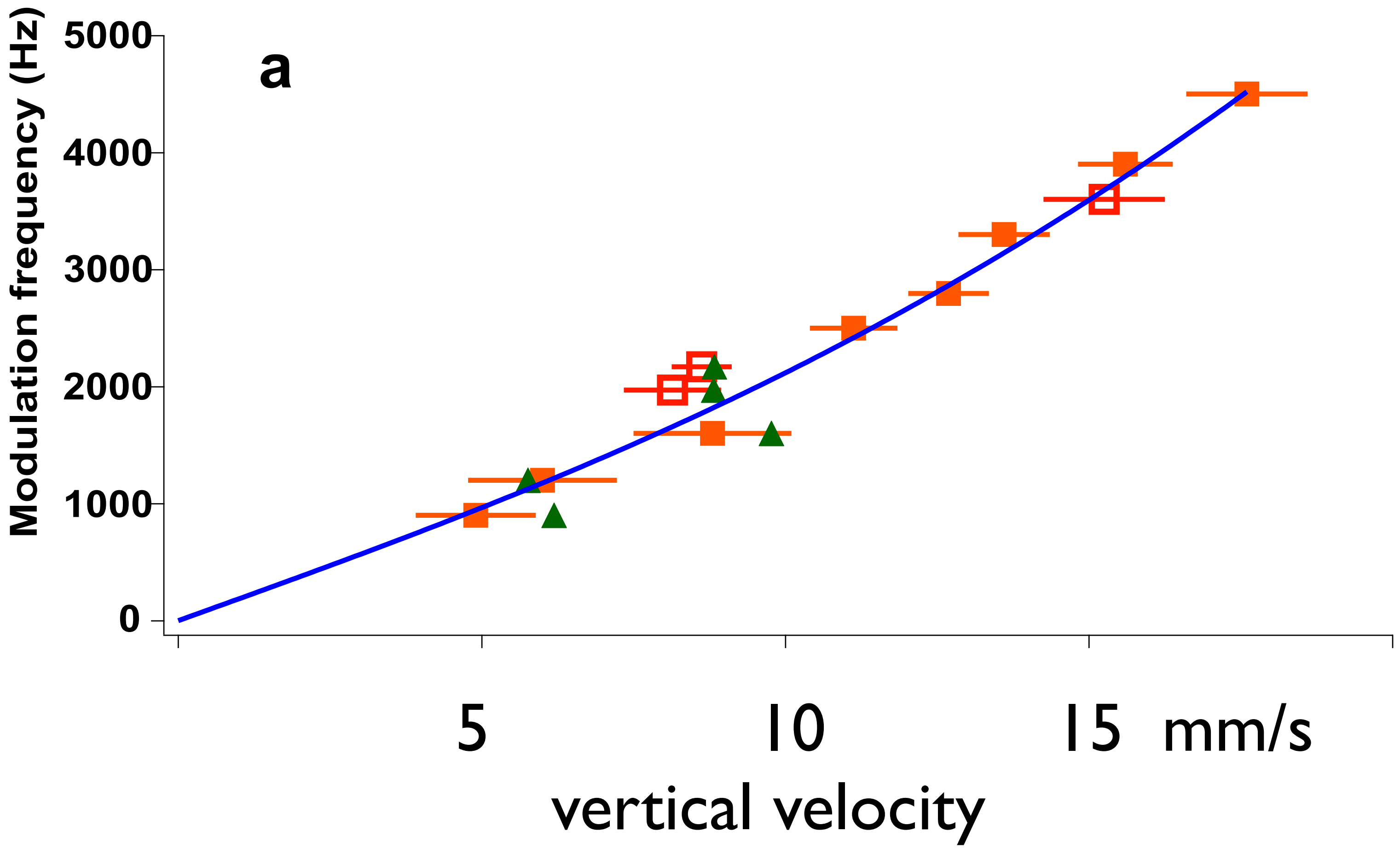
Demonstrate entanglement for dynamical Casimir

Go after Hawking radiation

Thanks

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

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

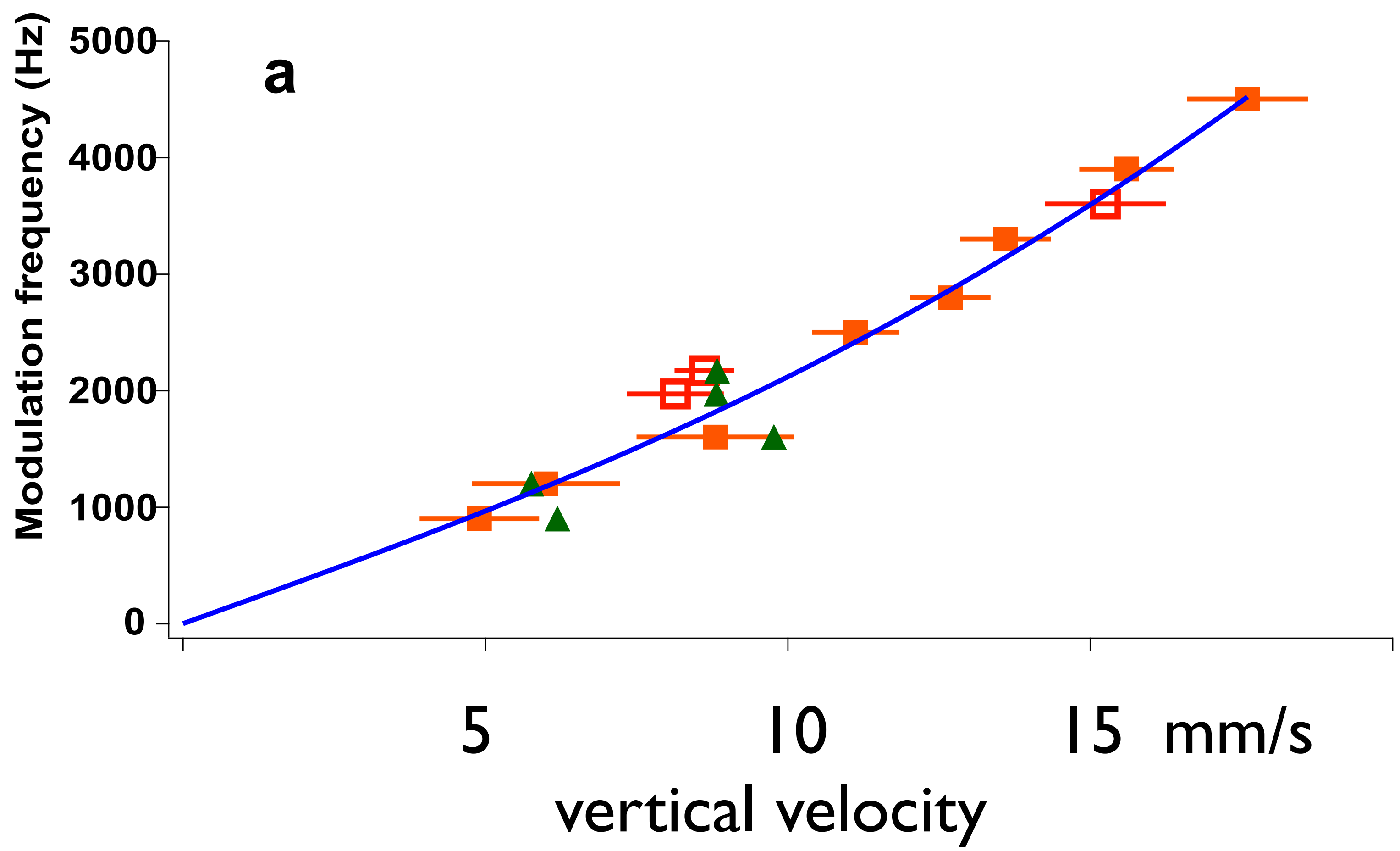


■ from density

▲ from correlation function

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

$$\omega_{\text{mod}} = 2\omega_k = \alpha\sqrt{\frac{\hbar^2 k^2}{2m}\left(\frac{\hbar^2 k^2}{2m} + 2mc^2\right)}$$



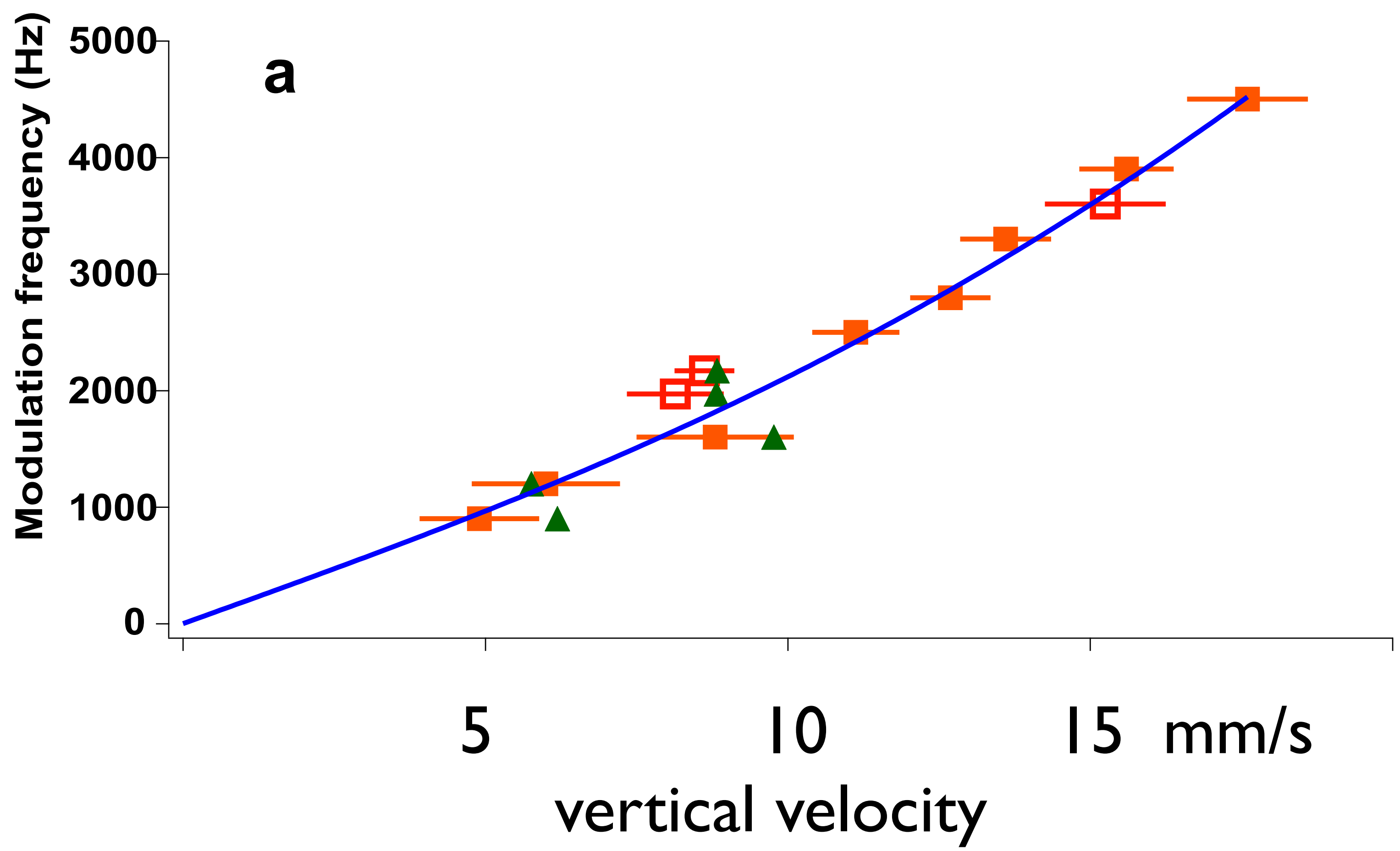
- ■ from density
- ▲ from correlation function

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

$$\omega_{mod} = 2\omega_k = \alpha \sqrt{\frac{\hbar^2 k^2}{2m}\left(\frac{\hbar^2 k^2}{2m} + 2mc^2\right)}$$

fit: $\alpha = 2.2$

$c = 8$ mm/s



- ■ from density
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How to show $\omega_{\mathrm{mod}} = \omega_k + \omega_{-k}$

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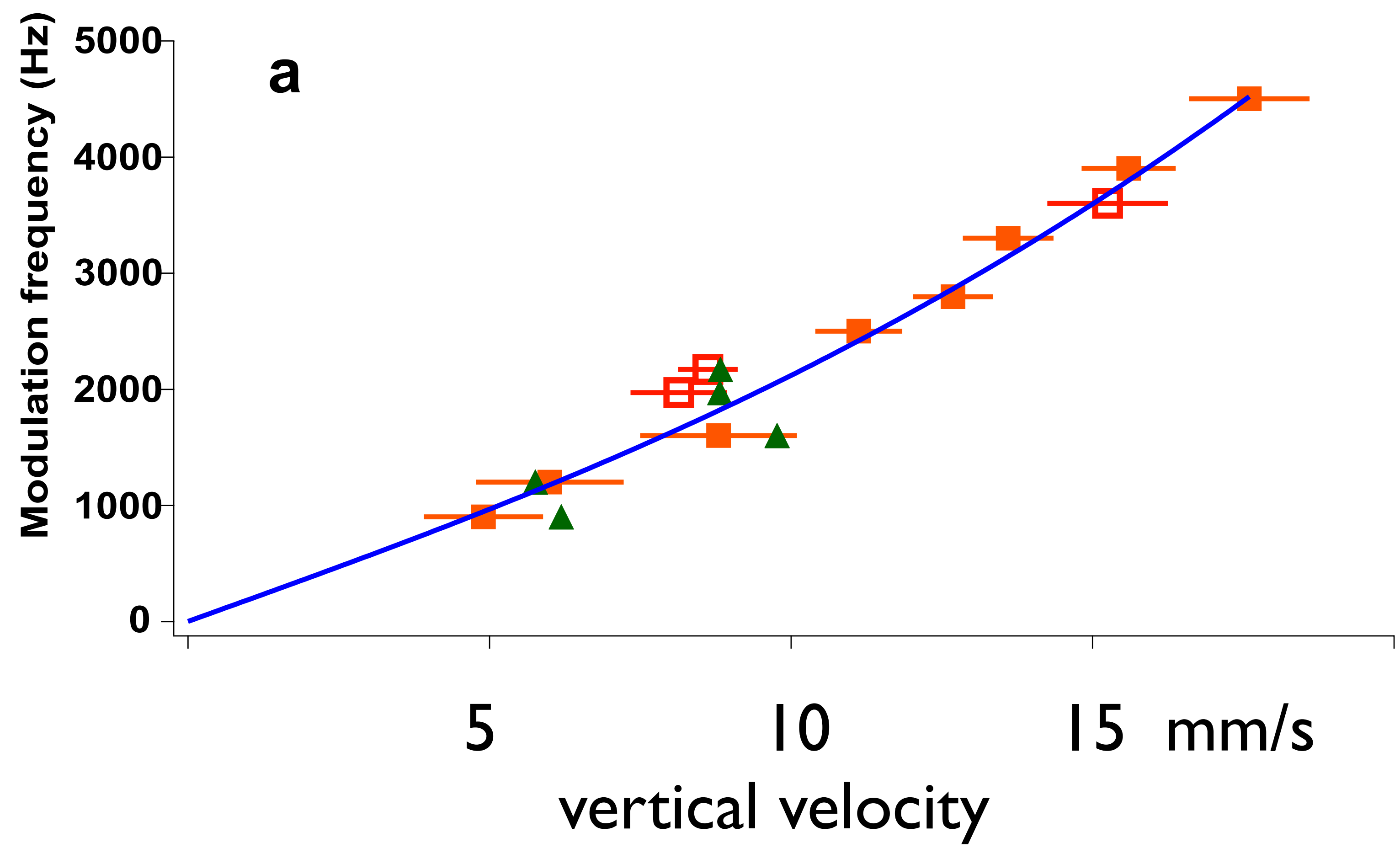
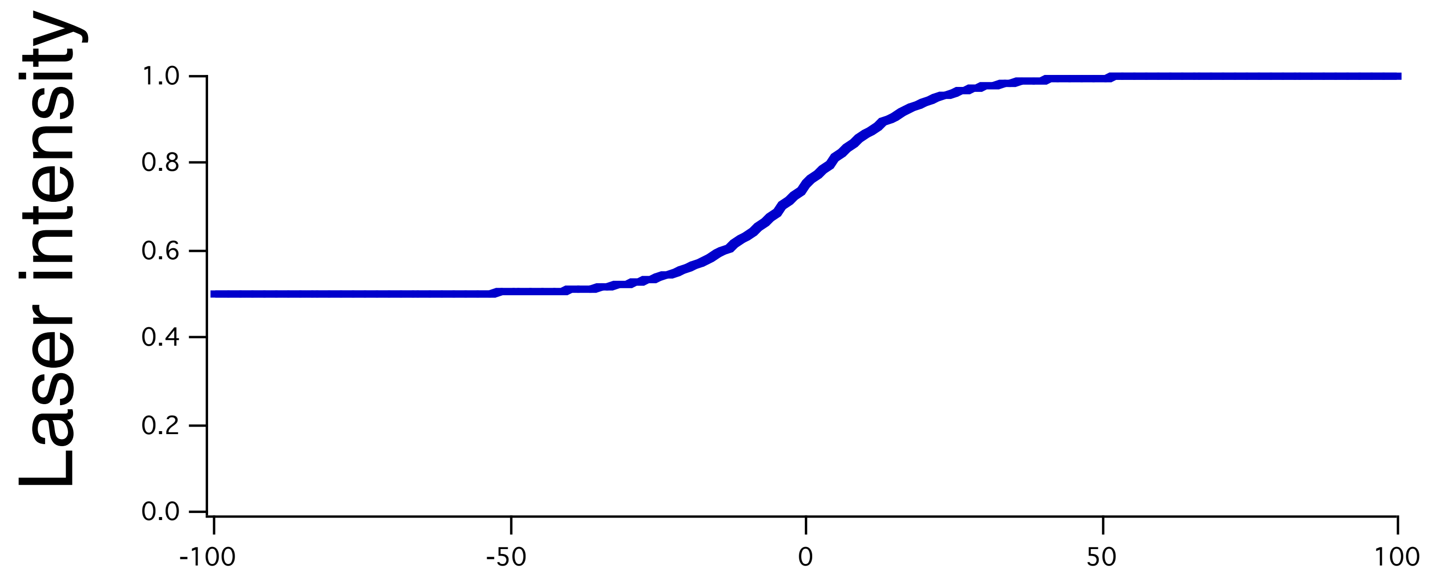


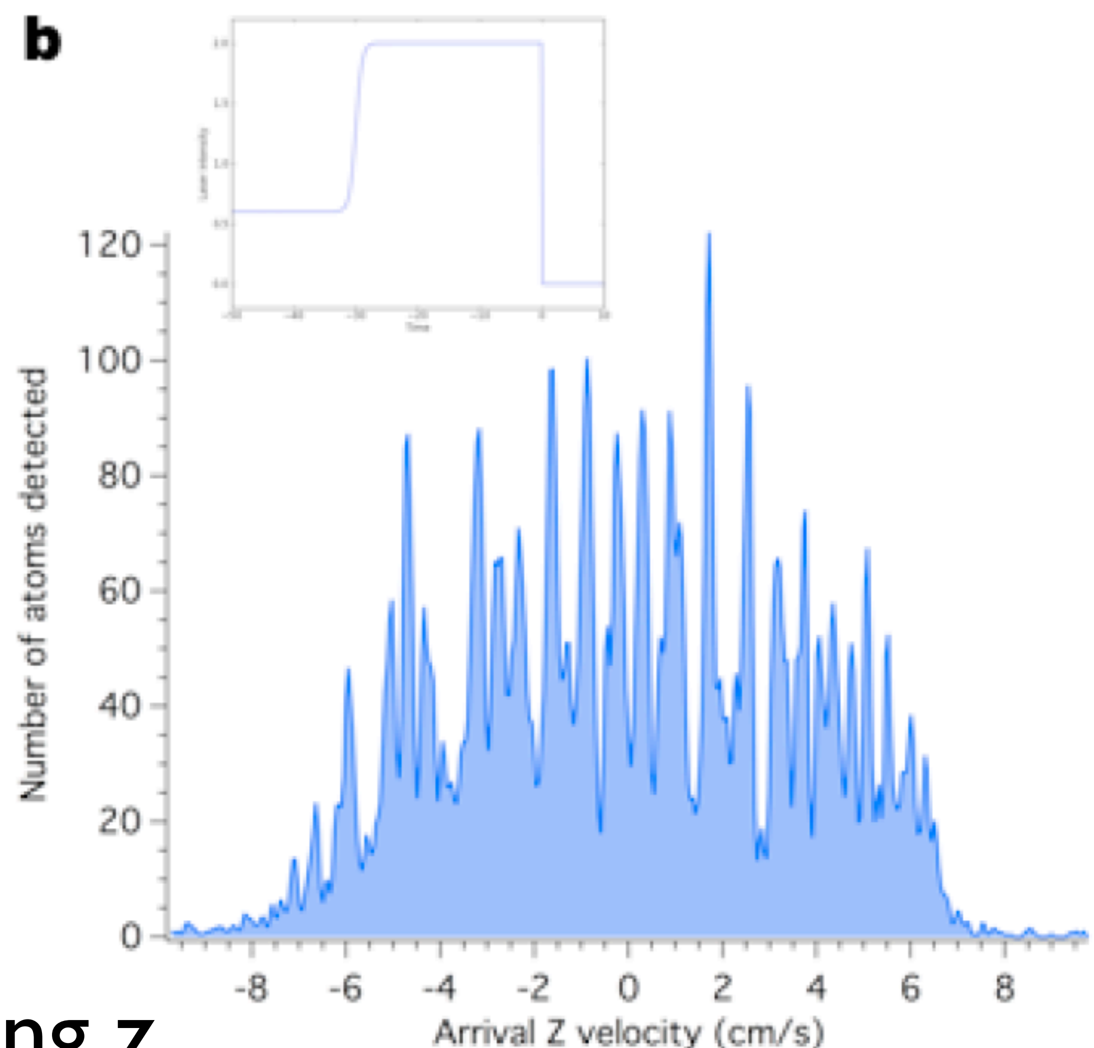
- ■ from density
- ▲ from correlation function

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

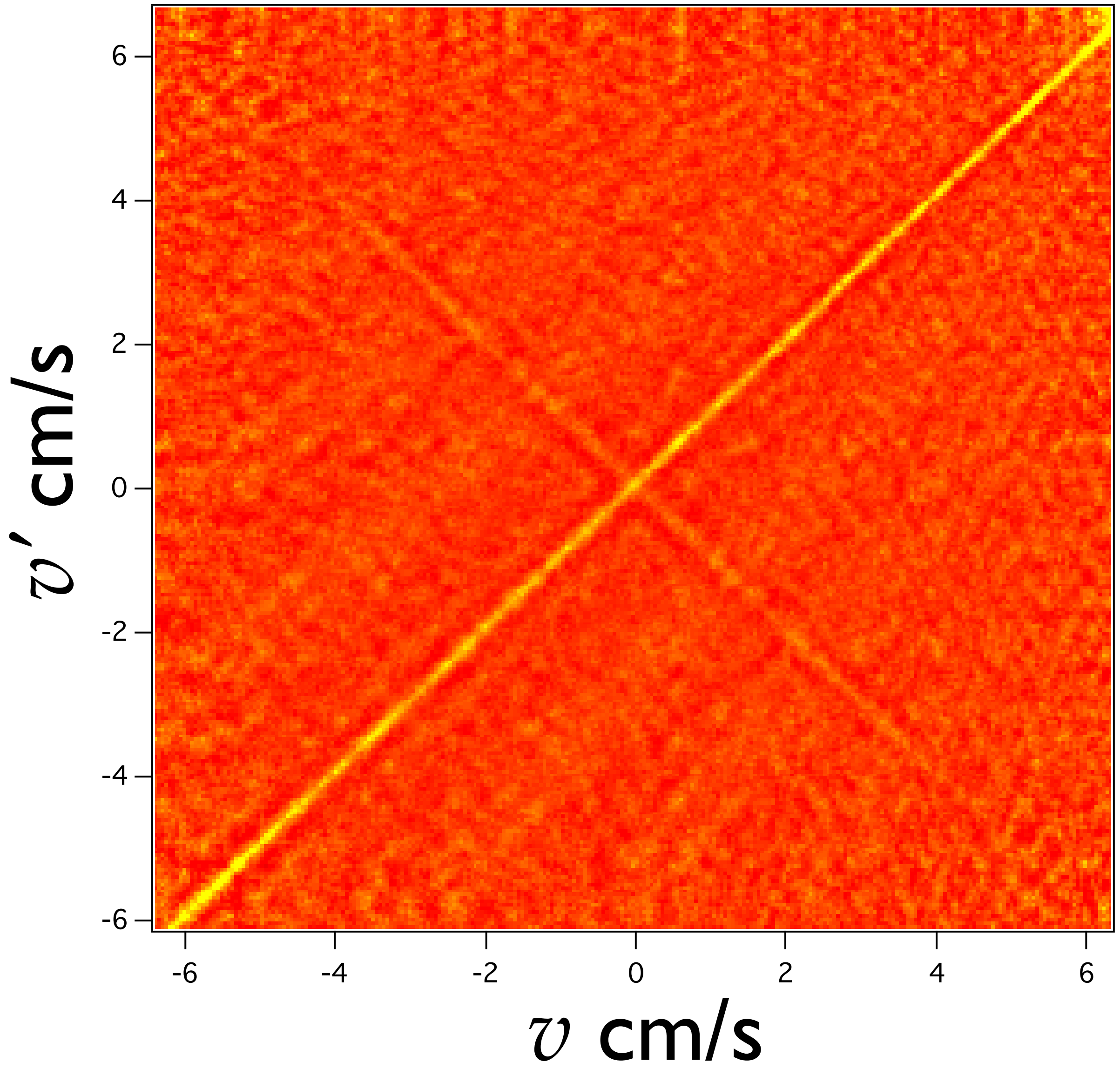


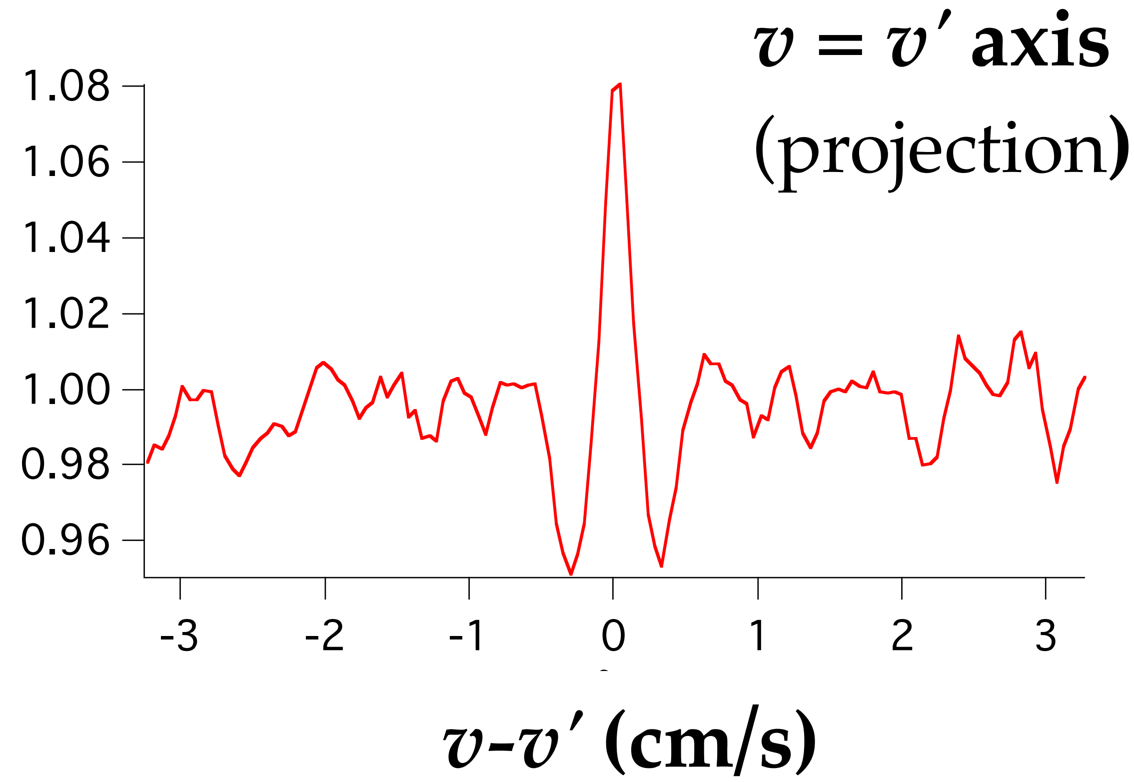


(quasi-)condensate parameters:
$l_z = 0.5$ mm
$\omega_\varrho = 1.5$ kHz, $\omega_z = 7$ Hz
Highly elongated
$\mu \sim 3$ kHz
c ~ 1 cm/s
$\xi = 500$ nm

Distribution along z

Correlations in the v - v′ plane





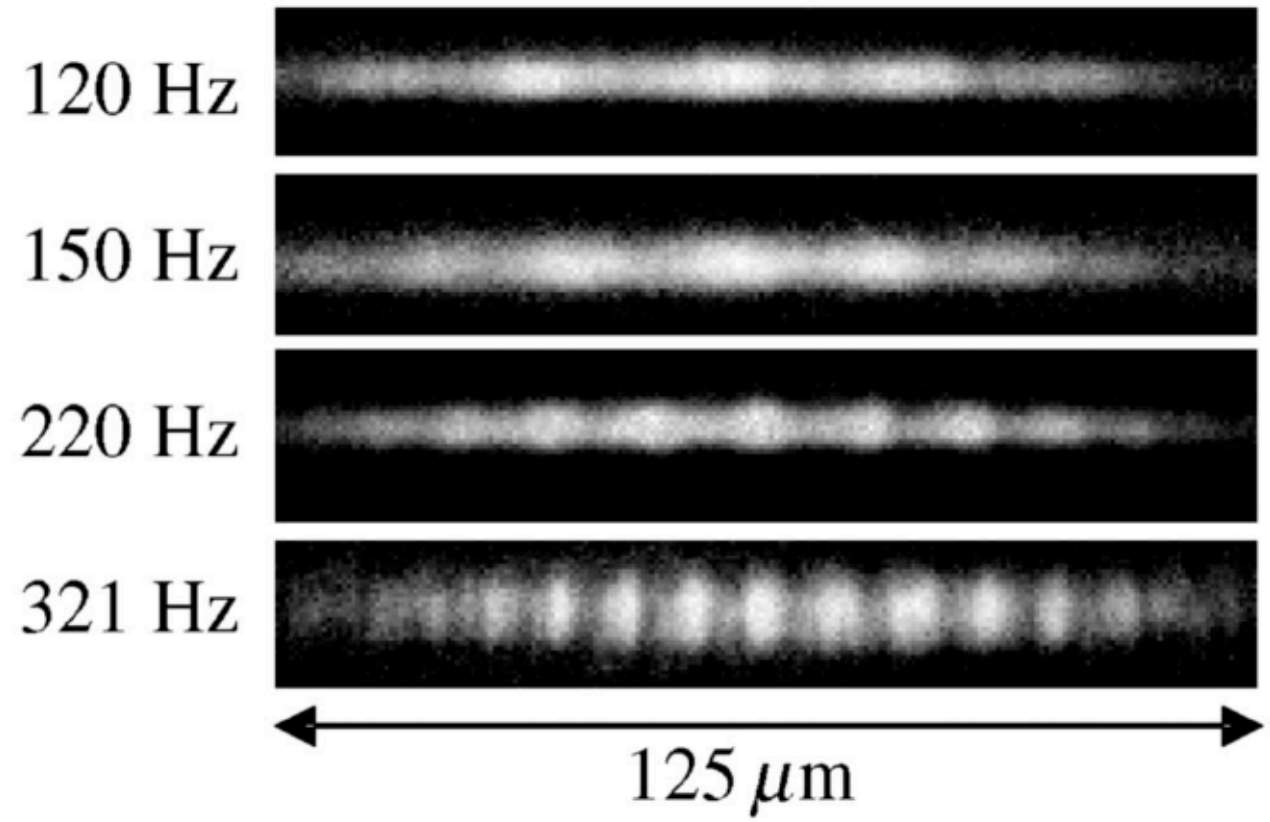
$$g^{(2)}(v,v') = \frac{\text{pair histogram of single shots}}{\text{histogram of different shots}}$$

HBT effect

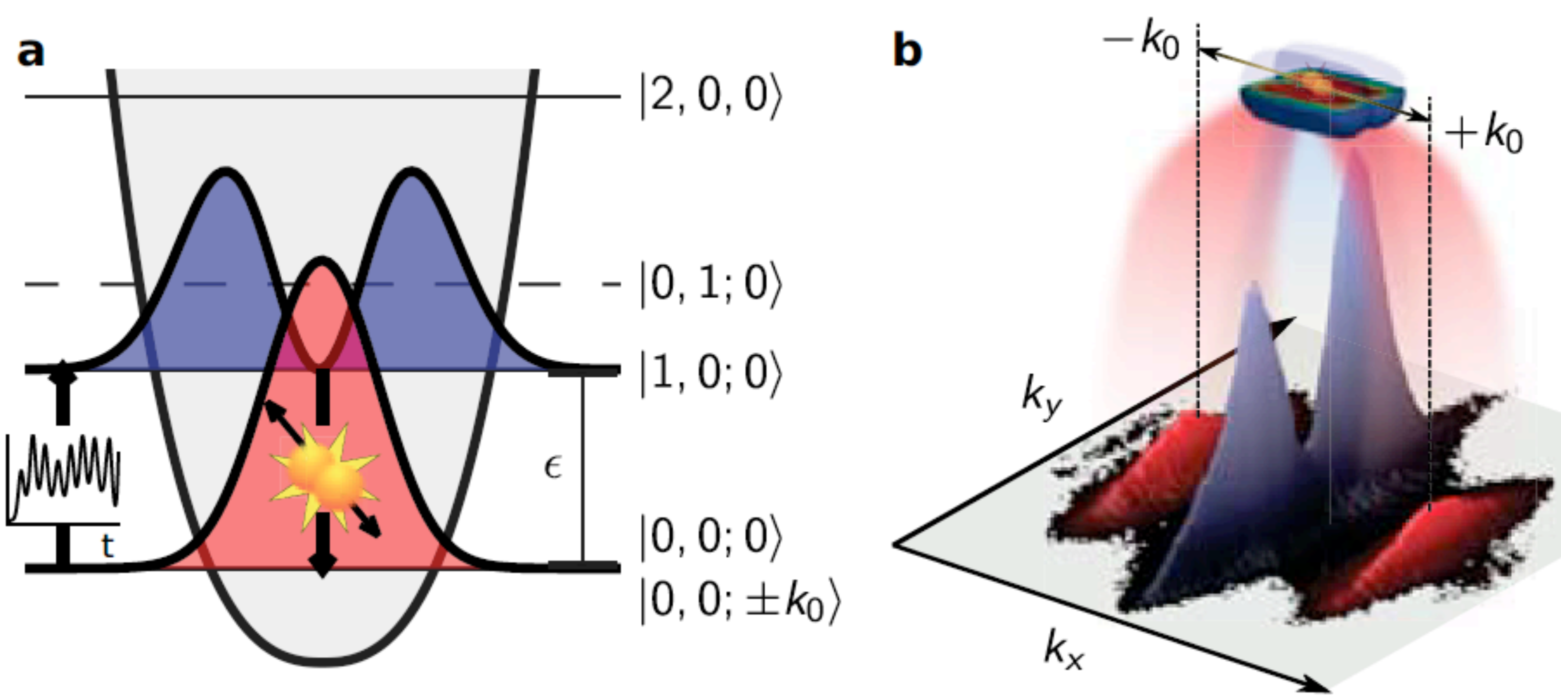
$v,-v$ correlation

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 $\omega/2$

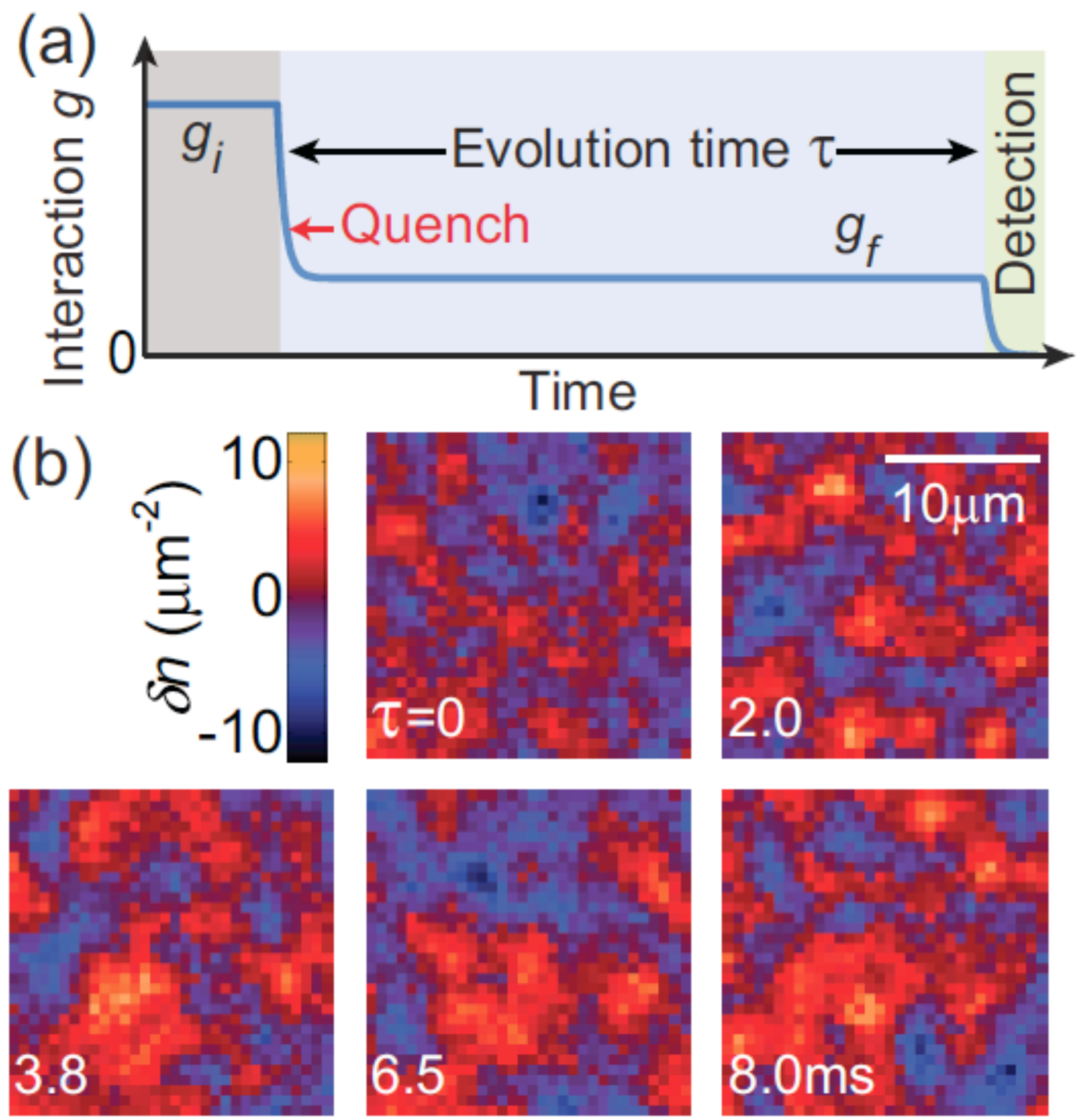


“Twin atom beams”
Bücker et al.
Nat. Phys. 7, 608 (2011)
Modulate trap centre to excite transverse mode
collisions produce longitudinally moving atoms.
Subpoissonian difference
$\Delta N^2 \sim 0.37$ (or 0.11)



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.



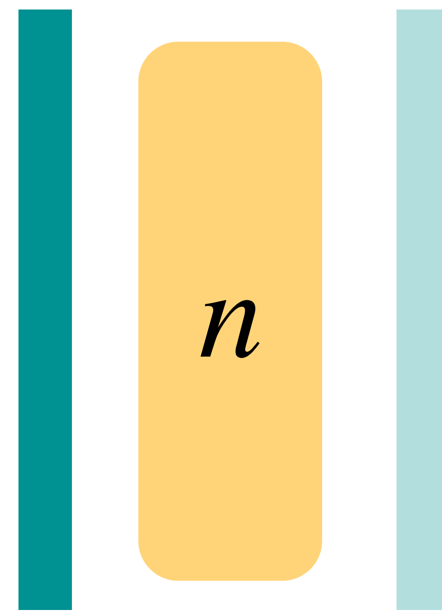
Recalls theoretical proposals by
Fedichev and Fischer PRA 2004
Jain, Weinfurtner, Visser and Gardiner, PRA 2007

Realizing the dynamical Casimir effect

move a mirror

$v = v_0 \cos \omega t$

change an index (change $c_{e.m.}$)



$n(t) = n\,(1 + \varepsilon \cos \omega t)$

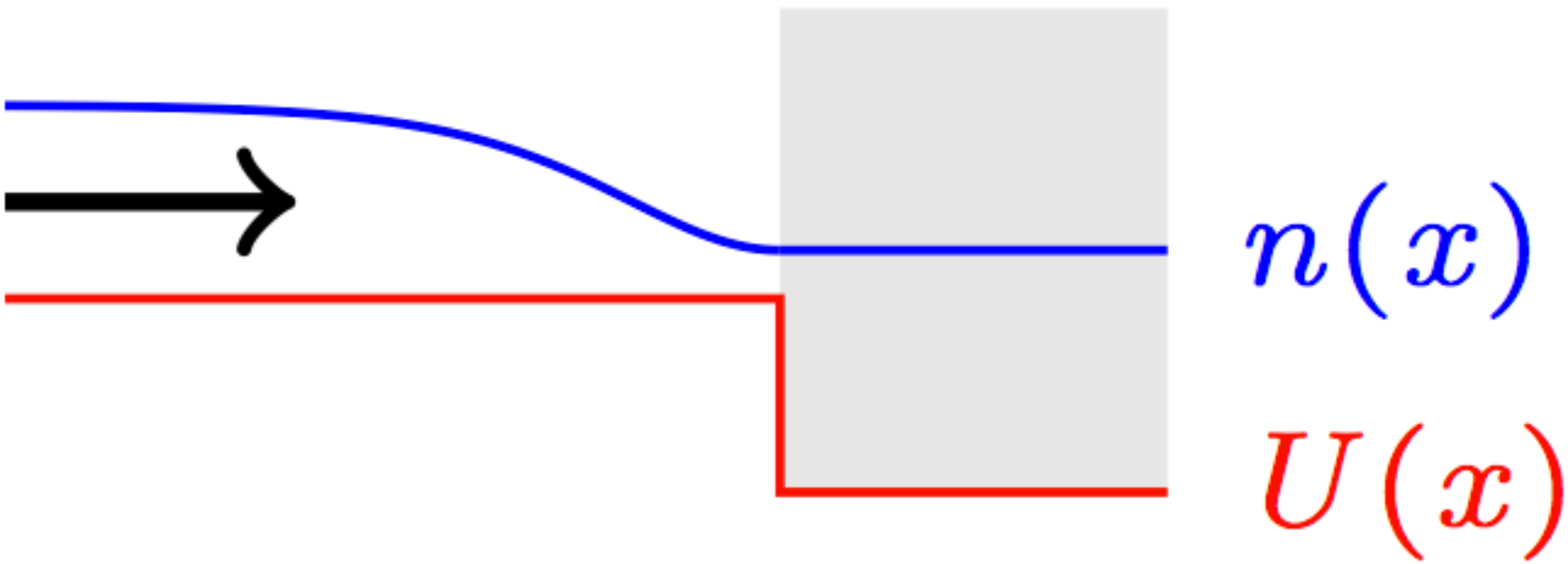
change c_s in a BEC

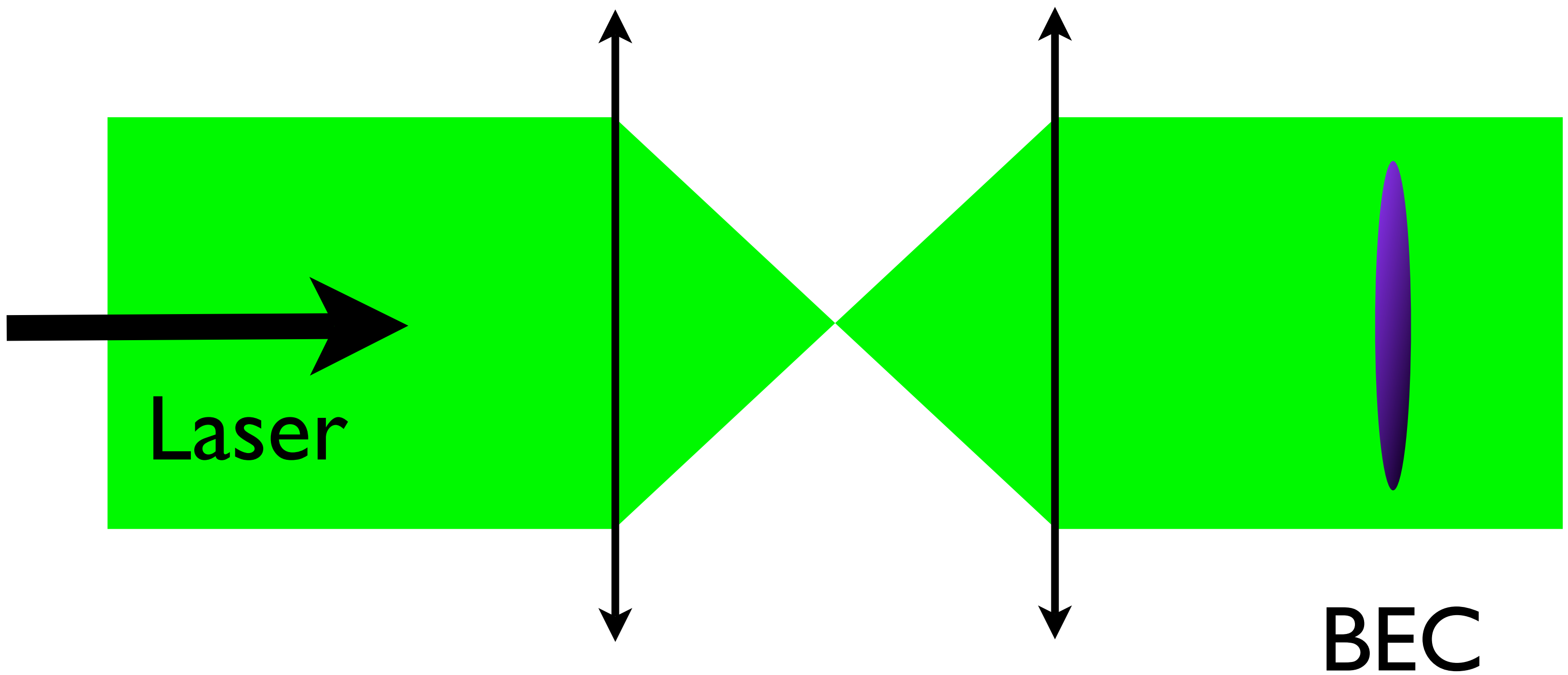
$c_s^2 = (4\pi\,\hbar^2)\; a\, \varrho / m^2$

real excitation pairs (photons or phonons) with

$\omega_1 + \omega_2 = \omega$

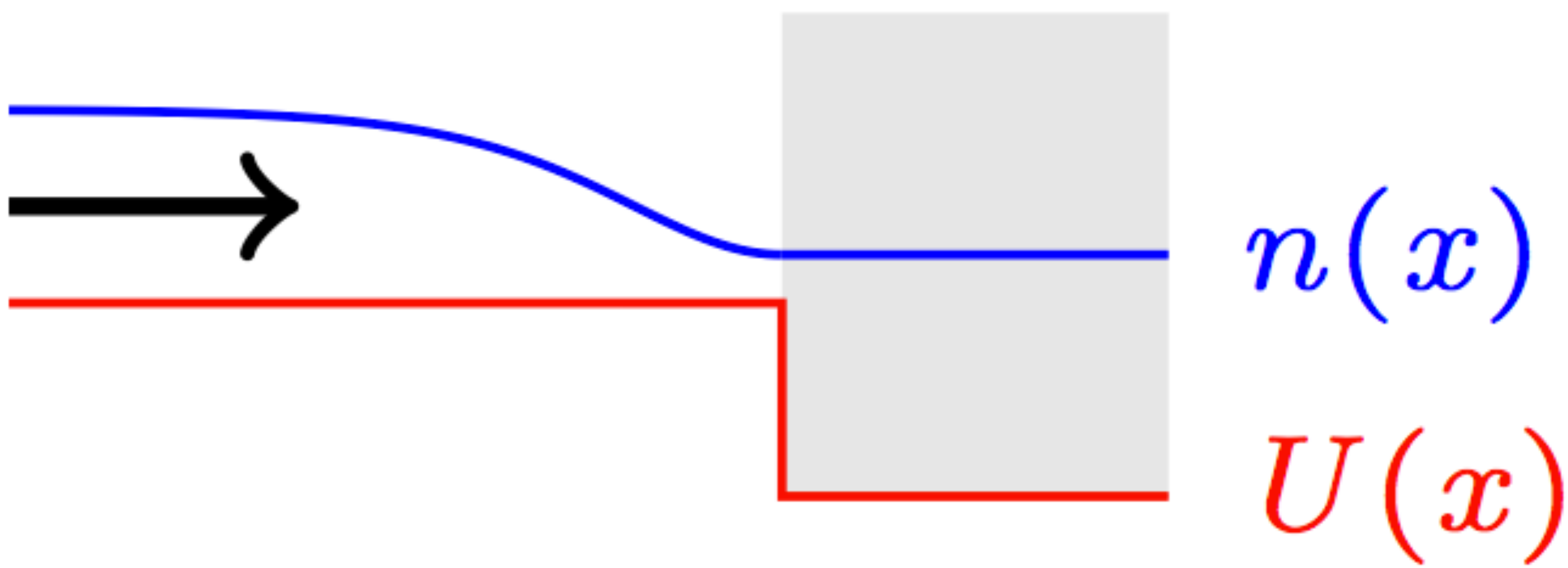
Experimental realization of a horizon

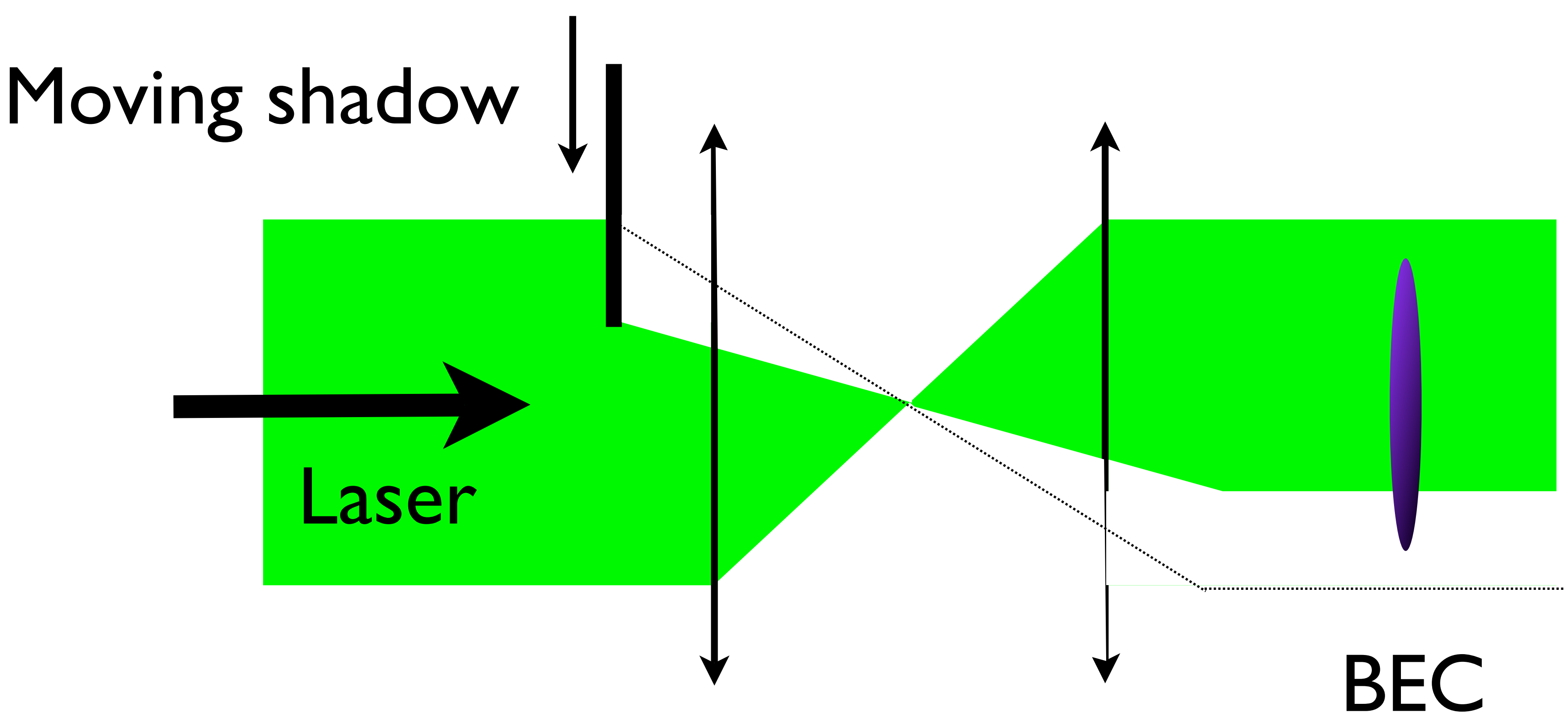




$v \sim 1$ cm/s
$d \sim 1$mm
$t \sim 100$ ms

Experimental realization of a horizon



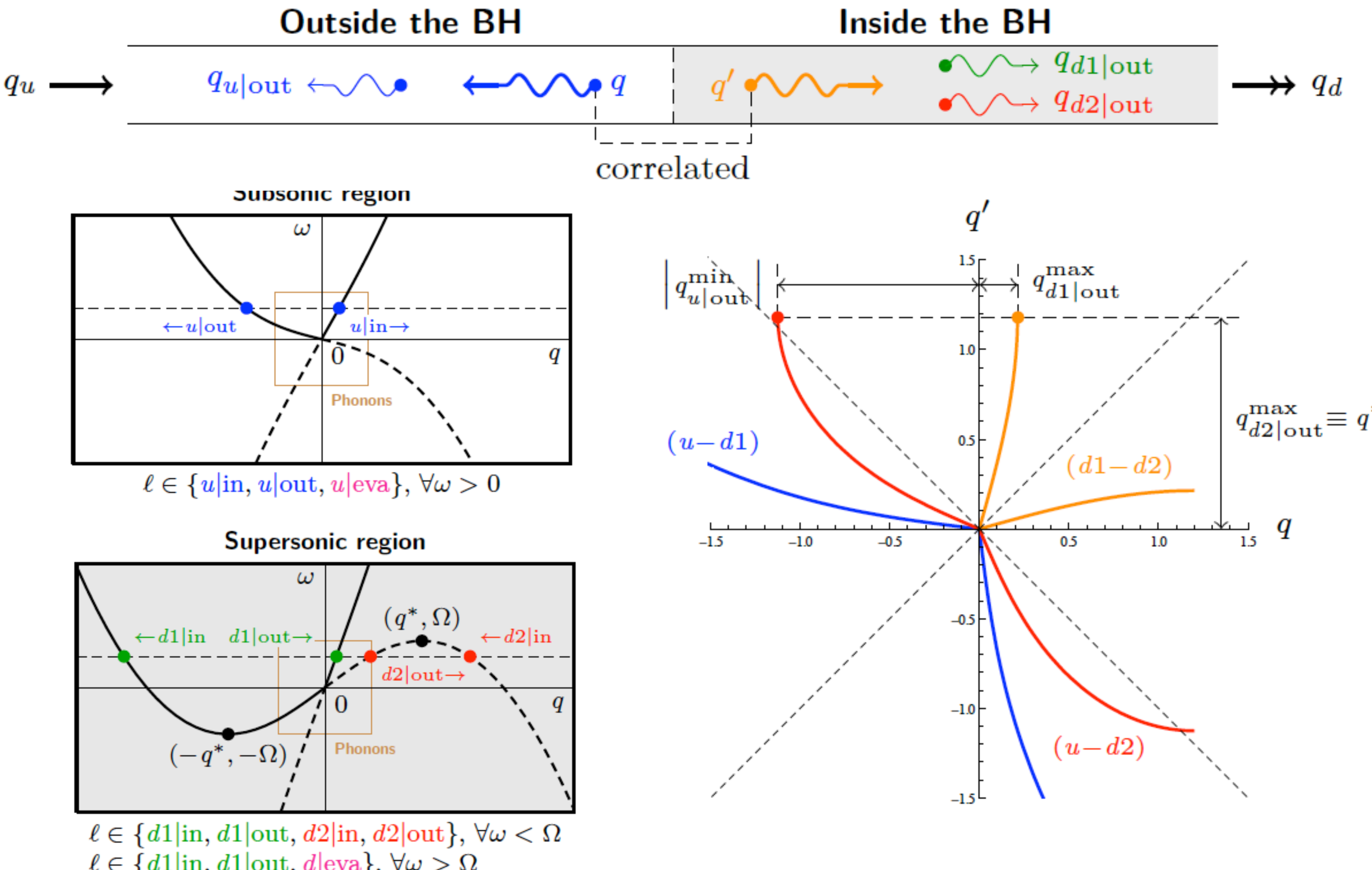


$v \sim 1$ cm/s

$d \sim 1$mm

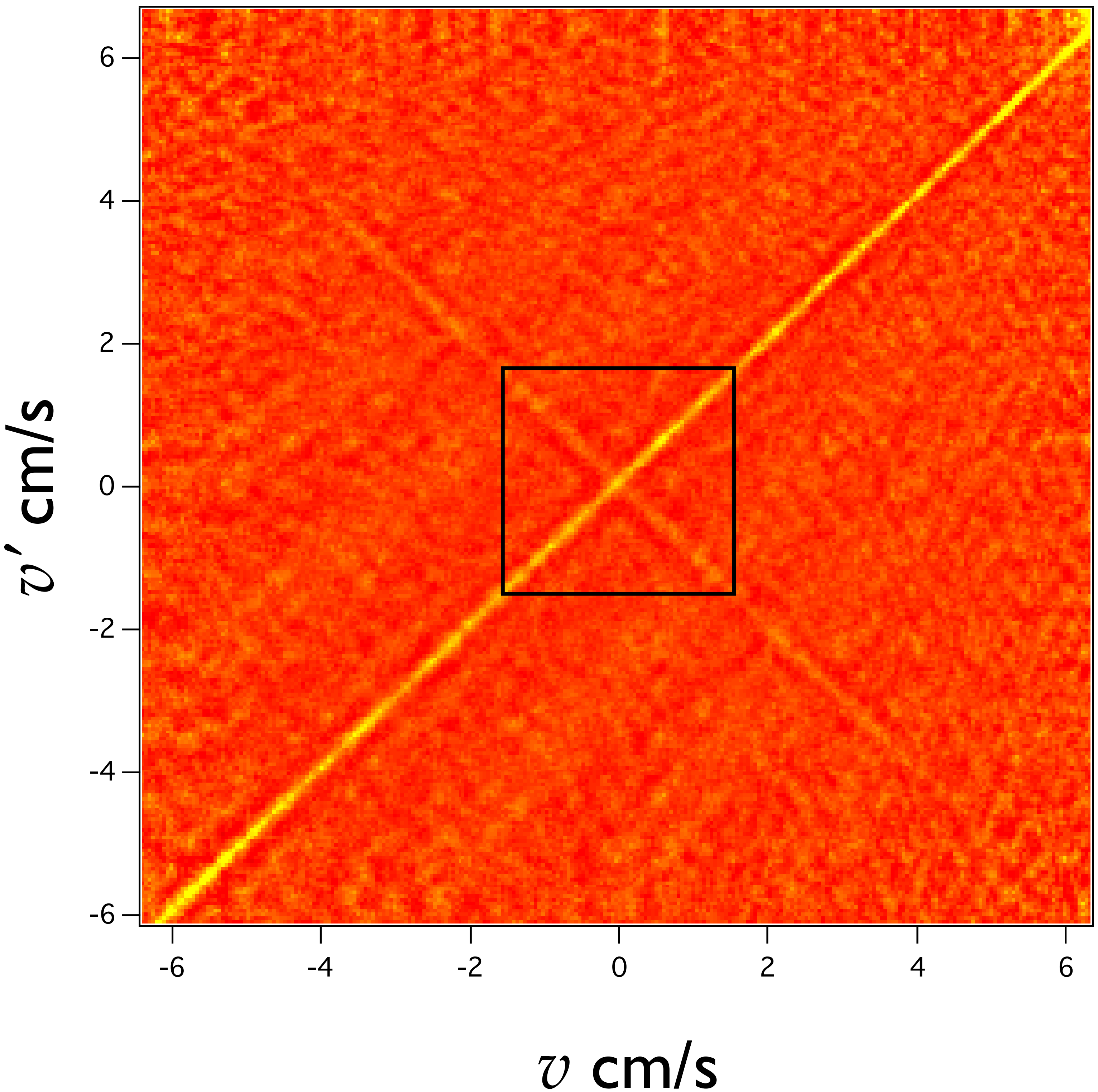
$t \sim 100$ ms

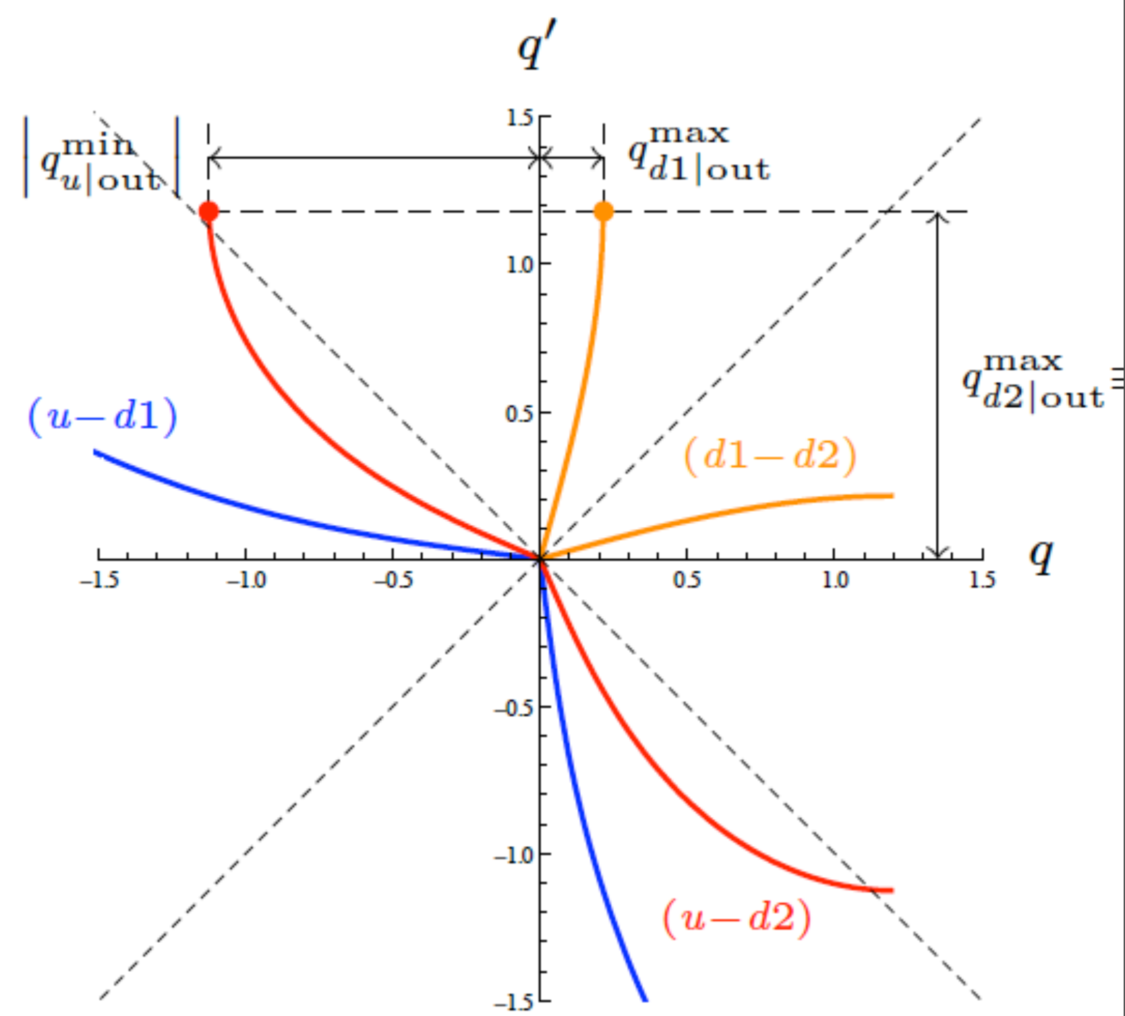
Signature of Hawking radiation in p-space



P.-E. Larré, N. Pavloff

Correlations in momentum space





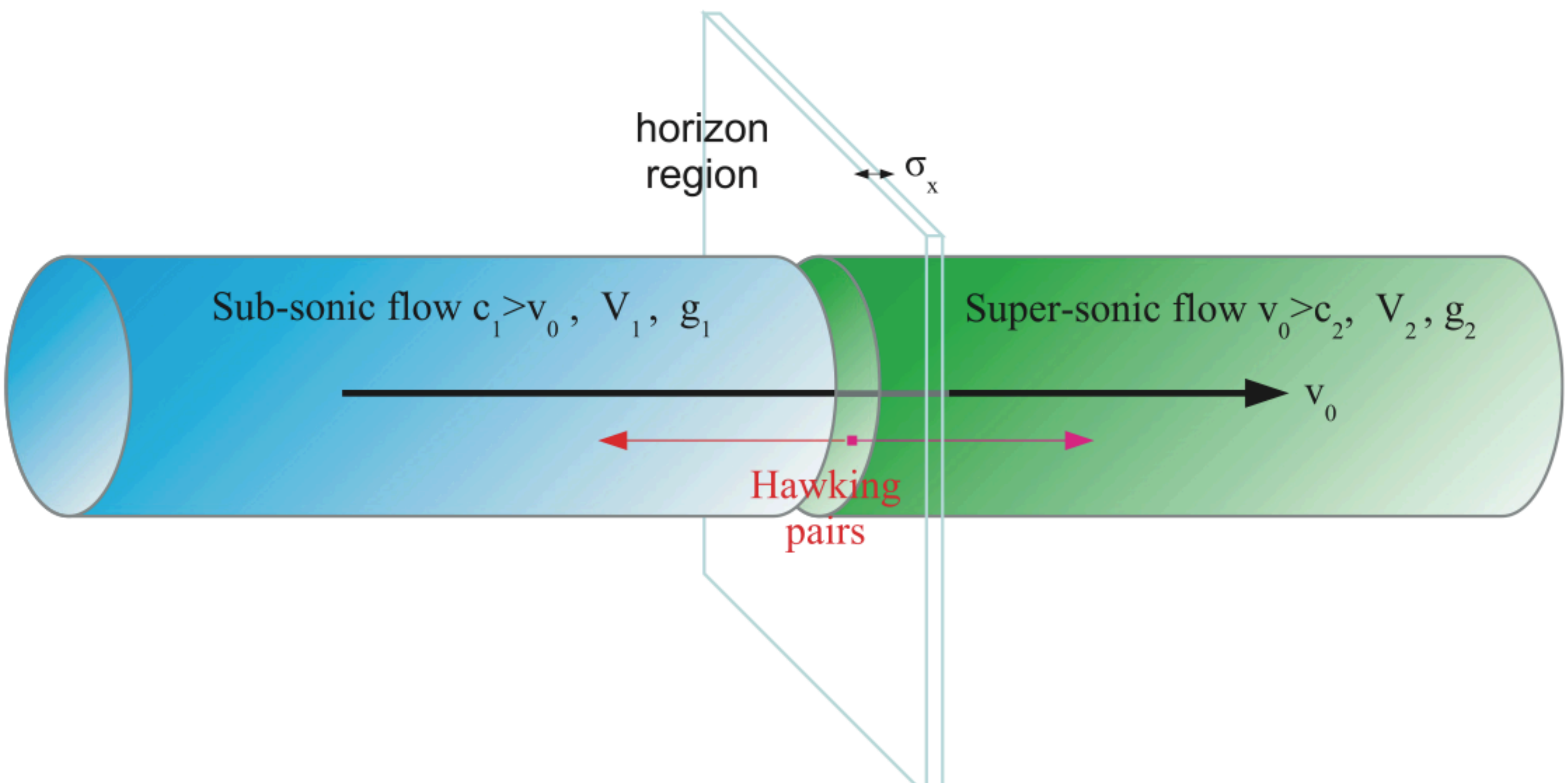
Amplitude of correlations?

Black holes in BEC's

Low temperature: quantum Hawking radiation?
$T_{Hawking}$~10 nk

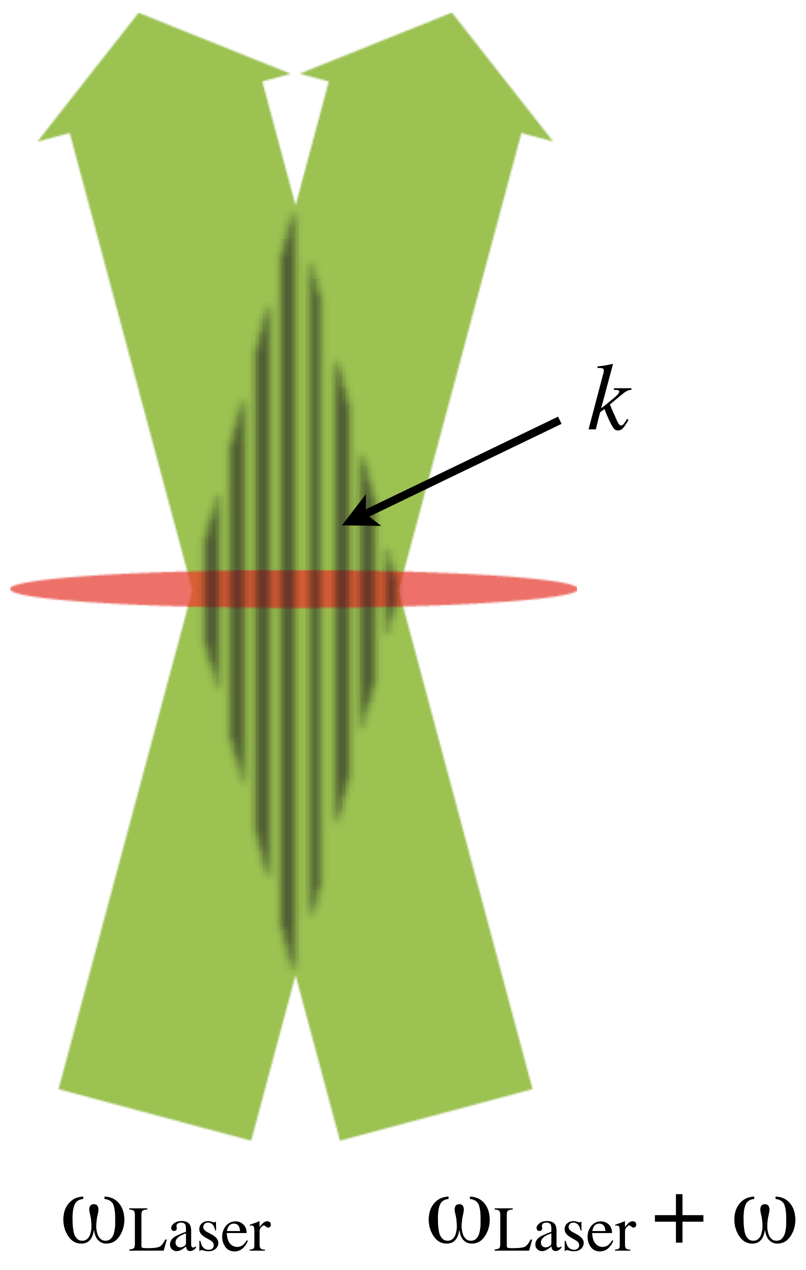
Speed of sound in a BEC $c_s^2 = (4\pi\hbar^2)\, a\, \varrho / m^2$

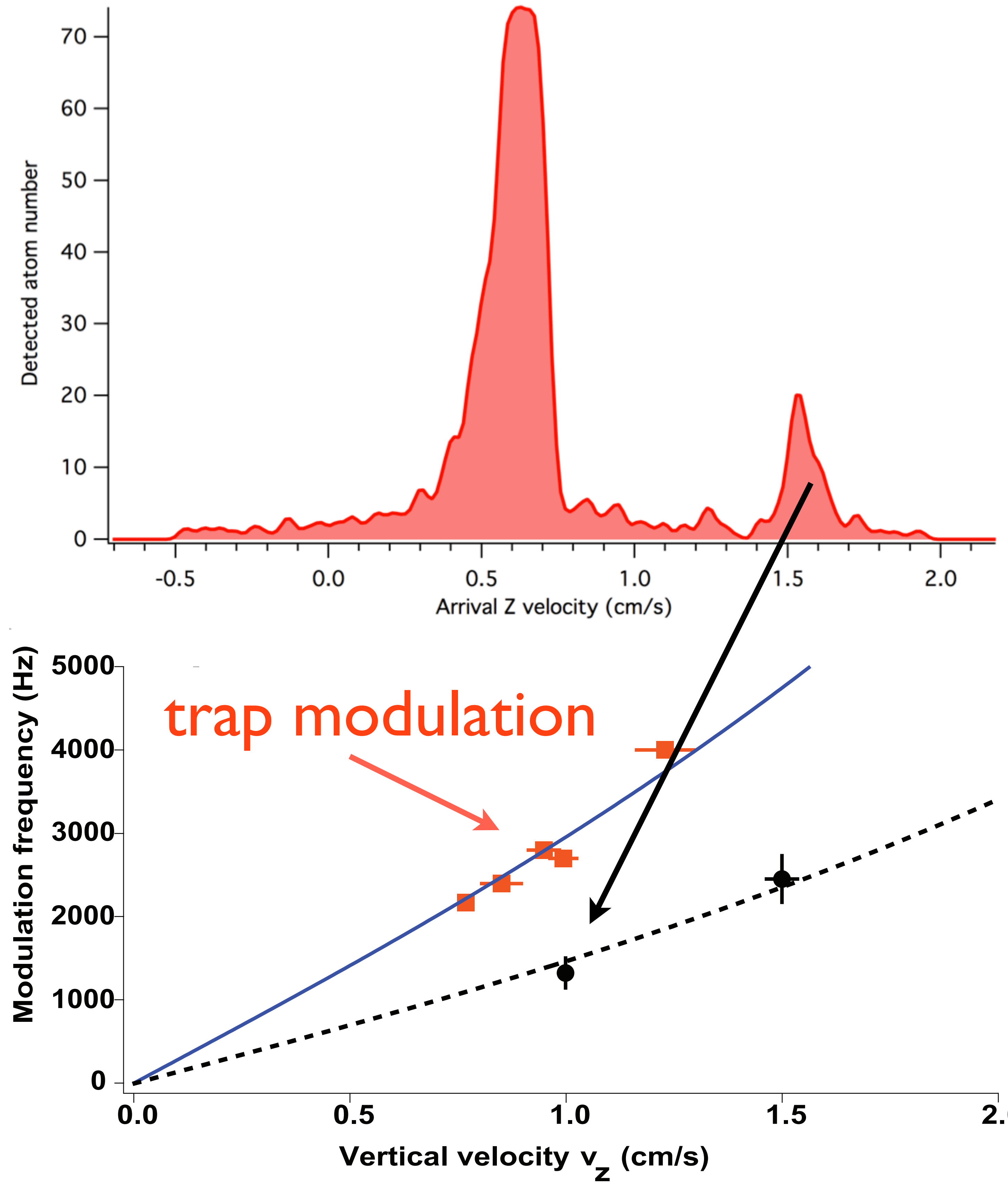
Carusotto et al. New J. Phys 2008:



Bragg scattering

Impose a wave vector k
and a frequency ω
→ find a resonance





In a BEC, the Bogoliubov Hamiltonian

Hamiltonian in terms of single particle operators ($a_{k=0}$ is treated as a c-number)

$$H = E_0 + \sum_{k\neq 0}(E_k + \mu)\left(a_k^\dagger a_k + a_{-k}^\dagger a_{-k}\right) + \mu\left(a_k^\dagger a_{-k}^\dagger + a_k a_{-k}\right)$$

Bogoliubov transformation

$$b_k = u_k a_k + v_k a_{-k}^\dagger$$

$$b_k^\dagger = u_k a_k^\dagger + v_k a_{-k}$$

Hamiltonian with new operators

$$H = E_0' + \sum \hbar\omega_k b_k^\dagger b_k \qquad \omega_k = \sqrt{c^2 k^2 + \left(\frac{\hbar k^2}{2m}\right)^2}$$

The Bogoliubov ground state

Definition of ground state

$$b_k\,|\,\psi_0\rangle = 0 = \left(u_k\, a_k + v_k\, a^{\dagger}_{-k}\right)\Big|\,\psi_0\Big\rangle$$

Ground state in terms of single particle states (see Huang, Ch. 13)

$$|\,\psi_0\rangle = Z \sum \left(-\frac{v_k}{u_k}\right)^{n_k} \Big|\, n_k\,,\, n_{-k}\Big\rangle, \quad n_{-k} = n_k$$

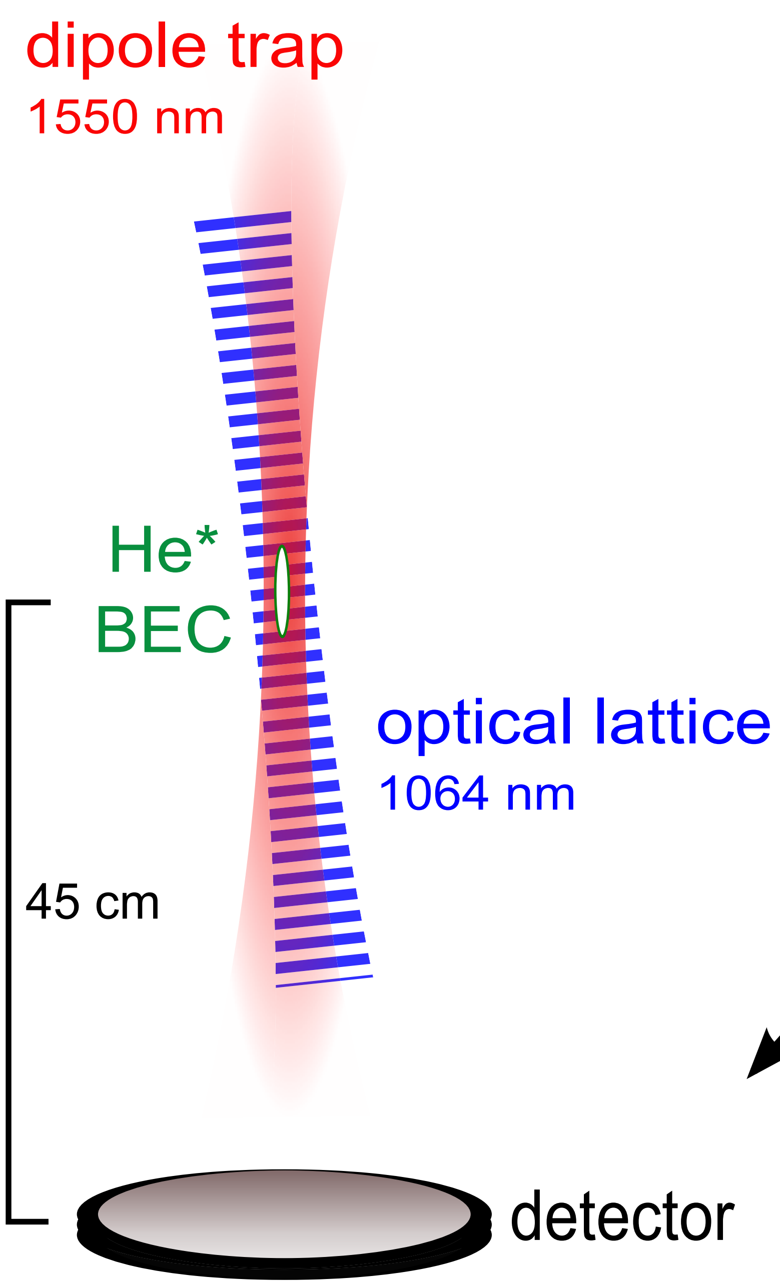
Ground state looks like squeezed vacuum contains pairs.

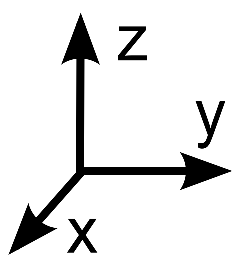
$\frac{v_k}{u_k}$ depends on μ

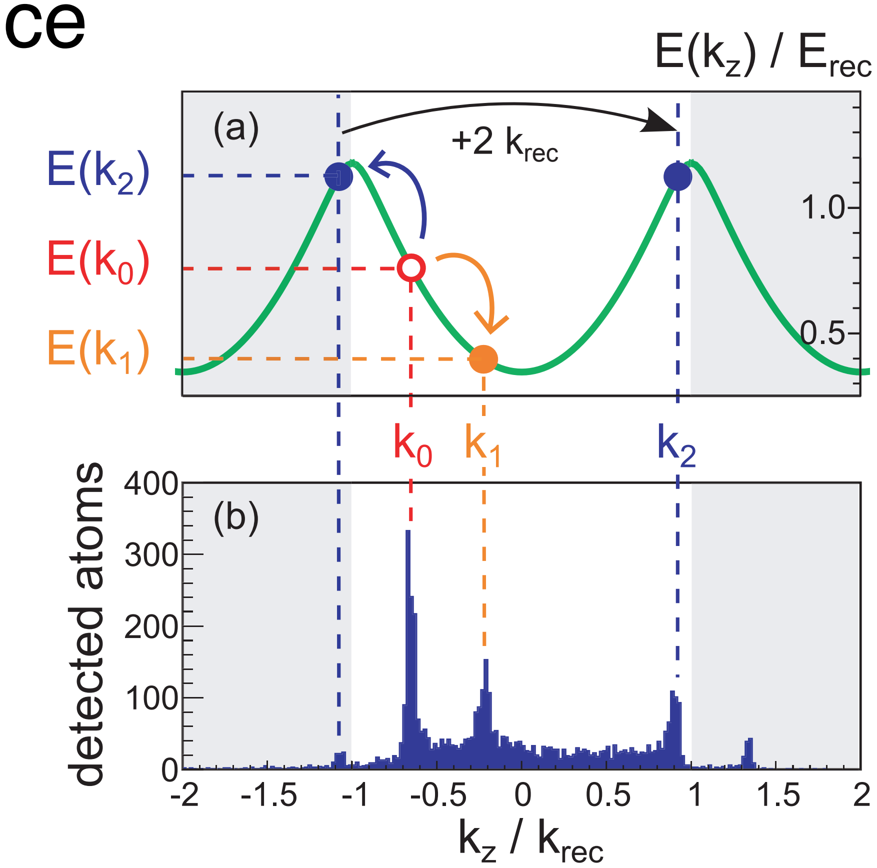
If μ changes, the ground state changes

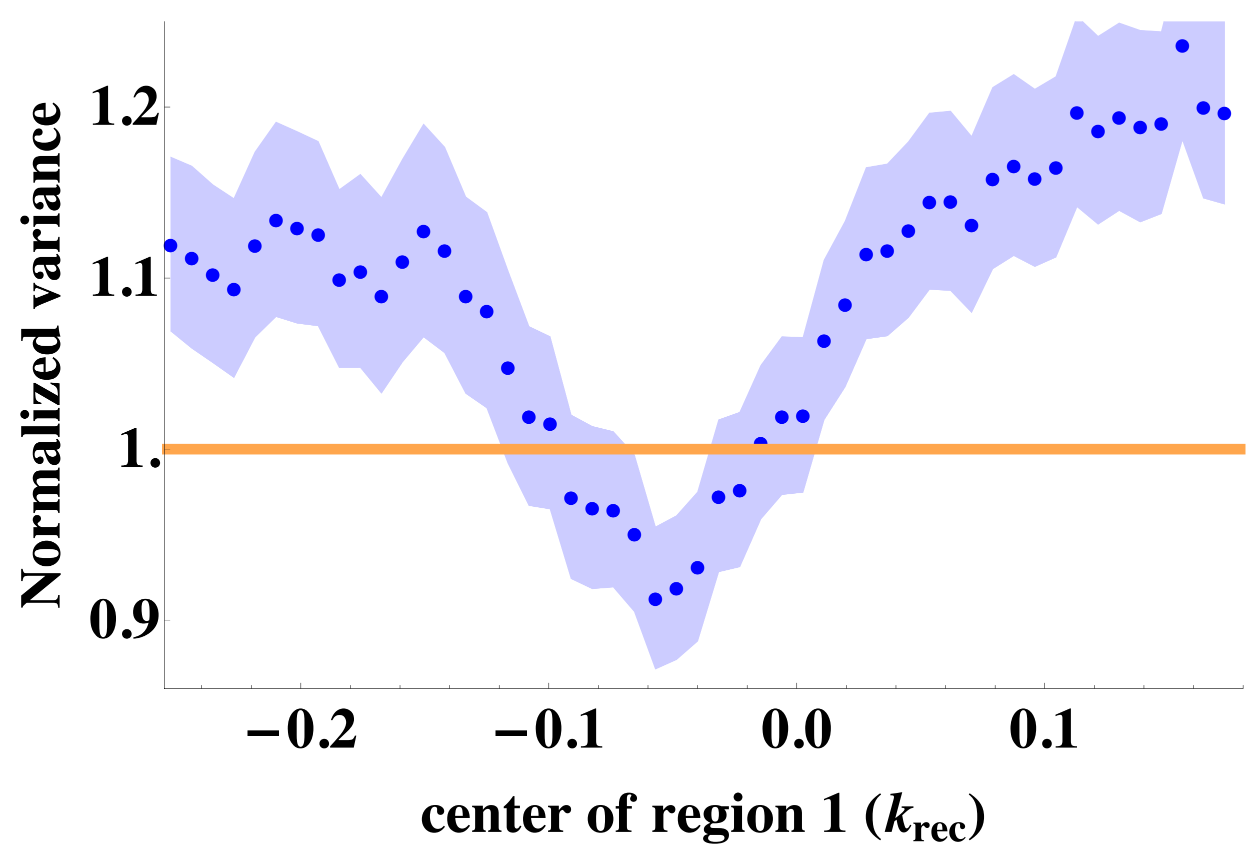
It is possible to violate the CS inequality

Creation of pairs by 4 wave mixing in a lattice









Bonneau et al. 1212.6315

Without motion: changing the speed of light

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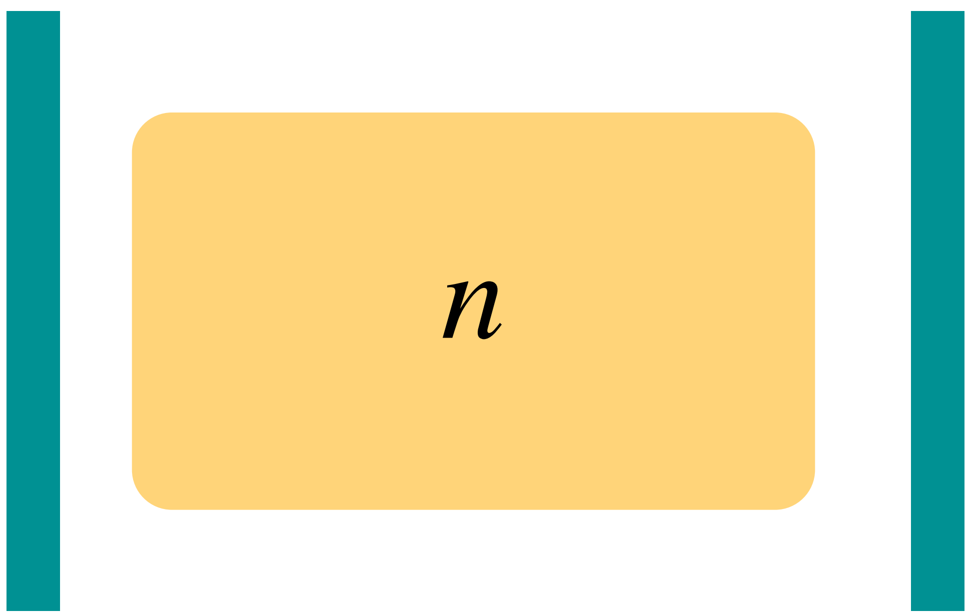
Accelerating Reference Frame for Electromagnetic Waves in a Rapidly Growing Plasma: Unruh-Davies-Fulling-DeWitt Radiation and the Nonadiabatic Casimir Effect

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