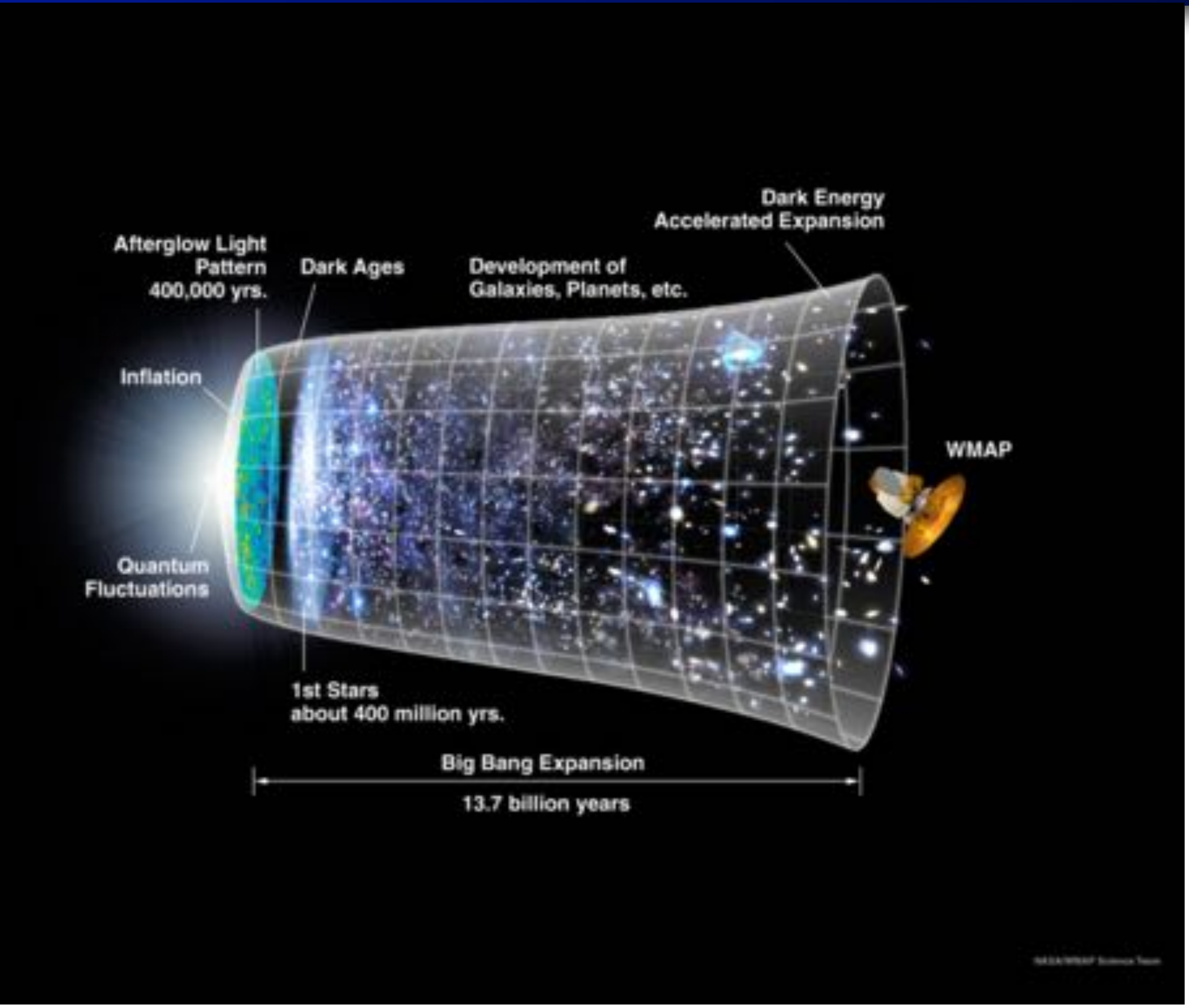
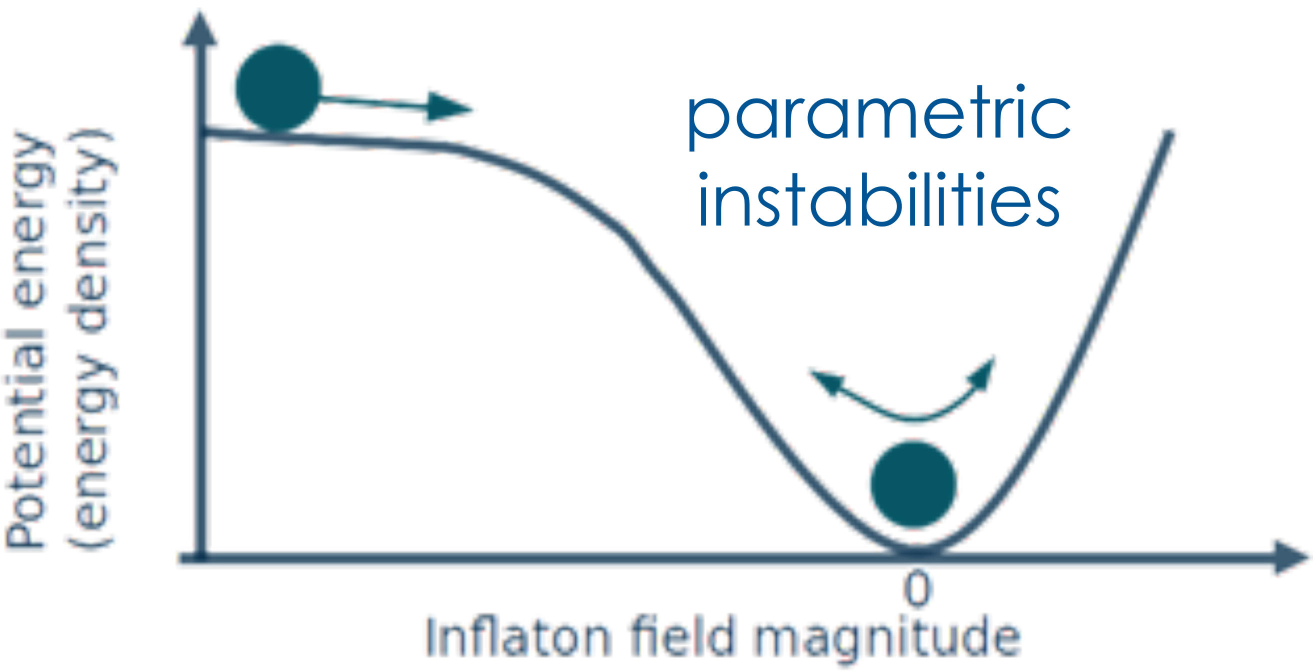
Simulation of the early universe with a BEC

Chris Westbrook
Laboratoire Charles Fabry, Palaiseau

Benasque workshop on analogue gravity
31 May 2023

The story of universe





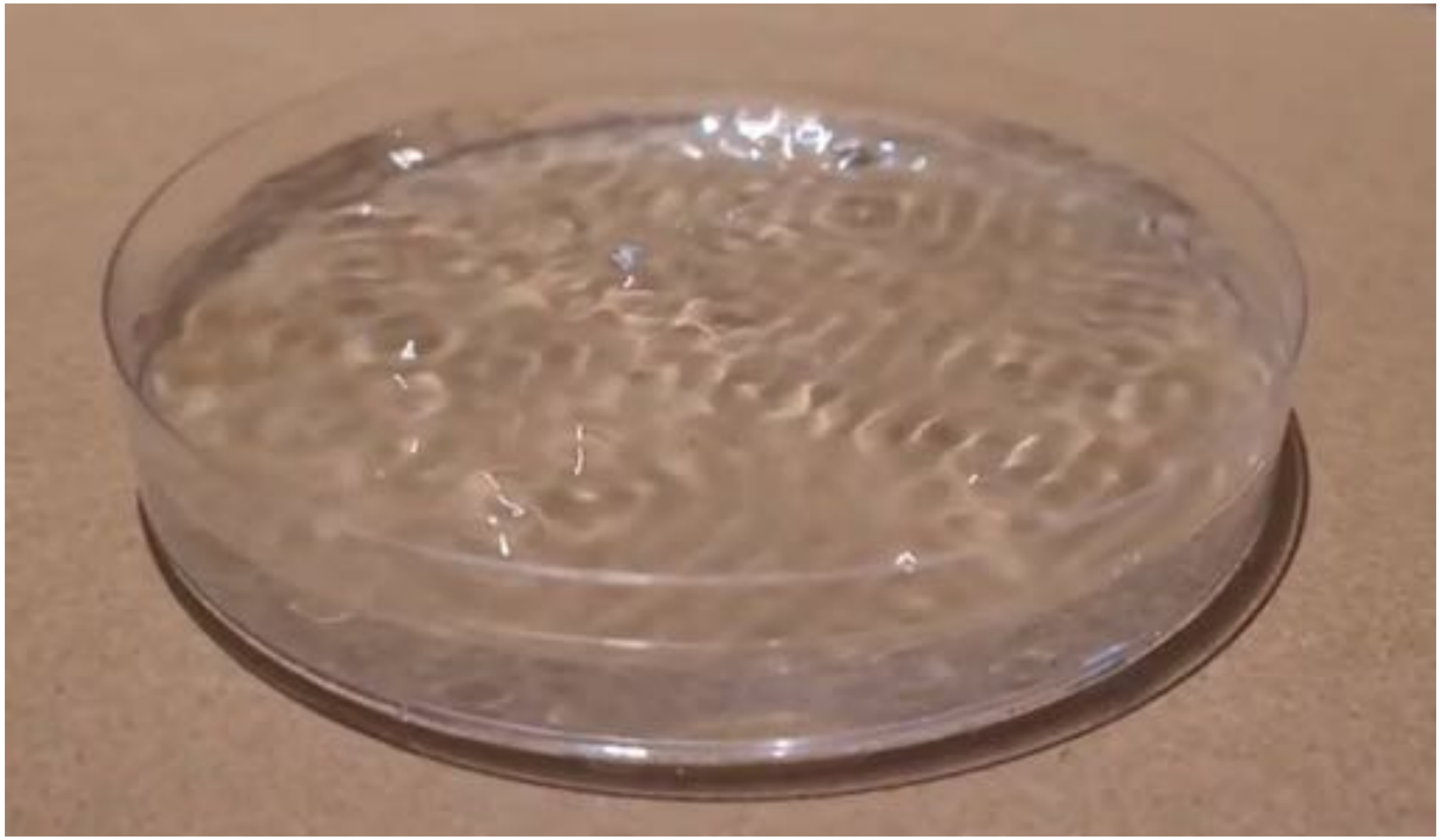
the universe "inflates" → "inflaton" oscillates and generates entangled particle pairs → particles interact, decoherence thermalisation

"preheating" "reheating"

Parametric oscillators, Faraday waves

$$x'' + \gamma\, x' + \omega^2(1 + \alpha \cos \nu t)\, x = 0$$

Water in a vibrating container



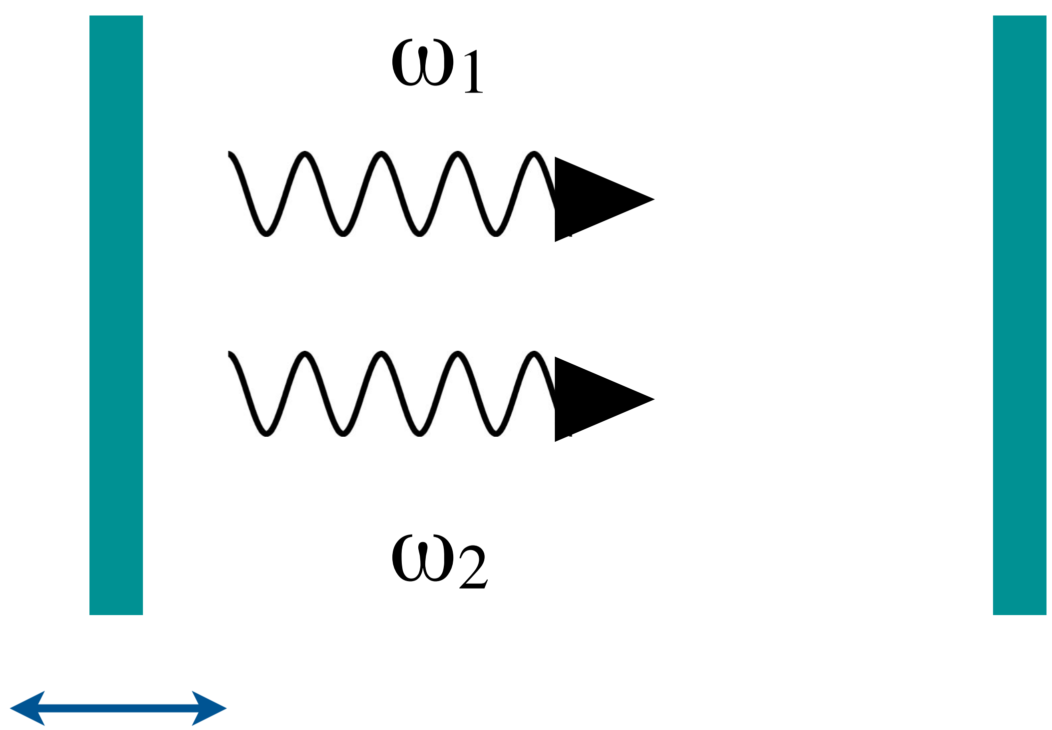
Hat tip to the Nottingham group.

Also, entanglement in quantum optics with nonlinear crystals

Also works in a vacuum

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

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)
E. Yablonovich, PRL 62, 1742 (1989)
...
P. Nation, J. Johansson, M. Bloncowe, F Nori, Rev. Mod. Phys. 84, 1 (2012)



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

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

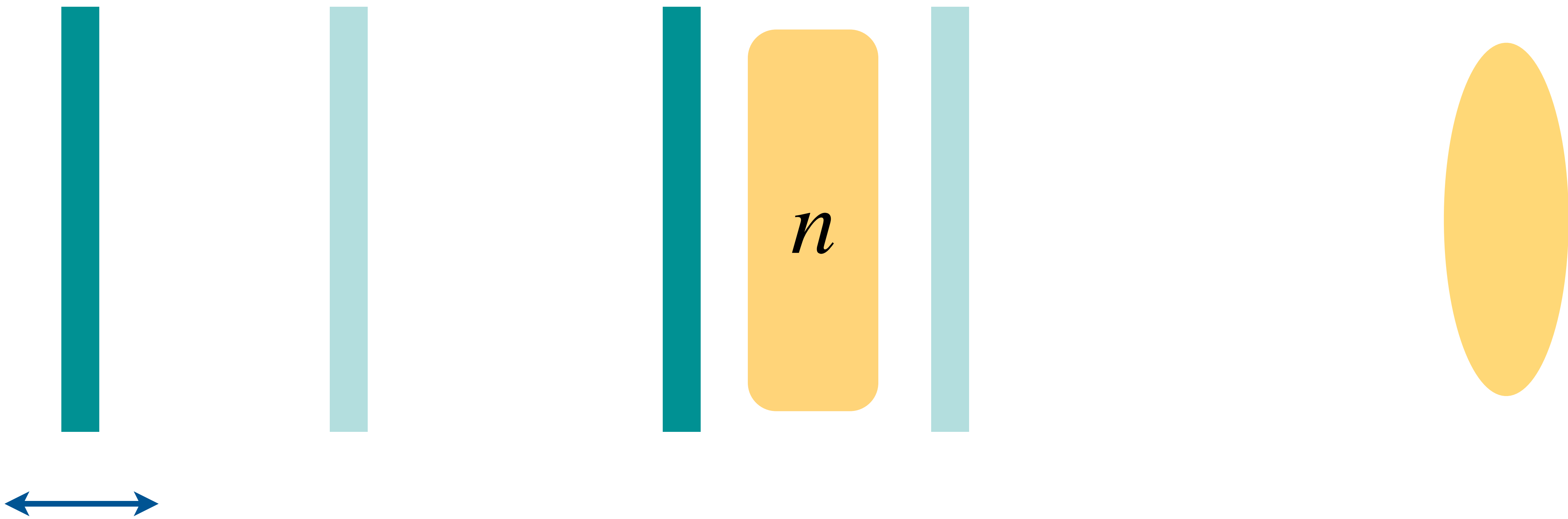
Photon Pairs in a vibrating cavity:
A. Lambrecht, M.-T. Jaekel, S. Reynaud, Phys. Rev. Lett. 77, 615 (1996)

Downconversion: the dynamical Casimir effect

move a mirror

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

change c_s in a BEC



$v = v_0 \cos \omega t$

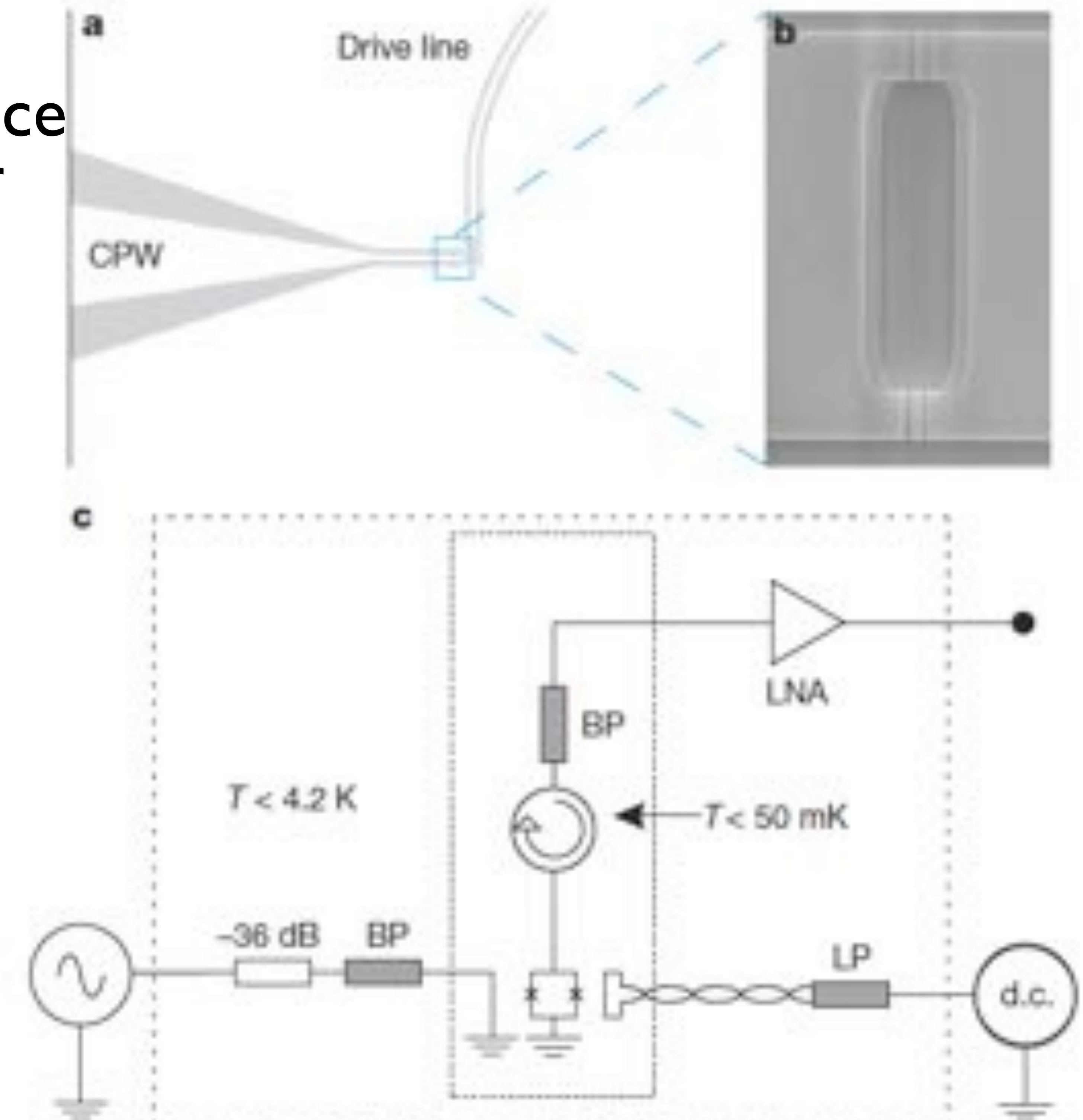
$n(t) = n\,(1 + \varepsilon \cos \omega t)$

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

real excitation pairs (photons or phonons) with $\omega_1 + \omega_2 = \omega$

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

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



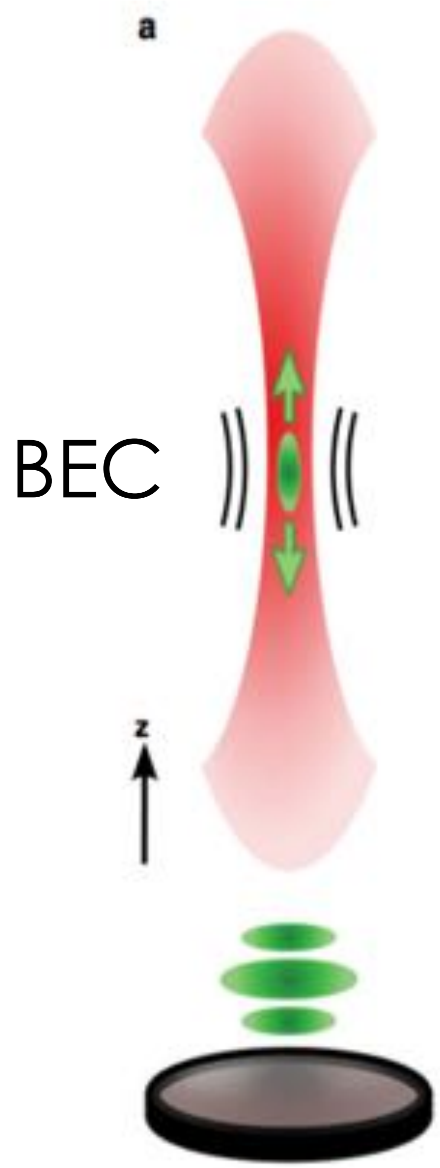
2 Josephson junctions
50 mK

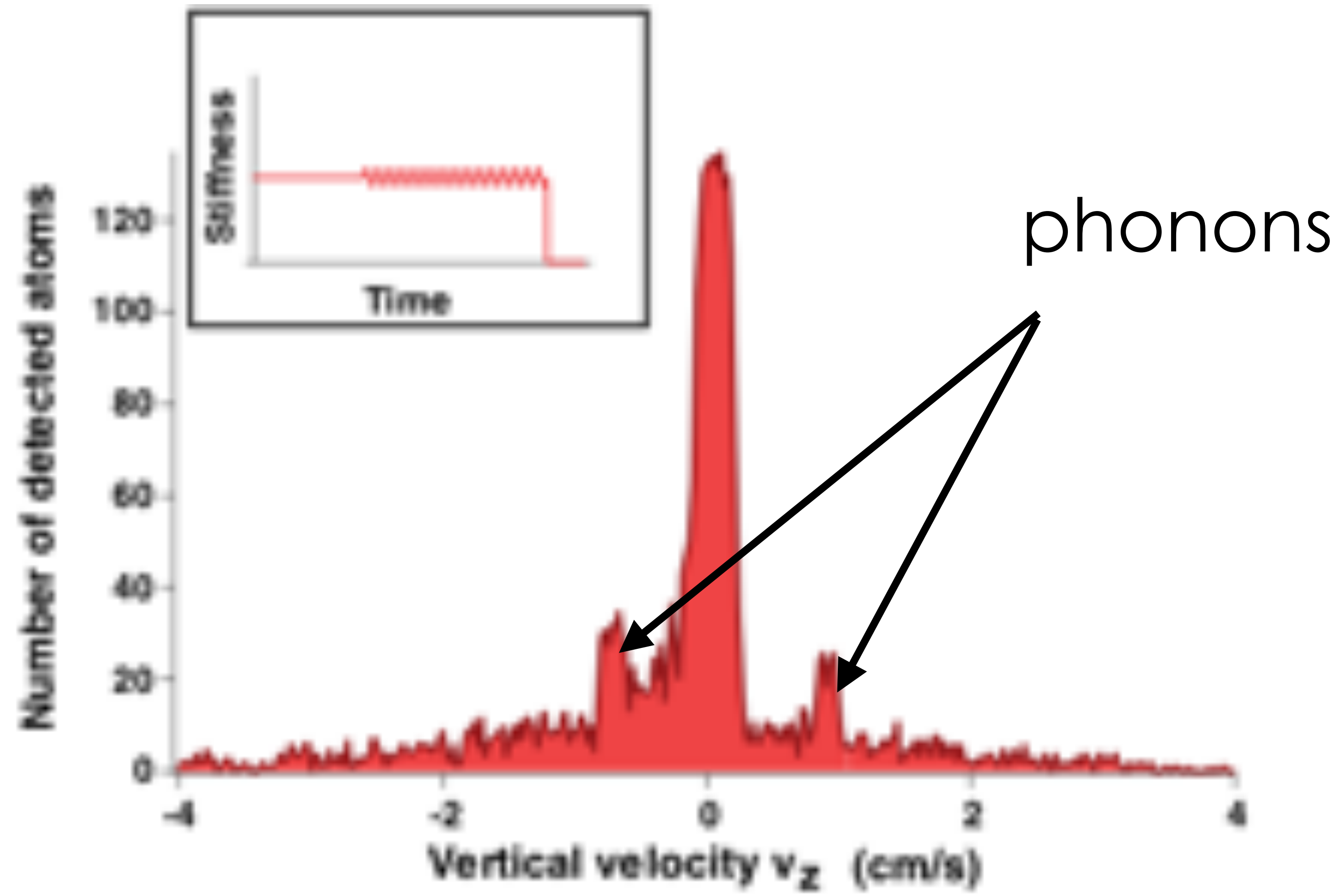
Output analysed at
$\omega_1 = \omega/2+\Delta$
$\omega_2 = \omega/2-\Delta$

Drive:
$\omega/2\pi = 10$ GHz

see also Lahteenmaki et al. PNAS (2013)

The acoustic dynamical Casimir effect in a BEC



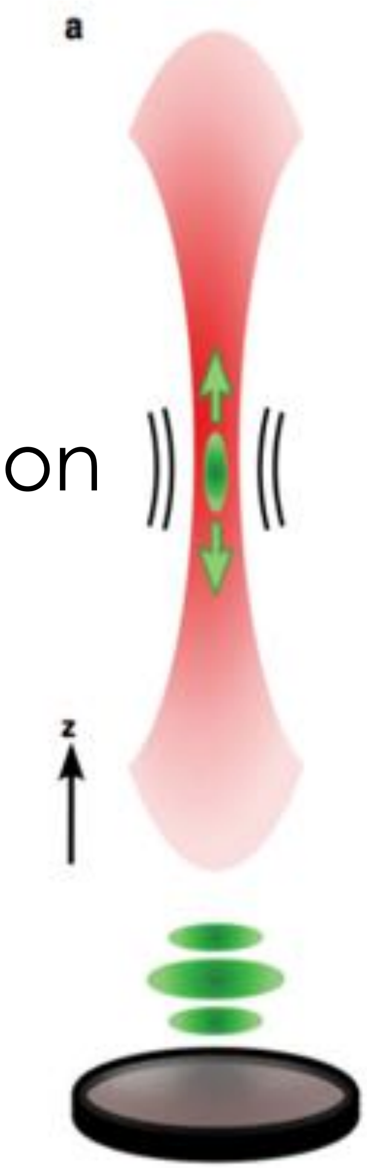


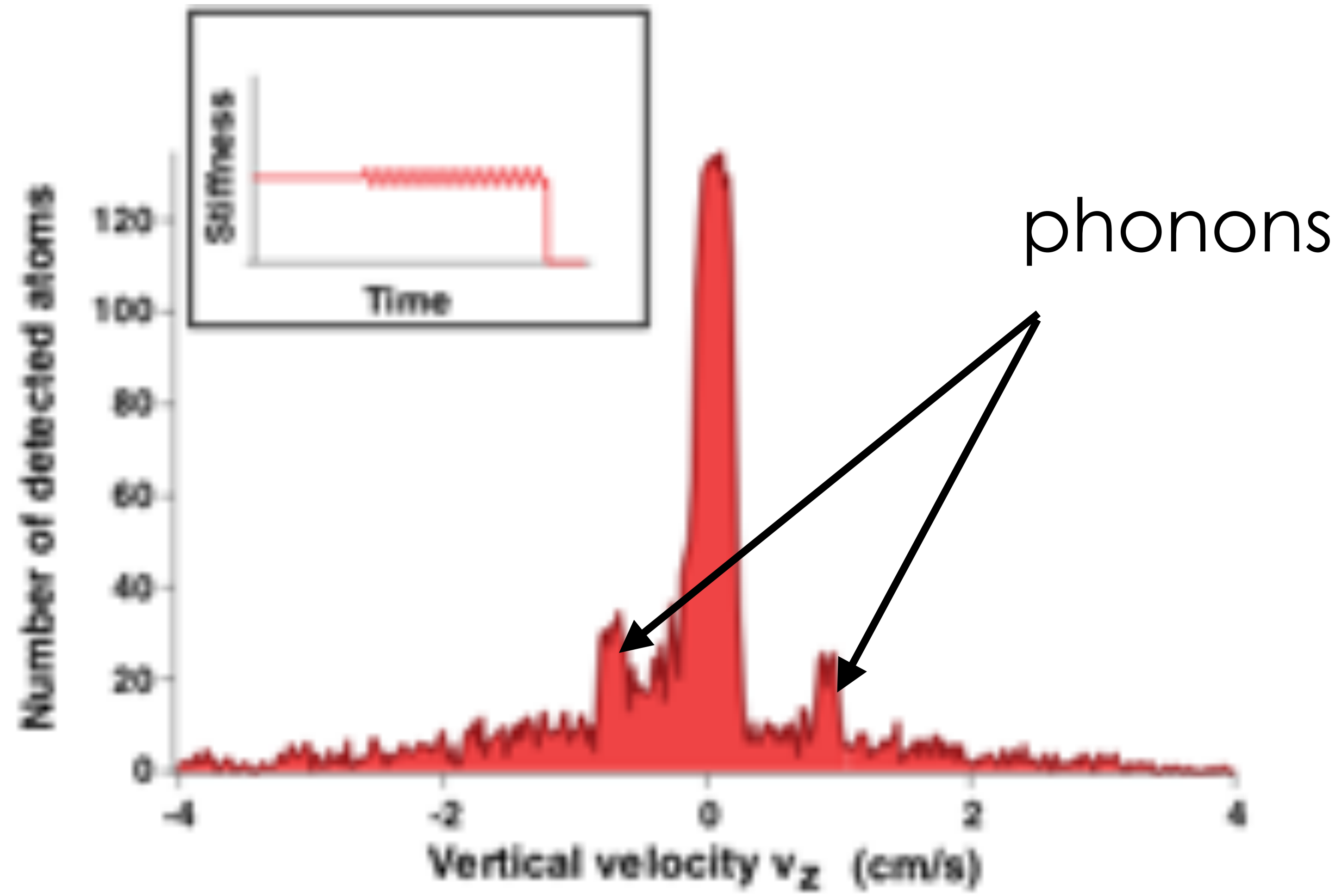
Jaskula, *et al*.. PRL ***109***, 220401 (2012)

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

The simulation of the universe in a BEC

inflaton





Jaskula, *et al*.. PRL ***109***, 220401 (2012)

make a BEC → force BEC oscillation generate entangled phonon pairs → phonons interact, decoherence thermalisation

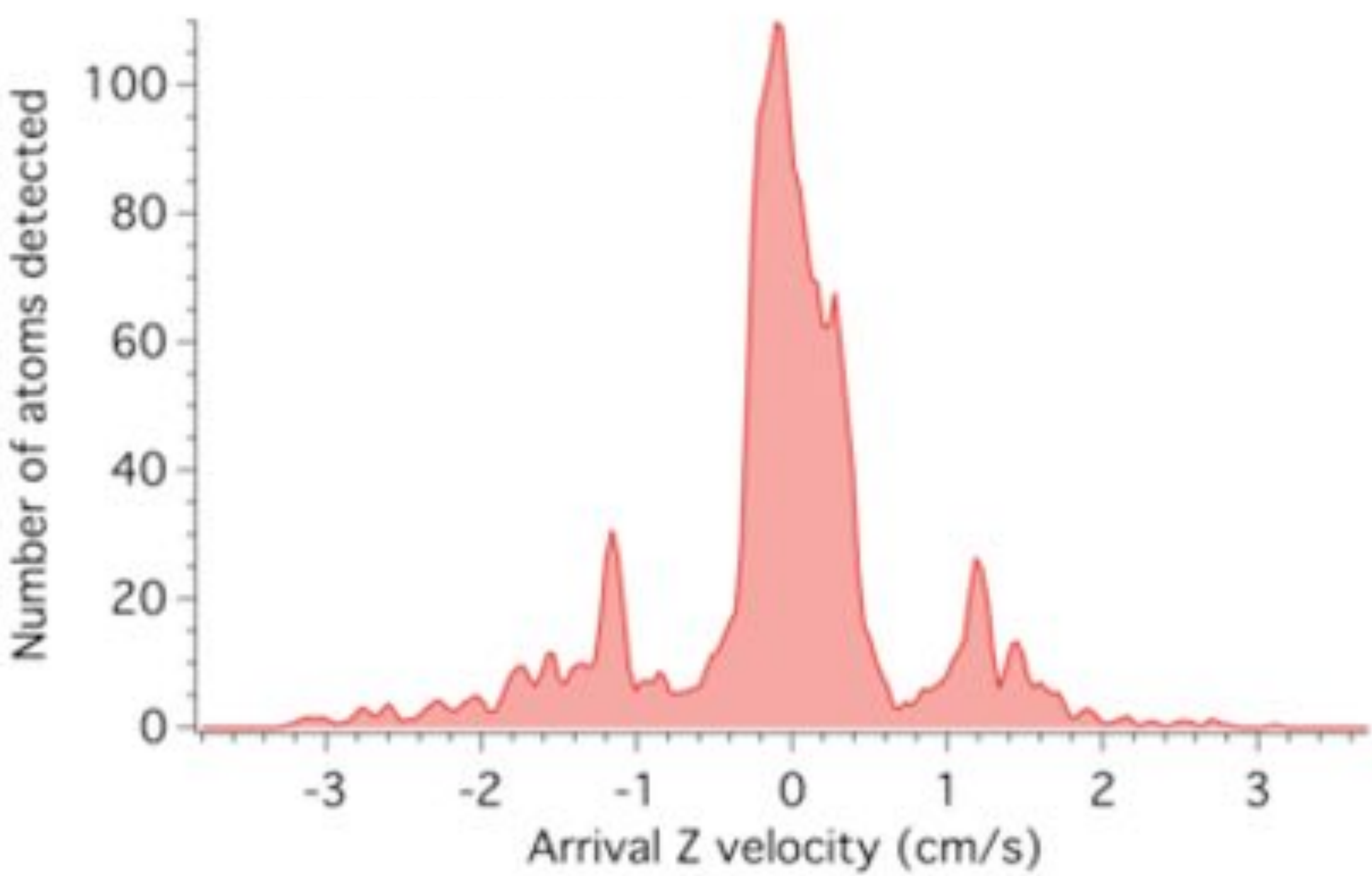
Apparatus

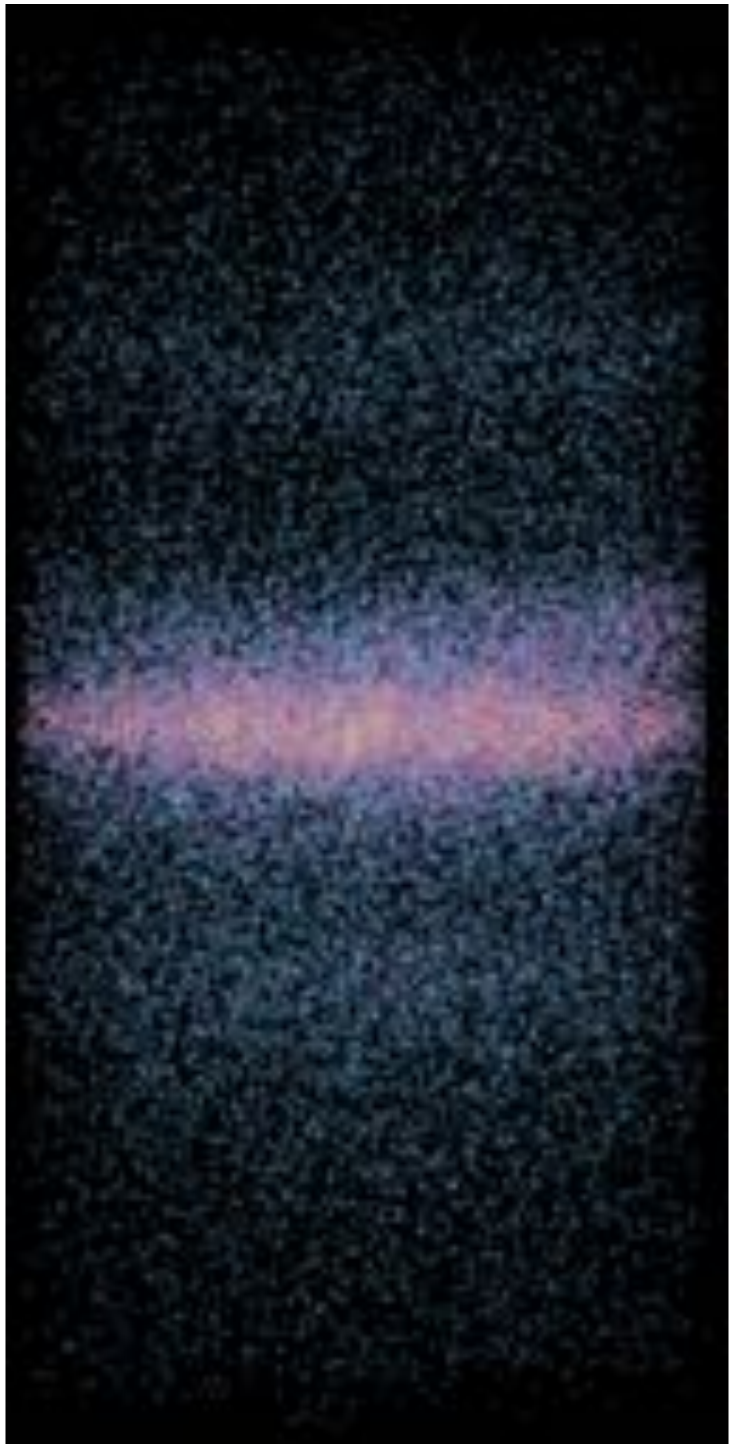
Detect atoms in a cloud of He* in momentum space.
Long time of flight
He*: the 2^3S_1 state 20 eV
size ~ 100 microns
T ~ 100 nK

modulate
laser intensity
→ fluid density
at 0.5 - 5 kHz

velocity distribution of *particles*

$n(v)$





each dot is an atom

Phonon evaporation

"Phonon evaporation in freely expanding condensates"
C. Tozzo and F. Dalfovo, Phys. Rev. A69, 053606 (2004)

Bogoliubov phonon creation operator $c_k^\dagger$

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

$$\frac{v_k}{u_k} \to 1 \qquad \text{for } k^2 \ll 8\pi\, a\, \rho$$

$$\frac{v_k}{u_k} \to 0 \qquad \text{for } k^2 \gg 8\pi\, a\, \rho \quad \text{(particle-like)}$$

as density (ρ) decreases, phonons $\to$ particles

Metastable Helium, He*

Lifetimes:

2^3S_1: 8000 s

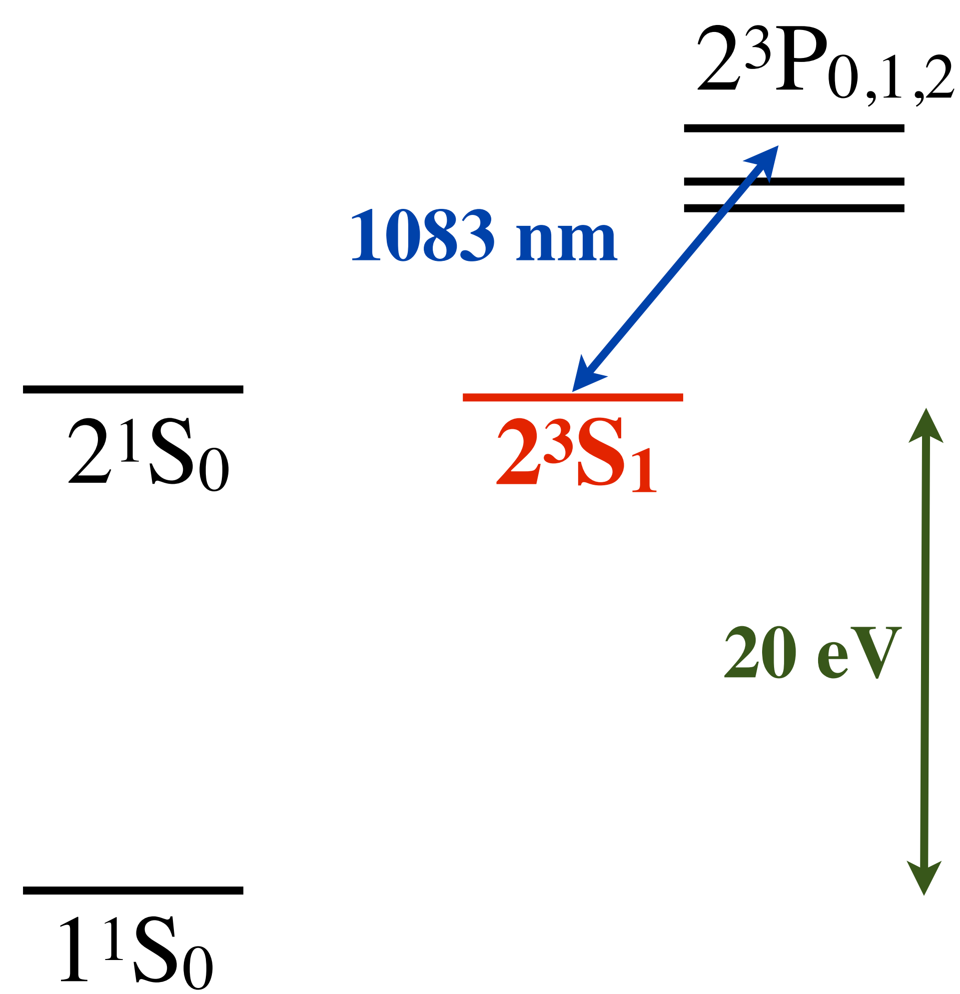
2^3P_J: 100 ns

Collisions:

- elastic scattering length 7.5 nm
- inelastic rate collision rate

  $He^* + He^* \rightarrow He + He^+ + e^-$

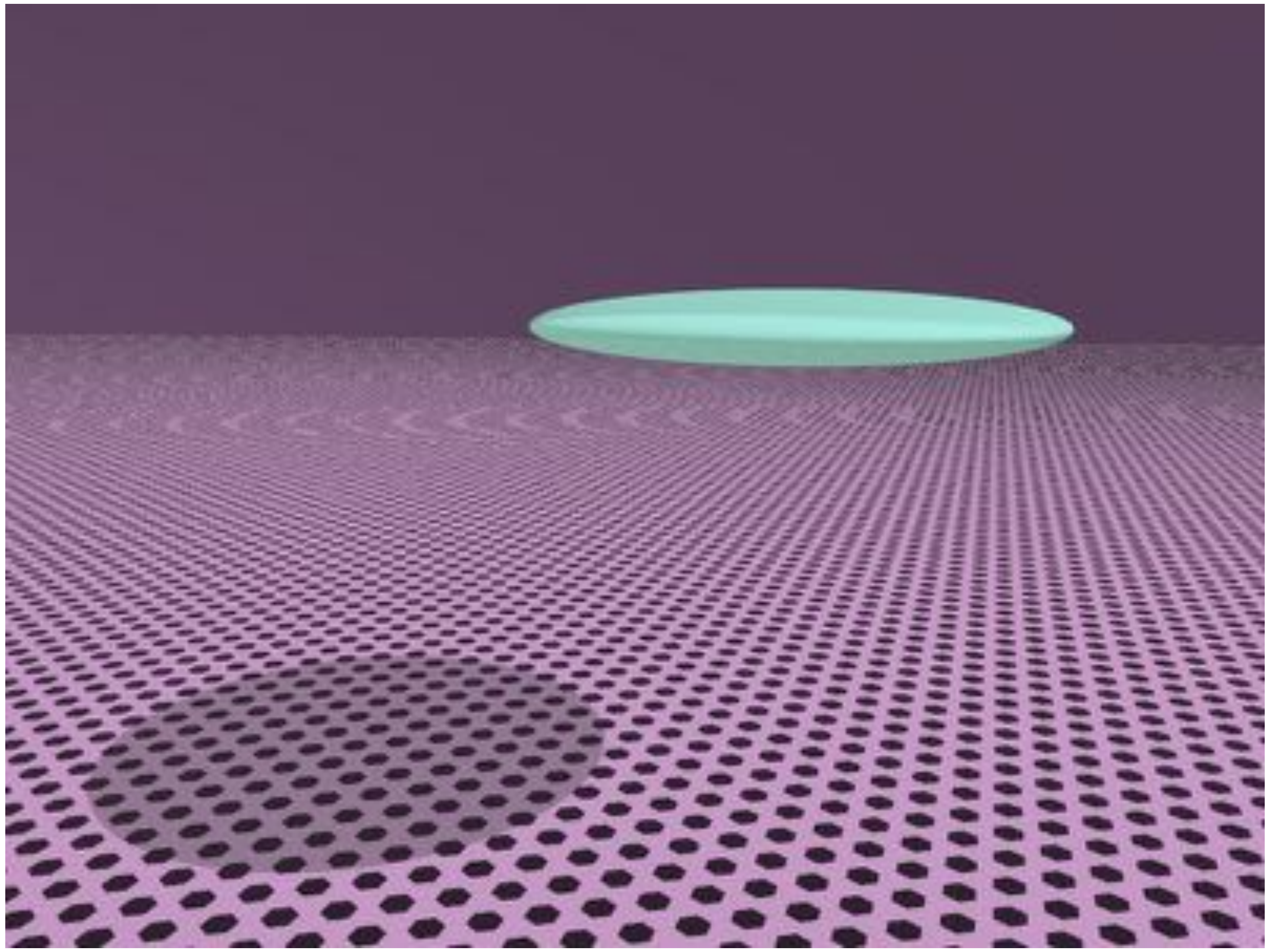
polarized	2×10^{-14} cm^3/s
unpolarized	2×10^{-10} cm^3/s



^{4}He (no nuclear spin)

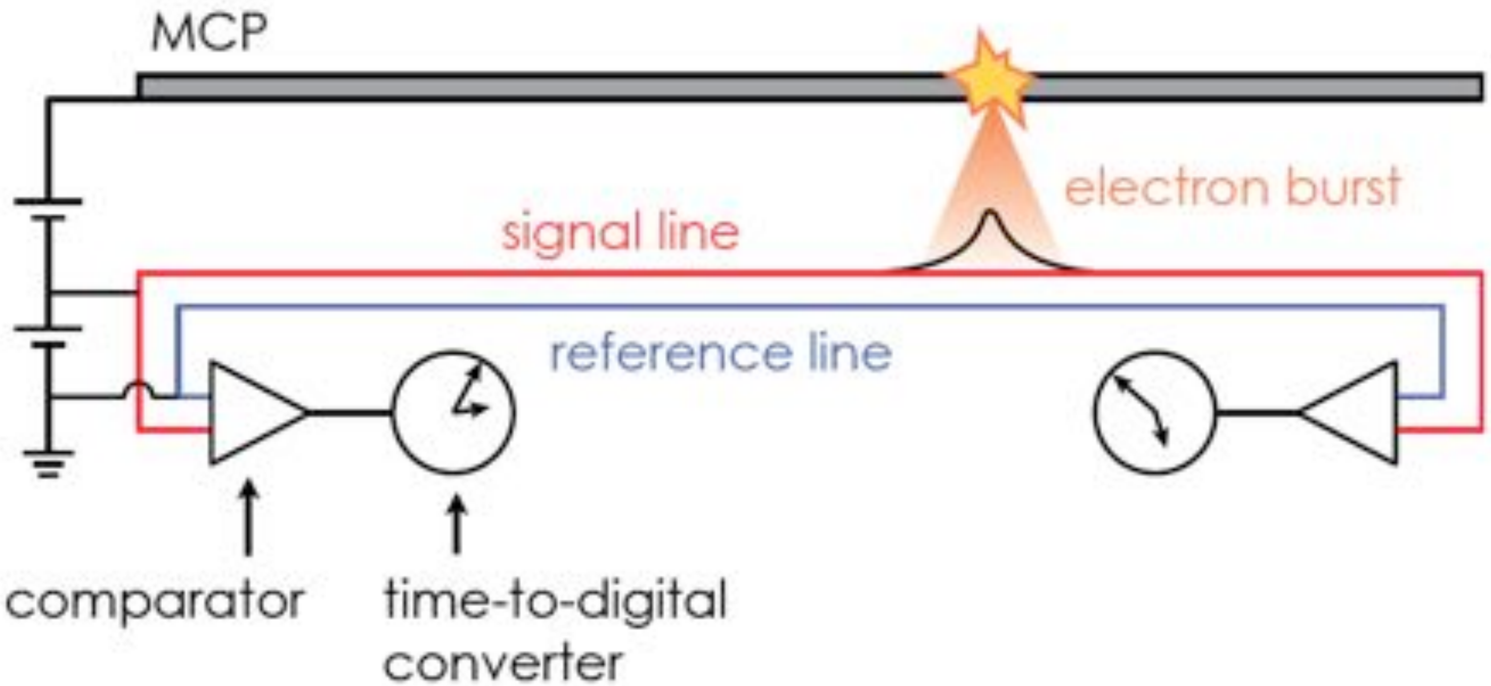
- excitation in discharge
- deexcitation enables electronic detection: $He^* \rightarrow He + e^-$

Detection MCP and delay line



hole separation: 24 μm
spatial resolution ~250 μm
5×10^4 detectors in //
q. e. for He* ~ 25%

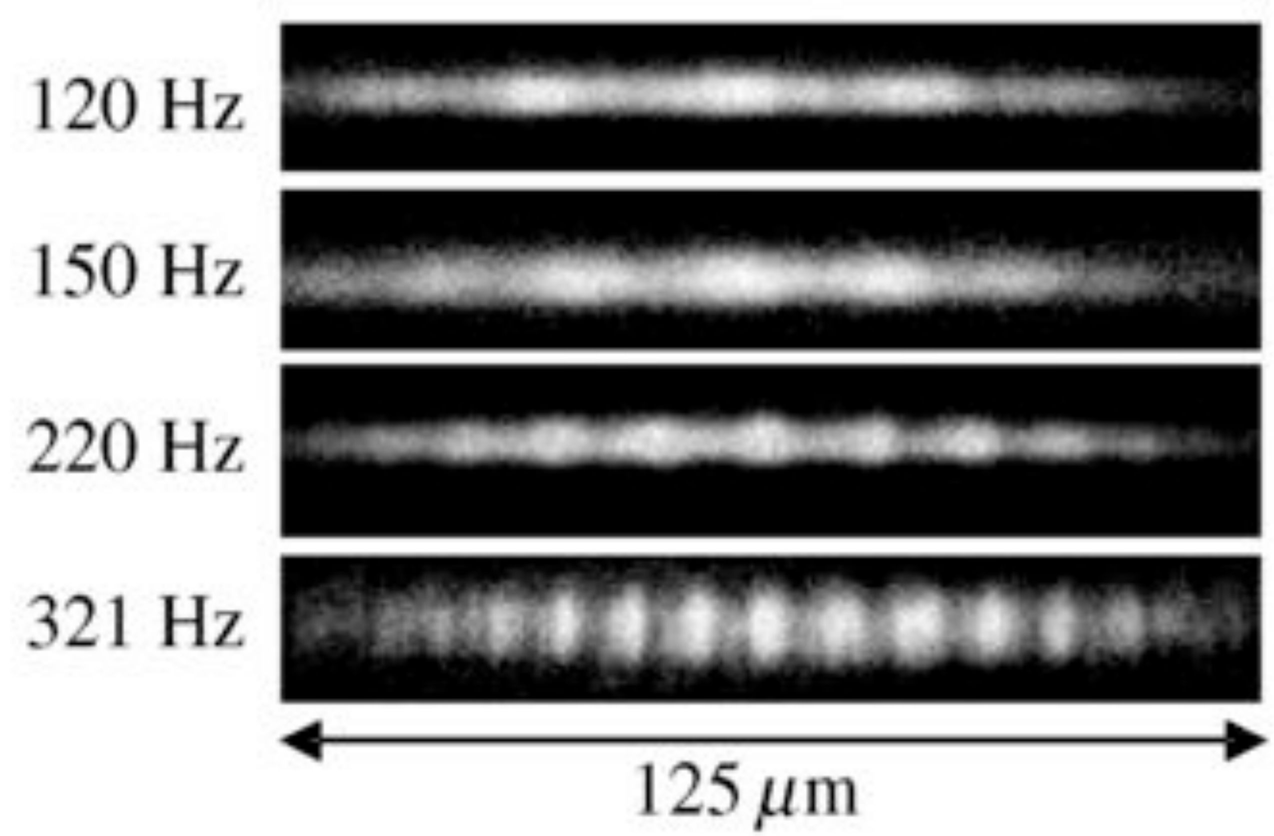
must be careful about saturation

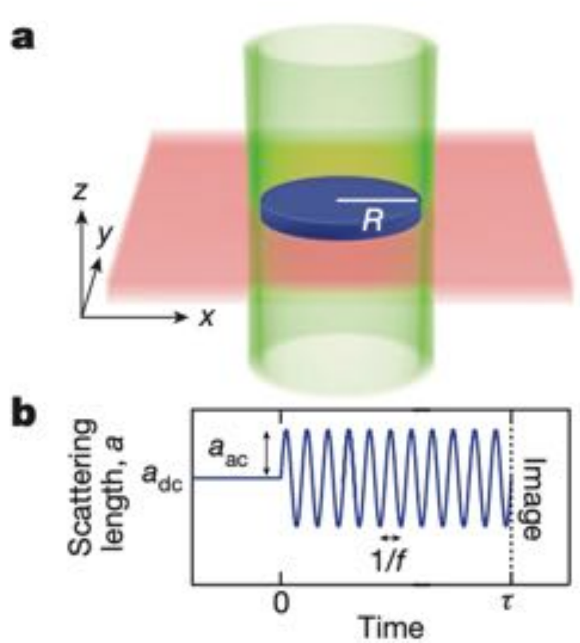


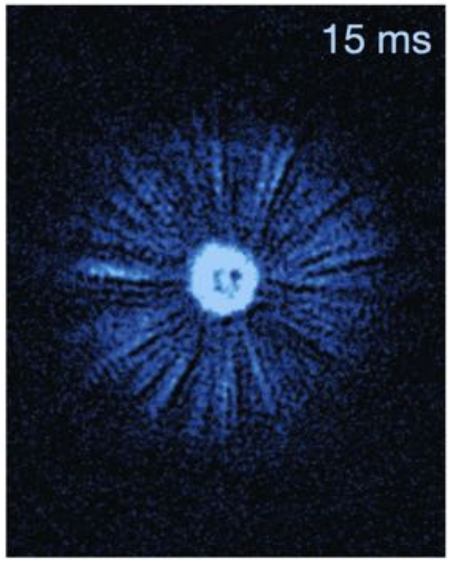
time differences give the position on MCP
digitizing step: 275 ps

Other experiments "simulating the universe" with a BEC

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



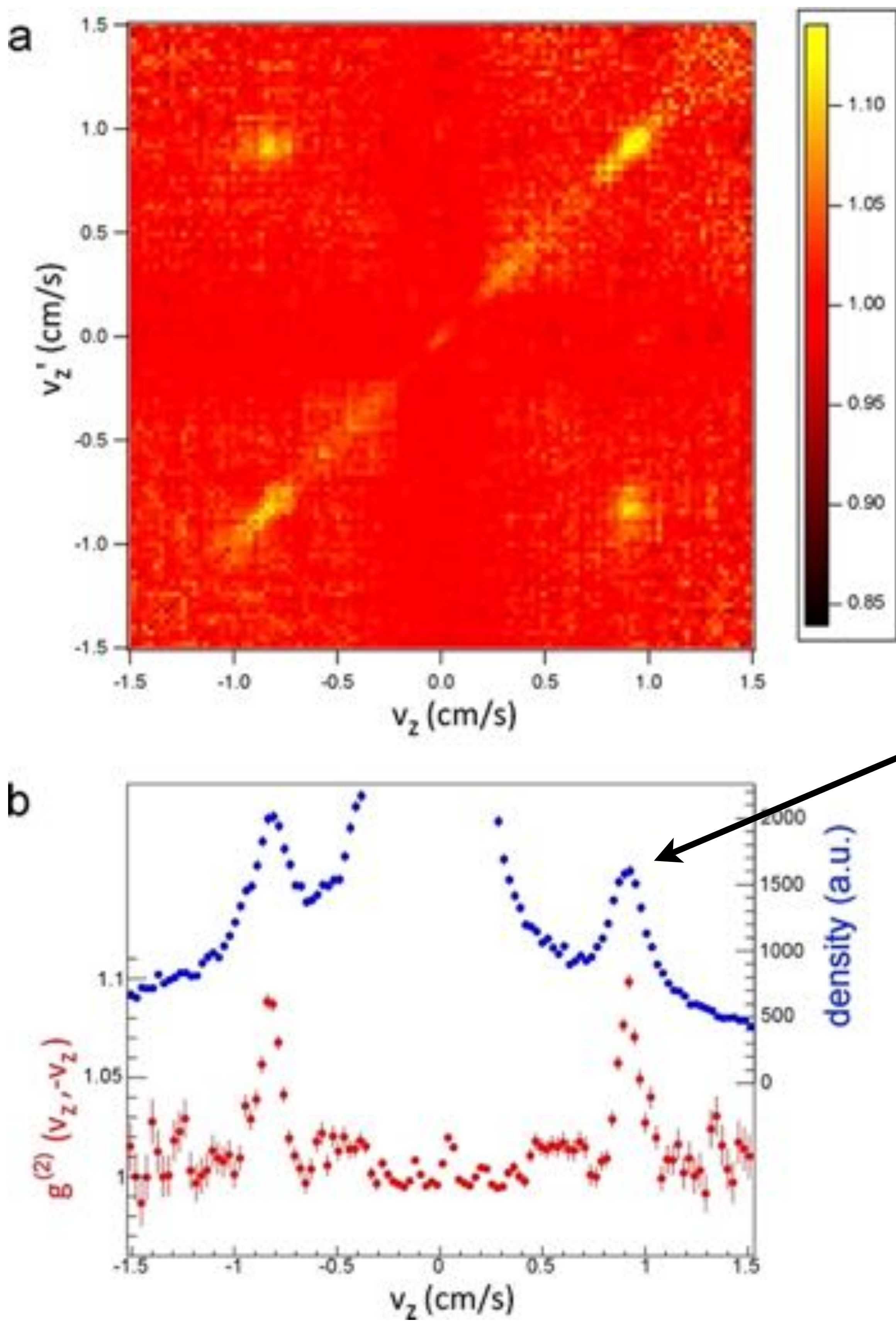




Modulating the scattering length by a Feshbach res.
U. of Chicago
observation of correlated "jets"
Nature **551**, 365 (2017)

also: other talks at this workshop

Correlation function



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

the energy of this excitation is $\hbar\omega/2$

$n(v)$

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

Correlation; yes but small

Cauchy-Schwarz inequality for correlations

2 boson modes, a, b

$$g_{aa}^{(2)} = \frac{\langle a^\dagger a^\dagger a a\rangle}{\langle a^\dagger a\rangle^2},\quad g_{bb}^{(2)} = \frac{\langle b^\dagger b^\dagger b b\rangle}{\langle b^\dagger b\rangle^2},\quad g_{ab}^{(2)} = \frac{\langle a^\dagger b^\dagger b a\rangle}{\langle a^\dagger a\rangle\langle b^\dagger b\rangle}$$

Then for classical distributions:

$$g_{ab}^{(2)} \le \sqrt{g_{aa}^{(2)} g_{bb}^{(2)}}$$

If the distributions are "non-classical", the inequality is violated.
If the modes are populated by identical bosons, violation of the inequality implies non-separability

Multi-mode case in the experiment is more complex
However, we have $g_{aa}{}^{(2)} = 2$ and $g_{ab}{}^{(2)} = 1.1$

Cauchy-Schwarz and sub-Poissonian statistics

Variance in the number difference (normalized to shot noise)

$$V_{ab} = \frac{\Delta(n_a - n_b)^2}{\langle n_a \rangle + \langle n_b \rangle}$$

If distributions have the same mean $\langle n_a \rangle = \langle n_b \rangle$

$$V_{ab} = 1 + \langle n_a \rangle (g^{(2)}_{aa} - g^{(2)}_{ab})$$

so the variance of the number difference is also an entanglement witness.

So far so good, but...

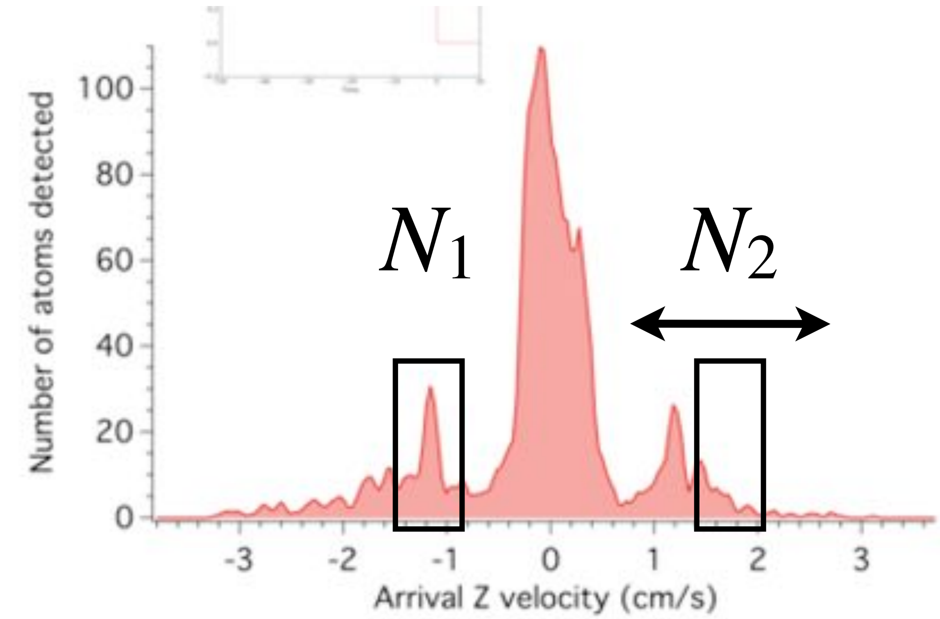
Perfect correlation implies

$$N_1 - N_2 = 0$$

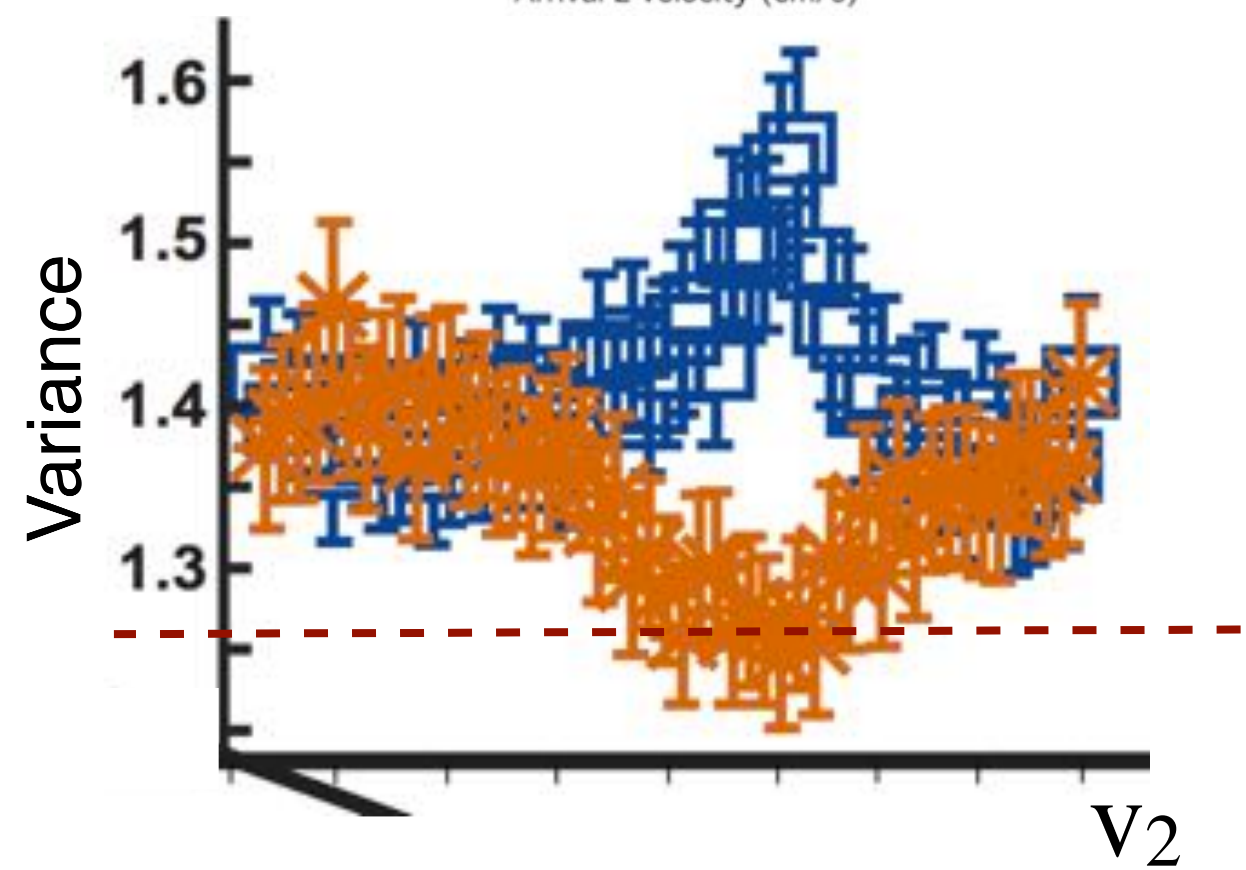
or at least

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

sub-Poissonian statistics



no



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

Discussion of the 2012 expt

atoms spilling out -- crossed dipole trap

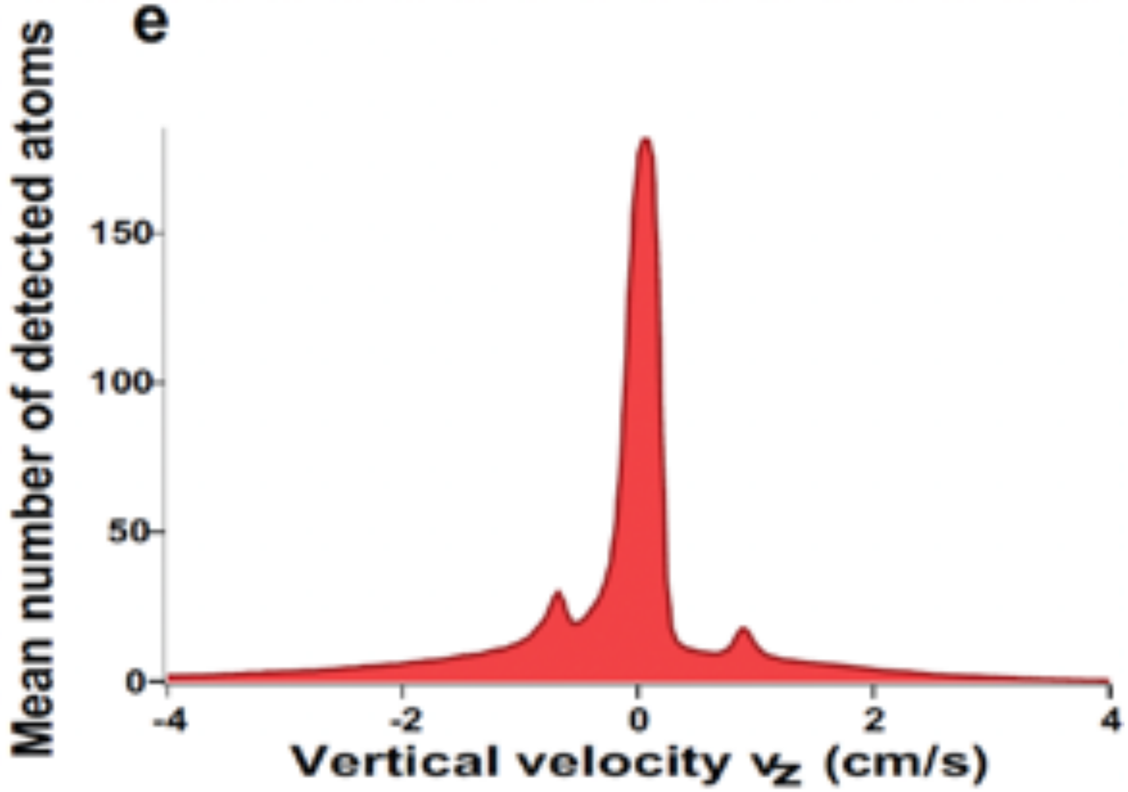
non-zero temperature -- ~100 nK (2 kHz)

large mode occupation numbers

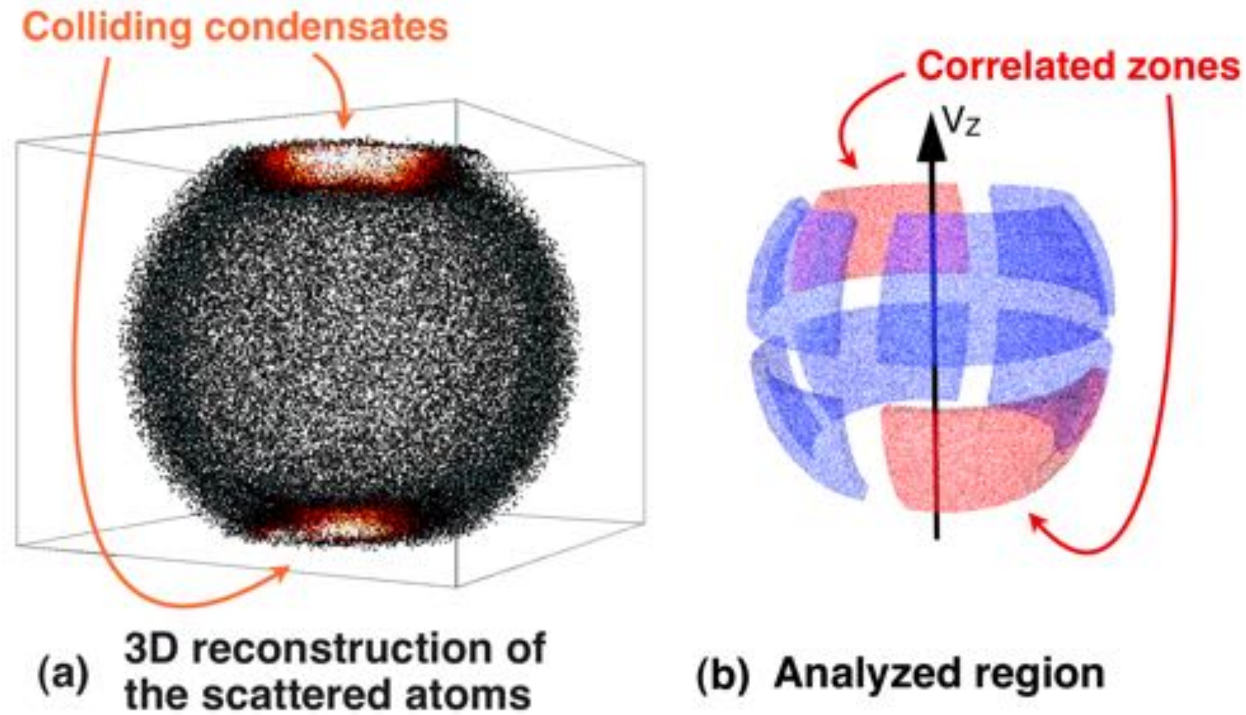
ideally, $g_{ab}^{(2)} = 2 + 1/\langle n \rangle$

so lower $\langle n \rangle$ and do more averaging

reheating -- talk by Amaury Micheli and Scott Robertson



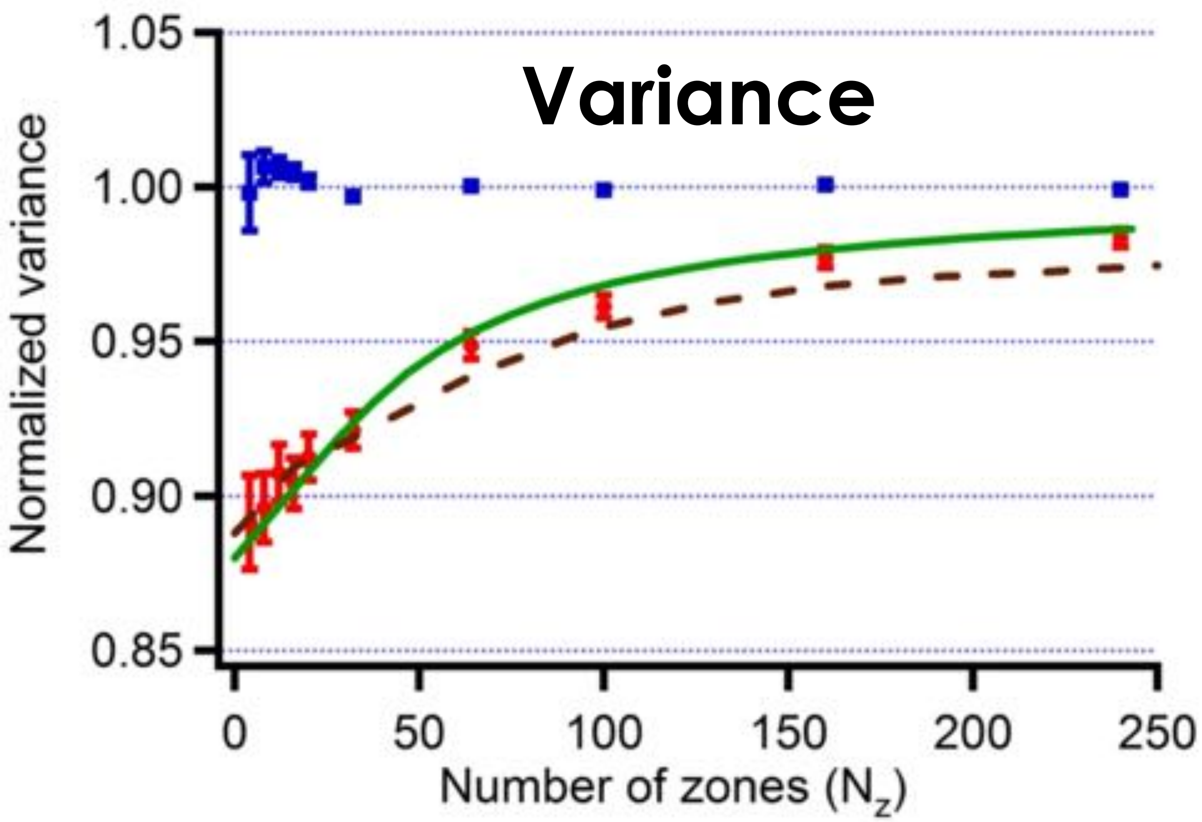
Number difference variance may still be more robust



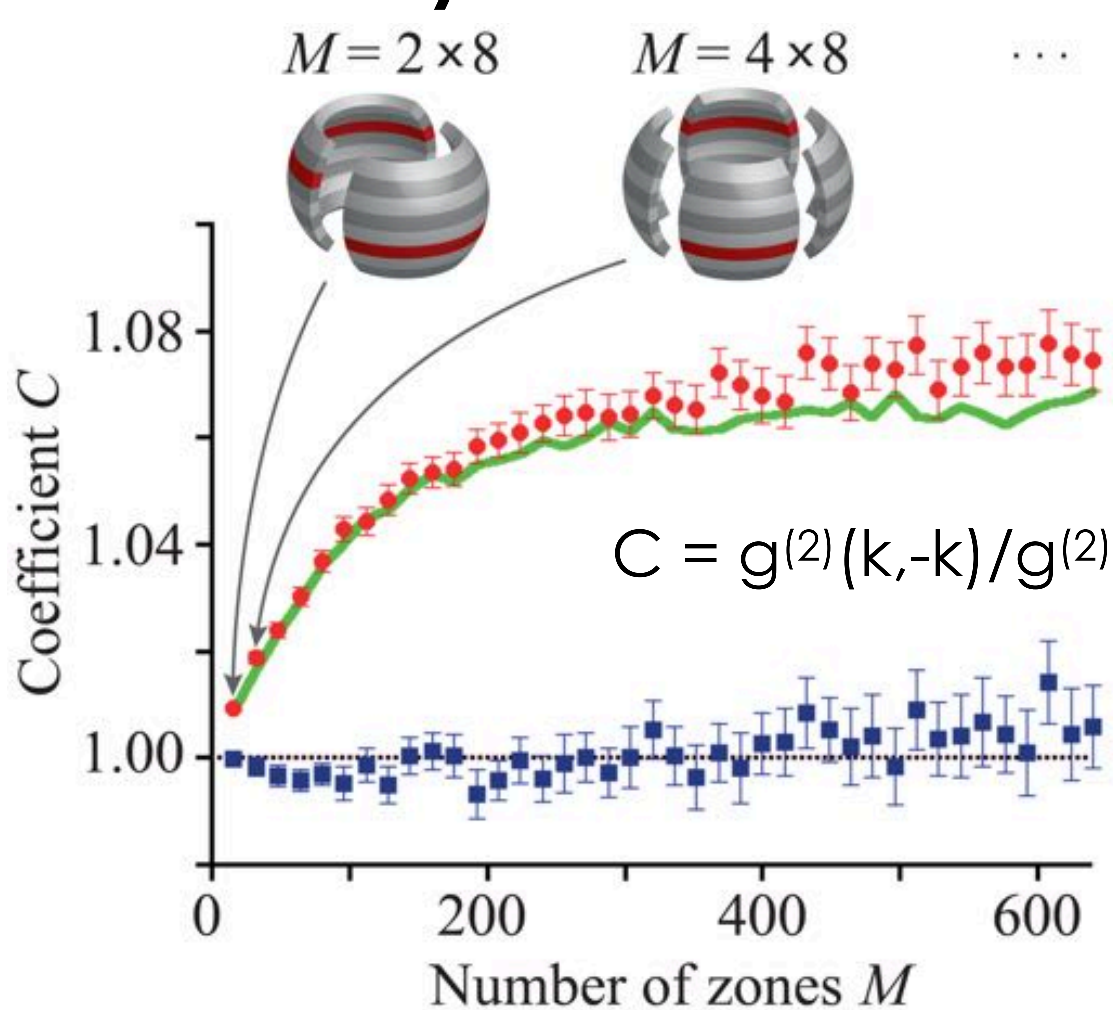
Example from the scattered halo from a BEC collision.

Jaskula et al. PRL 2010

Kheruntsyan et al. PRL 2012

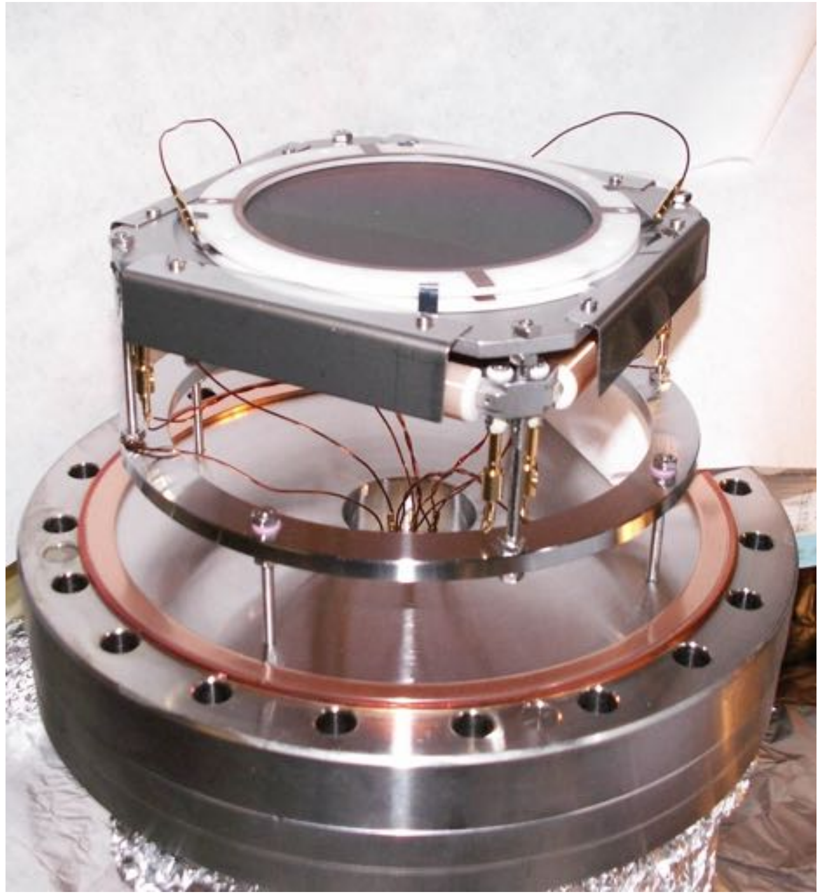


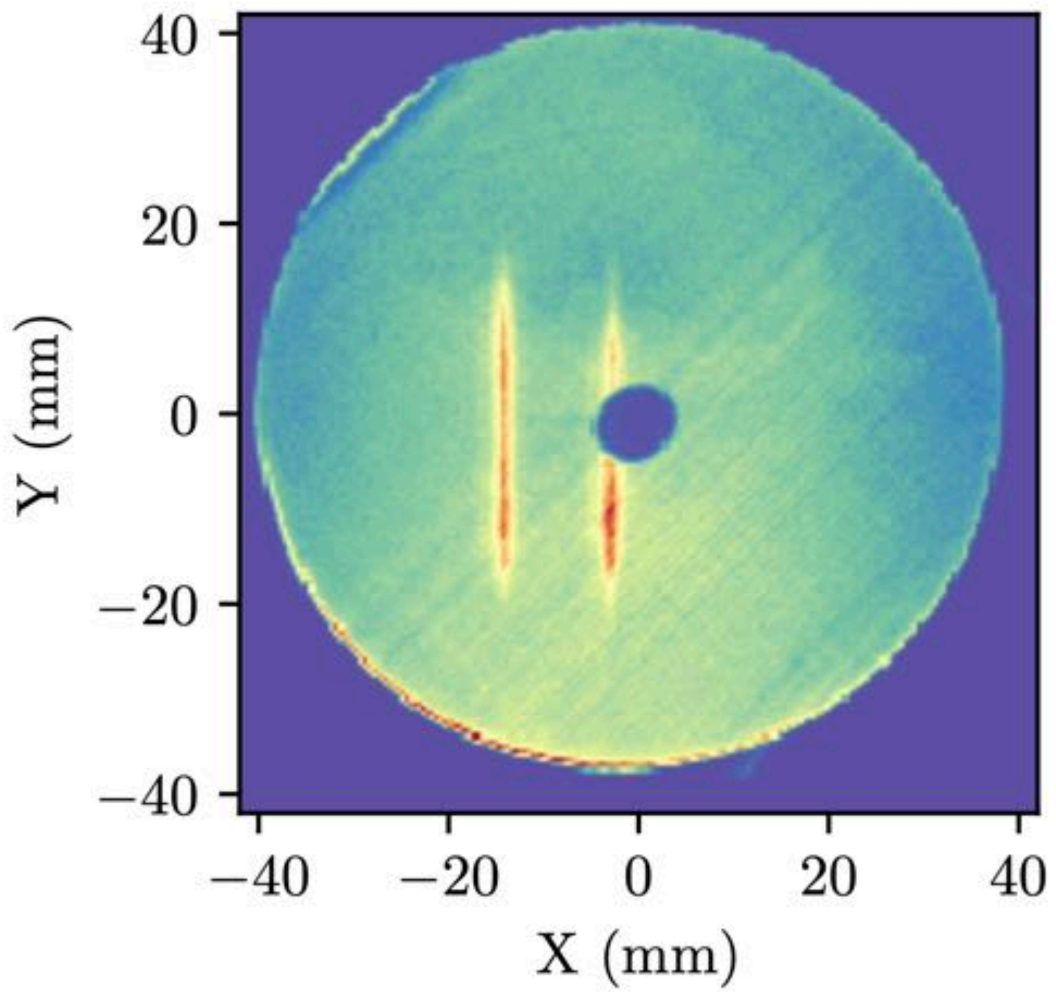
Cauchy-Schwarz violation



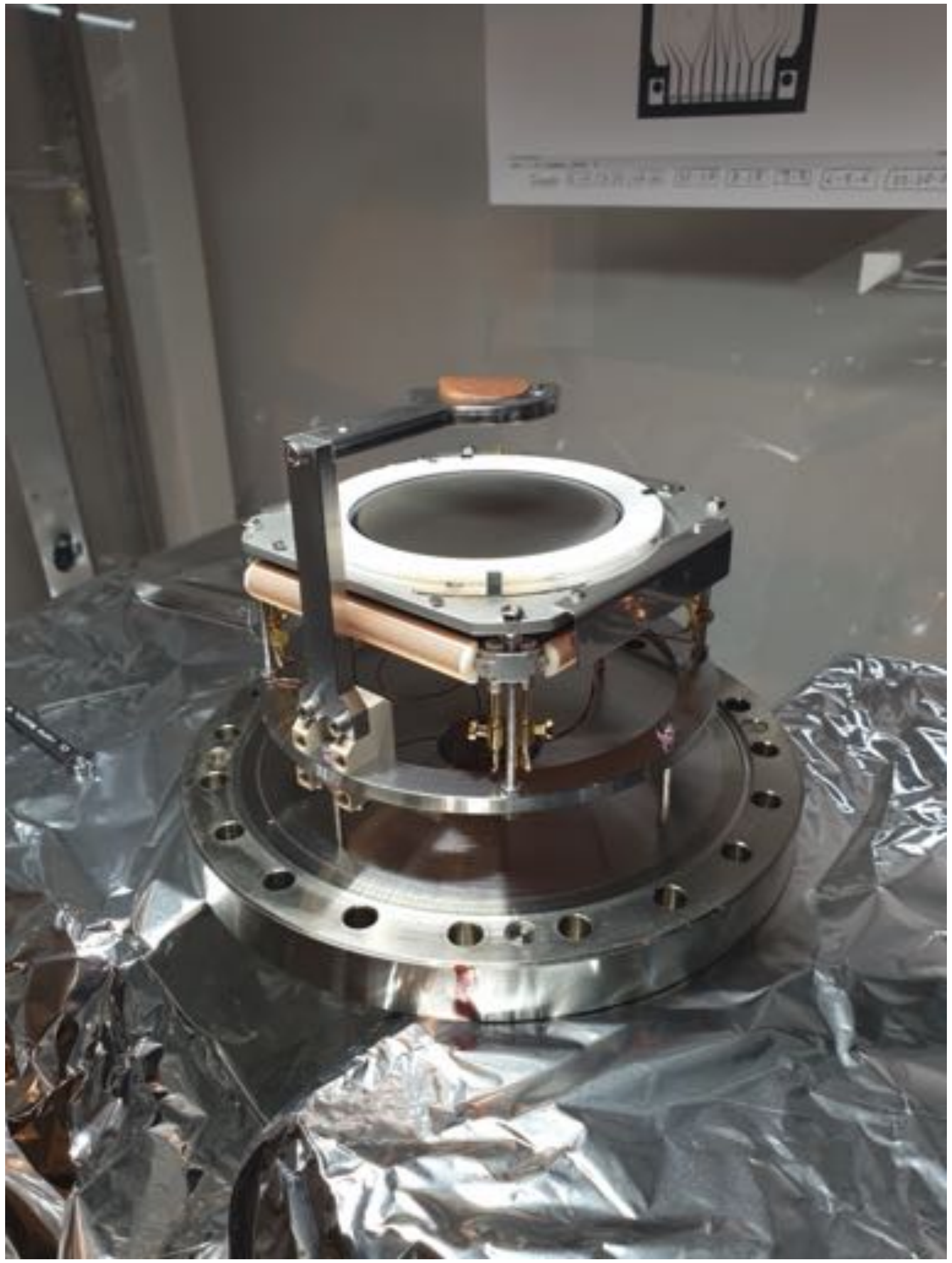
$C = g^{(2)}(k,-k)/g^{(2)}(k,k)$

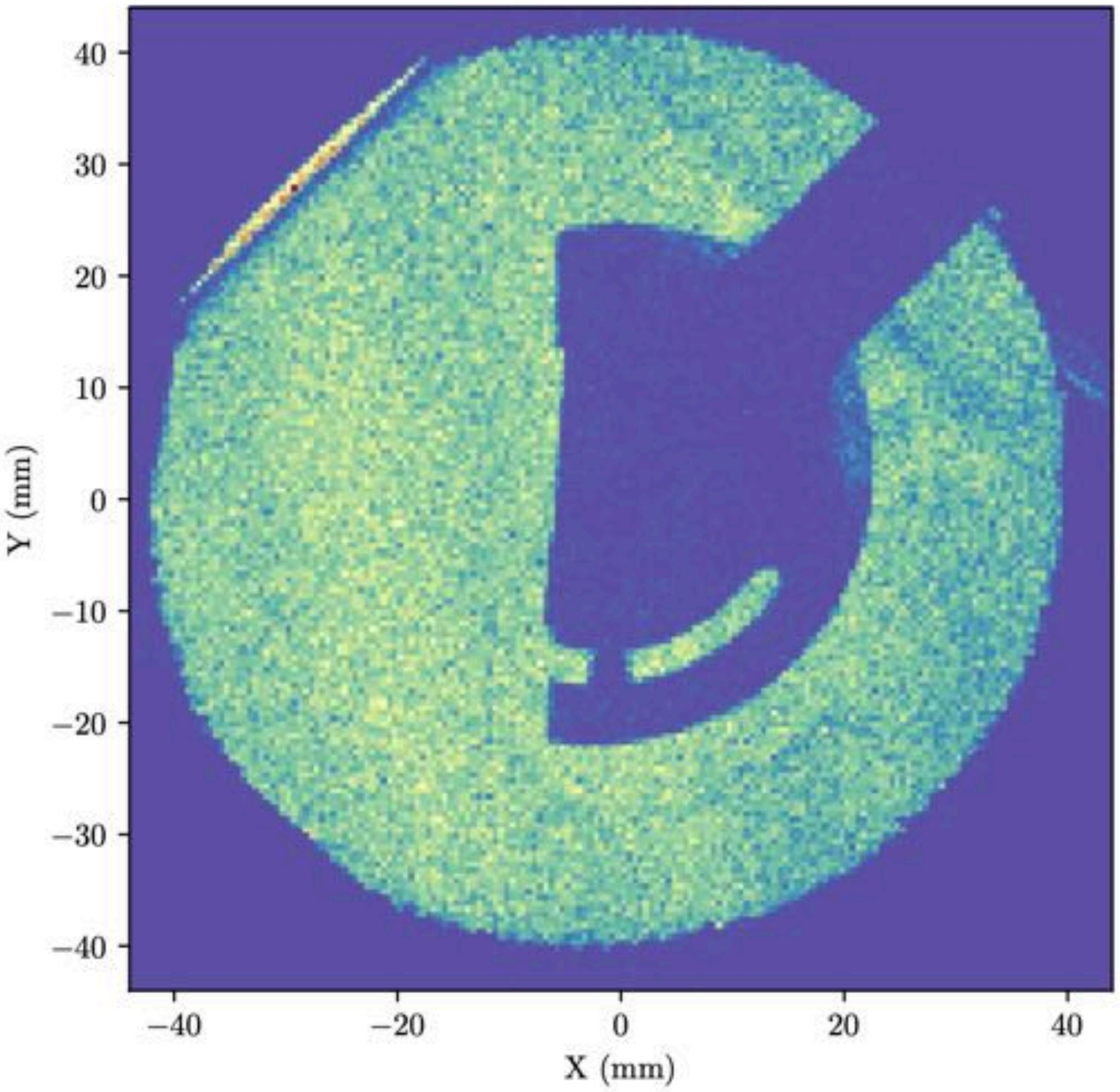
"Fun" with the detector



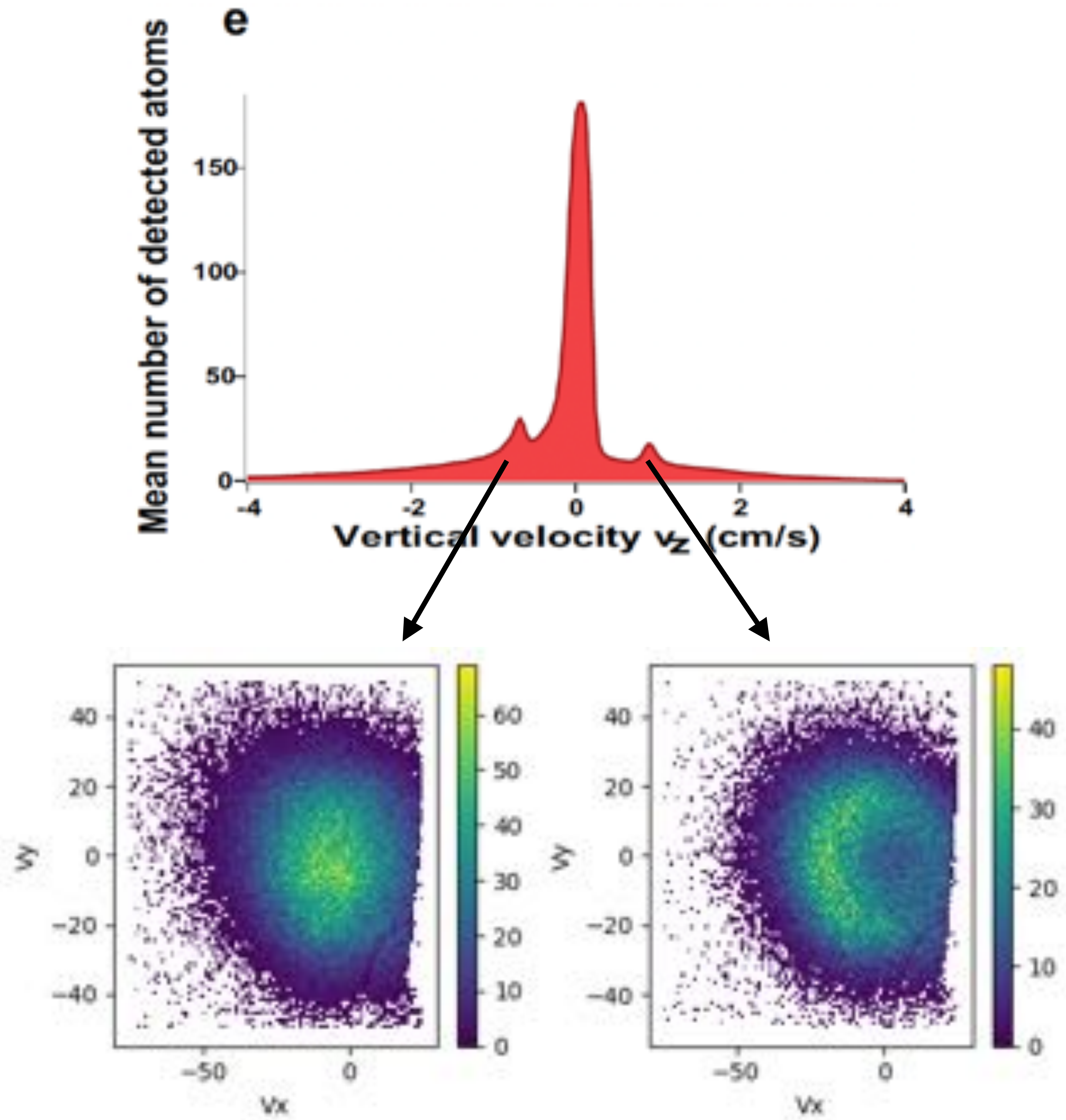


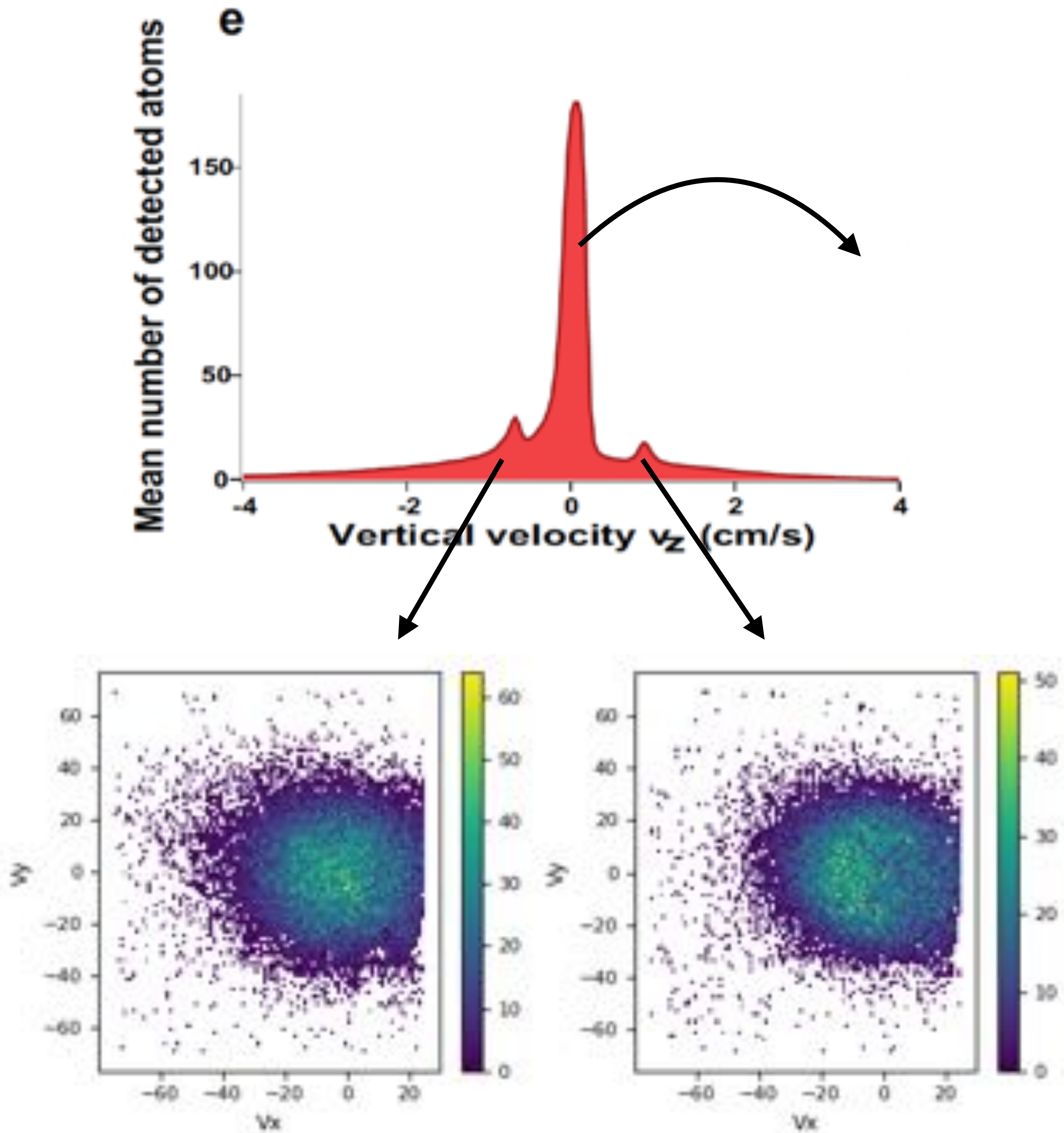
The cure





Another issue: saturation




e
Mean number of detected atoms
150
100
50
0
-4
-2
0
2
4
Vertical velocity v_z (cm/s)
Vy
Vx
60
40
20
0
−20
−40
−60
50
30
10

Conclusions. So?

Suppose we do observe a signature of entanglement ...

entangled phonons! cool!

atomic physicists learn about cosmology

What have we (the cosmologists) learned about the early universe?

validation of a preheating model

what else ?

Collaborators

Lab. Charles Fabry

<u>Quentin Marolleau</u>
Charlie Leprince
<u>Victor Gondret</u>
Clothilde Lamirault
Alexandre Dareau
Marc Cheneau
Denis Boiron

IJCLab

<u>Scott Robertson</u>
<u>Amaury Micheli</u>

Renaud Parentani 1962 - 2020
Professor of Physics at
Université de Paris-Saclay

- Study of quantum effects in gravitational fields with applications to the early universe (inflation), and to black holes
- Black hole thermodynamics, quantum entanglement, decoherence
- Analogue gravity experiments

His work with Scott Robertson and Florent Michel was the primary motivation for the work discussed in this talk

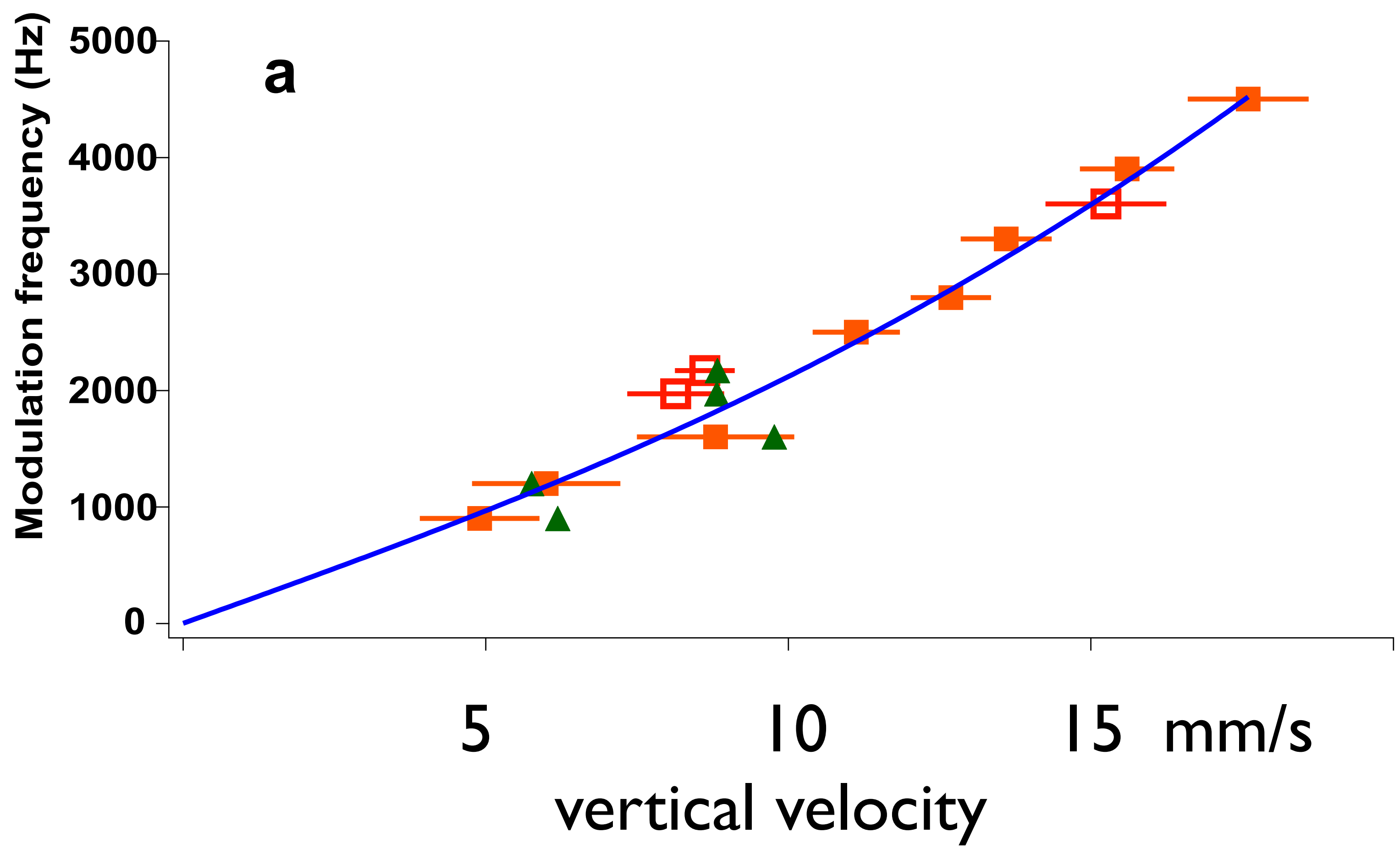
That's all

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

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

fit: $\alpha = 2.2$

$c = 8$ mm/s



- from density
- from correlation function

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