Creation and non-separability of phonon pairs in a modulated BEC

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Denis Boiron, Chris Westbrook, Amaury Micheli and Scott Robertson

Benasque 2023

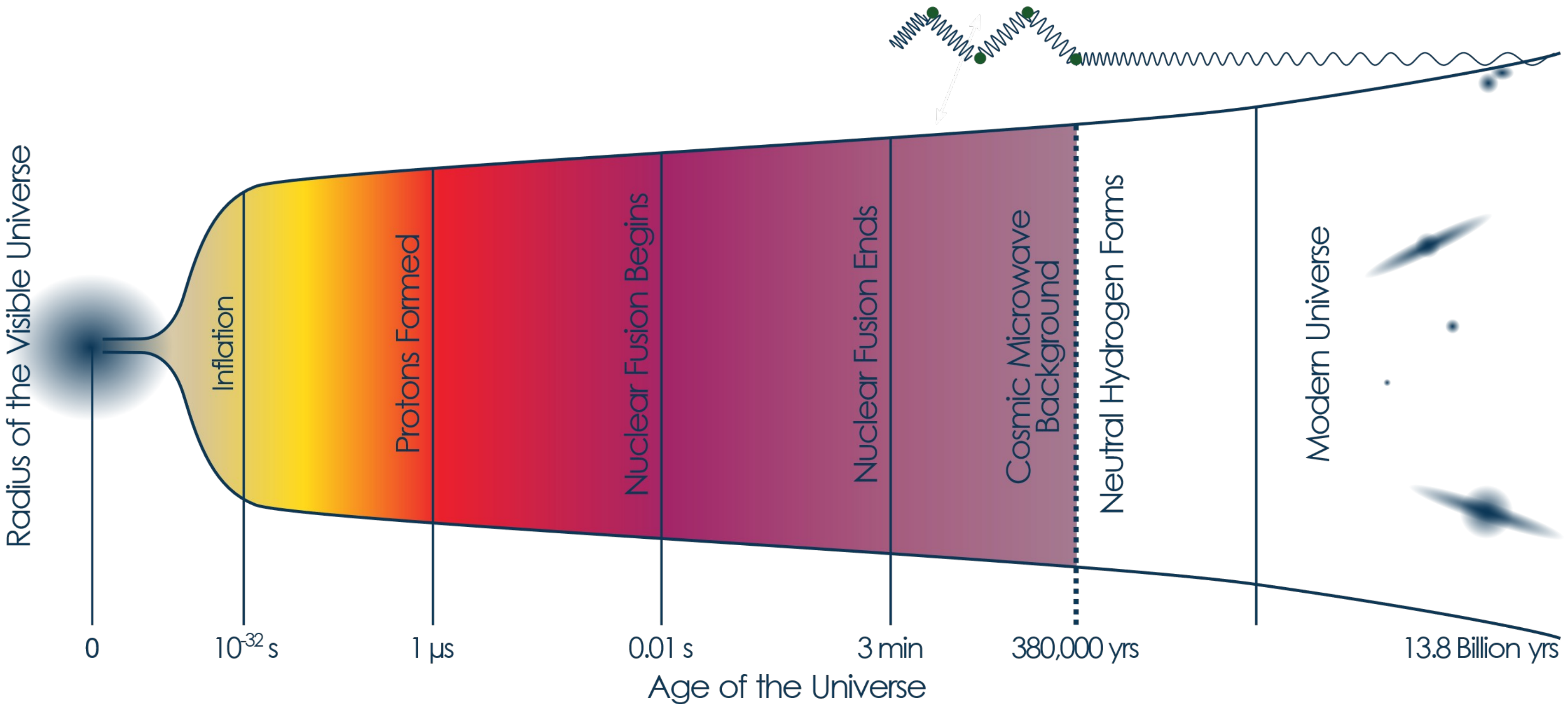
Outline

① Context

② Experimental setup

③ First results (work in progress)

The story of the universe in a nutshell



Inflation
⇩
Preheating
⇩
Re-heating

Analogy : simulating the early universe in our lab

COSMOLOGY

Oscillation of the inflaton ⇨ Entangled particles pairs

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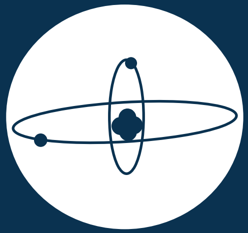
(Pre?)(Re?)-heating

Oscillation of the speed of sound in a BEC ⇨ Entangled phonons pairs

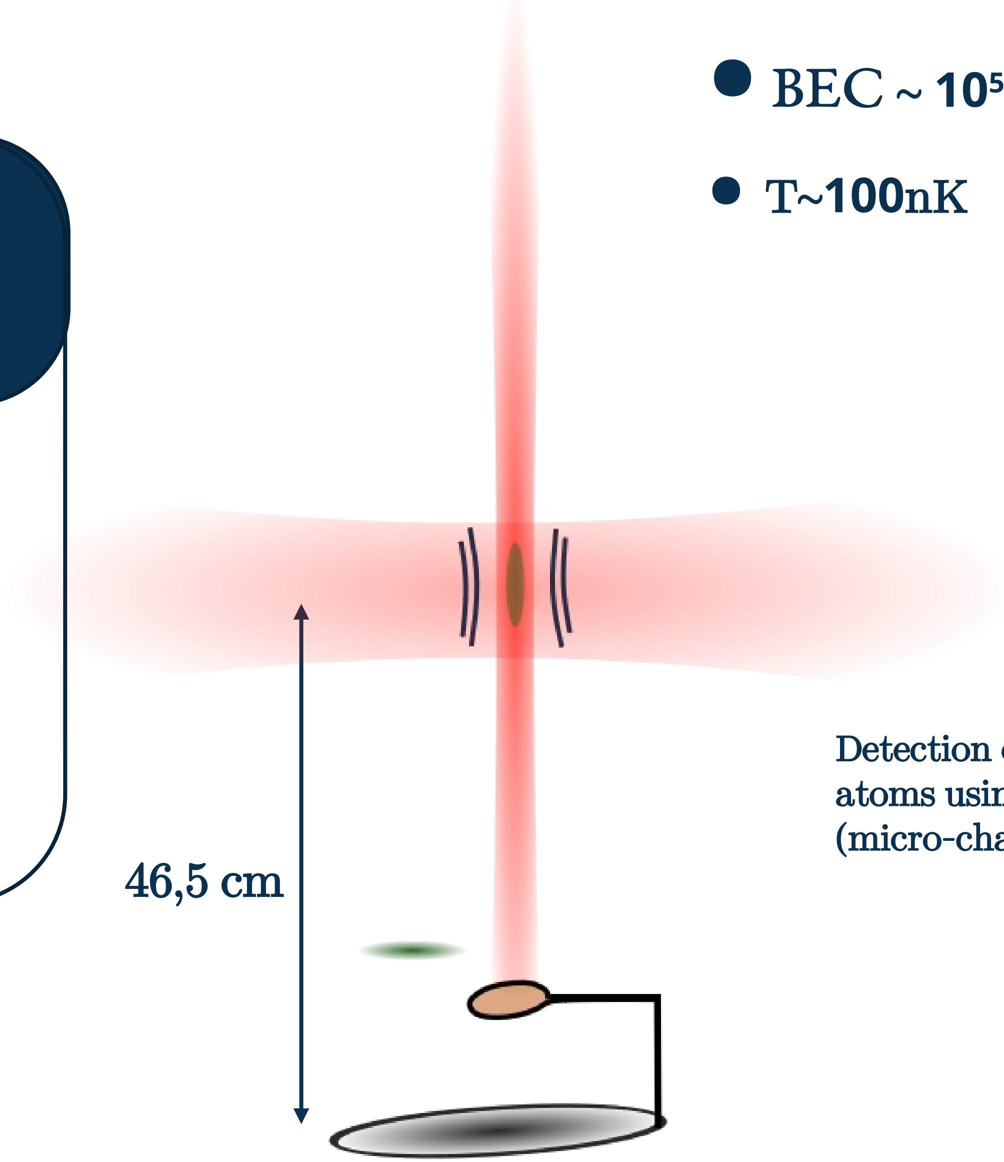
LAB SIMULATION

Experimental setup



Metastable Helium 4

- Large half-life time (2h)
- Large internal energy (20 eV)
- Cooled with 1083 nm transition

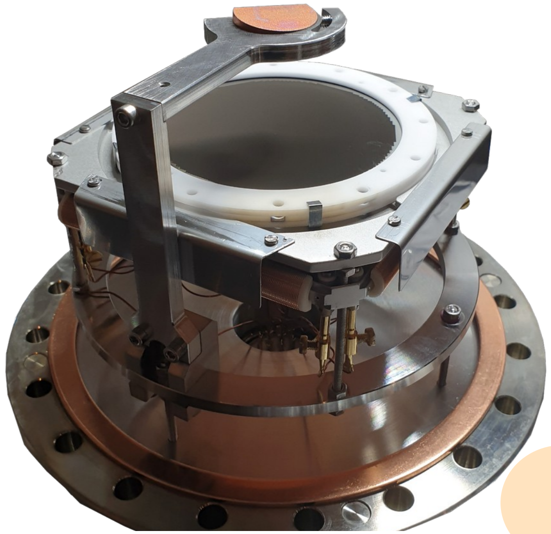


- BEC ~ **10^5 atoms** (10 seconds duty cycle)
- **T~100nK**

crossed dipole trap

- 70 Hz (vertical)
- 1,3 kHz (radial)

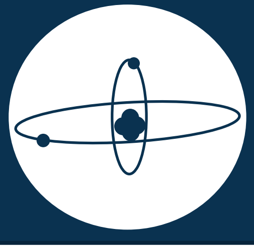
Detection of individual atoms using a MCP (micro-channel plate)



Experimental setup

LABORATOIRE CHARLES FABRY

He*



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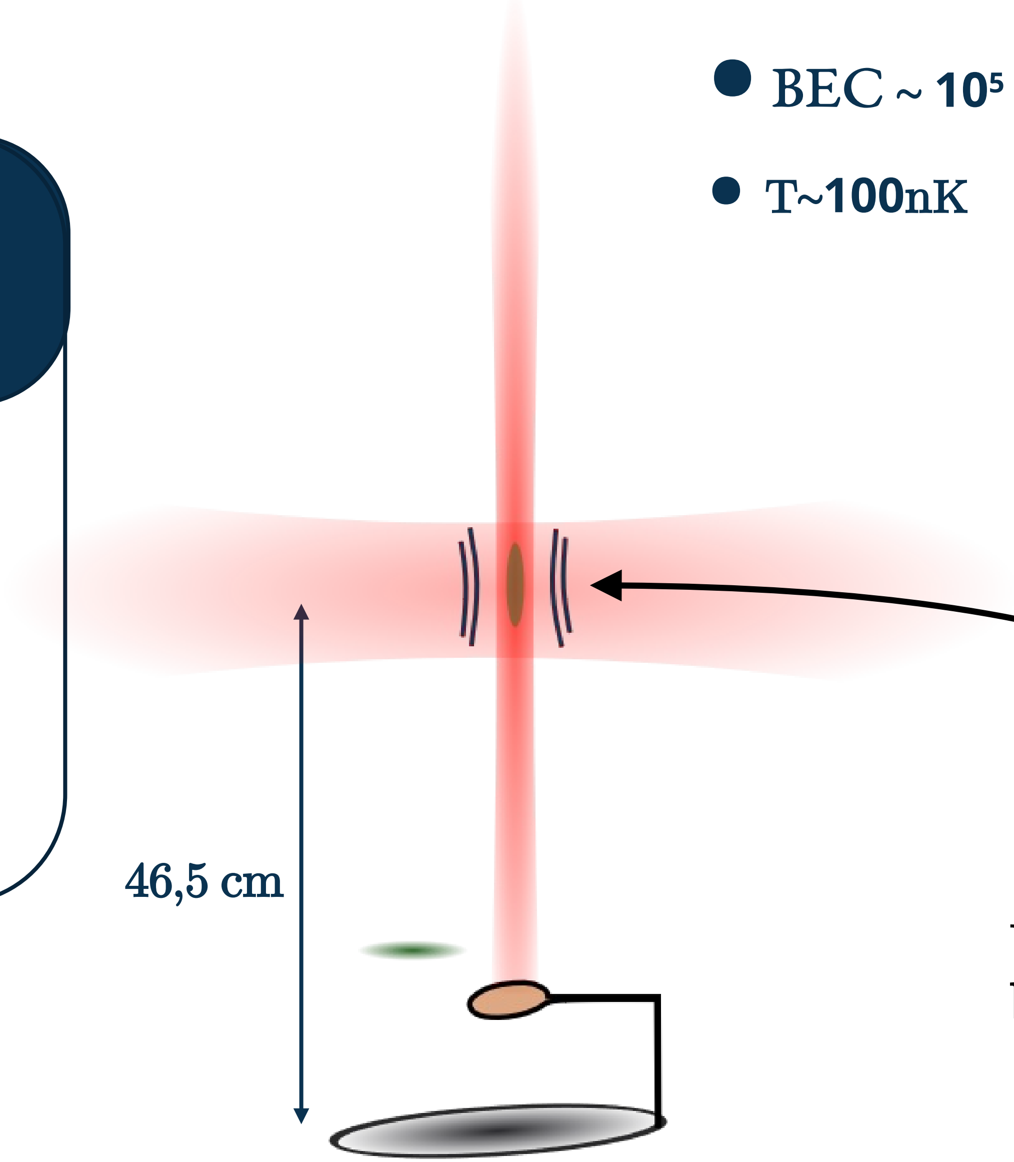
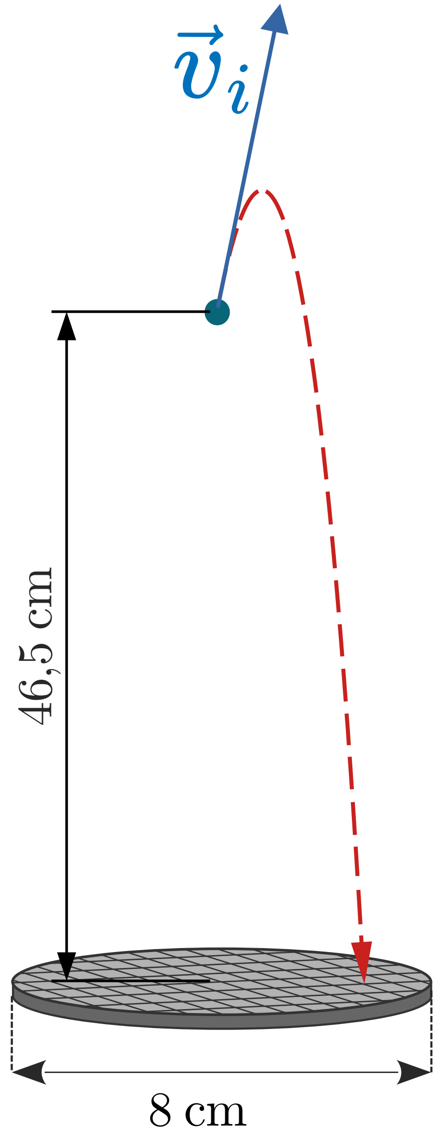
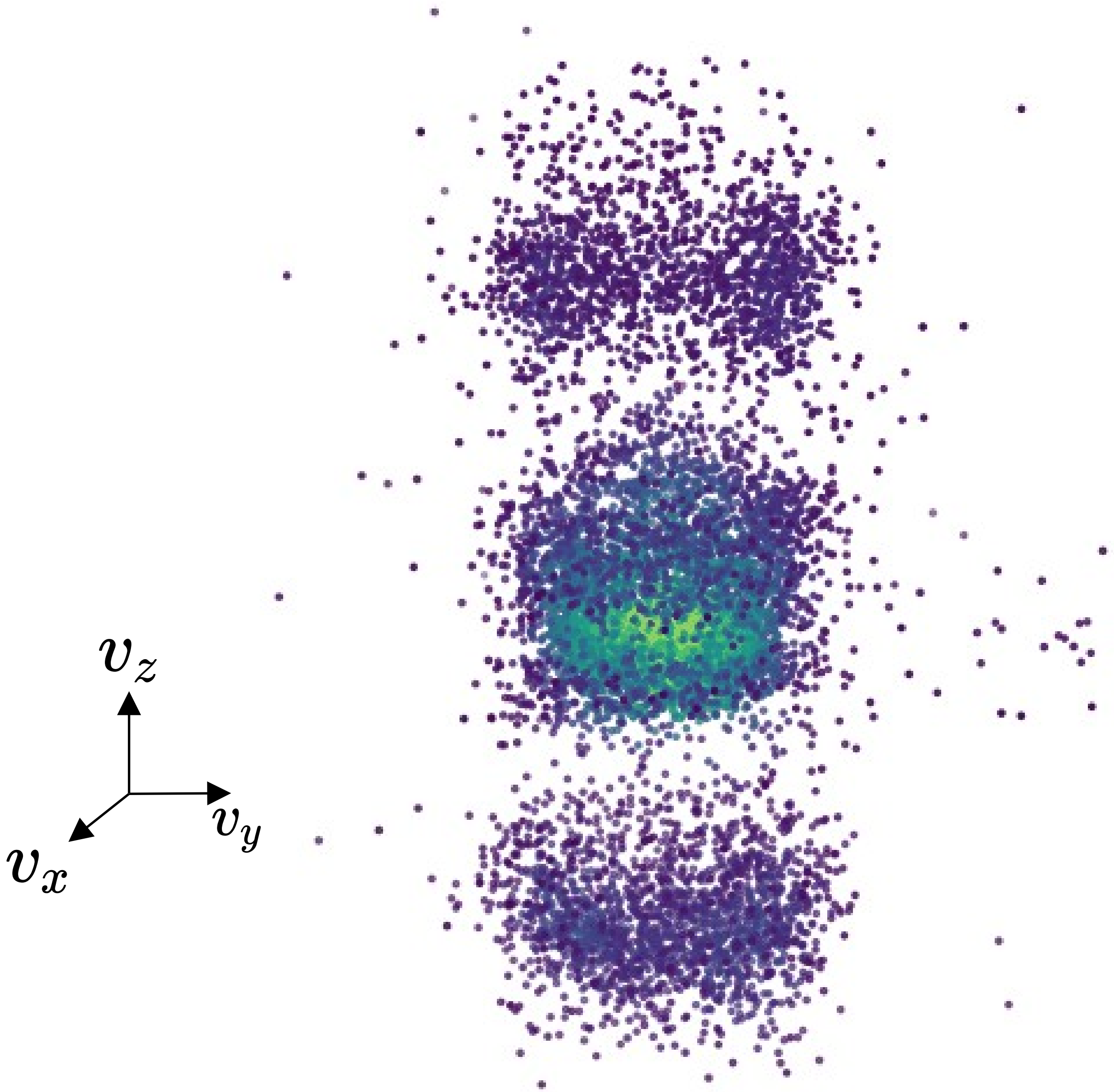


We periodically squeeze the cloud by modulating the laser intensity

Experimental setup





Phonon pair creation

Squeezing the gas at angular frequency ω_{mod} $\Longrightarrow$ $\hat{H} \propto \hat{a}^\dagger_{v_z}\hat{a}^\dagger_{-v_z} + \hat{a}_{v_z}\hat{a}_{-v_z}$ $\Longrightarrow$ Correlated pairs of excitations (phonons) with opposite velocities

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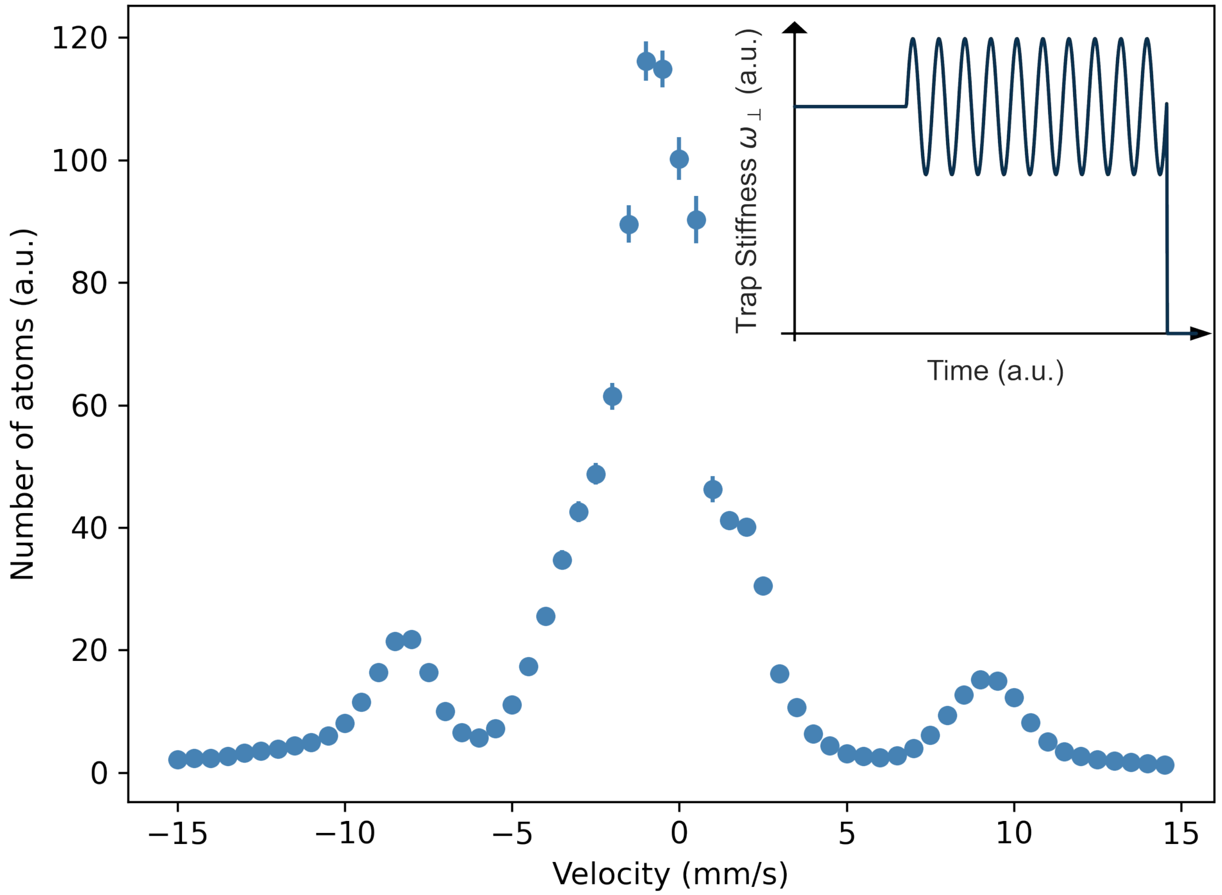

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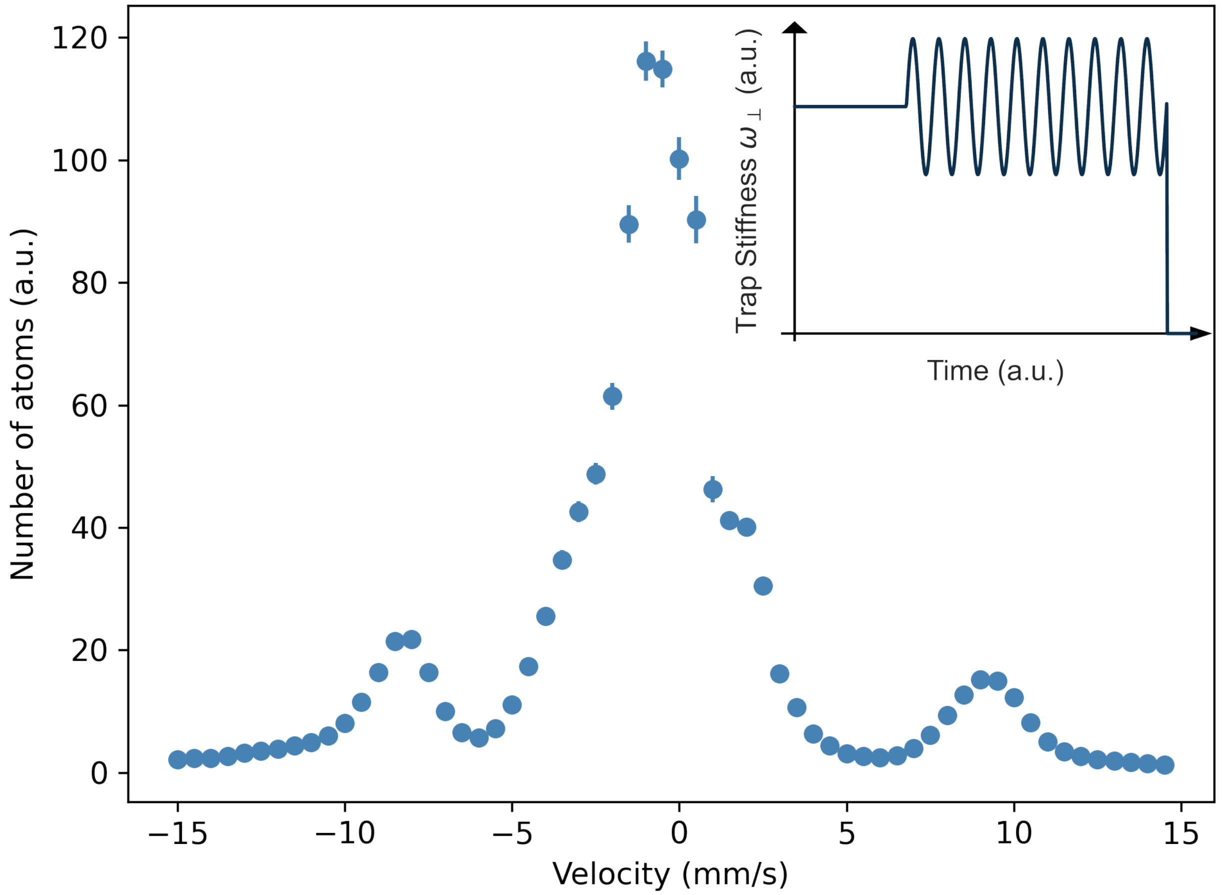

Dispersion relation (Bogoliubov-de Gennes):

$$\hbar\omega_{mod} = \alpha\sqrt{(cp)^2 + \left(\frac{p^2}{2m}\right)^2}$$

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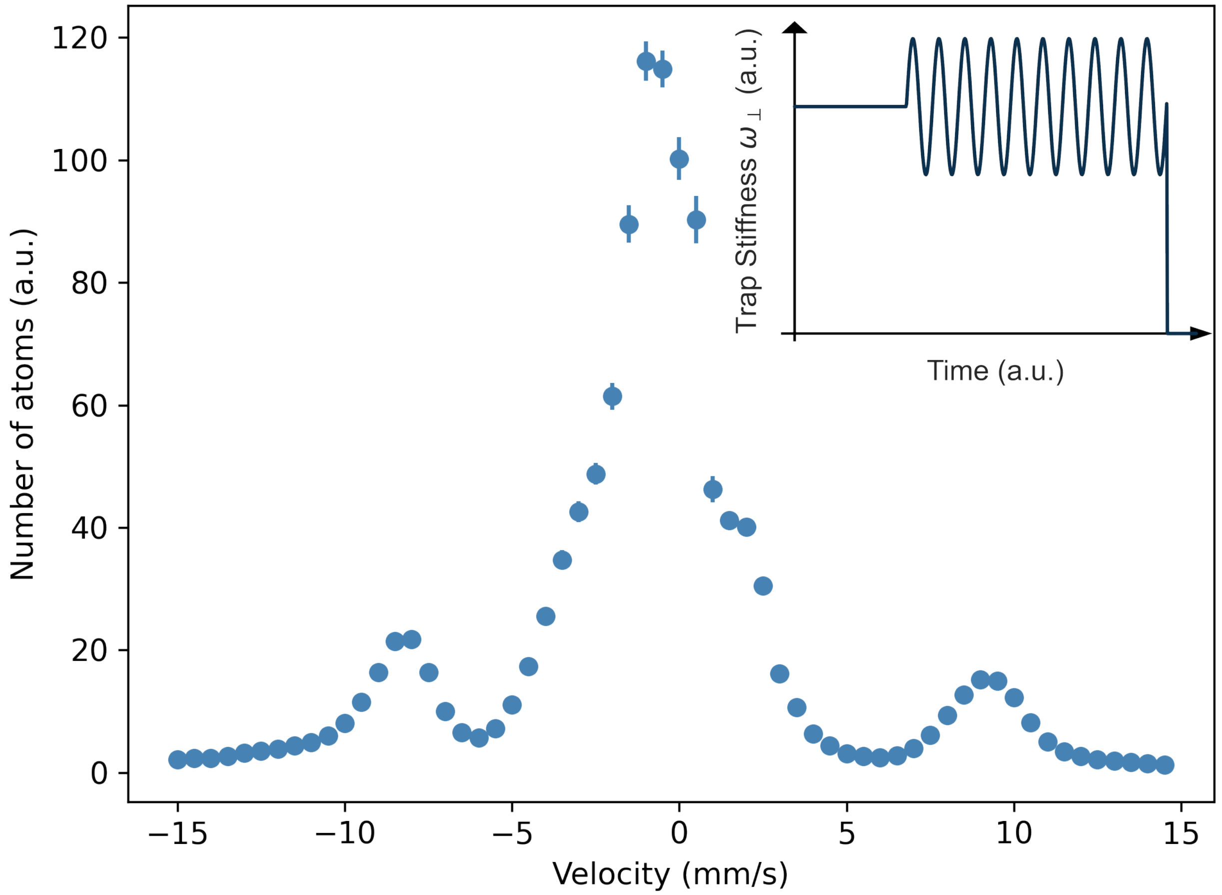

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Pairwise generation

$\alpha = 2$

Phonons (linear)

Free particles (quadratic)

Phonon pair creation

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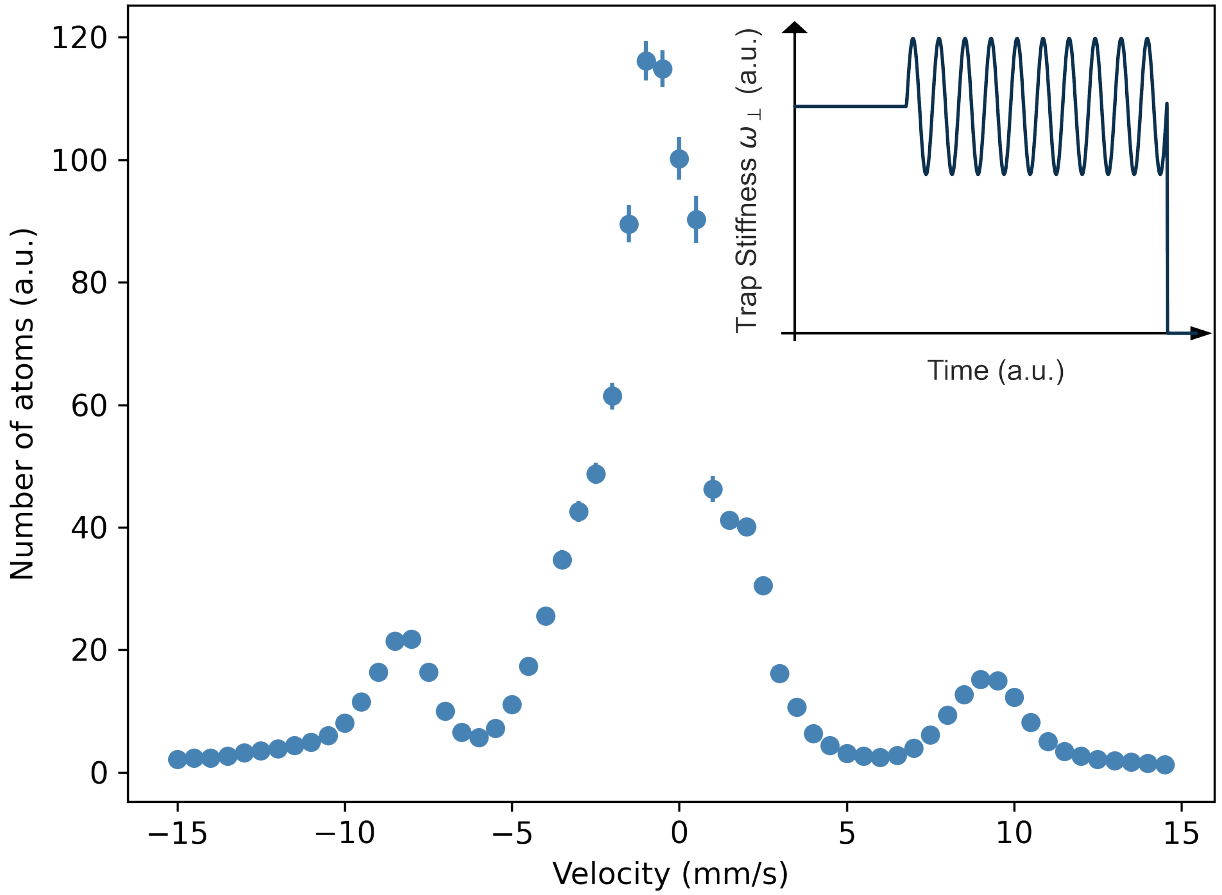

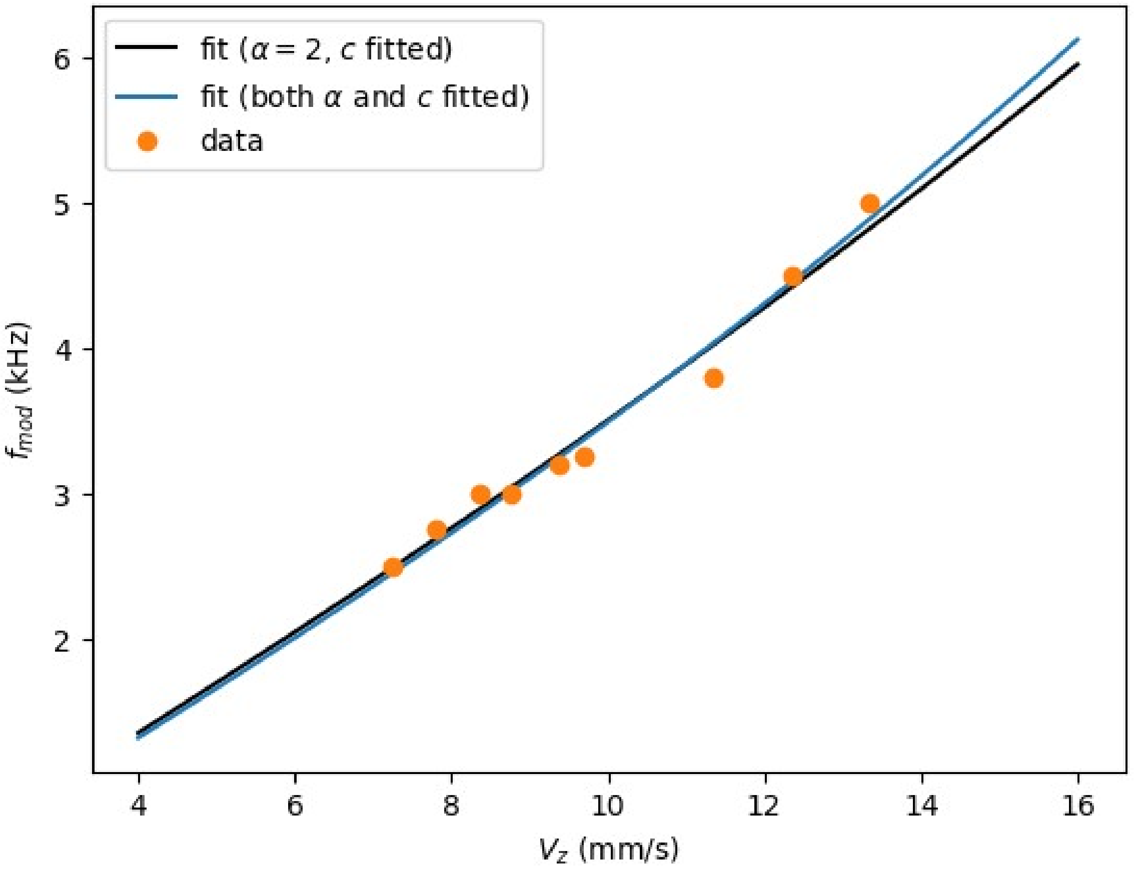

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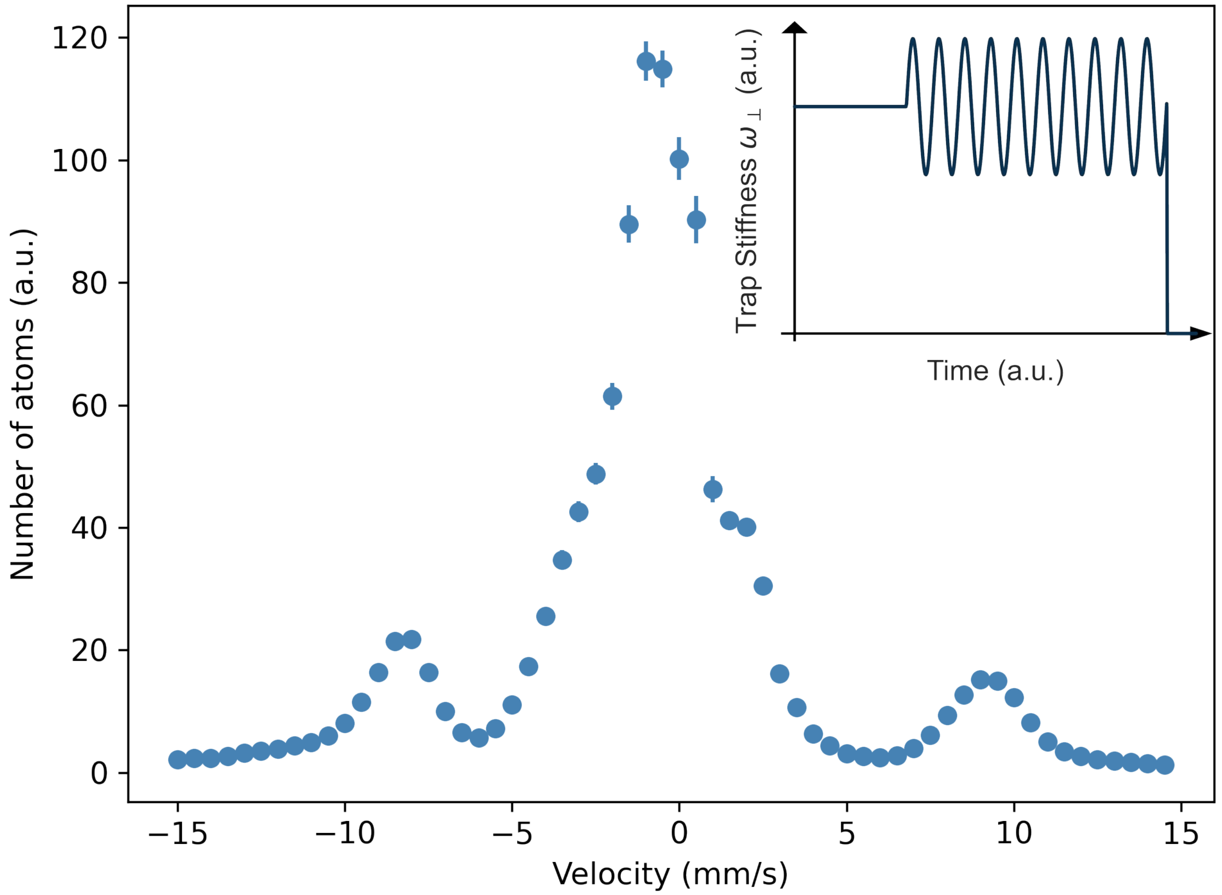
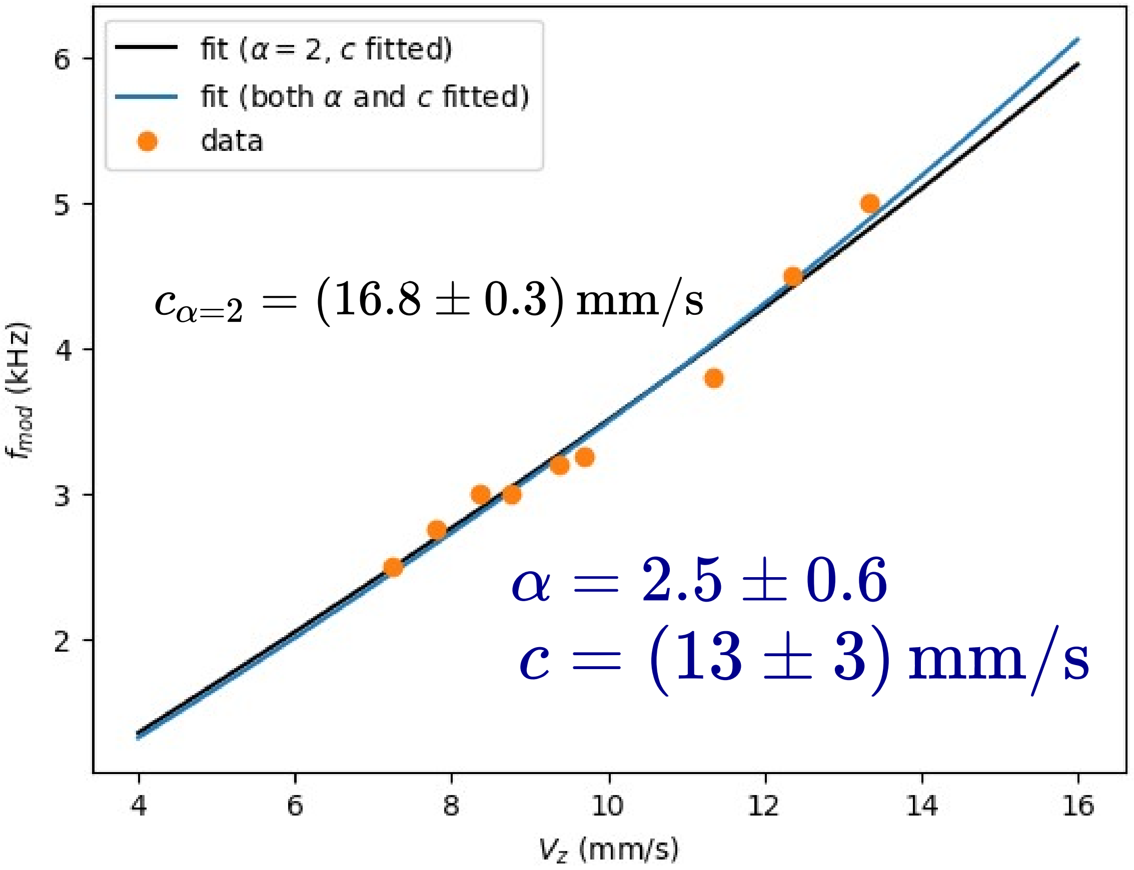
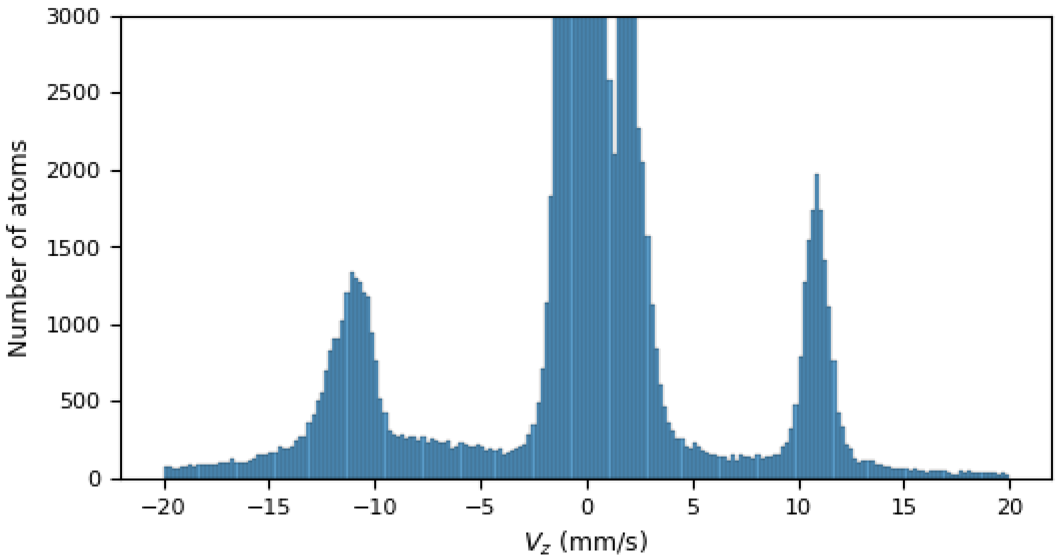




First experimental result



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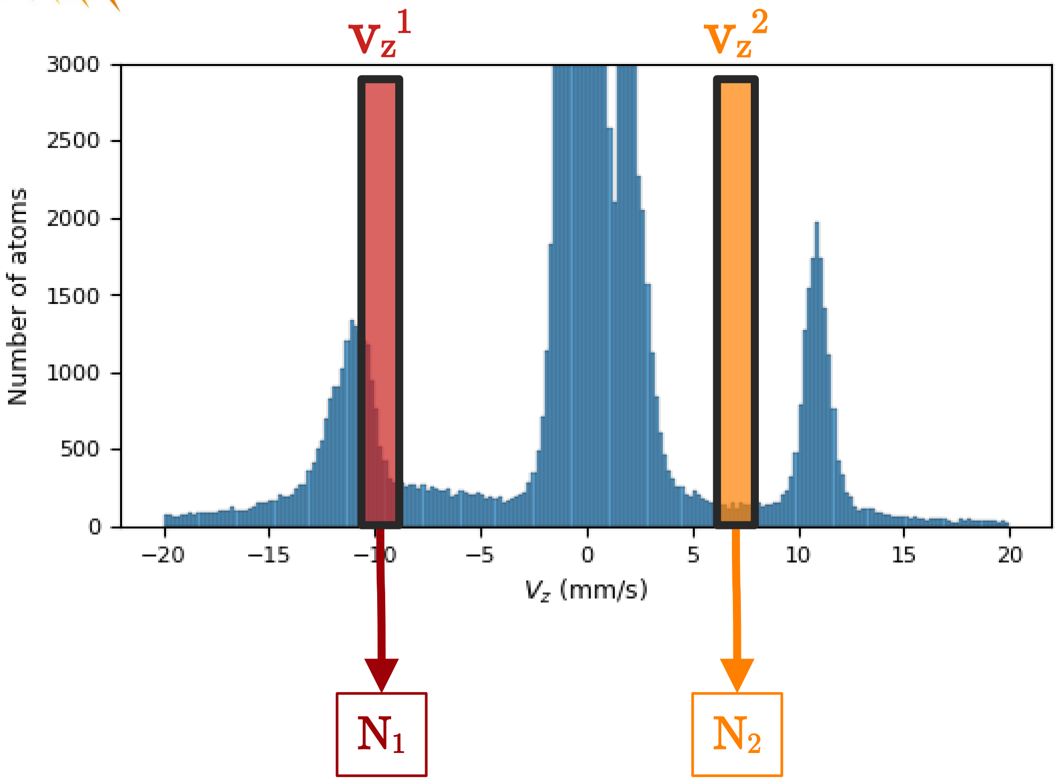

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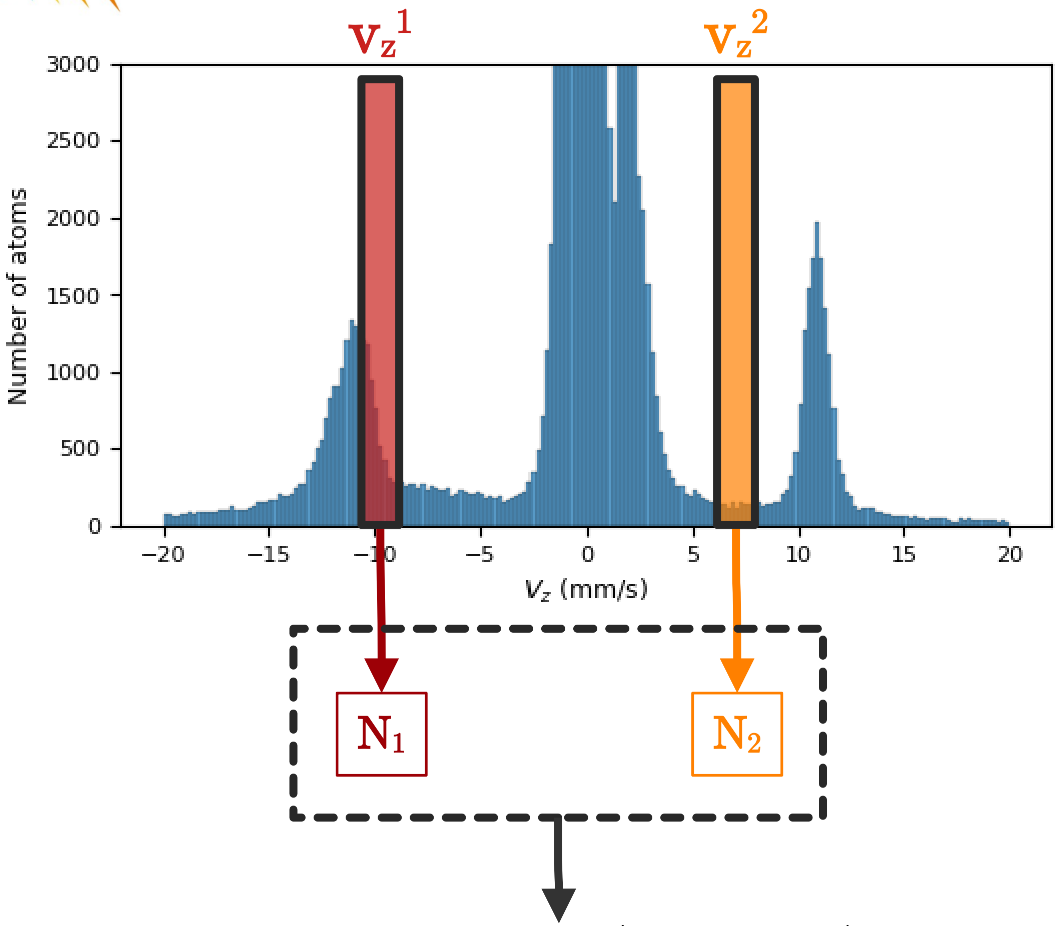

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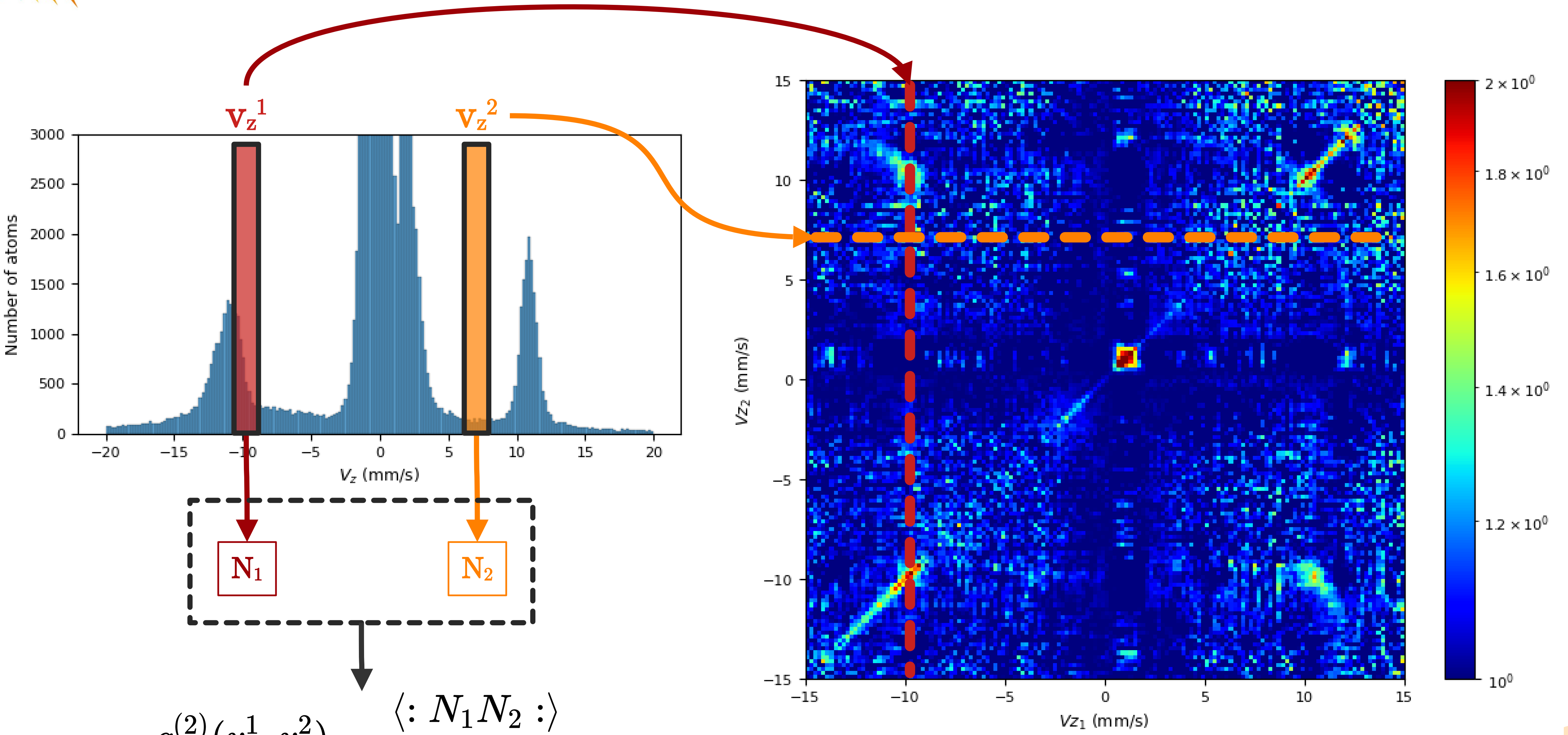

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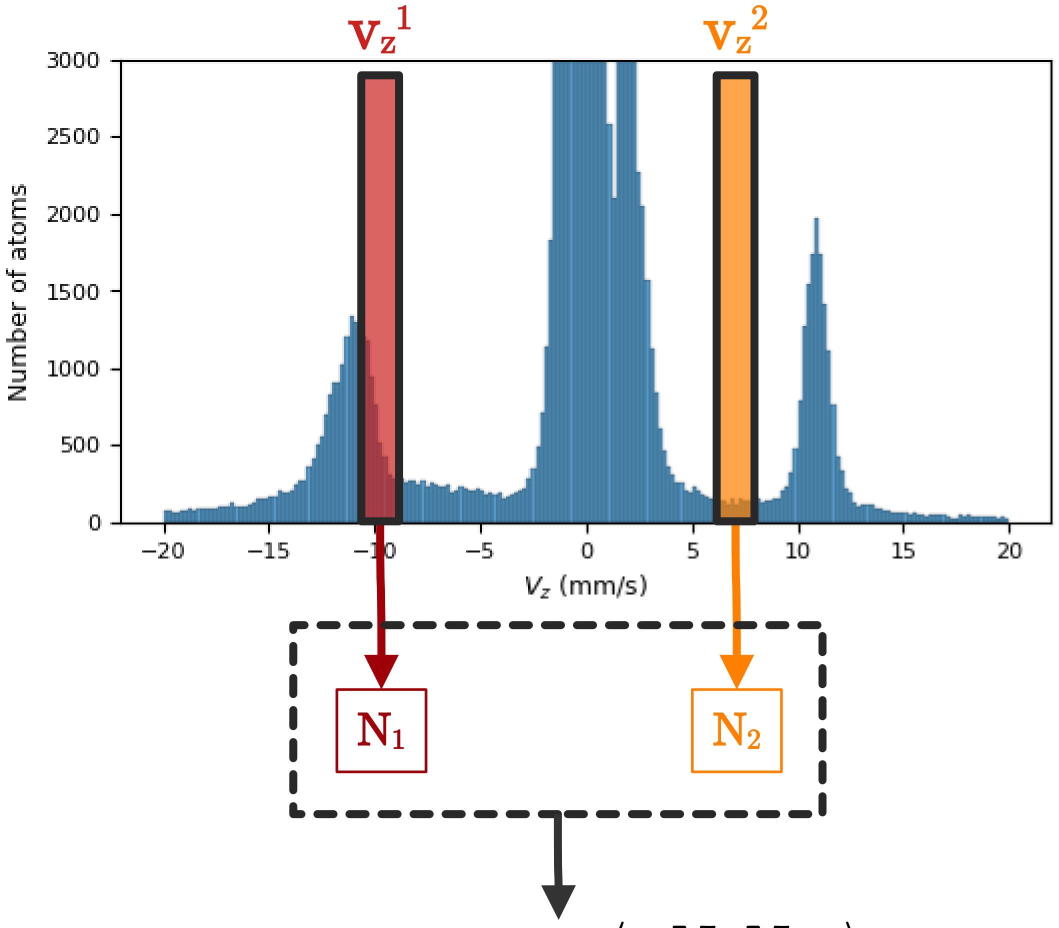

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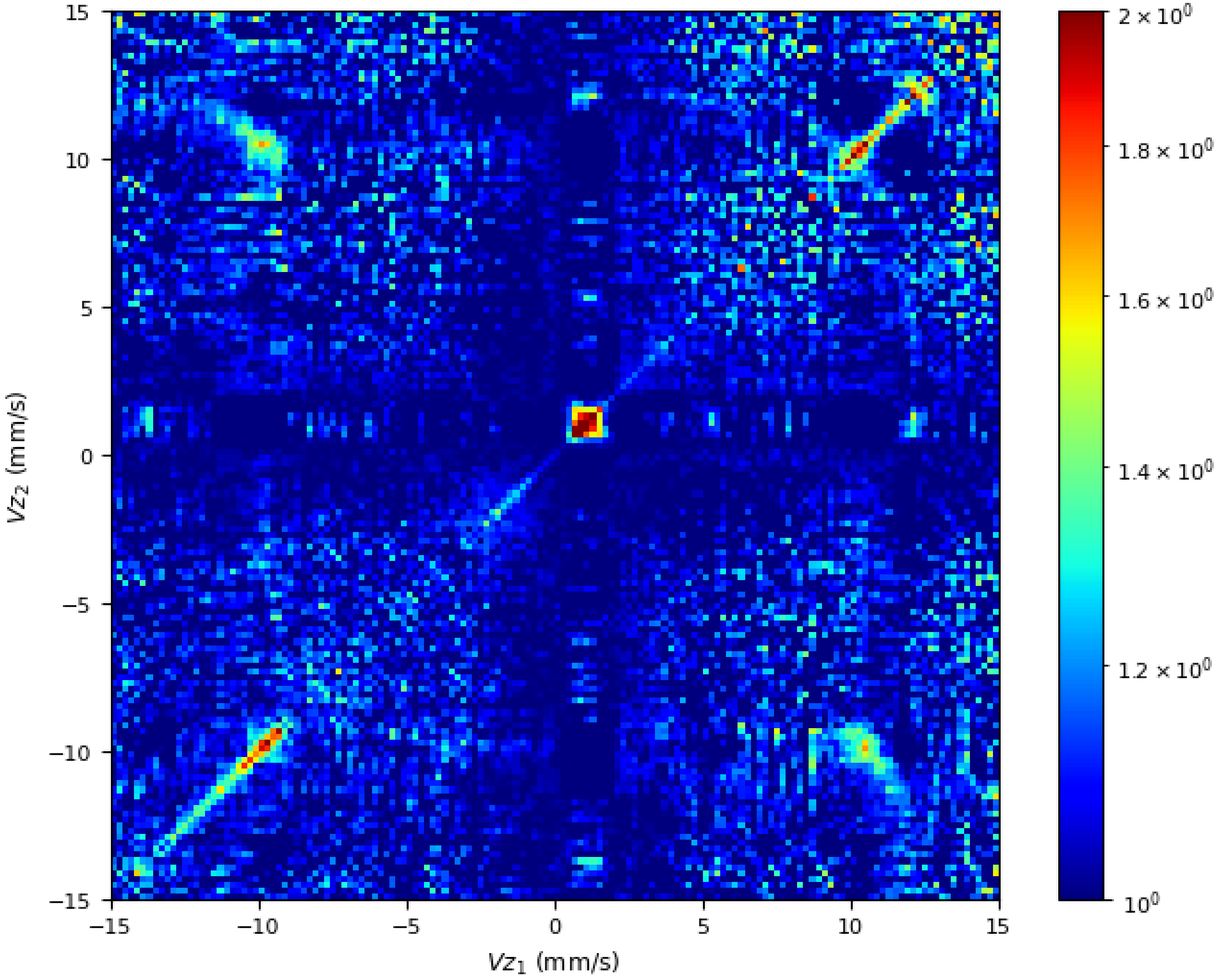

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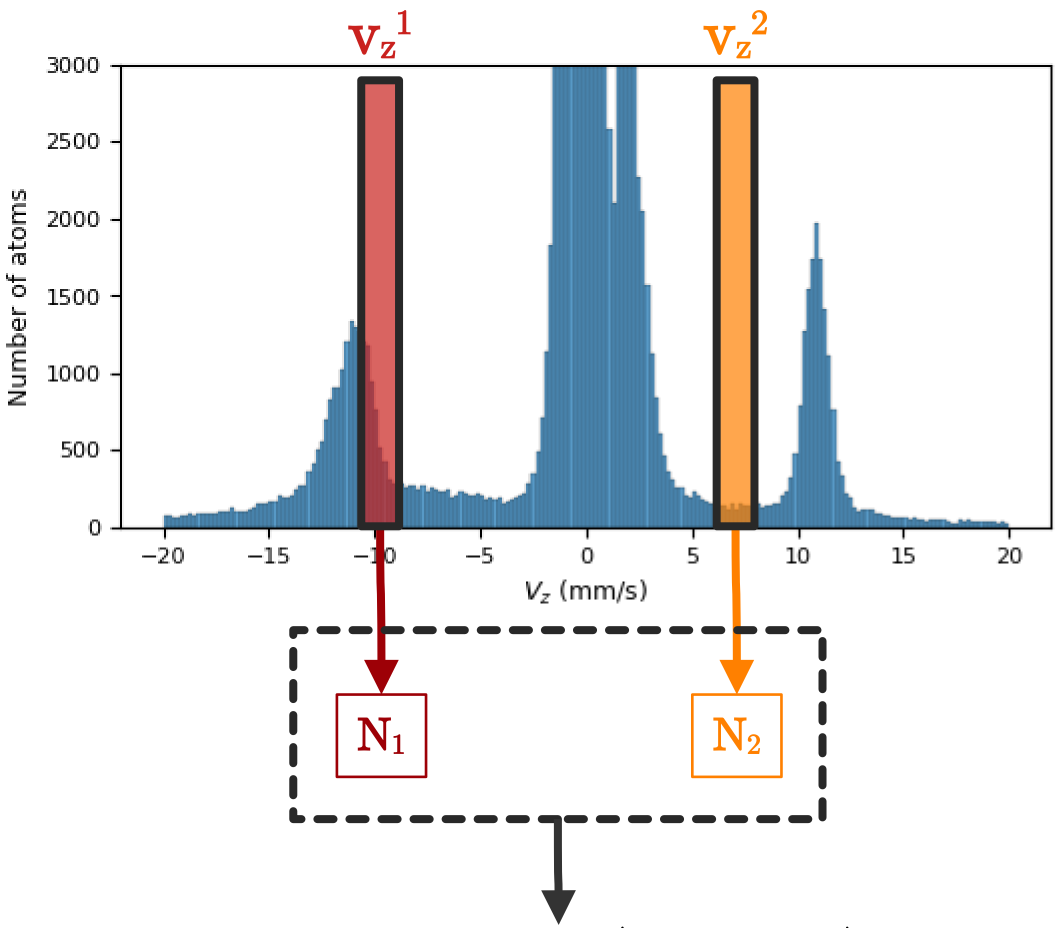

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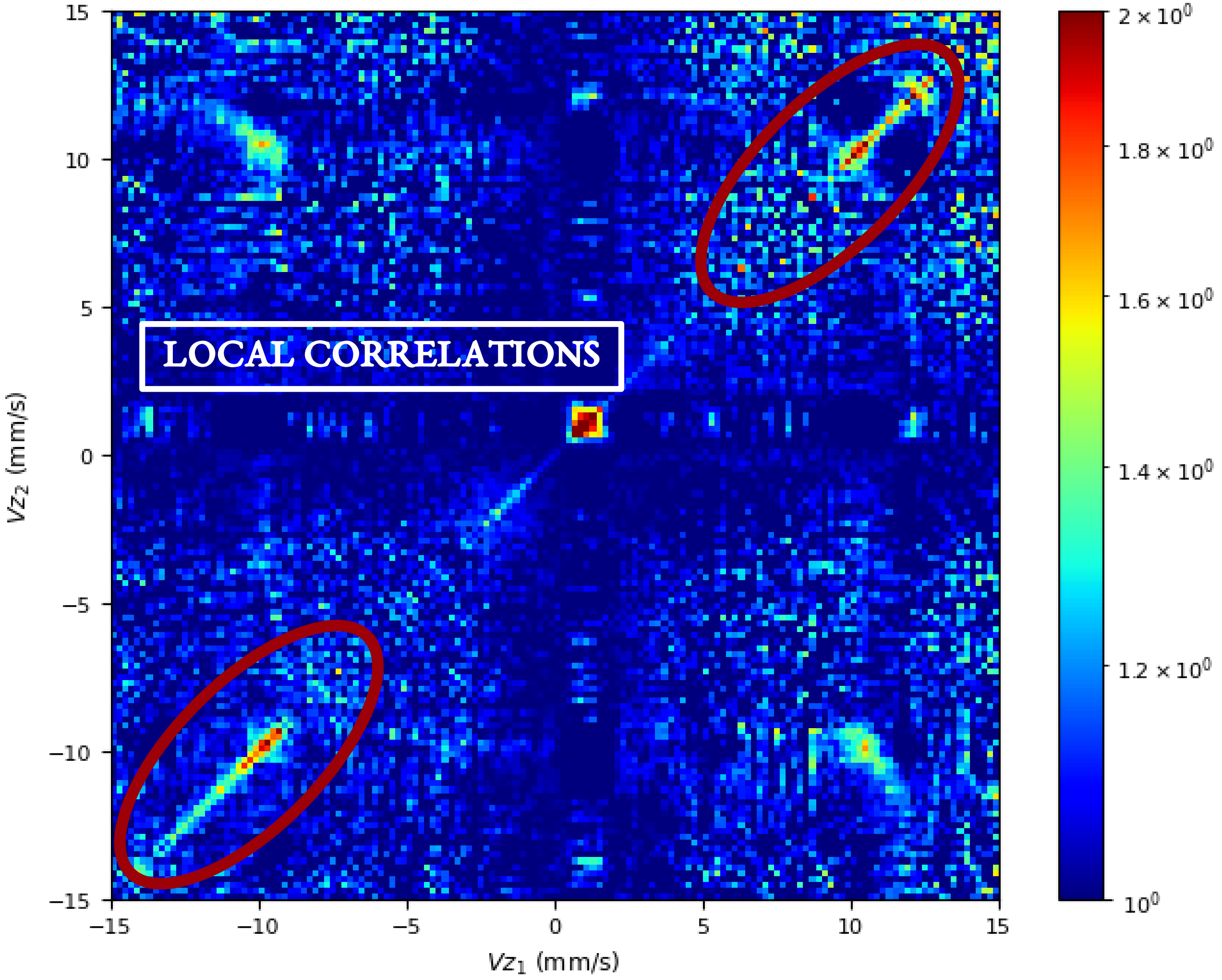

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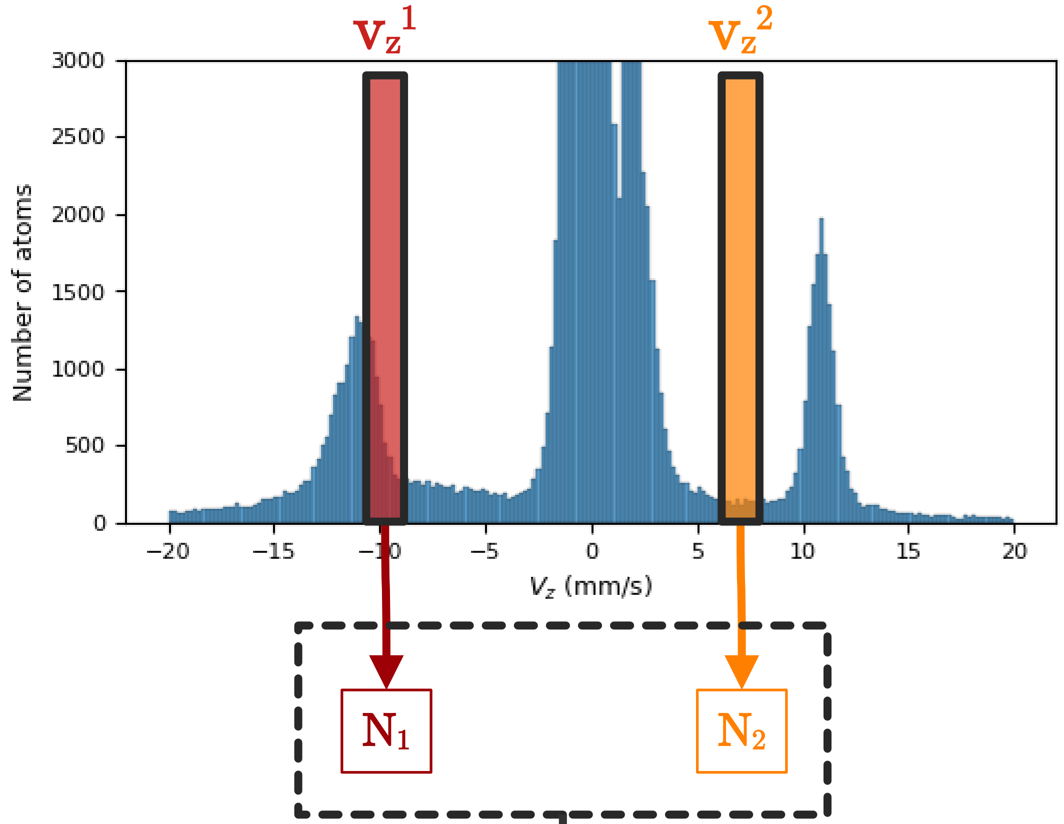

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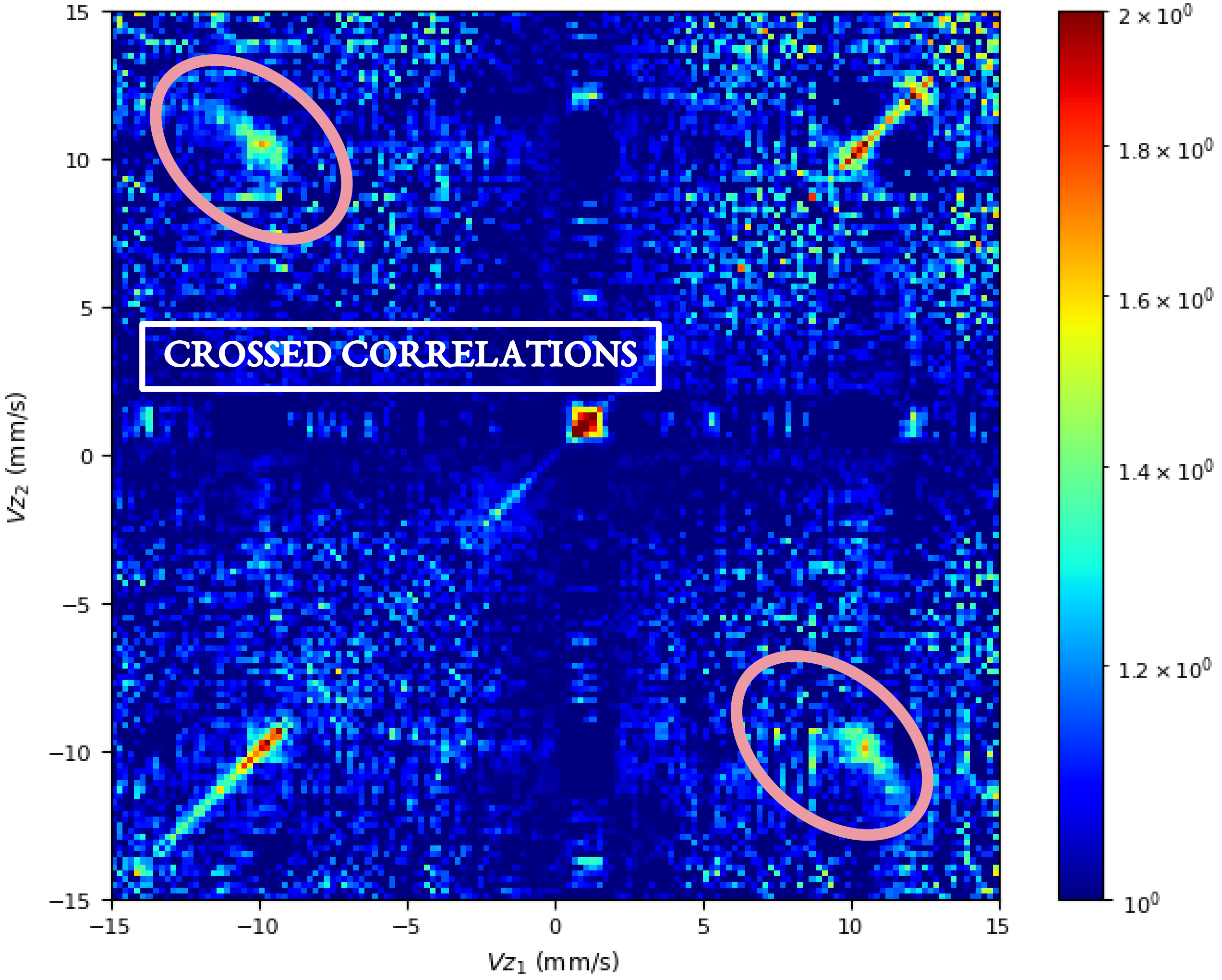

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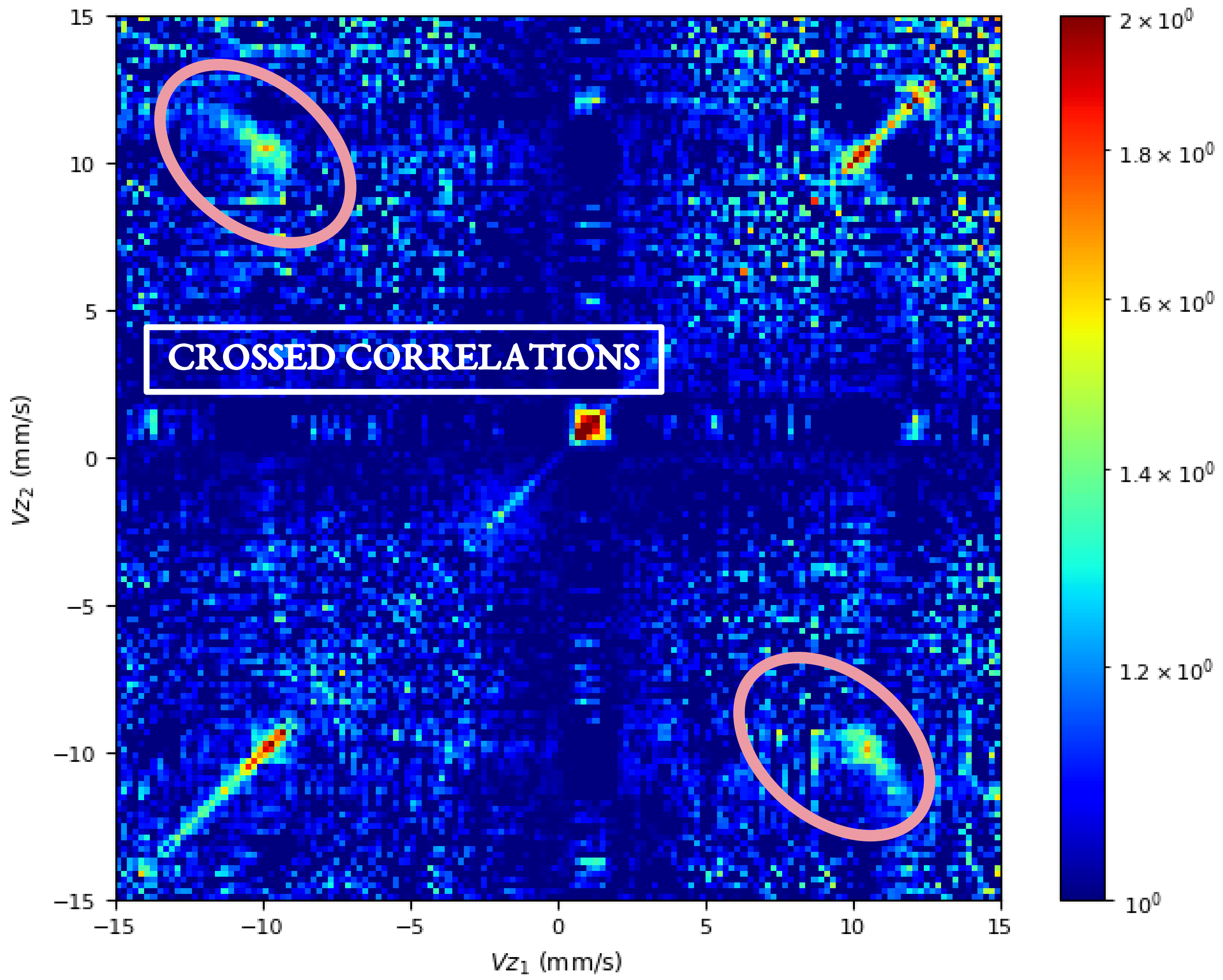
Cauchy-Schwarz inequality :

$$\langle : N_1 N_2 : \rangle < \sqrt{\langle : N_1^2 : \rangle \langle : N_2^2 : \rangle}$$



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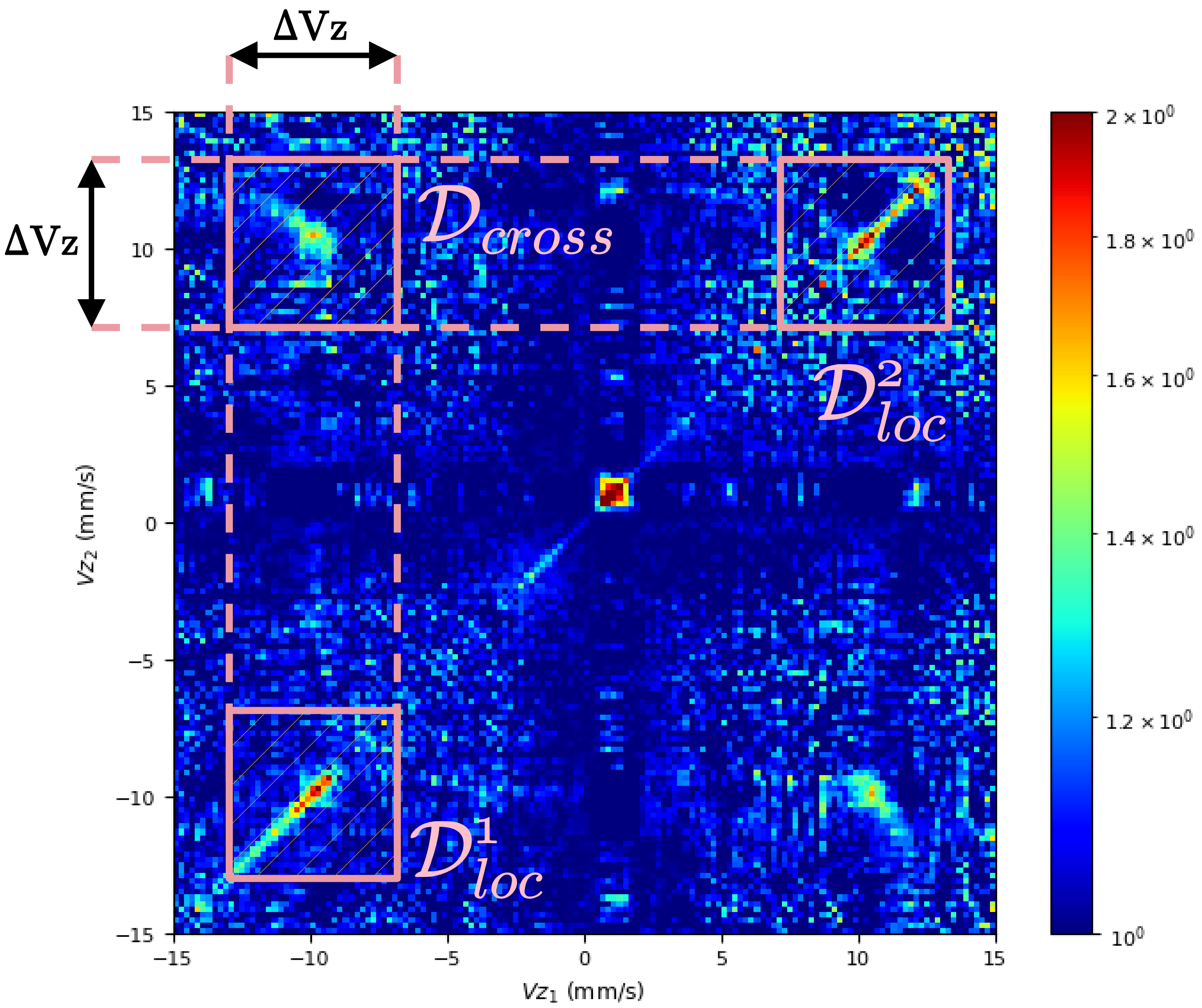
$$\mathcal{G}^{(2)}_{\mathcal{V}} = \int_{\mathcal{V}} \mathrm{d}V_1 \mathrm{d}V_2 \, G^{(2)}(V_1, V_2)$$

CS inequality :

$$CS = \frac{\mathcal{G}^{(2)}_{\mathcal{D}_{cross}}}{\sqrt{\mathcal{G}^{(2)}_{\mathcal{D}^1_{loc}} \mathcal{G}^{(2)}_{\mathcal{D}^2_{loc}}}} \leq 1$$



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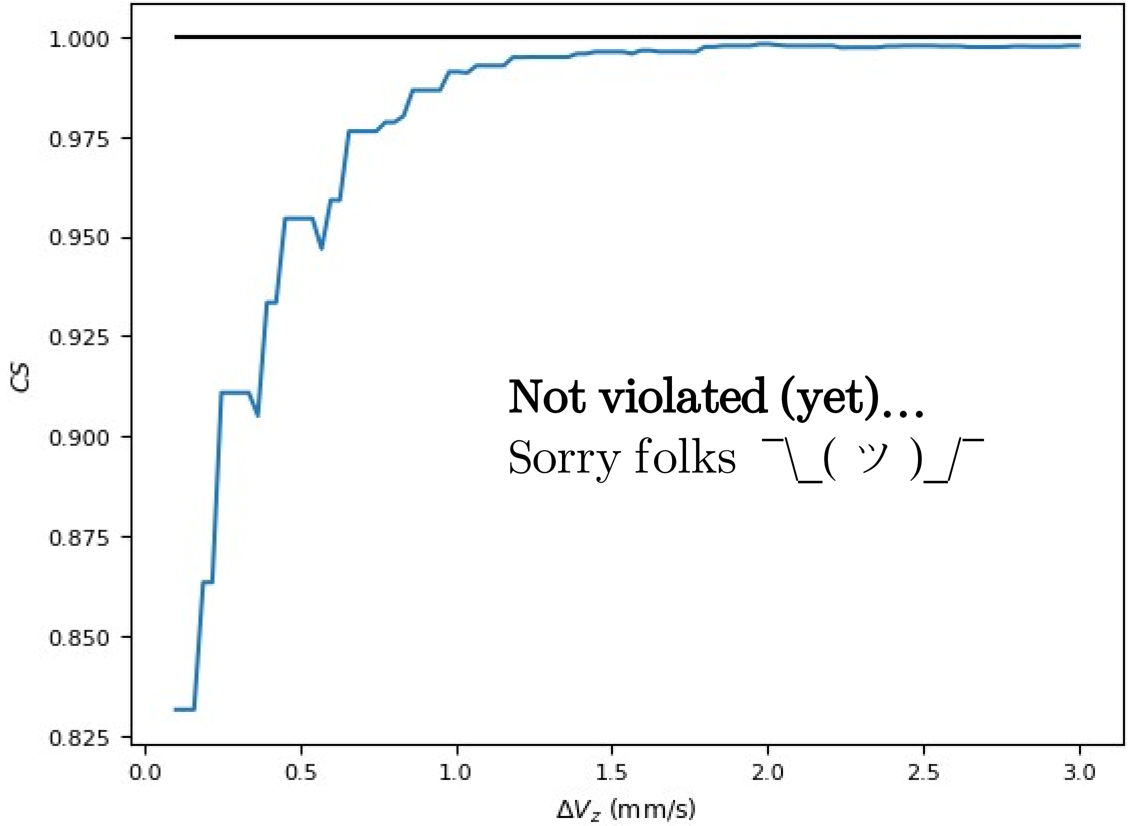
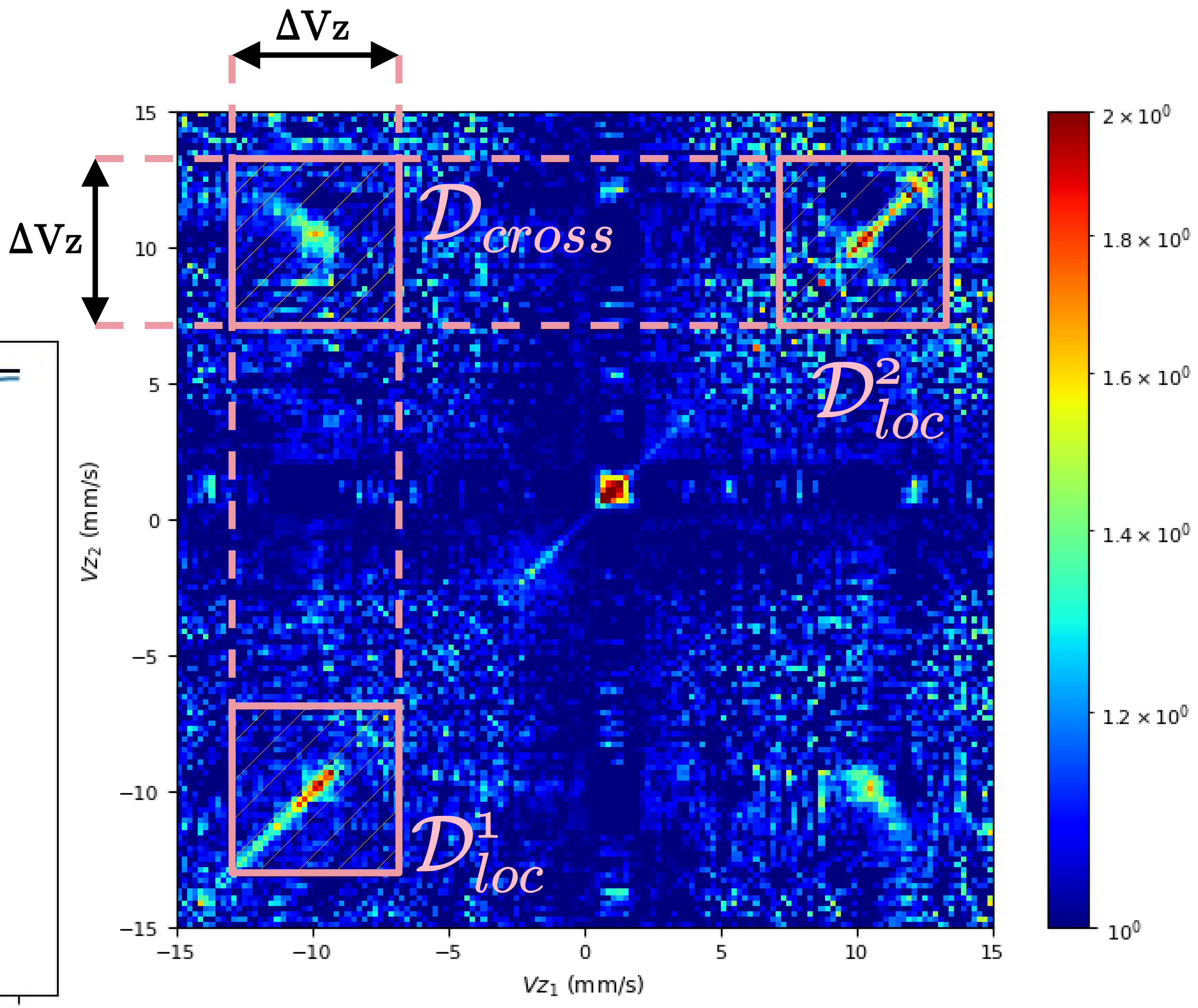


Not violated (yet)…

Sorry folks ¯_(ツ)_/¯



Supplement : checking the non-separability criteria

$$\langle : N_v N_{-v} : \rangle = \left\langle \hat{a}_v^\dagger \hat{a}_{-v}^\dagger \hat{a}_v \hat{a}_{-v} \right\rangle$$

$$= N_1 N_2 + \underbrace{\left| \left\langle \hat{a}_v^\dagger \hat{a}_{-v}^\dagger \right\rangle \right|^2}_{\text{If separable } <N_1N_2} + \underbrace{\left| \langle \hat{a}_v^\dagger \hat{a}{-v} \rangle \right|^2}_{\text{interference term } = 0\ ?}$$

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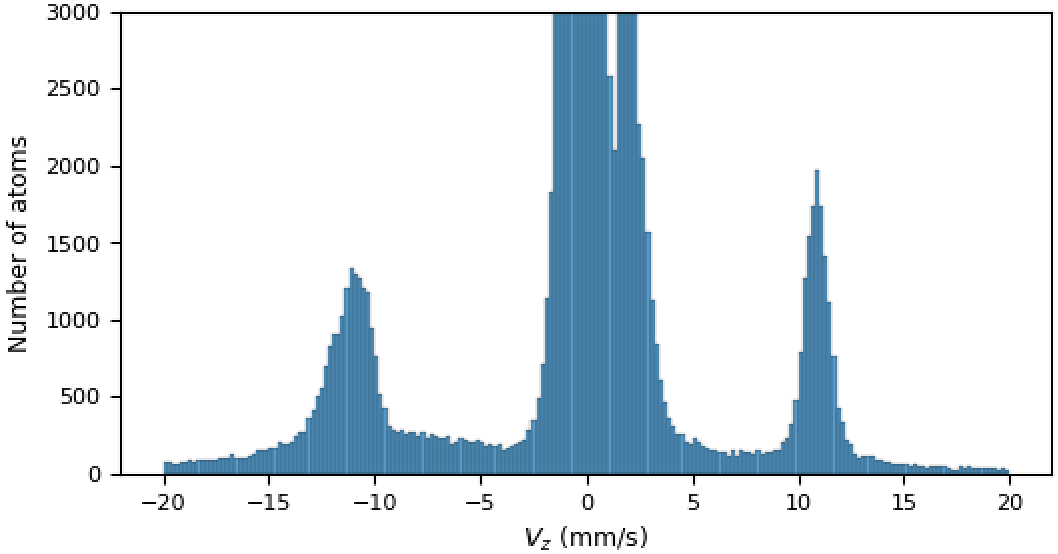

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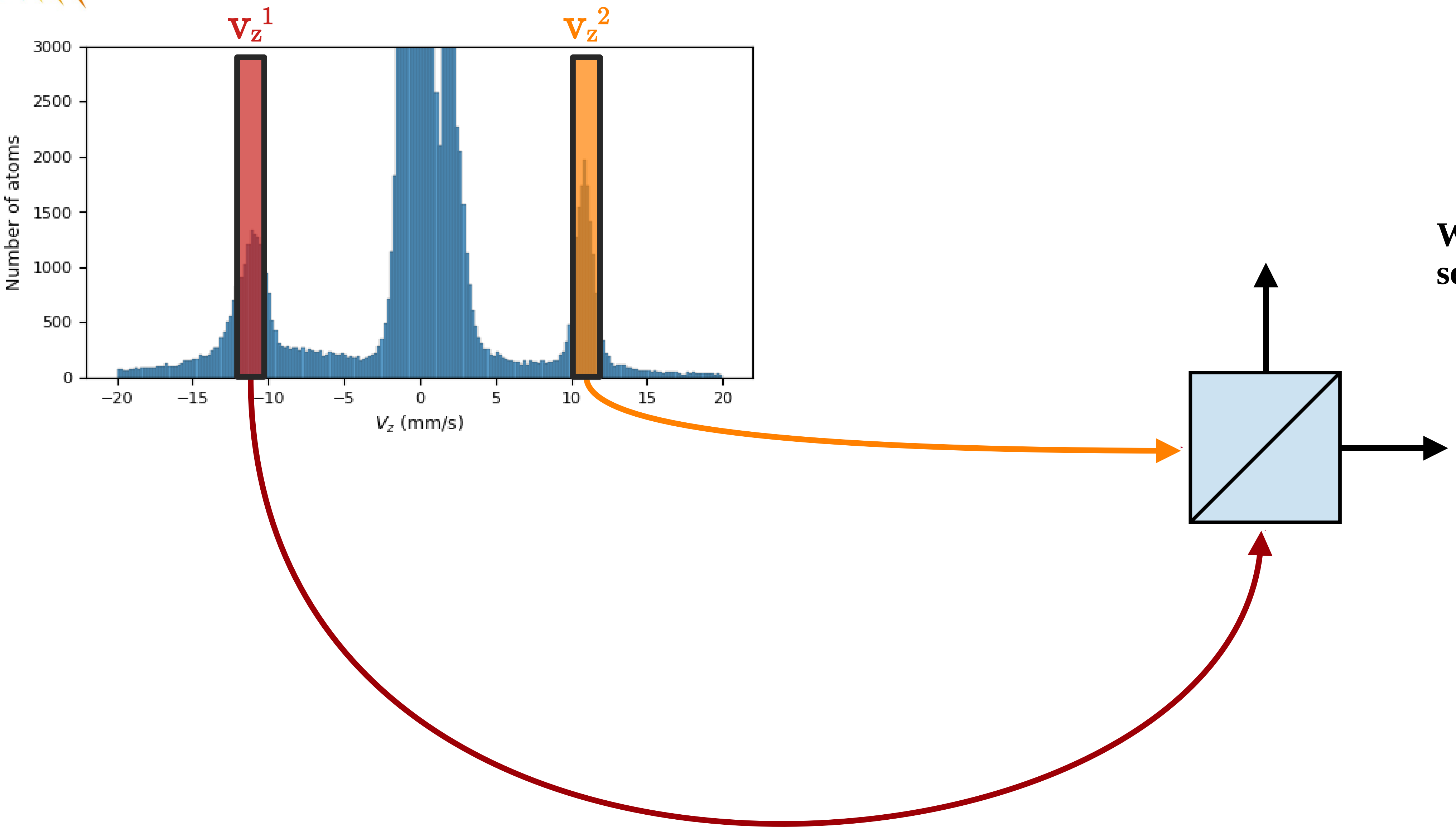

We should not see any fringes...

Experimental setup