Bose fireworks

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Seminar I

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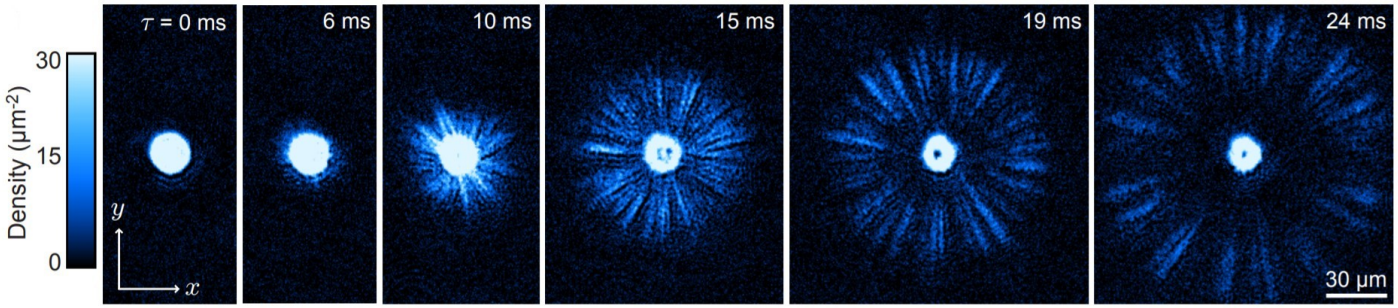

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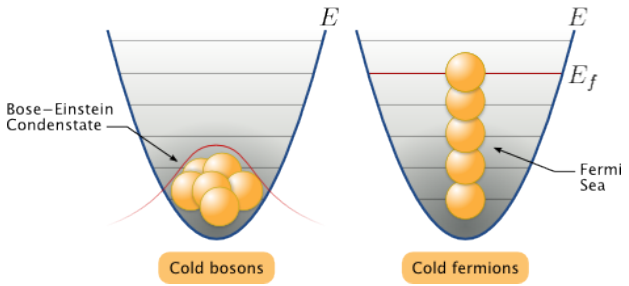
Bose-Einstein condensate

- Bose-Einstein condensate (BEC) is a state of matter that appears when a dilute gas of bosons is cooled to very low temperatures.

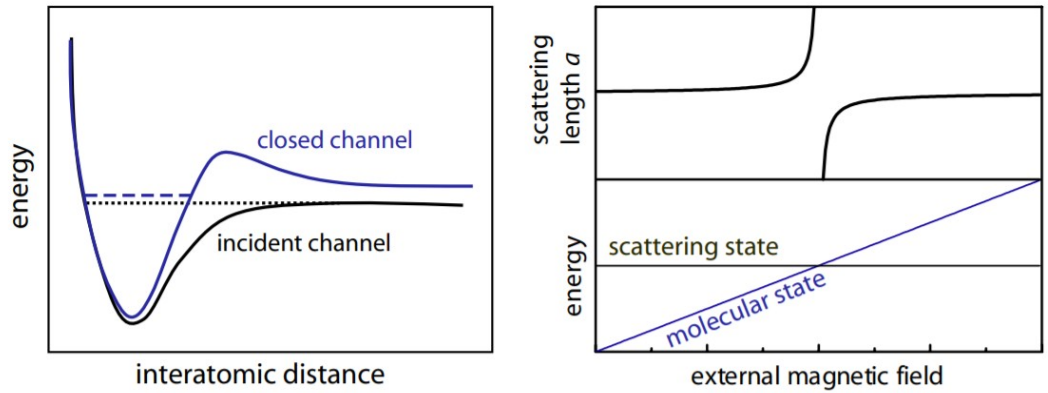


[https://culturacientifica.com/]

- Insight into the quantum nature of the world.
- Easily tunable by laser technology and magnetic fields.

Feshbach resonances

- Interaction potential $\rightarrow$ scattering channel.
- Tune a bound molecular state in degeneracy with the scattering state of two free atoms.

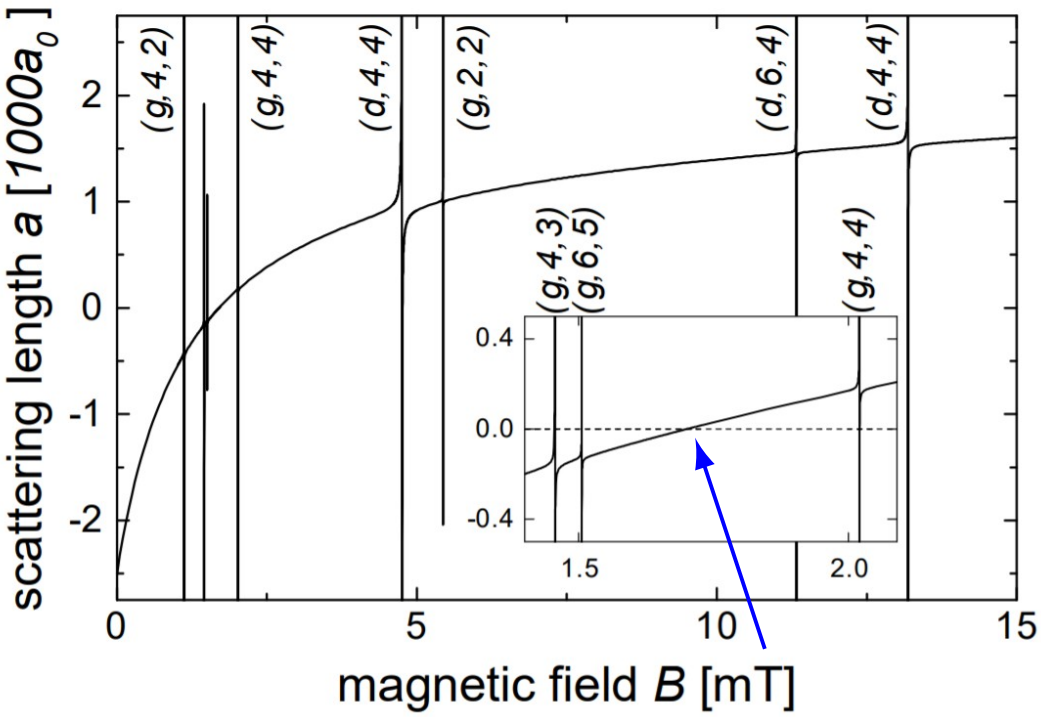


[M. Gustavsson, *A quantum gas with tunable interactions in an optical lattice*, Doctoral thesis (2008), Faculty of Mathematics, Computer Science and Physics, Innsbruck.]

- Scattering length diverges.

Feshbach resonances

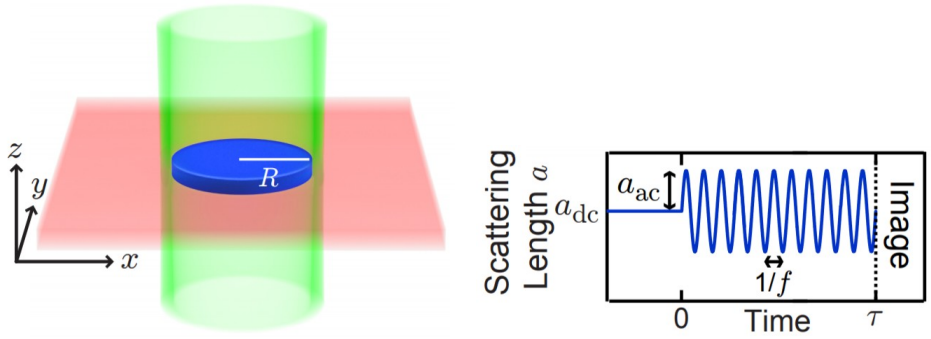
- Interaction between atoms $\rightarrow$ scattering length.
- Scattering length can be tuned by a magnetic field.

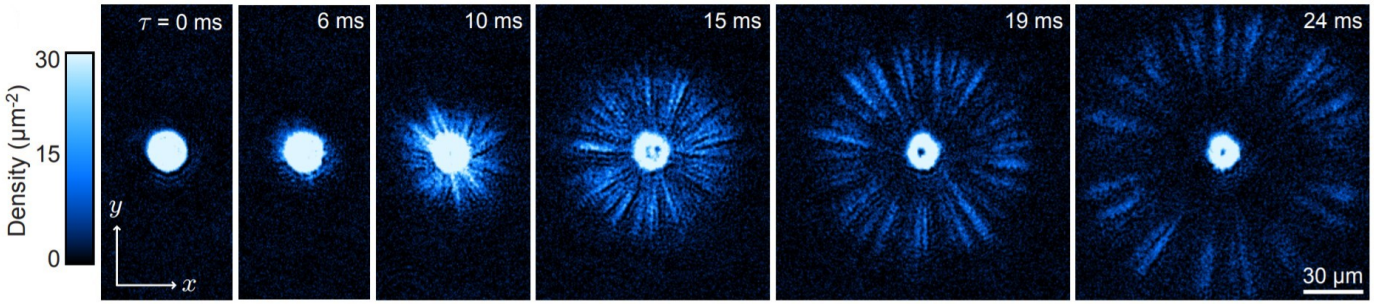


[C. Chin et al., *Precision Feshbach spectroscopy of ultracold Cs_2*, Phys. Rev. A **70** (2017), 032701.]

Bose fireworks

- Bose fireworks are matterwave jets, emitted from BEC as a result of modulation of the interaction between atoms in condensate.



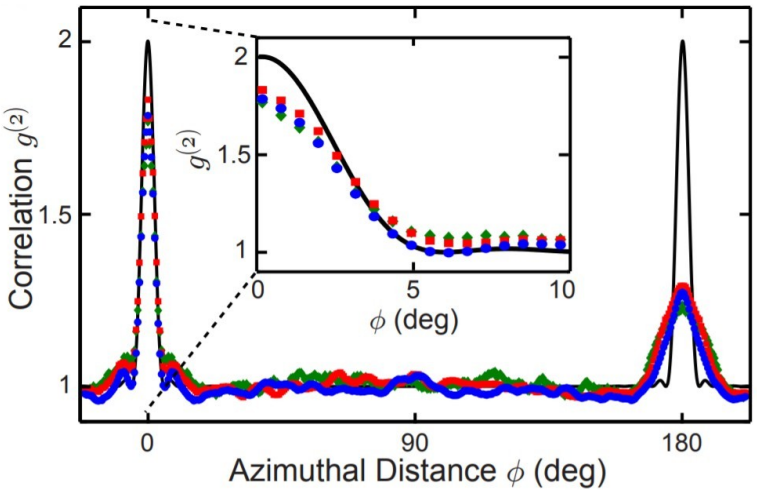


[L. Clark et al., *Collective emission of matter-wave jets from driven Bose-Einstein condensates*, Nature **551** (2017), 356–359.]

- Angular correlation function

$$g^{(2)}(\phi) = \frac{\langle \int d\theta n(\theta) \left[n(\theta + \phi) - \delta(\phi) \right] \rangle}{\langle \int d\theta n(\theta) \rangle^2} \tag{1}$$

- Symmetry breaking.



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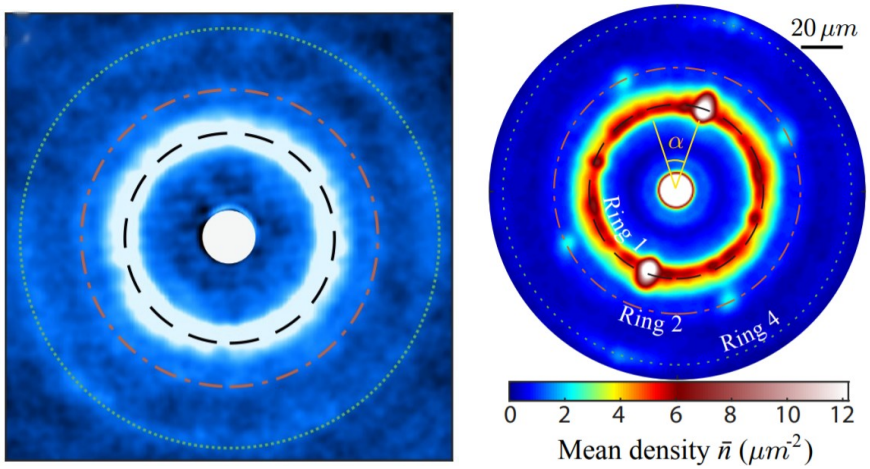
Pattern recognition

- Machine learning, rotating pictures to maximize angular variance of the mean image.

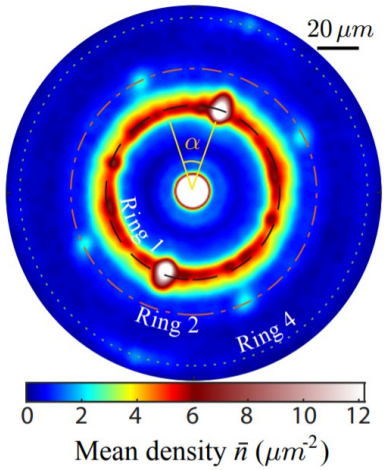


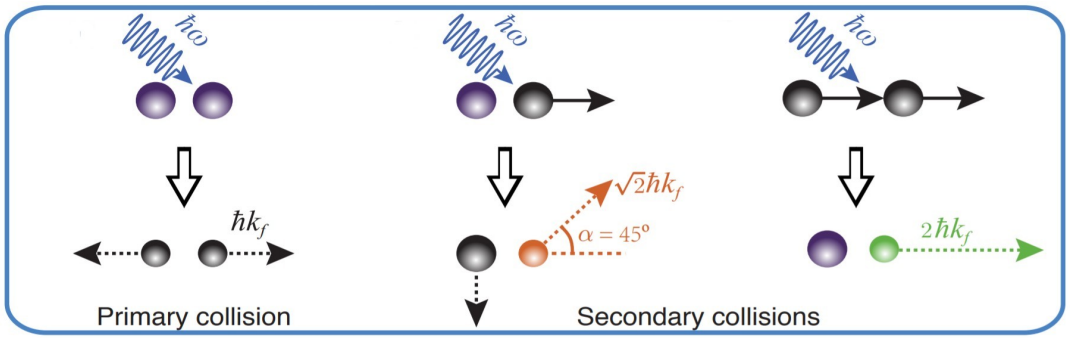
[L. Feng et al., *Complex correlations in high harmonic generation of matter-wave jets revealed by pattern recognition*, Science **362** (2019), 521-524.]

- Uniform rings $\rightarrow$ turtle pattern.

Microscopic processes

- Stimulated two-atom collisions.





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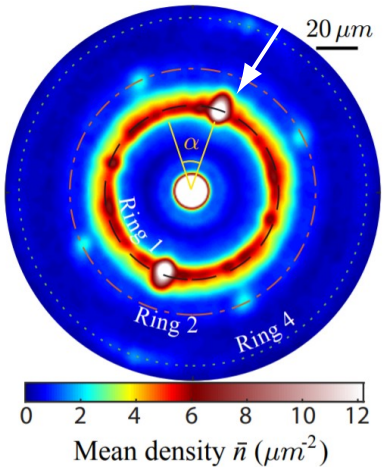

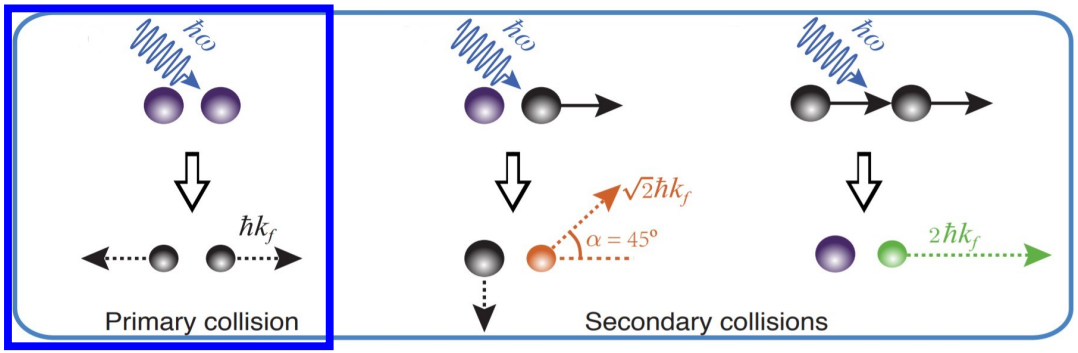

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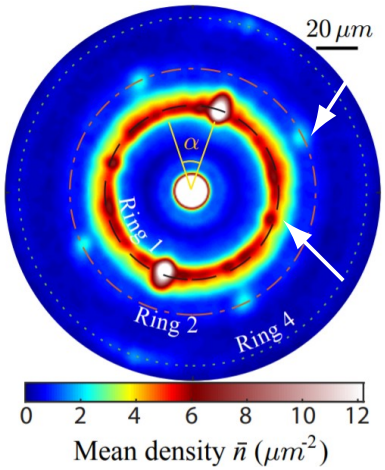

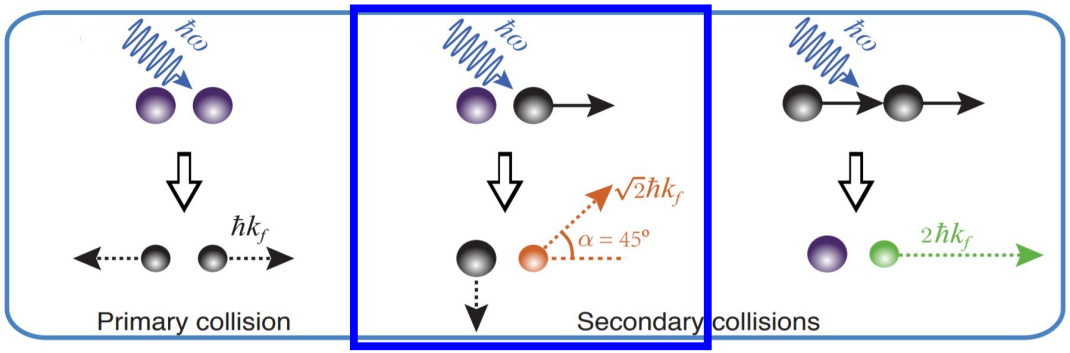

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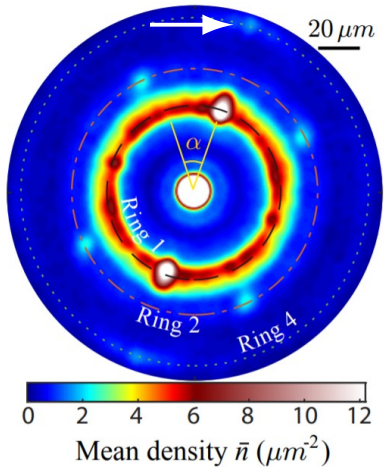

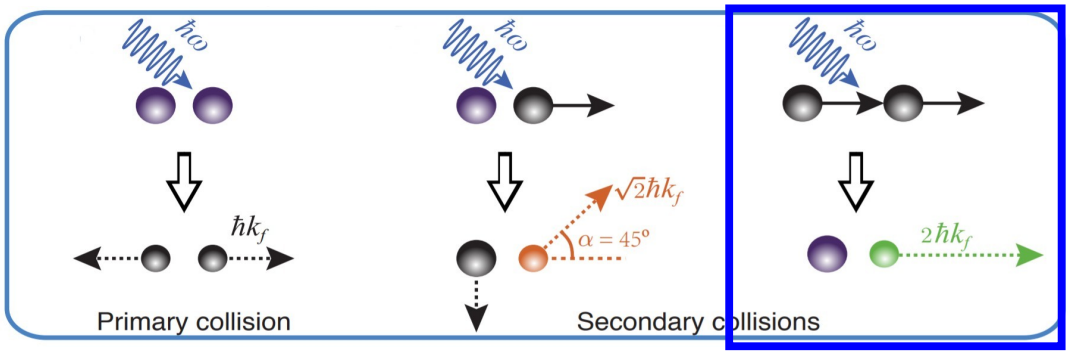

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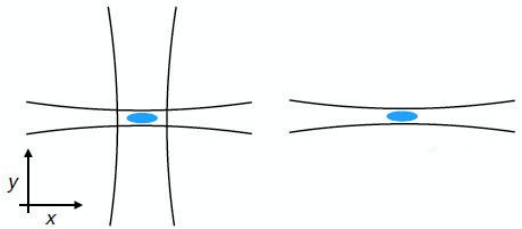
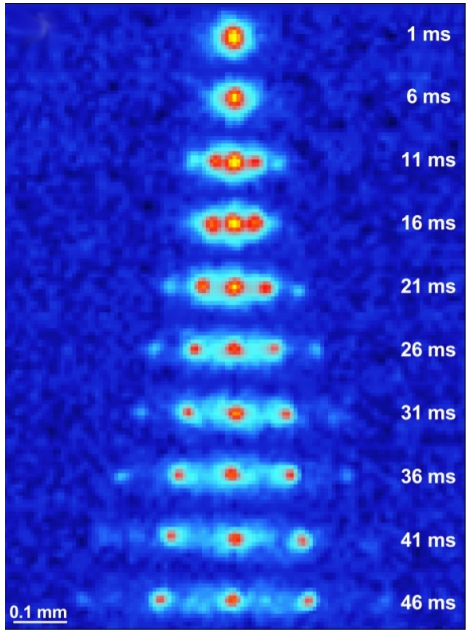
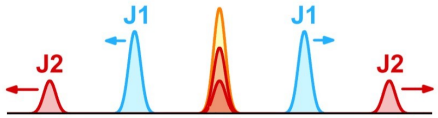
Bose fireworks in quasi-one-dimensional geometry

- Simple geometry → easier jet categorisation.







[T. Mežnaršič et al., *Emission of correlated jets from a driven matter-wave soliton in a quasi-one-dimensional geometry*, Phys. Rev. A **101 (3)** (2020), 031601.]

- Number of atoms in first-order jets → sub-Poissonian statistics → entanglement.

Bogoliubov approximation

$$H = \int dx \Psi^\dagger \frac{p^2}{2m} \Psi + \frac{g}{2} \int dx \Psi^\dagger \Psi^\dagger \Psi \Psi + \frac{1}{\mu_0} \int dx |B|^2 \qquad (2)$$

- Coupling constant $\rightarrow g = \frac{4\pi\hbar^2}{m} a_s$.

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- Interaction term, wave vector space.

$$\Psi(x,t) = \frac{1}{\sqrt{V}} \sum_k e^{ikx} a_k \qquad (3)$$

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- First-order jets:

$$H_I = \hbar\tilde{\nu} \left[a_k^\dagger a_{-k}^\dagger a_0 a_0 + h.c. \right] \qquad (4)$$

$$\tilde{\nu} = \frac{2\pi\hbar a_{ac}}{mV} \qquad (5)$$

Bogoliubov approximation

- First-order jets:

$$H_I = \hbar\tilde{\nu}\left[a_k^\dagger a_{-k}^\dagger a_0 a_0 + h.c.\right] = \hbar\tilde{\nu}N_0\left[a_k^\dagger a_{-k}^\dagger + h.c.\right] \quad (6)$$

Bogoliubov approximation: $a_0, a_0^\dagger \to \sqrt{N_0}$

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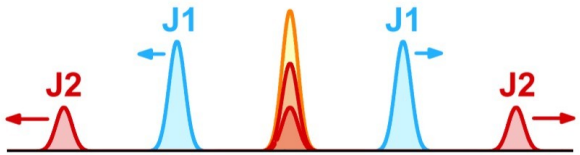

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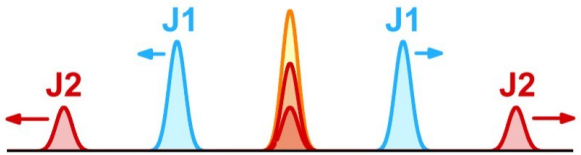


- Second-order jets:

$$H_{II} = \hbar\tilde{\nu}\left[a_{2k}^\dagger a_0^\dagger a_k a_k + h.c.\right] = \hbar\tilde{\nu}\sqrt{N_0}\left[a_{2k}^\dagger a_k a_k + h.c.\right] \quad (7)$$

Gross-Pitaevskii equation

$$i\hbar\frac{\partial}{\partial t}\psi(x,t) = \left[-\frac{\hbar^2}{2m}\nabla^2 + V(x,t)\right]\psi(x,t), \tag{8}$$

- Mean-field approximation.

$$V(x,t) = V_{ext} + g|\psi|^2 \tag{9}$$

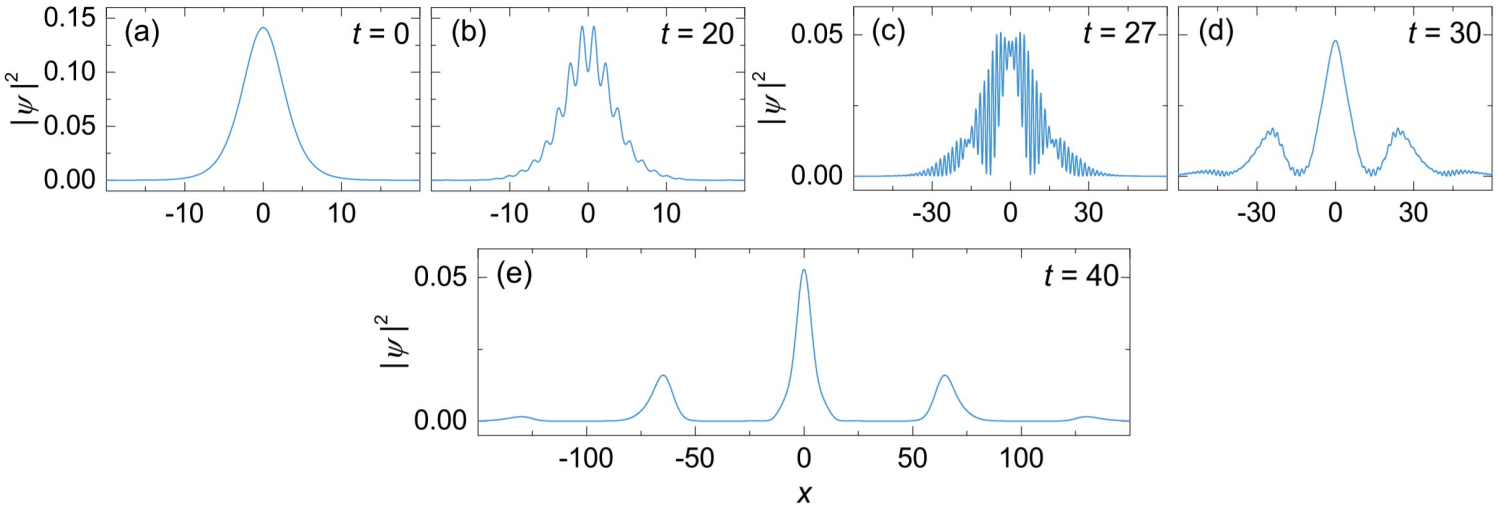
- Low density and contact interaction.

$$g = \frac{4\pi\hbar^2}{m}a_s \tag{10}$$

$$a_s(t) = a_{dc} + a_{ac}\sin\omega t. \tag{11}$$

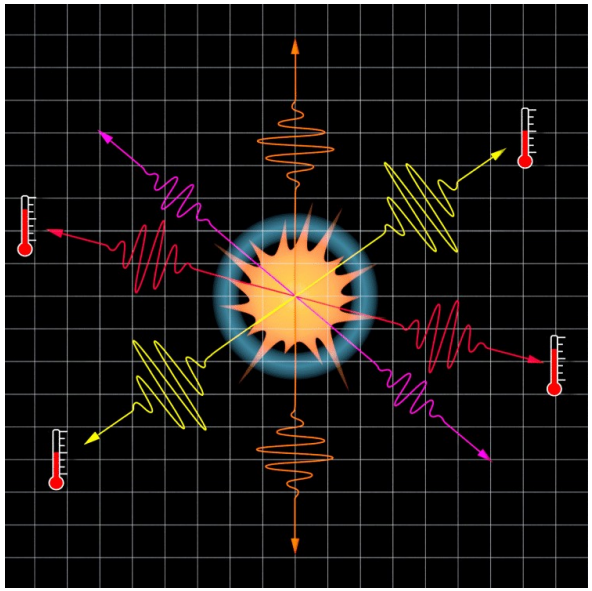
Density waves

- Density waves appear and amplify rapidly.



[T. Mežnaršič et al., *Emission of correlated jets from a driven matter-wave soliton in a quasi-one-dimensional geometry*, Phys. Rev. A **101 (3)** (2020), 031601.]

Unruh thermal radiation



- Minkowski vacuum is seen as a thermal state by an accelerating observer $T_U = \frac{\hbar A}{2\pi c k_B}$.
- Acceleration of $A = 2.5 \cdot 10^{14}\, m/s^2$ for $T_U = 1\,\mu K$.
- Rindler frame transformation can be simulated based on the evolution operator of a Hamiltonian of the first-order jet formation.
- Thermal distribution of the number of atoms in jets.
- Good agreement with Unruh's predictions.

[J. Hu et al., *Quantum Simulation of Coherent Hawking-Unruh Radiation*, Nat. Phys. **15 (8)** (2019), 1745-2481.]

Conclusion

- New physical phenomena discovered by modulating the interaction between the atoms in BEC.
- Stimulated two-atom collisions.
- The jets are potentially entangled.
- Use as a simulator for Unruh thermal radiation.