Department of Physics, University of Toronto, Toronto, 9/19/2019

Bose Fireworks

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James Franck institute
Enrico Fermi institute
Department of Physics
University of Chicago

FUNDING:

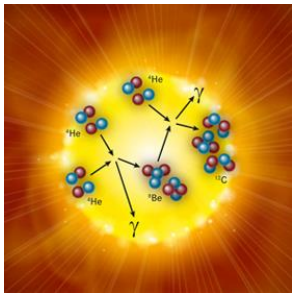
NSF

ARMY RESEARCH OFFICE 1951

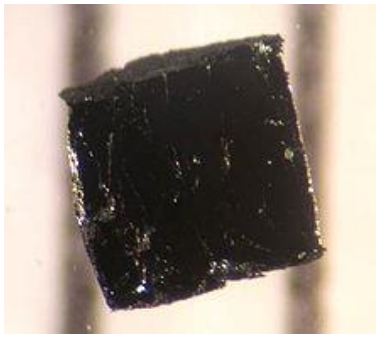
DEPARTMENT OF DEFENSE

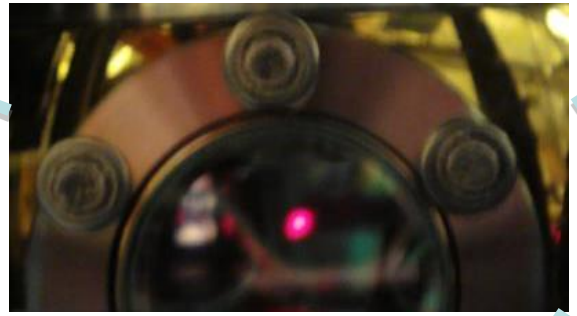
MRSEC

Chin Lab at UChicago



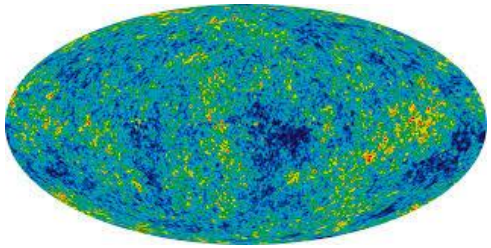
THE UNIVERSITY OF CHICAGO



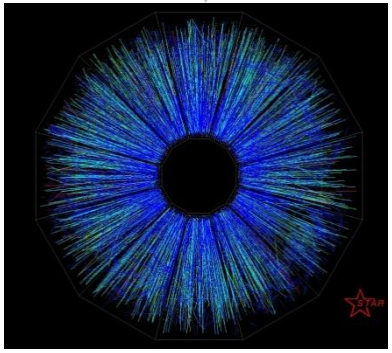


Nuclear Physics:
Feshbach dimer
Efimov trimer

Condensed Matter:
Quantum criticality
Exotic quasi-particles
Mediated interactions



Cosmology
Sakharov oscillations
Kibble mechanism
Unruh radiaiton



Particle Physics
Jet formation
Pattern recognition

Levitation of sand, paper, ice particles…

Synopsis

What is Bose Fireworks?

- *Bosons vs. Fermions*
- *Cold atom toolbox*

Surprises in the world of ultracold

- *An accidental discovery*
- *“It is turtles all the way down.”*

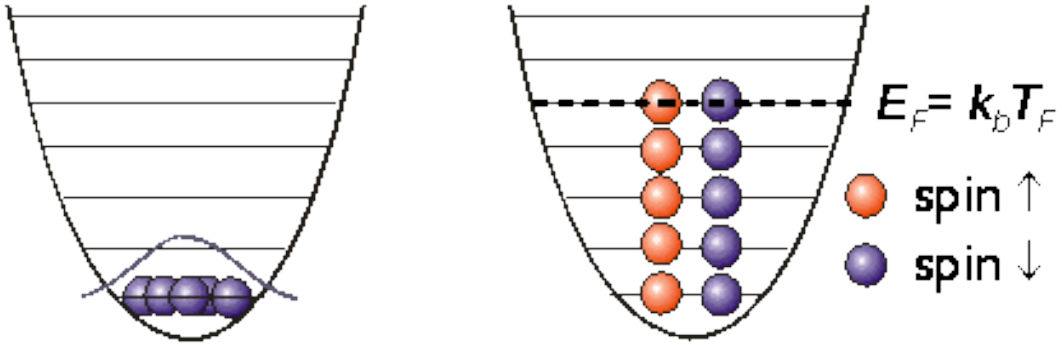
Connections to particle/gravitational physics

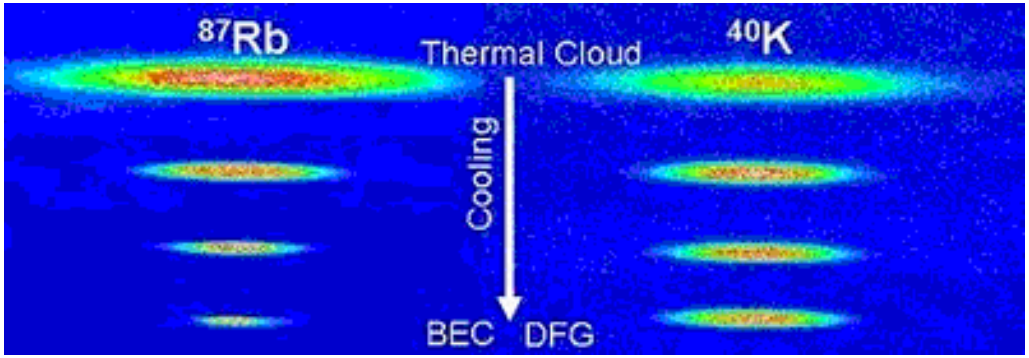
- *Jet structure*
- *Unruh effect*
- *Pattern formation*

Bosons vs. Fermions at low temperatures

Bose-Einstein condensate

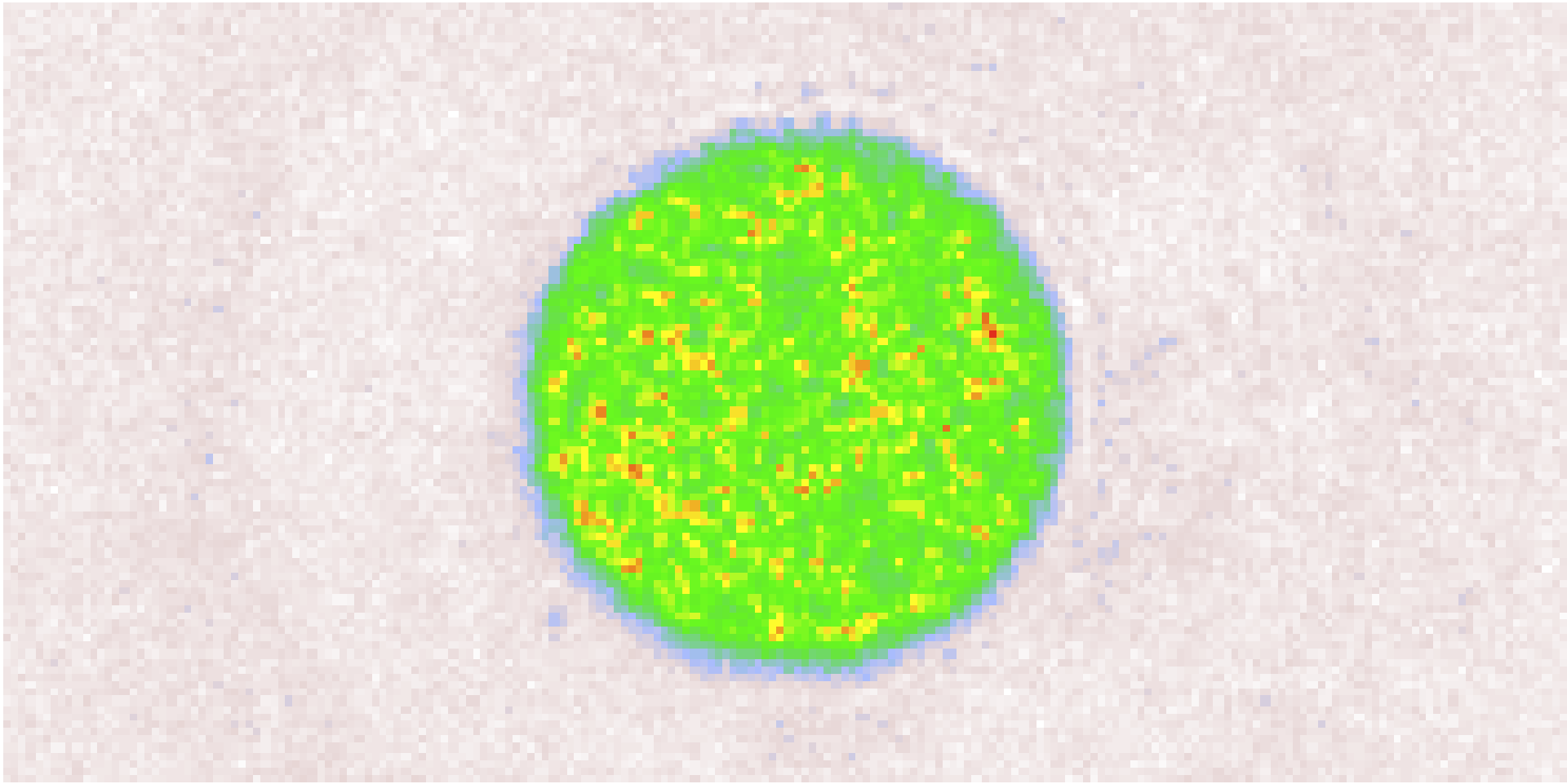
Degenerate Fermi gas





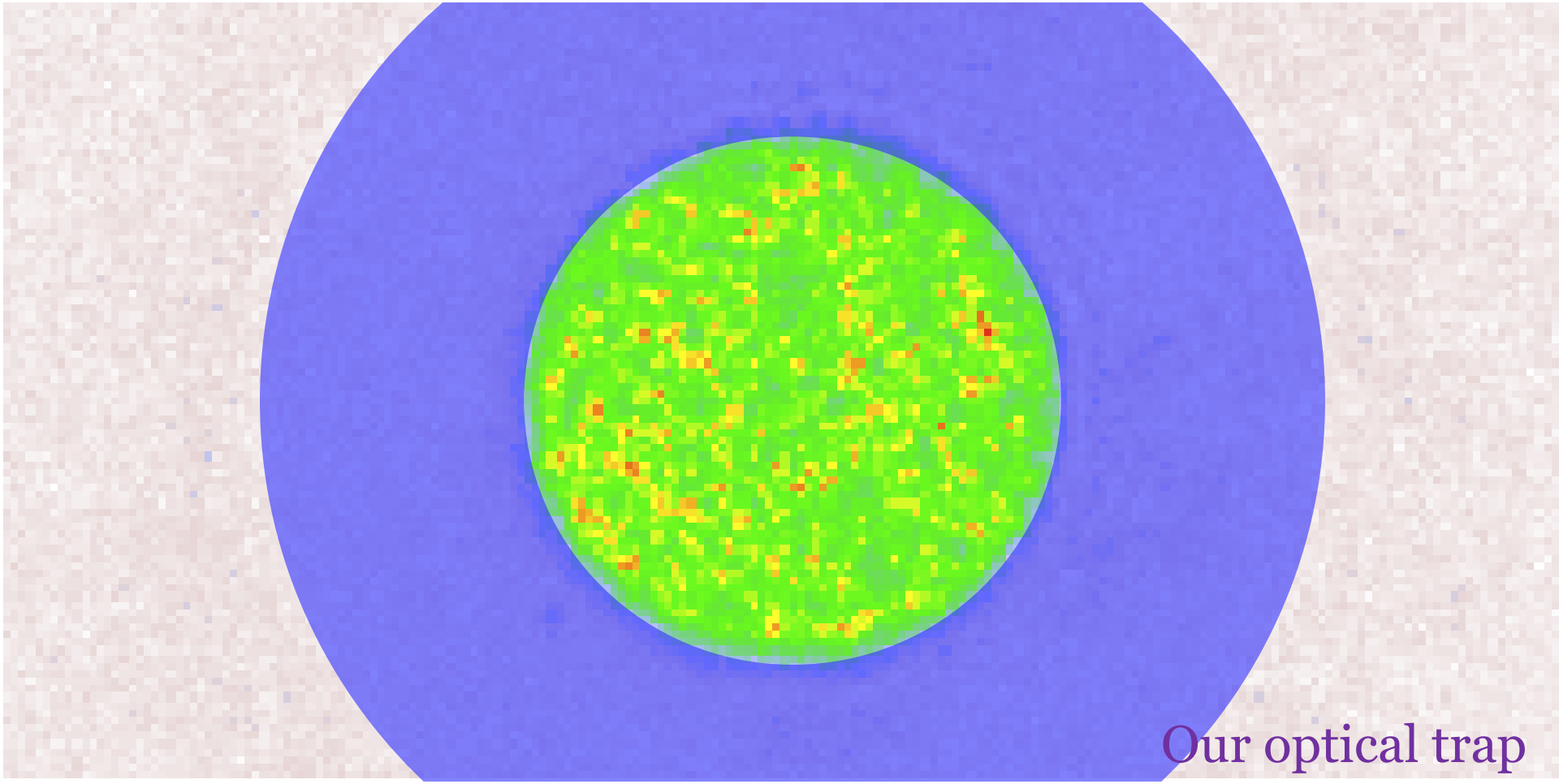
2001 Nobel Prize in Physics: Eric Cornell, Carl Wieman, Wolfgang Ketterle

Our Bose-Einstein condensate of cesium atoms



20,000~100,000 cesium atoms
Imaging resolution: 1.0 μm

In situ image of Cesium Bose condensate

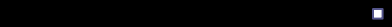


20,000~100,000 cesium atoms
Imaging resolution: 1.0 μm

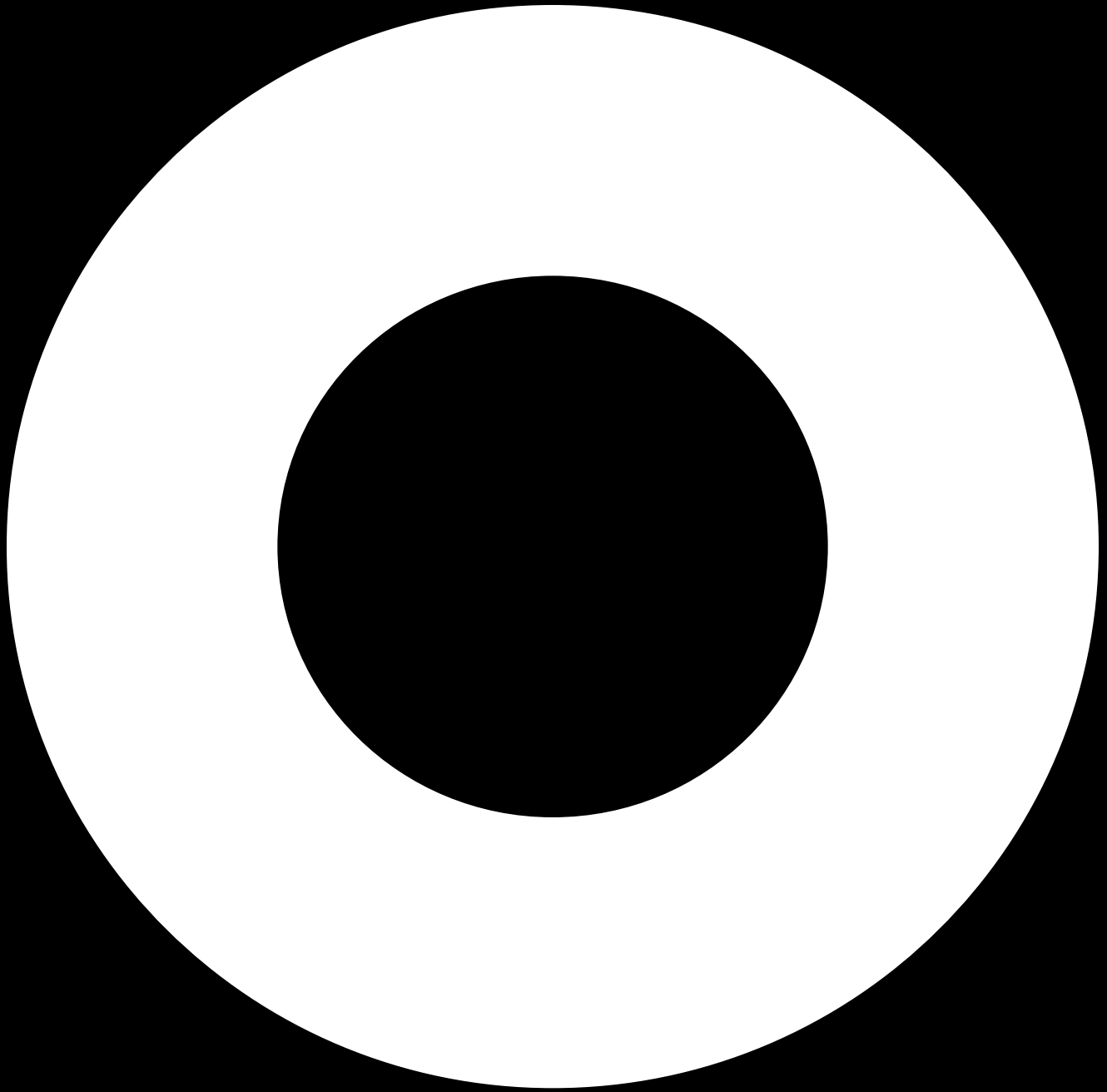
Demonstration of digital micromirror device (1 micromirror)

Demonstration of digital micromirror device (3x3 micromirrors)

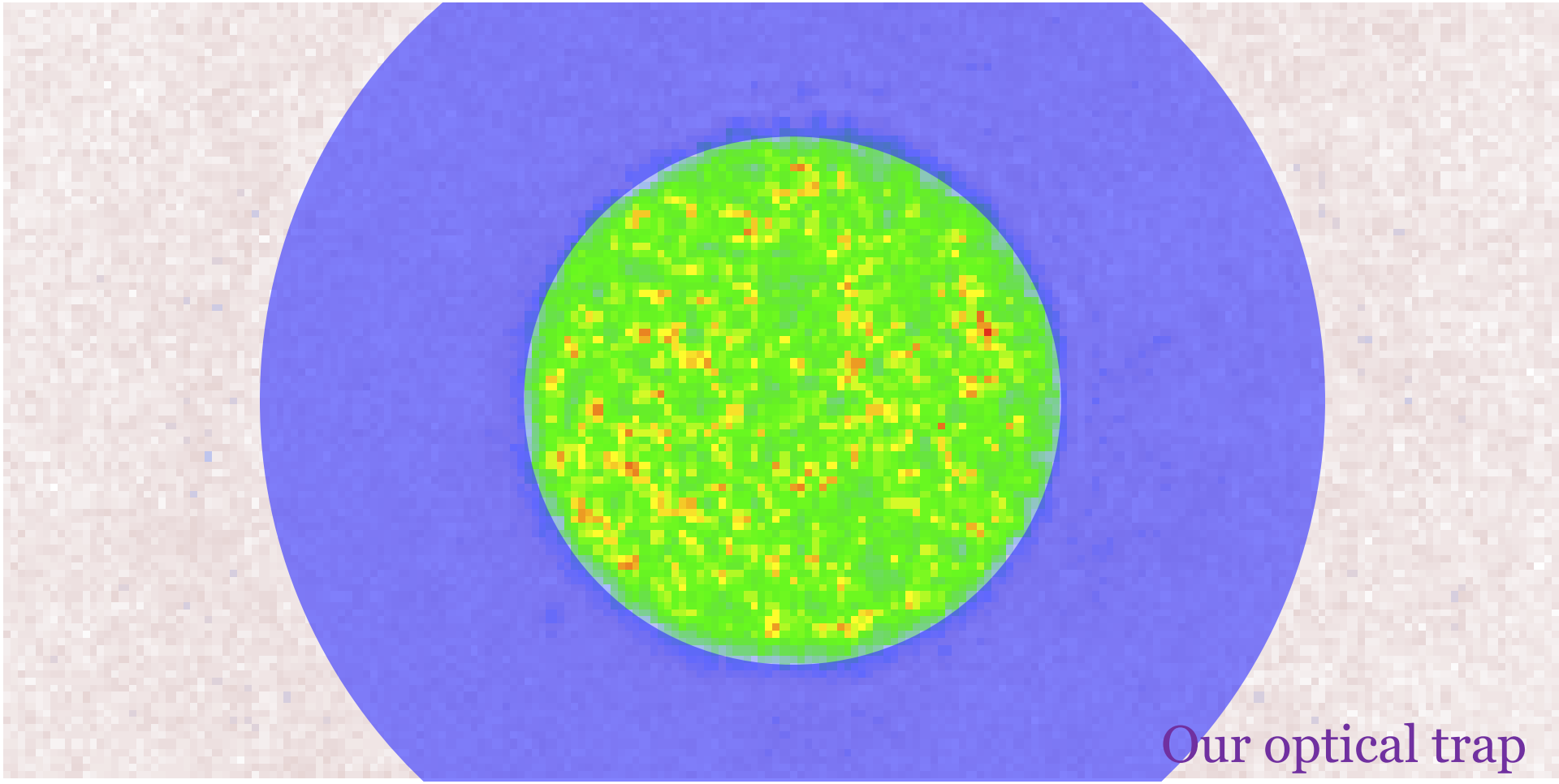
Demonstration of digital micromirror device (5x5 micromirrors)



Demonstration of digital micromirror device (many micromirrors)

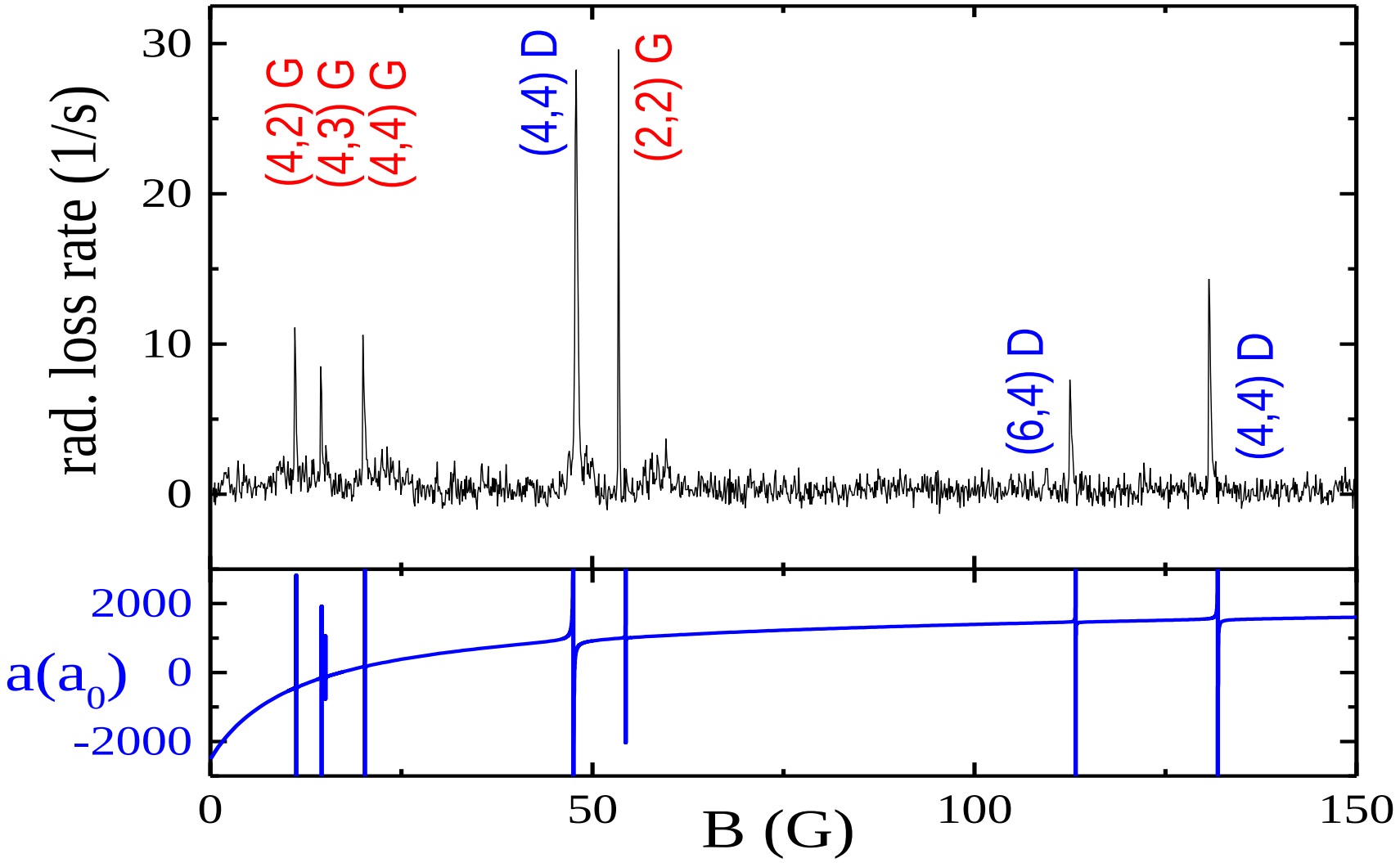


In situ image of Cesium Bose condensate



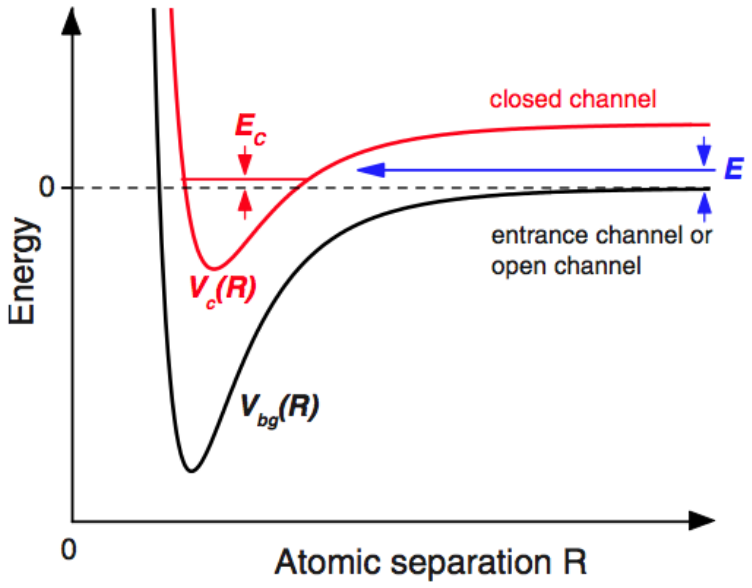
20,000~100,000 cesium atoms
Imaging resolution: 1.0 μm

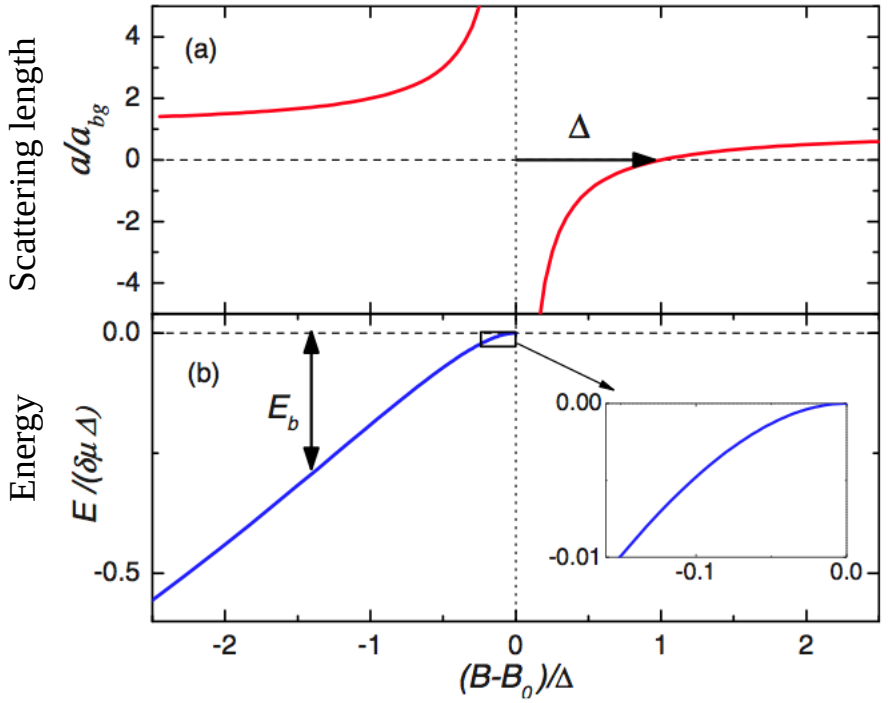
Feshbach resonances in Cesium atoms



CC et al., PRL 1999

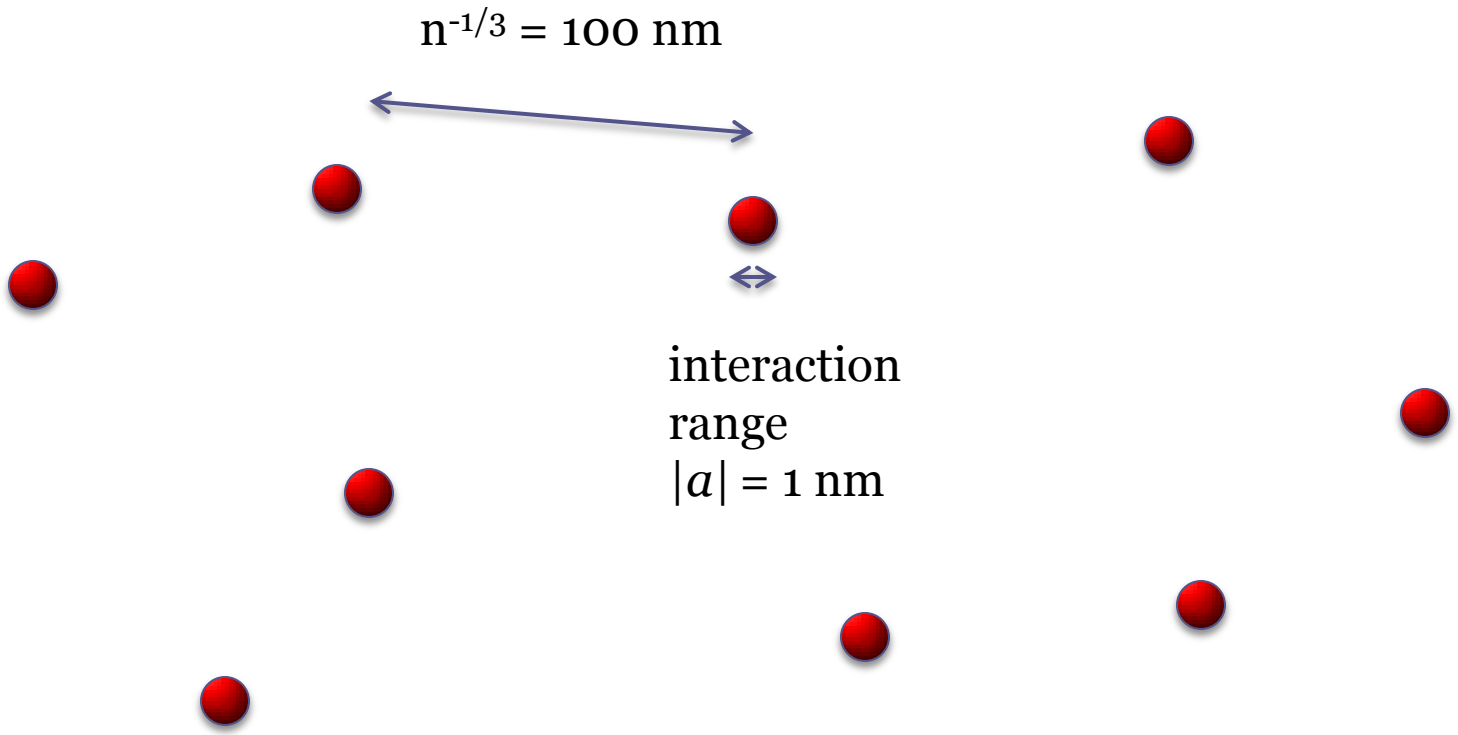
Feshbach resonance: resonant scattering of atoms





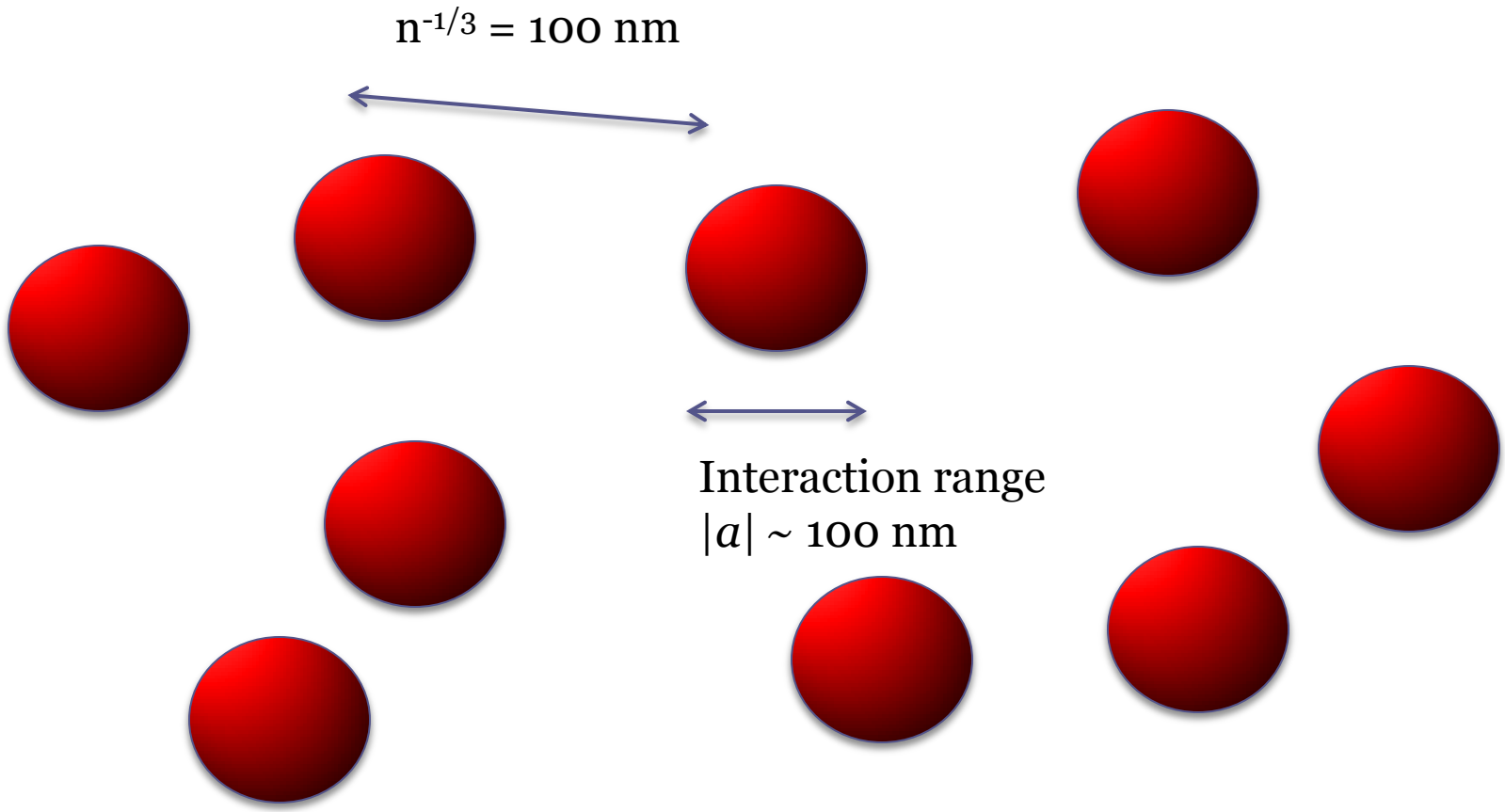
CC, Grimm, Julienne, Tiesinga, Review of Modern Physics 2010

Weakly vs. strongly interacting quantum gas



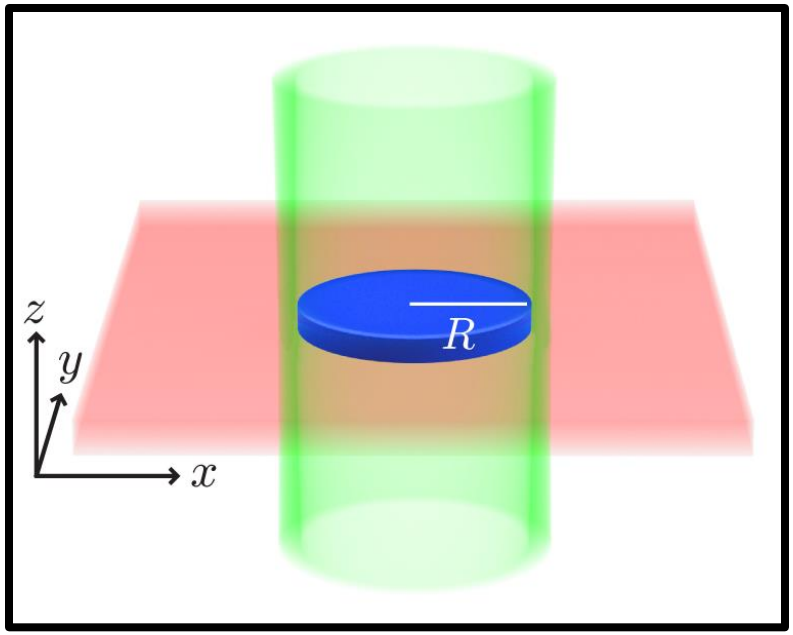
Gross-Pitaevskii equation: $$\left(-\frac{\hbar^2\nabla^2}{2m} + V(x) + \frac{4\pi a\hbar^2}{m} g|\psi|^2\right)\psi = \mu\psi$$

Weakly and strongly interacting quantum gas

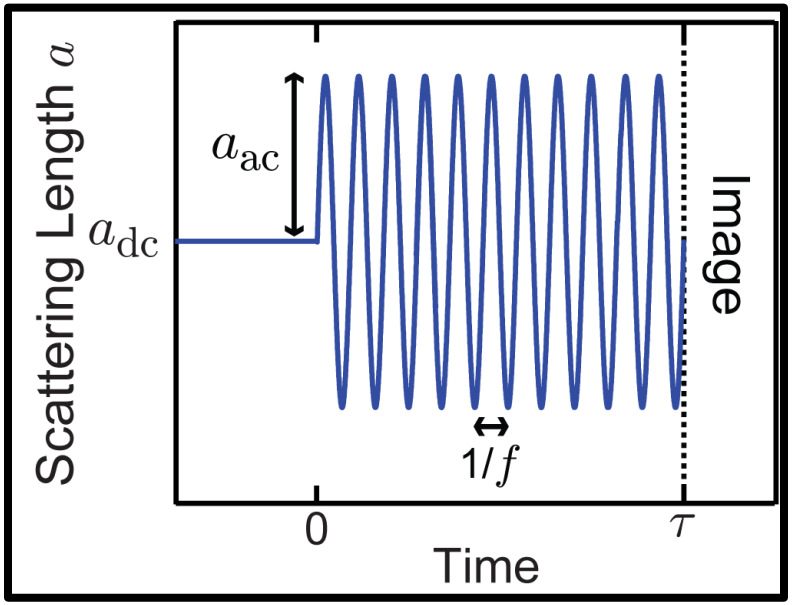


Condensates with Oscillating Interaction Strength

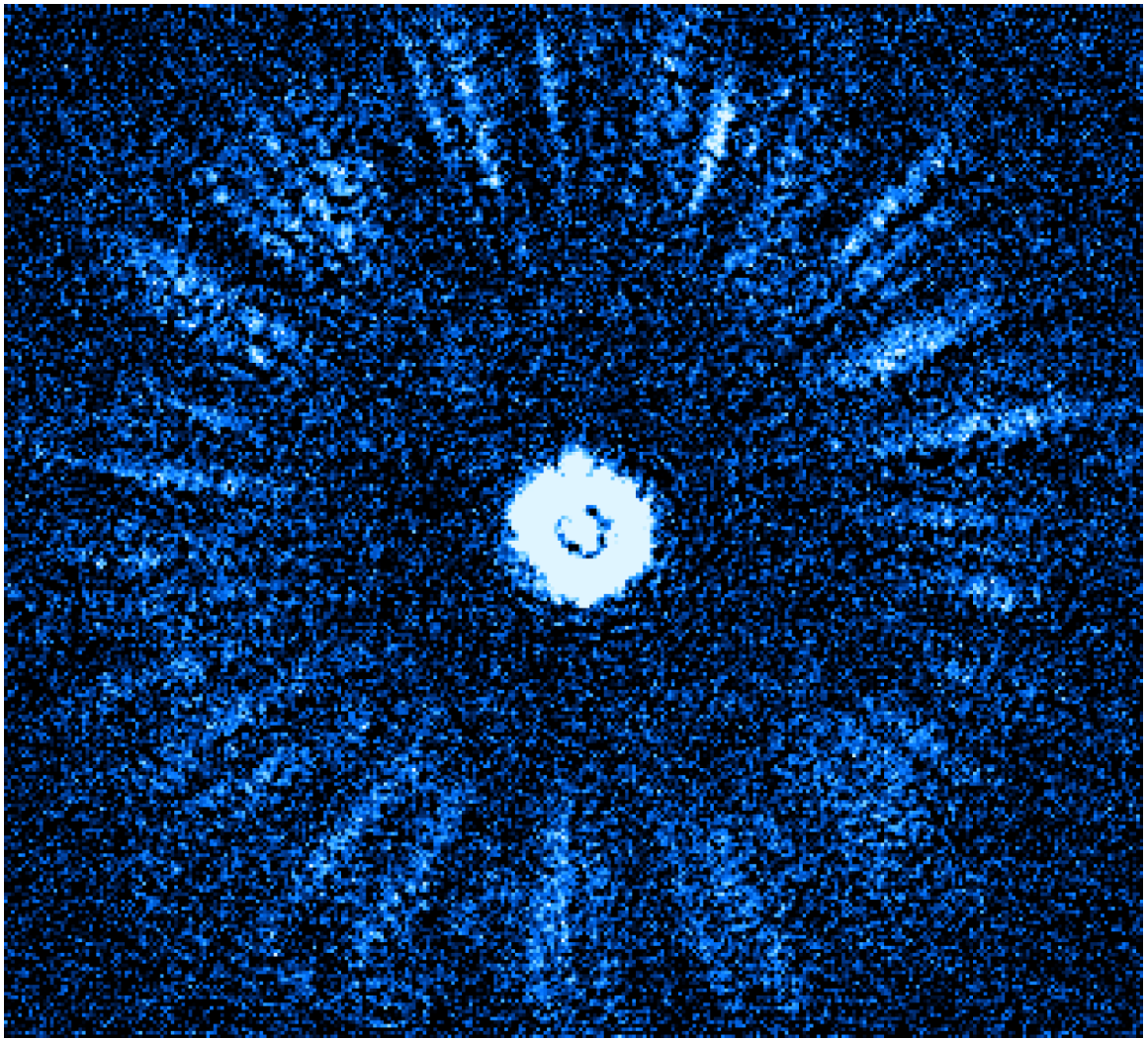
Step 1: Create thin, homogeneous Bose-Einstein condensates



Step 2: Modulate the interaction strength



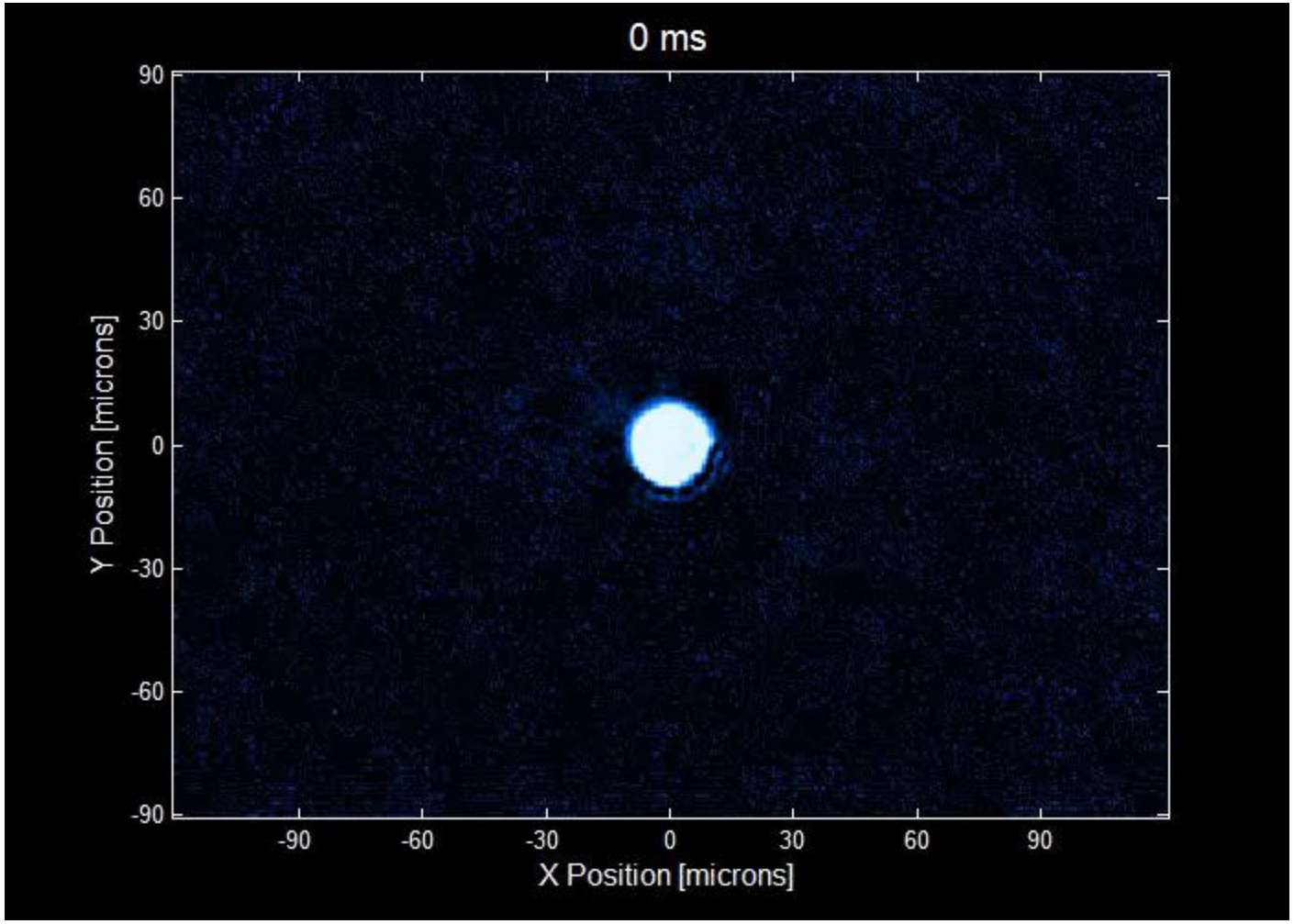
Bose fireworks (modulation of interactions)



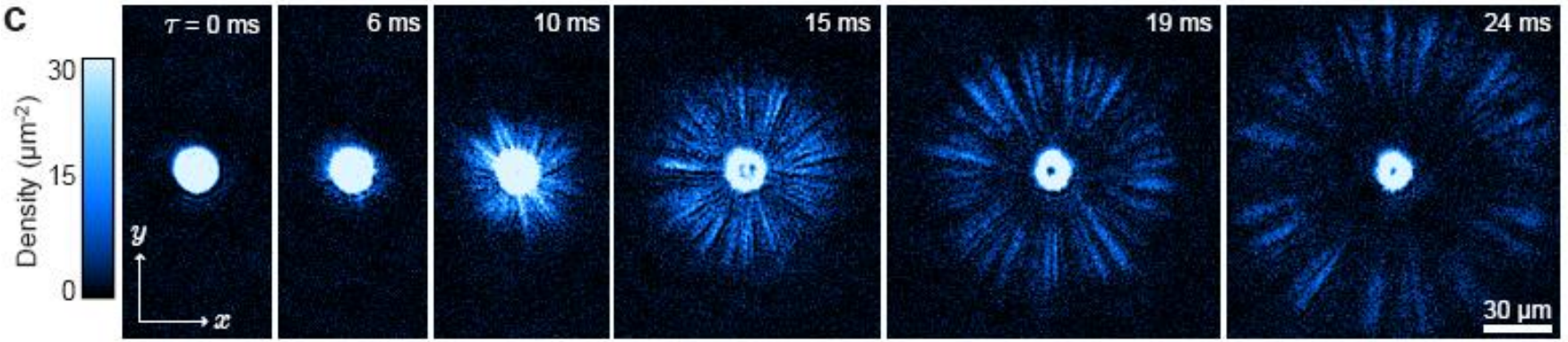
Nature 551, 356 (2017)

Bose Fireworks

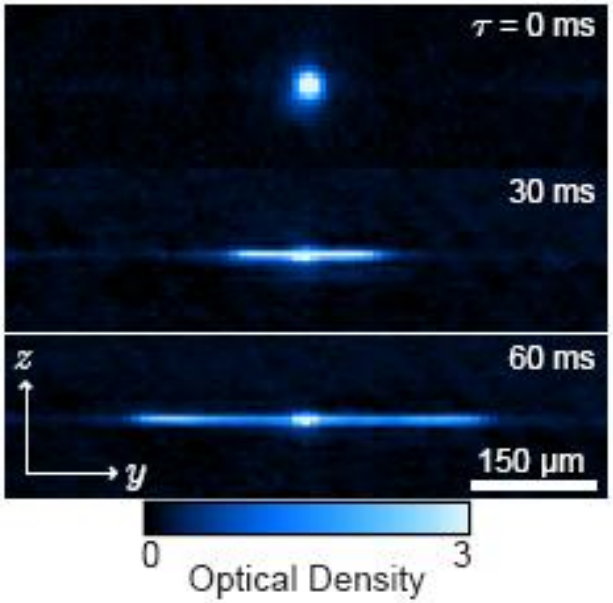
- Movie for **f=2.5 kHz**



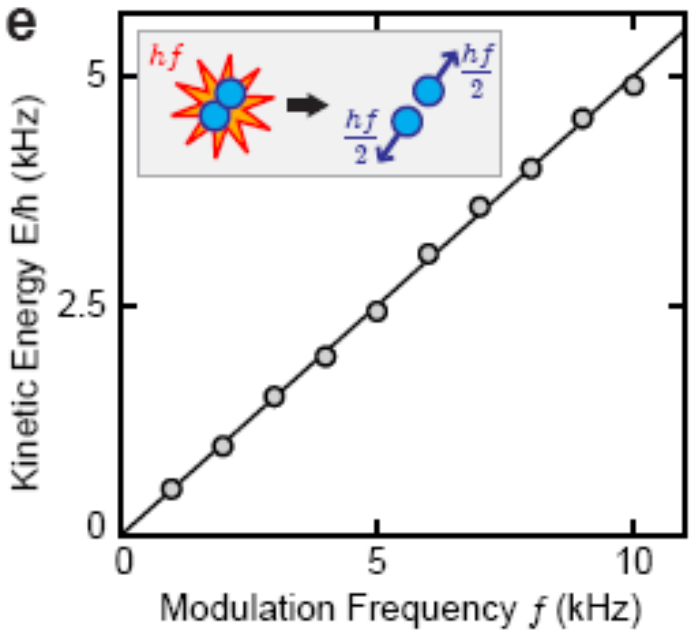
Top view



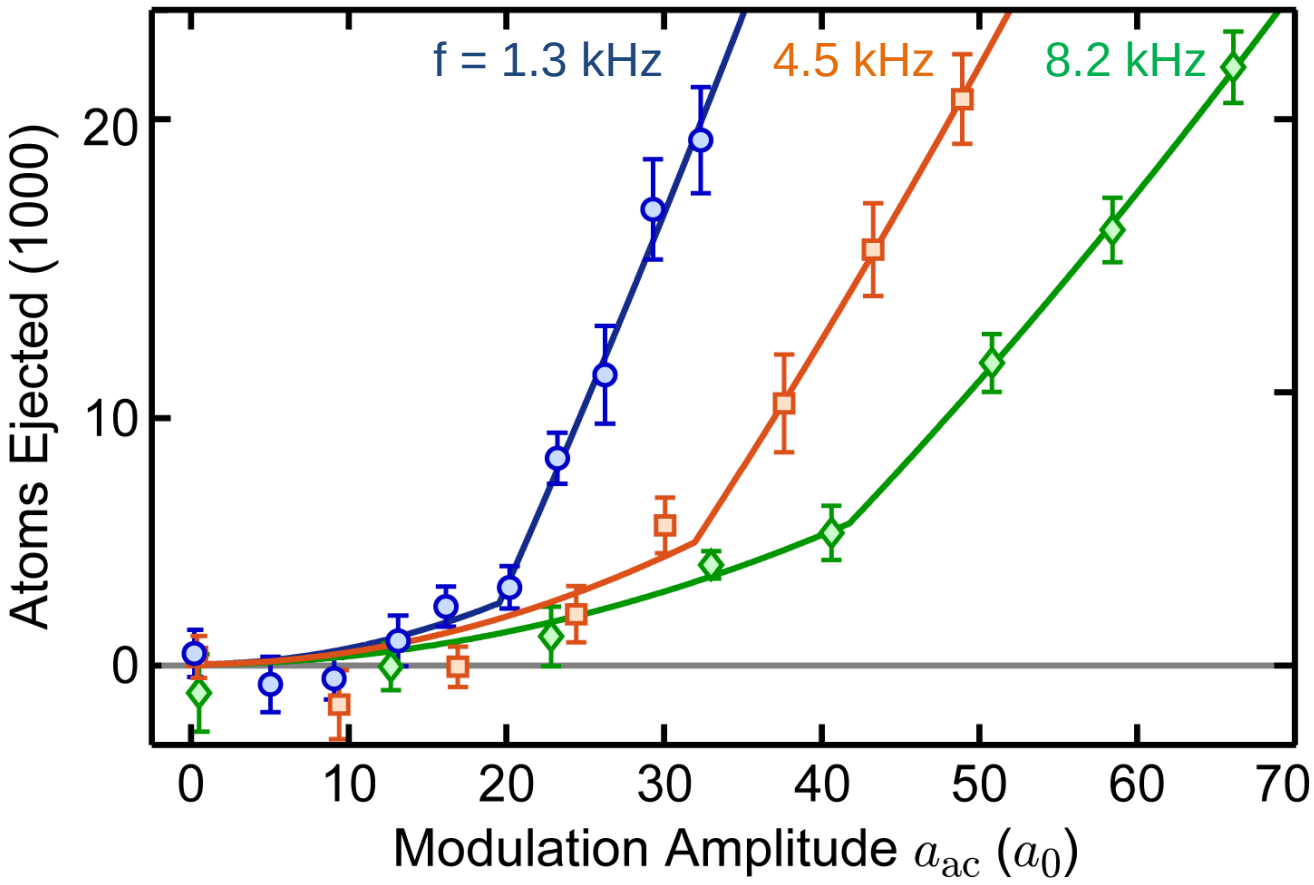
Side view



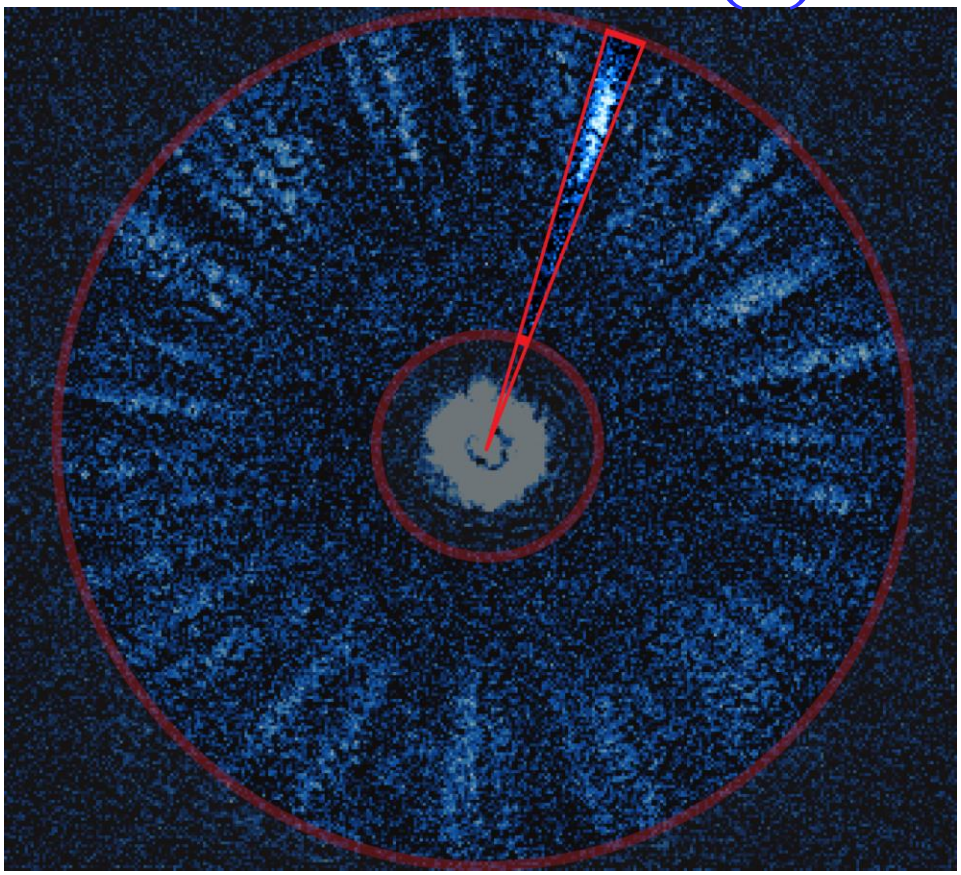
Jet energy



Jets only appear above threshold

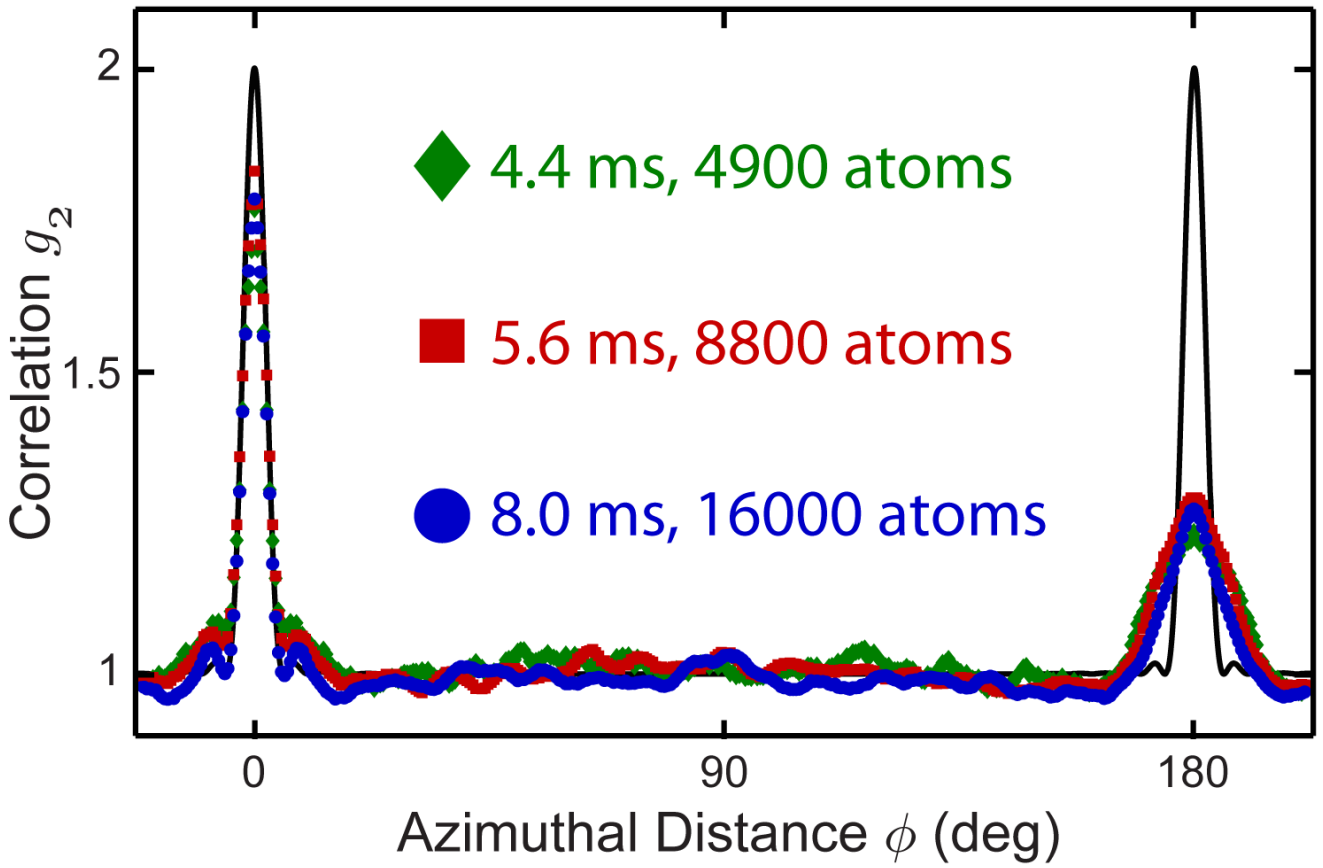


$N(\theta)$

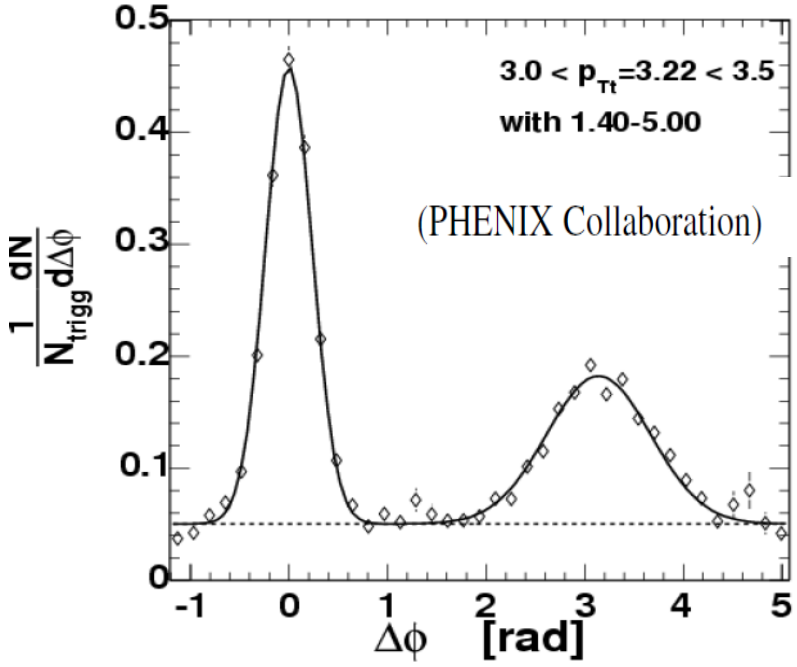


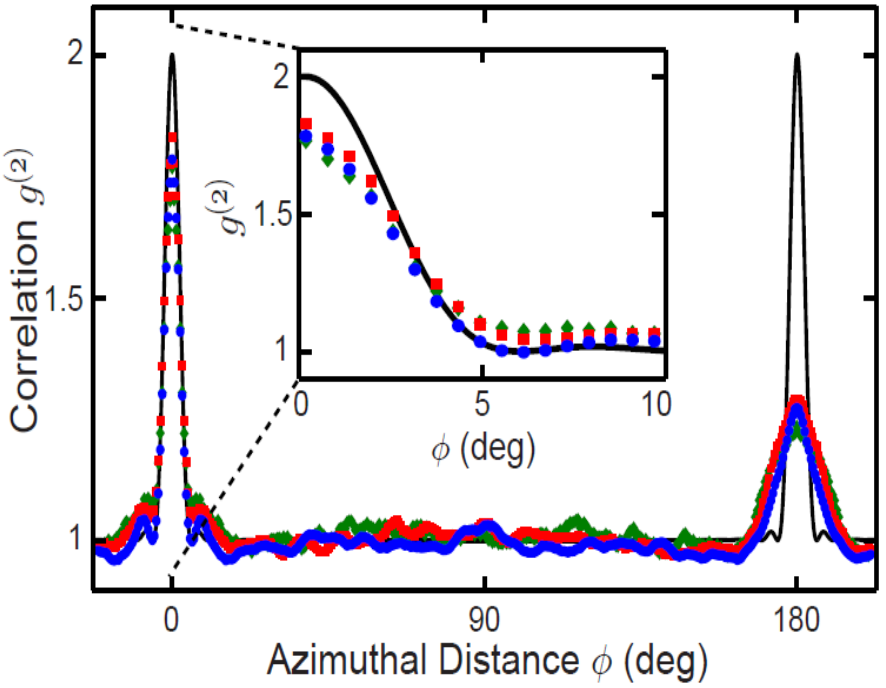
$$g_2(\phi) = \frac{\langle \int d\theta N(\theta)(N(\theta+\phi) - \delta(\phi)) \rangle}{\langle \int d\theta N(\theta) \rangle^2}$$

Mode structure and occupation



Connection between Bose fireworks and particle physics



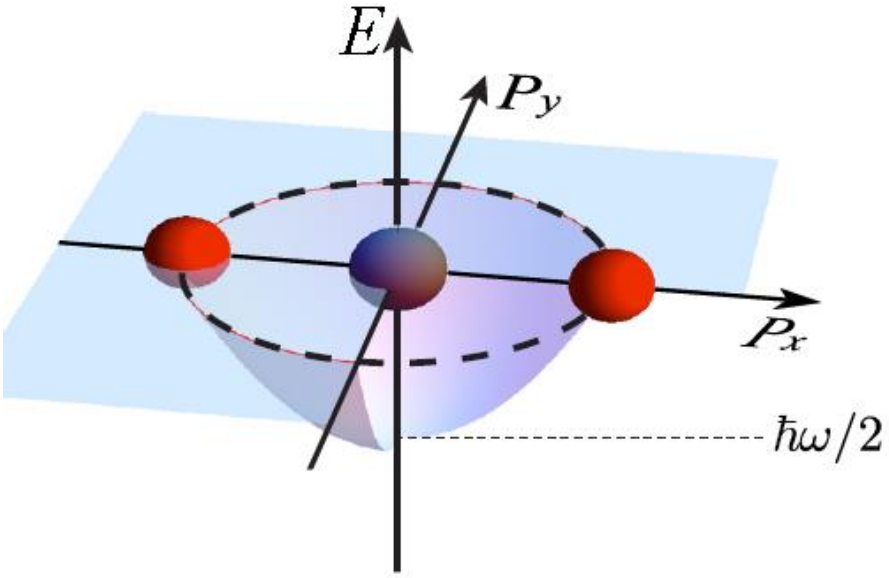


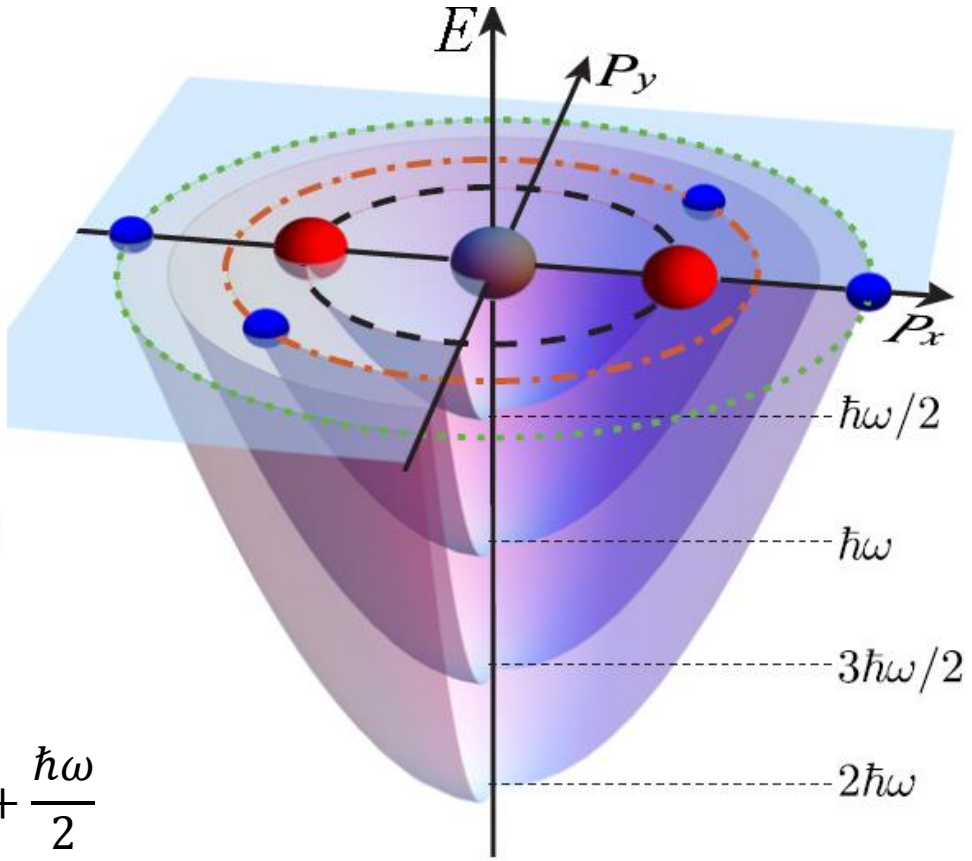
PHYSICAL REVIEW D **74,** 072002 (2006)

Jet properties from dihadron correlations in $p + p$ collisions at $\sqrt{s} = 200$ GeV

Miguel Arratia, J. Phys. B: At. Mol. Opt. Phys

Nested dispersion induced by interactions

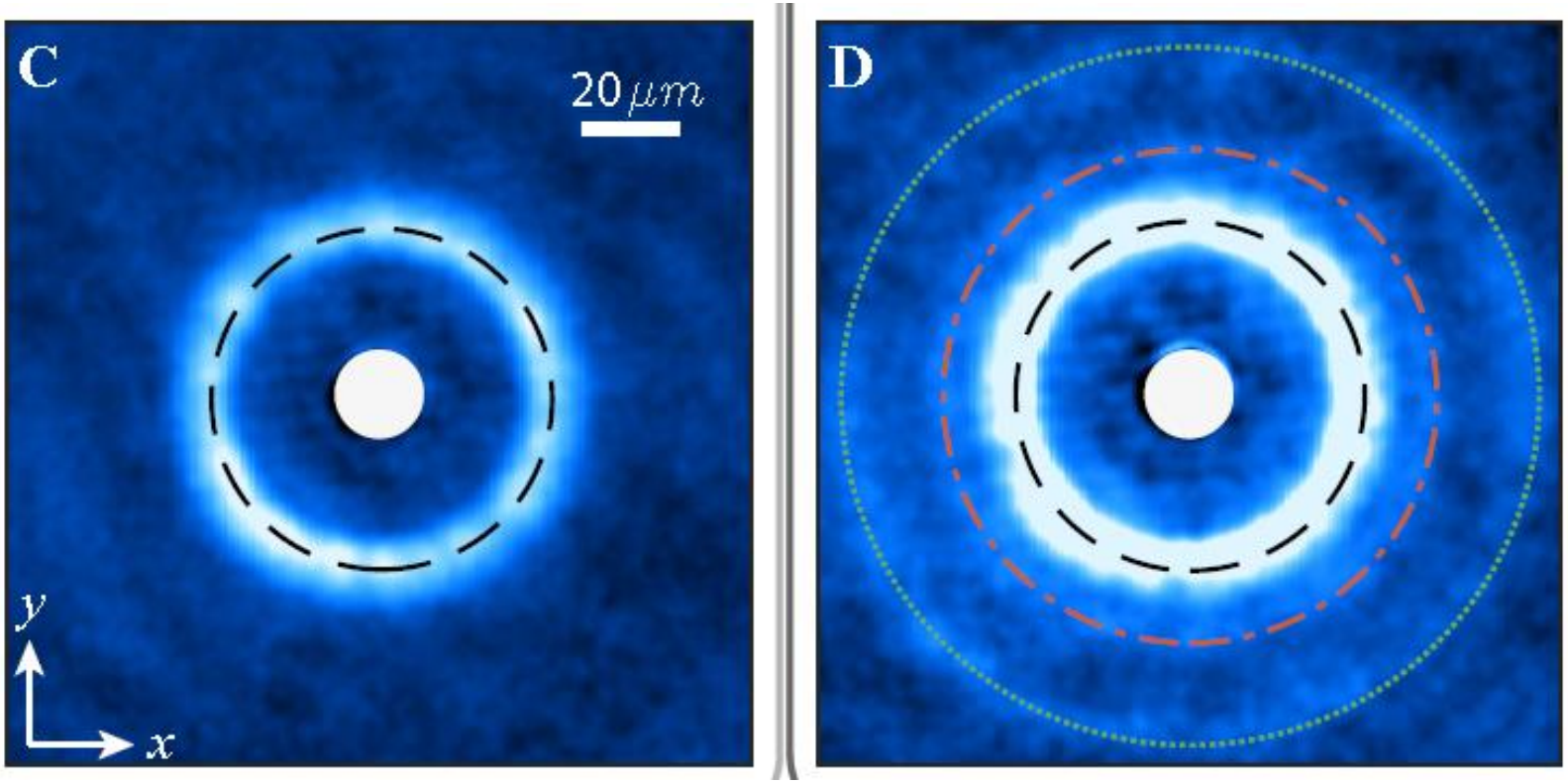




Energy conservation: $\hbar\omega = \frac{\hbar\omega}{2} + \frac{\hbar\omega}{2}$

Momentum conservation: $0 = p - p$

High harmonic generation of fireworks

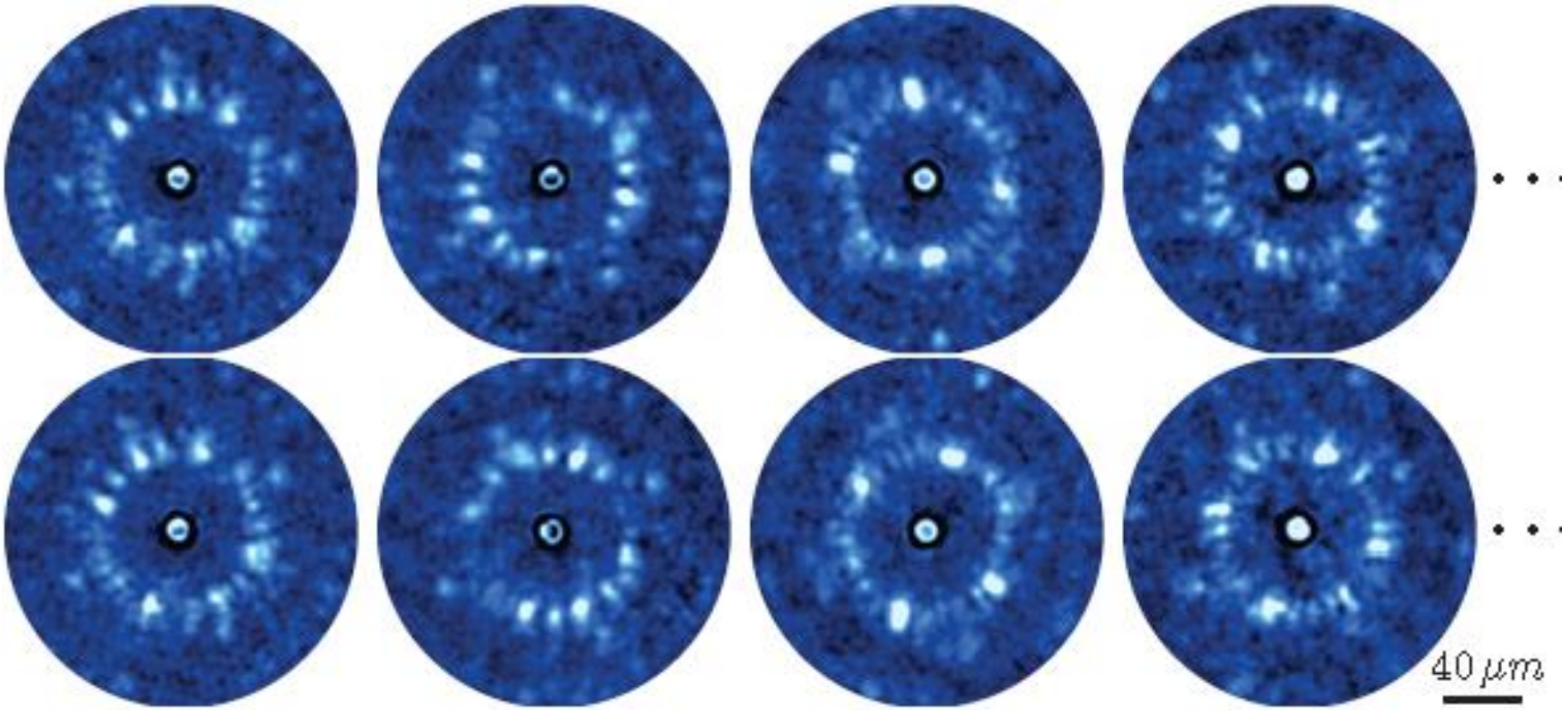


Modulation depth = 25 Bohr

Modulation depth = 45 Bohr

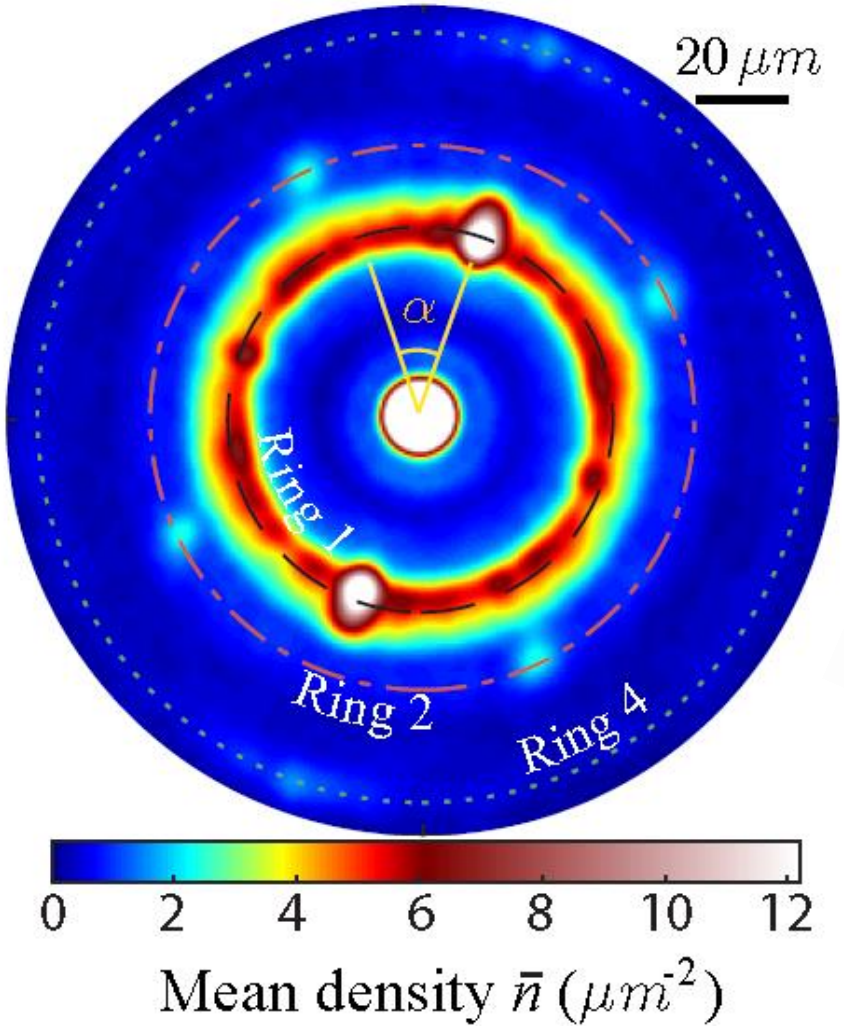
Pattern recognition and machine learning

Original images



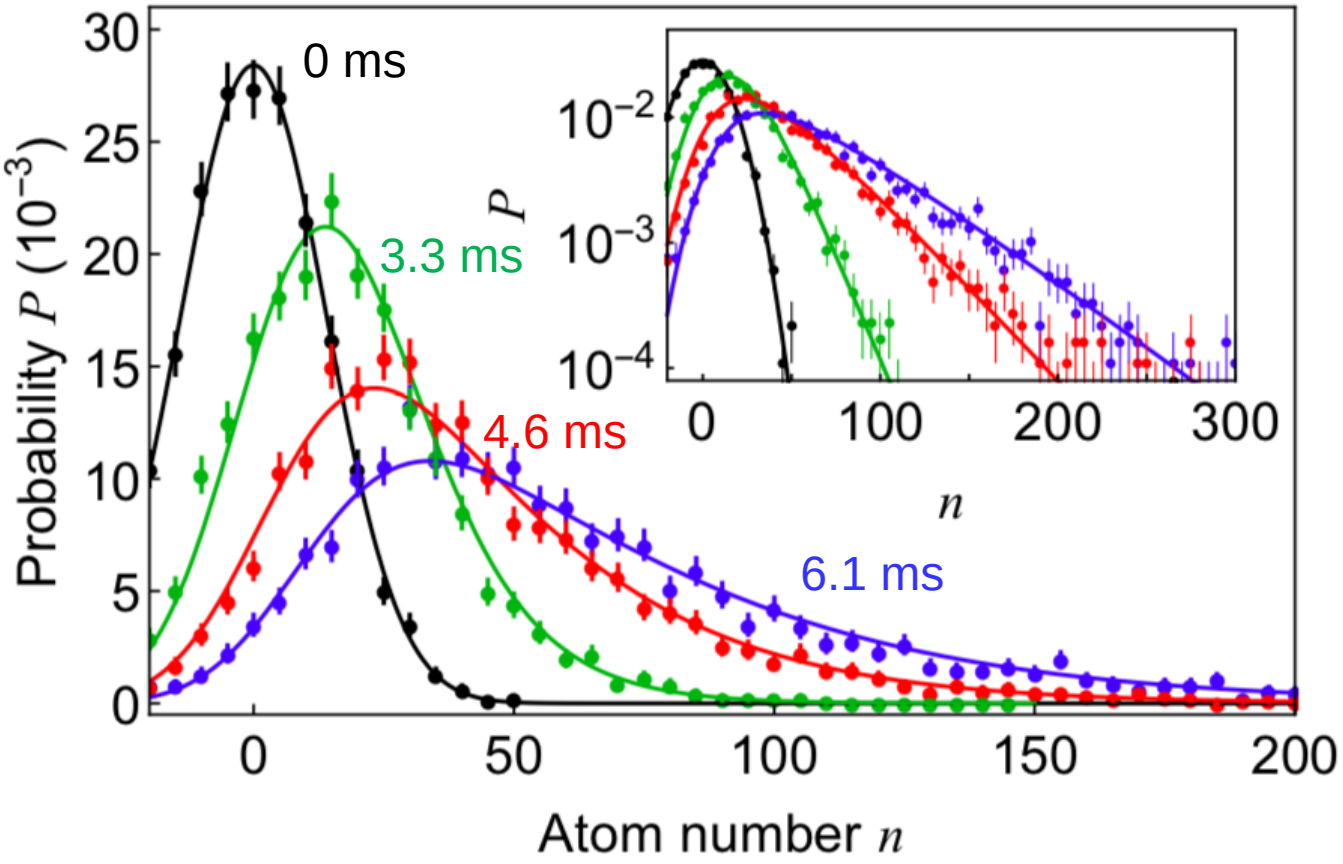
Rotated images

Averaging 209 rotated images: pattern recognition

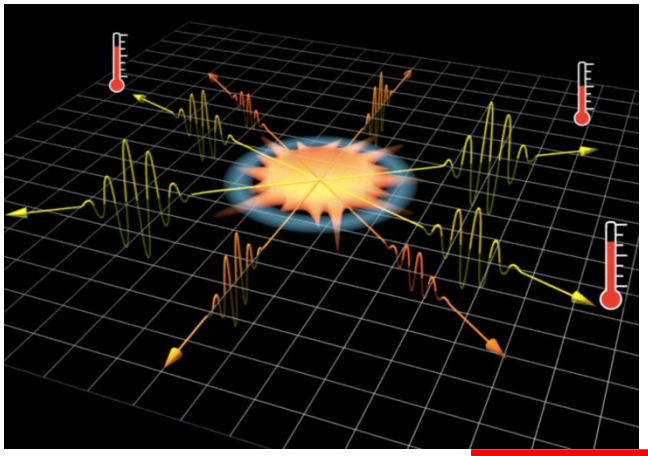


Feng et al, Science 363, 521 (2019)

Distribution of atom number in a jet



Bose Fireworks and Unruh thermal radiation



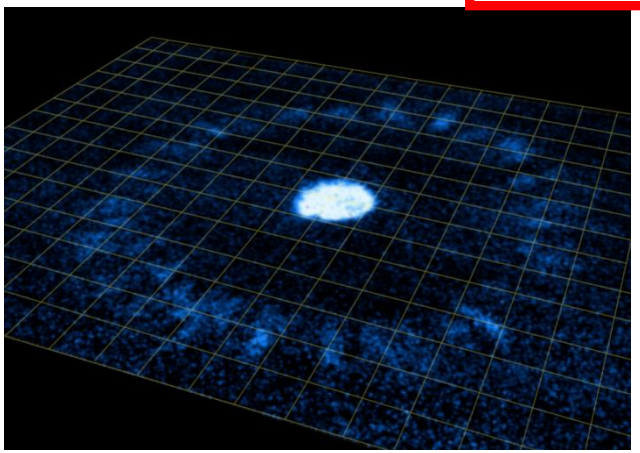
Vacuum in the frame with acceleration *A*

$|\text{vacuum}\rangle \rightarrow R_A\,|\text{vacuum}\rangle = |\text{"thermal"}\rangle$

Unruh temperature $T_U = \dfrac{\hbar A}{2\pi k_B c}$

T=1μK when A=2.5x10^{14} m/s^2

$$A = \frac{\pi\omega c}{2\ln\coth(g\tau)}$$



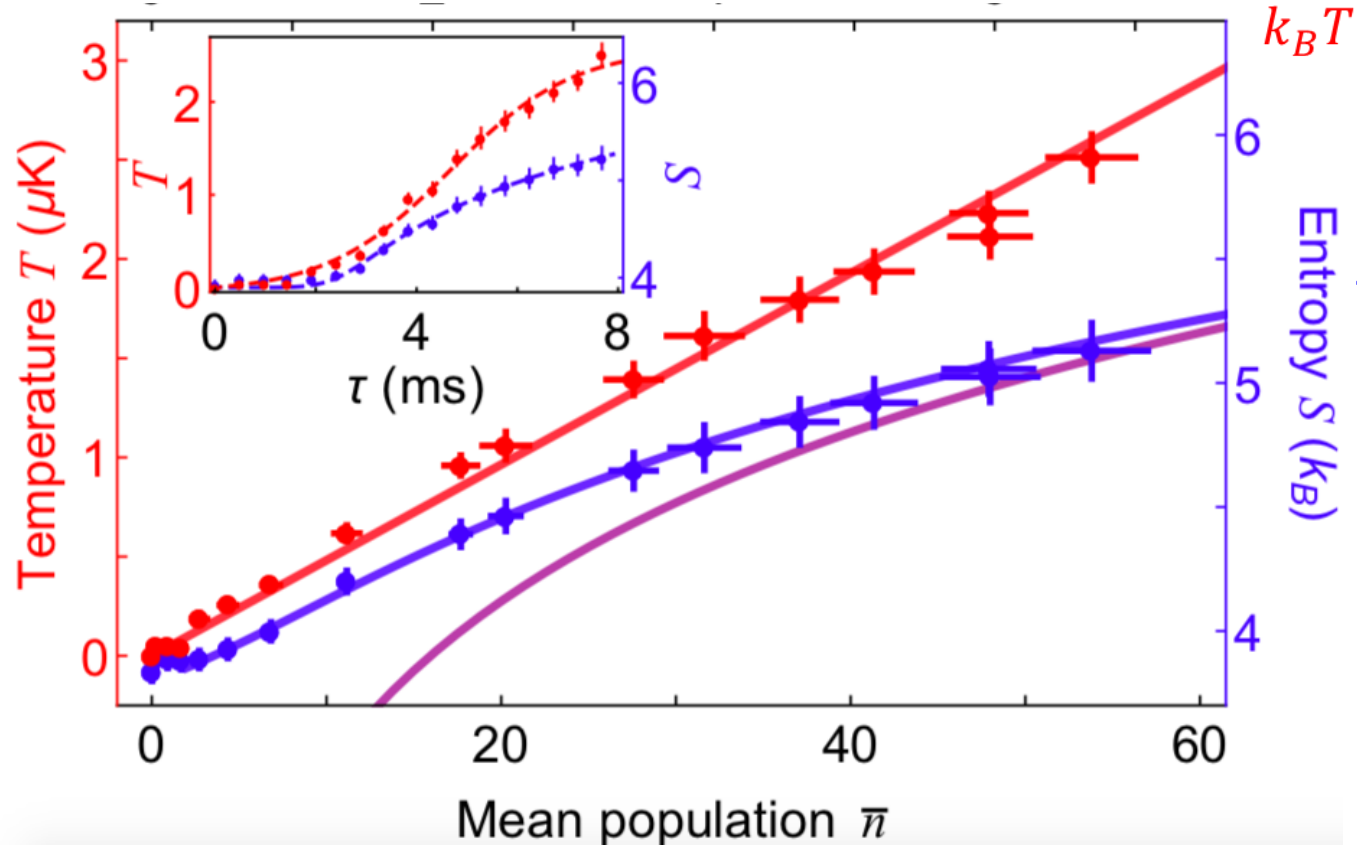
Quantum simulation of frame transformation

$$\hat{R}_A\Psi_0 = \hat{U}(\tau)\Psi_0$$

U(τ)=exp(-iHτ/ħ): evolution operator

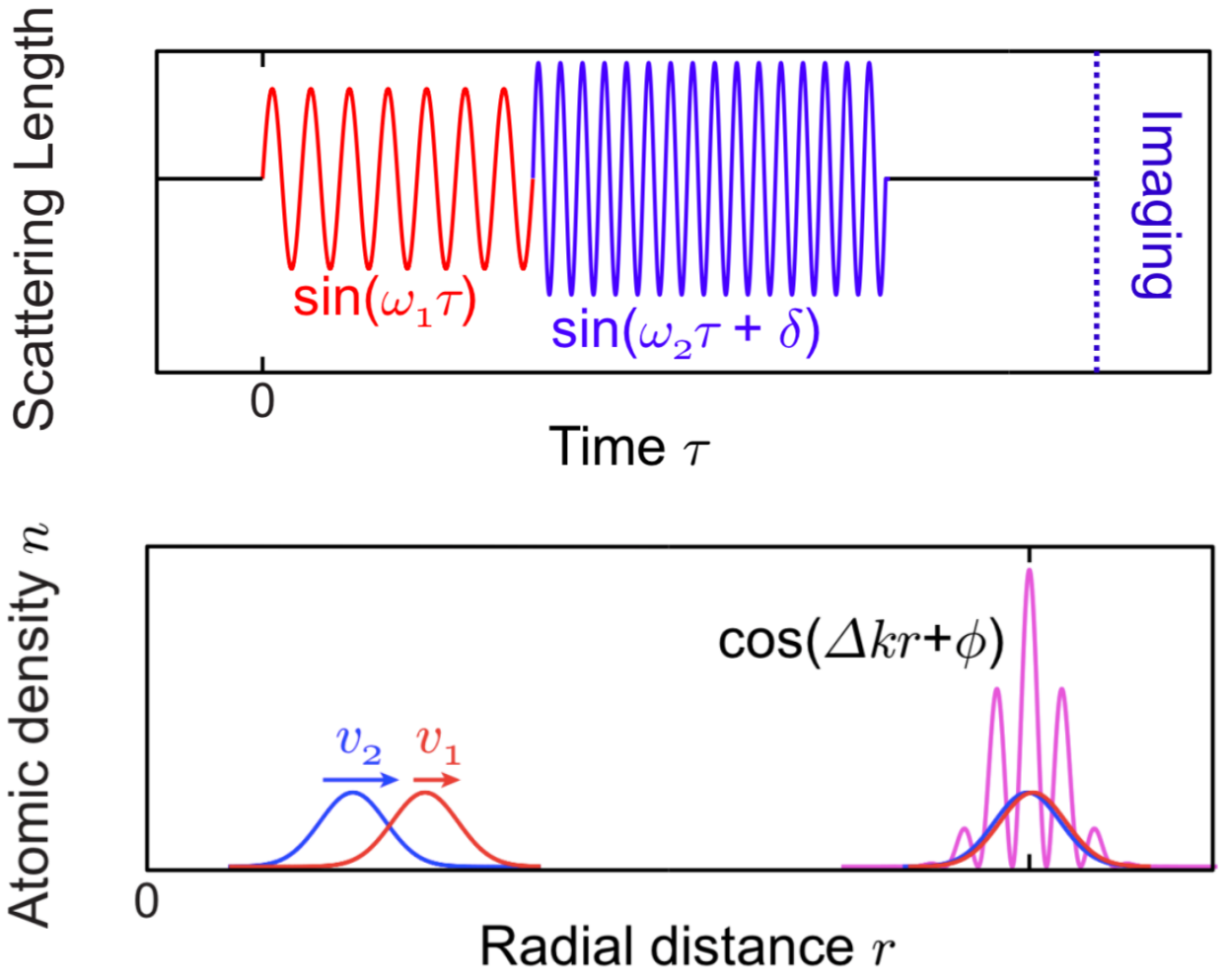
$$H = \sum_k g_k a_k^+ a_{-k}^+ + h.c.$$

Thermodynamics of fireworks:
temperature T and entropy S_{vN}

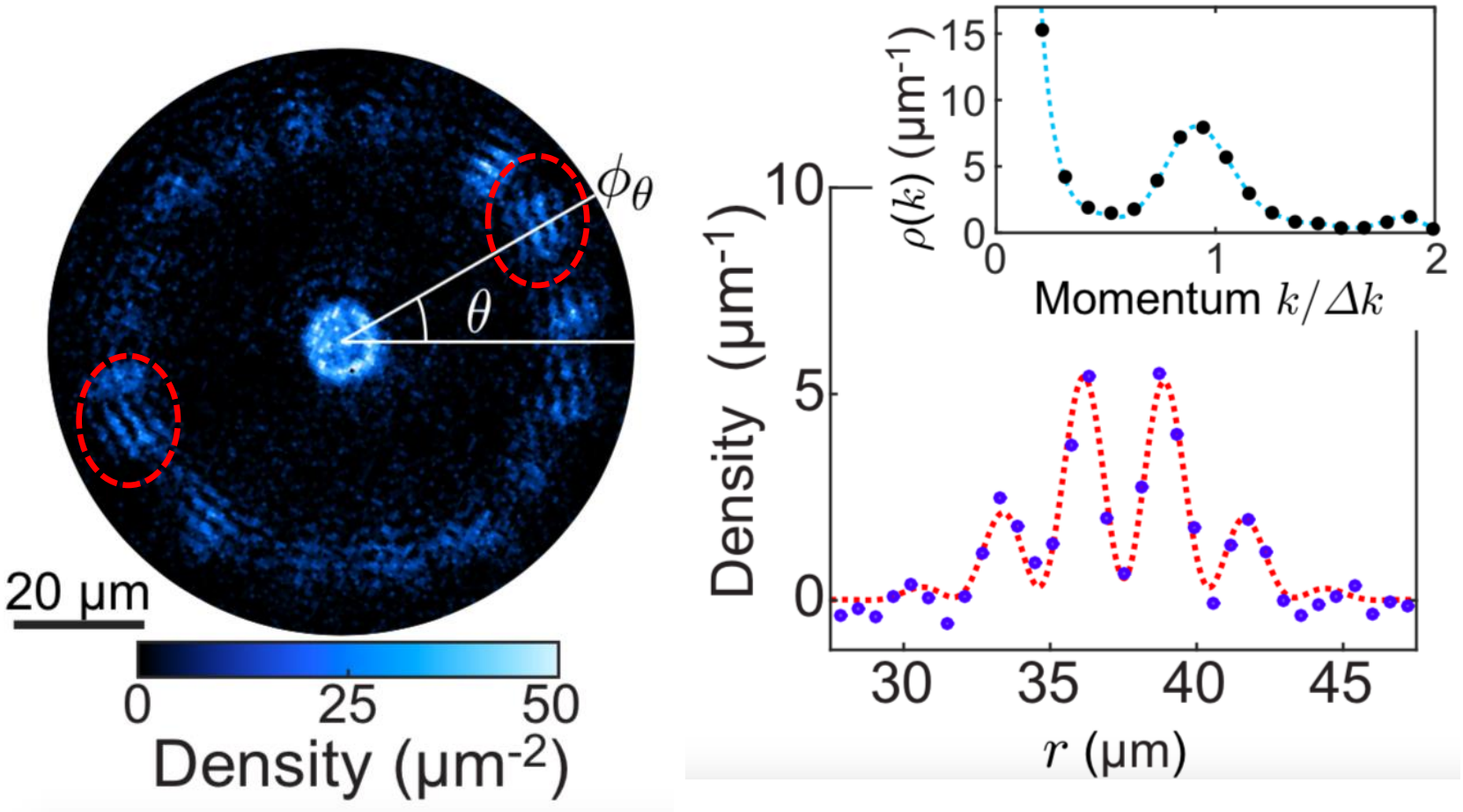


Quantum Simulation of Coherent Hawking-Unruh Radiation, arXiv: 1807.07504

Interference of thermal radiations!



Angular correlation pattern of matterwave interference



Interaction = nonlinear mixing of matterwaves

$$\text{Interaction U} = \frac{1}{2} g e^{i\omega t} |\psi|^4 = \frac{1}{2} g e^{i\omega t} \sum a_{k1}^{+} a_{k2}^{+} a_{k3} a_{k4} + h.c.$$

Momentum conservation: $\boldsymbol{k1 + k2 = k3 + k4}$

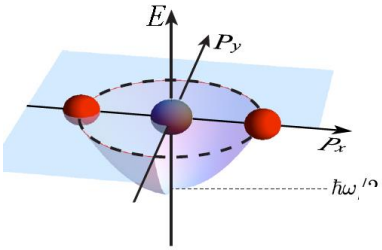
Energy conservation: $\boldsymbol{E1 + E2 = E3 + E4 + \hbar\omega}$

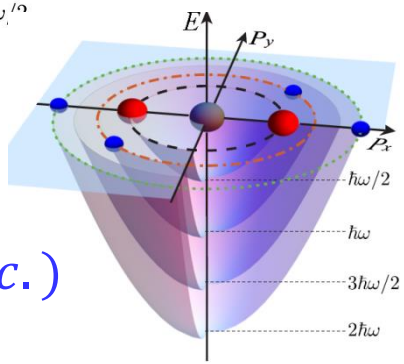
Assuming a Bose condensate has N_0 atoms in the ground state…

Bogoliubov approximation

$$\text{U} \approx g N_0 (a_k^{+} a_{-k}^{+} + h.c.)$$

Pair production





2nd order Bogoliubov approximation

$$\text{U} \approx g N_0 \sum (a_k^{+} a_{-k}^{+} + h.c.) + \text{g}\sqrt{N_0} \sum (a_{k1}^{+} a_{\text{k2}}^{+} a_{k1+k2} + h.c.)$$

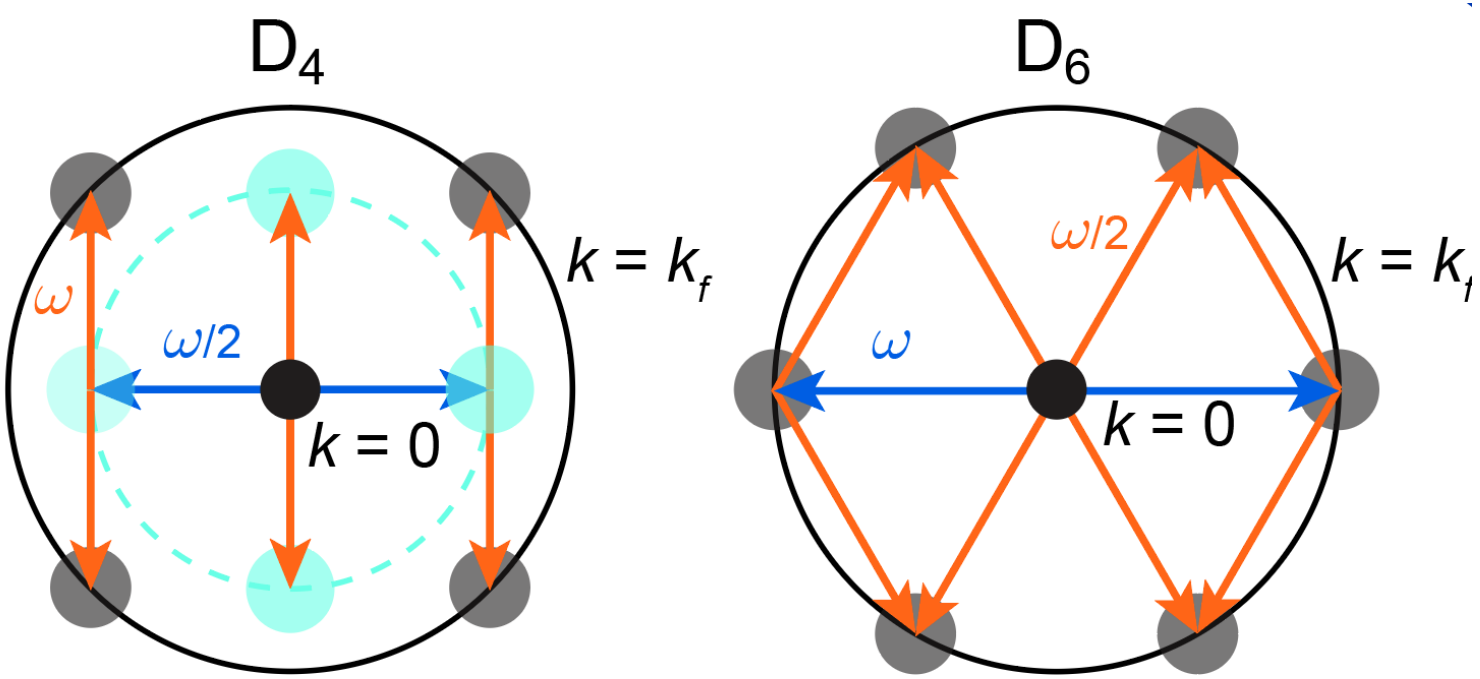
Nonlinear wave mixing

$\Rightarrow$ Quantum nonlinear wave mixing eqn:

$$\frac{d\hat{a}_k}{dt} = \gamma_1 a_{-k}^{+} + \gamma_2 \sum_{k1} \hat{a}_{k1-k}^{+} \hat{a}_{k1} - \gamma_2^{*} \sum_{k2} \hat{a}_{k2} \hat{a}_{k-k2}$$

Ideas to generate D4 and D6 patterns

Momentum space



Step 1: Pair creation at frequency $\omega/2$

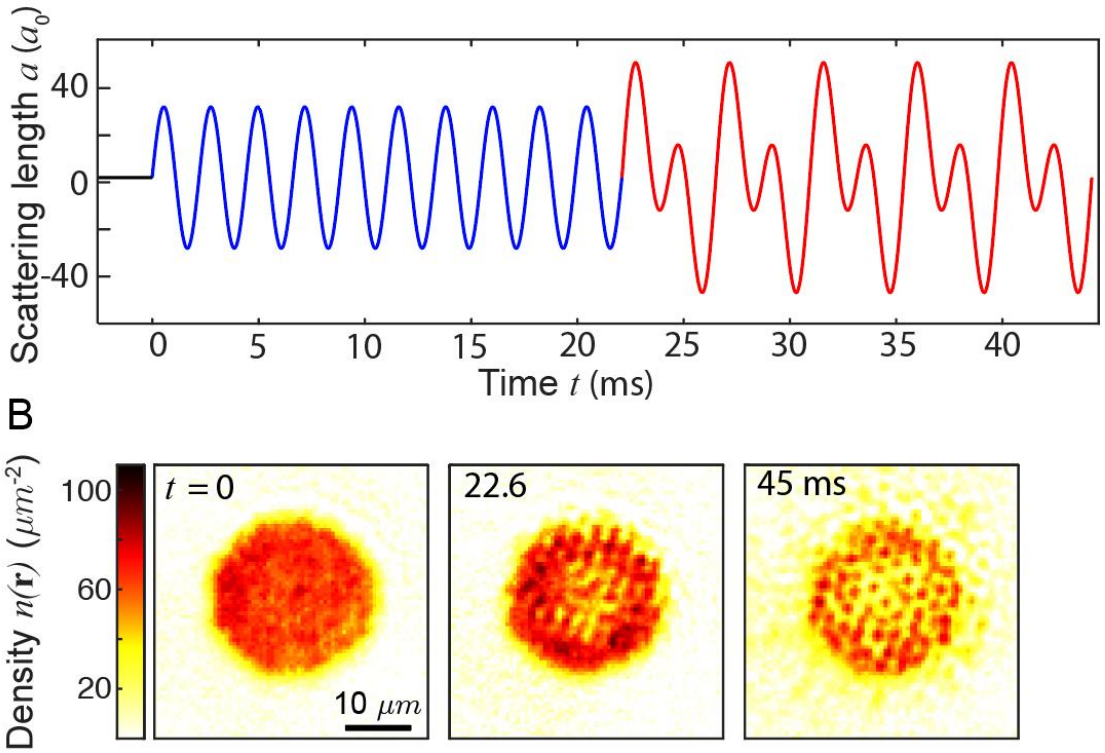
Step 2: Nonlinear wave mixing at ω

Frequency ω

Frequency $\frac{\omega}{2}$

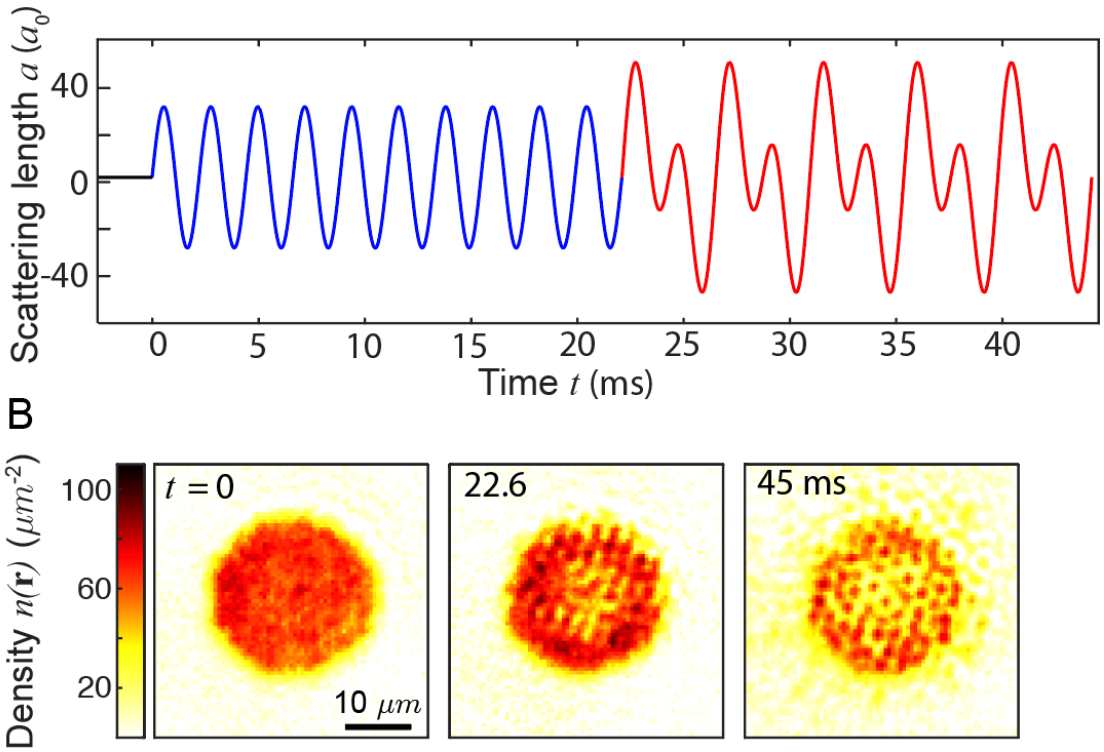
D6 modulation scheme

in situ imaging



D6 modulation scheme

in situ imaging

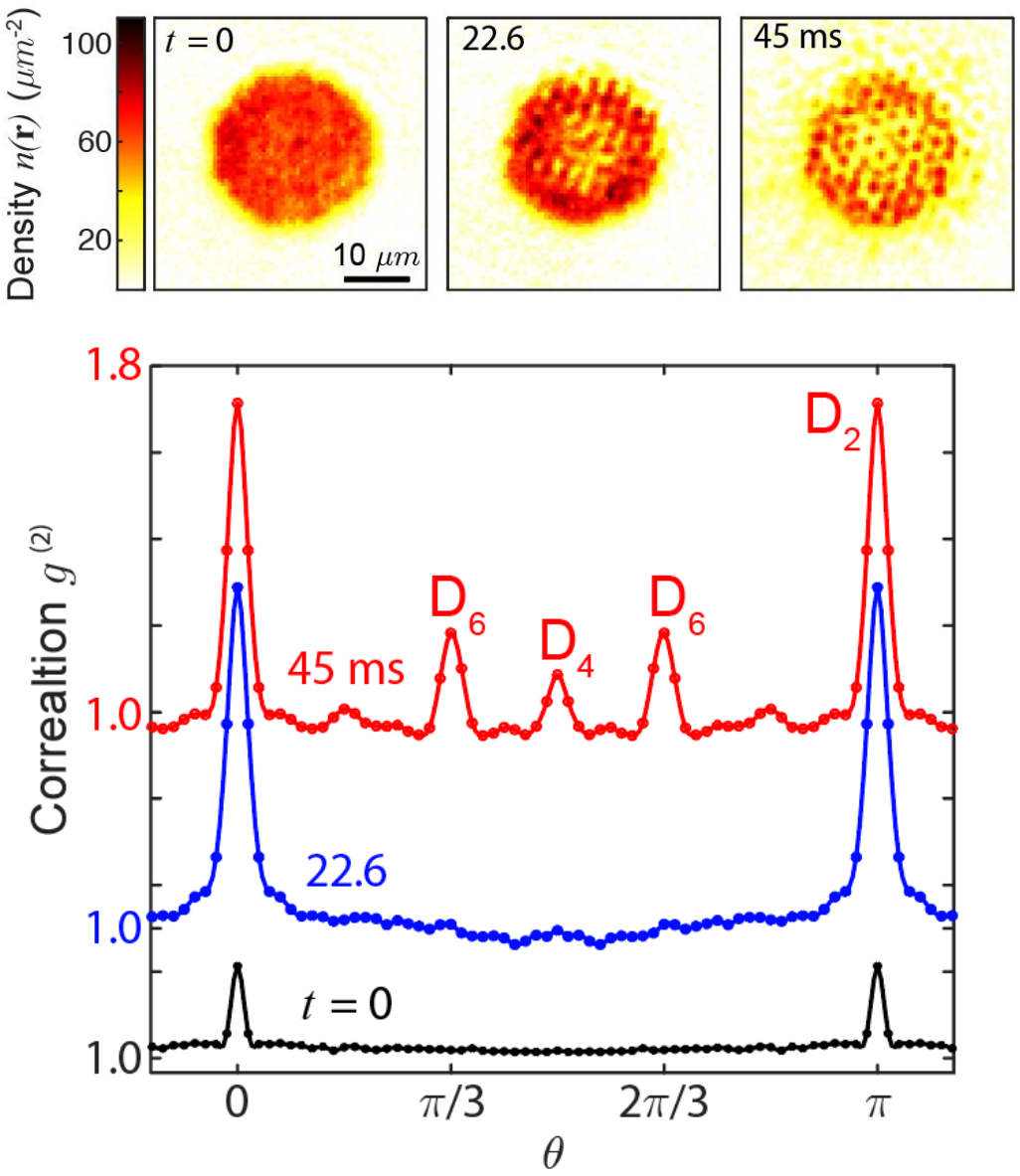


Density waves = interferences of excitations with BEC

$$n(x) = |a_0 + a_k e^{ikx} + a_{-k} e^{-ikx} + \cdots|^2$$

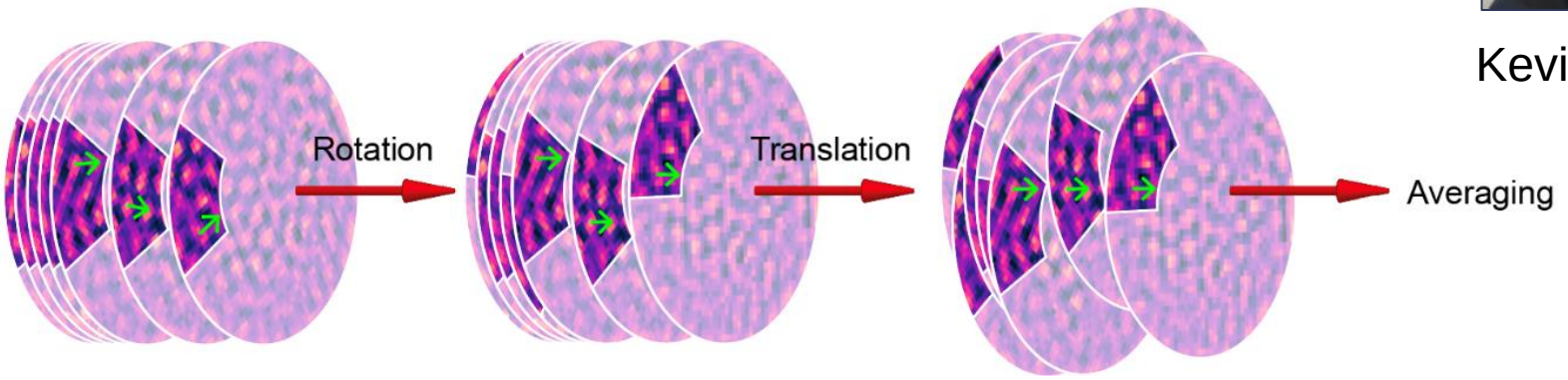
$$\approx n_0[1 + N_0^{-\frac{1}{2}} \sum_k (a_k + a_{-k}^{+}) e^{ikr}]$$

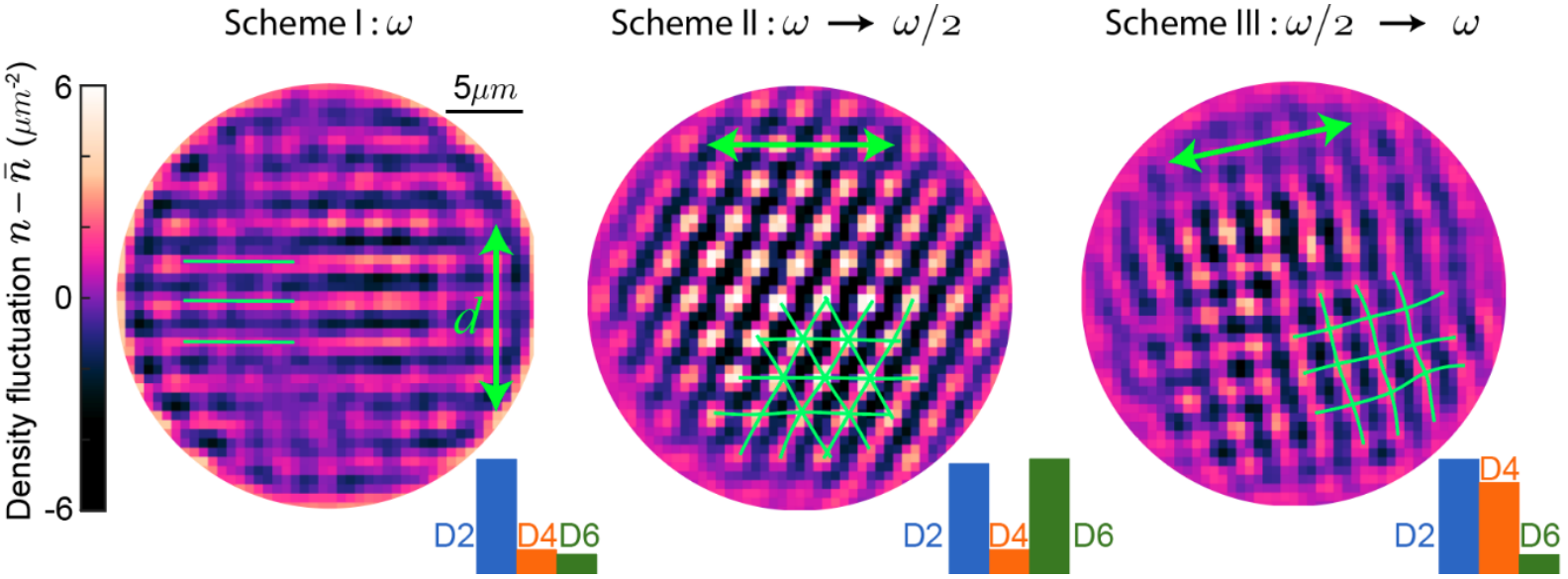
Angular density correlations



Real Space Pattern Recognition

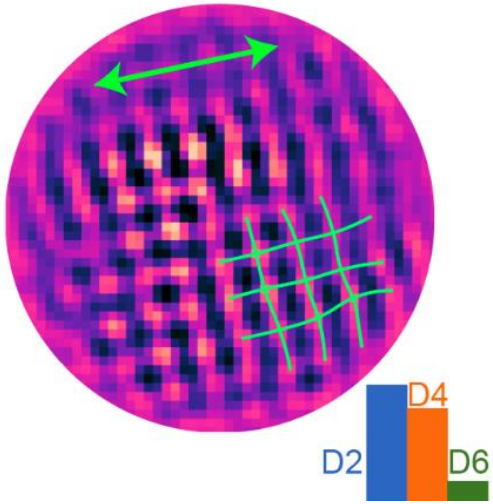
Kevin Yao

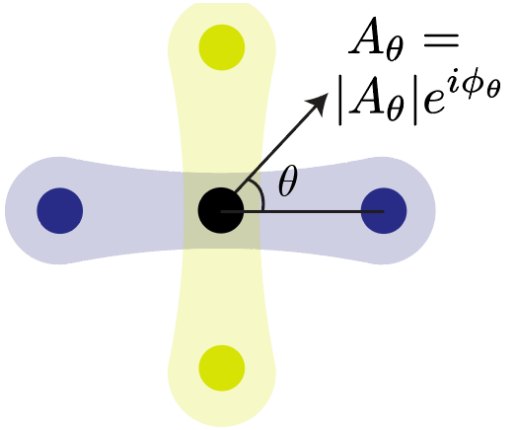


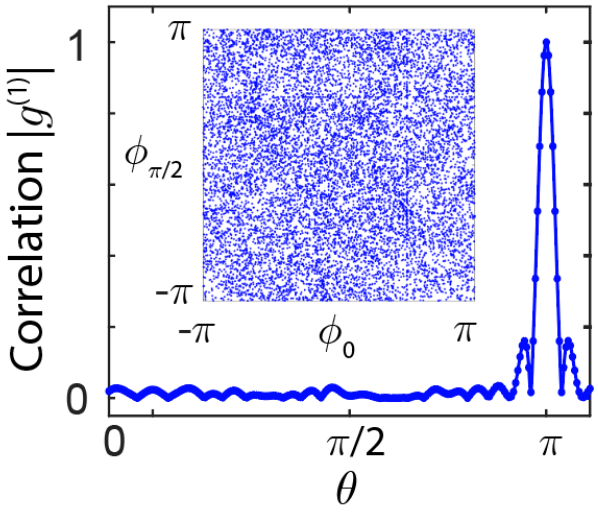


Are the patterns created coherently?

D4 pattern $\Rightarrow$ Fourier transform $\Rightarrow$ Phase correlation



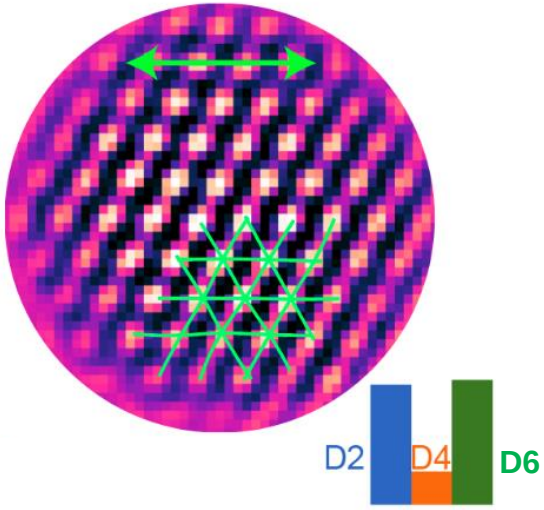




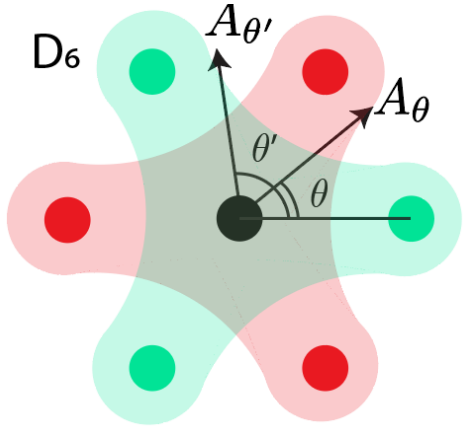
$$g^1 \equiv \frac{< A_\phi A_{\phi+\theta} >}{< |A_\phi|^2 >}$$

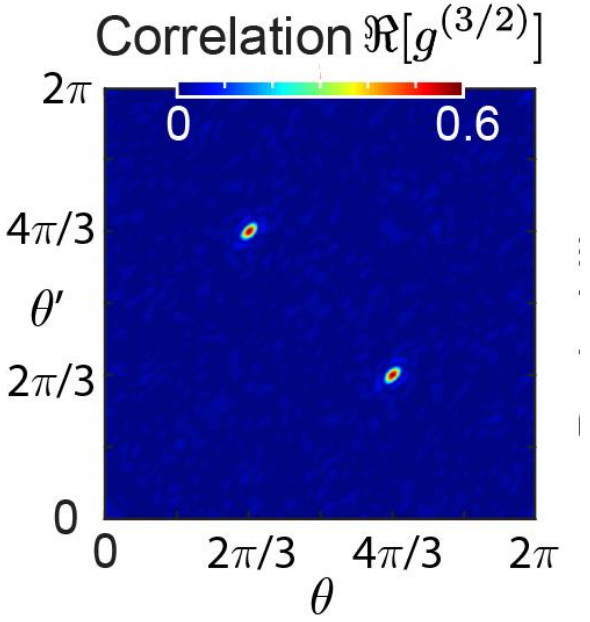
Resonant nonlinear wave mixing

D6 pattern $\Rightarrow$ Fourier transform $\Rightarrow$ Phase correlation



Symmetry decomposition

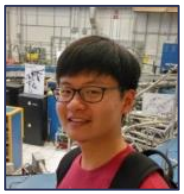




$$g^{(3/2)} \equiv \frac{< A_\phi A_{\phi+\theta} A_{\phi+\theta'} >}{< |A_\phi|^2 >^{3/2}}$$

Resonant nonlinear wave mixing

Prediction: $\frac{dA}{dt} = \gamma_1 A + \gamma_2 Re[g^{3/2}]A^2$



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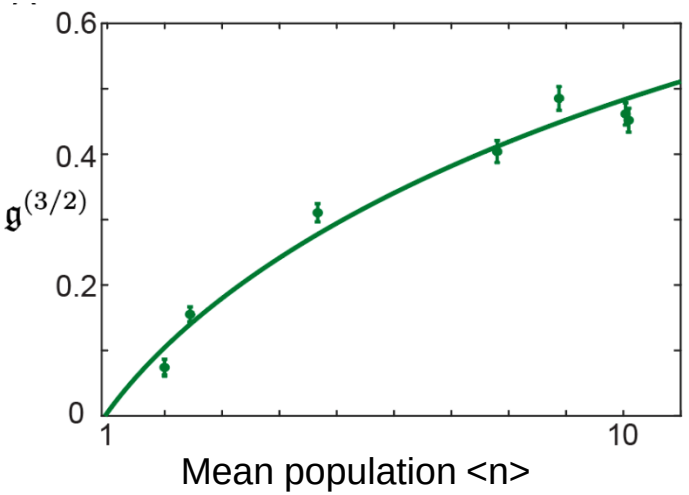
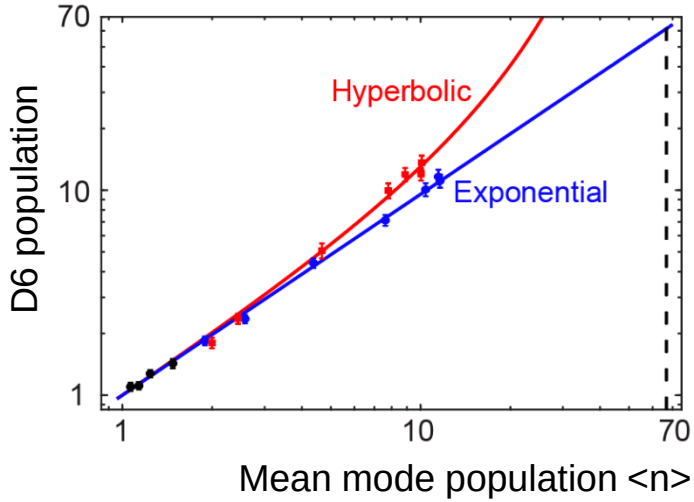
A: rms of C6 pattern amplitude



$\omega \rightarrow \omega/2$ modulation



ω modulation

Conclusion

Bose fireworks – spontaneous emission of matterwaves

- Jet emission from BECs with modulated interactions

  Nature 551, 356 (2017)
  Nature Physics 14, 269 (2018)
- Complex jet structure in the strong coupling regime

  Science 363, 521 (2019)
- Simulation of accelerated vacuum: Unruh effect

  Nature Phyiscs 15, 785 (2019)
- Pattern formation

  ArXiv: 1909.05536

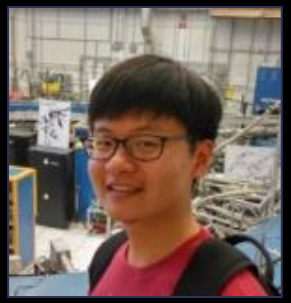
Theory collaboration: (K. Levin, UChicago) *Phys. Rev. Lett.* 121, 243001 (2018)

Group Members

Cs BEC

Q Matter Synthesizer

Li-Cs mixture



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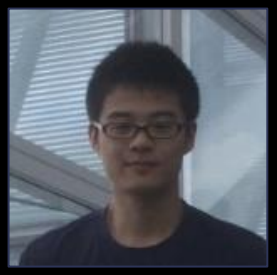

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Lei Feng

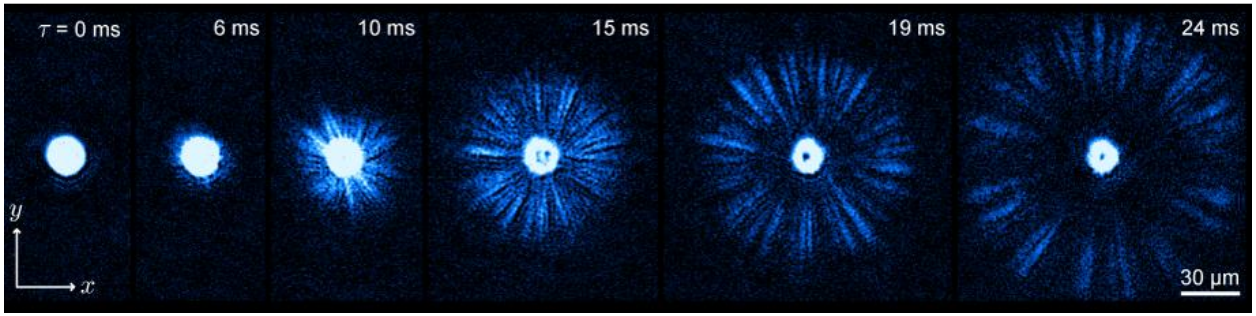
Conclusion

Bose Firework

- Stimulated amplification of quantum fluctuations
- Correlations in jet emission – particle physics
- Quantum nature of jets – Unruh effect

Prospects

- Simulation of other quantum phenomena in curved space time
- Reversal of many-body dynamics?



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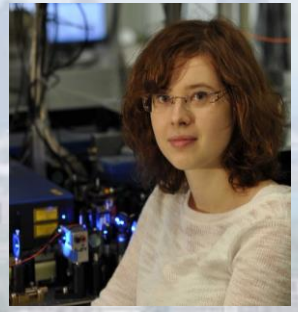

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