

Title: Quantum Crystals of Matter and Light

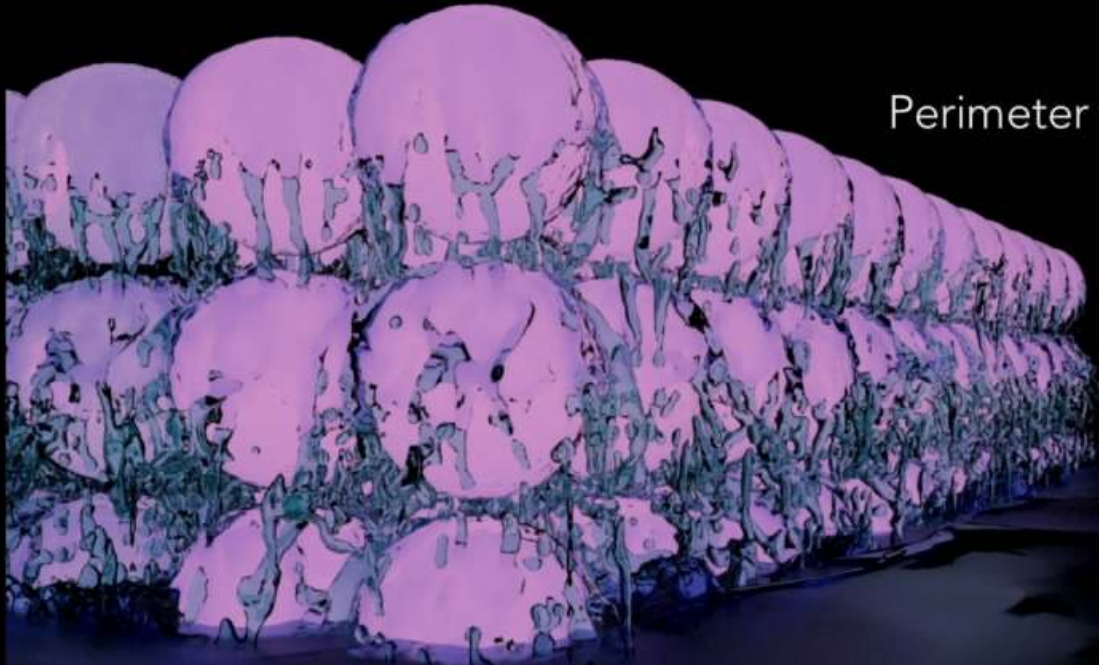
Date: Jun 18, 2018 03:00 PM

URL: <http://pirsa.org/18060033>

Abstract:

# QUANTUM CRYSTALS OF MATTER AND LIGHT

Perimeter Institute, Waterloo  
June 18, 2018



**ETH**

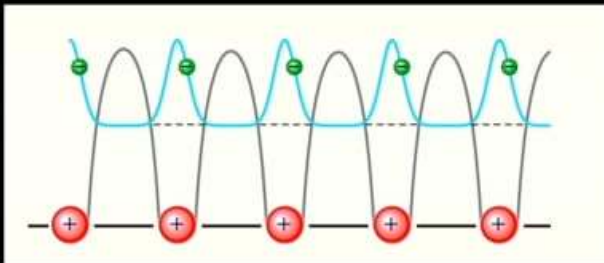


Julian Léonard  
Harvard University/ETH Zürich

# QUANTUM SIMULATIONS WITH ULTRACOLD ATOMS



Electrons moving over background of periodic atoms

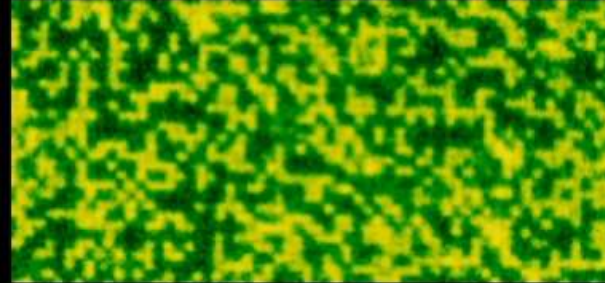


SMALL, FAST

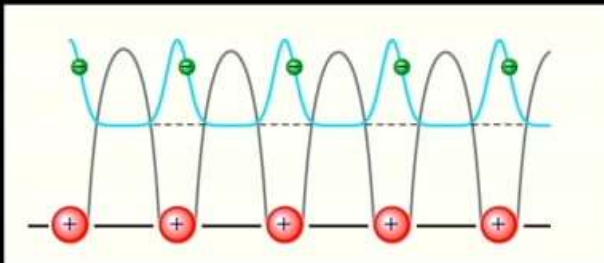
# QUANTUM SIMULATIONS WITH ULTRACOLD ATOMS



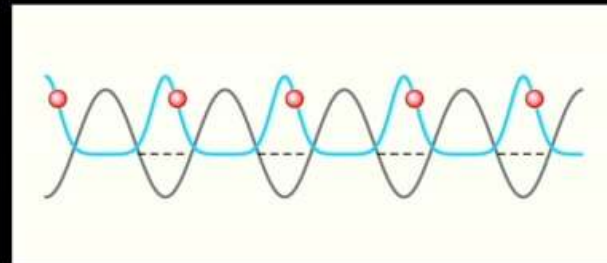
Electrons moving over background of periodic atoms



Atoms moving over background of periodic laser light

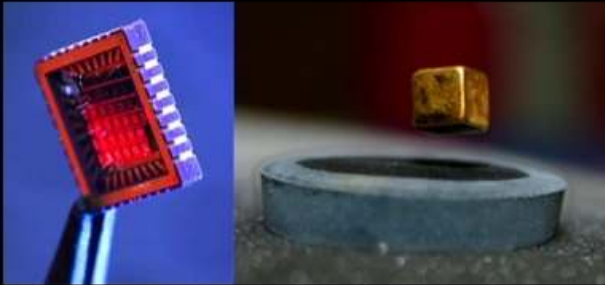


SMALL, FAST

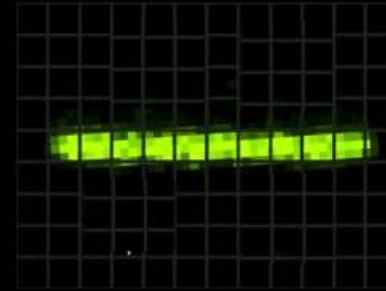


LESS SMALL, LESS FAST

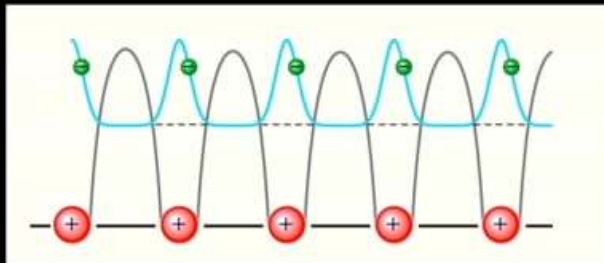
# QUANTUM SIMULATIONS WITH ULTRACOLD ATOMS



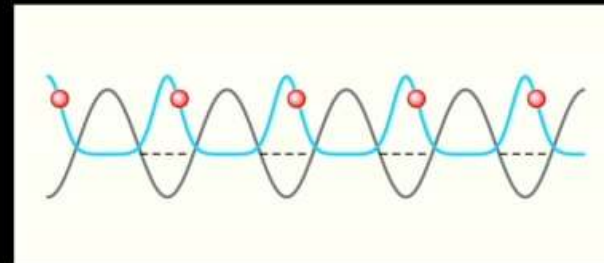
Electrons moving over background of periodic atoms



Atoms moving over background of periodic laser light

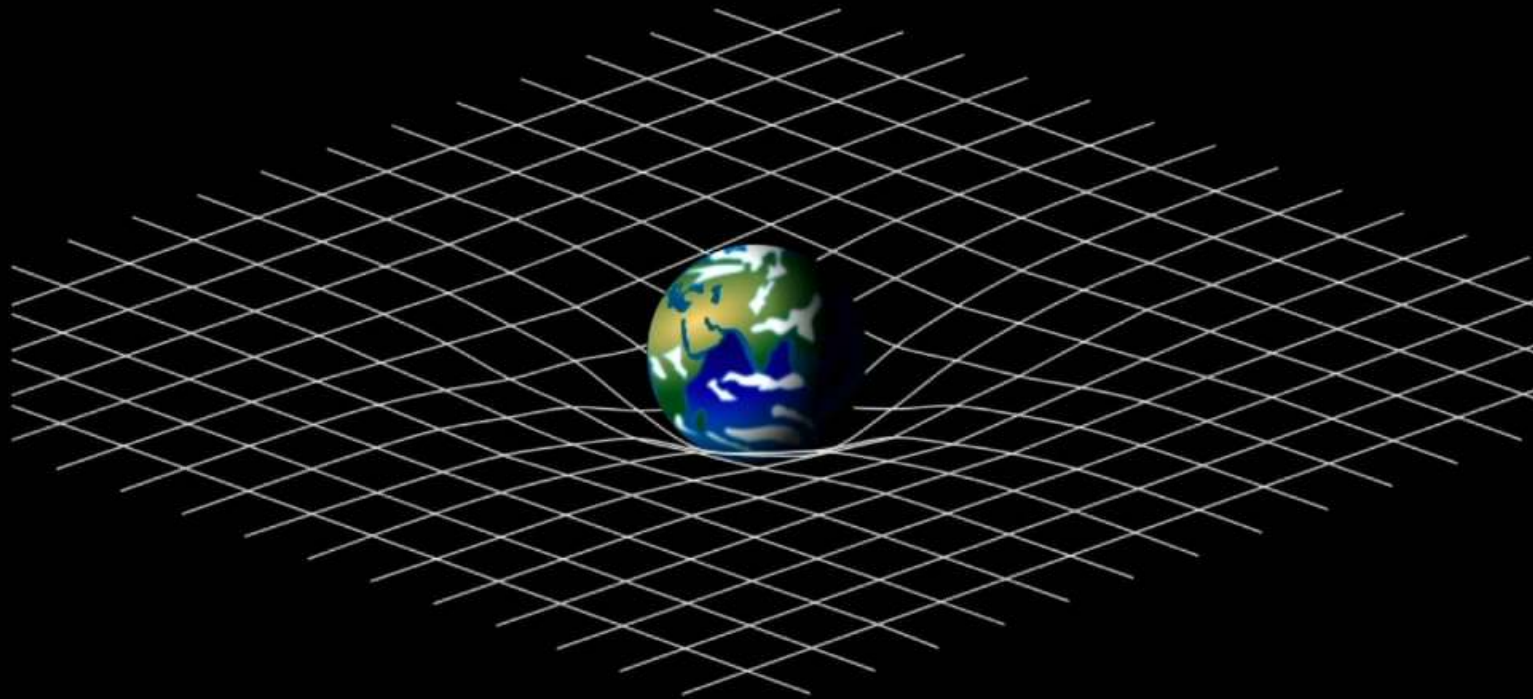


SMALL, FAST

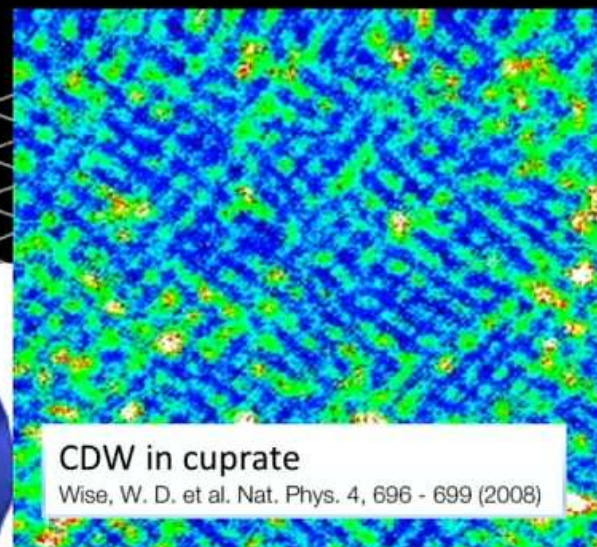
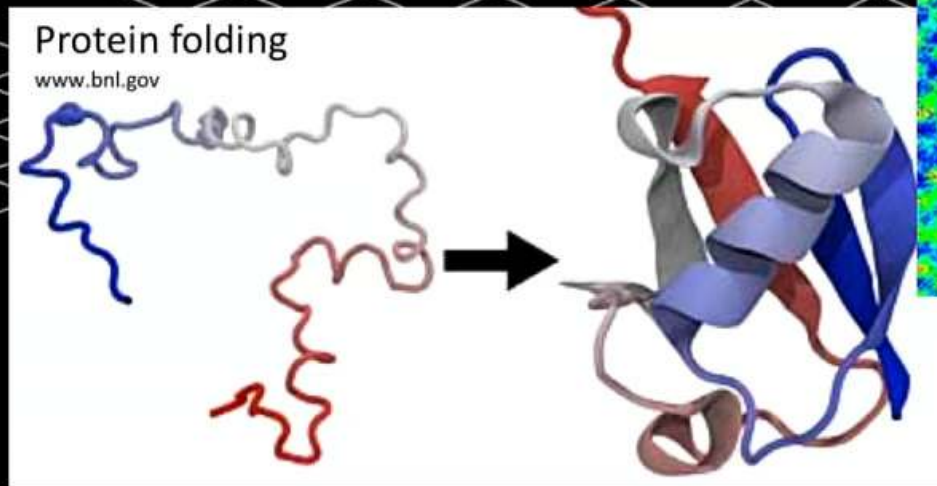


LESS SMALL, LESS FAST

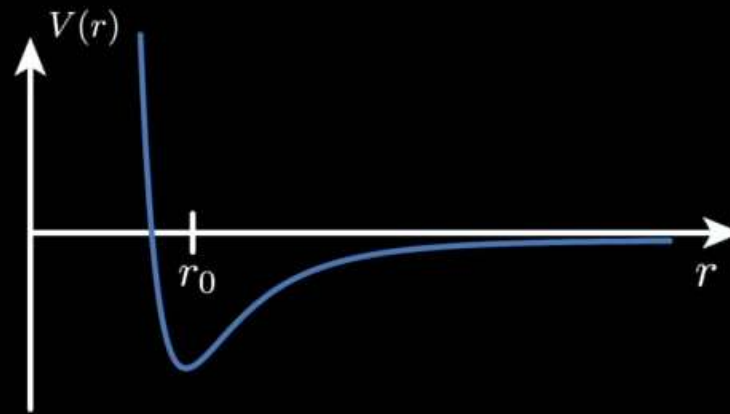
# LONG-RANGE INTERACTIONS



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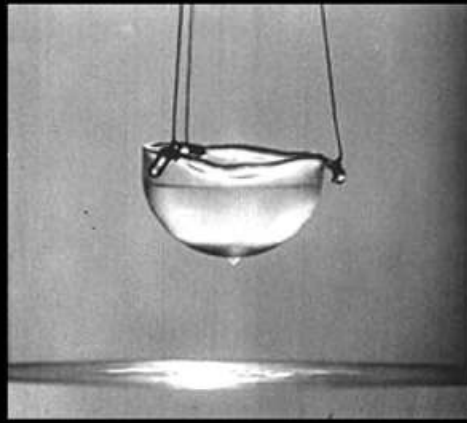
# LONG-RANGE INTERACTIONS



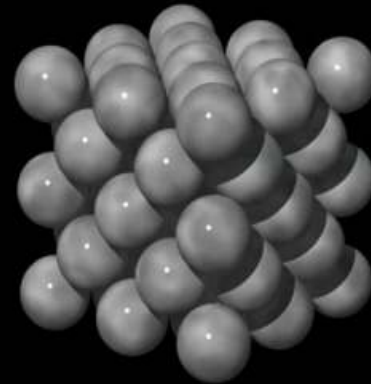
Lennard-Jones-type potential: minimum at distance  $r_0 \sim d$

# QUEST FOR SUPERSOLIDITY

Is structure formation possible in a coherent system?

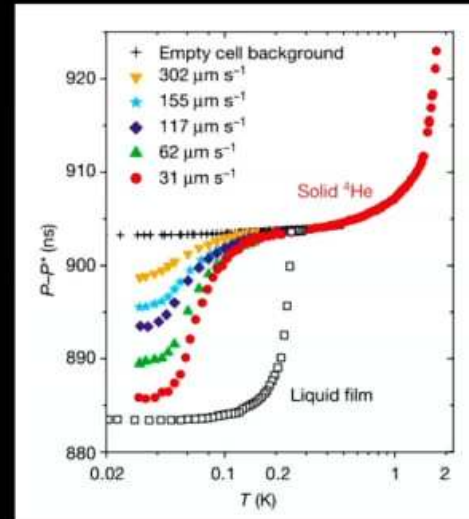
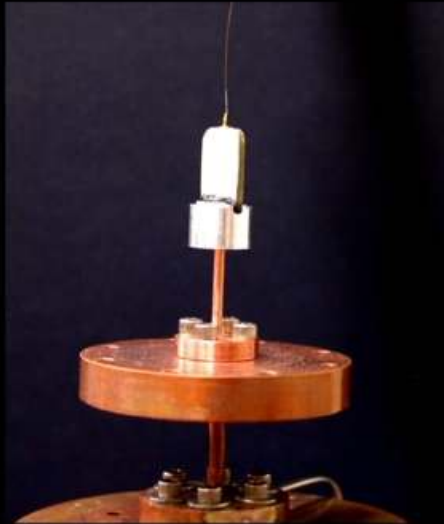


U(1) gauge symmetry



U(1) translational symmetry

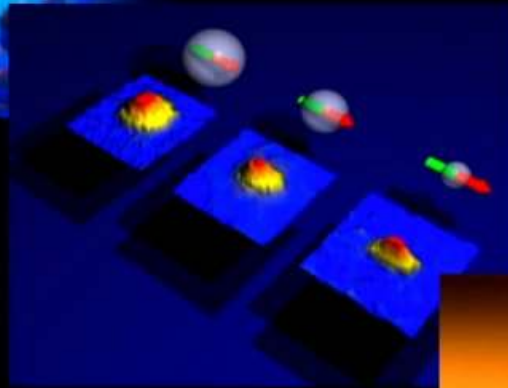
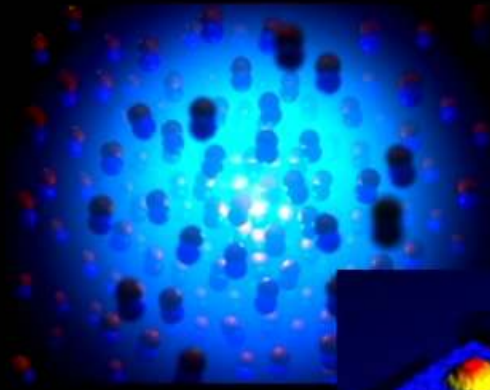
# QUEST FOR SUPERSOLIDITY



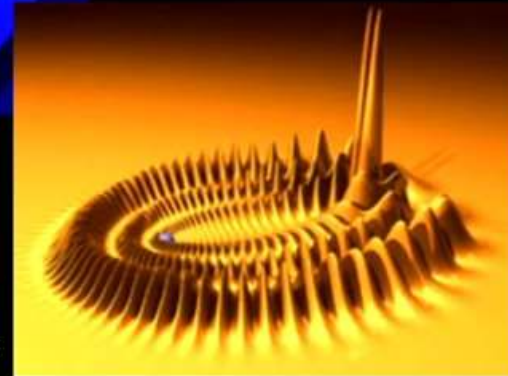
E. Kim and M. H. W. Chan, Nature 427, 225–227 (2004)  
D. Y. Kim and M. H. W. Chan, Phys. Rev. Lett. 109, 155301 (2012)

# LONG-RANGE INTERACTING QUANTUM GASES

Heteronuclear molecules



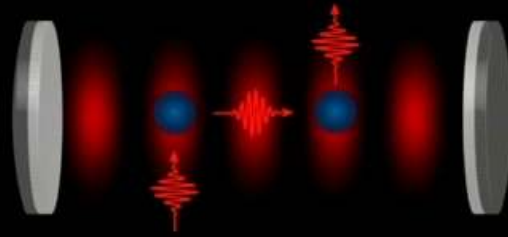
Strong magnetic dipole moments



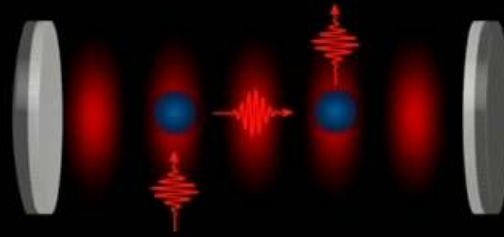
Rydberg atoms

Images: J. Ye, T. Pfau, C. Greene

# LIGHT-INDUCED INTERACTIONS



# LIGHT-INDUCED INTERACTIONS



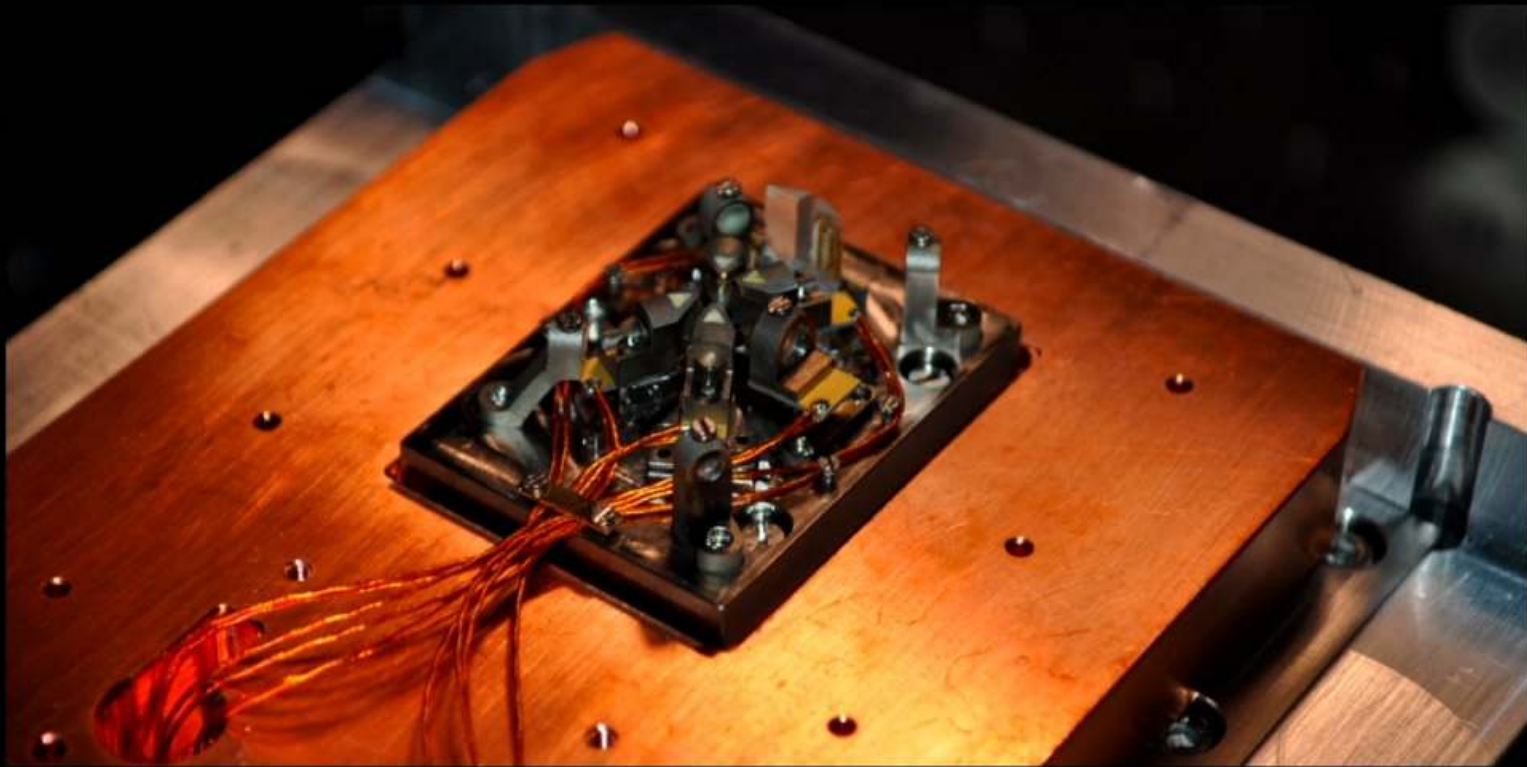
Scale:  
Wavelength

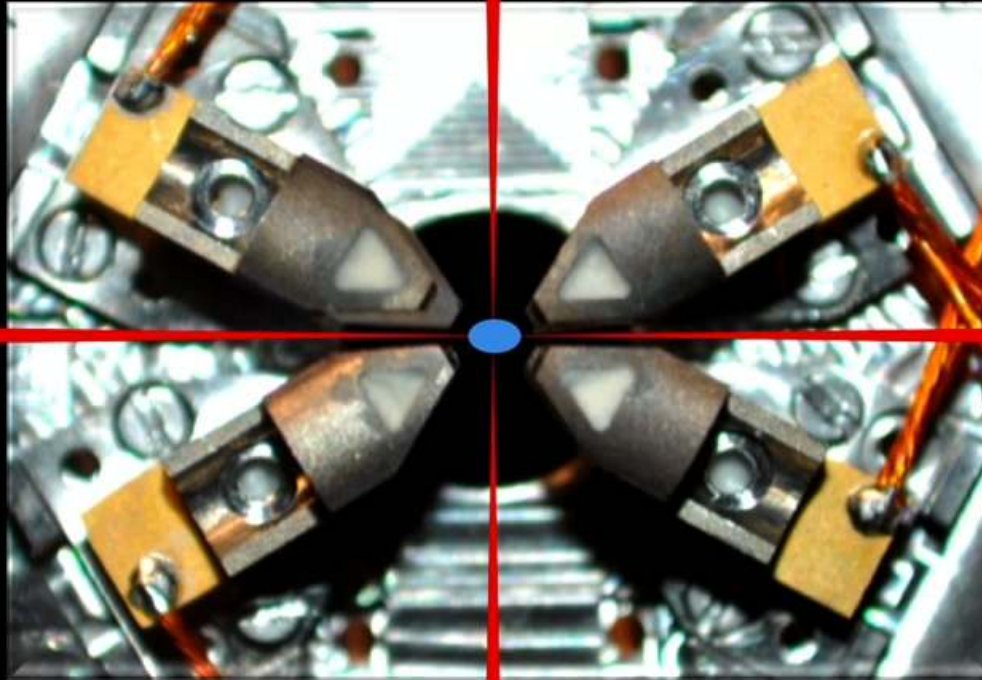


Strength:  
Atom-light coupling



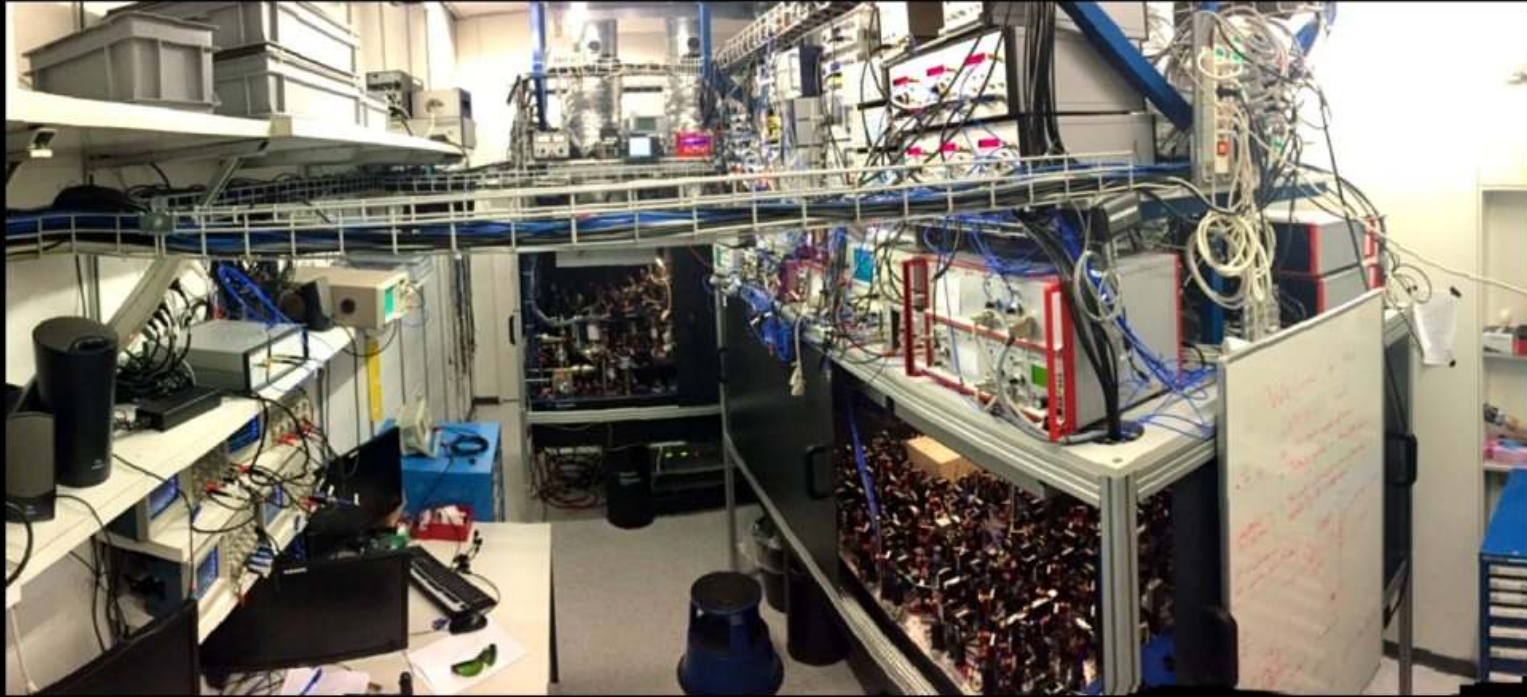
Shape:  
Scattering processes

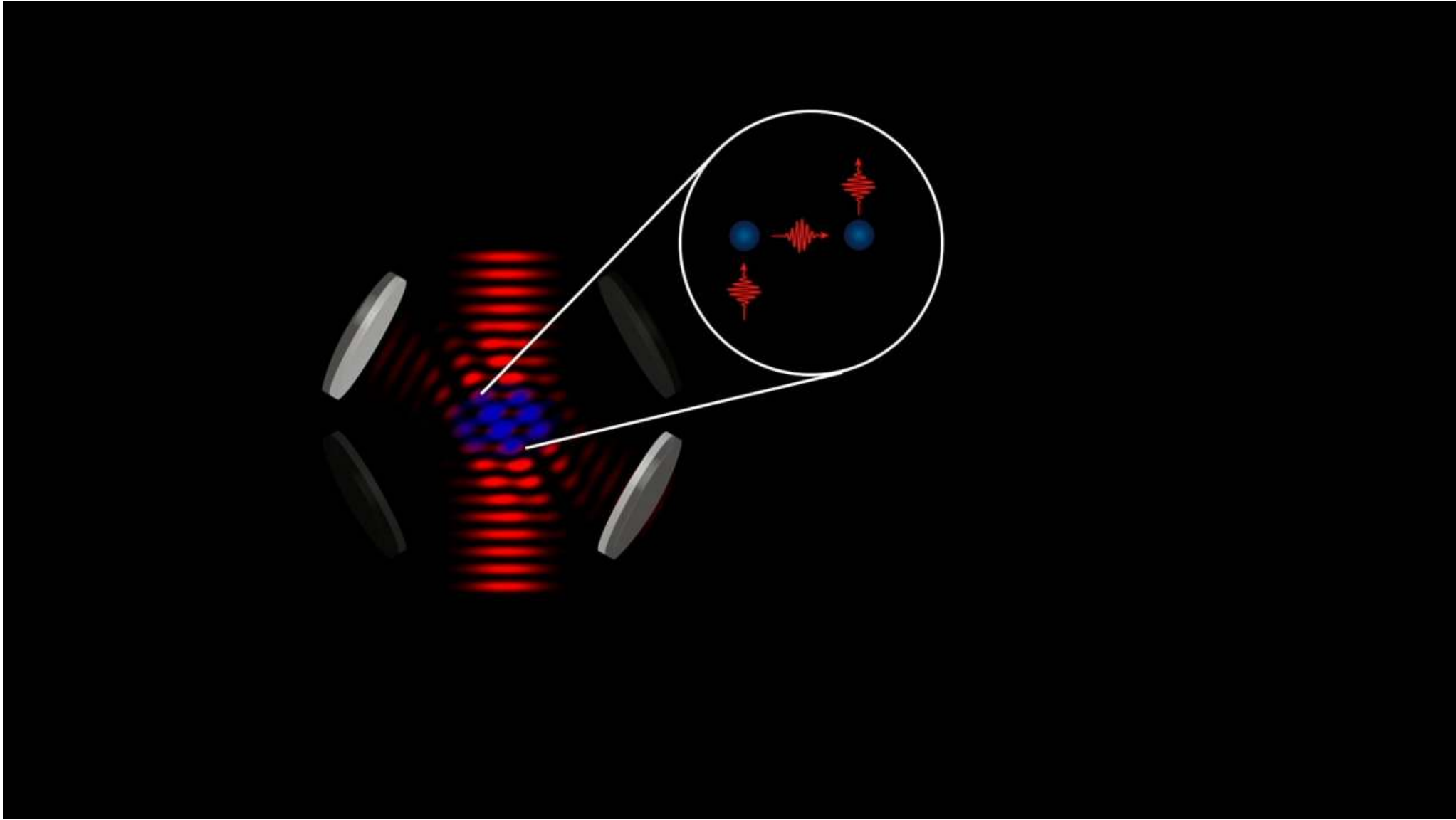


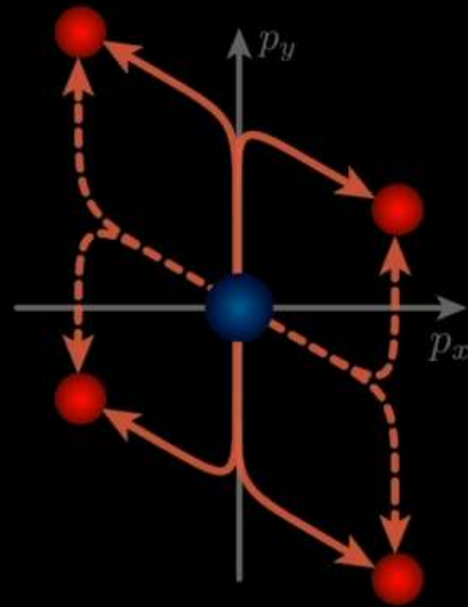
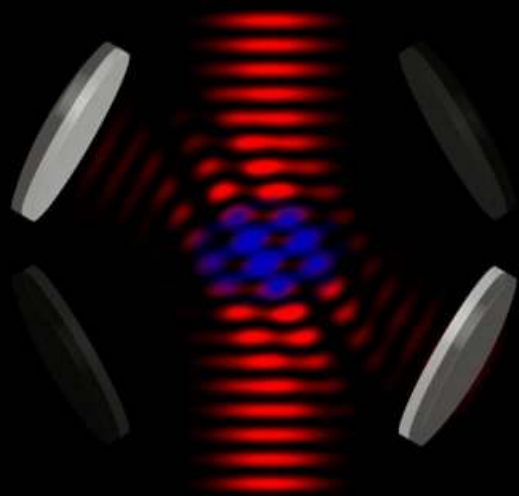


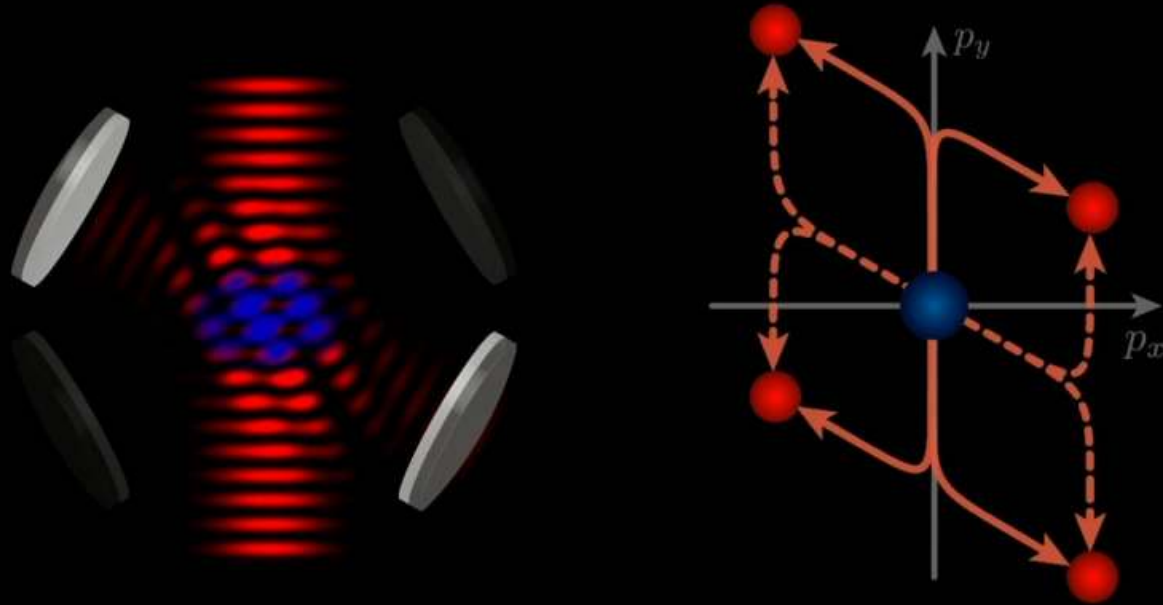
Bose-Einstein condensate  
 $2 \times 10^5$   $^{87}\text{Rb}$  atoms

Atom dynamics:  $\sim\text{kHz}$   
Photon dynamics:  $\sim\text{MHz}$   
Lattice constant:  $\sim\mu\text{m}$   
Cooperativity per atom:  $\sim 10$

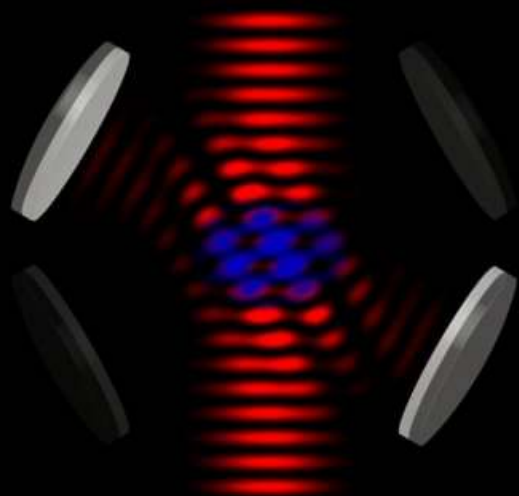








$$\hat{\mathcal{H}}_1/\hbar = \underbrace{-\Delta_1 \hat{a}_1^\dagger \hat{a}_1}_{\text{photon energy}} + \underbrace{\omega_+ \hat{c}_+^\dagger \hat{c}_+ + \omega_- \hat{c}_-^\dagger \hat{c}_-}_{\text{kinetic energy}} + \underbrace{\frac{\lambda}{\sqrt{N}} (\hat{a}_1^\dagger + \hat{a}_1) (\hat{c}_+^\dagger \hat{c}_0 + \hat{c}_-^\dagger \hat{c}_0 + h.c.)}_{\text{atom-cavity coupling}}$$

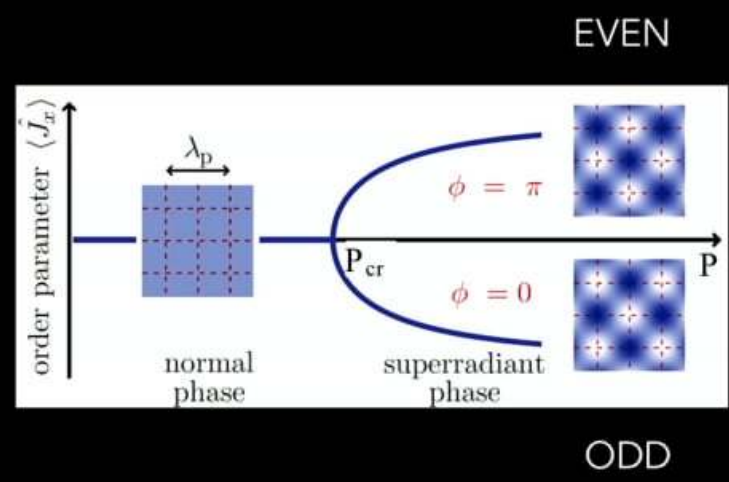
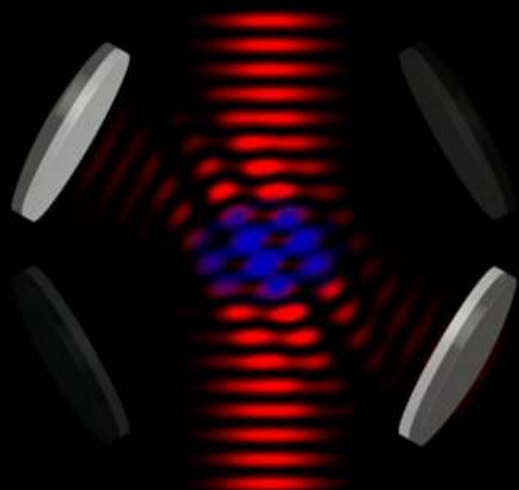


$\mathbb{Z}_2$  -symmetry

$$\hat{a}_1 \rightarrow -\hat{a}_1$$

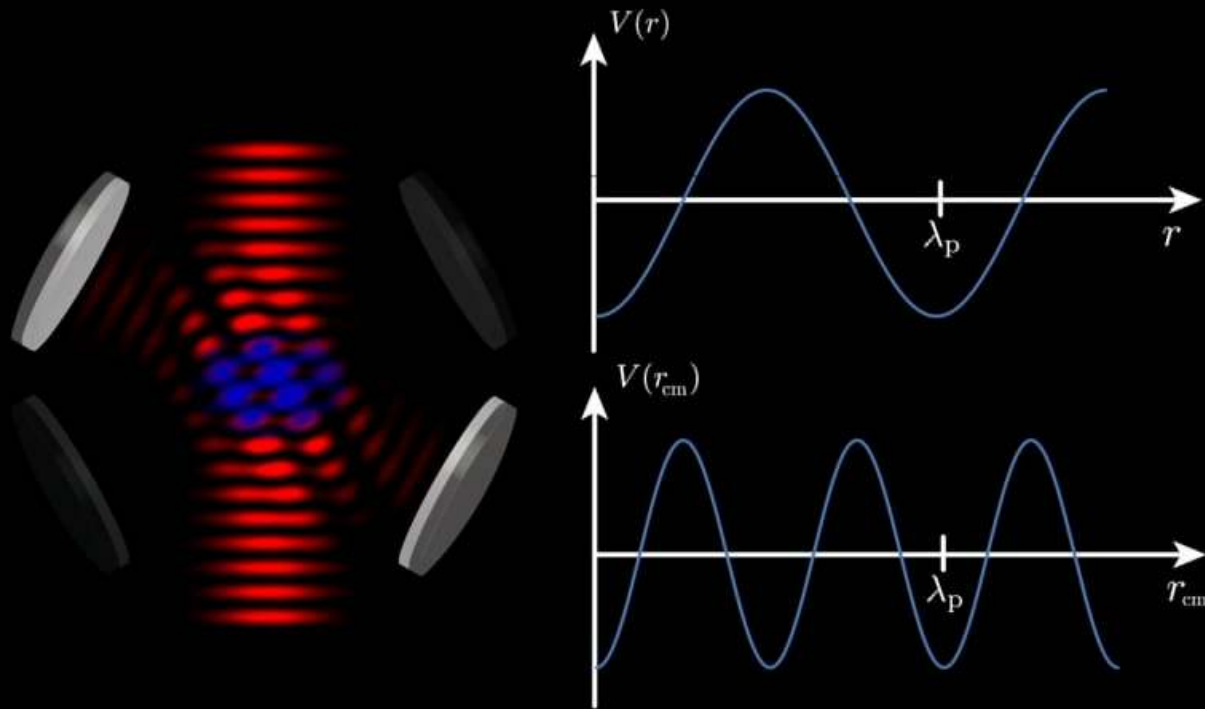
$$\hat{c}_\pm \rightarrow -\hat{c}_\pm$$

$$\hat{\mathcal{H}}_1/\hbar = \underbrace{-\Delta_1 \hat{a}_1^\dagger \hat{a}_1}_{\text{photon energy}} + \underbrace{\omega_+ \hat{c}_+^\dagger \hat{c}_+ + \omega_- \hat{c}_-^\dagger \hat{c}_-}_{\text{kinetic energy}} + \underbrace{\frac{\lambda}{\sqrt{N}} (\hat{a}_1^\dagger + \hat{a}_1) (\hat{c}_+^\dagger \hat{c}_0 + \hat{c}_-^\dagger \hat{c}_0 + h.c.)}_{\text{atom-cavity coupling}}$$



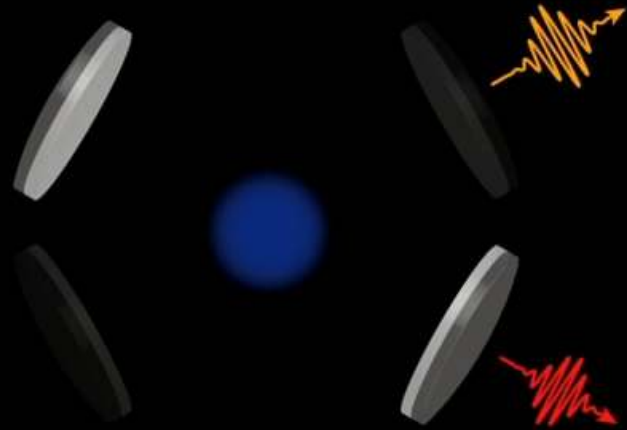
$$\hat{\mathcal{H}}_1/\hbar = \underbrace{-\Delta_1 \hat{a}_1^\dagger \hat{a}_1}_{\text{photon energy}} + \underbrace{\omega_+ \hat{c}_+^\dagger \hat{c}_+ + \omega_- \hat{c}_-^\dagger \hat{c}_-}_{\text{kinetic energy}} + \underbrace{\frac{\lambda}{\sqrt{N}} (\hat{a}_1^\dagger + \hat{a}_1) (\hat{c}_+^\dagger \hat{c}_0 + \hat{c}_-^\dagger \hat{c}_0 + h.c.)}_{\text{atom-cavity coupling}}$$

# LIGHT-INDUCED INTERACTIONS



Discrete symmetry + phase coherence  $\rightarrow$  *lattice supersolid*

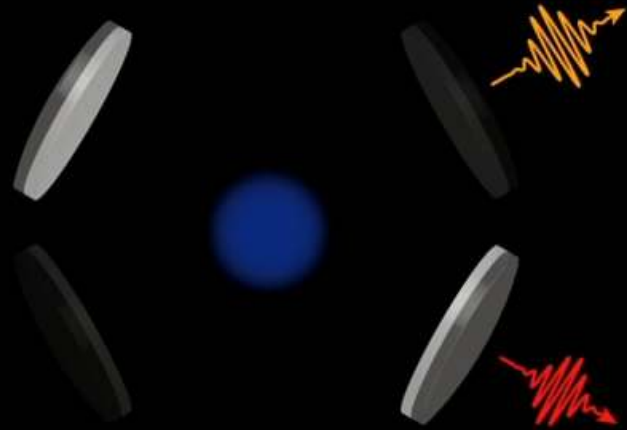
# DISCRETE TRANSLATIONAL SYMMETRY BREAKING



Leaking cavity photons  
→ intracavity photon number

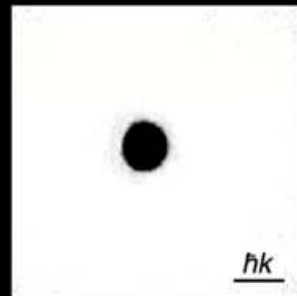
$$\bar{n} = |\alpha|^2$$

# DISCRETE TRANSLATIONAL SYMMETRY BREAKING



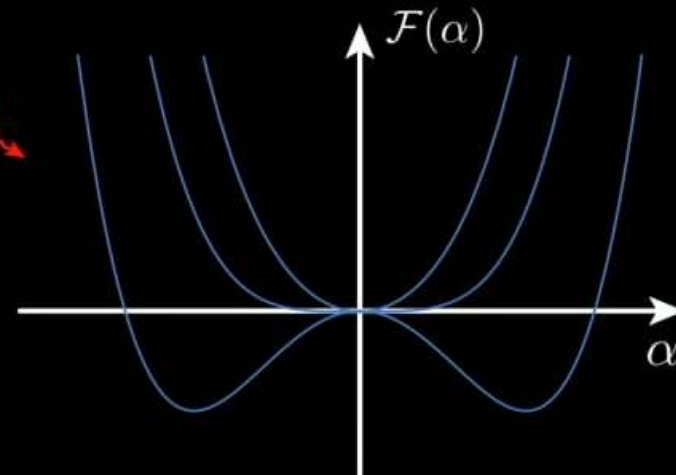
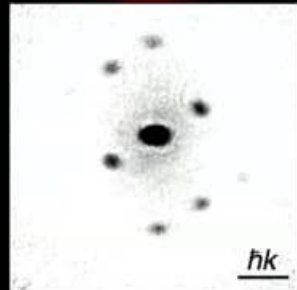
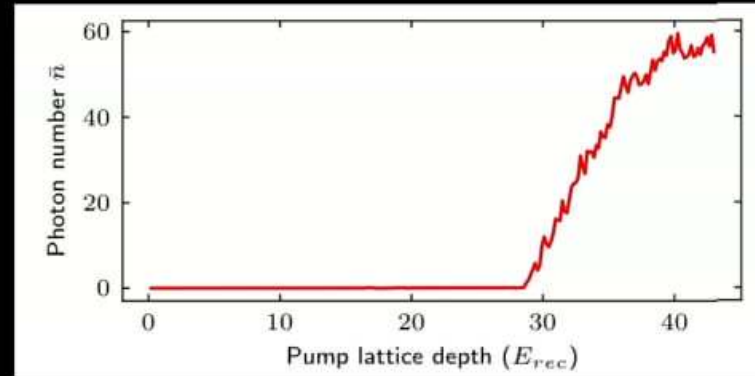
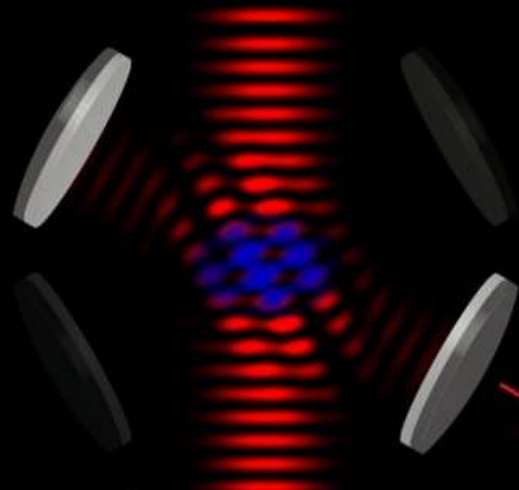
Leaking cavity photons  
→ intracavity photon number

$$\bar{n} = |\alpha|^2$$



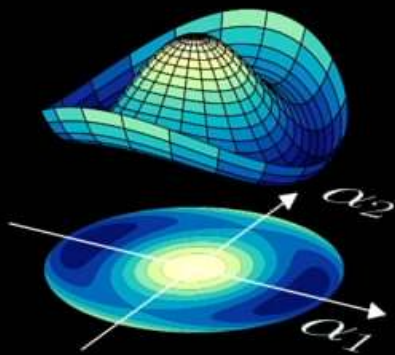
Absorption imaging  
after ballistic expansion  
→ momentum distribution

# DISCRETE TRANSLATIONAL SYMMETRY BREAKING

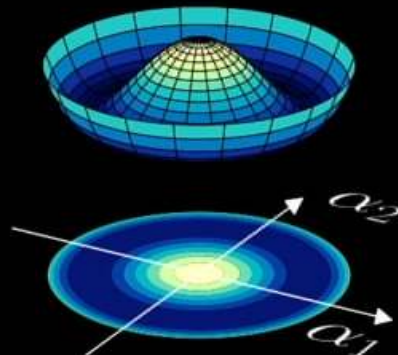


# OUTLINE

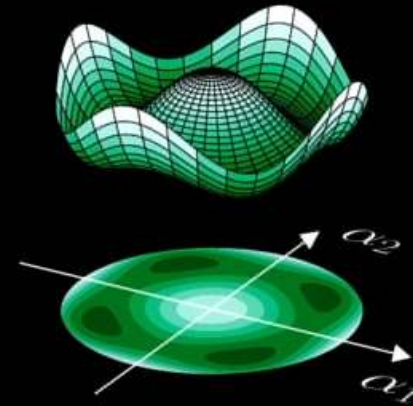
Lattice  
supersolid

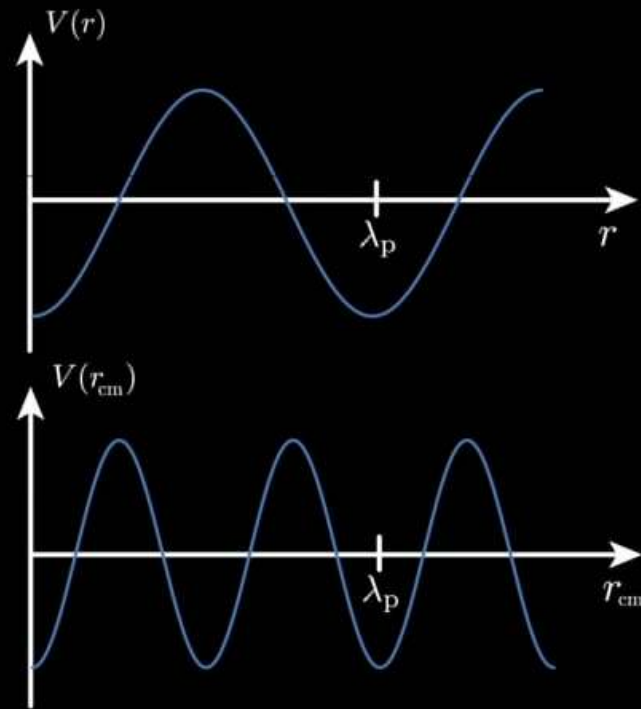
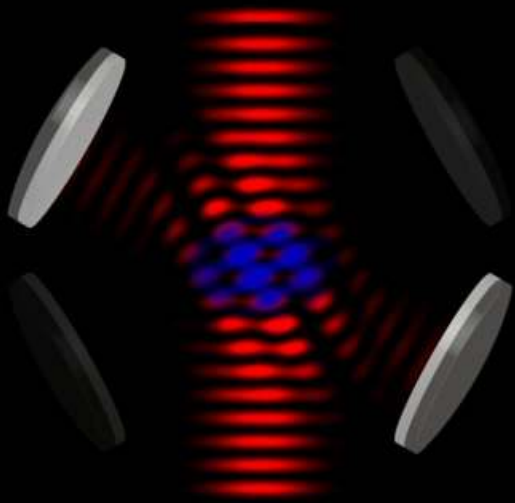


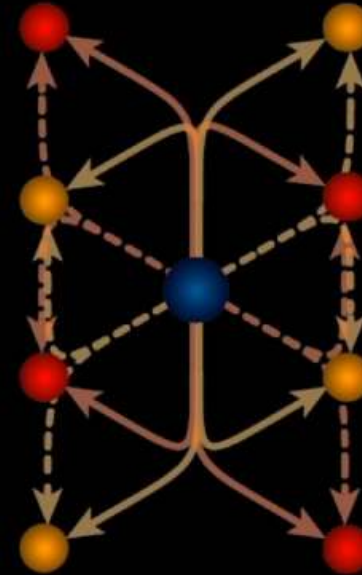
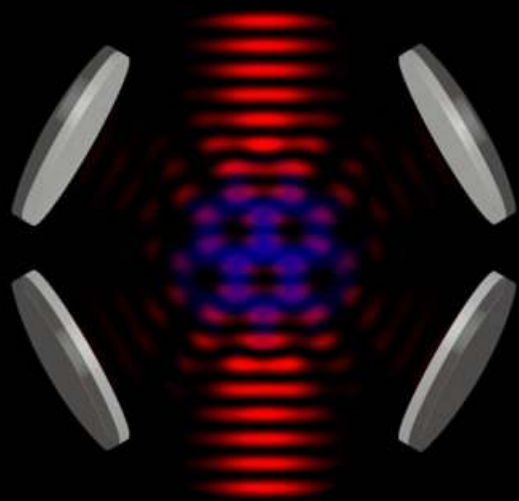
$U(1)$ -supersolid



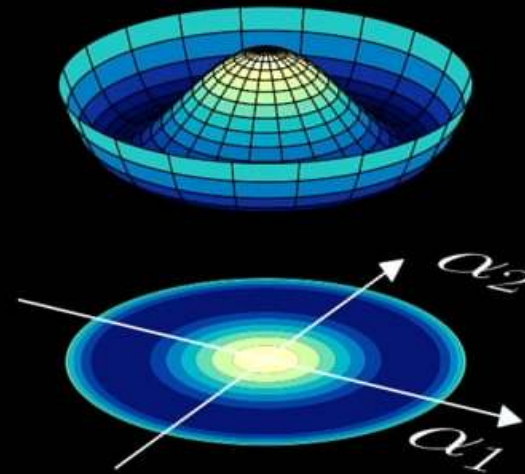
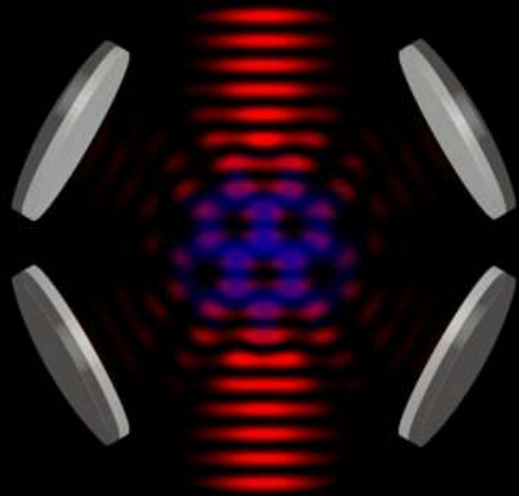
Intertwined  
order







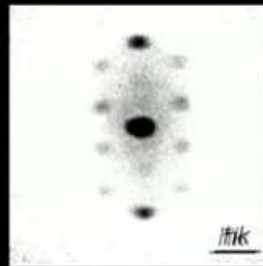
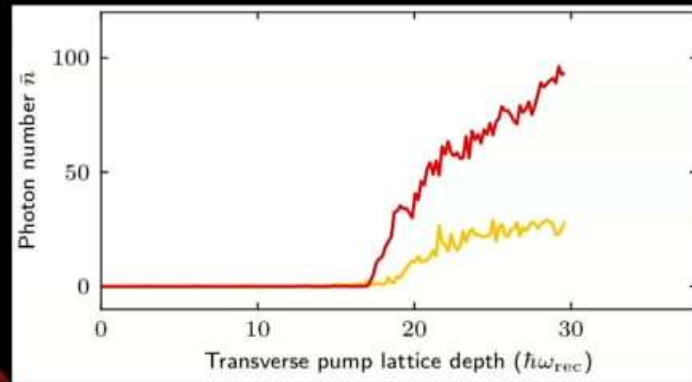
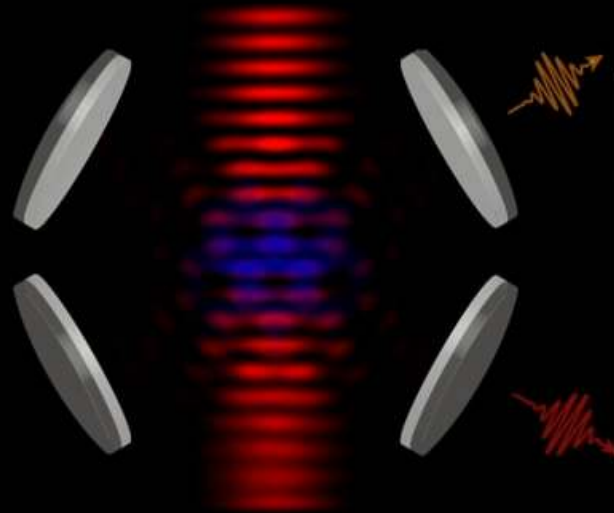
$$\hat{\mathcal{H}}/\hbar = (\hat{\mathcal{H}}_1 + \hat{\mathcal{H}}_2)/\hbar = \sum_{i \in \{1,2\}} \left[ -\Delta_i \hat{a}_i^\dagger \hat{a}_i + \omega_+ \hat{c}_{i+}^\dagger \hat{c}_{i+} + \omega_- \hat{c}_{i-}^\dagger \hat{c}_{i-} \right. \\ \left. + \frac{\lambda}{\sqrt{N}} (\hat{a}_i^\dagger + \hat{a}_i) (\hat{c}_{i+}^\dagger \hat{c}_0 + \hat{c}_{i-}^\dagger \hat{c}_0 + h.c.) \right]$$

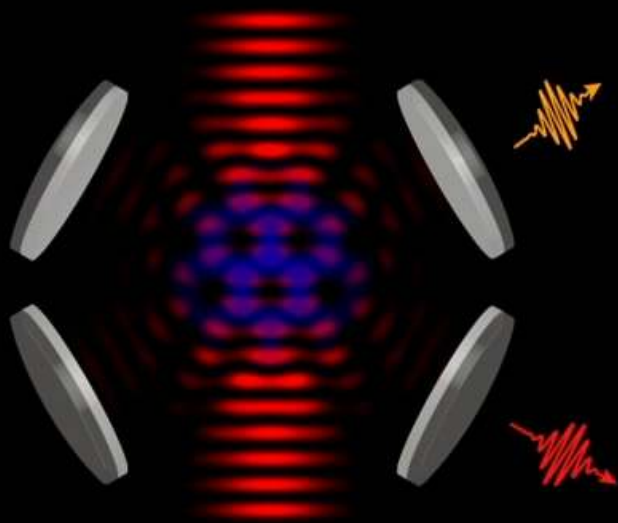


$$F = F(\alpha_1, \alpha_2) = r_1 \alpha_1^2 + r_2 \alpha_2^2 + g(\alpha_1^2 + \alpha_2^2)^2$$

$U(1)$  symmetry for  $r_1 = r_2$  ( $\Delta_1 = \Delta_2$ )

# CONTINUOUS TRANSLATIONAL SYMMETRY BREAKING

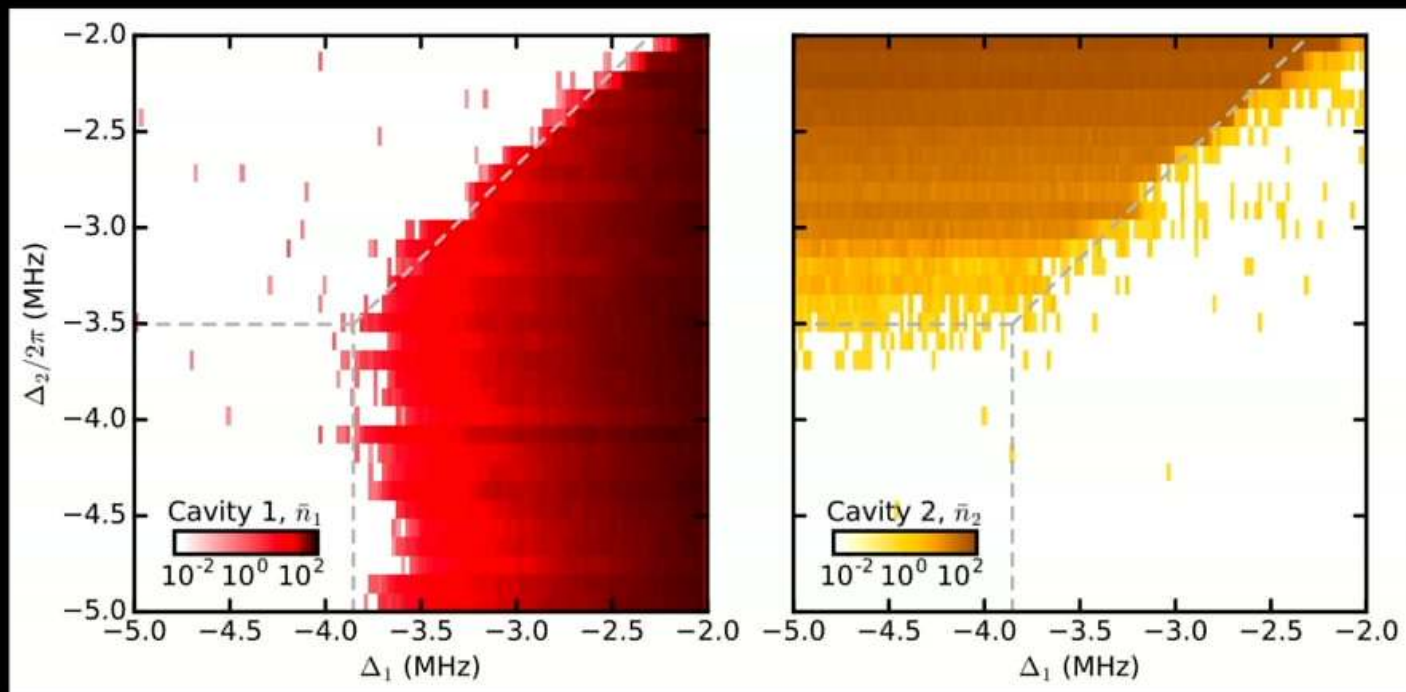




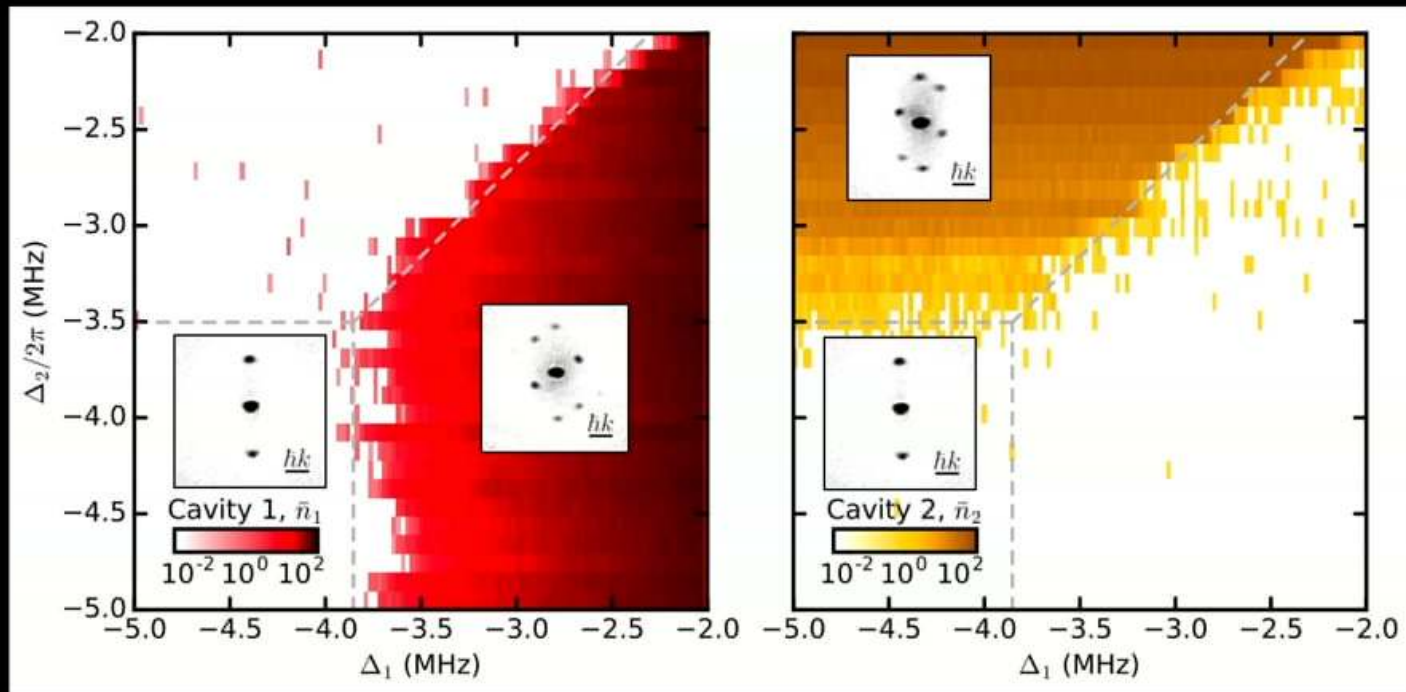
What happens for  
asymmetric coupling?

$$\Delta_1 \neq \Delta_2$$

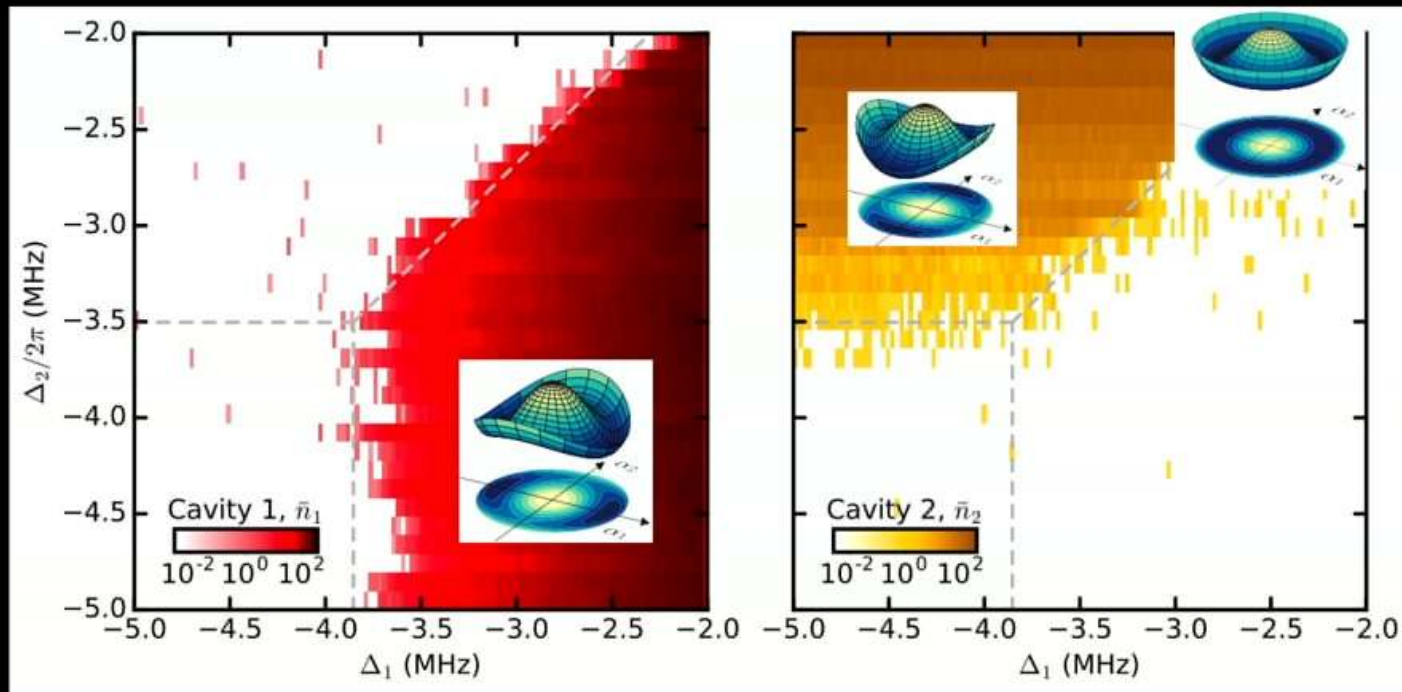
# TWO COMPETING ORDERS



# TWO COMPETING ORDERS

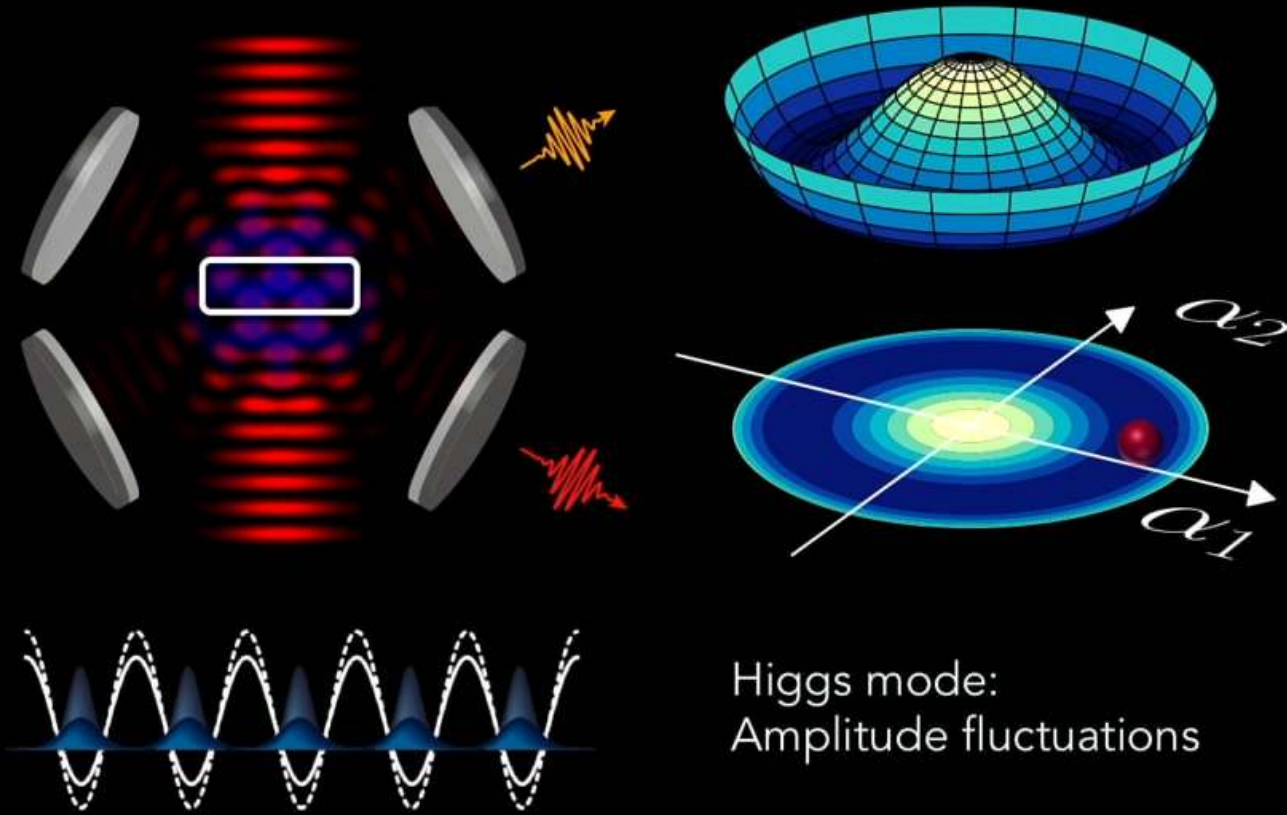


# TWO COMPETING ORDERS



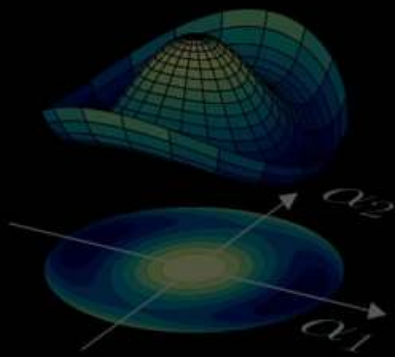
$$F = F(\alpha_1, \alpha_2) = r_1 \alpha_1^2 + r_2 \alpha_2^2 + g(\alpha_1^2 + \alpha_2^2)^2$$

# HIGGS AND GOLDSTONE MODES

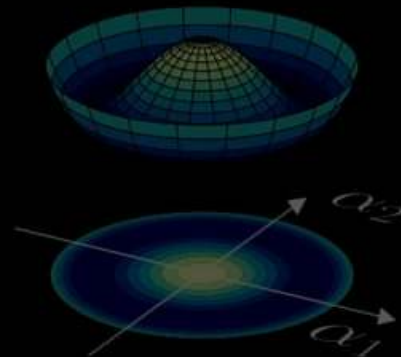


# OUTLINE

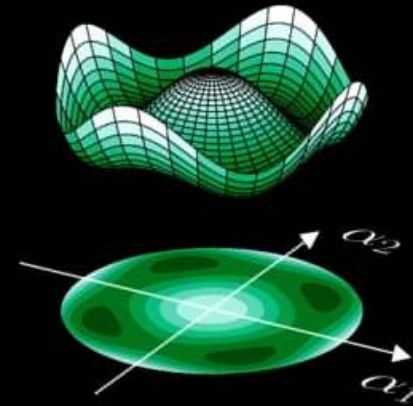
Lattice  
supersolid



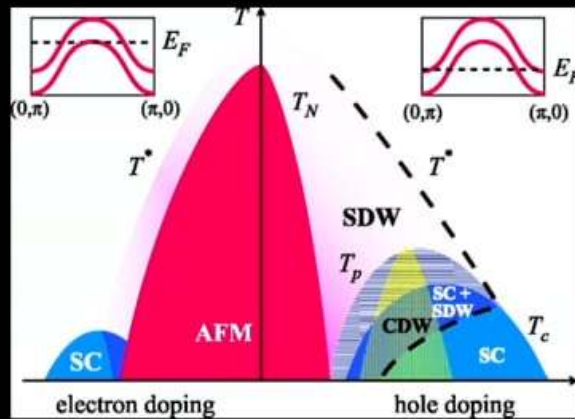
$U(1)$ -supersolid



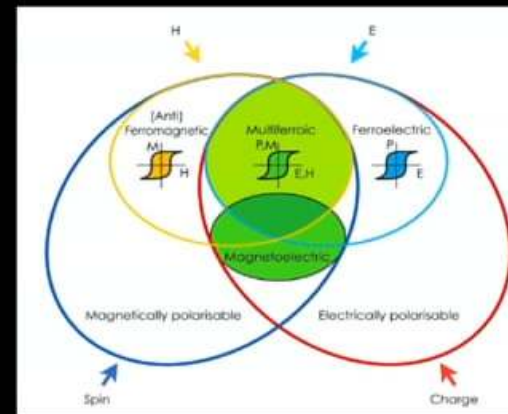
Intertwined  
order



# MULTIPLE ORDERS



High-temperature superconductors:  
Spin and charge order

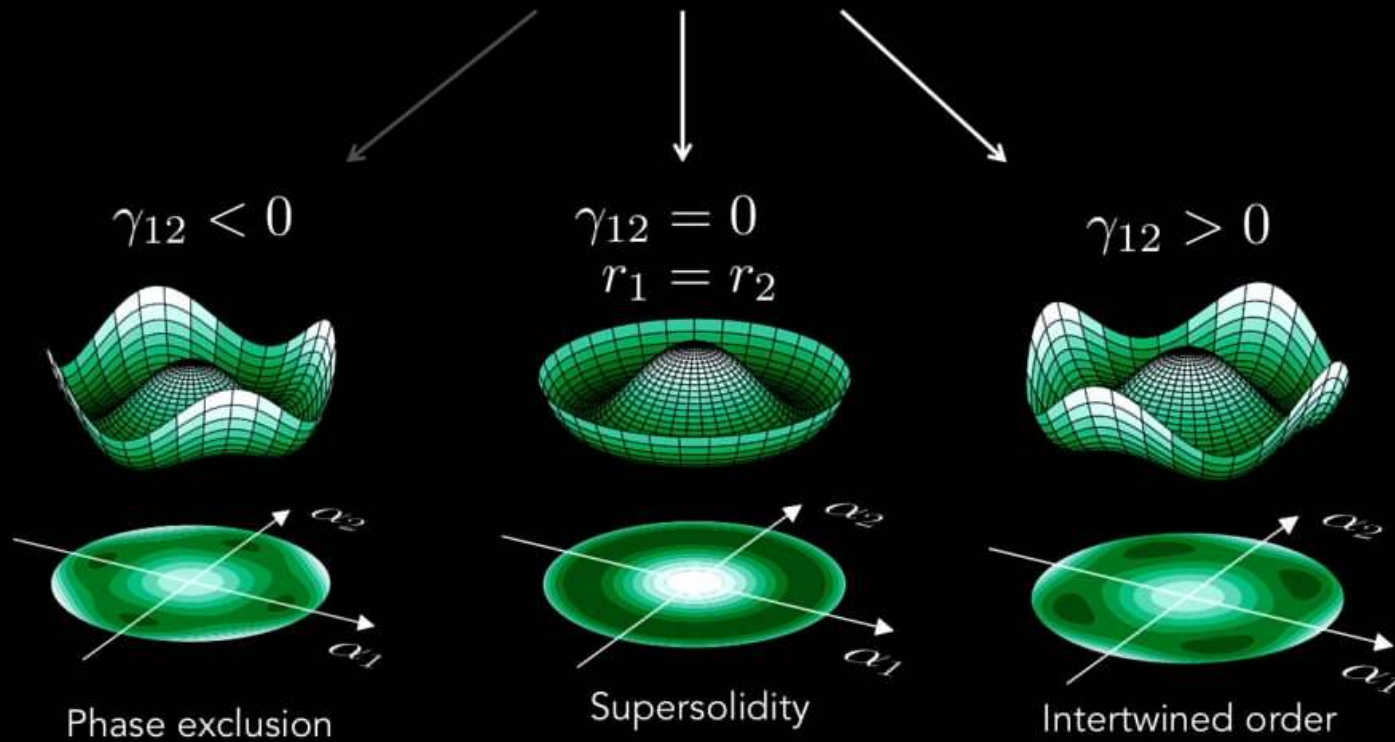


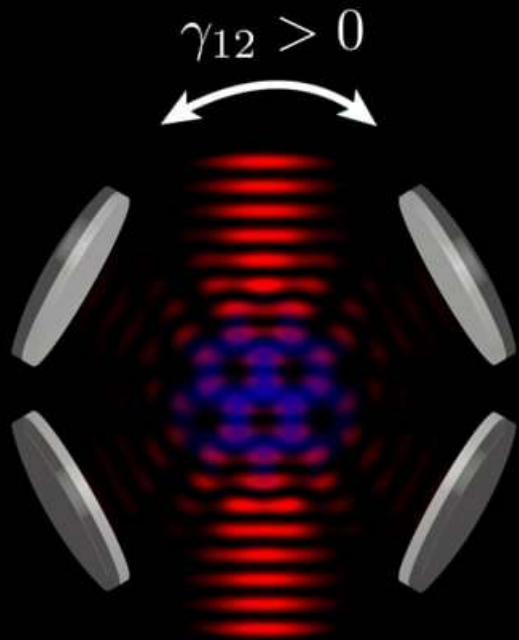
Multi-ferroics systems:  
Ferromagnetism and ferroelectricity

.....

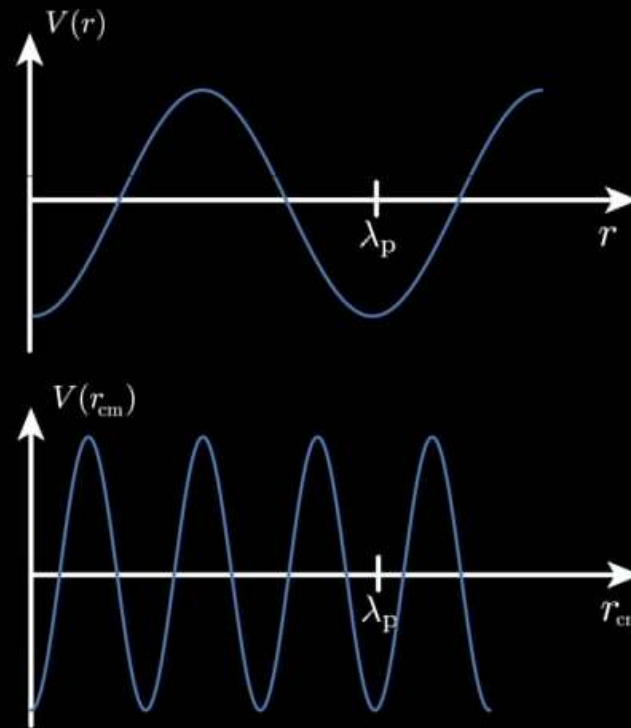
# COUPLED ORDERS

$$F = r_1\alpha_1^2 + r_2\alpha_2^2 + g(\alpha_1^2 + \alpha_2^2)^2 - \gamma_{12}\alpha_1^2\alpha_2^2 + \dots$$



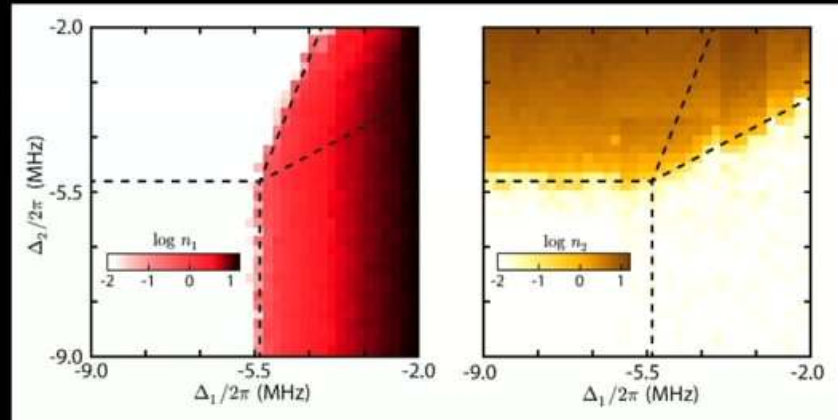
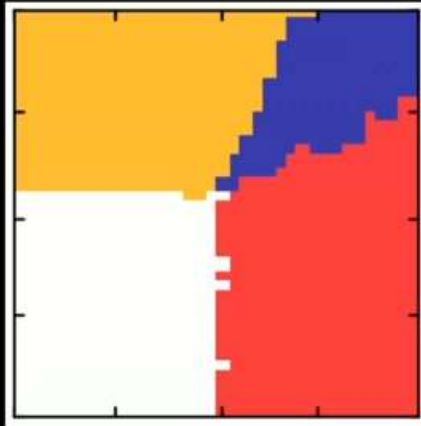


Intercavity scattering



# INTERTWINED ORDER

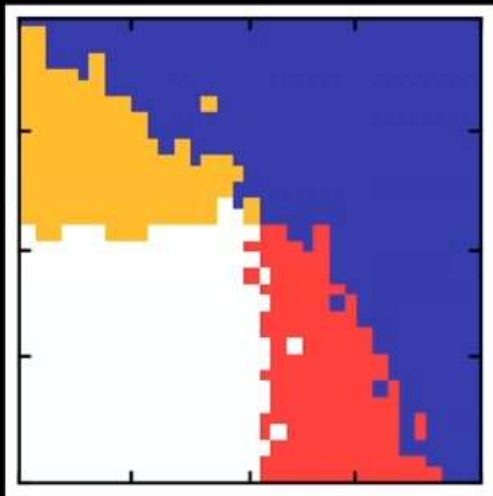
$$\Delta_A = 1\text{THz}$$



$$F = r_1\alpha_1^2 + r_2\alpha_2^2 + g(\alpha_1^2 + \alpha_2^2)^2 - \gamma_{12}\alpha_1^2\alpha_2^2 + \dots$$

# INTERTWINED ORDER

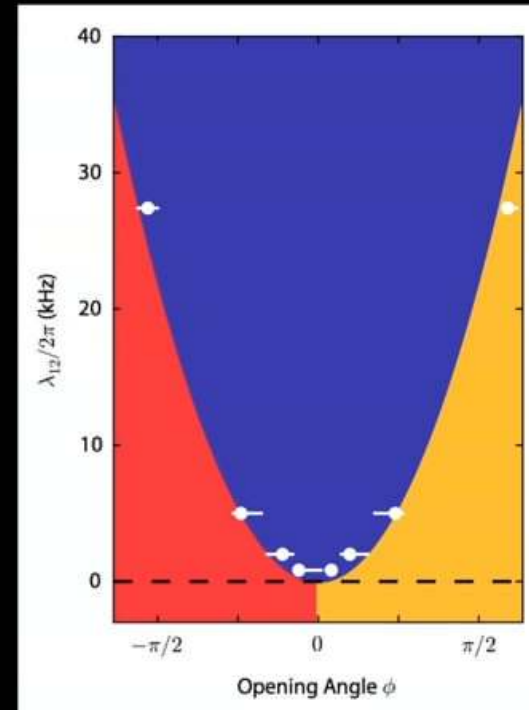
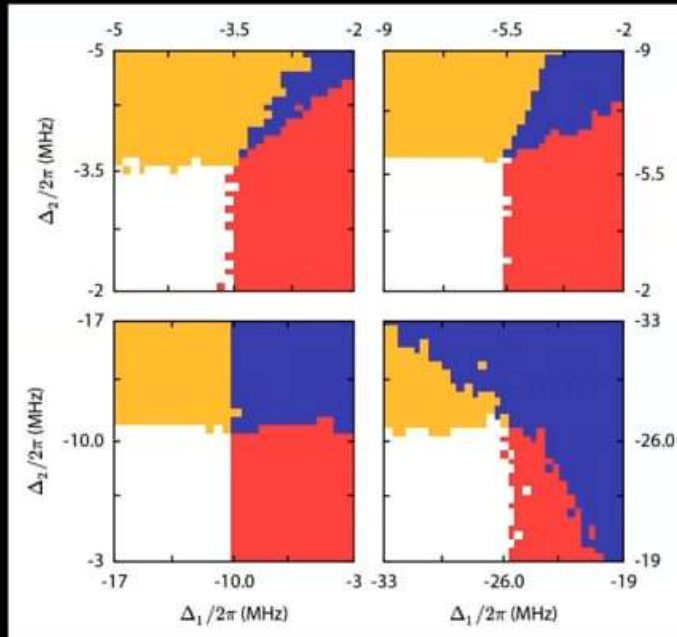
$$\Delta_A = 73\text{GHz}$$



One order parameter reduces the critical point of the other one!

$$F = r_1\alpha_1^2 + r_2\alpha_2^2 + g(\alpha_1^2 + \alpha_2^2)^2 - \gamma_{12}\alpha_1^2\alpha_2^2 + \dots$$

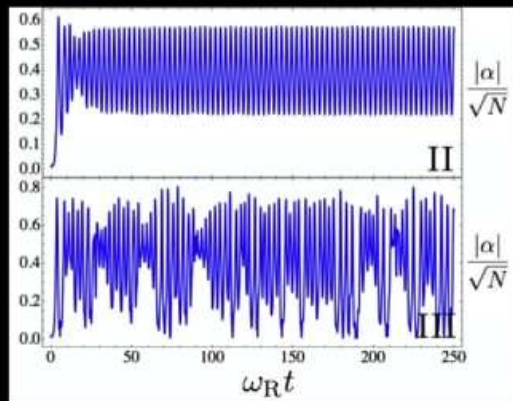
# INTERTWINED ORDER



$$F = r_1\alpha_1^2 + r_2\alpha_2^2 + g(\alpha_1^2 + \alpha_2^2)^2 - \gamma_{12}\alpha_1^2\alpha_2^2 + \dots$$

# OUTLOOK

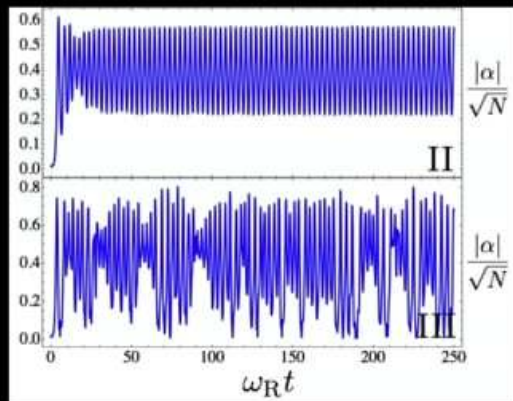
## Chaotic behaviour



F. Piazza, H. Ritsch,  
PRL 115, 163601 (2015)

# OUTLOOK

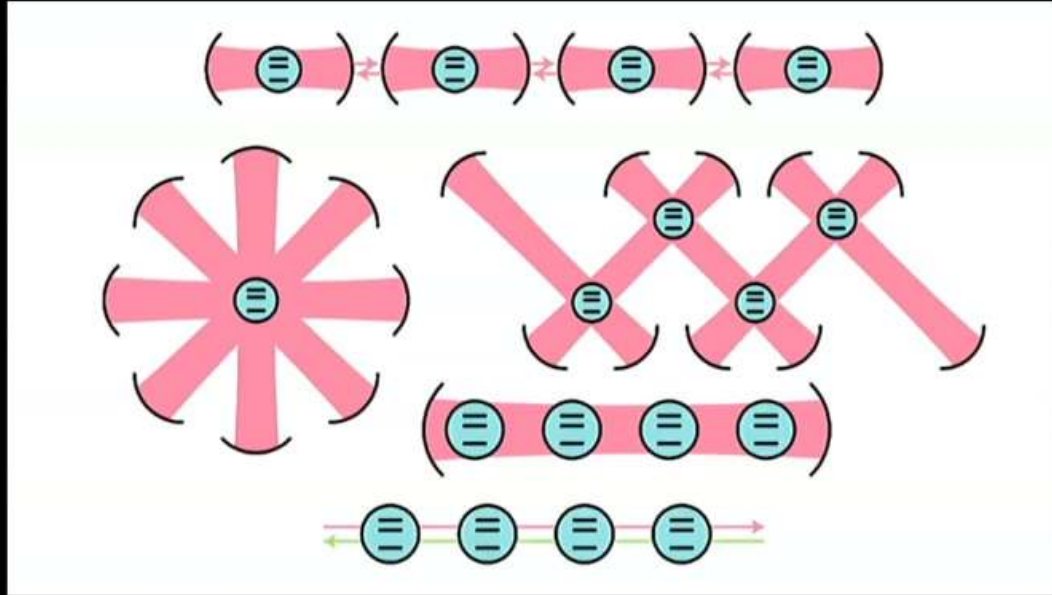
Chaotic behaviour

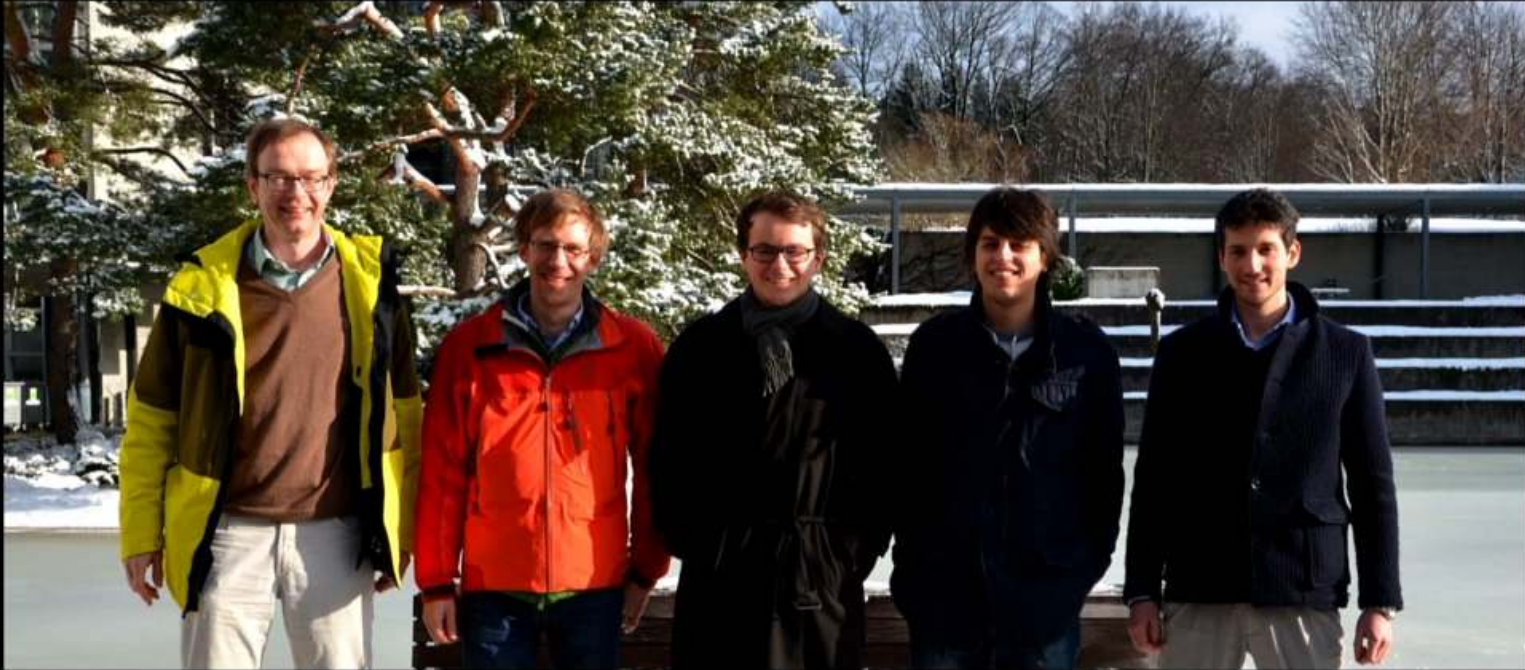


F. Piazza, H. Ritsch,  
PRL 115, 163601 (2015)

Quantum gas microscopy with cavities







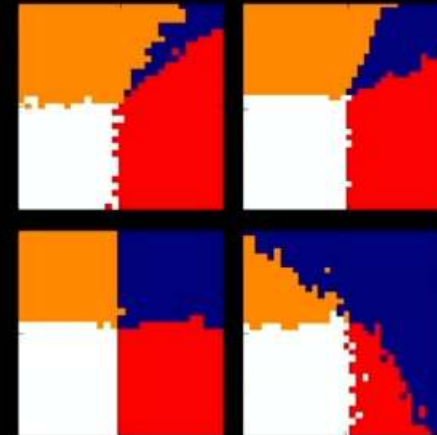
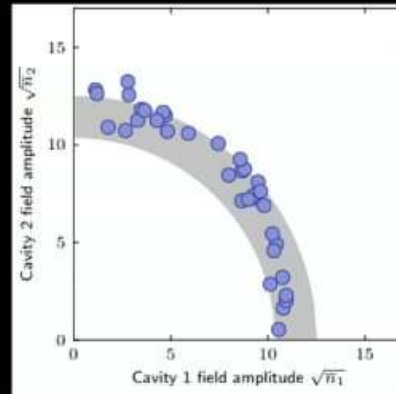
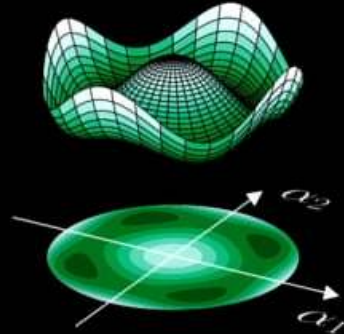
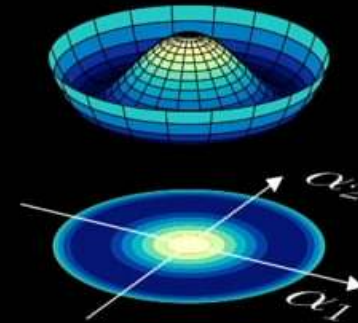
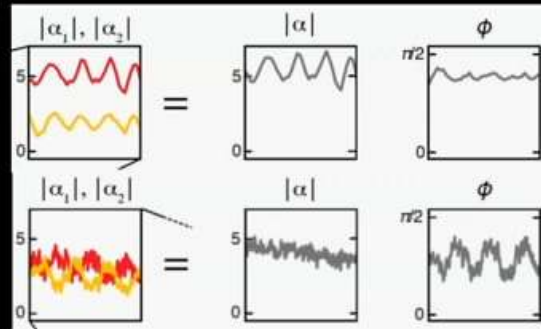
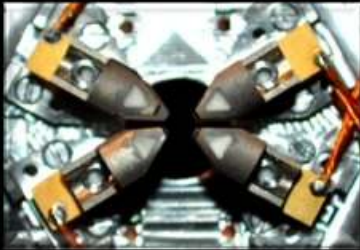
Tilman  
Esslinger

Tobias  
Donner

Philip  
Zupancic

J. L.

Andrea  
Morales



Supersolid:  
Higgs + Goldstone:  
Intertwined order:

J. Léonard et al., *Nature* 543, 87 (2017)  
J. Léonard et al., *Science* 358, 1415 (2017)  
A. Morales et al., *Nat. Materials* (in press)