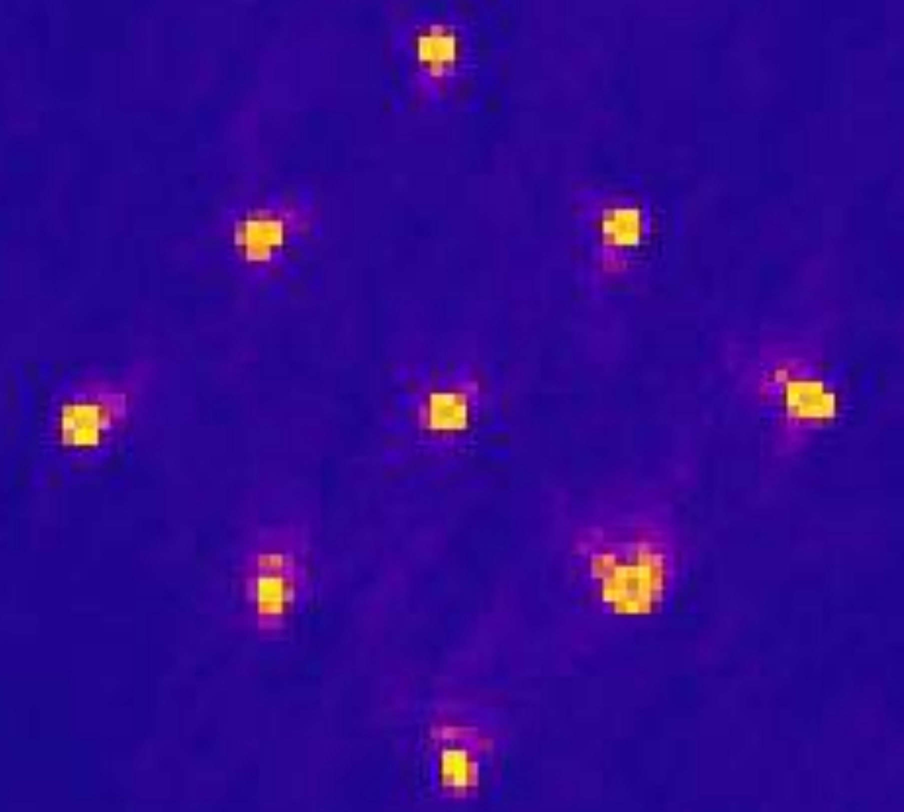
Collective optomechanics with optically trapped atoms and silica nanoparticles

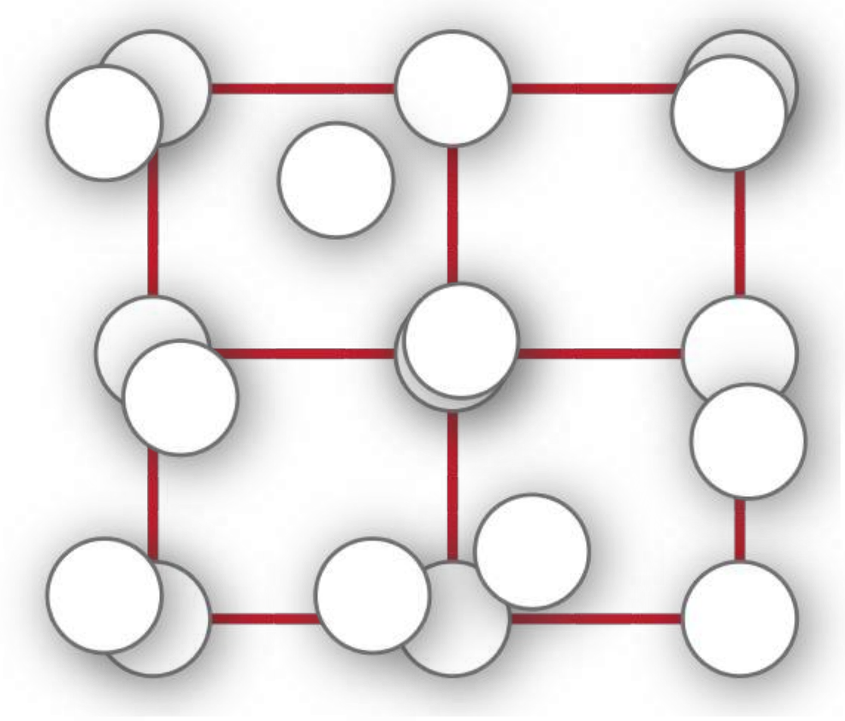


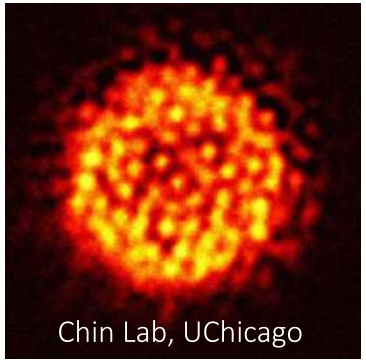
Uros Delic
TU Wien
www.deliclab.at

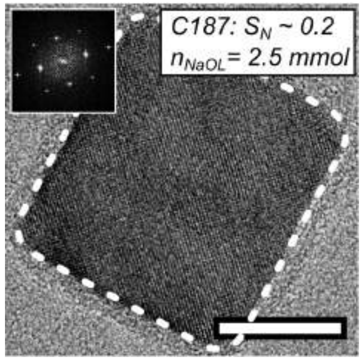
Ultracold Quantum Matter
August 2025

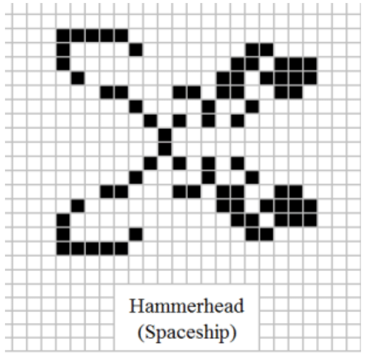
TECHNISCHE UNIVERSITÄT WIEN
VCQ Vienna Center for Quantum Science and Technology
quantA
wpi Wolfgang Pauli Institute

Interactions lead to self-organization







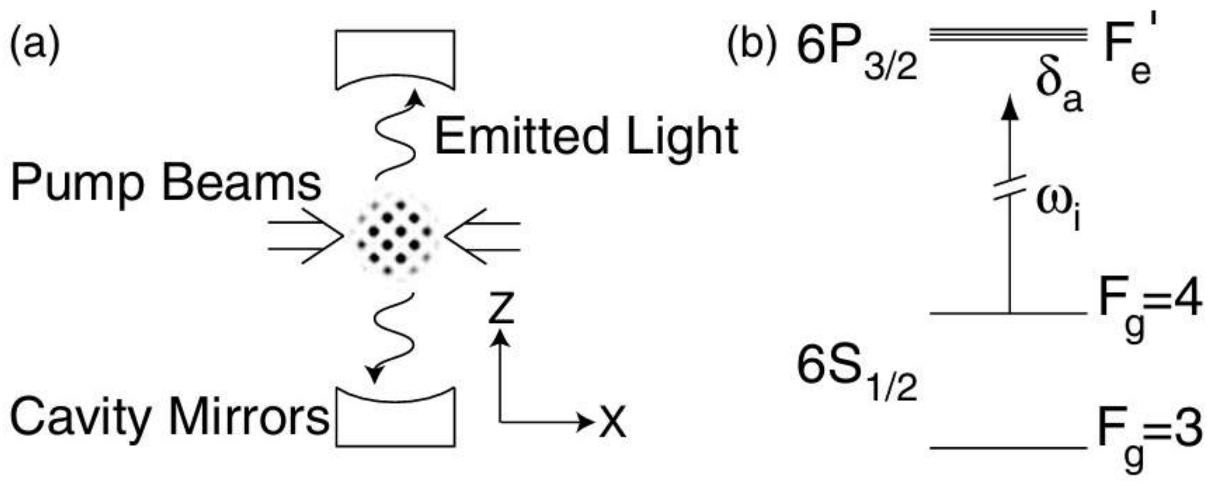


© Wikipedia

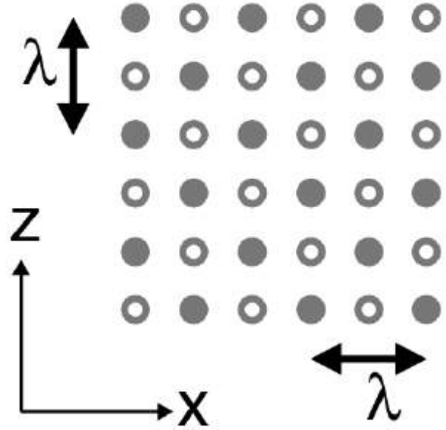
The behavior of large and complex aggregates of elementary particles, it turns out, **is not to be understood in terms of a simple extrapolation of the properties of a few particles. Instead, at each level of complexity entirely new properties appear,** and the understanding of the new behaviors requires research which I think is as fundamental in its nature as any other.

Phil W. Anderson, More is different (1972)

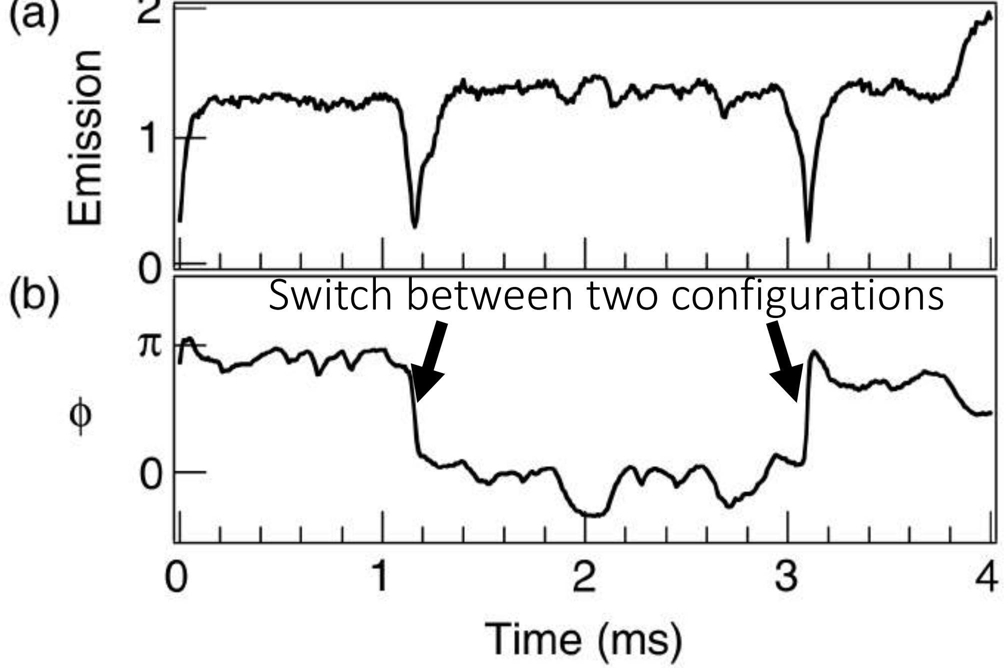
Self-organization and cooling of atoms



Two possible configurations:

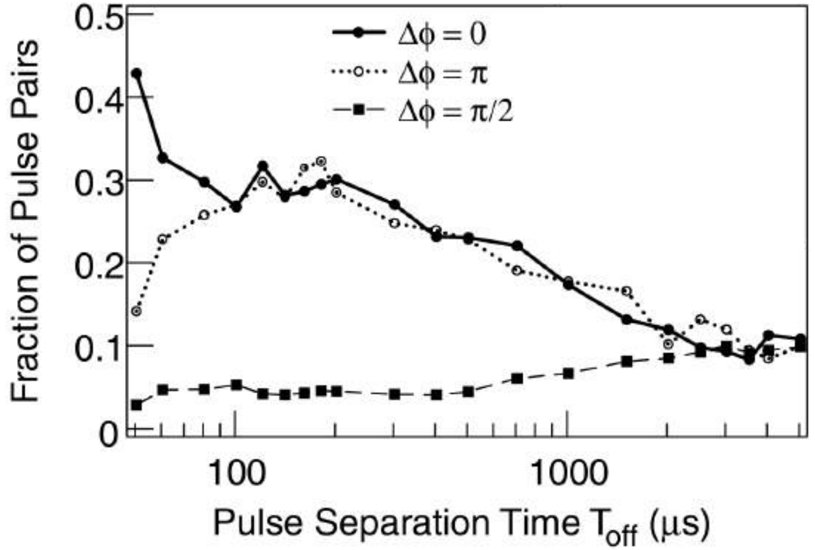


After applying a MOT pulse, atoms diffuse



Switch between two configurations

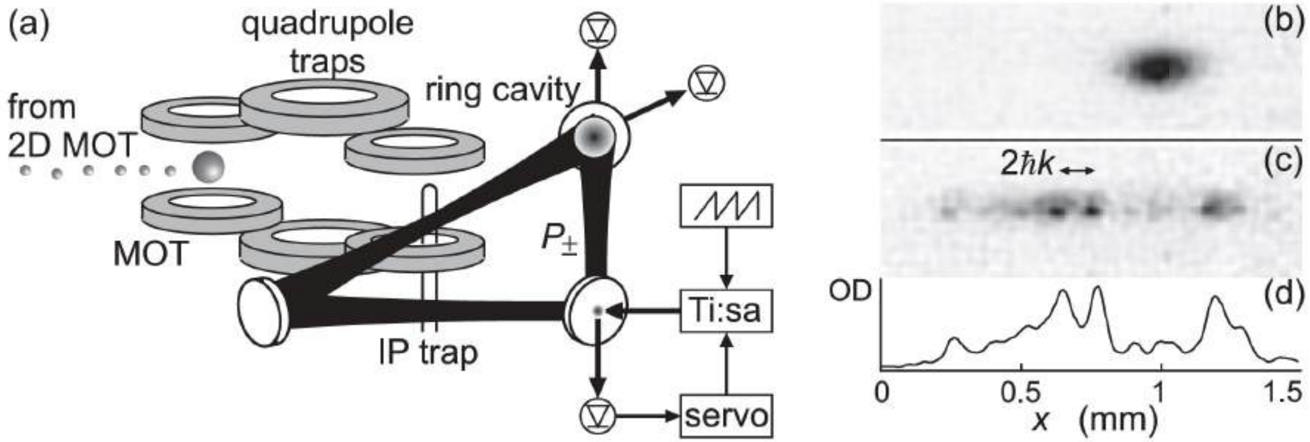
Signature of spontaneous symmetry breaking: equal probability of the two patterns



Black, Chan, Vuletić, Phys. Rev. Lett. 91, 203001 (2003)

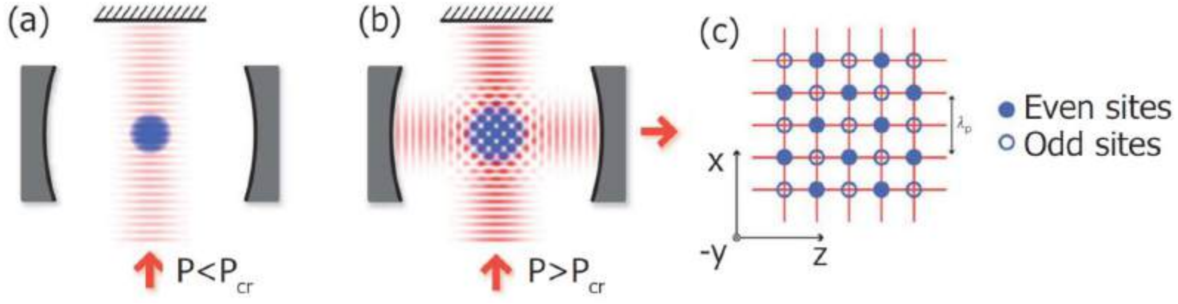
Self-organization with BECs

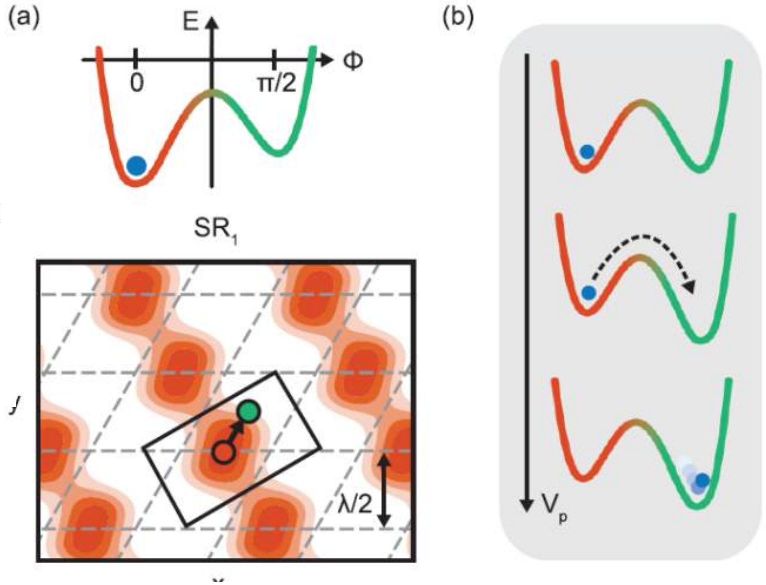
BECs automatically provide coherent scattering like a solid-state object



Slama et al., Phys. Rev. Lett. **98**, 053603 (2007)
Tübingen

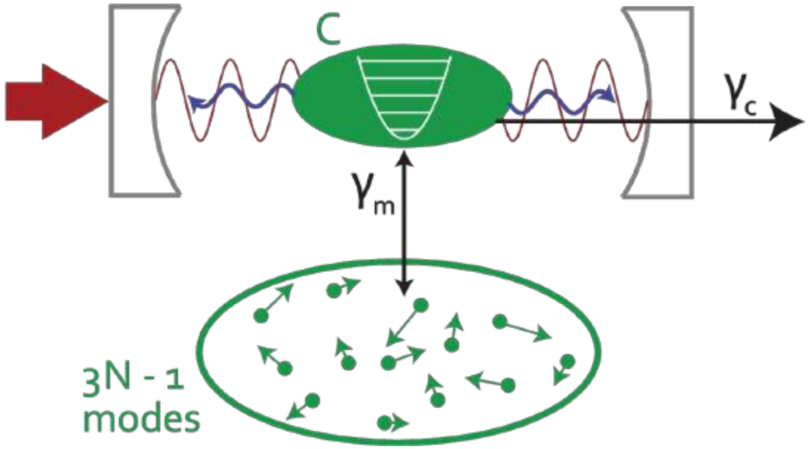
ETH Zurich

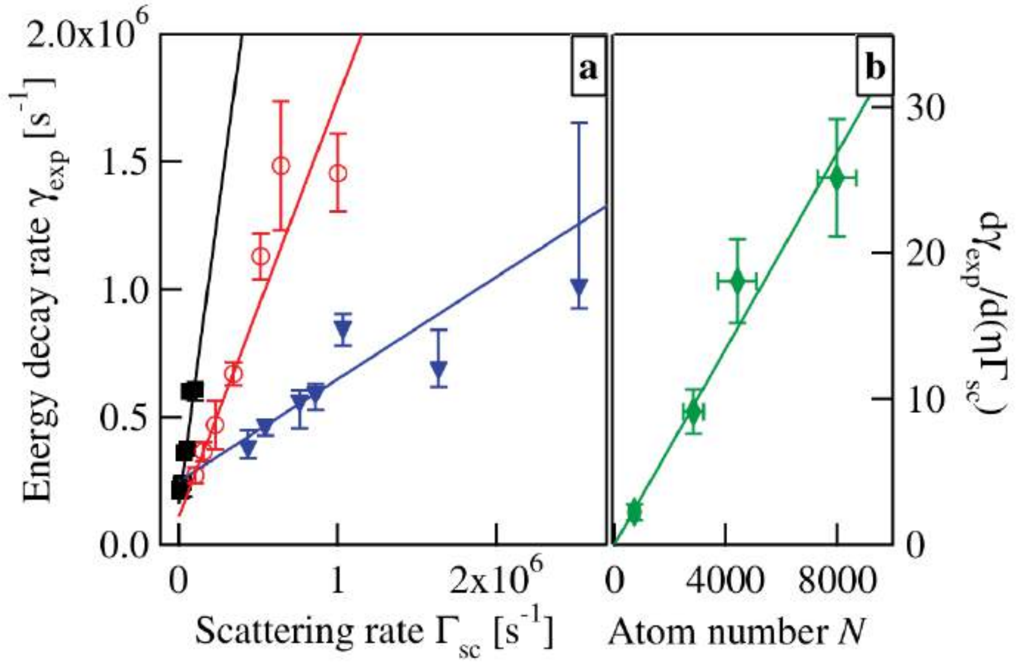




Li *et al.*, Phys. Rev. Research **3**, L012024 (2021)

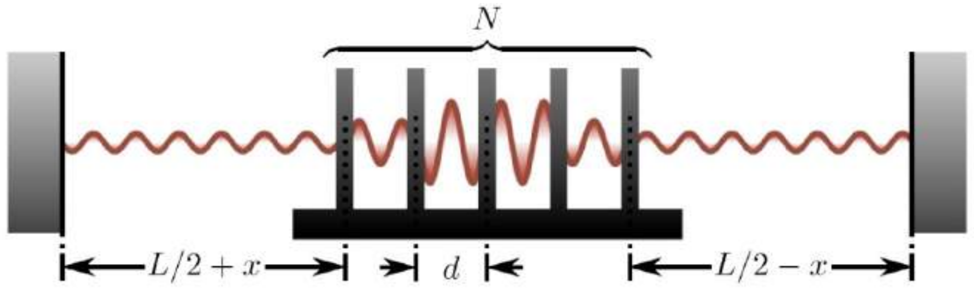
Enhanced cooling

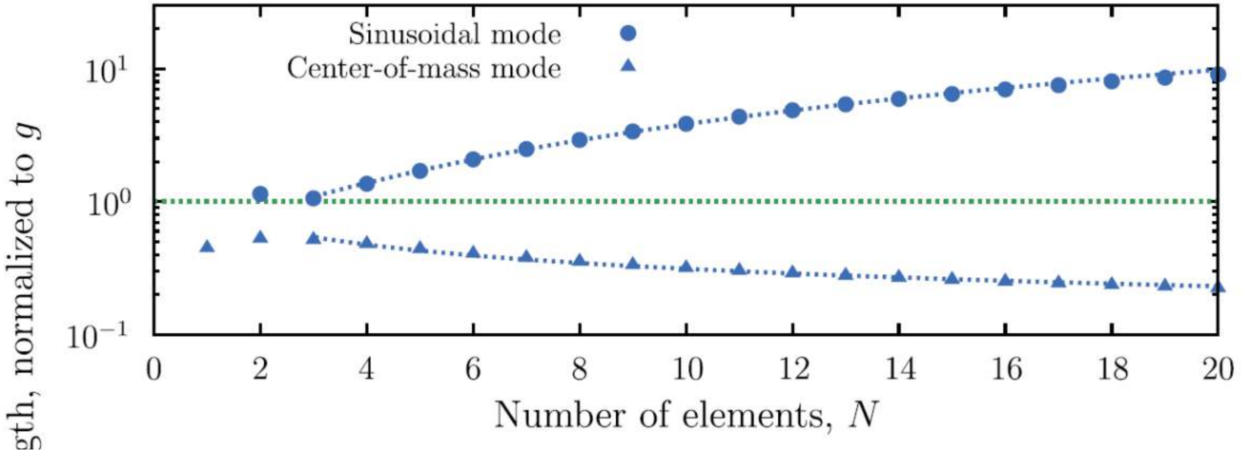




Schleier-Smith *et al.*, Phys. Rev. Lett. **107**, 143005 (2011)

Optimal arrangement would lead to a large enhancement

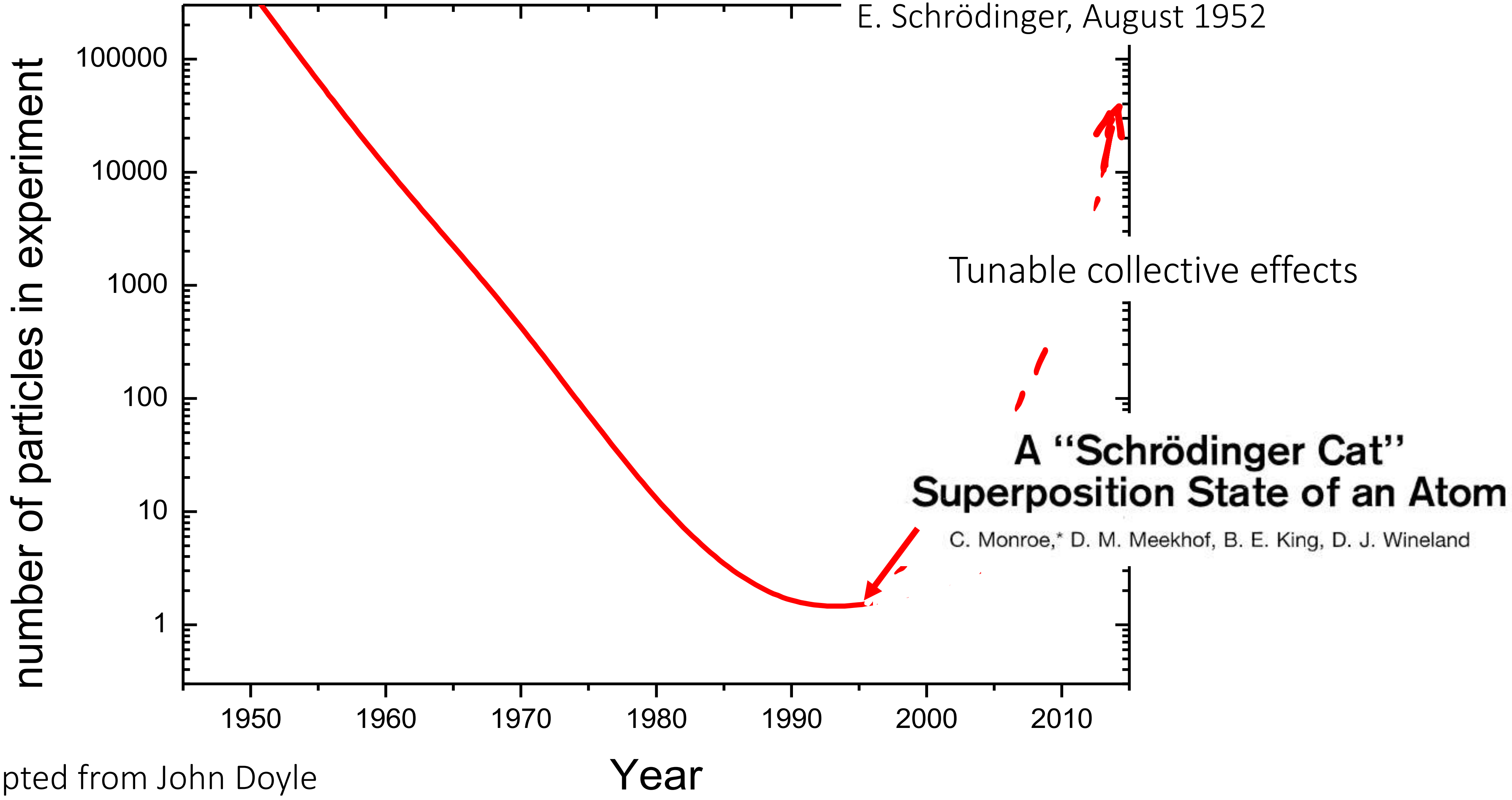




Domokos, Ritsch, PRL 89, 253003 (2002)
Heinrich *et al.*, PRL, 043603 (2011)
Xuereb, Genes, Dantan, PRL 109, 223601 (2012)

In the first place it is fair to state that we are not *experimenting* with single particles, any more than we can raise Ichthyosauria in the zoo. We are scrutinising records of events long after they have happened. That the interval of time is shorter and that we have

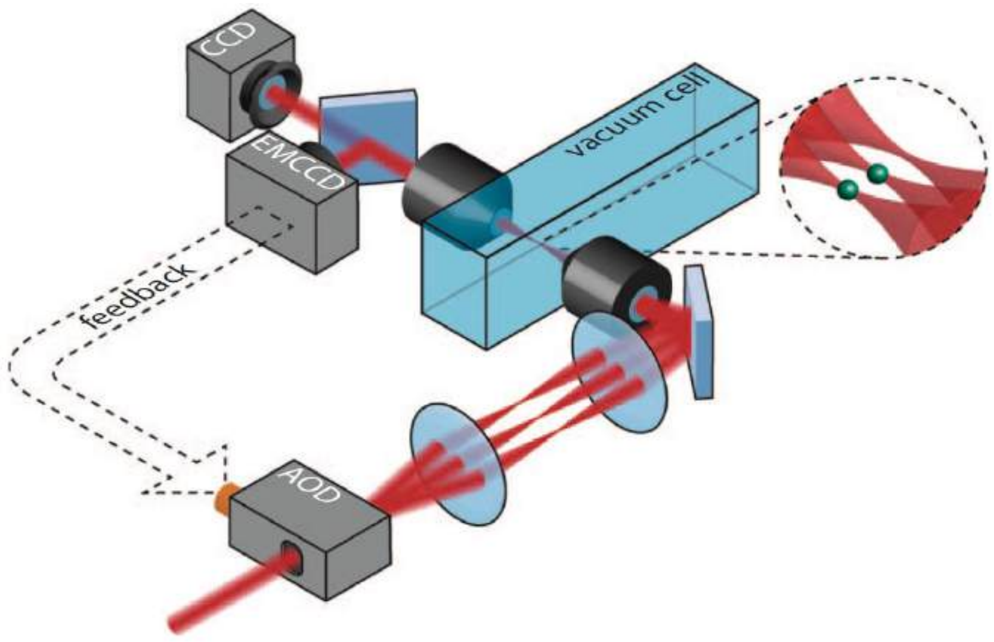
E. Schrödinger, August 1952

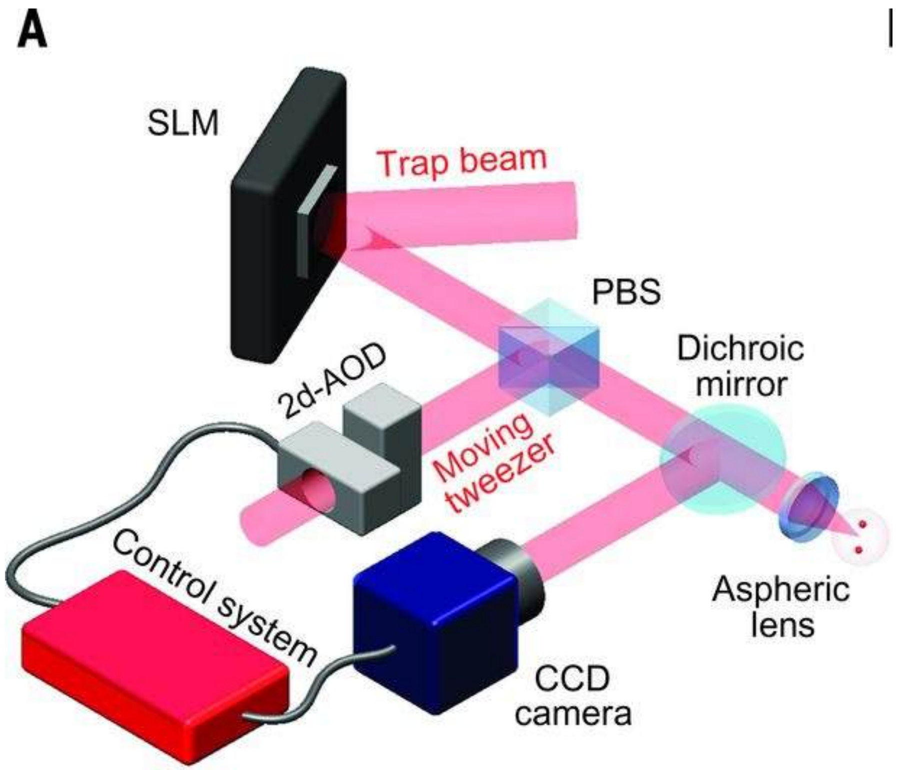


adapted from John Doyle

Tweezer arrays of atoms

Platform for quantum simulation, information science, and computing

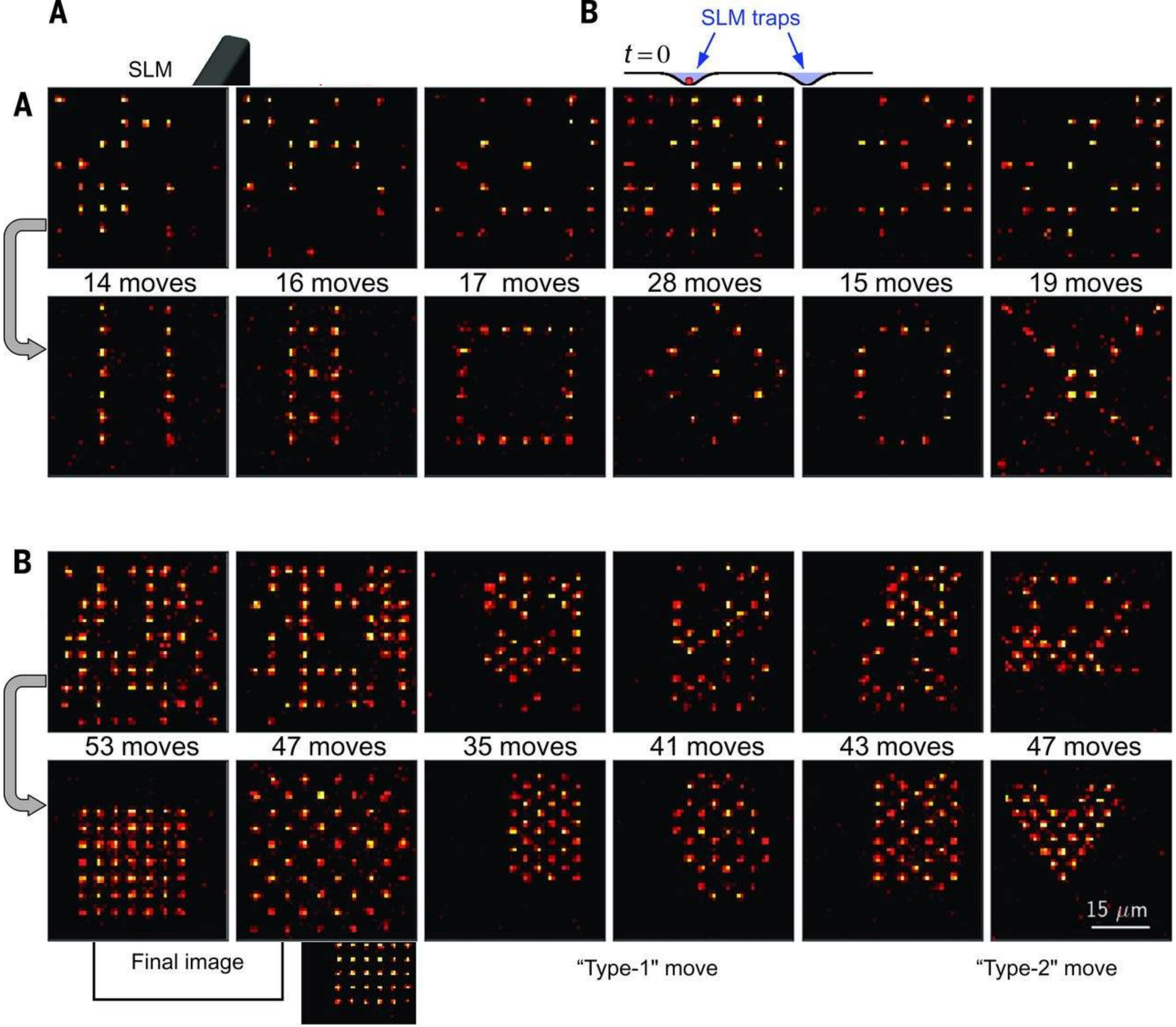




Barredo et al., Science 354, 1021 (2016)
Endres et al., Science 354, 1024 (2016)

Issue:
Probabilistic loading of ∼50%, imaging with a camera is currently the slowest task

Need to develop fast algorithms to detect and rearrange


A
SLM
B
SLM traps
$t=0$
A
14 moves
16 moves
17 moves
28 moves
15 moves
19 moves
B
53 moves
47 moves
35 moves
41 moves
43 moves
47 moves
15 μm
Final image
"Type-1" move
"Type-2" move

Integrating tweezer arrays of atoms with an optical cavity enables:

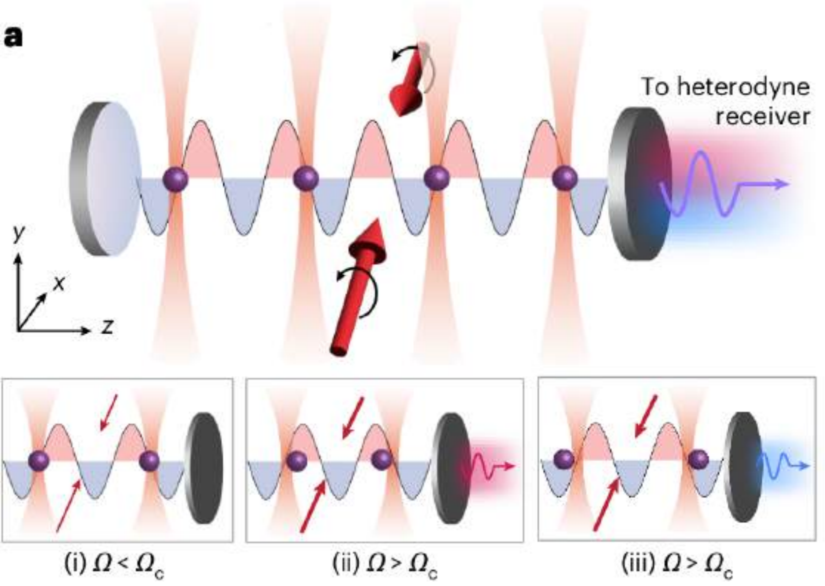
Programmable interactions, for example, entanglement of different tweezer arrays

Faster readout of atoms

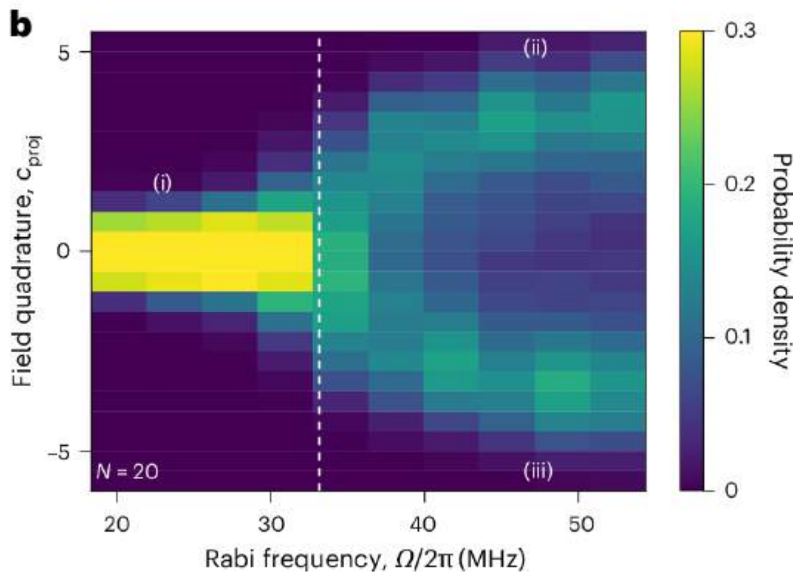
Studies of emergent phenomena, collective dynamics & phase transitions in a few-body system

Collective effects in a few-body system

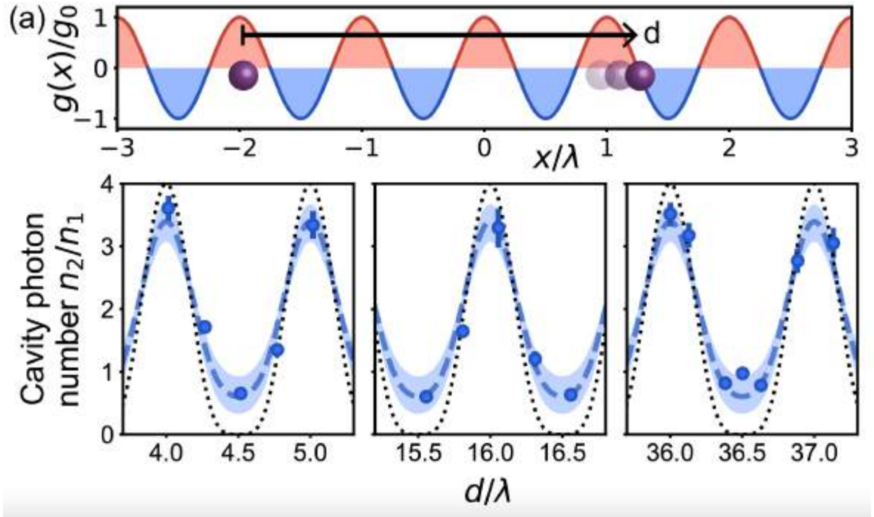
Dan Stamper-Kurn group



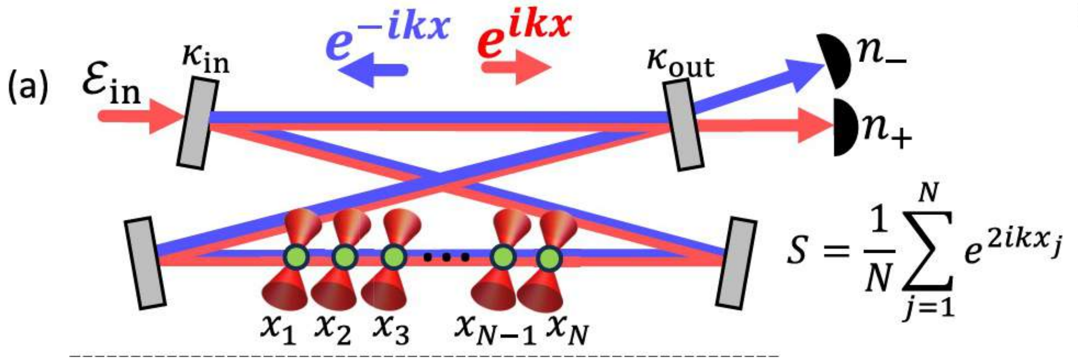
Two possible self-organized structures

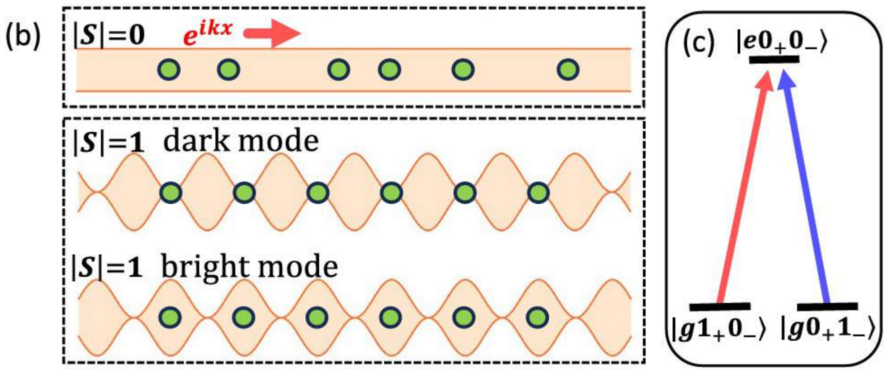


Superradiant Rayleigh scattering



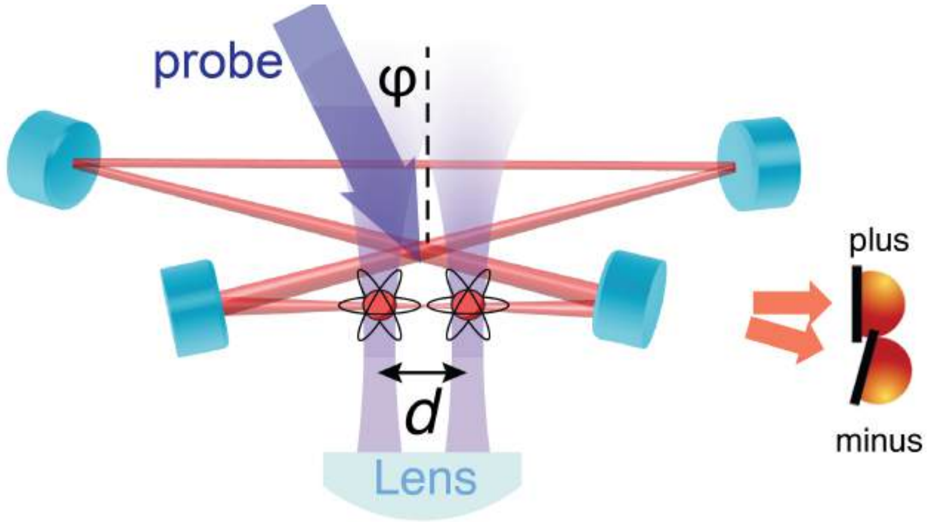
Dark/bright cavity modes through assembled structures





Hao Zhang's group, PRR 6, L042026 (2024)

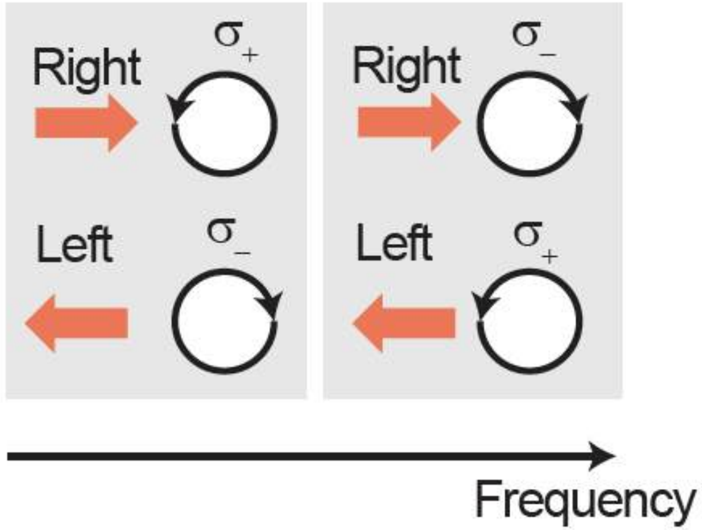
Chiral light scattering into a cavity

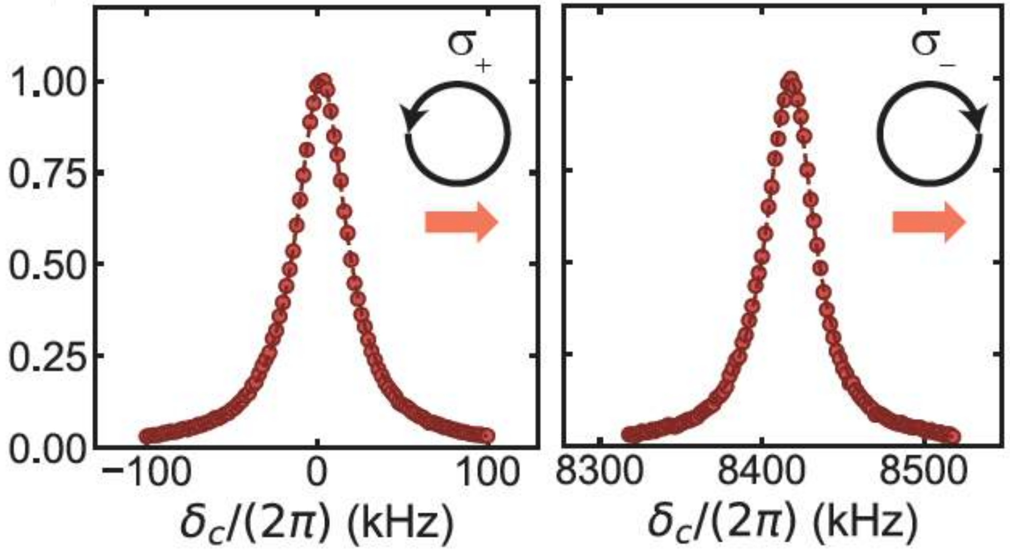


Traveling wave cavities
Ring: Hemmerich, Zimmerman & Slama, Courteille
Bow-tie: Bertoldi, Simon, Chen…

$\kappa/2\pi = 37$ kHz
Waist: 8 µm
Length: 18 cm

Twist out of the plane: non-degenerate σ^+ and σ^- modes
see: Schine et al., Nature 534, 671 (2016)



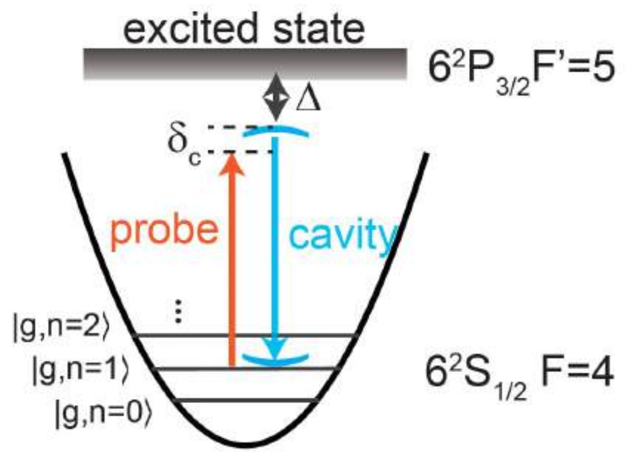


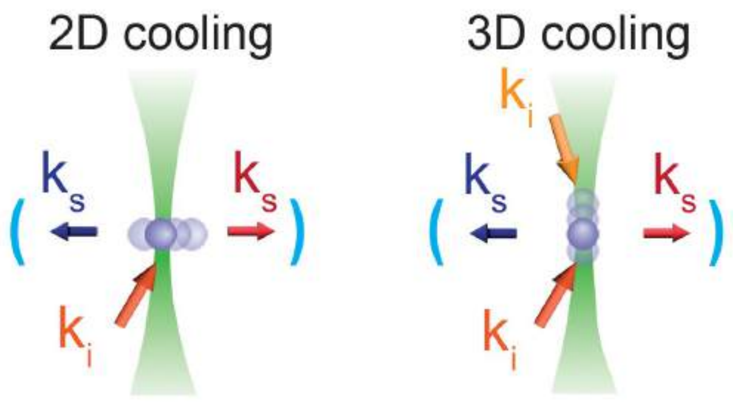
Wang, Spierings, Peters, Chen, **Delić**, Vuletić, *on arXiv soon*

Preliminary data

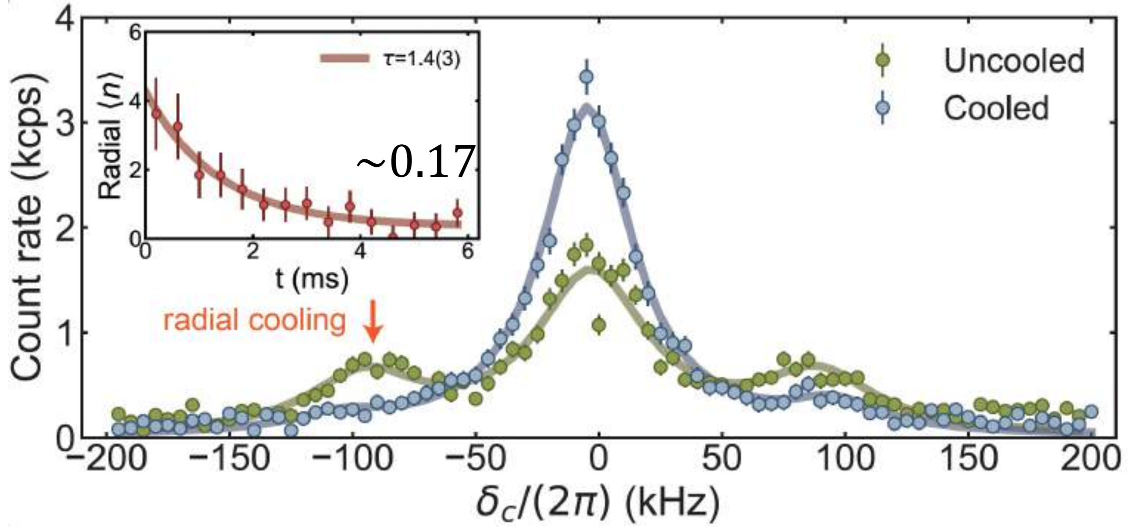
First cavity ground-state cooling

Preliminary data

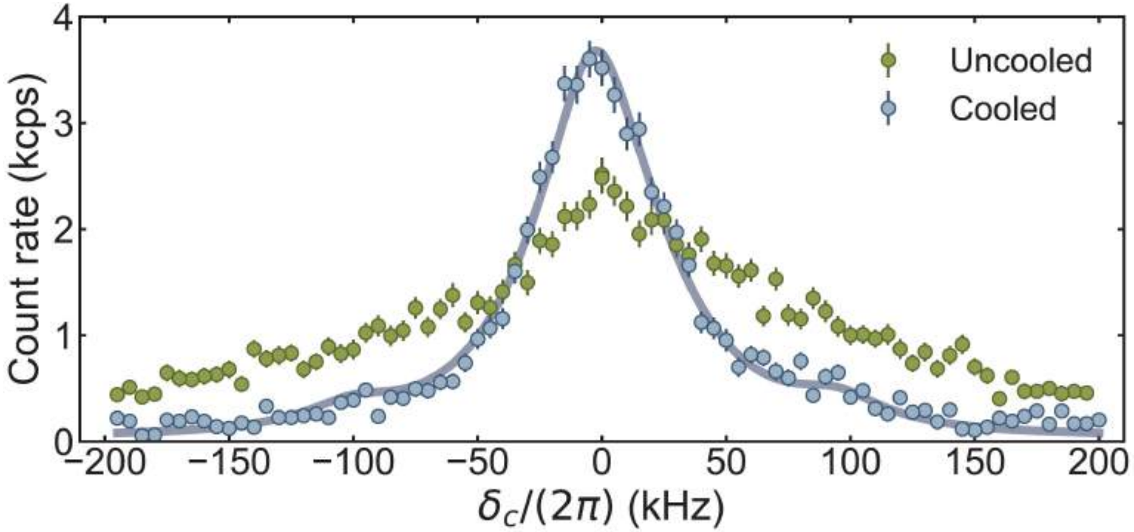




Radial cooling



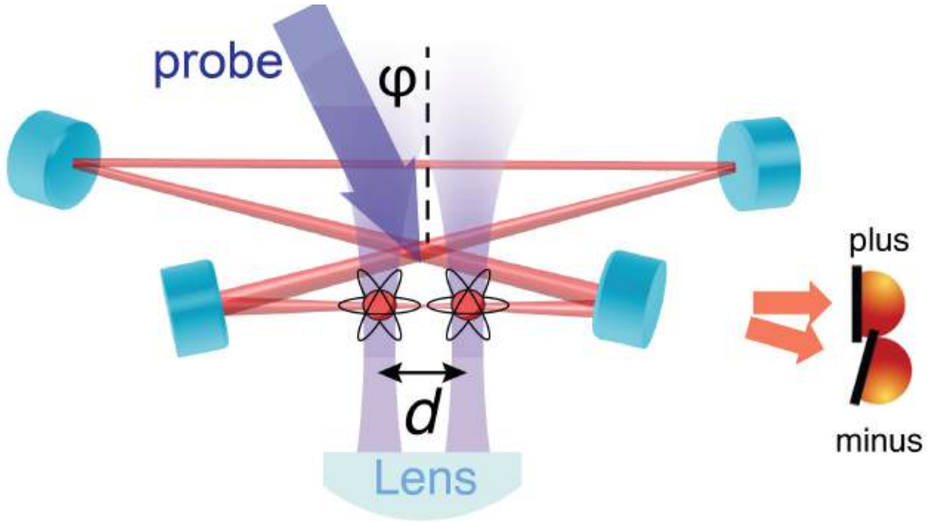
Radial & axial cooling

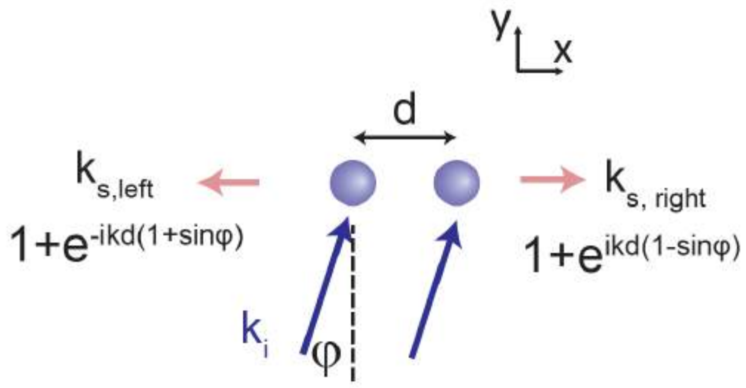


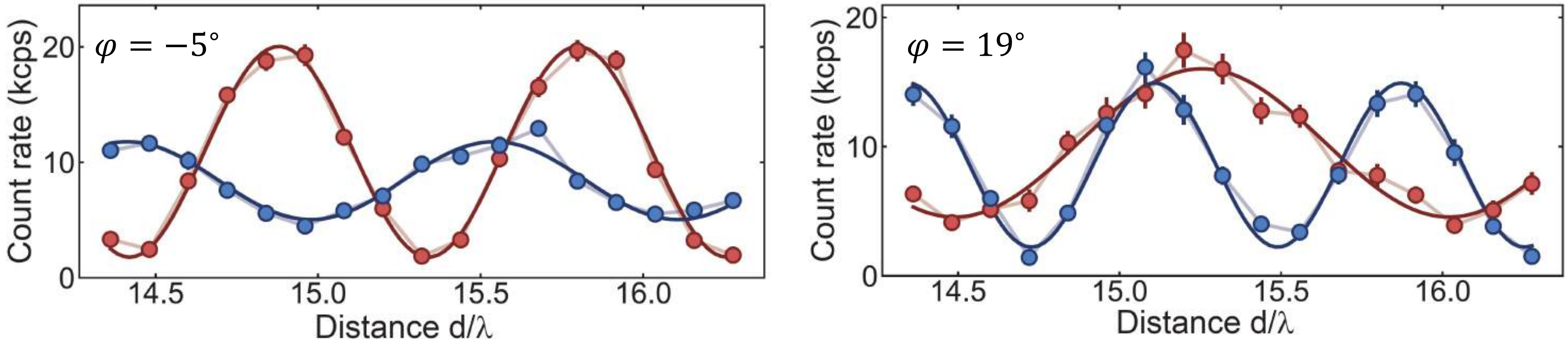
Wang, Spierings, Peters, Chen, **Delić**, Vuletić, *on arXiv soon*

Directional collective scattering

Preliminary data





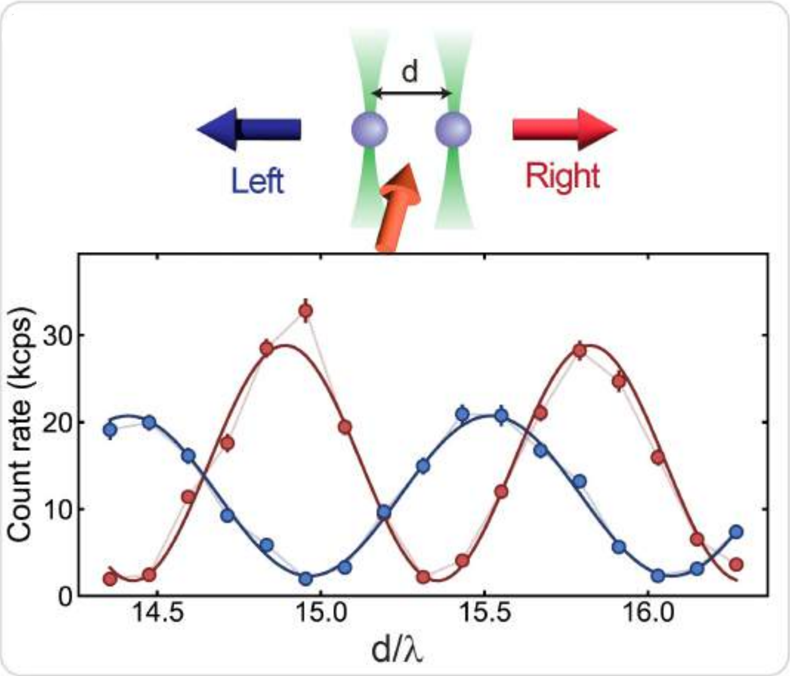


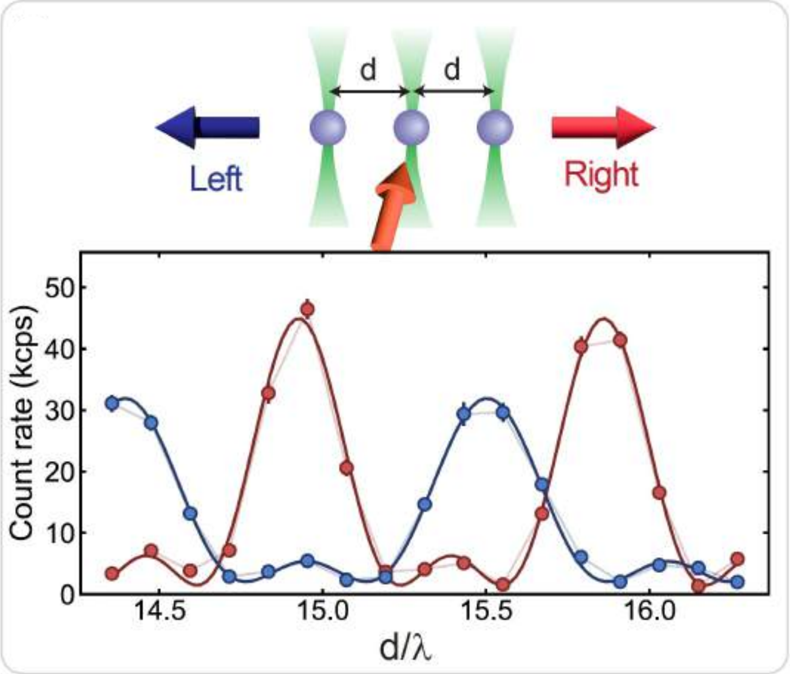
Wang, Spierings, Peters, Chen, **Delić**, Vuletić, *on arXiv soon*

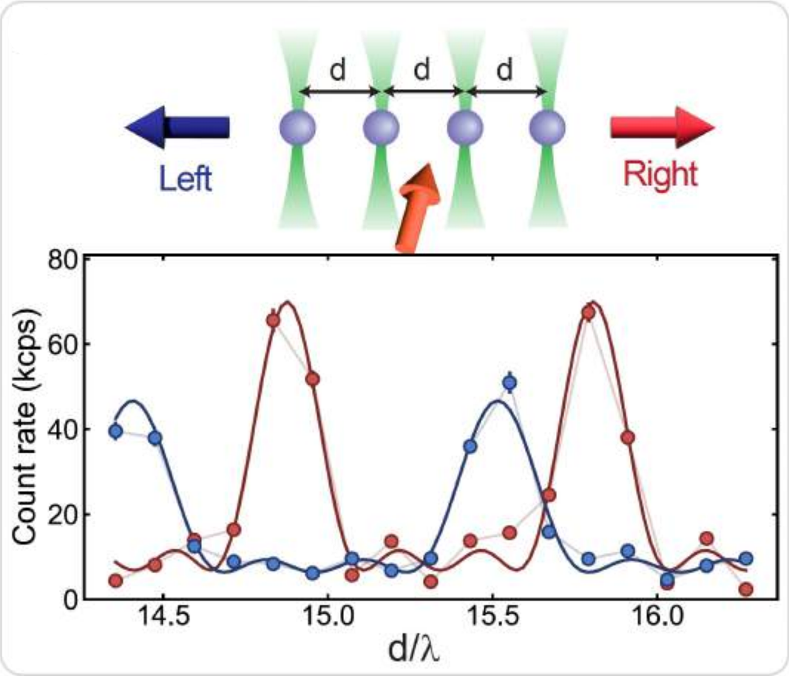
Bragg scattering

Preliminary data

number of atoms





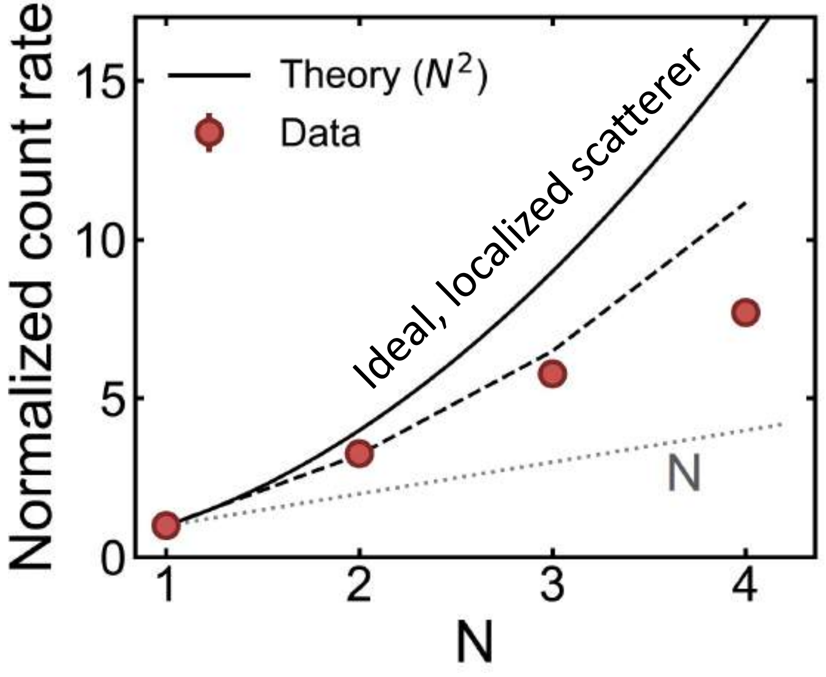


The peak increases and narrows: signature of Bragg diffraction

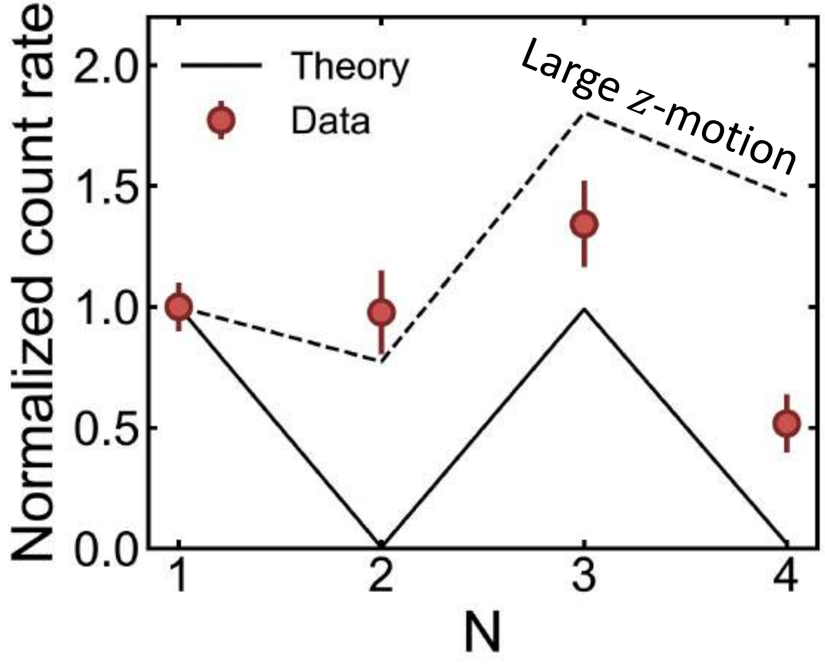
Wang, Spierings, Peters, Chen, **Delić**, Vuletić, *on arXiv soon*

Super- and subradiant Rayleigh scattering

Scattering enhancement



Scattering suppression



Wang, Spierings, Peters, Chen, **Delić**, Vuletić, *on arXiv soon*

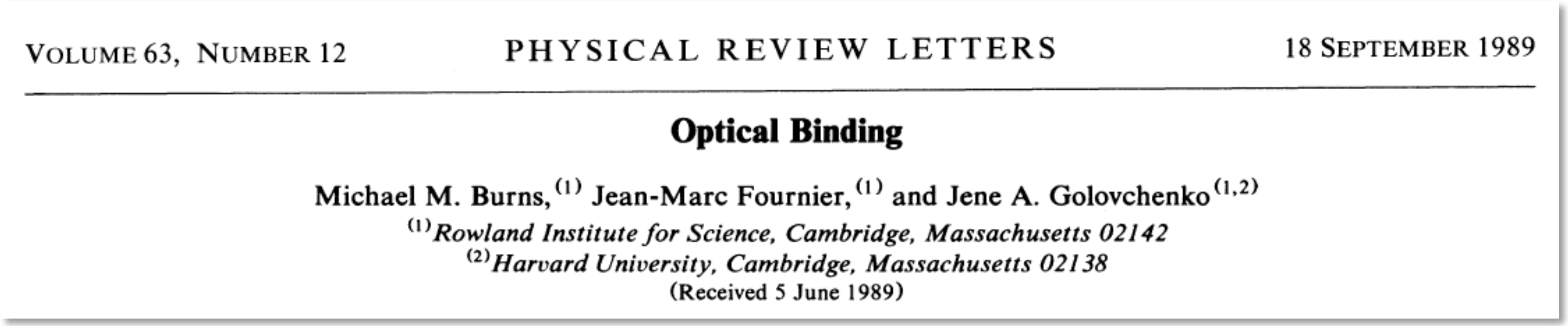
Issues with atoms: ground state motion is large, many internal levels, incoherent scattering, low scattering rates, limited trapping time… No studies of mechanical interaction yet

Tweezer arrays of nanoparticles with an optical cavity?

How can nanoparticles (but also atoms) interact?

What collective phenomena can we study? Better collective light scattering data?

Macroscopic entanglement?

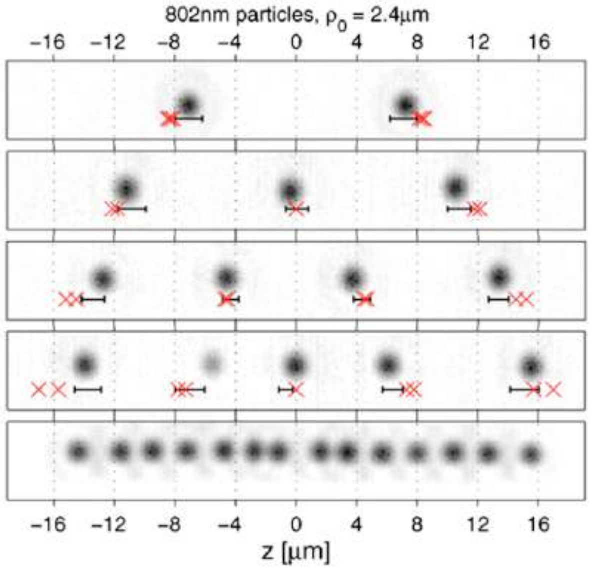


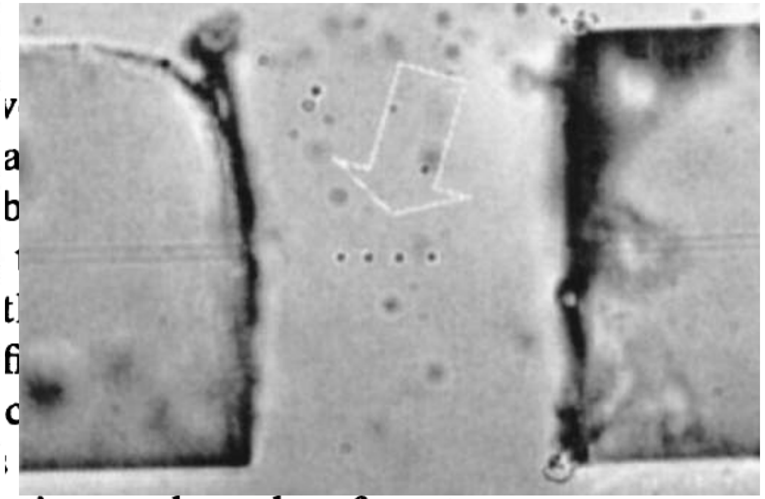
VOLUME 63, NUMBER 12 PHYSICAL REVIEW LETTERS 18 SEPTEMBER 1989

Optical Binding

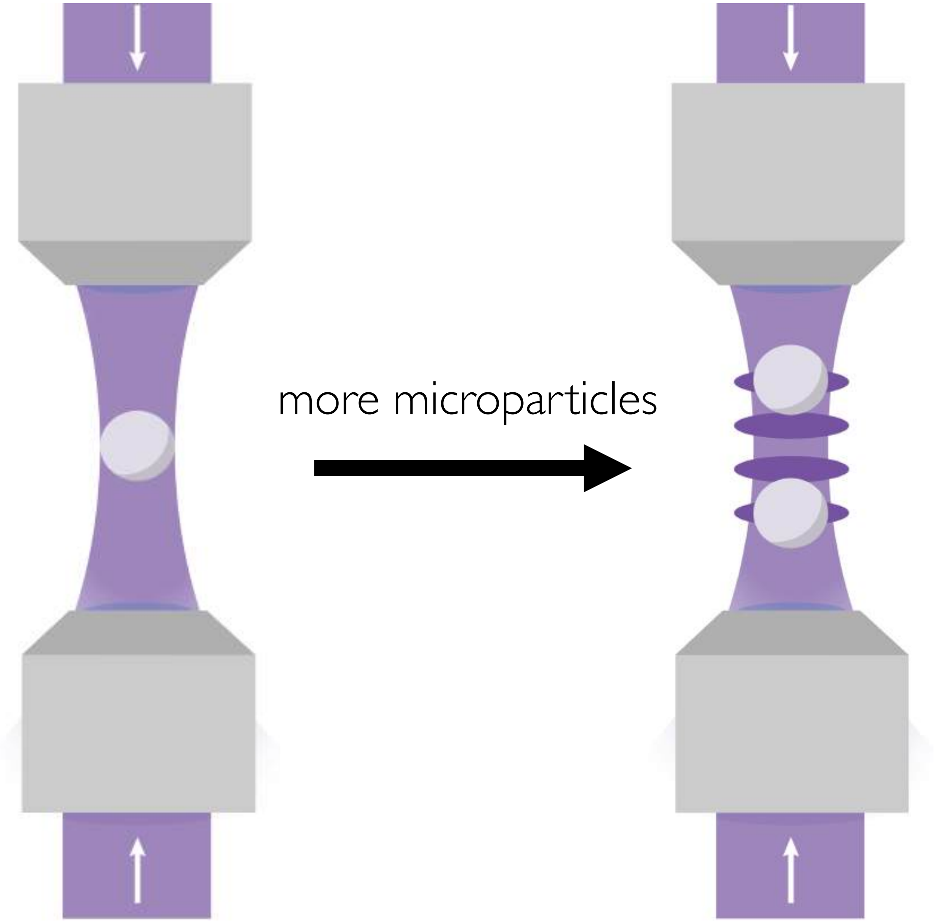
Michael M. Burns,[1] Jean-Marc Fournier,[1] and Jene A. Golovchenko[1,2]
[1] *Rowland Institute for Science, Cambridge, Massachusetts 02142*
[2] *Harvard University, Cambridge, Massachusetts 02138*

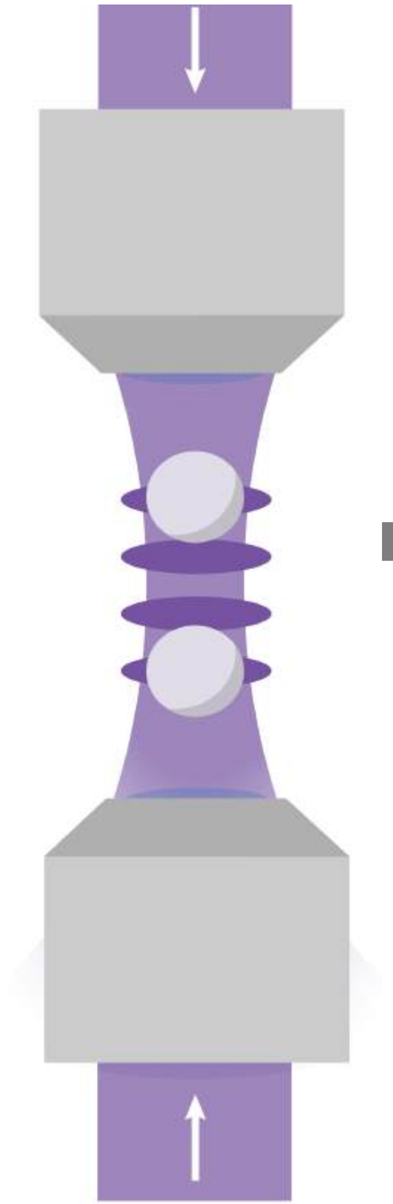
(Received 5 June 1989)

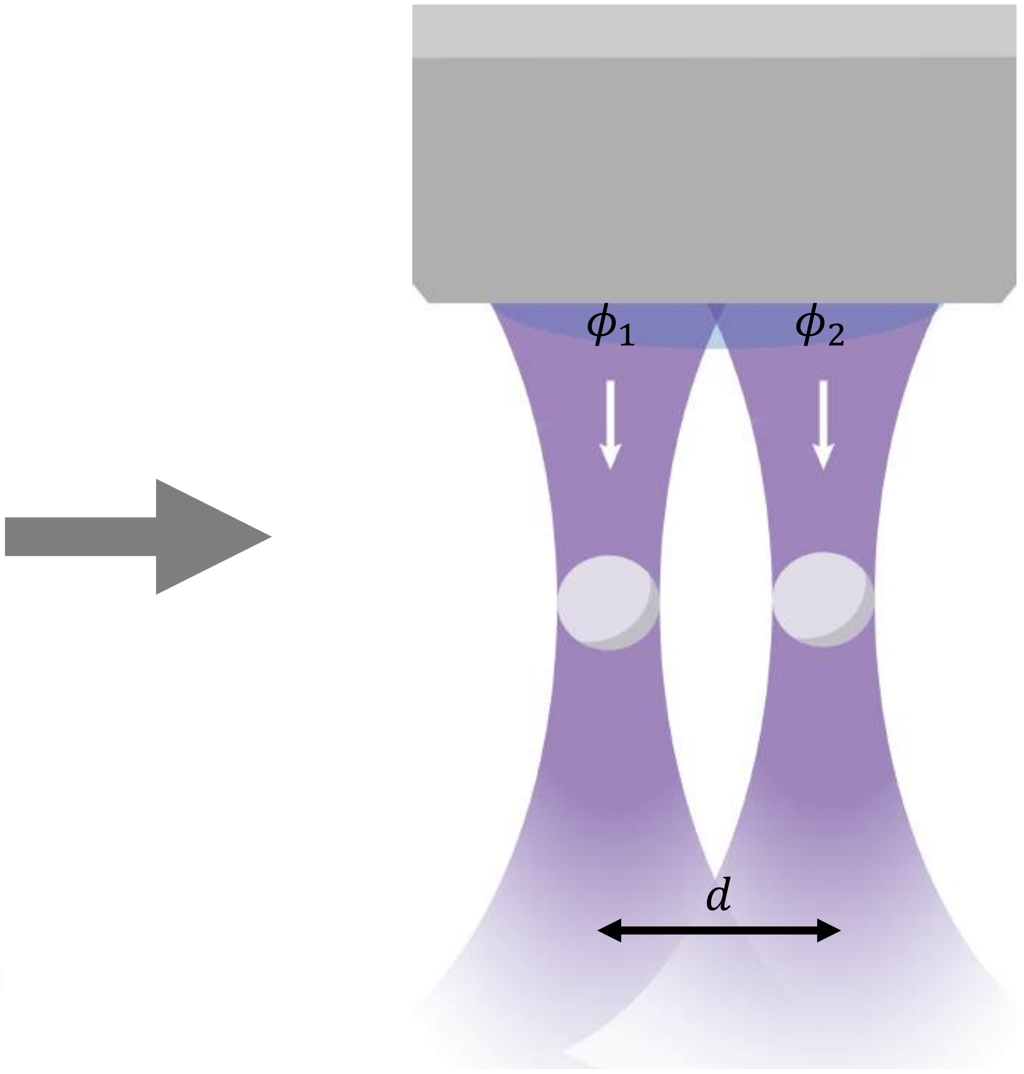




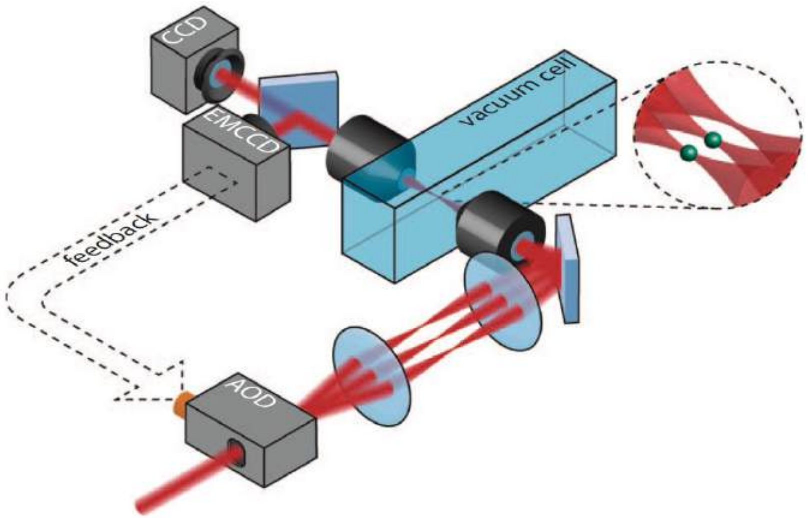
Tatarkova, Carruthers, Dholakia PRL 89, 283901 (2002)
Singer,…, Ritsch-Marte, JOSA B 20, 7 (2003)
Karásek,…, Dholakia, Zemánek PRL 101, 143601 (2008)
Svak,…, Zemánek, Brzobohatý, Optica 8, 220-229 (2021)
Review: Zemánek & Dholakia Rev. Mod. Phys. 82, 1767 (2010)







Single-atom tweezer arrays



Barredo et al., Science 354, 1021 (2016)
Endres et al., Science 354, 1024 (2016)

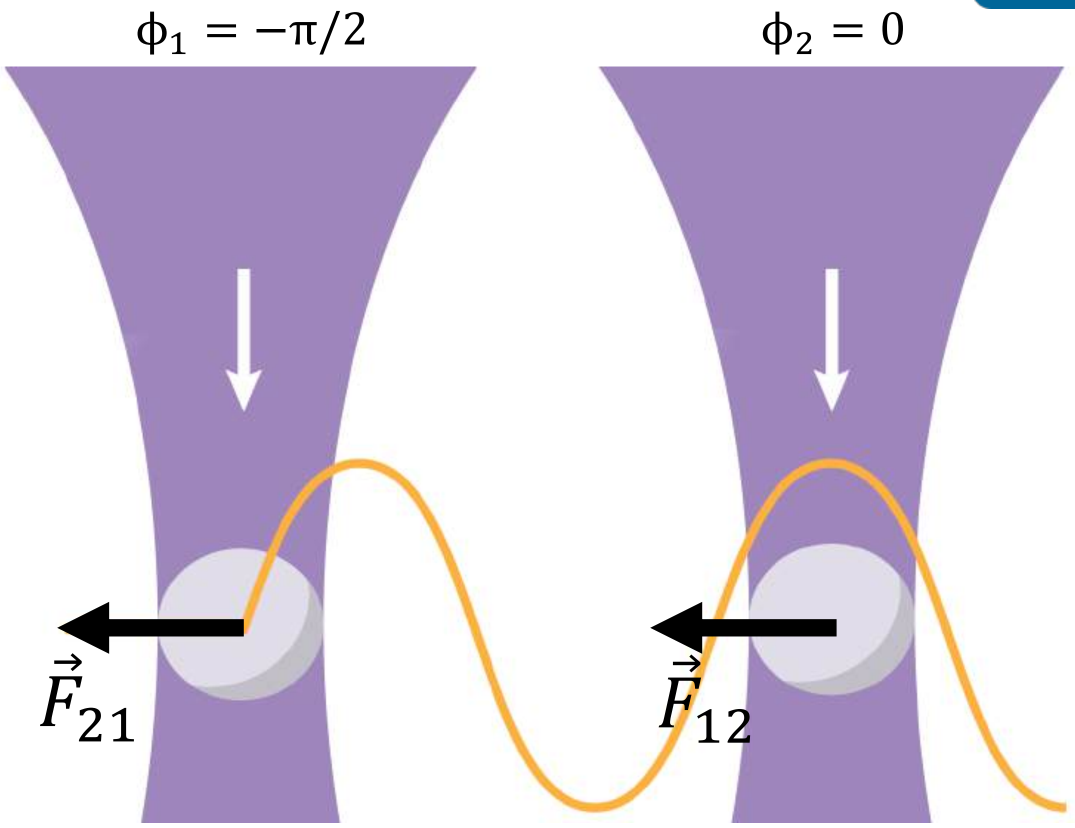
Independent control over individual mechanical and light modes in phase-coherent tweezers

For $\phi_1 = \phi_2$, the system is fully symmetric: forces are reciprocal

Symmetry is maximally broken for:

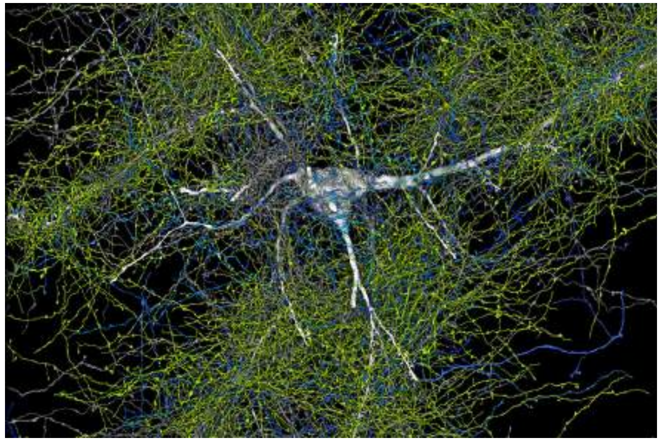
$$\phi_2 = 0, \qquad \phi_1 = -\pi/2$$
$$kd_0 = \pi/2$$

Forces are maximally nonreciprocal:
"predator – prey" dynamics
or "anti-reciprocal" interaction



Nonreciprocal interactions are ubiquitous in nature

Biological systems, flocking, swarming, social interactions…



©Google & Lichtman Lab

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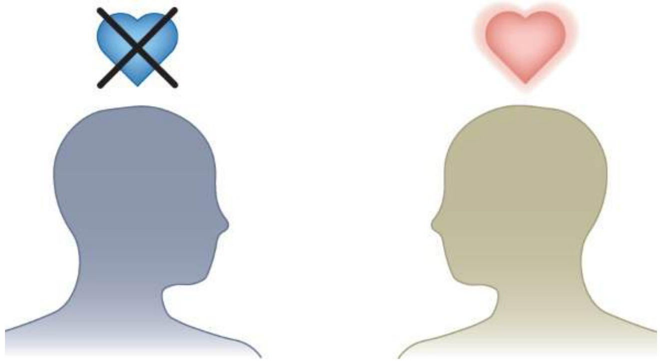
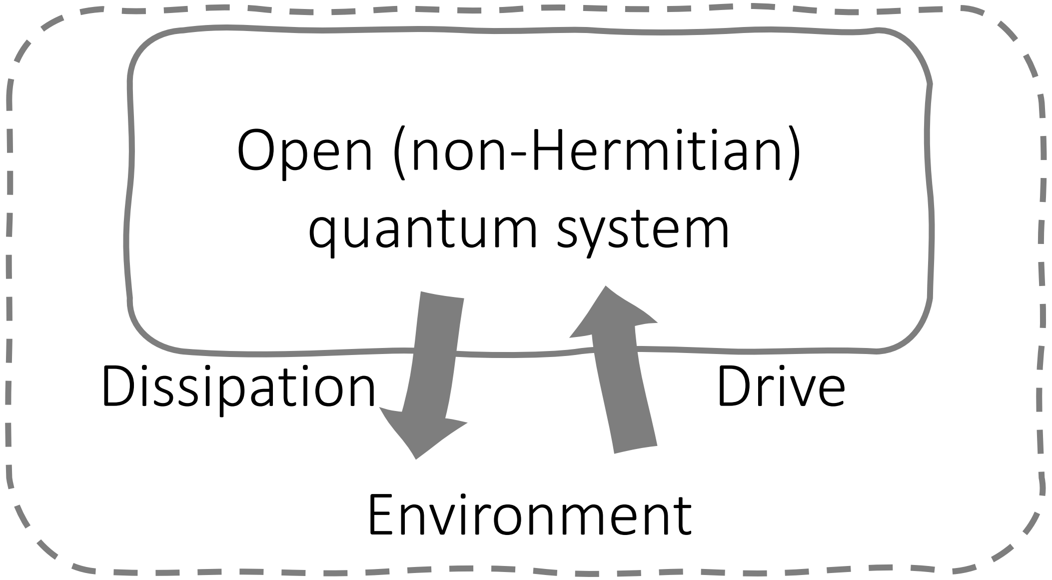


Nature Nano 18, 8–9 (2023)

…and in technology

Electronic and optical diodes

Nonreciprocity in the quantum regime

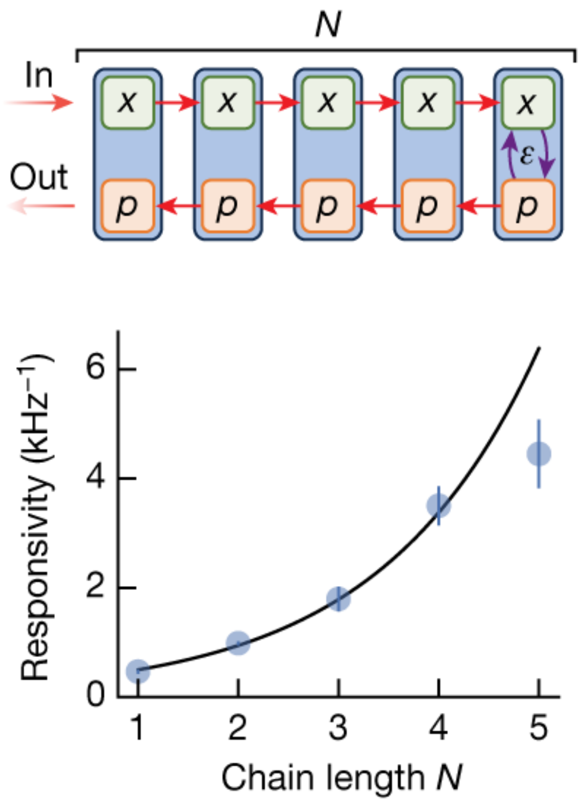


Non-Hermitian dynamics always occurs in open quantum systems

What about nonreciprocity?

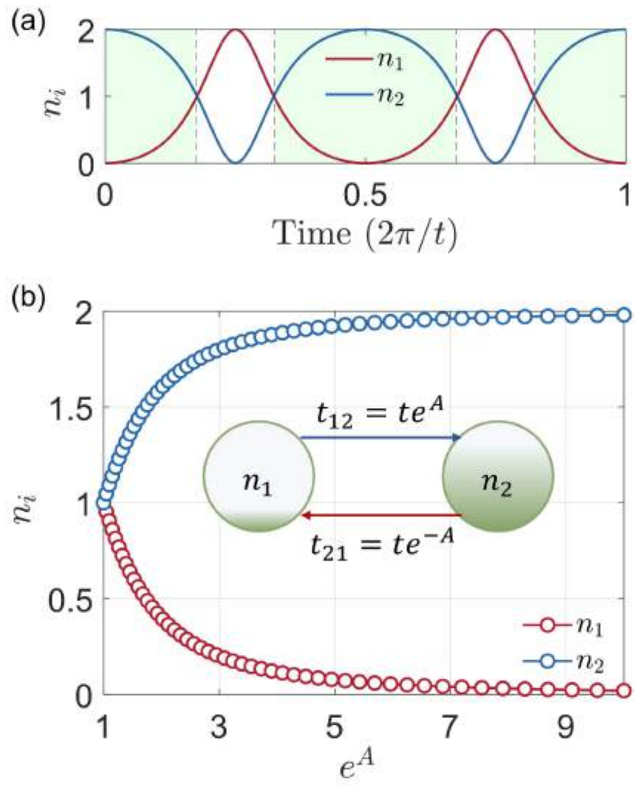
Applications

Studying non-Hermitian and topological physics, amplifying signals over classical noise



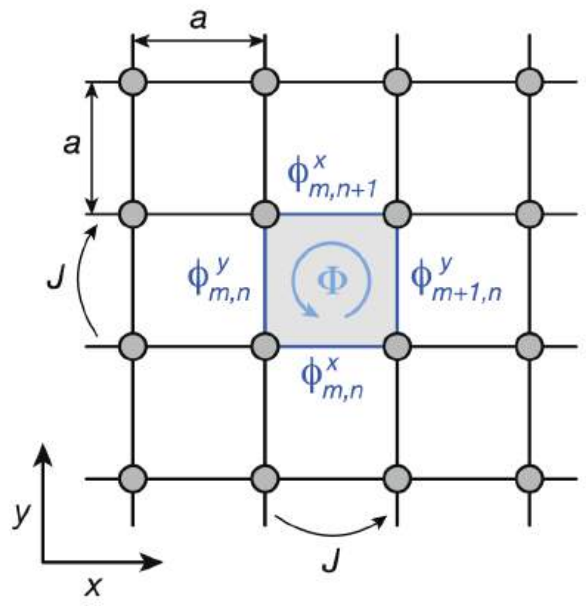
Amsterdam, Yale, Caltech, Vienna…

Exploring the quantum limits of interaction and thermodynamics out of equilibrium



Amsterdam, Yale, Vienna…

Floquet engineering for synthetic gauge fields



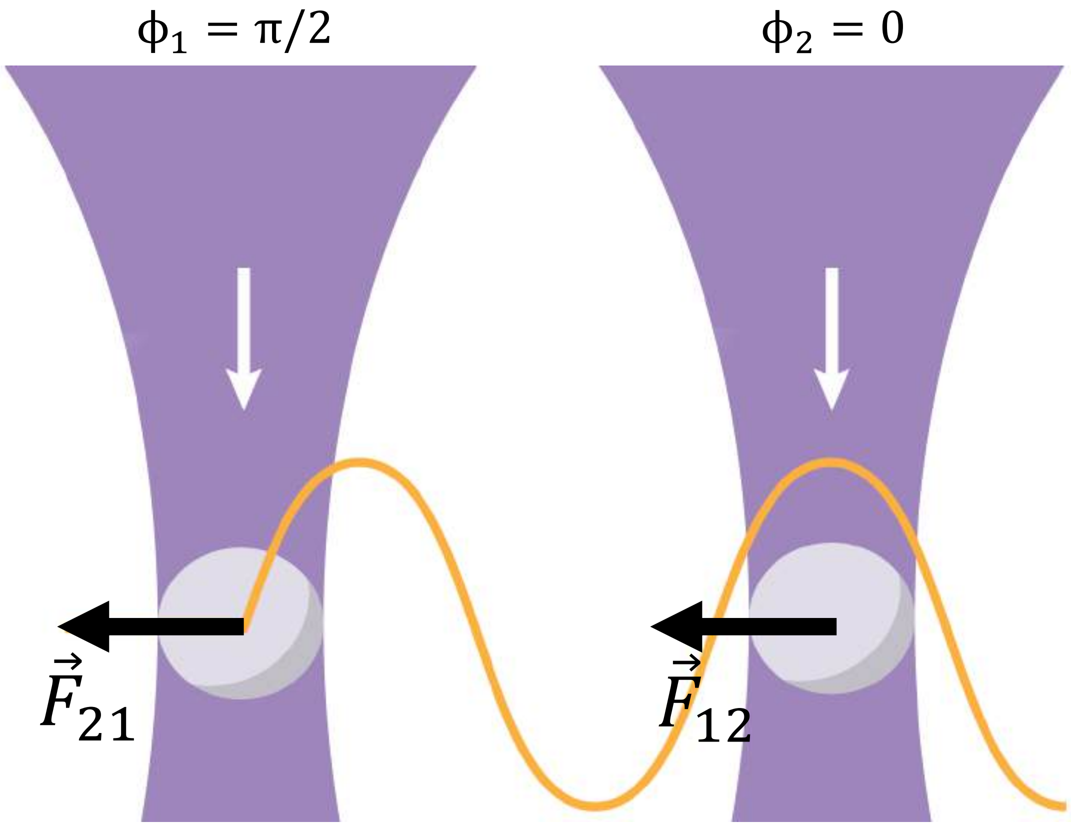
Munich, Caltech, Yale, Amsterdam…
Reviews:
Rev. Mod. Phys. 83, 1523 (2011)
Phys. Rev. X 4, 031027 (2014)

Optical interactions: Breaking of the "Newton reciprocity"

Forces are nonlinear in operators:
Nonreciprocity is preserved in its full form

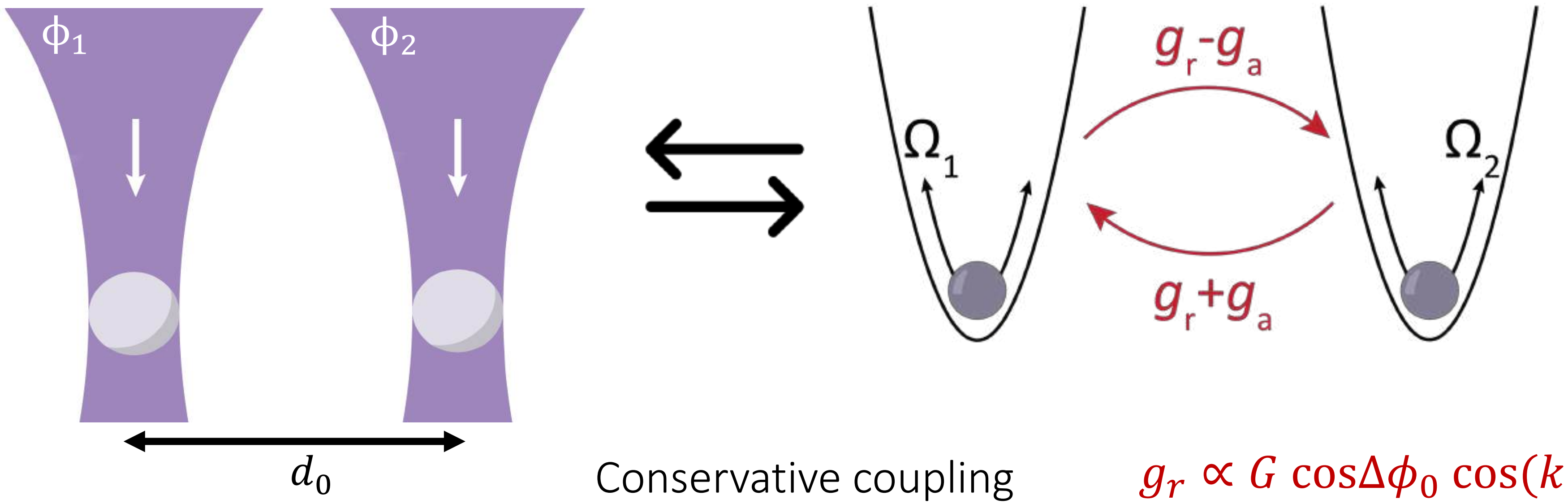
In this example:

$$\vec{F}_{12} \propto \sin(k(x_1 - x_2))\mathbf{e}_x$$
$$\vec{F}_{21} \propto \sin(k(x_1 - x_2))\mathbf{e}_x$$



Light-induced dipole-dipole interaction

“Quantum optical binding”



Ben Stickler
Ulm University

Conservative coupling $\quad g_r \propto G\cos\Delta\phi_0 \cos(kd_0)/kd_0$

Non-conservative coupling $\quad g_a \propto G\sin\Delta\phi_0 \sin(kd_0)/kd_0$

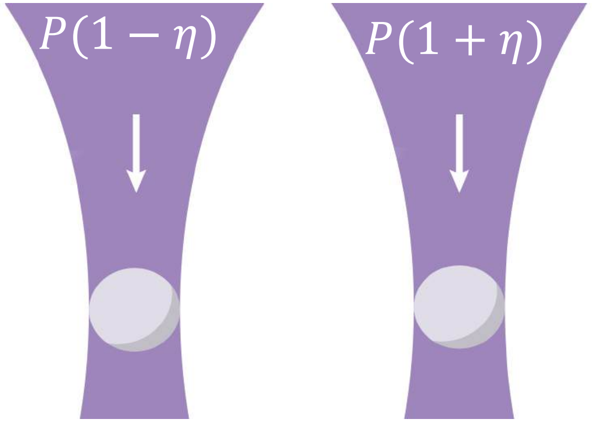
$$\begin{pmatrix}\ddot{z}_1\\ \ddot{z}_2\end{pmatrix} = -\Omega\begin{pmatrix}\Omega(1+\eta)+2(g_r+g_a) & \boxed{-2(g_r+g_a)}\\ \boxed{-2(g_r-g_a)} & \Omega(1-\eta)+2(g_r-g_a)\end{pmatrix}\begin{pmatrix}z_1\\ z_2\end{pmatrix}+\begin{pmatrix}\xi_1\\ \xi_2\end{pmatrix}$$ Non-Hermitian dynamics

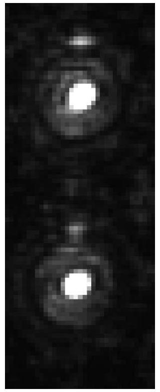
In general: $\langle\xi_1\xi_2\rangle \neq 0$

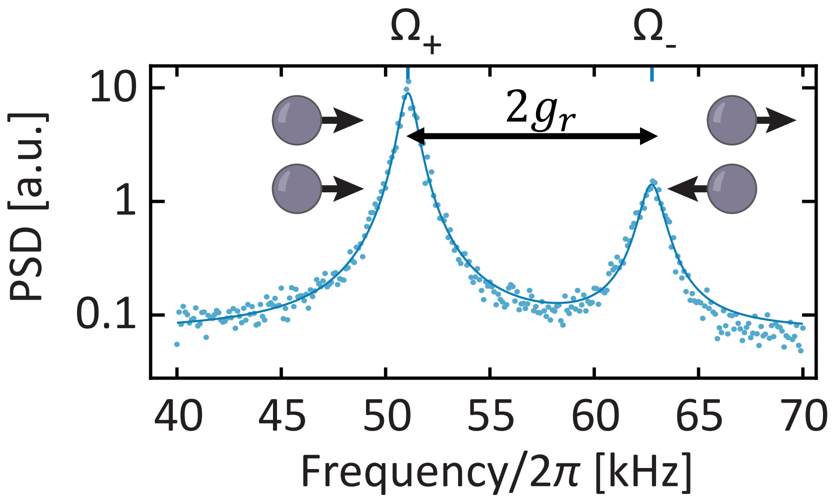
Quantum master equation: quantum noise correlations, non-Hermitian dynamics, entanglement, etc:

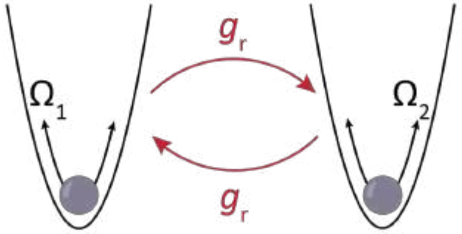
Rudolph, Delic, Hornberger, Stickler: PRL 133, 233603 & PRA 110, 063507 (2024)

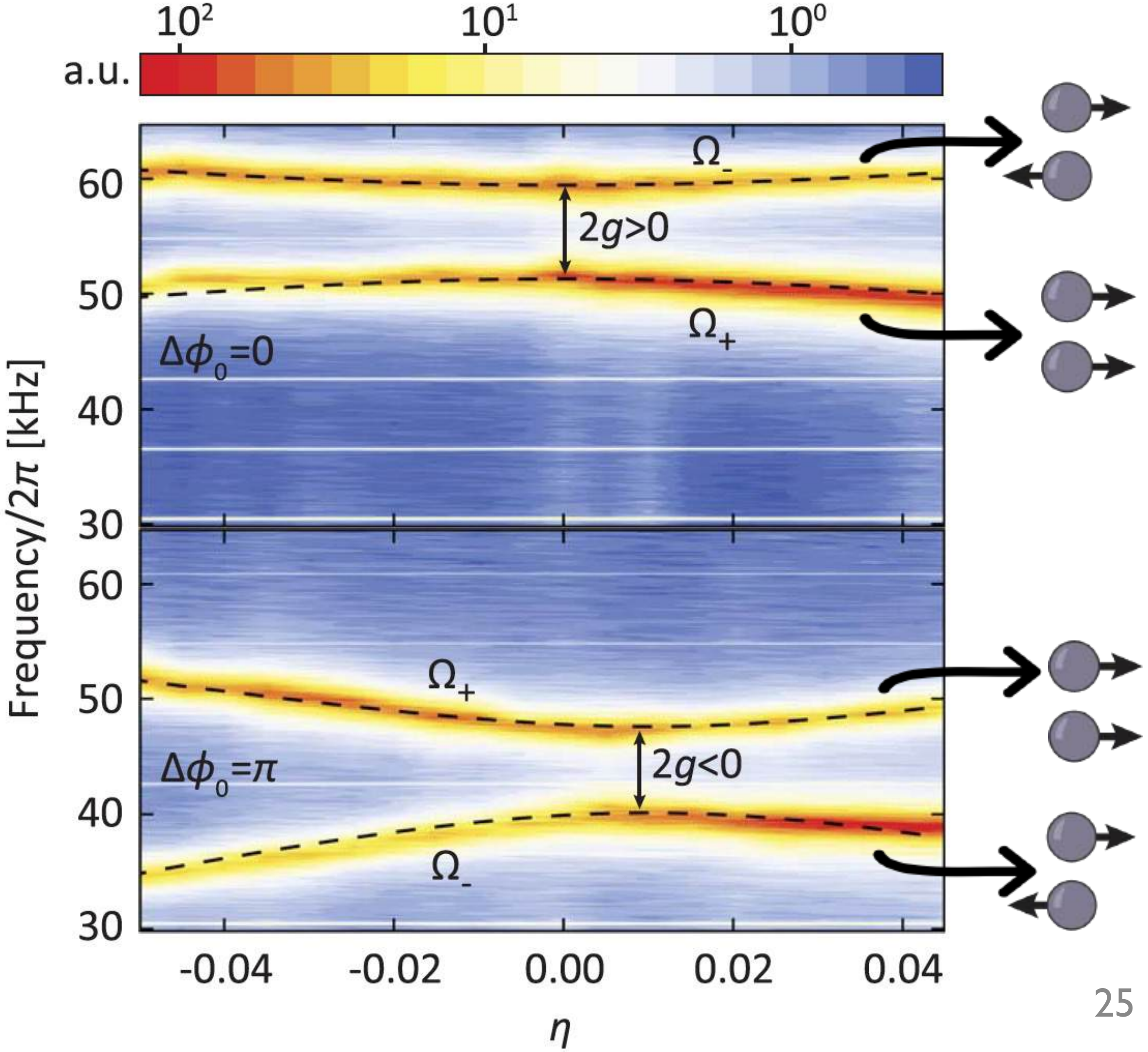
Reciprocal interaction







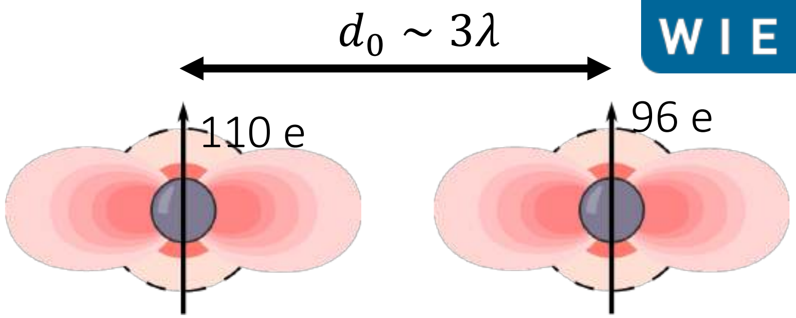


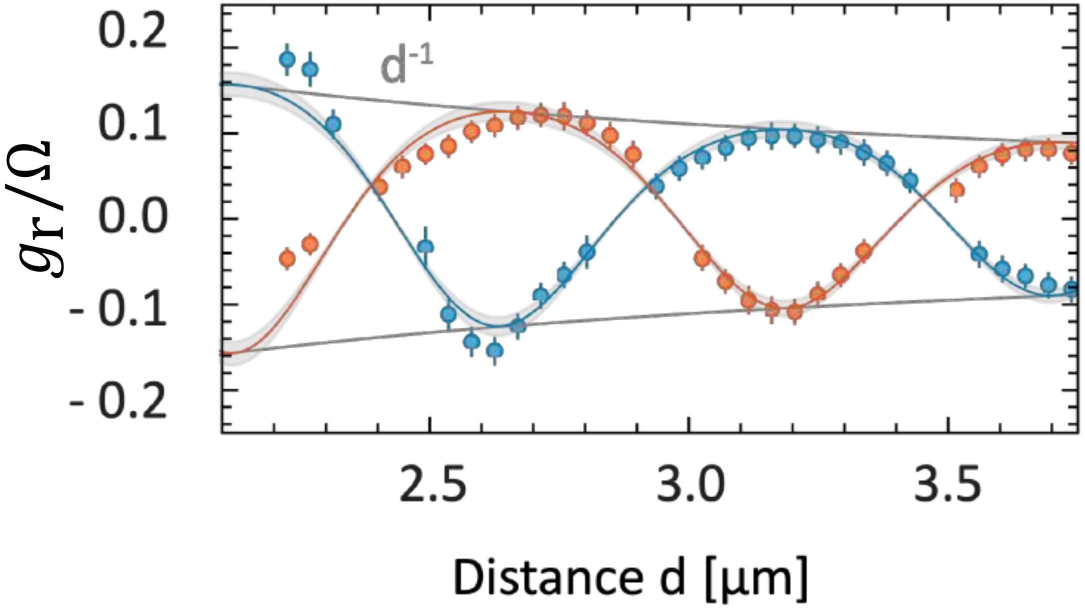


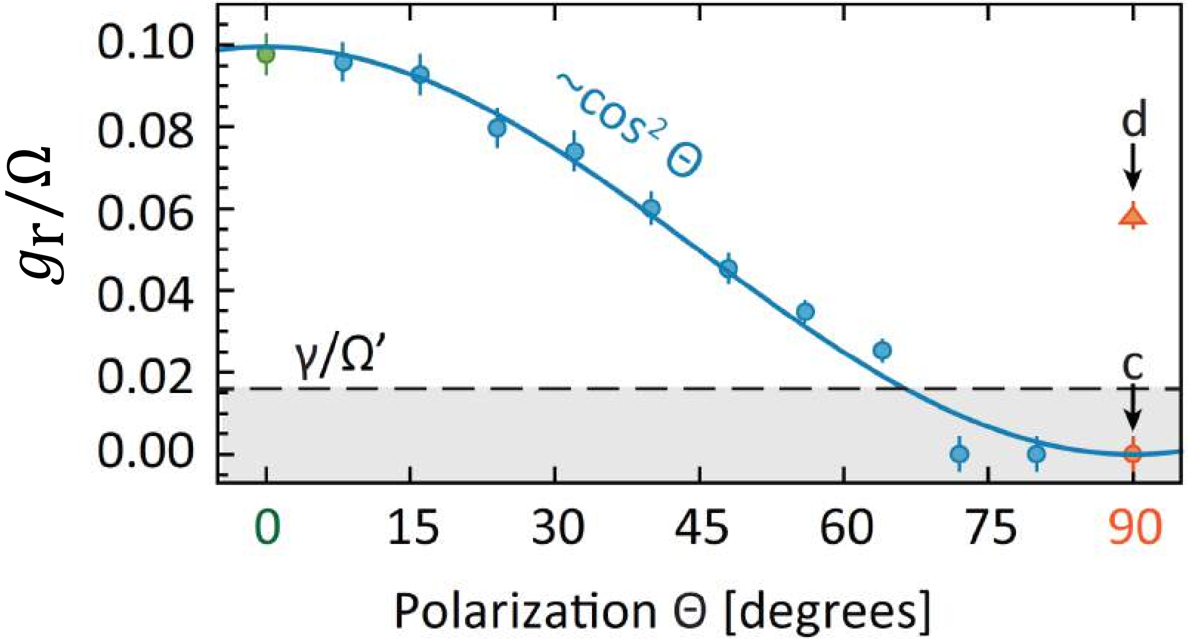
Eigenfrequencies: $\Omega_+ = \Omega$, $\Omega_- = \Omega + 2g_r$, $g_r \propto \cos\Delta\phi_0$

Rieser,..., Delic, **Science 377, 987 (2022)**

Reciprocal interaction





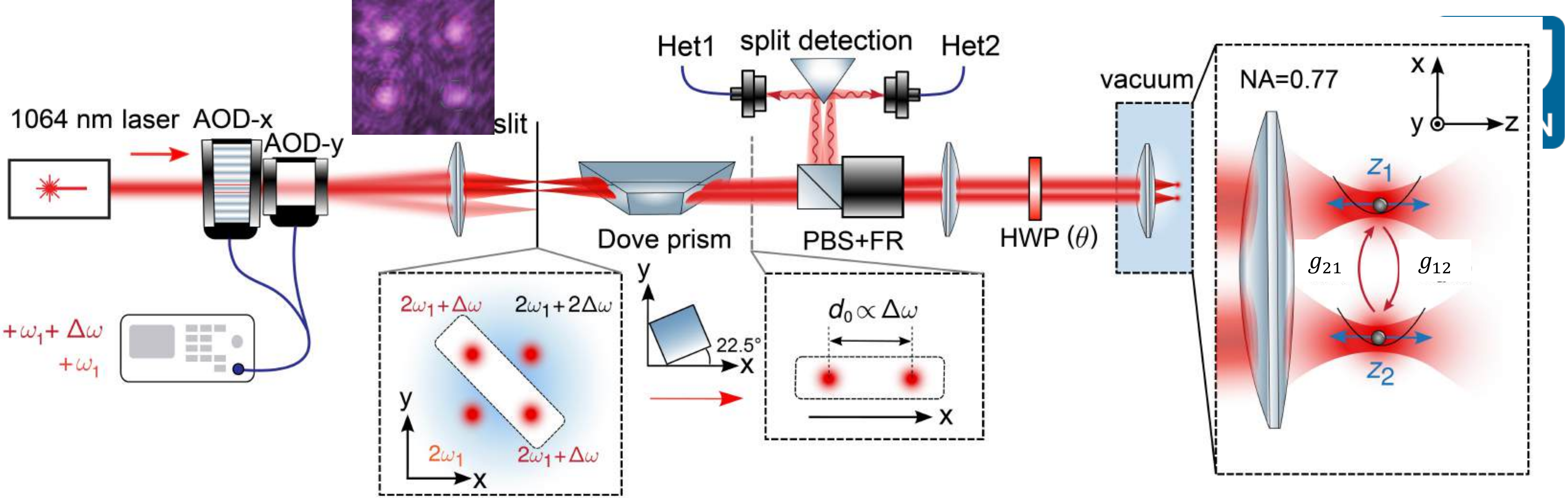


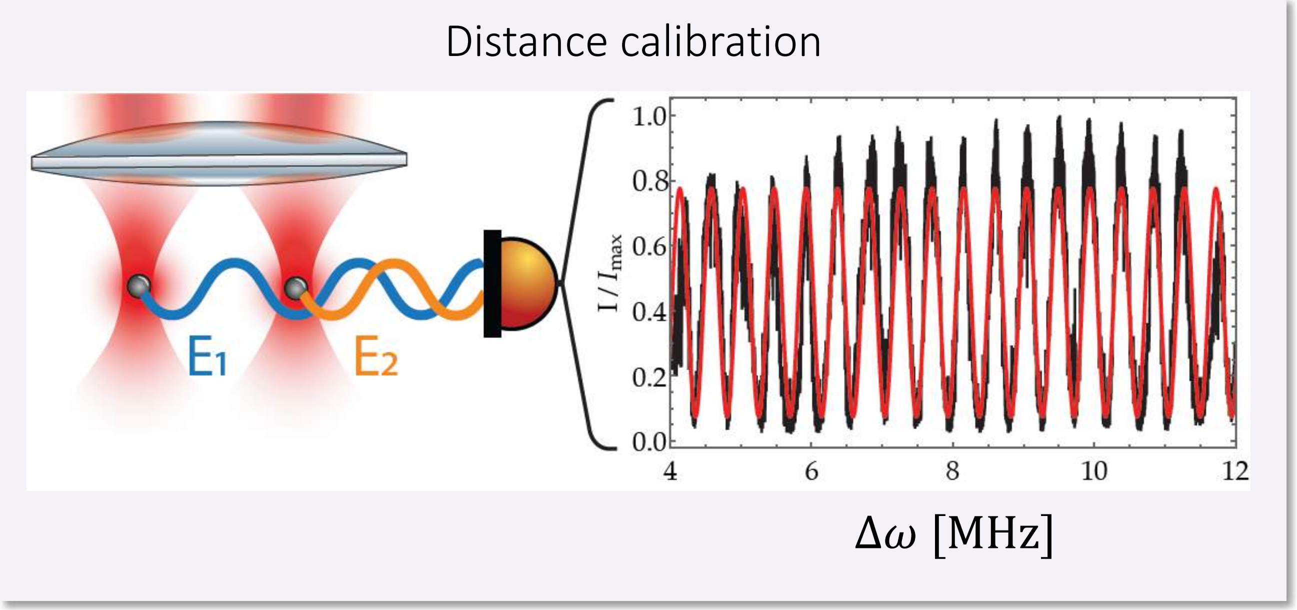
Distance larger than wavelength:
far-field dipole radiation: $g_r \propto \cos(kd)\cos\Delta\phi_0/d$

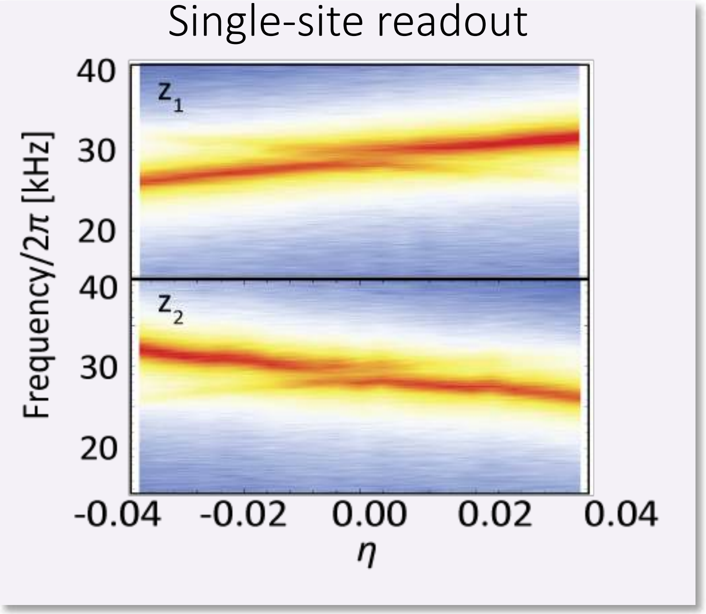
Far-field approximation: no magic angle

Rieser,..., Delic, **Science 377, 987 (2022)**

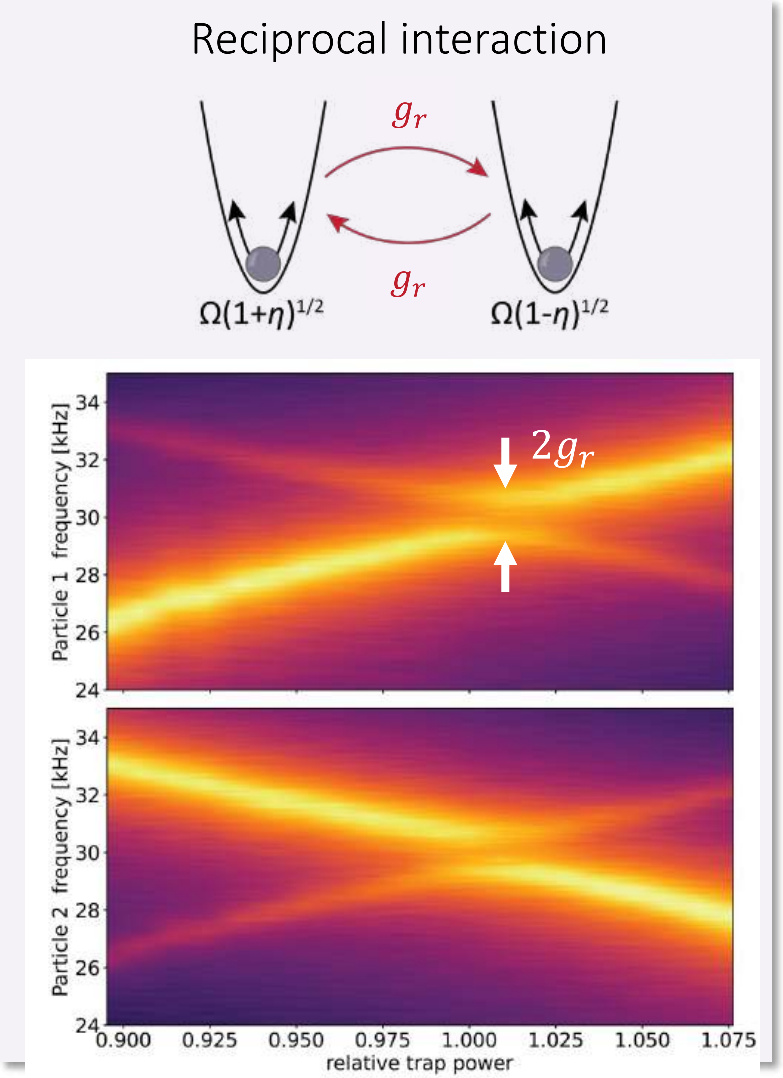
Also: Zemánek (Brno), Vijayan (Manchester) & Novotny (ETH), Marin (Florence), Huizhu Hu (Zheijang)

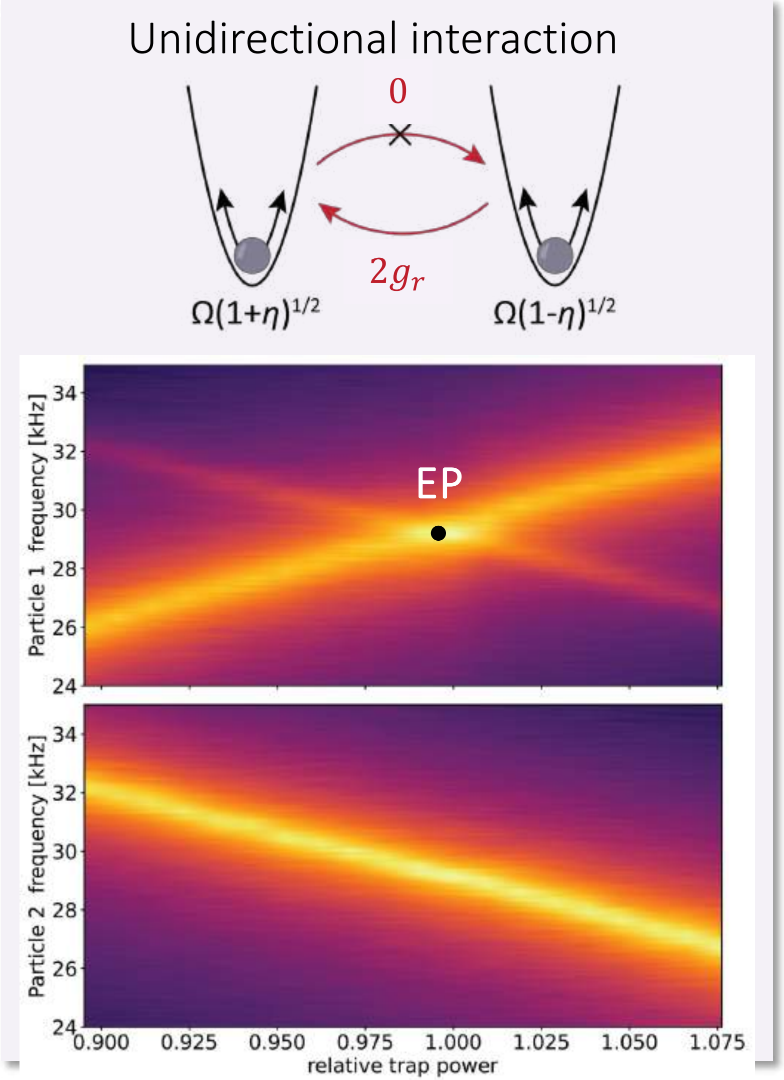

1064 nm laser
AOD-x
AOD-y
slit
Het1
split detection
Het2
vacuum
NA=0.77
Dove prism
PBS+FR
HWP (θ)
$+\omega_1+\Delta\omega$
$+\omega_1$
$2\omega_1+\Delta\omega$
$2\omega_1+2\Delta\omega$
$2\omega_1$
$2\omega_1+\Delta\omega$
22.5°
$d_0 \propto \Delta\omega$
z_1
z_2
g_{21}
g_{12}

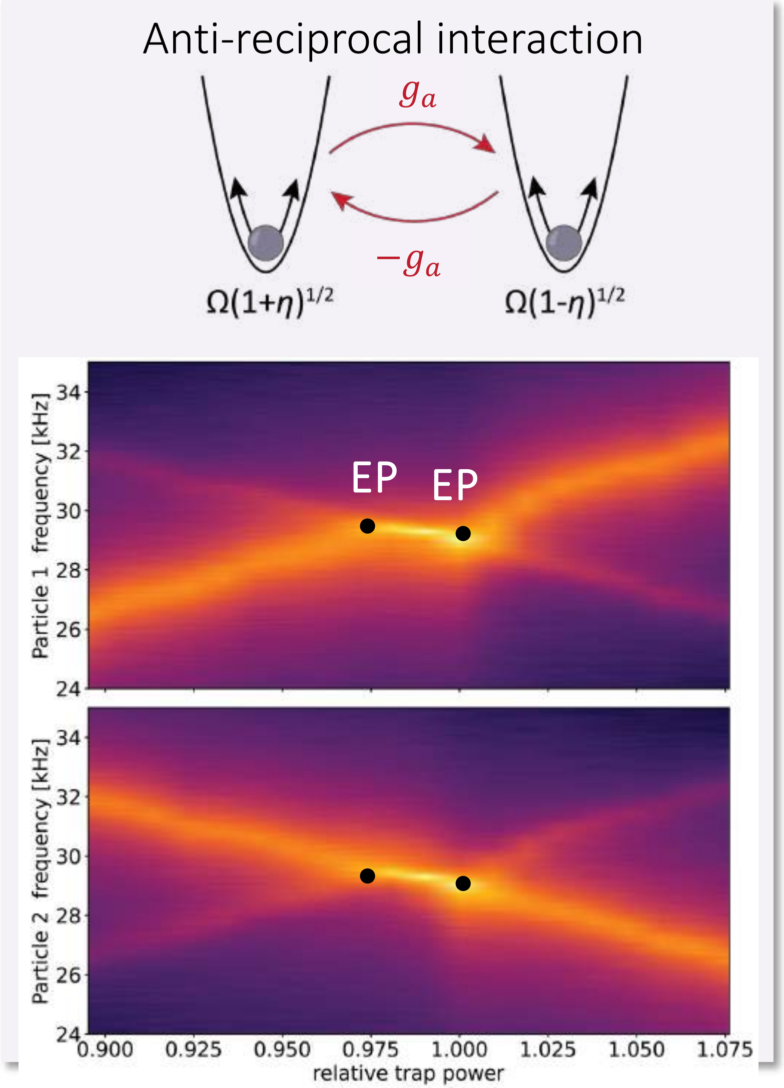

Distance calibration
E1
E2
I / I_max
Δω [MHz]


Single-site readout
Frequency/2π [kHz]
z1
z2
η

Interaction types

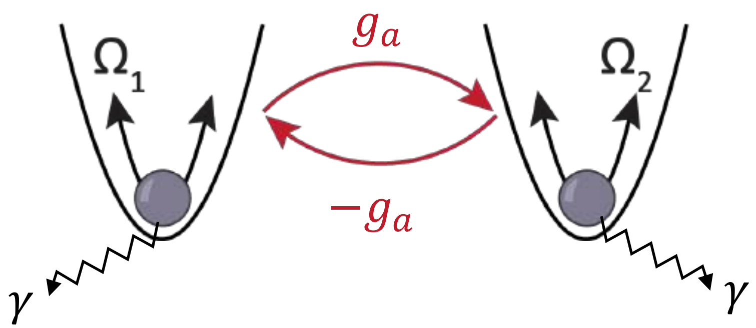






Anti-reciprocal interaction

"Predator-prey" dynamics

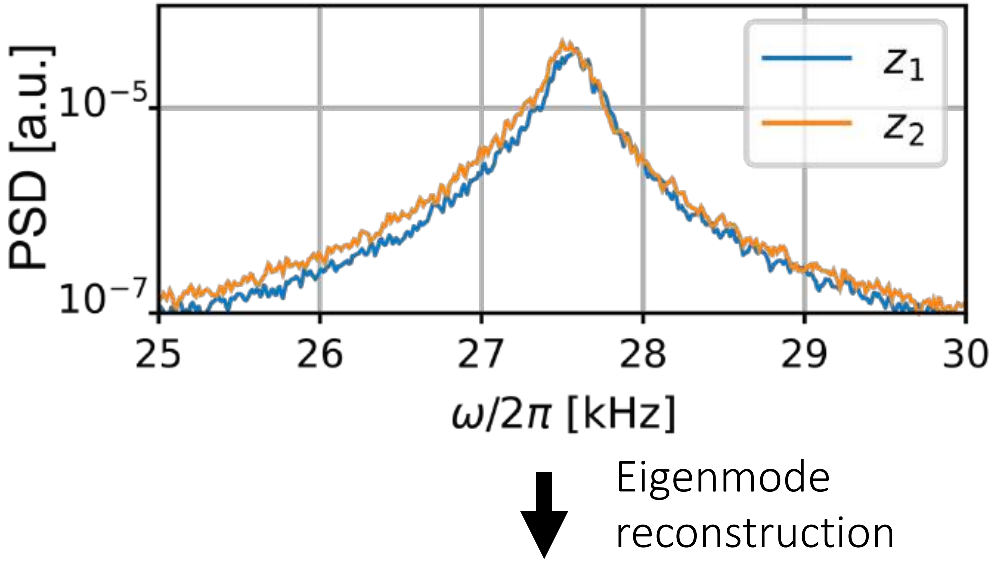


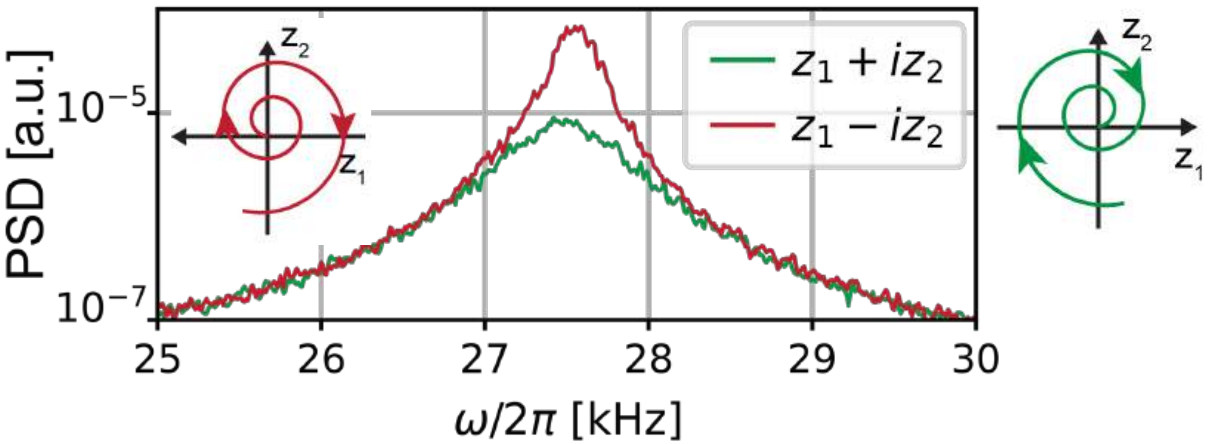
General eigenmode frequencies:

$$\Omega_\pm = \Omega + g_r + \mathrm{i}\frac{\gamma}{2} \mp \sqrt{g_r^2 - g_a^2}$$

For purely non-conservative interaction:

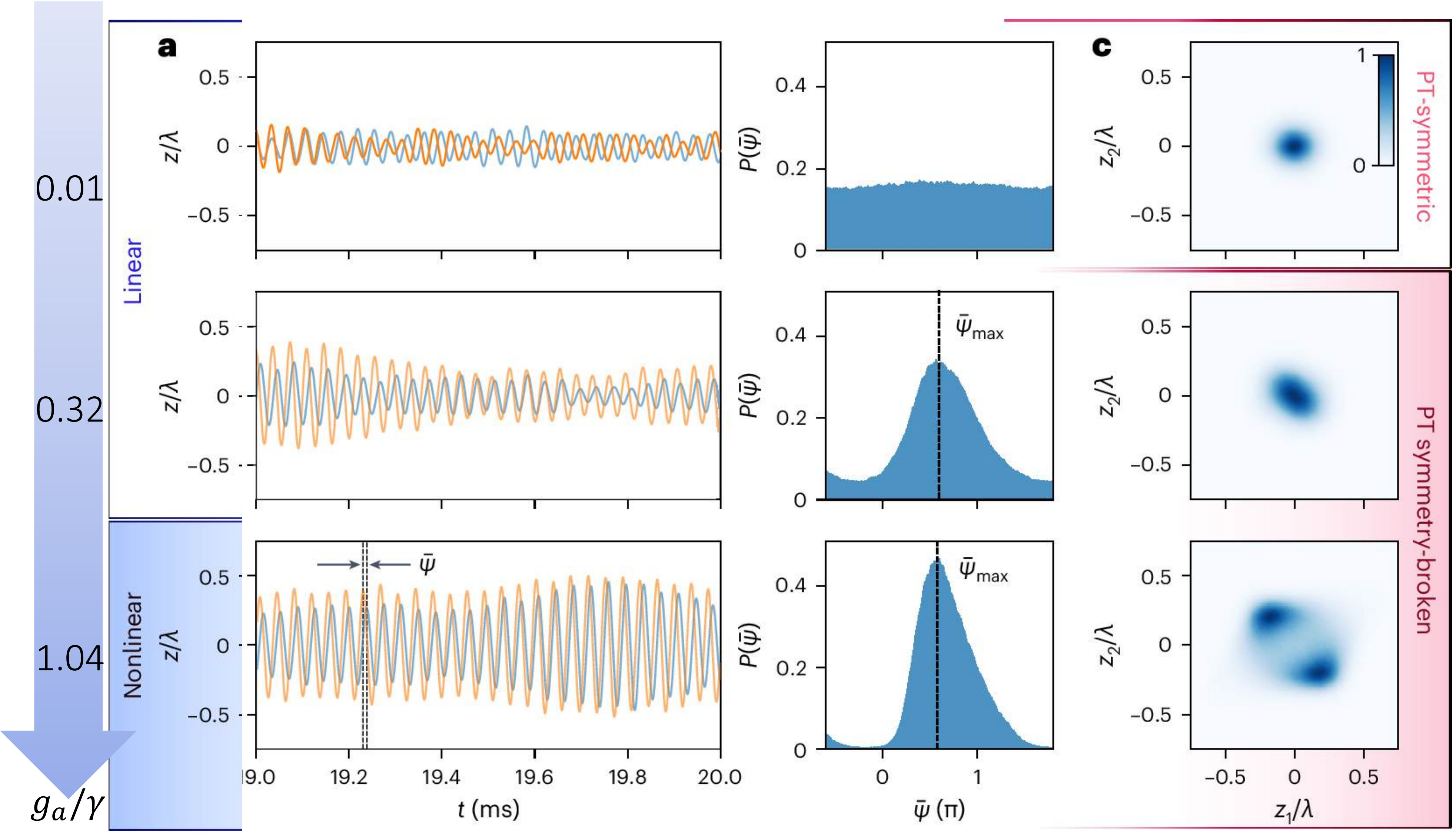
$$\boxed{\Omega_+ = \Omega + \mathrm{i}\left(\frac{\gamma}{2} - |g_a|\right),\ \Omega_- = \Omega + \mathrm{i}\left(\frac{\gamma}{2} + |g_a|\right)}$$





Reisenbauer, Rudolph, Egyed *et al.*, Nature Physics 20, 1629 (2024)

Non-Hermitian "phase transition"



Non-degenerate frequency
Degenerate damping
No cross-correlation

Degenerate frequency
Non-degenerate damping
Fixed relative phase

Degenerate frequency
Non-degenerate damping
Fixed relative phase
Equal amplitudes & limit cycle

Reisenbauer, Rudolph, Egyed *et al.*, Nature Physics 20, 1629 (2024)

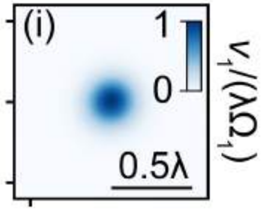
Hopf bifurcation into limit cycles

Due to the **nonlinear forces** (and not due to trap nonlinearity):

small g_a/γ

1 $A = 0$

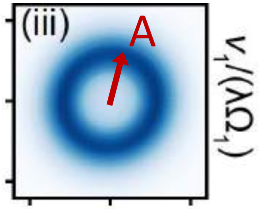
$$\sin\left(\frac{\psi}{2}\right) = \sqrt{\Delta\Omega/4g_a}$$



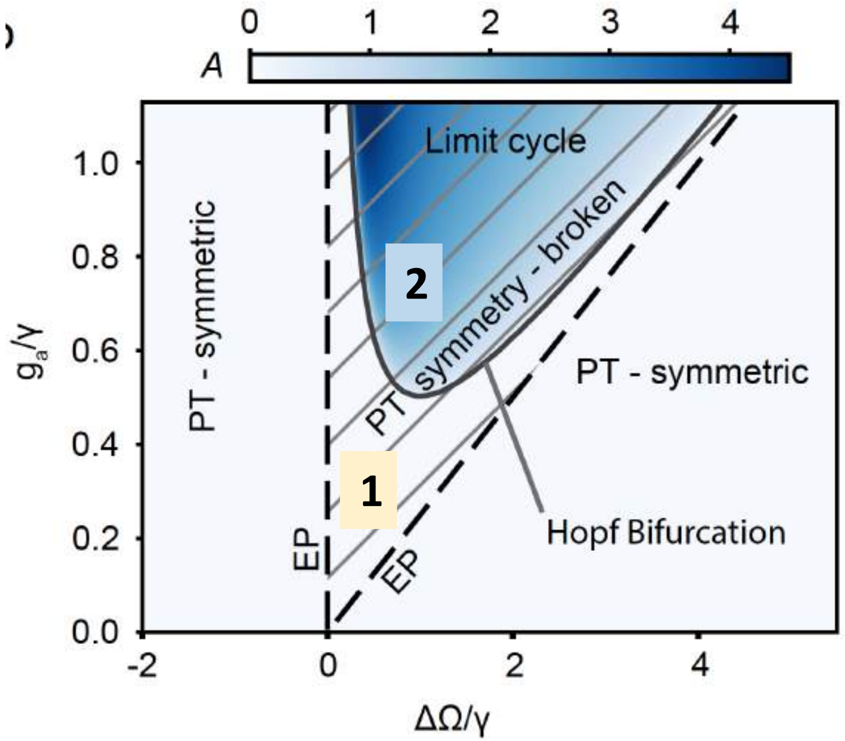
large g_a/γ

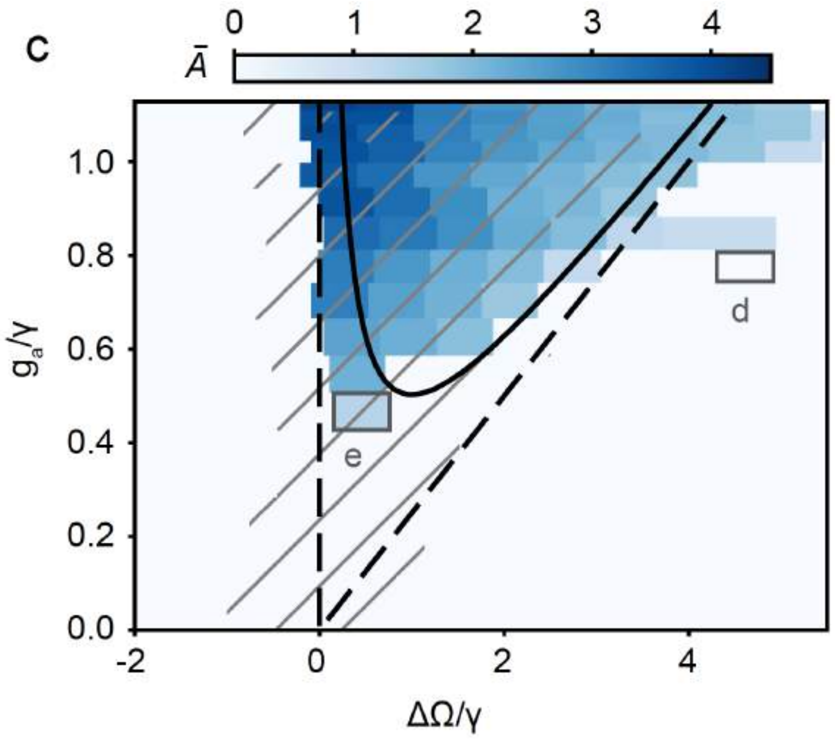
2 $A \neq 0$

$$\tan\left(\frac{\psi}{2}\right) = \frac{\Delta\Omega}{\gamma}$$



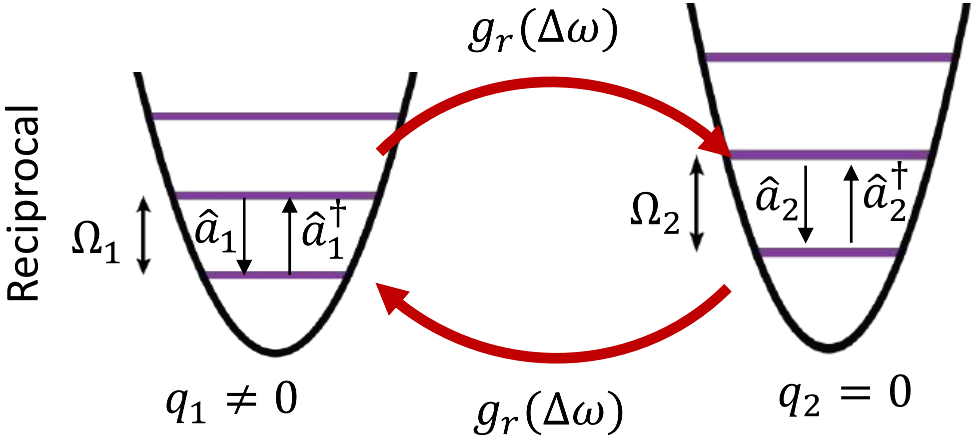
"mechanical lasing"
"superradiance"

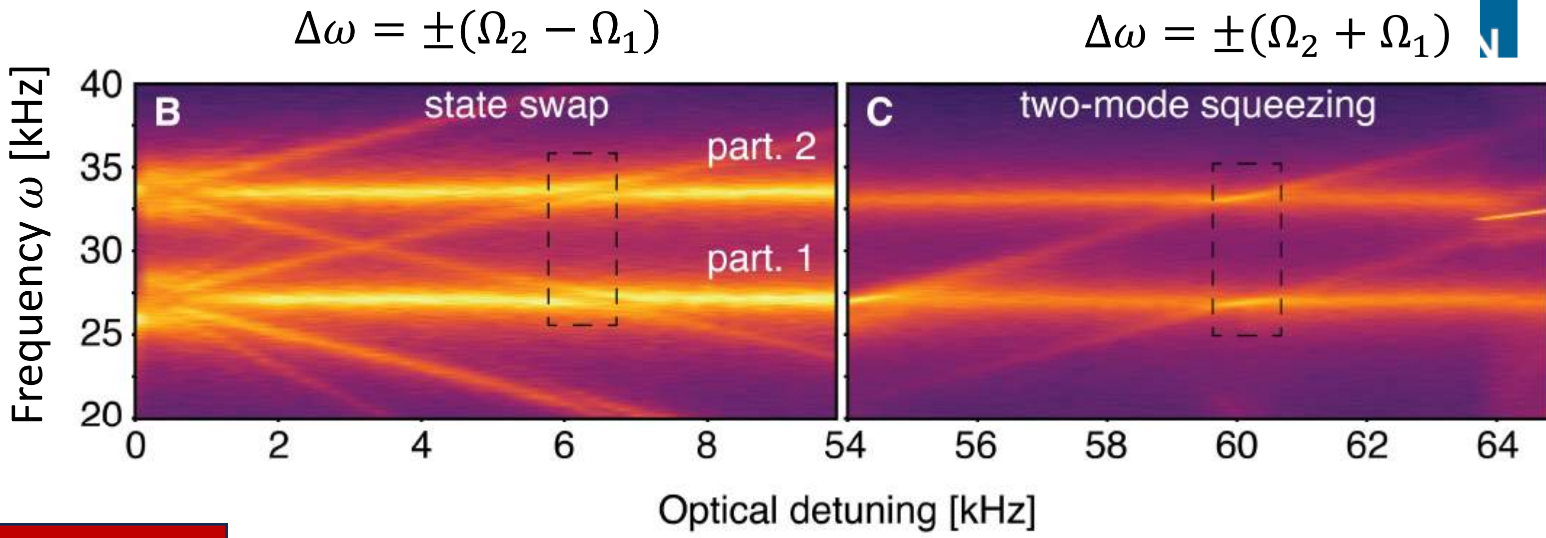


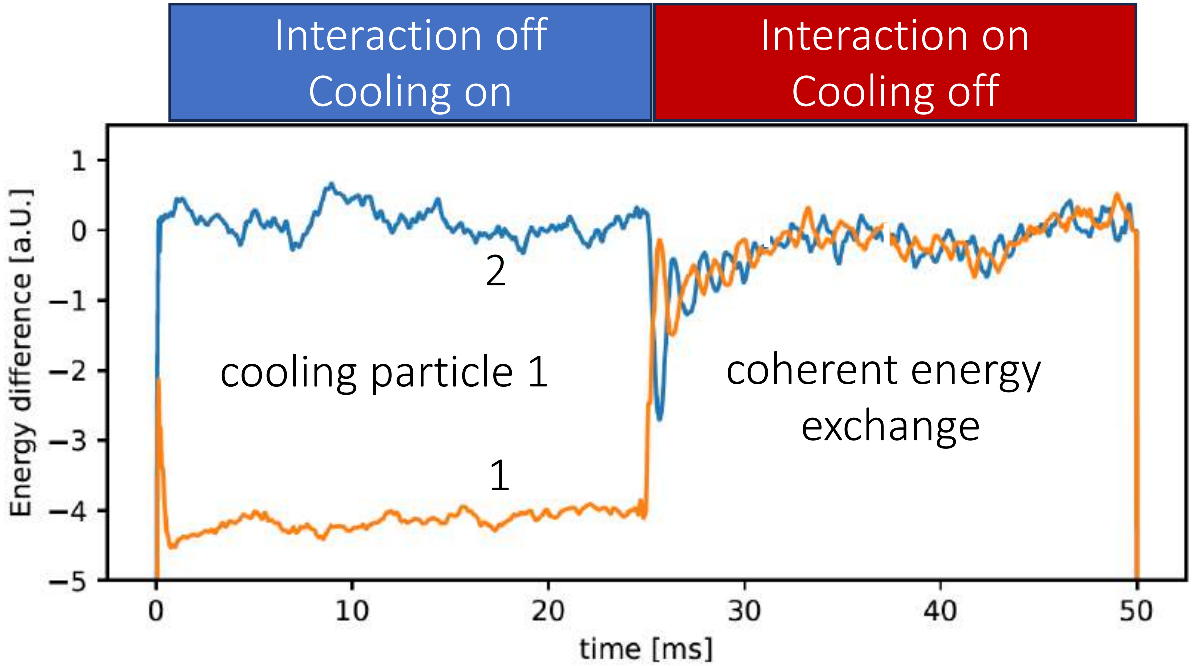


Reisenbauer, Rudolph, Egyed *et al.*, Nature Physics 20, 1629 (2024)

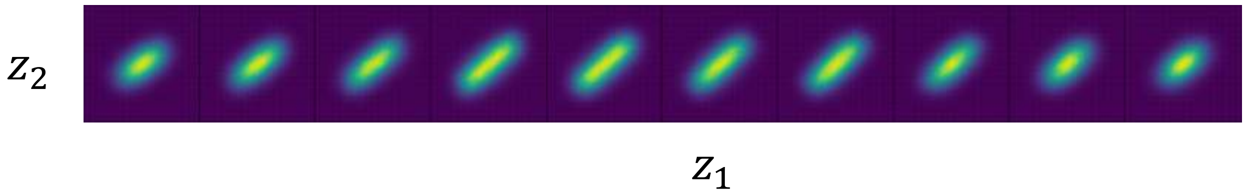
Floquet engineering of interactions





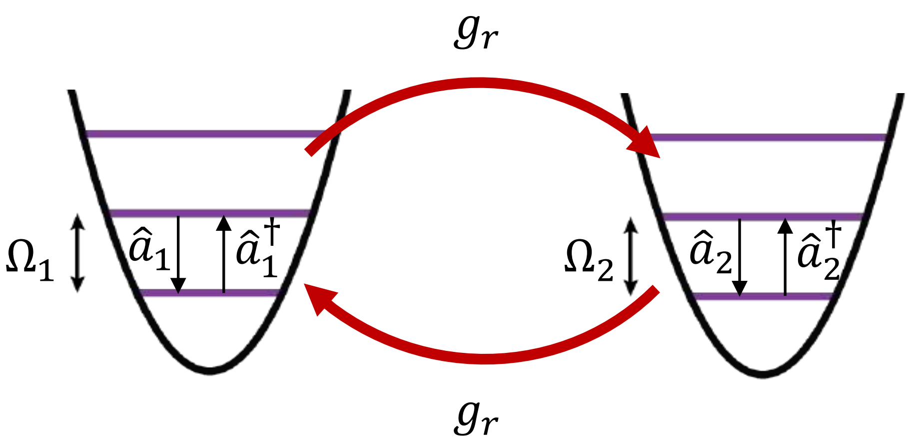


Two-mode squeezing

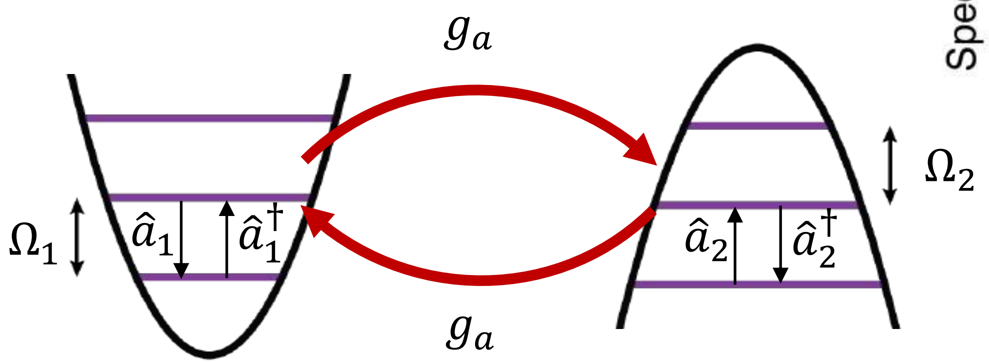


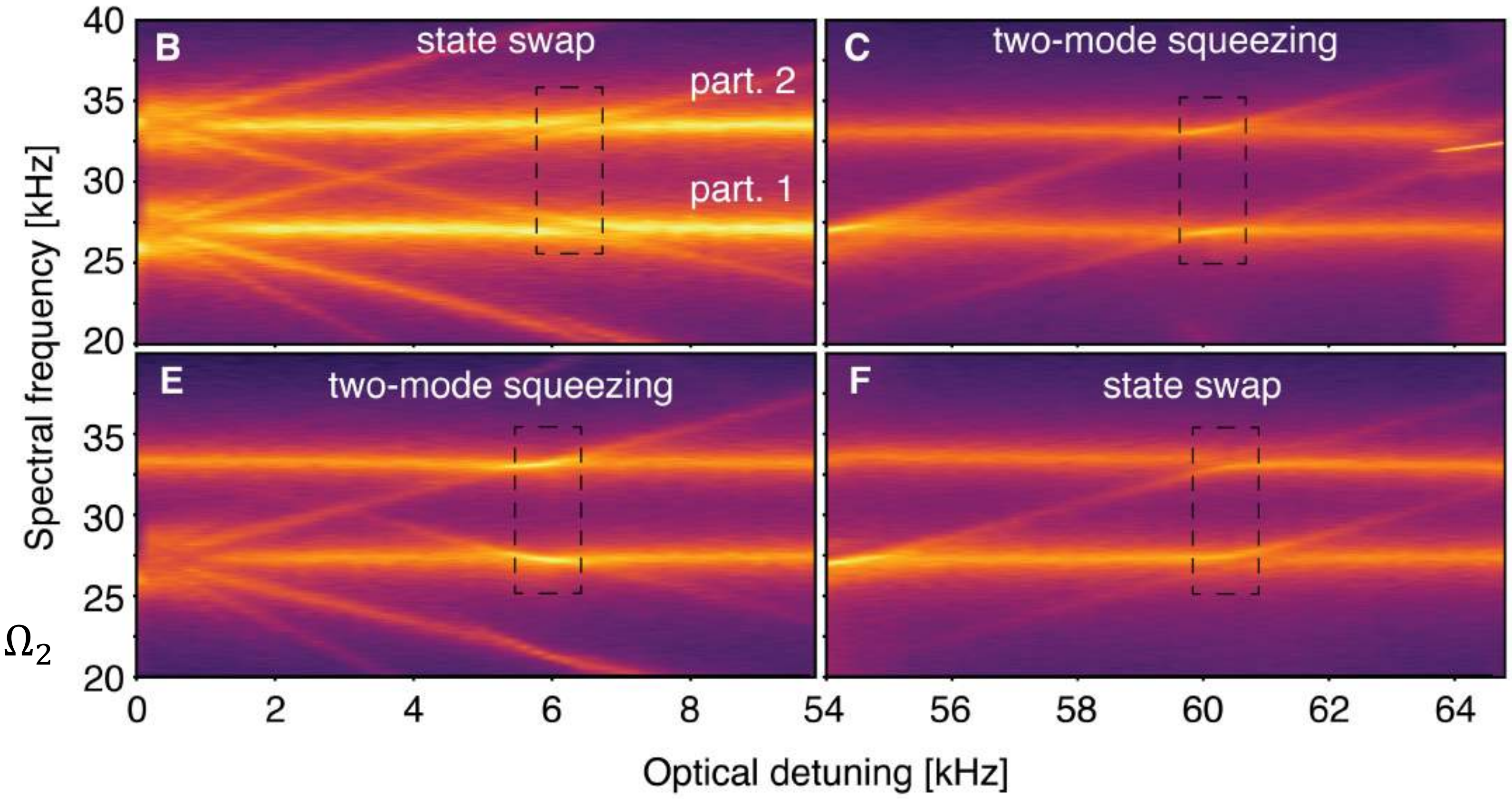
Egyed, Abuzarli, Reisenbauer, Coroli, Stickler, **Delic**, *in preparation*

Preliminary data



Effective picture in the rotating frame



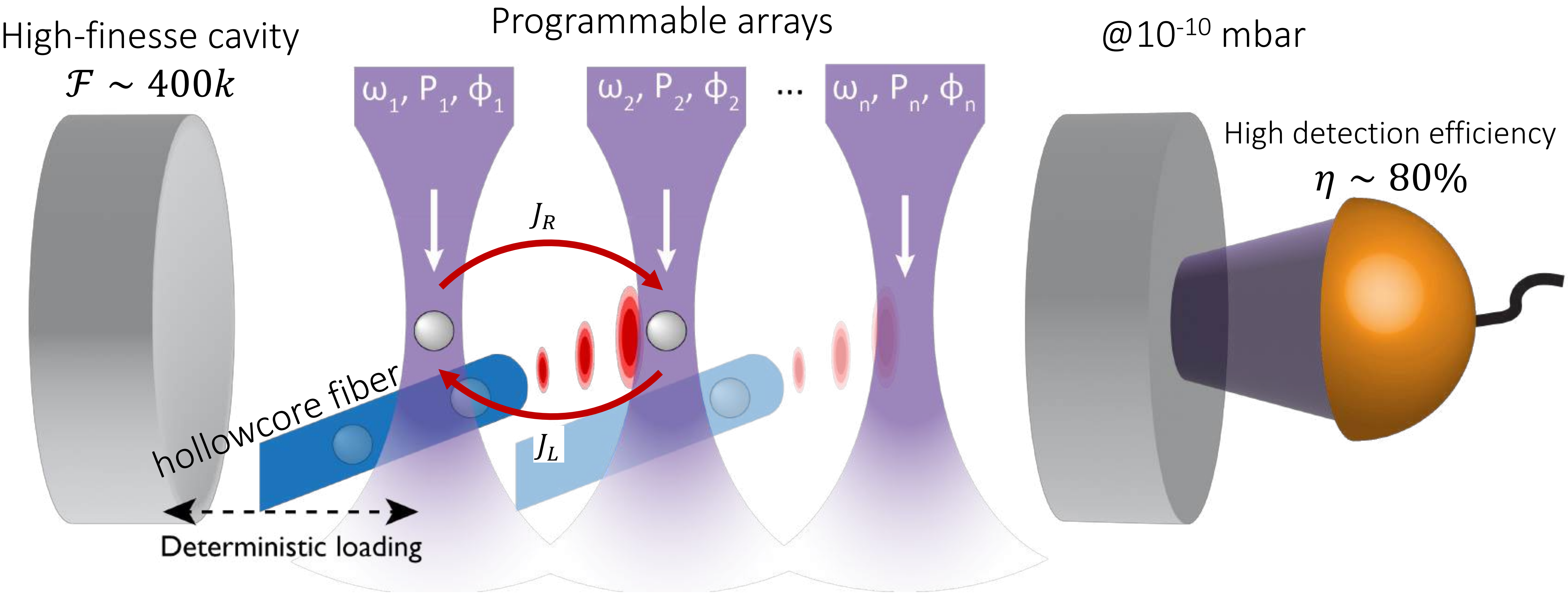


See also: Treutlein, Polzik, Sillanpää

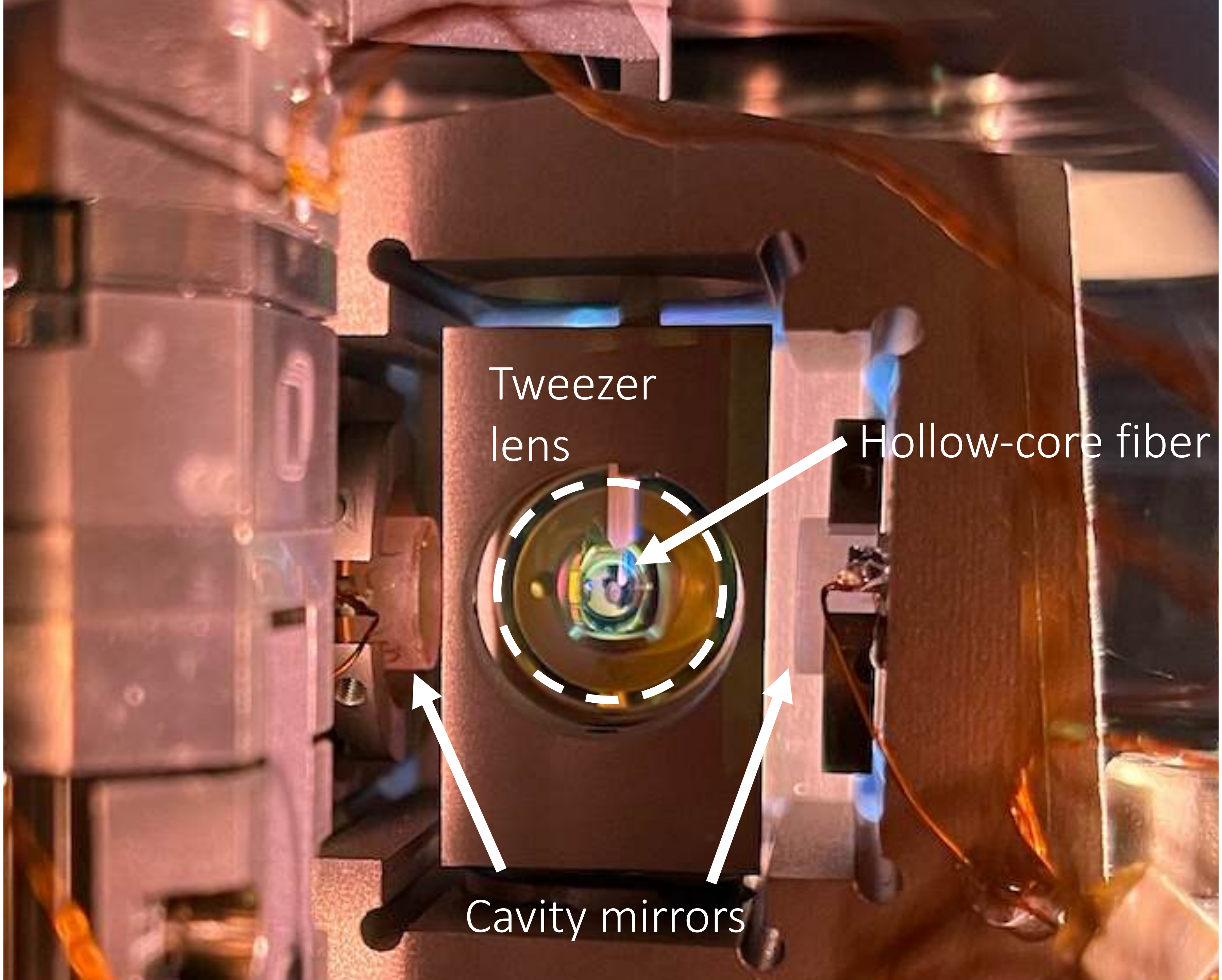
Egyed, Abuzarli, Reisenbauer, Coroli, Stickler, **Delic**, *in preparation*

Preliminary data

Next step: Integration with a cavity

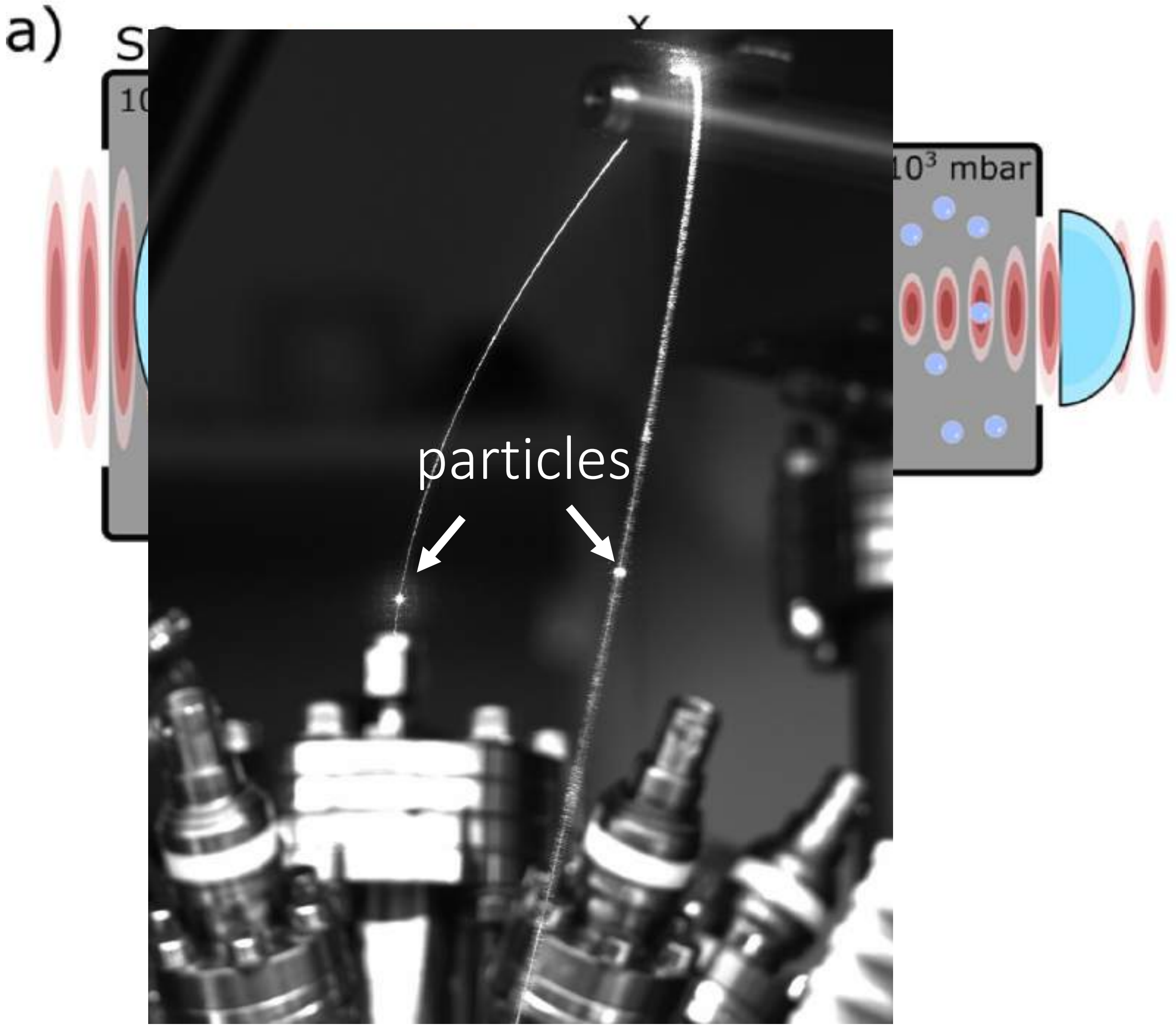


Loading through a hollowcore fiber: Appl. Phys. Lett. 124, 143501 (2024)


Tweezer
lens
Hollow-core fiber
Cavity mirrors

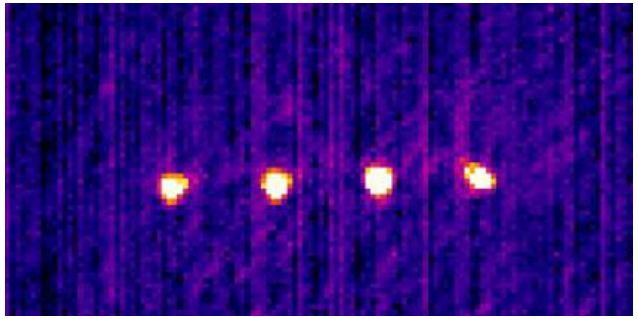

Iurie Coroli

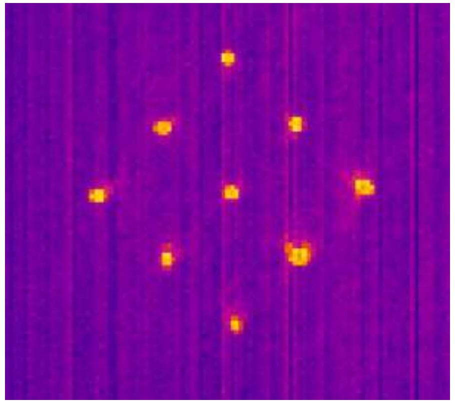
Loading through a hollow-core fiber

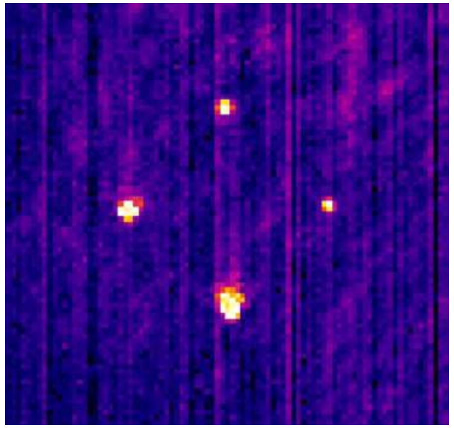


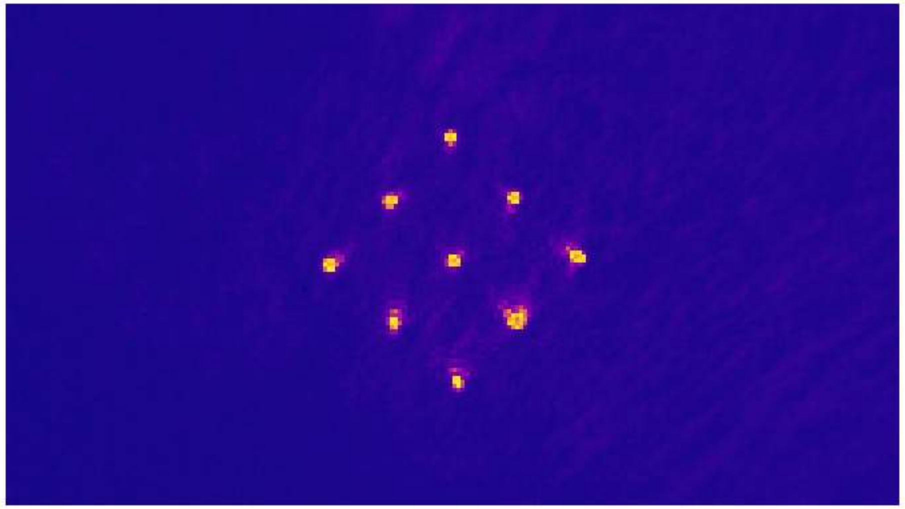
Kiesel group, Appl. Phys. Lett. 124, 143501 (2024)

Deterministic tweezer arrays


4-particle 1D array, equal optical frequencies
5 µm spacing


3x3-particle array
15 µm spacing

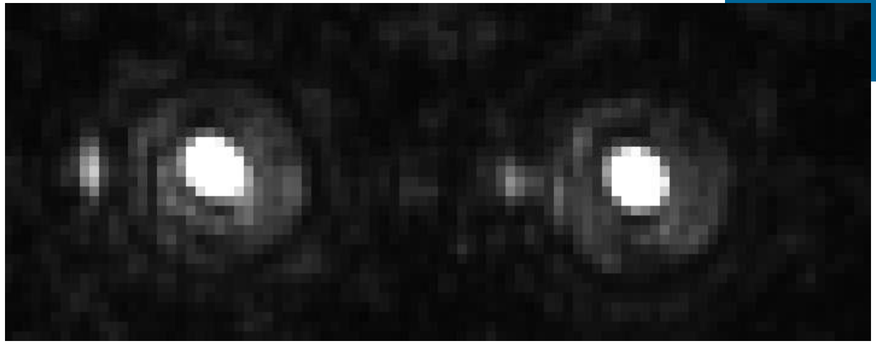

2x2-particle array
15 µm spacing


3x3-particle array
shrinking spacing from 15µm to 5 µm

Our research

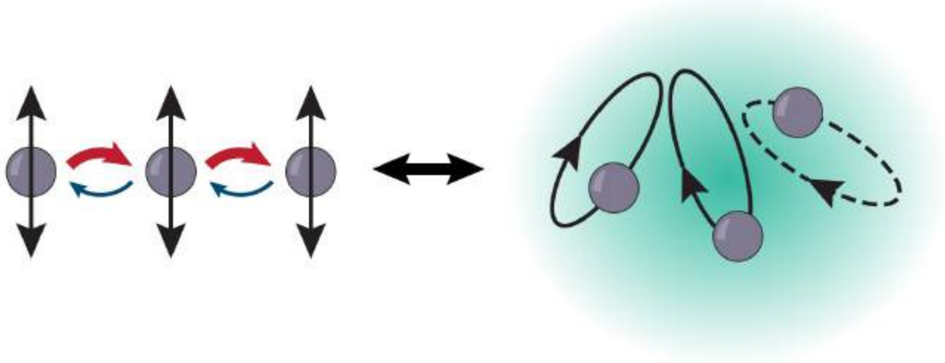
Light-induced dipole-dipole forces

Exploring the quantum limits of the light-mediated interaction



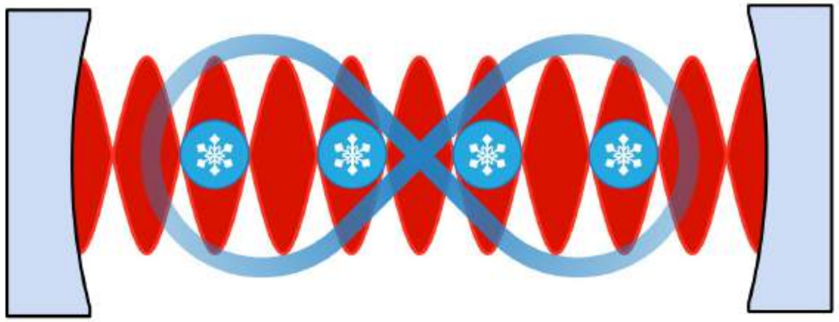
Collective quantum effects in nonreciprocal systems

Investigating nonreciprocal frustration and nonreciprocal/non-Hermitian phase transitions



Cavity engineering of quantum states

Using reservoir engineering for quantum many-body states

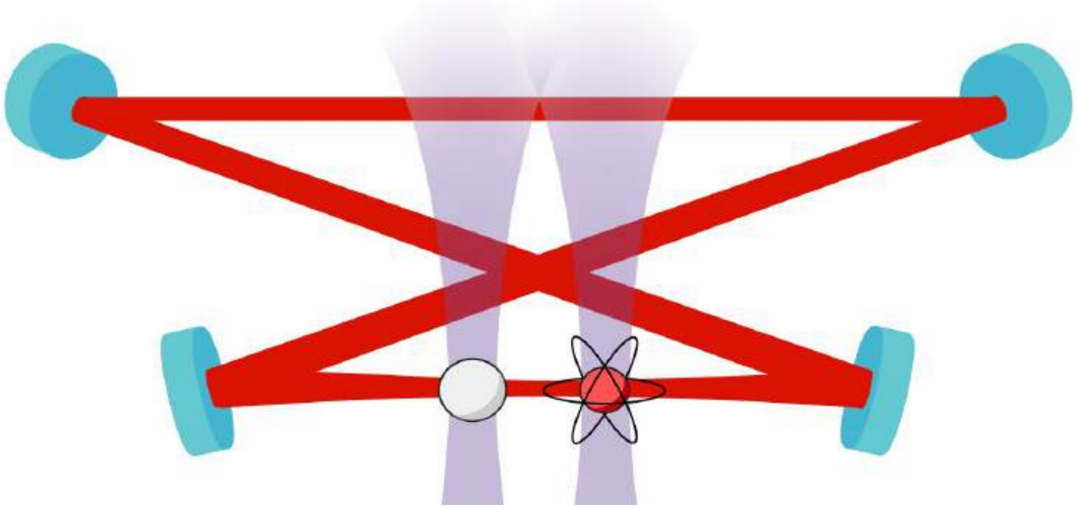


LIDD interactions enable hybrid systems

Hybrid atom – particle systems

polarizability of a single Cs atom, 100 MHz detuned = polarizability of a 150 nm nanoparticle

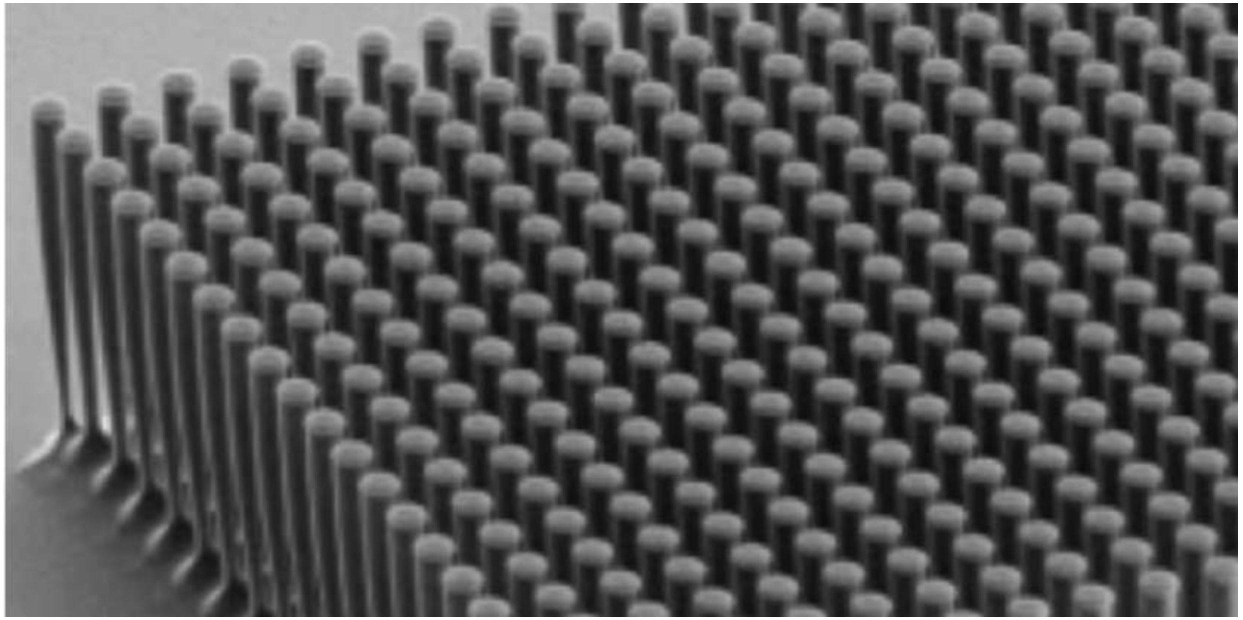
"impedance matching": polarizability/mass$^{1/2}$ can be easily tuned

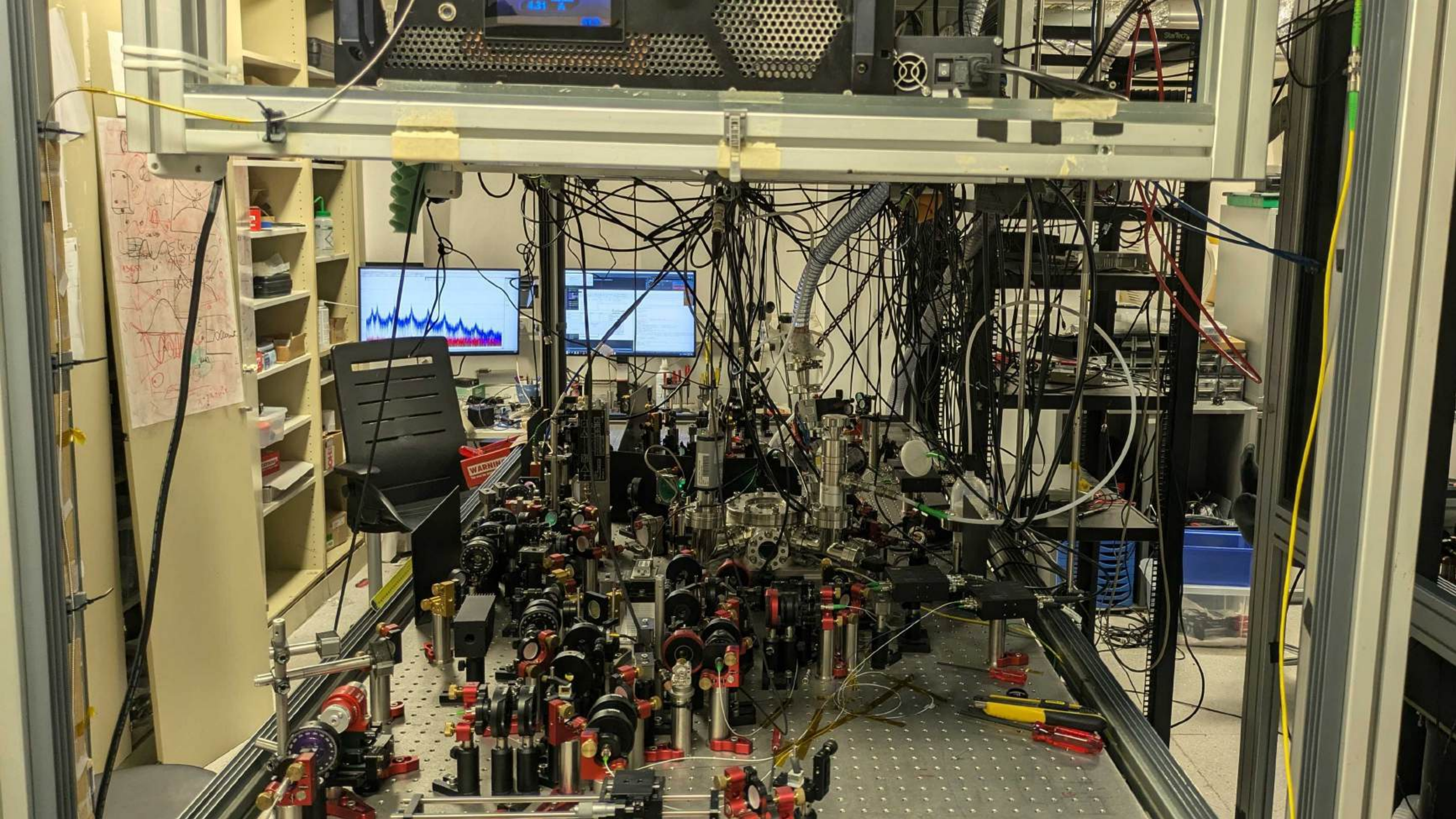


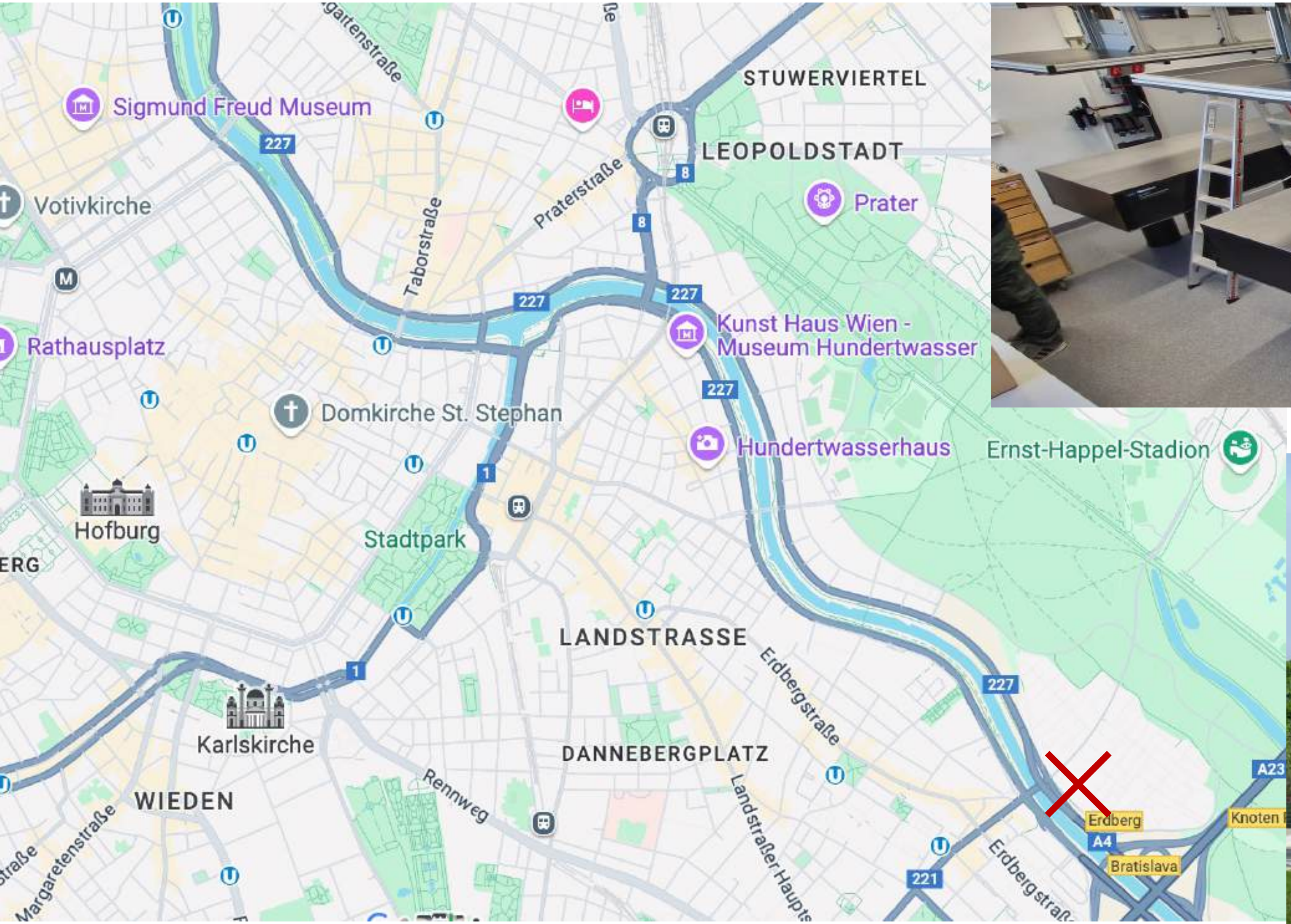
Nanopillar arrays

Studies of nonreciprocal long-range interactions for topology, localization, non-Hermitian physics…

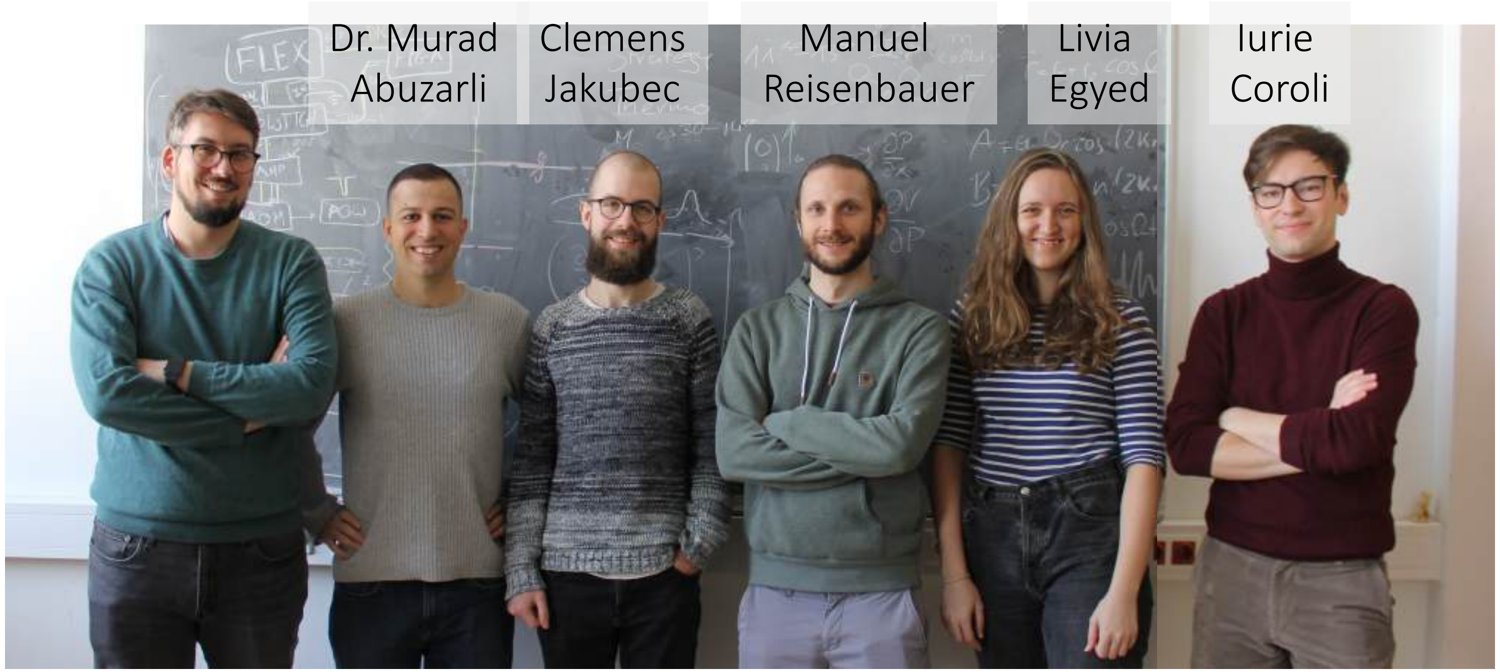
Pillars can be functionalized with quantum dots, rare-earth ions, or NV centers in diamond







Atominstitut of the TU Wien



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Ludovico Ricciardelli

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You?

TU WIEN

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