B6N Dimensional Crossover in Trapped Photon Gases

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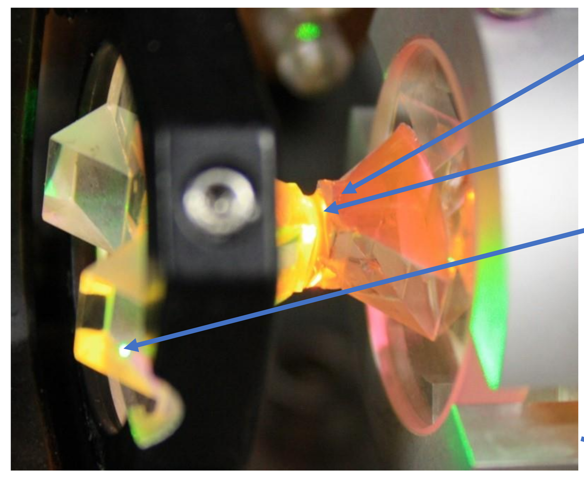
Preliminary work

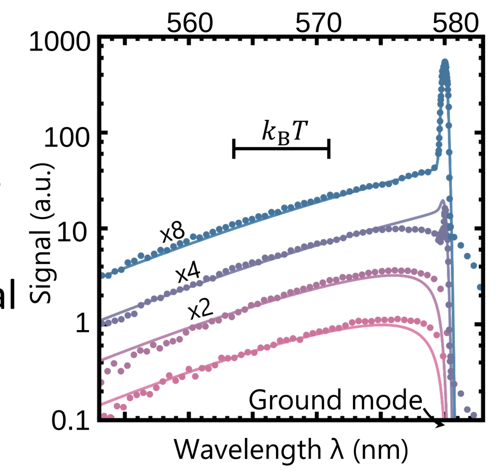
Bose-Einstein condensation of photons

B1

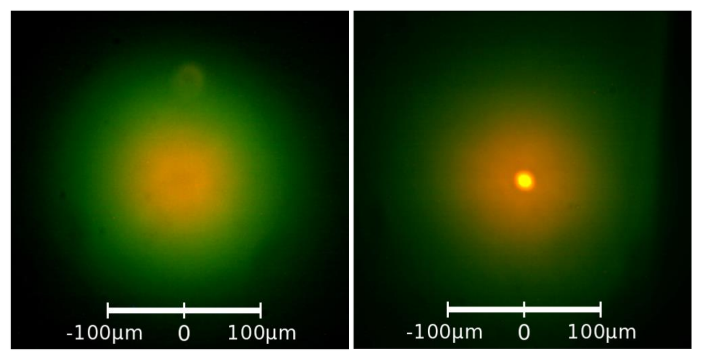


- High finesse cavity: Provides energy cutoff
- Dye solution: Heat and particle reservoir
- Pump radiation: Provides chemical potential

Energy distribution ⇒ Thermodynamic properties



Spatial information



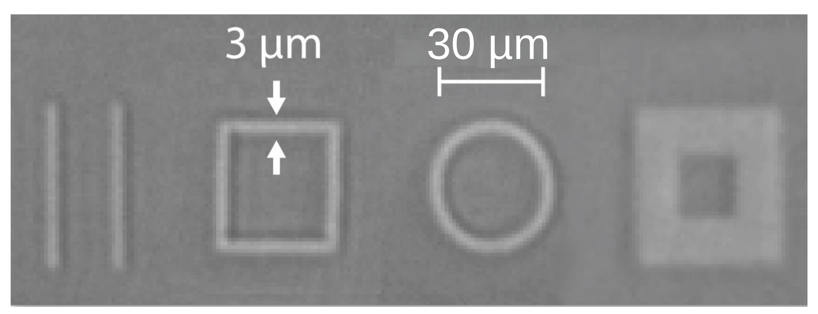
[1] J. Klaers *et al.* Nature **468**, 545 (2010)
[2] J. Klaers *et al.* Nat. Phys. **6**, 512 (2010)
[P2] T. Damm *et al.* Nature Commun. **7**, 11340 (2016)

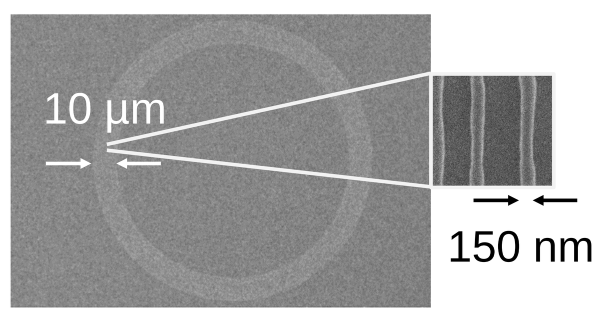
Structured mirror surfaces

Bonn
- Permanent structuring by mirror heating
- Transient structuring (thermosensitive polymer)

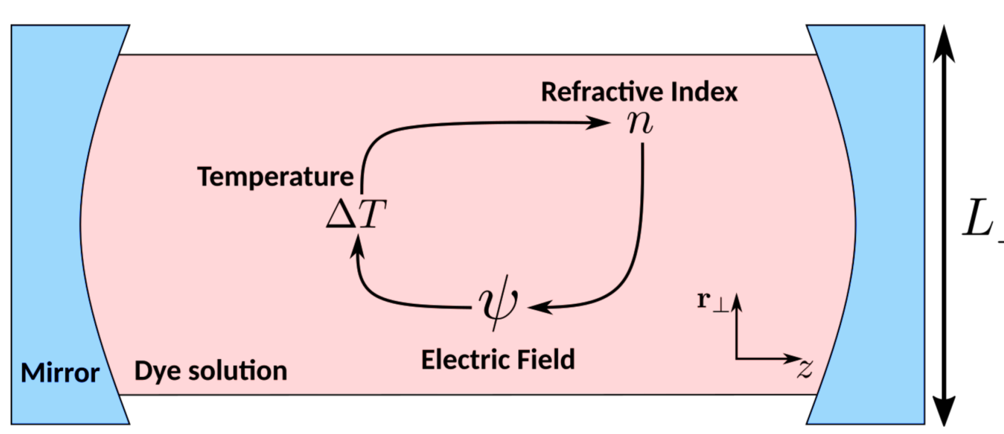
Kaiserslautern
- Direct laser writing
- Lithography

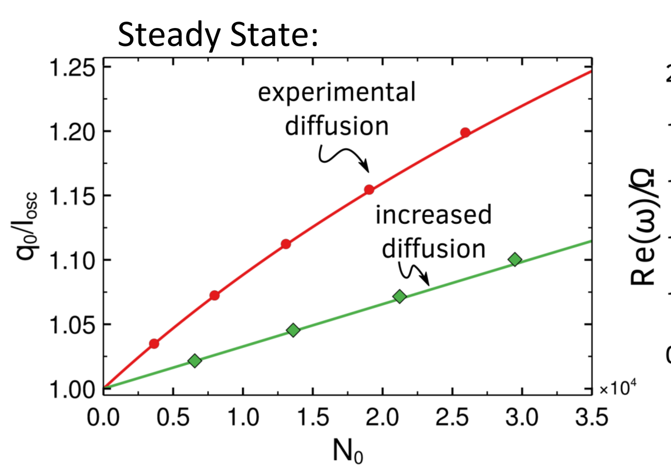
[P1] D. Dung *et al.* Nature Phot. **11**, 565 (2017)
[3] C. Kurtscheid *et al.* Science **366**, 894 (2019)

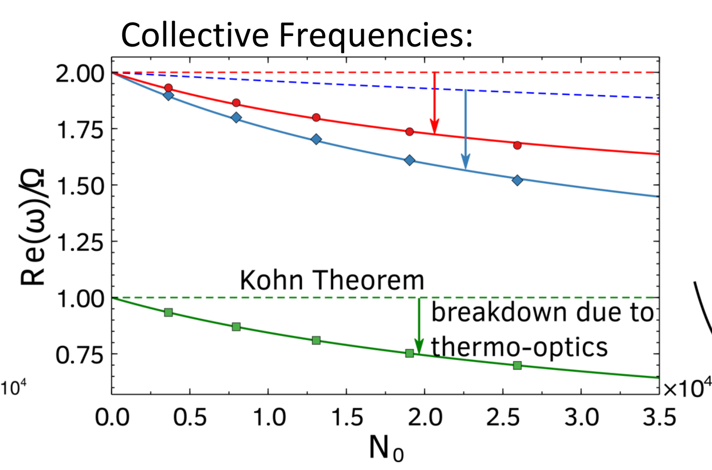


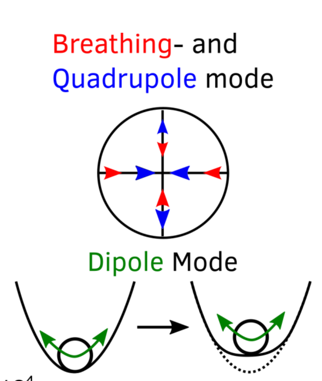


Mean-field model









Interaction strength: $\tilde{g} \propto L_\perp^2$

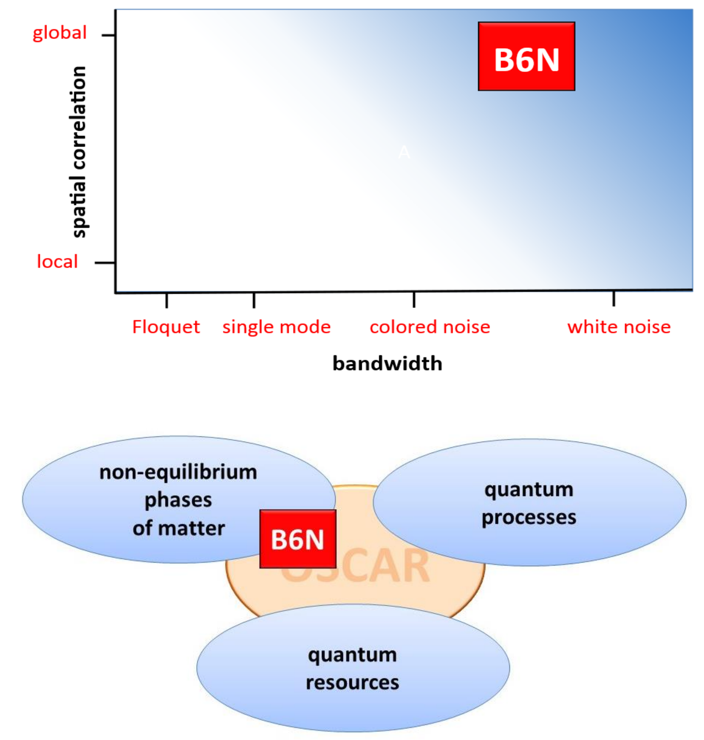
To be done: Decay rate $\mathrm{Im}(\omega)$ wrong due to exclusion of matter

[P7] M. Radonjić *et al.* NJP **20**, 055014 (2018); [P8] E. Stein *et al.* NJP **21**, 103044 (2019)

Motivation

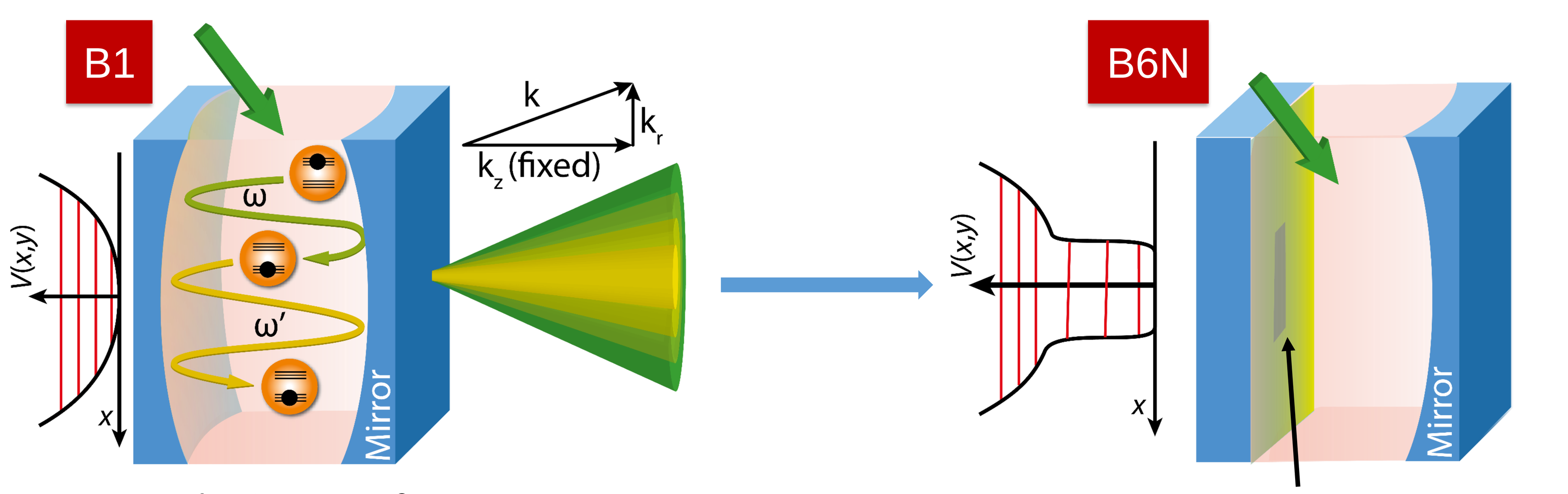
Vision
- Achieve first 1D photon condensate
- Understand dimensional crossover 2D ⟷ 1D
- Study dynamics of the system

Contribution to central questions
- Investigate steady-state properties of trapped photon gas in presence of external heat bath and particle reservoir, close to transition from 2D to 1D.
- Unravel influence of bath on thermodynamic properties (QB2)
- Determine correlations in presence of particle reservoir (QB2)



Trapping photons in structured potentials

Comparison: Photon BECs in OSCAR



Curved mirror surface ⇒ Parabolic potential

Microstructured mirror surface ⇒ Arbitrary confining potential

Task 1: Create potential landscapes for photons

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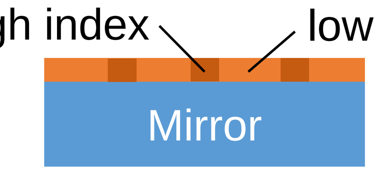
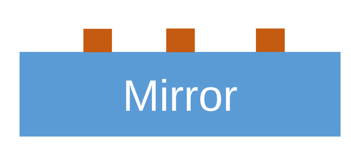
Refractive index contrast

high index low index



- As_2S_3: $\Delta n \approx 0.1$
- IP-L : $\Delta n \approx 0.01$

Lithography



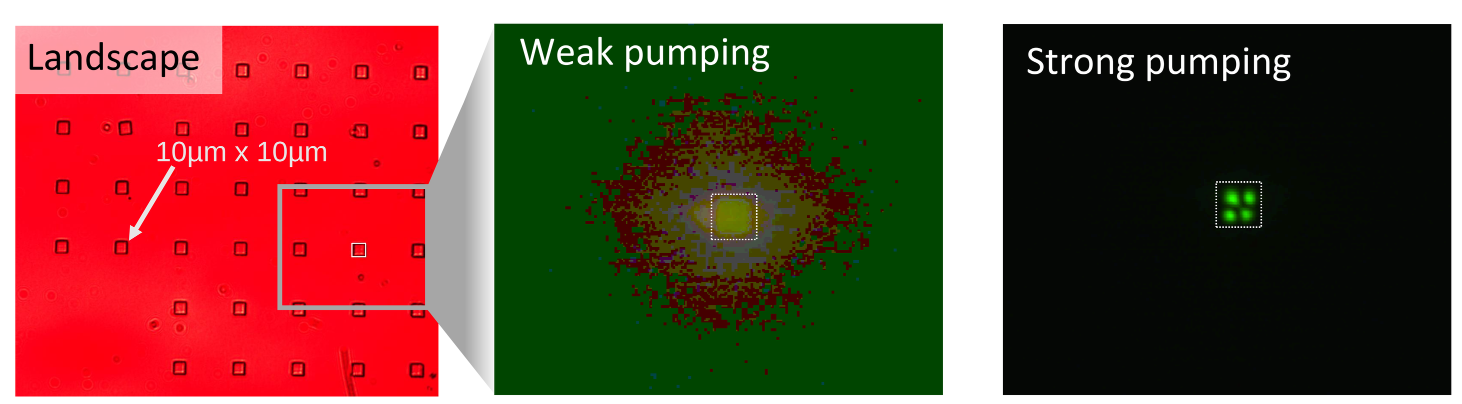
- $\Delta n \approx 0.1$

Focused ion beam milling

- He-ion FIB: to be installed 2021@KL

[P4] M. Deubel *et al.* Nature Mater. **3**, 444 (2004)
[P5] J.K. Hohmann *et al.* Adv. Optical Mater. **3**, 1488 (2015)
[P6] S.H. Wong *et al.* Adv. Mater. **18**, 26 (2006)

First test structures: IP-L on cavity mirror



Investigating trapped photons

Task 2: Extending mean-field model

Aim
- Revisit collective frequencies of harmonic trap as crosscheck
- Analyse steady-state properties of 1D gas and crossover 2D ⟷ 1D

Tools: Projected Gross-Pitaevskii Equation

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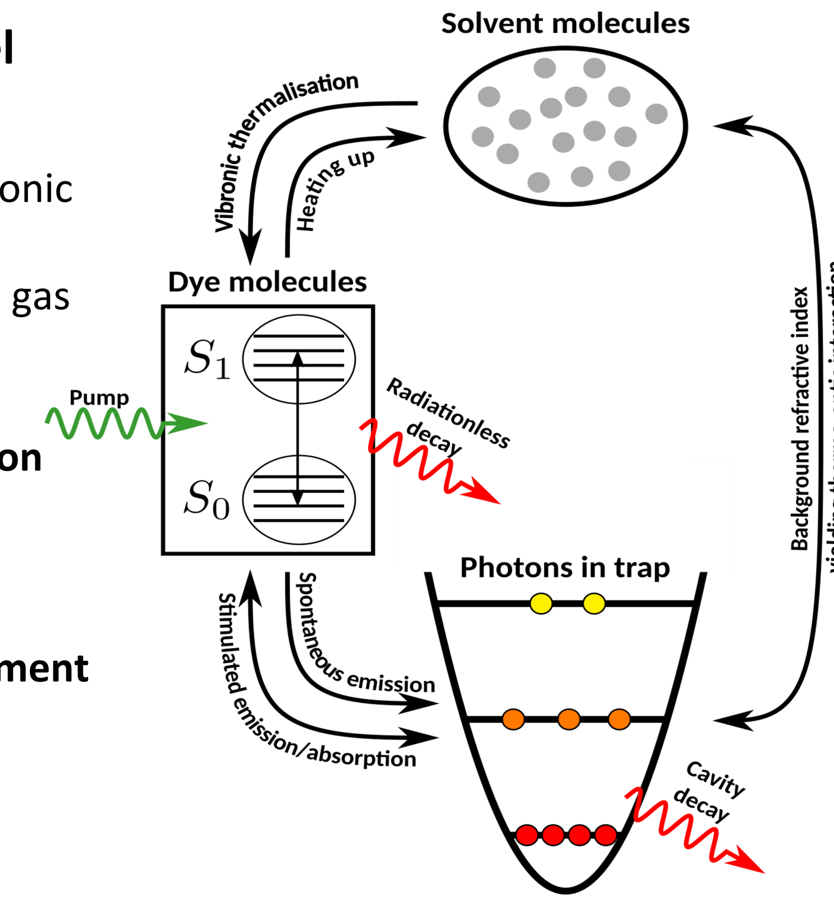
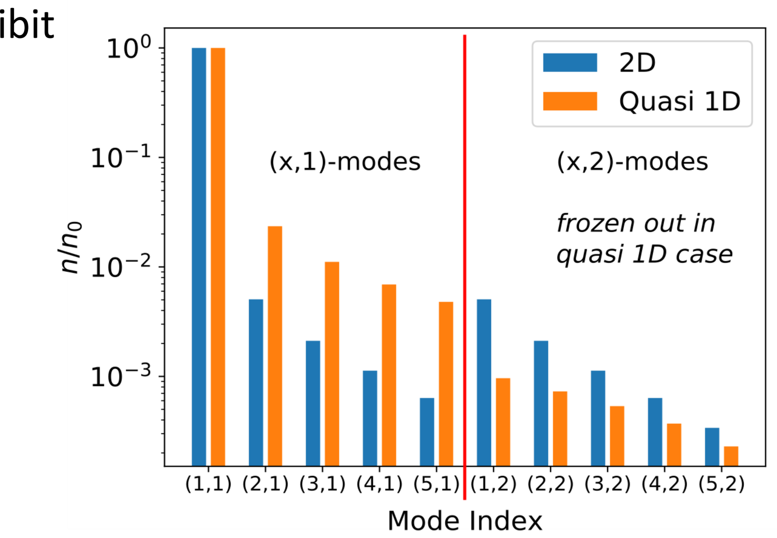
Tuning knobs: Feedback to/from experiment
- Coupling from bath to photons
- Loss rate
- Reservoir size



Task 3: Thermodynamic properties at dimensional crossover

Quasi-one-dimensional photon gases exhibit interesting physics:
- Effective thermo-optic photon-photon interaction mediated by bath
- Bath serves as particle reservoir ⇒ Particle number fluctuations
- Driving and loss tunable ⇒ Equilibrium vs. non-equilibrium
- Integrability broken due to reservoir



Task 4: Study superfluid properties of the photon gas

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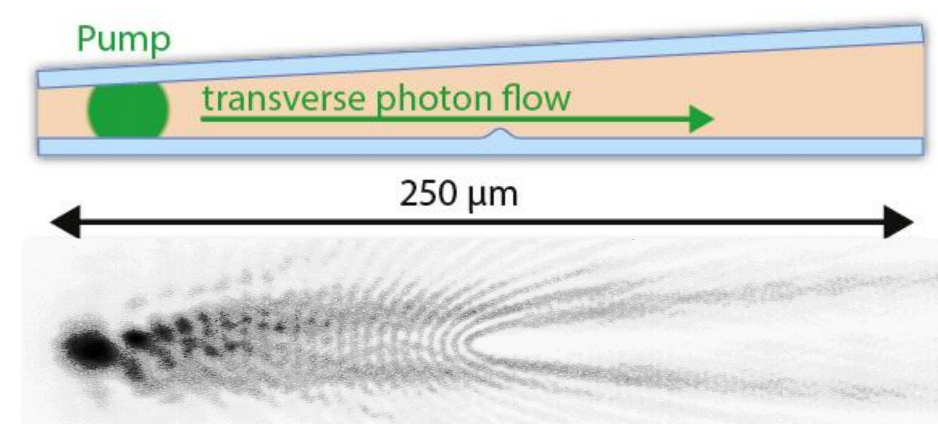
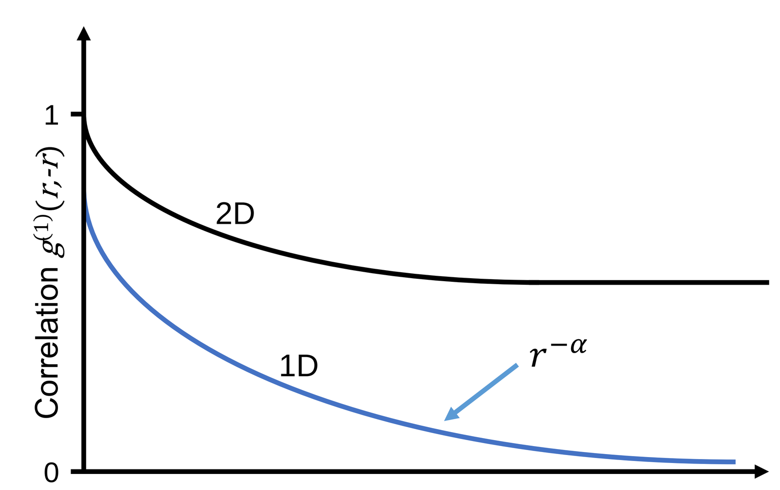
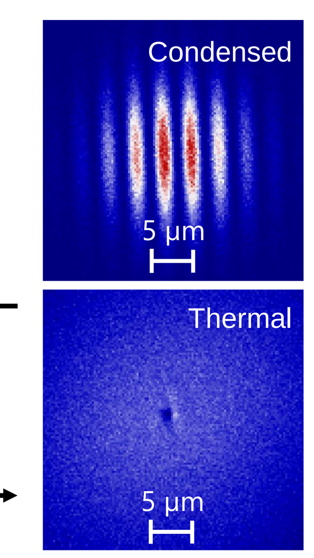


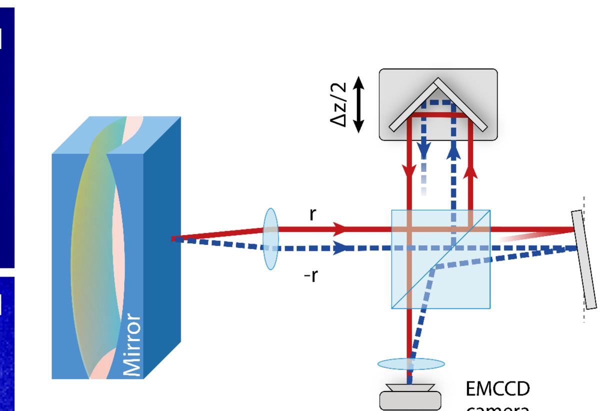
Open-Dissipative Systems
- Definition of superfluidity
- Influence of retarded interaction
- Validity of Goldstone theorem

Anisotropic Potential
- Superfluid density as tensor
- Behaviour at 2D ⟷ 1D crossover
- Flow over obstacle

Task 5: Correlation properties at dimensional crossover







[P3] T. Damm *et al.* Nature Commun. **8**, 158 (2017)