Thermalization and condensation dynamics of a photon Bose-Einstein condensate

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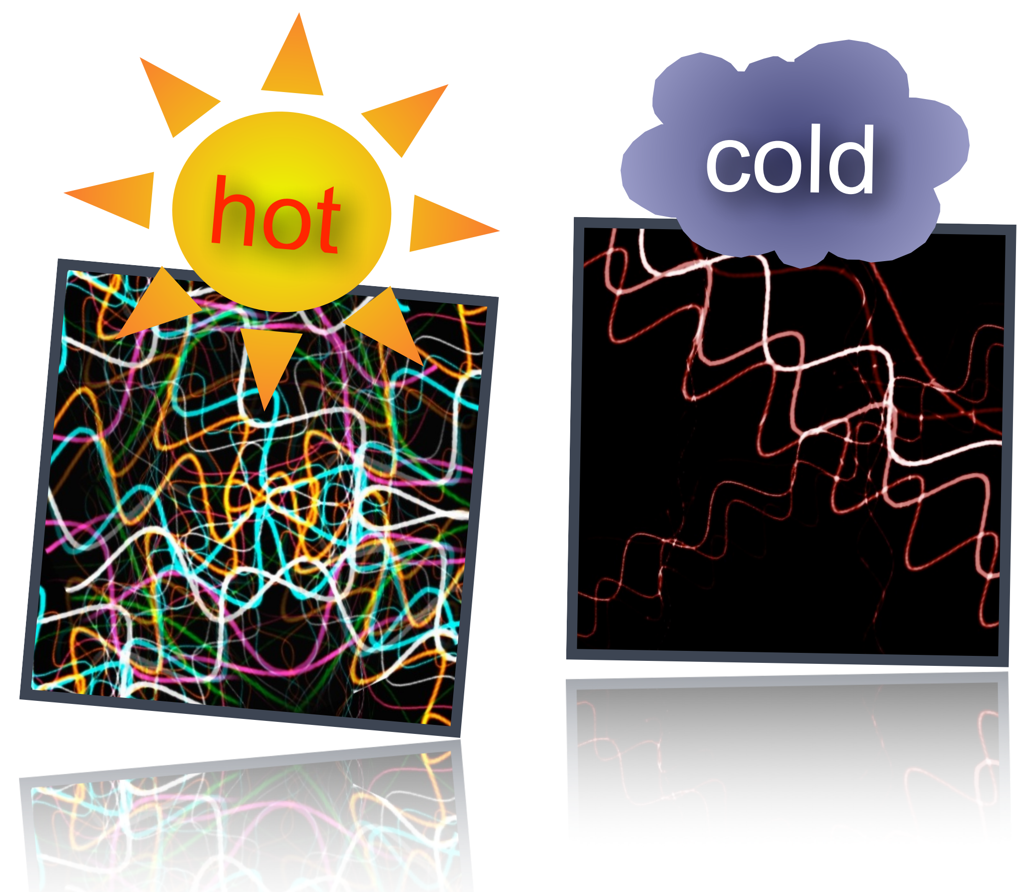
»Does a photon gas condense?«

Its bosonic and ideal (interaction-free) nature should make a photon gas an obvious candidate for a Bose-Einstein condensation. But:

Planck`s blackbody radiation:

$$\nu_{\max} \propto T$$
$$U \propto T^4$$

(Wien, Stefan-Boltzmann)



At low temperatures, photons disappear in the cavity walls, instead of condensing into the cavity ground mode.

»Related work«

Compton scattering in plasmas

Y.B. Zel'dovich, E.V. Levich, Sov. Phys. JETP 28, 1287 (1969)

Near-colinear four-wave mixing

e.g. R.Y. Chiao, Optics Communication 179, 157 (2000)

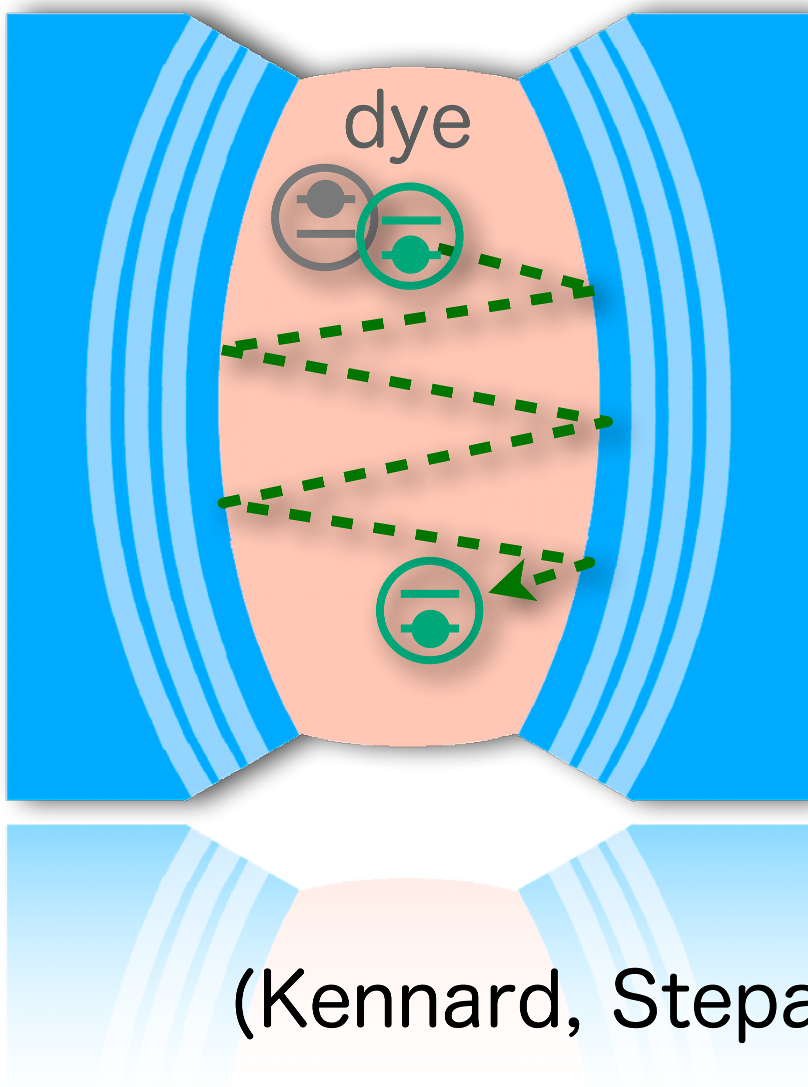
Strong light-matter coupling / exciton polaritons

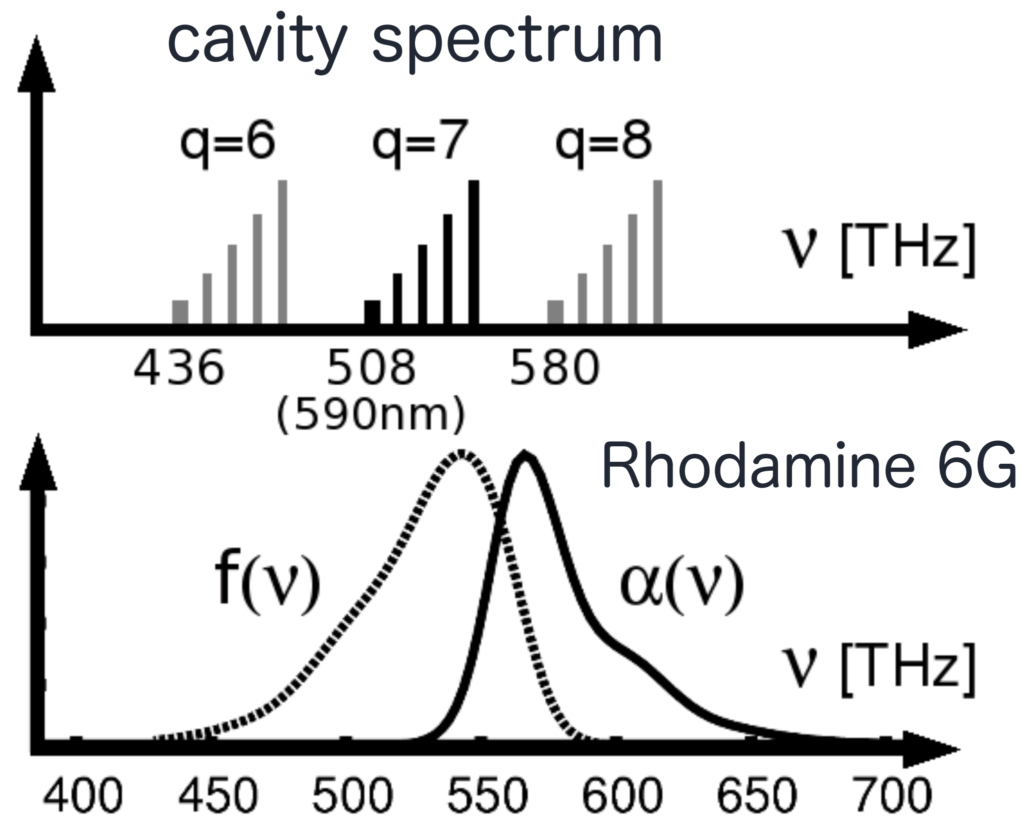
Review: H. Deng, H. Haug, Y. Yamamoto, Rev. Mod. Phys. 82, 1489 (2010)

Classical wave condensation (nonlinear optics)

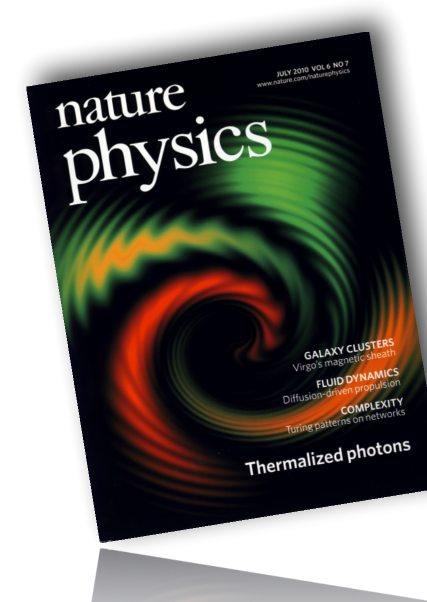
C. Sun et al, Nature Physics 8, 470 (2012)

»2d photon gas in dye-microcavity«





(Kennard, Stepanov) $$\frac{B_{21}(\omega)}{B_{12}(\omega)} = e^{-\frac{\hbar(\omega-\omega_{\mathrm{ZPL}})}{k_{\mathrm{B}}T}}$$



Klaers, Schmitt, Vewinger, Weitz, Nature 468, 545 (2010)
Klaers, Vewinger, Weitz, Nature Phys. 6, 512 (2010)
Schmitt et al., PRL 112, 030401 (2014)
Klaers et al., PRL 108, 160403 (2012)

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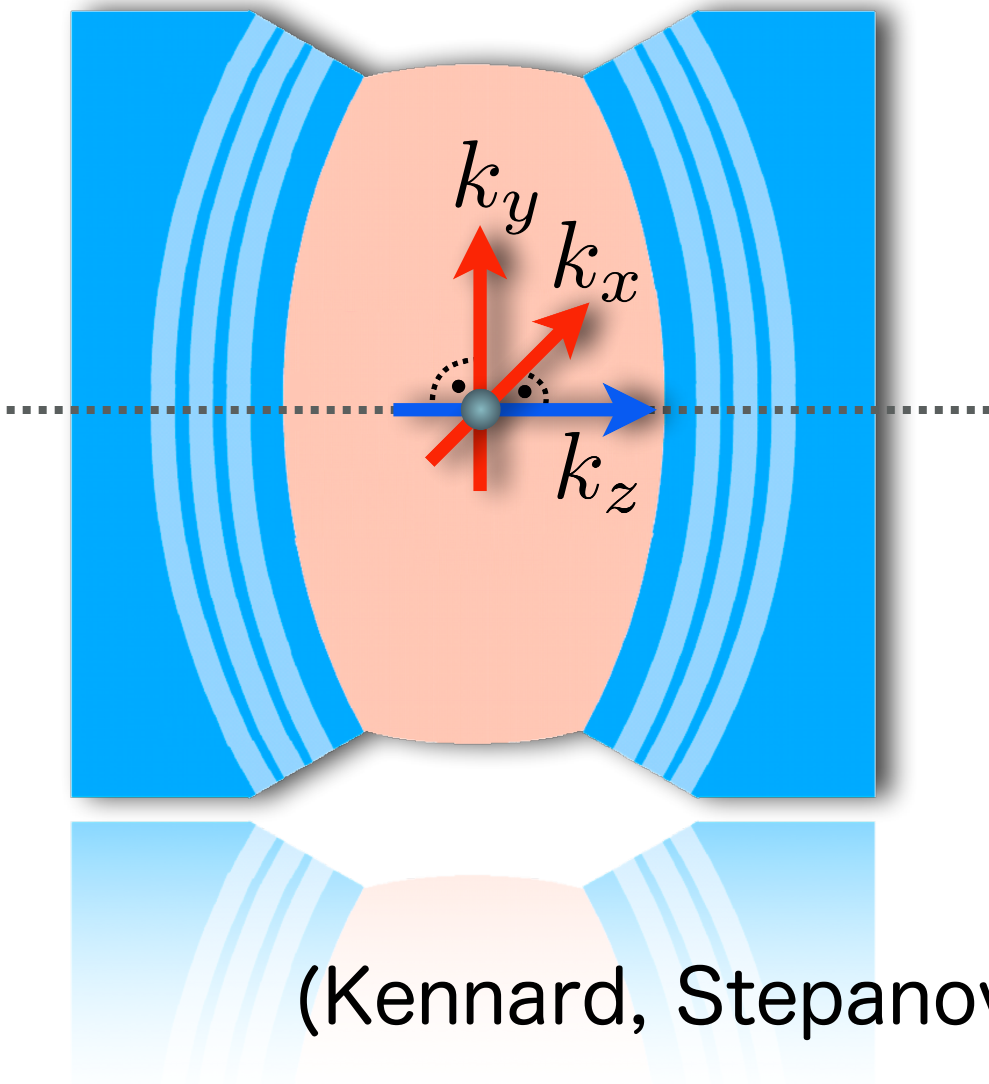

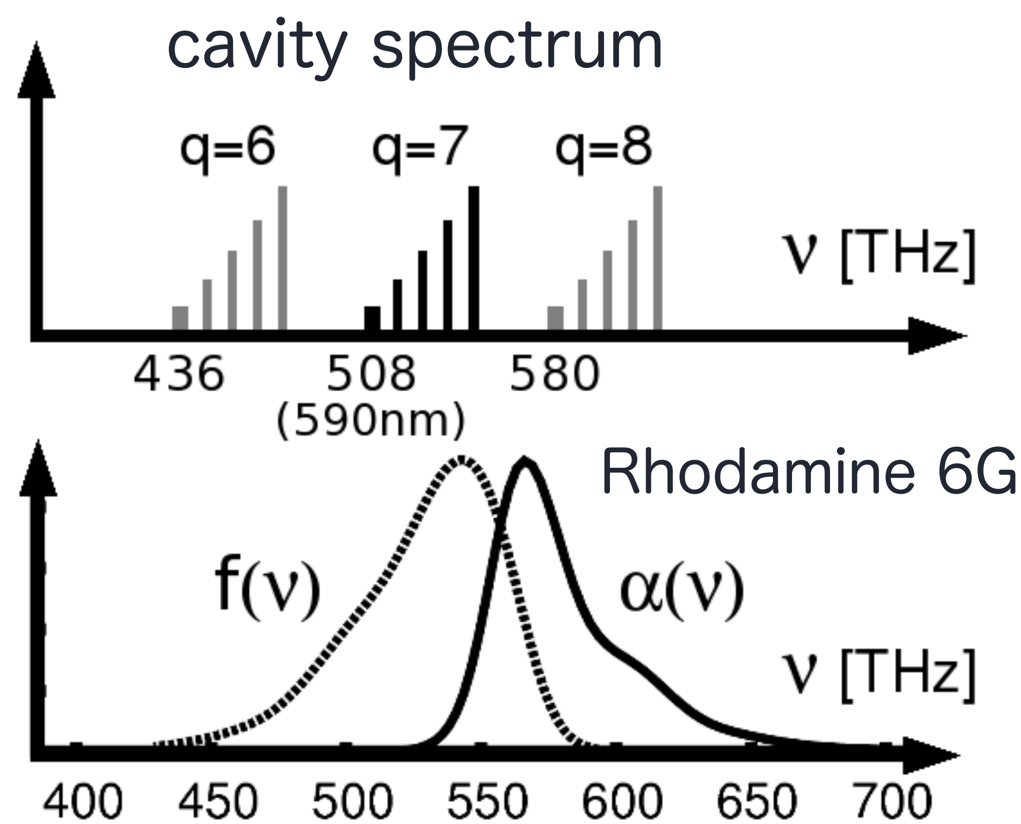

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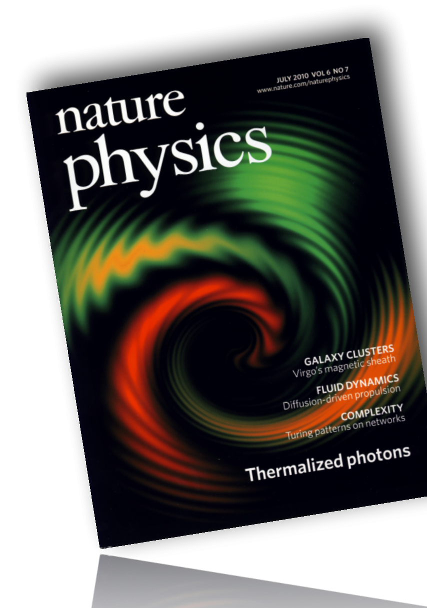

Klaers, Schmitt, Vewinger, Weitz, Nature 468, 545 (2010)
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Klaers et al., PRL 108, 160403 (2012)

»Massive photons in a trap«

Energy of cavity photons:

$$E \simeq m\tilde{c}^2 + \frac{(\hbar k_r)^2}{2m} + \frac{1}{2} m\Omega^2 r^2$$

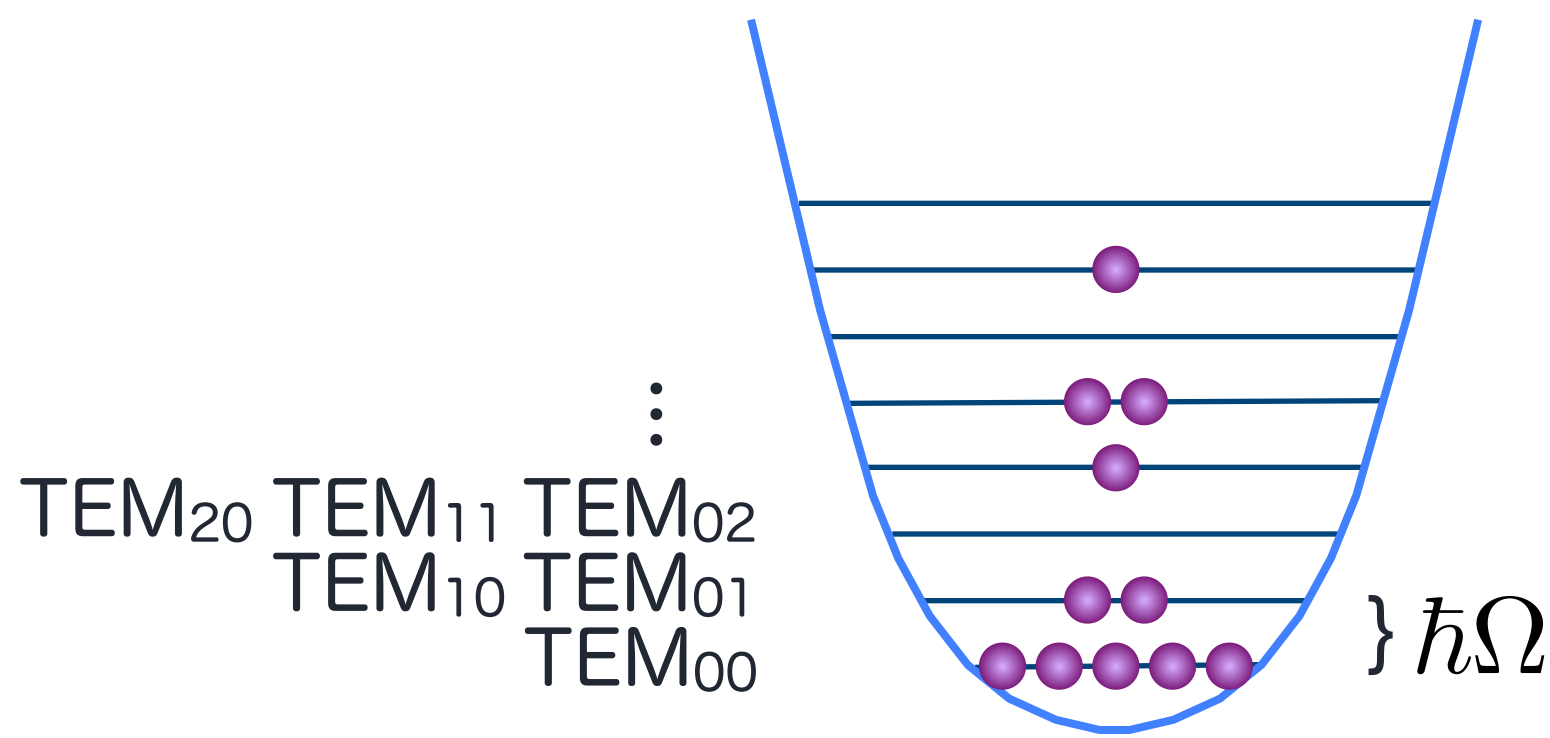
mirror curvature

BEC @

$$T_\mathrm{c} = \frac{\sqrt{3}\hbar\Omega}{\pi k_\mathrm{B}} \sqrt{N}$$

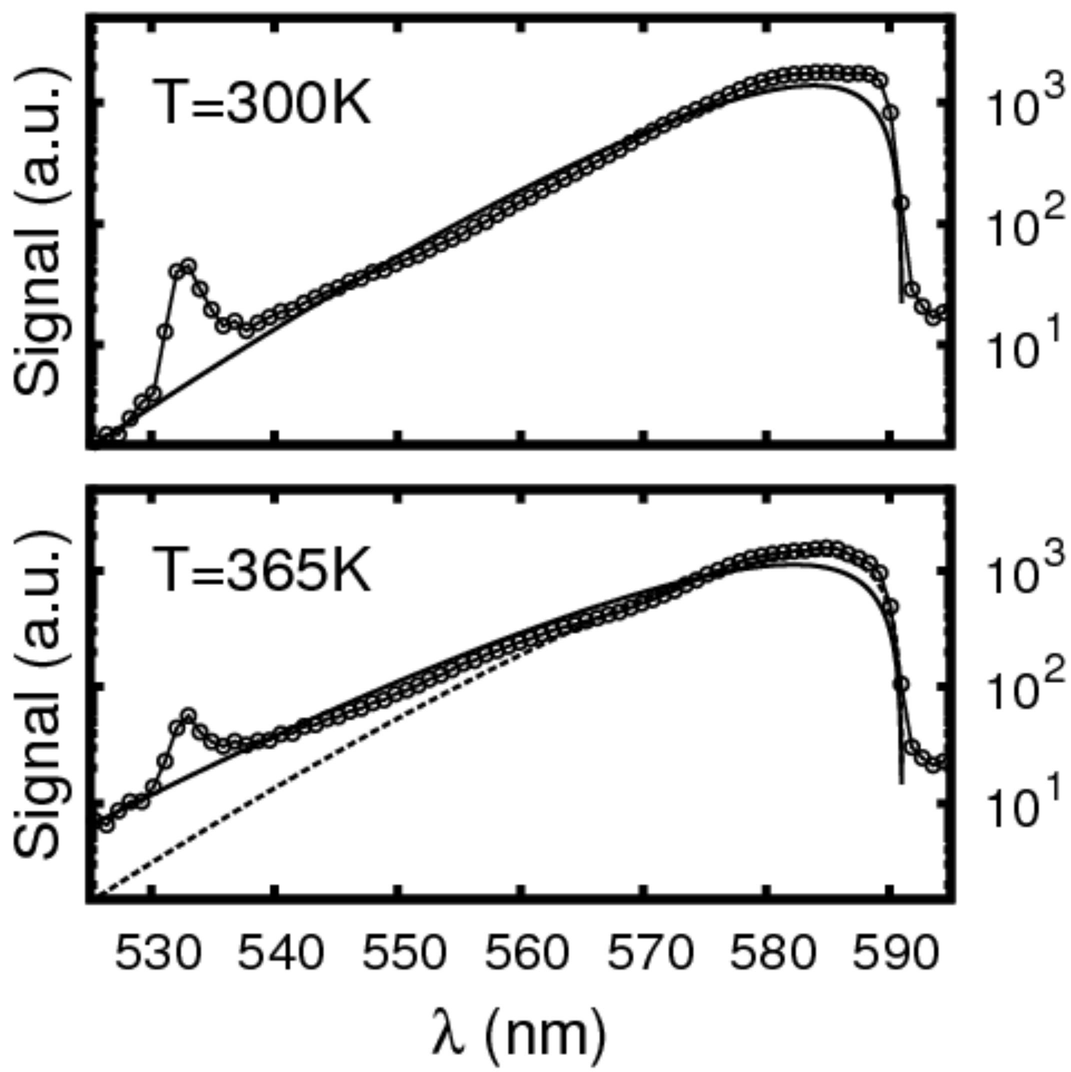
$$m \simeq 10^{-36}\,\mathrm{kg}$$

$$\Omega \simeq 2\pi \cdot 40\,\mathrm{GHz}$$

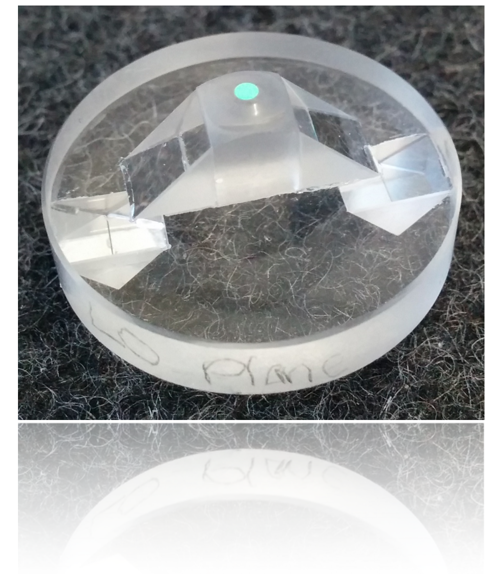


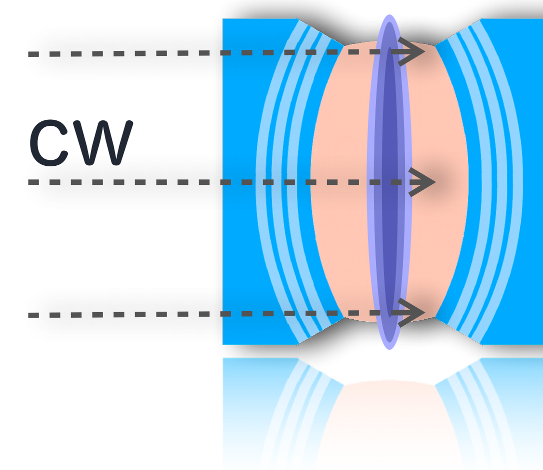
»Thermalization«

Bose-Einstein distribution

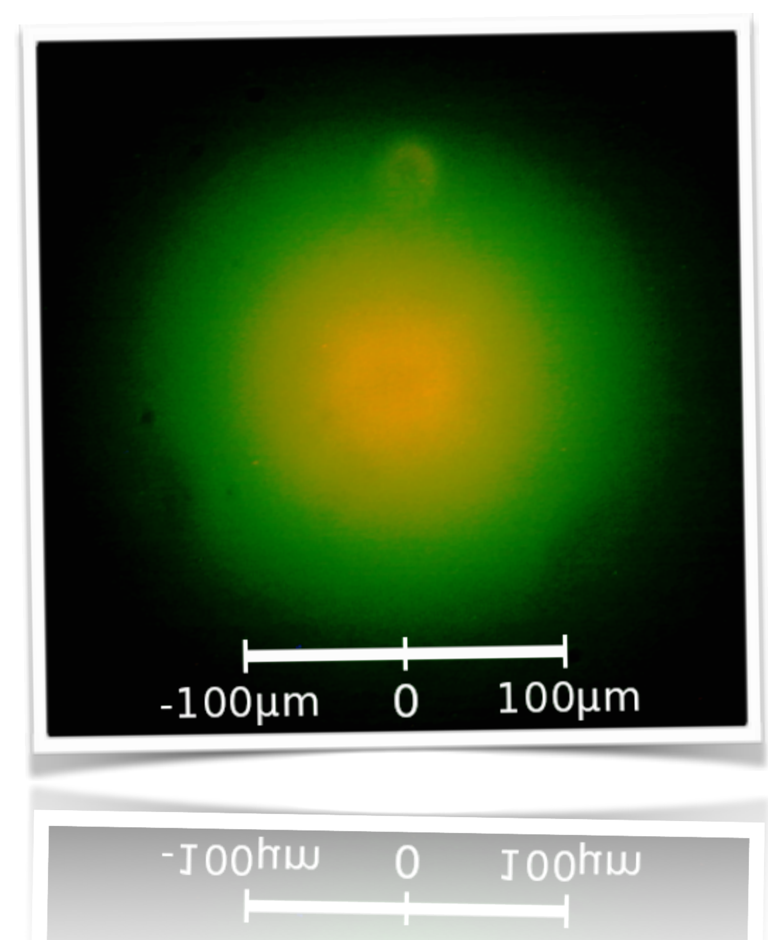


Nature Phys. 6, 512 (2010)



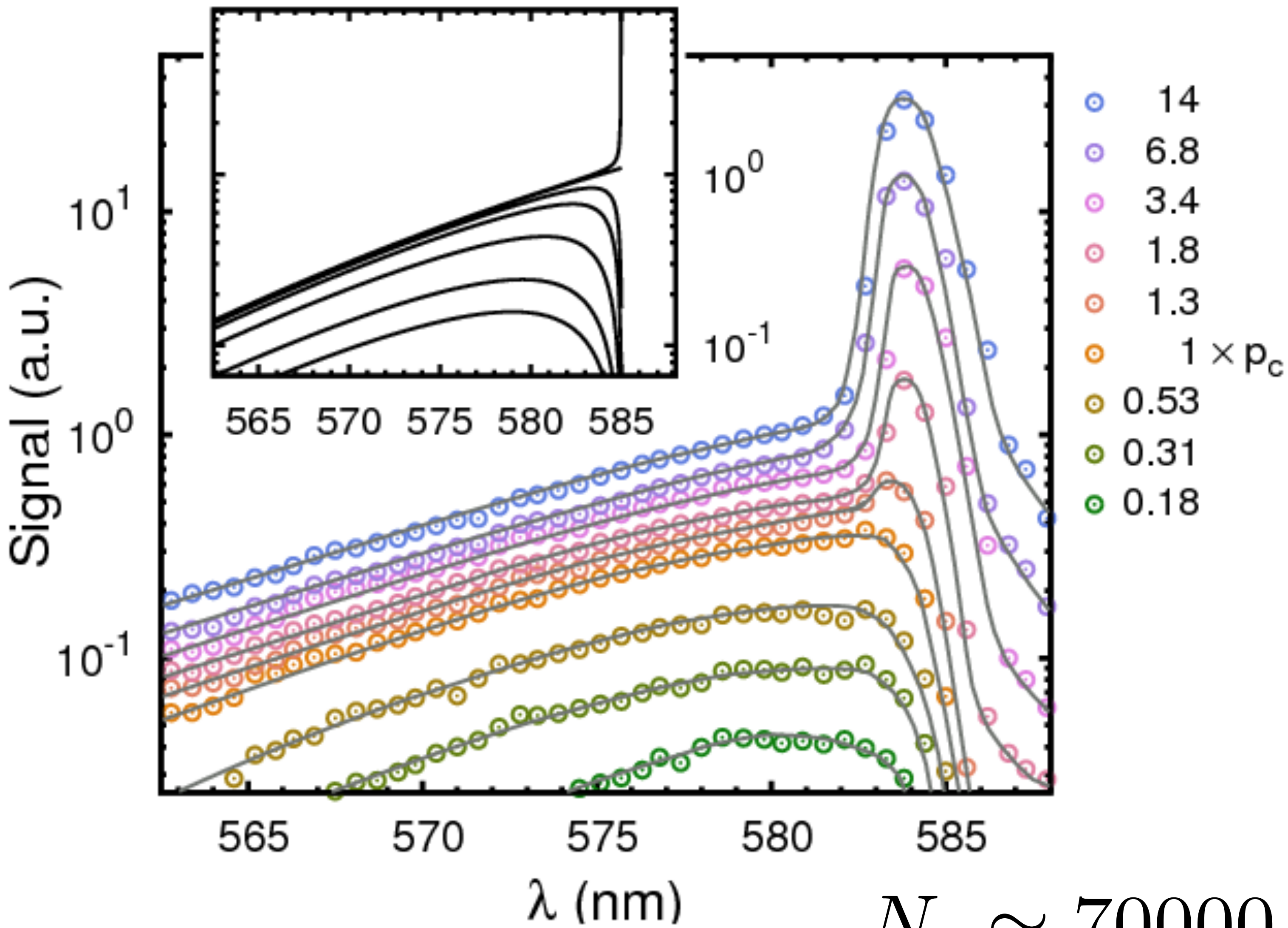


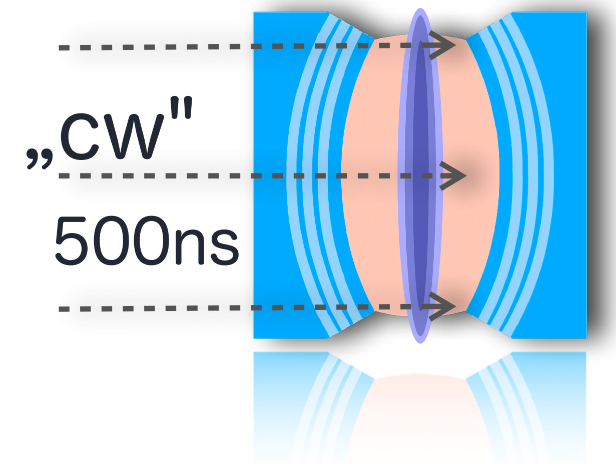
$$N \simeq 50$$

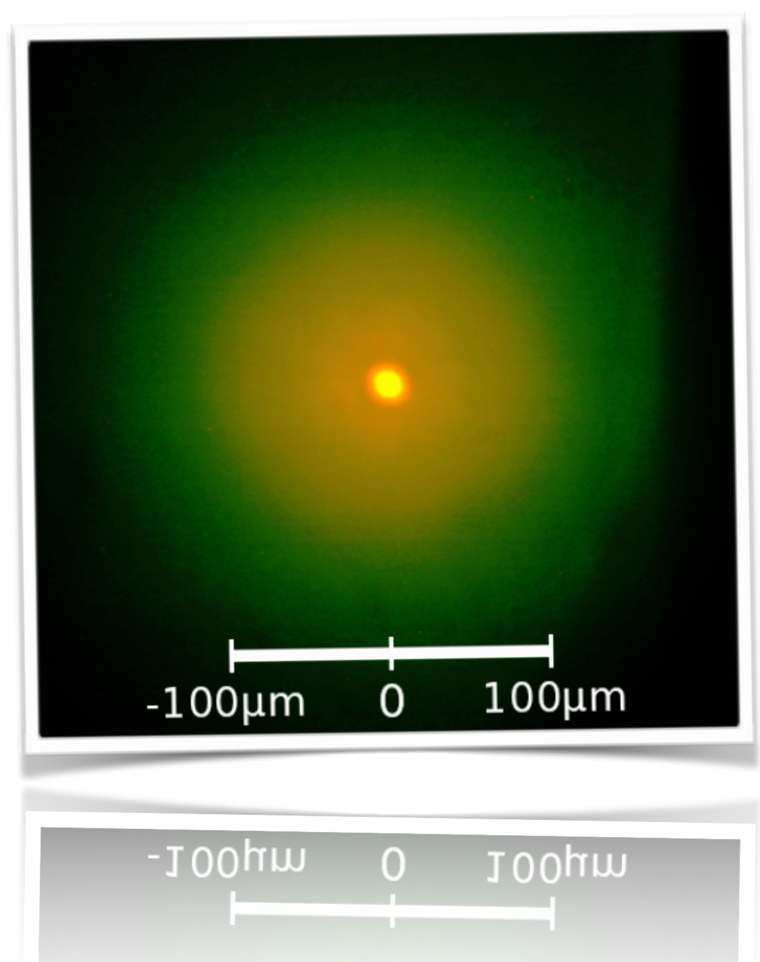


»Bose-Einstein condensation«

300K Bose-Einstein distributions
for increasing chemical potential





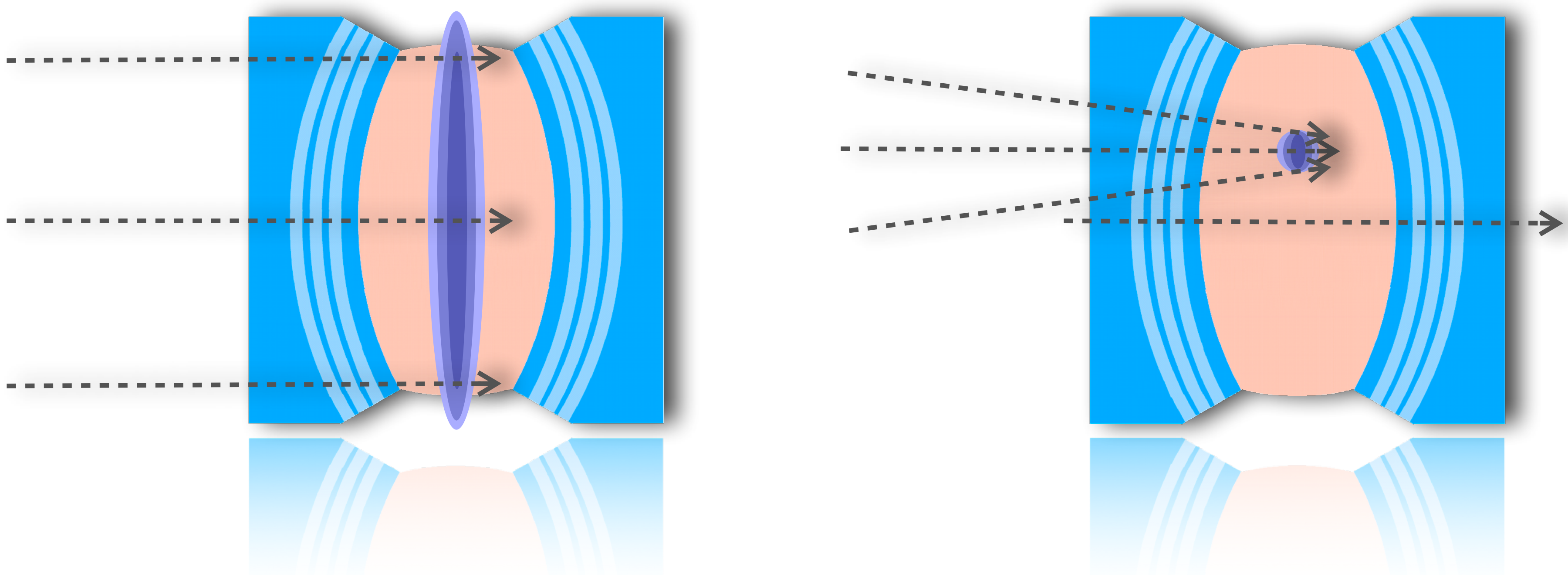


$N_c \simeq 70000$

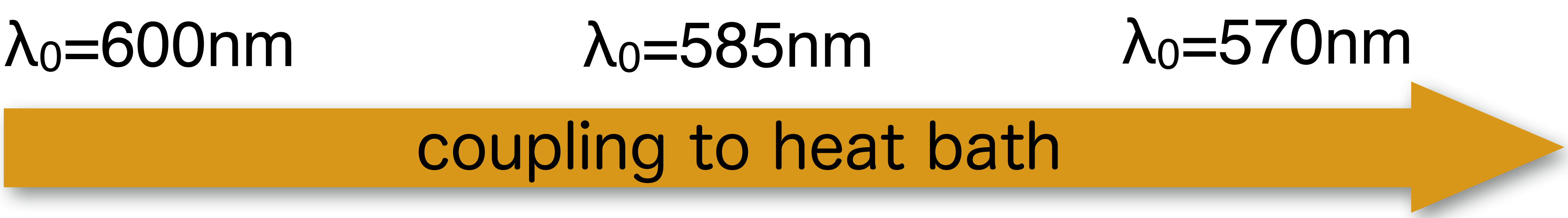
Nature 468, 545 (2010)

»Thermalization dynamics«

▷ Set initial excitation level of medium

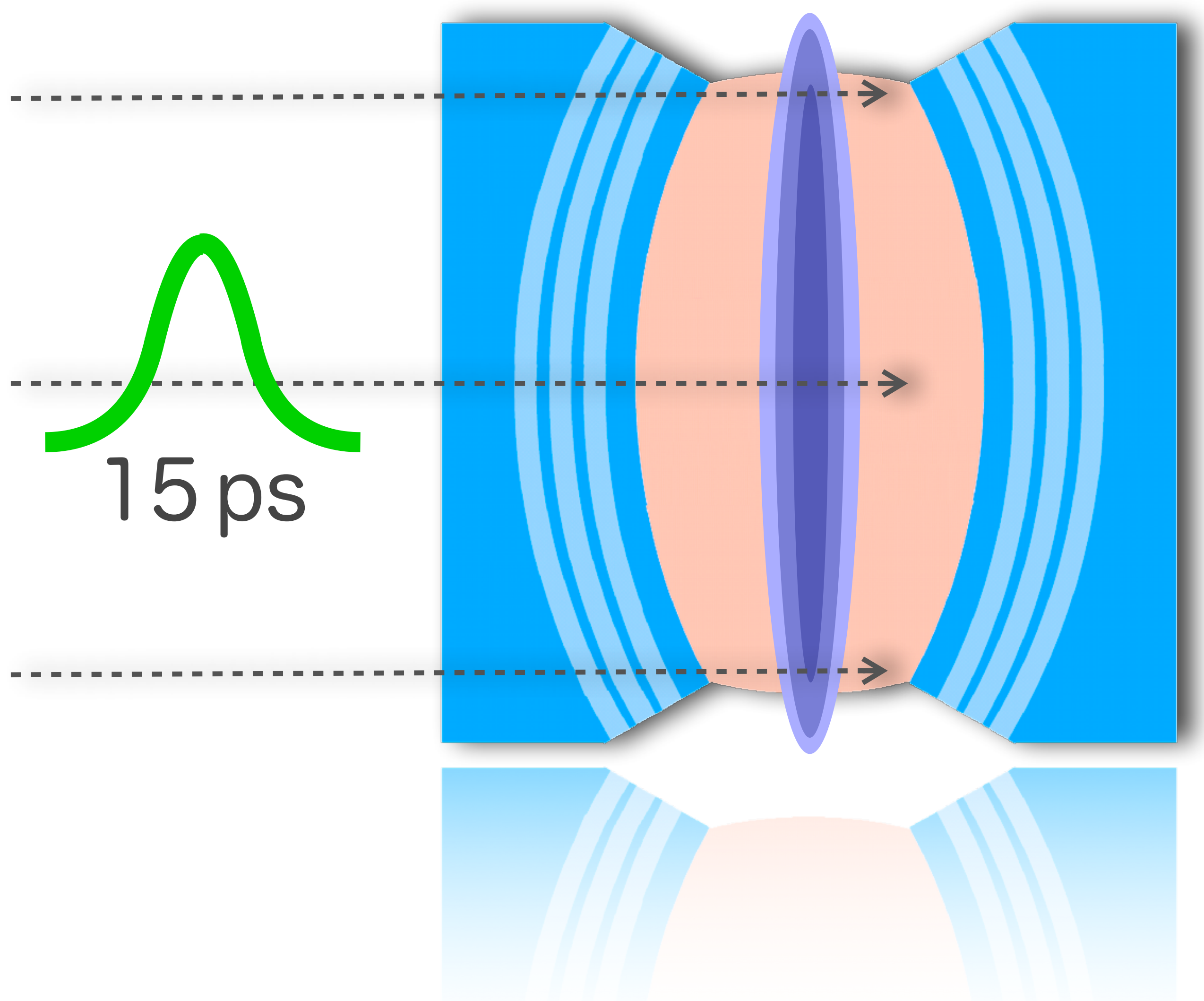


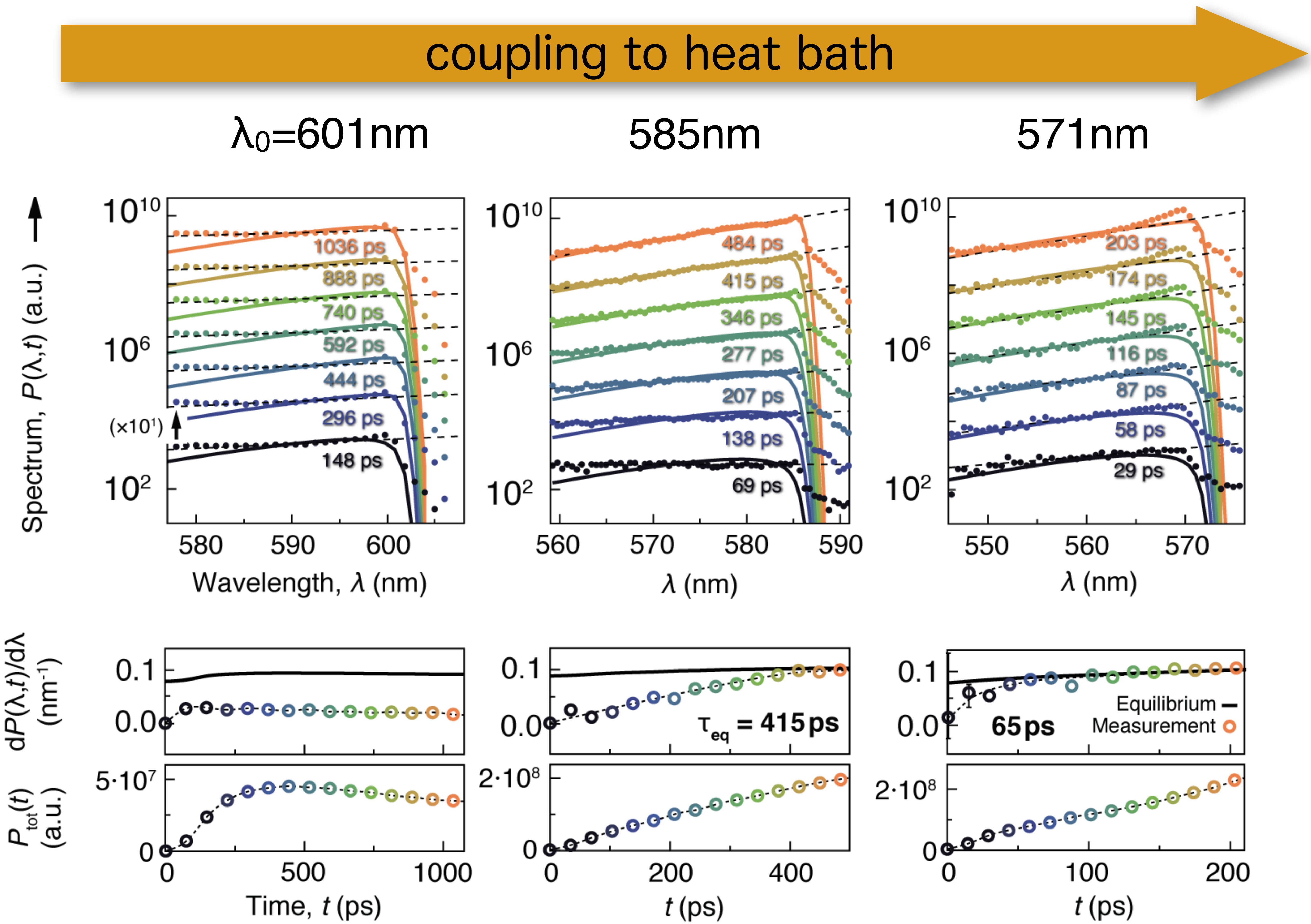
▷ Set coupling strength to heat bath



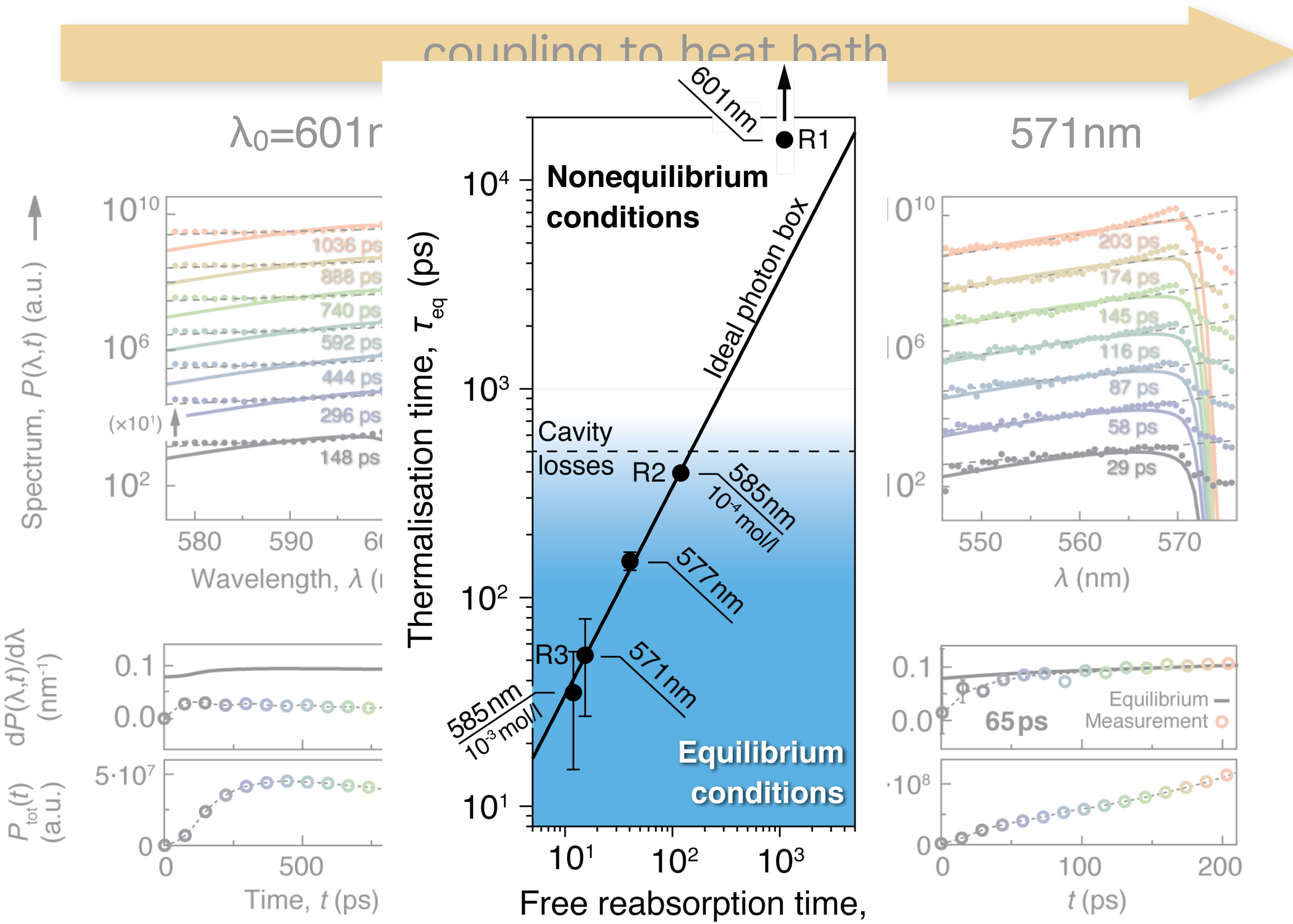
»Spatially homogeneous excitation«

temporally: 15 ps
spatially: homogeneous



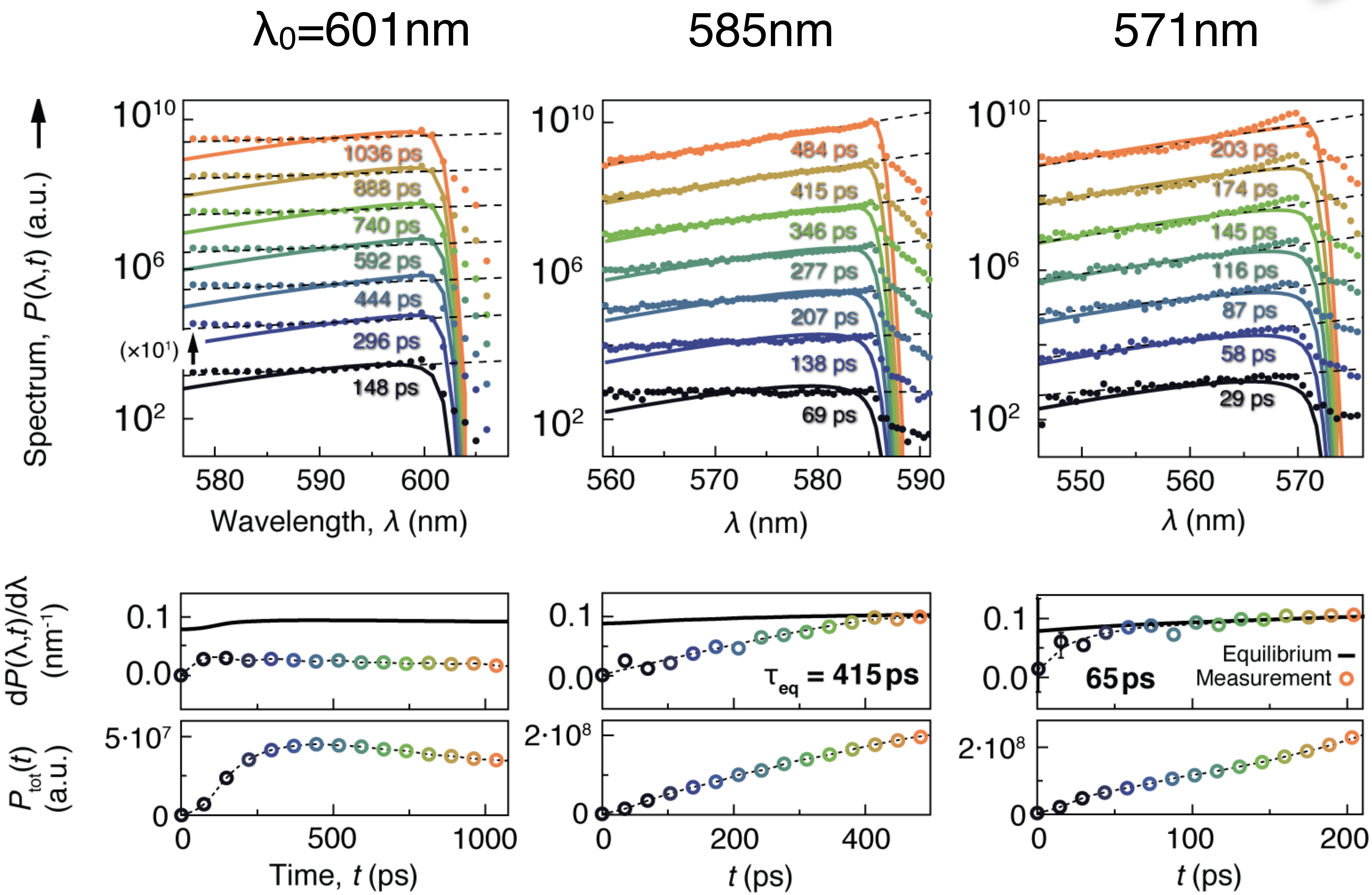


[EQ. vs Non-EQ.: Kirton, Keeling, PRL 111, 100404 (2013)]



[EQ. vs Non-EQ.: Kirton ... 013)]

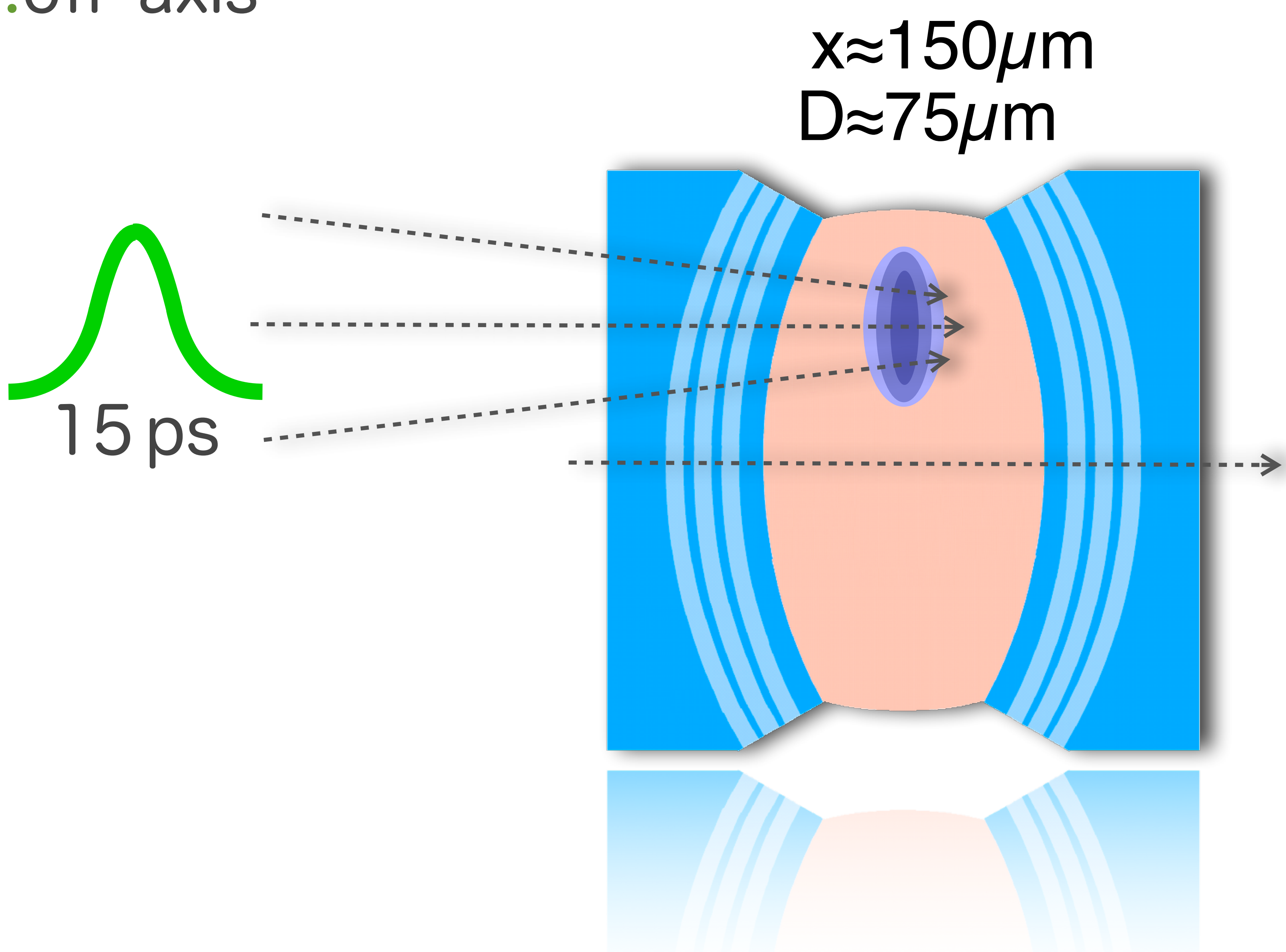
coupling to heat bath



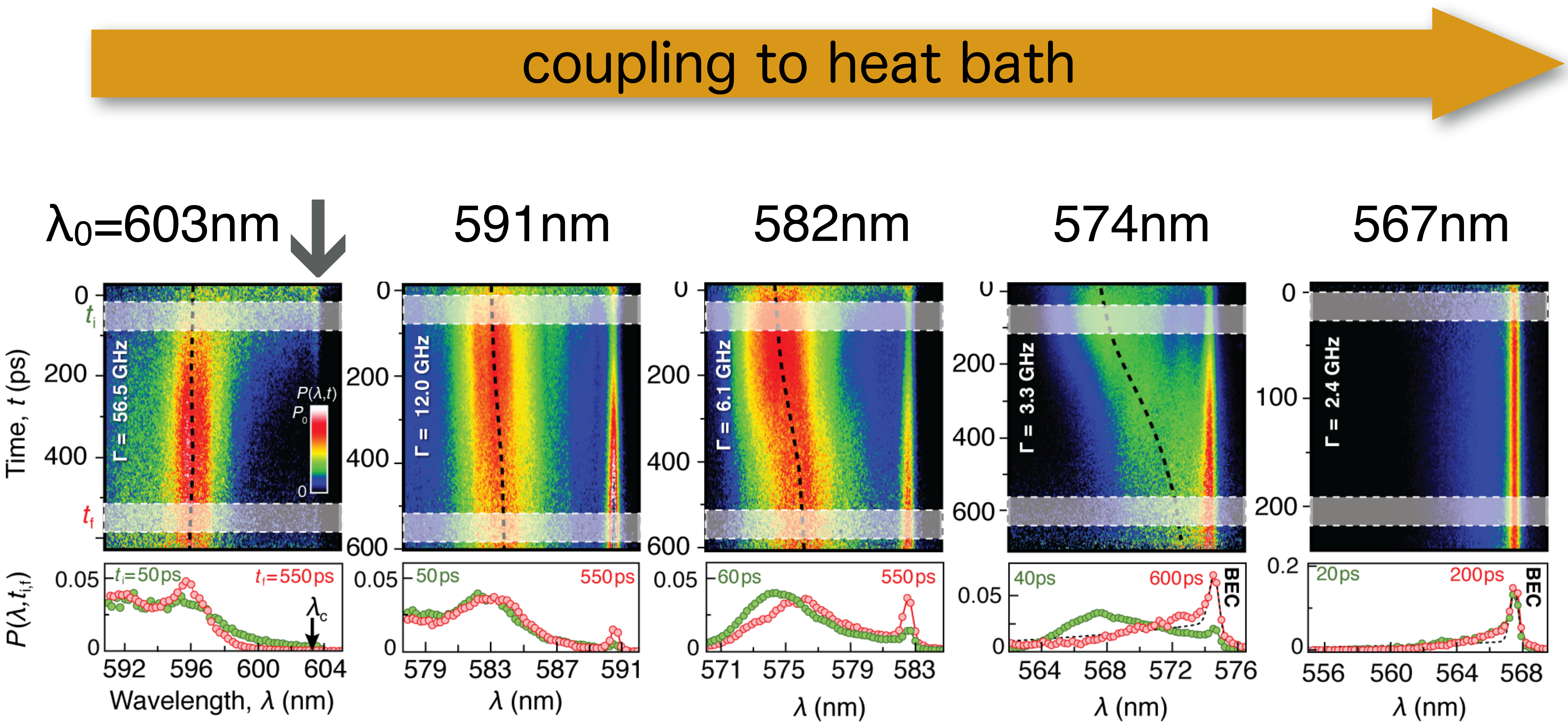
[EQ. vs Non-EQ.: Kirton, Keeling, PRL 111, 100404 (2013)]

»Spatially inhomogeneous excitation«

temporally: 15 ps
spatially: off-axis



»Spatially inhomogeneous excitation«

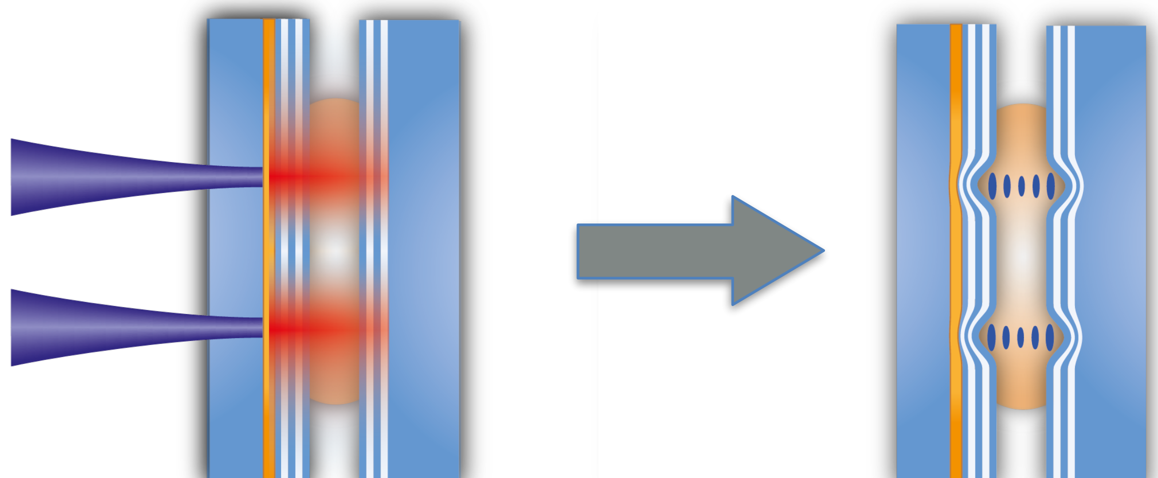


»(Thermo-)optical lattices«

- reversible microstructuring technique
- based on local index changes of a thermo-sensitive polymer
- generates attractive potentials

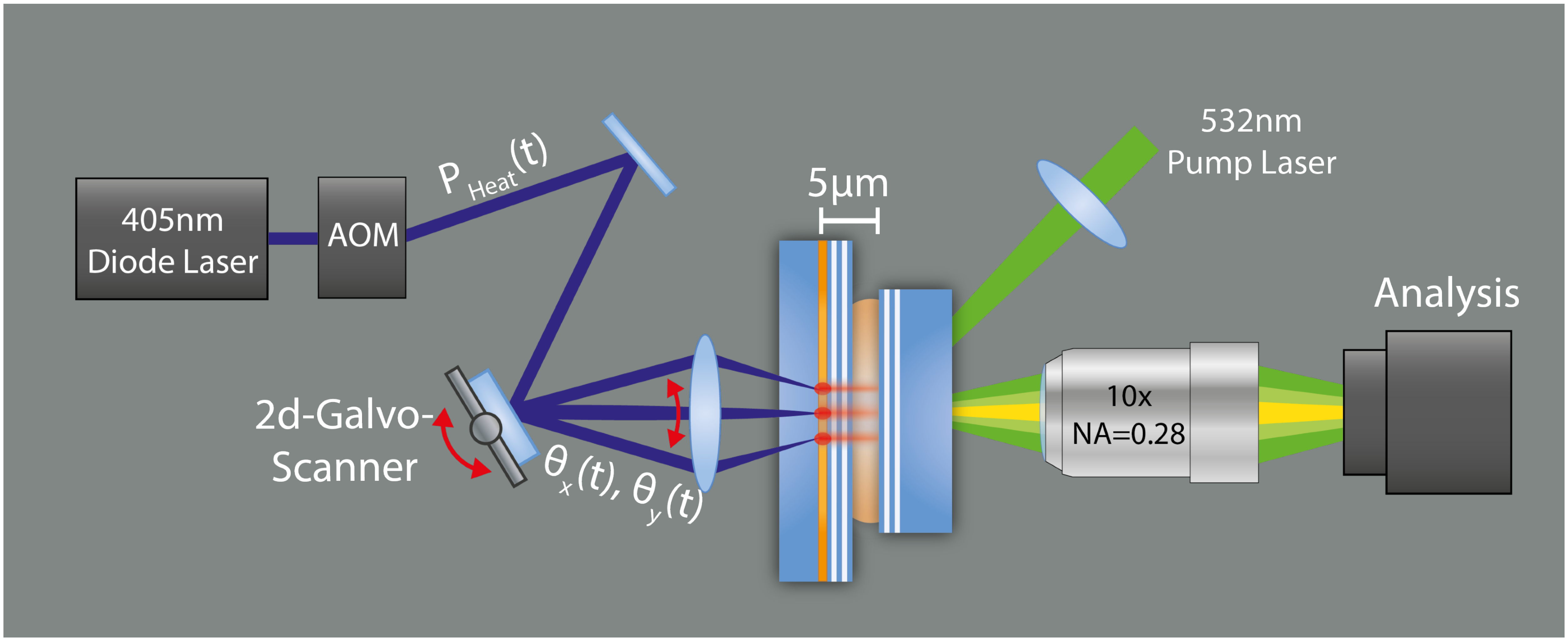
pNIPAM

„heating“ beam
@405nm

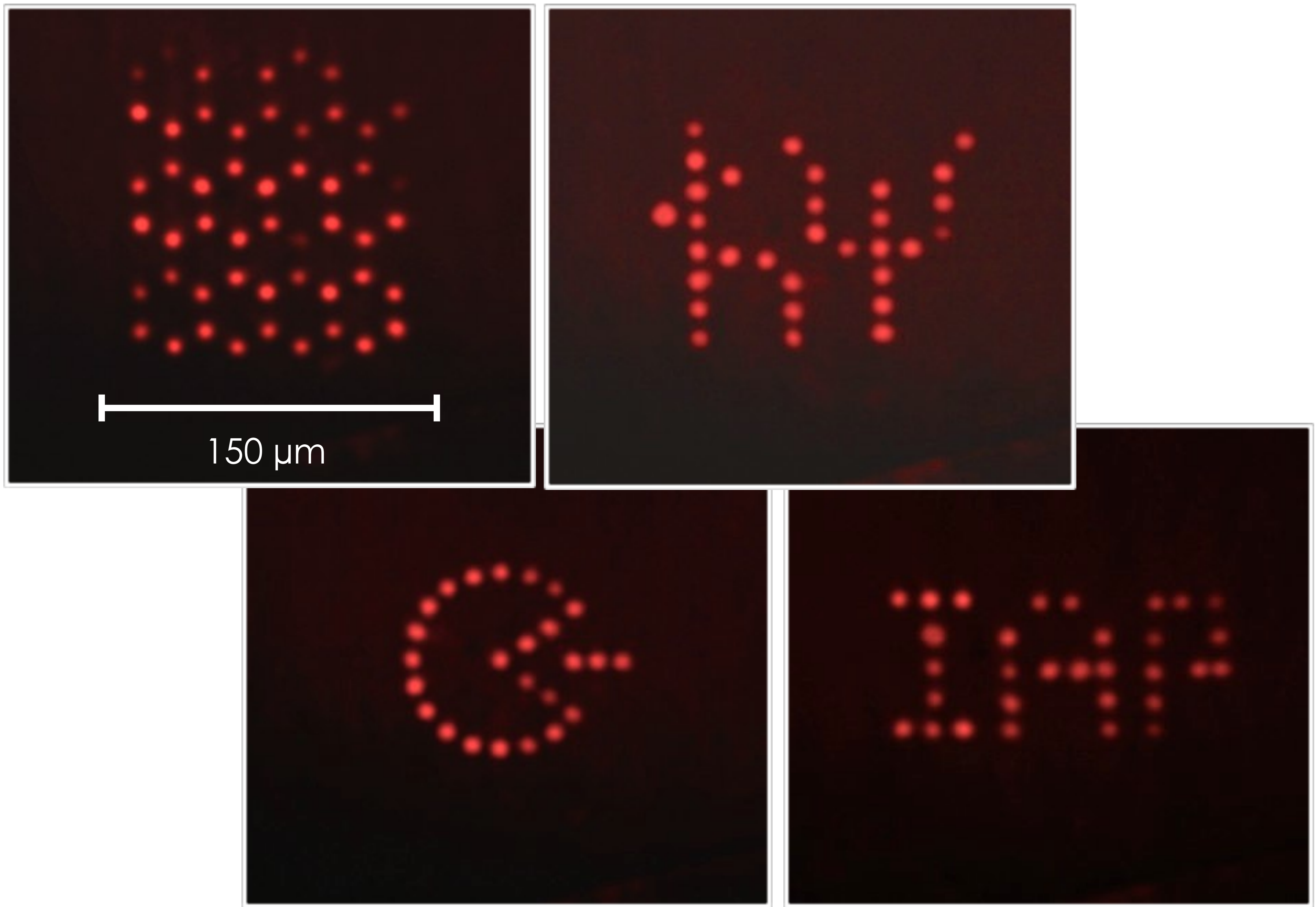


local temperature >33°C

»(Thermo-)optical lattices II«



»Lattices of micro-condensates«



»Summary«

1. A photon gas can show Bose-Einstein condensation, if the thermalisation process is restricted to two motional degrees of freedom.

2. The thermal energy distribution of the photon gas is reached on a timescale given by the photon reabsorption time.

3. Optical lattices can be induced by generating local heat gradients within a thermo-sensitive polymer.

Photon BEC team @Bonn

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- Tobias Damm (PhD)
- David Dung (PhD)
- Christian Wahl (PhD)
- Qi Liang (Master)
- Frank Vewinger (Postdoc)
- Jan Klaers (Postdoc)
- Martin Weitz (Head)