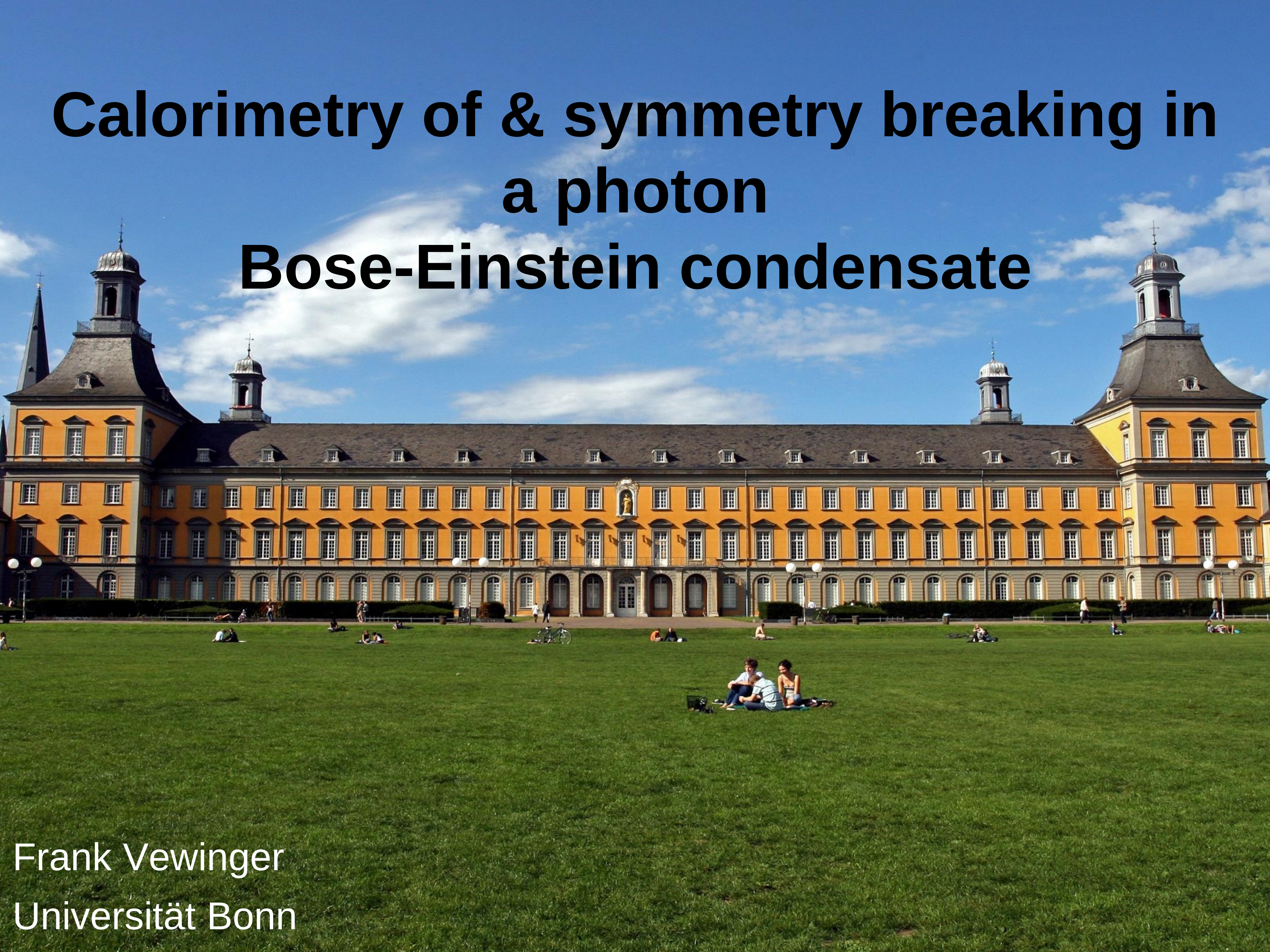
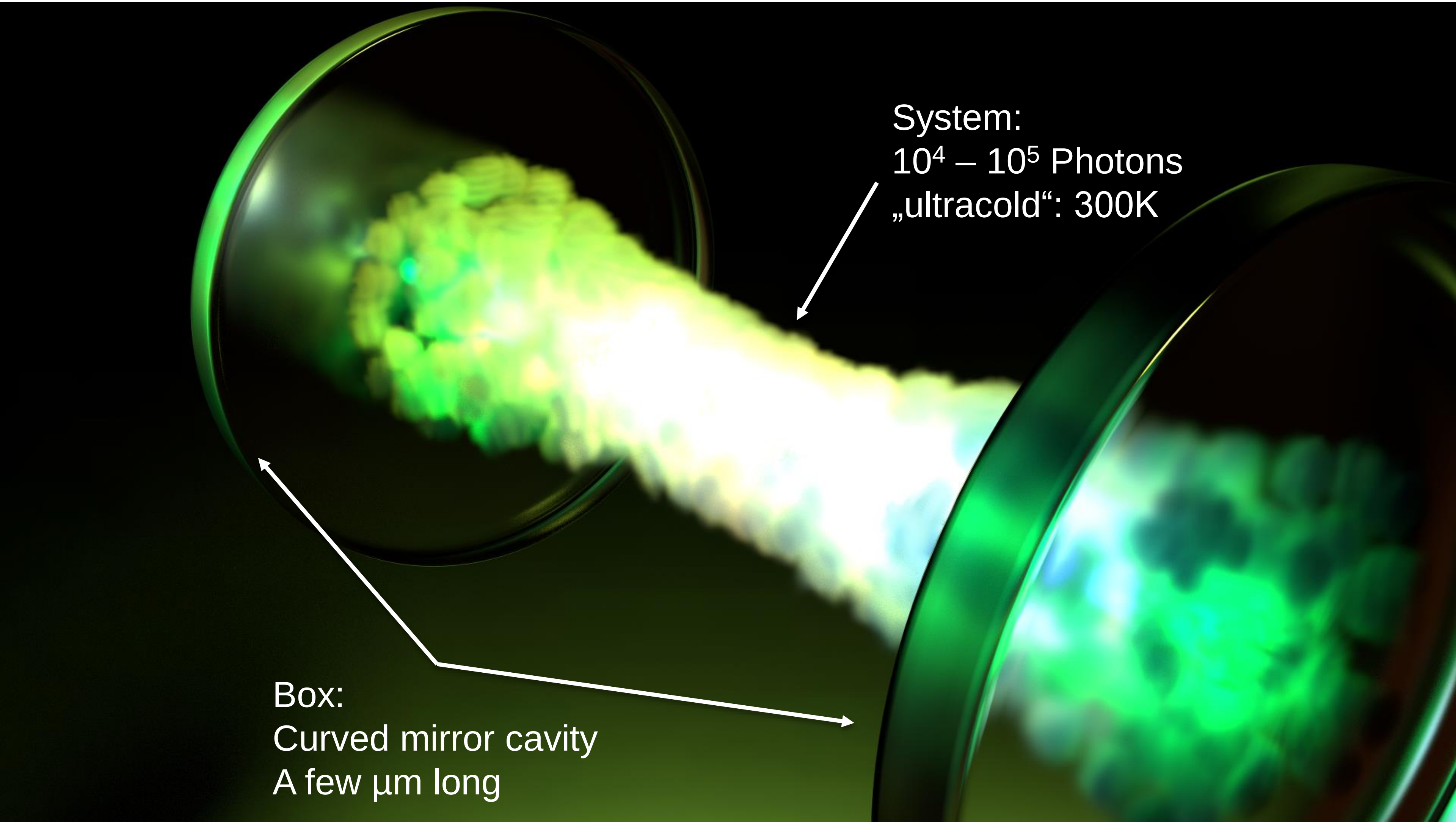
Calorimetry of & symmetry breaking in a photon Bose-Einstein condensate



Frank Vewinger
Universität Bonn

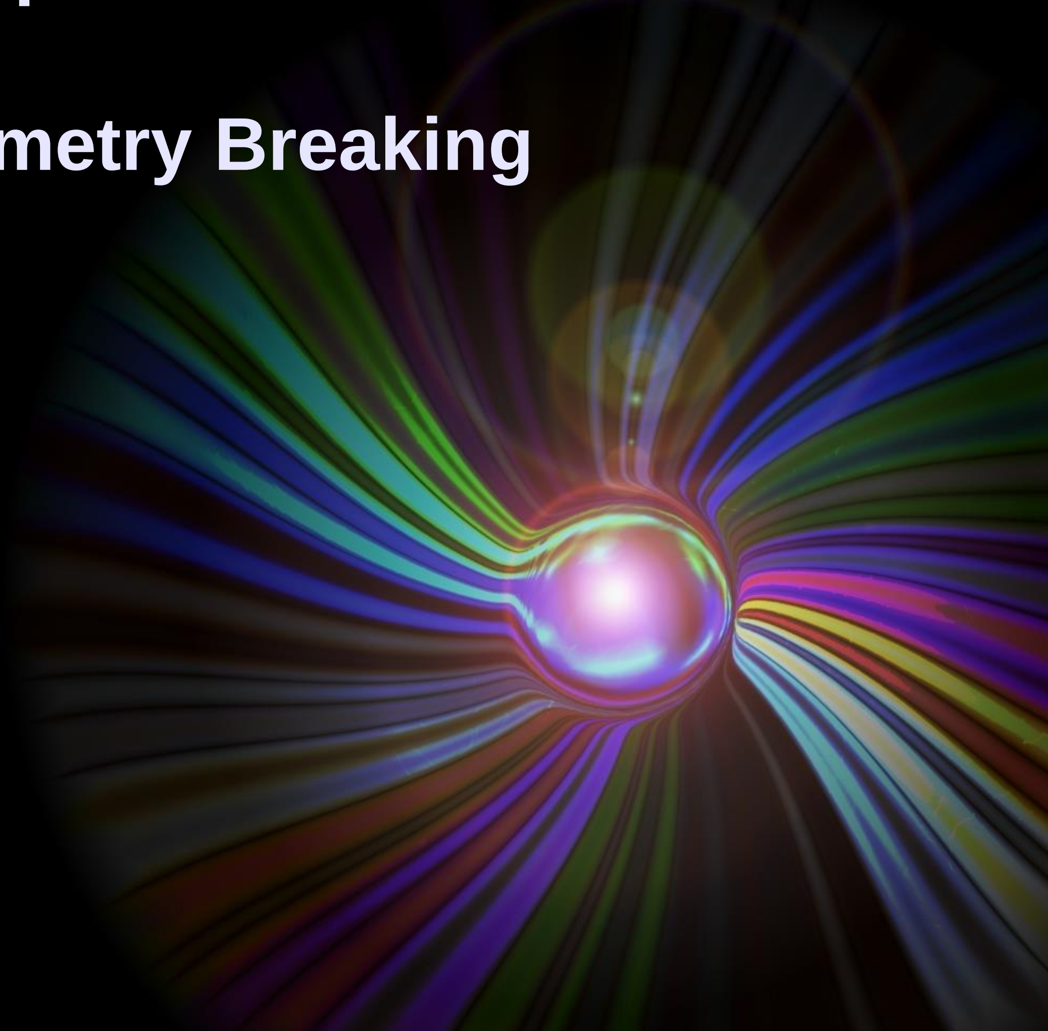
What are we dealing with?



1) Photon BEC: HowTo

2) Thermodynamic Properties of Photons

3) Fluctuations & Symmetry Breaking



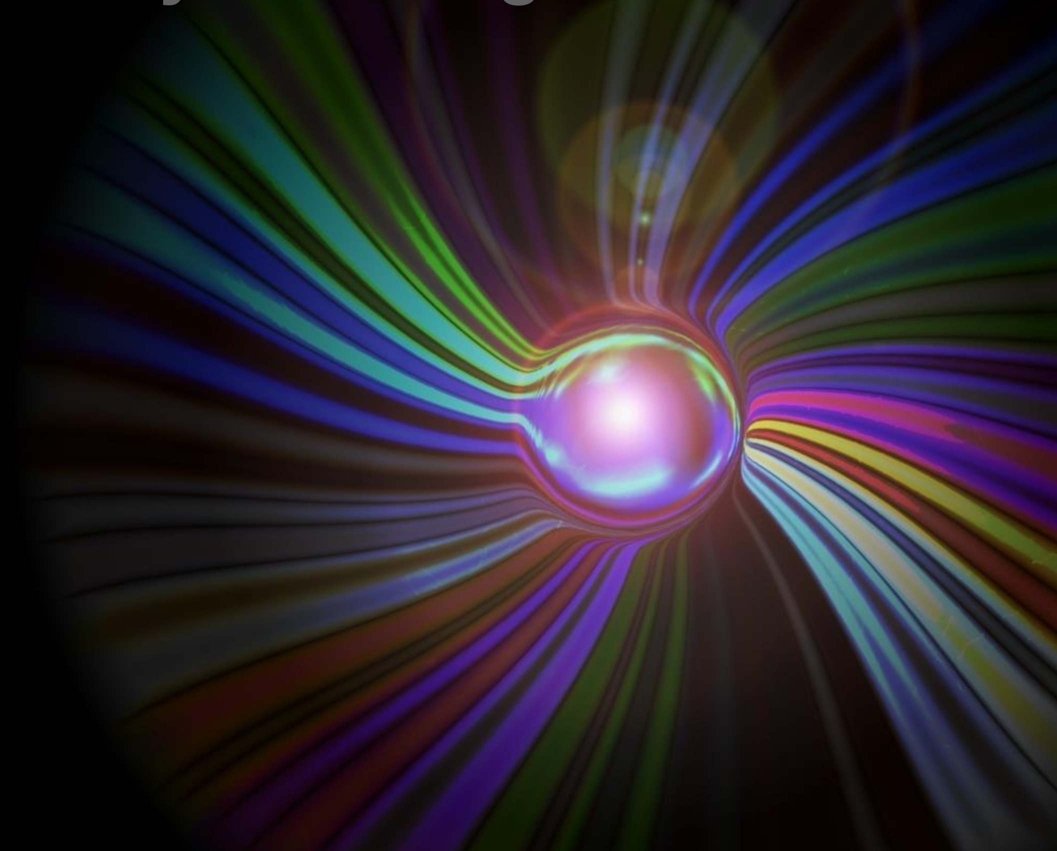
Work done with

Julian Schmitt
Tobias Damm
Jan Klaers (now@ETH Zürich)
Martin Weitz

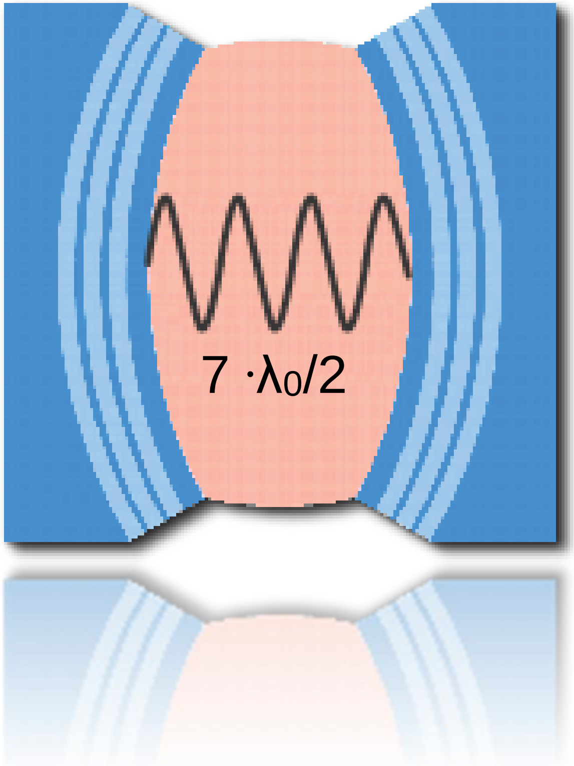
1) Photon BEC: HowTo

2) Thermodynamic Properties of Photons

3) Fluctuations & Symmetry Breaking



dye photon box



The box: Dispersion

$$E = \frac{\hbar c}{n}\sqrt{k_z^2 + k_r^2} \approx \frac{\hbar c}{n}\left(k_z + \frac{k_r^2}{2\,k_z^2}\right)$$

$$= \frac{\pi\hbar c q}{n\,D_0} + \frac{\pi\hbar c q}{n\,R\,D_0^2} r^2 + \frac{\hbar c\,D_0}{2\pi q n} k_r^2$$

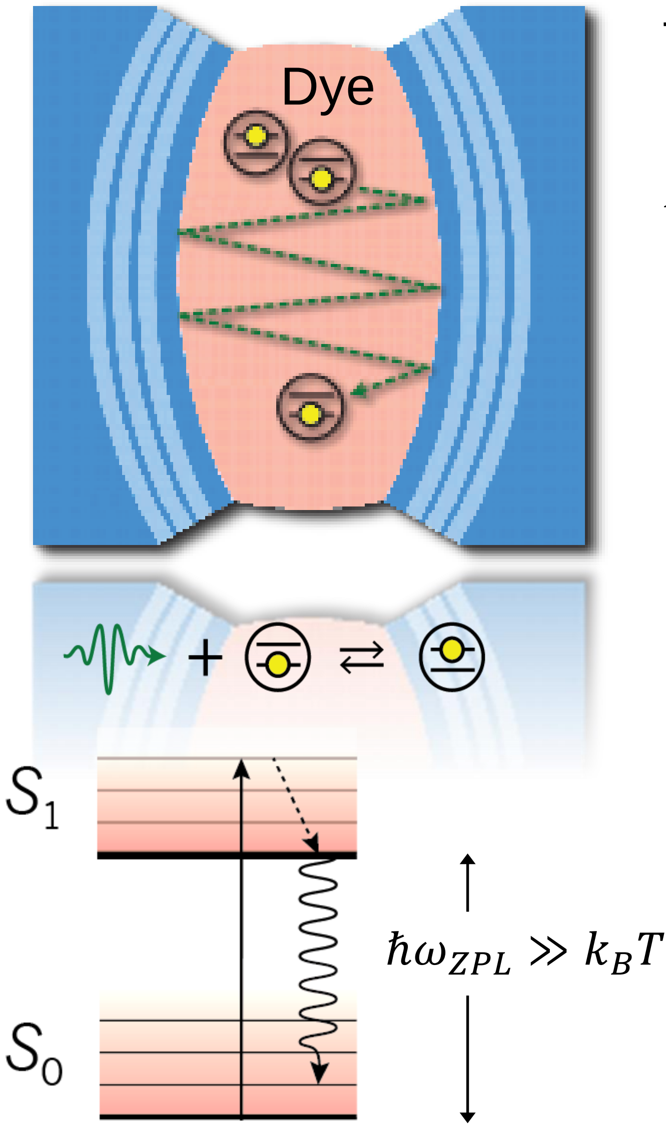
$$= m_0 c^2 + \frac{1}{2} m_0\,\Omega^2\,r^2 + \frac{k_r^2}{2m_0}$$

⇒ Photons in the microcavity behave as

- Massive particles
- Two-dimensional
- Harmonically trapped

Klaers, Vewinger & Weitz, *Nature Physics* **6**, 512 (2010)

dye photon box



The box: Dispersion

$$E = \frac{\hbar c}{n}\sqrt{k_z^2 + k_r^2} \approx \frac{\hbar c}{n}\left(k_z + \frac{k_r^2}{2\,k_z^2}\right)$$

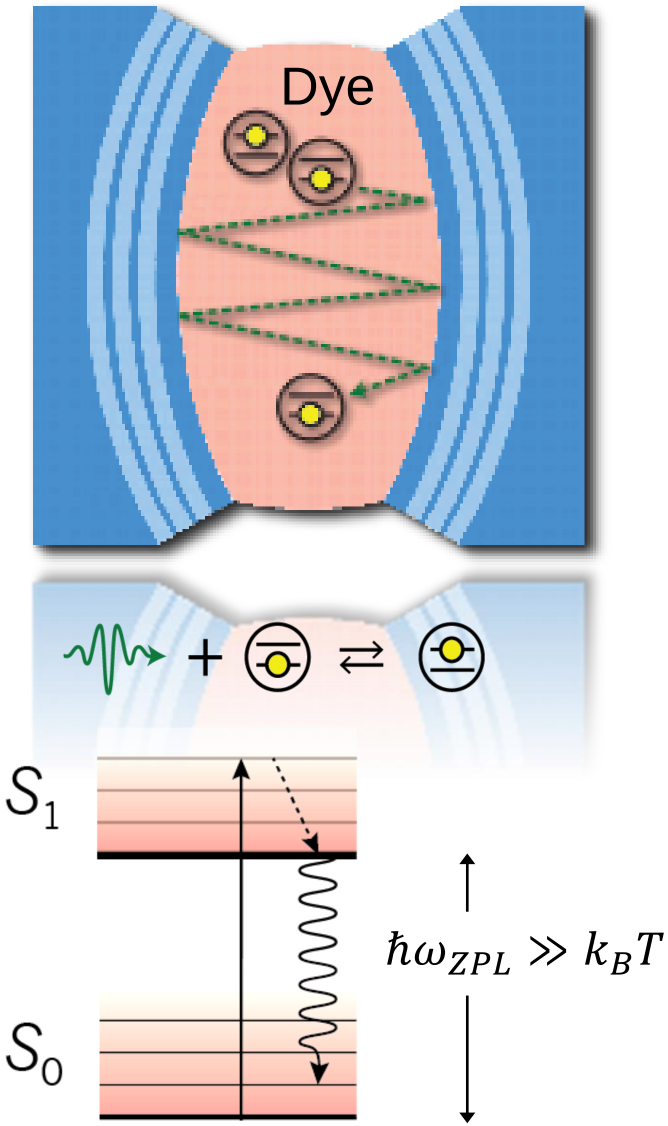
$$= \frac{\pi\hbar c q}{n\,D_0} + \frac{\pi\hbar c q}{n\,R\,D_0^2} r^2 + \frac{\hbar c\,D_0}{2\pi q n} k_r^2$$

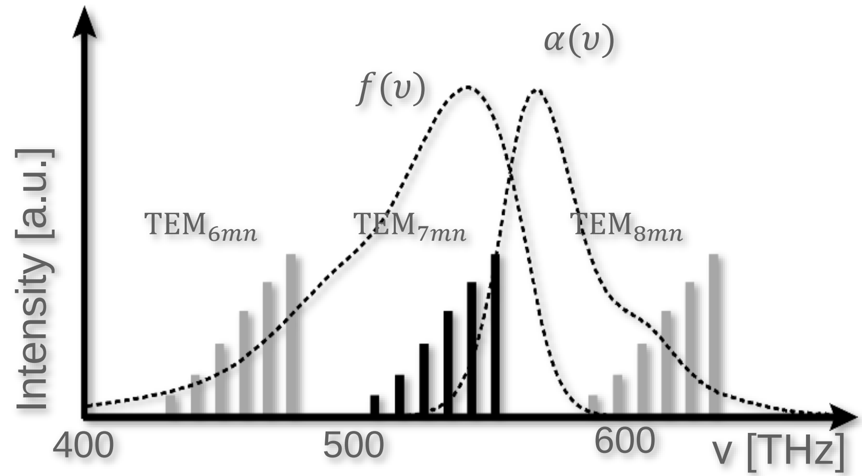
$$= m_0 c^2 \quad + \frac{1}{2} m_0\,\Omega^2\,r^2 + \frac{k_r^2}{2 m_0}$$

⇒ Photons in the microcavity behave as
- Massive particles
- Two-dimensional
- Harmonically trapped

Klaers, Vewinger & Weitz, *Nature Physics* **6**, 512 (2010)

dye photon box





Dye reservoir:

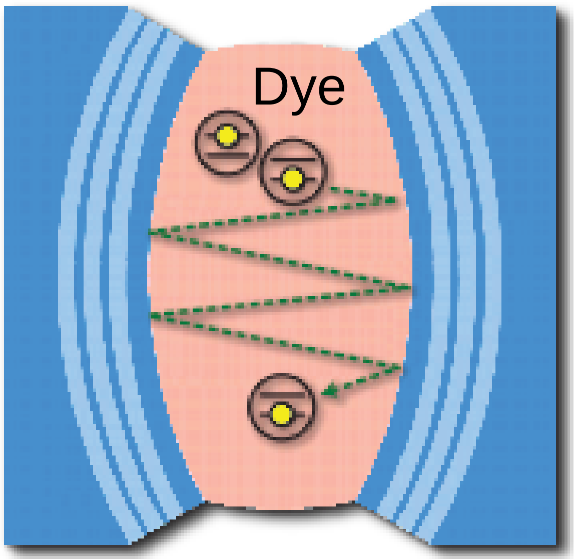
- Thermalizes gas
- Sets chemical potential

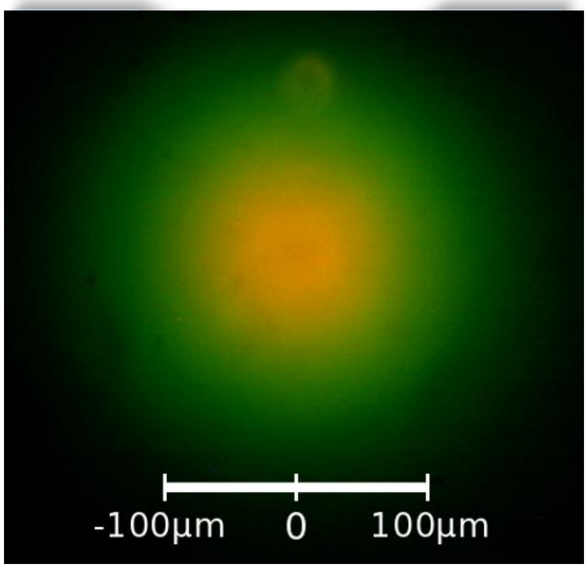
$$e^{\frac{\mu_\gamma}{k_B T}} = \frac{w_\downarrow M_\uparrow}{w_\uparrow M_\downarrow} e^{\frac{\hbar(\omega_C - \Delta)}{k_B T}}$$

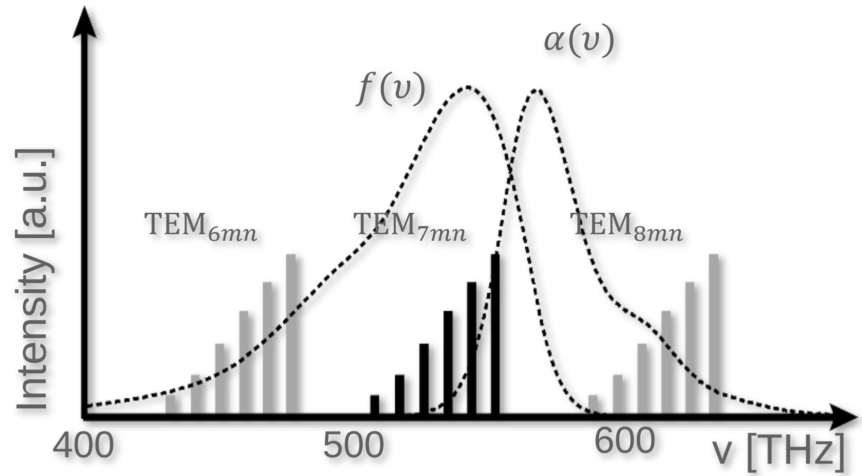
Klaers, Vewinger & Weitz, *Nature Physics* **6**, 512 (2010)

universitätbonn

dye photon box







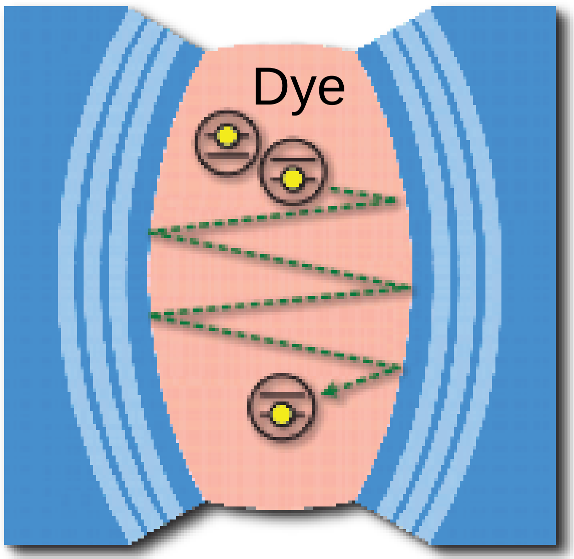
Dye reservoir:
- Thermalizes gas
- Sets chemical potential

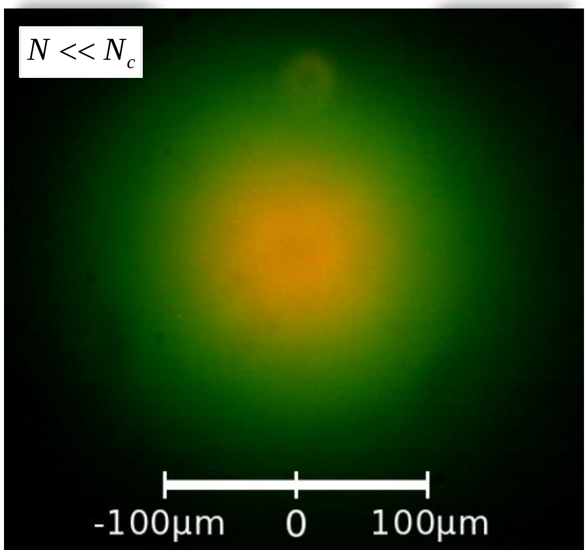
$$e^{\frac{\mu_\gamma}{k_B T}} = \frac{w_\downarrow M_\uparrow}{w_\uparrow M_\downarrow} e^{\frac{\hbar(\omega_C - \Delta)}{k_B T}}$$

Klaers, Vewinger & Weitz, *Nature Physics* **6**, 512 (2010)

universitätbonn

Scales





Energy scales

Trap frequency	$\hbar\Omega \approx 150\mu\text{eV}$
Thermal energy	$k_B T \approx 25\text{meV}$
Cavity cutoff	$\hbar\omega_{\text{cutoff}} \approx 2.1\text{eV}$

➔Photon mass $\approx 10^{-7}\, m_e$

➔Critical particle number

$$N_c \cong \frac{\pi^2}{3}\left(\frac{k_\text{B}T}{\hbar\Omega}\right)^2 \approx 80.000\,@\,300K$$

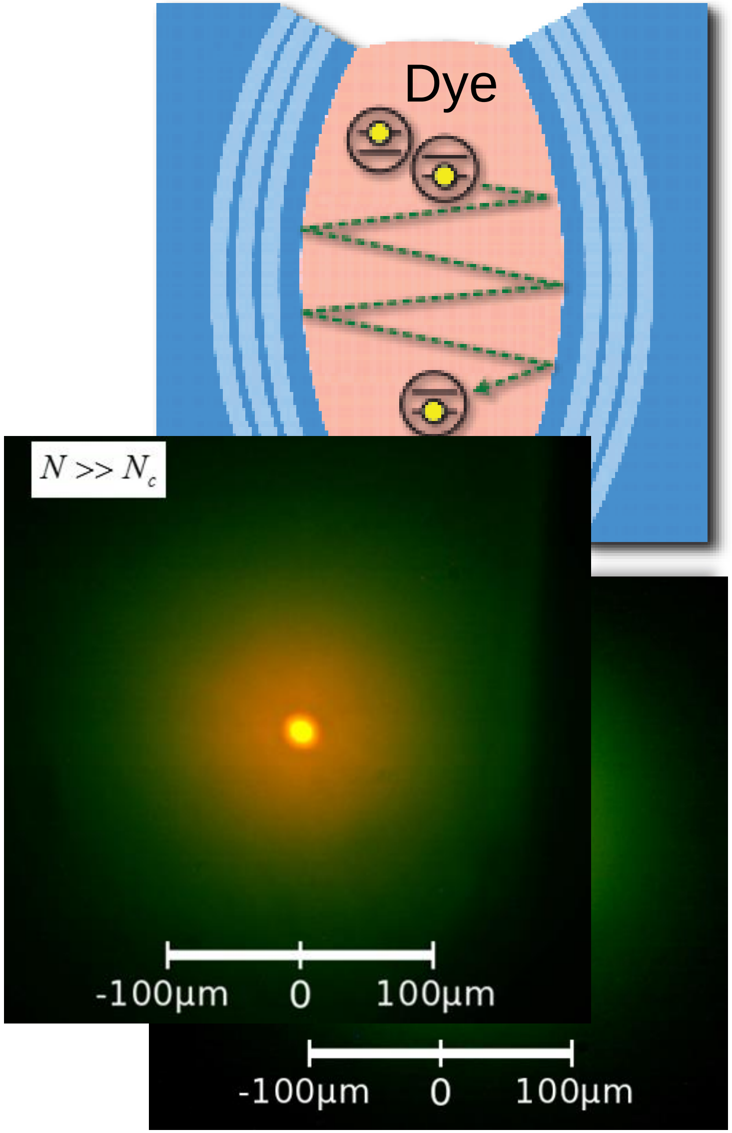
➔Critical phase space density

$$n_c \cong 1.3/\mu m^2$$

Klaers, Schmitt, Vewinger & Weitz, *Nature* **468**, 545 (2010)
See also Marelic & Nyman, PRA **91**, 033826 (2015)

universitätbonn

Scales



Energy scales

Trap frequency	$\hbar\Omega \approx 150\mu eV$
Thermal energy	$k_B T \approx 25 meV$
Cavity cutoff	$\hbar\omega_{cutoff} \approx 2.1 eV$

➔Photon mass $\approx 10^{-7}\, m_e$

➔Critical particle number

$$N_c \cong \frac{\pi^2}{3}\left(\frac{k_B T}{\hbar\Omega}\right)^2 \approx 80.000 \,@\, 300K$$

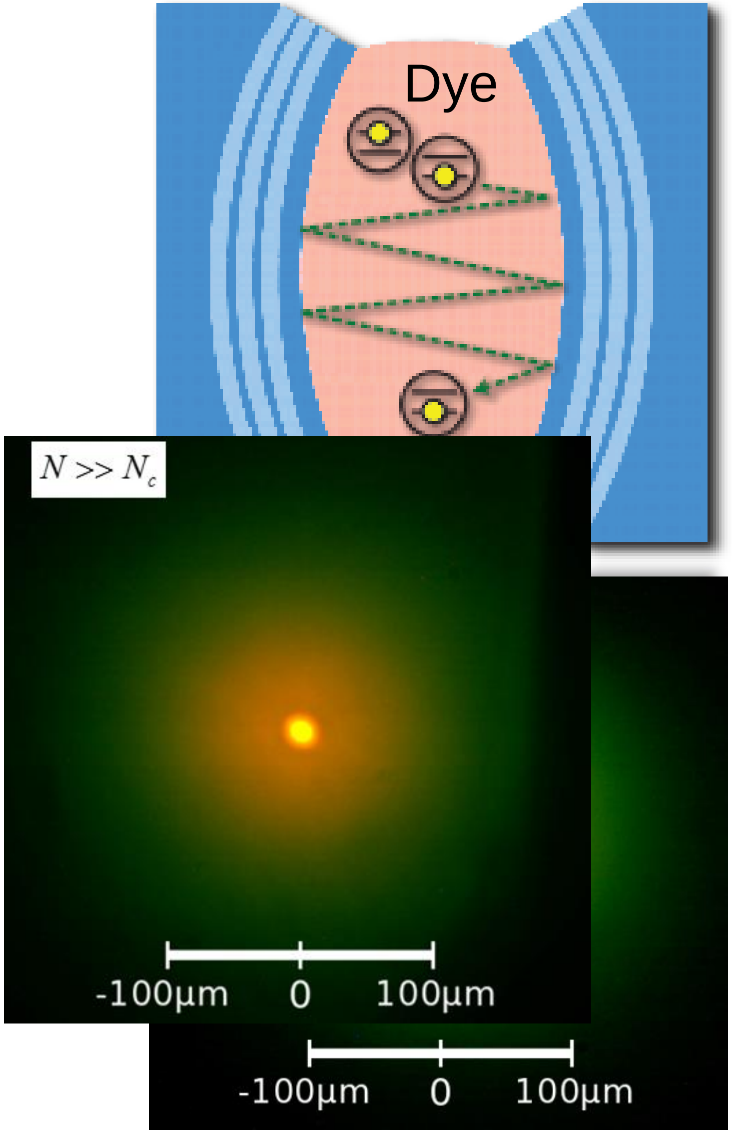
➔Critical phase space density

$$n_c \cong 1.3/\mu m^2$$

Klaers, Schmitt, Vewinger & Weitz, *Nature* **468**, 545 (2010)
See also Marelic & Nyman, PRA **91**, 033826 (2015)

universitätbonn

Scales



Energy scales

Trap frequency	$\hbar\Omega \approx 150\mu eV$
Thermal energy	$k_B T \approx 25meV$
Cavity cutoff	$\hbar\omega_{cutoff} \approx 2.1eV$

➔Photon mass $\approx 10^{-7}\, m_e$

➔Critical particle number

$$N_c \cong \frac{\pi^2}{3}\left(\frac{k_B T}{\hbar\Omega}\right)^2 \approx 80.000 \,@\, 300K$$

➔Critical phase space density

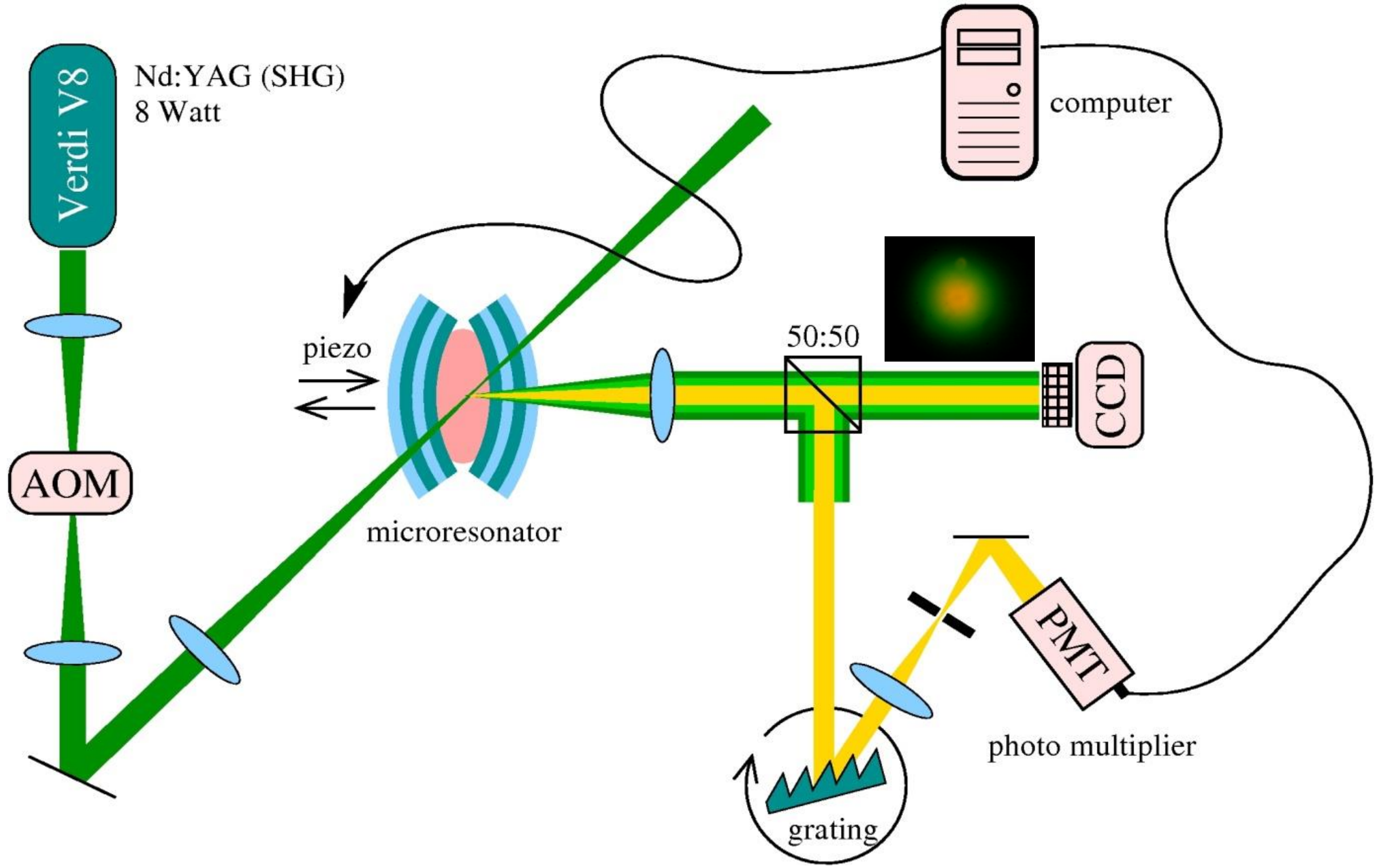
$$n_c \cong 1.3/\mu m^2$$

Brute force theory:
Appl Phys B 105, 17–33 (2011)

Microscopic models:
de Leeuw, PRA 88, 033829 (2013).
Kirton/Keeling, PRL 111,100404 (2013)
Kopylov et al., PRA 92, 063832 (2015)

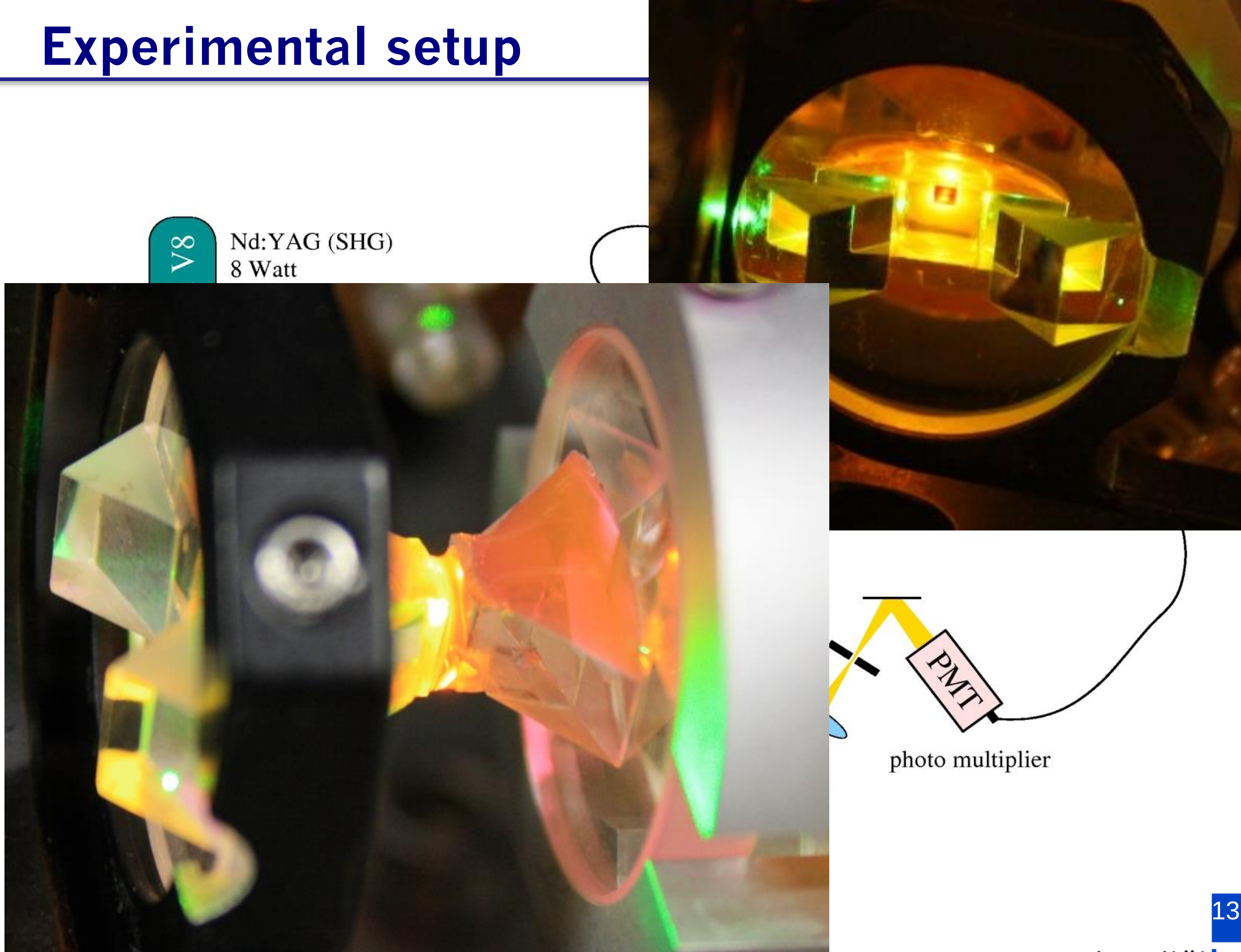
Klaers, Schmitt, Vewinger & Weitz, *Nature* **468**, 545 (2010)
See also Marelic & Nyman, PRA **91**, 033826 (2015)

Experimental setup

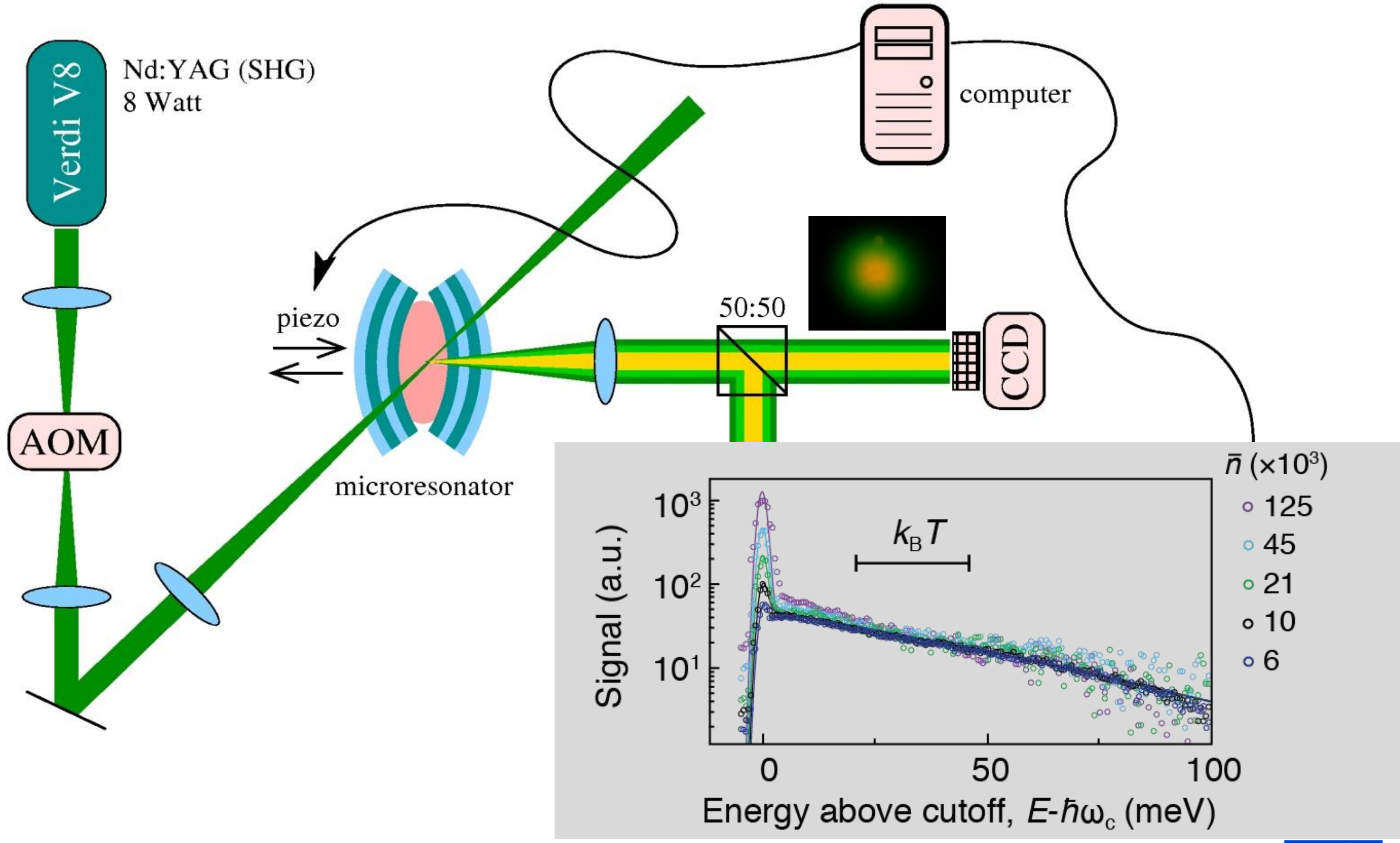


universitätbonn

Experimental setup

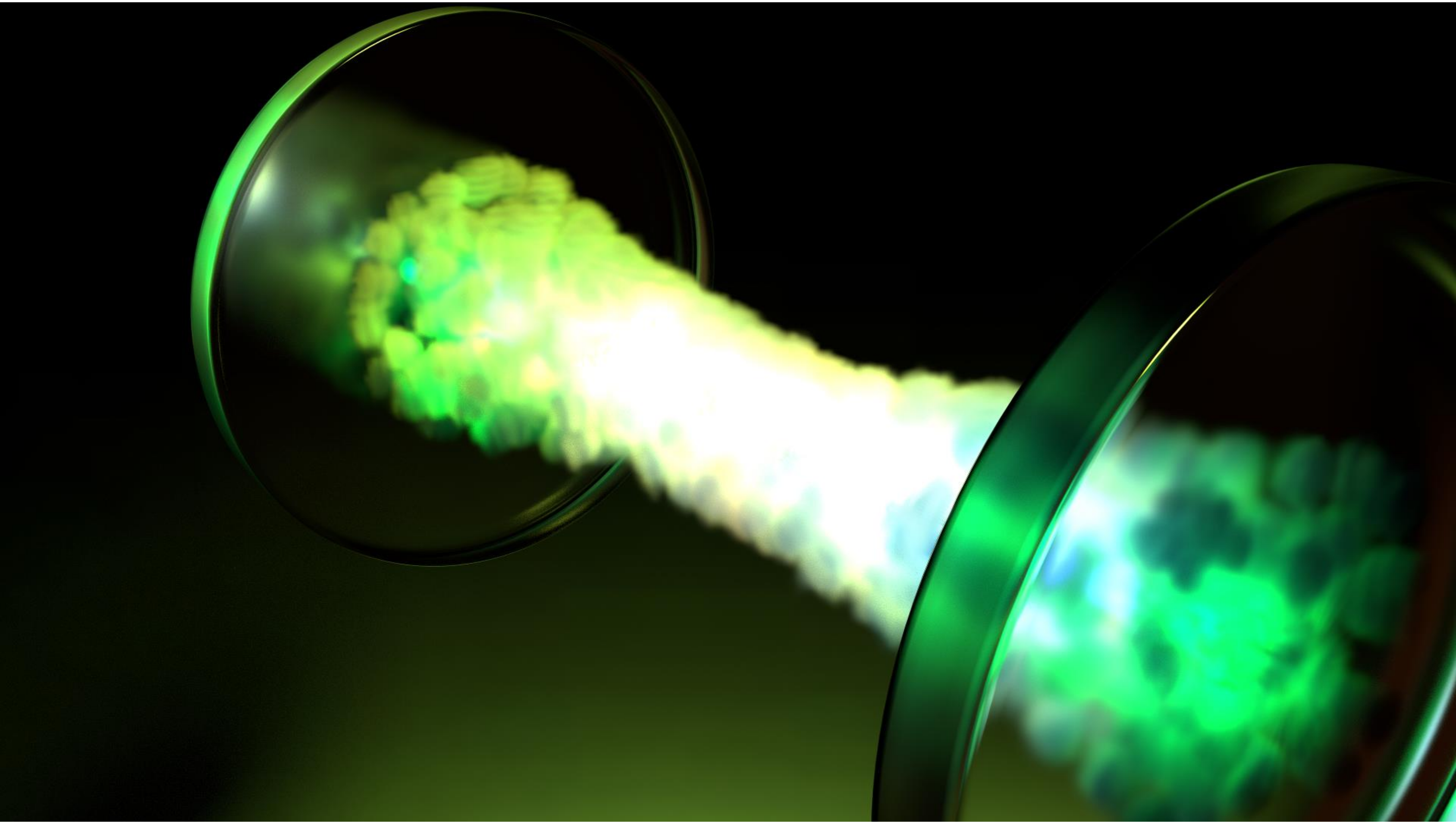


Experimental setup

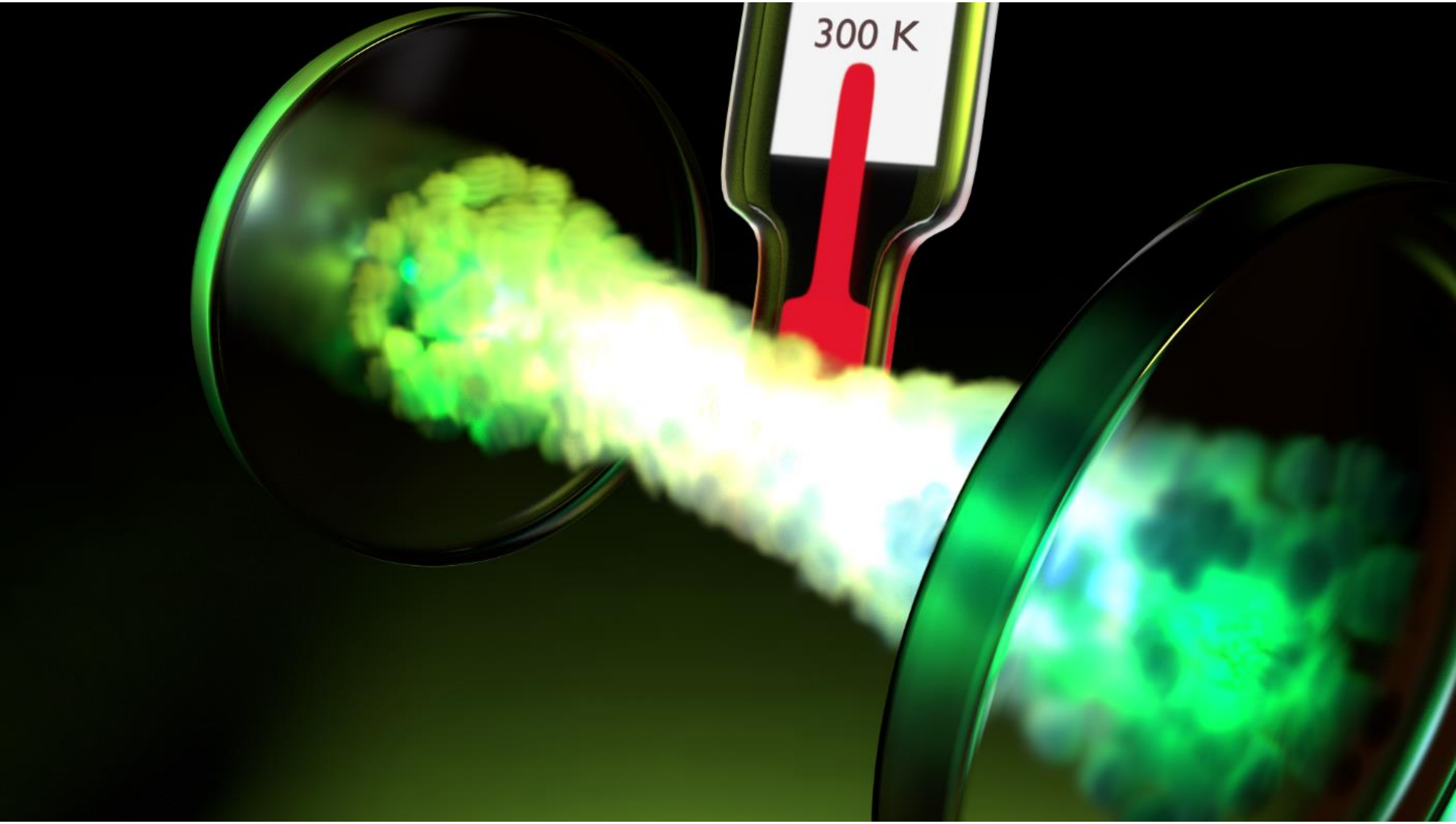


universitätbonn

Properties?



Properties?



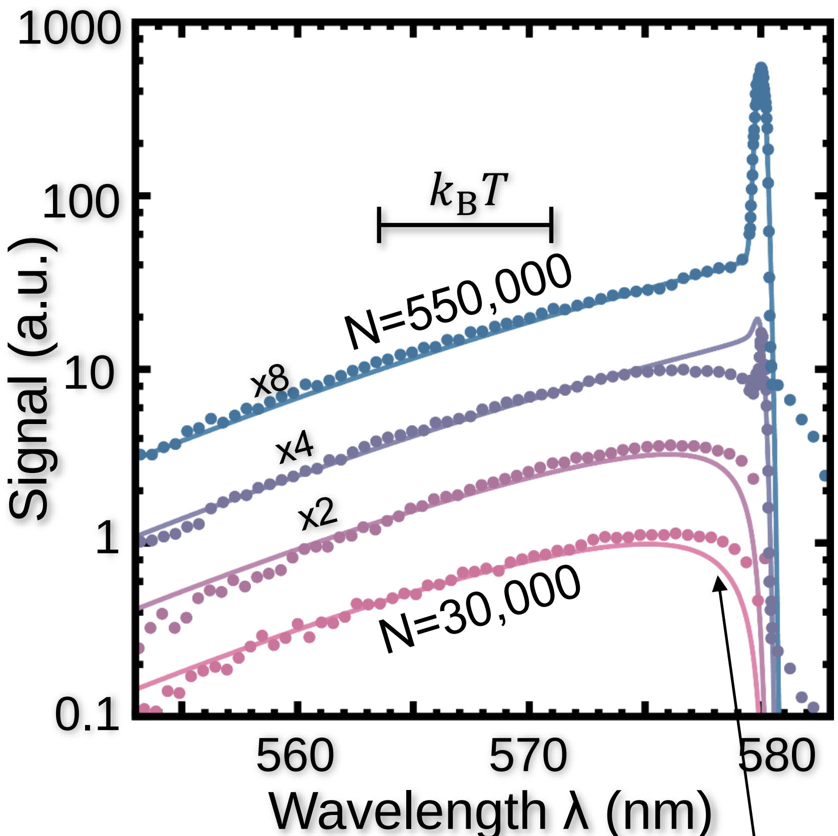
universitätbonn

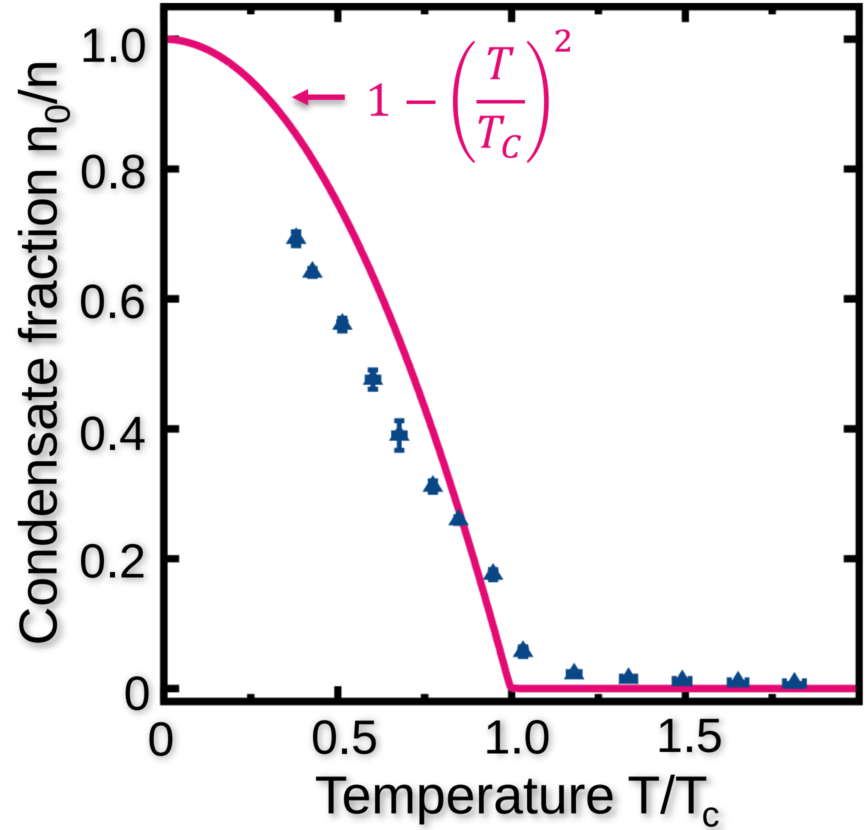
1) Photon BEC: HowTo

2) Thermodynamic Properties of Photons

3) Fluctuations & Symmetry Breaking

Condensate Fraction





Bose-Einstein distribution

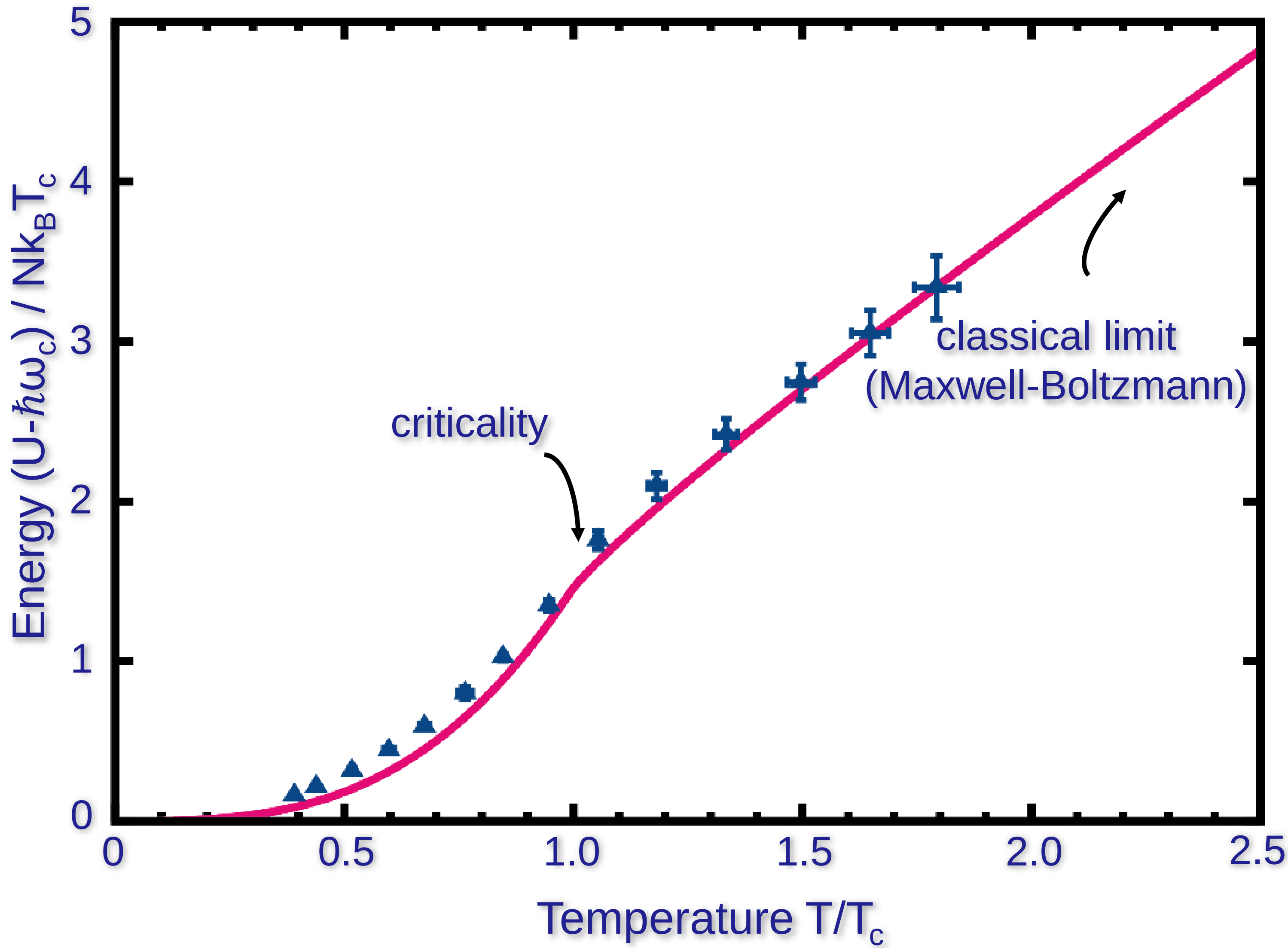
$$T/T_c = \sqrt{N_c/N}$$

≈ 80.000

Damm, Schmitt,… Nature Comm. 7,11340 (2016)

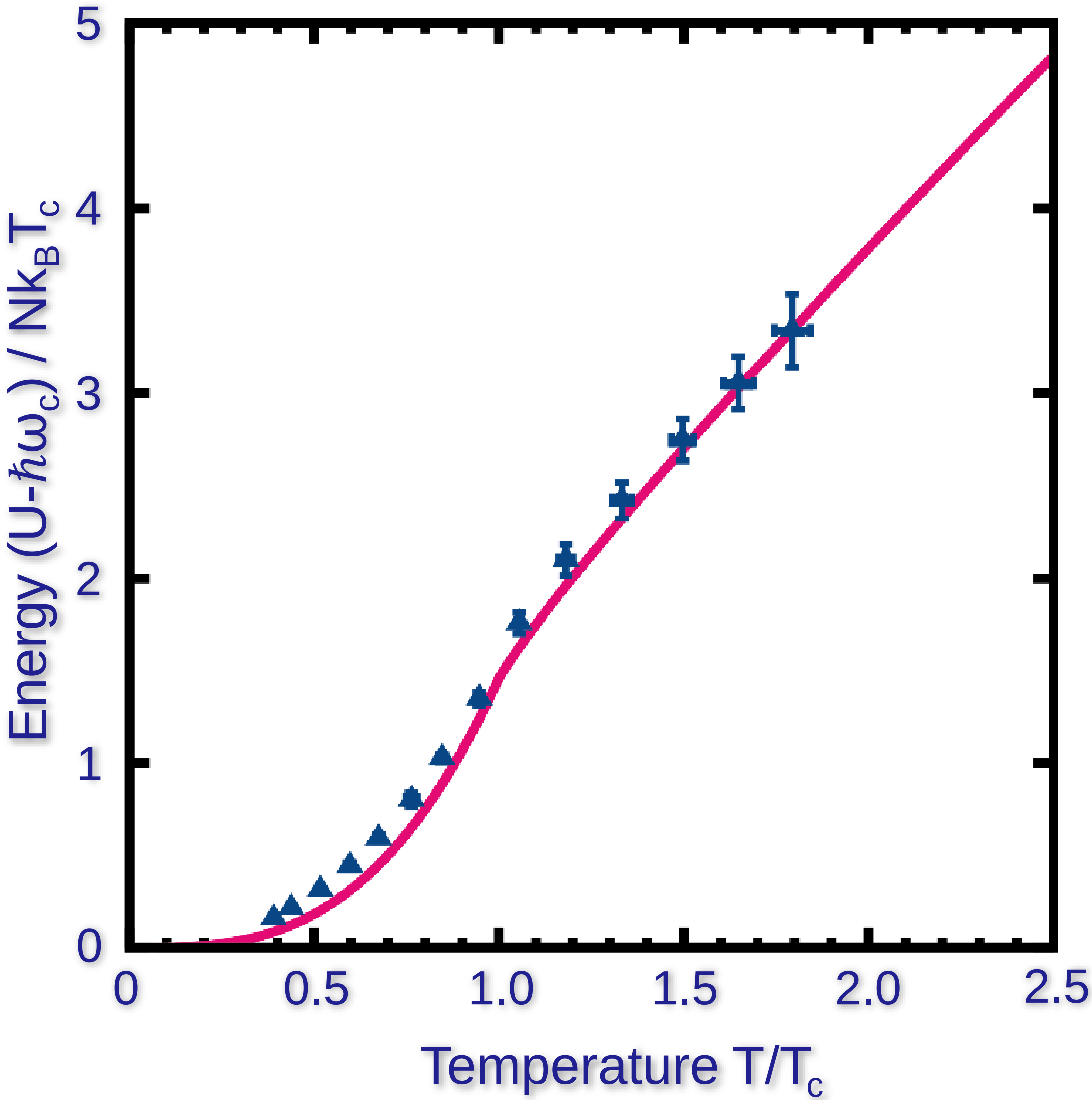
universitätbonn

Internal Energy

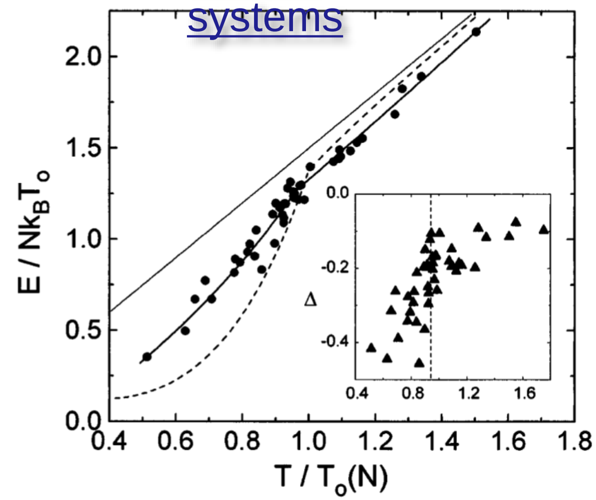


universitätbonn

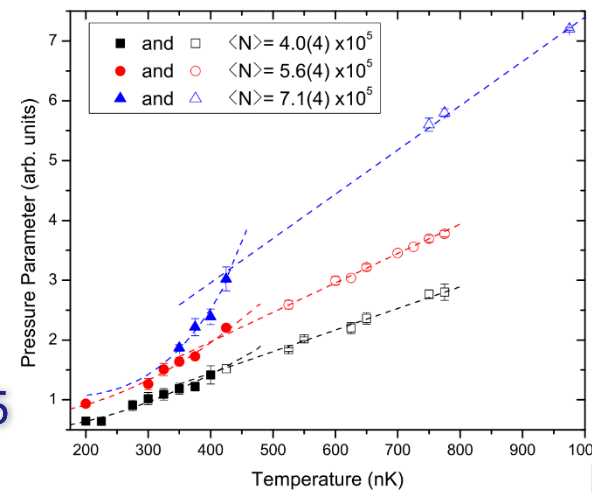
Internal Energy



Atomic systems

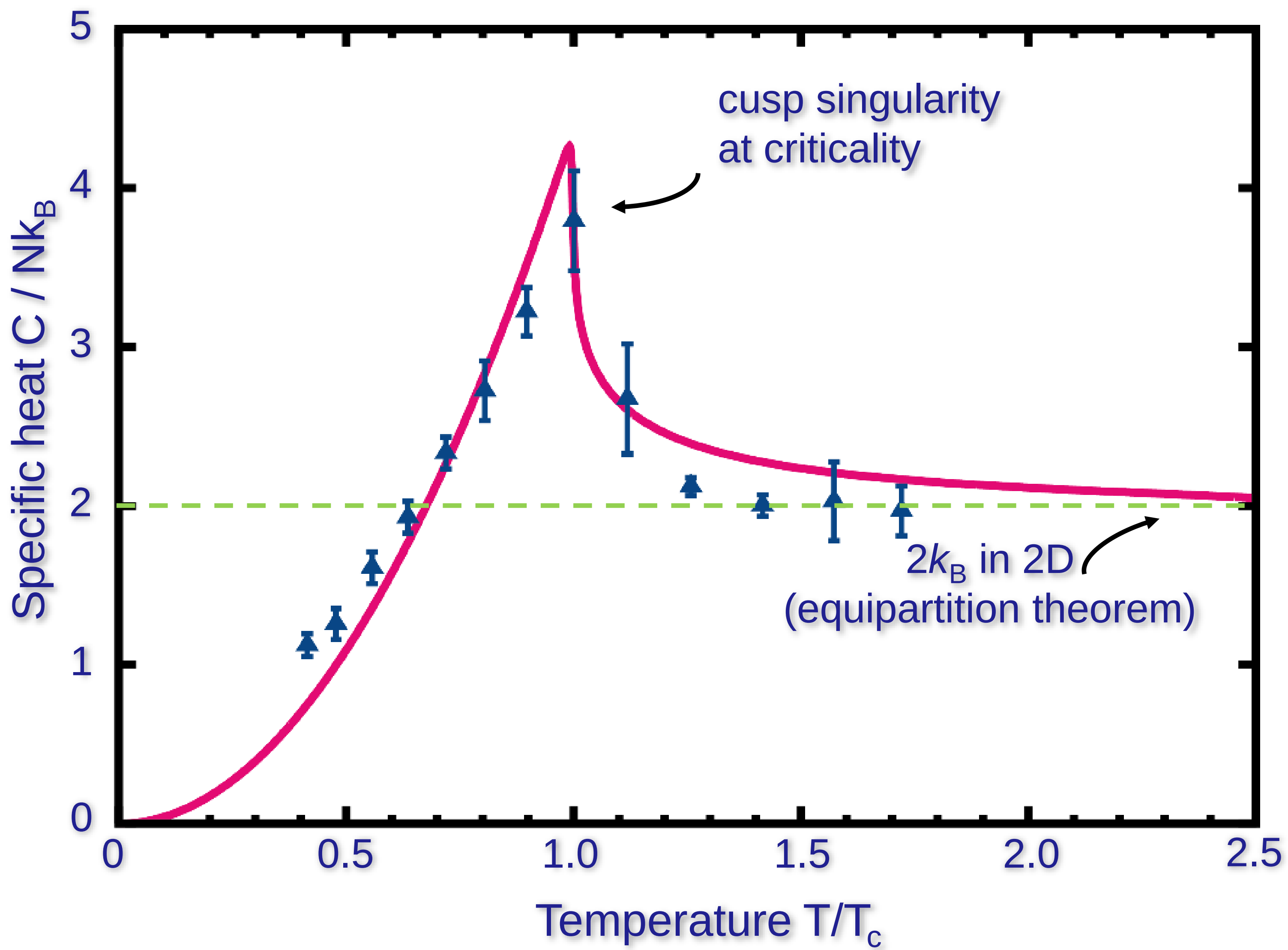


Phys. Rev. Lett. **77**, 4984-4987 (1996)



Phys. Rev. **A** 90, 043640 (2014)

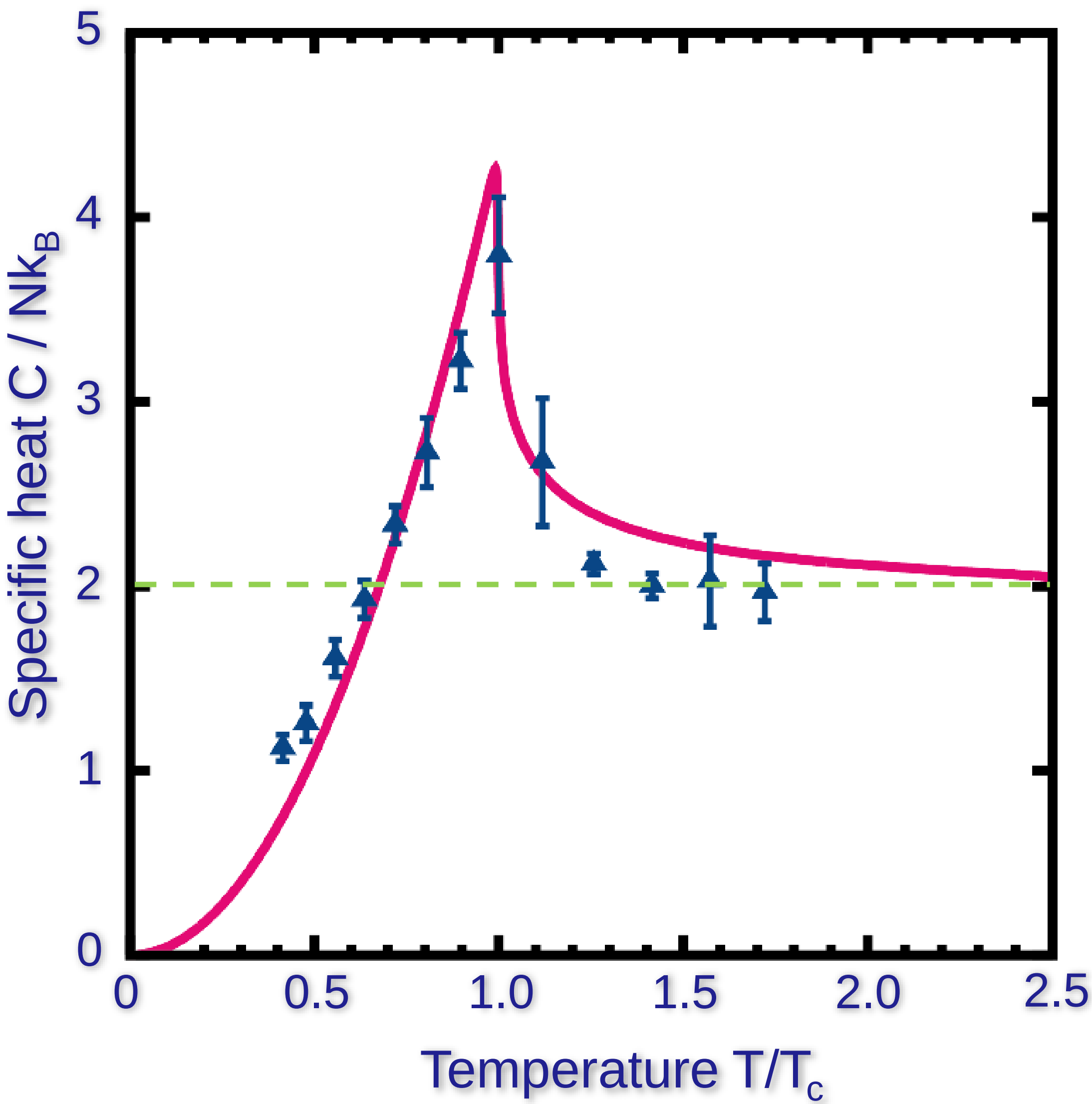
Specific Heat



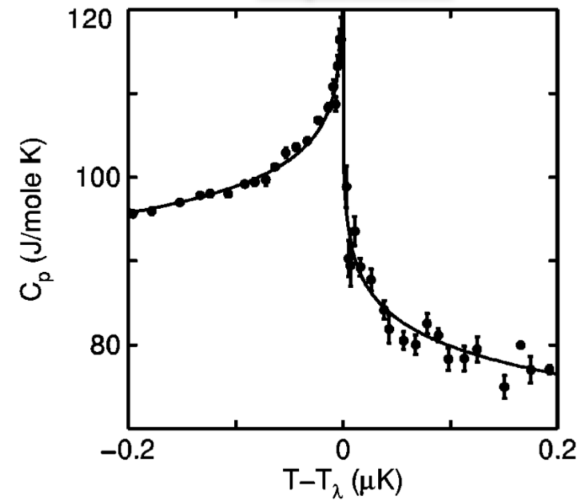
Klünder & Pelster, EPJB 68, 457 (2009): $C=4.38\ k_BT$, TD limit

universitätbonn

Specific Heat

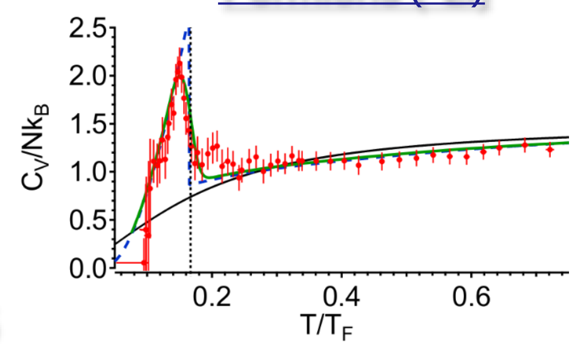


Liquid ^{4}He



Phys. Rev. B **68**, 174518 (2003)

Fermions (^{6}Li)

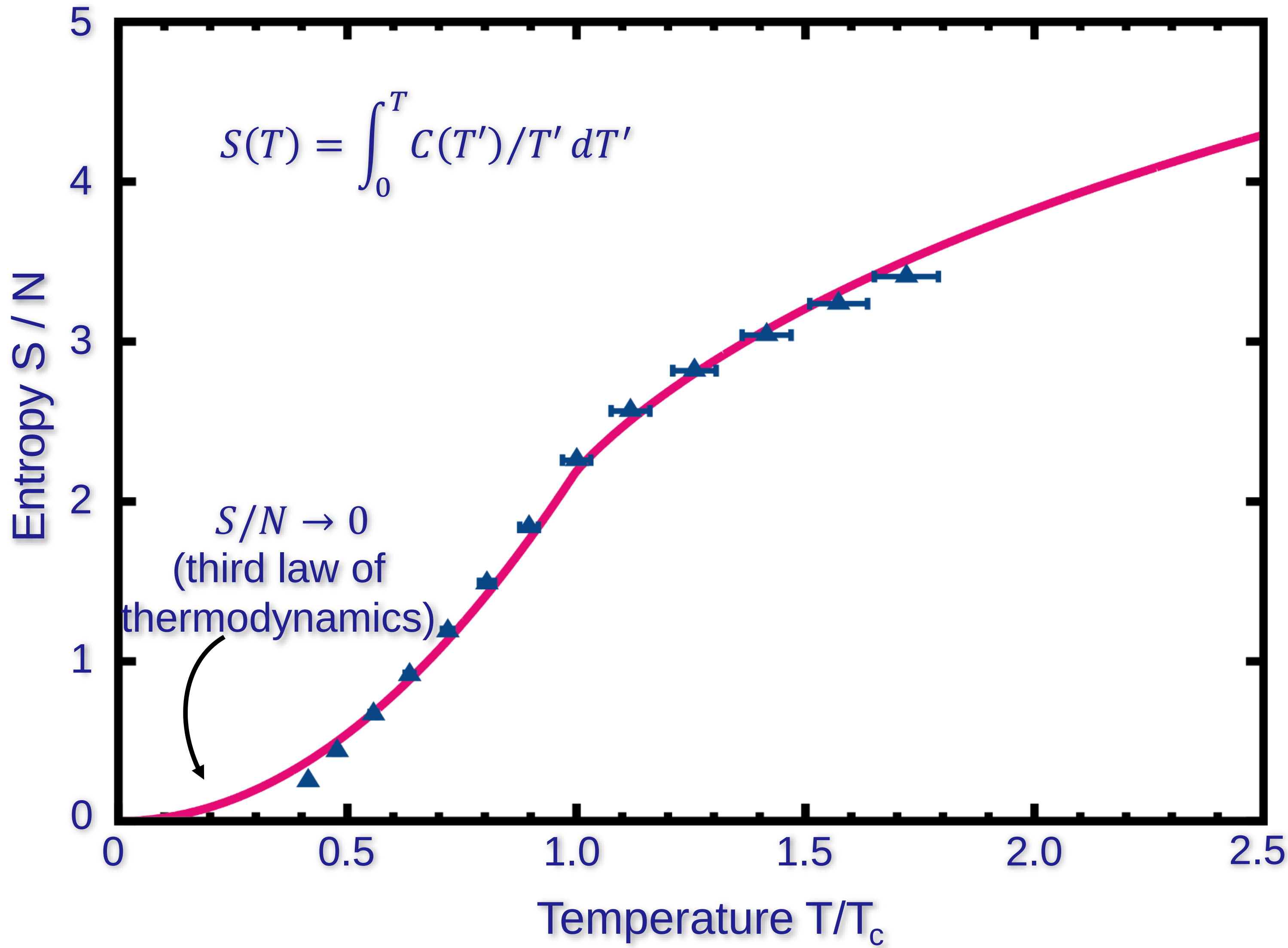


Science **335**, 563-567 (2012)

Klünder & Pelster, EPJB 68, 457 (2009): C=4.38 $k_B T$, TD limit

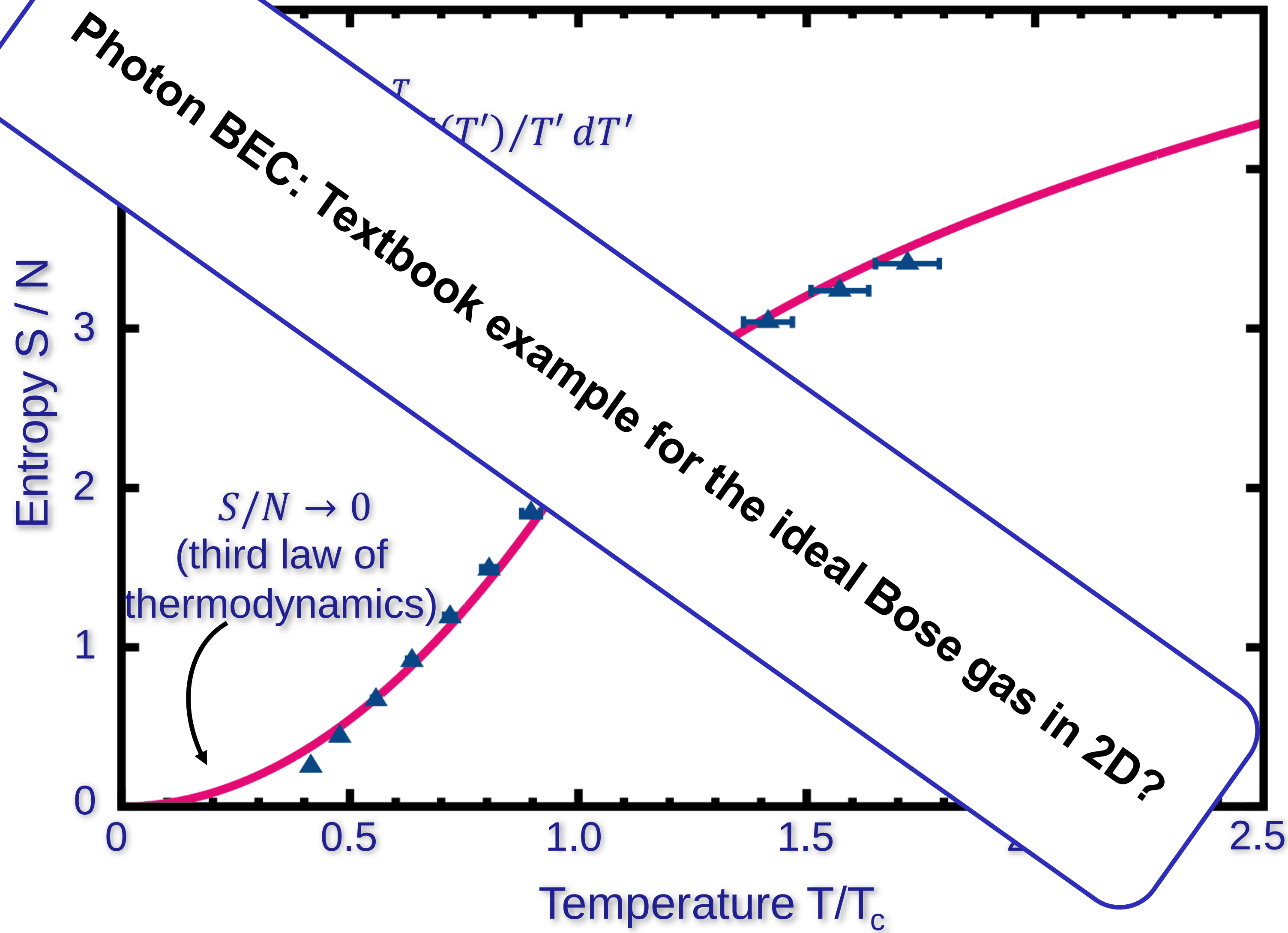
universitätbonn

Entropy per Particle



Entropy per Particle

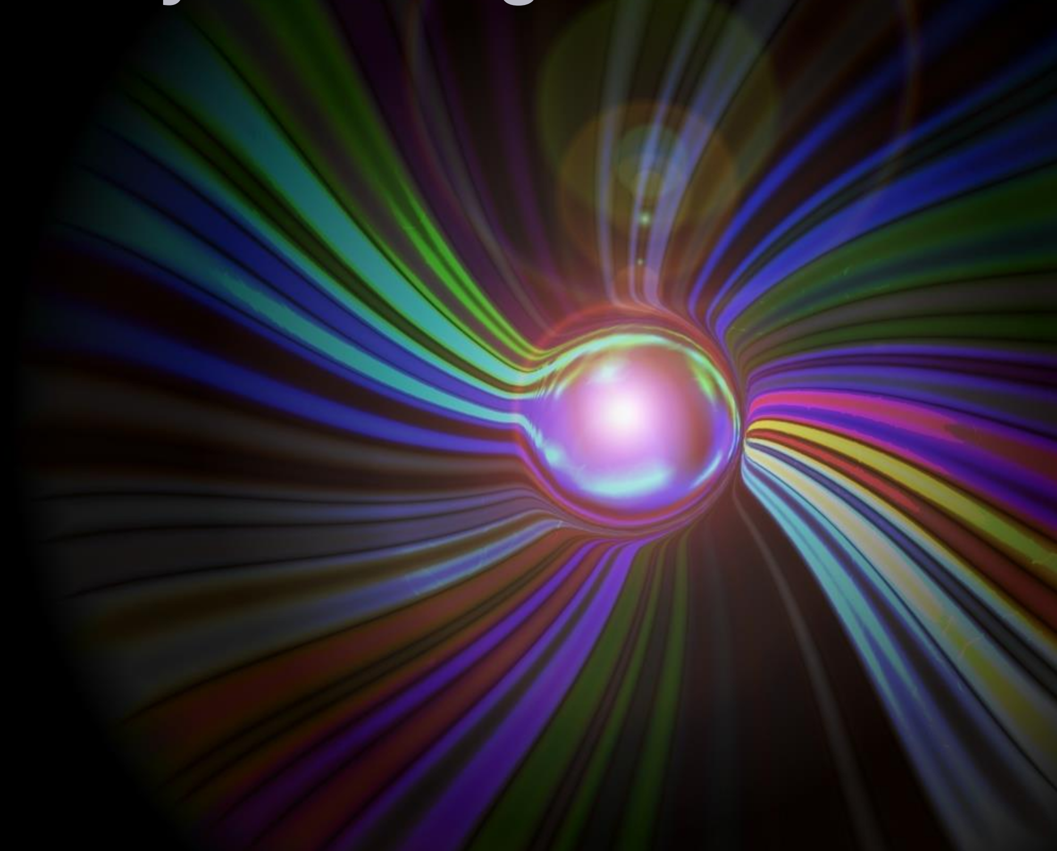
Photon BEC: Textbook example for the ideal Bose gas in 2D?



1) Photon BEC: HowTo

2) Thermodynamic Properties of Photons

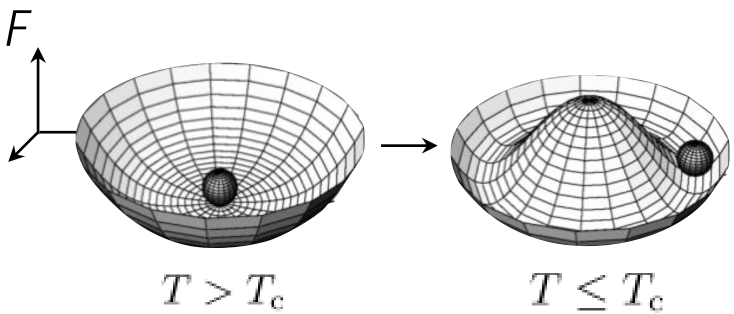
3) Fluctuations & Symmetry Breaking



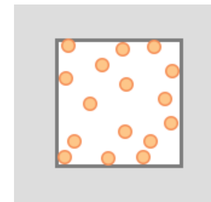
Coherence of a Bose-Einstein condensate

P. W. Anderson (1986): "Do two superfluids which have never 'seen' one another possess a relative phase?"

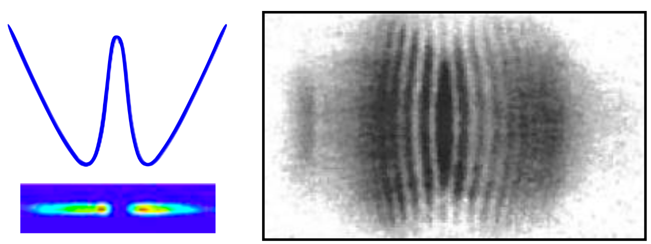
Spontaneous symmetry breaking



$$|\psi\rangle = e^{i\phi}|\phi_0\rangle$$
$$\phi = \text{konst.}$$

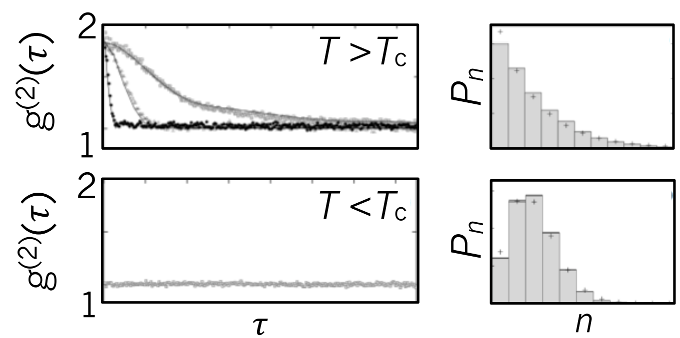


Phase selection: long-range order



Andrews et al., *Science* **275** (1997)

Damping of density fluctuations



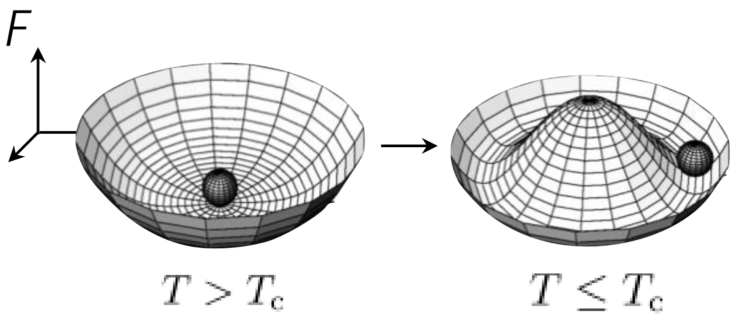
Öttl et al., *PRL* **95** (2005)

universitätbonn

Coherence of a Bose-Einstein condensate

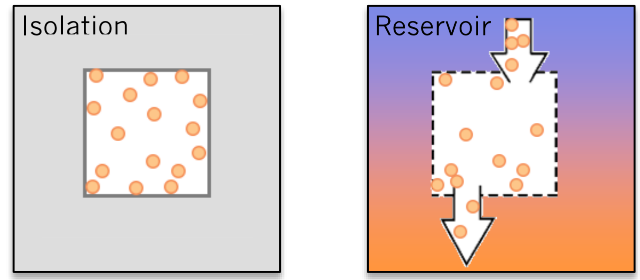
P. W. Anderson (1986): "Do two superfluids which have never 'seen' one another possess a relative phase?"

Spontaneous symmetry breaking



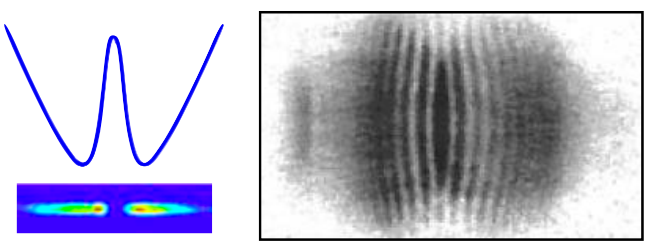
$$|\psi\rangle = e^{i\phi}|\phi_0\rangle$$
$$\phi = \text{konst.}$$

Closed vs. open system



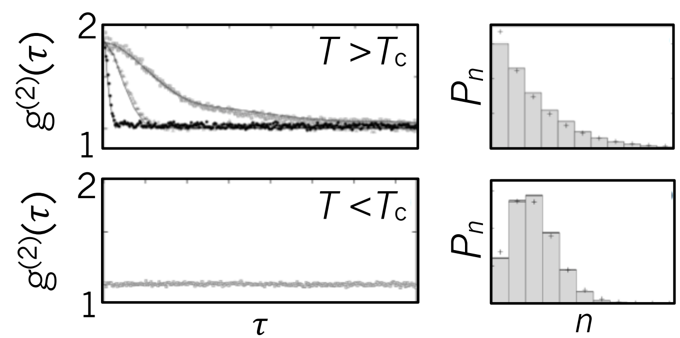
$\Delta n, \Delta E \simeq 0$ $\Delta n, \Delta E \neq 0$

Phase selection: long-range order



Andrews et al., *Science* **275** (1997)

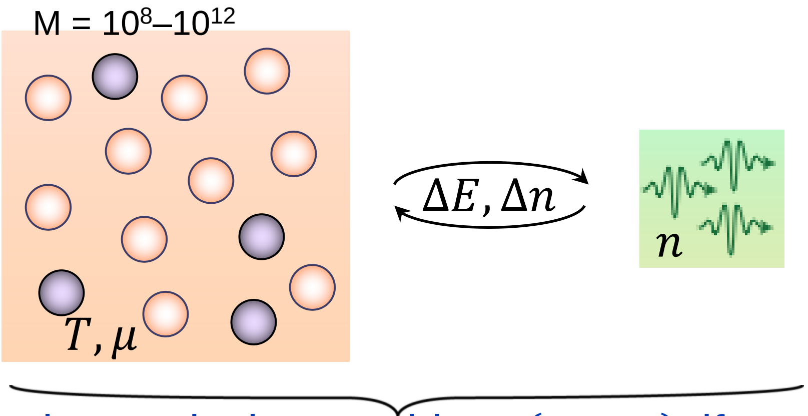
Damping of density fluctuations



Öttl et al., *PRL* **95** (2005)

→ BEC correlations in open environments?

Heat bath and particle reservoir for light

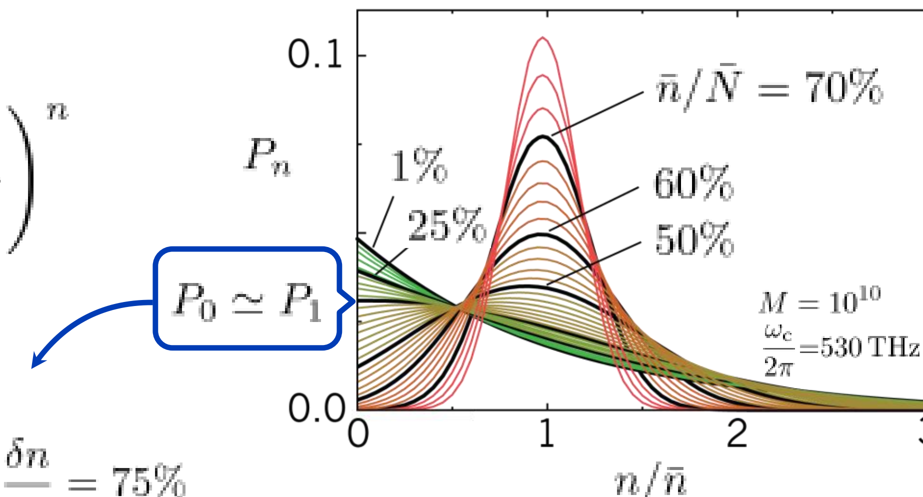


Grand canonical ensemble, $\Omega(T, V, \mu)$ if $M \gg n$

Photon number distribution

Master equation

$$\frac{P_n}{P_0} = \frac{(M - X + n)!}{(X - n)!} \left(\frac{\hat{B}_{21}(\omega_c)}{\hat{B}_{12}(\omega_c)} \right)^n$$



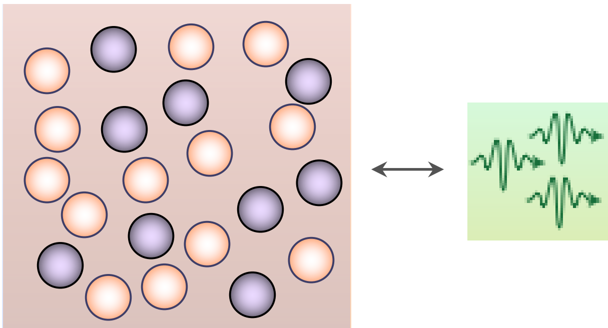
$$\frac{\bar{n}}{\bar{N}} = 33\%, \frac{\delta n}{\bar{n}} = 75\%$$

Klaers et al., *PRL* **108** (2012)
Sob'yanin, *PRE* 85 (2012)

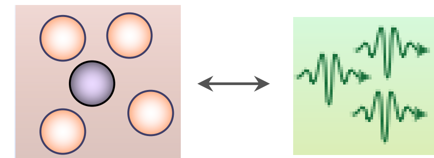
universitätbonn

Limiting cases for BEC number statistics

Grand-canonical ensemble ($M \gg n^2$)

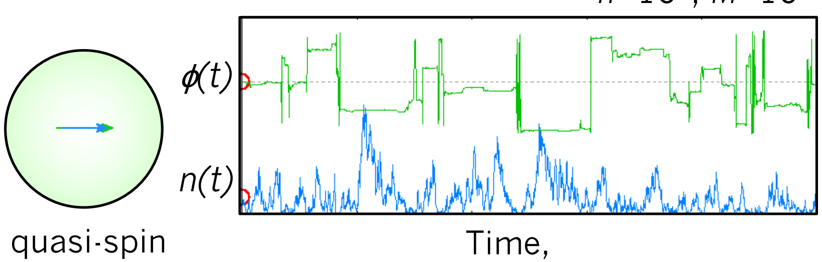


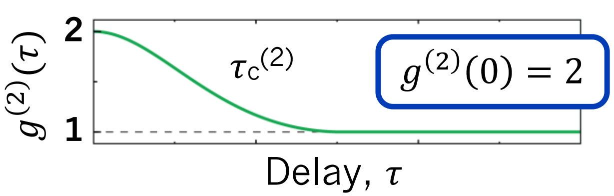
Canonical ensemble ($M < n^2$)



Bose-Einstein statistics ("flickering" BEC)

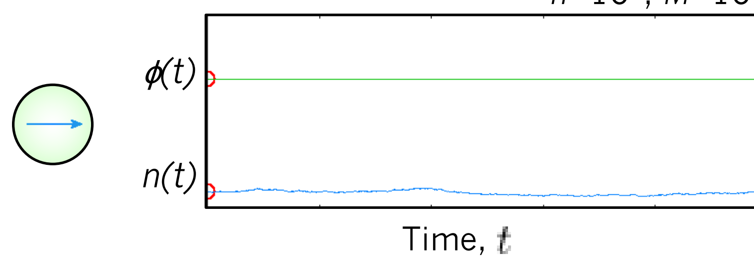
n=10^3, M=10^7

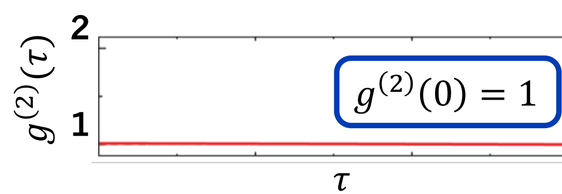




Poisson statistics ("quiet" BEC)

n=10^3, M=10^4



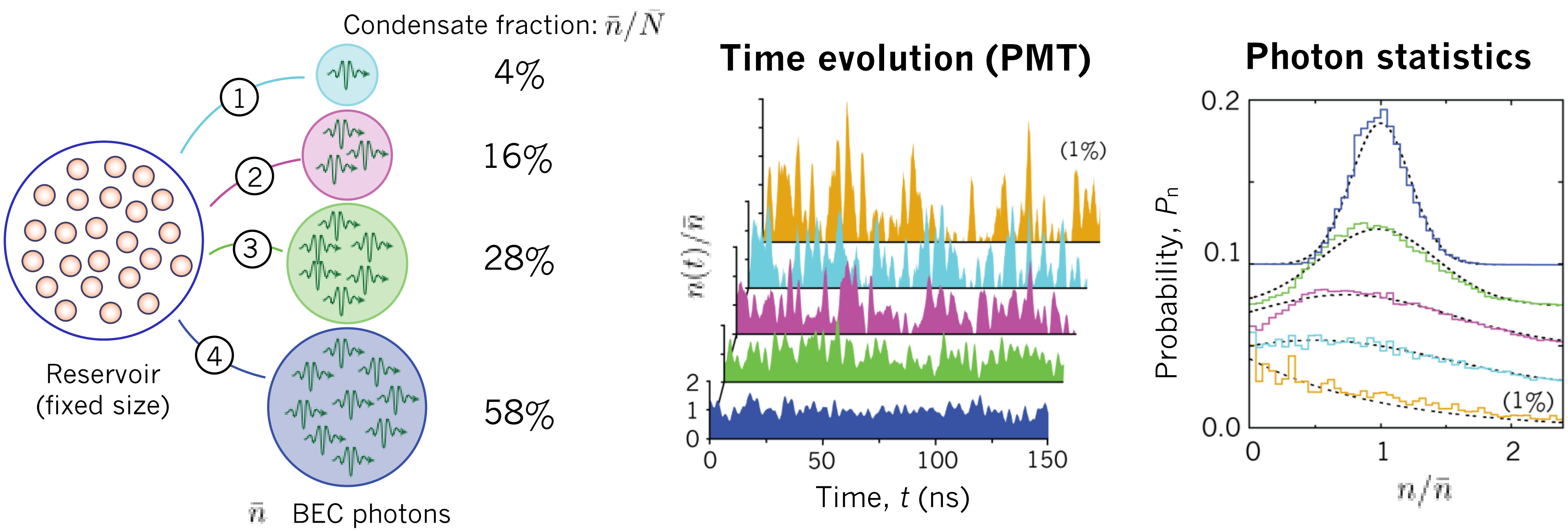


Autocorrelation

$\triangleq$

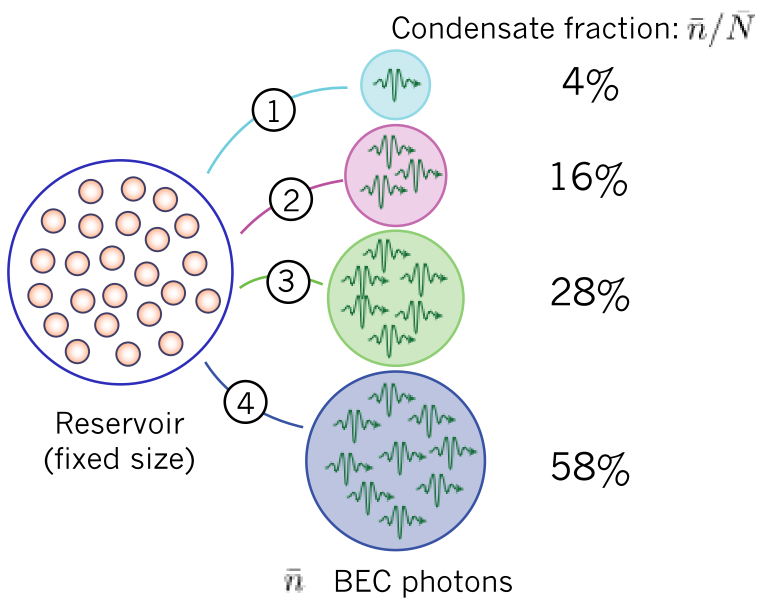
Fluctuation level

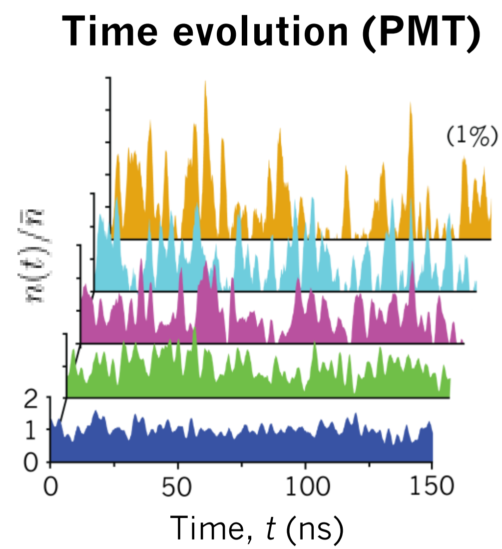
Experiment: intensity correlations of BEC

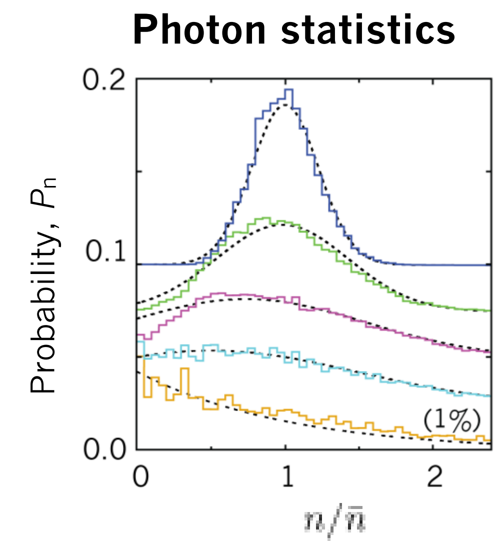


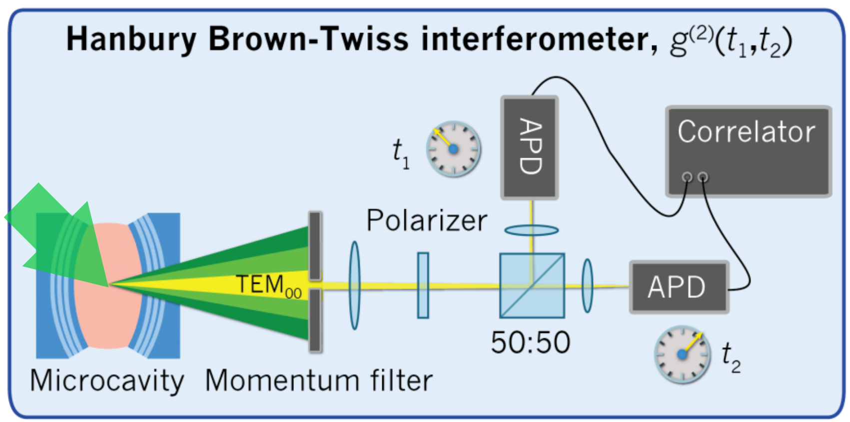
Schmitt et al., *Phys. Rev. Lett.* **112**, 030401 (2014)
see also: *Physics* **7** (2014)

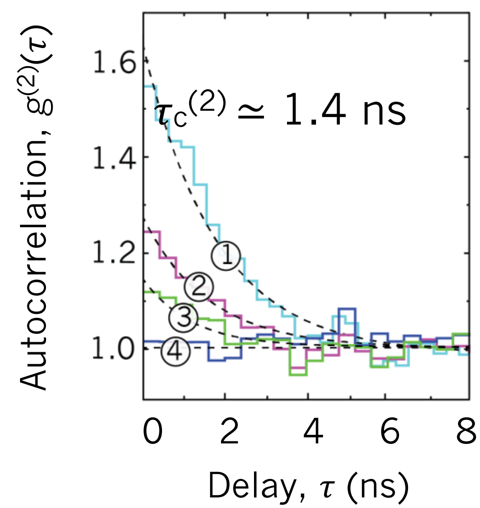
Experiment: intensity correlations of BEC











Crossover from
Bose-Einstein
$(M \gg \bar{n}^2)$

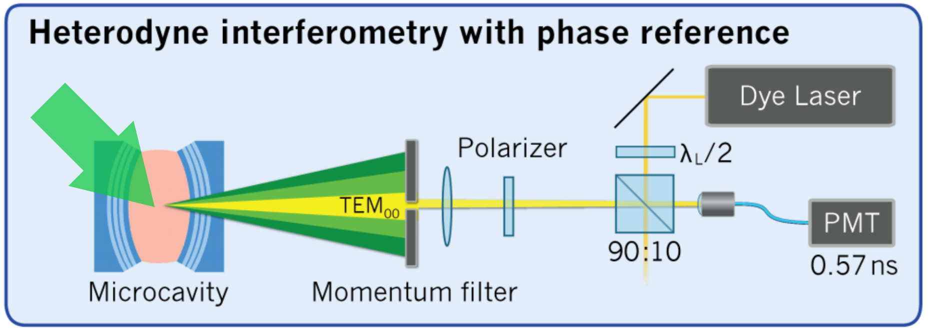
to
Poisson statistics
$(M \leq \bar{n}^2)$

Schmitt et al., *Phys. Rev. Lett.* **112**, 030401 (2014)
see also: *Physics* **7** (2014)

universitätbonn

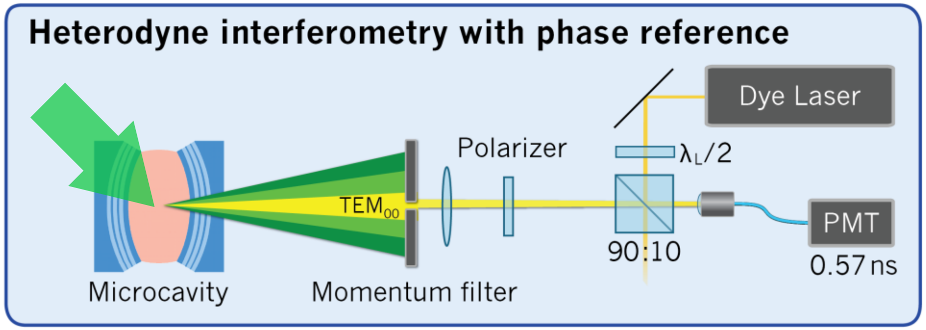
Temporal phase evolution

Response of condensate phase $\phi(t)$ to statistical fluctuations?

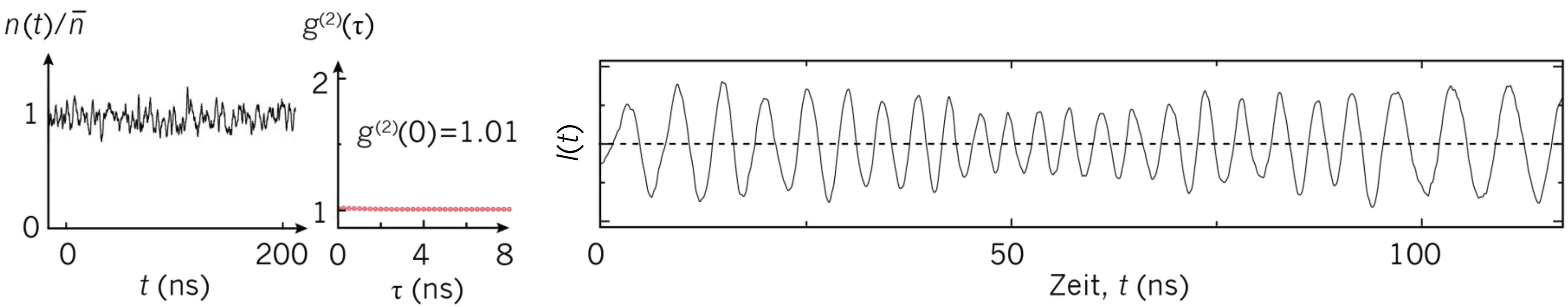


Temporal phase evolution

Response of condensate phase $\phi(t)$ to statistical fluctuations?



Canonical ensemble ($M \leq \bar{n}^2$, second-order coherence)



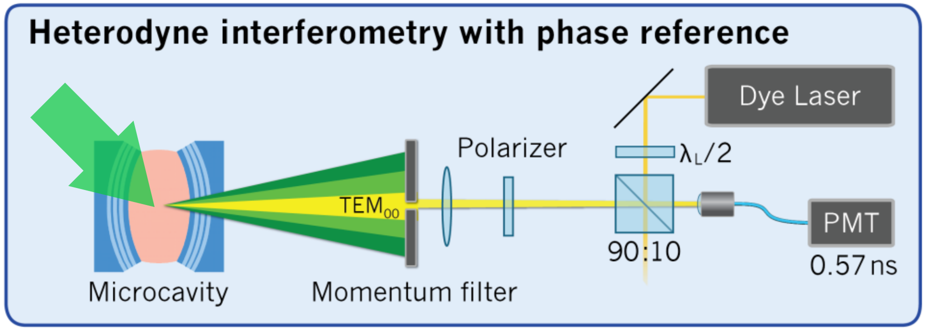
↳ regular beating without phase jumps

Schmitt et al., *Phys. Rev. Lett.* **116**, 033604 (2016)

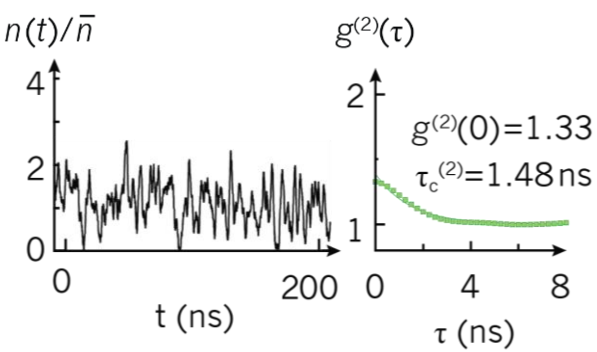
universitätbonn

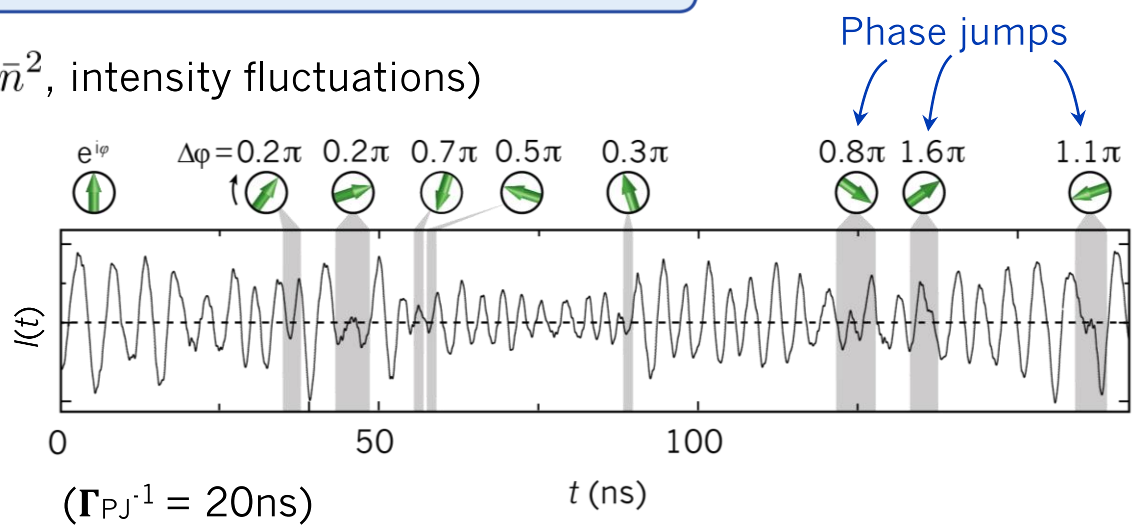
Temporal phase evolution

Response of condensate phase $\phi(t)$ to statistical fluctuations?



Grand-canonical ensemble ($M \geq \bar{n}^2$, intensity fluctuations)

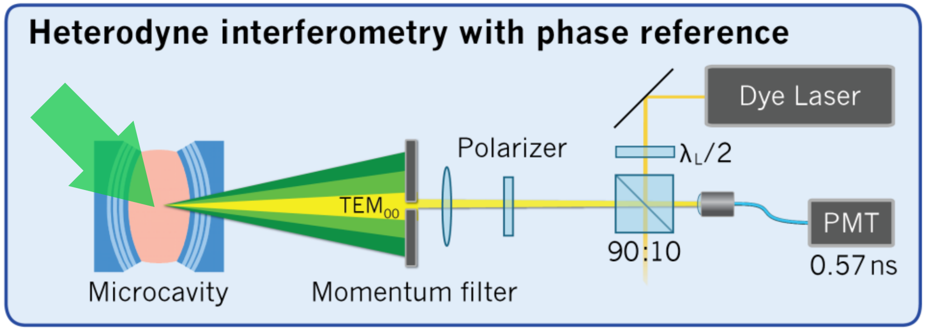




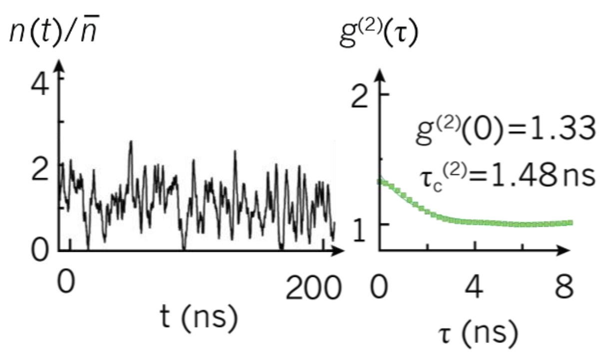
Schmitt et al., *Phys. Rev. Lett.* **116**, 033604 (2016)

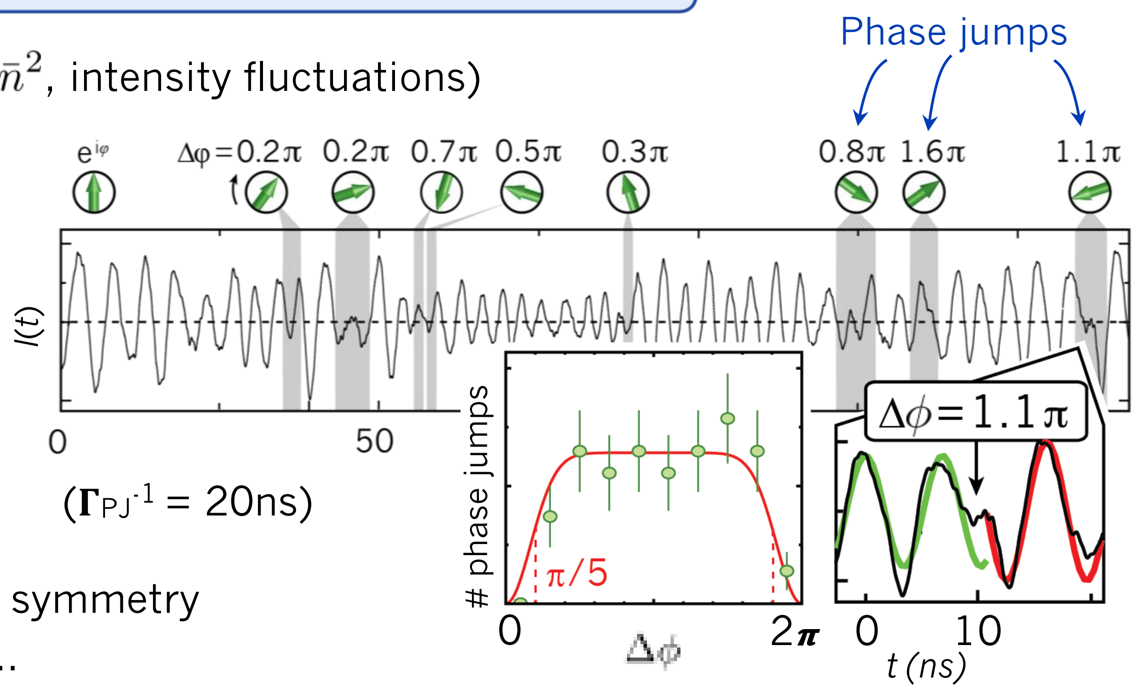
Temporal phase evolution

Response of condensate phase $\phi(t)$ to statistical fluctuations?



Grand-canonical ensemble ($M \geq \bar{n}^2$, intensity fluctuations)



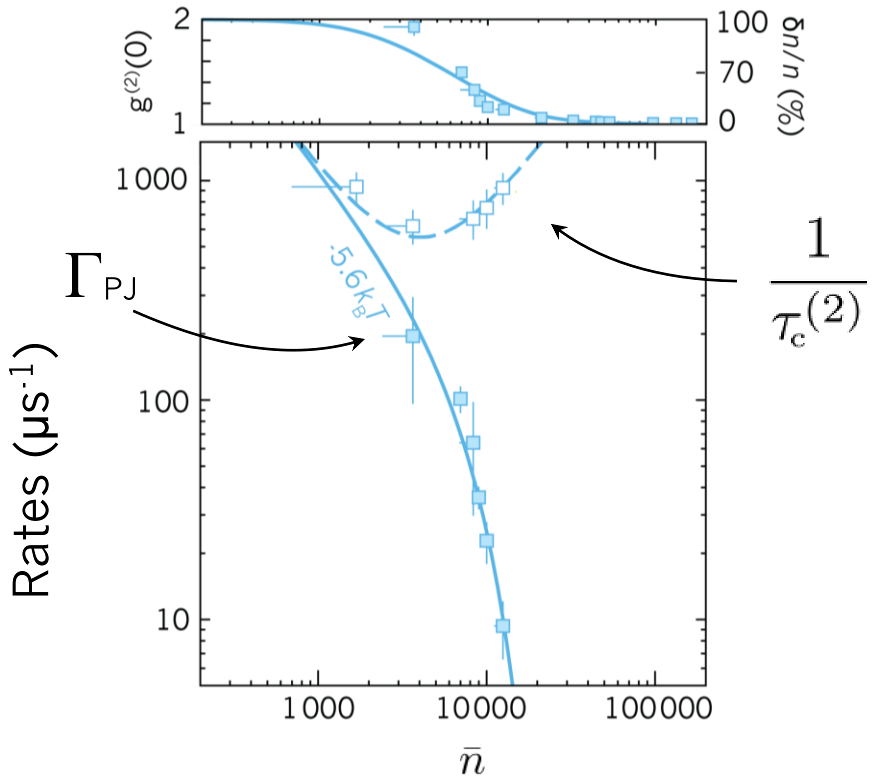


- Random distribution: $U(1)$ symmetry
- Separation of time scales…

Schmitt et al., *Phys. Rev. Lett.* **116**, 033604 (2016)

Separation of correlation times

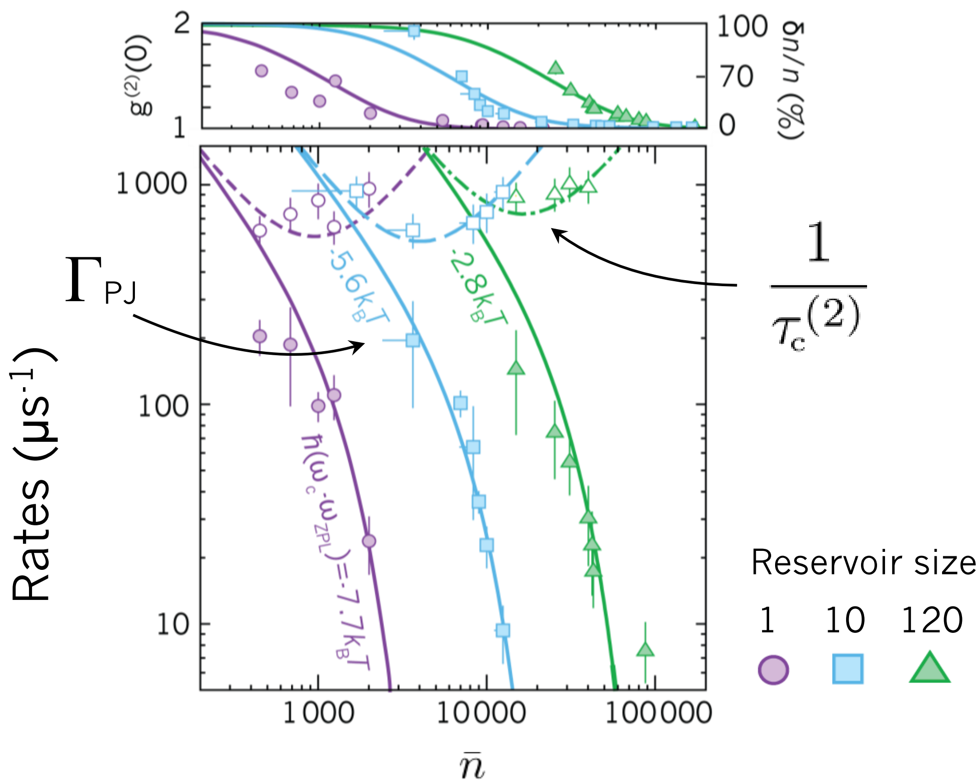
- Rate of fluctuations & phase jumps ($1/\tau_c^{(2)}$ & Γ_{PJ}) vs. increasing system size $\bar{n}$
- Suppressed fluctuations & phase jumps



Schmitt et al., *Phys. Rev. Lett.* **116**, 033604 (2016)
Analysis ignores phase diffusion,
Lewenstein et al., *PRL* **77** (1996), Imamoḡlu et al., *PRL* **78** (1997), De Leeuw et al., *PRA* **90** (2014), …

Separation of correlation times

- Rate of fluctuations & phase jumps ($1/\tau_c^{(2)}$ & Γ_{PJ}) vs. increasing system size $\bar{n}$
- Suppressed fluctuations & phase jumps

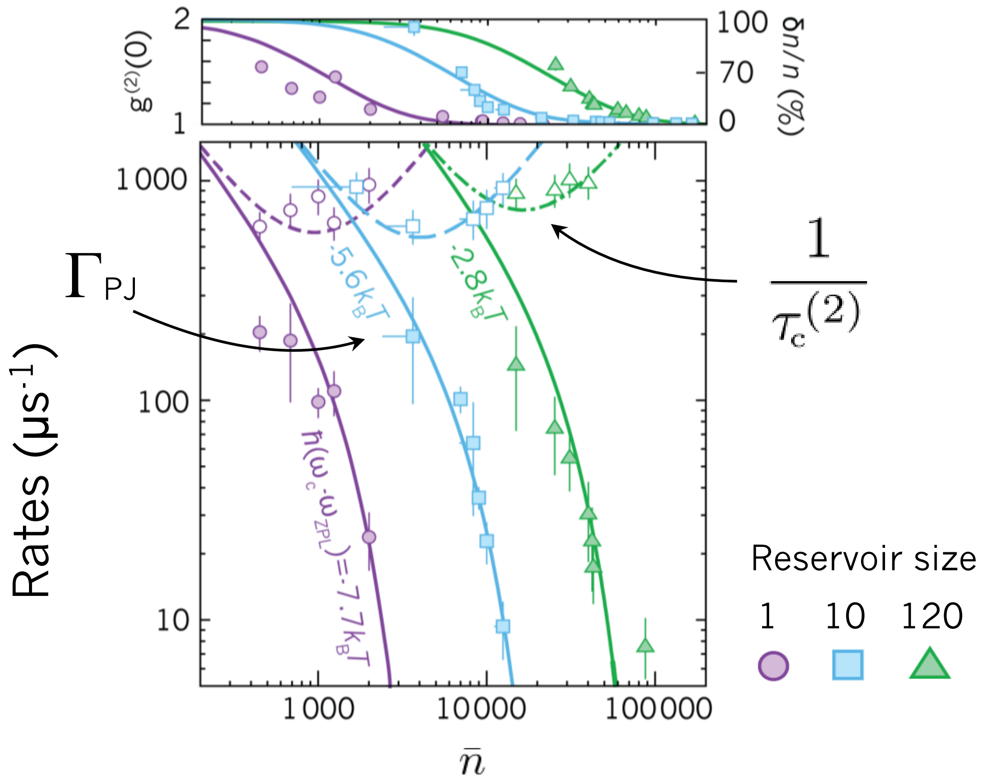


Schmitt et al., *Phys. Rev. Lett.* **116**, 033604 (2016)
Analysis ignores phase diffusion,
Lewenstein et al., *PRL* **77** (1996), Imamoğlu et al., *PRL* **78** (1997), De Leeuw et al., *PRA* **90** (2014), …

universitätbonn

Separation of correlation times

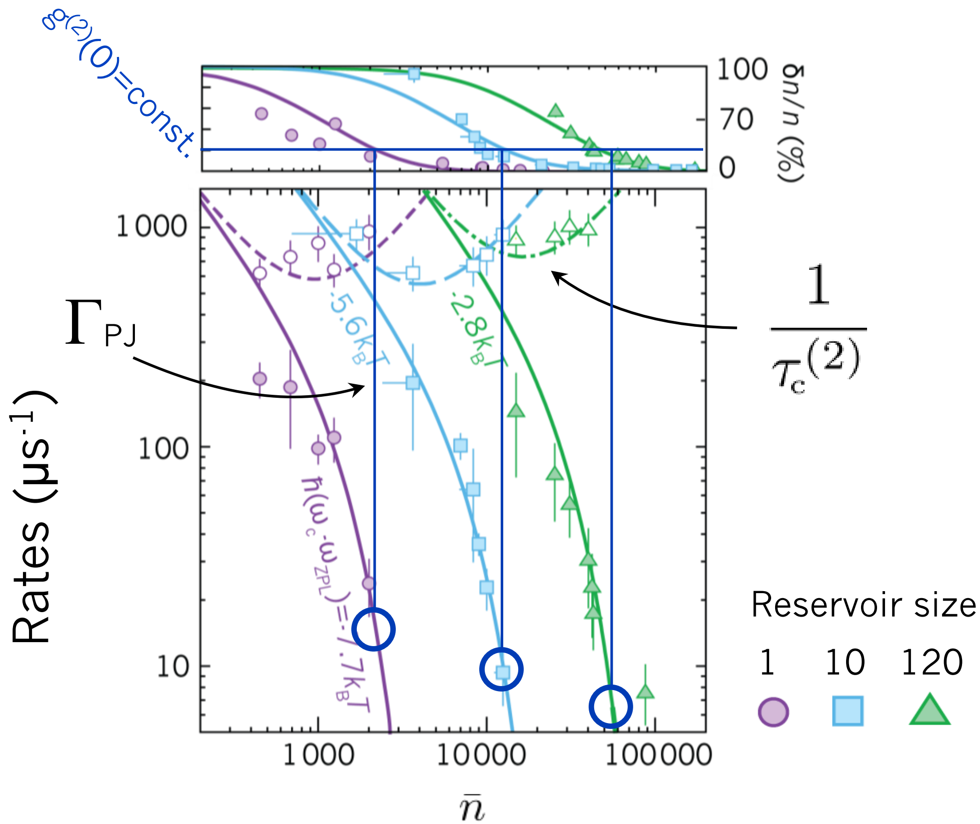
- Rate of fluctuations & phase jumps ($1/\tau_c^{(2)}$ & Γ_{PJ}) vs. increasing system size $\bar{n}$
- Suppressed fluctuations & phase jumps



Schmitt et al., *Phys. Rev. Lett.* **116**, 033604 (2016)
Analysis ignores phase diffusion,
Lewenstein et al., *PRL* **77** (1996), Imamoğlu et al., *PRL* **78** (1997), De Leeuw et al., *PRA* **90** (2014), …

Separation of correlation times

- Rate of fluctuations & phase jumps ($1/\tau_c^{(2)}$ & Γ_{PJ}) vs. increasing system size $\bar{n}$
- Suppressed fluctuations & phase jumps

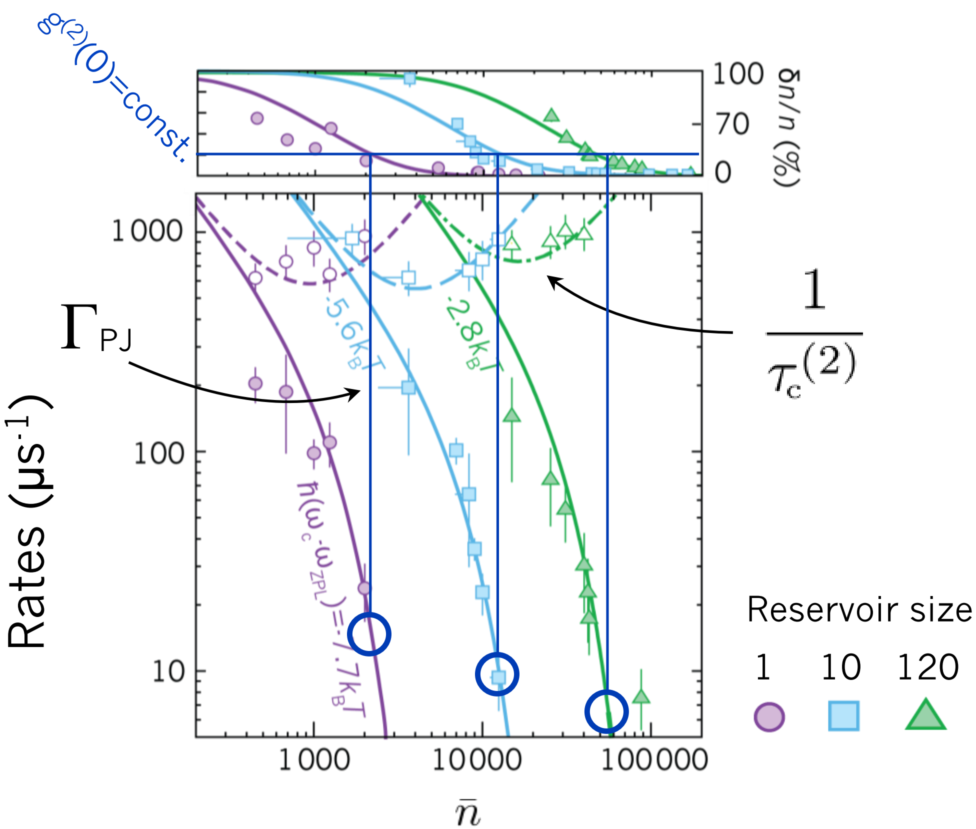


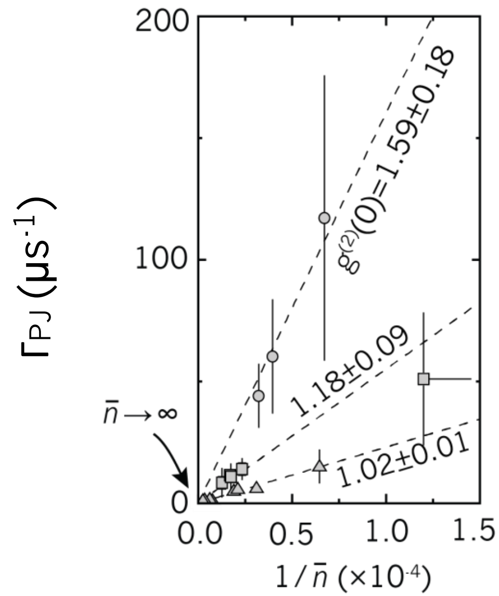
Schmitt et al., *Phys. Rev. Lett.* **116**, 033604 (2016)
Analysis ignores phase diffusion,
Lewenstein et al., *PRL* **77** (1996), Imamoḡlu et al., *PRL* **78** (1997), De Leeuw et al., *PRA* **90** (2014), …

universitätbonn

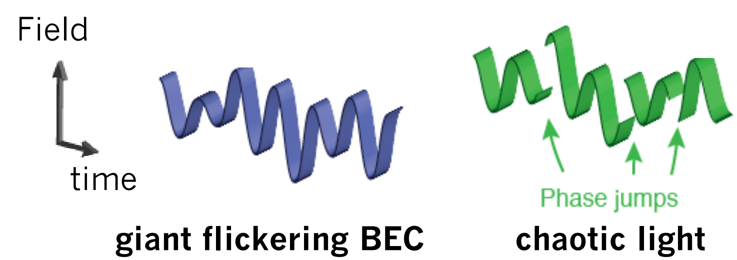
Separation of correlation times

- Rate of fluctuations & phase jumps ($1/\tau_c^{(2)}$ & Γ_{PJ}) vs. increasing system size $\bar{n}$
- Suppressed fluctuations & phase jumps





Suppression of phase jumps despite bunching!



Schmitt et al., *Phys. Rev. Lett.* **116**, 033604 (2016)
Analysis ignores phase diffusion,
Lewenstein et al., *PRL* **77** (1996), Imamoḡlu et al., *PRL* **78** (1997), De Leeuw et al., *PRA* **90** (2014), …

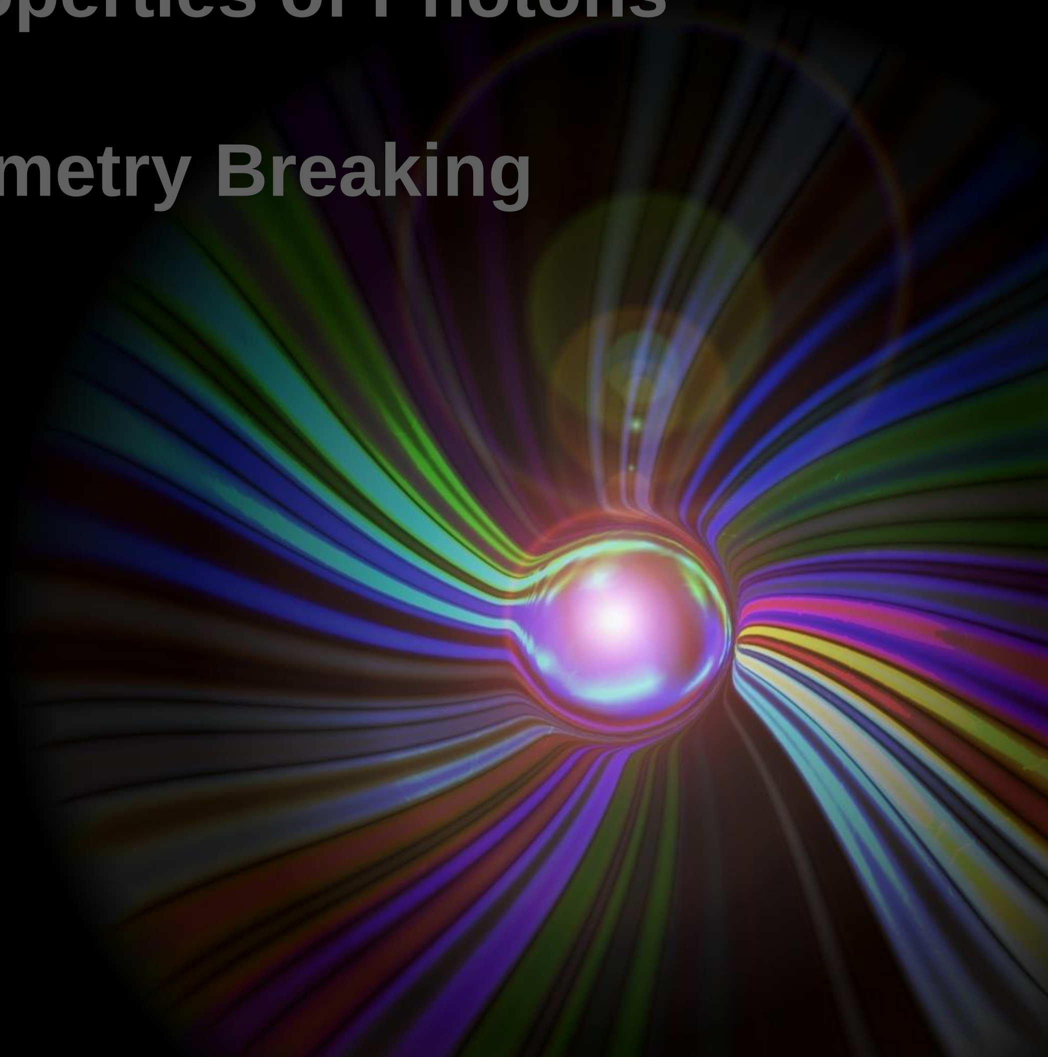
universitätbonn

1) Photon BEC: HowTo

2) Thermodynamic Properties of Photons

3) Fluctuations & Symmetry Breaking

4) Conclusion

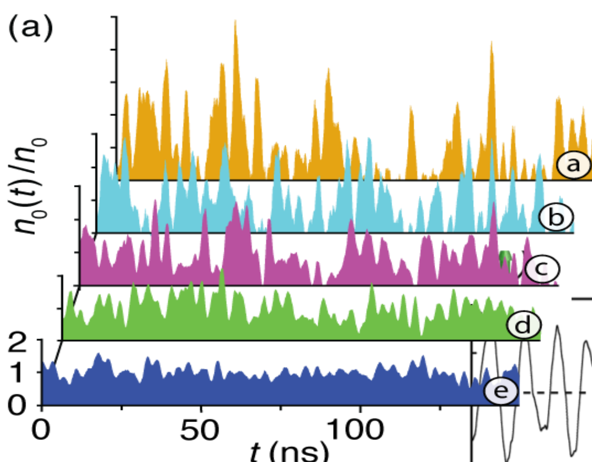


Photon BEC: Summary

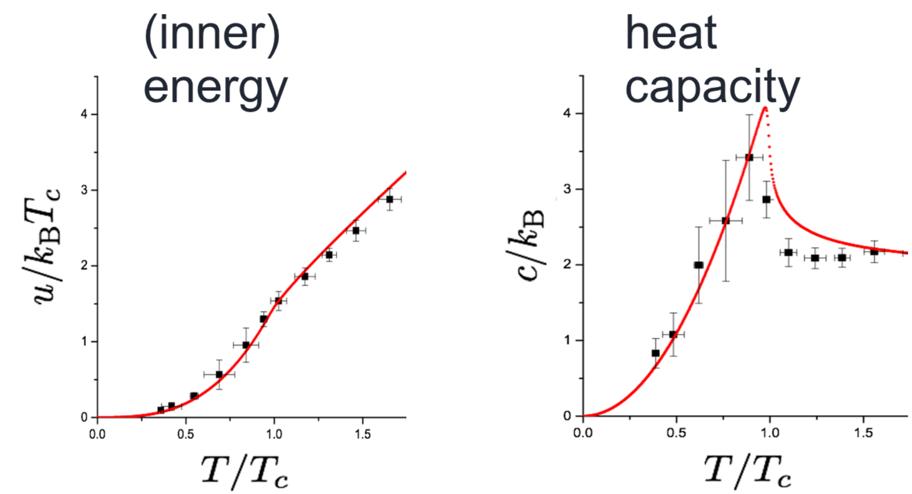
Photon BEC → versatile platform

- grand canonical physics
- open & closed system dynamics
- reservoir effects
- mediated interaction
- …

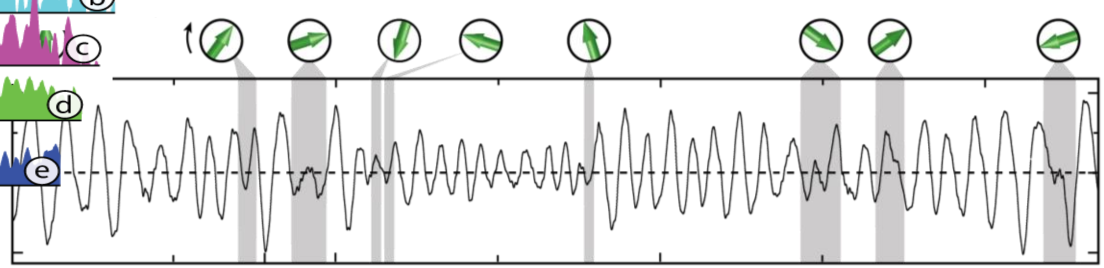
Statistics:
Tunable from canonical to grand canonical
→Effective temperature



Calorimetry:
„Textbook" properties of the ideal Bose gas



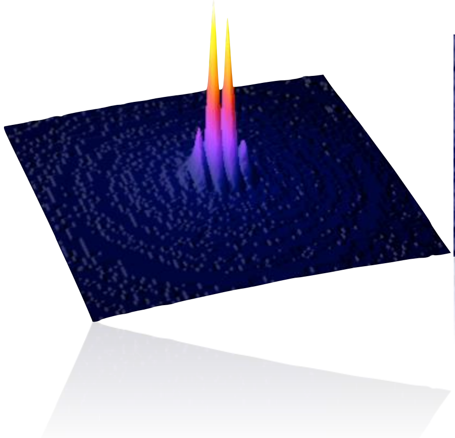
Phase evolution:
Fluctuation-induced phase jumps

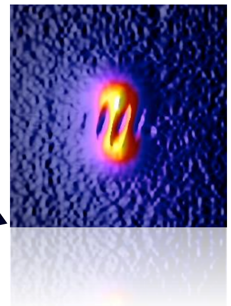


universitätbonn

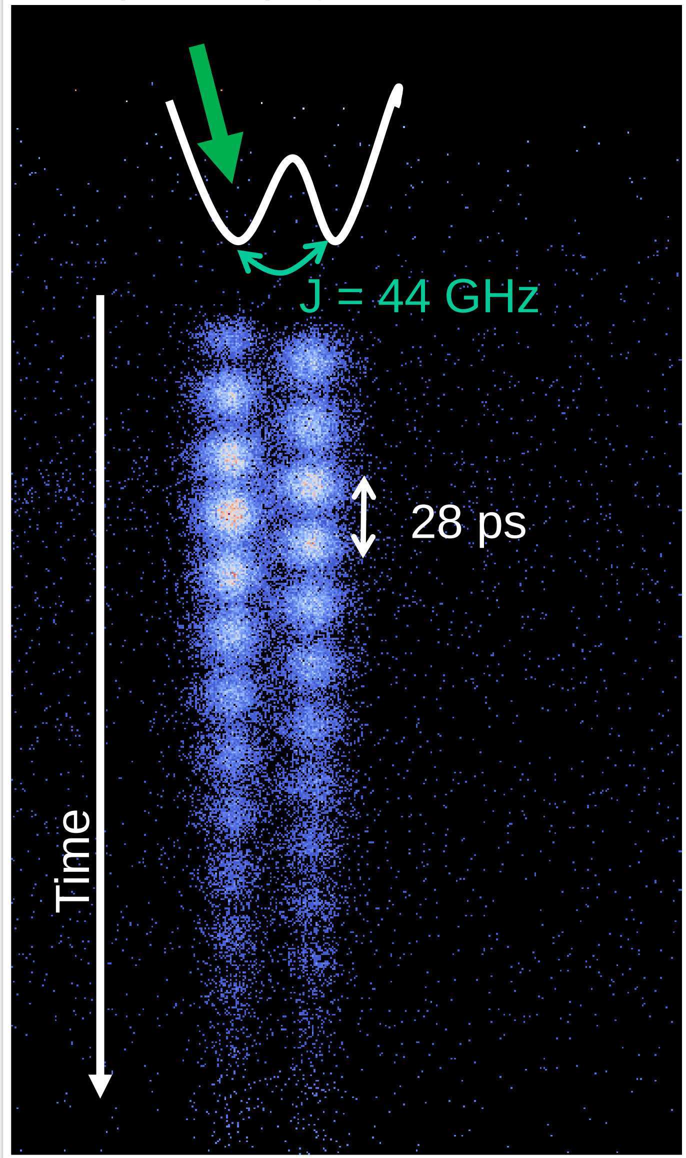
What‘s next?

Spatial phase coherence

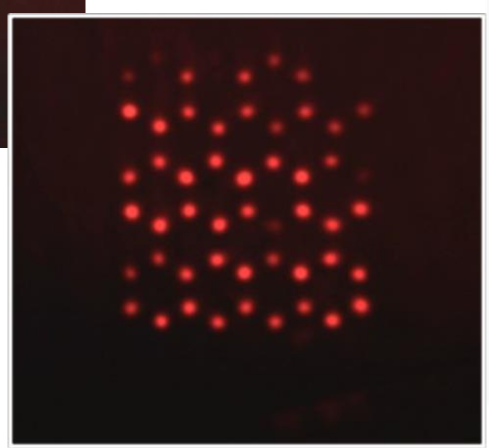




Josephson physics with reservoir



Arbitrary potentials



Photon BEC Team
Erik Busley
Christian Kurtscheid
Christian Schilz
Tobias Damm
David Dung
Fahri Öztürk
Hadiseh Alaeian
Julian Schnmitt
Frank Vewinger
Jan Klärs
Martin Weitz

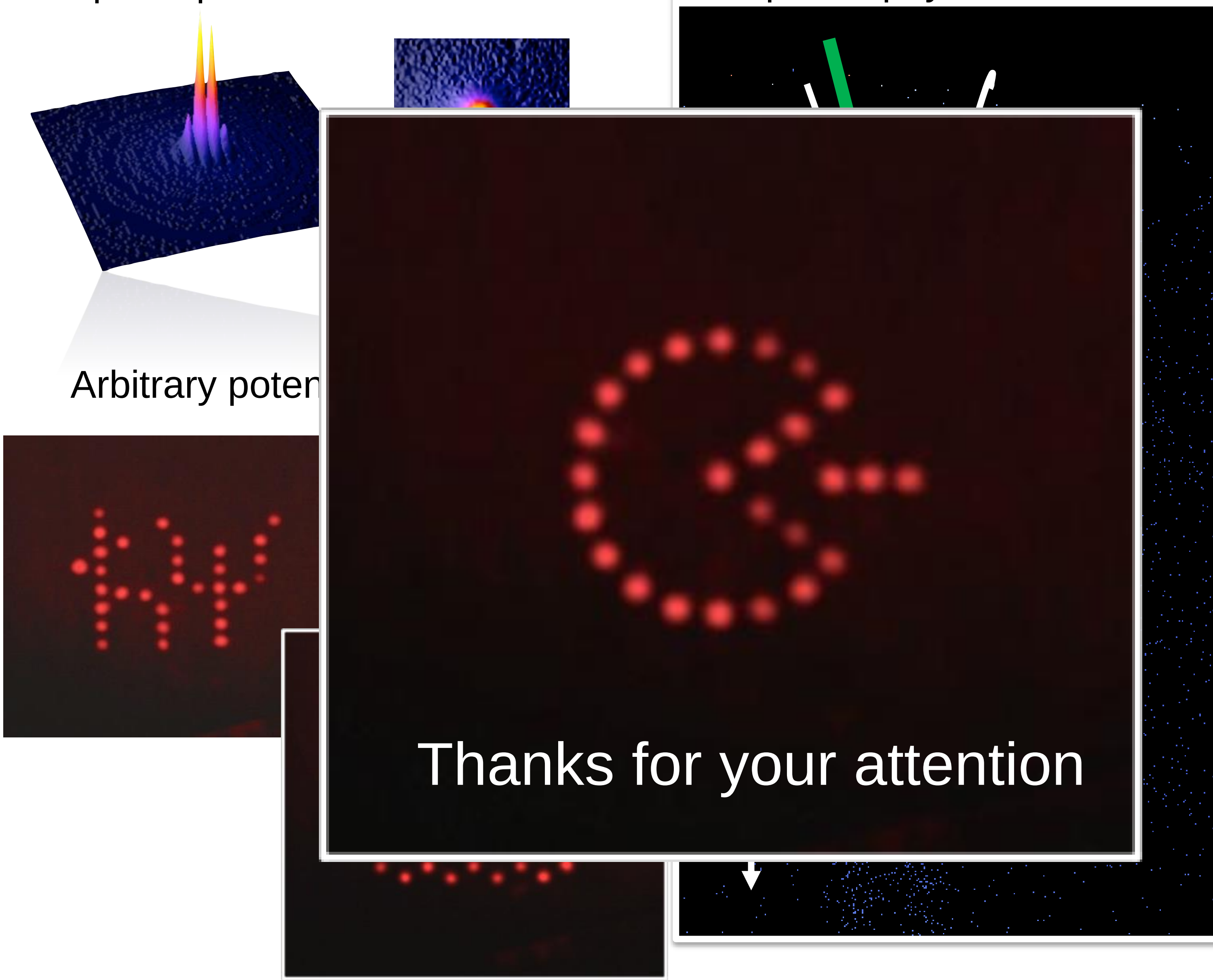
Bonn-Cologne Graduate School of Physics and Astronomy

What‘s next?

Spatial phase coherence

Josephson physics with reservoir

Arbitrary poten



Photon BEC Team
Erik Busley
Christian Kurtscheid
Christian Schilz
Tobias Damm
David Dung
Fahri Öztürk
Hadiseh Alaeian
Julian Schnmitt
Frank Vewinger
Jan Klärs
Martin Weitz

Bonn-Cologne Graduate School of Physics and Astronomy