Cavity QED with a Bose-Einstein condensate

Michael Köhl

www.quantumoptics.eu

UNIVERSITY OF CAMBRIDGE

Collaborators

@ ETH Zürich
(Tilman Esslinger‘s group)

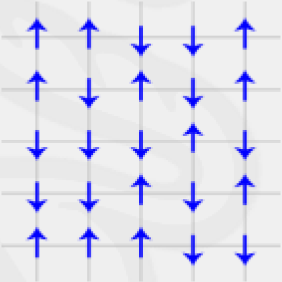
@ Cambridge
(since 2007)

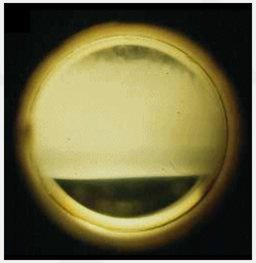
PhD:
A. Öttl, S. Ritter, T. Donner, F. Brennecke
Postdoc:
Thomas Bourdel

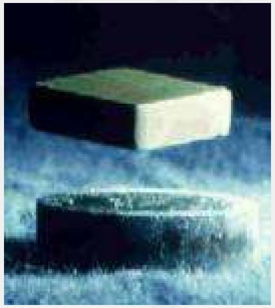
PhD:
M. Feld, B. Fröhlich, S. Palzer, C. Zipkes
Postdoc:
C. Sias

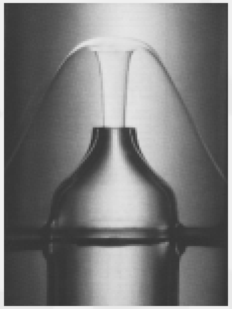
Correlations at the Bose-Einstein phase transition

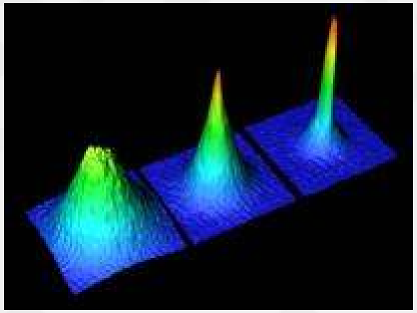
2^{nd} Order Phase Transitions


uniaxial magnet

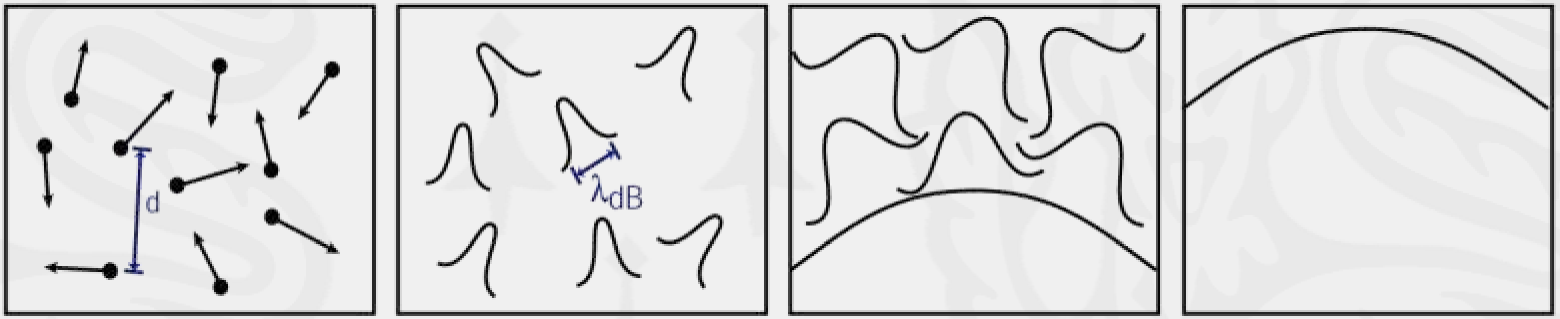

critical opalescence


superconductor


superfluid He

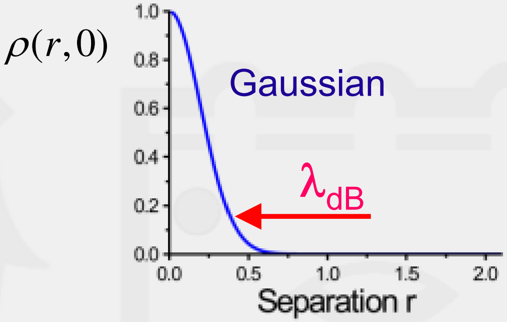

Bose-Einstein condensation

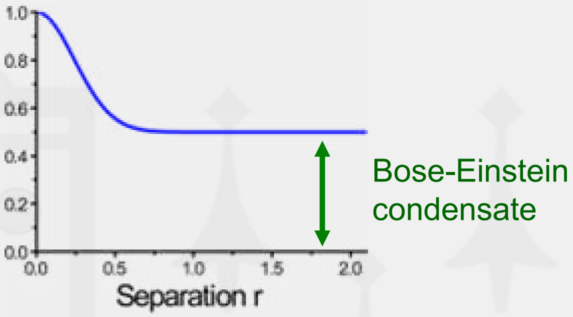
What is a Bose-Einstein condensate?



$$\begin{aligned}\rho(r_1,r_2) &= \left\langle \hat{\Psi}^{\dagger}(r_1)\hat{\Psi}(r_2)\right\rangle \\ &= \underset{\text{condensate wavefunction}}{\underline{\Psi^{*}(r_1)\Psi(r_2)}} + \underset{\text{fluctuations}}{\underline{\left\langle \delta\hat{\Psi}^{\dagger}(r_1)\delta\hat{\Psi}(r_2)\right\rangle}}\end{aligned}$$

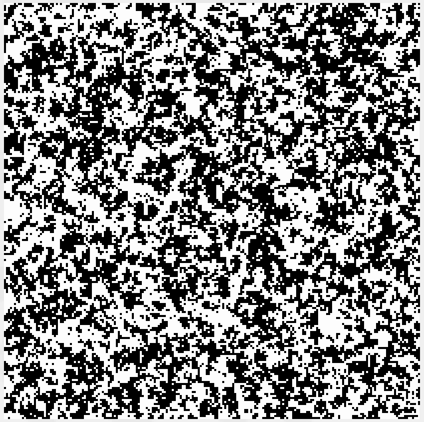
Penrose and Onsager (1956)



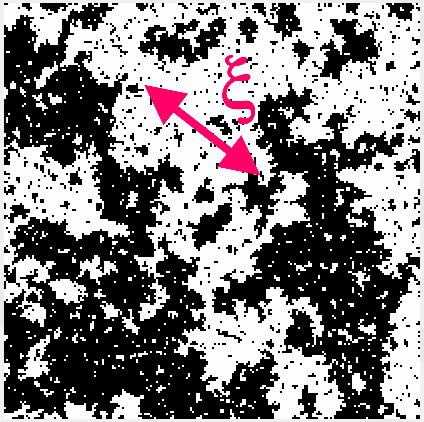


What drives a phase transition?

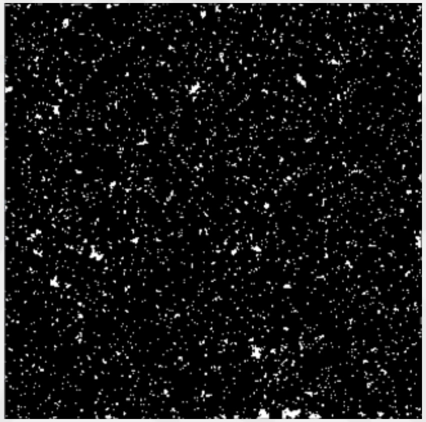
$T>T_c$



$T=T_c$

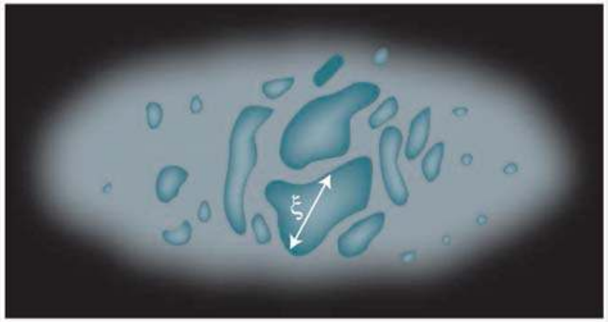


$T<T_c$



Correlation length ξ: typical range in which fluctuations are correlated

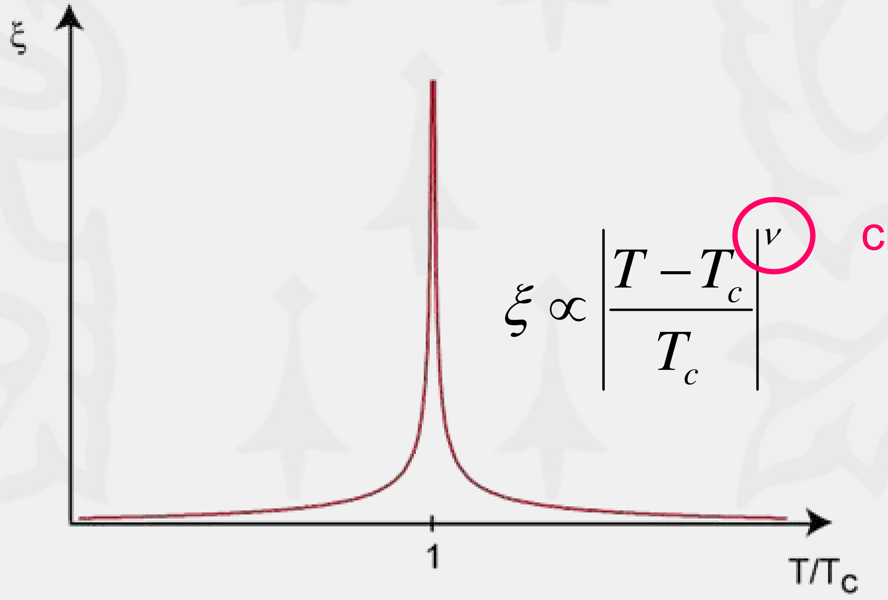
in BEC:



Ising model simulation from http://www.ibiblio.org/e-notes/

Critical correlations

Correlation length ξ is temperature dependent:



$$\xi \propto \left| \frac{T - T_c}{T_c} \right|^{\nu}$$

critical exponent (universal)

Decay of the correlation function close to Tc: $\rho(r,0) \propto \frac{\exp(-r/\xi)}{r^{d-2+\eta}}$

i.e. algebraic decay at Tc

Critical exponents and universality

- Divergences at the phase transition $\left|\frac{T-T_c}{T_c}\right|^{-x}$

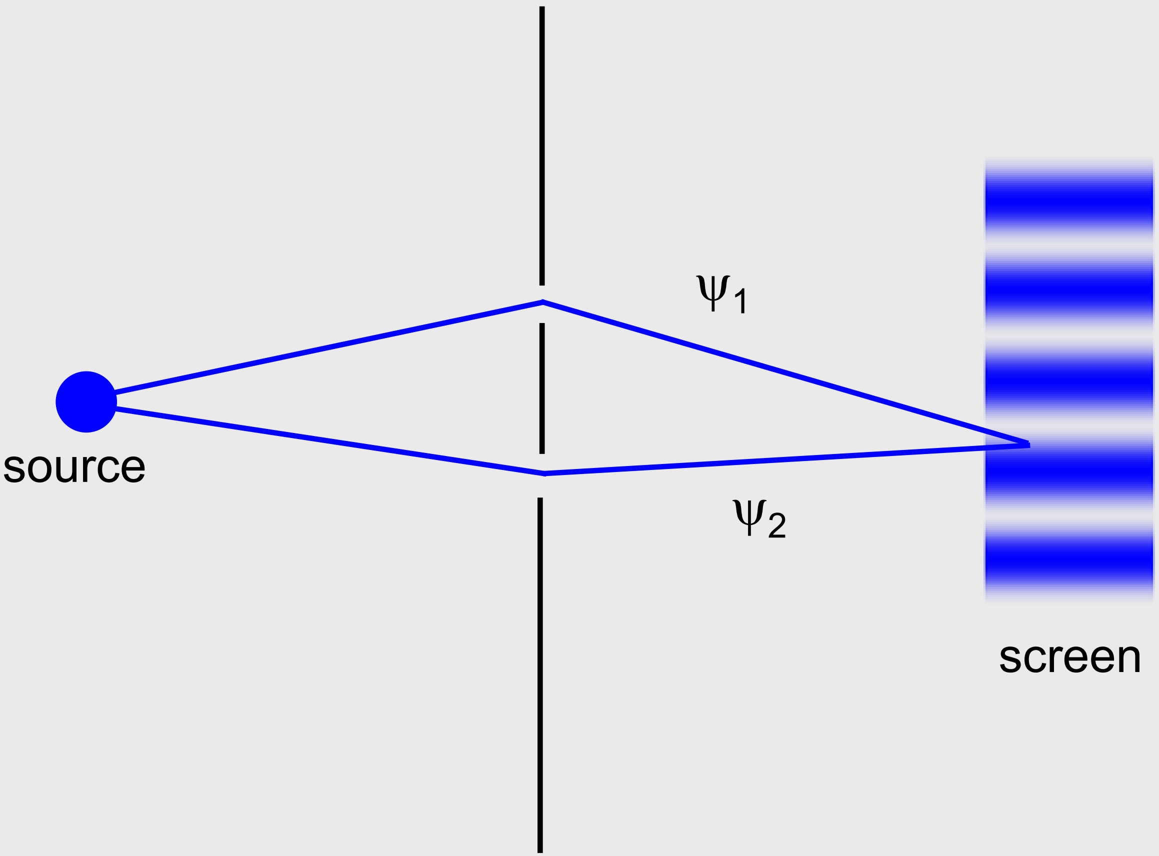
x =	α	β	γ	ν
	specific heat	magnetization	susceptibility	correlation length

- Scaling relations e.g. $\nu d=2-\alpha$ (d: dimension)

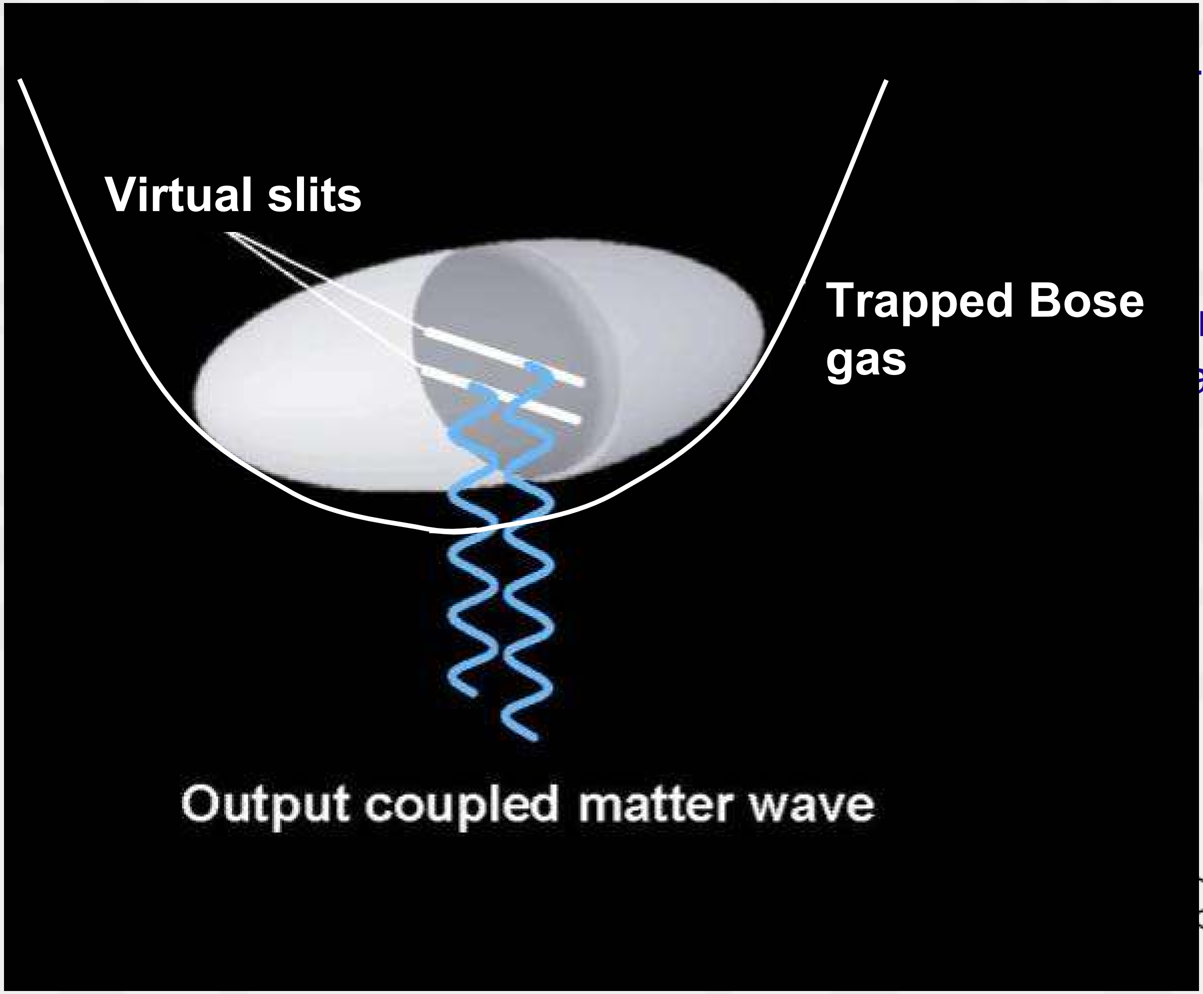
- Systems in the same universality class have the same exponents.

How to measure this?

Young‘s double slit experiment



Double slit experiment



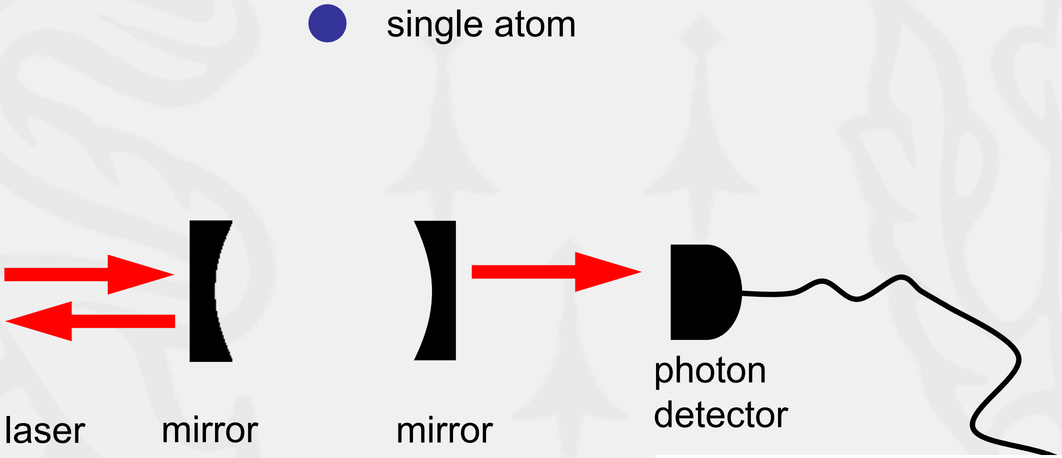
rapped Bose gas

nterfering
atomic beams

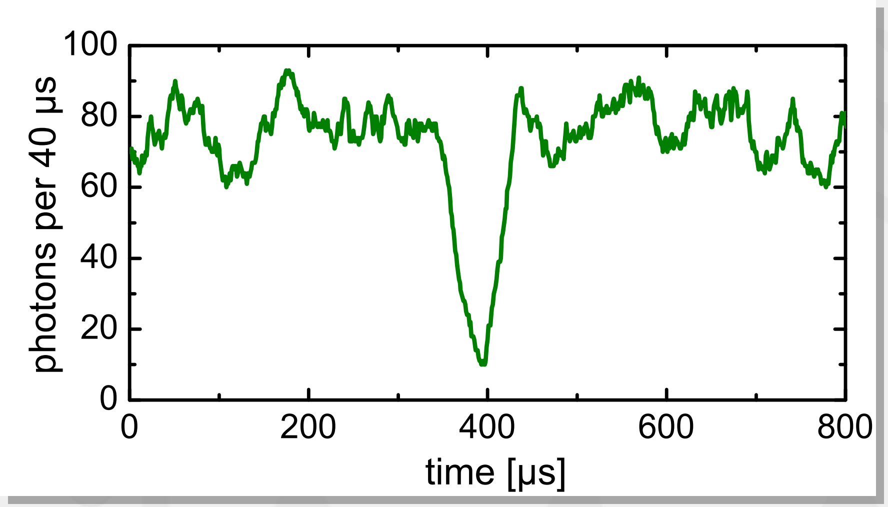
Single atom
detector
(optical cavity)

I. Bloch, T. Hänsch, T. Esslinger, Nature 403, 166 (2000).
T. Bourdel, T. Donner, S. Ritter, A. Öttl, M.K., T. Esslinger, Phys. Rev. A 73, 043602 (2006).

Single atom detection in cavity-QED

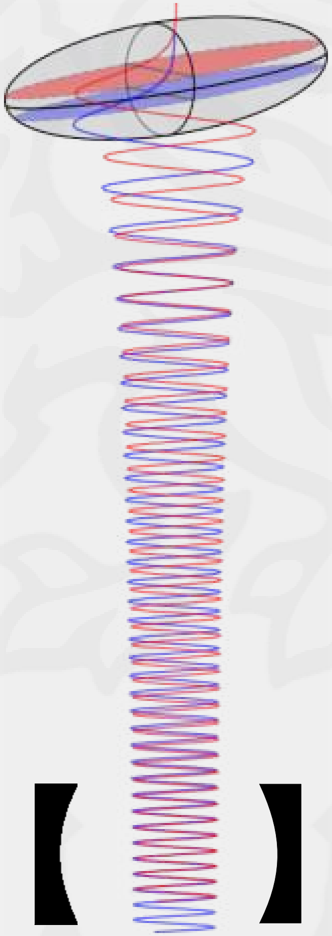


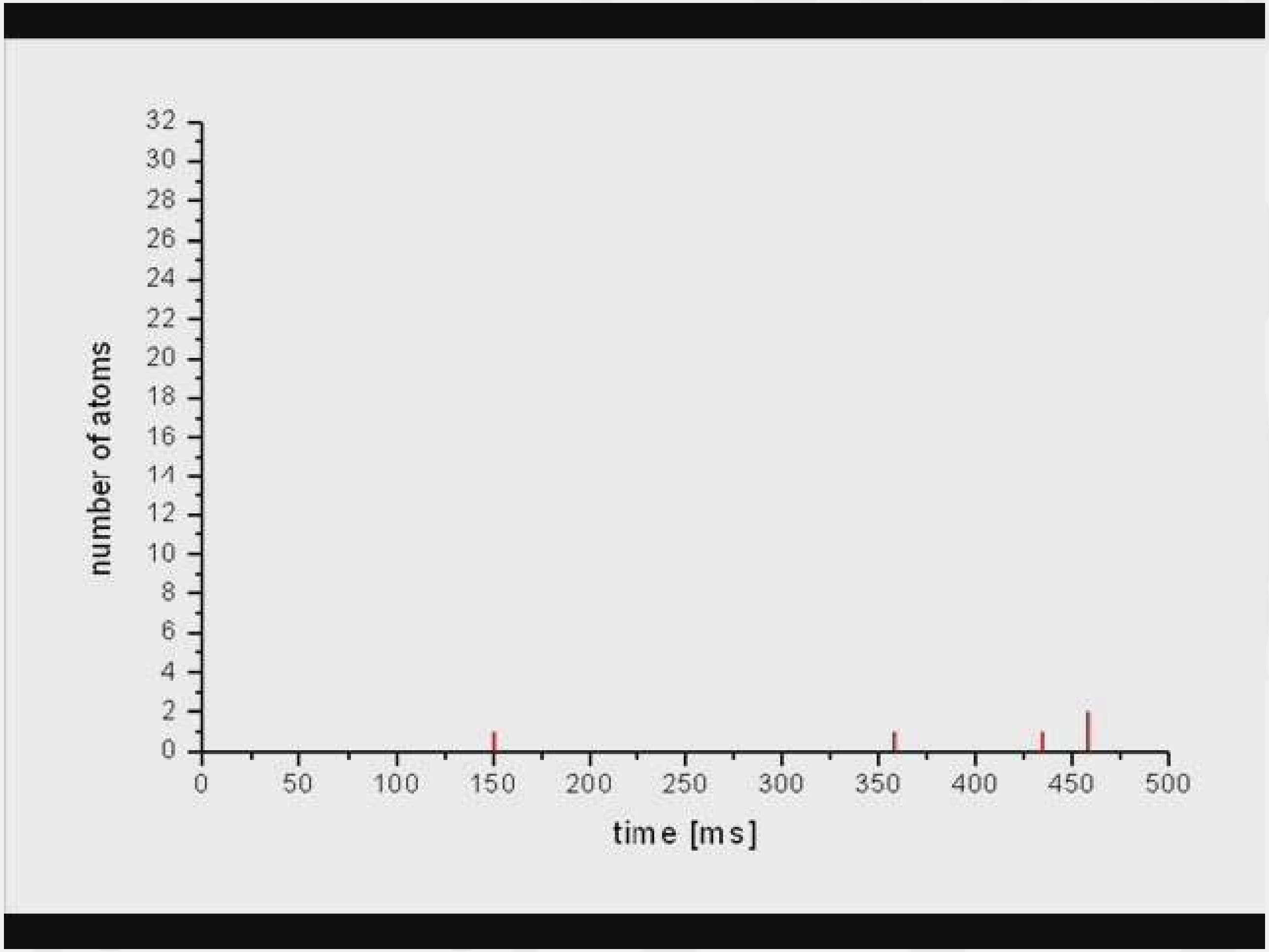
Cavity transmission:



First demonstration: H. Mabuchi et al., Opt. Lett. **21**, 1393 (1996)

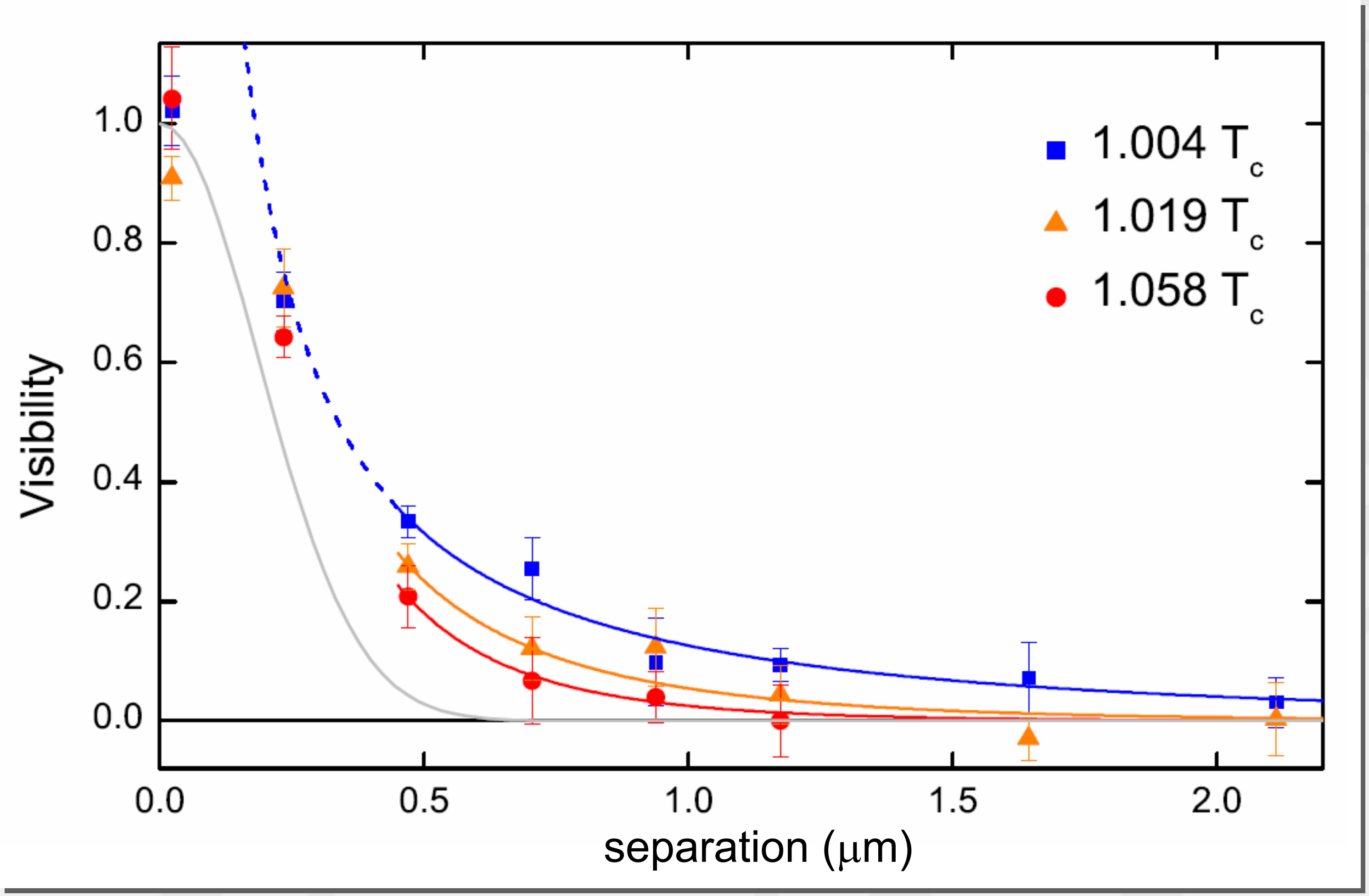
An interference pattern from single atoms



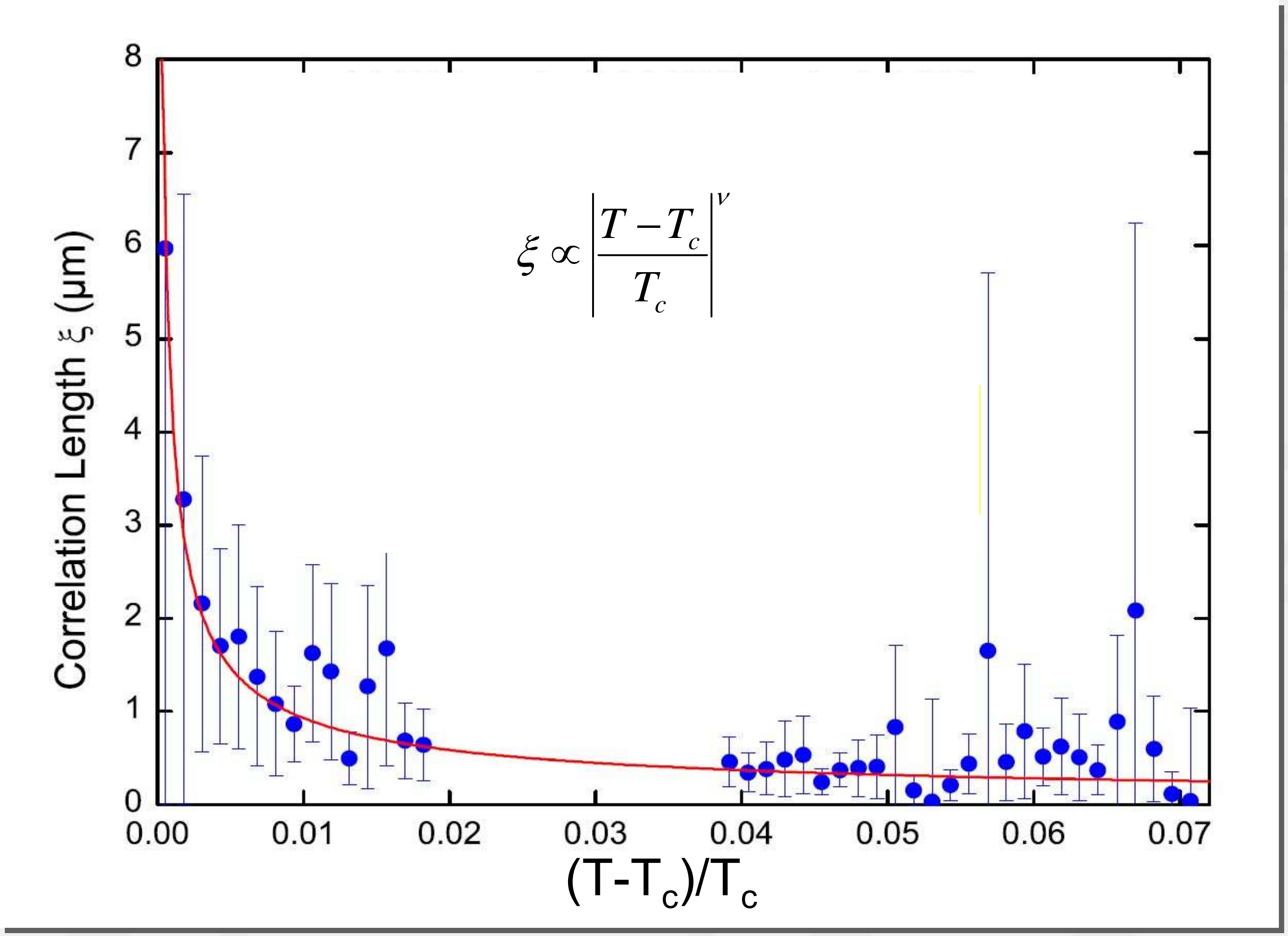


T. Bourdel, T. Donner, S. Ritter, A. Öttl, M.K., T. Esslinger, Phys. Rev. A 73, 043602 (2006).

Correlations near Tc



Divergence of ξ



T. Donner, S. Ritter, T. Bourdel, A. Öttl, M.K., T. Esslinger, Science 315, 1556 (2007).

The critical exponent ν

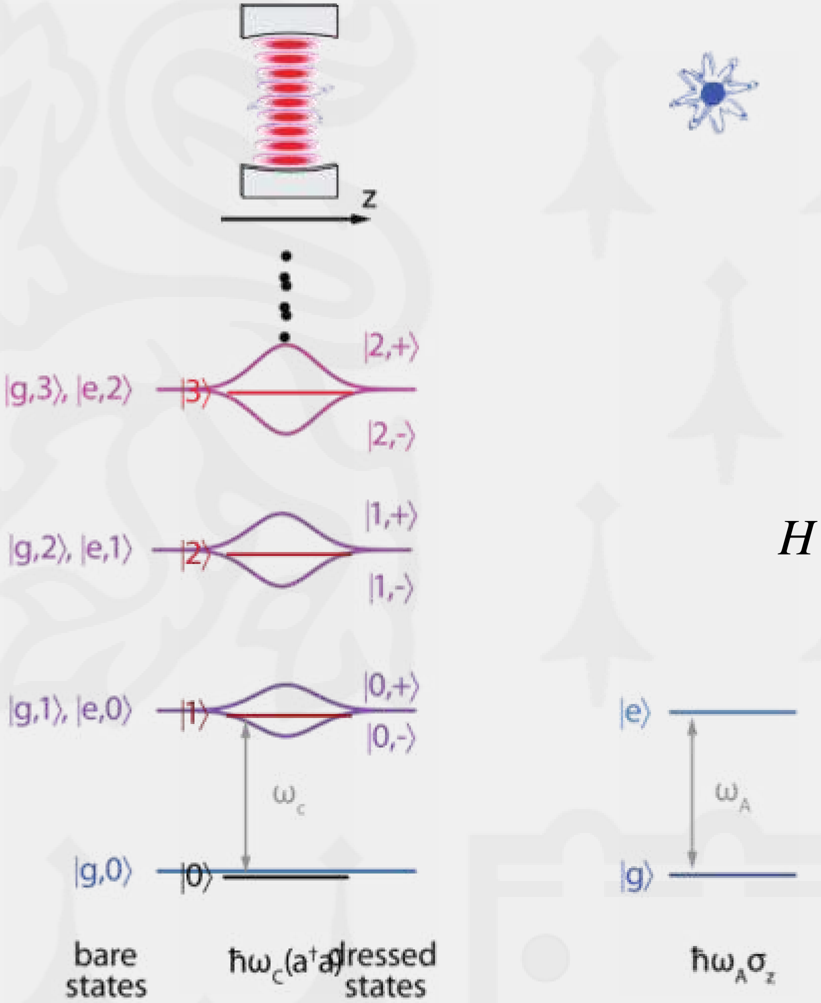
System	ν
Ideal Bose gas in a box:	1
Ideal Bose gas in a harmonic trap:	0.5
Landau‘s theory of phase transitions: (homogeneous & interacting)	0.5
RG theory of the XY universality class: (homogeneous & interacting) Campostrini et al., PRB 63, 214503 (2001).	0.67155(3)
Determined in liquid Helium: Lipa et al., PRB 68, 174518 (2003).	0.6705(6)
Now measured in a harmonic trap: with a dilute Bose gas	0.67(13)

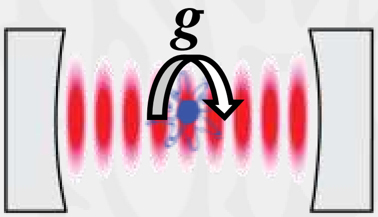
ten orders of magnitude different in density !

Universality works ☺

A new collective state of light and matter

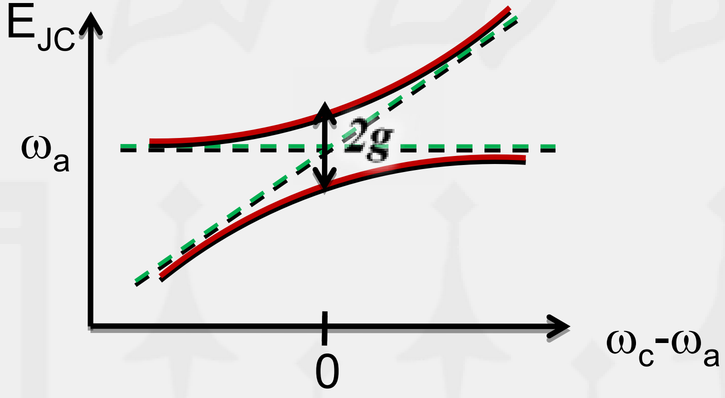
Single atom cavity QED



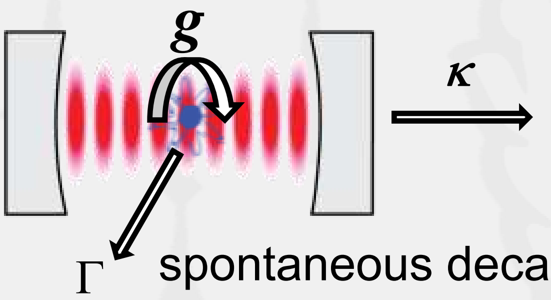


Jaynes-Cummings model

$$H_{JC} = \tfrac{1}{2}\hbar\omega_a\hat{\sigma}_z + \hbar\omega_c\hat{a}^+\hat{a} + \hbar g(r)\left[\hat{\sigma}_+\hat{a} + \hat{a}^+\hat{\sigma}_-\right]$$



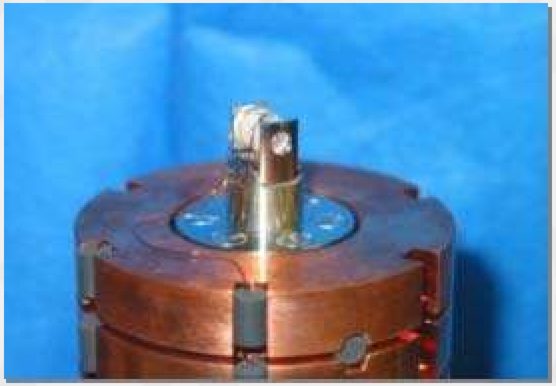
Dissipation and strong coupling



Cavity losses

spontaneous decay
of the atom

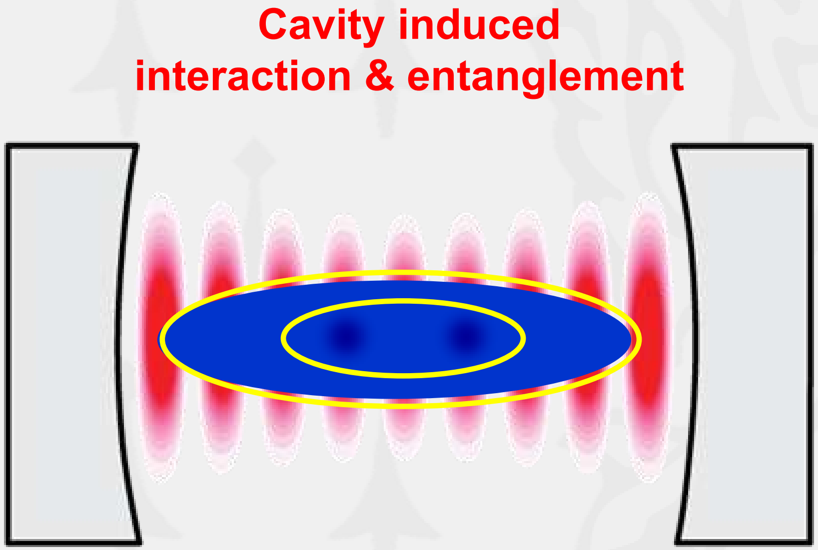
Strong coupling regime of cavity QED: $g >> \kappa, \Gamma$



g = 2π 10.4 MHz
Γ = 2π 3.0 MHz
κ = 2π 1.4 MHz

related work: M. Chapman, S. Haroche, E. Hinds, H.J. Kimble, D. Meschede, J. Reichel, G. Rempe, D. Stamper-Kurn, H. Walther ...

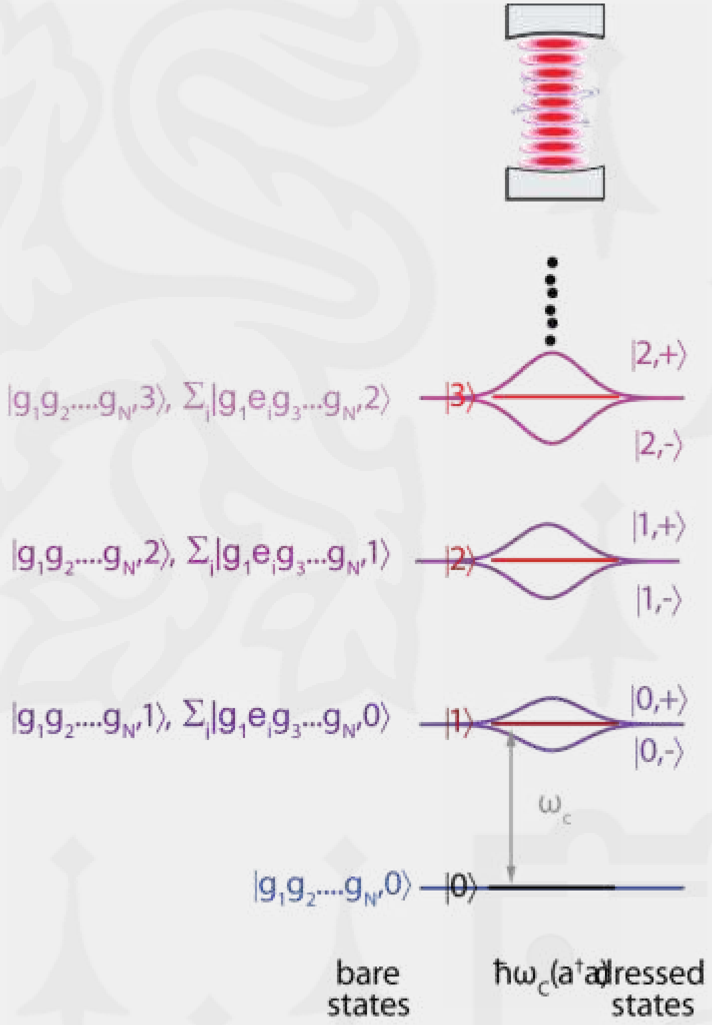
From one to many



One excitation coherently shared by
10^5 indistinguishable atoms.

Proposals by Cirac & Zoller, Moelmer, ...

Cavity QED with many identical atoms

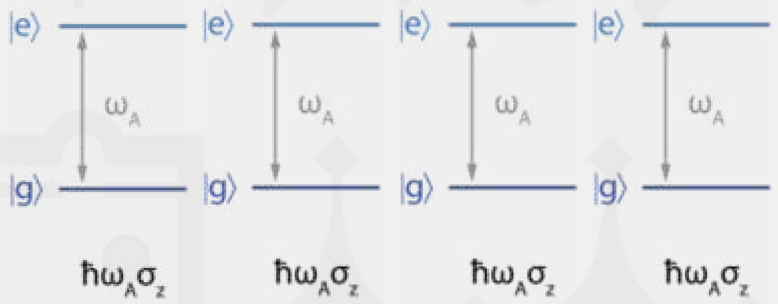


Tavis-Cummings model

$$H_{TC} = \hbar\omega_c \hat{a}^+ \hat{a} + \sum_{i=1}^{N} \tfrac{1}{2}\hbar\omega_a \hat{\sigma}_{i,z} + \hbar g(r_i)\left[\hat{\sigma}_{i,+}\hat{a} + \hat{a}^+\hat{\sigma}_{i,-}\right]$$

Collective mode splitting
for N atoms (and weak excitation)

$$\pm\sqrt{N}\,g$$



Atomic ensembles in optical cavities

- Cavity as a light-matter interface in QIP:

  Conversion of a single photon (“flying qubit”) into a collective atomic excitation (“memory qubit”) and back

  SNR ~ $g^2/\kappa\Gamma$ → **enhancement of factor N !**

  (exp. realized for a low-Q cavity: Vuletic et al., PRL (2007))

- Nonlinear optics: huge Kerr non-linearities

  (with ultracold atoms: Stamper-Kurn, Chapman, ...)

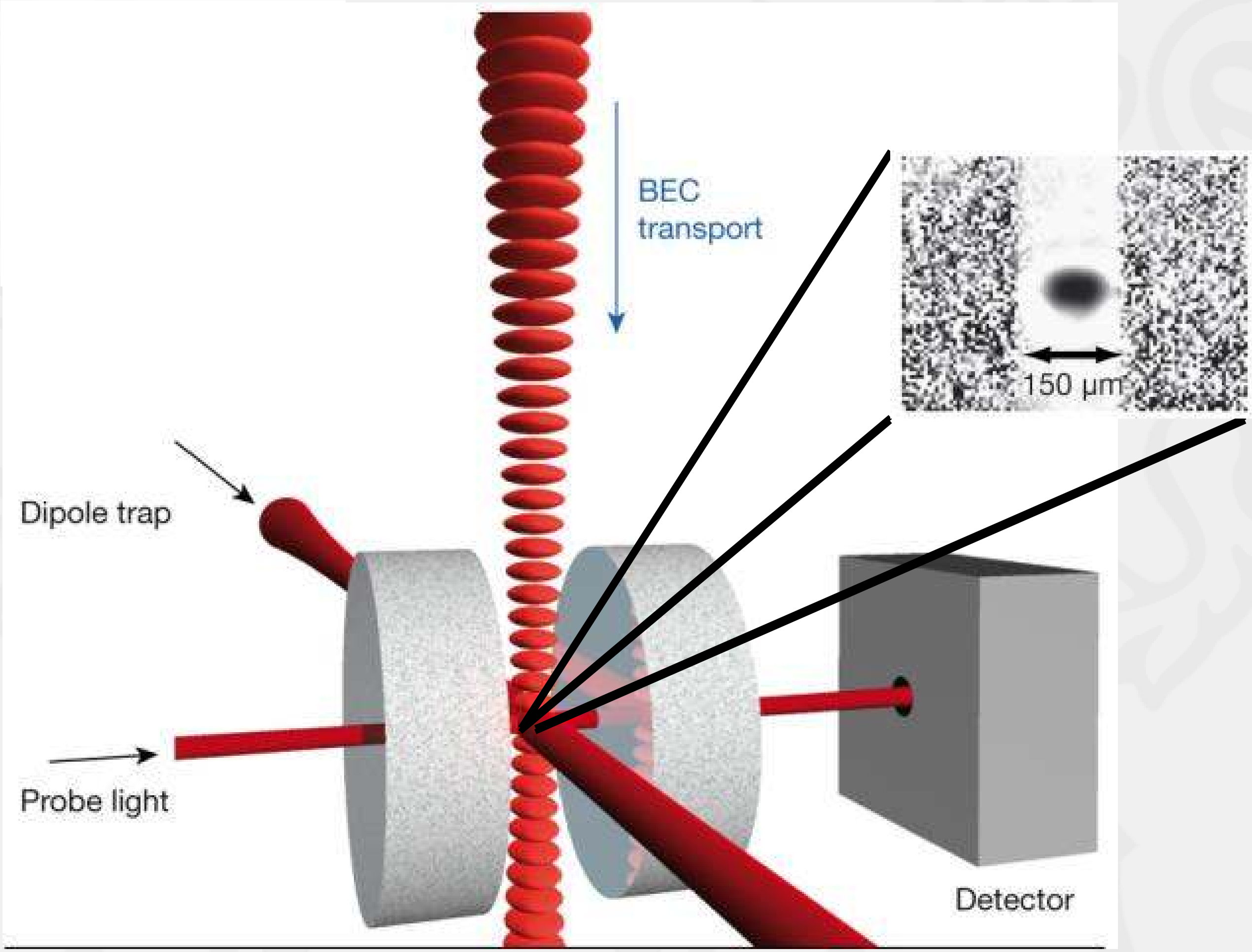
- Spin squeezing, measurement induced quantum manipulations, ...

  (e.g. Mabuchi et al., Science (2004), Zoller et al. PRL (2001), ...)

What can quantum degenerate gases offer?

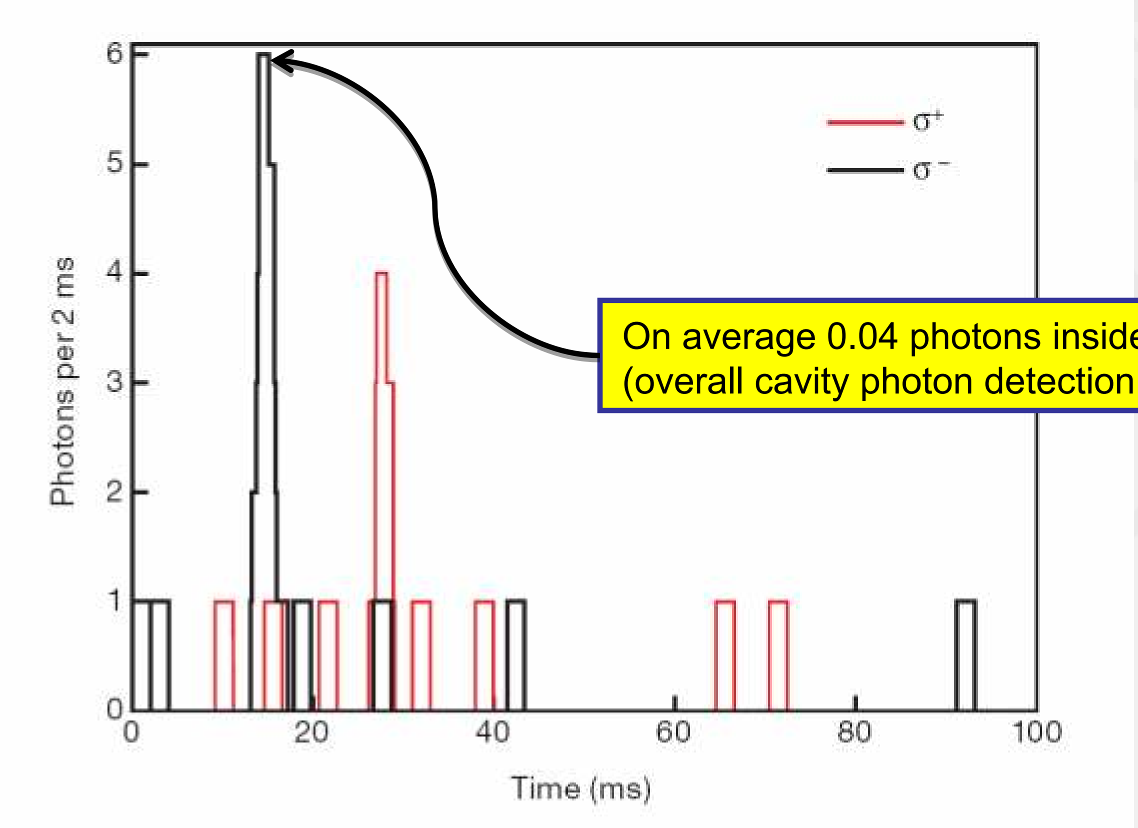
- No motional decoherence
- Highest densities
- Indistinguishable atoms, all atoms couple exactly equal to the cavity mode
- Correlated quantum phases in optical lattices:
  new probing techniques, new interactions
  (Theory: H. Ritsch, P. Meystre, M. Lewenstein, I. Carussotto ...)

Delivery of the Bose-Einstein condensate



F. Brennecke, T. Donner, S. Ritter, T. Bourdel, M. K., T. Esslinger, Nature 450, 268 (2007

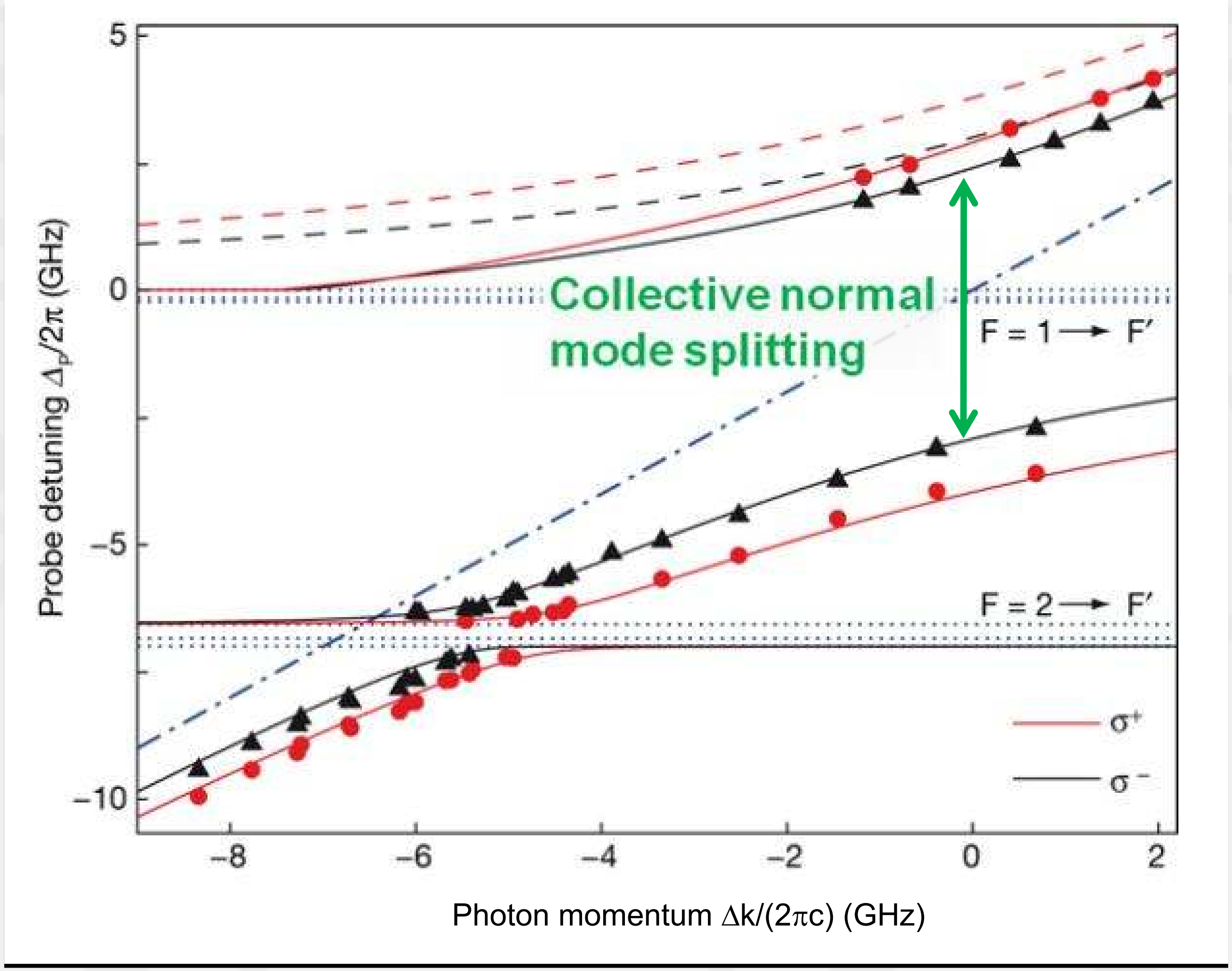
Sample measurement



On average 0.04 photons inside the cavity
(overall cavity photon detection efficiency: 5%)

Probe laser scan rate 25 MHz/ms

Cavity spectrum



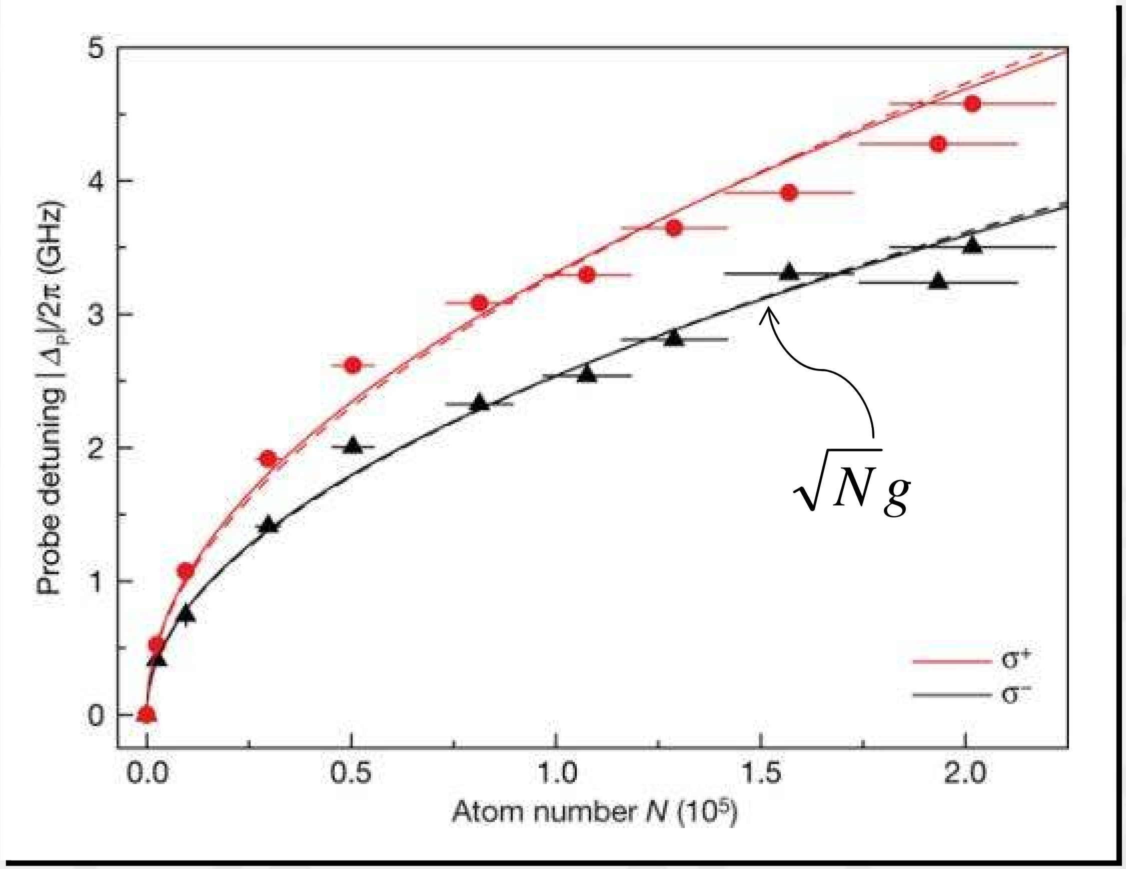
photon

“exciton”

“exciton”

F. Brennecke, T. Donner, S. Ritter, T. Bourdel, M. K., T. Esslinger, Nature 450, 268 (2007).
See also: Y. Colombe et al. Nature 450, 271 (2007).

Collective mode splitting



Summary

- Measurement of the critical exponent of a trapped weakly interacting Bose gas
- Eigenenergy spectrum of a Bose-Einstein condensate in an ultra-high finesse cavity