

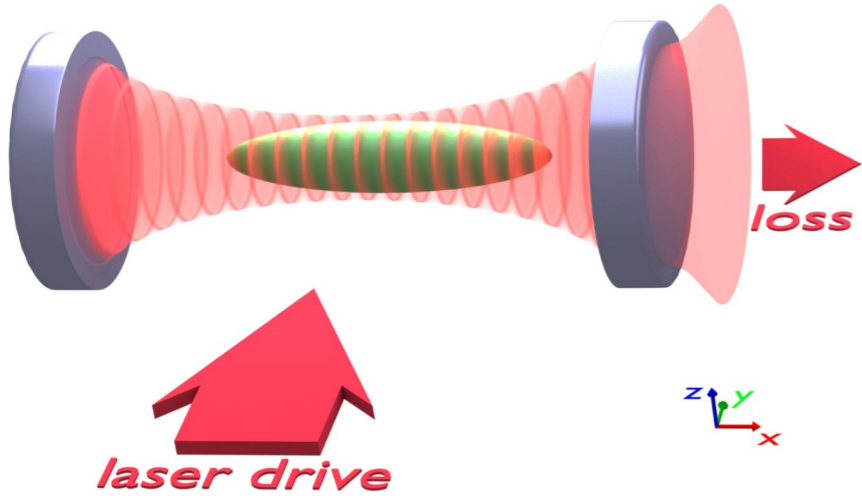
Cold atoms in an optical cavity: from phase transitions to subradiant scattering

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Budapest, Hungary



Monitoring ultracold atoms with an optical cavity

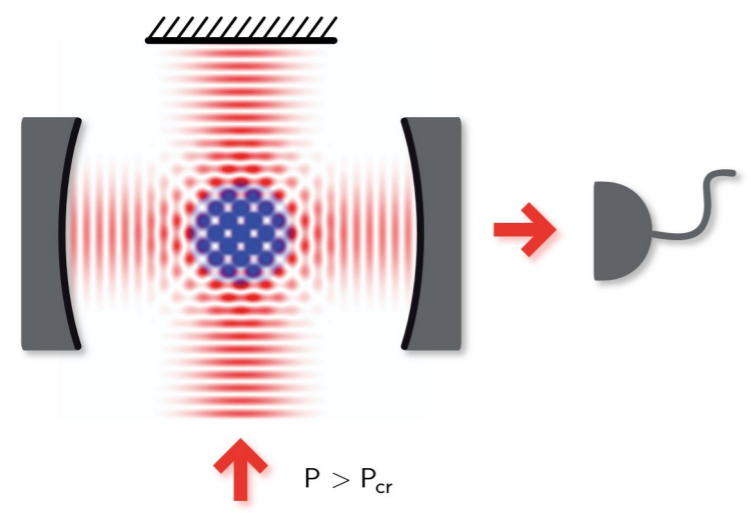


Advantages

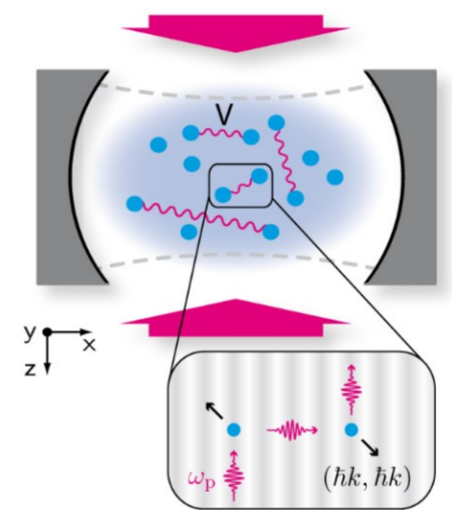
- enhanced atom-light interaction
- collective coupling \rightarrow increased SNR
- non-destructive measurements allow continuous monitoring
- access to quantum correlations and many-body dynamics

Phys. Rev. A 98, 063608 (2018)

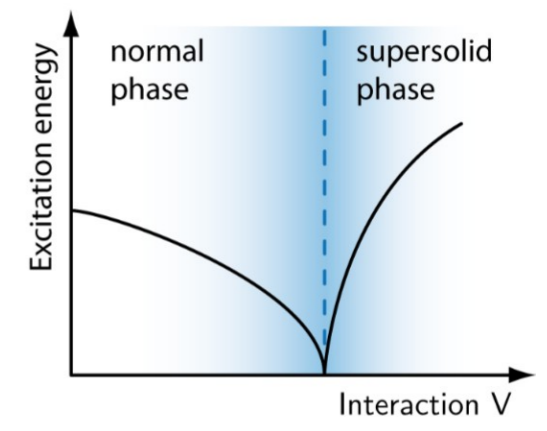
cavity-mediated long-range interaction \rightarrow phase transitions



Nature 464, 1301 (2010)

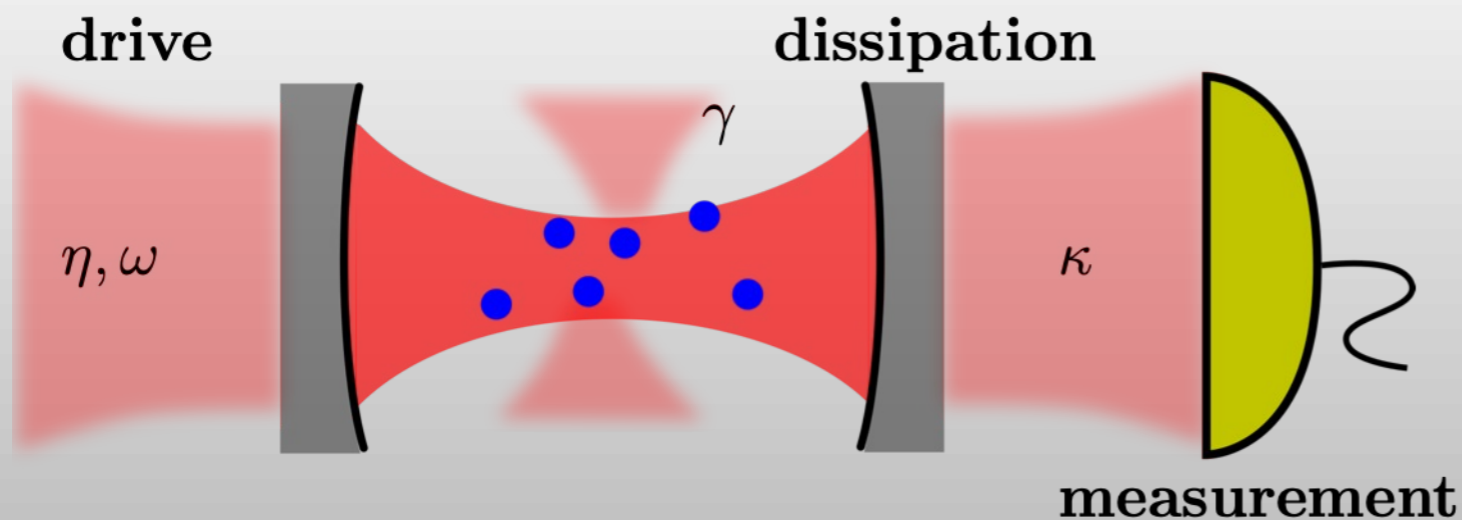


Science 336, 1570 (2012)



Driven-dissipative open quantum systems

Cavity QED scheme



“many-body”

few atoms but
large cooperativity

$$\mathcal{C} \gg 1$$

$$\mathcal{C} = \frac{\mathcal{F}}{\pi} \times N \times \frac{\sigma_A}{\mathcal{A}}$$

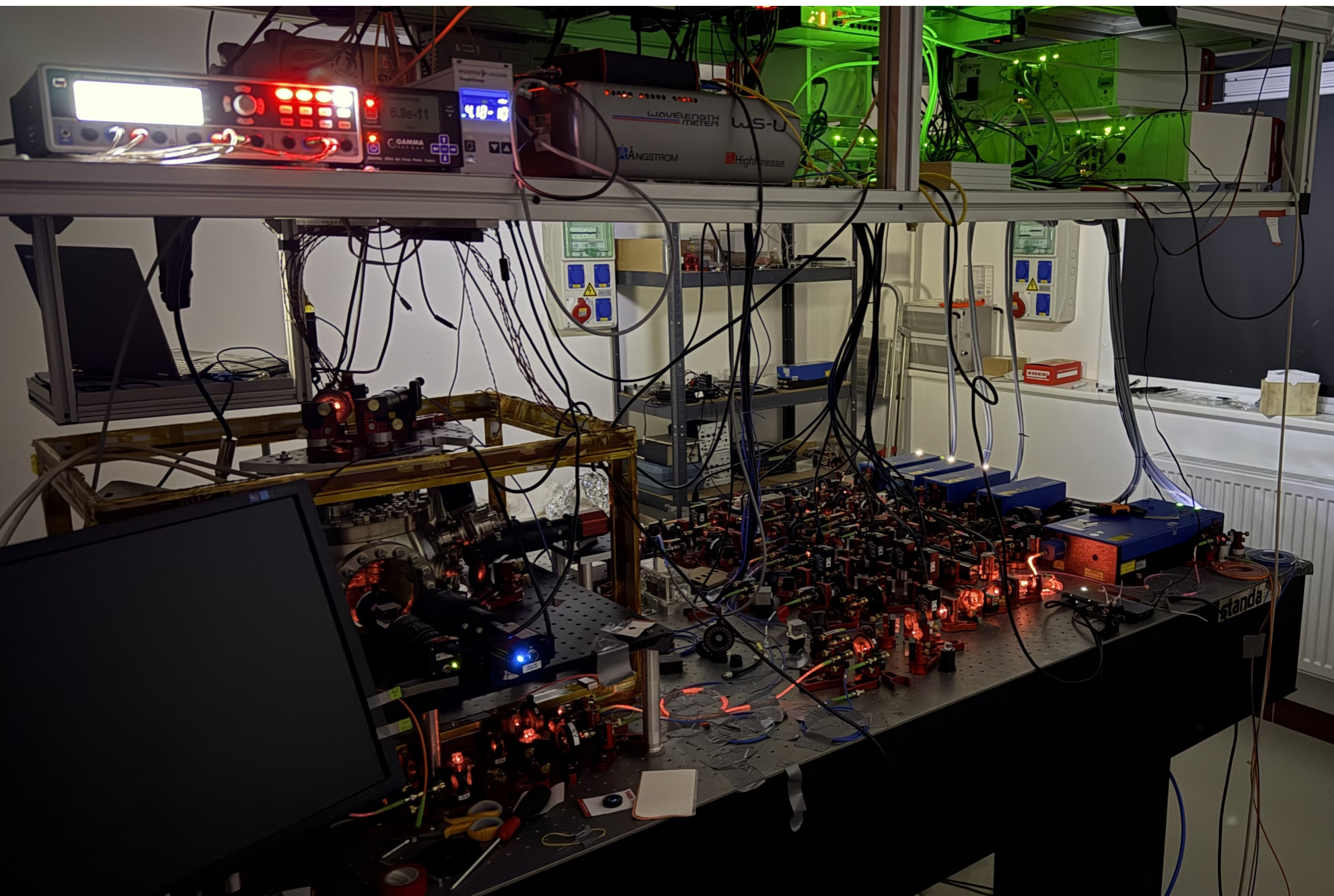
Phases

- stationary states: dynamical equilibrium of driving and dissipation
- continuous measurement due to dissipation
- order parameter: macroscopic observable

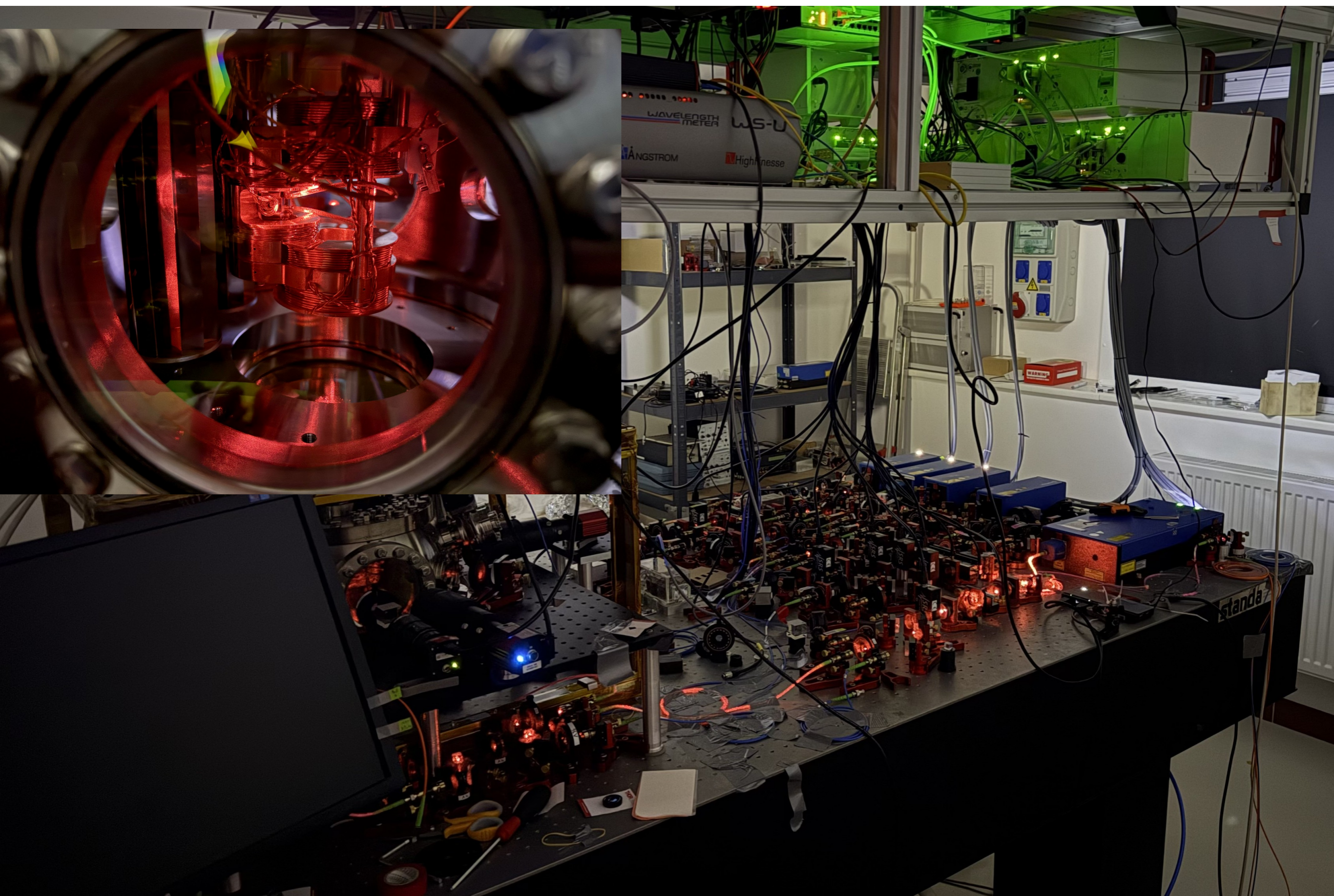
Phase transition

- non-analytic change of the order parameter as a
- control parameter is continuously tuned through
- a critical point (region)

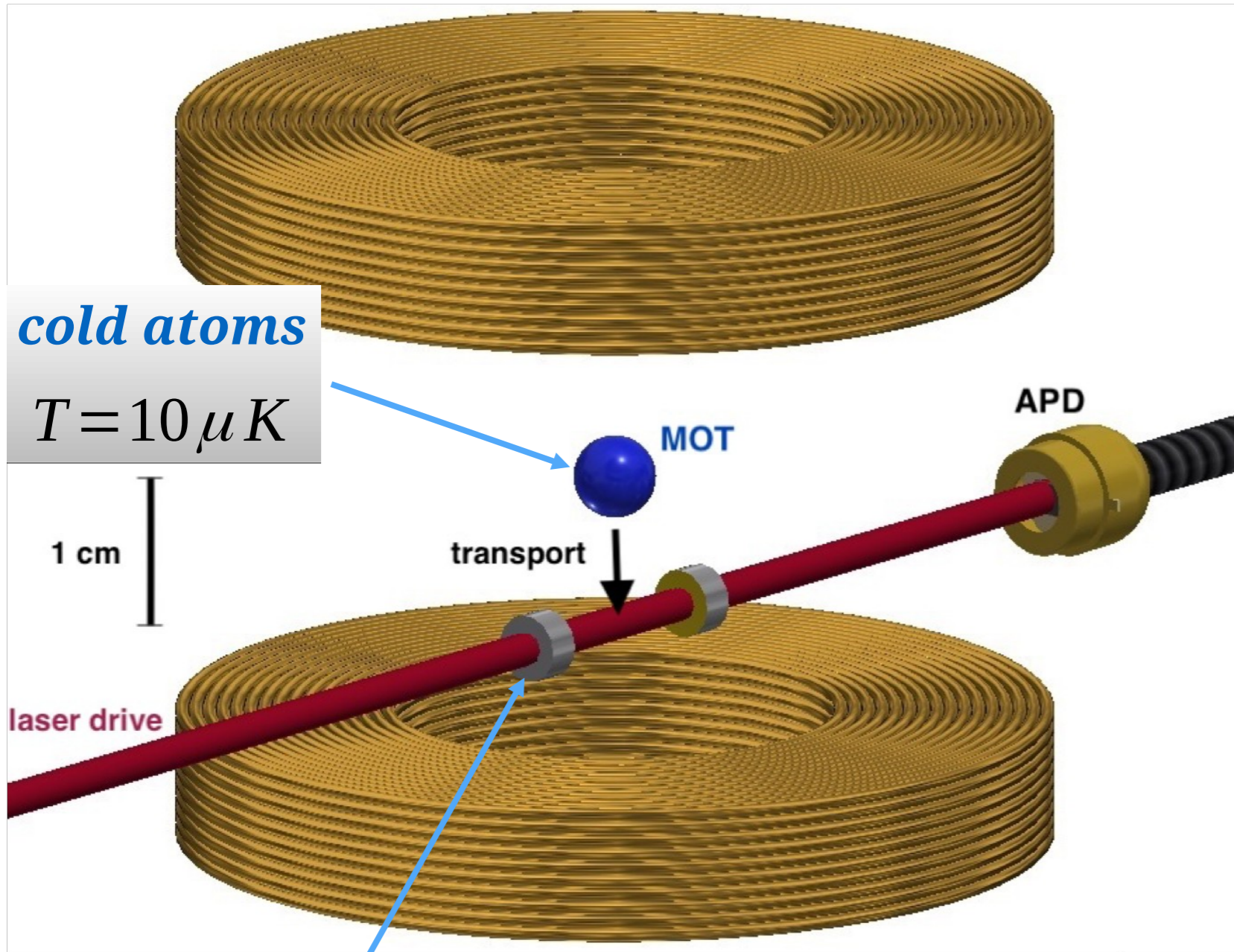
Quantum optics lab @Wigner RCP



Quantum optics lab @Wigner RCP



Cold atom cavity QED experiment @Wigner RCP



cold atoms

$$T = 10 \mu K$$

1 cm

MOT

transport

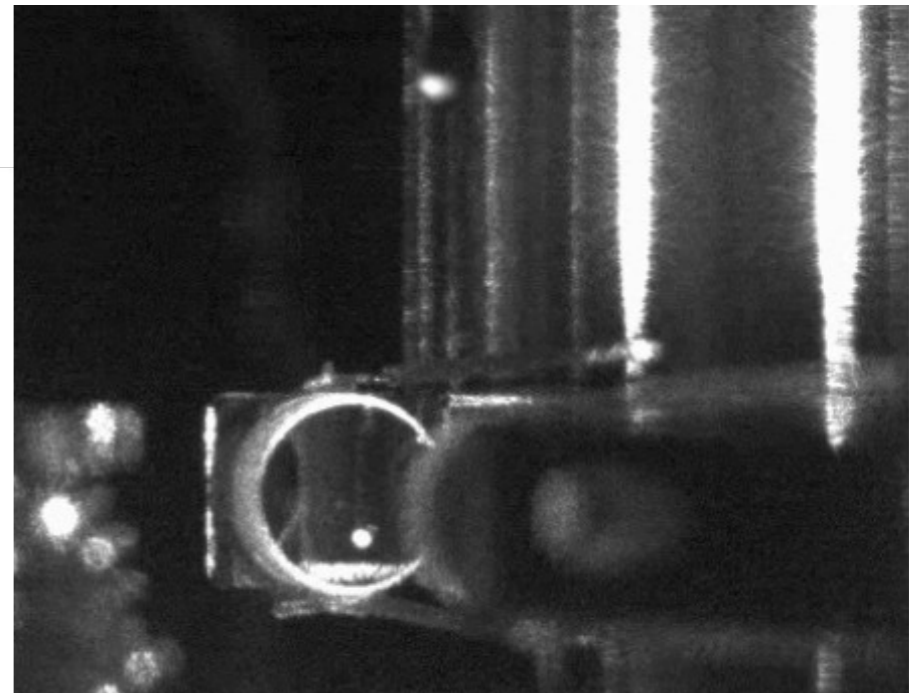
APD

laser drive

optical resonator

$$l = 1.5 \text{ cm}$$

$$w = 150 \mu\text{m}$$



CQED parameters

$$\kappa = 2\pi \cdot 3.2 \text{ MHz}$$

$$g = 2\pi \cdot 0.33 \text{ MHz}$$

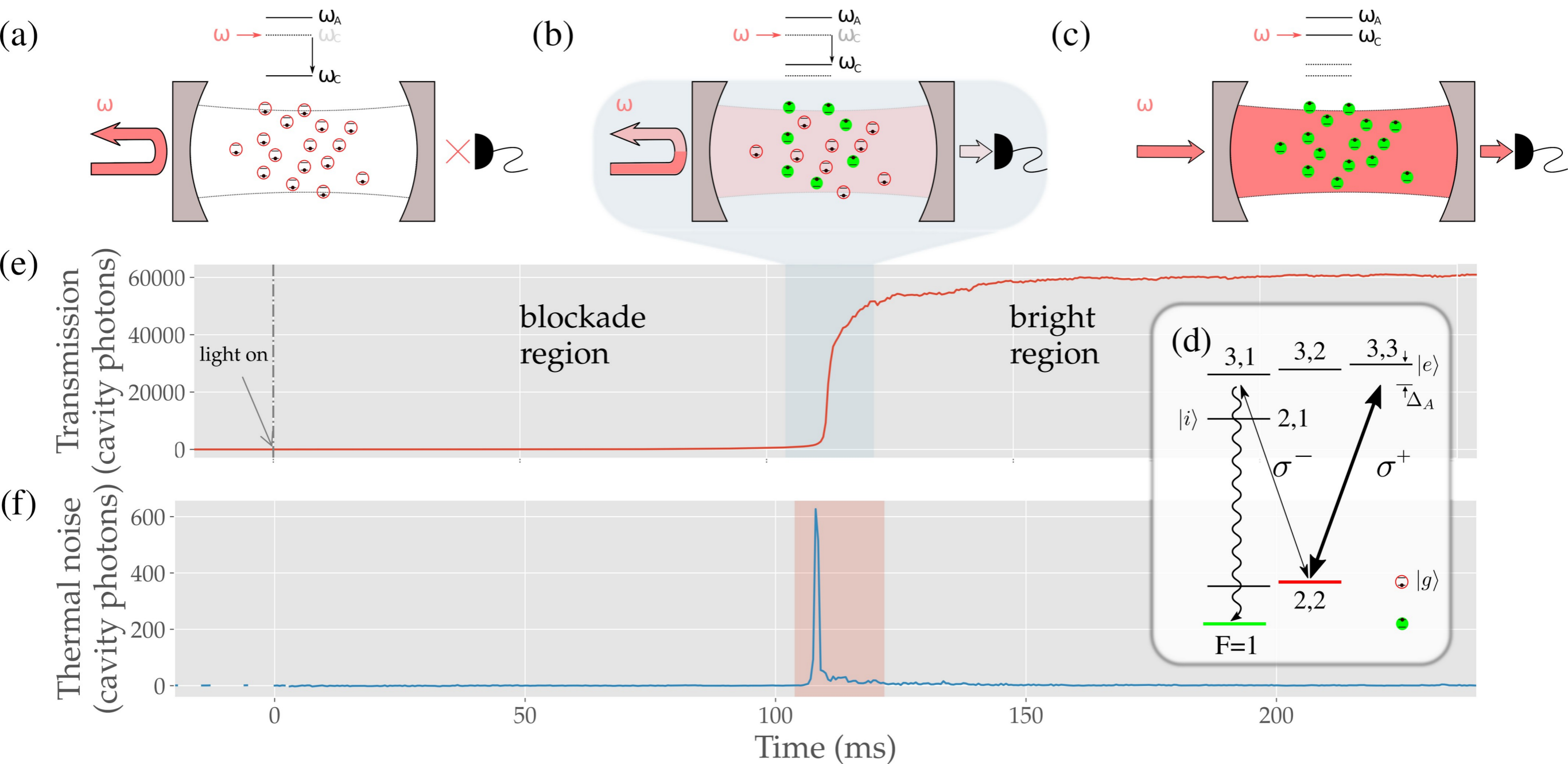
$$\gamma = 2\pi \cdot 3 \text{ MHz } (^{87}\text{Rb D2 line})$$

$$N \sim 10^5$$

collective strong coupling

$$\mathcal{C} > 100$$

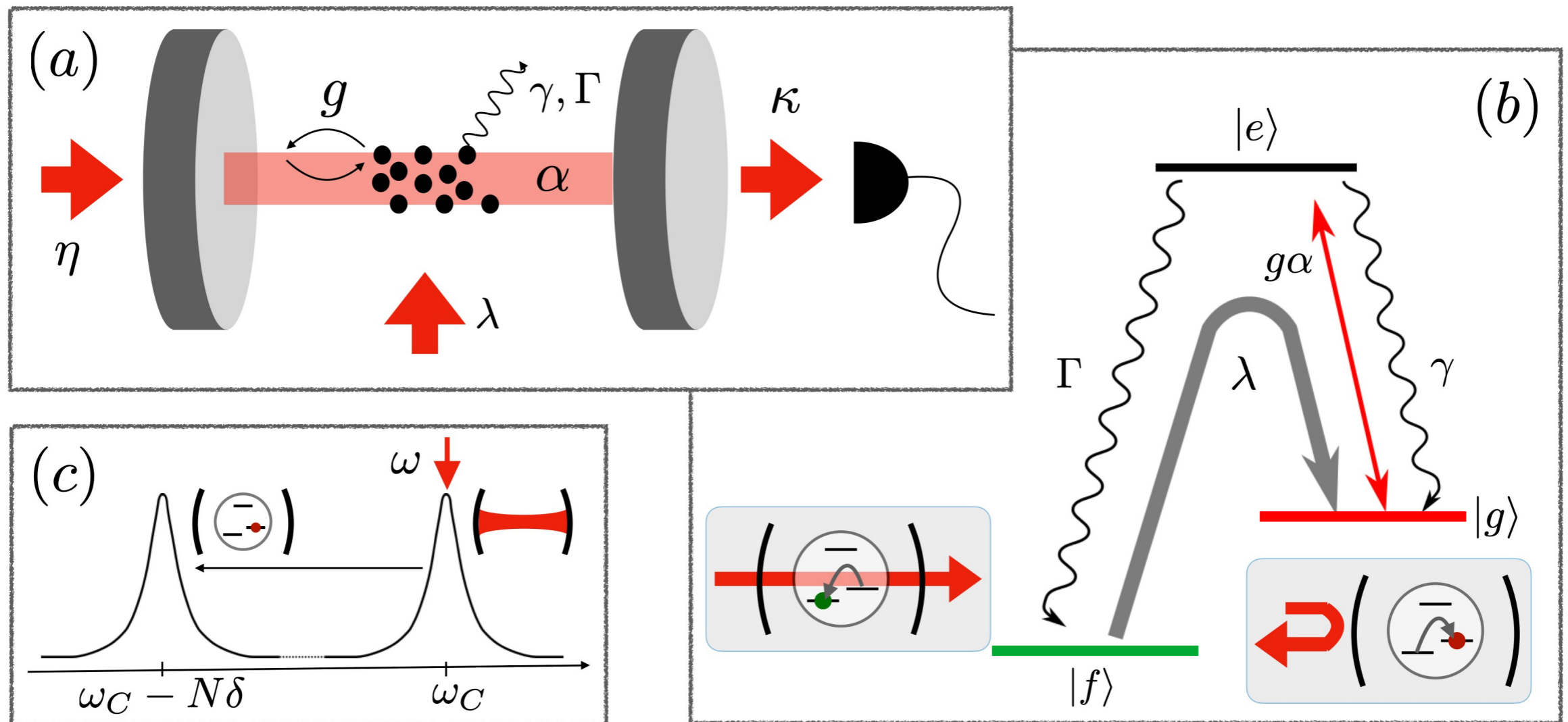
Transmission Blockade Breakdown



Time resolved observation of the 'freezing of overcooled water'

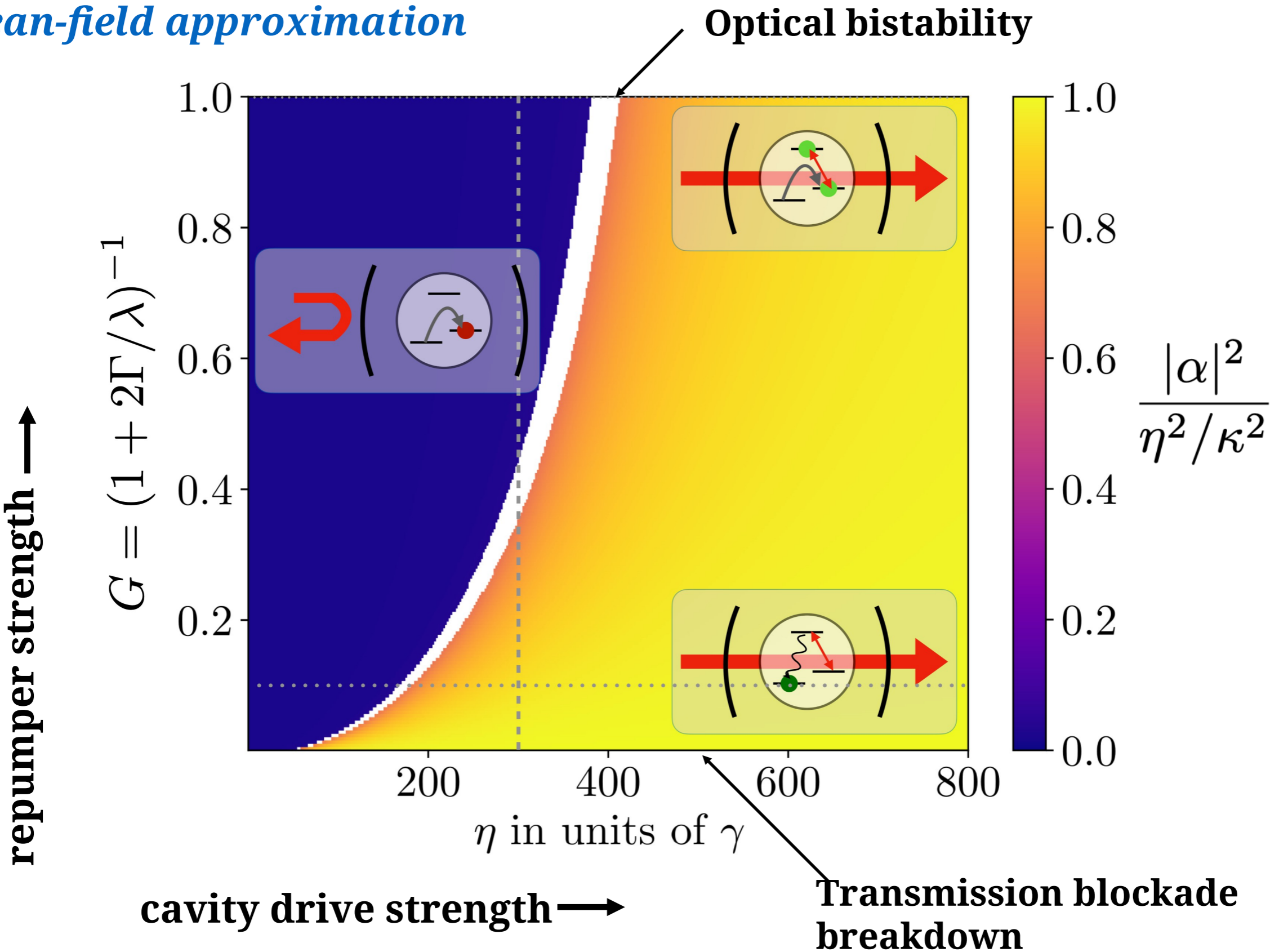
Reversible first-order phase transition - GS bistability

Repumper laser stabilizes the blockaded phase

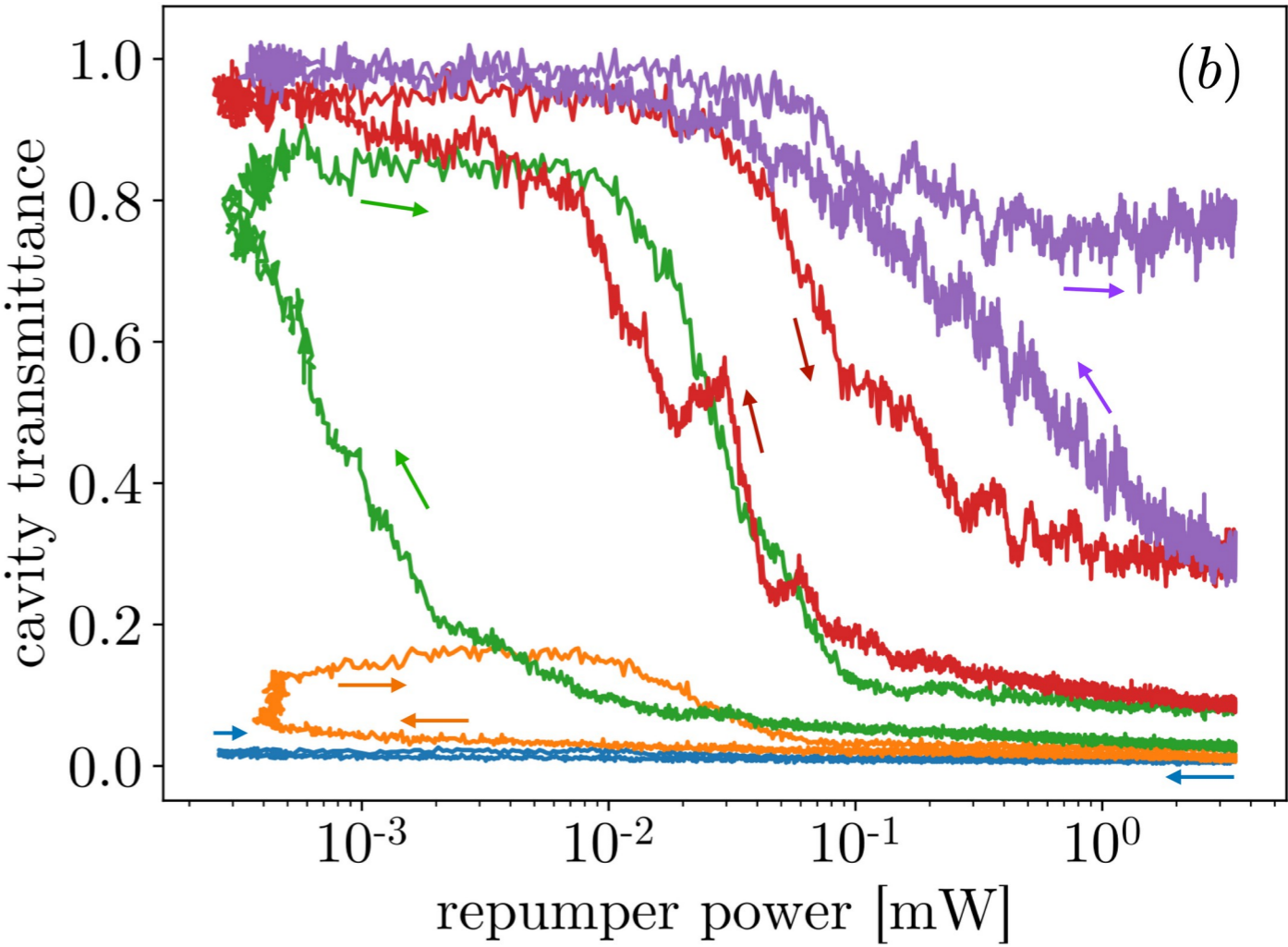
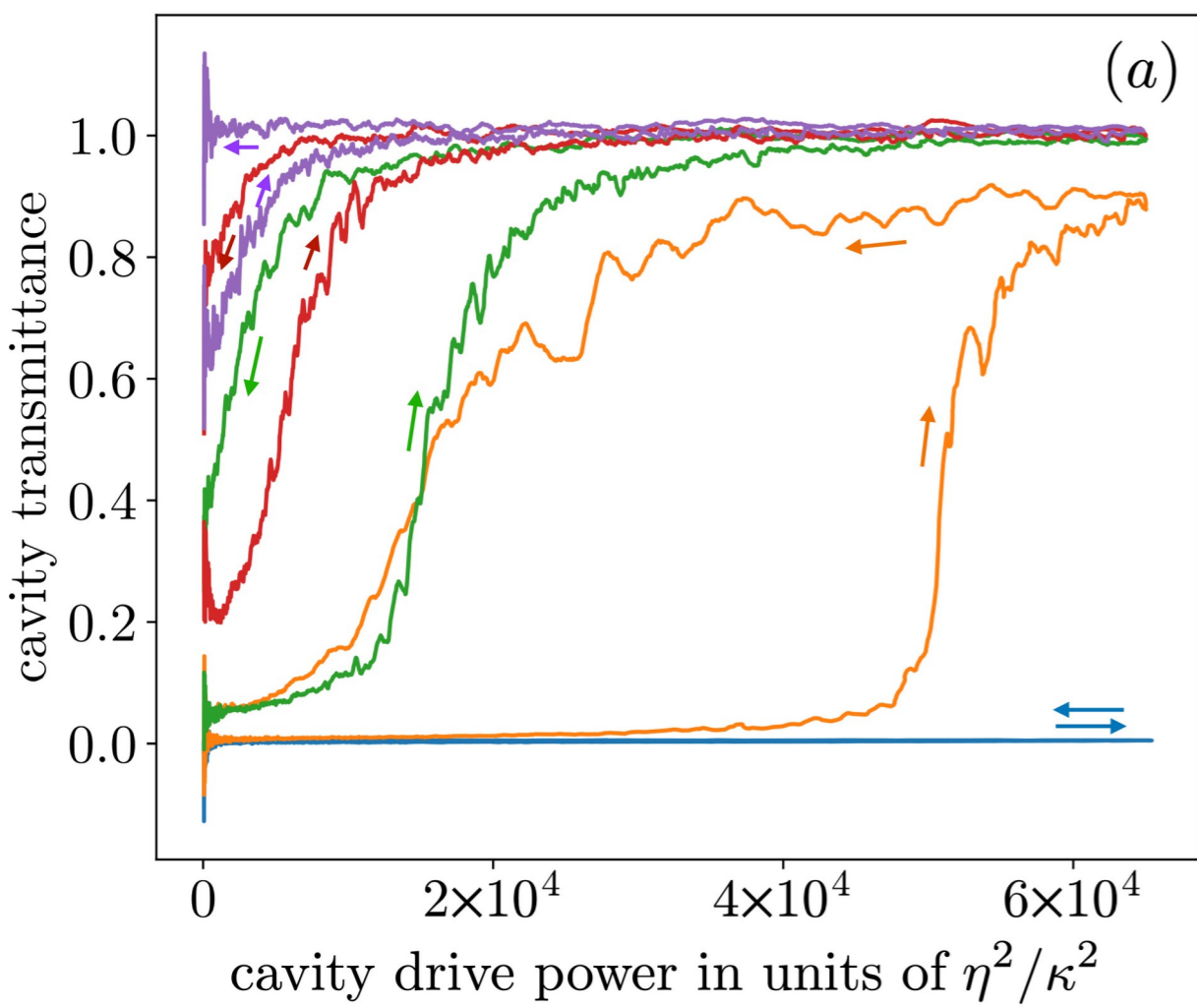
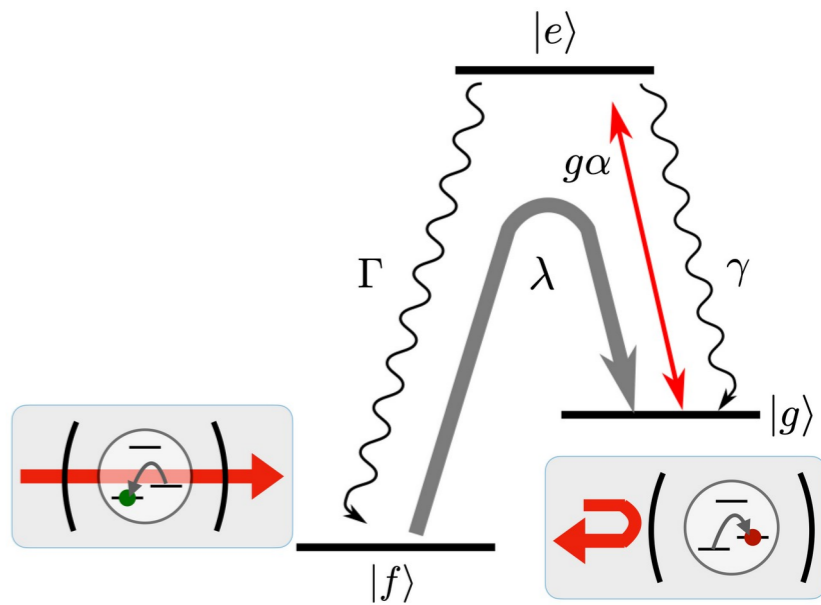
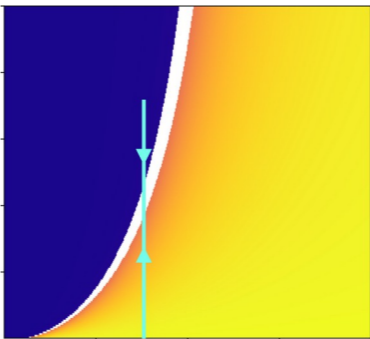
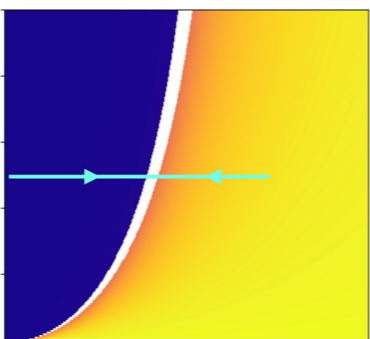


Steady-state phase diagram

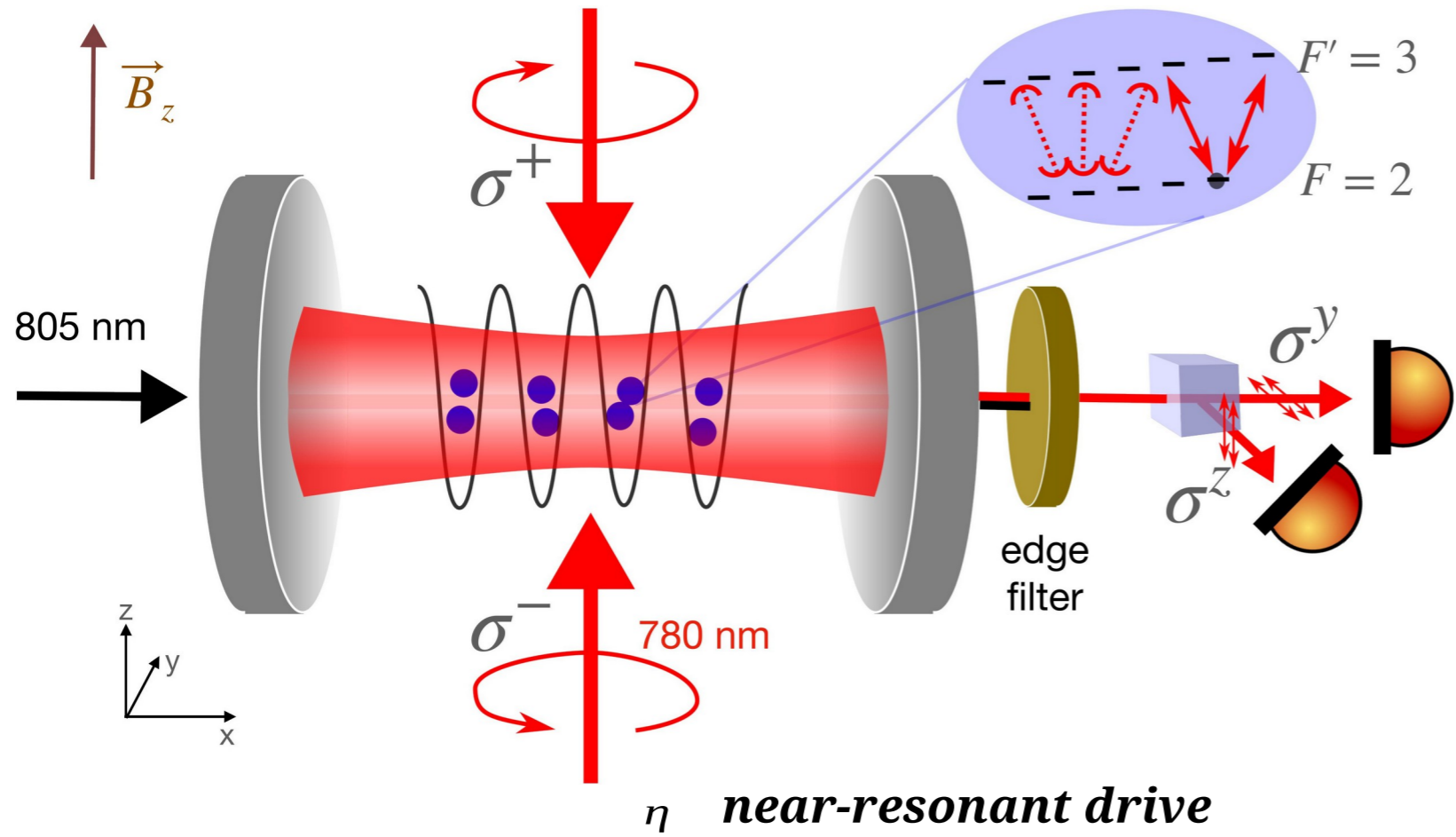
mean-field approximation



Demonstration of the hysteresis



Scattering from a subradiant atom array



Spatial subradiance

- incommensurate lattice
- weak transverse drive
- destructive interference

Linear scatterer model

$$\vec{d} \propto \epsilon_0 \chi(\omega) \vec{E}(\vec{r})$$

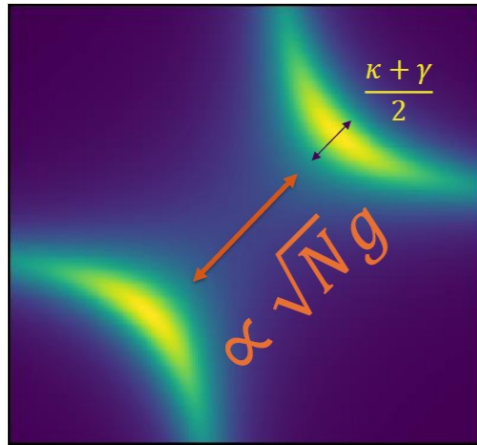
$$\alpha_y = \frac{\eta g \sum_a \cos kx_a \cos kz_a}{(i\Delta_A - \gamma)(i\Delta_C - \kappa) + g^2 \sum_a \cos^2 kx_a}$$

mean $\langle \sum_a \cos kx_a \cos kz_a \rangle = 0$

variance $\left\langle \left| \sum_{a=1}^N \cos kx_a \cos kz_a \right|^2 \right\rangle \approx N^\beta / 4$

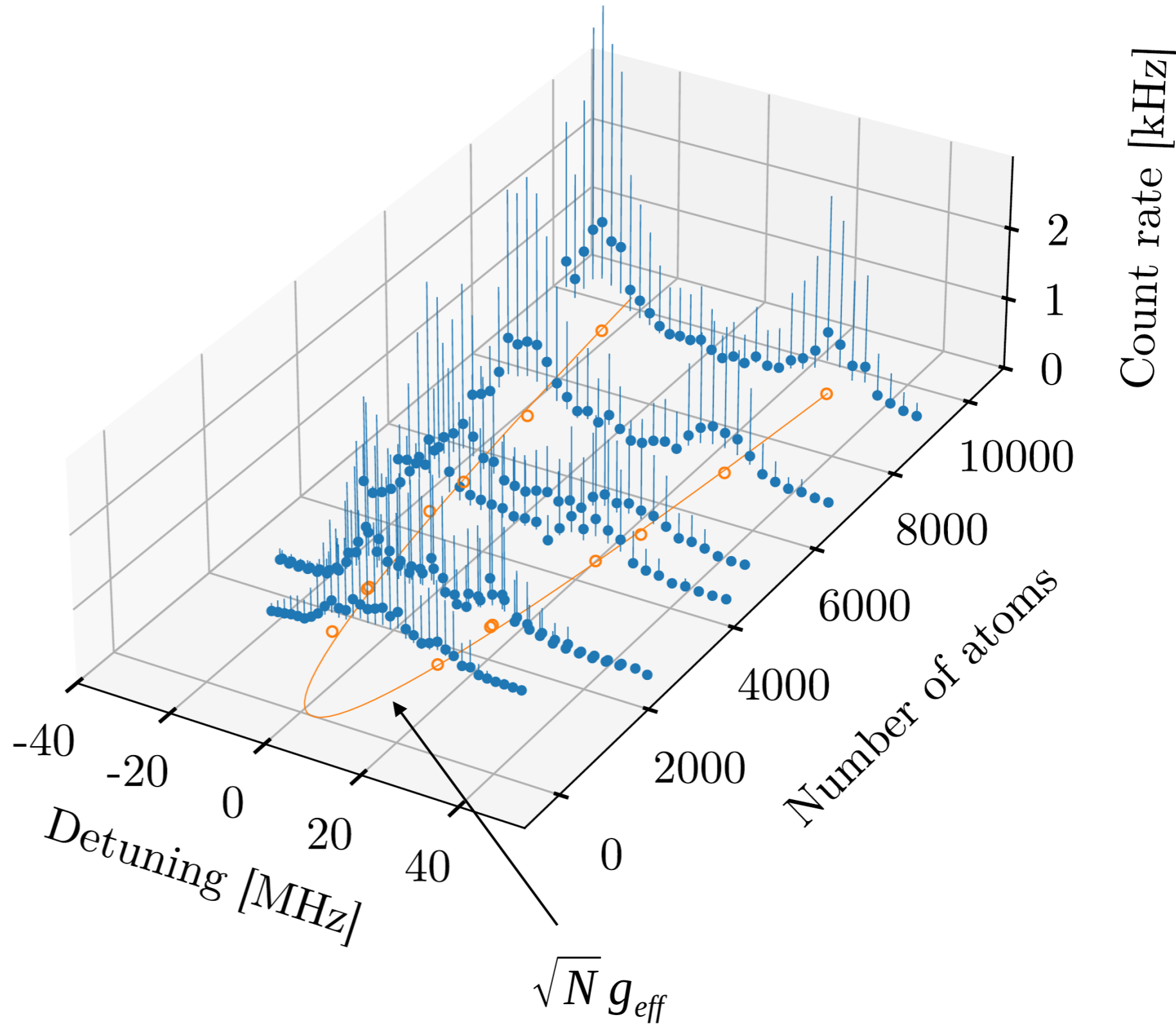
Vacuum Rabi splitting

atomic detuning



cavity detuning

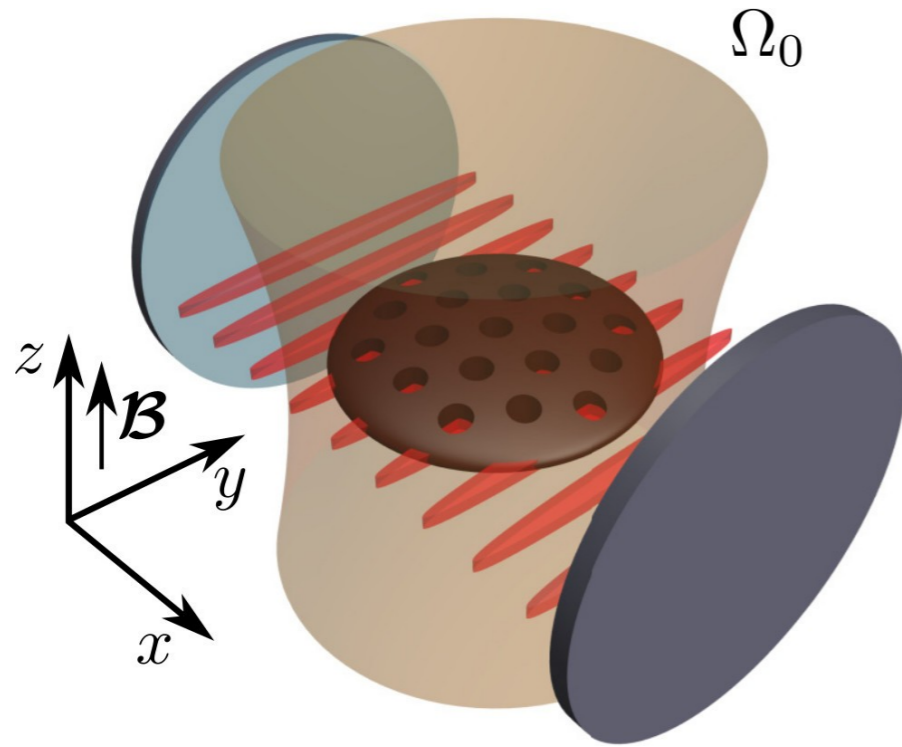
$$g_{eff} = 2 \pi \times (0.26 \pm 0.01) \text{ MHz}$$



Conclusions

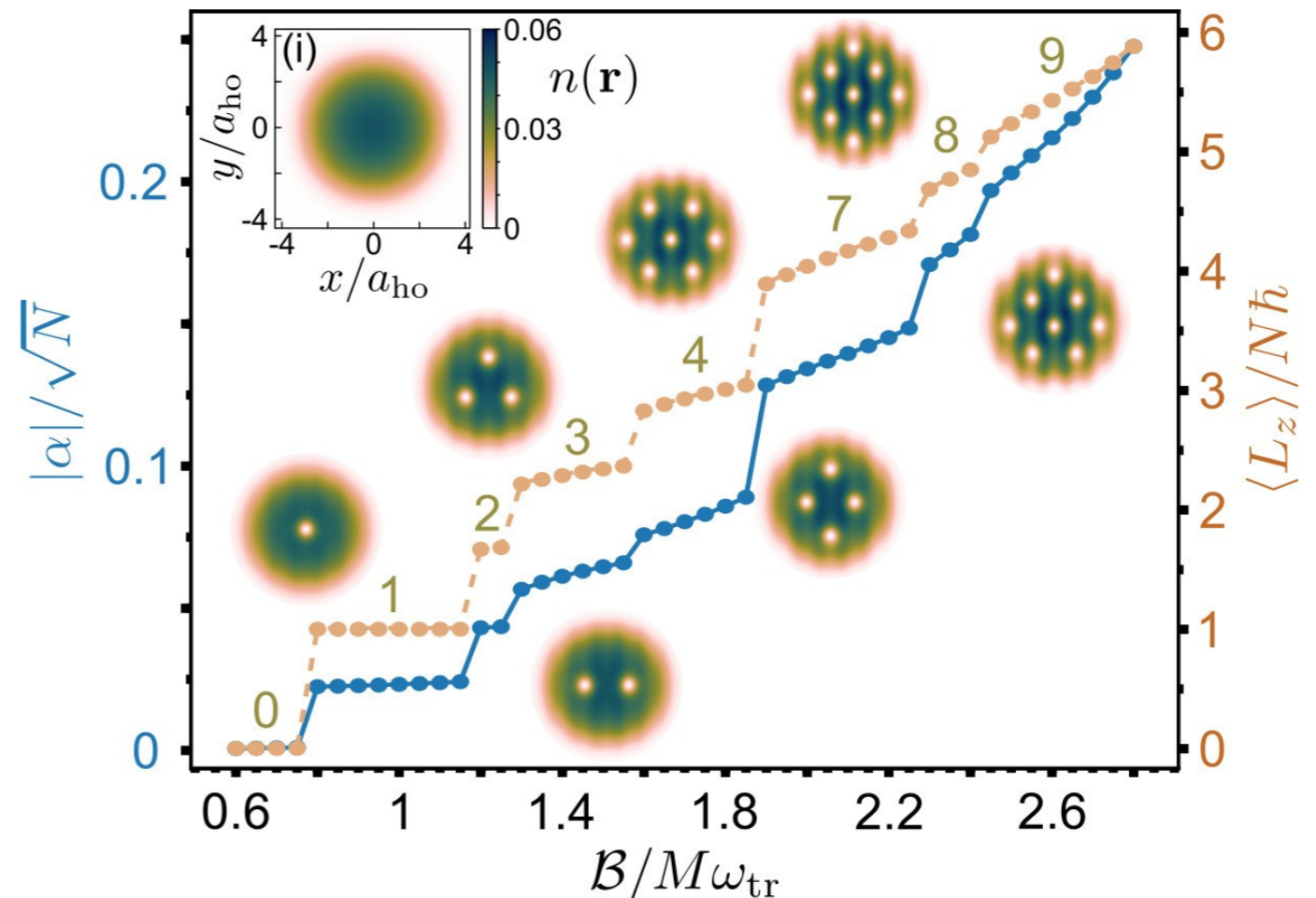
- **Cavity QED systems can provide a new class of phase transitions**
- **Experiment I: Dynamical phase transition characterized by measuring the fluctuations.**
- **Experiment II: We demonstrated bistability between hyperfine ground states.**
- **Rabi splitting was measured from the spectrum of cavity-field fluctuations, atom-number scaling justified subradiant scattering.**

Outlook: Rotational superradiance of a BEC in a cavity



- synthetic B – field breaks time-reversal symmetry
- vortex formation and superradiance
- jumps in the cavity output

cavity detects vortices



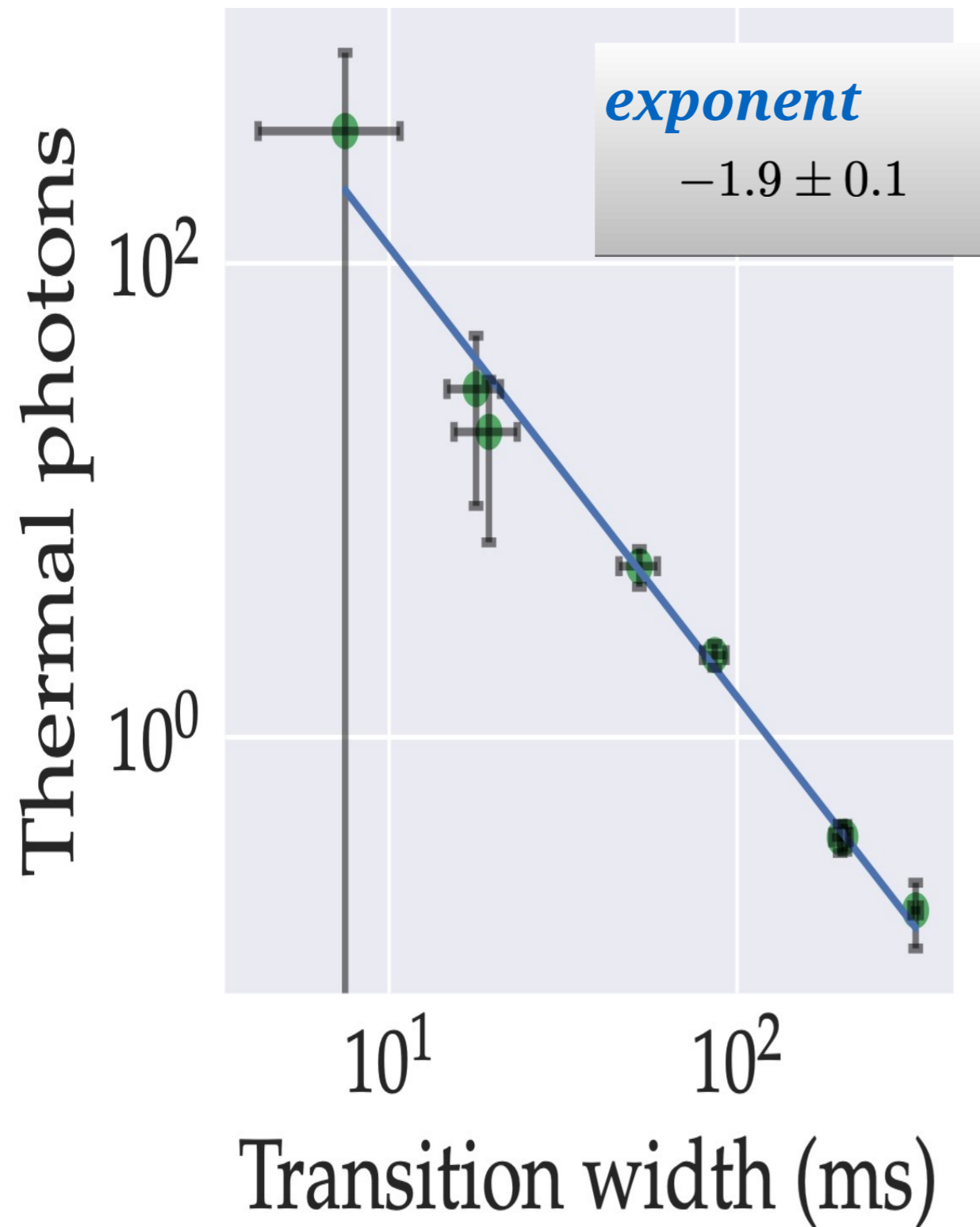
The quantum optics team @ Wigner.SZFI



Dániel Varga Bálint Sárközi Thomas Clark Árpád Kurkó
Dávid Nagy Adwaith KV András Dombi Bence Gábor
Peter Domokos András Vukics

Additional material

Finite-size scaling of fluctuations



**measured
photo-current noise**



displaced thermal state

$$P_{\text{th,disp}}(\alpha) = \frac{1}{\pi n_{\text{th}}} \exp(-|\alpha - \beta|^2 / n_{\text{th}})$$

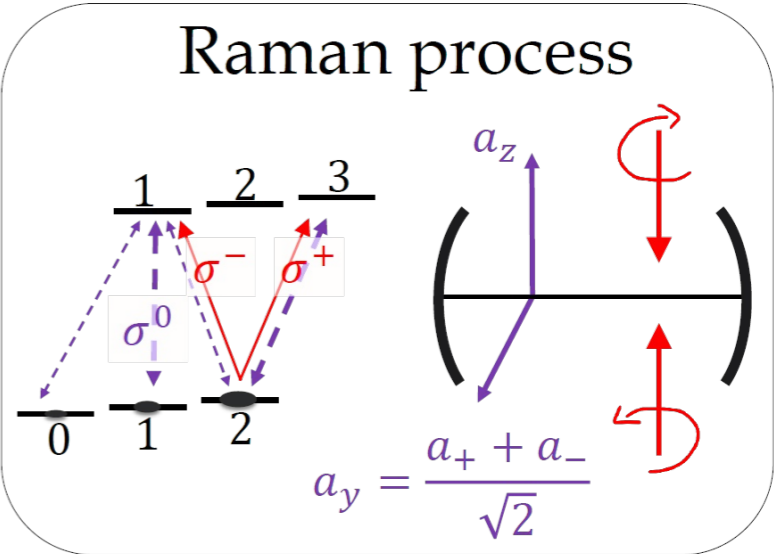
$$\beta : 0 \rightarrow \eta/\kappa$$

$$g^{(2)}(0) = 2 - \frac{|\beta|^4}{(n_{\text{th}} + |\beta|^2)^2}$$

derived from measurement

Rayleigh and Raman scattering

horizontal
al



vertical

Polarization rotation →



Scaling of the peak heights \rightarrow subradiant scattering

$$\beta = 0.875 \pm 0.009$$

$$\beta = 0.853 \pm 0.031$$

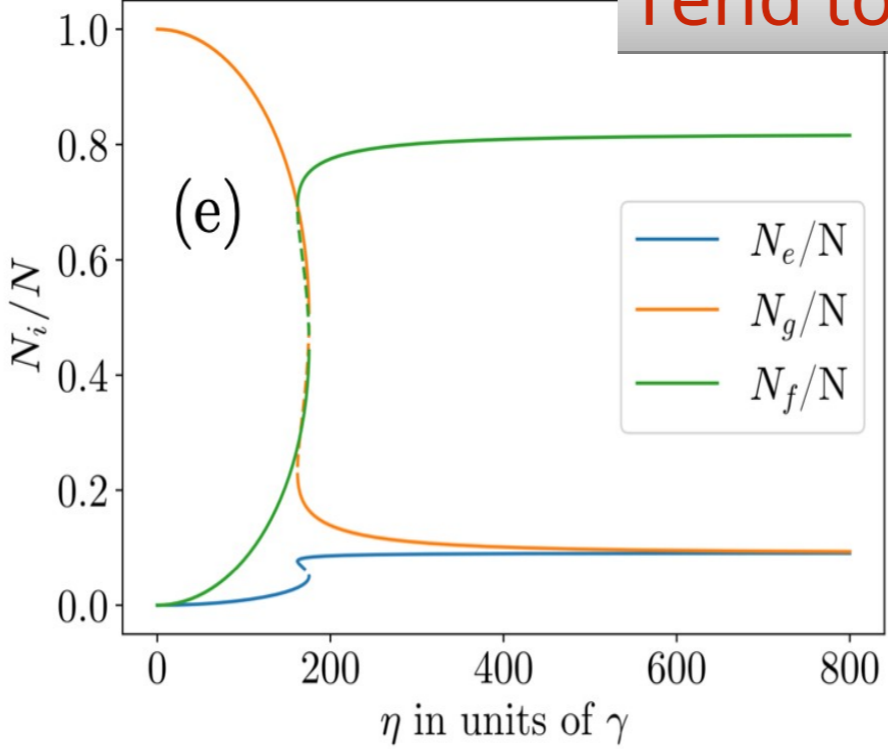
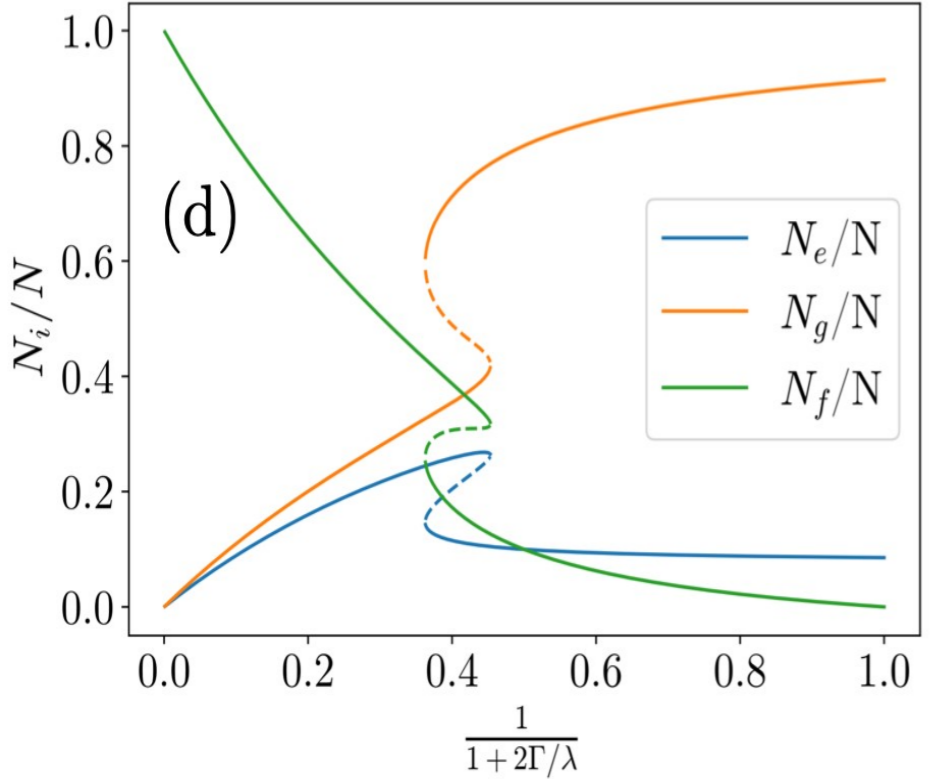
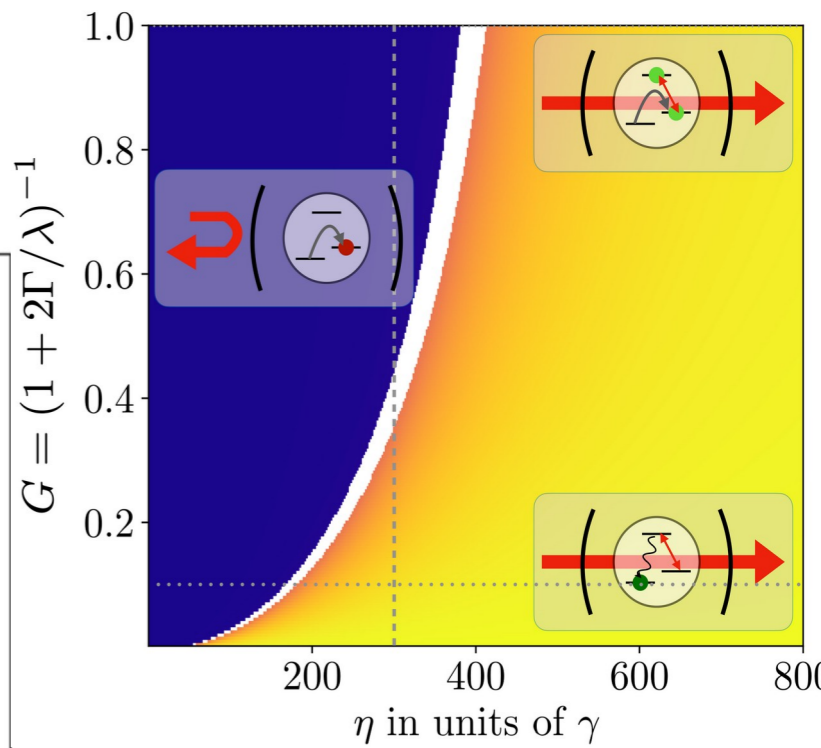
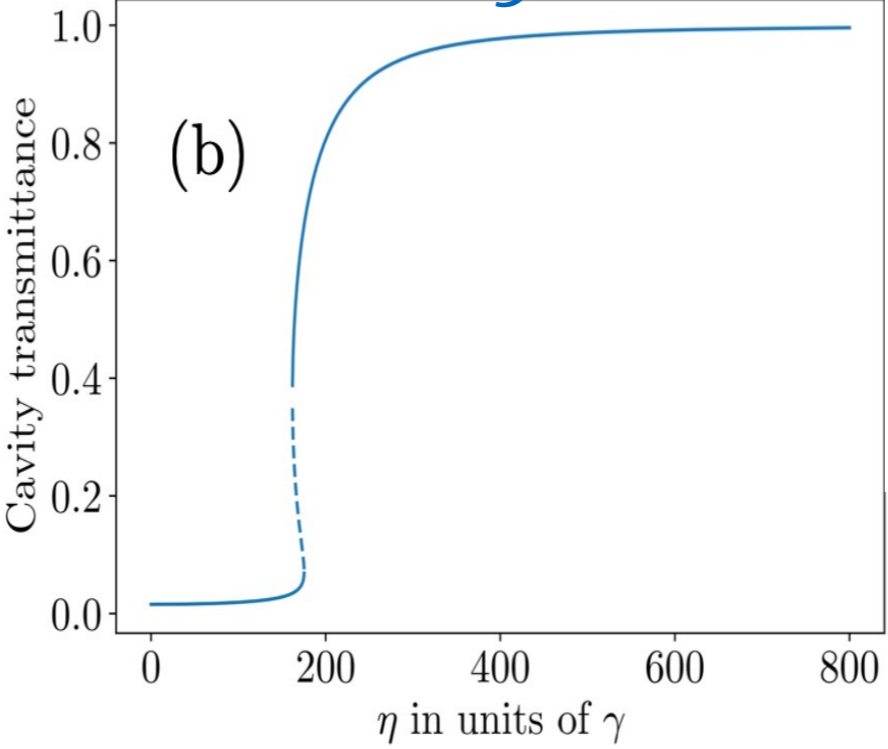
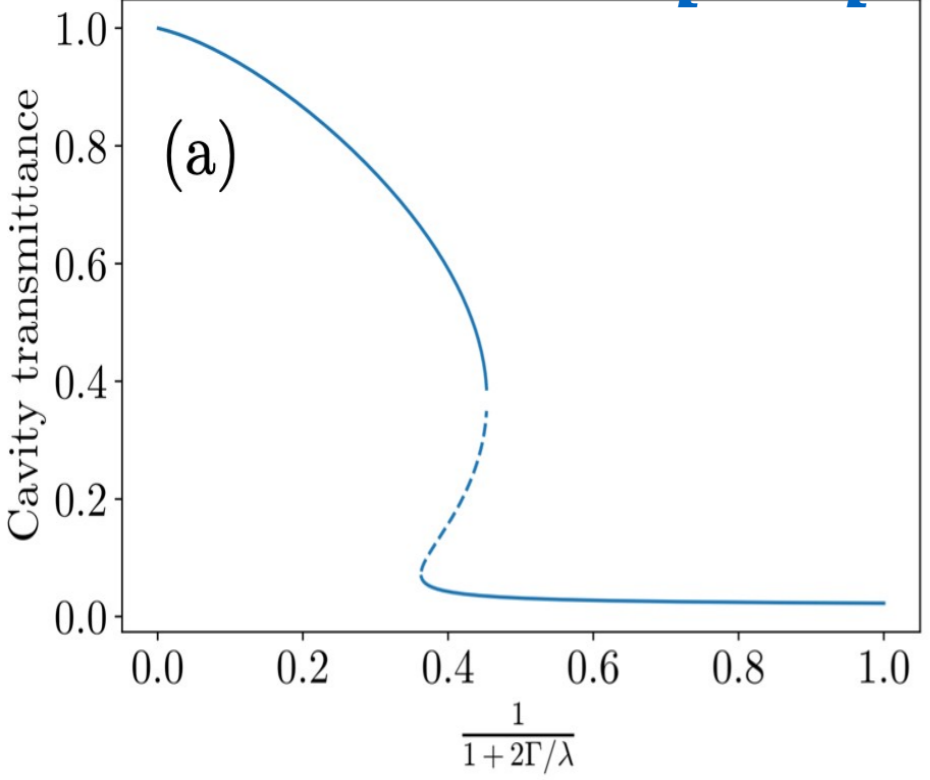


Subradiant $\rightarrow \beta = 1$

Sweeping the control parameters

repumper

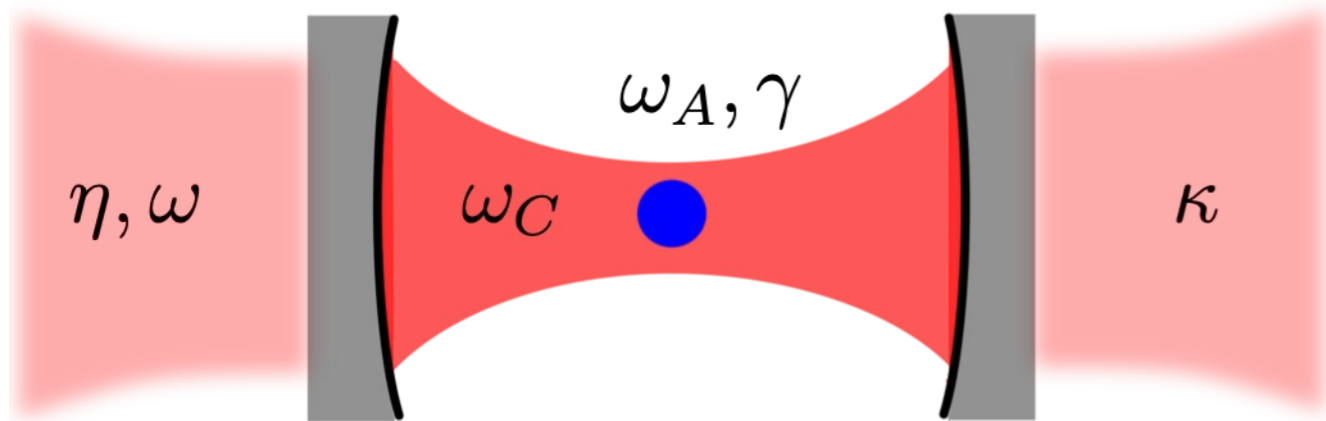
cavity drive



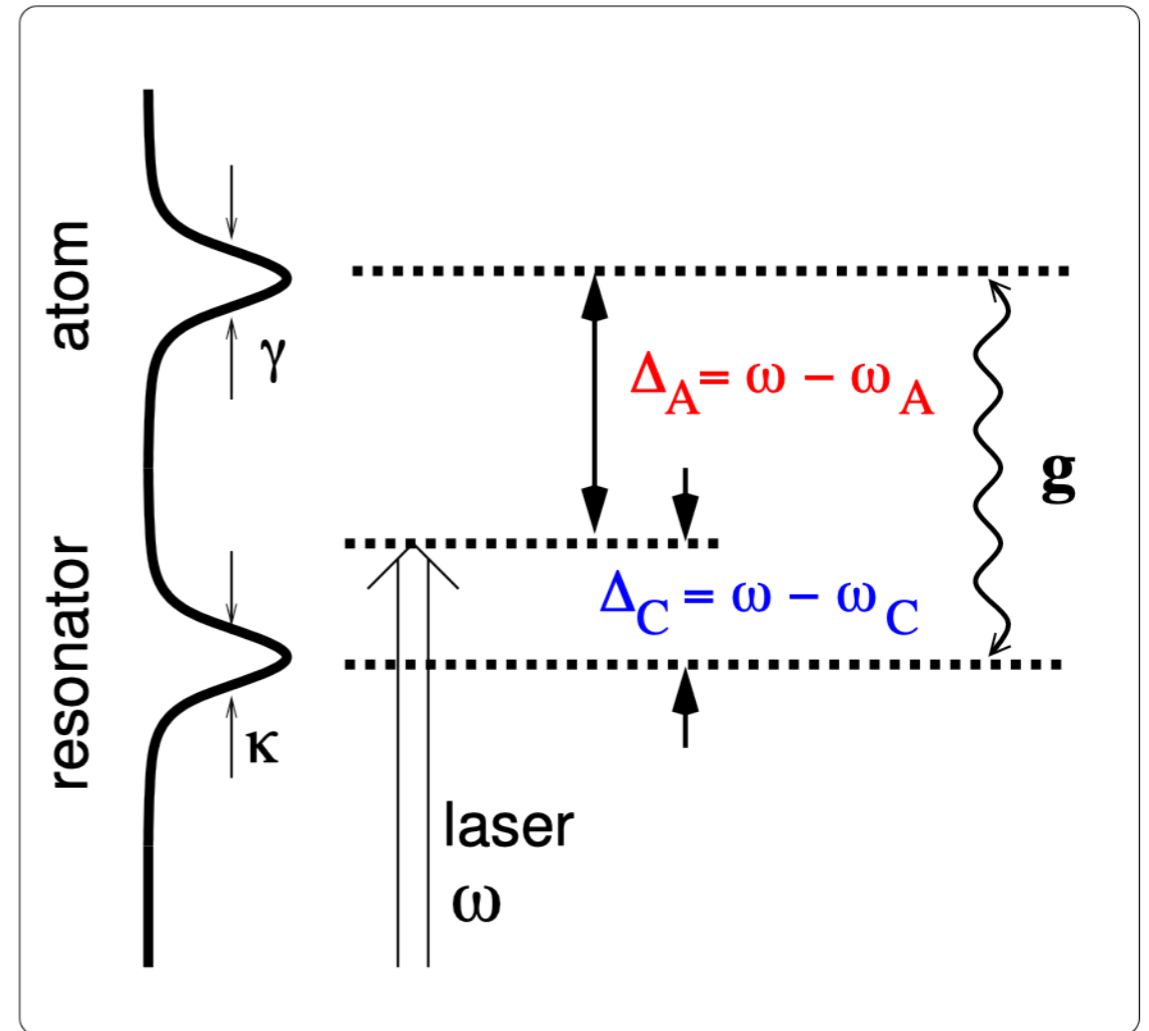
Tend to pure quantum states



Resonance shift of the cavity mode



Excitation of ground state atoms

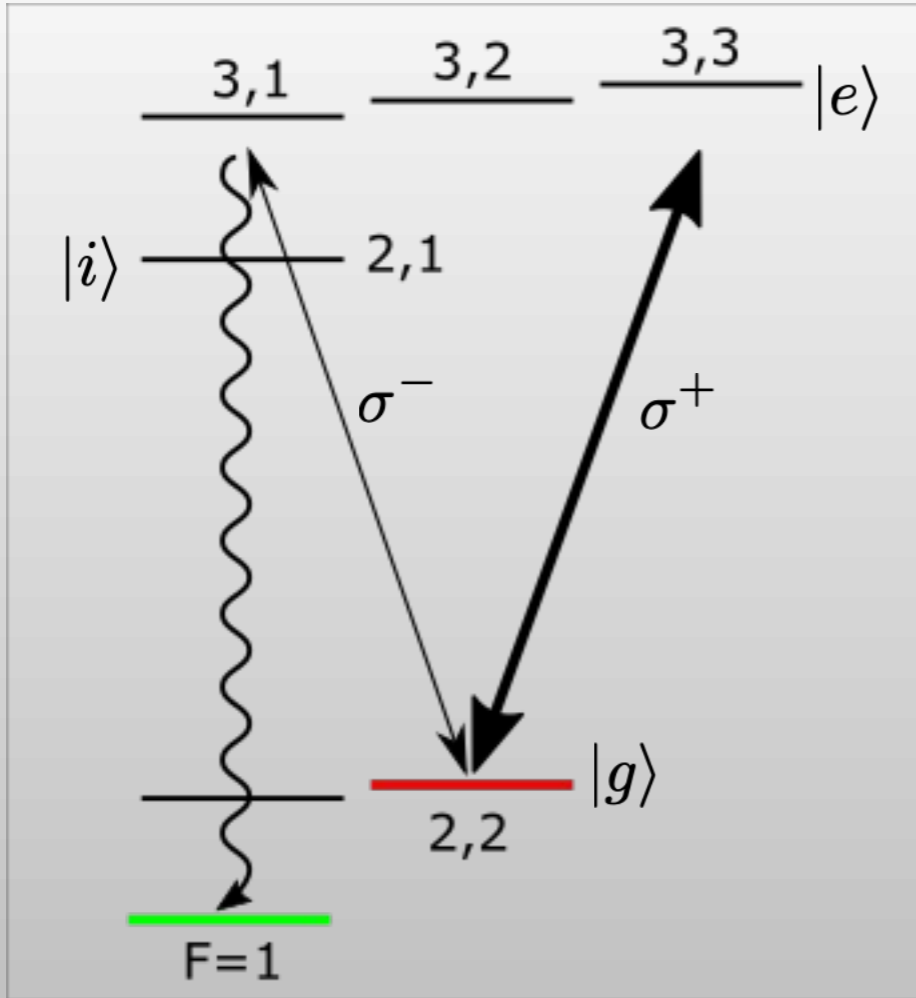


dispersive limit

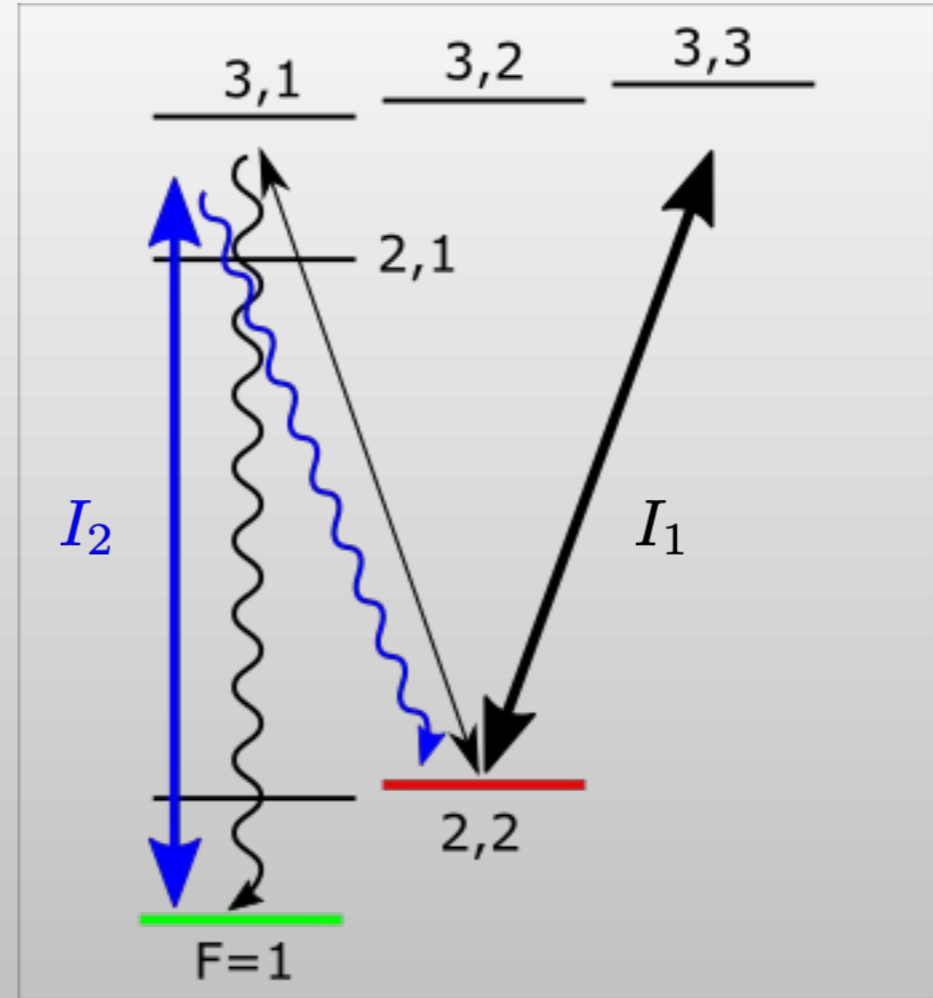
$$\Delta_A = -2\pi \cdot 35 \text{ MHz}$$
$$\delta \approx \frac{g^2}{\Delta_A} = -2\pi \cdot 3 \text{ kHz}$$

Control parameter

original scheme



extended scheme

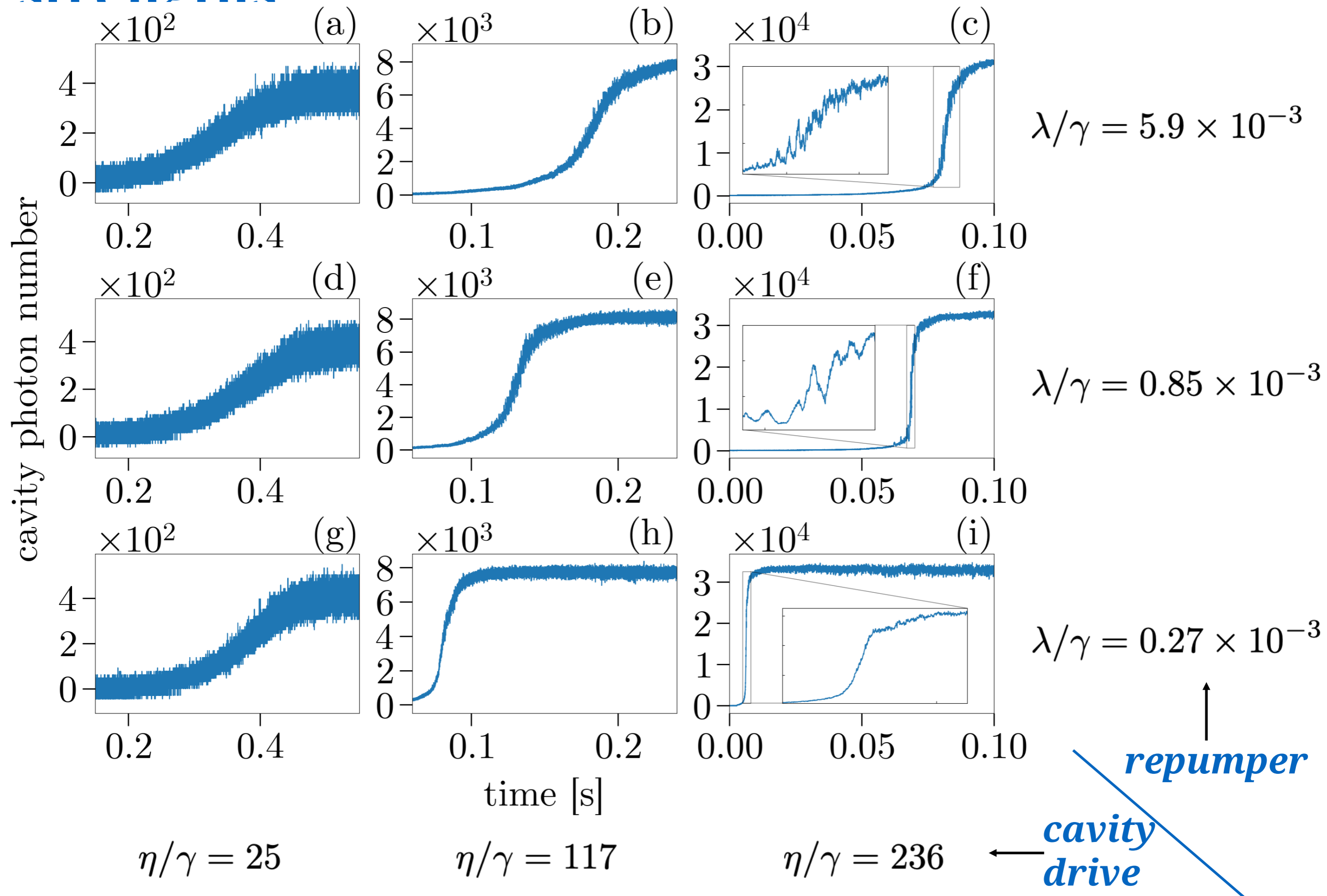


$$I_1/I_2 \Rightarrow \begin{cases} I_2 = 0, I_1/I_2 = \infty \\ I_1 \neq 0, I_2 \neq 0 \\ I_1 = 0, I_1/I_2 = 0 \end{cases}$$

green state
co-existence
red state

← present experiment

Time evolution for various drive strengths



Mean-field approximation

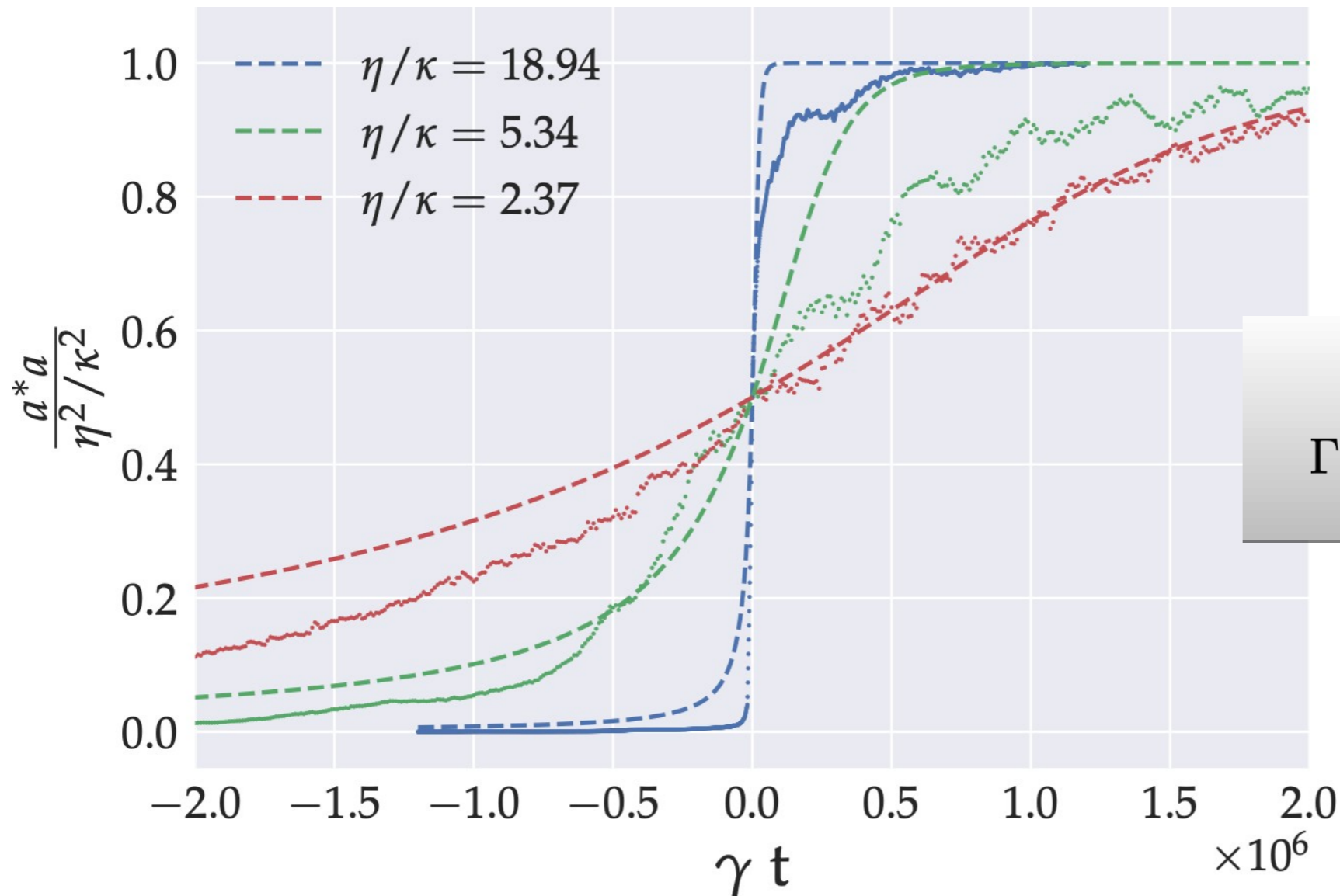
approximations $|f(\mathbf{r}_j)|^2 = \frac{1}{2}$
 $\mathcal{N} = 10^4$

initial condition $N_g = \mathcal{N}$

$N_e = M = a = 0$

$$\begin{aligned} \dot{a} &= (i\Delta_C - \kappa)a + gM + \eta, \\ \dot{M} &= (i\Delta_A - \gamma - \Gamma)M + g[N_e - N_g]a, \\ \dot{N}_e &= -g[a^*M + M^*a] - 2(\gamma + \Gamma)N_e \\ \dot{N}_g &= g[a^*M + M^*a] + 2\gamma N_e, \end{aligned}$$

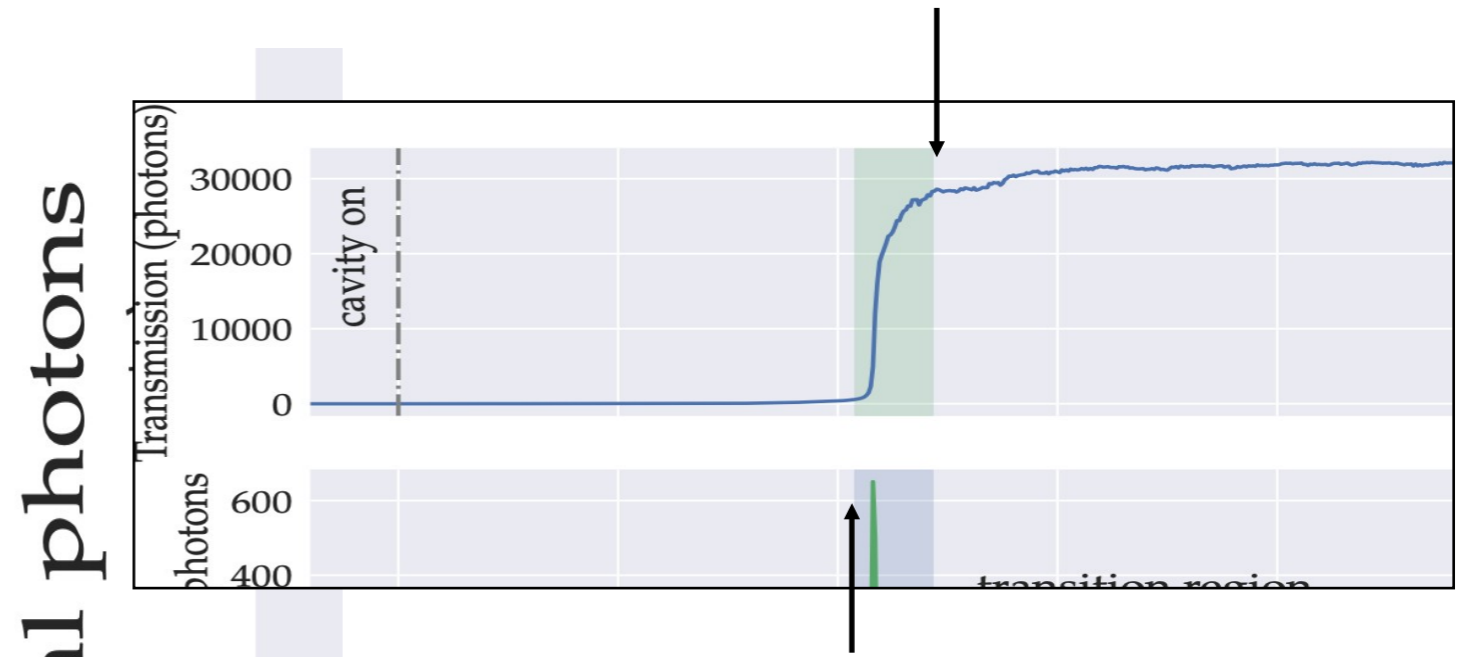
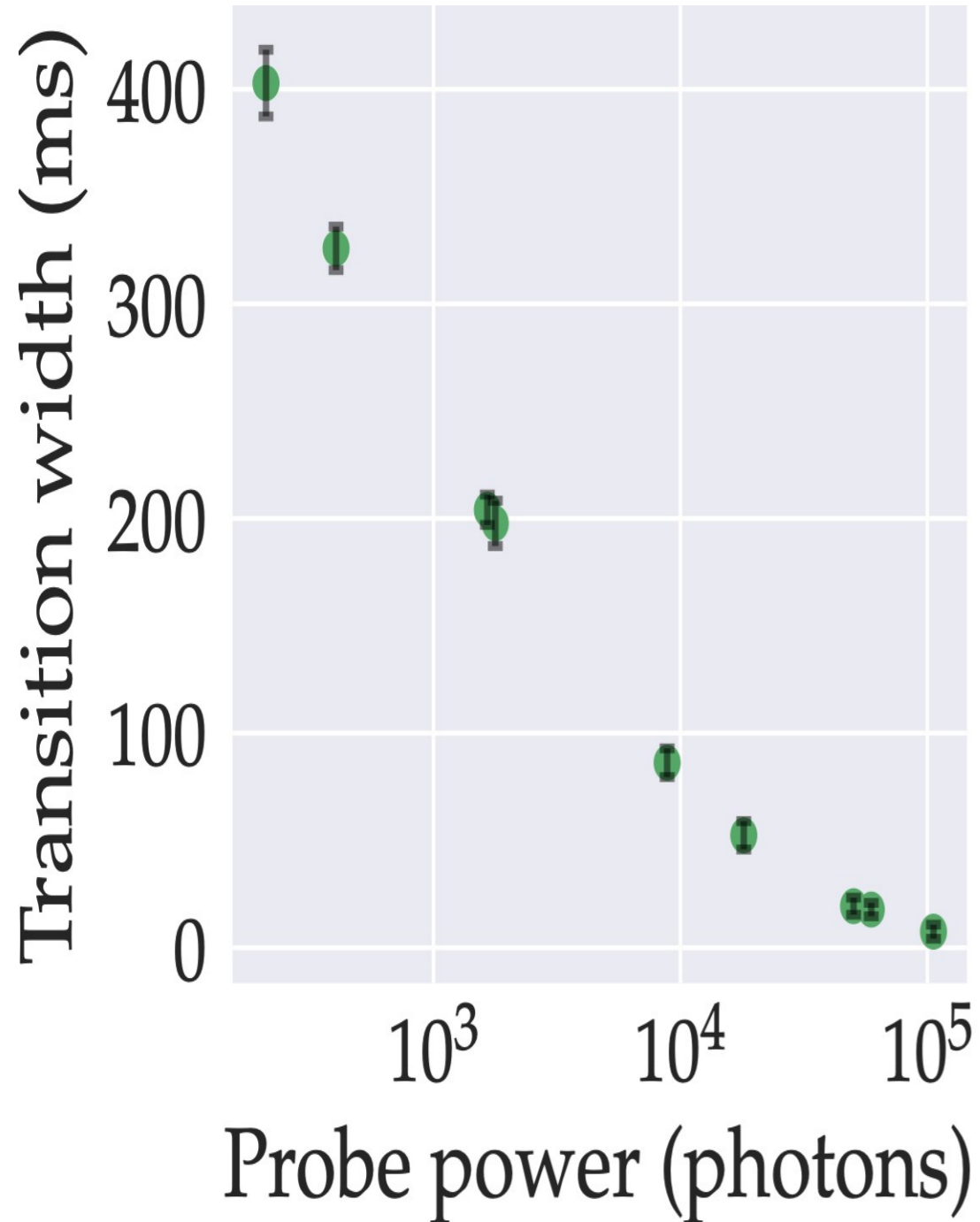
control parameter η



$\Gamma = 0.93 \cdot 10^{-3} \gamma$

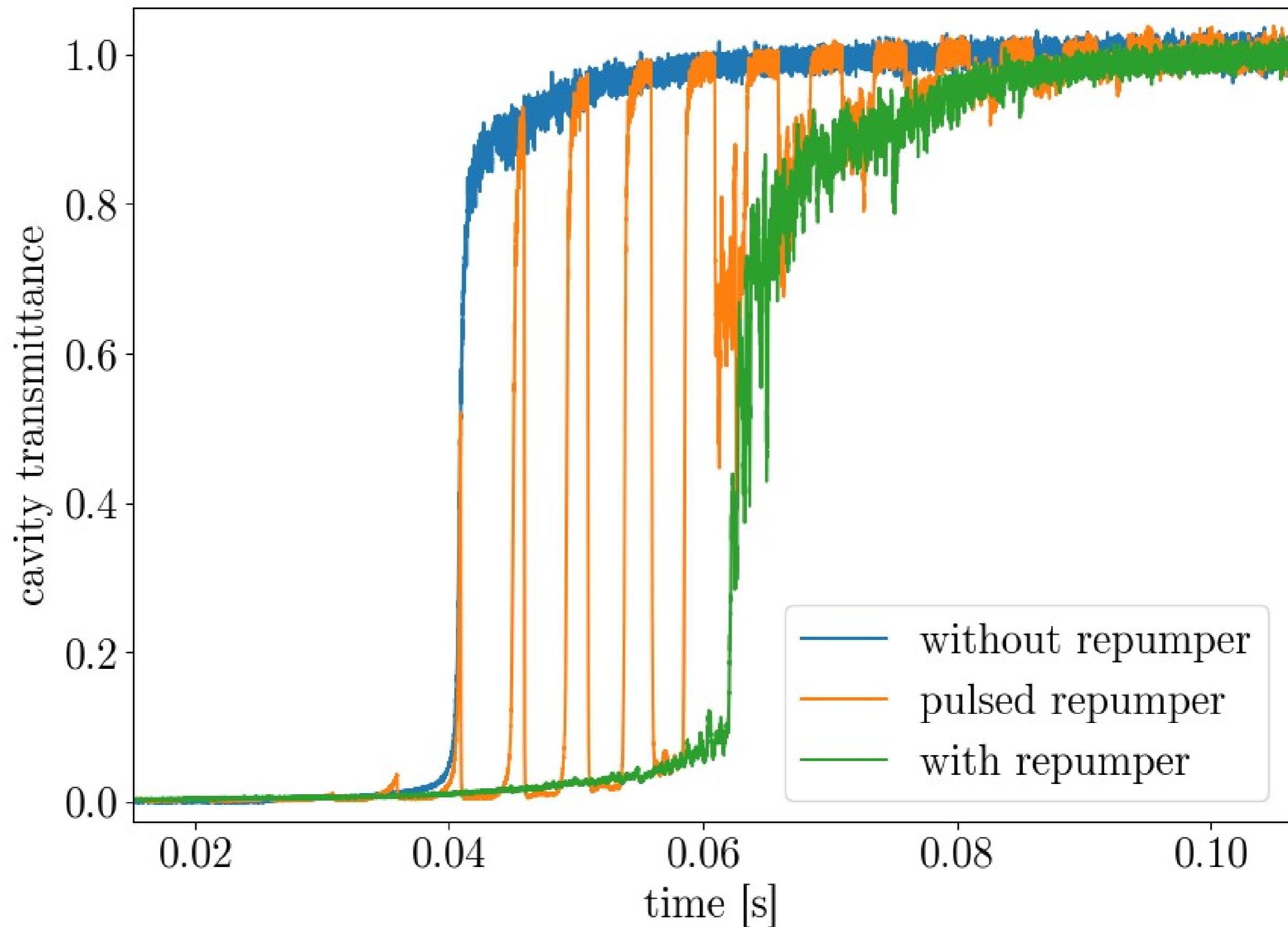
Defining and calibrating a finite-size measure

Thermodynamic limit: $\mathcal{C} \rightarrow \infty, \eta \rightarrow \infty$

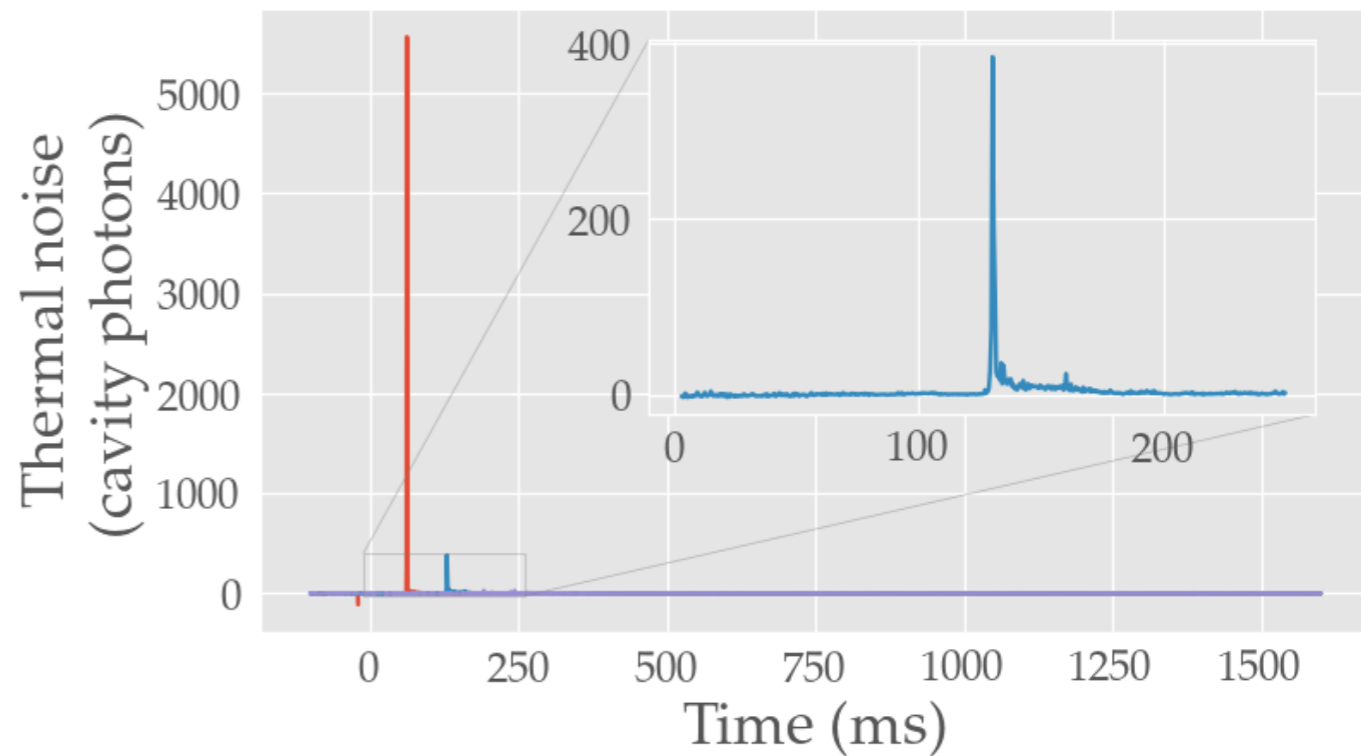
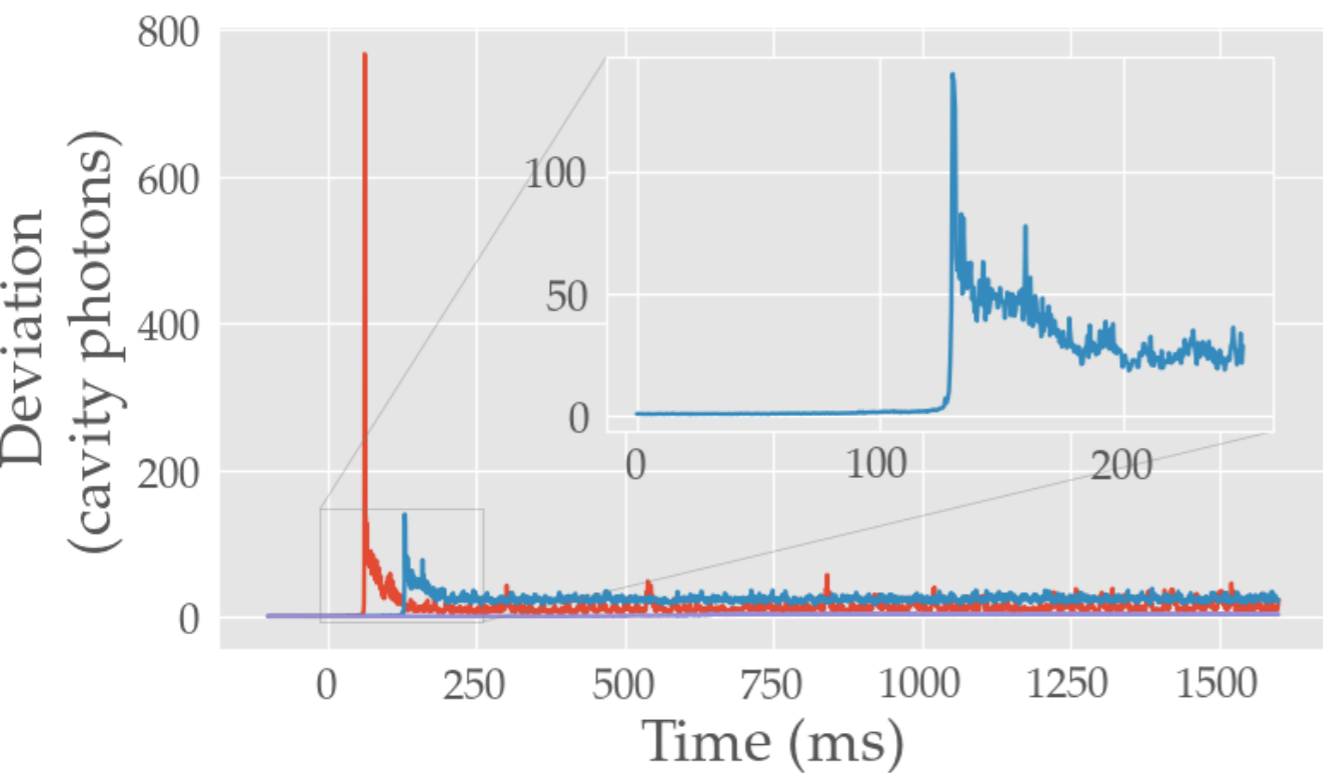
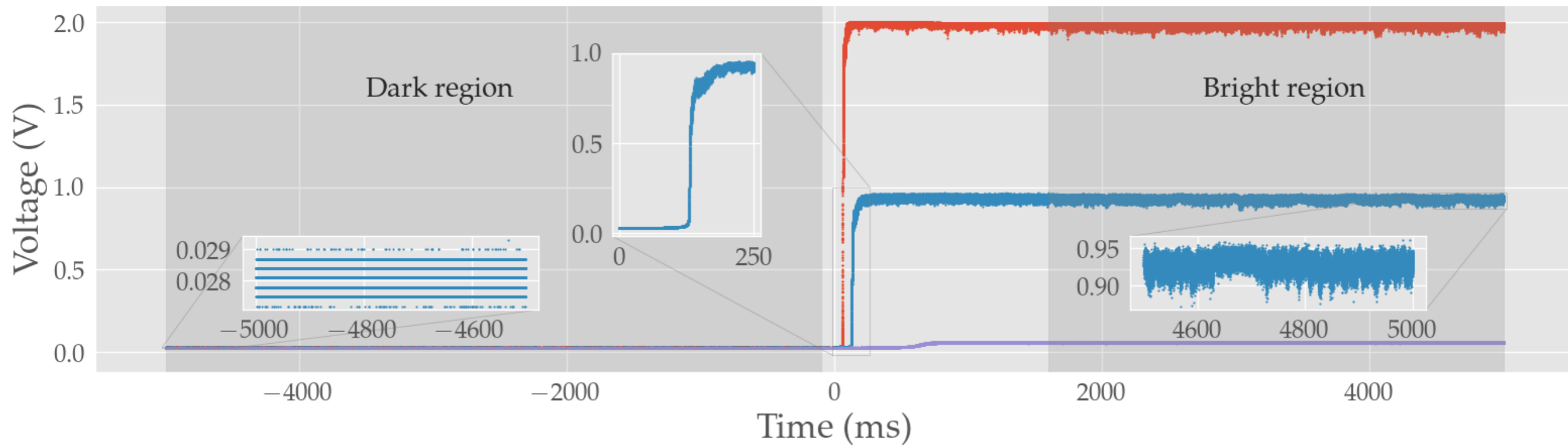


Two orders of magnitude covered!

Reversibility of the switching between the hyperfine ground states



Experimental data



'Freezing of overcooled water'

