What is the difference between Dicke superradiance and lasing?

P Kirton, M M Roses, J Keeling, and E G Dalla Torre, "Introduction to the Dicke model: from equilibrium to nonequilibrium, and vice versa." *arXiv:1805.09828*

Nonequilibrium Quantum Dynamics

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http://www.facebook.com/nonequilibrium

Like

What is the difference between Dicke superradiance and lasing?

A. SR is quantum and lasing is classical

B. Lasing in quantum and SR is classical

C. Only one of them is a phase transition

D. There is no real difference

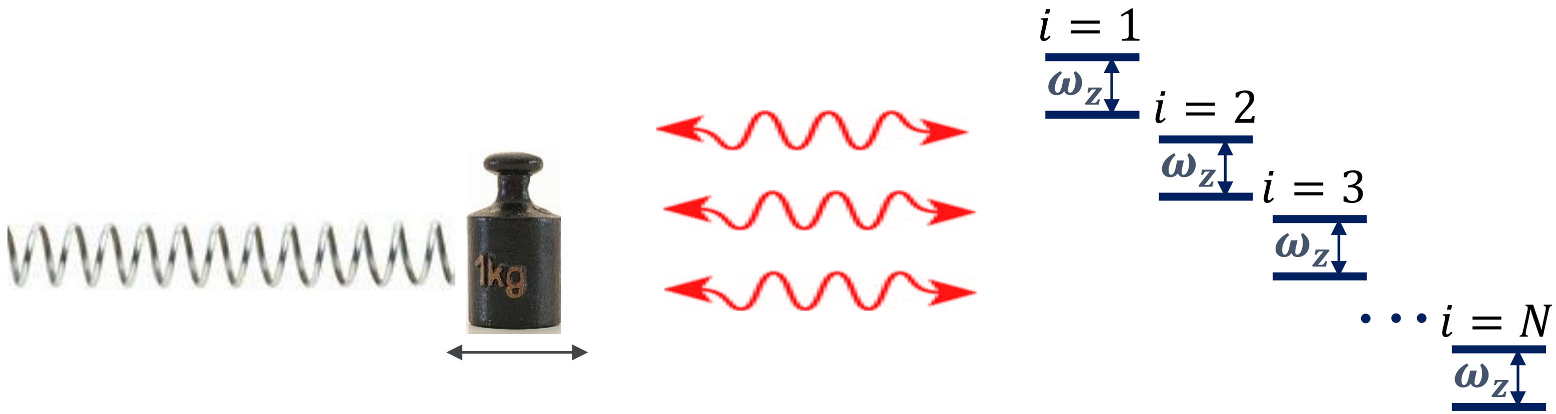
Outline

Dicke superradiance (8 slides)

Lasing (4 slides)

Extras (2 slides)

Dicke model



$$H = \frac{1}{2}\left(X^2 + P^2\right) \quad + \frac{\lambda}{\sqrt{N}} \sum_{i=1}^{N} X\, \sigma_i^x \quad + \omega_z \sum_{i=1}^{N} \sigma_i^z$$

"Ising model of quantum optics"

Credit: MASS - http://www.fotocommunity.de/photo/1-kilogramm-kajo-schmitz/20034234
SPRING http://depositphotos.com/10120691/stock-photo-metal-spring-isolated-on-white.html

Timeline of Dicke superradiance

1970s

Gibbs ensemble: equilibrium transition (both $T \neq 0$ and $T = 0$)

Hepp & Lieb (AoP, 1973),
Wang & Hioe (PRA, 1973),
Duncan (PRA, 1974)

Bialynnicki-Birula & Rzaźewski (PRL, 1979)

1980s-1990s

No-go theorem for atom-cavity dipolar coupling

2000s

Proposal: nonequilibrium stimulated Raaman coupling

Dimer,…, Carmichael (PRA, 2007)
Nagy, …, Domokos (PRL, 2010)

Baumann, …, Esslinger (Nature, 2010)
Baden, …, Barret (PRL, 2014)

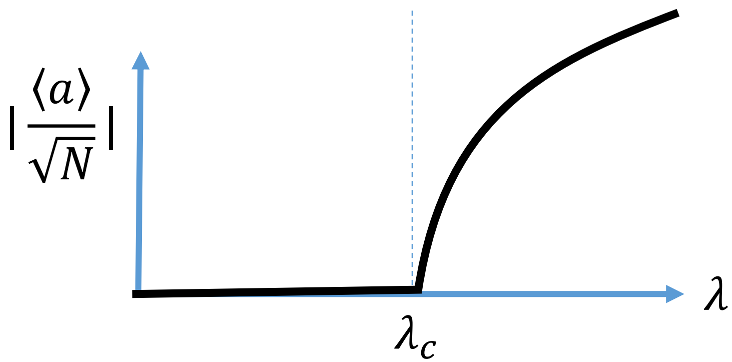
2010s

Experimental realization of the nonequilibrium transition

Dicke superradiant transition

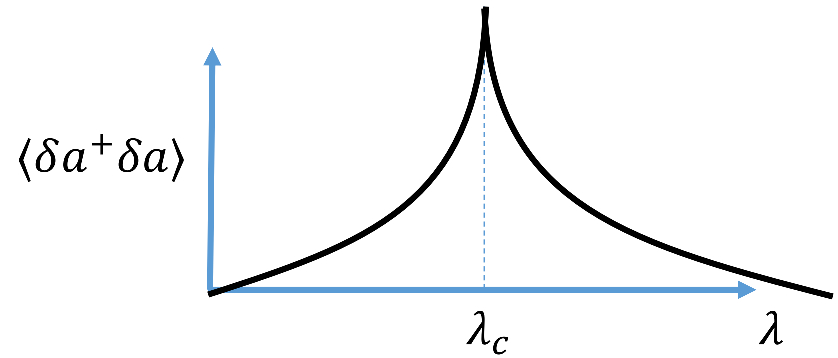
$$H = \omega_0 a^+ a + \frac{\boldsymbol{\lambda}}{\sqrt{\boldsymbol{N}}}(\boldsymbol{a}+\boldsymbol{a}^+)\boldsymbol{S}^x + \boldsymbol{\omega}_z \boldsymbol{S}^z$$

Conservation of the total spin $\vec{S} = \sum_i \vec{\sigma_i}$



Ising mean field

$$\langle a \rangle = |\lambda - \lambda_c|^{-1/2}$$



“Flux exponent”

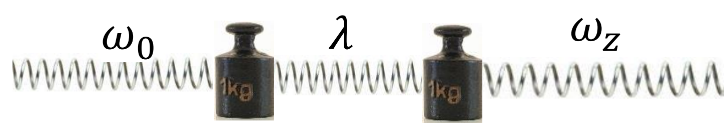
$$\langle \delta a^+ \delta a \rangle = |\lambda - \lambda_c|^{-1}$$

Tureci & Domokos groups (2014)

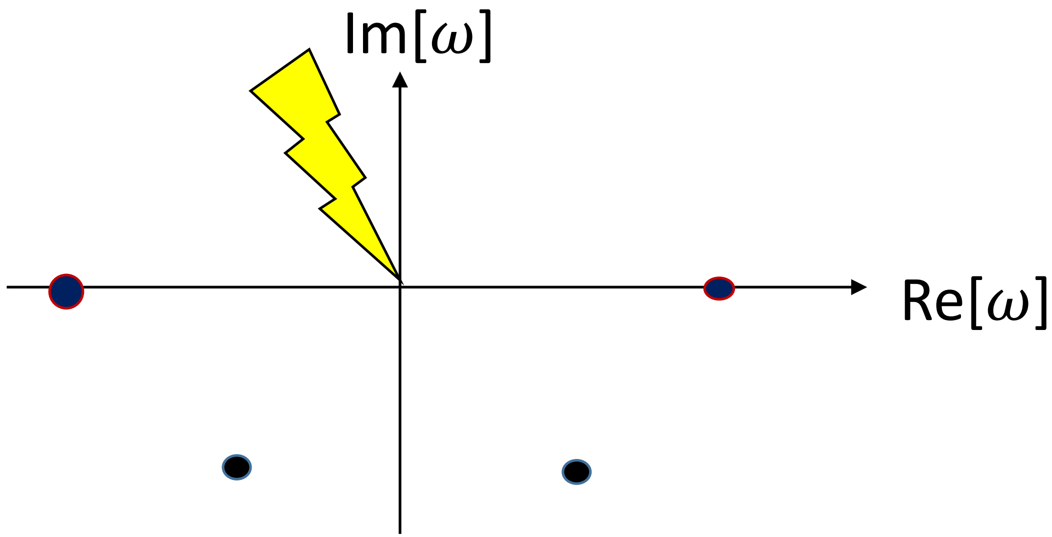
Dicke superradiance – critical theory

$$H = \omega_0 a^+ a + \frac{\boldsymbol{\lambda}}{\sqrt{\boldsymbol{N}}}(\boldsymbol{a} + \boldsymbol{a}^+)\boldsymbol{S}^x + \boldsymbol{\omega_z S^z}$$

Holstein-Primakoff (linearization) $S^+ \approx \sqrt{N}\, b^+$

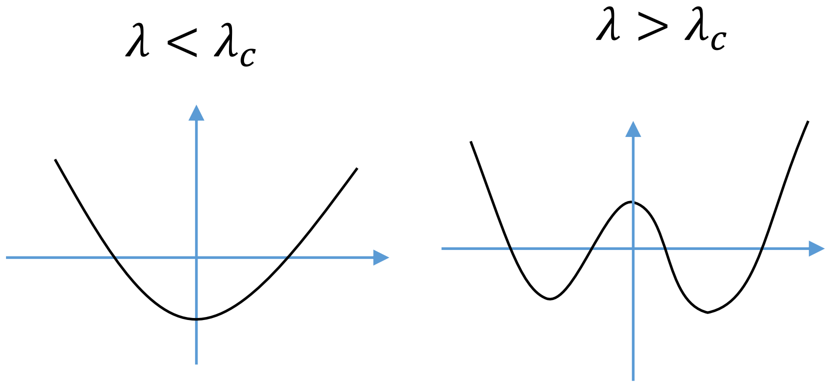


$\lambda = 0$



Dicke superradiance – critical theory

Mean field phase transition (Landau)



$$H = \frac{p^2}{2m} + \frac{1}{2}(\lambda - \lambda_c)x^2 + \beta x^4$$

Critical theory:

$$H = \frac{p^2}{2m} + \frac{1}{2}(\lambda - \lambda_c)x^2$$

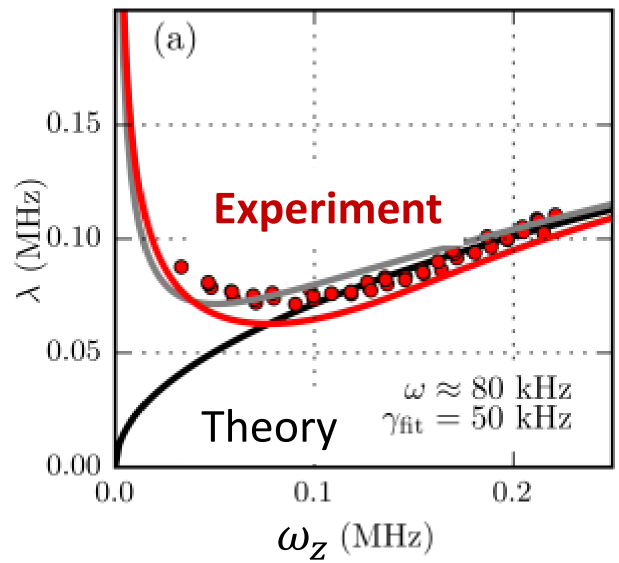
Equipartition:

$$\langle(\lambda - \lambda_c)x^2\rangle = k_B T \;\Rightarrow\; \langle x^2\rangle = \frac{k_B T}{|\lambda - \lambda_c|}$$

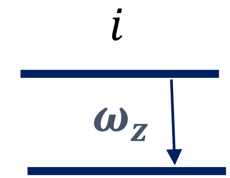
Dalla Torre etal PRA (2013)

Dicke transition - revisited

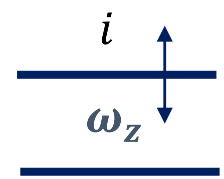
Zhiqiang et al, PRA (2018)



Single-atom decay

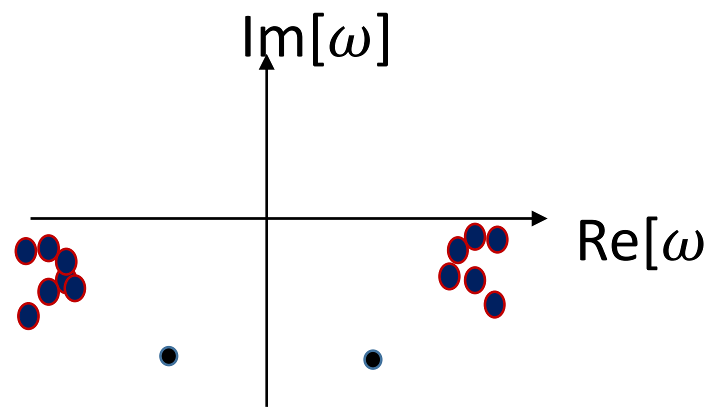


Single-atom dephasing
(transverse Doppler shift)



Total spin not conserved

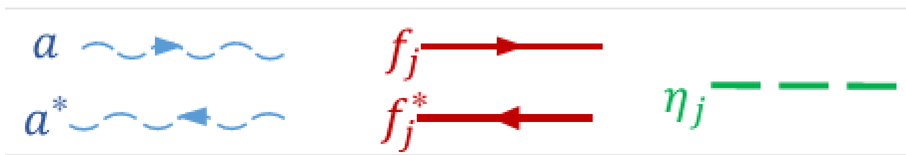
$$H = \omega_0 a^+ a + \frac{\lambda}{\sqrt{N}} (a + a^+) \sum_{i=1}^{N} \sigma_i^x + \omega_z \sum_{i=1}^{N} \sigma_i^z$$



Diagrammatic approach to the Dicke transition

Fermionic representation of spin-1/2 $\sigma_i^z = f_i^\dagger f_i - \frac{1}{2}$, $\sigma_i^- = \eta_i f_i$

Bare terms:



Leading 1/N term:

*** controlled 1/N expansion ***

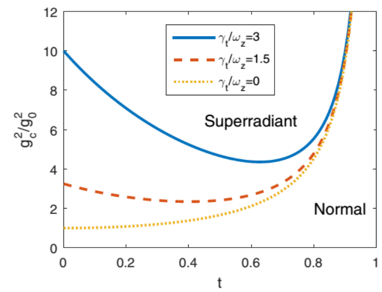
Result 1 – critical coupling

$$\boxed{\lambda_c^{-2} = \frac{2}{N} \sum_{i=1}^{N} \int_0^{\infty} dt \;\; \langle [\, \sigma_i^x(0), \sigma_i^x(t)] \,\rangle}$$

✓ Equilibrium ($T = 0$ and $T \neq 0$)

✓ Nonequilibrium with spin conservation

NEW: Nonequilibrium without spin conservation



Polarization = sufficient condition for Dicke transition

(no correlations or entanglement)

- Cfr. Lamb theory of lasing transition

Dalla Torre etal PRA (2017), Kirton and Keeling PRL (2017)

Outline

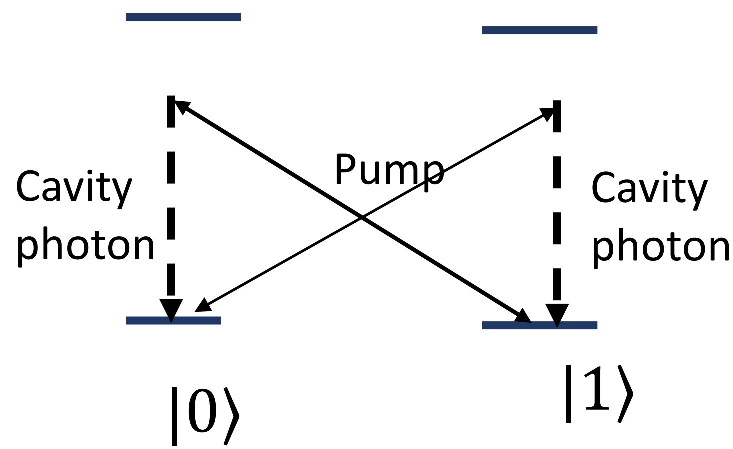
Dicke superradiance (8 slides)

Lasing (4 slides)

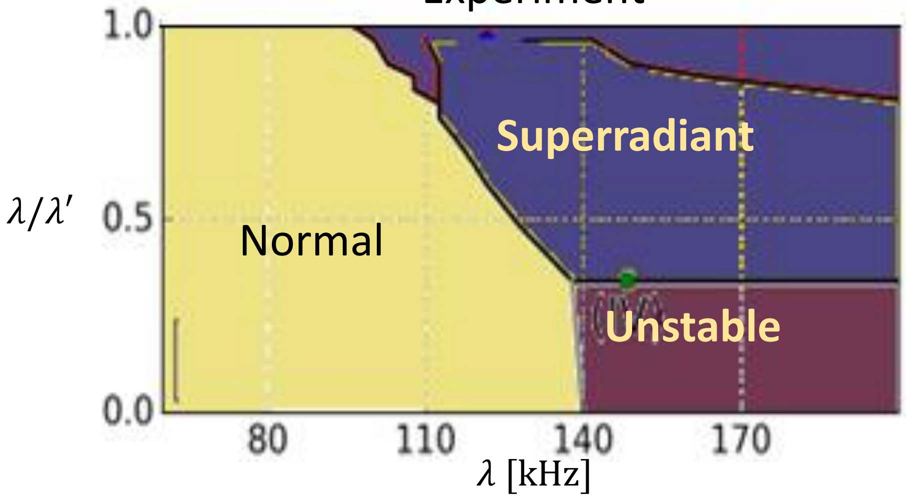
Extras (4 slides)

Generalized Dicke model

$$H = \omega_0 a^+ a + \boldsymbol{\omega_z \sum_{i=1}^{N} \sigma_i^z}$$
$$+ \frac{\lambda}{\sqrt{N}} a \sum_{i=1}^{N} \sigma_i^+ + \frac{\lambda'}{\sqrt{N}} a^+ \sum_{i=1}^{N} \sigma_i^+ + H.c.$$

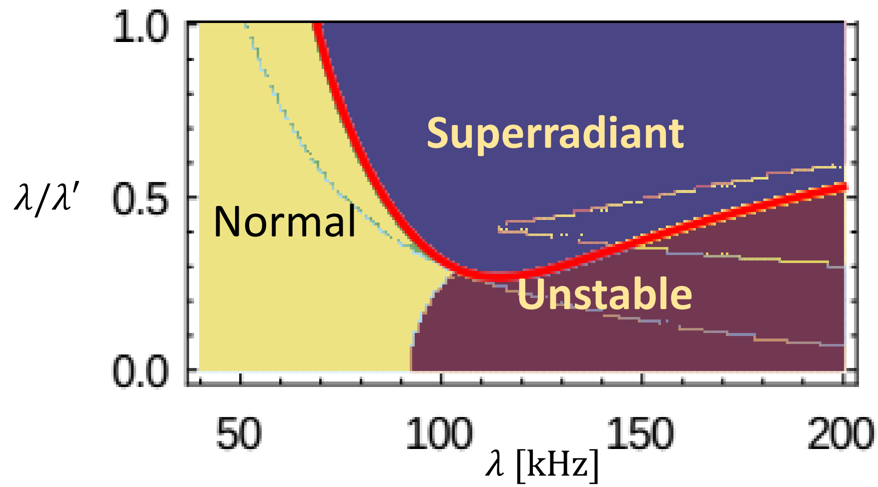


Experiment



Zhiquiang et al Optica (2017)

Theory

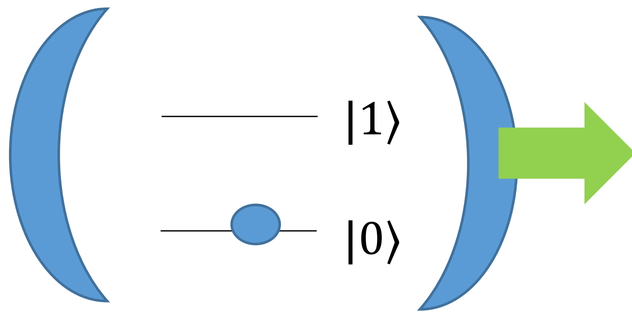


Sh

Presented in Cargese on May 11, 2017.
cfr. With Kirton, Keeling, arxiv:1710.06212

Anti-Jaynes-Cummings model

$$H = \omega_0 a^+ a + \frac{\lambda'}{\sqrt{N}} \sum_{i=1}^{N} a^+ \sigma_i^+ + a\,\sigma_i^- + \omega_z \sum_{i=1}^{N} \sigma_i^z$$



Threshold: Fermi Golden rule $$\frac{(\lambda')^2}{\omega_0 - \omega_z} = \kappa$$

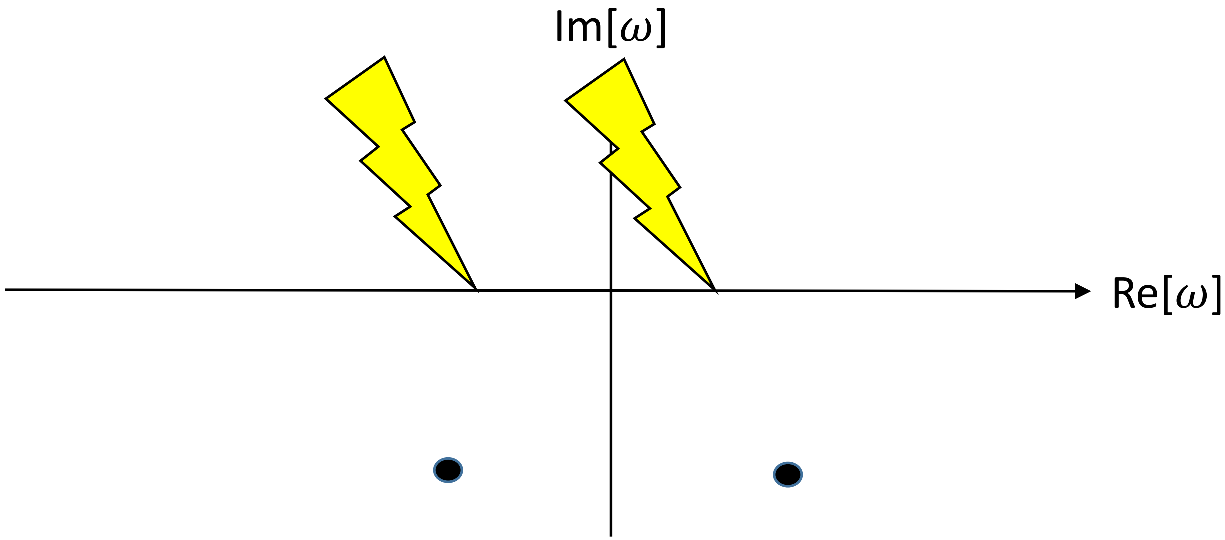
Decay $|1\rangle \rightarrow |0\rangle$ = "counter-repumping"

→ Counterlasing

Kirton, Keeling, NJP (2018), Shchadilova et al arxiv (2018)

Counterlasing transition – critical theory

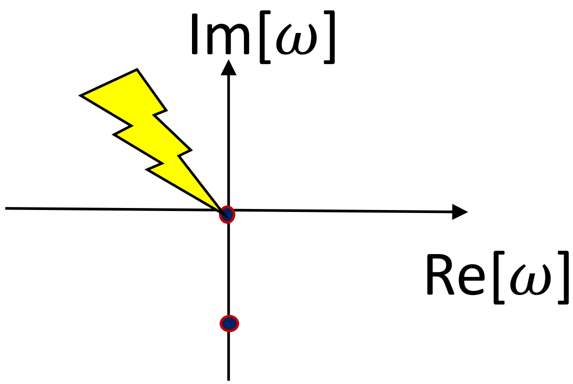
$$H = \omega_0 a^+ a + \frac{\lambda'}{\sqrt{N}} a^+ \sum_{i=1}^{N} \sigma_i^+ + \omega_z \sum_{i=1}^{N} \sigma_i^z$$



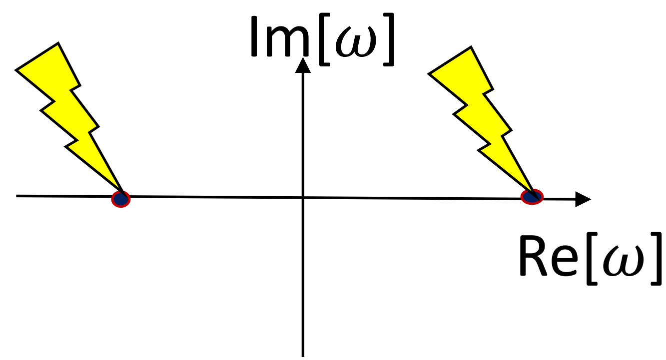
- No Diverging fluctuations
- Phase degree of freedom

Dicke superradiance vs Lasing

Pitchfork

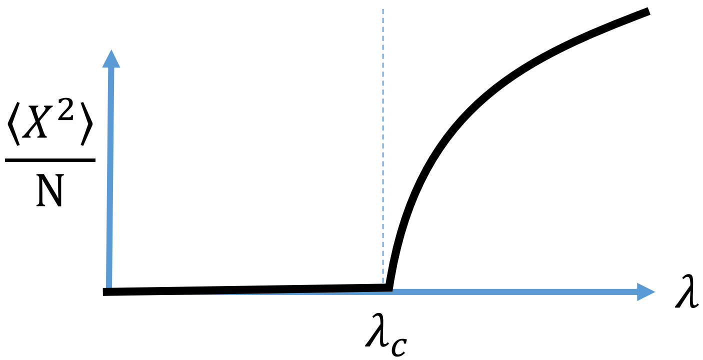


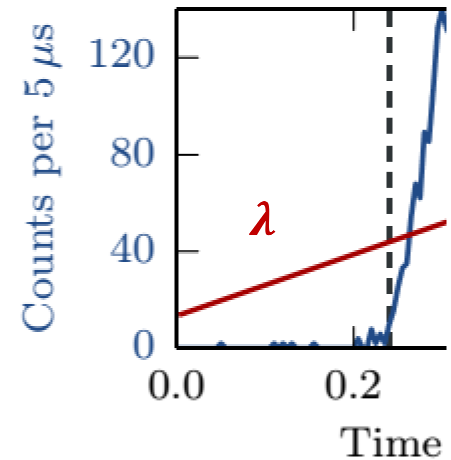
Hopf instability

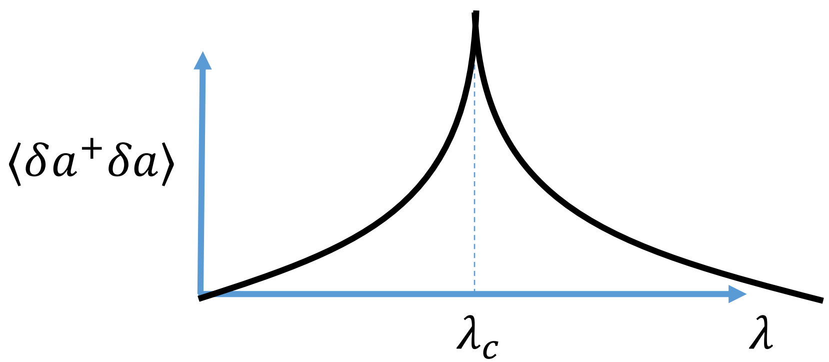


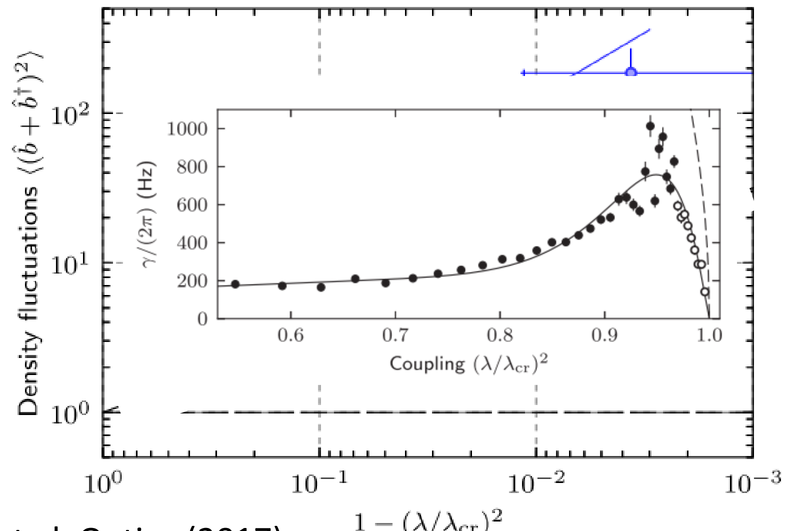
- Dive ,
- Stat me)

The end of the story?



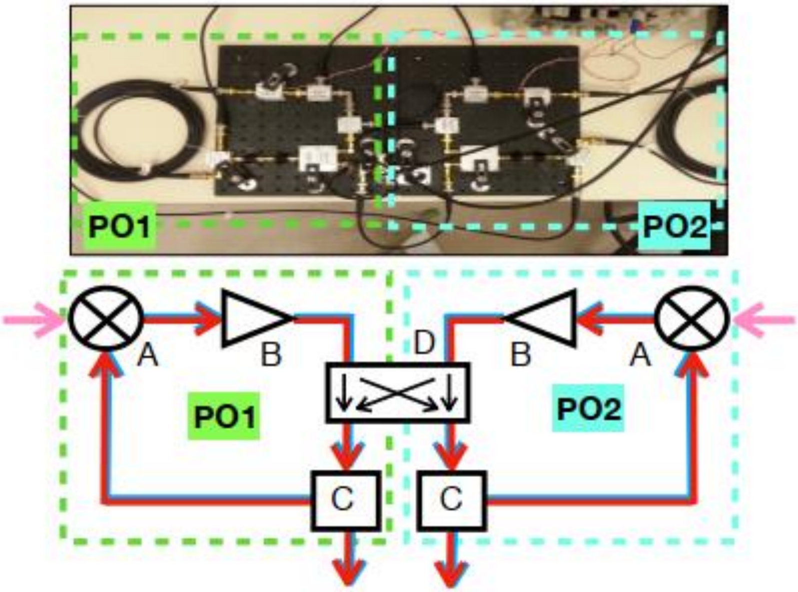


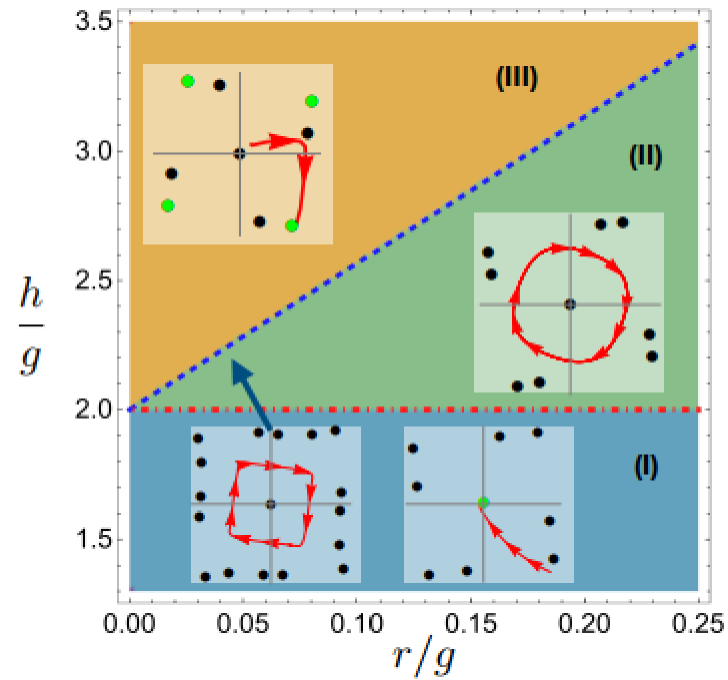




Brennecke et al PNAS (2013), Zhiqiang et al, Optica (2017)

Another system with the same physics





L. Bello, M. Calvanese Strinati, E. G. Dalla Torre, A. Pe'er (in preparation)

Non-equilibrium Quantum Dynamics

Periodically-driven systems

Dr. Atanu Rajak:
Dynamic localization of
a many-body kicked rotor

Topological phases

Ben Yamin:
Measuring entanglement
in quantum computers

Dynamics of closed systems

Meitar Goldferb:
Multicomponent
ultracold atoms

Quantum optics

Mor Roses:
Real-time dynamics
of the extended Dicke model

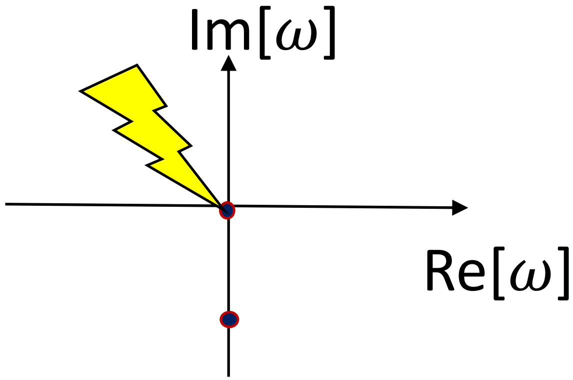
Strongly correlated materials

David Dentelski:
Short vs. Long-range
superconducting fluctuations

Dr. Marcello Strinati:
Simulation of spin systems
in (quantum) optics

Dicke superradiance vs Lasing

Pitchfork



Hopf instability