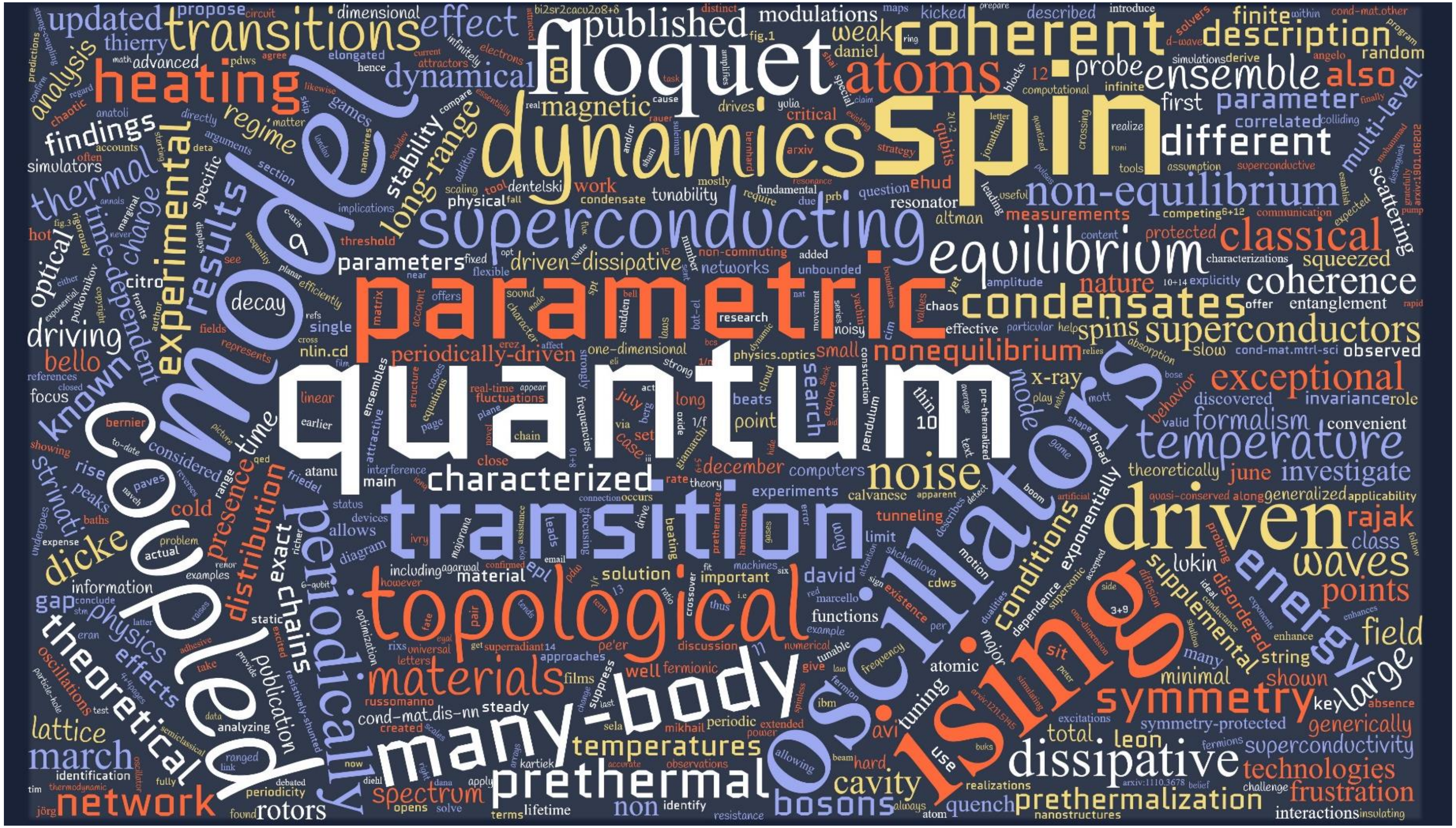
MBCQED, Aspen, December 7, 2021



Bar-Ilan University

Emanuele Dalla Torre

http://www.nonequilibrium.org

QUEST QUANTUM ENTANGLEMENT SCIENCE & TECHNOLOGY BAR-ILAN UNIVERSITY

Quantum Dynamics of Complex Systems

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On sabbatical with

rigetti

SQMS

What is the difference between steady-state 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

E. None of the above

Outline

Superradiance (3 slides)

Lasing (3 slides)

Extras (3 slides)

Superradiant transition (steady state)

Dicke model (Hepp&Lieb 1973)

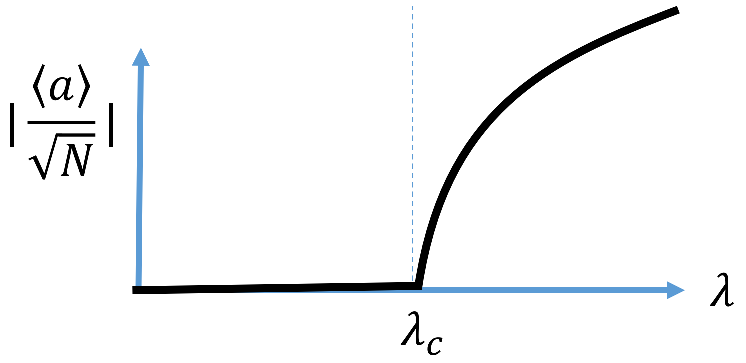
$$H = \omega_0 a^+ a + \frac{\boldsymbol{\lambda}}{\sqrt{\boldsymbol{N}}}(\boldsymbol{a} + \boldsymbol{a}^+)\sum_{i=1}^{N} \boldsymbol{\sigma}_i^x + \boldsymbol{\omega}_z \sum_{i=1}^{N} \boldsymbol{\sigma}_i^z$$

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

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

"Ising model of quantum optics"

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

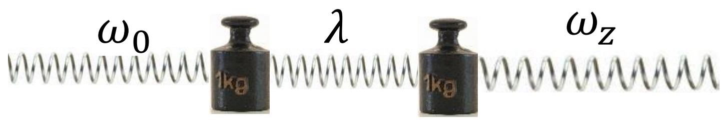


See Intro: Kirton, Roses, Keeling, Dalla Torre (2019) and **Wikipedia page "Dicke model"**

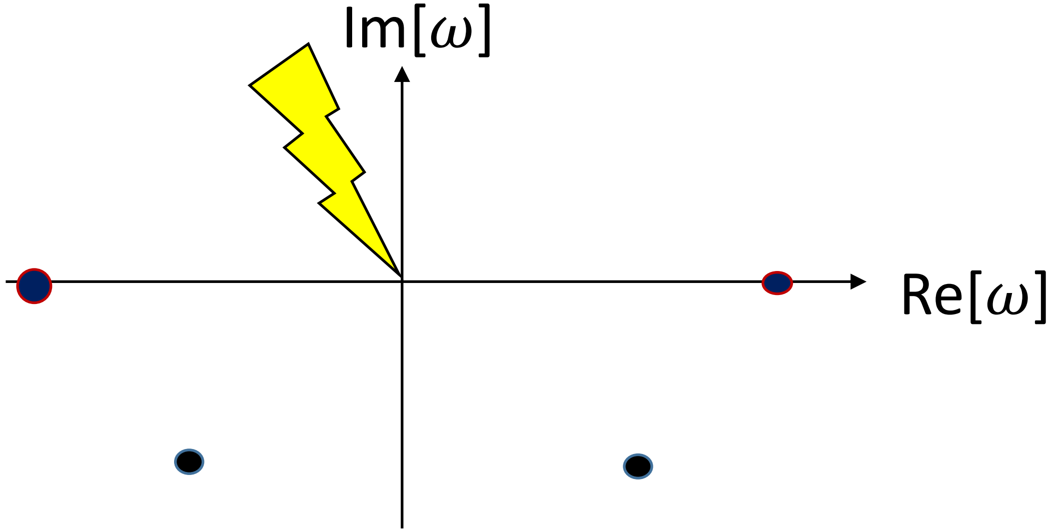
Superradiance – linear stability

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

Holstein-Primakoff (linearization) $S^+ \approx \sqrt{N}\, b^+$ $H = \omega_0 a^+ a + \boldsymbol{\lambda}\,(\boldsymbol{a}+\boldsymbol{a}^+)(\boldsymbol{b}+\boldsymbol{b}^+) + \boldsymbol{\omega_z b^+ b}$



$\lambda = 0$



Experiments: single atom decay or Doppler shift?

$$H = \omega_0 a^+ a + \frac{\boldsymbol{\lambda}}{\sqrt{\boldsymbol{N}}}(\boldsymbol{a}+\boldsymbol{a}^+)\sum_{i=1}^{N}\boldsymbol{\sigma}_i^x + \boldsymbol{\omega}_z\sum_{i=1}^{N}\boldsymbol{\sigma}_i^z$$

Controlled 1/N diagrammatic approach:

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

- ✓ Equilibrium ($T = 0$ and $T \neq 0$)
- ✓ Nonequilibrium with or without spin conservation
- ✓ **Polarization = sufficient condition for Dicke transition** (no correlations or entanglement)
  - Cfr. Lamb theory of lasing transition

Dalla Torre, Shchadilova, Wilner, Lukin, Demler, PRA (2017). Kirton and Keeling PRL (2017)

Outline

Superradiance (3 slides)

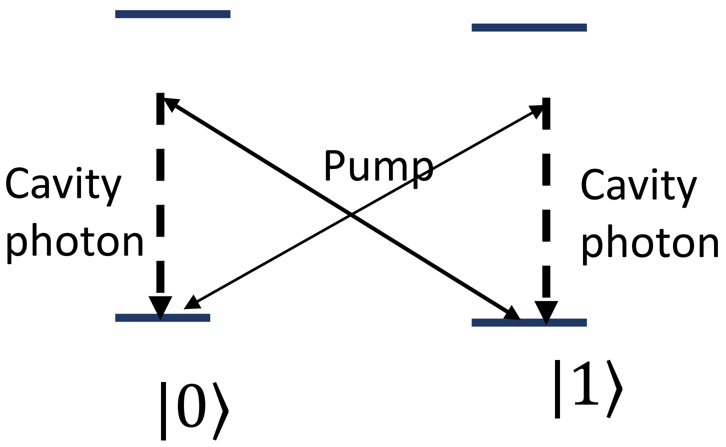
Lasing (3 slides)

Extras (3 slides)

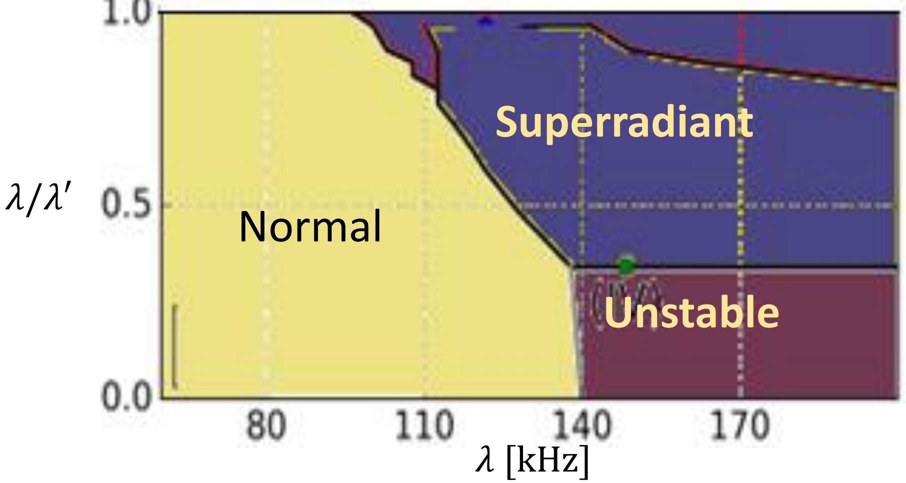
Generalized Dicke model

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

See also lecture by Scott Parkins

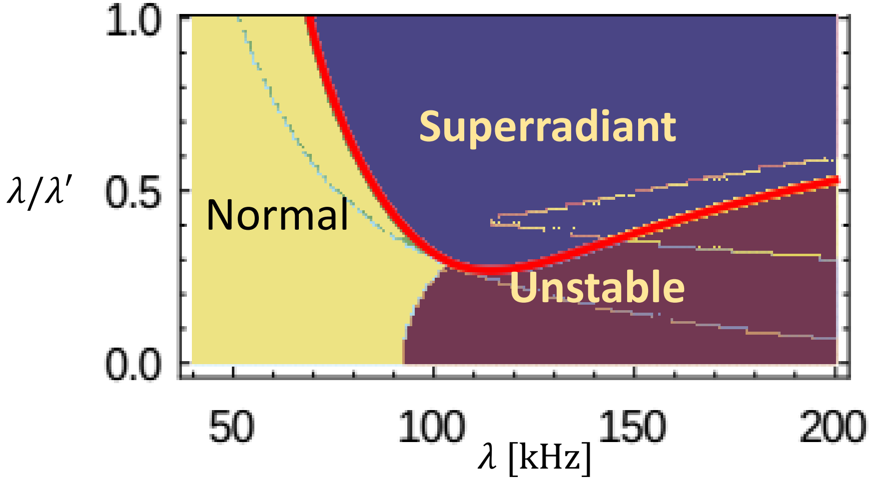


Experiment



Zhiquiang et al Optica (2017)

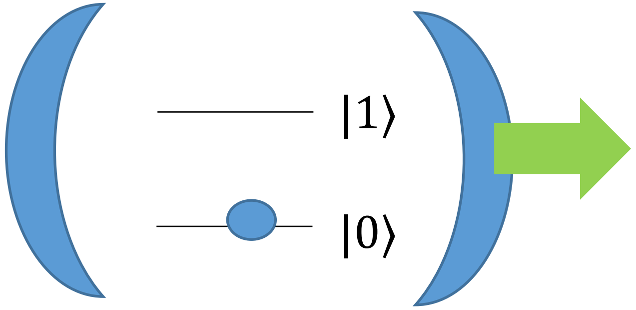
Theory



Shchadilova et al, PRA (2020), Kirton, Keeling, NJP (2018)

Anti-Tavis-Cummings model ($\lambda = 0$)

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



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

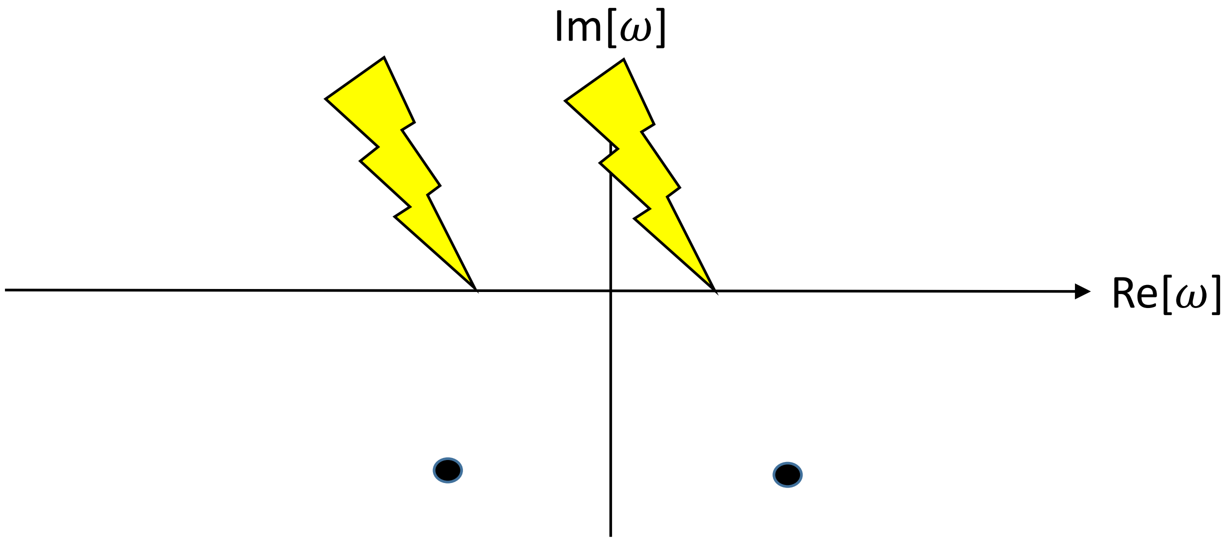
Decay $|1\rangle \rightarrow |0\rangle$ = "counter-repumping"

→ Counterlasing

Shchadilova et al PRA (2020) , Kirton, Keeling, NJP (2018)

Counterlasing transition – linear analysis

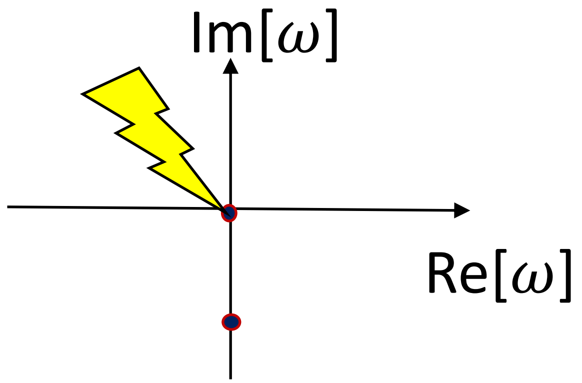
$$H = \omega_0 a^+ a + \frac{\lambda'}{\sqrt{N}} a^+ \sum_{i=1}^{N} \sigma_i^+ + \omega_z \sum_{i=1}^{N} \sigma_i^z$$



- No Diverging fluctuations
- Phase degree of freedom

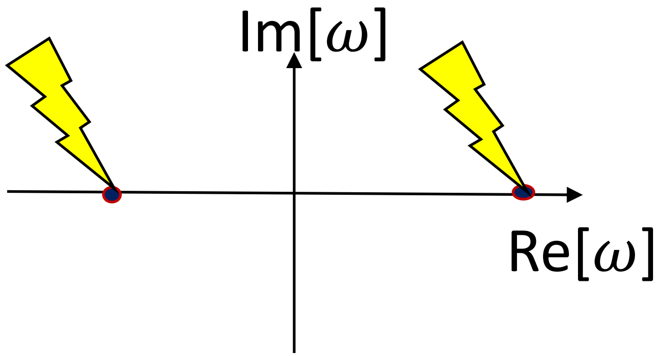
Summary: superradiance vs (counter)lasing

Pitchfork



- Diverging fluctuations
- Static (in the pump frame)
- Discrete time crystal

Hopf instability



- No Diverging fluctuations
- Rotating (in the pump frame)
- Continuous time crystal

See also lecture by Hans Kessler

Outline

Superradiance (3 slides)

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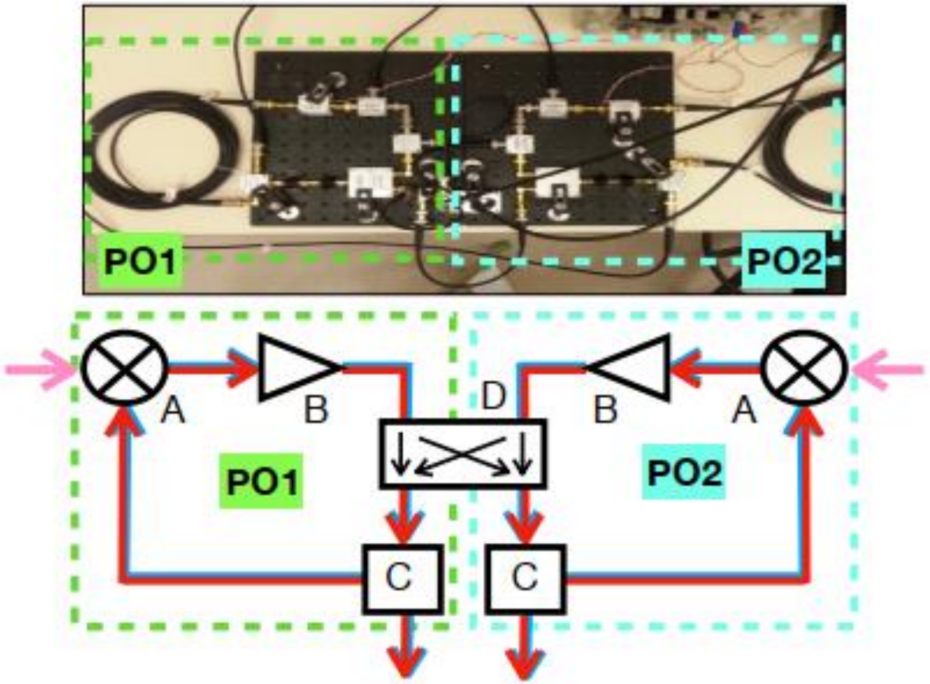
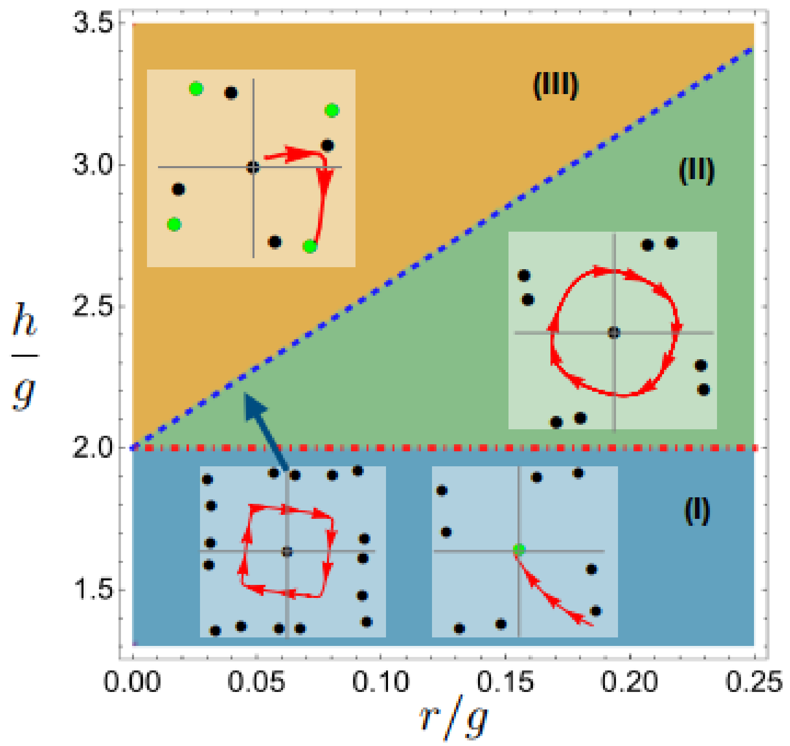
Extra: coupled parametric oscillators

See also lecture by Peter McMahon

Parametric instability: simplest example of discrete time crystal (period doubling)





L. Bello, M. Calvanese Strinati, E. G. Dalla Torre, A. Pe'er, PRL&PRA (2020), NJP (2020)

Many coupled PO : coherent Ising machines (CIM)

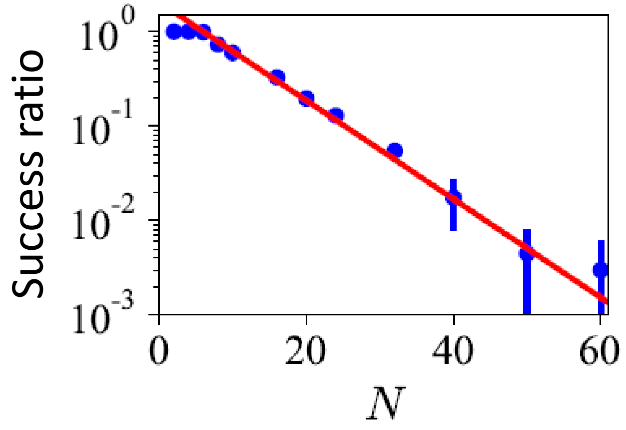
Goal: eurisitic solution of the Ising problem (NP hard)

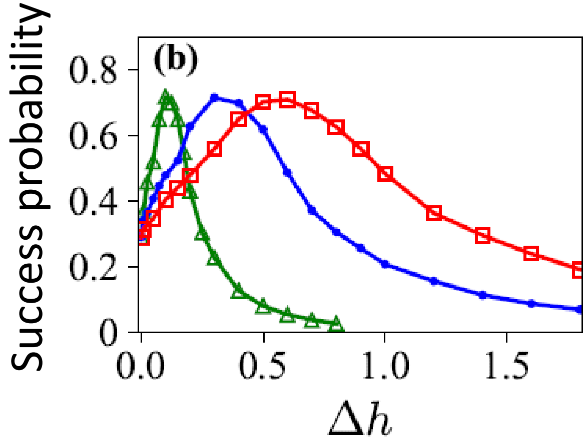
CIM = dissipative Ising model [Yamamoto]

$H = \sum_{i,j} J_{i,j} \sigma_i \sigma_j$ with $\sigma_i = \pm 1$

Linear analysis:

Maximal eigenvalue of $J_{i,j}$???





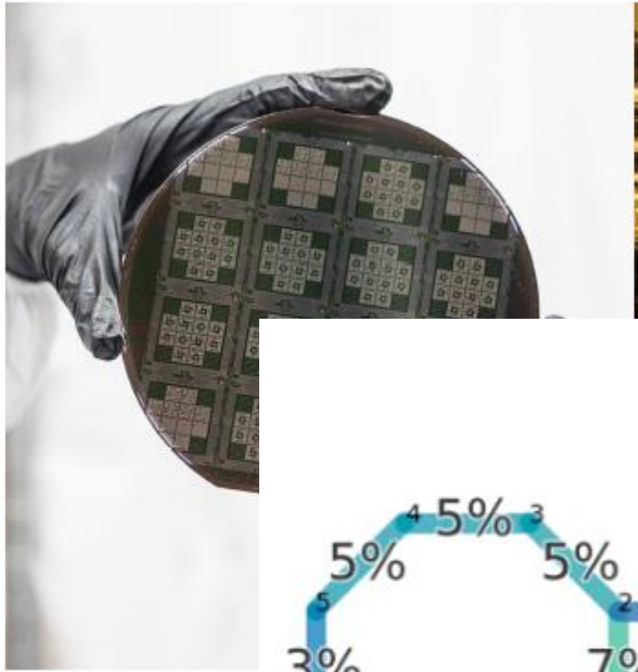
Nonlinearities can help find the correct solution (euristically)

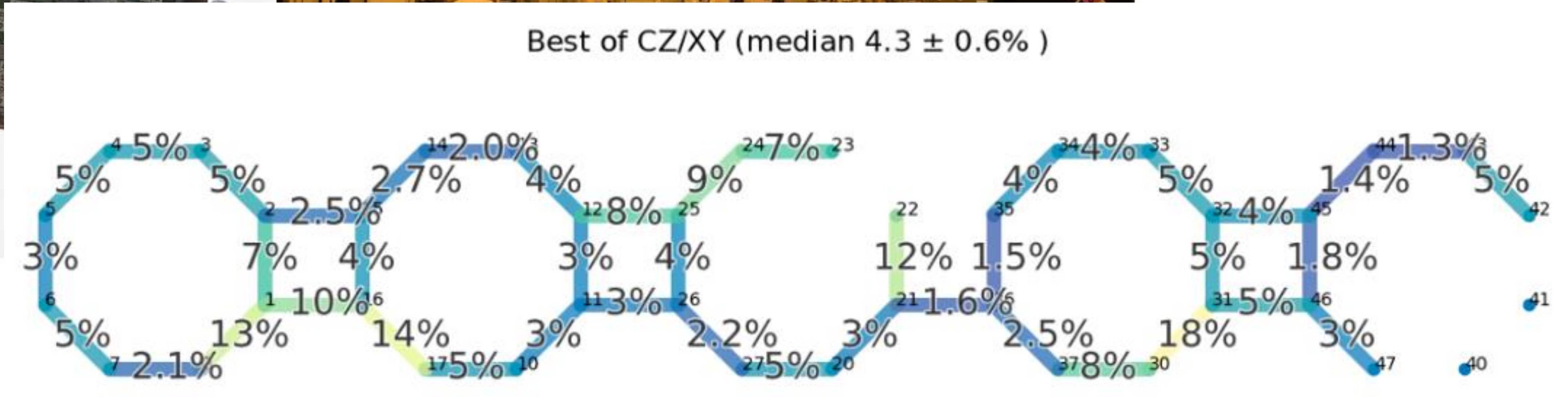
M. Calvanese Strinati, L. Bello, E. G. Dalla Torre, A. Pe'er, PRL (2021)

Extra 2 - Rigetti (Berkeley, CA)

Full Stack Quantum Computing founded by Chad Rigetti in 2013

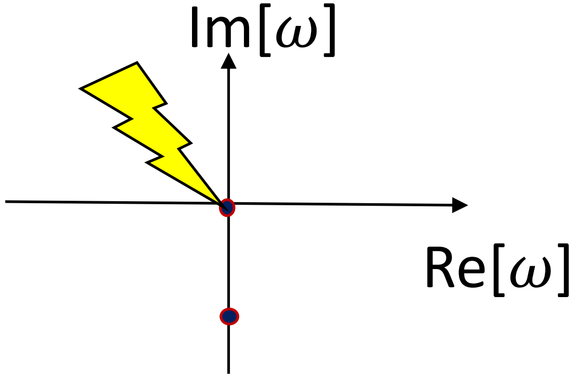
QuIC fabrication facility / foundry service: **Fast iteration + flexible, fine tuned control over process**





Summary: superradiance vs (counter)lasing

Pitchfork



- Diverging fluctuations
- Static (in the pump frame)
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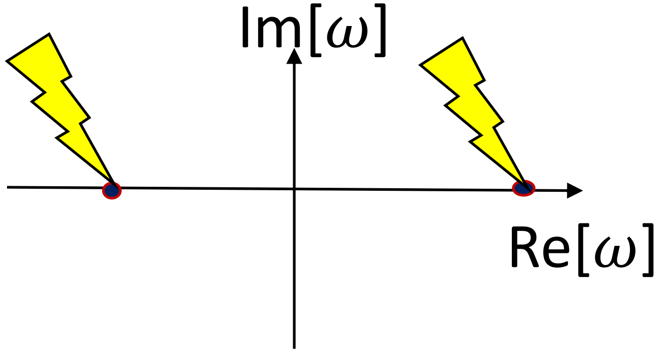
Hopf instability



- No Diverging fluctuations
- Rotating (in the pump fram

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See also lecture by Hans Kessler

Idea by Alessandro Silva