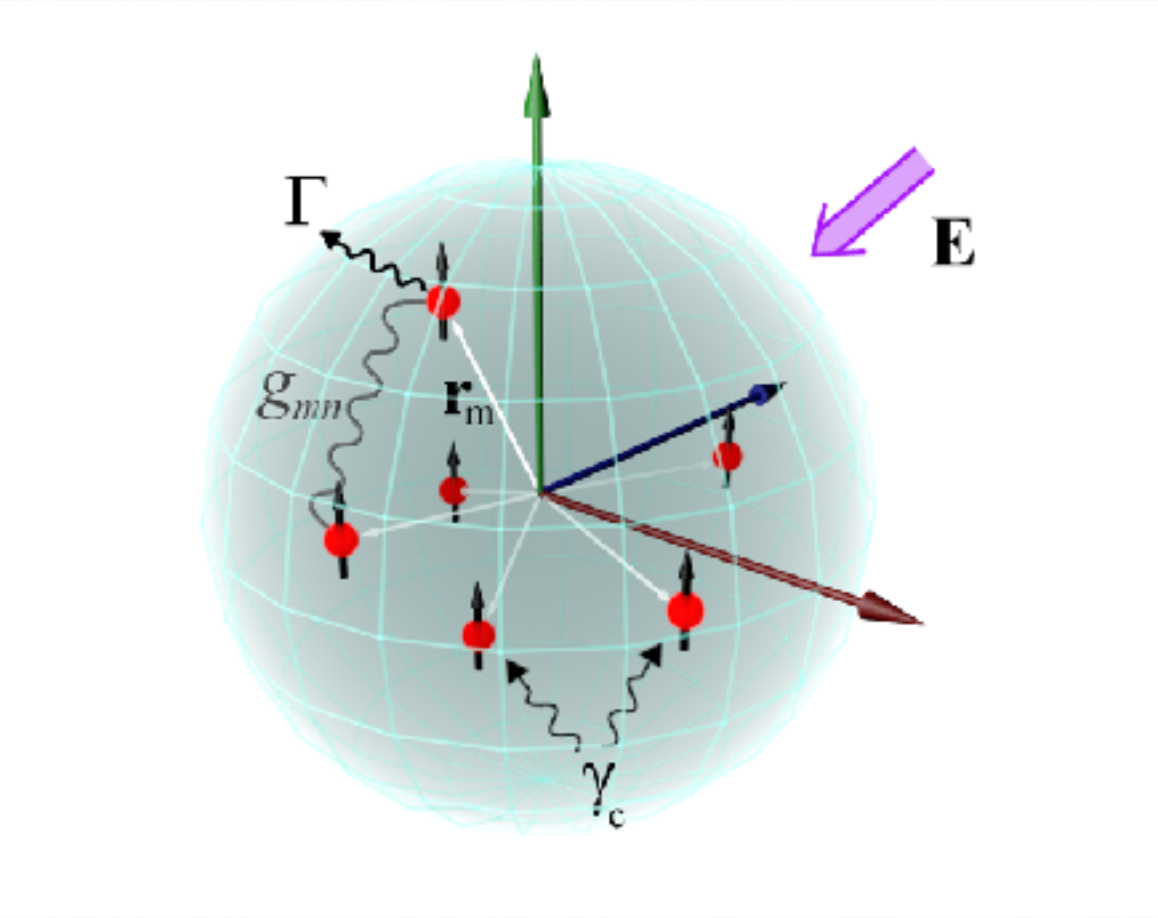


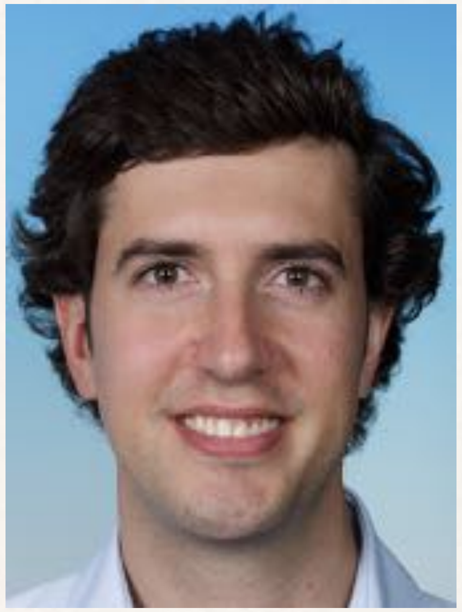
Cooperative Effects in Closely Packed Quantum Emitters with Collective Dephasing

B. Prasanna Venkatesh, Institute for Quantum Optics and Quantum Information, Innsbruck

Open Quantum Systems Workshop, ICTS Bangalore

In collaboration with …

Mathieu Juan



Oriol Romero-Isart

arXiv:1705.07847

Plan of the talk

- Introduction, Motivation, & System description
- Main Results
- Conclusions & Outlook

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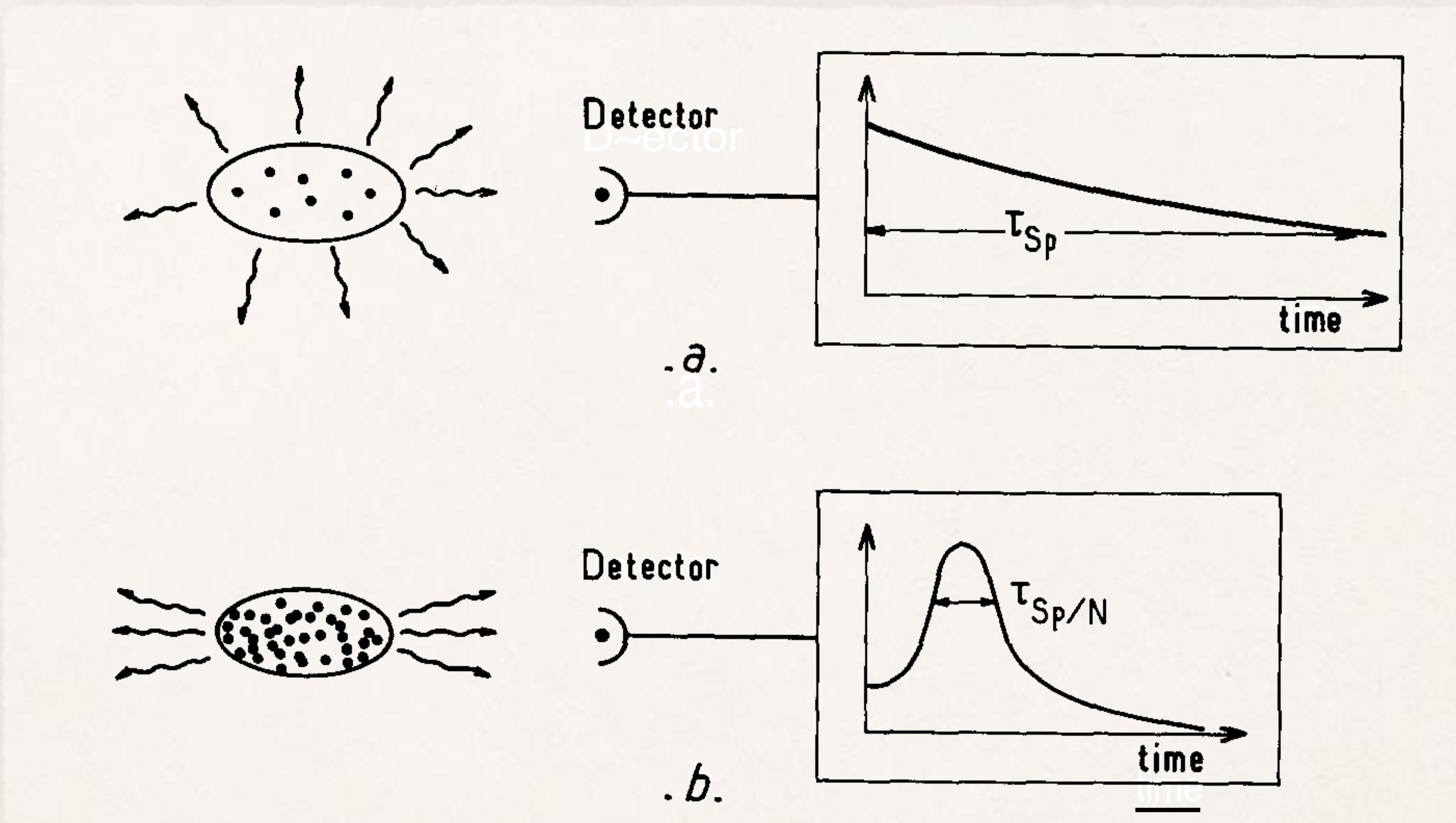
Superradiance

R. H. Dicke, Phys. Rev. 93, 99 (1954).



G. S. Agarwal, Springer Tracts in Modern Physics, 70, 1-128 (1974)
M. Gross and S. Haroche, Phys. Repts. 93, 301 (1982).

Permutation Symmetry - Dicke Basis

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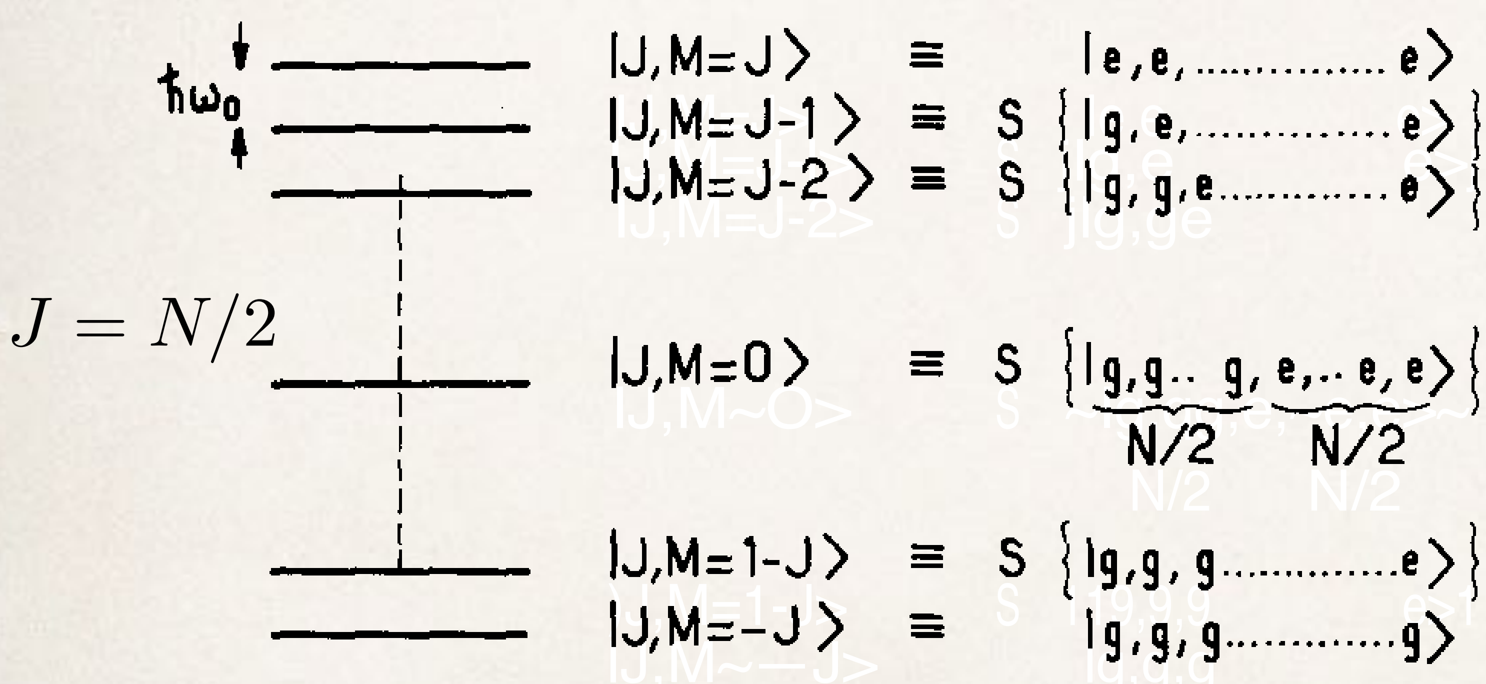
$$\hat{S}^z = \sum_{m=1}^{N} \hat{\sigma}^z_m \qquad \hat{S}^+ = \sum_{m=1}^{N} \hat{\sigma}^+$$

$$\hat{\mathbf{S}}^2 |J, M\rangle = 4J(J+1)|J, M\rangle$$

$$\hat{S}^z |J, M\rangle = 2M|J, M\rangle$$

Emission Rates

$$\Gamma\langle \hat{S}^+ \hat{S}^- \rangle = \Gamma(J+M)(J-M+1)$$



$\rightarrow \Gamma N$

$\rightarrow \Gamma N(N+2)/4$

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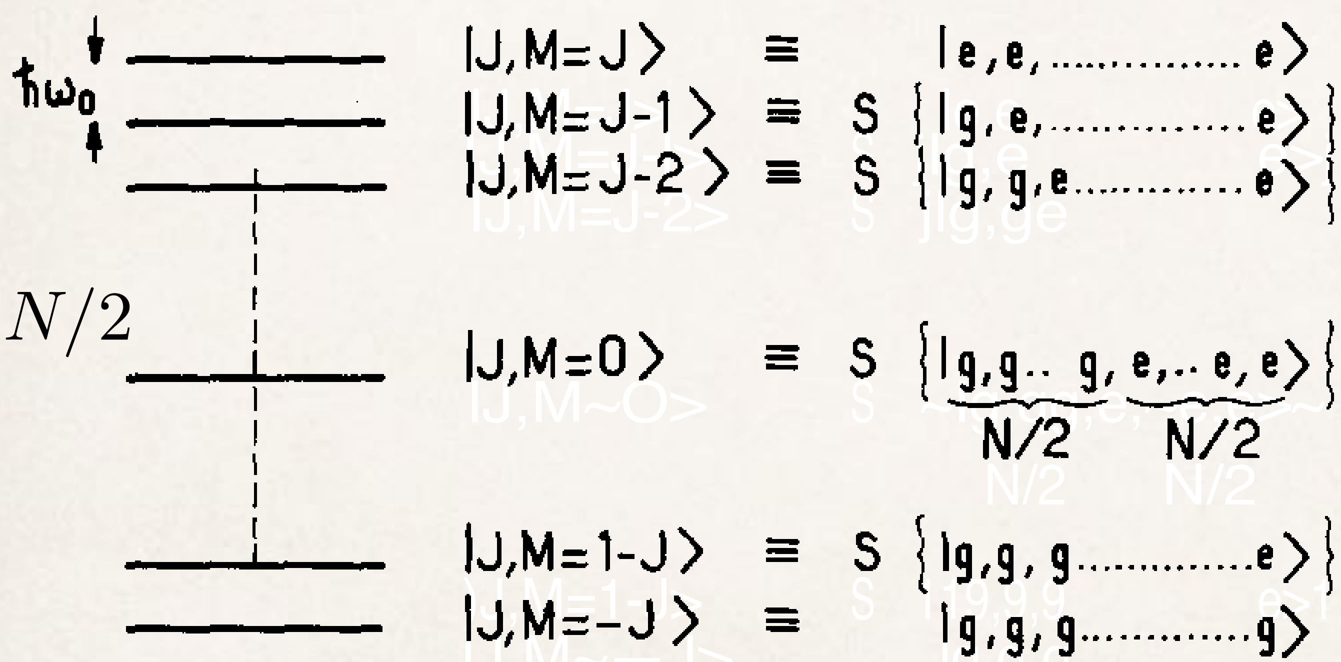

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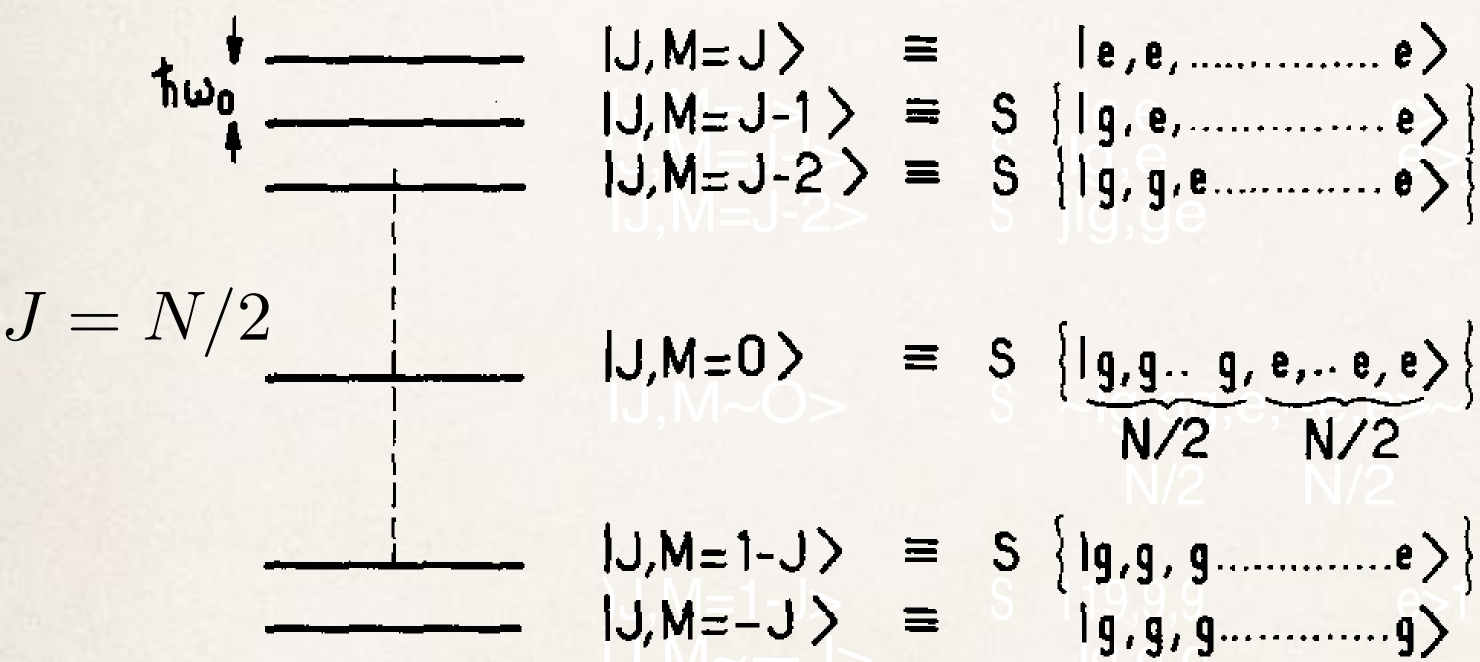

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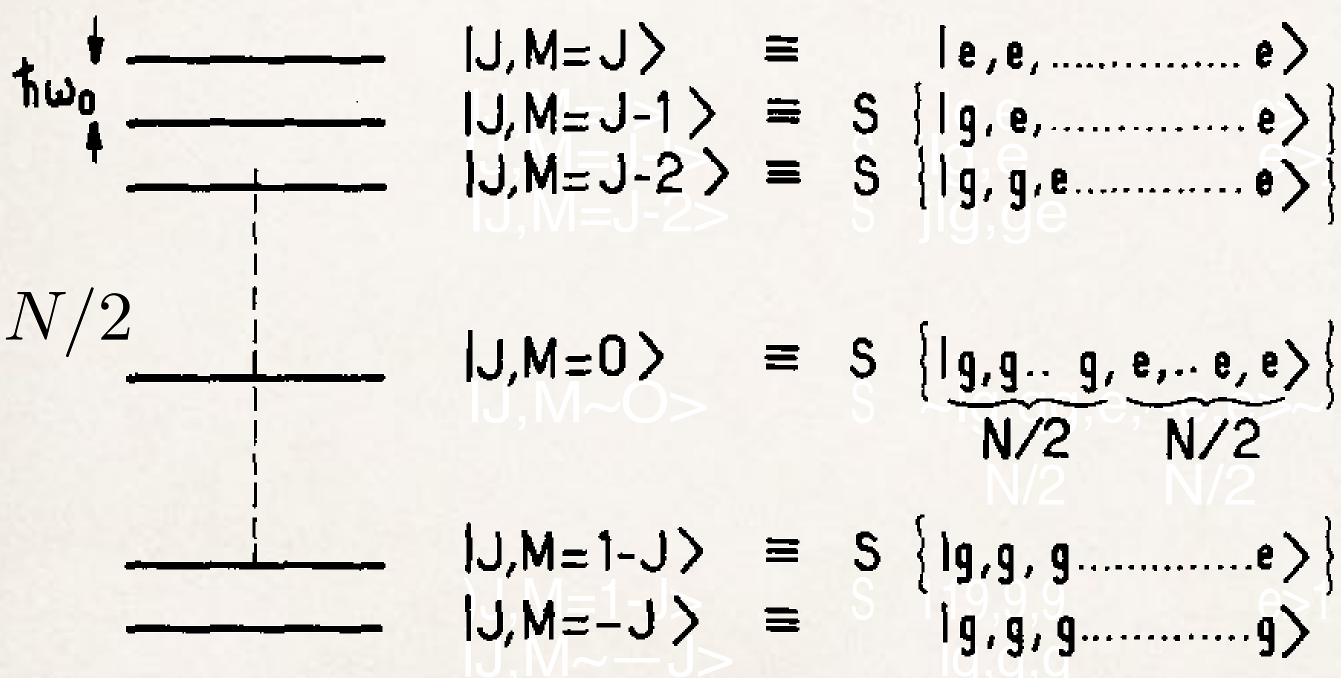

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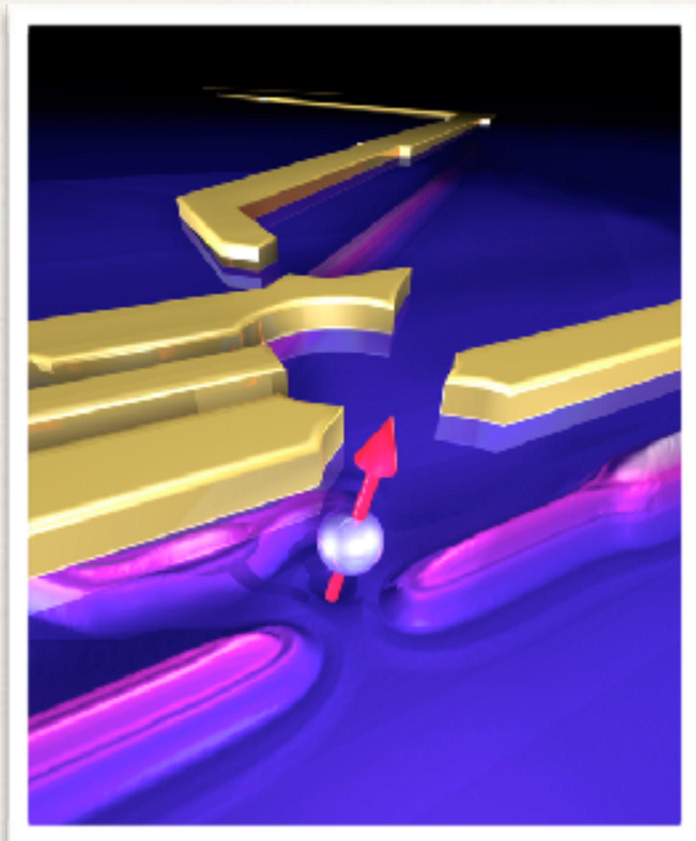
Why is it interesting?

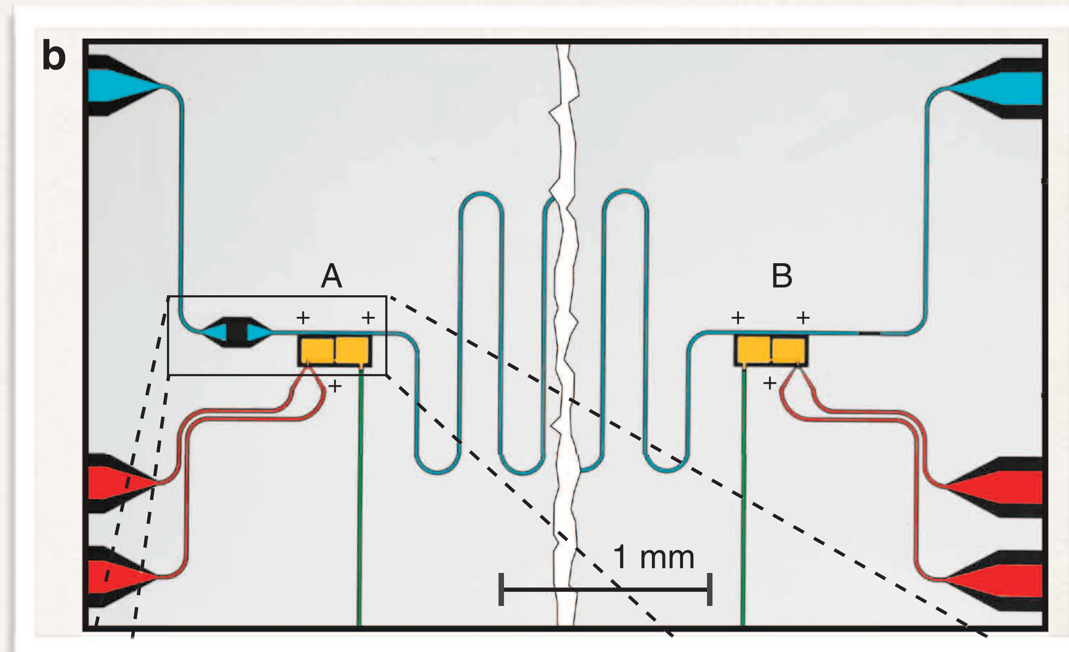
- Vacuum induced interactions, many body physics
- Connections to Laser Physics
- Optical lattice clocks and subradiance

G. S. Agarwal, Springer Tracts in Modern Physics, 70, 1-128 (1974)
M. Gross and S. Haroche, Phys. Repts. 93, 301 (1982).

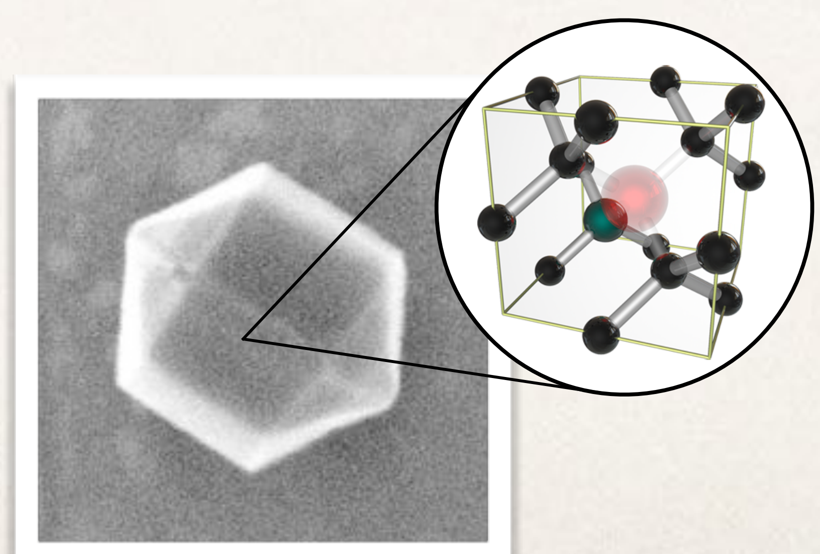
Collective Effects with Artificial Atoms



vandersypenlab.tudelft.nl/research/spin-qubits/spin-qubits-image-gallery/



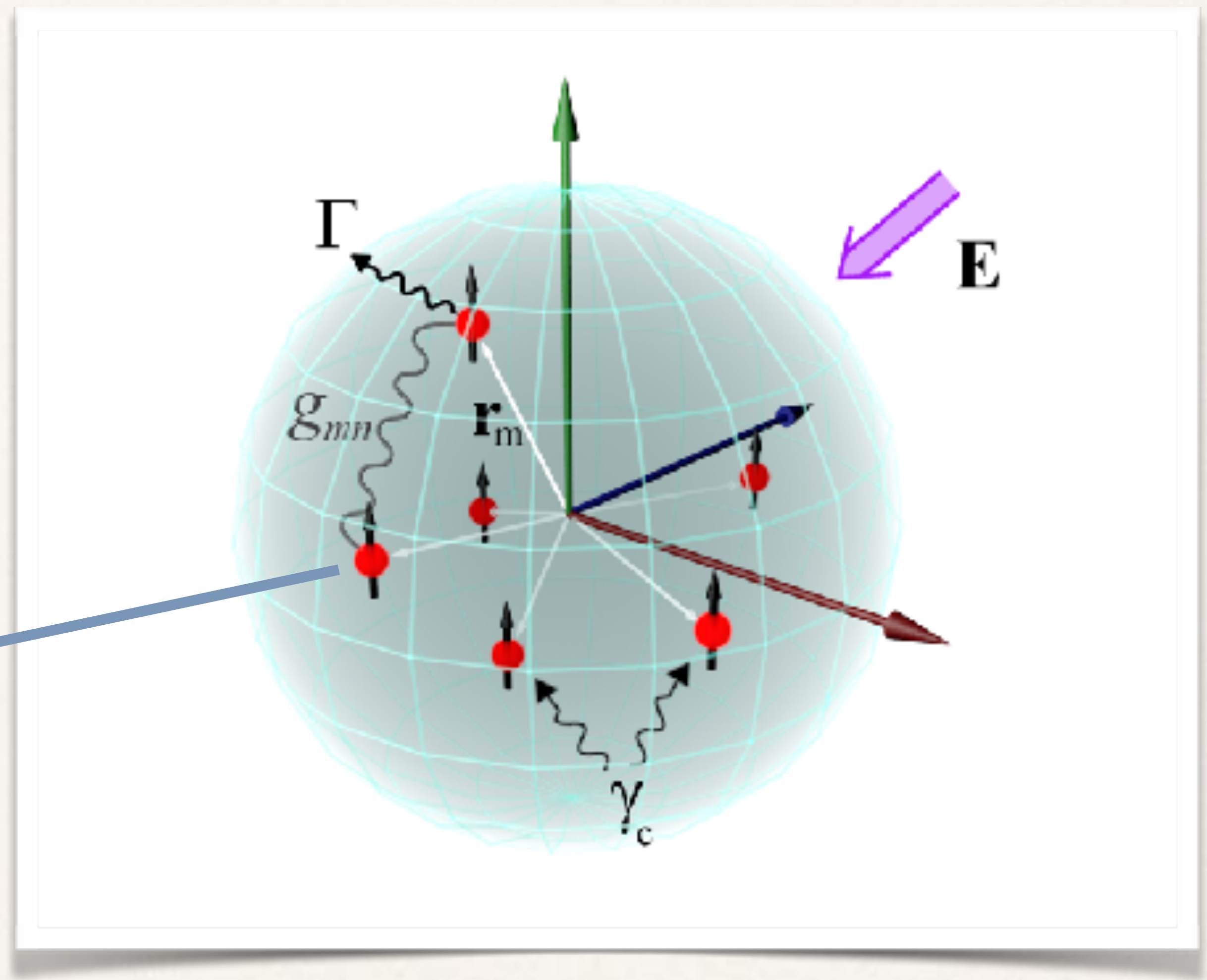
J.A. Mlynek et. al, Nature Communications 5, Article number: 5186 (2014).

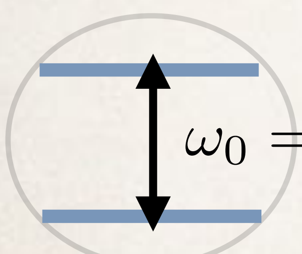


M. L. Juan et.al., Nature Physics, Advanced Online Publication (2016).

System

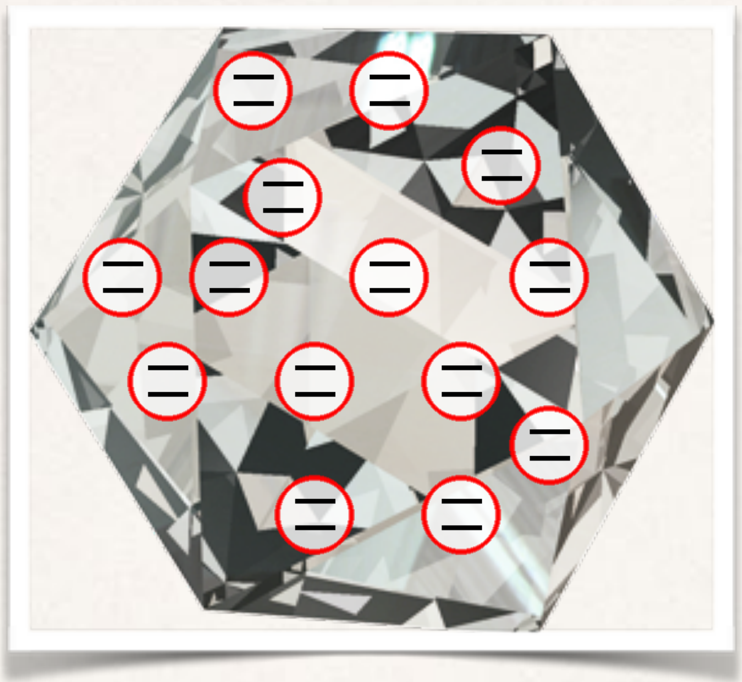
$$\mathbf{F}_{\mathrm{dp}} \propto -\alpha \nabla |\mathbf{E}(\mathbf{x})|^2$$





$$\omega_0 = \frac{2\pi c}{\lambda_0}$$

Dipole force on nano-diamonds + NV



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M. L. Juan et.al., Nature Physics,
Nature Physics 13, 241–245 (2017)

including collective effects

M. L. Juan et.al., Nature Physics,
Nature Physics 13, 241–245 (2017)

independent emitters x 55

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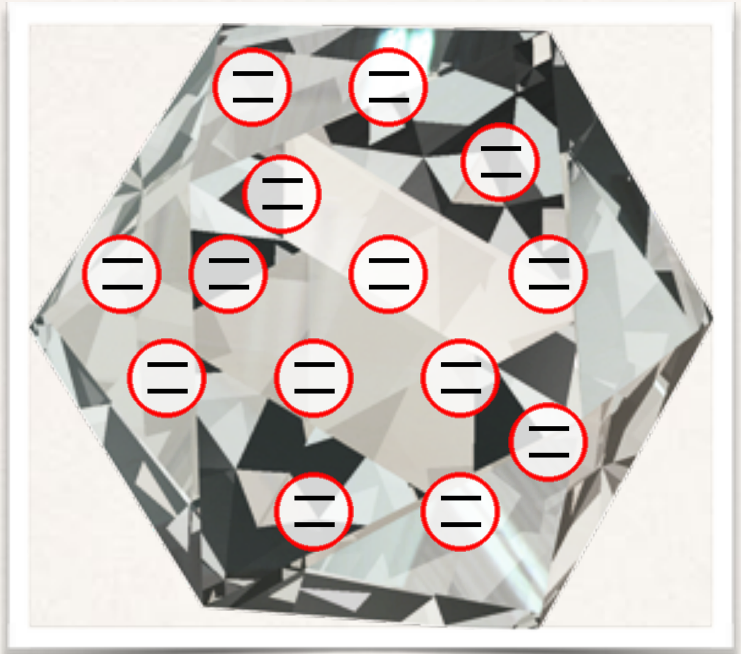

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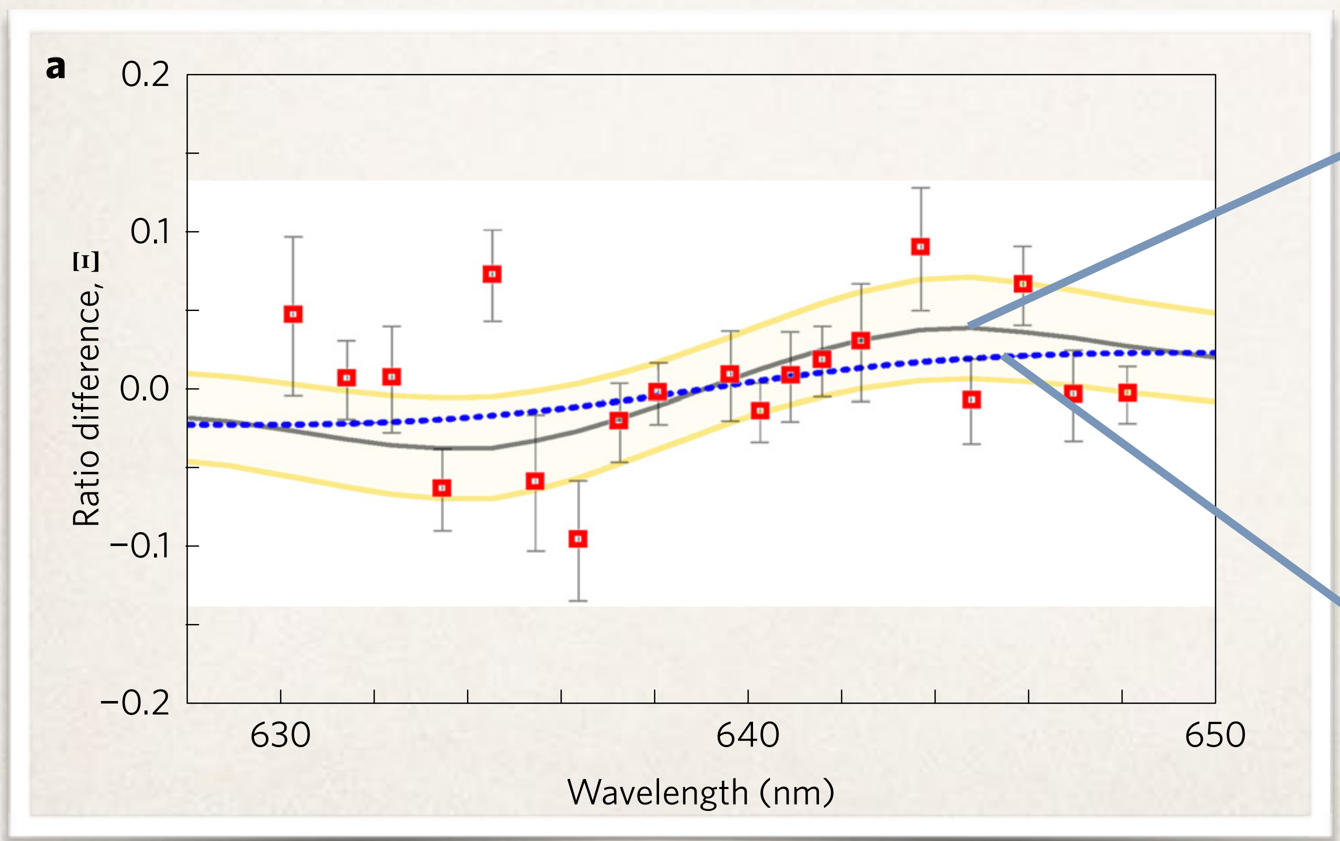


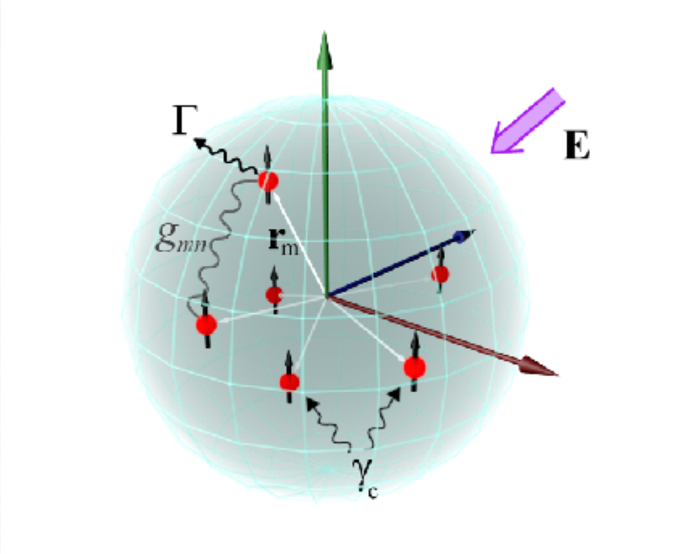
including collective effects

independent emitters x 40

M. L. Juan et.al., Nature Physics, Nature Physics 13, 241–245 (2017)

Master Equation

$$\dot{\hat{\rho}} = \mathcal{L}\hat{\rho} \equiv \left(\mathcal{L}_H + \mathcal{L}_\Gamma + \mathcal{L}_\gamma\right)\hat{\rho}$$



Collective Dephasing

$$\mathcal{L}_\gamma \hat{\rho} \equiv -\frac{\gamma_c}{4}[\hat{S}^z, [\hat{S}^z, \hat{\rho}]]$$

$$\hat{S}^\alpha \equiv \sum_{m=1}^{N} \hat{\sigma}_m^\alpha$$

Free Hamiltonian

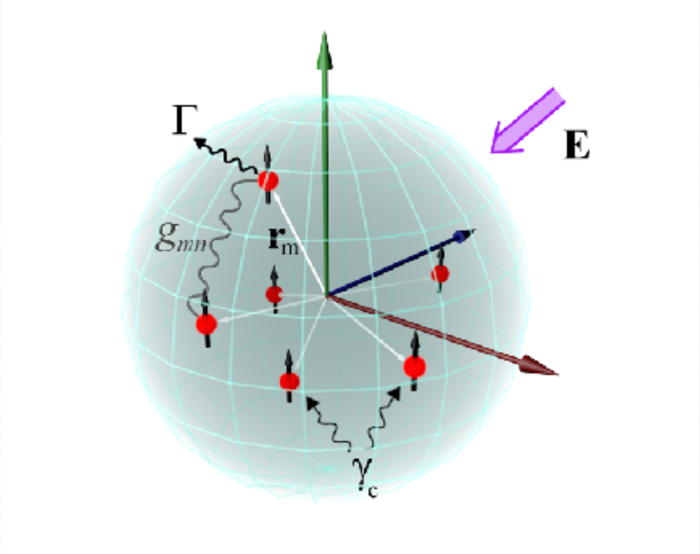
$$\mathcal{L}_H \hat{\rho} \equiv \frac{1}{\hbar}[\hat{H}_A + \hat{H}_I, \hat{\rho}]$$

$$\hat{H}_A \equiv \frac{\hbar\Omega(\mathbf{x})}{2}\hat{S}^x - \frac{\hbar\Delta}{2}\hat{S}^z.$$

$$\Delta \equiv \omega_d - \omega_0$$

$$\Omega_0 \equiv -2\mathbf{E}(\mathbf{x}_0) \cdot d\epsilon_a / \hbar$$

Master Equation



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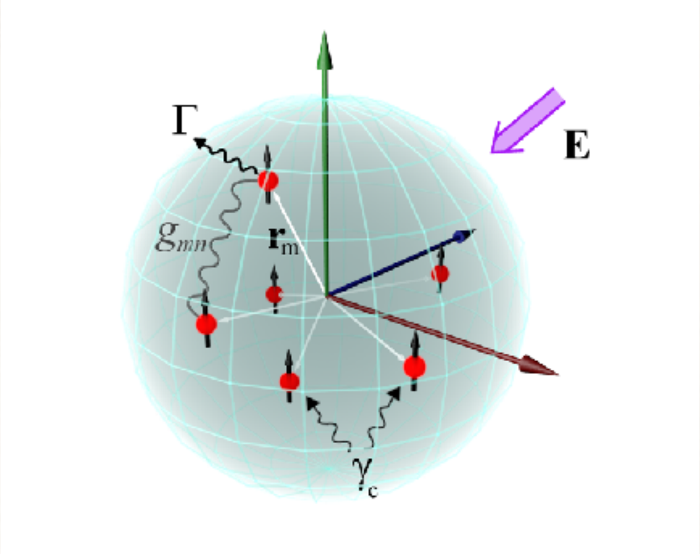

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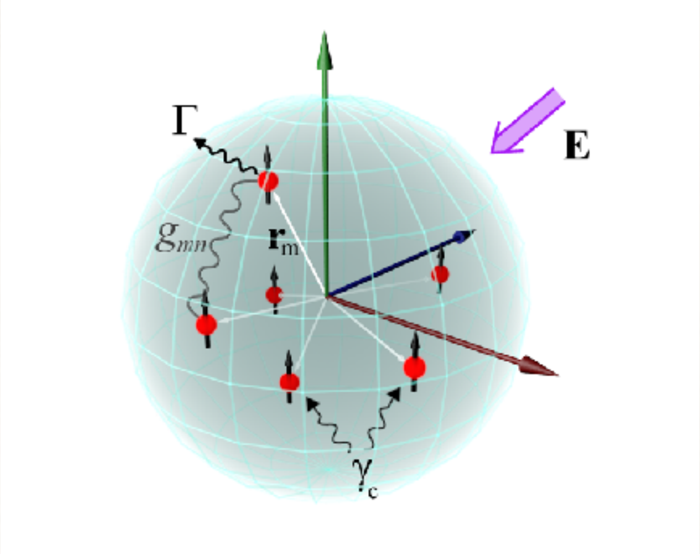

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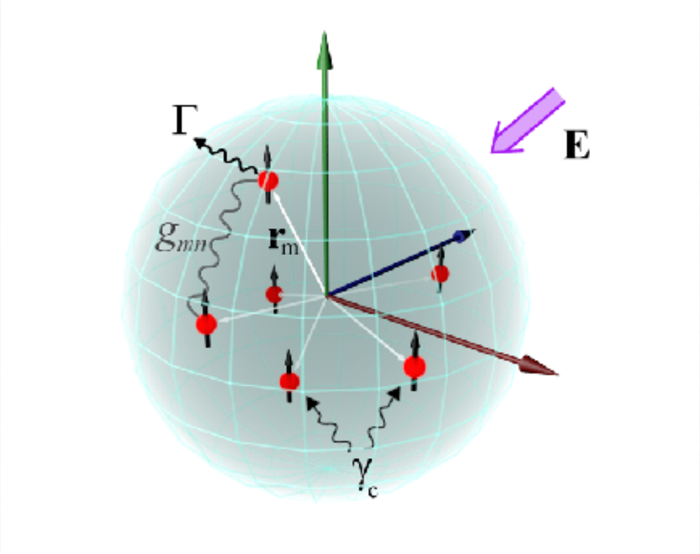

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Dipole-Dipole Interaction

$$\mathcal{L}_H\hat{\rho} \equiv \frac{1}{\hbar}[\hat{H}_A + \hat{H}_I, \hat{\rho}] \qquad \hat{H}_I \equiv \sum_{m\neq n} \hbar g_{mn}\hat{\sigma}_m^+\hat{\sigma}_n^-,$$

Can break permutation symmetry!

Master Equation

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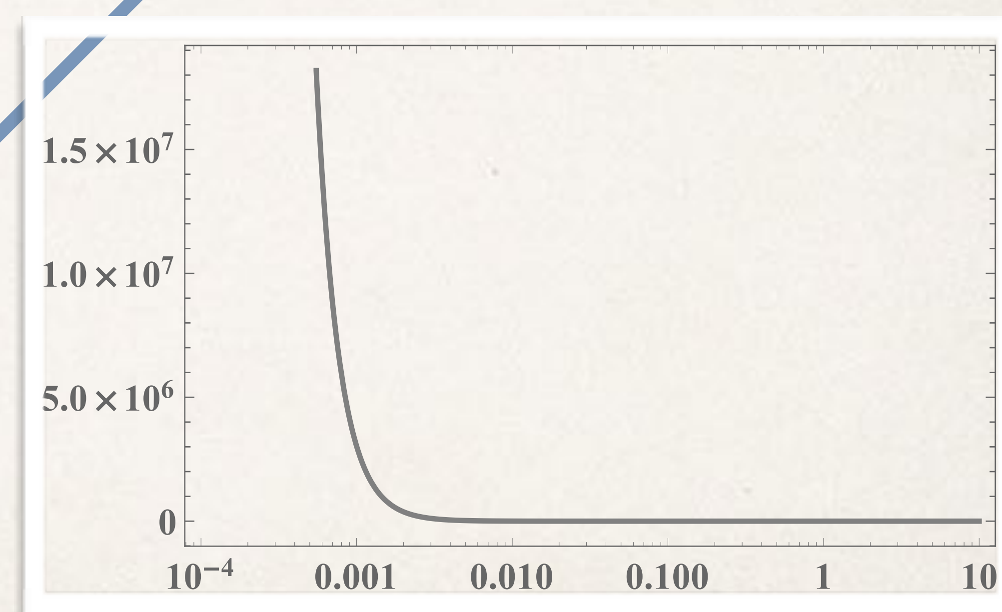

g_{12}/Γ

r_{12}/λ_0

Master Equation

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Cooperative Spontaneous Emission

$$\mathcal{L}_\Gamma\hat{\rho} \equiv \sum_{mn} \Gamma_{mn}\left(2\hat{\sigma}_m^-\hat{\rho}\hat{\sigma}_n^+ - \hat{\sigma}_m^+\hat{\sigma}_n^-\hat{\rho} - \hat{\rho}\hat{\sigma}_m^+\hat{\sigma}_n^-\right),$$

$$\Gamma_{mm} \equiv \Gamma/2$$

Dicke/Small sample limit

$$\Gamma_{mn} \equiv \Gamma/2, \forall m, n$$

$$\mathcal{L}_\Gamma\hat{\rho} \equiv \frac{\Gamma}{2}\left(2\hat{S}^-\hat{\rho}\hat{S}^+ - \hat{S}^+\hat{S}^-\hat{\rho} - \hat{\rho}\hat{S}^+\hat{S}^-\right)$$

Not perfectly collective

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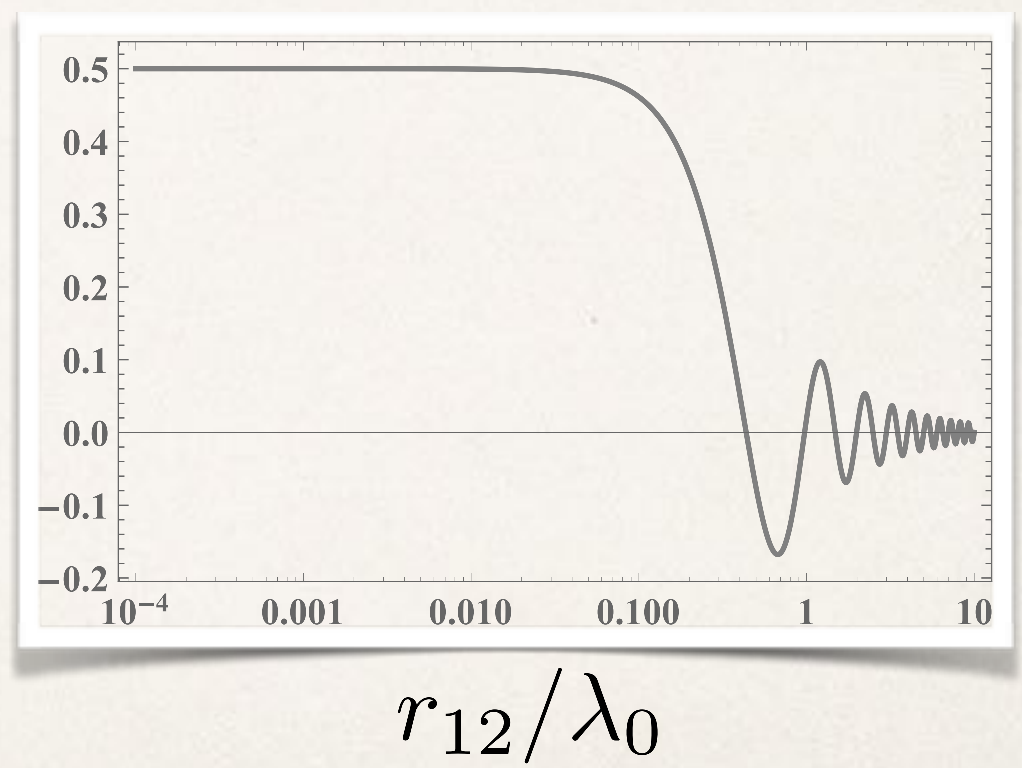
$$\Gamma_{12}/\Gamma$$



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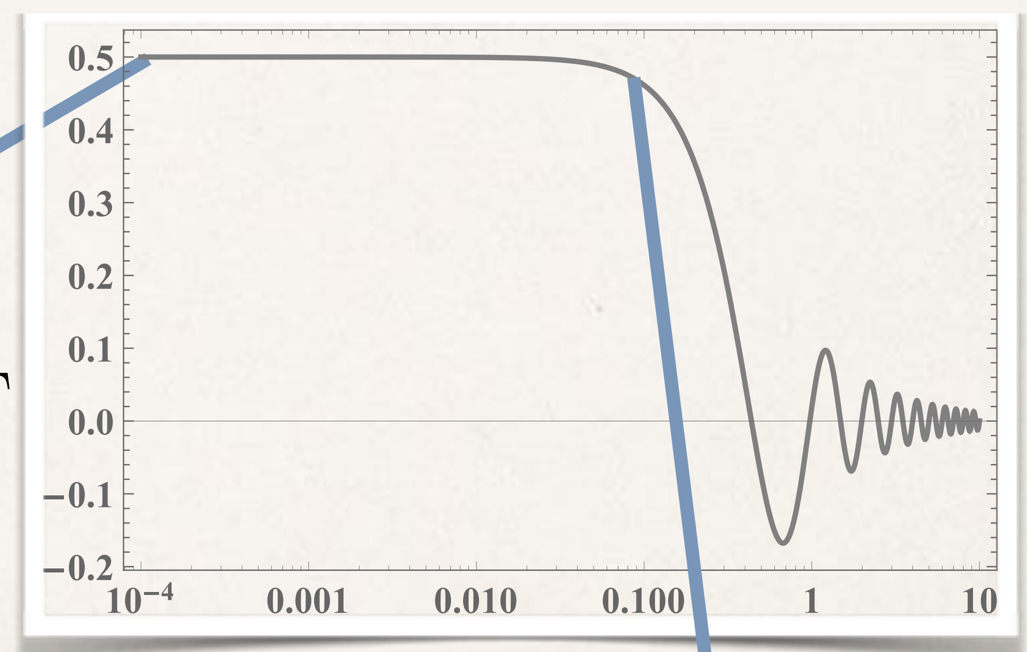

Γ_{12}/Γ

r_{12}/λ_0

Not perfectly collective

Dipole Force & Cooperative Enhancement

$$\mathbf{F}_{\mathrm{dp}} = -\frac{\hbar \nabla \Omega(\mathbf{x})|_{\mathbf{x}_0}}{2} \langle \hat{S}^x \rangle,$$

$$\langle \hat{S}^x \rangle \equiv \mathrm{tr}[\hat{S}^x \hat{\rho}_s]$$

$$\eta \equiv \frac{\langle \hat{S}^x \rangle}{\langle \hat{S}^x \rangle_{\mathrm{ind}}}$$

Cooperative Enhancement $\eta > 1$

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When is $\eta > 1$?

N = 2, Hamiltonian and Dicke Basis

$$\mathcal{L}_H \hat{\rho} \equiv \frac{1}{2\mathrm{i}}[\Omega_0 \hat{S}^x - (\Delta_0 + \bar{g})\hat{S}^z + 2\bar{g}\hat{S}^+\hat{S}^-, \hat{\rho}].$$

$$\mathcal{L}_\Gamma \hat{\rho} = \frac{\frac{\Gamma}{2} + \overline{\Gamma}}{2}\left(2\hat{S}^-\hat{\rho}\hat{S}^+ - \hat{S}^+\hat{S}^-\hat{\rho} - \hat{\rho}\hat{S}^+\hat{S}^-\right) + \frac{\frac{\Gamma}{2} - \overline{\Gamma}}{2}\left(2\hat{\Sigma}^-\hat{\rho}\hat{\Sigma}^+ - \hat{\Sigma}^+\hat{\Sigma}^-\hat{\rho} - \hat{\rho}\hat{\Sigma}^+\hat{\Sigma}^-\right)$$

$$\hat{\Sigma}^- = \hat{\sigma}_1^- - \hat{\sigma}_2^-$$

Z. Ficek, and R. Tanas, Physics Reports **372**, 369 (2002).

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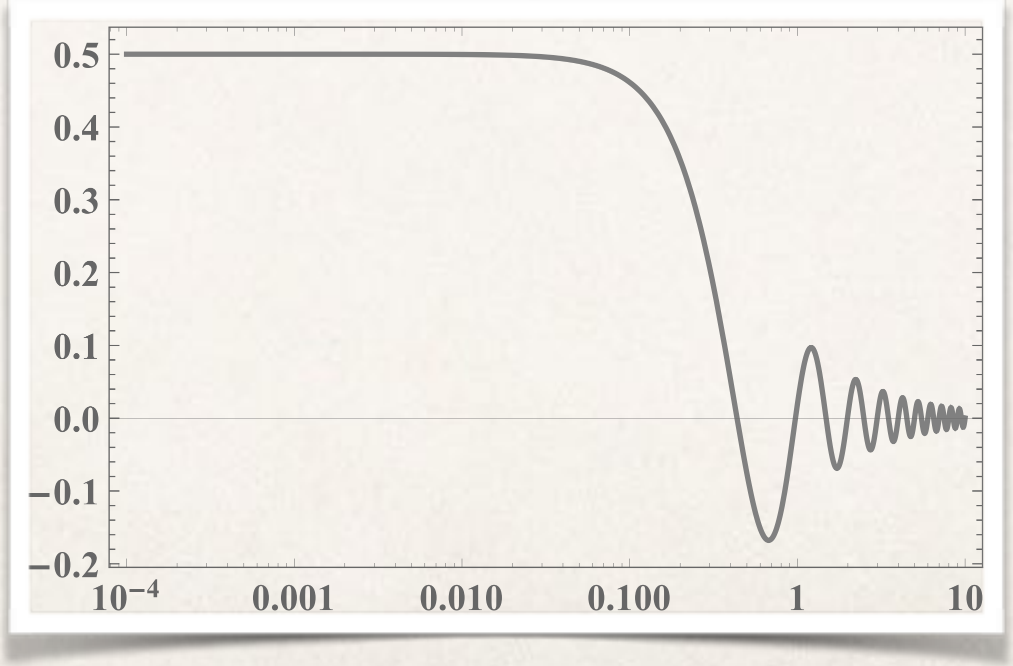

$\overline{\Gamma}/\Gamma$

r_{12}/λ_0

Z. Ficek, and R. Tanas, Physics Reports **372**, 369 (2002).

N=2, Perfect collective

$$\overline{\Gamma} = \Gamma/2$$

$\eta > 1$ when $\Omega_0 \gg \{\Gamma, \gamma_c, \bar{g}\}$

N=2, Perfect cooperative emission

$$|1,1\rangle = |ee\rangle \qquad |1,-1\rangle = |gg\rangle$$

$$|0,0\rangle = \frac{1}{\sqrt{2}}\left(|eg\rangle - |ge\rangle\right) \qquad |1,0\rangle = \frac{1}{\sqrt{2}}\left(|eg\rangle + |ge\rangle\right)$$

A. S. J. Amin and J. G. Cordes, Phys. Rev. A **18**, 1298 (1978).
G. S. Agarwal, L. M. Narducci, D. H. Feng, and R. Gilmore, Phys. Rev. Lett. **42**, 1260 (1979).

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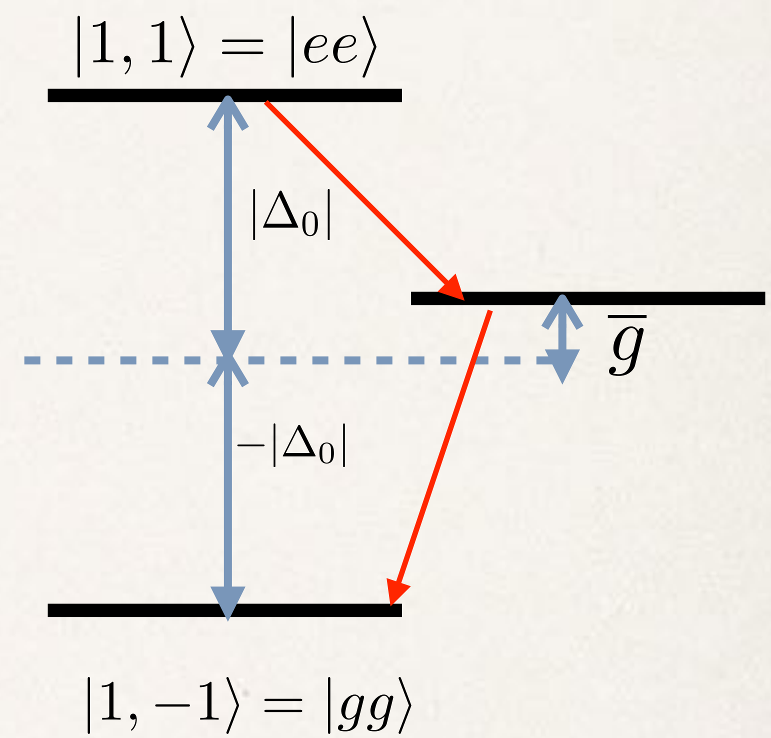
$$\overline{\Gamma} = 0$$



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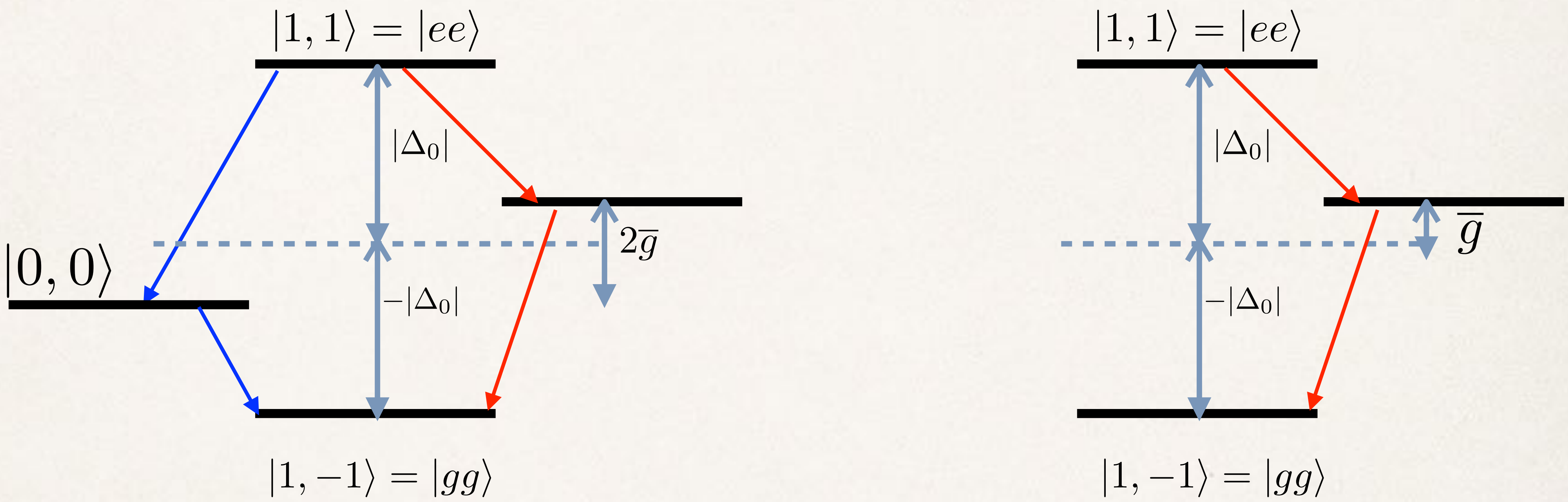
N=2, Perfect cooperative emission

$|1,1\rangle = |ee\rangle$ $\qquad$ $|1,-1\rangle = |gg\rangle$

$|0,0\rangle = \frac{1}{\sqrt{2}}(|eg\rangle - |ge\rangle)$ $\qquad$ $|1,0\rangle = \frac{1}{\sqrt{2}}(|eg\rangle + |ge\rangle)$

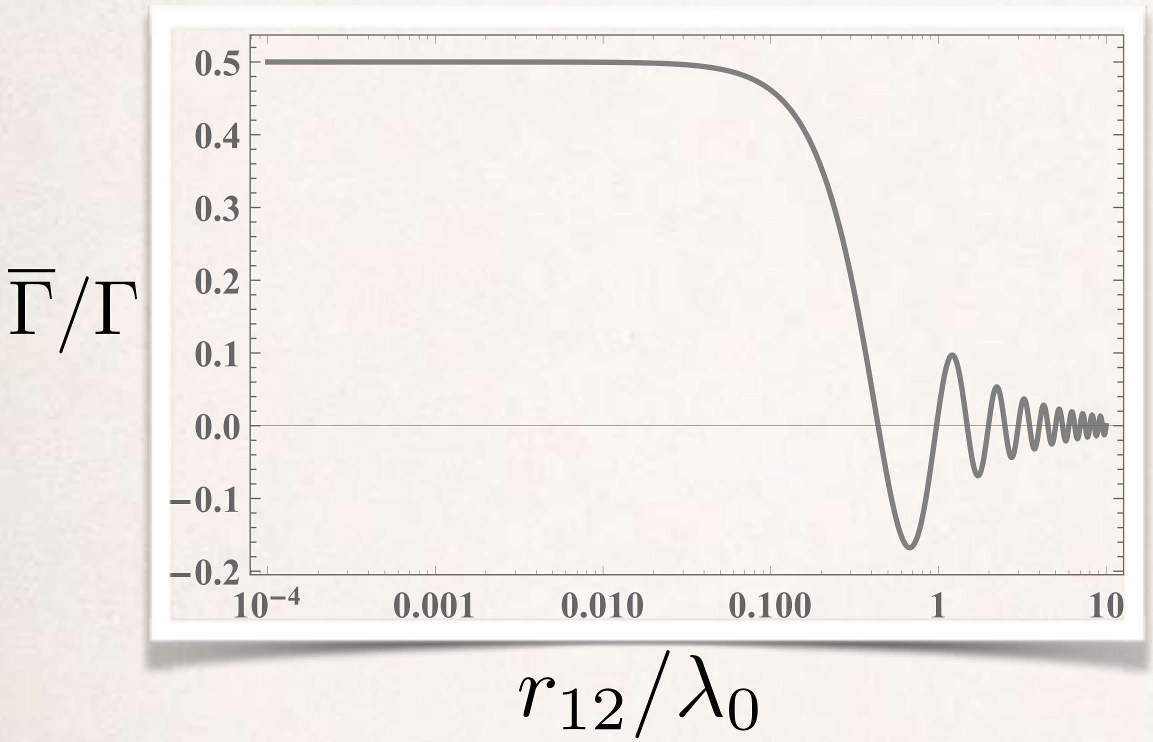


$\overline{\Gamma} = 0$ $\qquad$ $\overline{\Gamma} = \Gamma/2$

A. S. J. Amin and J. G. Cordes, Phys. Rev. A **18**, 1298 (1978).

G. S. Agarwal, L. M. Narducci, D. H. Feng, and R. Gilmore, Phys. Rev. Lett. **42**, 1260 (1979).

N=2, non-perfect cooperative emission

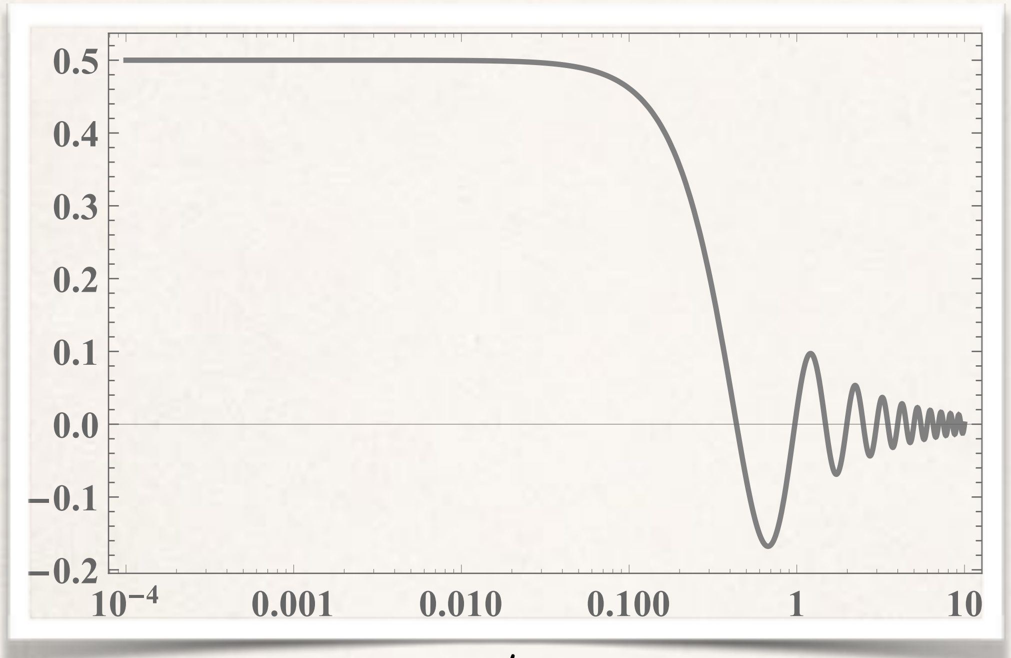


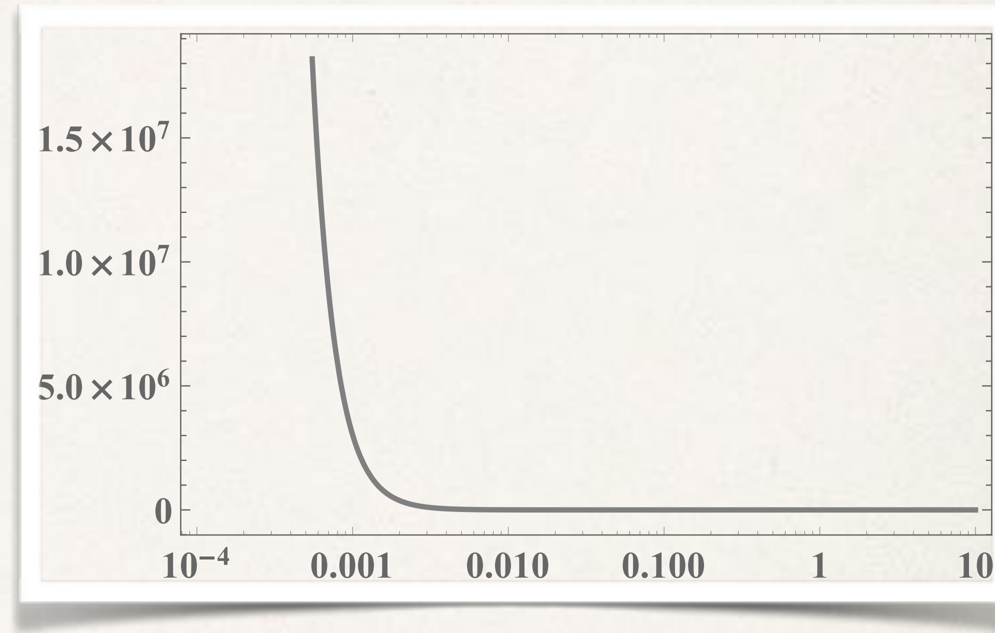
$\gamma_c \equiv 0$ $\quad$ $\eta < 1$

$\chi \equiv 2\overline{\Gamma}/\Gamma < 1$

$\gamma_c \gg \Gamma$ $\quad$ $\eta > 1$ if $\Omega_0^2 > (1+\chi)\Gamma^2$

N=2, non-perfect cooperative emission





$\gamma_c \equiv 0$ $\eta < 1$

$\chi \equiv 2\overline{\Gamma}/\Gamma < 1$

$\gamma_c \gg \Gamma$ $\eta > 1 \text{ if } \Omega_0^2 > (1+\chi)\Gamma^2$

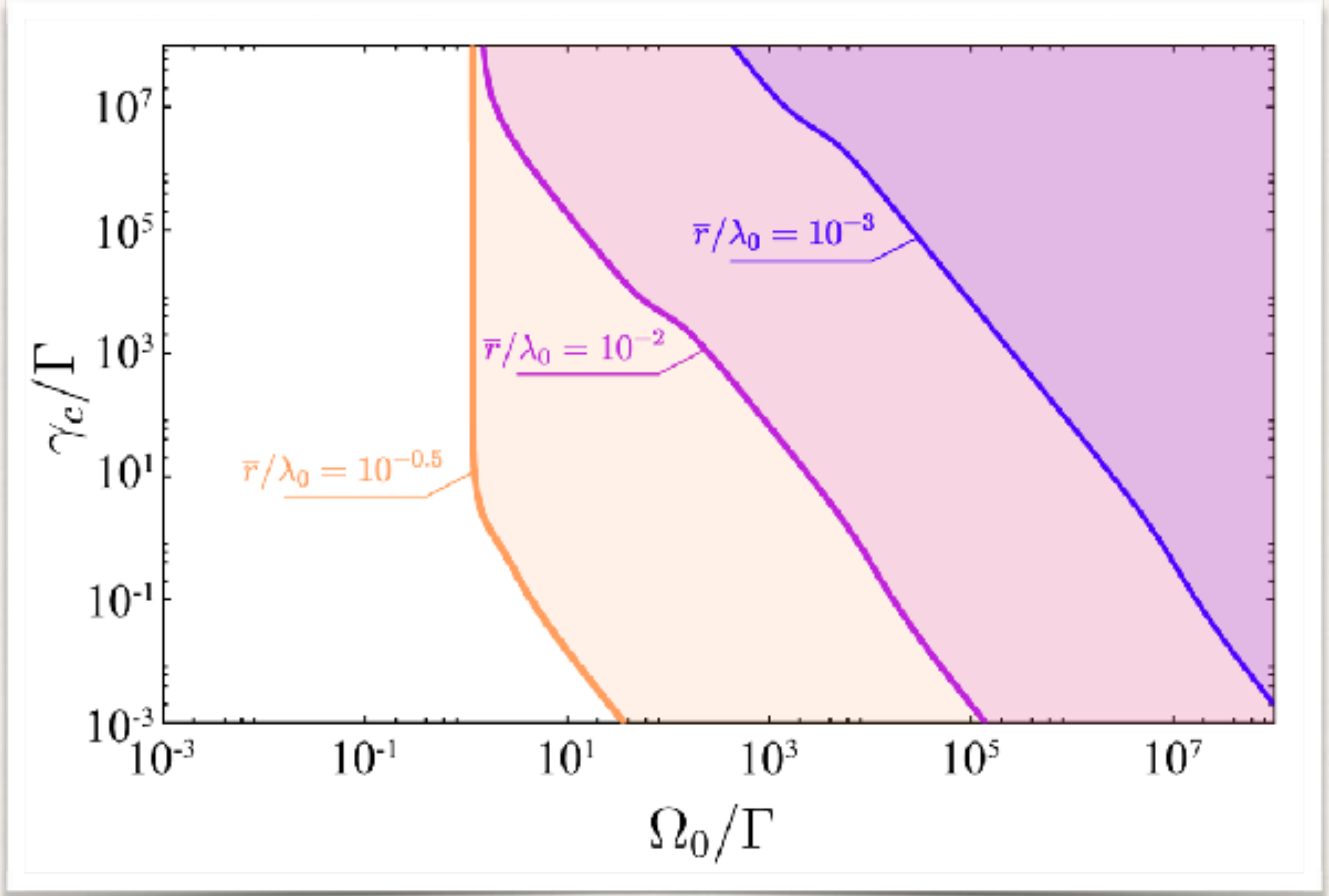
N=2, non-perfect cooperative emission

$$\gamma_c \equiv 0 \qquad \eta < 1$$

$$\chi \equiv 2\overline{\Gamma}/\Gamma < 1$$

$$\gamma_c \gg \Gamma \qquad \eta > 1 \text{ if } \Omega_0^2 > (1+\chi)\Gamma^2$$

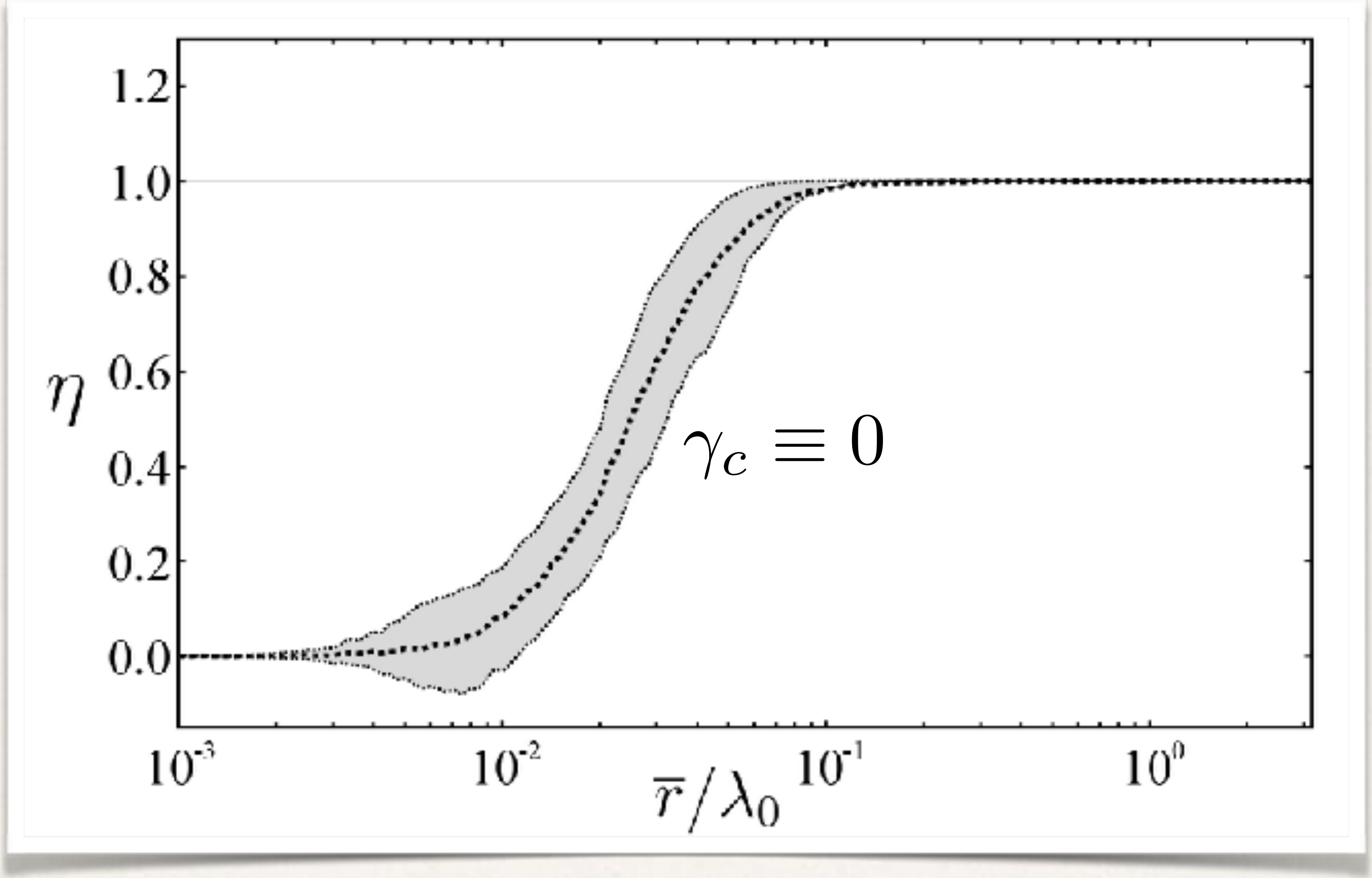
N=2, non-perfect cooperative emission



$$\eta > 1 \text{ if } \Omega_0^2 > (1+\chi)\Gamma^2$$

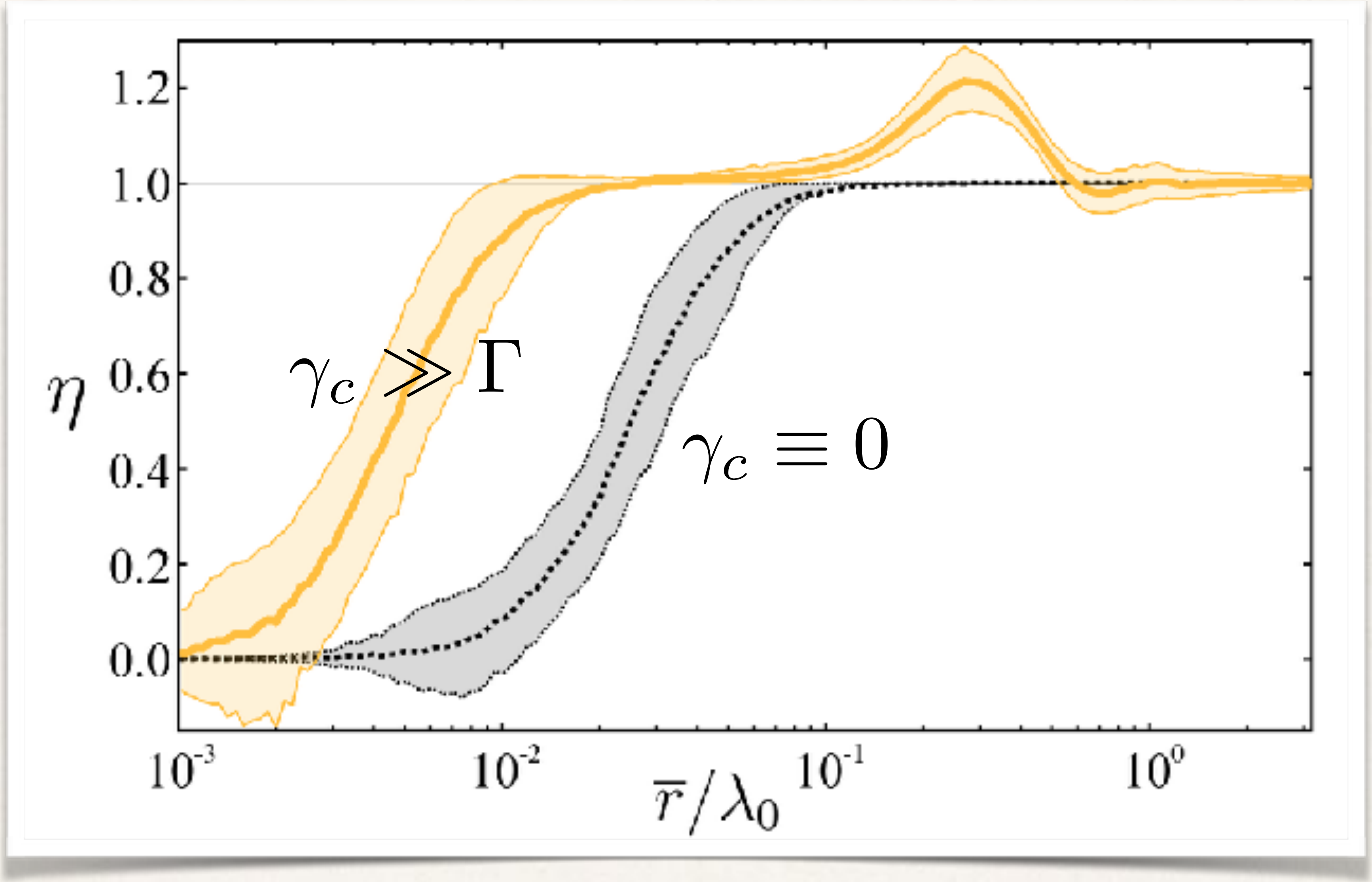
N=6 Result

$$\Omega_0 \gg \Gamma$$



N=6 Result

$\Omega_0 \gg \Gamma$



When is $\eta > 1$?

Large Ω_0 & γ_c

Plan of the talk

- Introduction, Motivation, & System description
- Main results and methods
- Conclusions & Outlook

Conclusions & Outlook

- Collective dephasing and strong driving can restore cooperative effects
- In NV + nano diamond system - Collective dephasing T dependent
- Superconducting qubit implementation?

Thank you!