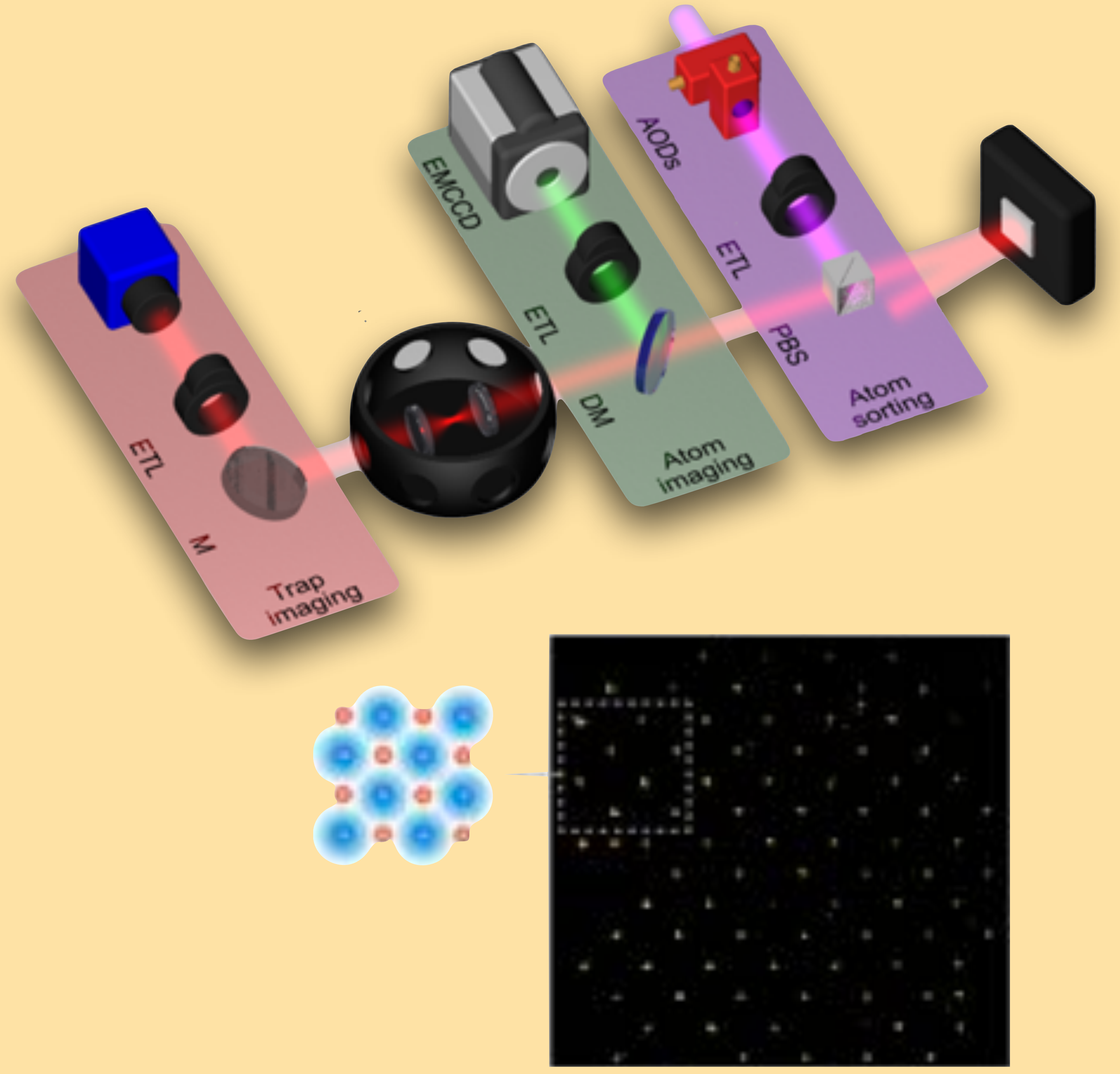
Superradiant phase transition in free-space atomic clouds

Igor Ferrier-Barbut
Laboratoire Charles Fabry, Institut d’Optique

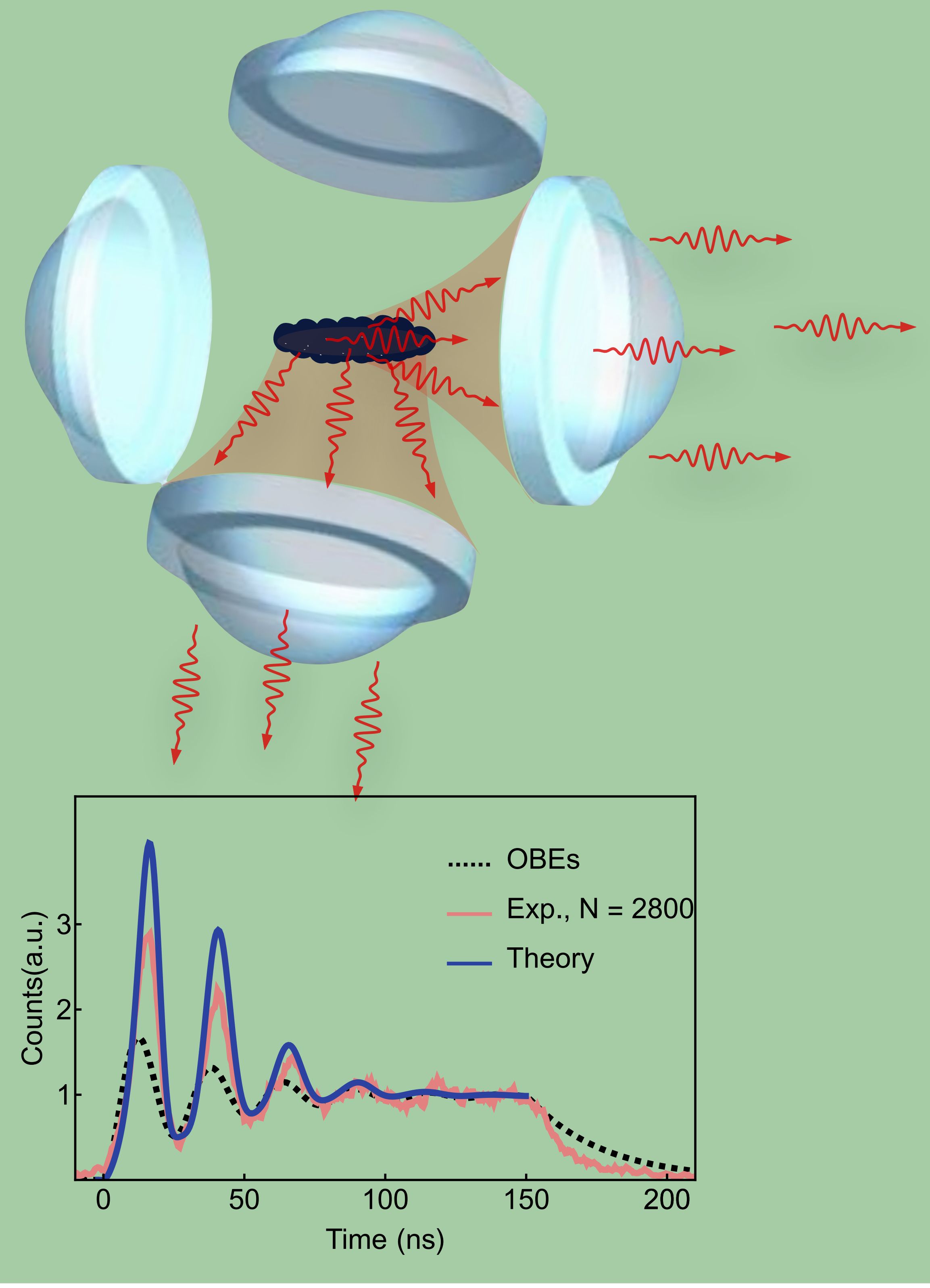
Quantum optics - atoms @ LCF

Group thematics

Quantum simulation with Rydberg arrays

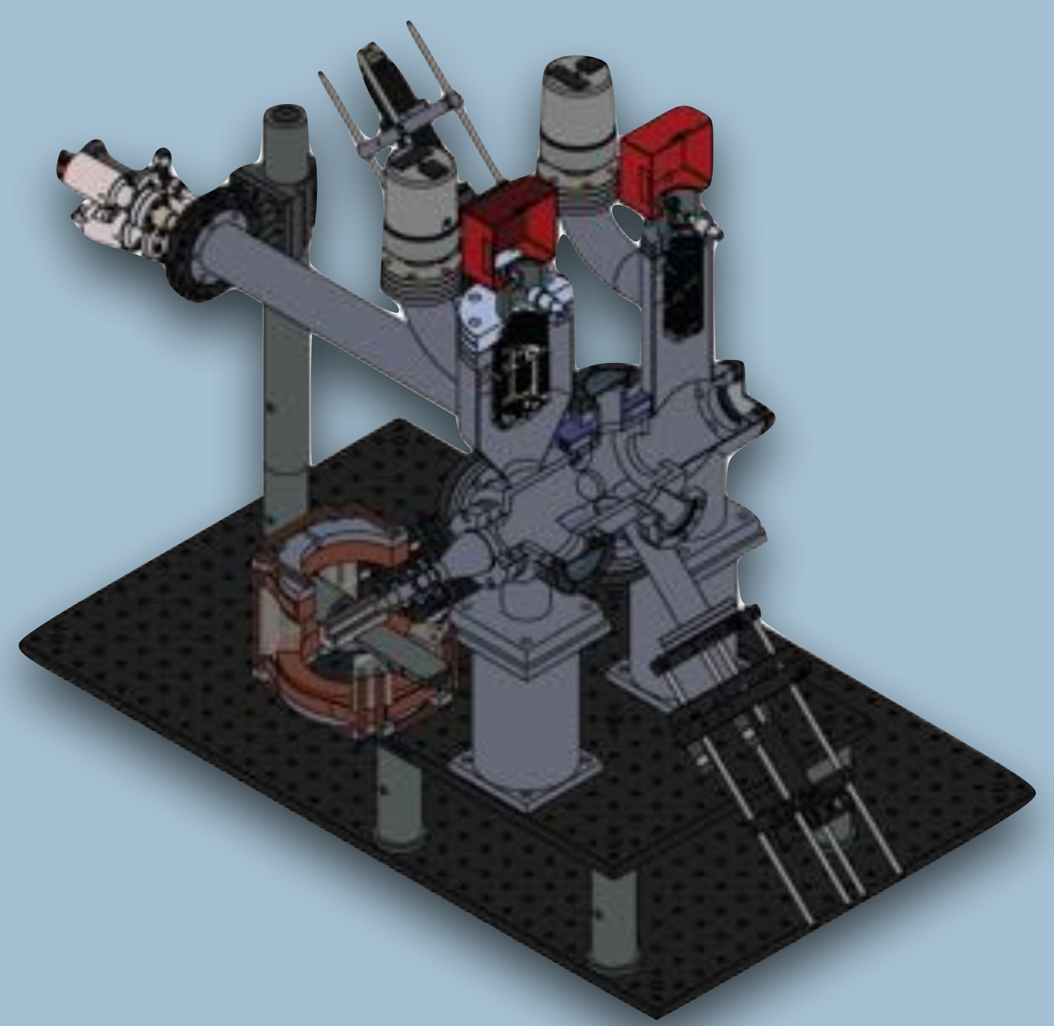


Light scattering in dense clouds



Dy tweezers arrays for light scattering

(under construction)



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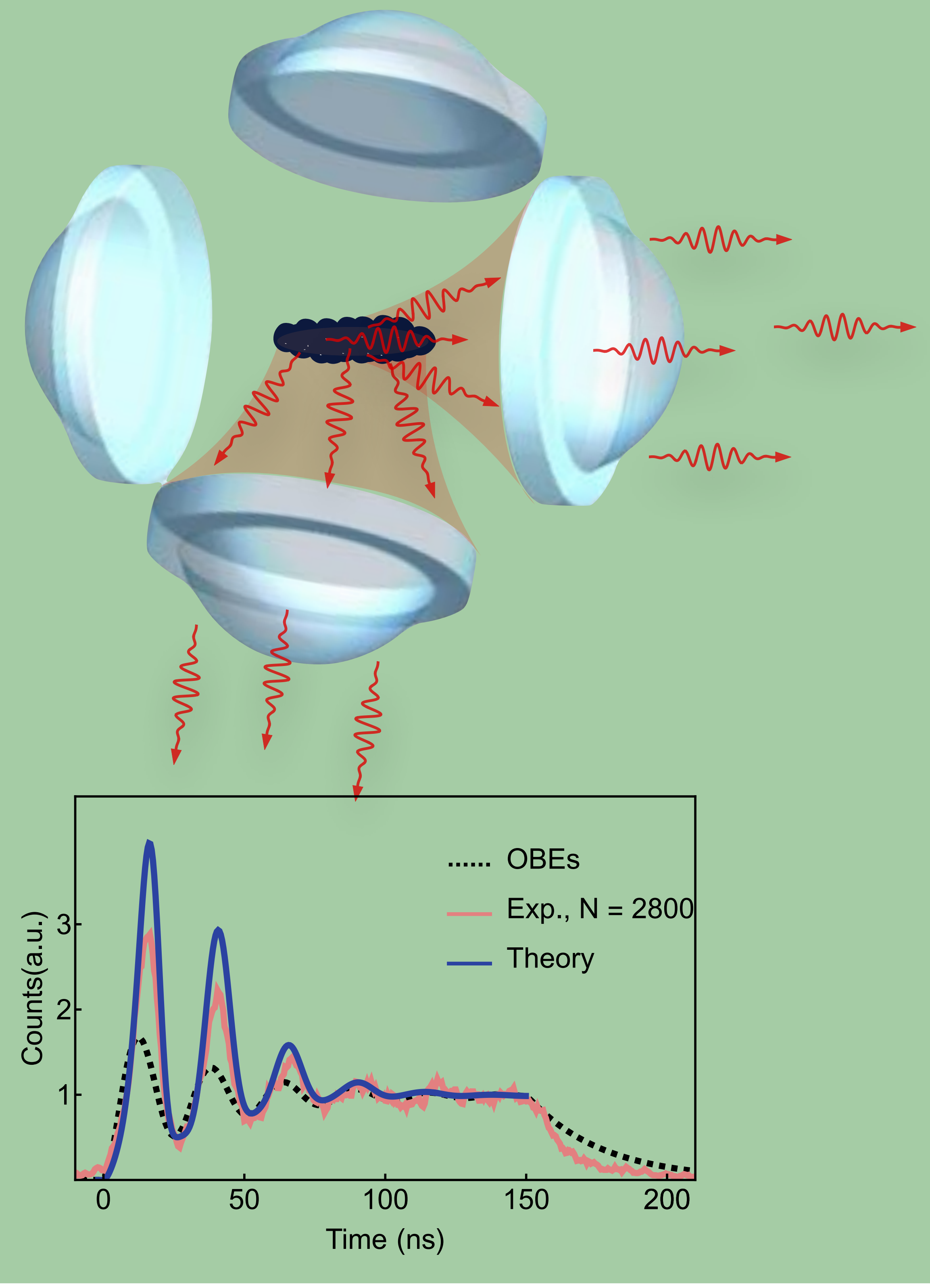

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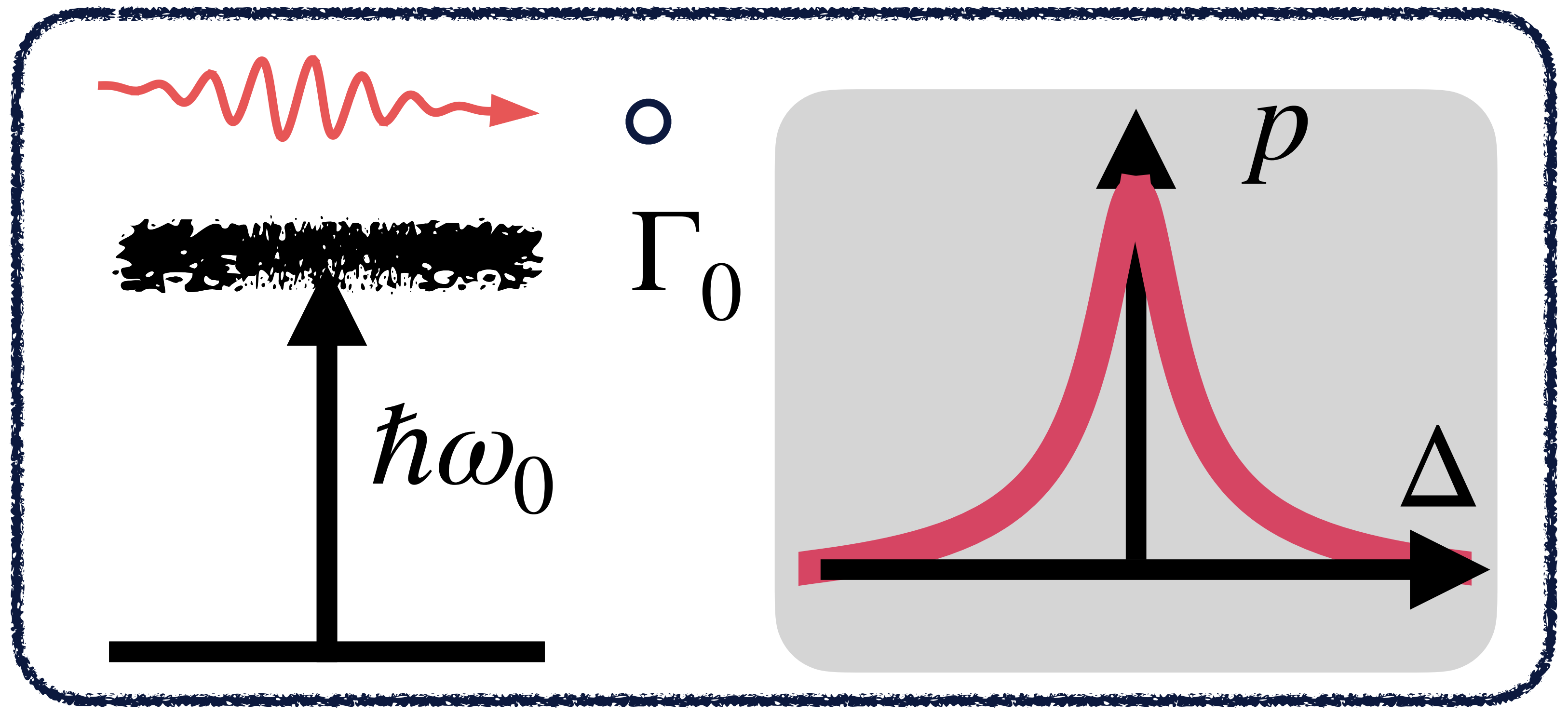
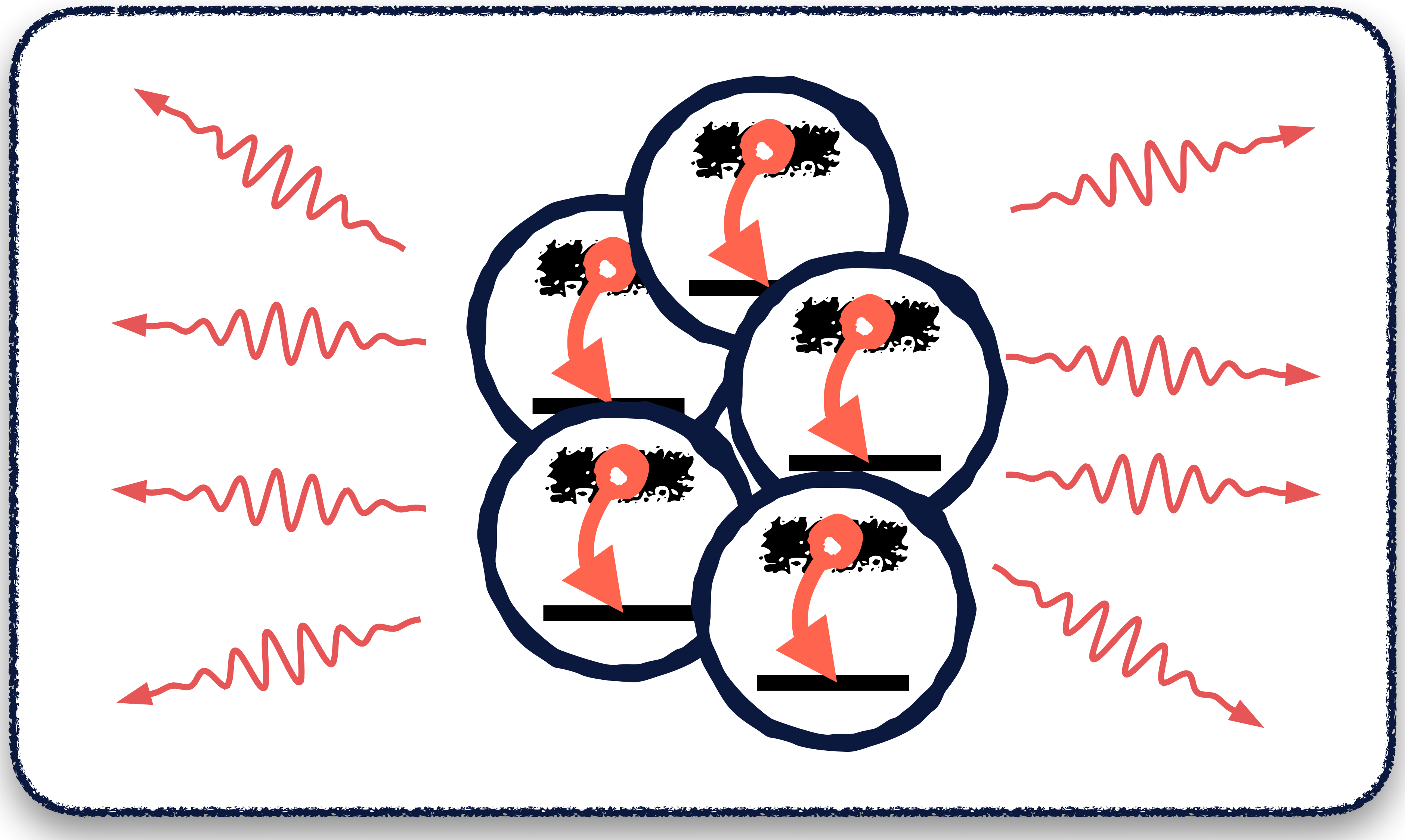
Collective spontaneous emission

Single atom in **free space**



N-atom spontaneous emission



N atoms

An atomic mirror

Bettles *et al.*, *Phys. Rev. Lett.* 116, 103602 (2016).

Shahmoon *et al.*, *Phys. Rev. Lett.* 118, 113601 (2017).

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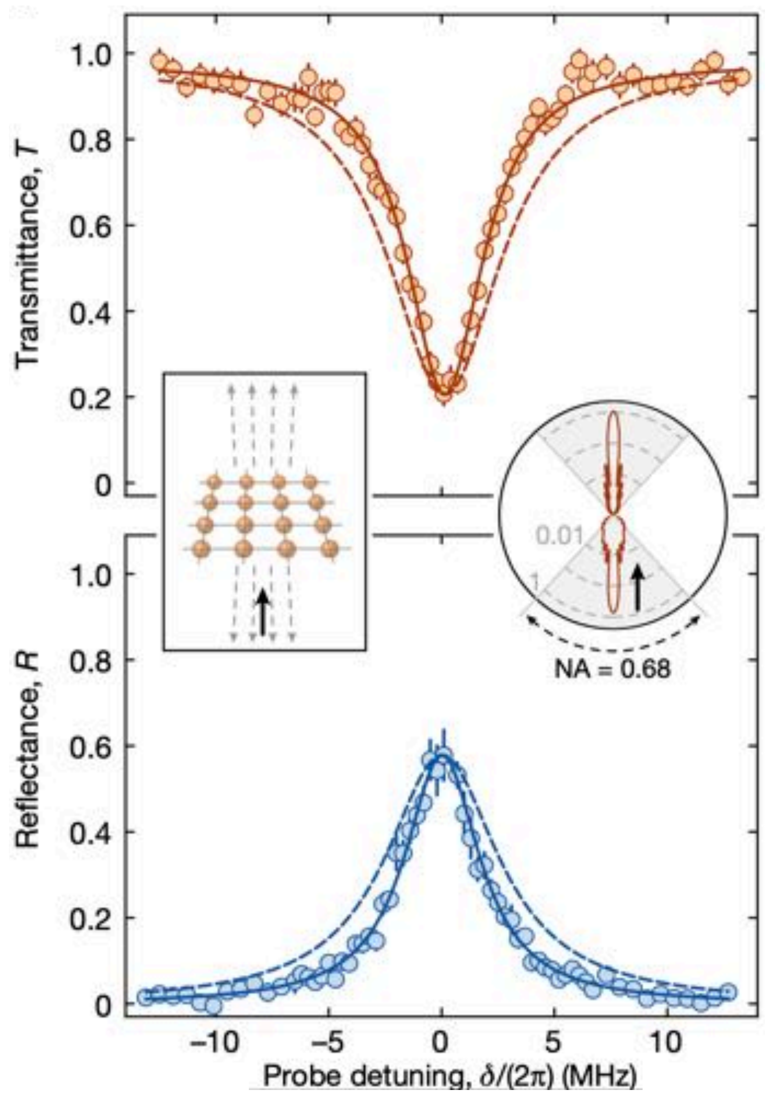

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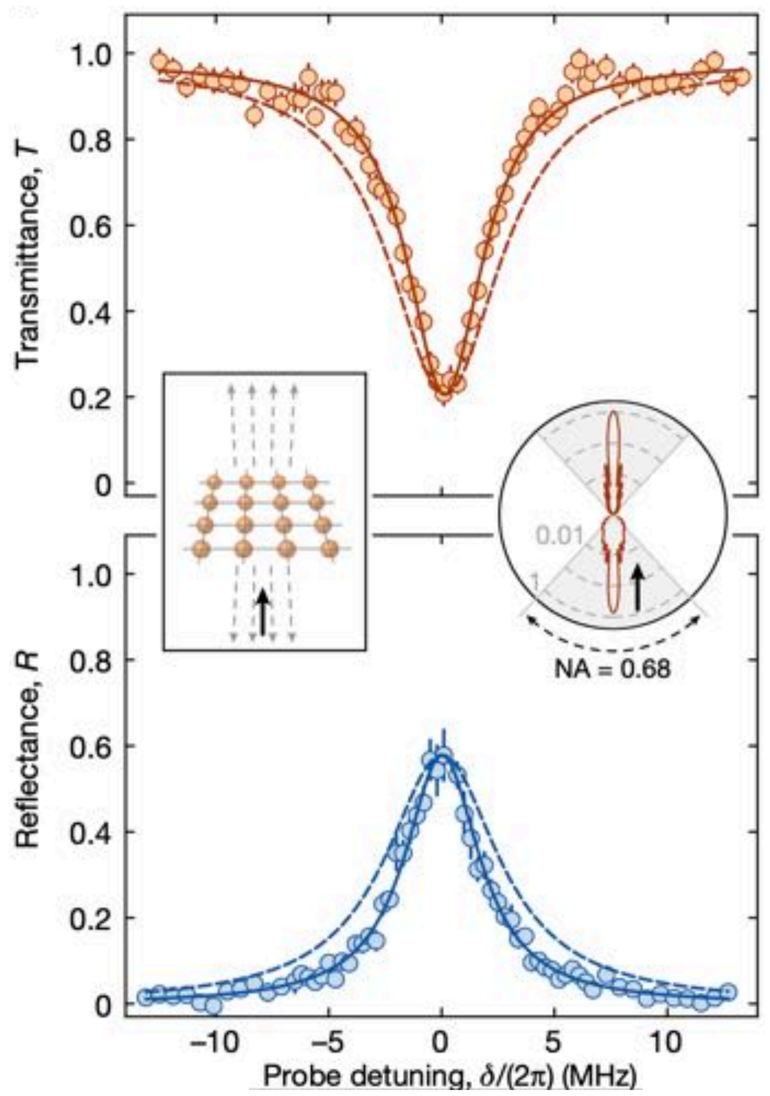
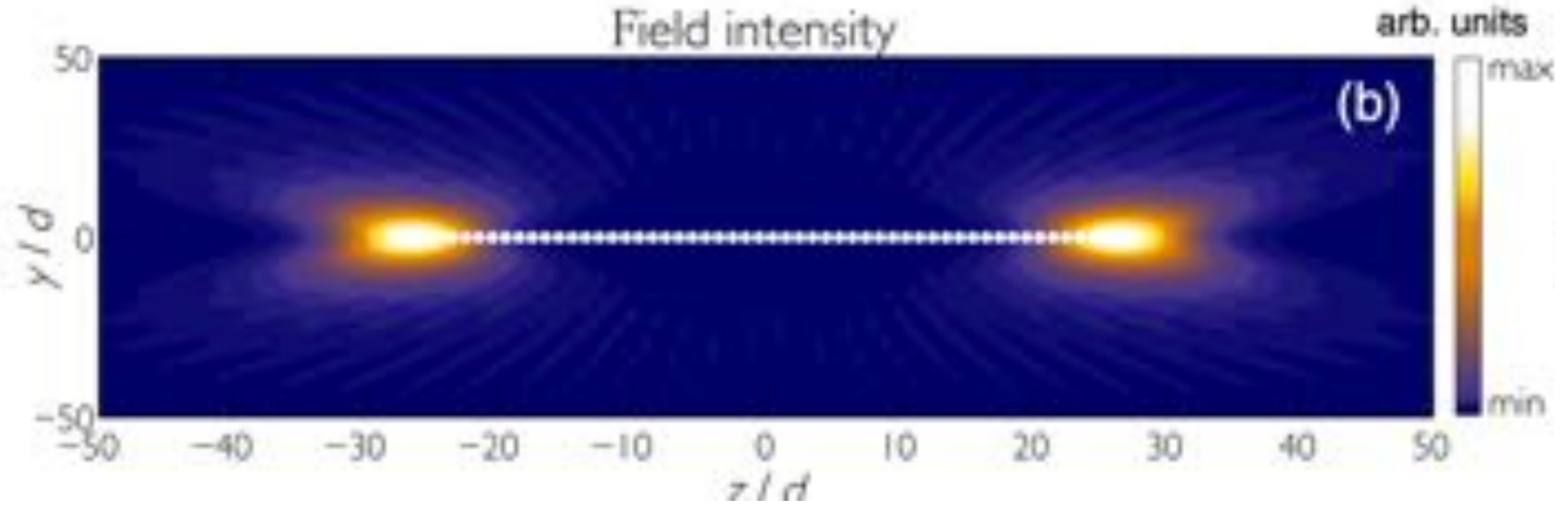


Subradiance as a light storage medium?

Asenjo-Garcia *et al.*, Phys. Rev. X 7, 031024 (2017).



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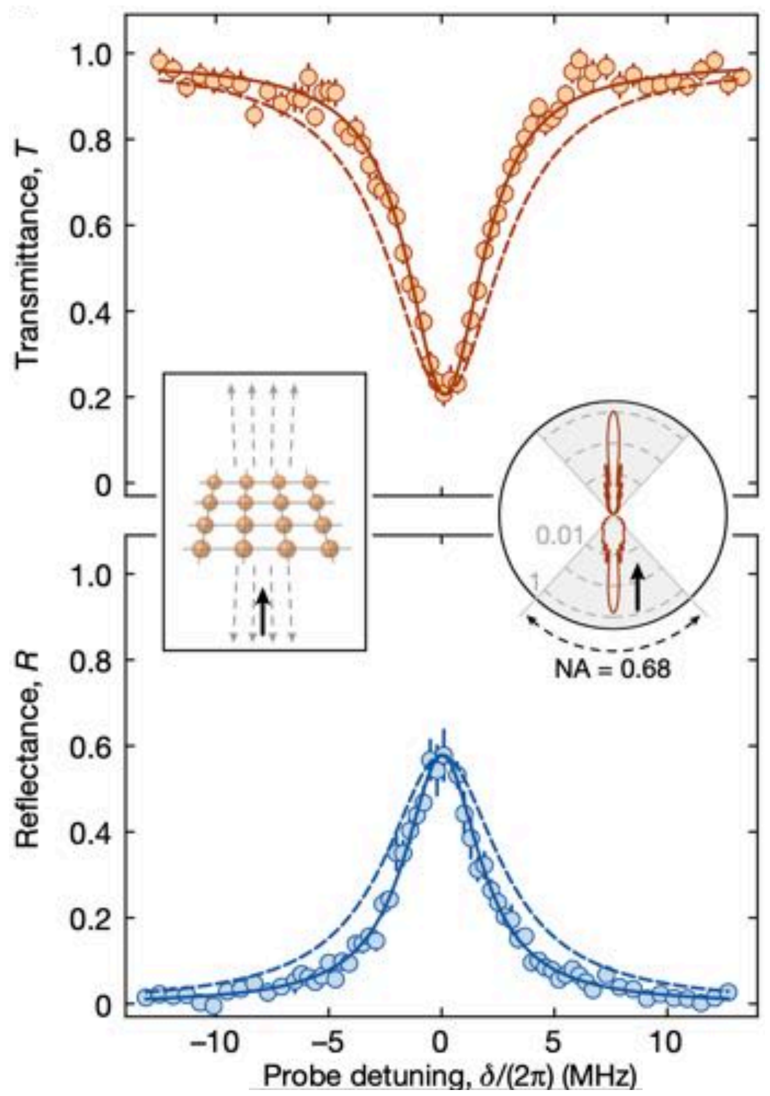

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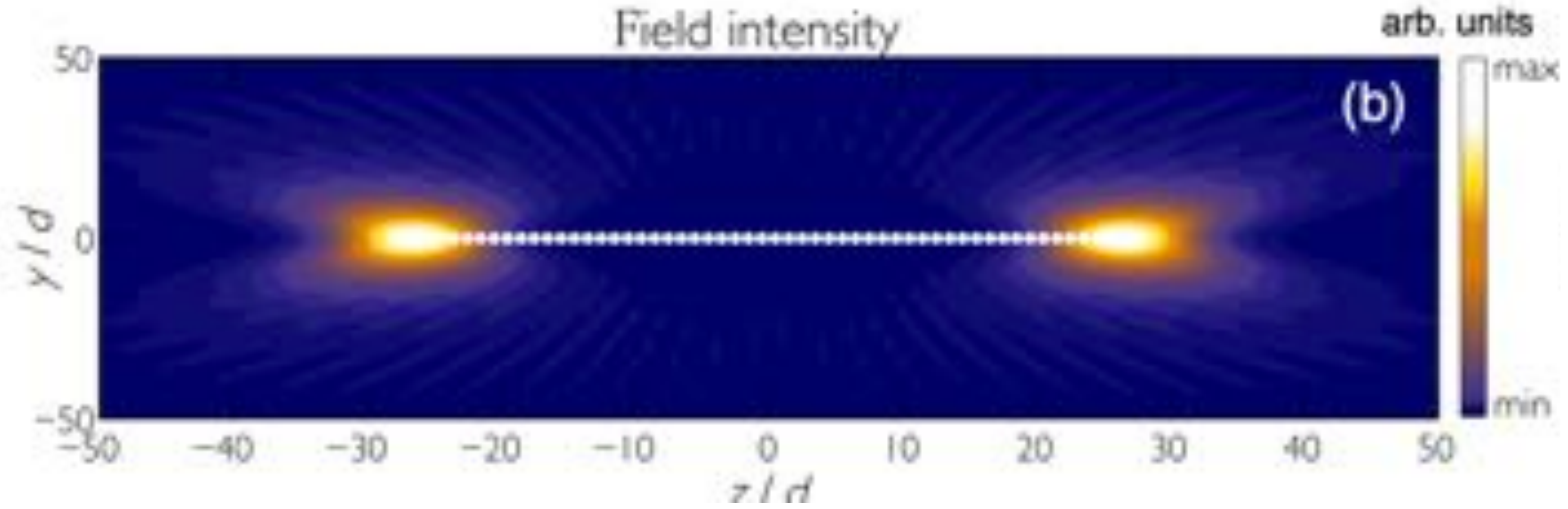
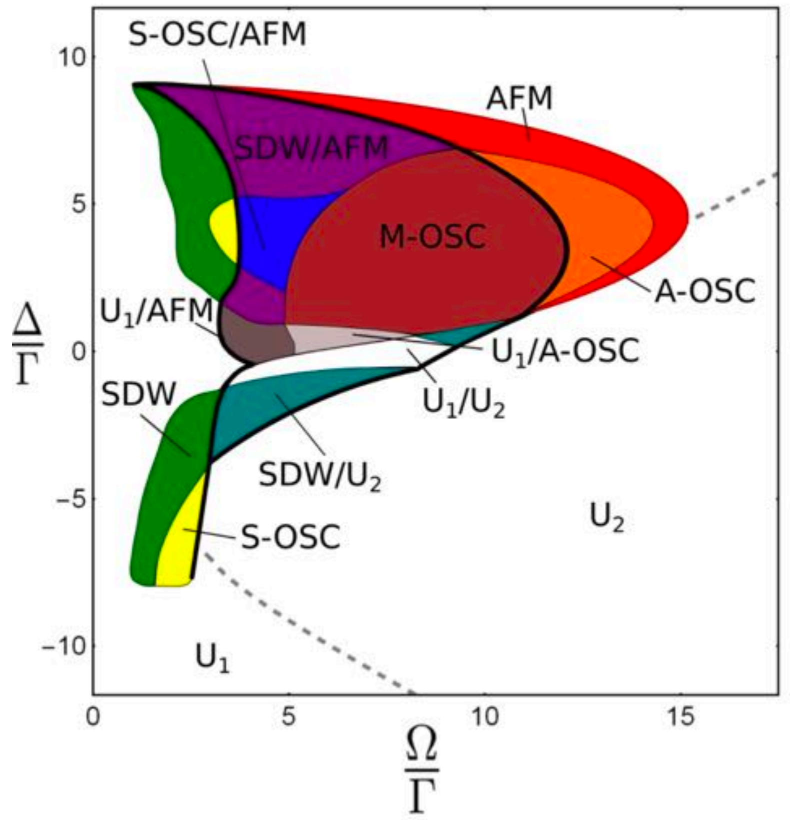


Phase transitions in driven-dissipative many-body systems.

Olmos *et al.*, *Phys Rev A* **89**, 023616 (2014).

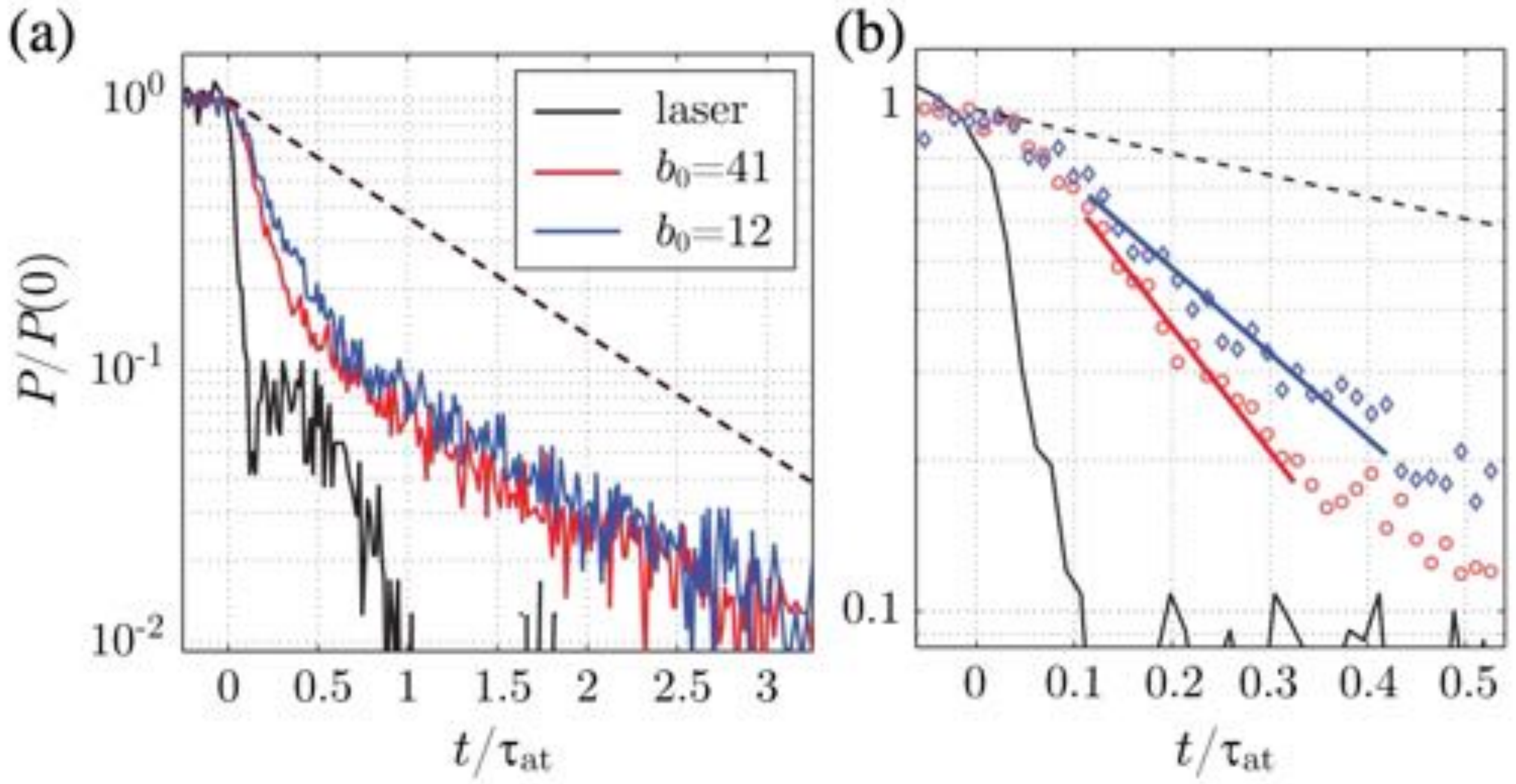
Parmee & Cooper, *Phys Rev A* **97**, 053616 (2018).



Collective spontaneous emission

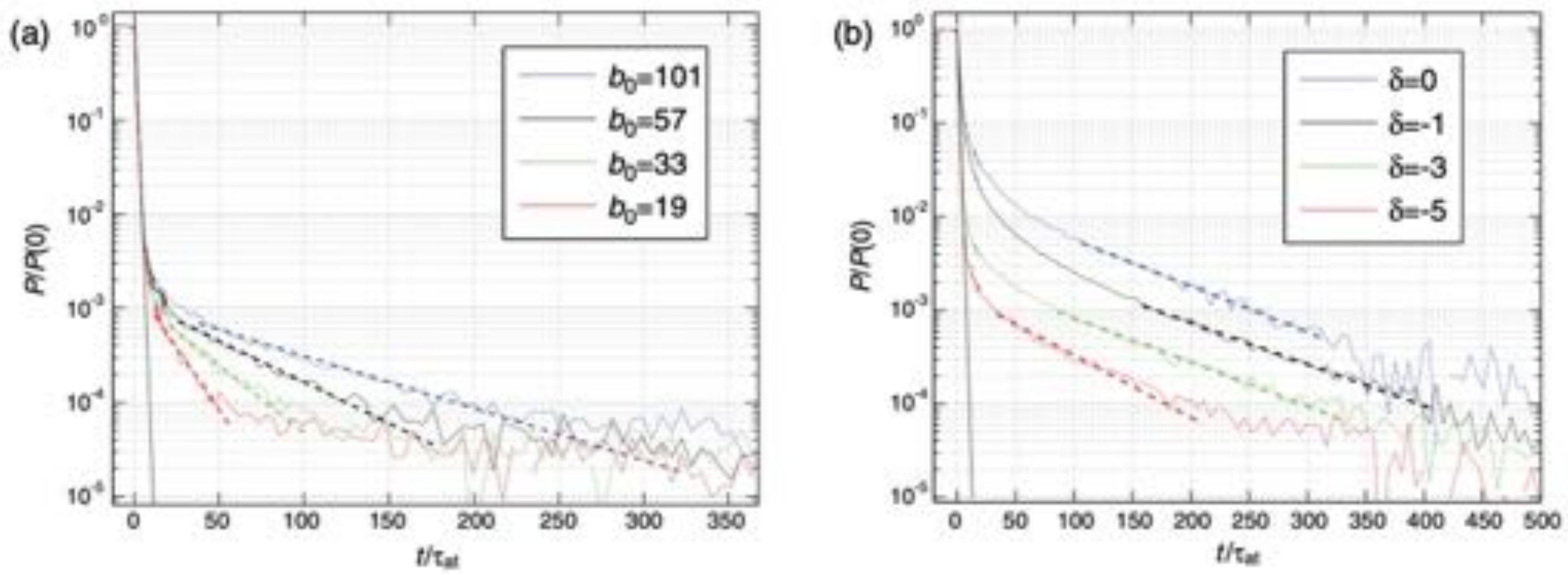
Dilute atomic clouds $L/\lambda_0 \gg 1$ (Nice, Wisconsin, Norfolk…)

Superradiance



Araújo *et al.*, *Phys Rev Lett* **117**, 073002 (2016).

Subradiance



Guerin *et al.*,. *Phys Rev Lett* **116**, 083601 (2016).

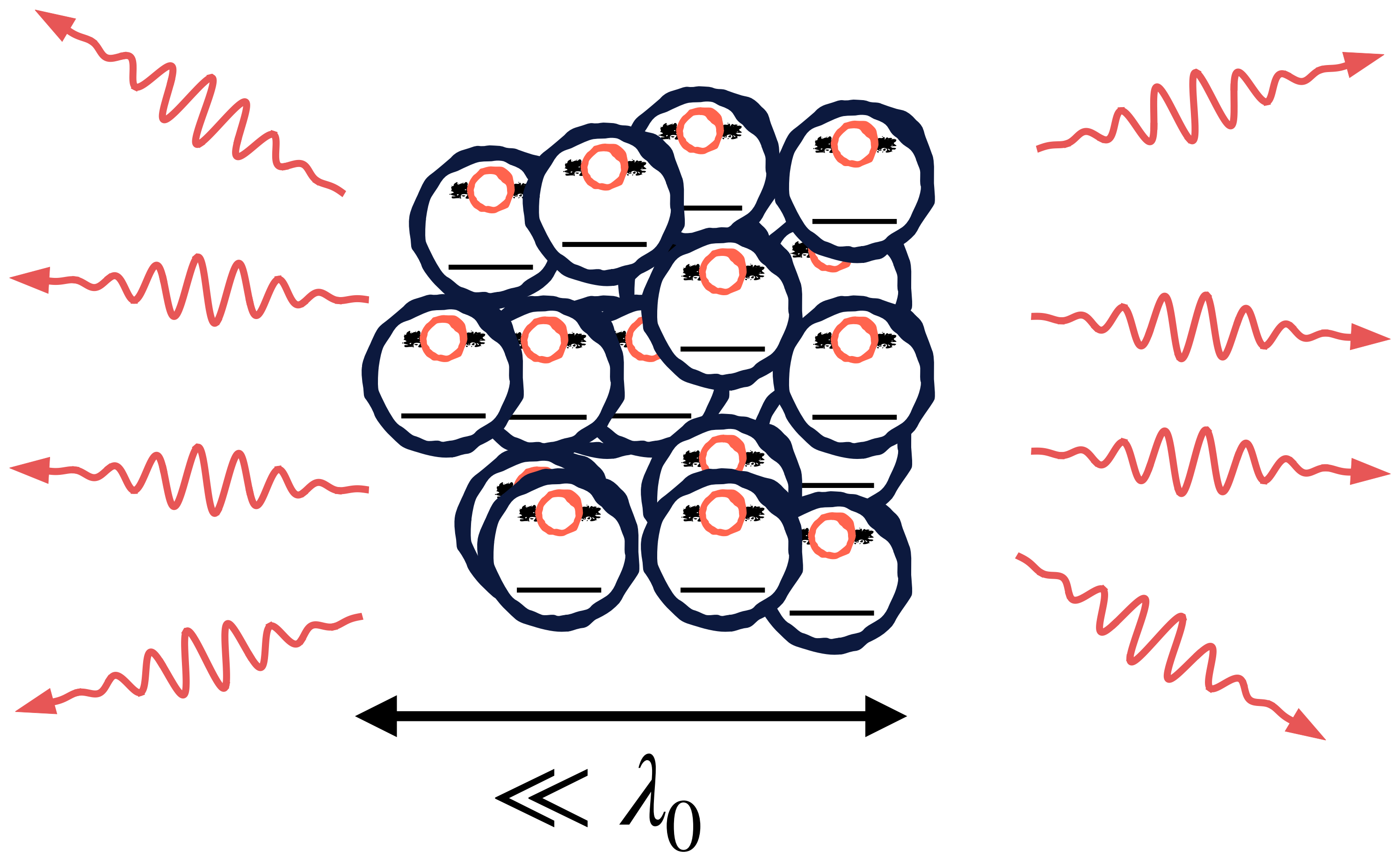
This talk

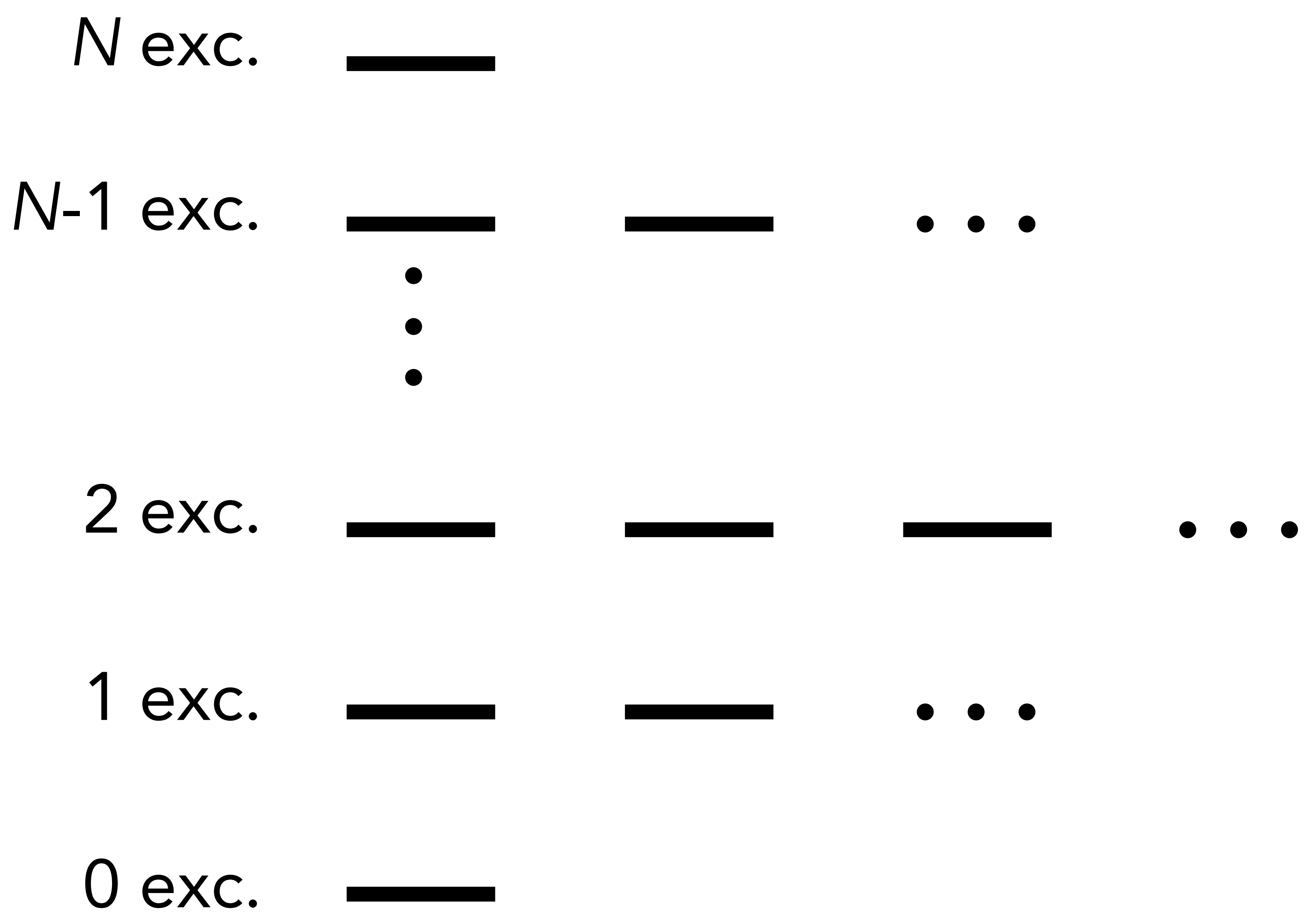
Small atomic clouds $L/\lambda_0 \lesssim 1$

Quantum regime: $n_{exc} \gg 1$

N-atom spontaneous emission

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





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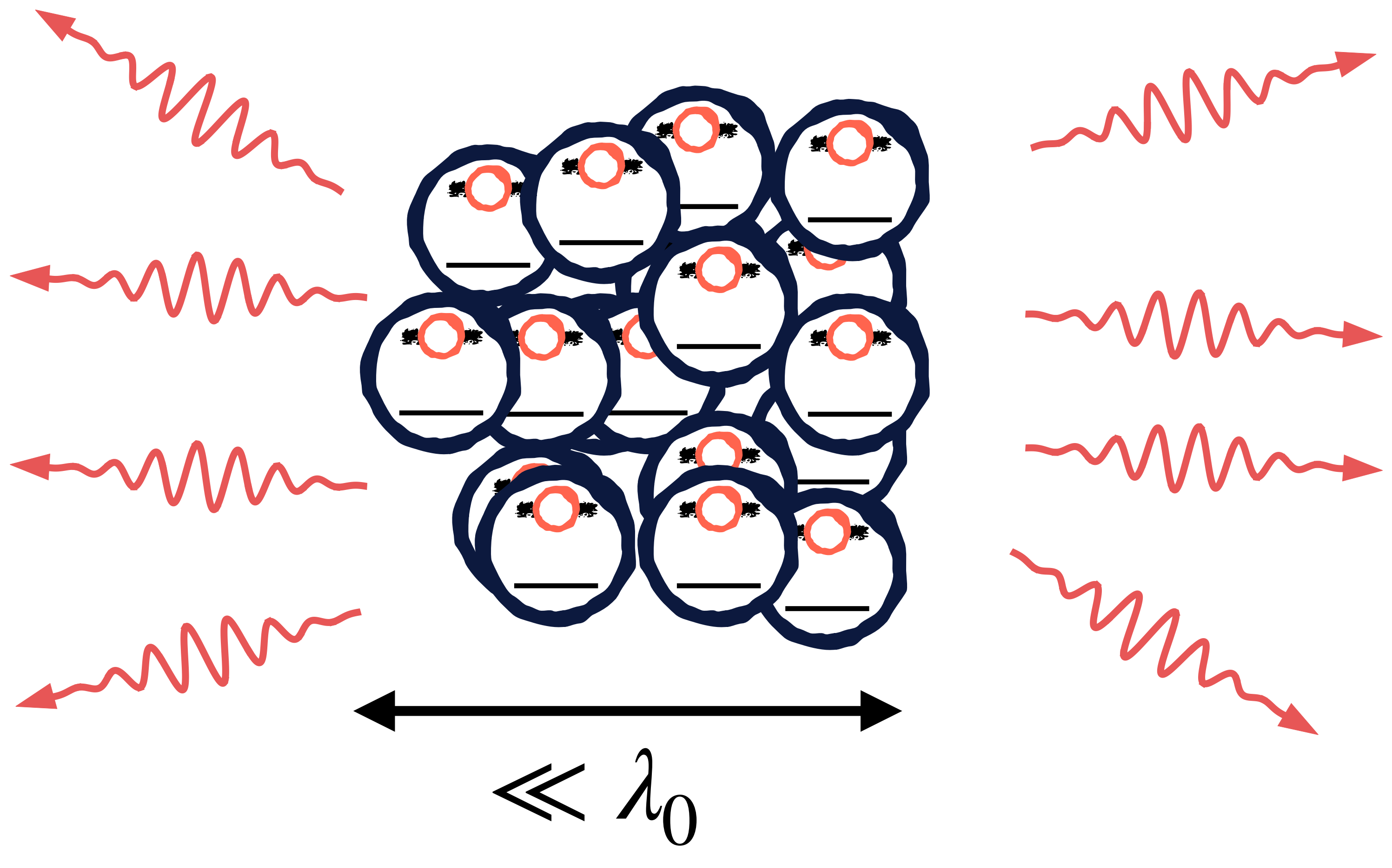

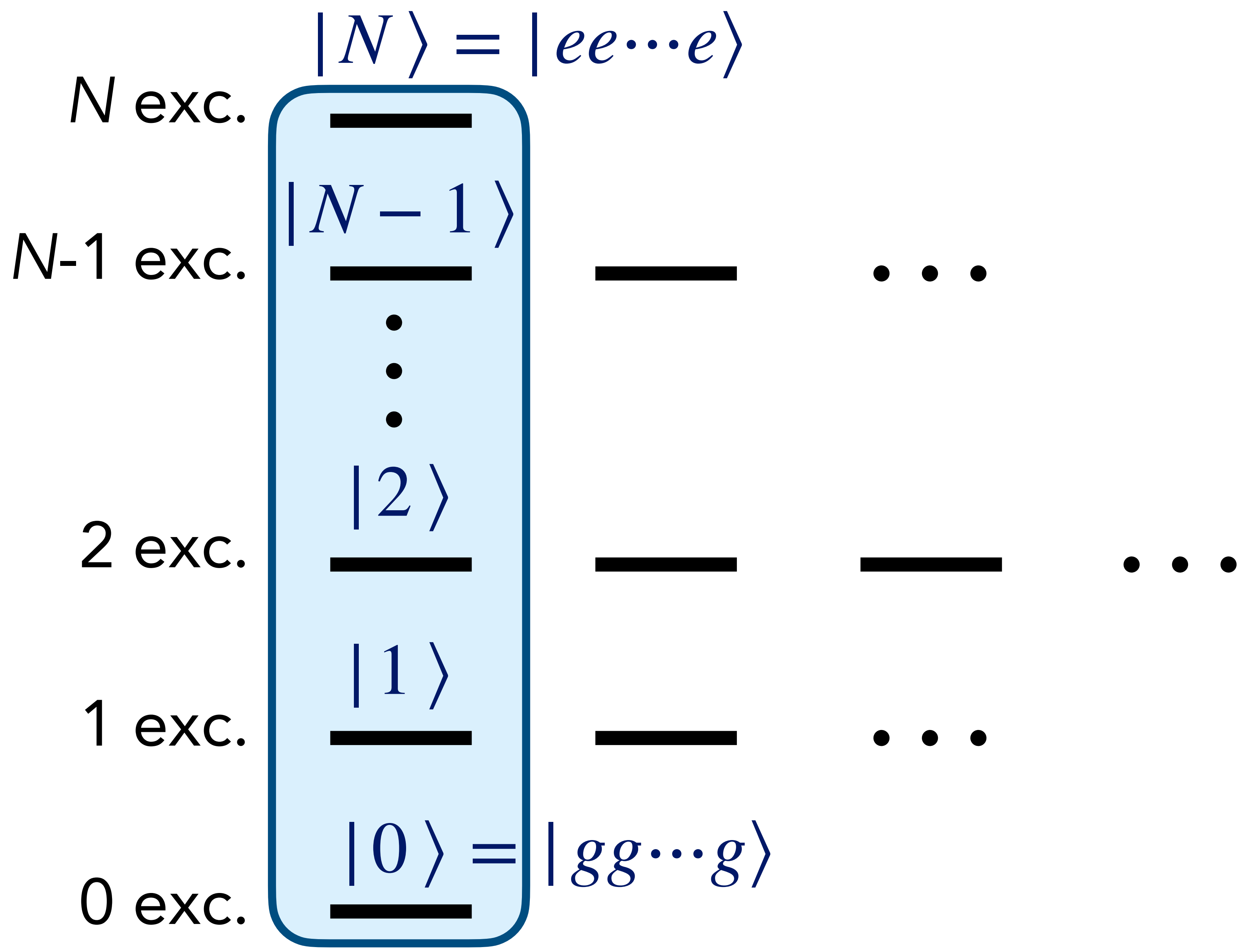

Dicke states $\quad |n\rangle \propto (\hat{S}^+)^n |0\rangle \qquad \hat{S}^+ = \sum_{i=1}^{N} \hat{\sigma}_i^+$

$\Gamma_N = \Gamma_0\, n(N-n+1)$ in state $|n\rangle$

Reaches maximum for $|n\rangle = |N/2\rangle$, with $\Gamma_N \simeq N^2\Gamma_0/4$

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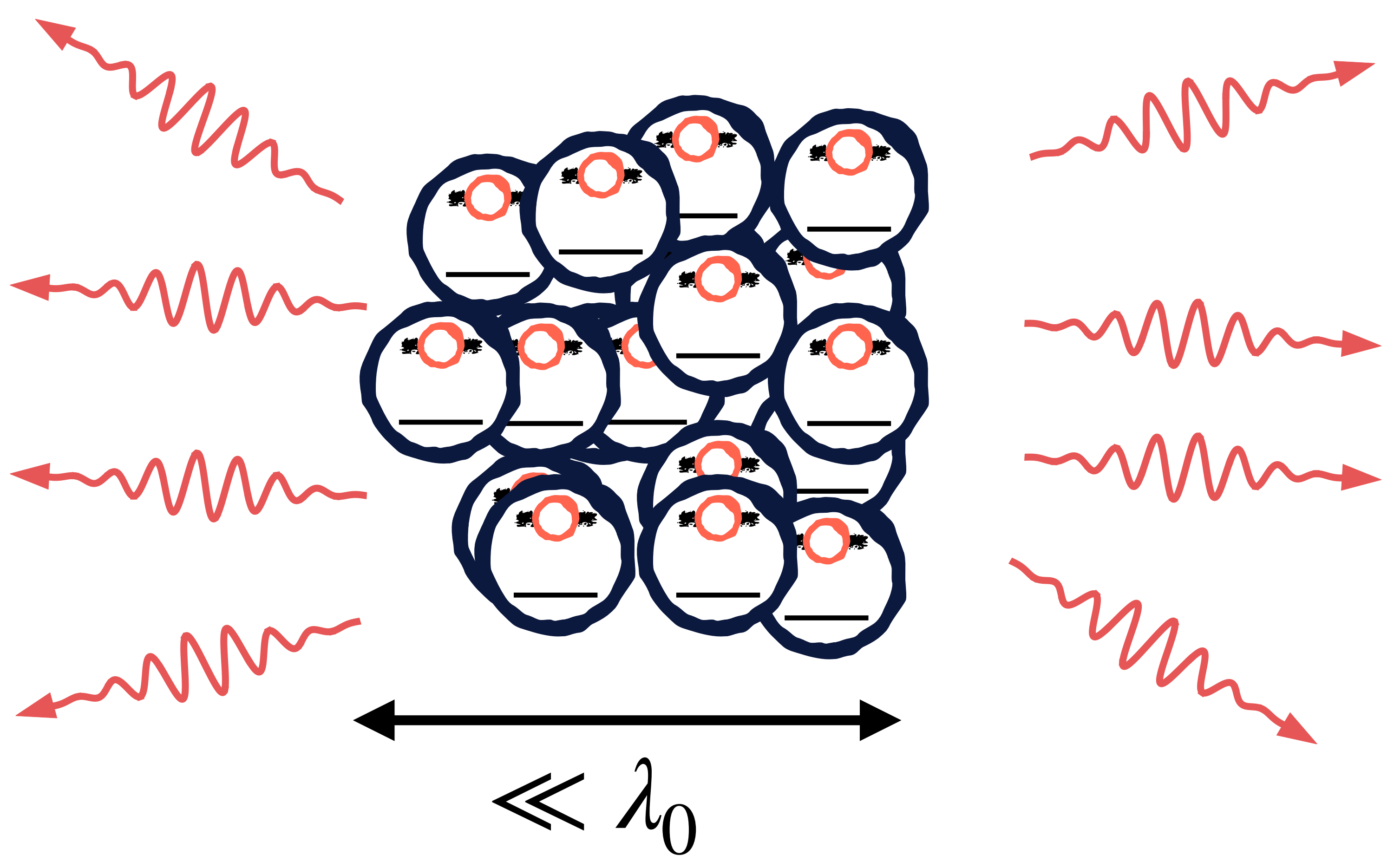

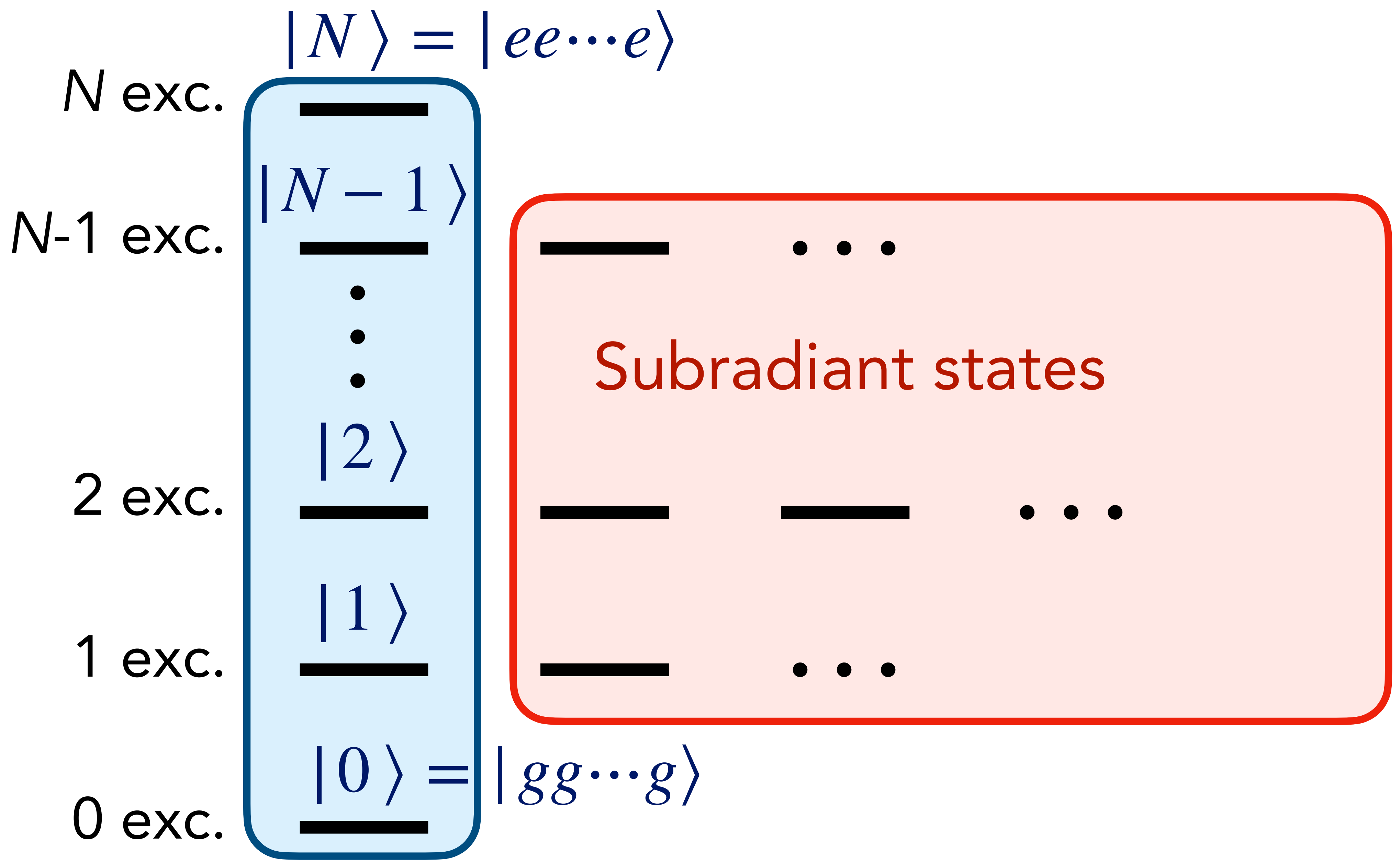

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Break Dicke symmetry:

Finite-size effects, dipole-dipole interactions…

Glicenstein *Optics Letters* **47**, 1542 (2022)

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See also Nice group (Kaiser Guerin)…

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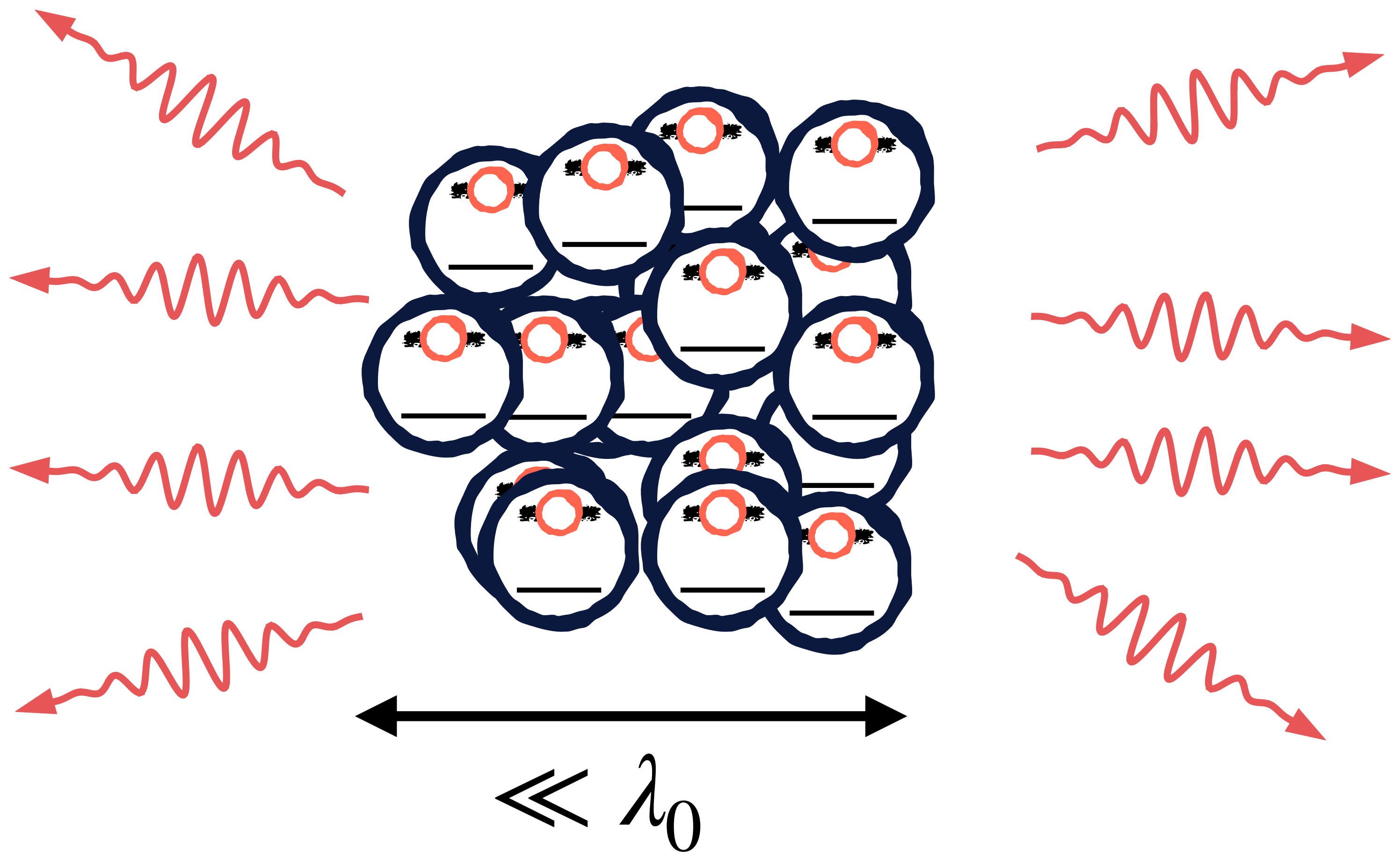

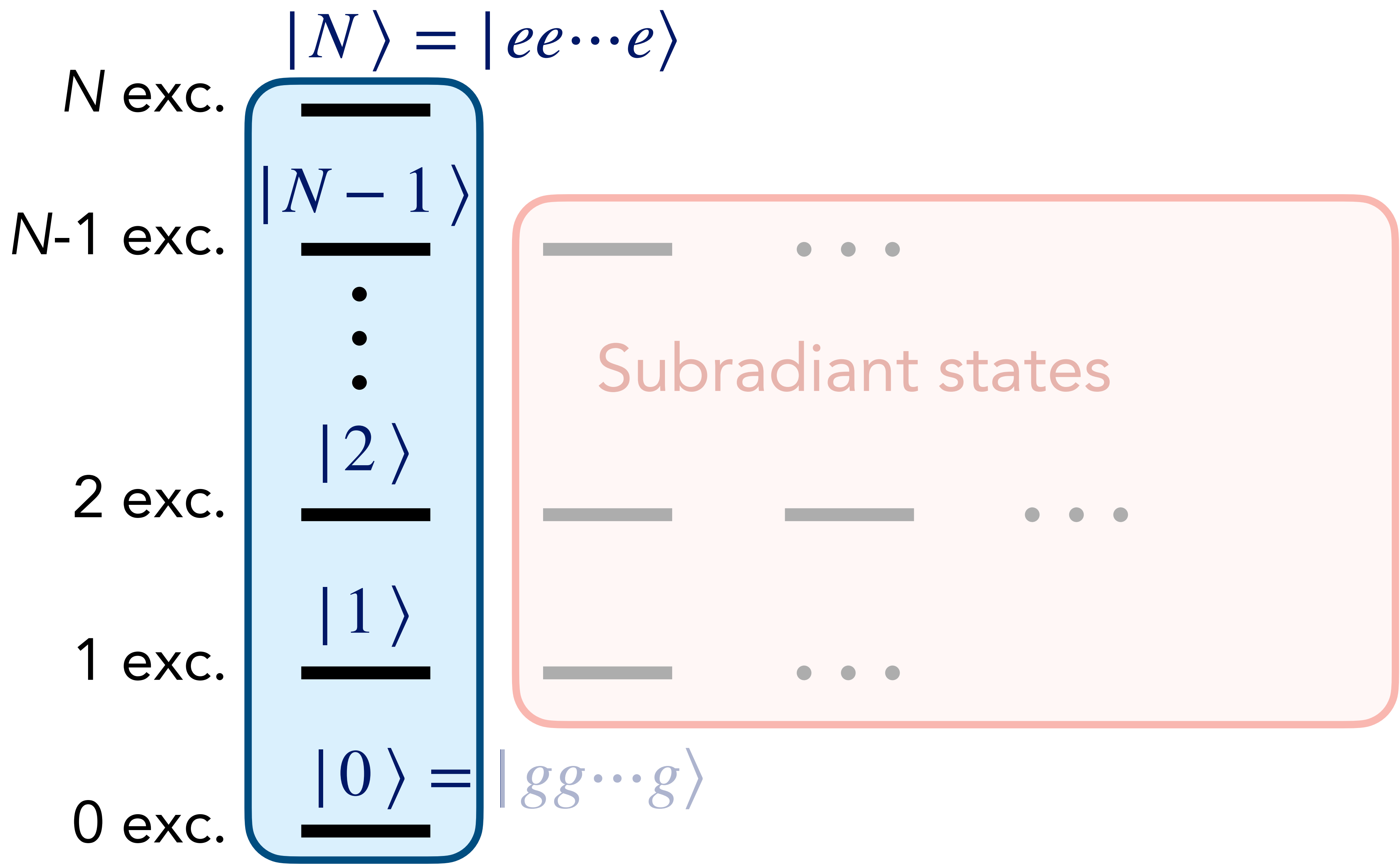

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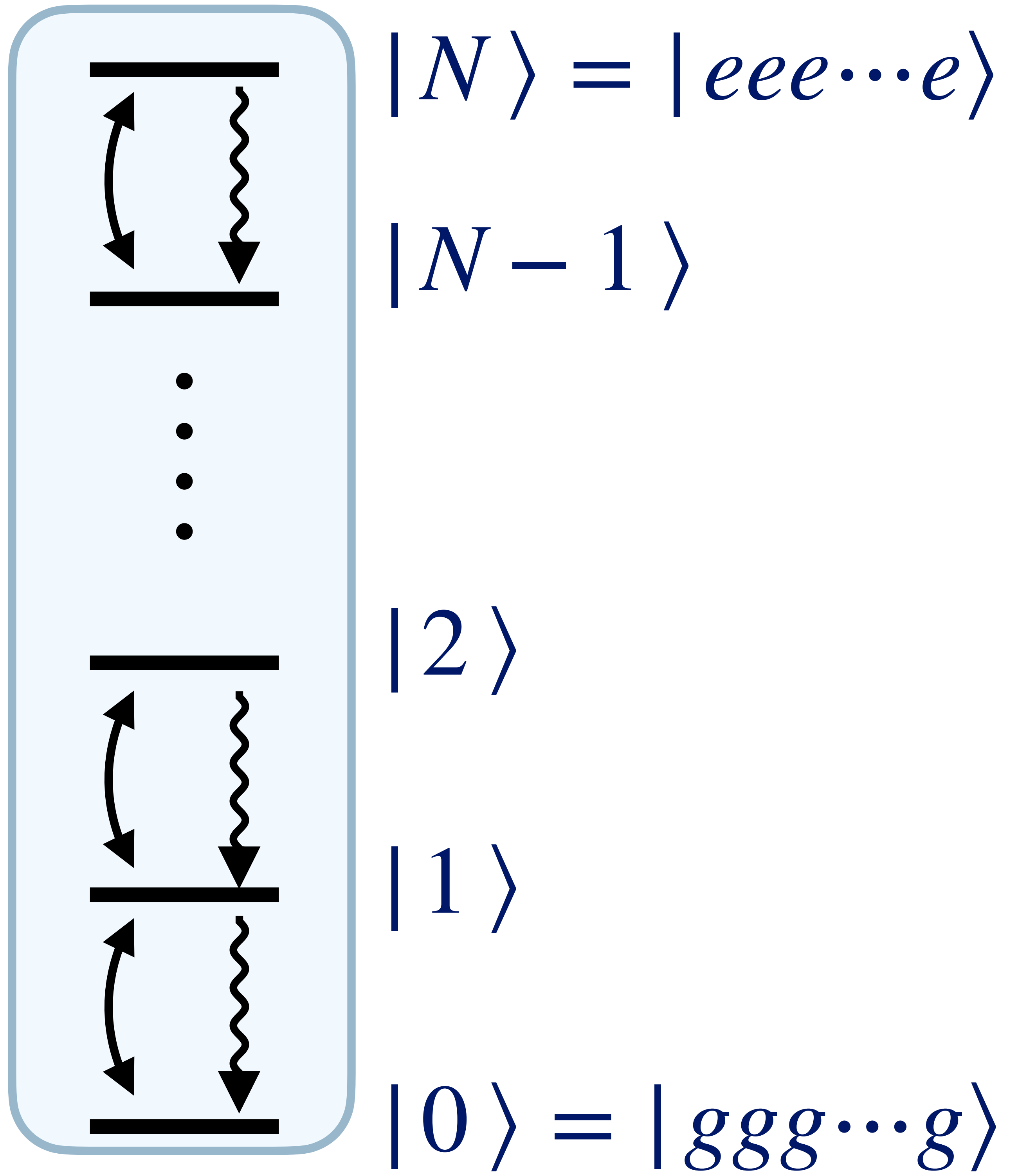
N driven atoms

Dicke symmetric conditions + classical drive

$$\dot{\hat{\rho}} = \frac{i}{\hbar}\left[\hat{\rho}, \hat{H}\right] + \frac{\Gamma_0}{2}\sum_{i,j=1}^{N} 2\hat{\sigma}_j^-\hat{\rho}\hat{\sigma}_i^+ - \hat{\sigma}_i^+\hat{\sigma}_j^-\hat{\rho} - \hat{\sigma}_i^+\hat{\sigma}_j^-\hat{\rho}$$

$$\hat{H} = \frac{\hbar\Omega_D}{2}\sum_{i=1}^{N}\hat{\sigma}_i^+ + \hat{\sigma}_i^-$$

Classical electric dipole of a single atom: $\langle\hat{\sigma}_i^-\rangle$



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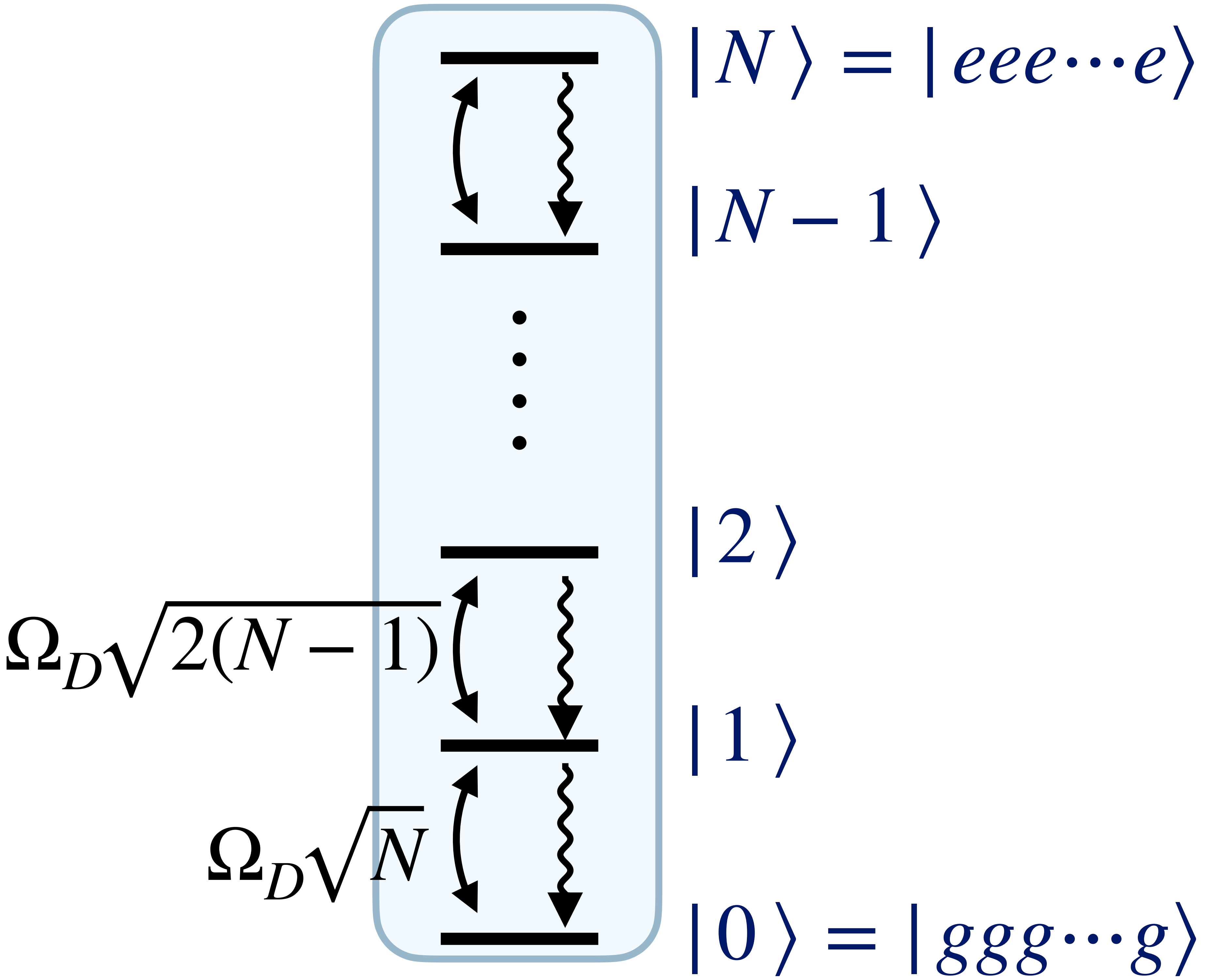
Dicke symmetric conditions + classical drive

$$\dot{\hat{\rho}} = \frac{i}{\hbar}\left[\hat{\rho}, \hat{H}\right] + \frac{\Gamma_0}{2}\left(2\hat{S}^-\hat{\rho}\hat{S}^+ - \hat{S}^+\hat{S}^-\hat{\rho} - \hat{\rho}\hat{S}^+\hat{S}^-\right)$$

$$\hat{H} = \frac{\hbar\Omega_D}{2}(\hat{S}^+ + \hat{S}^-) \qquad \hat{S}^+ = \sum_{i=1}^{N} \hat{\sigma}_i^+$$

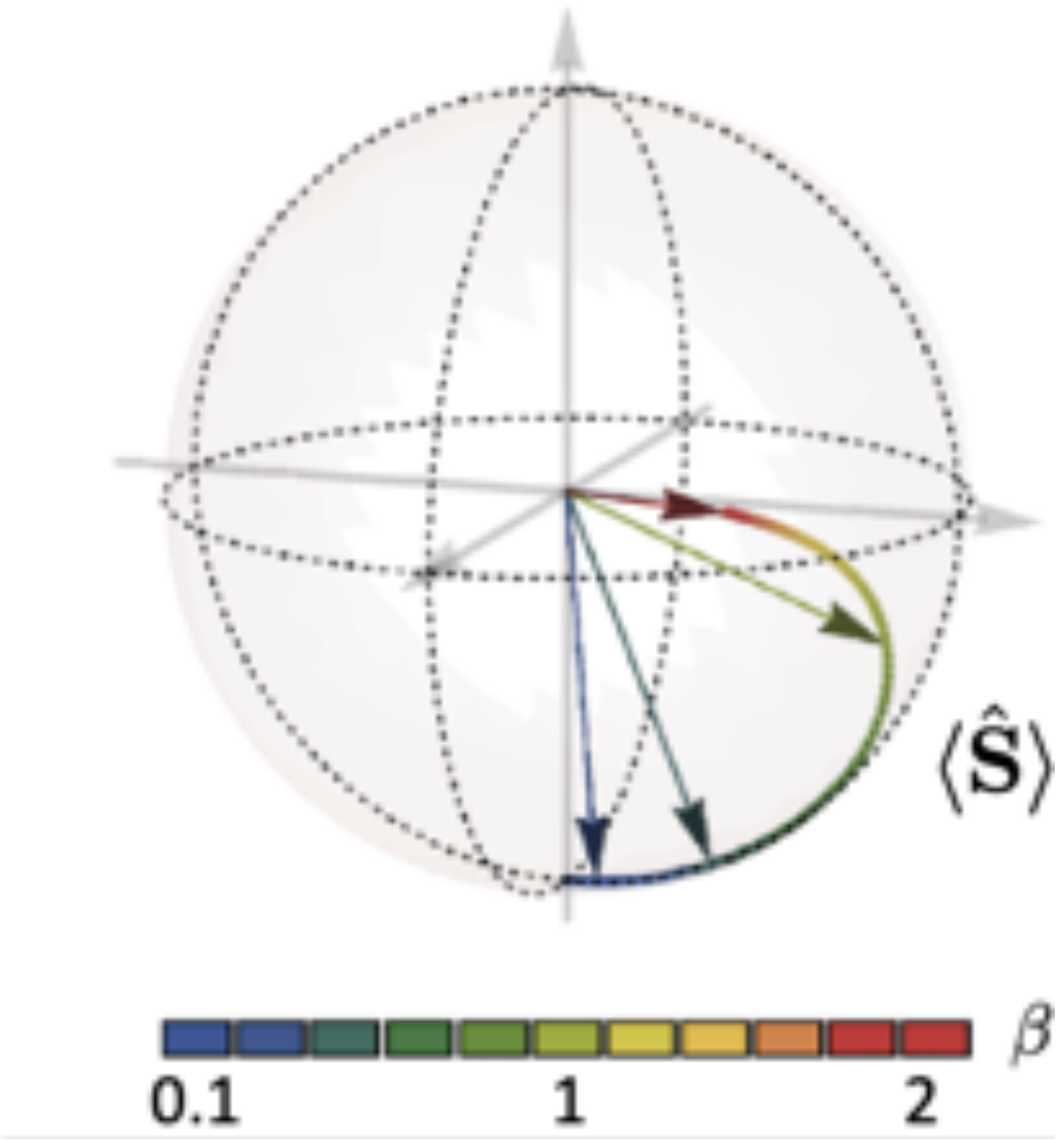
Classical electric dipole of a single atom: $\langle \hat{\sigma}_i^- \rangle$



Driven Dicke model

$$\dot{\hat{\rho}} = i\frac{\Omega_D}{2}\left(\hat{\rho}\hat{S}^{+} + \hat{\rho}\hat{S}^{-} - \hat{S}^{+}\hat{\rho} - \hat{S}^{-}\hat{\rho}\right) + \frac{\Gamma_0}{2}\left(2\hat{S}^{-}\hat{\rho}\hat{S}^{+} - \hat{S}^{+}\hat{S}^{-}\hat{\rho} - \hat{\rho}\hat{S}^{+}\hat{S}^{-}\right)$$

$$\frac{d\langle\hat{S}^{-}\rangle}{dt} = i\Omega_D\langle\hat{S}^{z}\rangle + \frac{\Gamma_0}{2}\left[\langle\hat{S}^{z}\hat{S}^{-}\rangle + \langle\hat{S}^{-}\hat{S}^{z}\rangle\right] - \frac{\Gamma_0}{2}\langle\hat{S}^{-}\rangle$$



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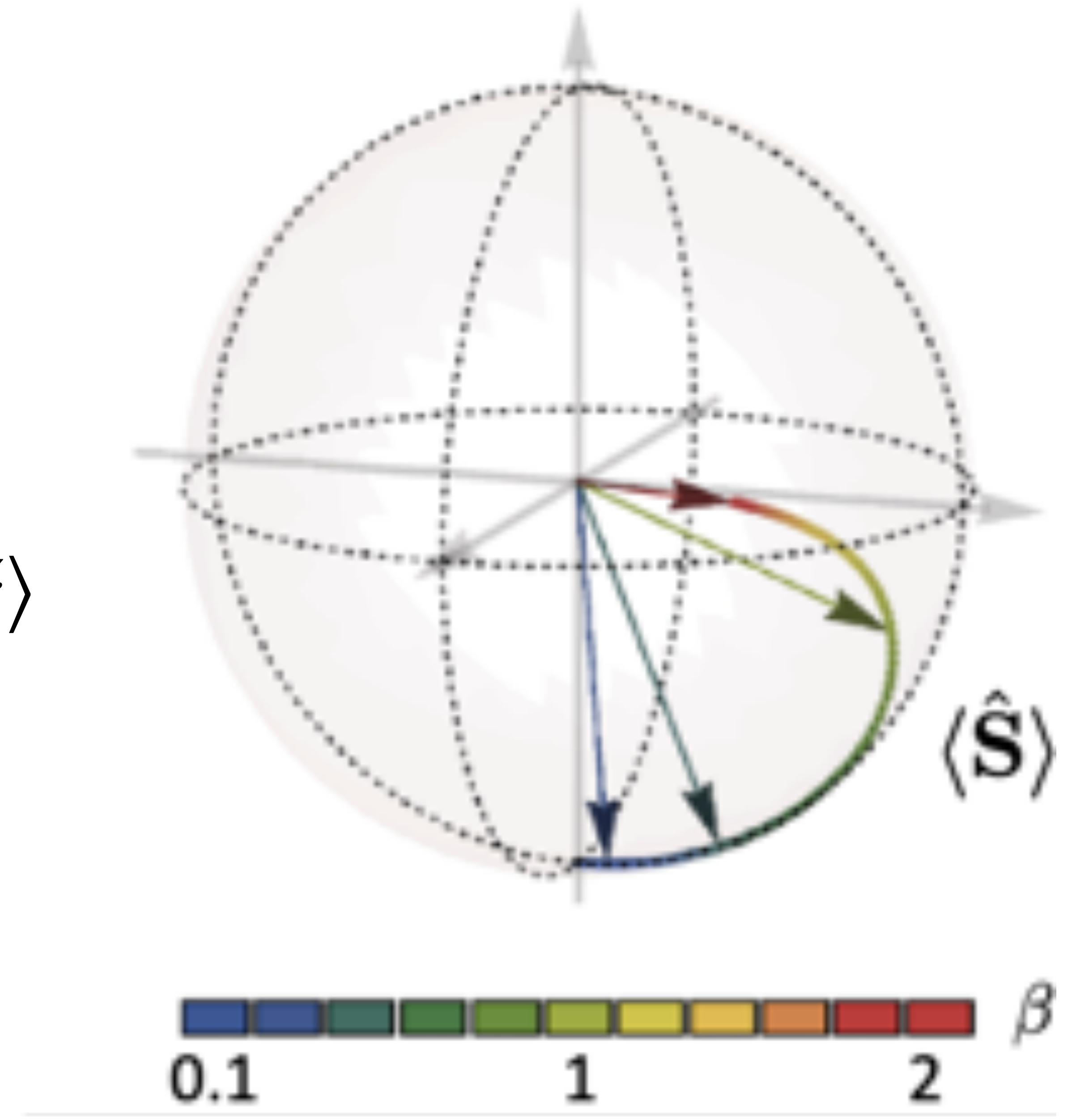
$$\dot{\hat{\rho}} = i\frac{\Omega_D}{2}\left(\hat{\rho}\hat{S}^+ + \hat{\rho}\hat{S}^- - \hat{S}^+\hat{\rho} - \hat{S}^-\hat{\rho}\right) + \frac{\Gamma_0}{2}\left(2\hat{S}^-\hat{\rho}\hat{S}^+ - \hat{S}^+\hat{S}^-\hat{\rho} - \hat{\rho}\hat{S}^+\hat{S}^-\right)$$

$$\frac{d\langle\hat{S}^-\rangle}{dt} = i\Omega_D\langle\hat{S}^z\rangle + \frac{\Gamma_0}{2}\left[\langle\hat{S}^z\hat{S}^-\rangle + \langle\hat{S}^-\hat{S}^z\rangle\right] - \frac{\Gamma_0}{2}\langle\hat{S}^-\rangle$$

$$\frac{d\langle\hat{S}^-\rangle}{dt} = \left(i\Omega_D + \Gamma_0\langle\hat{S}^-\rangle\right)\langle\hat{S}^z\rangle - \frac{\Gamma_0}{2}\langle\hat{S}^-\rangle$$

assuming $\langle\hat{S}^-\hat{S}^z\rangle = \langle\hat{S}^-\rangle\langle\hat{S}^z\rangle$



Effective Rabi frequency: $\Omega_{\mathrm{eff}} = \Omega_D - i\Gamma_0\langle\hat{S}^-\rangle$

Screening by collective dipole

Driven Dicke model

$$\frac{d\langle \hat{S}^- \rangle}{dt} = i\Omega_D \langle \hat{S}^z \rangle + \frac{\Gamma_0}{2}\left[\langle \hat{S}^z \hat{S}^- \rangle + \langle \hat{S}^- \hat{S}^z \rangle\right] - \frac{\Gamma_0}{2}\langle \hat{S}^- \rangle$$

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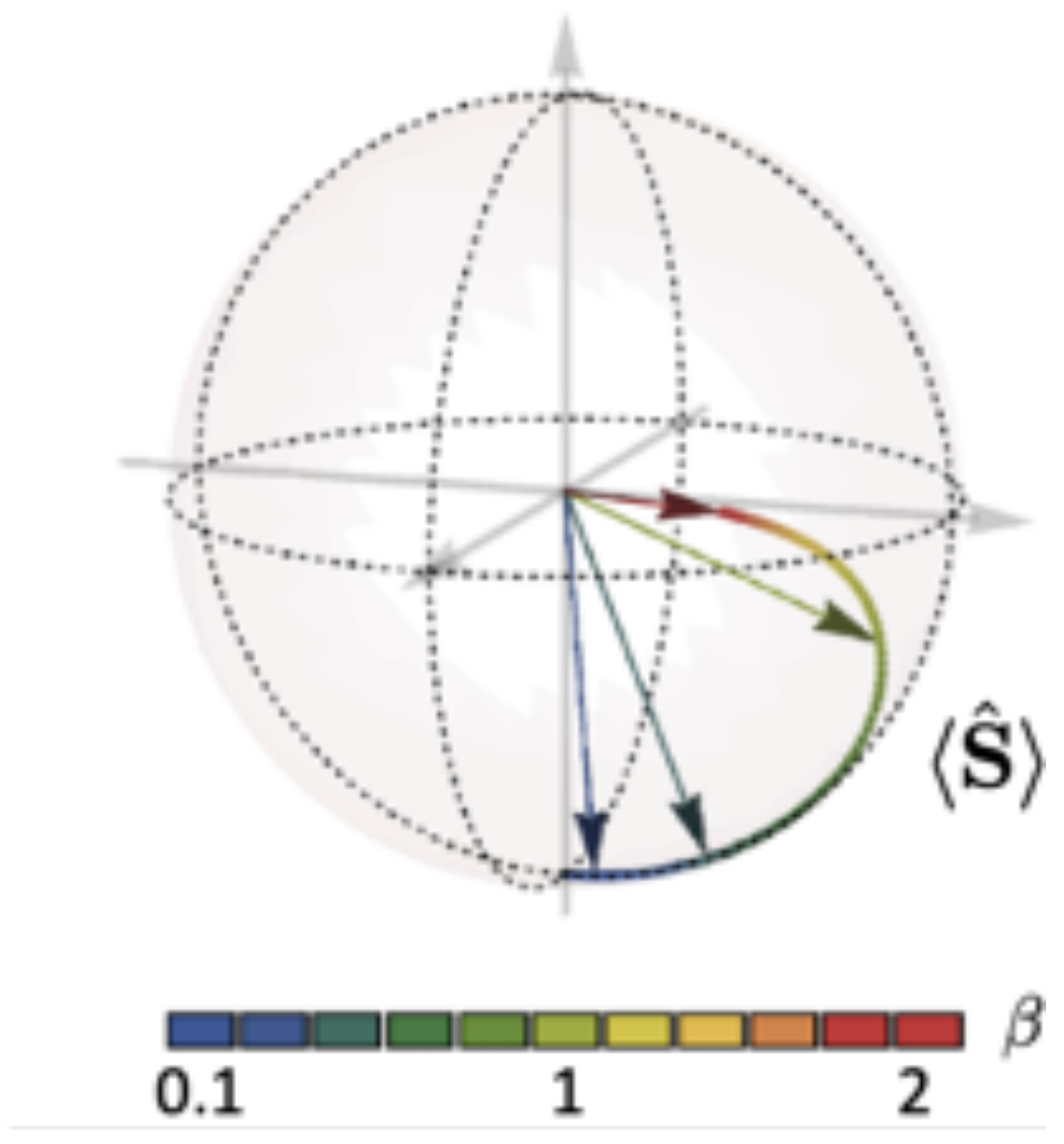

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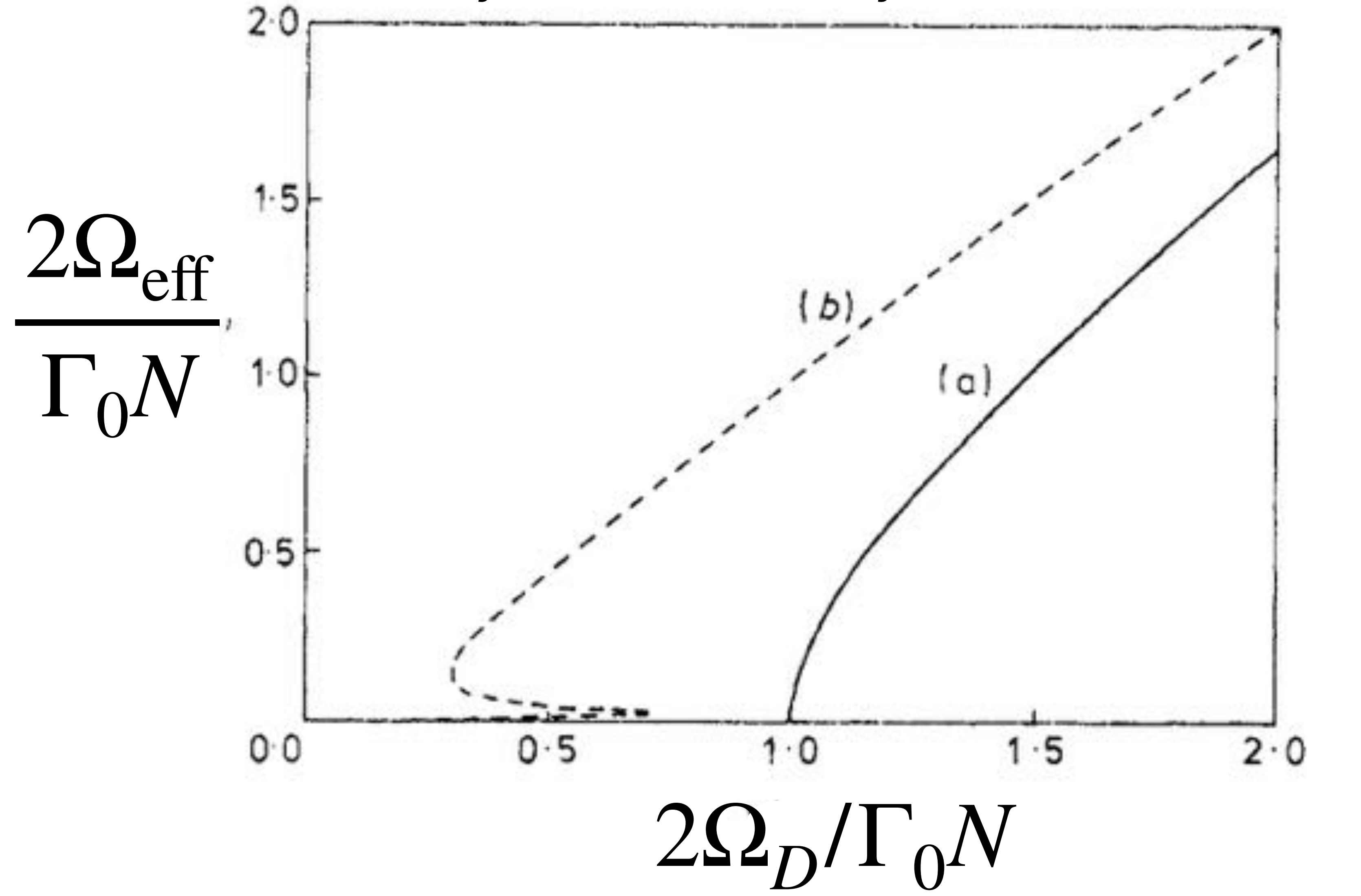
D. F. Walls, *J. Phys. B At. Mol. Phys.* **13**, 2001 (1973).



Maximum achievable dipole: $\langle\hat{S}^-\rangle \simeq -iN/2$

Recover Rabi oscillations for $\Omega_D > N\Gamma_0/2$

Scaling with $\beta = 2\Omega_D/\Gamma_0 N$

Driven Dicke model

- $\beta < 1$ Magnetised phase

Collective dipole established

Emission rate $\Gamma_0 \langle \hat{S}^+ \hat{S}^- \rangle \propto \Omega_D^2 / \Gamma_0$

- $\beta > 1$ Superradiant phase

Superradiant collective spont. em. dominates

Emission rate $\Gamma_0 \langle \hat{S}^+ \hat{S}^- \rangle \propto N^2 \Gamma_0$

Driven Dicke model

- $\beta < 1$ Magnetised phase

Collective dipole established

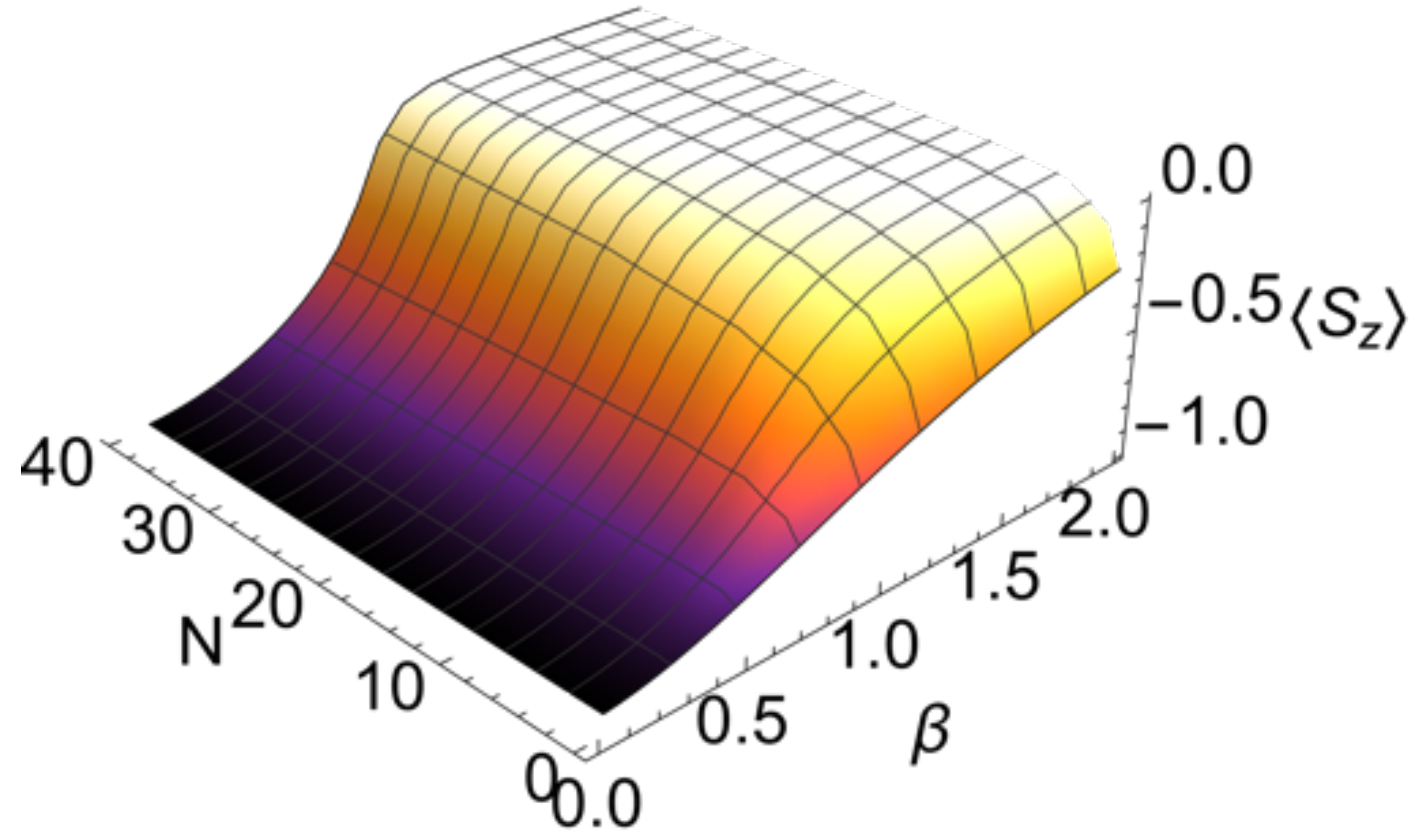
Emission rate $\Gamma_0 \langle \hat{S}^+ \hat{S}^- \rangle \propto \Omega_D^2 / \Gamma_0$

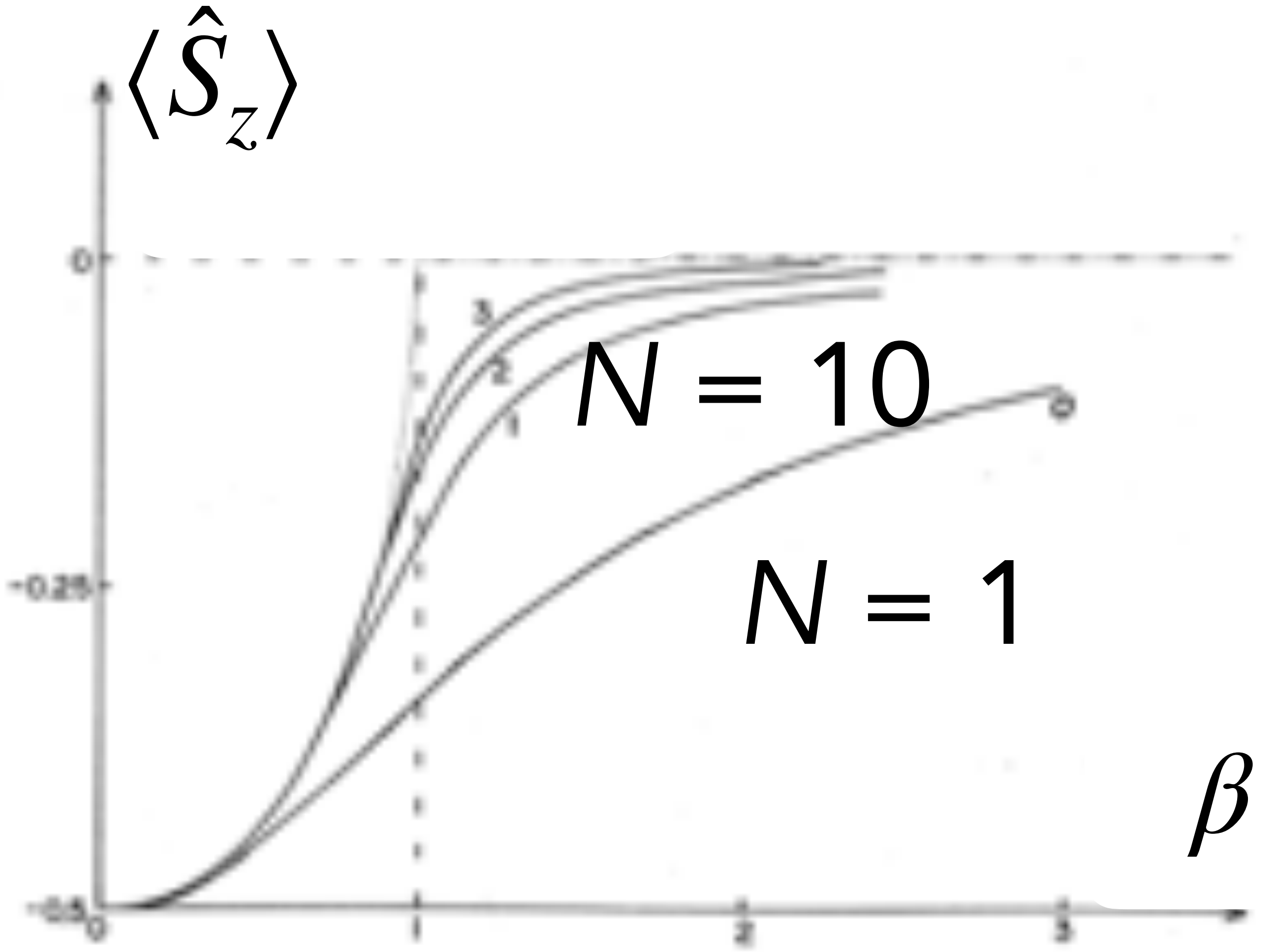
Phase transition for $N \to \infty$

- $\beta > 1$ Superradiant phase

Superradiant collective spont. em. dominates

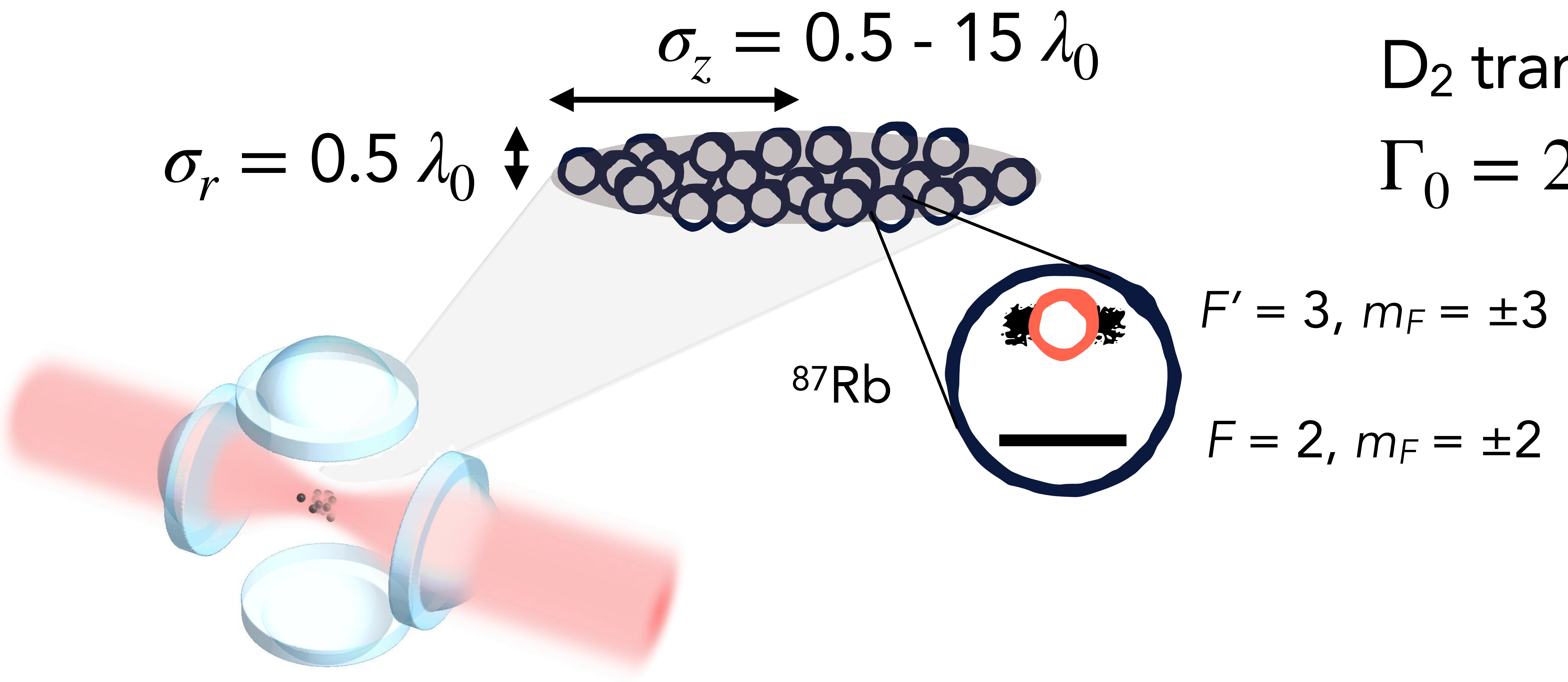
Emission rate $\Gamma_0 \langle \hat{S}^+ \hat{S}^- \rangle \propto N^2 \Gamma_0$





Narducci *et al.*, *Phys Rev A* **18**, 1571–1576 (1978).

Dense clouds of 2-level atoms



D$_2$ transition, $\lambda_0 = 780$ nm,

$\Gamma_0 = 2\pi \times 6$ MHz, $\tau_0 \simeq 25$ ns

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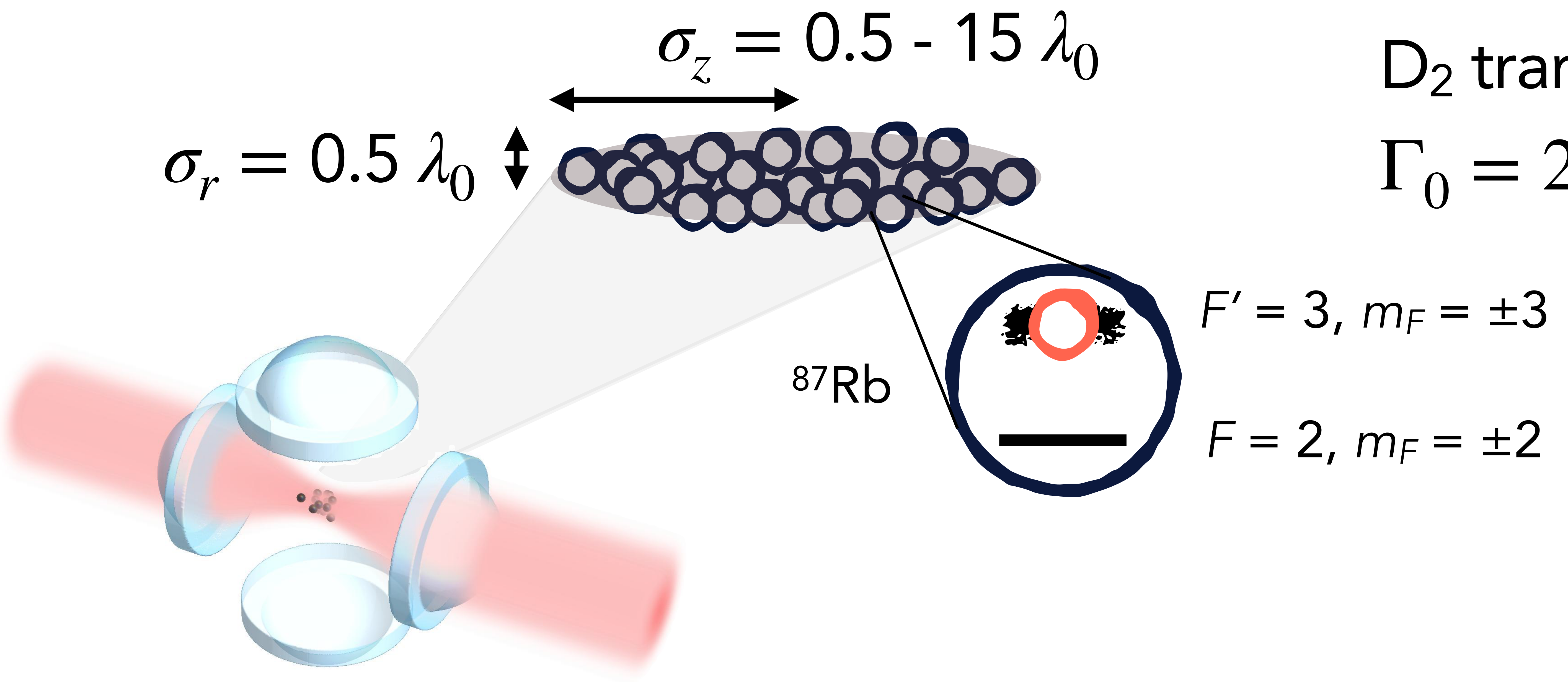

D_2 transition, $\lambda_0 = 780$ nm,

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Tight optical dipole trap (waist 1.5 - 3 μm)

Clouds of $N = 100 - 5000$ atoms

$T \sim 500$ μK: no Doppler broadening, frozen distribution

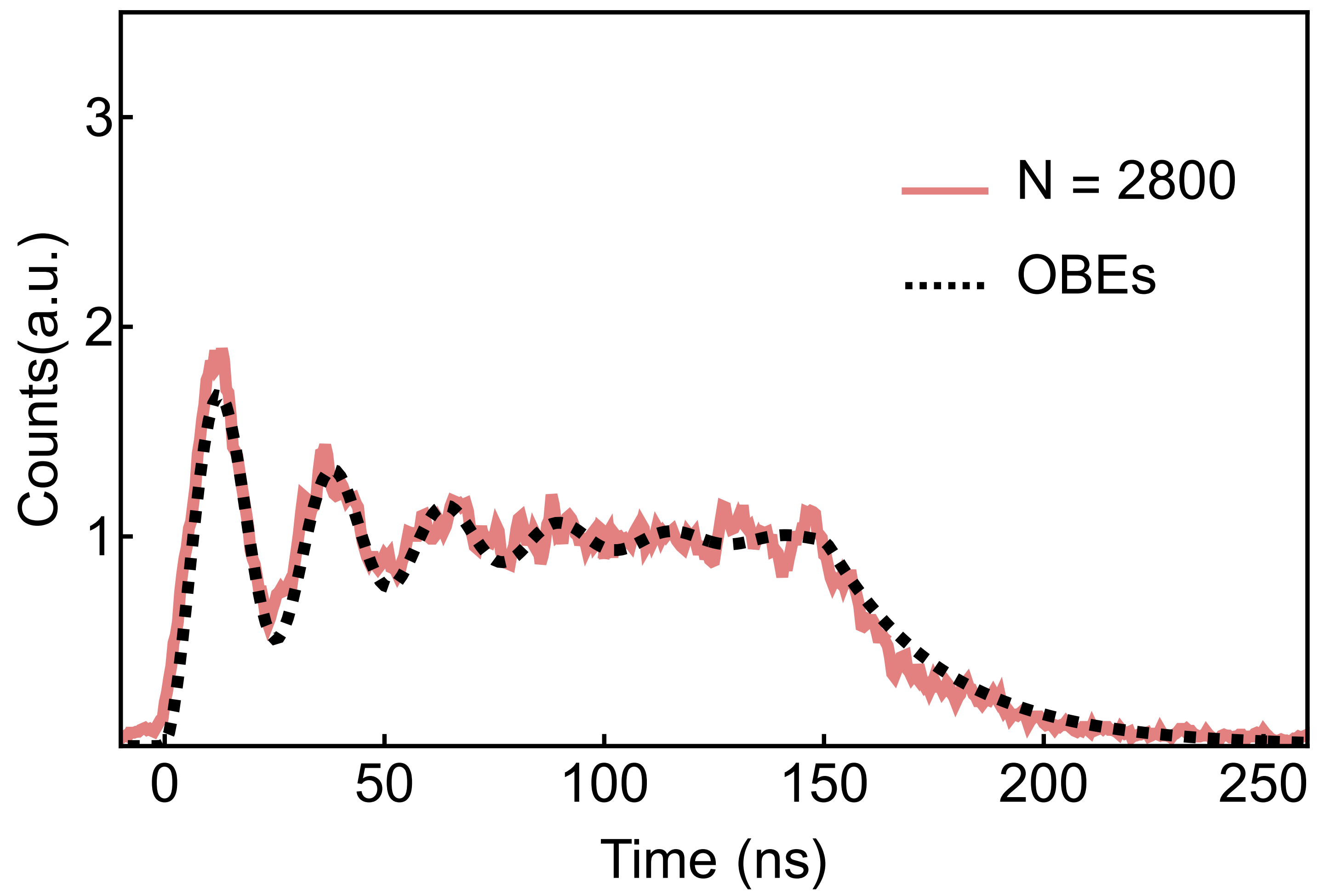
Optical pumping + magnetic field isolate 2 levels

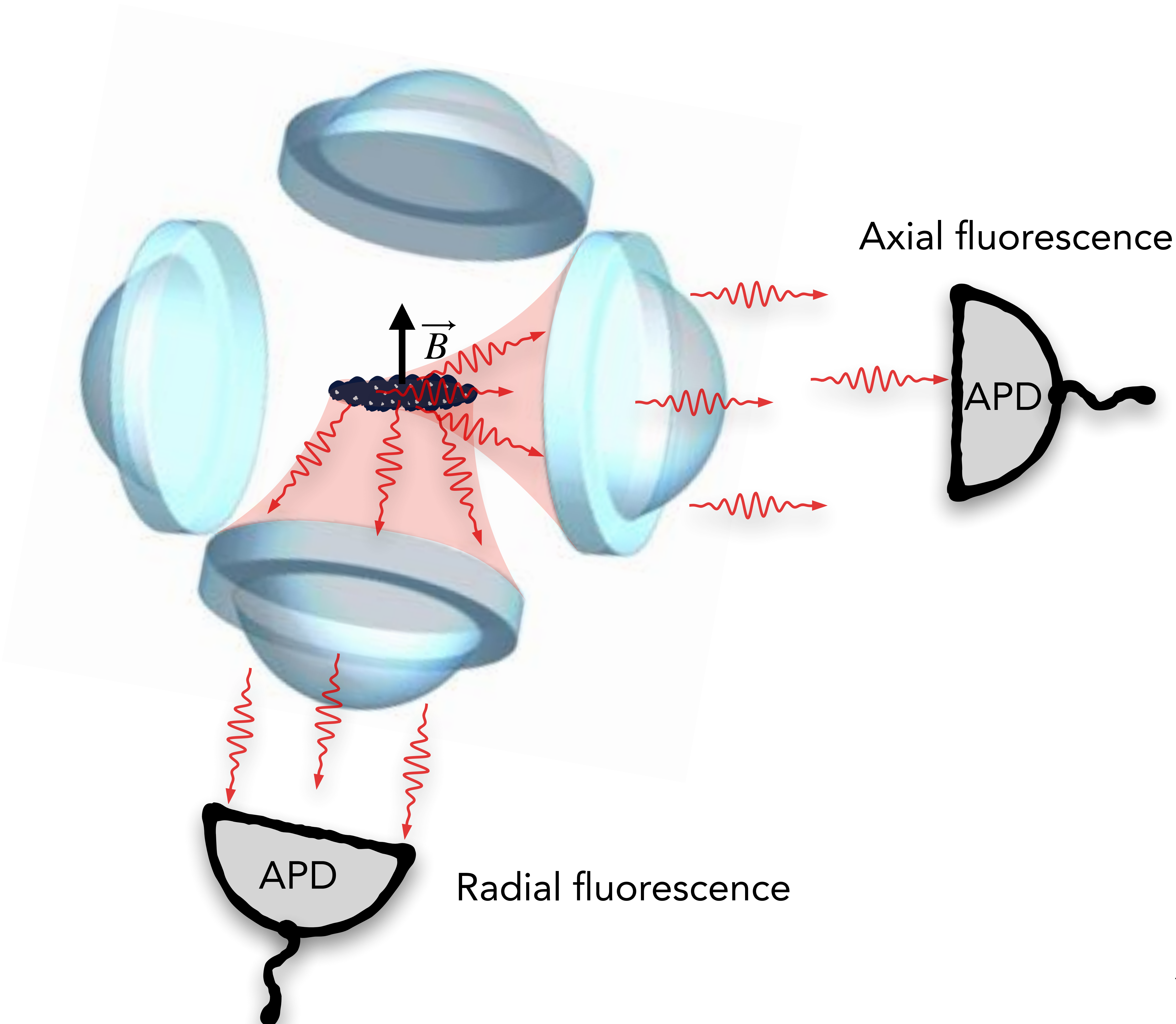
Dense clouds of 2-level atoms

Observations

Single photon detection (NA=0.45)

Along two directions





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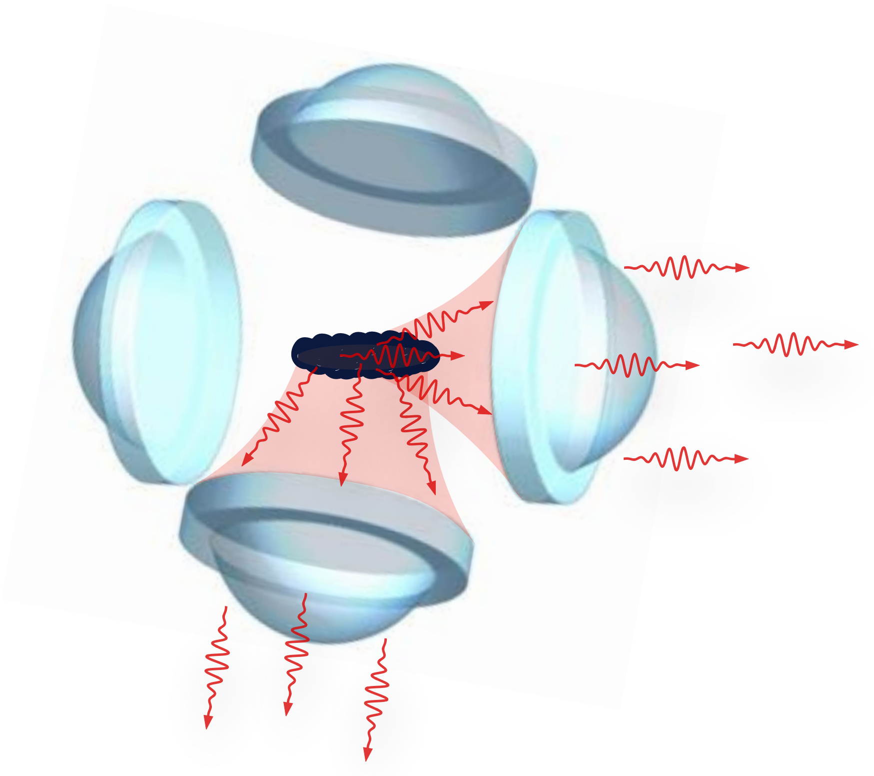
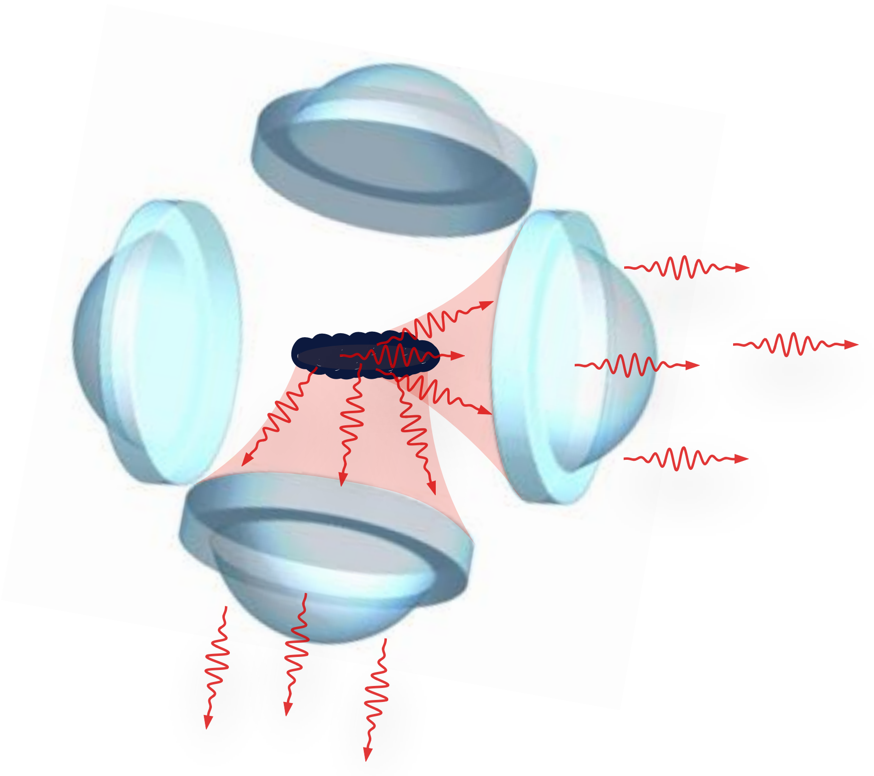


N-atom spontaneous emission

Intensity $I(\boldsymbol{r}) = \langle \hat{E}^-(\boldsymbol{r})\hat{E}^+(\boldsymbol{r})\rangle$

$$\hat{E}^+(\boldsymbol{r}) \propto \sum_n G(\boldsymbol{r}, \boldsymbol{r}_i, \omega_0)\hat{\sigma}_n^-$$



$$I_N(\boldsymbol{k}) = I_1(\boldsymbol{k}) \sum_n \left[\langle \hat{e}_n \rangle + \sum_{m \neq n} e^{i\boldsymbol{k}\cdot(\boldsymbol{r}_m - \boldsymbol{r}_n)} \langle \hat{\sigma}_m^+ \hat{\sigma}_n^- \rangle \right]$$

Dissipation

N-atom spontaneous emission

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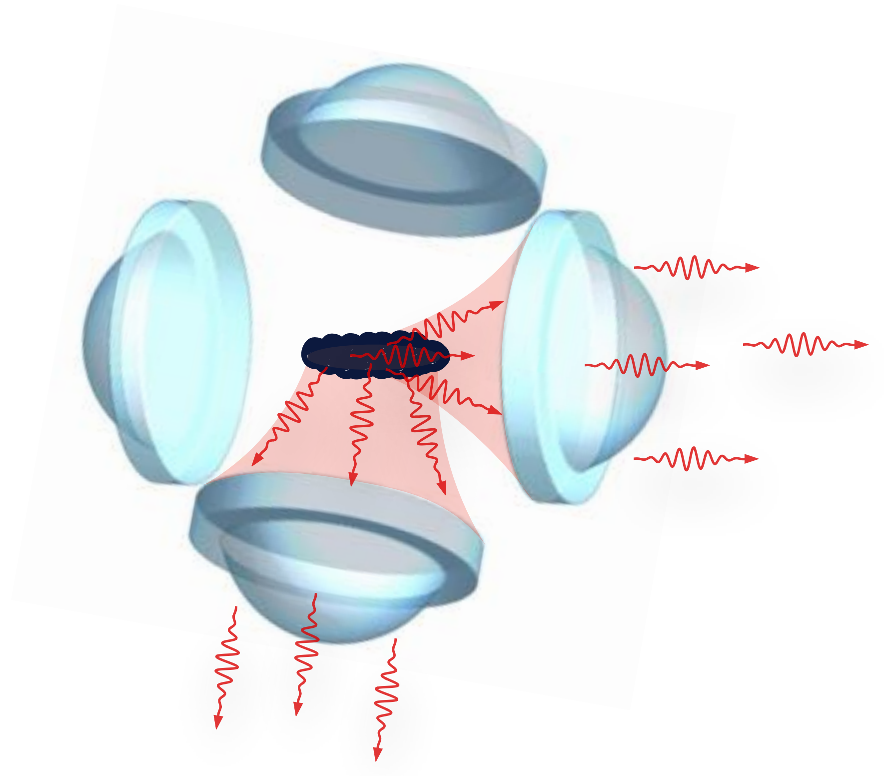

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Dissipation

Correlations

N-atom spontaneous emission

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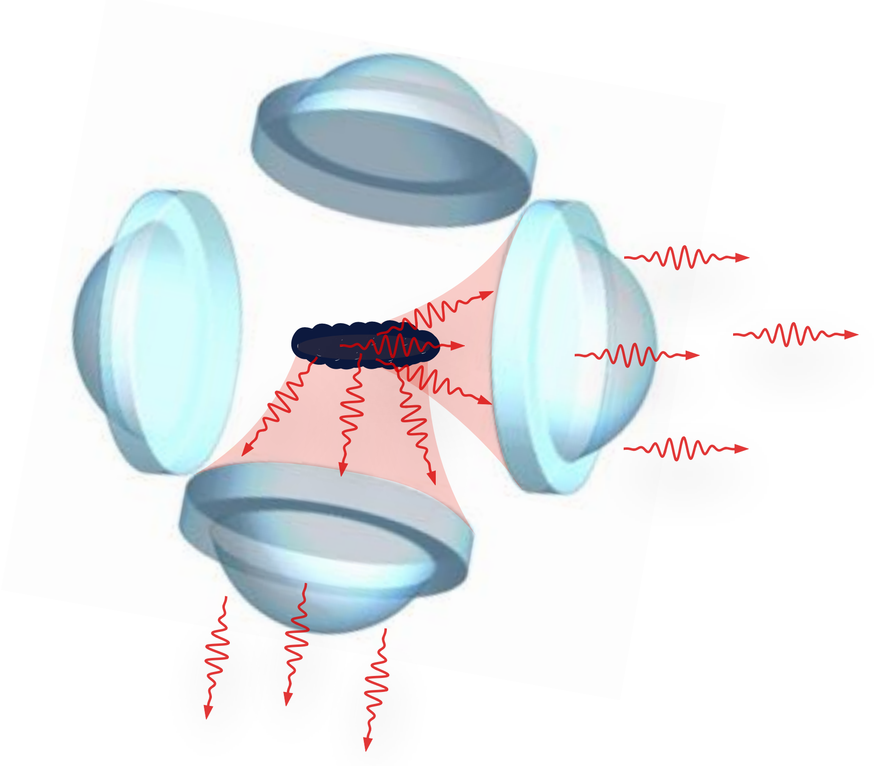

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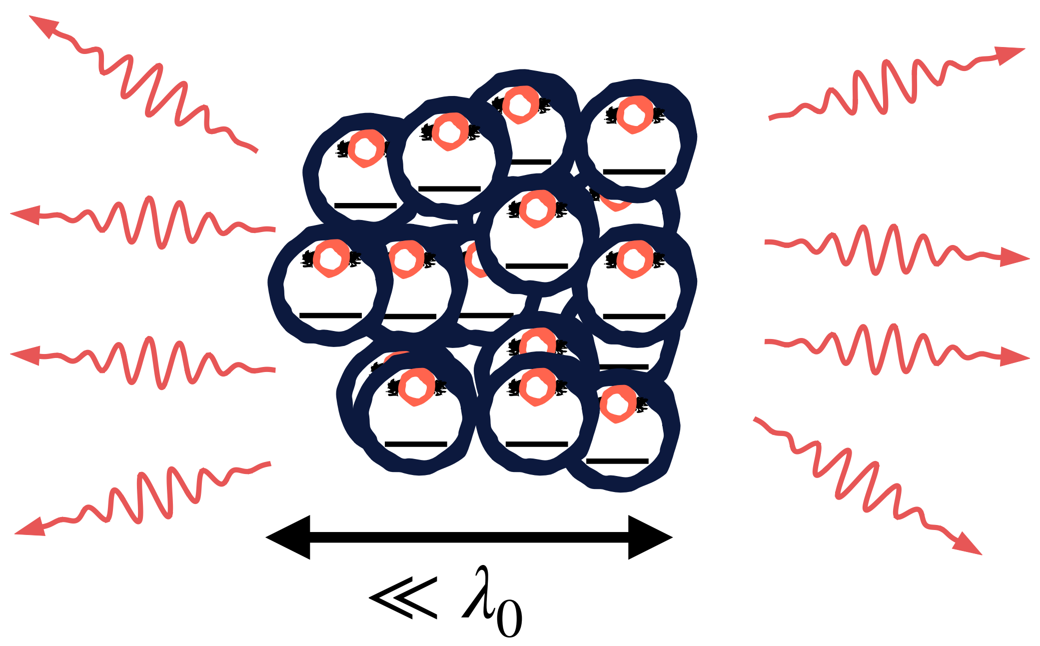

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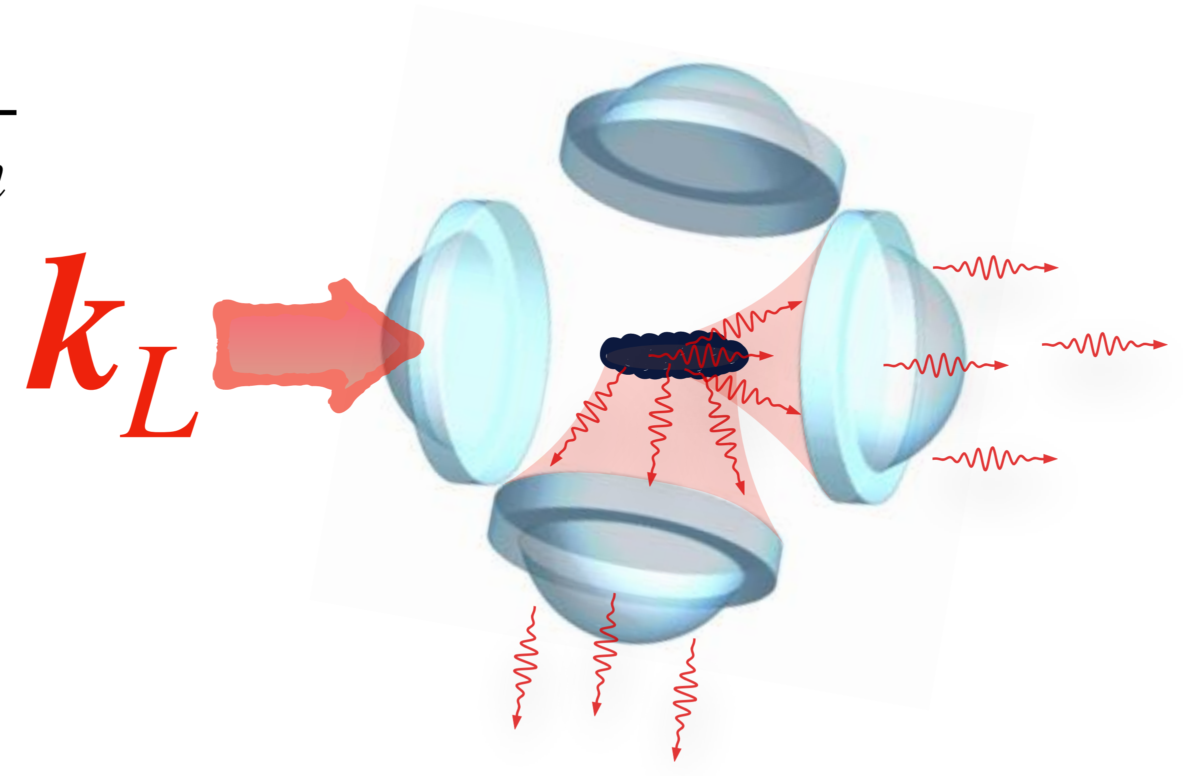

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Correlations

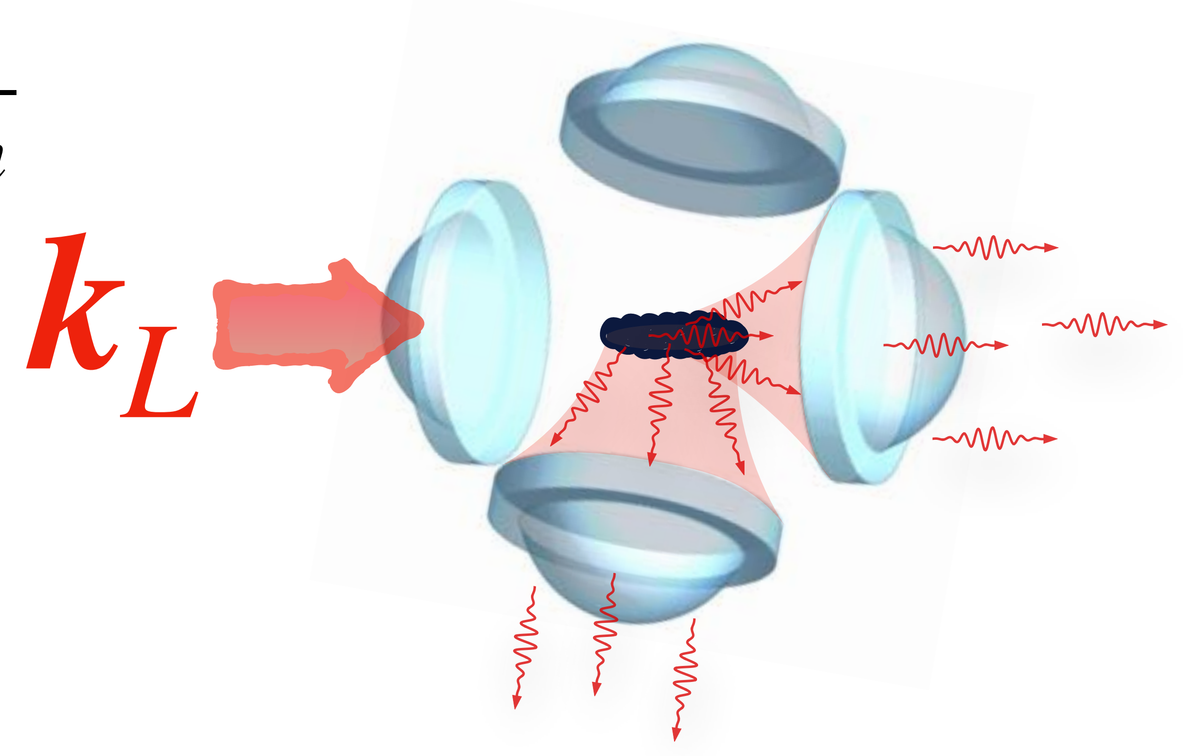
Gross & Haroche, *Physics Reports* **93**, 301 (1982).

Allen & Eberly, *Optical resonance and two-level atoms*, Courier Corp. (1987)

N-atom spontaneous emission

Intensity $I(\boldsymbol{r}) = \langle \hat{E}^{-}(\boldsymbol{r})\hat{E}^{+}(\boldsymbol{r})\rangle$

$$\hat{E}^{+}(\boldsymbol{r}) \propto \sum_{n} G(\boldsymbol{r}, \boldsymbol{r}_i, \omega_0)\hat{\sigma}_n^{-}$$



$$I_N(\boldsymbol{k}) = I_1(\boldsymbol{k}) \sum_n \left[\langle \hat{e}_n \rangle + \sum_{m \neq n} e^{i\boldsymbol{k}\cdot(\boldsymbol{r}_m - \boldsymbol{r}_n)} \langle \hat{\sigma}_m^{+} \hat{\sigma}_n^{-} \rangle \right]$$

Dissipation

Correlations

Spin wave: $\langle \hat{\sigma}_m^{+} \hat{\sigma}_n^{-} \rangle = e^{-i\boldsymbol{k}_{SW}\cdot(\boldsymbol{r}_m - \boldsymbol{r}_n)} \langle \hat{\sigma}_1^{+} \hat{\sigma}_2^{-} \rangle$

E.g. laser driving: $|\psi\rangle = \prod_n \left(\cos\theta |g_n\rangle + e^{-i\boldsymbol{k}_L\cdot\boldsymbol{r}_n} \sin\theta |e_n\rangle \right)$

$$\langle \hat{\sigma}_1^{+} \hat{\sigma}_2^{-} \rangle = \cos\theta \sin\theta$$

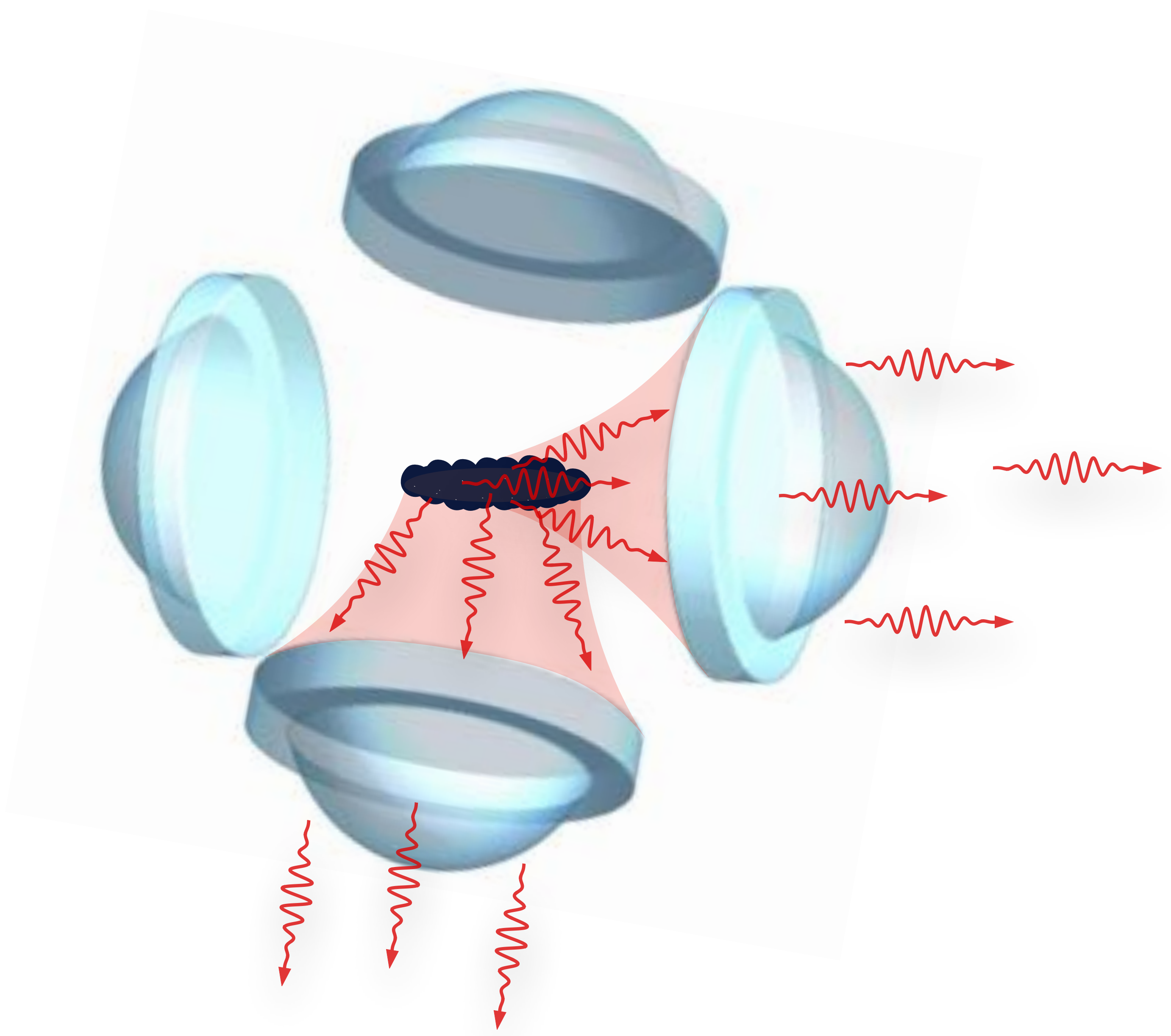
$$I_N(\boldsymbol{k}) = I_1(\boldsymbol{k}) \left[\sum_n \langle \hat{e}_n \rangle + \langle \hat{\sigma}_1^{+} \hat{\sigma}_2^{-} \rangle \sum_{m,n} e^{i(\boldsymbol{k} - \boldsymbol{k}_{SW})\cdot(\boldsymbol{r}_m - \boldsymbol{r}_n)} \right]$$

Gross & Haroche, *Physics Reports* **93**, 301 (1982).

Allen & Eberly, *Optical resonance and two-level atoms*, Courier Corp. (1987)

N-atom spontaneous emission

$$I_N(\boldsymbol{k}) = I_1(\boldsymbol{k}) \left[N\langle \hat{e} \rangle + N^2 \langle \hat{\sigma}_1^+ \hat{\sigma}_2^- \rangle \left| \frac{1}{N} \sum_n e^{i(\boldsymbol{k}-\boldsymbol{k}_{SW})\cdot \boldsymbol{r}_n} \right|^2 \right]$$



Gross & Haroche, *Physics Reports* **93**, 301 (1982).

Allen & Eberly, *Optical resonance and two-level atoms*, Courier Corp. (1987)

N-atom spontaneous emission

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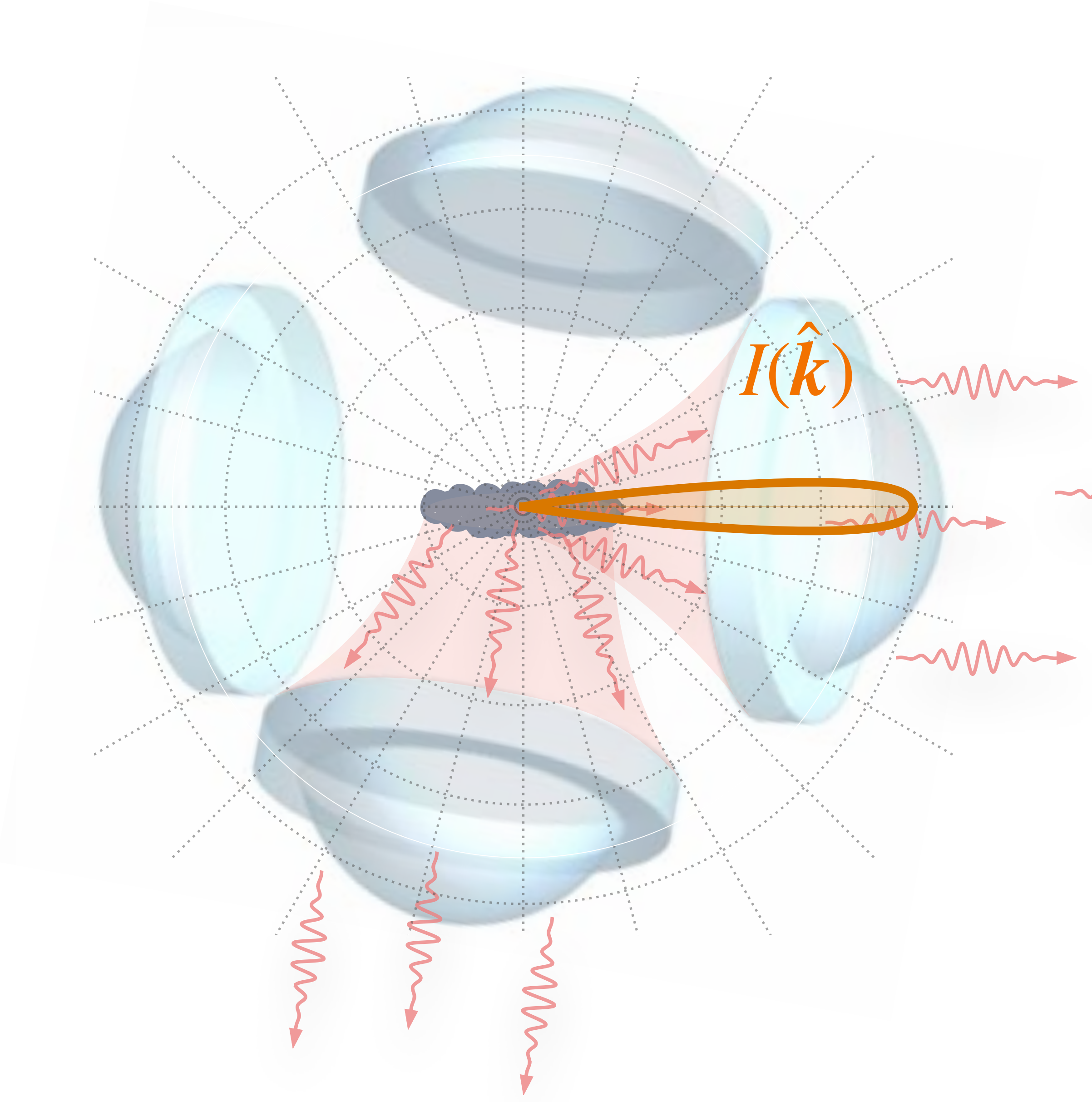

$\Delta\Omega \sim 1/L_{\text{cloud}}$

$$\mu(\boldsymbol{k}_{SW}) = \frac{P_{\text{coop}}}{NP_1} \sim \frac{\Delta\Omega}{4\pi} \qquad C = \mu N$$

Dicke case: $\mu = 1$

General case: Effective atom number

$$N \to \tilde{N} = \mu N$$

For large, dilute clouds, one has $\mu N = OD$

Gross & Haroche, *Physics Reports* **93**, 301 (1982).

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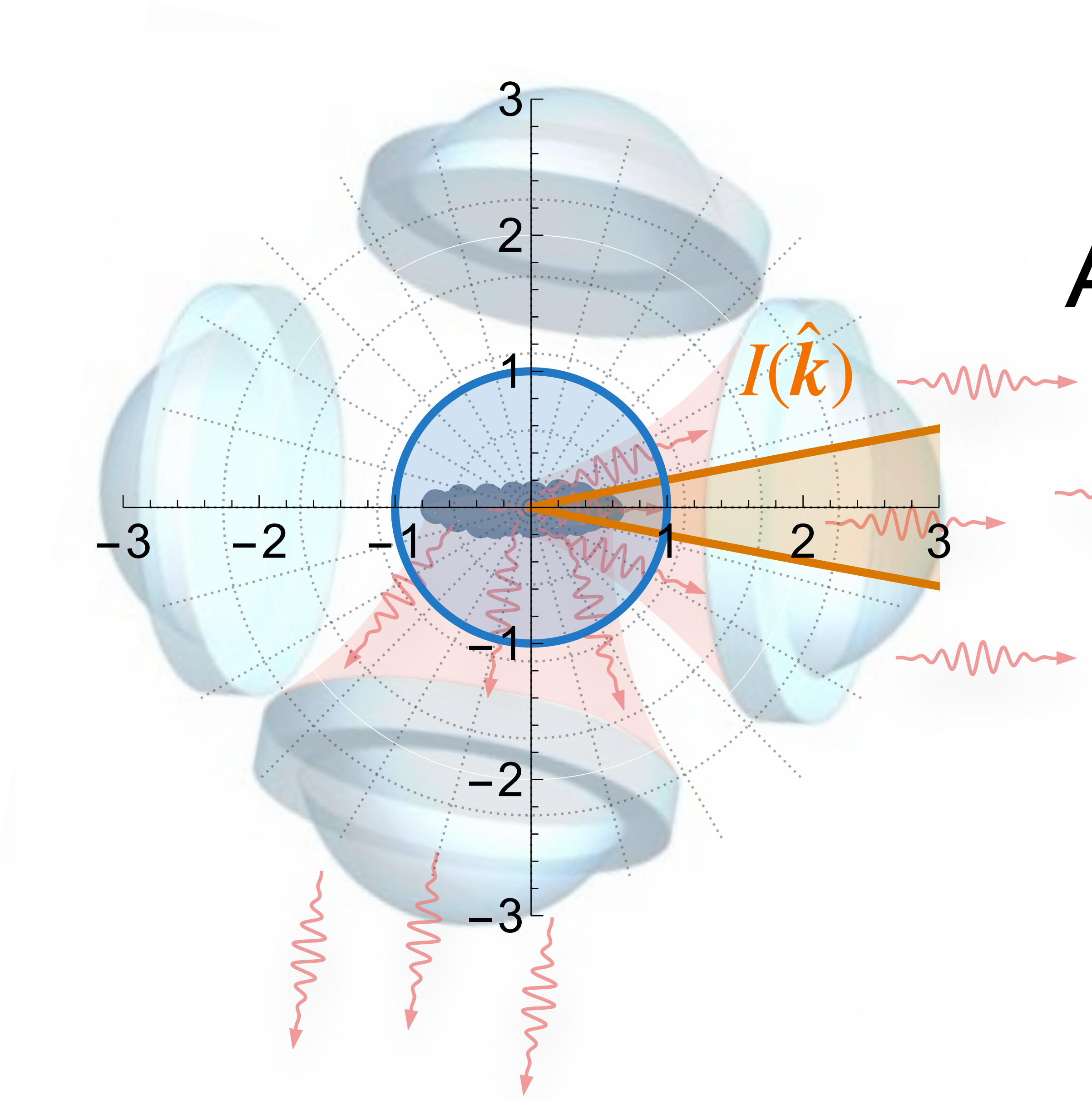


Axial rate: correlations

$\Delta\Omega \sim 1/L_{\text{cloud}}$

Radial rate: population

Dicke case: $\mu = 1$

General case: Effective atom number

$$N \rightarrow \tilde{N} = \mu N$$

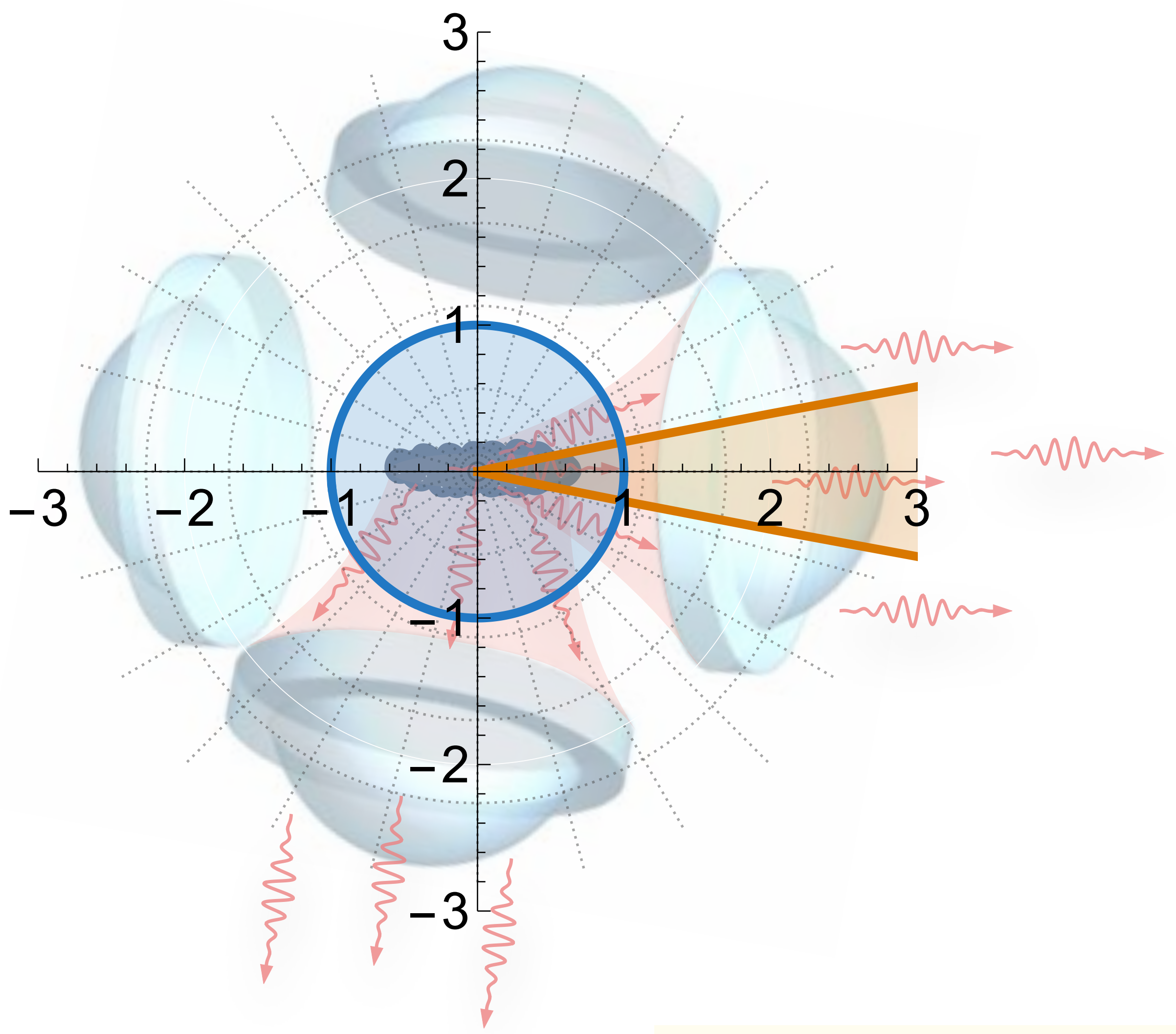
For large, dilute clouds, one has $\mu N = OD$

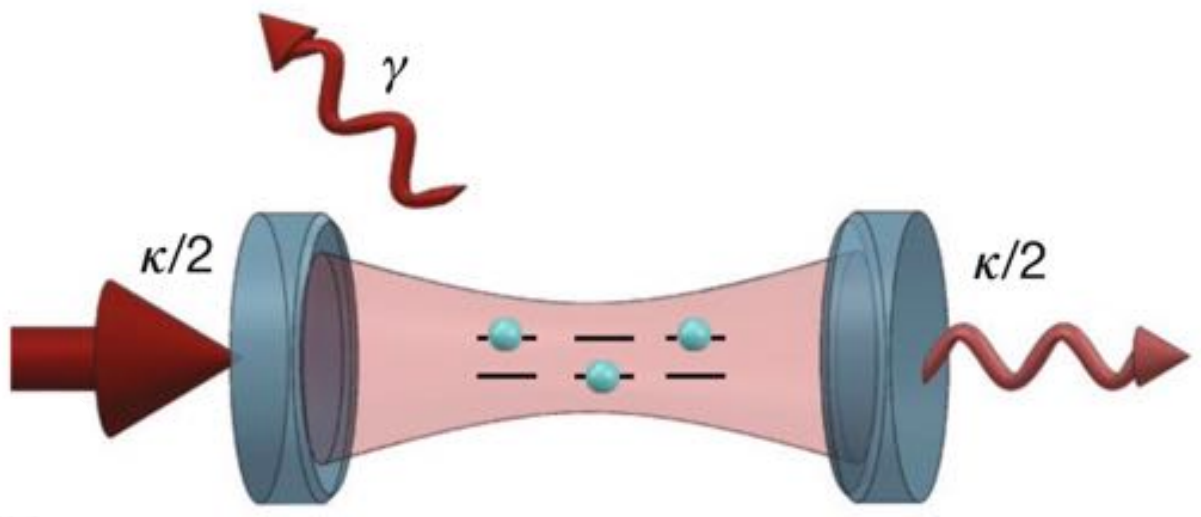
Gross & Haroche, *Physics Reports* **93**, 301 (1982).

Allen & Eberly, *Optical resonance and two-level atoms*, Courier Corp. (1987)

Analogy with clouds in cavity

	Small clouds	Clouds in cavity
Collective coupling to:	Difraction pattern	Cavity mode
Set by:	Cloud shape / structure factor	Cavity geometry
Cooperativity $C_N = P_{\text{coop}}/P_1$	$N \times \mu$	$N \times (g^2/\kappa\gamma)$

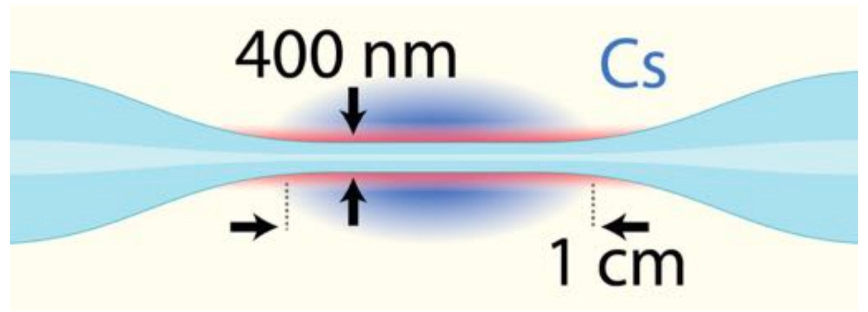




from: *Nature* **580**, 602 (2020)

Similarities with nanofiber-coupled atoms

See *e.g.* arXiv: 2211.08940 (2022)

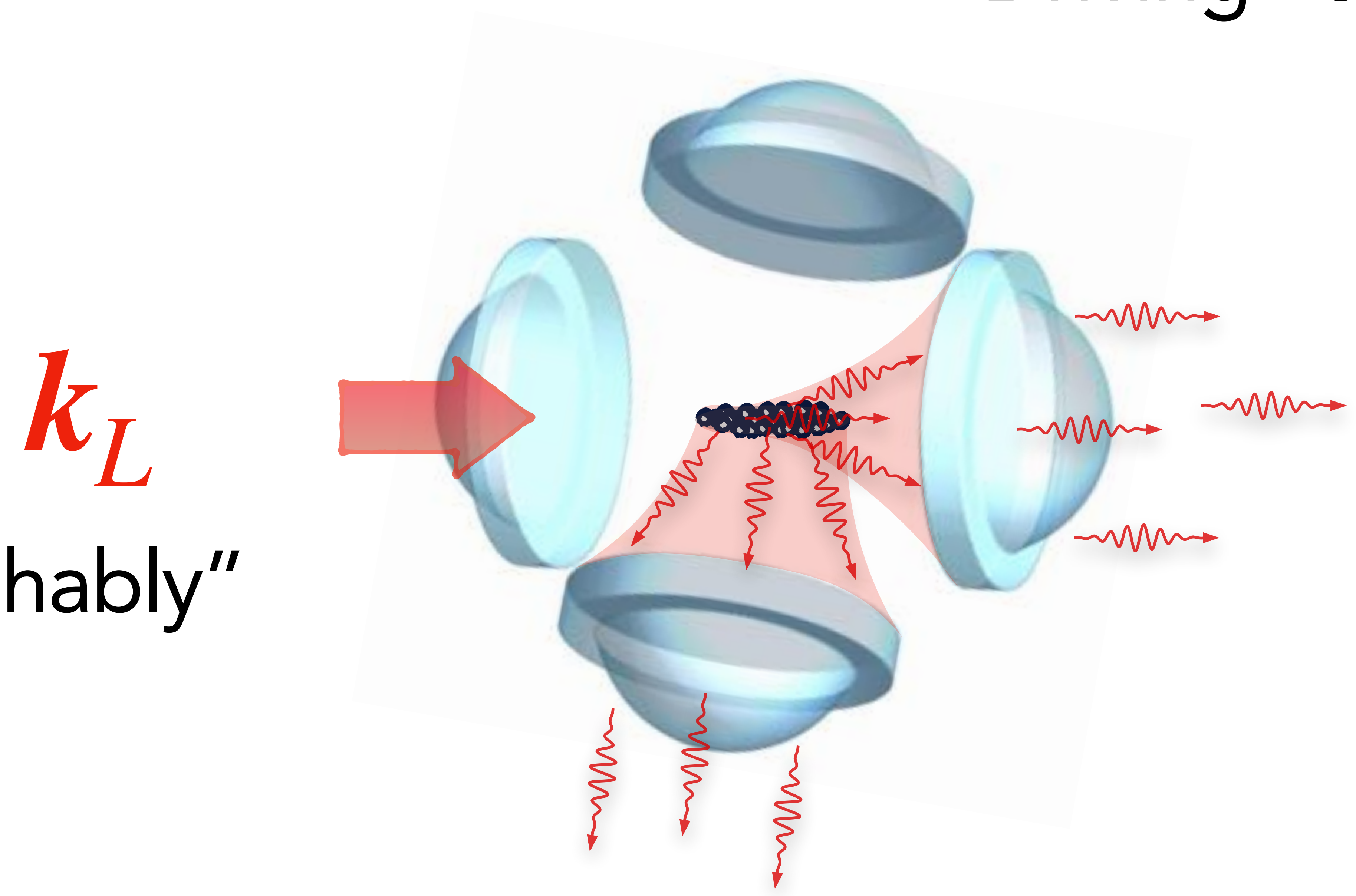


Driving axially: Dicke symmetry restored

Dicke case: Indistinguishable coupling to

- Emission mode ✓
- Driving mode ✓

Driving "distinguishably"



Superradiant mode

Atoms indistinguishably coupled

Driving "indistinguishably"

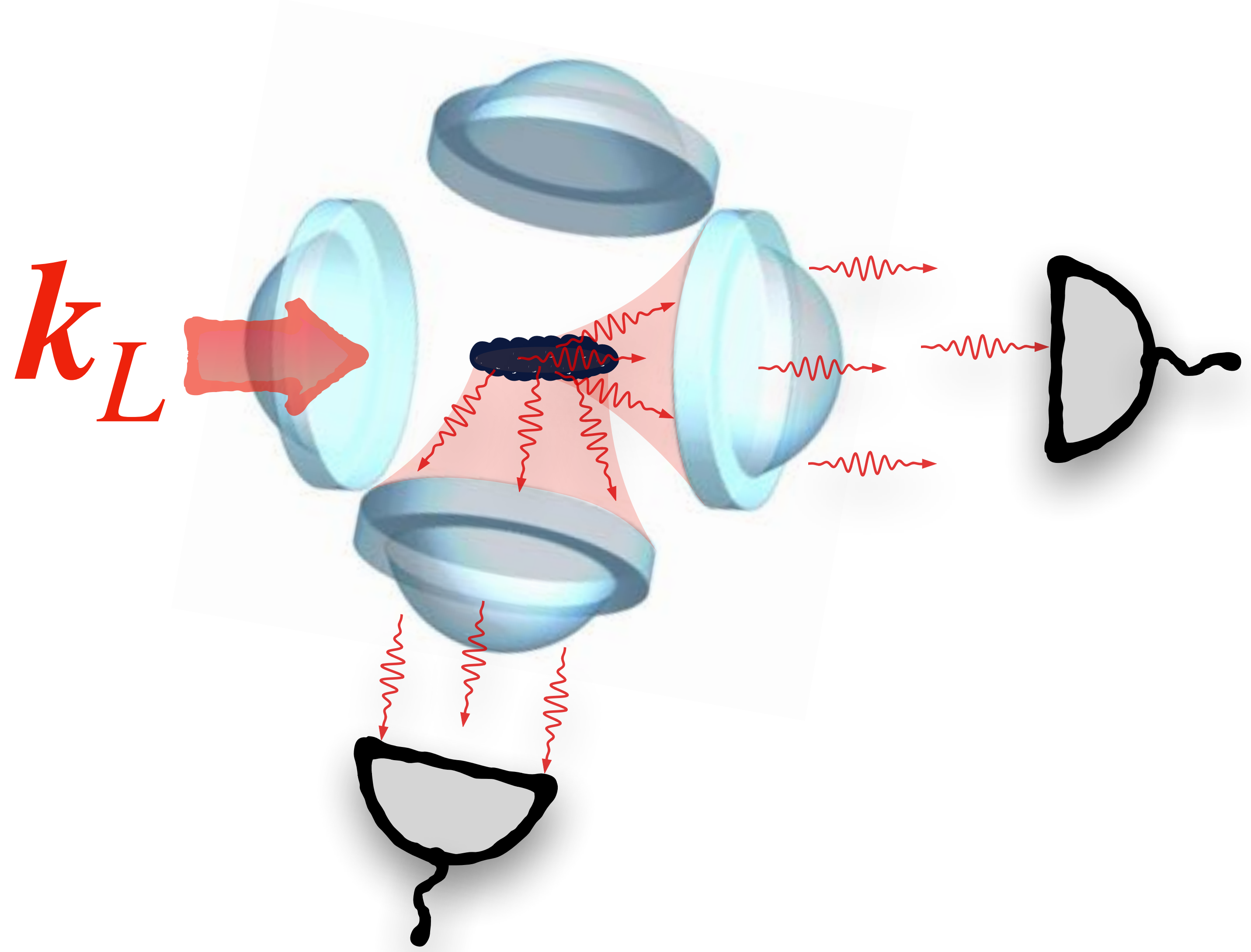
Driving axially: Dicke symmetry restored

Classically: dipole $d_n \propto \langle \sigma_n^- \rangle$

$$\sim \Gamma_0 \frac{e^{ik_0|\boldsymbol{r}_m - \boldsymbol{r}_n|}}{4\pi k_0 |\boldsymbol{r}_m - \boldsymbol{r}_n|}$$

$$\frac{d\langle \hat{\sigma}_n^- \rangle}{dt} = i\Omega_D e^{i\boldsymbol{k}_L \cdot \boldsymbol{r}_n} \langle \hat{\sigma}_n^z \rangle - \frac{\Gamma_0}{2} \langle \hat{\sigma}_n^- \rangle + \sum_{m \neq n} \frac{\Gamma_{mn}}{2} \left[\langle \hat{\sigma}_n^z \hat{\sigma}_m^- \rangle + \langle \hat{\sigma}_m^- \hat{\sigma}_n^z \rangle \right]$$

*Ignoring real part of DDI



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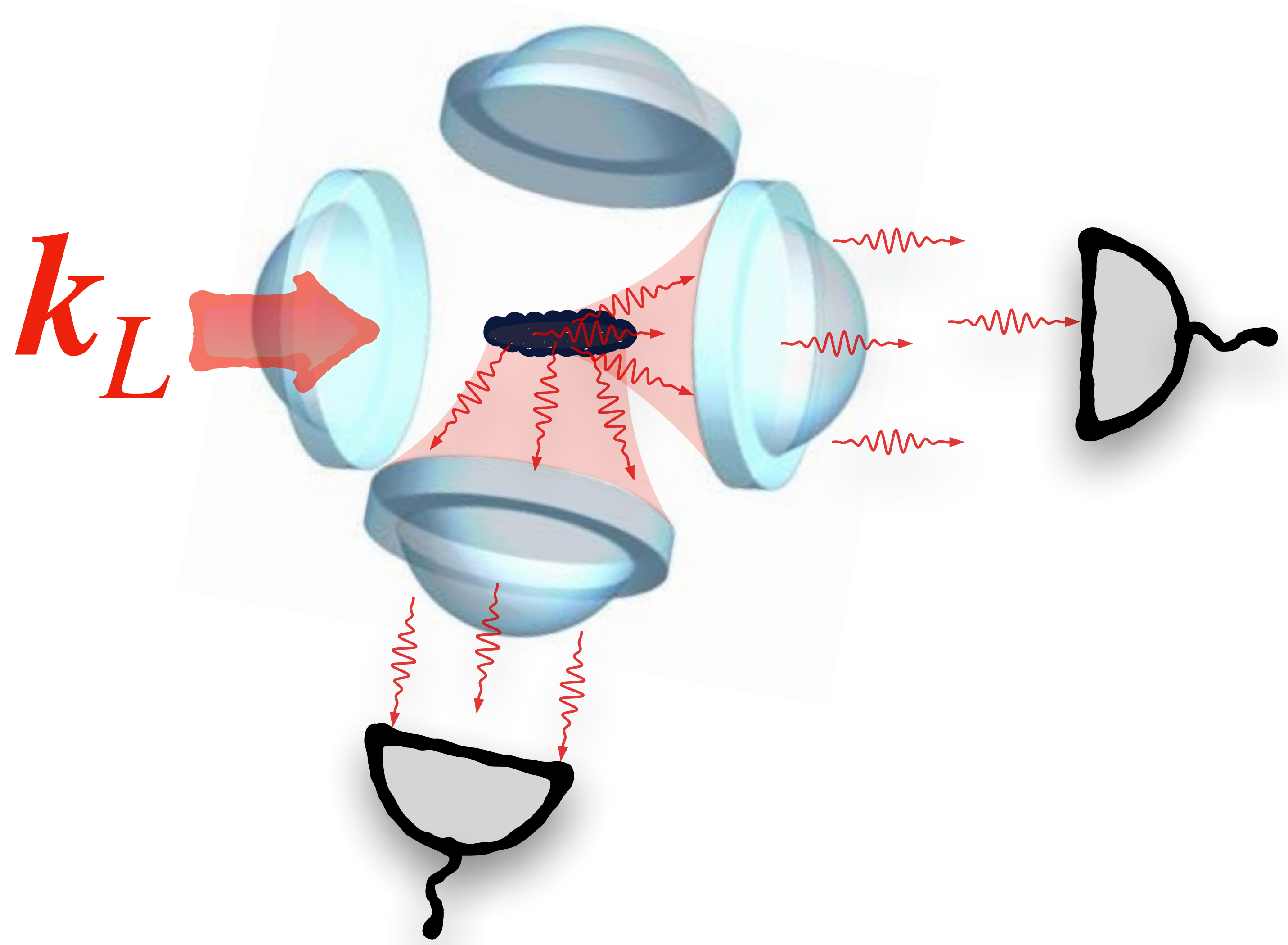
*Ignoring real part of DDI

Mean-field ansatz: $\langle \hat{\sigma}_n^- \rangle = \langle \hat{\sigma}^- \rangle e^{i\boldsymbol{k}_L \cdot \boldsymbol{r}_n}$ $\langle \hat{\sigma}_n^z \rangle = \langle \hat{\sigma}^z \rangle$ Allen & Eberly (1987)

$$\frac{d\langle \hat{\sigma}^- \rangle}{dt} = \left(i\Omega_D + \Gamma_0 \mu N \langle \hat{\sigma}^- \rangle \right) \langle \hat{\sigma}^z \rangle - \frac{\Gamma_0}{2} \langle \hat{\sigma}^- \rangle$$



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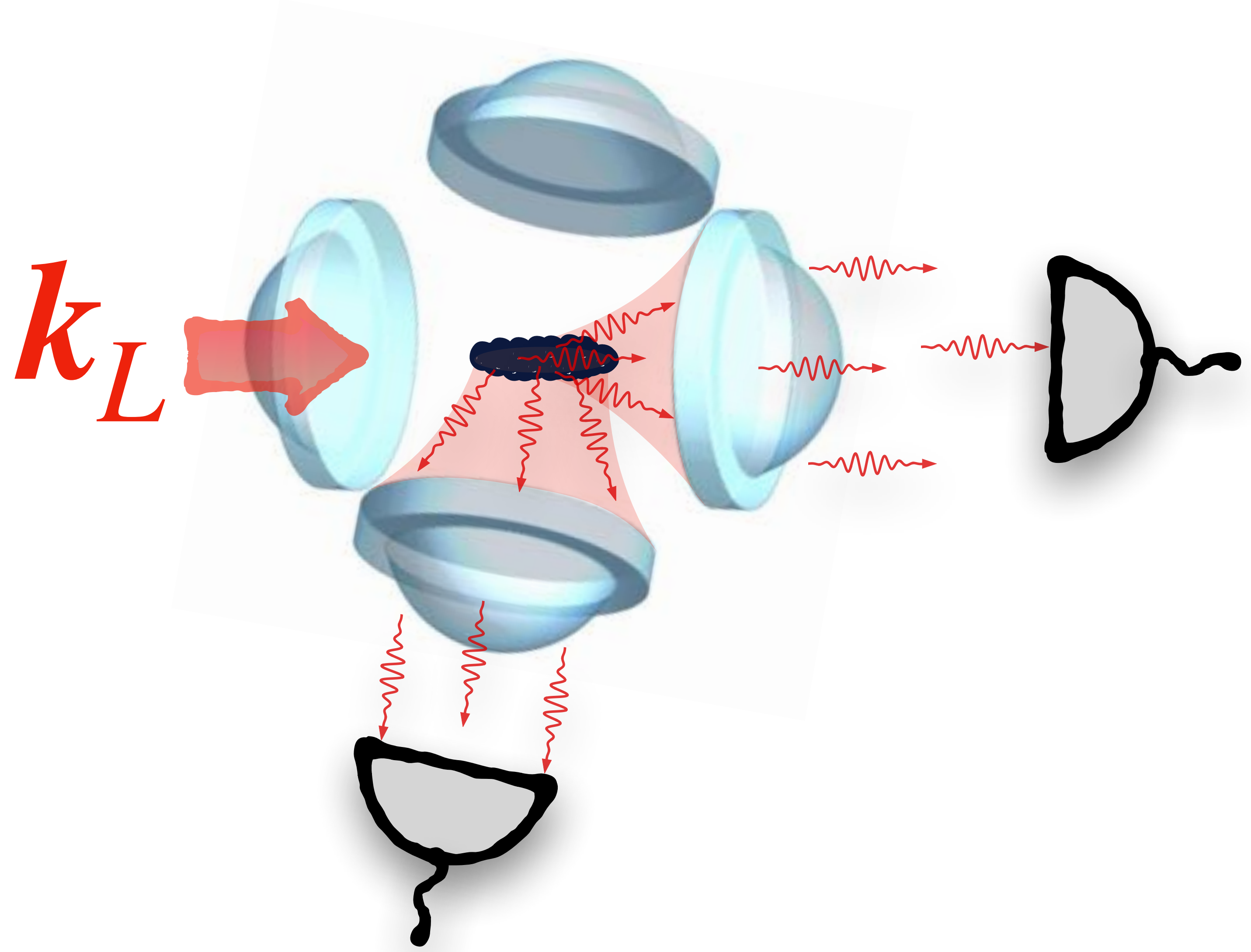
Mean-field ansatz: $\langle \hat{\sigma}_n^- \rangle = \langle \hat{\sigma}^- \rangle e^{i\boldsymbol{k}_L \cdot \boldsymbol{r}_n}$ $\quad \langle \hat{\sigma}_n^z \rangle = \langle \hat{\sigma}^z \rangle$ Allen & Eberly (1987)

$$\frac{d\langle \hat{\sigma}^- \rangle}{dt} = \left(i\Omega_D + \Gamma_0 \mu N \langle \hat{\sigma}^- \rangle \right) \langle \hat{\sigma}^z \rangle - \frac{\Gamma_0}{2} \langle \hat{\sigma}^- \rangle$$

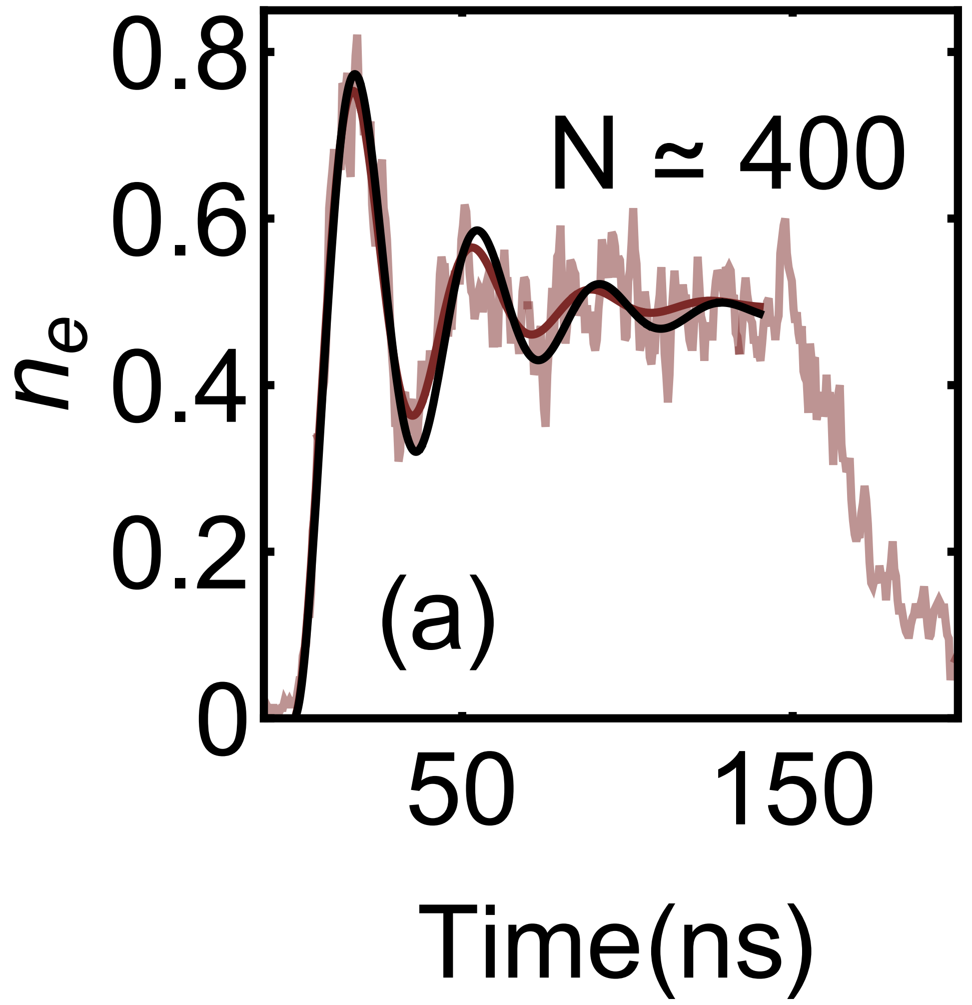
$$N \to \tilde{N} = \mu N$$

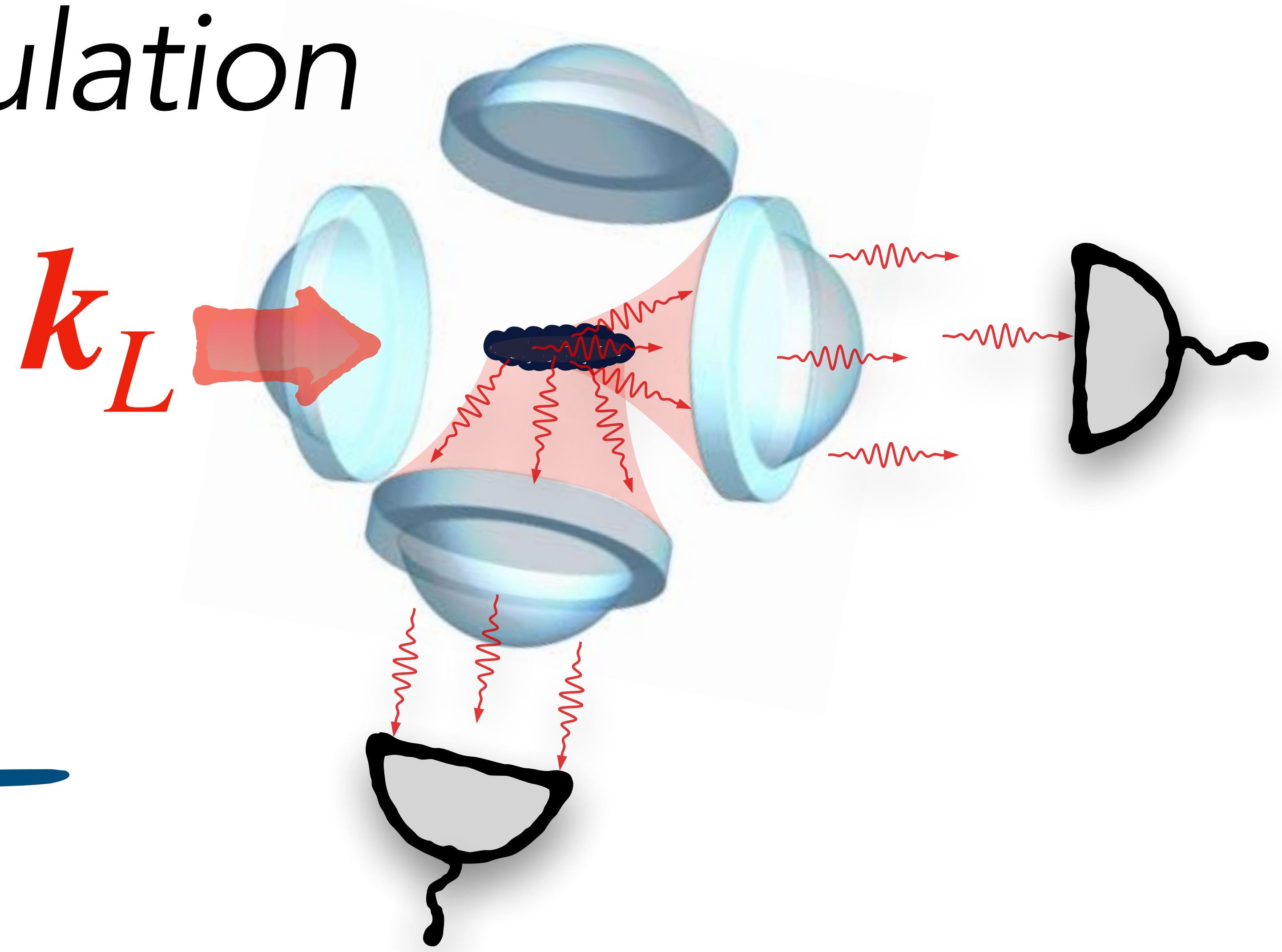
$$\frac{d\langle \hat{\sigma}^- \rangle}{dt} = \left(i\Omega_D + \Gamma_0 N \langle \hat{\sigma}^- \rangle \right) \langle \hat{\sigma}^z \rangle - \frac{\Gamma_0}{2} \langle \hat{\sigma}^- \rangle$$ Dicke case



Rabi oscillations driving Axially

Modification of Rabi oscillations in the *population*





G. Ferioli *et al.*, arXiv:2207.10361 (2022)

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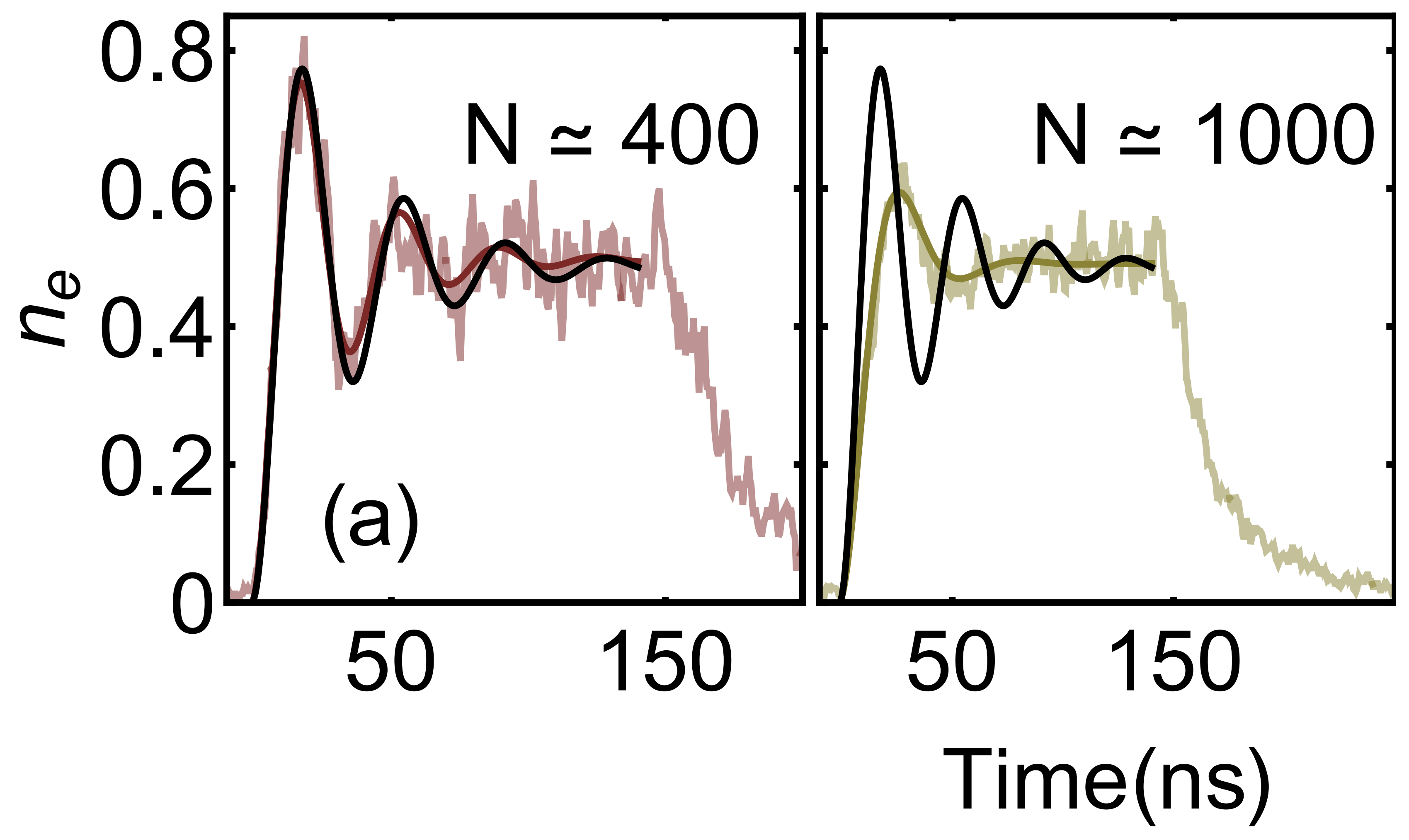

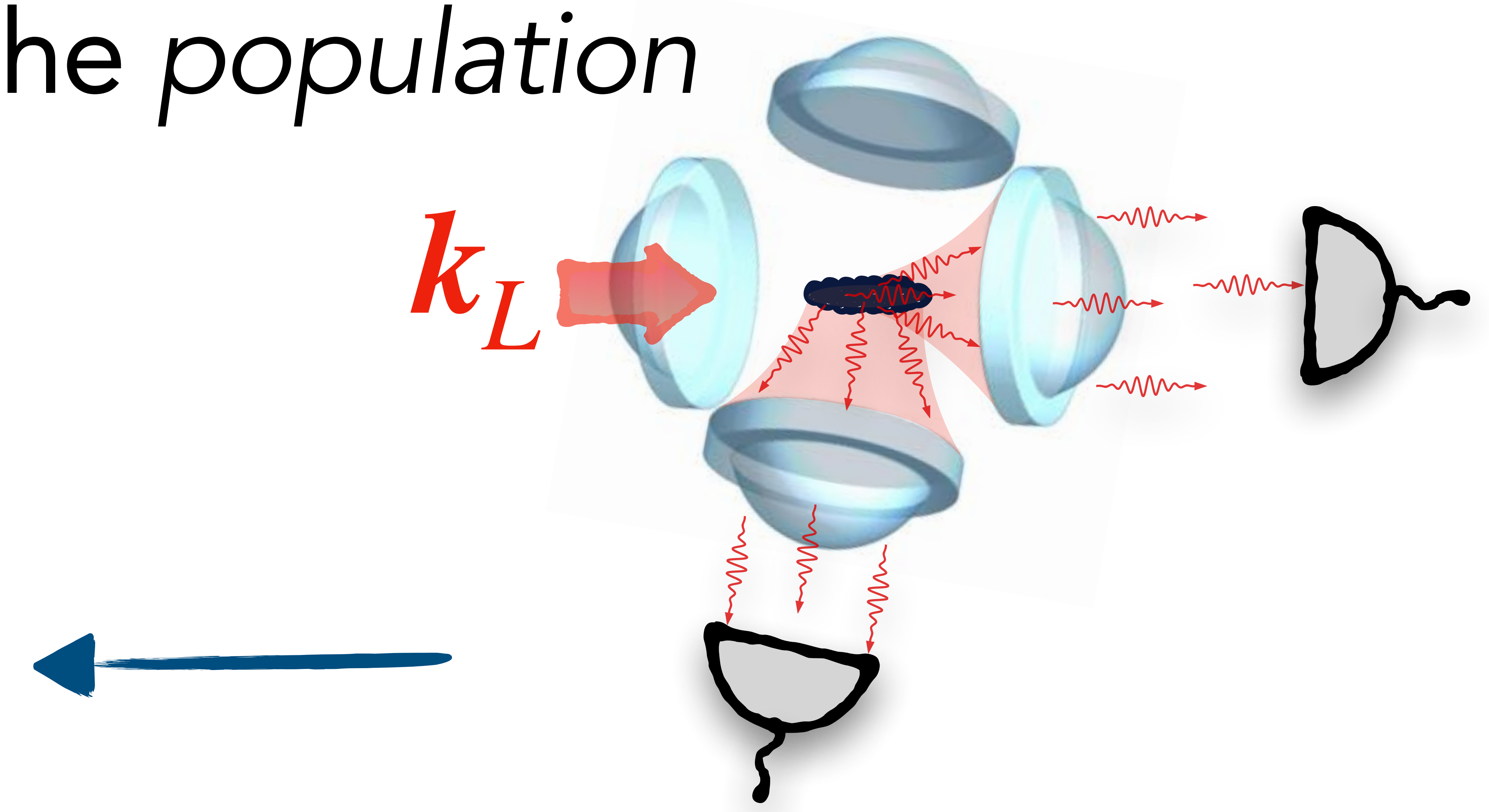

G. Ferioli *et al.*, arXiv:2207.10361 (2022)

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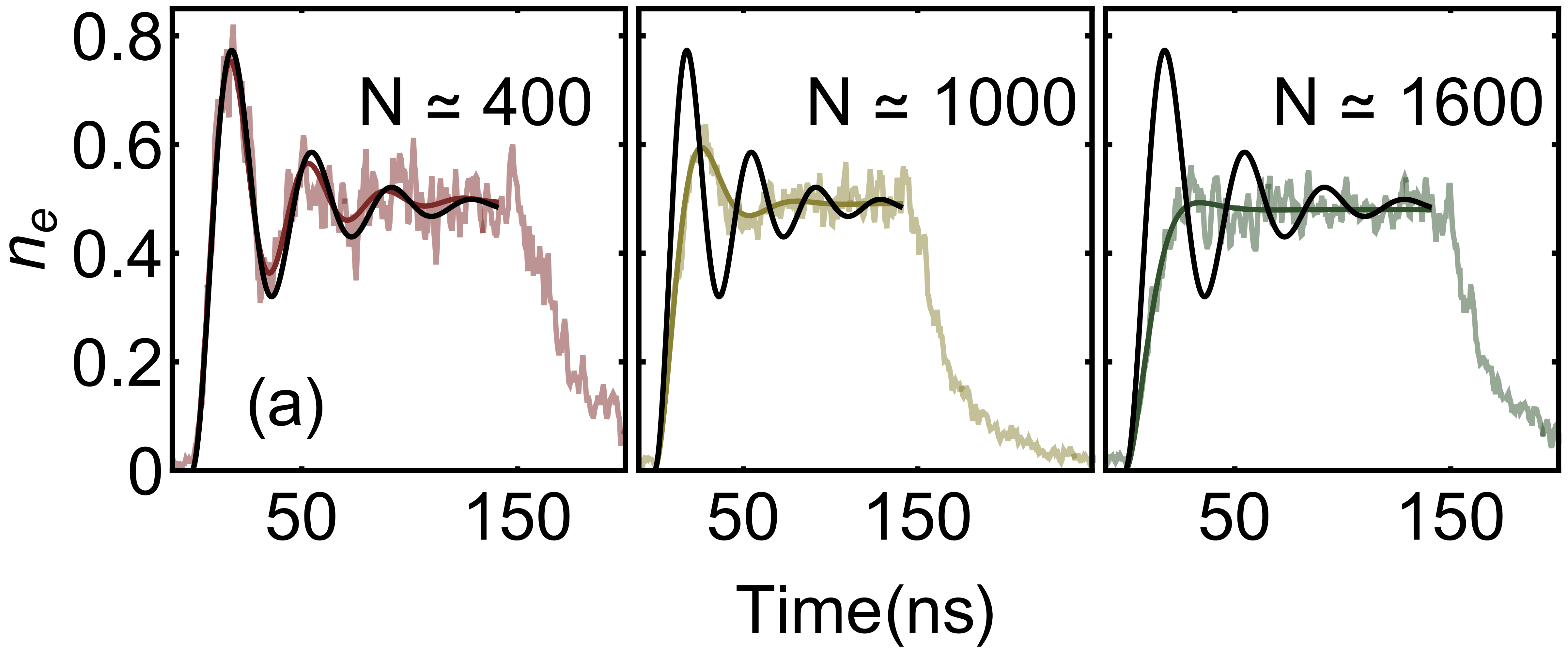
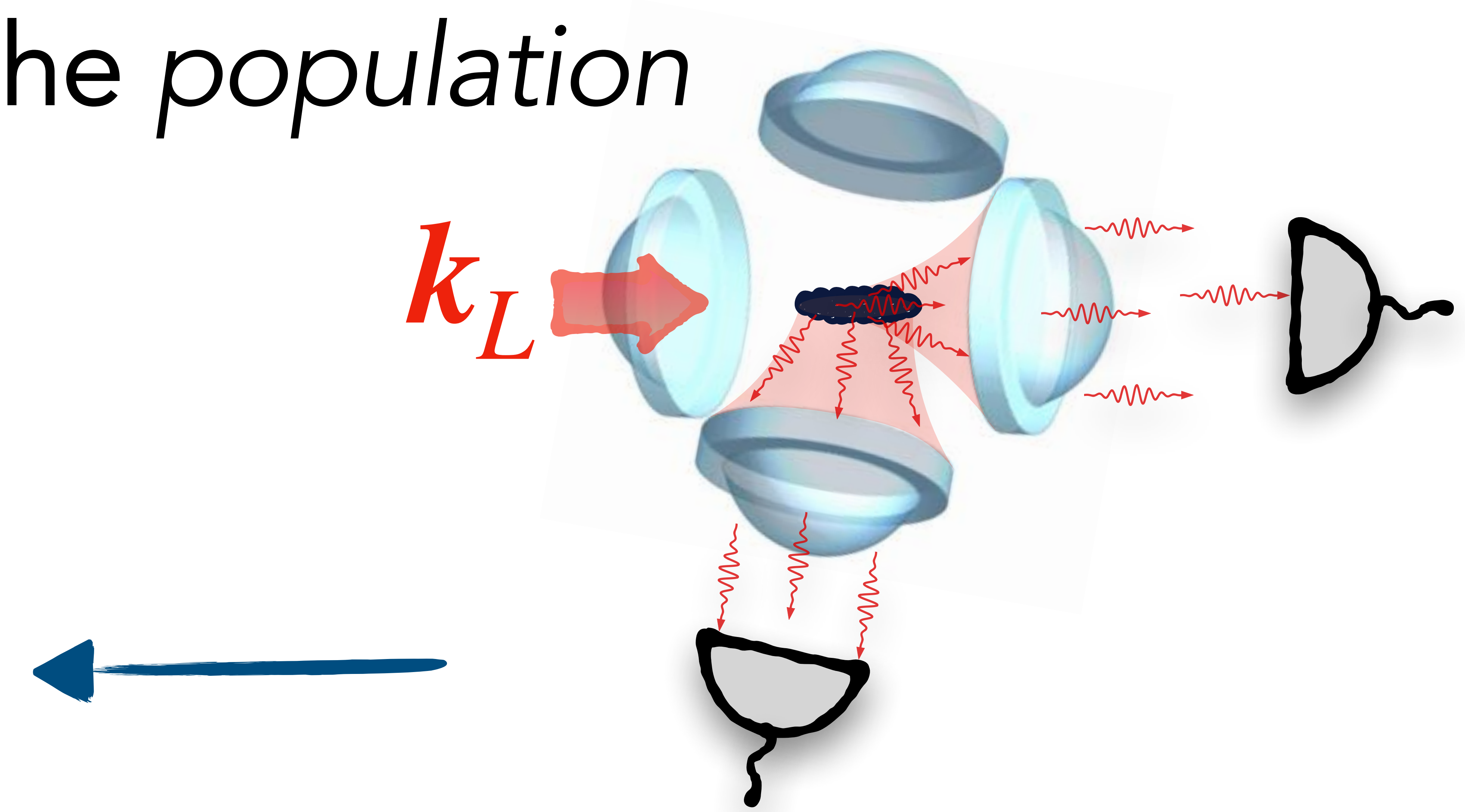


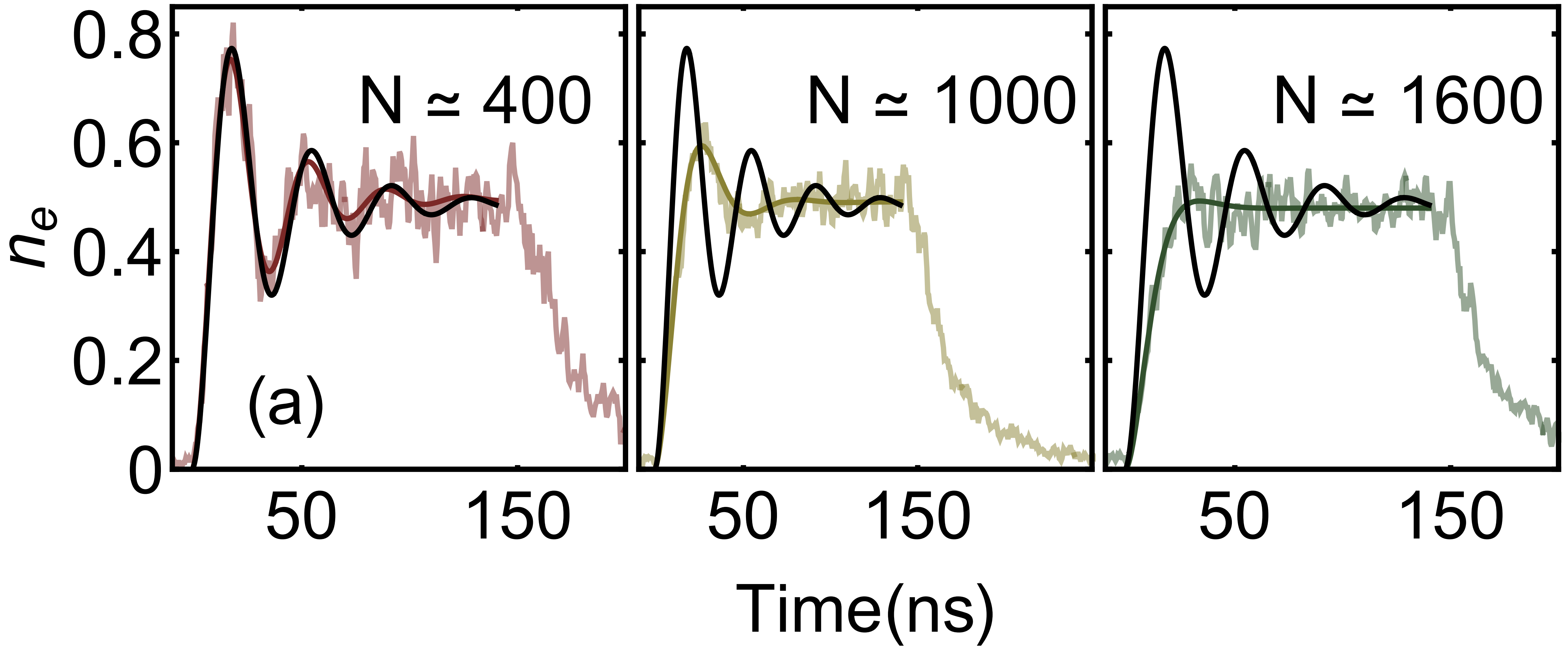


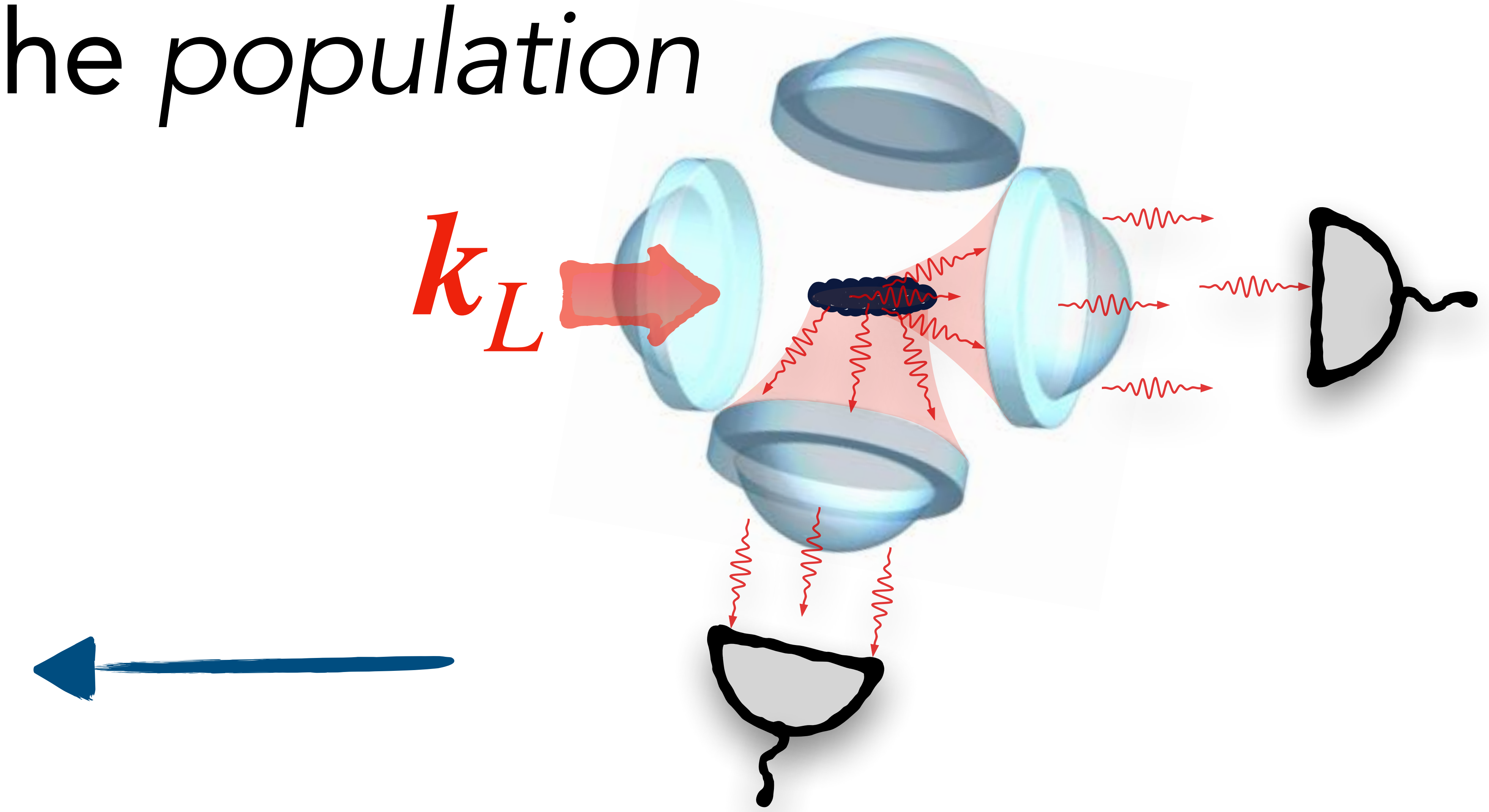
$\Omega_{\rm eff}$ suppressed at at large *N*

G. Ferioli *et al.*, arXiv:2207.10361 (2022)

Rabi oscillations driving Axially

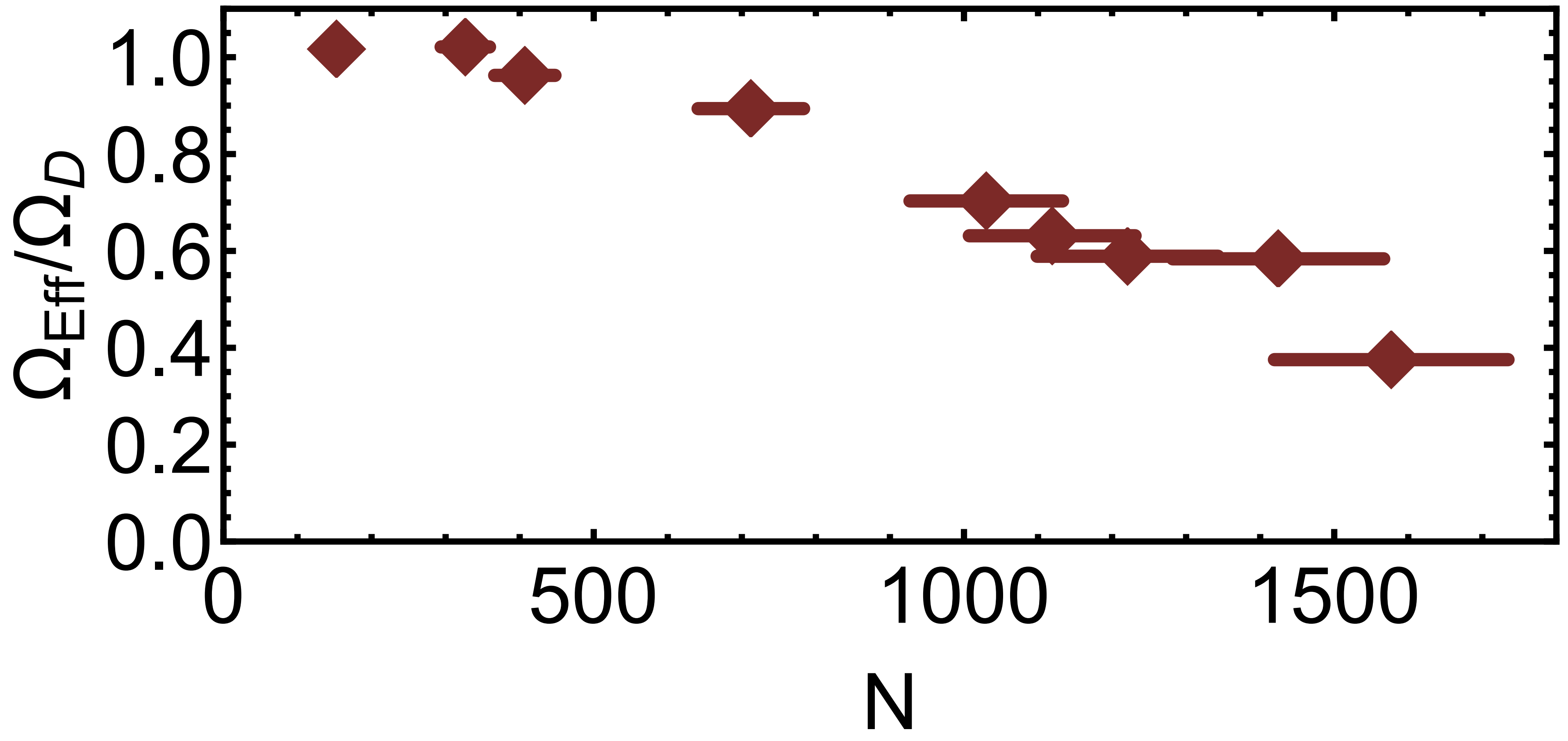
Modification of Rabi oscillations in the *population*





Ω_{eff} suppressed at at large N

Effective Rabi frequency extracted by fit



G. Ferioli *et al.*, arXiv:2207.10361 (2022)

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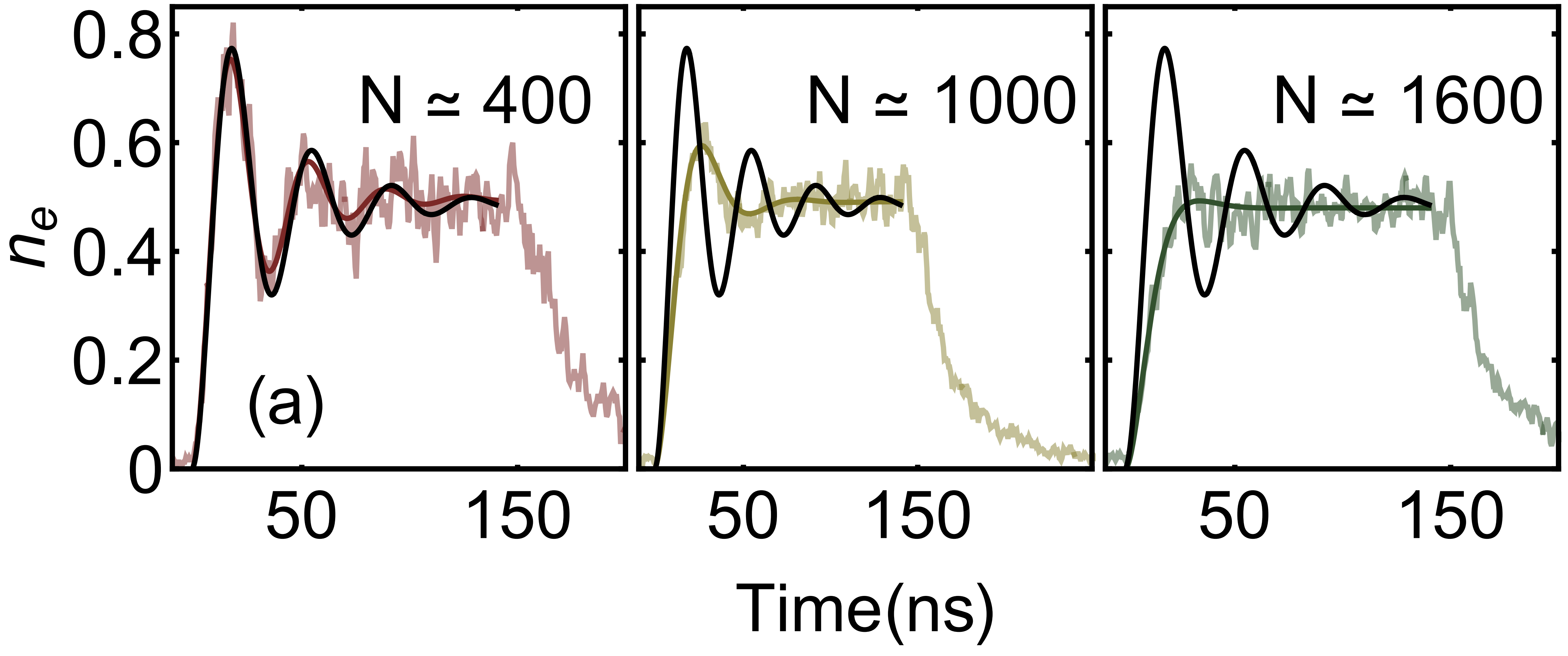
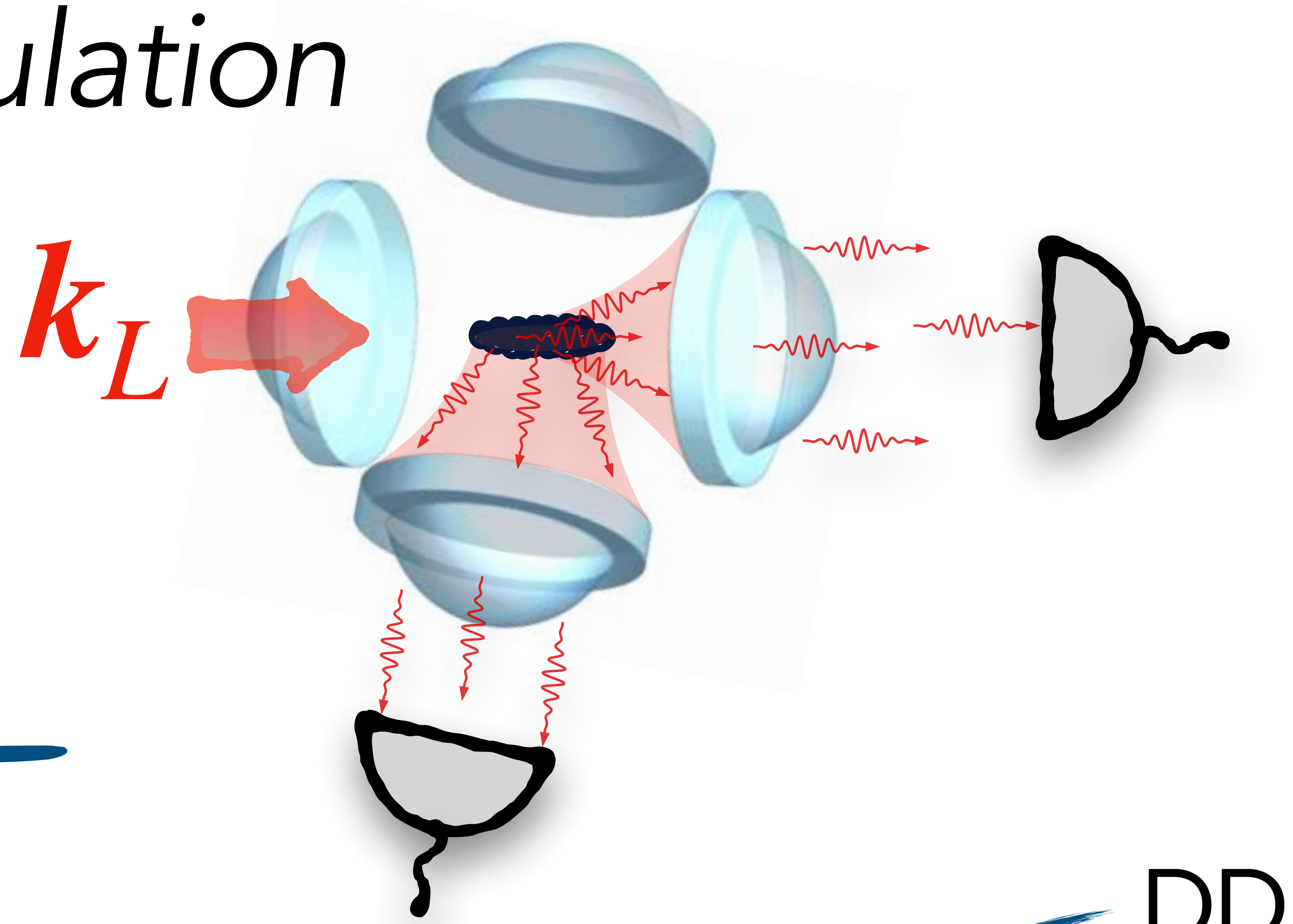
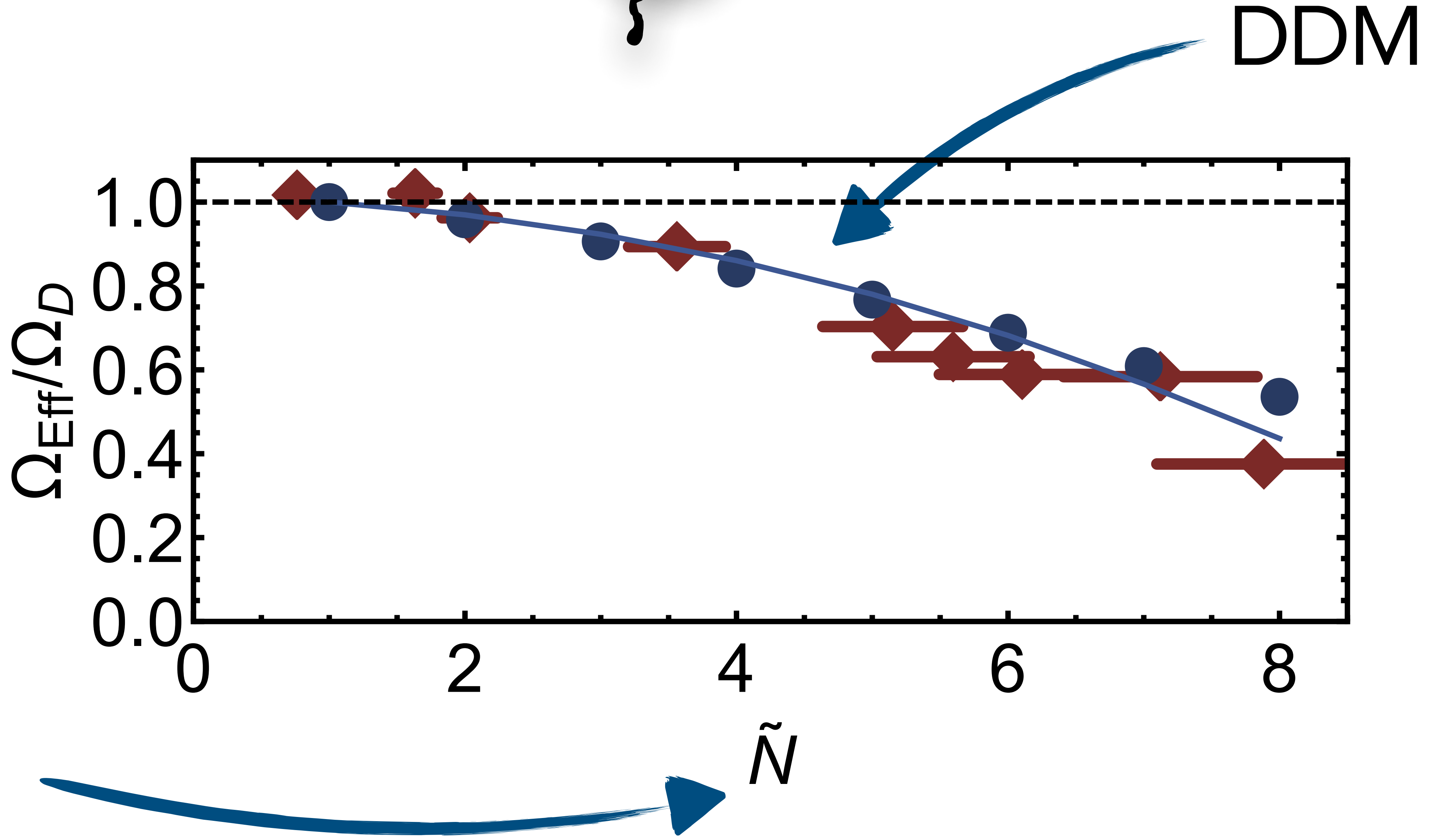






Ω_{eff} suppressed at at large N

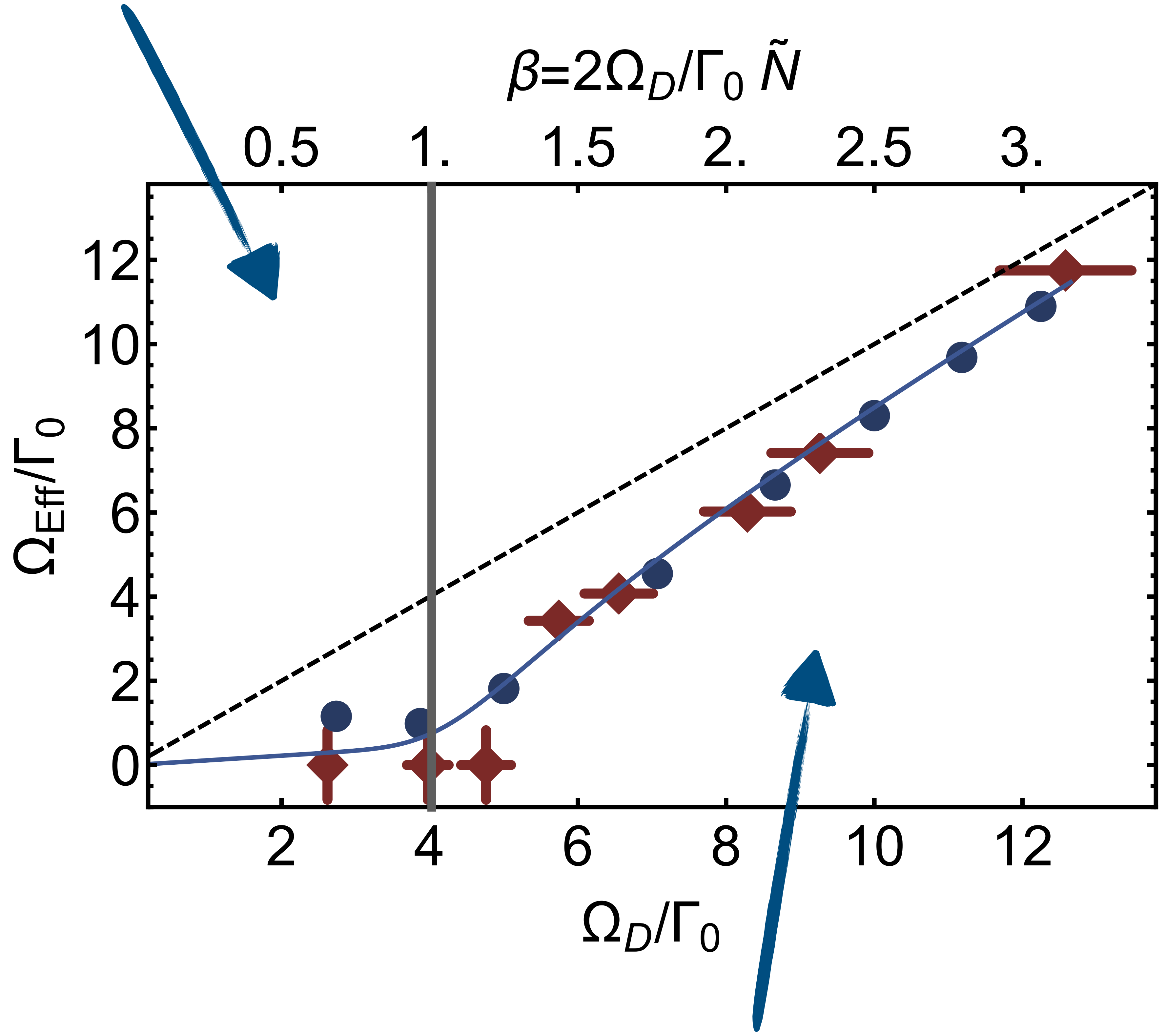
Effective Rabi frequency extracted by fit

Data rescaled to $\tilde{N} = \mu N$ with $\mu = 0.005$

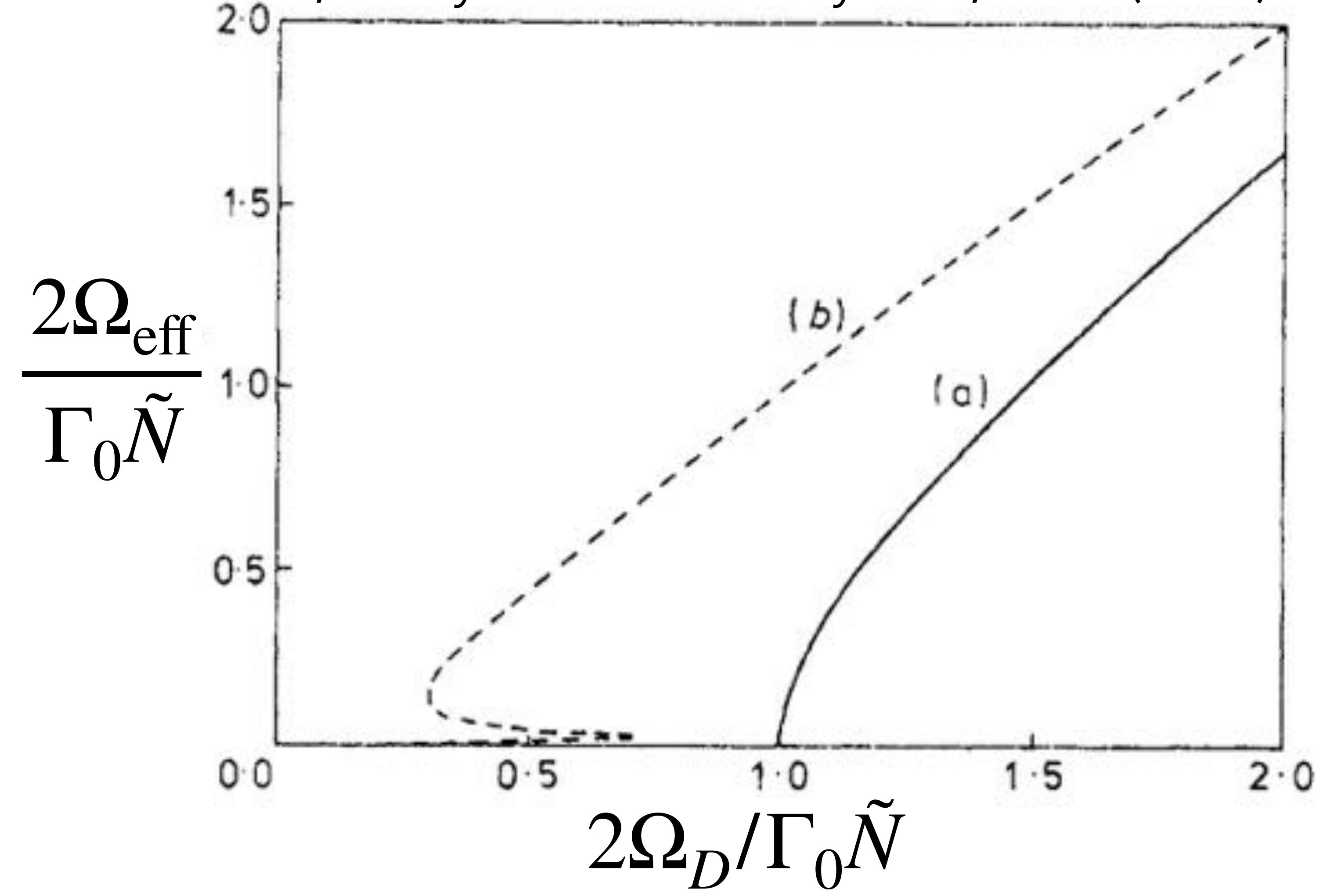
G. Ferioli *et al.*, arXiv:2207.10361 (2022)

Phase transition

Magnetic phase, collective dipole screening $\Omega_{\text{eff}} = \Omega_D - i\Gamma_0\langle \hat{S}^- \rangle \to 0$



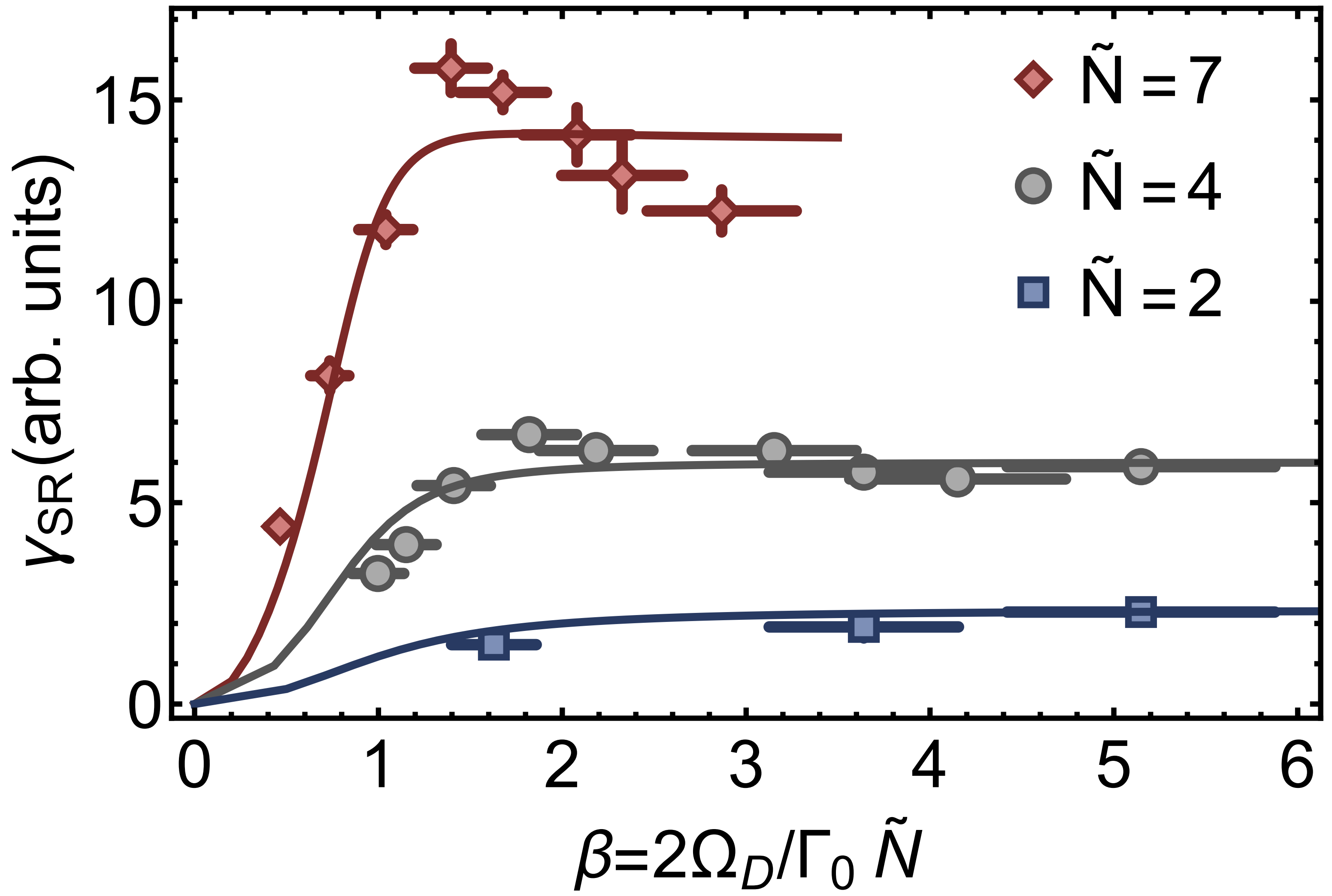
D. F. Walls, *J. Phys. B At. Mol. Phys.* **13**, 2001 (1973).

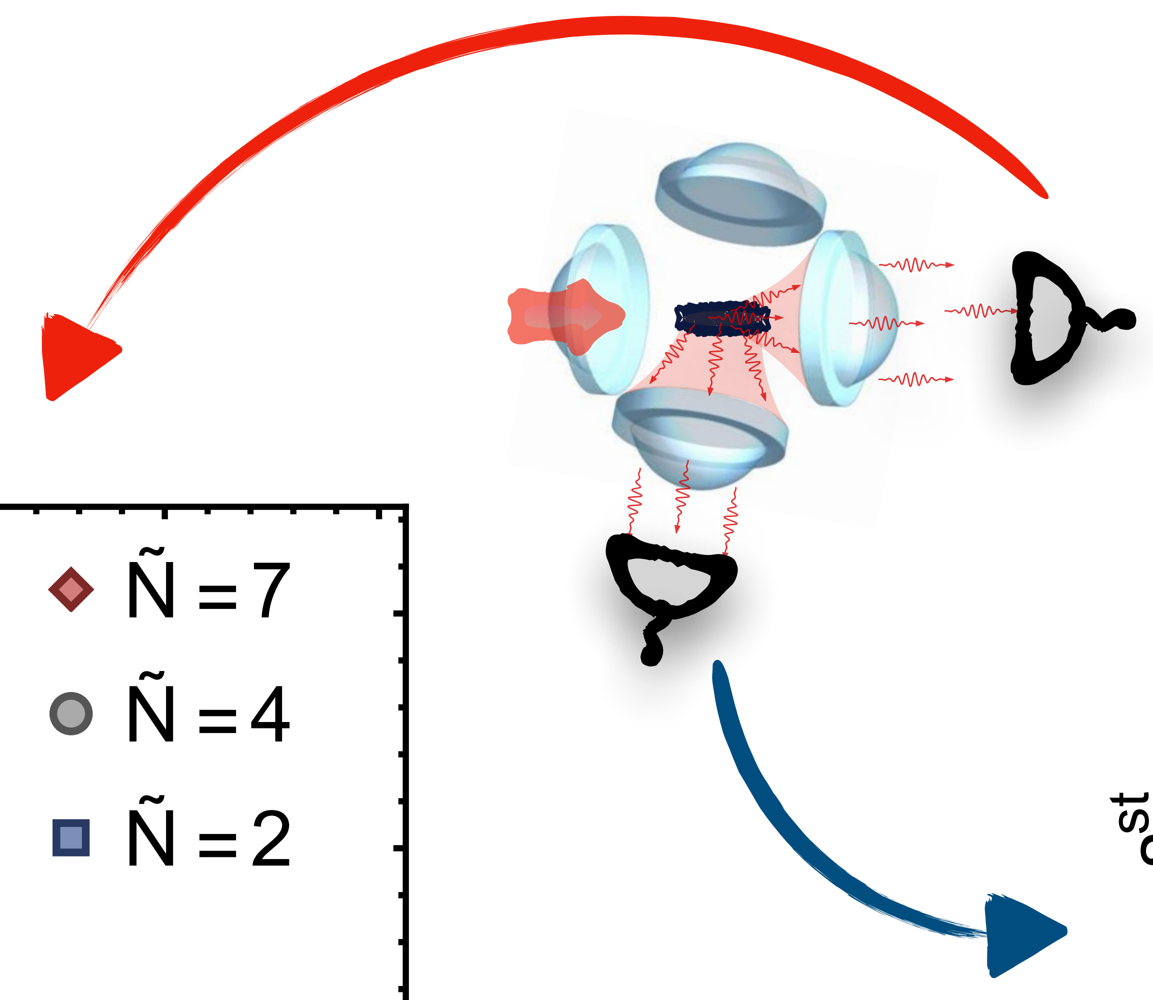


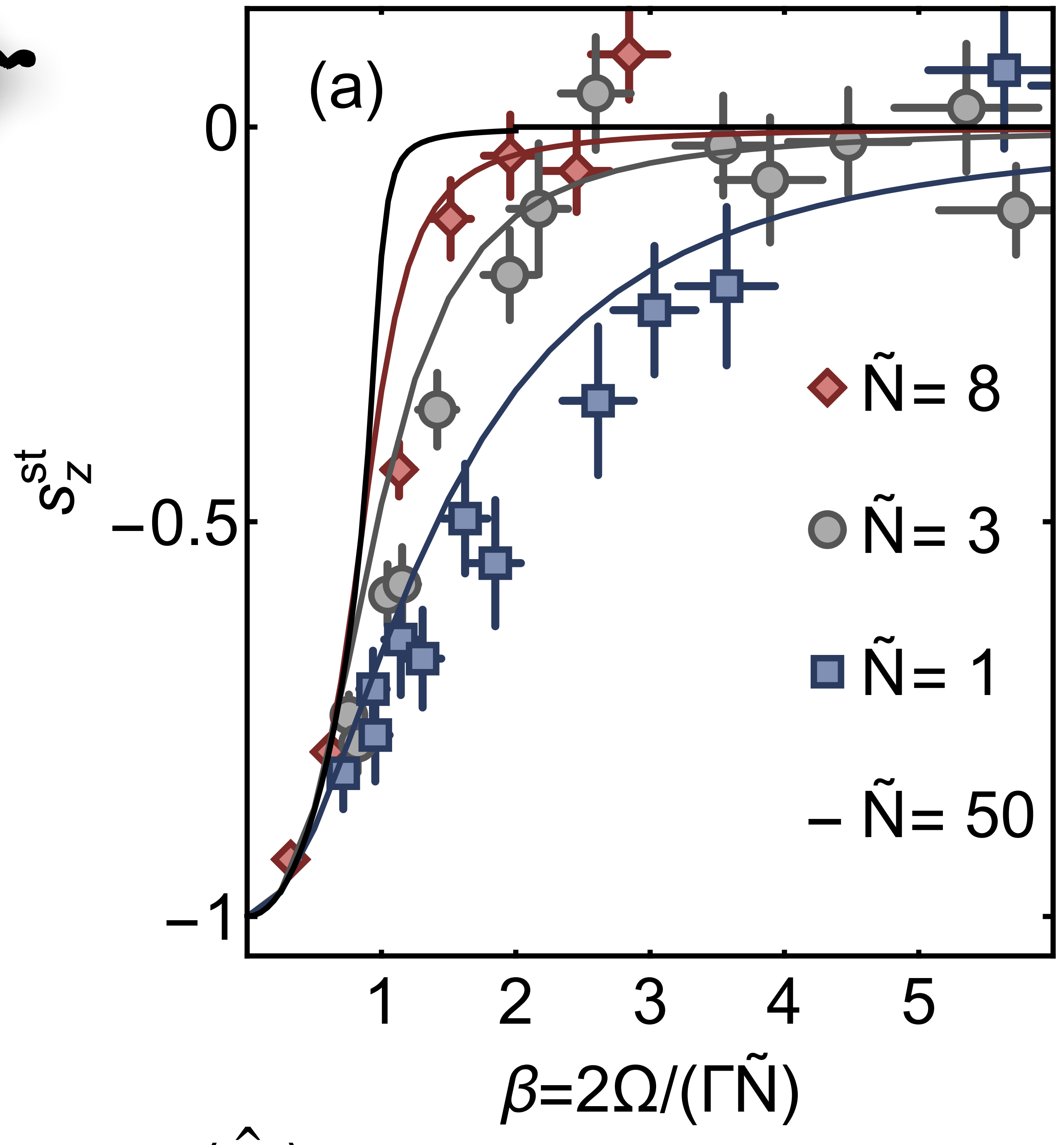
Superradiant phase for strong driving $\beta > 1$

G. Ferioli *et al.*, arXiv:2207.10361 (2022)

Superradiant transition

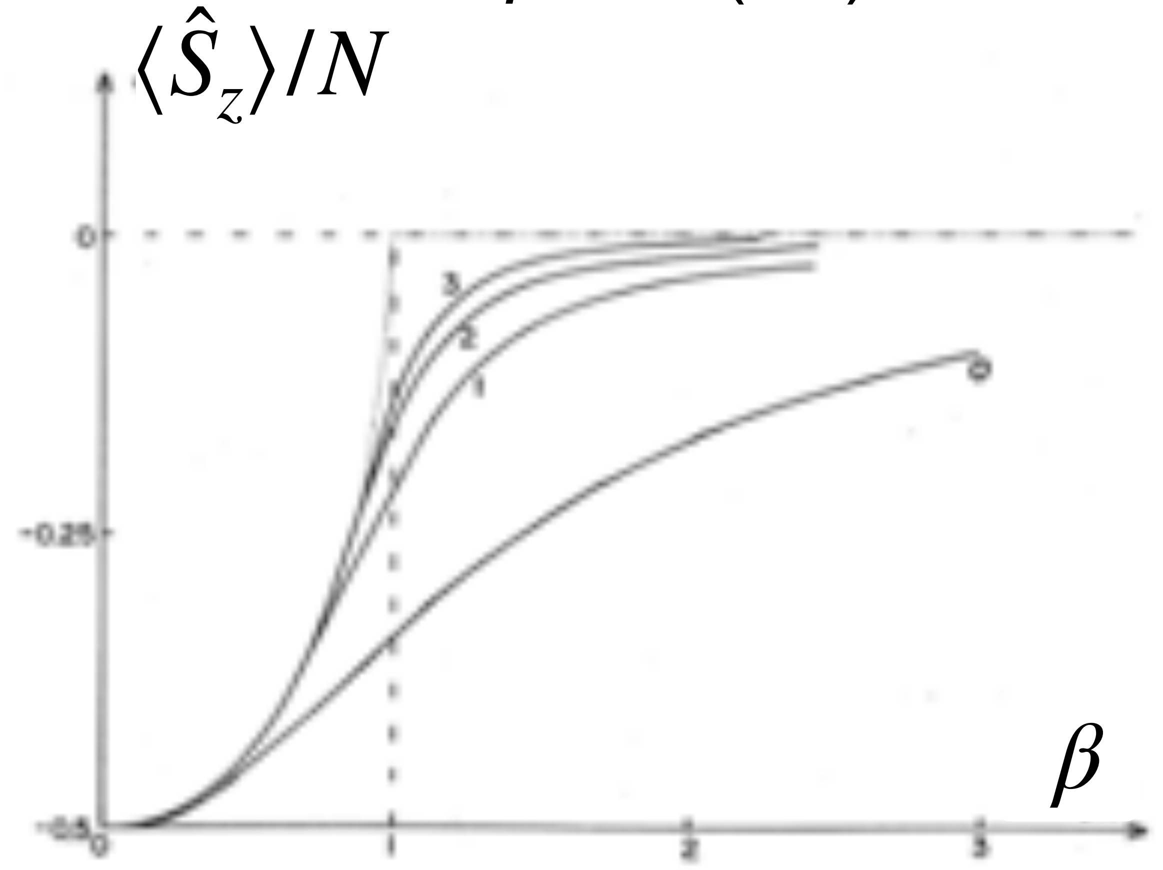






Clear scaling with $\beta = 2\Omega_D/\Gamma_0\tilde{N}$

Convergence towards universal curve for $\tilde{N} \to \infty$



G. Ferioli *et al.*, arXiv:2207.10361 (2022)

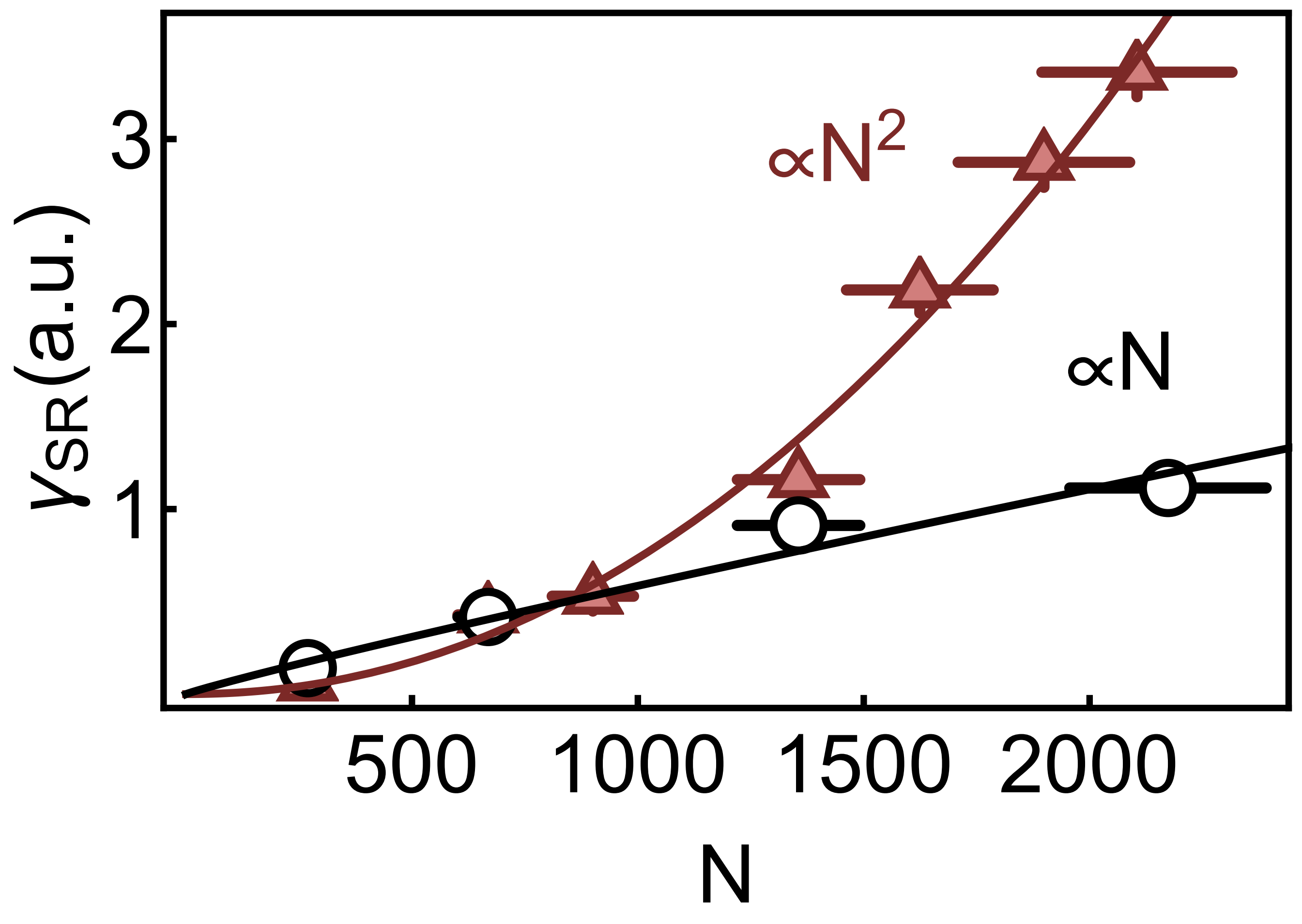
Narducci *et al.*, *Phys Rev A* **18**, 1571–1576 (1978).

Superradiant transition

Two collective steady-states

$\beta \ll 1$

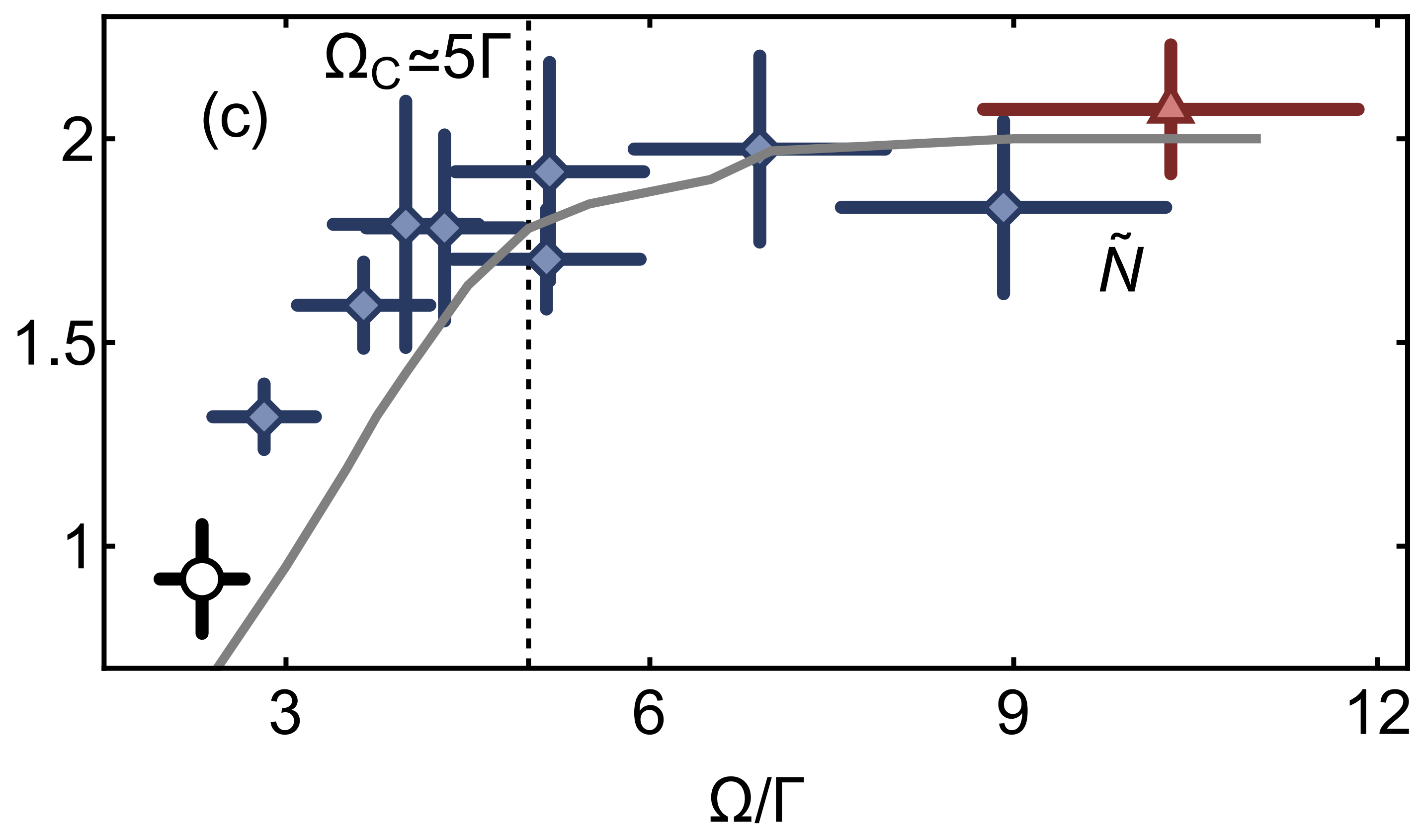
Magnetic phase



$\beta \geqslant 1$

Superradiant phase

Dicke state with $\Gamma_{\tilde{N}} \propto \tilde{N}^2$



G. Ferioli *et al.*, arXiv:2207.10361 (2022)

Superradiant transition

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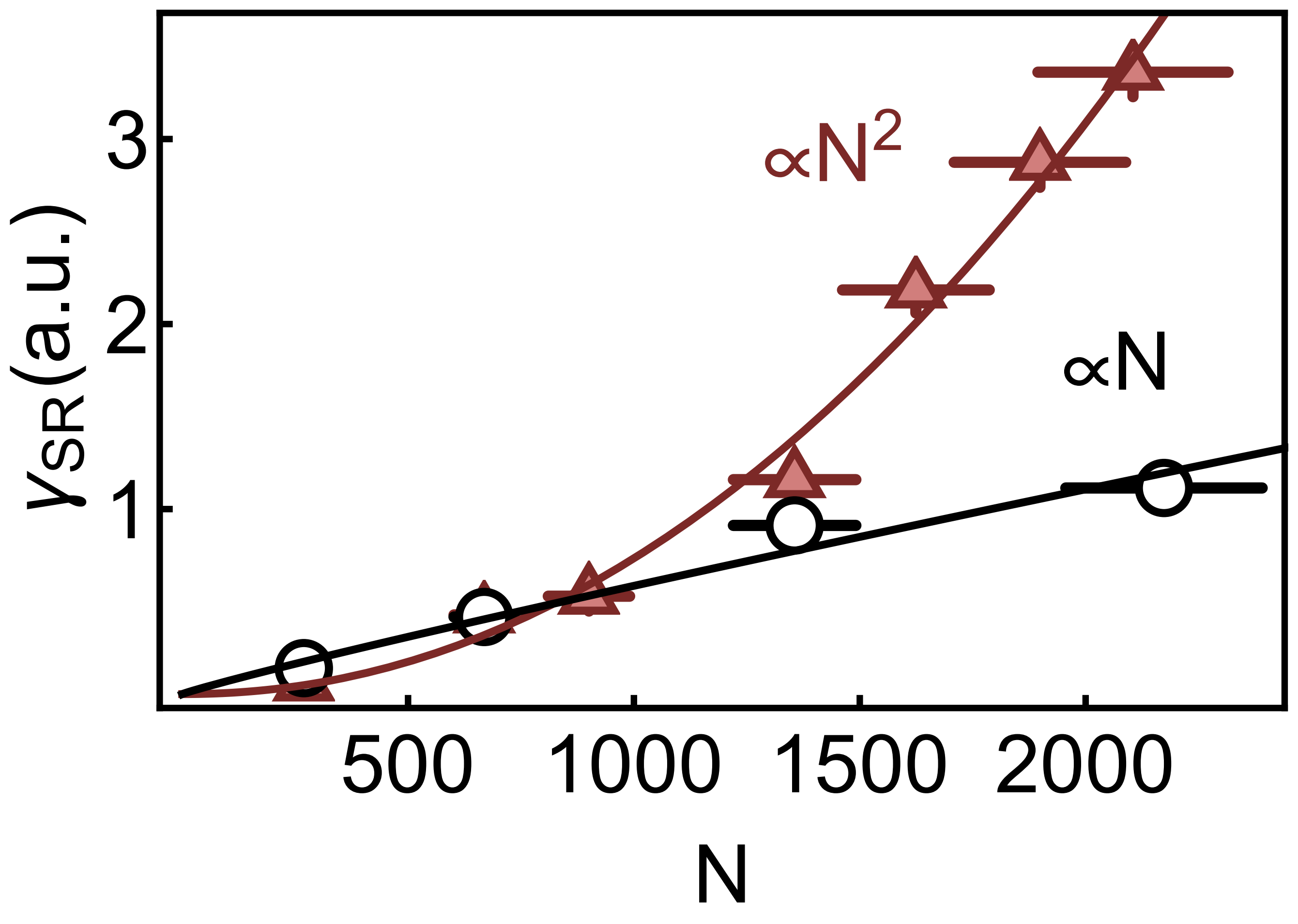

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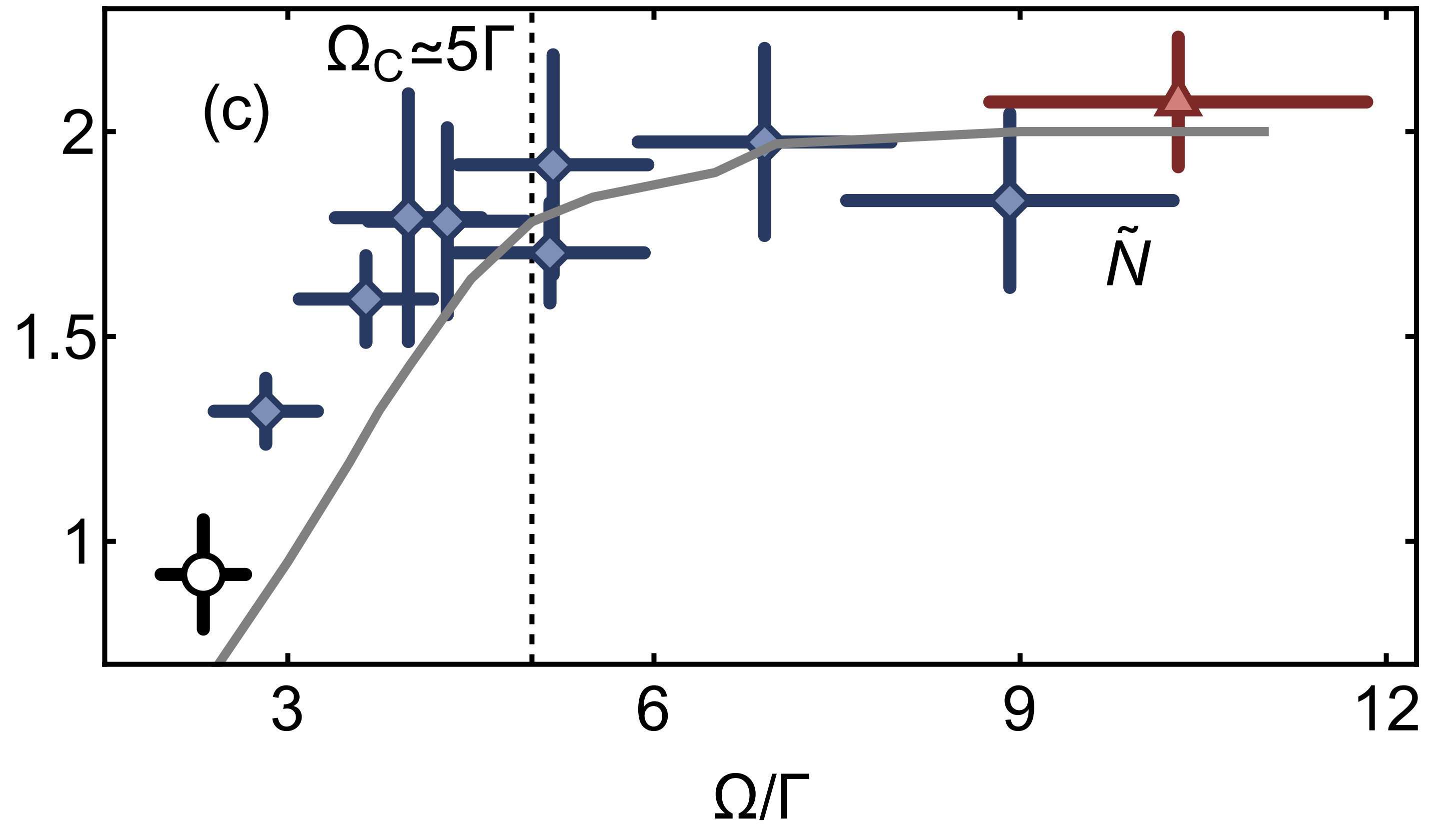
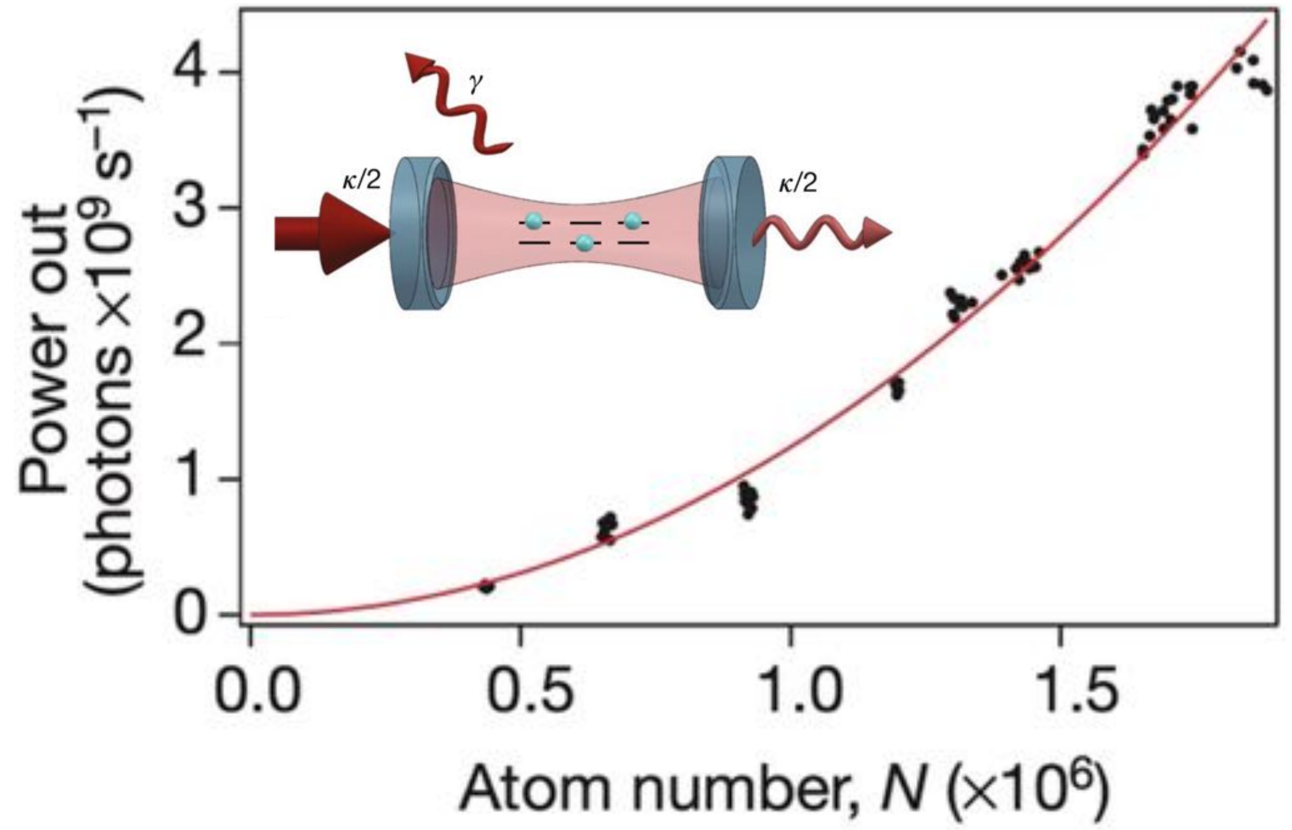
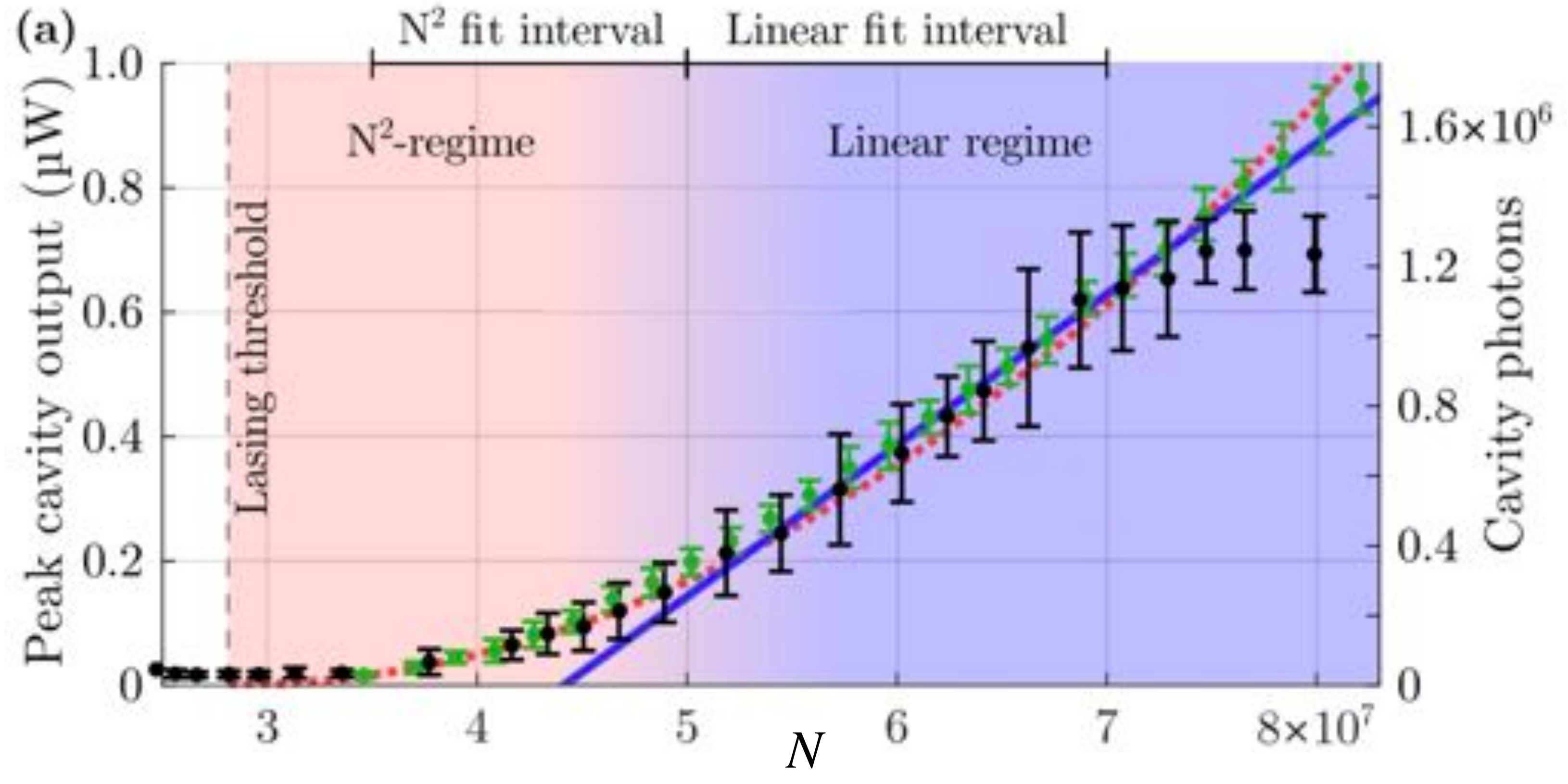


Superradiant lasers

J. G. Bohnet *et al.*, *Nature* **484**, 78–81 (2012).



S. A. Schäffer *et al.*, *Phys Rev A* **101**, 013819 (2020).



G. Ferioli *et al.*, arXiv:2207.10361 (2022)

Superradiant transition

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Superradiant phase

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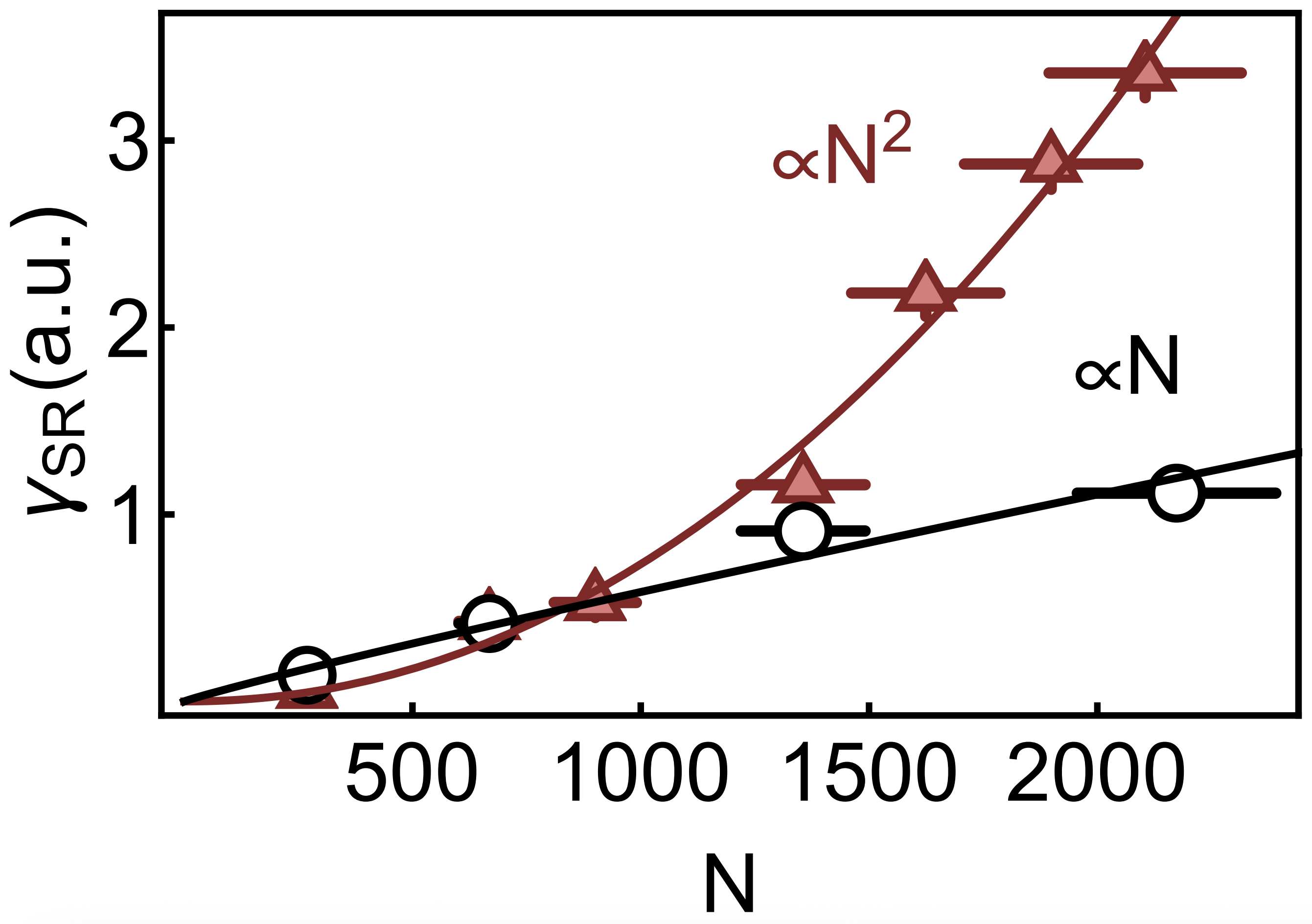

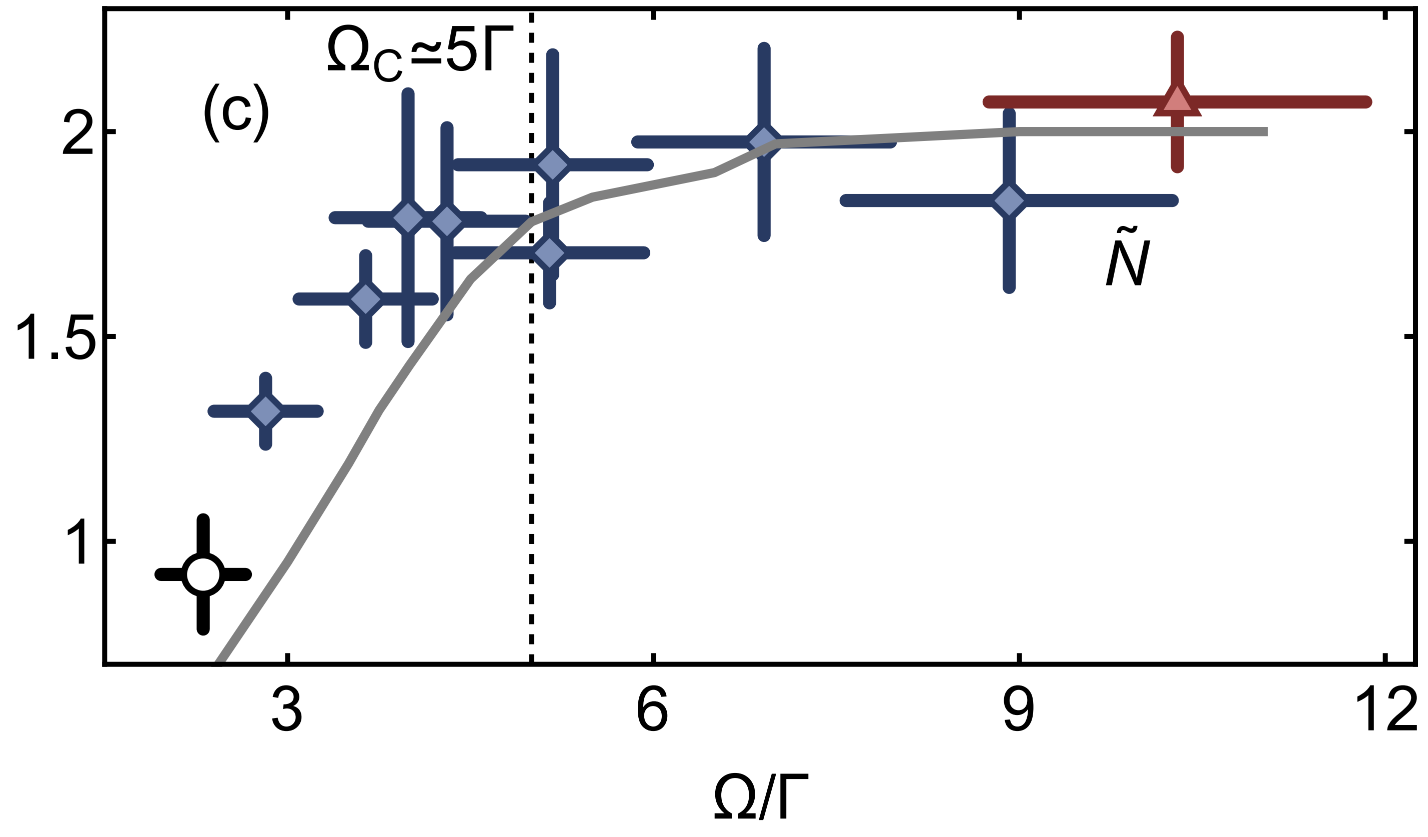

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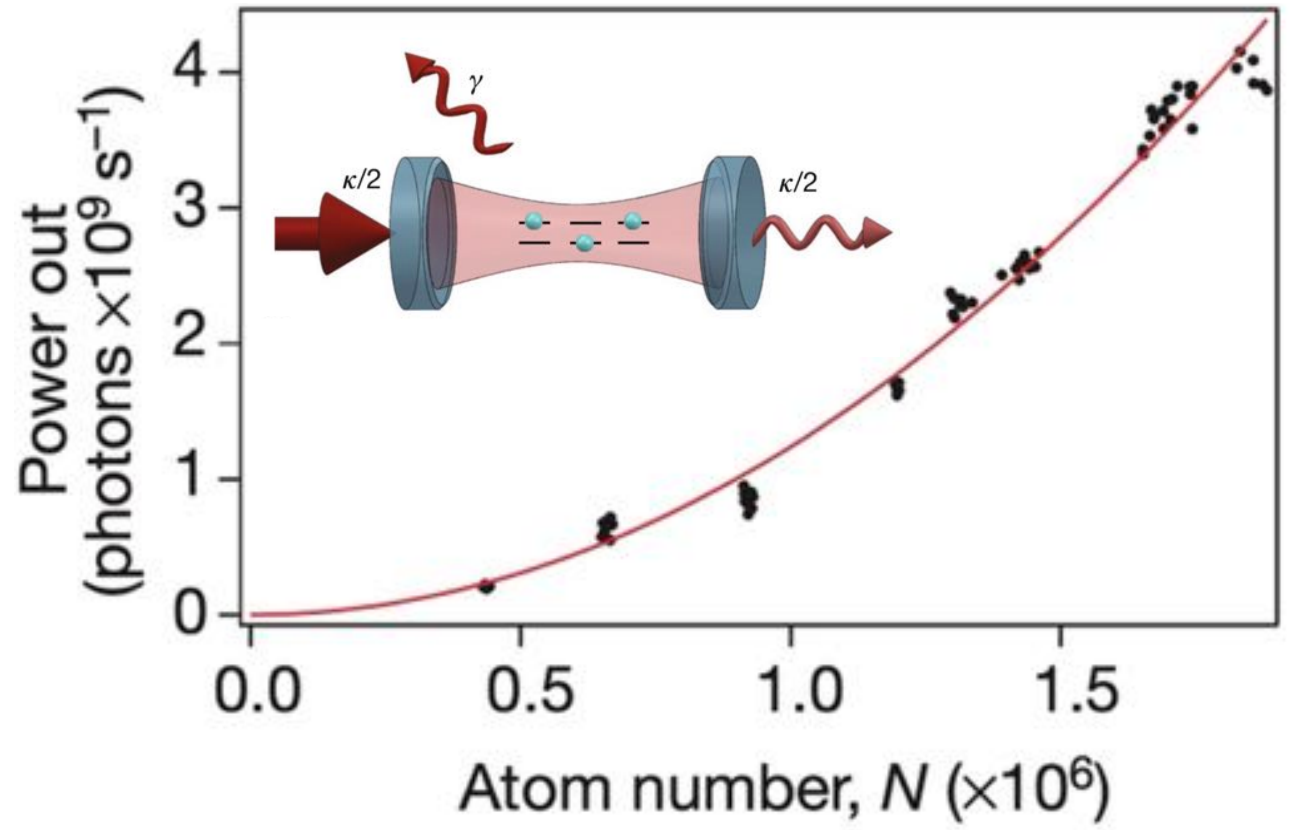
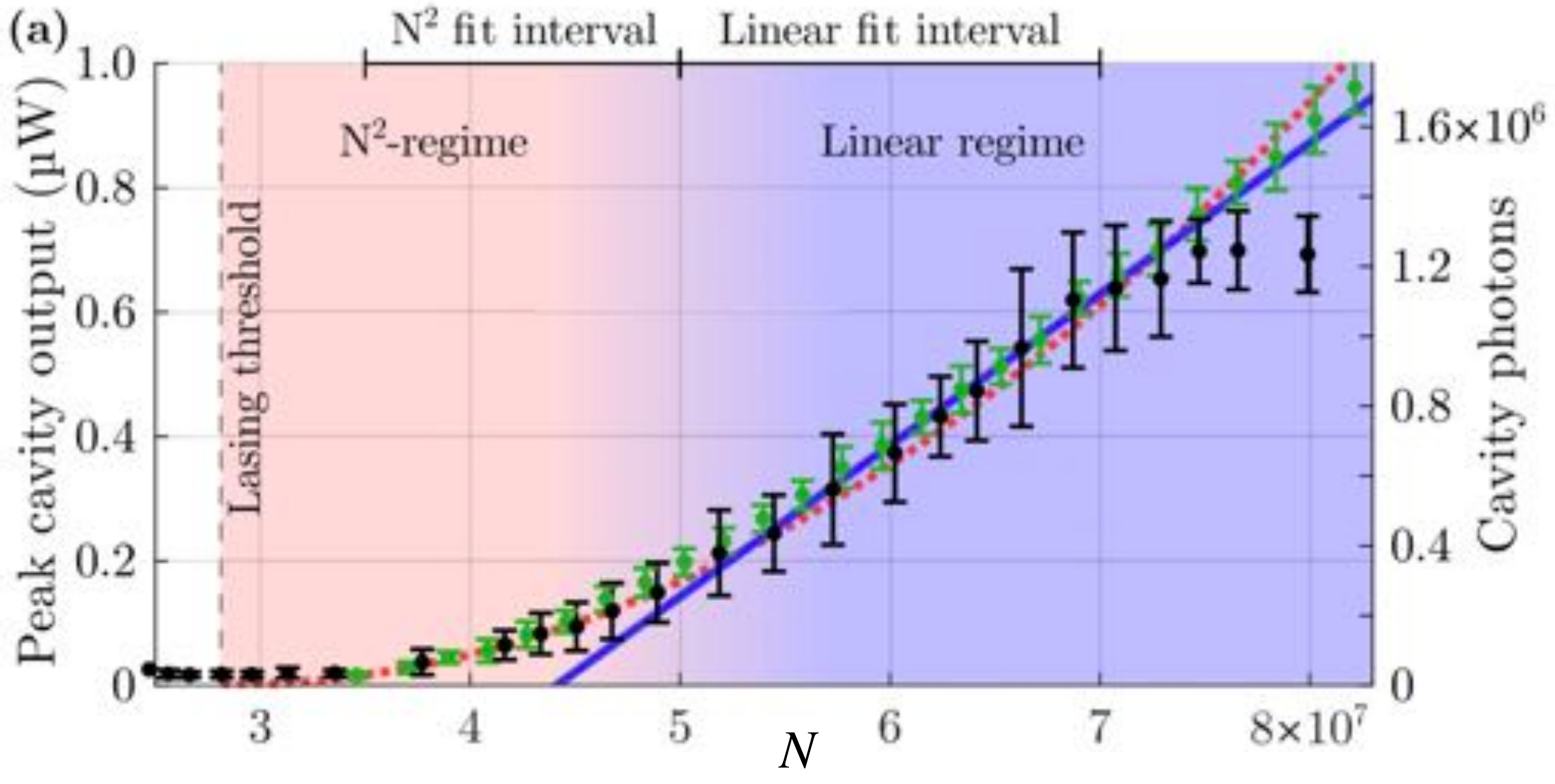
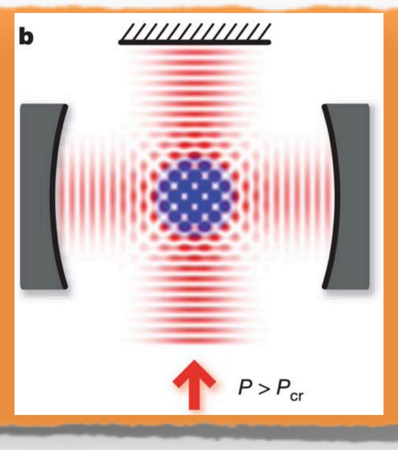


S. A. Schäffer *et al.*, *Phys Rev A* **101**, 013819 (2020).



Mapping with Dicke transition in cavity

?



K. Baumann *et al.*, *Nature* **464**, 1301 (2010).

G. Ferioli *et al.*, arXiv:2207.10361 (2022)

Thank you

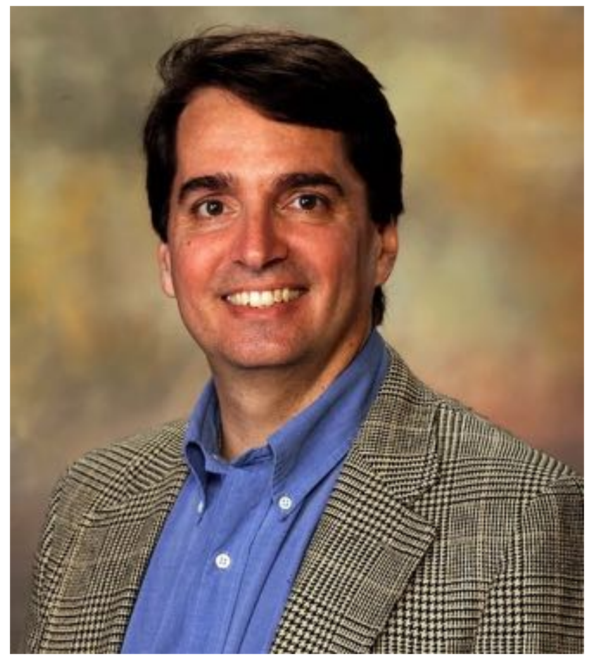
Antoine Browaeys

Sara Pancaldi

Giovanni Ferioli

Antoine Glicenstein

Francis Robicheaux



Collab.

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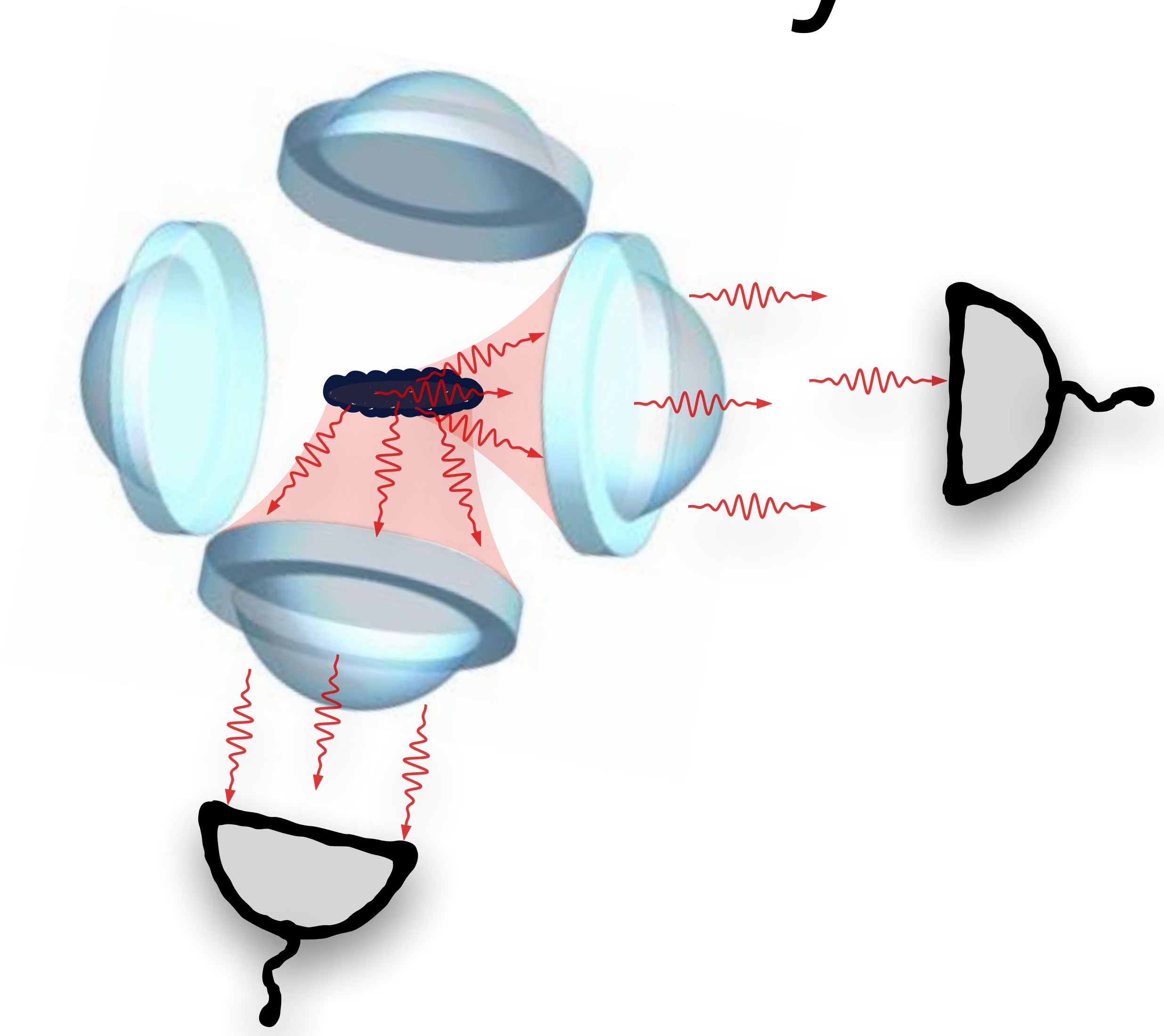
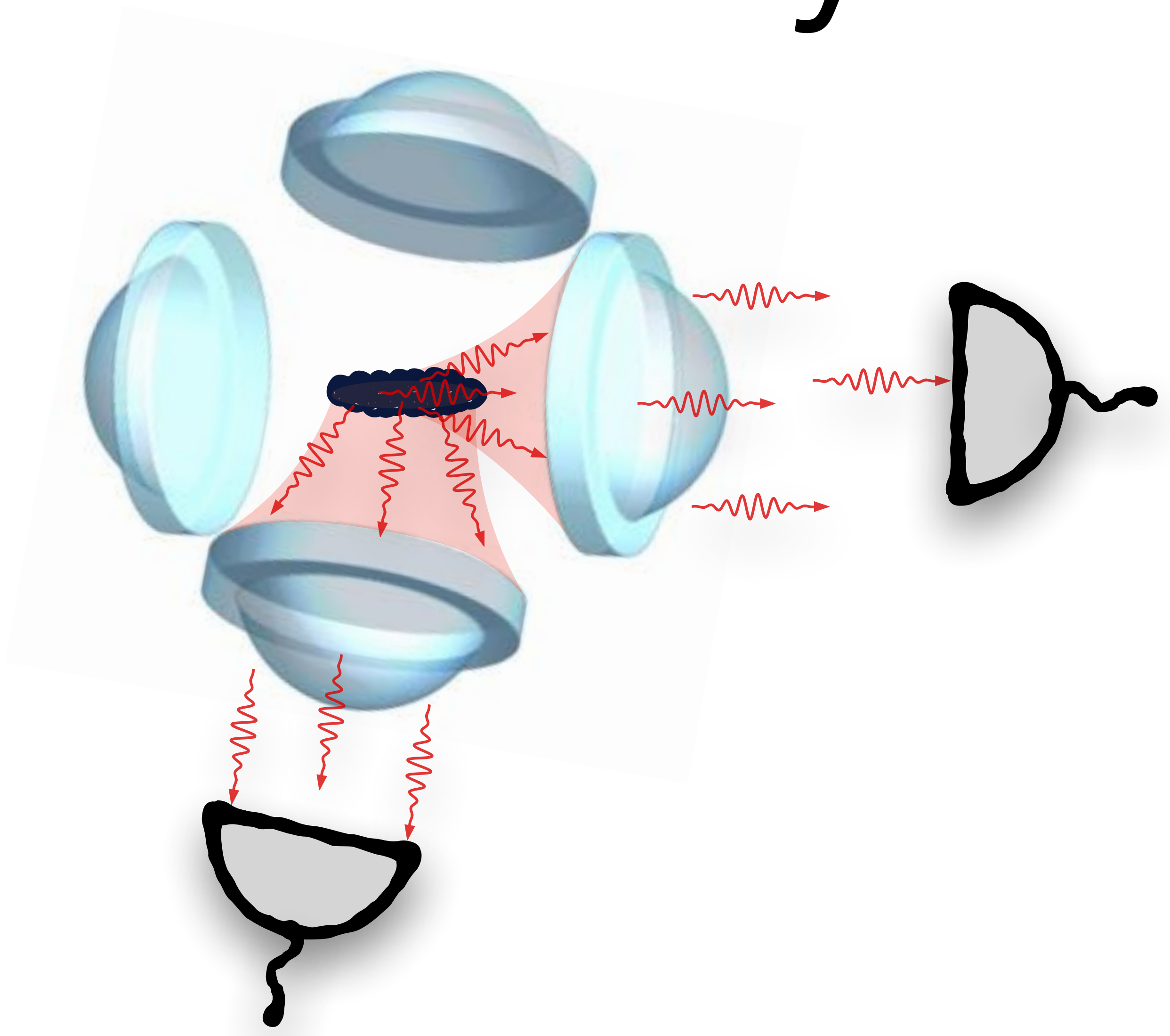
Beyond intensity: light correlations

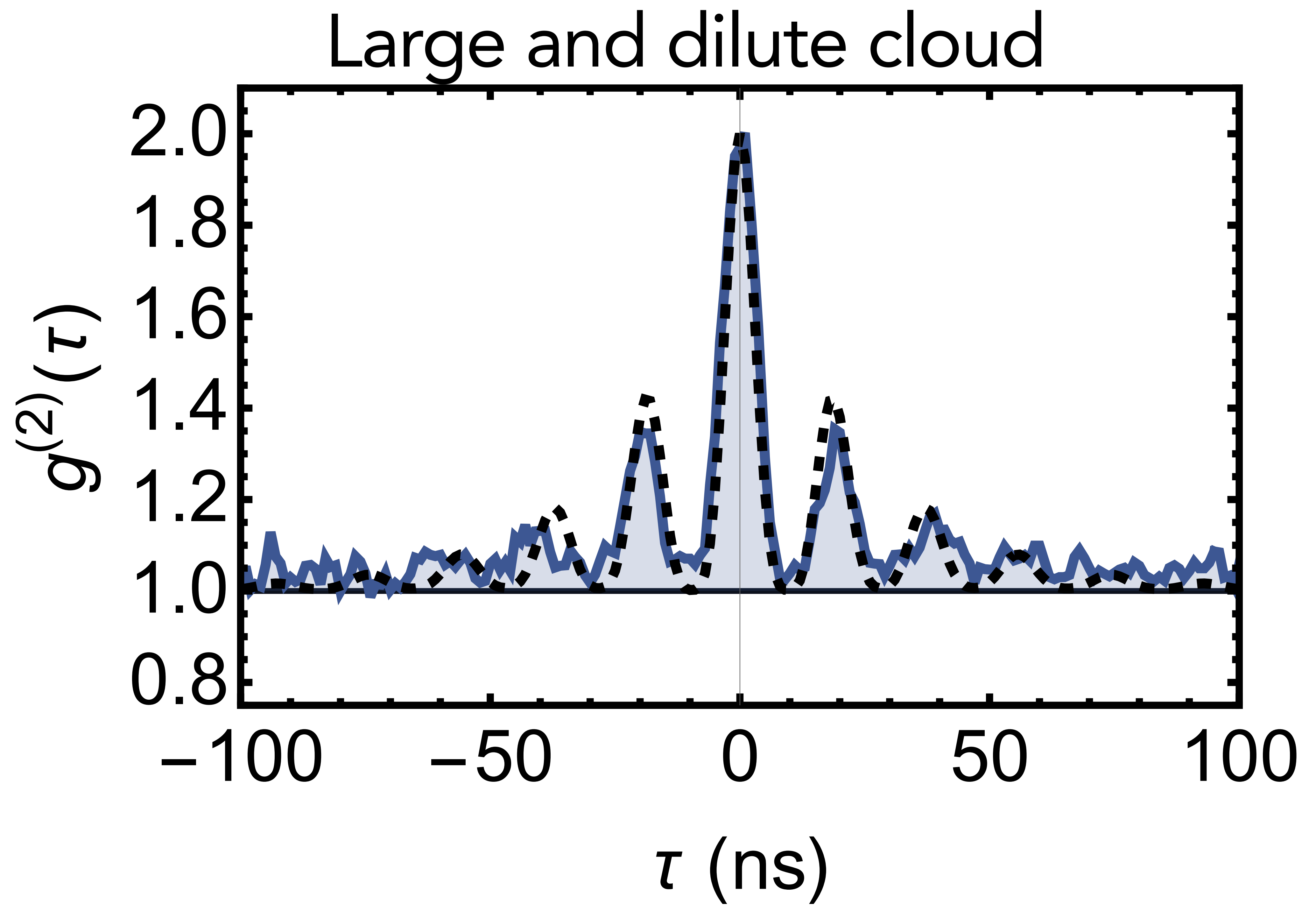


Two-photon correlations $g_2(\tau) = \dfrac{\langle n(t)n(t+\tau)\rangle}{\langle n(t)\rangle\langle n(t+\tau)\rangle}$

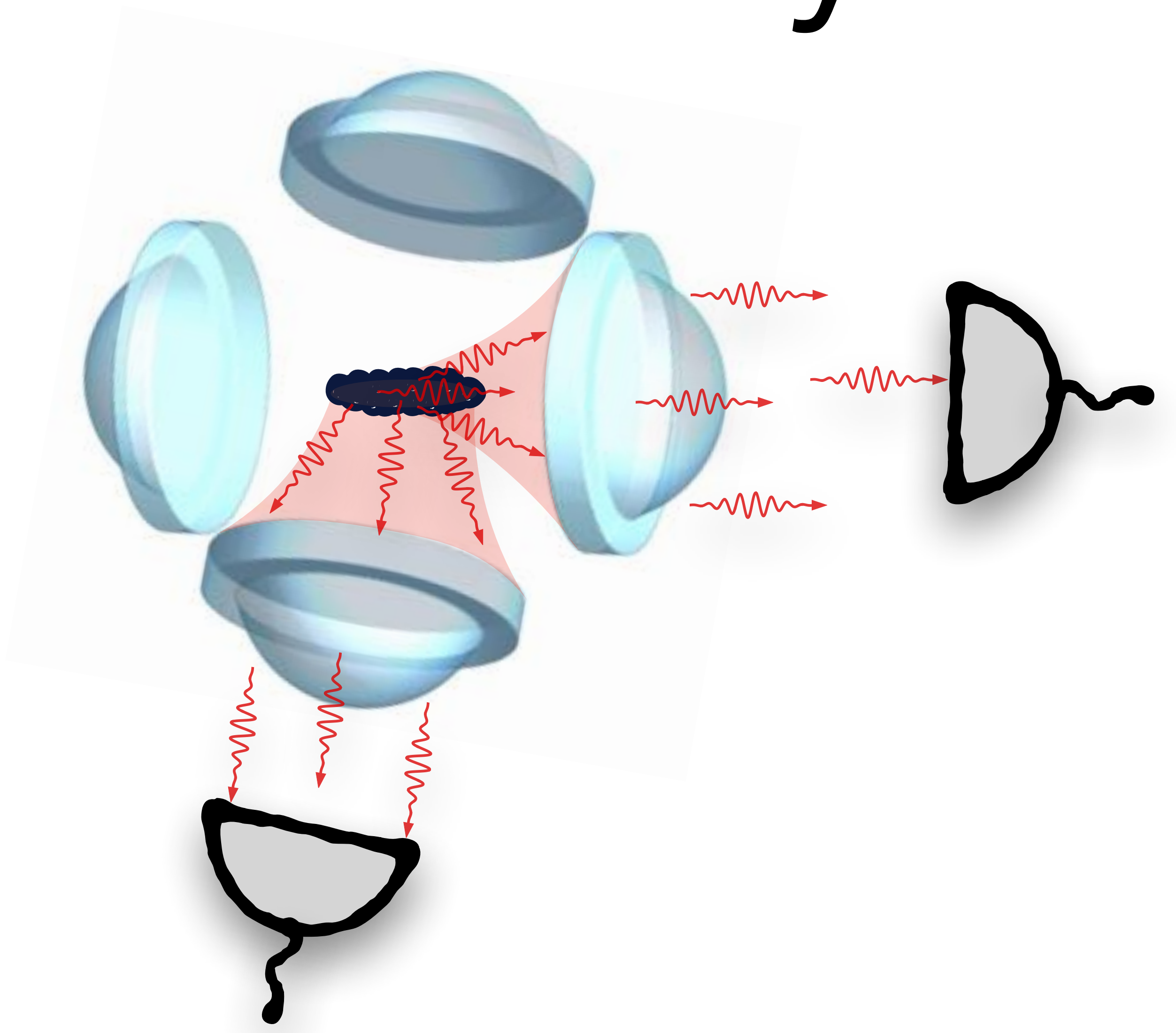
Beyond intensity: light correlations



Two-photon correlations $$g_2(\tau) = \frac{\langle n(t)n(t+\tau)\rangle}{\langle n(t)\rangle\langle n(t+\tau)\rangle}$$

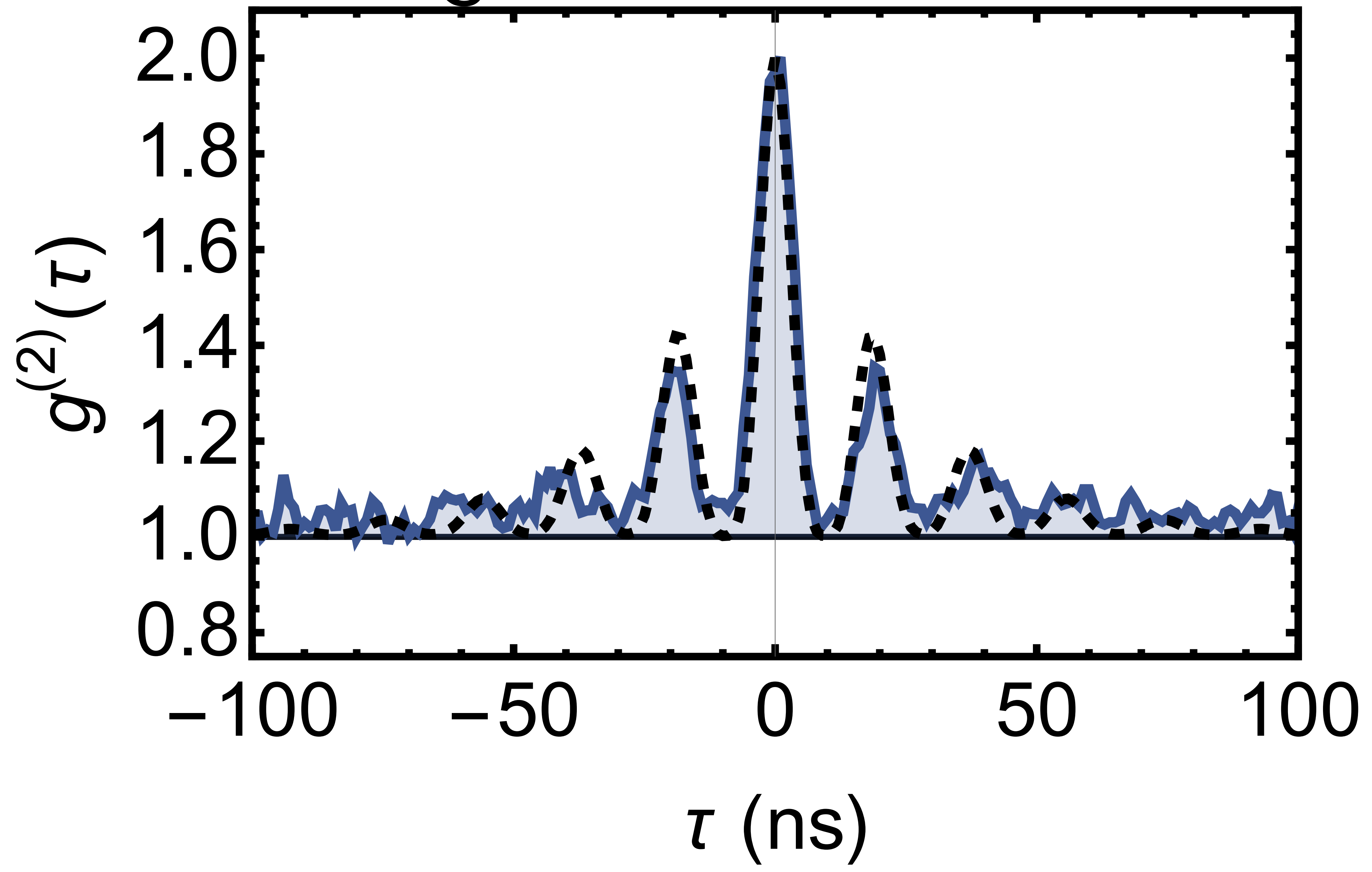


Beyond intensity: light correlations



Two-photon correlations $$g_2(\tau) = \frac{\langle n(t)n(t+\tau)\rangle}{\langle n(t)\rangle\langle n(t+\tau)\rangle}$$

Large and dilute cloud



Independent emitters: Siegert relation

$$g_2^{(N)}(\tau) \underset{N\to\infty}{=} 1 + \left|g_1^{(1)}(\tau)\right|^2 + \frac{1}{N}g_2^{(1)}(\tau)$$

Large clouds of atoms verify Siegert

See *e.g.* Ferreira *et al.*, *Am J Phys* **88**, 831–837 (2020).

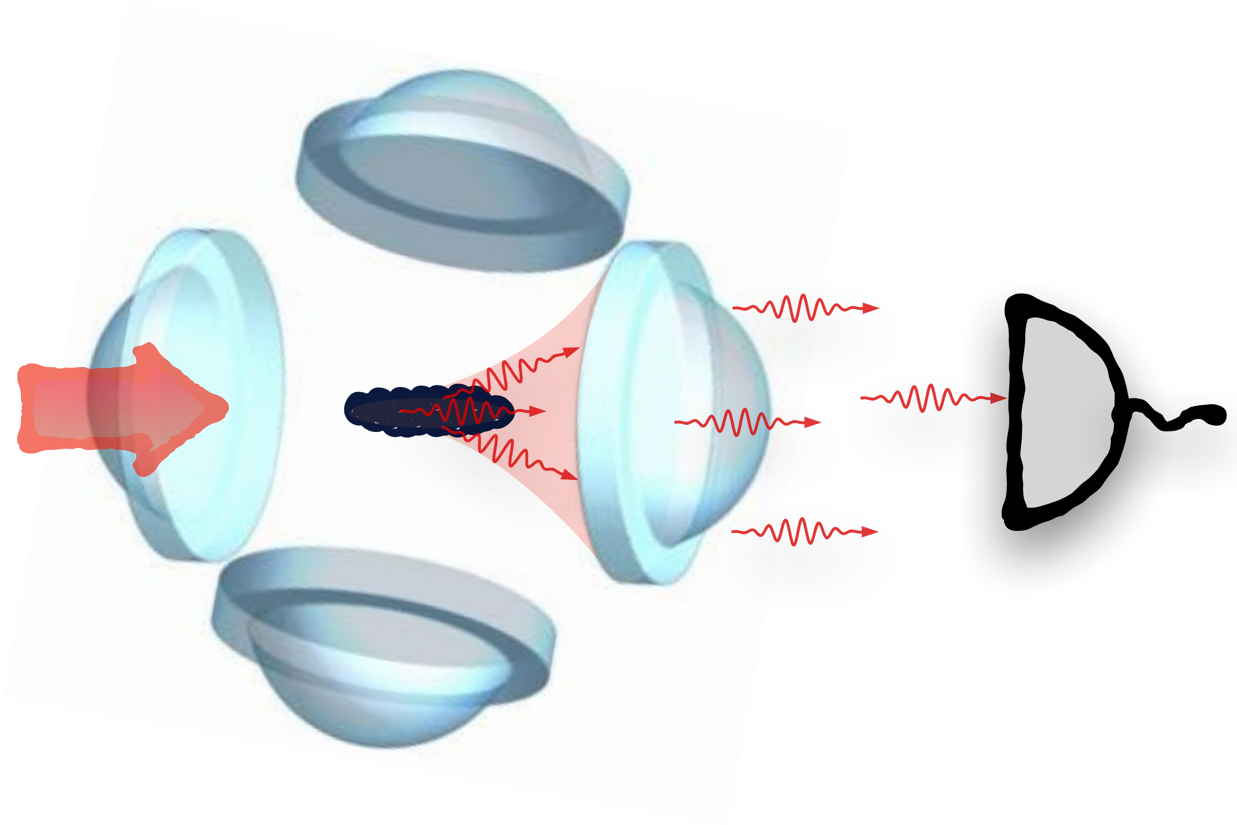
Nice group (Hugbart, Kaiser…)

Beyond intensity: light correlations

General case very challenging

$$g_2(0,\boldsymbol{k}) = \frac{\sum_{k,l,m,n} e^{i\boldsymbol{k}\cdot(\boldsymbol{r}_k+\boldsymbol{r}_l-\boldsymbol{r}_m-\boldsymbol{r}_n)}\langle \hat{\sigma}_k^+ \hat{\sigma}_l^+ \sigma_m^- \hat{\sigma}_n^- \rangle}{\left[\sum_{m,n} e^{i\boldsymbol{k}\cdot(\boldsymbol{r}_m-\boldsymbol{r}_n)}\langle \sigma_m^+ \hat{\sigma}_n^- \rangle\right]^2}$$

Superradiant ensembles



G. Ferioli *et al.*, arXiv:2207.10361 (2022)

Beyond intensity: light correlations

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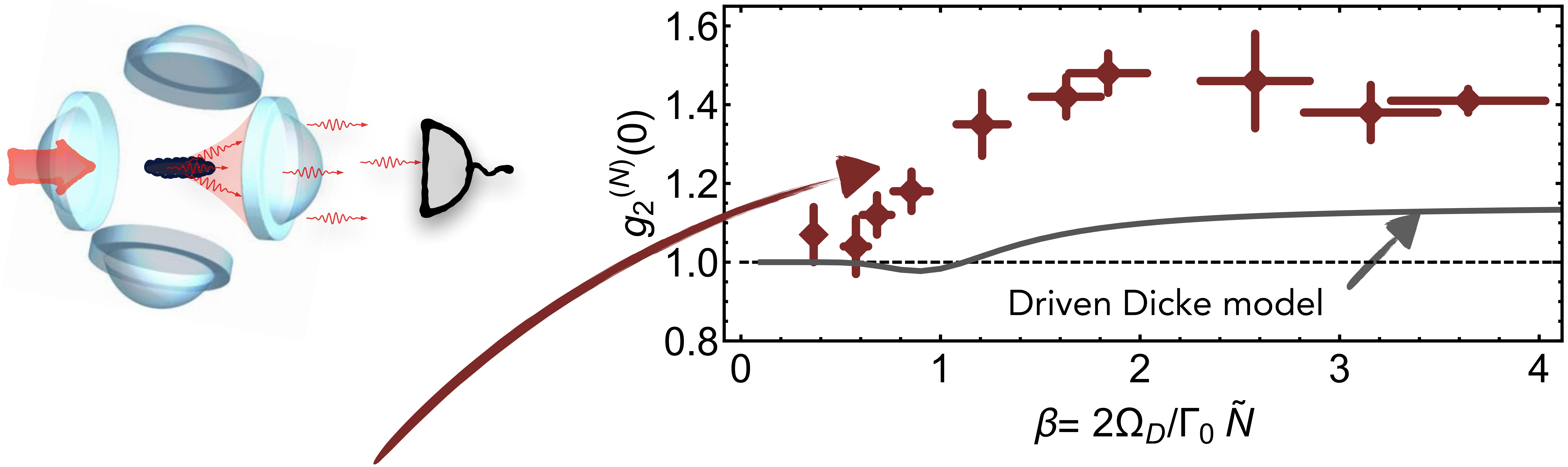
Superradiant ensembles



Strong variation : $g_2(0) = 1$ (coherent state from large collective dipole)

G. Ferioli *et al.*, arXiv:2207.10361 (2022)

Beyond intensity: light correlations

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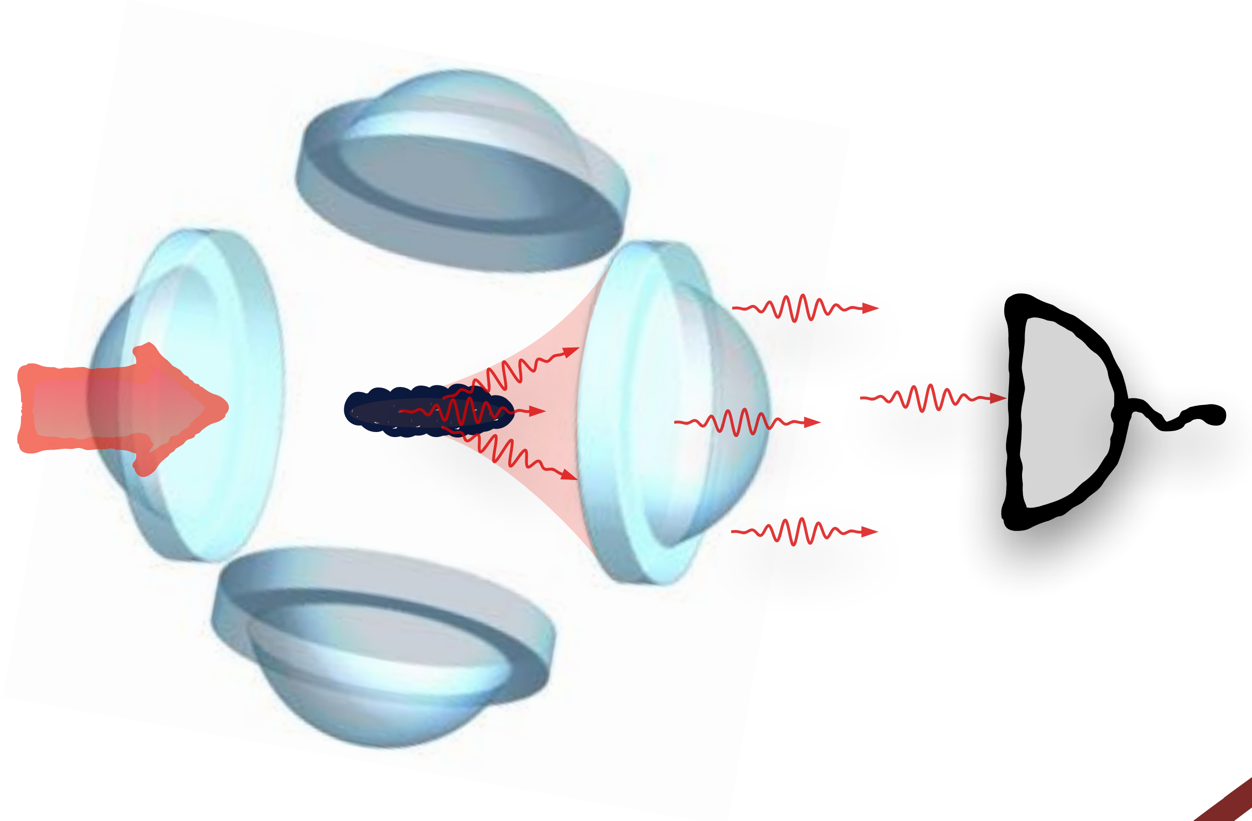
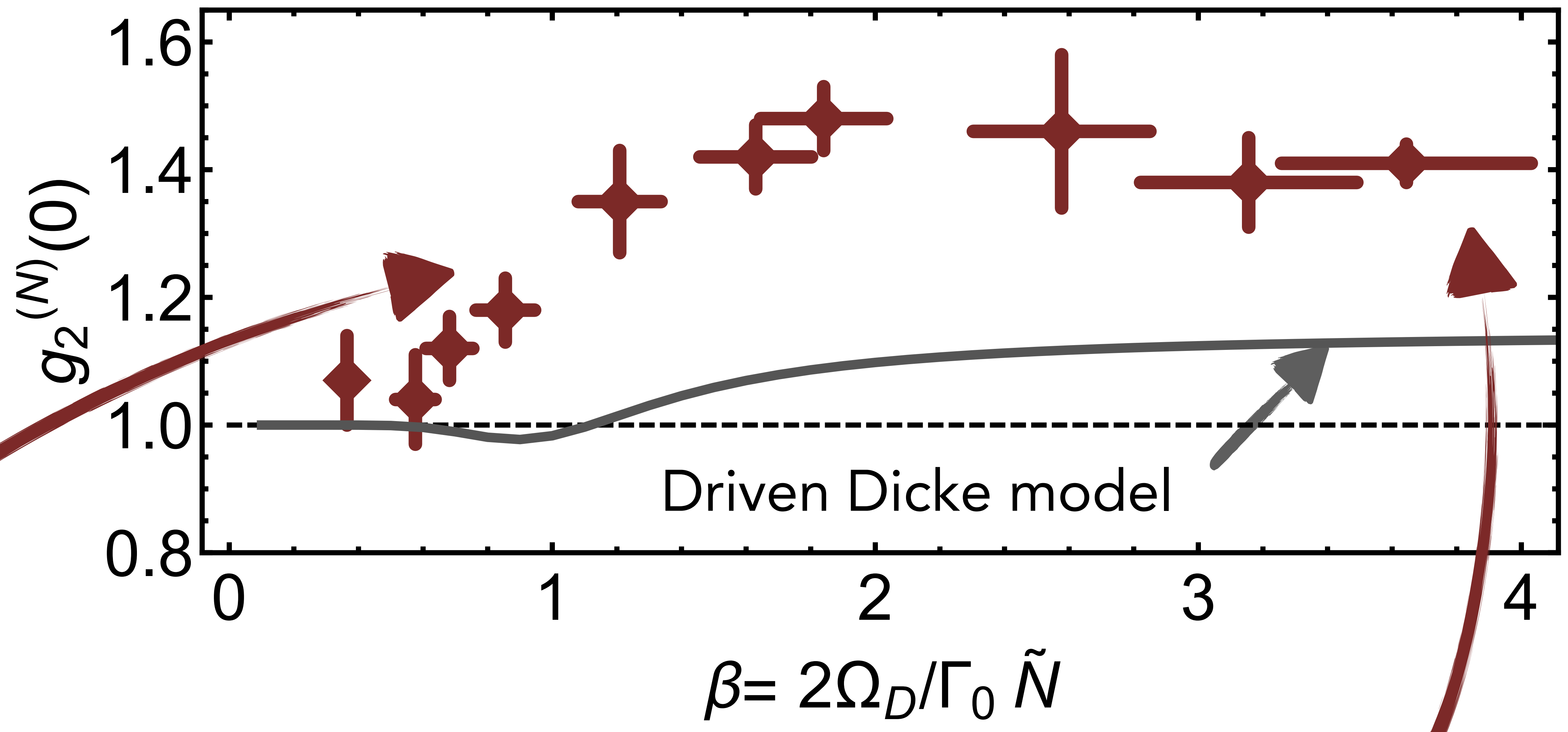
Superradiant ensembles





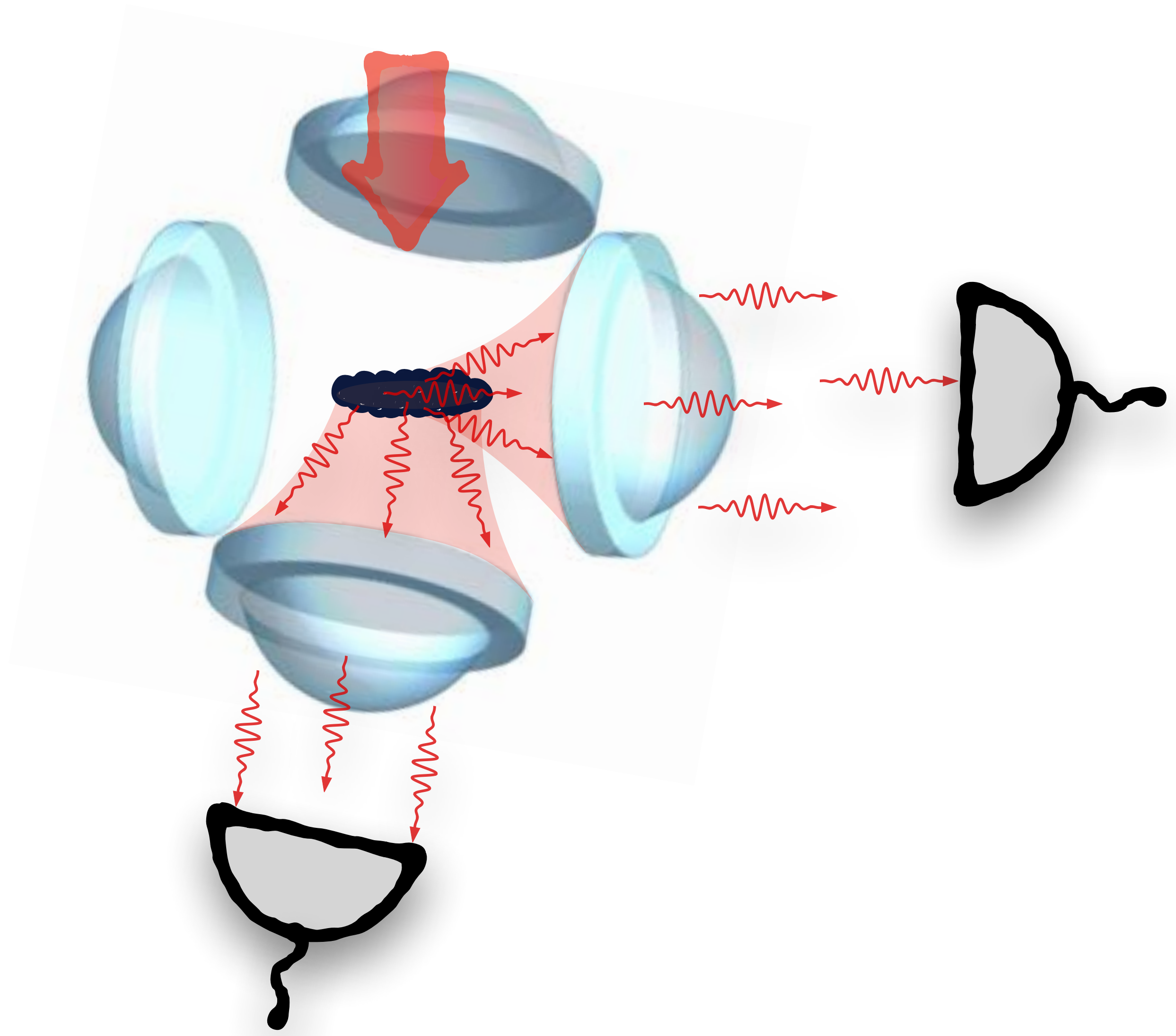
Strong variation : $g_2(0) = 1$ (coherent state from large collective dipole)

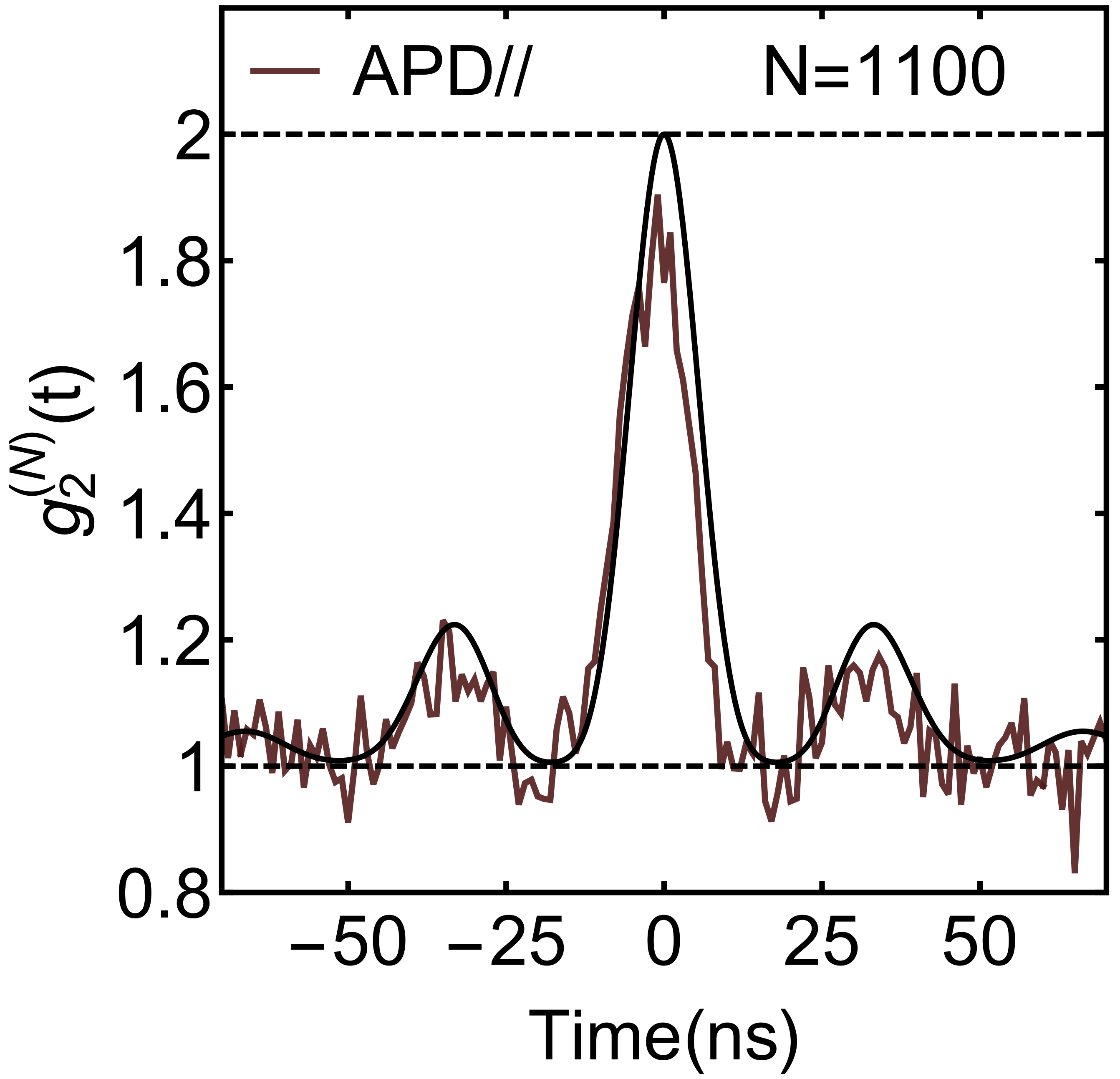
$2 > g_2(0) > 1$ correlated emitters

G. Ferioli *et al.*, arXiv:2207.10361 (2022)

Beyond intensity: light correlations

Directional correlations





Work in progress

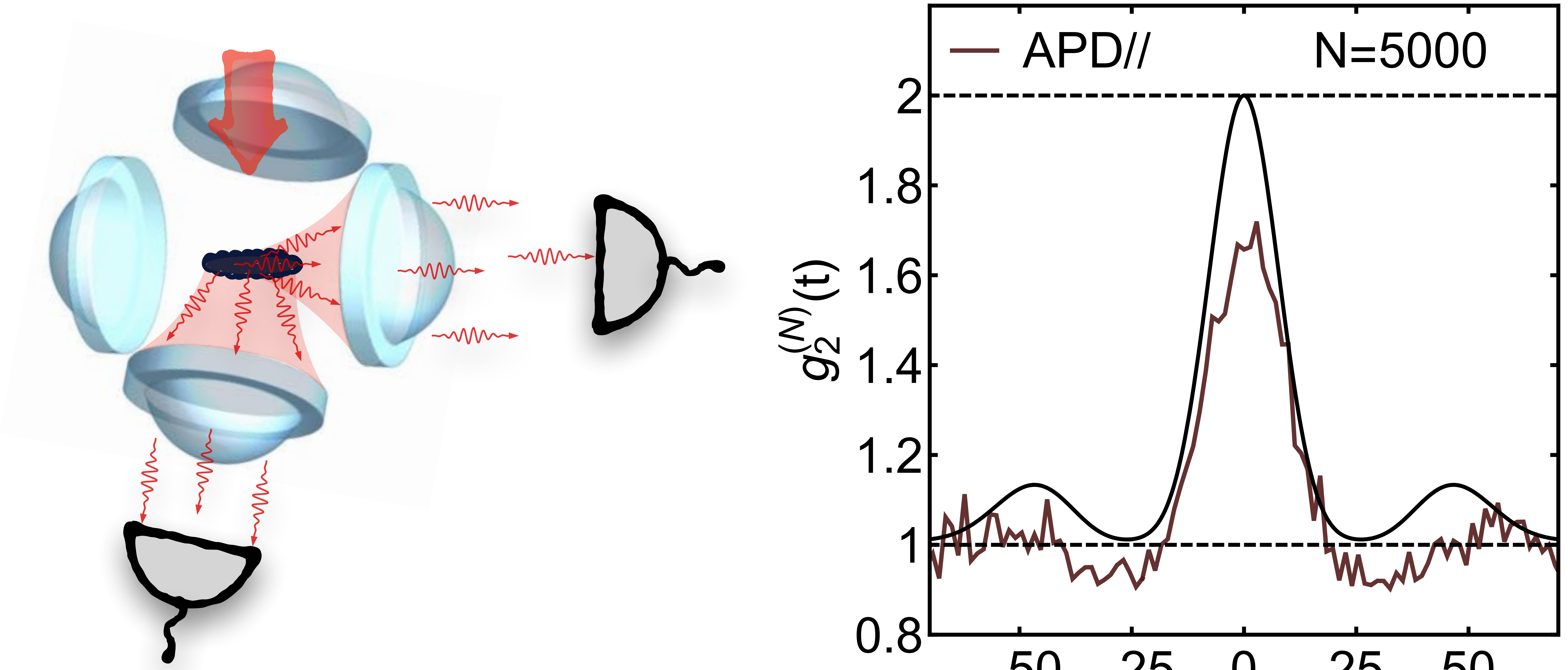
Beyond intensity: light correlations

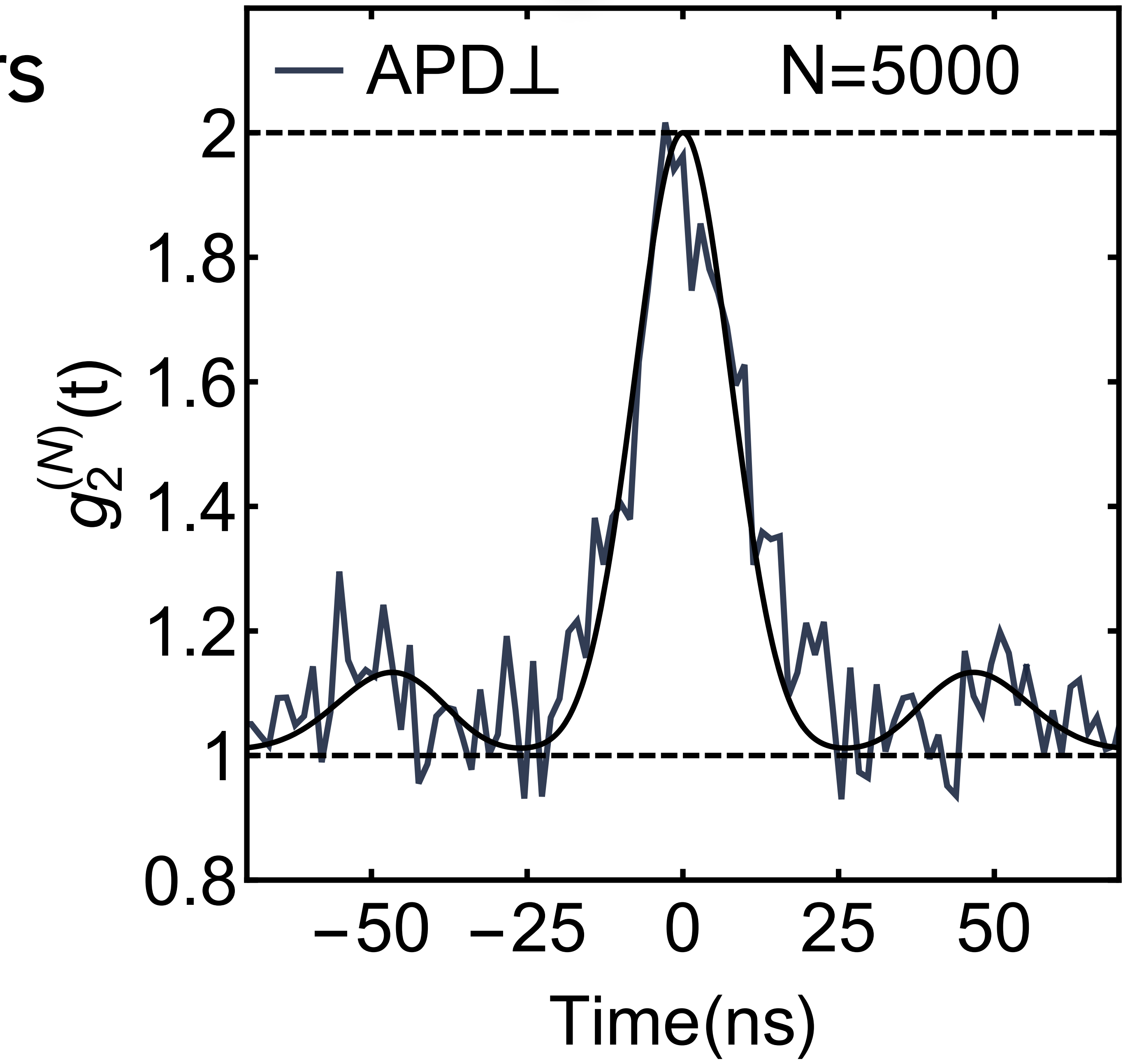
Directional correlations

Axially: violation of Siegert

- $g_2(0) < 2$
- $g_2(\tau) < 1$

Radially: independent scatterers

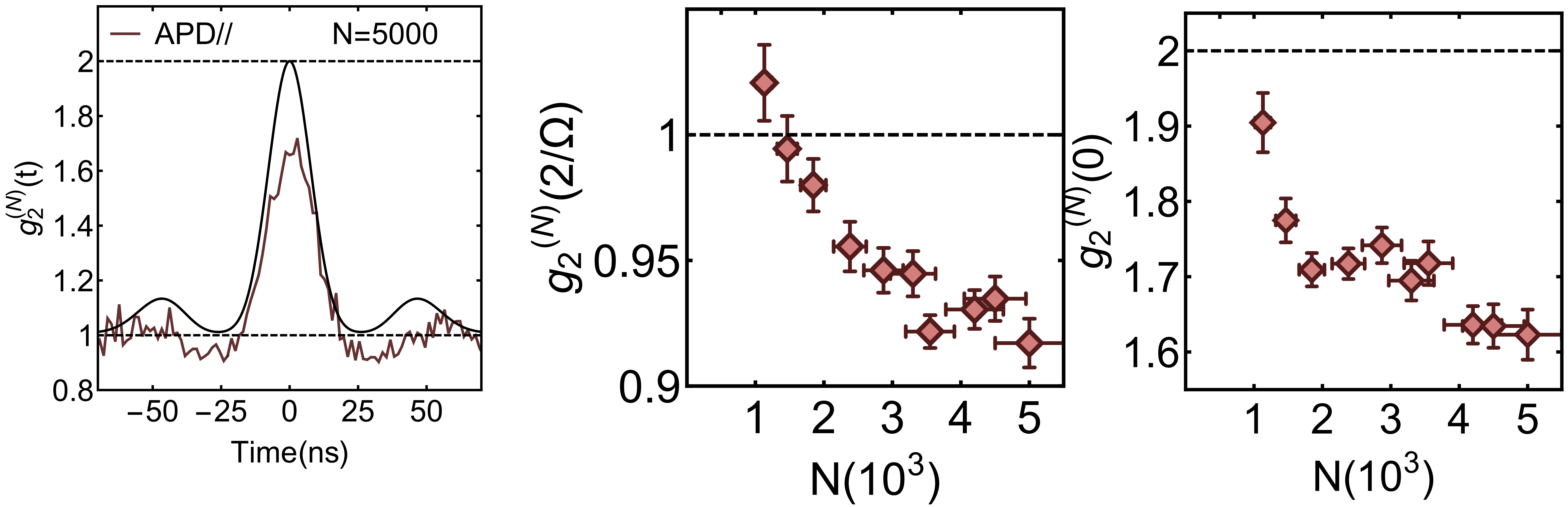




Work in progress

Beyond intensity: light correlations

Growth of collective effects



Atomic correlations ? Photonic correlations

Work in progress