Macroscopic quantum electrodynamics:

Engineering atom–field interactions

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Outline

Introduction: quantum vacuum

Macroscopic quantum electrodynamics: a toolbox

Atom–surface interactions: enhancement by surface plasmons

Cavity QED: effective modes

Resonance energy transfer: impact of environments

Introduction:

Quantum vacuum

The quantum vacuum

"It must be that what can be spoken and thought is, for it is there for being. And there is no such thing as *nothing*."

Parmenides

"There is no more reason for thing to exist than for *no-thing* to exist."

Democritus

M. Brüderlin, *Japan und der Westen: Die erfüllte Leere* (Dumont, 2007);
R. Waterfield, *The First Philosophers* (Oxford University Press, 2009)

The quantum vacuum

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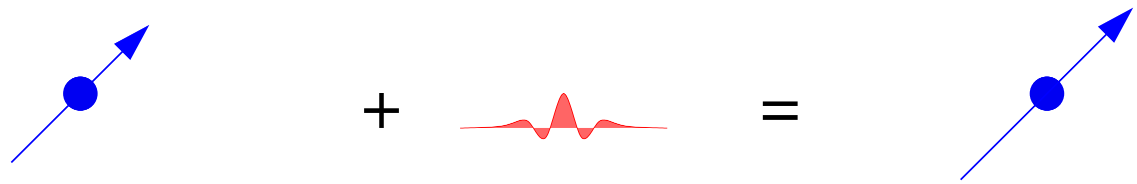
Quantum vacuum: fluctuating electromagnetic fields

Virtual photons: where do they matter?

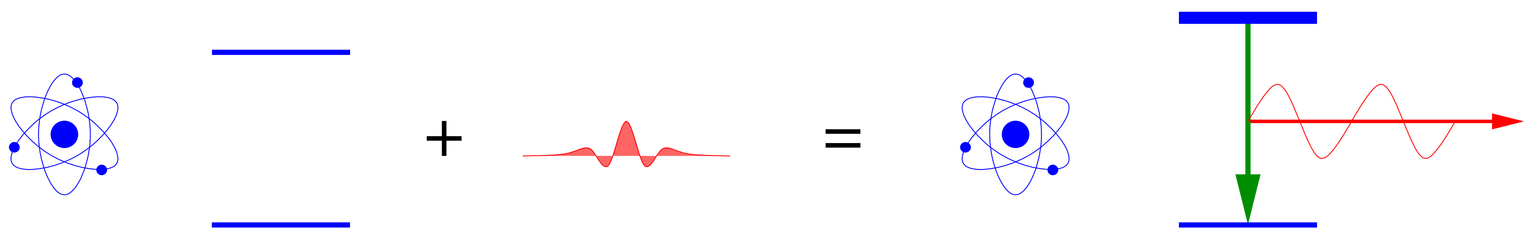
M. Brüderlin, *Japan und der Westen: Die erfüllte Leere* (Dumont, 2007);
R. Waterfield, *The First Philosophers* (Oxford University Press, 2009)

Vacuum effects in free space

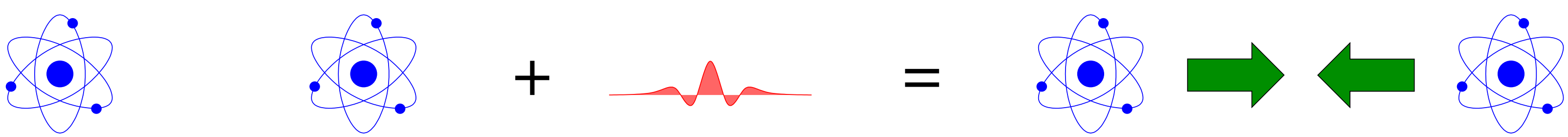
Electron: anomalous magnetic moment



Single atom: Lamb shift, spontaneous decay



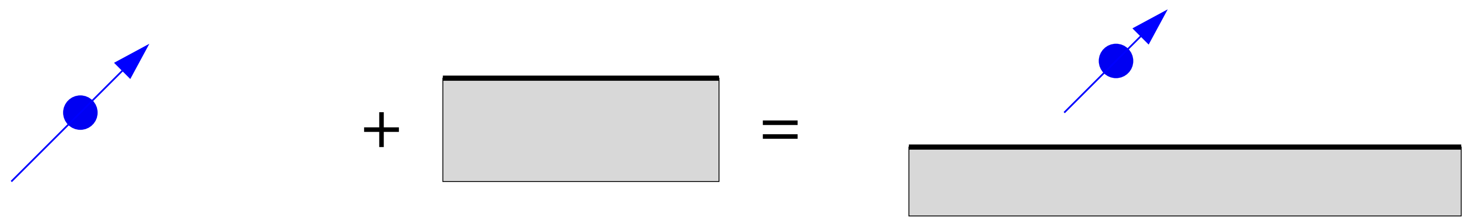
Two atoms: Van der Waals force



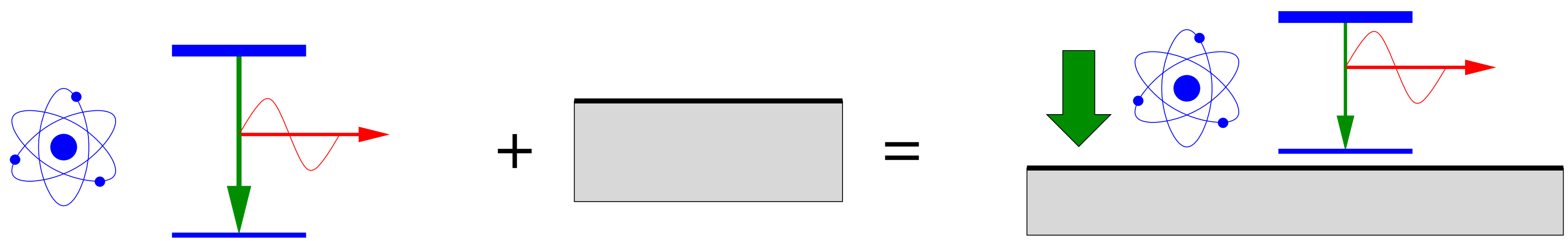
J. Schwinger, PR **73**, 416 (1948)
W. E. Lamb, R. C. Retherford, PR **72**, 241 (1947)
H. B. G. Casimir, D. Polder, PR **73**, 360 (1948)

Environment-affected vacuum effects

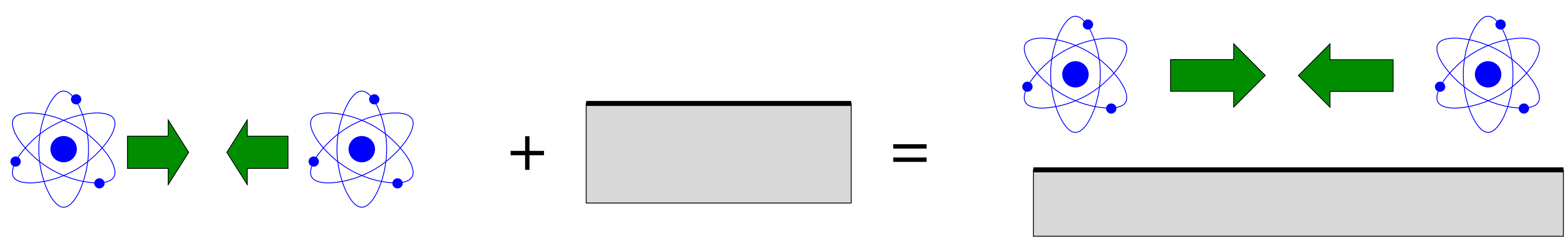
Electron: Position-dependent anomalous magnetic moment



Single atom: Casimir–Polder force, Purcell effect



Two atoms: Modified van der Waals force



G. Barton, N. S. J. Fawcett, Phys. Rep. **170**, 1 (1988); H. B. G. Casimir, D. Polder, PR **73**, 360 (1948); E. M. Purcell, PR **69**, 681 (1946); J. Mahanty, B. W. Ninham, J. Phys. A **6** 1140 (1973)

Background:

Macroscopic quantum electrodynamics

Maxwell equations + Green's tensor

Maxwell equations

$$\nabla\cdot\hat{\boldsymbol{B}} = 0 \qquad \nabla\times\hat{\boldsymbol{E}} - \mathrm{i}\omega\hat{\boldsymbol{B}} = \boldsymbol{0}$$

$$\nabla\cdot\hat{\boldsymbol{D}} = 0 \qquad \nabla\times\hat{\boldsymbol{H}} + \mathrm{i}\omega\hat{\boldsymbol{D}} = \boldsymbol{0}$$

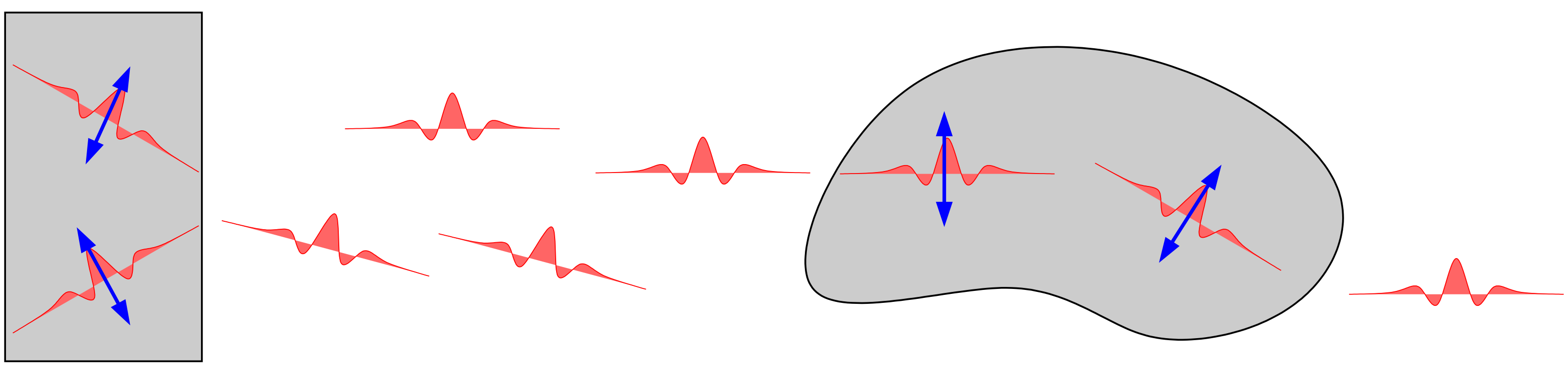
Constitutive relation

$$\hat{\boldsymbol{D}} = \varepsilon_0\varepsilon\hat{\boldsymbol{E}} + \hat{\boldsymbol{P}}_{\mathrm{N}}$$

Electric field: $\hat{\boldsymbol{E}}(\boldsymbol{r}) = \mu_0\omega^2\int \mathrm{d}^3r'\,\mathbf{G}(\boldsymbol{r},\boldsymbol{r}',\omega)\cdot\hat{\boldsymbol{P}}_{\mathrm{N}}(\boldsymbol{r}')$

Green's tensor:

$$\nabla\times\nabla\times\mathbf{G}(\boldsymbol{r},\boldsymbol{r}',\omega) - \frac{\omega^2}{c^2}\varepsilon(\boldsymbol{r},\omega)\mathbf{G}(\boldsymbol{r},\boldsymbol{r}',\omega) = \boldsymbol{\delta}(\boldsymbol{r}-\boldsymbol{r}')$$



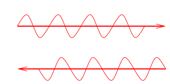
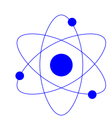
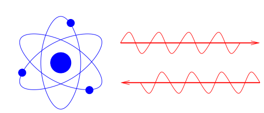
L. Knöll, S. Scheel, D.-G. Welsch, in *Coherence and Statistics of Photons and Atoms*, ed. by J. Peřina (Wiley, New York, 2001)

Quantisation + atom–field coupling

Bosonic variables: $\left[\hat{\boldsymbol{f}}(\boldsymbol{r},\omega),\hat{\boldsymbol{f}}^\dagger(\boldsymbol{r}',\omega')\right] = \boldsymbol{\delta}(\boldsymbol{r}-\boldsymbol{r}')\delta(\omega-\omega')$

$$\underline{\hat{\boldsymbol{P}}}_{\mathsf{N}}(\boldsymbol{r},\omega) = \sqrt{\frac{\hbar\varepsilon_0}{\pi}\,\mathrm{Im}\,\varepsilon(\boldsymbol{r},\omega)}\,\hat{\boldsymbol{f}}(\boldsymbol{r},\omega)$$

Hamiltonian: $\boxed{\hat{H} = \hat{H}_{\mathsf{F}} + \sum_{\mathsf{A}} \hat{H}_{\mathsf{A}} + \sum_{\mathsf{A}} \hat{H}_{\mathsf{AF}}}$

- *Body–Field:* $\hat{H}_{\mathsf{F}} = \int \mathrm{d}^3r \int_0^\infty \mathrm{d}\omega\,\hbar\omega\,\hat{\boldsymbol{f}}^\dagger(\boldsymbol{r},\omega)\cdot\hat{\boldsymbol{f}}(\boldsymbol{r},\omega)$ 
- *Atom:* $\hat{H}_{\mathsf{A}} = \frac{\hat{\boldsymbol{p}}_{\mathsf{A}}^2}{2m_{\mathsf{A}}} + \sum_n E_n|n\rangle\langle n|$ 
- *Electric-dipole coupling:* $\hat{H}_{\mathsf{AF}} = -\hat{\boldsymbol{d}}\cdot\hat{\boldsymbol{E}}(\boldsymbol{r}_{\mathsf{A}})$ 

L. Knöll, S. Scheel, D.-G. Welsch, in *Coherence and Statistics of Photons and Atoms*, ed. by J. Peřina (Wiley, New York, 2001)

Consistency with other theories

Classical electrodynamics: Maxwell eqs. + Lorentz force $\surd$

$$\nabla\cdot\hat{\boldsymbol{B}}=0 \qquad \nabla\times\hat{\boldsymbol{E}}+\dot{\hat{\boldsymbol{B}}}=\boldsymbol{0}$$

$$\nabla\cdot\hat{\boldsymbol{D}}=\hat{\rho}_A \qquad \nabla\times\hat{\boldsymbol{H}}-\dot{\hat{\boldsymbol{D}}}=\hat{\boldsymbol{j}}_A$$

$$m_\alpha\ddot{\hat{\boldsymbol{r}}}_\alpha=q_\alpha\hat{\boldsymbol{E}}(\hat{\boldsymbol{r}}_\alpha)+q_\alpha\mathcal{S}\Big[\dot{\hat{\boldsymbol{r}}}_\alpha\times\hat{\boldsymbol{B}}(\hat{\boldsymbol{r}}_\alpha)\Big]$$

Statistical physics: Fluctuation–dissipation theorem $\surd$

$$\Big\langle\mathcal{S}\Big[\Delta\hat{\boldsymbol{E}}(\boldsymbol{r},\omega)\Delta\hat{\boldsymbol{E}}^\dagger(\boldsymbol{r}',\omega')\Big]\Big\rangle=\frac{\hbar}{2\pi}\mu_0\omega^2\,\mathrm{Im}\,\mathbf{G}(\boldsymbol{r},\boldsymbol{r}',\omega)\delta(\omega-\omega')$$

Free-space QED: Fundamental commutators $\surd$

$$\Big[\hat{\boldsymbol{E}}(\boldsymbol{r}),\hat{\boldsymbol{B}}(\boldsymbol{r}')\Big]=\frac{\mathrm{i}\hbar}{\varepsilon_0}\nabla\times\boldsymbol{\delta}(\boldsymbol{r}-\boldsymbol{r}') \quad \text{for } \varepsilon(\boldsymbol{r},\omega)\to 1$$

L. Knöll, S. Scheel, D.-G. Welsch, in *Coherence and Statistics of Photons and Atoms*, ed. by J. Peřina (Wiley, New York, 2001)

Atom–surface interactions:

Enhancement by surface plasmons

Laser-induced atom–surface interactions

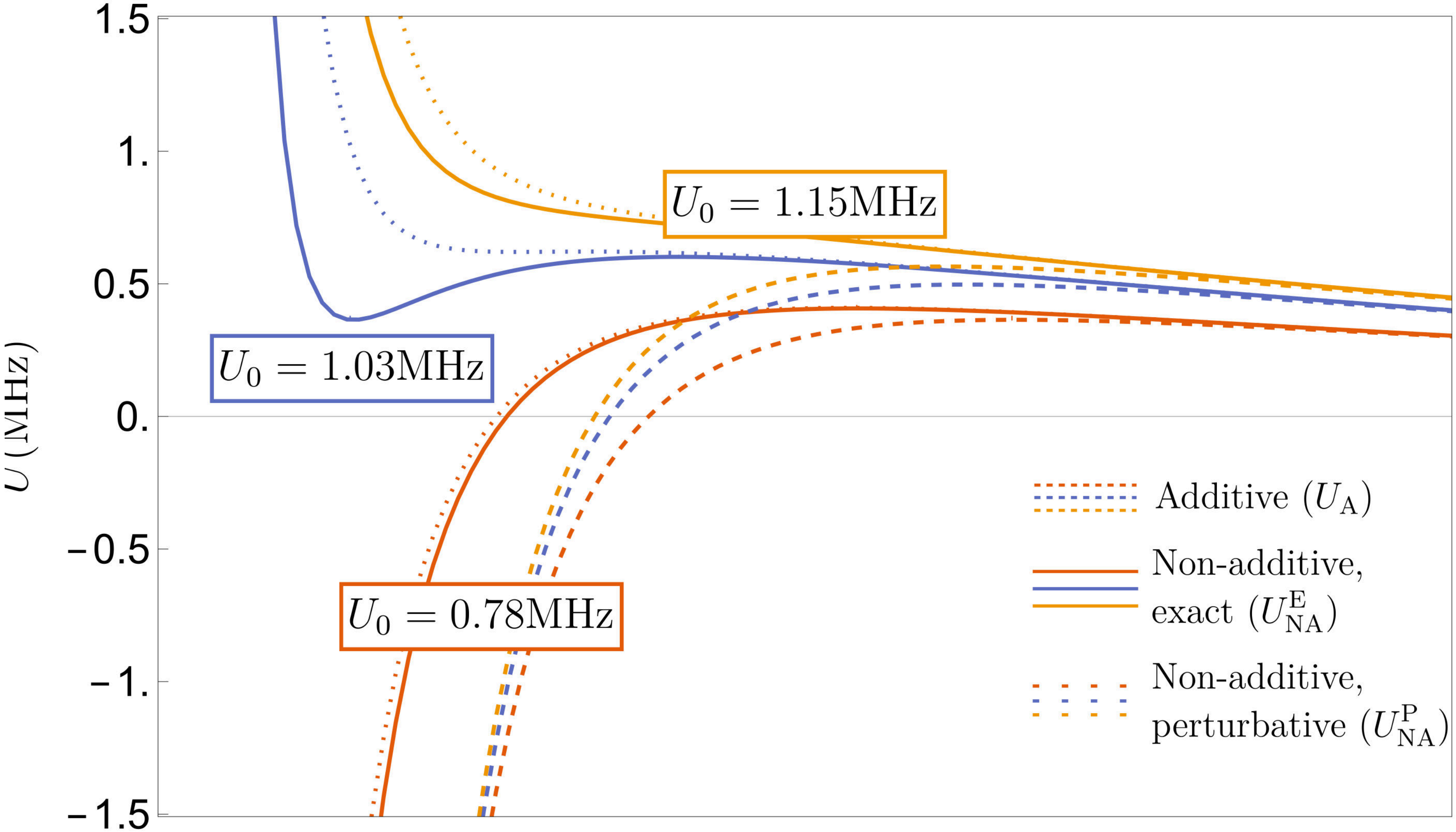
Setup: atom near surface + evanescent laser

Interactions: $\hat{H}_{\text{int}} = -\hat{\boldsymbol{d}} \cdot \boldsymbol{E}_{\text{laser}}(\boldsymbol{r}_{\text{A}}) - \hat{\boldsymbol{d}} \cdot \hat{\boldsymbol{E}}(\boldsymbol{r}_{\text{A}})$

S. Fuchs et al., PRL **121**, 083603 (2018)

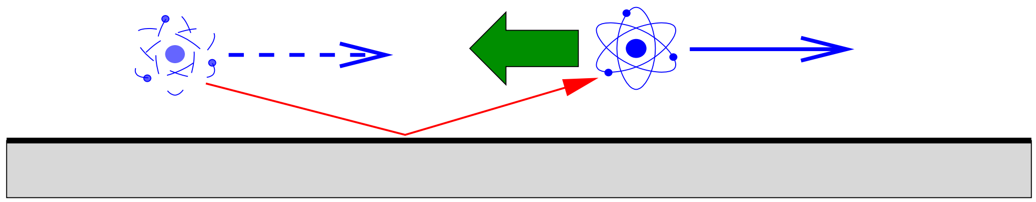
Laser-induced atom–surface interactions

Setup: atom near surface + evanescent laser



S. Fuchs et al., PRL **121**, 083603 (2018)

Force on a moving atom



Starting point: $\boldsymbol{F} = \nabla \left\langle \hat{\boldsymbol{d}} \cdot \left[\hat{\boldsymbol{E}}(\boldsymbol{r}) + \boldsymbol{v} \times \hat{\boldsymbol{B}}(\boldsymbol{r}) \right] \right\rangle \Big|_{\boldsymbol{r}=\boldsymbol{r}_{\mathrm{A}}}$

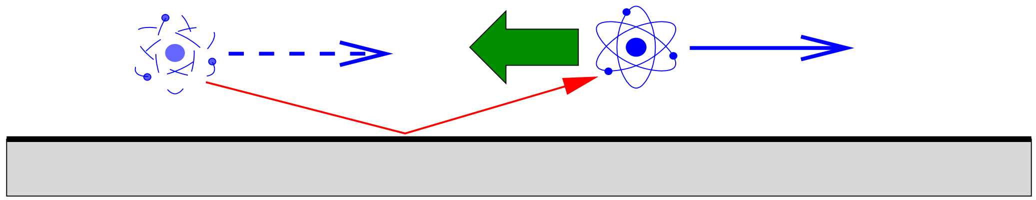
Calculation: integrate coupled atom–field dynamics,
Markov approximation, linear order in $\boldsymbol{v}$

Motion-dependent force:

- *Delay effect:* Main contribution
- *Röntgen interaction:* Relevant at large distances
- *Doppler effect:* Present for normal motion

S. Scheel, S.Y.B., PRA **80**, 042902 (2009)

Ground-state atom



$$\boldsymbol{F}_0 = -\frac{3\omega_S \boldsymbol{v}}{64\pi\varepsilon_0 z_A^5} \sum_k \frac{\Gamma_k \left(2 d_{0k}^{\perp\,2} + d_{0k}^{\parallel\,2}\right)}{(\omega_{k0} + \omega_S)^3}$$

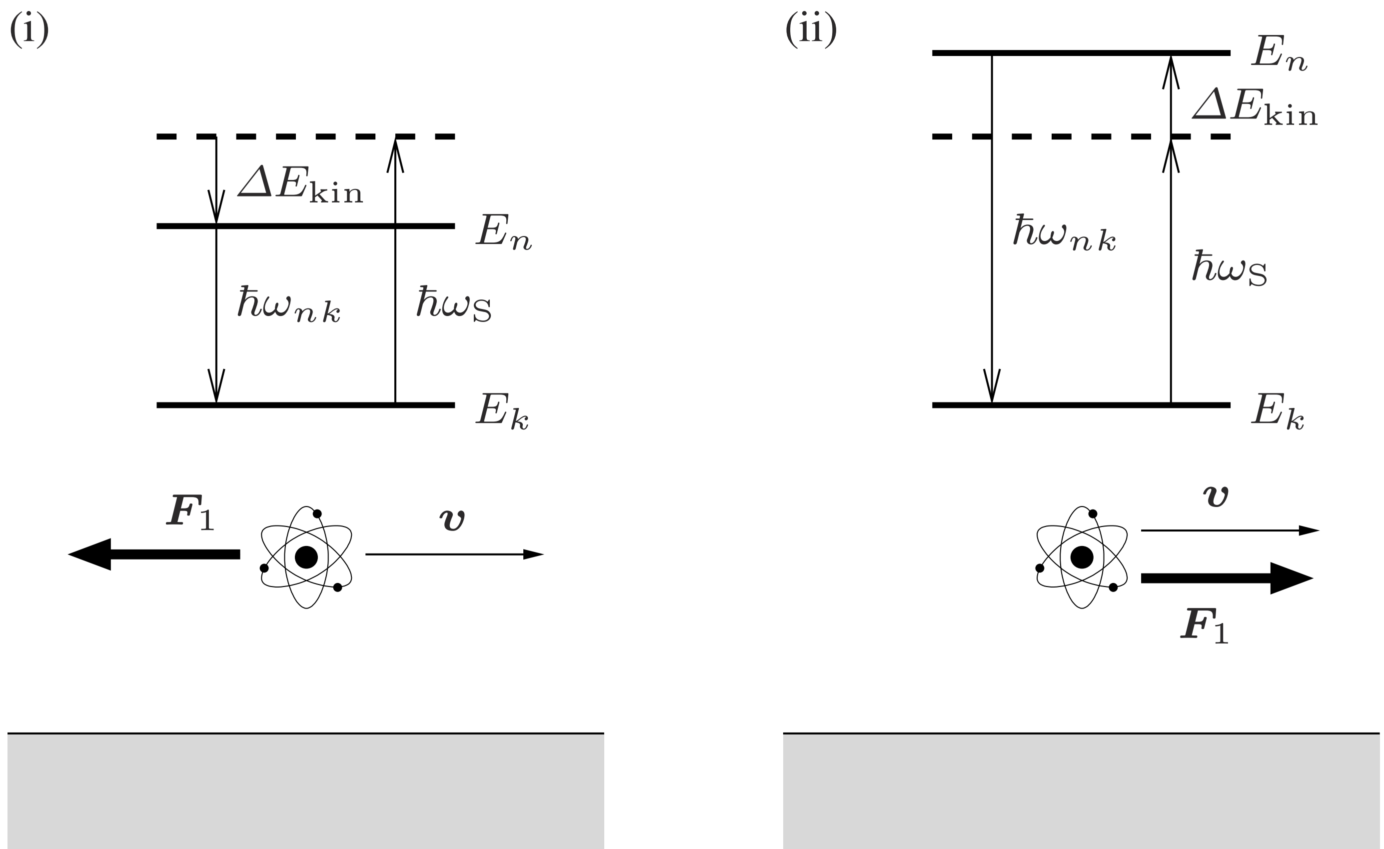
Example: Rb atom near Au surface

$$\boldsymbol{a} = -\boldsymbol{v}\left(1.1\,\mathrm{s}^{-1}\right)\left[\frac{1\,\mathrm{nm}}{z_A}\right]^8$$

Caveat: Markov approximation breaks down

S. Scheel, S.Y.B., PRA **80**, 042902 (2009)
G. Barton, NJP **12**, 113045 (2010)

Excited Atom

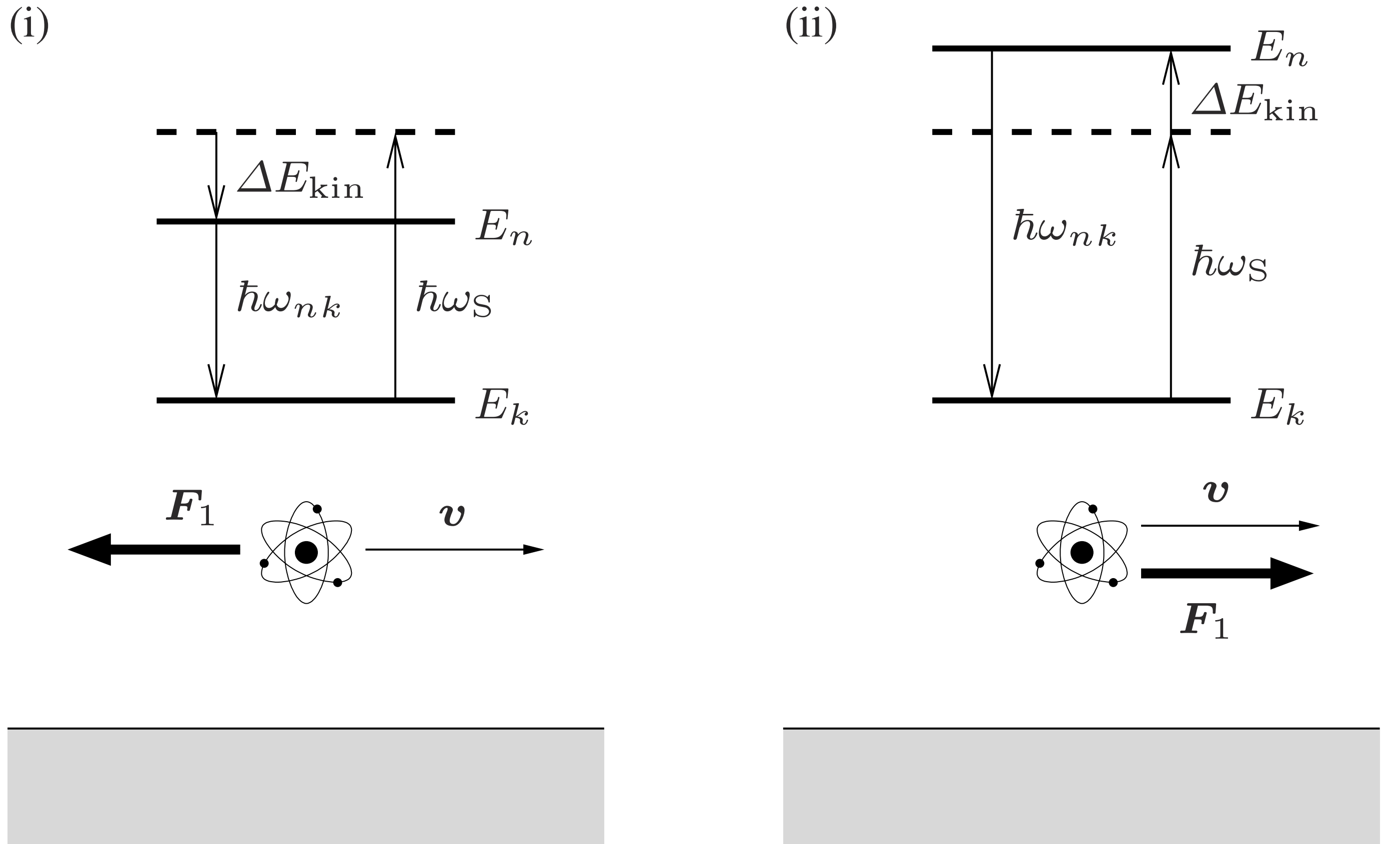


Example (i): Rb atom near Au surface

$$\boldsymbol{a} = -\boldsymbol{v}\left(1.1 \times 10^4\,\mathrm{s}^{-1}\right)\left[\frac{1\,\mathrm{nm}}{z_A}\right]^5$$

S. Scheel, S.Y.B., PRA **80**, 042902 (2009)

Excited Atom



Example (ii): Cs atom near Sapphire surface

$$\boldsymbol{a} = +\boldsymbol{v}\left(7.1 \times 10^{11}\,\mathrm{s}^{-1}\right)\left[\frac{1\,\mathrm{nm}}{z_A}\right]^5$$

S. Scheel, S.Y.B., PRA **80**, 042902 (2009)

Cavity QED:

Effective modes

Jaynes–Cummings model

Identical two-level atoms: $\hat{\boldsymbol{d}}_{\mathsf{A}} = \boldsymbol{d}\hat{\sigma}_{\mathsf{A}} + \boldsymbol{d}^*\hat{\sigma}_{\mathsf{A}}^\dagger$

$$\hat{H}_{\mathsf{AF}} = \hbar \int_0^\infty \mathrm{d}\omega\, g_{\mathsf{A}}(\omega)\Big[\hat{a}_{\mathsf{A}}(\omega)\hat{\sigma}_{\mathsf{A}}^\dagger + \hat{a}_{\mathsf{A}}^\dagger(\omega)\hat{\sigma}_{\mathsf{A}}\Big] \quad \text{(rotating wave app.)}$$

Effective field operators: $\Big[\hat{a}_{\mathsf{A}}(\omega), \hat{a}_{\mathsf{B}}^\dagger(\omega')\Big] = \dfrac{g_{\mathsf{AB}}^2(\omega)}{g_{\mathsf{A}}(\omega)g_{\mathsf{B}}(\omega)}\delta(\omega-\omega')$

$$g_{\mathsf{AB}}^2(\omega) = \frac{\mu_0}{\hbar\pi}\omega^2 \boldsymbol{d}\cdot \mathrm{Im}\,\mathbf{G}(\boldsymbol{r}_{\mathsf{A}}, \boldsymbol{r}_{\mathsf{B}}, \omega)\cdot\boldsymbol{d}^*, \qquad g_{\mathsf{AA}}^2(\omega) \equiv g_{\mathsf{A}}^2(\omega)$$

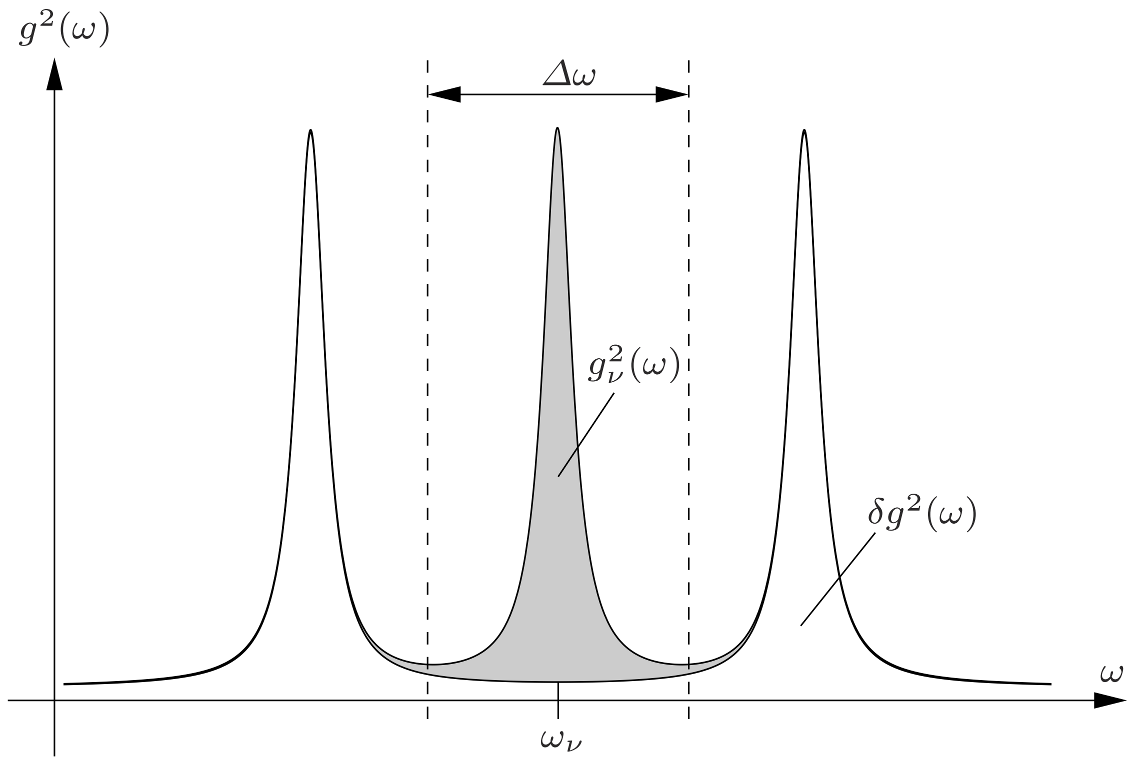
S.Y. Buhmann, D.-G. Welsch, PRA **77**, 012110 (2008)

Jaynes–Cummings model

Identical two-level atoms: $\hat{\boldsymbol{d}}_{\mathsf{A}} = \boldsymbol{d}\hat{\sigma}_{\mathsf{A}} + \boldsymbol{d}^*\hat{\sigma}_{\mathsf{A}}^\dagger$

$$\hat{H}_{\mathsf{AF}} = \hbar \int_0^\infty \mathrm{d}\omega \, g_{\mathsf{A}}(\omega) \left[\hat{a}_{\mathsf{A}}(\omega)\hat{\sigma}_{\mathsf{A}}^\dagger + \hat{a}_{\mathsf{A}}^\dagger(\omega)\hat{\sigma}_{\mathsf{A}}\right] \quad \text{(rotating wave app.)}$$

Single-mode approximation: $g_{\mathsf{AB}}^2(\omega) = g_{\mathsf{AB}}^2(\omega_\nu)\dfrac{\gamma_\nu^2/4}{(\omega-\omega_\nu)^2 + \gamma_\nu^2/4}$



S.Y. Buhmann, D.-G. Welsch, PRA **77**, 012110 (2008)

Strong coupling: two atoms

Hamiltonian: basis states $|+\rangle|0_\nu\rangle$, $|0_\mathrm{A}0_\mathrm{B}\rangle|1_\nu\rangle$, $|-\rangle|0_\nu\rangle$

$$\hat{H} = \frac{\hbar}{2}\begin{pmatrix} 0 & \sqrt{\gamma_\nu\pi N} & 0 \\ \sqrt{\gamma_\nu\pi N} & \Delta & \sqrt{\frac{\gamma_\nu\pi}{N}}[g_\mathrm{A}^2(\omega_\nu) - g_\mathrm{B}^2(\omega_\nu)] \\ 0 & \sqrt{\frac{\gamma_\nu\pi}{N}}[g_\mathrm{A}^2(\omega_\nu) - g_\mathrm{B}^2(\omega_\nu)] & 0 \end{pmatrix}$$

$$N = g_\mathrm{A}^2(\omega_\nu) + g_\mathrm{B}^2(\omega_\nu) + 2g_\mathrm{AB}^2(\omega_\nu), \quad \Delta = \omega_\nu - \omega_\mathrm{A}$$

S. Esfandiarpour et al., J. Phys. B **51**, 094004 (2018)

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$$N = g_A^2(\omega_\nu) + g_B^2(\omega_\nu) + 2g_{AB}^2(\omega_\nu), \quad \Delta = \omega_\nu - \omega_A$$

Eigenenergies: $E_\pm = \frac{\hbar}{2}\Delta \pm \frac{\hbar}{2}\sqrt{\Omega^2(\boldsymbol{r}_A, \boldsymbol{r}_B) + \Delta^2}$, $E_0 = 0$

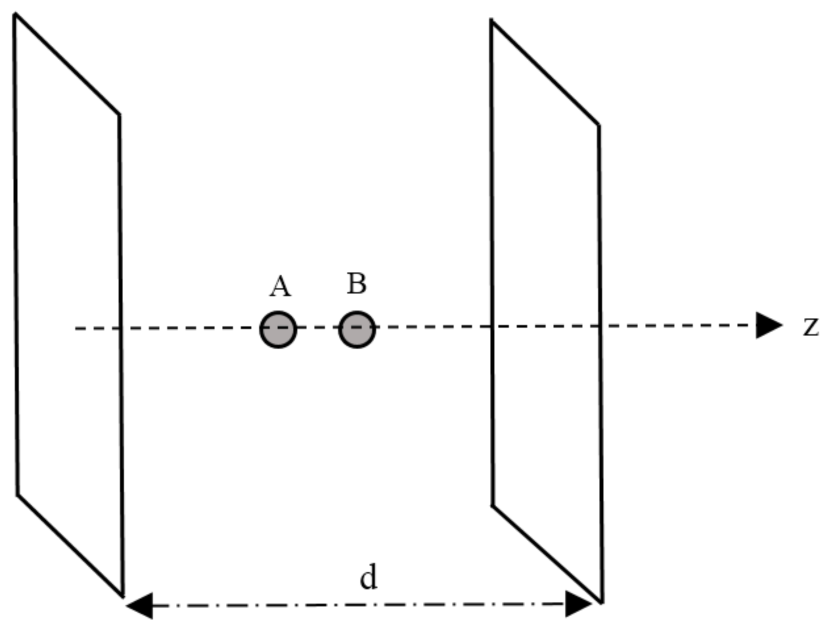
$$\Omega^2(\boldsymbol{r}_A, \boldsymbol{r}_B) = 2\gamma_\nu\pi \frac{[g_A^2(\omega_\nu) + g_{AB}^2(\omega_\nu)]^2 + [g_B^2(\omega_\nu) + g_{AB}^2(\omega_\nu)]^2}{g_A^2(\omega_\nu) + g_B^2(\omega_\nu) + 2g_{AB}^2(\omega_\nu)}$$

S. Esfandiarpour et al., J. Phys. B **51**, 094004 (2018)

Example: Planar cavity

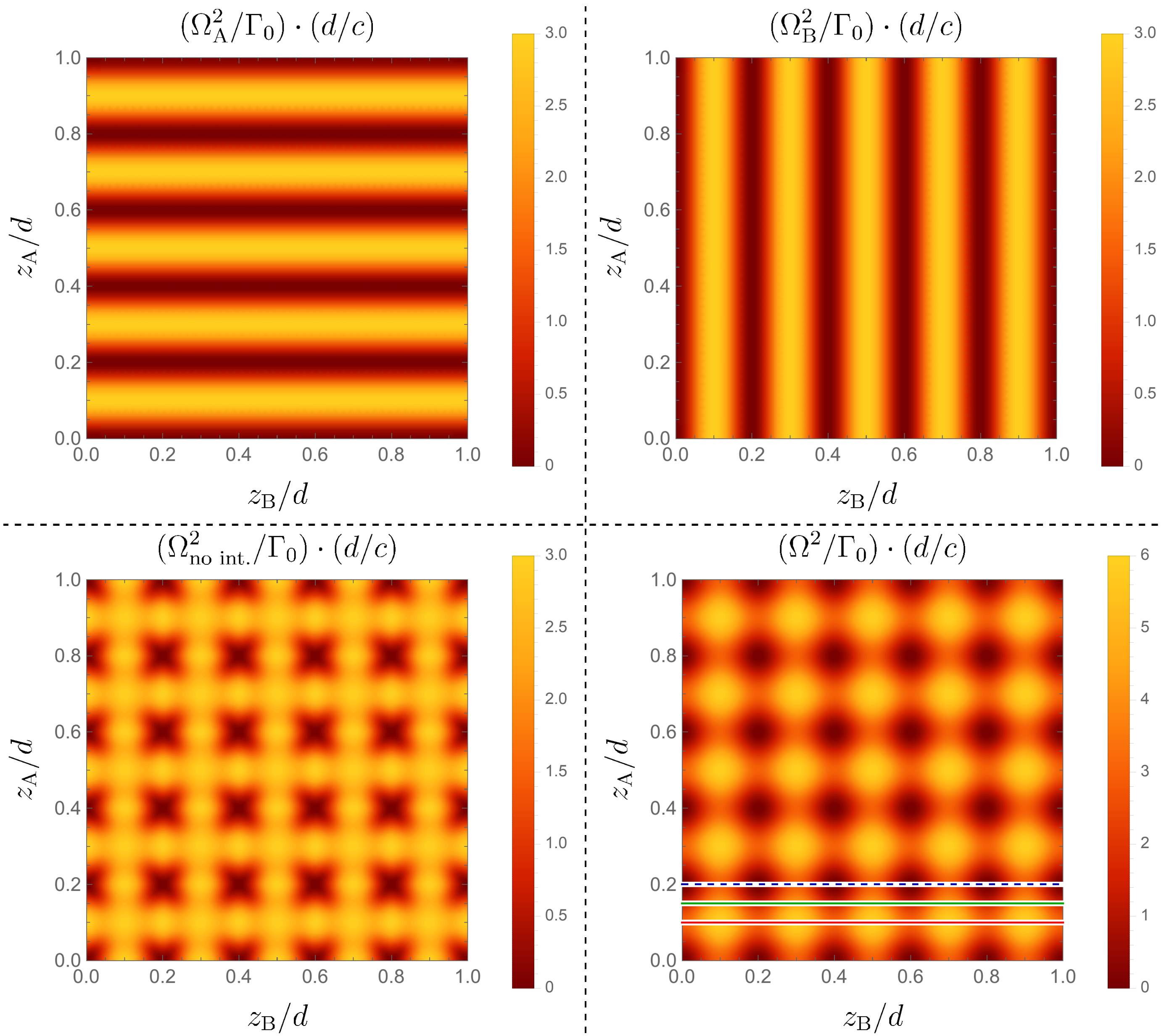
Two perfect mirrors: $r_p = -r_s = 1 - \delta \Rightarrow \gamma_\nu = 2c\delta/d$

$$\gamma_\nu \pi g^2_{\mathsf{AB}}(\omega_\nu) = \frac{3c\Gamma}{8d}\left\{\cos\left[\frac{(2d-z_{\mathsf{A}}-z_{\mathsf{B}})\omega_\nu}{c}\right]-\cos\left[\frac{(2d+z_{\mathsf{A}}-z_{\mathsf{B}})\omega_\nu}{c}\right]\right.$$
$$\left.-\cos\left[\frac{(2d-z_{\mathsf{A}}+z_{\mathsf{B}})\omega_\nu}{c}\right]-\cos\left[\frac{(z_{\mathsf{A}}+z_{\mathsf{B}})\omega_\nu}{c}\right]\right\}$$



S. Esfandiarpour et al., J. Phys. B **51**, 094004 (2018)

Example: Planar cavity



S. Esfandiarpour et al., J. Phys. B **51**, 094004 (2018)

Photonic Bose–Einstein condensate

Normal Bose–Einstein condensate: atoms in a trap

- *Conserved number of particles*
- *Thermalisation by collisions*
- *Cooling below critical temperature*

$\Rightarrow$ **Macroscopic occupation of ground state**

Photonic Bose–Einstein condensate

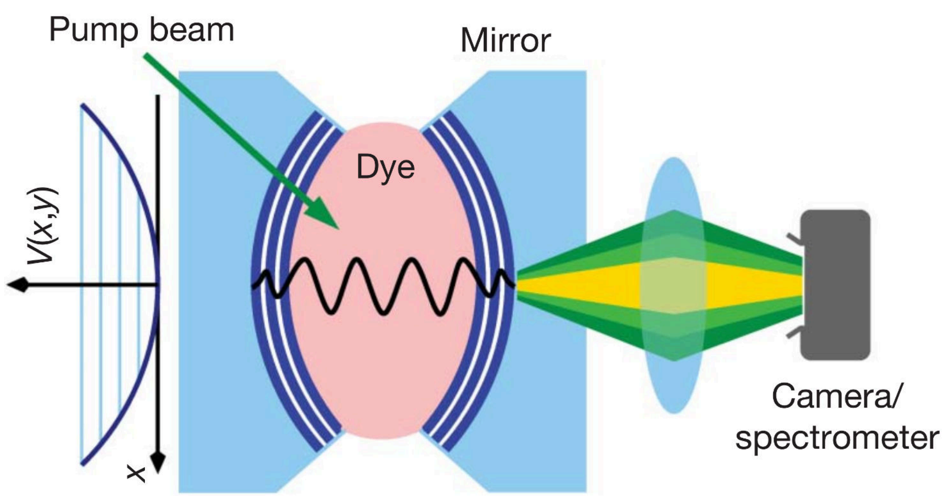
Photonic Bose–Einstein condensate: photons

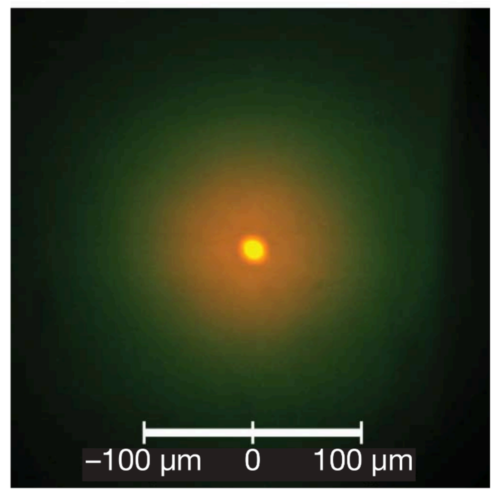
- *Conserved number of particles*?
- *Thermalisation by collisions*?
- *Cooling below critical temperature*?

Photonic Bose–Einstein condensate

Photonic Bose–Einstein condensate: photons + dye in cavity

- *Conserved number of particles:* driving laser
- *Thermalisation by collisions:* absorption/emission by dye molecules
- *Cooling below critical temperature:* driving beyond threshold

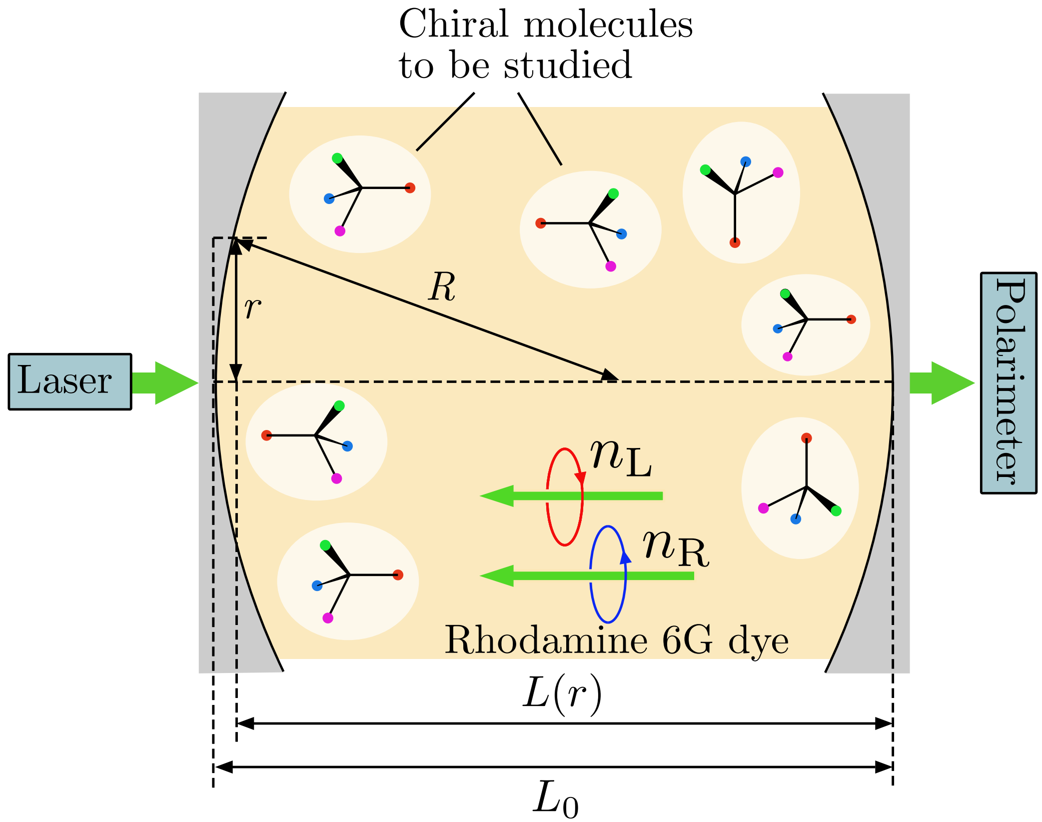




⇒ **Macroscopic occupation of lowest-energy mode**

J. Klaers, J. Schmitt, F. Vewinger, M. Weitz, Nature **468**, 545 (2010)

Symmetry breaking: setup and dynamics

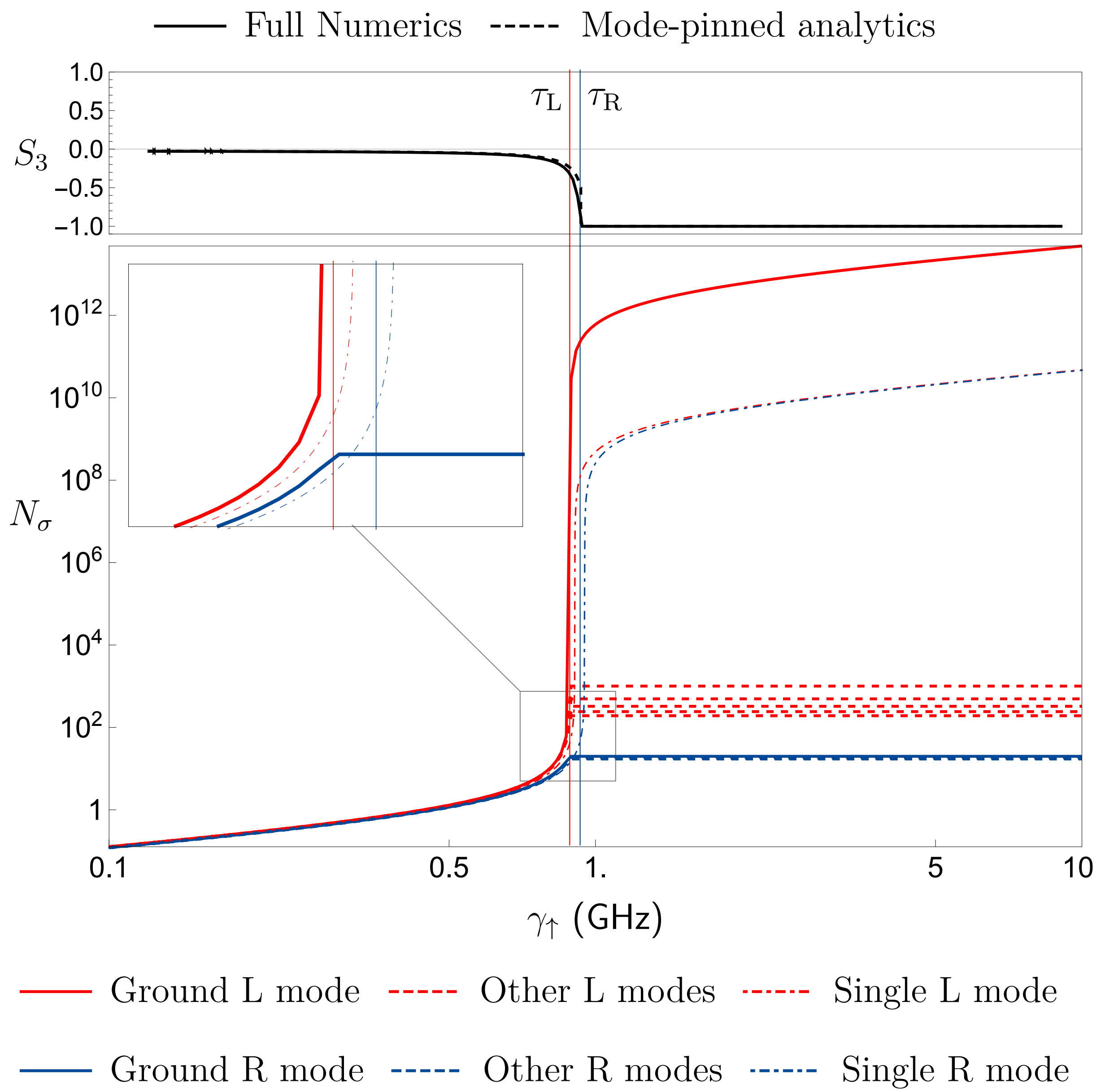


$$\dot{N}_\nu = \kappa N_\nu - \gamma_{\uparrow\nu} N_\nu M(1-p_{\mathrm{e}}) + \gamma_{\downarrow\nu}(N_\nu+1) M p_{\mathrm{e}}$$

$$\dot{p}_{\mathrm{e}} = -\left[\gamma_\downarrow + \sum_\nu (l+1)(N_\nu+1)\gamma_{\downarrow\nu}\right] p_e + \left[\gamma_\uparrow + \sum_\nu (l+1) N_\nu \gamma_{\uparrow\nu}\right](1-p_{\mathrm{e}})$$

R. Bennett, Y. Gorbachev, S.Y.B, arXiv:1905.07590 (2019)

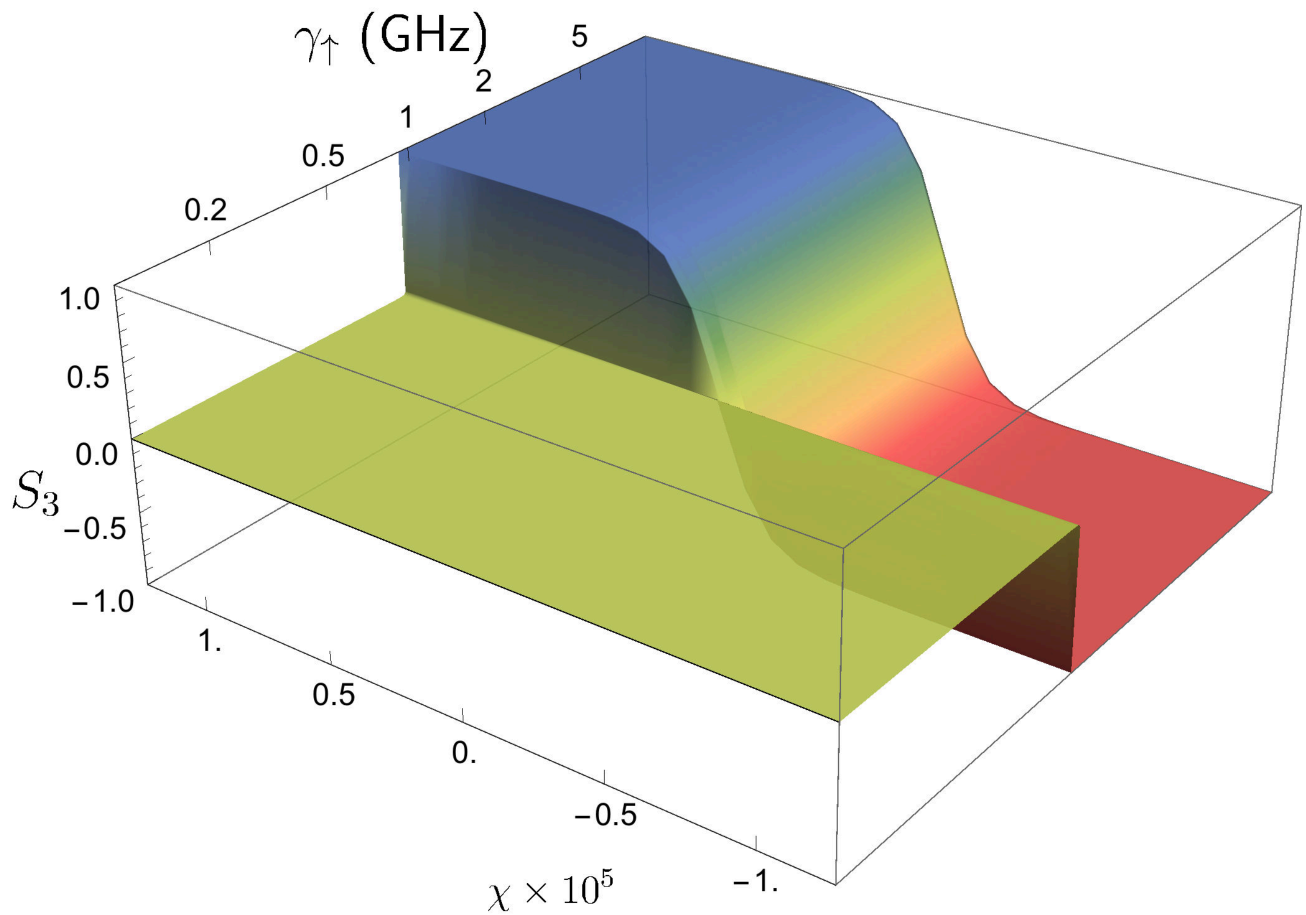
Driven–dissipative equilibrium



R. Bennett, Y. Gorbachev, S.Y.B, arXiv:1905.07590 (2019)

Detecting enantiomeric excess

Stokes parameter: $S_3 = \dfrac{N_{\mathrm{R}} - N_{\mathrm{L}}}{N_{\mathrm{R}} + N_{\mathrm{L}}}$



R. Bennett, Y. Gorbachev, S.Y.B, arXiv:1905.07590 (2019)

Resonance energy transfer:

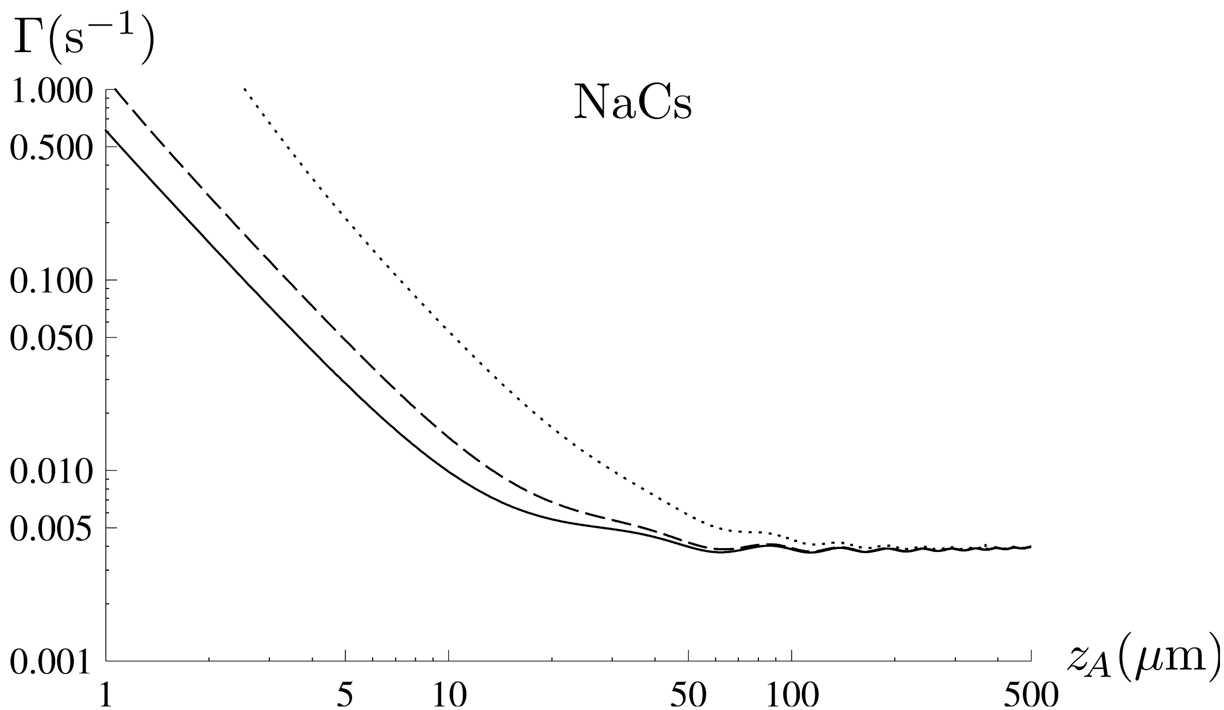
Impact of environments

The Purcell effect

Fermi's golden rule: $\Gamma = \frac{2\pi}{\hbar} \sum_f |M_{fi}|^2 \delta(E_i - E_f)$

Spontaneous decay: $M_{fi} = \langle 1_\lambda(\boldsymbol{r},\omega)|\langle k_\mathsf{A}| - \hat{\boldsymbol{d}}\cdot\hat{\boldsymbol{E}}(\boldsymbol{r}_\mathsf{A})|n_A\rangle|\{0\}\rangle$

$$\Gamma_n = \sum_{k<n} \Gamma_{n\to k} = \frac{2\mu_0}{\hbar} \sum_{k<n} \omega_{nk}^2 \boldsymbol{d}_{nk}\cdot\mathrm{Im}\,\mathbf{G}(\boldsymbol{r}_\mathsf{A},\boldsymbol{r}_\mathsf{A},\omega_{nk})\cdot\boldsymbol{d}_{kn}$$



E.M. Purcell, PR **69**, 674 (1946); S.Y.B. et al., PRA **78**, 052901 (2008)

Interatomic Coulombic decay

Process:

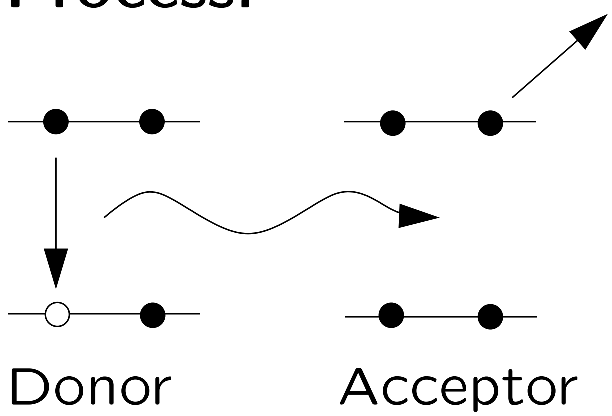
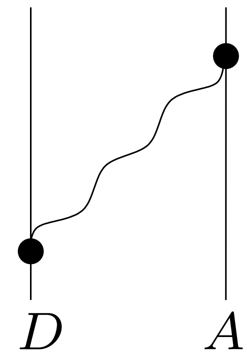


Diagram:



L. S. Cederbaum *et al.*, PRL **79**, 4478 (1997)

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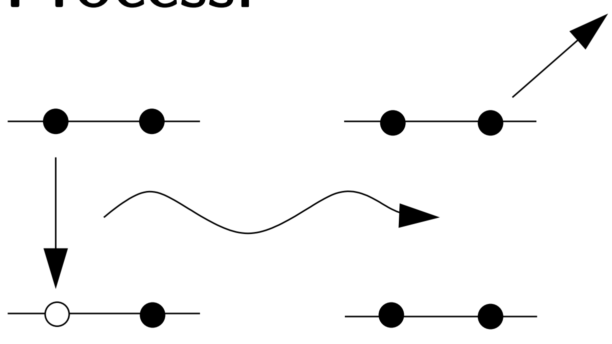

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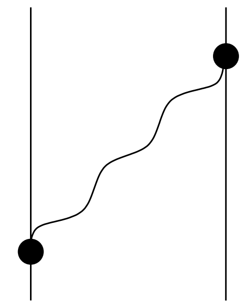


Fermi's golden rule: $\Gamma = \frac{2\pi}{\hbar}\sum_f |M_{fi}|^2\delta(E_i - E_f)$

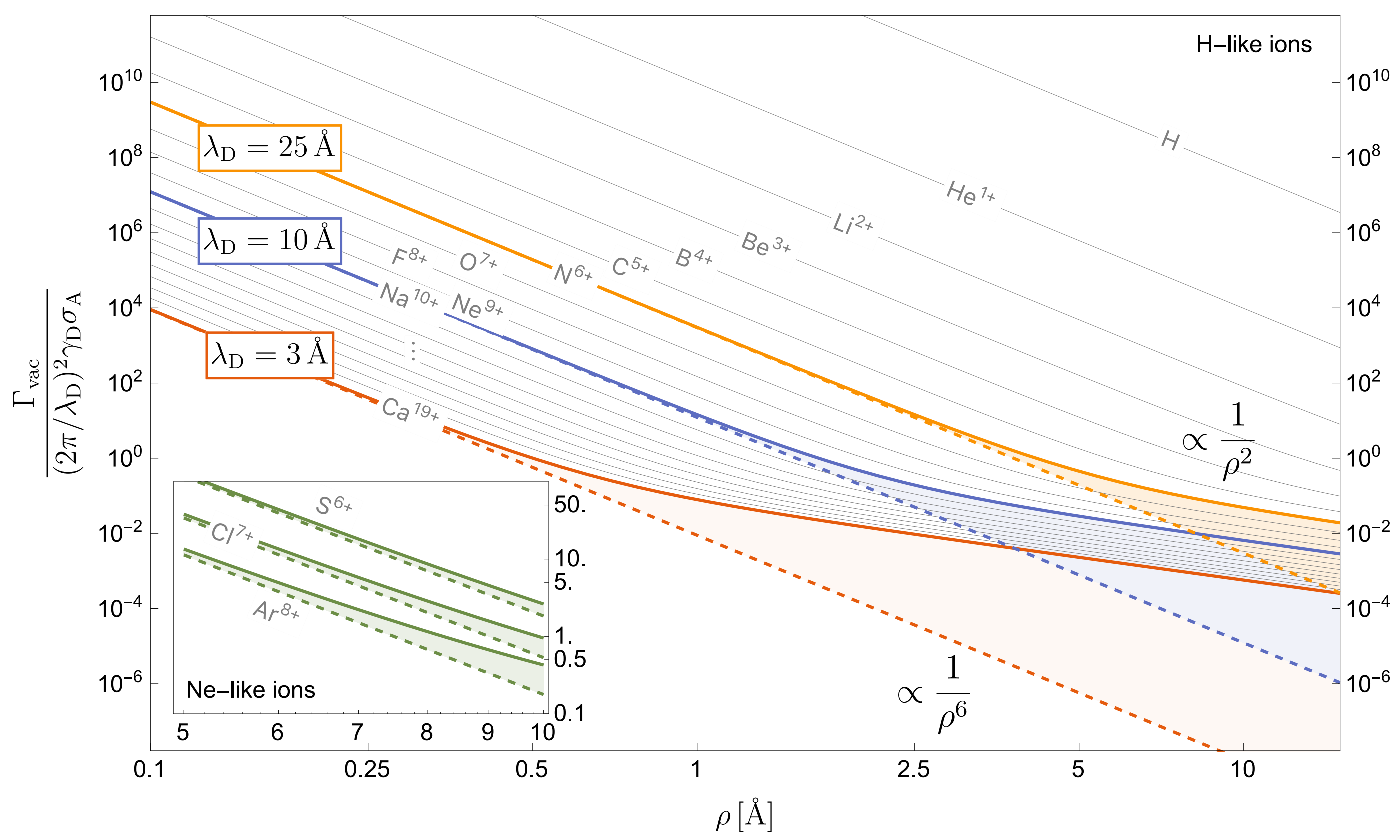
Matrix element: $M_{fi} = \sum_\psi \frac{\langle f|\hat{H}_{\text{int}}|\psi\rangle\langle\psi|\hat{H}_{\text{int}}|i\rangle}{E_i - E_\psi + \mathrm{i}\epsilon}$

$$\Gamma = 2\pi^2 \sum_{k<n} \Gamma^D_{n\to k}\sigma_A(\hbar\omega_{nk})\mathrm{tr}[\mathbf{G}(\boldsymbol{r}_D,\boldsymbol{r}_A,\omega_{nk})\cdot\mathbf{G}^*(\boldsymbol{r}_A,\boldsymbol{r}_D,\omega_{nk})]$$

L. S. Cederbaum *et al.*, PRL **79**, 4478 (1997);
J. L. Hemmerich, R. Bennett and S.Y.B., Nature Commun. **9**, 2934 (2018)

Retardation

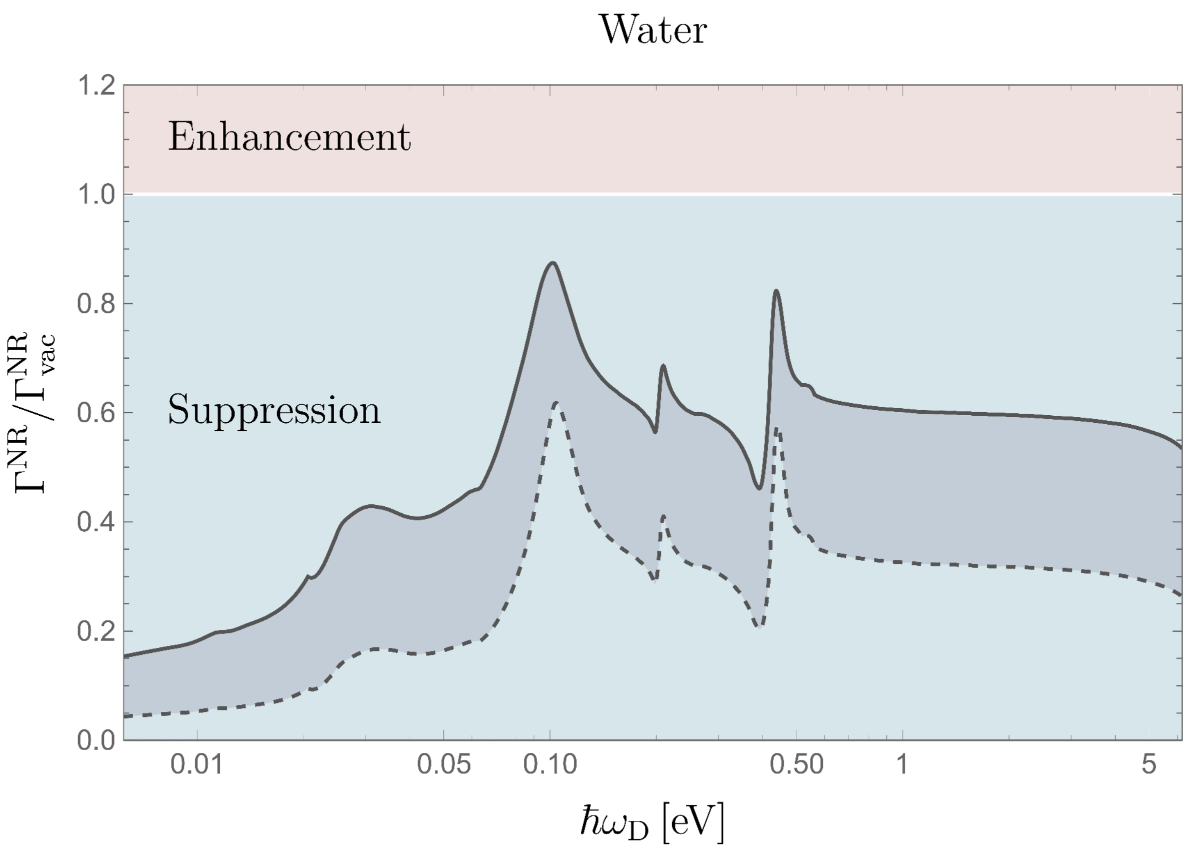
$$\Gamma = \begin{cases} \sum_{k<n} \frac{3c^4 \Gamma^D_{n\to k} \sigma_A(\hbar\omega_{nk})}{4\omega_{nk}^4 r_{DA}^6} & \text{(nonretarded)} \\ \sum_{k<n} \frac{\Gamma^D_{n\to k} \sigma_A(\hbar\omega_{nk})}{4 r_{DA}^2} & \text{(retarded)} \end{cases}$$



J. L. Hemmerich, R. Bennett and S.Y.B., Nature Commun. **9**, 2934 (2018)

Bulk medium

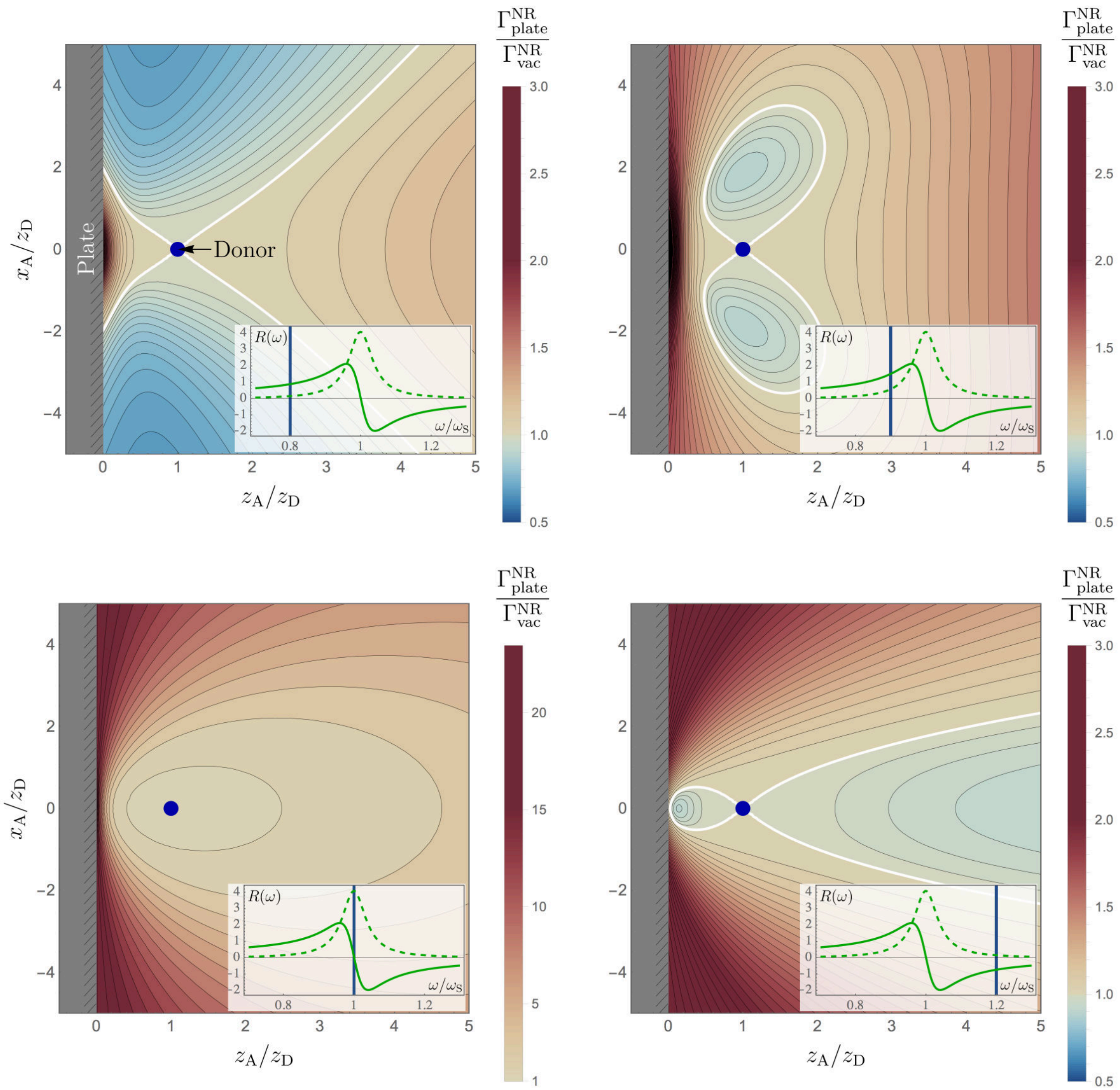
ICD rate in medium: $\Gamma = \frac{1}{|\varepsilon|^2}\left|\frac{3\varepsilon}{2\varepsilon+1}\right|^4 \Gamma^{(0)}$



Effect of medium: screening by polarisable medium

J. L. Hemmerich, R. Bennett and S.Y.B., Nature Commun. **9**, 2934 (2018)

Surface



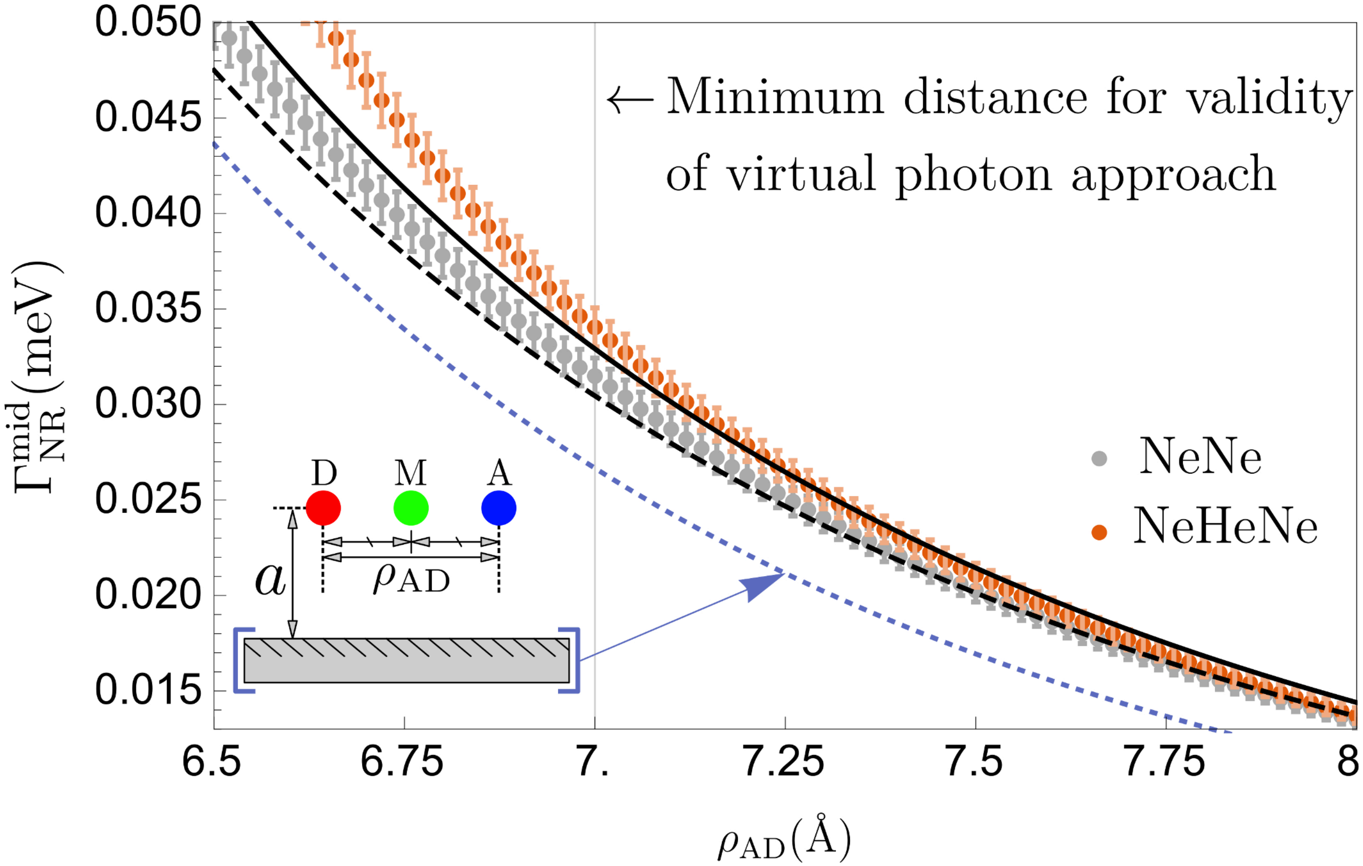
Effect of surface: position-dependent enhancement/suppression

J. L. Hemmerich, R. Bennett and S.Y.B., Nature Commun. **9**, 2934 (2018)

Mediator atom

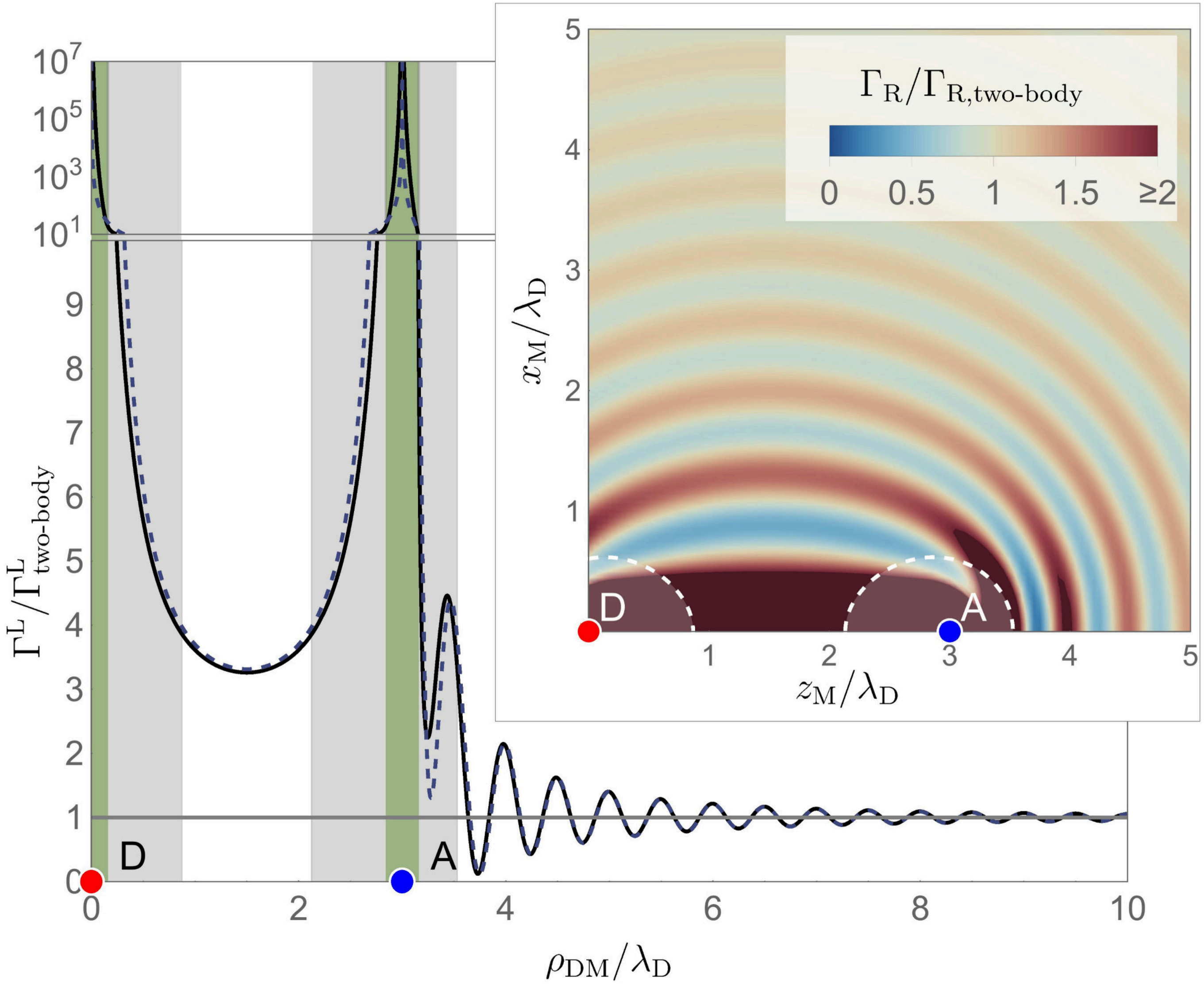
Passive mediator: polarisability α_M

$$\mathbf{G}(\boldsymbol{r},\boldsymbol{r}') = \mathbf{G}^{(0)}(\boldsymbol{r},\boldsymbol{r}') + \mu_0\omega^2\alpha_\mathrm{M}\mathbf{G}^{(0)}(\boldsymbol{r},\boldsymbol{r}_\mathrm{M})\cdot\mathbf{G}^{(0)}(\boldsymbol{r}_\mathrm{M},\boldsymbol{r}')$$



T. Miteva et al., PRL **119**, 083403 (2017);
R. Bennett et al., PRL **122**, 153401 (2019)

Mediator atom



T. Miteva et al., PRL **119**, 083403 (2017);
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Conclusions

Macroscopic QED: atoms, photons, bodies

Atom–surface interactions: surface plasmons
⇒ non-additive laser-induced surface potential
⇒ enhanced quantum friction

Cavity QED: effective modes
⇒ position-dependent two-atom Rabi coupling
⇒ photon BEC as chiral sensor

Resonance energy transfer: impact of environments
⇒ solvent medium, surface, mediator