mpipks

Quantum Optics IX, Danzig 2017

Interaction-induced transparency in the strong coupling regime of polaritons in photonic crystal waveguides

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(TU Munich)

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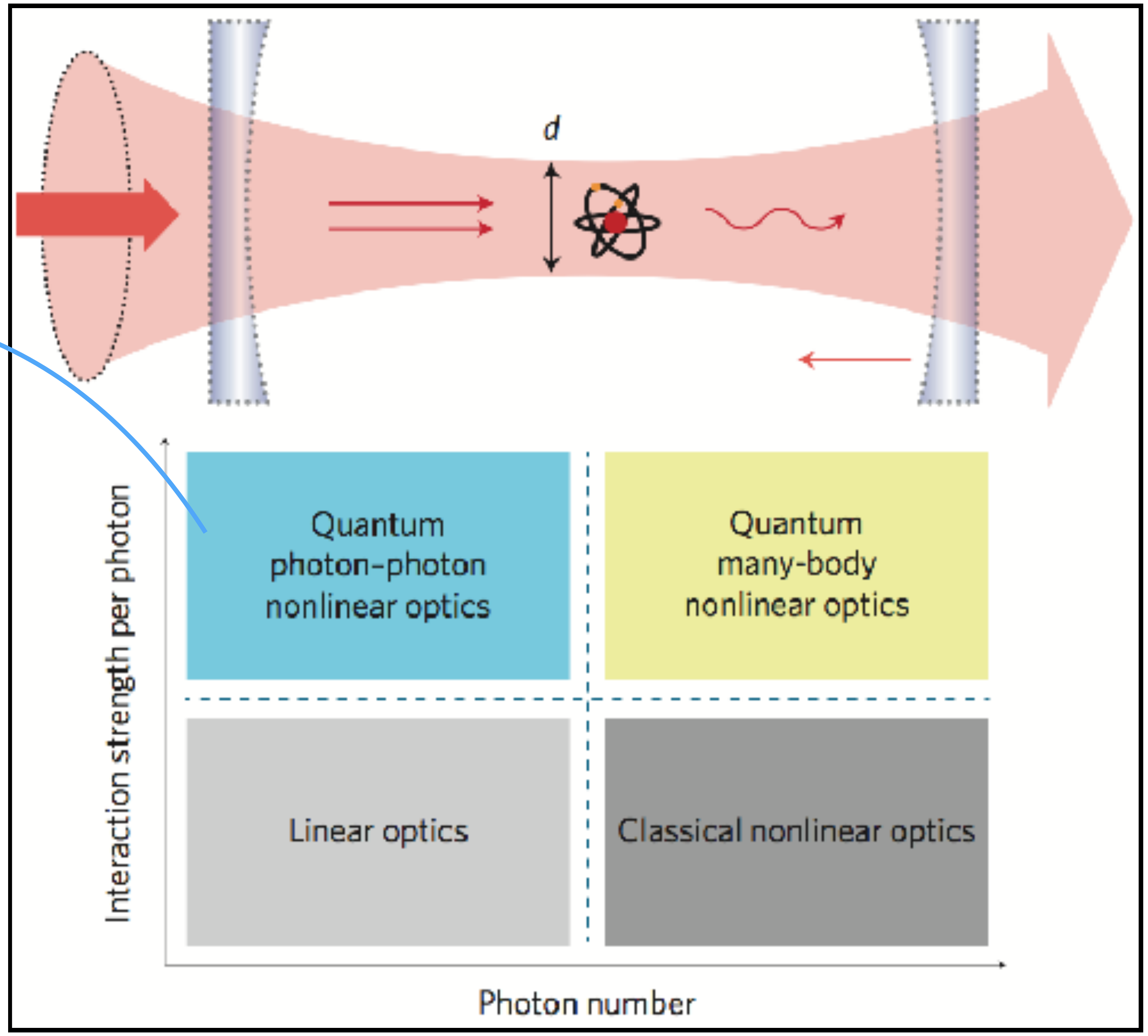
(ICFO Barcelona)

J. Lang, D. Chang, FP, arXiv:…(2018)

Quantum nonlinear optics

Review: Chang, Vuletic, Lukin, Nat. Phot. 8, 685 (2014).

<u>Technological</u> motivation:
Quantum Internet

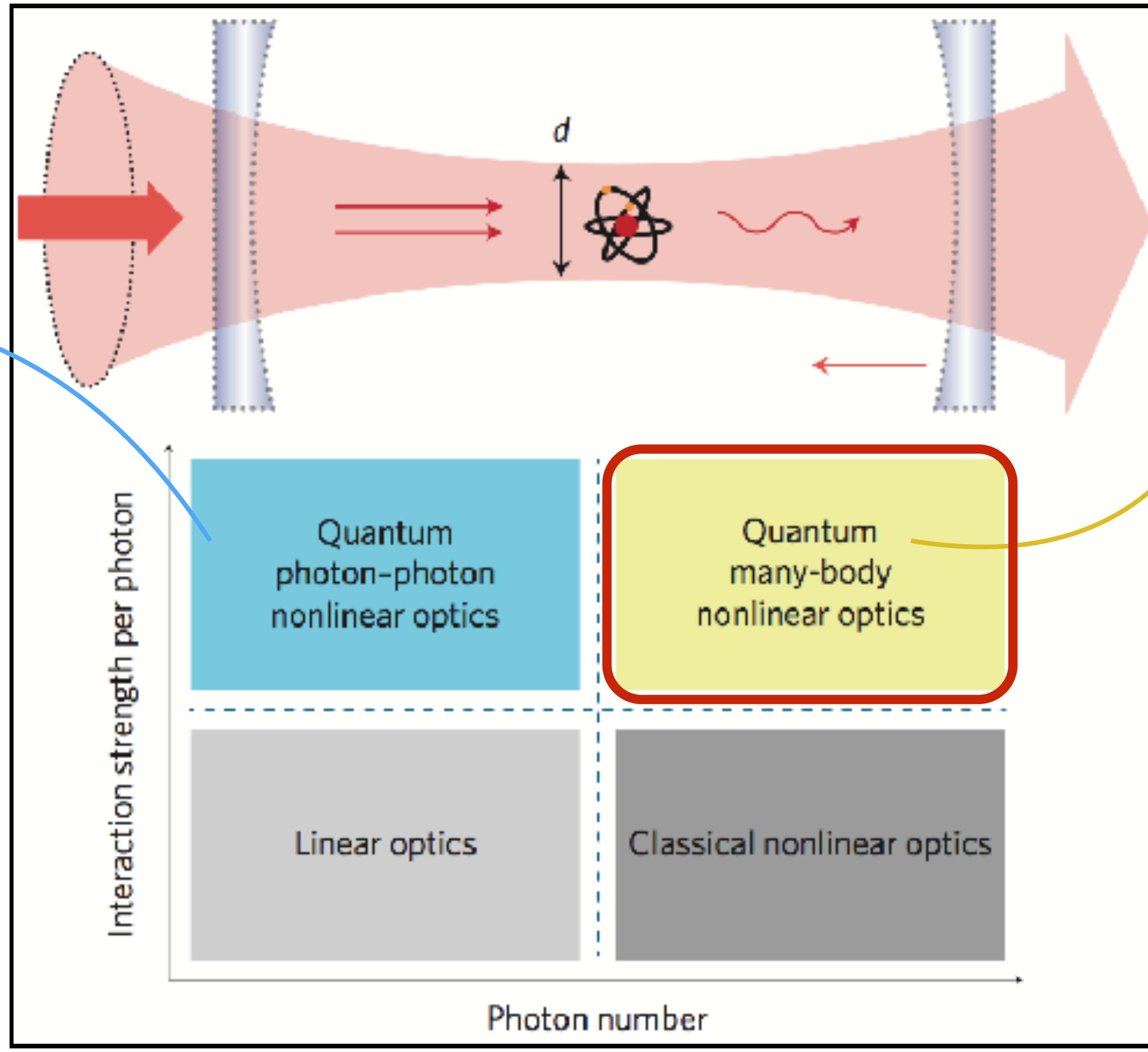


Progress has been made with several devices, coupling the electromagnetic field to:

- Trapped ions (Innsbruck)
- Molecules (Erlangen)
- Superconducting circuits (Paris, Yale, Santa Barbara, ETH, New York)
- Neutral Atoms

The challenge of quantum nonlinear optics

Review: Chang, Vuletic, Lukin, Nat. Phot. 8, 685 (2014).



Technological motivation:
Quantum Internet

Fundamental motivation:
Novel paradigms in many-body physics

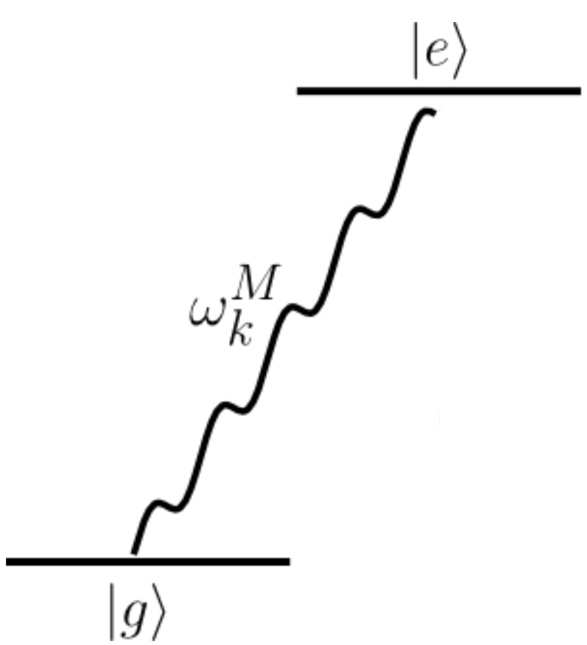
Progress has been made with several devices, coupling the electromagnetic field to:

- Trapped ions (Innsbruck)
- Molecules (Erlangen)
- Superconducting circuits (Paris, Yale, Santa Barbara, ETH, New York)
- **Neutral Atoms**

Electromagnetically-Induced Transparency (EIT)

Increase light/atom interaction probability by

slowing down the light without absorbing it



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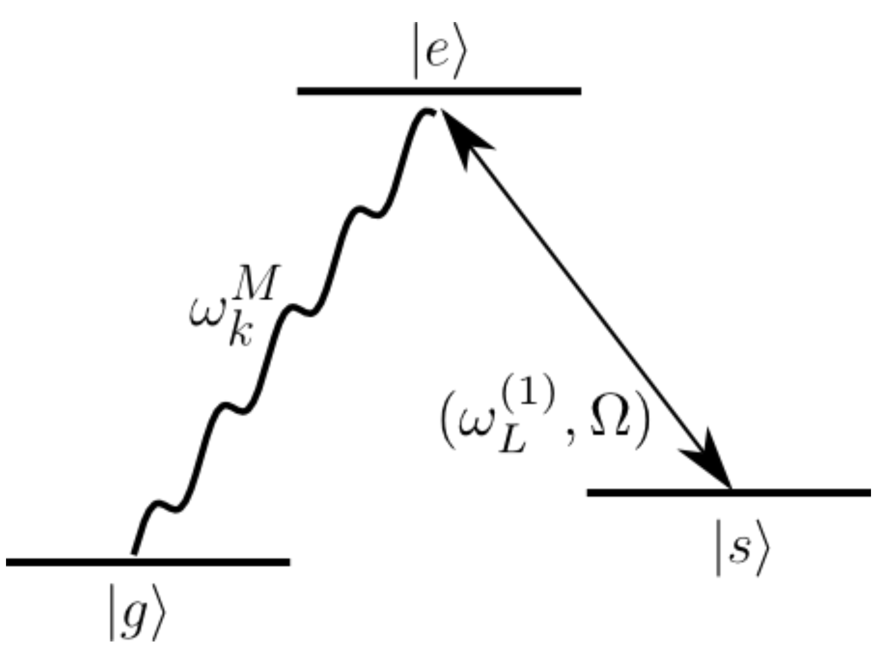
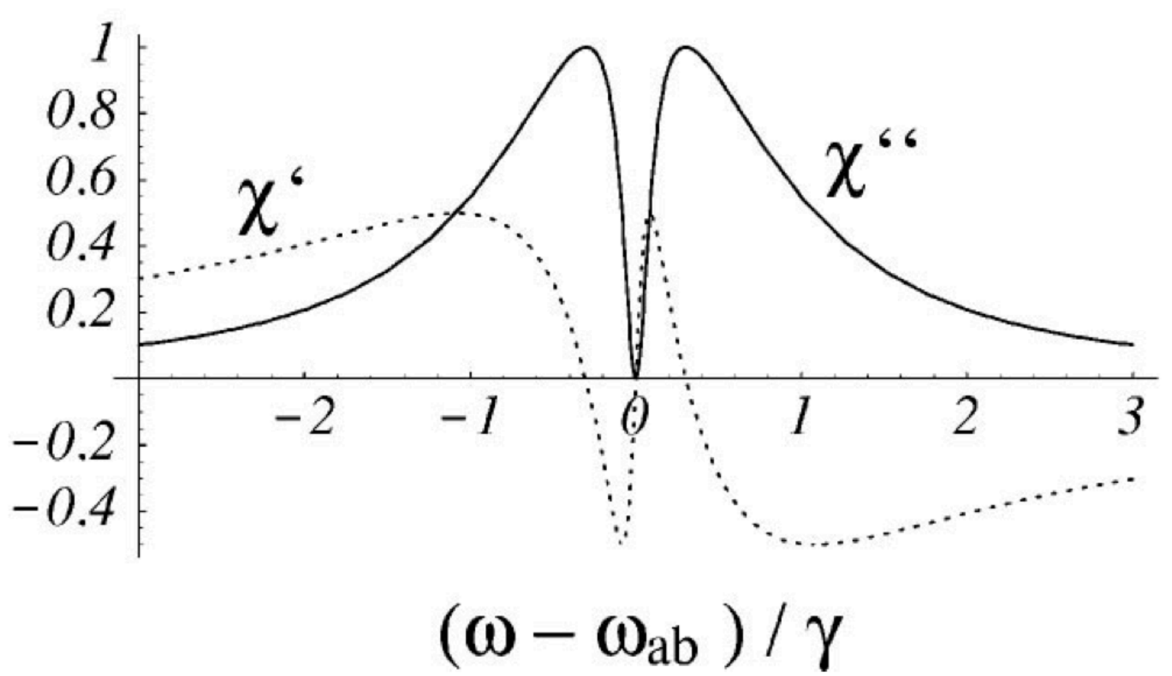
Atomic levels

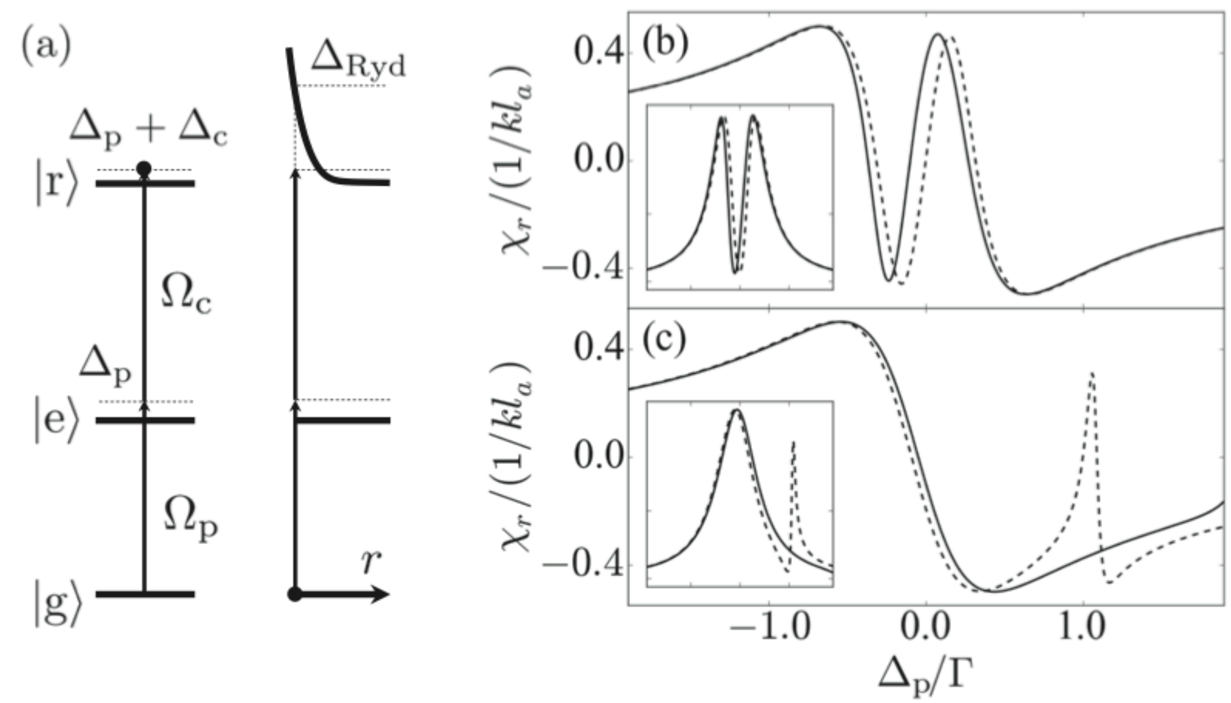
Fleischhauer, Lukin (2002)





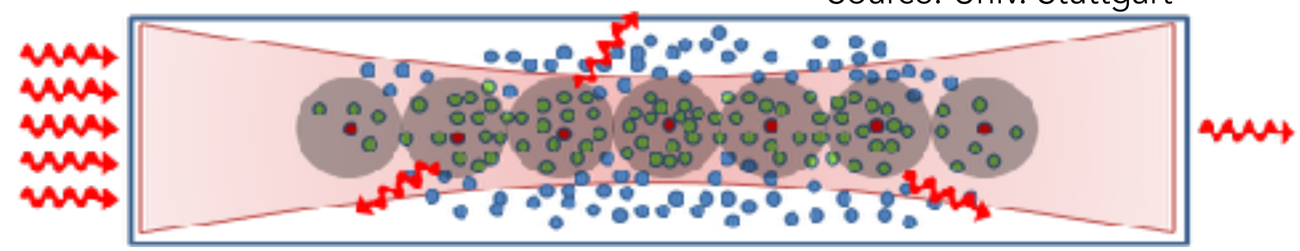
EIT with Rydberg interactions

J. Phys. B: At. Mol. Opt. Phys. **49** (2016) 152003 To

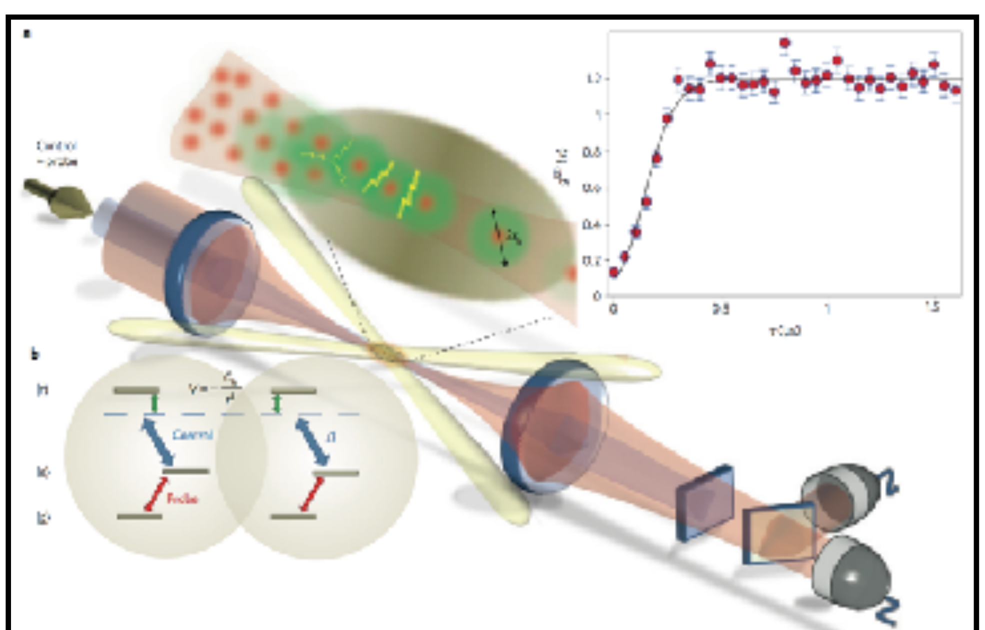


Rydberg atom interact strongly over a **blockade radius**
Only one atom can be excited within radius

Source: Univ. Stuttgart

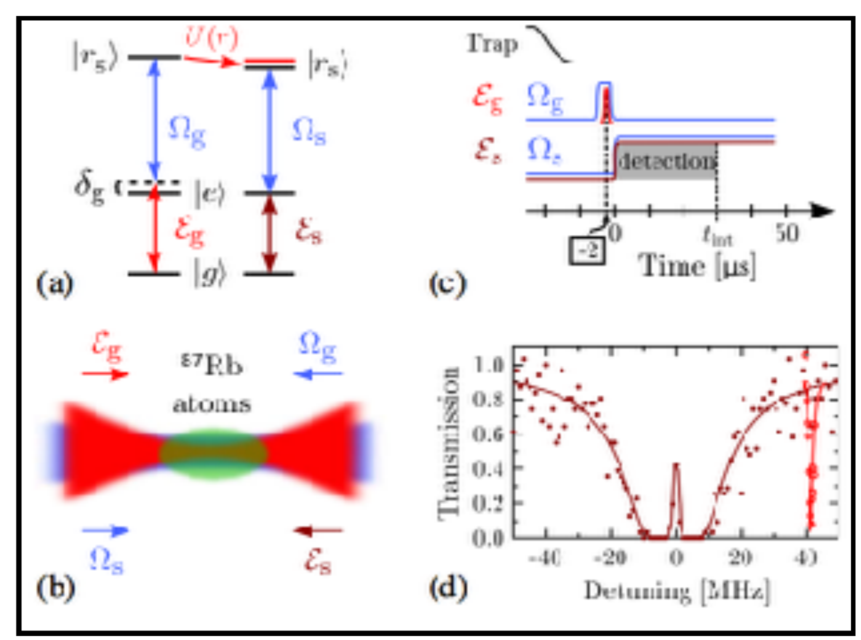


Application: Photon Blockade



Exp.: Peyronel, et al., Nature 488, 57 (2012).

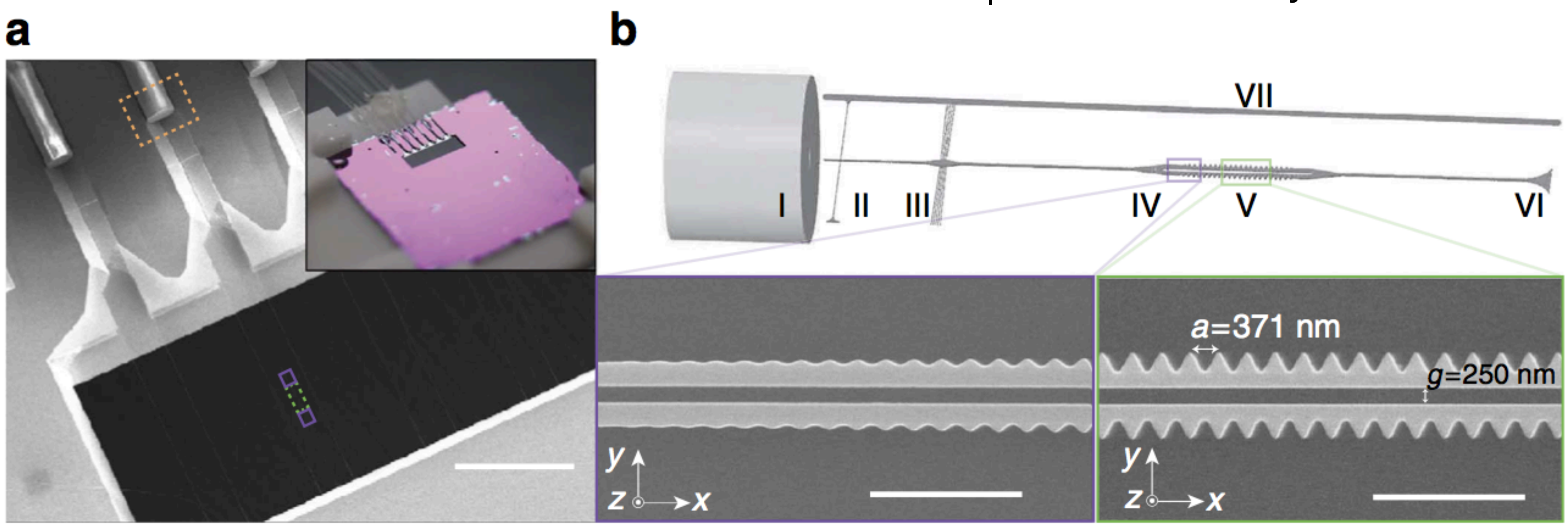
Application: All optical single-photon transistor



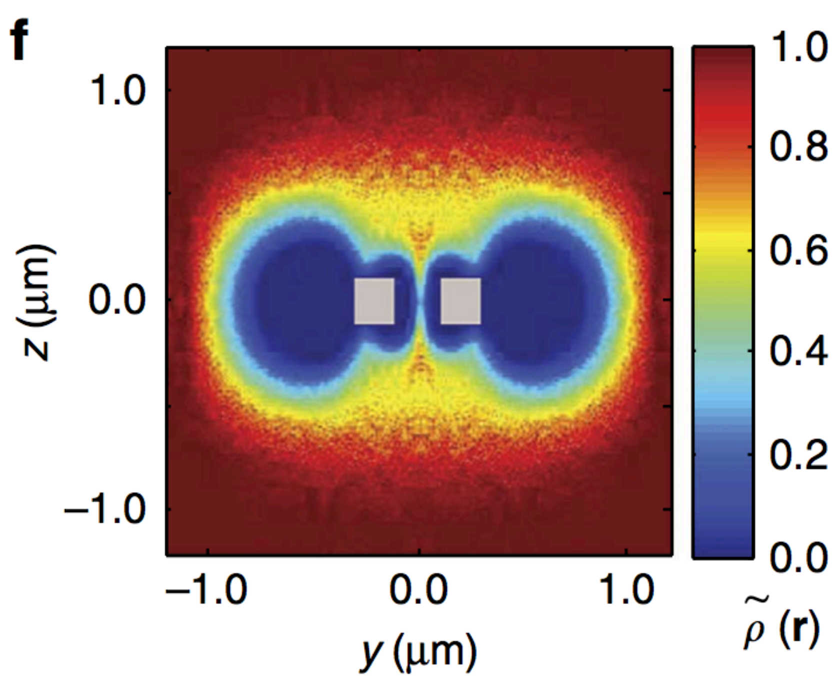
Exp.: Gorniaczyc, et al., Phys. Rev. Lett. 113, 053601

Experiment: atoms coupled to photonic crystal waveguides

Optical fiber cavity

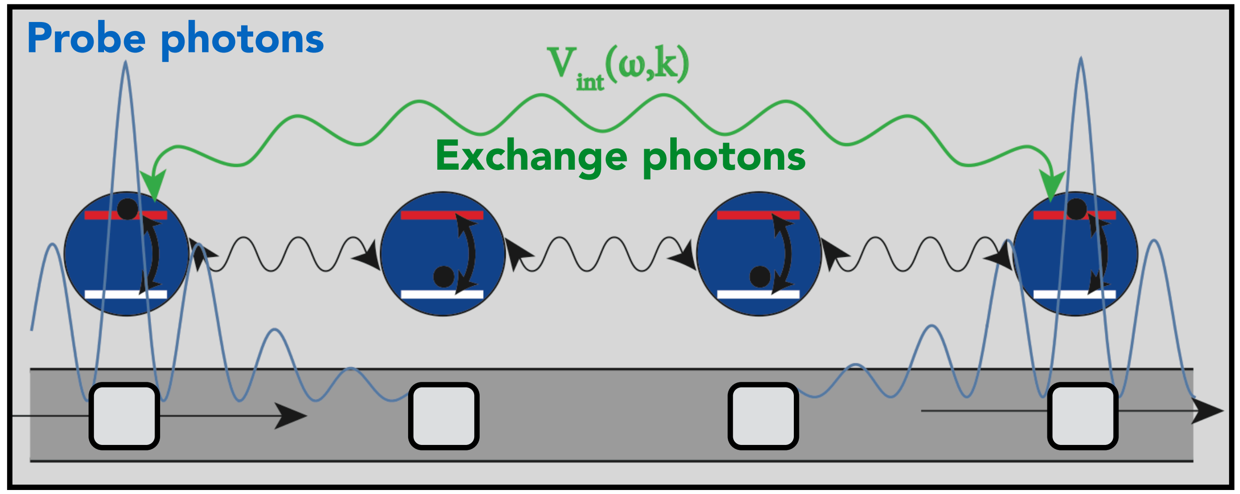


Goban et al., Nat. Comm. 5 (2014)



Atoms trapped using evanescent wave

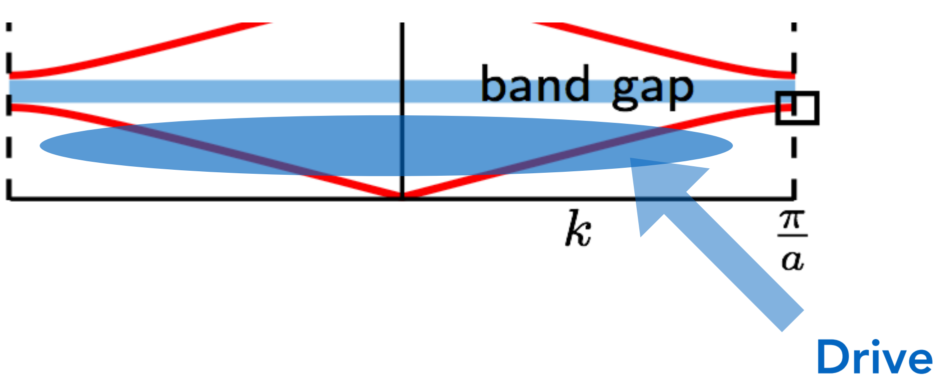
Interacting polaritons in photonic crystal waveguides



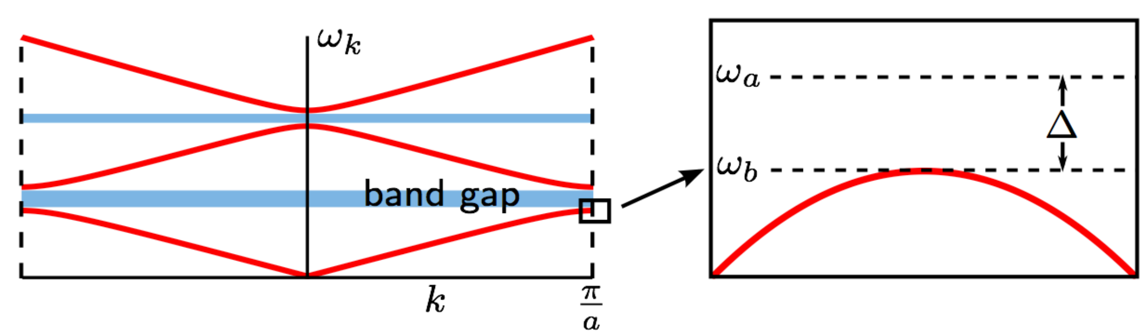
Hybrid atom-photon architecture

- Multi-level atoms fixed positions
- Probe photons within propagating band of lattice
- Exchange photons mediating interactions

Probe photons



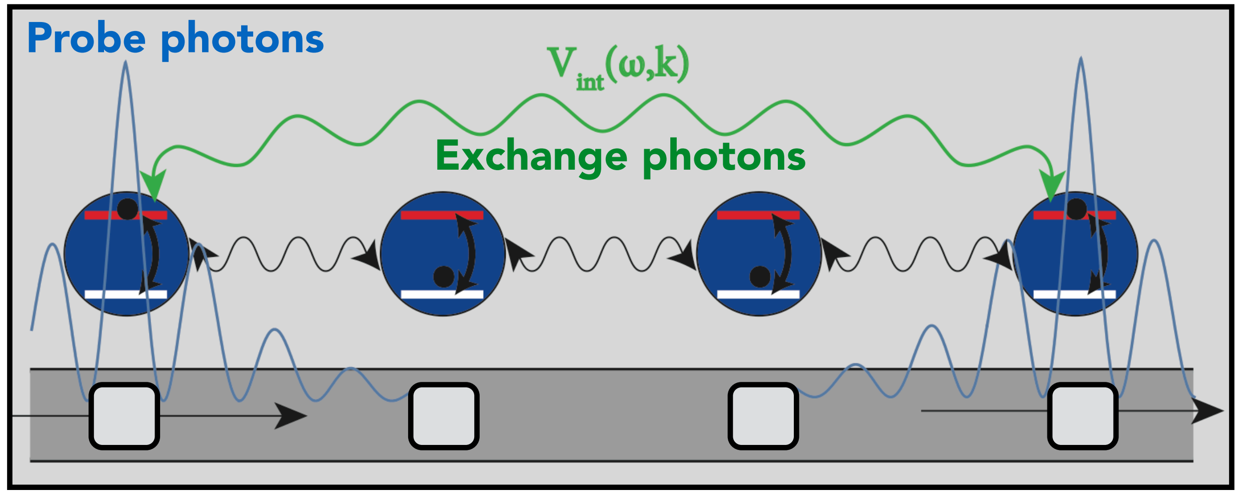
Exchange photons



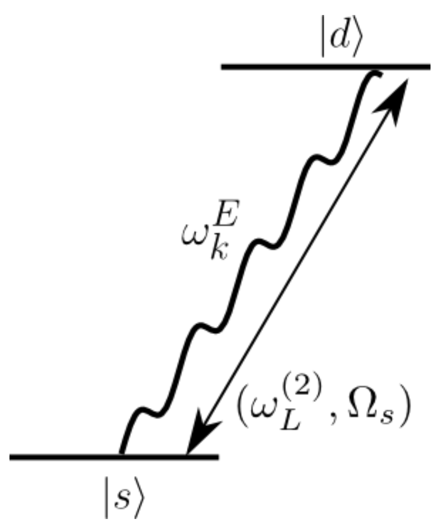
- Tune shape of interactions in space-time

J. S. Douglas, et al., Nat Photon 9, 326 (2015)

Shaping the light-mediated interactions



Atomic levels



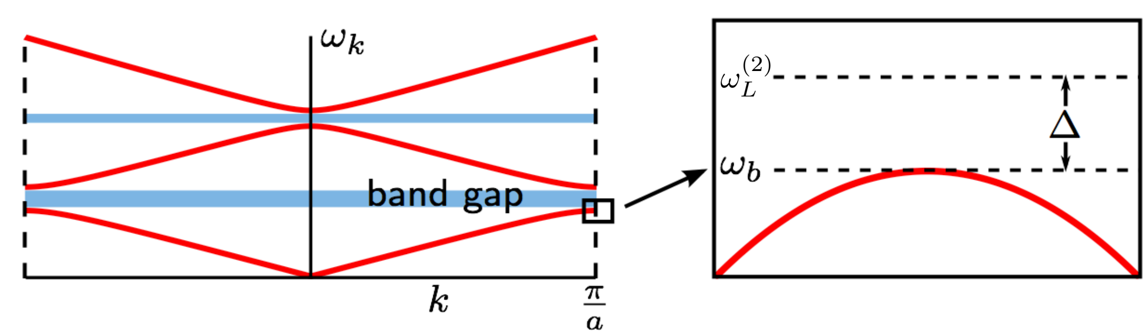
$$\hat{H}_{\text{int}} = \sum_z \left[\Omega_s e^{-i\omega_L^{(2)} t} \hat{a}_d^\dagger(z)\hat{a}_s(z) + g_E \hat{a}_E(k) e^{ikz} u_k^E(z) \hat{a}_d^\dagger(z)\hat{a}_s(z) + h.c. \right]$$

$$\hat{H}_{\text{int}}^{\text{eff}} \sim \sum_{zz'} \hat{a}_s(z)^\dagger \hat{a}_s(z) e^{-|z-z'|/L_E} \hat{a}_s^\dagger(z')\hat{a}_s(z') \qquad \text{(adiabatic elimination)}$$

Exponential interaction range: $L_E \simeq \sqrt{\dfrac{\alpha_E}{\Delta}}$

Probe photons

Exchange photons



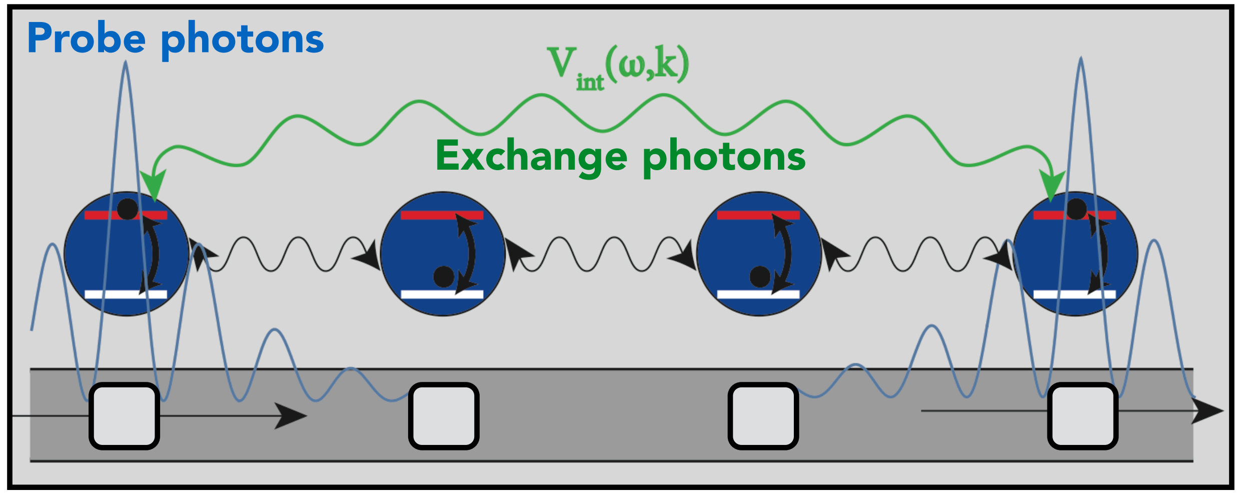
Dispersion:

$$\int \frac{dk}{2\pi} \left(\alpha_E (k-k_0)^2\right) \hat{a}_E^\dagger(k)\hat{a}_E(k)$$

Losses:

$$\kappa_E \mathcal{D}[\hat{a}_E(k)]$$

Probe photons propagation: Electromagnetically-Induced Transparency



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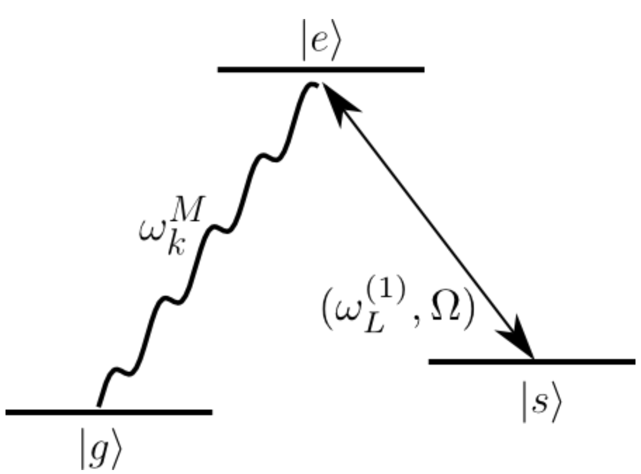
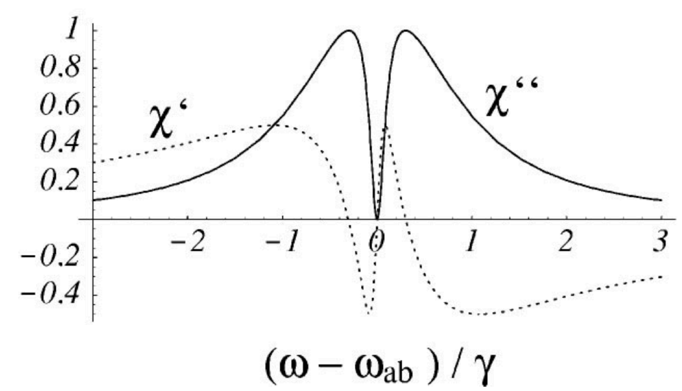


$$\hat{H}_{\text{int}} = \sum_z \left[\Omega e^{-i\omega_L^{(1)} t} \hat{a}_e^\dagger(z)\hat{a}_s(z) + g_M \hat{a}_M(k) e^{ikz} u_k^M(z) \hat{a}_e^\dagger(z)\hat{a}_g(z) + h.c. \right]$$



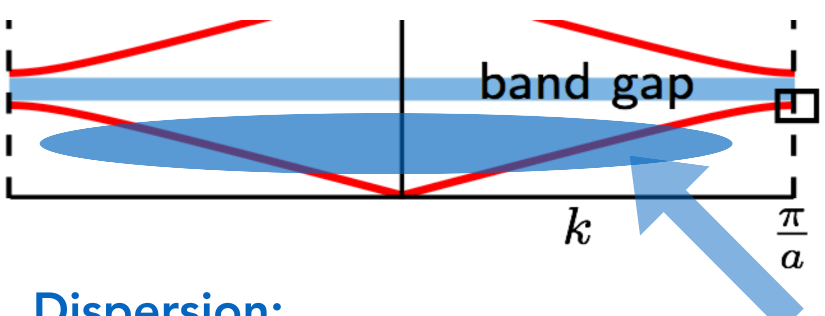
$$\omega_M(k) = \omega_{sg} - \omega_L^{(1)}$$

Large dispersion without absorption

EIT propagation range:

$$L_M \simeq \frac{v_M}{\kappa_M}$$

Probe photons



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Dispersion:

$$\int \frac{dk}{2\pi} J_M \left(1 - \cos(ka)\right) \hat{a}_M^\dagger(k) \hat{a}_M(k)$$

Incoh. Drive:

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Exchange photons

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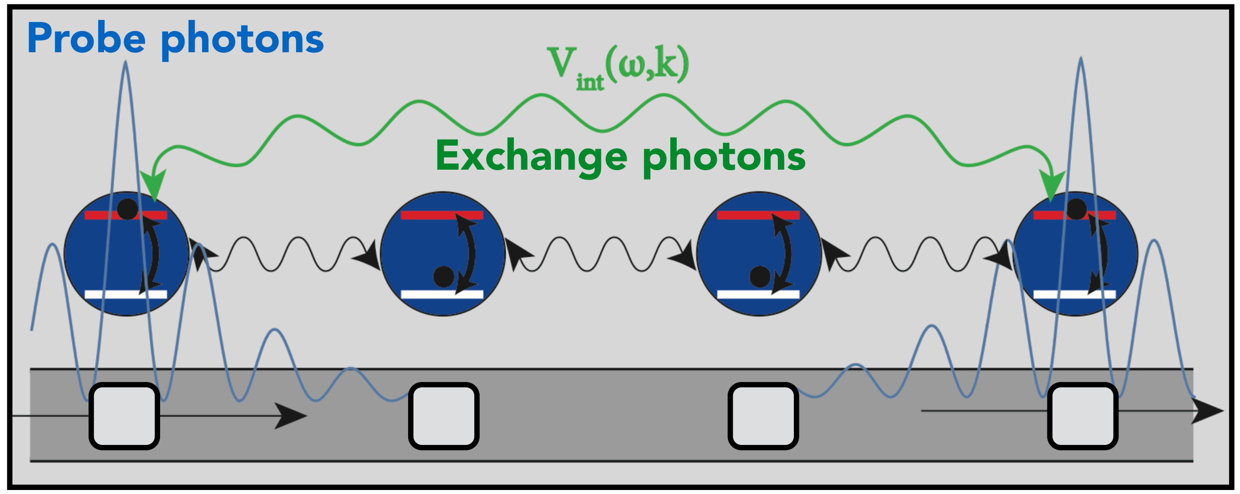

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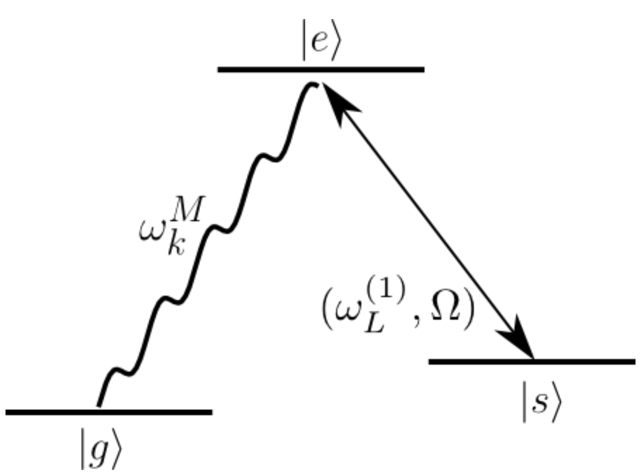

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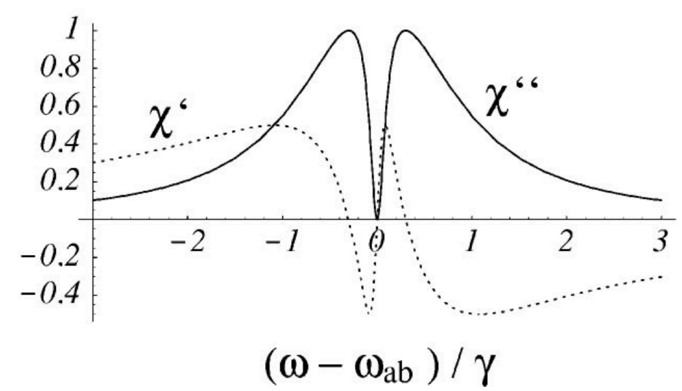

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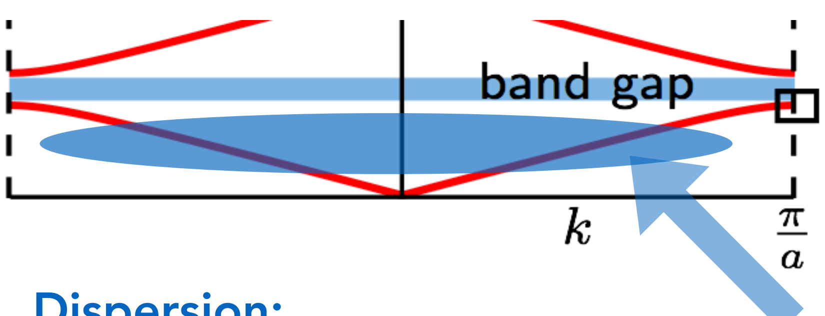

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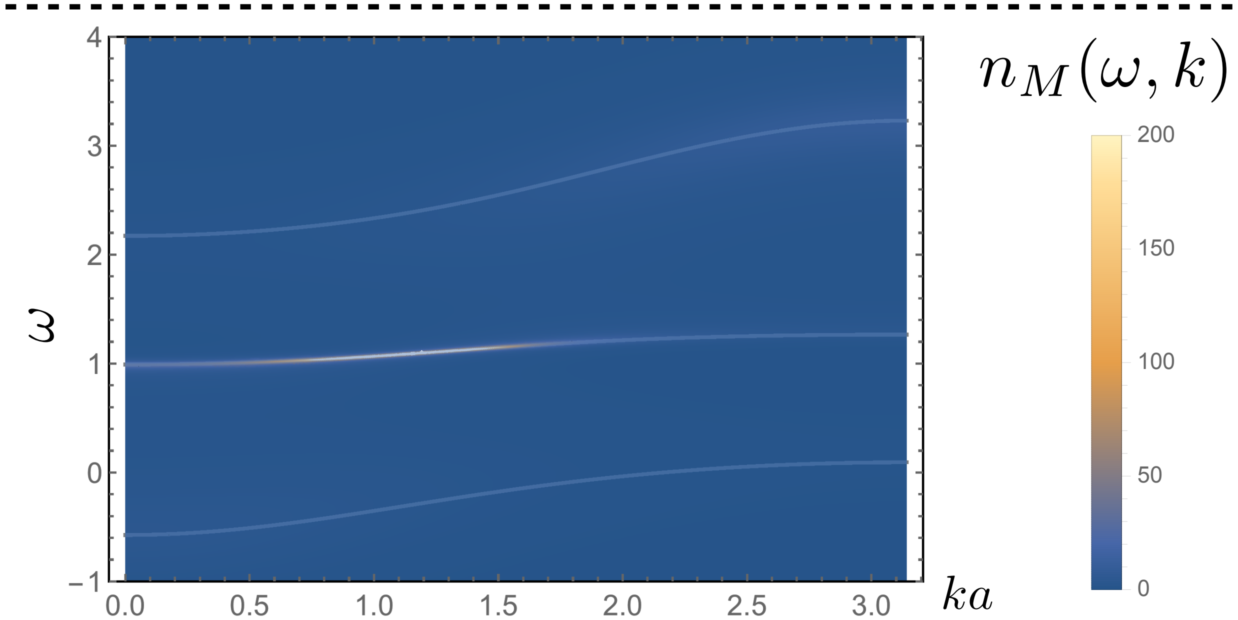
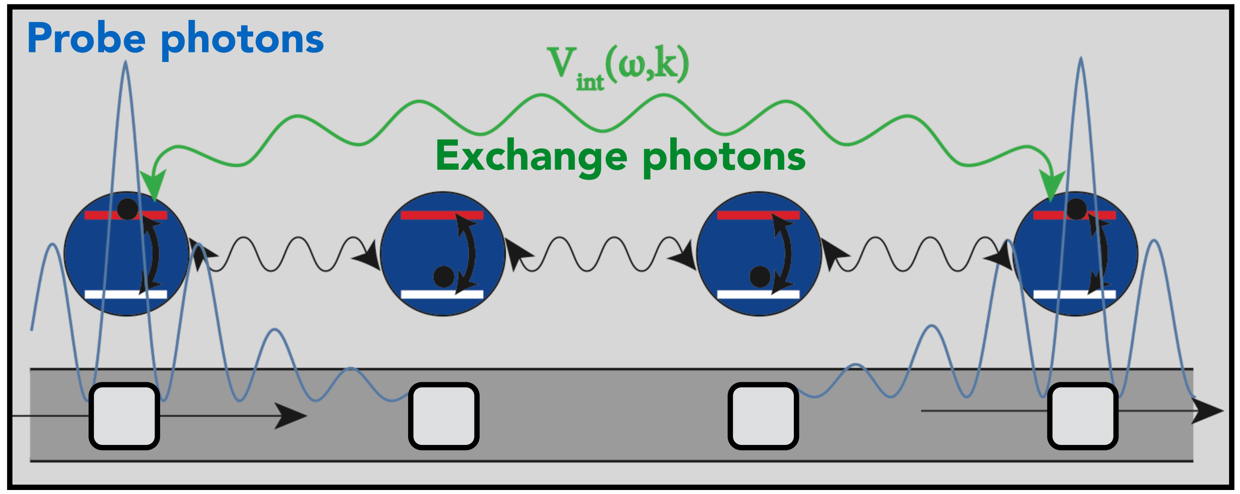


Interacting EIT polaritons



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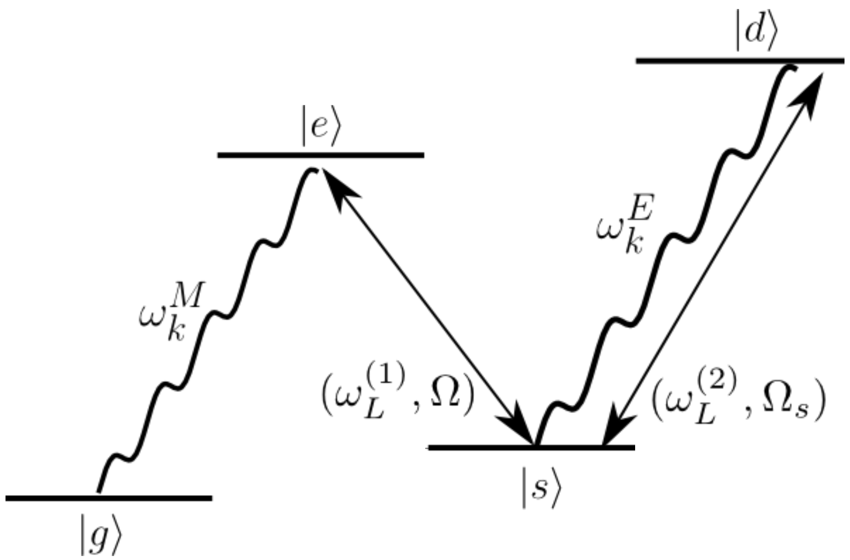
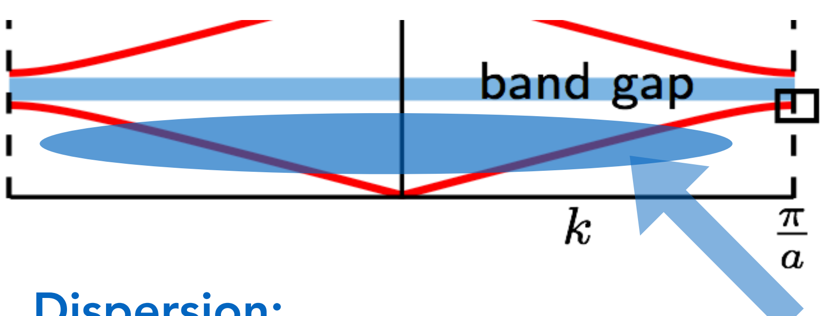


EIT propagation range: $L_M \simeq \frac{v_M}{\kappa_M}$

Exponential interaction range: $L_E \simeq \sqrt{\frac{\alpha_E}{\Delta}}$

Probe photons



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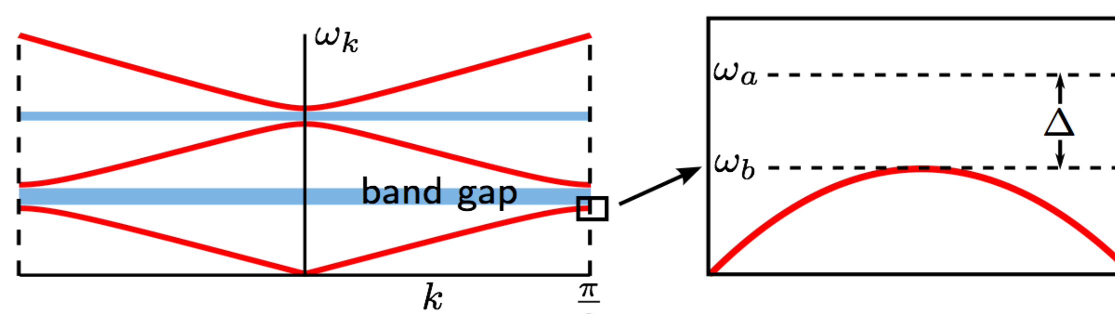

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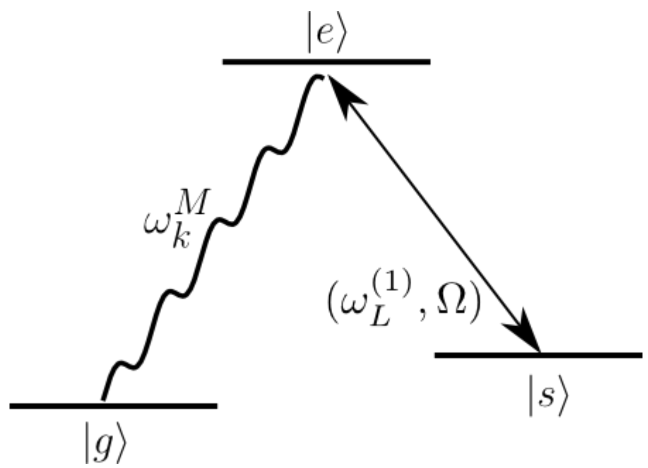
Non-equilibrium diagrammatic approach to EIT

Atomic levels



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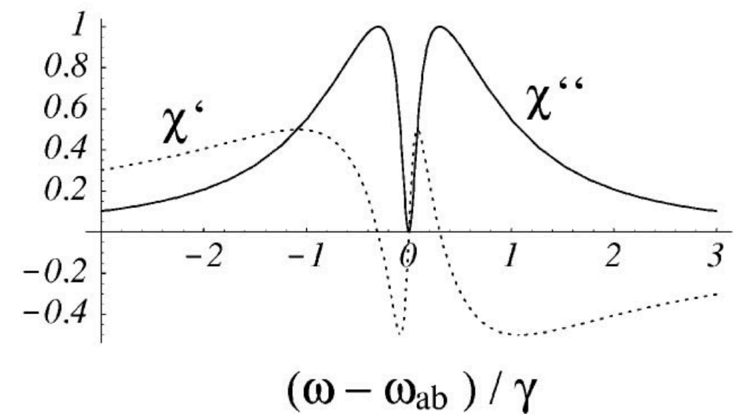
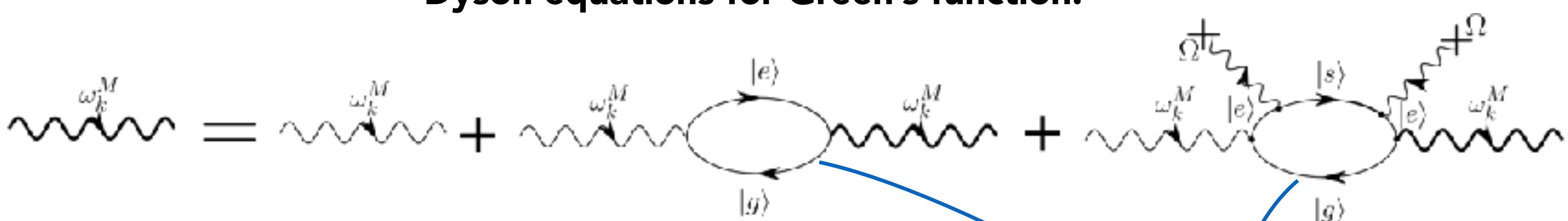


Large dispersion without absorption

EIT propagation range:

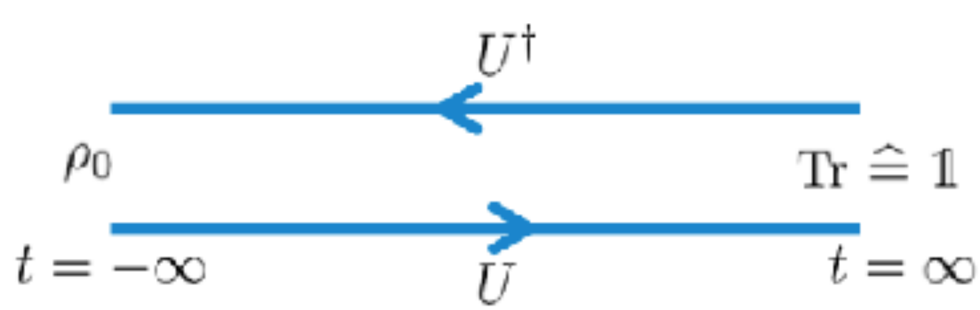
Dyson equations for Green's function:



$$\chi(\omega, k) = \frac{g_M^2 |u_k^M(0)|^2}{\omega - \omega_e - \frac{\Omega^2}{\omega - \omega_s - \omega_L^{(1)} + i\gamma_e/2}}$$

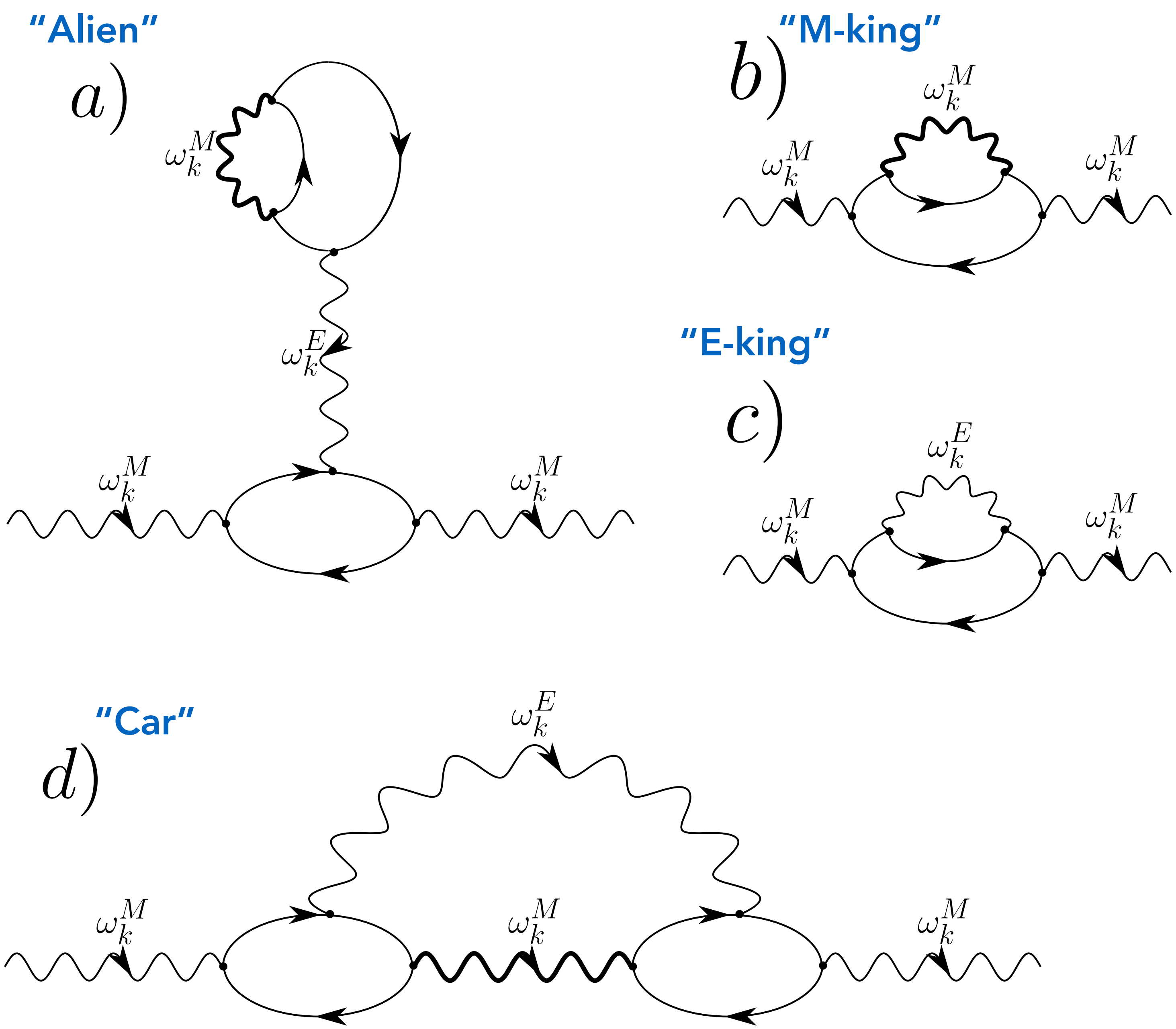
destructive interference = EIT

Keldysh real-time contour:



Forward-backward branch: double # of GF's

Controlled 1/range expansion for the interaction diagrams



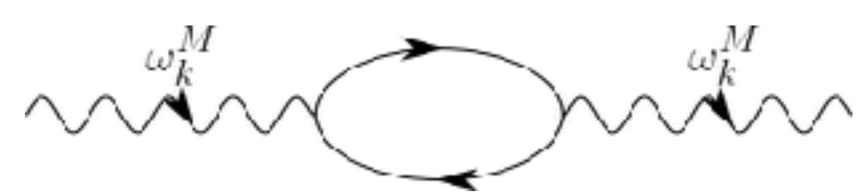
All next-to-leading order O(1/L) diagrams
for probe photons
(Keldysh structure and atom internal structure not shown)

- **Expansion for large propagation range**

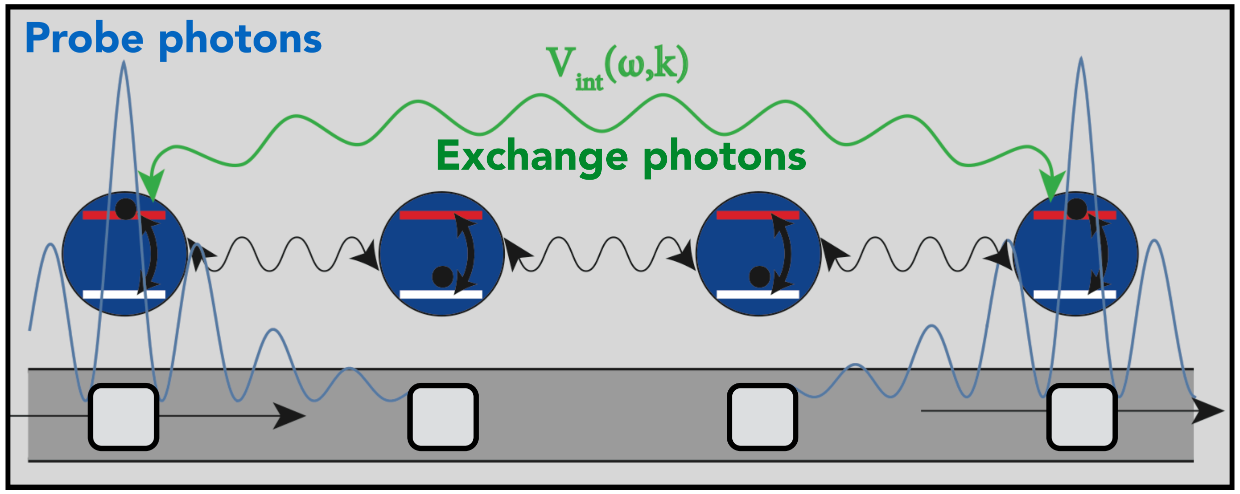
Effective coupling scales like $1/\sqrt{L}$:
multiple scattering suppressed

$$\left(\frac{a}{L}\right)^{\#\text{loops}-\#\text{atom-loops}}$$

- **EIT is leading order O(1):**

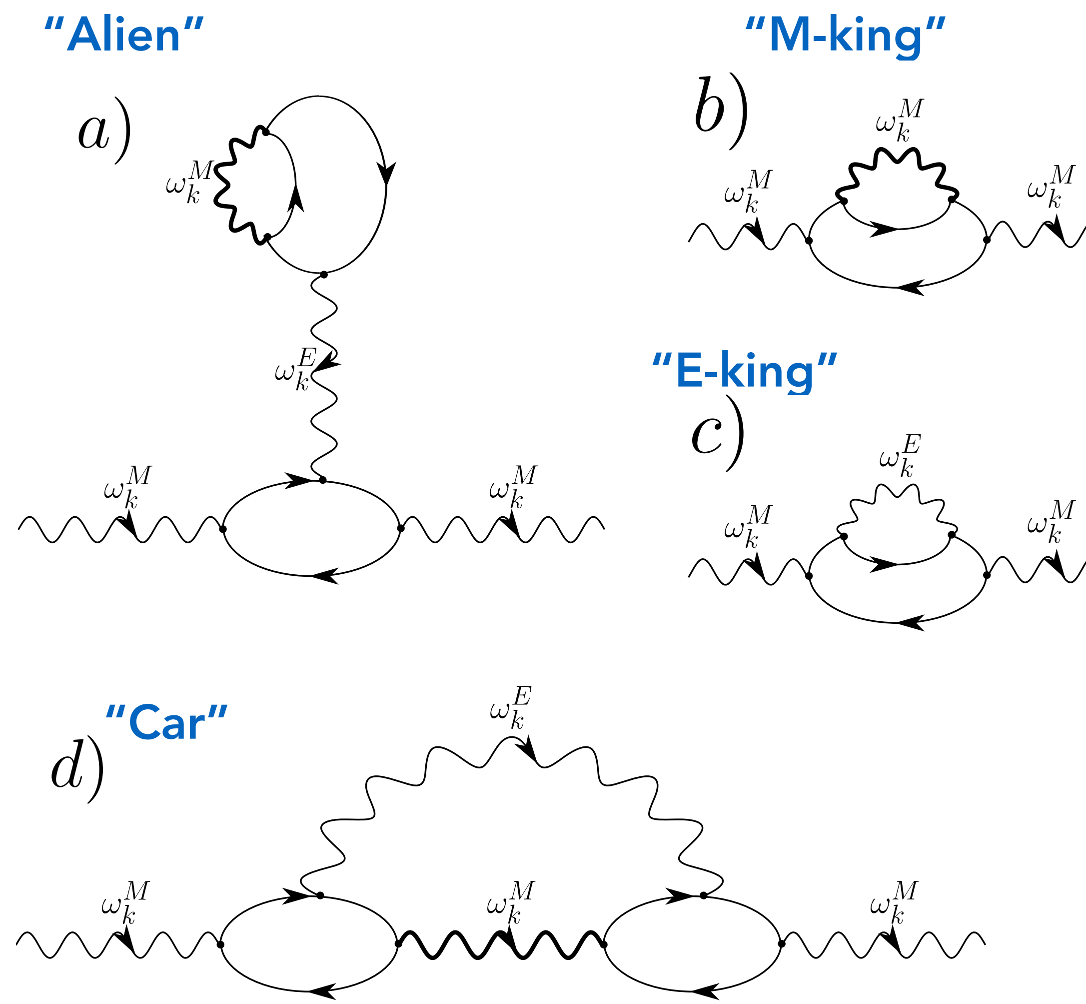


Parameter regimes for selected interaction processes



Still very complex theory at order a/L:

- Three-loop (leading interaction contribution)
- 4 atom + 2 photon degrees of freedom
- Keldysh structure

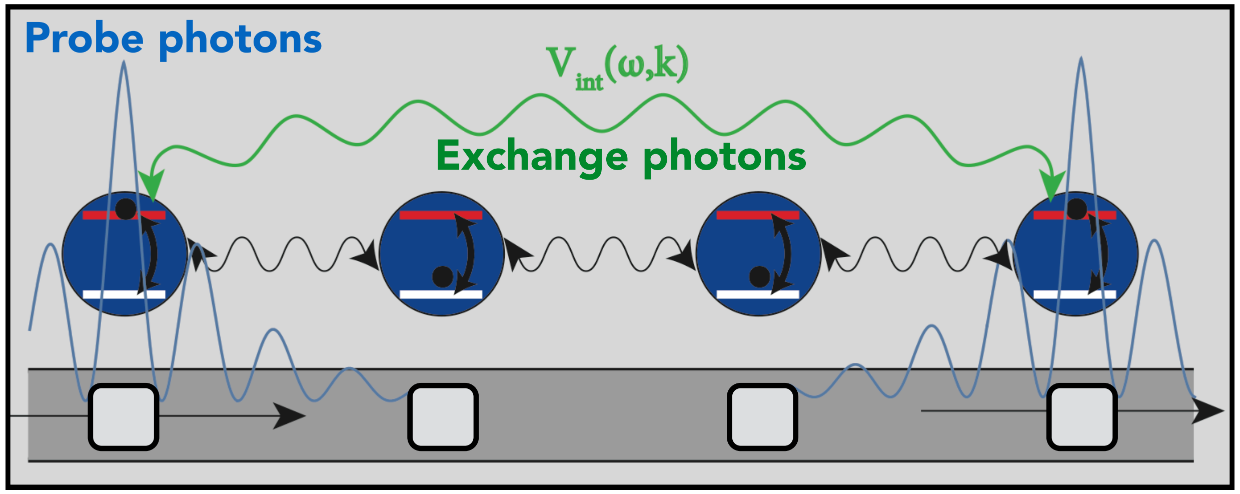


Tuneability:

EIT propagation range: $L_M \simeq \frac{v_M}{\kappa_M}$

Exponential interaction range: $L_E \simeq \sqrt{\frac{\alpha_E}{\Delta}}$

Parameter regimes for selected interaction processes



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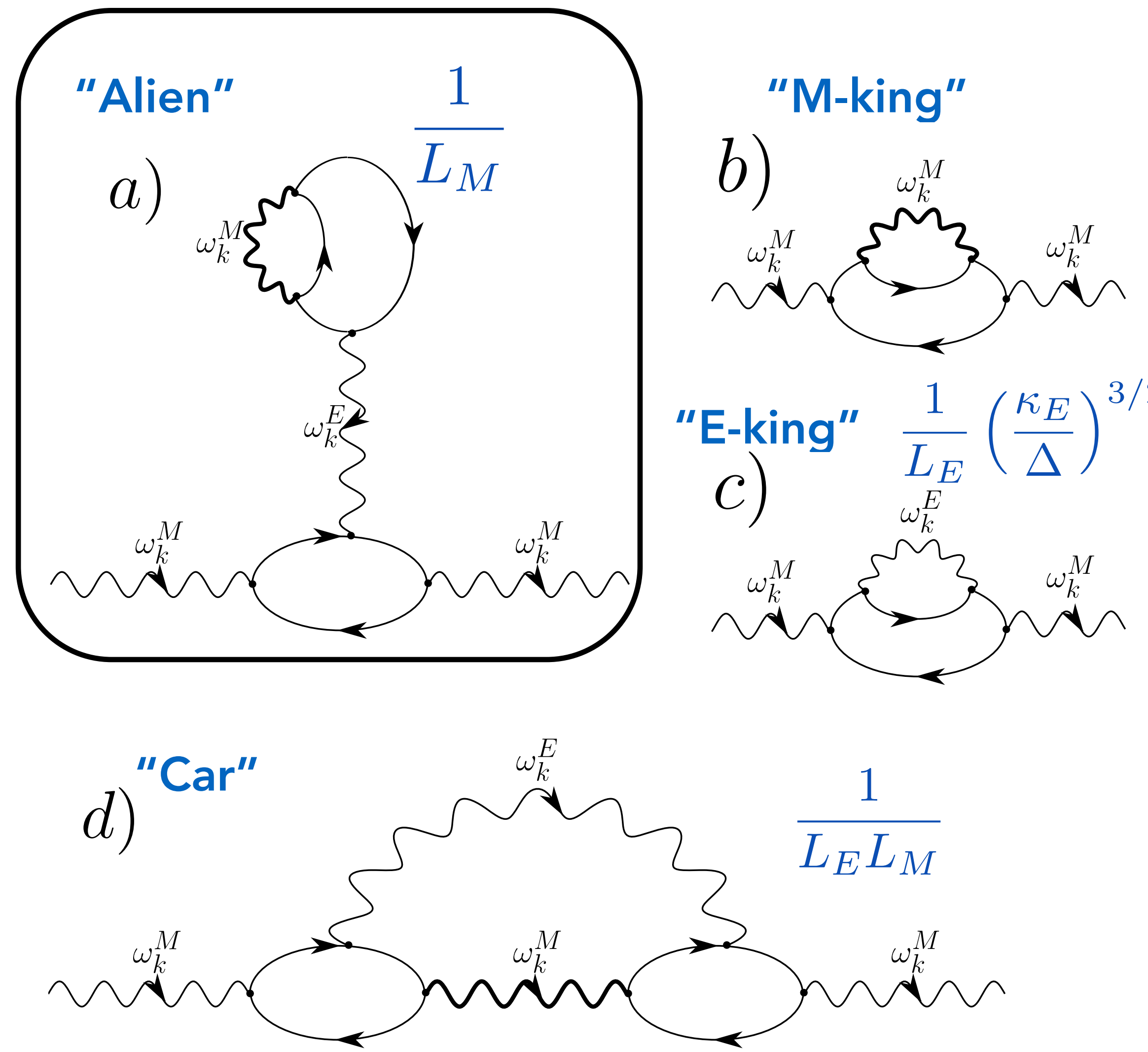


Tuneability:

EIT propagation range: $L_M \simeq \frac{v_M}{\kappa_M}$

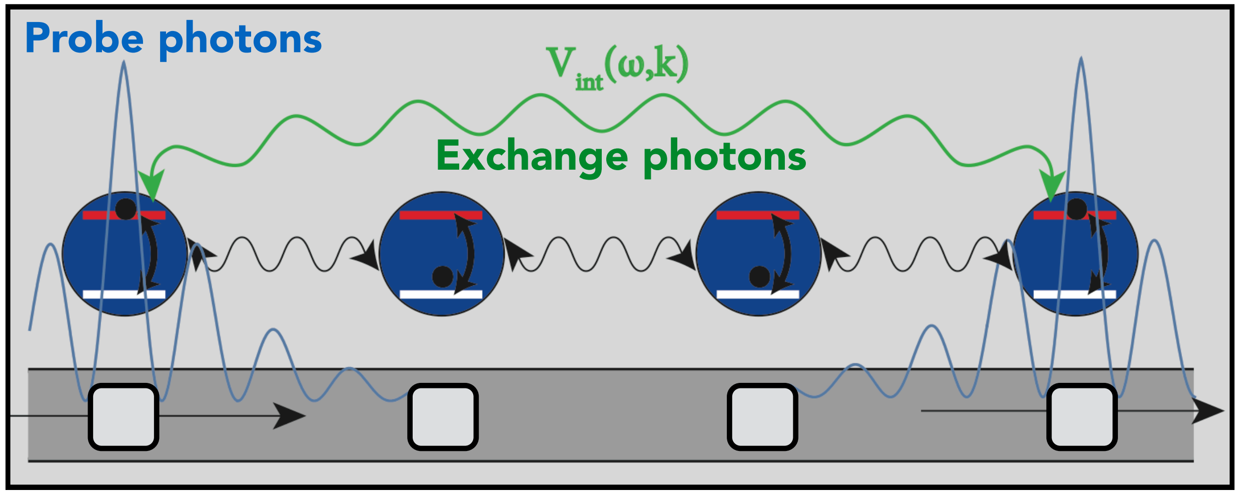
Exponential interaction range: $L_E \simeq \sqrt{\frac{\alpha_E}{\Delta}}$

Large interaction range: $\frac{L_E}{L_M} \gg \left|\frac{\kappa_E}{\Delta}\right|^{3/2}$

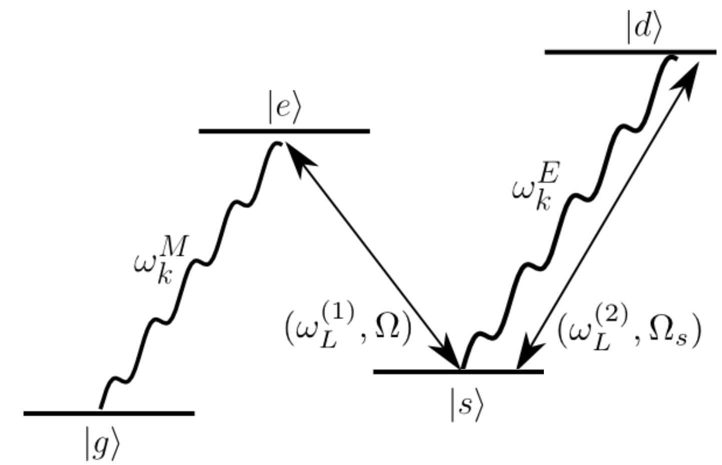
Interaction-induced shifts dominate over scattering

"Alien" (Hartree) diagram dominates

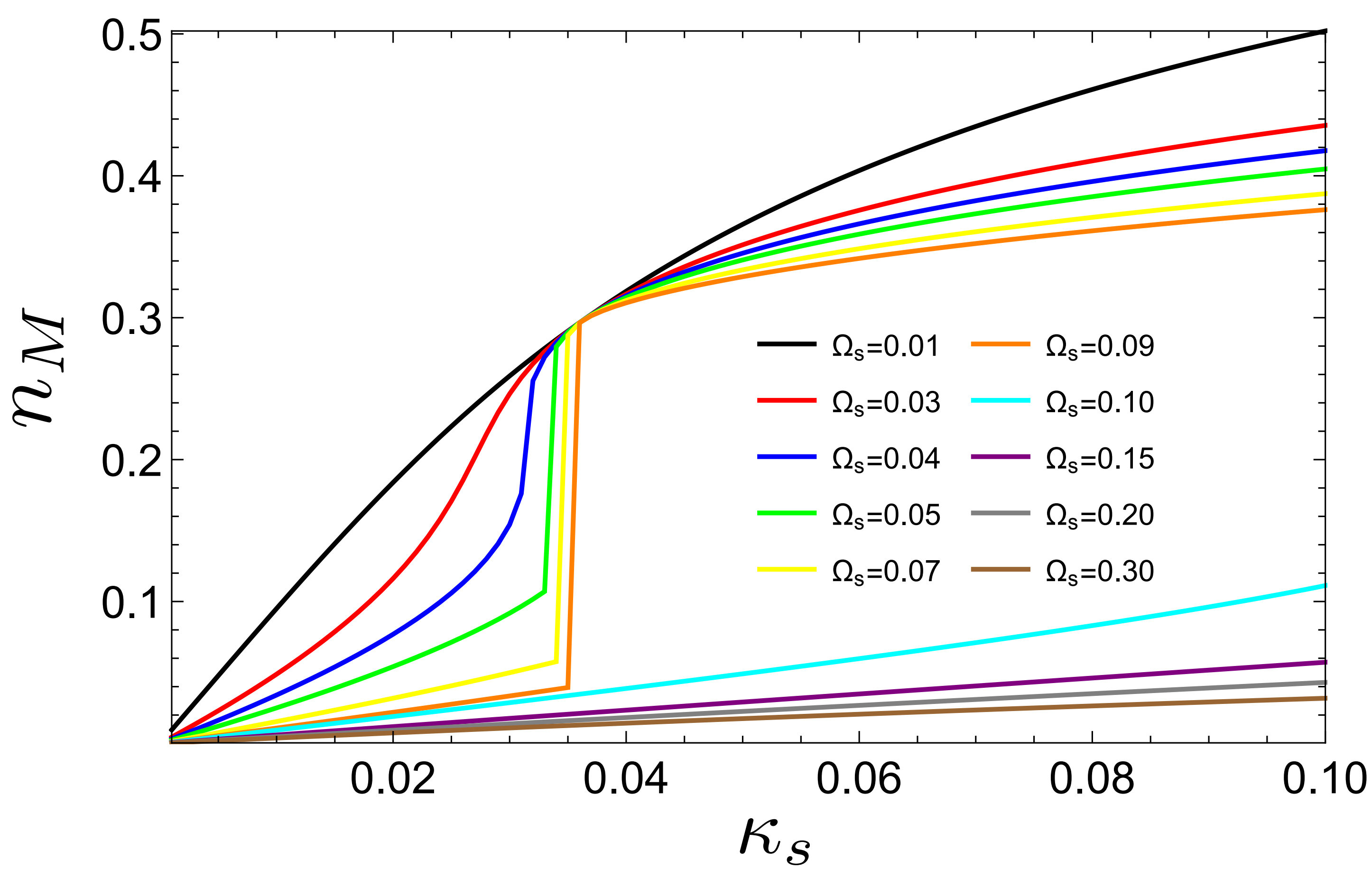
Non-equilibrium phase transition



Atomic levels



Number of probe photons in the steady state



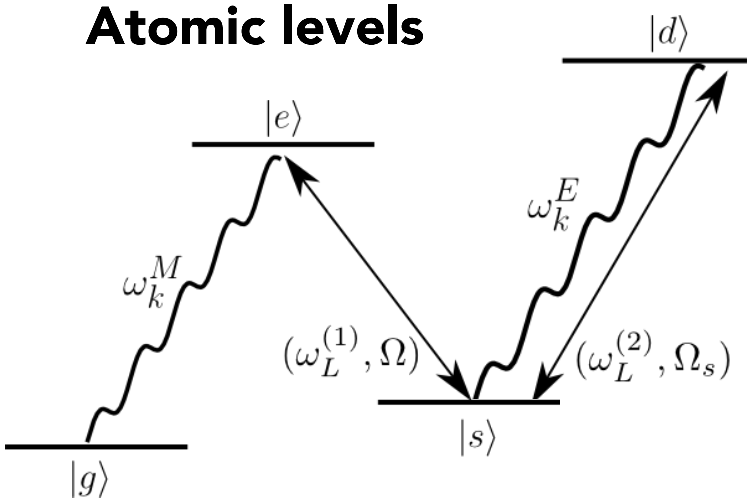
- **Transition between bright and dark phase**

First order, culminates in bi-critical point

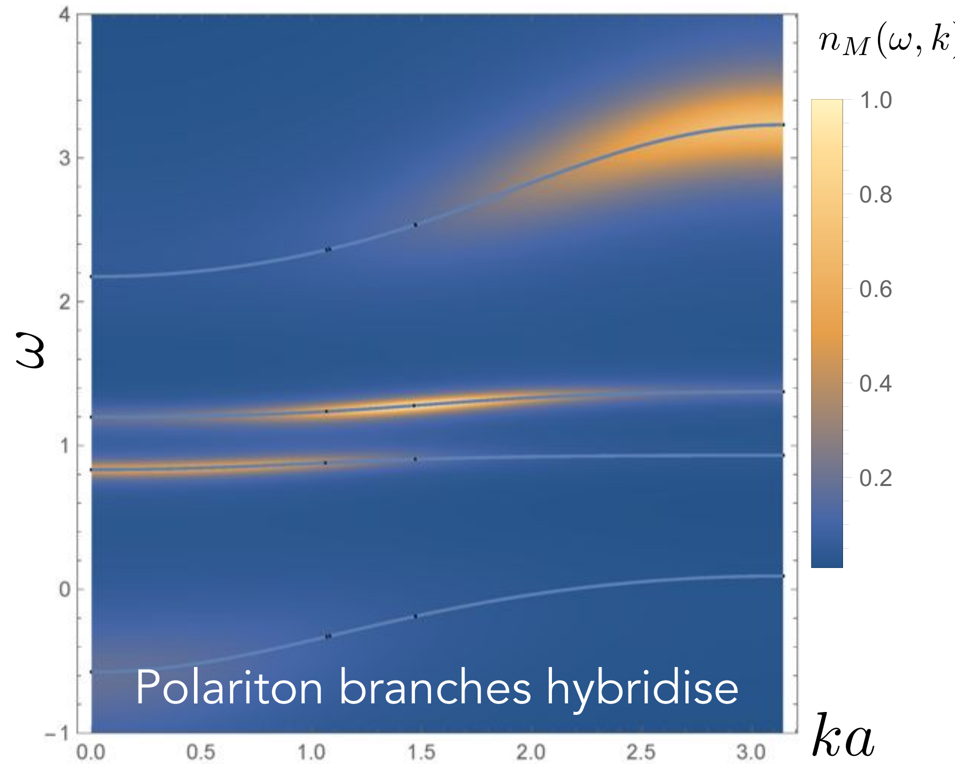
Interaction-induced transparency

Probe-photons occupation:

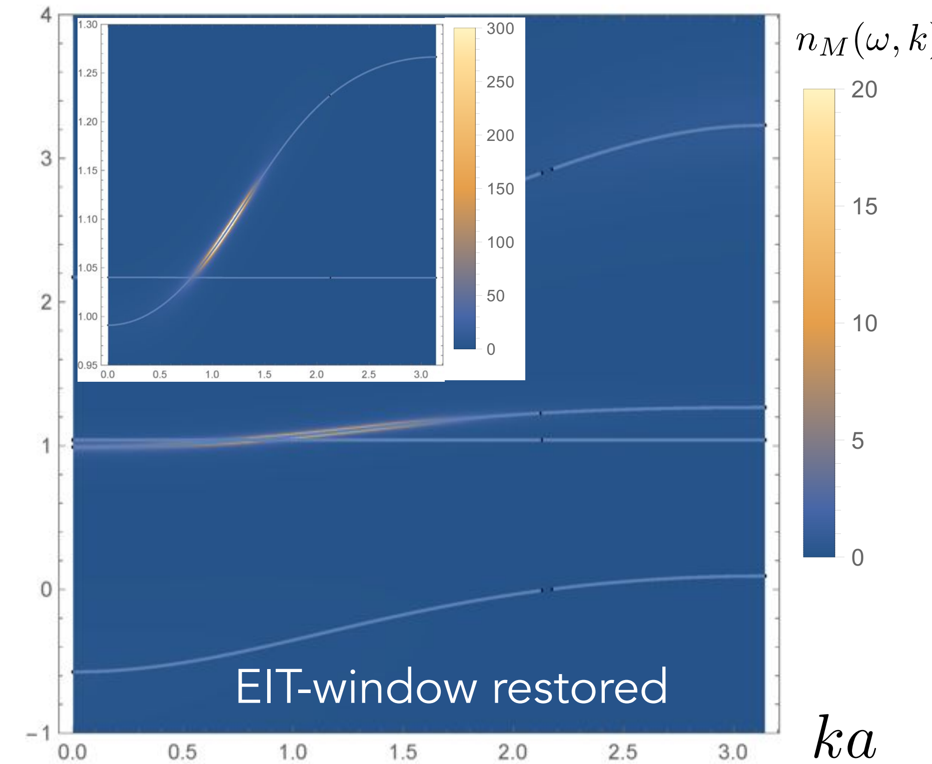
Atomic levels



Dark phase



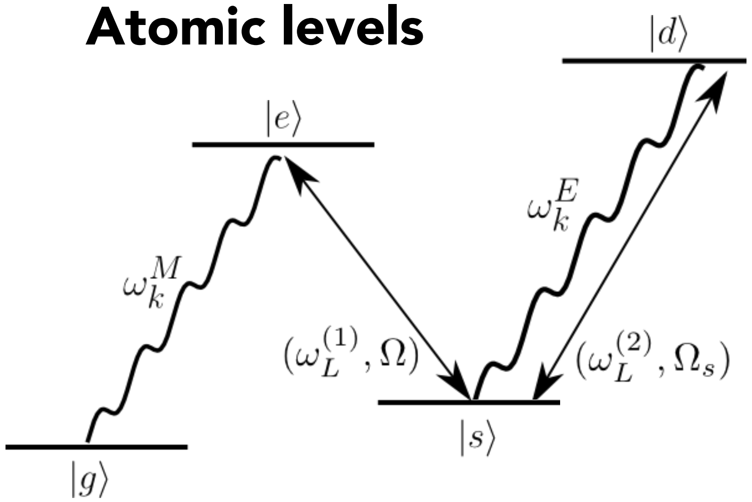
Bright phase



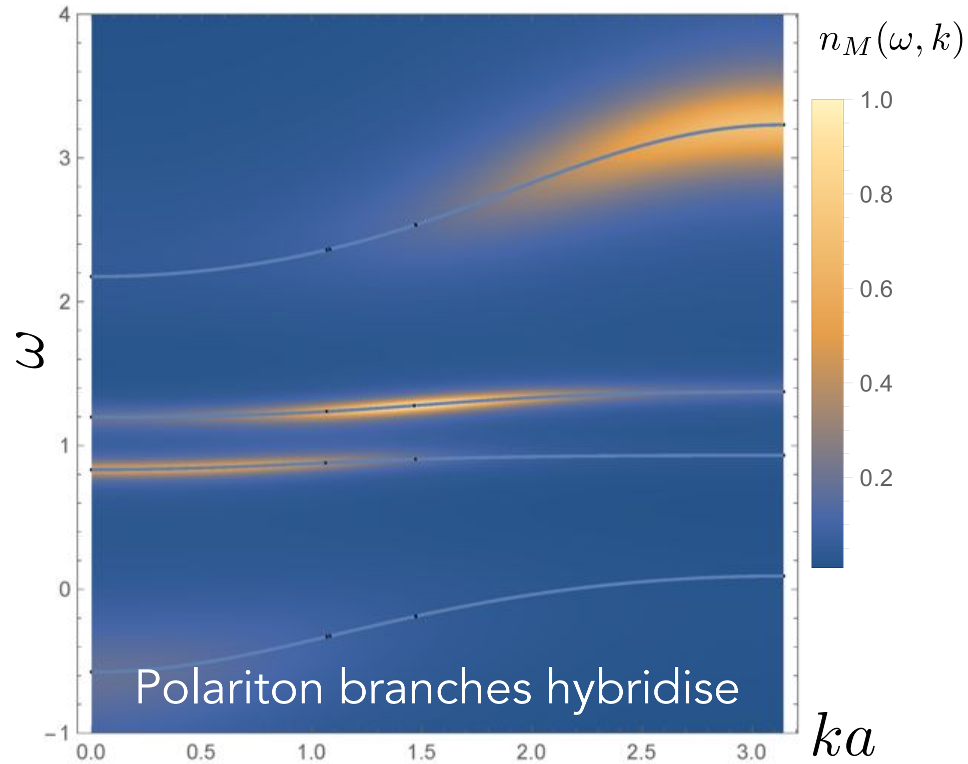
Interaction-induced transparency

<u>Probe-photons occupation:</u>

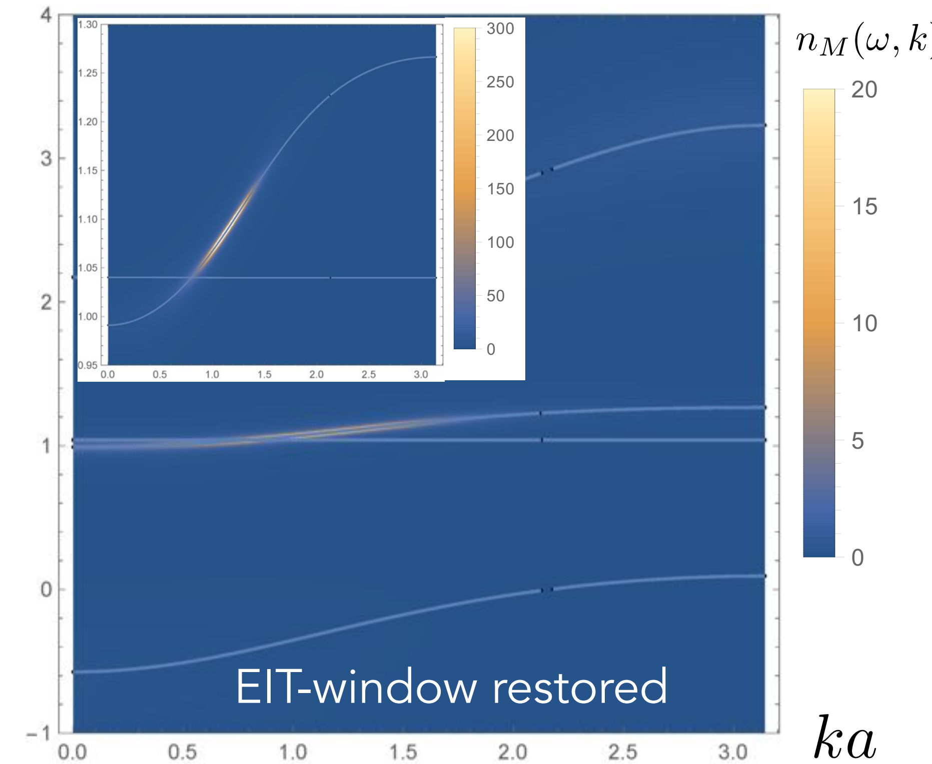
Atomic levels



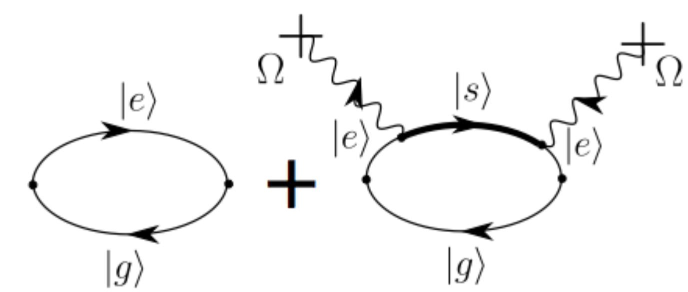
Dark phase



Bright phase



<u>Electromagnetically Induced Transparency (EIT):</u> $\chi_{\mathrm{EIT}} =$



Interaction-induced transparency

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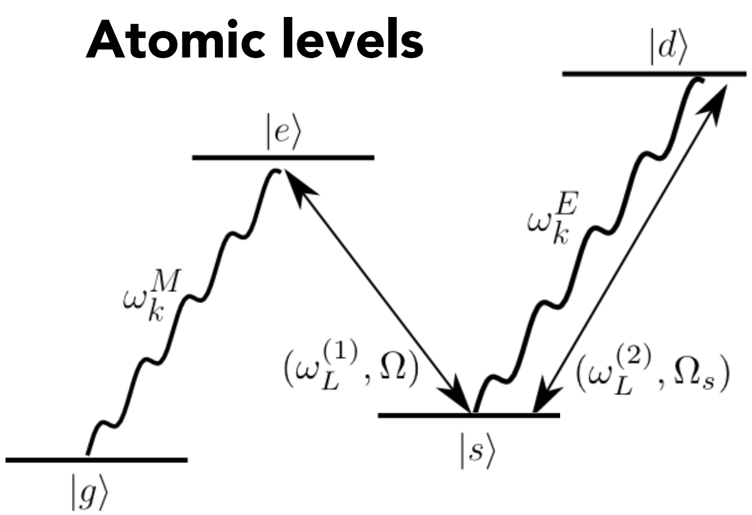
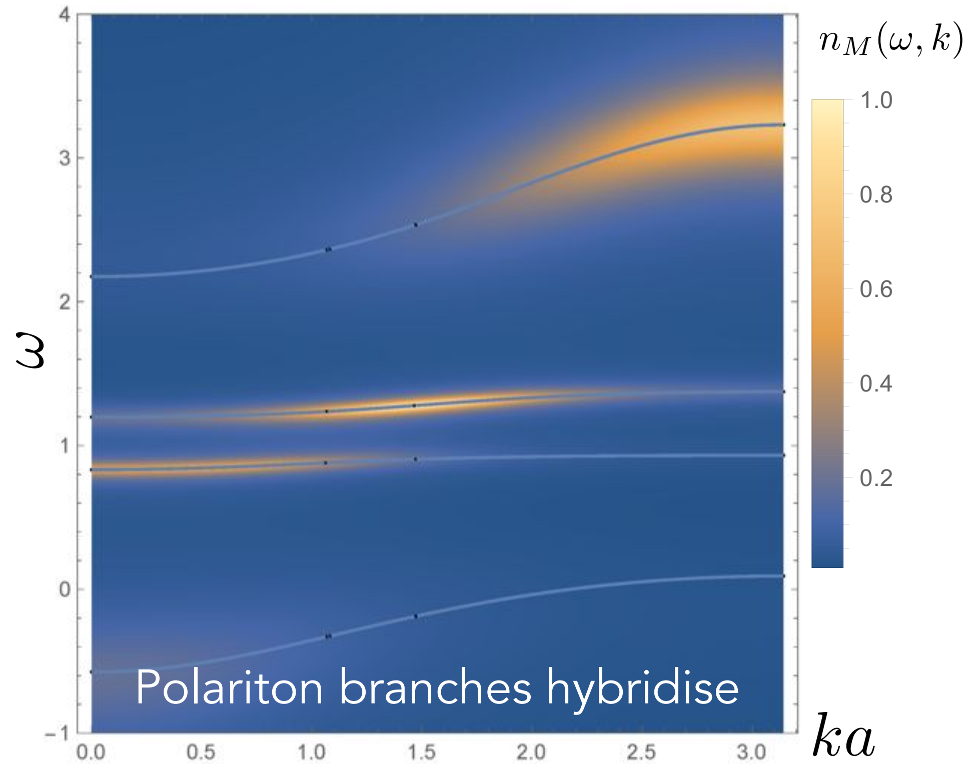
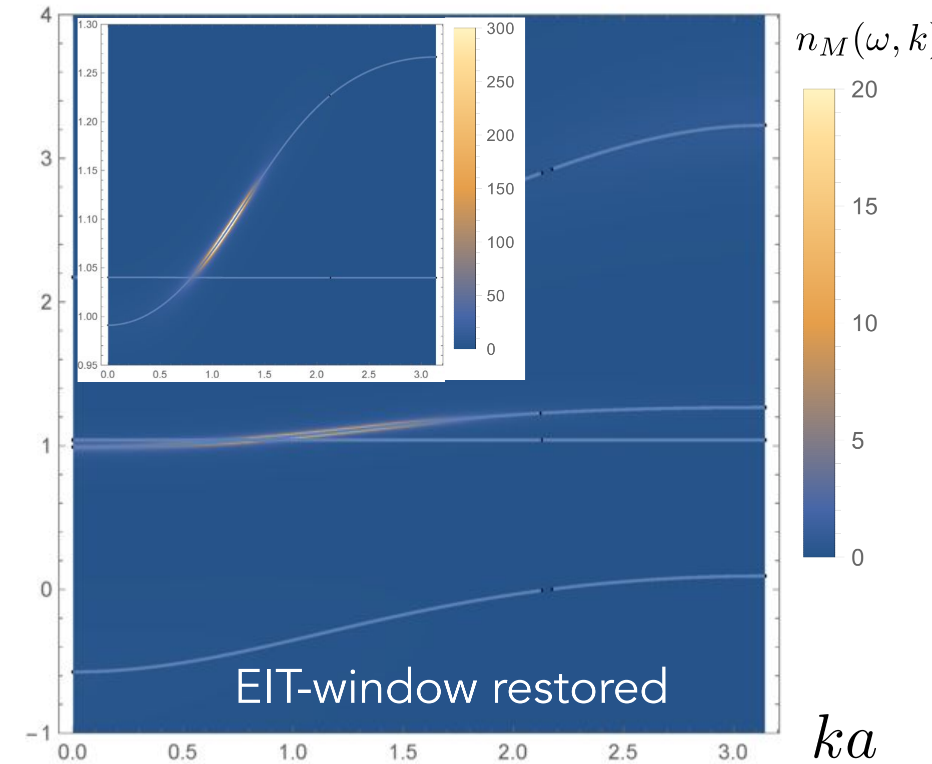
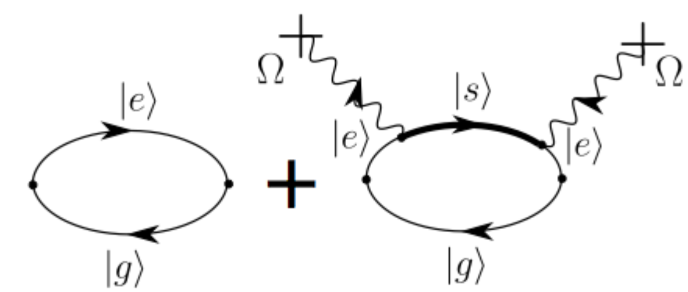


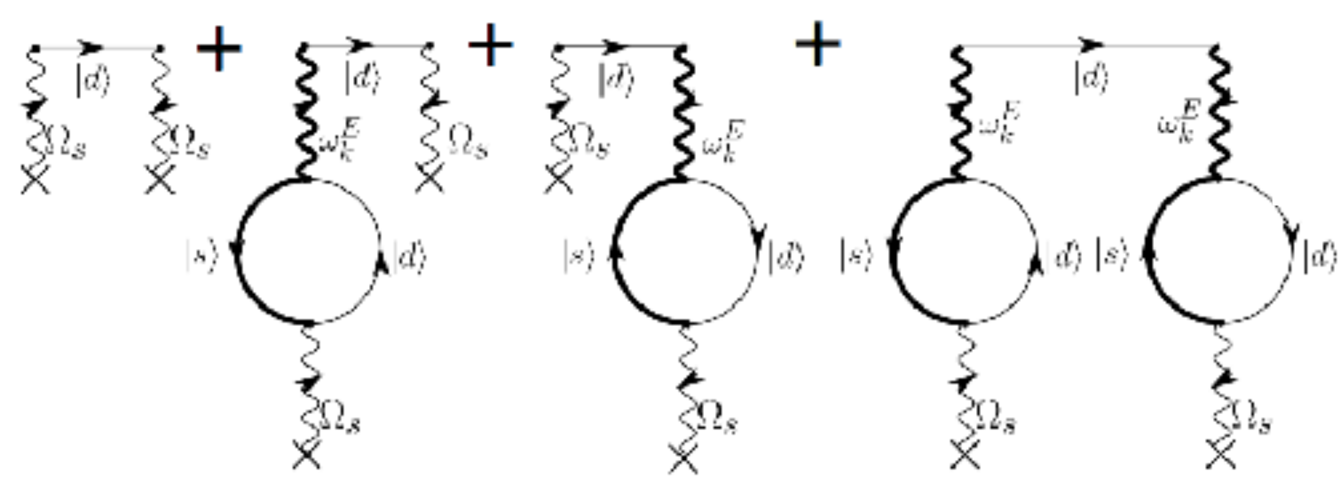




Electromagnetically Induced Transparency (EIT): $\chi_{\mathrm{EIT}} =$



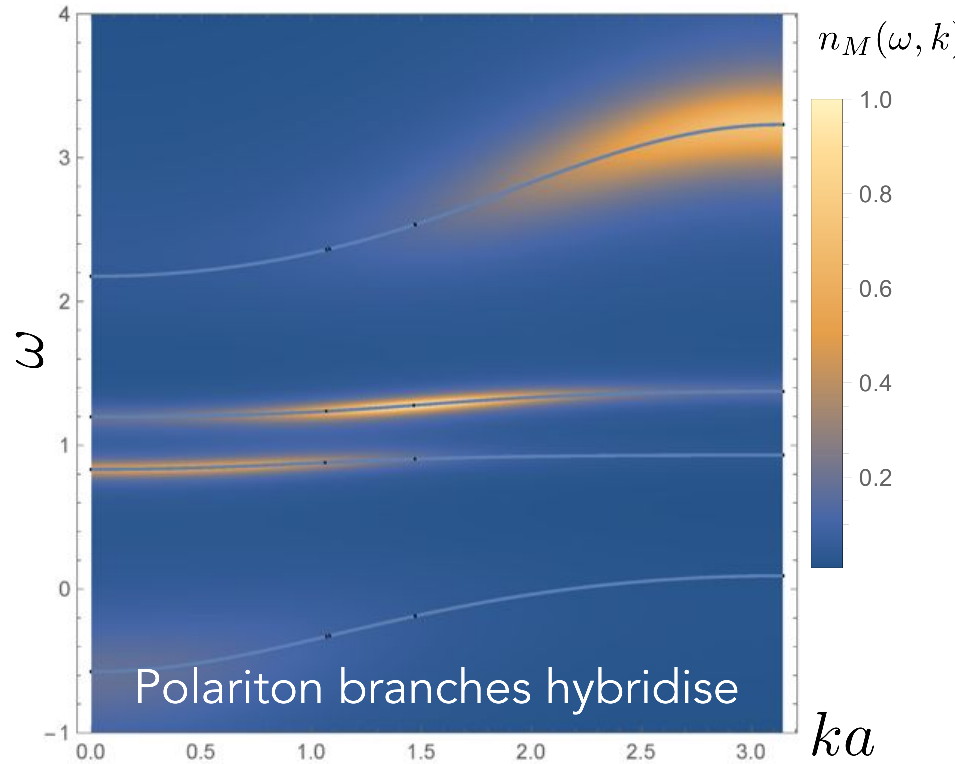
Interaction-Induced Transparency (IIT): $\chi_{\mathrm{IIT}} =$



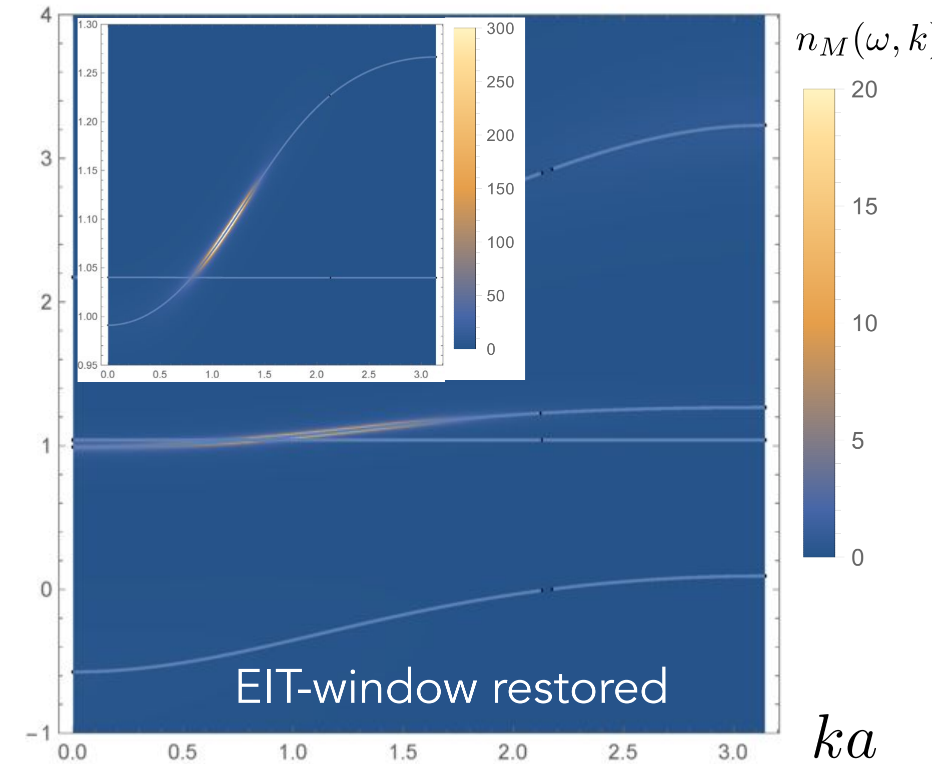
Bistability

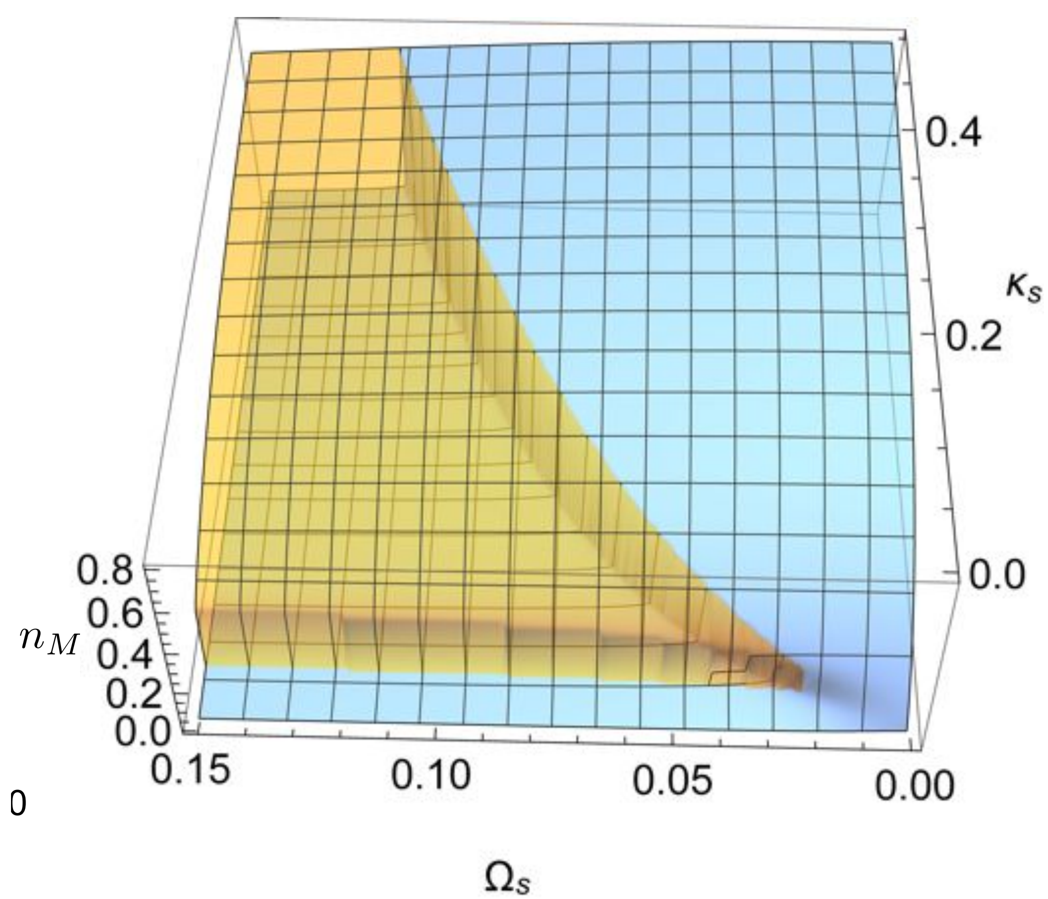
Probe-photons occupation:

Dark phase



Bright phase



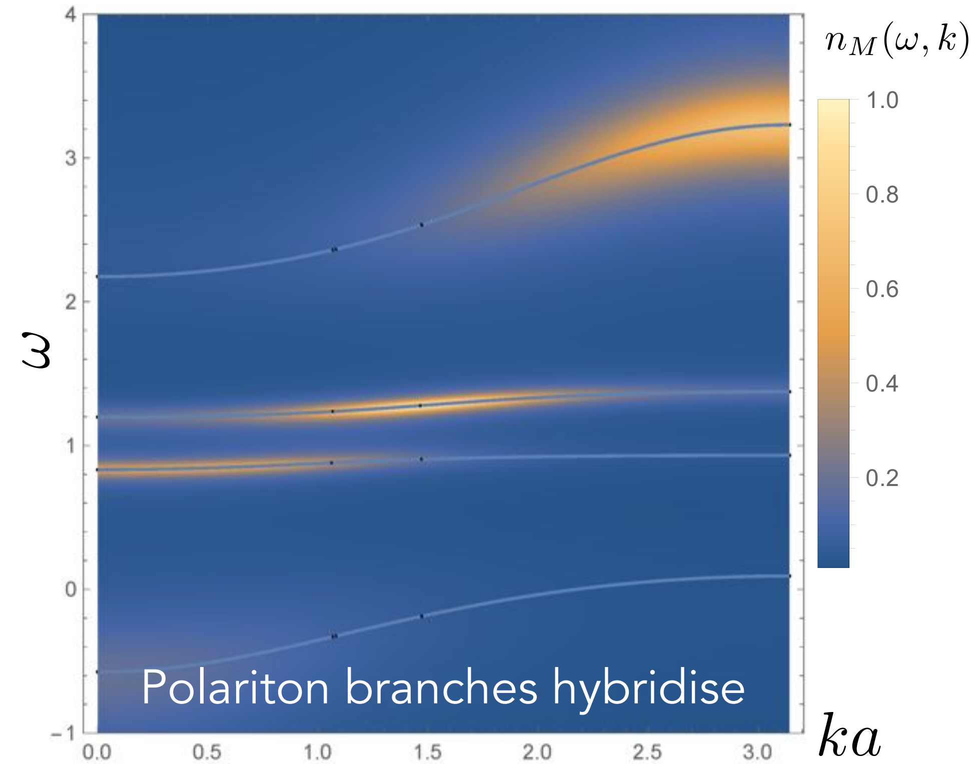


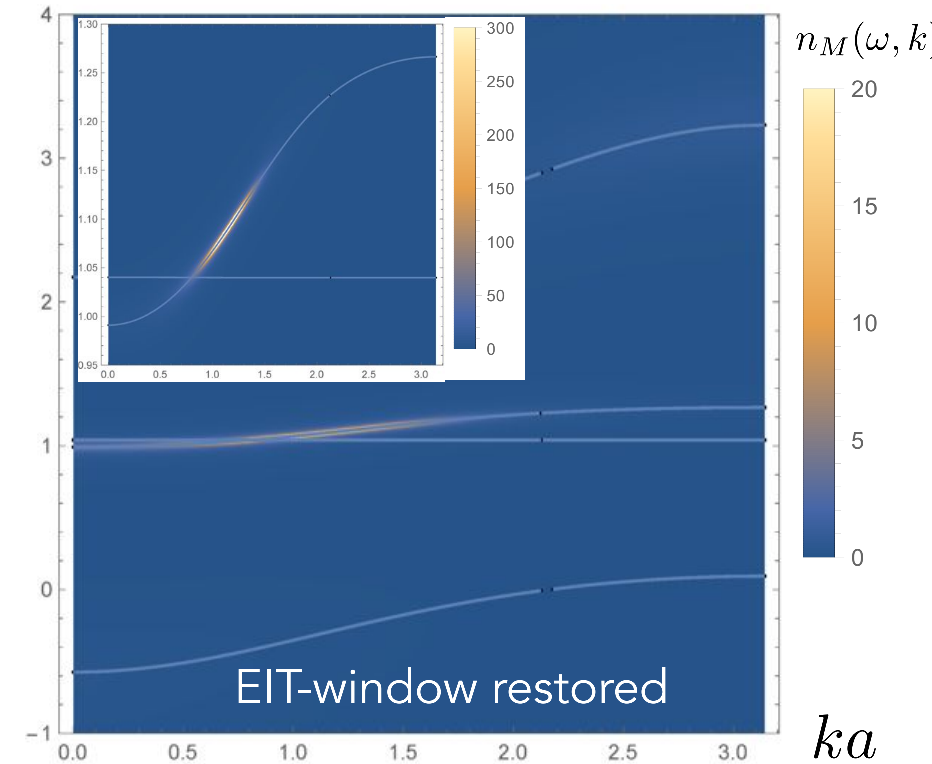
- **Transition between bright and dark phase**
  First order, culminates in bi-critical point
- **Interactions can restore the EIT window**
  Destructive interference between s-d excitation paths involving exchange photons
- **Bistability between dark and bright phase**
  One interference path involves polariton interactions i.e. is nonlinear

Screening effects

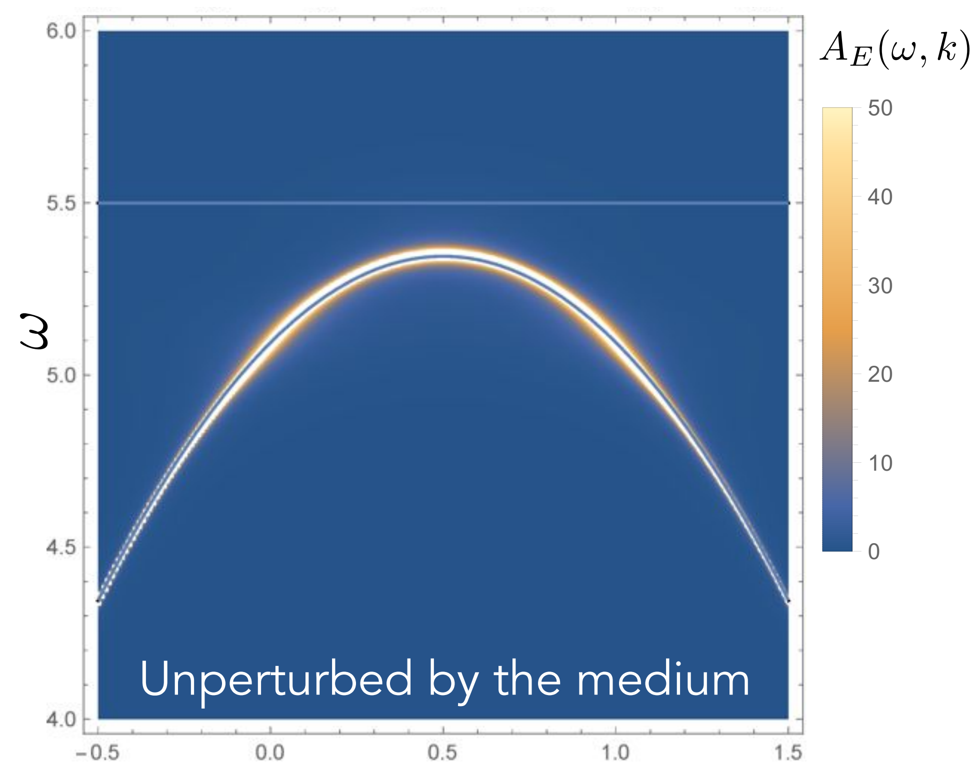
Probe-photons occupation:

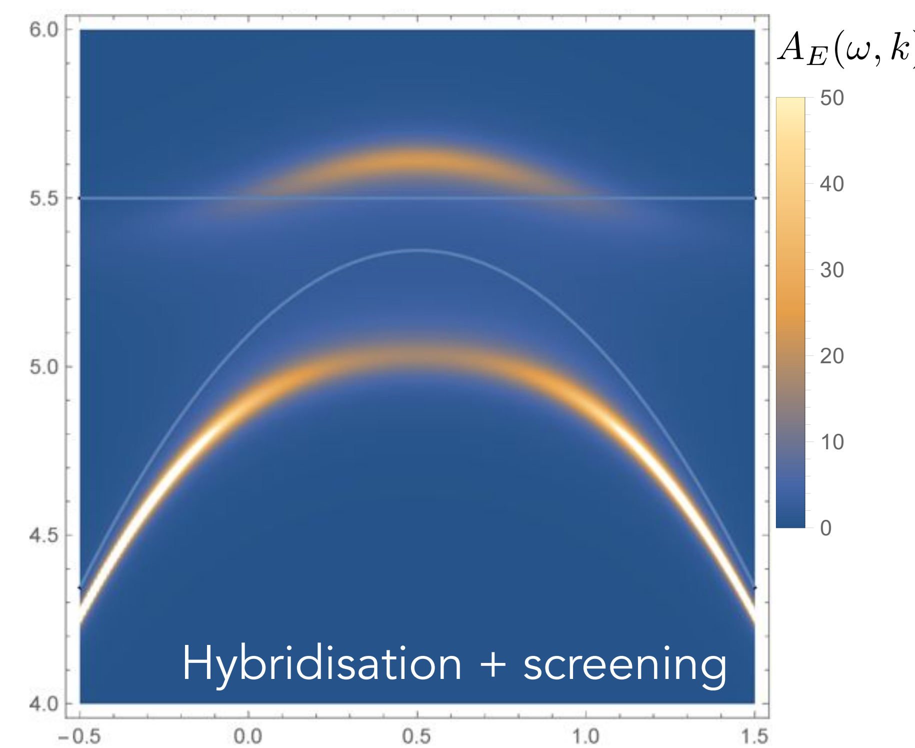
Dark phase | Bright phase





Exchange-photons spectrum:

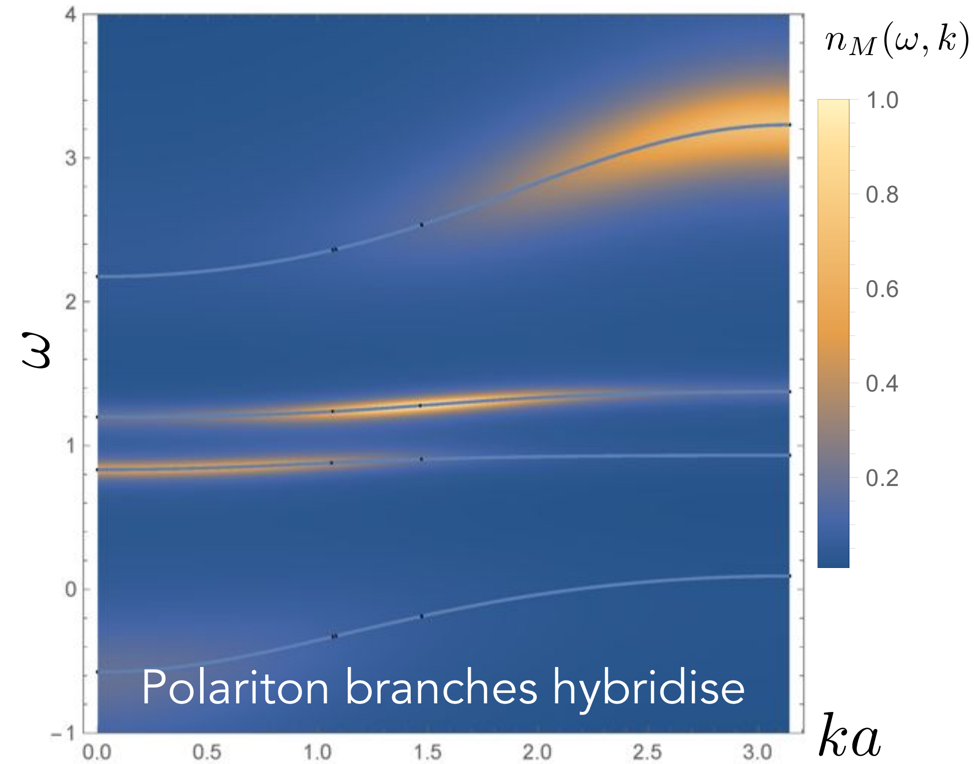




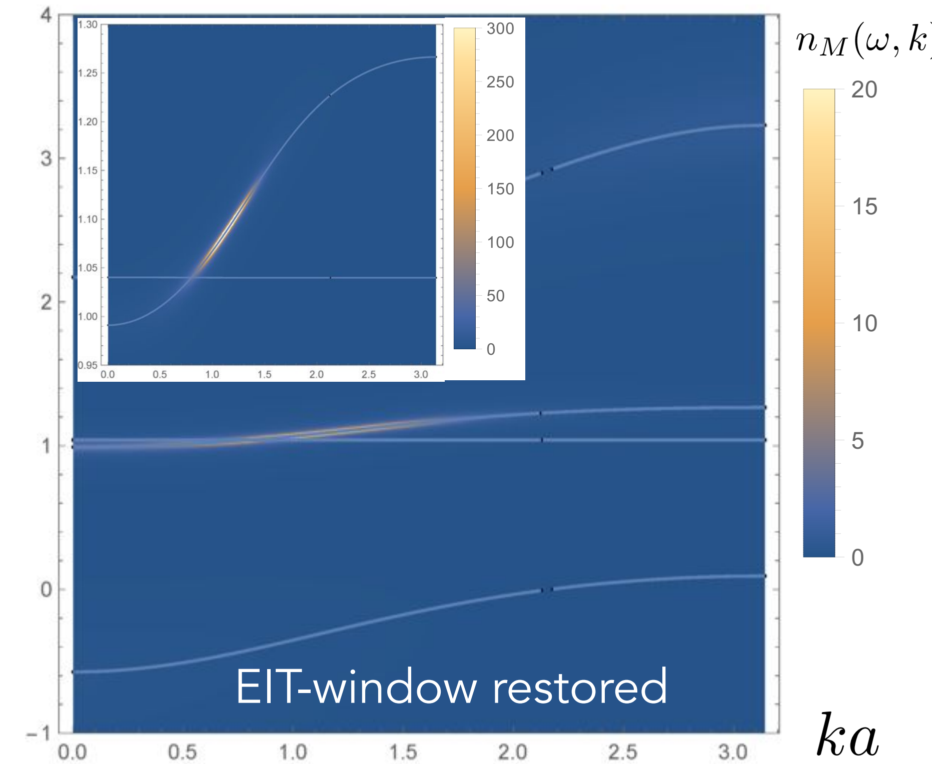
Intrinsic non-equilibrium nature

Probe-photons occupation:

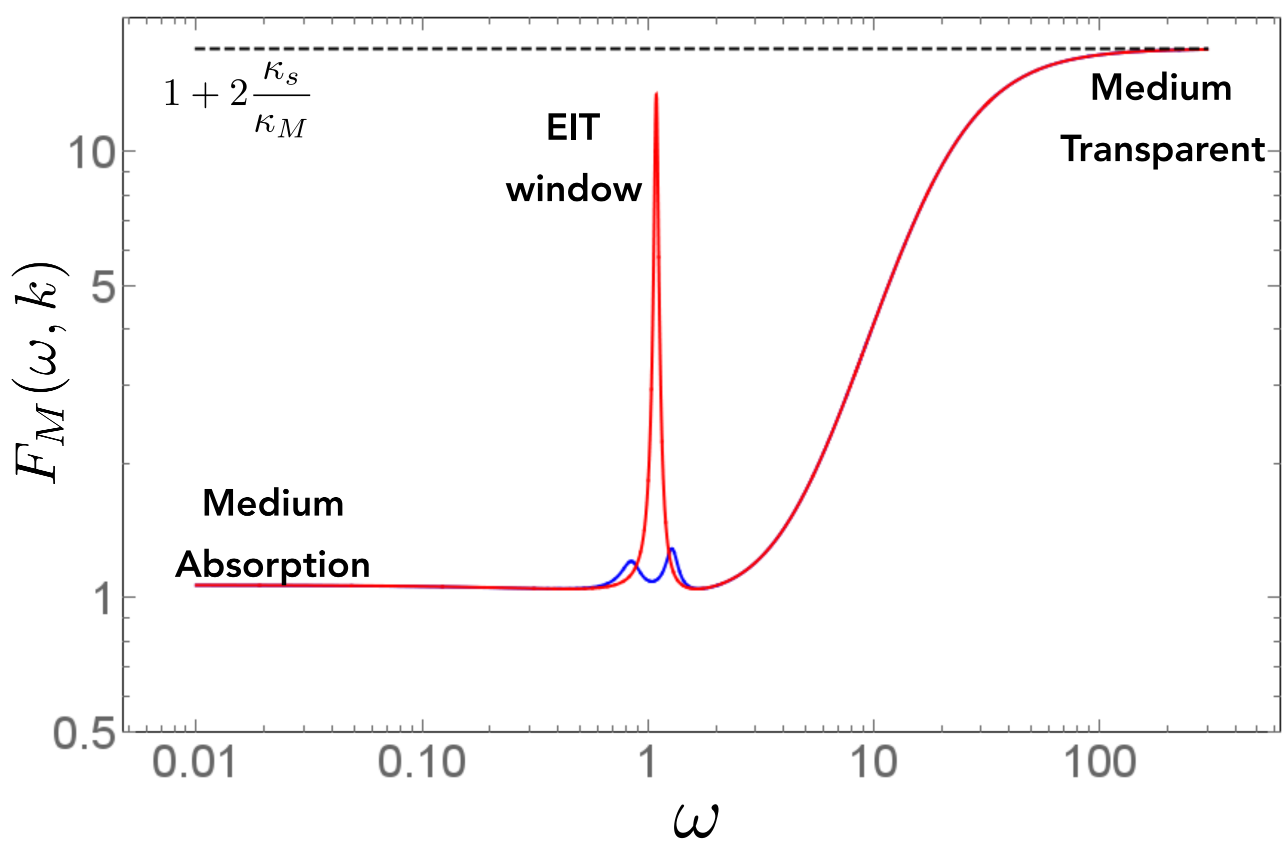
Dark phase



Bright phase



Probe-photons distribution function:



No effective thermal equilibrium

- EIT window emerges between Markov regions of total transparency and total absorption
- EIT peak is a sharp Lorentzian: no effective thermalisation

Summary

1. Controlled diagrammatic approach to strongly interacting EIT polaritons

A. Non-perturbative diagrammatic expansion in 1/range for non-equilibrium GFs

B. Tuneability of photon dispersion allows to select interaction processes

C. Identify parameter regimes for quantitative relevance

2. Non-equilibrium phase transition on the EIT-window

D. Transition between a dark and bright phase where interactions restore the EIT-window

E. Bistability culminating in bi-critical point

F. The EIT effect makes the transition of non-equilibrium nature

Outlook

i) Dynamics of inhomogeneously driven system: How to ideally enter the bright phase experimentally?

ii) Universality class of the non-equilibrium transition

iii) Include scattering diagrams and treat photon crystallization.