Strongly interacting Rydberg slow light polaritons

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Strongly interacting
Rydberg slow light
polaritons

SFB TRR21:
Tailored quantum matter

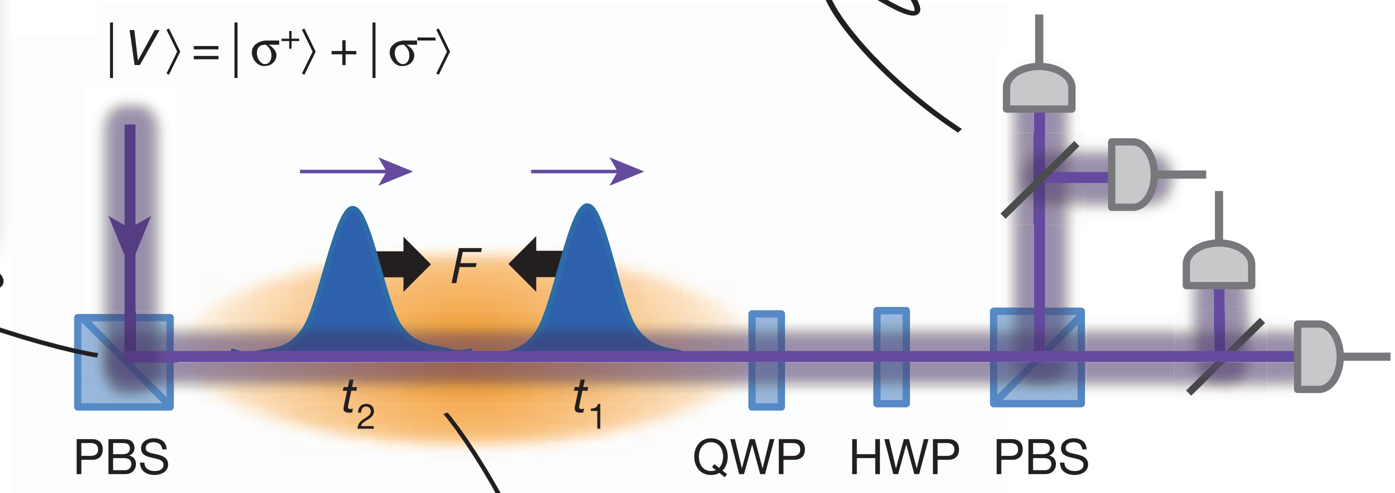
Interacting Rydberg slow light polaritons

Input:

- photons in a single transverse channel
- no-backscattering as atomic cloud is smooth
- chiral-one-dimensional photons

Readout:

- detection transmitted photons
- photon correlations



Firstenberg et al 2013

Media:

- cold atomic gases
- strongly interacting slow light polaritons in one-dimension

Slow light polaritons

Electromagnetic induced transparency (EIT)

- photons in an atomic media

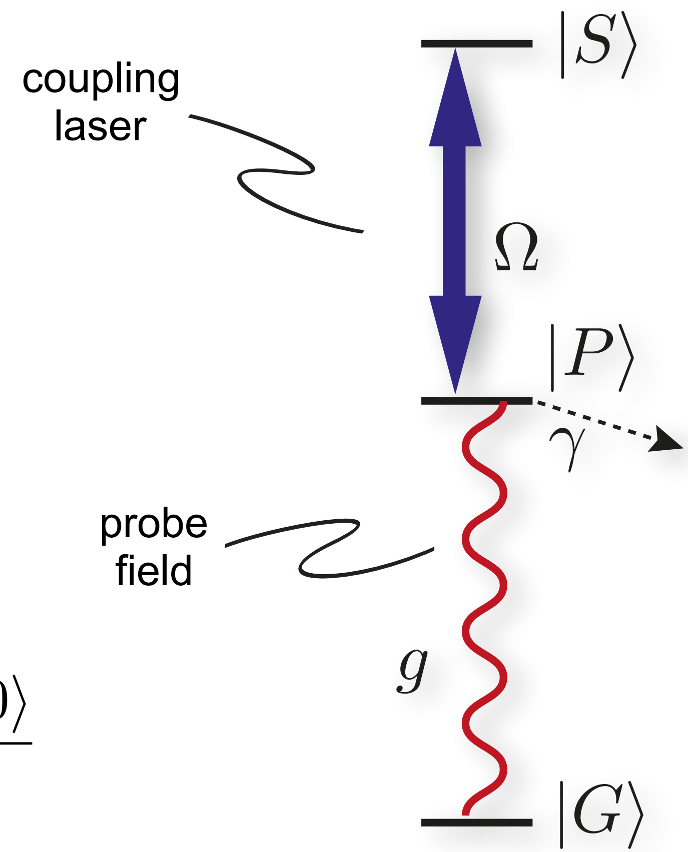
- three level setup for the atoms

  - coupling laser
  - probe field
  - losses only from intermediate p-level

- dark state

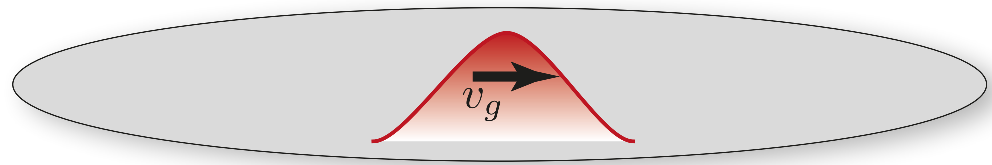
  - dissipation free state
  - polariton: superposition of photon and excited state

$$\frac{\Omega|G,1\rangle - g|S,0\rangle}{\sqrt{\Omega^2+g^2}}$$



Slow light polaritons

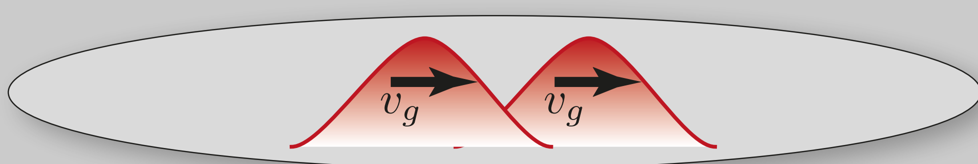
photon wave packet



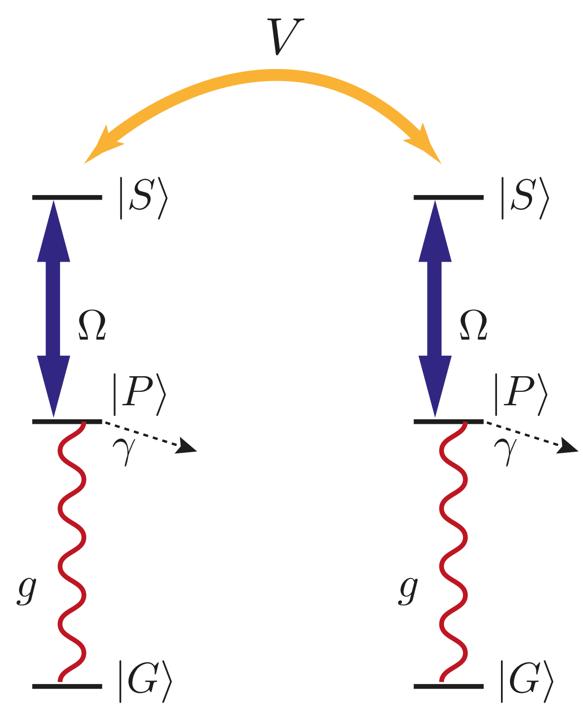
slowed down and compressed
within the media

- slow light (~ 1 m/s)
- single photon storage (a few seconds)
- light pulse to width of $20 \mu\mathrm{m}$

Is it possible to induce a strong interaction between the photons?



- yes, if we use Rydberg states as an excited state
- Rydberg slow light polaritons



Rydberg excitations

Rydberg-Rydberg interaction

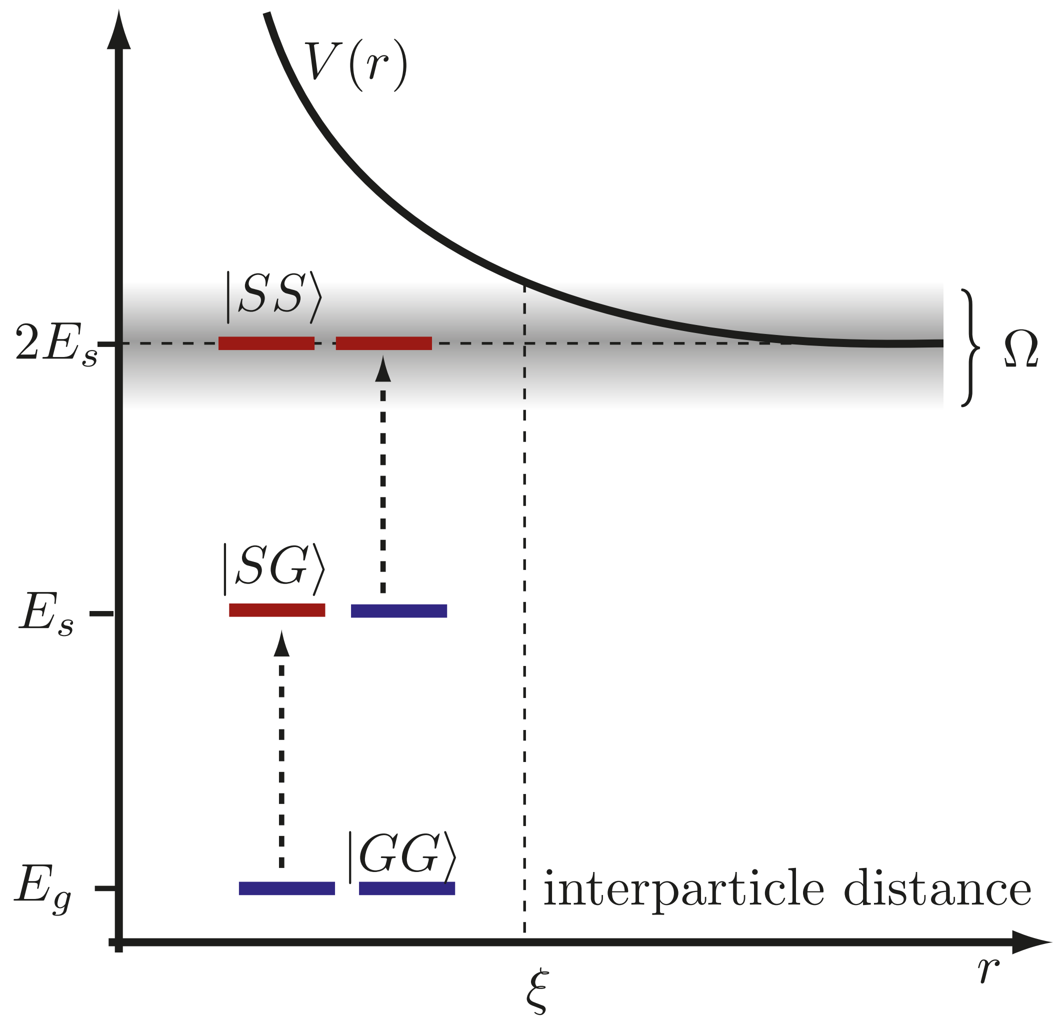
- strong van der Waals interactions for s-wave states
    - depending on n attractive or repulsive
    - $C_6 \sim n^{11}$
- dipole-dipole interactions in presence of an electric field

  $d \sim n^2 e a_0$

Blockade phenomena

- once a Rydberg atom is excited, further excitatons are shifted out of resonance
- Blockade radius

  $\xi = (C_6/\hbar\Omega)^{1/6} \sim 5\mu m$



Exp: T. F. Gallagher, Charlottesville; M. Weidemüller, Freiburg; P. Pillet, Orsay; Rolston, JQI; van den Heuvell, Amsterdam; P. Gould, Storrs; T. Pfau Stuttgart, A. Browaeys, P. Grangier, Orsay; M. Saffman.
Th: Robicheaux and Hernández, Ates, Pohl, Pattard, Rost, Stanojevic, Côté, Lukin, Fleischhauer, Cirac, Zoller,

References

Theory:

Friedler, Petrosyan, Fleischhauer, Kurizki, (2005);
Gorshkov, Otterbach, Fleischhauer, Pohl, Lukin (2011);
Otterbach, Muth, Moos, Fleischhauer (2013);
Peytrosyan, Otterbach, Fleischhauer (2011);
He, Sharypov, Shen, Simon, Xiao (2014);
Bienias, Choi, Firstenberg, Maghrebi, Gullan, Lukin, Gorshkov, Büchler (2014);

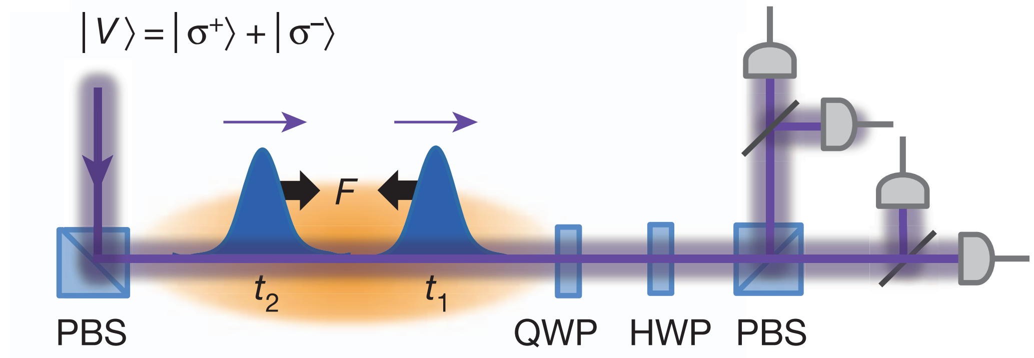
Exp:

Jones, Adams, Durham
Rempe, Dürr, Munich
Firstenberg, Peyronel, Liang, Gorshkov, Lukin, Vuletic (2013);
Peyronel, Firstenberg, Liang, Hofferberth, Gorshkov, Pohl, Lukin, Vuletic (2012);
Parigi, Bimbard, Stanojevic, Hilliard, Nogrette, Tualle-Brouri, Ourjoumtsev, Grangier (2012);
Dudin and Kuzmich, (2012);
Pritchard, Maxwell, Gauguet, Weatherill, Jones, Adams (2010);

S. Hofferberth (Stuttgart)
O. Firstenberg (Weizmann)
J. Simon (Chicago)

Interacting Rydberg slow light polaritons

(Firstenberg et al 2013)

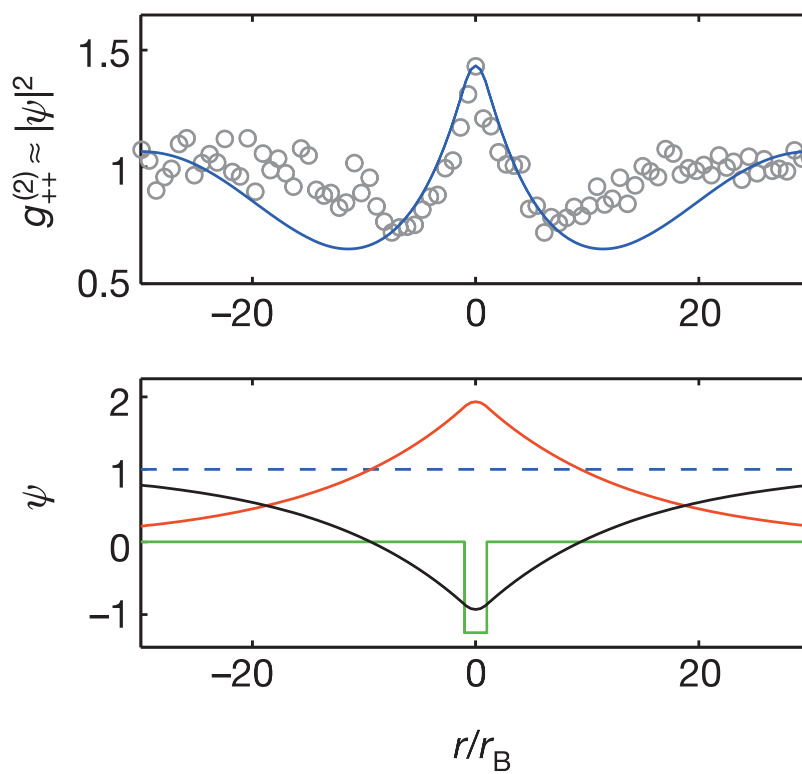


Photonic bound state

- low intensity coherent light on EIT resonance

- two-photon correlations after the media

characteristic correlations as expected for a bound state

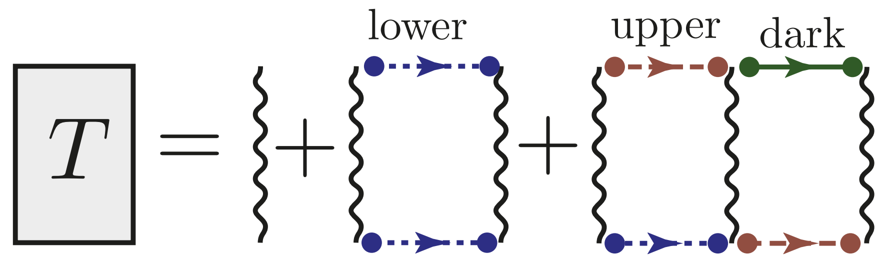


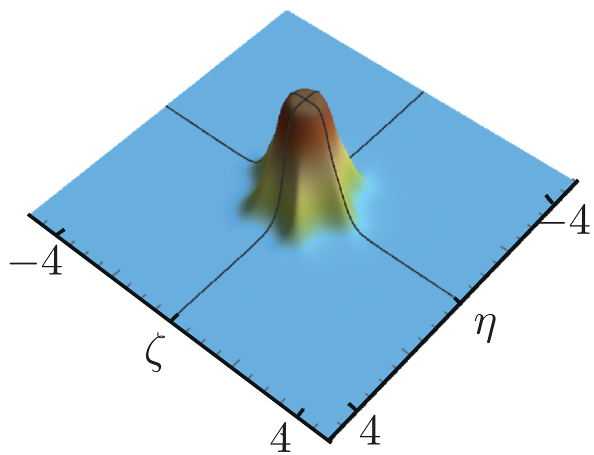
Theorie: - full numerical simulations for two photons
- approximative equation derived by comparison with full solution

Outline

Many-body theory

- microscopic derivation
- two-photon: bound states
  and scattering states



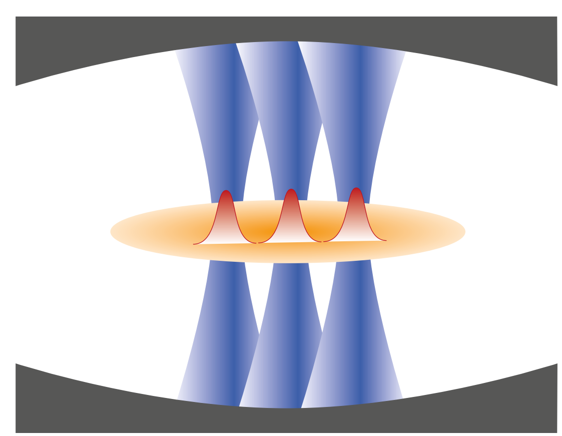


Three-body interactions

- demonstration of strong influence

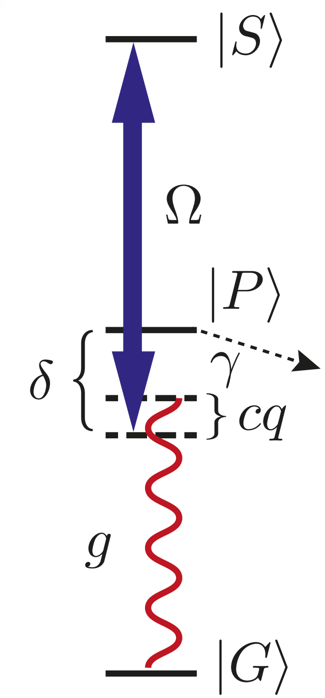
Applications

- extension into two-dimensions
- multi-mode cavity
- phase gates



Microscopic Hamiltonian

- restriction to a single transverse mode
- continuous distribution of atoms
- photonic density much smaller than atomic density



kinetic energy for photons

$$H_0 = \hbar \int dz \begin{pmatrix} \psi_e^\dagger \\ \psi_p^\dagger \\ \psi_s^\dagger \end{pmatrix} \begin{pmatrix} -ic\partial_z & g & 0 \\ g & \Delta & \Omega \\ 0 & \Omega & 0 \end{pmatrix} \begin{pmatrix} \psi_e \\ \psi_p \\ \psi_s \end{pmatrix}$$

- rotating frame and rotating wave approximation
- chiral photonic field

➡ no back scattering as spatial variations are smooth on the photonic wave length

- collective coupling: $g = g_0 \sqrt{n}$ — atomic density
- detuning: $\Delta = \delta - i\gamma$ — decay from p-level

$\psi_e^\dagger(z)$: photon creation operator with transverse mode

$$u_\perp(\mathbf{x}) e^{ik_c z}$$

$\psi_p^\dagger(z)$: creation operator for the excitation into p-level

$\psi_s^\dagger(z)$: creation operator for the excitation into s-level

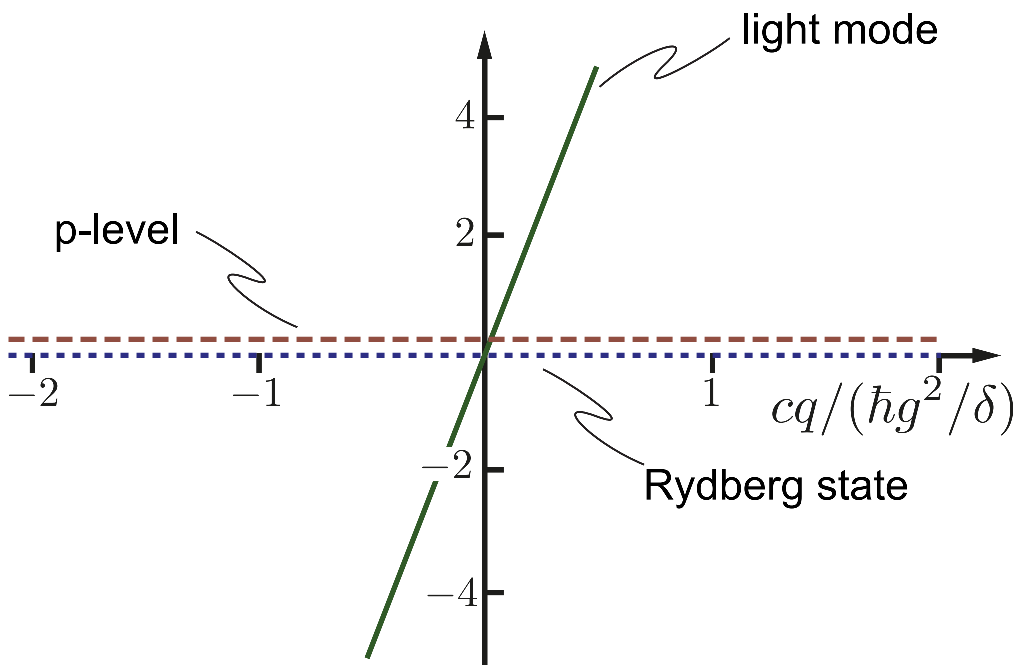
Hamiltonian

Non-interacting polaritons

$$H_0 = \hbar \int dz \begin{pmatrix} \psi_e^\dagger \\ \psi_p^\dagger \\ \psi_s^\dagger \end{pmatrix} \begin{pmatrix} -ic\partial_z & g & 0 \\ g & \Delta & \Omega \\ 0 & \Omega & 0 \end{pmatrix} \begin{pmatrix} \psi_e \\ \psi_p \\ \psi_s \end{pmatrix}.$$

$$H_0 = \sum_{q,\alpha\in 0,\pm 1} \epsilon_{\alpha q} \tilde{\psi}^\dagger_{\alpha q} \tilde{\psi}_{\alpha q}$$

$$\tilde{\psi}_{\alpha q} = \sum_{\beta \in \{e,p,s\}} U_\alpha^\beta(q) \psi_{\beta q}$$



- dispersion for slow light polariton

$$\epsilon_0 = v_g q + \frac{\hbar^2}{2m} q^2 + \dots$$

slow light velocity: $$v_g = \frac{\Omega^2}{g^2 + \Omega^2} c$$

effective mass: $$m = \hbar \frac{(g^2 + \Omega^2)^3}{2c^2 g^2 \Delta \Omega^2}$$

Hamiltonian

Non-interacting polaritons

$$H_0 = \hbar \int dz \begin{pmatrix} \psi_e^\dagger \\ \psi_p^\dagger \\ \psi_s^\dagger \end{pmatrix} \begin{pmatrix} -ic\partial_z & g & 0 \\ g & \Delta & \Omega \\ 0 & \Omega & 0 \end{pmatrix} \begin{pmatrix} \psi_e \\ \psi_p \\ \psi_s \end{pmatrix}.$$

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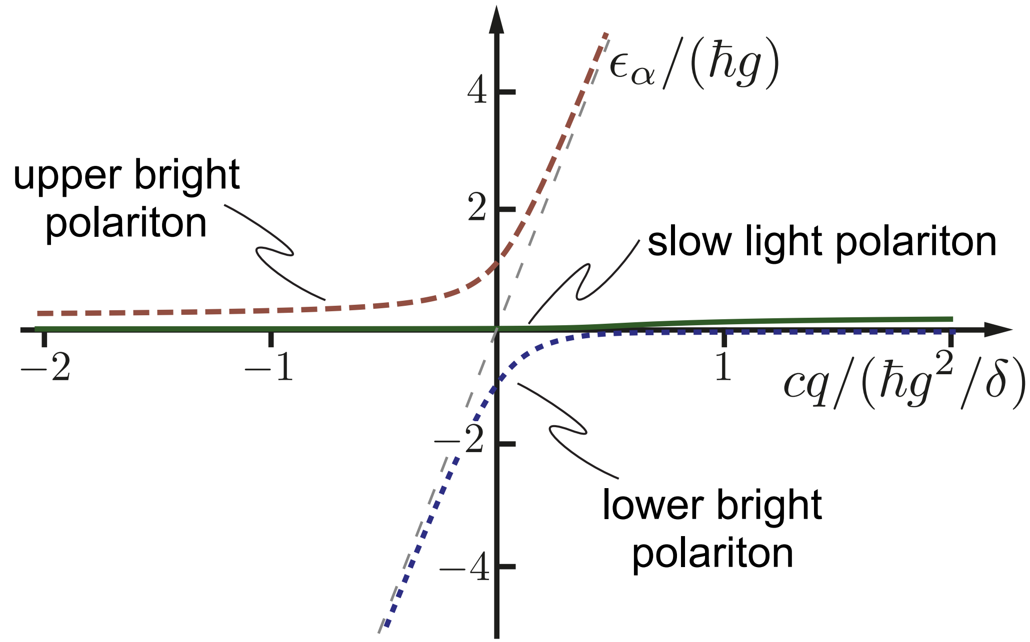

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Microscopic Hamiltonian

Interaction Hamiltonian

- strong van der Waals interaction between Rydberg atoms

$$V(z) = \frac{C_6}{z^6}$$

: attractive as well as repulsive interactions are possible

$$H_{\mathrm{int}} = \frac{1}{2}\int dz dz' V(z-z')\psi_s^\dagger(z)\psi_s^\dagger(z')\psi_s(z')\psi_s(z)$$

$$H = H_0 + H_{\mathrm{int}}$$

: three bosonic fields with quartic interaction

: energy and momentum conservation

: broken Galilei/Lorenz invariance

Goal

Is there a many-body theory
for slow light polaritons alone?

Two-polariton problem

- scattering properties
- two-photon bound states

- effective interaction potential
- pseudo-potential for slow light polaritons
- many-body theory in dilute regime
- three-body interactions as small correction

In analogy:

- interactions in cold atoms are determined by s-wave scattering length

$$V_{\mathrm{eff}}(r) = \frac{4\pi\hbar^2 a_s}{m}\delta(r)\partial_r r$$

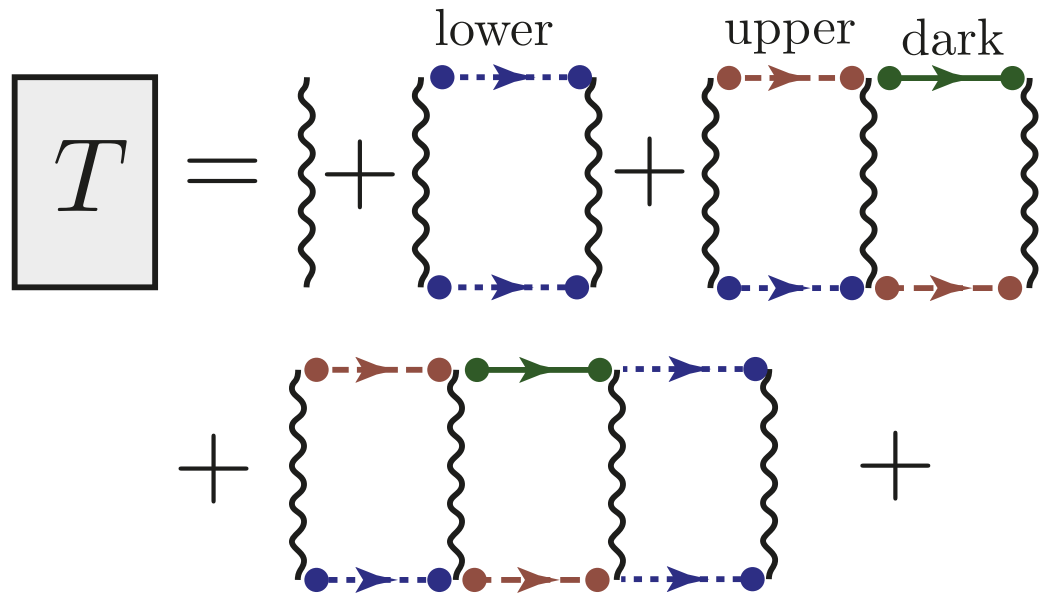
Two-body problem

Two-body probem

- general equation involves
  9 wave functions

$$\psi_{\alpha\beta}(z,z') \quad \alpha,\beta \in \{e,p,s\}$$

- fixed energy and center
  of mass momentum: $\hbar\omega \quad \hbar K$



- T-matrix for the Rydberg part:
  resummation of all ladder diagrams

$$T_{kk'}(K,\omega) = V_{k-k'} + \int \frac{dq}{2\pi} V_{k-q}\, \chi_q(K,\omega) T_{qk'}(K,\omega)$$

- two-particle propagator

$$\chi_q\,(K,\omega) = \sum_{\alpha,\beta\in\{0,\pm1\}} \frac{\bar{U}_s^{\alpha}(p) U_\alpha^s(p) \bar{U}_s^{\beta}(p') U_\beta^s(p')}{\hbar\omega - \epsilon_\alpha(p) - \epsilon_\beta(p') + i\eta},$$

$$p = K/2 + q$$
$$p' = K/2 - q$$

Two-particle propagator

General behavior

$$\chi_q = \bar{\chi} + \frac{\alpha}{\hbar\bar{\omega} - \hbar^2 q^2/m + i\eta} + \frac{\alpha_{\rm B}}{\hbar\bar{\omega}_{\rm B} - \hbar^2 q^2/m + i\eta}$$

- saturation for large relative momenta

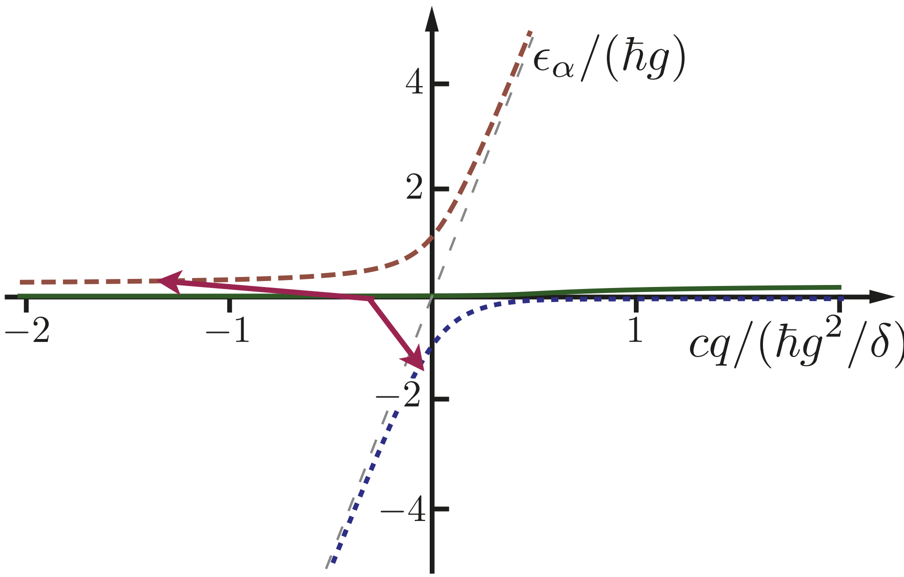
$$\bar{\chi}(\omega) = \frac{1}{\hbar} \frac{\Delta - \frac{\omega}{2} - \frac{\Omega^2}{\Delta - \omega}}{\omega\left(\Delta - \frac{\omega}{2}\right) + 2\Omega^2}$$

- pole for propagation of slow light polariton:

$$\bar{\omega}(K,\omega) \qquad \alpha(K,\omega)$$

- resonant excitation into two bright polaritons

$$\bar{\omega}_{\rm B}(K,\omega) \quad \alpha_{\rm B}(K,\omega)$$



Two-particle propagator

$$\chi_q = \bar{\chi} + \frac{\alpha}{\hbar\bar{\omega} - \hbar^2 q^2/m + i\eta} + \frac{\alpha_{\rm B}}{\hbar\bar{\omega}_{\rm B} - \hbar^2 q^2/m + i\eta}$$

Effective interaction potential

- T-matrix equation

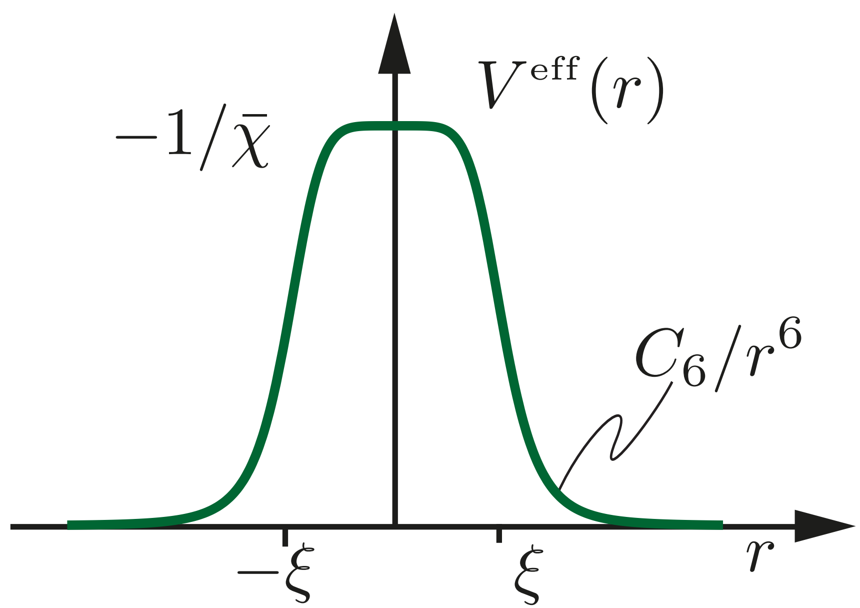
$$\begin{aligned} T_{kk'}(K,\omega) &= V_{k-k'} + \int \frac{dq}{2\pi} V_{k-q}\, \chi_q(K,\omega) T_{qk'}(K,\omega) \\ &= V^{\rm eff}_{k-k'} + \int \frac{dq}{2\pi} V^{\rm eff}_{k-q}\, \left[\chi_q(K,\omega) - \bar{\chi}(\omega)\right] T_{qk'}(K,\omega) \end{aligned}$$

Two-particle propagator

$$\chi_q = \bar{\chi} + \frac{\alpha}{\hbar\bar{\omega} - \hbar^2 q^2/m + i\eta} + \frac{\alpha_{\rm B}}{\hbar\bar{\omega}_{\rm B} - \hbar^2 q^2/m + i\eta}$$

Effective interaction potential

$$V^{\rm eff}(r) = \frac{V(r)}{1 - \bar{\chi}(\omega)V(r)}$$

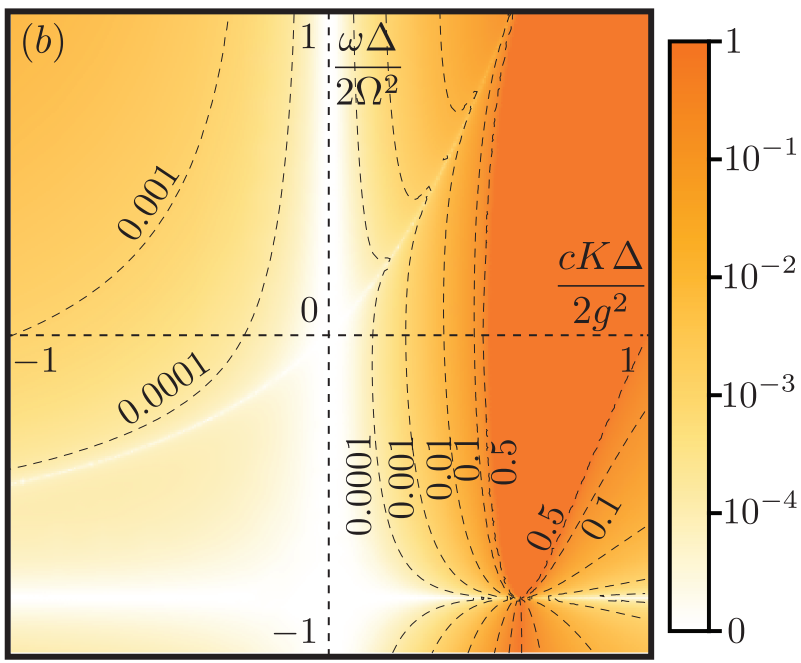


saturation on the blockade radius $\xi = (|C_6|\bar{\chi})^{1/6}$

resonance feature for two-Rydberg excitations possible

Two-particle propagator

$$\chi_q = \bar{\chi} + \frac{\alpha}{\hbar\bar{\omega} - \hbar^2 q^2/m + i\eta} + \frac{\alpha_{\mathrm{B}}}{\hbar\bar{\omega}_{\mathrm{B}} - \hbar^2 q^2/m + i\eta}$$



$$\zeta(K,\omega) = \sqrt{|(\bar{\omega}\alpha_{\mathrm{B}}^2)/(\bar{\omega}_{\mathrm{B}}\alpha^2)|}$$

Influence of resonant excitation into bright polaritons

- second pole vanishes for

  - low momenta and energy regime
  - far detuning $\Omega \ll |\Delta|$

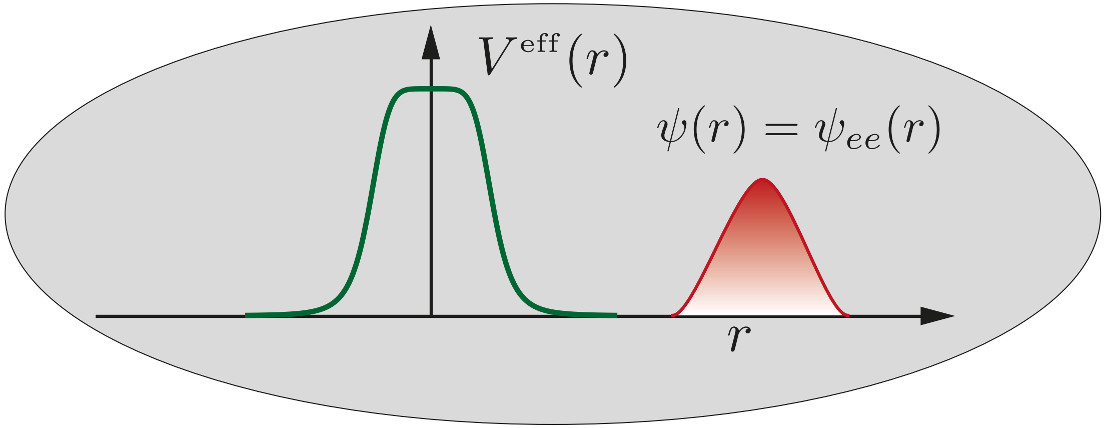
- extremely small for many experimentally relevant regimes

Effective Schrödinger equation

Effective Schrödinger equation

- wave function two polaritons

- Schrödinger equation for two-polariton wave function



$$\hbar\bar{\omega}\psi(r) = \left[-\frac{\hbar^2}{m}\partial_r^2 + \alpha V_{\text{eff}}(r)\right]\psi(r)$$

on-shell condition

massive particles

overlap of polaritons into Rydberg state

effective interaction

- parameters depend on total energy and center of mass $\bar{\omega}(K,\omega)$ $\alpha(K,\omega)$

Low energy and momentum regime

Interaction strength: ξ/λ

$\lambda = \sqrt{|\hbar^2\bar{\chi}/(\alpha m)|}$ de-Broglie wavelength

$\xi = (|C_6\bar{\chi}|)^{1/6}$ blockade radius

Scattering properties

- weak interactions

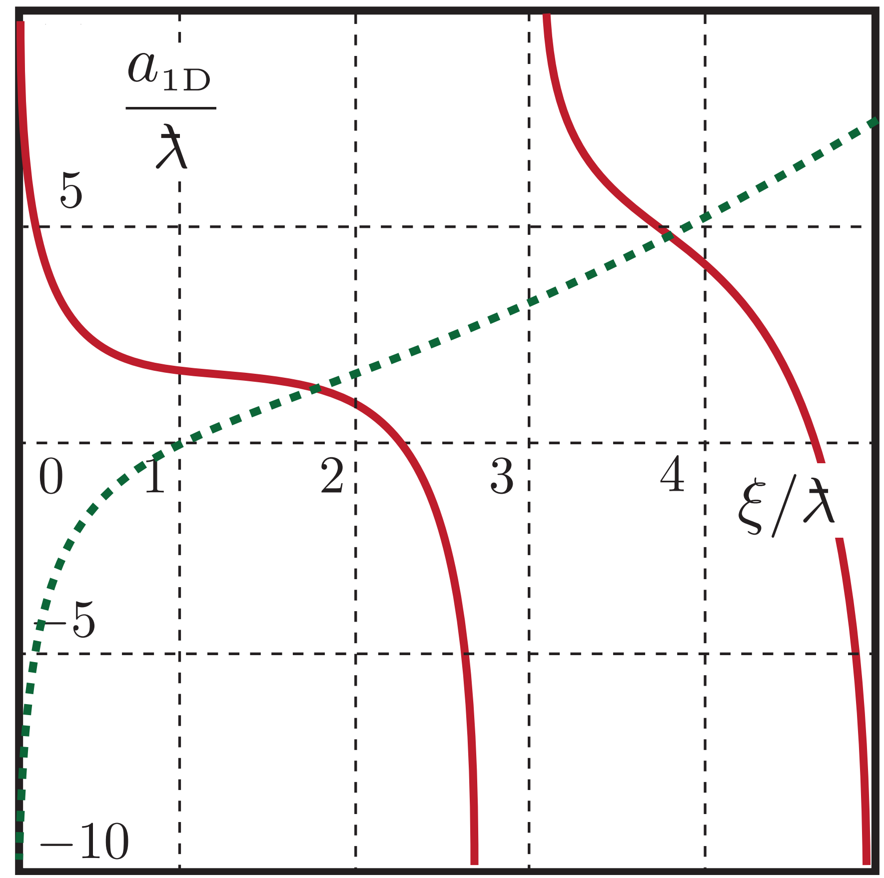
$$a_{1D} = \frac{3}{\pi}\left(-\frac{\bar{\chi}^5}{C_6}\right)^{1/6}\frac{\hbar^2}{\alpha m}$$

- repulsive interaction

  zero crossing for the
  1D scattering length

- attractive interaction

  scattering resonances
  for each additional bound
  state appearing



"universal" low energy scattering length

Far detuned regime $(\Omega \ll |\Delta|)$

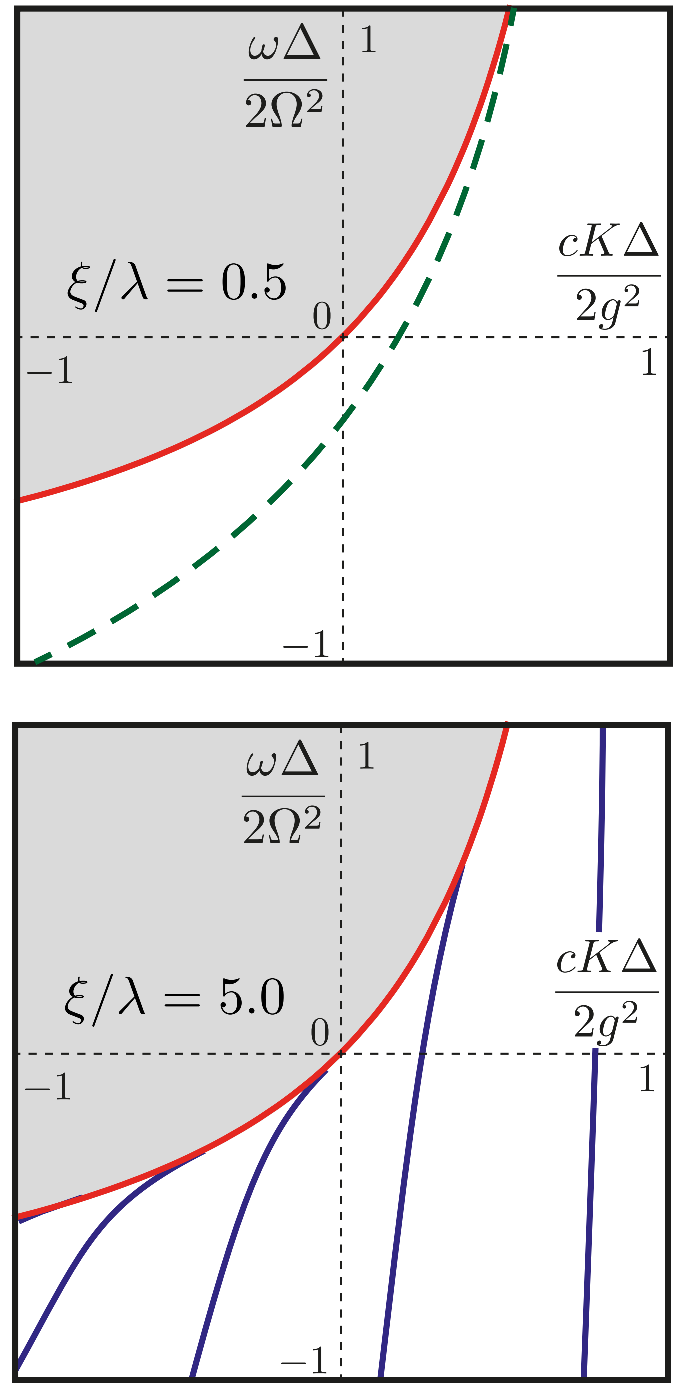
Bound state structure

- bound state energy depends on interaction strength and center of mass momentum

- requires self-consistent evaluation

- appearance of several bound states

- bound states have a higher group velocity higher than



Many-body theory

Effective theory for Rydberg slow light polaritons

kinetic energy

$$H = \int dx \psi^\dagger \left(-i\hbar v_g \partial_z - \frac{\hbar^2}{2m}\partial_z^2 \right)\psi$$

$$+\frac{1}{2}\int dx dy \, V^{\rm eff}(x-y)\psi^\dagger(x)\psi^\dagger(y)\psi(y)\psi(x) + \ldots$$

two-body interaction

higher body interactions

Validity:

- low energy and momentum regime
- three-body interaction
  - suppressed for weak interactions: $\xi/\lambda \ll 1$
  - suppressed in dilute regime: $n_d \xi \ll 1$

- Lieb-Liniger model $a_{1\rm D} < 0$
- Super Tonks-Girardeau $a_{1\rm D} > 0$

Many-body theory

Experimental probe
of many-body interactions?

parameter regime, where mass
can be negelected

$$H = \int dx \psi^\dagger \left(-i\hbar v_g \partial_z - \frac{\hbar^2}{2m}\partial_z^2 \right) \psi$$

$$+ \frac{1}{2} \int dx dy\, V^{\text{eff}}(x-y) \psi^\dagger(x) \psi^\dagger(y) \psi(y) \psi(x) + \ldots$$

two-body interaction

higher body
interactions

Exact solvable theory for
arbitrary input
(Bienias, HPB, arXiv 2016)

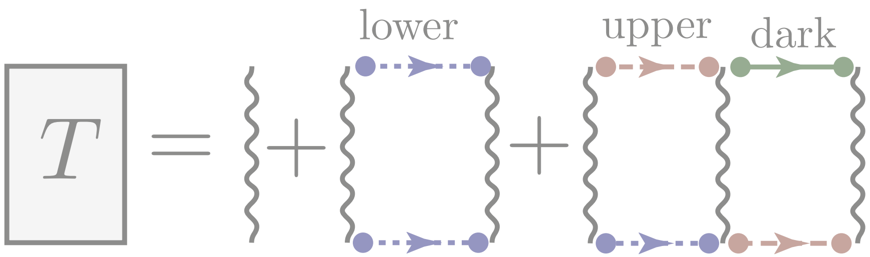
- two photon solution

$$\phi^{\text{out}}(x,y,t) = e^{-i\varphi(x-y)} \phi^{\text{in}}(x-ct', y-ct')$$

- effective interaction
  accessible in homodyne
  detection

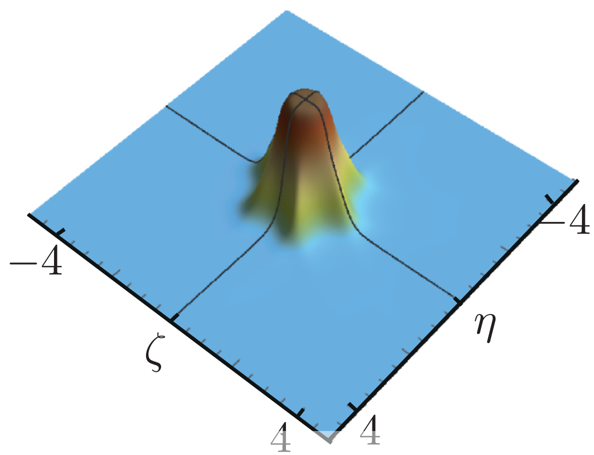
$$\varphi(u) \quad = \quad \frac{1}{\hbar c} \int_{-\infty}^{\infty} dw\, \tilde{n}(w+u) \tilde{n}(w) \tilde{V}(w+u, w)$$

Outline



Many-body theory

- microscopic derivation
- two-photon: bound states and scattering states



Three-body interactions

- demonstration of strong influence

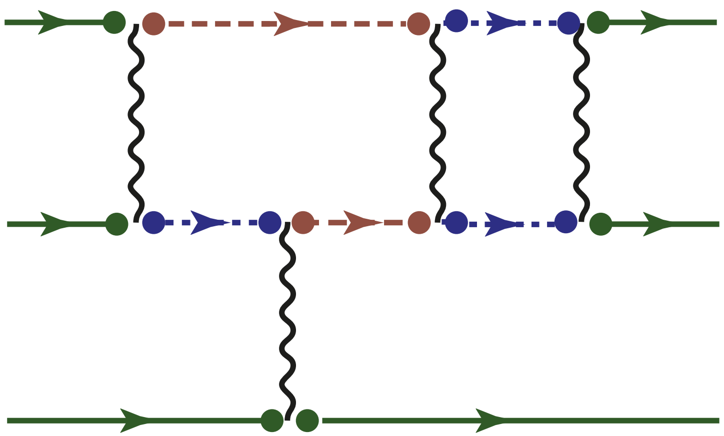
Applications

- extension into two-dimensions
- multi-mode cavity
- phase gates

Three-body interactions

(Jachymski, Bienas, HPB, PRL 2016; see also Gullans et al, PRL 2016)

Simple estimation of interaction strength inside the blockade radius: (far detuned regime $|\Delta \gg \Omega|$)



Probablity to find 1 Rydberg state and (n-1) Photons: $$n g^2 \frac{\Omega^{2(n-1)}}{(g^2+\Omega^2)^n}$$

Dispersive energy shift of a photon inside the blockade regime: $$-\frac{\hbar g^2}{\Delta}$$

Total dispersive energy shift: $$-\frac{\hbar g^2}{\Delta}\ (n-1)\ n g^2 \frac{\Omega^{2(n-1)}}{(g^2+\Omega^2)^n}$$

Two-body: $$-\frac{2\hbar\Omega^2}{\Delta}\frac{g^4}{(\Omega^2+g^2)^2}$$

Three-body interactions: $$-\frac{6\hbar\Omega^2}{\Delta}\frac{\Omega^2 g^4}{(\Omega^2+g^2)^3} + 3\frac{2\hbar\Omega^2}{\Delta}\frac{g^4}{(\Omega^2+g^2)^2} = \frac{6\hbar\Omega^2}{\Delta}\frac{g^6}{(\Omega^2+g^2)^3}$$

repulsive and very strong for slow light polaritons

Single mode cavity

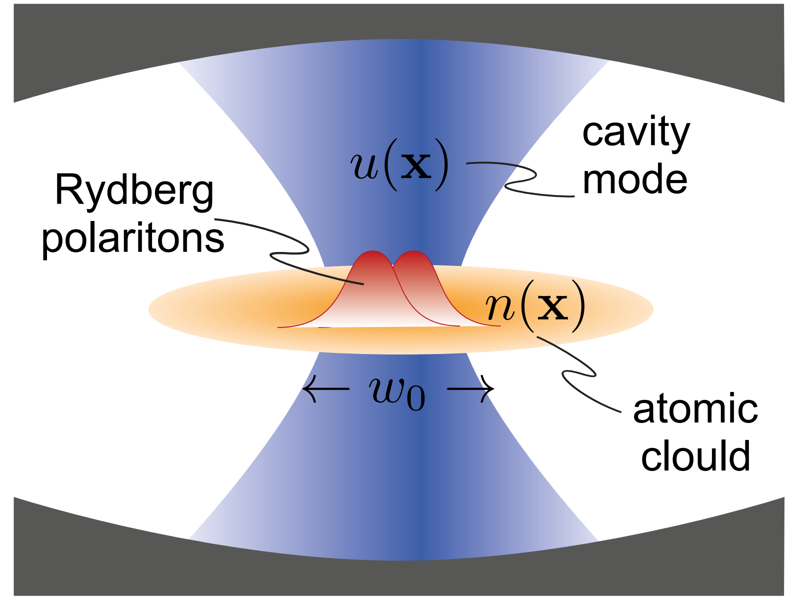
Energy shift for two polaritons in a cavity

- large cavity mode: $w_0 \gg \xi$

$$\Delta E = \int d\mathbf{x}d\mathbf{y}\, |h(\mathbf{x})|^2\, |h(\mathbf{y})|^2\, V^{(2)}_{\text{eff}}(\mathbf{x}-\mathbf{y})$$

polariton wave function: $h(\mathbf{x}) = \sqrt{n(\mathbf{x})}u(\mathbf{x})$

Effective interaction



$$\alpha = \frac{g^2}{\Omega^2 + g^2}$$

: Probability for the polariton in the Rydberg state

$$V^{(2)}_{\text{eff}}(\mathbf{x}) = \alpha^2 \frac{V(\mathbf{x})}{1-\bar{\chi}V(\mathbf{x})}$$

Derivation

- two photon wave function
- set of coupled equations
- expansion in small energy shift

$$\omega\phi_0 = -2\nu\phi_0 + \int dx\, \phi_1(x)h^*(x),$$

$$\omega\phi_1(x) = -(\nu + \frac{1}{\nu})\phi_1(x) + 2h(x)\phi_0 + 2\int dy\, \phi_2(x,y)h^*(y),$$

$$\omega\phi_2(x,y) = -\frac{2}{\nu}\phi_2(x,y) + \frac{h(x)\phi_1(y)+h(y)\phi_1(x)}{2} + V(x-y)\phi_2(x,y).$$

Three-body interaction

- Energy shift for three polaritons in the cavity

$$\Delta E = \int d\mathbf{x}_1 d\mathbf{x}_2 d\mathbf{x}_3 \, |h(\mathbf{x}_1)|^2 \, |h(\mathbf{x}_2)|^2 \, |h(\mathbf{x}_3)|^2 \, U(\mathbf{x}_1, \mathbf{x}_2, \mathbf{x}_3)$$

- includes two- and three-body interactions

$$U(\mathbf{x}_1, \mathbf{x}_2, \mathbf{x}_3) = \sum_{i<j} V_{\mathrm{eff}}^{(2)}(\mathbf{x}_i - \mathbf{x}_j) + V_{\mathrm{eff}}^{(3)}(\mathbf{x}_1, \mathbf{x}_2, \mathbf{x}_3)$$

- analytical expression for three-body interaction

$$V_{\mathrm{eff}}^{(3)}(\mathbf{x}_1, \mathbf{x}_2, \mathbf{x}_3) = \alpha^3 \sum_{i<j} \frac{V_3(\mathbf{x}_1, \mathbf{x}_2, \mathbf{x}_3) - V(\mathbf{x}_i - \mathbf{x}_j)}{1 - \bar{\chi} V(\mathbf{x}_i - \mathbf{x}_j)}$$

$$V_3(\mathbf{x}_1, \mathbf{x}_2, \mathbf{x}_3) = \frac{\sum_{i<j} V(\mathbf{x}_i - \mathbf{x}_j)}{3 - 2\chi \sum_{i<j} V(\mathbf{x}_i - \mathbf{x}_j)}$$

- analog derivation

$$\begin{aligned}
\omega\phi_0 &= -3\nu\phi_0 + \int dx \; \phi_1(x) h^*(x), \\
\omega\phi_1(x) &= -(2\nu + \frac{1}{\nu})\phi_1(x) + 3h(x)\phi_0 + 2\int dy \; \phi_2(x,y) h^*(y), \\
\omega\phi_2(x,y) &= -(\nu + \frac{2}{\nu})\phi_2(x,y) + h(x)\phi_1(y) + h(y)\phi_1(x) + 3\int dz \; \phi_3(x,y,z) h^*(z) + V(x-y)\phi_2(x,y), \\
\omega\phi_3(x,y,z) &= -\frac{3}{\nu}\phi_3(x,y,z) + h(z)\phi_2(x,y) + h(y)\phi_2(x,z) + h(x)\phi_2(y,z) + W(x,y,z)\phi_3(x,y,z).
\end{aligned}$$

Three-body interactions

Three body interactions

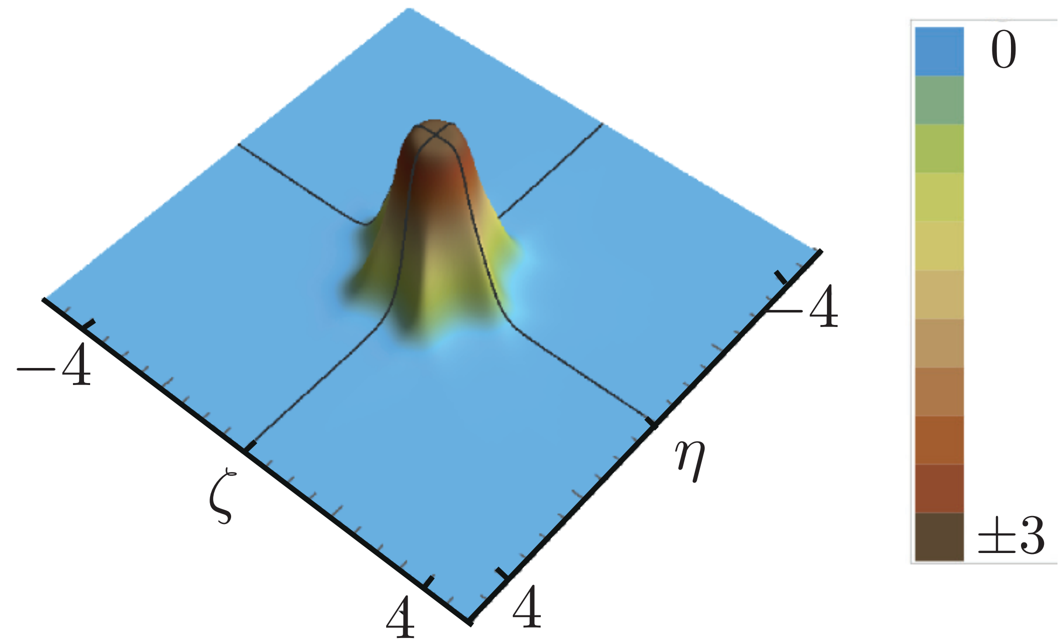
- Jacobi coordinates:

$$\eta = \frac{\mathbf{x}_1 - \mathbf{x}_2}{\sqrt{2}\,\xi}$$

$$\zeta = \frac{\sqrt{2}}{\sqrt{3}\,\xi}\left(\frac{\mathbf{x}_1 + \mathbf{x}_2}{2} - \mathbf{x}_3\right)$$

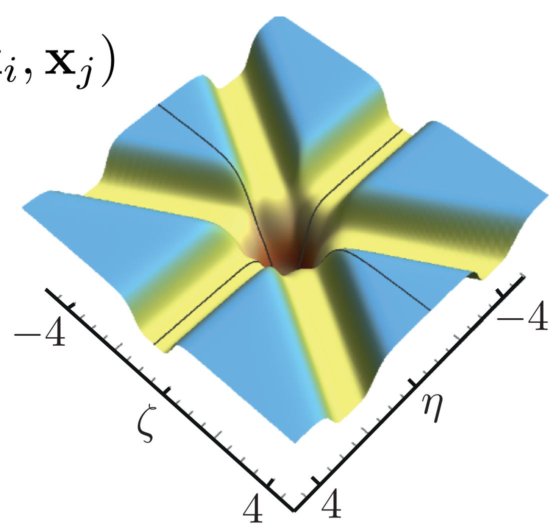
- strong repulsion inside the blockade radius

- compensates the two-body attraction for $\Omega^2 \ll g^2$



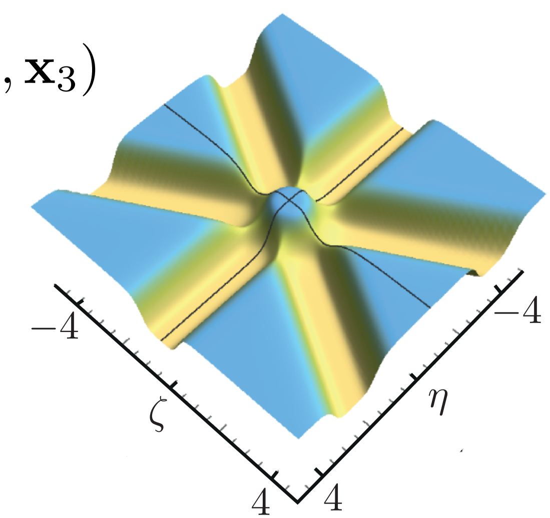
Two-body contribution

$$\sum_{i<j} V^{(2)}_{\text{eff}}(\mathbf{x}_i, \mathbf{x}_j)$$



Combined interaction

$$U(\mathbf{x}_1, \mathbf{x}_2, \mathbf{x}_3)$$



Three-body bound states

Rydberg slow light polaritons in 1D

- experimental observation of two-body bound states

- two-body interactions provide also three-body bound state (Lieb-Liniger model)

- for δ - function interaction

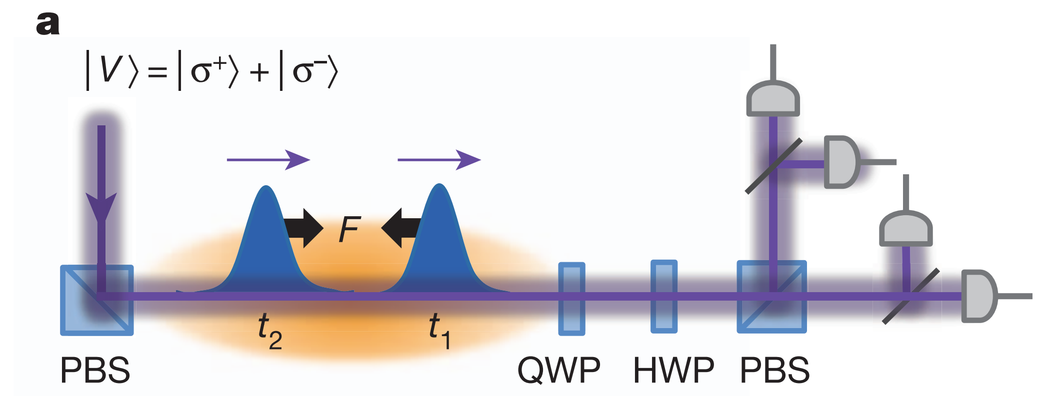
  B : two-body bound state energy

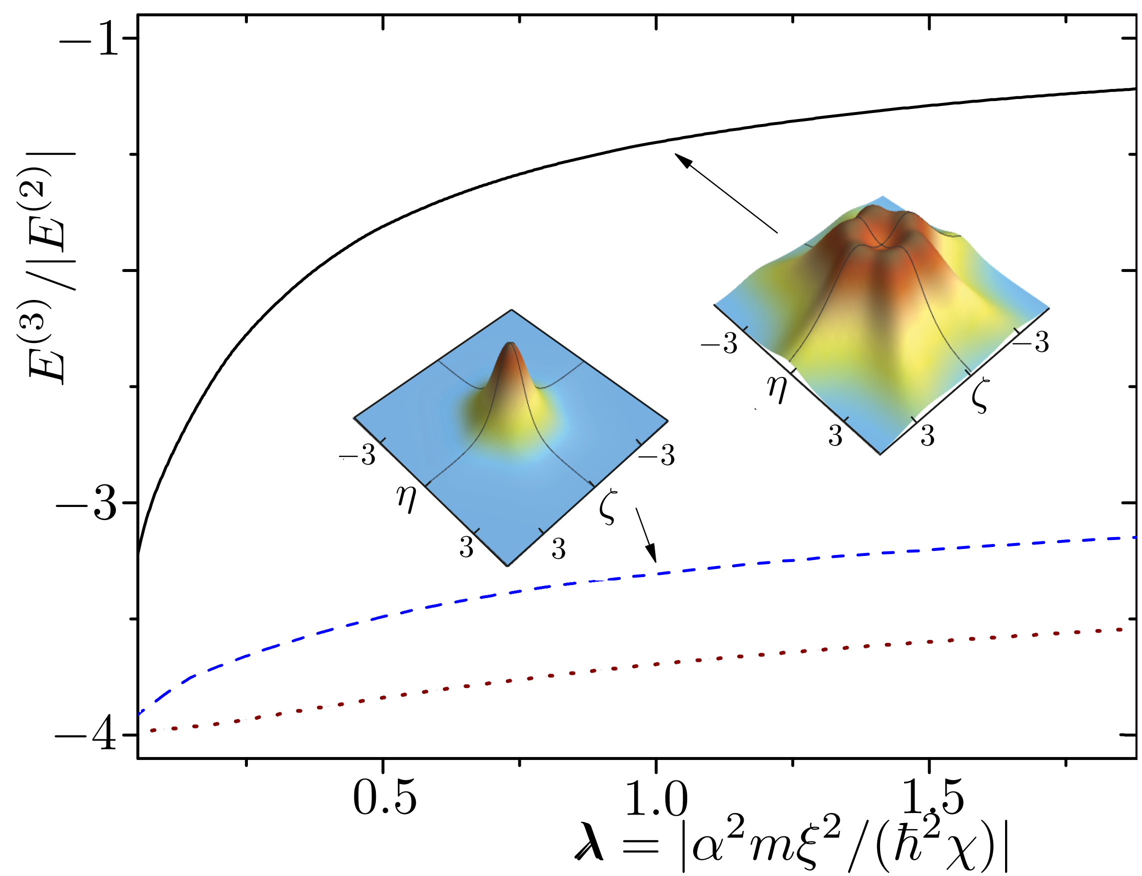
  $4B$: three-body bound state energy

- strong modifications by three-body interaction

  - three body bound state for arbitrary interacitons

  - characteristic shape on short distances due to repulsion



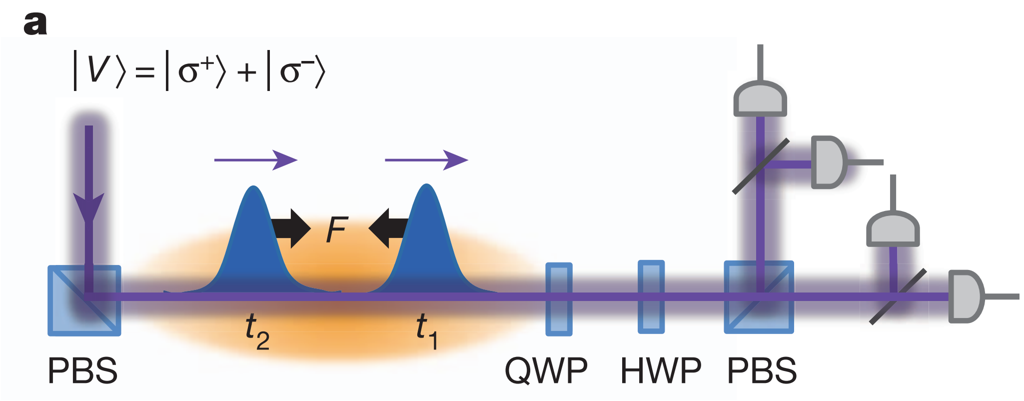


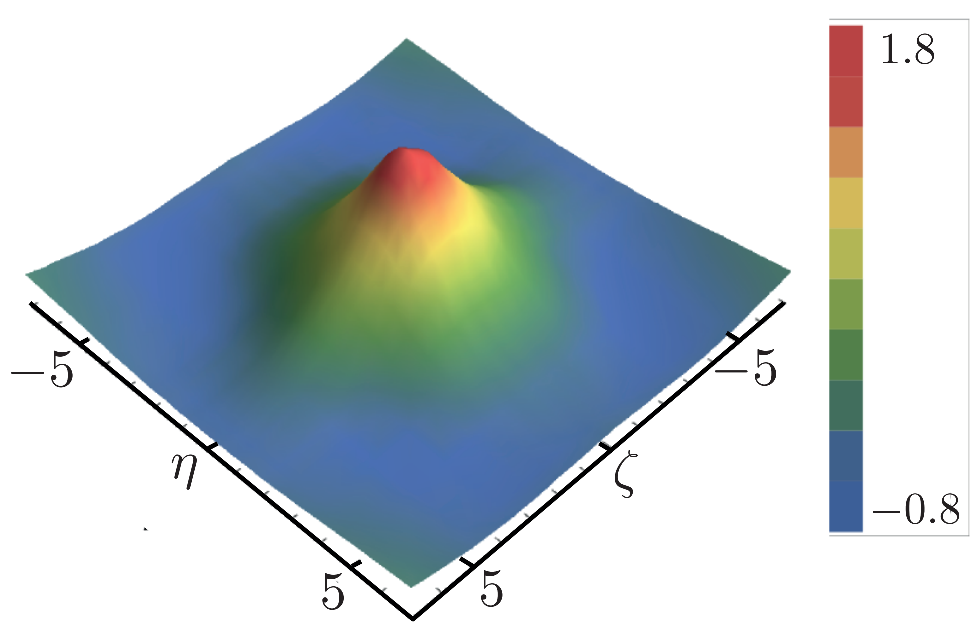
Three-body correlations

Intensity correlations for the transmitted light

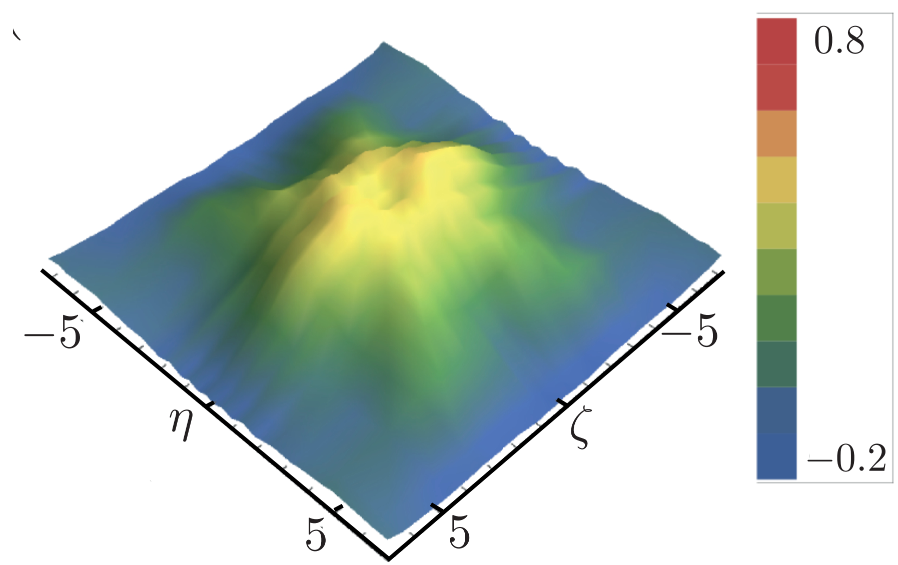
- g_2 characteristic peak for two-body bound state

- g3 characteristic behavior of the bound state in the bunching of photons





without three-body interaciton

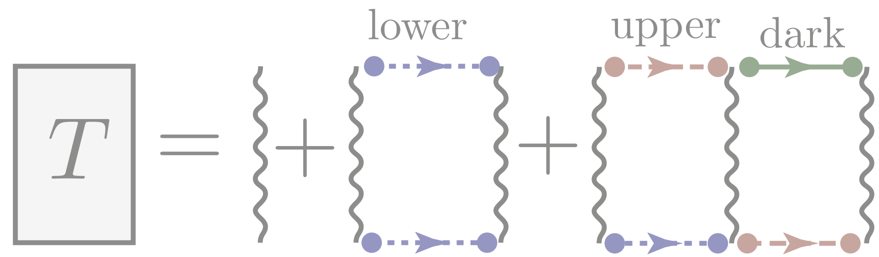


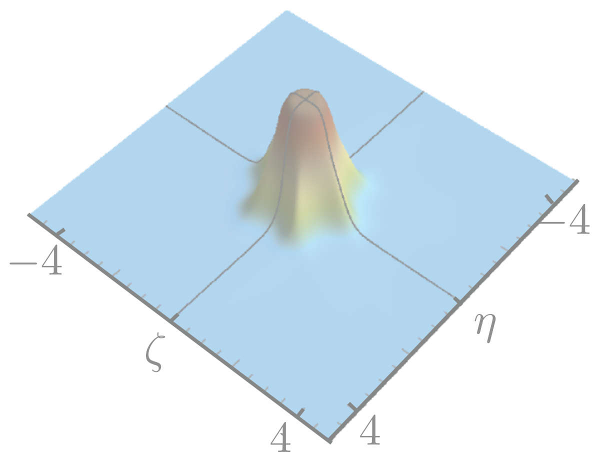
with three-body interaciton

Outline

Many-body theory

- microscopic derivation
- two-photon: bound states
  and scattering states



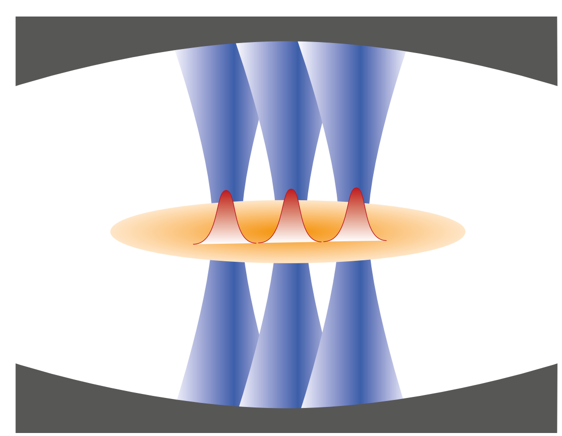


Three-body interactions

- demonstration of strong influence

Applications

- extension into two-dimensions
- multi-mode cavity
- phase gates



Extension into two dimensions

Optical multi mode cavity: - several transverse near degenerate modes

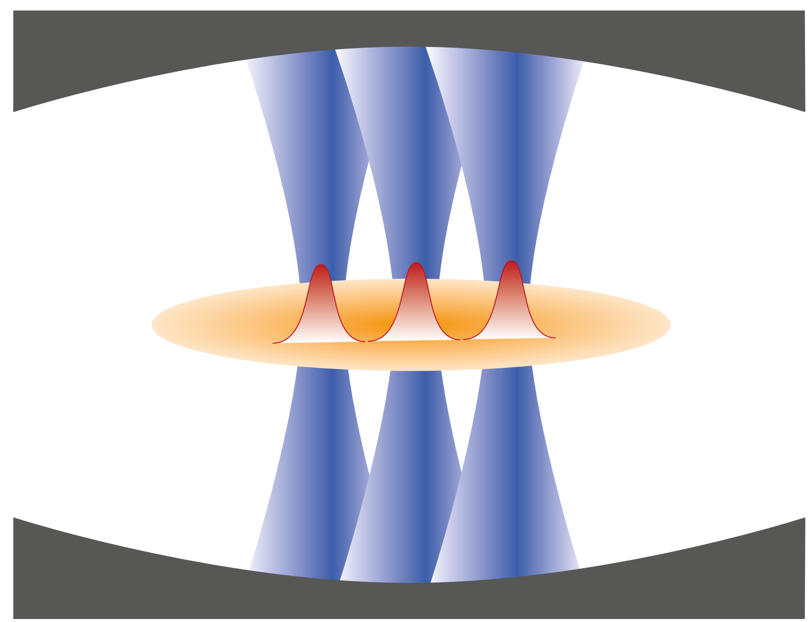
Exp: Confocal cavity
- harmonic oscillators for photons
- only even oscillator functions

- kinetic energy of the polaritons:

cavity mode spectrum reduced by slow light velocity

- interaction energy

effective interaction

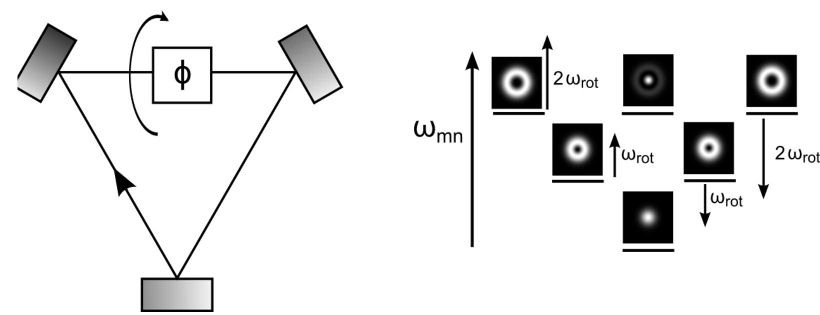


A. Sommer, H.P. Büchler, J. Simon, arXiv 2016.

Extension into two dimensions

The design of the cavity determines the kinetic energy of the photons:

Ring cavity with a phase shift



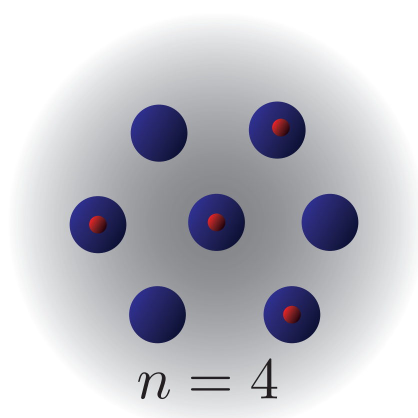
Example: Confocal cavity

- dominating interaction energy

- harmonic oscillators for photons

- only even oscillator functions

- ordered structure for strong interactions



- low energy photonic modes are Laughling states

- topological states of matter?

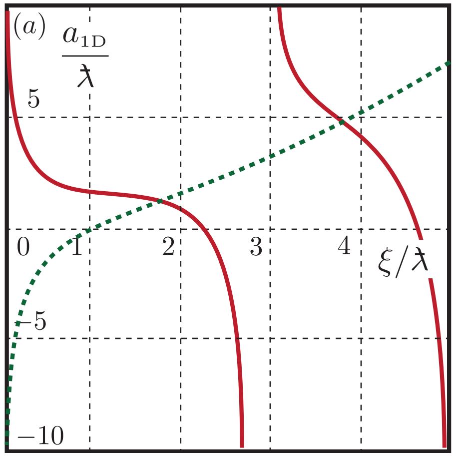
- novel states of matter?

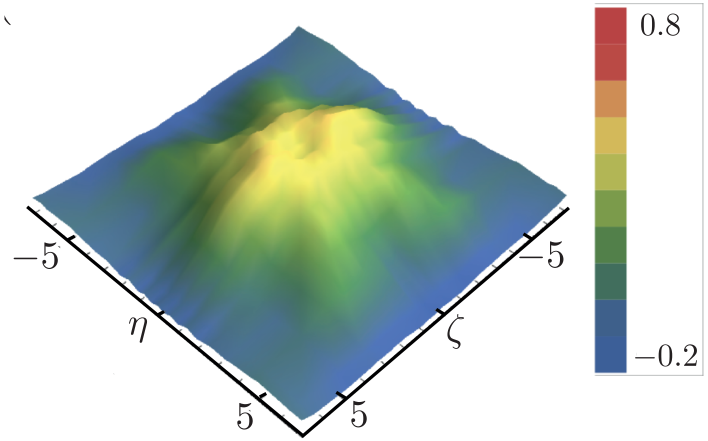
A. Sommer, H.P. Büchler, J. Simon, arXiv 2016.

Conclusions

Theoretical framework for analyzing Rydberg slow light polaritons

- effective theory for slow light polaritons alone
- two-particle properties
- low energy many-body Hamiltonian





Three-body interaction

- correction to many-body theory
- applications on bound states and correlations

Applications

- tool engineer interesting states of quantum matter in 2D