Quantum Many-Body Physics with Multimode Cavity QED

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FOUNDED 1413

SUPA®

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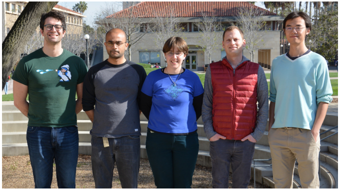
Acknowledgments

Experiment (Stanford):
Benjamin Lev



Theory:

Ben Simons (Cambridge), Joe Bhaseen (KCL), James Mayoh (Southampton)

Sarang Gopalakrishnan (CUNY)
Surya Ganguli, Jordan Cotler (Stanford)
Peter Kirton, **Kyle Ballantine**, Laura Staffini (St Andrews)

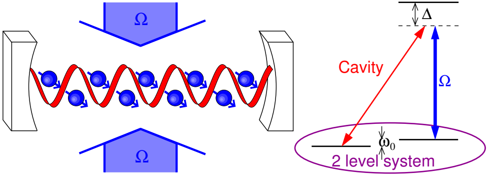
The Leverhulme Trust

EPSRC Engineering and Physical Sciences Research Council

topnes Topological Protection and Non-Equilibrium States in Strongly Correlated Electron Systems

Synthetic cavity QED: Raman driving

- Tunable coupling via Raman



$$H_{\text{eff}} = \ldots \frac{\Omega g}{\Delta}\left(\sigma_n^+ a + \text{H.c.}\right)$$

- Real systems: loss $\partial_t \rho = -i[H, \rho] + \kappa \mathcal{L}[a, \rho] + \ldots$
- To balance loss, counter-rotating:

$$H_{\text{eff}} = \ldots \frac{\Omega g}{\Delta} \sigma_n^x (a + a^\dagger)$$

[Dimer *et al.* PRA '07]

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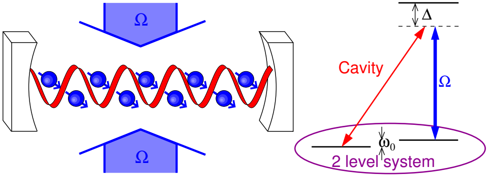

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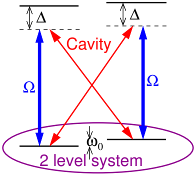

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(Multimode) cavity QED

$$H = \sum_k \omega_k a_k^\dagger a_k + \sum_n \omega_0 \sigma_n^+ \sigma_n^- + \sum_{n,k} g_{k,n}(a_k^\dagger + a_{-k})(\sigma_n^+ + \sigma_n^-)$$

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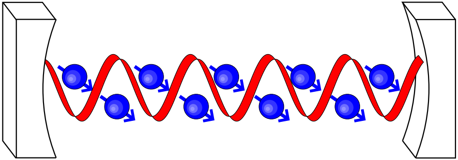
- Compare g (or $g\sqrt{N}$) vs:
  - κ, γ



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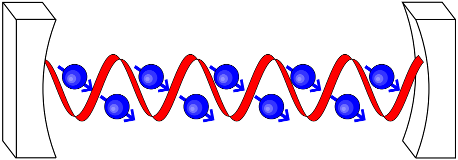

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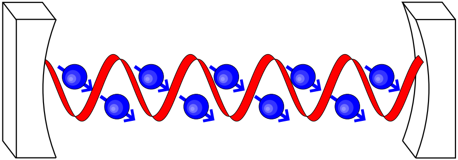
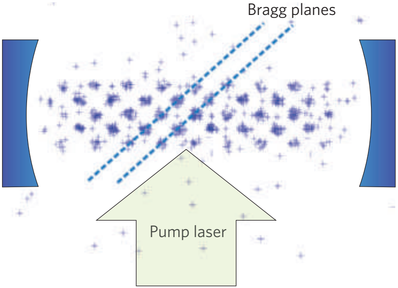


Single mode experiments



Ritsch *et al.* PRL ’02

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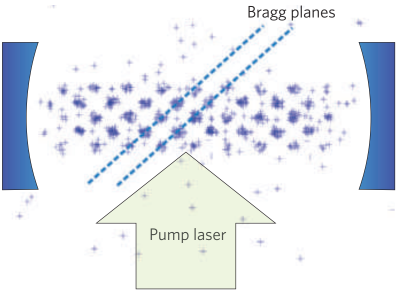

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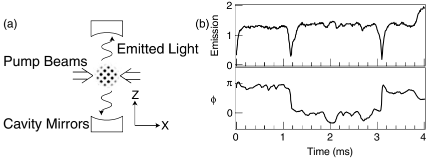
Thermal atoms, momentum state



Vuletic *et al.* PRL ’03 (MIT)

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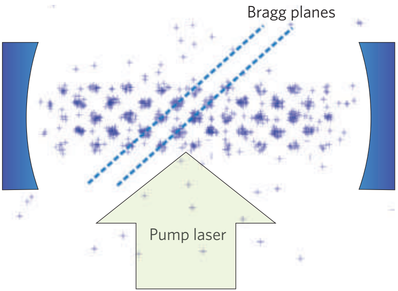

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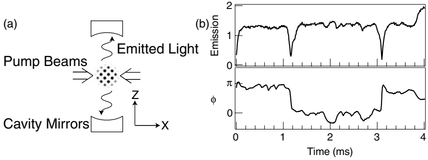

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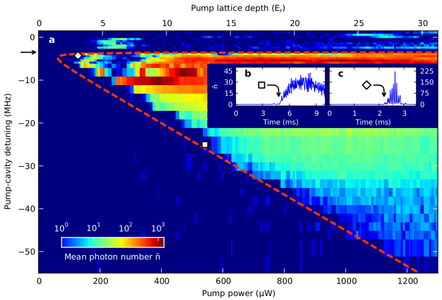

Baumann *et al.* Nature '10 (ETH)

Kinder *et al.* PRL '15 (Hamburg)

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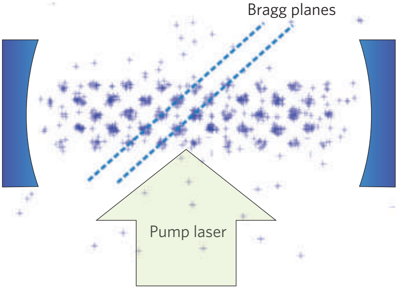

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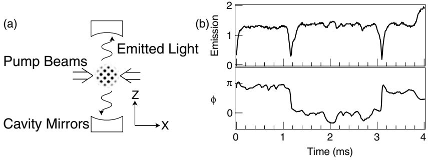

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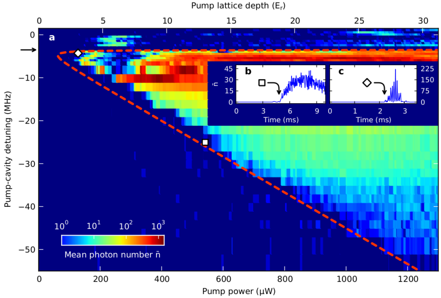

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BEC, hyperfine states

Baden *et al.* PRL '14 (Singapore)

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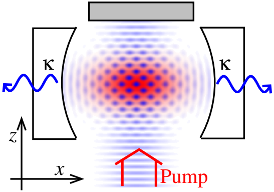
2 Spin-non-conserving loss

3 Supermode density wave polariton condensation

4 Meissner-like effect

Single mode theory



- Momentum degrees of freedom:
  $\psi = \psi_{\Downarrow} + \psi_{\Uparrow} \cos(kx)\cos(kz)$
- Effective 2LS $(\psi_{\Downarrow}, \psi_{\Uparrow})$

$$H_{\text{eff}} = \underbrace{(\omega_c - \omega_P)}_{-\Delta_c} a^\dagger a + \sum_n \frac{\omega_0}{2}\sigma_n^z + \underbrace{\frac{\Omega g_0}{\Delta}}_{g_{\text{eff}}} \sigma_n^x (a + a^\dagger)$$

- Extra "feedback" term U, cavity loss κ

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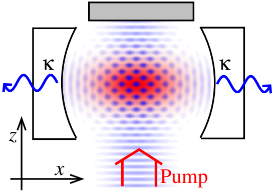

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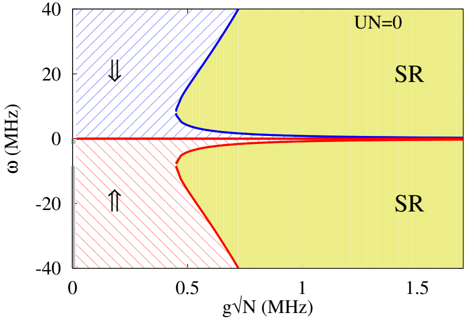
Classical dynamics

Changing U:

$U = 0$

$U < 0$

$U > 0$



[JK *et al.* PRL '10, Bhaseen *et al.* PRA '12]

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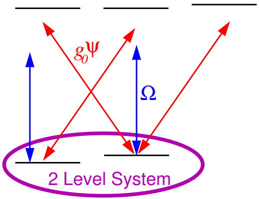
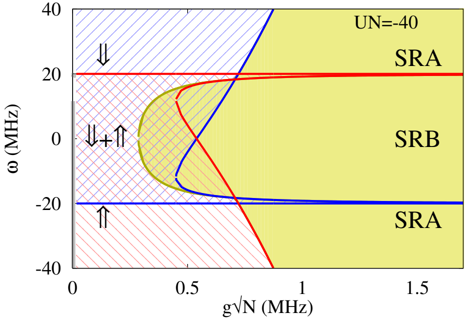


$$U \propto \frac{g_0^2}{\omega_c - \omega_a}$$



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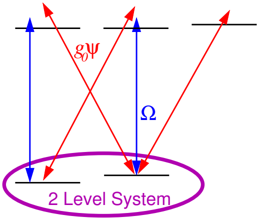

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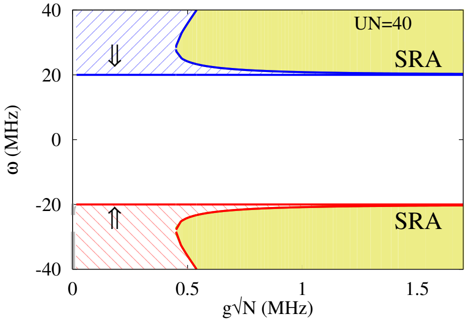

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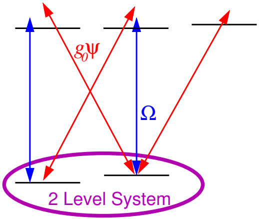

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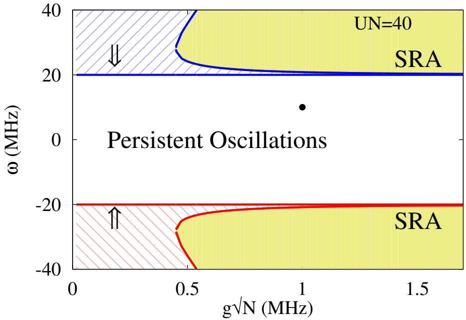

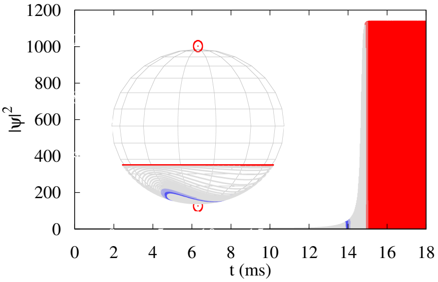

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Effect of particle losses

- Adding other loss terms

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$$\mathcal{L}[X] = X\rho X^\dagger - (X^\dagger X \rho + \rho X^\dagger X)/2$$

- $\Gamma_\downarrow, \Gamma_\phi$ break S conservation.
- Mean field: confusing result:

[Dalla Torre *et al.* , PRA (Rapid) 2016, Kirton & JK, PRL 2017]

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- Wigner function $W(\hat{a} = \hat{x} + i\hat{p})$

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- Asymptotic scaling

- $N = 30$: no symmetry breaking

[Kirton & JK, PRL 2017]

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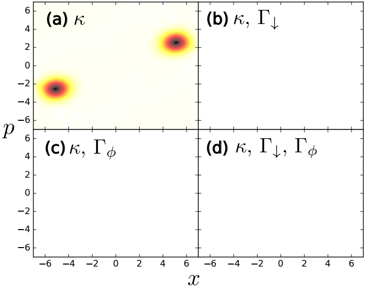

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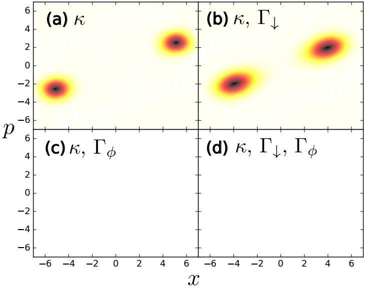

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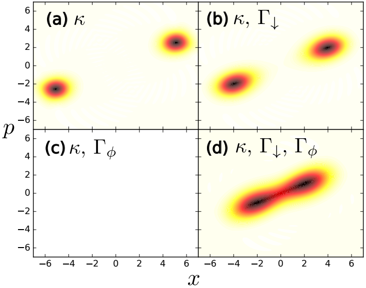

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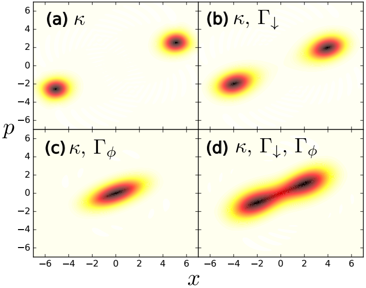

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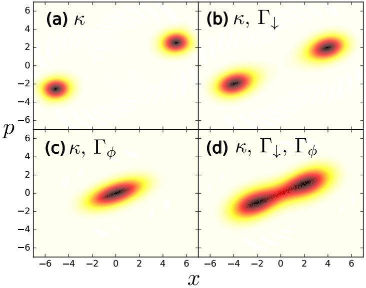

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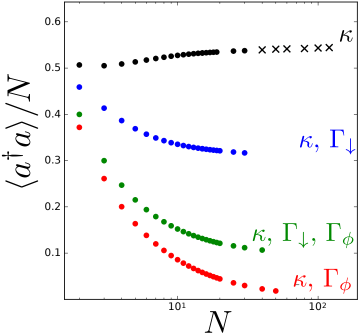

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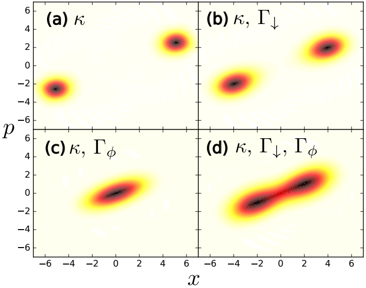

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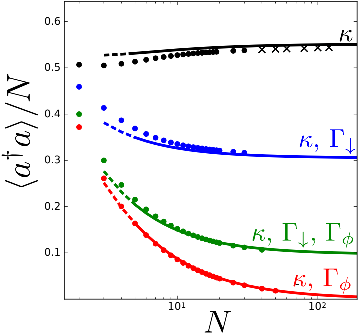

Supermode density wave polariton condensation

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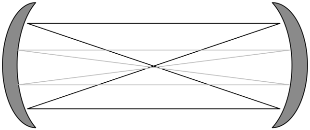
Multimode cavities

Confocal cavity $L = R$:



- Modes
  $\Xi_{l,m}(\mathbf{r}) = H_l(x)H_m(y)$,
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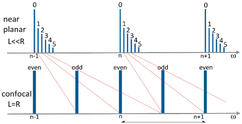
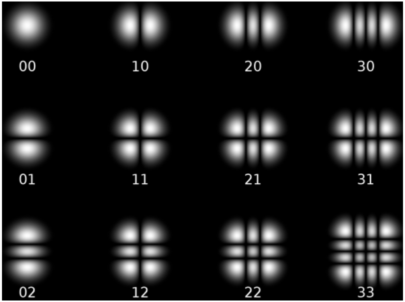


- Tune between degenerate *vs* non-degenerate



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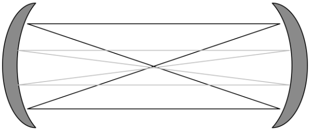

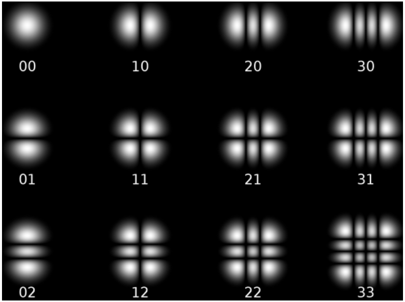

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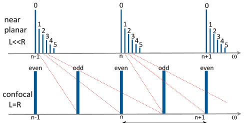

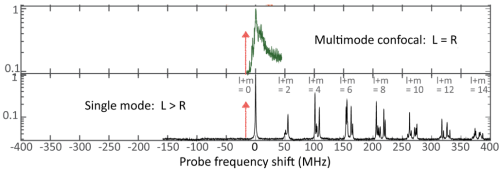

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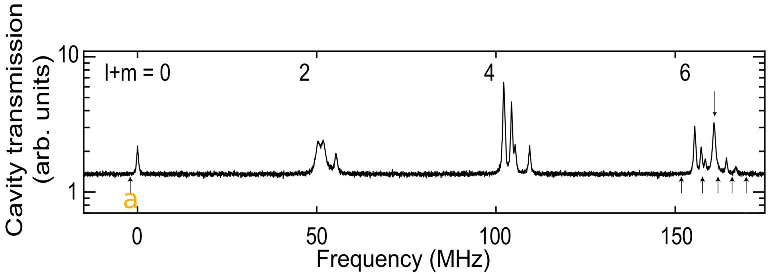
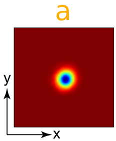
Superradiance in multimode cavity: Even family





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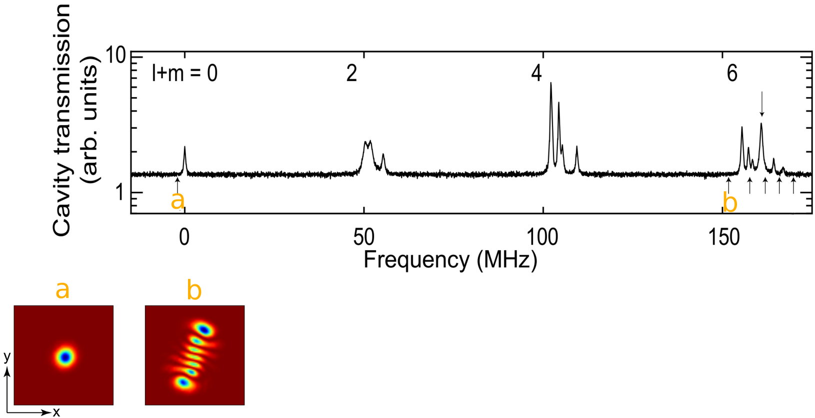

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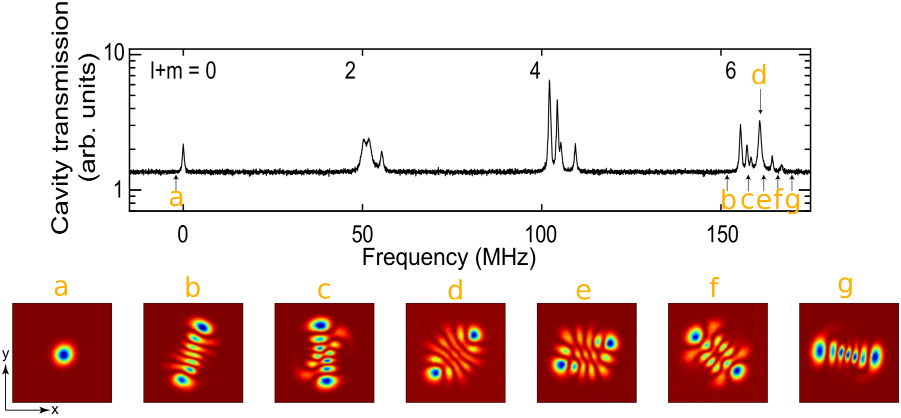
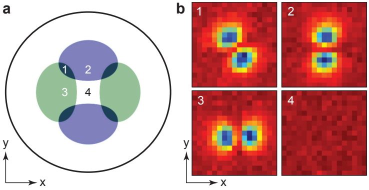


Superradiance in multimode cavity: Odd family

- Dependence on cloud position



- Atomic time-of-flight — structure factor
- Near-degeneracy of (1, 0), (0, 1) modes broken by matter-light coupling.

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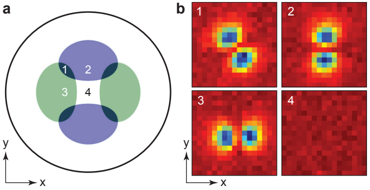

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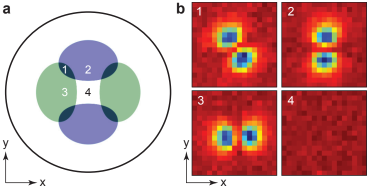

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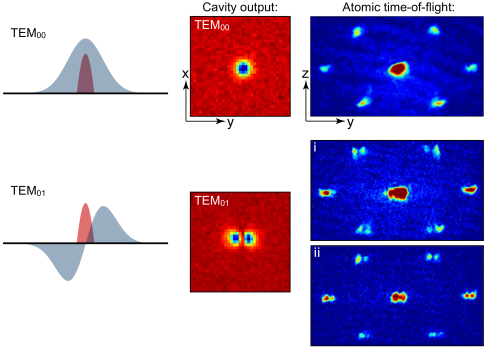


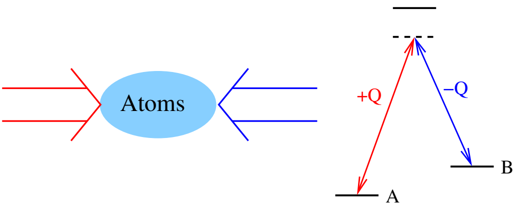
Meissner-like effect

1. Introduction: Tunable multimode Cavity QED
2. Spin-non-conserving loss
3. Supermode density wave polariton condensation
4. Meissner-like effect

Cavity QED and synthetic gauge fields

- [Spielman, PRA '09] scheme, hyperfine states A, B

$$H = \begin{pmatrix} \psi_A & \psi_B \end{pmatrix} \begin{pmatrix} E_A + (\nabla - Q\hat{x})^2 & \Omega/2 \\ \Omega/2 & E_B + (\nabla + Q\hat{x})^2 \end{pmatrix} \begin{pmatrix} \psi_A \\ \psi_B \end{pmatrix}$$



- Feedback
  - Why?
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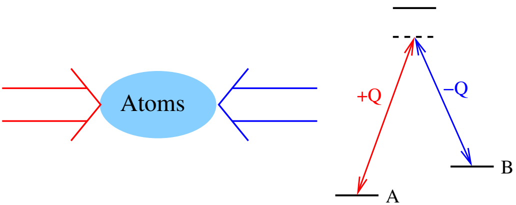

Ground state:

$$E_{-}(\mathbf{k}) \simeq \frac{(\mathbf{k} - \frac{(E_B - E_A)Q\hat{\mathbf{x}}}{\Omega})^2}{2m^*}$$

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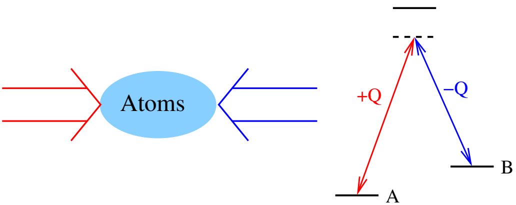

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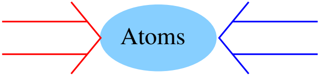

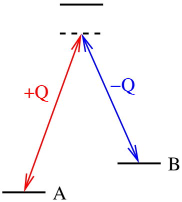

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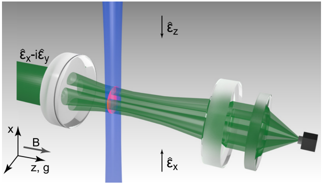

- $E_A, E_B \propto |\varphi|^2$ from cavity Stark shift
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- Multimode cQED → local matter-light coupling
- Variable profile synthetic gauge field?
- Reciprocity: matter affects field

[Ballantine *et al.* PRL 2017]

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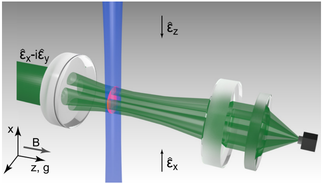

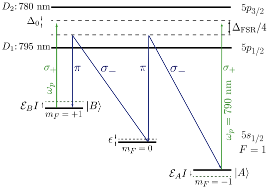

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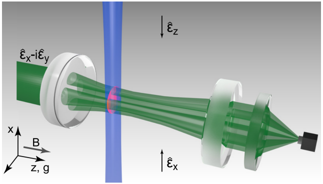

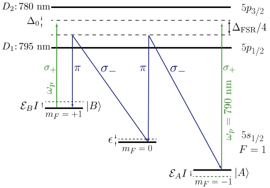

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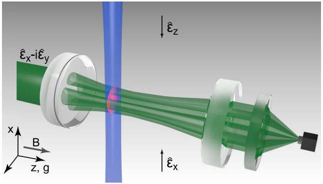

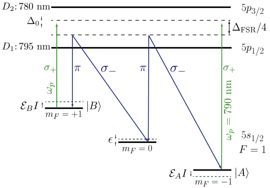

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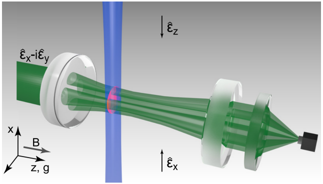

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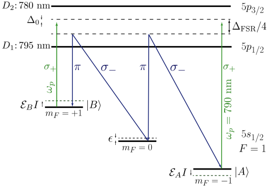

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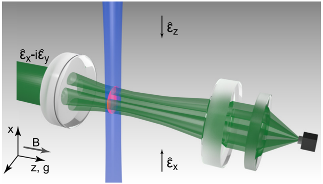

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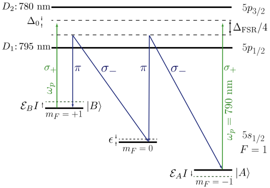

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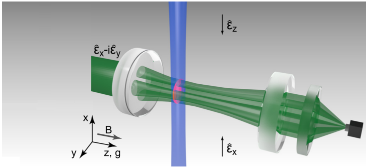

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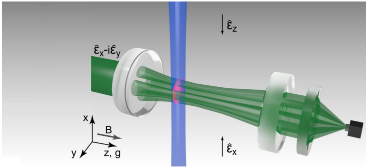

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[Ballantine *et al.* PRL 2017]

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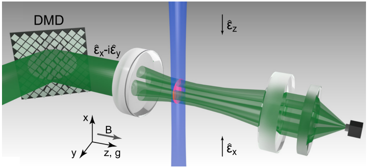

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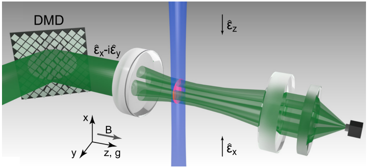

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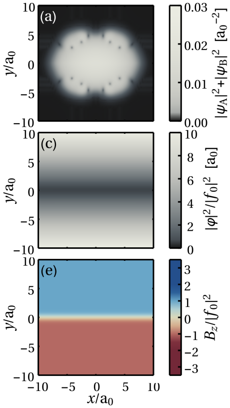
Meissner-like physics: numerical simulations

Atoms

Cavity light

Synthetic field



- Consider $f(\mathbf{r})$ such that $|\varphi|^2 \propto y$.
- Without feedback ($\mathcal{E}_\Delta = 0$) for field

[Ballantine *et al.* PRL 2017]

See Poster by K. Ballantine!

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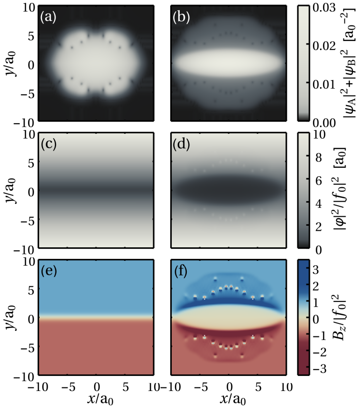

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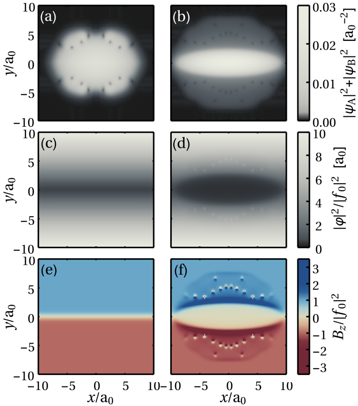

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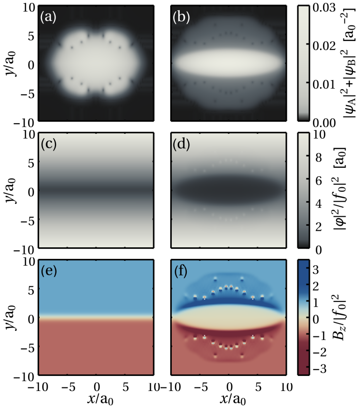

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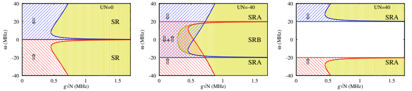
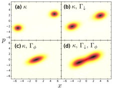
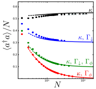
Summary

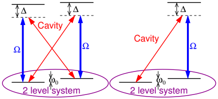
- Open Dicke model, $\kappa, \Gamma_\phi, \Gamma_\downarrow$ [Kirton & JK, PRL 2017]

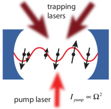




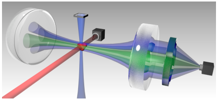
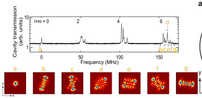


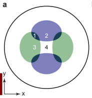
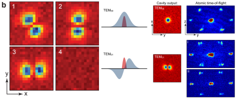
- Many possibilities of multimode cavity QED





- Supermode polariton condensation [Kollár *et al.* Nat. Comms. 2017]

- Meissner like effect [Ballantine *et al.* PRL 2017]