Supermode-density-wave-polariton condensation, and Meissner-like effect with multimode cavity-QED

Jonathan Keeling

Trento, January 2017

Supermode-density-wave-polariton condensation, and Meissner-like effect with multimode cavity-QED

Jonathan Keeling

Trento, January 2017

What can quantum systems do?

Condensed matter physics: two types of question

What physics is needed to explain the material properties we do see

What can quantum systems do?

Condensed matter physics: two types of question

What physics is needed to explain the material properties we do see

What can quantum systems do?

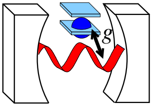
Condensed matter physics: two types of question

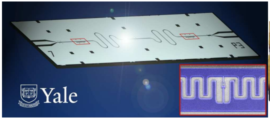
What physics is needed to explain the material properties we do see

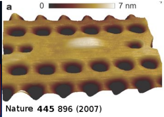
to

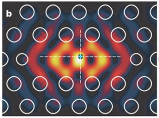
What material properties can be possible from quantum physics?

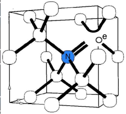
Once upon a time there was cavity QED . . .





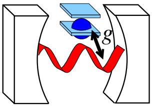


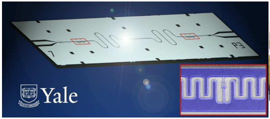


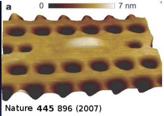


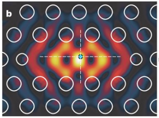
- Precision tests of quantum optics
  - Purcell effect, strong coupling
  - Rabi oscillations, collapse & revival
  - Resonant fluorescence, EIT
- Many atom physics
  - Phase transitions: Lasing, superfluoresence, superradiance

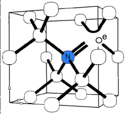
Once upon a time there was cavity QED . . .





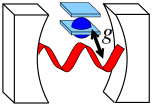


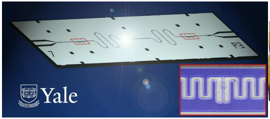


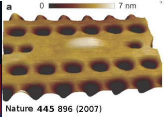


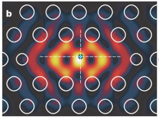
- Precision tests of quantum optics
  - Purcell effect, strong coupling
  - Rabi oscillations, collapse & revival
  - Resonant fluoresecence, EIT
- Many atom physics
  - Phase transitions: Lasing, superfluoresence, superradiance

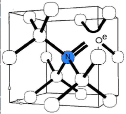
Once upon a time there was cavity QED . . .



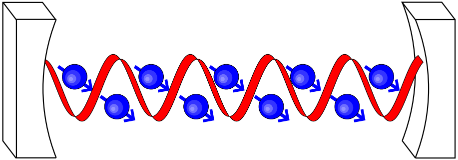






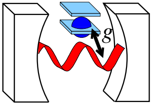


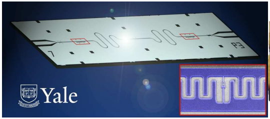
- Precision tests of quantum optics
  - Purcell effect, strong coupling
  - Rabi oscillations, collapse & revival
  - Resonant fluoresecence, EIT
- Many atom physics

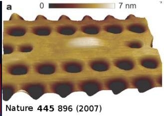


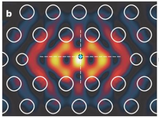
  - Phase transitions: Lasing, superfluoresence, superradiance

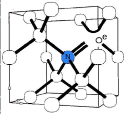
Once upon a time there was cavity QED . . .



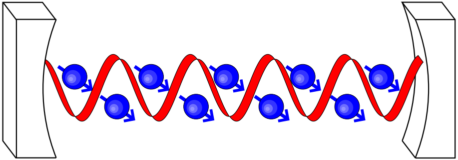
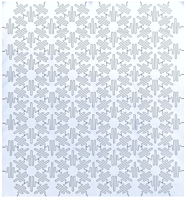








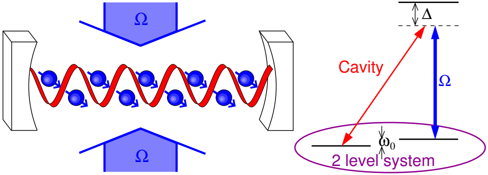
- Precision tests of quantum optics
  - Purcell effect, strong coupling
  - Rabi oscillations, collapse & revival
  - Resonant fluoresecence, EIT
- Many atom physics

  - Phase transitions: Lasing, superfluoresence, superradiance

Synthetic cavity QED: Raman driving

- Tunable coupling via Raman

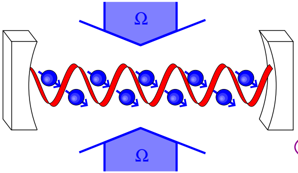


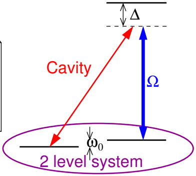
$$H_{\text{eff}} = \ldots \frac{\Omega g}{\Delta}\left(\sigma_n^+ a + \text{H.c.}\right)$$

[Dimer *et al.* PRA '07]

Synthetic cavity QED: Raman driving

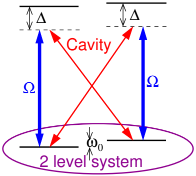
- Tunable coupling via Raman





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

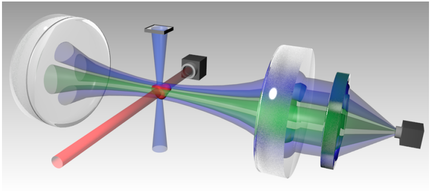
- Real systems: loss $\partial_t \rho = -i[H, \rho] + \kappa \mathcal{L}[a, \rho] + \ldots$
- To balance loss, counter-rotating:



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

[Dimer *et al.* PRA '07]

Multimode cavity QED



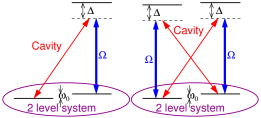
- Full model:

$$H_{\text{eff}} = \sum_{\mu} \underbrace{(\omega_\mu - \omega_P)}_{-\Delta_\mu} a^\dagger_\mu a_\mu + \sum_{N} \frac{\omega_0}{2} \sigma^z_n + \underbrace{\frac{\Omega g_0}{\Delta}}_{g_{\text{eff}}} \sum_{\mu} \Xi_\mu(\mathbf{r}_n) \sigma^x_n (a + a^\dagger)$$

[Gopalakrishnan, Lev, Goldbart. Nat. Phys '09, PRA '10]

Possibilities

- XY *vs* Ising



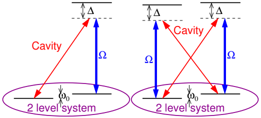
- Momentum state *vs* hyperfine state

- Single mode *vs* **multimode**

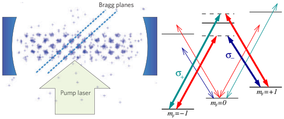
- Thermal gas *vs* BEC *vs* disorder localised

Possibilities

- XY *vs* Ising



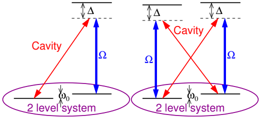
- Momentum state *vs* hyperfine state



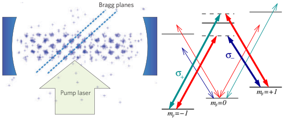
- Single mode *vs* multimode
- Thermal gas *vs* BEC *vs* disorder localised

Possibilities

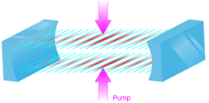
- XY *vs* Ising

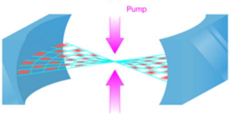


- Momentum state *vs* hyperfine state



- Single mode *vs* **multimode**



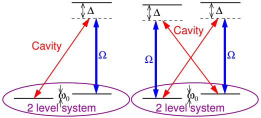


Credit: Alan Stonebreaker, Physics 3, 88 (2010)

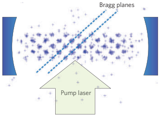
- Thermal gas *vs* BEC *vs* disorder localised

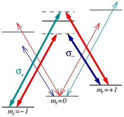
Possibilities

- XY *vs* Ising

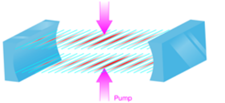


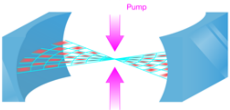
- Momentum state *vs* hyperfine state





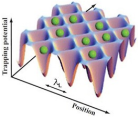
- Single mode *vs* **multimode**

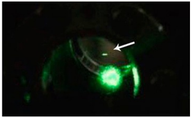


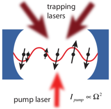


Credit: Alan Stonebreaker, Physics 3, 88 (2010)

- Thermal gas *vs* BEC *vs* disorder localised



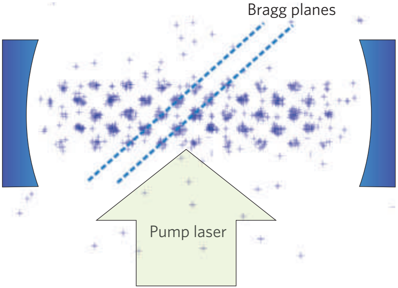




Introduction: Tunable multimode Cavity QED

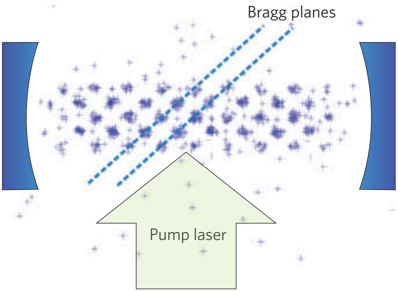
Single mode cavity QED

Single mode experiments



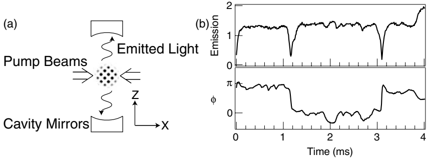
Ritsch *et al.* PRL '02

Single mode experiments



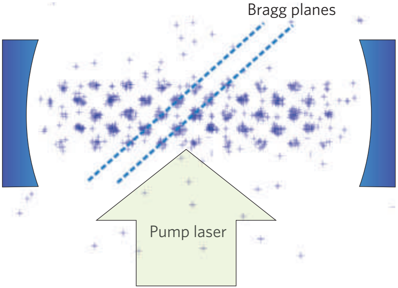
Ritsch *et al.* PRL '02

Thermal atoms, momentum state



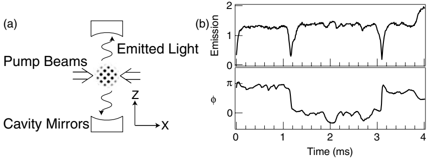
Vuletic *et al.* PRL '03 (MIT)

Single mode experiments



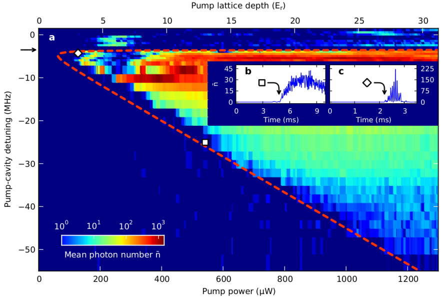
Ritsch *et al.* PRL '02

Thermal atoms, momentum state



Vuletic *et al.* PRL '03 (MIT)

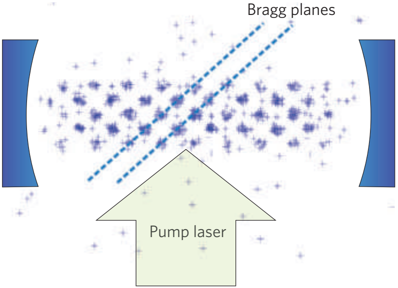
BEC, momentum state



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

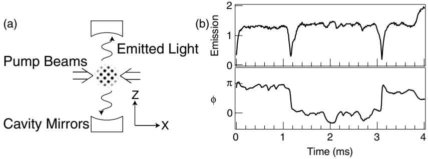
Kinder *et al.* PRL '15 (Hamburg)

Single mode experiments



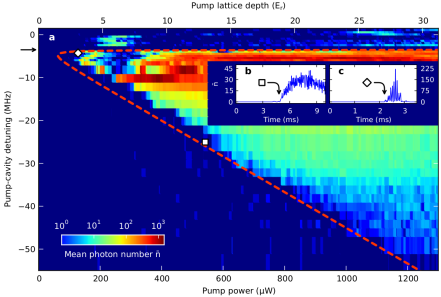
Ritsch *et al.* PRL ’02

Thermal atoms, momentum state



Vuletic *et al.* PRL ’03 (MIT)

BEC, momentum state



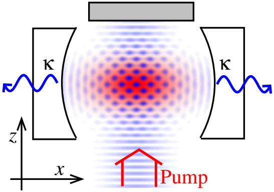
Baumann *et al.* Nature ’10 (ETH)

Kinder *et al.* PRL ’15 (Hamburg)

BEC, hyperfine states

Badeen *et al.* PRL ’14 (Singapore)

Single mode theory



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

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

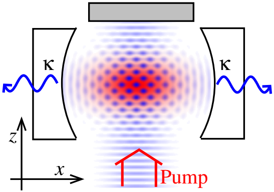
- Extra "feedback" term U, cavity loss κ
- Single mode – mean-field EOM, $\alpha = \langle \hat{a} \rangle$, $S^i = \sum_n \sigma_n^i/2$.

$$\dot{S}^- = -i(\omega_0 + U|\alpha|^2)S^- + 2ig_{\text{eff}}(\alpha + \alpha^*)S^z$$

$$\dot{S}^z = ig_{\text{eff}}(\alpha + \alpha^*)(S^- - S^+)$$

$$\dot{\alpha} = -[\kappa + i(-\Delta_c + US^z)]\alpha - ig_{\text{eff}}(S^- + S^+)$$

Single mode theory



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

$$H_{\text{eff}} = \underbrace{(\omega_c - \omega_P)}_{-\Delta_c} a^\dagger a + \sum_n \frac{\omega_0}{2}\sigma_n^z + \underbrace{\frac{\Omega g_0}{\Delta}}_{g_{\text{eff}}} \sigma_n^x (a + a^\dagger) - \underbrace{\frac{{g_0}^2}{4\Delta}}_{U} \sigma_n^z a^\dagger a$$

- Extra "feedback" term U, cavity loss κ
- Single mode – mean-field EOM, $\alpha = \langle \hat{a} \rangle$, $S^i = \sum_n \sigma_n^i/2$.

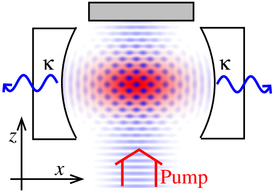
$$\dot{S}^- = -i(\omega_0 + U|\alpha|^2)S^- + 2ig_{\text{eff}}(\alpha + \alpha^*)S^z$$

$$\dot{S}^z = ig_{\text{eff}}(\alpha + \alpha^*)(S^- - S^+)$$

$$\dot{\alpha} = -[\kappa + i(-\Delta_c + US^z)]\alpha - ig_{\text{eff}}(S^- + S^+)$$

Single mode theory

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



$$H_{\text{eff}} = \underbrace{(\omega_c - \omega_P)}_{-\Delta_c} a^\dagger a + \sum_n \frac{\omega_0}{2}\sigma^z_n + \underbrace{\frac{\Omega g_0}{\Delta}}_{g_{\text{eff}}} \sigma^x_n (a + a^\dagger) - \underbrace{\frac{{g_0}^2}{4\Delta}}_{U} \sigma^z_n a^\dagger a$$

- Extra "feedback" term U, cavity loss κ
- Single mode – mean-field EOM, $\alpha = \langle \hat{a} \rangle$, $S^i = \sum_n \sigma^i_n/2$.

$$\dot{S}^- = -i(\omega_0 + U|\alpha|^2)S^- + 2ig_{\text{eff}}(\alpha + \alpha^*)S^z$$

$$\dot{S}^z = ig_{\text{eff}}(\alpha + \alpha^*)(S^- - S^+)$$

$$\dot{\alpha} = -[\kappa + i(-\Delta_c + US^z)]\alpha - ig_{\text{eff}}(S^- + S^+)$$

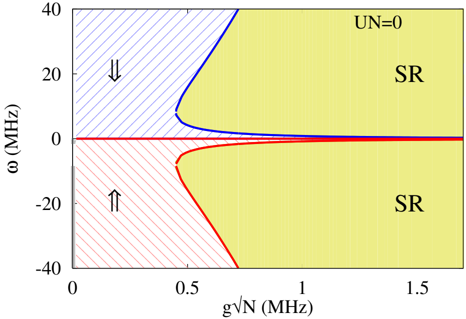
Classical dynamics

Changing *U*:

$U = 0$

$U < 0$

$U > 0$



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

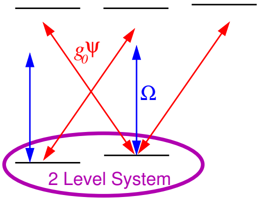
Classical dynamics

Changing U:

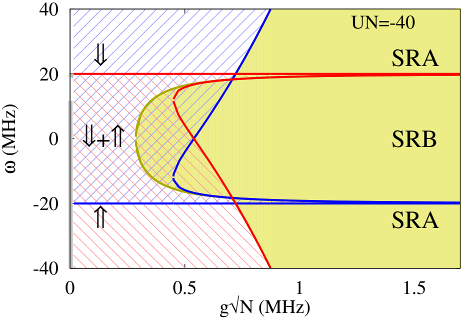
$U = 0$

$U < 0$

$U > 0$



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



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

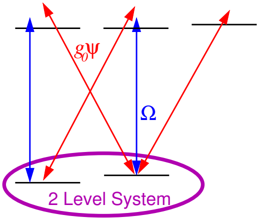
Classical dynamics

Changing U:

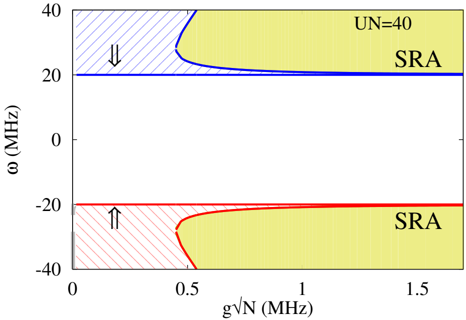
$U = 0$

$U < 0$

$U > 0$



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



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

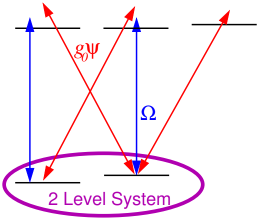
Classical dynamics

Changing U:

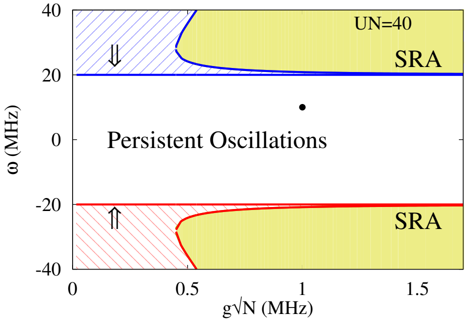
$U = 0$

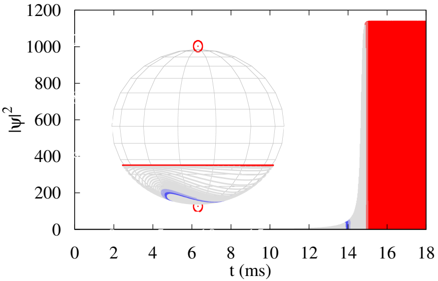
$U < 0$

$U > 0$



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





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

Effect of particle losses

- Adding other loss terms

$$\partial_t \rho = -i[H, \rho] + \kappa \mathcal{L}[\hat{a}] + \sum_i \Gamma_\downarrow \mathcal{L}[\sigma_i^-] + \Gamma_\phi \mathcal{L}[\sigma_i^z]$$

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

- $\Gamma_\downarrow, \Gamma_\phi$ break **S** conservation.

[Dalla Torre *et al.* , PRA (Rapid) 2016, Kirton & JK, arXiv:1611.03342]

Effect of particle losses

- Adding other loss terms

$$\partial_t \rho = -i[H, \rho] + \kappa \mathcal{L}[\hat{a}] + \sum_i \Gamma_\downarrow \mathcal{L}[\sigma_i^-] + \Gamma_\phi \mathcal{L}[\sigma_i^z]$$

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

- $\Gamma_\downarrow, \Gamma_\phi$ break **S** conservation.

[Dalla Torre *et al.* , PRA (Rapid) 2016, Kirton & JK, arXiv:1611.03342]

Effect of particle losses

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

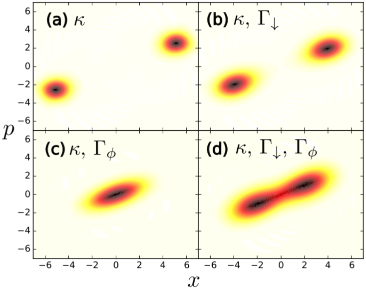
- Γ_ϕ only: MFT $\rightarrow$ no SR
- Asymptotic scaling

- Finite N: no symmetry breaking

[Kirton & JK, arXiv:1611.03342]

Effect of particle losses

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

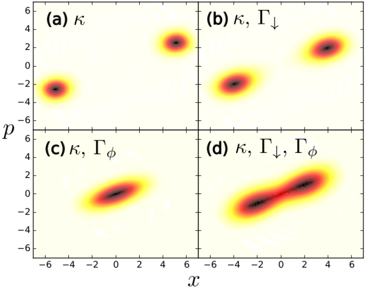


- Γ_ϕ only: MFT $\rightarrow$ no SR
- Asymptotic scaling
- Finite N: no symmetry breaking

[Kirton & JK, arXiv:1611.03342]

Effect of particle losses

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



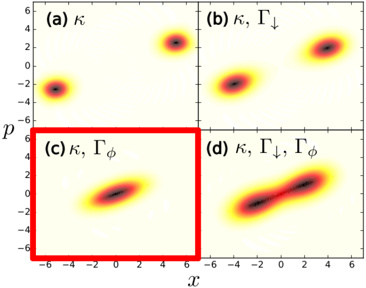
- Finite N: no symmetry breaking

[Kirton & JK, arXiv:1611.03342]

- Γ_ϕ only: MFT → no SR
- Asymptotic scaling

Effect of particle losses

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



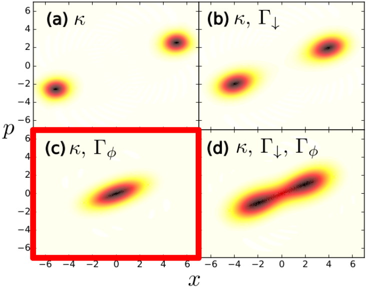
- Finite N: no symmetry breaking

[Kirton & JK, arXiv:1611.03342]

- Γ_{ϕ} only: MFT $\rightarrow$ no SR
- Asymptotic scaling

Effect of particle losses

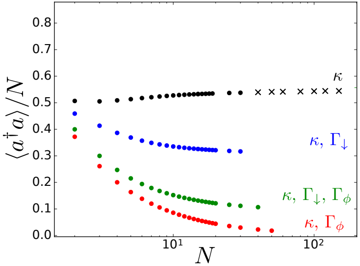
- Wigner function $W(\hat{a} = \hat{x} + i\hat{p})$



- Finite N: no symmetry breaking

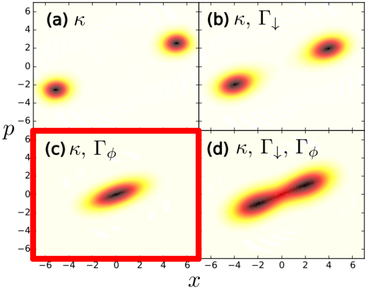
[Kirton & JK, arXiv:1611.03342]

- Γ_ϕ only: MFT $\rightarrow$ no SR
- Asymptotic scaling



Effect of particle losses

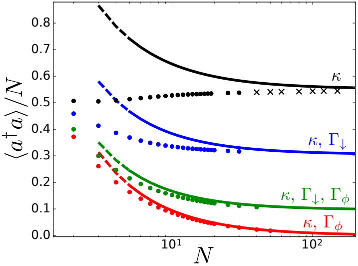
- Wigner function $W(\hat{a} = \hat{x} + i\hat{p})$



- Finite N: no symmetry breaking

[Kirton & JK, arXiv:1611.03342]

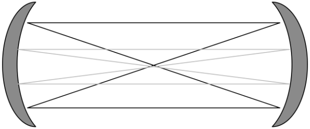
- Γ_ϕ only: MFT $\rightarrow$ no SR
- Asymptotic scaling



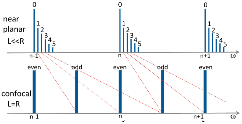
Multimode cavity QED experiments

Multimode cavities

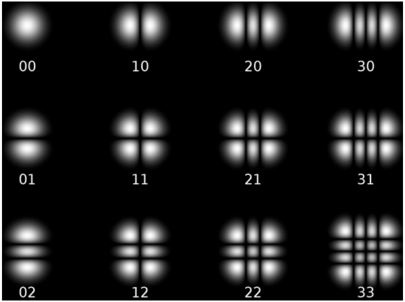
Confocal cavity $L = R$:



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

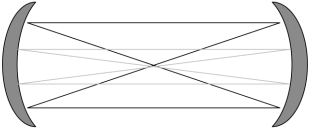


- Extra distinction: degenerate *vs* non-degenerate

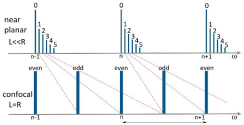


Multimode cavities

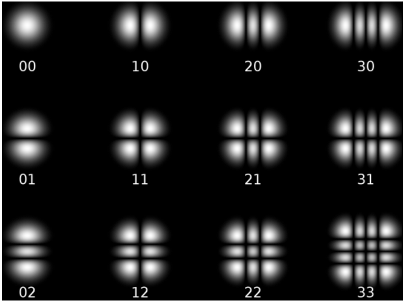
Confocal cavity $L = R$:

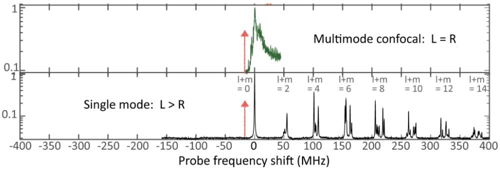


- Modes $\Xi_{l,m}(\mathbf{r}) = H_l(x)H_m(y)$, $l + m$ fixed parity

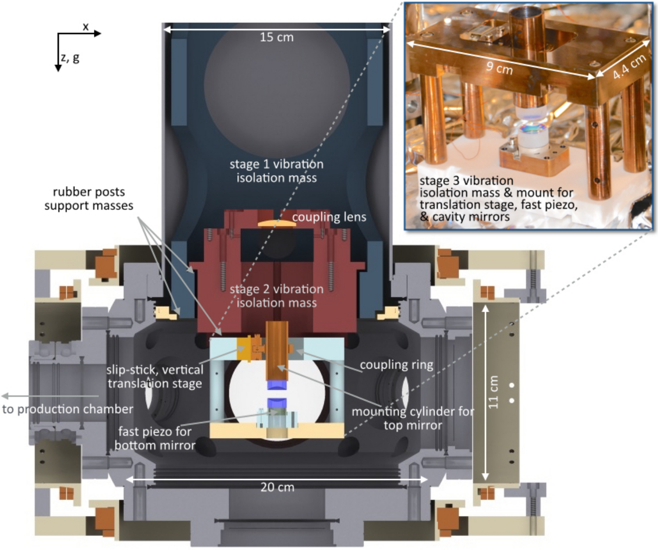


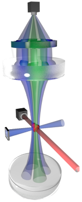
- Extra distinction: degenerate *vs* non-degenerate





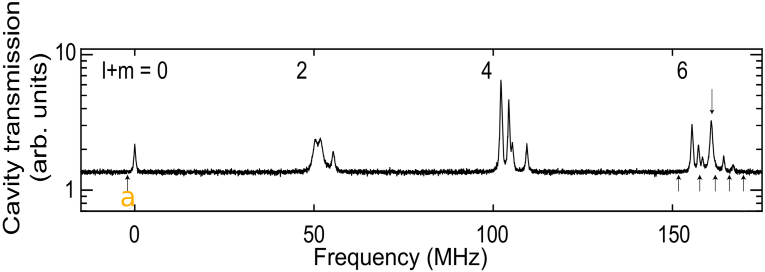
Adjustable length multimode cavity

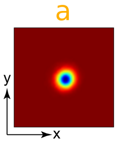




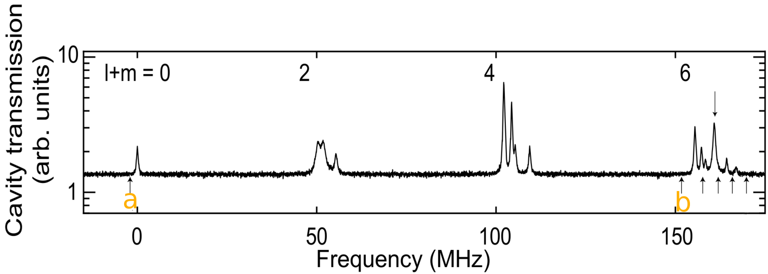
[Kollár, Papgeorge, Baumann, Armen & Lev, NJP '15]

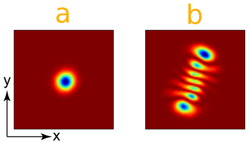
Superradiance in multimode cavity: Even family



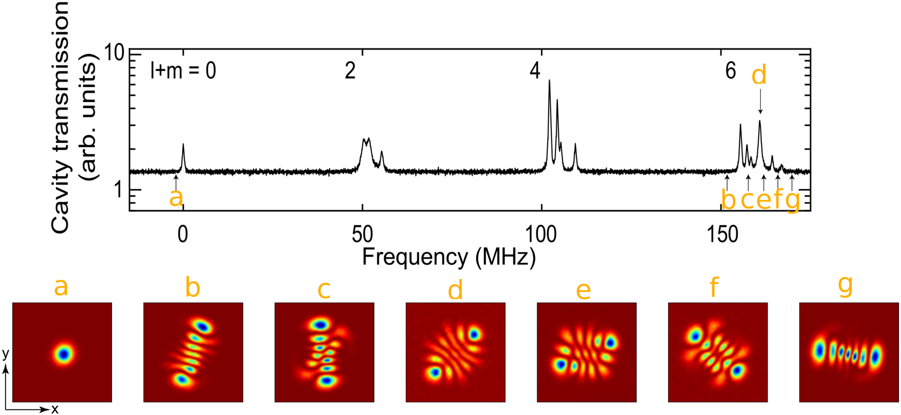


Superradiance in multimode cavity: Even family





Superradiance in multimode cavity: Even family



Supermodes vs polariton condensation

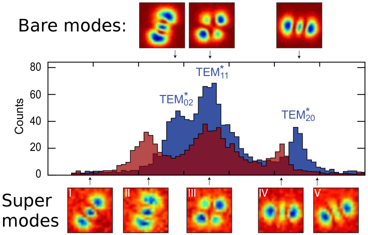
Supermode density-wave polariton:

- Hybrid cavity photon and atomic density wave
- Atoms remix cavity modes → superposition
- Condensation of polaritons remixes again

Supermodes vs polariton condensation

Supermode density-wave polariton:

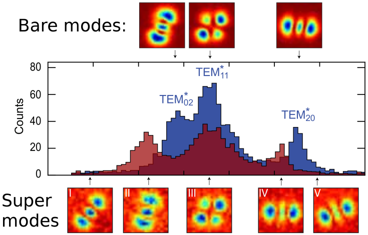
- Hybrid cavity photon and atomic density wave
- Atoms remix cavity modes → superposition
- Condensation of polaritons remixes again

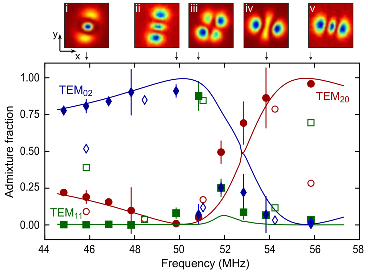


Supermodes vs polariton condensation

Supermode density-wave polariton:

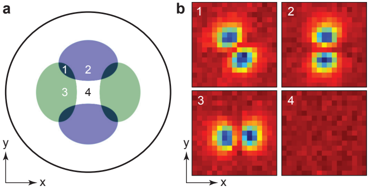
- Hybrid cavity photon and atomic density wave
- Atoms remix cavity modes → superposition
- Condensation of polaritons remixes again





Superradiance in multimode cavity: Odd family

- Dependence on cloud position

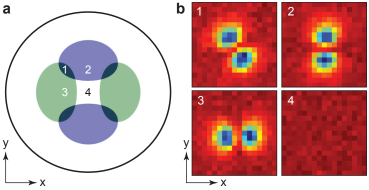


- Atomic time-of-flight — structure factor

- Near-degeneracy of (1, 0), (0, 1) modes broken by matter-light coupling.

Superradiance in multimode cavity: Odd family

- Dependence on cloud position

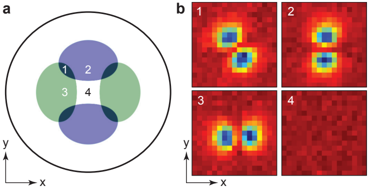


- Near-degeneracy of $(1, 0), (0, 1)$ modes broken by matter-light coupling.

- Atomic time-of-flight — structure factor

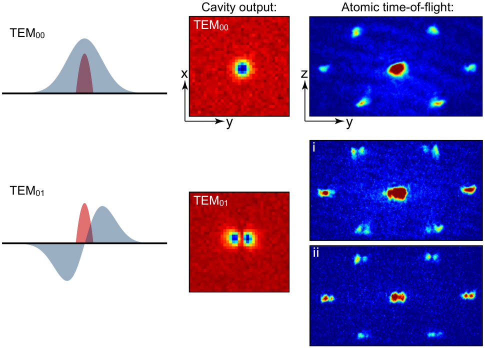
Superradiance in multimode cavity: Odd family

- Dependence on cloud position



- Near-degeneracy of $(1,0),(0,1)$ modes broken by matter-light coupling.

- Atomic time-of-flight — structure factor



Theoretical possibilities

Theoretical possibilities

1. Introduction: Tunable multimode Cavity QED
2. Single mode cavity QED
   - Spin-non-conserving loss
3. Multimode cavity QED experiments
   - Experimental setup
   - Supermode density wave polariton condensation
4. Theoretical possibilities
   - Spin glass, Hopfield memory
   - Meissner-like effect

Disordered atoms

- Multimode cavity, Hyperfine states,

$$H_{\text{eff}} = -\sum_{\mu} \Delta_\mu a^\dagger_\mu a_\mu + \sum_n \frac{\omega_0}{2}\sigma^z_n + \frac{\Omega g_0}{\Delta}\sum_\mu \Xi_\mu(\mathbf{r}_n)\sigma^x_n(a_\mu + a^\dagger_\mu)$$

- Random atom positions – queched disorder

- Effective XY/Ising spin glass

$$H_{\text{eff}} = \sum_{n,m} J_{n,m} \begin{cases} \sigma^x_n \sigma^x_m & \text{Ising} \\ \sigma^+_n \sigma^-_m & XY \end{cases}, \qquad J_{nm} = \sum_\mu \frac{\Omega^2 g_0^2 \Xi_\mu(\mathbf{r}_n)\Xi_\mu(\mathbf{r}_m)}{\Delta^2 \Delta_\mu}$$

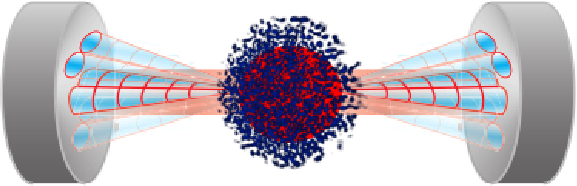
[Gopalakrishnan, Lev and Goldbart. PRL ’11, Phil. Mag. ’12]

Disordered atoms

- Multimode cavity, Hyperfine states,

$$H_{\text{eff}} = -\sum_{\mu} \Delta_\mu a^\dagger_\mu a_\mu + \sum_n \frac{\omega_0}{2}\sigma^z_n + \frac{\Omega g_0}{\Delta}\sum_\mu \Xi_\mu(\mathbf{r}_n)\sigma^x_n(a_\mu + a^\dagger_\mu)$$

- Random atom positions – queched disorder



- Effective XY/Ising spin glass

$$H_{\text{eff}} = \sum_{n,m} J_{nm} \begin{cases} \sigma^x_n \sigma^x_m & \text{Ising} \\ \sigma^+_n \sigma^-_m & XY \end{cases} \qquad J_{nm} = \sum_\mu \frac{\Omega^2 g_0^2 \Xi_\mu(\mathbf{r}_n)\Xi_\mu(\mathbf{r}_m)}{\Delta^2 \Delta_\mu}$$

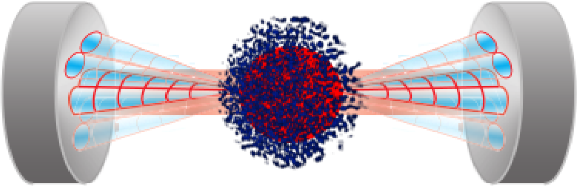
[Gopalakrishnan, Lev and Goldbart. PRL '11, Phil. Mag. '12]

Disordered atoms

- Multimode cavity, Hyperfine states,

$$H_{\text{eff}} = -\sum_{\mu} \Delta_{\mu} a^{\dagger}_{\mu} a_{\mu} + \sum_{n} \frac{\omega_0}{2} \sigma^z_n + \frac{\Omega g_0}{\Delta} \sum_{\mu} \Xi_{\mu}(\mathbf{r}_n) \sigma^x_n (a_{\mu} + a^{\dagger}_{\mu})$$

- Random atom positions – queched disorder



- Effective XY/Ising spin glass

$$H_{\text{eff}} = \sum_{n,m} J_{n,m} \begin{cases} \sigma^x_n \sigma^x_m & \textit{Ising} \\ \sigma^+_n \sigma^-_m & \textit{XY} \end{cases}, \quad J_{nm} = \sum_{\mu} \frac{\Omega^2 {g_0}^2 \Xi_{\mu}(\mathbf{r}_n) \Xi_{\mu}(\mathbf{r}_m)}{\Delta^2 \Delta_{\mu}}$$

[Gopalakrishnan, Lev and Goldbart. PRL '11, Phil. Mag. '12]

Tunable spin glass

$$H_{\text{eff}} = \sum_{n,m} J_{n,m} \sigma_n^x \sigma_m^x \qquad J_{nm} = \sum_{\mu} \frac{\Omega^2 {g_0}^2 \Xi_\mu(\mathbf{r}_n) \Xi_\mu(\mathbf{r}_m)}{\Delta^2 \Delta_\mu}$$

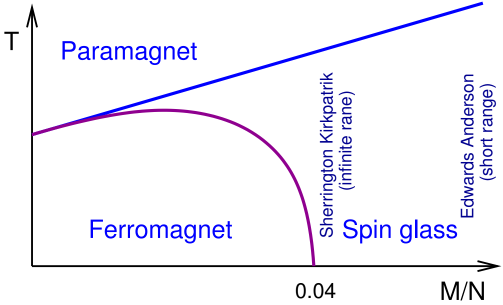
- Tunable complexity
- Explore RSB/Droplet order
- Open system spin-glass.
  [Strack & Sachdev PRL '11]

[Gopalakrishnan, Lev and Goldbart. PRL '11, Phil. Mag. '12]

Tunable spin glass

$$H_{\text{eff}} = \sum_{n,m} J_{n,m} \sigma^x_n \sigma^x_m \qquad J_{nm} = \sum_{\mu} \frac{\Omega^2 {g_0}^2 \Xi_\mu(\mathbf{r}_n) \Xi_\mu(\mathbf{r}_m)}{\Delta^2 \Delta_\mu}$$

- Tunable complexity
- Explore RSB/Droplet order
- Open system spin-glass. [Strack & Sachdev PRL '11]

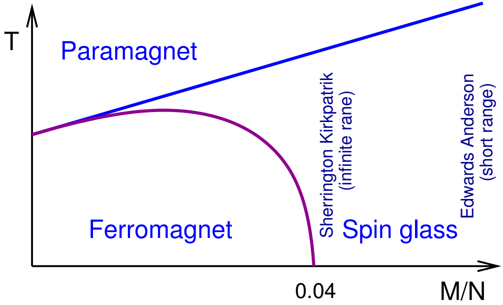


[Gopalakrishnan, Lev and Goldbart. PRL '11, Phil. Mag. '12]

Tunable spin glass

$$H_{\text{eff}} = \sum_{n,m} J_{n,m}\sigma_n^x\sigma_m^x \quad J_{nm} = \sum_{\mu} \frac{\Omega^2 g_0{}^2 \Xi_\mu(\mathbf{r}_n)\Xi_\mu(\mathbf{r}_m)}{\Delta^2\Delta_\mu}$$

- Tunable complexity
- Explore RSB/Droplet order
- Open system spin-glass.
  [Strack & Sachdev PRL '11]

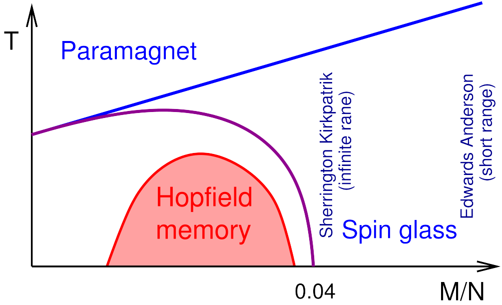


[Gopalakrishnan, Lev and Goldbart. PRL '11, Phil. Mag. '12]

Tunable spin glass

$$H_{\text{eff}} = \sum_{n,m} J_{n,m} \sigma^x_n \sigma^x_m \quad J_{nm} = \sum_{\mu} \frac{\Omega^2 {g_0}^2 \Xi_\mu(\mathbf{r}_n)\Xi_\mu(\mathbf{r}_m)}{\Delta^2 \Delta_\mu}$$

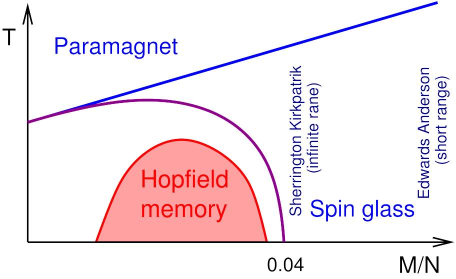
- Tunable complexity
- Explore RSB/Droplet order
- Open system spin-glass.
  [Strack & Sachdev PRL ’11]



[Gopalakrishnan, Lev and Goldbart. PRL ’11, Phil. Mag. ’12]

Hopfield memory

- Between Mean-Field and Spin-Glass
- Multiple fixed points
- Recover corrupted image



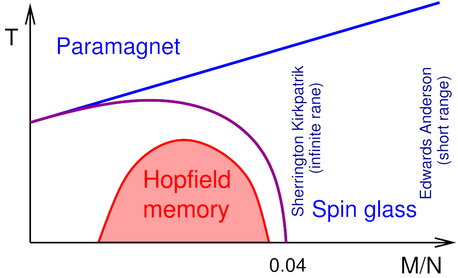
[Gopalakrishnan, Lev and Goldbart. PRL '11, Phil. Mag. '12]

Low dimensional cartoon:

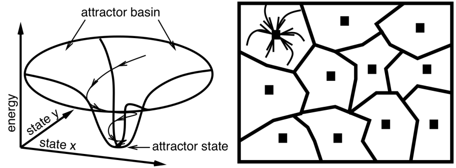
- Neurons → Spins
- Synapses → Modes
- Plasticity → Atom movement
- Need $|s_n| = 1$ (hard spins)

Hopfield memory

- Between Mean-Field and Spin-Glass
- Multiple fixed points
- Recover corrupted image



Low dimensional cartoon:



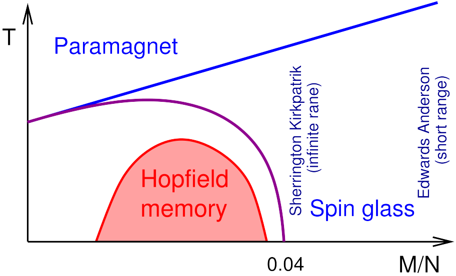
[Hertz, Krogh,Palmer '91]

- Neurons → Spins
- Synapses → Modes
- Plasticity → Atom movement
- Need $|s_n| = 1$ (hard spins)

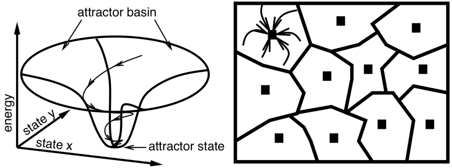
[Gopalakrishnan, Lev and Goldbart. PRL '11, Phil. Mag. '12]

Hopfield memory

- Between Mean-Field and Spin-Glass
- Multiple fixed points
- Recover corrupted image



Low dimensional cartoon:



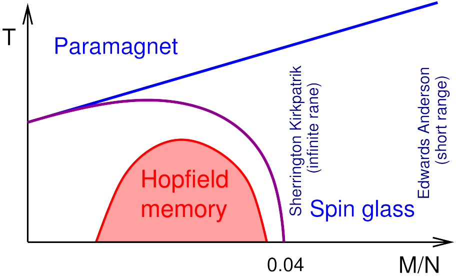
[Hertz, Krogh,Palmer '91]

- Neurons → Spins
- Synapses → Modes
- Plasticity → Atom movement

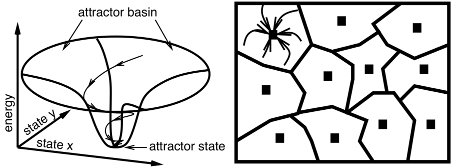
[Gopalakrishnan, Lev and Goldbart. PRL '11, Phil. Mag. '12]

Hopfield memory

- Between Mean-Field and Spin-Glass
- Multiple fixed points
- Recover corrupted image



Low dimensional cartoon:



[Hertz, Krogh,Palmer '91]

- Neurons $\rightarrow$ Spins
- Synapses $\rightarrow$ Modes
- Plasticity $\rightarrow$ Atom movement
- Need $|\mathbf{s}_n| = 1$ (hard spins)

[Gopalakrishnan, Lev and Goldbart. PRL '11, Phil. Mag. '12]

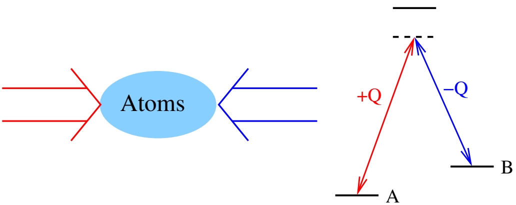
Theoretical possibilities

1. Introduction: Tunable multimode Cavity QED
2. Single mode cavity QED
   - Spin-non-conserving loss
3. Multimode cavity QED experiments
   - Experimental setup
   - Supermode density wave polariton condensation
4. Theoretical possibilities
   - Spin glass, Hopfield memory
   - Meissner-like effect

Cavity QED and synthetic gauge fields

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

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

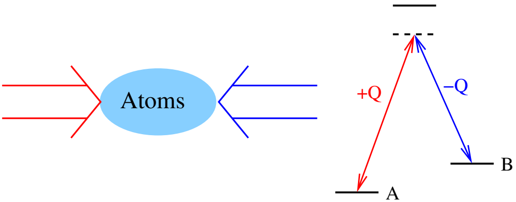


- Feedback
  - Why?
    - Meissner effect, Anderson-Higgs mechanism, confinement-deconfinement transition.

Cavity QED and synthetic gauge fields

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

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



Ground state:

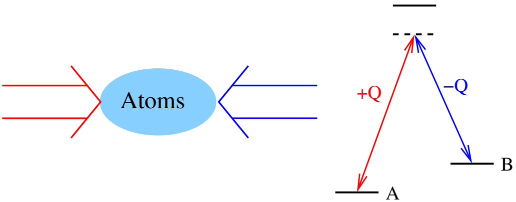
$$E_{-}(\mathbf{k}) \simeq \frac{\left(\mathbf{k} - \frac{(E_B - E_A)Q\hat{\mathbf{x}}}{\Omega}\right)^2}{2m^*}$$

- Feedback
  - Why?
    - Meissner effect, Anderson-Higgs mechanism, confinement-deconfinement transition.

Cavity QED and synthetic gauge fields

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

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



Ground state:

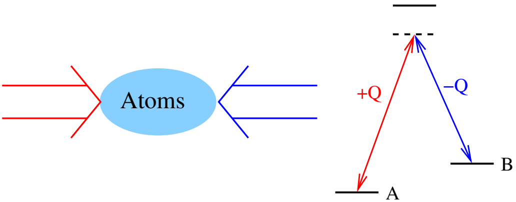
$$E_-(\mathbf{k}) \simeq \frac{(\mathbf{k} - \frac{(E_B - E_A)Q\hat{\mathbf{x}}}{\Omega})^2}{2m^*}$$

- Feedback
  - Why?
    - ★ Meissner effect, Anderson-Higgs mechanism, confinement-deconfinement transition.
  - How?
    - ★ Multimode cavity QED

Cavity QED and synthetic gauge fields

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

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



Ground state:

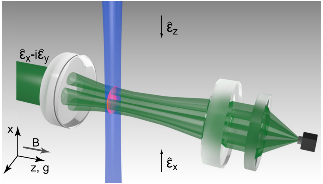
$$E_-(\mathbf{k}) \simeq \frac{\left(\mathbf{k} - \frac{(E_B - E_A)Q\hat{\mathbf{x}}}{\Omega}\right)^2}{2m^*}$$

- Feedback
  - Why?
    - ★ Meissner effect, Anderson-Higgs mechanism, confinement-deconfinement transition.
  - How?
    - ★ Multimode cavity QED

Meissner-like physics: idea

- Follow Spielman scheme

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

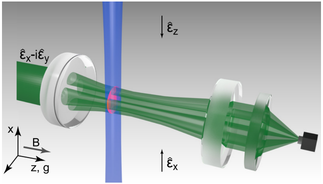


[Ballantine *et al.* arXiv:1608.07246]

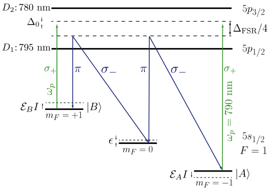
Meissner-like physics: idea

- Follow Spielman scheme

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



- $E_A, E_B \propto |\varphi|^2$ from cavity Stark shift
- Ground state $E_-(\mathbf{k}) \propto (\mathbf{k} - Q\hat{x}|\varphi|^2)^2$



[Ballantine *et al.* arXiv:1608.07246]

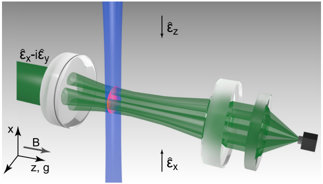
- Multimode cQED → local matter-light coupling
- Variable profile synthetic gauge field?
- Reciprocity: matter affects field

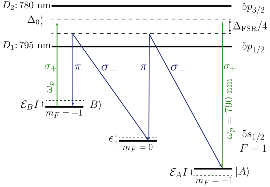
Meissner-like physics: idea

- Follow Spielman scheme

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

- $E_A, E_B \propto |\varphi|^2$ from cavity Stark shift
- Ground state $\quad E_-(\mathbf{k}) \propto (\mathbf{k} - Q\hat{\mathbf{x}}|\varphi|^2)^2$





[Ballantine *et al.* arXiv:1608.07246]

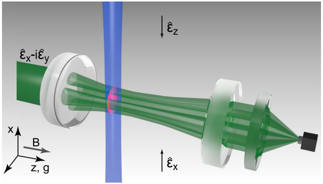
- Multimode cQED → local matter-light coupling
- Variable profile synthetic gauge field?
- Reciprocity: matter affects field

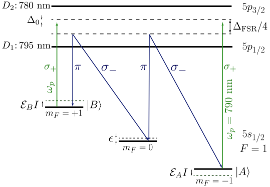
Meissner-like physics: idea

- Follow Spielman scheme

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

- $E_A, E_B \propto |\varphi|^2$ from cavity Stark shift
- Ground state $\quad E_-(\mathbf{k}) \propto (\mathbf{k} - Q\hat{\mathbf{x}}|\varphi|^2)^2$





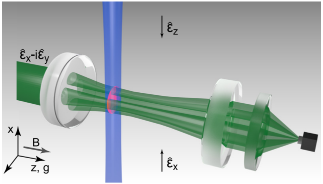
[Ballantine *et al.* arXiv:1608.07246]

- Multimode cQED → local matter-light coupling
- Variable profile synthetic gauge field?
- Reciprocity: matter affects field

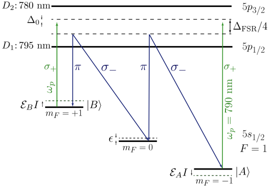
Meissner-like physics: idea

- Follow Spielman scheme

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



- $E_A, E_B \propto |\varphi|^2$ from cavity Stark shift
- Ground state $E_-(\mathbf{k}) \propto (\mathbf{k} - Q\hat{\mathbf{x}}|\varphi|^2)^2$



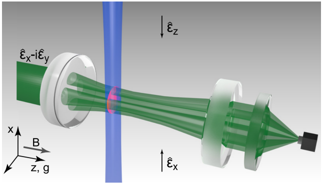
[Ballantine *et al.* arXiv:1608.07246]

- Multimode cQED → local matter-light coupling
- Variable profile synthetic gauge field?
- Reciprocity: matter affects field

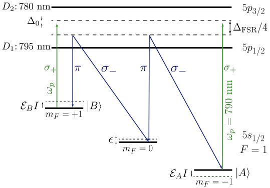
Meissner-like physics: idea

- Follow Spielman scheme

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



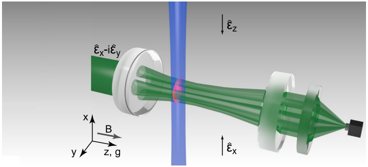
- $E_A, E_B \propto |\varphi|^2$ from cavity Stark shift
- Ground state $E_-(\mathbf{k}) \propto (\mathbf{k} - Q\hat{\mathbf{x}}|\varphi|^2)^2$



[Ballantine *et al.* arXiv:1608.07246]

- Multimode cQED → local matter-light coupling
- Variable profile synthetic gauge field?
- Reciprocity: matter affects field

Meissner-like physics: setup

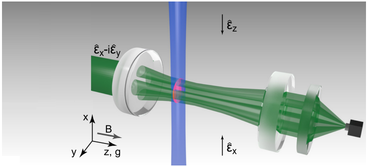


- Atoms:

$$i\partial_t \begin{pmatrix} \psi_A \\ \psi_B \end{pmatrix} = \left[-\frac{\nabla^2}{2m} + \begin{pmatrix} -\mathcal{E}_\Delta |\varphi|^2 + i\frac{q}{m}\partial_x & \Omega/2 \\ \Omega/2 & \mathcal{E}_\Delta |\varphi|^2 - i\frac{q}{m}\partial_x \end{pmatrix} + \dots \right] \begin{pmatrix} \psi_A \\ \psi_B \end{pmatrix}.$$

[Ballantine *et al.* arXiv:1608.07246]

Meissner-like physics: setup



- Atoms:

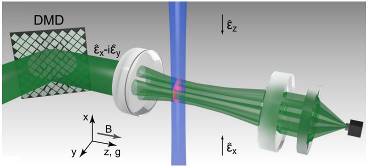
$$i\partial_t \begin{pmatrix}\psi_A\\ \psi_B\end{pmatrix} = \left[-\frac{\nabla^2}{2m} + \begin{pmatrix}-\mathcal{E}_\Delta|\varphi|^2 + i\frac{q}{m}\partial_x & \Omega/2 \\ \Omega/2 & \mathcal{E}_\Delta|\varphi|^2 - i\frac{q}{m}\partial_x\end{pmatrix} + \dots\right]\begin{pmatrix}\psi_A\\ \psi_B\end{pmatrix}.$$

- Light:

$$i\partial_t\varphi = \left[\frac{\delta}{2}\left(-l^2\nabla^2 + \frac{r^2}{l^2}\right) - \Delta_0 - i\kappa - N\mathcal{E}_\Delta(|\psi_A|^2 - |\psi_B|^2)\right]\varphi \qquad .$$

[Ballantine *et al.* arXiv:1608.07246]

Meissner-like physics: setup



- Atoms:

$$i\partial_t \begin{pmatrix} \psi_A \\ \psi_B \end{pmatrix} = \left[-\frac{\nabla^2}{2m} + \begin{pmatrix} -\mathcal{E}_\Delta |\varphi|^2 + i\frac{q}{m}\partial_x & \Omega/2 \\ \Omega/2 & \mathcal{E}_\Delta |\varphi|^2 - i\frac{q}{m}\partial_x \end{pmatrix} + \ldots \right] \begin{pmatrix} \psi_A \\ \psi_B \end{pmatrix}.$$

- Light:

$$i\partial_t \varphi = \left[\frac{\delta}{2} \left(-l^2\nabla^2 + \frac{r^2}{l^2} \right) - \Delta_0 - i\kappa - N\mathcal{E}_\Delta (|\psi_A|^2 - |\psi_B|^2) \right] \varphi + f(\mathbf{r}).$$

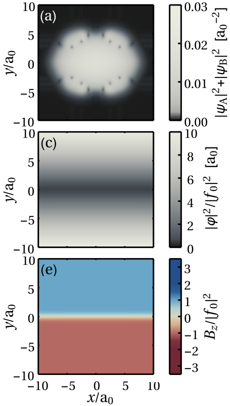
[Ballantine *et al.* arXiv:1608.07246]

Meissner-like physics: numerical simulations

Atoms

Cavity light

Synthetic field



[Ballantine *et al.* arXiv:1608.07246]

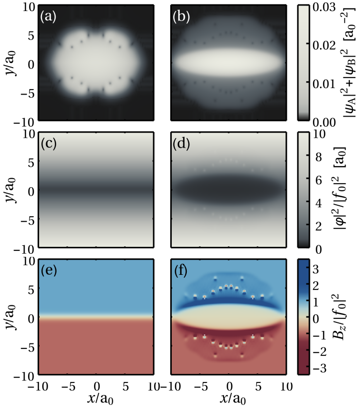
- Consider $f(\mathbf{r})$ such that $|\varphi|^2 \propto y$.
- Without feedback ($\mathcal{E}_\Delta = 0$) for field
- With feedback

Meissner-like physics: numerical simulations

Atoms

Cavity light

Synthetic field



[Ballantine *et al.* arXiv:1608.07246]

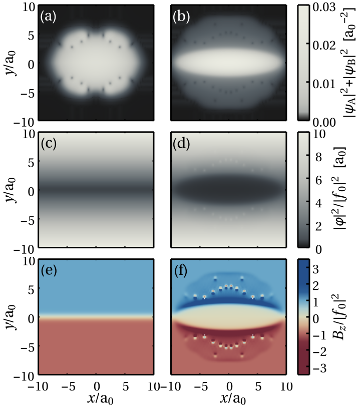
- Consider $f(\mathbf{r})$ such that $|\varphi|^2 \propto y$.
- Without feedback ($\mathcal{E}_\Delta = 0$) for field
- With feedback
  - Field expelled
  - Cloud shrinks

Meissner-like physics: numerical simulations

Atoms

Cavity light

Synthetic field



[Ballantine *et al.* arXiv:1608.07246]

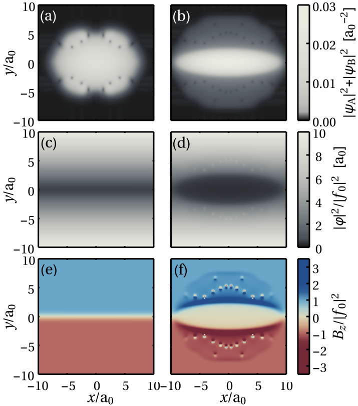
- Consider $f(\mathbf{r})$ such that $|\varphi|^2 \propto y$.
- Without feedback ($\mathcal{E}_\triangle = 0$) for field
- With feedback
  - Field expelled
  - Cloud shrinks

Meissner-like physics: numerical simulations

Atoms

Cavity light

Synthetic field

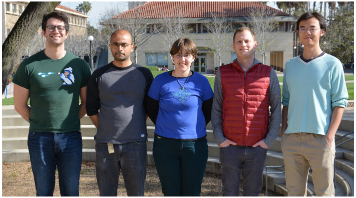


[Ballantine *et al.* arXiv:1608.07246]

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

Acknowledgments

Experiment (Stanford):
Benjamin Lev



STANFORD UNIVERSITY
GORDON AND BETTY MOORE FOUNDATION
the David & Lucile Packard FOUNDATION

Theory:

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

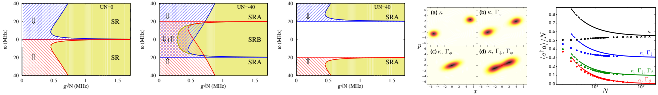
Sarang Gopalakrishnan (CUNY)
Surya Ganguli, Jordan Cotler (Stanford)
Peter Kirton, Kyle Ballantine, Laura Staffini (St Andrews)

The Leverhulme Trust

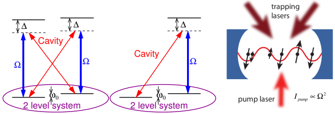
EPSRC
Engineering and Physical Sciences Research Council

Summary

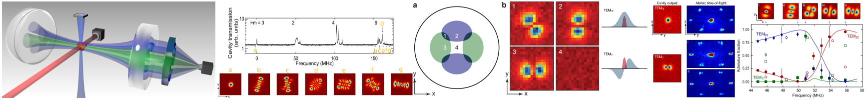
- Open Dicke model, $\kappa, \Gamma_\phi, \Gamma_\downarrow$ [Kirton & JK, arXiv:1611.03342]



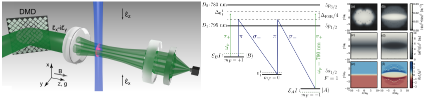
- Many possibilities of multimode cavity QED



- Supermode polariton condensation [Kollár *et al.* arXiv:1606.04127]



- Meissner like effect [Ballantine *et al.* arXiv:1608.07246]



1. Introduction: Tunable multimode Cavity QED

2. Single mode cavity QED
   - Spin-non-conserving loss

3. Multimode cavity QED experiments
   - Experimental setup
   - Supermode density wave polariton condensation

4. Theoretical possibilities
   - Spin glass, Hopfield memory
   - Meissner-like effect

5 Training Hopfield

How to train your atoms

- Input/output by cavity modes, $Q_\mu = \langle \hat{a}_\mu \rangle$

$$H_{\text{eff}} = -\sum_\mu \Delta_\mu a^\dagger_\mu a_\mu + \sum_n \frac{\omega_0}{2}\sigma^z_n + E_P \sum_{\mu,n} \Xi_\mu(\mathbf{r}_n)\sigma^x_n(a_\mu + a^\dagger_\mu) + \sum_\mu f_\mu a^\dagger_\mu + \text{H.c.}$$

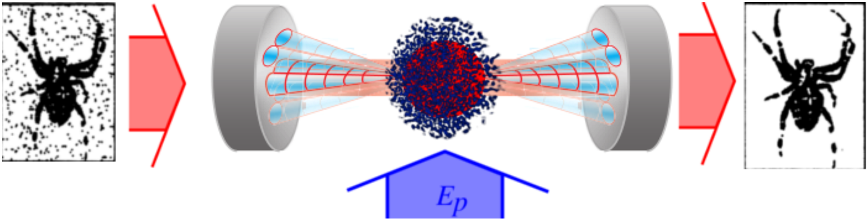
- Effective problem:

$$H_{\text{eff}} = -E_P \sum_\mu (f_\mu + Q_\mu)^2, \quad Q_\mu = \sum_n \Xi_\mu(\mathbf{r}_n)\sigma^x_n$$

How to train your atoms

- Input/output by cavity modes, $Q_\mu = \langle \hat{a}_\mu \rangle$

$$H_{\text{eff}} = -\sum_\mu \Delta_\mu a^\dagger_\mu a_\mu + \sum_n \frac{\omega_0}{2}\sigma^z_n + E_P \sum_{\mu,n} \Xi_\mu(\mathbf{r}_n)\sigma^x_n(a_\mu + a^\dagger_\mu)$$
$$+ \sum_\mu f_\mu a^\dagger_\mu + \text{H.c.}$$



- Effective problem:

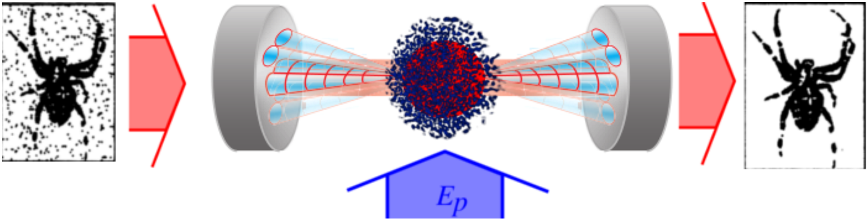
$$H_{\text{eff}} = -E_P \sum_\mu (f_\mu + Q_\mu)^2, \quad Q_\mu = \sum_n \Xi_\mu(\mathbf{r}_n)\sigma^x_n$$

How to train your atoms

- Input/output by cavity modes, $Q_\mu = \langle \hat{a}_\mu \rangle$

$$H_{\text{eff}} = -\sum_\mu \Delta_\mu a_\mu^\dagger a_\mu + \sum_n \frac{\omega_0}{2}\sigma_n^z + E_P \sum_{\mu,n} \Xi_\mu(\mathbf{r}_n)\sigma_n^x(a_\mu + a_\mu^\dagger)$$

$$+ \sum_\mu f_\mu a_\mu^\dagger + \text{H.c.}$$

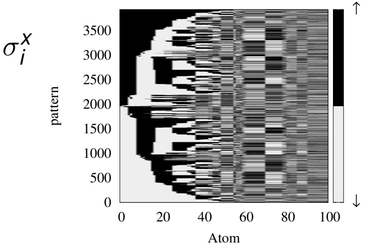


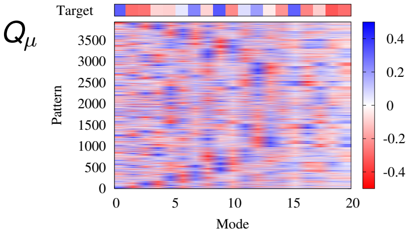
- Effective problem:

$$H_{\text{eff}} = -E_p \sum_\mu (f_\mu + Q_\mu)^2, \quad Q_\mu = \sum_n \Xi_\mu(\mathbf{r}_n)\sigma_n^x$$

How to train your atoms

- Before training, many fixed points

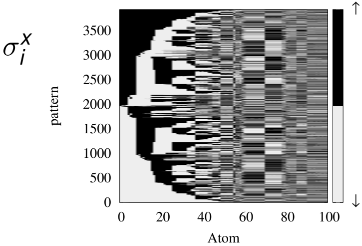


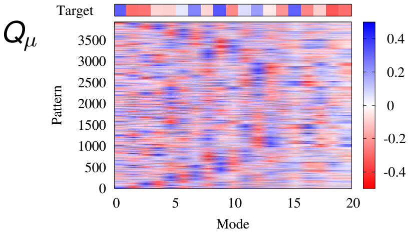


- Train by moving atoms:
- Recover corrupted image

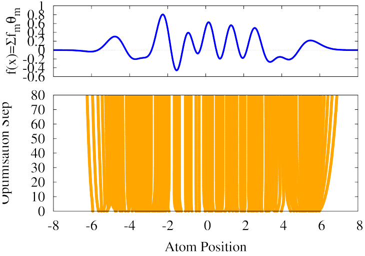
How to train your atoms

- Before training, many fixed points





- Train by moving atoms:

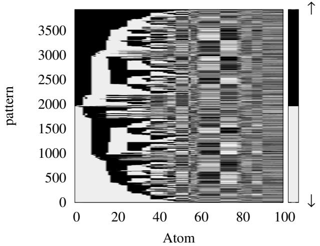


- Recover corrupted image

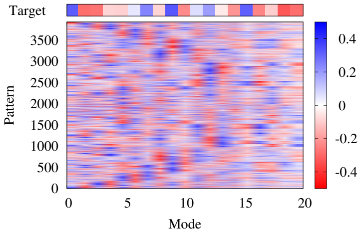
How to train your atoms

- Before training, many fixed points

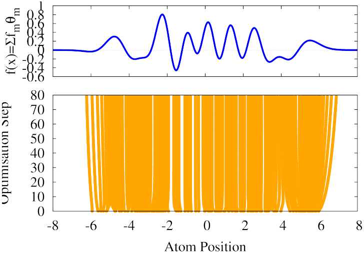
σ_i^x



Q_μ



- Train by moving atoms:



- Recover corrupted image