Nonequilibrium quantum condensates: from microscopic theory to macroscopic phenomenology

J. M. J. Keeling
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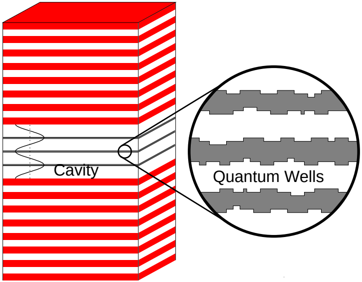
Research Council

Pembroke College

Microcavity Polaritons



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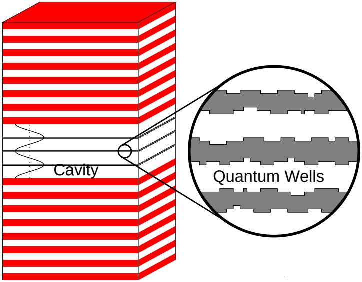

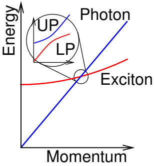

[Pekar, JETP(1958)]
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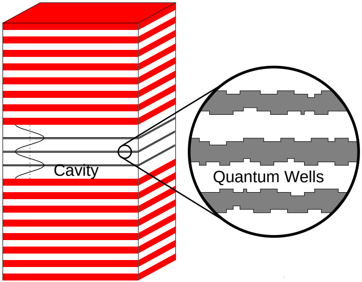

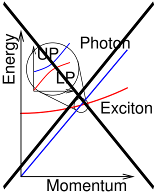

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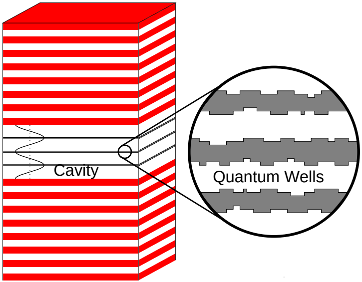

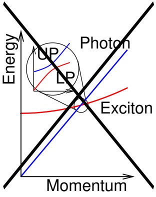

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Cavity photons:

$$\omega_k = \sqrt{\omega_0^2 + c^2 k^2}$$
$$\simeq \omega_0 + k^2/2m^*$$
$$m^* \sim 10^{-4} m_e$$

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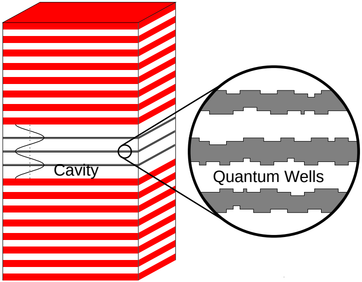

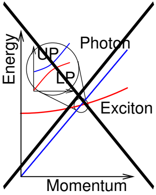

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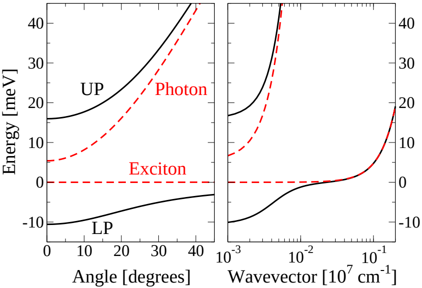
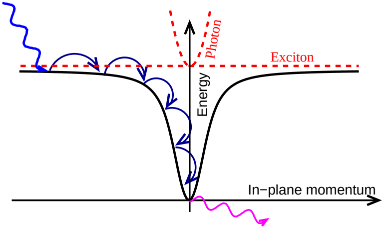
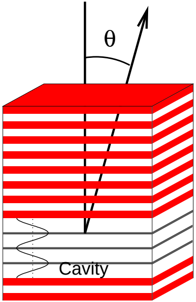
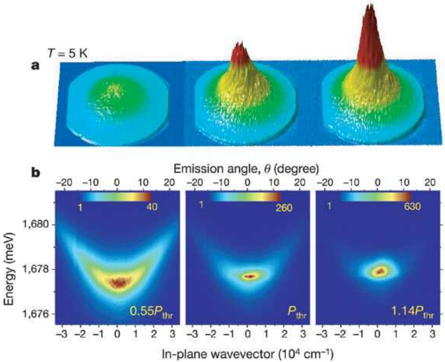


Non-equilibrium: flux and baths

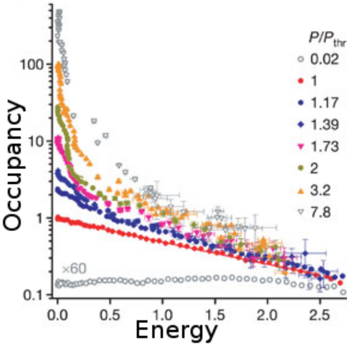




Polariton experiments: Momentum/Energy distribution

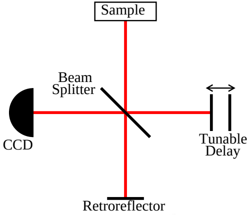


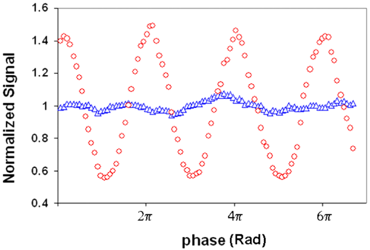
[Kasprzak, et al., Nature, 2006]



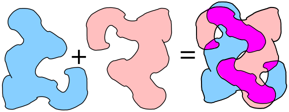
Polariton experiments: Coherence

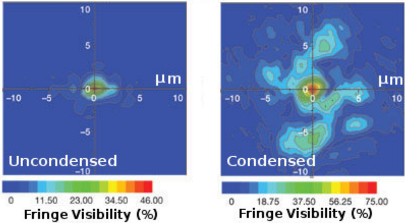
Basic idea:





Coherence map:

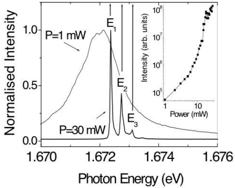


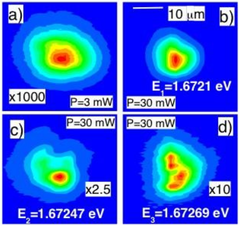


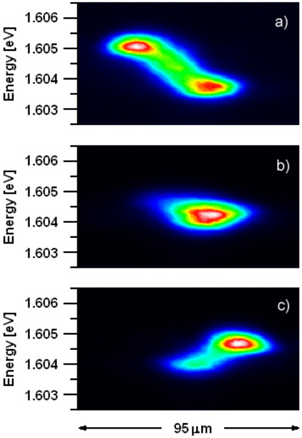
[Kasprzak, et al., Nature, 2006]

Other polariton condensation experiments

- Stress traps for polaritons
  [Balili *et al* Science 316 1007 (2007)]
- Temporal coherence and line narrowing
  [Love *et al* Phys. Rev. Lett. 101 067404 (2008)]

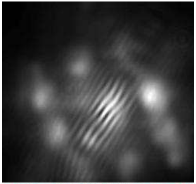




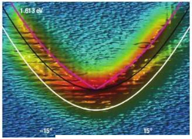


Other polariton condensation experiments

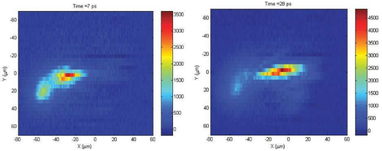
- Quantised vortices in disorder potential
  [Lagoudakis *et al* Nature Phys. 4, 706 (2008)]



- Changes to excitation spectrum
  [Utsunomiya *et al* Nature Phys. 4 700 (2008)]



- Soliton propagation
  [Amo *et al* Nature 457 291 (2009)]
- Driven superfluidity
  [Amo *et al* Nature Phys. (2009)



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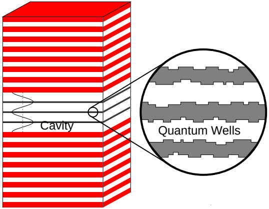
Excitons in a disorderd Quantum well



Exciton states in disorder:

$$\left[-\frac{\nabla^2_{\mathbf{R}}}{2m_X} + V(\mathbf{R})\right]\Phi_\alpha(\mathbf{R}) = \varepsilon_\alpha \Phi_\alpha(\mathbf{R})$$

$V(\vec{R})$ smoothed by exciton Bohr radius

[PRL 96 066405 (2006); PRB 76 115326 (2007)]

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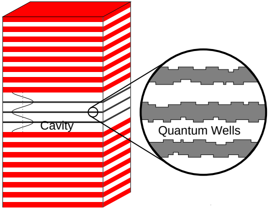

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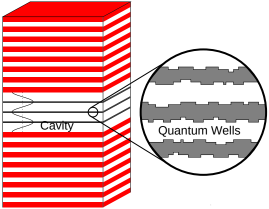

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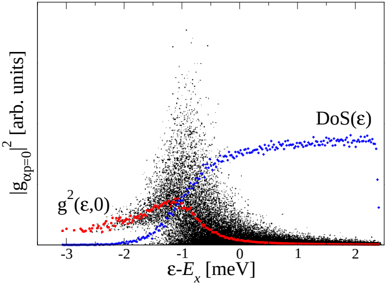

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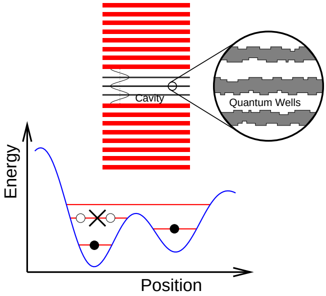
Polariton system model

Polariton model

- Disorder-localised excitons
- Treat disorder sites as two-level (exciton/no-exciton)
- Propagating (2D) photons
- Exciton–photon coupling g.



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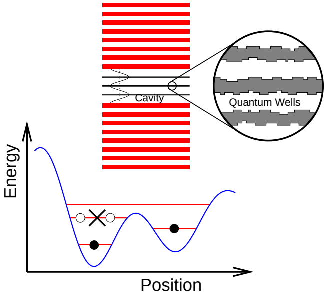
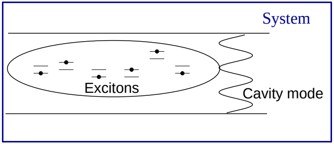


$$H_{\text{sys}} = \sum_{\mathbf{k}} \omega_{\mathbf{k}} \psi^{\dagger}_{\mathbf{k}} \psi_{\mathbf{k}} + \sum_{\alpha} \left[\epsilon_{\alpha} \left(b^{\dagger}_{\alpha} b_{\alpha} - a^{\dagger}_{\alpha} a_{\alpha} \right) + \frac{1}{\sqrt{\text{Area}}} g_{\alpha,\mathbf{k}} \psi_{\mathbf{k}} b^{\dagger}_{\alpha} a_{\alpha} + \text{H.c.} \right]$$



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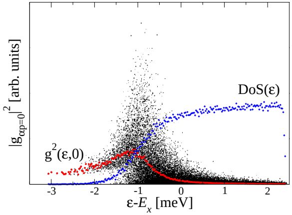

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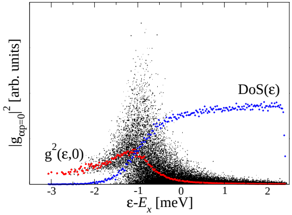
Mean-field theory:
Self-consistent polarisation and field

$$\left[i\partial_t + \omega_0 - \frac{\nabla^2}{2m} \right] \psi = \frac{1}{\sqrt{A}} \sum_\alpha g_\alpha P_\alpha$$



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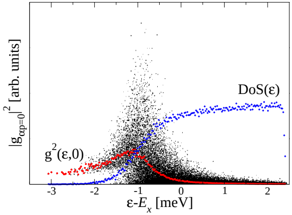

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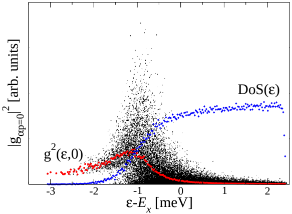

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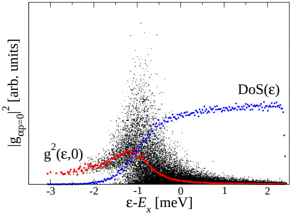

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$$\rho = |\psi|^2 + \frac{1}{A} \sum_\alpha \left[\frac{1}{2} - \frac{\epsilon_\alpha - \mu}{4E_\alpha} \tanh(\beta E_\alpha) \right]$$

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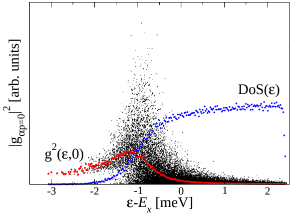

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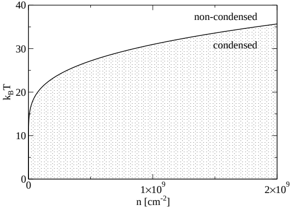

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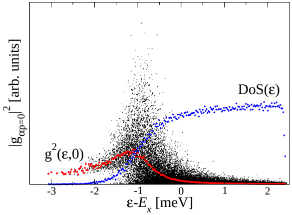

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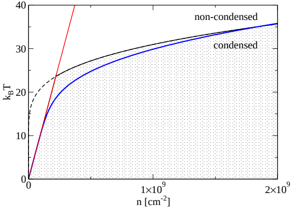

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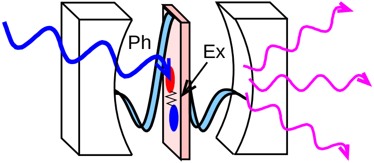

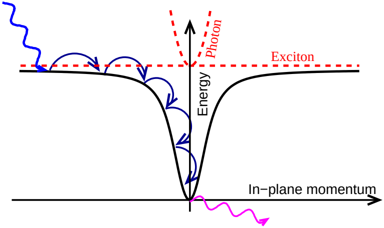

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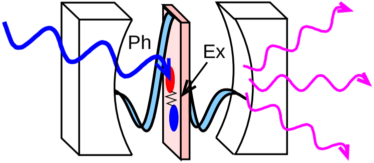

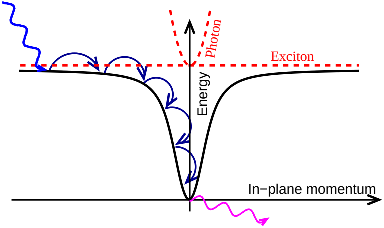

	Lifetime	Thermalisation
Atoms	10s	10ms
Excitons[a]	50ns	0.2ns
Polaritons	5ps	0.5ps
Magnons[b]	1μs(??)	100ns(?)

[a] Coupled quantum wells. [Hammack et al PRB 76 193308 (2007)]
[b] Yttrium Iron Garnett. [Demokritov et al, Nature 443 430 (2007)]

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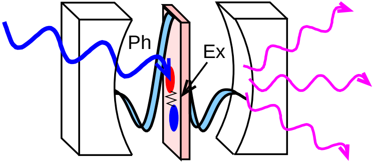
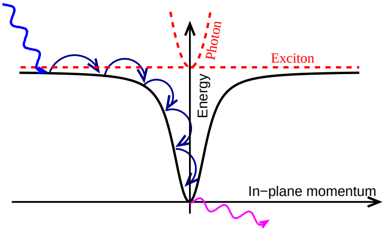
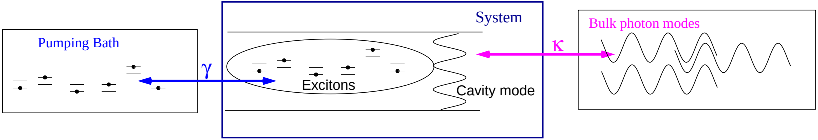




	Lifetime	Thermalisation	Linewidth	Temperature	
Atoms	10s	10ms	2.5×10^{-13}meV	10^{-8}K	10^{-9}meV
Excitons[a]	50ns	0.2ns	5×10^{-5}meV	1K	0.1meV
Polaritons	5ps	0.5ps	0.5meV	20K	2meV
Magnons[b]	1μs(??)	100ns(?)	2.5×10^{-6}meV	300K	30meV

[a] Coupled quantum wells. [Hammack et al PRB 76 193308 (2007)]
[b] Yttrium Iron Garnett. [Demokritov et al, Nature 443 430 (2007)]

Non-equilibrium model: baths



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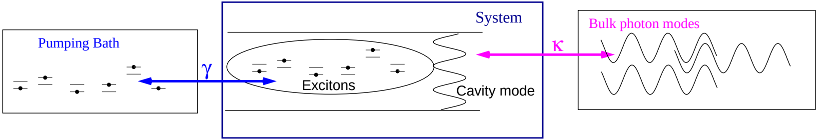

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Schematically: pump γ, decay κ

$$H_{\rm sys,bath} \simeq \sum_{\mathbf{p},\vec{k}} \sqrt{\kappa}\psi_{\mathbf{k}}\Psi^\dagger_{\mathbf{p}} + \sum_{\alpha,\beta}\sqrt{\gamma}\left(a^\dagger_\alpha A_\beta + b^\dagger_\alpha B_\beta\right) + \text{H.c.}$$

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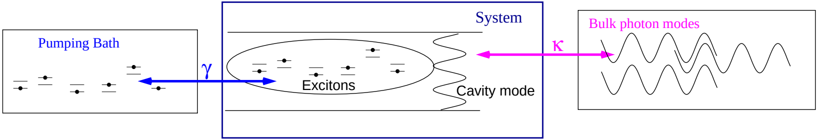

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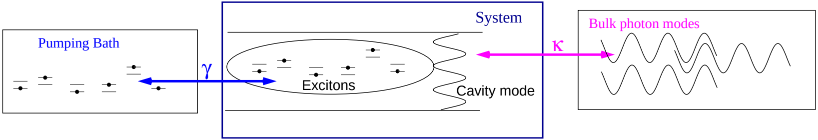

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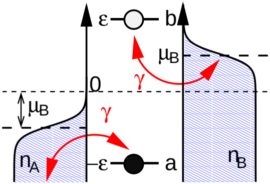

Non-equilibrium theory; mean-field

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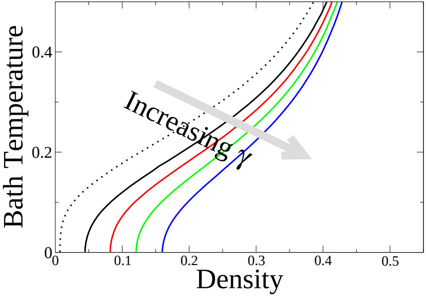

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Overview

Fluctuations $\rightarrow$ Stability, Luminescence, Absorption

Keldysh approach:

$$D^{R,A} = \mp i\theta[\pm(t-t')]\left\langle\left[\psi,\psi^\dagger\right]_-\right\rangle$$

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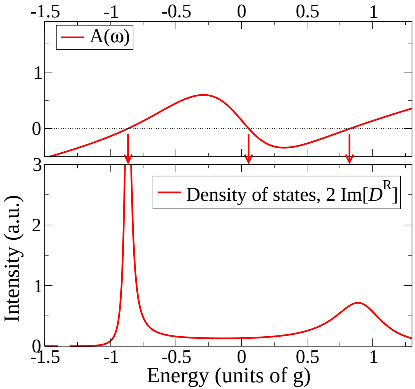

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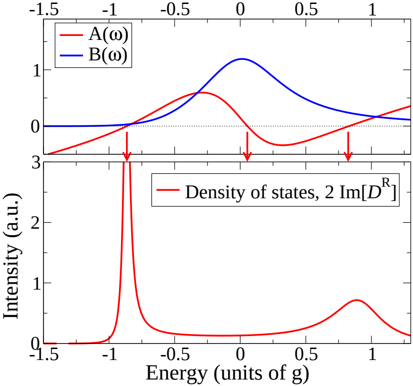

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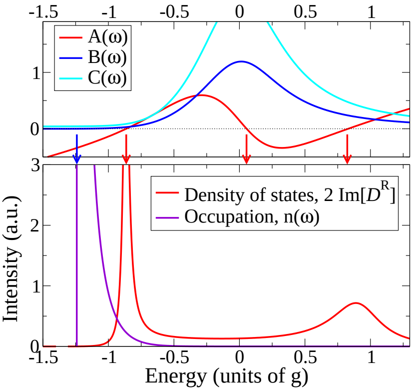

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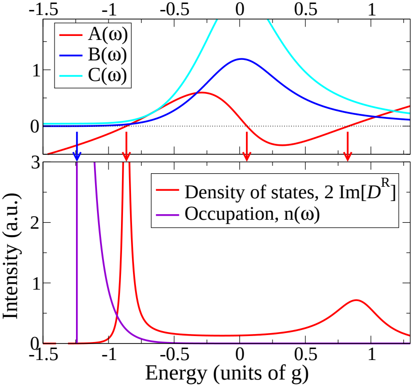
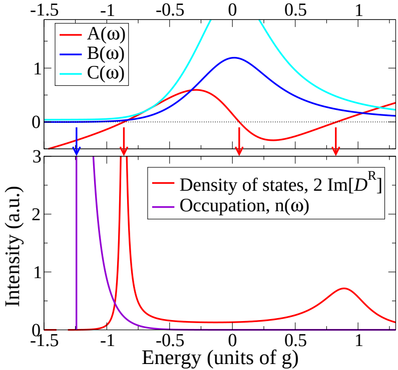


Linewidth, inverse Green's function and gap equation



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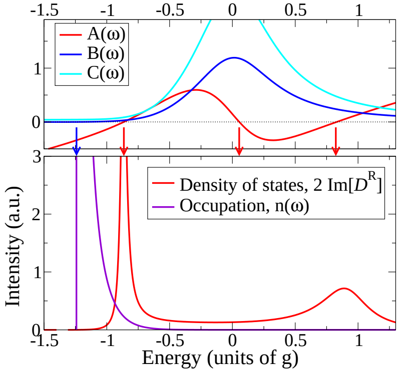
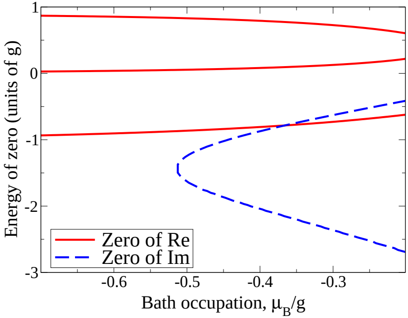
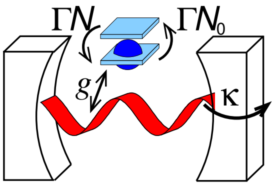




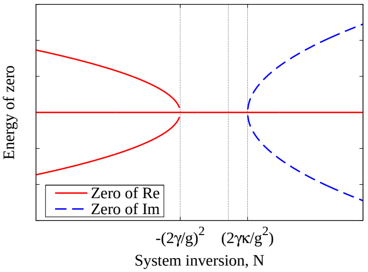
$[\mathcal{D}^R]^{-1}$ for a laser



Maxwell-Bloch equations:

$$\partial_t \psi = -i\omega_k \psi - \kappa\psi + gP$$
$$\partial_t P = -2i\epsilon P - \Gamma P + g\psi N$$
$$\partial_t N = \Gamma(N_0 - N) - 2g(\psi^* P + P^* \psi)$$

$$\left[D^R(\omega)\right]^{-1} = \omega - \omega_k + i\kappa + \frac{g^2 N_0}{\omega - 2\epsilon + i\Gamma}$$



Fluctuations above transition

When condensed

$$\mathrm{Det}\left[D^R(\omega, \mathbf{k})\right]^{-1} = \omega^2 - c^2\mathbf{k}^2$$

Poles:

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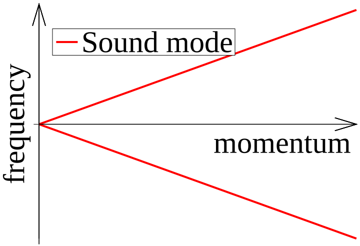

[Szymańska et al., PRL '06; PRB '07]

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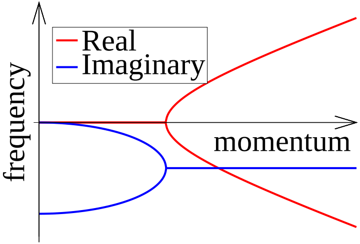

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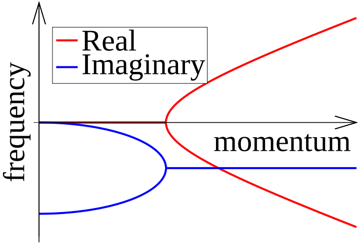

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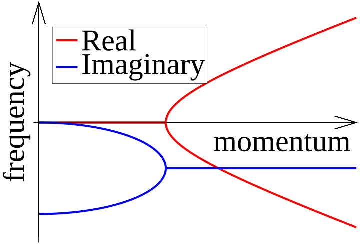

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$$\left\langle \psi^\dagger(\mathbf{r},t)\psi(0,0)\right\rangle \simeq |\psi_0|^2 \exp\left[-\eta\begin{cases}\ln(r/\xi) & r\to\infty, t\simeq 0\\ \frac{1}{2}\ln(c^2t/x\xi^2) & r\simeq, t\to\infty\end{cases}\right]$$

[Szymańska et al., PRL '06; PRB '07]

Finite size effects: Single mode vs many mode

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$\mathcal{D}_{\phi\phi}(t,r,r')$ from sum of phase modes. Study $ct \gg r$ limit:

$$\mathcal{D}_{\phi\phi}(t,r,r) \propto \sum_n^{n_{max}} \int \frac{d\omega}{2\pi} \frac{|\varphi_n(r)|^2(1-e^{i\omega t})}{|(\omega+ix)^2+x^2-(n\Delta)^2|^2}$$

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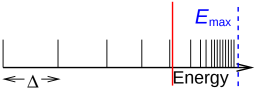
$\Delta \ll \sqrt{x/t} \ll E_{\max}$



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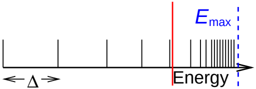

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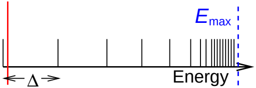

$\mathcal{D}_{\phi\phi} \sim \left(\frac{\pi C}{2x}\right)\left(\frac{t}{2x}\right)$

Overview

Limits of gap equation

Gap equation:

$$(\mu_s - \omega_0 + i\kappa)\,\psi = \chi(\psi, \mu_s)\psi$$

- Local density limit:

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Nonlinear, complex susceptibility $\chi(\psi(r,t))$

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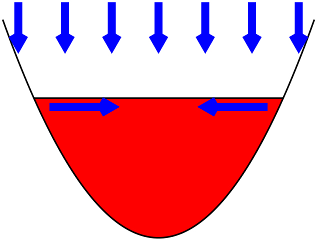

[Keeling & Berloff, PRL, '08]

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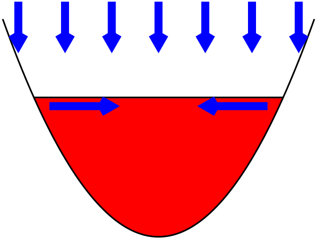

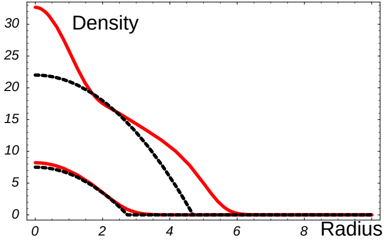

[Keeling & Berloff, PRL, '08]

Stability of Thomas-Fermi solution

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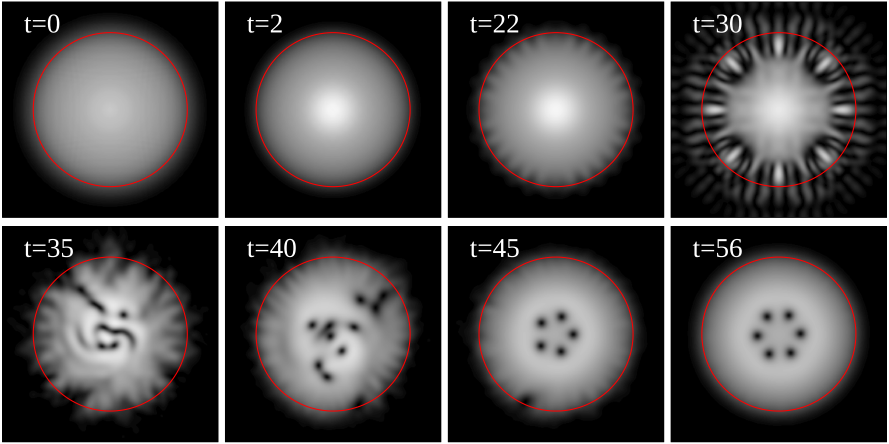
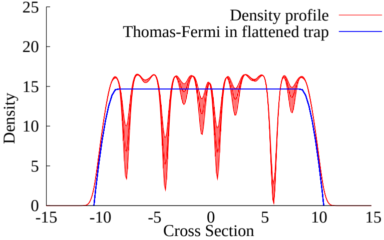
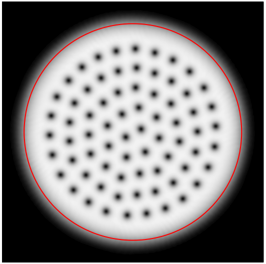


[Keeling & Berloff, PRL, '08]

Why vortices





$$\nabla \cdot [\rho(\mathbf{v} - \Omega \times \mathbf{r})] = \left(\gamma_{net}\Theta(r_0 - r) - \Gamma\rho\right)\rho,$$

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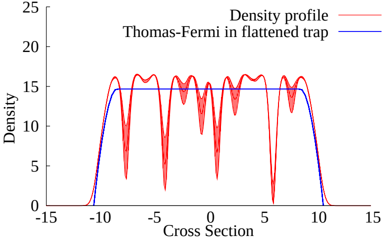

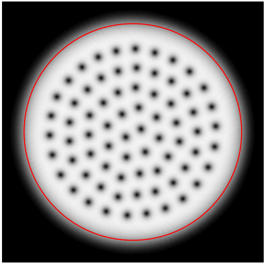

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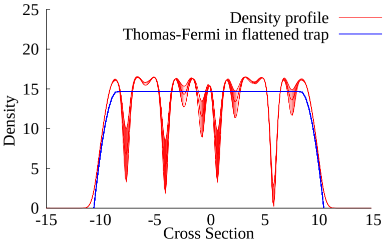

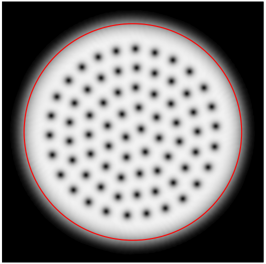

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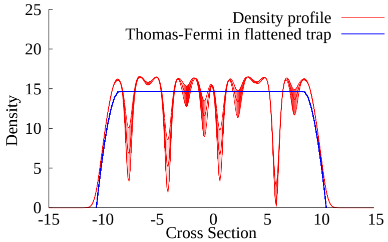

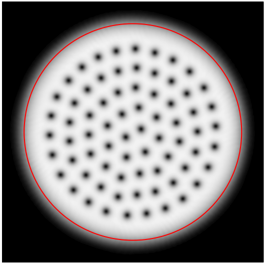

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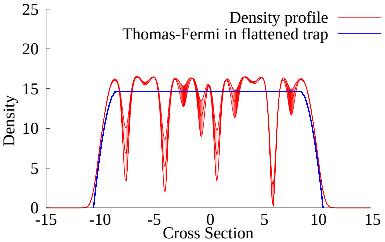

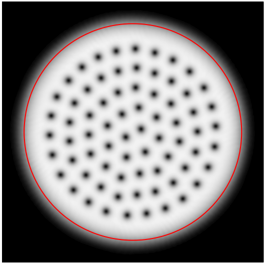

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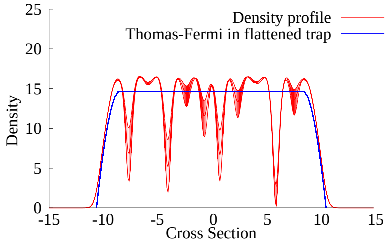

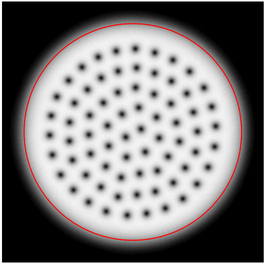

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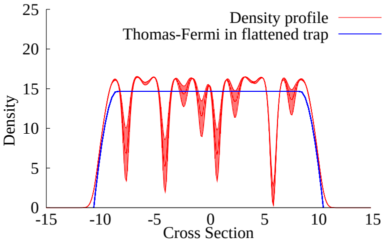

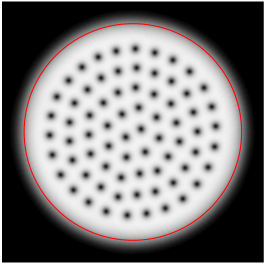

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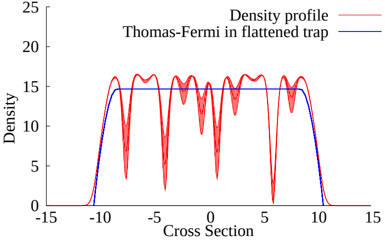

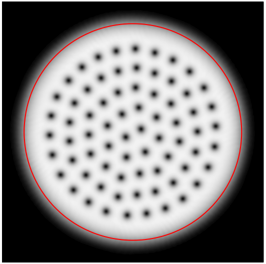

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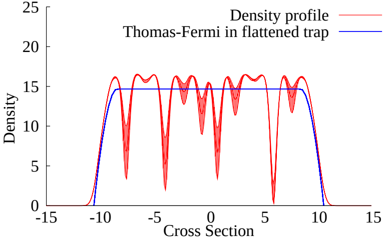

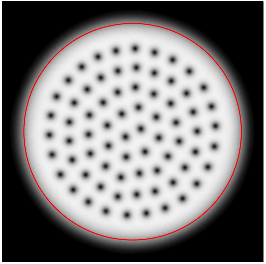

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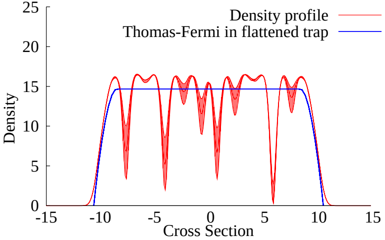

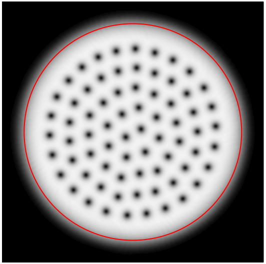

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Overview

Polariton spin degree of freedom

- Left- and Right-circular polarised states.
- Spinor Gross-Pitaevskii equation:

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- Two-mode case (neglect spatial variation): [Wouters PRB '08]
- Many modes — interaction of $J_{\parallel}$ and currents.

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  - Tendency to biexciton formation: U_1
  - Magnetic field: Δ
  - Broken rotation symmetry: J_1
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  - Magnetic field: Δ
  - Broken rotation symmetry: J_1
- Two-mode case (neglect spatial variation): [Wouters PRB '08]
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- Left- and Right-circular polarised states.
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Non-equilibrium spinor system: two-mode model

Write:

$$\psi_L = \sqrt{R+z}e^{i\phi+i\theta/2}, \quad \psi_R = \sqrt{R-z}e^{i\phi-i\theta/2}$$

Josephson regime: $J_1 \ll U_1 R$, $z \ll R$,

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$V(r) = m\omega^2 \frac{r^2}{2}, \quad \gamma_{\text{net}}(r) = J_1 \Theta(r_0 - r).$ $r_0 \le r_{TF}$

Plot $\mu_{L,R} = \partial_t \phi \pm \partial_t \theta / 2$ vs Δ.

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vortices/spin/phPortJ1_0R3303_20_ $\Delta = 3.20$

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vortices/spin/phPortJ1_0R33D3_20_

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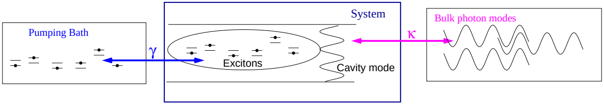
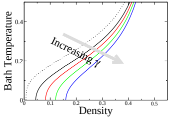
vortices/spin/phPortJ1_0R33D3_25_

$\Delta = 3.25$

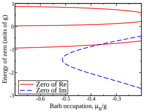
Conclusions

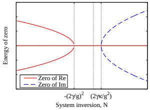
- Effects of pumping on mean-field theory



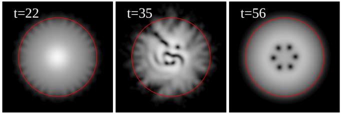


- Instability of normal state
  Translating: condensation ↔ lasing

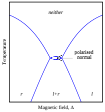




- Modification to Thomas-Fermi profile
  Spontaneous rotating vortex lattice



- Spinor model.
  Steady states & fluctuations.



vortices/spin/phPortJ1_0R

Extra slides

Fluctuation corrections to phase boundary

Fluctuation corrections to density

$$\rho \to \rho_0 + \sum_q \langle \delta\psi^\dagger \delta\psi \rangle$$

In 2D system: modified critical condition:

$$\rho_s = \rho - \rho_{\text{normal}} = \# \frac{2m^2}{\hbar} k_B T$$

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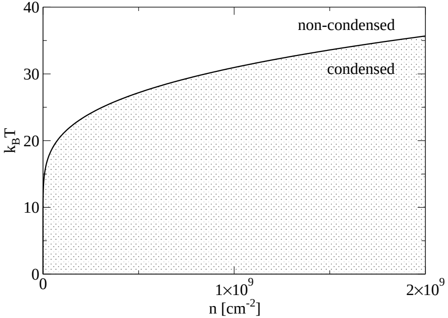

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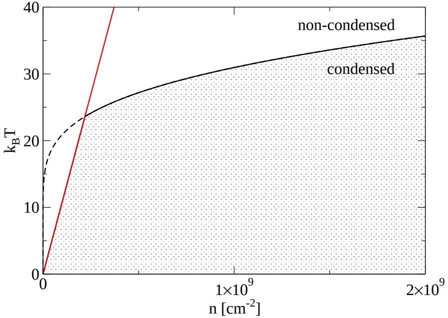

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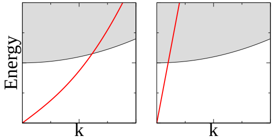

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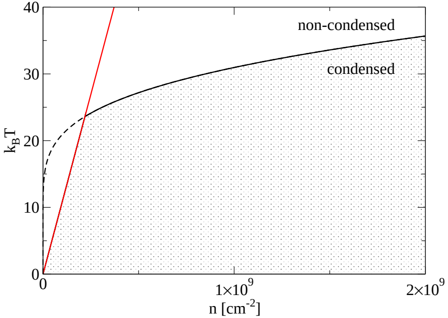

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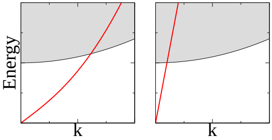

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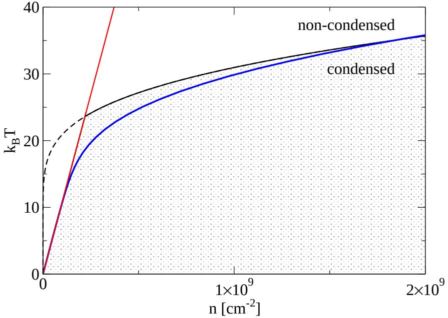

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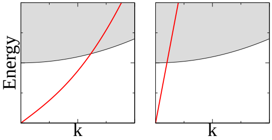

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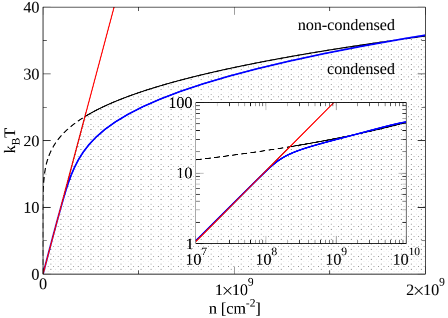

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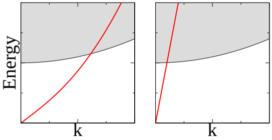

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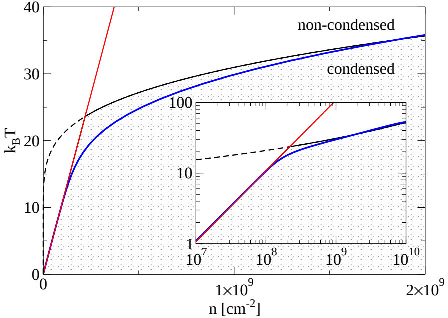
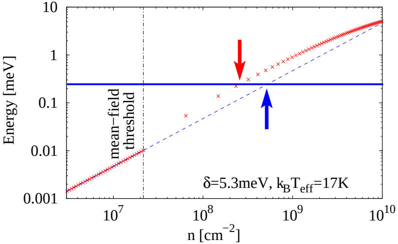


Second BCS crossover at $na_B^2 \simeq 1$

Blueshfit and experimental phase boundary

Blueshift:



Clean limit:

$$\delta E_{\mathrm{LP}} \simeq \mathcal{R}y_{\mathrm{X}} a_{\mathrm{X}}^2 n + \Omega_{\mathrm{R}} a_{\mathrm{X}}^2 n$$

Here: $\Omega_{\mathrm{R}} a_{\mathrm{X}}^2 \to \Omega_{\mathrm{R}} \xi^2$
[PRB 77 235313]

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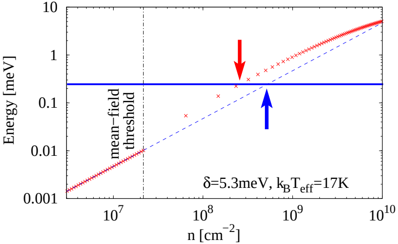

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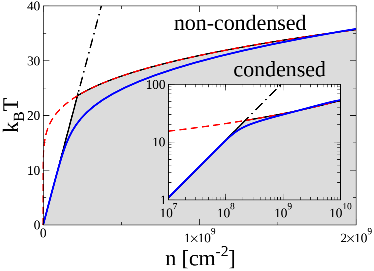

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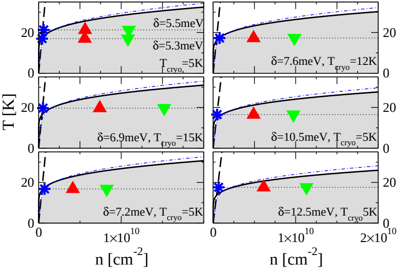
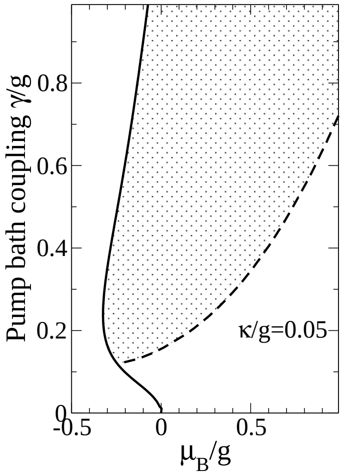


Zero temperature phase diagram

$$\tilde{\omega}_0 - i\kappa = g^2\gamma \sum_\alpha \int \frac{d\nu}{2\pi} \frac{(F_a + F_b)\nu + (F_b - F_a)(\tilde{\epsilon}_\alpha + i\gamma)}{[(\nu - E_\alpha)^2 + \gamma^2][(\nu + E_\alpha)^2 + \gamma^2]}.$$



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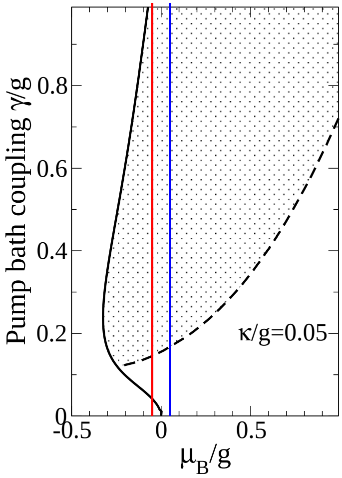

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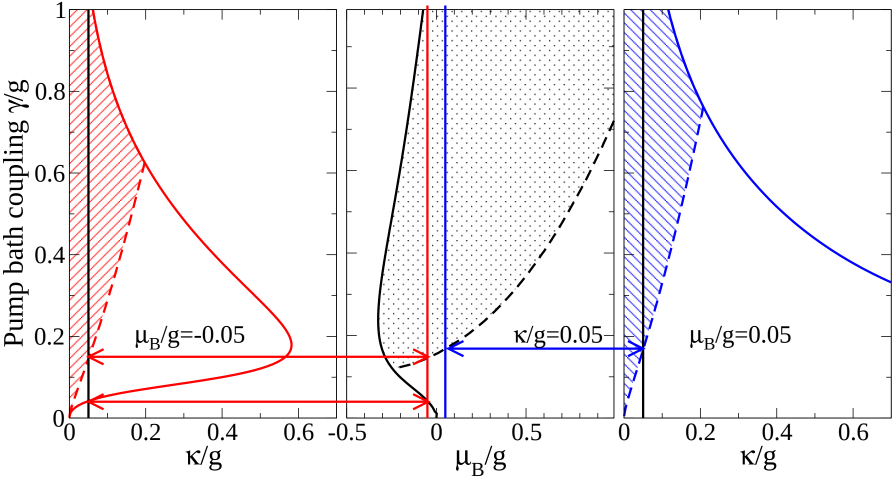

Relating finite-size spectrum to self phase modulation

Single mode spectrum:

$$\mathcal{D}_{\phi\phi}(t, r, r) \propto \int \frac{d\omega}{2\pi} \frac{|\varphi_n(r)|^2 (1 - e^{i\omega t})}{|(\omega + ix)^2 + x^2 - (n\Delta)^2|^2}$$

Connection to Kubo Formula [Eastham and Whittaker, arXiv:0811.4333]

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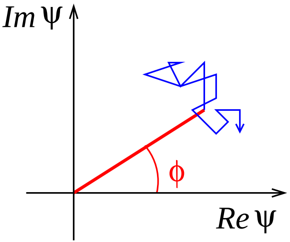

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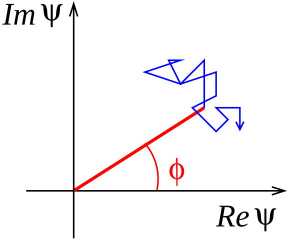

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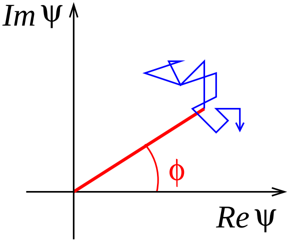

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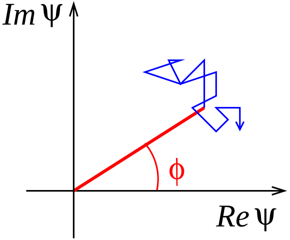

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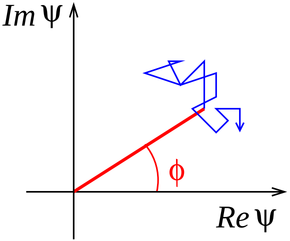

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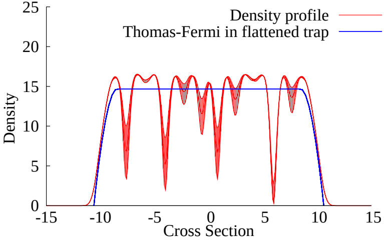
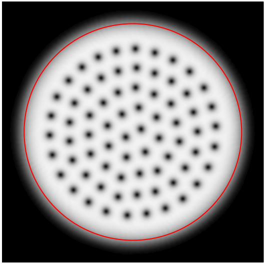
Add weak pumping/decay:

$$\omega_{n,n} \to \omega_{n,m} + i\gamma_{\mathrm{net}}\left[\frac{m(1+2n) + 2n(n+1) - m^2}{2m(1+2n) + 4n(n+1) + m^2}\right]$$

Instability

Why vortices





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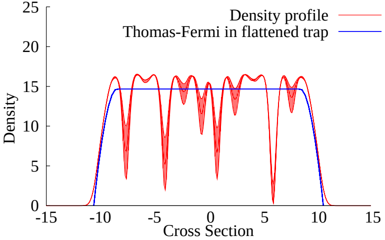

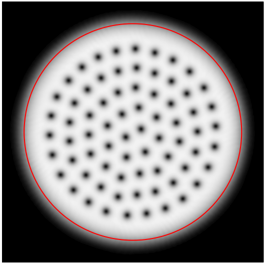

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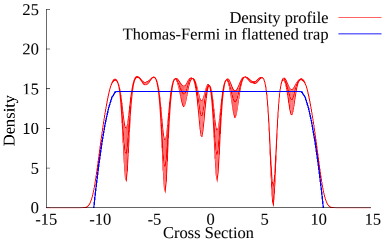

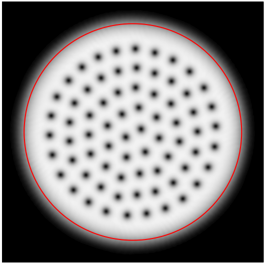

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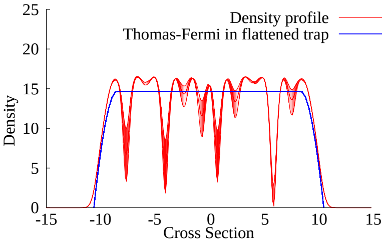

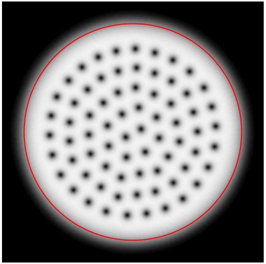

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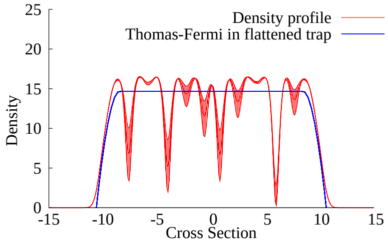

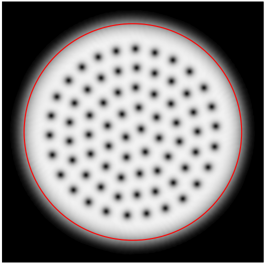

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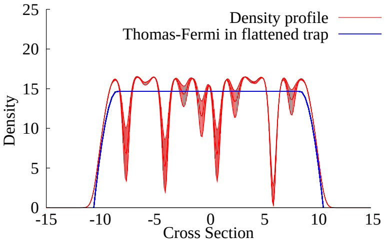

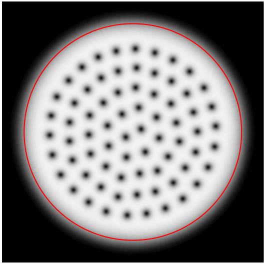

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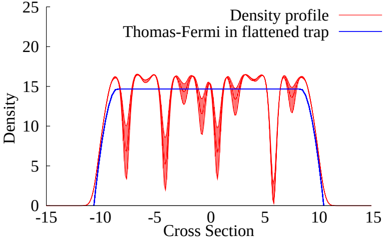

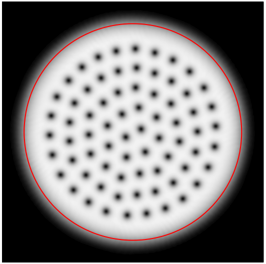

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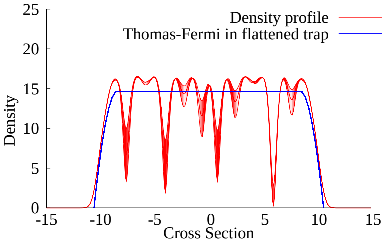

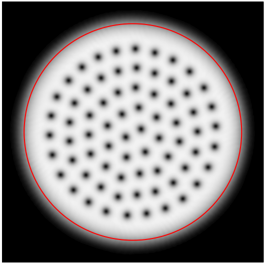

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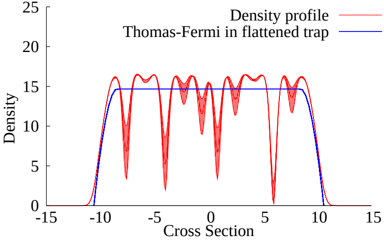

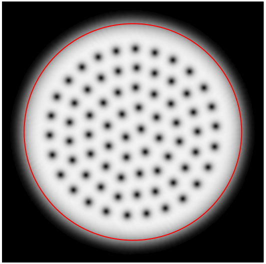

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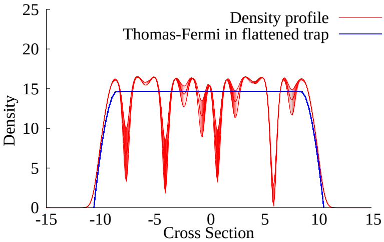

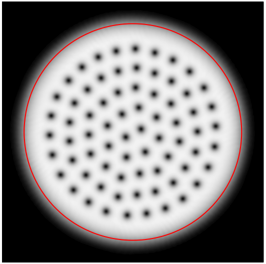

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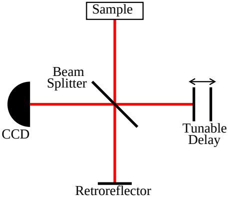
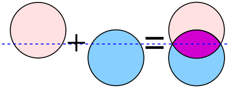
Why vortices: chemical potential vs size

$$\text{Thomas-Fermi}: \mu = f(r_0) \quad \text{Vortex}: \mu = \frac{U\gamma_{\text{net}}}{\Gamma}$$

Observing vortices: fringe pattern





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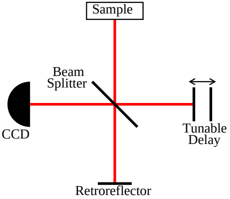

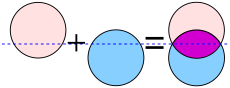

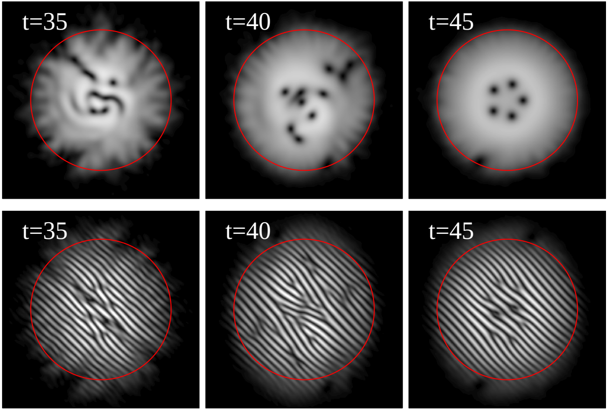

Spin in terms of ~~two~~four-level systems

To include spin, replace 2 level system with 4 levels: $|0\rangle, |L\rangle, |R|\rangle, |LR\rangle$

- Bi-exciton binding $E_{XX} \leftrightarrow U_1$
- Mean-field: find polarisation given ψ_L, ψ_R.
- E_{XX} has weak effect on T_c

[Marchetti *et al* PRB, '08]

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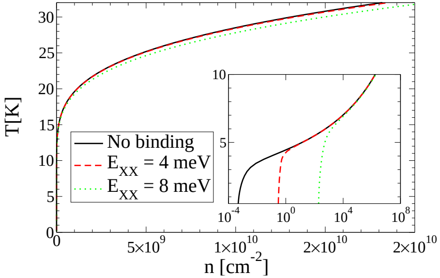

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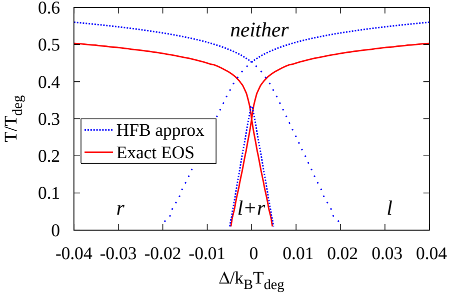
Equilibrium phase diagrams

$J_1 = J_2 = 0$.

For $U_1 = 0.5$, $\Psi_{L,R}$ decouple.



Circular → Eliptical transitions.

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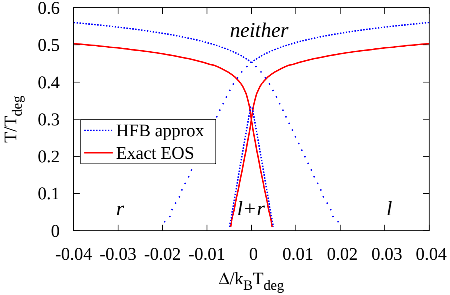

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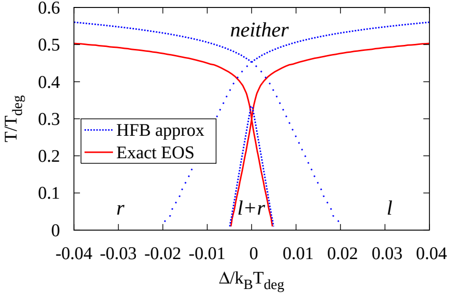

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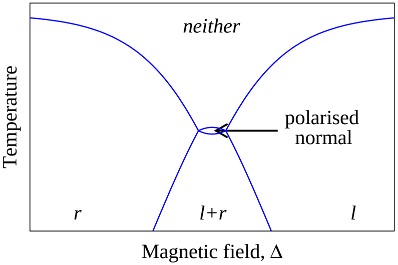

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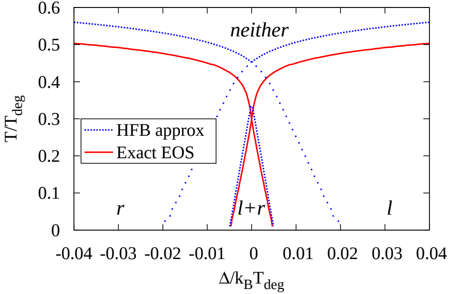

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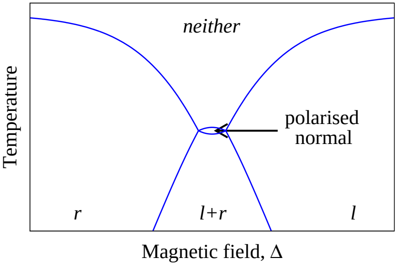

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$J_1 \neq 0$: Eqbm state locked.

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Mathematical outline

- 2D Single component equation of state: $n(\mu, T) = Tf(x = \mu/T)$
- For two components:

$$n_0 = T\left[f\left(\frac{\mu+\Omega}{T}\right) + f\left(\frac{\mu-\Omega}{T}\right)\right]$$

- At critical point for one component:

$$n_0 = T\left[f_c + f\left(x_c + \frac{2\Omega}{T}\right)\right]$$

- Hence:

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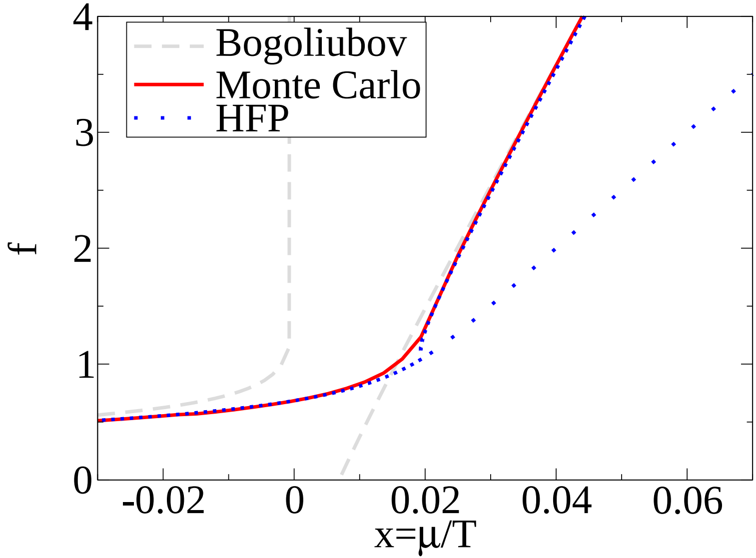

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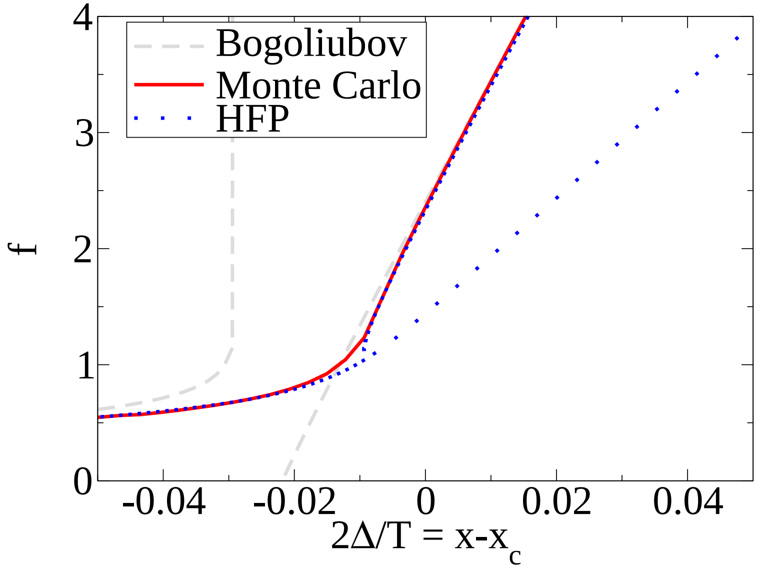

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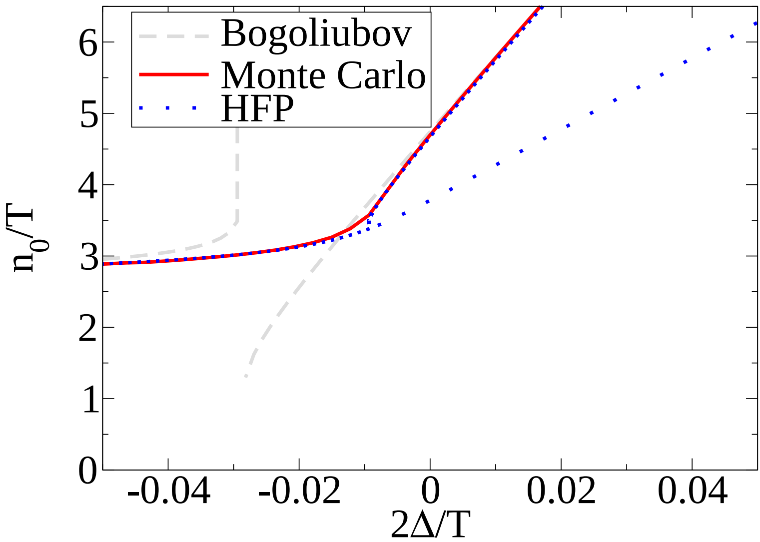

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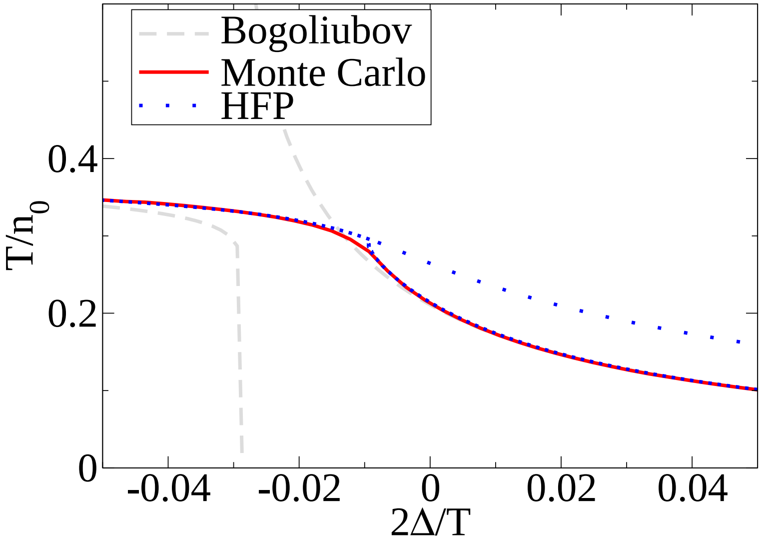

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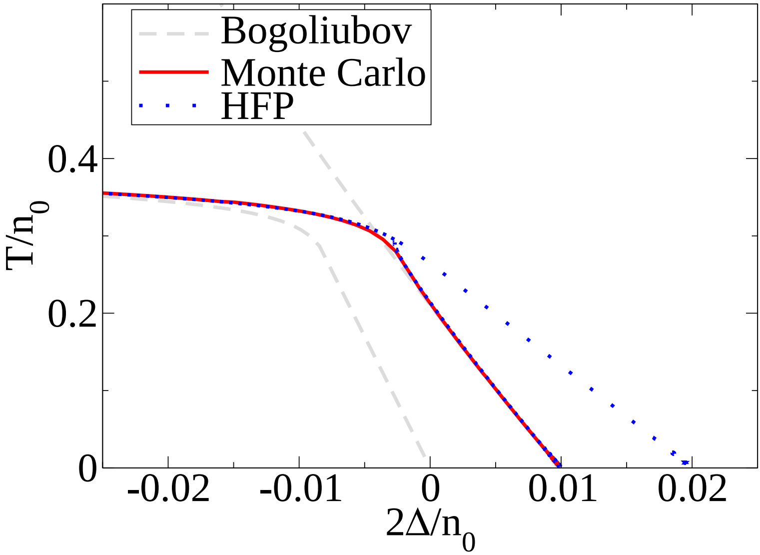

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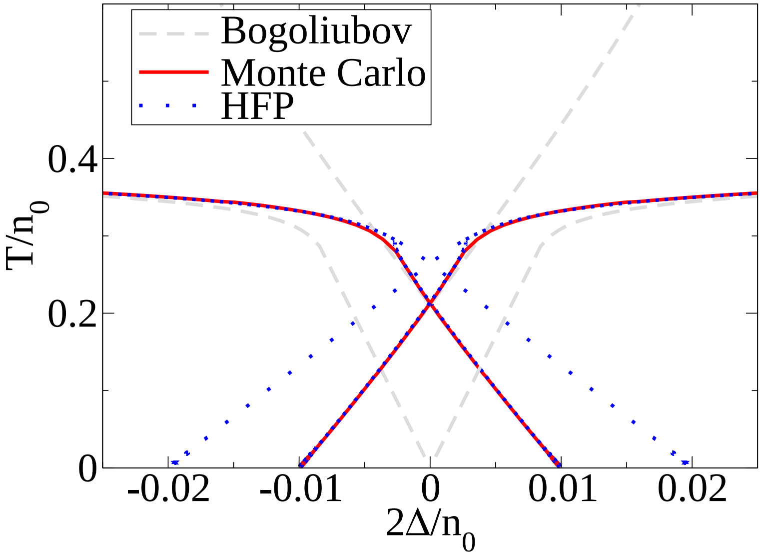

Two-mode model bistability

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$\Delta \gtrsim \Delta_c$: $\omega \simeq [\ln(\Delta - \Delta_c)]^{-1}$

Spatial freedom: Homgeneous case $\Delta < \Delta_c$

$$\ddot{\theta} + 2\gamma_{\text{net}}\dot{\theta} = 8U_1 J_1 R_0 \sin(\theta) - 2\gamma_{\text{net}}\Delta$$

- Steady state condition: $8U_1 J_1 R_0 \sin(\theta) = 2\gamma_{\text{net}}\Delta$
- $\psi_{L,R} \to e^{-i\mu t}\left(\psi^0_{L,R} + u_1 e^{-ik\cdot r+(-i\omega-\kappa)t} + v_1^* e^{ik\cdot r+(i\omega-\kappa)t}\right)$
- Define $\Omega_p^2 = -8U_1 J_1 R_0 \cos(\theta)$. At $k = 0$

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$$\omega - i\kappa = 0, -2i\gamma_{\text{net}}$$

$$-i\gamma_{\text{net}} \pm i\sqrt{\gamma_{\text{net}} - \Omega_p^2}$$

Stability requires $\Omega_p^2 > 0$. If $\Omega_p^2 < \gamma_{\text{net}}$ overdamped.

Spatial variation

Varieties of behaviour possible as $\theta(\mathbf{r})$, not $\bar{\theta}$ needed to define state.

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Plot $J_1 \sin(\theta)$ vs r.

$J_1 = 0.5; r_0 > r_{TF}; \Delta = 6$

$J_1 = 1; r_0 > r_{TF}; \Delta = 6$
Counter-rotating.

Superfluidity

Superfluidity:

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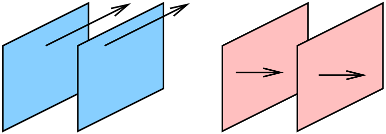

$$\begin{aligned}\chi_{ij}(\omega = 0, \mathbf{q} \to 0) &= \langle J_i(\mathbf{q}) J_j(\mathbf{q})\rangle \\ &= \chi_T(q)\left(\delta_{ij} - \frac{q_i q_j}{q^2}\right) + \chi_L(q)\frac{q_i q_j}{q^2}\end{aligned}$$

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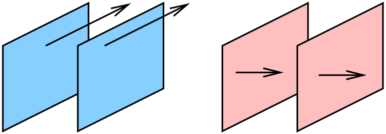

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Superfluid part,
$\rho_s \propto \lim_{q\to 0}(\chi_L - \chi_T)$.

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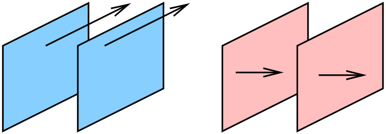

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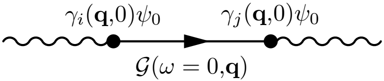
$\Delta\chi_{ij}(q) =$  $+ \dots$

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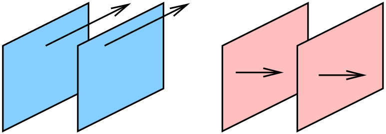

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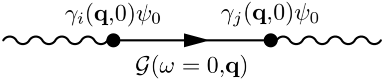

$+ \ldots$

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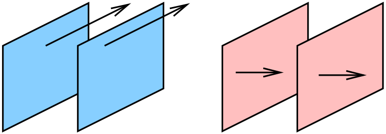

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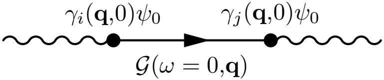
$\Delta\chi_{ij}(q) =$ 

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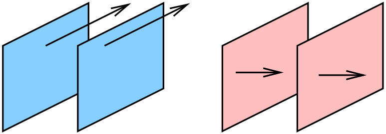

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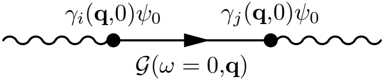
Static ρ_S survies

$$\Delta\chi_{ij}(q) =$$  $+ \ldots$

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