Pattern formation, Superfluidity and Coherence of Polariton Condensates.

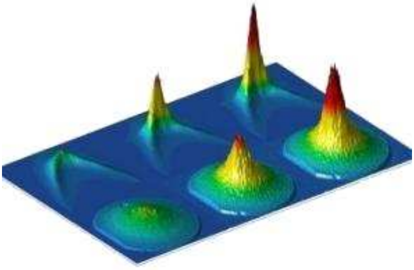
Jonathan Keeling

UMass Amherst, January 2012

Funding: EPSRC
Engineering and Physical Sciences Research Council

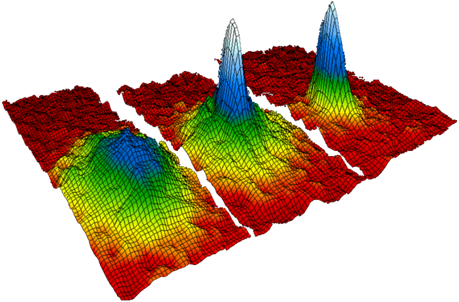
Bose-Einstein condensation: macroscopic occupation

Polaritons. $\sim 20K$



[Kasprzak *et al.* Nature, '06]

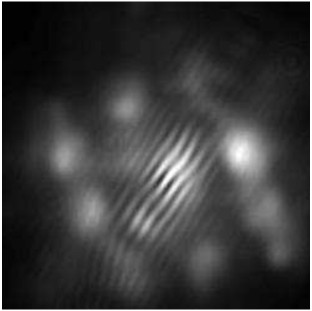
Atoms. $\sim 10^{-7}K$



[Anderson *et al.* Science '95]

Macroscopic coherence: vortices

Polaritons:



[Lagoudakis *et al.* Nat. Phys. '08]

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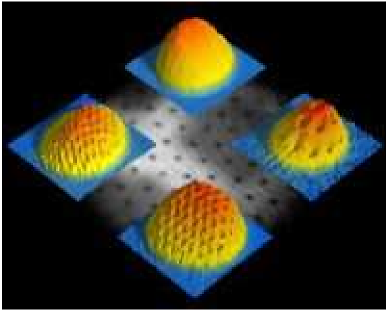
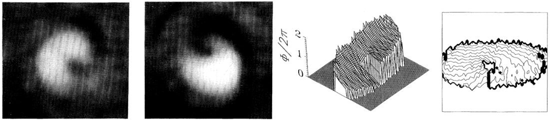


[Abo-Shaeer *et al.* Science '01]

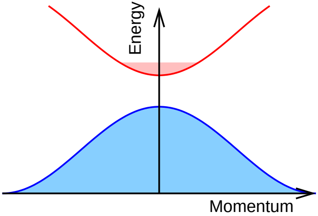
But also, nonlinear optics:

[Arecchi *et al.* PRL '91]



Excitons

Electronic spectrum:



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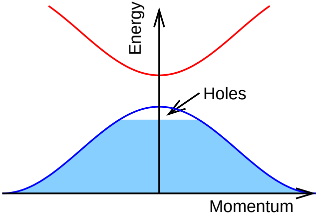

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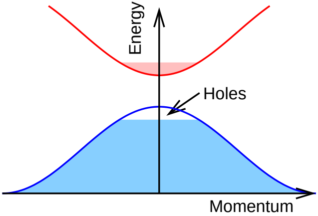

$$H = \sum_i T_i^e + T_i^h + \sum_{ij} V_{ij}^{ee} + V_{ij}^{hh} - V_{ij}^{eh}$$

$$T_i = \frac{p_i^2}{2m_j} \qquad V_{ij} = \frac{e^2}{\epsilon_r |r_i - r_j|}$$

Excitons

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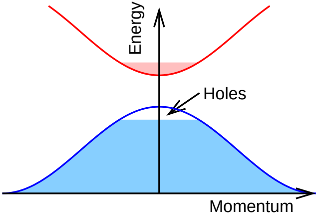

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Bound state: Exciton,
$M \sim m_e + m_h$

Approximate Bose statistics:
$[c_{\text{exciton},k}, c^\dagger_{\text{exciton},k'}] \simeq \delta_{k,k'}$
If $\rho(a_{B,\text{exciton}})^D \ll 1$

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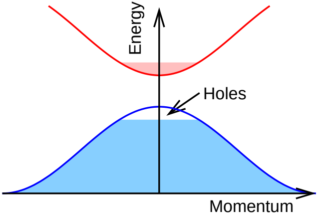

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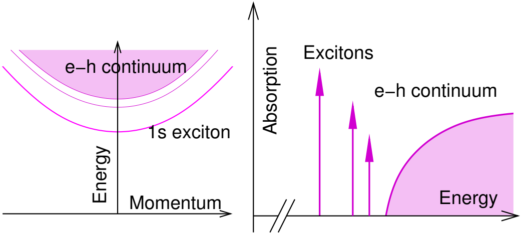
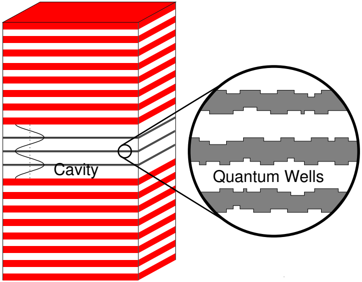
Optical spectrum



Microcavity polaritons



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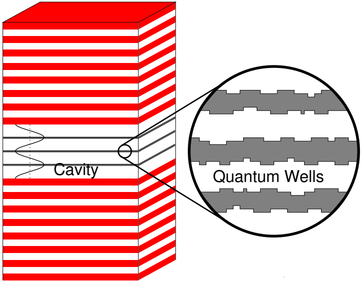
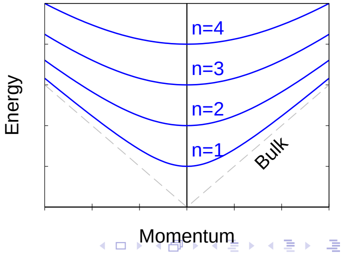


Cavity photons:

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



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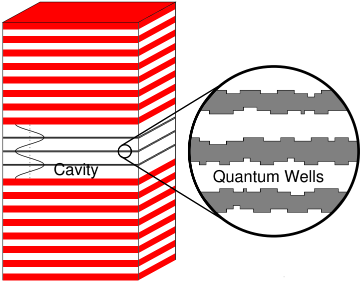

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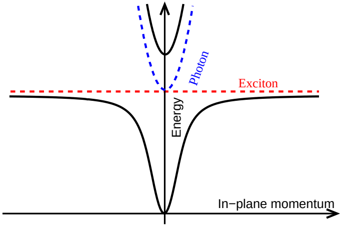

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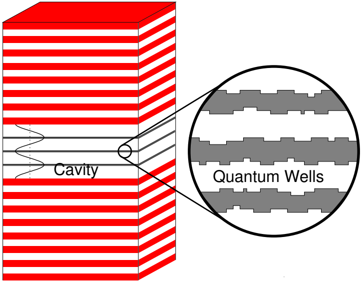

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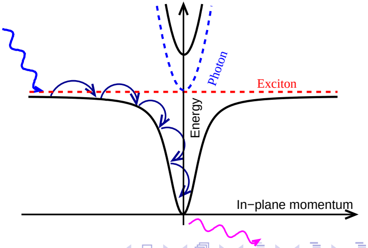

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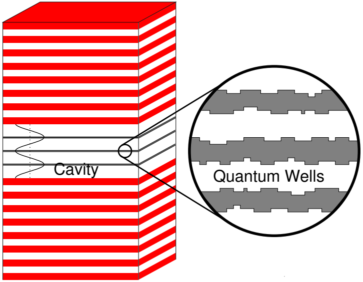

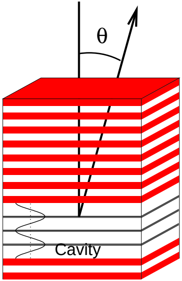

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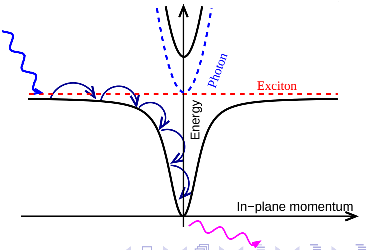
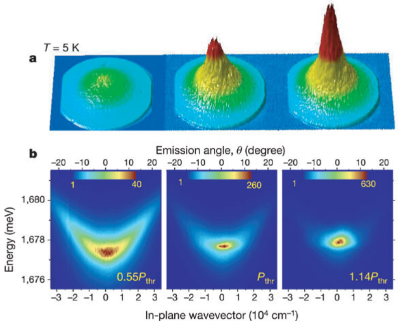
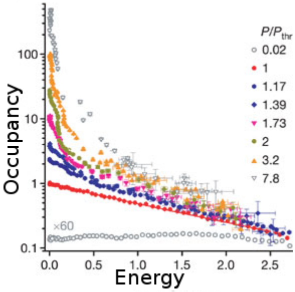


Polariton experiments: occupation and coherence





[Kasprzak, *et al.* Nature, '06]

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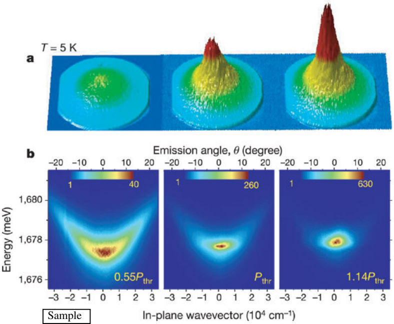
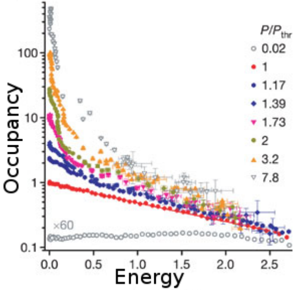
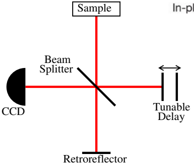
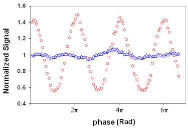
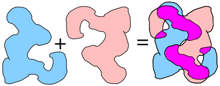


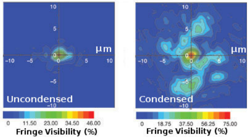






Coherence map:

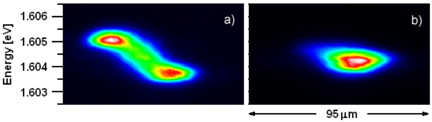




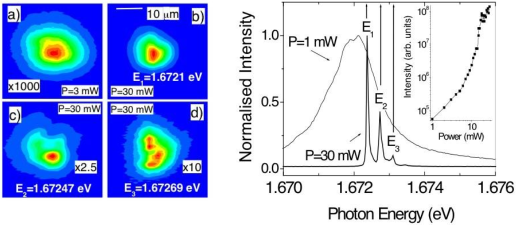
[Kasprzak, *et al.* Nature, ’06]

(Some) other polariton condensation experiments

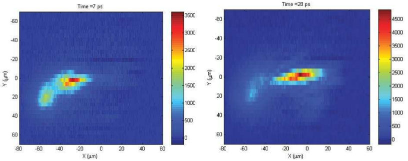
- Polariton traps
  [**Balili *et al.* Science '07)**]



- Multimode condensate and sharp lines
  [**Love *et al.* PRL '08**]

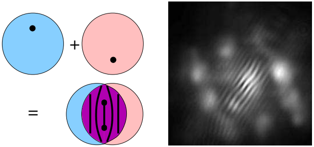


- Wavepacket propagation
  [**Amo *et al.* Nature '09**]

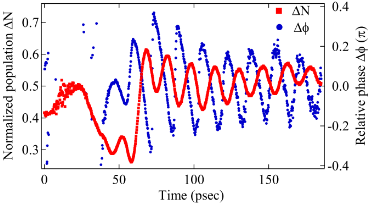


(Some) other polariton condensation experiments

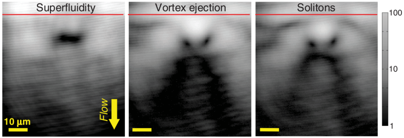
- Quantised vortices
  [**Lagoudakis *et al.* Nat. Phys. '08**. Science '09, PRL '10; Sanvitto *et al.* Nat. Phys. '10; Roumpos *et al.* Nat. Phys. '10]



- Josephson oscillations
  [**Lagoudakis *et al.* PRL '10**]

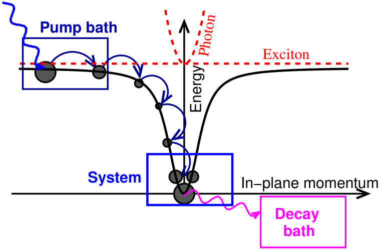


- Pattern formation/Hydrodynamics
  [**Amo *et al.* Science '11**, Nature '09; Wertz *et al.* Nat. Phys '10]



1. Introduction to polariton condensation
   - What are excitons and polaritons
   - Experimental features
   - Approaches to modelling
2. Pattern formation
   - Experiments
   - Modelling pattern formation
3. Superfluidity
   - Non-equilibrium condensate spectrum
   - Experiments and aspects of superfluidity
   - Current-current response function
4. Coherence
   - Experiments
   - Power law decay of coherence

Non-equilibrium approach: Steady state, and fluctuations



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$$H_{\text{sys}} = \sum_k \omega_k \psi_k \psi_k^\dagger + \sum_\alpha g_\alpha (\phi_\alpha^\dagger \psi_k + \text{H.c.}) + H_{\text{ex}}[\phi_\alpha, \phi_\alpha^\dagger]$$

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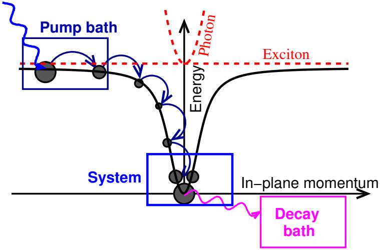

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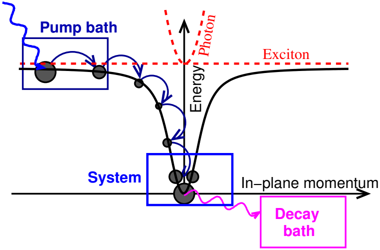

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Self-consistent equation: $(i\partial_t - \omega_0 + i\kappa)\,\psi = \sum_\alpha g_\alpha \langle \phi_\alpha \rangle$

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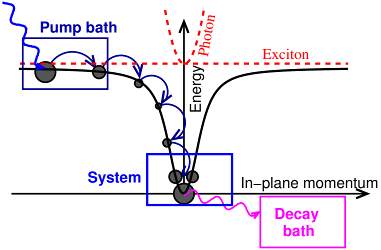

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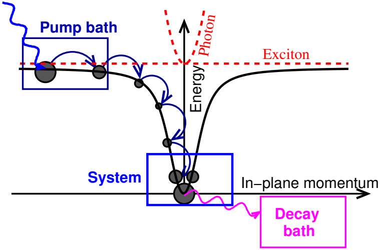

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Fluctuations

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

Non-equilibrium approach: Steady state, and fluctuations

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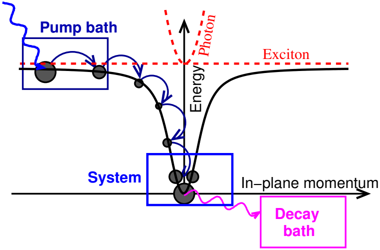

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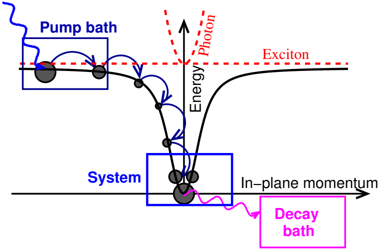

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Non-equilibrium approach: Steady state, and fluctuations

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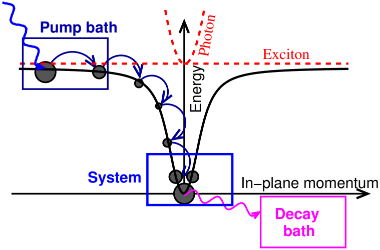

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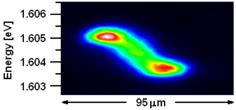
$$D^K(t, t') = -i \left\langle \left[\psi(t), \psi^\dagger(t')\right]_+ \right\rangle \qquad D^K(\omega) = (2n(\omega) + 1)\text{DoS}(\omega)$$

Pattern formation:

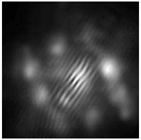
Pattern formation in experiments

Polariton Traps



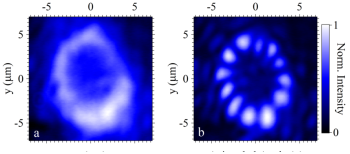
[Balili *et al.* Science ’07]

Vortex formation



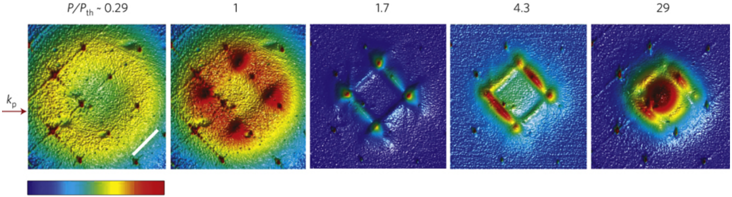
[Lagoudakis *et al.* Nat. Phys ’08]

Elliptical ring pump



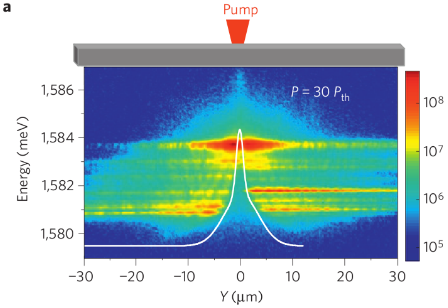
[Manni *et al.* PRL ’11]

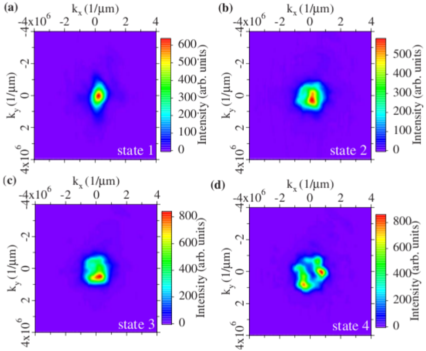
Patterned lattice: Momentum space image



[Kim *et al.* Nat. Phys ’11]

Non-equilibrium features in experiment





Flow from pumping spot
[Wertz *et al.* Nat. Phys. '10]

$|\psi(\mathbf{k})|^2 \neq |\psi(-\mathbf{k})|^2$:
Broken time-reversal symmetry.
[Krizhanovskii *et al.* PRB '09]

Complex Gross-Pitaevskii equation

Steady state equation:

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

- Local density limit:

Complex Gross-Pitaevskii equation

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$$\left(i\partial_t + i\kappa - \left[V(r) - \frac{\nabla^2}{2m}\right]\right)\psi(r) = \chi(\psi(r,t))\psi(r,t)$$

Nonlinear, complex susceptibility

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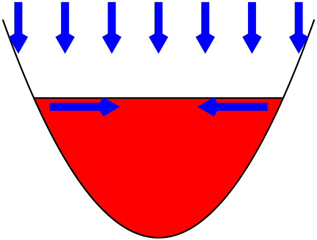
$$i\partial_t\psi = \left[-\frac{\nabla^2}{2m} + V(r) + U|\psi|^2 + i\left(\gamma_{\text{eff}} - \kappa - \Gamma|\psi|^2\right)\right]\psi$$

Gross-Pitaevskii equation: Harmonic trap

$$i\partial_t\psi = \left[-\frac{\nabla^2}{2m} + \frac{m\omega^2}{2}r^2 + U|\psi|^2 + i\left(\gamma_{\text{eff}} - \kappa - \Gamma|\psi|^2\right)\right]\psi$$



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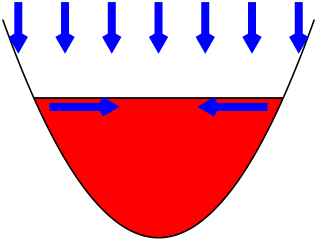
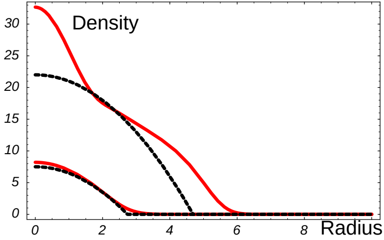
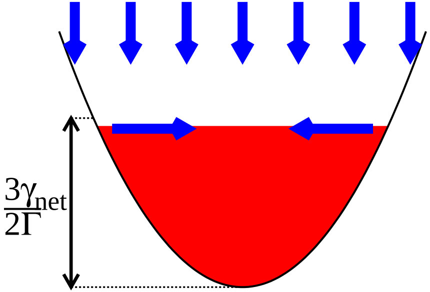




Stability of Thomas-Fermi solution

$$\frac{1}{2}\partial_t \rho + \nabla \cdot (\rho \mathbf{v}) = (\gamma_{\text{net}} - \Gamma\rho)\rho$$



Stability of Thomas-Fermi solution

High m modes: $\delta\rho_{n,m} \simeq e^{im\theta} r^m \ldots$

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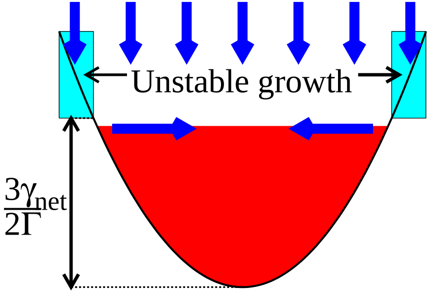

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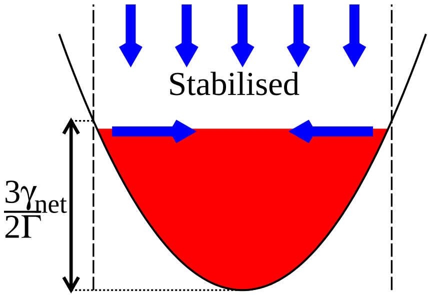

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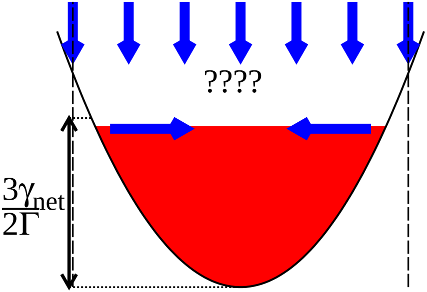
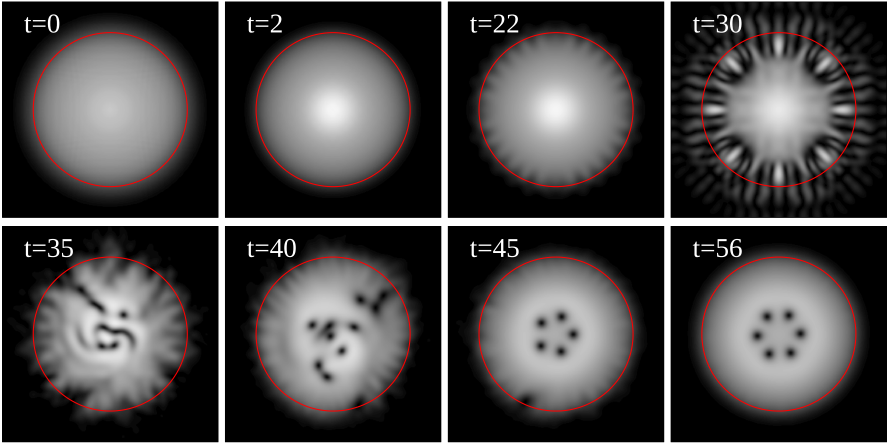
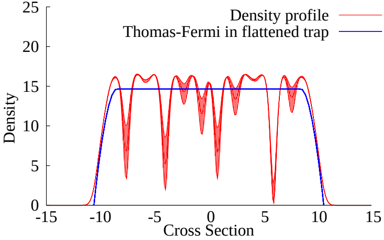


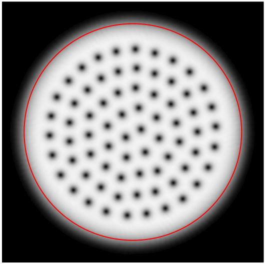
Time evolution:



[Keeling & Berloff PRL '08]

Why vortices





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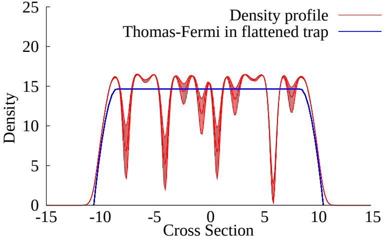

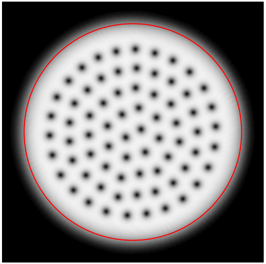

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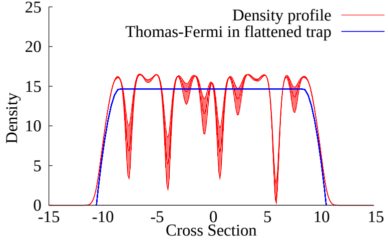

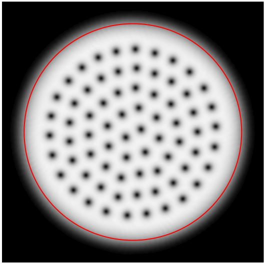

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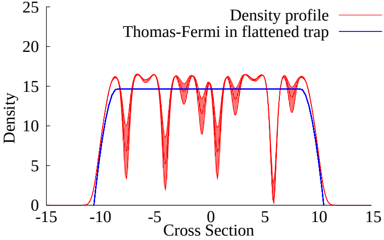

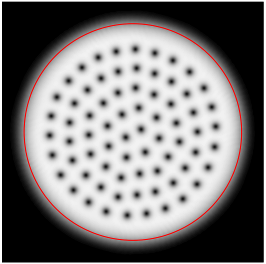

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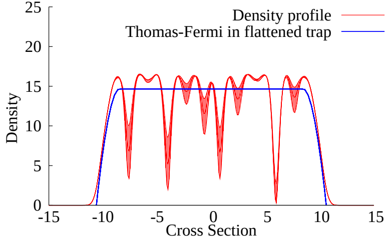

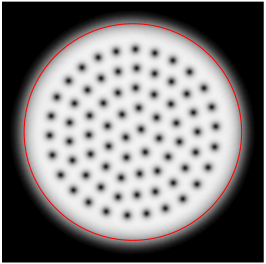

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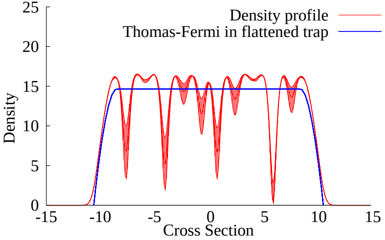

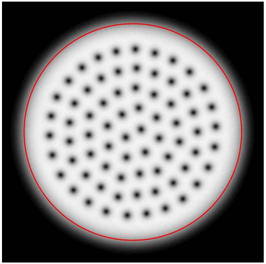

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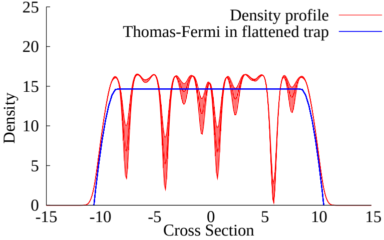

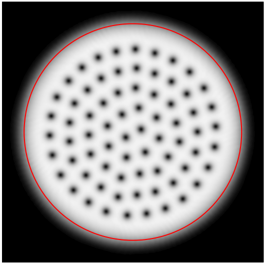

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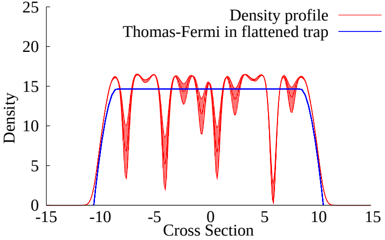

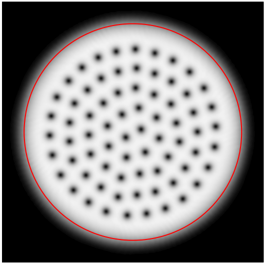

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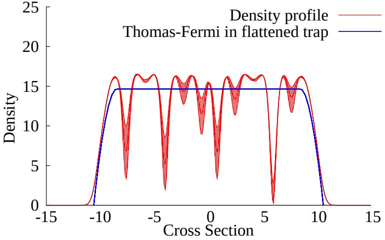

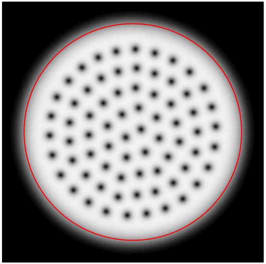

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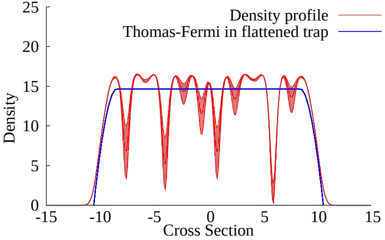

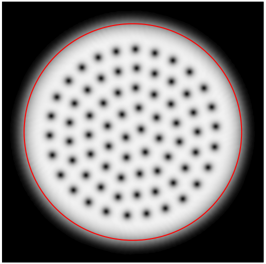

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Superfluidity

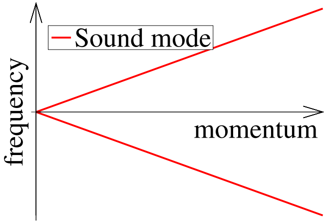
Fluctuations above transition

When condensed

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

With $\xi_k \simeq ck$
Poles:

$$\omega^* = \xi_k$$



- Generic structure of Green's function:

$$[D^R]^{-1} = \begin{pmatrix} \omega + i\gamma_{\mathrm{net}} - \epsilon_k - \mu & i\gamma_{\mathrm{net}} - \mu \\ -i\gamma_{\mathrm{net}} - \mu & -\omega - i\gamma_{\mathrm{net}} - \epsilon_k - \mu \end{pmatrix}$$

Fluctuations above transition

When condensed

$$\mathrm{Det}\left[D^R(\omega, k)\right]^{-1} = (\omega + i\gamma_{\mathrm{net}})^2 + \gamma_{\mathrm{net}}^2 - \xi_k^2$$

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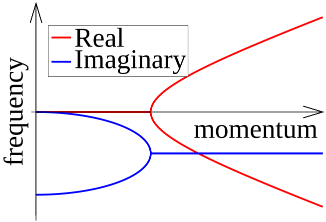

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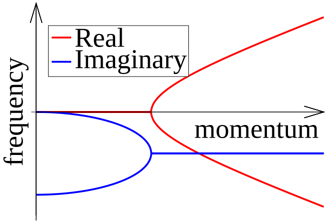

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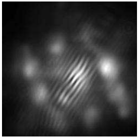
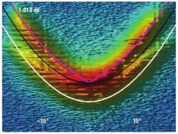
Polariton “superfluidity” experiments

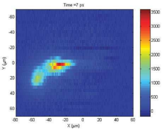
- Quantised vortices in disorder potential
  [Lagoudakis *et al.* Nature Phys. ’08]

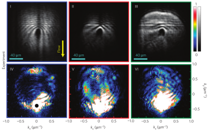


- Changes to excitation spectrum
  [Utsunomiya *et al.* Nature Phys. ’08]



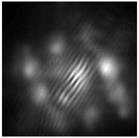
- Wavepacket propagation
  [Amo *et al.* Nature ’09]
- Driven superfluidity
  [Amo *et al.* Nature Phys. (’09)

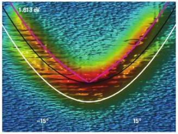


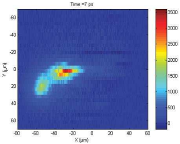


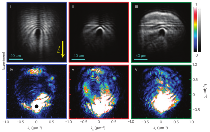
Aspects of superfluidity

	Quantised vortices	Landau critical velocity	Metastable persistent flow	Two-fluid hydrody-namics	Local thermal equilib-rium	Solitary waves
Superfluid ^{4}He/cold atom Bose-Einstein condensate	✔	✔	✔	✔	✔	✔
Non-interacting Bose-Einstein condensate	✔	✗	✗	✔	✔	✗
Classical irrotational fluid	✗	✔	✗	✔	✔	✔
Incoherently pumped polariton condensates	✔	✗	?	?	✗	?









Lagoudakis *et al.* Nat. Phys. '08. Utsunomiya *et al.* Nat. Phys. '08. Amo *et al.* Nature '09; Nat. Phys. '09

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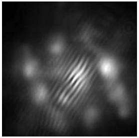

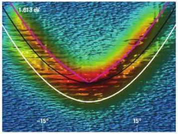

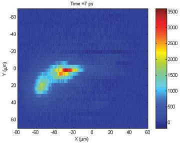

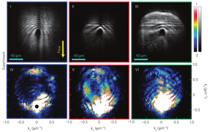

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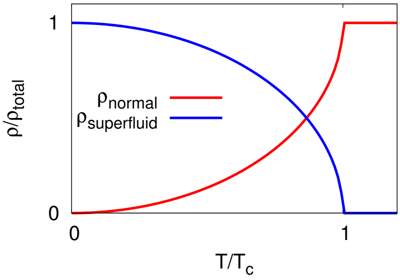
Superfluid density

- Two-fluid hydrodynamics



- ρ_s, ρ_n distinguished by slow rotation

- Experimentally, rotation:

- To calculate, transverse/longitudinal:

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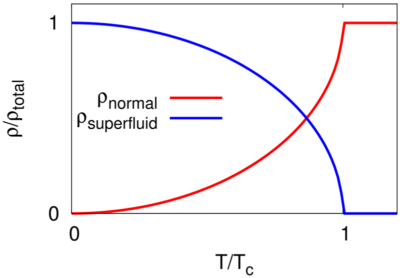

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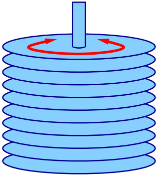

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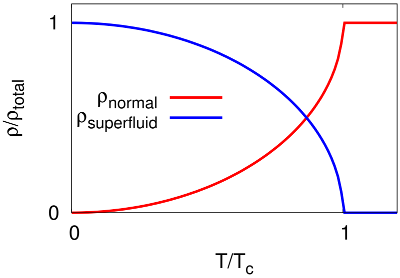

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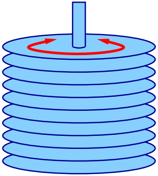

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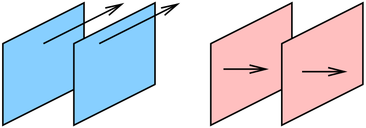

Superfluid density

- Currrent:

$$\mathbf{J} = \rho \mathbf{v} = \psi^\dagger i \nabla \psi = |\psi|^2 \nabla \phi$$

$$J_i(\mathbf{q}) = \psi^\dagger_{\mathbf{k}+\mathbf{q}} \frac{2k_i + q_i}{2m} \psi_{\mathbf{k}}$$

- Response function:

$$H \to H - \sum_q \mathbf{f}(\mathbf{q}) \cdot \mathbf{J}_i(\mathbf{q}) \qquad J_i(\mathbf{q}) = \chi_{ij}(\mathbf{q}) f_j(\mathbf{q})$$

- Vertex corrections essential for superfluid part.

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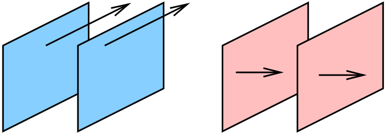

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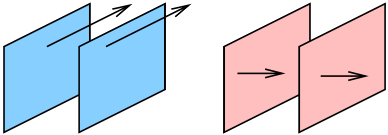

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Calculating superfluid response function

- Using Keldysh generating functional

$$\chi_{ij}(q) = -\frac{i}{2}\frac{d^2\mathcal{Z}[f,\theta]}{df_i(q)d\theta_j(-q)}, \qquad \mathcal{Z}[f,\theta] = \int \mathcal{D}\psi \exp(iS[f,\theta])$$

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$$S[f,\theta] = S + \sum_{k,q} \begin{pmatrix} \bar{\psi}_{cl} & \bar{\psi}_q \end{pmatrix}_{k+q} \begin{pmatrix} \theta_i & f_i + \theta_i \\ f_i - \theta_i & -\theta_i \end{pmatrix}_q \frac{2k_i + q_i}{2m} \begin{pmatrix} \psi_{cl} \\ \psi_q \end{pmatrix}_k$$

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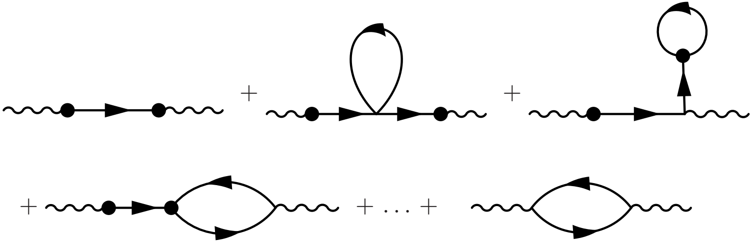

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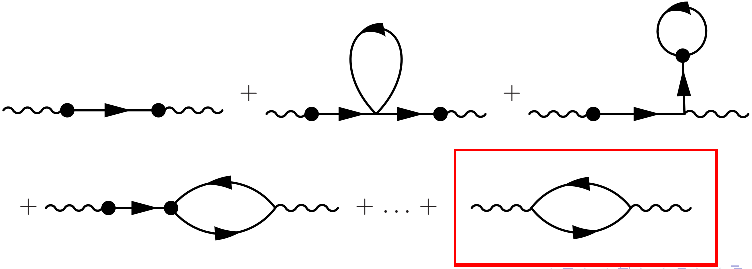
- Saddle point + fluctuations: Only one diagram for χ_N



Non-equilibrium superfluid response

- Superfluid response exists because:

$$= \frac{i\psi_0 q_i}{2m} (1, -1)\, D^R(q, \omega = 0) \begin{pmatrix} 1 \\ -1 \end{pmatrix} \frac{i\psi_0 q_j}{2m}$$

- $D^R(\omega = 0) \propto 1/\epsilon_q$ despite pumping/decay — superfluid response exists.
- Normal density:

$$\rho_N = \int d^d k \epsilon_k \int \frac{d\omega}{2\pi} \mathrm{Tr}\left[\sigma_z D^K \sigma_z (D^R + D^A)\right]$$

- Is affected by pump/decay:
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[JK PRL '11]

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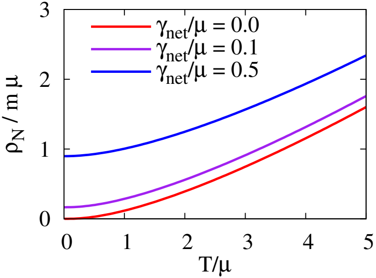


[JK PRL '11]

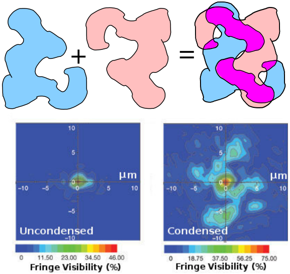
Coherence:

1. Introduction to polariton condensation
   - What are excitons and polaritons
   - Experimental features
   - Approaches to modelling
2. Pattern formation
   - Experiments
   - Modelling pattern formation
3. Superfluidity
   - Non-equilibrium condensate spectrum
   - Experiments and aspects of superfluidity
   - Current-current response function
4. Coherence
   - Experiments
   - Power law decay of coherence

Correlations in a 2D Gas

Correlations:

$$g_1(\mathbf{r}, \mathbf{r}', t) = \left\langle \psi^\dagger(\mathbf{r}, t)\psi(\mathbf{r}', 0) \right\rangle$$



- $D^< = D^K - D^R + D^A$
- Generally, get:

$$\left\langle \psi^\dagger(\mathbf{r}, t)\psi(0, 0) \right\rangle \simeq |\psi_0|^2 \exp\left[-a_p \begin{cases} \ln(r/r_0) & t \simeq 0 \\ \frac{1}{2}\ln(c^2 t/\gamma_{net} r_0^2) & r \simeq 0 \end{cases} \right]$$

[Szymańska *et al.* PRL '06; PRB '07]

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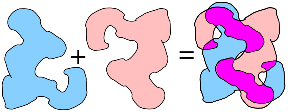

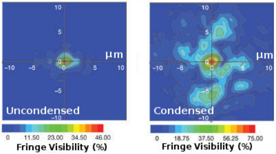

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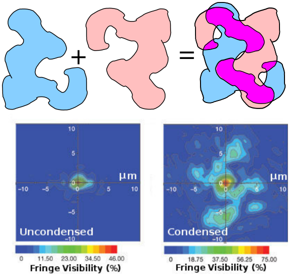

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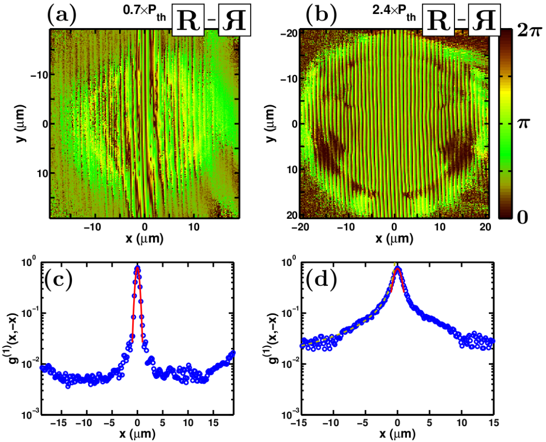
Experimental observation of power-law decay



G. Rompos, Y. Yamamoto *et al.* submitted

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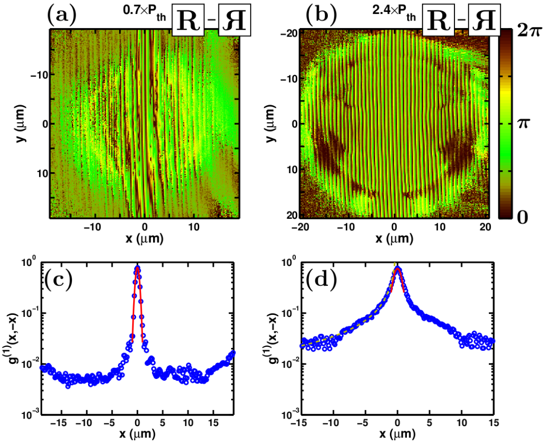
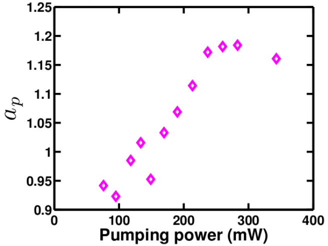


$$g_1(\mathbf{r}, -\mathbf{r}) \propto \left(\frac{r}{r_0}\right)^{-a_p}$$



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Exponent in a non-equilibrium 2D gas

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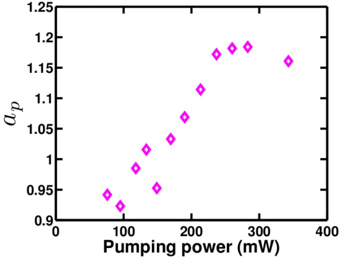
- Experimentally, $a_P \simeq 1.2$
- In equilibrium $a_p = \frac{mk_B T}{2\pi\hbar^2 n_s} < \frac{1}{4}$ (BKT transition)
- Non-equilibrium theory depends on thermalisation.



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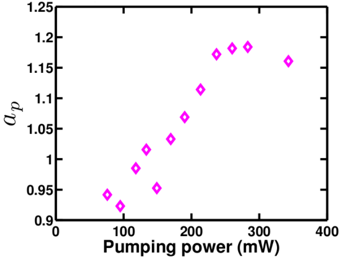

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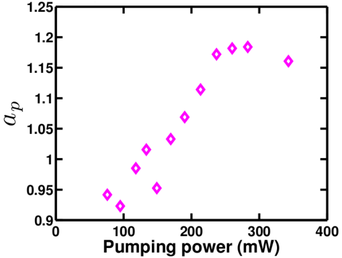
  - Thermalised (yet diffusive modes)
    $$a_p = \frac{mk_B T}{2\pi\hbar^2 n_s}$$
  - Non-thermalised,
    $$a_P \propto \frac{\text{Pumping noise}}{n_s}$$



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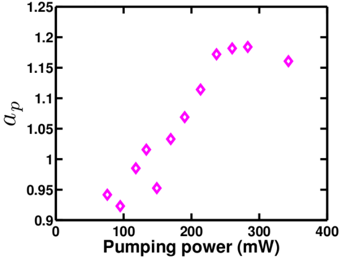
- In equilibrium $a_p = \dfrac{mk_B T}{2\pi\hbar^2 n_s} < \dfrac{1}{4}$ (BKT transition)
- Non-equilibrium theory depends on thermalisation.
  - Thermalised (yet diffusive modes)
    $$a_p = \frac{mk_B T}{2\pi\hbar^2 n_s}$$
  - Non-thermalised,
    $$a_P \propto \frac{\text{Pumping noise}}{n_s}$$



Exponent in a non-equilibrium 2D gas

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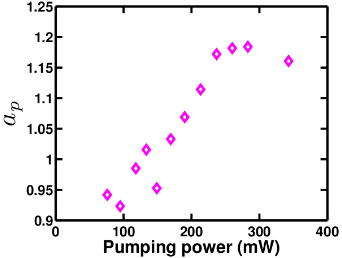
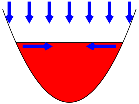
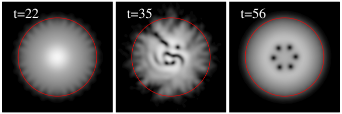


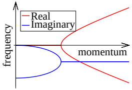
Conclusion

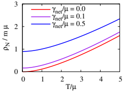
- Instability of Thomas-Fermi and spontaneous rotation



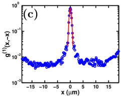


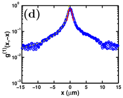
- Survival of superfluid response

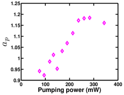




- Power law decay of correlations





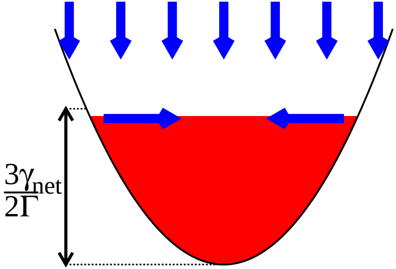


Extra slides

Instability of Thomas-Fermi: details

$$\frac{1}{2}\partial_t \rho + \nabla \cdot (\rho \mathbf{v}) = (\gamma_{\text{net}} - \Gamma \rho)\rho$$

$$\partial_t \mathbf{v} + \nabla\left(U\rho + \frac{m\omega^2}{2} r^2 + \frac{m}{2}|\mathbf{v}|^2\right) = 0$$



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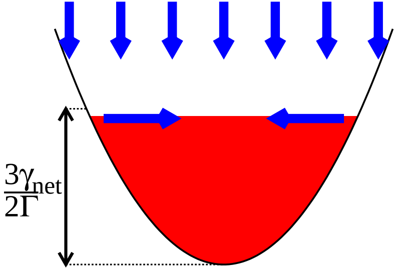

Normal modes for $\gamma_{\text{net}}, \Gamma \to 0$:

$$\delta\rho_{n,m}(r,\theta,t) = e^{im\theta} h_{n,m}(r) e^{i\omega_{n,m} t}$$

$$\omega_{n,m} = \omega 2\sqrt{m(1+2n) + 2n(n+1)}$$

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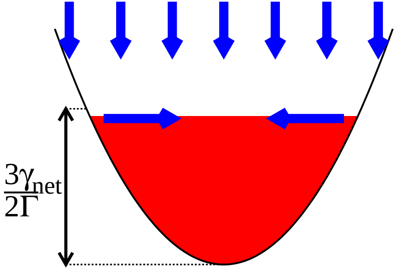

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Add weak pumping/decay:

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

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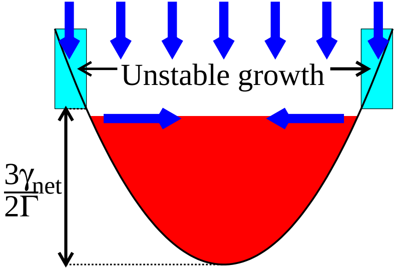

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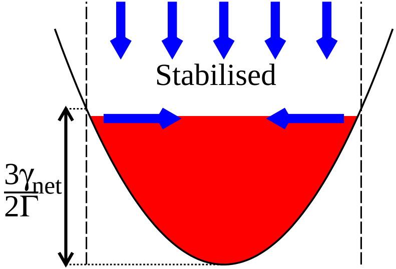

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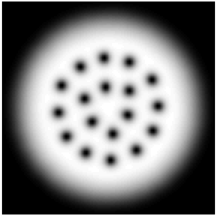
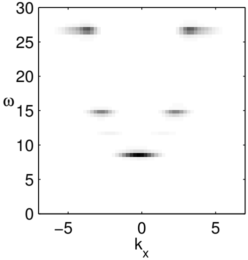
Detecting vortex lattices

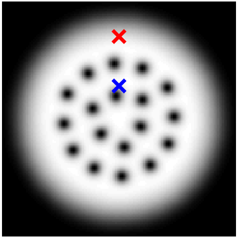
Snapshot

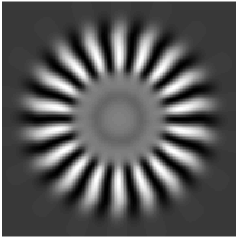


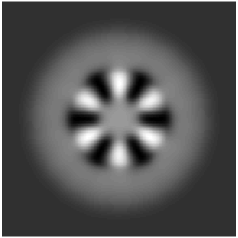
Spectrum:



Defocussed homodyne intereference:





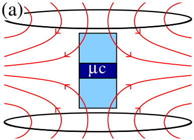


Measuring superfluid density

1. Effect rotating frame

Polariton polarization: $(\psi_{\circlearrowleft}, \psi_{\circlearrowright})$

$$H = \lambda \begin{pmatrix} \ell^2 & r^2 e^{2i\phi} \\ r^2 e^{-2i\phi} & -\ell^2 \end{pmatrix}$$



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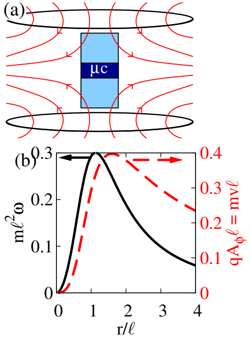
Ground state Berry phase:

$$q\mathbf{A}_{\text{eff}} = m\omega \times \mathbf{r} = \frac{\hat{\phi}}{r}\left[1 - \frac{\ell^2}{\sqrt{r^4 + \ell^4}}\right]$$



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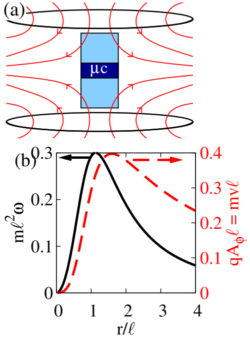
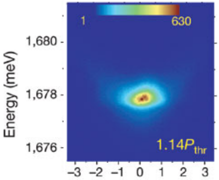
2. Measure resulting current

Energy shift of normal state:

$\Delta E = (1/2)mv^2 = 0.08/m\ell^2 \simeq 0.1\text{meV}$





Finite size effects: Single mode vs many mode

$$\left\langle \psi^\dagger(\mathbf{r},t)\psi(\mathbf{r}',0)\right\rangle \simeq |\psi_0|^2 \exp\left[-D^{<}_{\phi\phi}(\mathbf{r},\mathbf{r}',t)\right]$$

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

$$D^<_{\phi\phi}(\mathbf{r},\mathbf{r},t) \propto \sum_n^{n_{max}} \int \frac{d\omega}{2\pi} \frac{|\varphi_n(\mathbf{r})|^2(1-e^{i\omega t})}{\left|(\omega+i\gamma_{\text{net}})^2+\gamma_{\text{net}}^2-\xi_n^2\right|^2}$$

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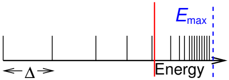
$$\Delta\xi \ll \sqrt{\frac{\gamma_{\mathrm{net}}}{t}} \ll E_{\mathrm{max}}$$



$$D^<_{\phi\phi} \sim 1 + \ln\left(E_{\mathrm{max}}\sqrt{\frac{t}{\gamma_{\mathrm{net}}}}\right)$$

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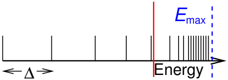

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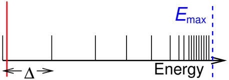

$D^<_{\phi\phi} \sim \left(\frac{\pi C}{2\gamma_{\text{net}}}\right)\left(\frac{t}{2\gamma_{\text{net}}}\right)$

(Recovers Schawlow-Townes laser linewidth)