Spinor dynamics in a polariton condensate: Macroscopic effects of non-equilibrium condensation

J. Keeling

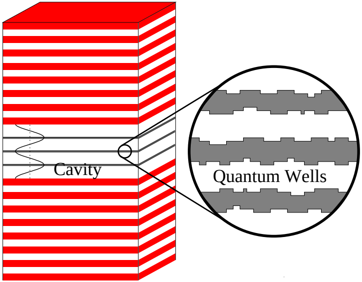
N. G. Berloff, M. O. Borgh, P. B. Littlewood, M. H. Szymanska.




CMMP, December 2009

Funding: EPSRC Engineering and Physical Sciences Research Council

Microcavity Polaritons



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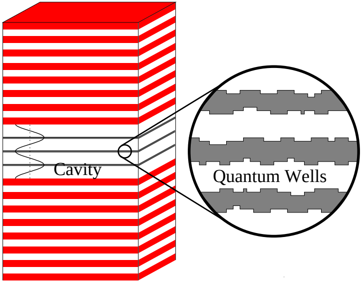
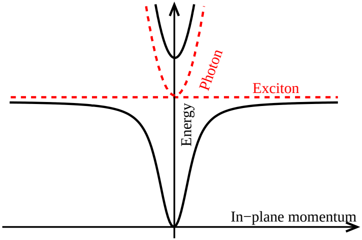


Cavity photons:

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



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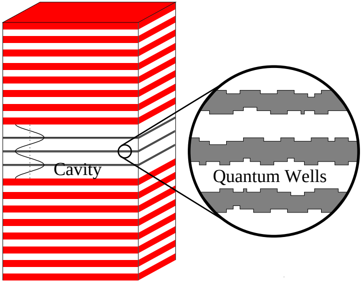

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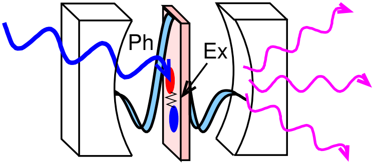
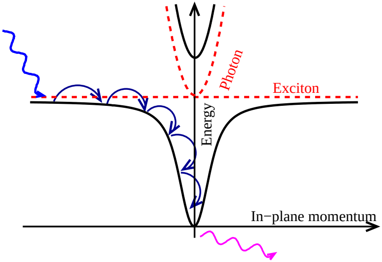
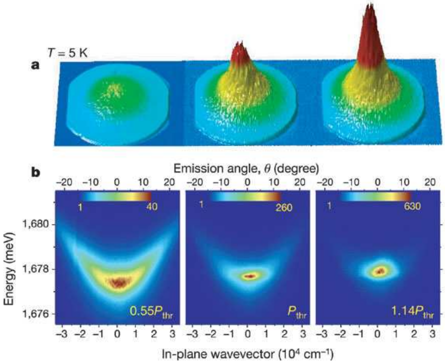
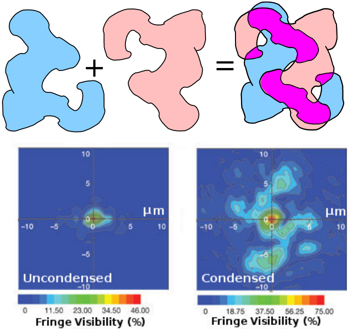




Polariton condensation: distribution and coherence

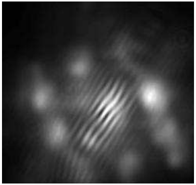


[Kasprzak, et al., Nature, 2006]

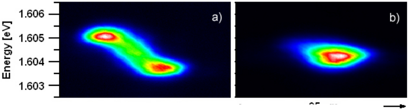


Other (relevant) experiments

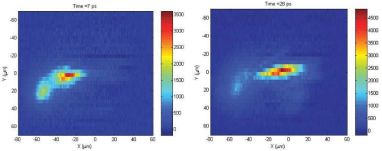
- Quantised vortices in disorder potential
  [Lagoudakis *et al* Nature Phys. 4, 706 (2008)]



- Stress traps for polaritons
  [Balili *et al* Science 316 1007 (2007)]



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



Overview

Gross-Pitaevskii equation: Harmonic trap

$$i\partial_t \psi = \left[-\frac{\nabla^2}{2m} + \frac{m\omega^2}{2} r^2 + U|\psi|^2 \right] \psi$$

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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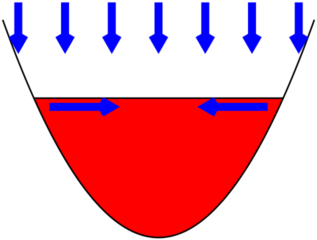

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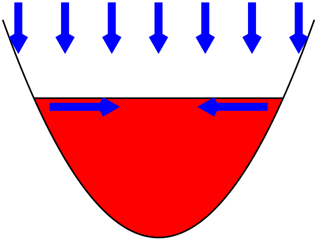
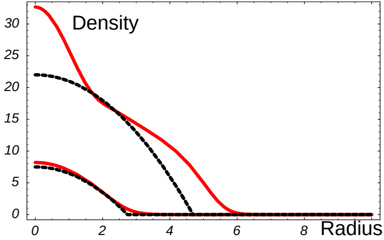
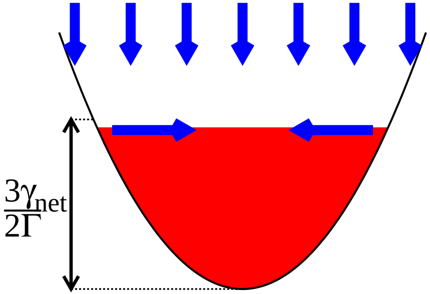




Stability of Thomas-Fermi solution

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



Stability of Thomas-Fermi solution

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

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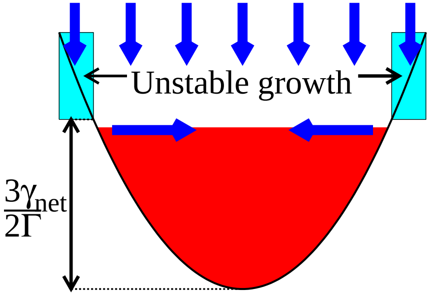

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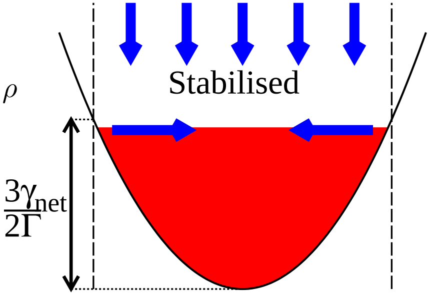

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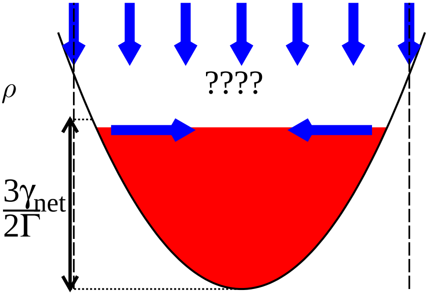
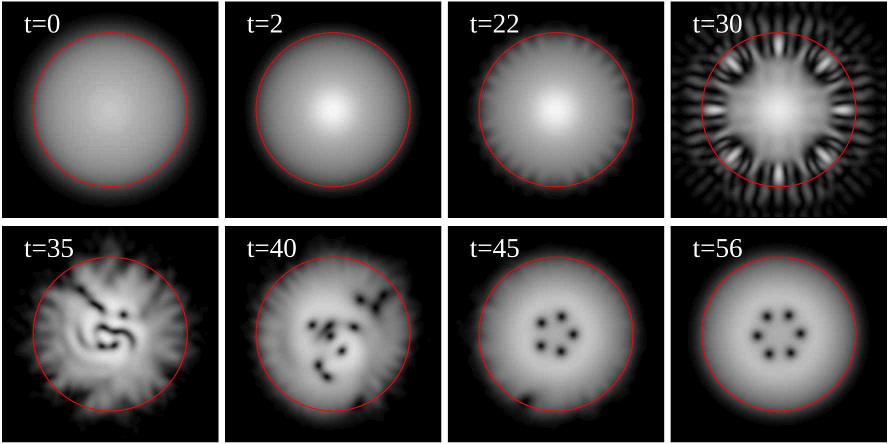


Time evolution:



[Keeling & Berloff, PRL, '08]

Polariton spin degree of freedom

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

$$i\partial_t\psi_L = \left[-\frac{\nabla^2}{2m} + V(r) + U_0|\psi_L|^2 + i\left(\gamma_{\text{eff}} - \kappa - \Gamma|\psi_L|^2\right)\right]\psi_L$$

- Two-mode case (neglect spatial variation): [Wouters PRB '08]
- Many modes — interaction of J_1 and currents.

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  - Tendency to biexciton formation: U_1
  - Magnetic field: Δ
  - Broken rotation symmetry: J_1
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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: $J_1 \ll U_1 R$, $z \ll R$,

$$\dot{\theta} = -\Delta - 4U_1 z,$$
$$\dot{z} = -2\gamma_{\text{net}} z - 2J_1 \frac{\gamma_{\text{net}}}{\Gamma} \sin(\theta)$$

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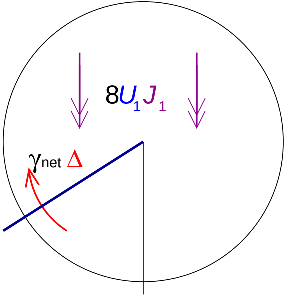

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Damped, driven pendulum

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

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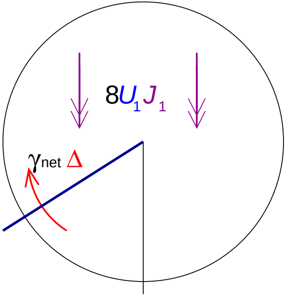

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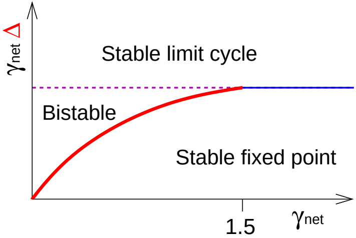
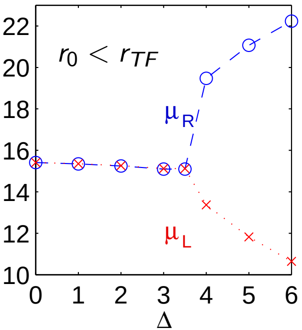


Damped, driven pendulum

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

Trapped spinor system

$V(r) = m\omega^2 \frac{r^2}{2}$, $\gamma_{\mathrm{net}}(r) = J_1 \Theta(r_0 - r)$.
Plot $\mu_{L,R} = \partial_t \phi \pm \partial_t \theta / 2$ vs Δ.



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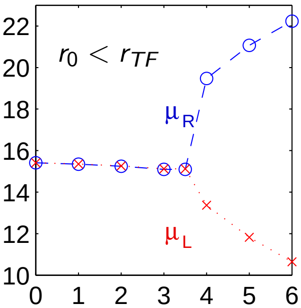
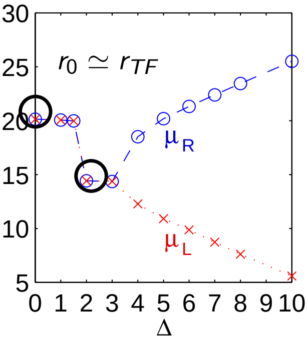
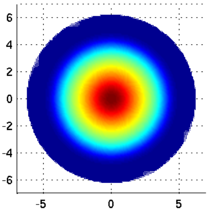
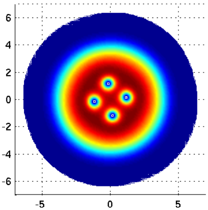
$\dot{\theta} = -\Delta - 4 U_1 z = 0$

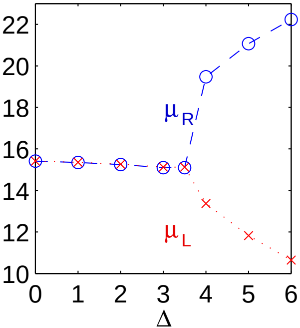


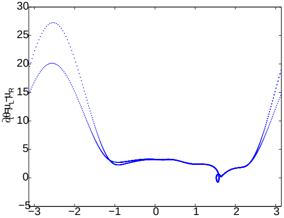




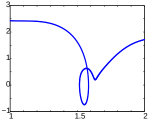


Trapped spinor system — phase portraits



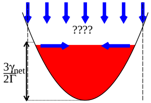


$\Delta = 3.20$



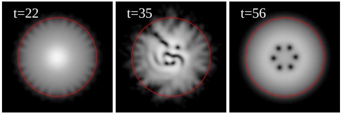
Examine phase portrait $\partial_t \theta$ vs θ

Conclusions

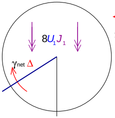


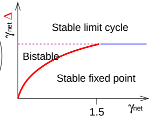
- Modification to Thomas-Fermi profile
  Spontaneous rotating vortex lattice

  [JK, NGB. PRL **100** 250401 (2008)]



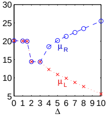
- Spinor model: Steady states

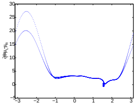




- Coupled spin and spatial dynamics

  [MOB, JK, NGB. `arXiv:0911:4486`]

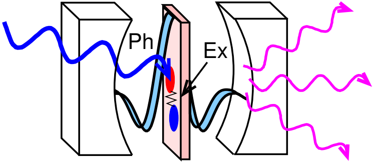


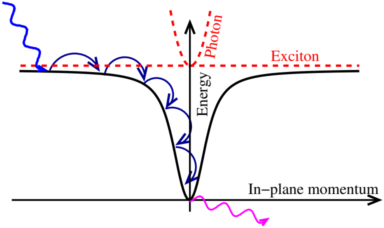


Extra slides

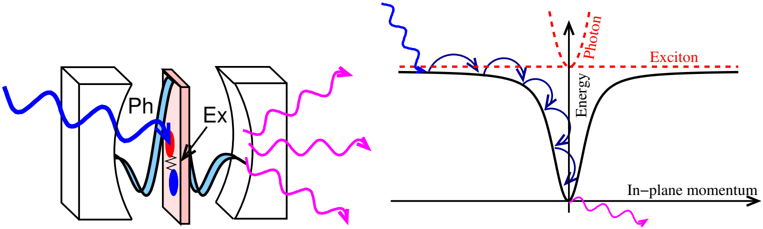
5. Non-equilibrium timescales
6. Polariton experiments
7. Spinor bistability
8. Spinor spectrum

Non-equilibrium: Timescales





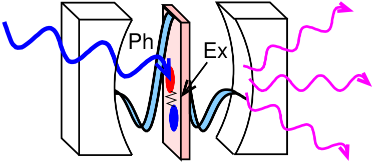
Non-equilibrium: Timescales

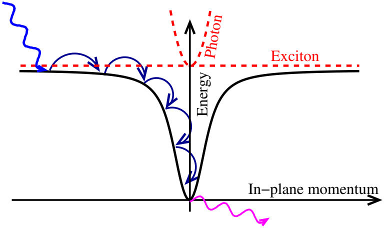


	Lifetime	Thermalisation
Atoms	10s	10ms
Excitons[a]	50ns	0.2ns
Polaritons	5ps	0.5ps
Magnons[b]	1μs(??)	100ns(?)

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

Non-equilibrium: Timescales

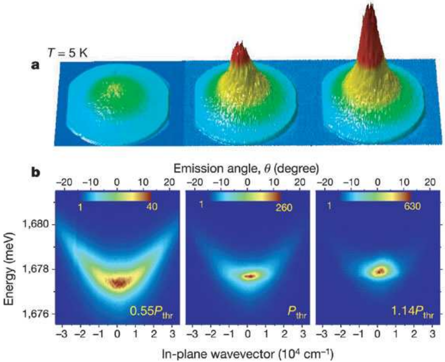




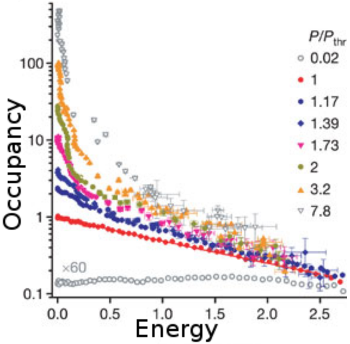
	Lifetime	Thermalisation	Linewidth	Temperature	
Atoms	10s	10ms	2.5×10^{-13}meV	10^{-8}K	10^{-9}meV
Excitons[a]	50ns	0.2ns	5×10^{-5}meV	1K	0.1meV
Polaritons	5ps	0.5ps	0.5meV	20K	2meV
Magnons[b]	1μs(??)	100ns(?)	2.5×10^{-6}meV	300K	30meV

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

Polariton experiments: Momentum/Energy distribution

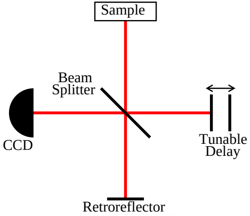


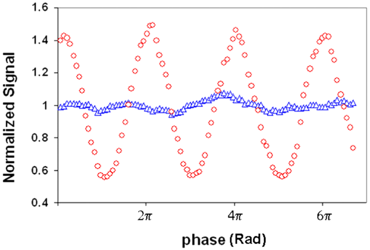
[Kasprzak, et al., Nature, 2006]



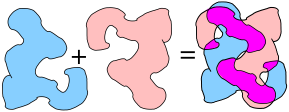
Polariton experiments: Coherence

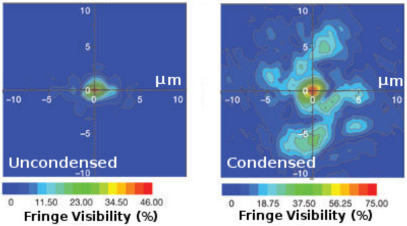
Basic idea:





Coherence map:

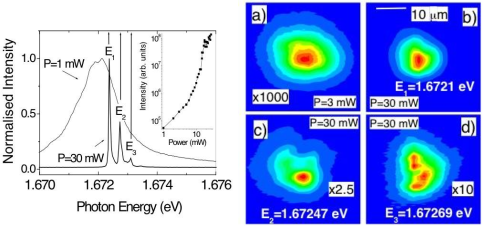


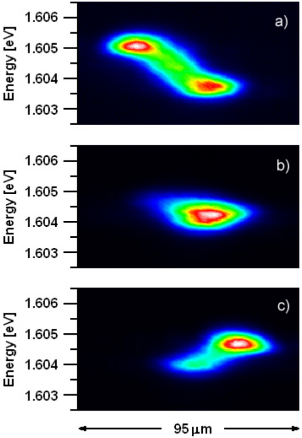


[Kasprzak, et al., Nature, 2006]

Other polariton condensation experiments

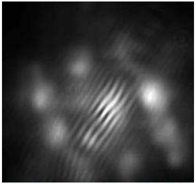
- Stress traps for polaritons
  [Balili *et al* Science 316 1007 (2007)]
- Temporal coherence and line narrowing
  [Love *et al* Phys. Rev. Lett. 101 067404 (2008)]



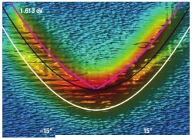


Other polariton condensation experiments

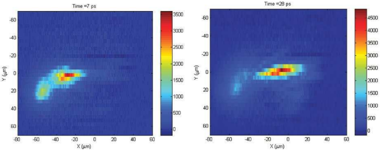
- Quantised vortices in disorder potential
  [Lagoudakis *et al* Nature Phys. 4, 706 (2008)]



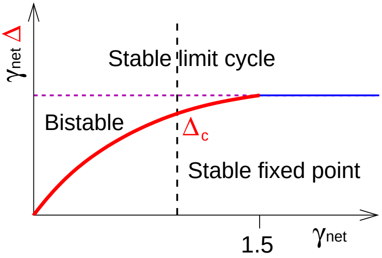
- Changes to excitation spectrum
  [Utsunomiya *et al* Nature Phys. 4 700 (2008)]



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



Two-mode model bistability



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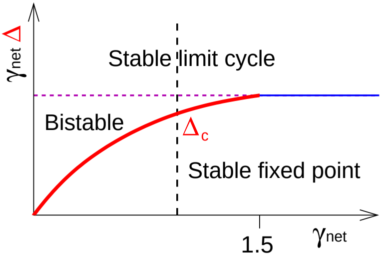

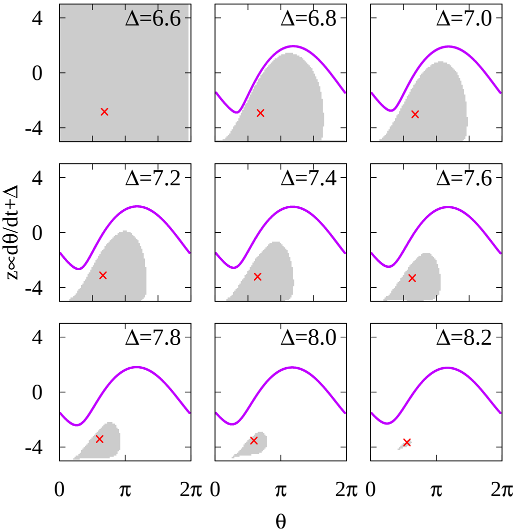

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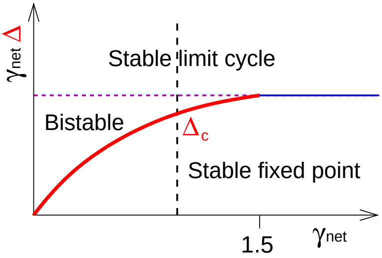
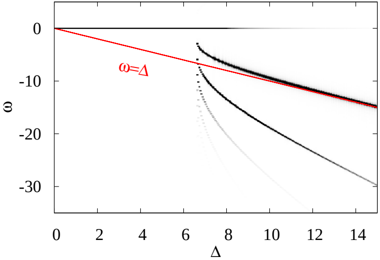
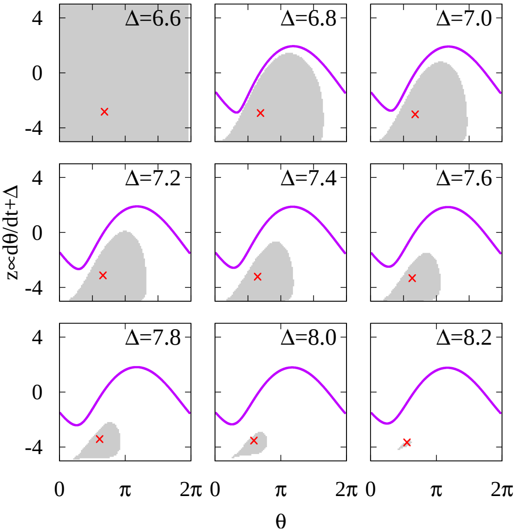






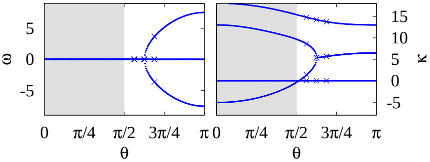
$$\Delta \gtrsim \Delta_c \colon \ \omega \simeq [\ln(\Delta - \Delta_c)]^{-1}$$

Homogenous case: stability at $\Delta < \Delta_c$

Damped oscillations

$\Omega_p^2 = -8 U_1 J_1 R_0 \cos(\theta)$

$$\omega - i\kappa \simeq \begin{cases} 0 \\ -i\gamma_{\text{net}} \pm i\sqrt{\gamma_{\text{net}} - \Omega_p^2} \\ -2i\gamma_{\text{net}} \end{cases}$$



If $\Omega_p^2 = \gamma_{\text{net}}$ degenerate modes:

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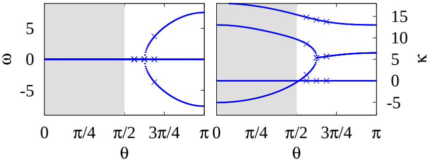

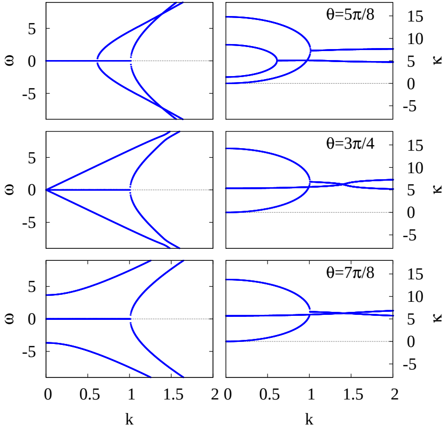

If $\Omega_p^2 = \gamma_{\text{net}}$ degenerate modes:

$\omega \propto k$ for spin wave.