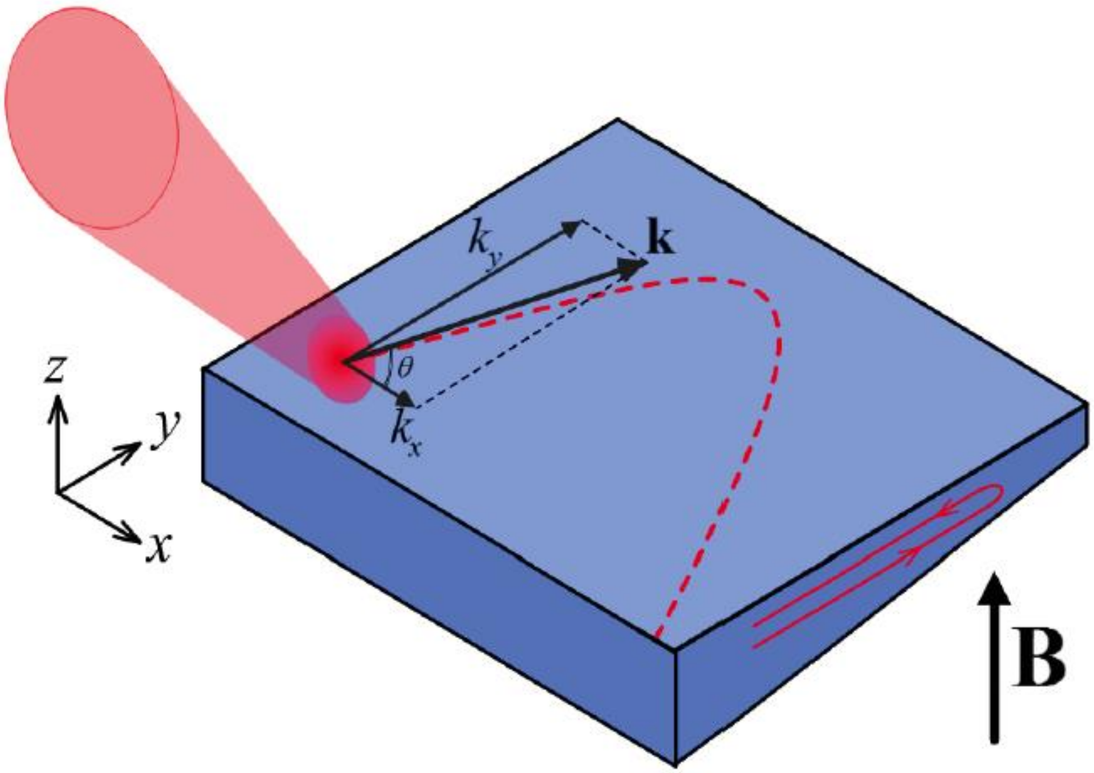
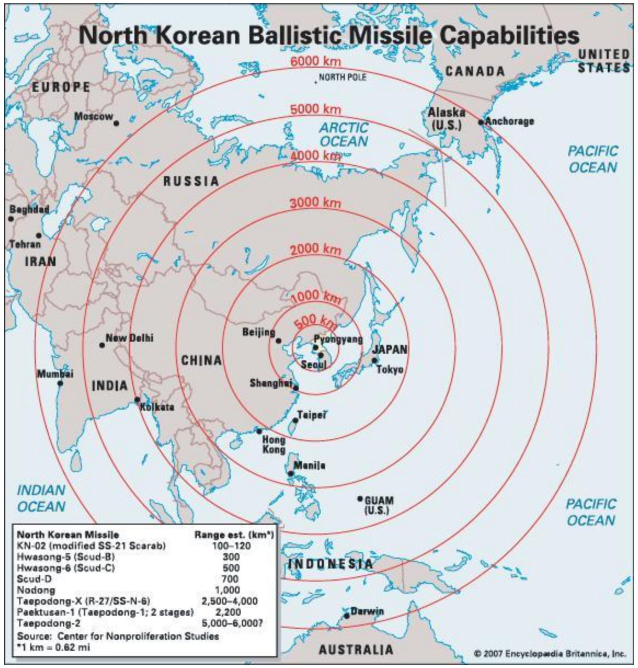
UNIVERSITY OF Southampton

Artificial gravity effect on exciton-polaritons

Evgeny Sedov and Alexey Kavokin



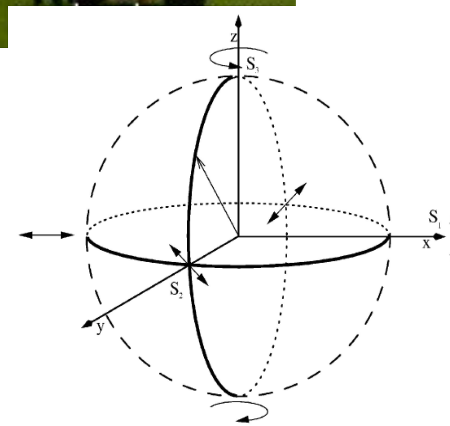


Microcavity wedges in the focus

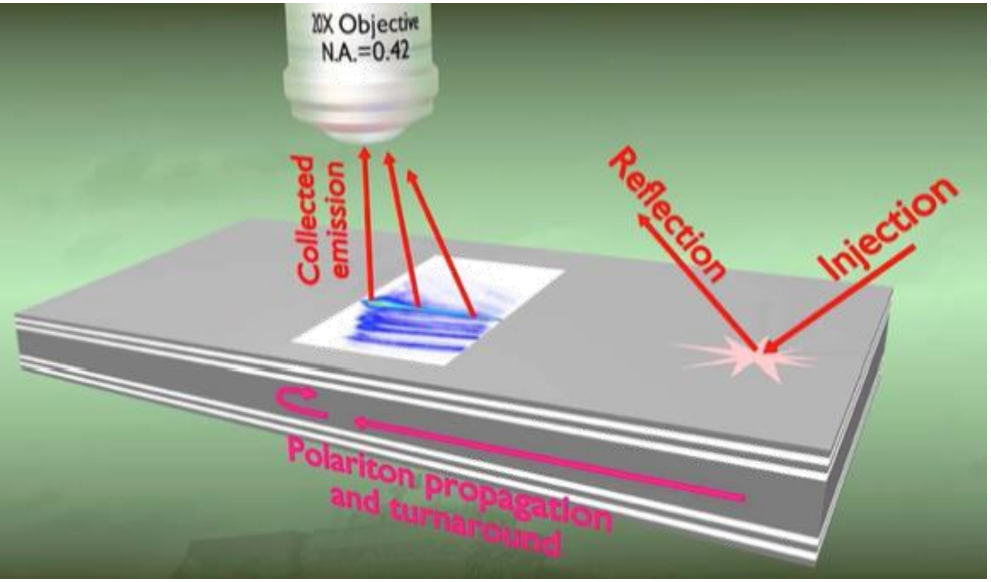
May 17, 2017

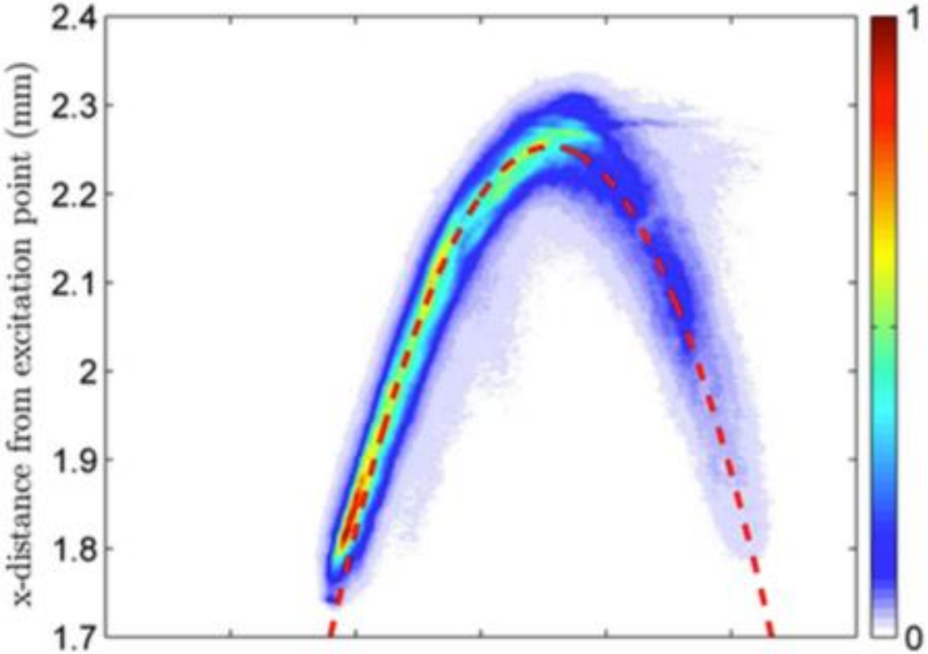
What happens with a polariton pseudospin on a ballistic trajectory?

$$a = -\frac{1}{m^*}\frac{\partial E}{\partial y};$$



Motivation 1

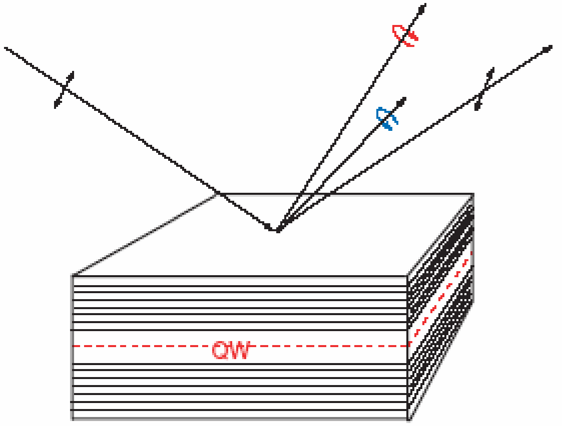


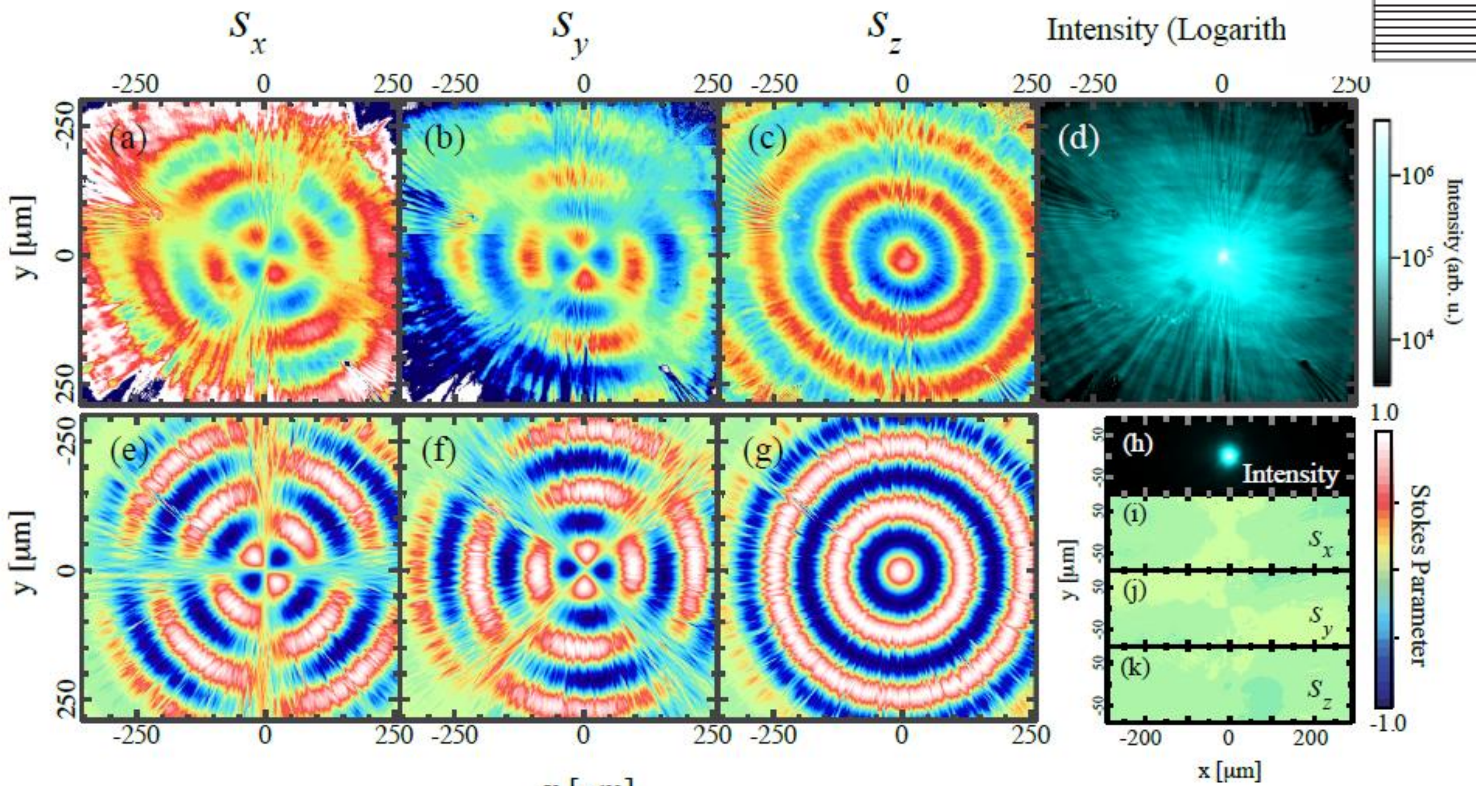


M. Steger, *et al.*, Optica **2**, 1 (2015).
B. Nelsen, *et al.*, Phys. Rev. X **3**, 041015 (2013).
Y. Sun, *et al.*, 2016, arXiv:1601.02581v2

Ballistic propagation of polaritons over 0.5 mm documented

Motivation - 2



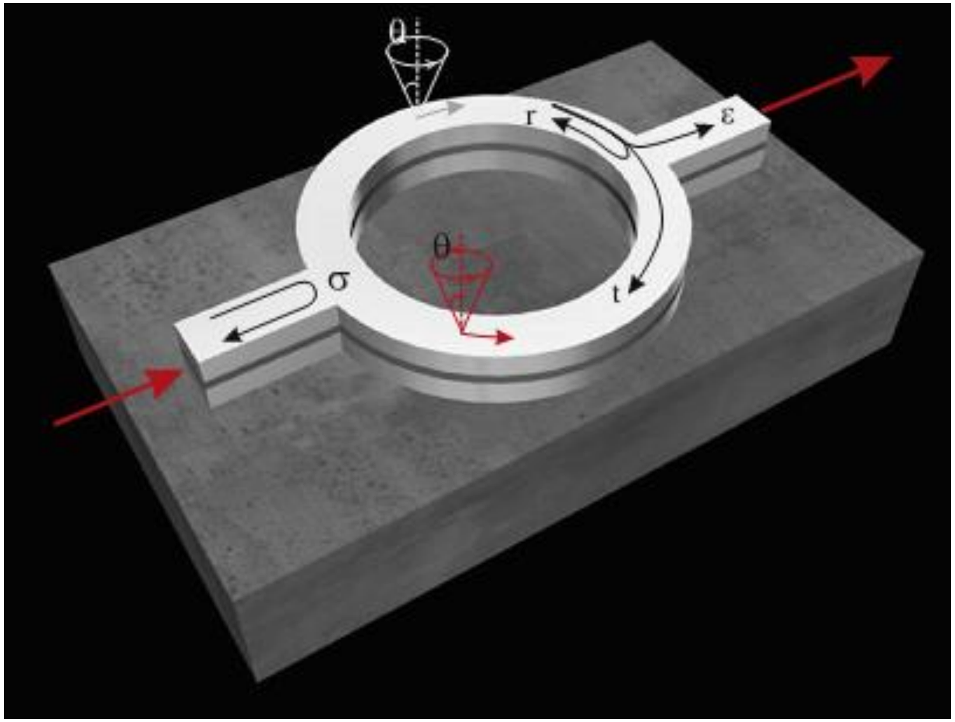


E. Kammann, T. C. H. Liew, H. Ohadi, P. Cilibrizzi, P. Tsotsis, Z. Hatzopoulos, P. G. Savvidis, A. V. Kavokin, and P. G. Lagoudakis, *Non-linear optical spin Hall effect and long-range spin transport in polariton lasers,* Phys. Rev. Letters, 109, 036404 (2012).

Tens of works on the Optical Spin Hall effect after 2005

Kavokin, A. V., Malpuech, G. & Glazov, M. M. Optical spin Hall effect. *Phys. Rev. Lett.* **95**, 136601 (2005).

Motivation - 3

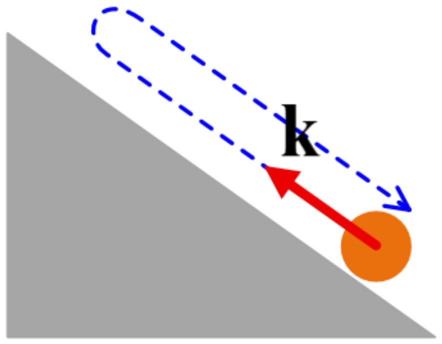


I.A. Shelykh, *et al.*,
Phys. Rev. Lett. **102**,
046407 (2009).

Berry phase interferometer: the effective field is wave-vector dependent

Propagation in microcavity wedges: Topological effects involved?

The Hamiltonian



$$\widehat{H} = \widehat{T} + \widehat{V} + \widehat{H}_{\mathrm{LT}} + \widehat{H}_{\mathrm{M}}$$

$$\widehat{T} = \frac{\hbar^2 \widehat{k}^2}{2m^*} \widehat{I}$$

$$\widehat{V} = \hbar \beta y \widehat{I}$$

$$\widehat{H}_{\mathrm{LT}} = \frac{\hbar}{2} \begin{bmatrix} 0 & \left(\widehat{\Omega}_x - i\widehat{\Omega}_y\right) \\ \left(\widehat{\Omega}_x + i\widehat{\Omega}_y\right) & 0 \end{bmatrix}$$

$$\widehat{H}_{\mathrm{M}} = \frac{\hbar}{2} \begin{bmatrix} \widehat{\Omega}_z & 0 \\ 0 & -\widehat{\Omega}_z \end{bmatrix}$$

The “gravitational force” $F = -\hbar\beta$

The solution: $\mathbf{\Psi}(t, \mathbf{r}) = \left(\Psi_+(t, \mathbf{r}), \Psi_-(t, \mathbf{r})\right)^{\mathrm{T}}$

Is it trivial or too complex?

The center of mass trajectory:

$$x_c = \hbar k_{x0} t / m^*, \; y_c = \hbar k_{y0} t / m^* - \hbar \beta t^2 / 2m^*$$

$$\mathbf{\Psi}(t, \mathbf{r}) = e^{i\chi(t)} \mathbf{\Phi}(t, \mathbf{r} - \mathbf{r}_c)$$

$$\chi(t) = -\frac{\hbar \beta t^2}{12 m^*} \left(3k_{y0} - \beta t \right)$$

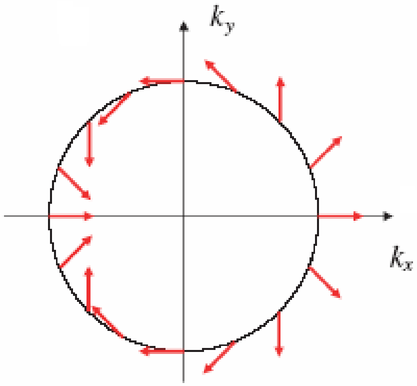
The polarisation dynamics is given by:

$$i\partial_t \Phi_\pm = \pm \frac{1}{2} \Omega_{cz} \Phi_\pm + \frac{1}{2} \left(\Omega_{cx} \mp i \Omega_{cy} \right) \Phi_\mp$$

The pseudospin

$$S_x = \frac{1}{2} \left(\Phi_+ \Phi_-^* + \Phi_+^* \Phi_- \right), \; S_y = \frac{i}{2} \left(\Phi_+ \Phi_-^* - \Phi_+^* \Phi_- \right), \; S_z = \frac{1}{2} \left(|\Phi_+|^2 - |\Phi_-|^2 \right)$$

What about effective fields?



$$\omega_m^{TM}(\theta) - \omega_m^{TE}(\theta)$$

$$\simeq \frac{L_c L_{\mathrm{DBR}}(0)}{L_{\mathrm{eff}}(0)^2} \frac{2\cos\theta_{\mathrm{eff}}\sin^2\theta_{\mathrm{eff}}}{1-2\sin^2\theta_{\mathrm{eff}}}[\omega_s(0)-\omega_c(0)].$$

$$\omega_c = m\pi c/n_c L_c \cos\theta_c \qquad \omega_s(\theta) = \pi c/[n_{\mathrm{eff}}(a+b)\cos\theta_{\mathrm{eff}}]$$

G. Panzarini, L. C. Andreani, A. Armitage, D. Baxter, M. S. Skolnick, V. N. Astratov, J. S. Roberts, A. V. Kavokin, M. R. Vladimirova, and M. A. Kaliteevski. Cavity-polariton dispersion and polarization splitting in single and coupled semiconductor microcavities. *Phys. Solid State*, 41:1223, 1999a.

- **Dependence on the in-plane wave-vector**
- **Dependence on the detuning of the cavity mode and the center of the stop-band**

Exciton-polaritons versus photons

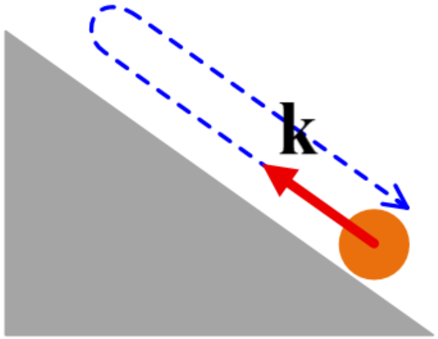
Hopfield coefficients are detuning dependent:

$$|C|^2 = \frac{1}{2}\left[1 - \frac{E_c - E_x}{\sqrt{\hbar^2\Omega^2 + (E_c - E_x)^2}}\right]$$

controls TE-TM splitting

$$|X|^2 = \frac{1}{2}\left[1 + \frac{E_c - E_x}{\sqrt{\hbar^2\Omega^2 + (E_c - E_x)^2}}\right]$$

controls Zeeman splitting



Effective fields acting upon the polariton pseudospin

$$\frac{d\mathbf{S}}{dt} = \mathbf{\Omega} \times \mathbf{S},$$

$$\widehat{\Omega}_x = \Delta_{\mathrm{LT}} \left(\widehat{k}_x^2 - \widehat{k}_y^2 \right) |C|^2$$

$$\widehat{\Omega}_y = 2\Delta_{\mathrm{LT}} \widehat{k}_x \widehat{k}_y |C|^2$$

$$\widehat{\Omega}_z = \frac{\mu_{\mathrm{B}} g B}{\hbar} |X|^2$$

Coordinate dependent

Wave vector dependent

Rather complex!

… but it becomes even more complex if we account for the interference effects!

$$\frac{d\mathbf{S}}{dt} = \mathbf{\Omega}_c \times \mathbf{S}$$

The amplitudes and phases matter

$$S_0 = E_x E_x^* + E_y E_y^*,$$
$$S_x = E_x E_x^* - E_y E_y^*,$$
$$S_y = 2\Re\left(E_x E_y^*\right),$$
$$S_z = 2\Im\left(E_x E_y^*\right).$$

$$\mathbf{E} = e^{i(\omega t - \mathbf{kr})} \begin{pmatrix} E_x \\ E_y \end{pmatrix}$$

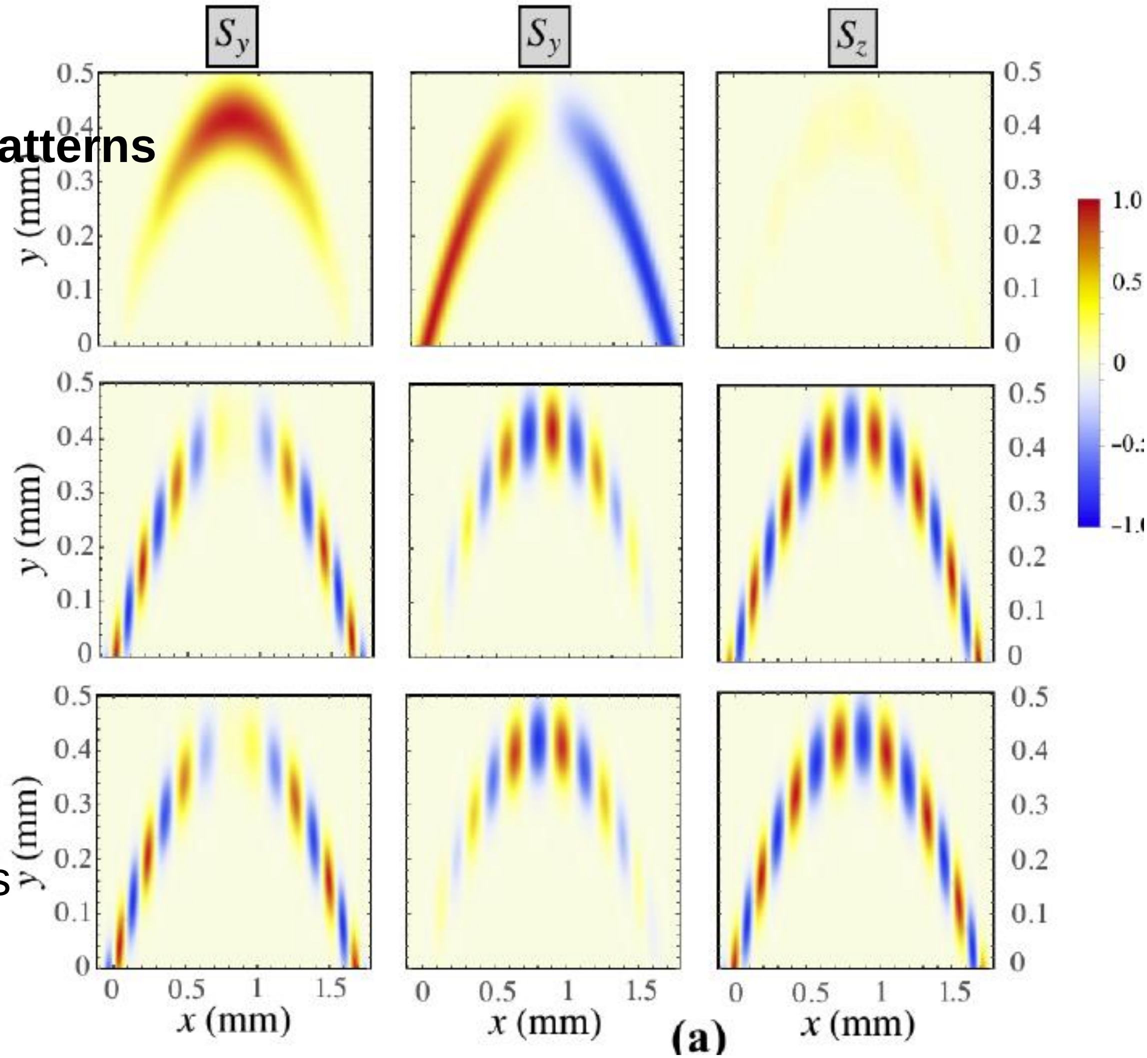
And we need to take care of the initial conditions

Simplifying assumptions:

- Constant detuning
- Constant Hopfield coefficients

Allow for the analytical descriptions of:

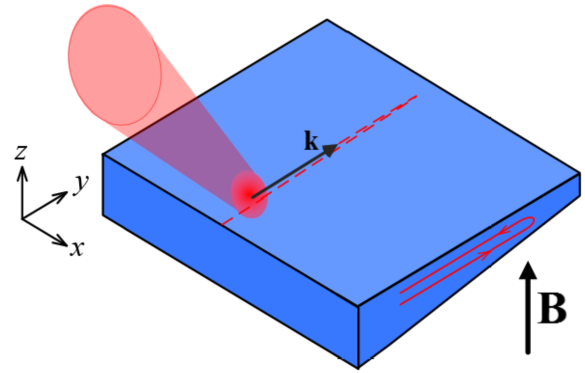
- **Polarisation patterns**
- **Self-interference intensity patterns**
- **The slow mirror effect**



Examples of polarisation patterns at oblique incidence

Linear propagation along the cavity thickness gradient (no self-interference) $B = 0$

$$\Omega_{cy} = \Omega_{cz} = 0$$



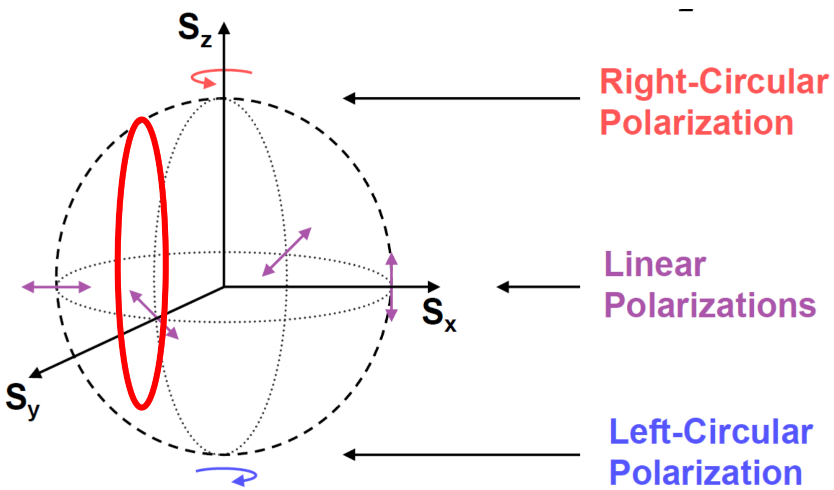
$$S_x = S_{x0}$$

$$S_y = S_{y0} \cos\left[\kappa(t)\right] + S_{z0} \sin\left[\kappa(t)\right]$$

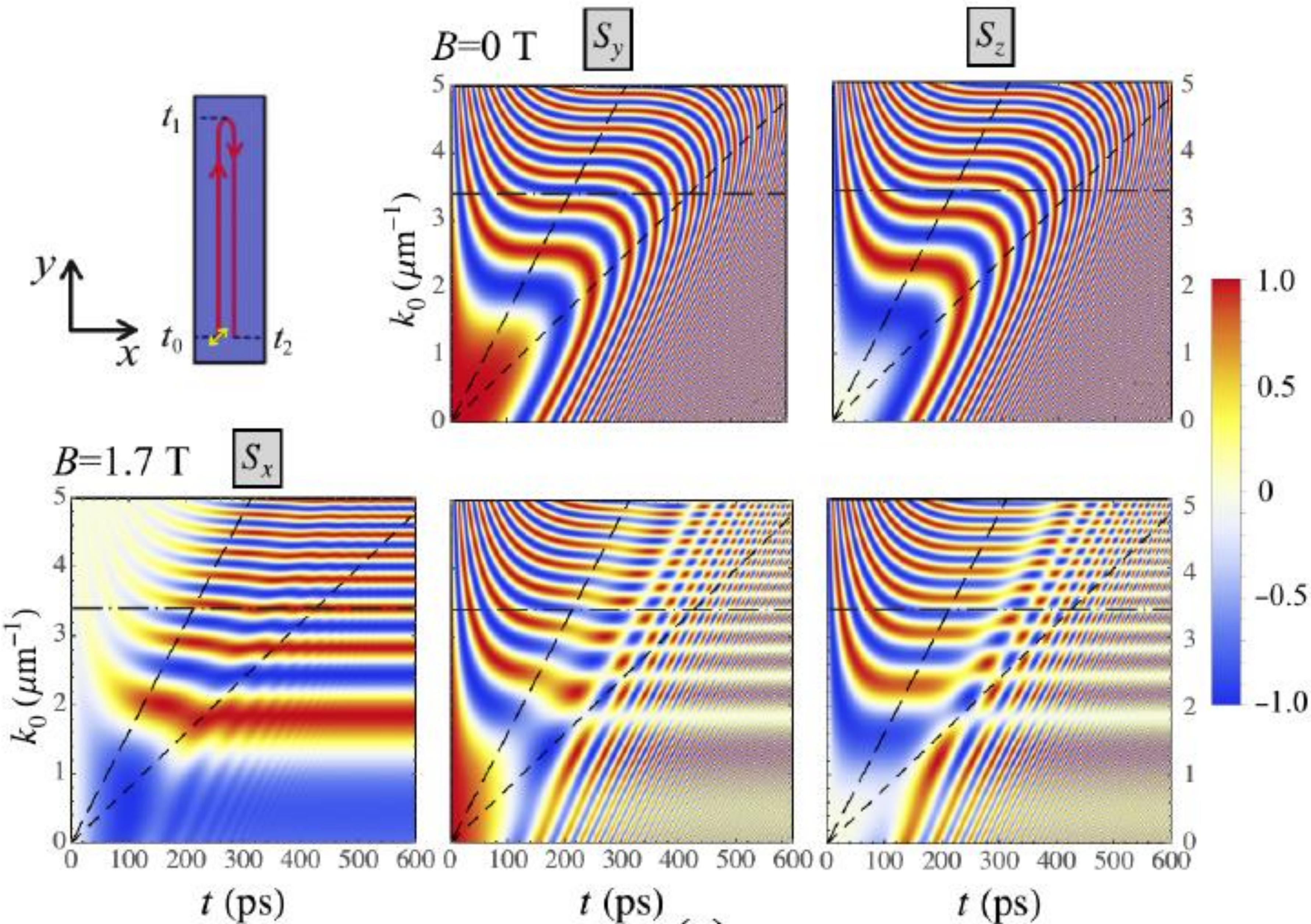
$$S_z = S_{z0} \cos\left[\kappa(t)\right] - S_{y0} \sin\left[\kappa(t)\right]$$

$$\kappa(t) = \Delta_{\mathrm{LT}} t \left[k_{y0}^2 - k_{y0}\beta t + \beta^2 t^2 / 3\right]$$

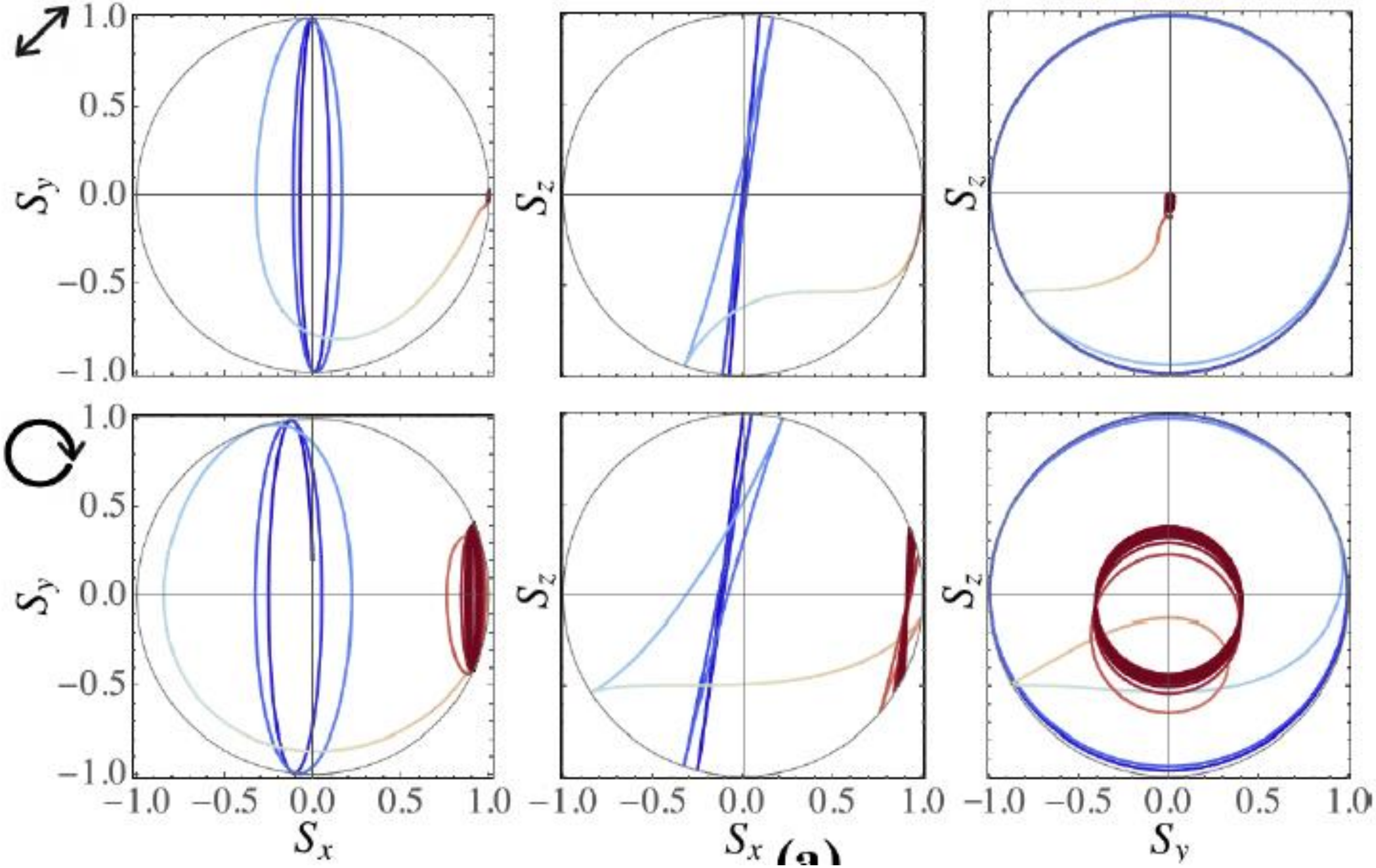
A closed trajectory on the Poincare sphere!



The magnetic field effect



Trajectories on the Poincare sphere



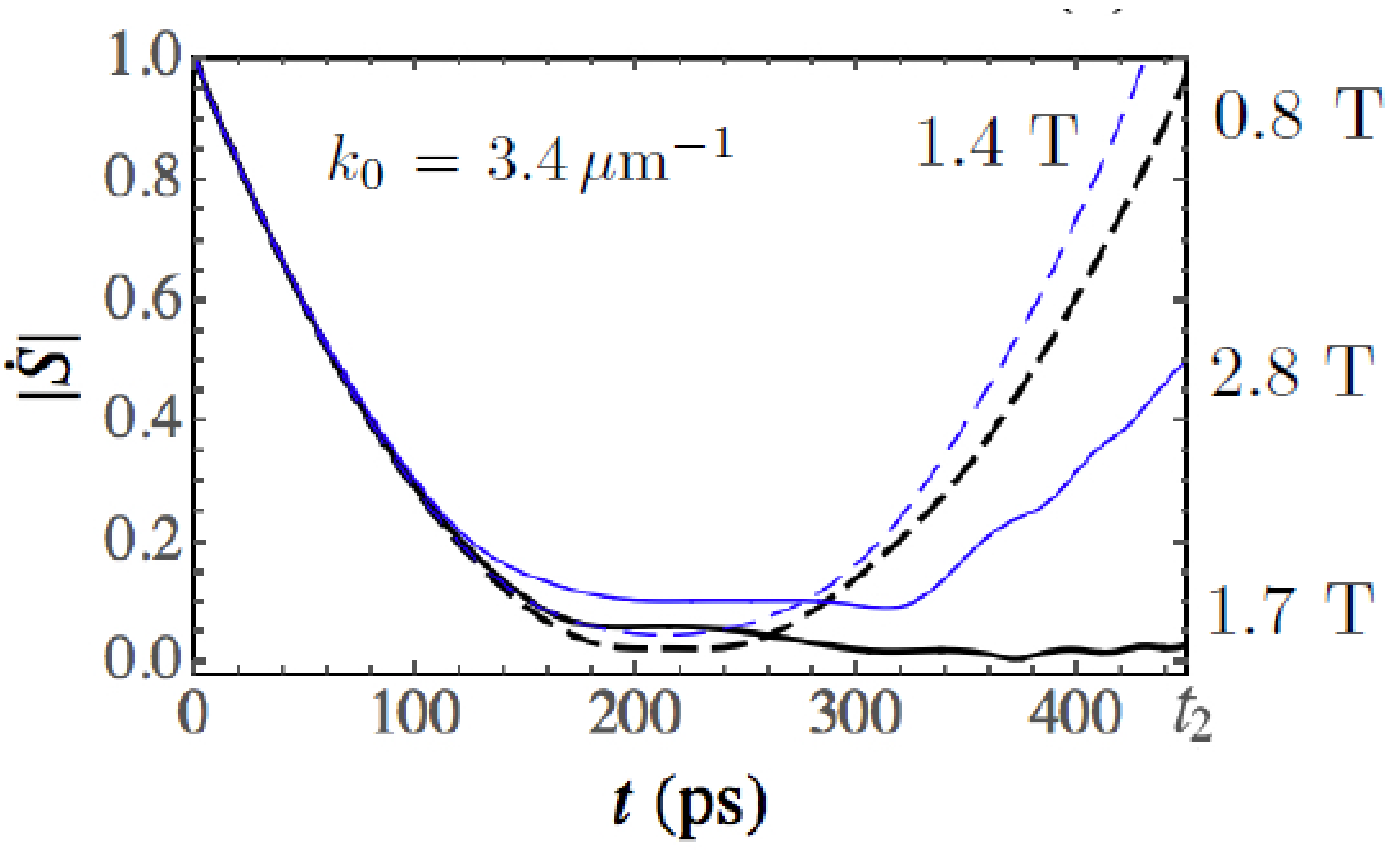
$B = 1.7$ T

$B = 2.8$ T

Blue from $t = 0$ to t_1

Red after t_1

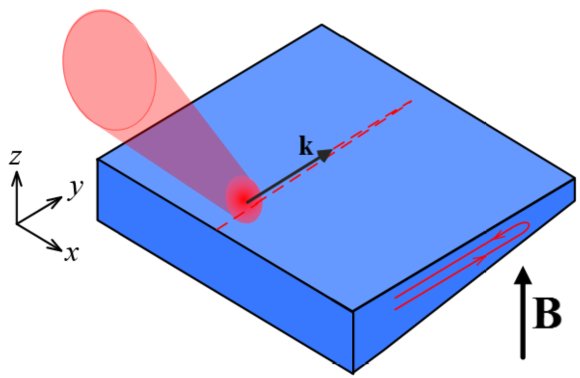
The Stokes vector dynamics may tend to an attractor



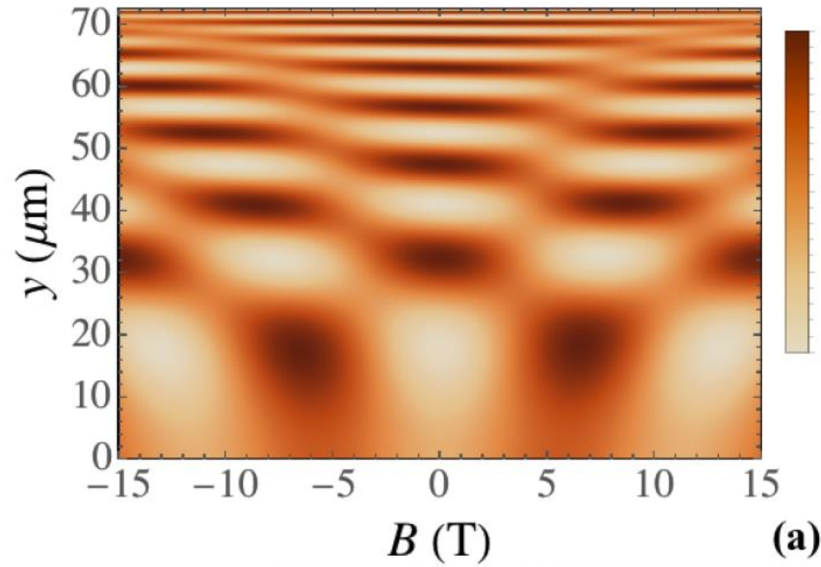
$$|\dot{\mathbf{S}}|^2 = \Omega_{cx}^2\left(S_y^2 + S_z^2\right) + \Omega_{cz}^2\left(S_x^2 + S_y^2\right) - 2\Omega_{cx}\Omega_{cz}S_xS_z$$

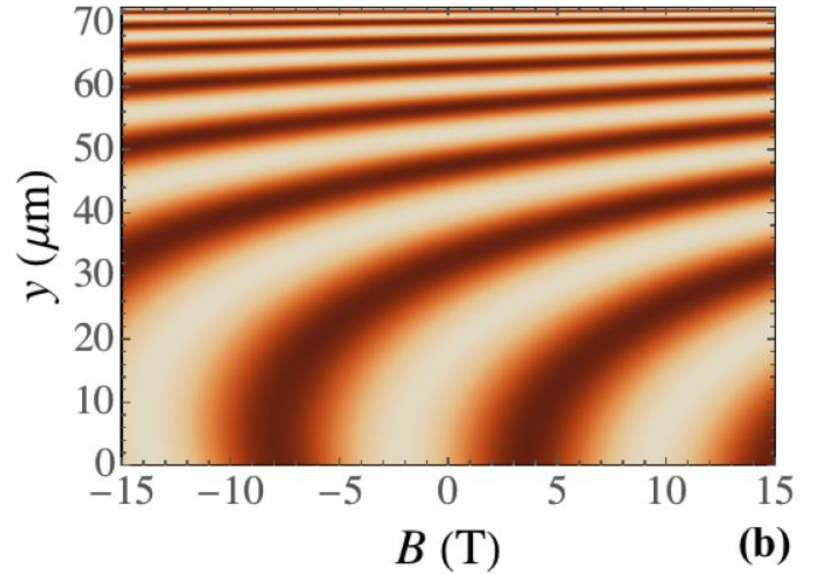
Self-interference patterns

Diagonal initial polarisation



Circular initial polarisation





At B=0

$\tau \equiv \tau(y)$ time of flight

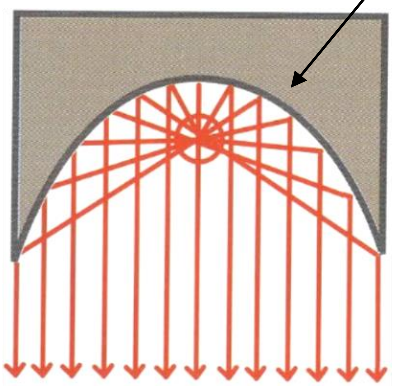
$$I_{y>0} = 2 + \cos\left[k_{cy}(\tau) d_p(\tau)\right] + \cos\left[k_{cy}(\tau) d_m(\tau)\right]$$

$$d_{p,m}(\tau) = -\left[\left(k_{cy}(\tau)\right)^2 \left(2m^* \Delta_{\mathrm{LT}} \mp \hbar\right) \pm 3\hbar k_{y0}^2\right] / 6m^* \beta$$

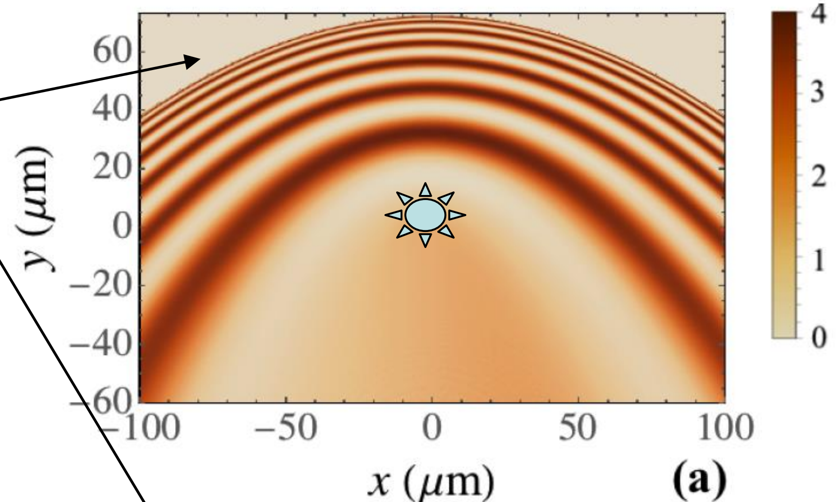
A point-like CW source: Berry phase interferometer!

Circular polarisation, initially $k_0 = 1\,\mu\mathrm{m}^{-1}$

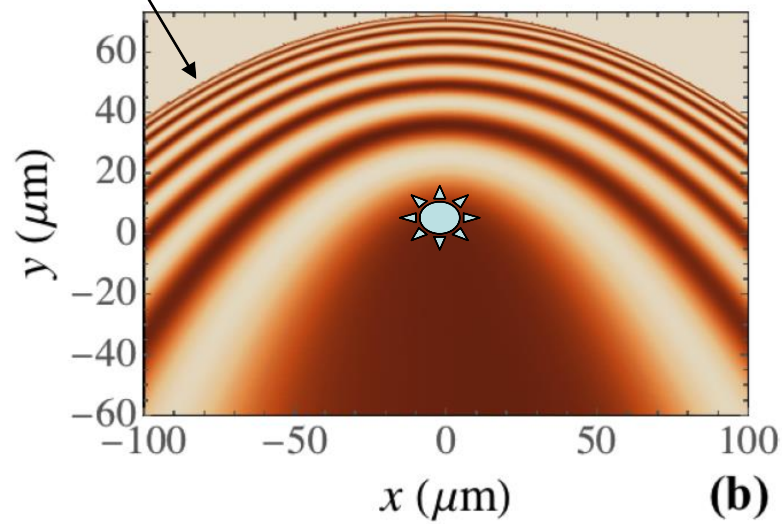
$$y_{\mathrm{SM}} = \frac{\hbar k^2}{2\beta m} - \frac{\beta m}{\hbar k^2} x^2$$



The slow mirror



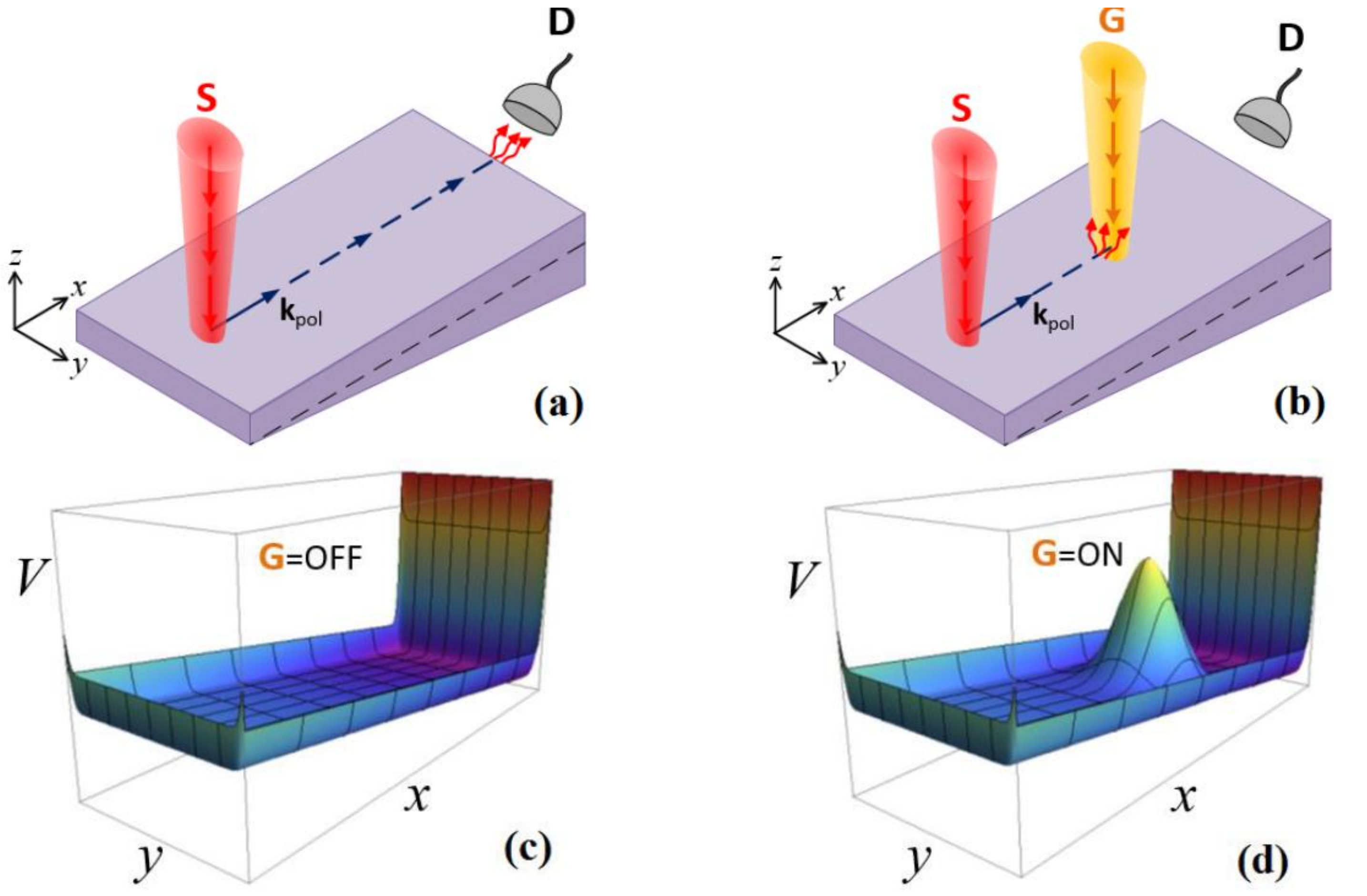
$B = 0$



$B = 3$ T

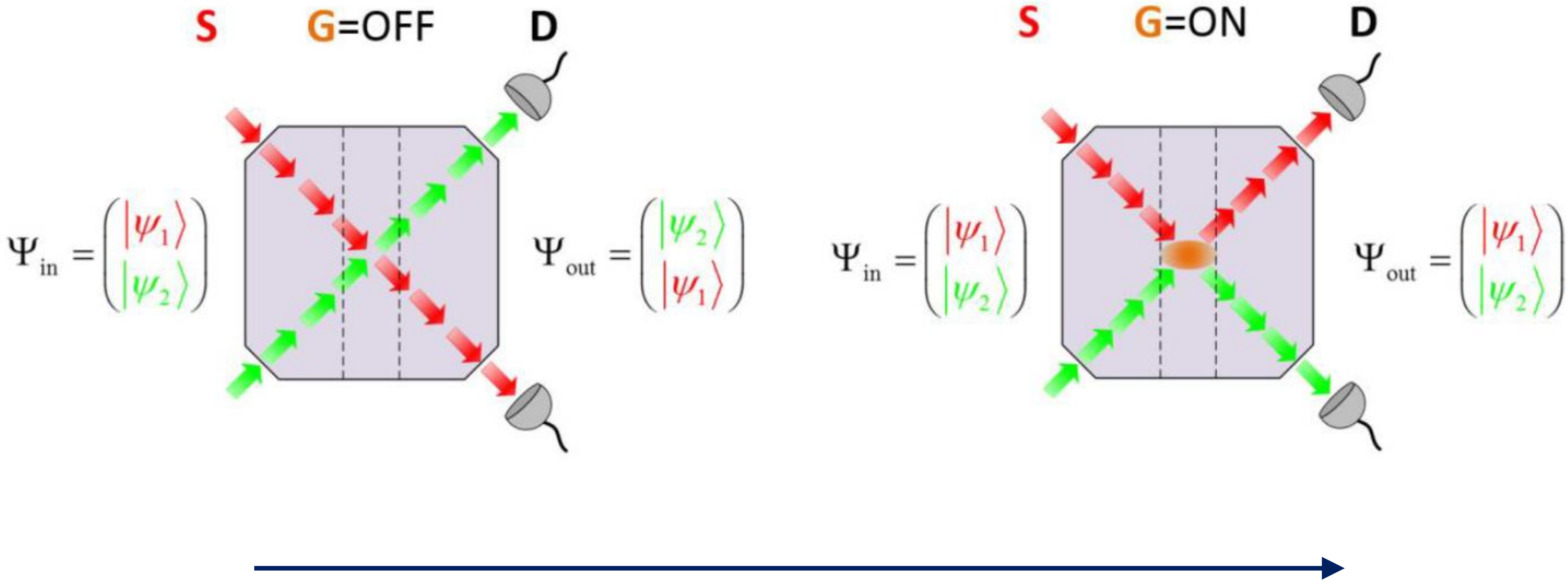
At B=0: $I_{y<0} = 2 + \cos\left[k_0^3(\Delta_{\mathrm{LT}} + \hbar/m^*)/\,3\beta\right] + \cos\left[k_0^3(\Delta_{\mathrm{LT}} - \hbar/m^*)/\,3\beta\right]$

What else? Applications?



Polariton spin transistors (requires a non-linearity)?

2x2 photonic switches?



“gravitational force”

Conclusions

- The cavity thickness gradient plays the role of artificial gravity.
- Polarization patterns in the real space due to the optical spin Hall effect and “slow reflection” are formed.
- At the specific combinations of the magnetic field and the initial polariton wave vector the polariton Stokes vector tends to an attractor on the surface of the Poincaré sphere.
- A point-like source at the cavity wedge induces a parabolic “slow” mirror.
- Applications: Berry phase interferometers, spin transistors, switches…