Investigating Topology of Spin in Surface Plasmon Polariton Fields

THE UNIVERSITY OF MELBOURNE

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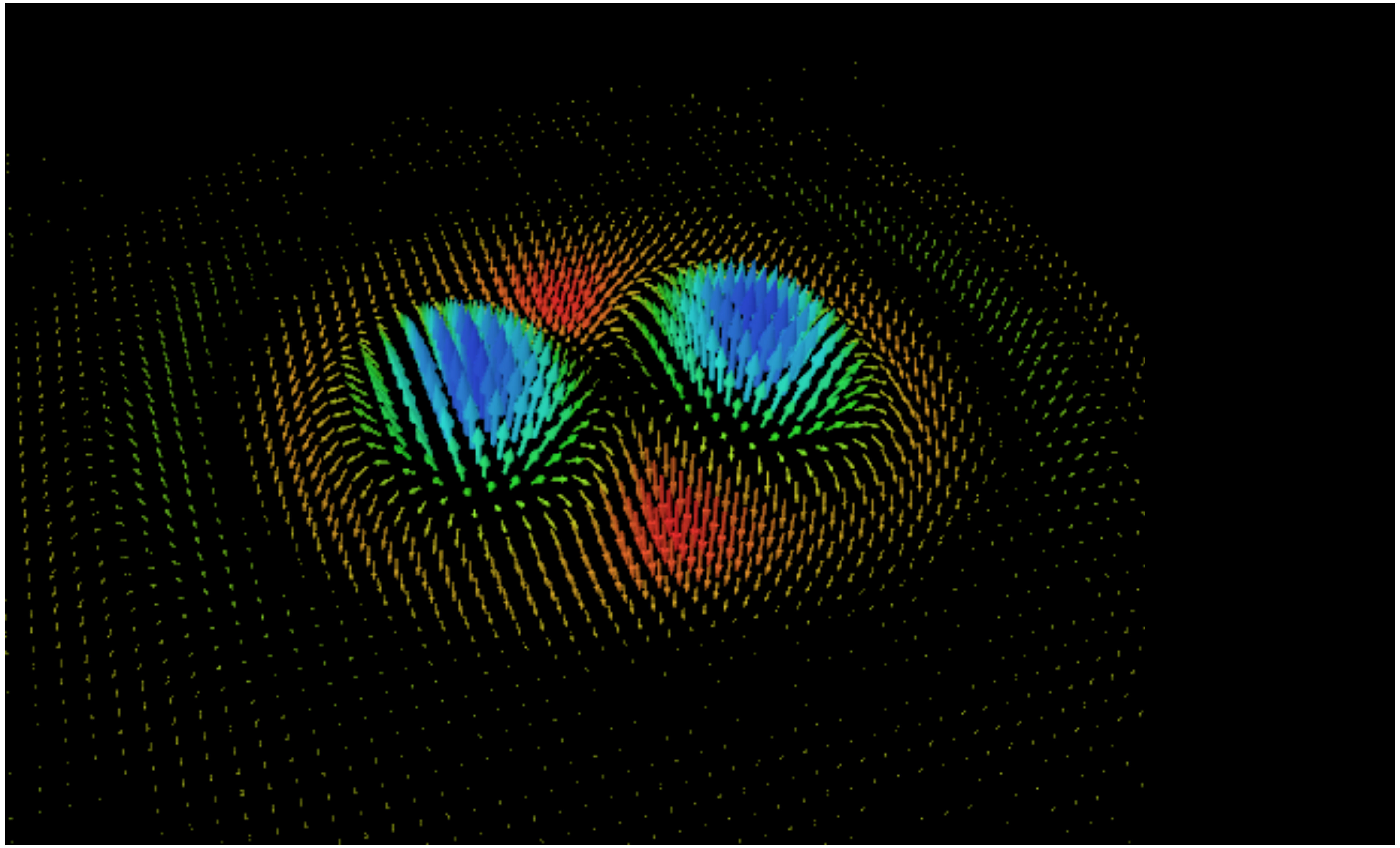
Offen im Denken



Tim Davis

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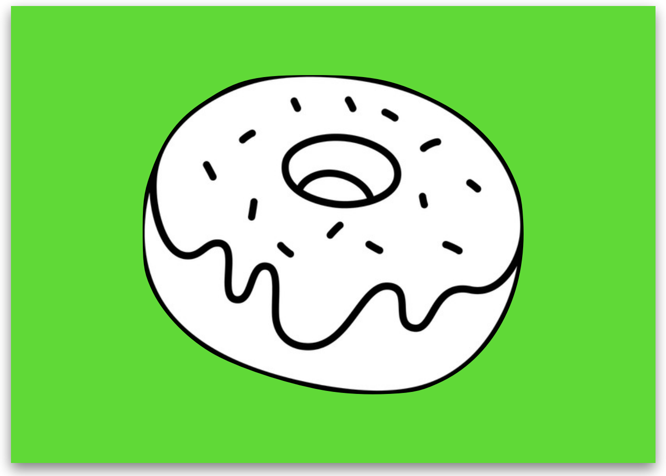
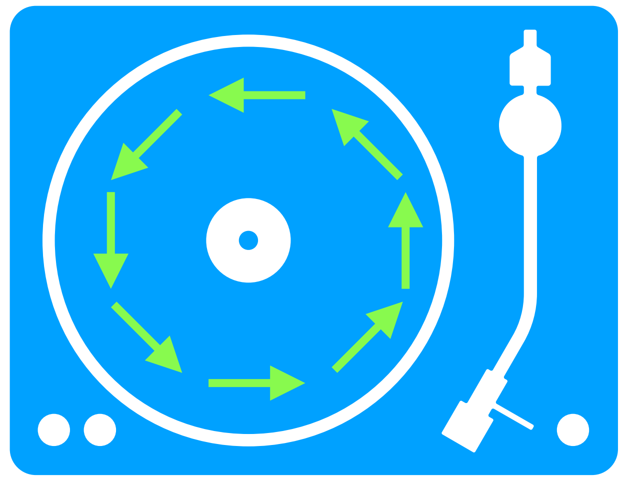
Outline

Surface plasmons and spin

Some spin topologies



In-plane vectors on a disk and topological constraints

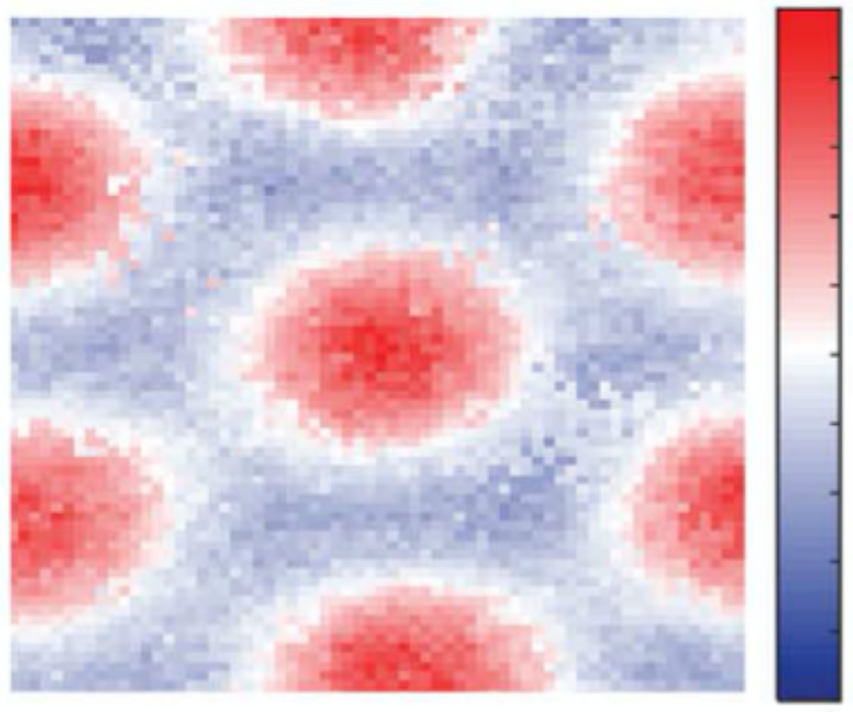


Conclusions

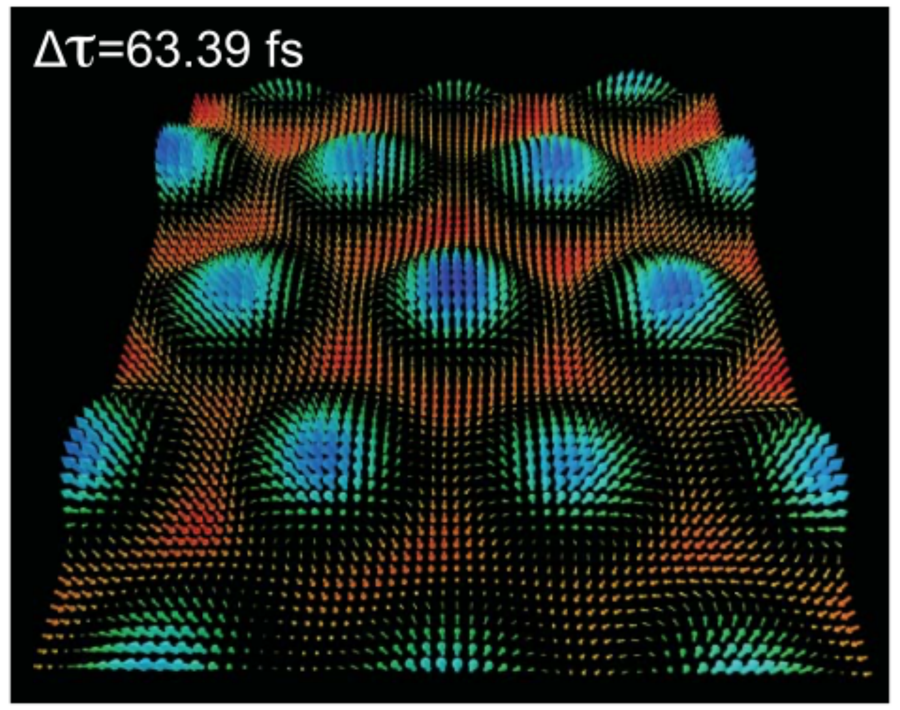
SPP vector topology

Examples of surface plasmon polariton vector distributions with skyrmion and meron-like topologies

SPP electric field skyrmion lattices

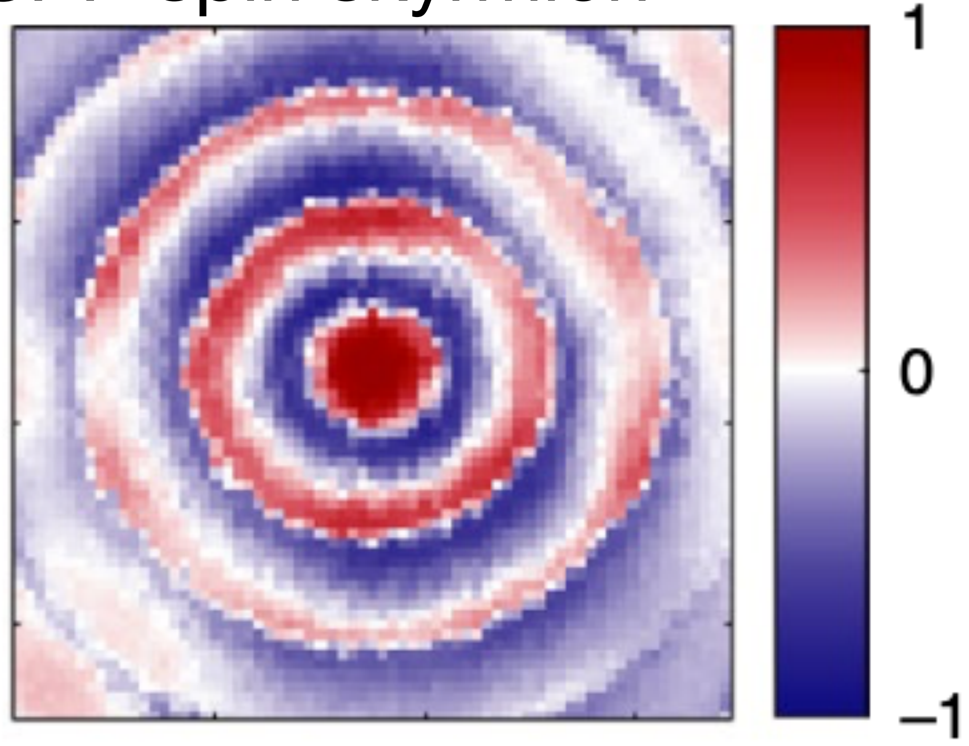


Tsesses et al.
Science **361** 993 (2018)



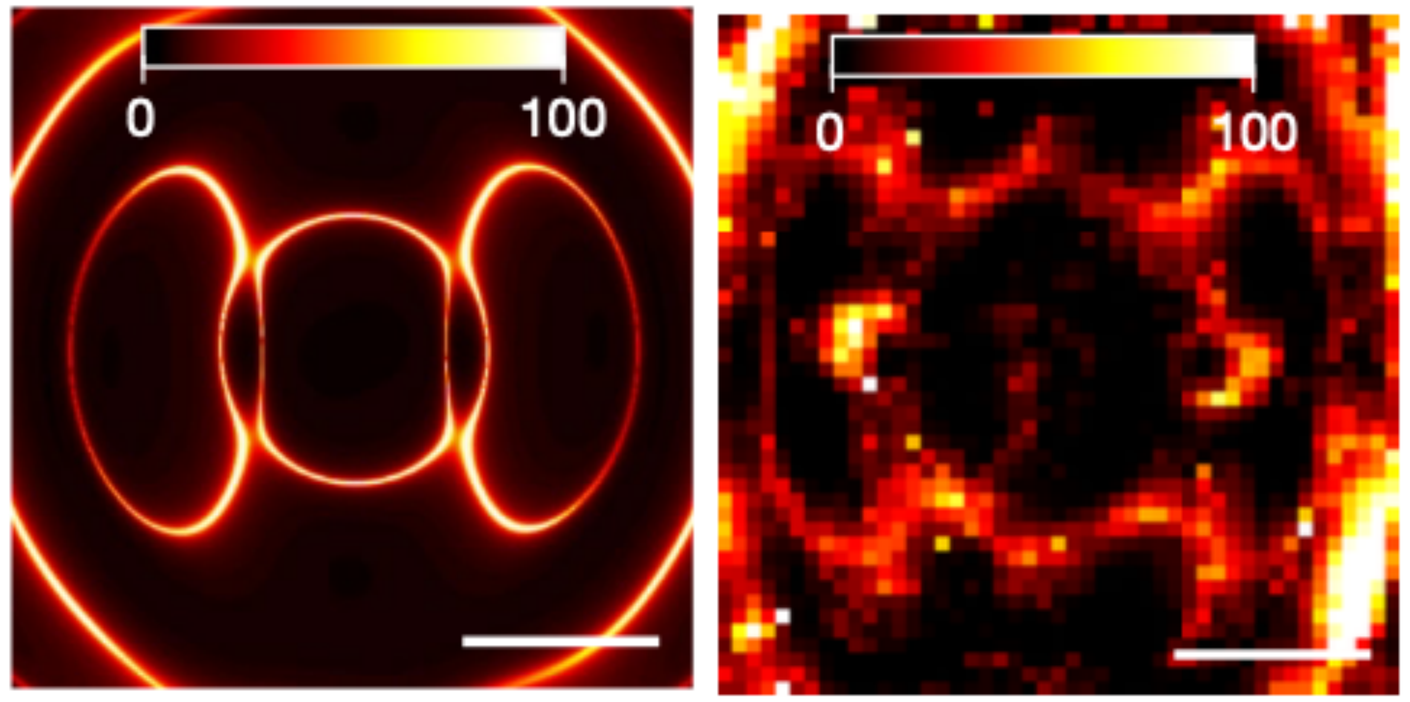
Davis et al.
Science **368**, eaba6415 (2020)

SPP spin skyrmion



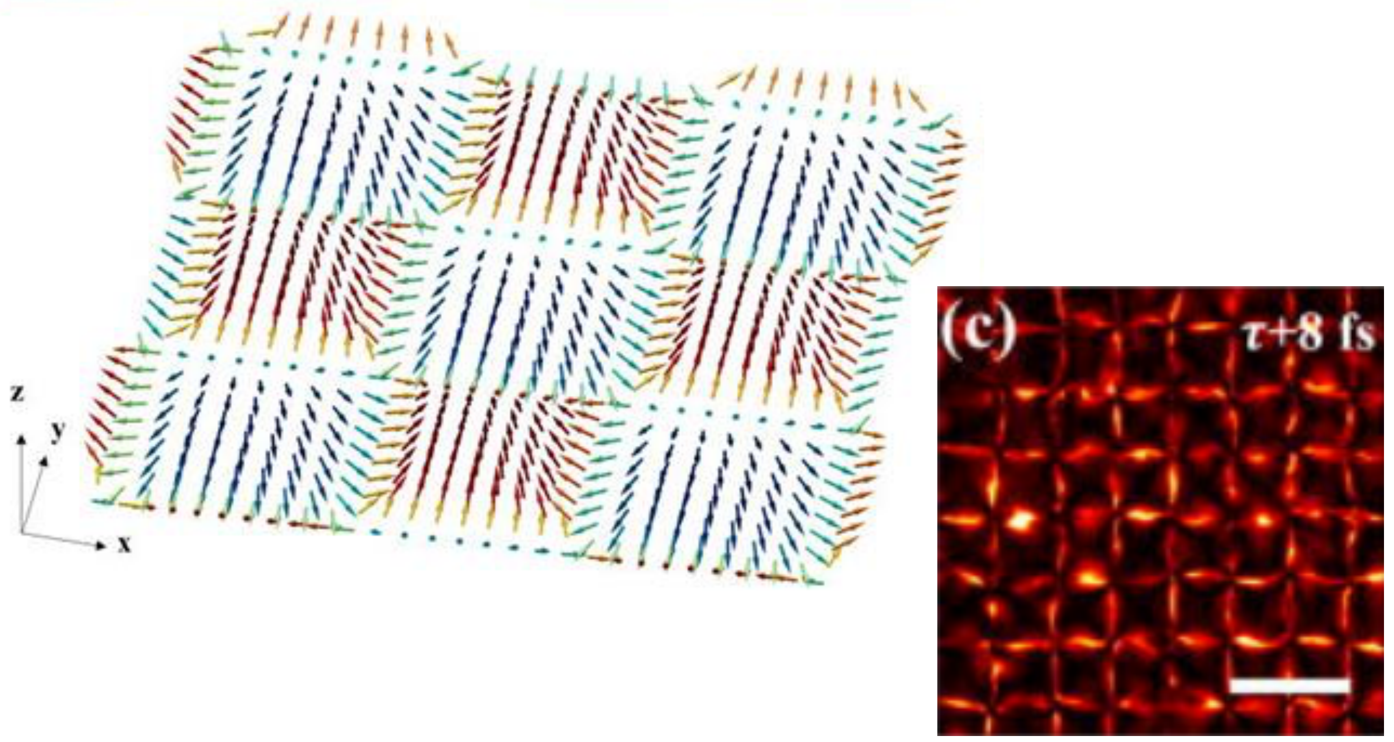
Du et al.
Nature Physics **15**, 650 (2019)

SPP spin merons



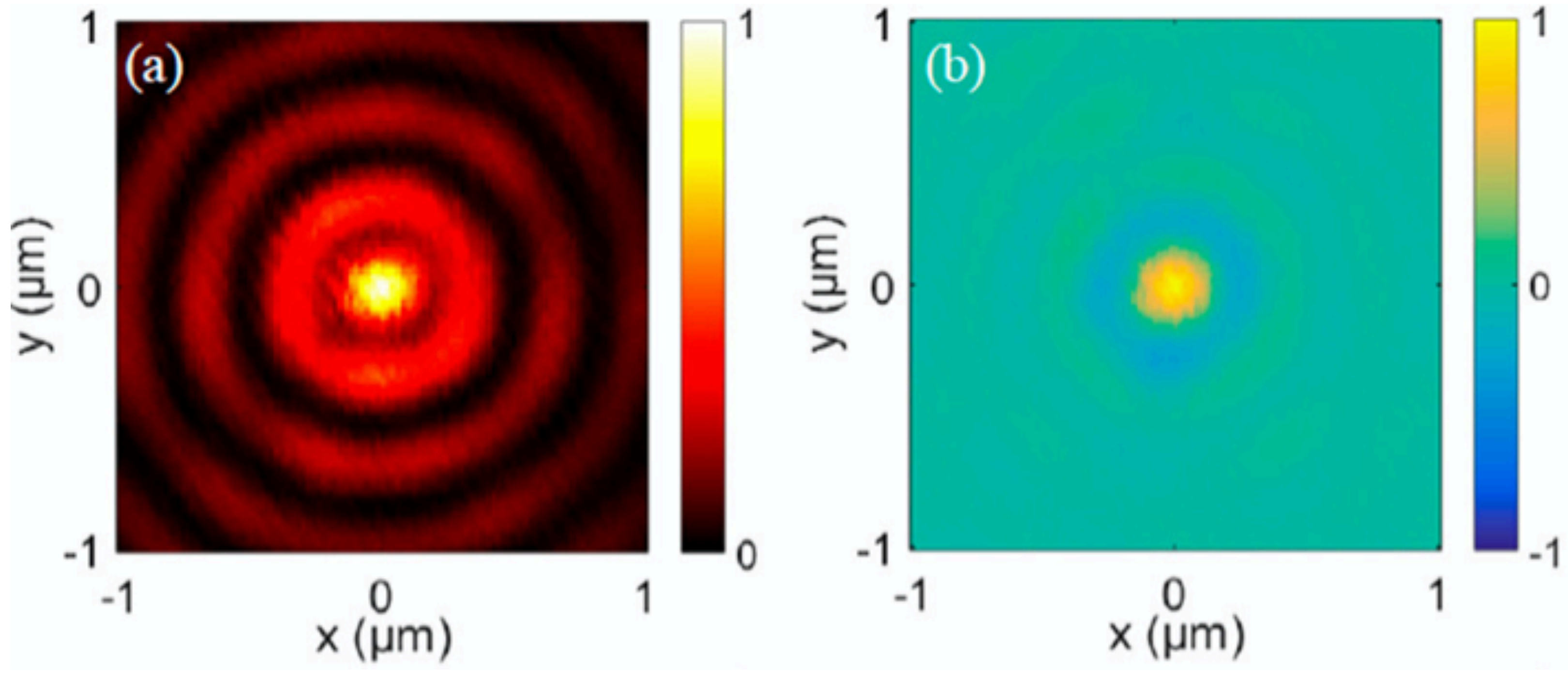
Dai et al. *Nature* **588**, 616 (2020)

SPP spin meron lattice



Gosh et al.
Appl. Phys. Rev. **8**, 041413 (2021)

SPP spin skyrmion dynamic control



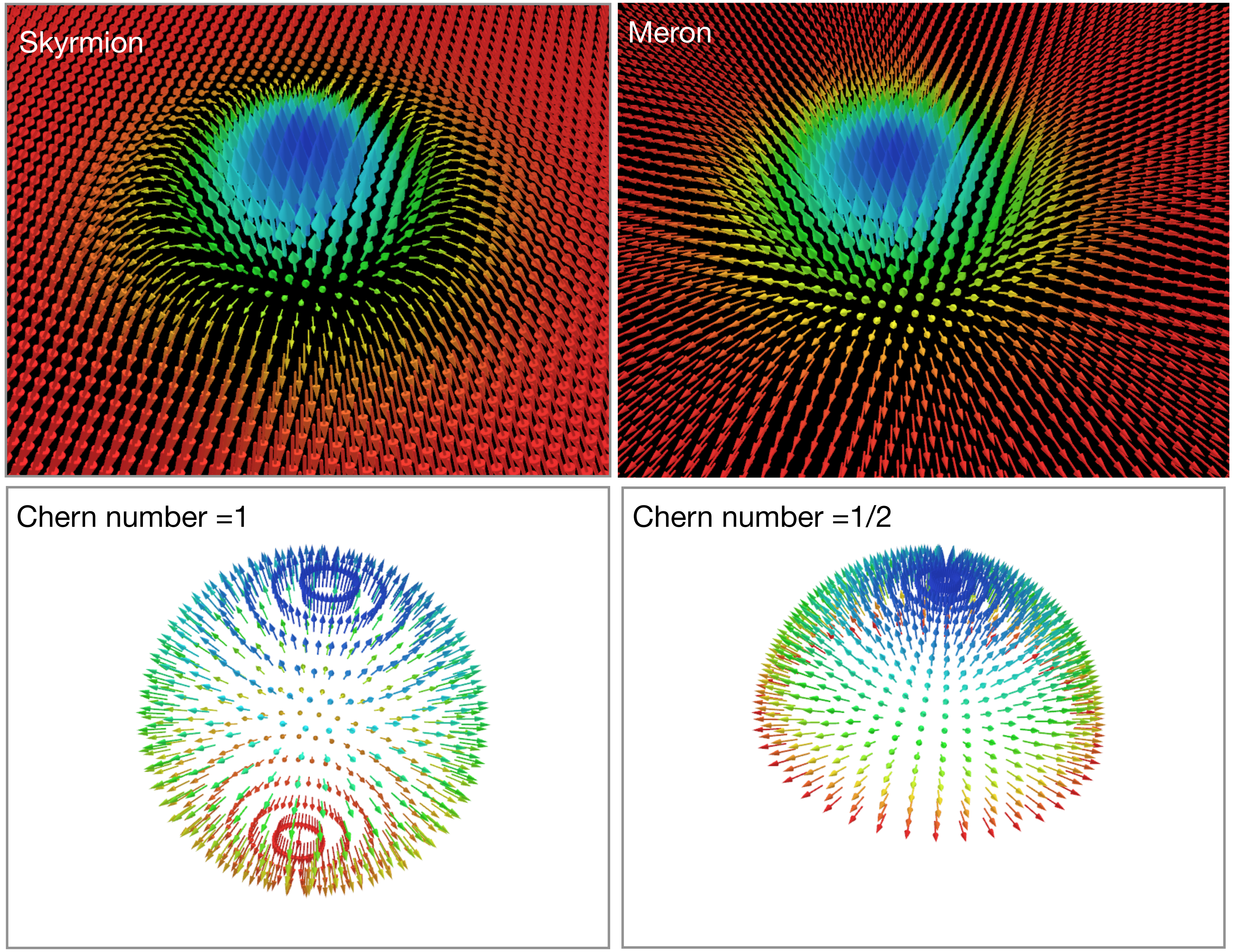
Lin et al.
ACS Photonics **8**, 9 (2021)

Topologies of vectors

Interested in the topology of vectors associated with surface plasmon polaritons

How do the vectors map the surface?

How do the vectors map the plane?



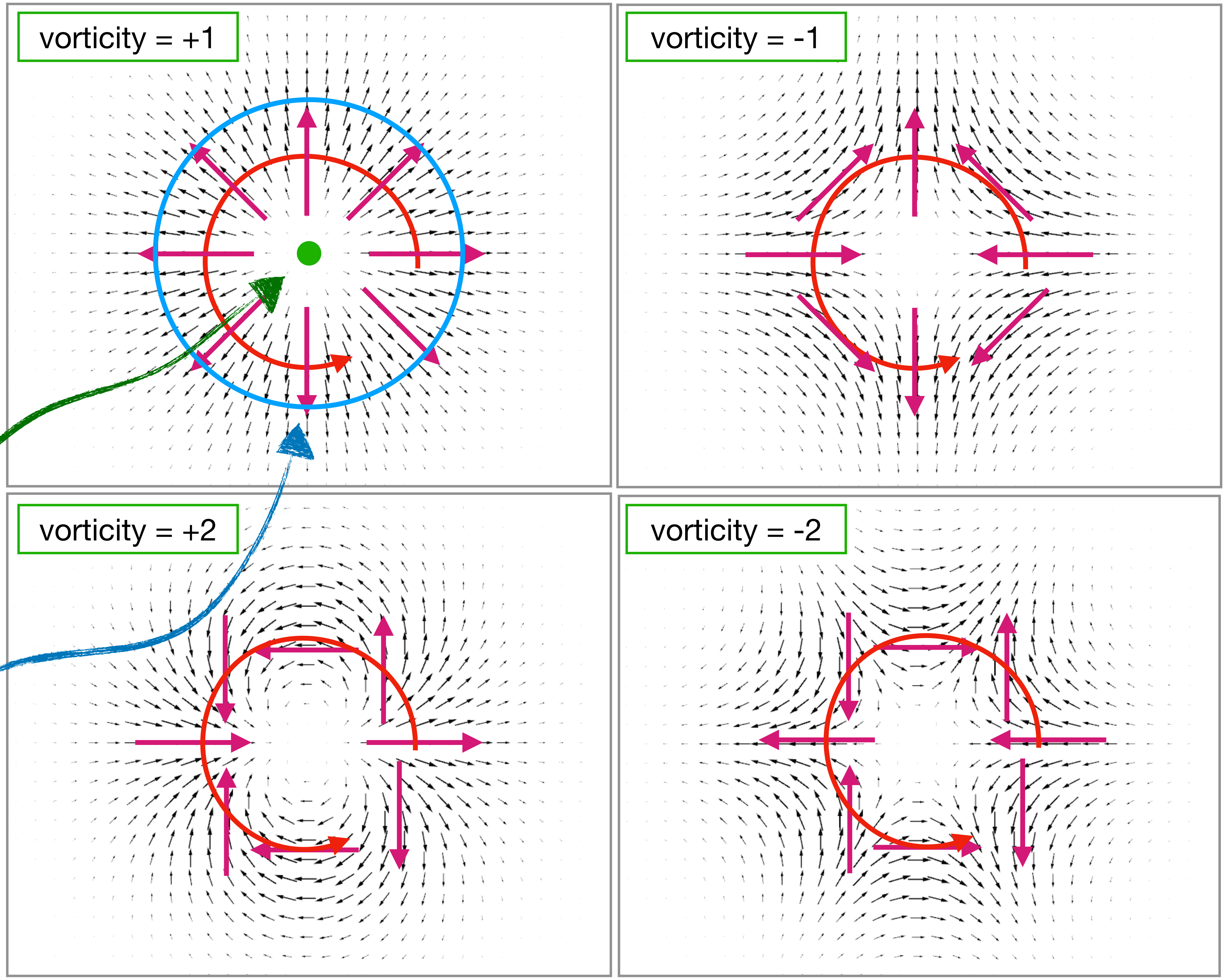
Topologies of vectors

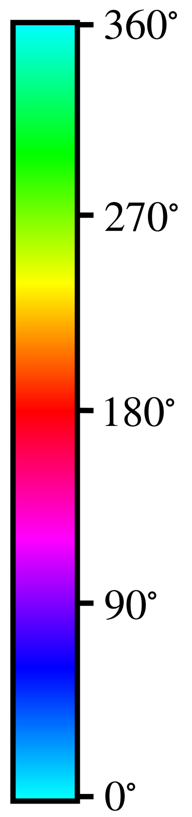
Interested in the topology of vectors associated with surface plasmon polaritons

How do the vectors map the surface?

How do the vectors map the plane?

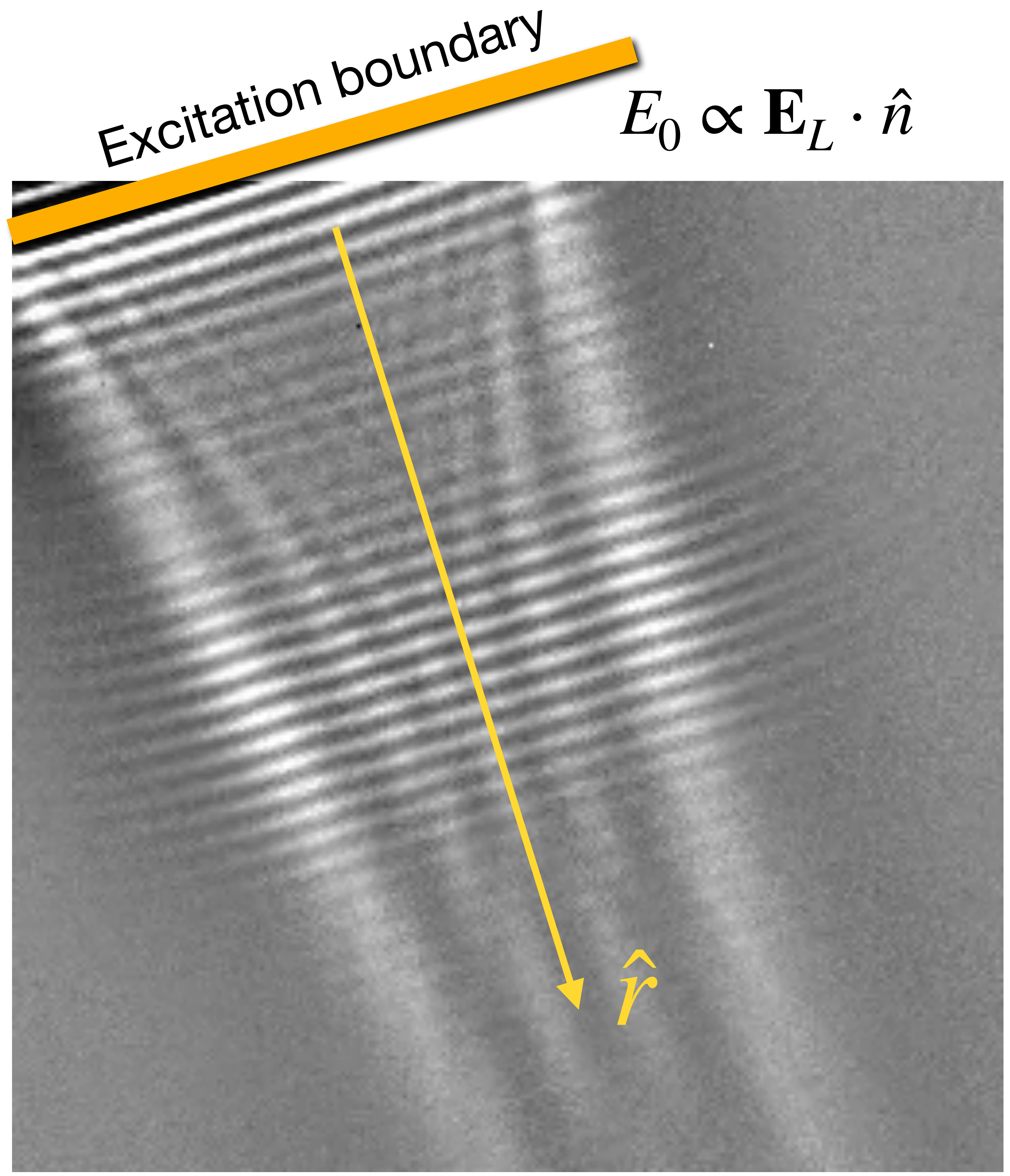
Look at how the vector directions change about the “zeroes” of the in-plane vector field





C-point
perfect circular
polarisation

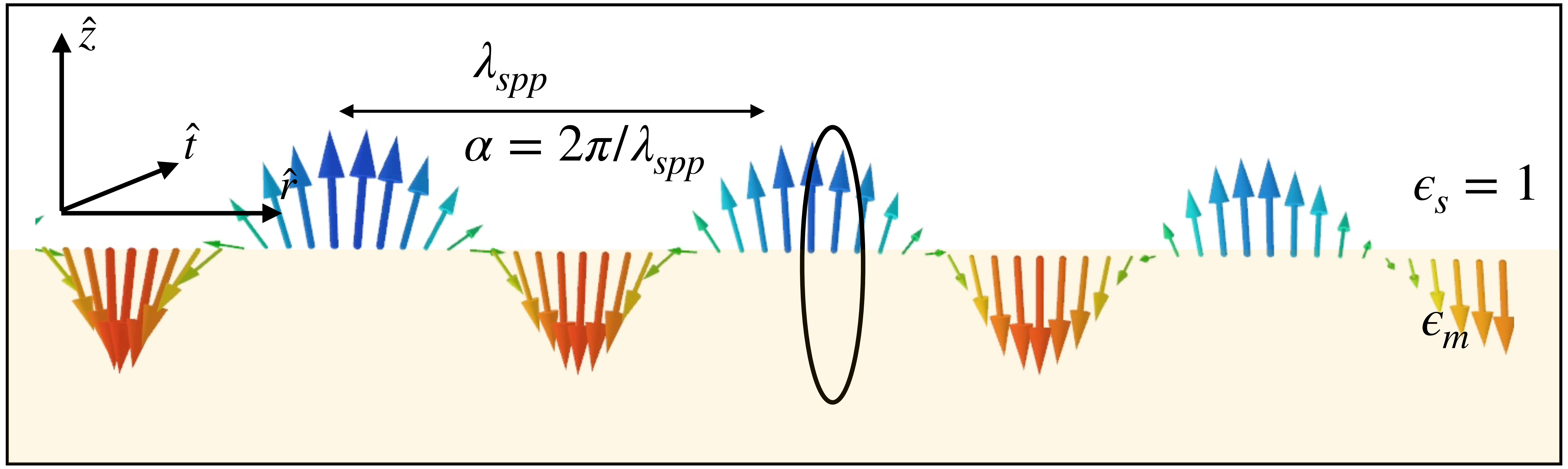
L-line
line of linear
polarisation



$E_0 \propto \mathbf{E}_L \cdot \hat{n}$

2PPE-PEEM
Pump-probe measurement

SPP electric field reconstruction from experimental data



Solution to Maxwell's equations

$$\mathbf{E} = E_0 \left(\alpha\hat{z} - i\gamma\hat{r}\right) e^{i\alpha\hat{r}\cdot\mathbf{r} - \gamma z - i\omega t}$$

$$\mathbf{H} = -E_0 \left(k/c\mu_0\right) \hat{t} e^{i\alpha\hat{r}\cdot\mathbf{r} - \gamma z - i\omega t}$$

$$\alpha = k\sqrt{\frac{\epsilon_s\epsilon_m}{\epsilon_s + \epsilon_m}}$$

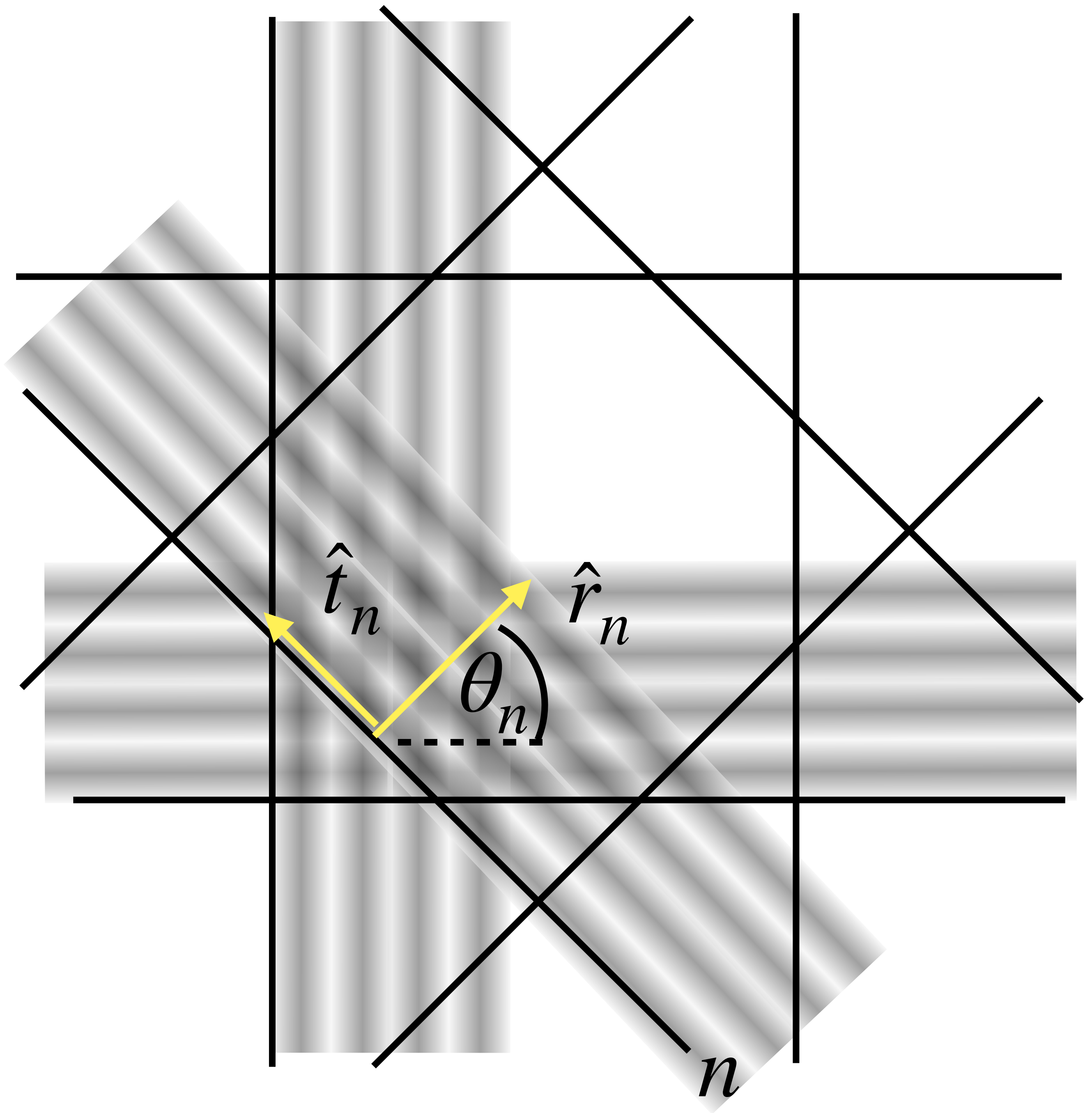
$$\gamma = \sqrt{\alpha^2 - \epsilon_s k^2}$$

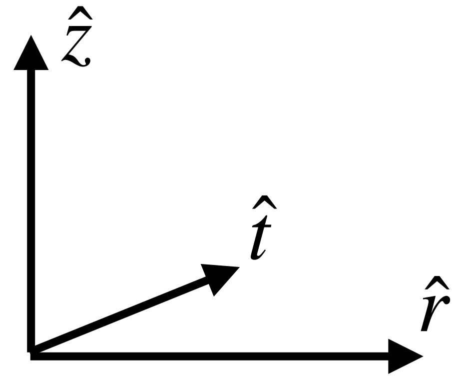
Davis et al,Science (368), eaba6415 (2020)

SPP Spin Model

Launch SPP plane waves from a series of straight line boundaries

Study the resulting interference pattern at the centre





The maths …

Amplitude of SPP from *n*-th boundary

Phase

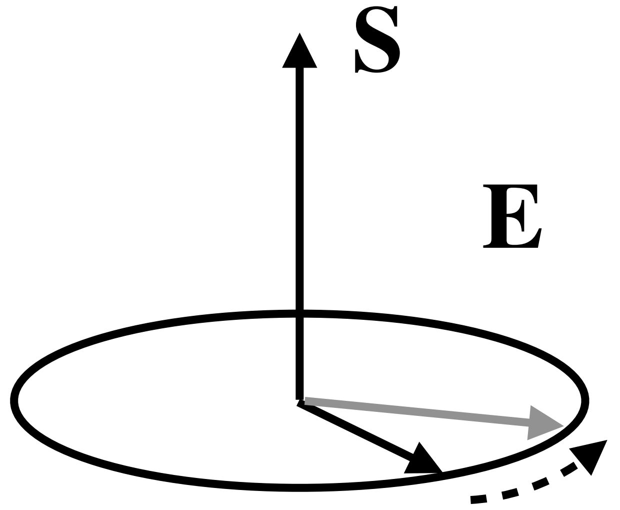
$$\mathbf{E} = \sum_n a_n \left(\alpha \hat{z} - i\gamma \hat{r}_n\right) e^{i\alpha \hat{r}_n \cdot \mathbf{r} + i\phi_n}$$

Propagation direction

$$\mathbf{H} = -\left(k/c\mu_0\right) \sum_n a_n \hat{t}_n e^{i\alpha \hat{r}_n \cdot \mathbf{r} + i\phi_n}$$

Spin (angular momentum density)

$$\mathbf{S} = \frac{\epsilon_0}{4\omega} \mathrm{Im}\left(\mathbf{E}^* \times \mathbf{E} + (\mu_0/\epsilon_0)\mathbf{H}^* \times \mathbf{H}\right)$$



$$\frac{\partial \mathbf{E}}{\partial t} = -i\omega \mathbf{E}$$

We find that the out-of-plane spin arises from the interference of waves from non-parallel boundaries.

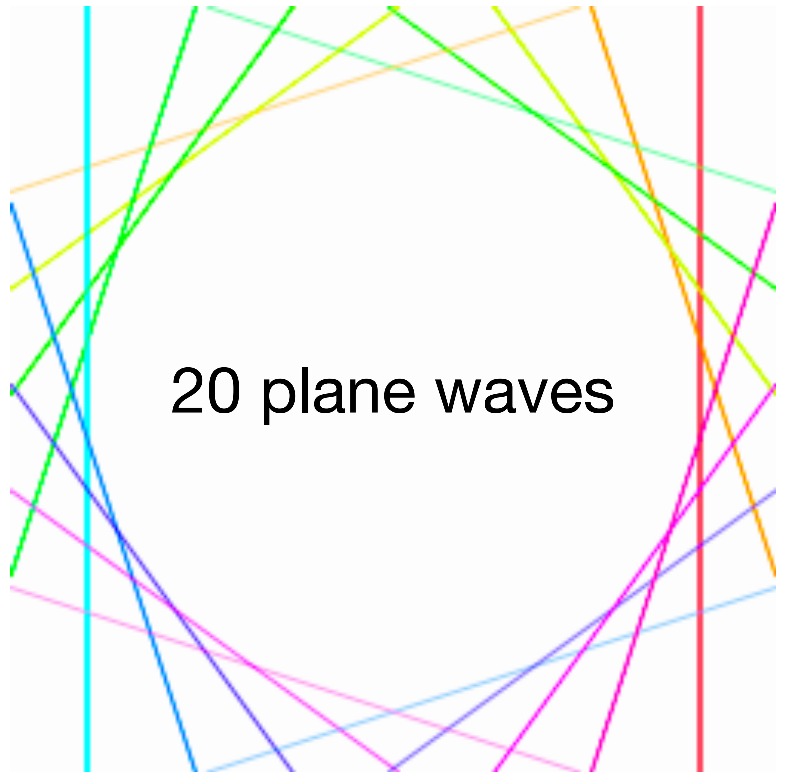
Davis et al. *ACS Photonics* **4**, 2461 (2017)

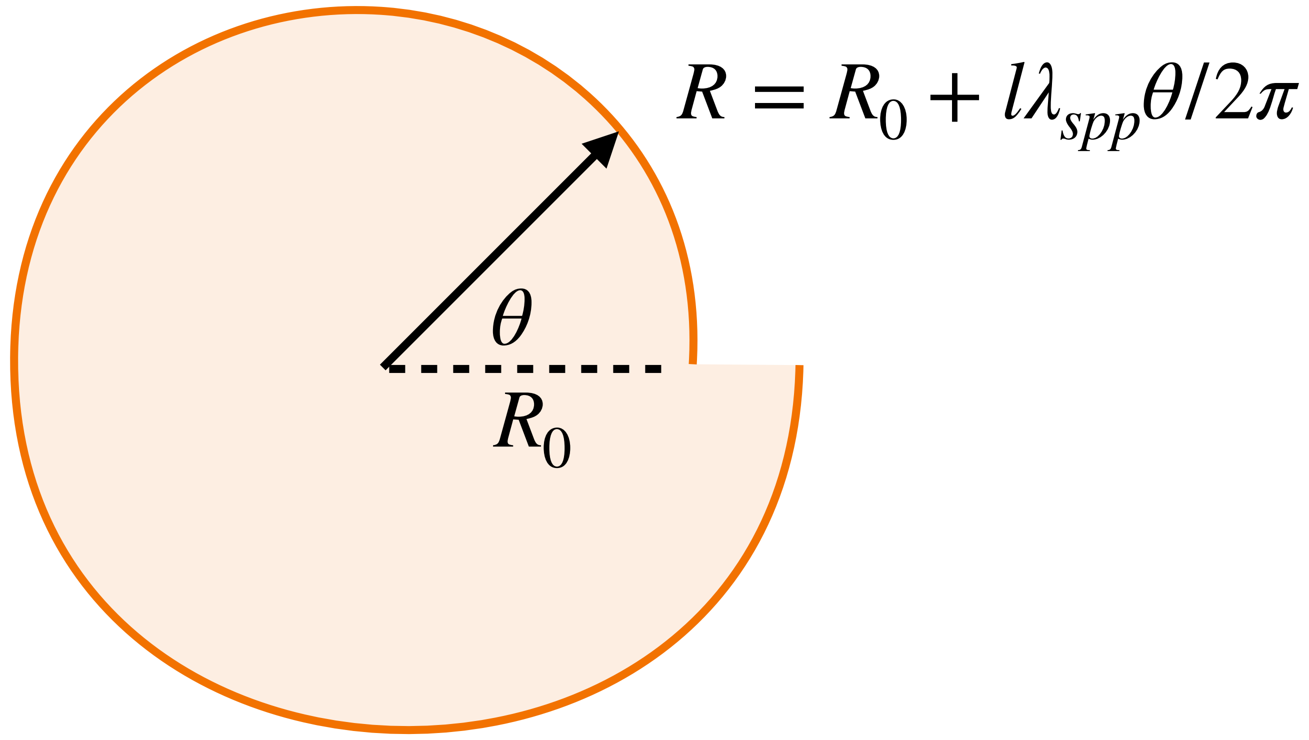
SPP Spin Examples

Three meron spin created by linearly polarised light incident on an Archimedean spiral with $l = 2$

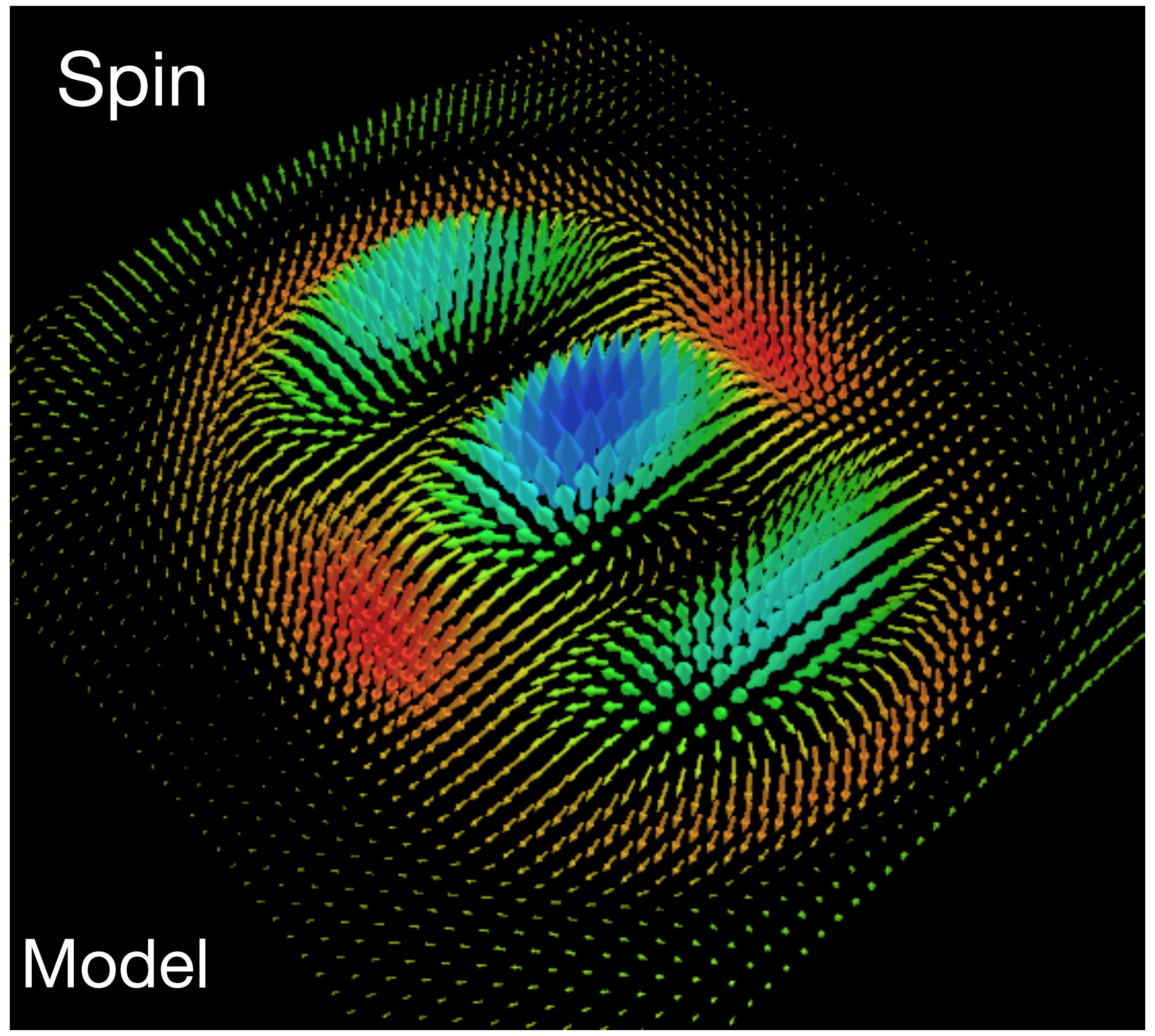
Amplitude depends on cosine of the angle (linearly polarised light on a circular boundary) $a_n = \cos\theta_n$

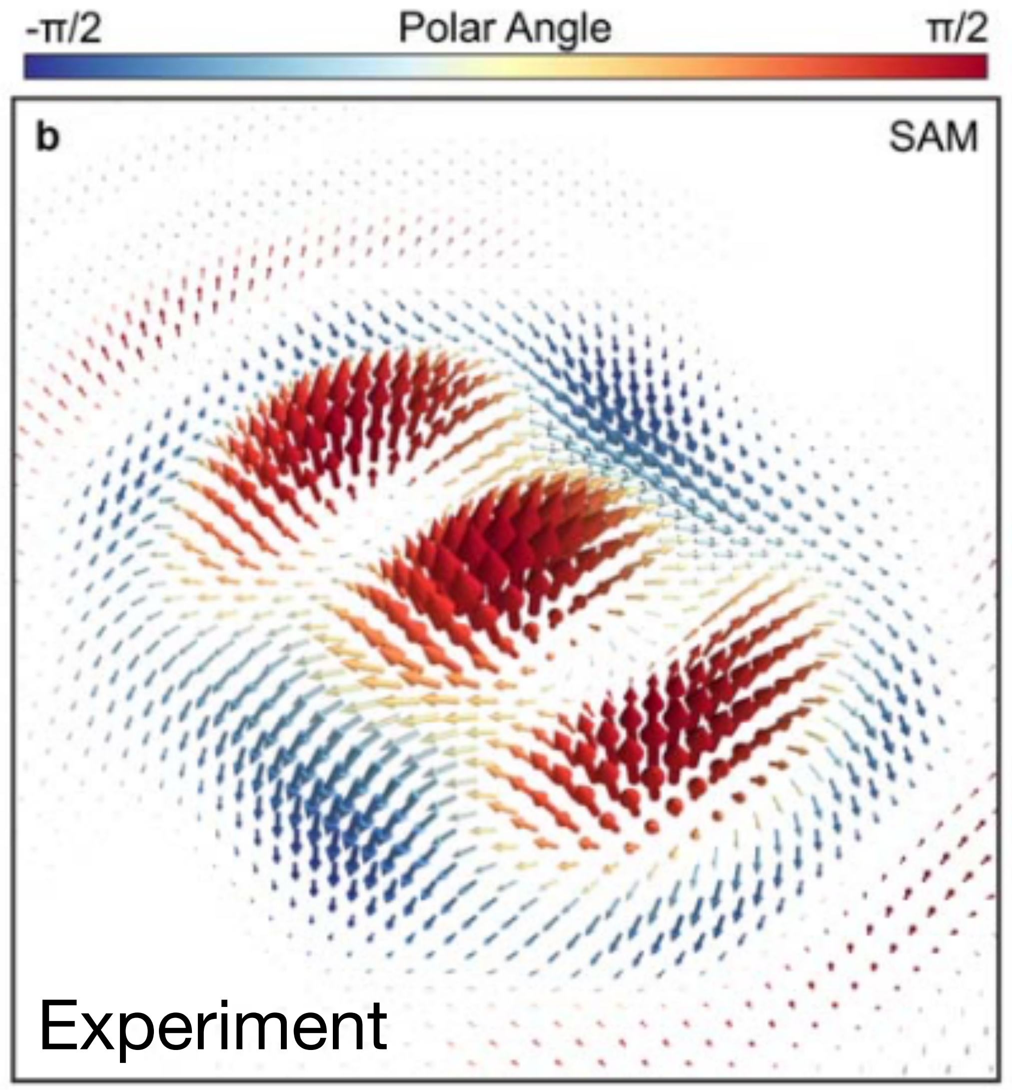
Phase follows twice the orientation of the boundary $\phi_n = 2\theta_n$

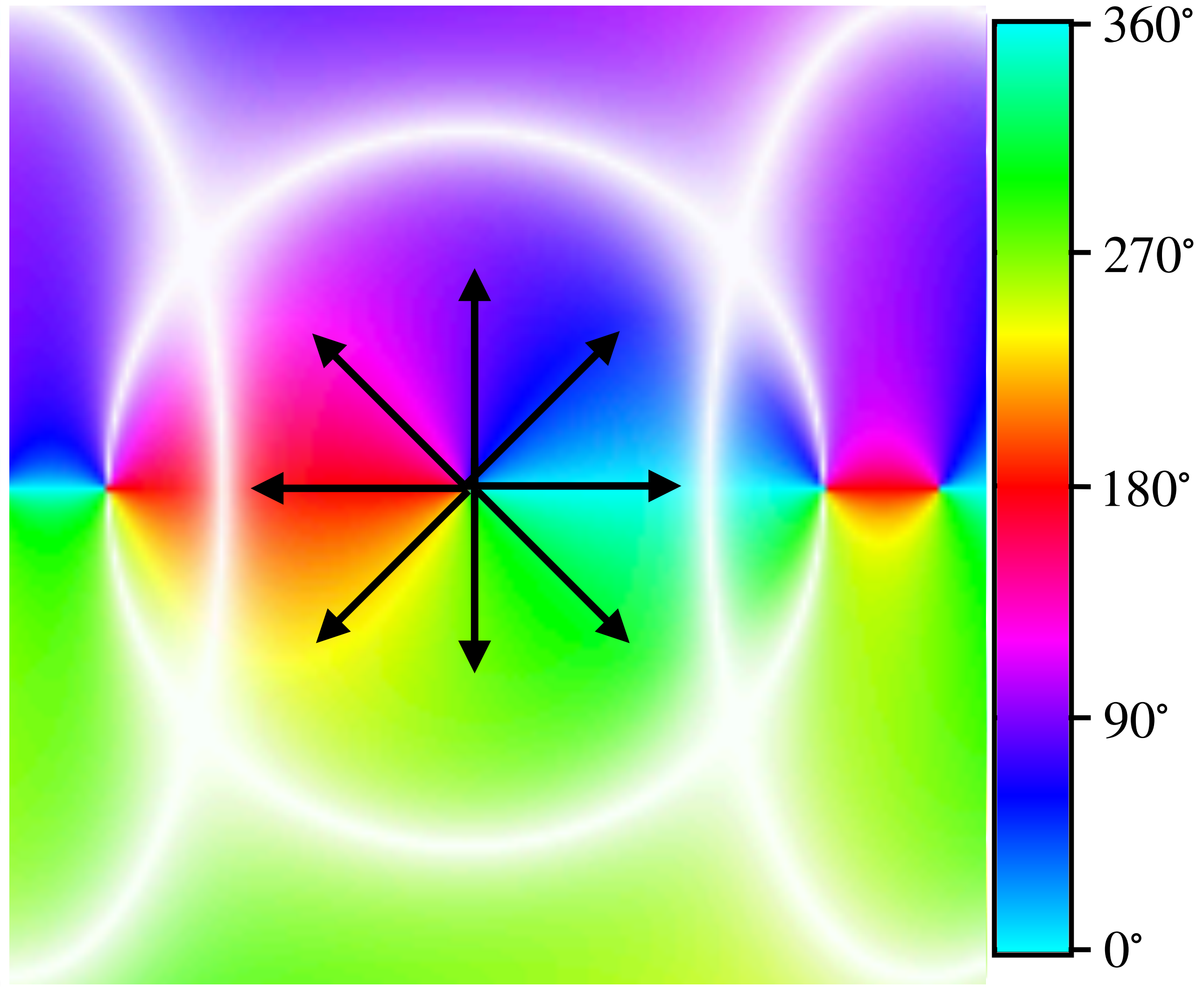




L-lines: lines of "linear" polarisation for in-plane vectors ($S_z = 0$)







Chern numbers C=1/2 only in regions bounded by L-lines. This is a consequence of wave interference that extends beyond the topological features of interest.

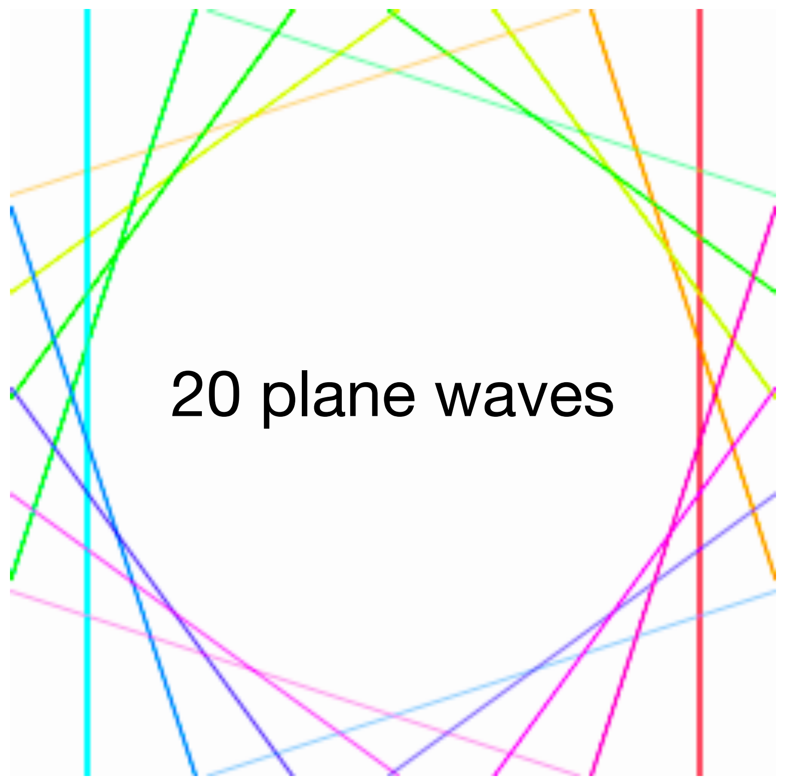
Dreher et al submitted 2024

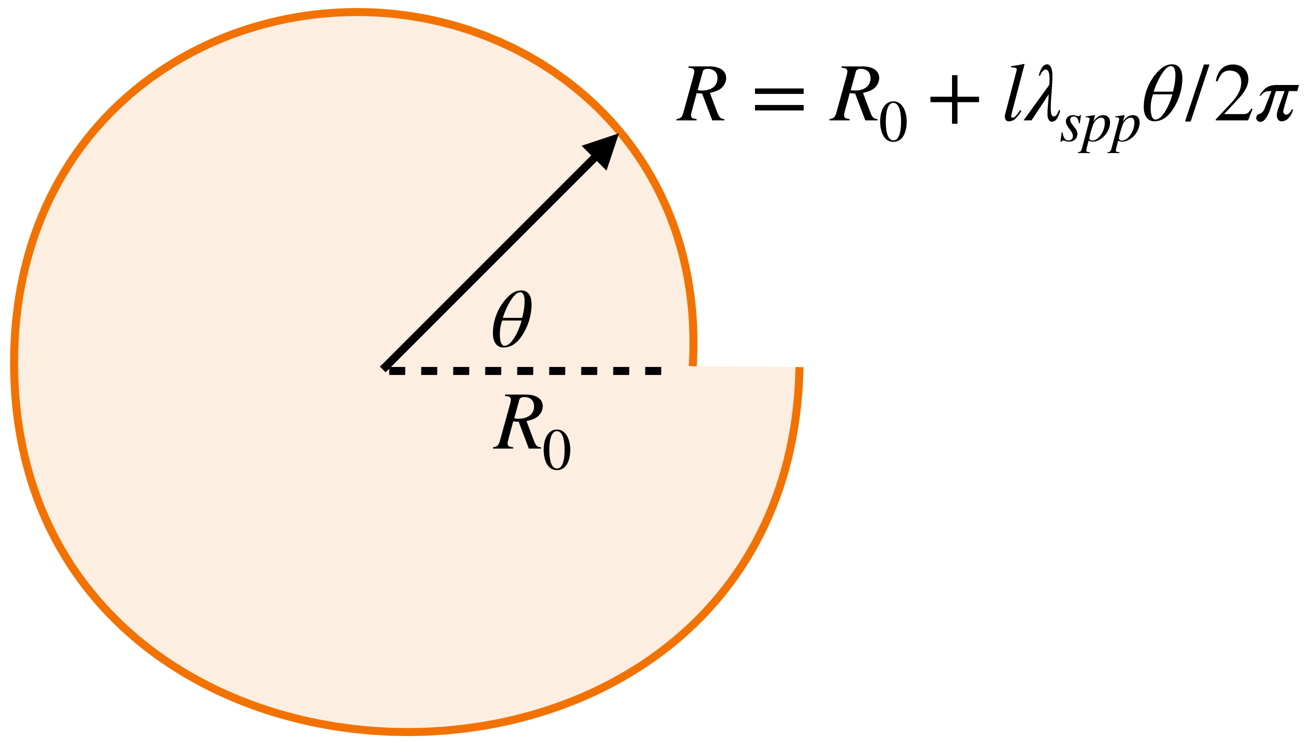
SPP Spin Examples

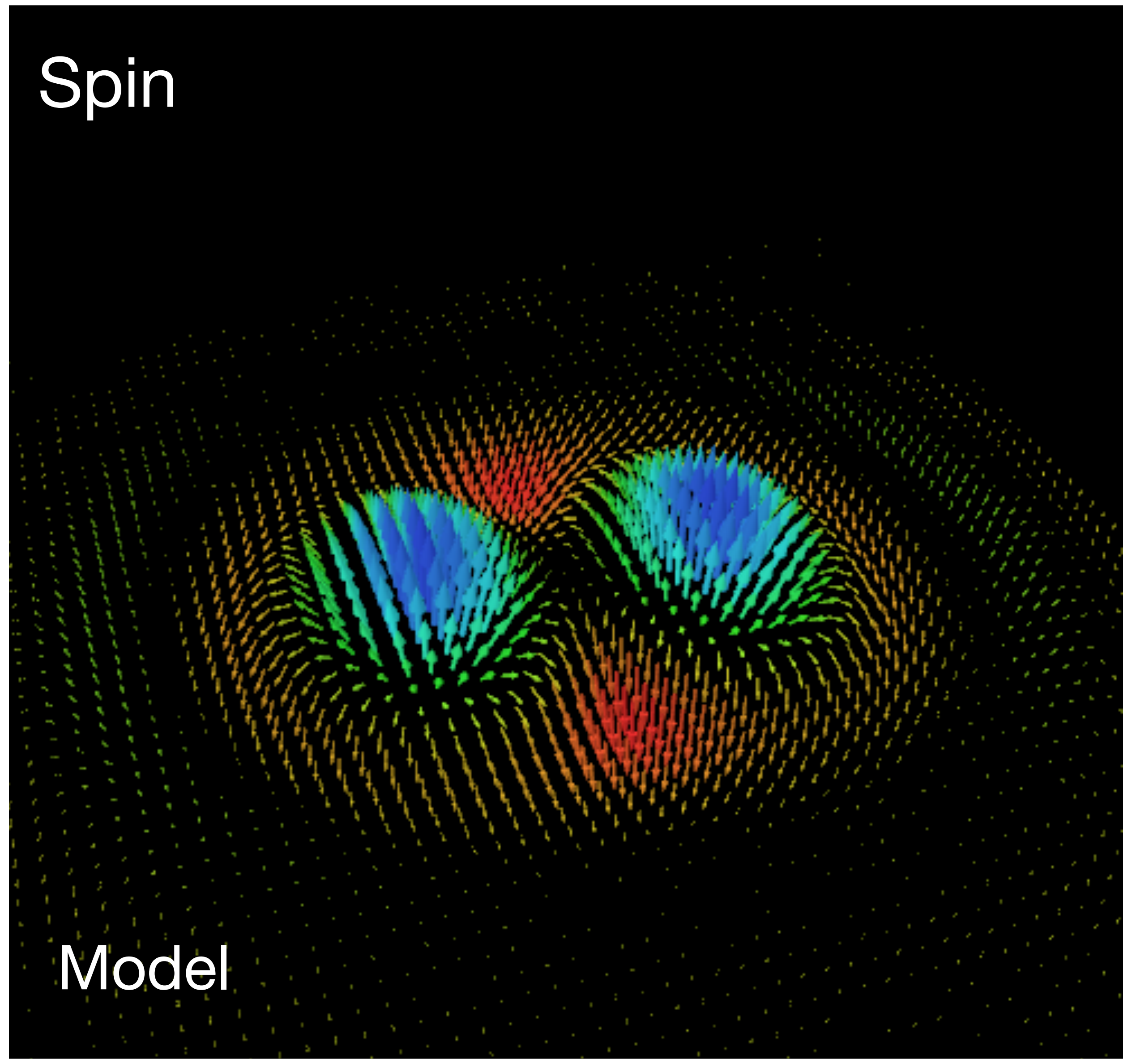
Meron pair spin created by linearly polarised light incident on an Archimedean spiral with $l = 1$

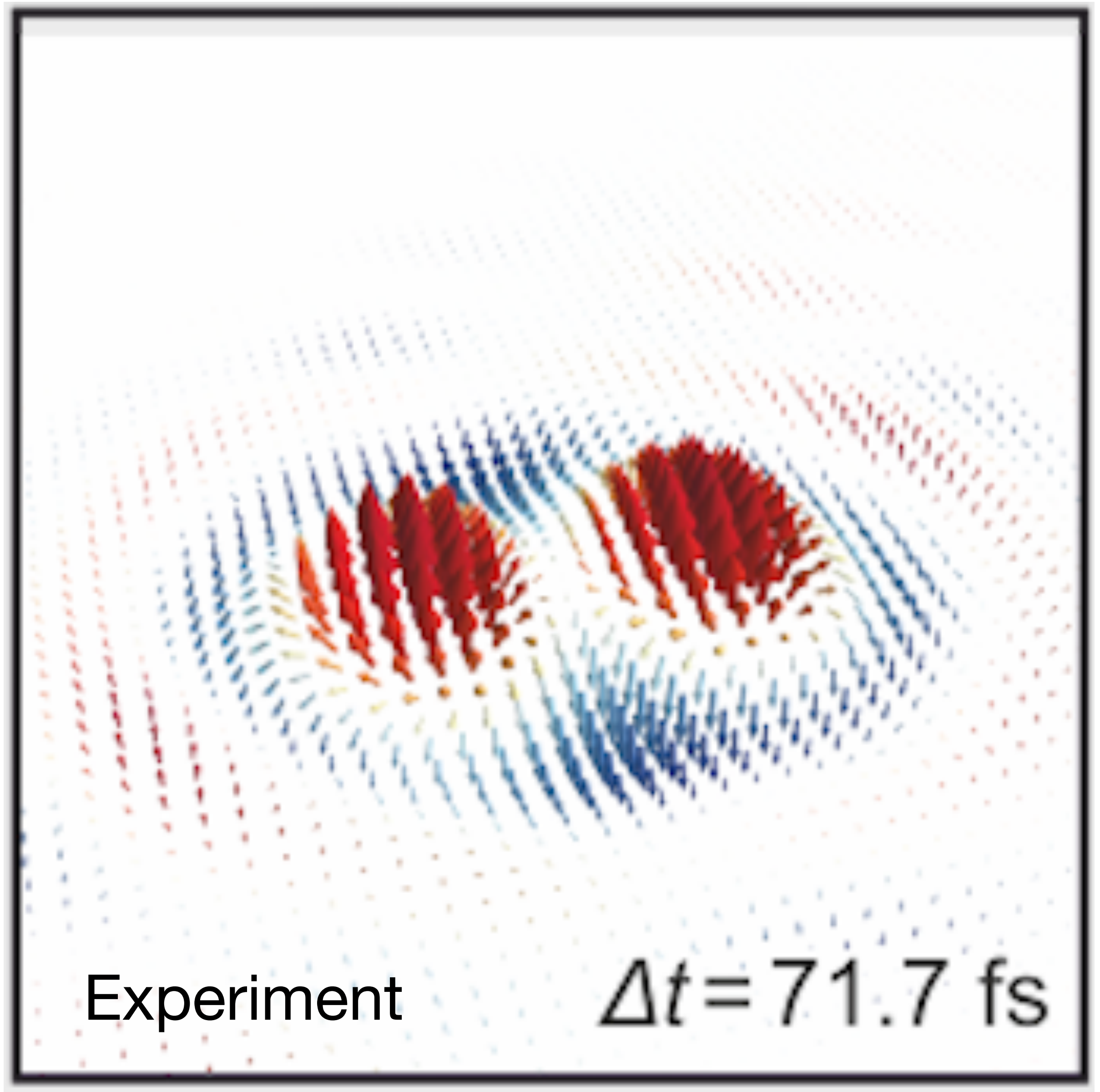
Amplitude depends on cosine of the angle (linearly polarised light on a circular boundary) $a_n = \cos\theta_n$

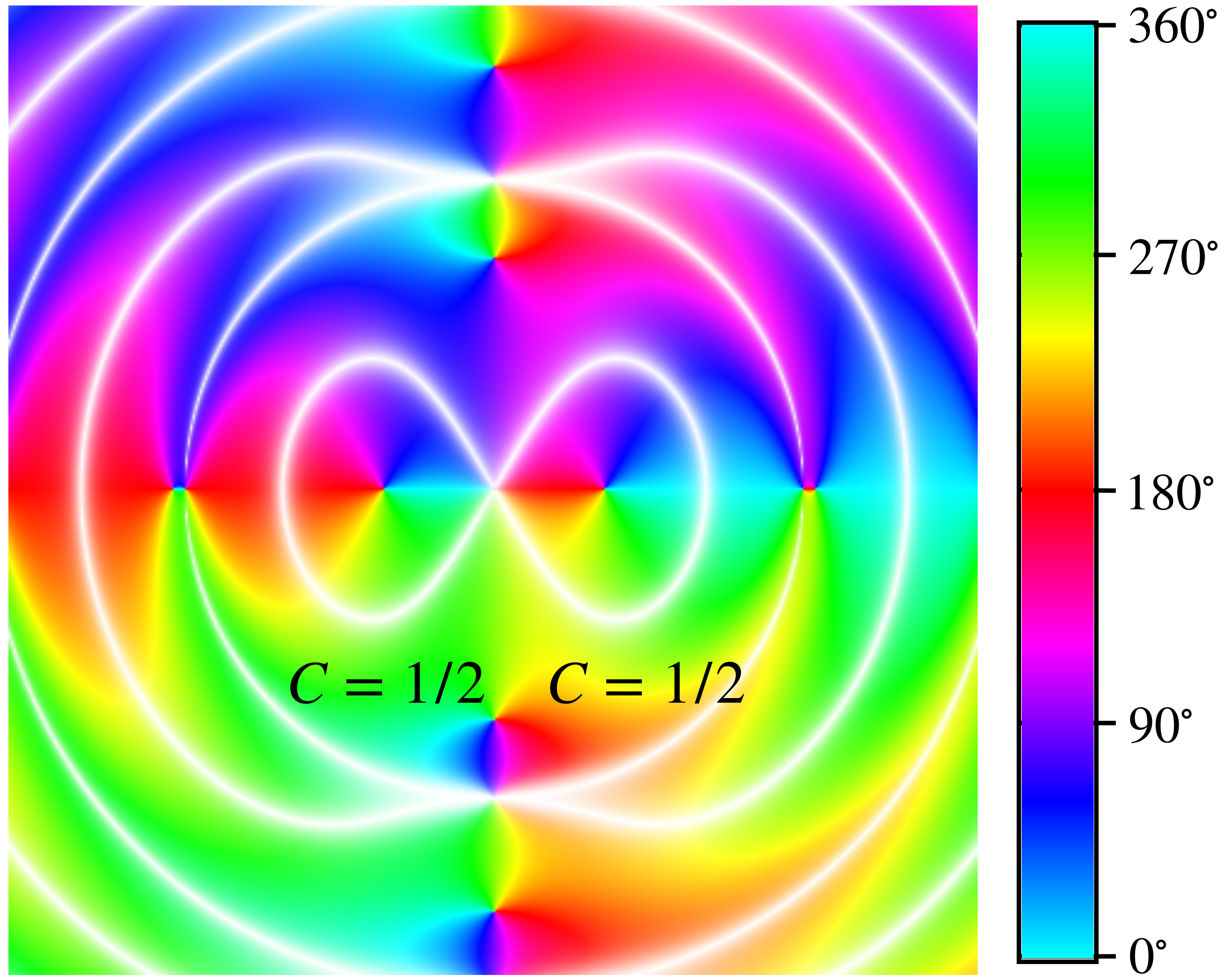
Phase follows the orientation of the boundary $\phi_n = \theta_n$











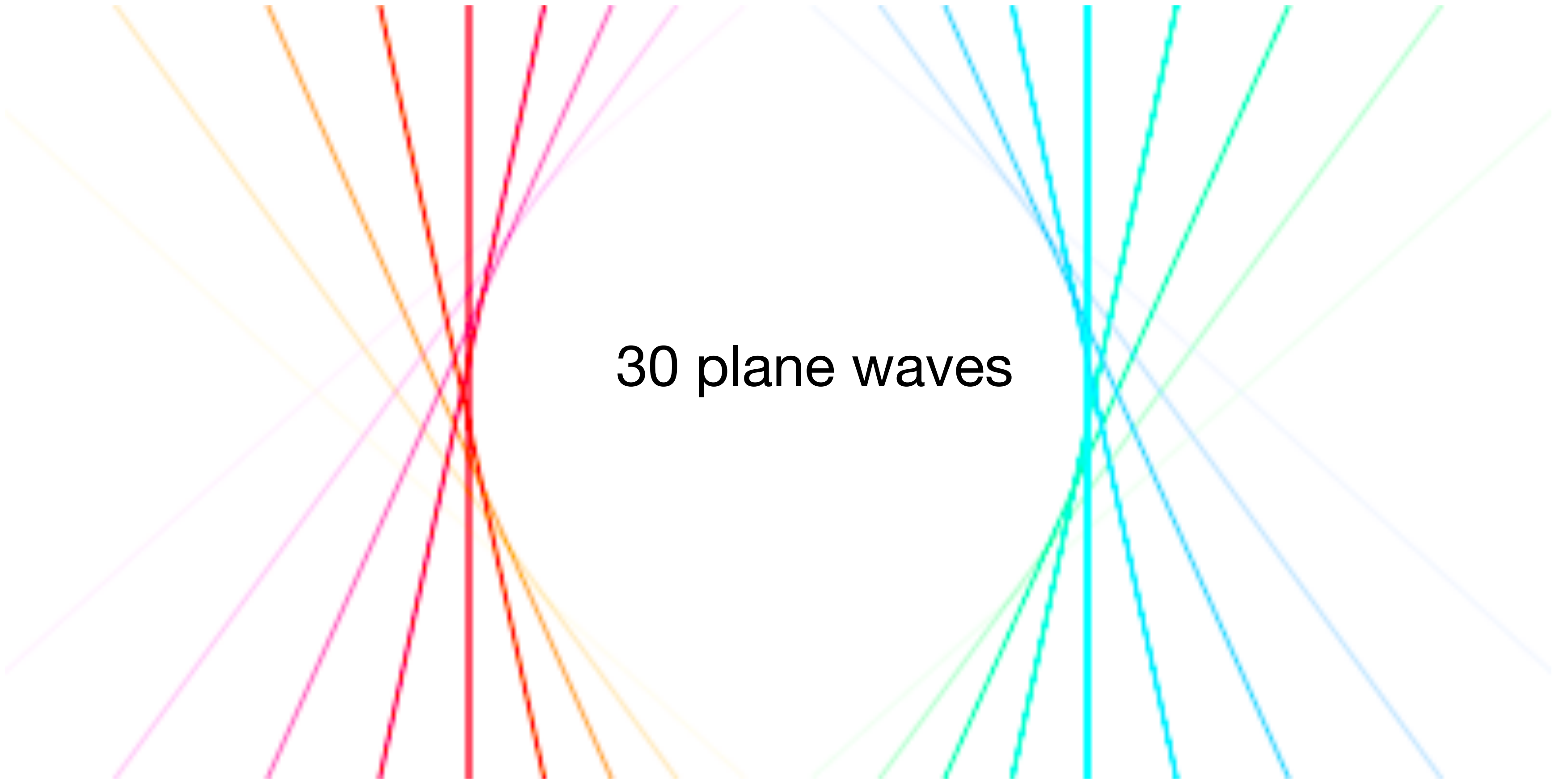
Dreher et al submitted 2024

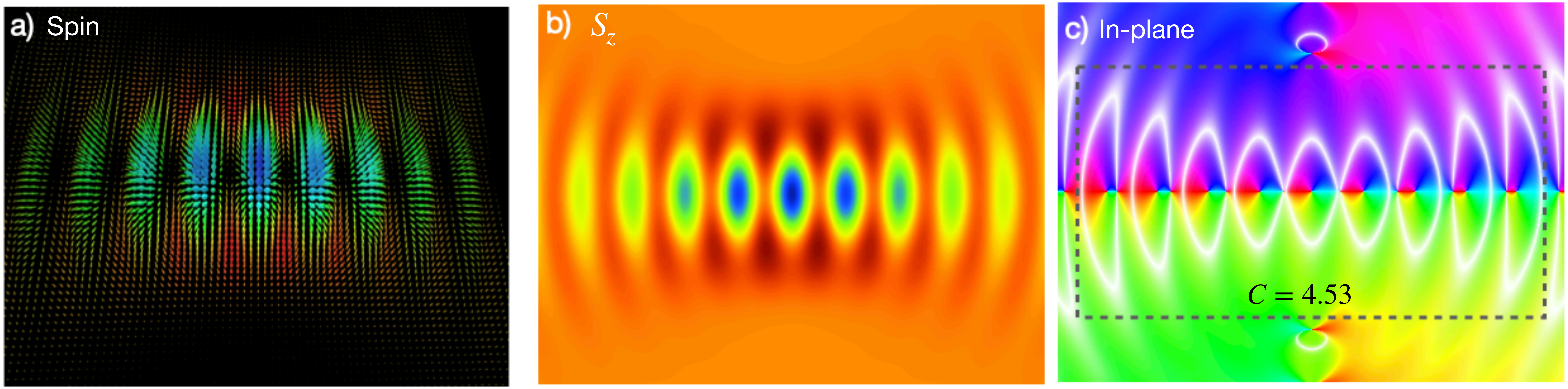
SPP Spin Examples

Meron spin street

Amplitude is biased towards the left and right ends to create a “focussing” effect $a_n = \cos^8 \theta_n$

Phase follows the orientation of the boundary $\phi_n = \theta_n$





SPP Spin Examples

Surface plasmon spin wheels

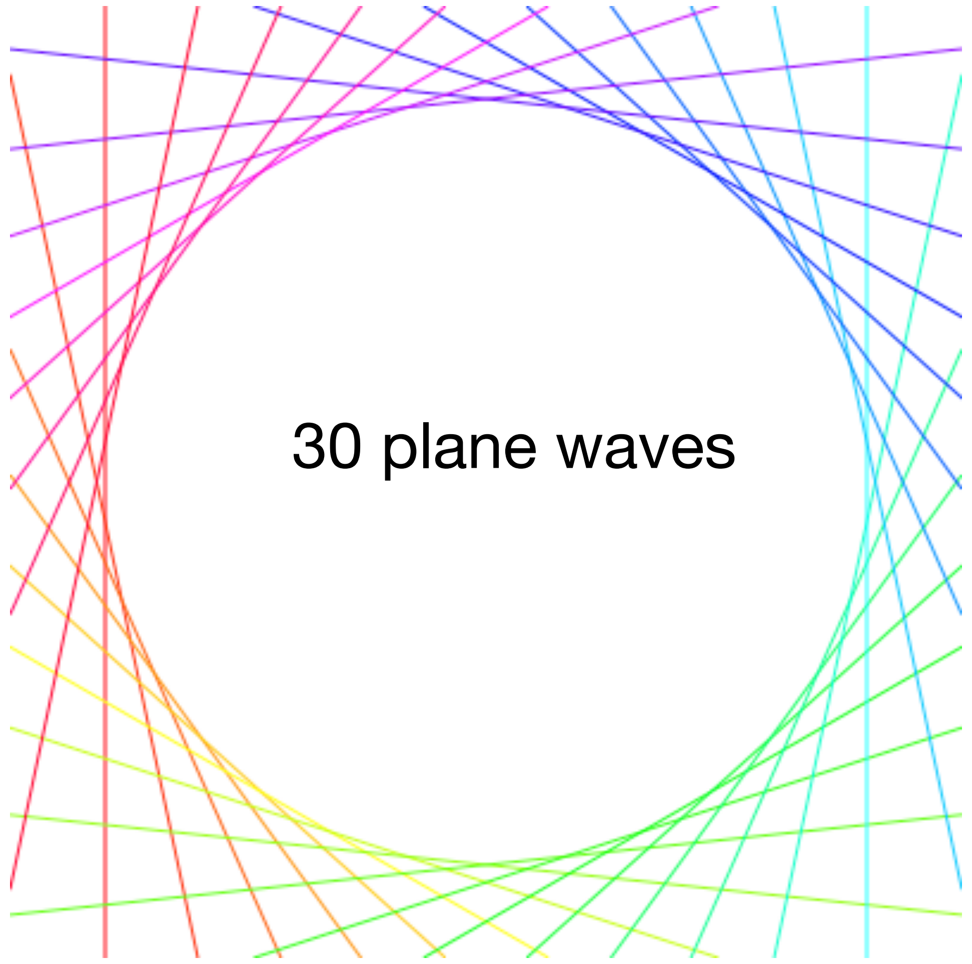
The spin topology is fixed by the boundary conditions on the SPP waves

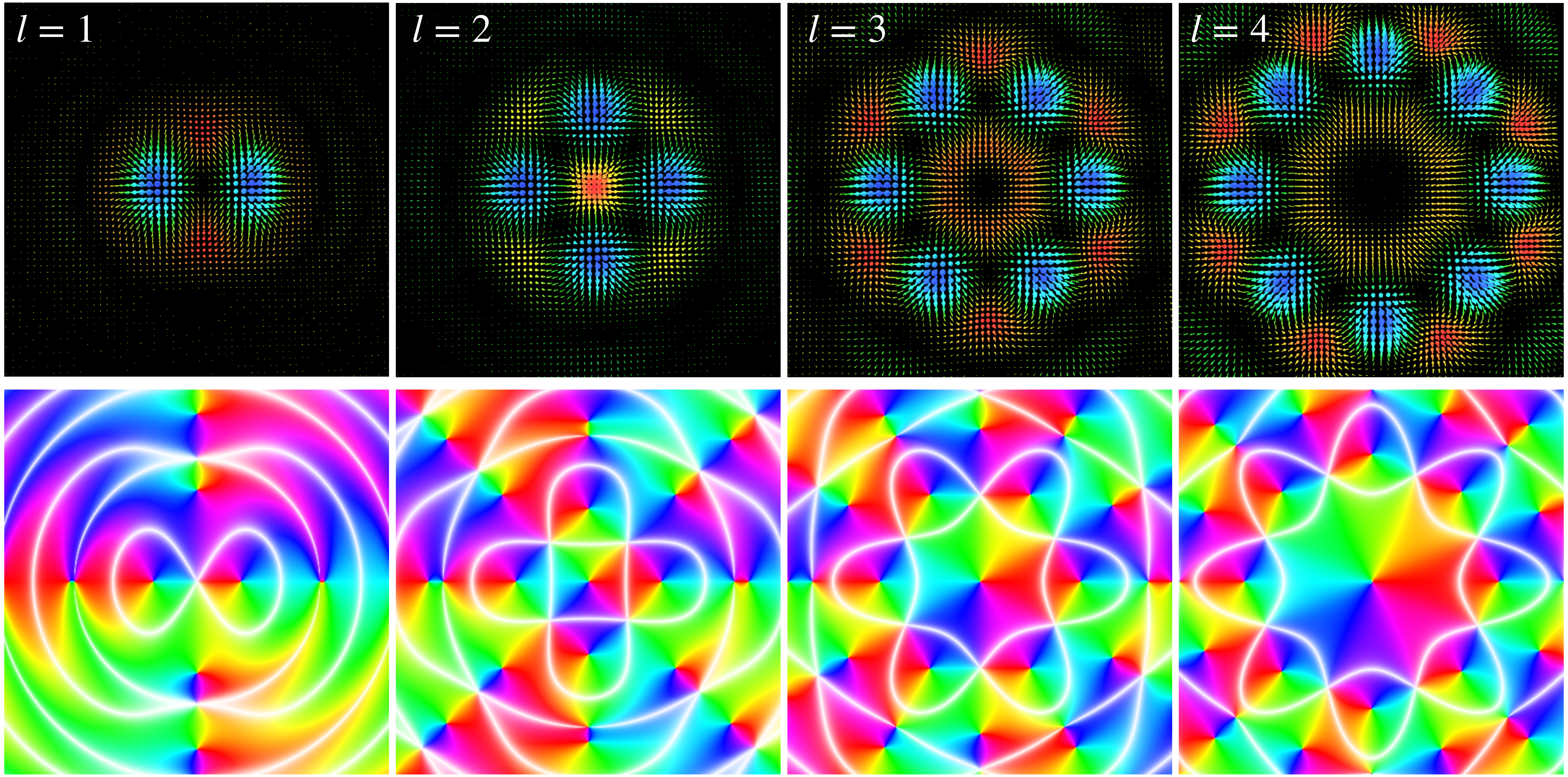
Amplitude modulated by the orientation of the boundary

$$a_n = \cos l\theta_n$$

Phase follows the orientation of the boundary

$$\phi_n = \theta_n$$





In-plane components: Poincaré-Hopf theorem

The Euler characteristic is a topological invariant of a space. For a surface in three dimensions it is found by tessellating the surface with triangles and computing

$$\chi = F + V - E$$

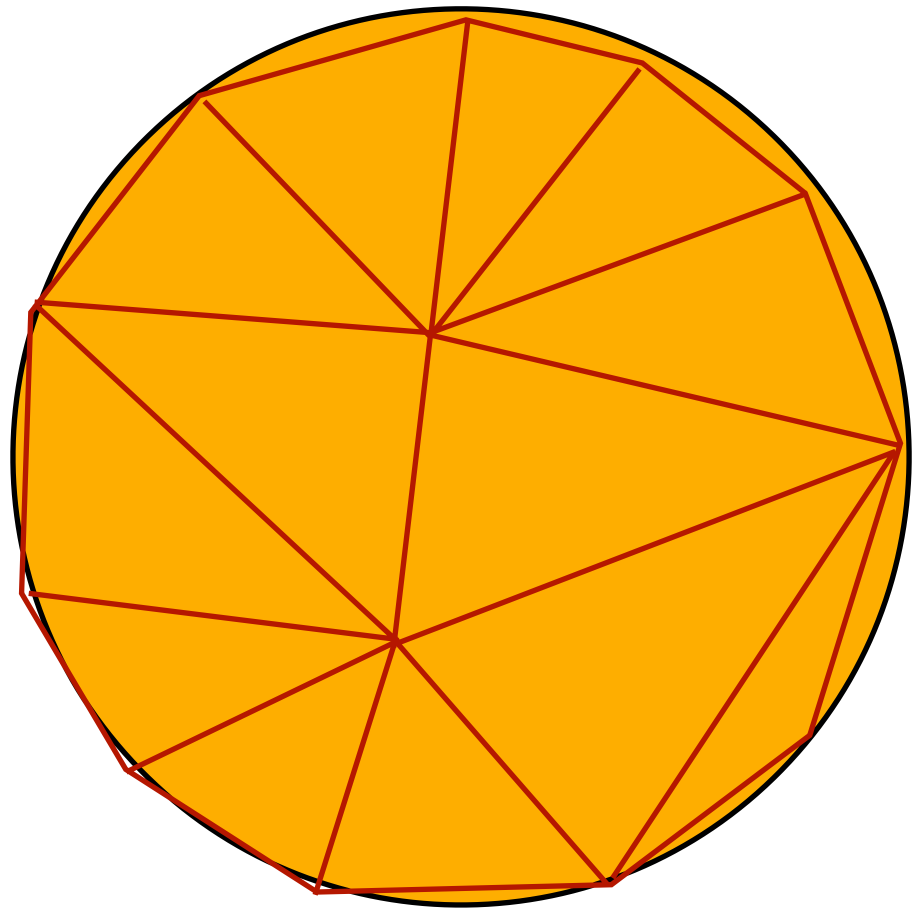
where F is the number of faces, E is the number of edges and V is the number of vertices.

Poincaré found that the sum of the vorticities of all the zeroes of an in-plane vector field is equal to the Euler characteristic of the geometric surface.

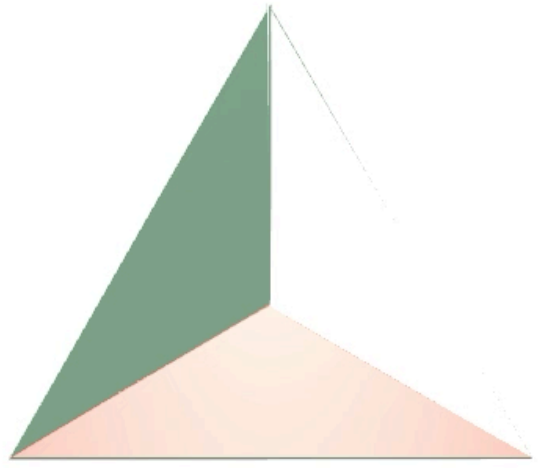
This theorem linked differential geometry to topology.

A disk is half a sphere $\chi = 1$

$$\chi = 13F + 13V - 25E = 1$$

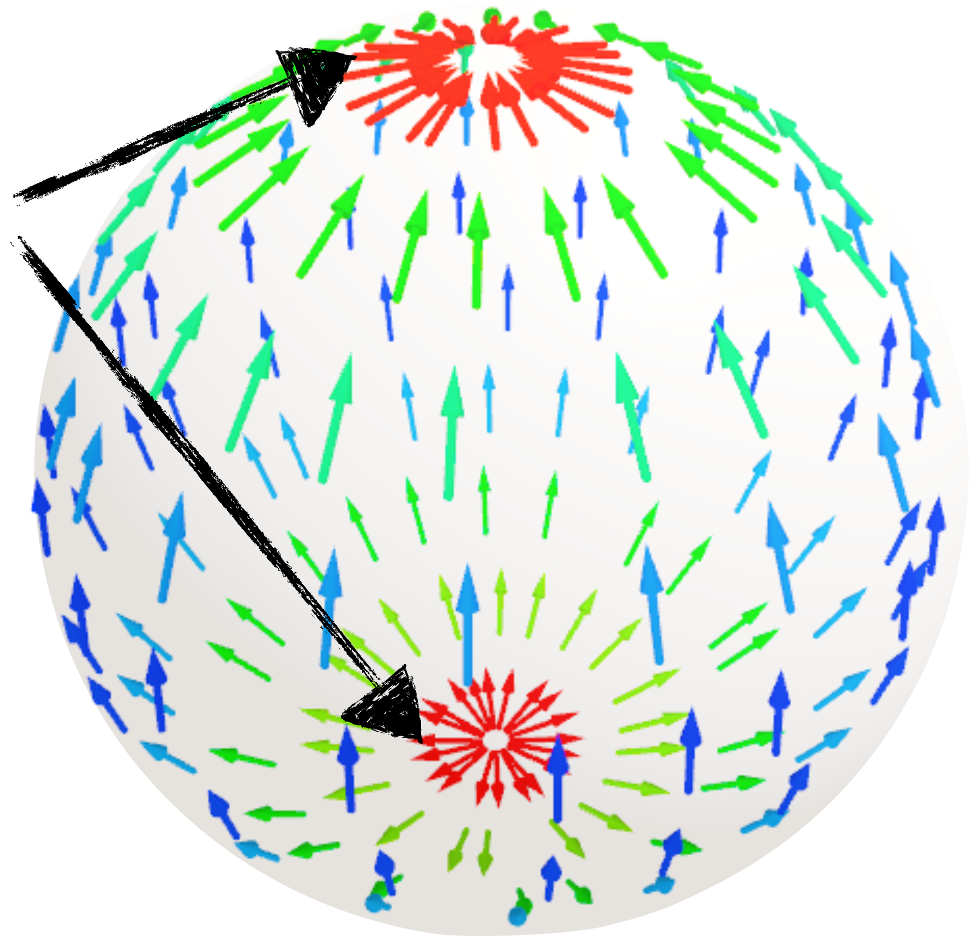


Simple surface (tetrahedron) in three dimensions



$$\chi = 4F + 4V - 6E = 2$$

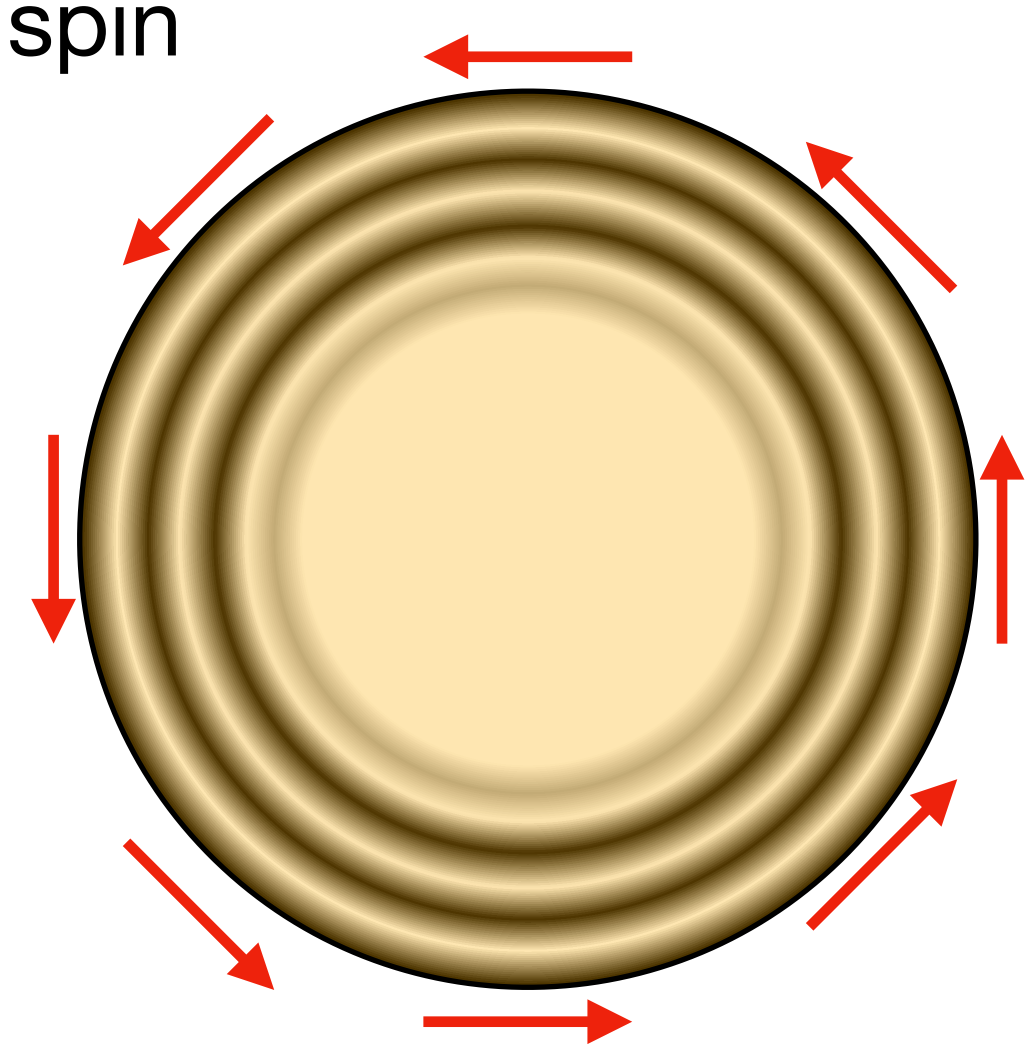
Same topology as a sphere $\chi = 2$



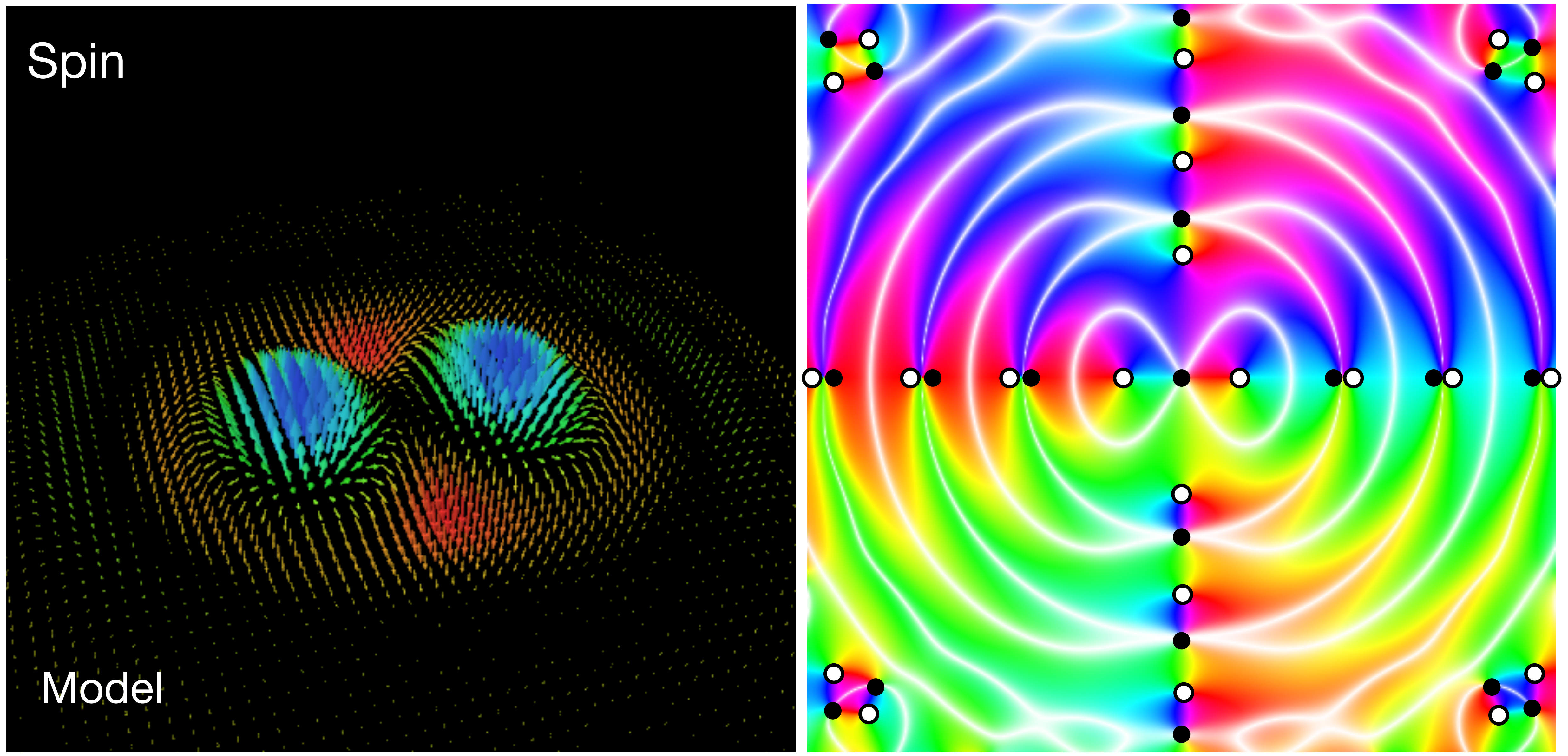
In-plane components: Poincaré-Hopf theorem

If a vector field on a disk has the same orientation with respect to the boundary - then the Poincaré-Hopf theorem holds.

SPP spin



In-plane SPP spin vectors obey the Poincaré-Hopf theorem.



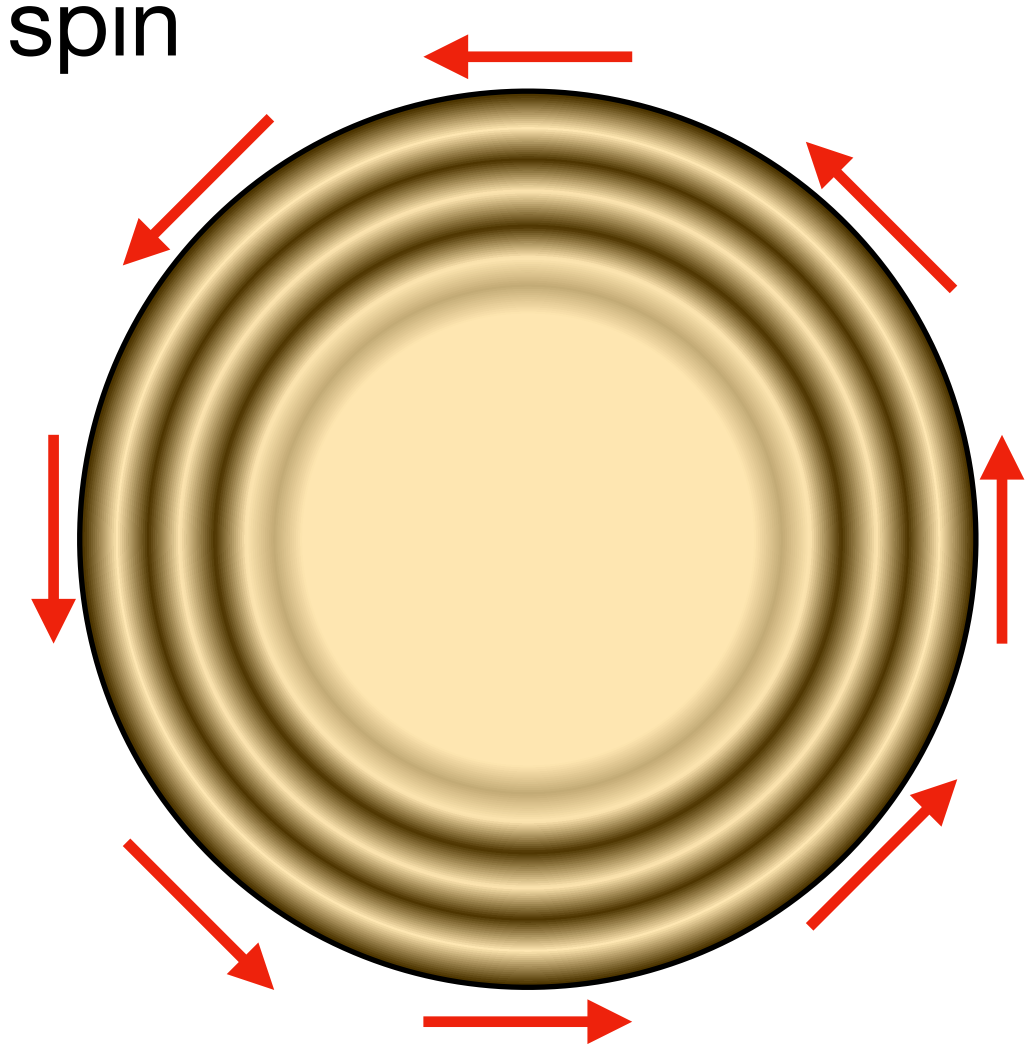
RGB vorticity +1, BGR vorticity -1

Since the total vorticity of the zeroes of the in-plane spin vectors must equal $\chi = 1$ then they can only be created in pairs of opposite vorticity.

In-plane components: Poincaré-Hopf theorem

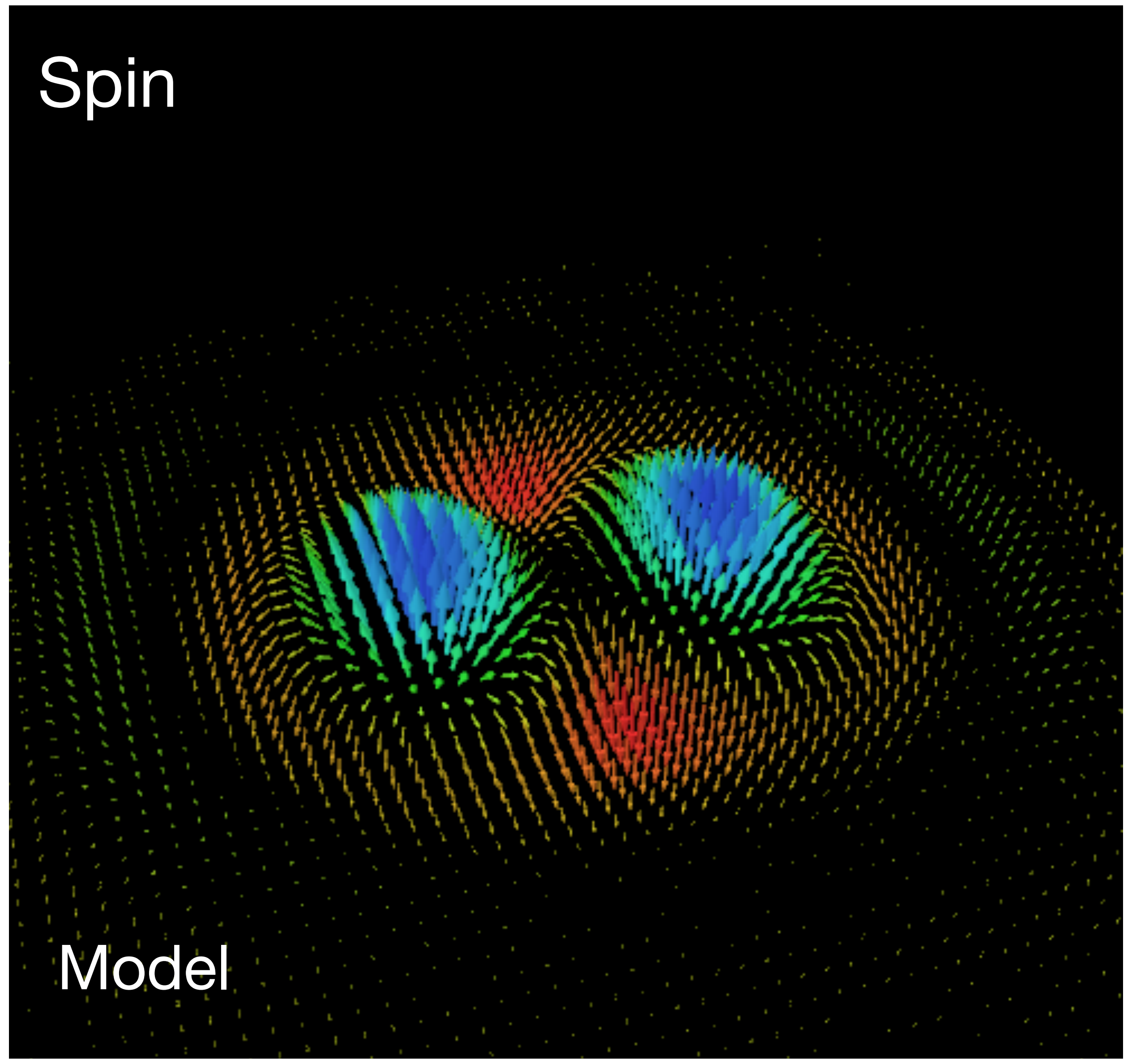
If a vector field on a disk has the same orientation with respect to the boundary - then the Poincaré-Hopf theorem holds.

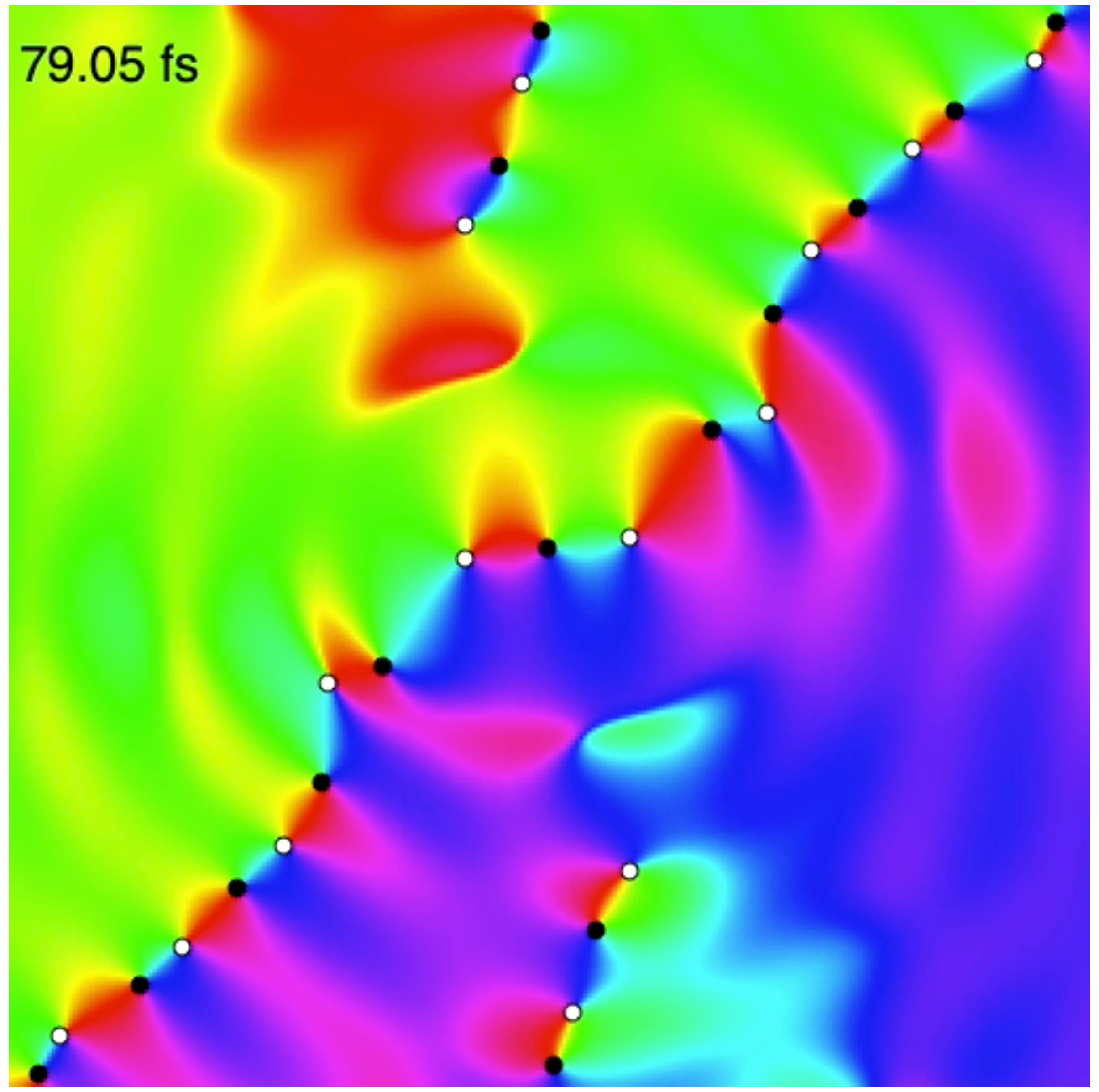
SPP spin



In-plane SPP spin vectors obey the Poincaré-Hopf theorem.

SPP spin - 2PPE-PEEM Experiment





Since the total vorticity of the zeroes of the in-plane spin vectors must equal $\chi = 1$ then they can only be created in pairs of opposite vorticity.

Dreher et al submitted 2024

Conclusion and outlook

So far …

Developed a simple model for the spin field of surface plasmons excited from complex boundaries.

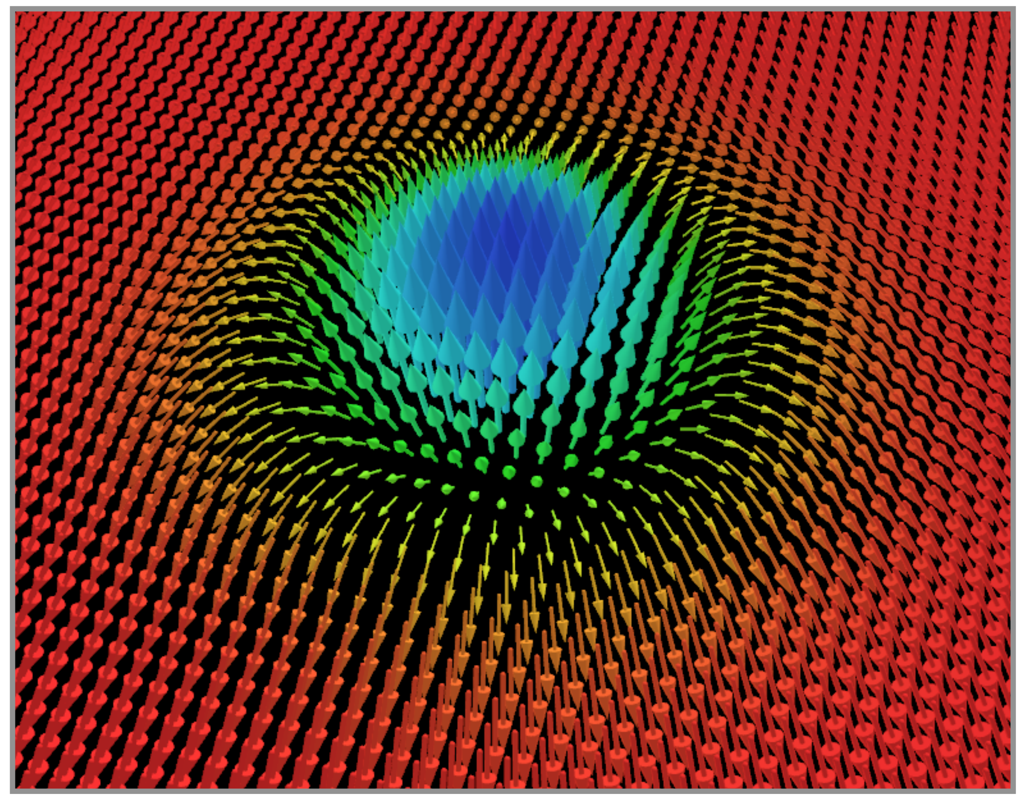
Given an overview of actual and possible spin topologies arising from interfering surface plasmon polaritons.

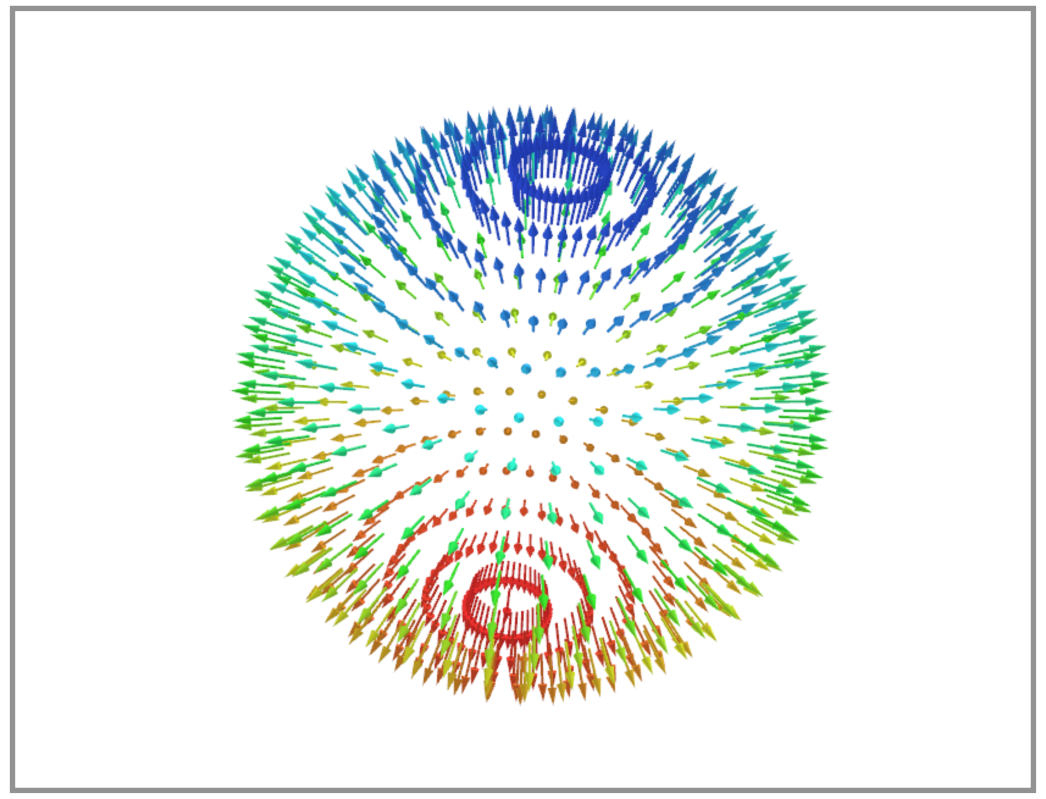
Highlighted the topology associated with in-plane vector fields and how they relate to the topology of the surface on which they are embedded.

Where next …

Currently all linear systems - interference of SPP waves

Interest in searching for optical systems with non-linearity that can model magnetic-like interactions.





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Thank you for your attention

SPICE Workshop July 2024