Frustrated light:
Working around Berry phases

Martina Hentschel

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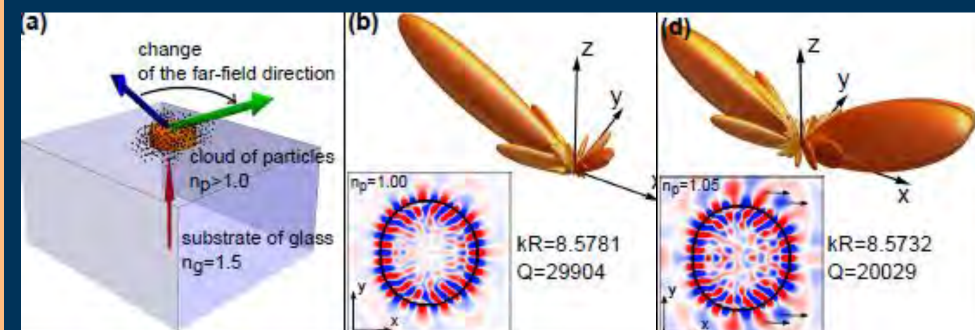
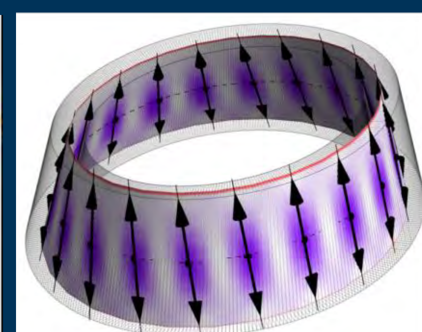
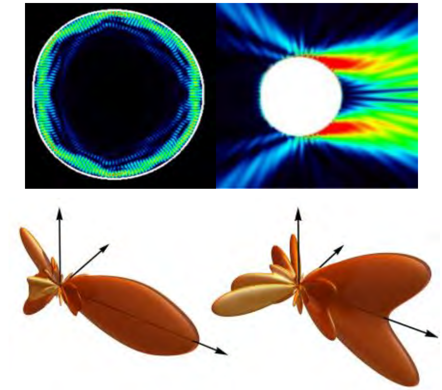




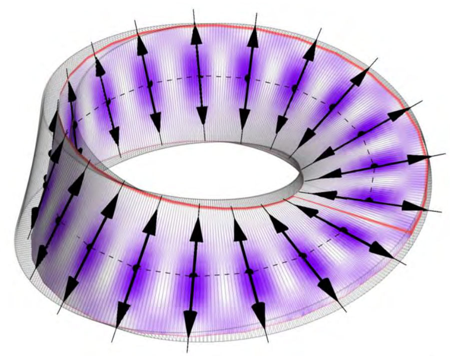
Emmy Noether-Programm
Deutsche Forschungsgemeinschaft DFG

Outline

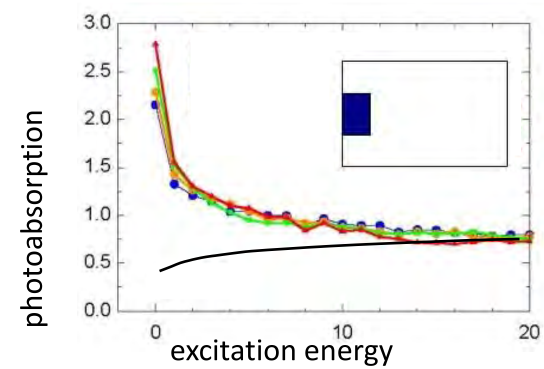
1. **Motivation – optical microcavities or Honey, we shrunk the laser**



2. **Polarization evolution in 3d microcavities**



3. **Fermi-edge singularities and sample geometry**



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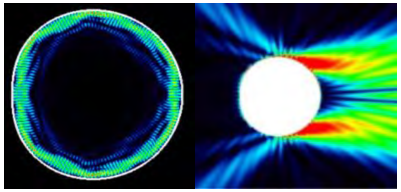
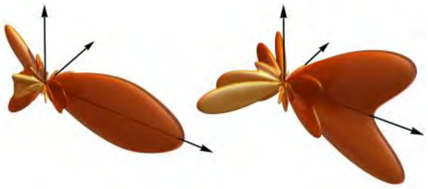
   or Honey, we shrunk the laser





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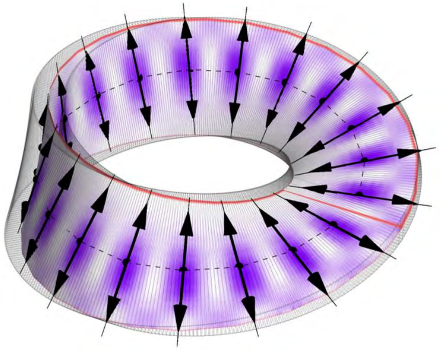

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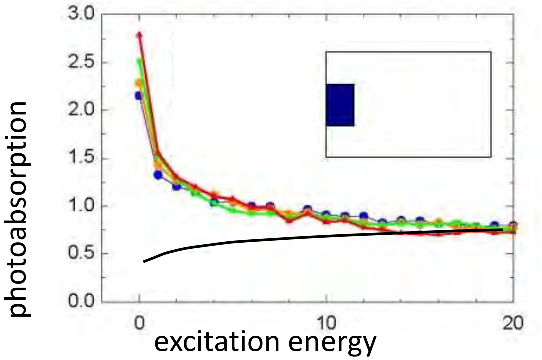
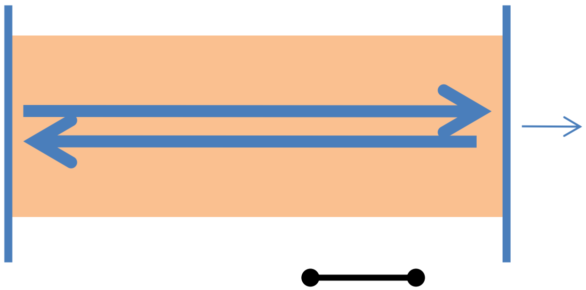


Laser concepts

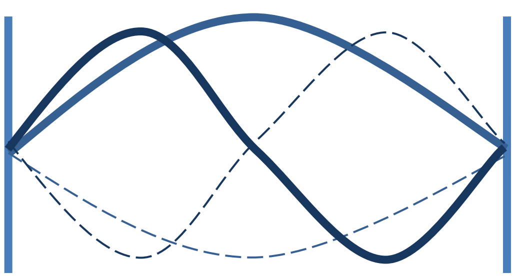
Fabry-Perot



mirrors

Q intermediate

miniaturization limited



Laser

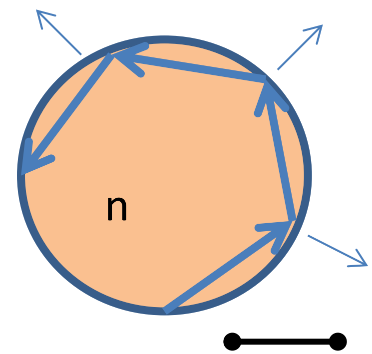
monochromatic

coherent & parallel

active material

Q factor

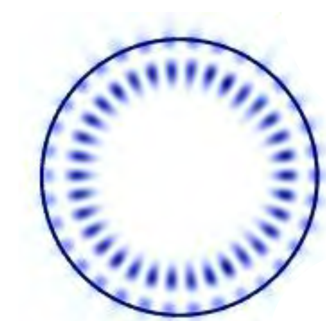
Microdisk



total reflection, index n

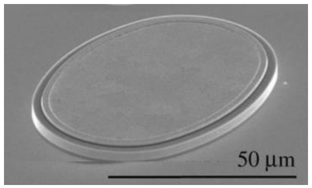
Q high

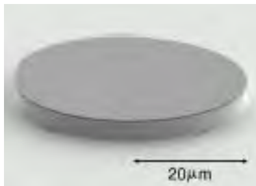
no parallel light output



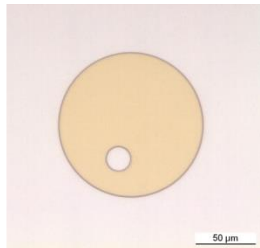
Quest for directional emission from microdisks

- have to destroy rotational symmetry → "deformed microdisk lasers"

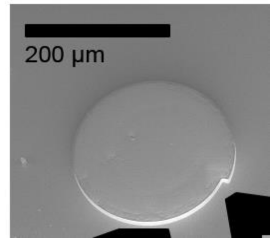




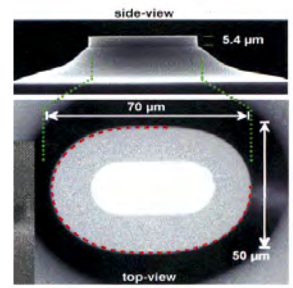
Harayama Lab
(Kyoto)



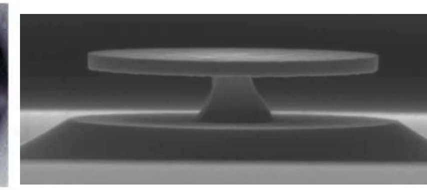
Zyss Lab
(Paris)



Capasso Lab
(Harvard)



Bell Labs
(New Jersey)

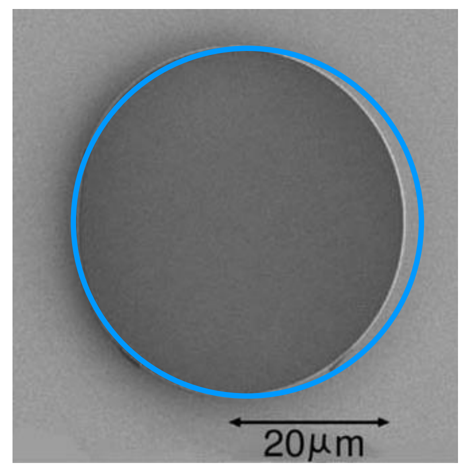


Cao Lab
(Yale)

- Limaçon shape $r(\phi) = R\,(1 + \varepsilon \cos \phi)$

  with directional emission:

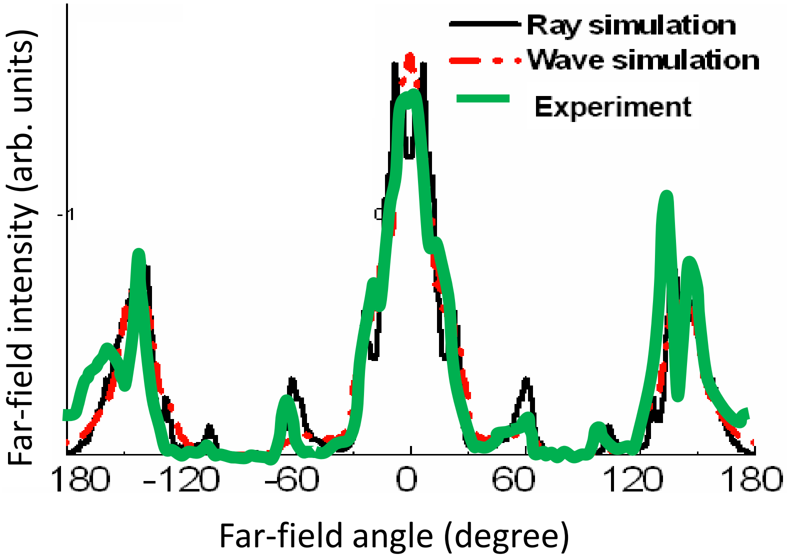
  - theoretical prediction
    J. Wiersig and M. Hentschel, PRL **100**, 2008
  - experimental confirmation
    Q. Song et al. (Cao group, Yale), PRA **80**, 2009
    S. Shinohara et al. (Harayama group, Kyoto), PRA **80**, 2009
    Ch. Yan et al. (Capasso group, Harvard), APL **94**, 2009
    C.-H. Yi et al. (Chil-Min Kim group, Seoul), APL **95**, 2009

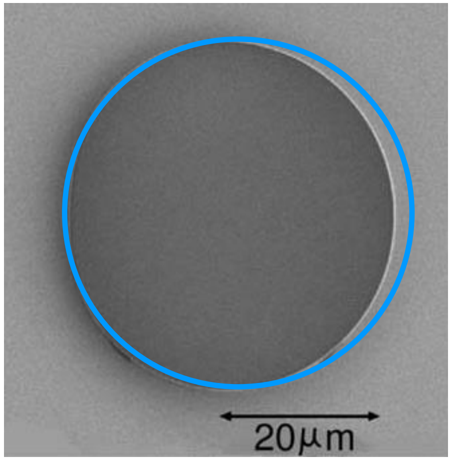


Harayama Lab

Directional emission from Limaçon cavities

- Far-field of Limaçon cavity

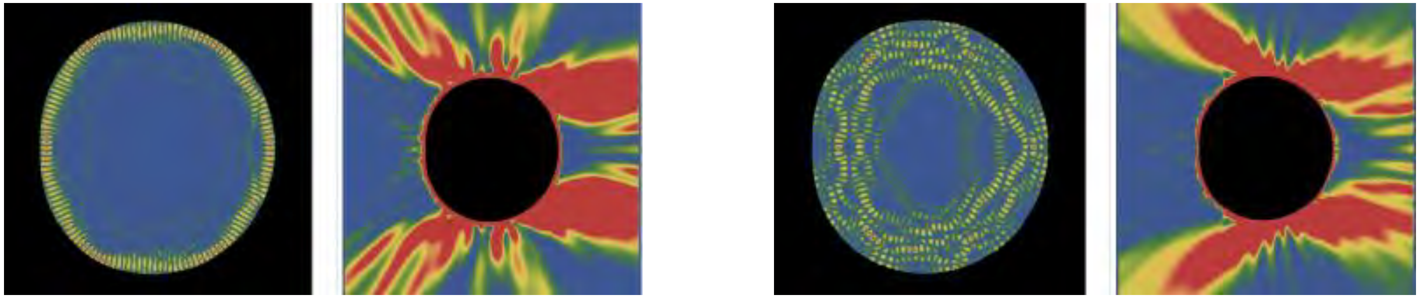




Harayama Lab
(Kyoto)

J. Wiersig and M.H., PRL **100**, 2008
in cooperation with Capasso group (Harvard)

- Origin of directionality ?

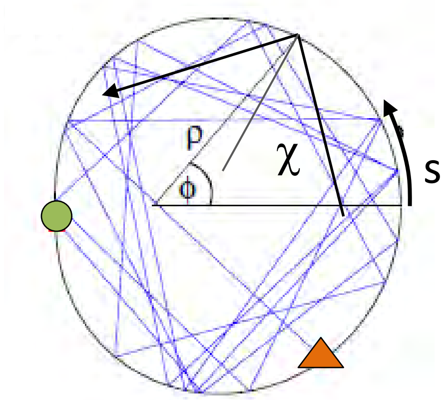


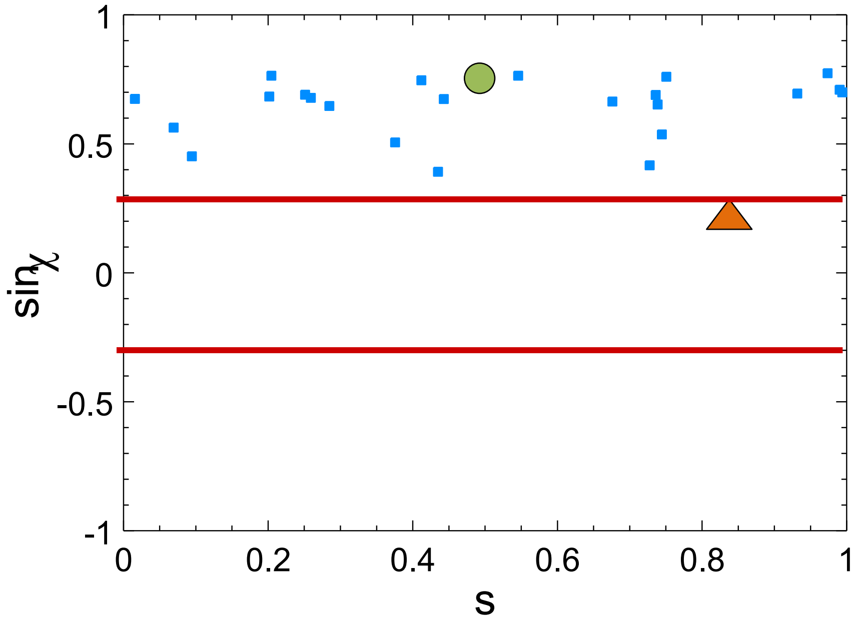
Directionality from chaotic dynamics

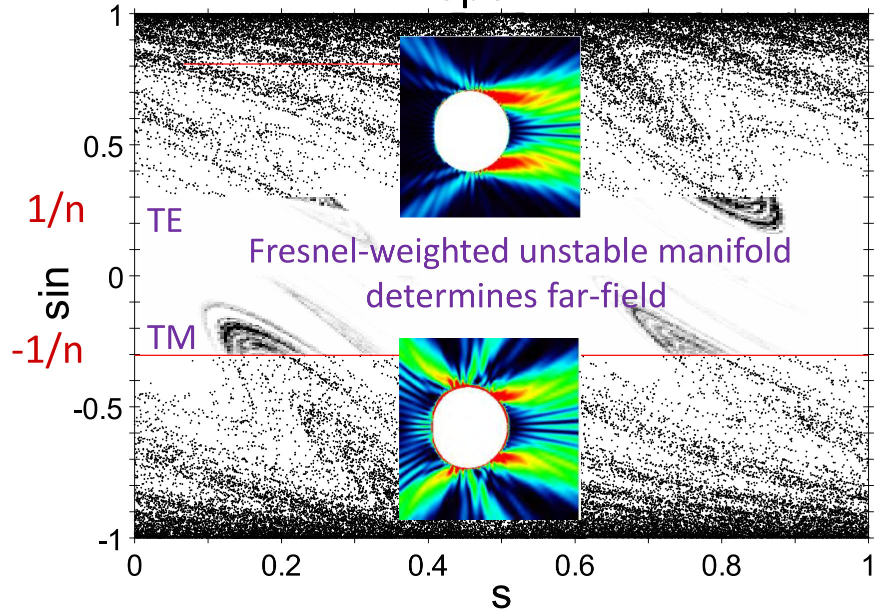
Limaçon resonator

$r(\phi) = R(1 + \varepsilon \cos \phi)$

$n = 3.3, \quad \varepsilon = 0.4$







- Universal, resonance-independent and robust far-field properties of high-Q modes

Flash: Chirality in spiral optical cavities

e.g. Jan Wiersig, Sang-Wook Kim, M.H., PRA 2008

- pairs of non-orthogonal modes
- ccw propagation dominates

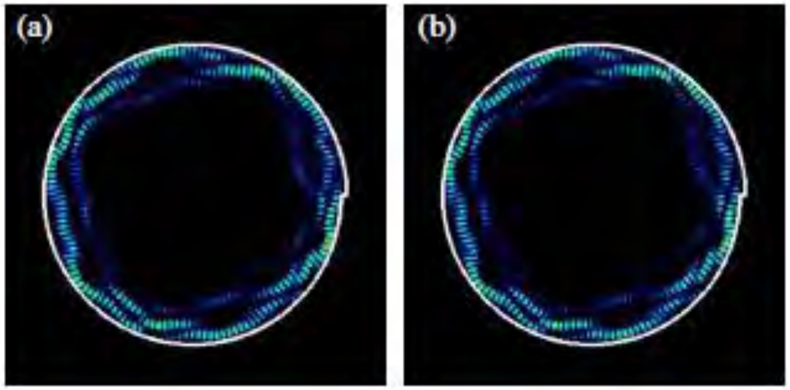


FIG. 5. (Color online) Calculated intensity $|\psi|^2$ of the nearly degenerate WG-like modes 1 (a) and 2 (b).

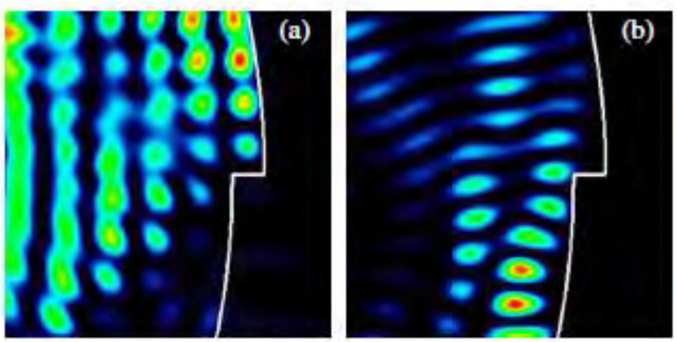


FIG. 9. (Color online) Magnification of the intensity pattern $|\psi|^2$ near the notch. (a) Quasiscar mode 2, as in the right panel of Fig. 2. (b) WG-like mode 2, cf. the right panel of Fig. 5.

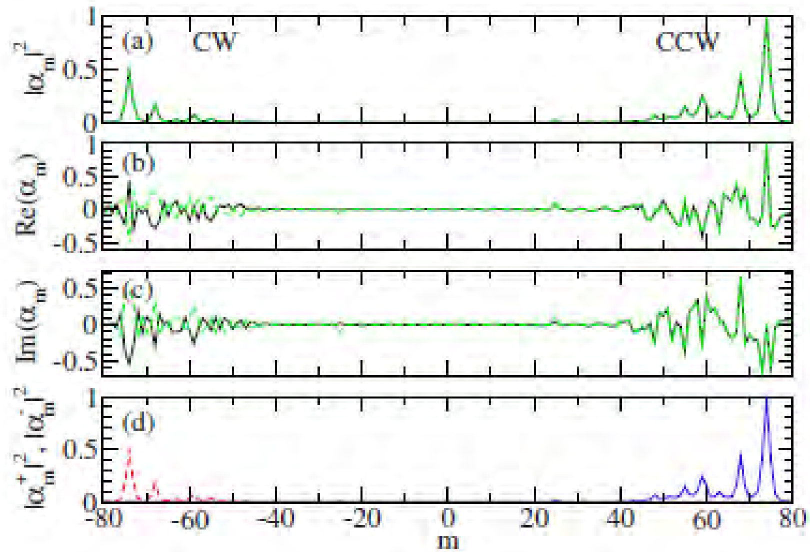
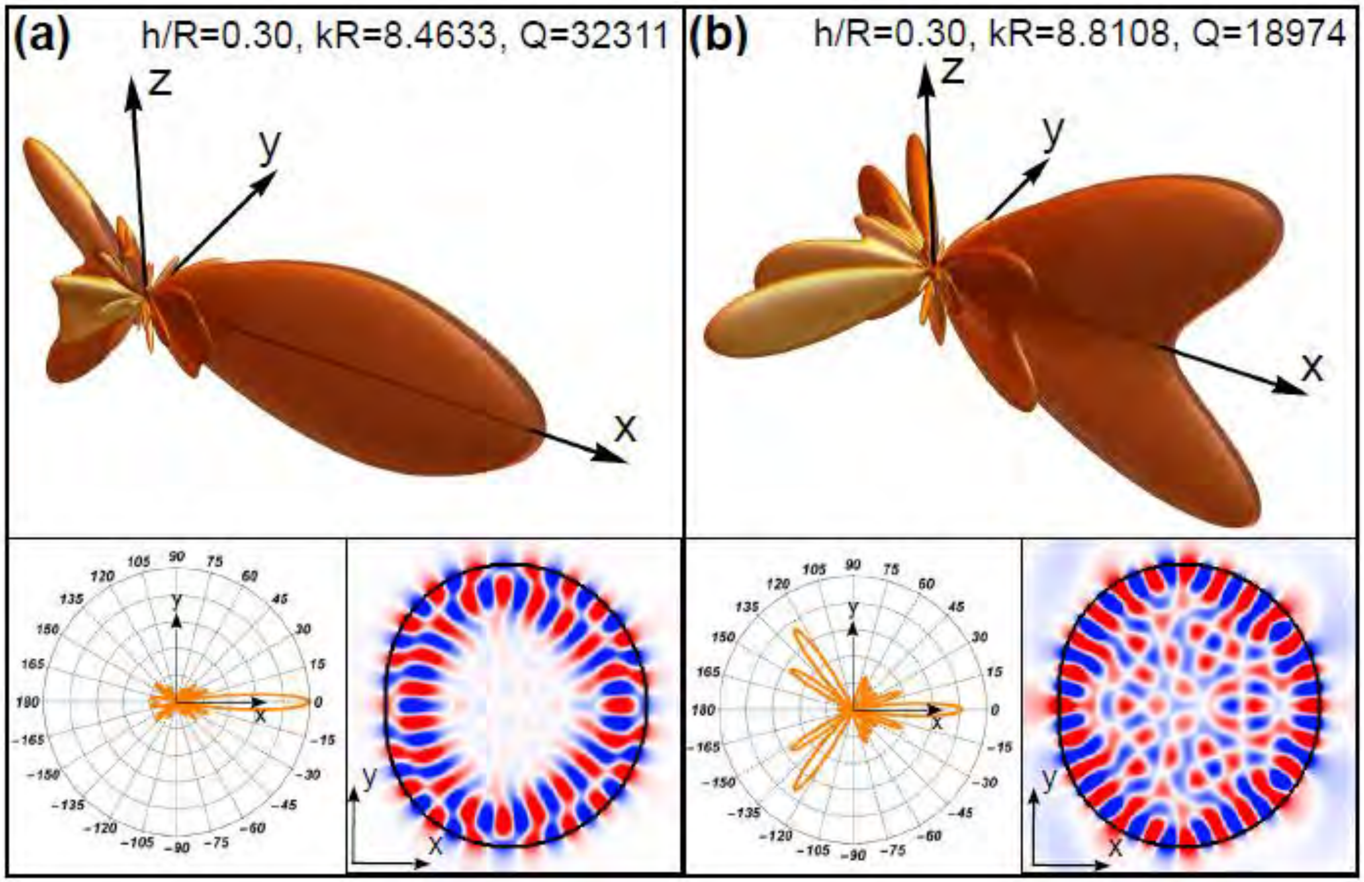


FIG. 6. (Color online) Angular momentum distributions $\alpha_m^{(1)}$ (solid line) and $\alpha_m^{(2)}$ (dashed) of WG-like modes (see Fig. 5) normalized to 1 at maximum: (a) absolute value squared, (b) real, and (c) imaginary part. (d) Superpositions $\alpha_m^+ = (\alpha_m^{(1)} + \alpha_m^{(2)})/2$ (solid) and $\alpha_m^- = (\alpha_m^{(1)} - \alpha_m^{(2)})/2$ (dashed).

Cavity height as 3rd dimension

- higher Q factors
- two types of modes in the 3d Limaçon
- Sensor application



higher Q, 2d-like

lower Q, 3d with novel properties

J. Kreismann, S. Sinzinger, and M.H., PRA (2017)

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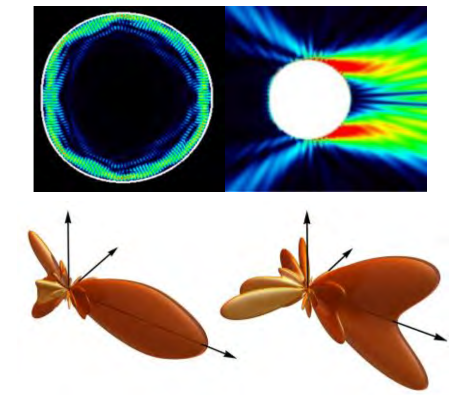

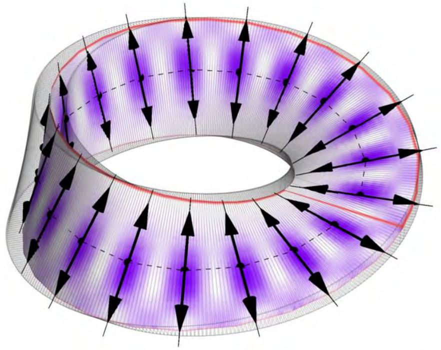

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   in 3d microcavities

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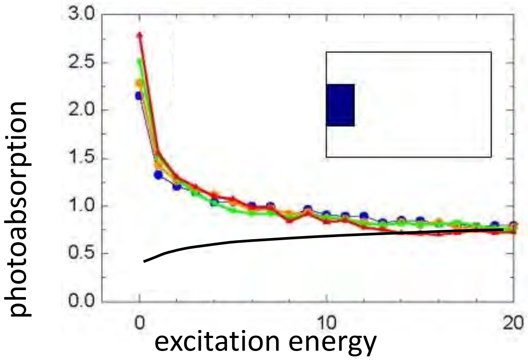
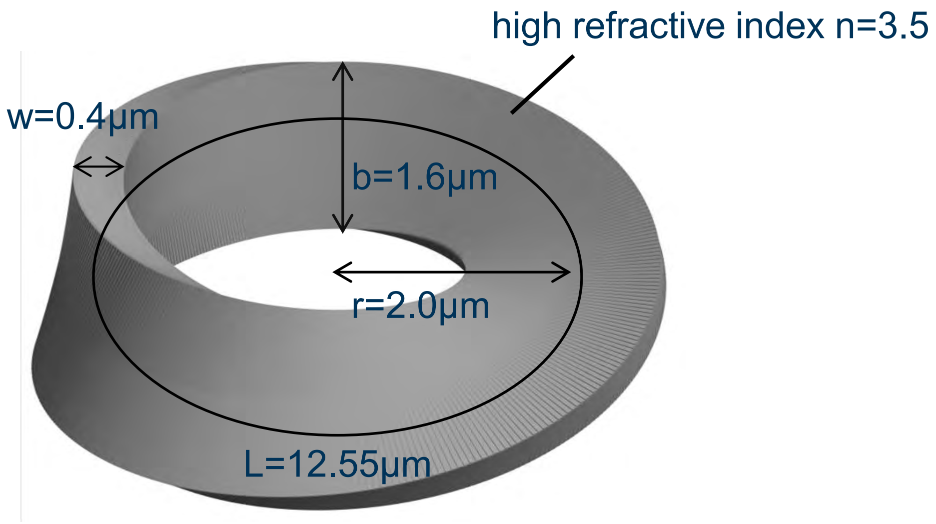
   and sample geometry

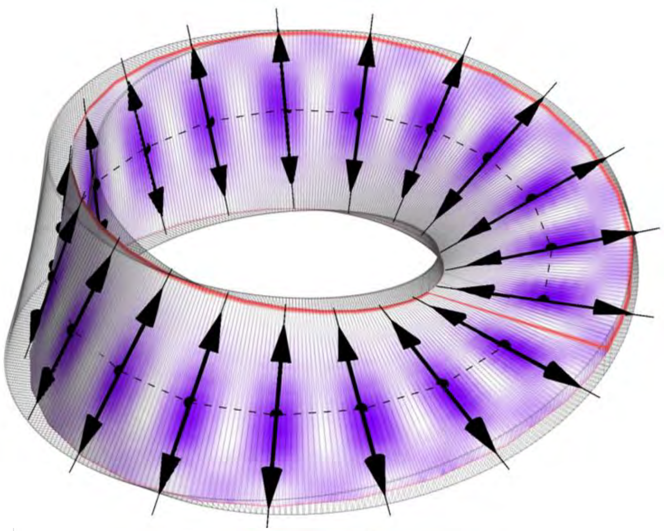


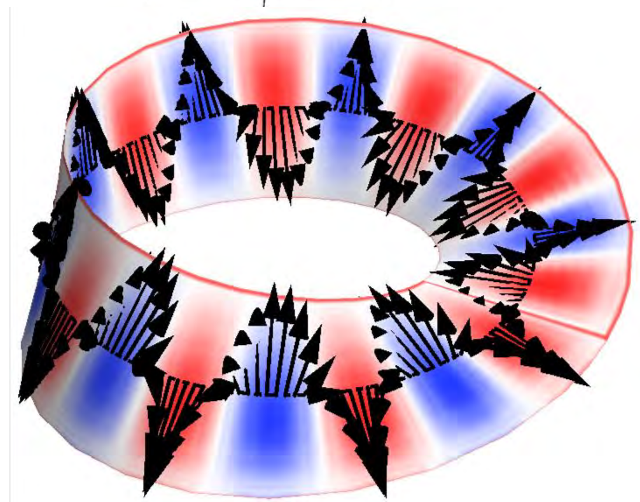
Polarization evolution in Möbius strips

The dielectric Möbius-strip:



Intensity and polarization





w=0.4μm, λ=3375nm, N=19

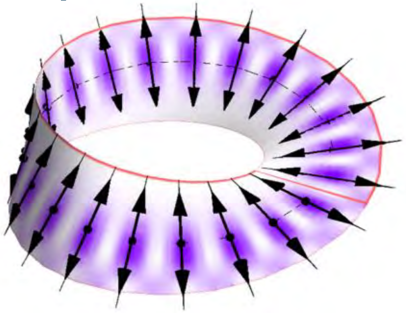
Jakob Kreismann and M.H., in preparation

N=19 intensity maxima → m=9.5 ?

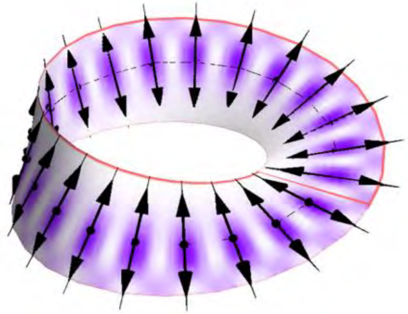
Möbius-strip in physics:
[1] Ballon and Voss, PRL 101, 247701 (2008) in electrical circuits
[2] Yin et al., arXiv:1611.07217 in plasmonics

Polarization evolution at varying thickness

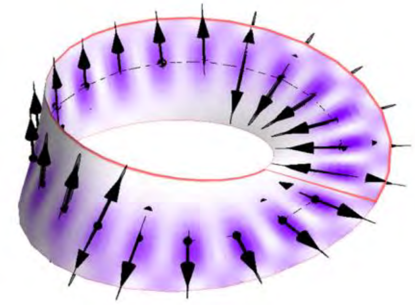
w=0.5μm, N=21
λ=3.35μm



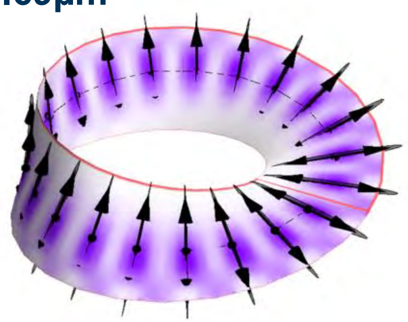
w=0.6μm, N=21
λ=3.48μm



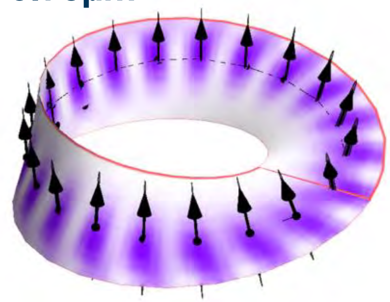
w=0.7μm, N=21
λ=3.59μm



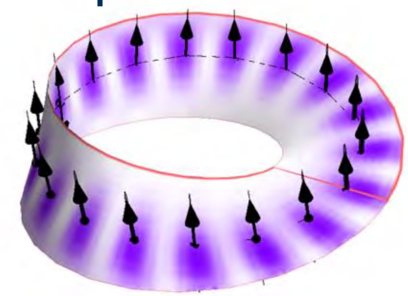
w=0.8μm, N=21
λ=3.69μm



w=0.9μm, N=20
λ=3.78μm



w=1μm, N=18
λ=4.15μm

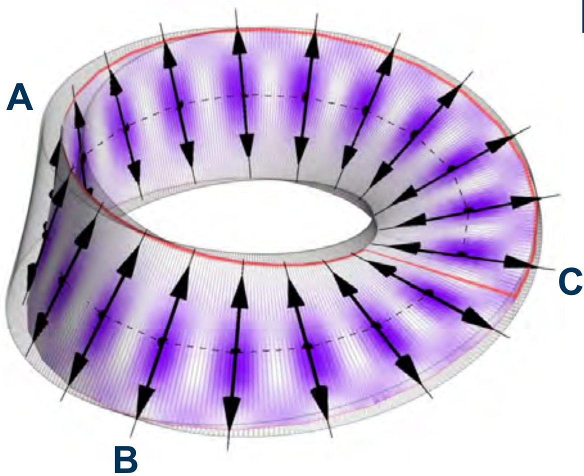


thicker, but still Möbius strip:

- N even
- E-field ignores topology of Möbius strip?!

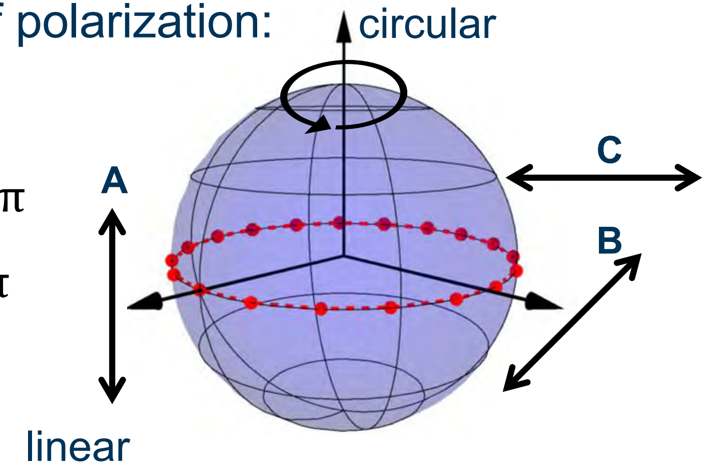
Polarization manipulation in Möbius strips

- Berry phase $\gamma=\pi$ → $\Delta m=0.5$ due to Möbius character



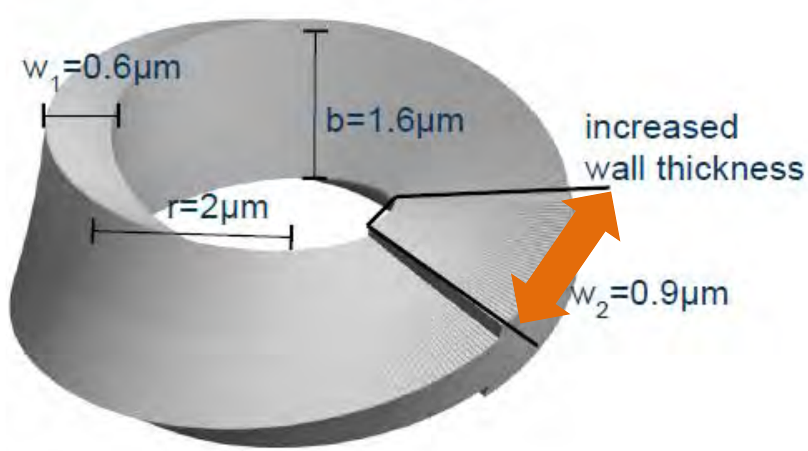
Poincare sphere of polarization:

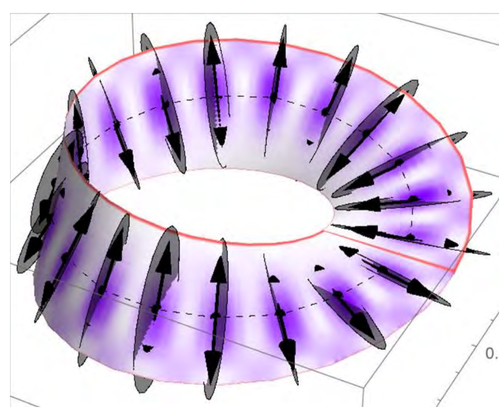
$$\Omega = 2\pi$$
$$\gamma = \frac{\Omega}{2} = \pi$$

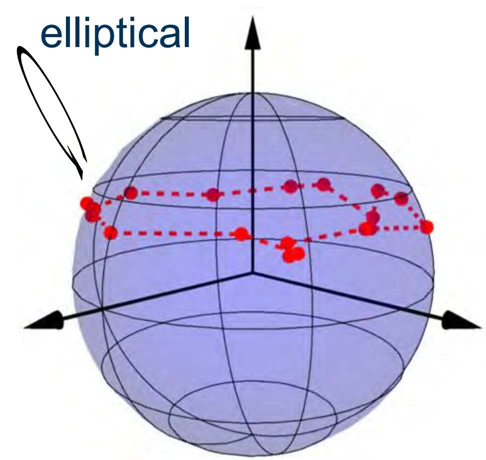


- Change geometry to induce ellipt. polarization → arbitrary geometric phase

inhomogenius Möbius-strip

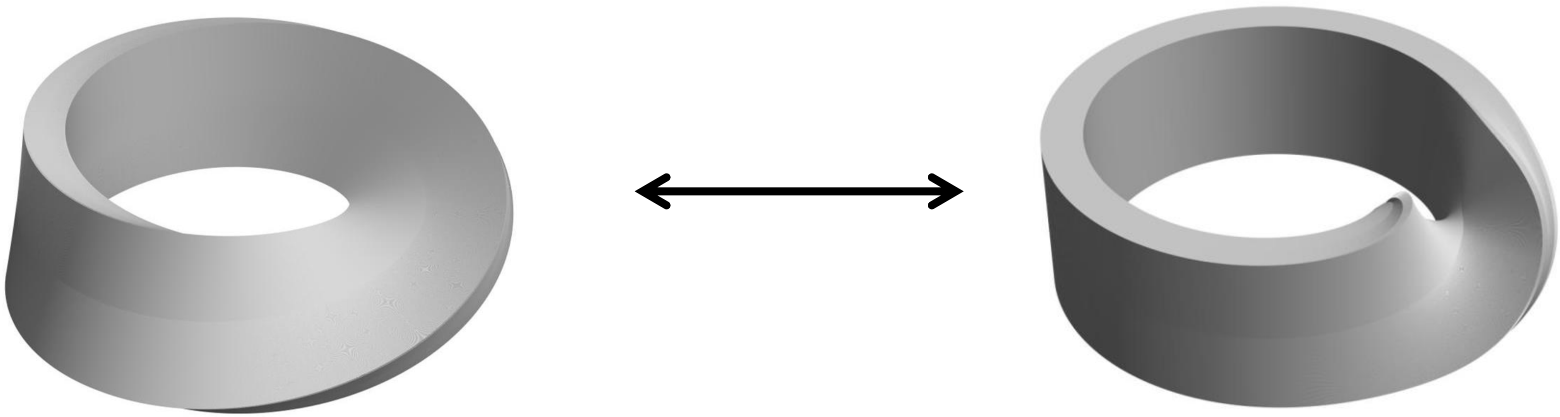






Jakob Kreismann and M.H., in preparation

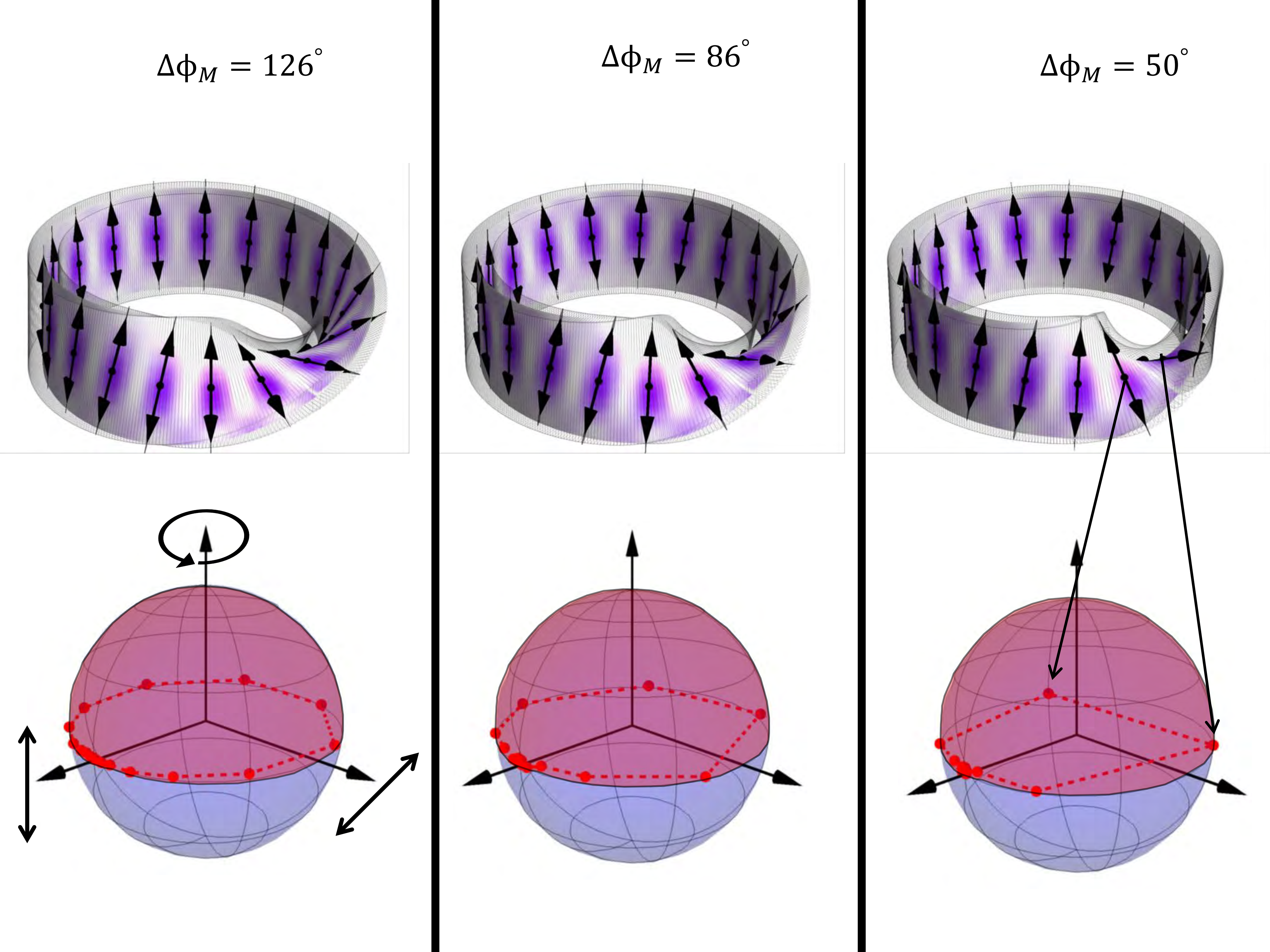
Manipulate sample geometry:
How much `Möbius‘ needs a Möbius strip?



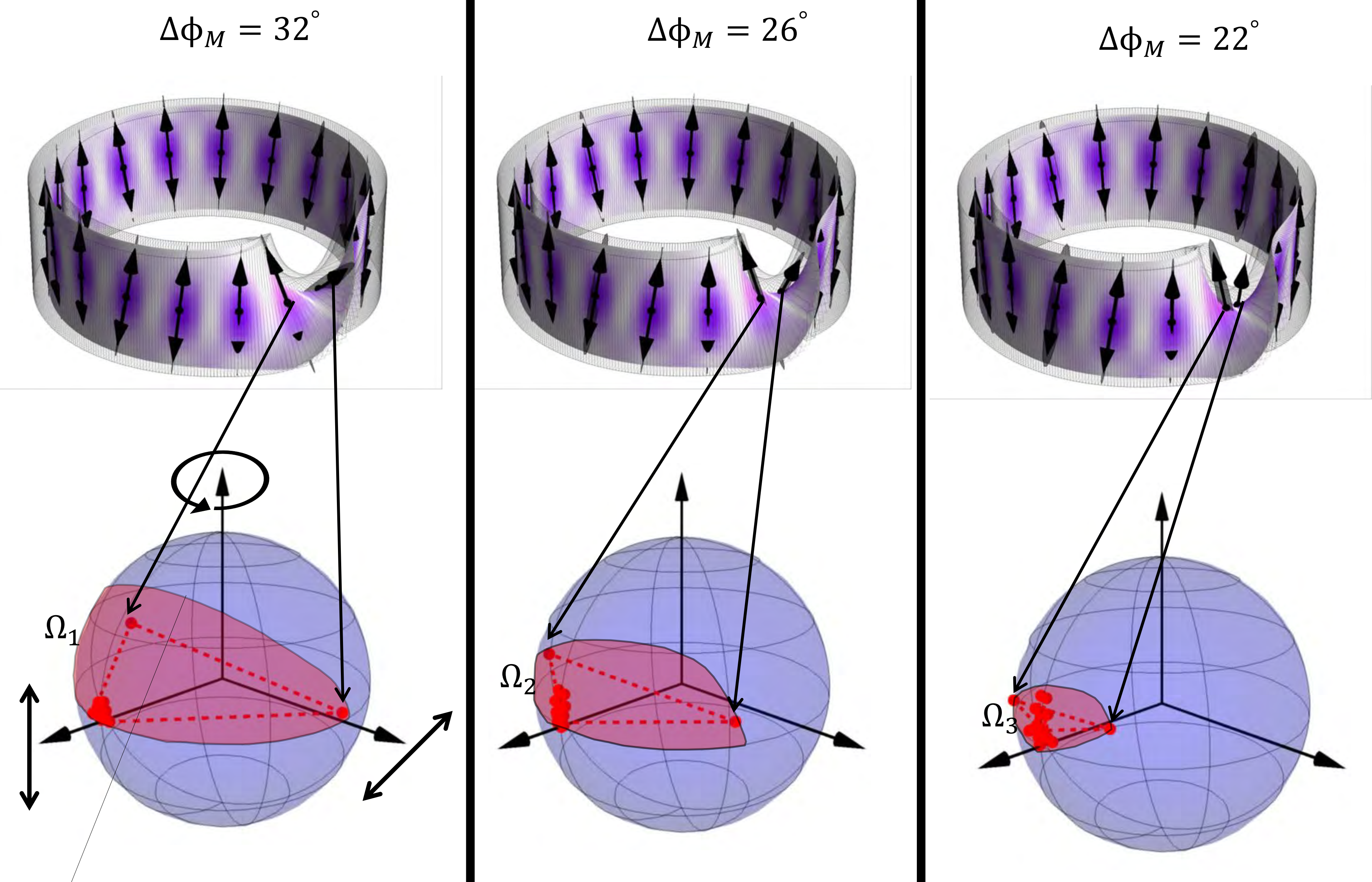
$\Delta\phi_M = 360^\circ$

$\Delta\phi_M = 50^\circ$

Can we `switch on‘ topology?



$\Delta\phi_M = 126^{\circ}$
$\Delta\phi_M = 86^{\circ}$
$\Delta\phi_M = 50^{\circ}$

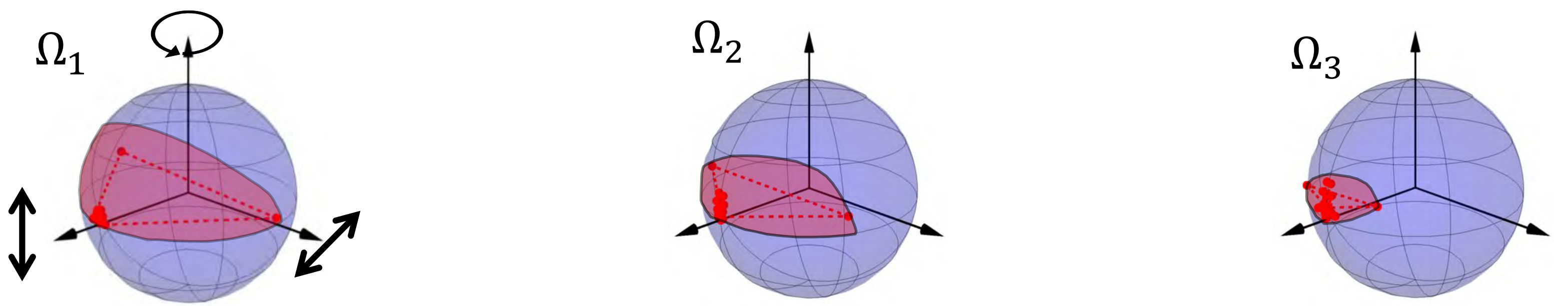


solid angle is spanned by geodesic arcs

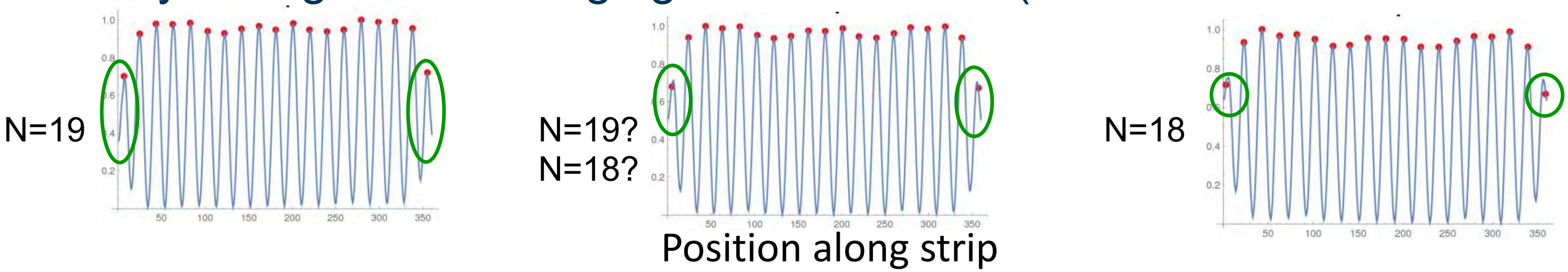
- Geometric phase reduced
- Reminiscent of non-adiabatic Berry phase

How much topology needs a Möbius strip?

- Smooth change in geometry induces smooth change in geometric phase

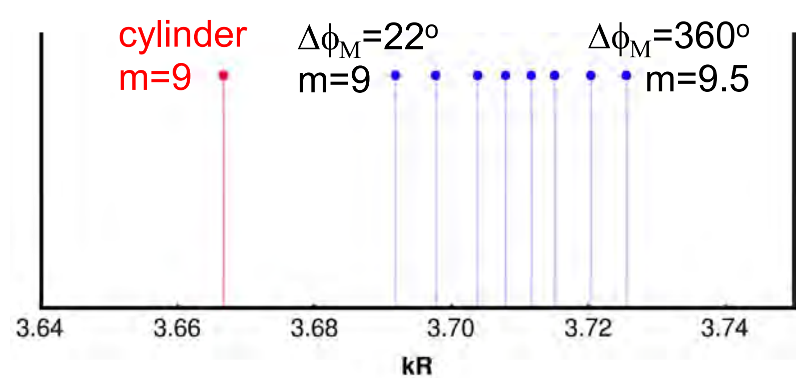


- Intensity at ring center: Merging of two maxima (smooth transition N=19 → 18 max.)

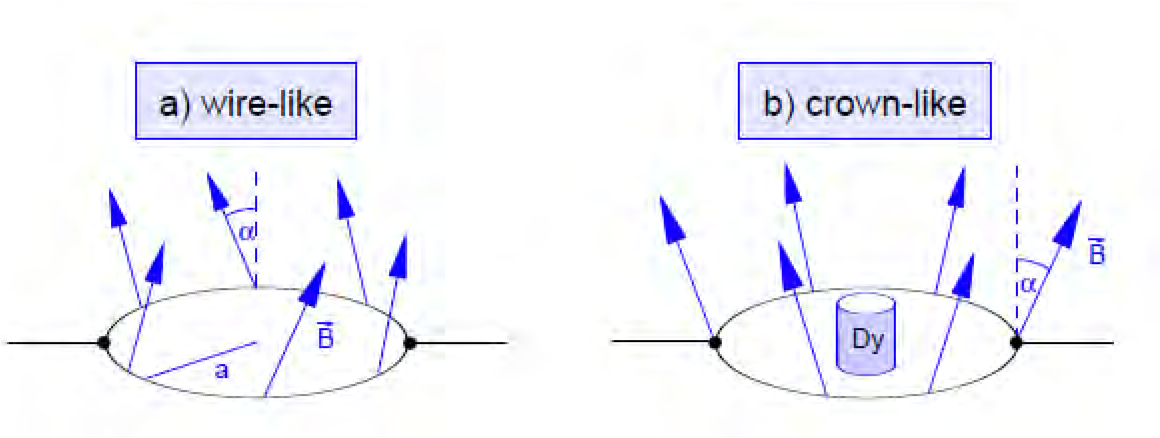


- wave number kR = f(geometric phase),

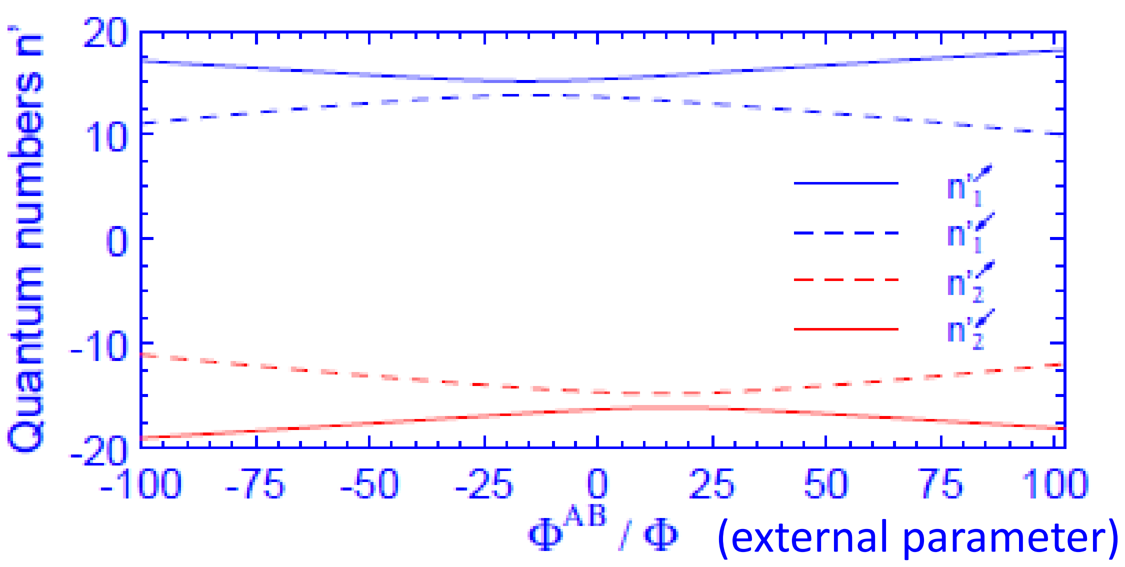
  transition from adiabatic (Berry) to non-adiabatic (Aharonov-Anandan) phase



Analogy: Berry phases in magnetotransport



M.H./Diego Frustaglia, Klaus Richter,
PRL 2001, PRB 2003, PRB 2004



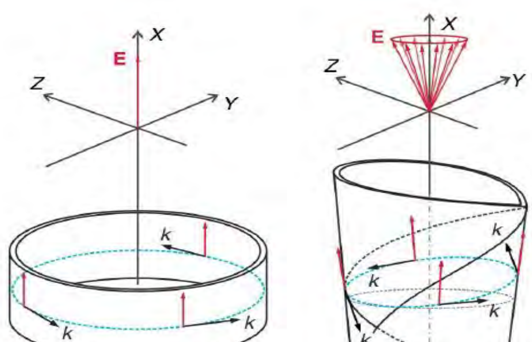
$$n'^{\nearrow(\swarrow)}_2 = -\frac{1-(+)\cos\gamma_2^{\nearrow(\swarrow)}}{2} - \sqrt{\widetilde{E}_F - \frac{\sin^2\gamma_2^{\nearrow(\swarrow)}}{4} + (-)\widetilde{\mu}B\cos(\gamma_2^{\nearrow(\swarrow)}+\alpha)}$$

Light propagation in anisotropic media

Birefringance: $NaNO_3$ crystal

(from Lipson, 2011)

- intrinsic anisotropy of crystal



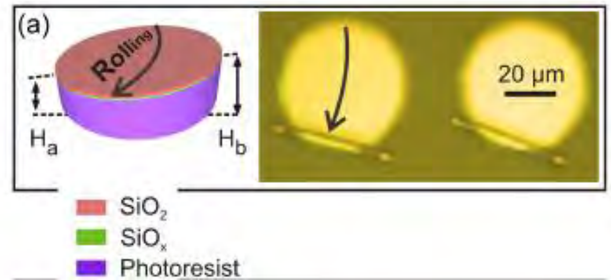
→ Berry phases

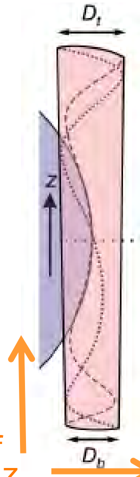
→ spin-orbit coupling of light

L. Ma,…, M.H. et al., Nat. Comm.(2016)

… and in microtube resonators

(O. Schmidt's group, IFW Dresden)





V.B.-Quinones, PhD thesis (2015)
L. Ma, M.H. et al., Nat. Comm. (2016)

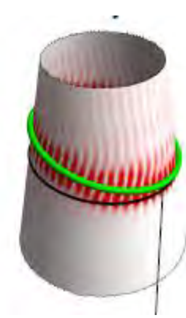
$n^{eff}_x < n^{eff}_z$

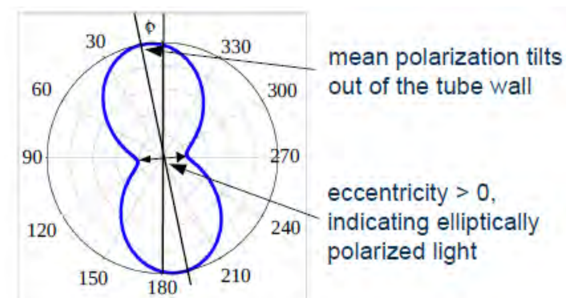
n^{eff}_x

- anisotropy induced through composite material and rolled-up geometry

→ **Manipulation of polarization**

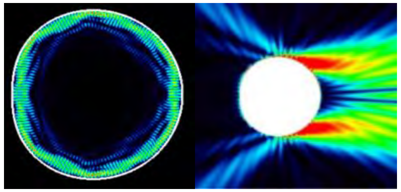
(MEEP simulations: Jakob Kreismann)

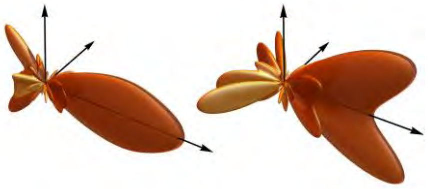




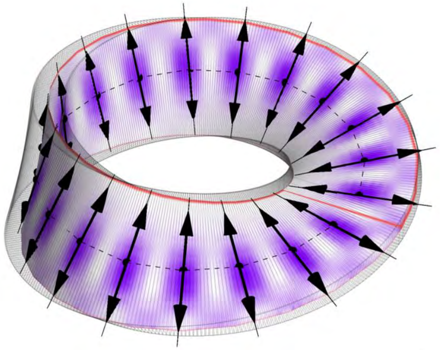
Outline

1. **Motivation – optical microcavities or Honey, we shrunk the laser**

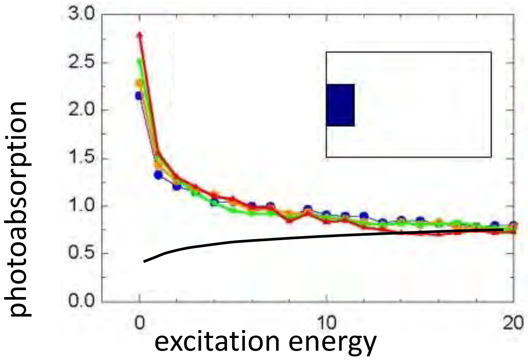




2. **Polarization evolution in 3d microcavities**

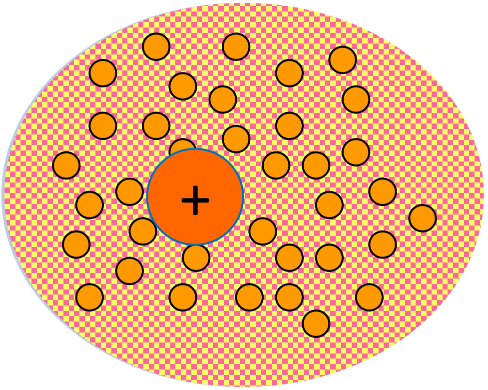


3. **Fermi-edge singularities and sample geometry**



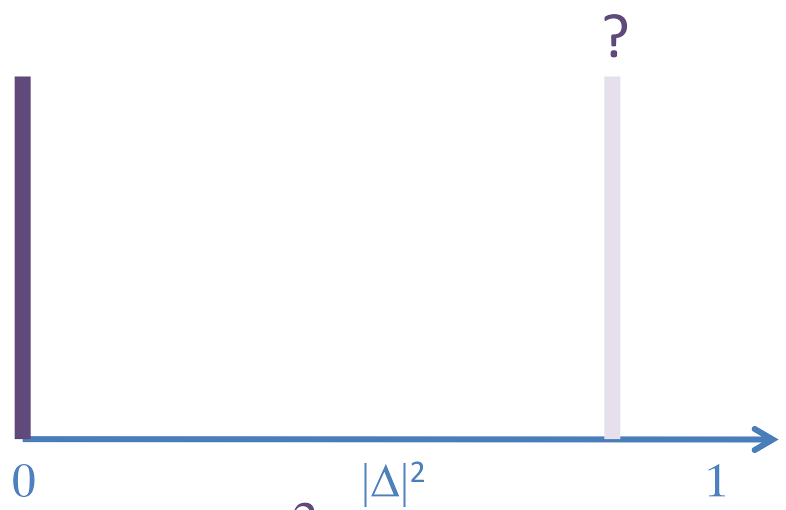
Anderson orthogonality catastrophe: Non-equilibrium meets the nano-world

- Fermi sea of electrons: apply sudden and localized perturbation
  → many-body ground state $|\Psi\rangle$ changed



- look at the Anderson overlap $|\Delta|^2 = |\langle\Psi_{pert} | \Psi_{unpert}\rangle|^2$

Metal

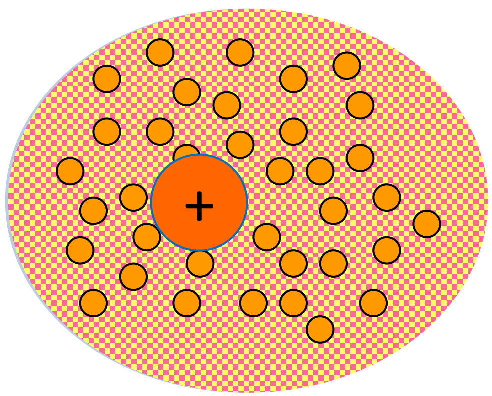


$$|\Delta|^2 \sim N^{-(\delta/\pi)^2}$$

δ … induced phase shift at E_F

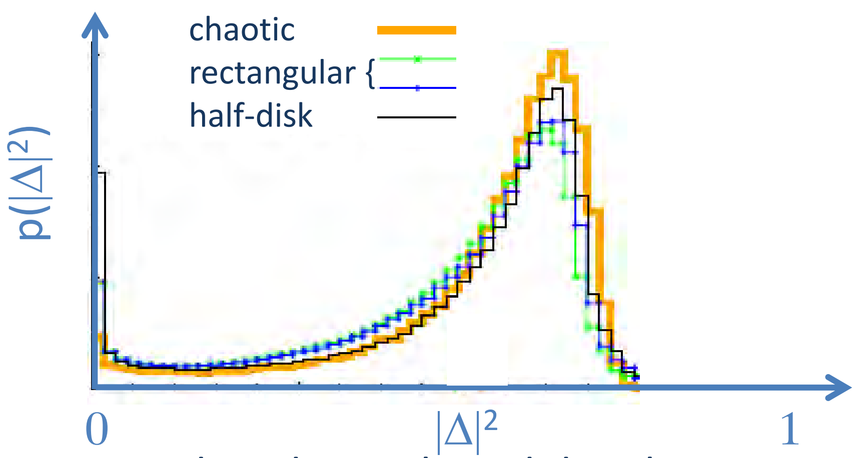
Anderson orthogonality catastrophe: non-equilibrium meets the nano-world

- Fermi sea of electrons: apply sudden and localized perturbation
  → many-body ground state $|\Psi\rangle$ changed

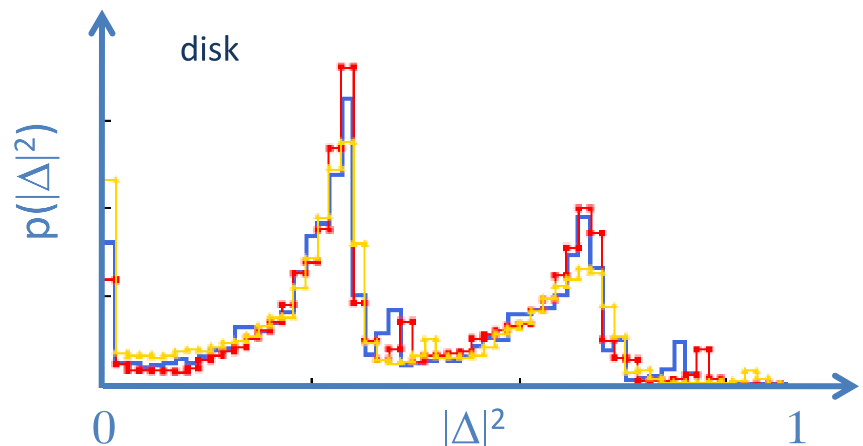


- look at the Anderson overlap $|\Delta|^2 = |\langle\Psi_{pert}|\Psi_{unpert}\rangle|^2$

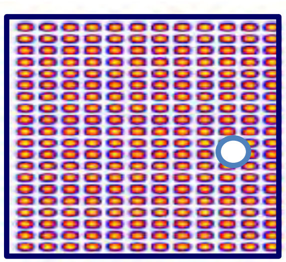
Mesoscopic systems (v/d= -0.3)

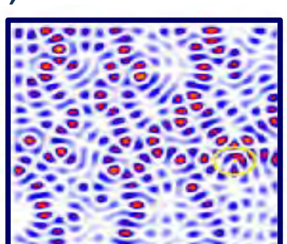


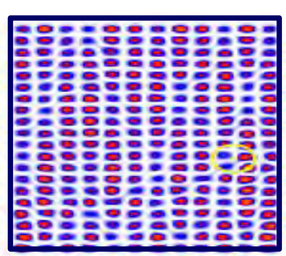
- reduced AOC, broad distribution



- level g-fold degenerate → g peaks



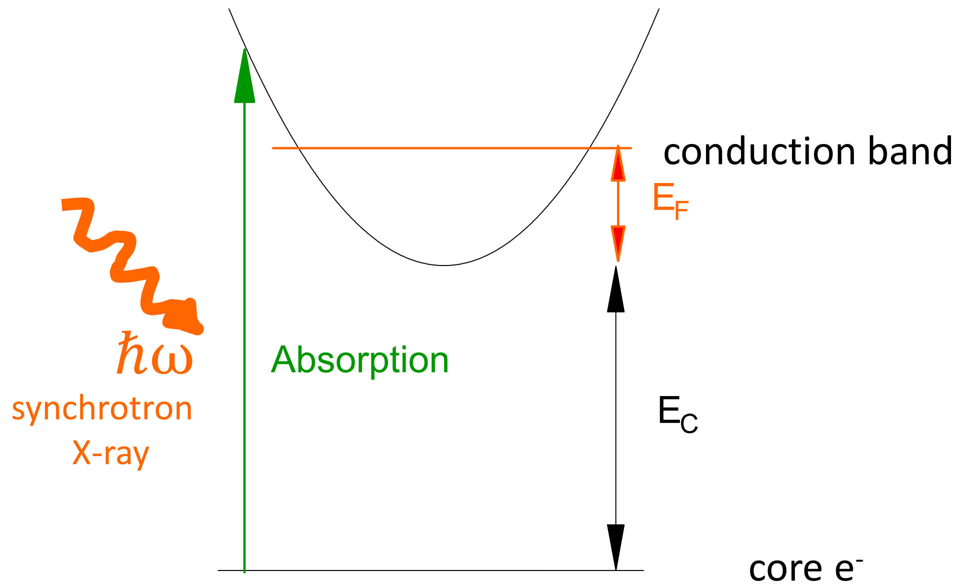




M.H. et al., PRL **93**, 2004
M.H. et al., PRB **72**, 2005
Georg Röder and M.H., PRB **82**, 2010
S. Bandopadhyay and M.H., PRB **83**, 2011
M. H. and F. Guinea, PRB **76**, 2007

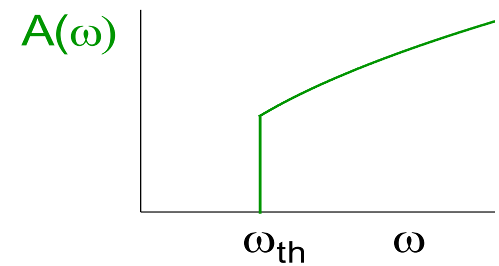
Fermi-edge singularities in photoabsorption: The X-ray edge problem

- **Metallic case**



Photoabsorption cross section

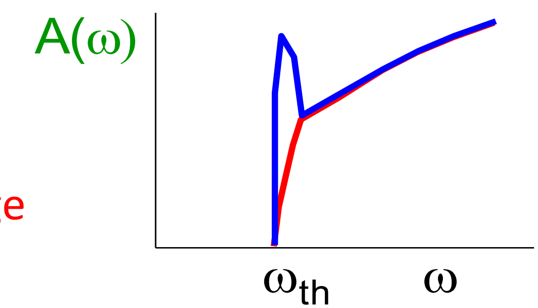
- Expected:



- Observed:

peaked edge

rounded edge

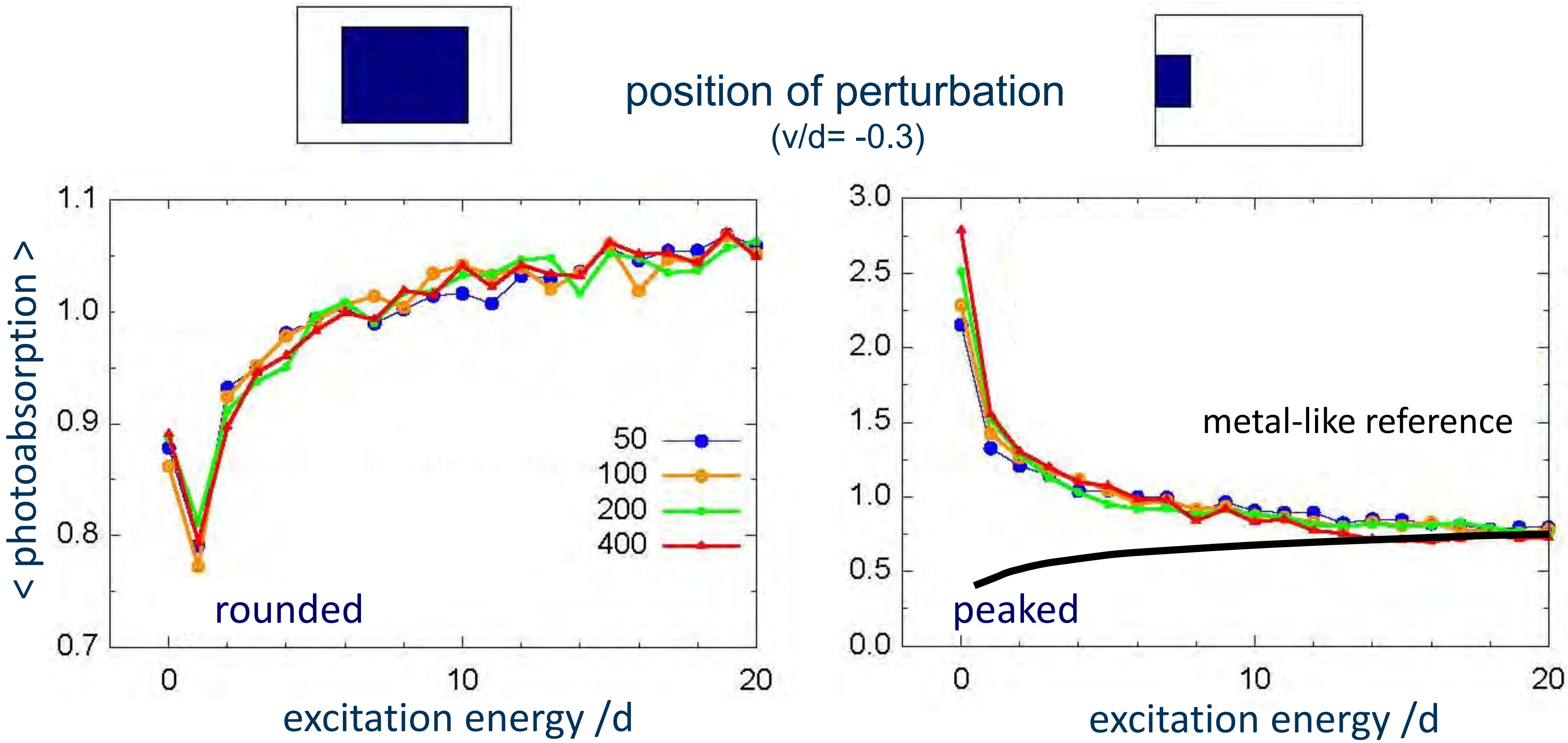


Reviews: Y. Tanabe and O. Othaka, RMP 1990
P.H.Citrin et al., PRB 1979

- **Mesoscopic case**
  - change in density of states (quantum dots → const., graphene → Dirac point)
  - discrete energy levels (mean spacing d)
  - geometry-dependent wave functions, avaraging

$$A(\omega) = 2\pi \sum_F \left| \langle \Psi_F | \hat{D} | \Phi_c \rangle \right|^2 \times \delta\left(E_F - E_i\right) \quad \text{with} \quad \hat{D} = \sum_{j=1}^{N} w_{cj} \, [\, c_j^{+} c_c + \text{h.c.} \,]$$

Boundary signatures in the photoabsorption

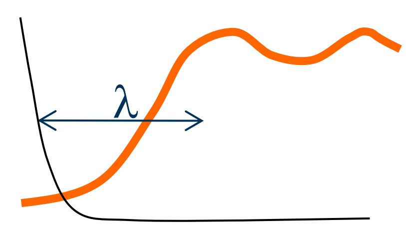


M. H. and G. Röder, EPJB 2014

→ boundary contribution dominates absorption cross section in mesoscopic systems

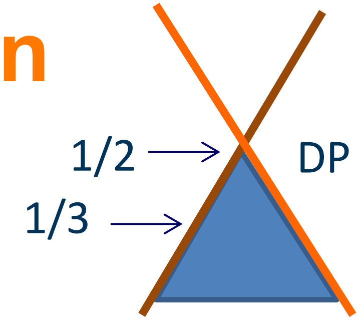
Reason:

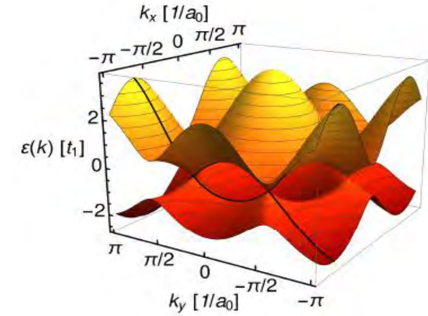
relation between ψ (→0) and ψ‘ (→ \`big‘) near boundary, enters via dipole matrix element



M. H. et al., PRL 2004
M. H. et al. PRB 2006

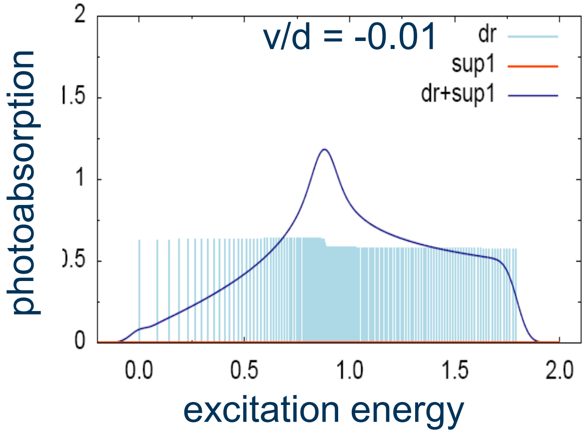
Graphene Photoabsorption

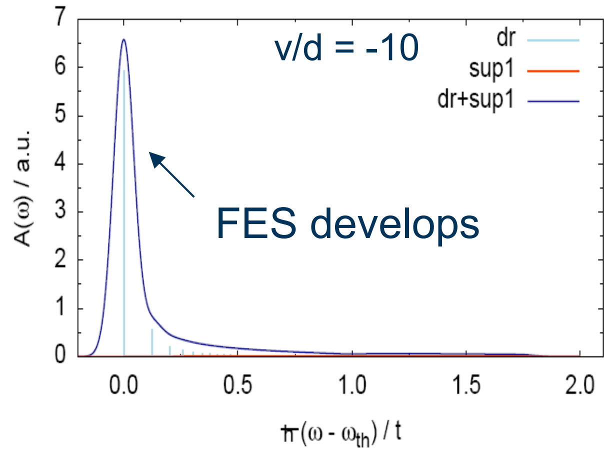


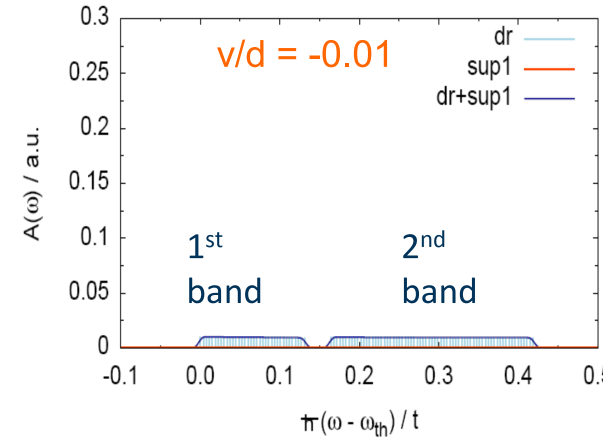


filling 1/2 (DP)

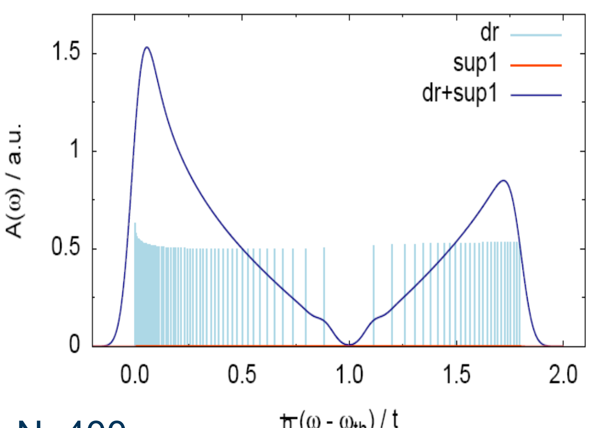
Comp.: metal with gap

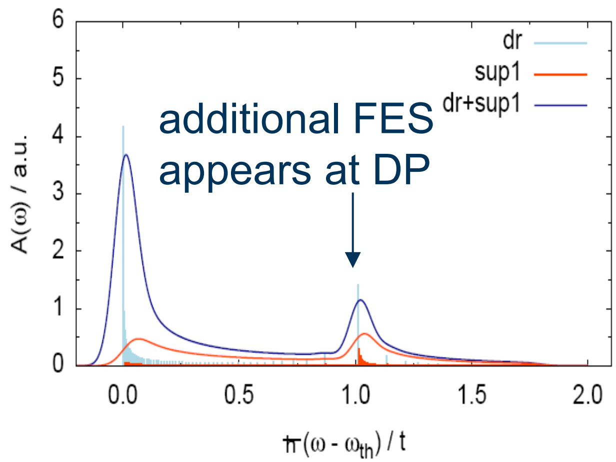


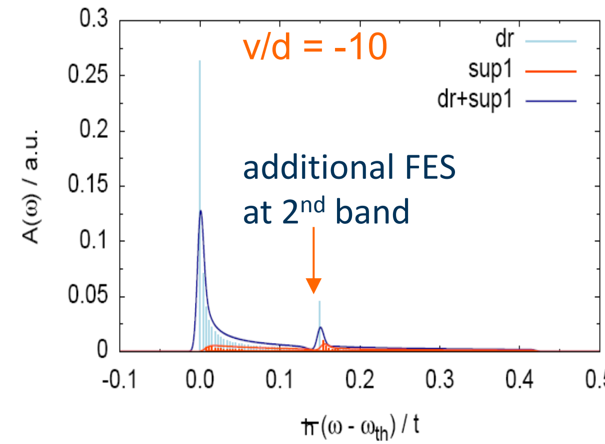




filling 1/3







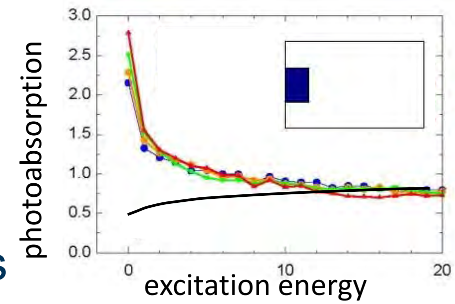
N=400

M. H. and F. Guinea, PRB **76**, 2007; G. Röder, G. Tkachov, and M.H., EPL **94**, 2011

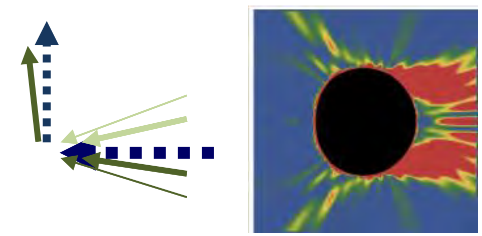
Conclusion

Mesoscopic physics with Electrons and Photons

- mesoscopic signatures of many-body effects
  deviate from the metallic case (X-ray edge, Kondo)
  - depend on local DOS and system boundary

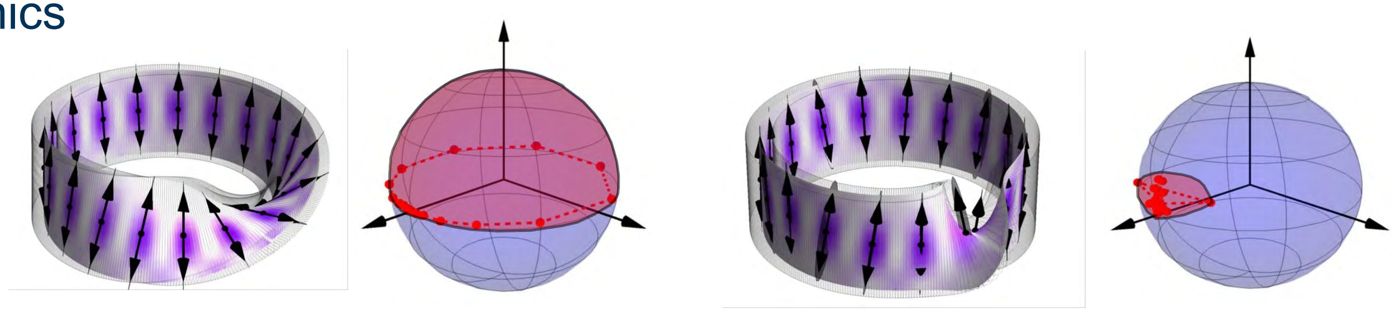


- microlaser with robust, directional far-field properties
  (Limaçon, also spiral, coupled cavities)



- semiclassical corrections to ray-wave correspondence
  (defocusing of light beams)

- Möbius strip and topology in optical transport,
  polarisation dynamics



- **Interference effects dominate physics**
- **Manipulation of interference – system geometry – boundaries – anisotropy/inhomogeneity: Analogies to condensed matter (TIs etc.)?**

Thanks to:

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