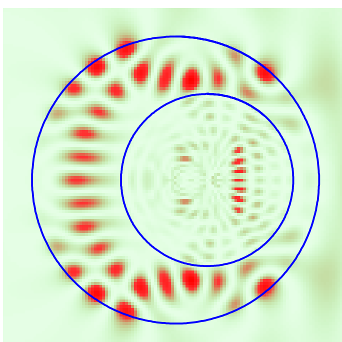
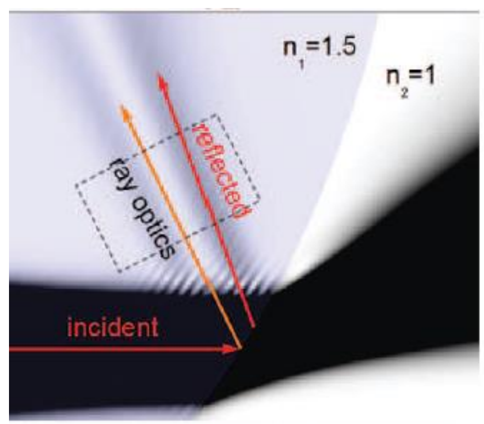
Boundary-induced phenomena in mesoscopic systems

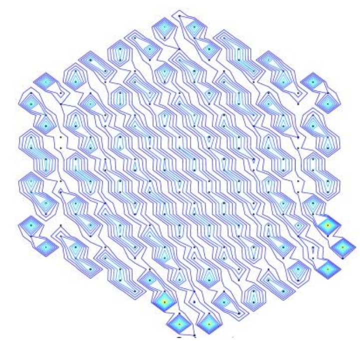
Martina Hentschel

Georg Röder, Pia Stockschläder, Jakob Kreismann, Philipp Müller, Lucia Baldauf

TU Ilmenau, Germany







TECHNISCHE UNIVERSITÄT ILMENAU

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Outline

I. Optical mesoscopic systems

Semiclassical effects at planar vs. curved interfaces

II. Electronic mesoscopic systems

X-ray edge problem: Boundary signal determines photoabsorption cross section

Graphene: edge-state effect on photoabsorption

III. Summary and Outlook

Research started at TU Ilmenau

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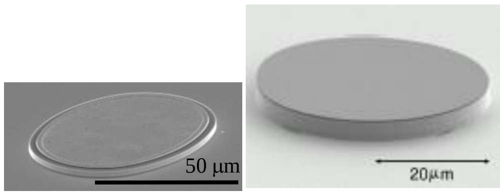
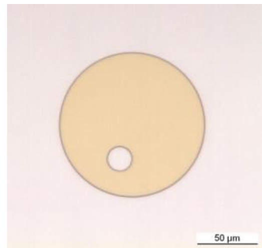
Motivation: microdisk laser

- destroy rotational symmetry to achieve farfield directionality
  → "deformed microdisk lasers"



Harayama Lab
(Kyoto)



Zyss Lab
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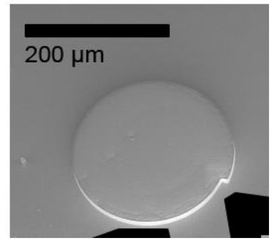
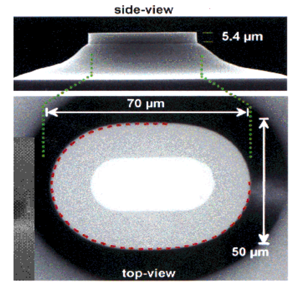
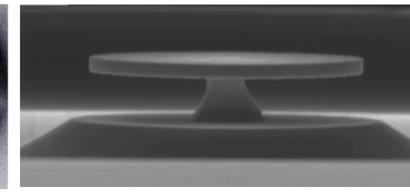


Capasso Lab
(Harvard)



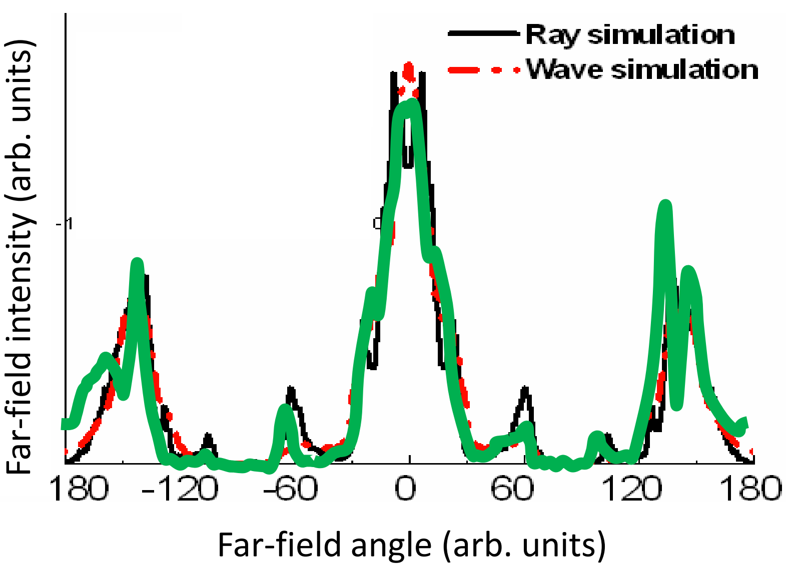
Bell Labs
(New Jersey)

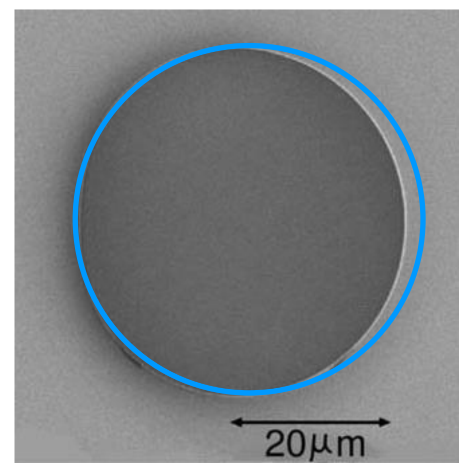


Cao Lab
(Yale)

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

J. Wiersig and M. Hentschel, PRL **100**, 2008



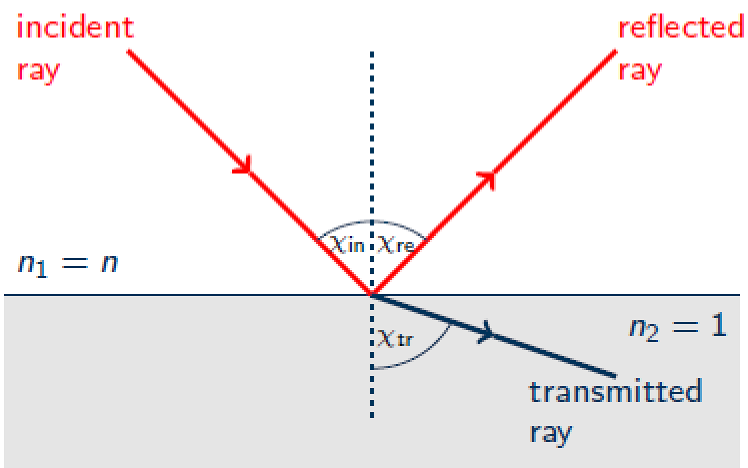


Harayama Lab
(Kyoto)

Goos-Hänchen shift (GHS) and Fresnel filtering (FF)

geometric optics

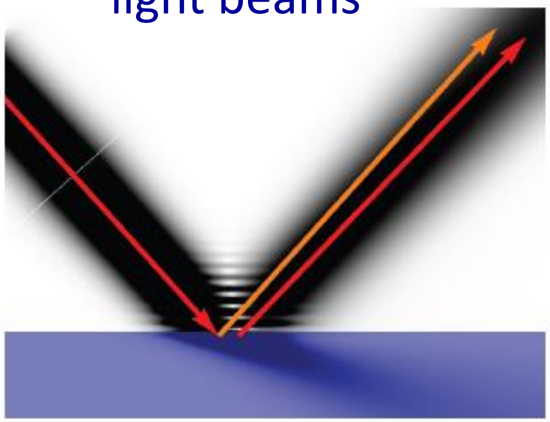
light rays



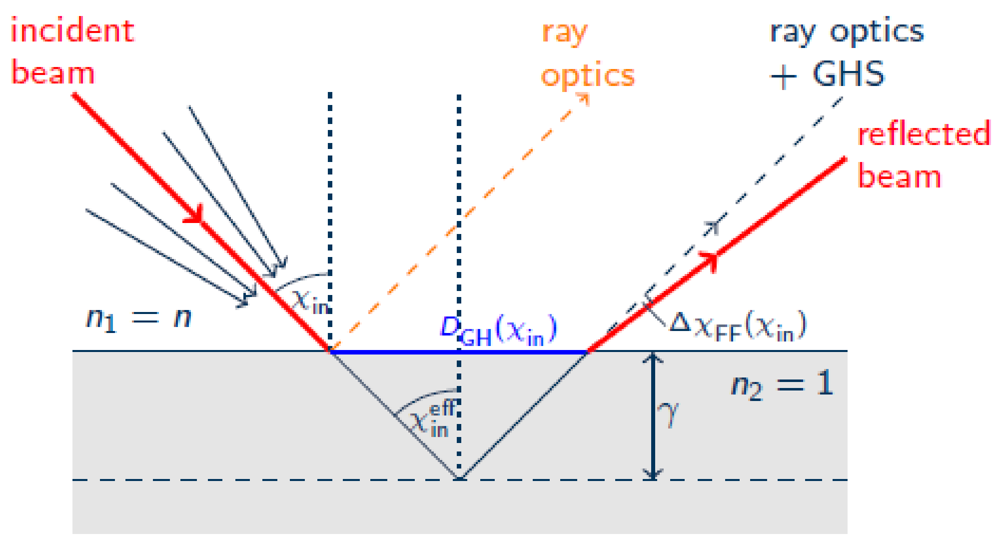
→ ray picture
works very well in many cases

in reality

light beams



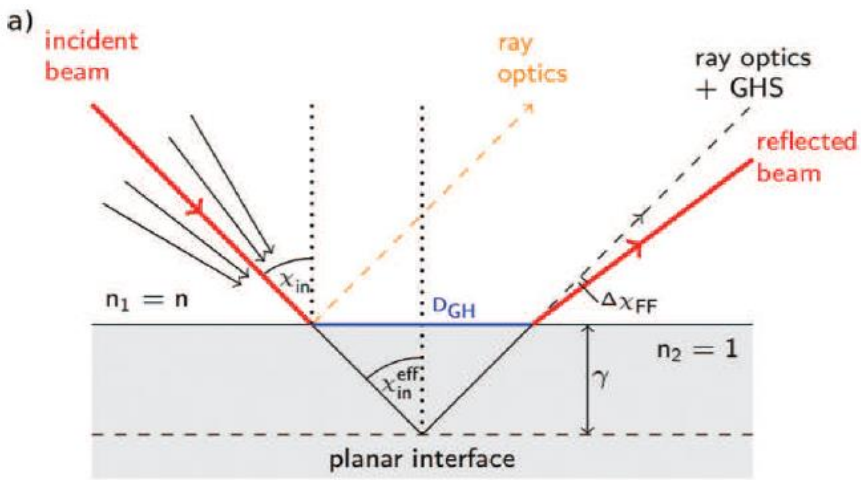
→ semiclassical corrections ~ λ



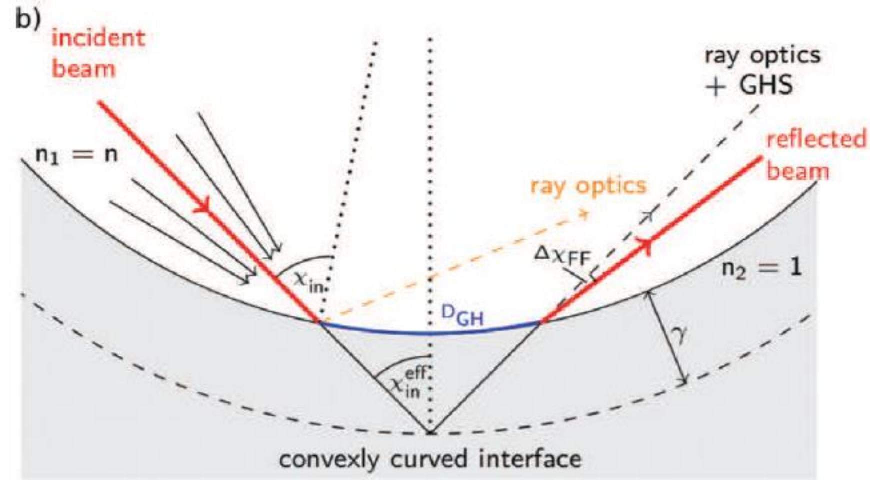
Goos and Hänchen, Ann. Phys. 1947
Artmann, Ann. Phys. 1948

H. Tureci, D. Stone, Opt. Lett. 2002

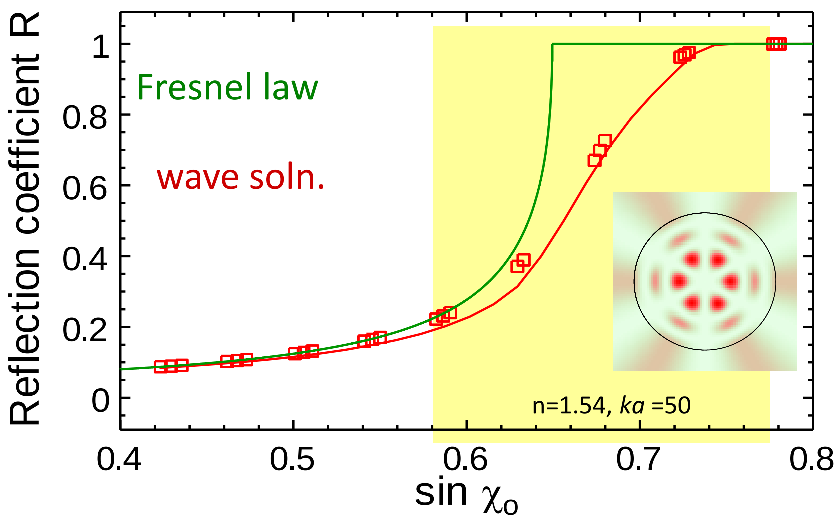
Curvature dependence:
effective angle of incidence and Fresnel laws



$\chi_{inc} = \chi_{inc}^{eff}$

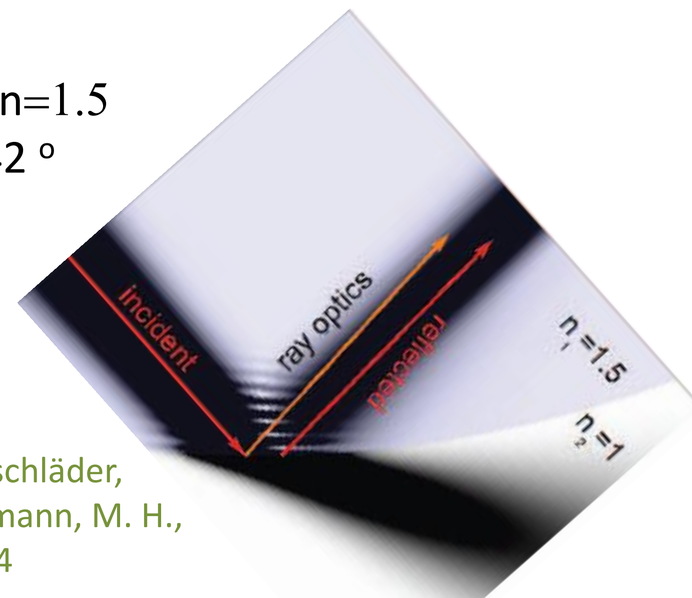


$\chi_{inc} > \chi_{inc}^{eff}$



M. Hentschel and H. Schomerus, PRE 2002

TE, n=1.5
χ=42 °



P. Stockschläder,
J. Kreismann, M. H.,
EPL 2014

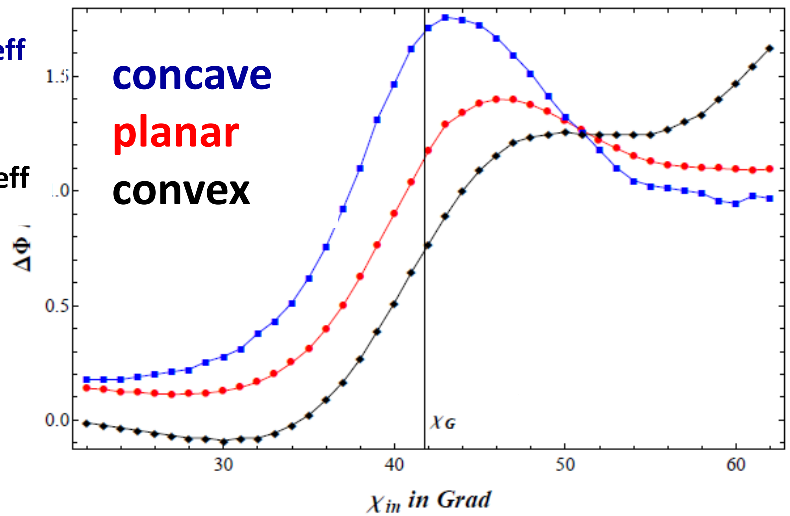
Results: Dependence on curvature κ = 1/R

GHS

$\chi_{inc} < \chi_{inc}^{eff}$ **concave**

χ_{inc} **planar**

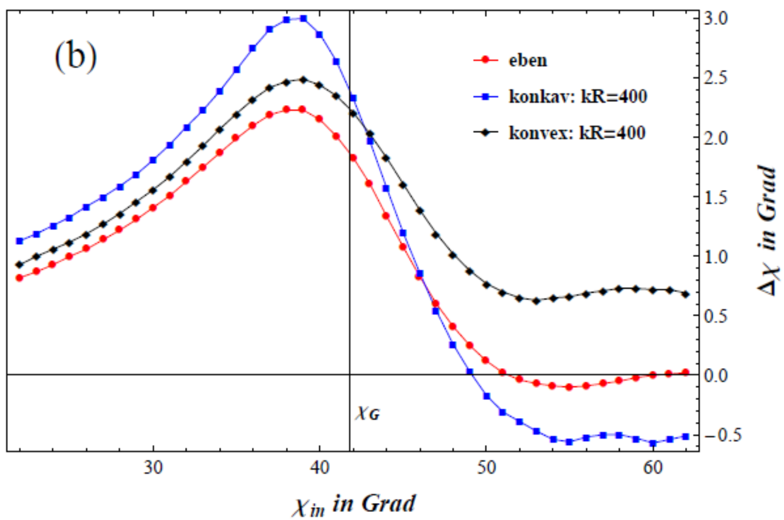
$\chi_{inc} > \chi_{inc}^{eff}$ **convex**



$D_{GH} \approx 2\,\gamma \tan\ \chi_{inc}^{eff}$

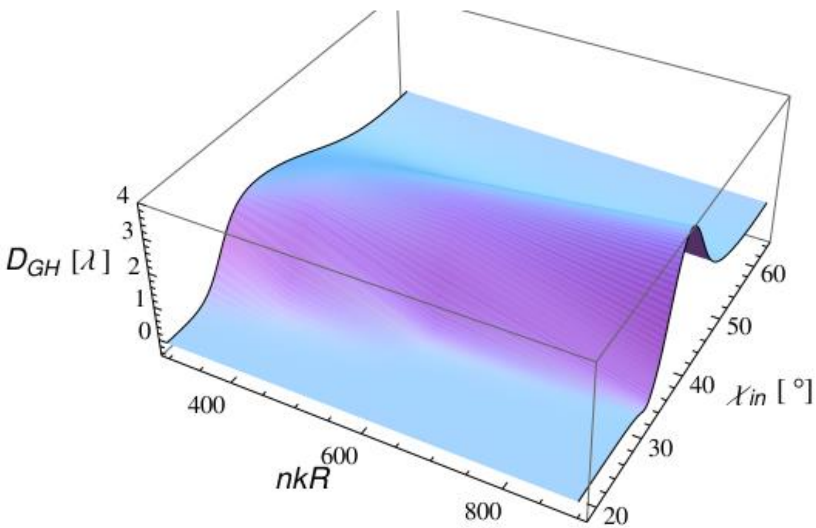
→ **GHS decreases** with curvature:

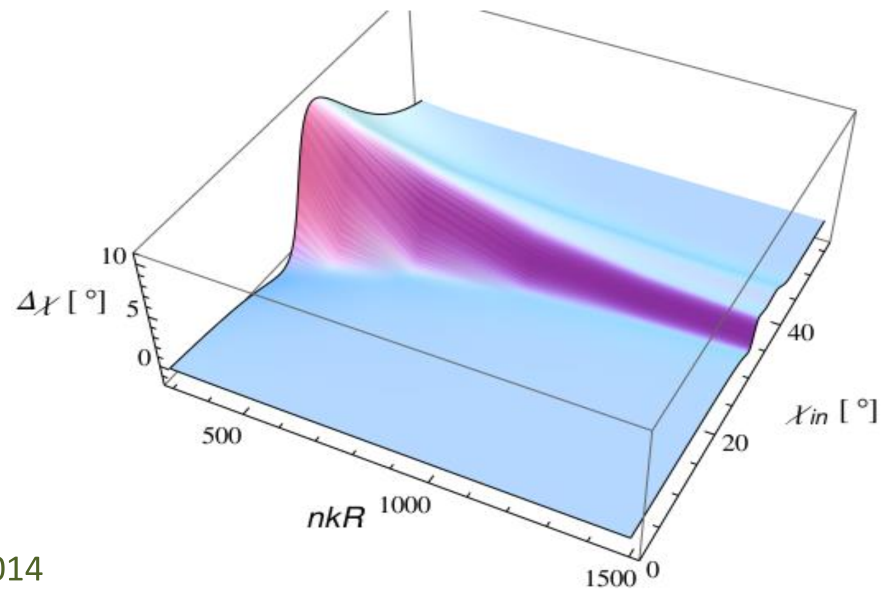
FF



→ **FF increases** with any curvature: broader distribution of χ_{inc}

TE





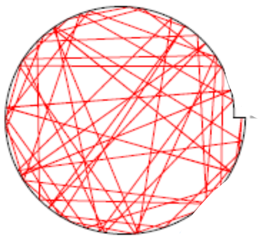
P. Stockschläder, J. Kreismann, and M. Hentschel, EPL 2014

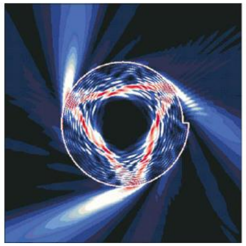
Effects due to FF and GHS

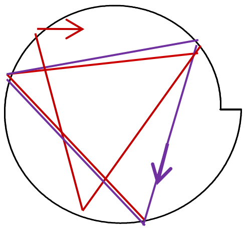
→ **GHS** explains Fresnel laws at curved boundaries
→ **GHS** can be implemented via an effective system boundary (depending on both λ and κ)

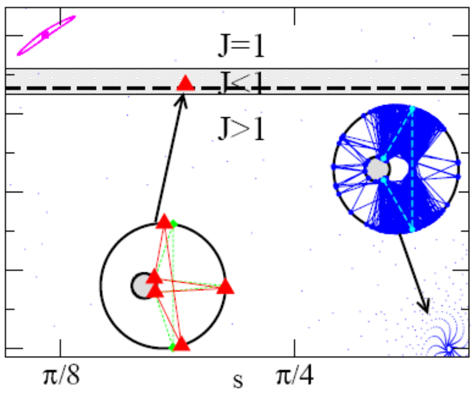
→ **FF** corrects far field emission, λ and κ dependent
→ **FF** destroys ray-path reversibility
→ **FF** brings chirality in asymmetric cavities

→ **FF** introduces non-Hamiltonian dynamics
→ **FF** tends to regularize classically chaotic orbits









Lee et al., PRL **93**,2004

E. Altmann, G. Del Magno, and **M.H.**, EPL **84**, 2008

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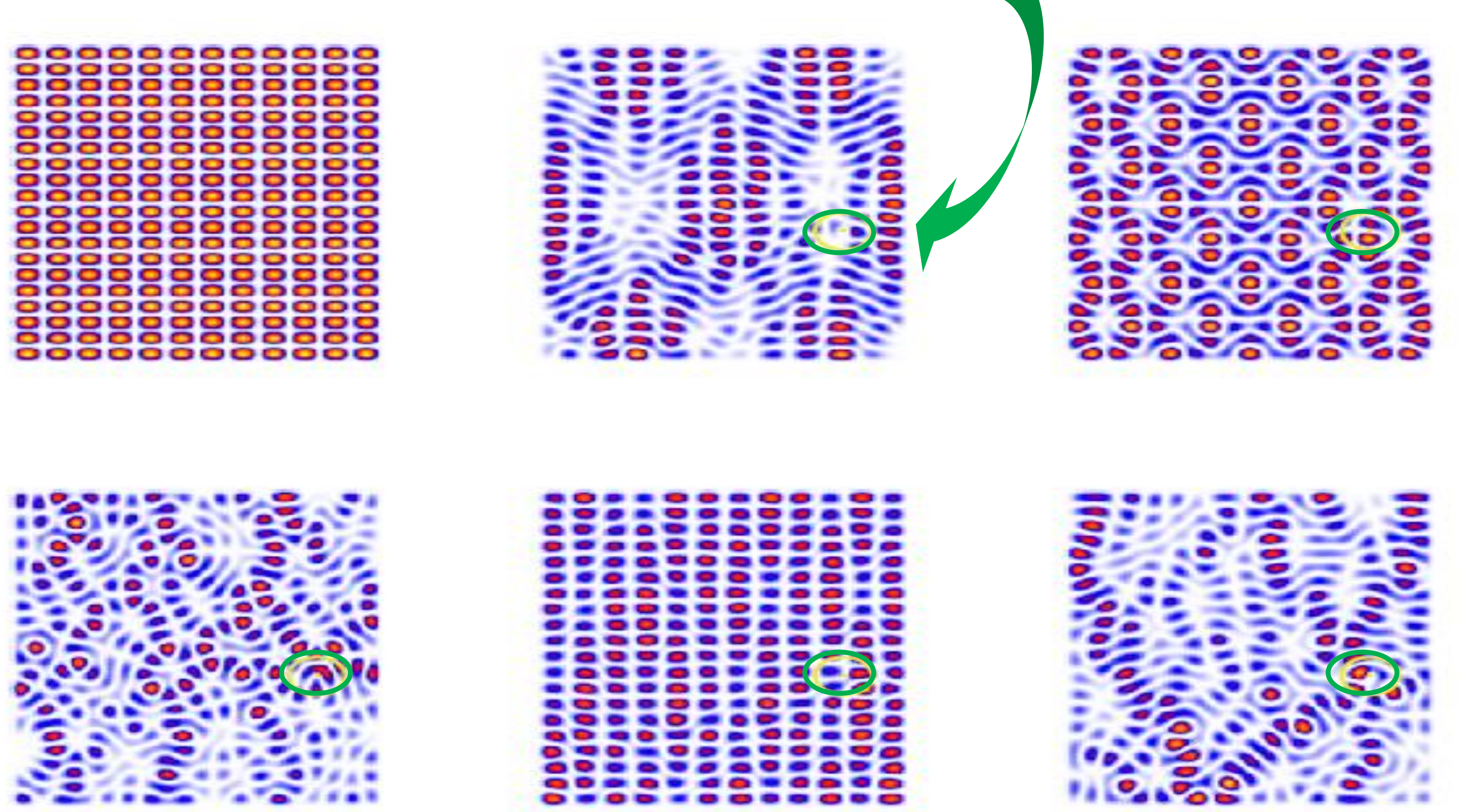
Many-body effects: An example

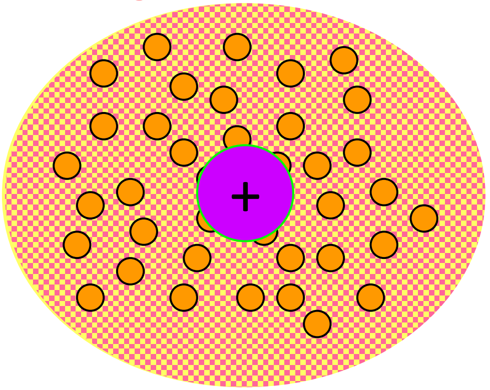
- rectangular quantum dot   under localized perturbation



Importance of

- mesoscopic fluctuations?
- finite particle number?
- boundary effects?

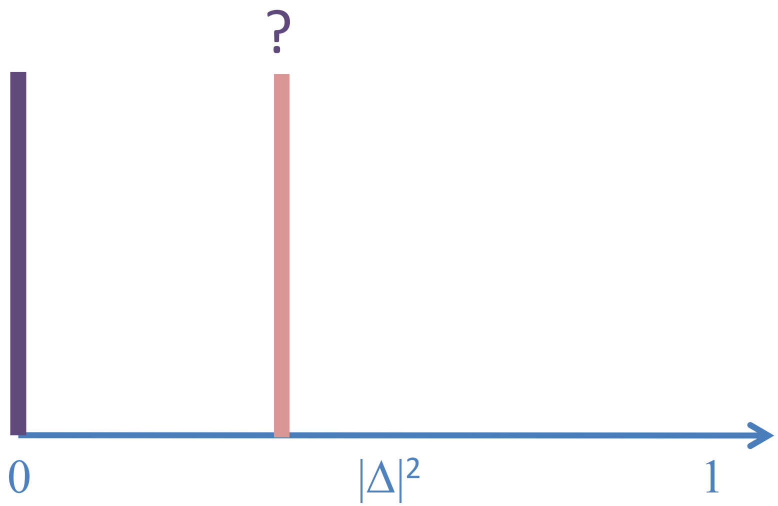
Example: Anderson Orthogonality Catastrophe



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

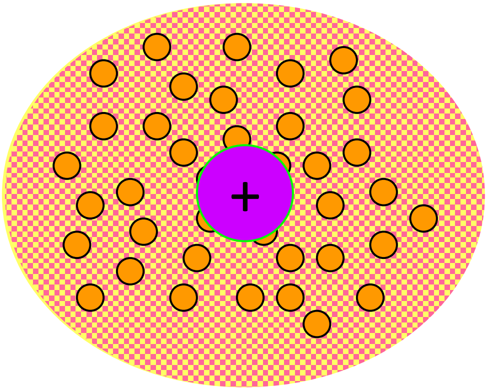
- look at the Anderson overlap $|\Delta|^2 = |\langle \Psi_{pert} \mid \Psi_{unpert} \rangle|^2$

Metal



$|\Delta|^2 \sim N^{-\varepsilon}$

Example: Anderson Orthogonality catastrophe in the mesoscopic case

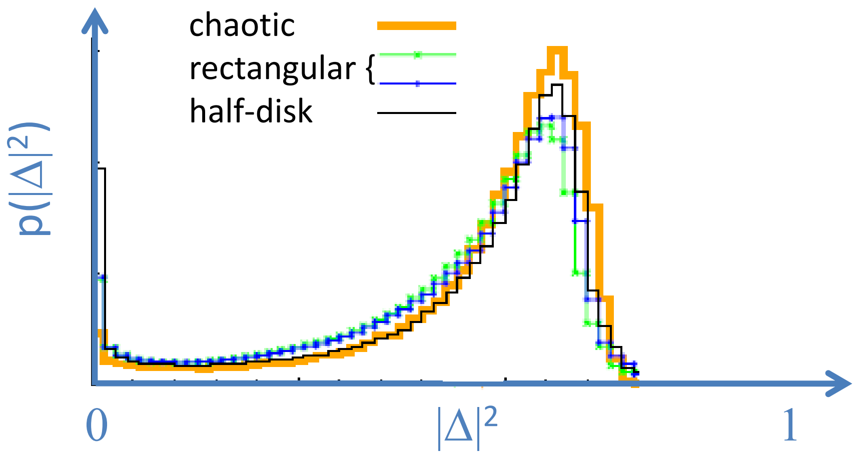


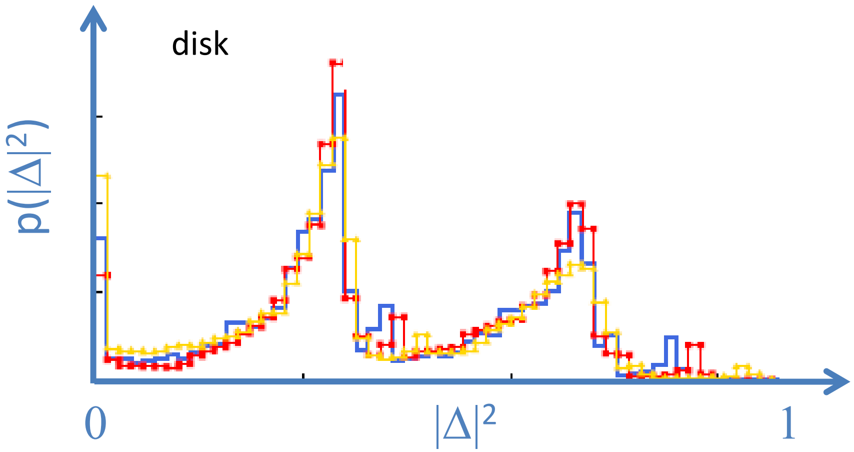
- Fermi sea of electrons: apply sudden and localized perturbation
  → many-body ground state $|\Psi\rangle$ changed

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

Mesoscopic systems

M.H. , D. Ullmo, H. Baranger, PRL **93**, 2004
M.H. , D. Ullmo, H. Baranger., PRB **72**, 2005
Georg Röder and **M.H.**, PRB **82**, 2010
S. Bandopadhyay and **M.H.**, PRB **83**, 2011



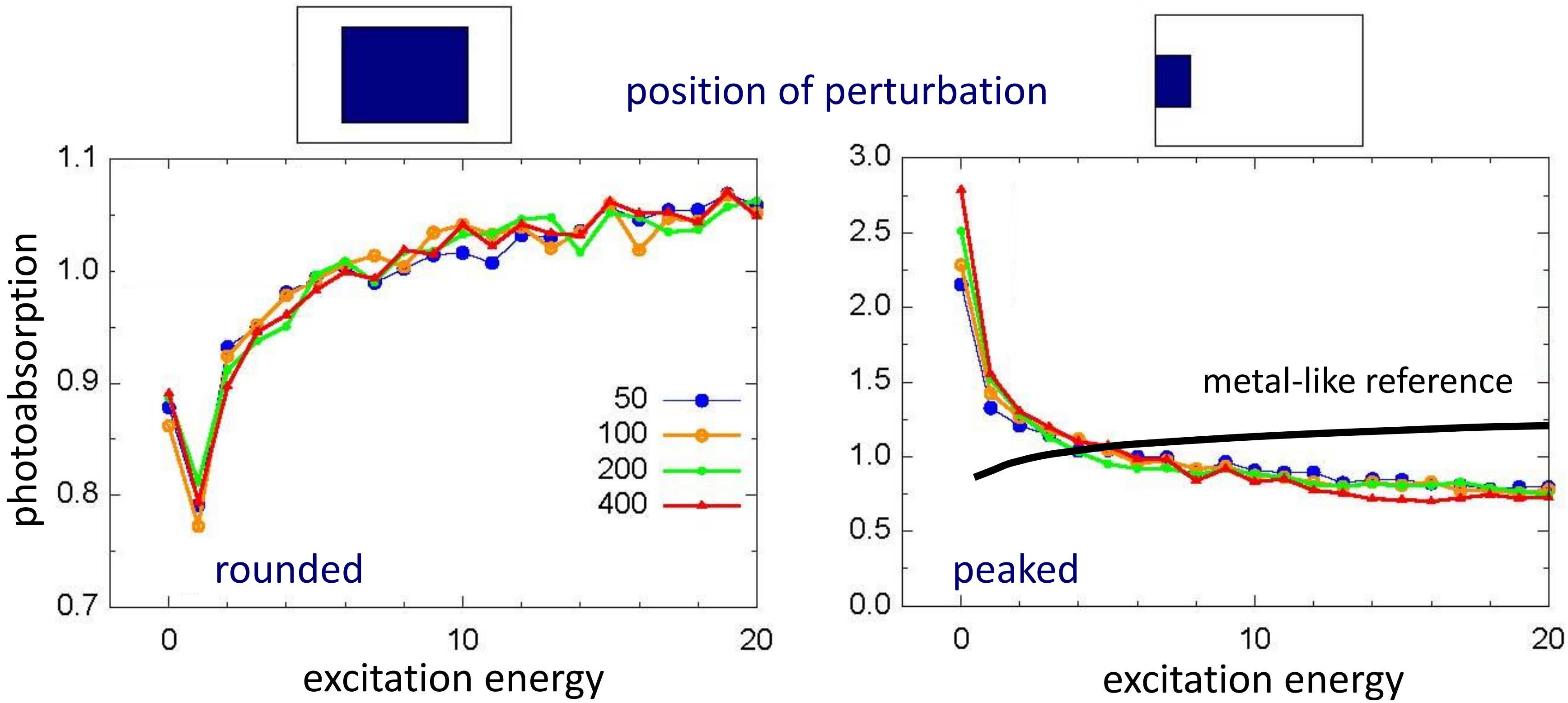


- N finite
- broad distributions

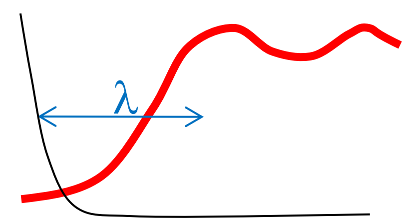
new features

- level degeneracies
- system boundary

Boundary signatures in the photoabsorption



Reason:
correlation between ψ and ψ’ near boundary,
enters via dipole matrix element



The mesoscopic x-ray edge problem:

→ experimentally accessible

→ example for “physics beyond RMT”

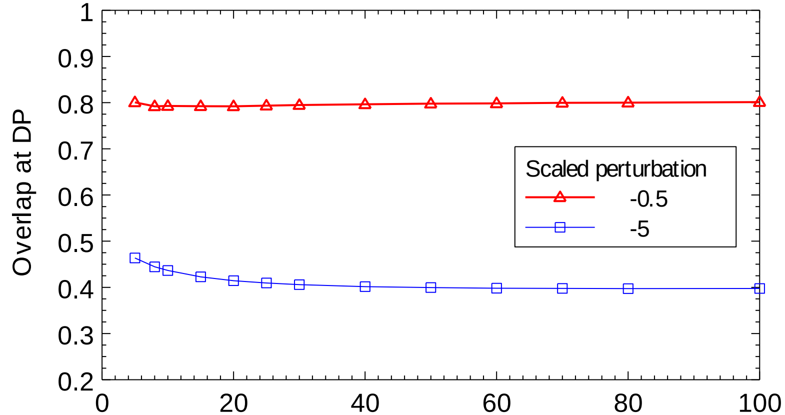
→ system boundary dominates photoabsorption

M.H., D. Ullmo, H. Baranger, PRL 2004,
PRB 2007
Georg Röder and M.H., EPJB 2014

Graphene: Anderson catastrophe

Comparison of different perturbation strengths:

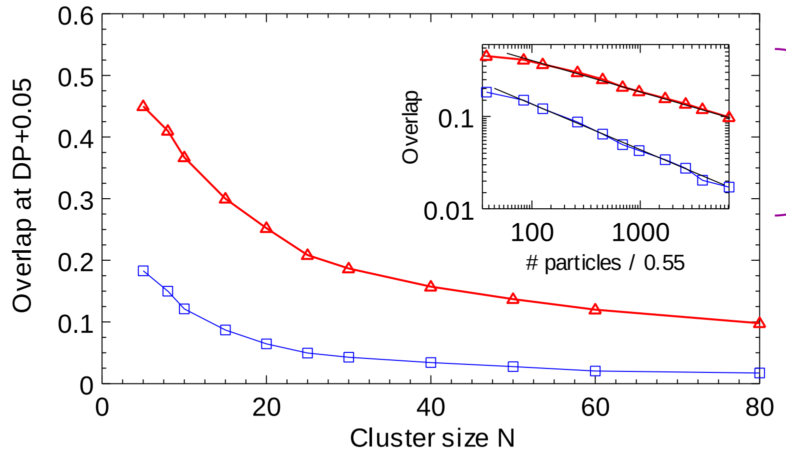
at Dirac point:



next to Dirac point:

– or *at* Dirac point but in presence of zero-energy states

- (zig-zag) edge states
- midgap states due to impurities



power law recovered

➔ AOC suppressed at Dirac point

➔ The presence or absence of zero-energy states significantly influences AOC as well as Kondo physics.

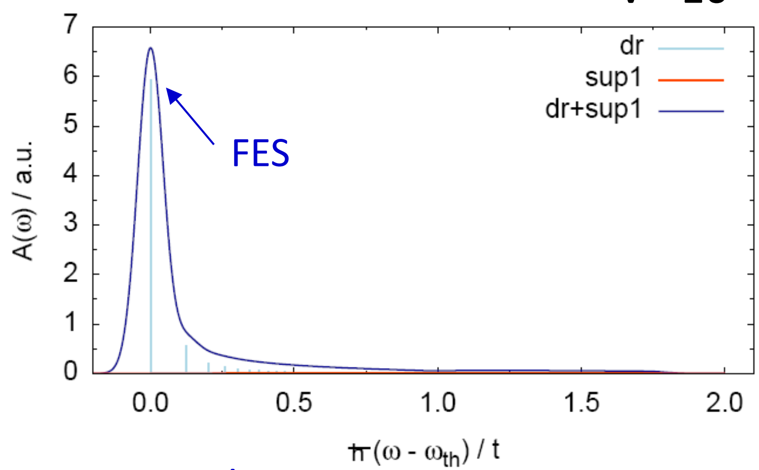
M. H. and F. Guinea, PRB **76** , 2007
G`. Röder, G.Tkachov, and M.H.,, EPL 2011

Graphene: Photoabsorption, no edge states

N=400

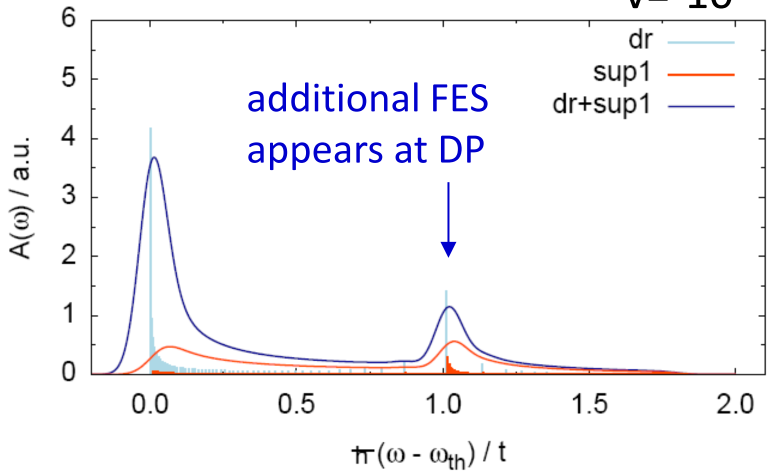
filling 1/2 (DP)

v=-10



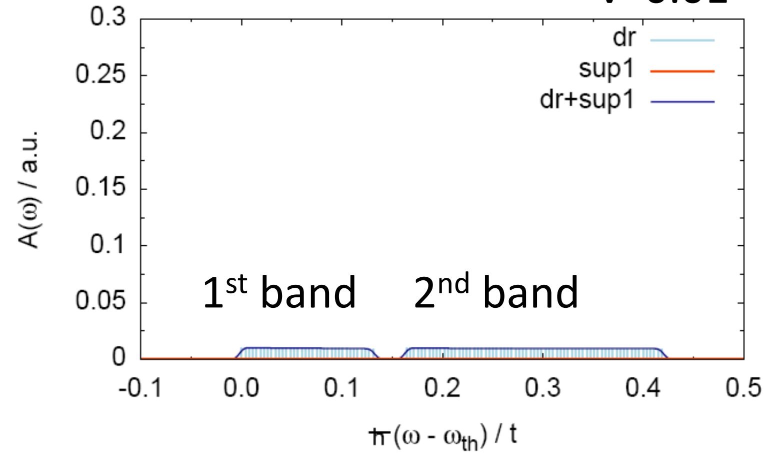
filling 1/3

v=-10

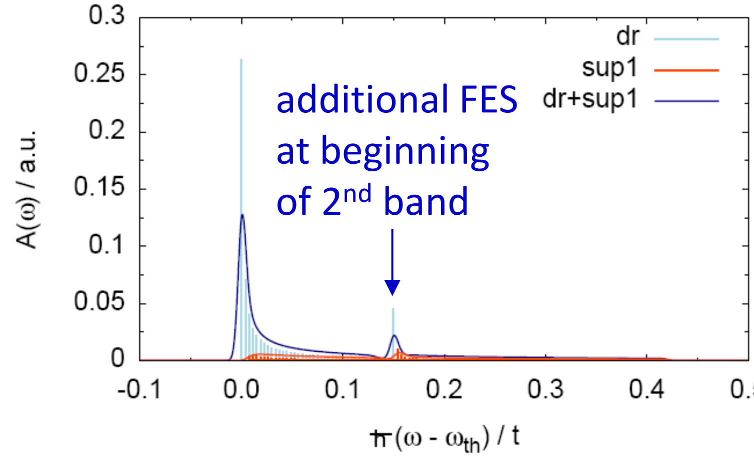


Origin: compare to photoabsorption of metal with gap

v=0.01

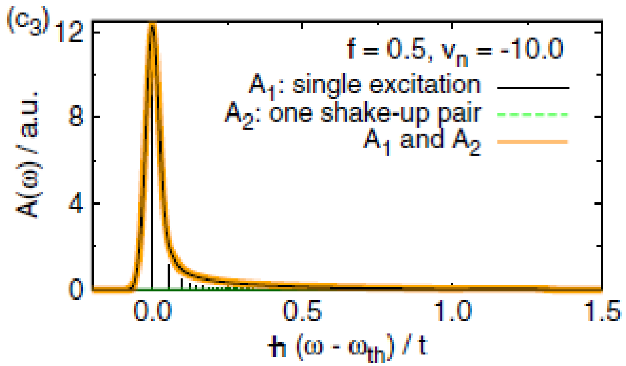


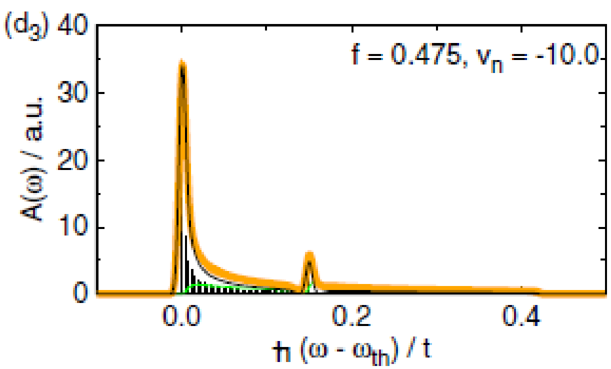
v=-10

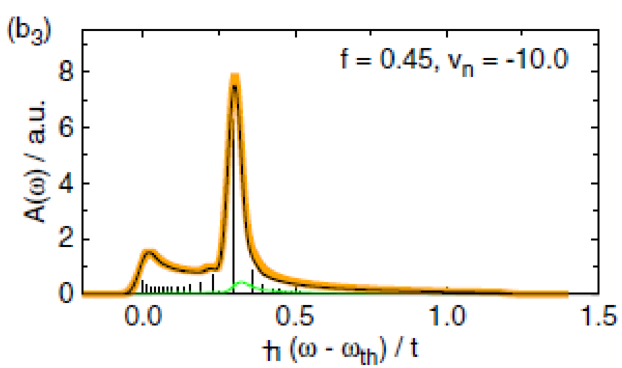


Graphene: Photoabsorption bulk vs. edge states

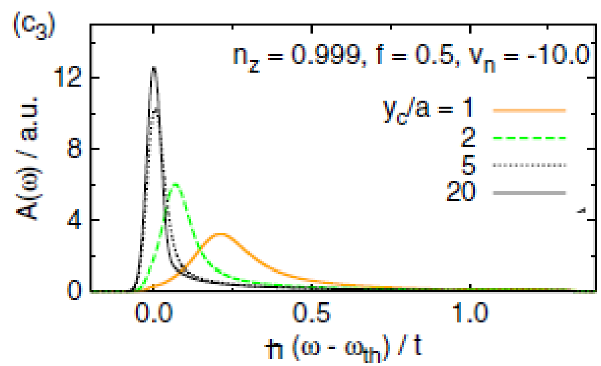
no edge states = "bulk"





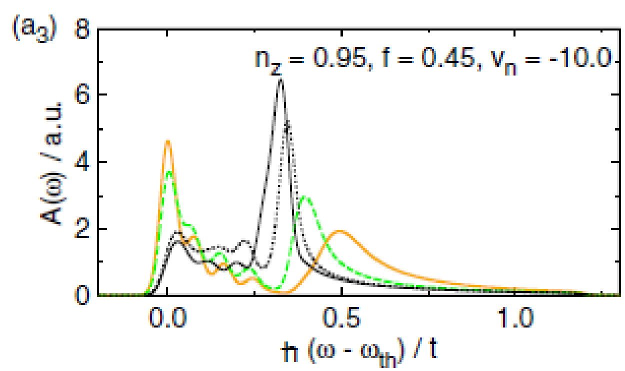


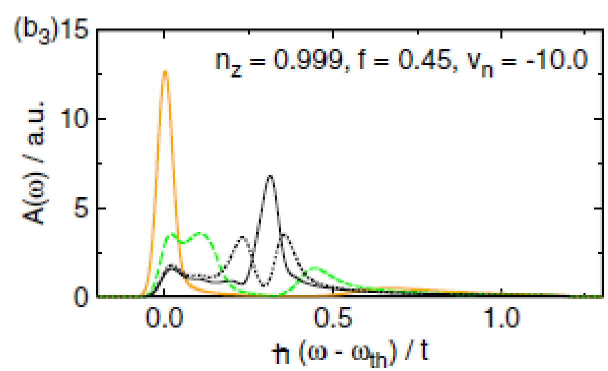
edge state contribution



close to boundary

"bulk"





\# edge states: less

more

Georg Röder, G.rigoy Tkachov, and M.H.,, EPL 2011

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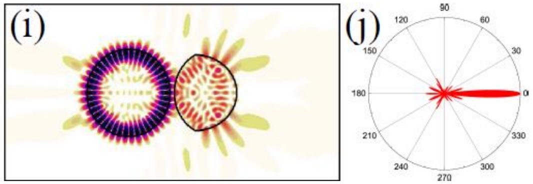
Summary of past years:

- GHS and FF at **curved** interfaces understood, including formula
- **boundary** contribution dominates **photoabsorption** signal
  via dipol matrix el. or presence of edge states

+ directional emission from optical microcavities
  (Limaçon, composite systems) + quasiattractor
  in coupled cavities + lasing cavities



J.-W. Ryu and **M.H.**, Opt. Lett. **36**, 2011

+

Friederike, 2009

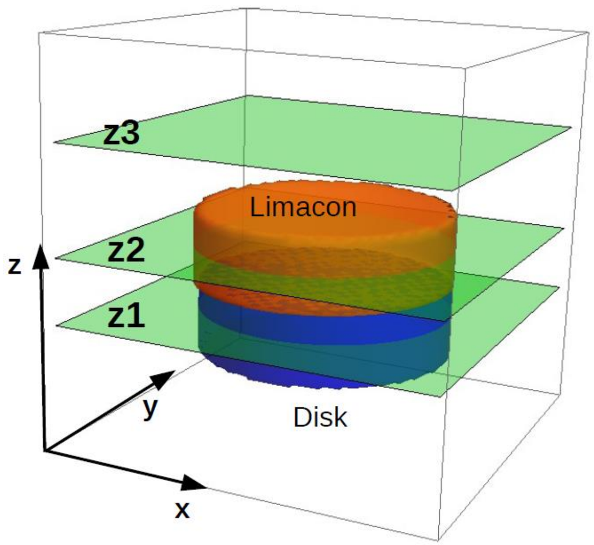
Wiebke, 2010

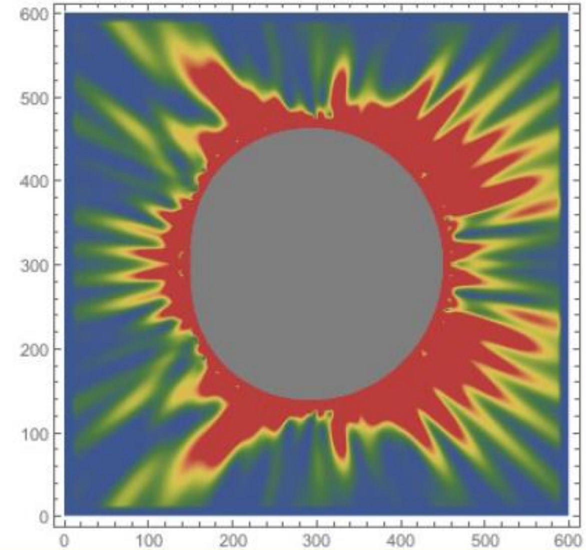
Ilmenau, April 2012

Imke, Dec. 2012

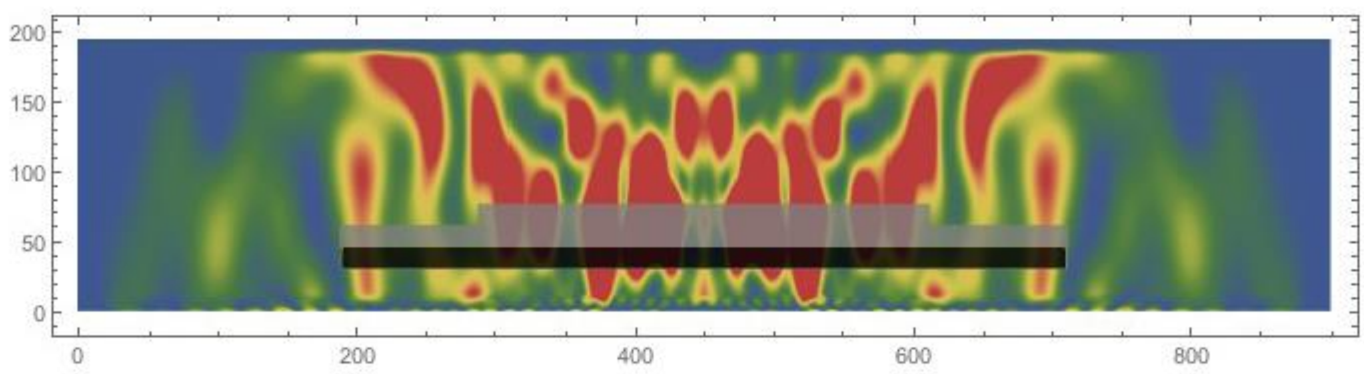
Work in progress

- 3d modelling of optical microcavity systems (meep, **Jakob Kreismann**)





z2



- edge states in photonic graphene (**Pia Stockschläder, Lucia Baldauf**)

  - Formation of edge states under strain

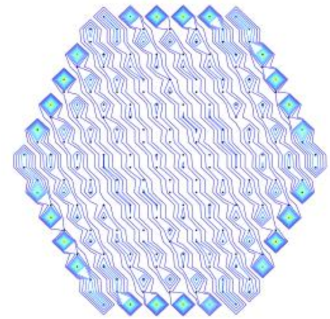
    (cf. Nice group paper)

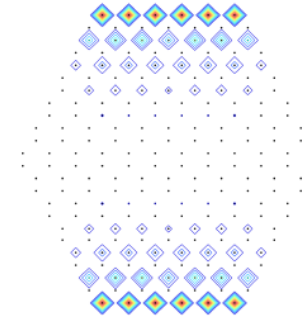
    → zigzag-boundary:
    edge states always exist,
    and persist

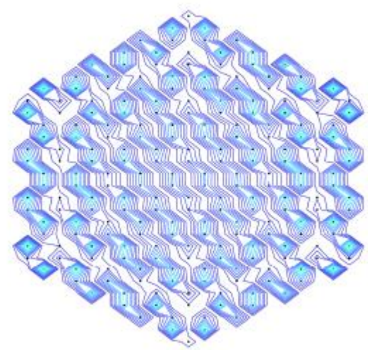
    shown: LDOS near Dirac energy

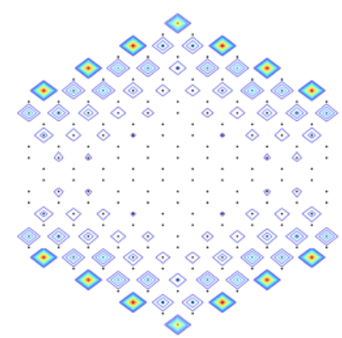
    → armchair-boundary:
    edge states form under strain

unstrained | strained, $\beta > \beta_c$

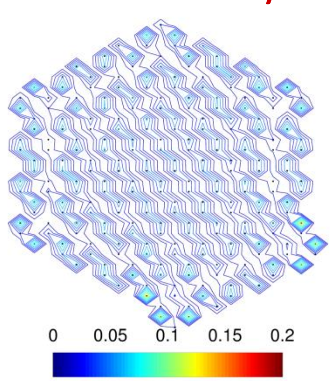


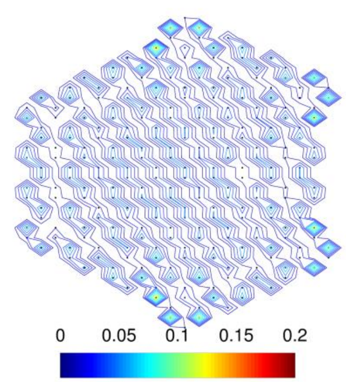


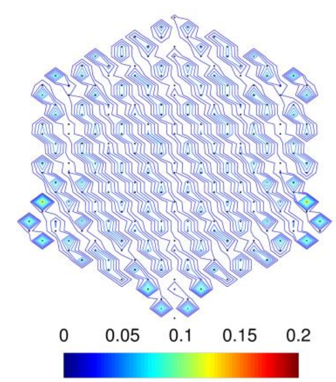




- Formation of edge states under symmetry breaking

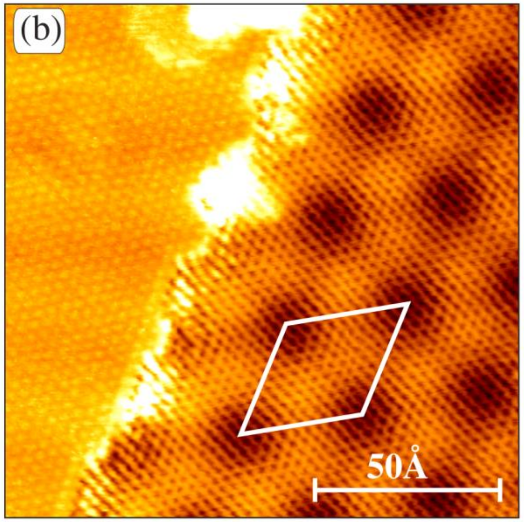






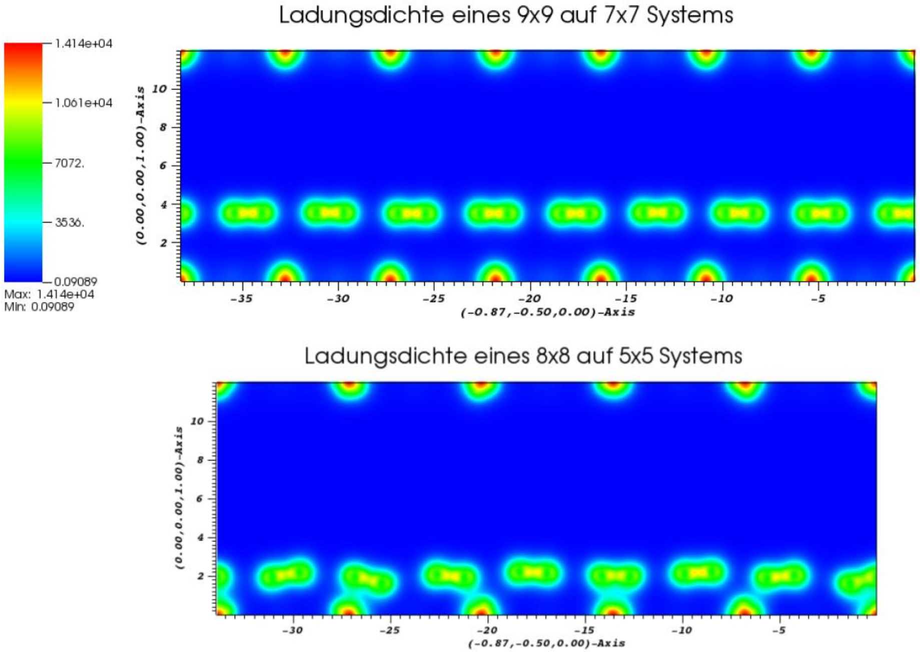
- graphene on iridium [111] (DFT calculation, VASP, **Philipp Müller**)

  - Experiments : Moiré superlattice

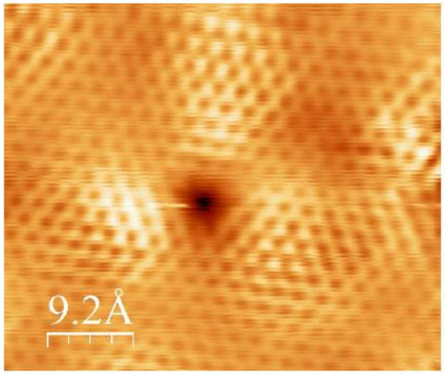


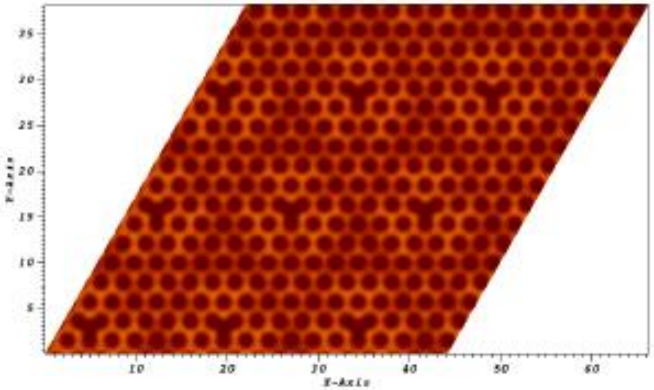
A. T. N'Diaye, J. Coraux, T. N. Plasa,
B. New. J. Phys. **10** (2008)

Modelling

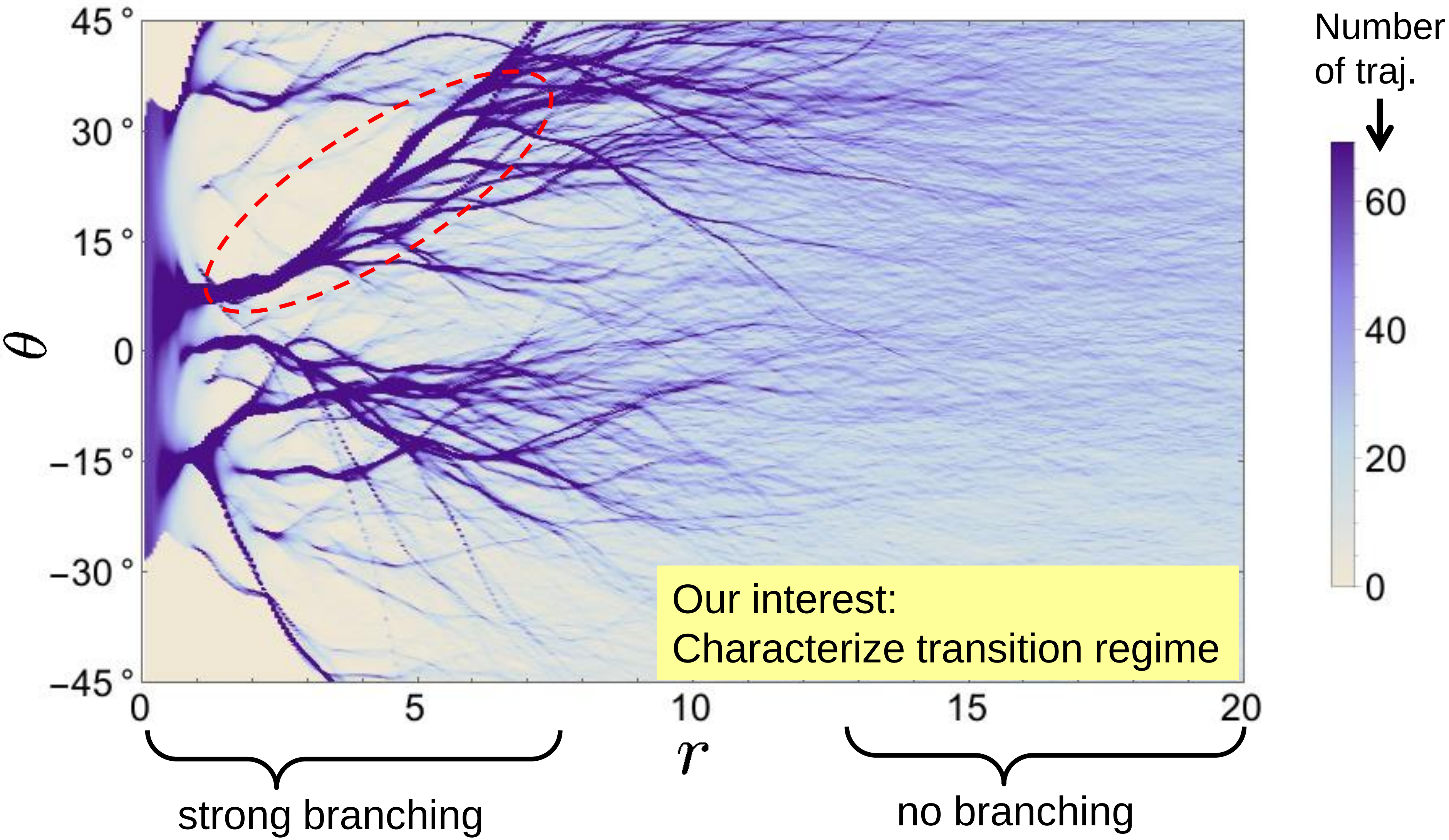


  - Experiments : Vacancies (Kröger group, Ilmenau): triangular structure reproduced





- mesoscopic transport in disordered potentials (**Kazuhiro Kubo**)



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M. A. Topinka et al., Nature **401**, 138 (2001) ;
J. J. Metzger, R. Fleischmann and T. Geisel,
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Summary

- GHS and FF at **curved** interfaces understood, including analytical formulae (convex microcavities).
  Only **FF** matters in **small** cavities.

- **Photoabsorption** signal and Anderson overlap show features of quantum-chaos like (RMT) universality away from system boundary, but **boundary** contribution dominates absorption spectrum via dipole matrix element or presence of edge states