Spontaneous out-of-equilibrium plasmonic magnetism

Justin Song

SPICE workshop on "Collective phenomena in driven quantum systems"

Mainz, 2018

NANYANG TECHNOLOGICAL UNIVERSITY SINGAPORE

A*STAR Institute of High Performance Computing

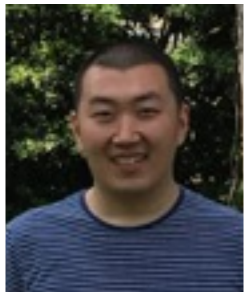
Berryogenesis: self-induced Berry flux and spontaneous out-of-equilibrium magnetism

MS Rudner, **JS**, arXiv 1807.01708 (2018)

Mark Rudner (KU)

Hidden (emergent) plasmon internal structure and plasmon Berry phase

LK Shi, **JS**, PRX 8, 021020 (2018)



Li-kun Shi (Singapore)

Funding:

NATIONAL RESEARCH FOUNDATION

NANYANG TECHNOLOGICAL UNIVERSITY SINGAPORE

Electronic matter close to equilibrium

determined by thermodynamics

Topological Insulators

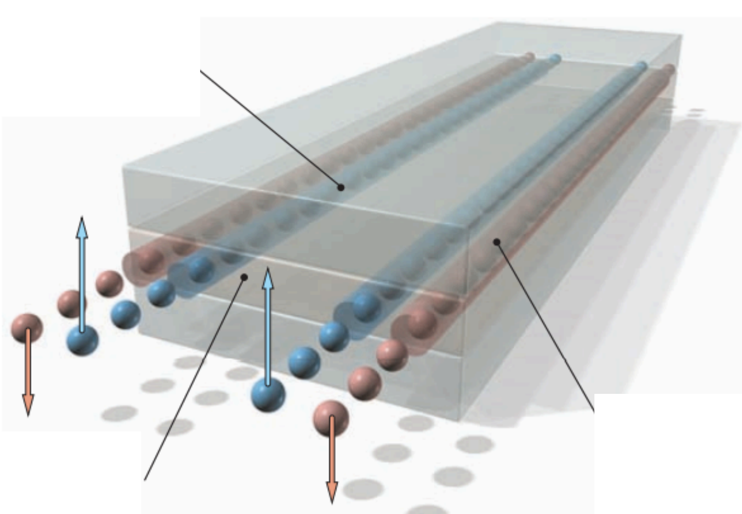
Surfaces of 3D TIs:
Bi_2Se_3, Bi_2Te_3 Bi_xSb_{1-x} ,…

Topological Crystalline Insulators:
Sn Te, …

Magnetic Topological Insulators:
Cr-doped BiSbTe

$Hg_xCd_{1-x}Te$ Quantum Wells,
InAs/GaSb QWs

Monolayer WTe2



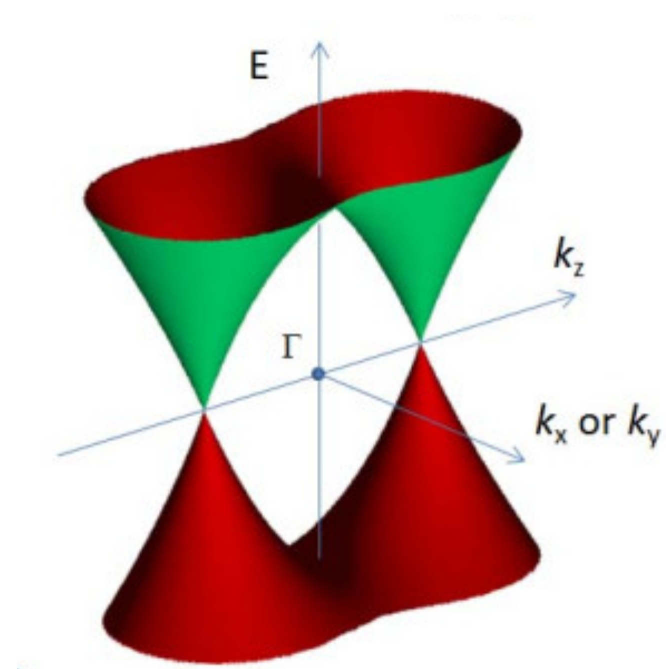
3D Dirac/Weyl

Experimentally Observed:
Cd_3As_2, Na_3Bi, TiBiSe
$TaAs_2$, …

Type II Weyl semimetals (candidates): (bulk) WTe2, MoTe2

Proposed in TI stacks;
HgCdTe Stacks

Nodal-line semimetals



2D Dirac Materials

(materials that host Berry curvature)

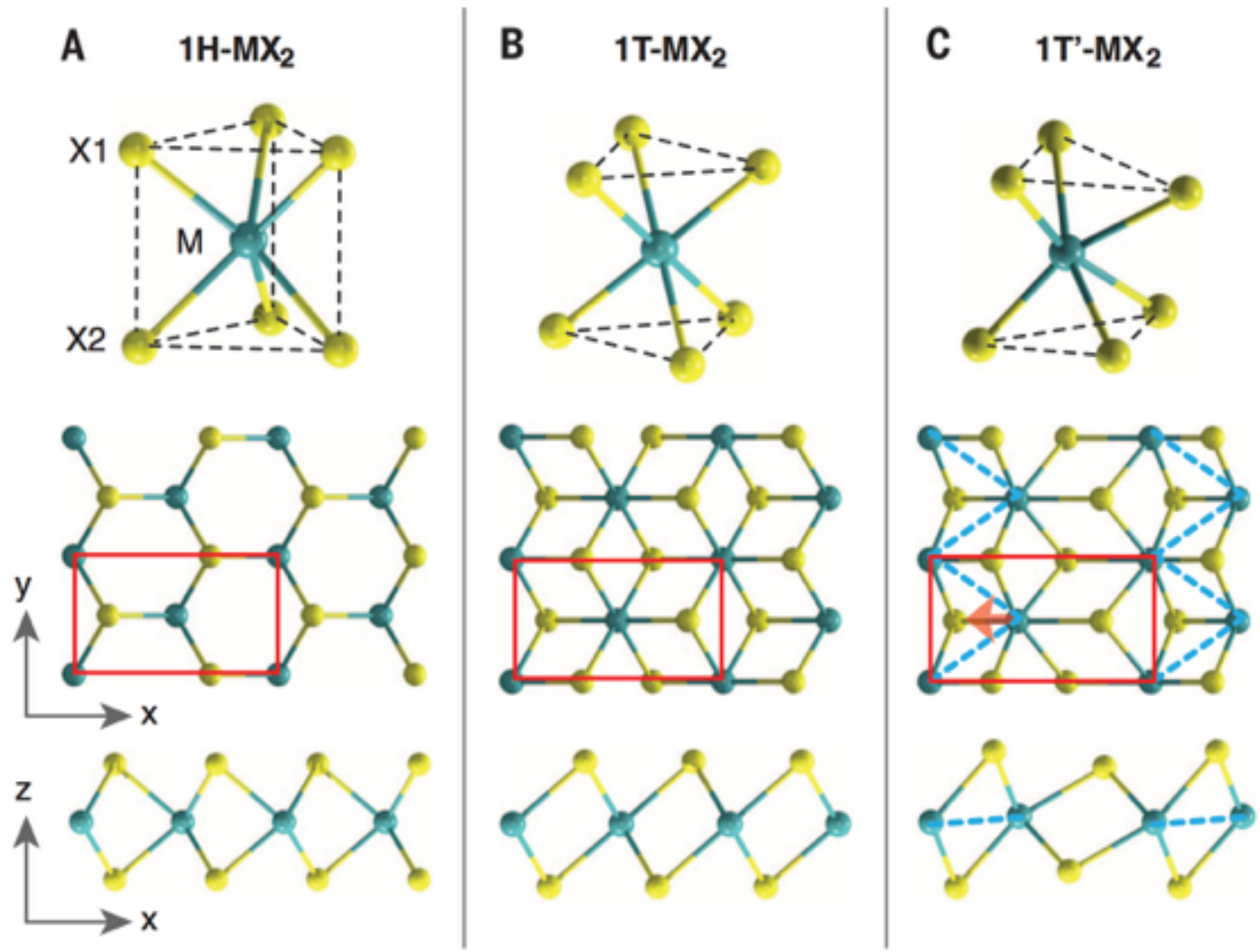
Graphene heterostructures:
G/hBN,
dual-gated Bilayer graphene, …

Transition metal dichalcogenides:
MoS_2, WS_2, WSe_2, $MoSe_2$,
$MoTe_2$, ….

Electronic matter close to equilibrium

determined by thermodynamics

variety of possible structures for MX2 monolayer

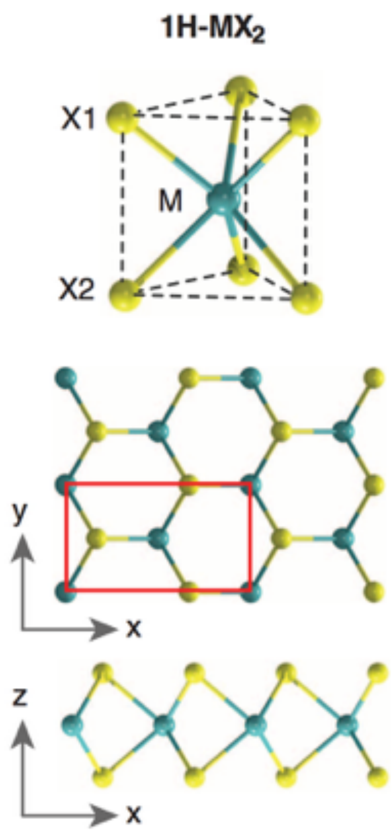


adapted from: Qian, Liu, Fu, Li Science (2014)

Electronic matter close to equilibrium

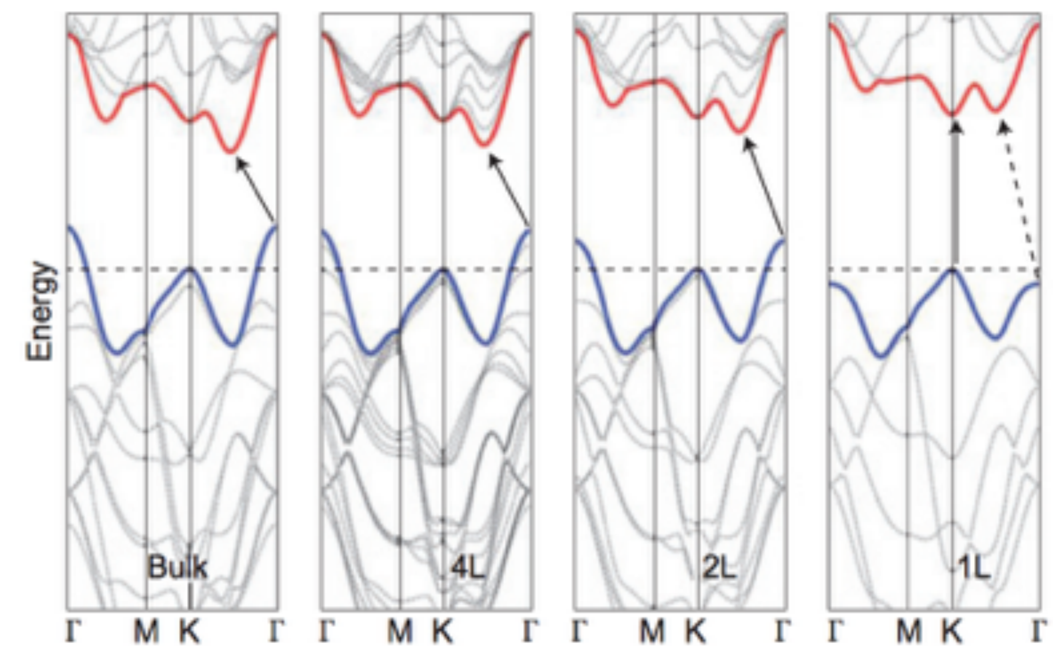
determined by thermodynamics

MoS2

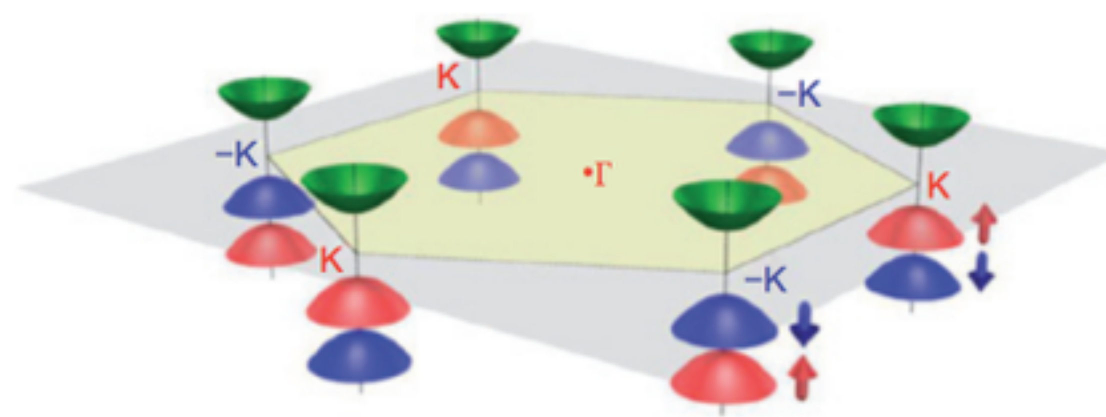


adapted from Qian, Liu, Fu, Li Science (2014)

bandstructure evolution from bulk to monolayer



valley-locked spin structure



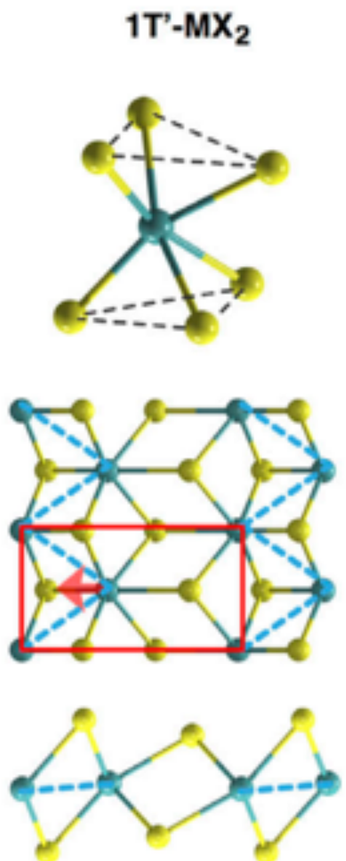
M Chhowalla et al, Nature Chemistry 2013

Electronic matter close to equilibrium

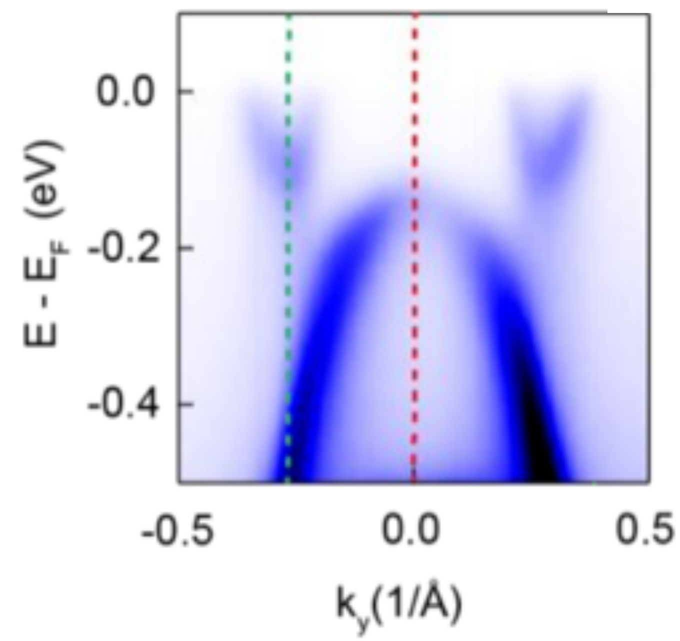
determined by thermodynamics

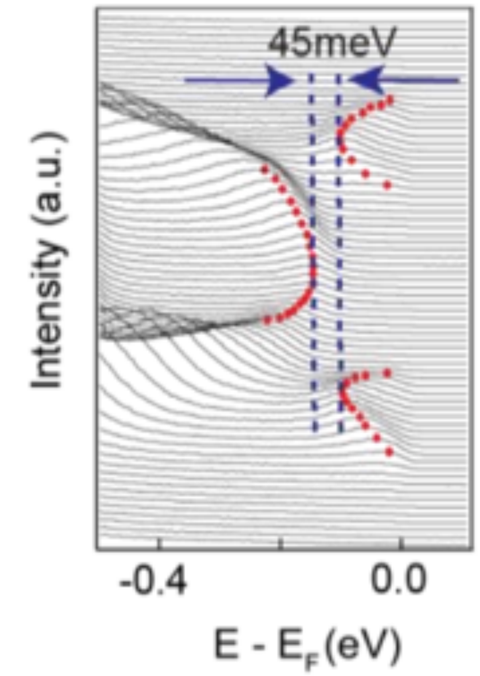
1T'-WTe2

[electronic bandstructure] ARPES data

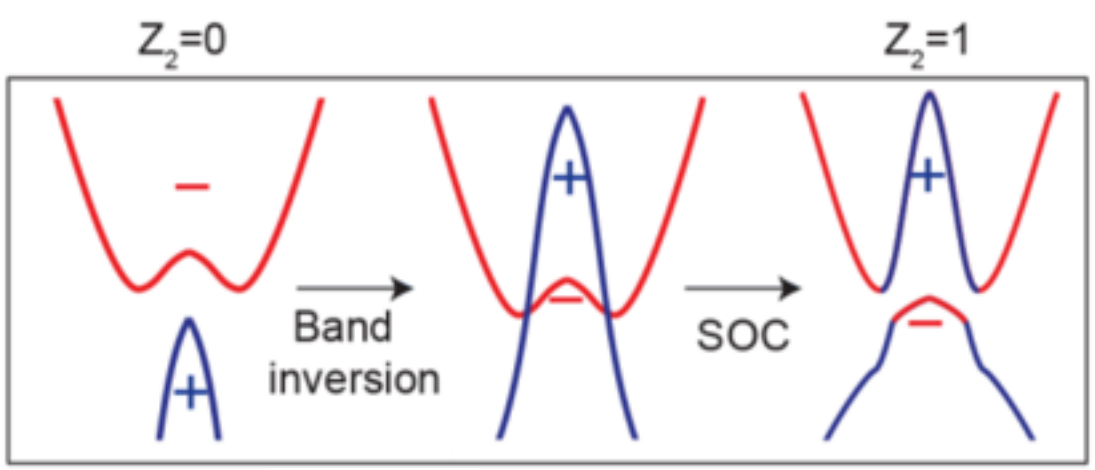


Qian, Liu, Fu, Li Science (2014)



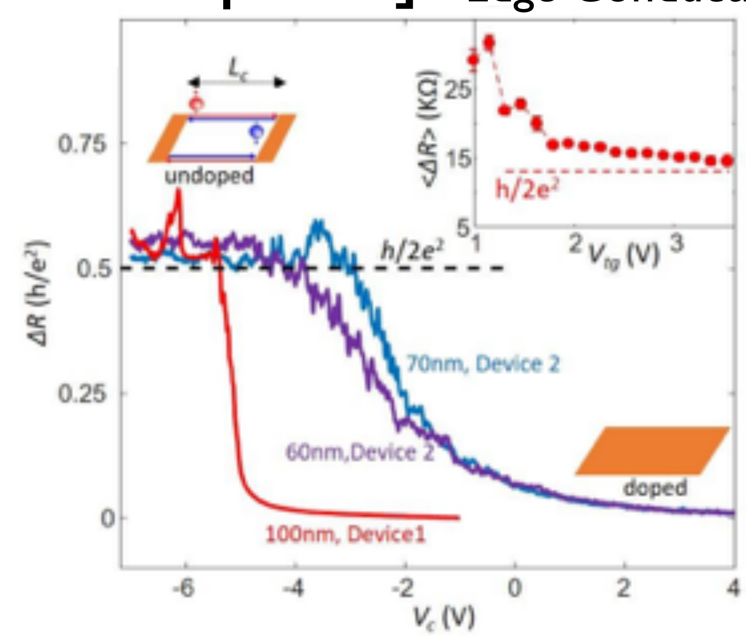


Tang et al, Nature Physics (2017)



adapted from Tang et al, Nature Physics (2017)

[electronic responses] Edge Conduction ("near quantized")



Wu, Fatemi, et al, Science (2018)

driven systems: out-of-equilibrium materials

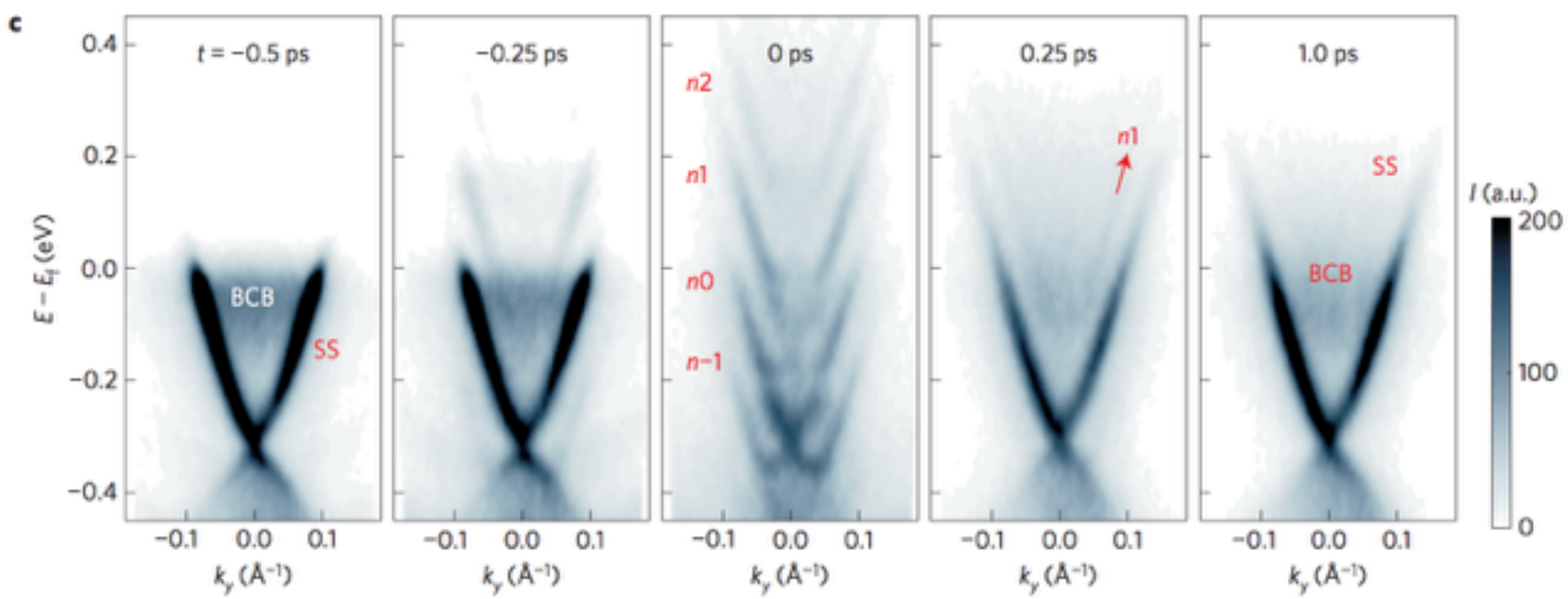
overcoming the tyranny of thermodynamics

some strategies:

a. non-equilibrium driving for designer hamiltonians
b. unconventional out-of-equilibrium responses
c. exploiting collective modes for new phases/structure

Non-equilibrium driving: tailored hamiltonians

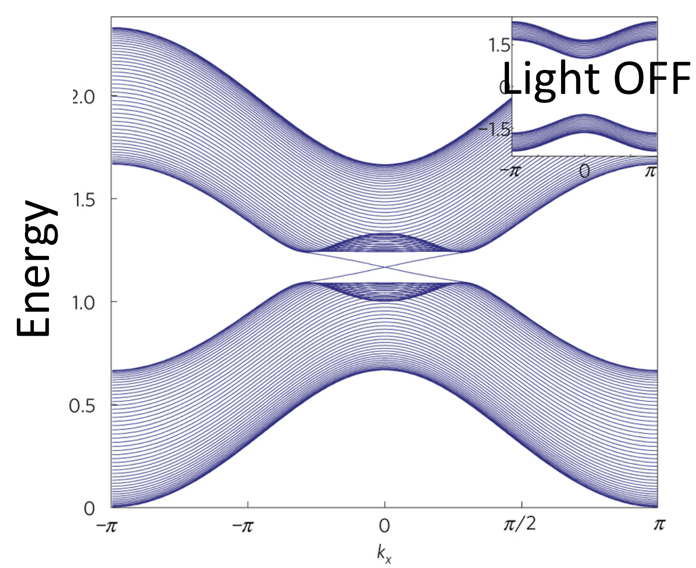
Floquet engineering



see e.g., Fahad's talk on Wednesday

F Mahmood, et al, Nature Physics (2016)

Floquet alchemy: transmuting trivial insulator into topological insulator

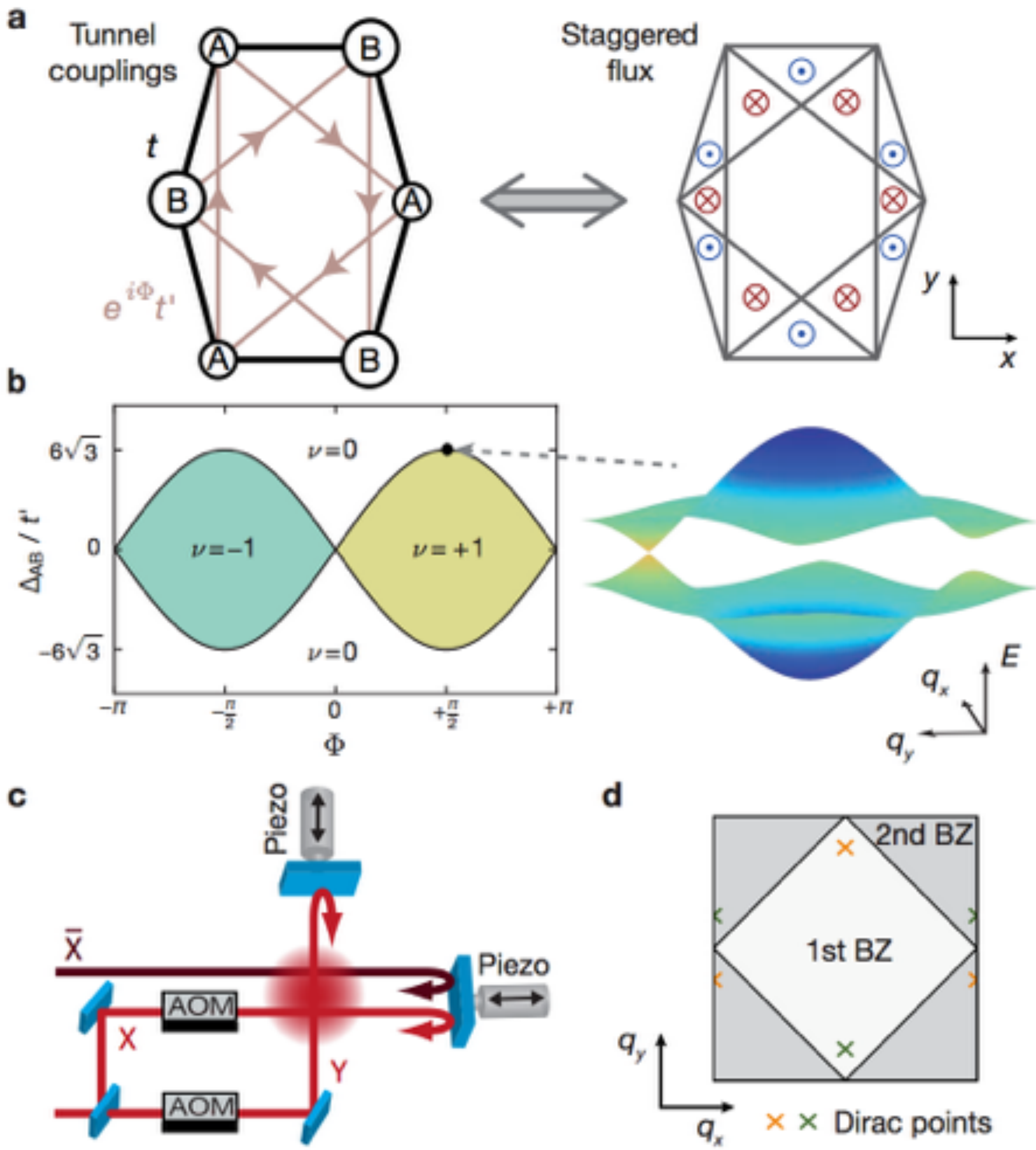


N Lindner, G Refael, V Galitski, Nature Physics (2011)

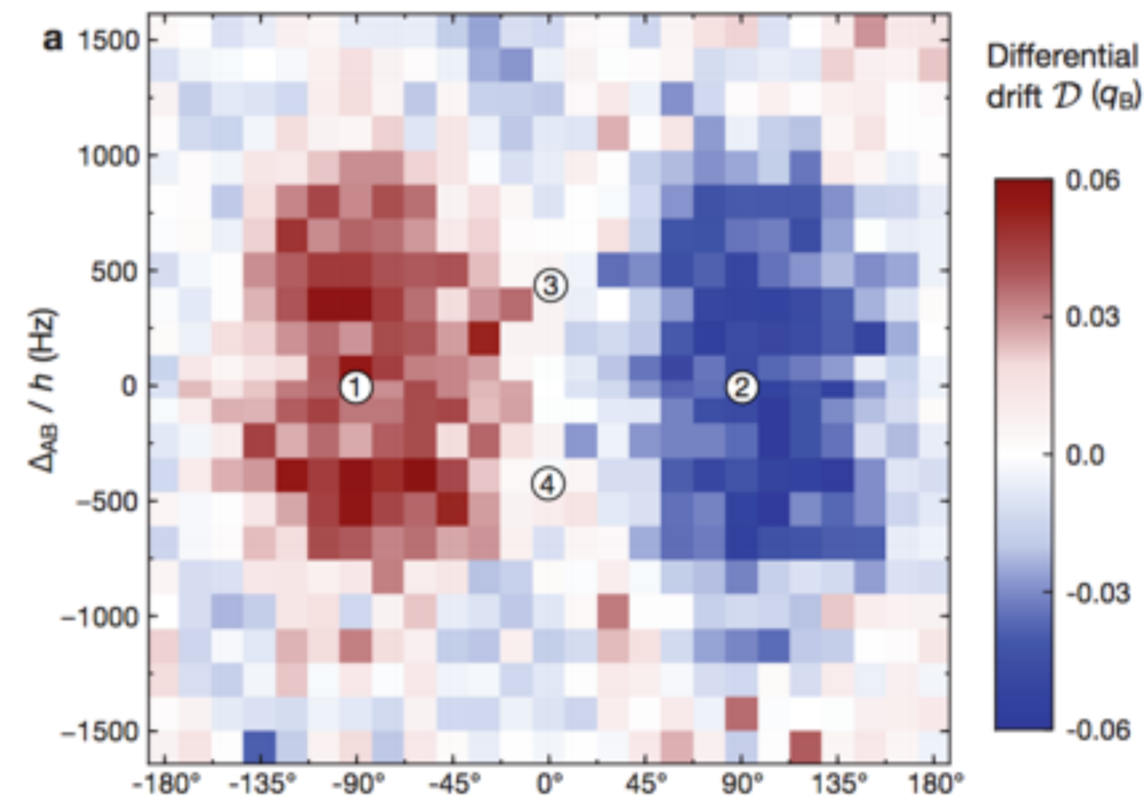
also large zoo of new Floquet effects:
e.g., Rudner, Berg, Lindner, Levin PRX 2013

Driven systems and Berry curvature

designer hamiltonians: engineering band structure



see e.g., Monika's talk on Tuesday

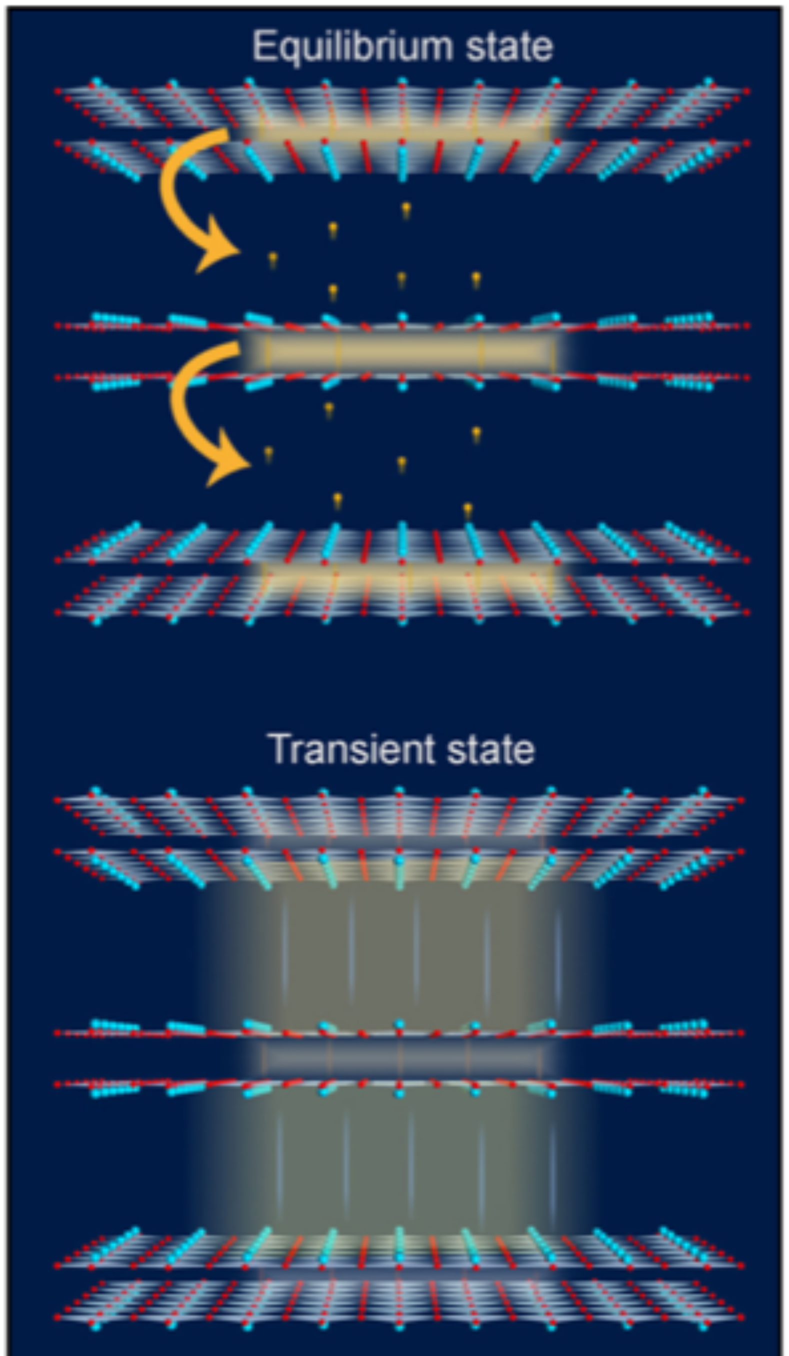


Jotzu, …, Esslinger, Nature (2014)

Driven systems: Out-of-equilibrium phases

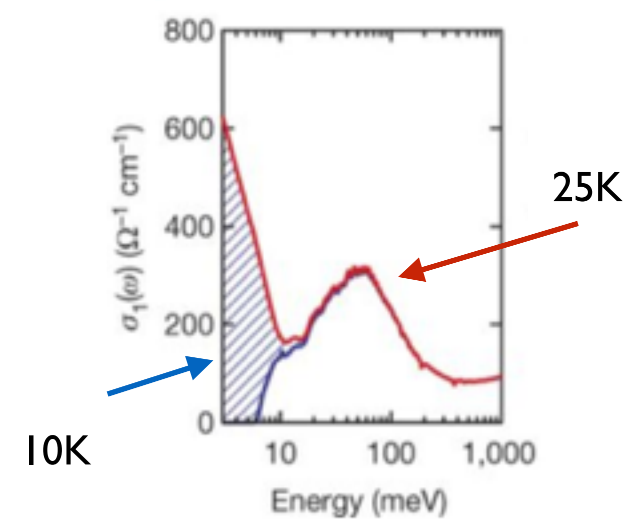
designer hamiltonians: engineering interactions

Light-induced superconductivity

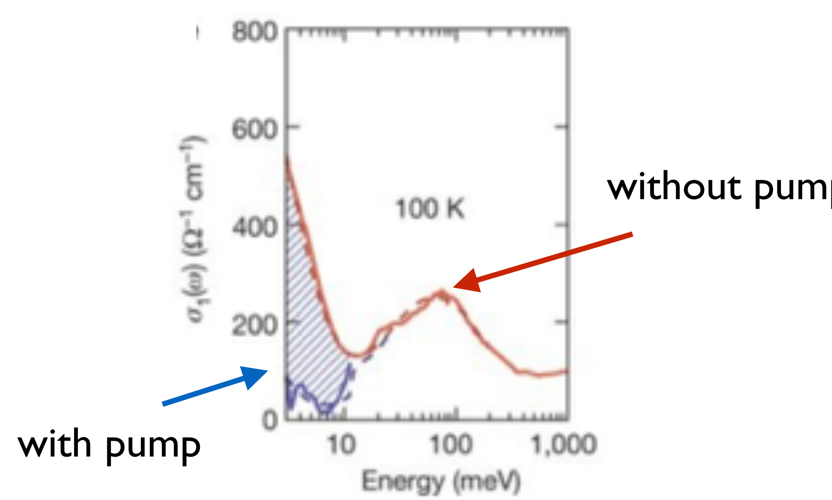


taken from cavilieri group website

equilibrium spectral weight transfer in K3C60



out-of-equilibrium spectral weight transfer in K3C60



M Mitrano, et al Nature (2016),

see e.g., D Fausti, et al Science (2011),

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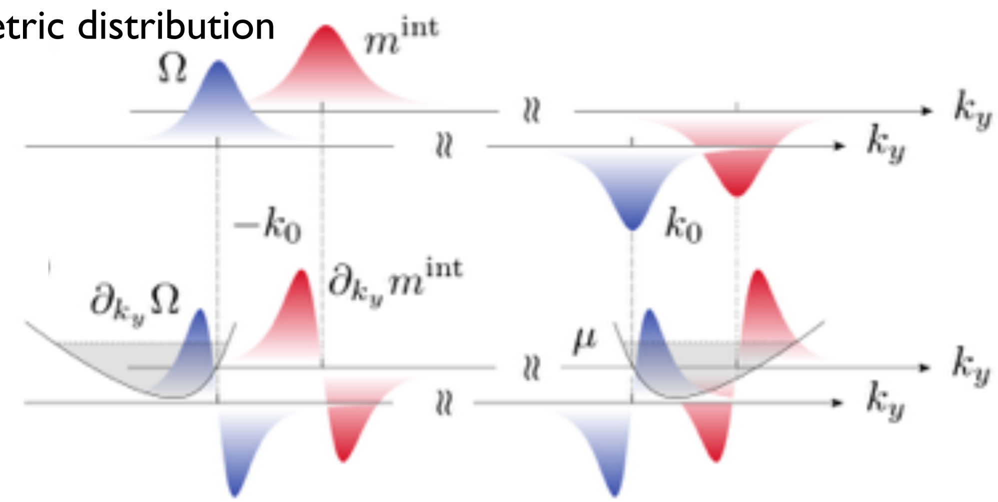
Hall responses in a TRS preserving system

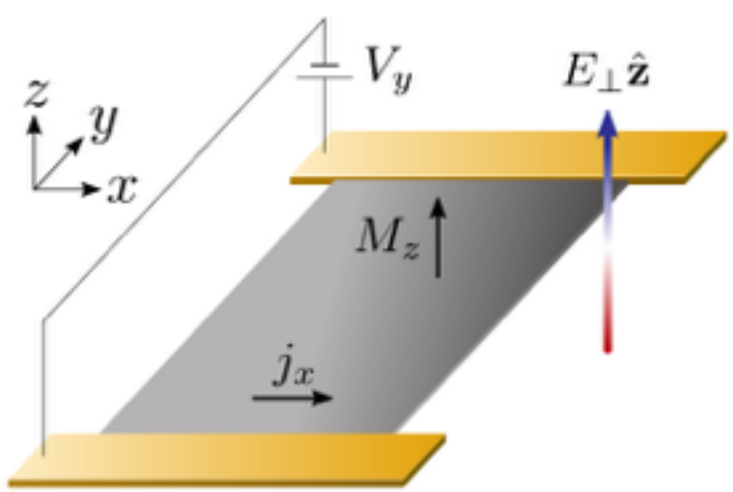
nonlinear Hall effect

Berry curvature dipoles mediate transverse current

asymmetric distribution

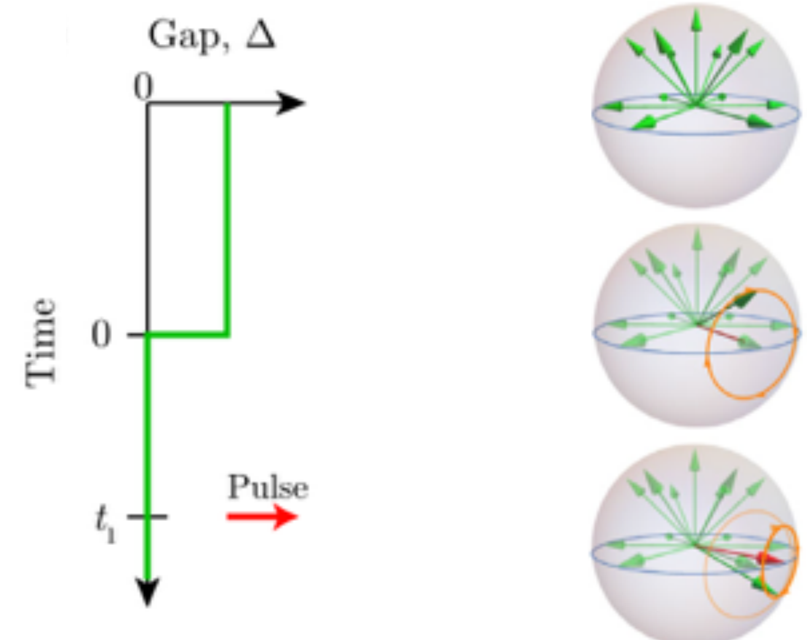
dipole:

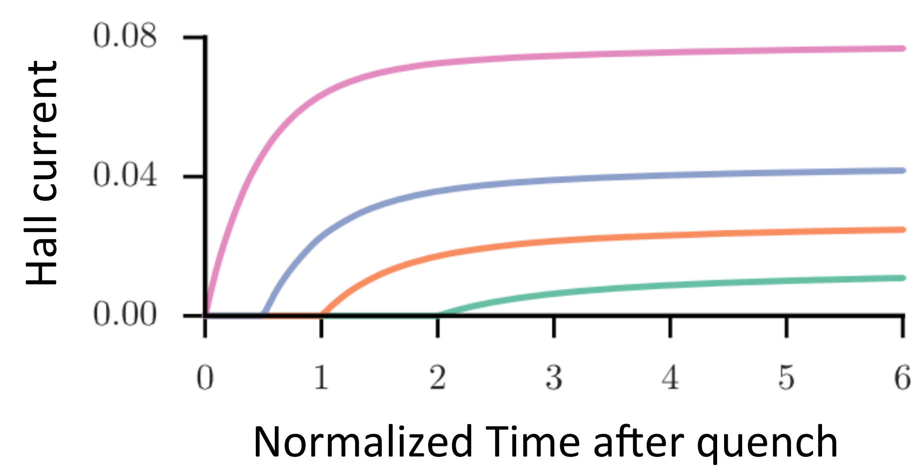




quench induced responses

remnant geometrical Hall effect in a quantum quench





J Wilson, JS, G Refael, PRL (2016)

see also Hu, Zoller, Buddich PRL (2016)

Anomalous Cyclotron motion without magnetic field

Slow center of mass/wavepacket dynamics

Group velocity

"Anomalous velocity"

$$\dot{\mathbf{x}} = \frac{\partial \epsilon}{\partial \mathbf{p}} + \frac{1}{\hbar}\mathbf{\Omega}(\mathbf{p}) \times \dot{\mathbf{p}}$$

$$\dot{\mathbf{p}} = -\frac{\partial V}{\partial \mathbf{x}}$$

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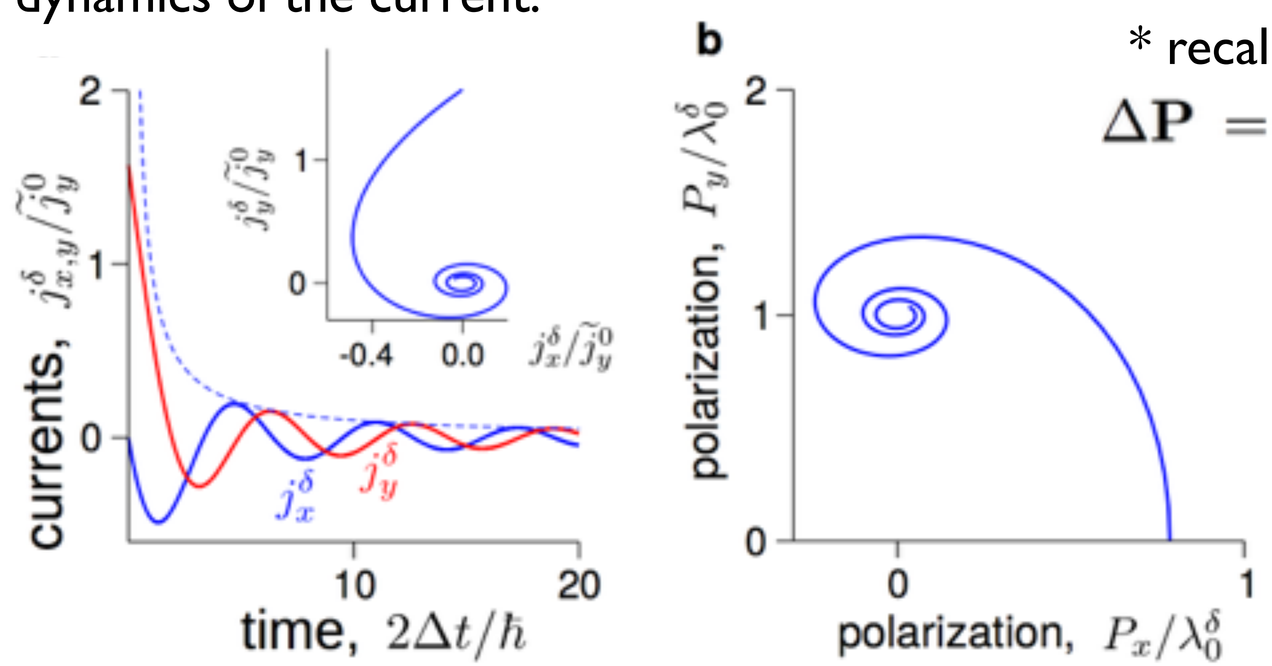
Intra-unit-cell dynamics

Pulse a (TRS broken) gapped Dirac system with $\mathbf{E} = A_x \delta(t)\hat{\mathbf{x}}$ /c

Track the dynamics of the current:



* recall:

$$\Delta \mathbf{P} = \int_0^t \mathbf{j}(t')dt'$$

EH Hasdeo, AJ Frenzel, **JS** arXiv (2018)

driven systems: out-of-equilibrium materials

overcoming the tyranny of thermodynamics

some strategies:

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what we will focus on in this talk

Rich tapestry of out-of-equilibrium excitations

large variety of excited states beyond nominal single-particle (bandstructure) excitations

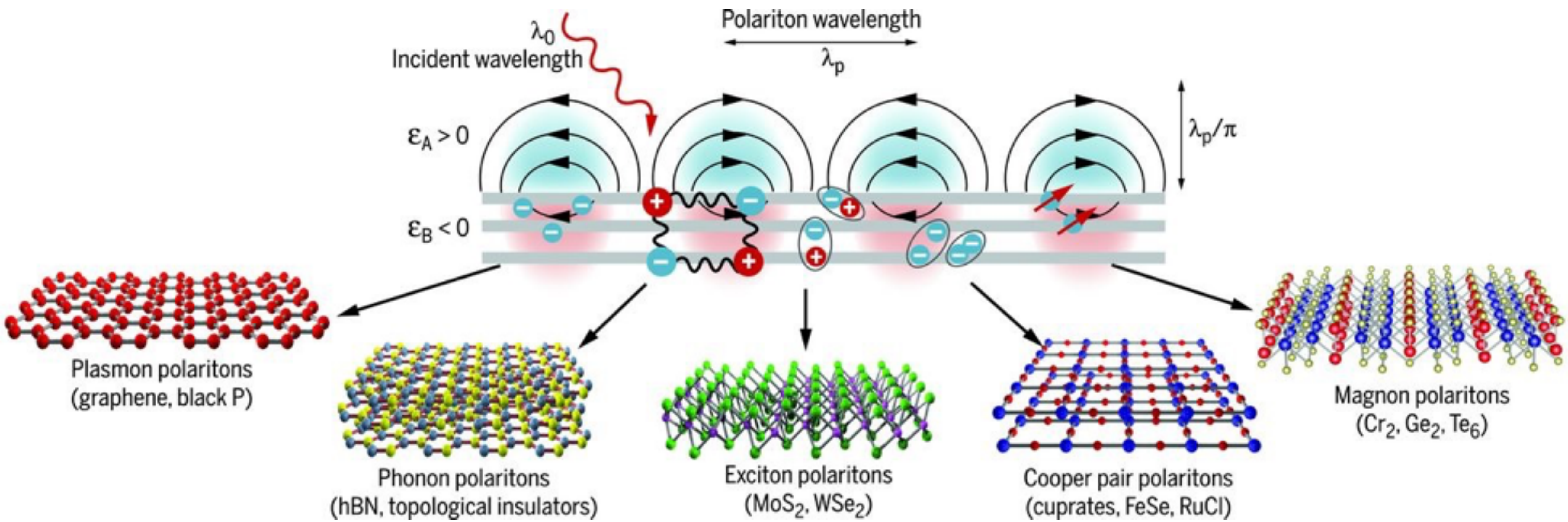


image from: Basov, Fogler, Garcia de Abajo, Science (2017)

Plan

Part I.

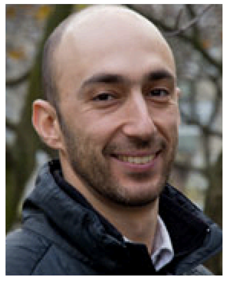
Exploiting out-of-equilibrium matter

Part II.

Spontaneous symmetry breaking in a collective mode

out-of-equilibrium plasmonic magnetism

MS Rudner **JS**, arXiv (2018)



Mark Rudner (KU)

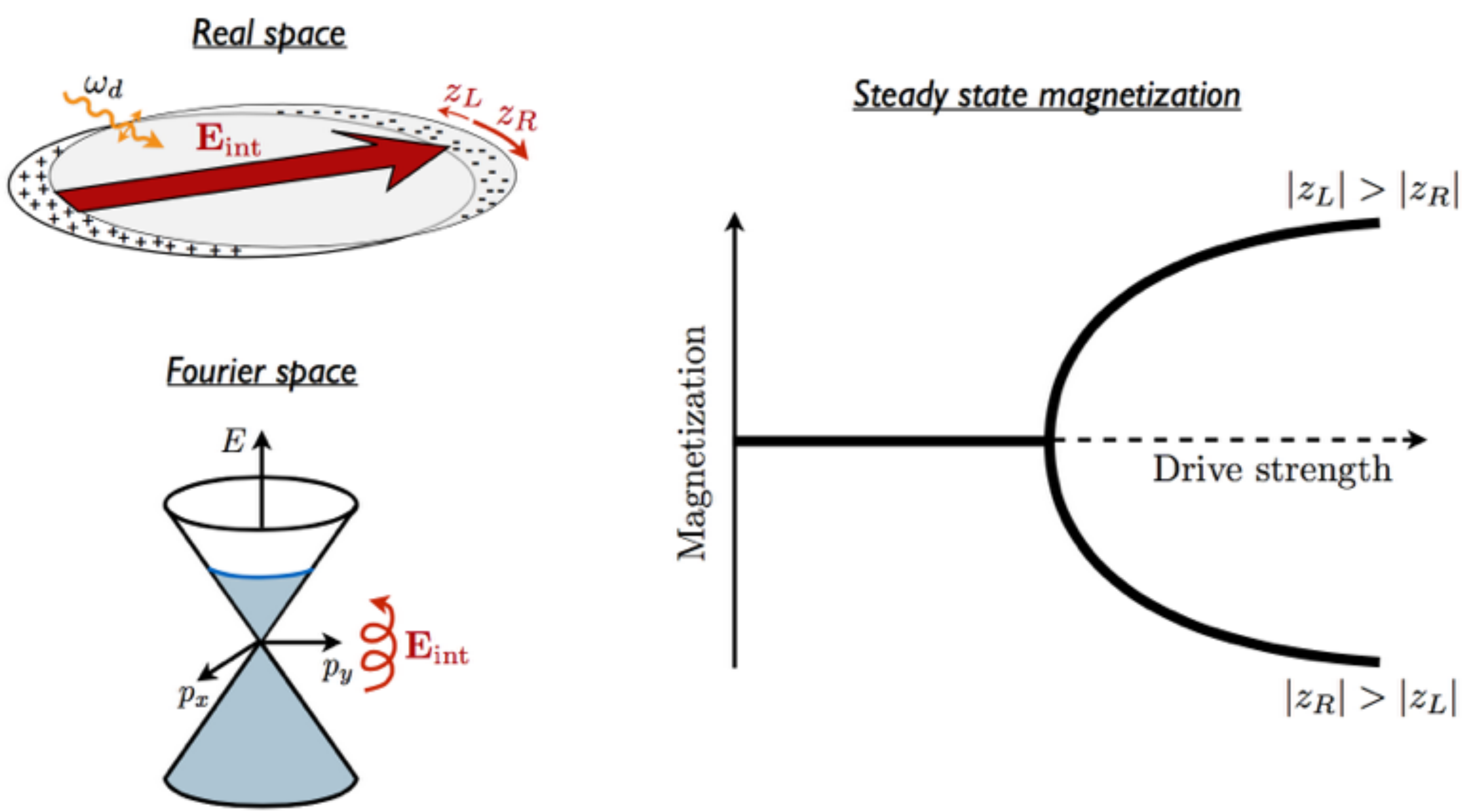
Part III.

Emergent internal structure of plasmons and geometry

LK Shi, **JS**, PRX (2018)

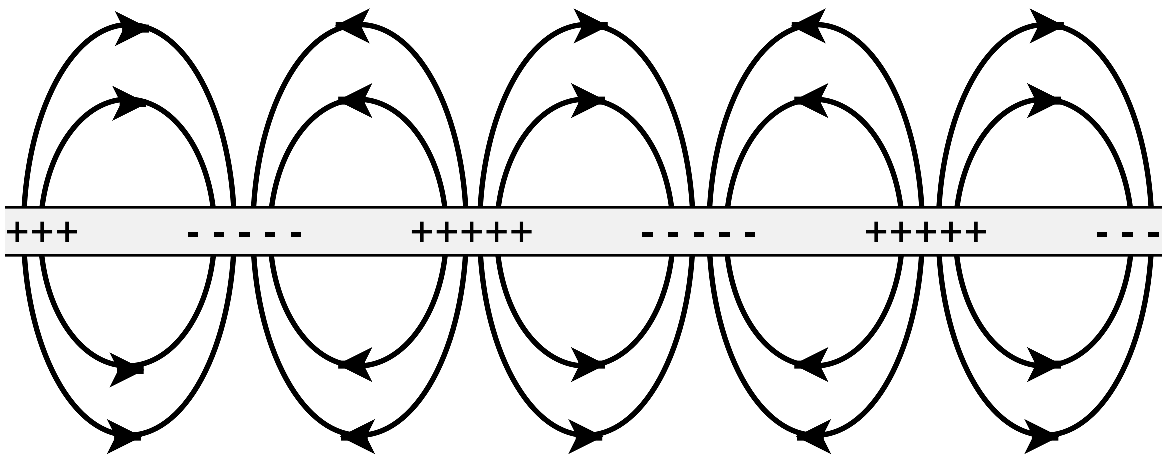
Li-kun Shi

Claim: collective motion of plasmons gives rise to spontaneous TRS breaking



Plasmons are collective density oscillations in metals

Plasmons



$$\mathbf{E} = -\nabla\phi$$

$$\boxed{\phi(\mathbf{x},t) = -e\int d^2\mathbf{x}'\,\frac{\delta n(\mathbf{x}',t)}{\kappa|\mathbf{x}-\mathbf{x}'|}}$$

continuity equation:

$$\partial_t \delta n + \nabla \cdot \mathbf{v} = 0$$

force equation:

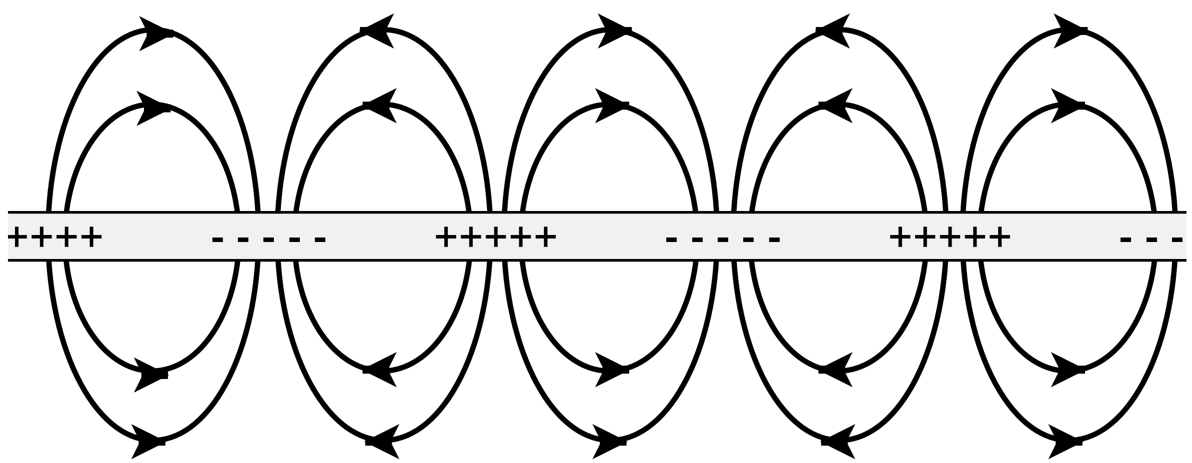
$$\partial_t \mathbf{p} + e n_0 \mathbf{E} = 0$$

"constitutive" relation:

$$\mathbf{v} = \mathbf{p}/m$$

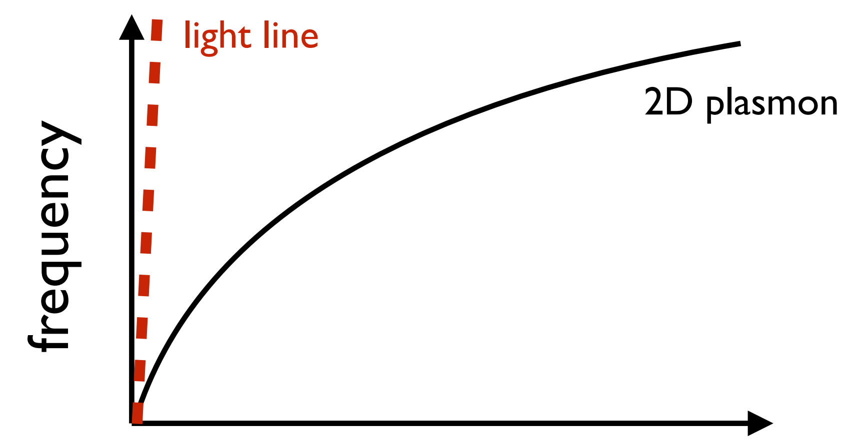
Plasmons and strong light-matter interaction

Plasmons



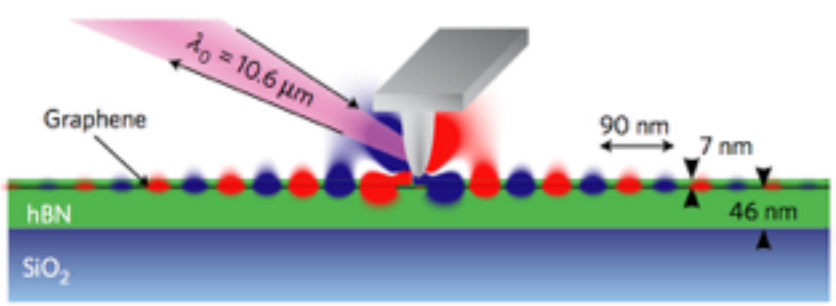
Large wavelength mismatch = high compression

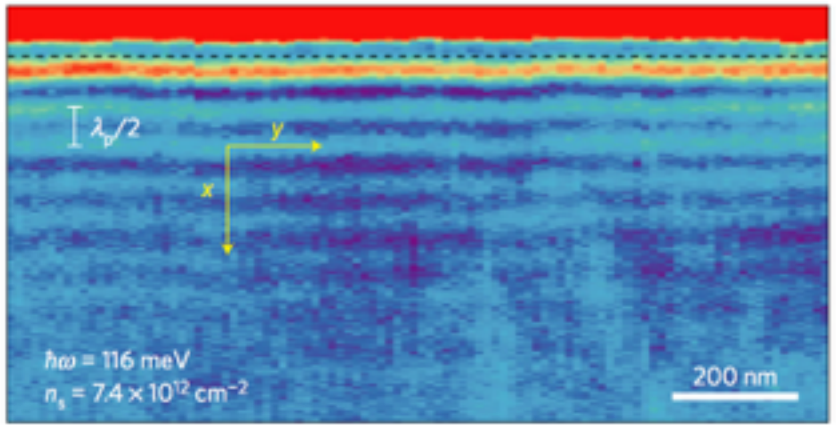
$$\lambda_{\mathrm{air}} \gg \lambda_{\mathrm{plasmon}}$$



wavevector, $\mathbf{q} = 2\pi/\lambda$

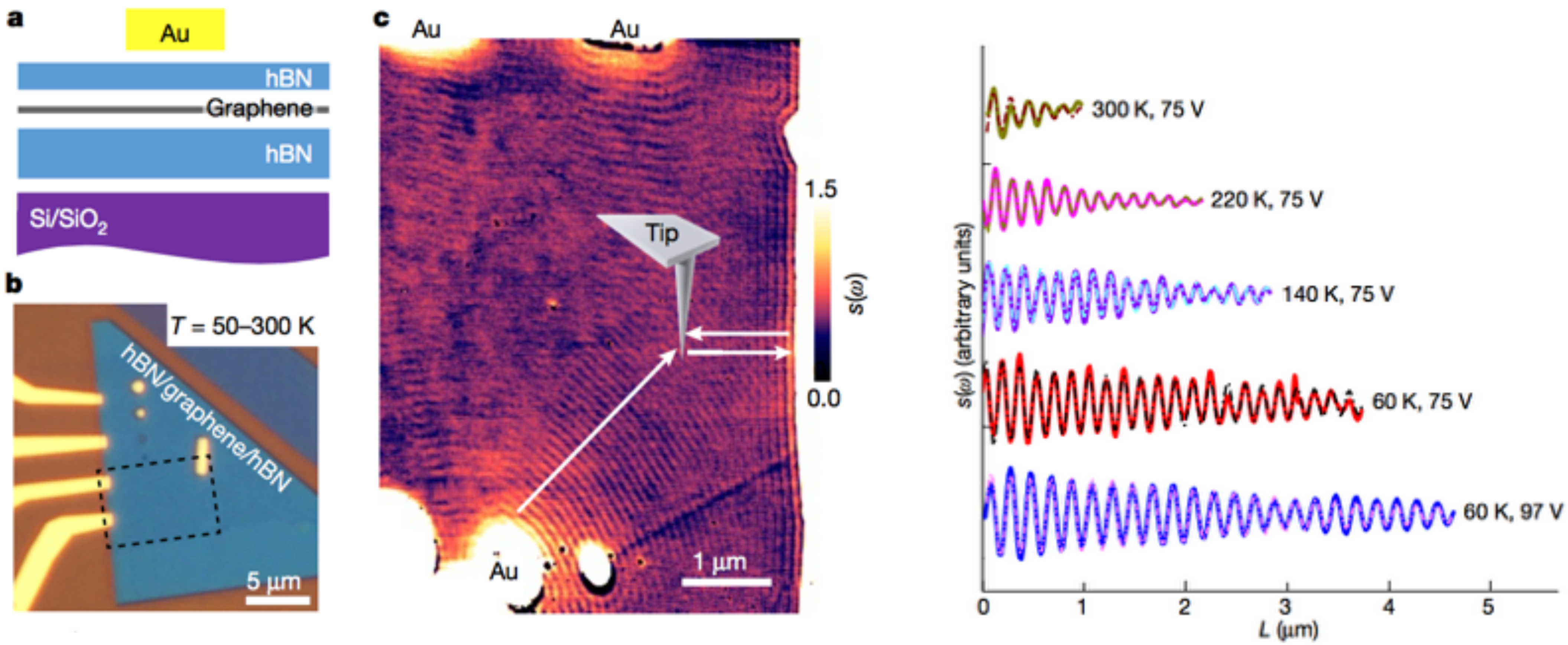
imaging/exciting plasmons in 2D materials using Scanning near-field optical microscope (SNOM)





e.g., Woesnner, et al, Nature Materials (2015)
first achieved in Koppens group (Nature 2013), and Basov group (Nature 2013)

High quality plasmons in graphene

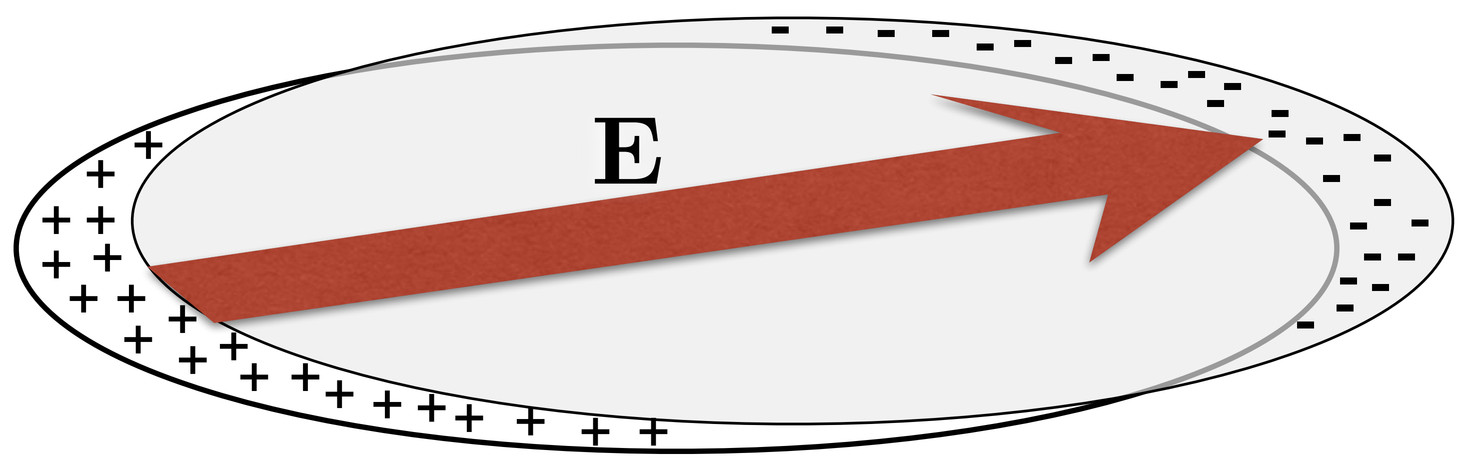


	Confinement ratio	Quality factor	Lifetime (fs)
Definition	λ_{IR}/λ_p	$Q_p = q'_p/q''_p$	$\tau = 2Q_p/\omega$
Graphene (experimental, $T = 60$ K)	66	130	1,600
Graphene (intrinsic, $T = 60$ K)	66	970	12,000
Ag[a,b] ($T = 10$ K)	~1	36	14
n-InSb[c], n-CdO[a] ($T = 300$ K)	<10	37	270

Ni et al., Nature (2018)

Equations of motion in a disk

$$\frac{d\{\mathbf{r}\}}{dt} = \frac{\{\mathbf{p}\}}{m} - \frac{\mathcal{F}[\mathbf{E}_{\mathrm{tot}}(t)]}{\hbar n_0}\hat{\mathbf{z}} \times e\mathbf{E}_{\mathrm{tot}}(t),$$
$$\frac{d\{\mathbf{p}\}}{dt} = -m\omega_0^2\{\mathbf{r}\} - \gamma\{\mathbf{p}\} - e\mathbf{E}_{\mathrm{drive}}(t),$$



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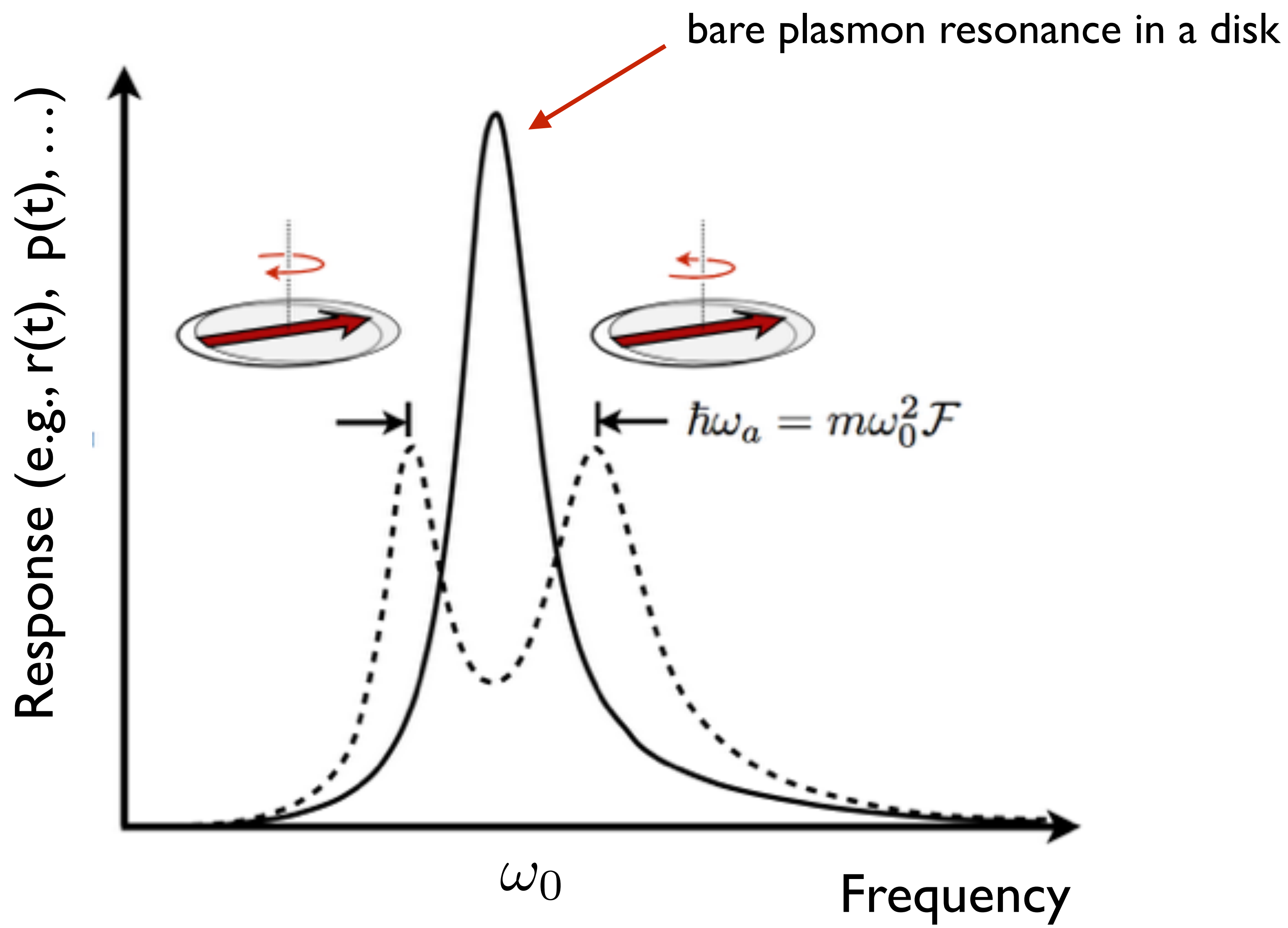
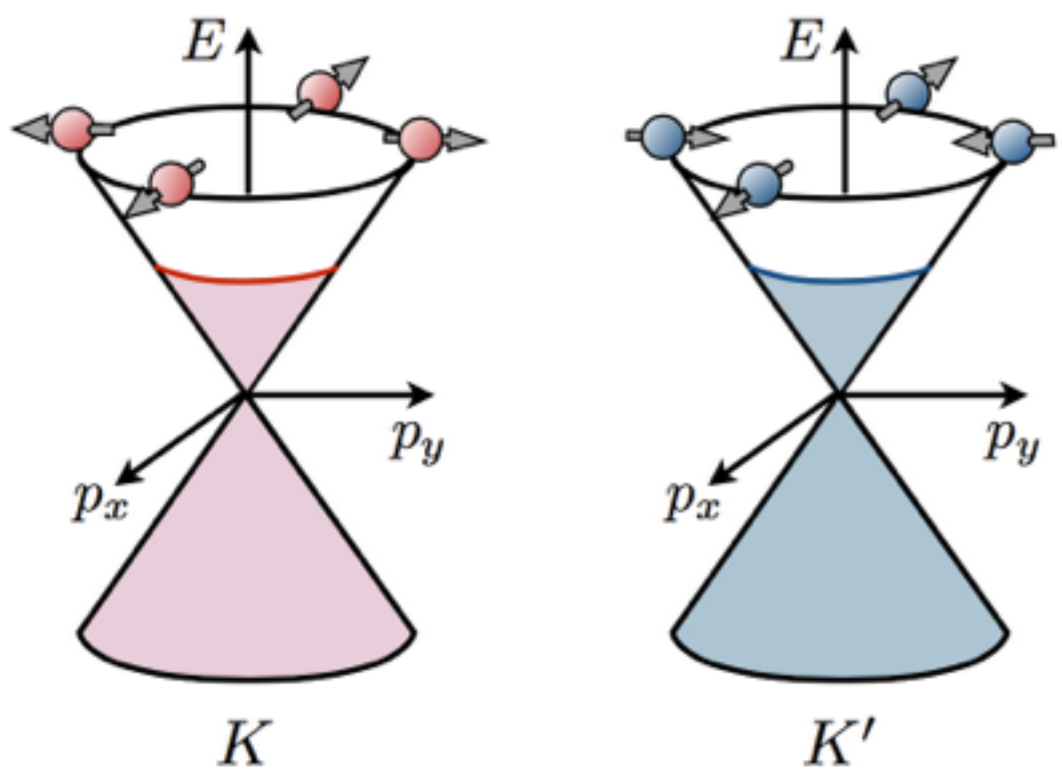


JS, M Rudner, PNAS (2016)

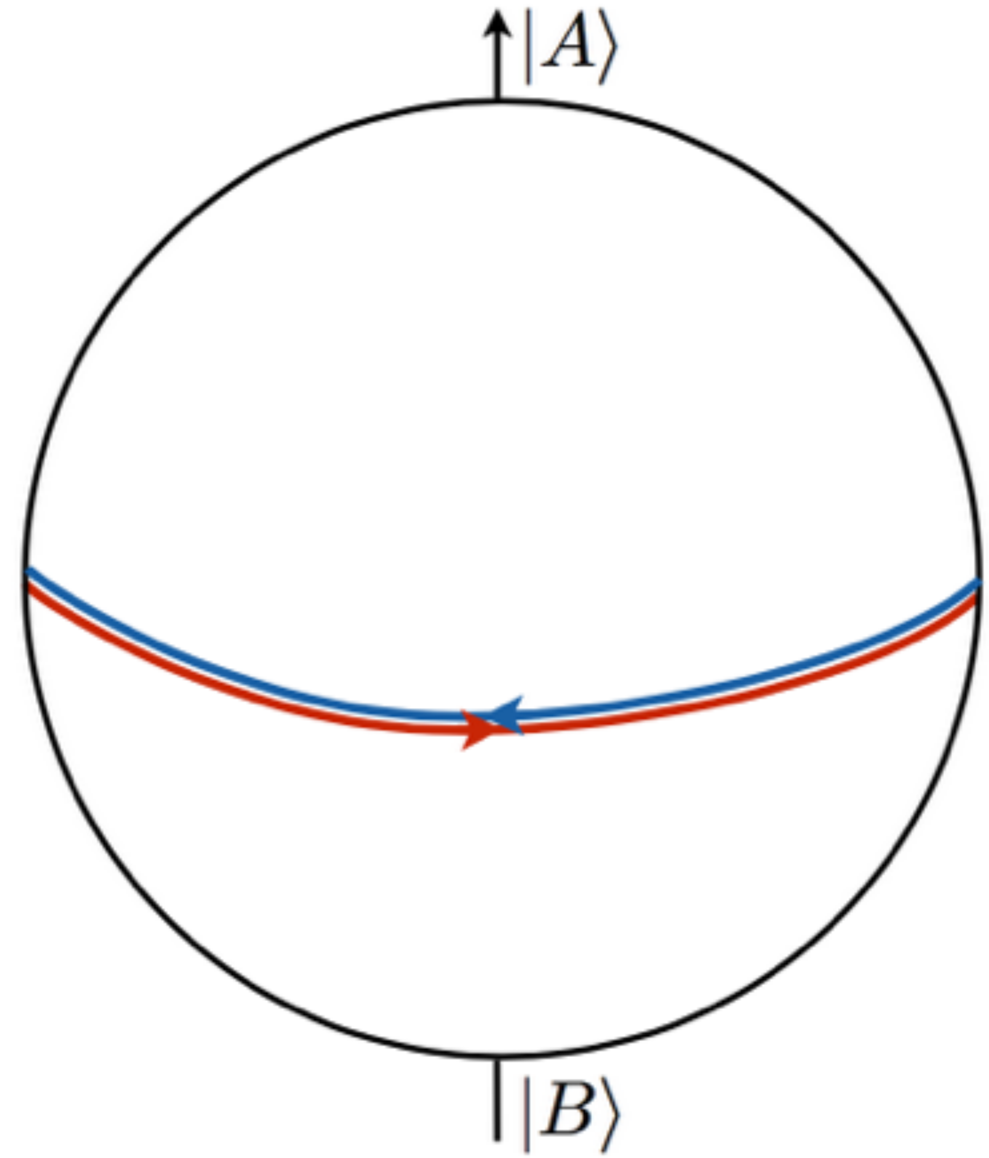
Graphene and Berry flux

$$\mathcal{H}_K = E_F \tilde{\mathbf{k}} \cdot \boldsymbol{\sigma} \qquad \mathcal{H}_K = E_F \tilde{\mathbf{k}} \cdot [\boldsymbol{\sigma}]^*$$



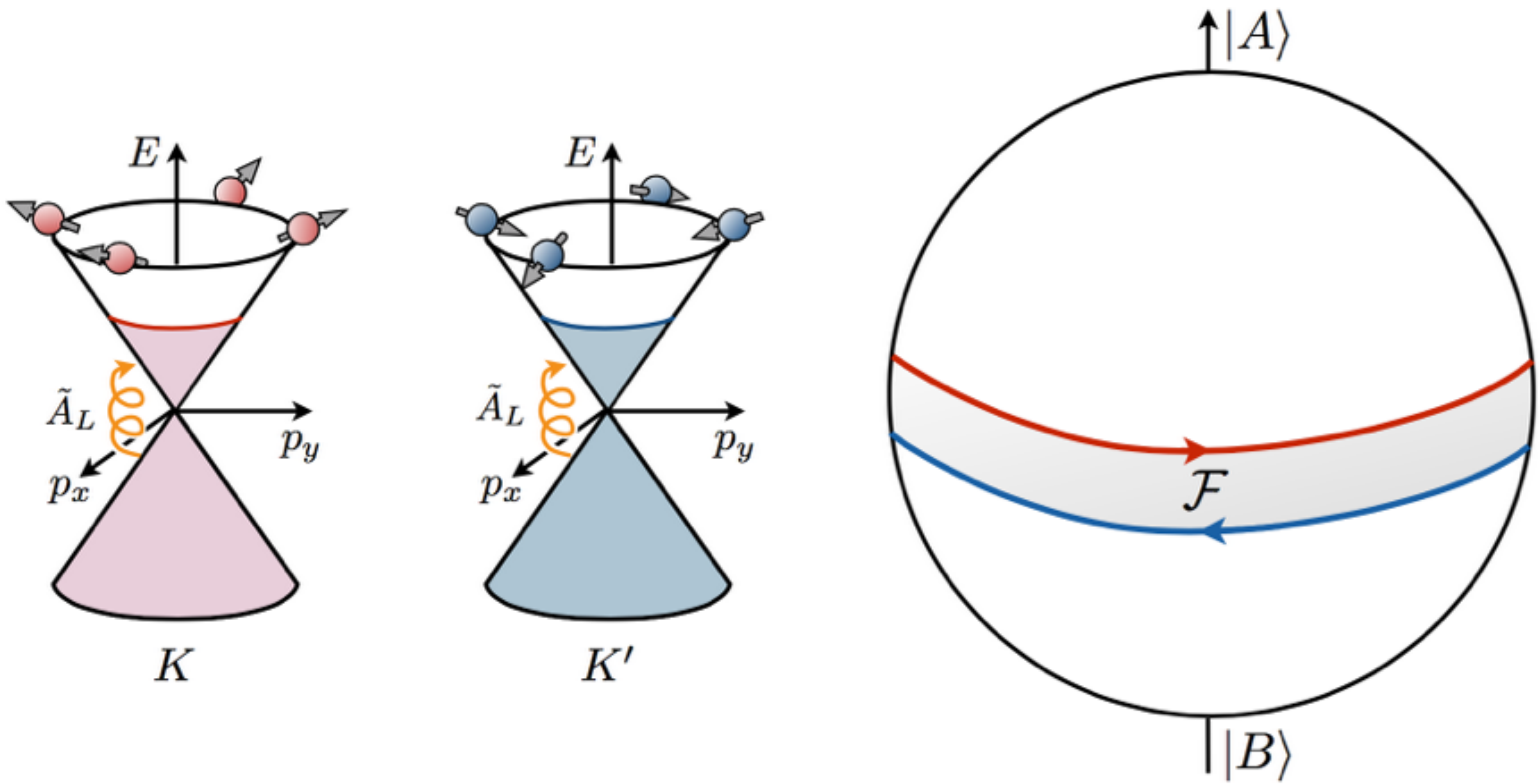
Berry flux as Berry phase across Fermi surface:

$$\mathcal{F} = \int d^2\mathbf{k}\Omega(\mathbf{k}) = \oint \mathbf{A}(\mathbf{k}) \cdot d\mathbf{k}$$



Generation of Berry flux

$$\mathcal{H}_K = E_F\left[\tilde{\mathbf{k}} - \tilde{\mathbf{A}}(t)\right] \cdot \boldsymbol{\sigma}, \qquad \mathcal{H}_{K'} = E_F[\tilde{\mathbf{k}} - \tilde{\mathbf{A}}(t)] \cdot \boldsymbol{\sigma}^* \qquad \tilde{\mathbf{A}}(t) = \frac{ev}{cE_F}\mathbf{A}(t),$$



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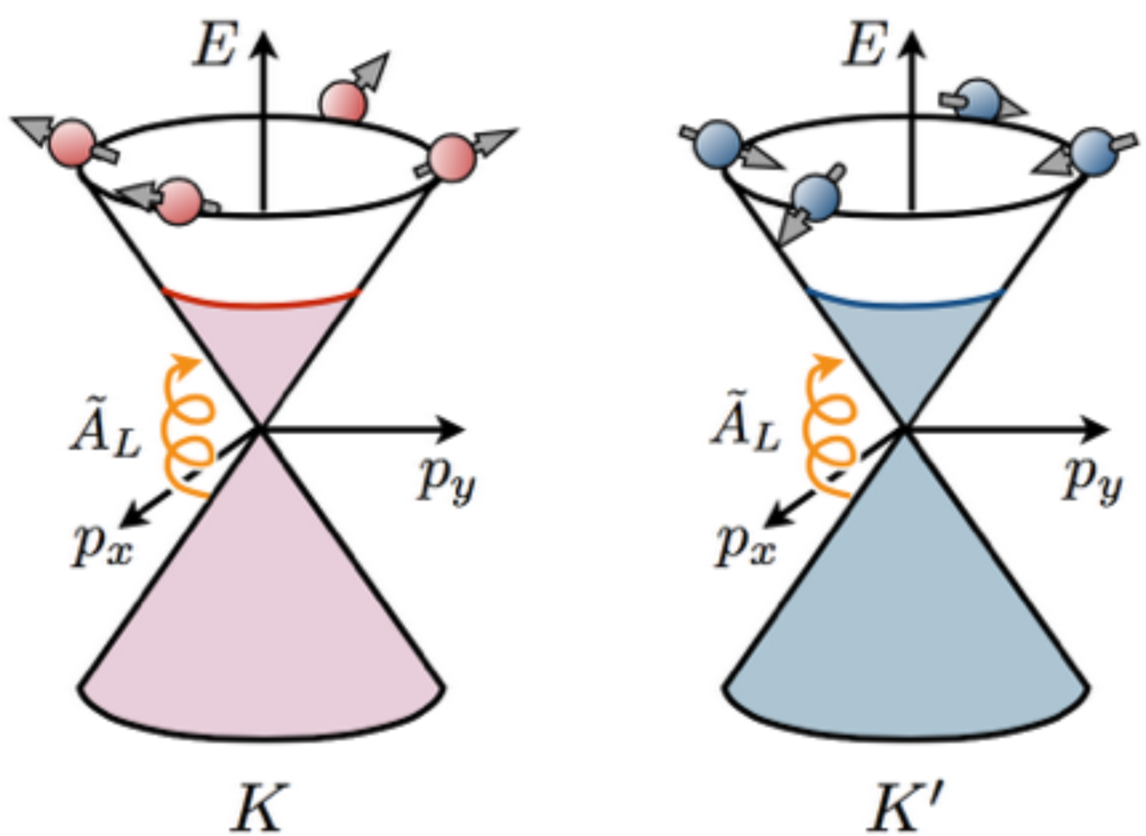
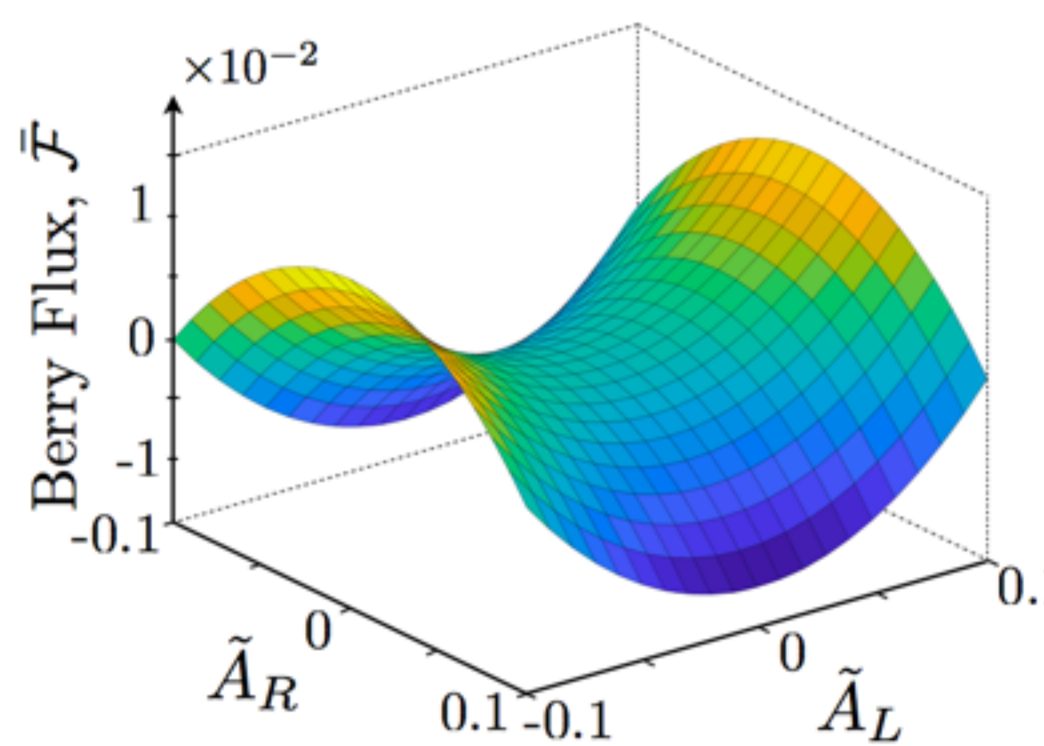


Steady state Berry flux generated



$$\bar{\mathcal{F}} = \beta(|\tilde{A}_L|^2 - |\tilde{A}_R|^2)$$

order unity dimensionless number

* For realistic graphene parameters (E_F = 160 meV, drive = 100 meV), we find beta =2.3

M Rudner, **JS**, arXiv (2018)

Feedback: Flux induced plasmon non-linearity

$$\frac{d\{\mathbf{r}\}}{dt} = \frac{\{\mathbf{p}\}}{m} - \frac{\mathcal{F}[\mathbf{E}_{\rm tot}(t)]}{\hbar n_0}\hat{\mathbf{z}} \times e\mathbf{E}_{\rm tot}(t),$$

$$\frac{d\{\mathbf{p}\}}{dt} = -m\omega_0^2\{\mathbf{r}\} - \gamma\{\mathbf{p}\} - e\mathbf{E}_{\rm drive}(t),$$

Generated by rotating electric fields (drive + internal)

$$\mathcal{F} = 0 + \mathcal{F}[\mathbf{E}_{\rm tot}(t)]$$

internally plasmonic enhanced electric fields
internal electric fields up to Q times larger

$$e\mathbf{E}_{\rm tot}(t) = e\mathbf{E}_{\rm drive}(t) + m\omega_0^2\{\mathbf{r}\}$$

graphene has zero flux

Flux depends on plasmon motion/displacement: plasmon non-linear

$$\boxed{\bar{\mathcal{F}} = f(|\mathcal{Z}_-^{(0)}|^2/l^2, |\mathcal{Z}_+^{(0)}|^2/l^2), \quad l^{-1} = \frac{vm\omega_0^2}{E_F\omega_d},}$$

complex representation for circular basis

$$\mathcal{Z}_\pm^{(0)} = \frac{1}{\sqrt{2}}[x^{(0)} \pm iy^{(0)}]$$

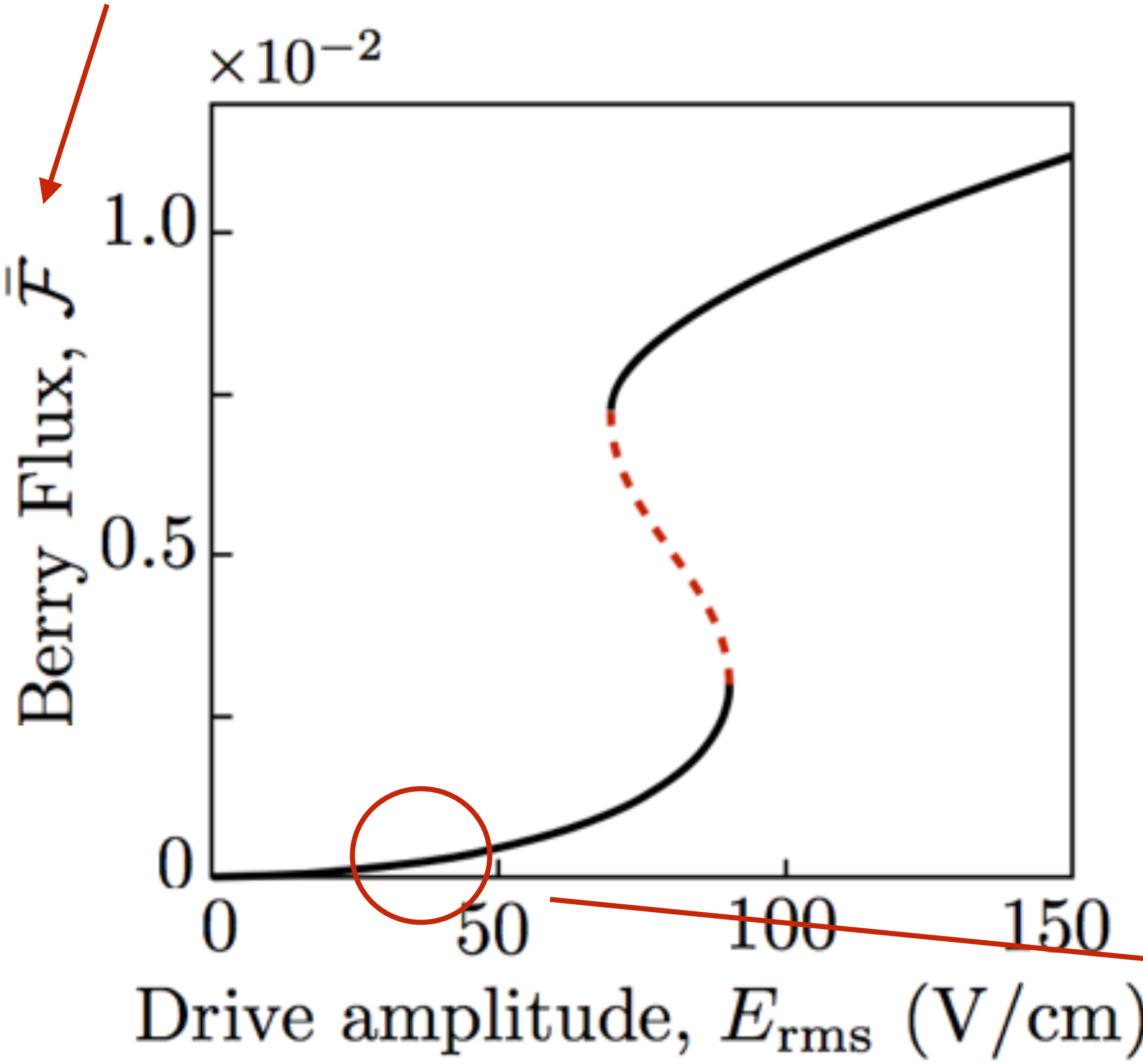
M Rudner, **JS**, arXiv (2018)

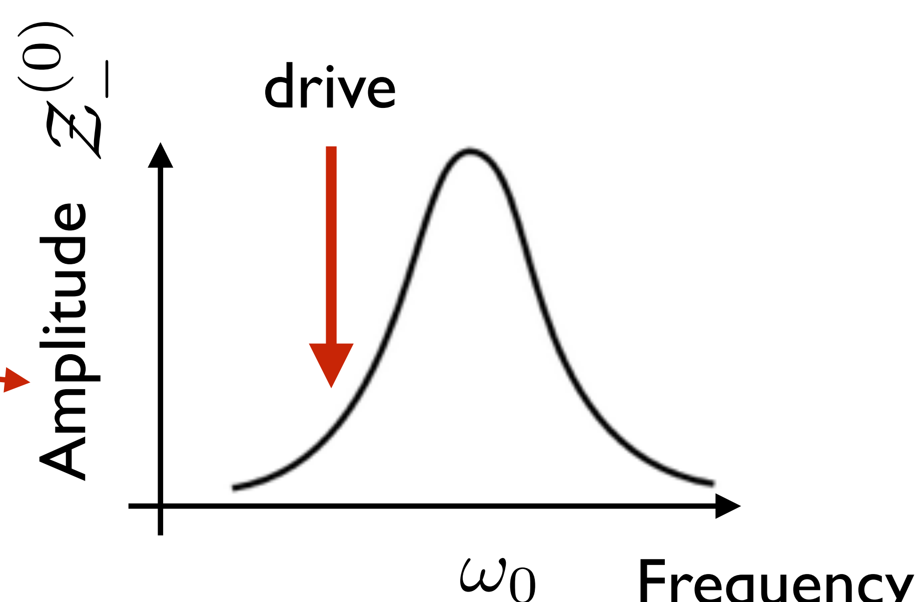
Feedback: nonlinearity and bistability

case 1: circularly polarized driving

Captures the amplitude of the
circular motion of the plasmons

$\mathcal{Z}_{\pm}^{(0)} = \frac{1}{\sqrt{2}}[x^{(0)} \pm iy^{(0)}]$





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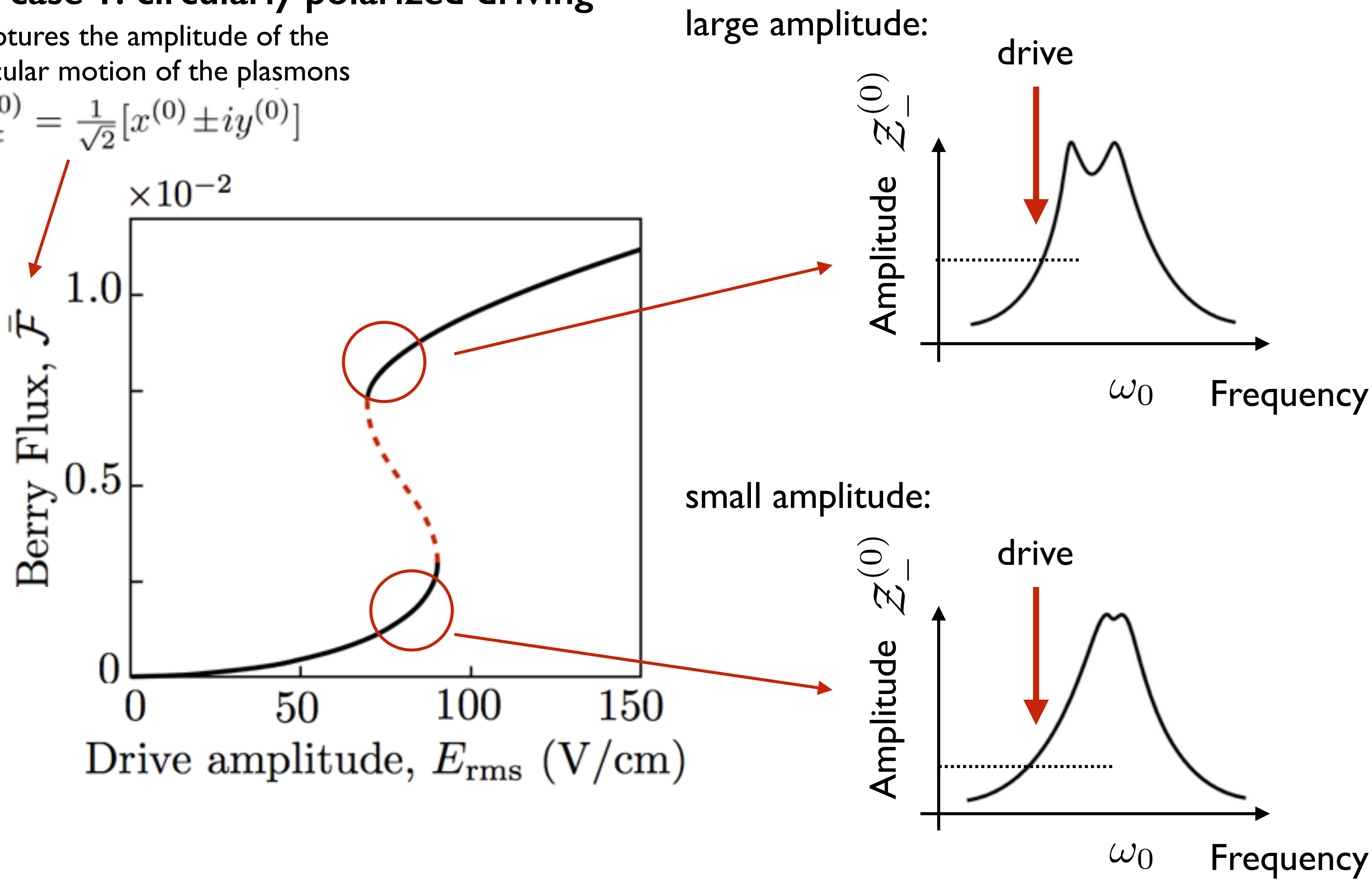


M Rudner, **JS**, arXiv (2018)

TRS preserving drives (e.g., linear polarization)?

Self-Floquet: spontaneous collective mode *magnetism*

case II: linearly polarized driving

$$\frac{d\{\mathbf{r}\}}{dt} = \frac{\{\mathbf{p}\}}{m} - \frac{\mathcal{F}[\mathbf{E}_{\mathrm{tot}}(t)]}{\hbar n_0}\hat{\mathbf{z}} \times e\mathbf{E}_{\mathrm{tot}}(t),$$

$$\frac{d\{\mathbf{p}\}}{dt} = -m\omega_0^2\{\mathbf{r}\} - \gamma\{\mathbf{p}\} - e\mathbf{E}_{\mathrm{drive}}(t),$$

self-consistent equation for symmetry breaking $\eta \equiv |\mathcal{Z}_+^{(0)}|^2 - |\mathcal{Z}_-^{(0)}|^2.$

$$\eta\left[1 + 4\nu\omega_d(\omega_d^2 + \gamma^2 - \omega_0^2)\frac{|eE_{\mathrm{rms}}/m|^2}{D_+D_-}\right] = 0,$$

where

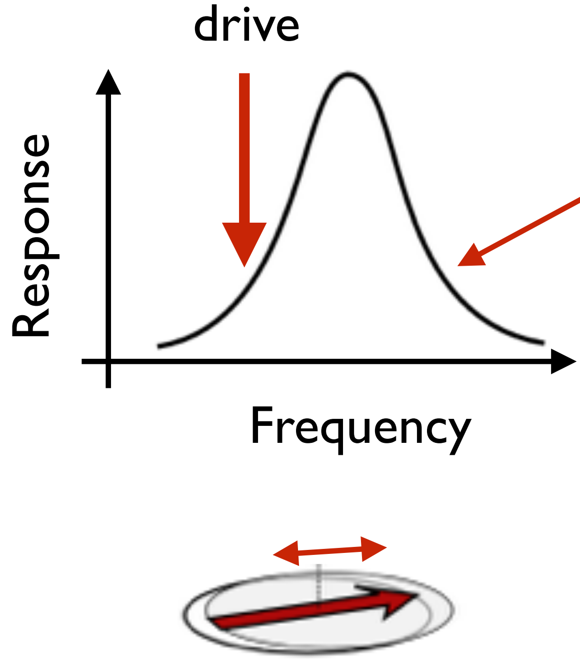
$$D_\pm = [\omega_0^2 - \omega_d^2 \mp \nu\omega_d\eta]^2 + \gamma^2(\omega_d \pm \nu\eta)^2$$

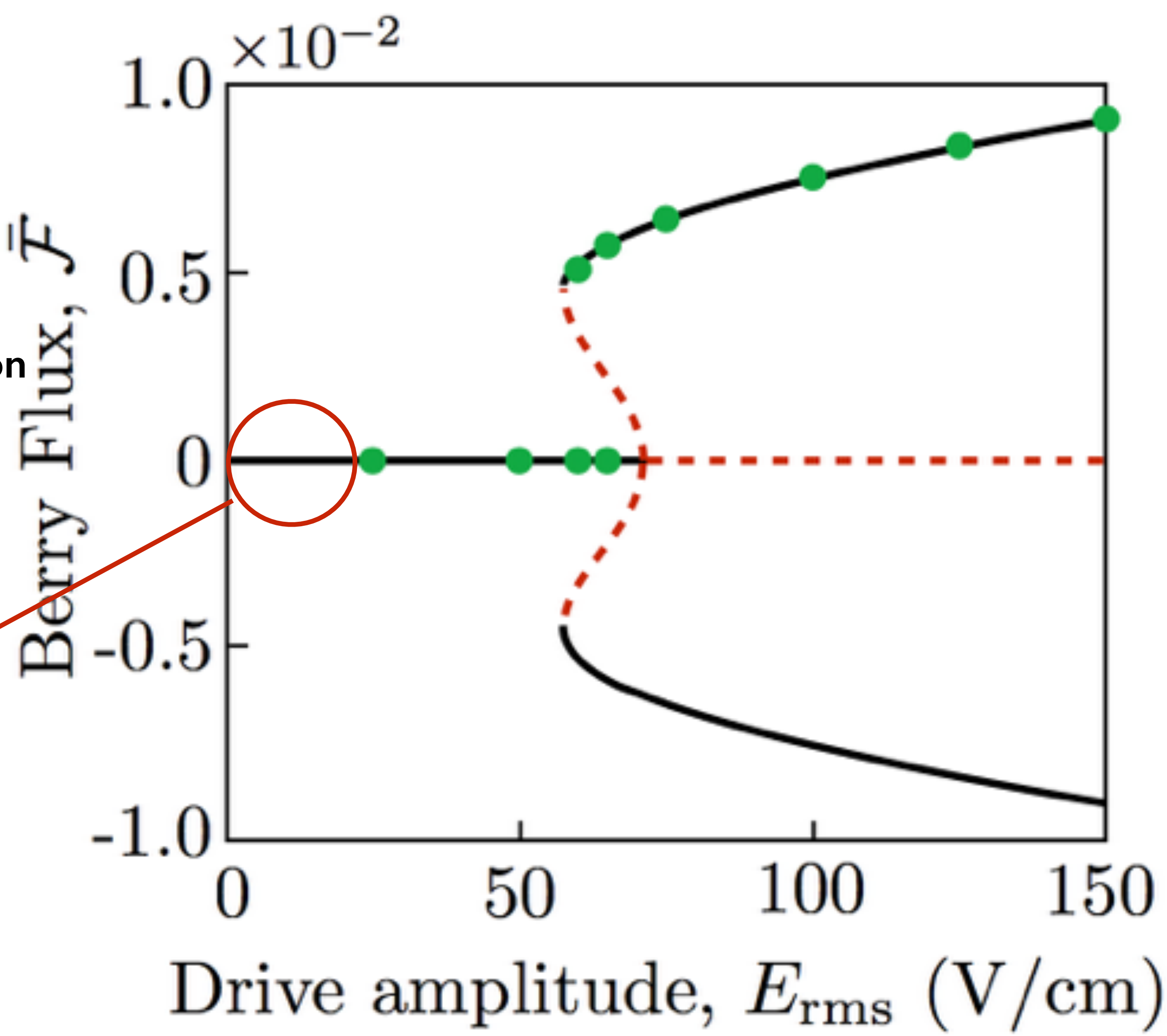
M Rudner, **JS**, arXiv (2018)

Spontaneous collective mode *magnetism*

case II: linearly polarized driving

Linearly polarized driving gives linearly polarized plasmon motion



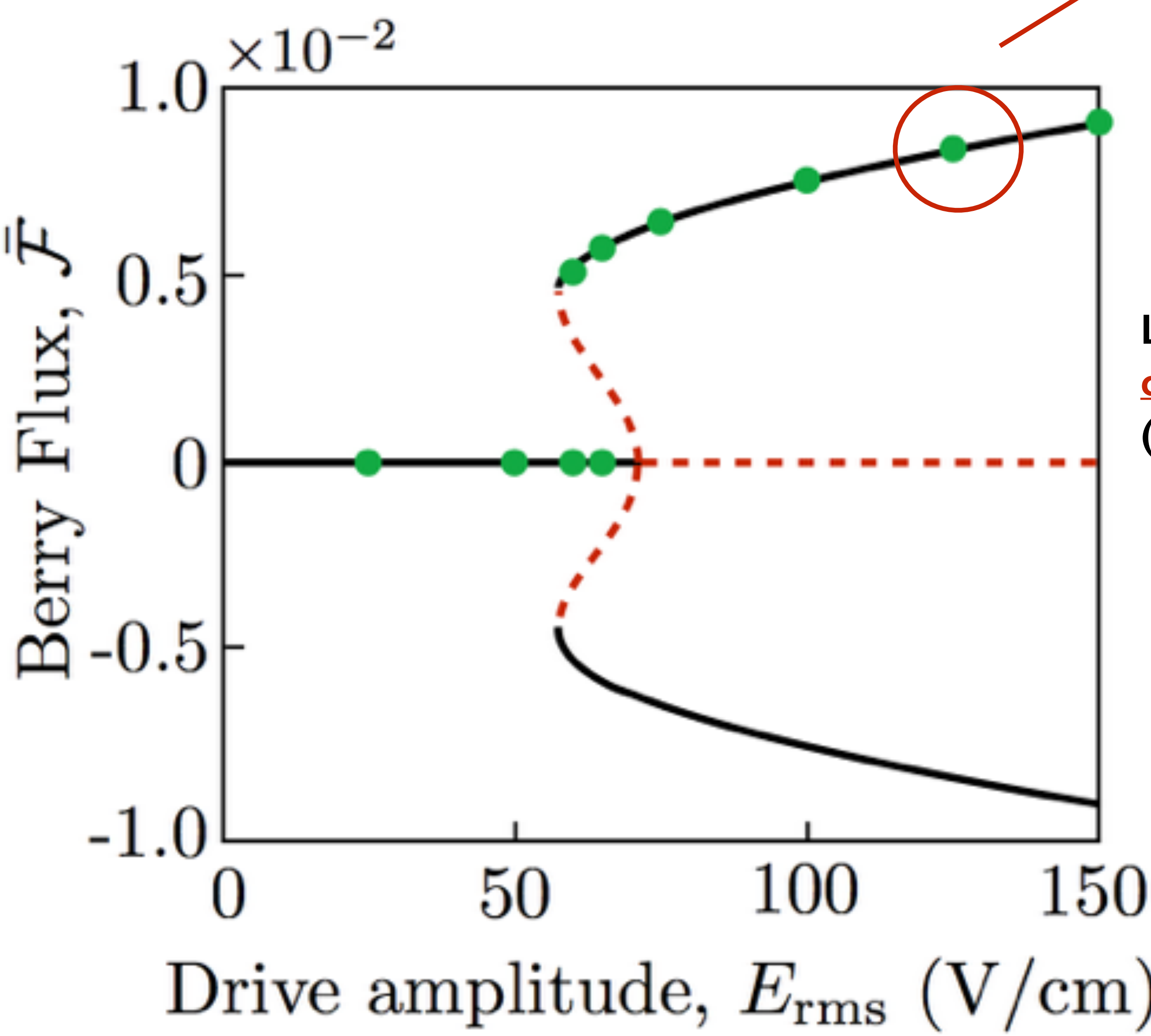


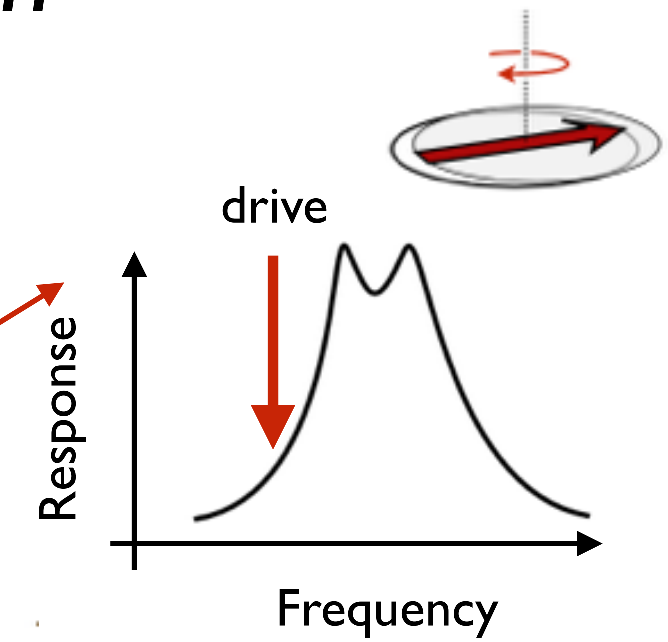
*sold lines from analytic expression of steady states, green dots from self-consistent full numerical simulation

M Rudner, **JS**, arXiv (2018)

Spontaneous collective mode *magnetism*

case II: linearly polarized driving





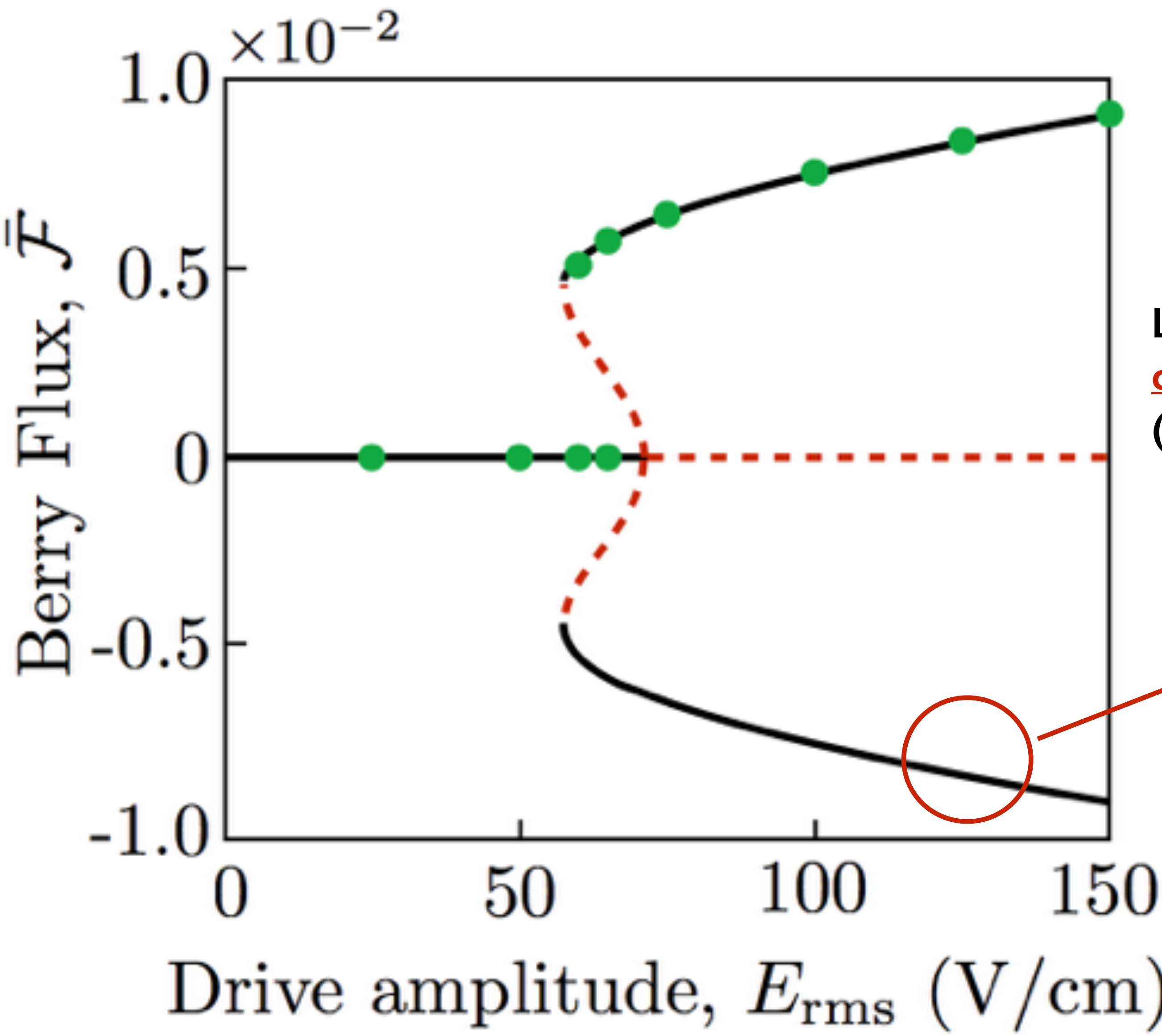
Linearly polarized driving gives <u>**circular plasmon motion**</u> **(spontaneously chosen)!**

*sold lines from analytic expression of steady states, green dots from self-consistent full numerical simulation

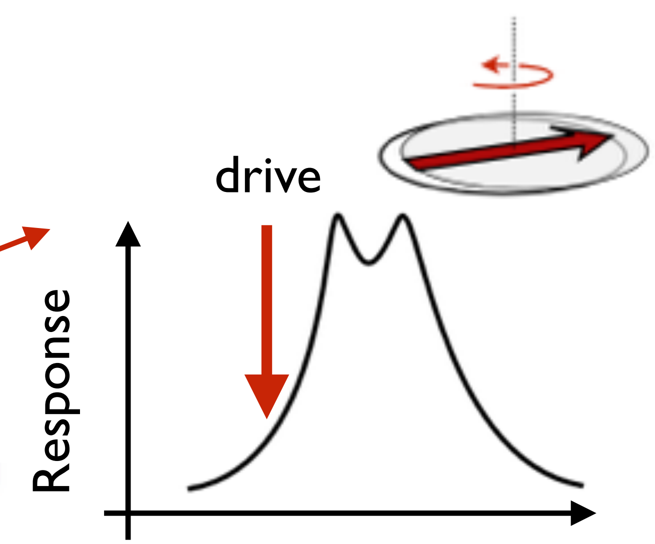
M Rudner, **JS**, arXiv (2018)

Spontaneous collective mode *magnetism*

case II: linearly polarized driving



Linearly polarized driving gives <u>circular plasmon motion</u> (spontaneously chosen)!

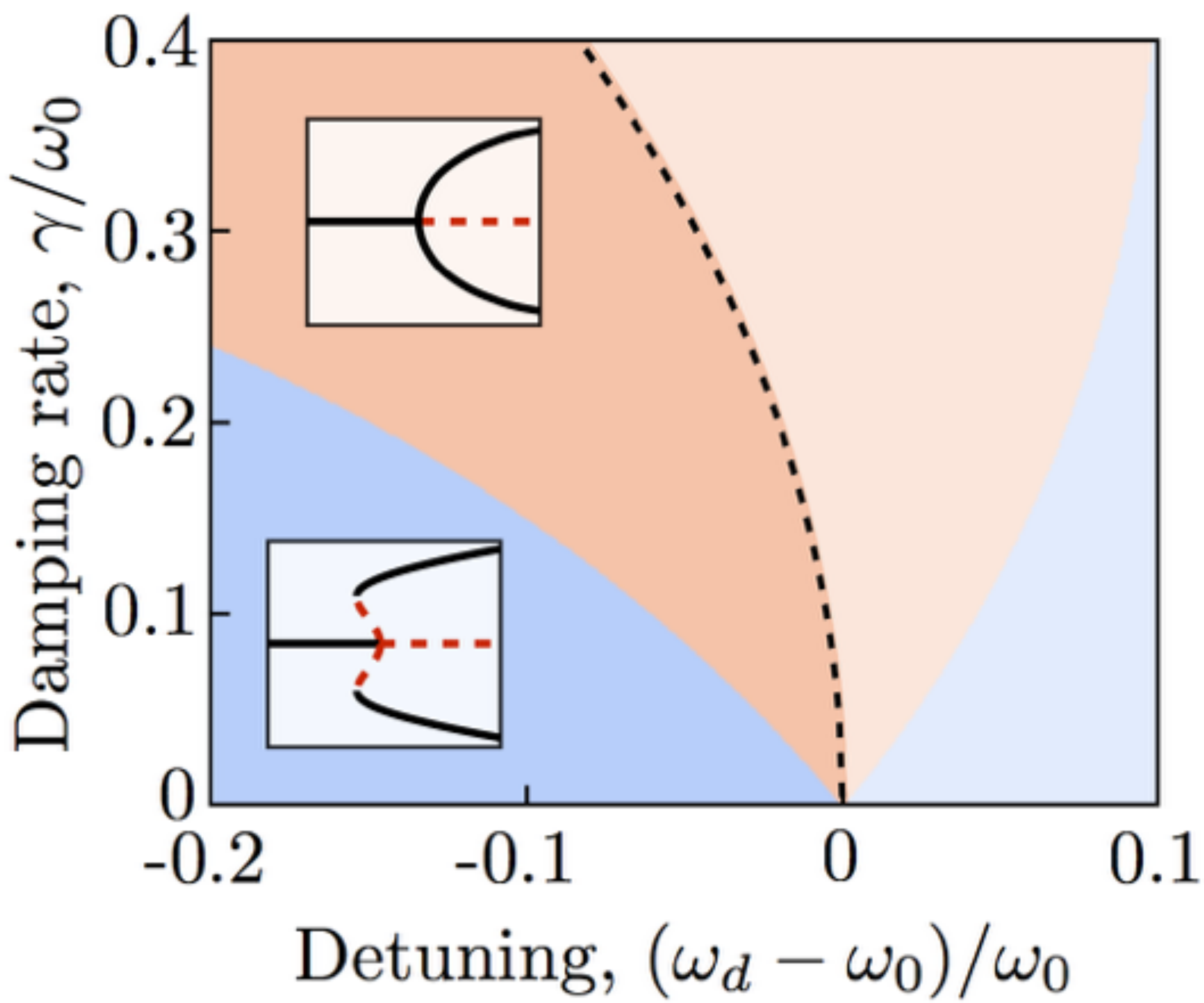


*sold lines from analytic expression of steady states, green dots from self-consistent full numerical simulation

M Rudner, **JS**, arXiv (2018)

Tuning the type of phase transition

case II: linearly polarized driving



M Rudner, **JS**, arXiv (2018)

Drives are outside particle-hole continuum

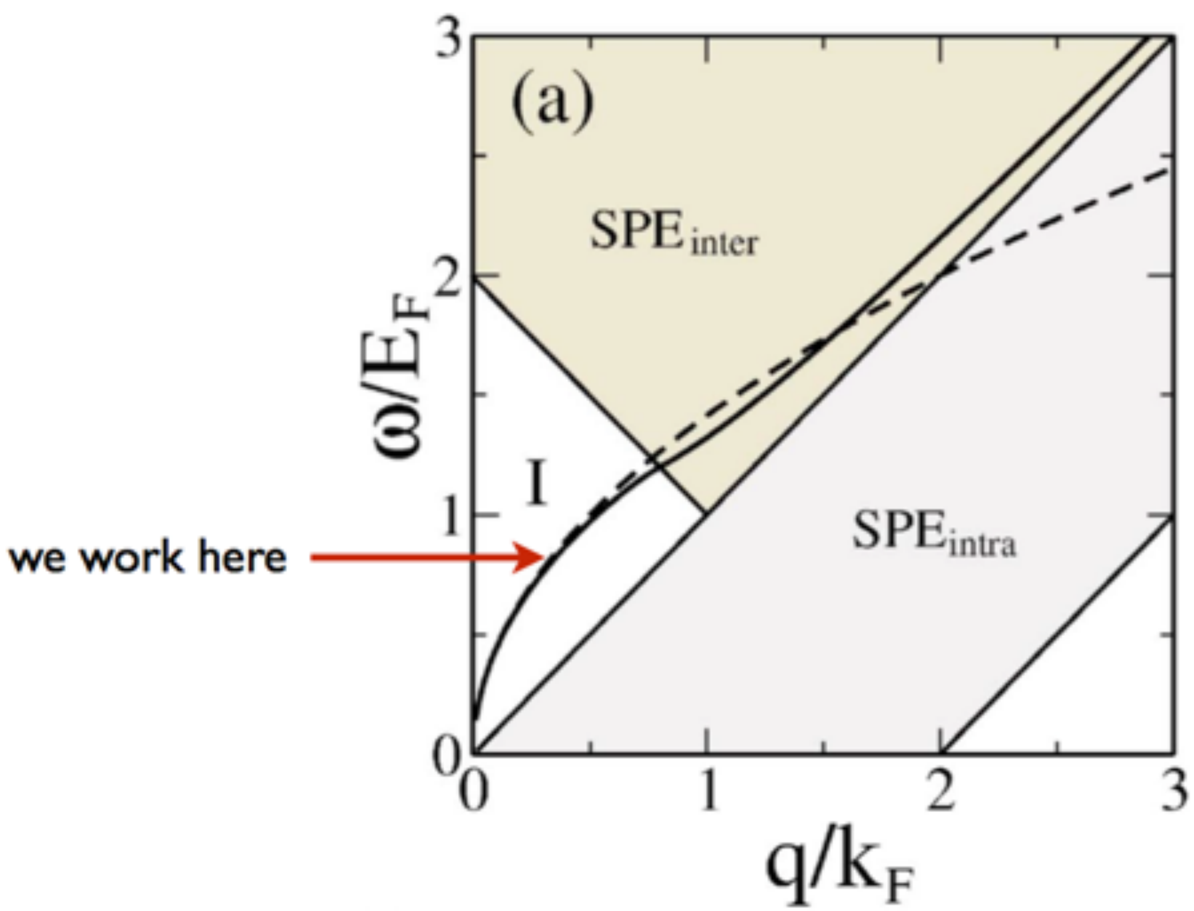
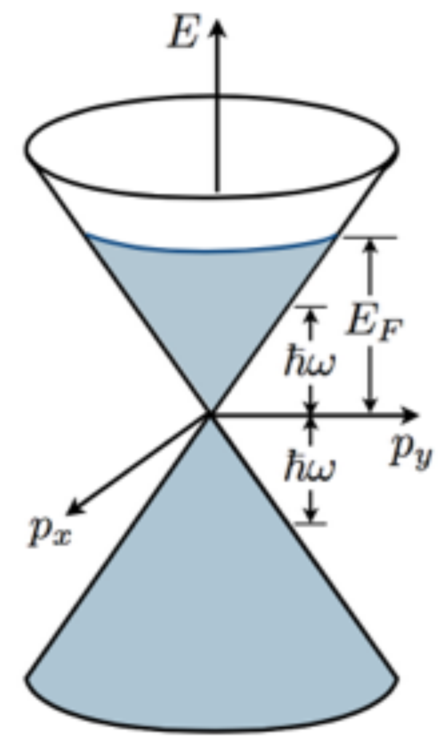


Figure from: Hwang and Das Sarma, PRB (2007)

Direct inter-band transitions are Pauli Blocked:



Plan

Part I.

Exploiting out-of-equilibrium matter

Part II.

Spontaneous symmetry breaking in a collective mode

out-of-equilibrium plasmonic magnetism

MS Rudner **JS**, arXiv (2018)

Part III.

Emergent internal structure of plasmons and geometry

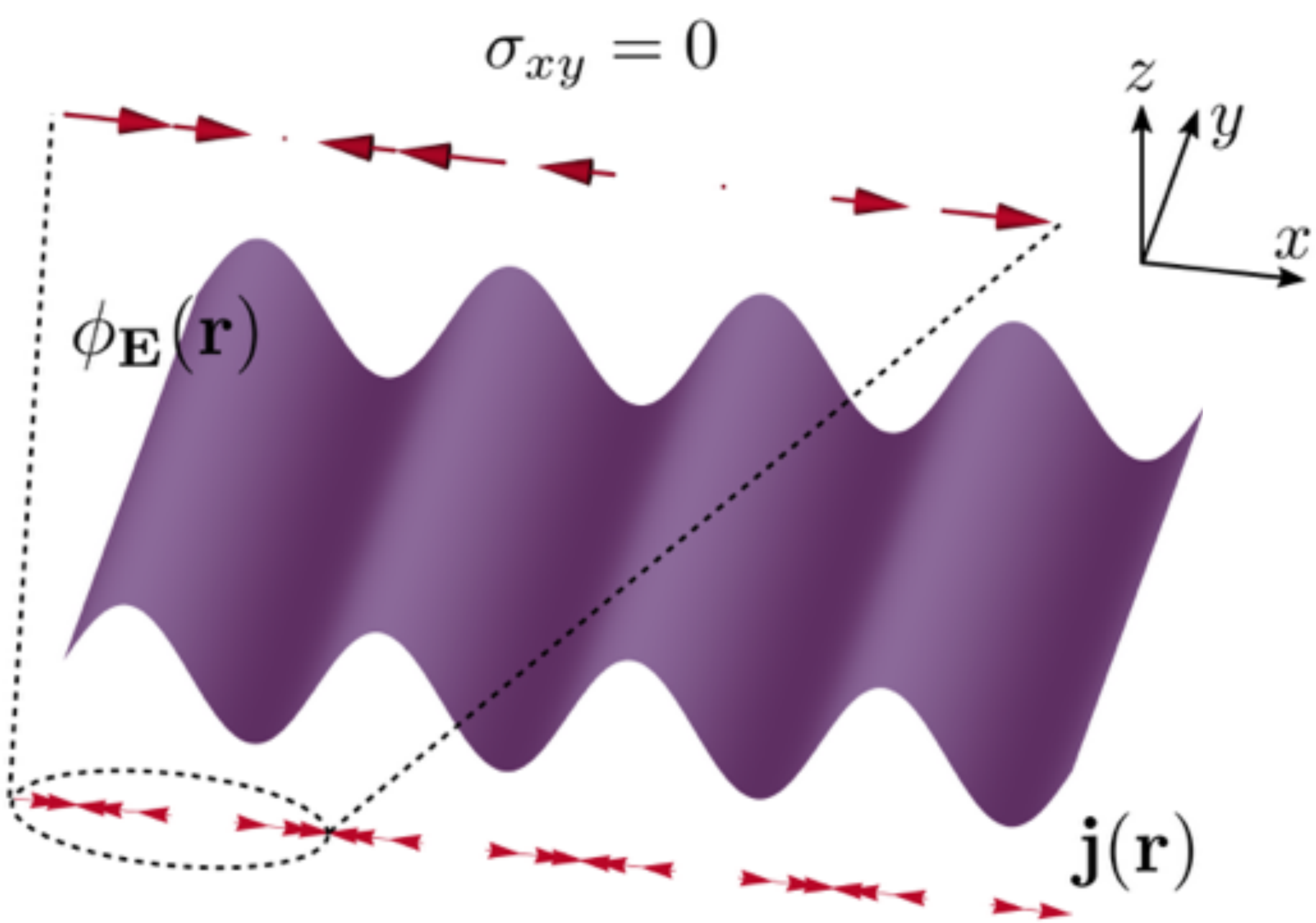
LK Shi, **JS**, PRX (2018)

Li-kun Shi

Plasmons: electric fields, density, and current density

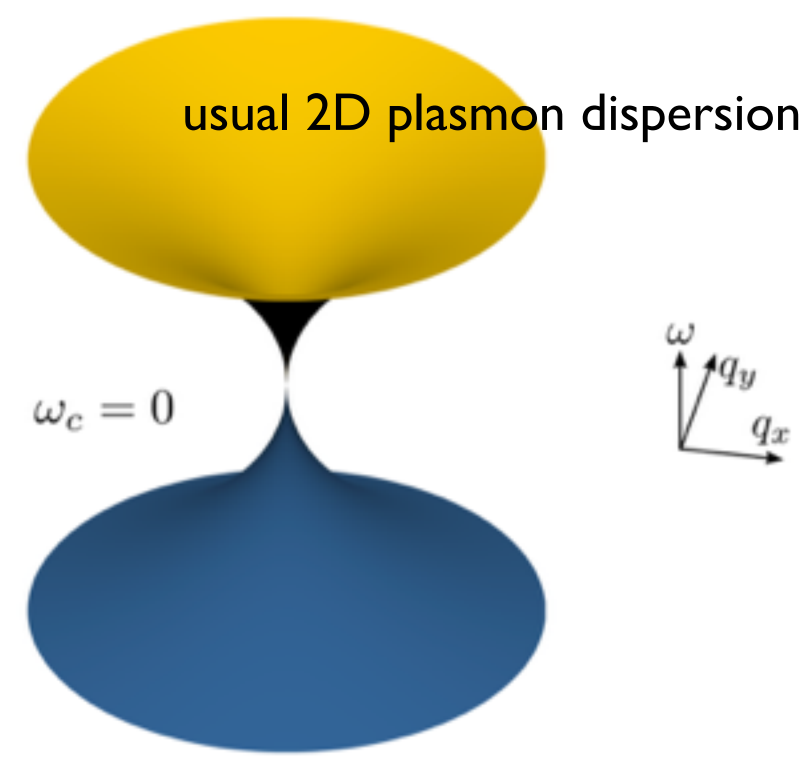
Longitudinal electric mode

locked orientations: $(\mathbf{q}, \mathbf{E}, \mathbf{j})$



charge dynamics:

$$\partial_t \delta n(\mathbf{r}, t) + \nabla \cdot [\boldsymbol{\sigma} \mathbf{E}(\mathbf{r}, t)] = 0$$



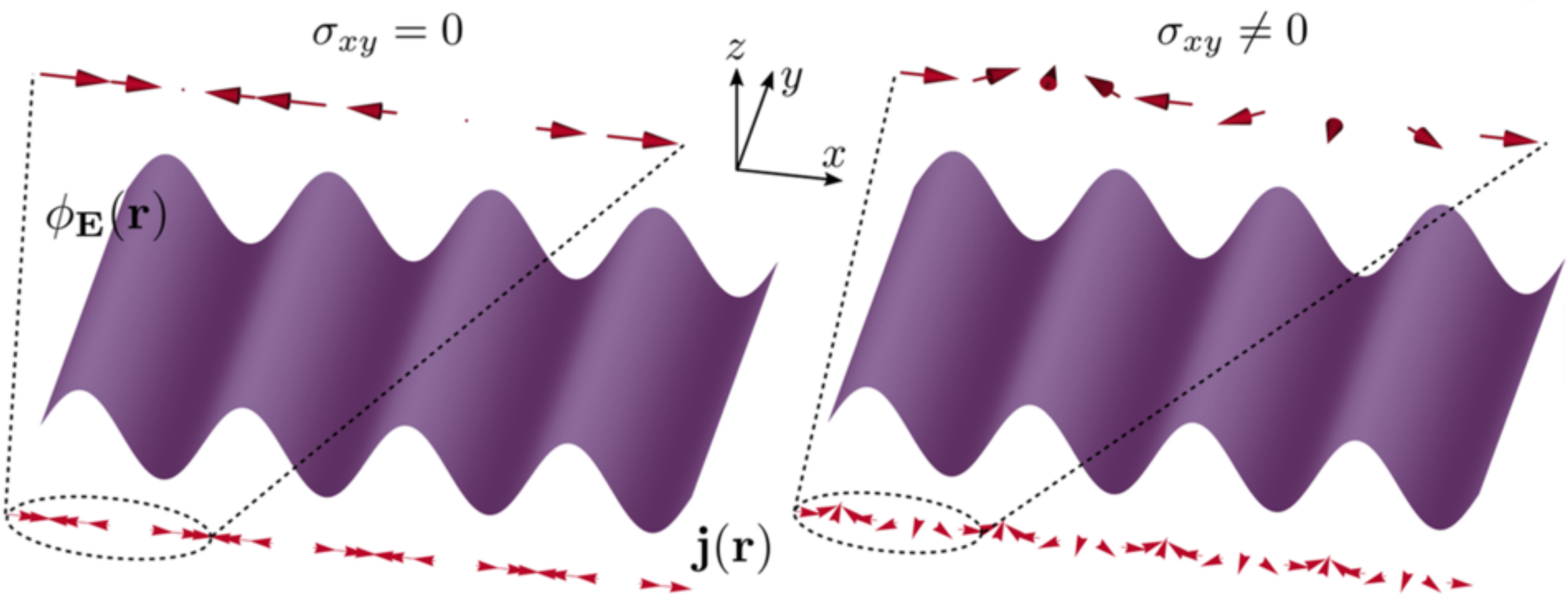
Plasmon internal current density structure

Longitudinal electric mode

locked orientations: $(\mathbf{q}, \mathbf{E}, \mathbf{j})$

Longitudinal electric mode

canted orientation: $(\mathbf{q}, \mathbf{E}) \nparallel \mathbf{j}$



LK Shi, **JS**, PRX (2018)

Internal current density structure

Formal treatment

Electric potential of plasmon determined by (full 3D) Maxwell's equation

$$\nabla \times [\nabla \times \boldsymbol{\mathcal{E}}(\mathbf{r}, z, t)] = \frac{\omega^2}{c^2} \boldsymbol{\mathcal{E}}(\mathbf{r}, z, t) - i \frac{4\pi\omega}{c^2} \boldsymbol{\mathcal{J}}(\mathbf{r}, z, t),$$

As a result, Maxwell demands that electric field inside the metallic (2D) plane is related to the current density

$$\begin{pmatrix} E_x \\ E_y \end{pmatrix} = \boldsymbol{\mathcal{F}} \begin{pmatrix} j_x \\ j_y \end{pmatrix}, \quad \boldsymbol{\mathcal{F}} = \frac{2\pi i}{\omega\beta} \begin{pmatrix} \beta^2 - q_y^2 & q_x q_y \\ q_x q_y & \beta^2 - q_x^2 \end{pmatrix}.$$

in non-retarded limit

$$\beta = \sqrt{\mathbf{q}^2 - \omega^2/c^2} \approx |\mathbf{q}|$$

Supplemented with the conductivity (constitutive relation of the metal) plasmons can be obtained as zero modes of

$$\boldsymbol{\mathcal{M}} \mathbf{j} = 0, \quad \boldsymbol{\mathcal{M}} = \boldsymbol{\mathcal{F}} - \boldsymbol{\sigma}^{-1},$$

where

$$\sigma_{xx} = \frac{(1 + i\omega\tau)\ \sigma_0}{(1 + i\omega\tau)^2 + (\omega_c\tau)^2}, \quad \sigma_{xy} = \frac{-\omega_c\tau\ \sigma_0}{(1 + i\omega\tau)^2 + (\omega_c\tau)^2}.$$

yielding magneto-plasmon solutions as

$$\omega = \sqrt{2\pi D_0 |\mathbf{q}| + \omega_c^2}$$

$$\mathbf{u}(\mathbf{q}) = \begin{pmatrix} j_x(\mathbf{q}) \\ j_y(\mathbf{q}) \end{pmatrix} = \frac{\mathcal{N}}{q} \begin{pmatrix} -iq_x + \eta_q q_y \\ +iq_y - \eta_q q_x \end{pmatrix}.$$

looks like a "spinor wavefunction"!

$$\omega_c/\omega_{\mathbf{q}}$$

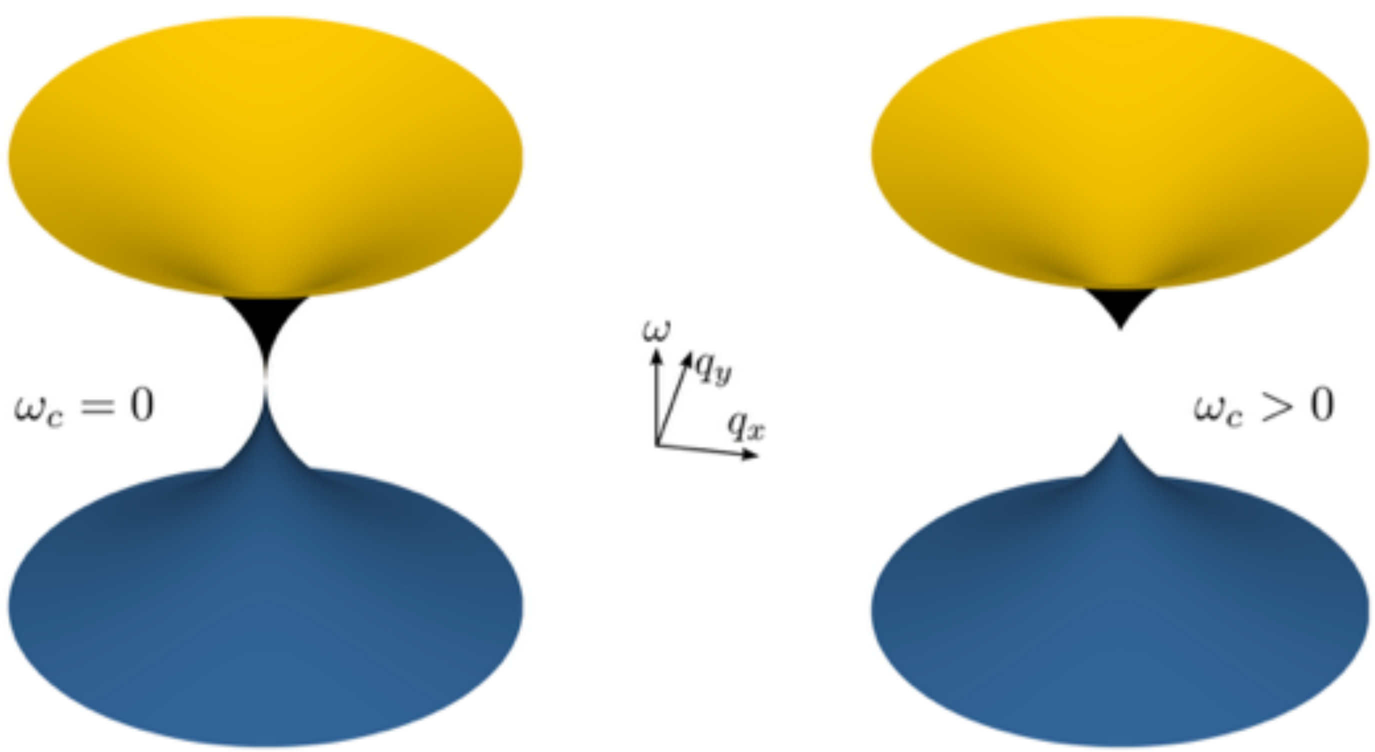
LK Shi, **JS**, PRX (2018)

Plasmon *emergent* pseudo-spin

plasmon "pseudo-spin" tracks canted orientation

$$\langle \mathbf{s}_{1,2,3} \rangle = \langle \mathbf{j} | \boldsymbol{\tau}_{1,2,3} | \mathbf{j} \rangle$$

Pauli matrices



Zero magnetic field $\omega_c = 0$

Finite magnetic field $\omega_c \neq 0$

LK Shi, **JS**, PRX (2018)

Plasmon *emergent* pseudo-spin

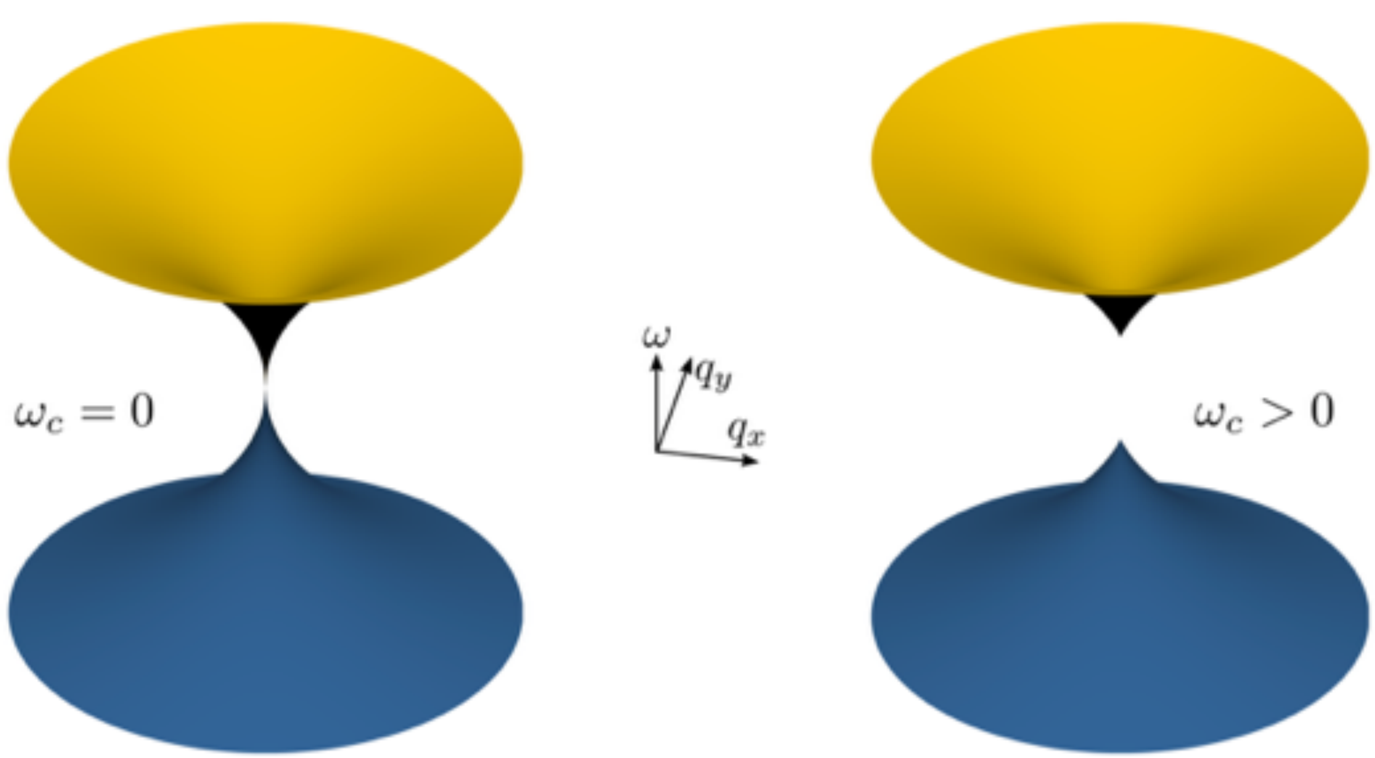
$\omega_c/\omega_{\mathbf{q}}$

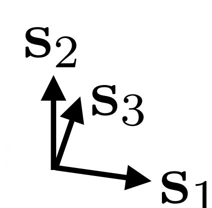
$$s_1 = \frac{1-\eta_q^2}{1+\eta_q^2}\sin 2\phi_s, \quad s_2 = \frac{-2\eta_q}{1+\eta_q^2}, \quad s_3 = \frac{1-\eta_q^2}{1+\eta_q^2}\cos 2\phi_s$$

plasmon “pseudo-spin” tracks canted orientation

$$\langle \mathbf{s}_{1,2,3} \rangle = \langle \mathbf{j} | \boldsymbol{\tau}_{1,2,3} | \mathbf{j} \rangle$$

Pauli matrices





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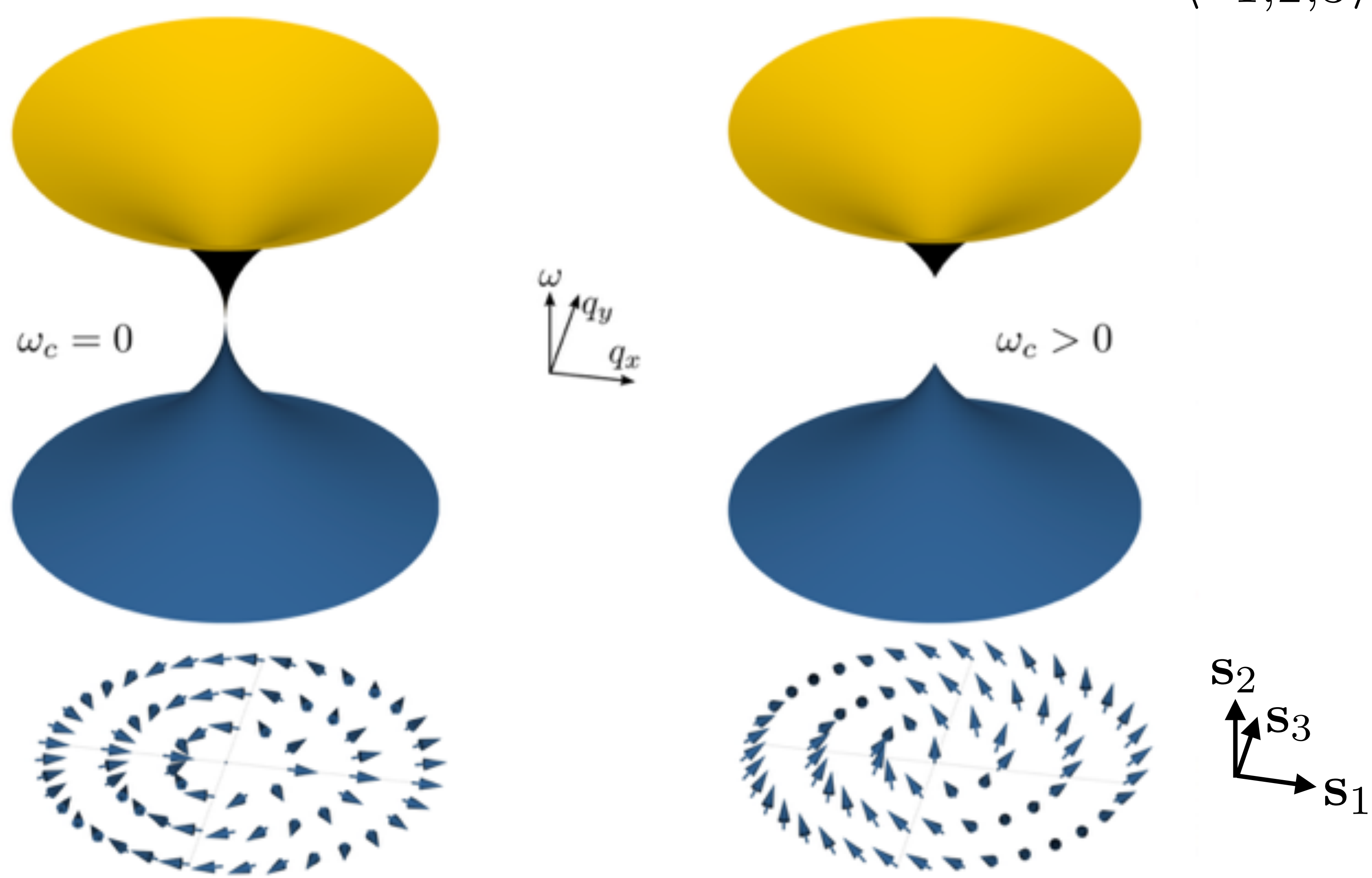
Pauli matrices



Zero magnetic field $\omega_c = 0$

Finite magnetic field $\omega_c \neq 0$

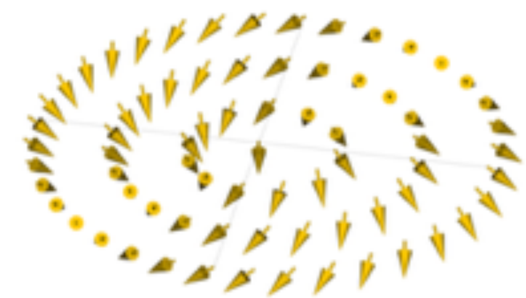
LK Shi, **JS**, PRX (2018)

"hidden" internal current density

Hall current does not contribute to dispersion relation in bulk

$$\mathcal{M}\mathbf{j} = 0, \quad \mathcal{M} = \mathcal{F} - \boldsymbol{\sigma}^{-1},$$

current density pattern possesses hedge-hog like texture



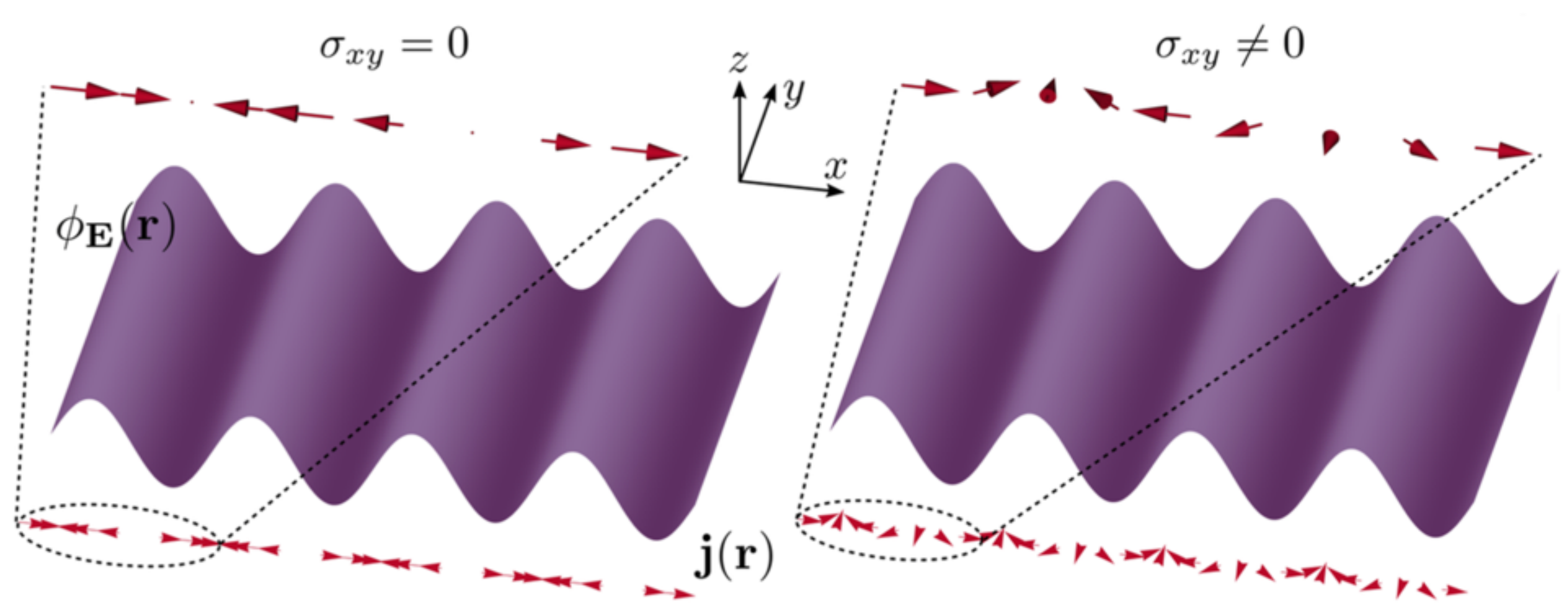
yielding solutions as

$$\mathbf{u}(\mathbf{q}) = \begin{pmatrix} j_x(\mathbf{q}) \\ j_y(\mathbf{q}) \end{pmatrix} = \frac{\mathcal{N}}{q} \begin{pmatrix} -iq_x + \eta_q q_y \\ +iq_y - \eta_q q_x \end{pmatrix}.$$

* note that even though current density cants in the presence of B field, electric field remains Longitudinal.

Longitudinal electric modes (as required for deep sub wavelength plasmons)

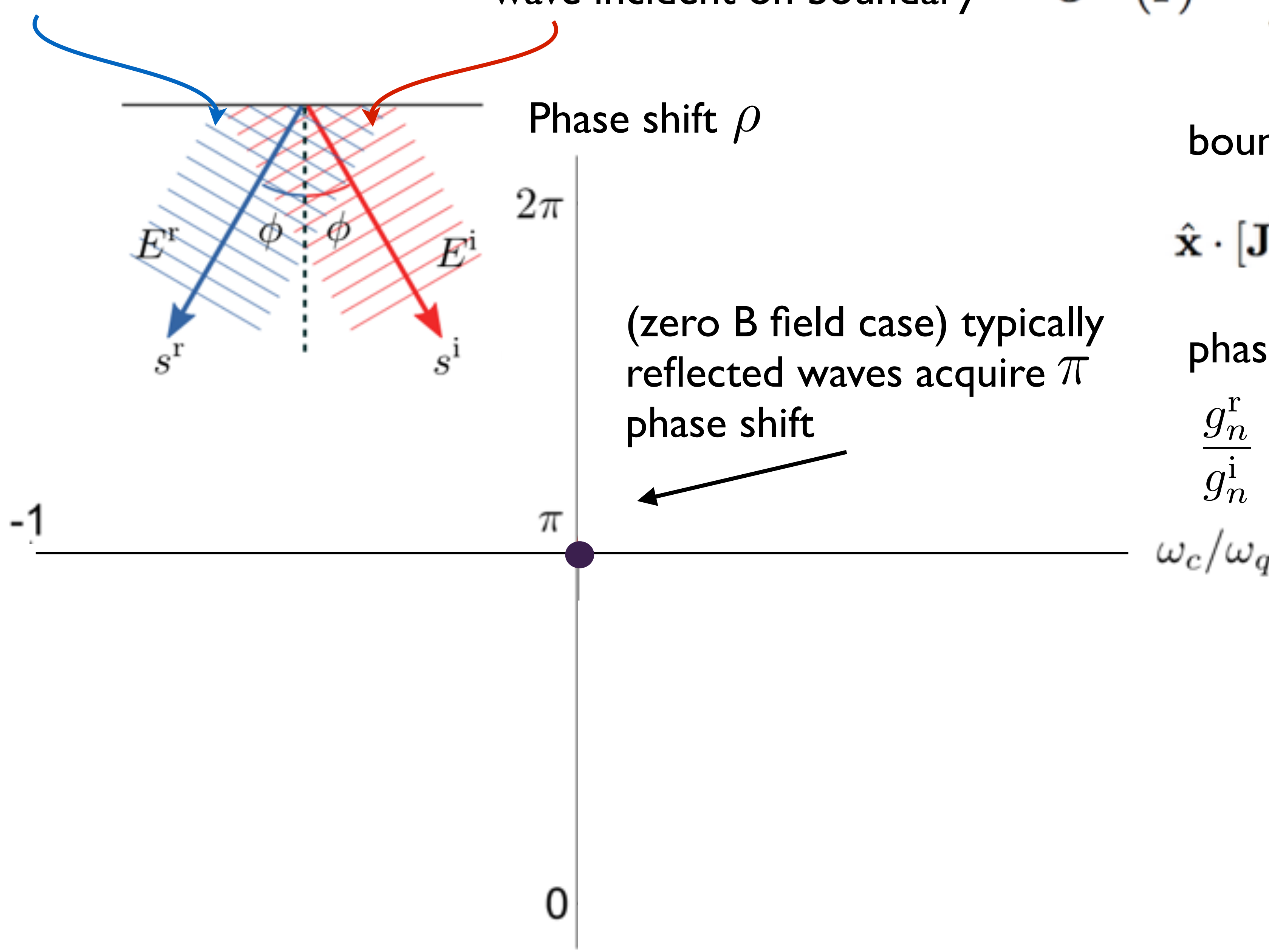
$$\boldsymbol{\varepsilon}(\mathbf{q}) = \mathcal{F}(\mathbf{q})\mathbf{u}(\mathbf{q}) = (2\pi\mathcal{N}/\omega_q)\mathbf{q},$$



Plasmon *geometrical* phases

wave reflected off boundary

wave incident on boundary



(zero B field case) typically reflected waves acquire π phase shift

complex number

eigen vector (spinor) for current density

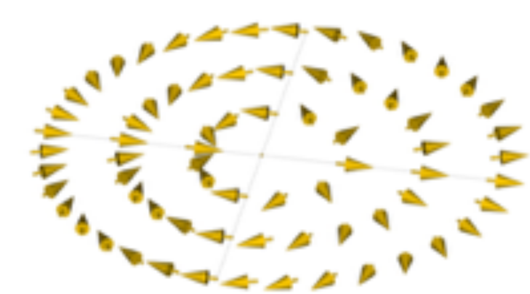
$$\mathbf{J}^{\mathrm{i,r}}(\mathbf{r}) = \sum_n g_n^{\mathrm{i,r}} \mathbf{u}(\mathbf{q}_n^{\mathrm{i,r}}) \exp(-i\mathbf{q}_n^{\mathrm{i,r}} \cdot \mathbf{r})$$

boundary condition

$$\hat{\mathbf{x}} \cdot [\mathbf{J}^{\mathrm{i}}(x=0,y) + \mathbf{J}^{\mathrm{r}}(x=0,y)] = 0.$$

phase shift:

$$\frac{g_n^{\mathrm{r}}}{g_n^{\mathrm{i}}} = -\frac{\hat{\mathbf{x}} \cdot \mathbf{u}(\mathbf{q}_n^{\mathrm{i}})}{\hat{\mathbf{x}} \cdot \mathbf{u}(\mathbf{q}_n^{\mathrm{r}})} = -\exp(i\rho_n)$$



plasmon current density spinor

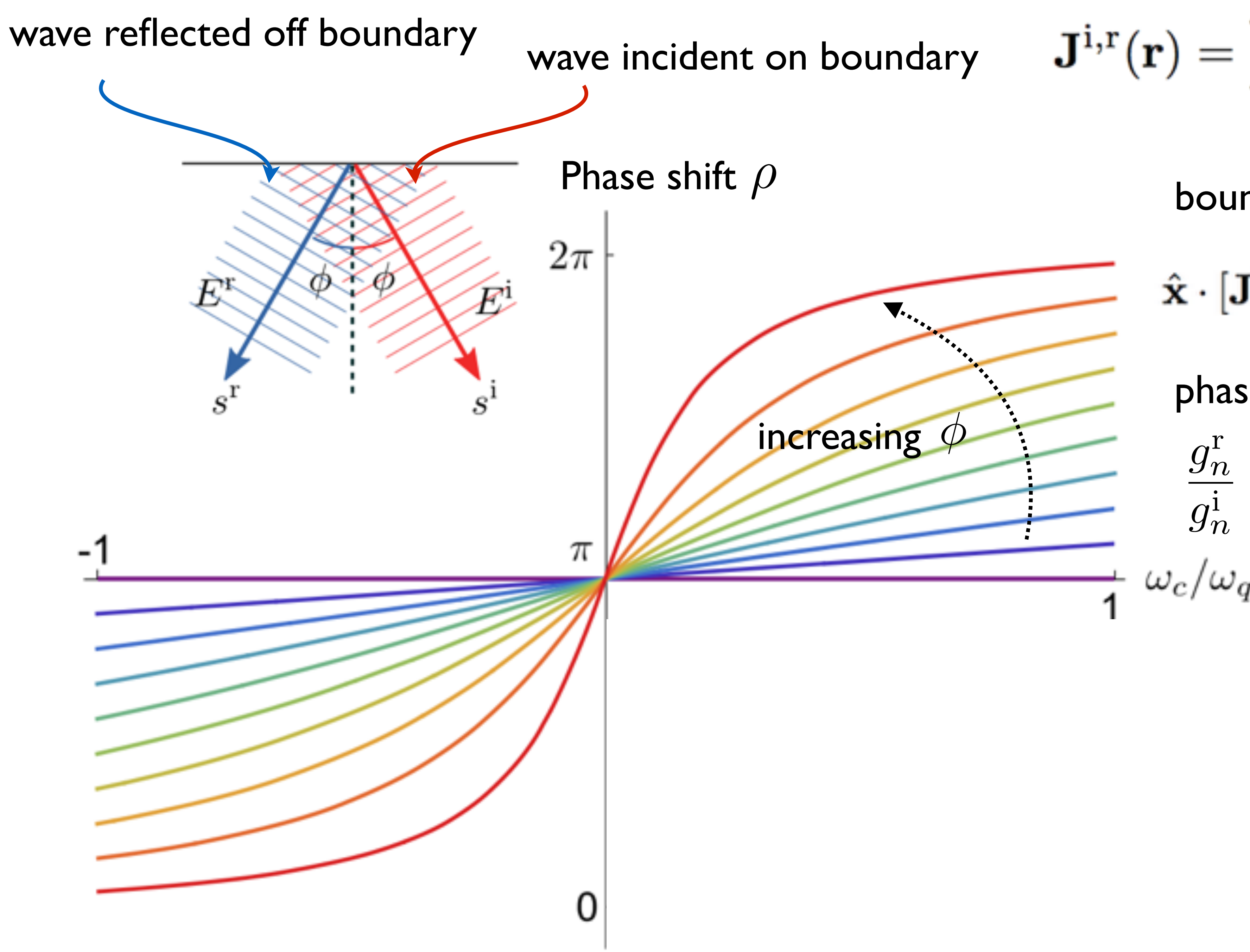
LK Shi, **JS**, PRX (2018)

Plasmon *geometrical* phases

complex number

eigen vector (spinor) for current density

$$\mathbf{J}^{\mathrm{i,r}}(\mathbf{r}) = \sum_n g_n^{\mathrm{i,r}} \mathbf{u}(\mathbf{q}_n^{\mathrm{i,r}}) \exp(-i\mathbf{q}_n^{\mathrm{i,r}} \cdot \mathbf{r})$$



boundary condition

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phase shift:

$$\frac{g_n^{\mathrm{r}}}{g_n^{\mathrm{i}}} = -\frac{\hat{\mathbf{x}} \cdot \mathbf{u}(\mathbf{q}_n^{\mathrm{i}})}{\hat{\mathbf{x}} \cdot \mathbf{u}(\mathbf{q}_n^{\mathrm{r}})} = -\exp(i\rho_n)$$

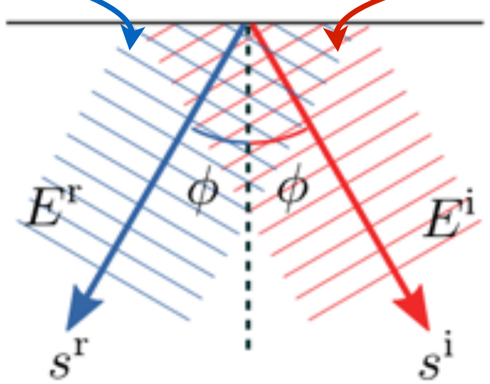
plasmon current density spinor

LK Shi, **JS**, PRX (2018)

Plasmon *geometrical* phases

wave reflected off boundary

wave incident on boundary



$$\frac{g_n^{\mathrm{r}}}{g_n^{\mathrm{i}}} = -\frac{\hat{\mathbf{x}} \cdot \mathbf{u}(\mathbf{q}_n^{\mathrm{i}})}{\hat{\mathbf{x}} \cdot \mathbf{u}(\mathbf{q}_n^{\mathrm{r}})} = -\exp(i\rho_n)$$

written more suggestively (take ϕ continuous determined by **q**)

$$\boldsymbol{\nabla}_{\mathbf{q}}\rho(\mathbf{q}) = \boldsymbol{\mathcal{A}}(\mathbf{q}_0^{\mathrm{r}}, \hat{\mathbf{n}}) - \boldsymbol{\mathcal{A}}(\mathbf{q}_0^{\mathrm{i}}, \hat{\mathbf{n}})$$

phase shift depends on a geometrical connection

$$\boldsymbol{\mathcal{A}}(\mathbf{q}, \hat{\mathbf{n}}) = \langle u_{\hat{\mathbf{n}}}(\mathbf{q}) | i\boldsymbol{\nabla}_{\mathbf{q}} | u_{\hat{\mathbf{n}}}(\mathbf{q}) \rangle$$

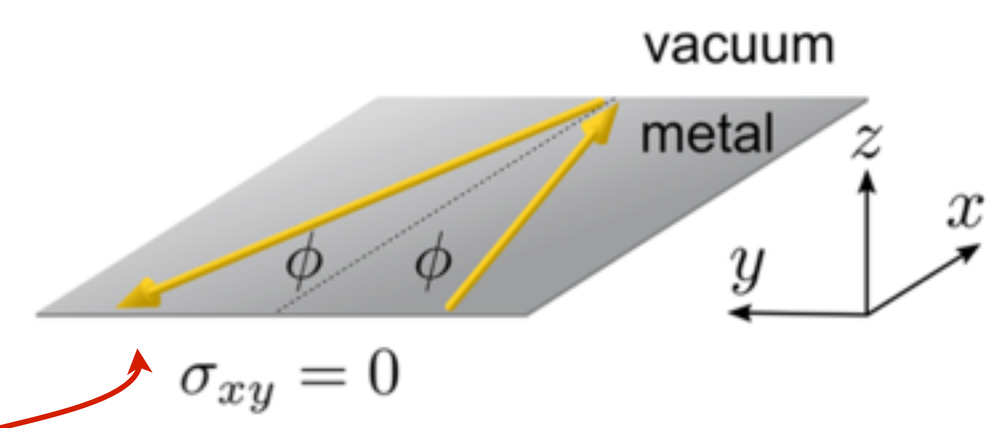
plasmon current density spinor

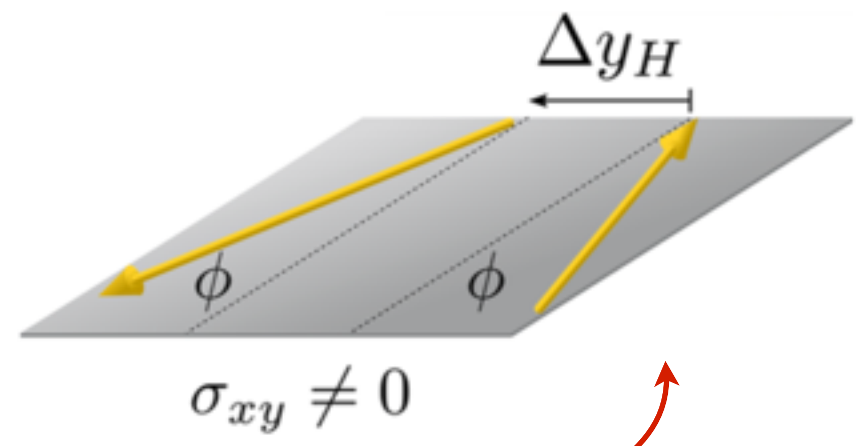
* not quite the berry connection since only normal component of **u** matters, nevertheless it captures geometry of pseudo-spinor texture

LK Shi, **JS**, PRX (2018)

Geometrical phases: Plasmon Hall effect

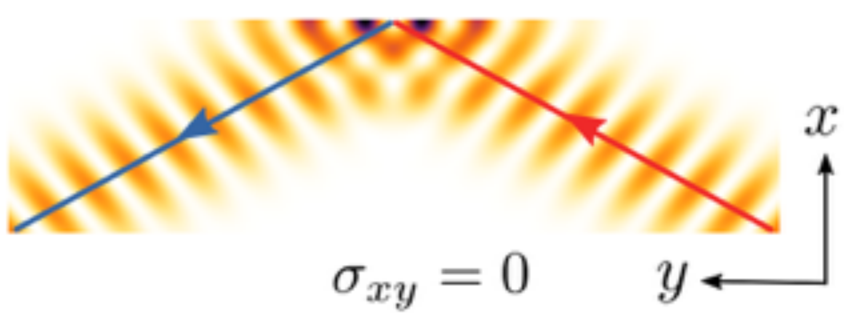
Geometric phase for multiple waves in a wave packet accumulate shifting the reflection trajectories

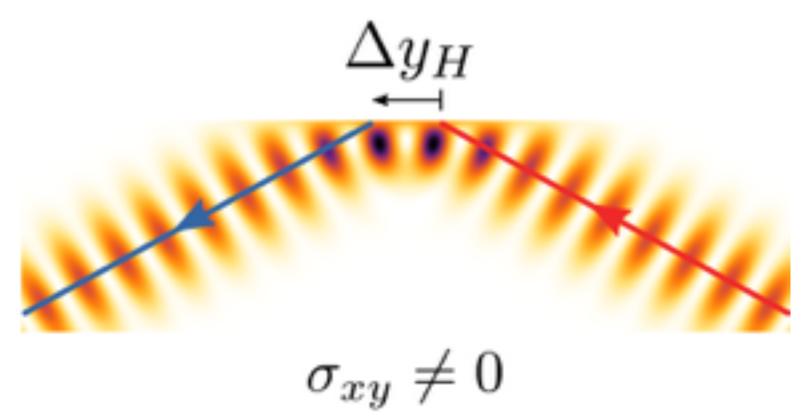




Conventional ray optics

Unconventional shift

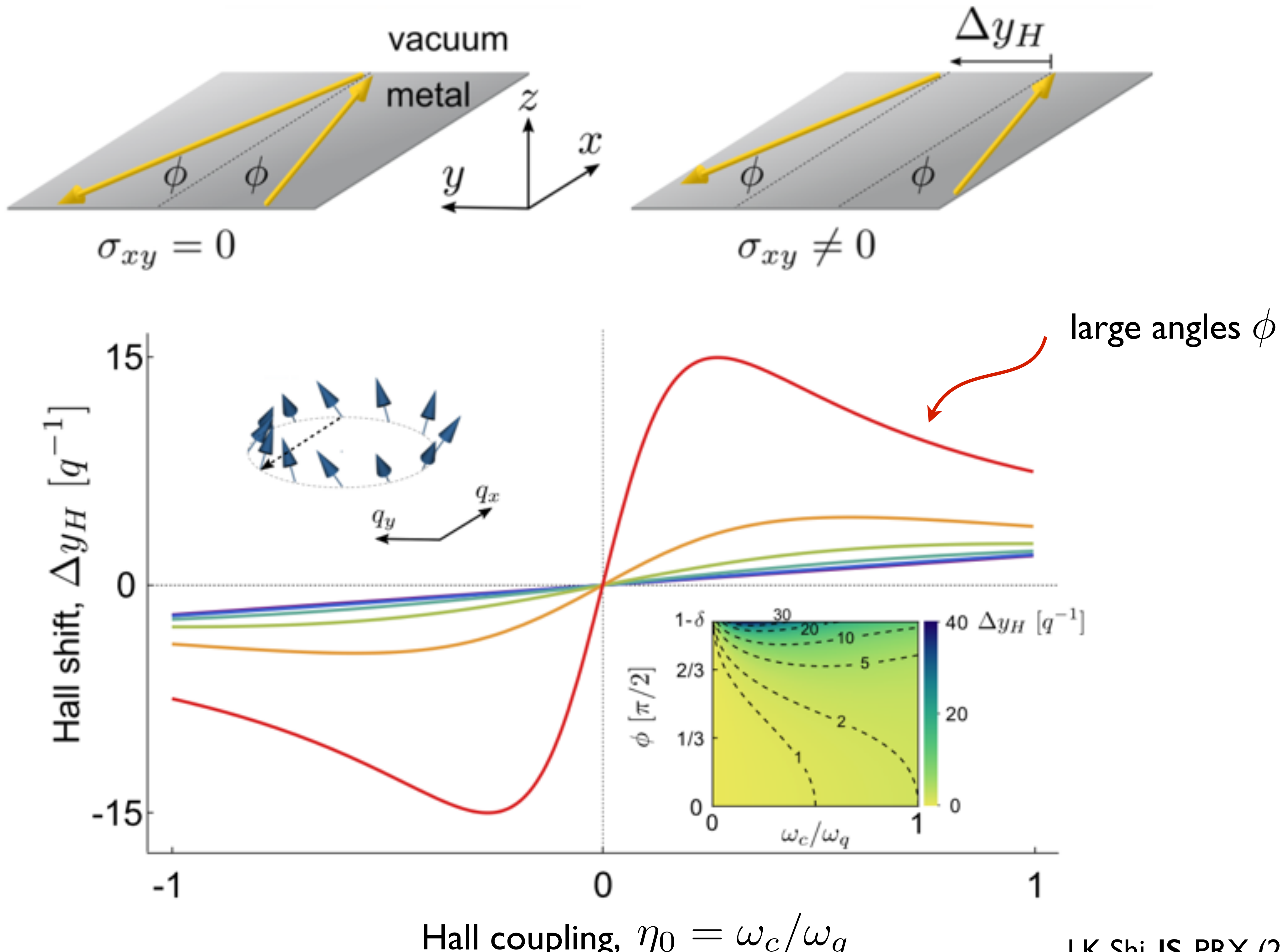




LK Shi, **JS**, PRX (2018)

Geometrical phases: Plasmon Hall effect

Plasmon wavepackets acquire geometrical phases, shifting their reflection trajectories



LK Shi, **JS**, PRX (2018)

Collective modes are platform for new out-of-equilibrium phenomena

* Collective modes can be a platform to realize new spontaneously broken phases

* Collective modes can possess an emergent structure distinct from that of the underlying crystal

References:

Berryogenesis: spontaneous out-of-equilibrium magnetism

MS Rudner, **JS**, arXiv (2018)

Plasmon internal structure and geometric phase

LK Shi, **JS**, PRX (2018)

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