INSTITUTO DE NANOCIENCIA
Y MATERIALES DE ARAGÓN

CSIC
CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

Universidad Zaragoza
1542

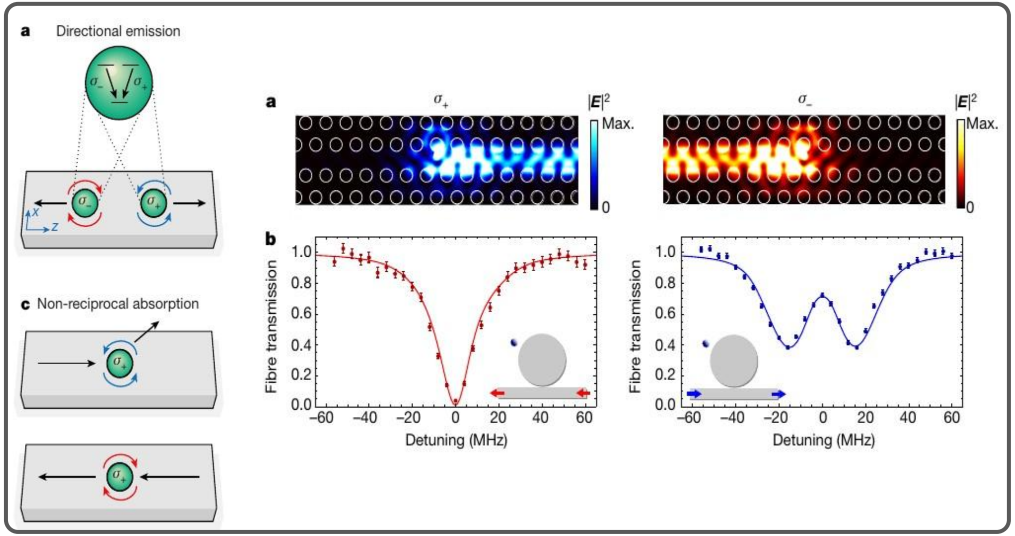
Spin-momentum locking in chiralitonic metasurfaces

Fernando Lorén

loren@unizar.es

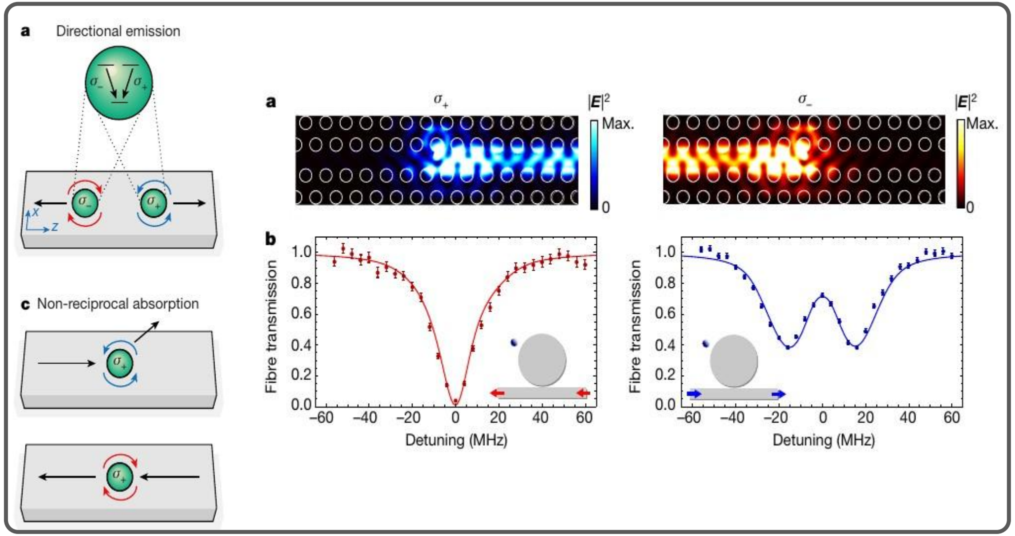
Nanolight 2022, Benasque

Spin-momentum locking



P. Lodahl *et al.*, *Nature* 541, 473-480 (2017)

Spin-momentum locking



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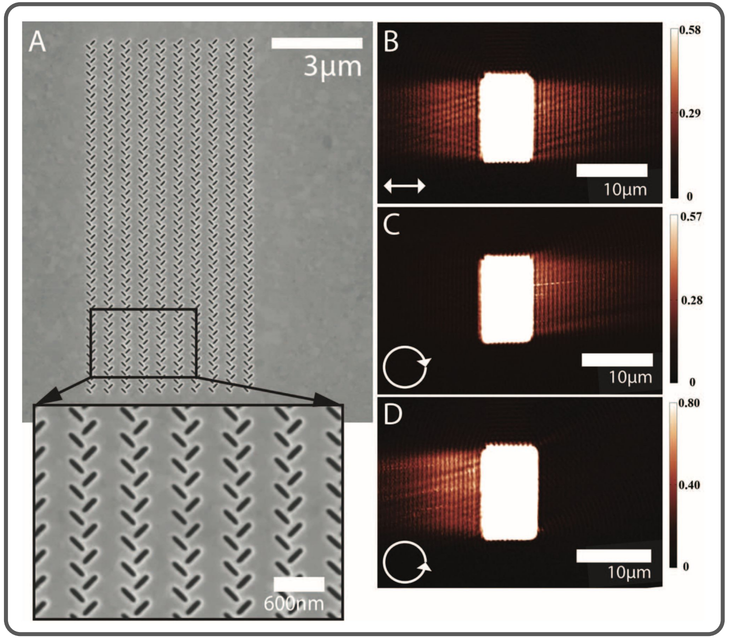
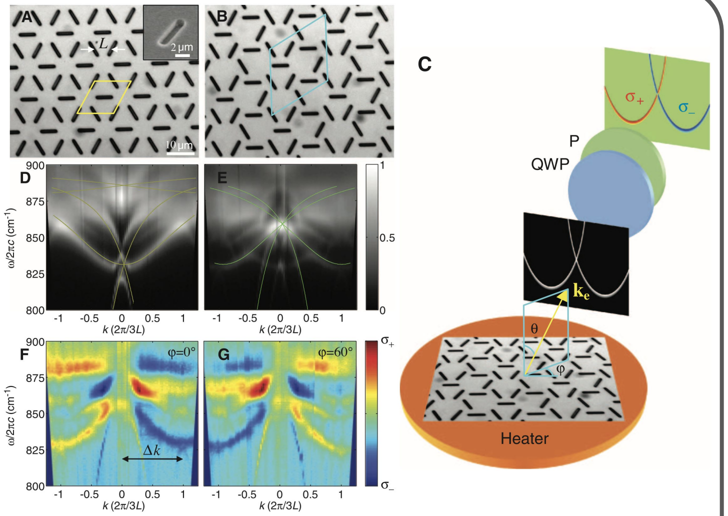


J. Lin *et al. Science* 340, 331-3 (2013)

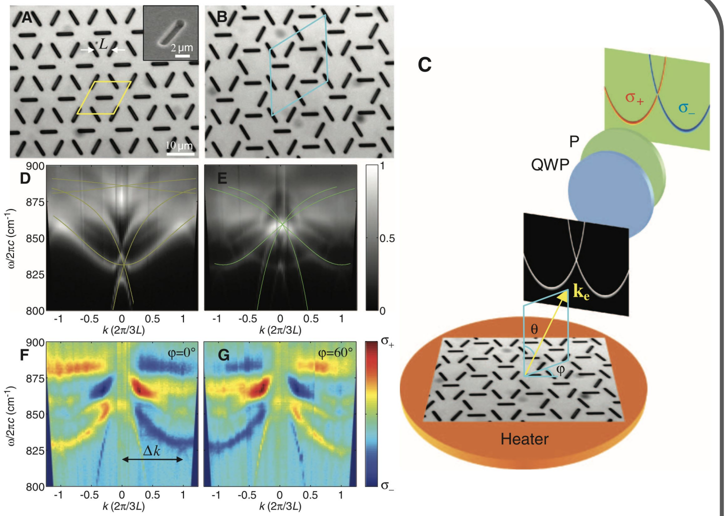
Motivation



$$\mathbf{k}_e^{\|}(\sigma) = \mathbf{k}_{SPP} + m\mathbf{G_1} + n\mathbf{G_2} - \sigma\mathbf{K_i}$$

N. Shitrit *et al.*, *Science* 340, 724-6, (2013)

Motivation



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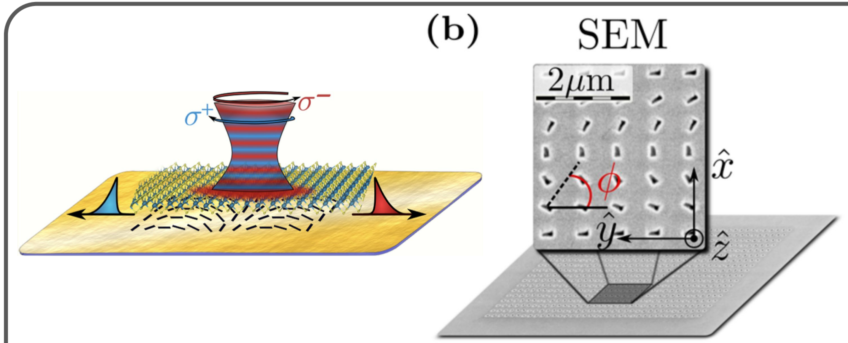
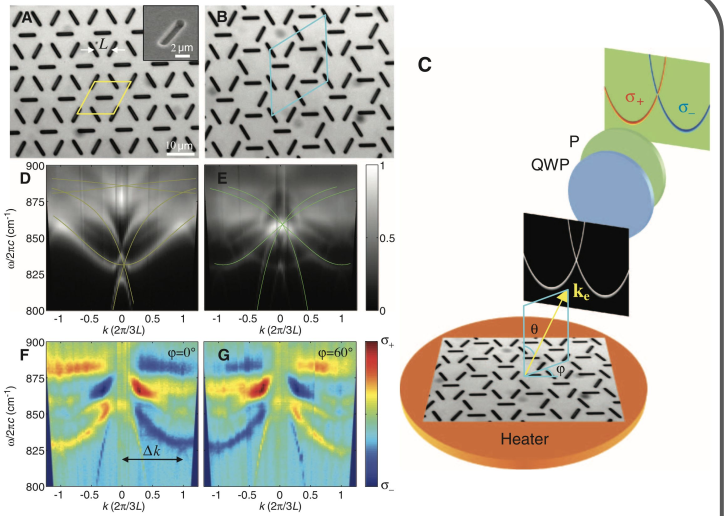


$$\mathbf{k}_{SP} = \mathbf{k}_{in} + 2\pi/\Lambda(n\hat{x} + m\hat{y}) + \mathbf{k}_g$$

T. Chervy *et al.*, *ACS Photonics 5*, 4, 1281–1287, (2018)

Motivation



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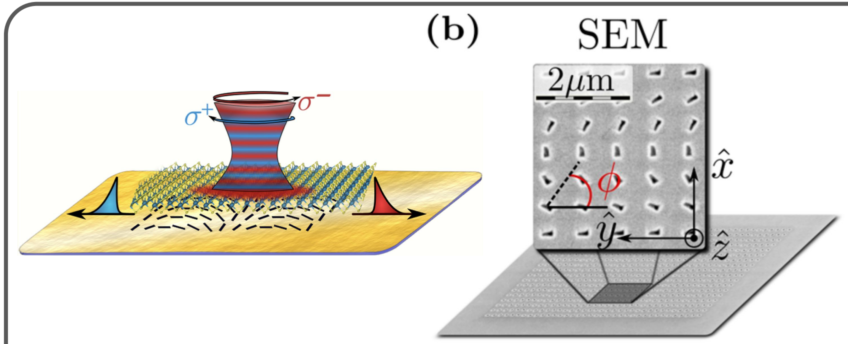

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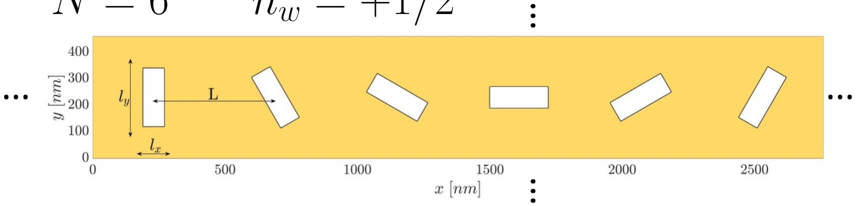
What is the origin of the spin-momentum locking in this corrugated surface without the global translation plus rotation symmetry?

Theoretical model: Coupled mode method

$N = 6$ $n_w = +1/2$



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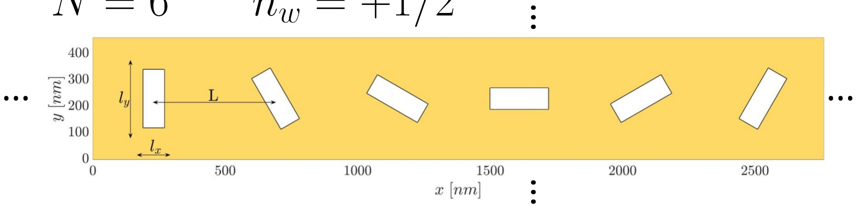

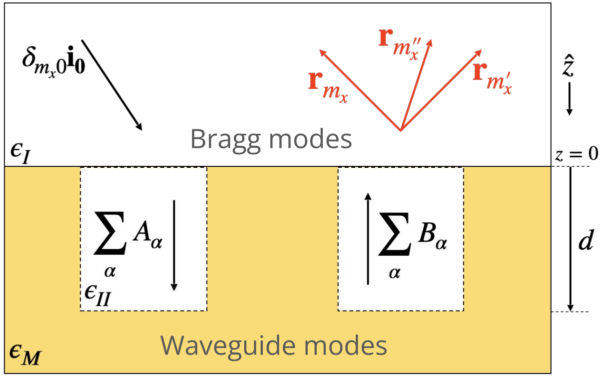

Bragg modes: $\mathbf{G} = m_x \frac{2\pi}{NL}\hat{u}_x + \xcancel{m_y \frac{2\pi}{L}\hat{u}_y}$

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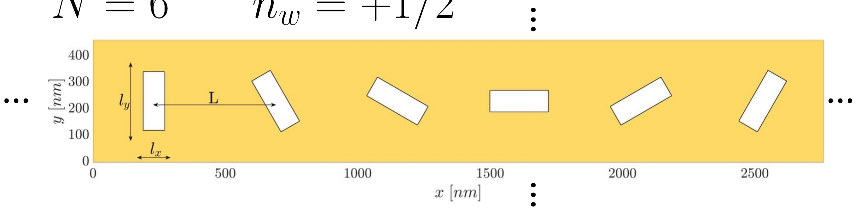

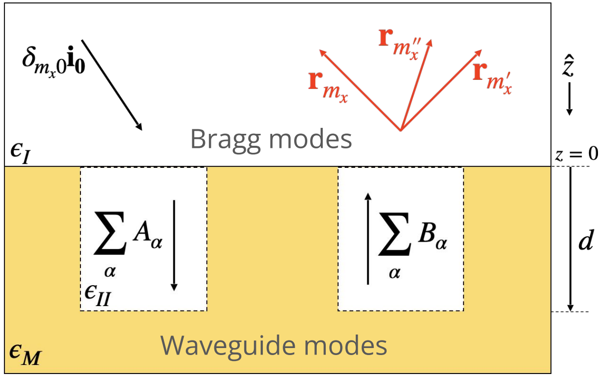

Far-field equations for the **reflection coefficients**

$$\boxed{\mathbf{r}_{m_x} = 2Z_{m_x 0}Y_0\delta_{m_x 0}\mathbf{i}_0 - \sum_{m_x'} Z_{m_x m_x'}Y_{m_x'}\mathbf{r}_{m_x'}}$$

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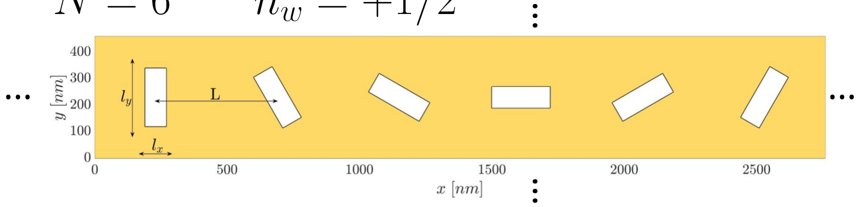

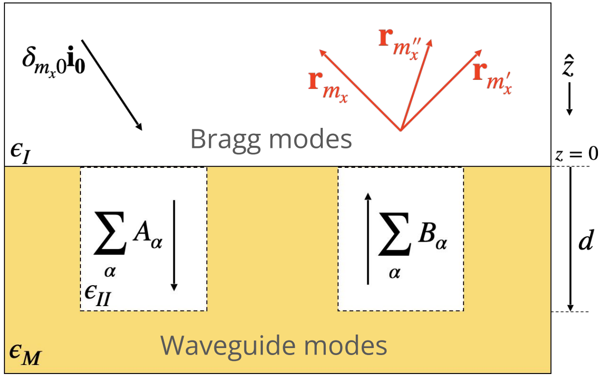

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(Geometric) couplings

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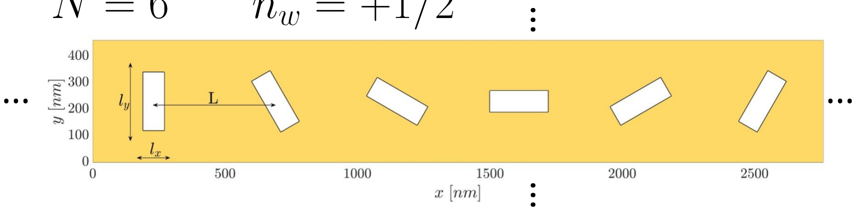

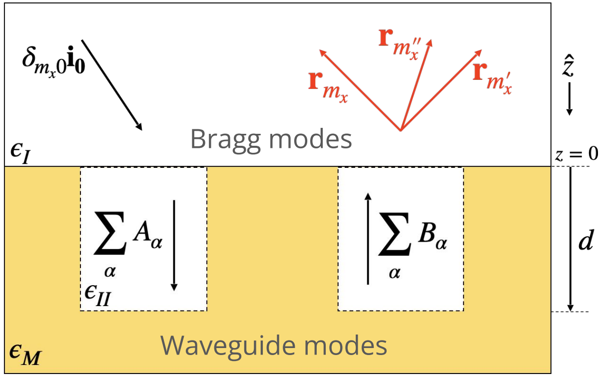

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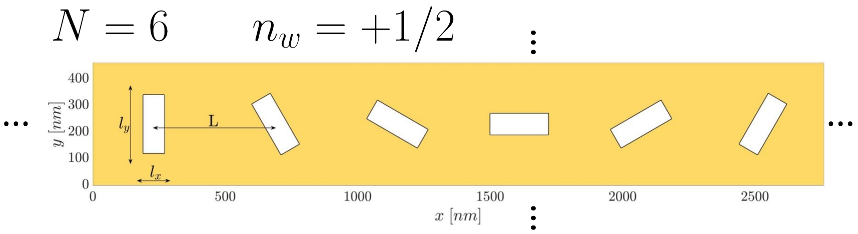
(Geometric) couplings

Modal admittances

Theoretical model: Coupled mode method



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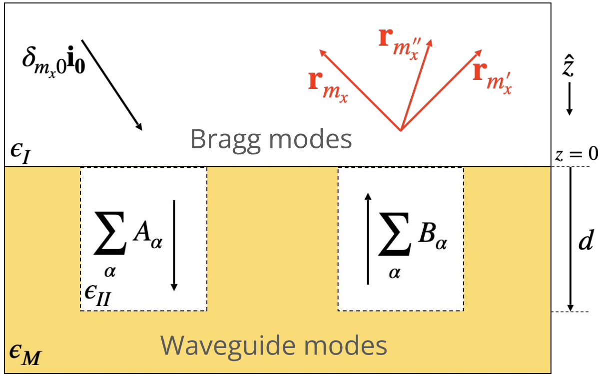

$$\mathbf{i}_0 = \begin{pmatrix} \langle p|\sigma_{in}\rangle \\ \langle s|\sigma_{in}\rangle \end{pmatrix} = \begin{pmatrix} \langle +|\sigma_{in}\rangle \\ \langle -|\sigma_{in}\rangle \end{pmatrix}$$

$$\mathbf{r}_{m'_x} = \begin{pmatrix} r_{m'_x,p} \\ r_{m'_x,s} \end{pmatrix} = \begin{pmatrix} r_{m'_x,+} \\ r_{m'_x,-} \end{pmatrix}$$

$$Y_{m'_x} = \begin{pmatrix} Y_{m'_x,p} & 0 \\ 0 & Y_{m'_x,s} \end{pmatrix}_{ps} = \frac{1}{2}\begin{pmatrix} Y_{m'_x,p} + Y_{m'_x,s} & Y_{m'_x,p} - Y_{m'_x,s} \\ Y_{m'_x,p} - Y_{m'_x,s} & Y_{m'_x,p} + Y_{m'_x,s} \end{pmatrix}_{\pm}$$

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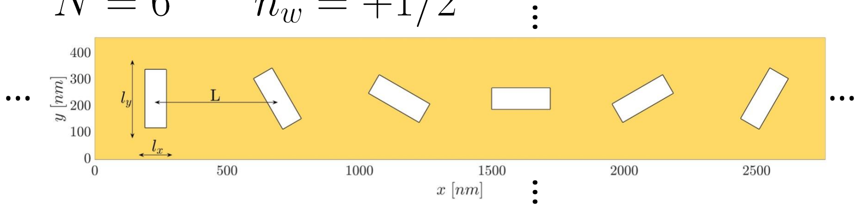

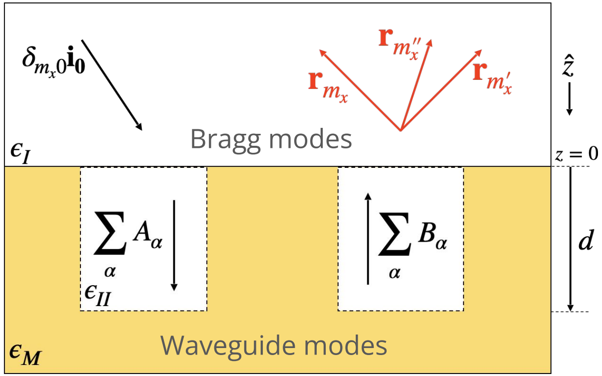

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$$\boxed{\begin{aligned} + &= RCP\\ - &= LCP\end{aligned}}$$

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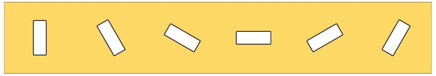
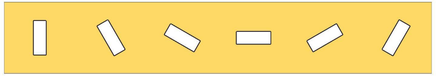
Analysis of the symmetries



$$Z_{m_x m'_x} = ZN \begin{array}{c} \begin{array}{cc} + \rightarrow + \qquad\qquad\qquad & - \rightarrow + \end{array} \\ \begin{pmatrix} \delta_{m_x,m'_x+nN} & \delta_{m_x,m'_x+nN-2n_w} \\ \delta_{m_x,m'_x+nN+2n_w} & \delta_{m_x,m'_x+nN} \end{pmatrix} \\ \begin{array}{cc} + \rightarrow - \qquad\qquad\qquad & - \rightarrow - \end{array} \end{array}$$

Analysis of the symmetries



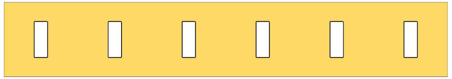
$$Z_{m_x m'_x} = ZN \begin{pmatrix} \overset{+\,\to\,+}{\color{blue}\delta_{m_x,m'_x+nN}} & \overset{-\,\to\,+}{\color{red}\delta_{m_x,m'_x+nN-2n_w}} \\ \underset{+\,\to\,-}{\color{red}\delta_{m_x,m'_x+nN+2n_w}} & \underset{-\,\to\,-}{\color{blue}\delta_{m_x,m'_x+nN}} \end{pmatrix}$$

$$\color{blue}\delta_{m_x,m'_x+nN}$$

standard Bragg's law

$$k_x^{out} = k_x^{in} + n\frac{2\pi}{L} = k_x^{in} + nG^0$$

It is like if the unit cell was...



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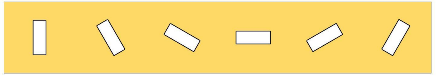

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$$\delta_{m_x,m'_x+nN}$$

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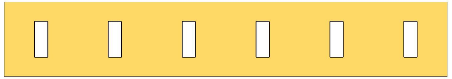

$$\delta_{m_x,m'_x+nN+\sigma_{in}2n_w}$$

spin-orbit Bragg's law

$$k_x^{out} = k_x^{in} + nG^0 + \sigma_{in}\underbrace{2n_w\frac{2\pi}{NL}}_{k_g}$$

SPIN-MOMENTUM LOCKING

Approximate spin-momentum locking

$$\mathbf{r}_{m_x} = 2Z_{m_x0}Y_0\delta_{m_x0}\mathbf{i}_0 - \sum_{m_x'} Z_{m_xm_x'}Y_{m_x'}\mathbf{r}_{m_x'}$$

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$$\Big\downarrow$$

$$\begin{aligned}\mathbf{r}_{m_x} = {} & \left(Y_{0,p} + Y_{0,s}\right) Z_{m_x 0}\, \delta_{m_x 0}\, \mathbf{i}_0 - \sum_{m'_x} \frac{1}{2} \left(Y_{m'_x,p} + Y_{m'_x,s}\right) Z_{m_x m'_x}\, \mathbf{r}_{m'_x} \\ & + \left(Y_{0,p} - Y_{0,s}\right) Z_{m_x 0}\, \sigma^x\, \delta_{m_x 0}\, \mathbf{i}_0 - \sum_{m'_x} \frac{1}{2} \left(Y_{m'_x,p} - Y_{m'_x,s}\right) Z_{m_x m'_x}\, \sigma^x\, \mathbf{r}_{m'_x}\end{aligned}$$

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perfect spin-momentum locking

$$\begin{aligned}\mathbf{r}_{m_x} = &\boxed{\left(Y_{0,p} + Y_{0,s}\right) Z_{m_x0}\, \delta_{m_x0}\, \mathbf{i}_0 - \sum_{m'_x} \frac{1}{2}\left(Y_{m'_x,p} + Y_{m'_x,s}\right) Z_{m_xm'_x}\, \mathbf{r}_{m'_x}} \\ &+ \left(Y_{0,p} - Y_{0,s}\right) Z_{m_x0}\, \sigma^x\, \delta_{m_x0}\, \mathbf{i}_0 - \sum_{m'_x} \frac{1}{2}\left(Y_{m'_x,p} - Y_{m'_x,s}\right) Z_{m_xm'_x}\, \sigma^x\, \mathbf{r}_{m'_x}\end{aligned}$$

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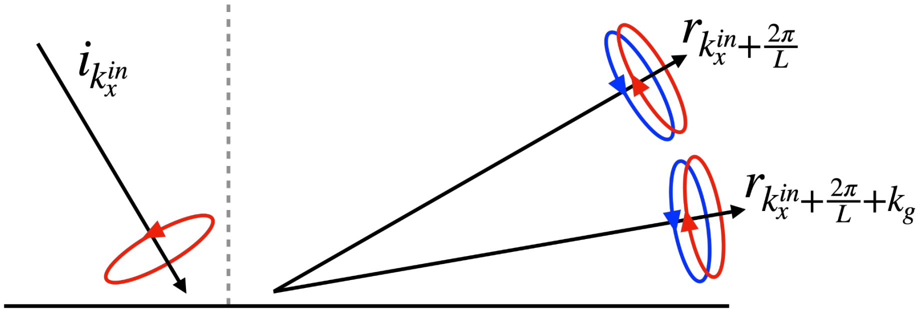
spin-momentum locking breakdown

Approximate spin-momentum locking



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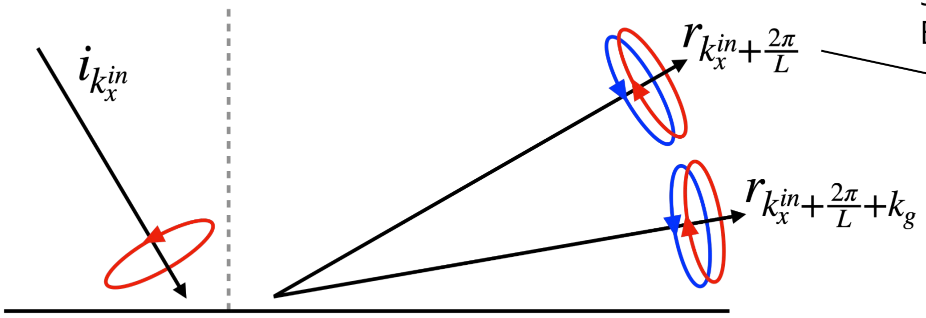
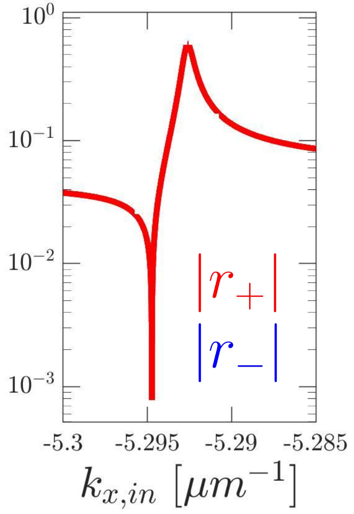


standard
Bragg's law



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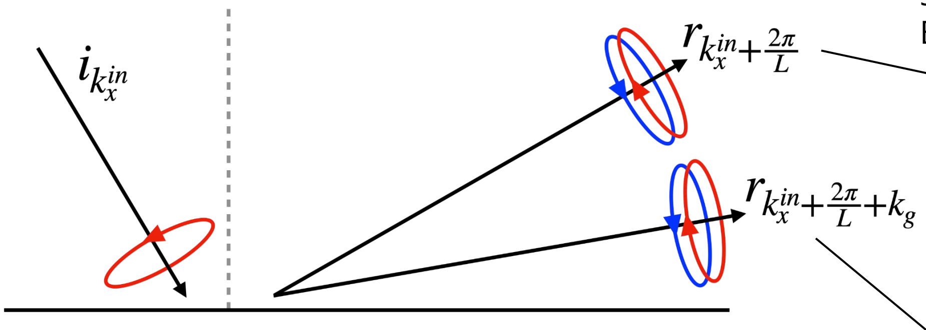
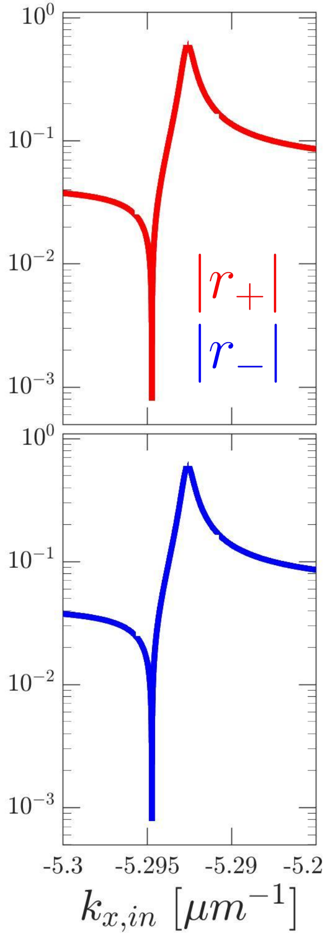


standard
Bragg’s law

spin-orbit
Bragg’s law



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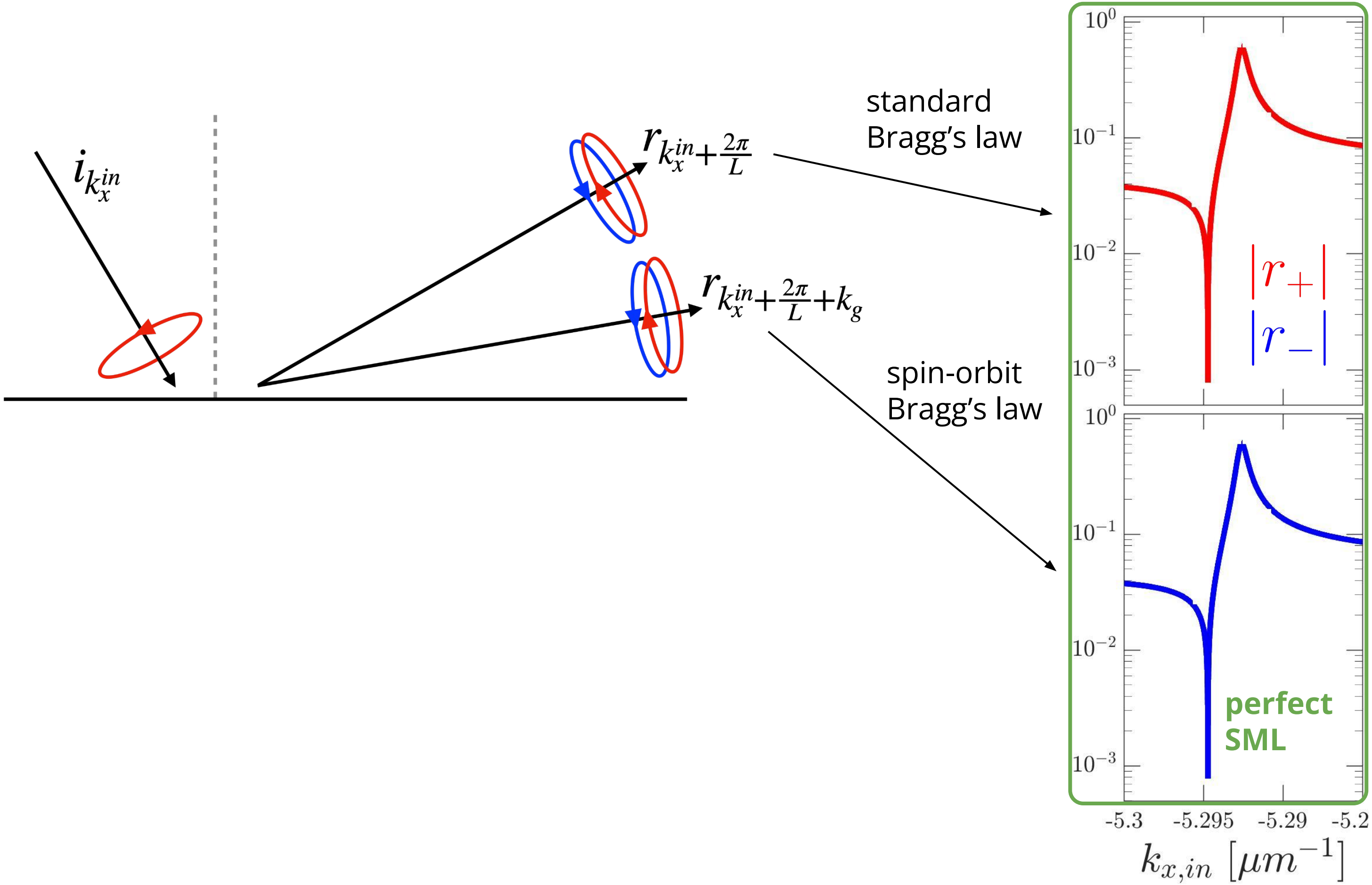

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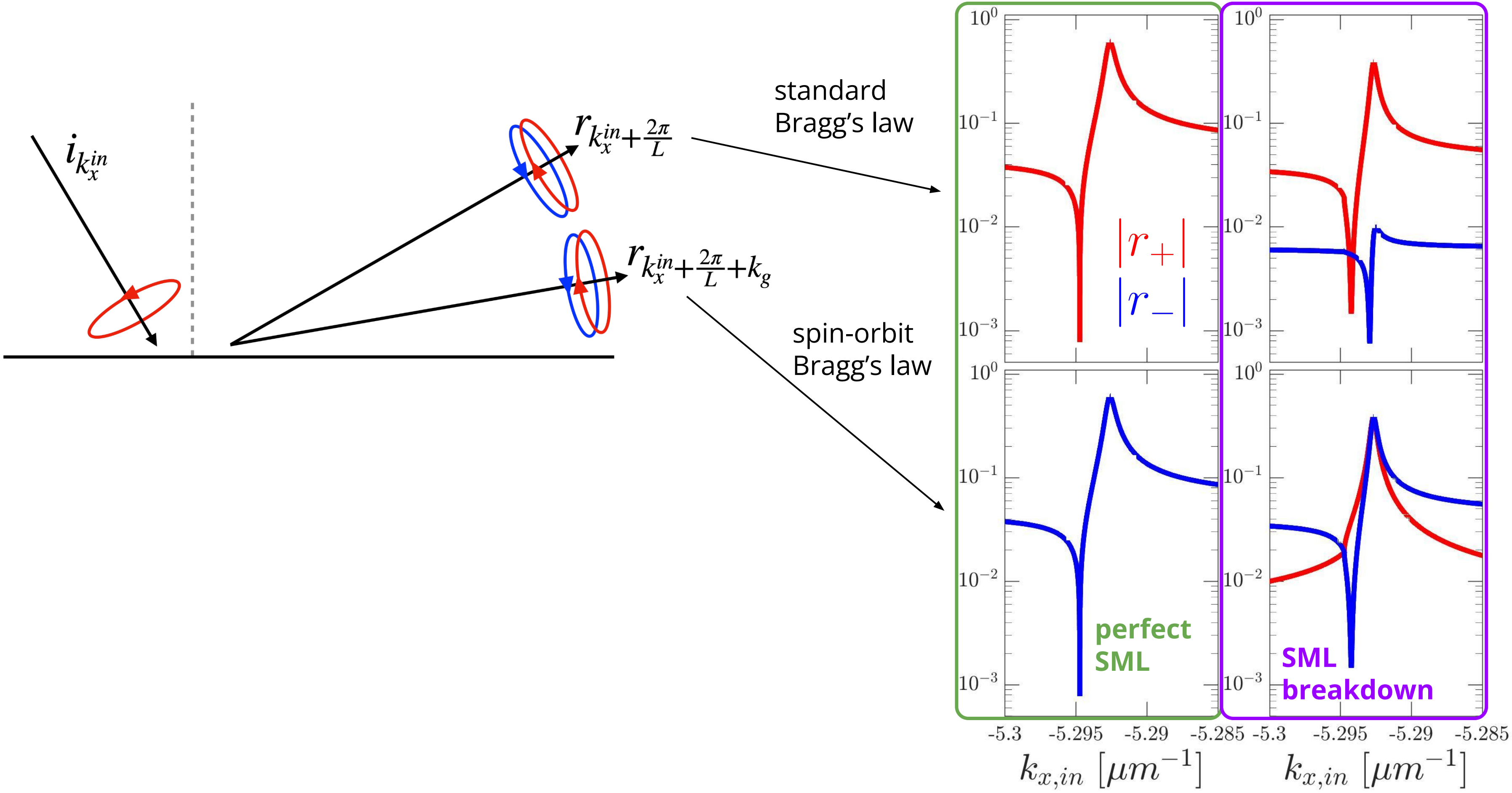

standard Bragg's law

spin-orbit Bragg's law

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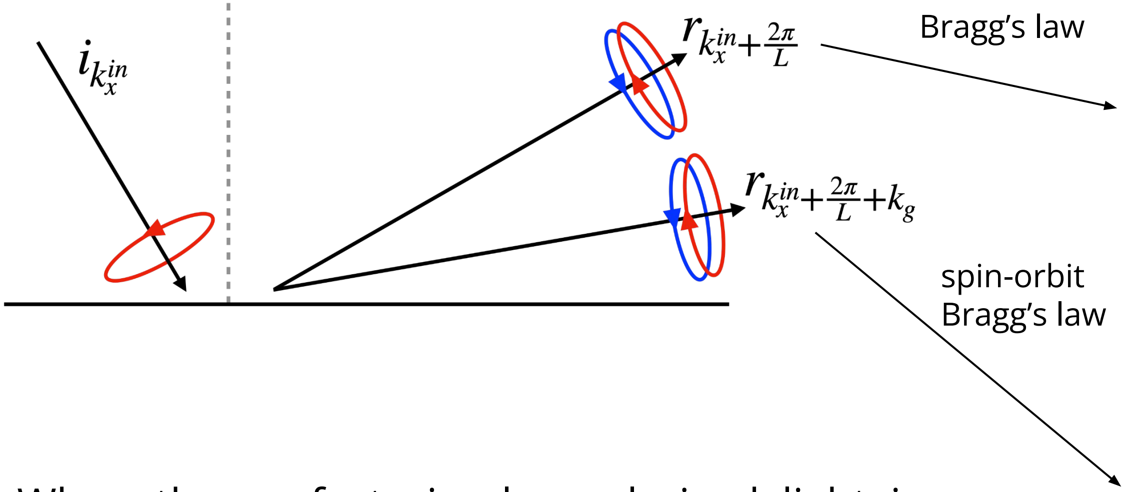

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spin-orbit
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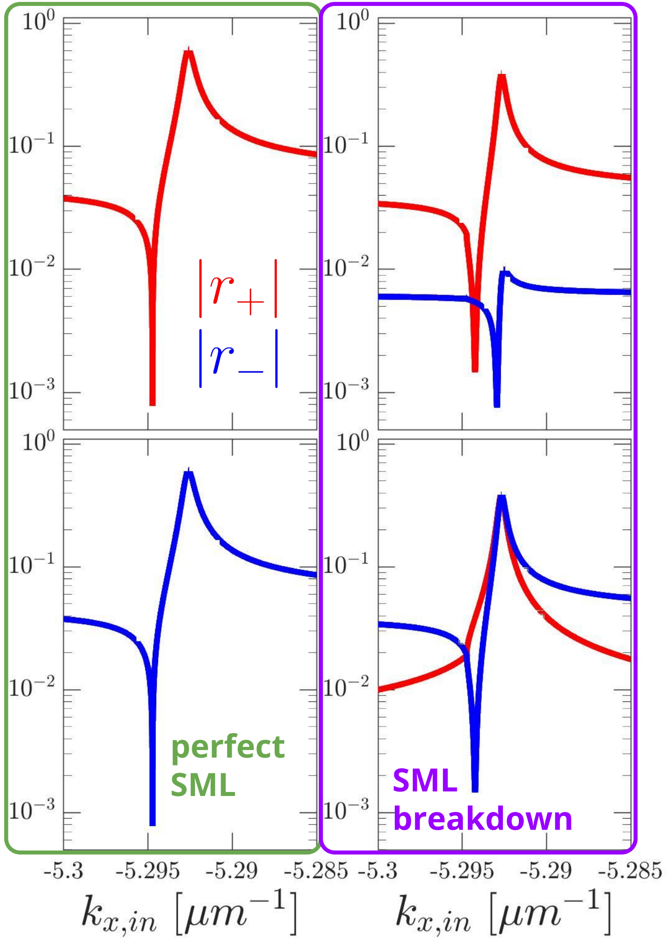

perfect SML

SML breakdown

When the perfect circular polarized light is projected onto the metasurface symmetries, it becomes helical and the **spin-momentum locking is spoiled in spin**

Mueller polarimetry

$$M_{30} = \frac{S^3_{out}}{S^0_{in}} = \frac{I^+_{out} - I^-_{out}}{I^0_{in}(\text{unpol.})}$$

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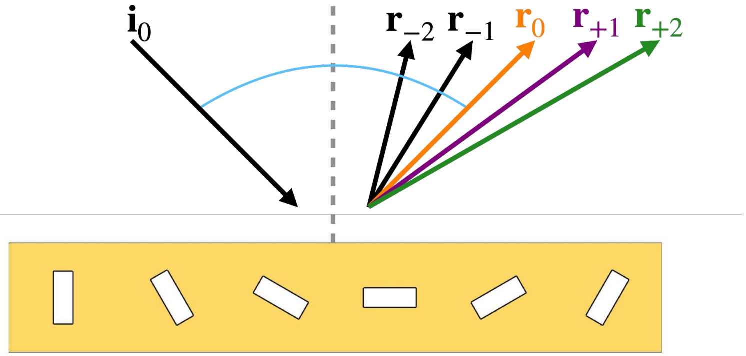

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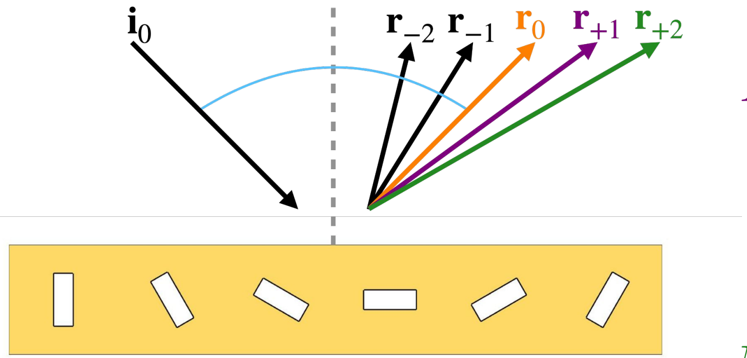
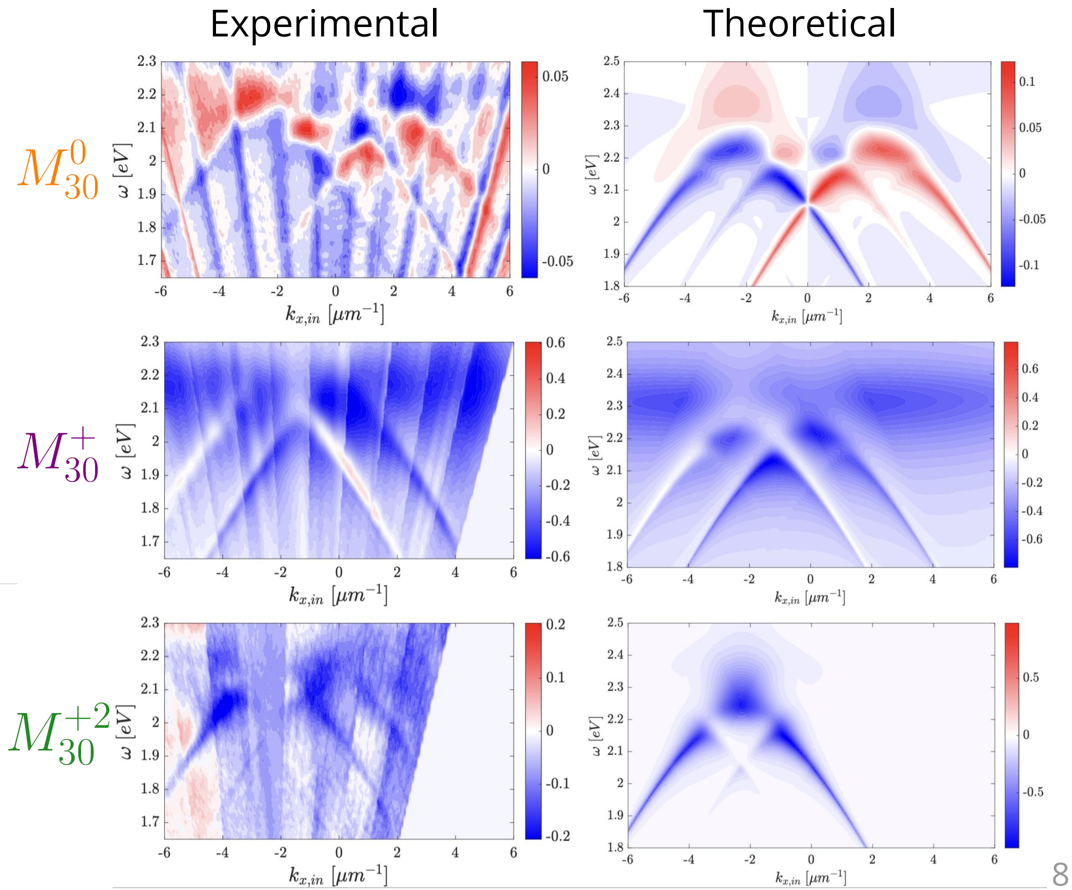


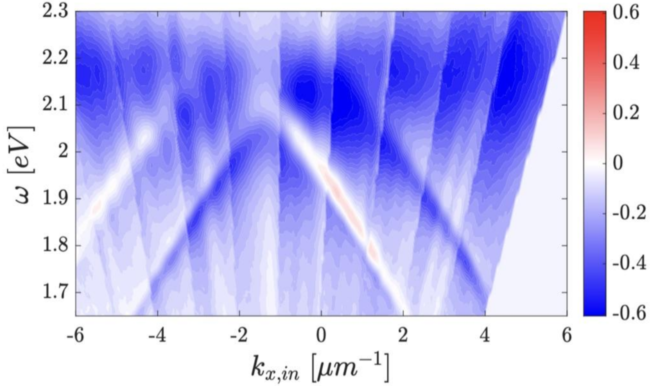


Mueller polarimetry

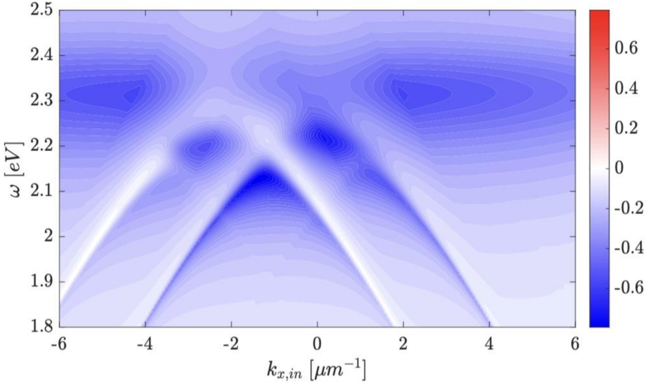
$$M_{30}^{+}$$

$$k_x^{out} = k_x^{in} + k_g$$

Experimental



Theoretical

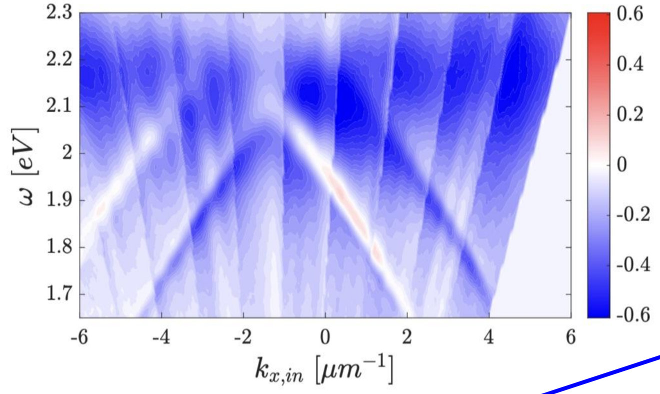


Mueller polarimetry

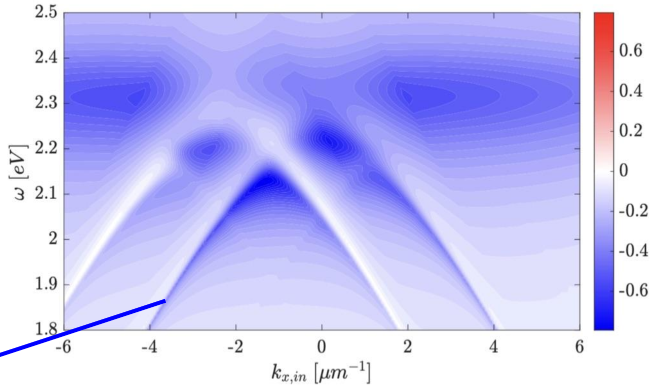
$$M_{30}^{+}$$

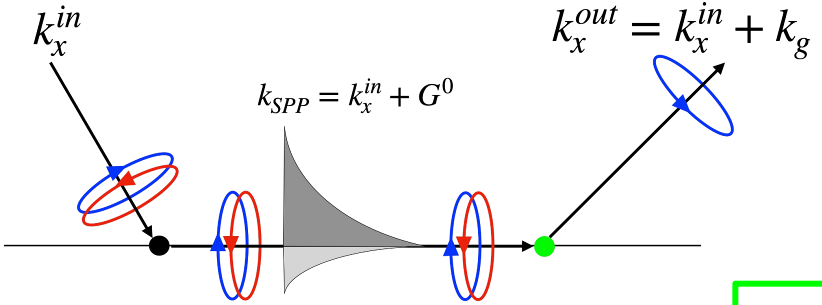
$$k_x^{out} = k_x^{in} + k_g$$

Experimental



Theoretical





standard
Bragg's law

spin-orbit
Bragg's law

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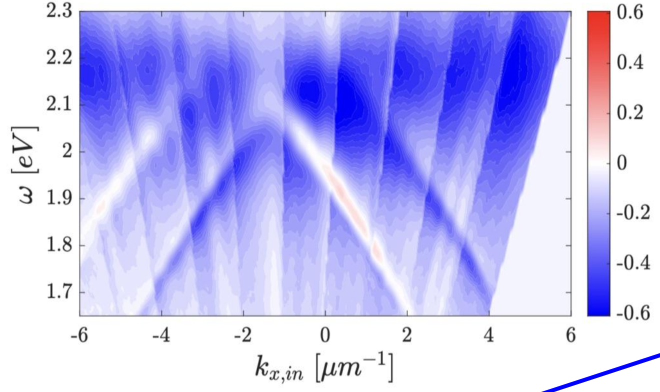
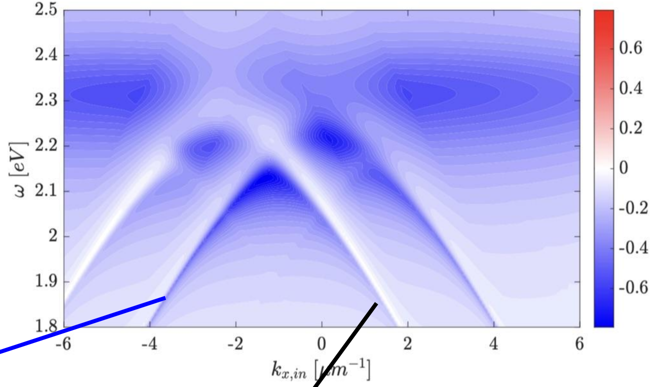
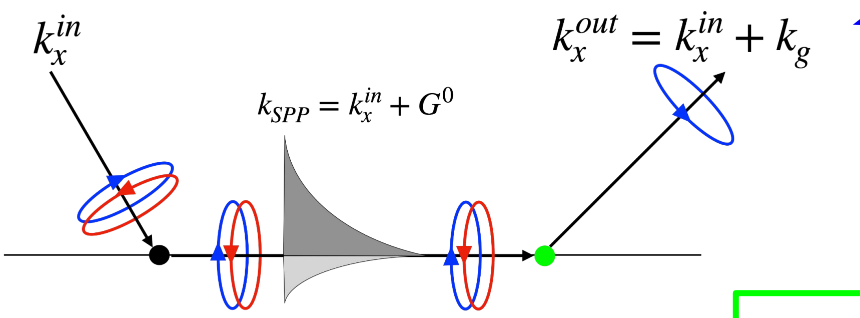
Experimental

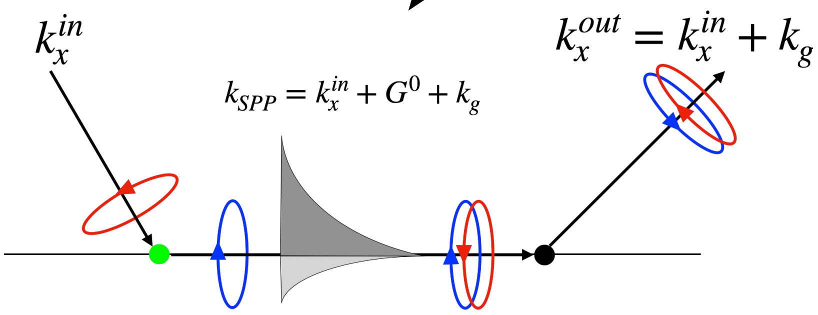


Theoretical





standard
Bragg's law



spin-orbit
Bragg's law

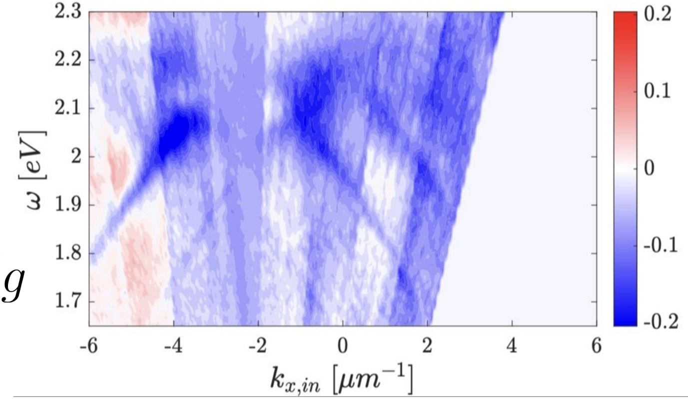
standard
Bragg's law

Mueller polarimetry

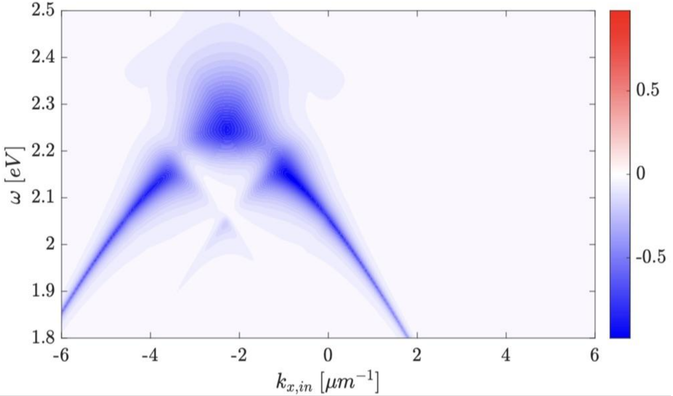
$$M_{30}^{+2}$$

$$k_x^{out} = k_x^{in} + 2k_g$$

Experimental



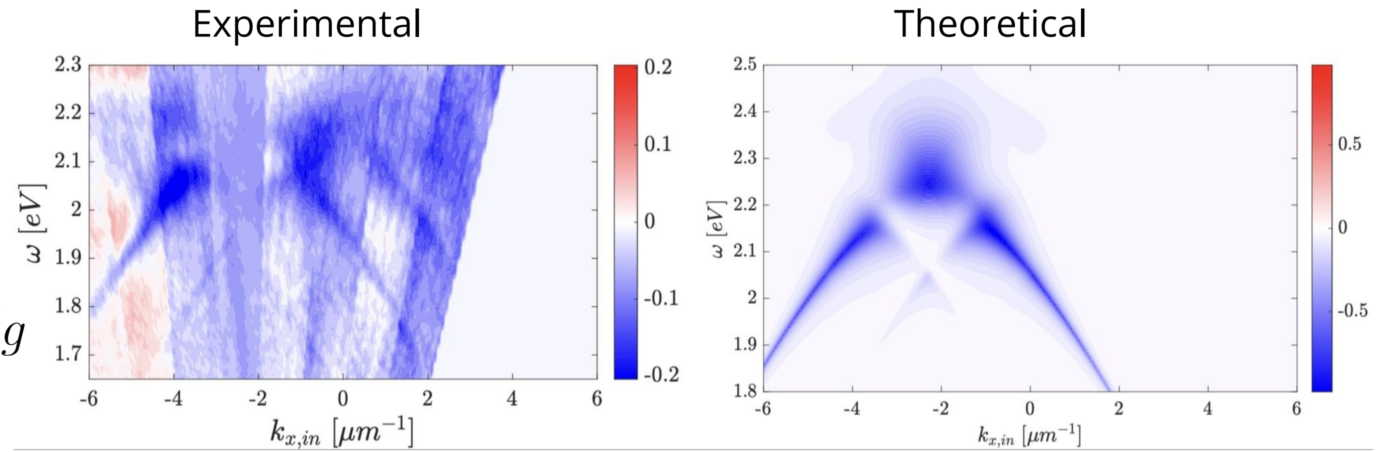
Theoretical



Mueller polarimetry

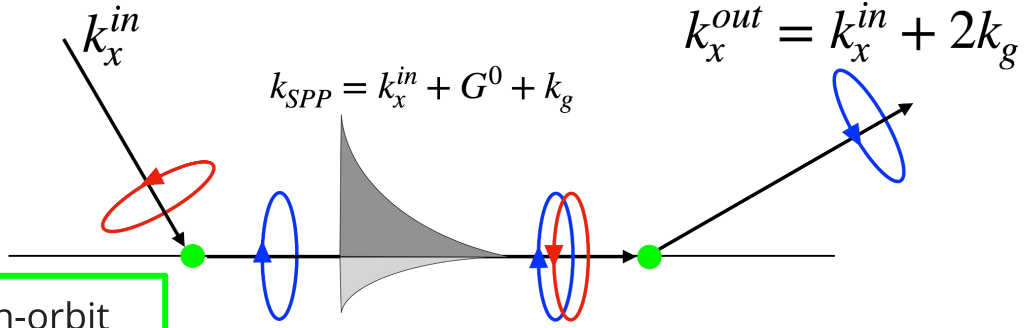
$$M_{30}^{+2}$$

$$k_x^{out} = k_x^{in} + 2k_g$$



Experimental

Theoretical



k_x^{in}

$k_{SPP} = k_x^{in} + G^0 + k_g$

$k_x^{out} = k_x^{in} + 2k_g$

spin-orbit
Bragg's law

Summary

- We have demonstrated that the **spin-momentum locking does not require global symmetries** and already appears when elements in the unit cell have a non-zero winding number.

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Summary

- We have demonstrated that the **spin-momentum locking does not require global symmetries** and already appears when elements in the unit cell have a non-zero winding number.

- In both cases, **spin-momentum locking is an approximate symmetry**. The reason for this is that circularly polarized light gets an elliptical projection onto the surface away from normal incidence.

- Mueller polarimetry demonstrates that, phenomenologically, we can explain the **plasmonic resonances as two-steps processes**.

Acknowledgements

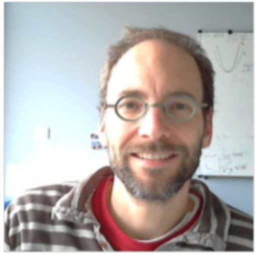
Supervisor

Luis Martín-Moreno

INMA
CSIC-Universidad de Zaragoza

Collaborators

Gian Lorenzo
Paravicini-Bagliani



Cyriaque Genet

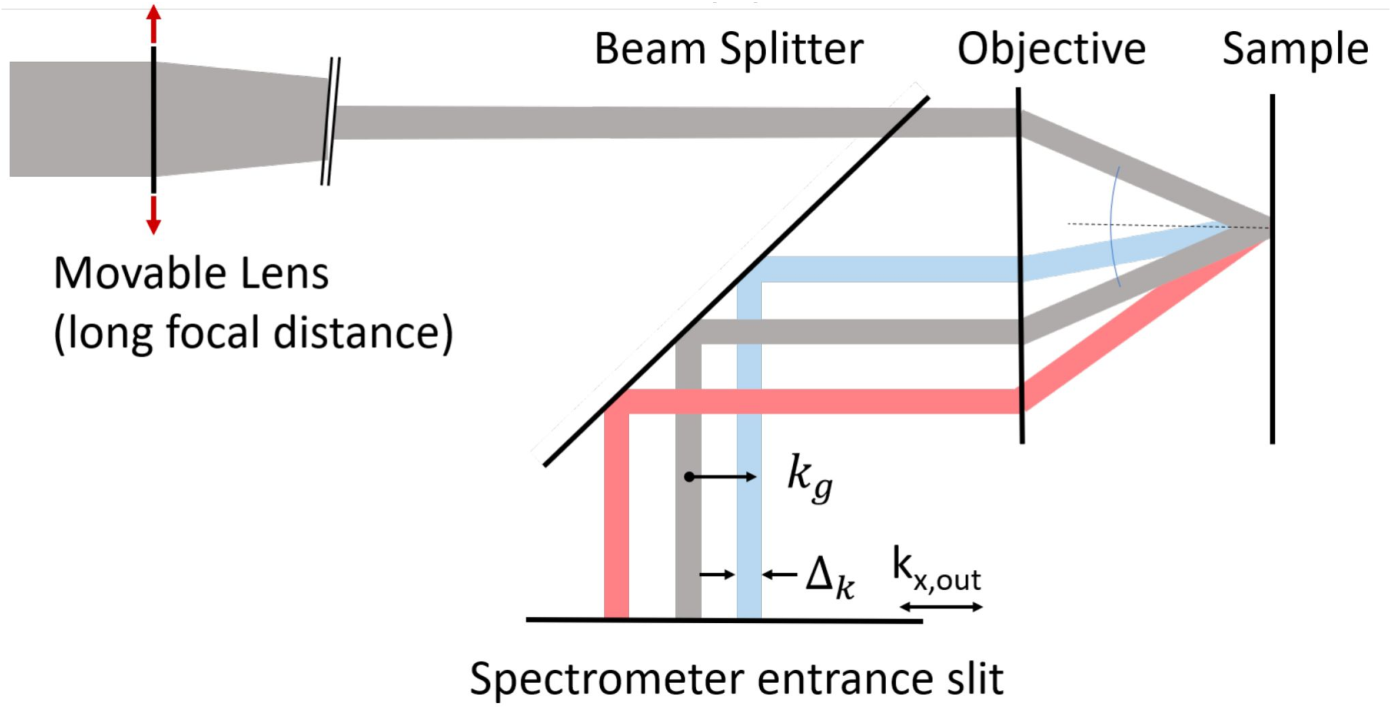
Sudipta Saha

ISIS
CNRS-Université de Strasbourg

Thank you for
your attention!

loren@unizar.es

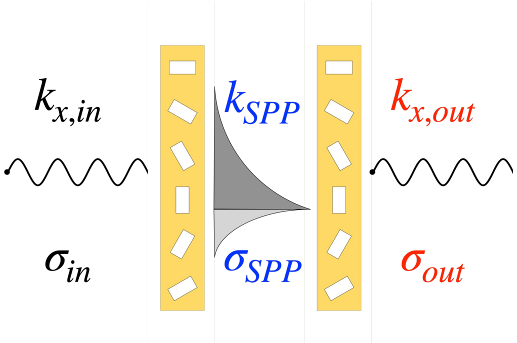
Experimental set-up



Photon-plasmon-photon scattering

At the **plasmonic resonance**

Two-steps scattering process
photon-plasmon-photon

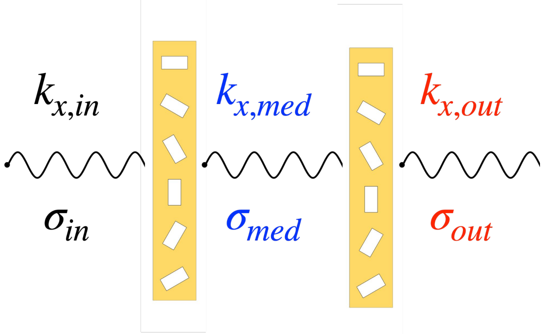


$$k_{SPP} = k_{x,in} + s_1 k_g$$
$$|\sigma_{SPP}\rangle = |p\rangle \langle p| \hat{\sigma}^{-s_1} |\sigma_{in}\rangle$$

$$k_{x,out} = k_{SPP} + s_2 k_g = k_{x,in} + (s_1 + s_2) k_g$$
$$|\sigma_{out}\rangle = \hat{\sigma}^{-s_2} |\sigma_{SPP}\rangle = \langle p| \hat{\sigma}^{-s_1} |\sigma_{in}\rangle \hat{\sigma}^{-s_2} |p\rangle$$

Out of the plasmonic resonance

Two-steps scattering process
photon-photon-photon

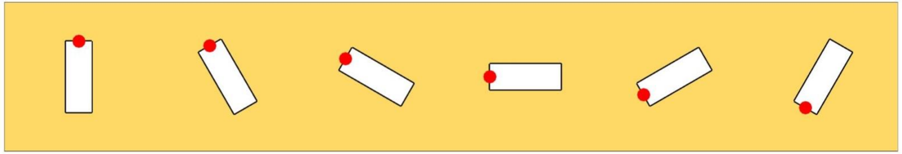


$$k_{x,med} = k_{x,in} + s_1 k_g$$
$$|\sigma_{med}\rangle = \hat{\sigma}^{-s_1} |\sigma_{in}\rangle$$

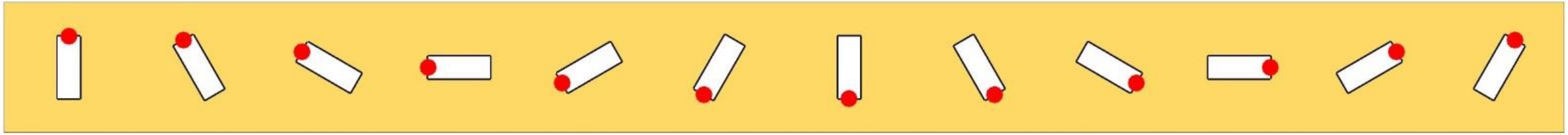
$$k_{x,out} = k_{x,med} + s_2 k_g = k_{x,in} + (s_1 + s_2) k_g$$
$$|\sigma_{out}\rangle = \hat{\sigma}^{-s_2} |\sigma_{med}\rangle = \hat{\sigma}^{-(s_1+s_2)} |\sigma_{in}\rangle$$

Winding number

$$N = 6 \qquad n_w = +1/2$$

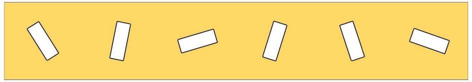


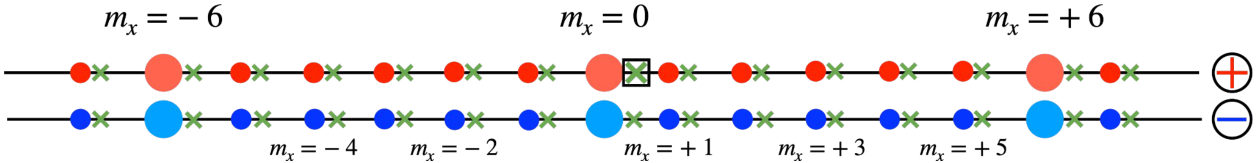
$$N = 12 \qquad n_w = +1$$



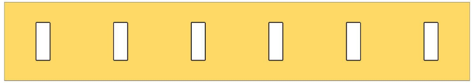
Fourier representation of the symmetries

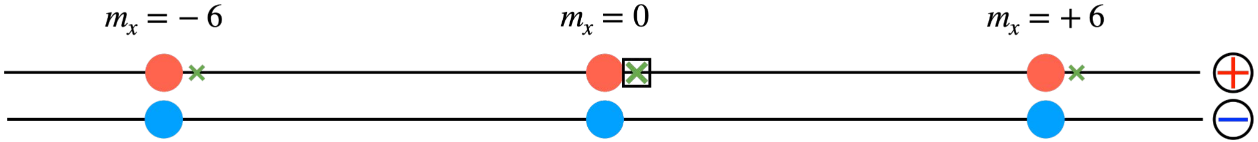
Disordered unit cell



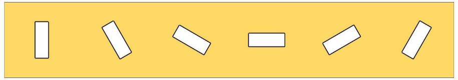


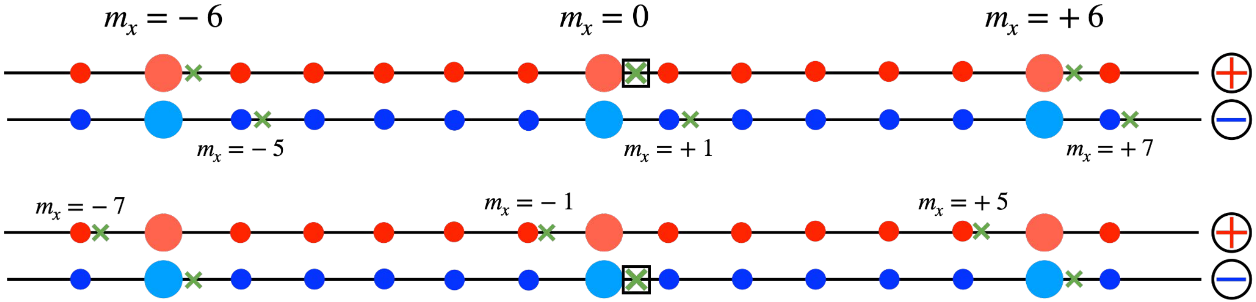
Ordered unit cell





Chiral unit cell



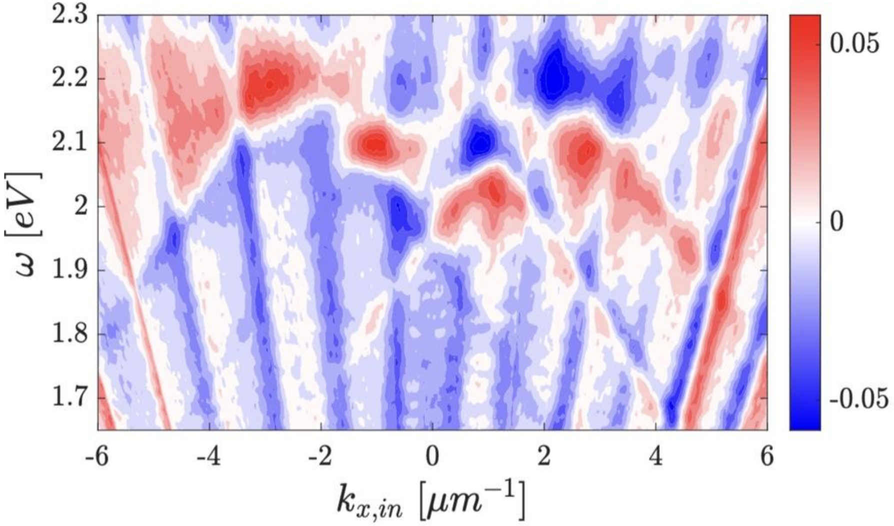


Mueller polarimetry

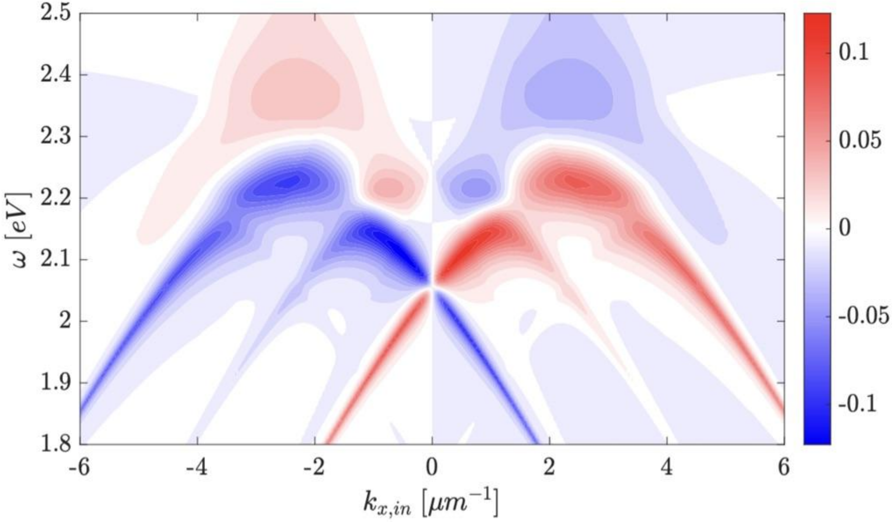
M_{30}^{0}

$$k_{x,out} = k_{x,in}$$

Experimental



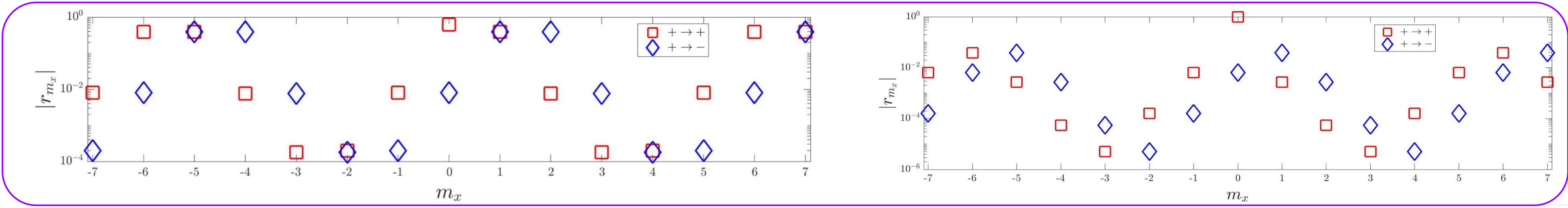
Theoretical



Breakdown hierarchy

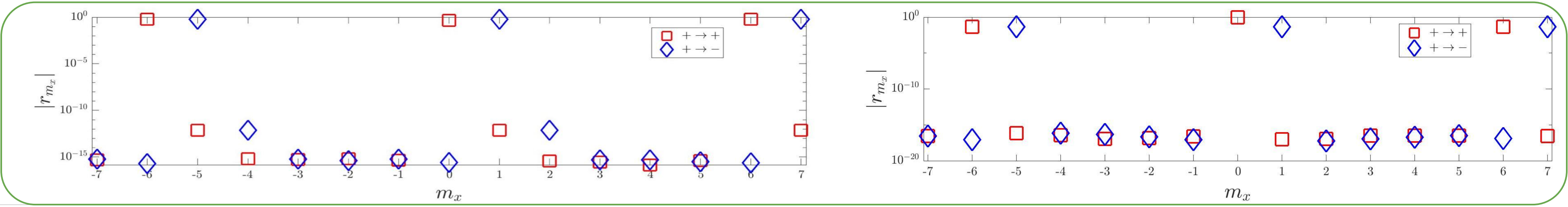
Plasmonic resonance

Out of plasmonic resonance

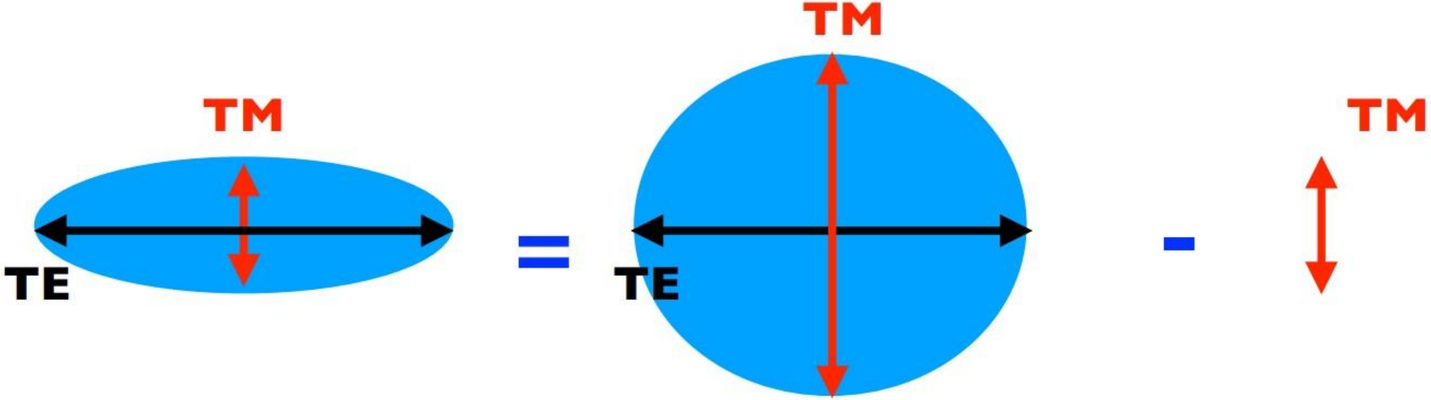


SML breakdown

perfect SML



Helical light



$\sim \ \sigma^+$

$\sim \ \sigma^+ + \sigma^-$