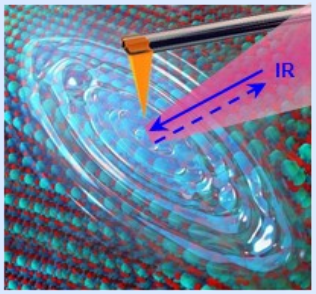
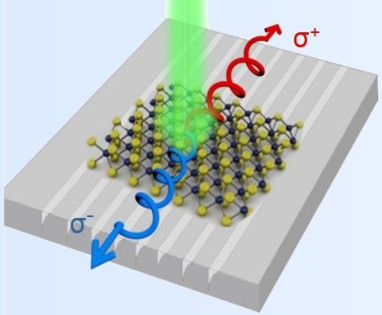
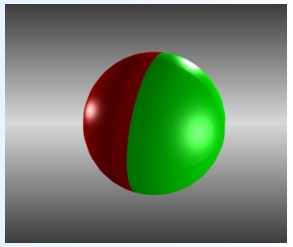




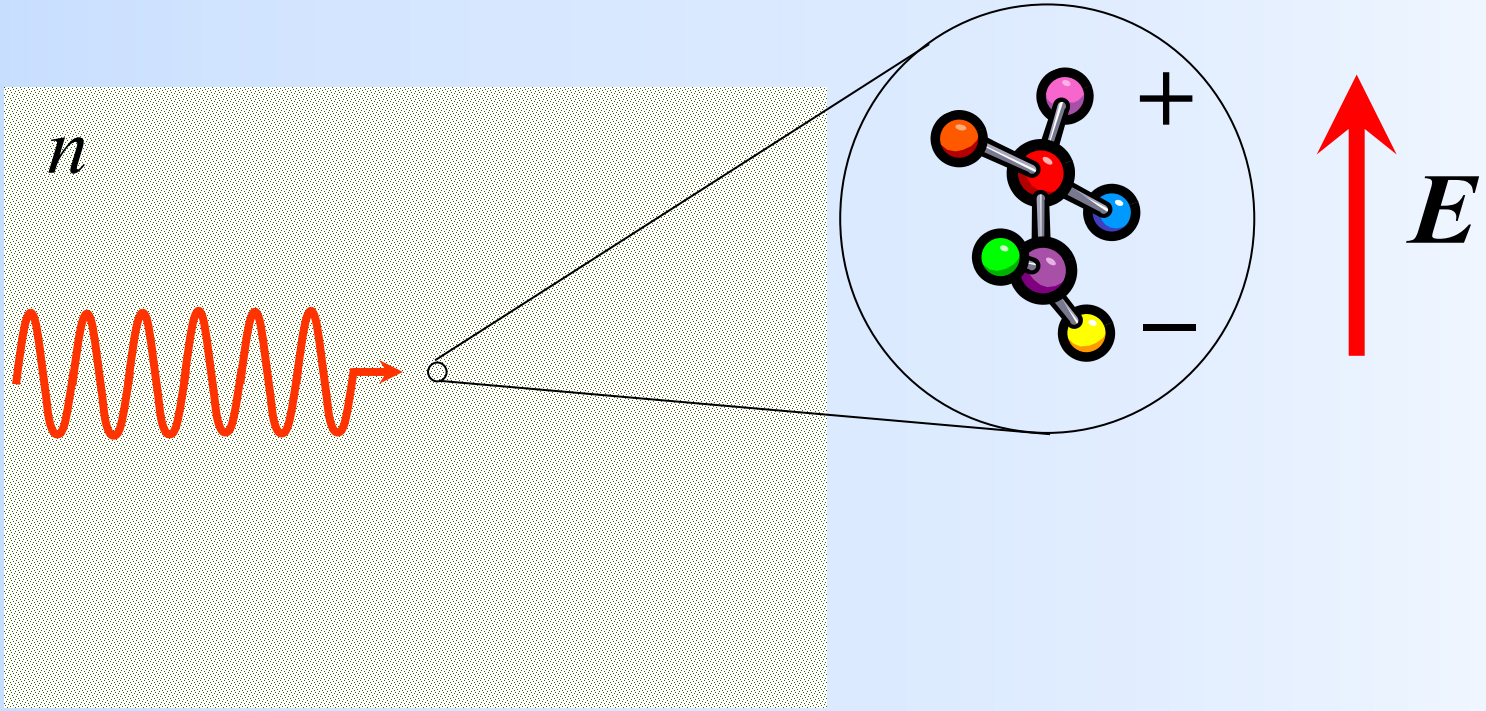


Optical Metamaterials Based on Broken Symmetries

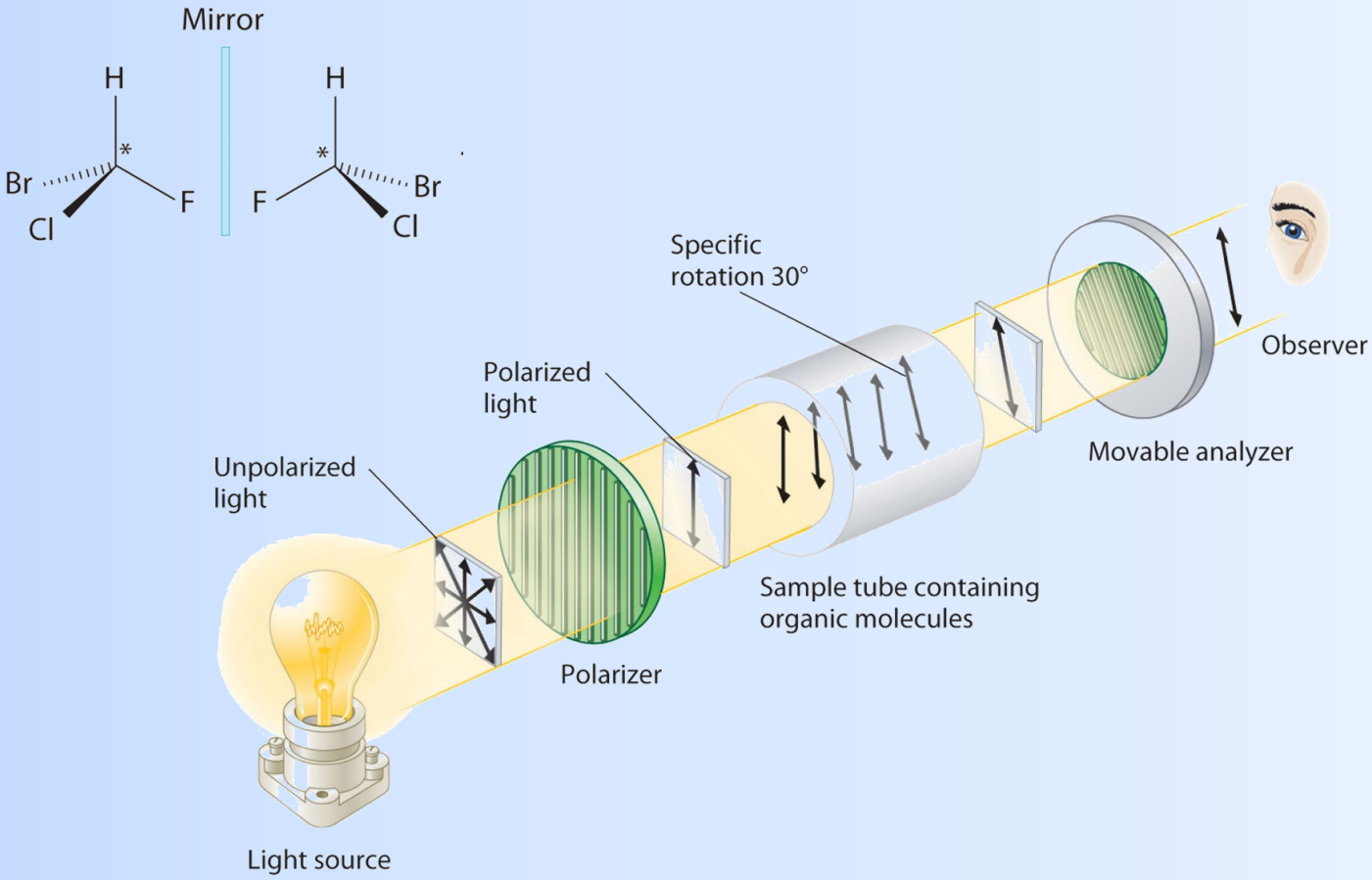
Andrea Alù

Photonics Initiative, CUNY Advanced Science Research Center
Physics Program, CUNY Graduate Center
Department of Electrical Engineering, City College of New York, CUNY
http://alulab.org, aalu@gc.cuny.edu

Light Interactions with Materials

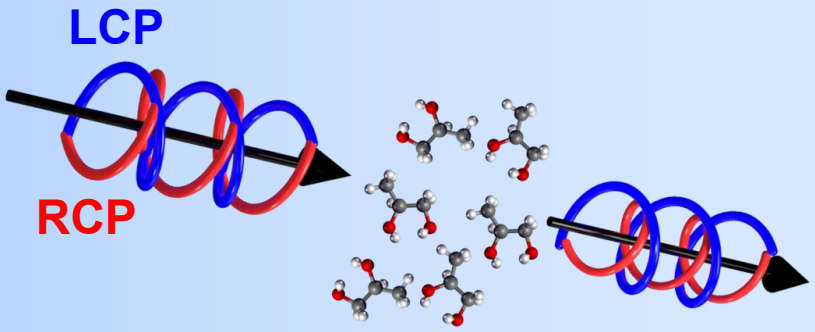


Chiral Molecules and Optical Activity

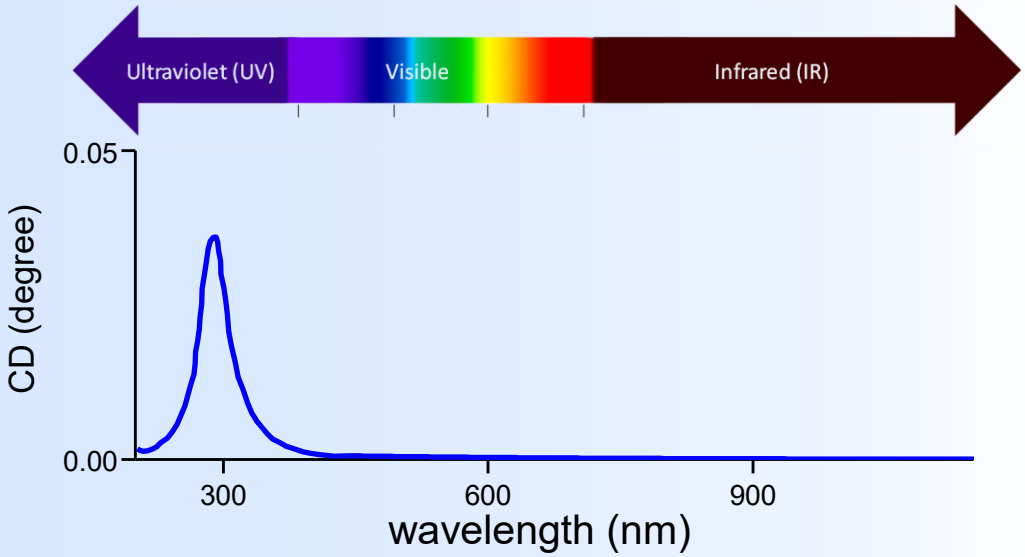


B. A. Averill, *General Chemistry: Principles and Applications* (2007)

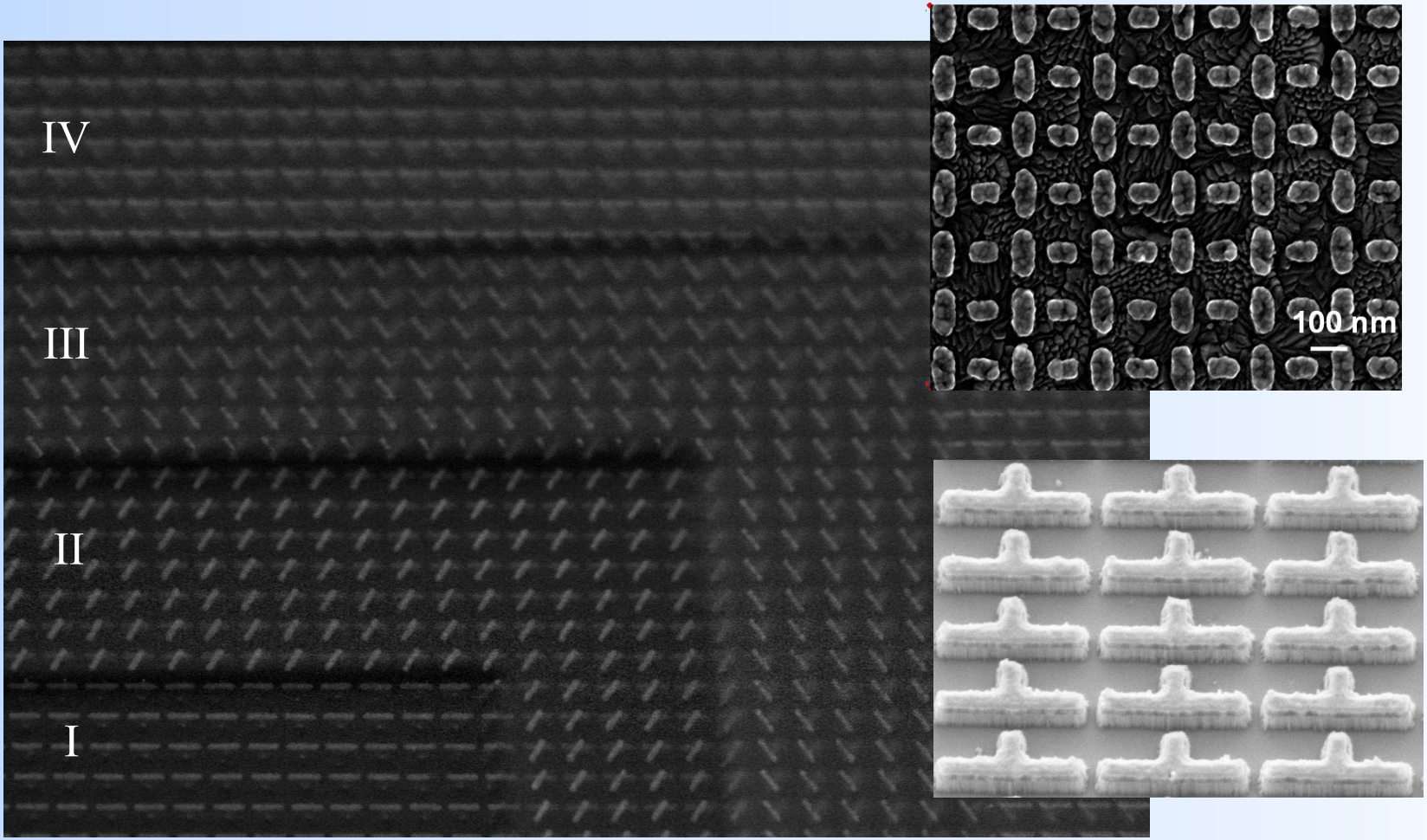
Circular Dichroism of Chiral Molecules



$$CD \propto A_{LCP} - A_{RCP}$$

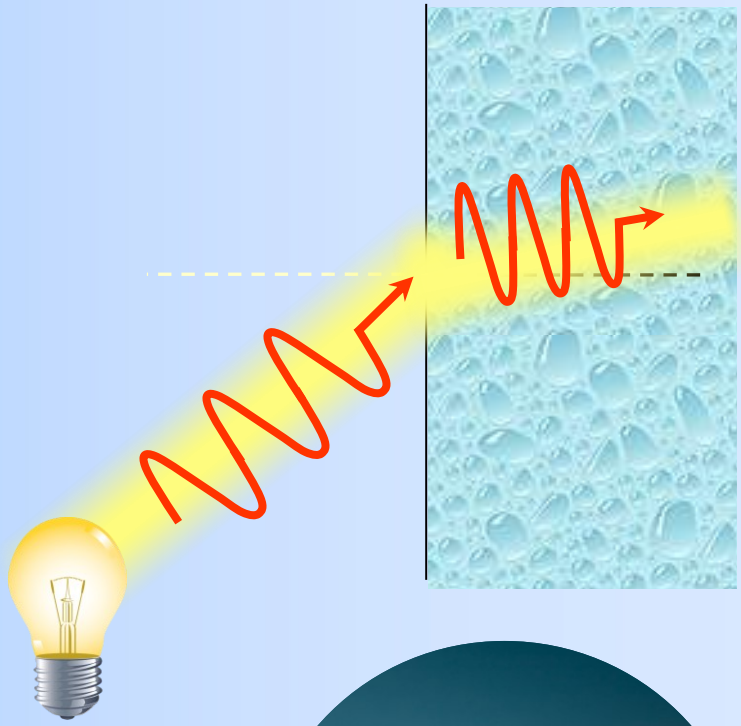


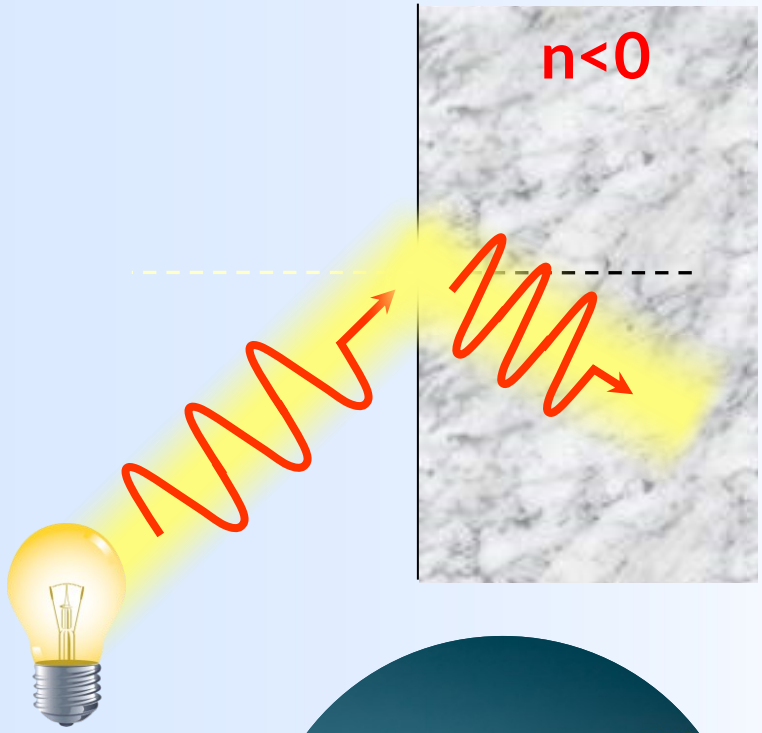
META-MATERIALS: *BEYOND* NATURE WITH ARTIFICIAL MATERIALS



Y. Zhao, M. Belkin, A. Alù, *Nature Comm.* **3**, 870 (2012)
Y. Zhao, A. Alù, *Nano Lett.* **13**, 1086 (2013)
J. Lee, et al., *Nature* **511**, 65 (2014)

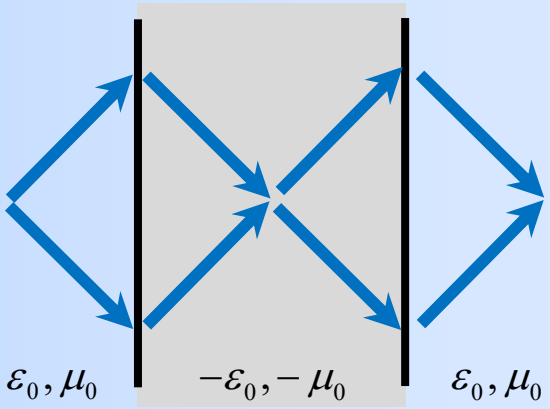
Negative Refraction



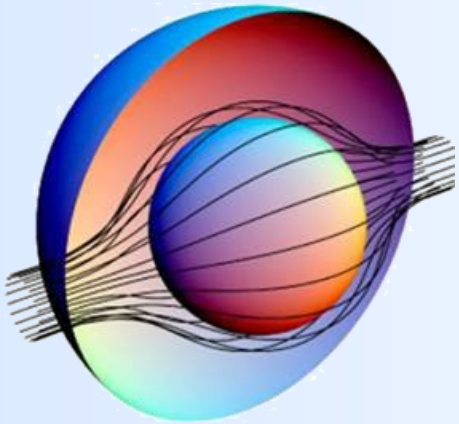


Metamaterials' Promises

'Perfect' lenses

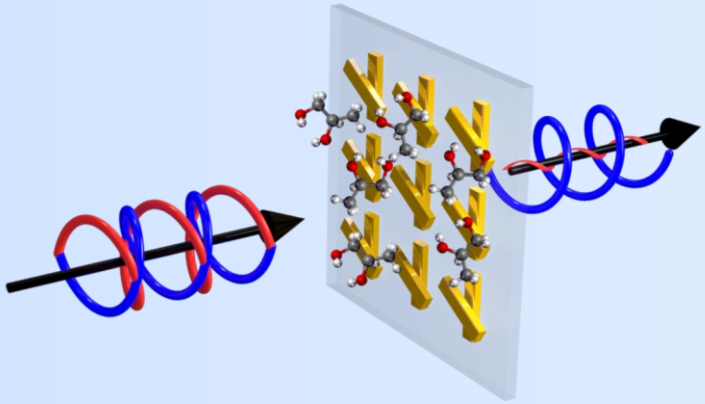


Invisibility cloaks

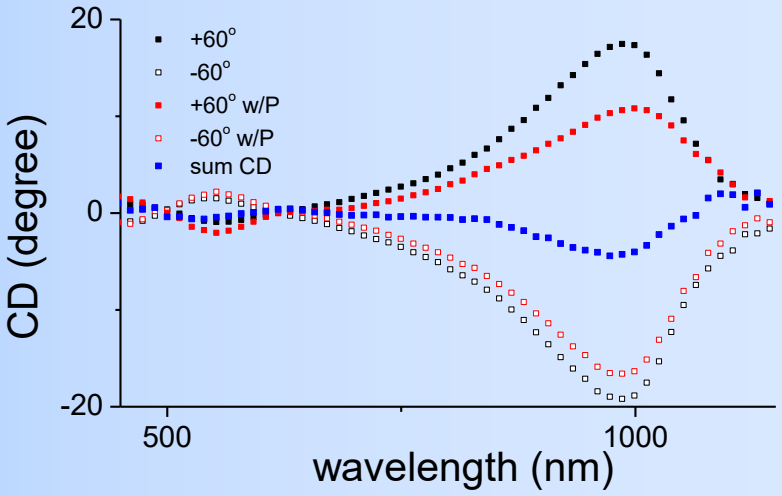


J. B. Pendry, *PRL* (2000), *Science* (2006)

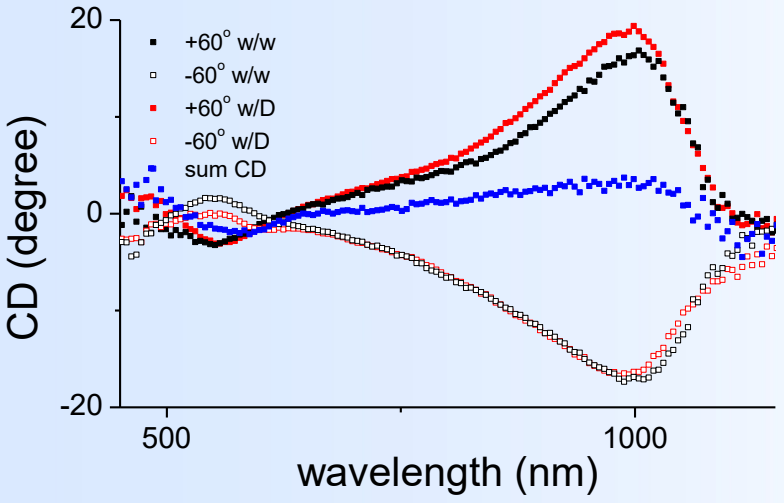
Enhanced Circular Dichroism with MTMs



Chiral protein: Concanavalin A

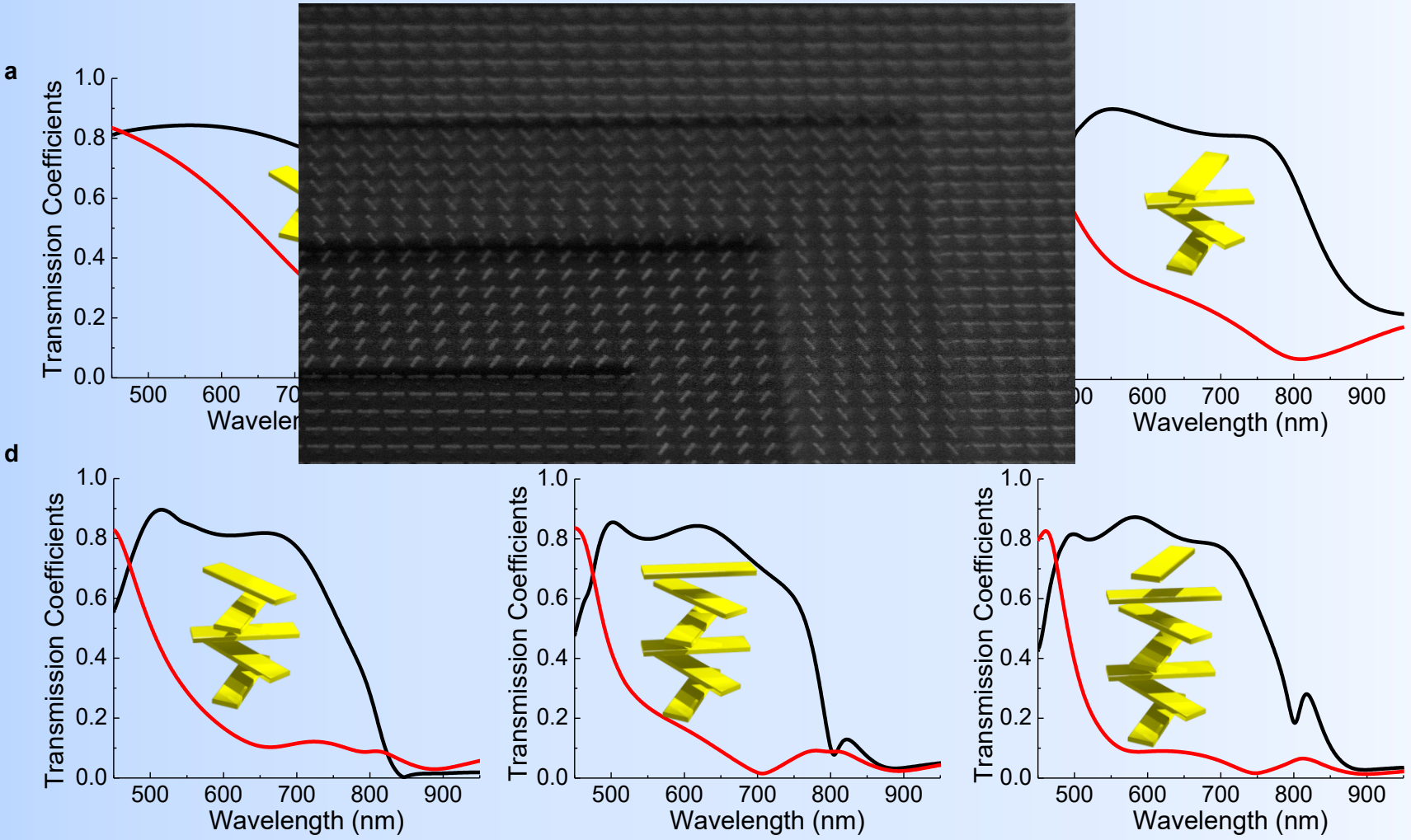


Chiral drug: Irinotecan Hydrochloride



Y. Zhao, A. N. Askarpour, L. Sun, J. Shi, X. Li, and A. Alù, *Nature Comm.* **8**, 14180 (2017)

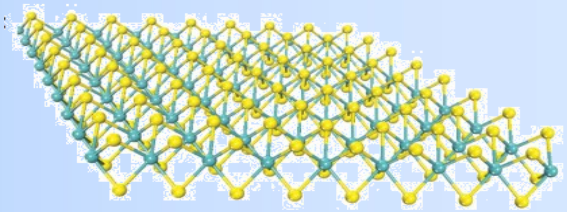
Twisted Metamaterials



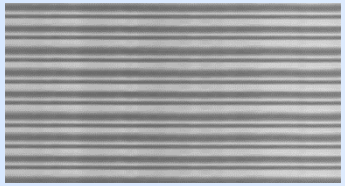
Y. Zhao, M. A. Belkin, and A. Alù, *Nature Comm.* **3**, 870 (2012)
Y. Zhao, J. Shi, L. Sun, X. Li, A. Alù, *Adv. Mat.* **26**, 1439 (2014)

2D Materials and Hybrid Metamaterials

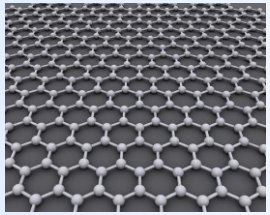
TMDs, TMOs



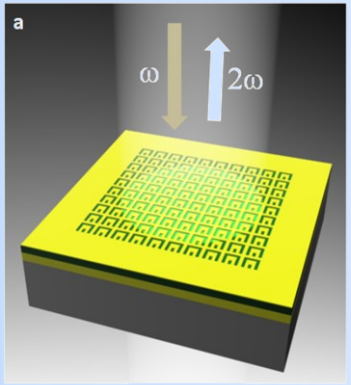
Doped multiple quantum wells (MQW)



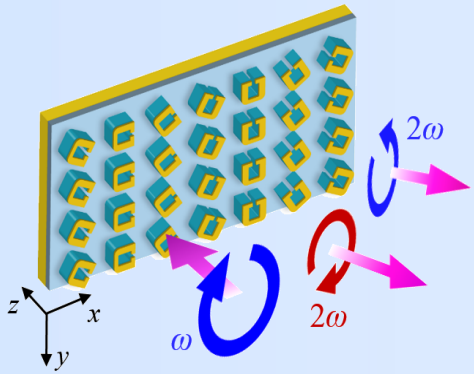
Graphene



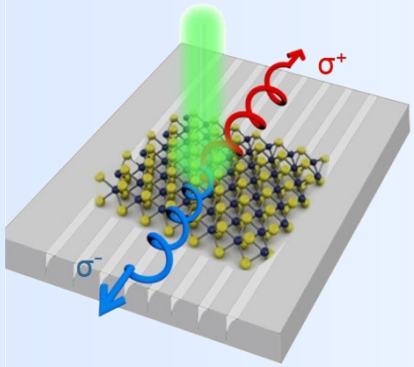
Lattice symmetries provide new degrees of freedom for light-matter interactions



Nature (2014)



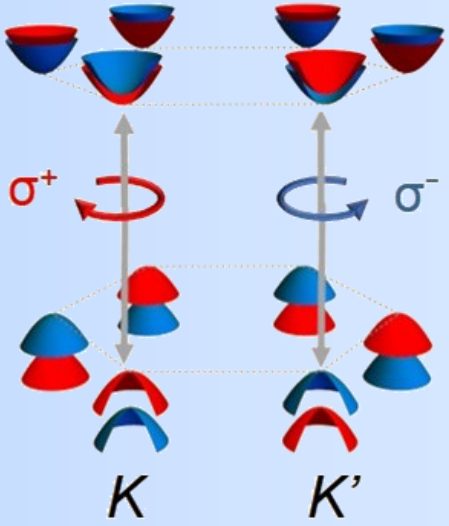
PRL (2015), *Optica* (2016)

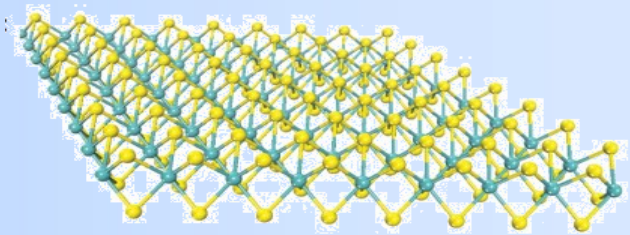


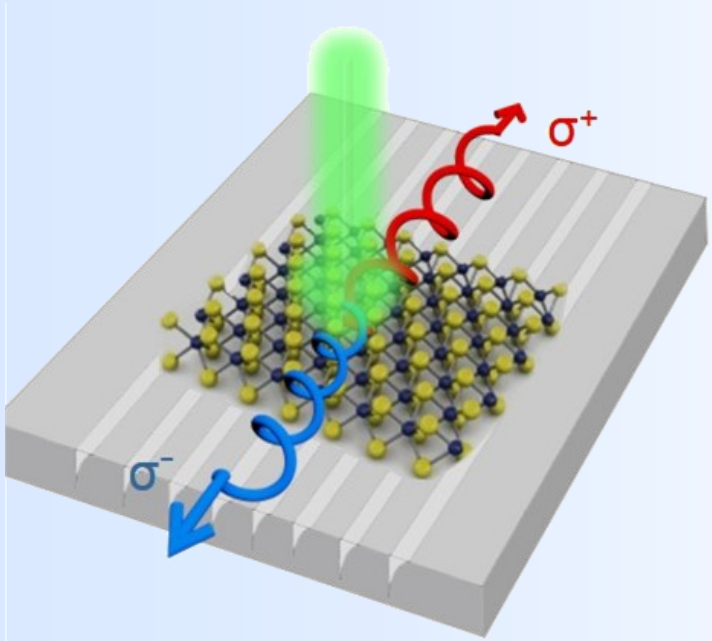
Nature Phot. (2019)

Hyperbolic Metaurfaces for Valleytronics

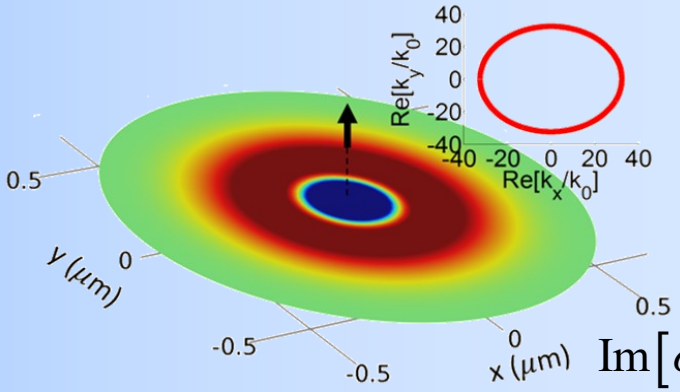
Enhancing and routing valley excitons with a metasurface using MoS2-loaded hyperbolic metasurfaces



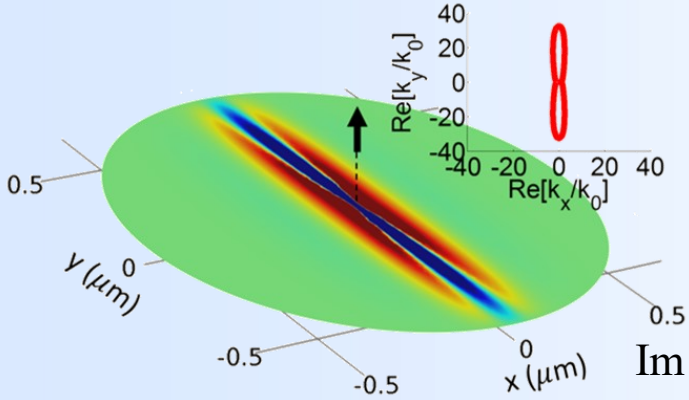




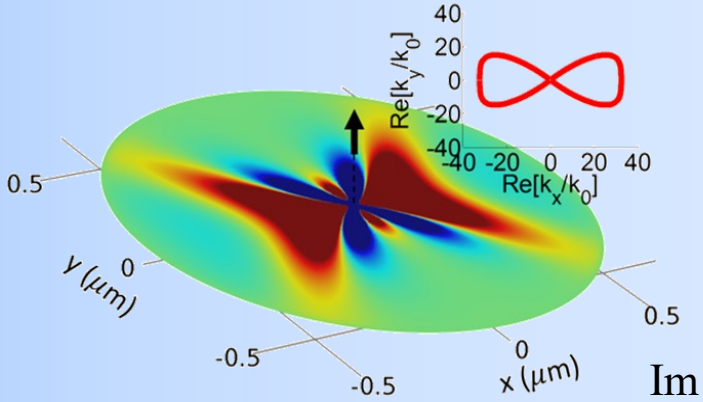
Uniaxial Metasurface Topologies



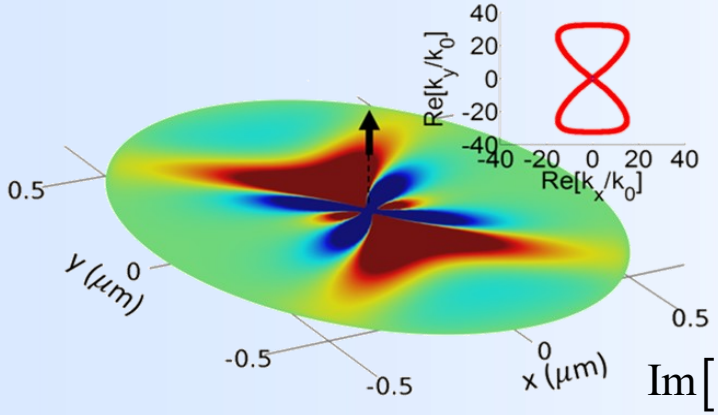
Elliptic topology $\mathrm{Im}\left[\sigma_{xx}\right] > 0$ $\mathrm{Im}\left[\sigma_{yy}\right] > 0$



σ-near zero topology $\mathrm{Im}\left[\sigma_{xx}\right] > 0$ $\mathrm{Im}\left[\sigma_{yy}\right] \approx 0$



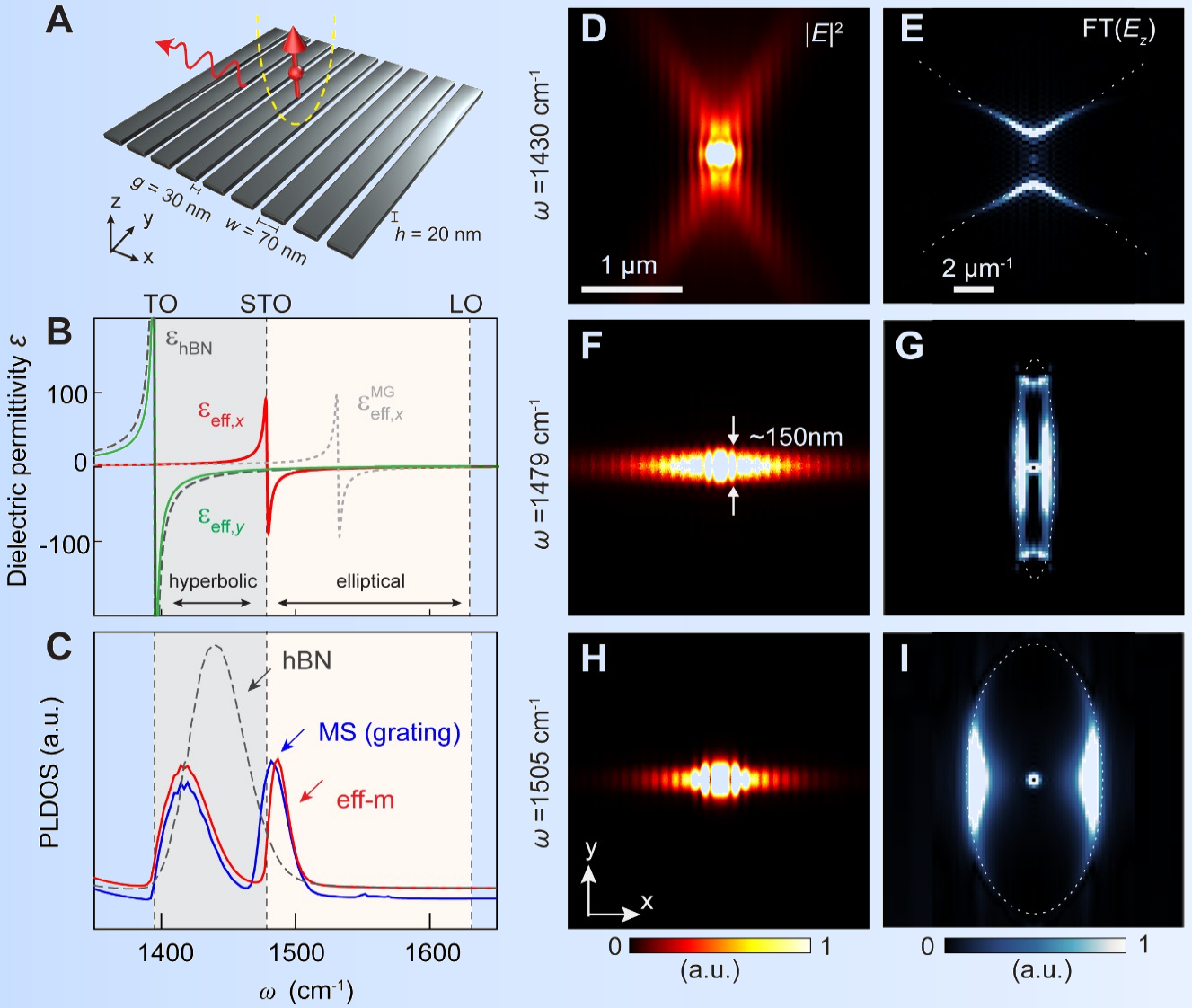
Hyperbolic topology $\mathrm{Im}\left[\sigma_{xx}\right] < 0$ $\mathrm{Im}\left[\sigma_{yy}\right] > 0$



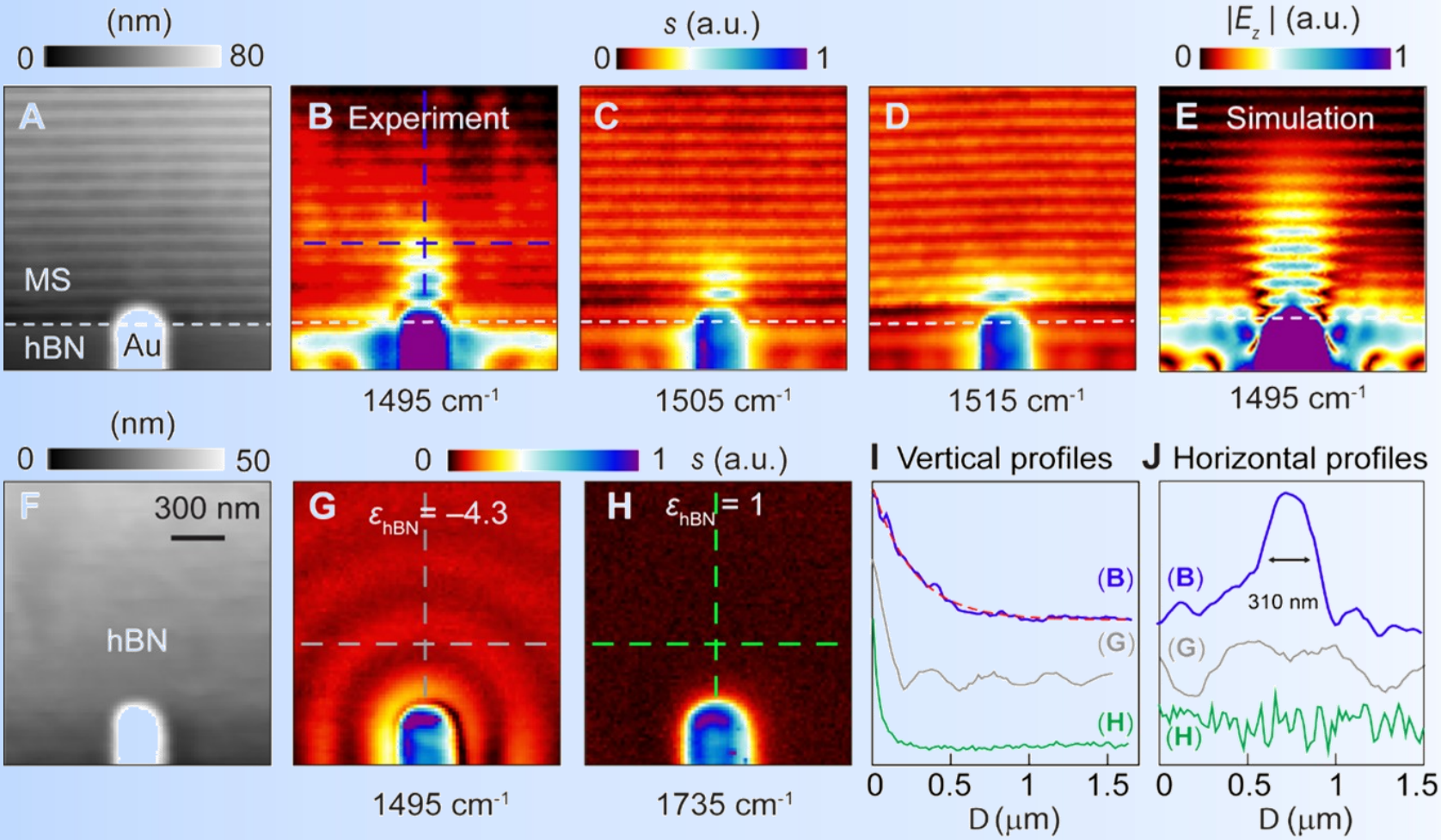
Hyperbolic topology $\mathrm{Im}\left[\sigma_{xx}\right] > 0$ $\mathrm{Im}\left[\sigma_{yy}\right] < 0$

J. S. Gomez-Diaz, M. Tymchenko, A. Alù, *Phys. Rev. Lett.* **114**, 233901 (2015)

Hyperbolic Metasurfaces with H-BN Nano-Ribbons

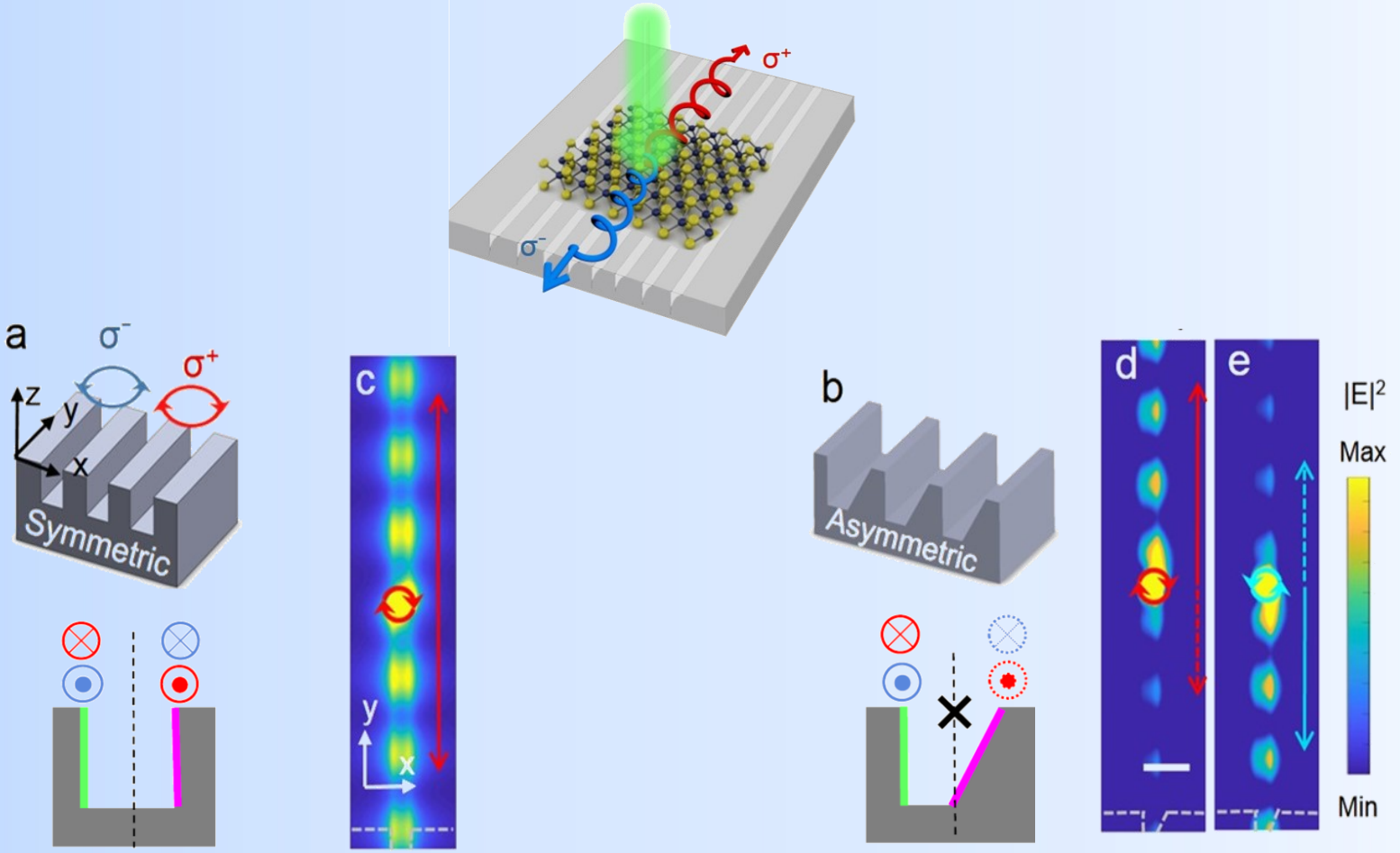


Hyperbolic Metasurfaces with H-BN Nano-Ribbons



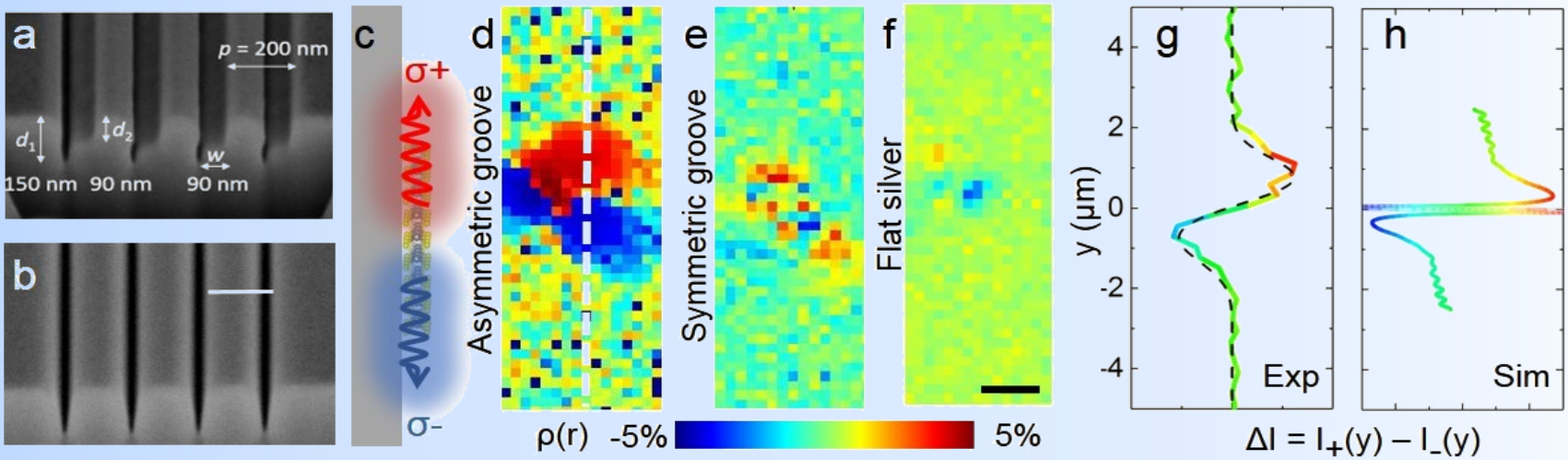
P. Li, G. Hu, I. Dolado, M. Tymchenko, …, A. Alù, R. Hillenbrand, *Nature Comm.* in press (2020)

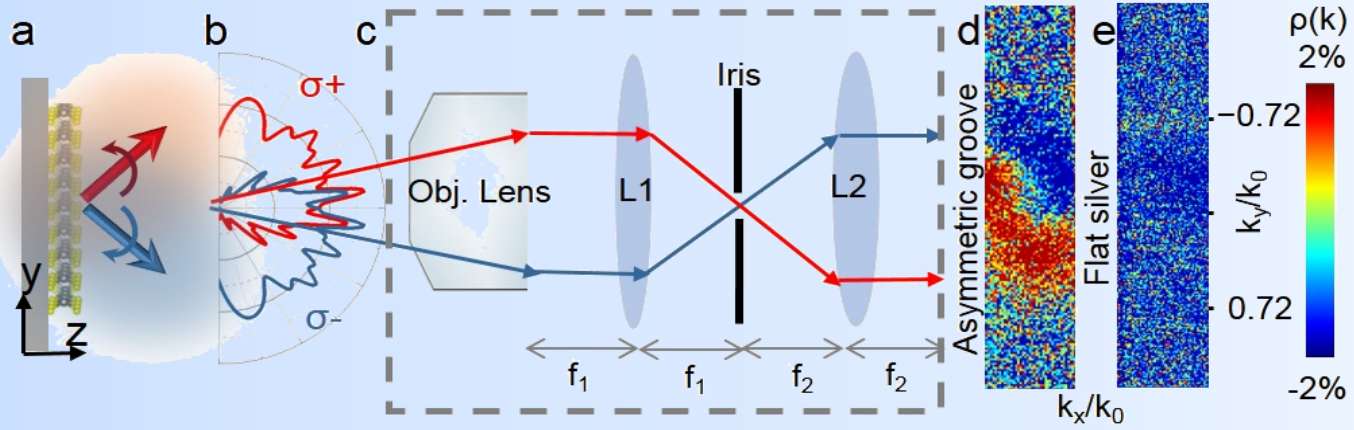
Symmetry-Breaking Hyperbolic Metasurface



L. Sun, C. Y. Wang, A. Krasnok, …, C. K. Shih, A. Alù, X. Li *Nature Photonics* **13**, 180 (2019)

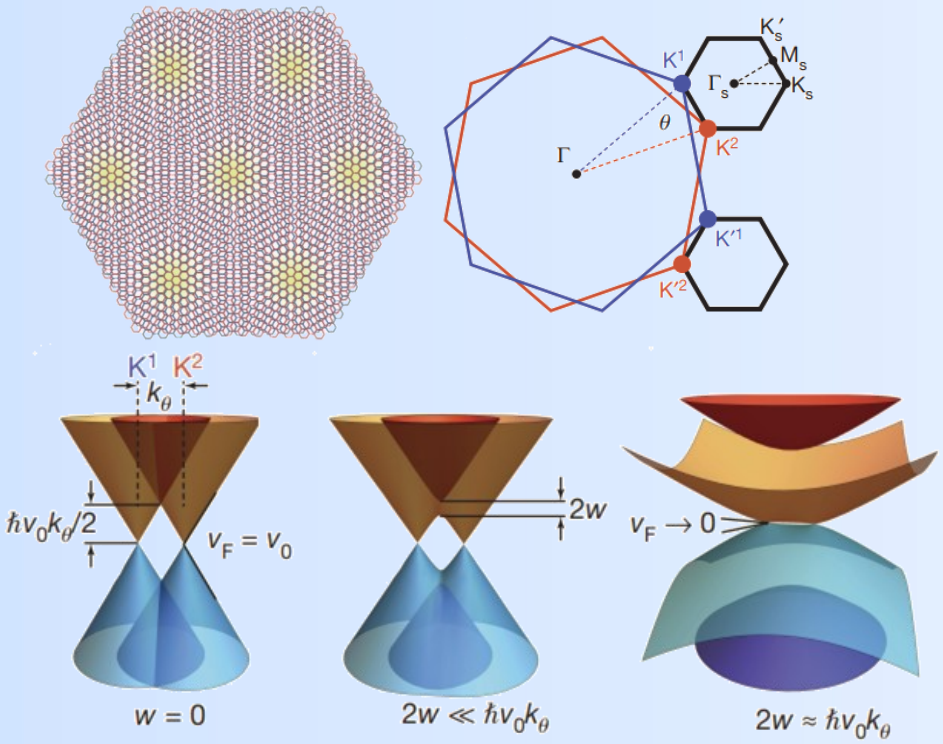
Enhancing, Sorting and Routing Valley Excitons





L. Sun, C. Y. Wang, A. Krasnok, …, C. K. Shih, A. Alù, X. Li *Nature Photonics* **13**, 180 (2019)

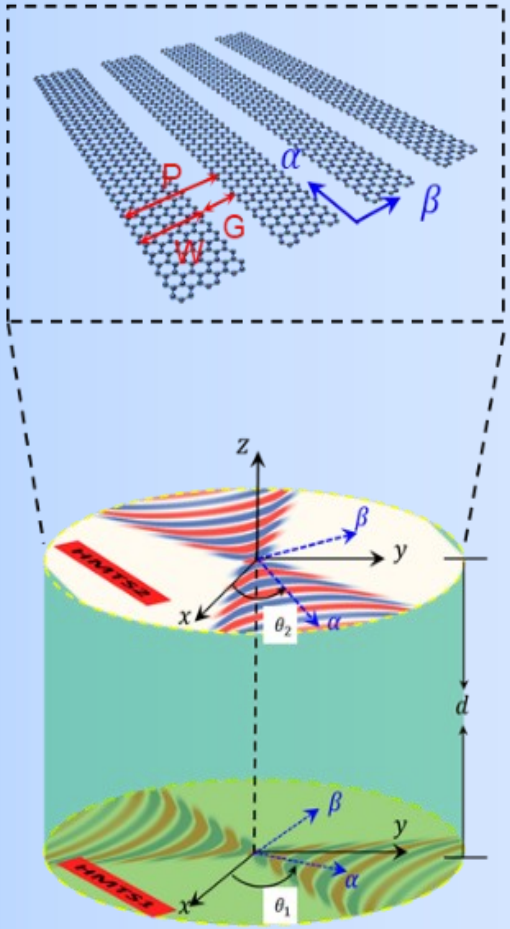
Moire Physics and Twistronics

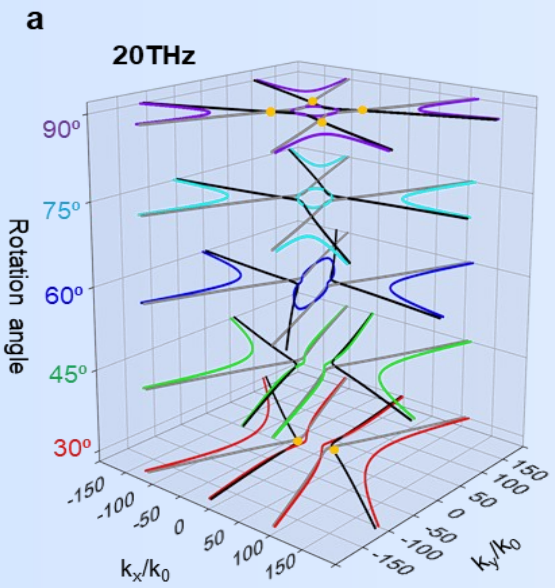


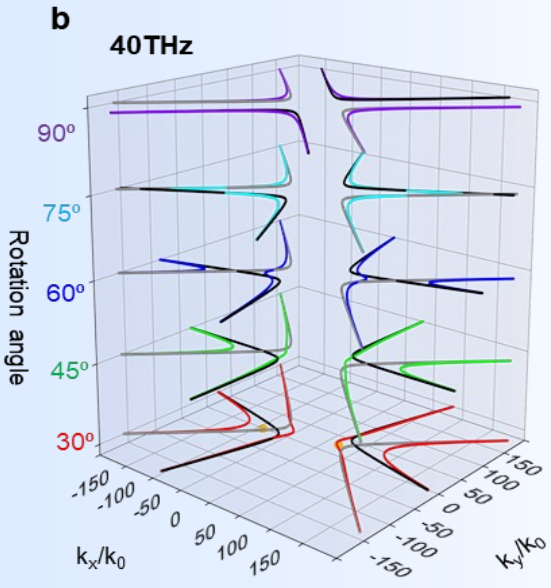
- Fermi-velocity goes to zero (superconductivity) and flat bands at *magic* twist angle of 1.1°
- Twisted-angle-dependent hopping energy

Y. Cao et al., Nature ***556***, 80-84, 2018
Y. Cao et al., Nature ***556***, 43-50, 2018
S. Carr et al., PRB ***95***, 075420, 2017

Twisted Hyperbolic Metasurfaces

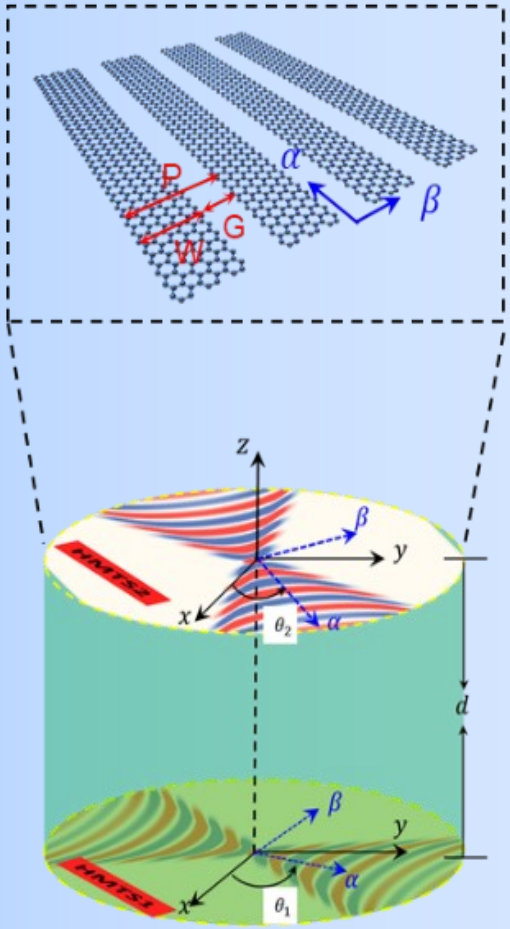


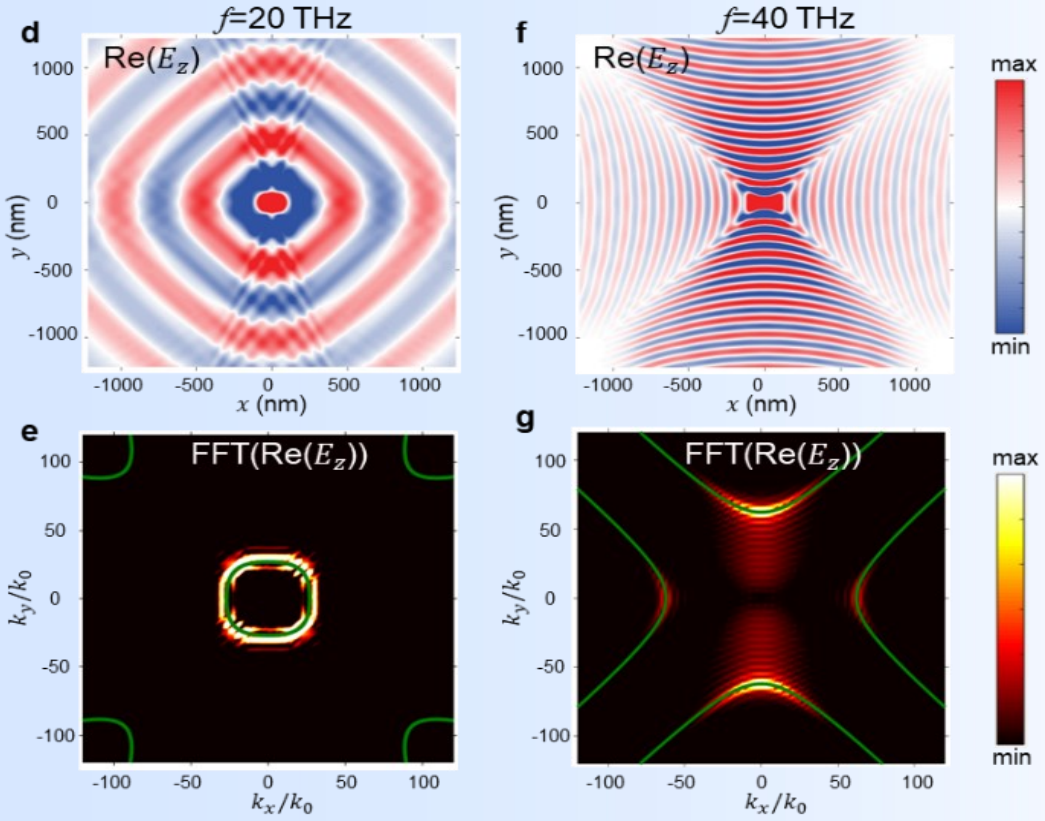




G. Hu, A. Krasnok, Y. Mazor, C. W. Qiu, A. Alù, *Nano Letters* **20**, 3217 (2020)

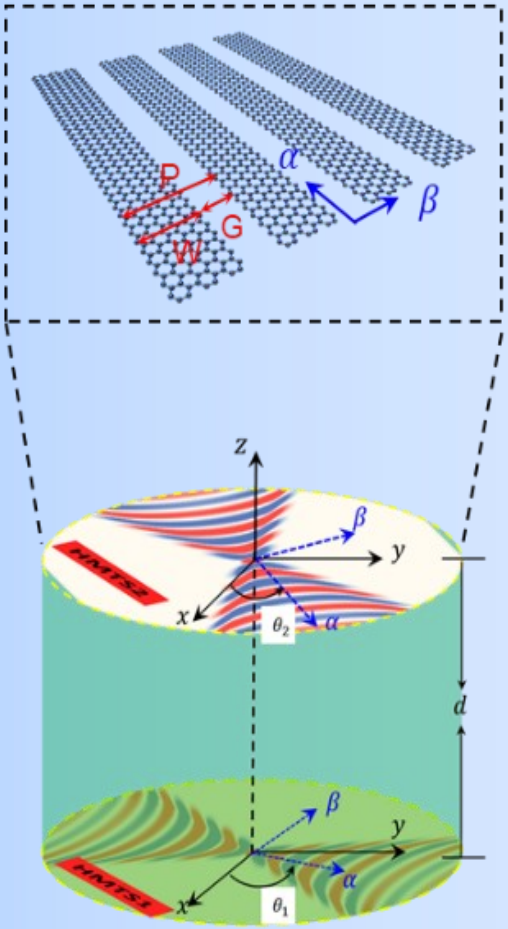
Twisted Hyperbolic Metasurfaces



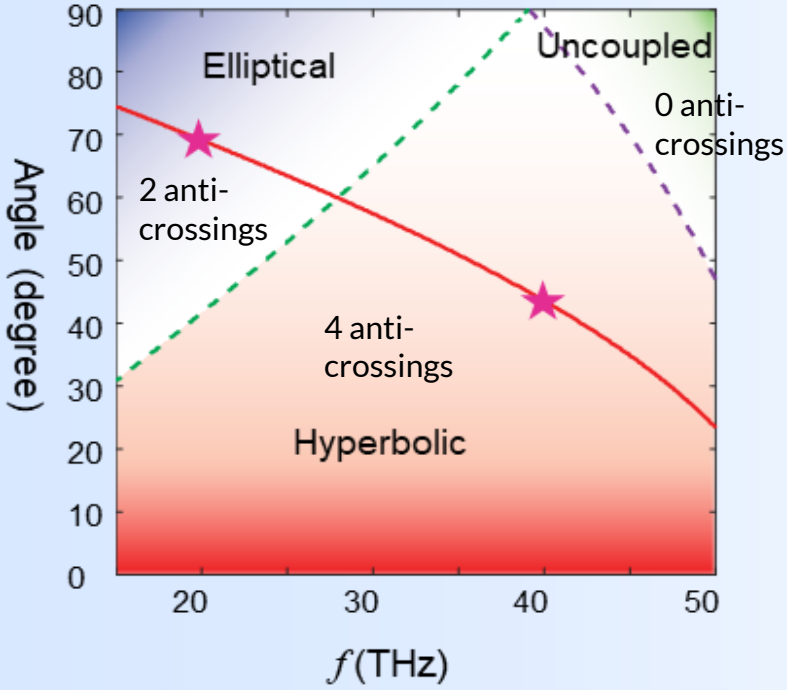


G. Hu, A. Krasnok, Y. Mazor, C. W. Qiu, A. Alù, *Nano Letters* **20**, 3217 (2020)

Twisted Hyperbolic Metasurfaces – Magic Angle

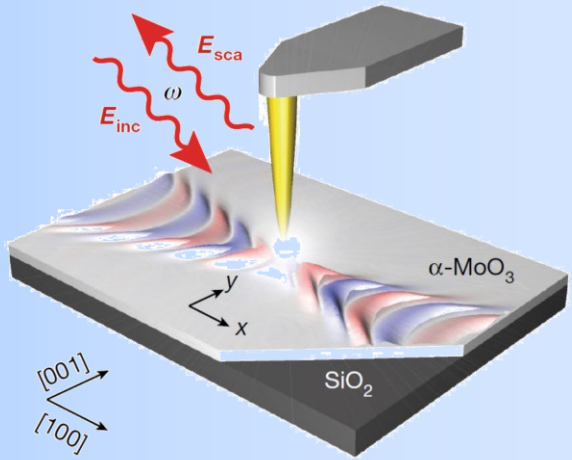


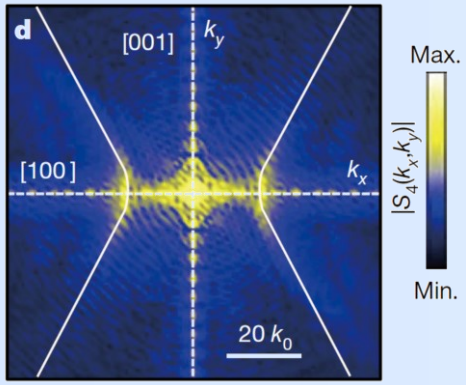
Transitions controlled by a topological invariant (integer)

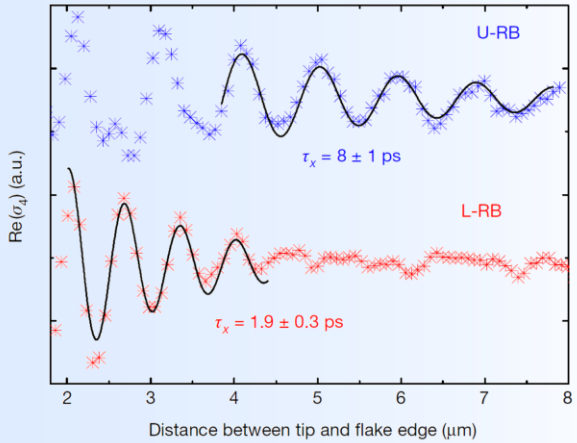


G. Hu, A. Krasnok, Y. Mazor, C. W. Qiu, A. Alù, *Nano Letters* **20**, 3217 (2020)

α-MoO_3 Monolayers as Hyperbolic Surfaces



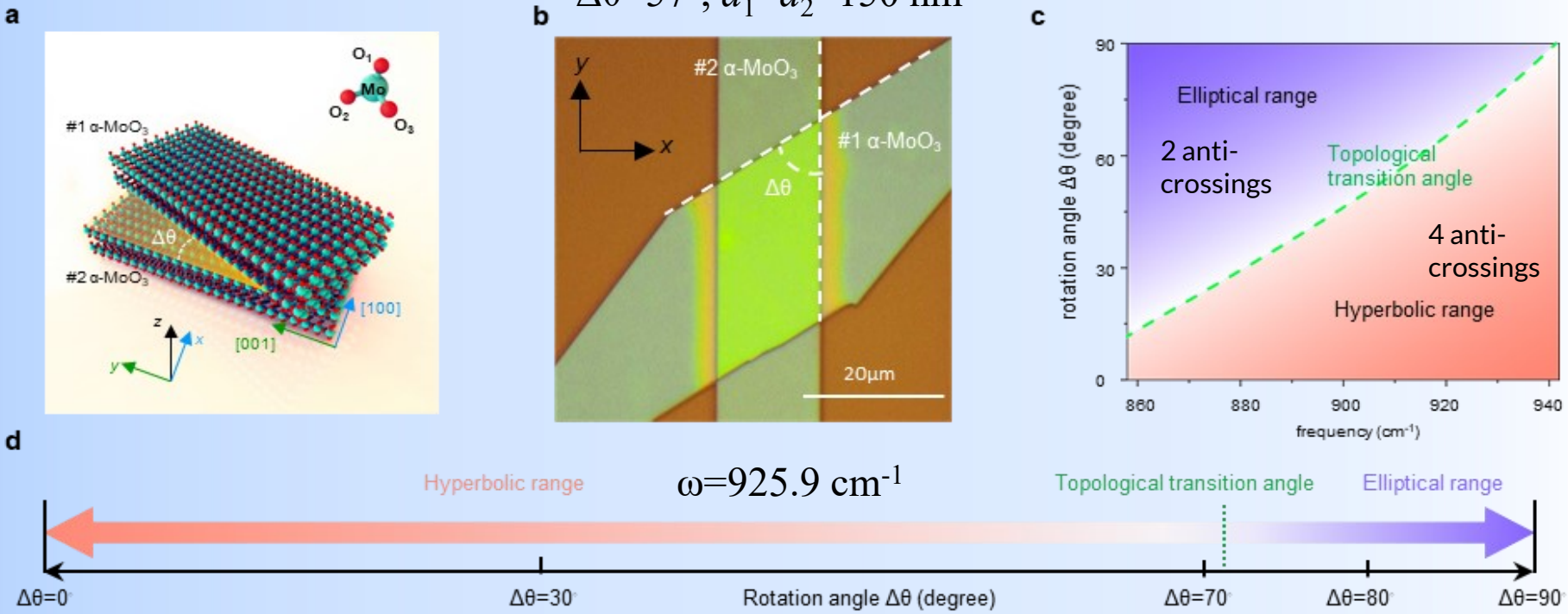




W. Ma, et al., R. Hillenbrand, Q. Bao, *Nature* **562**, 557 (2018)

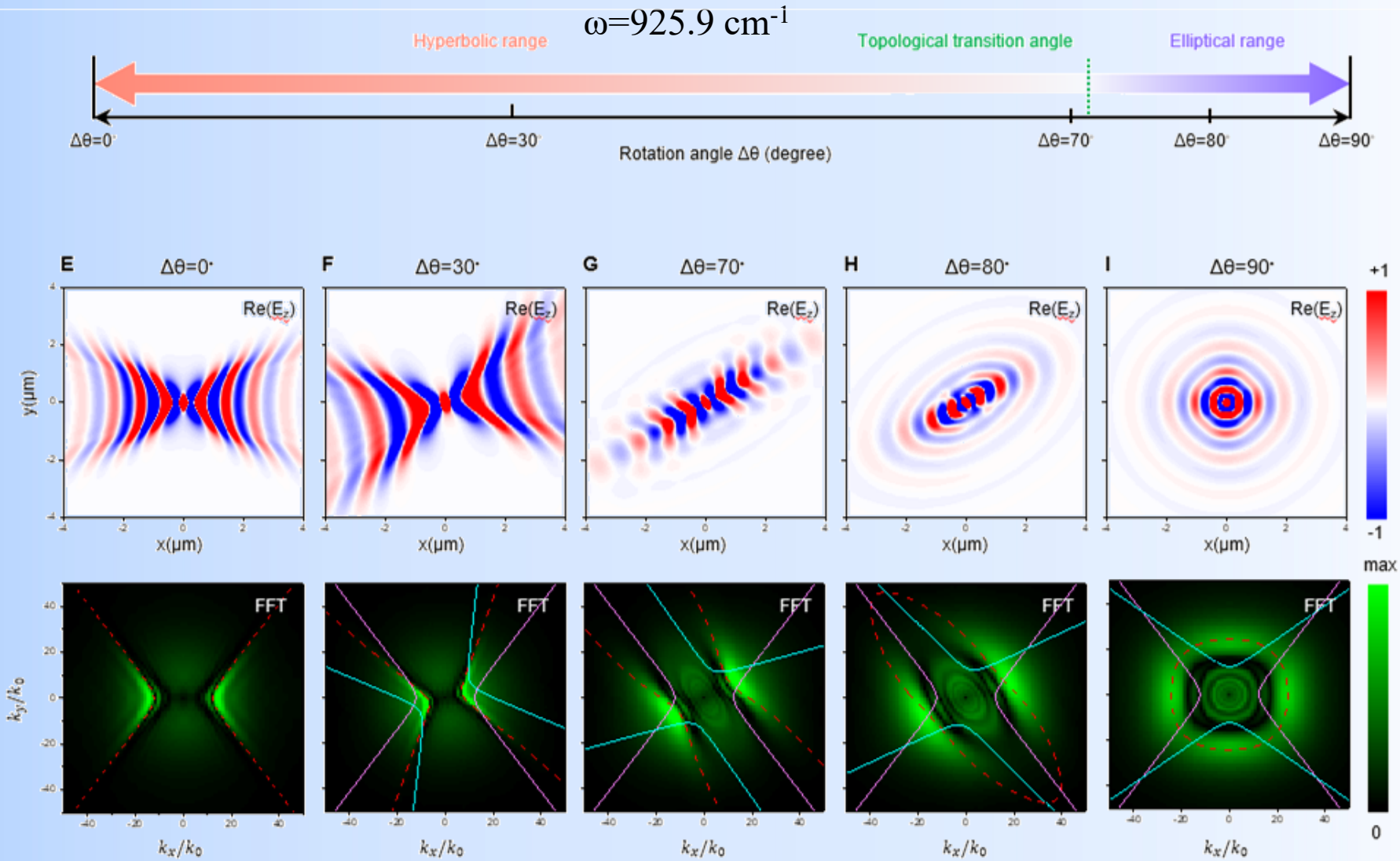
Twisted α-MoO_3 Bilayers

$\Delta\theta=57^\circ$, $d_1=d_2=150$ nm



G. Hu, Q. Ou, G. Si, Y. Wu, J. Wu, Z. Dai, A. Krasnok, Y. Mazor, Q. Zhang, Q. Bao, C. W. Qiu, A. Alù, *Nature* (2020)

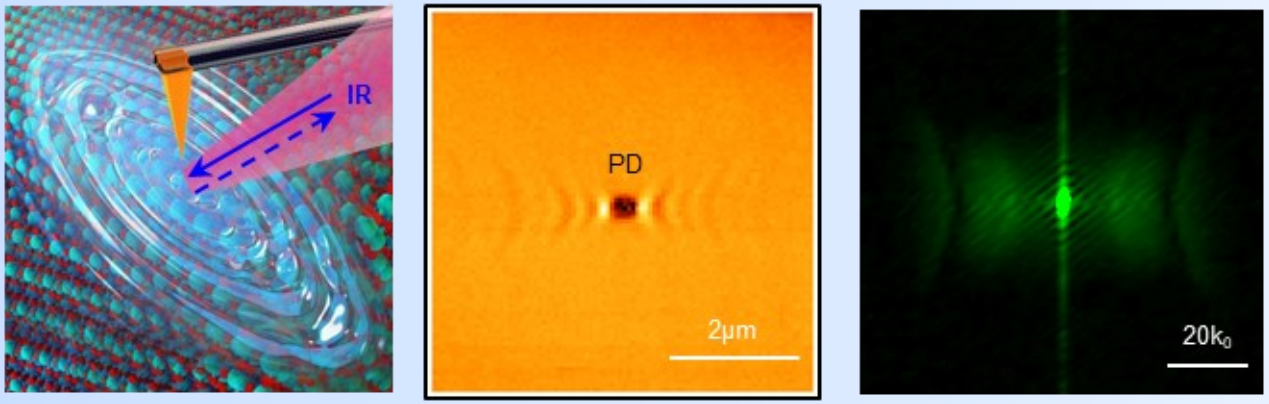
Twisted α-MoO_3 Bilayers



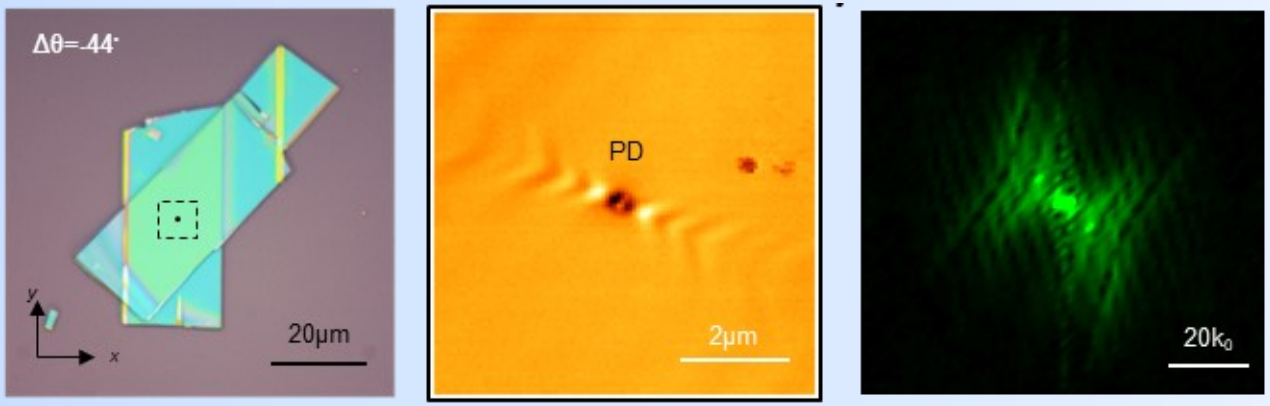
Experimental Verification in Twisted α-MoO_3 Bilayers

Single layer

ω=903.8 cm^{-1}



Bi-layer $\Delta\theta$=-44˚

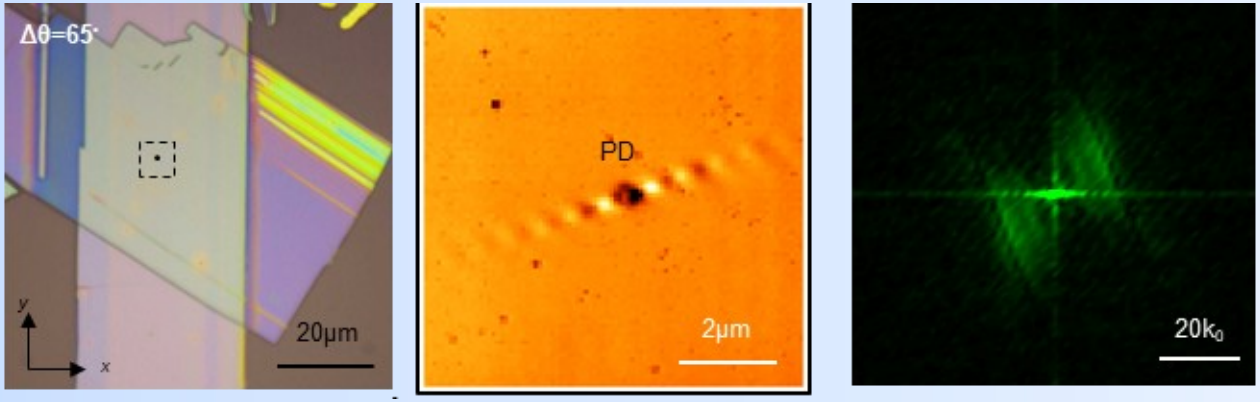


G. Hu, Q. Ou, G. Si, Y. Wu, J. Wu, Z. Dai, A. Krasnok, Y. Mazor, Q. Zhang, Q. Bao, C. W. Qiu, A. Alù, *Nature* (2020)

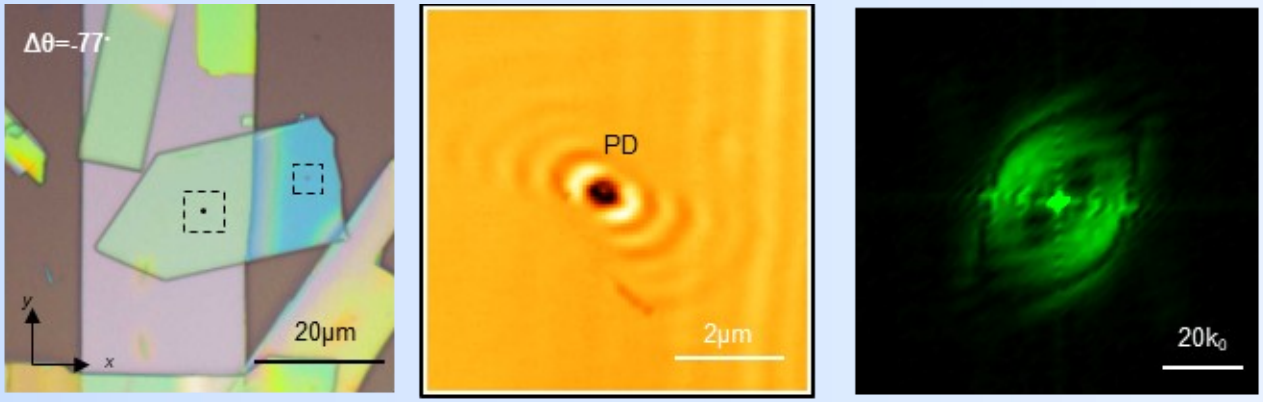
Experimental Verification in Twisted α-MoO_3 Bilayers

ω=903.8 cm^{-1}

Bi-layer $\Delta\theta$=65˚



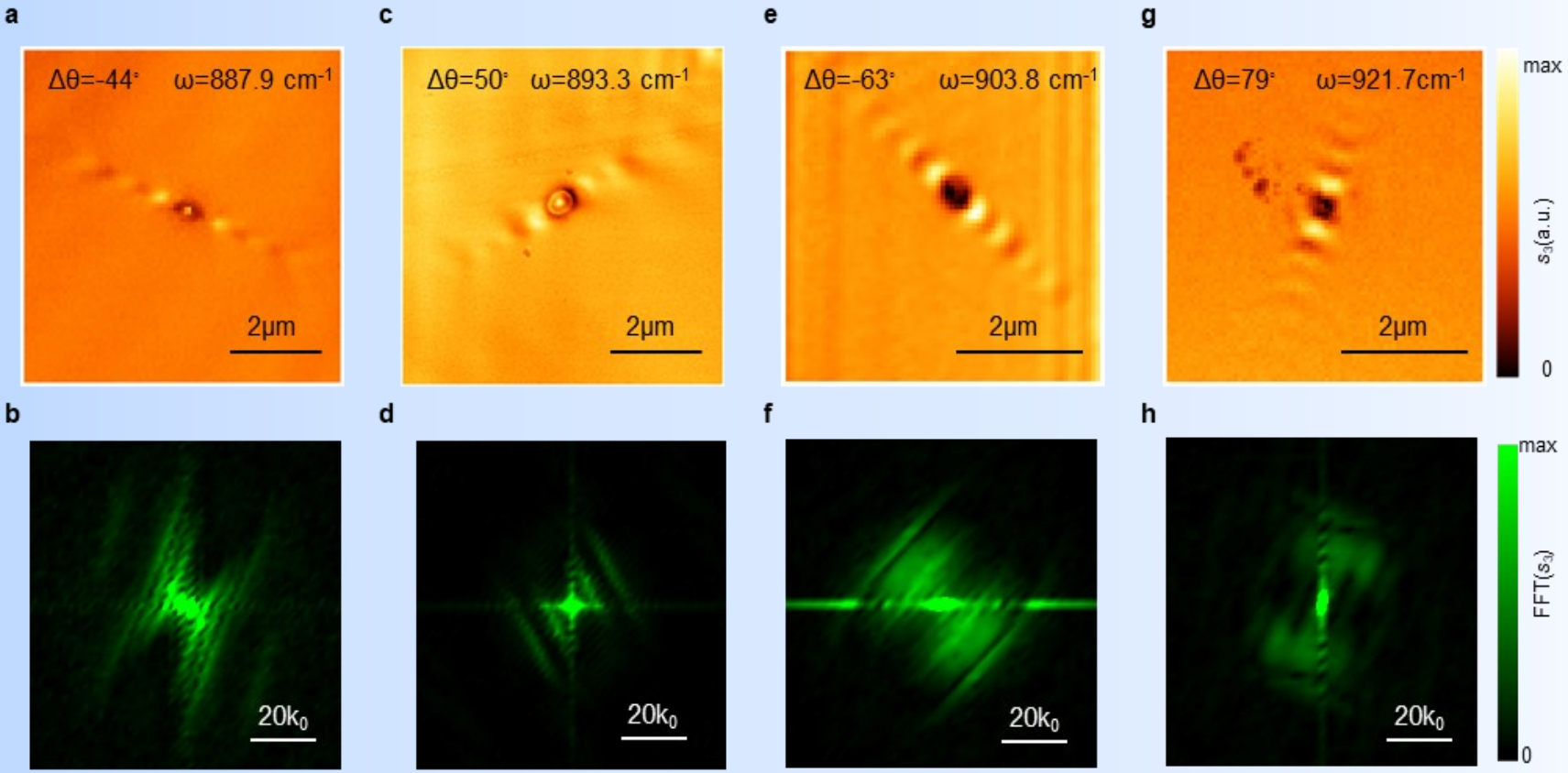
Bi-layer $\Delta\theta$=-77˚



G. Hu, Q. Ou, G. Si, Y. Wu, J. Wu, Z. Dai, A. Krasnok, Y. Mazor, Q. Zhang, Q. Bao, C. W. Qiu, A. Alù, *Nature* (2020)

Tracking the 'Photonic Magic Angle'

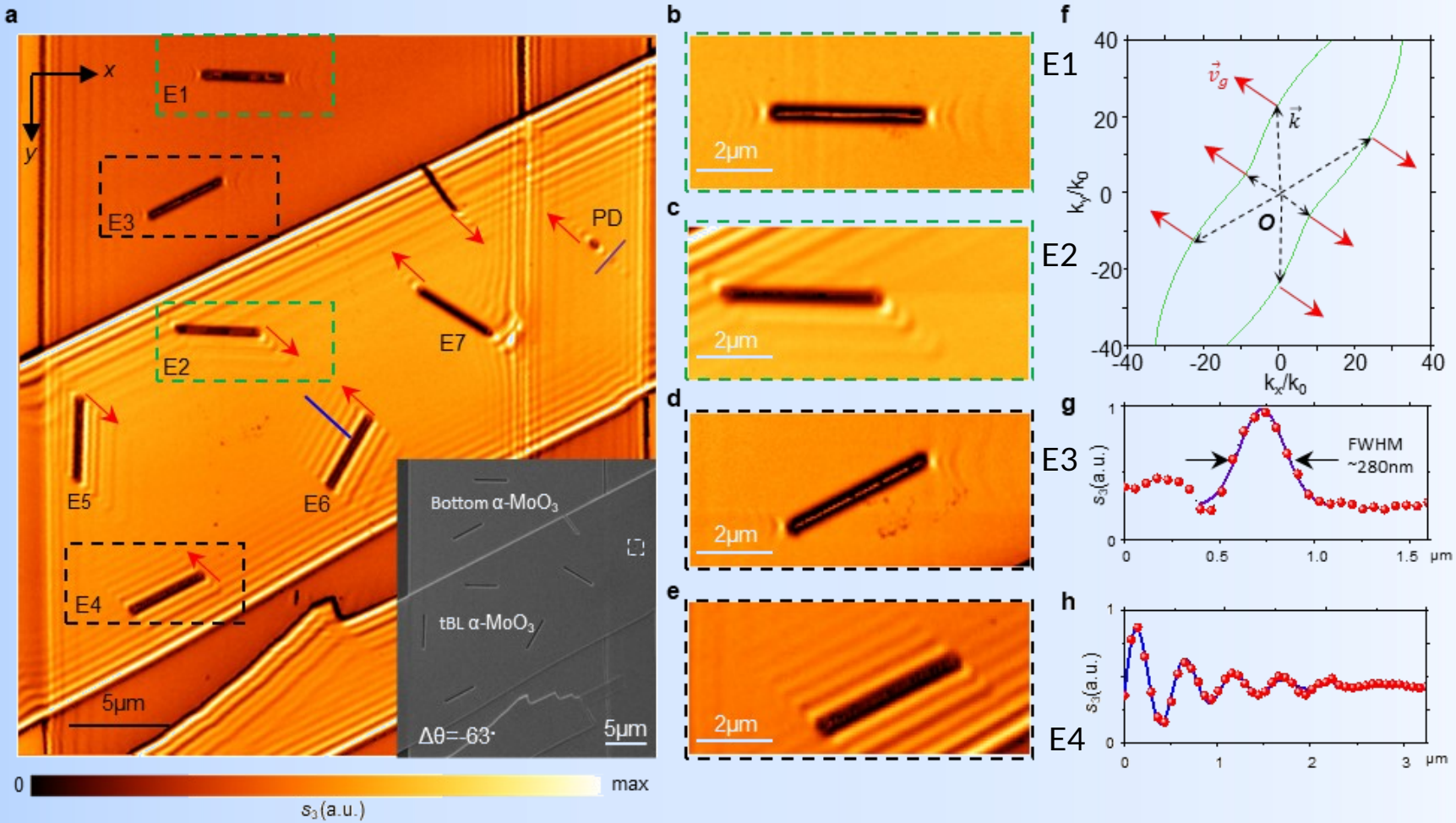
Tunable low-loss canalization regime for polaritons



G. Hu, Q. Ou, G. Si, Y. Wu, J. Wu, Z. Dai, A. Krasnok, Y. Mazor, Q. Zhang, Q. Bao, C. W. Qiu, A. Alù, *Nature* (2020)

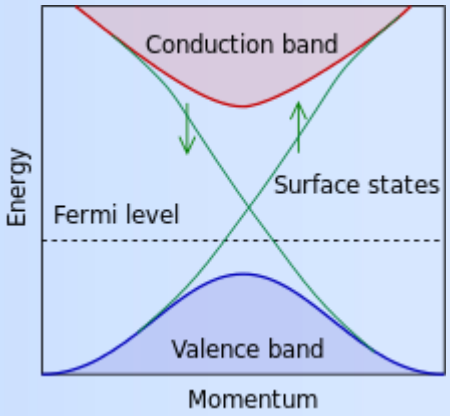
Observation of Low-Loss Polariton Canalization

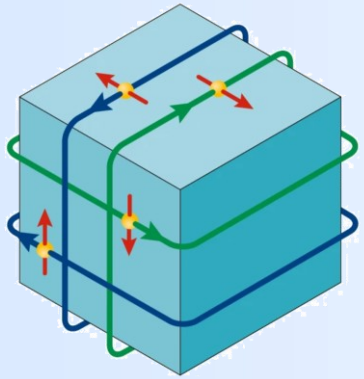
ω=903.8 cm^{-1}



G. Hu, Q. Ou, G. Si, Y. Wu, J. Wu, Z. Dai, A. Krasnok, Y. Mazor, Q. Zhang, Q. Bao, C. W. Qiu, A. Alù, *Nature* (2020)

Broken Symmetries and Topological Phases of Matter





A topological insulator is a material with non-trivial topological order, which enables the operation as an ***insulator*** in the bulk, but that ***conducts*** on the surface.

The conduction states are ***symmetry protected***, and they are associated with unusual phenomena, such as ***strong robustness to disorder***, and the ***quantum Hall effect***

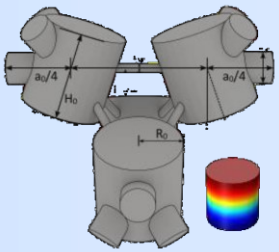
C. Kane, E. Mele, *Phys. Rev. Lett.* **95**, 146802 (2015)
Z. C. Gu, X. G. Wen, *Phys. Rev. B* **85**, 075125 (2009)
C. Kane. J. Moore, *Phys. World* **24**, 32 (2011)
Y. Tokura, K. Yasuda, A. Tsukazaki, *Nat. Rev. Phys.* **1**, 126 (2019)

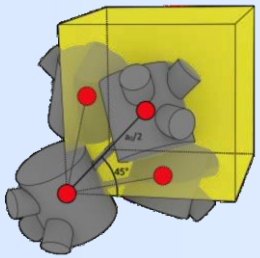
Topological Waves Based on Generalized Chirality

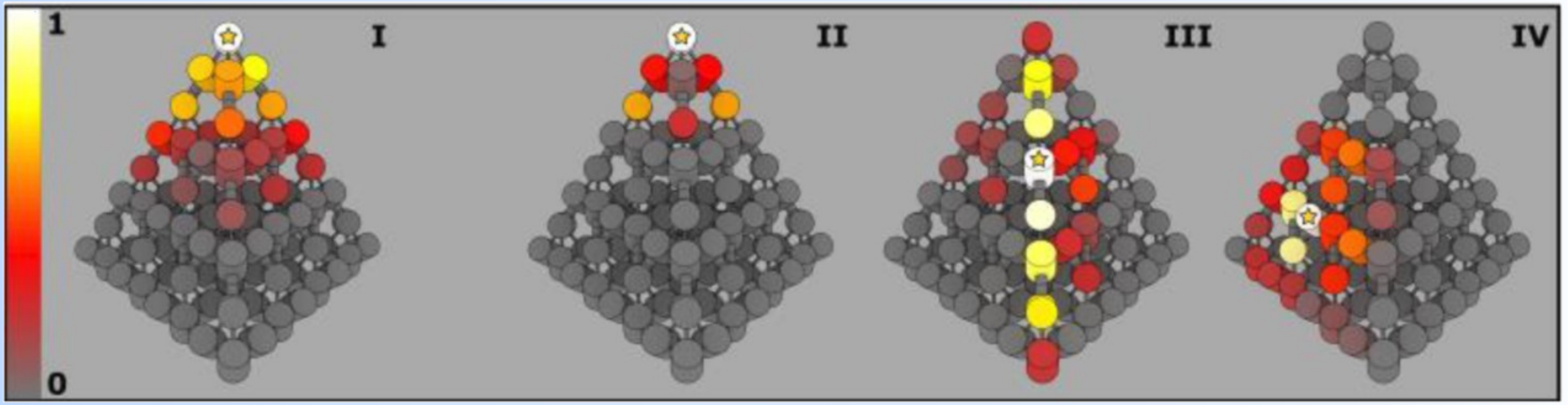
$$\hat{\Gamma}_3 \hat{H}_0 \hat{\Gamma}_3^{-1} = \hat{H}_1$$

$$\hat{\Gamma}_3 \hat{H}_1 \hat{\Gamma}_3^{-1} = \hat{H}_2$$

$$\hat{H}_0 + \hat{H}_1 + \hat{H}_2 = 0$$



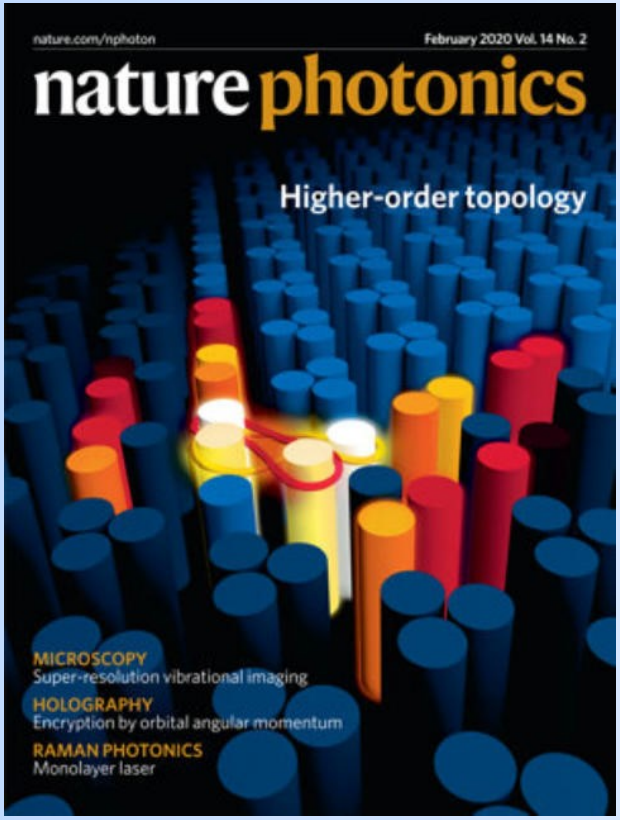


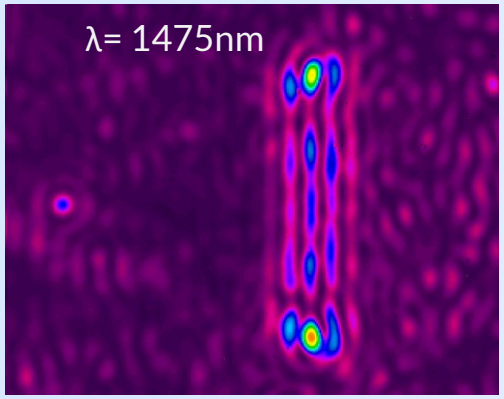


X. Ni, M. Weiner, A. Alù, A. B. Khanikaev, *Nature Materials* **18**, 113 (2018)
M. Weiner, X. Ni, M. Li, A. Alù, A. B. Khanikaev, *Science Advances* **6** 4166 (2020)

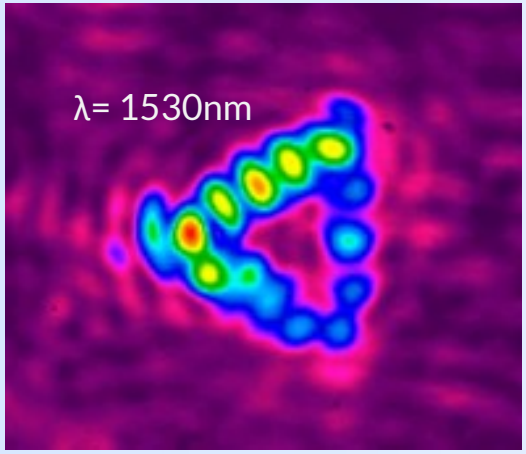
Higher-Order Topological Light in Metasurfaces

Wafer: Silicon on Insulator: Si 220nm, SiO_2 BOX 3um





Direct observation of resilient topological corner states

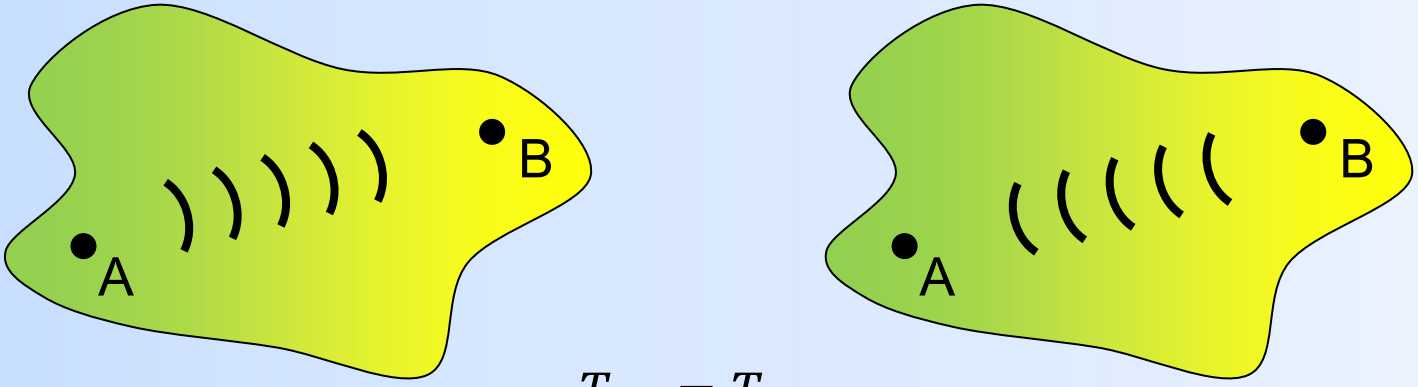


Direct observation of resilient topological edge states

M. Li, D. Zhirihin, M. Gorlach, X. Ni, D. Filonov, A. Slobozhanyuk, A. Alù, A. B. Khanikaev, *Nat. Photonics* **14**, 89 (2019)

Breaking Time-Reversal Symmetry and Reciprocity

Reciprocity: *symmetry in transmission for opposite propagation directions*



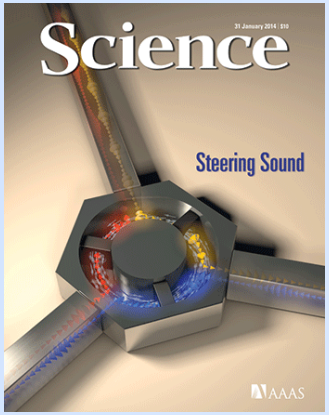
$$T_{BA} = T_{AB}$$

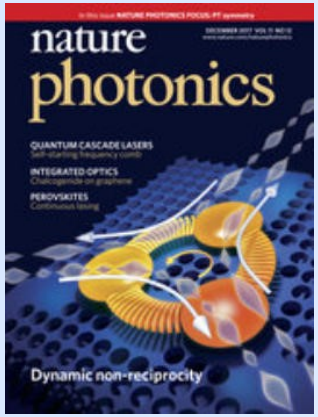
For TIs implies the ***necessary presence of a backward edge propagation channel***

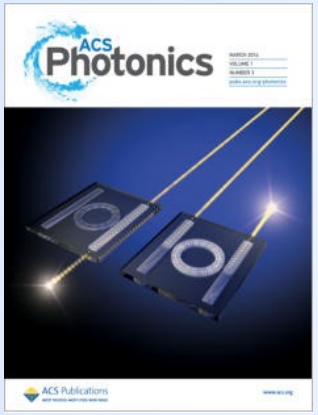
Moving media

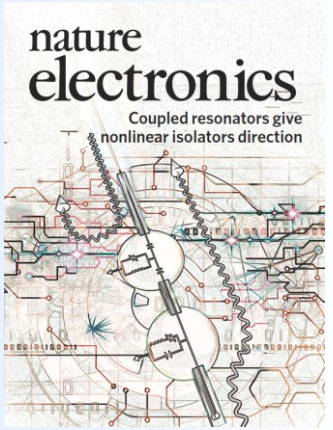
Time-varying materials

Nonlinearities



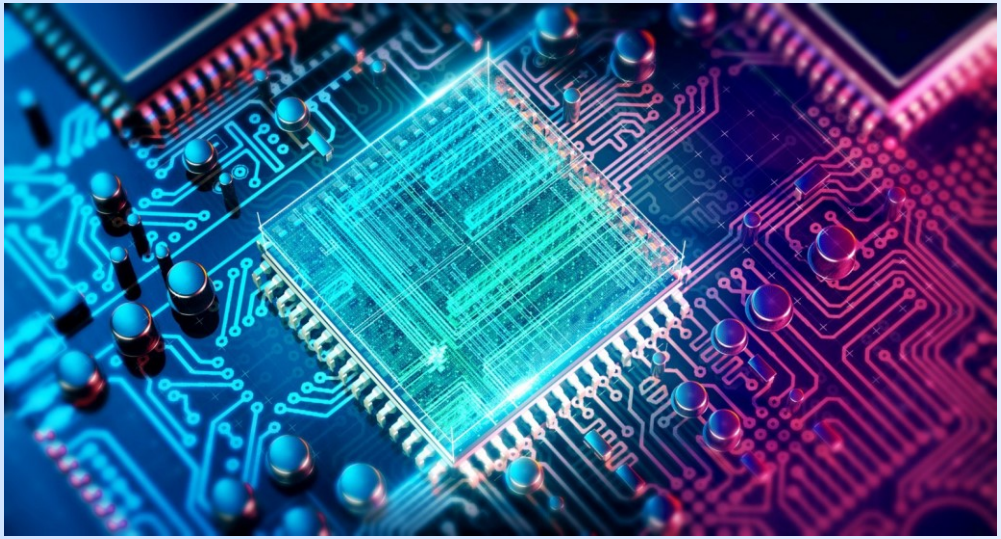




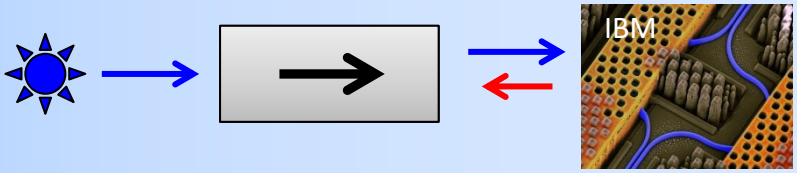


Magnet-Free Non-Reciprocity

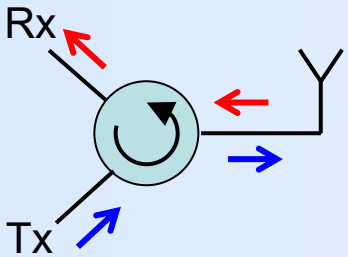
One-way flows of photons in an integrated platform



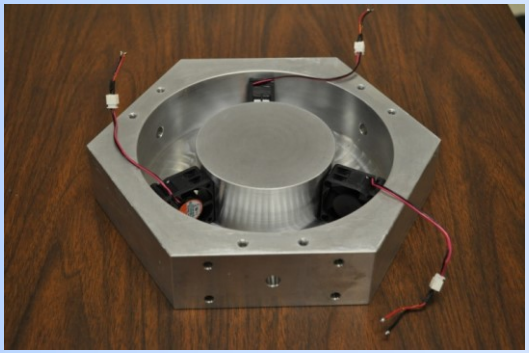
Isolators

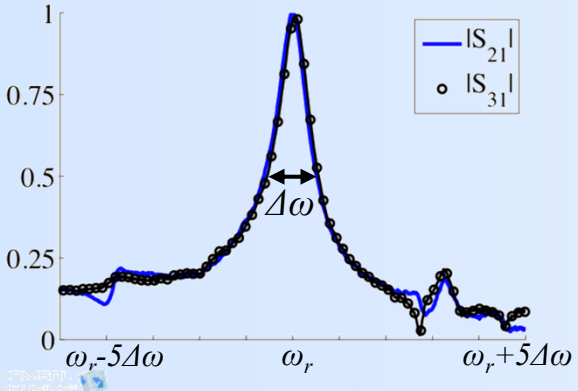


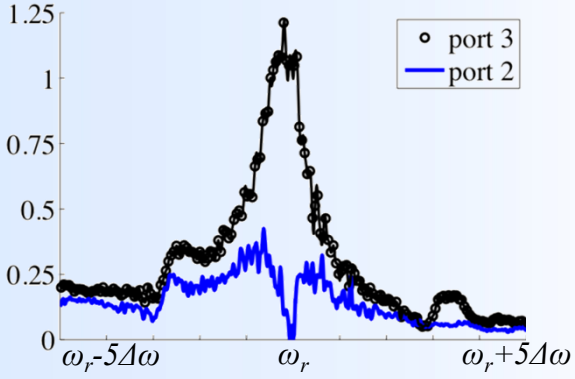
Circulators

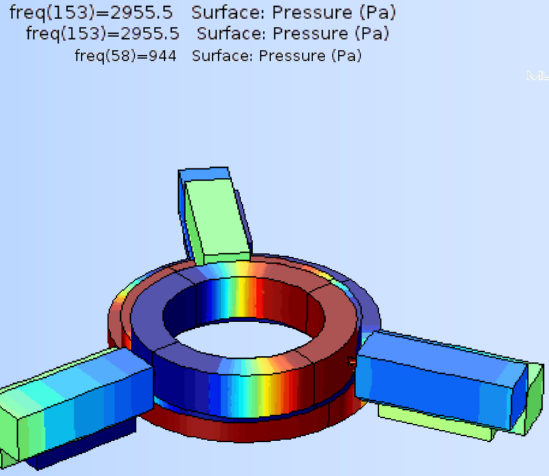


Angular-Momentum Bias

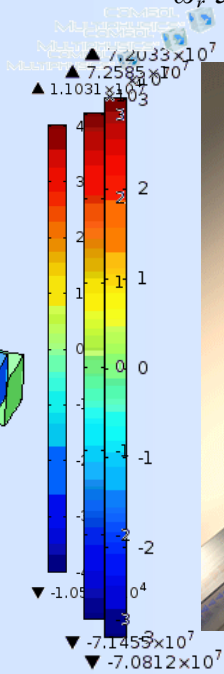


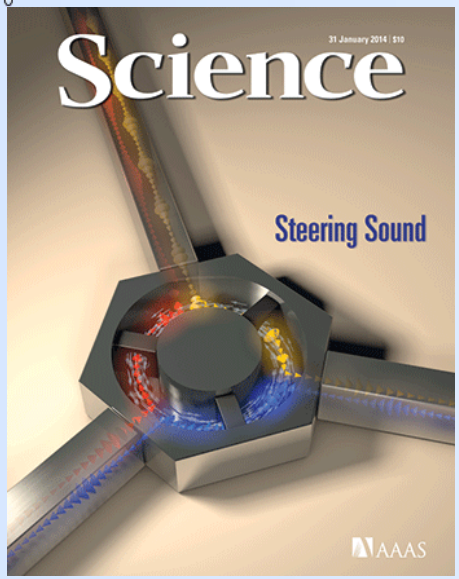


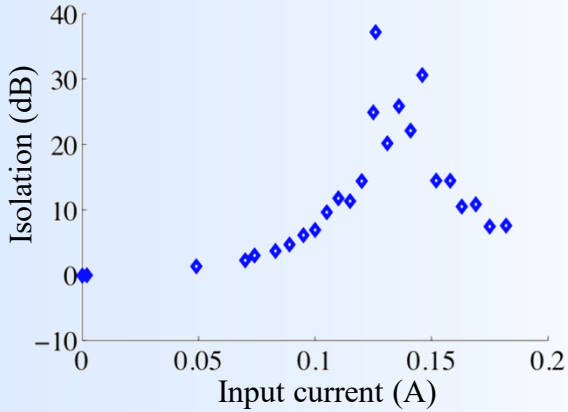




$v = 0.65\,m/s$

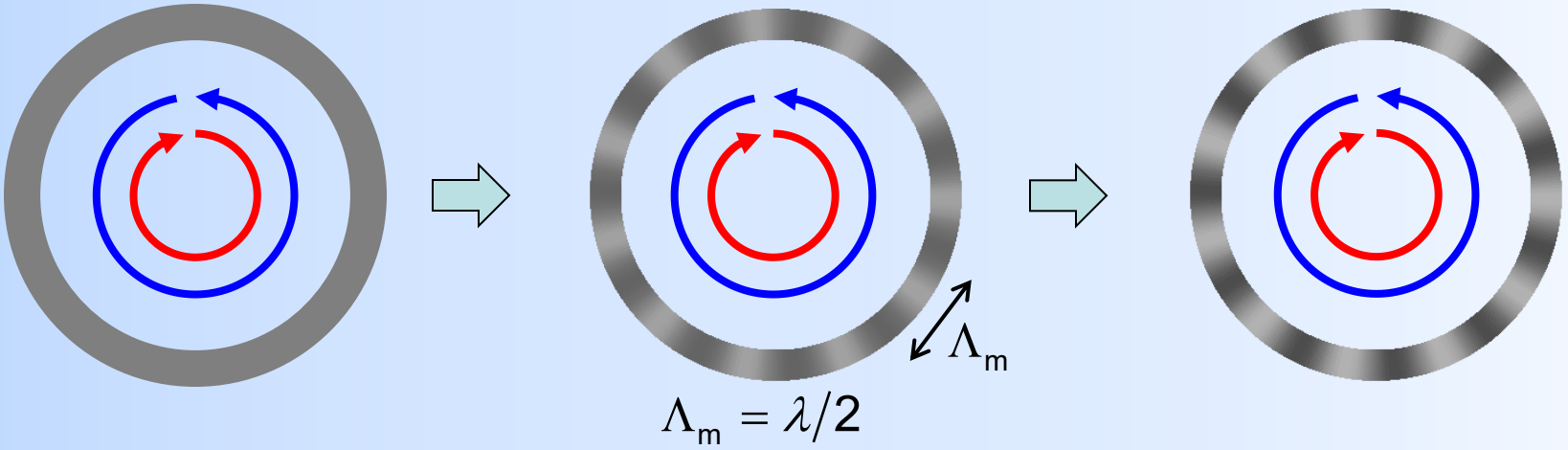


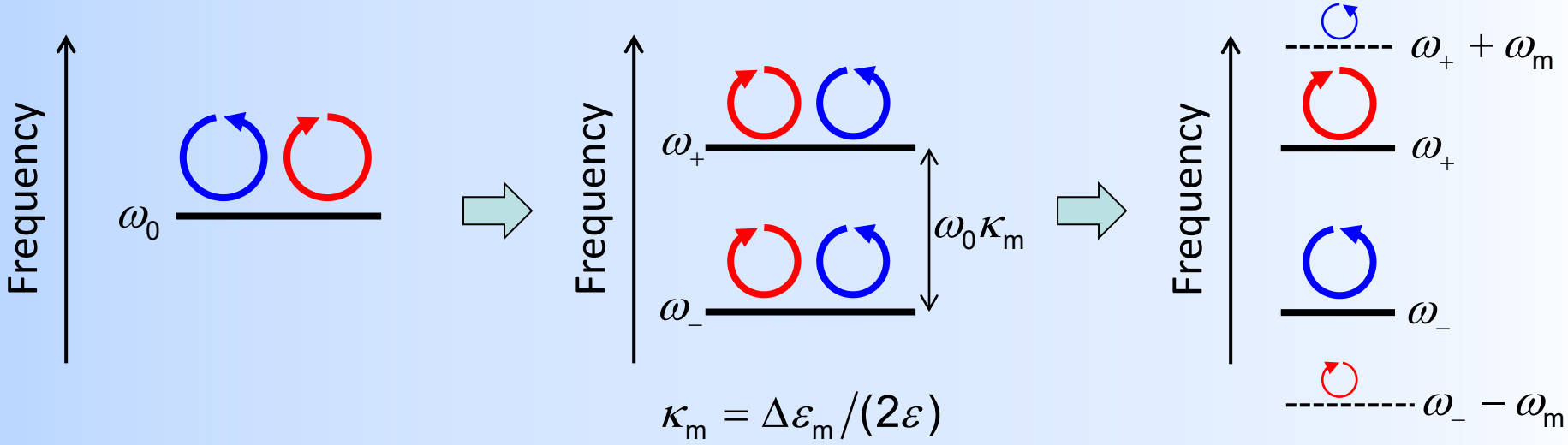




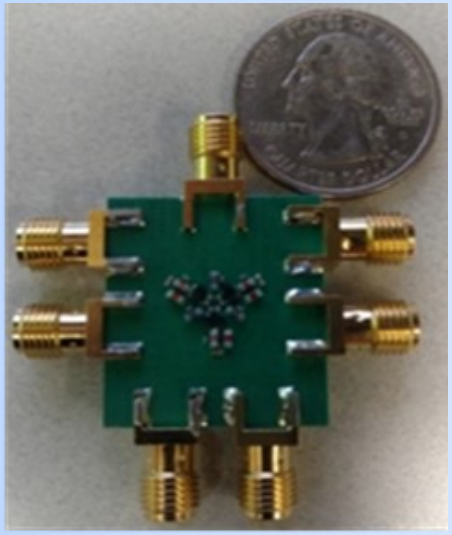
R. Fleury, D. L. Sounas, C. Sieck, M. Haberman, A. Alù, *Science* 343, 516 (2014)

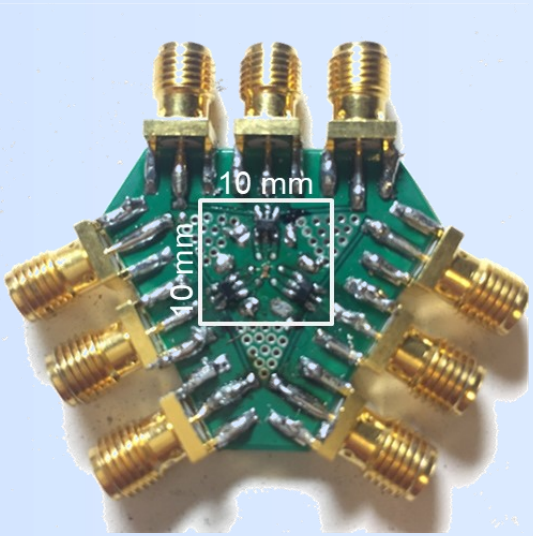
Synthetic Angular Momentum with Time Modulation

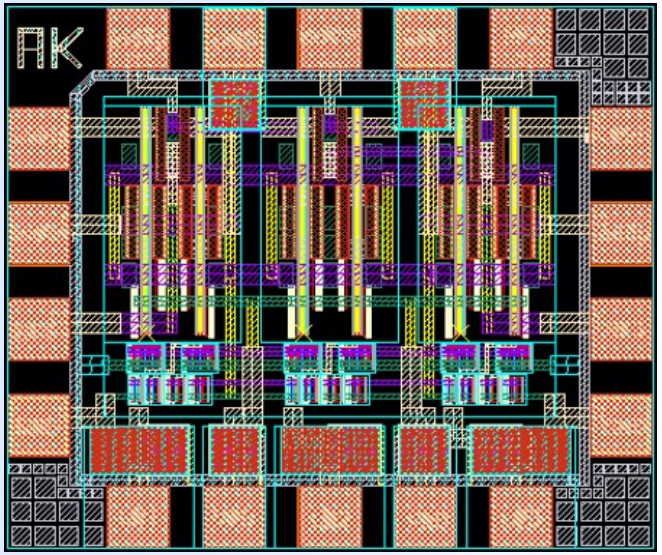


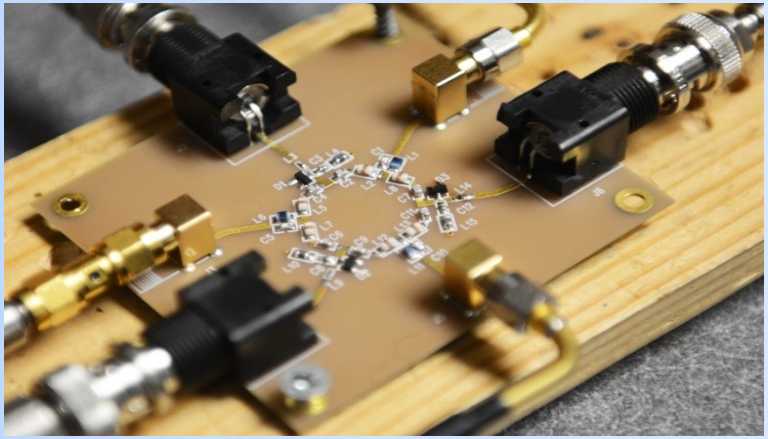


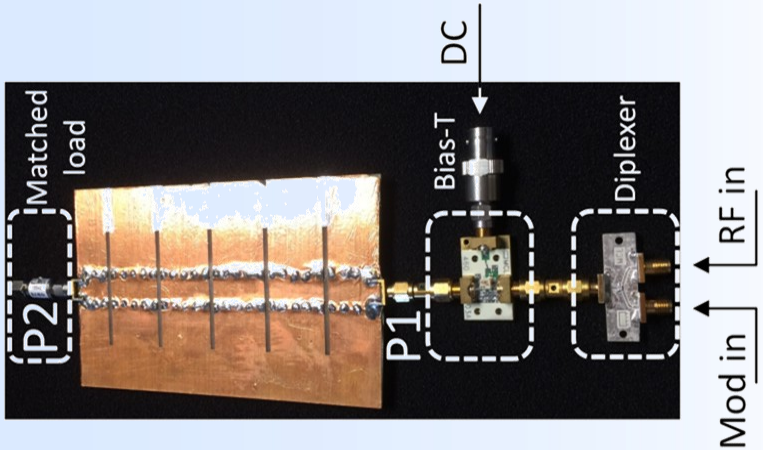
Recent Progress on Magnet-Less Circulators



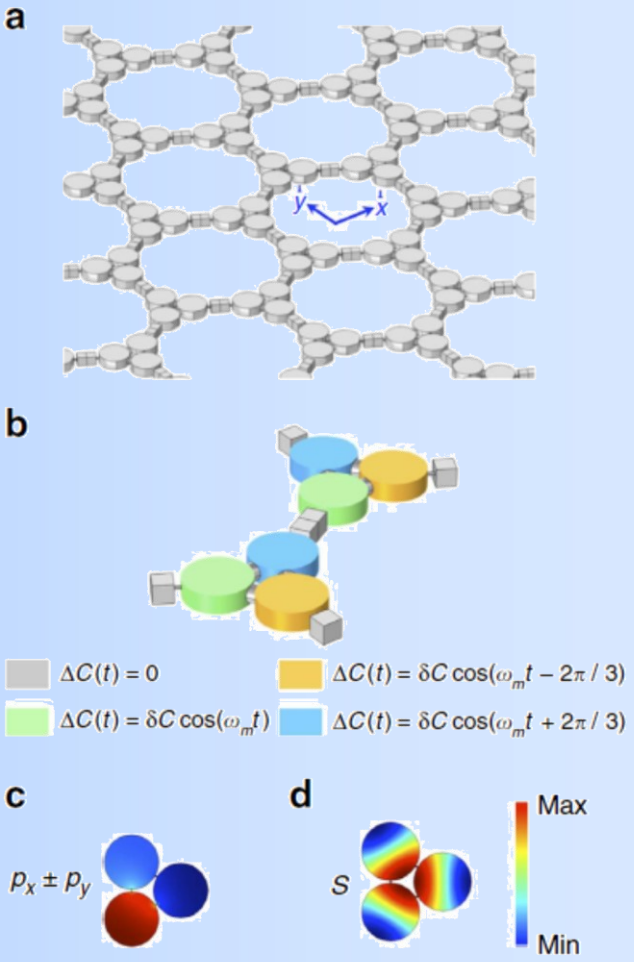


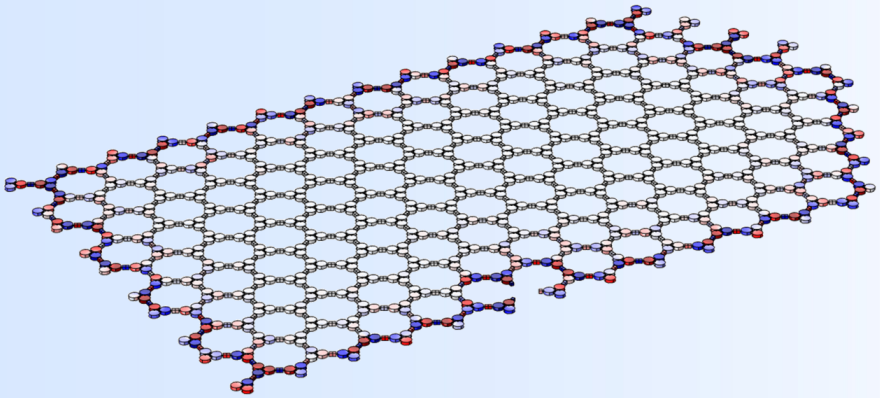


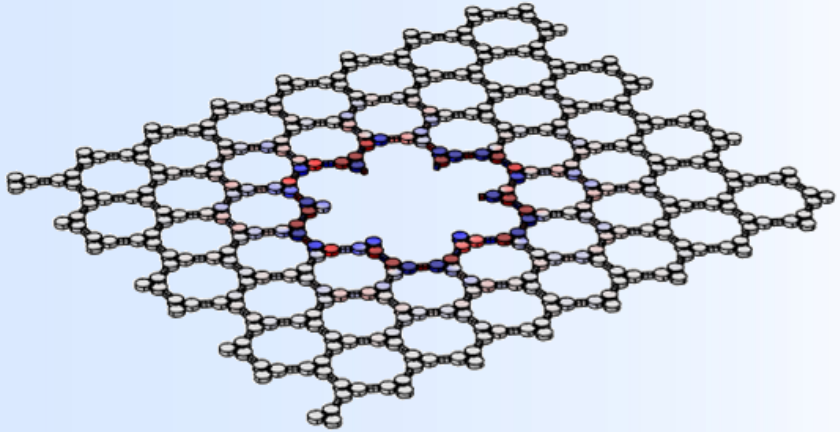




Non-Reciprocal Topological Waves

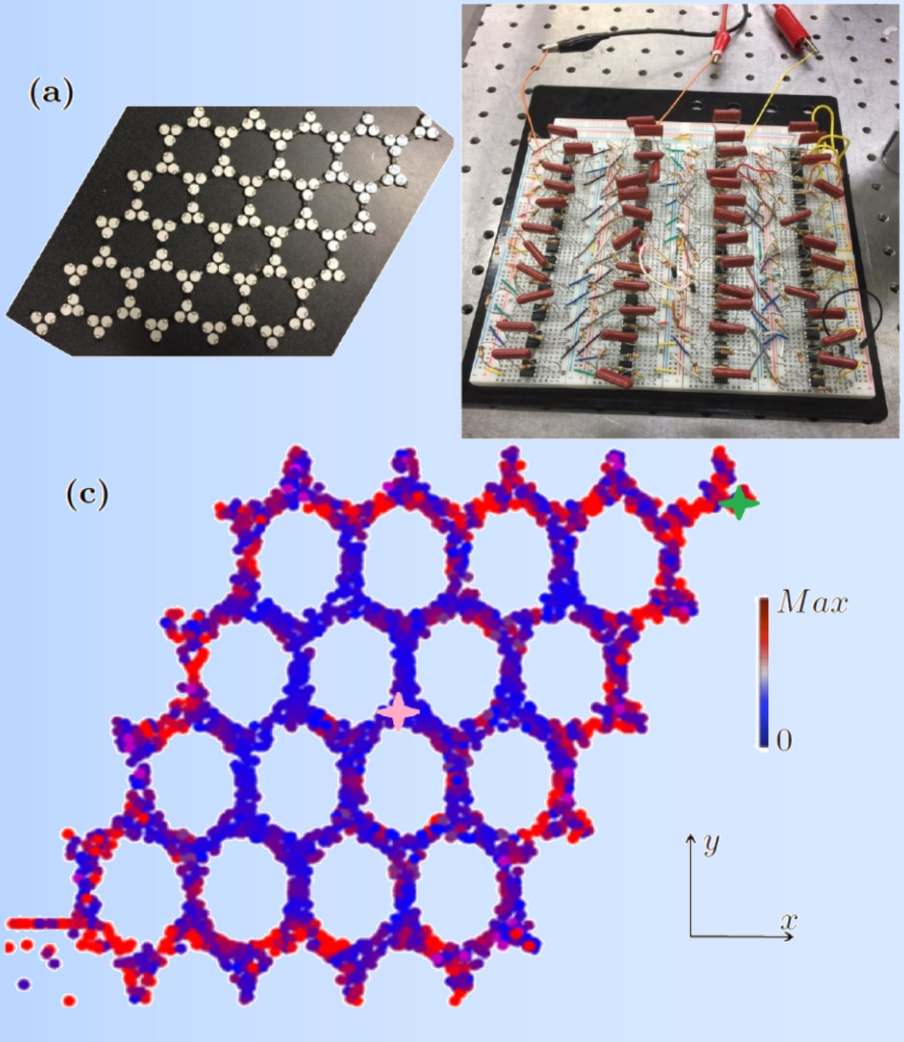


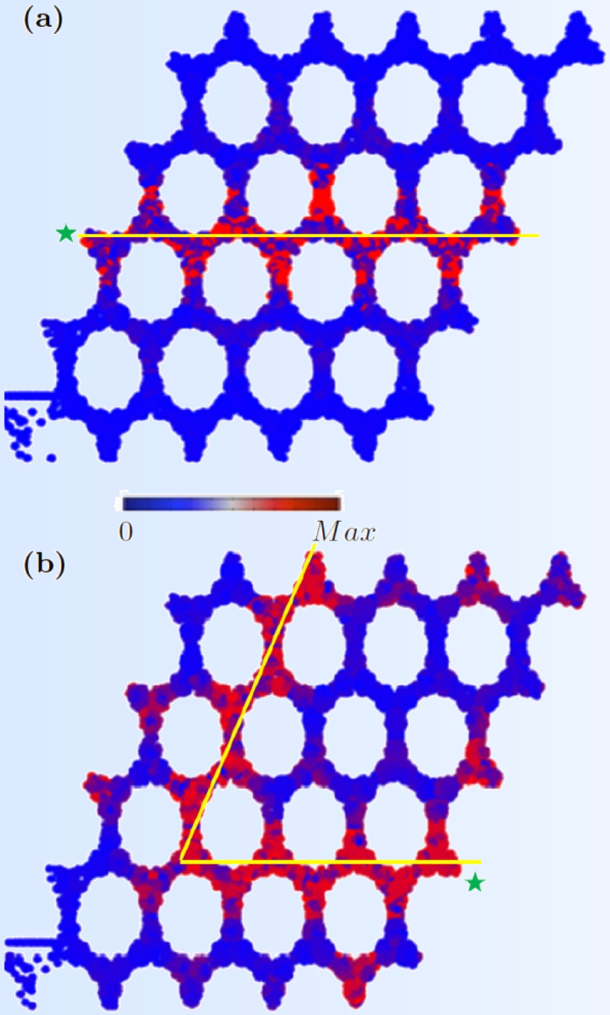




A. B. Khanikaev, R. Fleury, H. Mousavi, A. Alù, *Nature Comm.* **6**, 8260 (2015)
R. Fleury, A. B. Khanikaev, A. Alù, *Nature Comm.* **7**, 11744 (2016)

Floquet Topological Insulators for Elastic Waves





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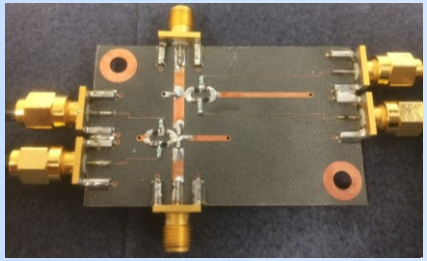
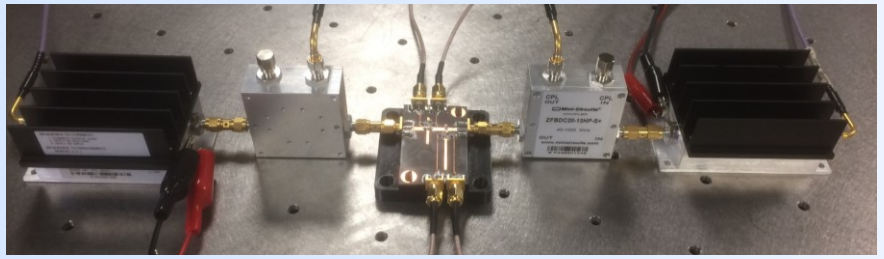
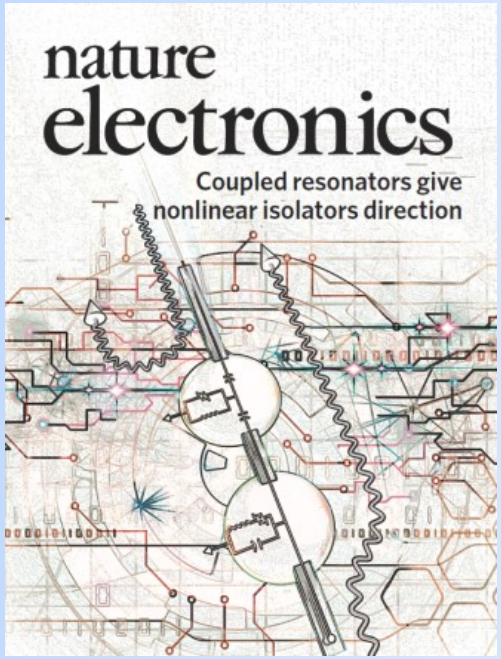
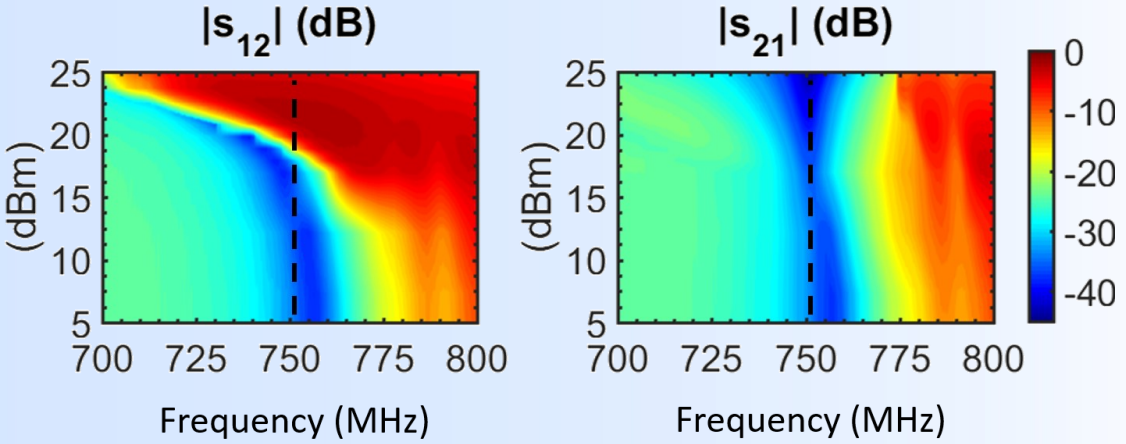
Non-Reciprocity Based on Nonlinearities

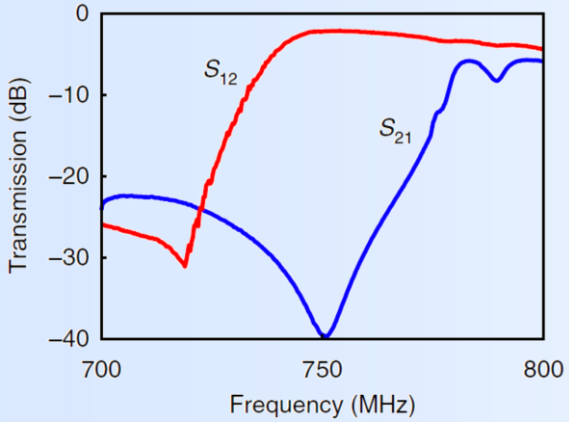




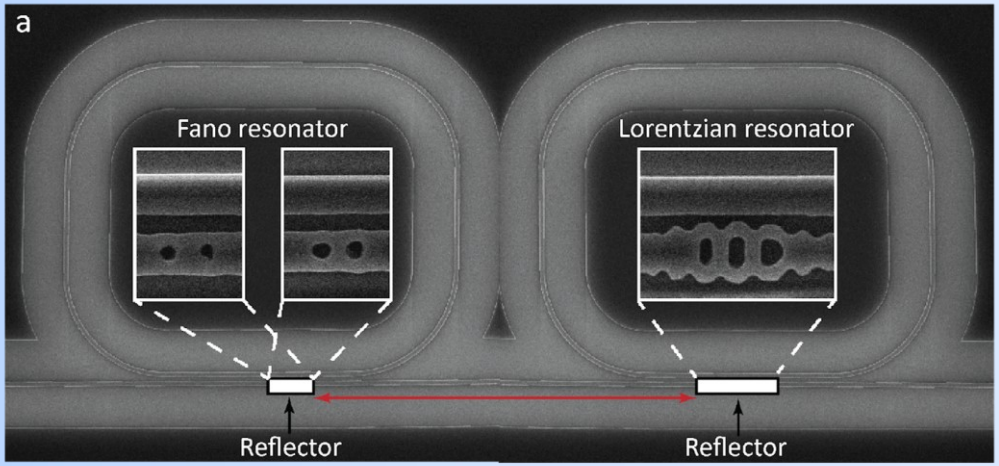


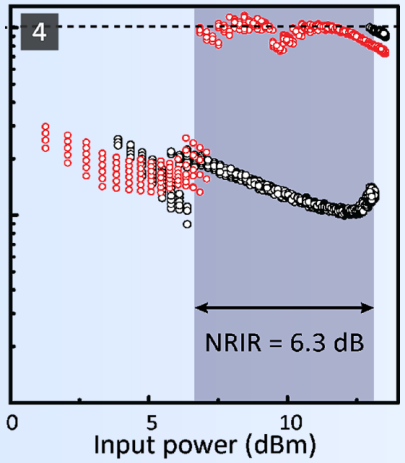
D. L. Sounas, J. Soric, and A. Alù
Nature Electron. **1**, 113 (2018)

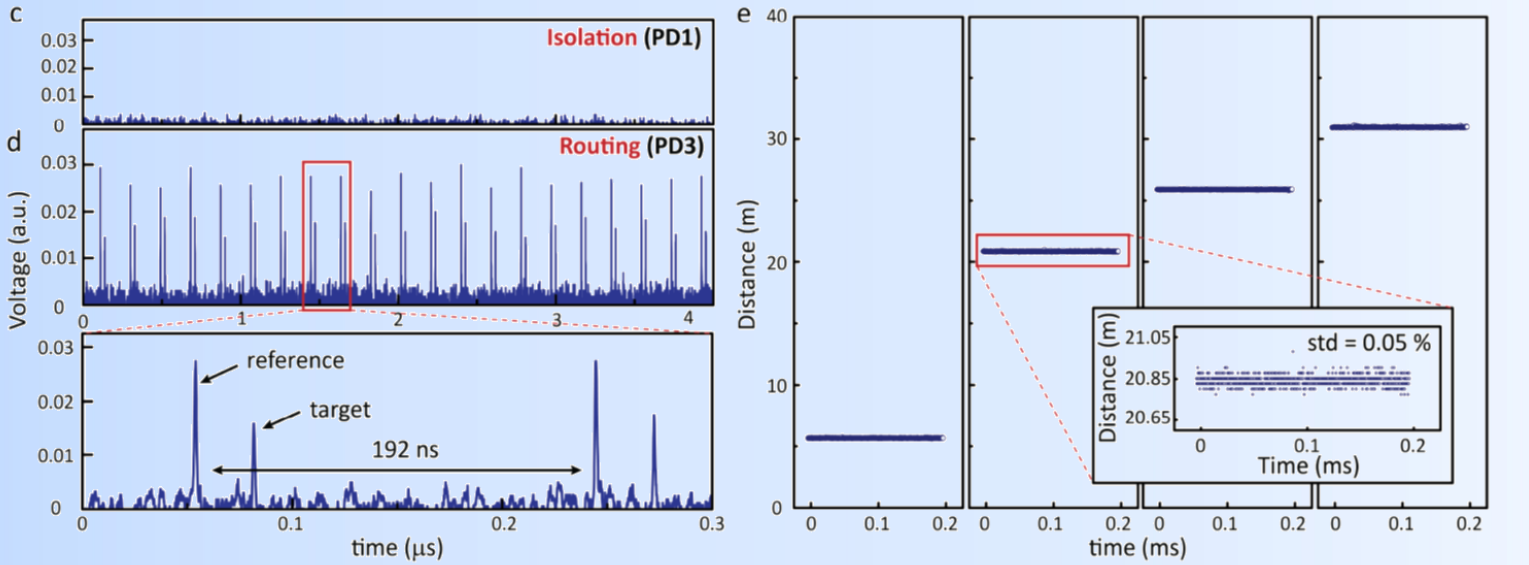




Non-Reciprocal Light Propagation with Non-Linearities





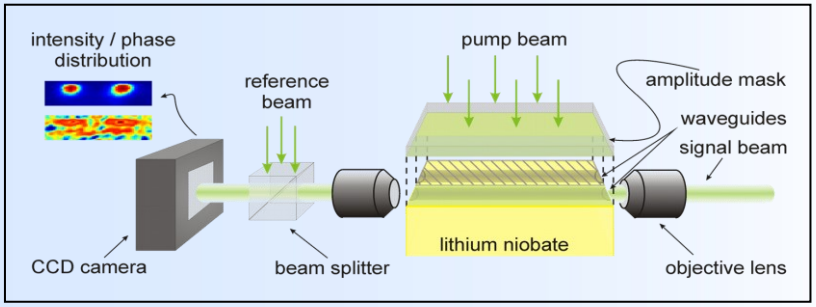


K. Y. Yang, J. Skarda, M. Cotrufo, …, A. Alù, J. Vuckovic, *Nature Photonics* (2020)

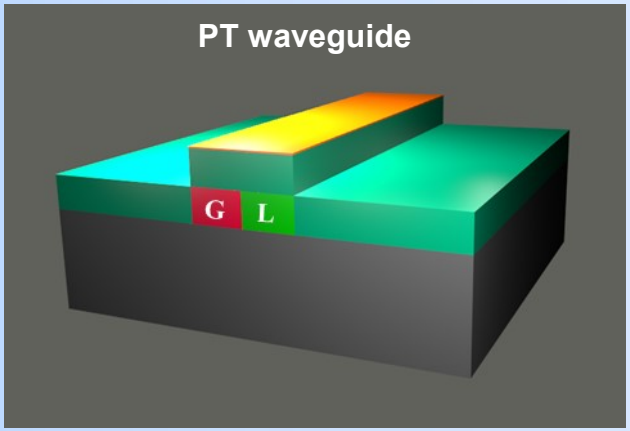
Parity-Time Symmetry

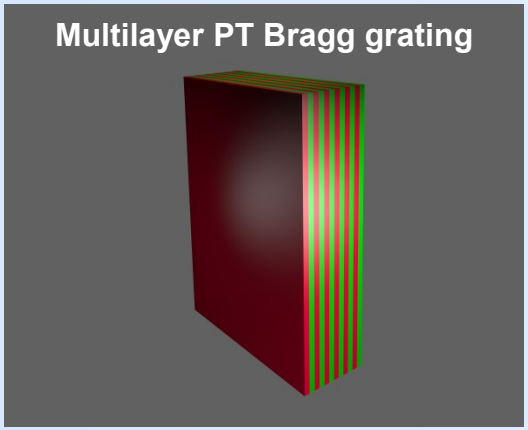
$$n(\boldsymbol{r}) = n^*(-\boldsymbol{r})$$

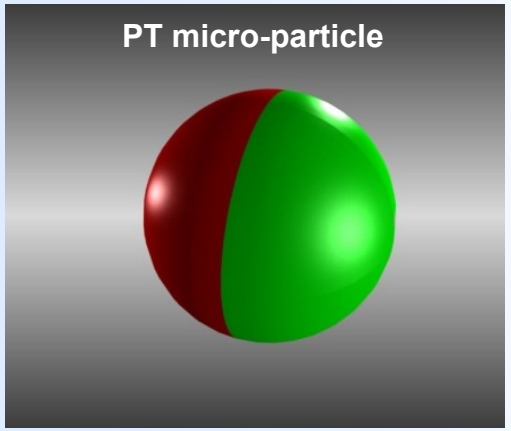
$$\boxed{\begin{aligned} n_R(-\boldsymbol{r}) &= +n_R(\boldsymbol{r}) \\ n_I(-\boldsymbol{r}) &= -n_I(\boldsymbol{r}) \end{aligned}}$$



Christodoulides, et al., Nat. Phys. (2010)

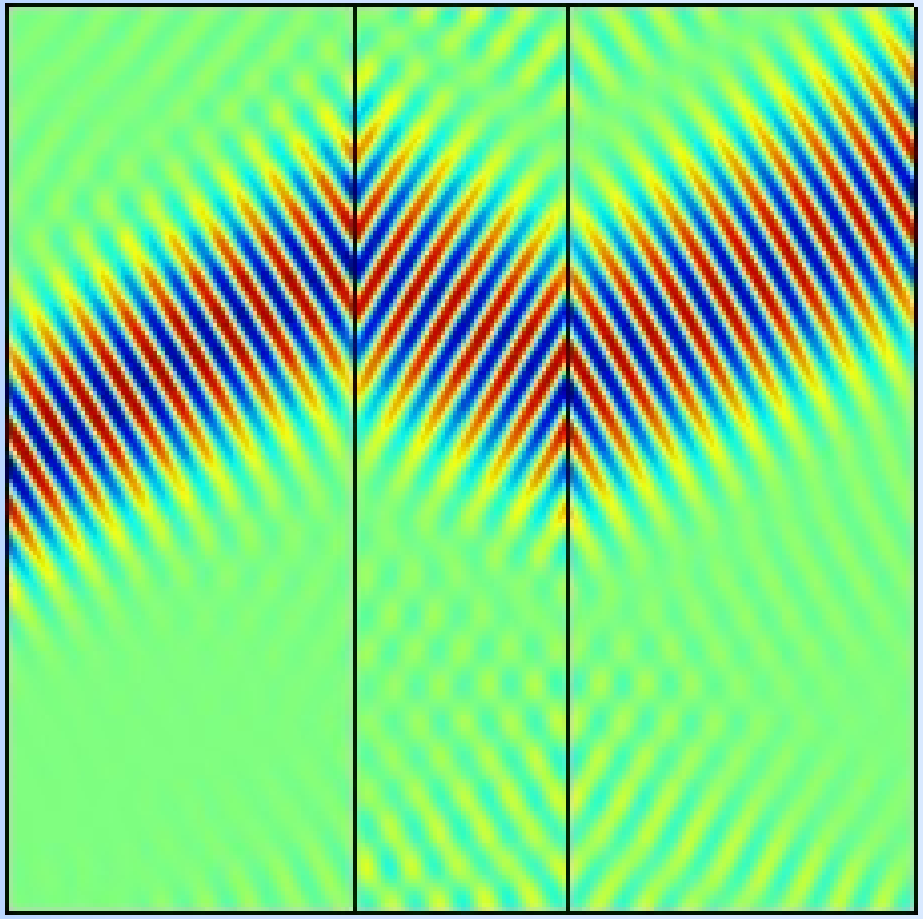




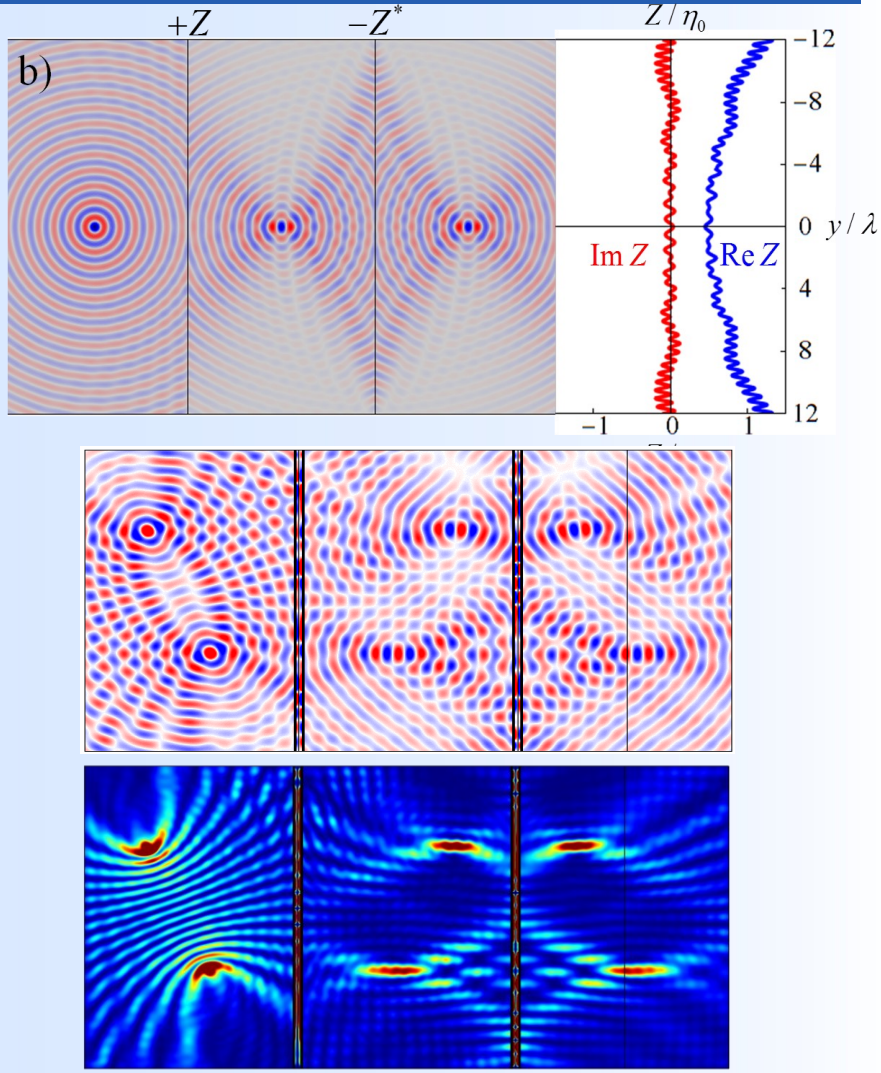


M. A. Miri, A. Alù, *Science* **363**, 42 (2019)

Negative Refraction and Focusing Based on PT Symmetry



$$\frac{+Z_0 \cos\vartheta}{2} \qquad \frac{-Z_0 \cos\vartheta}{2}$$



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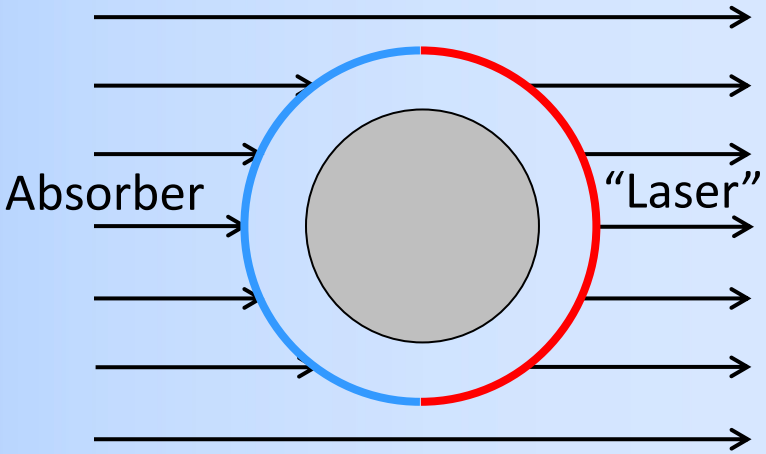
F. Monticone, C. Valagiannopoulos, A. Alù, *Phys. Rev. X* **6**, 041018 (2016)

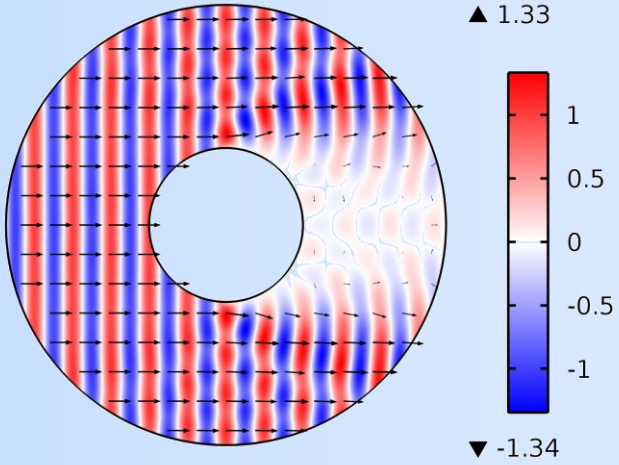
Cloaking with Parity-Time Symmetry



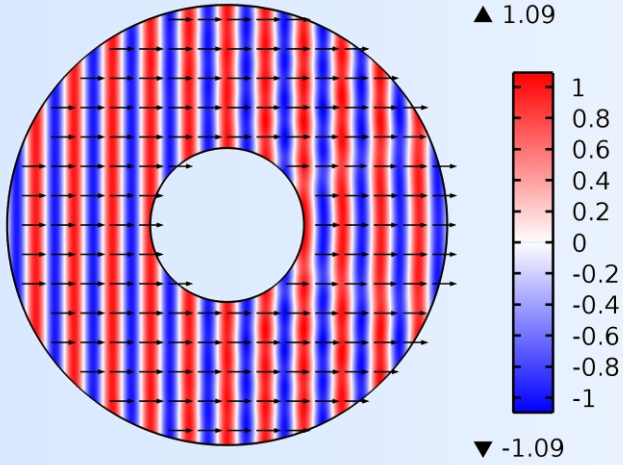
$$\mathrm{Re}\{Y_s\} = \begin{cases} Y_0 \left|\cos\varphi\right|, & \text{left side} \\ -Y_0 \left|\cos\varphi\right|, & \text{right side} \end{cases}$$

$$\mathrm{Im}\{Y_s\} = -Y_0 \left[\frac{1}{k(d-a)} - \frac{1}{2ka} \right]$$

Only passive

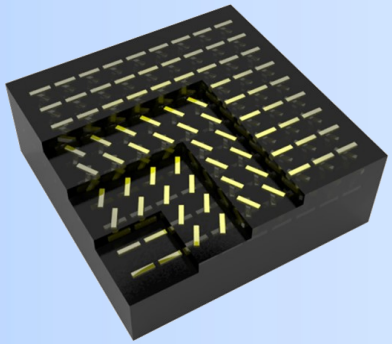


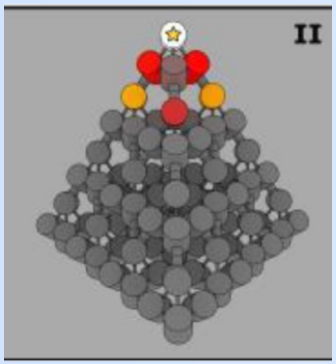
Passive + active



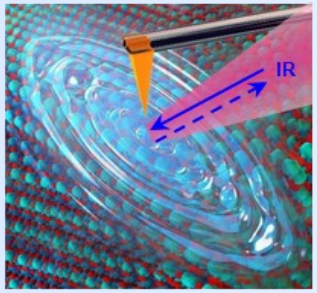
D. L. Sounas, R. Fleury, A. Alù, *Phys. Rev. Appl.* **4**, 014005 (2015)
A. Kord, D. L. Sounas, A. Alù, *Phys. Rev. Appl.* **10**, 054040 (2018)

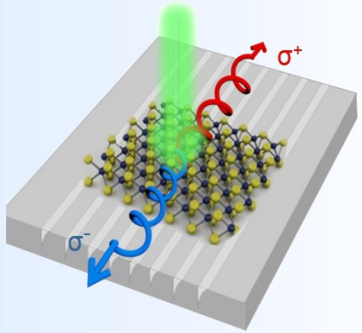
Optical Metamaterials Based on Broken Symmetries



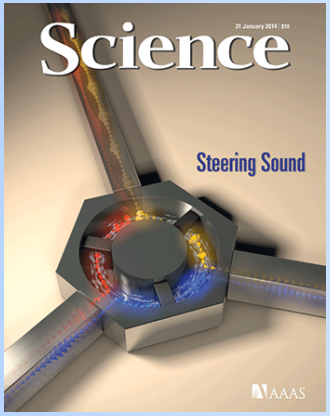


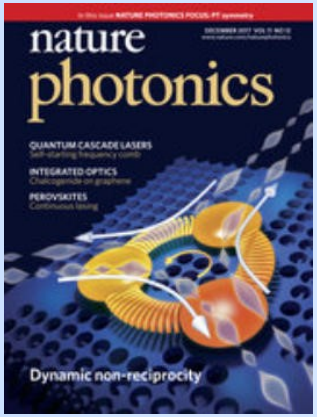
Broken geometrical symmetries for enhanced wave control and routing

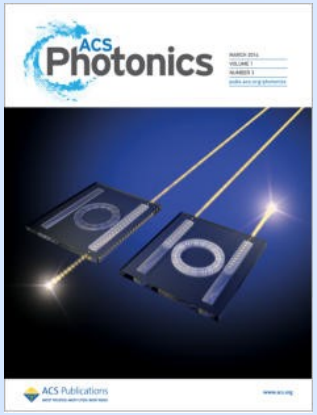


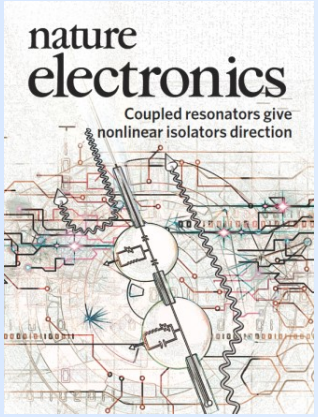


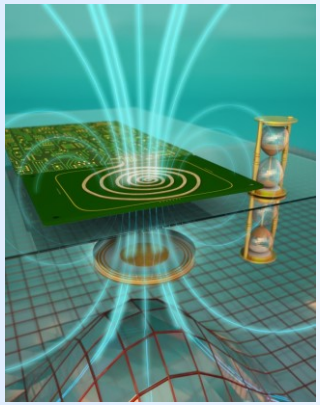
Twistronics in metasurface bilayers to mold the flow of light at the nanoscale

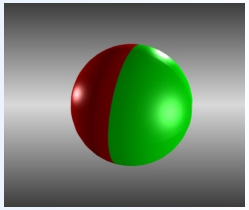












Magnetic-free, nonreciprocity at the nanoscale: angular-momentum bias and nonlinearities

Parity-time symmetry for exotic interactions beyond the limits of passive metamaterials