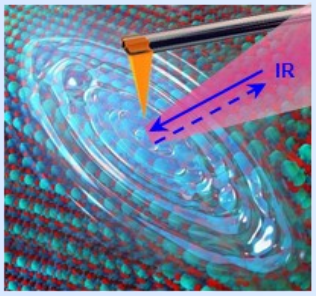
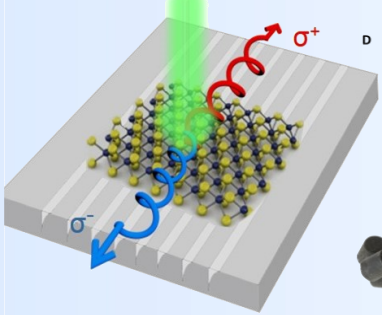
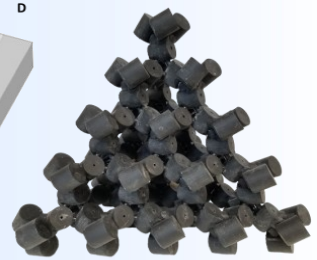




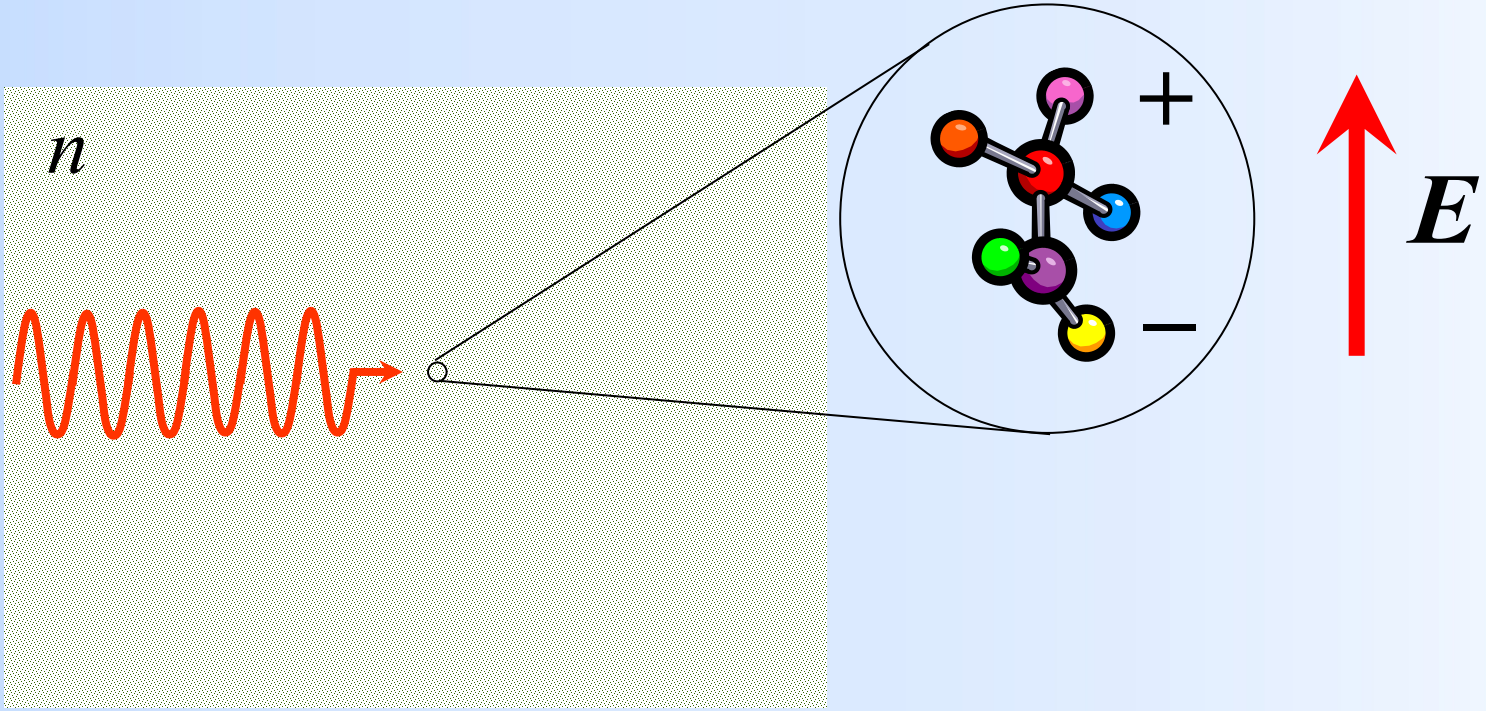


Exotic Wave-Matter Interactions Based on Metamaterials

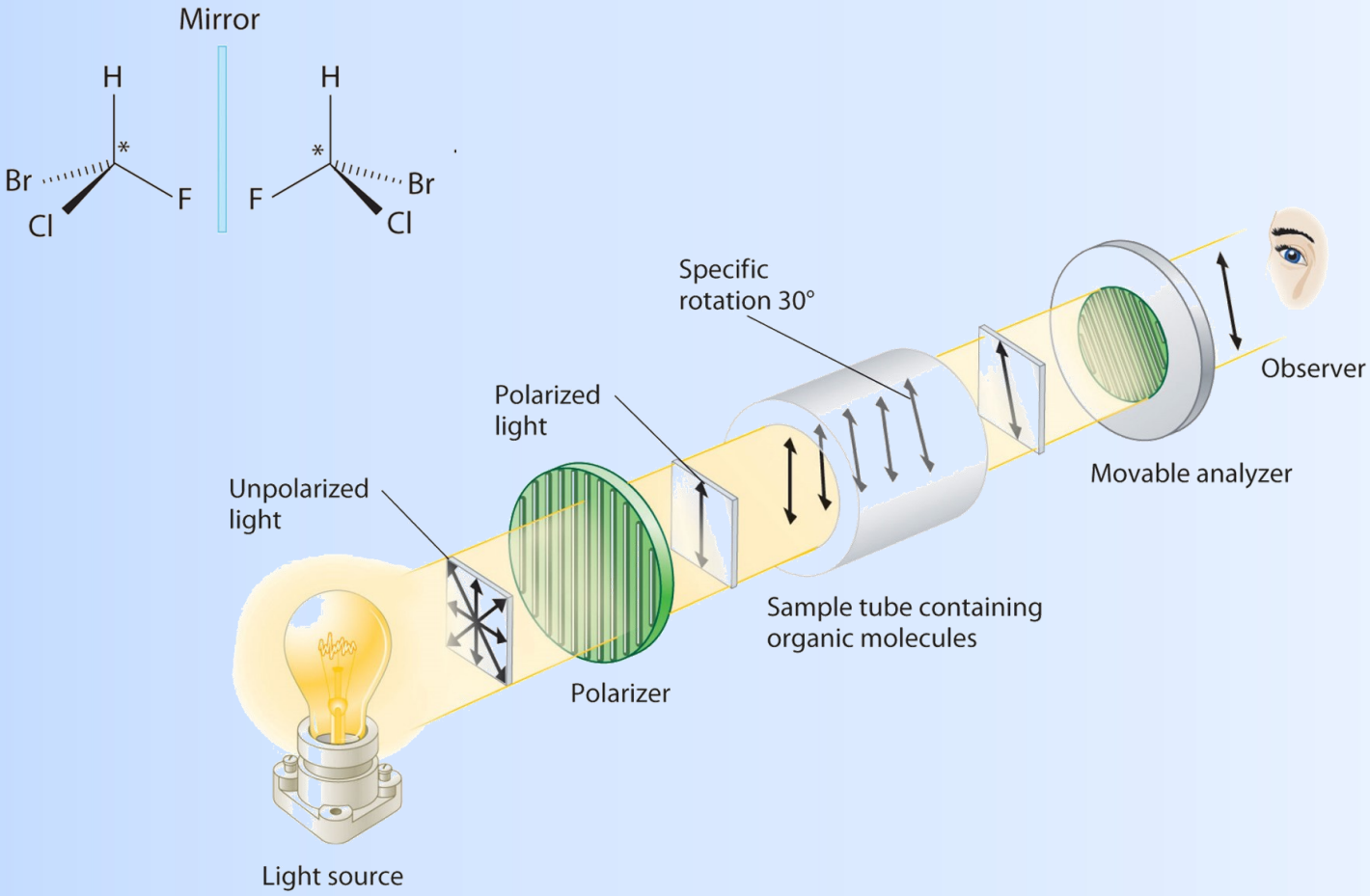
Andrea Alù

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

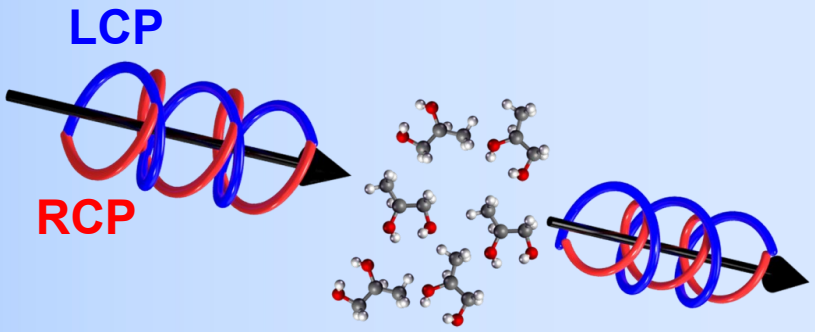


Optical Activity of Chiral Samples

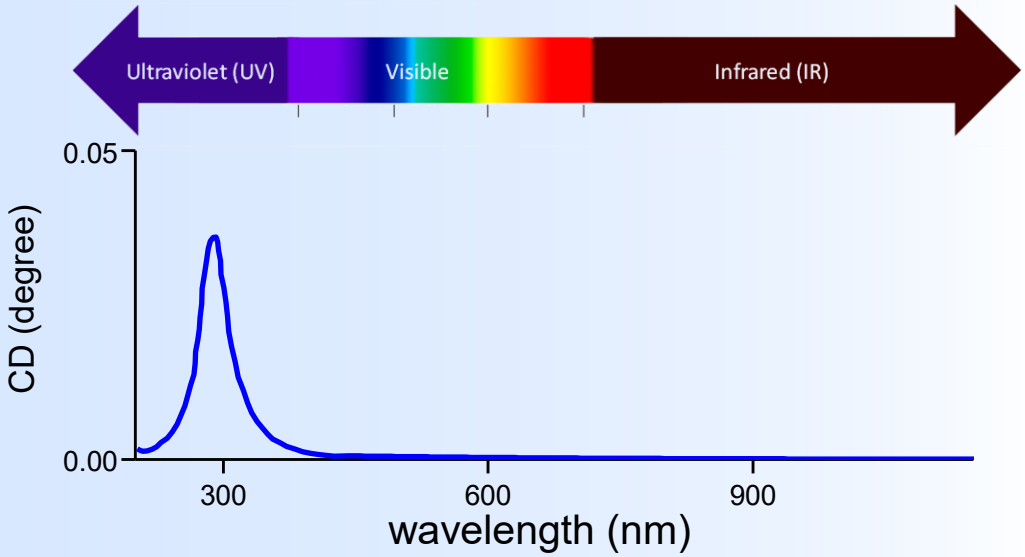


B. A. Averill, *General Chemistry: Principles and Applications* (2007)

Circular Dichroism of Chiral Molecules



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



Symmetry Breaking in Artificial Materials

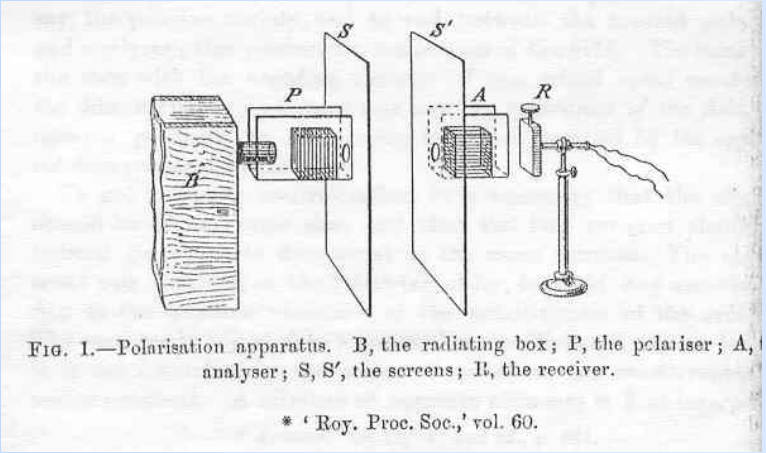


Fig. 1.—Polarisation apparatus. B, the radiating box; P, the polariser; A, analyser; S, S′, the screens; R, the receiver.

* 'Roy. Proc. Soc.,' vol. 60.

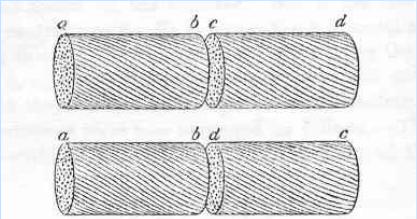
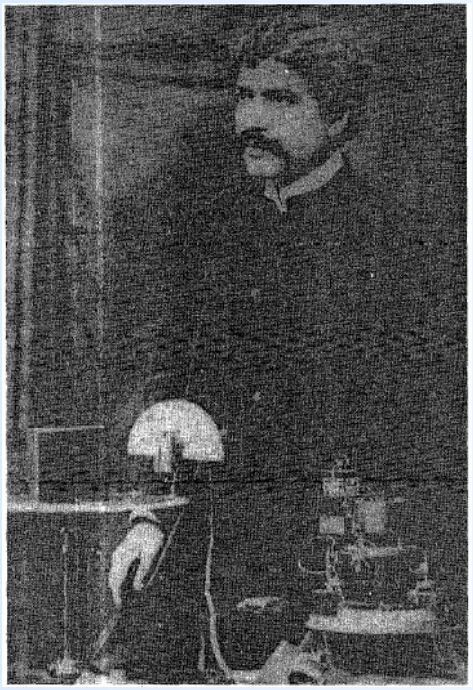


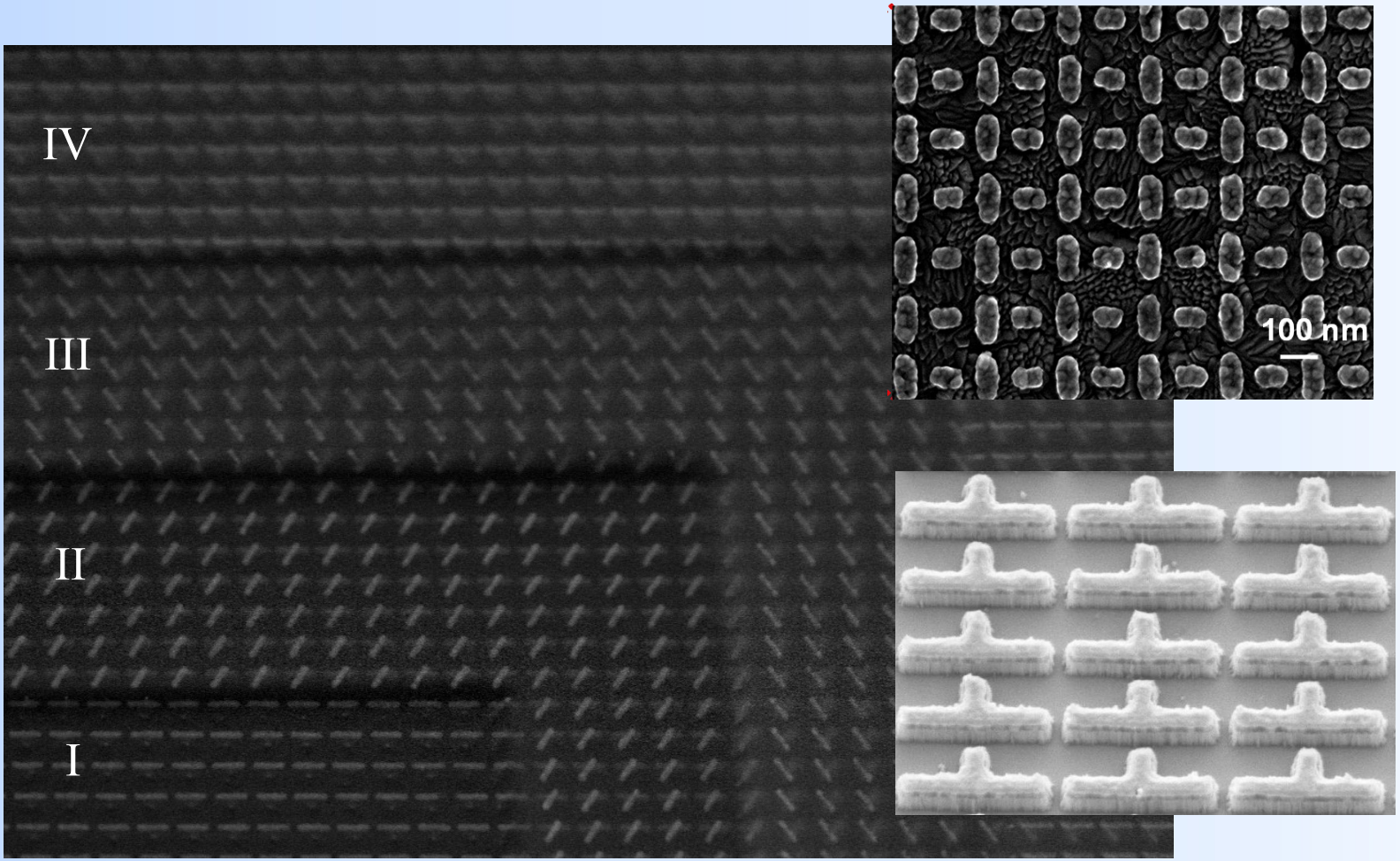
Fig. 2.—Jute elements.



From: T. K. Sarkar and D. L. Sengupta, "An appreciation of J. C. Bose's pioneering work in millimeter waves," *IEEE Antennas and Propagation Magazine*, Vol. 39, No. 5, pp. 55-63, 1997. Originally from P. Geddes, *The life and work of Sir Jadagish C. Bose*, New York, Longmans, Greens & Co, 1920.

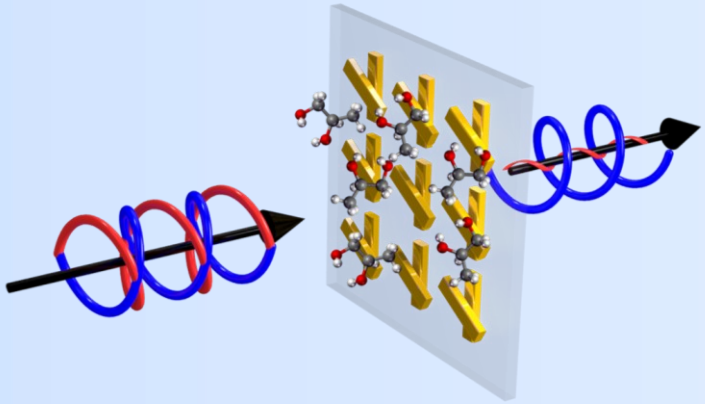
J. C. Bose, *Proc. Royal Soc.* **63**, 146 (1898)

META-MATERIALS: *BEYOND* NATURE WITH ARTIFICIAL MATERIALS

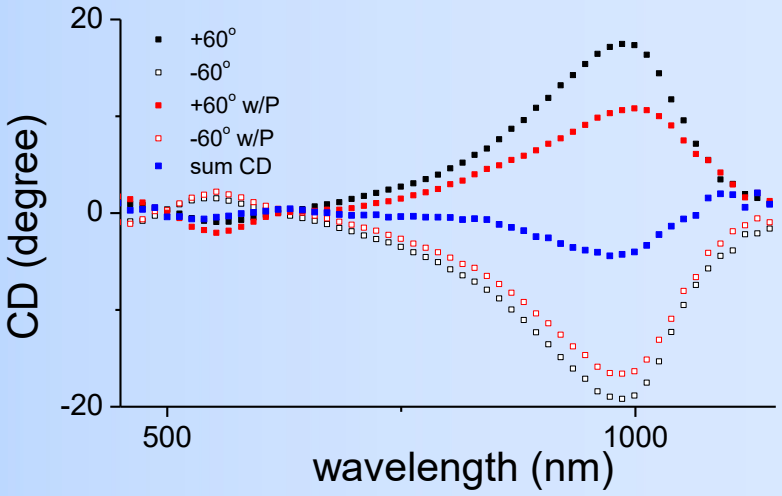


Y. Zhao, M. Belkin, A. Alù, *Nature Comm.* **3**, 870 (2012)
Y. Zhao, A. Alù, *Nano Lett.* **13**, 1086 (2013)
J. Lee, et al., *Nature* **511**, 65 (2014)

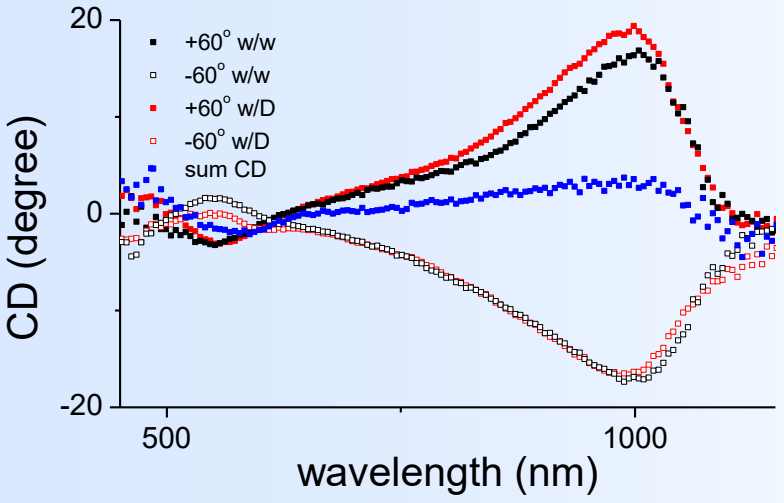
Enhanced Circular Dichroism and Chirality Detection



Chiral protein: Concanavalin A



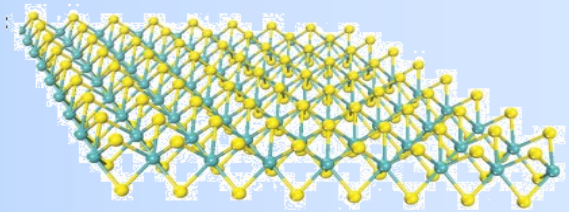
Chiral drug: Irinotecan Hydrochloride



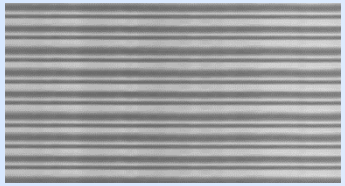
Y. Zhao, A. N. Askarpour, L. Sun, J. Shi, X. Li, and A. Alù, *Nature Comm.* **8**, 14180 (2017)

2D Materials and Hybrid Metamaterials

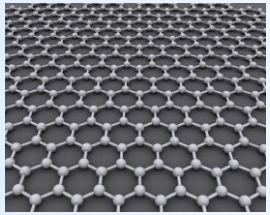
TMDs, TMOs



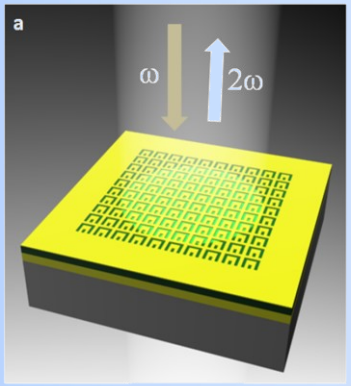
Doped multiple quantum wells (MQW)



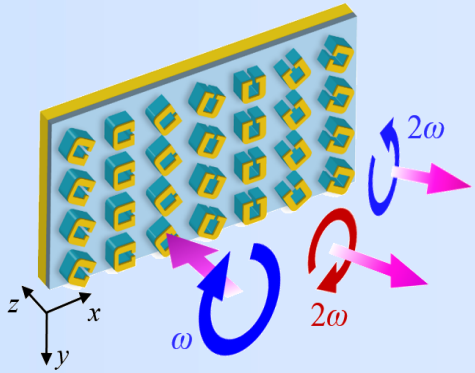
Graphene



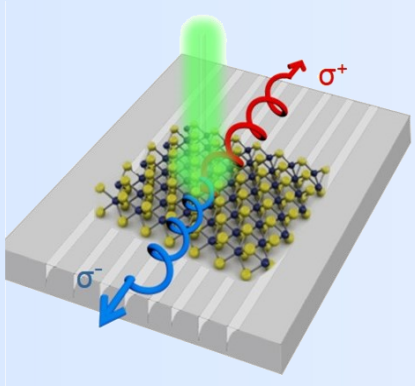
Lattice symmetries provide further opportunities to tailor light-matter interactions



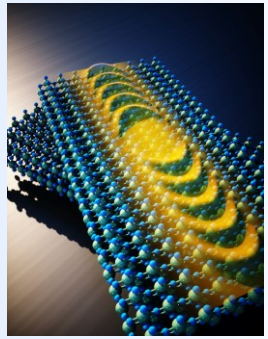
Nature (2014)



PRL (2015), *Optica* (2016)

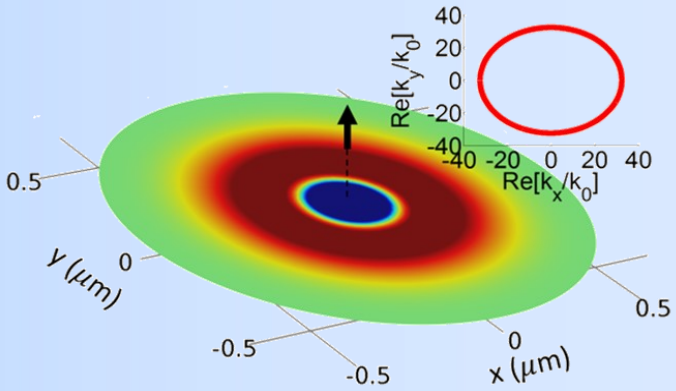


Nature Phot. (2019)



Nature (2020)

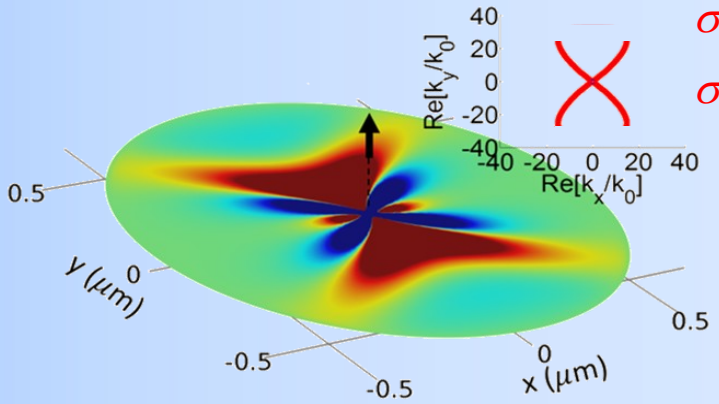
Extreme Asymmetry over a Meta-Surface



$\sigma_{xx} > 0$

$\sigma_{yy} > 0$

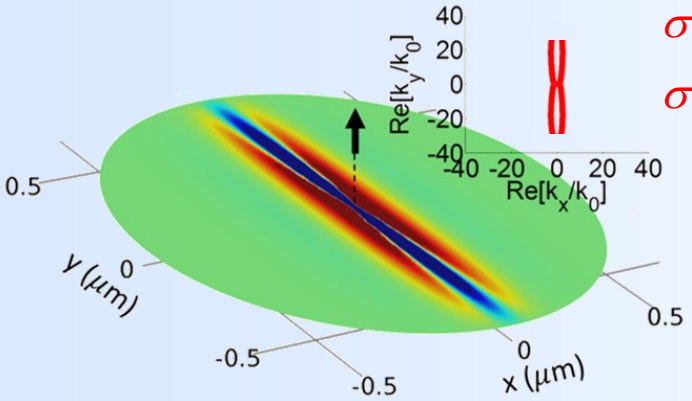
Elliptic propagation



$\sigma_{xx} > 0$

$\sigma_{yy} < 0$

Hyperbolic topology



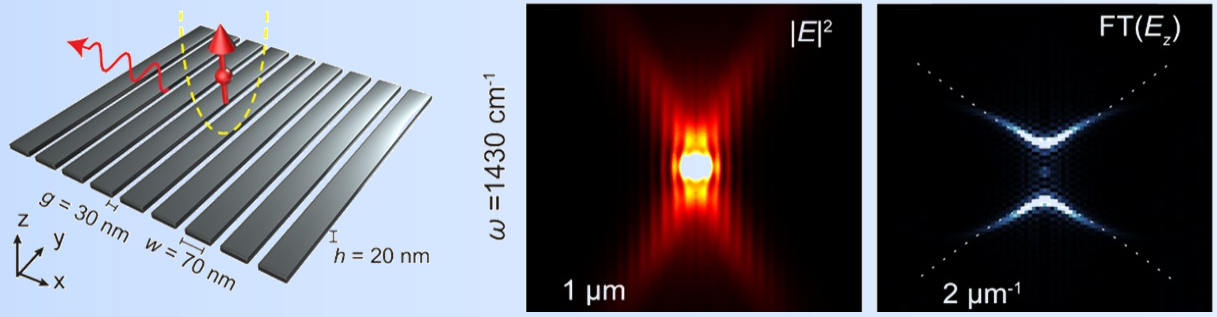
$\sigma_{xx} > 0$

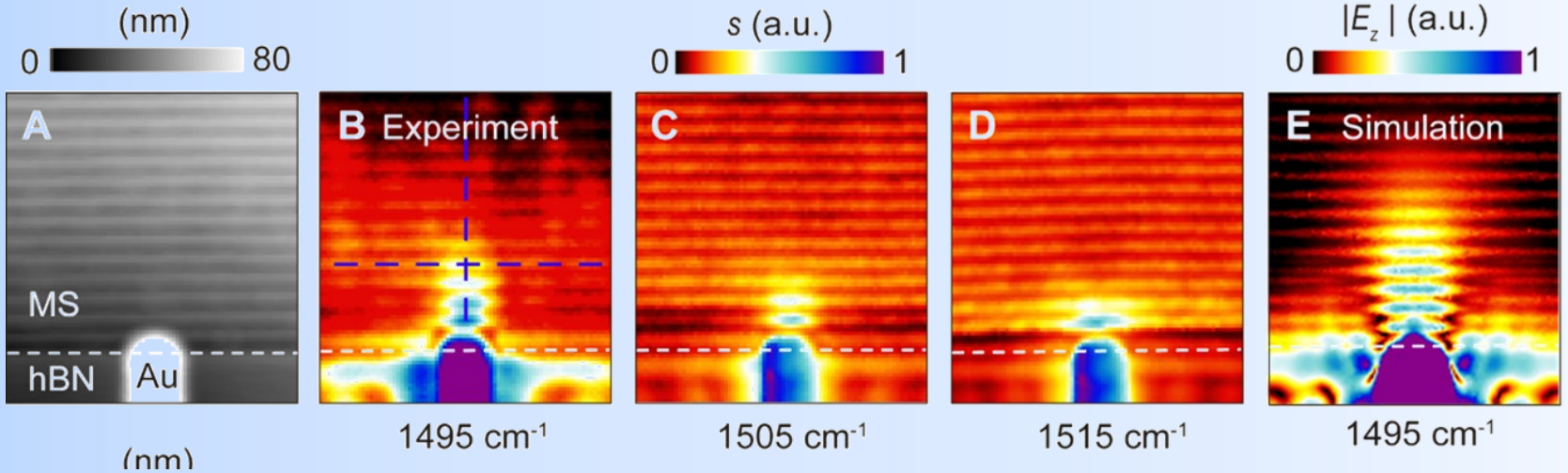
$\sigma_{yy} \approx 0$

Canalization regime

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

Hyperbolic Metasurfaces Based on H-BN Nano-Ribbons

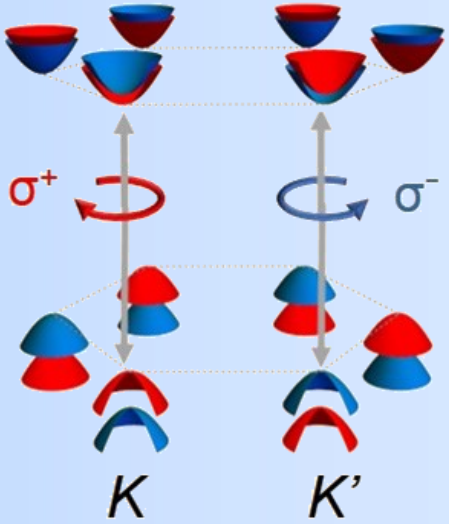


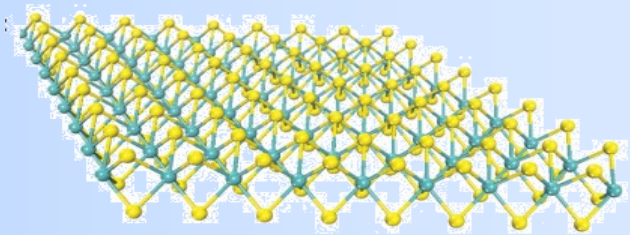


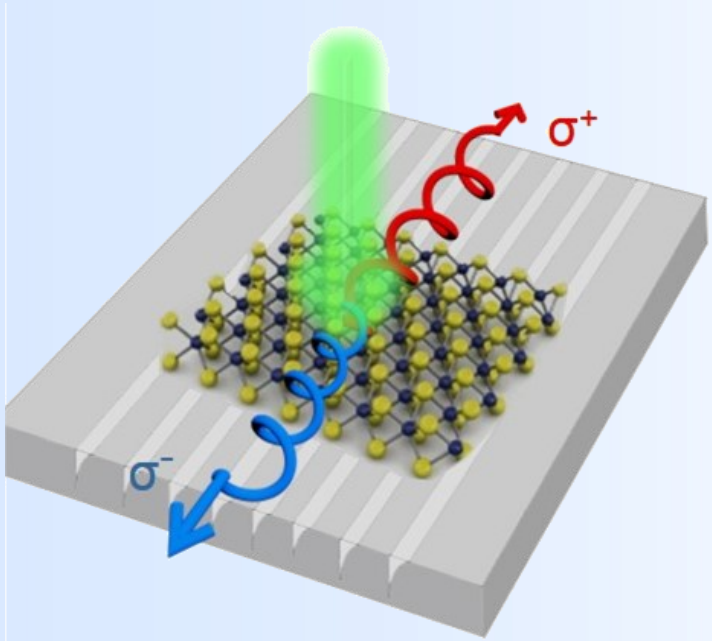
P. Li, G. Hu, I. Dolado, M. Tymchenko, C. W. Qiu, F. J. Alfaro-Mozaz, F. Casanova, L. E. Hueso, S. Liu, J. H. Edgar, S. Vélez, A. Alù, R. Hillenbrand, *Nature Comm.* **11**, 3663 (2020)

Hyperbolic Metaurfaces for Valleytronics

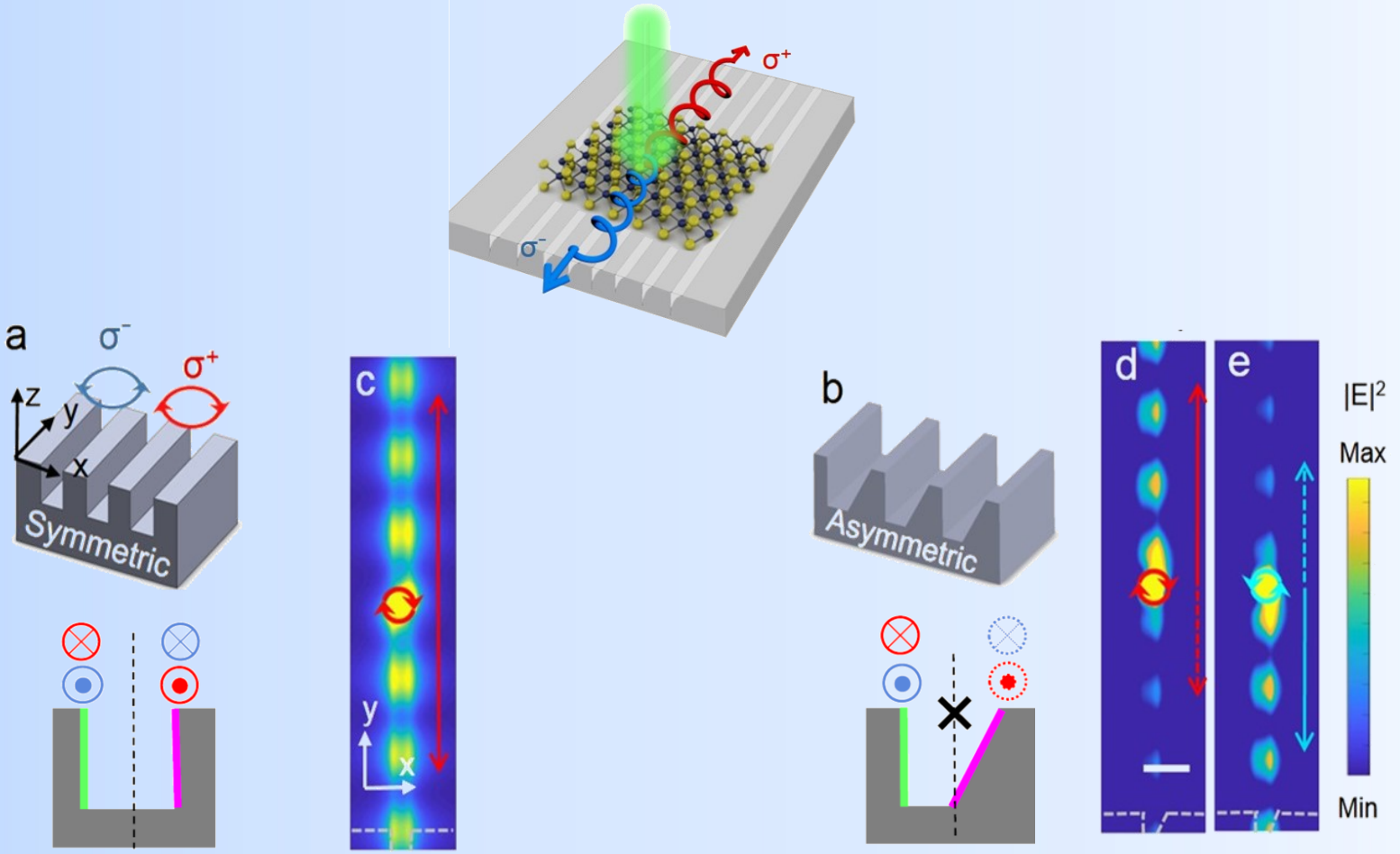
Enhancing and routing valley excitons with a metasurface using MoS2-loaded hyperbolic metasurfaces







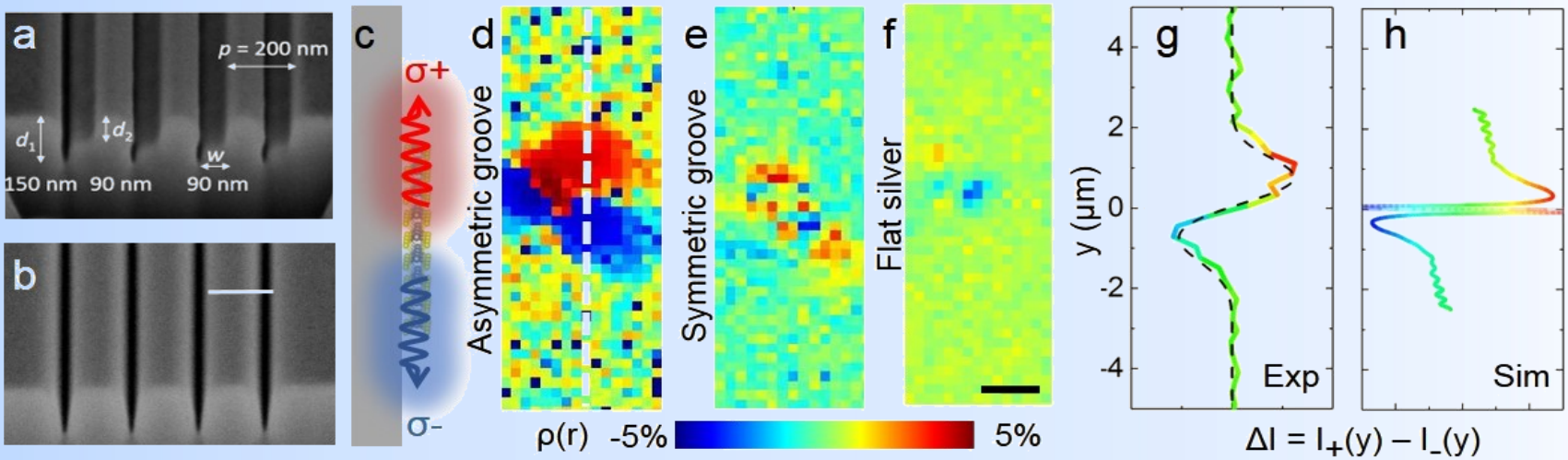
Symmetry-Breaking Hyperbolic Metasurface

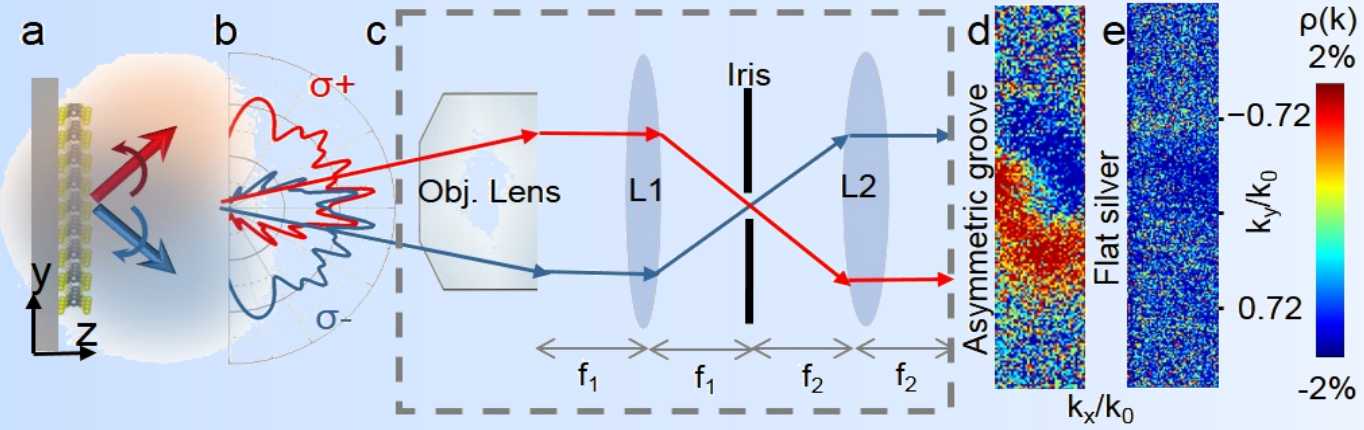


L. Sun, C.Y. Wang, A. Krasnok, J. Choi, J. Shi, J.S. Gomez-Diaz, A. Zepeda, S. Gwo, C. K. Shih, A. Alù, X. Li *Nature Phot.* **13**, 180 (2019)

Y. Mazor, A. Alù, *Phys. Rev. Appl.* **14**, 014029 (2020)

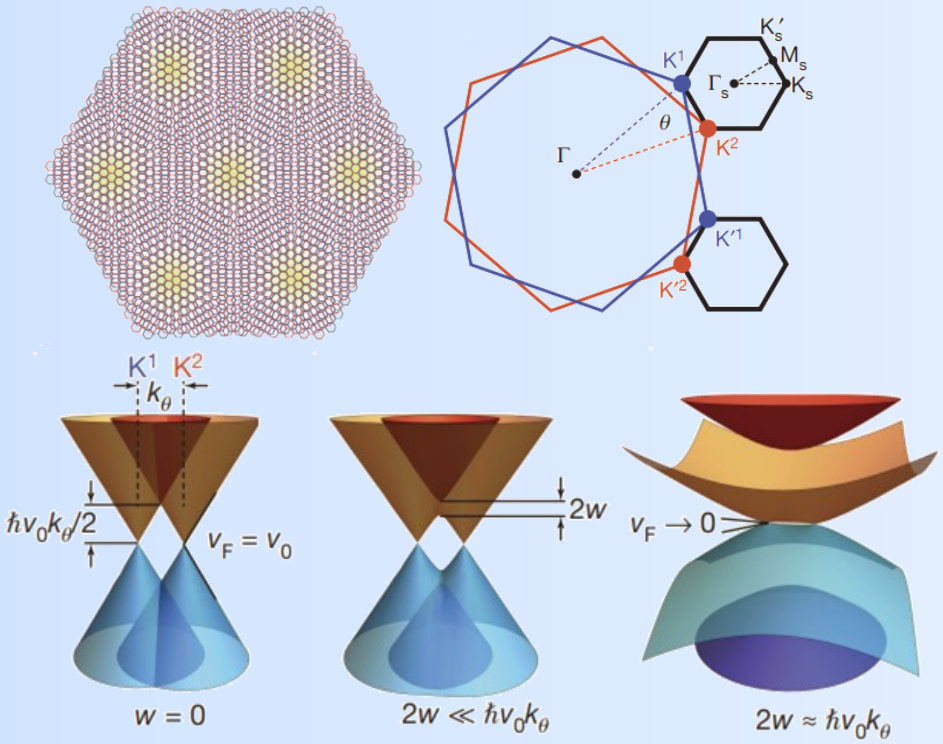
Enhancing, Sorting and Routing Valley Excitons





L. Sun, C.Y. Wang, A. Krasnok, J. Choi, J. Shi, J.S. Gomez-Diaz, A. Zepeda, S. Gwo, C. K. Shih, A. Alù, X. Li
Nature Phot. **13**, 180 (2019)

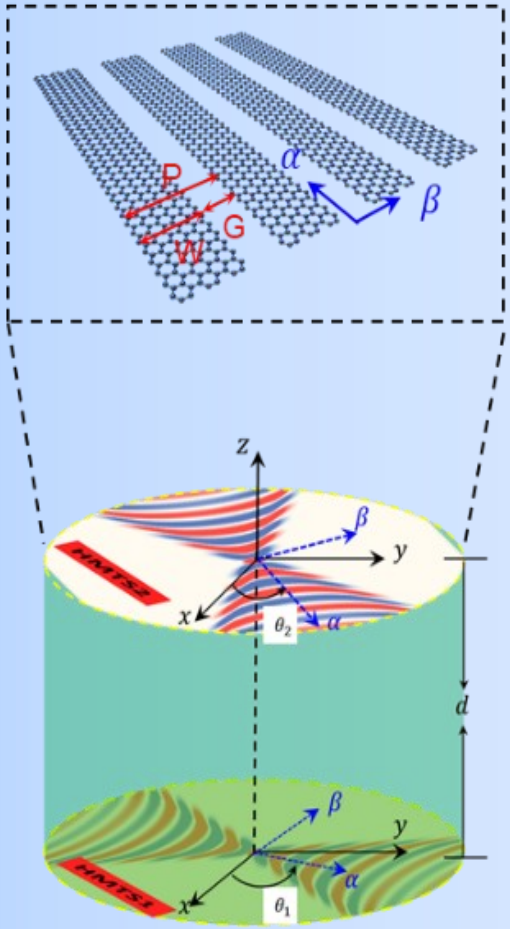
Moiré Physics and Twistronics

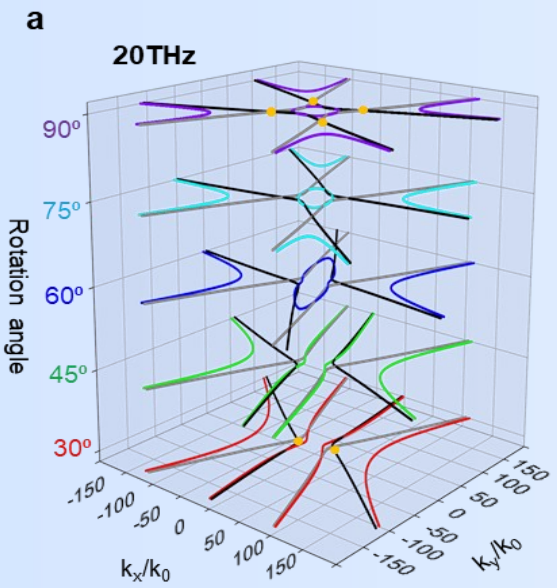


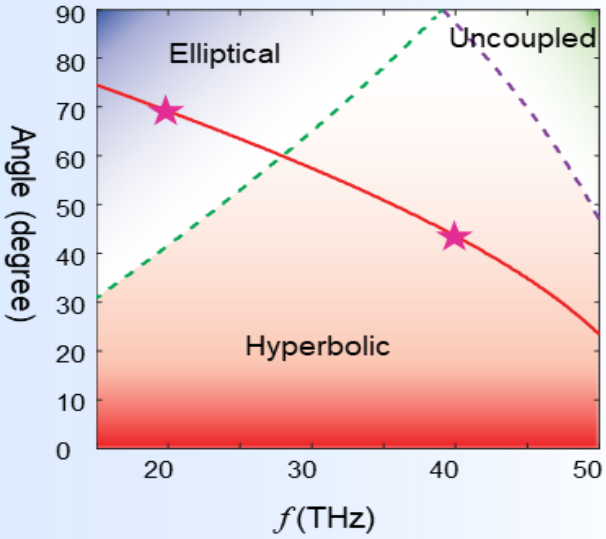
- Fermi-velocity goes to zero (superconductivity) and flat bands at *magic* twist angle of 1.1°
- Twisted-angle-dependent hopping energy

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

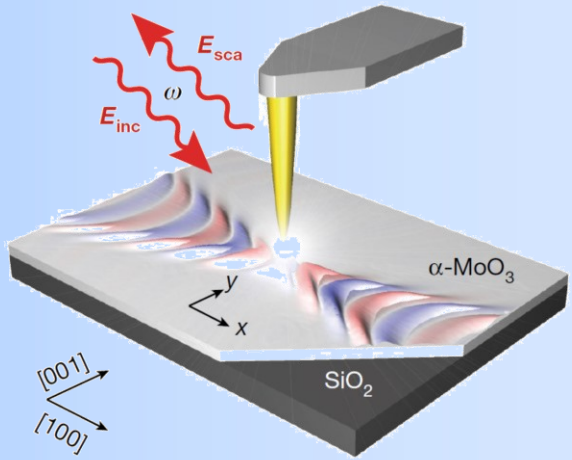


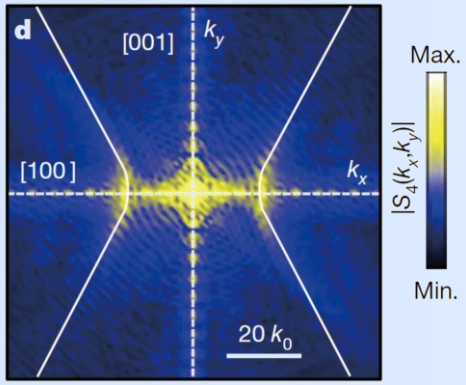


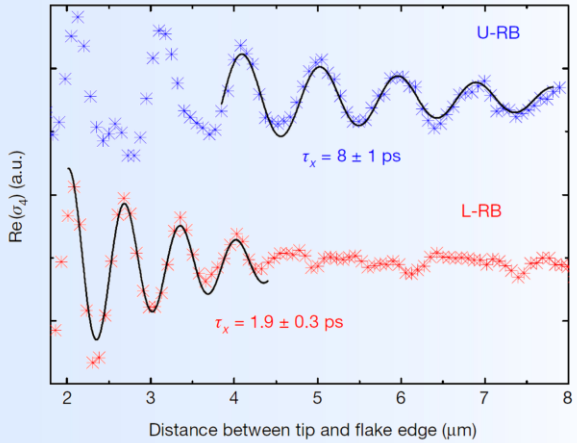


G. Hu, A. Krasnok, Y. Mazor, C. W. Qiu, A. Alù, *Nano Letters* **20**, 3217 (2020)

α-MoO_3 Monolayers as Hyperbolic Surfaces



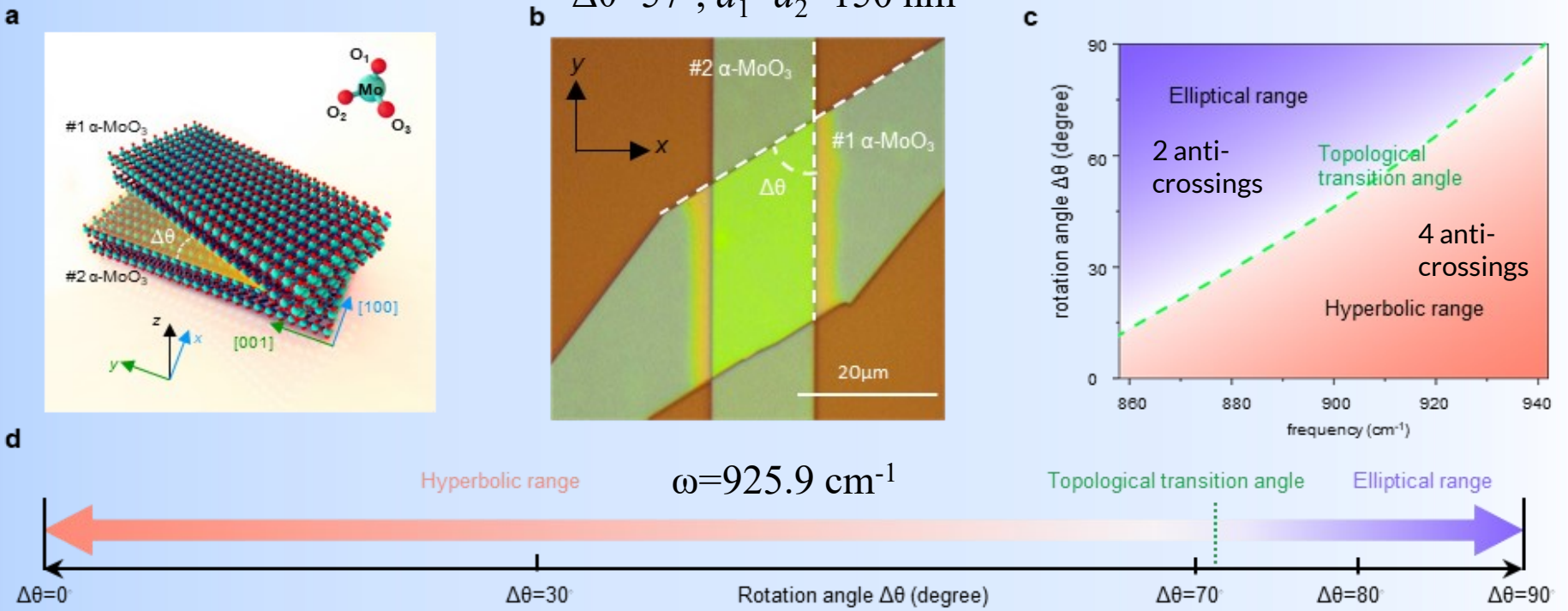




W. Ma, P. Alonso-González, S. Li, A. Y. Nikitin, J. Yuan, J. Martín-Sánchez, J. Taboada-Gutiérrez, I. Amenabar, P. Li, S. Vélez, C. Tollan, Z. Dai, Y. Zhang, S. Sriram, K. Kalantar-Zadeh, S. T. Lee, R. Hillenbrand, Q. Bao, *Nature* **562**, 557 (2018)

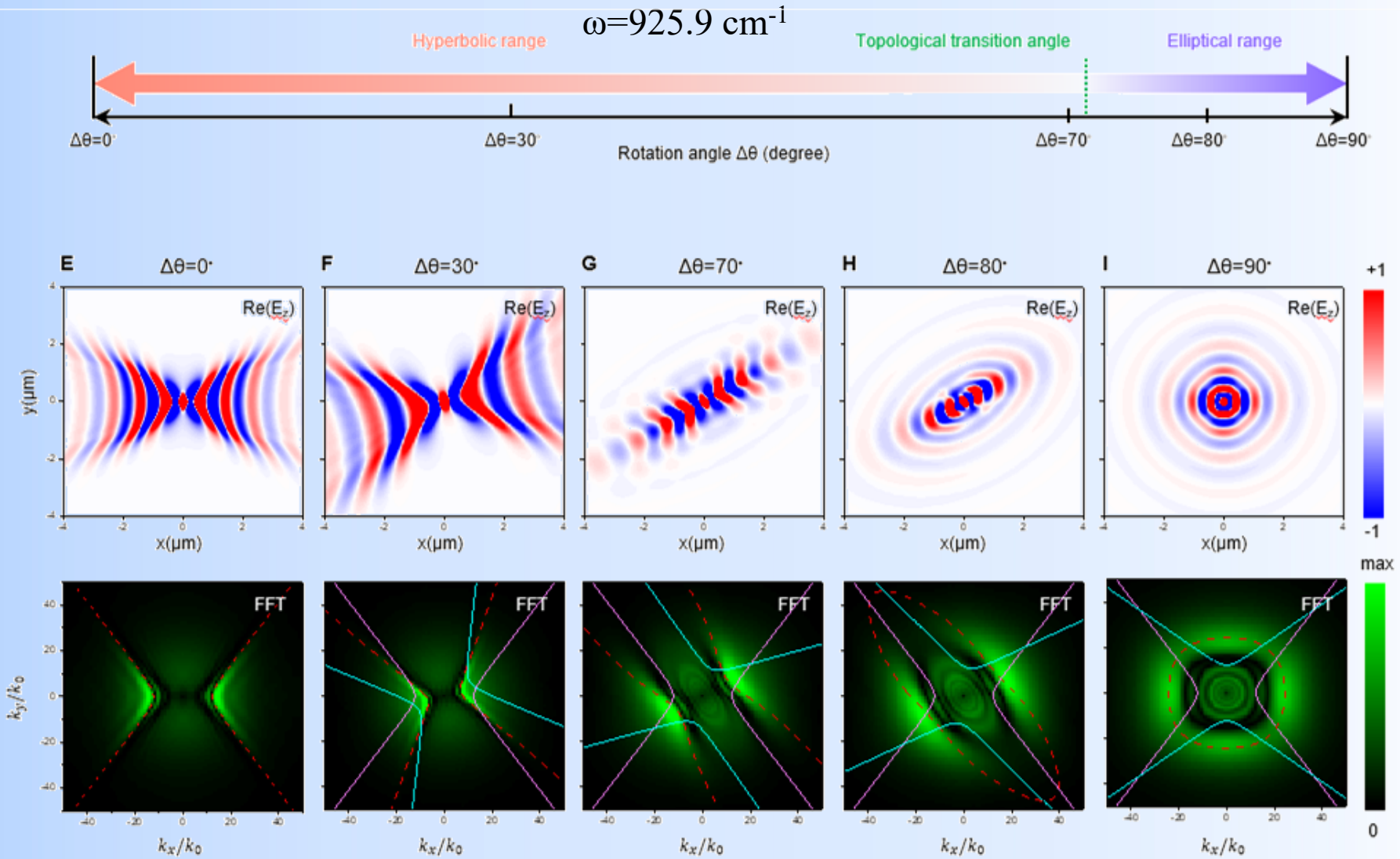
Twisted α-MoO_3 Bilayers

$\Delta\theta=57^\circ$, $d_1=d_2=150$ 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* **582**, 209 (2020)

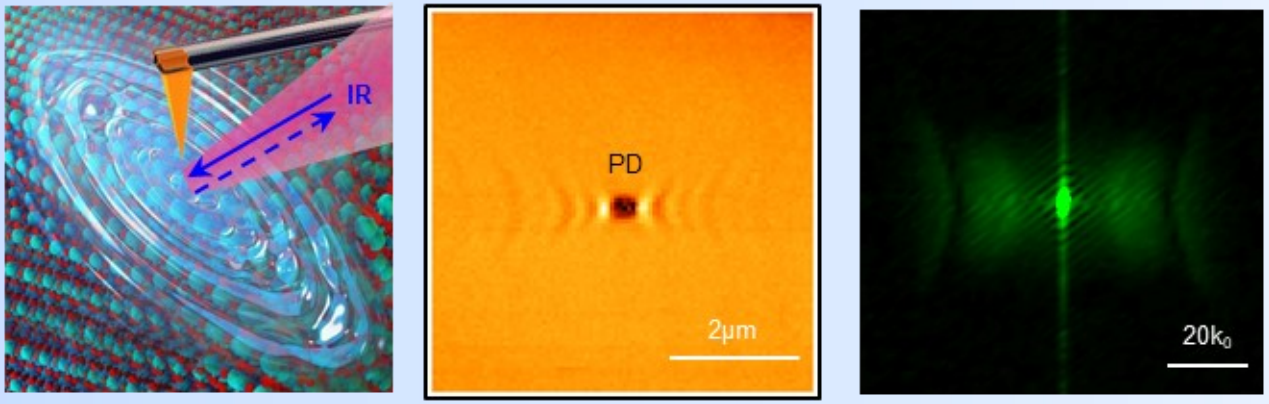
Twisted α-MoO_3 Bilayers



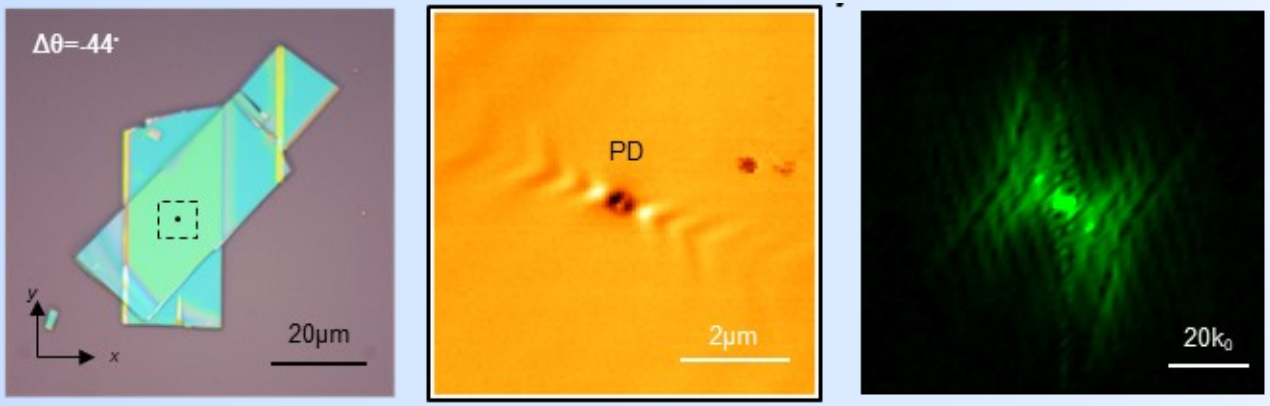
Experimental Verification in Twisted α-MoO_3 Bilayers

Single layer

ω=903.8 cm^{-1}



Bi-layer $\Delta\theta$=-44˚

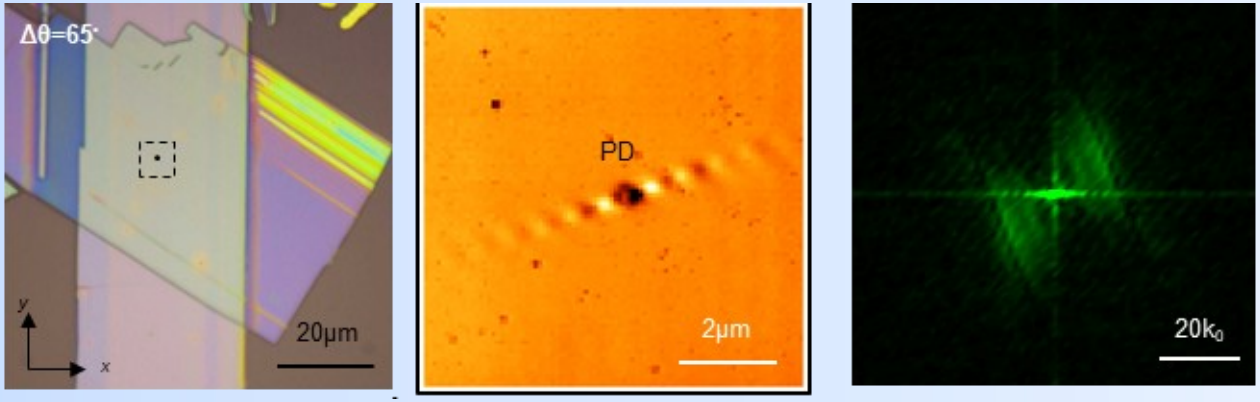


G. Hu, Q. Ou, G. Si, Y. Wu, J. Wu, Z. Dai, A. Krasnok, Y. Mazor, Q. Zhang, Q. Bao, C. W. Qiu, A. Alù, *Nature* **582**, 209 (2020)

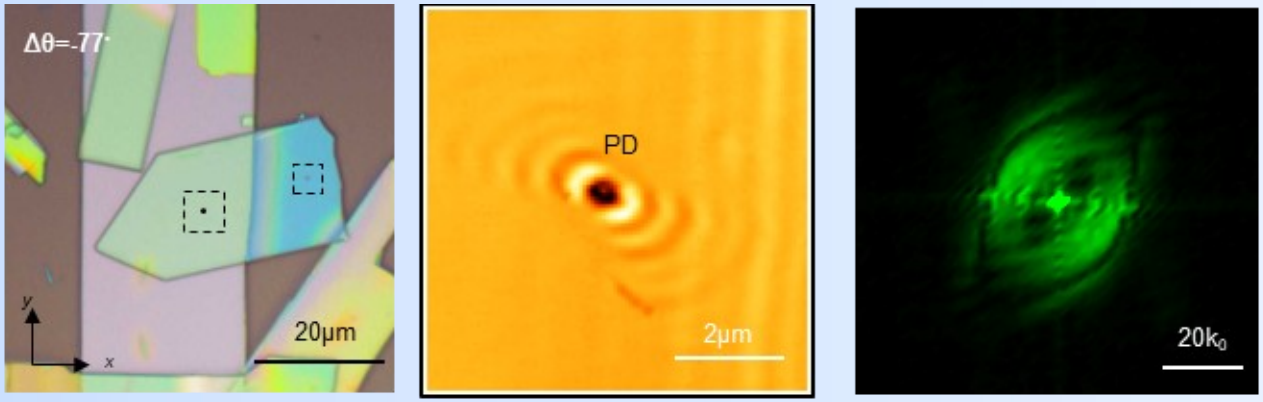
Experimental Verification in Twisted α-MoO_3 Bilayers

ω=903.8 cm^{-1}

Bi-layer $\Delta\theta$=65˚



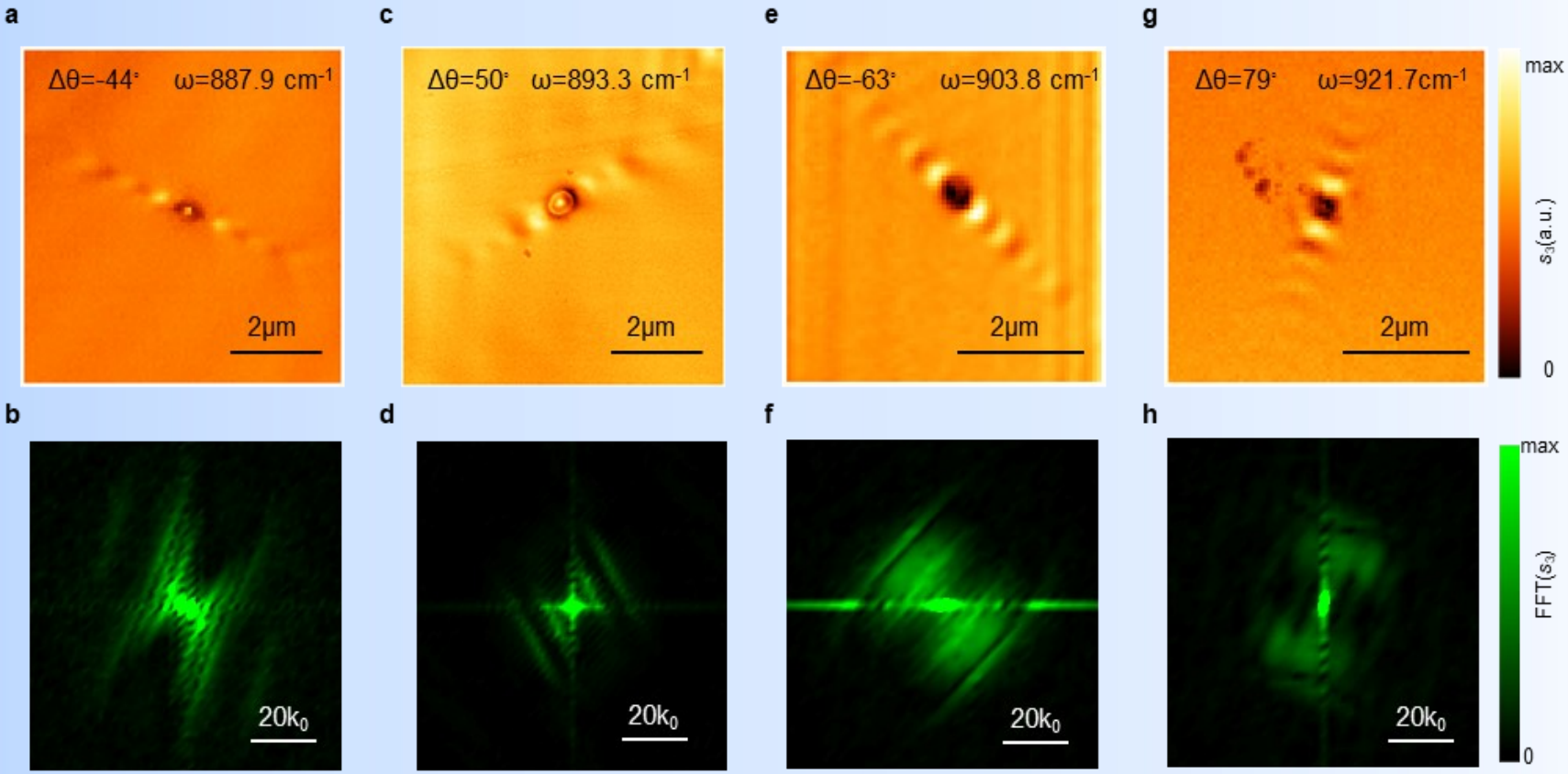
Bi-layer $\Delta\theta$=-77˚



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* **582**, 209 (2020)

Tracking the 'Photonic Magic Angle'

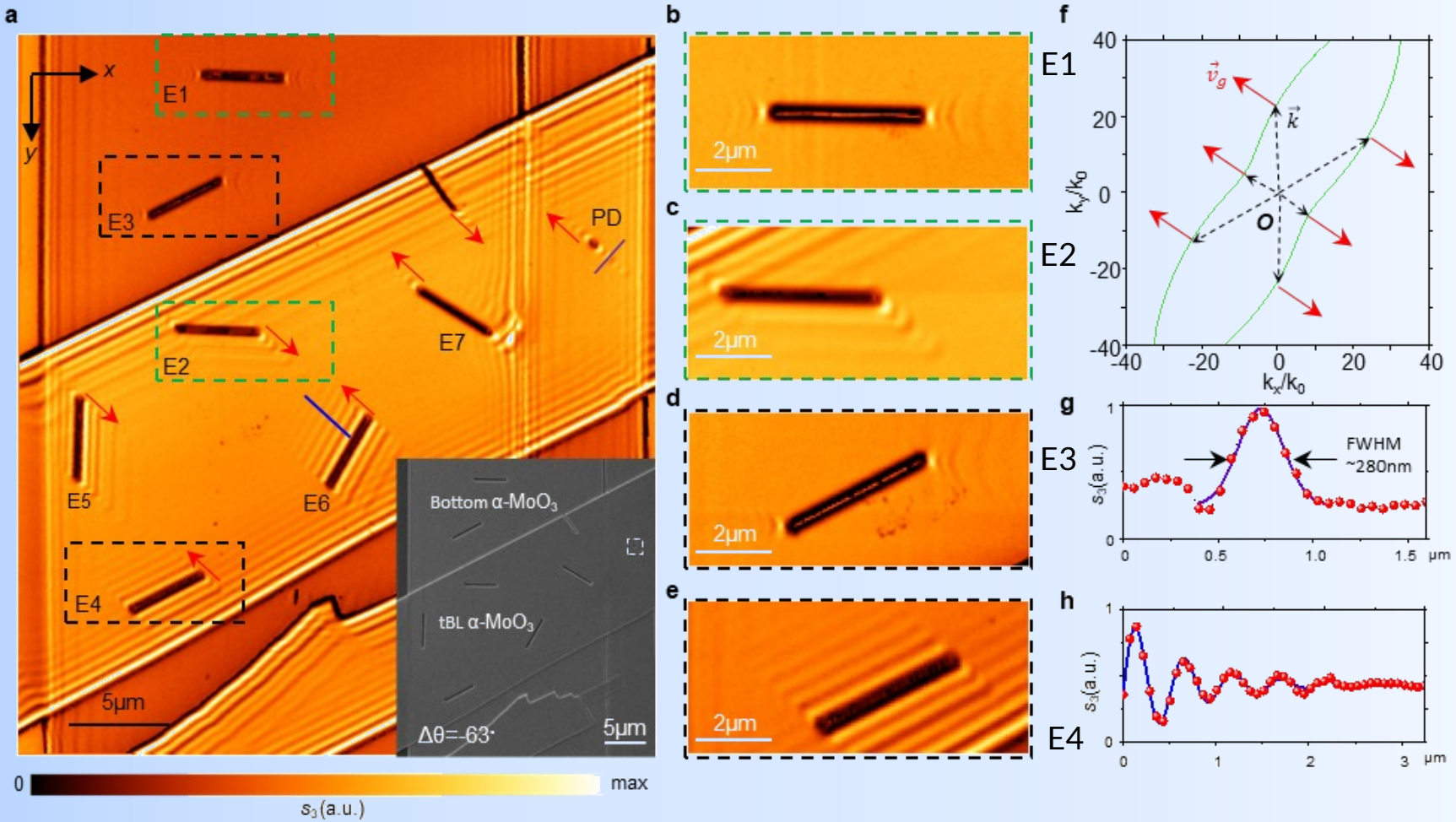
Tunable low-loss canalization regime for polaritons



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* **582**, 209 (2020)

Low-Loss Canalization of Light and Nano-Imaging

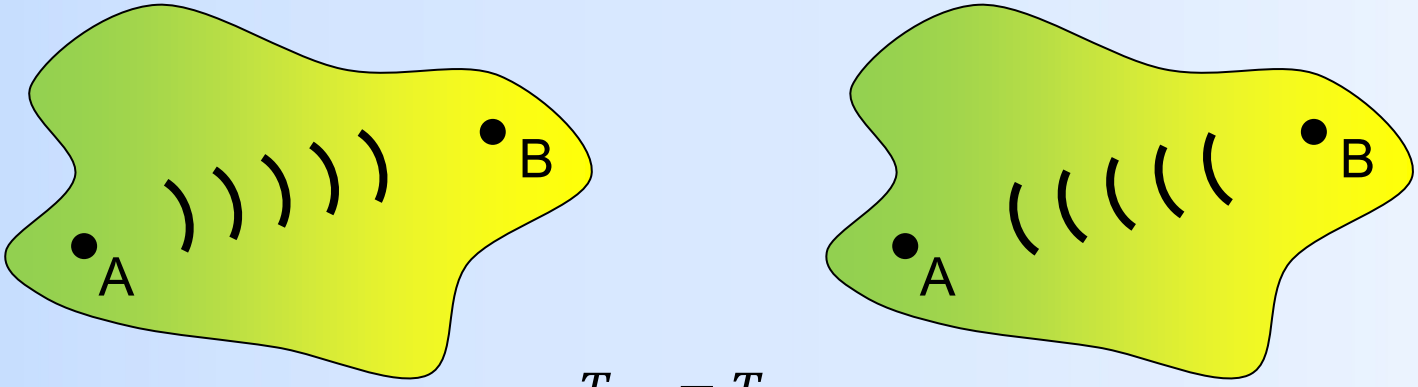
ω=903.8 cm^{-1}



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* **582**, 209 (2020)

Time-Reversal Symmetry and Nonreciprocity

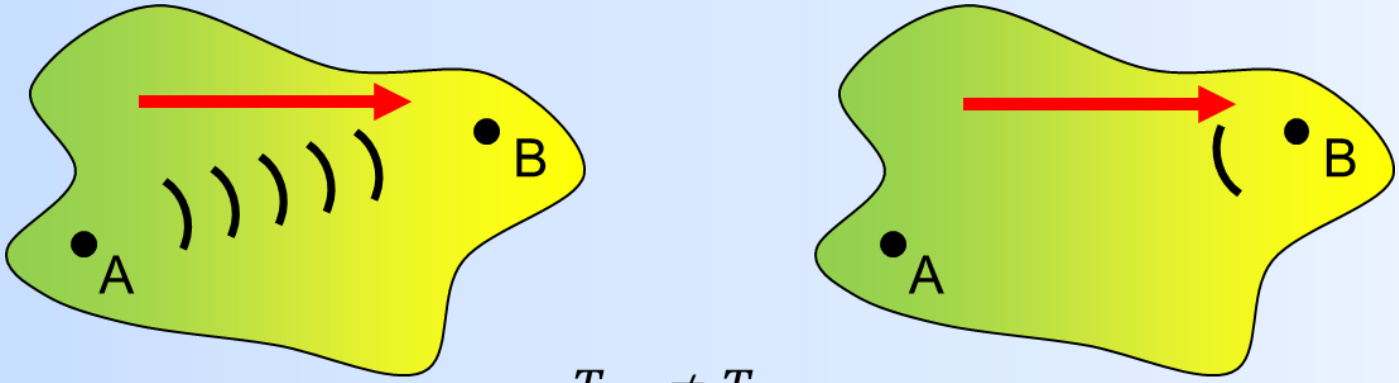
Reciprocity: *symmetry in transmission for opposite propagation directions*



$$T_{\mathrm{BA}} = T_{\mathrm{AB}}$$

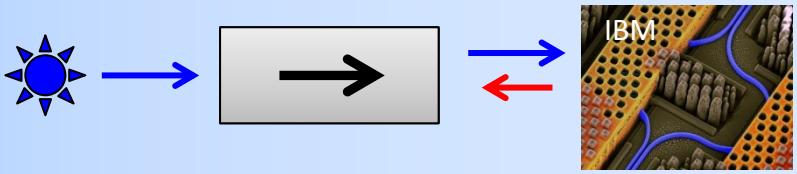
Time-Reversal Symmetry and Nonreciprocity

Reciprocity: *symmetry in transmission for opposite propagation directions*

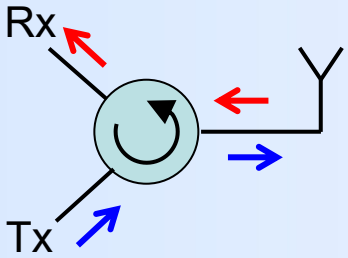


$$T_{BA} \neq T_{AB}$$

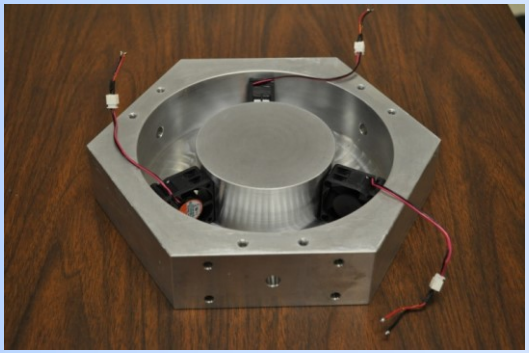
Isolators

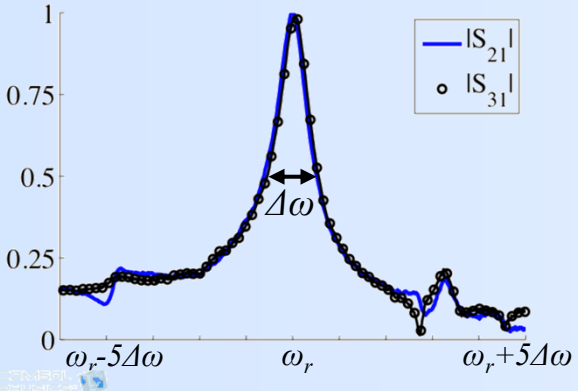


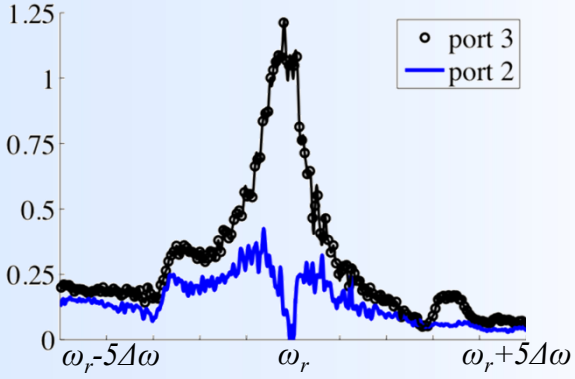
Circulators

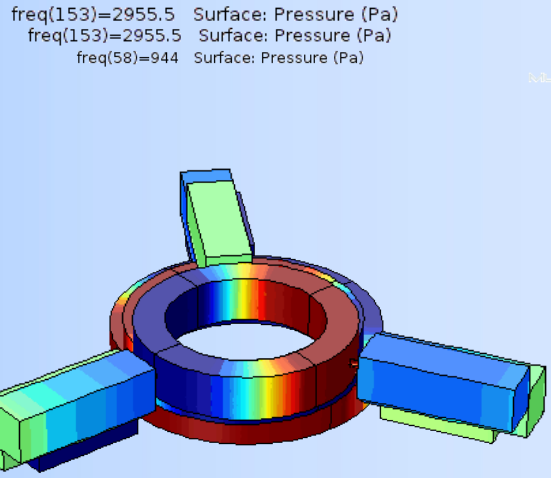


Angular-Momentum Bias

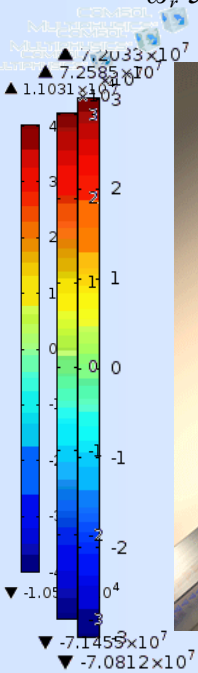


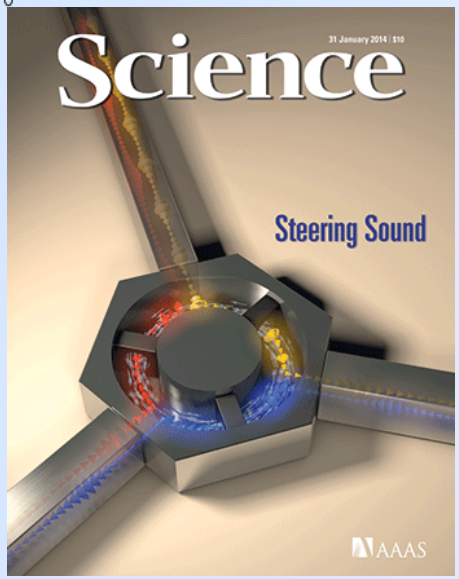


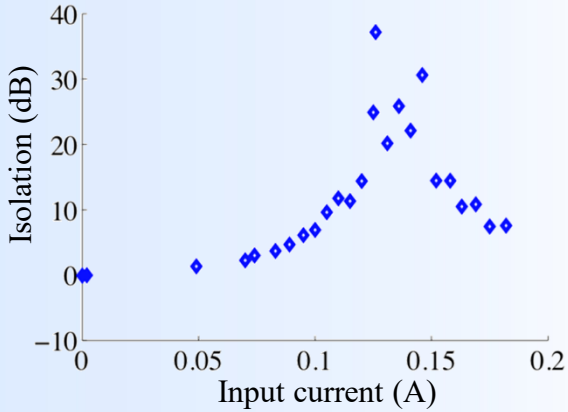




$v = 0.65\,m/s$

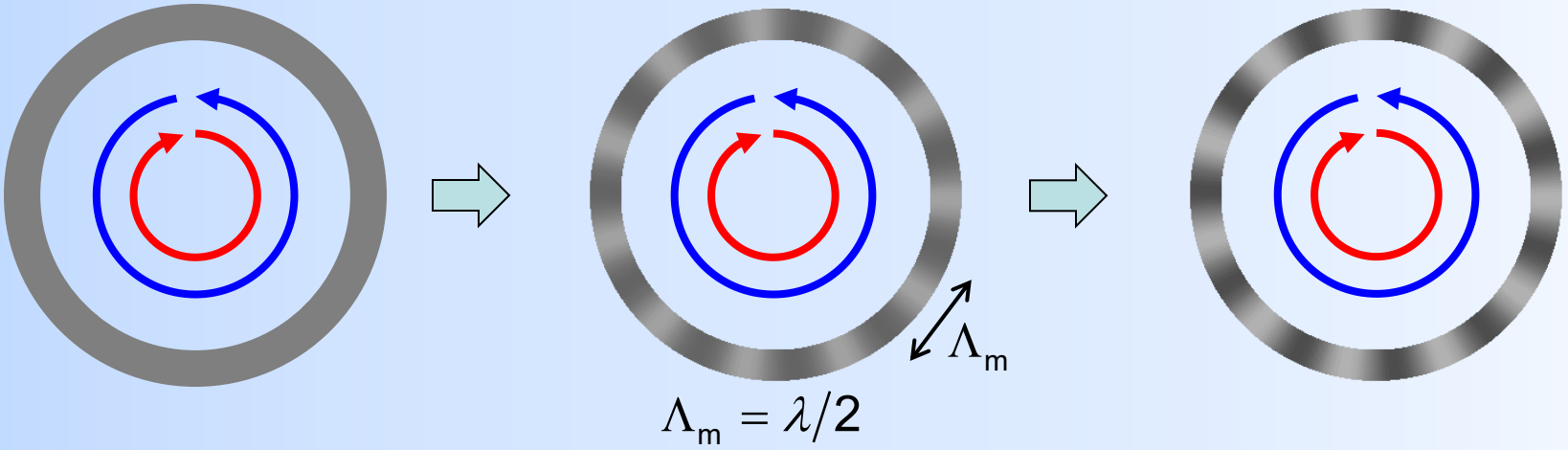


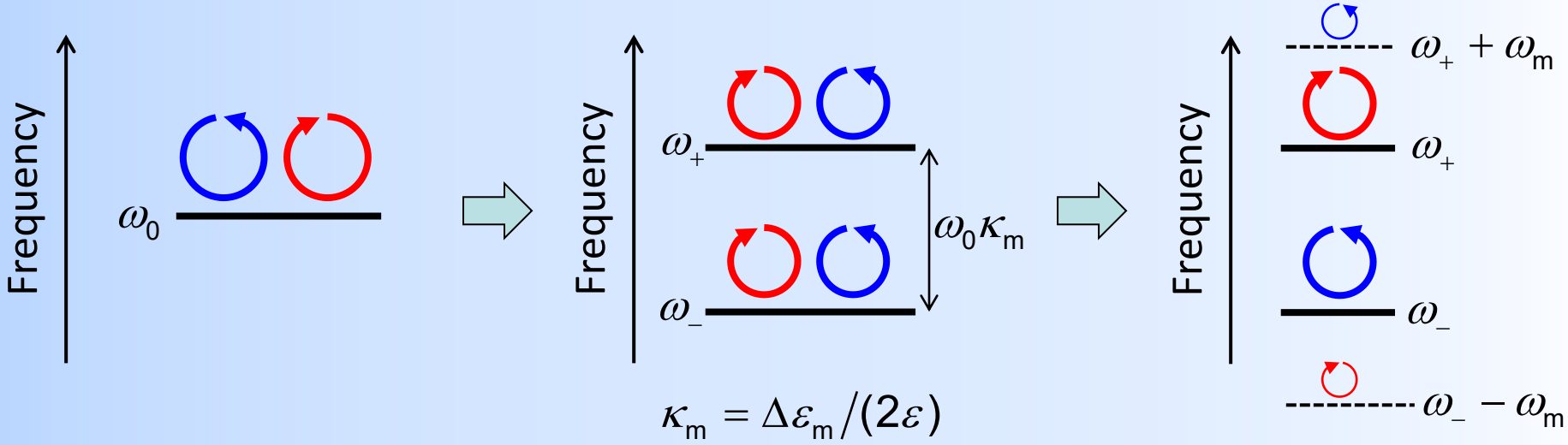




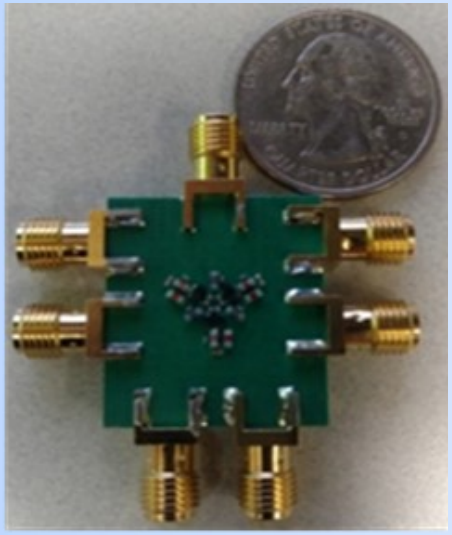
R. Fleury, D. L. Sounas, C. Sieck, M. Haberman, A. Alù, *Science* 343, 516 (2014)

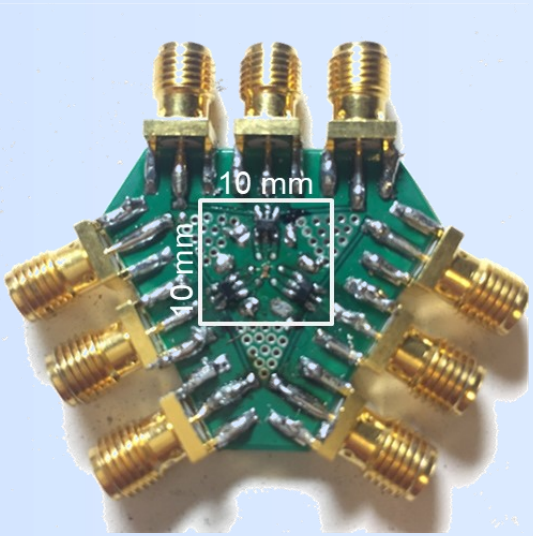
Synthetic Angular Momentum with Time Modulation

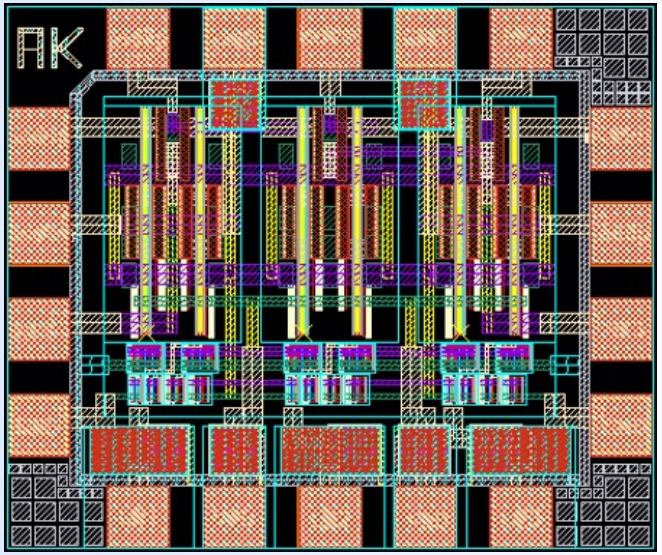


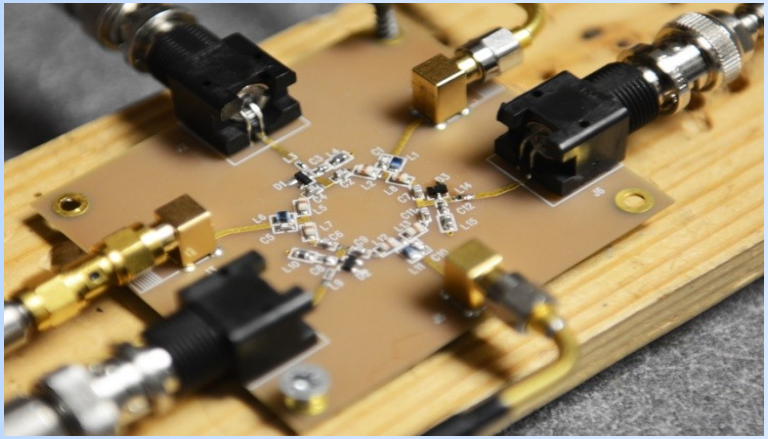


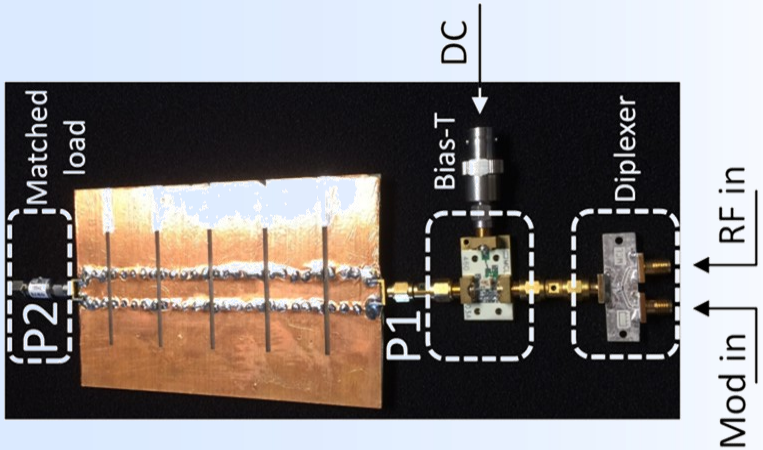
Recent Progress on Magnet-Less Circulators



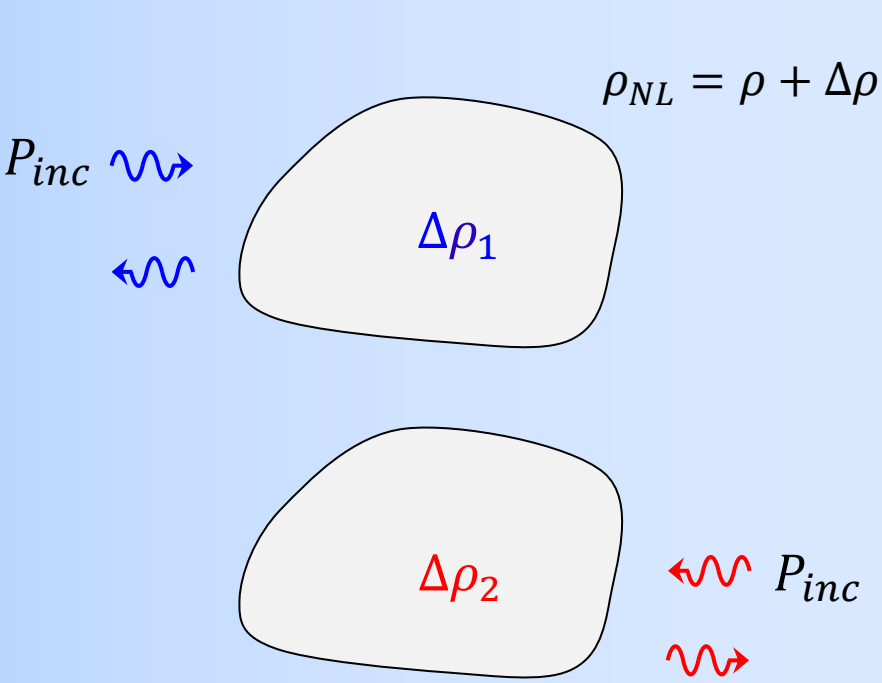




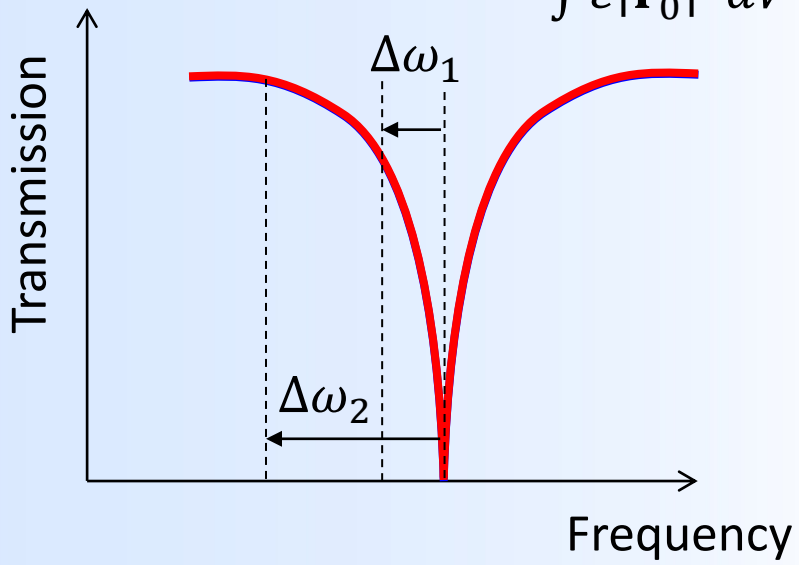




Nonlinearity-Based Nonreciprocity

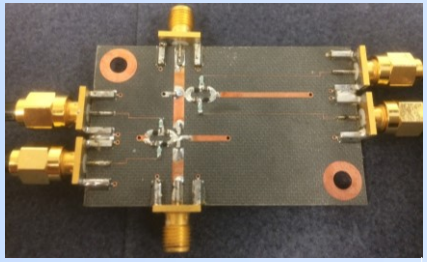


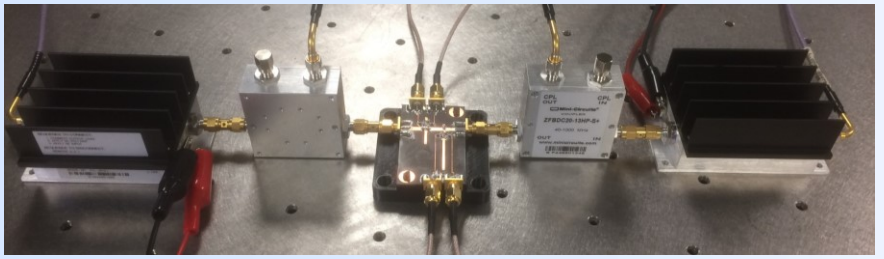
$$\Delta\omega = -\omega_0 \frac{\int \Delta\varepsilon |\mathbf{F}_0|^2 dV}{\int \varepsilon |\mathbf{F}_0|^2 dV}$$

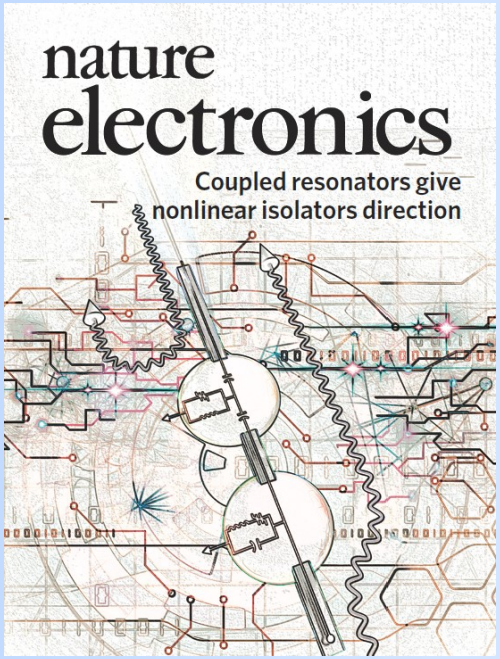


D. L. Sounas, A. Alù, *Phys. Rev. Lett.* **118**, 154302 (2017)
D. L. Sounas, A. Alù, *Phys. Rev. B* **97**, 115431 (2018)
D. L. Sounas, A. Alù, *IEEE AWPL* **17**, 1958 (2018)

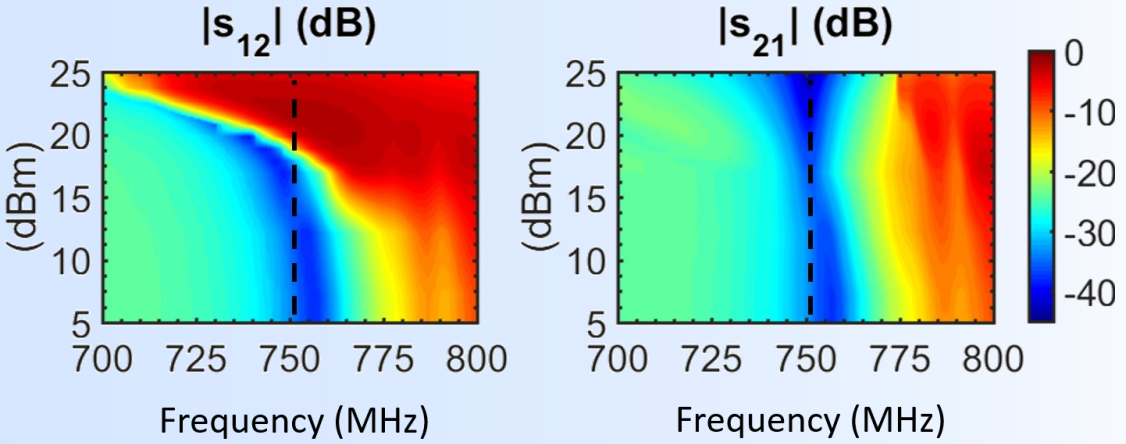
Nonreciprocity Based on Nonlinearities and Asymmetry

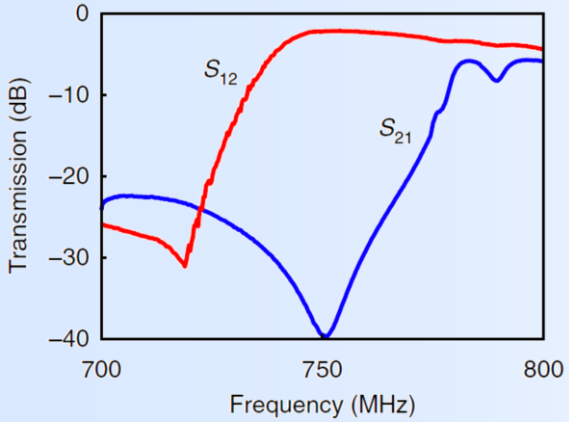




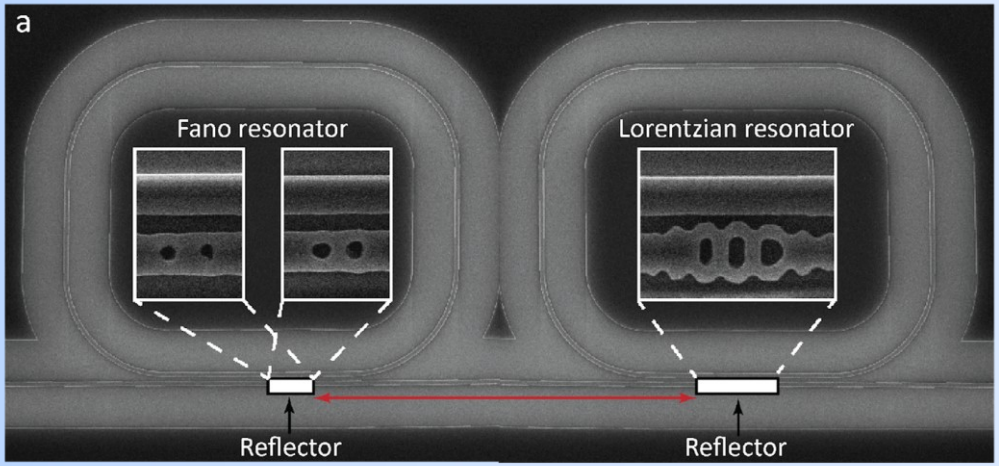


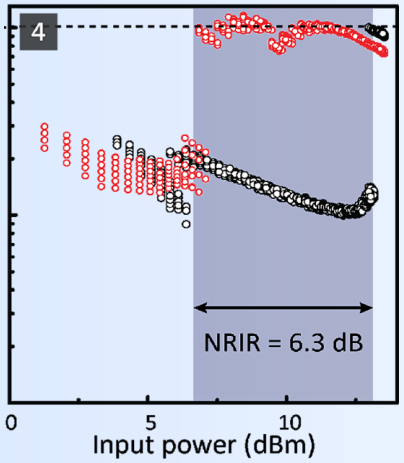
D. L. Sounas, J. Soric, and A. Alù
Nature Electron. **1**, 113 (2018)

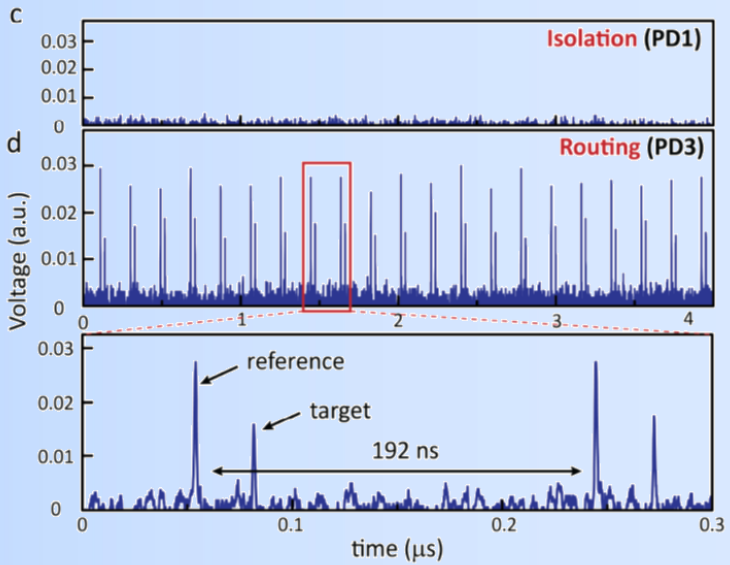


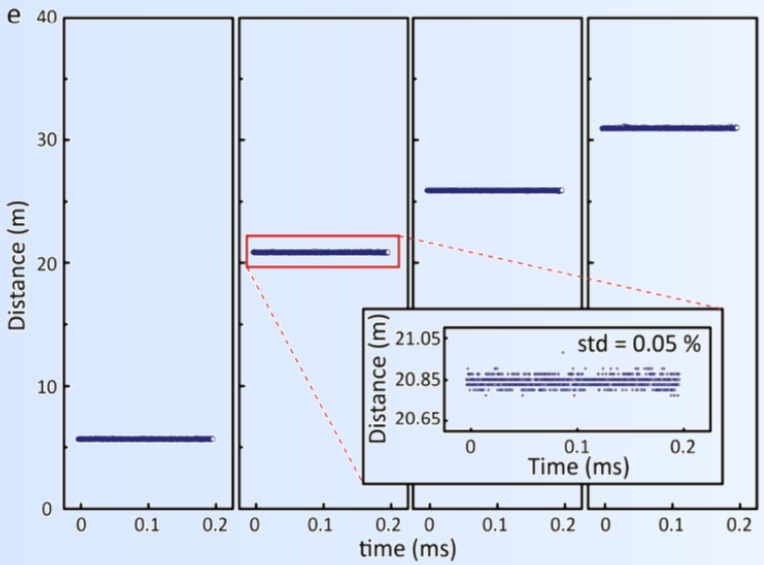


Non-Reciprocal Light Propagation with Non-Linearities



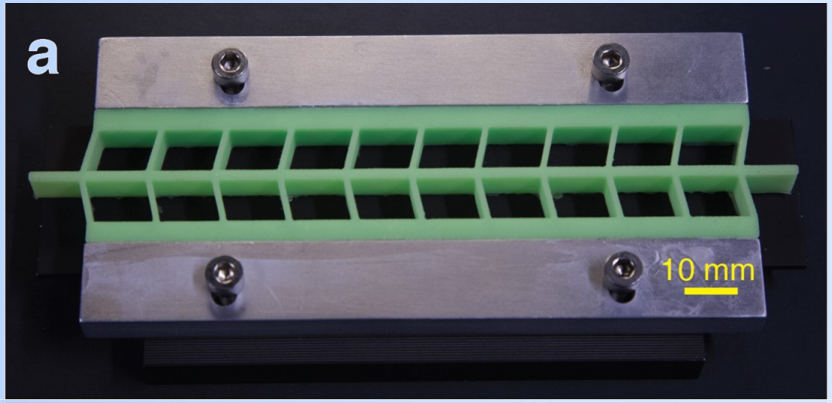


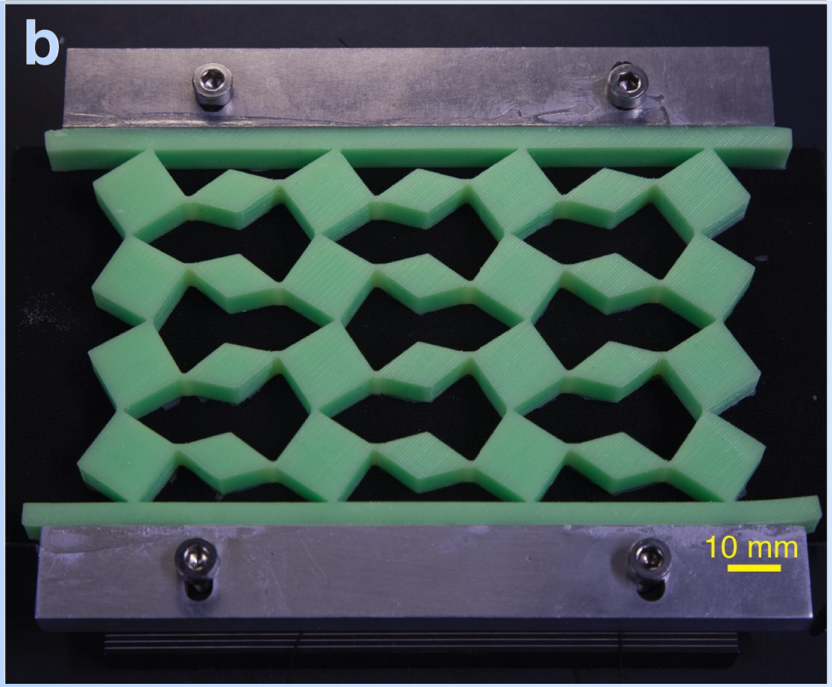


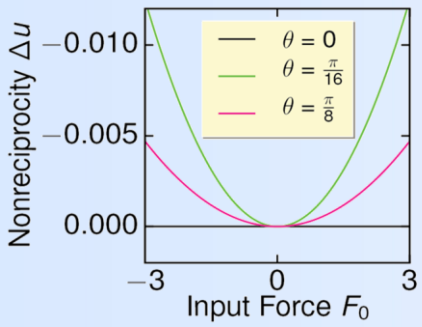


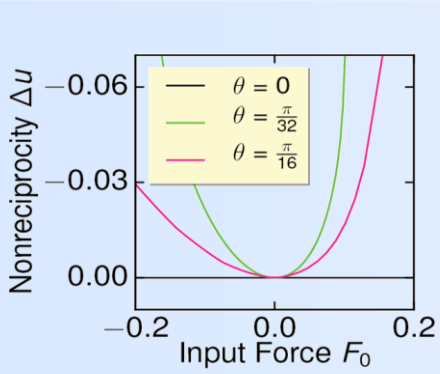
K. Y. Yang, J. Skarda, M. Cotrufo, et al. *Nature Photonics* **14**, 369 (2020)

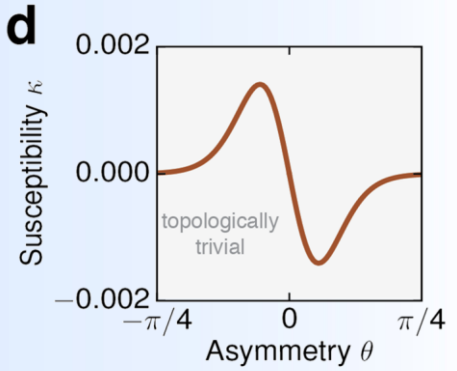
Static Nonreciprocity in Mechanical Metamaterials

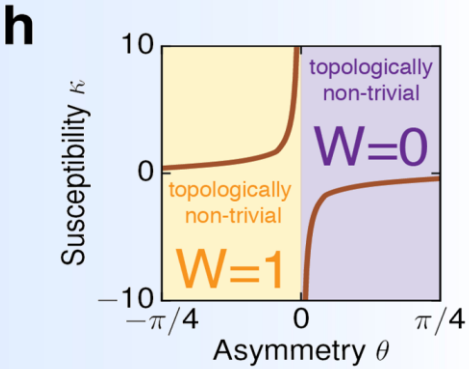










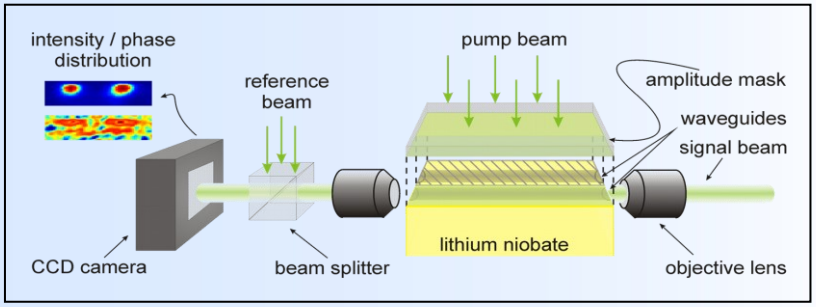


C. Coulais, D. Sounas, A. Alù, *Nature* **542**, 461 (2017)

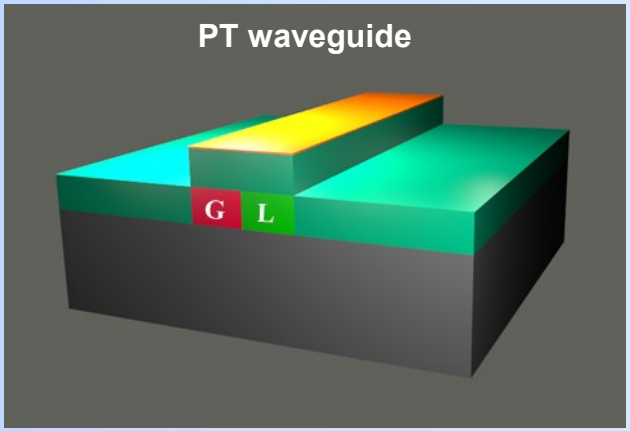
Parity-Time Symmetry

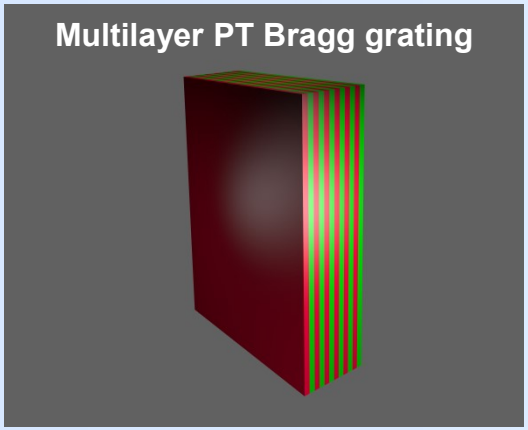
$$n(\boldsymbol{r}) = n^*(-\boldsymbol{r})$$

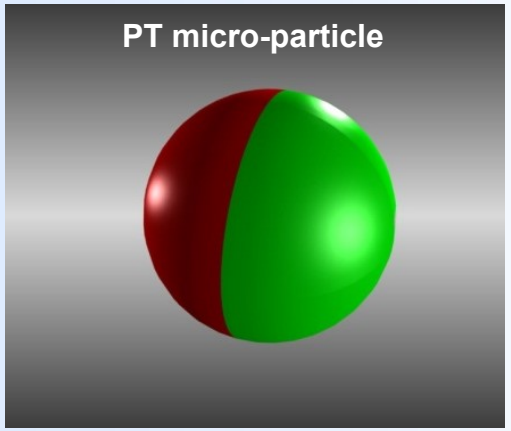
$$n_R(-\boldsymbol{r}) = +n_R(\boldsymbol{r})$$
$$n_I(-\boldsymbol{r}) = -n_I(\boldsymbol{r})$$



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



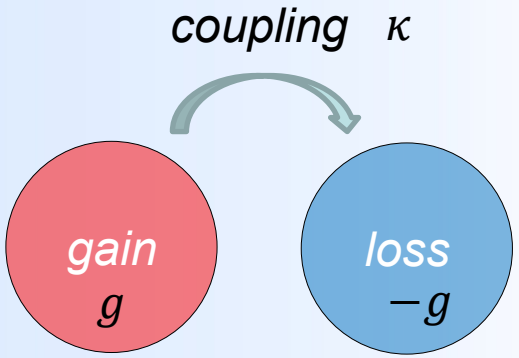


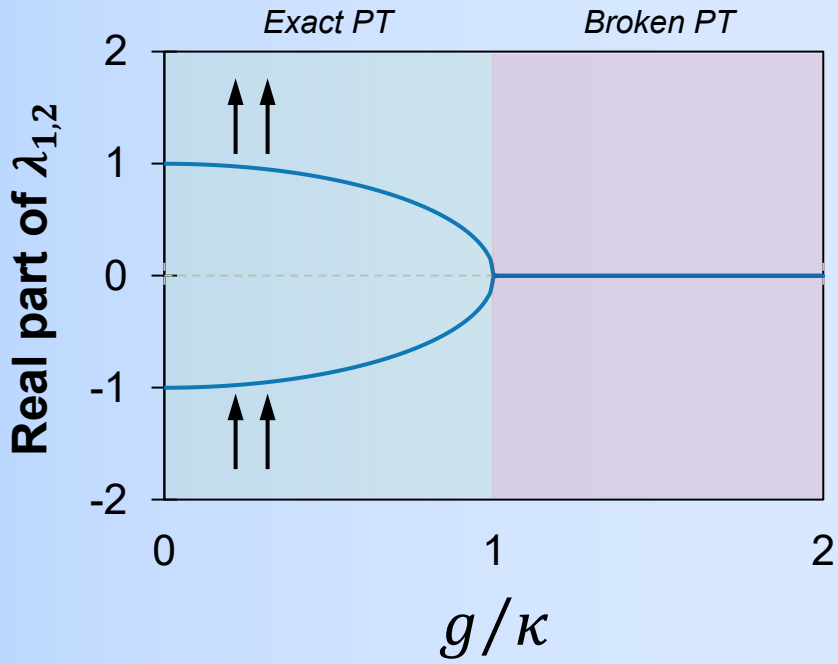


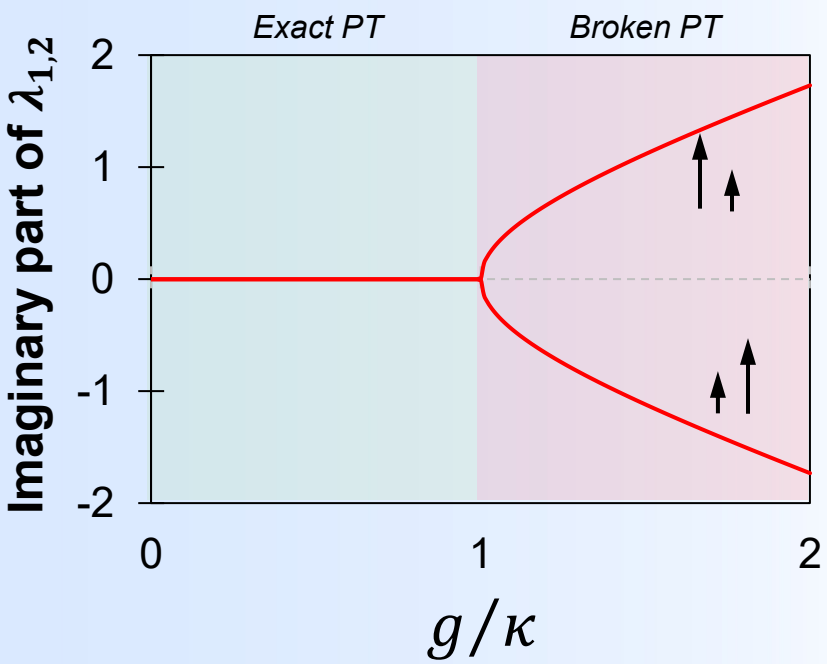
PT-Symmetry in Optics

$$\frac{da}{dz} = i\kappa b + ga$$
$$\frac{db}{dz} = i\kappa a - gb$$

$$\lambda_{1,2} = \sqrt{\kappa^2 - g^2}$$

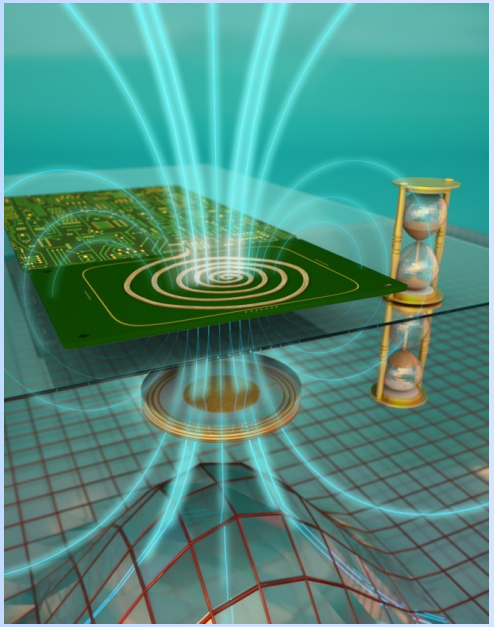


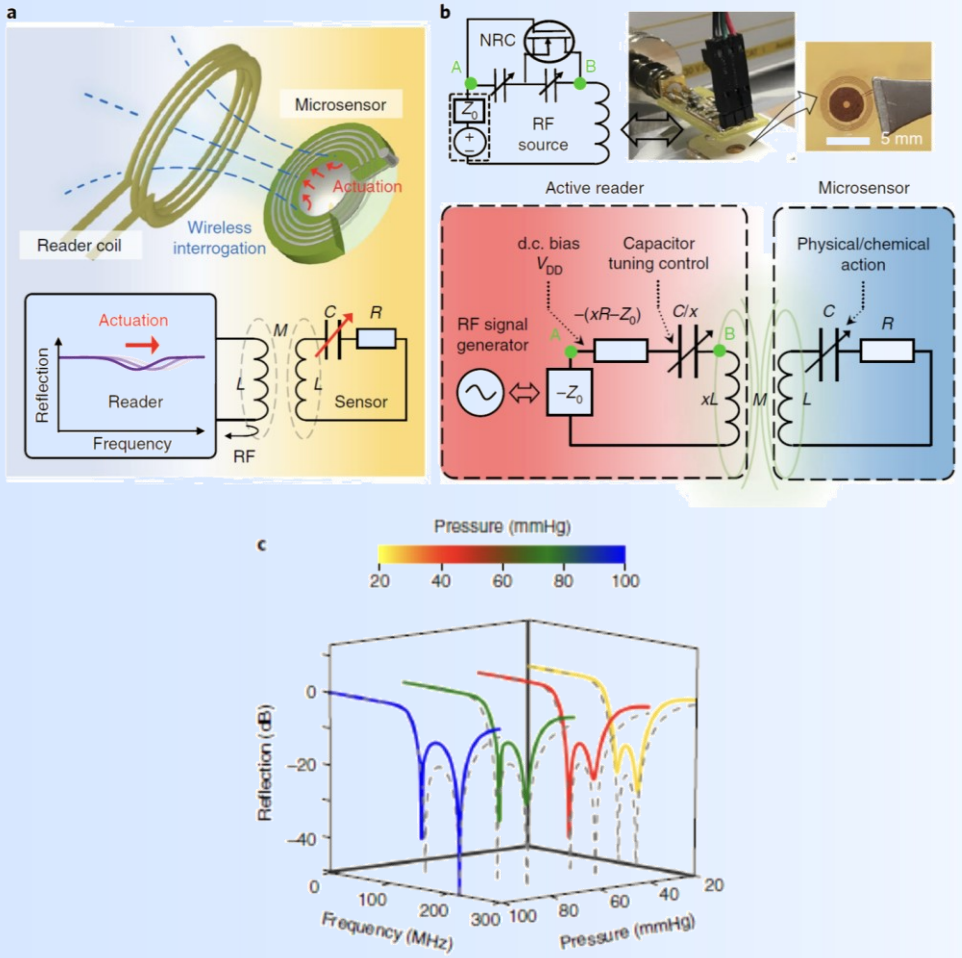




M. A.Miri, A. Alù, *Science* **363**, 42 (2019)

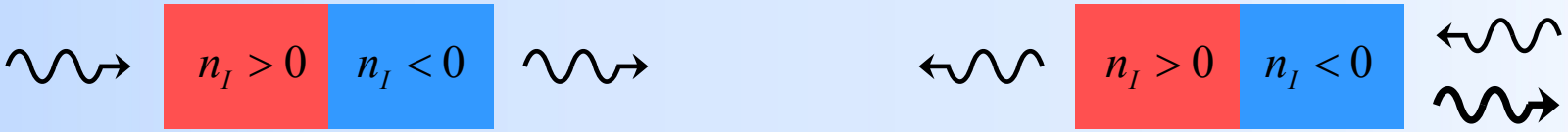
PT-Symmetric Sensors for Telemetry





P. Y. Chen, M. Sakhdari, M. Hajizadegan, Q. Cui, M. Cheng, R. El-Ganainy, A. Alù, *Nature Electronics* **1**, 297 (2018)

Unidirectional Invisibility

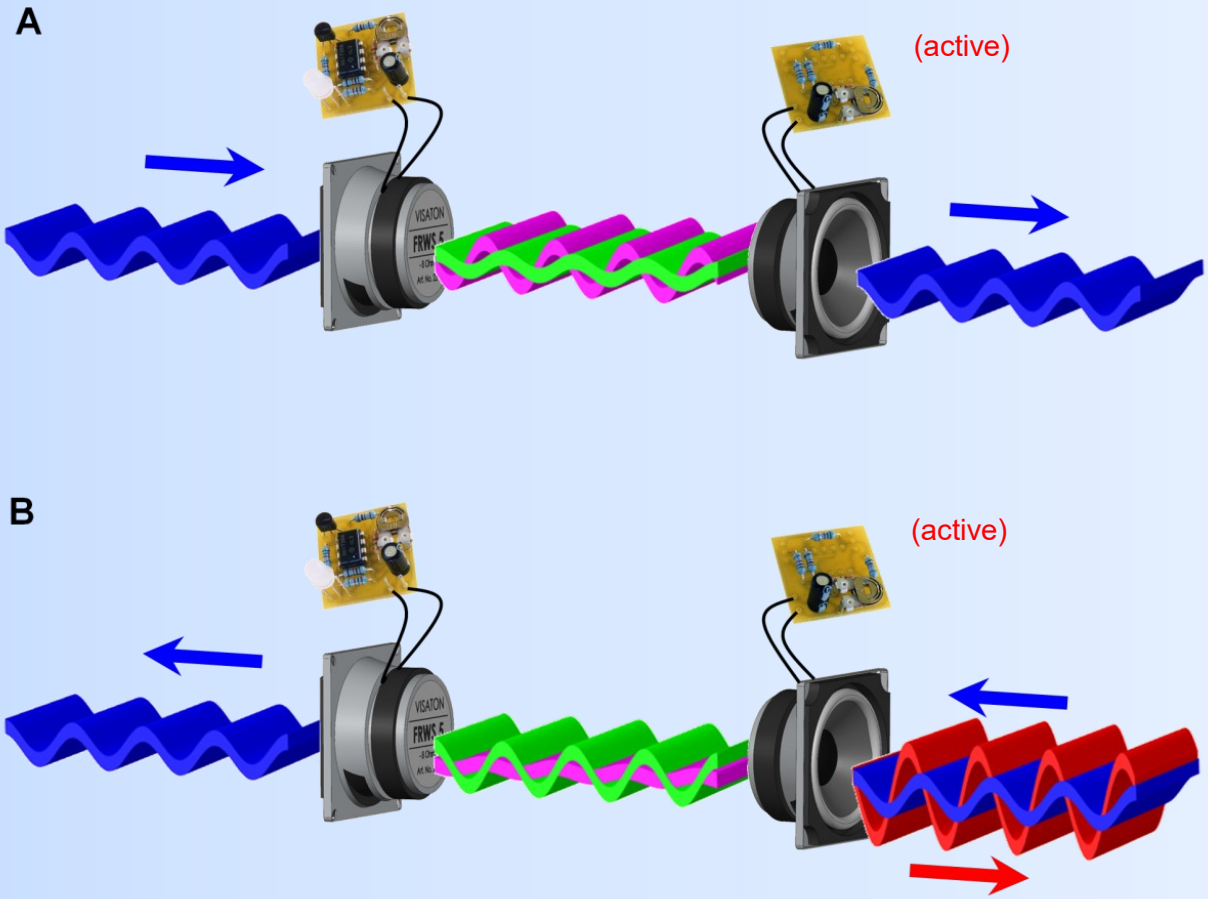


Acoustic PT-symmetry

$\mathrm{Re}\, Z_L^{(1)} > 0$

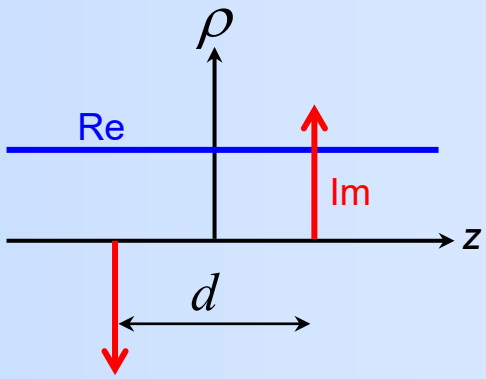
$\mathrm{Re}\, Z_L^{(1)} < 0$ **(active)**

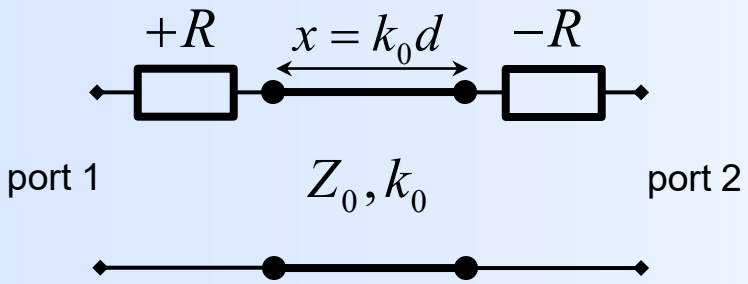
PT Acoustics : Stable, Balanced Loss/Gain

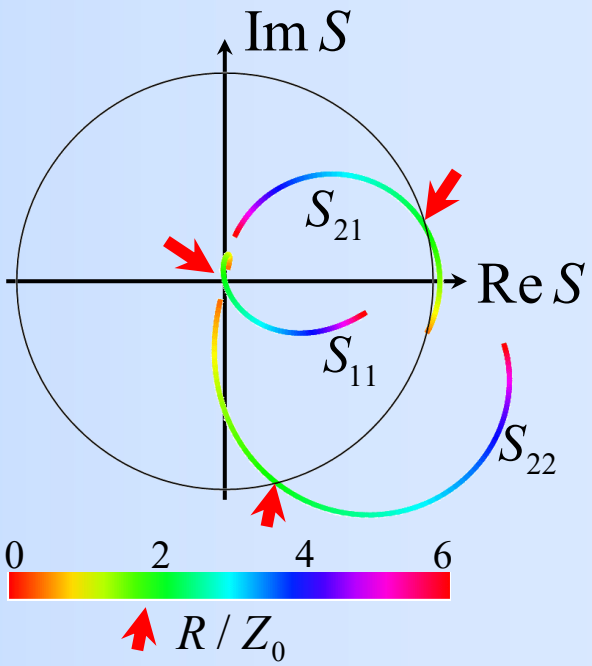


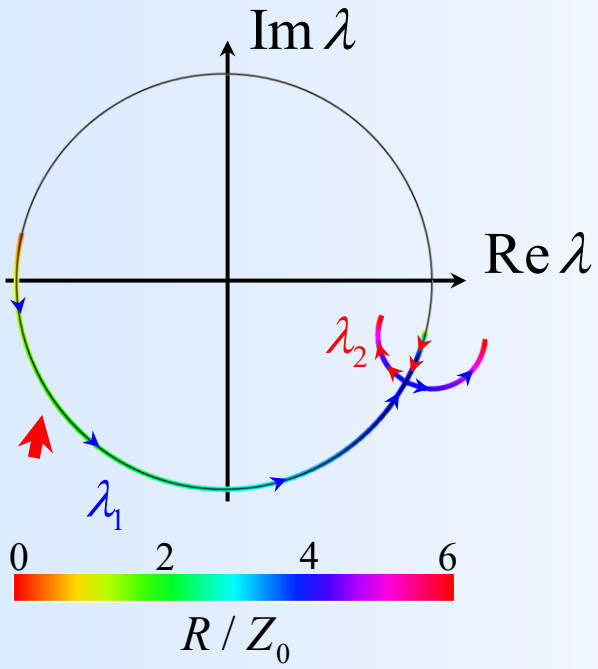
R. Fleury, D. L. Sounas, and A. Alù, *Nat. Comm.* **6**, 5905 (2015)

Scattering Parameters and S-Matrix Eigenvalues



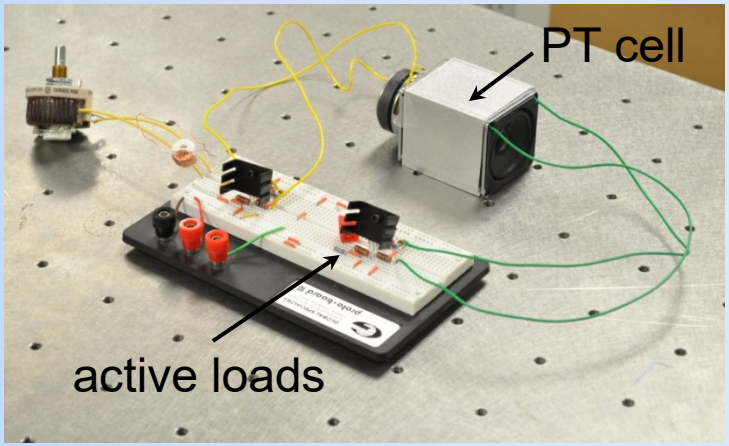




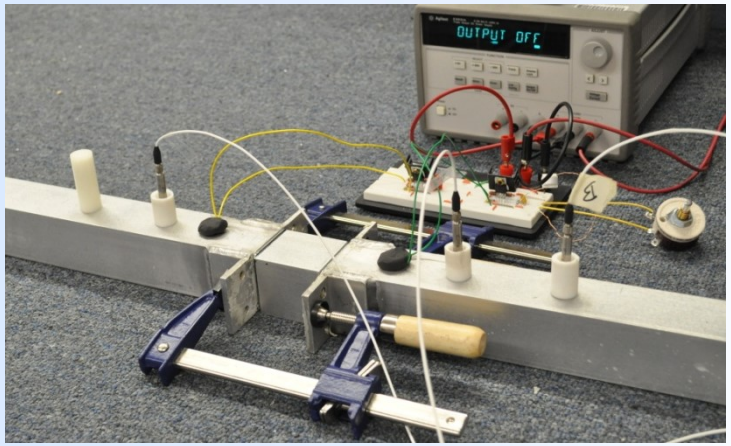


Experimental Validation

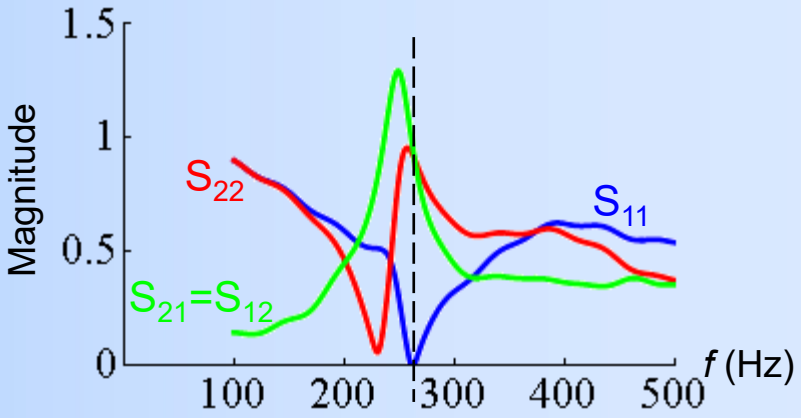
A



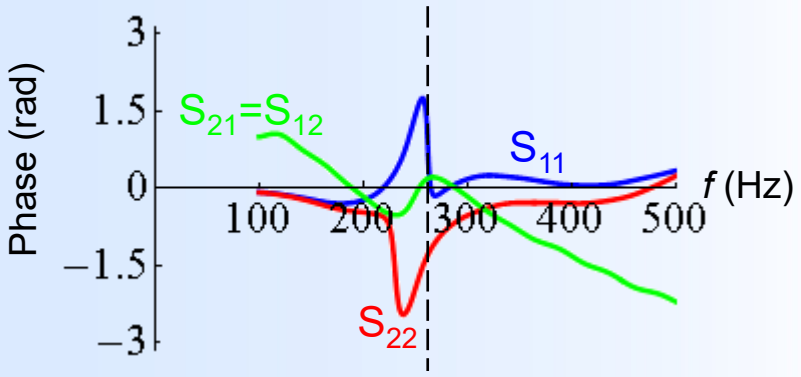
B



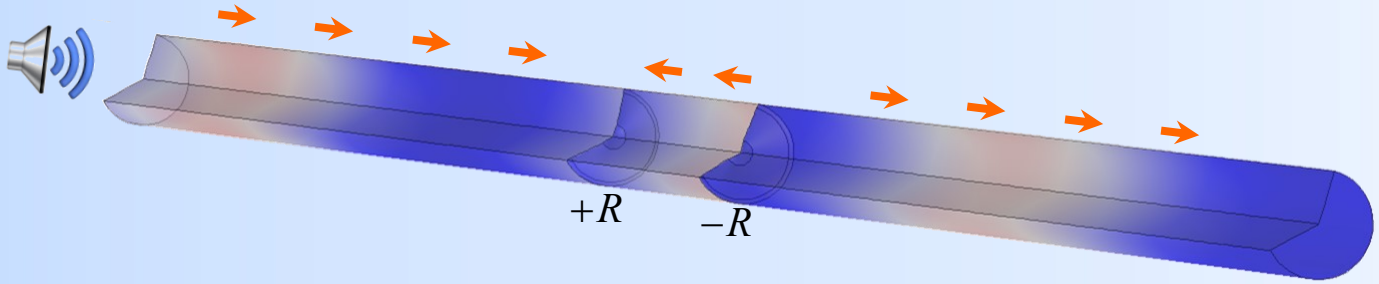
C

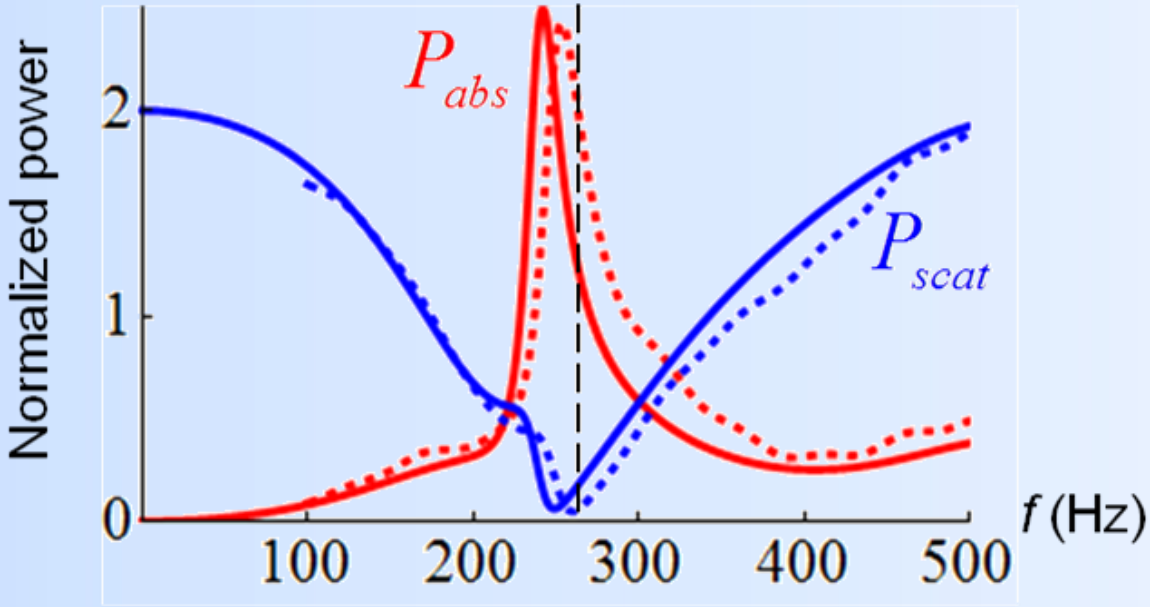


D



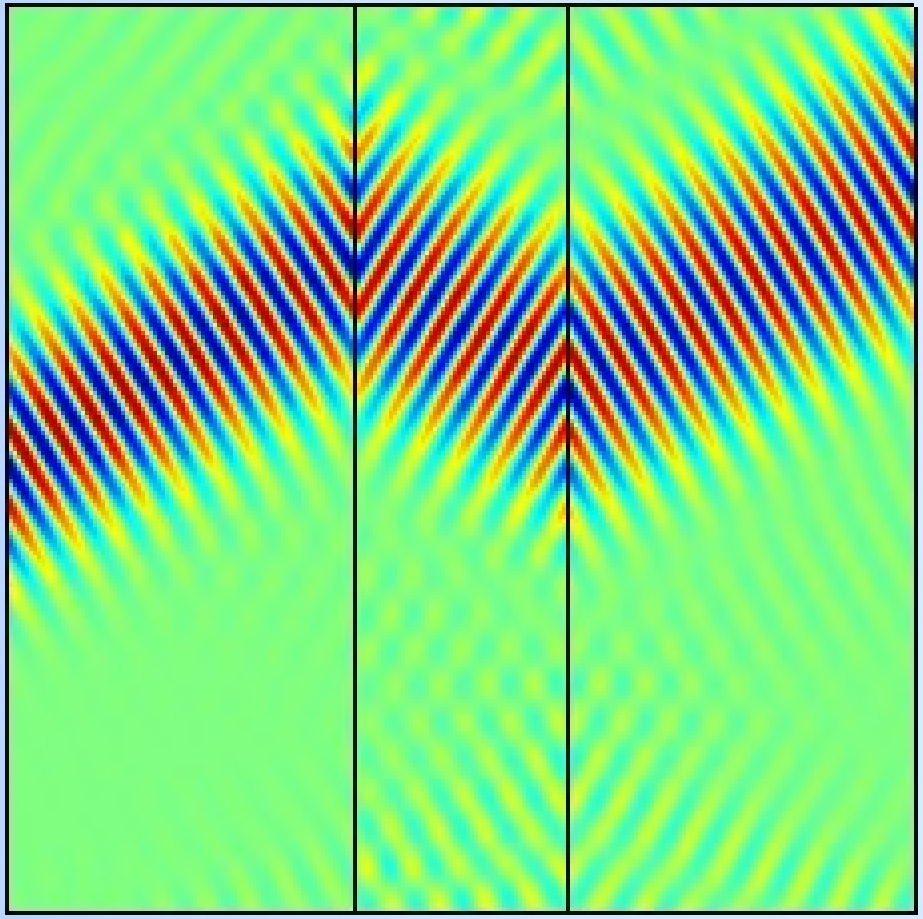
An Invisible Sensor



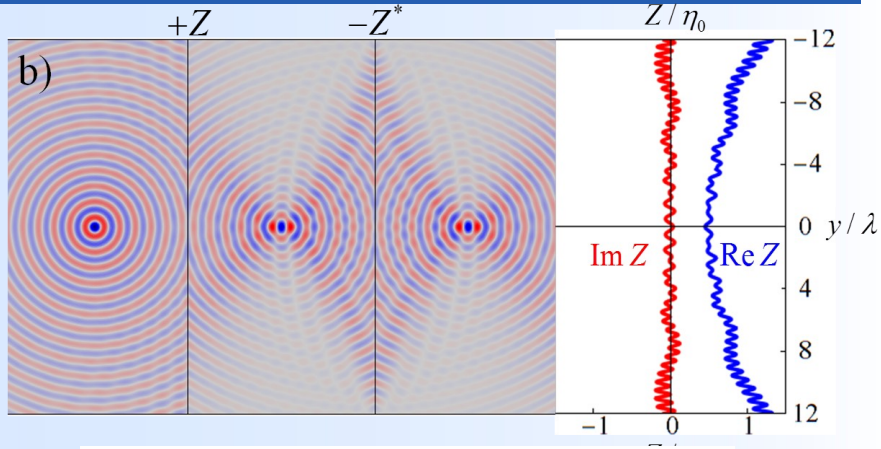


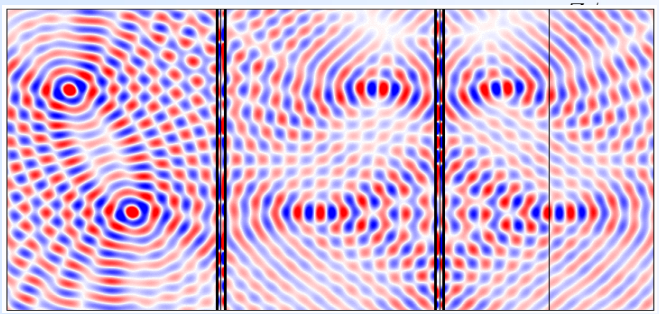
R. Fleury, D. L. Sounas, and A. Alù, *Nat. Comm.* **6**, 5905 (2015)

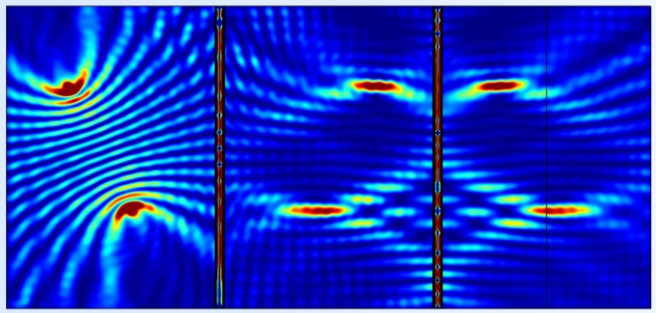
Negative Refraction and Focusing



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



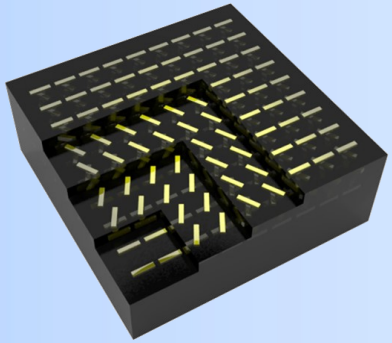


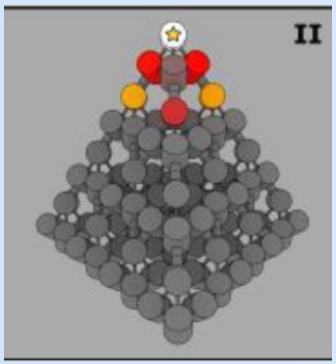


R. Fleury, D. Sounas, and A. Alù, *Phys. Rev. Lett.* **113**, 023903 (2014)

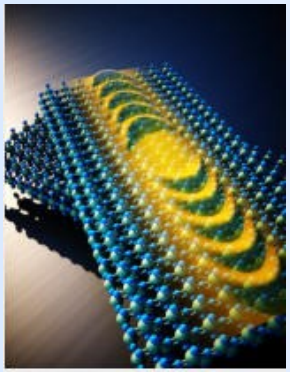
F. Monticone, C. Valagiannopoulos, A. Alù, *Phys. Rev. X* **6**, 041018 (2016)

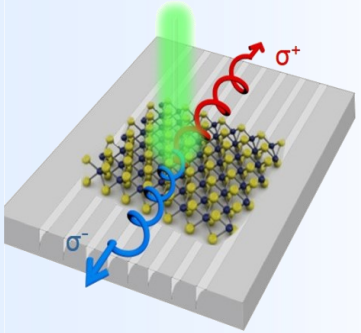
Broken Symmetries for Extreme Wave Interactions



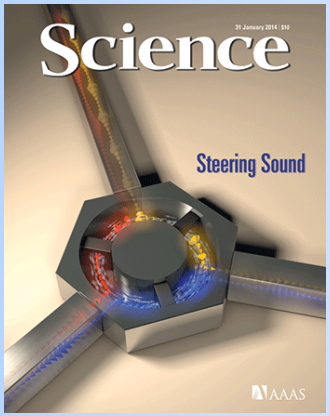


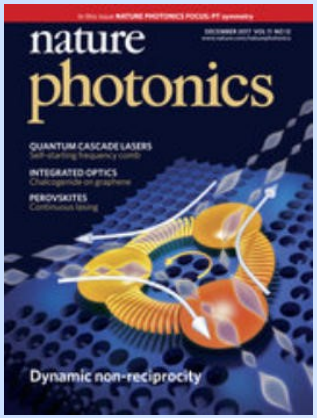
Broken geometrical symmetries for enhanced wave control and routing

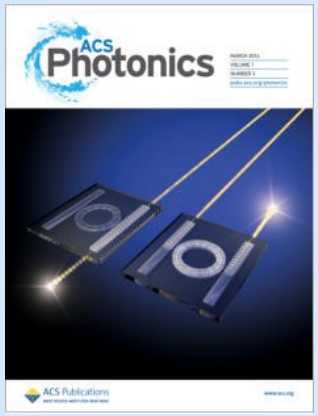


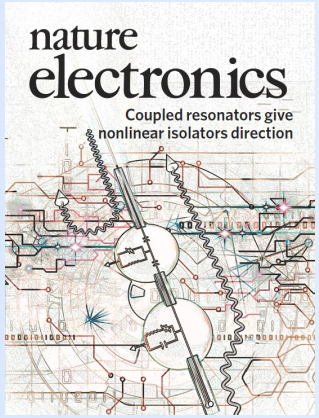


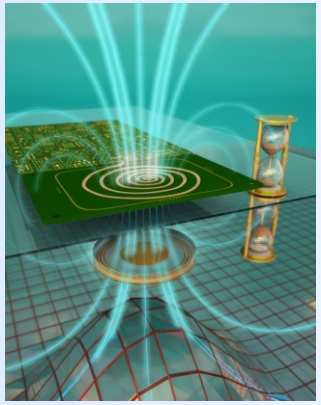
Twistronics and valleytronics to mold the flow of light at the nanoscale

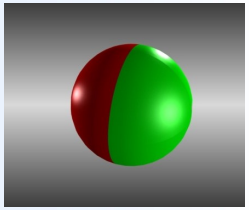












Broken TR symmetry for nonreciprocity and robust topological protection

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