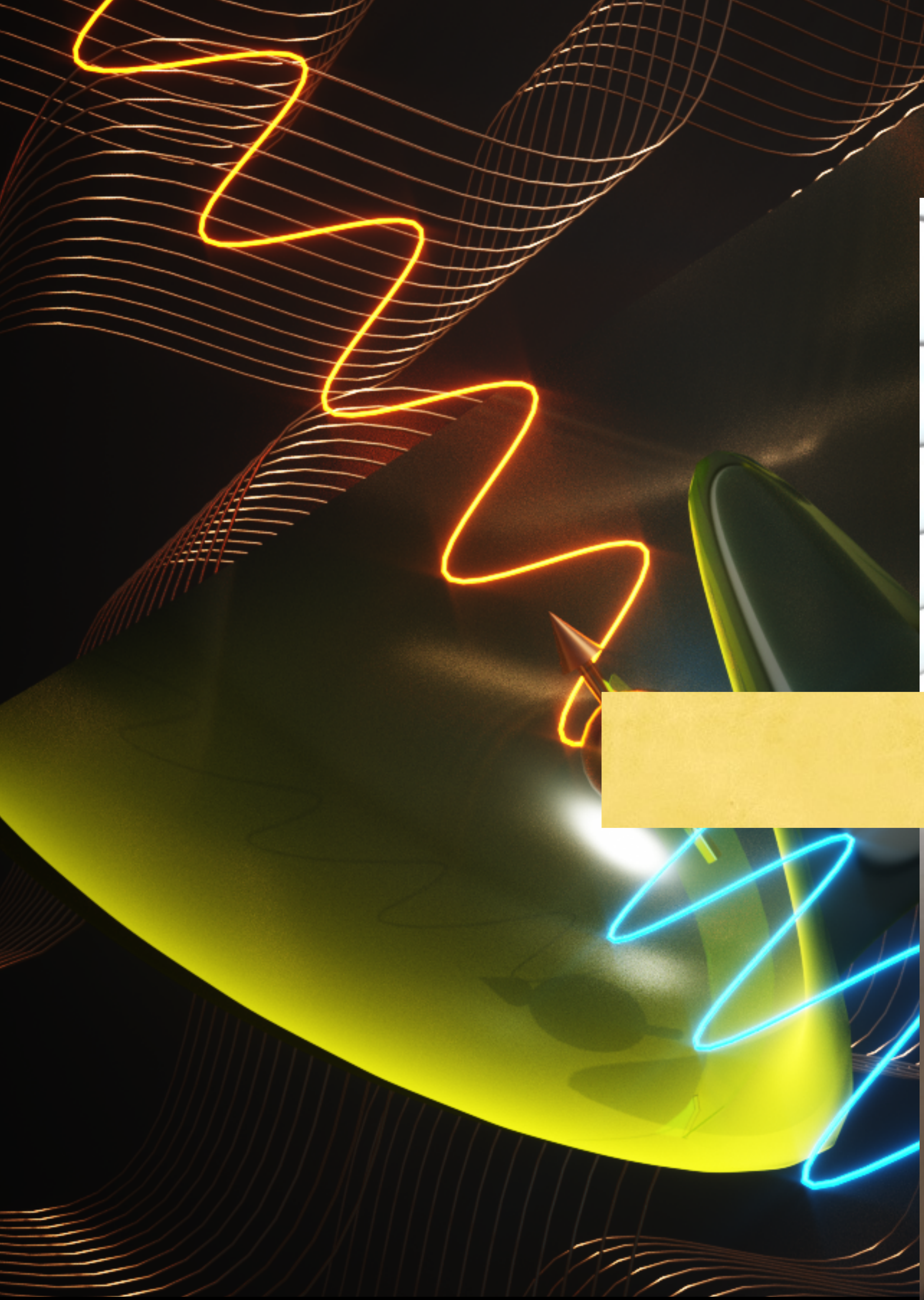

Axial Higgs Mode from
eometry +
nsity Wave

t al Nature (2022)

Fu

H

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MOLECULAR

l Research
chnology

GINERLABS

BURCH GROUP

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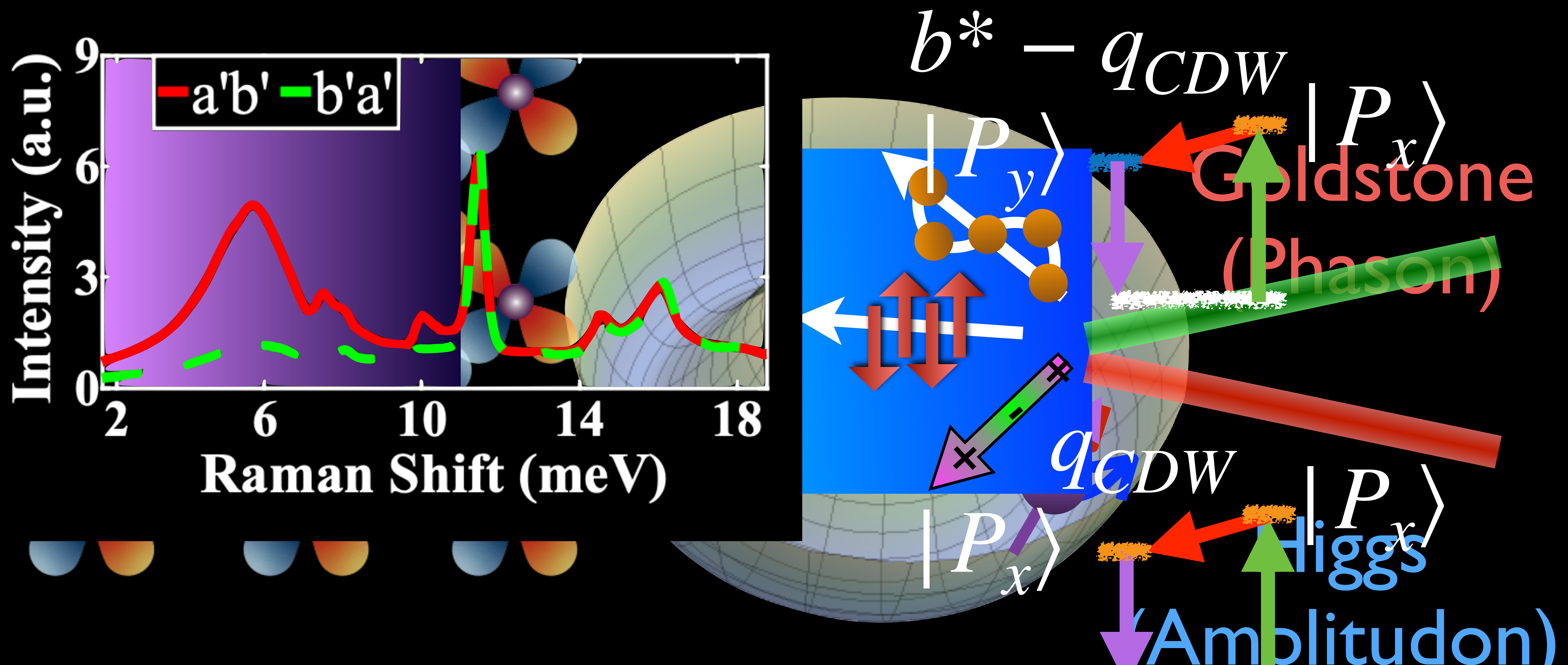
Axial Higgs Mode via Q.G. + C.D.W.

- **Higgs**
- **Square Scattering**
- **Interference**
- **Highlights**



Y. Wang, KSB, Nature (2022)

Funding:
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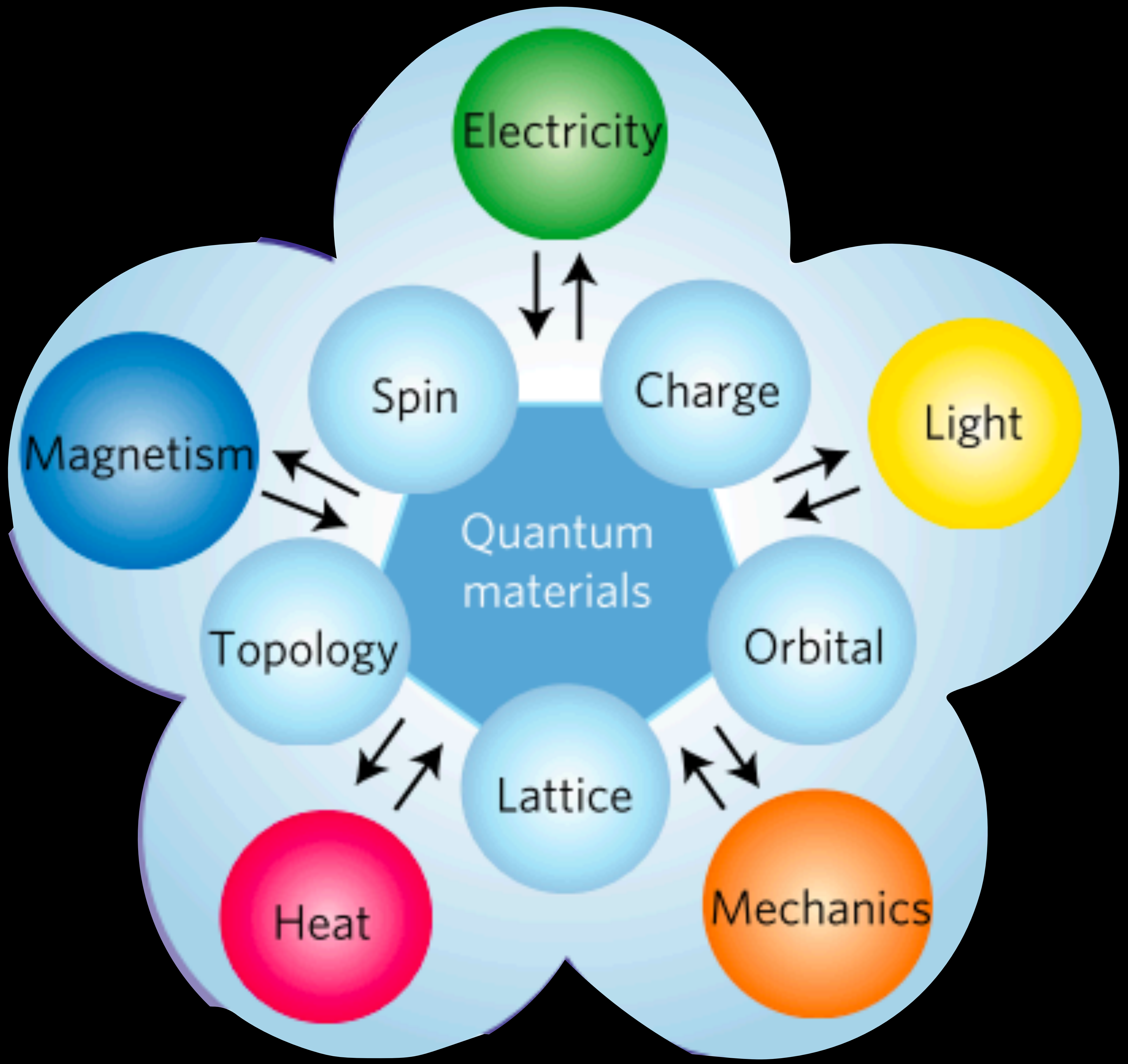
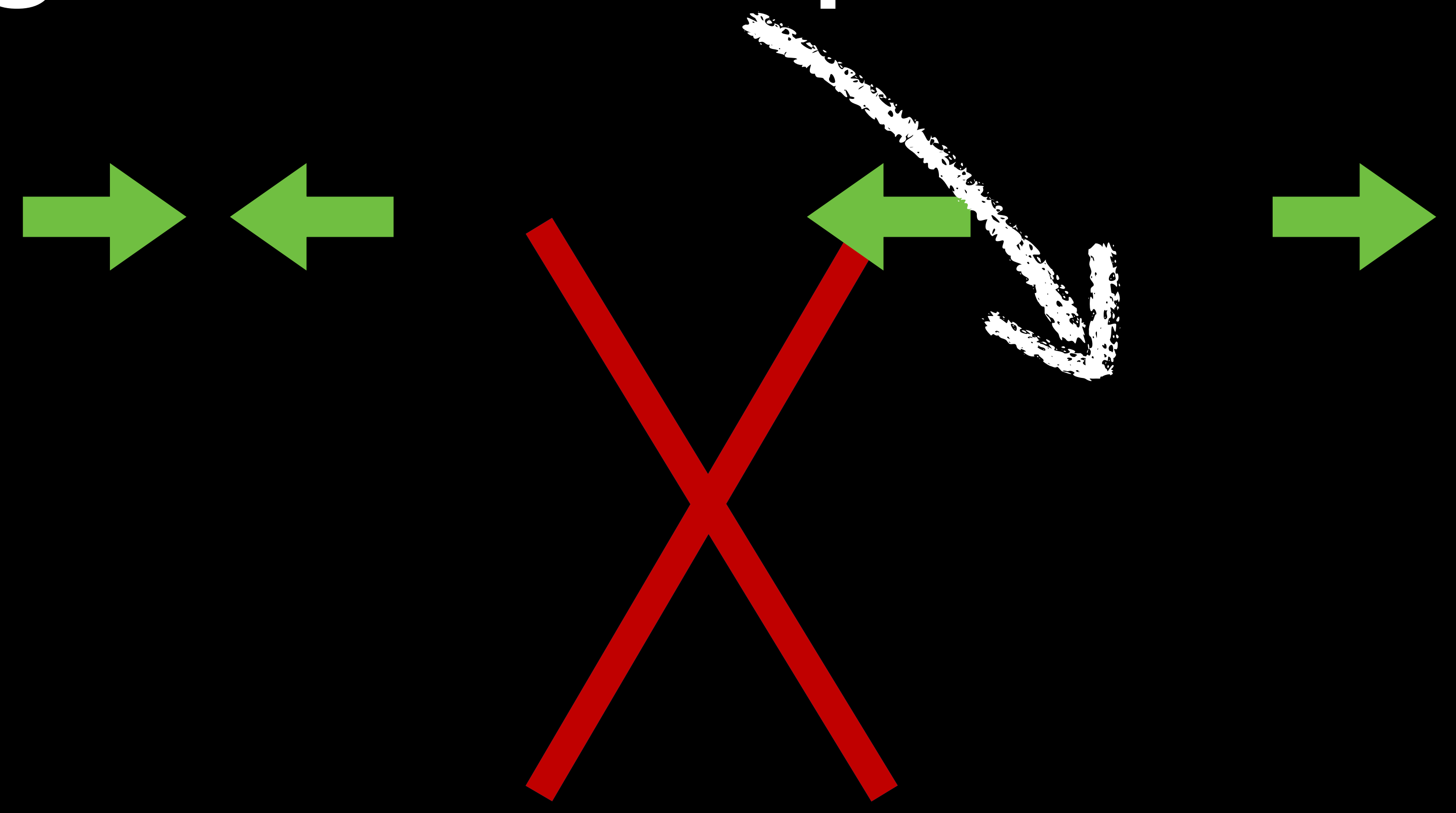
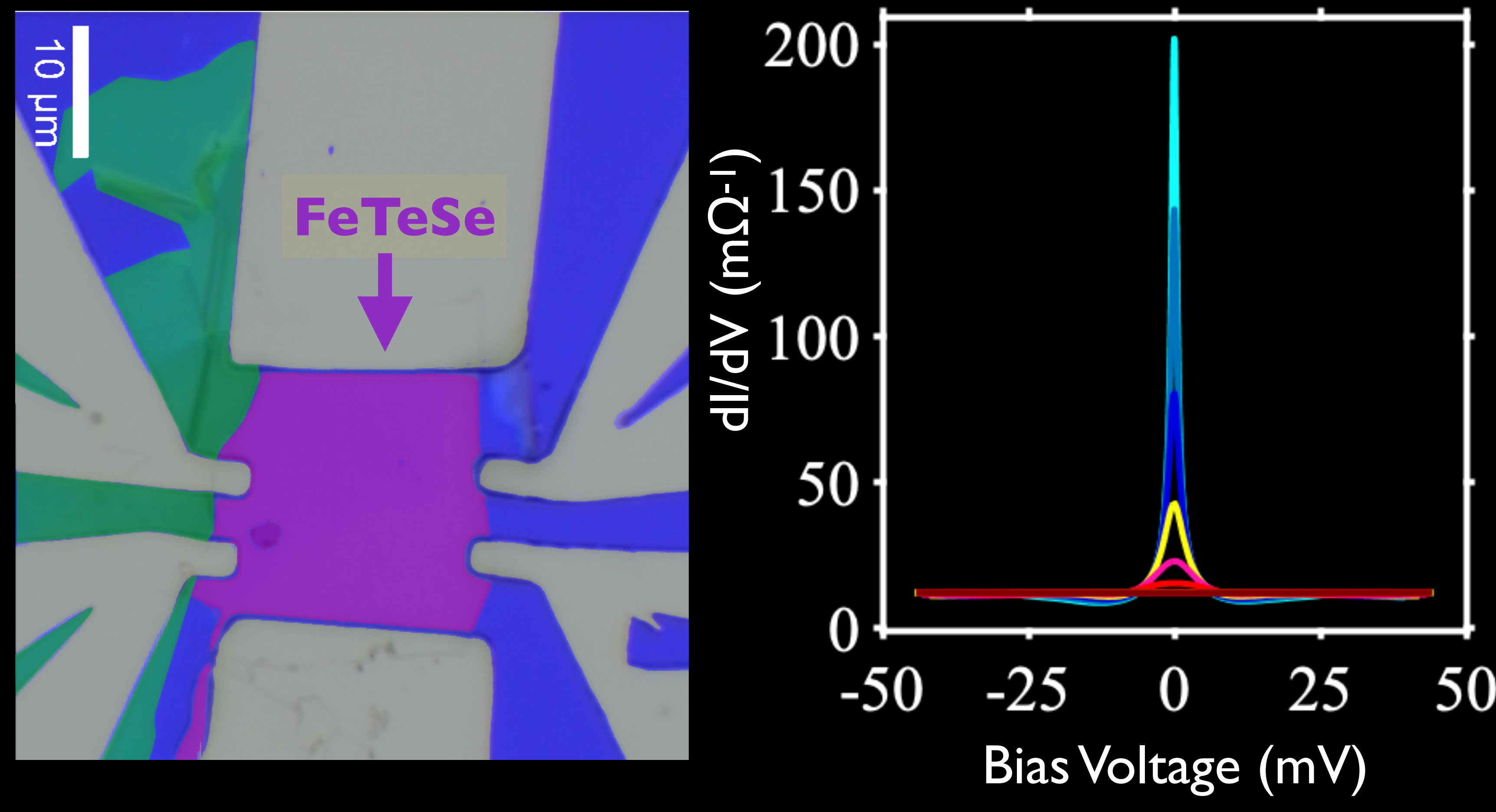
New Order

Magnetic Monopole



Y. Tokura et al., Nature Physics (2017)



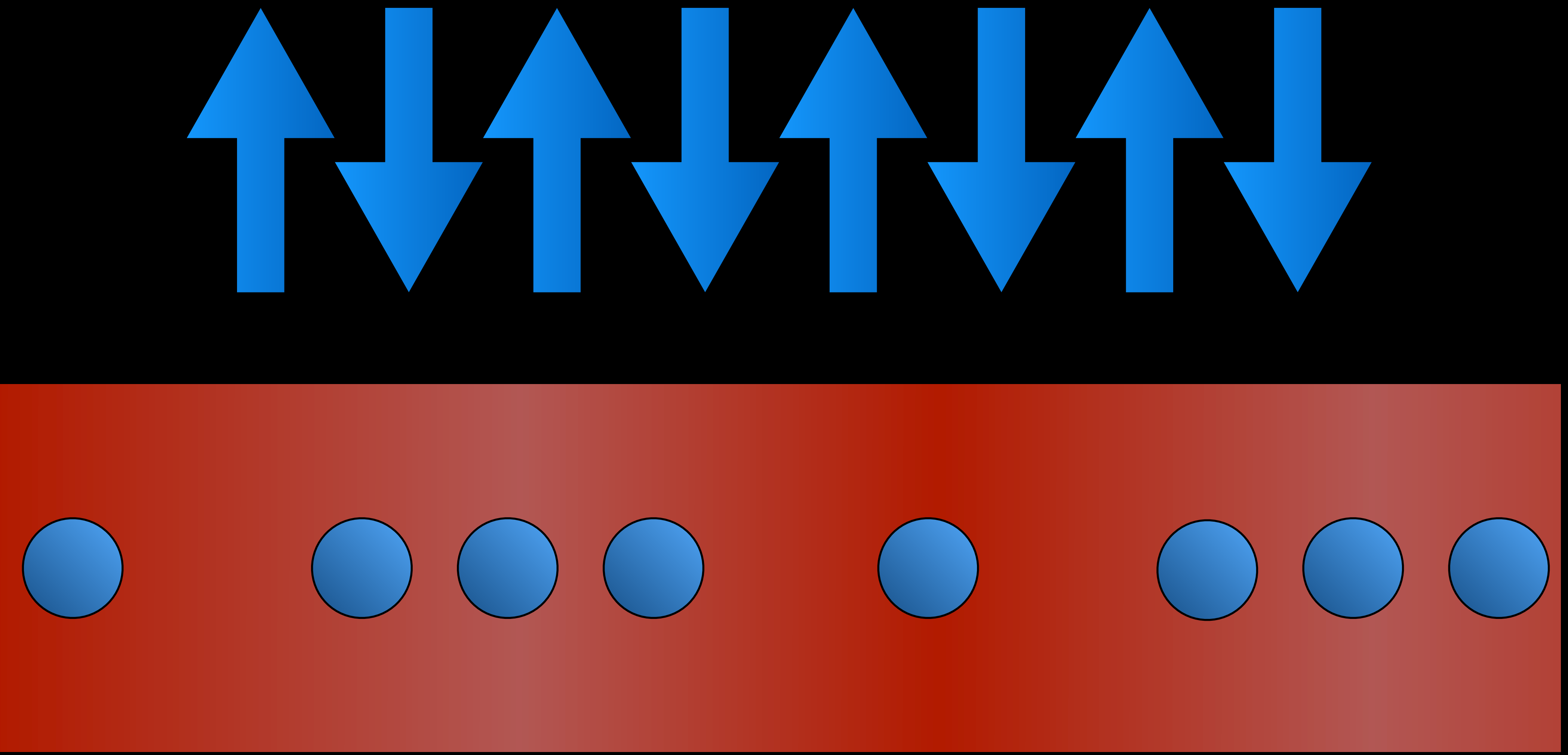


M. Gray, KSB et al, Nanoletters (2019)

Symmetry Breaking

$$\Psi(r,t) = |\Psi(r,t)|e^{i\phi(r,t)}$$

$$S = -\alpha\Psi^*\Psi + \beta(\Psi^*\Psi)^2 + \underline{\gamma(\nabla\Psi^*\nabla\Psi)}$$



Gauge?

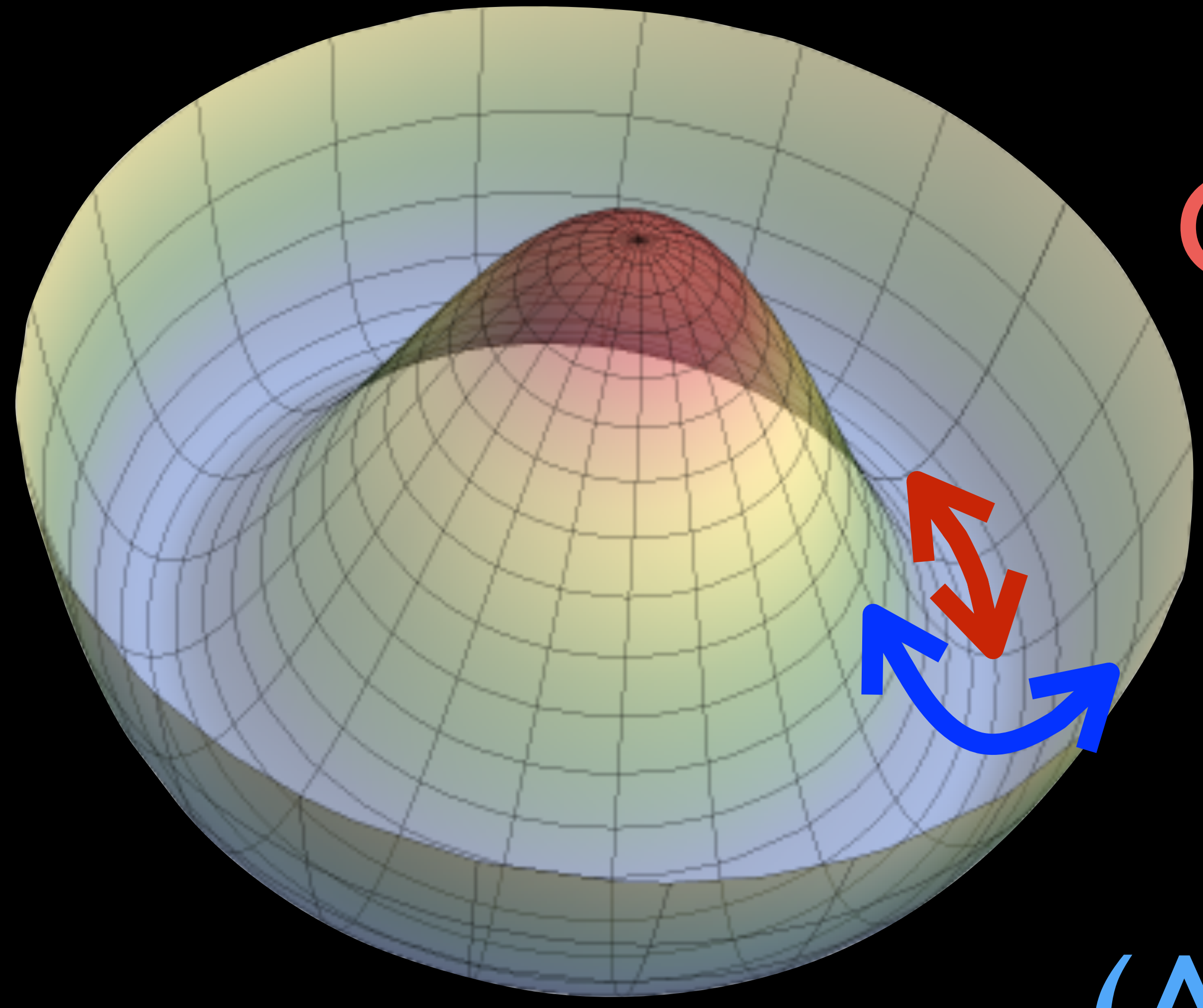
$$\nabla \rightarrow |\nabla - i(e/c)A|$$

D. Pekker and C. Varma Annu. Rev. CMP (2015)

Higgs…

Massive particles ← Plasmon (at ω_p)

Anderson



Goldstone (Phason)

Higgs (Amplitudon)

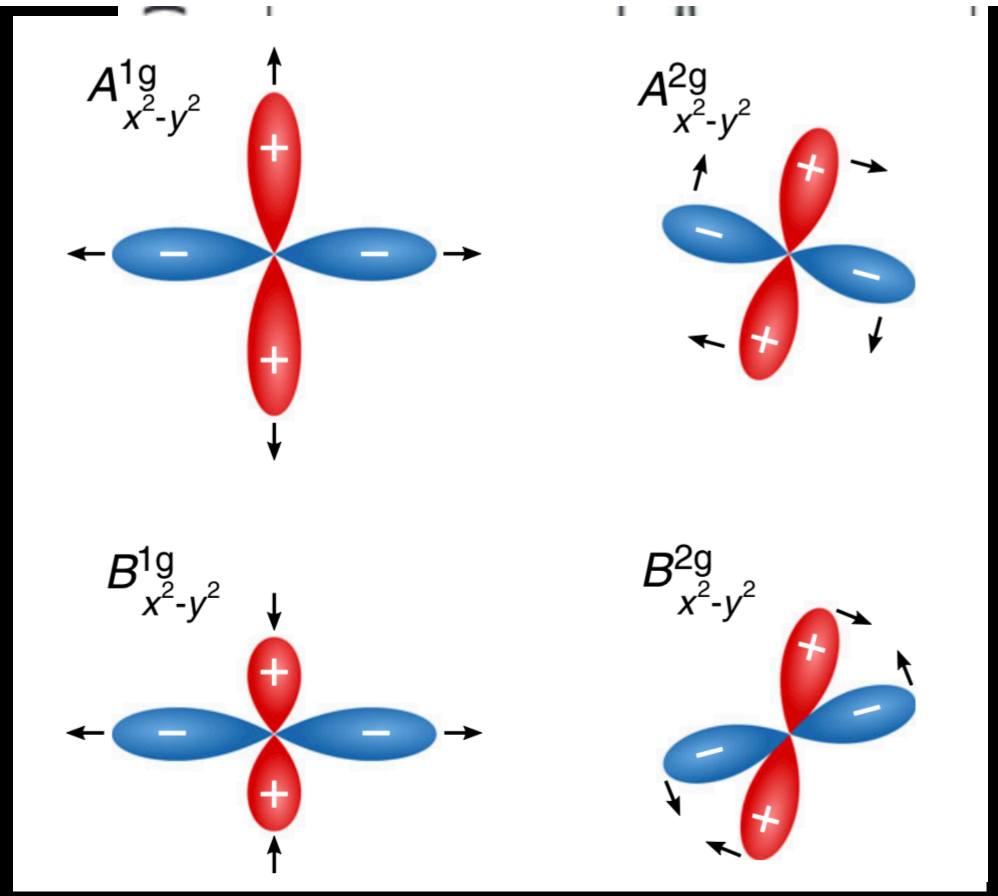
Higgs

“It is worth noting that an essential feature of this type of theory … is the prediction of an incomplete multiplet of scalar and vector bosons”

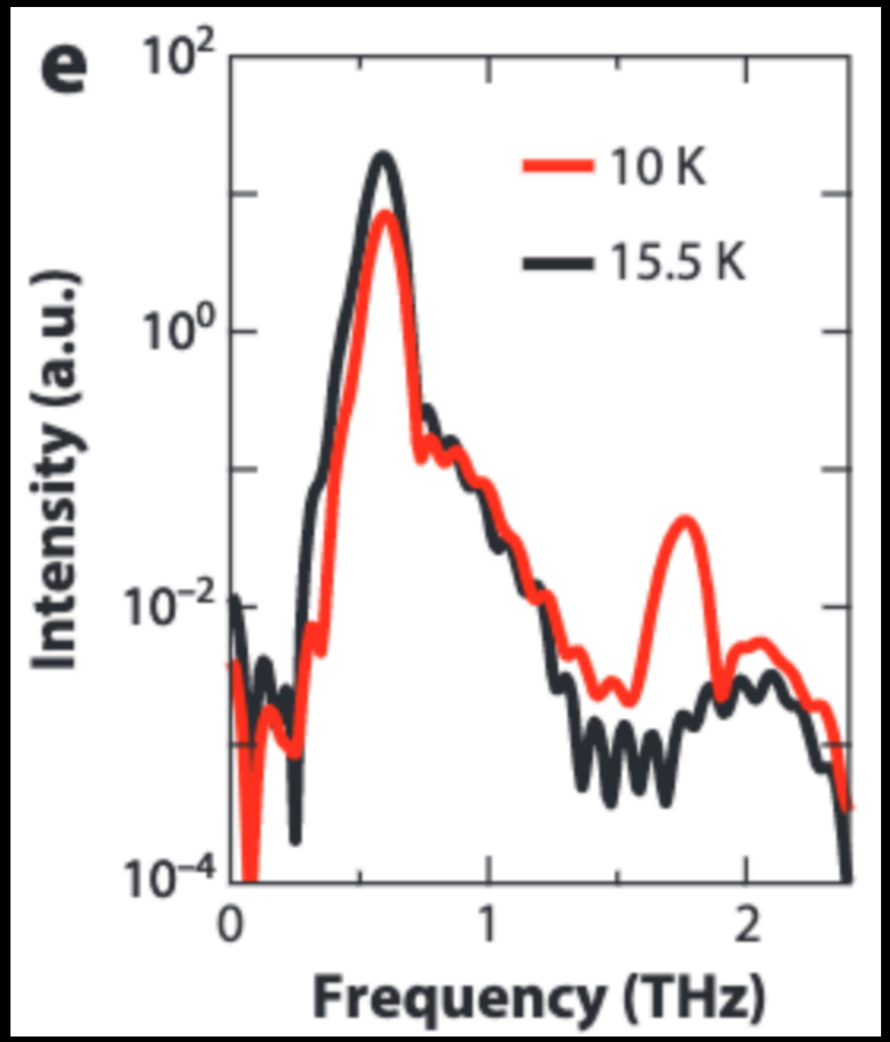
nature physics
LETTERS
PUBLISHED ONLINE: 27 MARCH 2017 | DOI: 10.1038/NPHYS4077

Higgs mode and its decay in a two-dimensional antiferromagnet

A. Jain[1,2†], M. Krautloher[1†], J. Porras[1†], G. H. Ryu[1‡], D. P. Chen[1], D. L. Abernathy[3], J. T. Park[4], A. Ivanov[5], J. Chaloupka[6], G. Khaliullin[1], B. Keimer[1*] and B. J. Kim[1,7*]



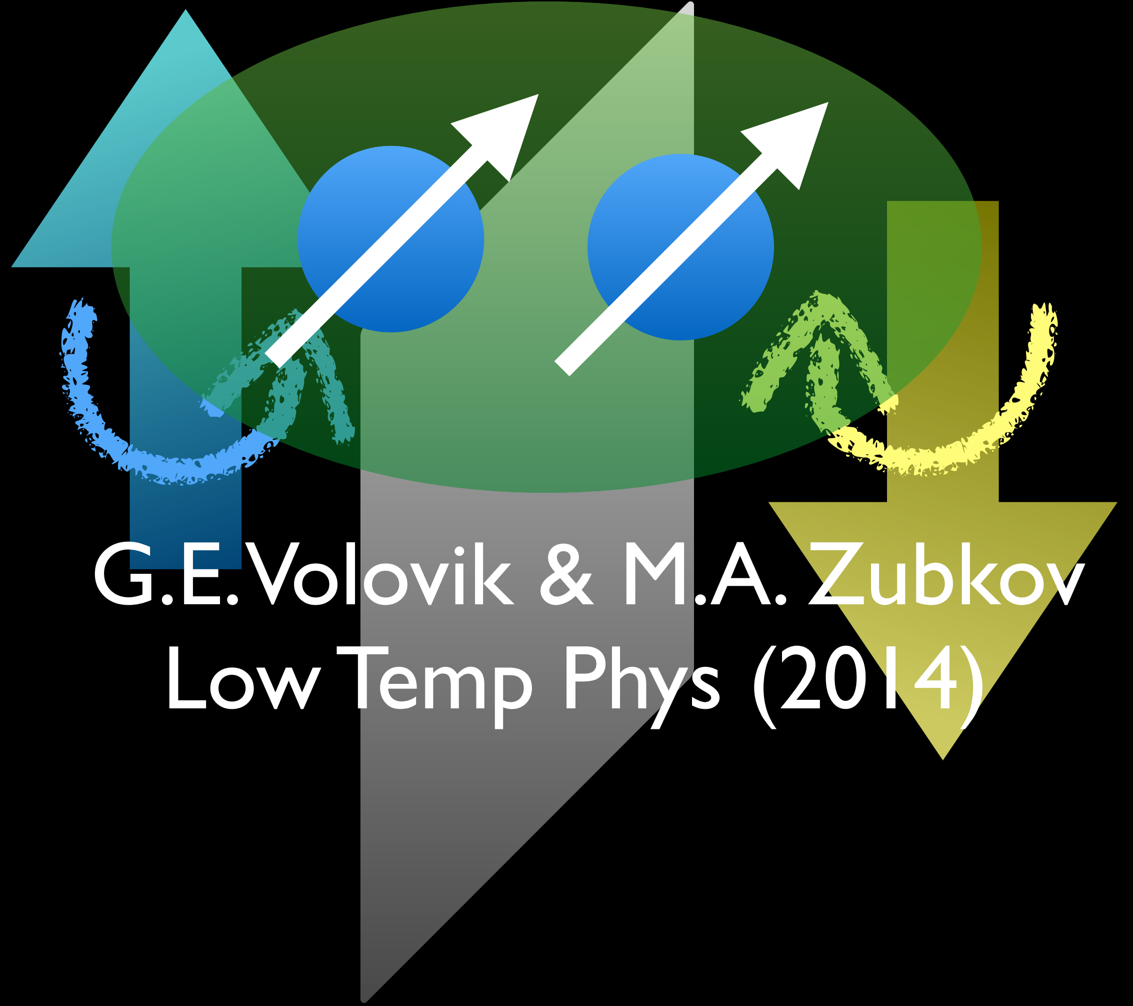
Nat. Comm 2020



Science 345, 1145 (2014)

Superfluid ^{3}He

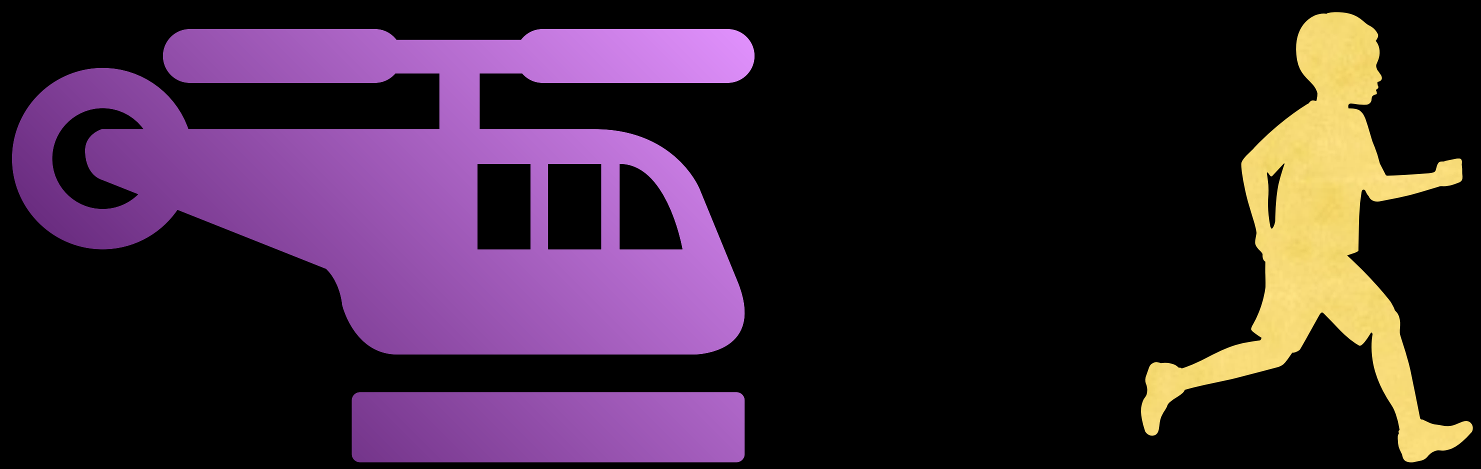
Axial

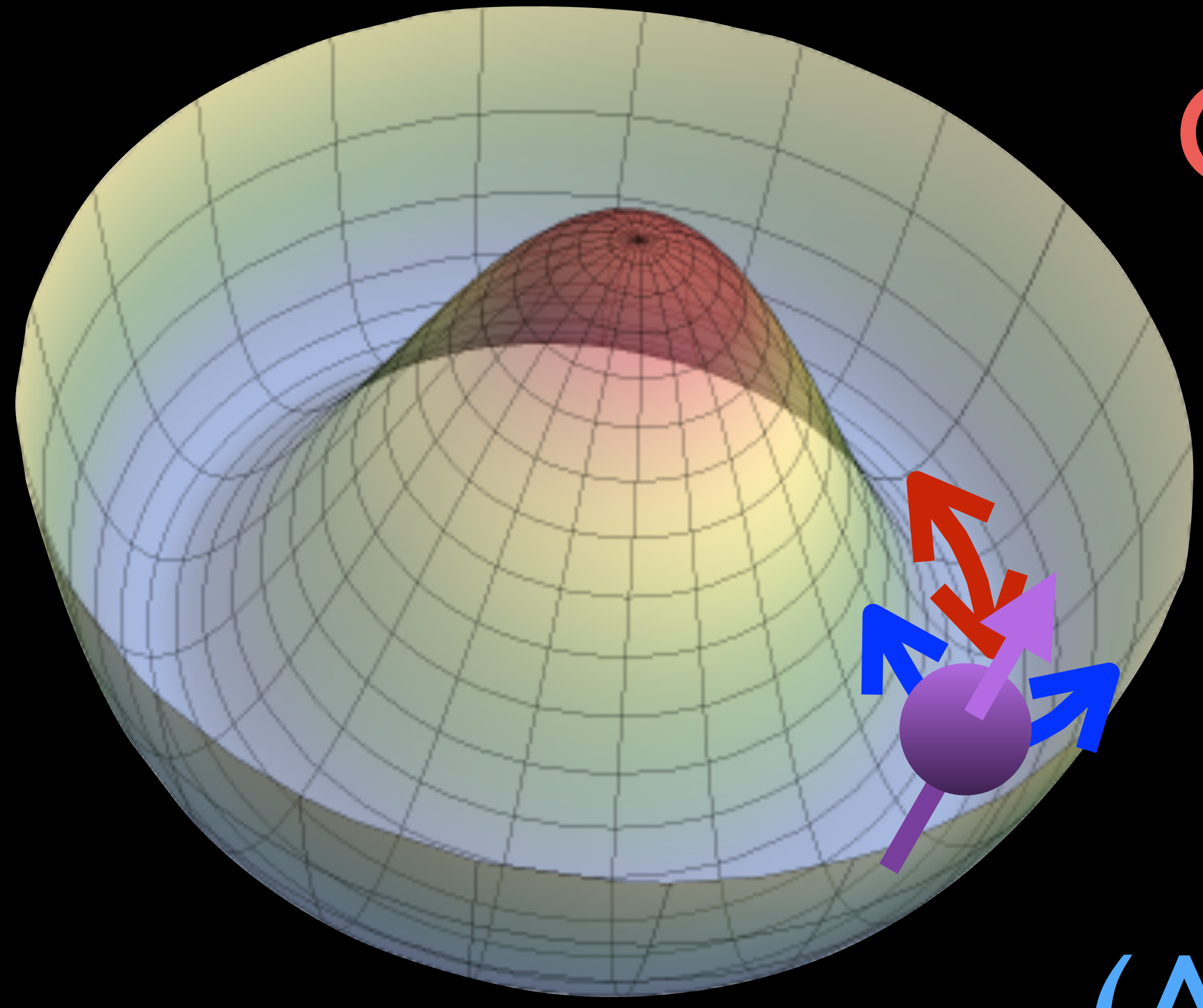


G.E. Volovik & M.A. Zubkov
Low Temp Phys (2014)

- ☐ Mirror
- ☐ Time Reversal
- ☑ 180°

Multiple Symmetry Breaking?





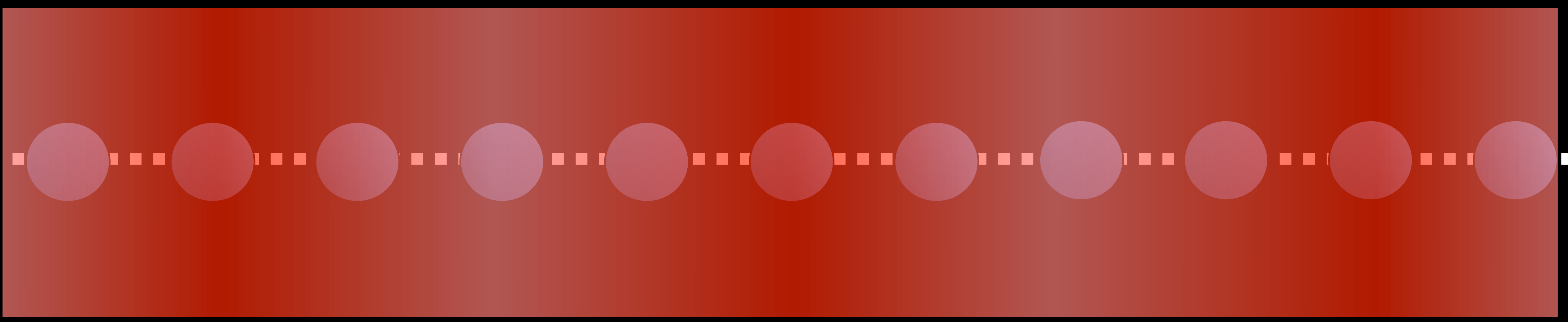
Goldstone (Phason)

Higgs (Amplitudon)

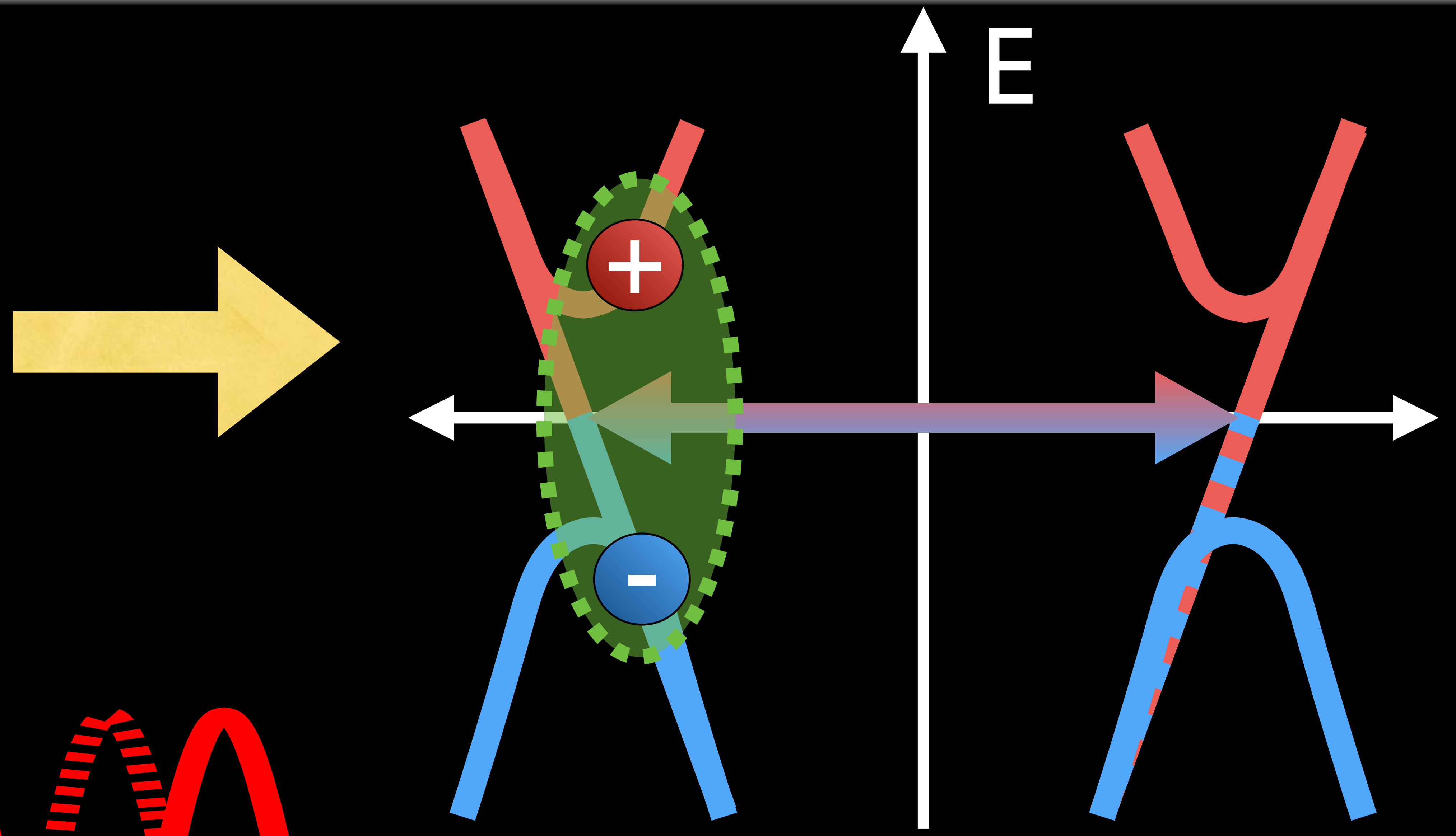
Square Scattering

Charge Density Waves

Fröhlich (1954) and Peierls (1955)

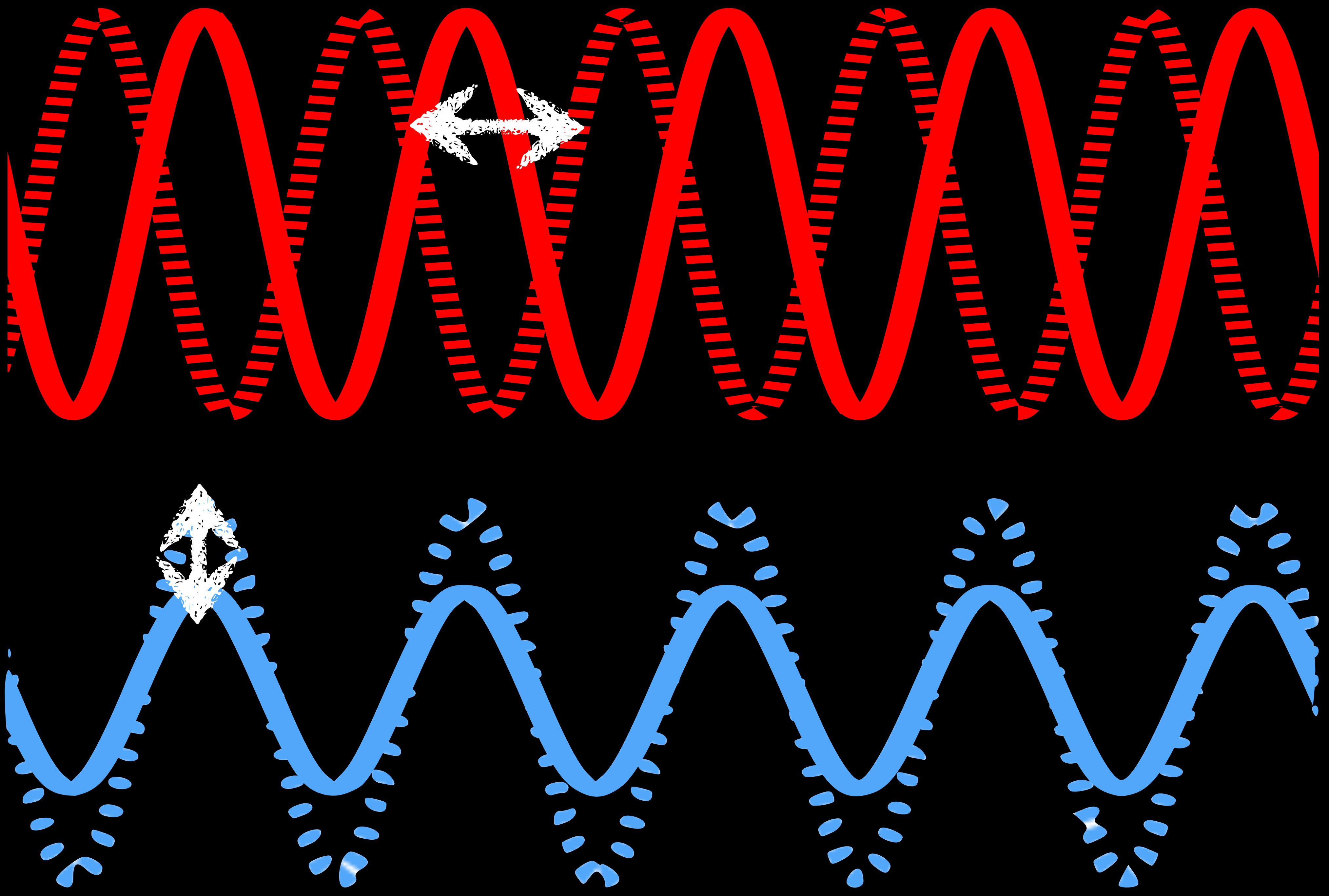


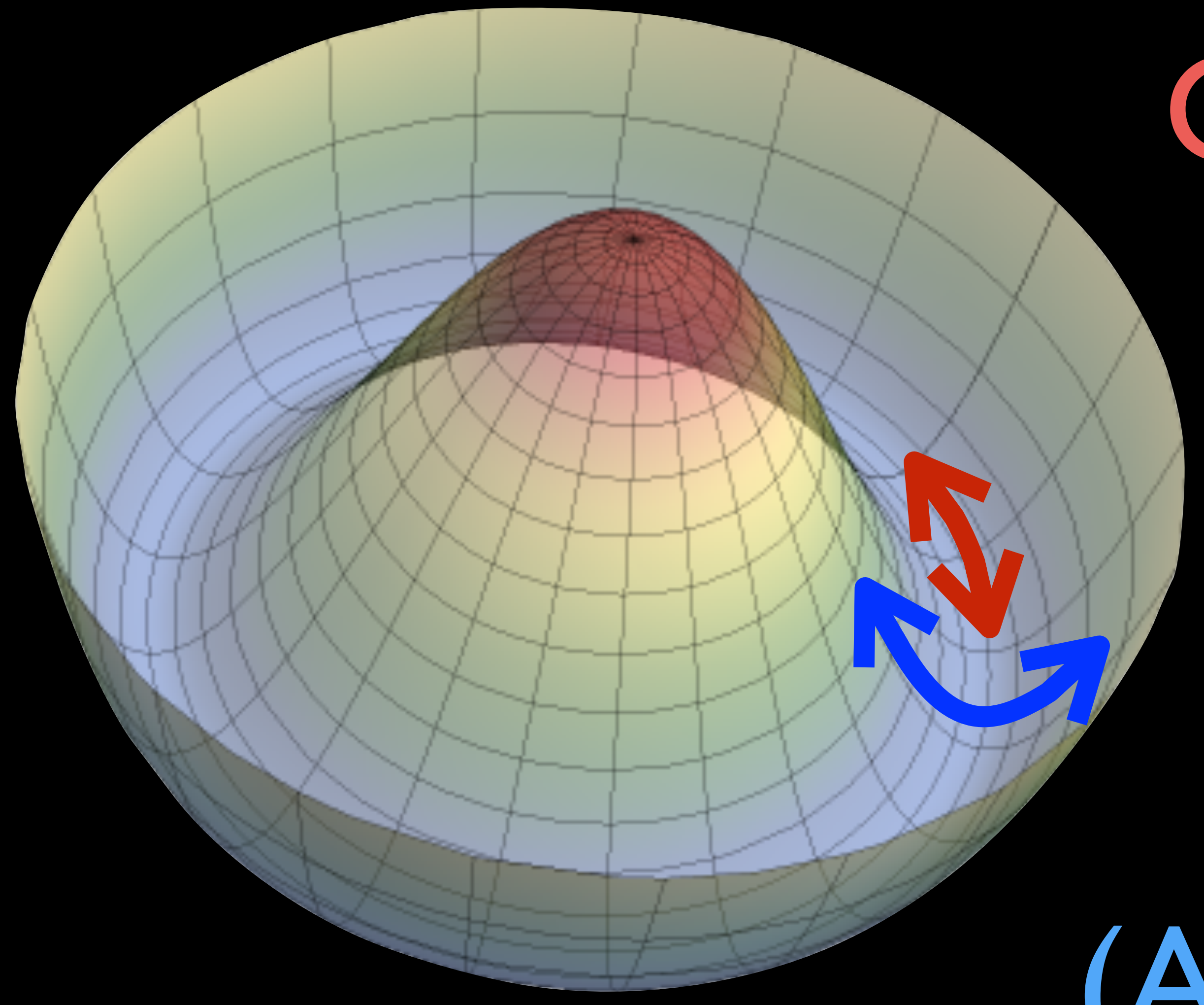
G. Gruner, RMP (1988)
M.D Johannes, I. Mazin PRB 2008



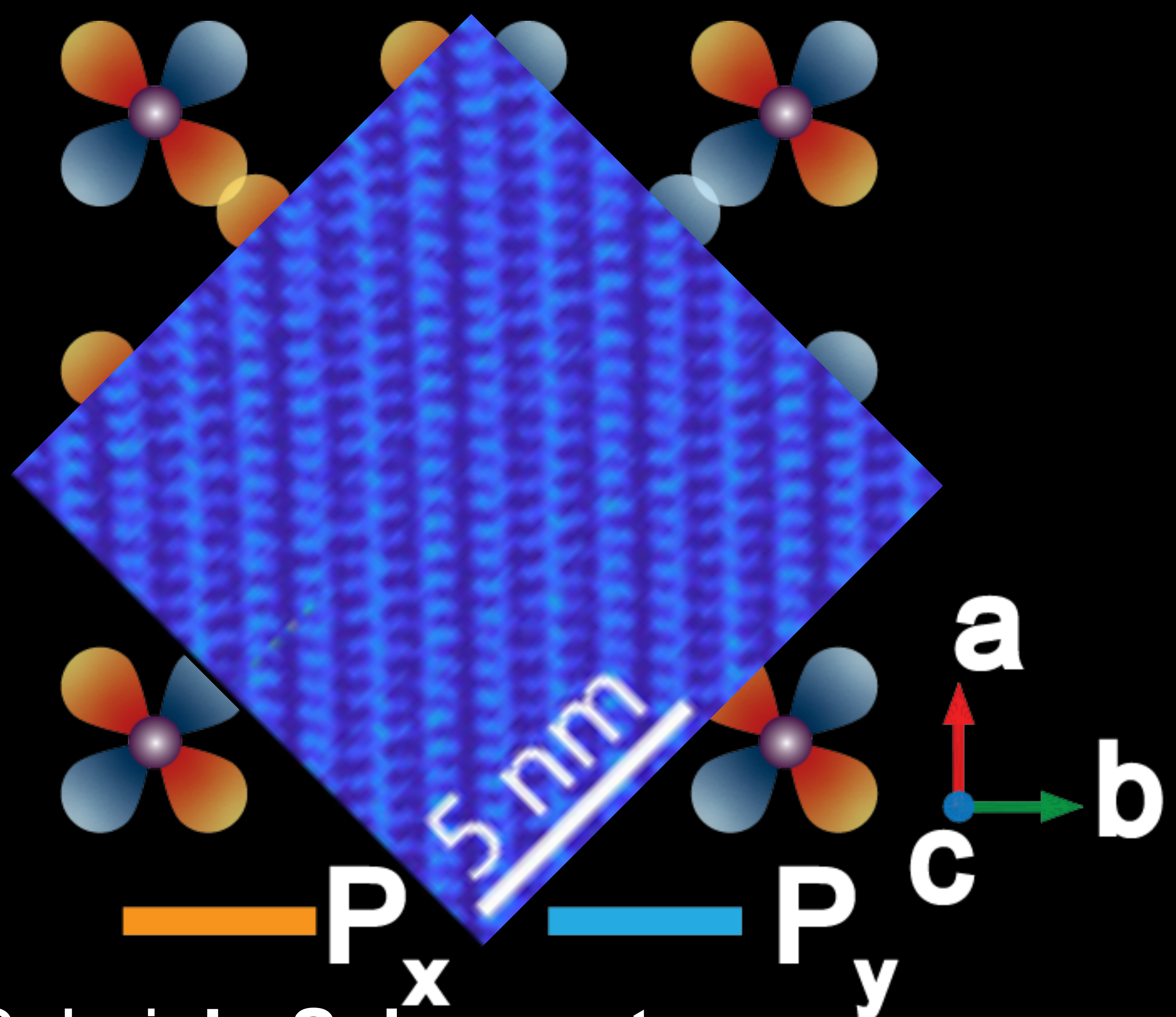
- Particle-Hole
- High T/E
- Applications

A. Balandin, et al,
APL (2021)

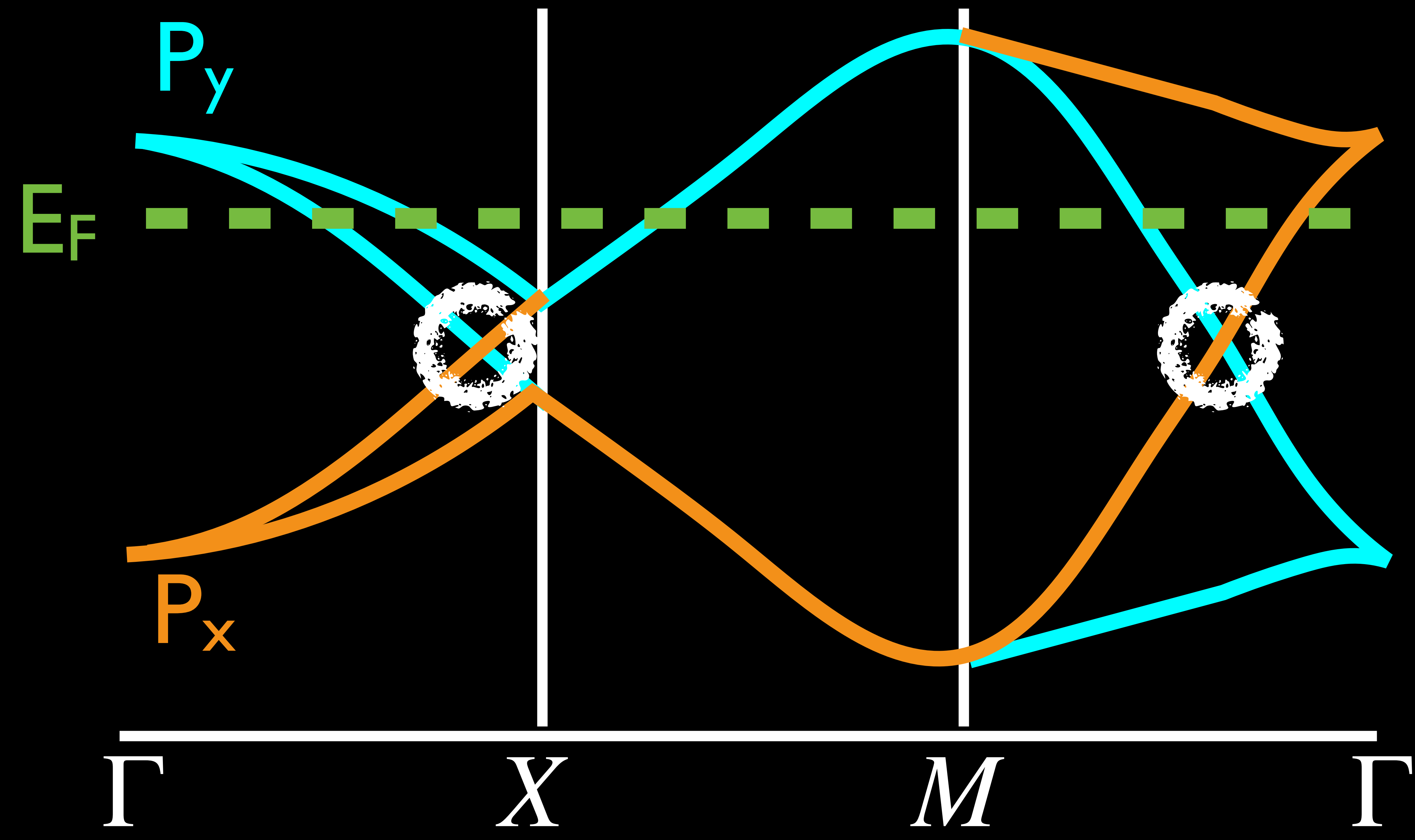


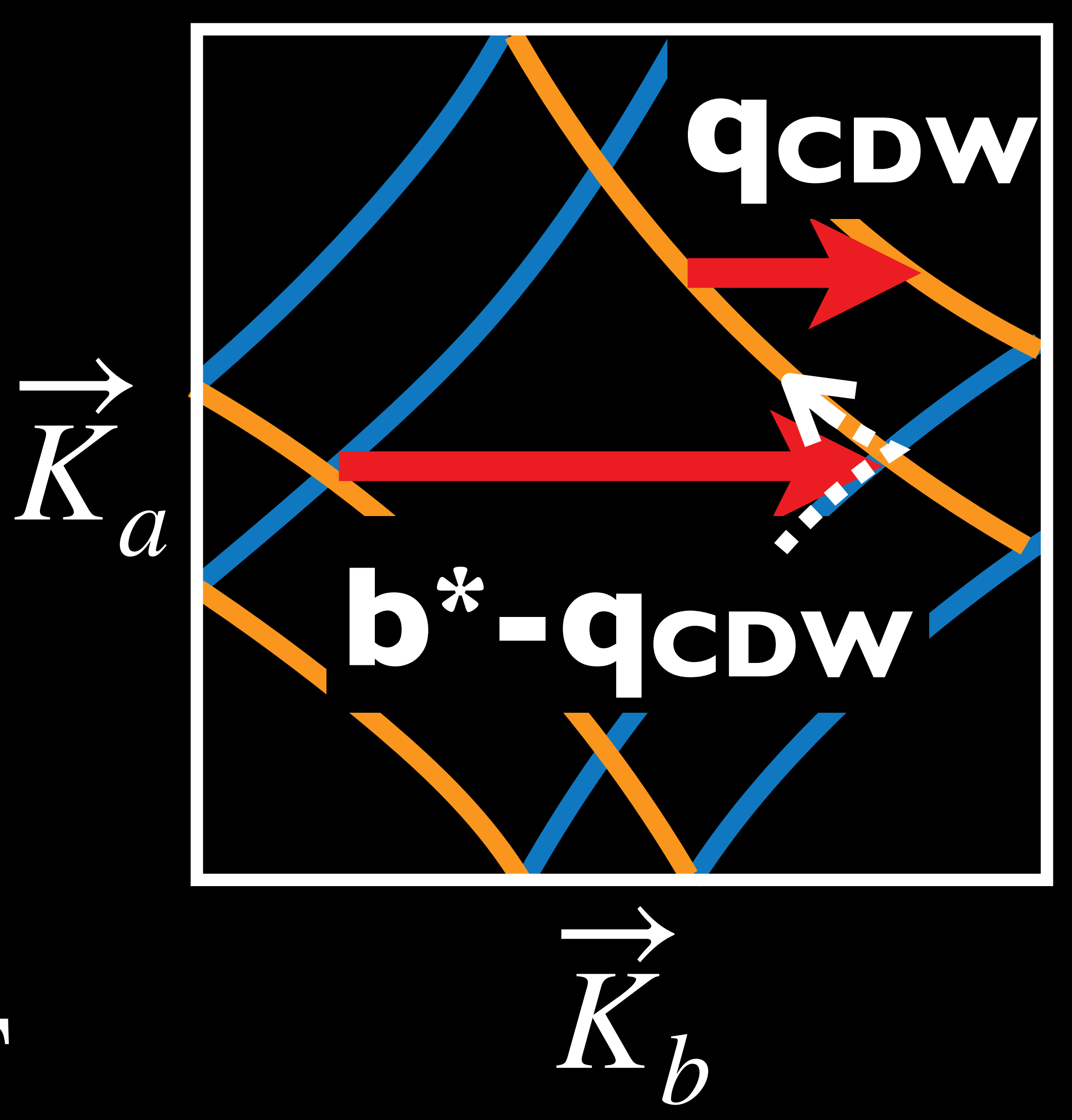


Materials



S. Lei, **L. Schoop et al** Sci. Adv. (2020)

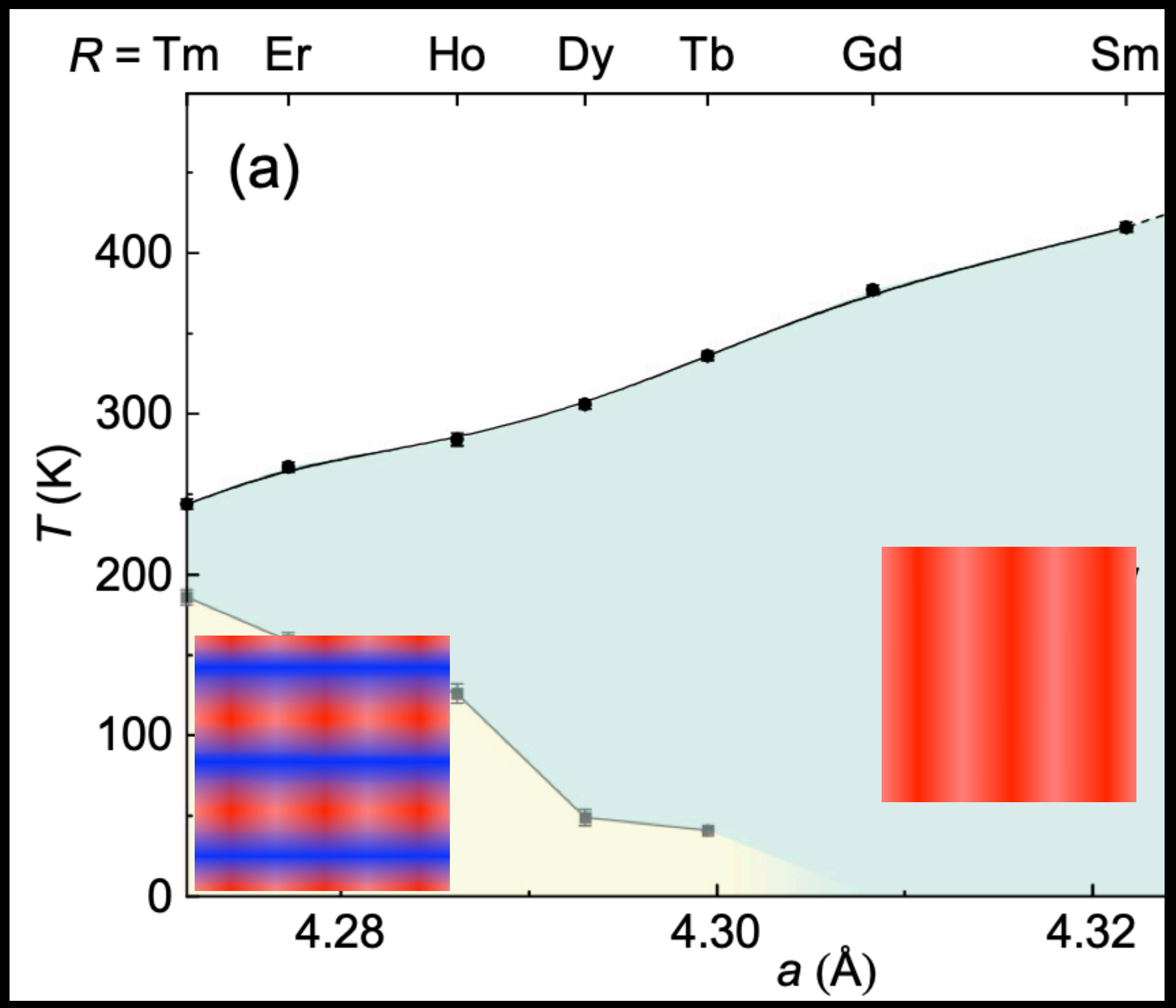




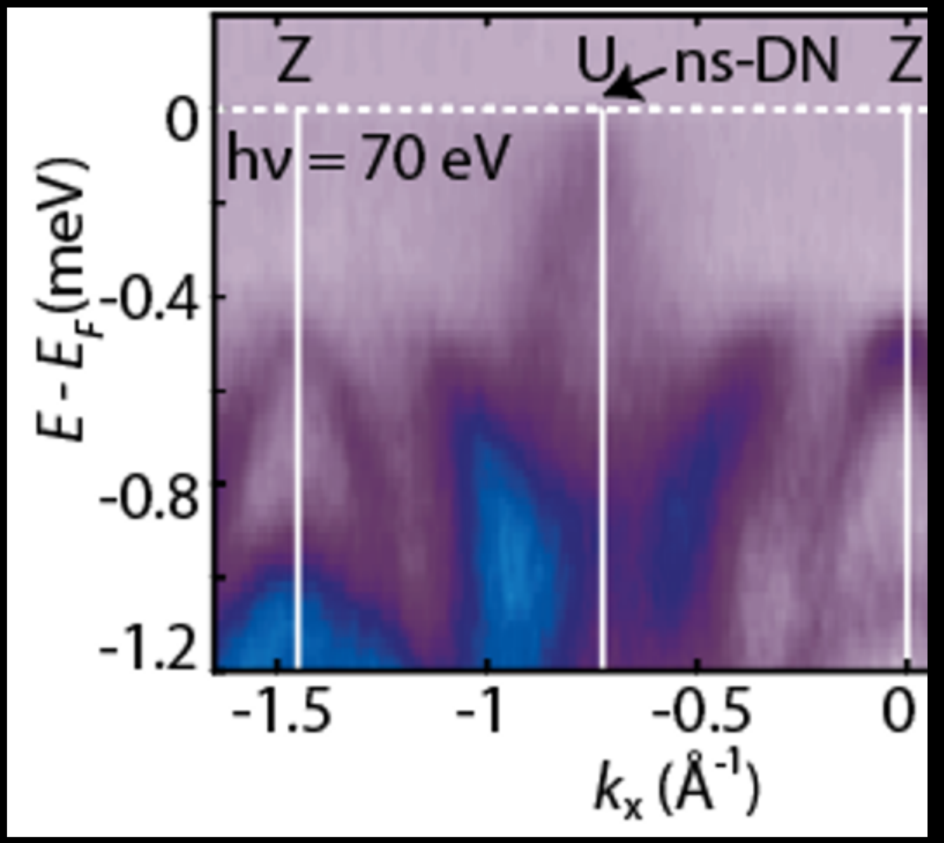
S. Klemenz, J. Cano, L. Schoop et al JACS (2020)

LnTe$_3$

P. Walmsley, I. Fisher et al, PRB 102, 045150 (2020)



LnSb$_x$Te$_{2-x}$



S. Lei, **L. Schoop et al** Adv. Materials (2021)

A Postpandemic Tool

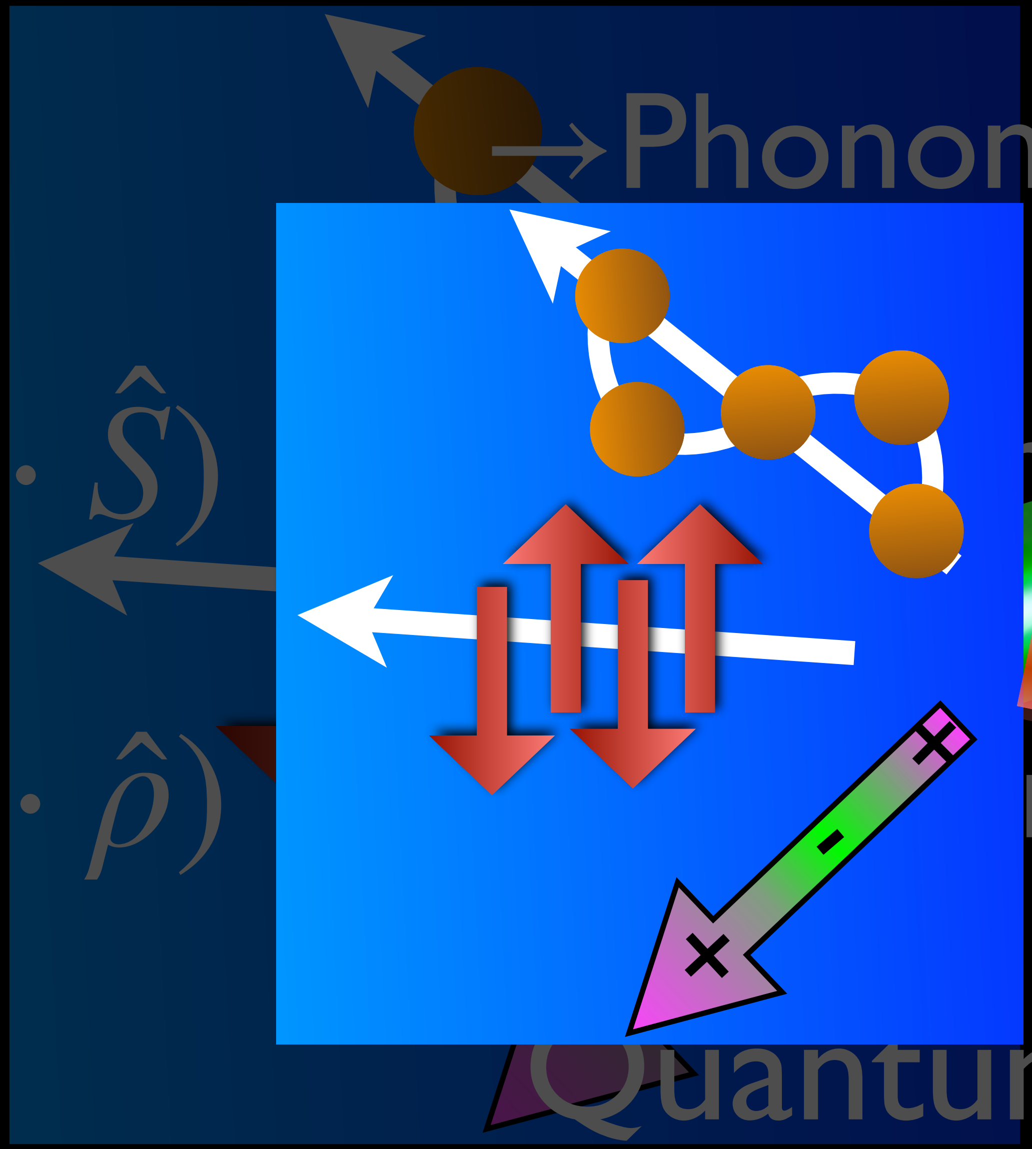
$$\vec{P} = \alpha\vec{E} = \left(\alpha_0 + \frac{d\alpha}{d\hat{O}}\delta\hat{O}\right)\vec{E}$$ Absorption/“Reflectance” Generate Sidebands

$$I_{ij}(\omega) = |\hat{\epsilon}_i \cdot R_{ij} \cdot \hat{\epsilon}_j|^2$$ → Symmetry

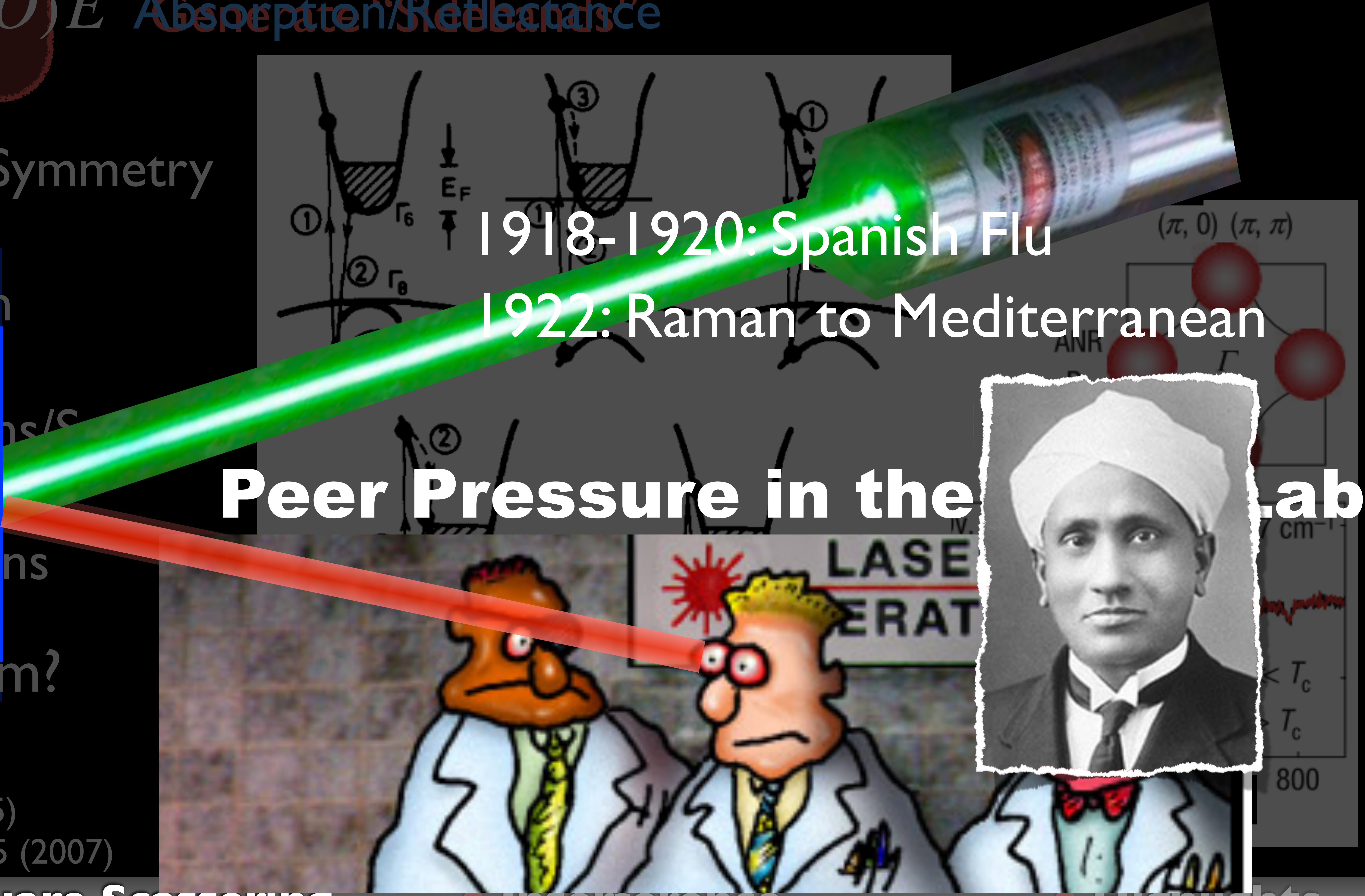
$\hat{O} = \hat{a}$ → Phonon

$\hat{O} = f(\hat{S}\cdot\hat{S})$ ns/S

$\hat{O} = f(\hat{\rho}\cdot\hat{\rho})$ ns


Quantum?

PRB 13, 169 (1976)
Proc. Phys. Soc. 86, 699 (1965)
T. Devereaux Rev. Mod Phys. 79, 175 (2007)

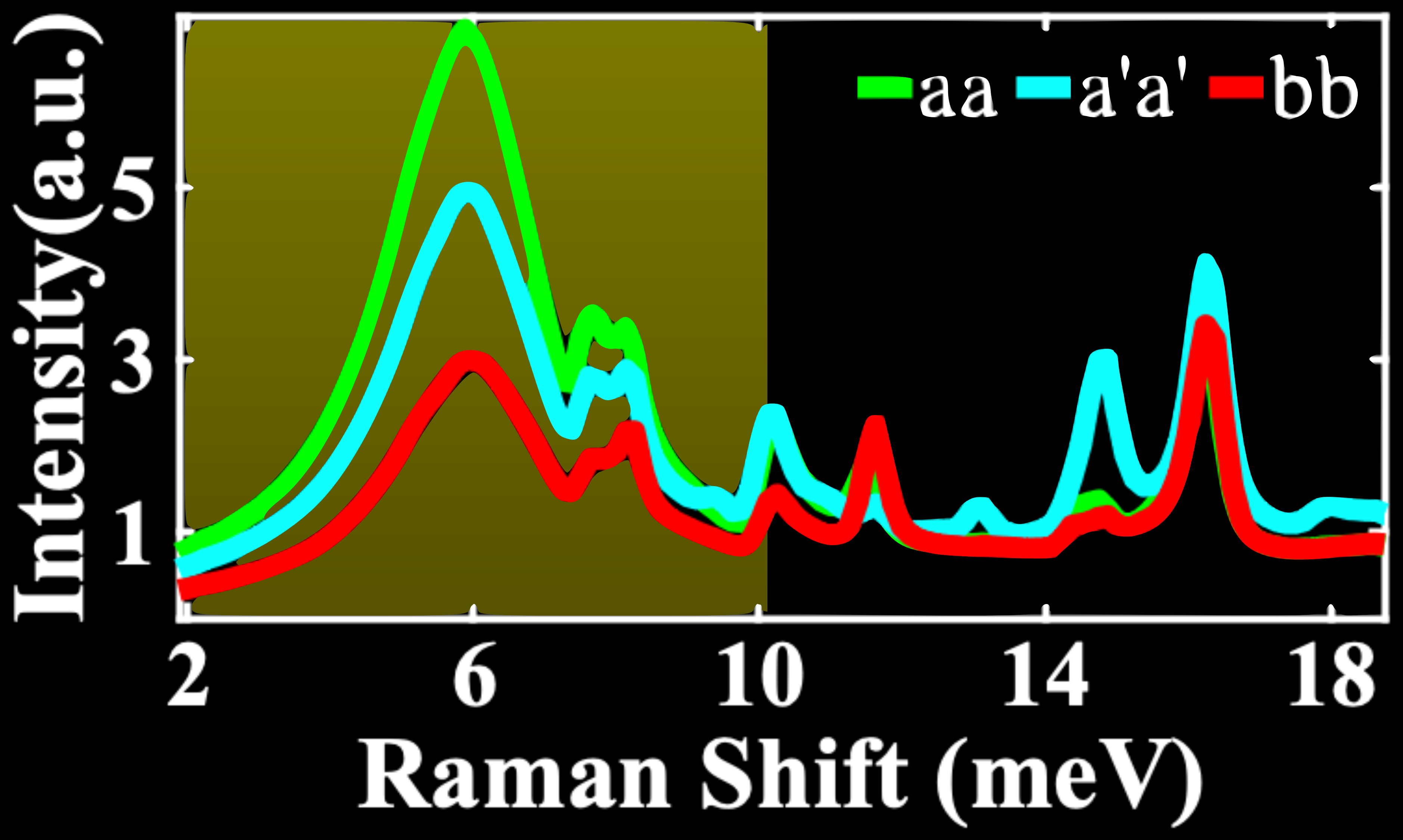


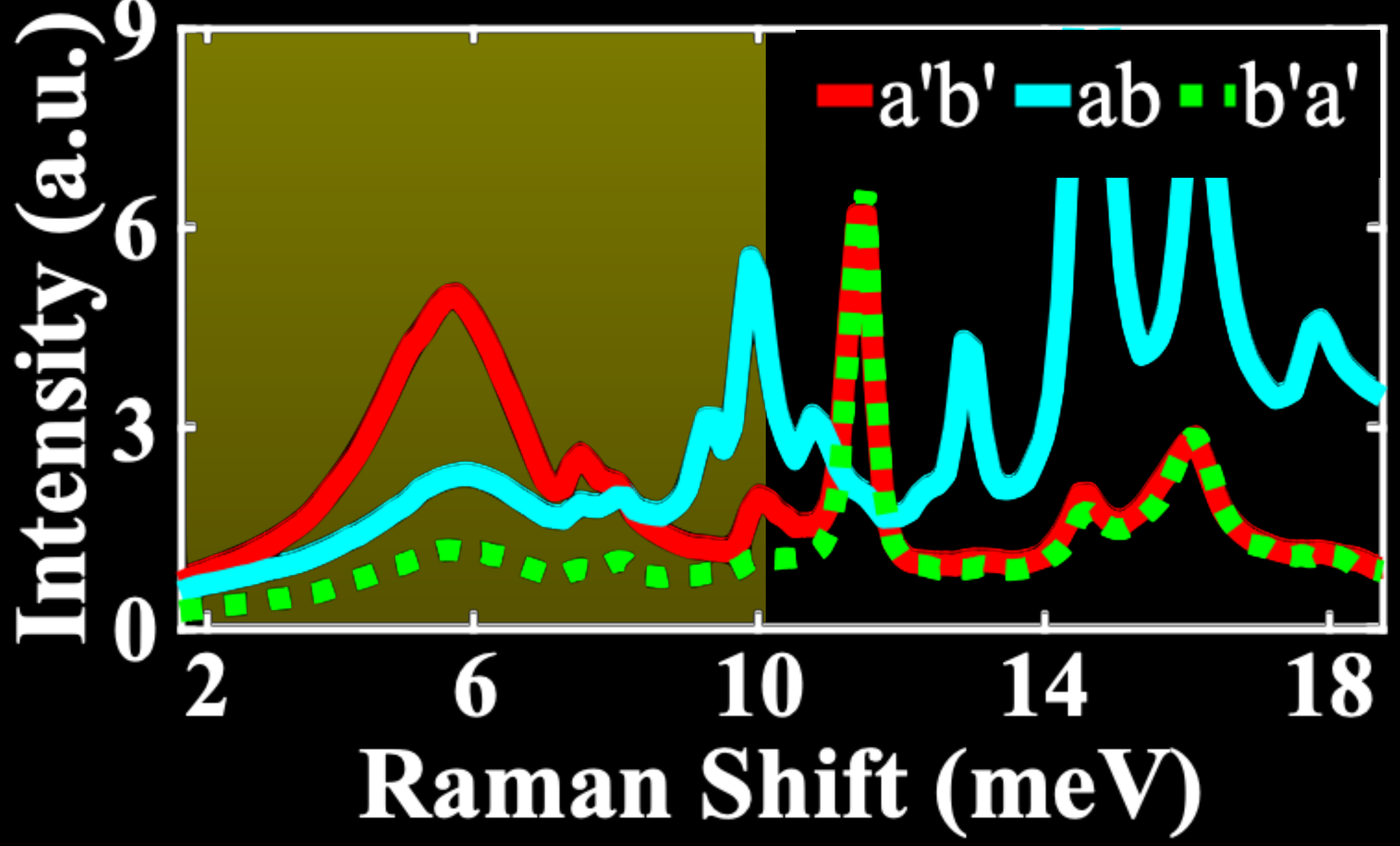
1918-1920: Spanish Flu
1922: Raman to Mediterranean

Peer Pressure in the Lab

Interference

Symmetry

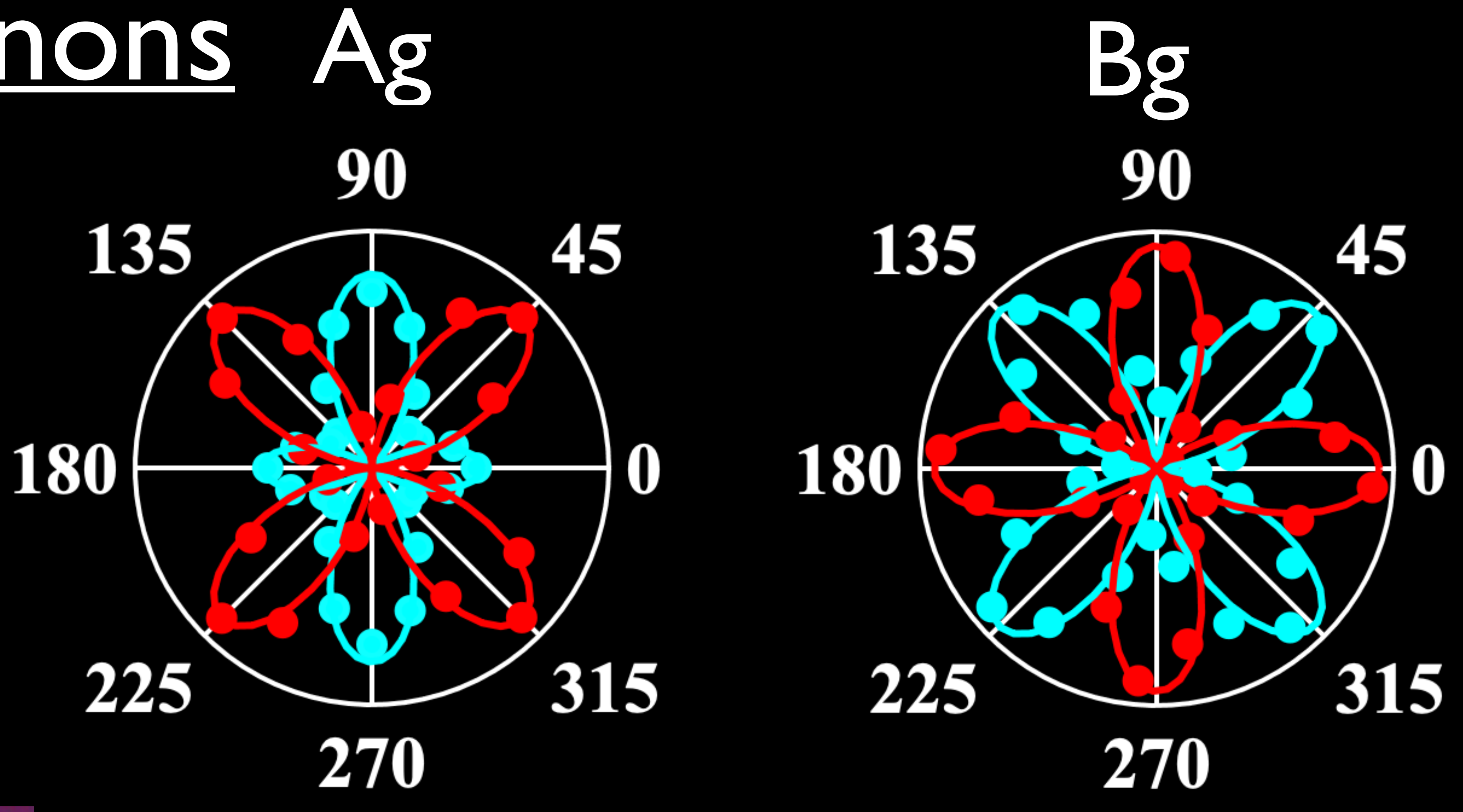




Phonons

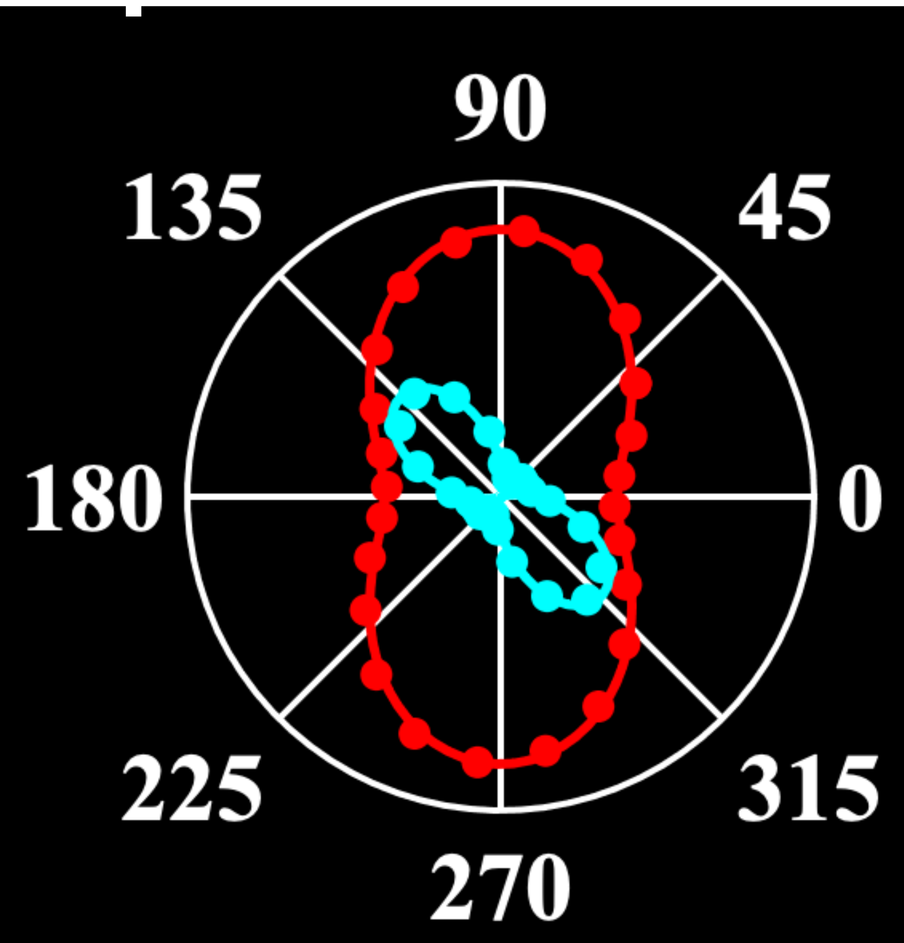
$\hat{e}_i || \hat{e}_s$

$\hat{e}_i \perp \hat{e}_s$



Y. Wang, L. Schoop, KSB et al (Nature - 2022)

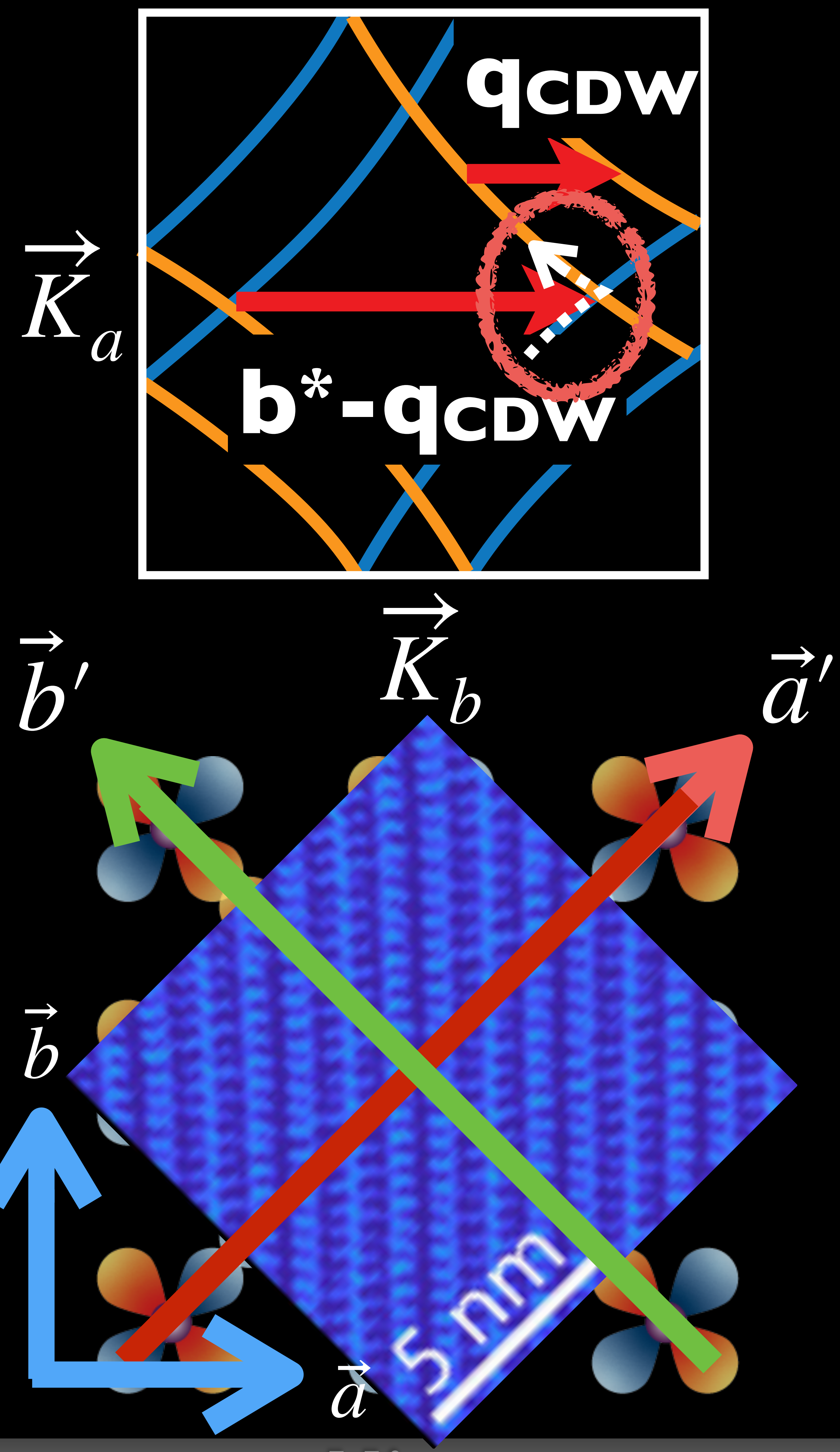
Amplitude Mode



XX vs. YY:
H.-M. Eiter, T. Devereaux, L. Degiorgi et al (PNAS - 2013)

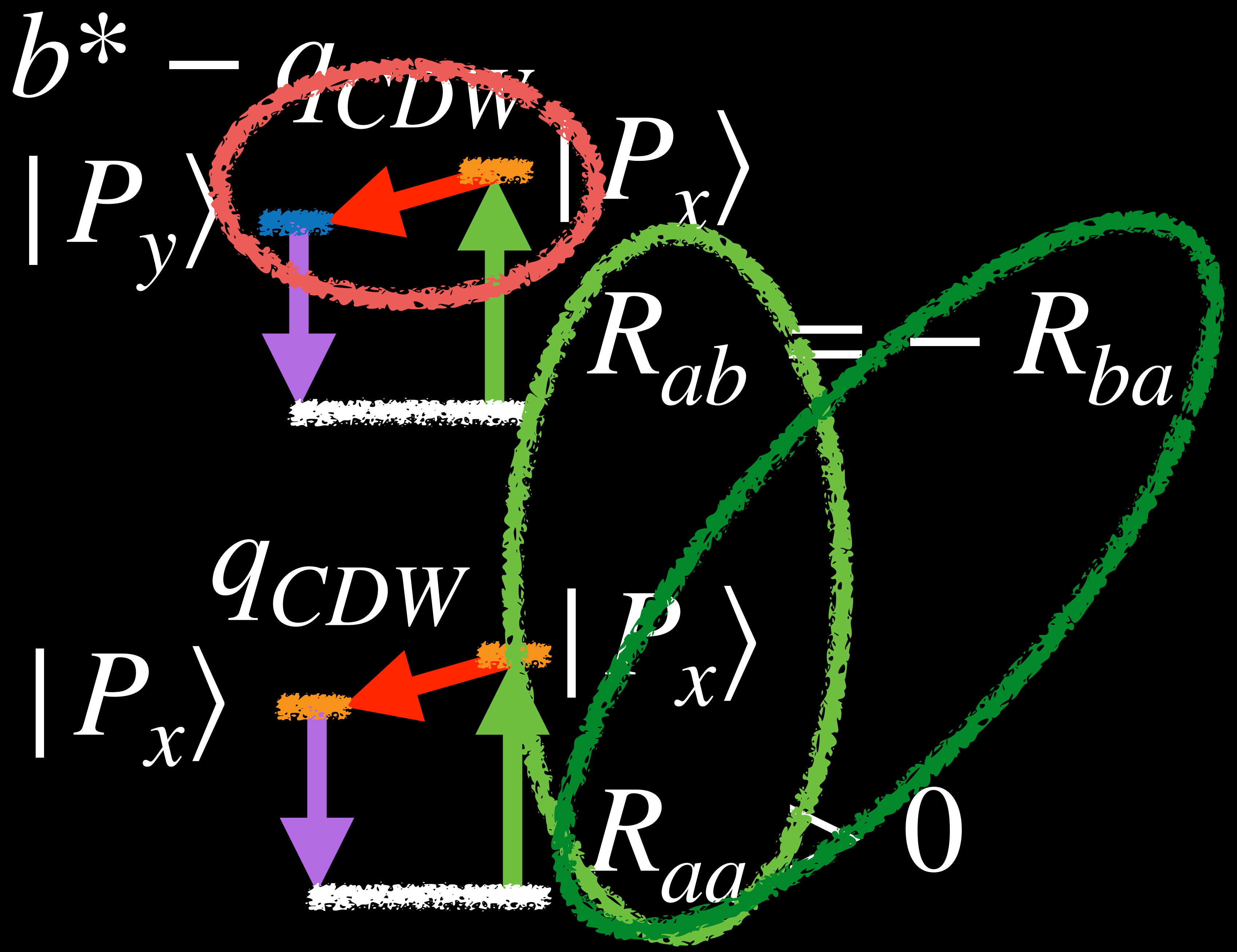
Axial Higgs

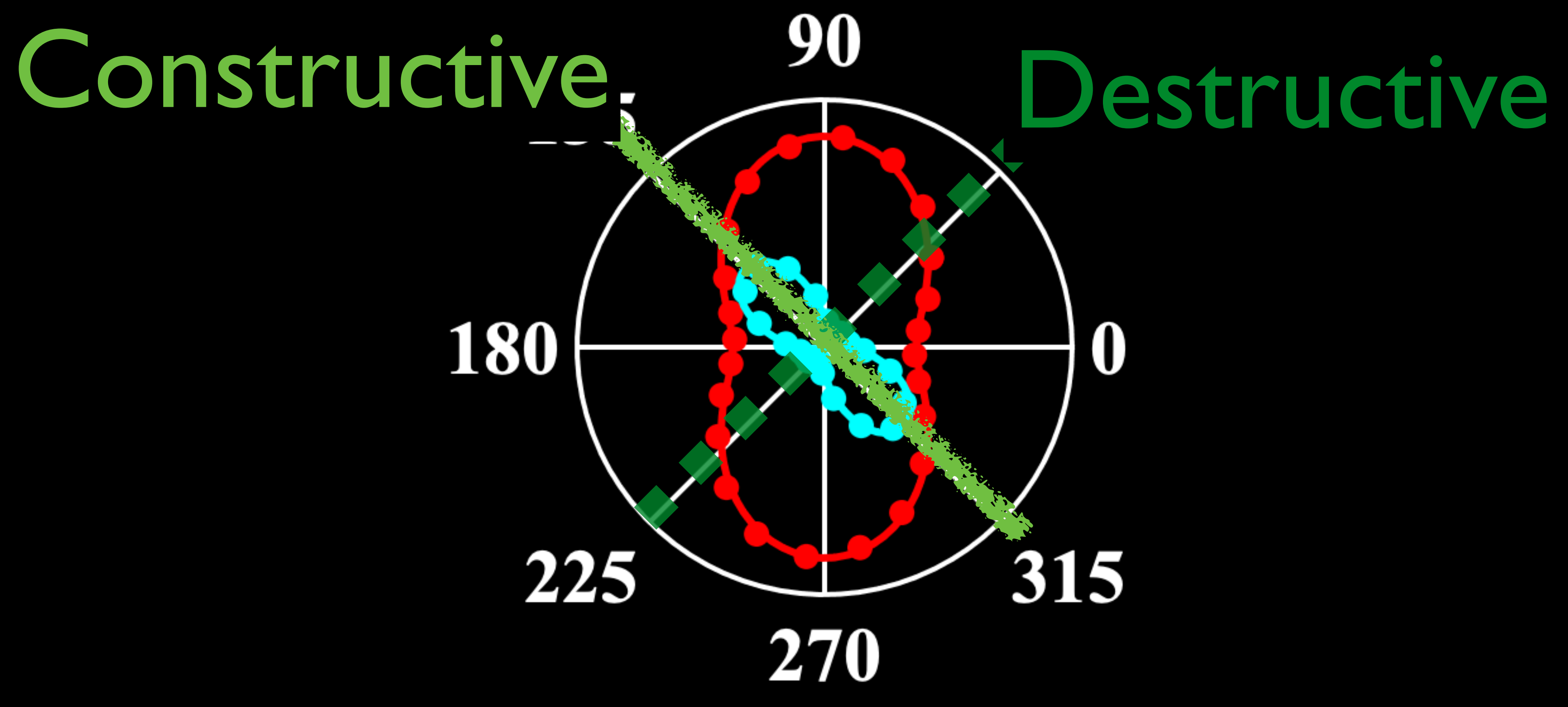
Amplitude Mode



$\hat{e}_i || \hat{e}_s$

$\hat{e}_i \perp \hat{e}_s$





Room T in $LaTe_3$ & $GdTe_3$

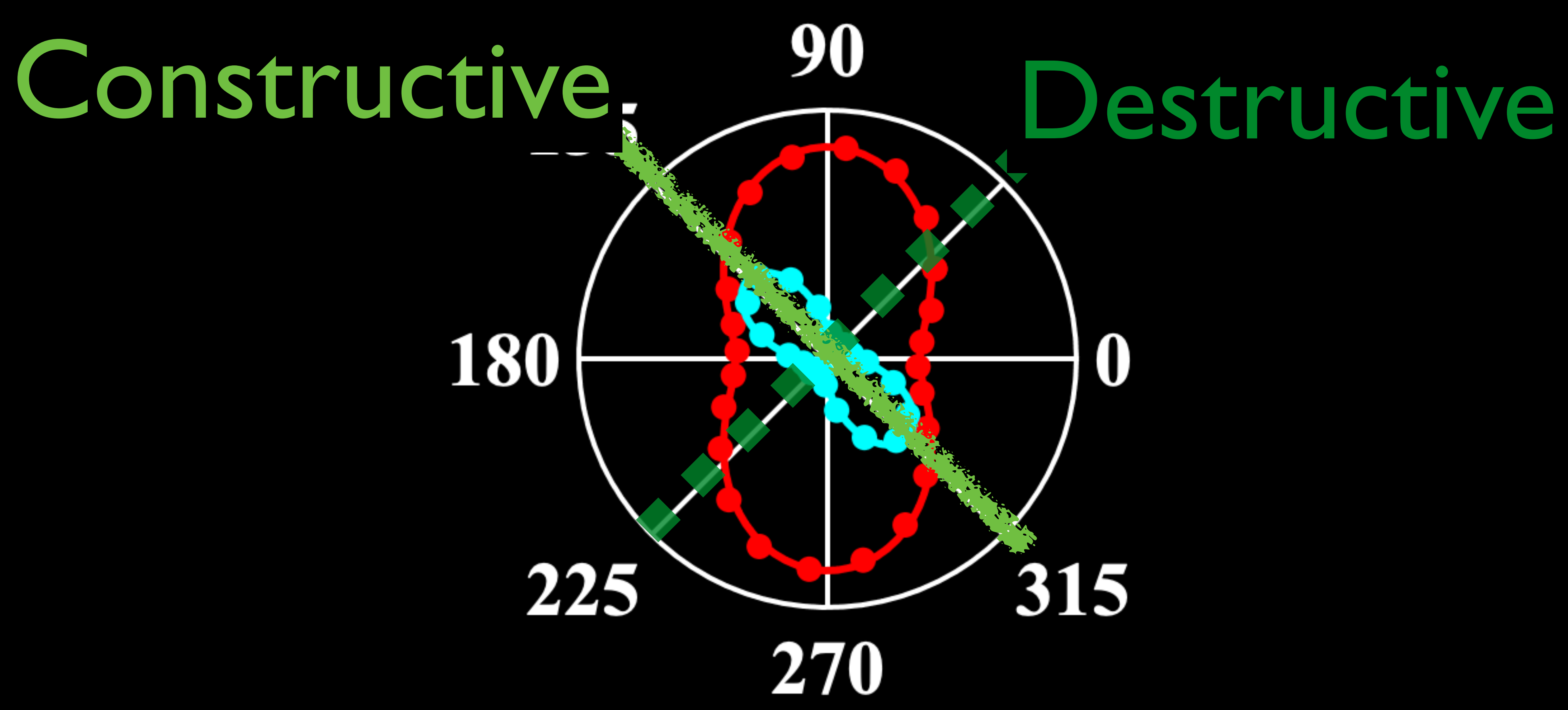
Y. Wang, L. Schoop, KSB et al (Nature - 2022)

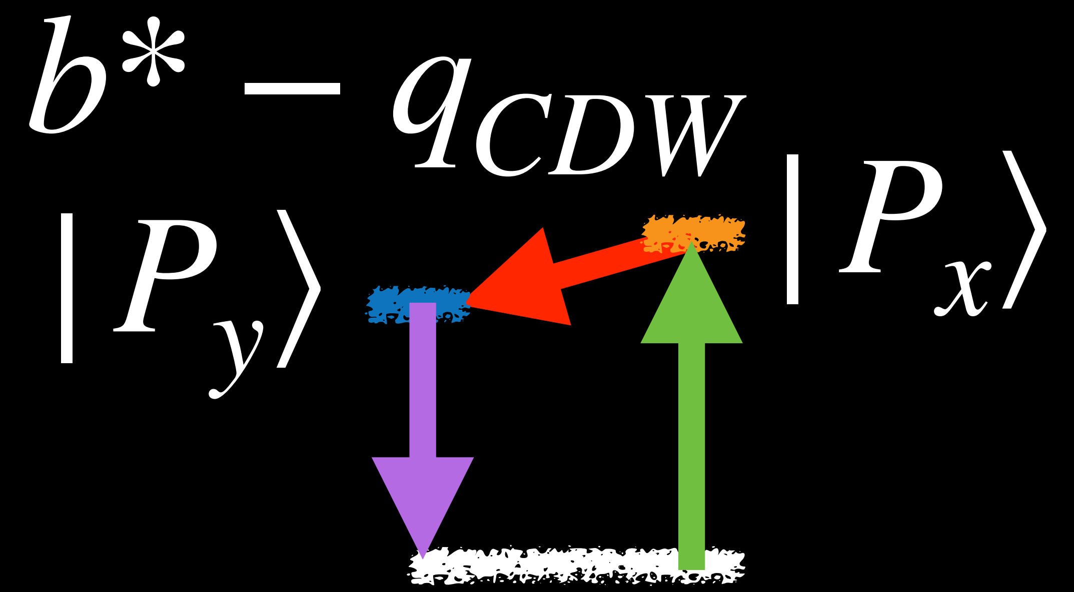
Highlights

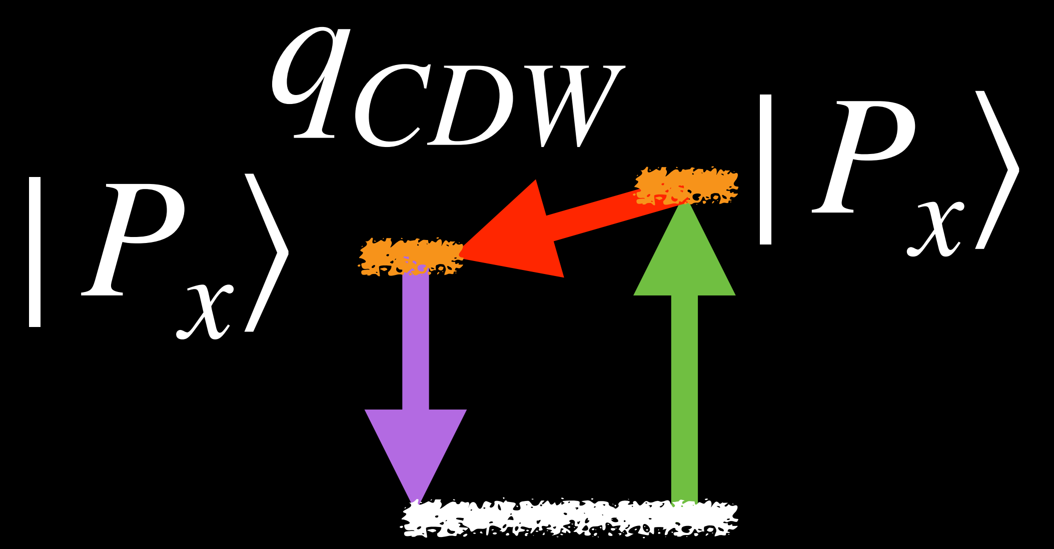
Open Questions

- What microscopically sets the phase?
- Unconventional CDW?
- CDW & Quantum Geometry?
- Sliding CDW + Topology?
- Quantum Optics for Quantum Materials?

Amplitude Mode





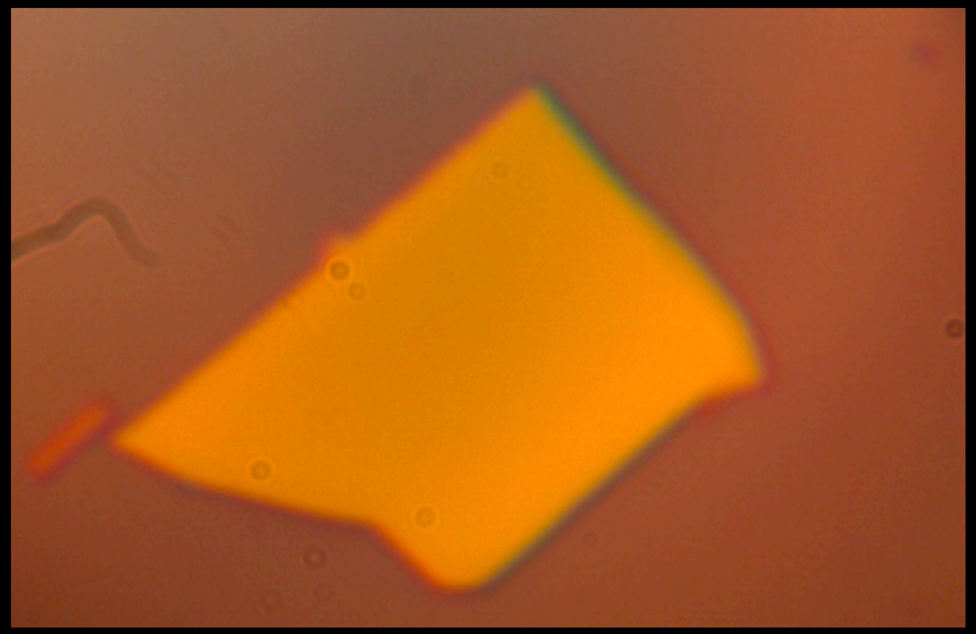


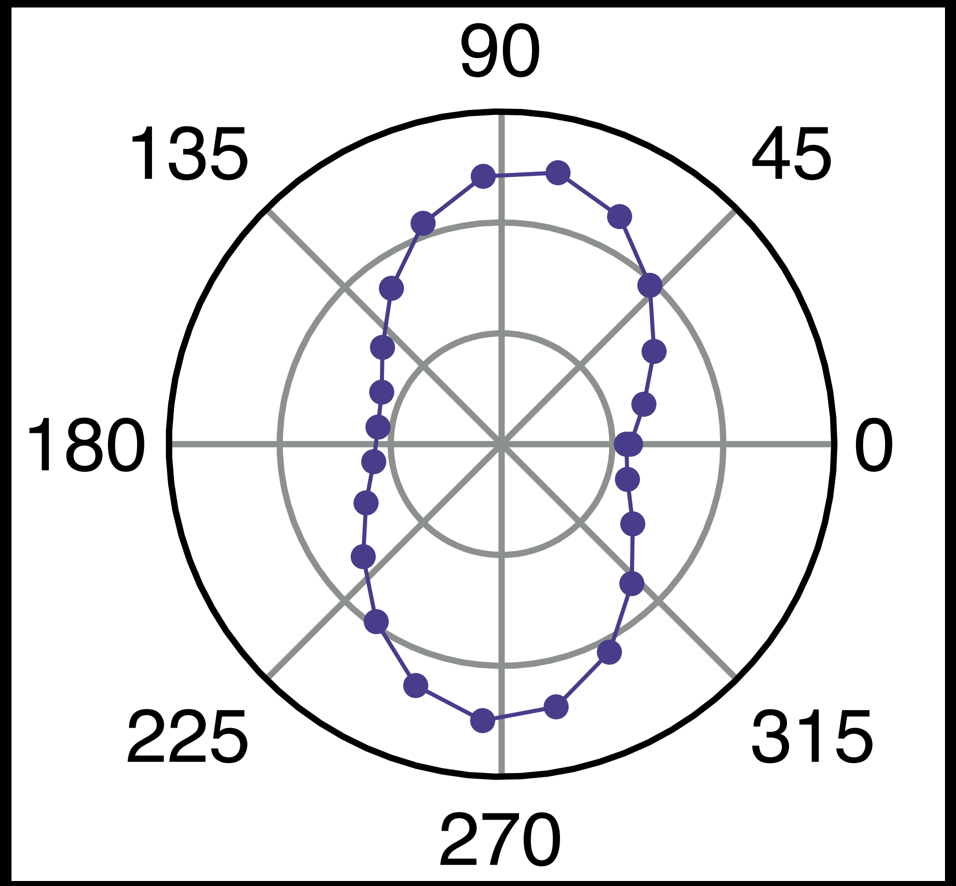
Domains?

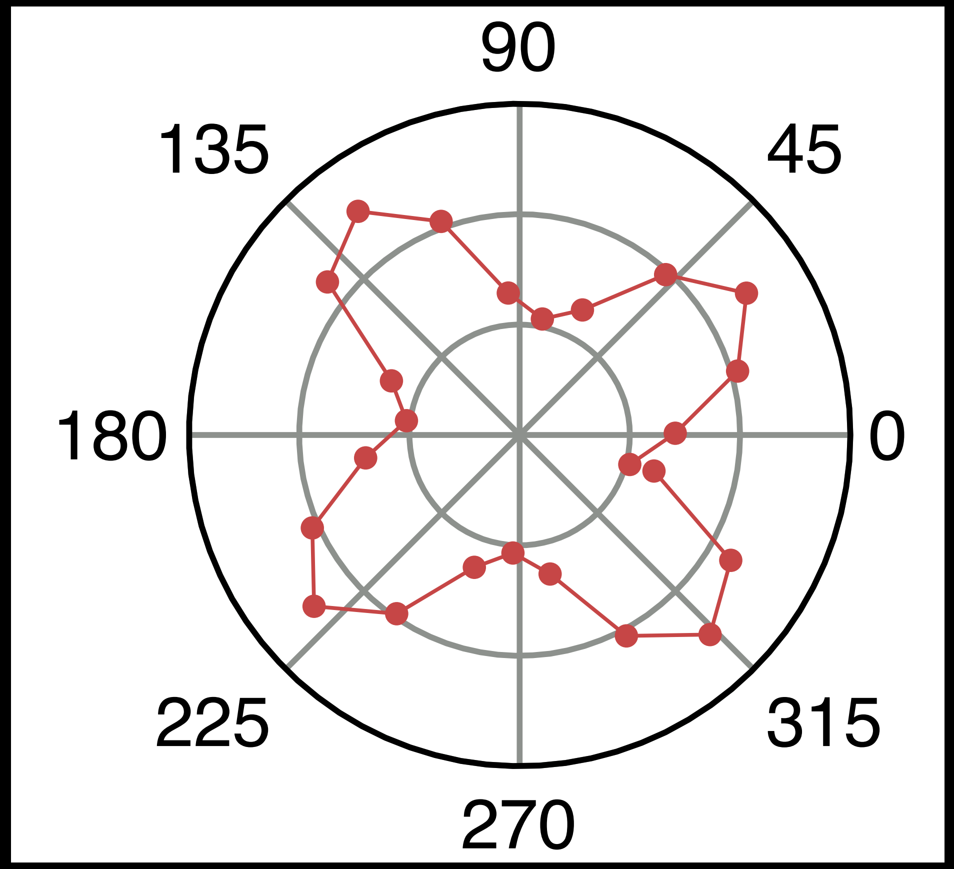
$\hat{e}_i || \hat{e}_s$

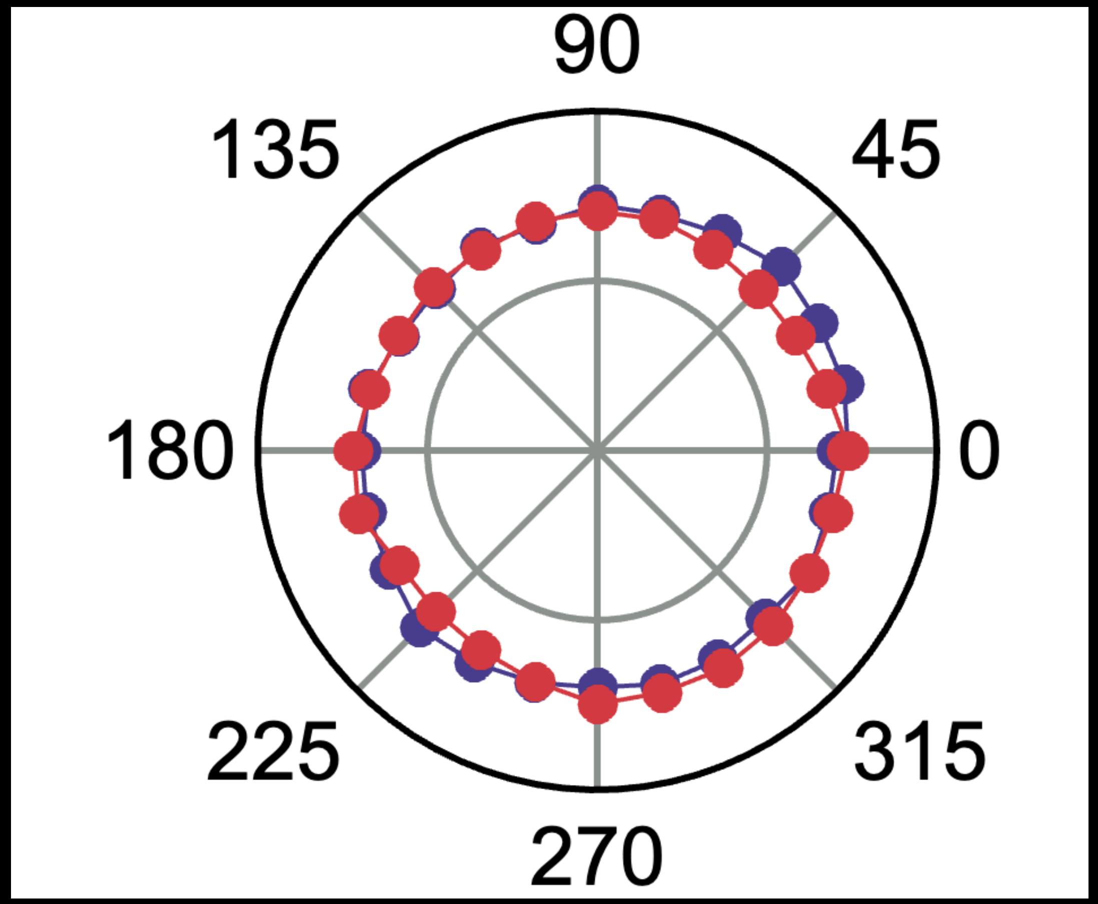
$\hat{e}_i \perp \hat{e}_s$

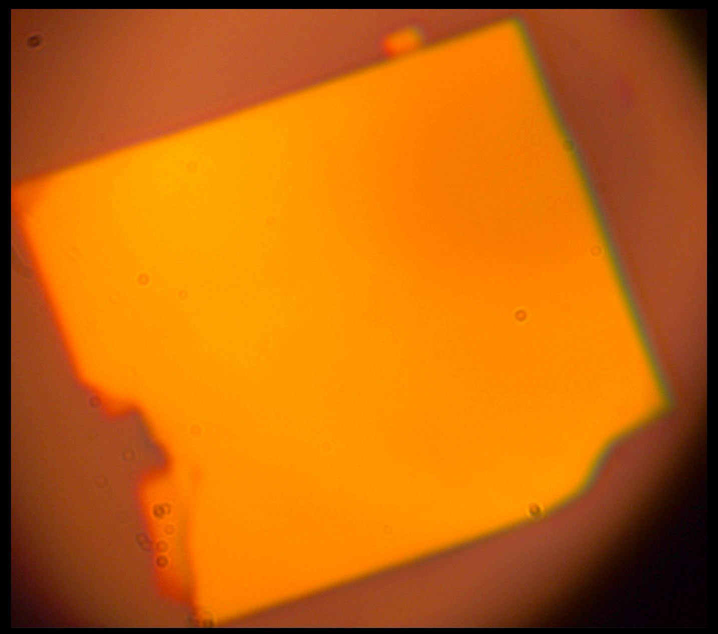
$\sigma^+\sigma^-$ $\sigma^-\sigma^+$

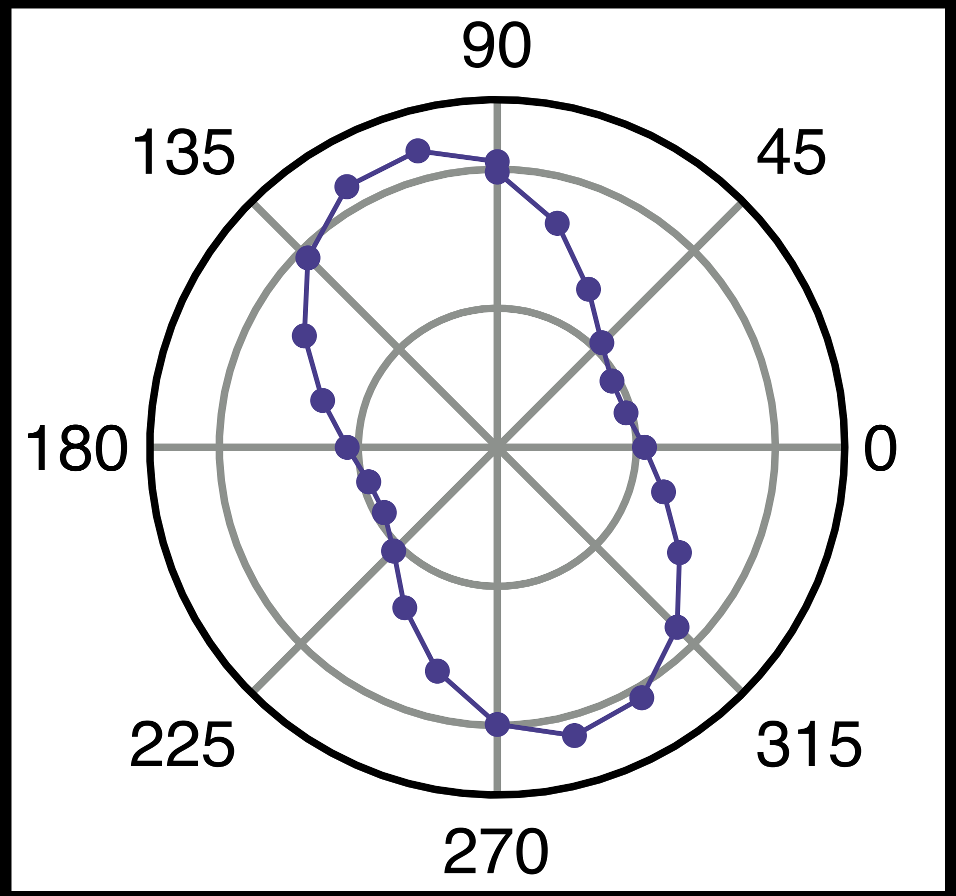


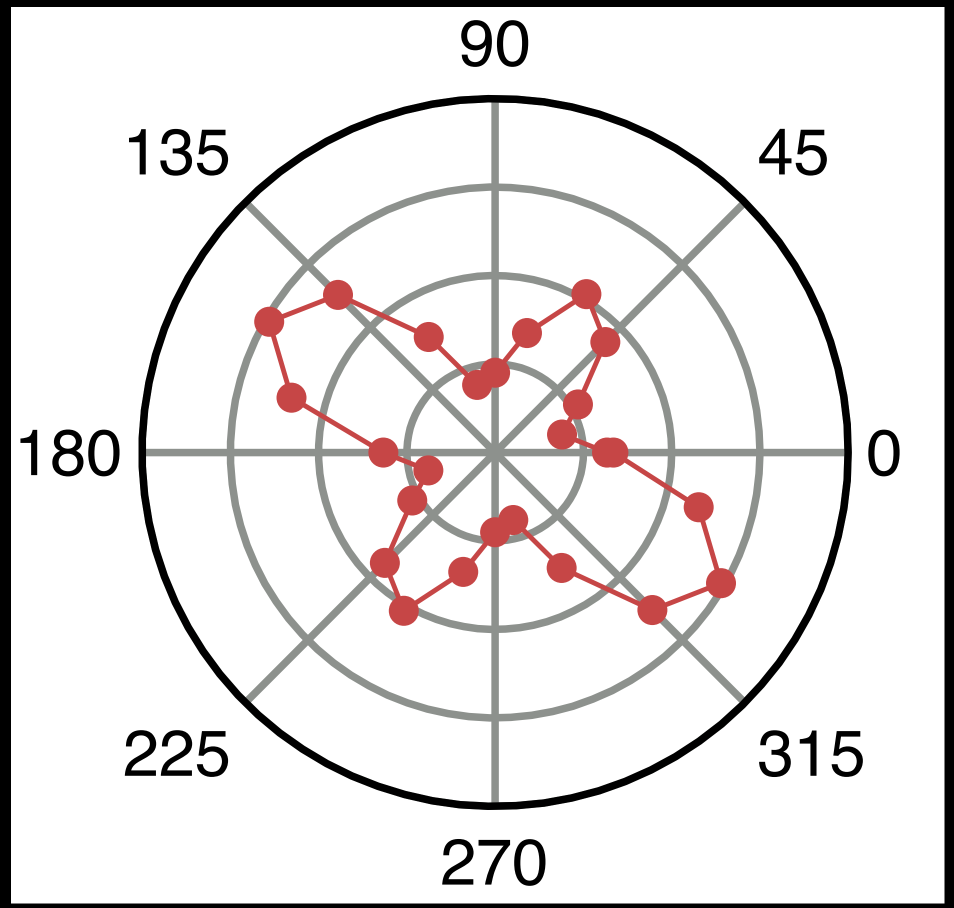


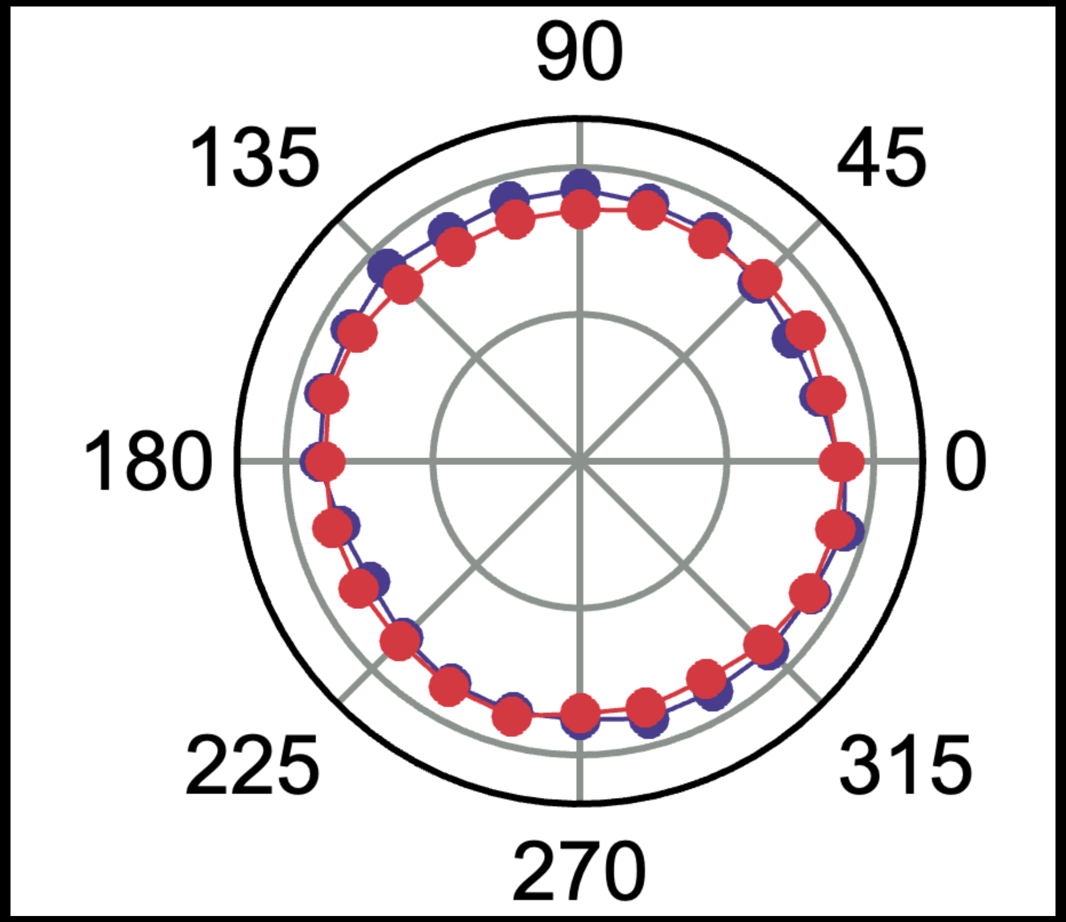




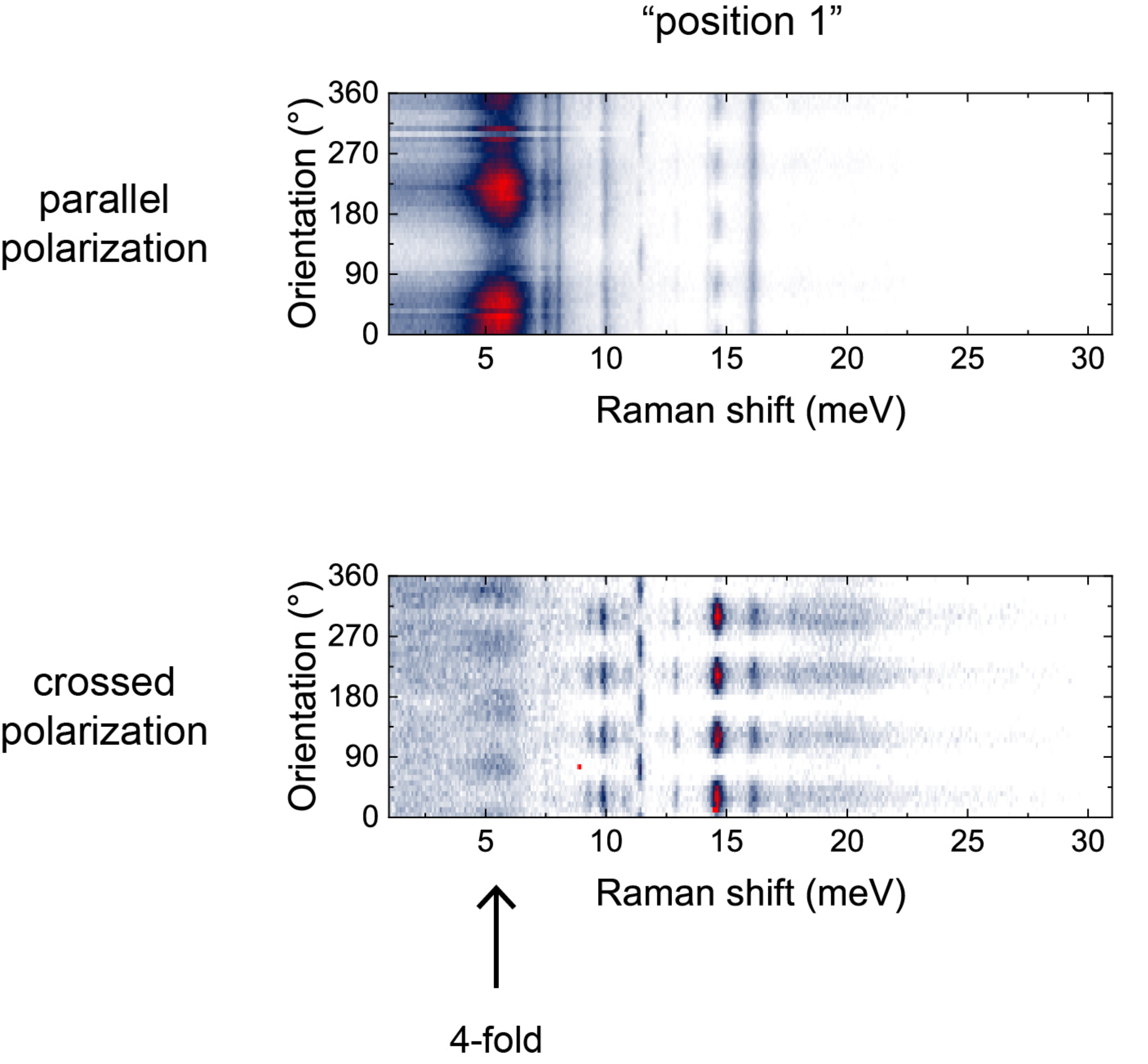








And others…

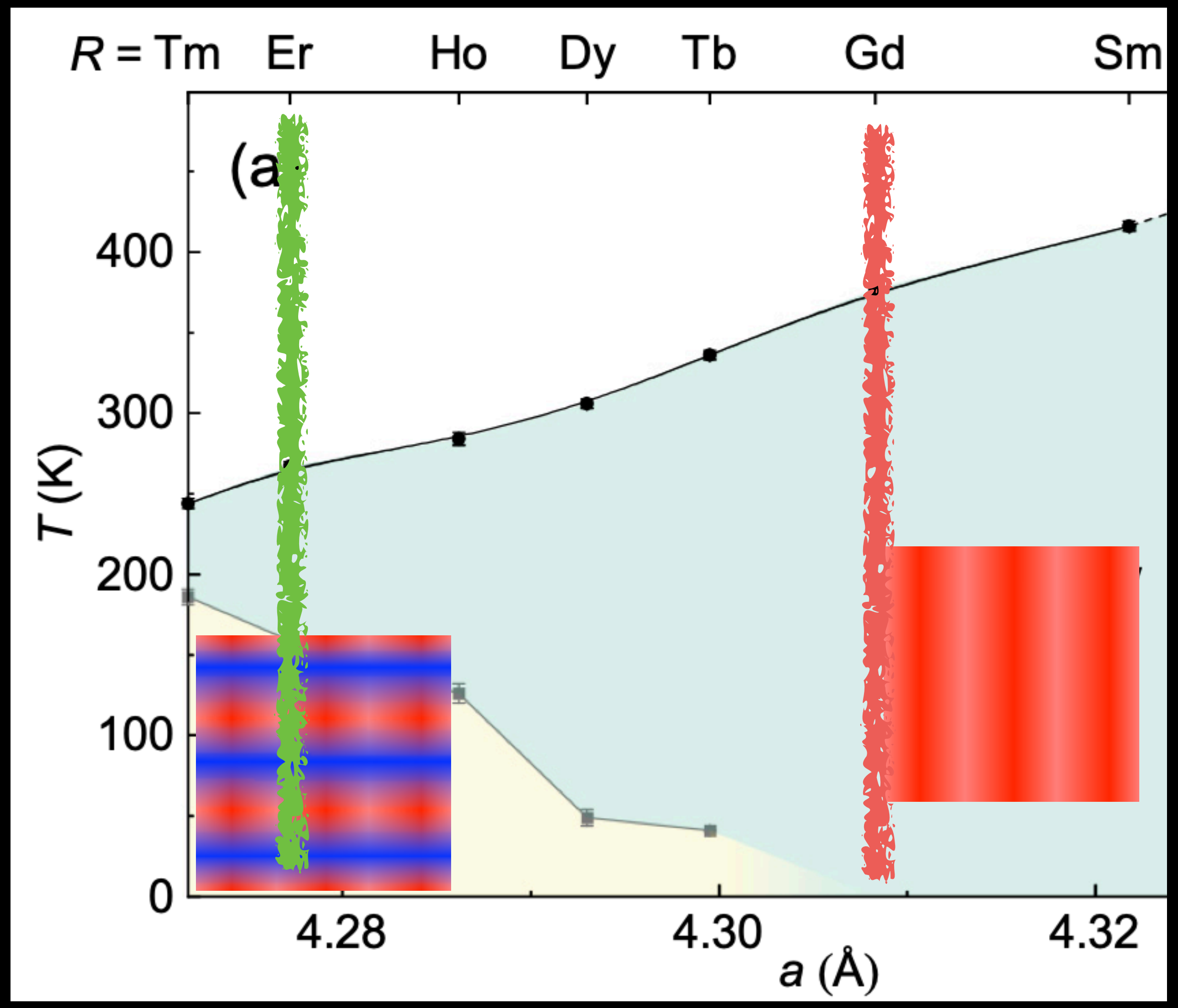


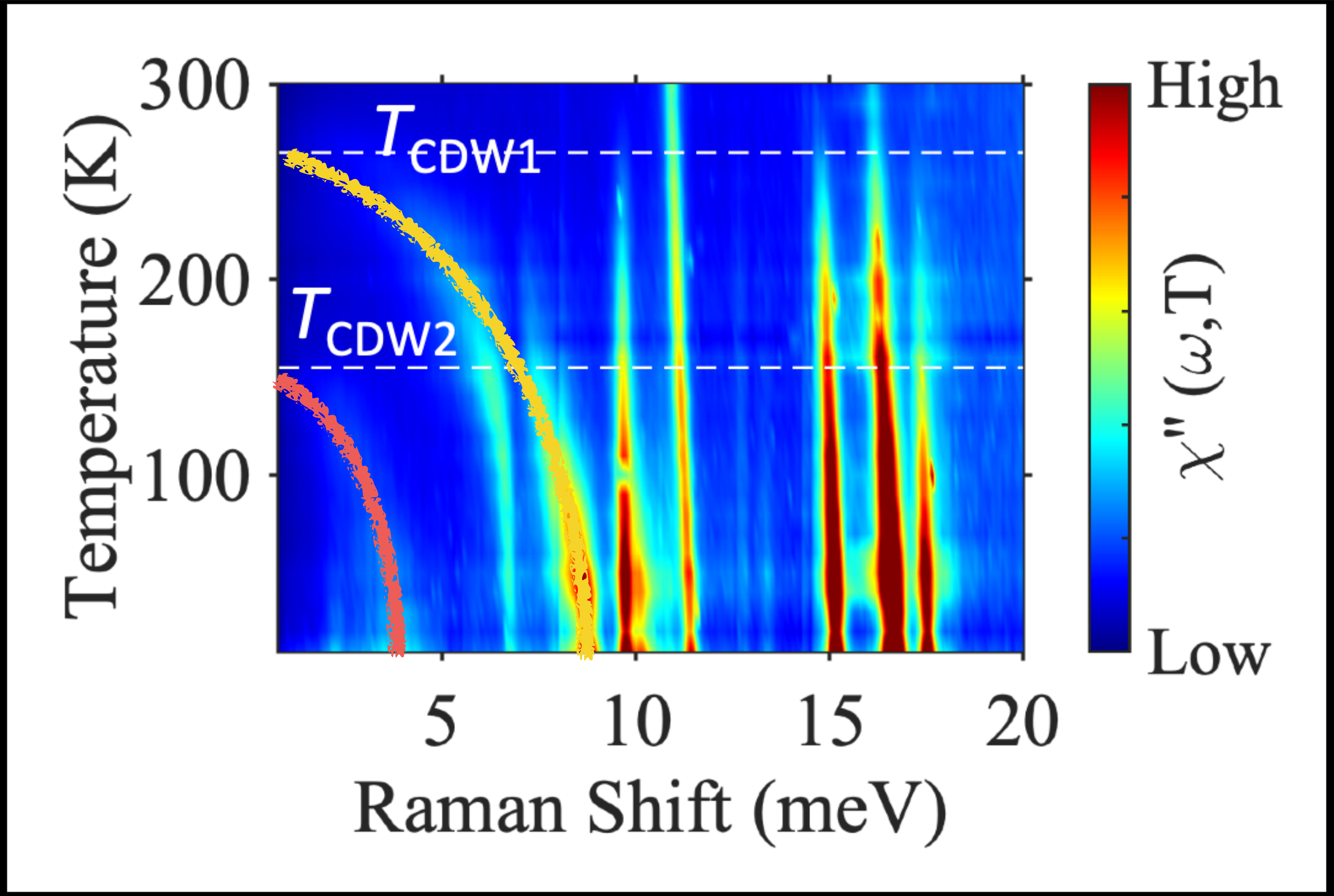
Dirk Wulferding and Changyoung Kim (SNU)

Rotation

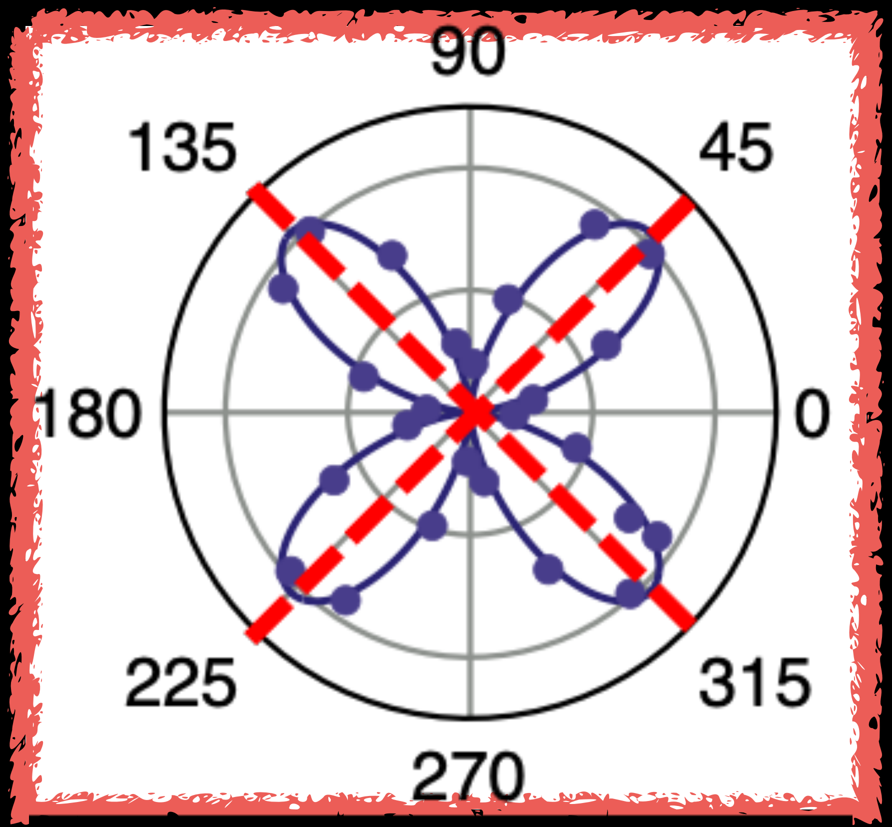
LnTe$_3$

P. Walmsley,
I. Fisher et al,
PRB 102, 045150
(2020)

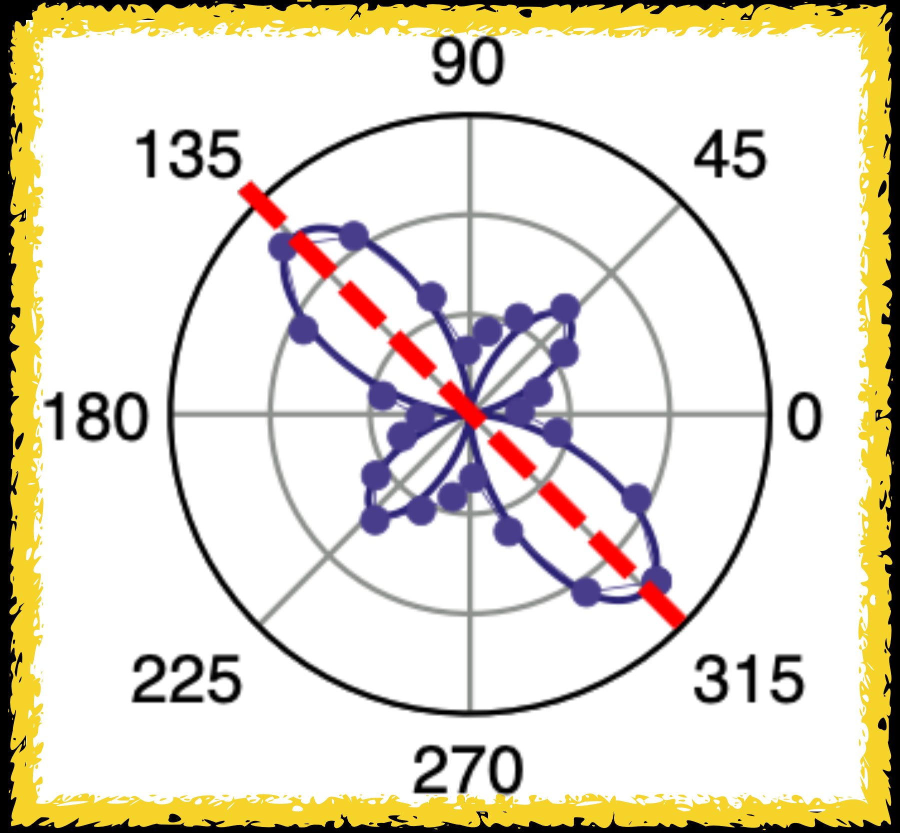




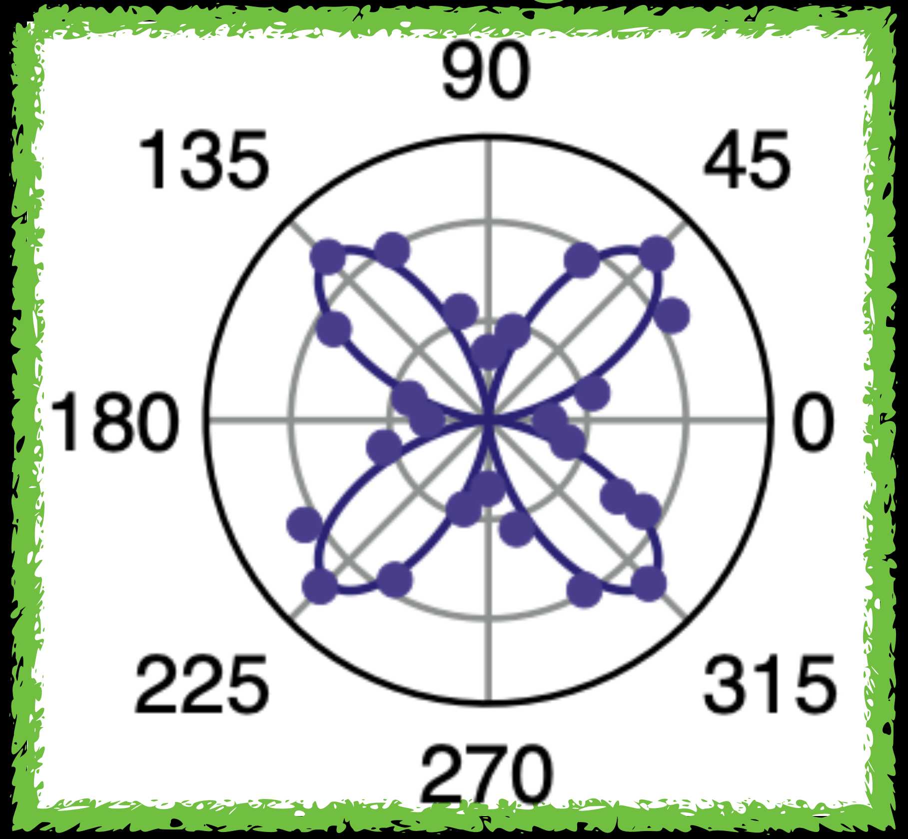
Amplitude 2



Amplitude 1



A_g



Thanks!

LASE Team

Yiping Wang (Columbia)
G. McNamara
B. Singh
V. Plisson
M. Geiwitz
G. Natale
W. Liu
G. Osterhoudt (Thorlabs)
M. Romanelli (UIUC)
M. Hosen (Intel)
N. Kumar (Giner)
M. Gray (Resonant)
R. O’Connor (Tufts)
E. Sheridan (AFRL)

$LnTe_3$
S. Lei (Rice)
L. Schoop (Princeton)

Theory:
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P. Narang (UCLA)
D. Xiao (U.W.)

TEM (Cornell):
J. Hart
J.J. Cha

Raman (UMass):
Y.C. Wu
J. Yan

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ONR Office of Naval Research Science & Technology
NSF
Air Force Office of Scientific Research
Department of Energy
Army Research Office
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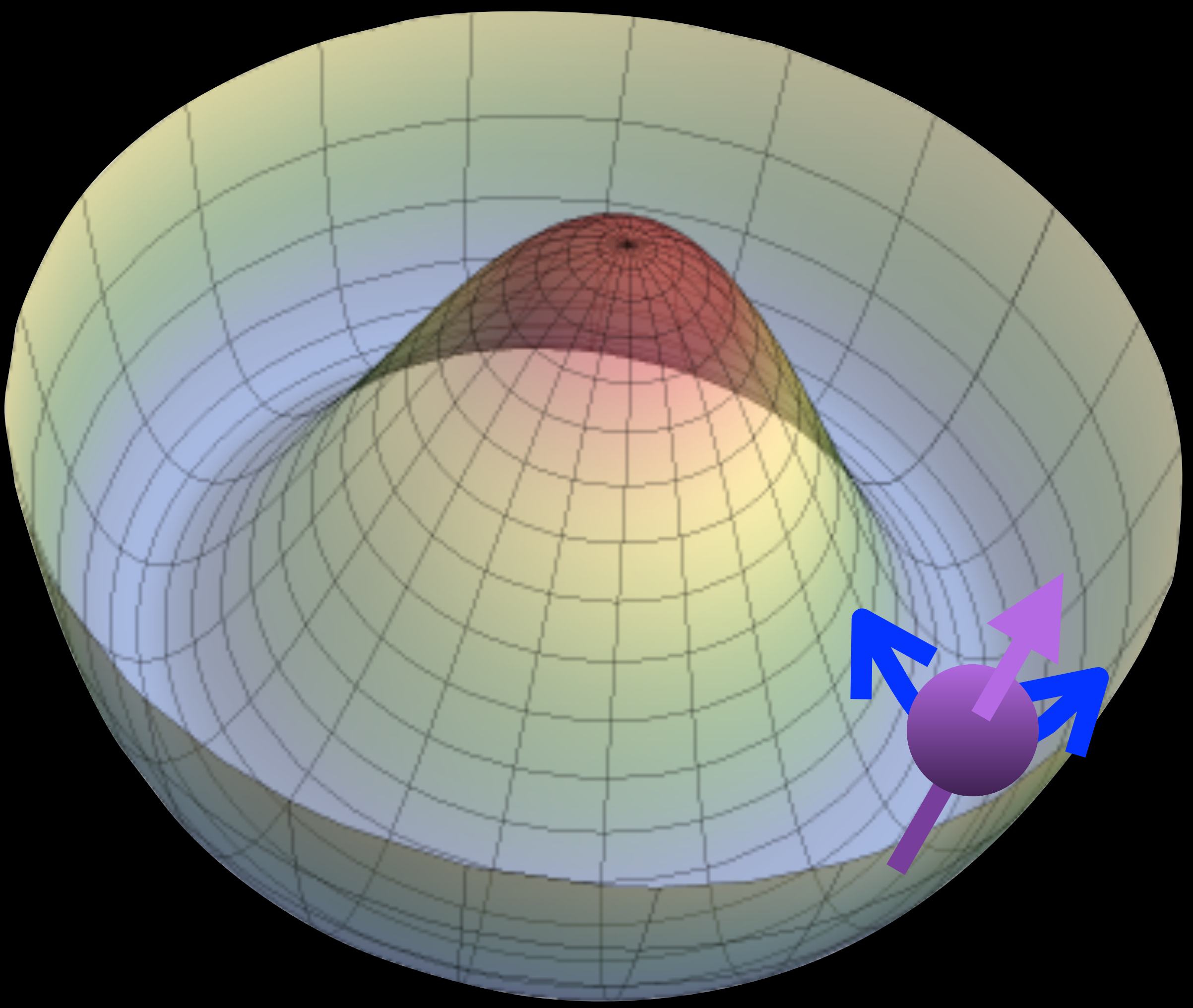
Summary

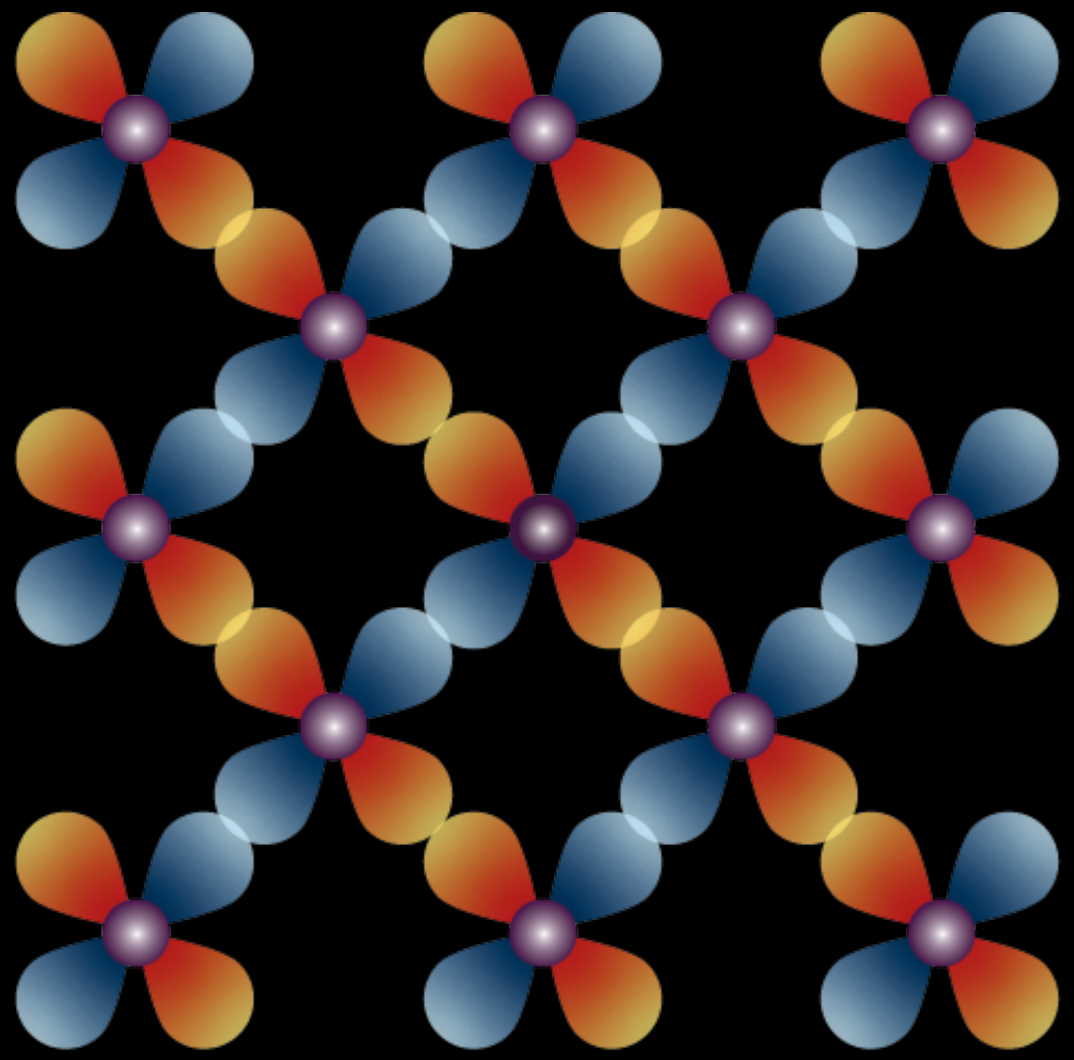
Higgs

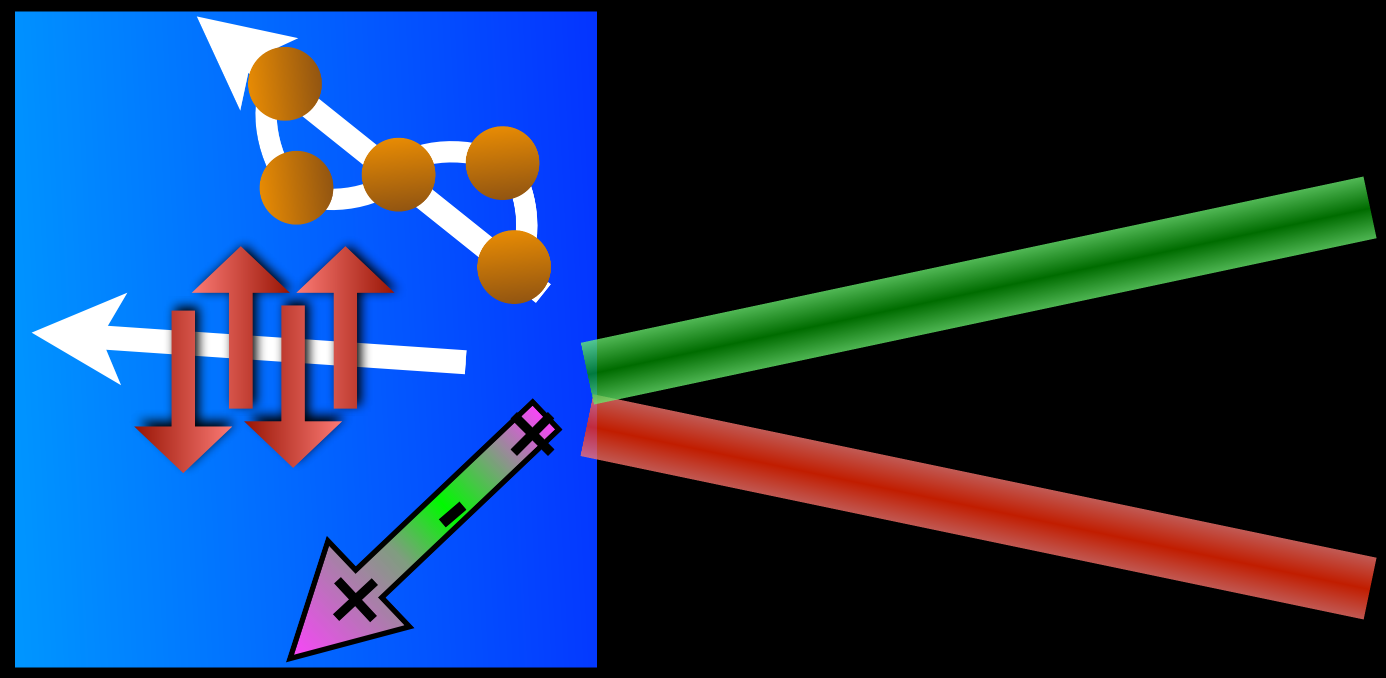
✗

+



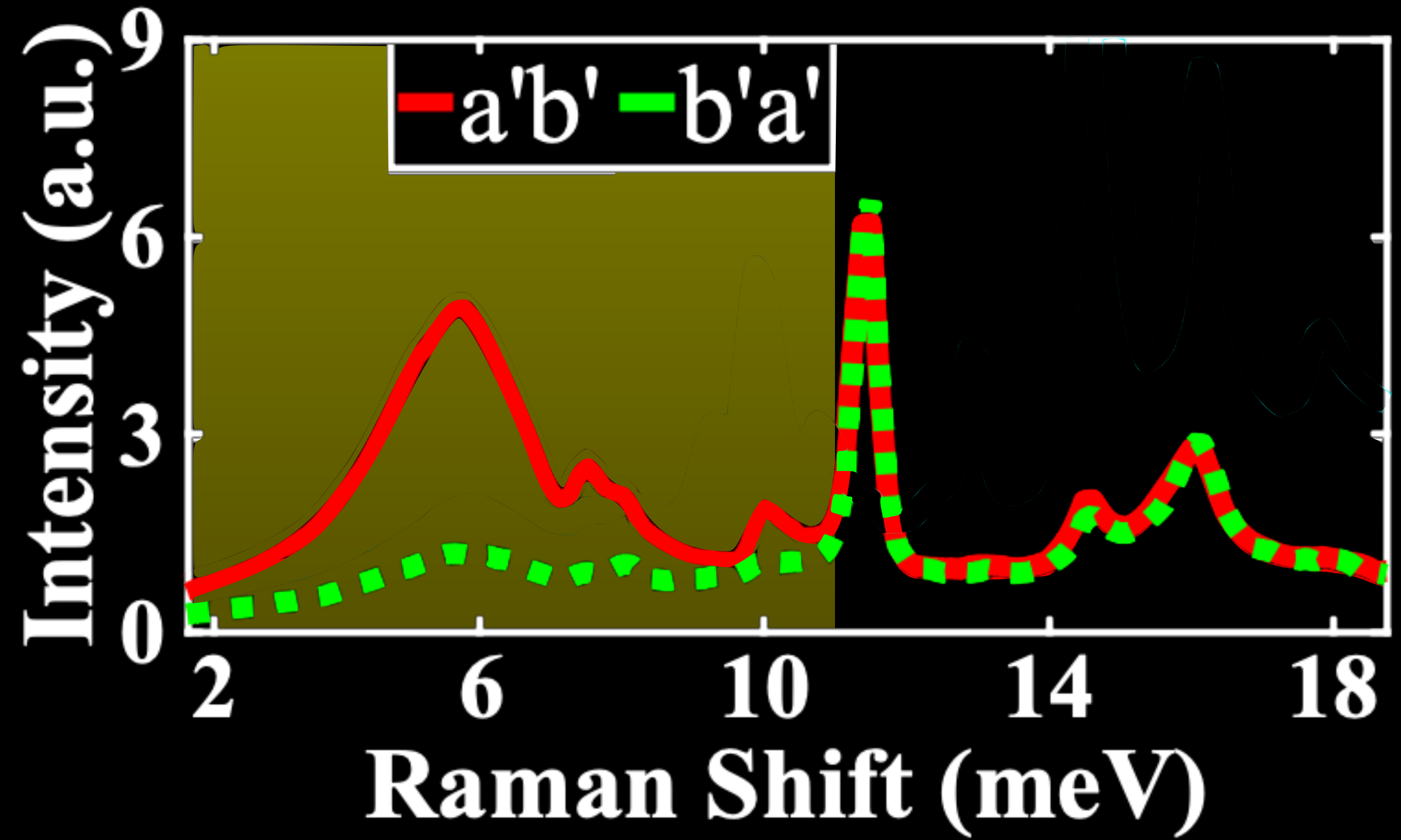
ks.burch@bc.edu
@Burch_Lab

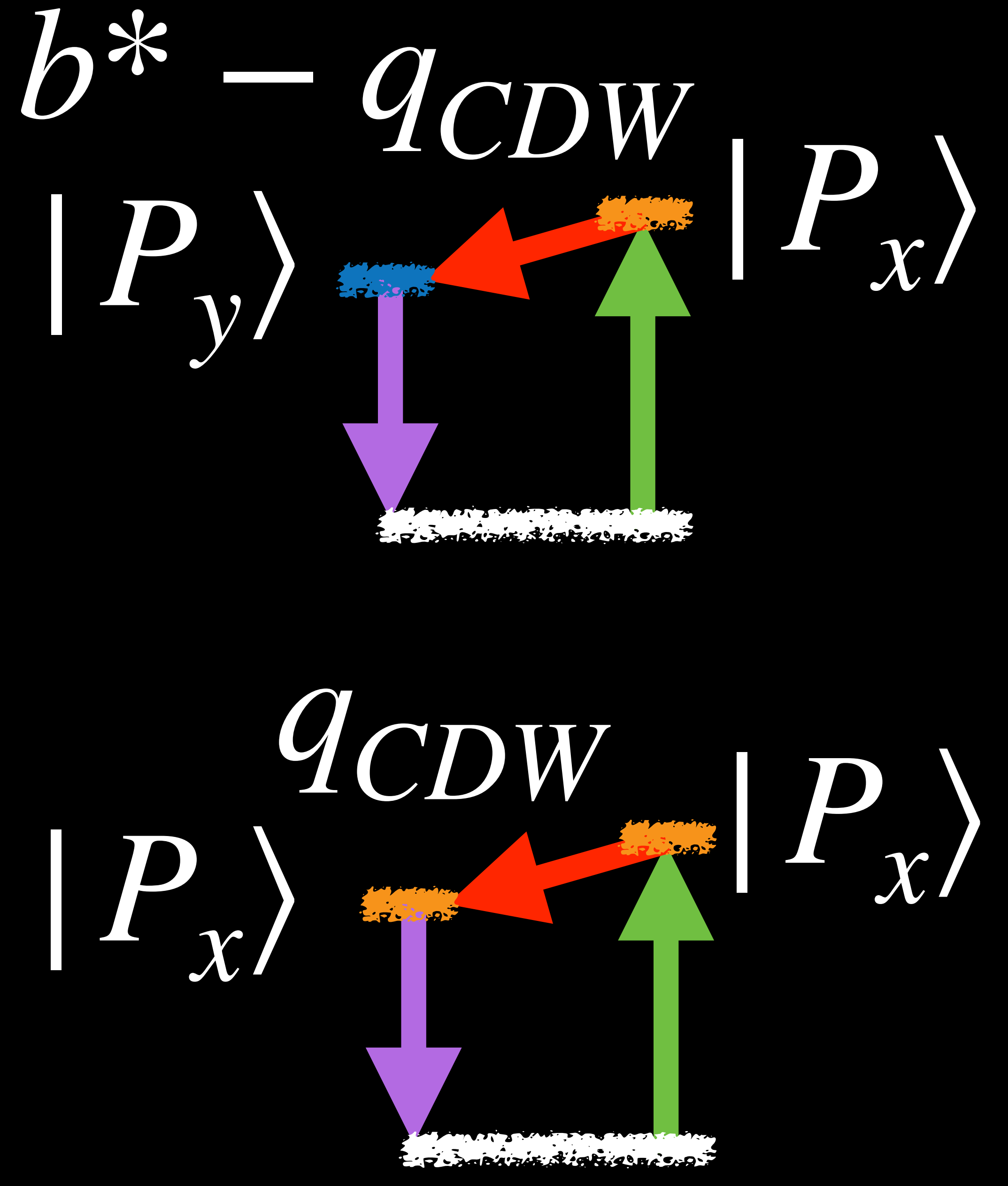




Square Scattering

Interference





Y. Wang, KSB et al, Nature (2022)

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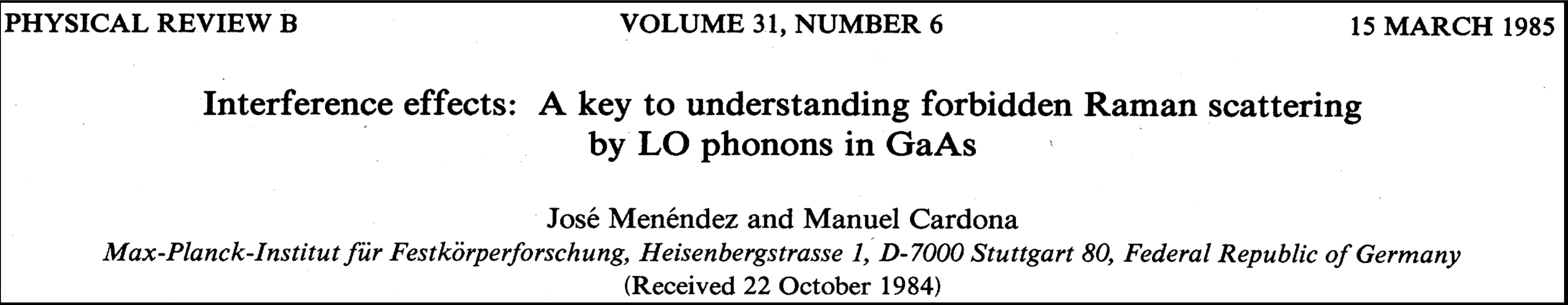
Interference and Axial in Raman



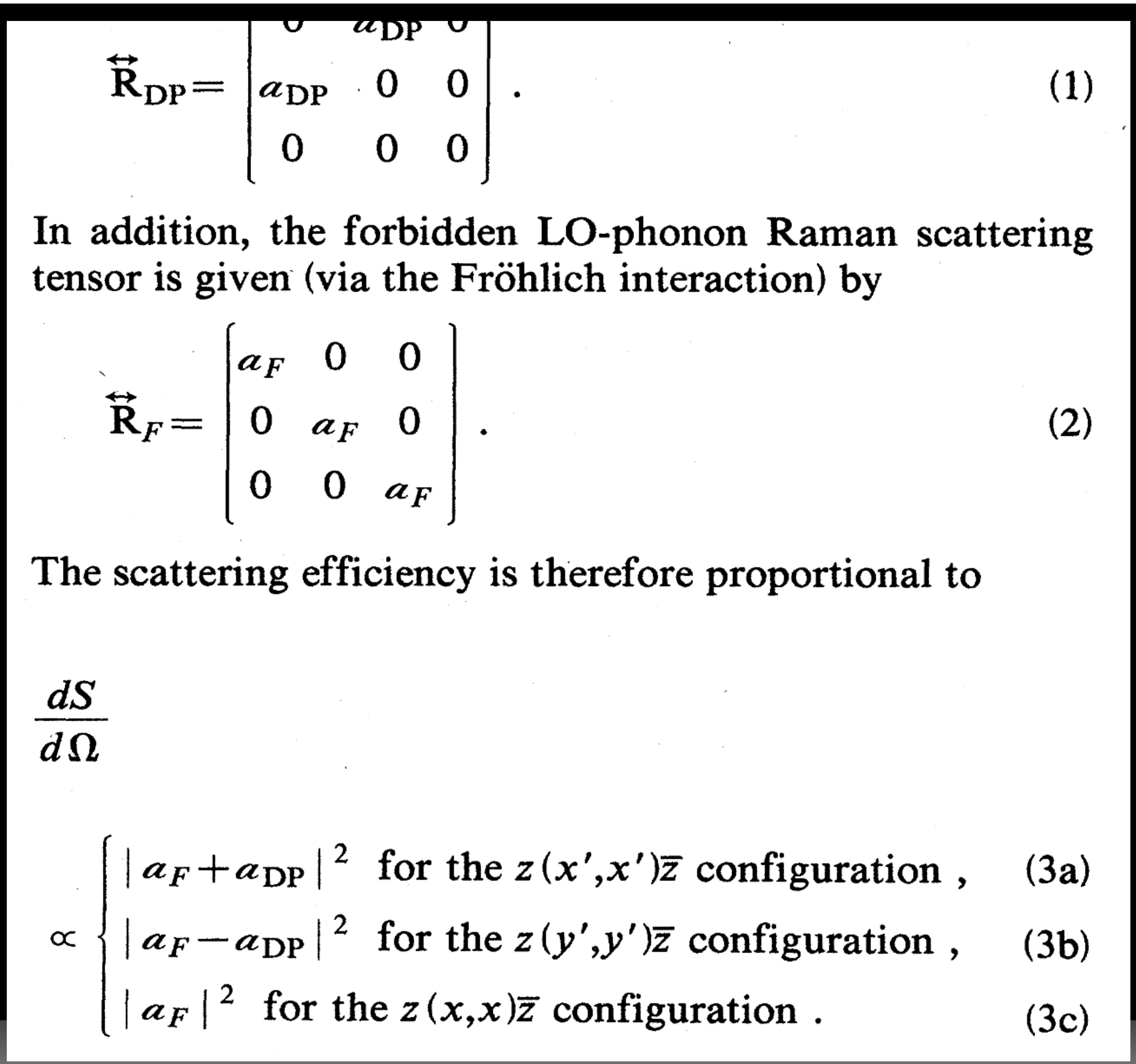
PHYSICAL REVIEW B VOLUME 31, NUMBER 6 15 MARCH 1985

Interference effects: A key to understanding forbidden Raman scattering by LO phonons in GaAs

José Menéndez and Manuel Cardona

Max-Planck-Institut für Festkörperforschung, Heisenbergstrasse 1, D-7000 Stuttgart 80, Federal Republic of Germany

(Received 22 October 1984)



$$\overleftrightarrow{R}_{DP} = \begin{vmatrix} 0 & a_{DP} & 0 \\ a_{DP} & 0 & 0 \\ 0 & 0 & 0 \end{vmatrix} . \tag{1}$$

In addition, the forbidden LO-phonon Raman scattering tensor is given (via the Fröhlich interaction) by

$$\overleftrightarrow{R}_F = \begin{vmatrix} a_F & 0 & 0 \\ 0 & a_F & 0 \\ 0 & 0 & a_F \end{vmatrix} . \tag{2}$$

The scattering efficiency is therefore proportional to

$$\frac{dS}{d\Omega}$$

$$\propto \begin{cases} |a_F + a_{DP}|^2 & \text{for the } z(x',x')\bar{z} \text{ configuration ,} & (3a) \\ |a_F - a_{DP}|^2 & \text{for the } z(y',y')\bar{z} \text{ configuration ,} & (3b) \\ |a_F|^2 & \text{for the } z(x,x)\bar{z} \text{ configuration .} & (3c) \end{cases}$$

MOLECULAR STRUCTURE

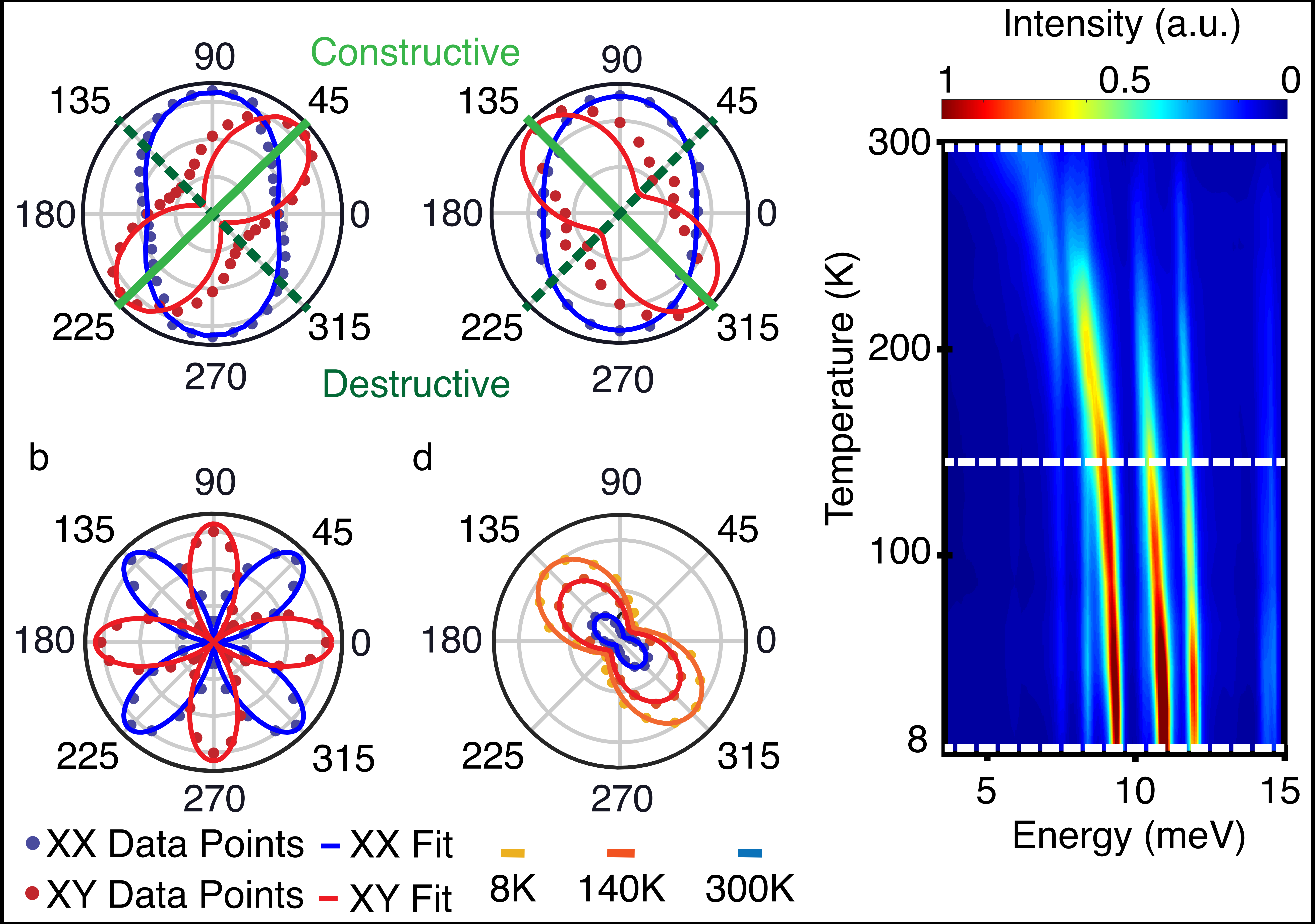
Experimental Observation of an Antisymmetric Raman Scattering Tensor

Trivalent Lanthanides

Electronic Raman

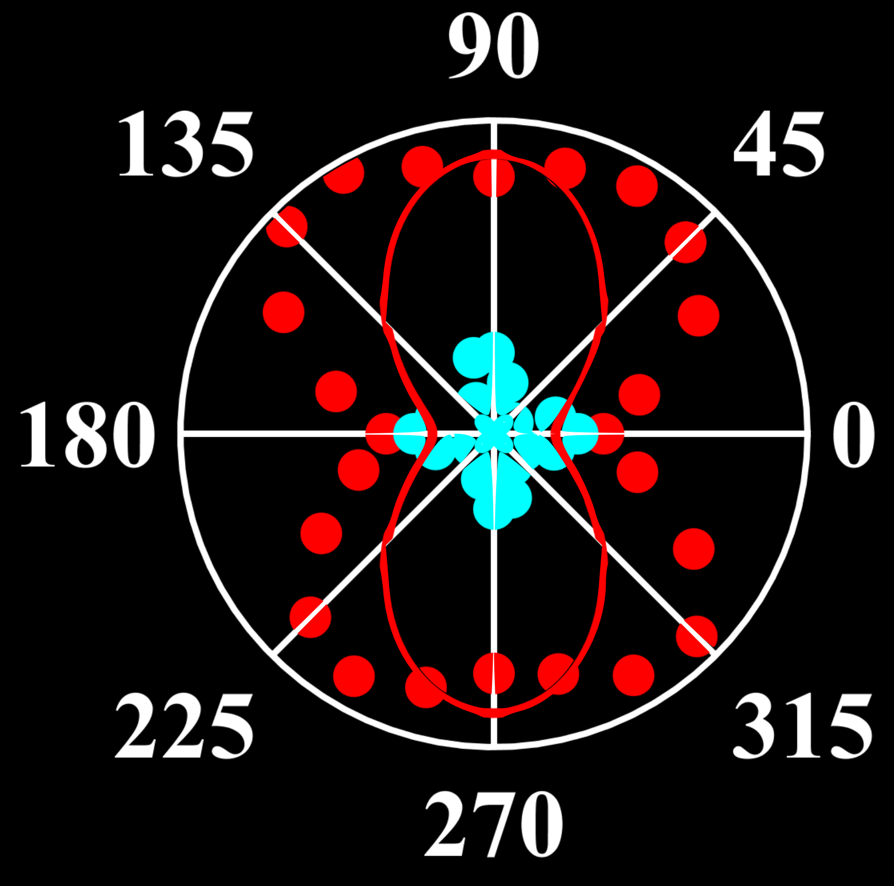
J.A. Koningstein et al, Nature (1968); J. Chem. Phys. 48, 3971 (1968)

Temperature

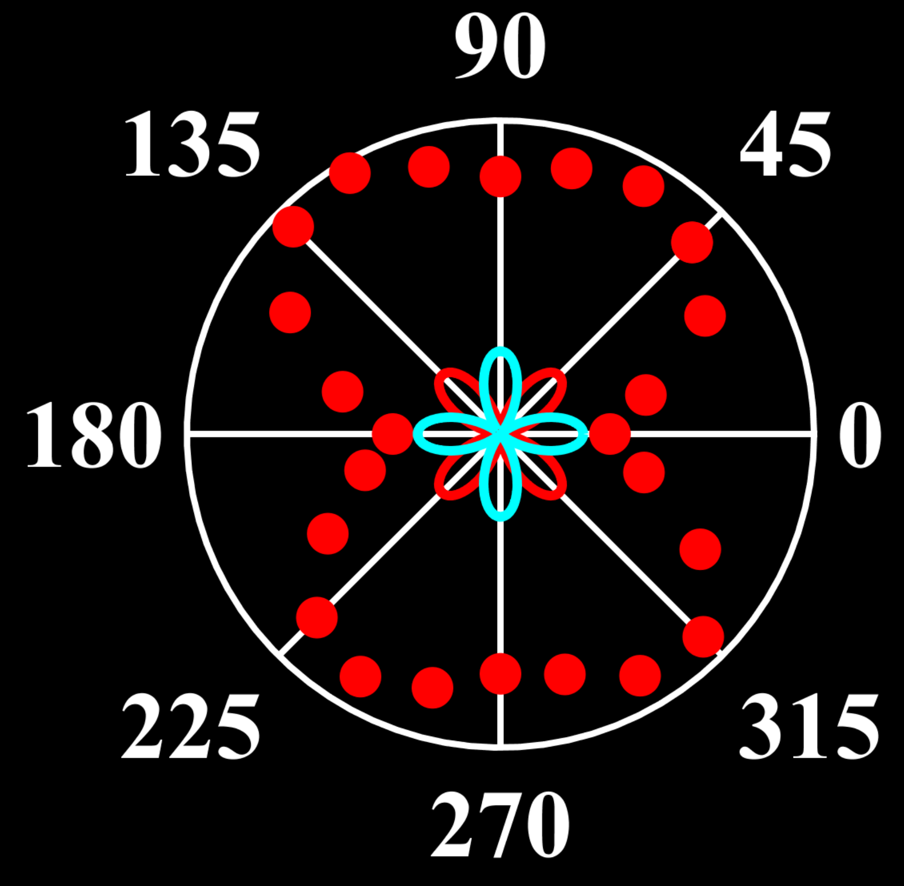


Interference vs Degeneracy

I_{Ag}



I_{Bg}

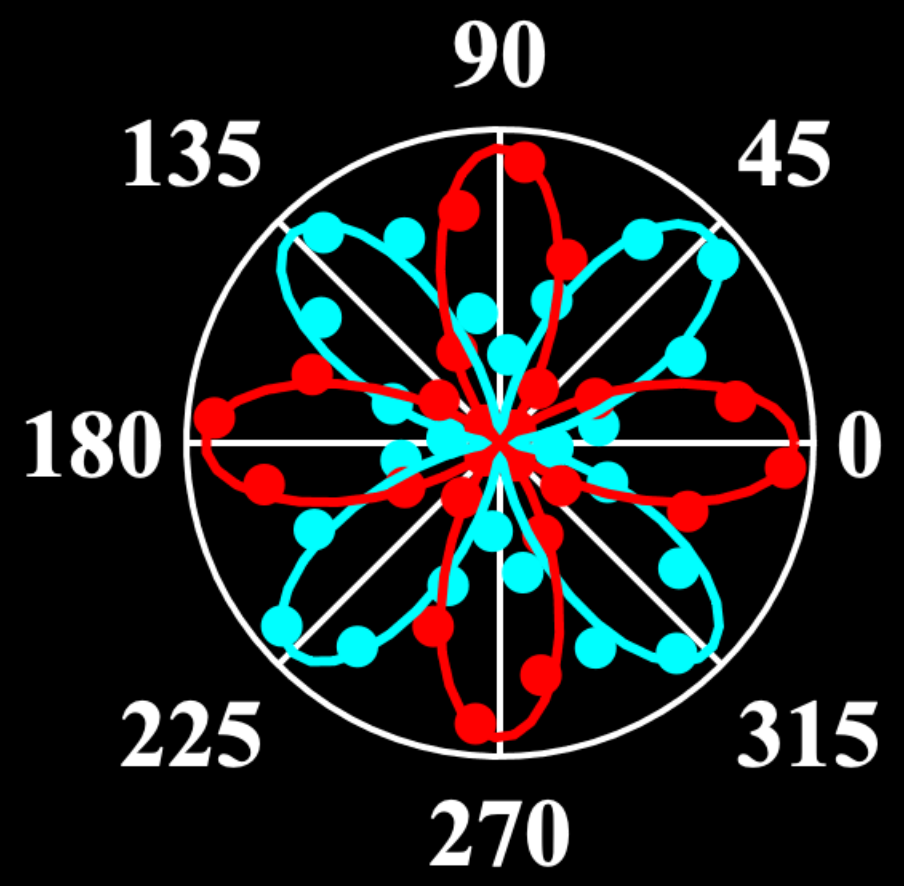


Phonons

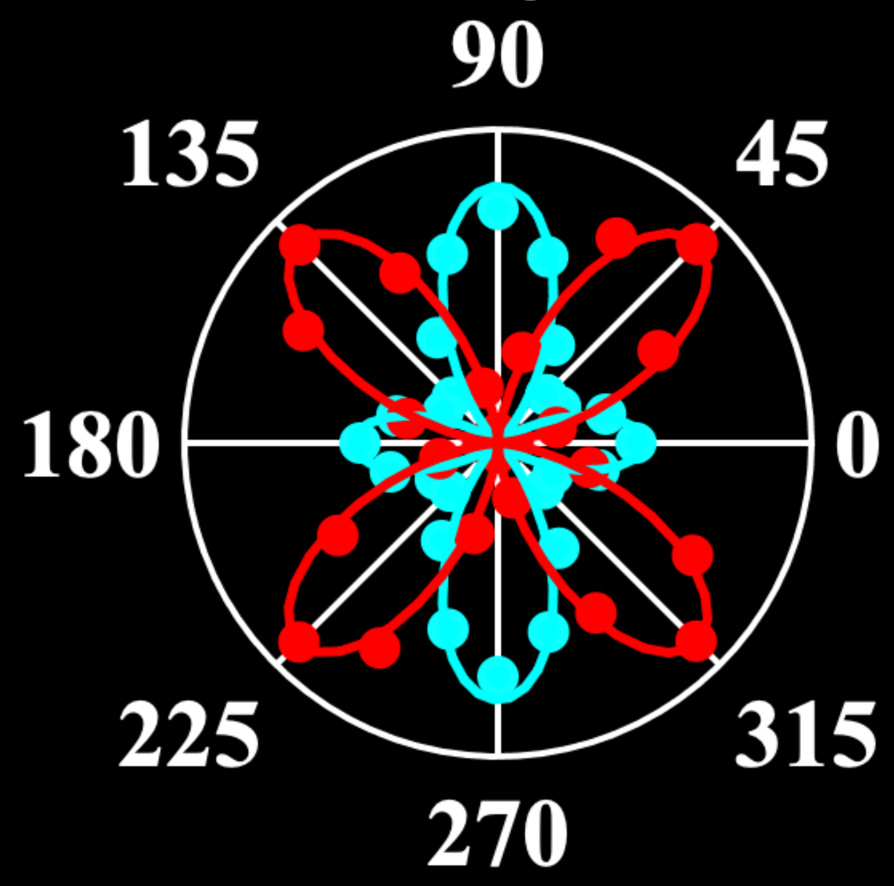
$\hat{e}_i || \hat{e}_s$

$\hat{e}_i \perp \hat{e}_s$

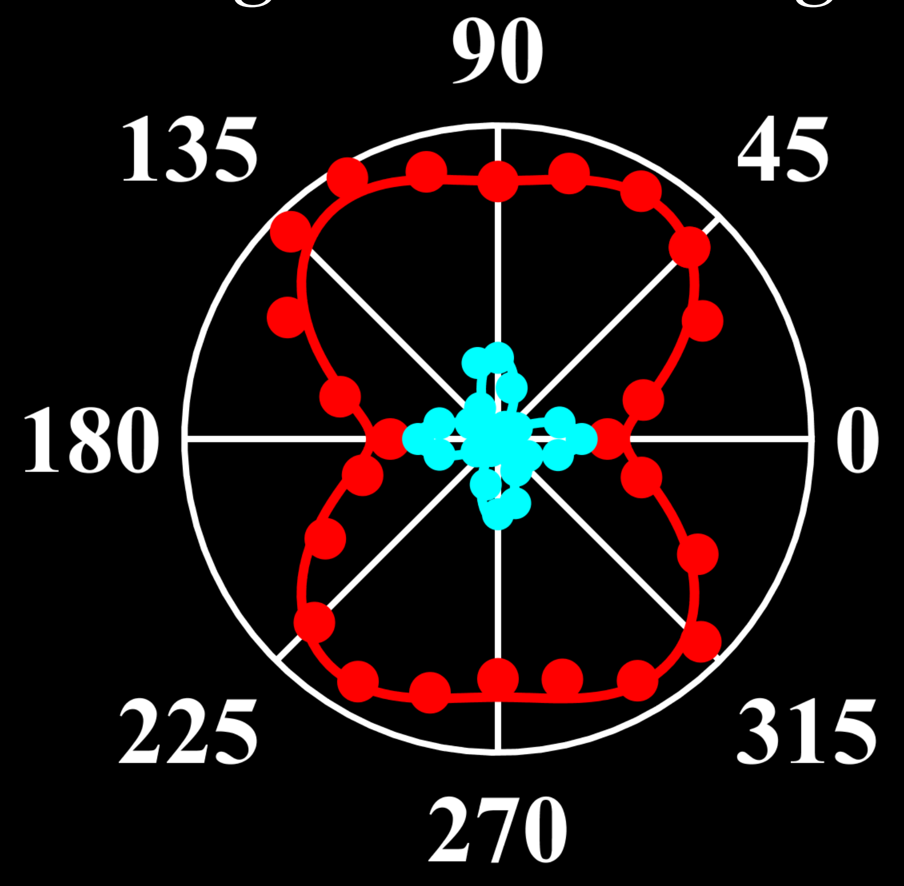
Ag



Bg



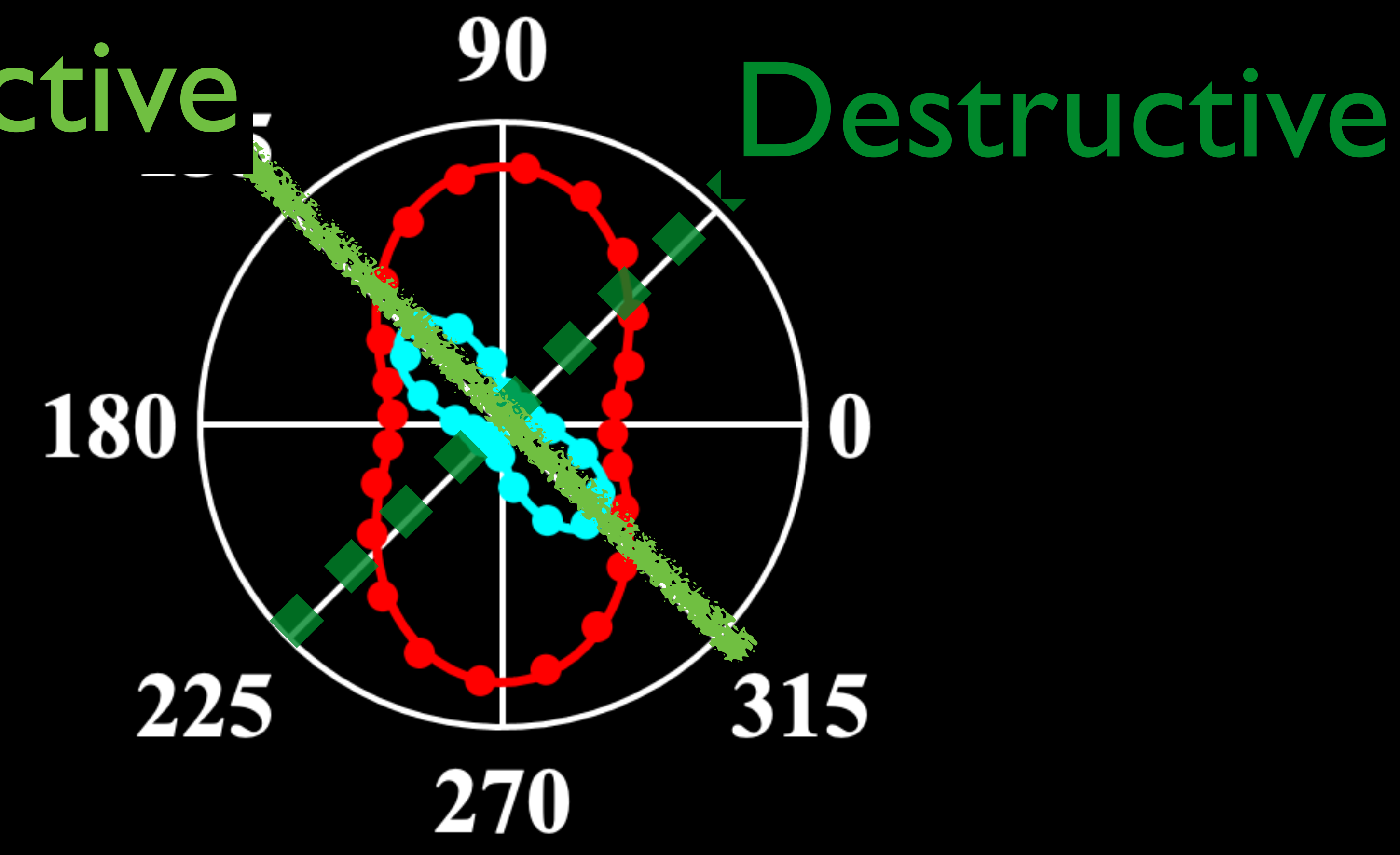
$$I = |R_{Ag}|^2 + |R_{Bg}|^2$$



Amplitude Mode

Constructive

$$I = |R_{Ag} + R_{aS}|^2$$



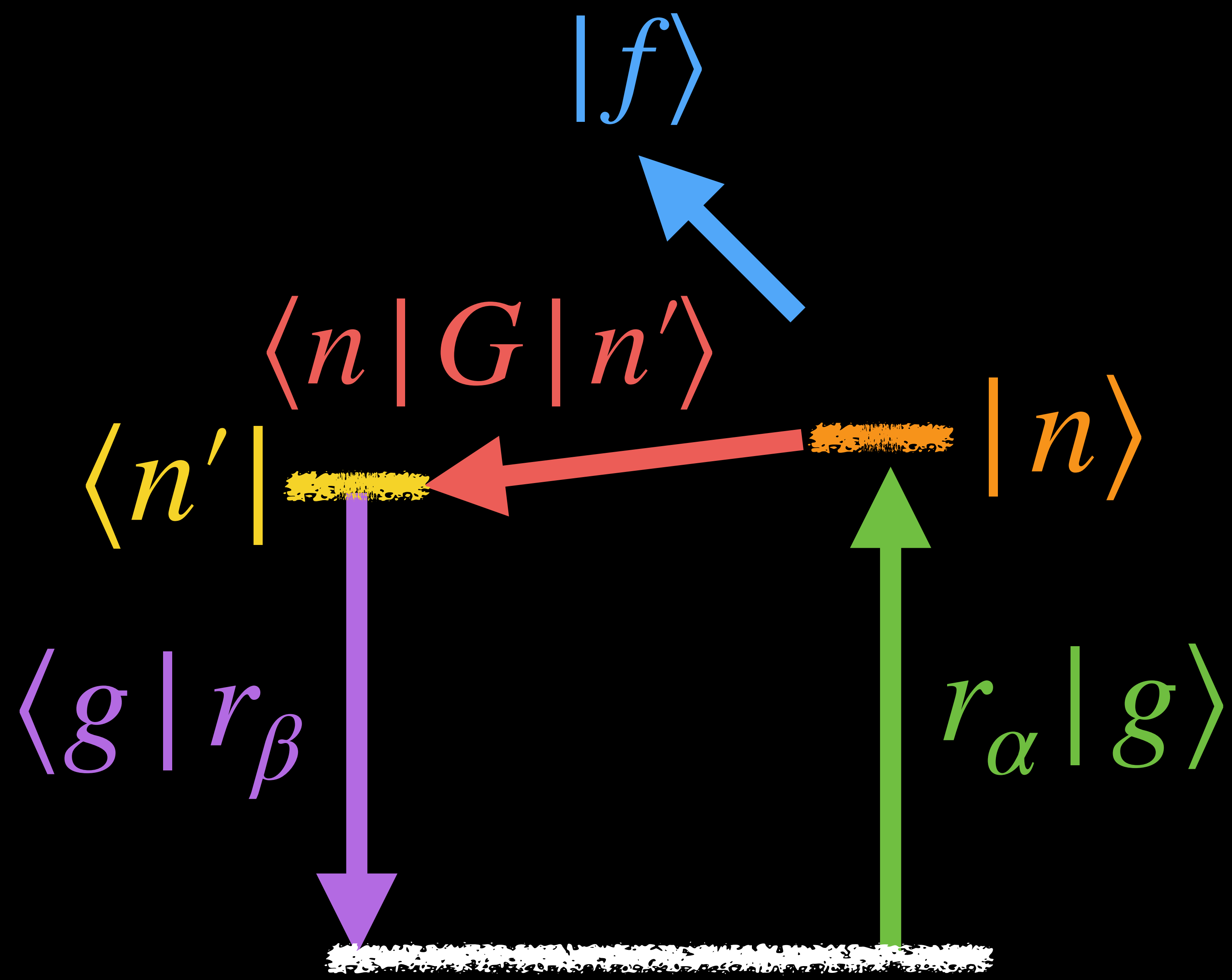
Y. Wang, L. Schoop,
KSB et al (Nature - 2022)

Interference in Raman

$$\overrightarrow{P} = \alpha\overrightarrow{E} = (\alpha_0 + \frac{d\alpha}{d\hat{O}}\delta\hat{O})\overrightarrow{E}$$

$$I_{ij}(\omega) = |\hat{\epsilon}_i \cdot R_{ij} \cdot \hat{\epsilon}_j|^2$$

$$R_{\alpha\beta} = \sum_{n,n'=1}^{2} \langle f|\langle g|er_\alpha|n\rangle\langle n|G|n'\rangle\langle n'|er_\beta|g\rangle|i\rangle$$



→2 states uncoupled double slits in electronic space

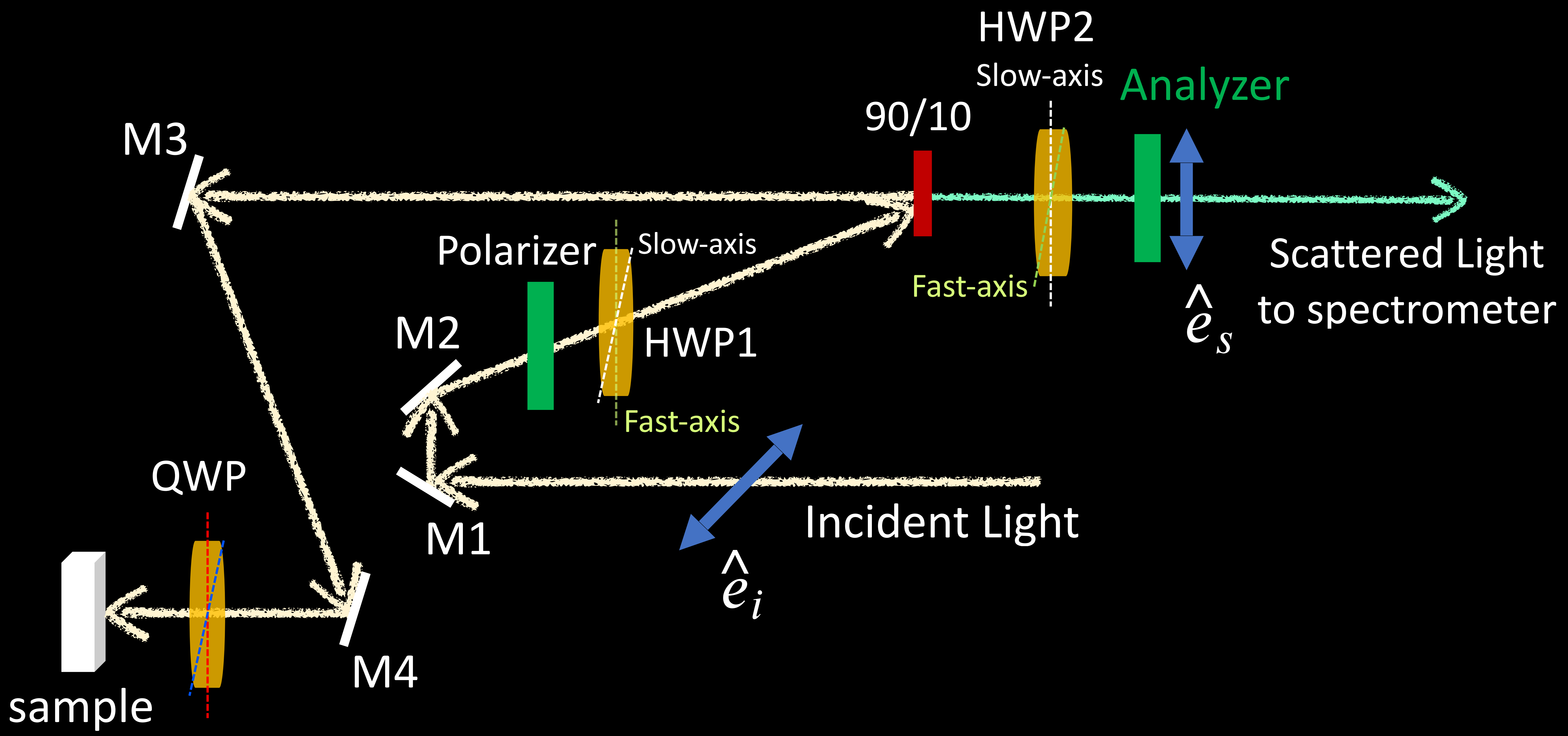
$$G_{nn'} = \delta_{nn'}G_n$$

no coupling between states: $R_{\alpha\beta} = R_{\beta\alpha}$

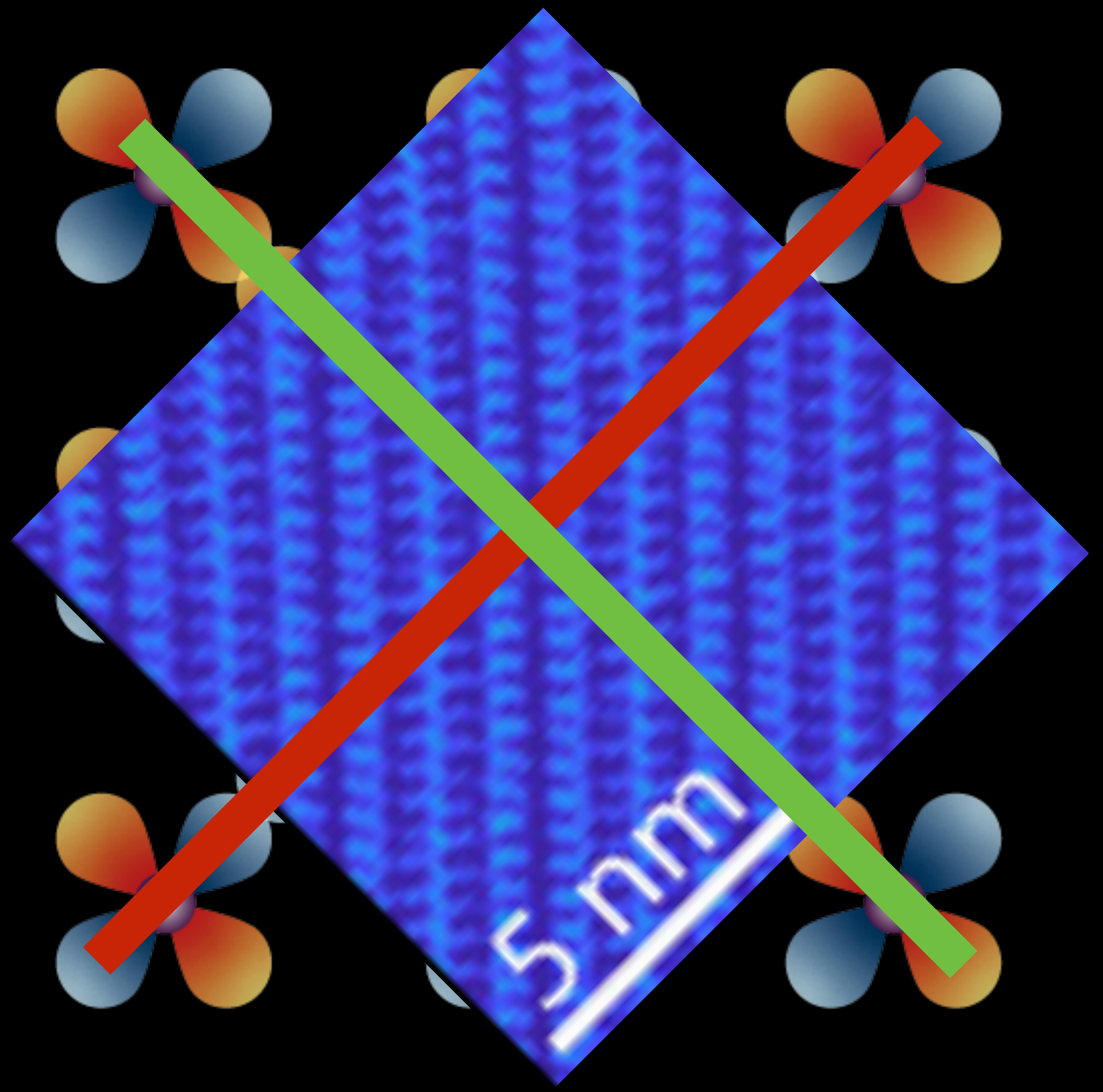
IE reverse process looks same
Can tell which path (commute?)
No interference

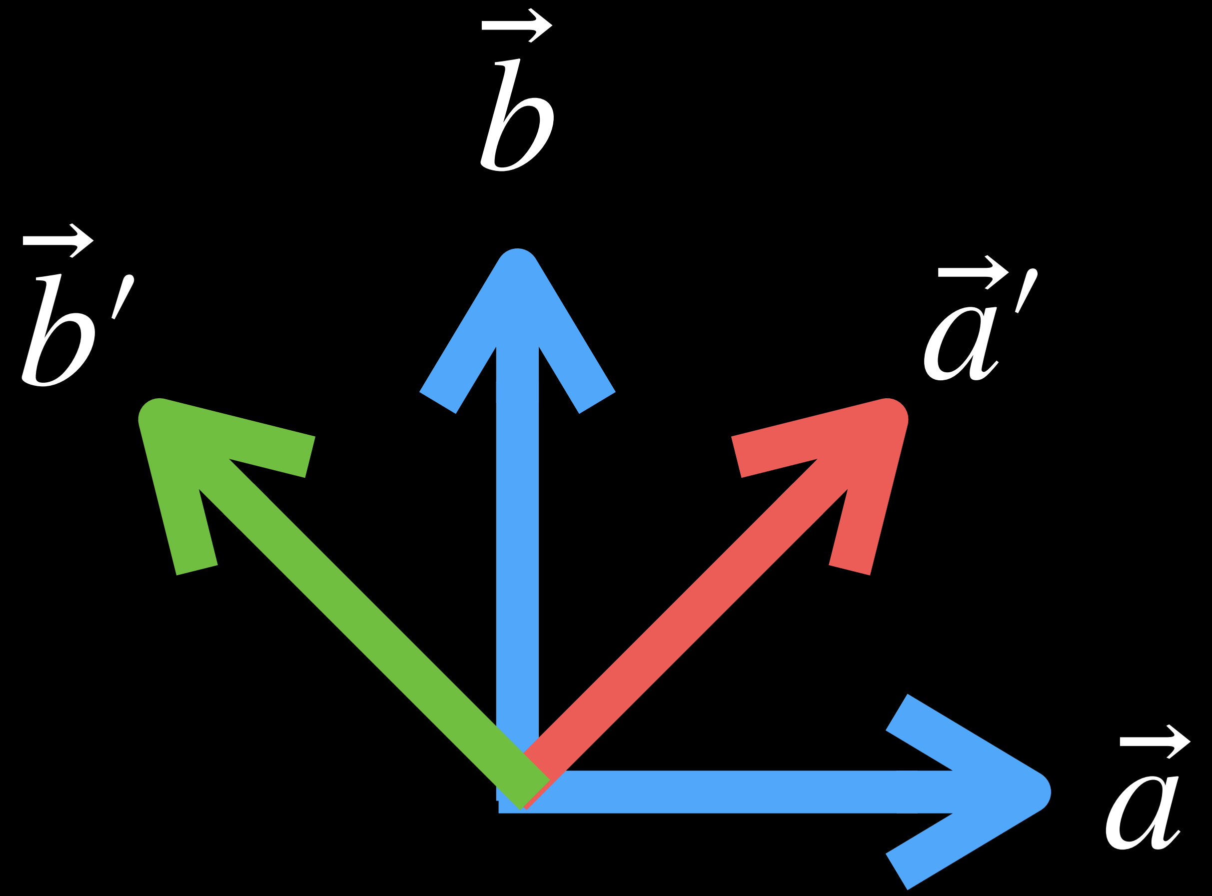
R.A. Harris et al, J. Chem Phys. 96, 15 1992

Improved Setup



Mirrors

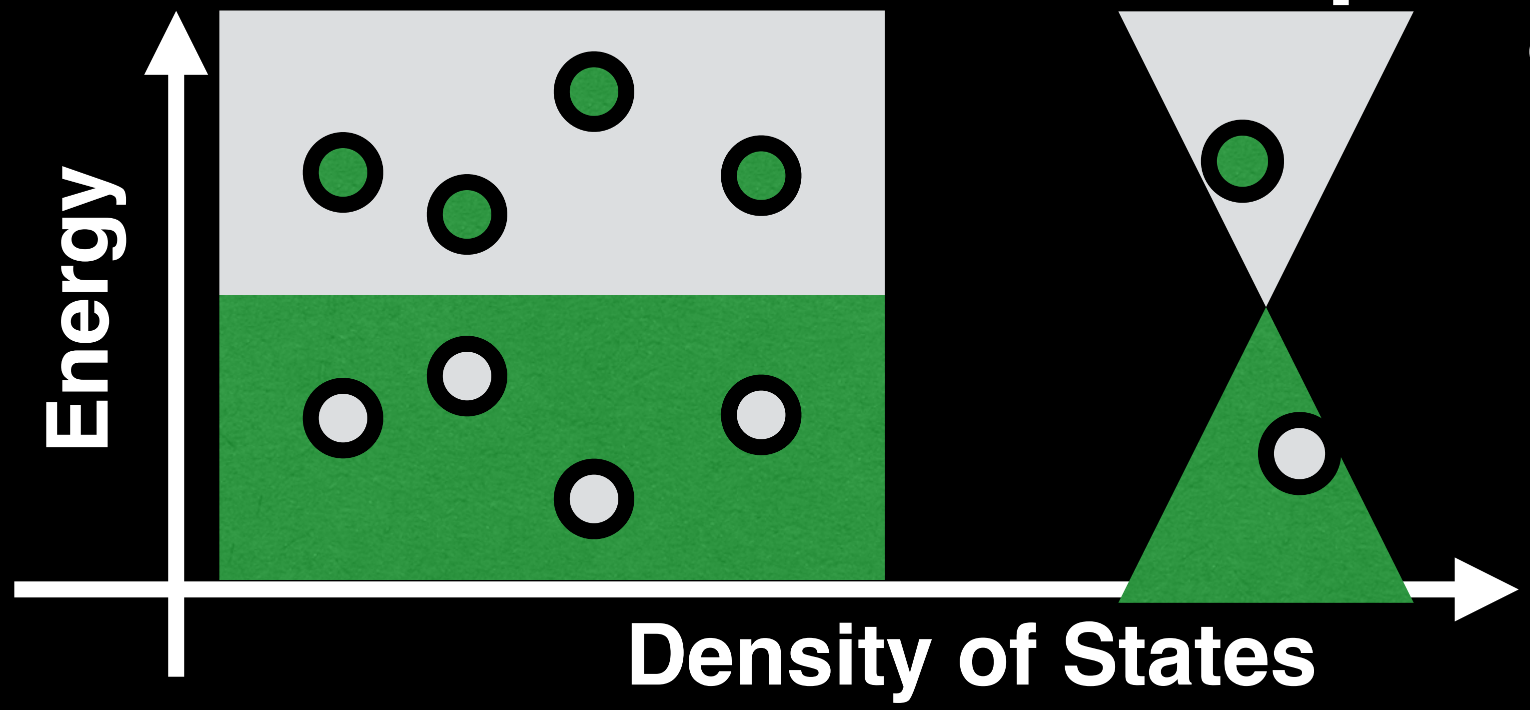




$$R_{ab} = -R_{ba}$$

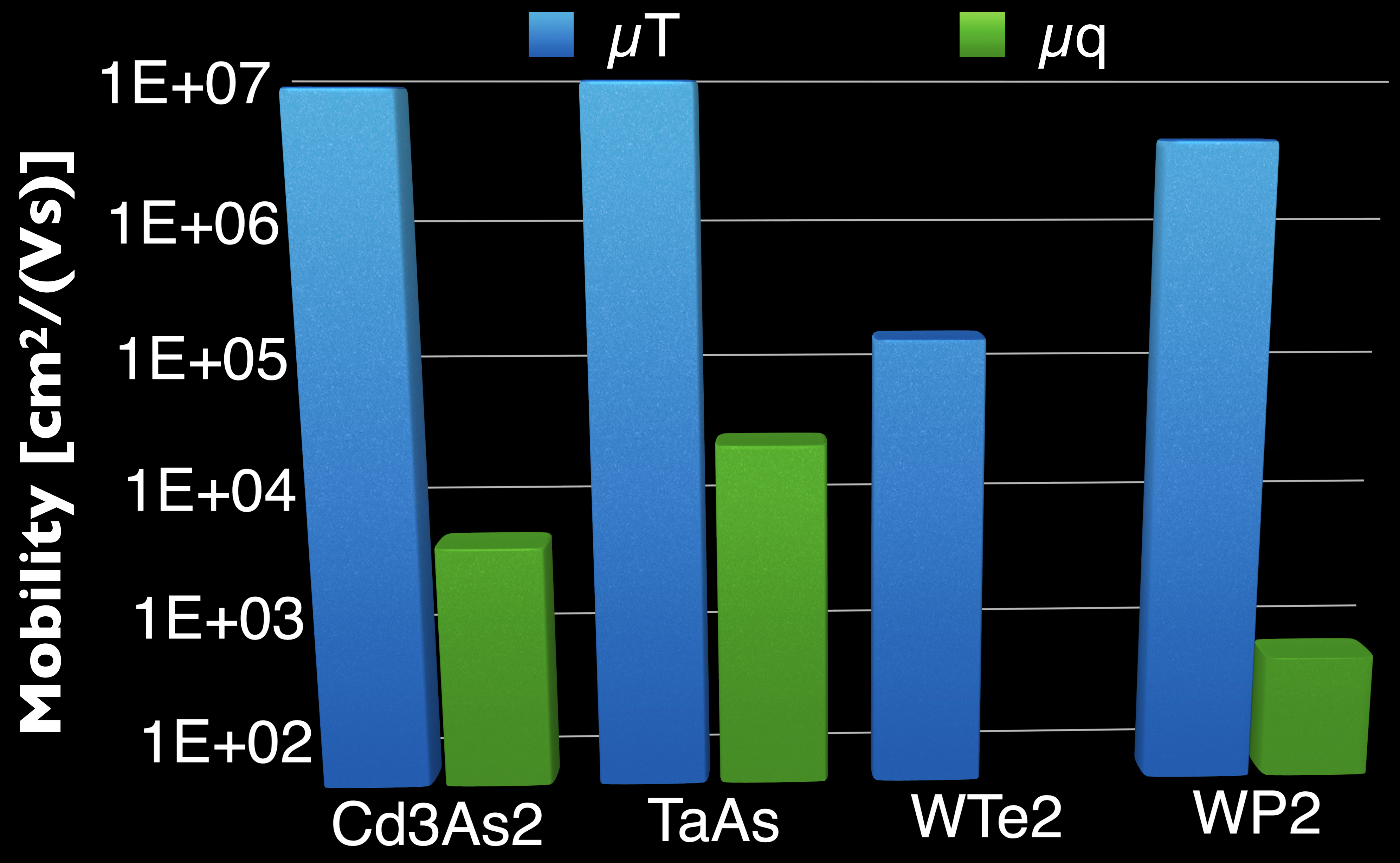
Transport

Reduced Phase Space



"Protected" by Symmetry?

"Protected" by Topology?

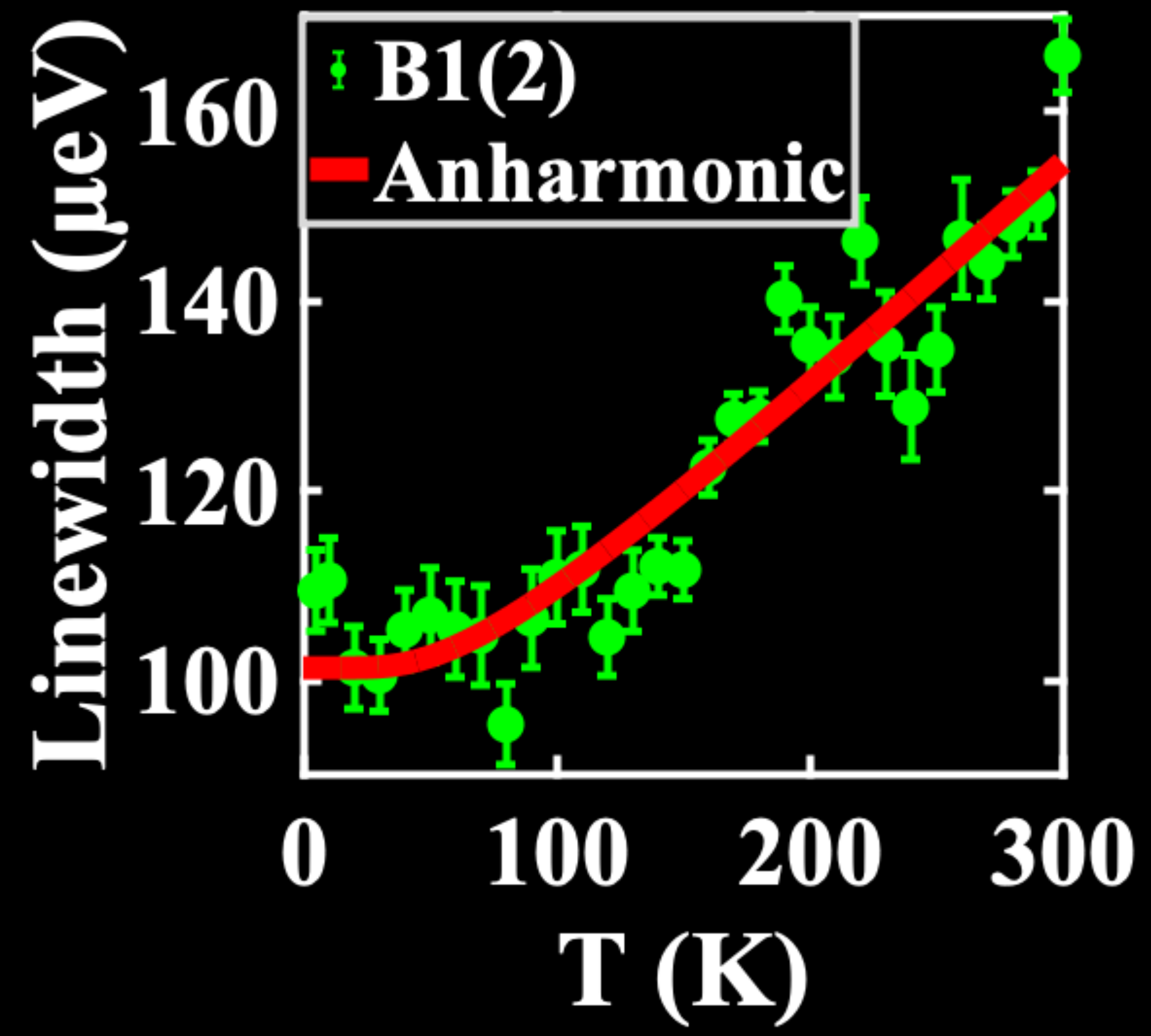


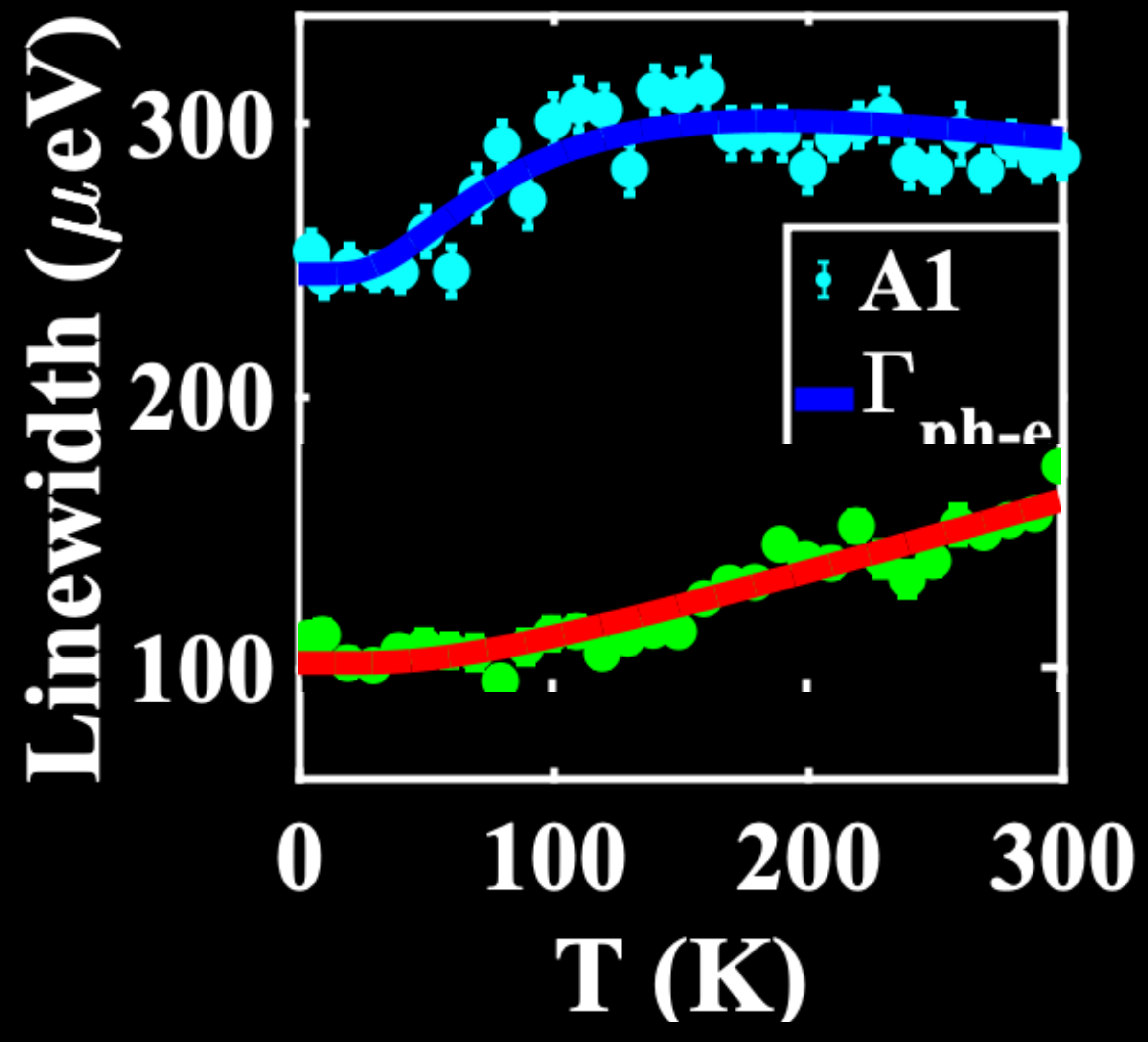
N. Kumar et. al., Nat. Comm. 8, 1 (2017); J. Hu et al., Ann. Rev. 49, 207 (2019); T.O. Wehling et al., Adv. Phys. 63, 1 (2014)

Phonons

(Ta,Nb)As

G. Osterhoudt, KSB Phys. Rev. B (2020)



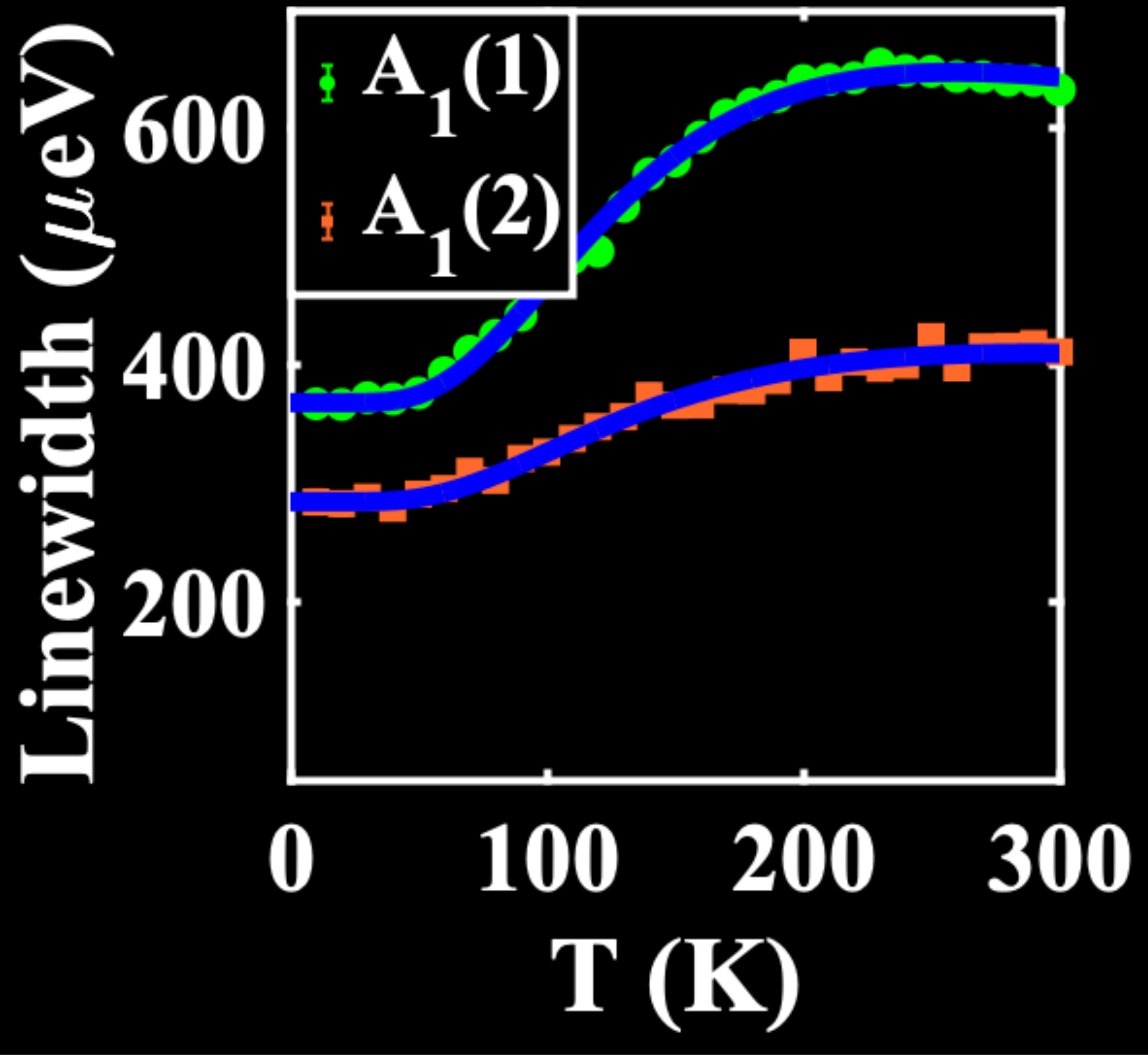


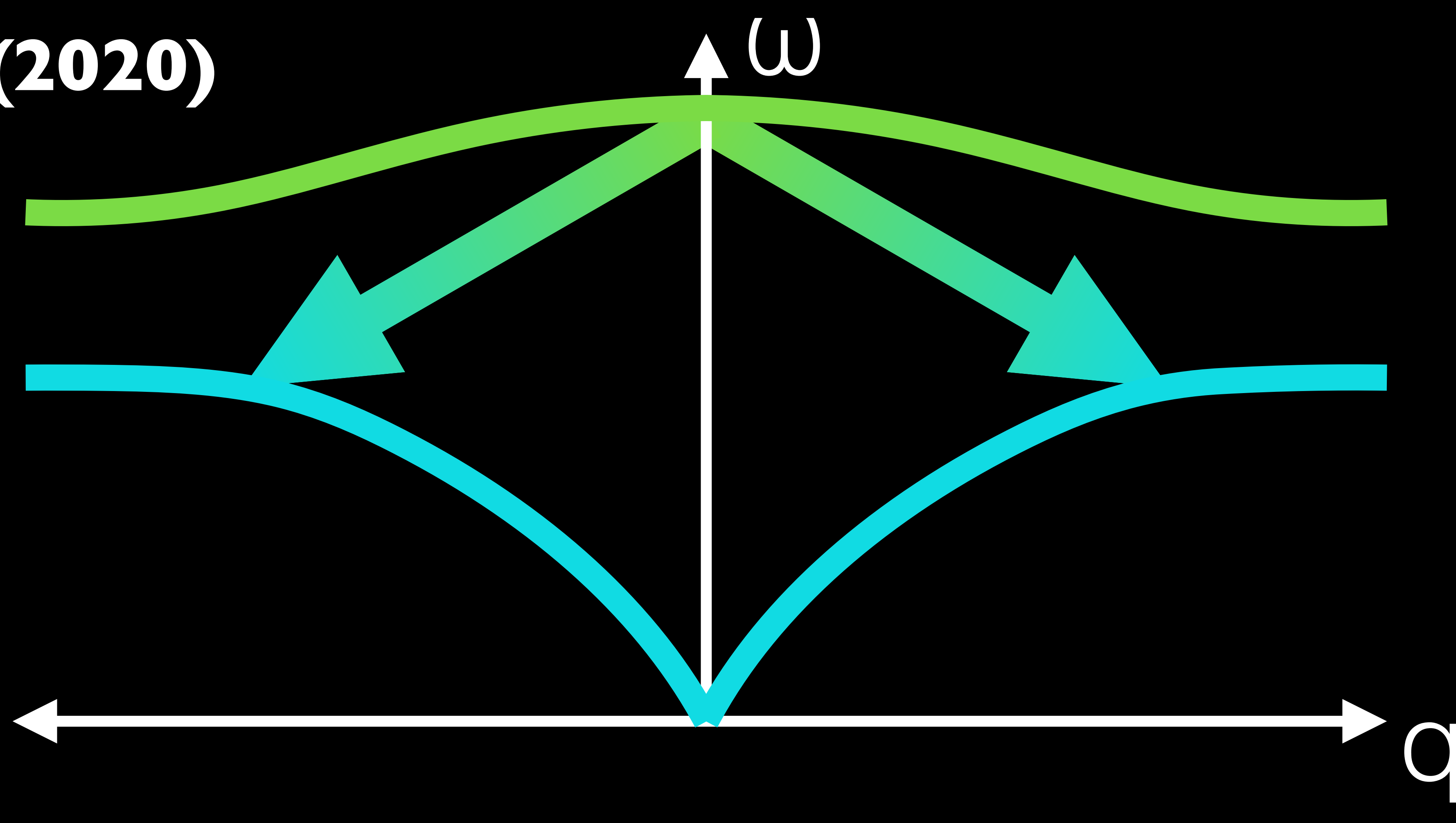
WP_2

G. Osterhoudt, KSB PRX (2021)

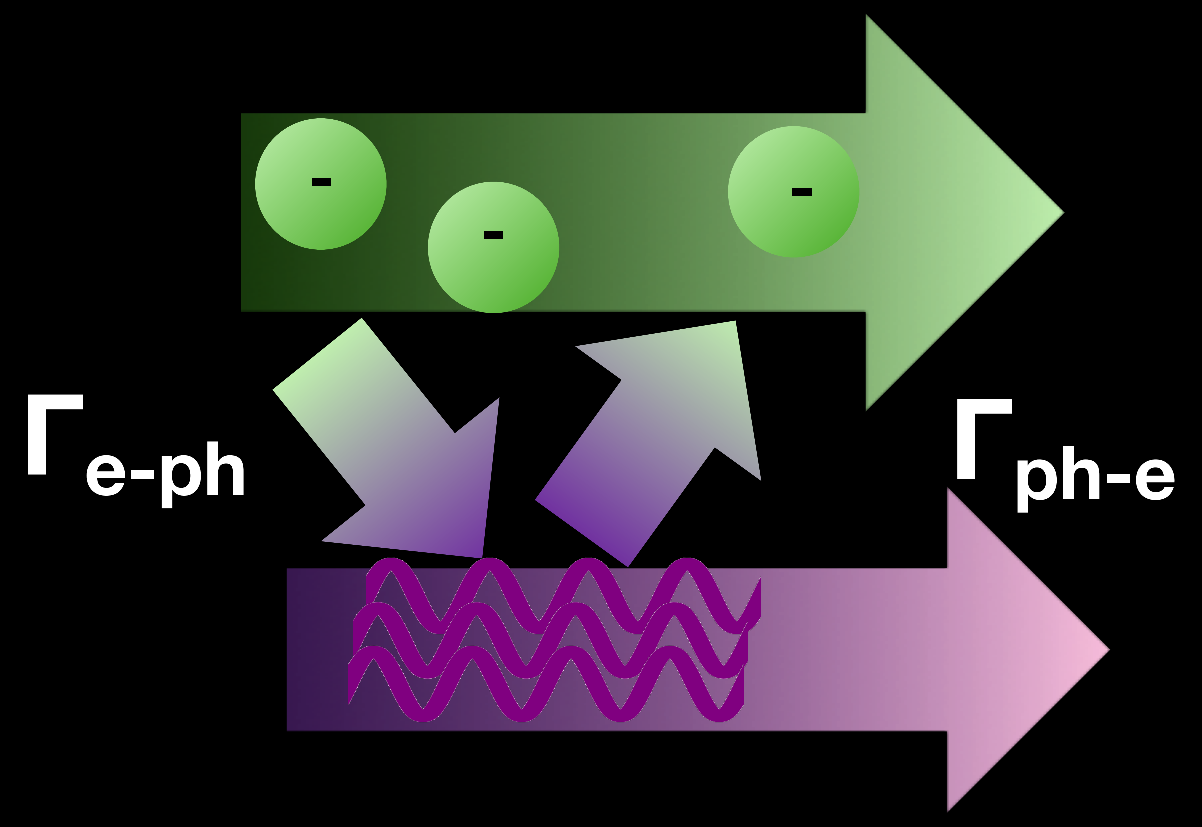
$NbGe_2$

H.-Y. Yang, KSB, Tafti
Nature Comm (2021)

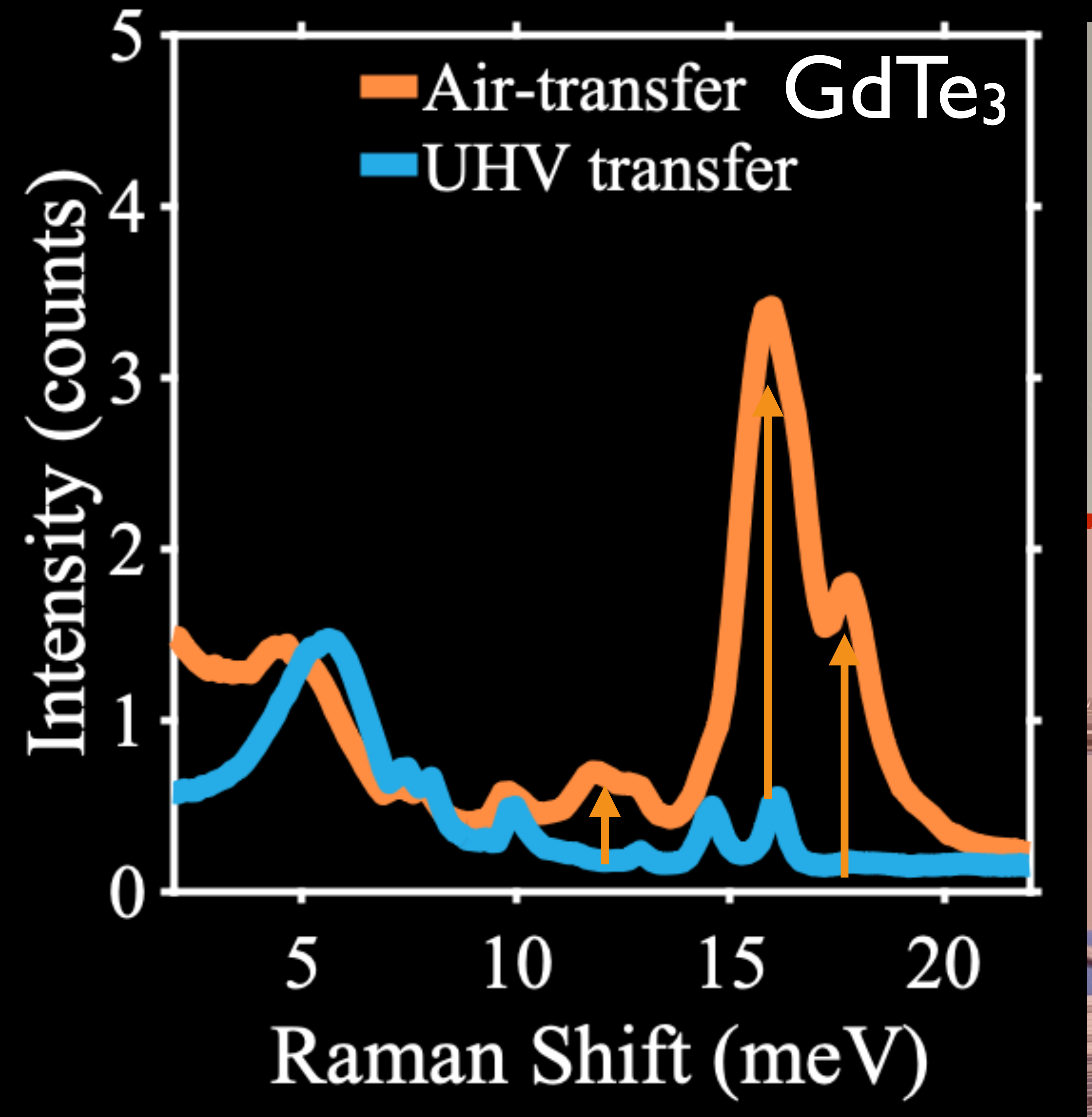


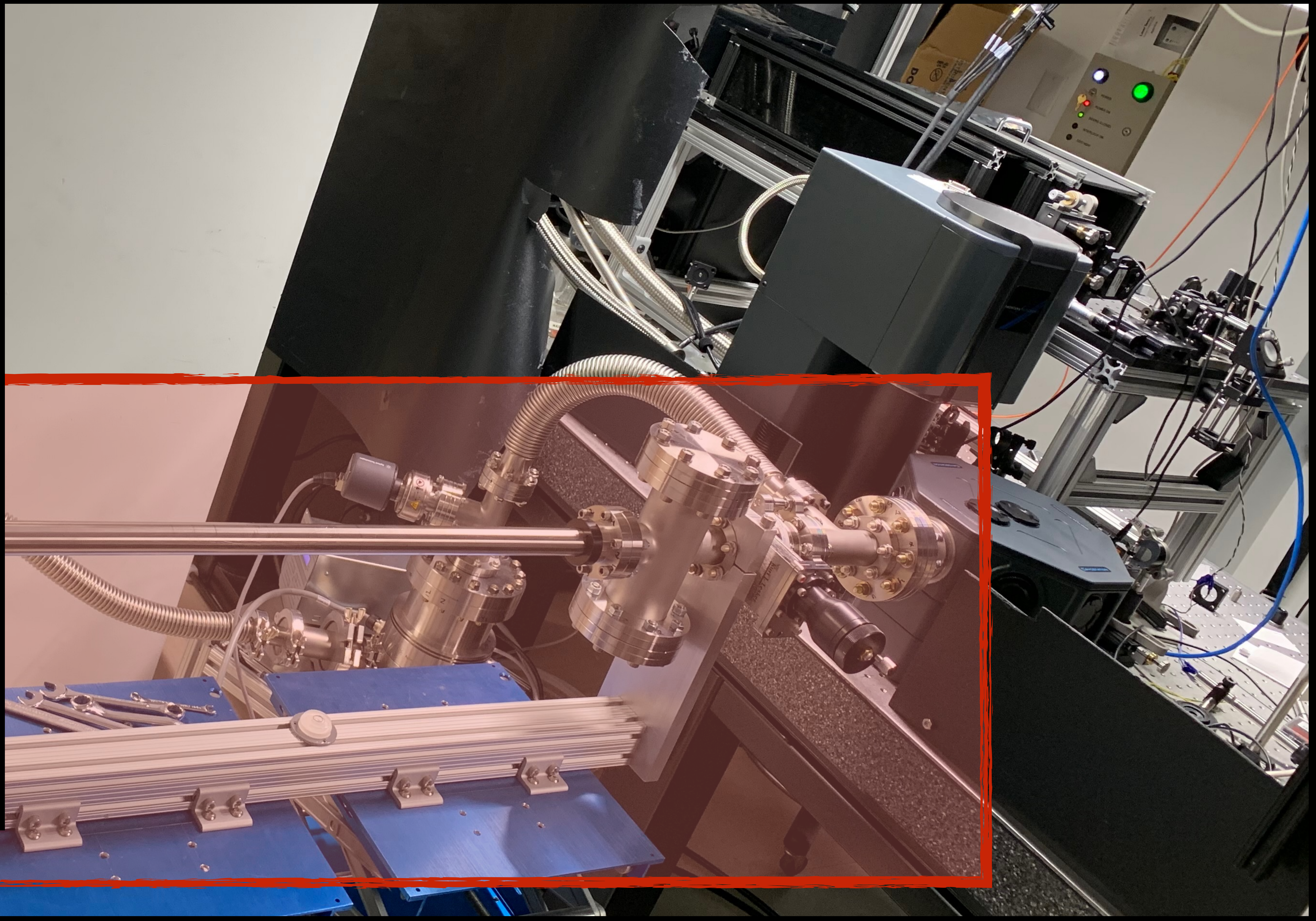


Phys. Rev. 148, 845 (1966).; PRB, 29, 2051 (1984)



Our Postpandemic Tool

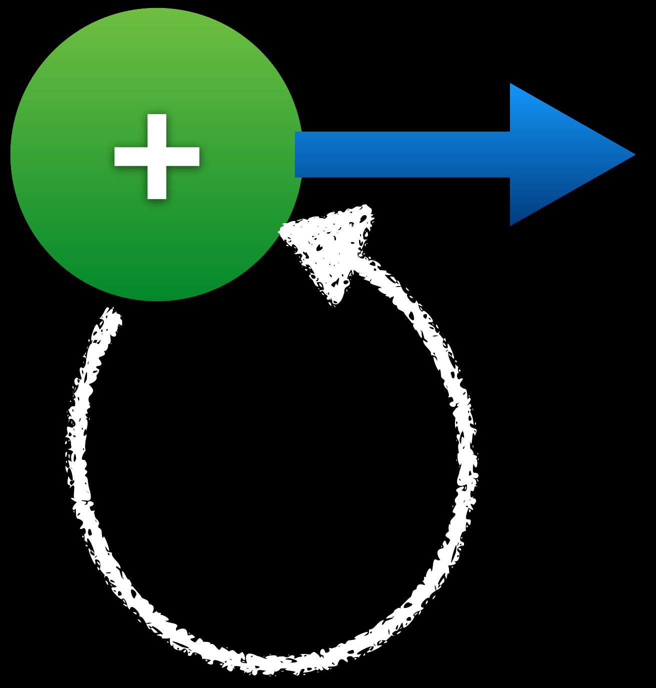




Y. Tian, KSB, et al Rev. Sci. Inst. 87, 4 (2016); M.Gray, KSB et al, RSI (2020)

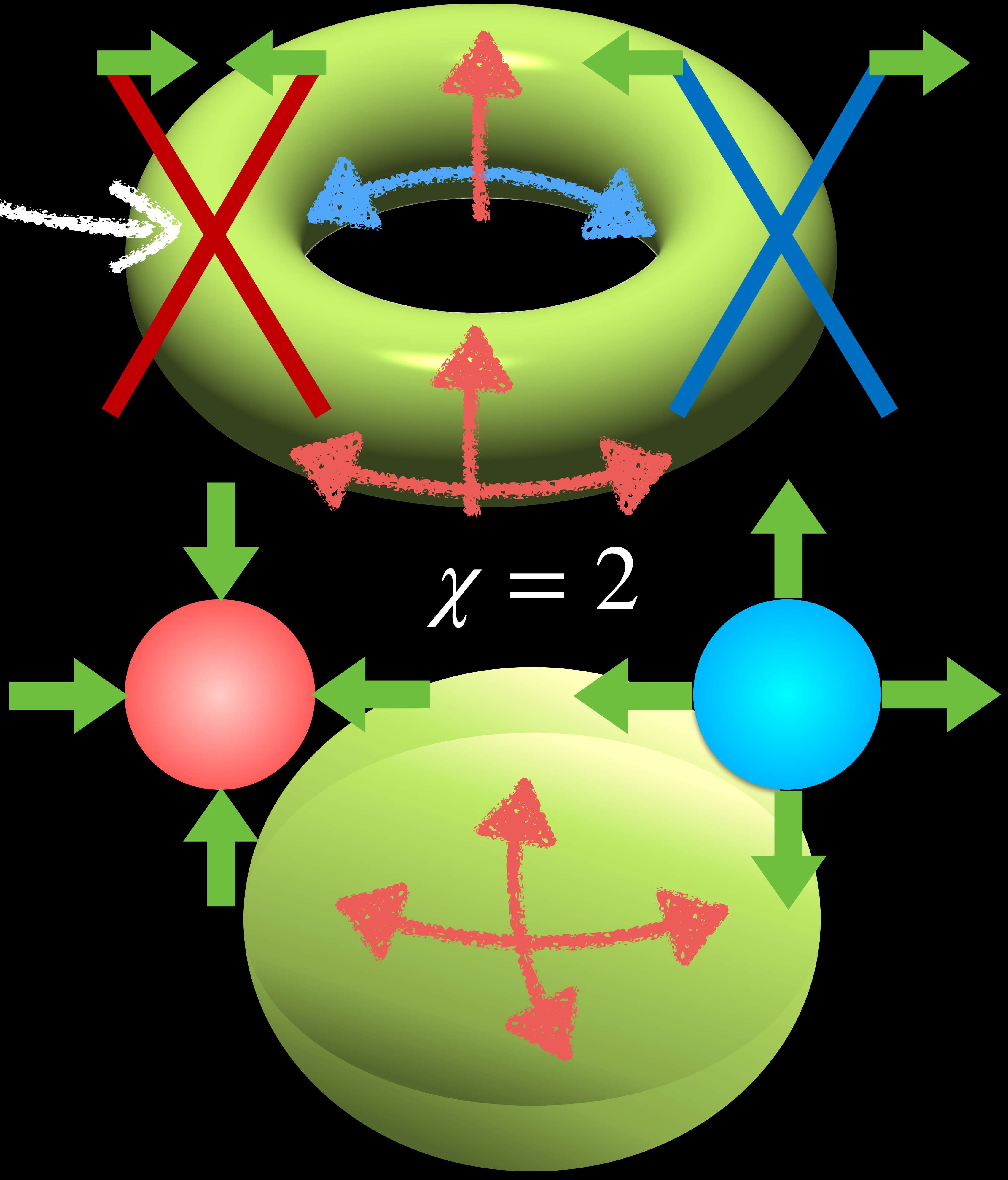
Quantum Topology

M. Berry



$\psi(0) \rightarrow \psi(0)e^{i\gamma}$

Magnetic Monopole → $\Omega(k), A(k) \rightarrow \infty$



Phase:

$$\gamma = \oint_C dk \cdot A(\vec{k}) = \iint_S dk^2 \cdot \Omega(\vec{k}) \approx \text{invariant}$$

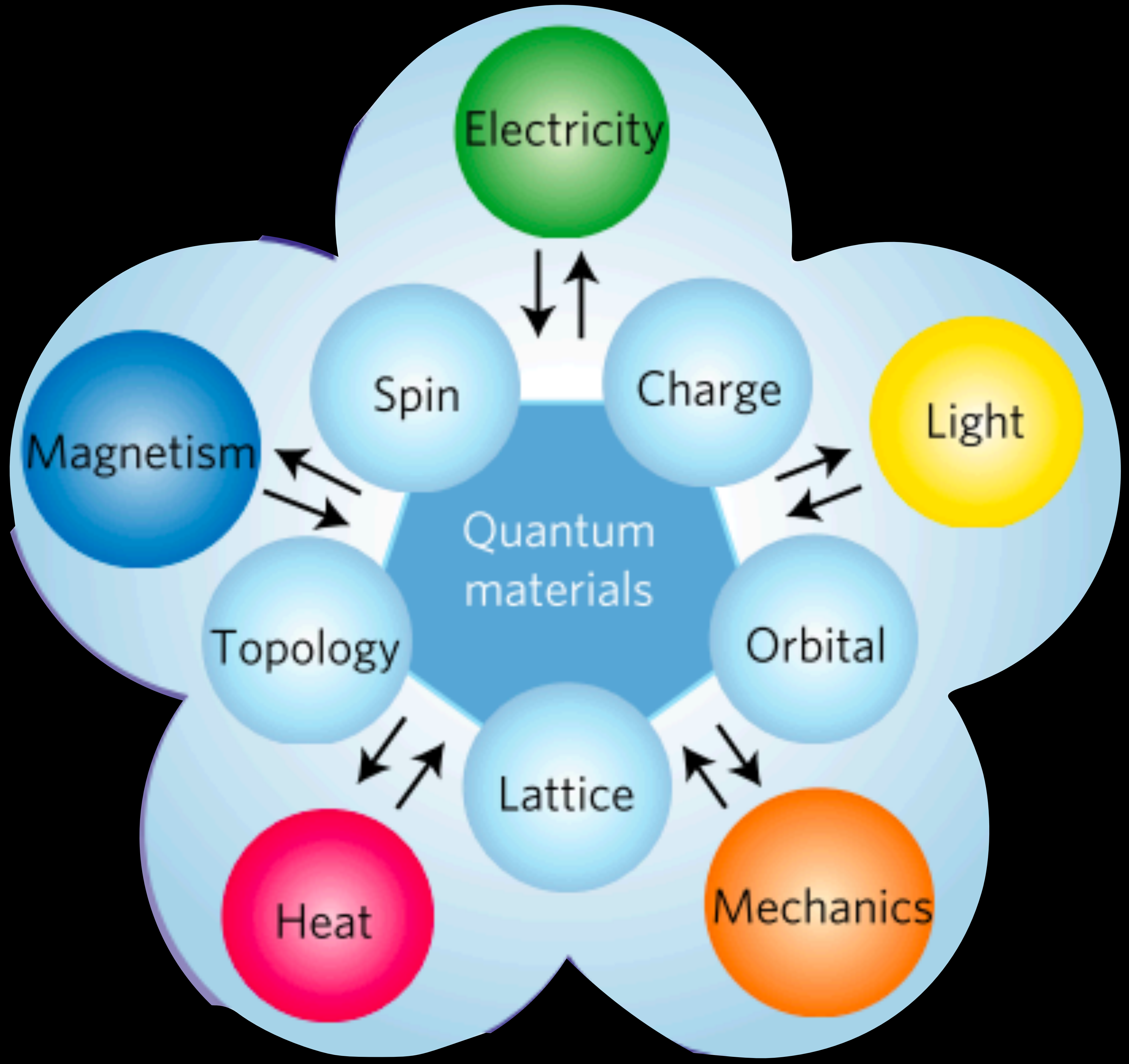
Curvature: $\Omega(\vec{k}) = \nabla_k \times A(\vec{k}) \approx \vec{B}(\vec{k})$

Connection: $A(\vec{k}) = \langle \psi(\vec{k}) | i \nabla_k | \psi(\vec{k}) \rangle \approx$ Potential

$$= \langle \, | \hat{r} | \, \rangle$$

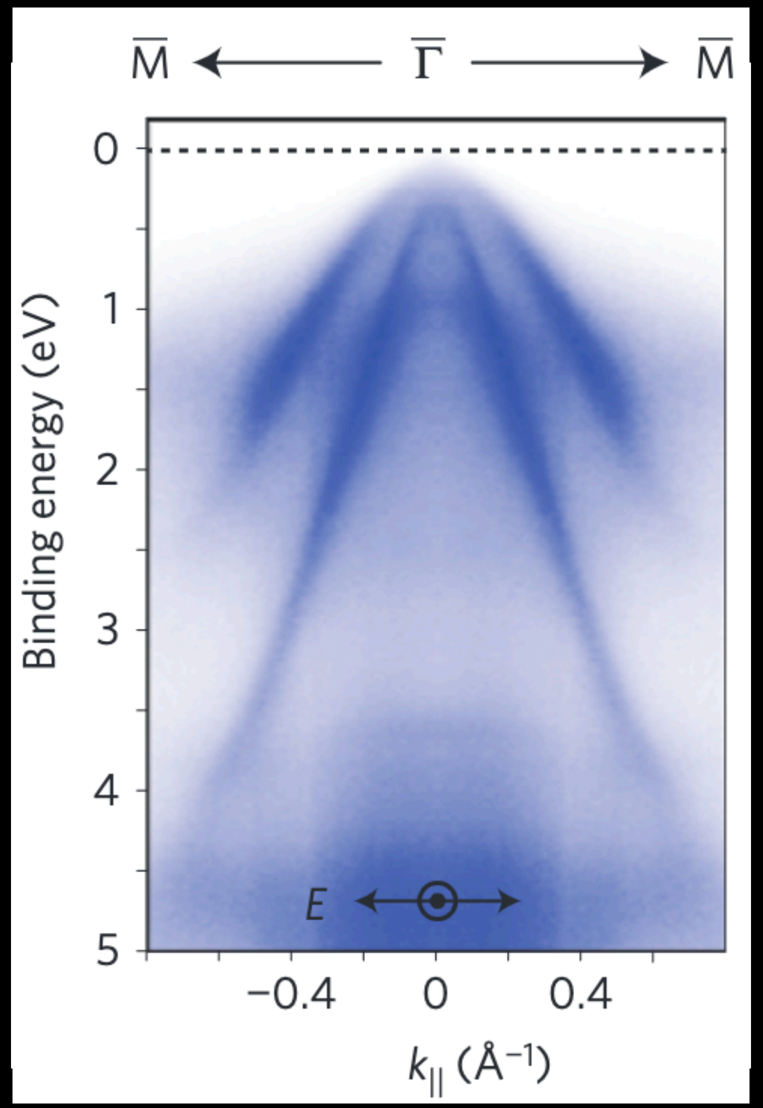
D. Xiao, et al. RMP 82, 1959 (2010)

Clean and Correlated



Y. Tokura et al., Nature Physics (2017)

Cd_3As_2



Nat. Materials 13, 677 (2014)

2D Toolbox

NANO LETTERS

pubs.acs.org/NanoLett Letter

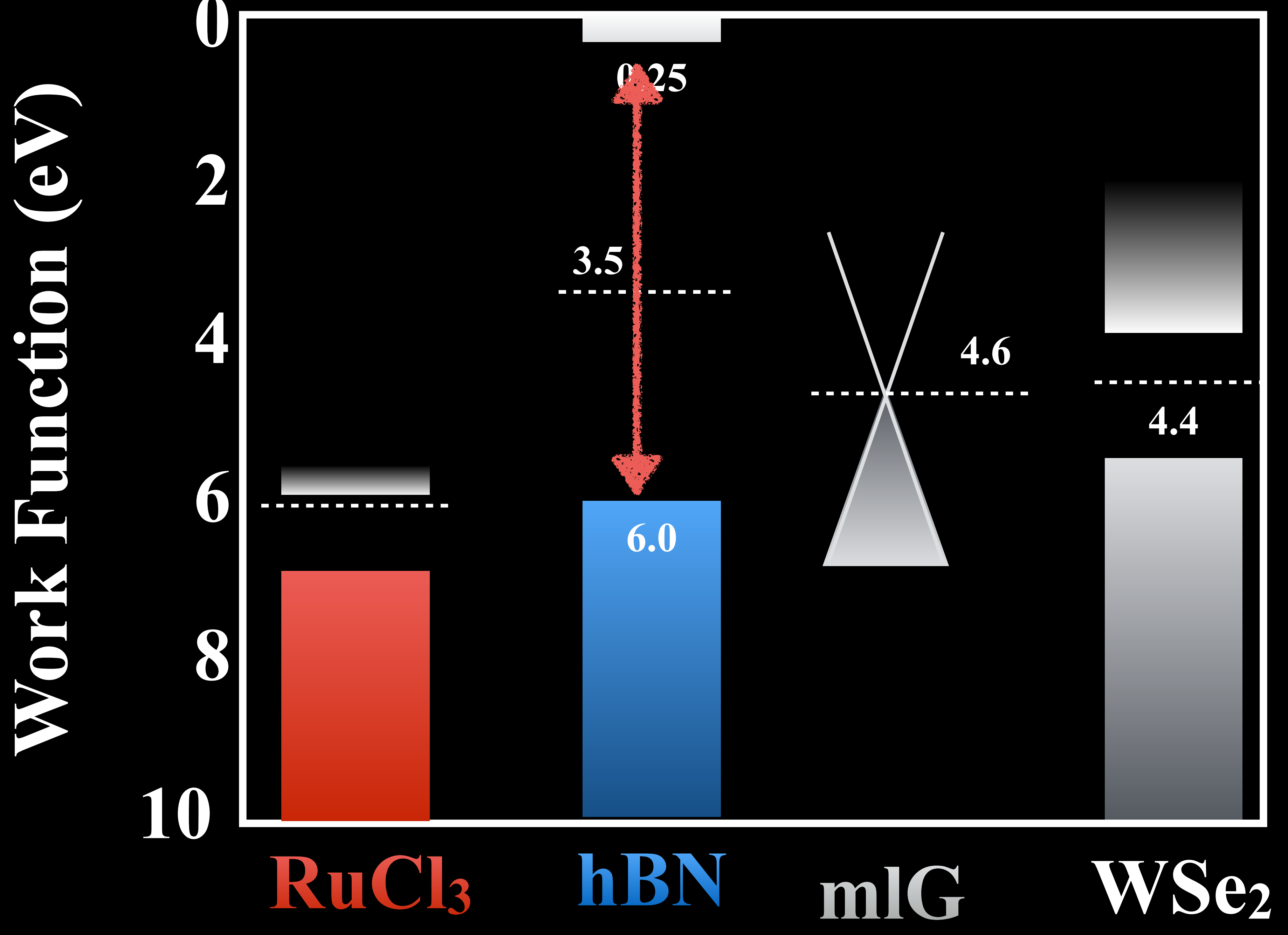
Modulation Doping via a Two-Dimensional Atomic Crystalline Acceptor

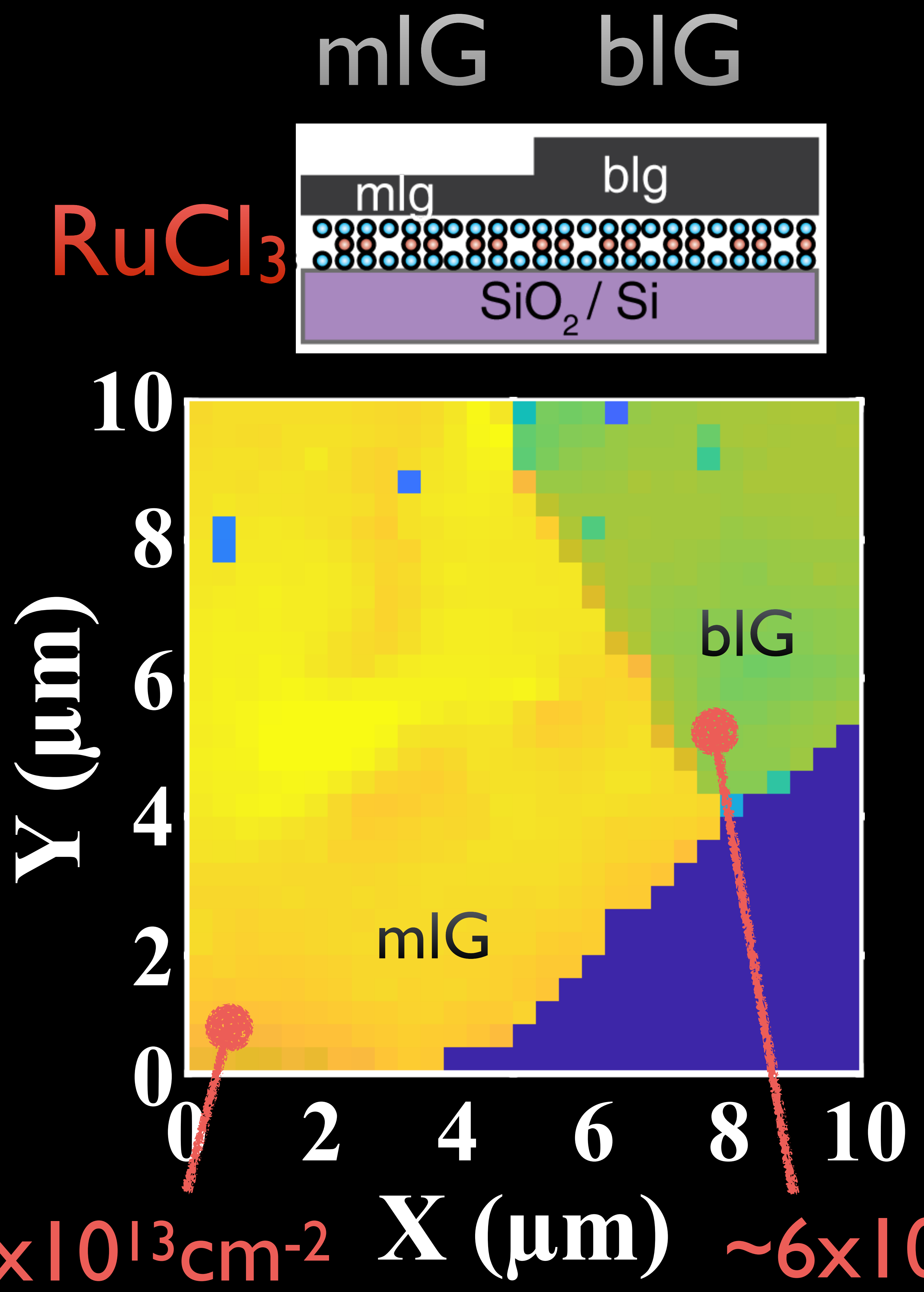
Yiping Wang,[□] Jesse Balgley,[□] Eli Gerber, Mason Gray, Narendra Kumar, Xiaobo Lu, Jia-Qiang Yan, Arash Fereidouni, Rabindra Basnet, Seok Joon Yun, Dhavala Suri, Hikari Kitadai, Takashi Taniguchi, Kenji Watanabe, Xi Ling, Jagadeesh Moodera, Young Hee Lee, Hugh O. H. Churchill, Jin Hu, Li Yang, Eun-Ah Kim, David G. Mandrus, Erik A. Henriksen,* and Kenneth S. Burch*

Cite This: *Nano Lett.* 2020, 20, 8446–8452

Read Online

Modulation Doping

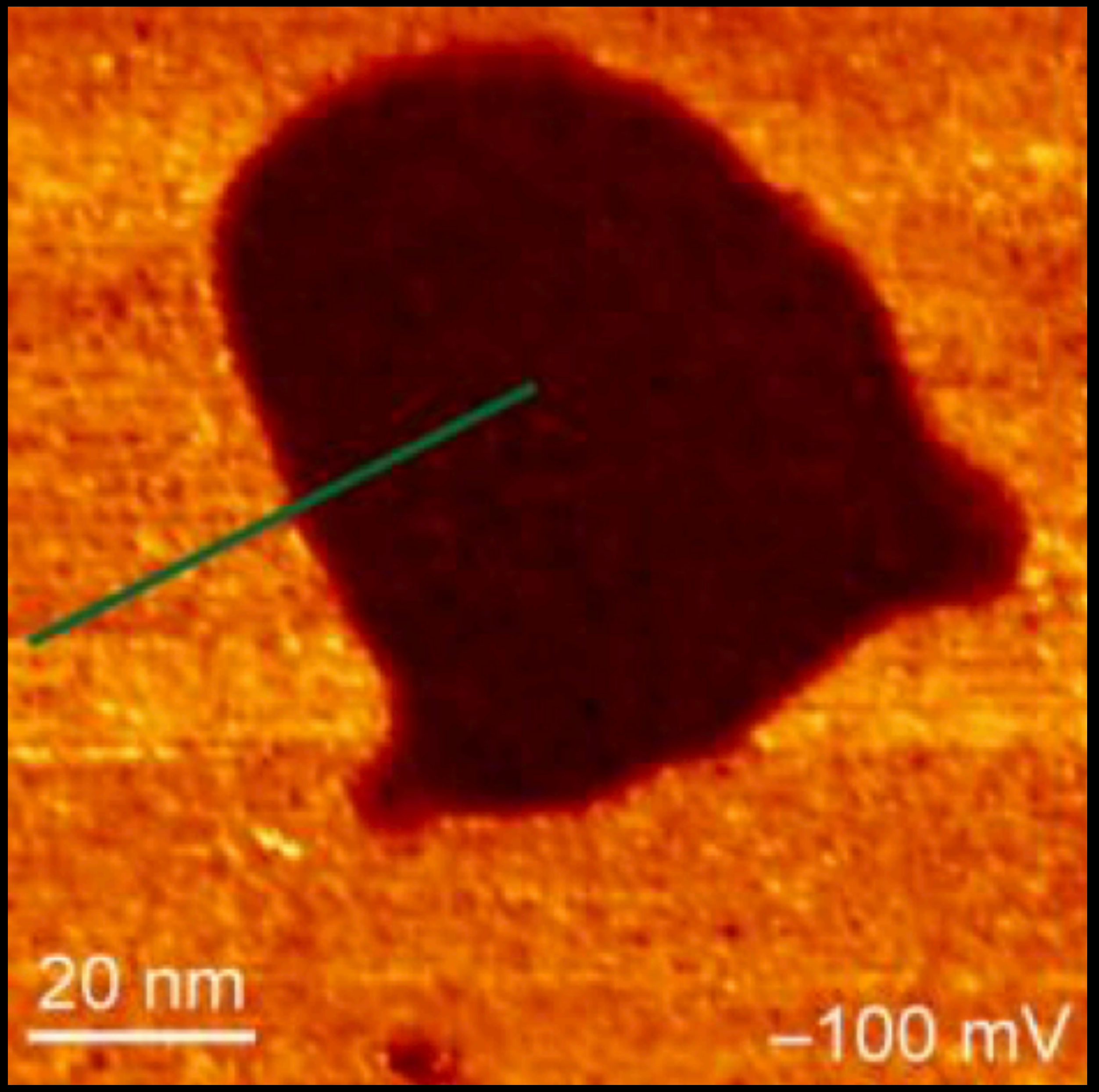




~3×10^{13}cm^{-2}

E$_F$~600meV

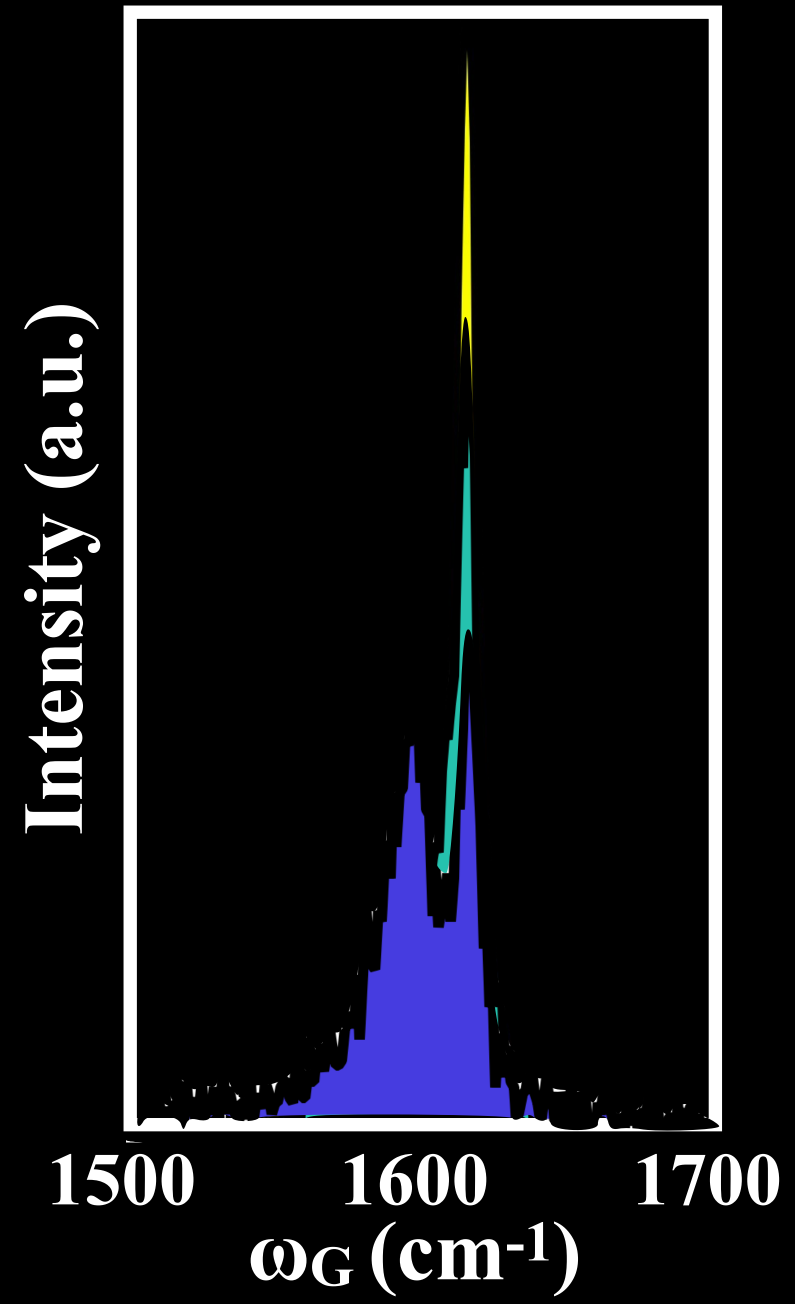
~6×10^{13}cm^{-2}

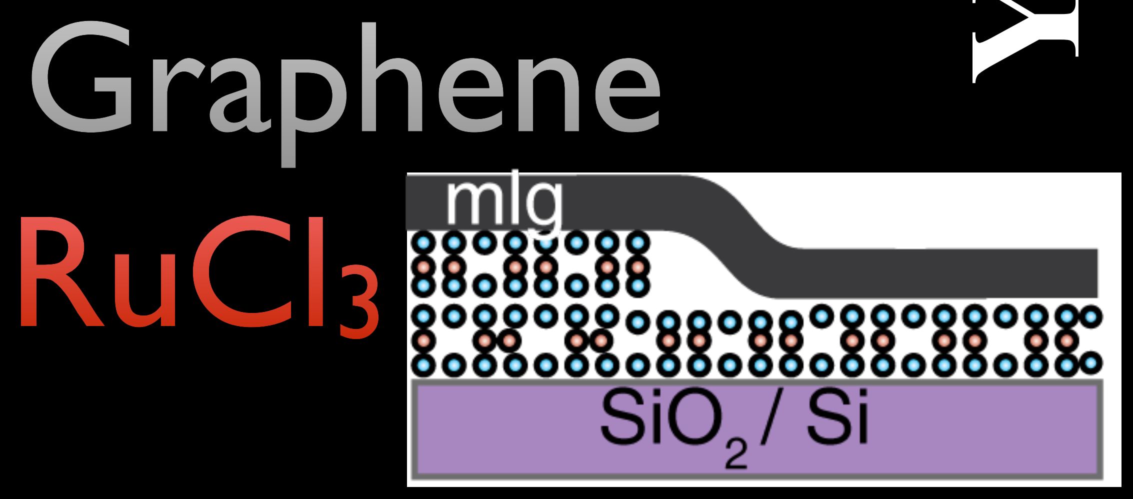


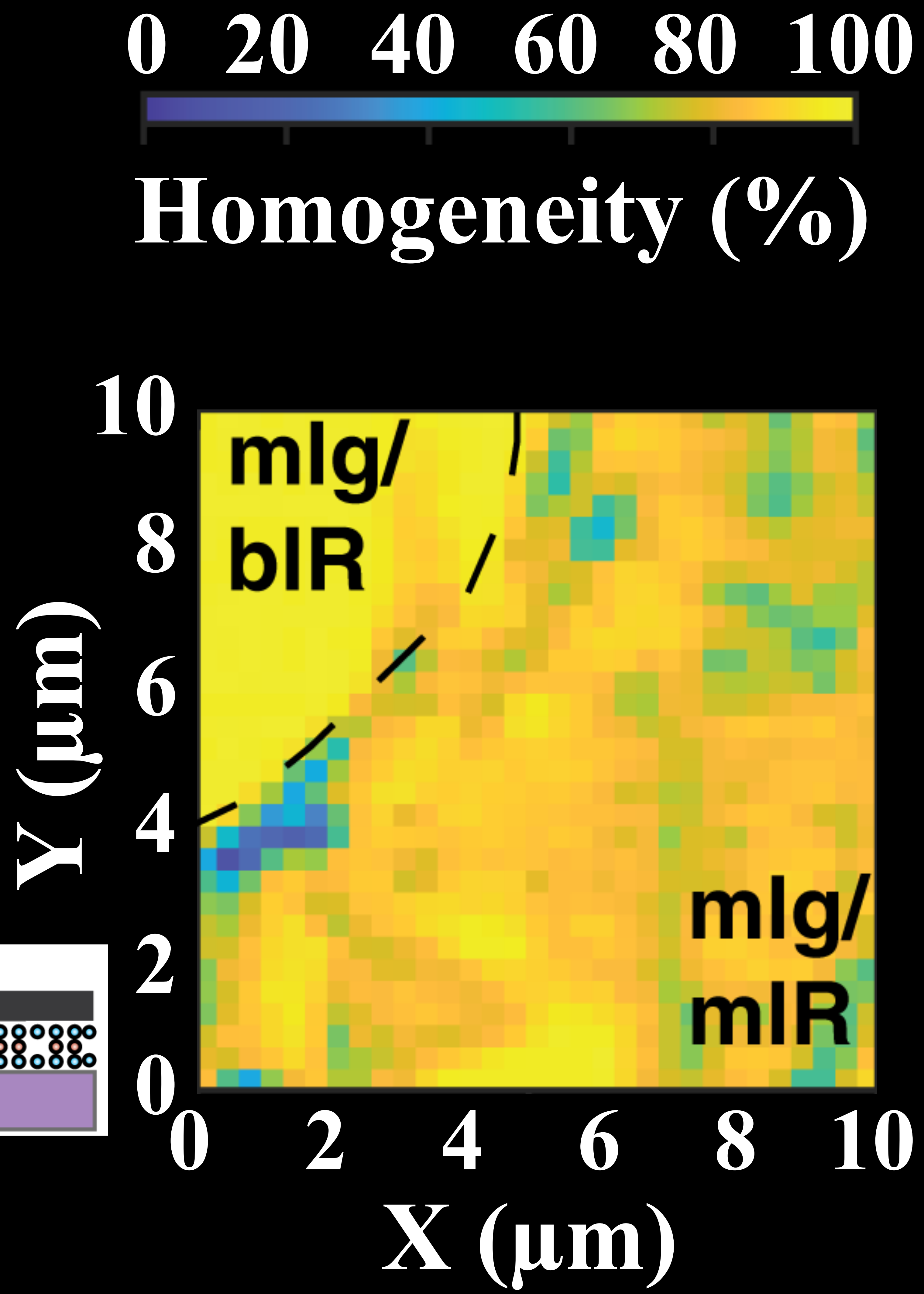
D. Rizzo et al, Nanoletters (2022)
J. Bagley et al, Nanoletter (2022)

Y. Wang, KSB et al, Nanoletters (2020)

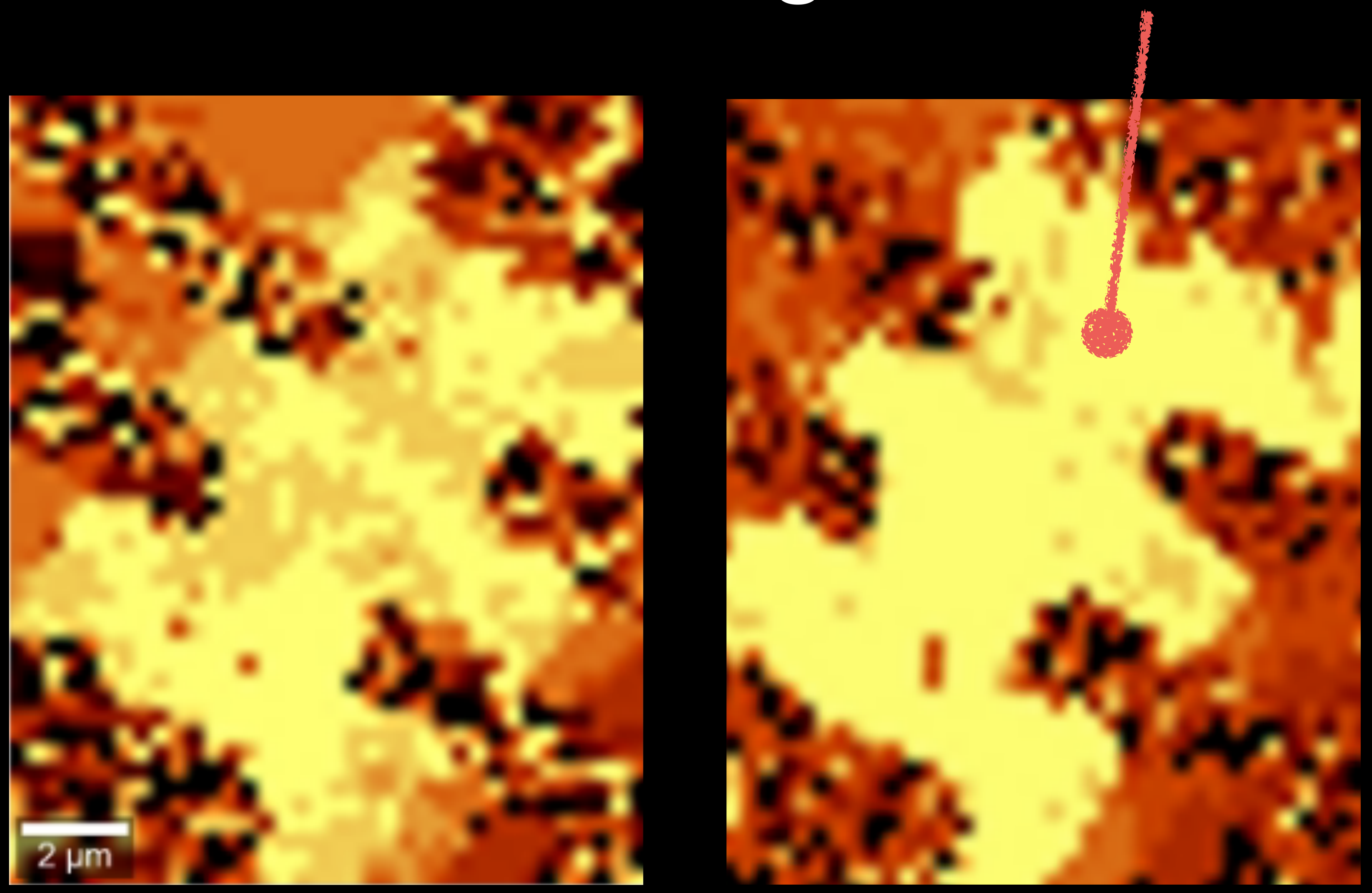
Optimal Modulation Doping







- ✓ Twist Agnostic
- ✓ Sweeping
- ✓ Annealing



~1.5×10^{14} cm^{-2}
E_F~1.2 eV

Nonlinear

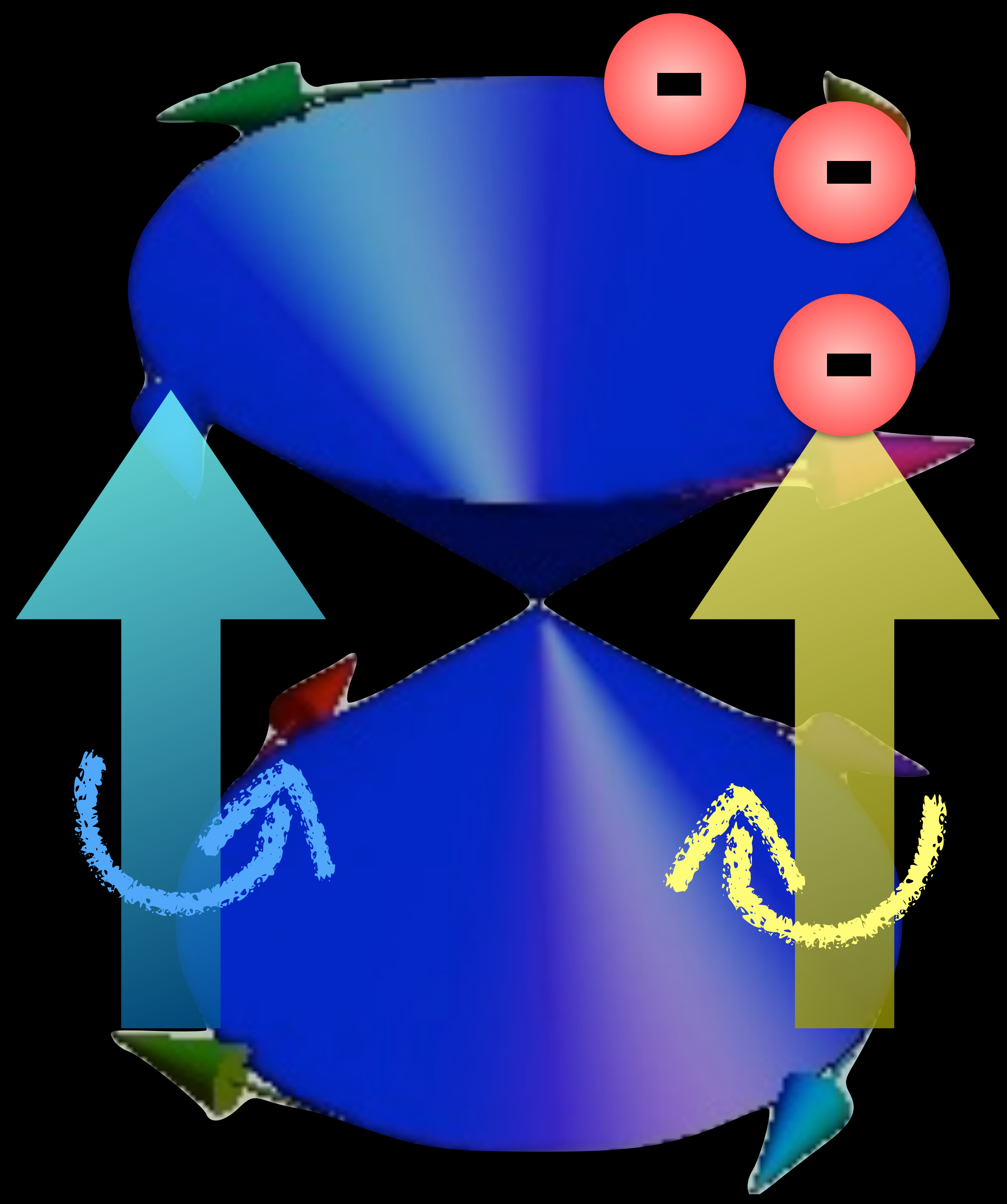
$$\Omega(\vec{k}) = \nabla_k \times A(\vec{k}) \approx \vec{B}(\vec{k})$$

$$A(\vec{k}) = \langle \psi(\vec{k}) | i\nabla_k | \psi(\vec{k}) \rangle$$

$$= \langle | \hat{r} | \rangle$$

Injection Current

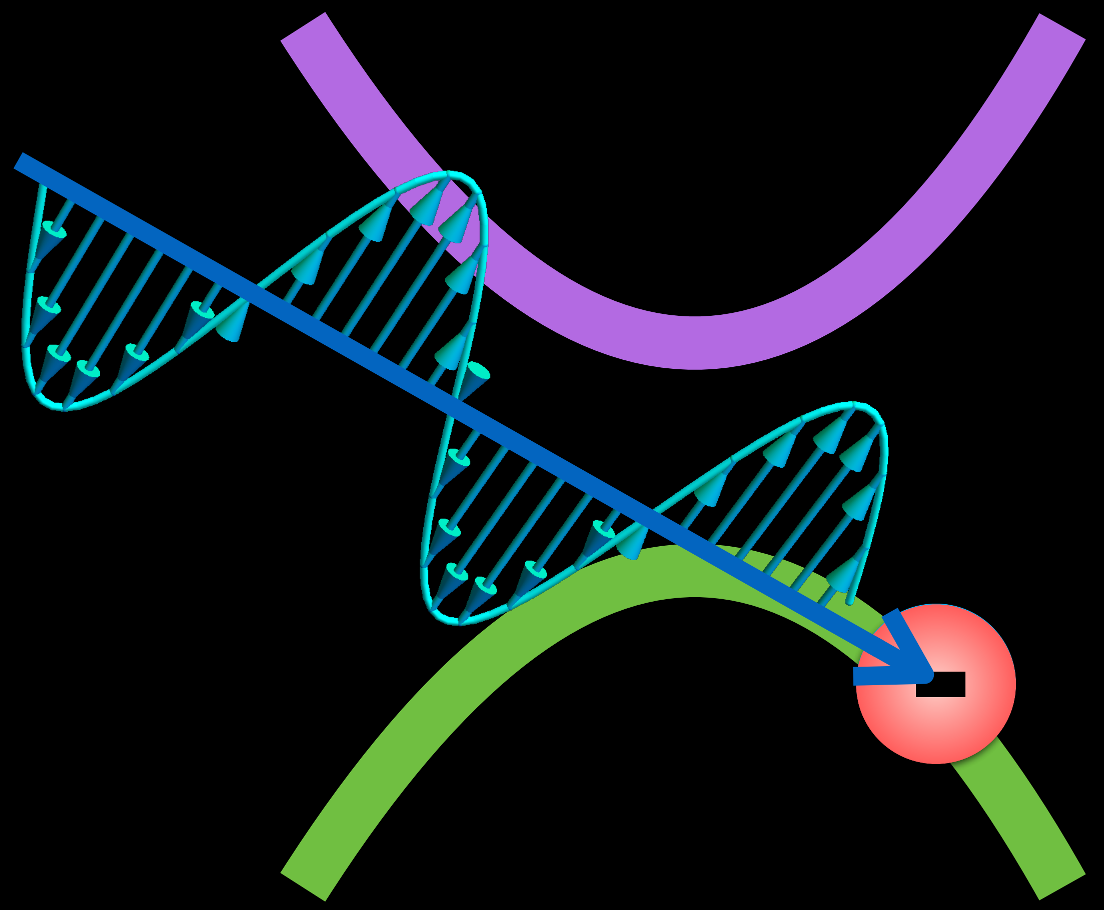
$$J_{inj} \propto \frac{dJ}{dt}\tau$$

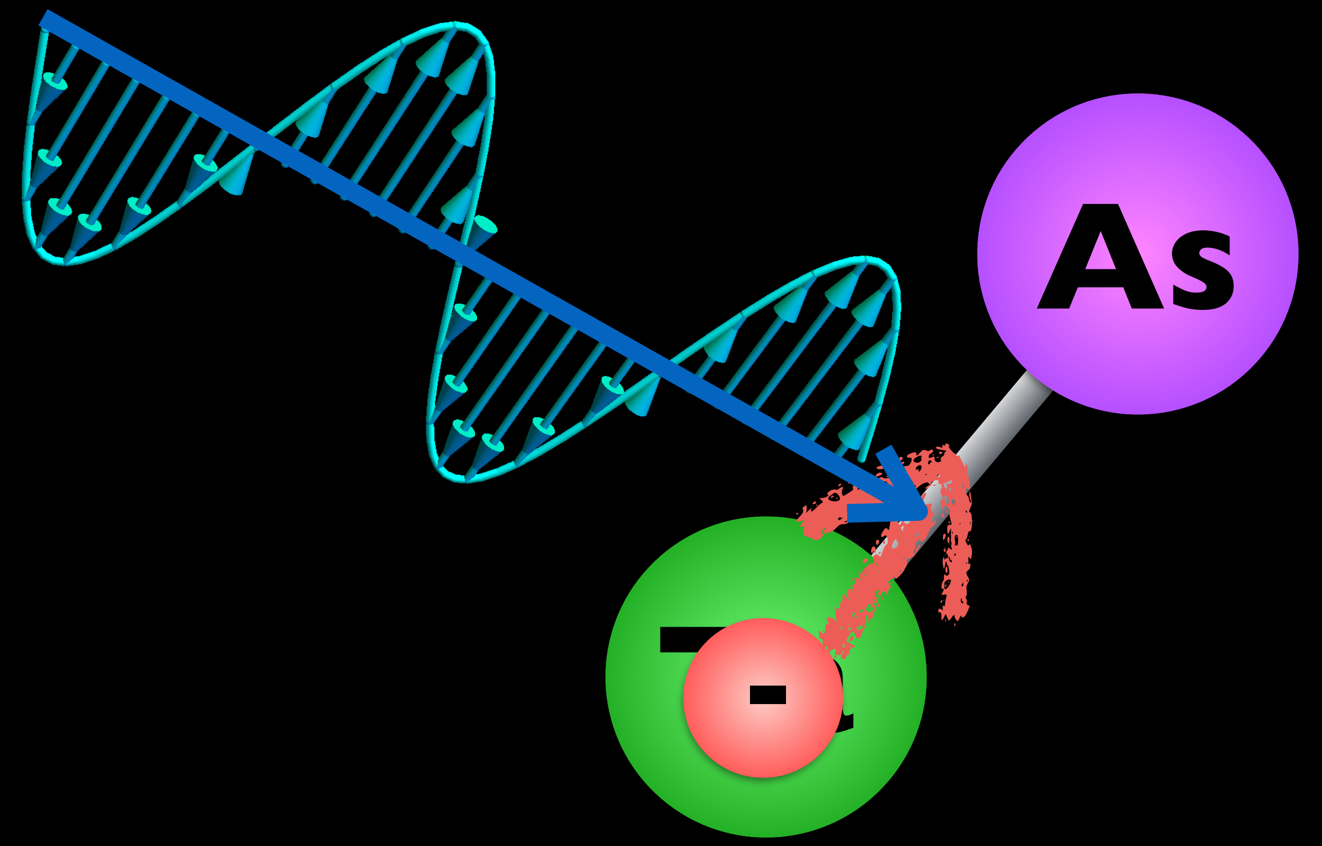


$$\Omega(k_x) = B_0 \hat{y}$$

Shift Current

$$\frac{d\vec{P}}{dt} = \vec{J}$$

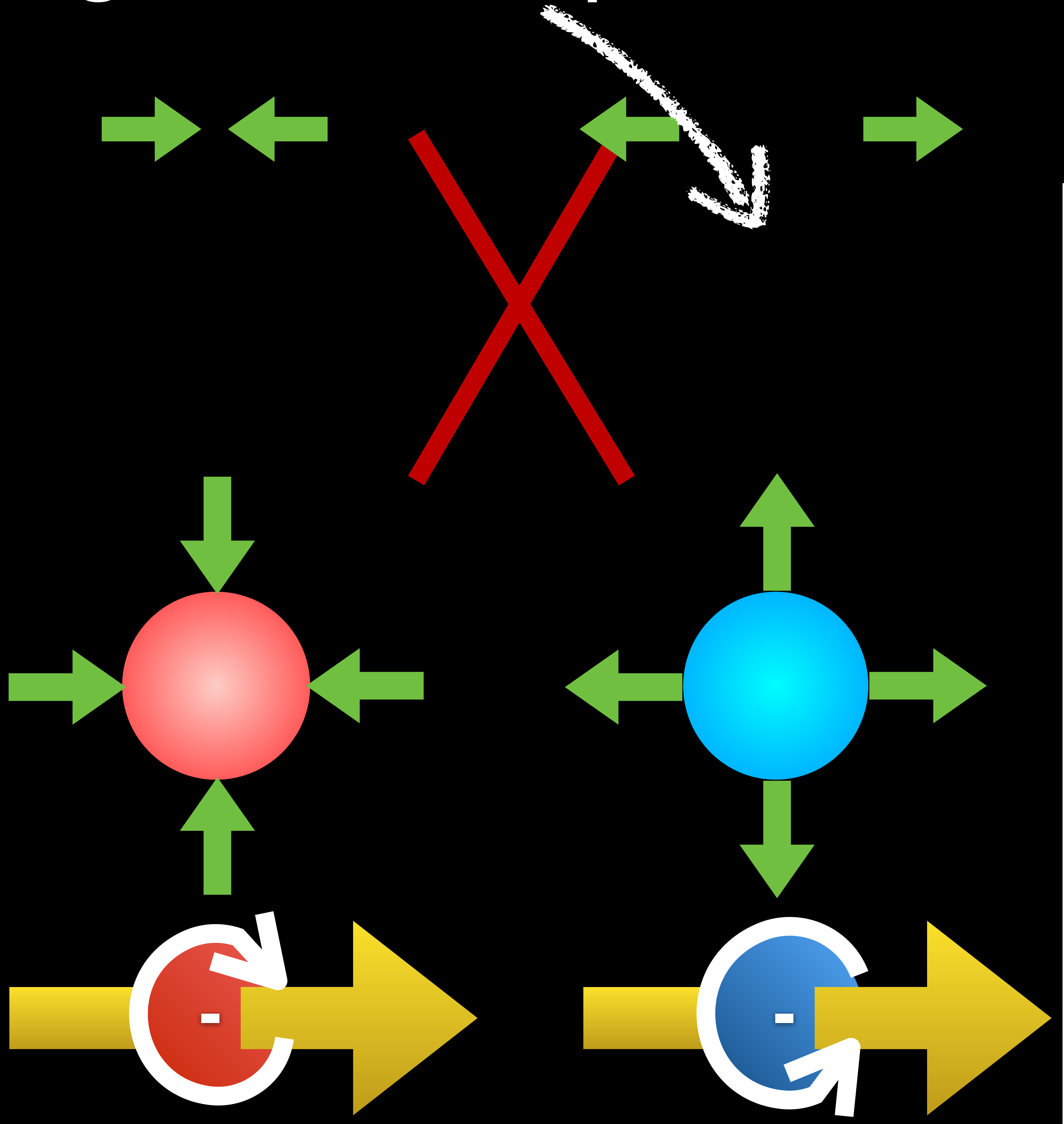




J.E. Sipe, & I. Shkrebtii, PRB 61, 5337 (2000)
T. Morimoto & N. Nagaosa , Sci. Adv. 2, 150524 (2016)
L.Z. Tan et al., NPJ Comp. Mat. 2, 16026 (2016)

Weyl

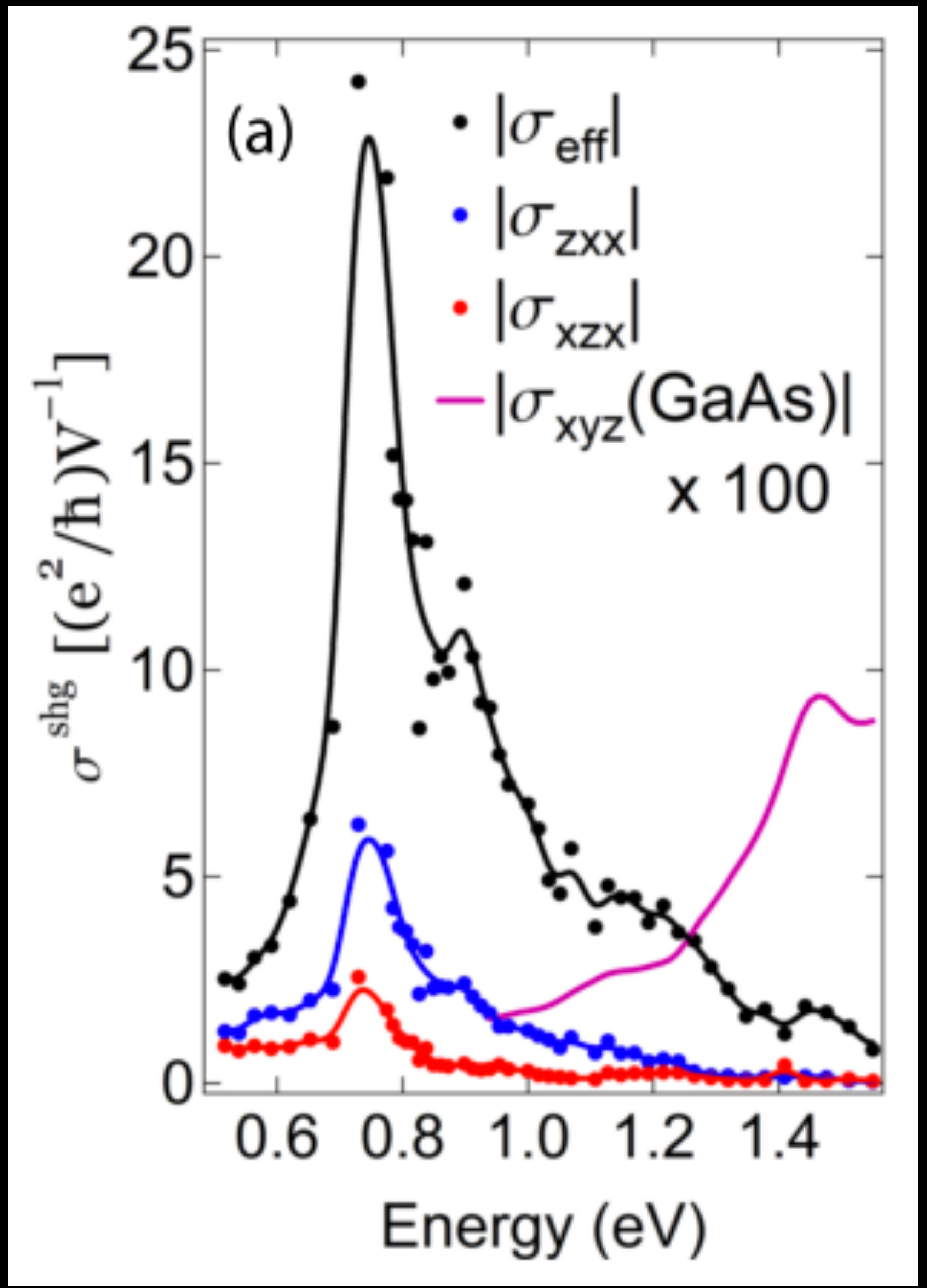
Magnetic Monopole → $\Omega(k),\ A(k) \rightarrow \infty$



X. Yang et al., arxiv 1712.09363
C.K. Chan et al., PRB 95, 41104

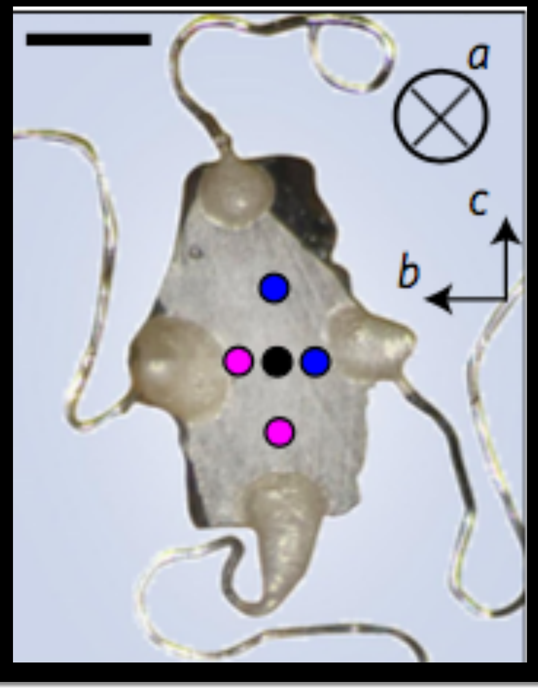
2nd harmonic

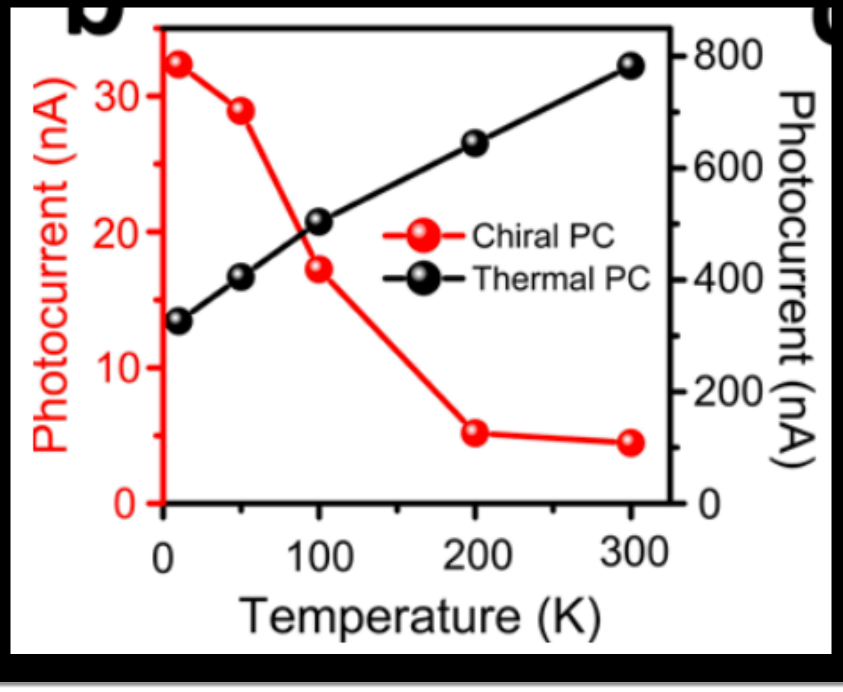
L. Wu et. al, Nature Physics (2017)

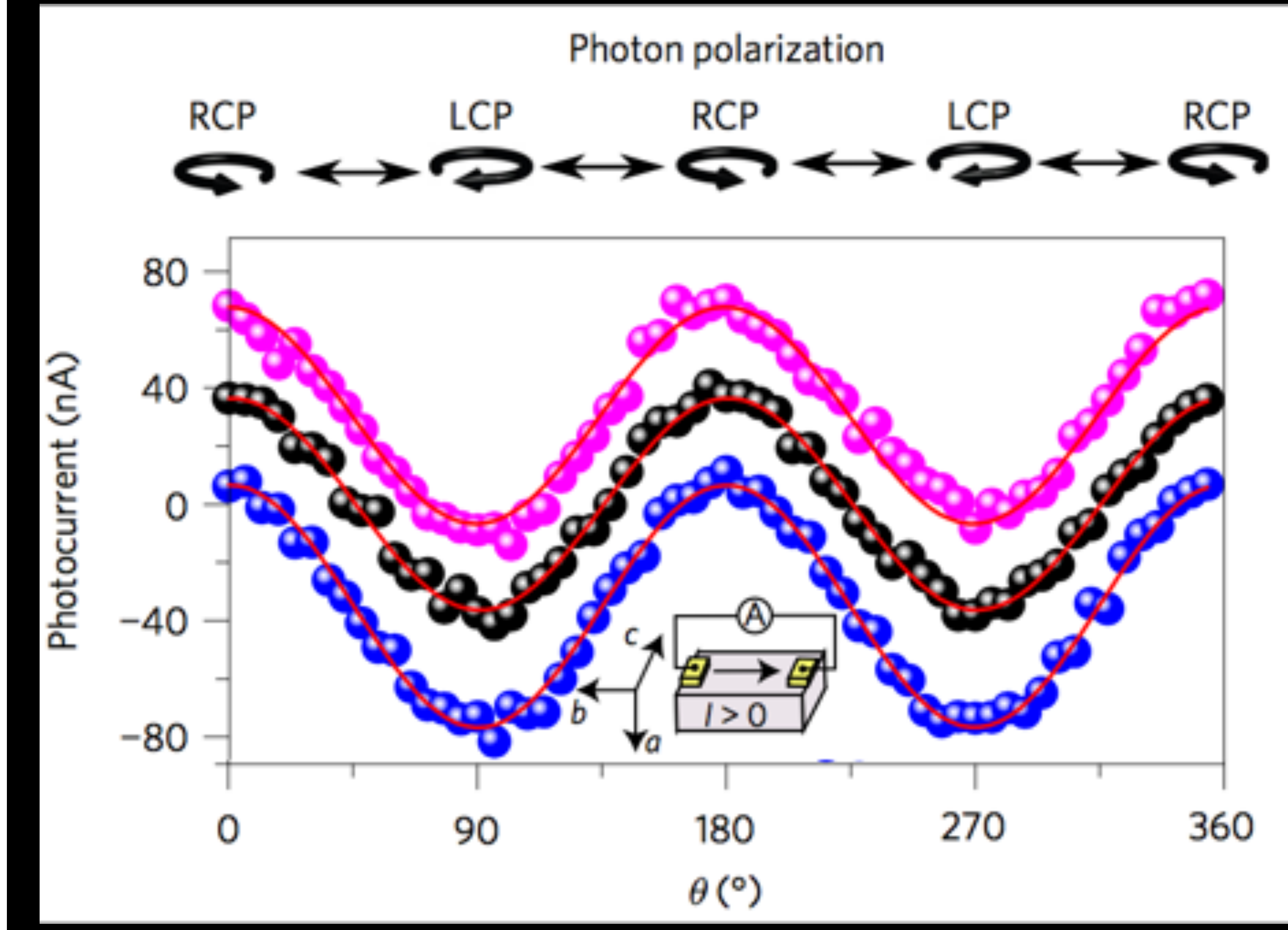


Injection Current

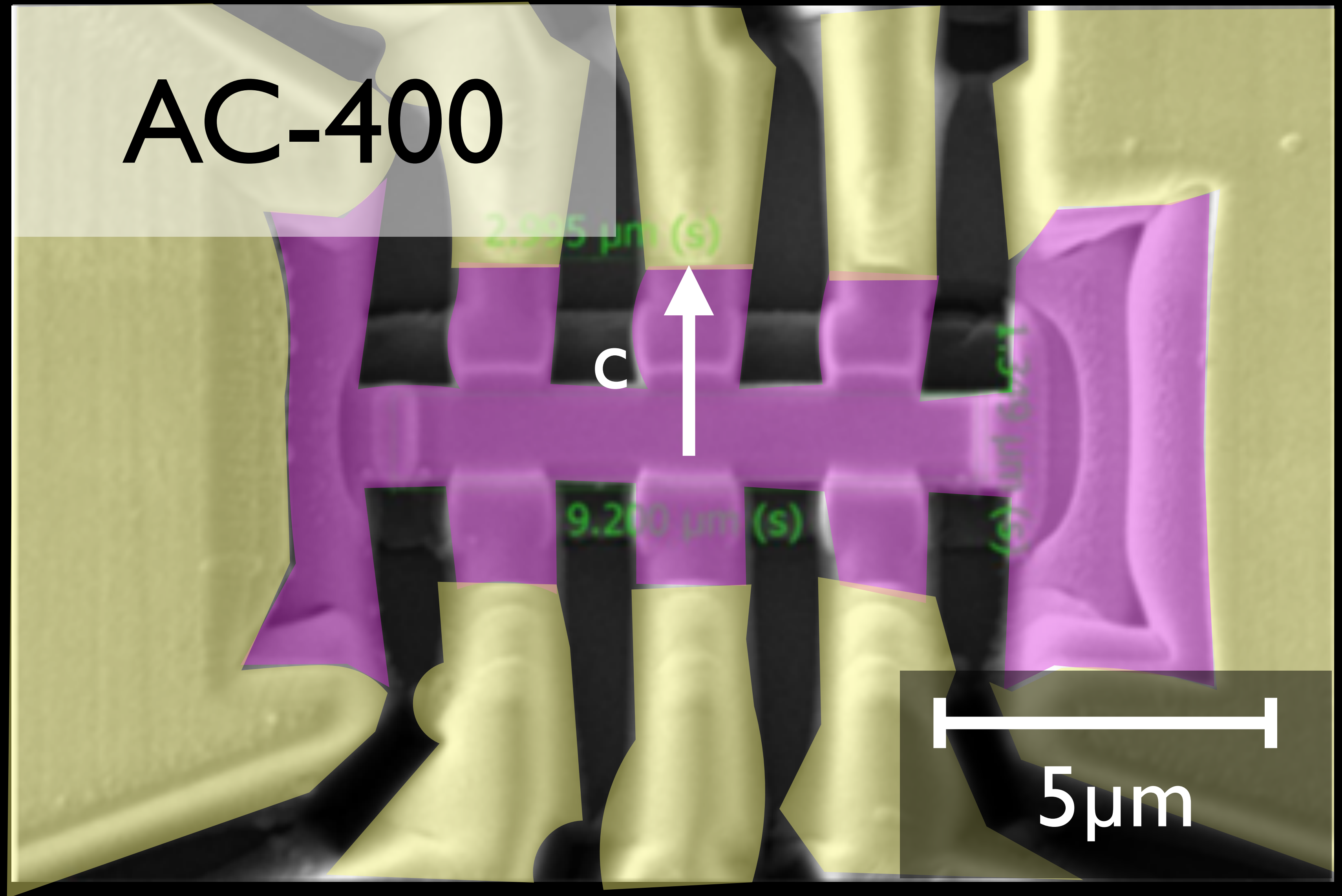
Q. Ma et. al, Nature Physics (2017)

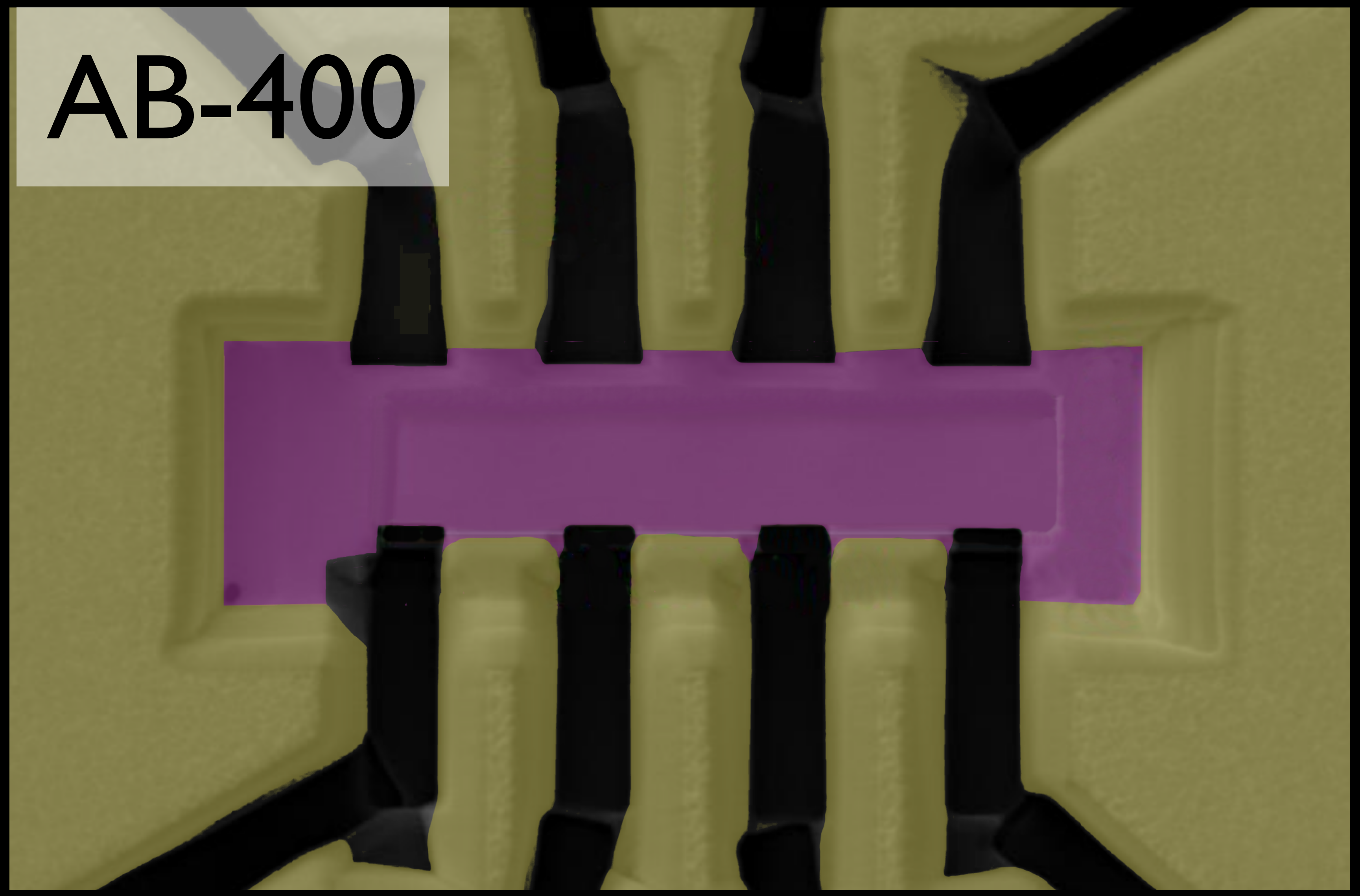




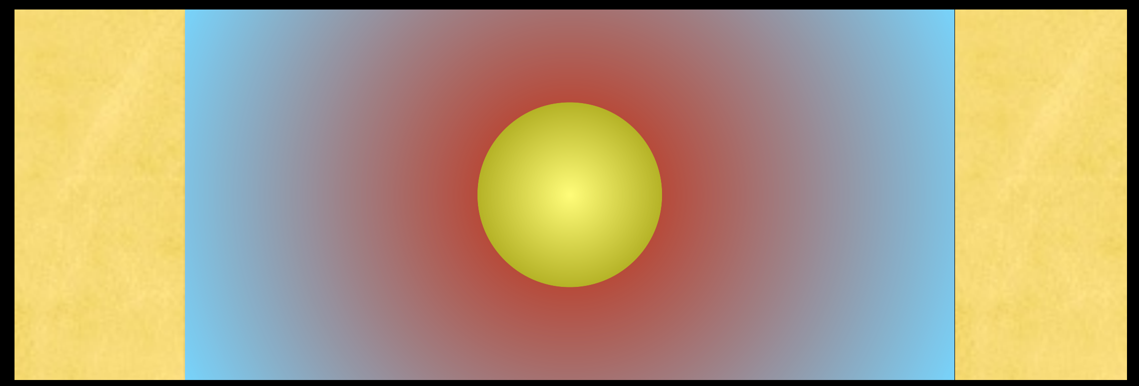


Device Design



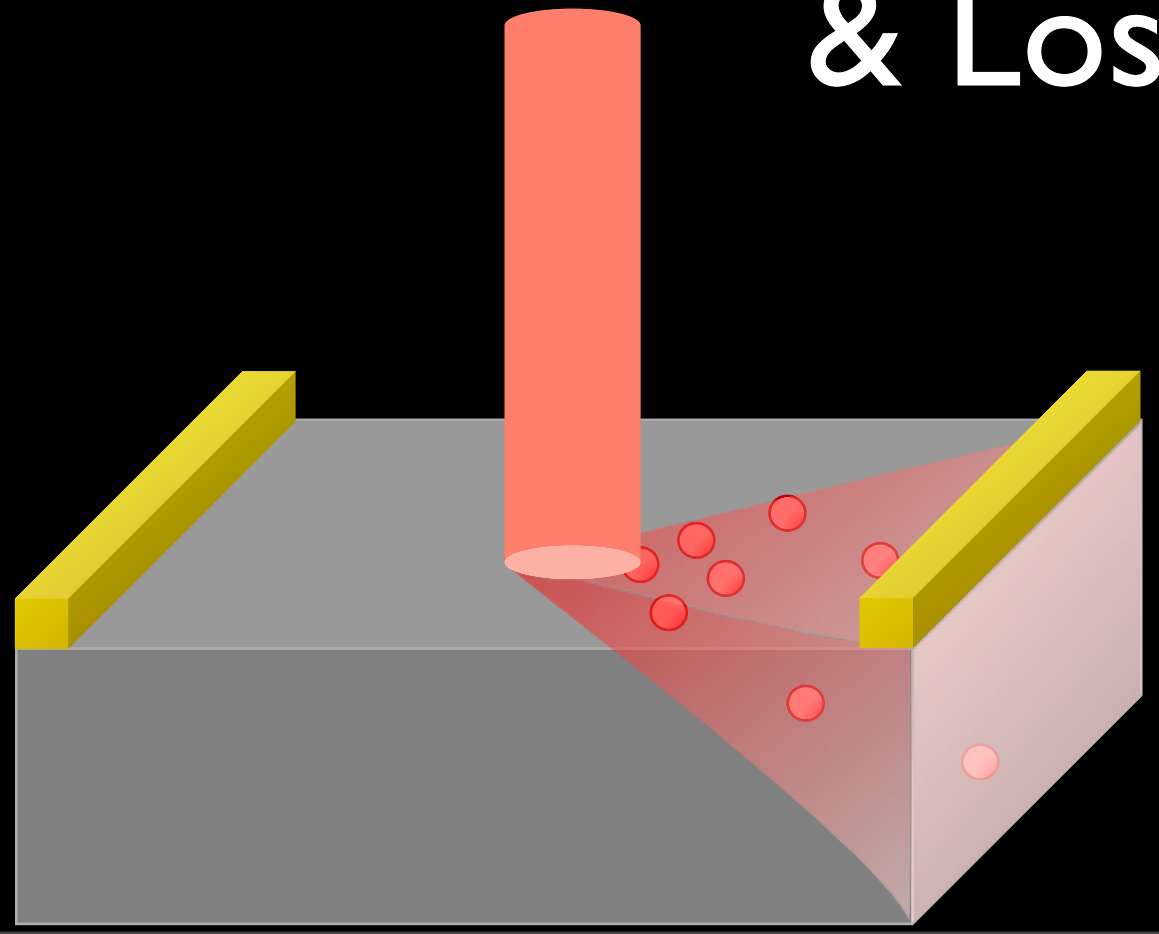


Seebeck



Symmetry

Penetration & Loss



Our Devices

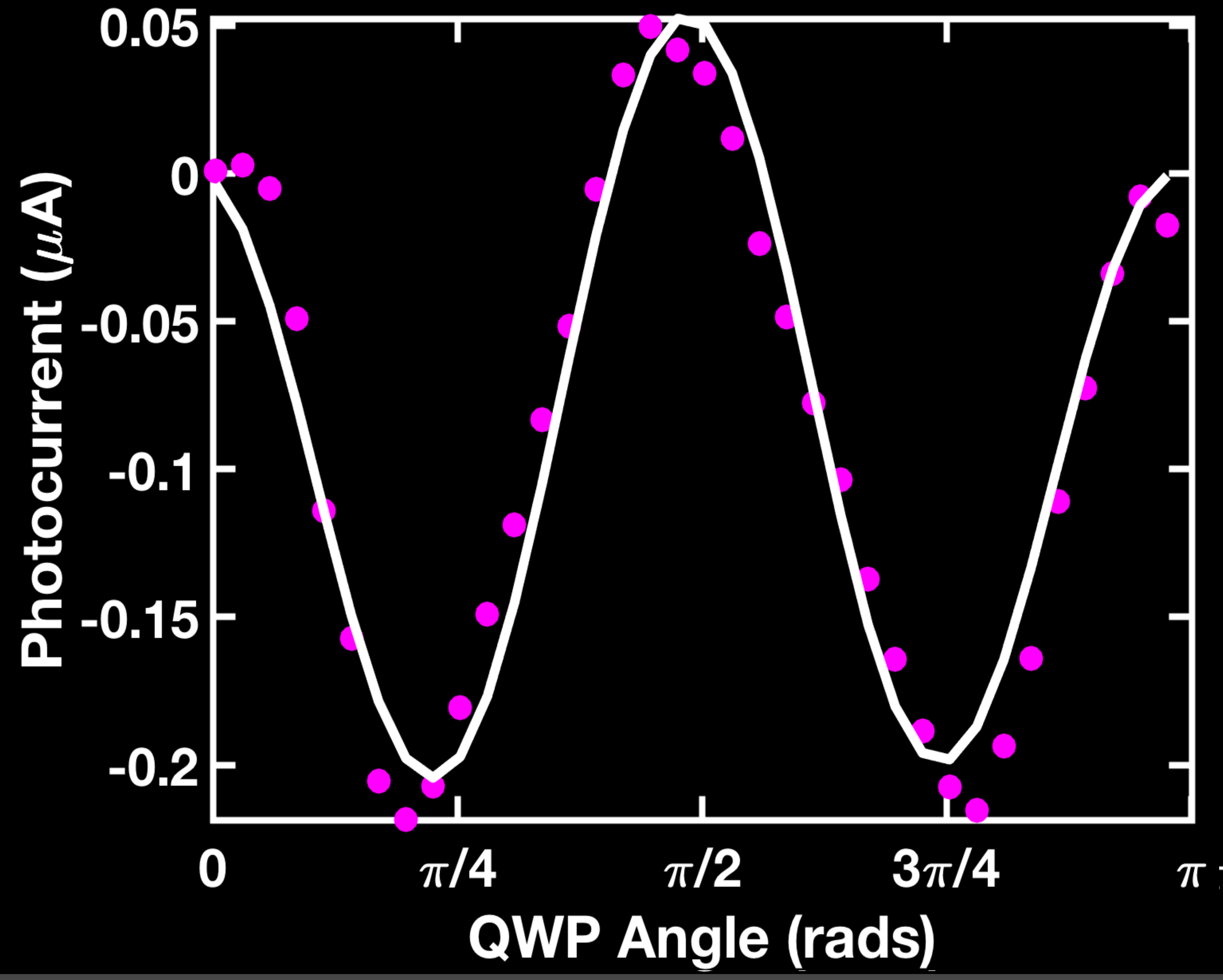
Nature Materials (2019)

Circular: $S_2Sin(2\theta)$

E_xE_y: $S_4Sin(4\theta)$

$|E_x|^2+|E_y|^2$: $D+C_2Cos(2\theta)+C_4Cos(4\theta)$

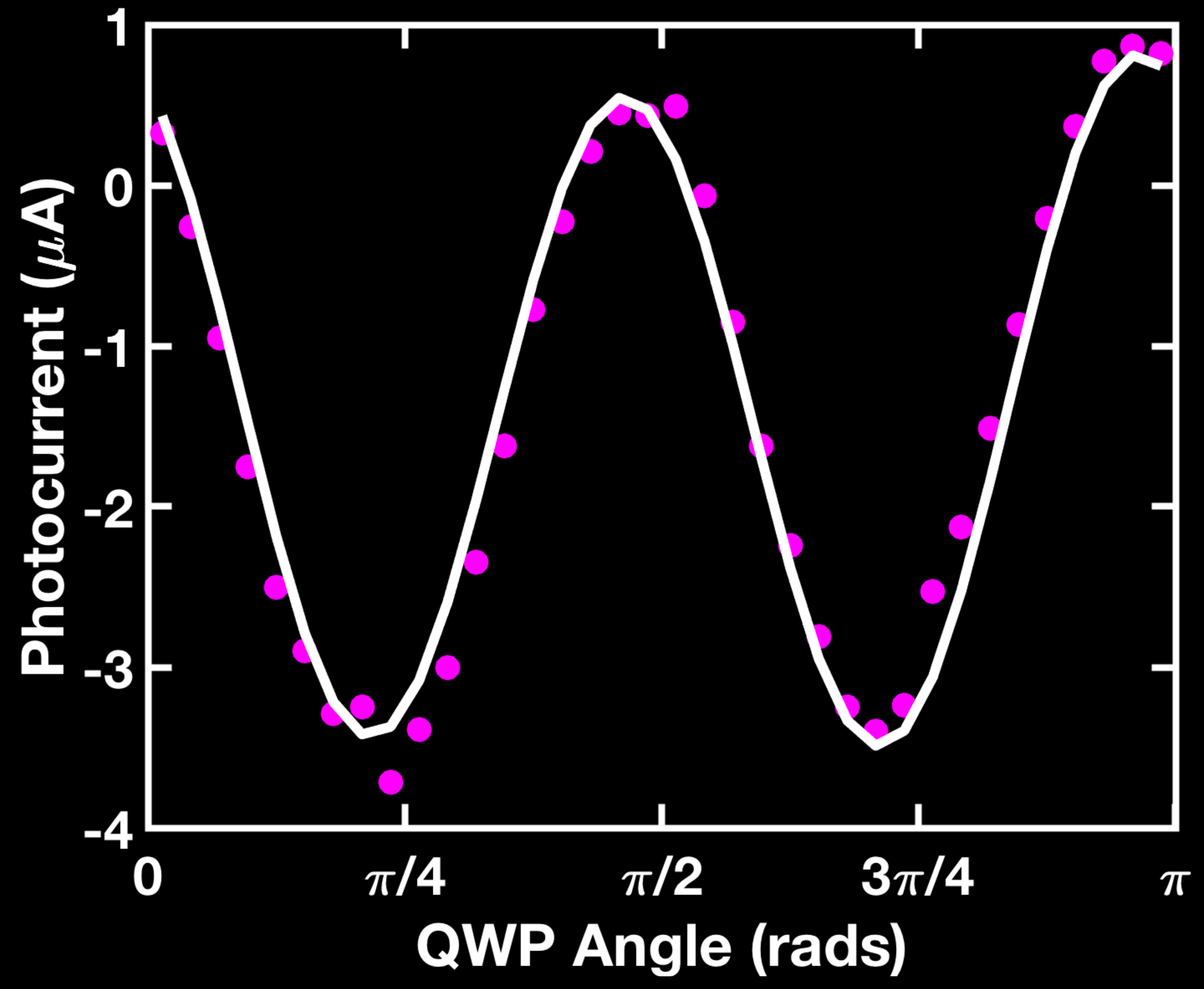
AC-400



$C_4=0.11$

$S_4=-0.02$

AB-400



$\Phi=-13^0$

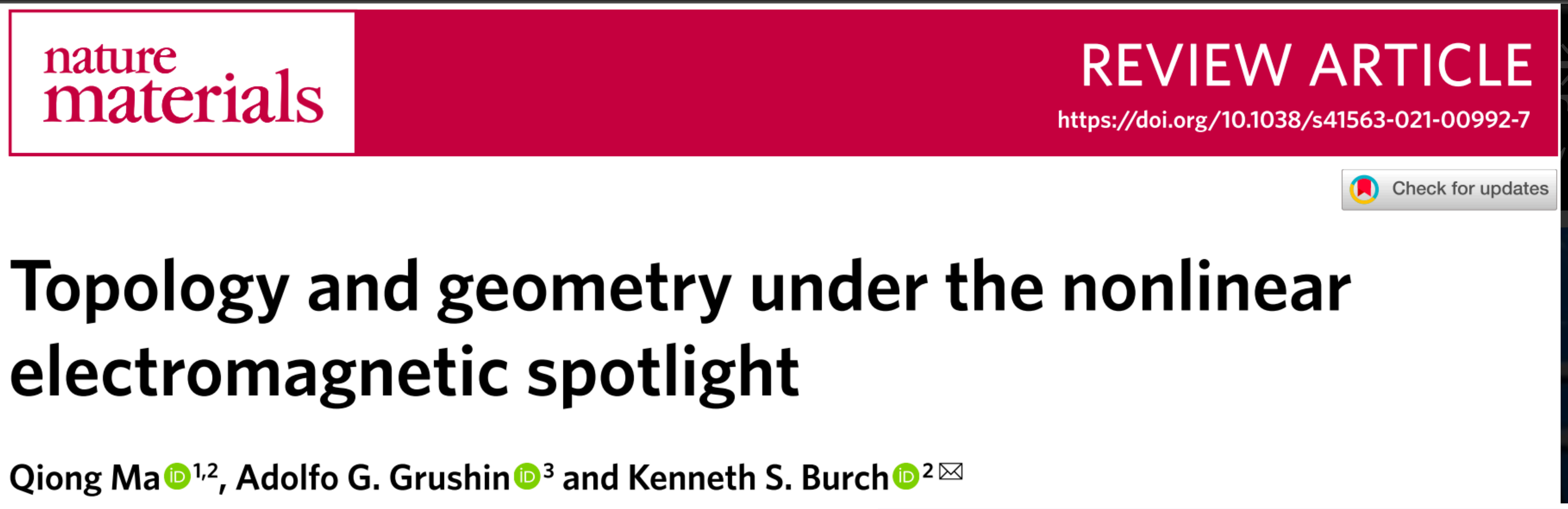
$C_4=1.86$

$S_4=-0.89$

BURCH GROUP

burchlab.org @Burch_Lab

Colossal!



nature materials

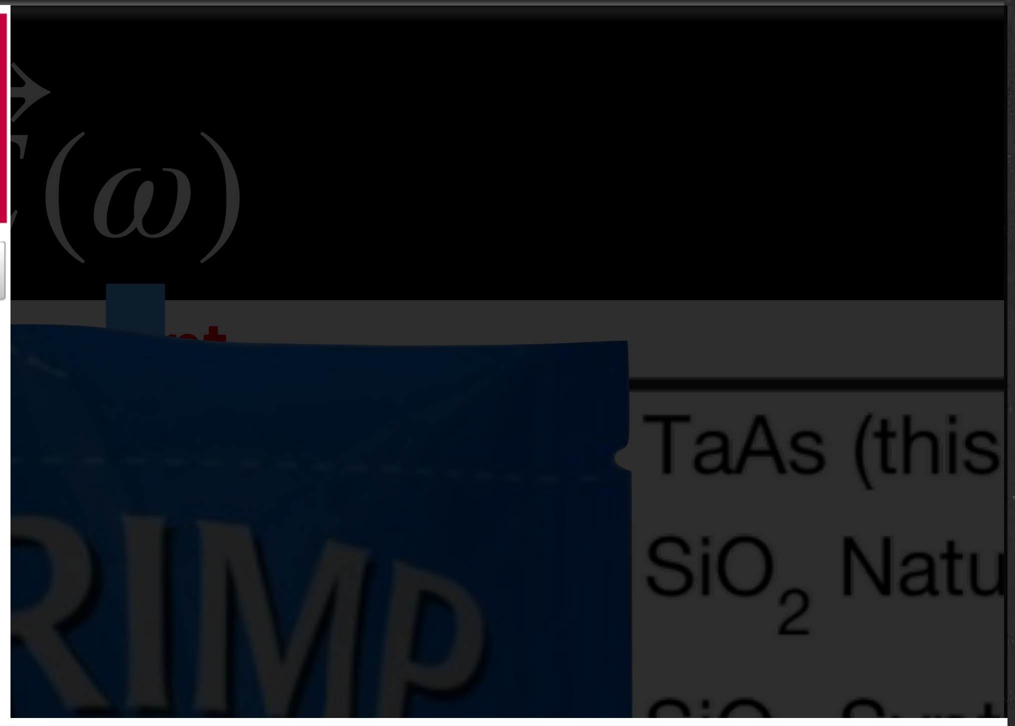
REVIEW ARTICLE

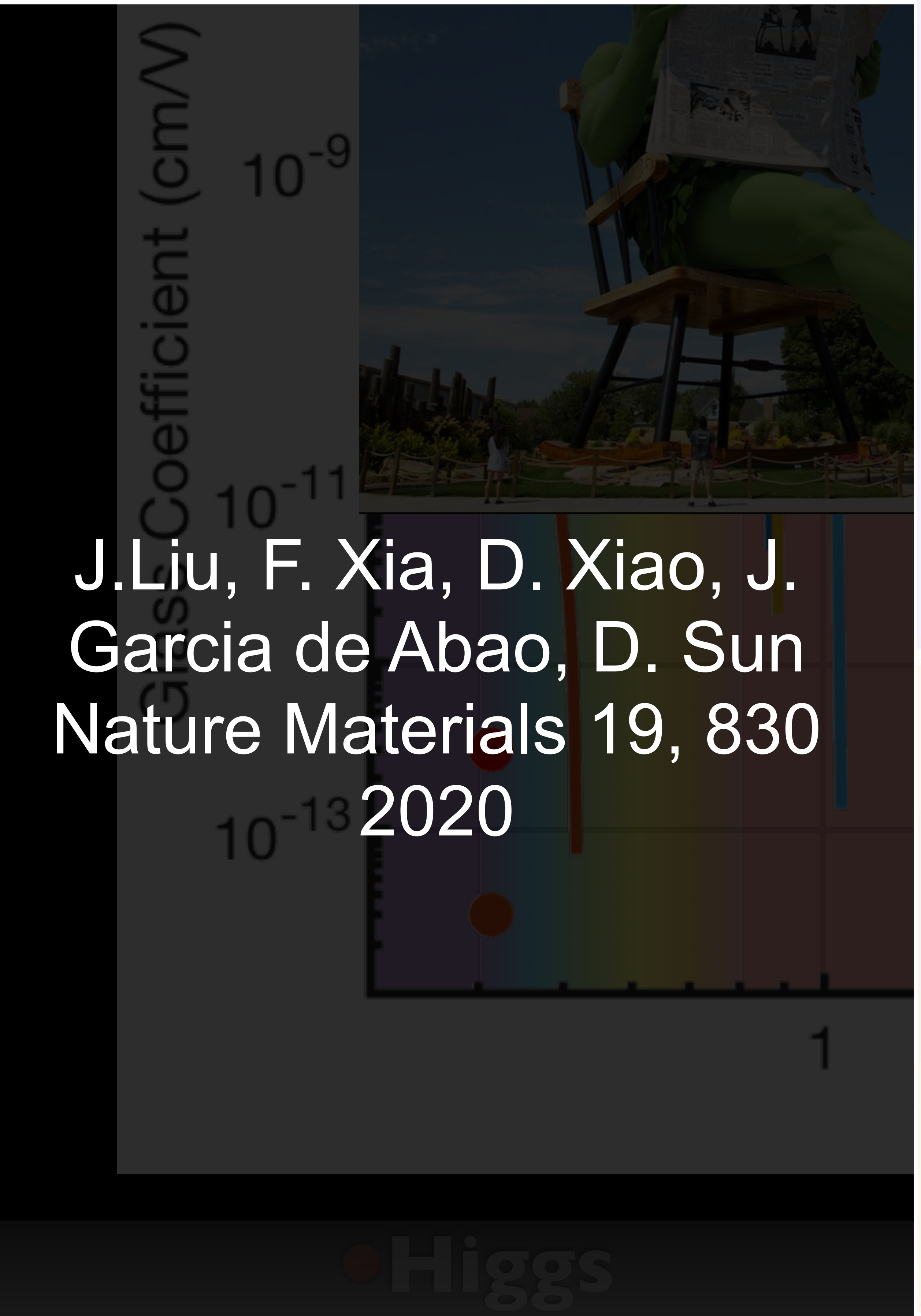
https://doi.org/10.1038/s41563-021-00992-7

Check for updates

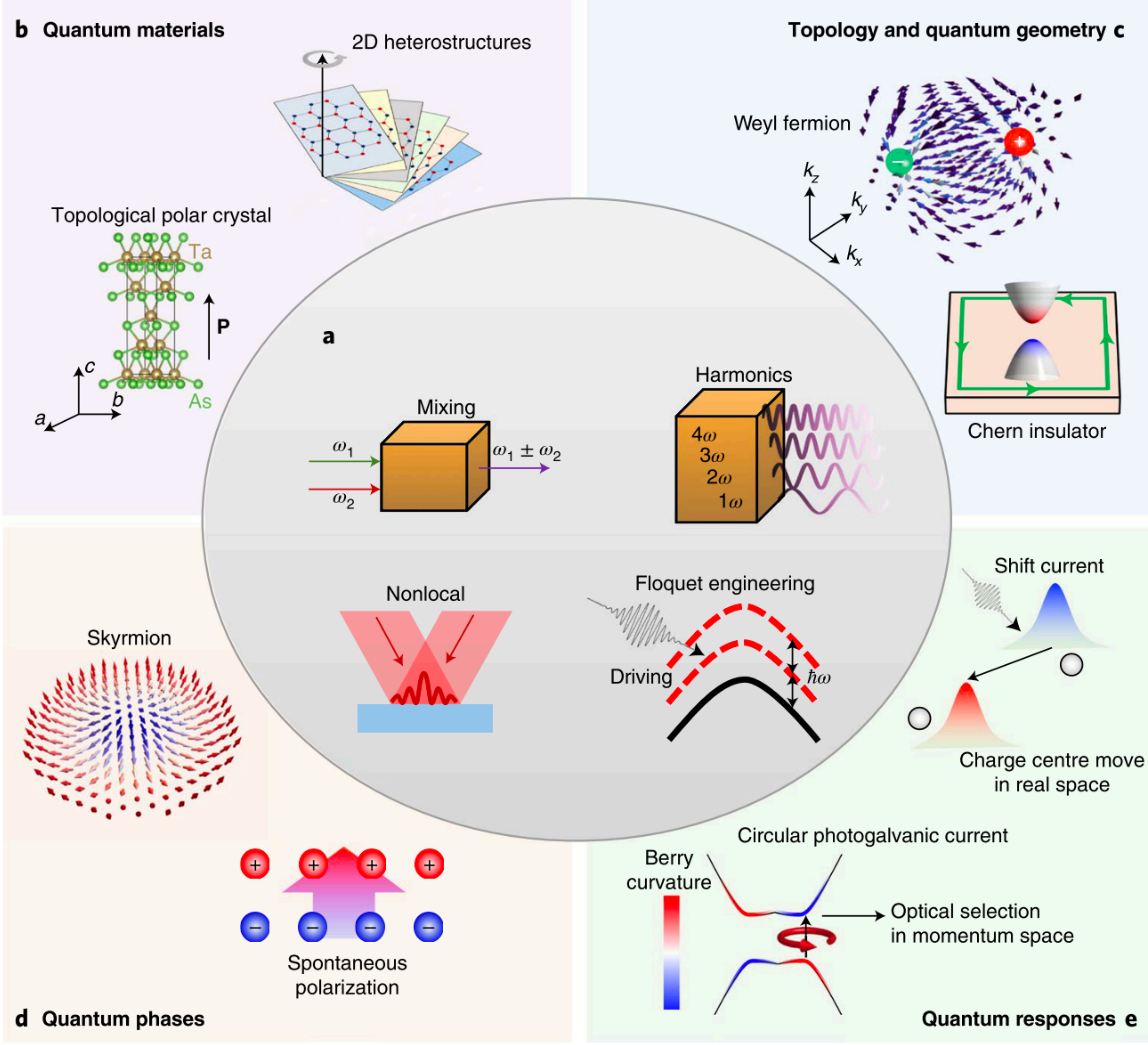
Topology and geometry under the nonlinear electromagnetic spotlight

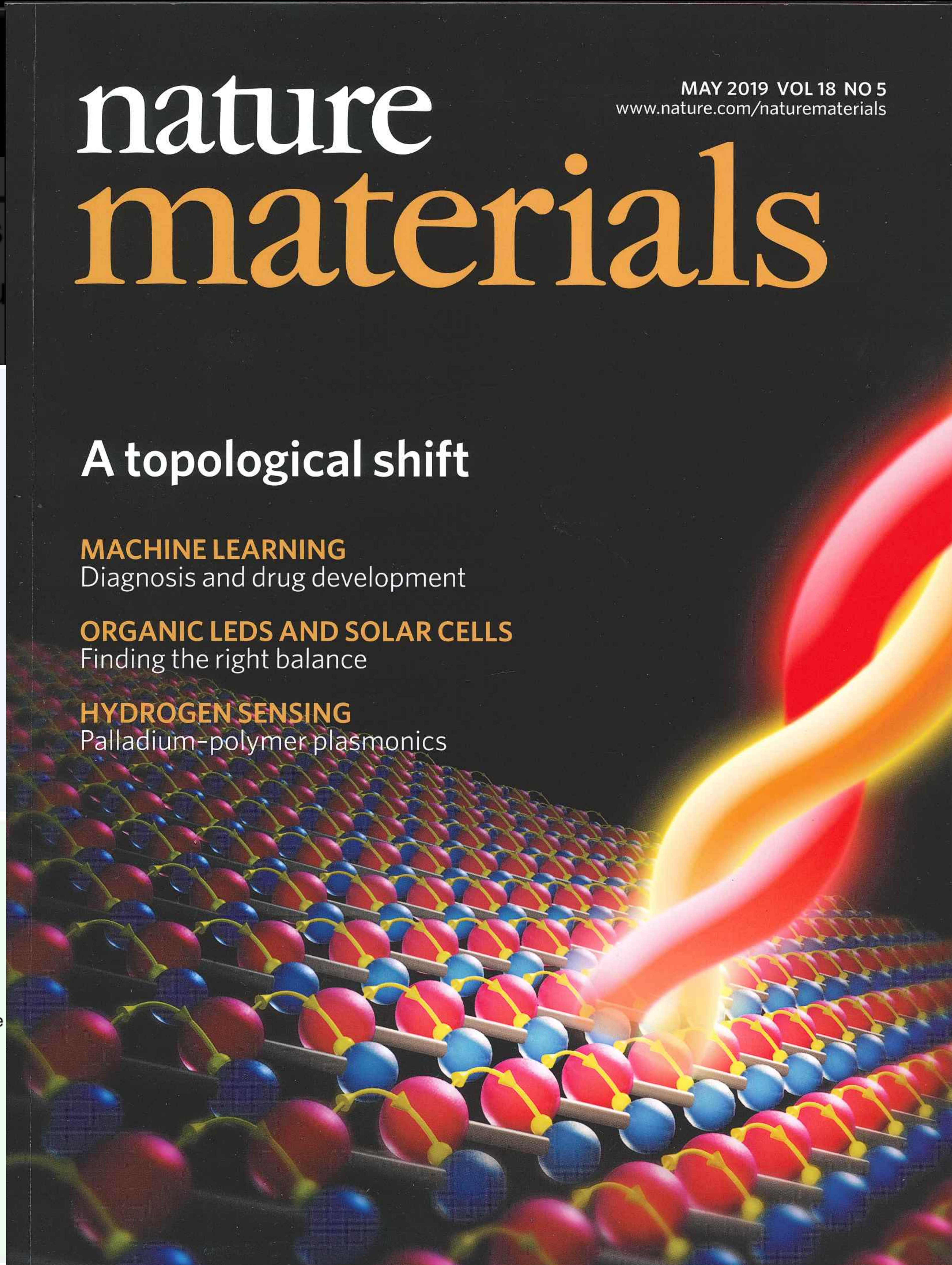
Qiong Ma[1,2], Adolfo G. Grushin[3] and Kenneth S. Burch[2]





J.Liu, F. Xia, D. Xiao, J. Garcia de Abao, D. Sun Nature Materials 19, 830 2020





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A topological shift

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