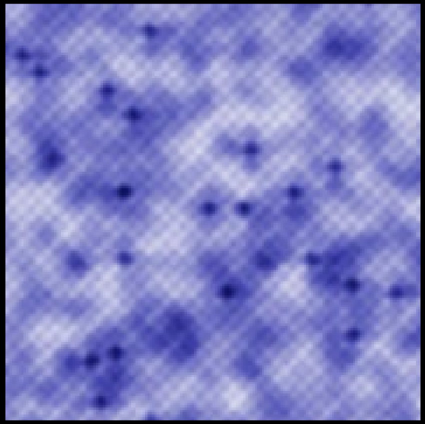
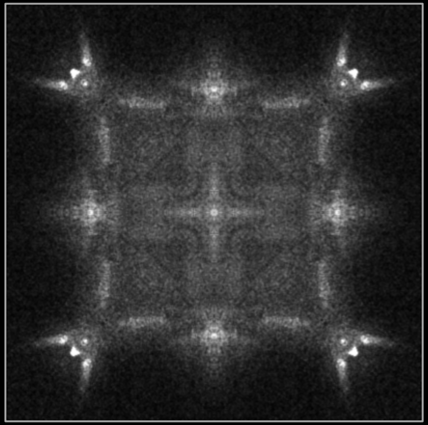
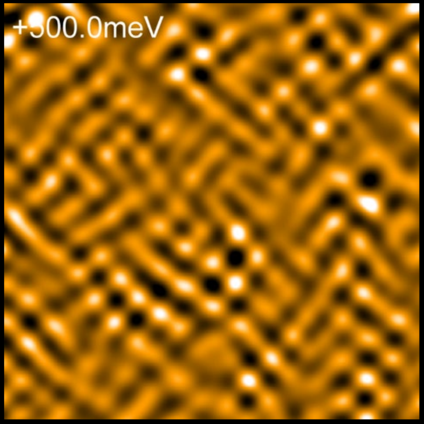
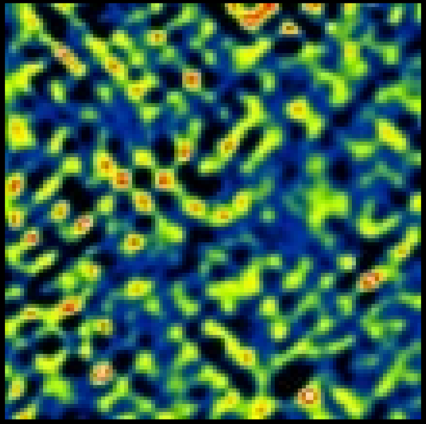
Direct Visualization of Electronic Liquid Crystal Phases in Correlated Topological Semimetals



Tien-Ming Chuang (장천명)
Institute of Physics, Academia Sinica, Taiwan

Team Members















中央研究院 ACADEMIA SINICA 1928

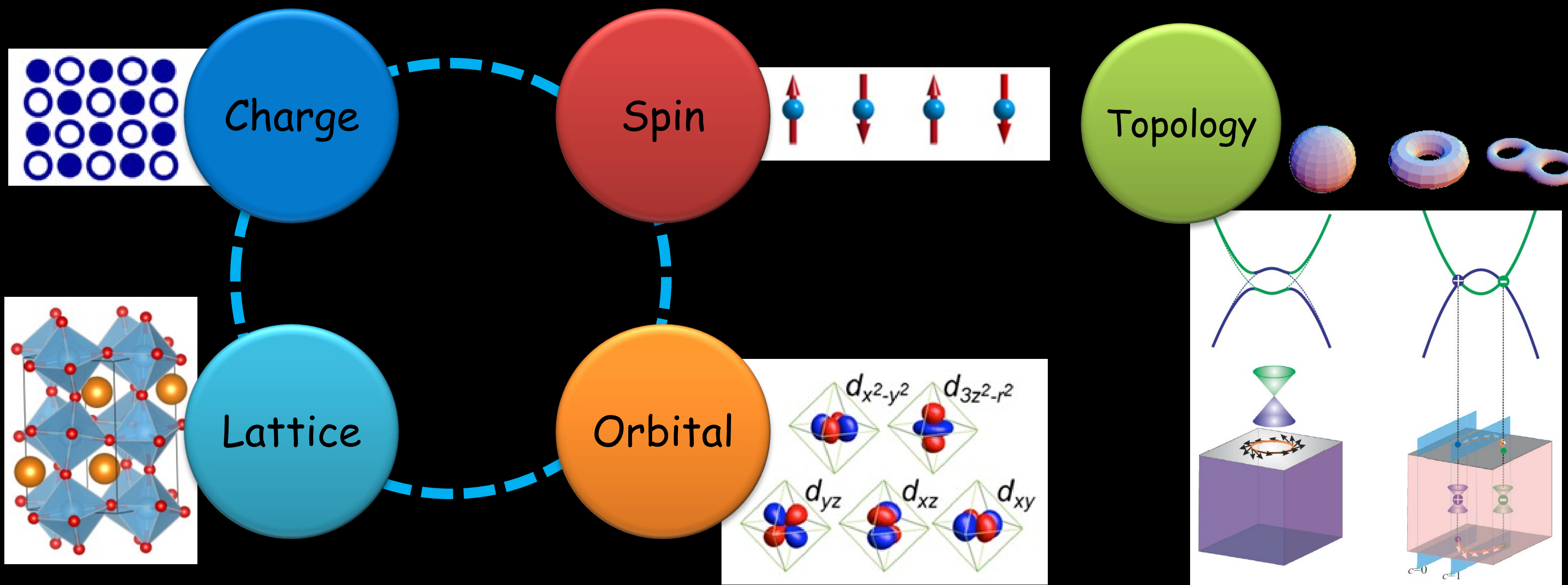
NSTC

KENDA

Quantum Materials

Strongly correlated electron systems (SCESs)

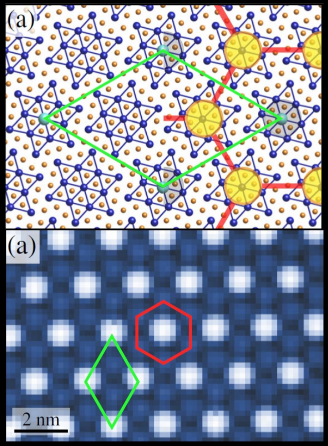
Topological materials



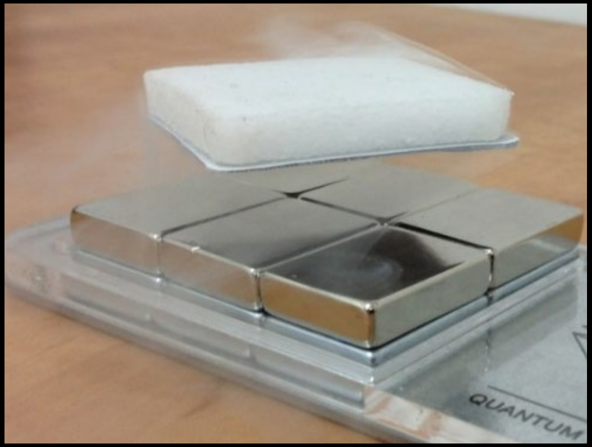
Interactions between these degrees of freedom leads to emergent quantum phases.

Strongly correlated electron systems (SCESs)

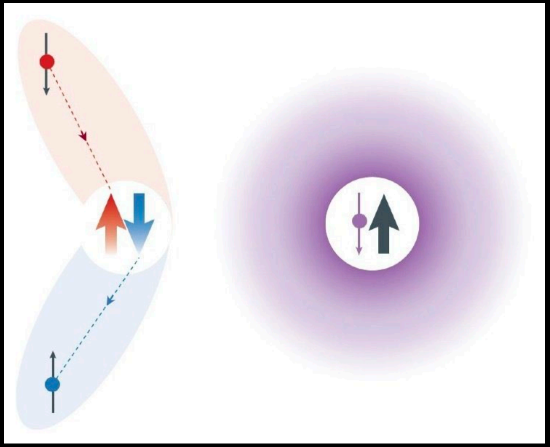
Mott insulators



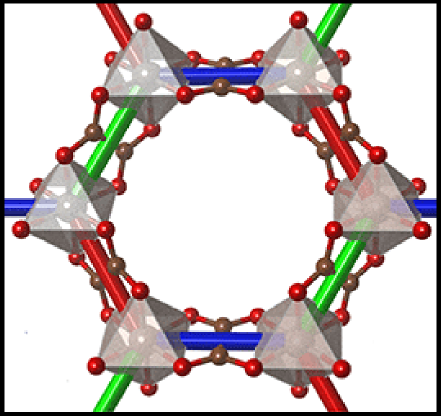
High Tc Superconductors



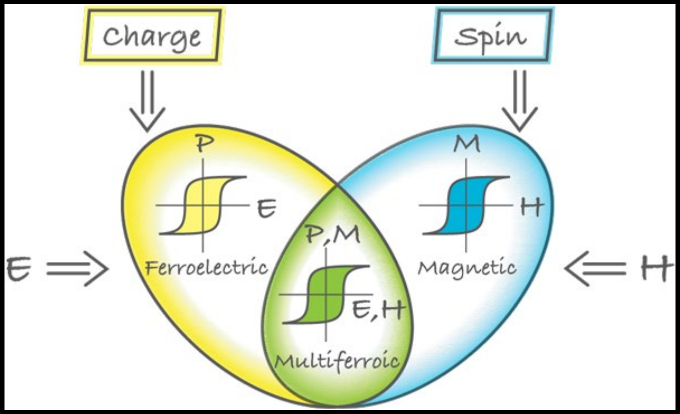
Heavy Fermions & Kondo systems



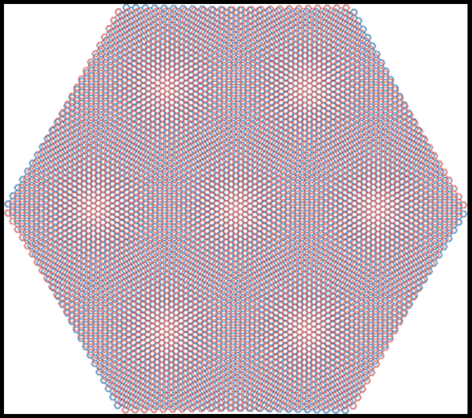
Quantum Spin Liquid



Multiferroics

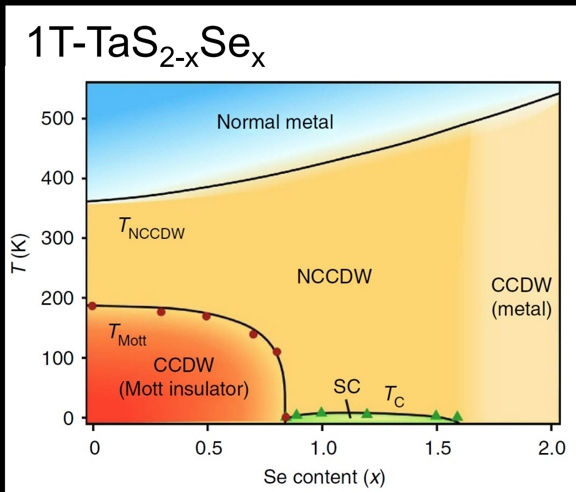


Twisted bilayer graphene

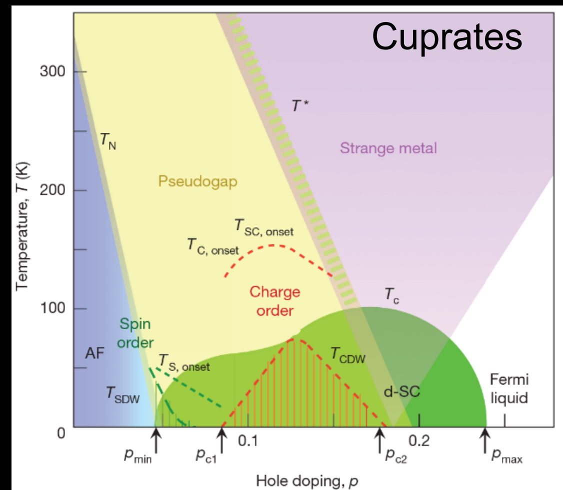


Complex phase diagrams in SCESs

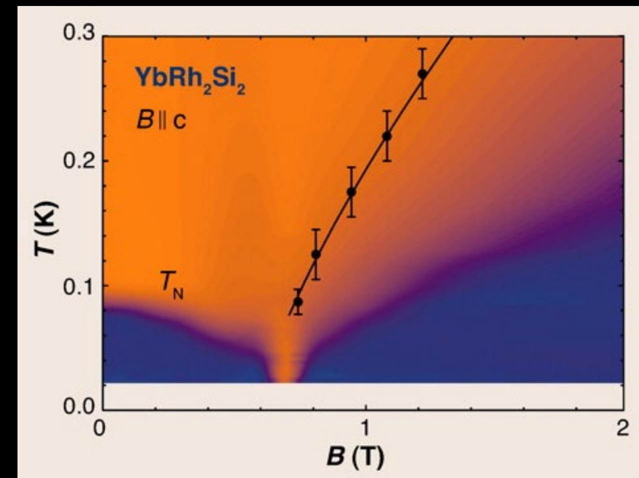
Mott insulators



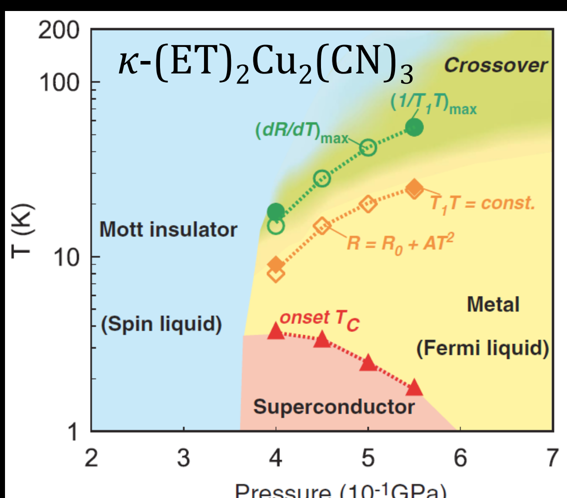
High Tc Superconductors



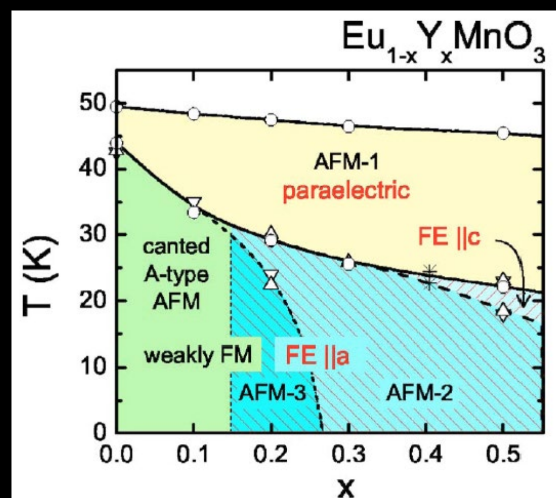
Heavy Fermions & Kondo systems



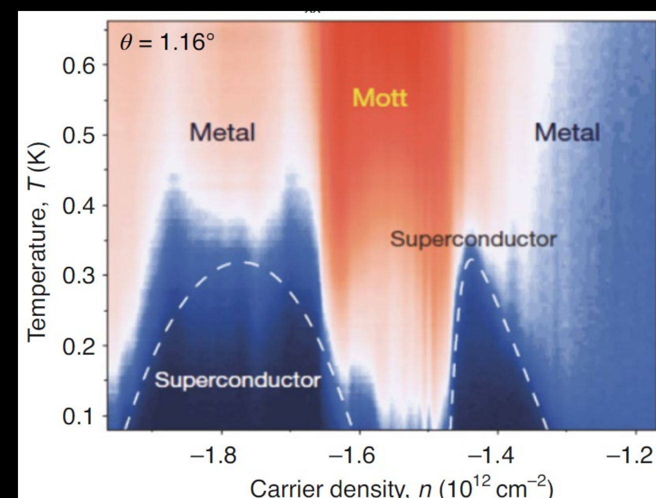
Quantum Spin Liquid



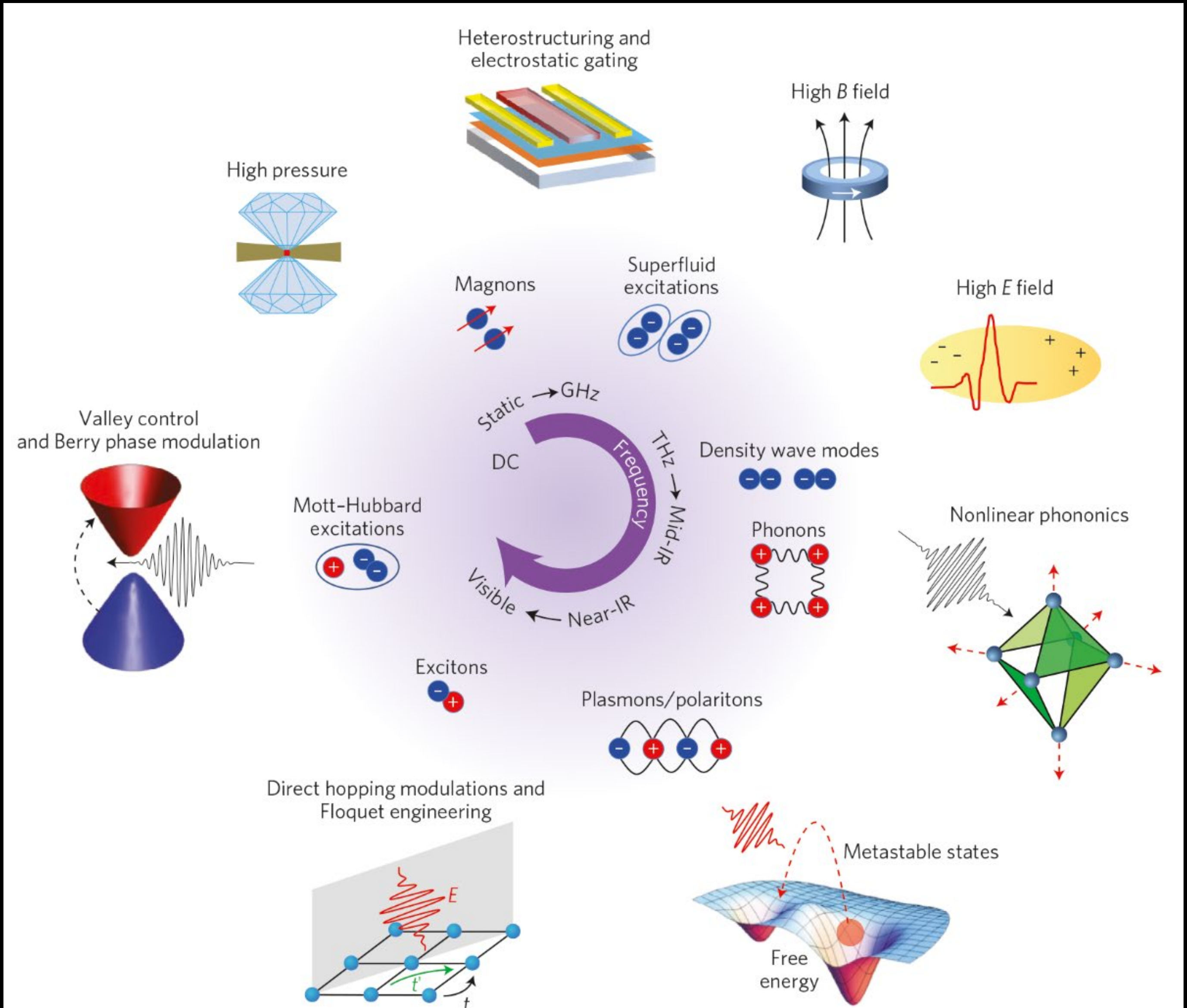
Multiferroics



Twisted bilayer graphene

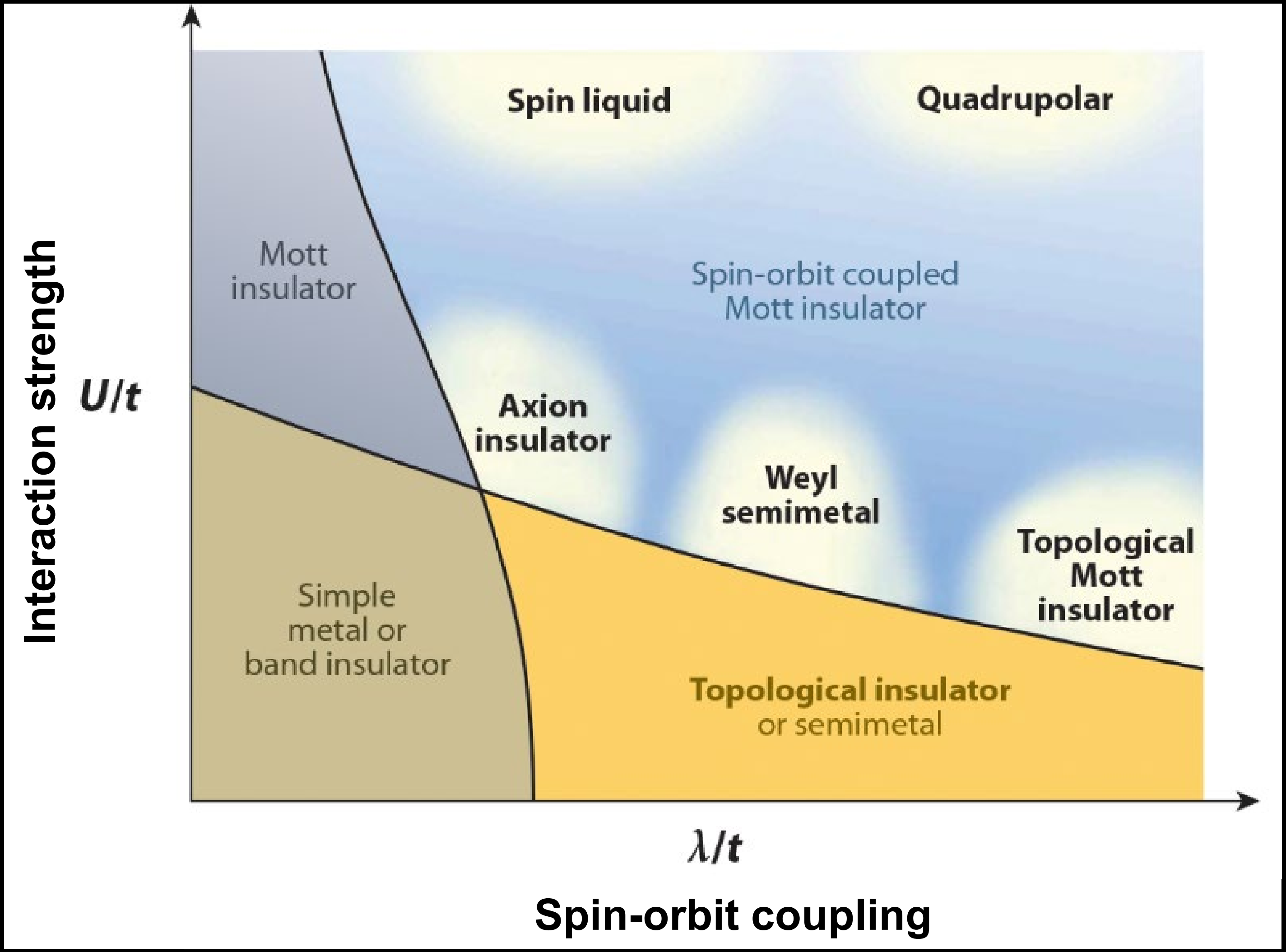


Many ways to control different phases



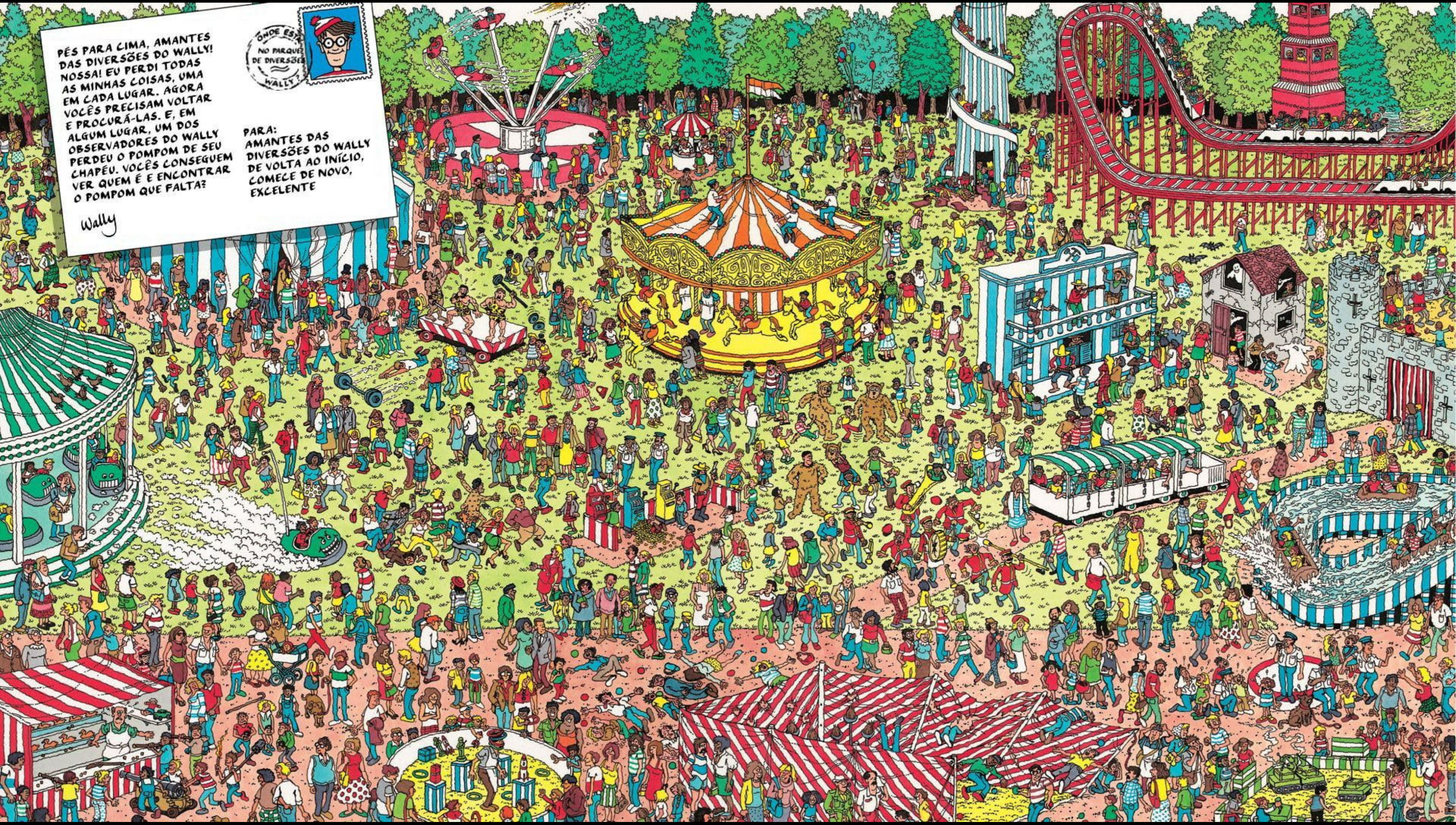
Nature Materials 16, 1077 (2017)

Topological Materials + Electron Correlation

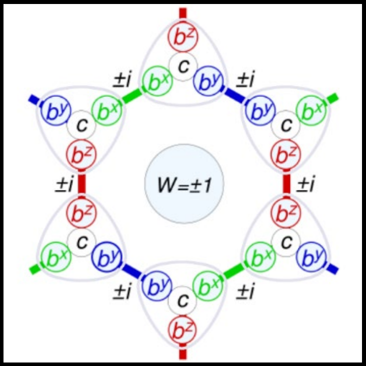


Witczak-Krempa *et al.*, Annu. Rev. Condens. Matter Phys. 5, 57 (2014)

Where to find the correlated topological materials?



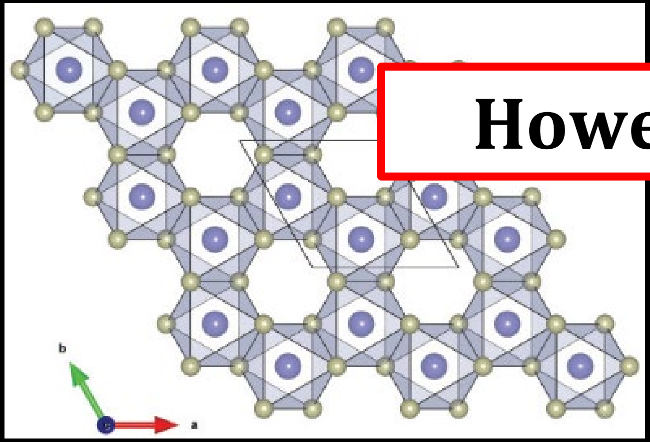
Kitaev quantum spin liquid (QSL)



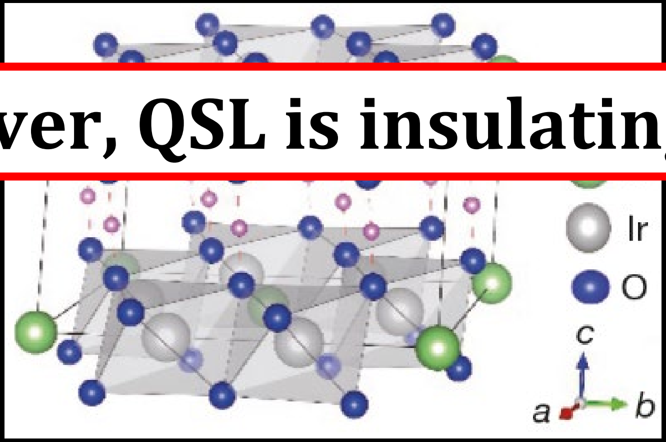
Ann. Phys. 321, 2 (2006)

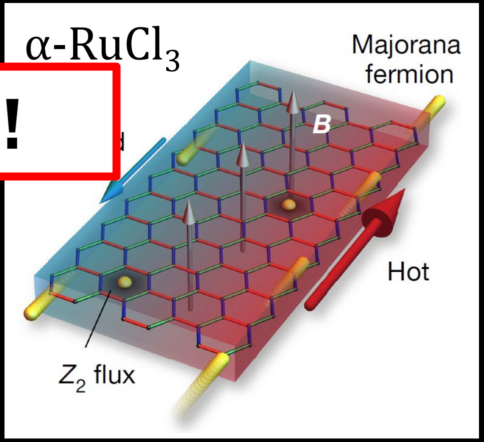
- Kitaev model : S = 1/2 spin on a 2D honeycomb lattice
- Ground state: topological QSL
- Spin fractionalization : Majorana fermions
- Half quantized thermal Hall conductance as a signature of chiral edge currents of Majorana fermions.

α-RuCl$_3$



$H_3LiIr_2O_6$





However, QSL is insulating!

Sandilands *et al.*, PRL 114, 147201 (2015)
Ziatdinov *et al.*, Nat. Comms. 7, 13774 (2016)

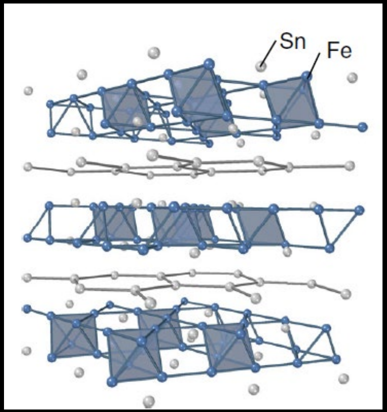
Kitagawa *et al.*, Nature 554, 341 (2018)

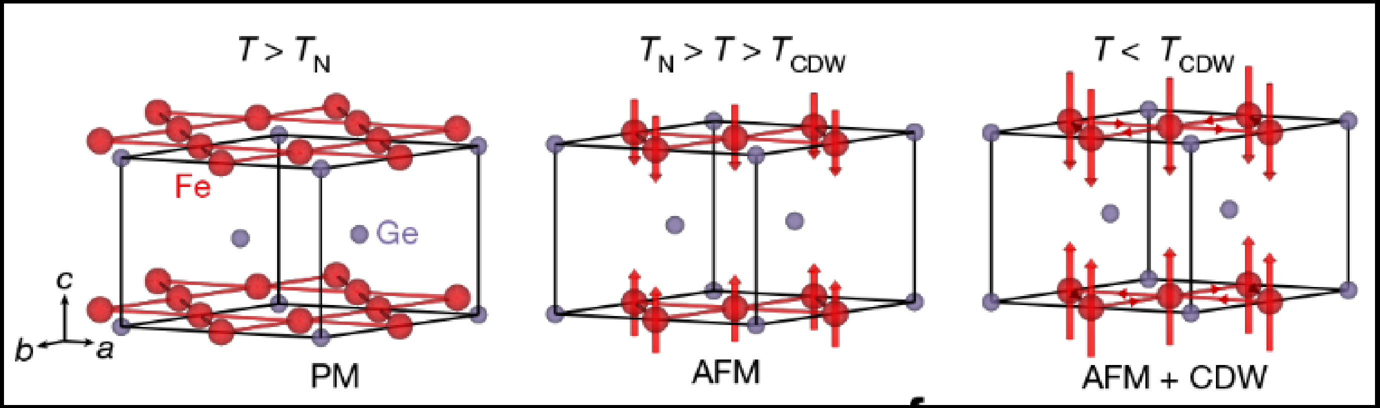
Kasahara *et al.*, Nature 559, 227 (2018)
T. Yokoi *et al.*, Science 373, 568 (2021)

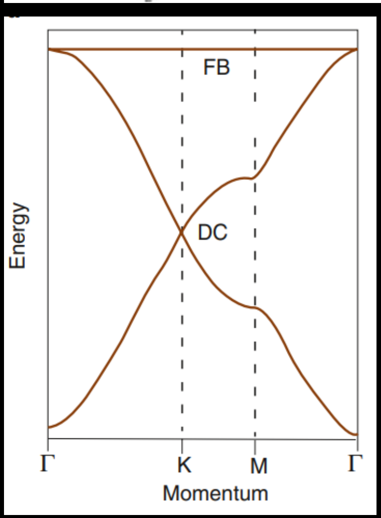
Kagome magnets

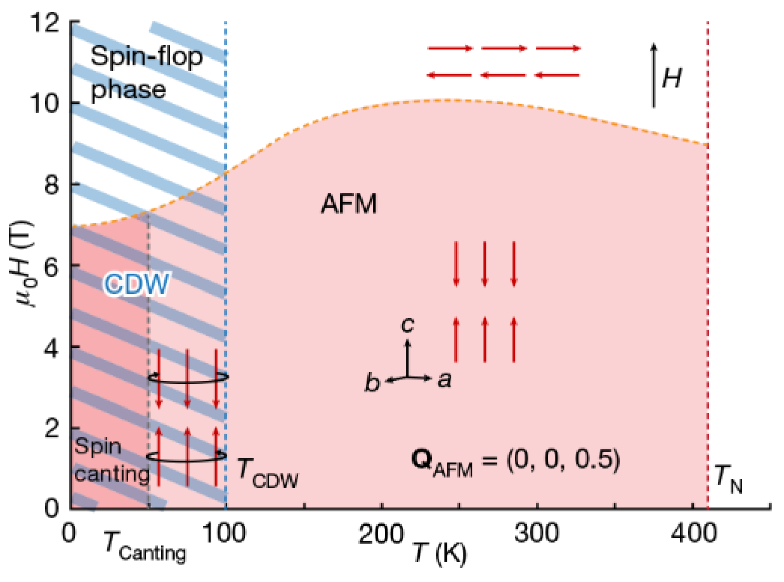
DSM Fe_3Sn_2

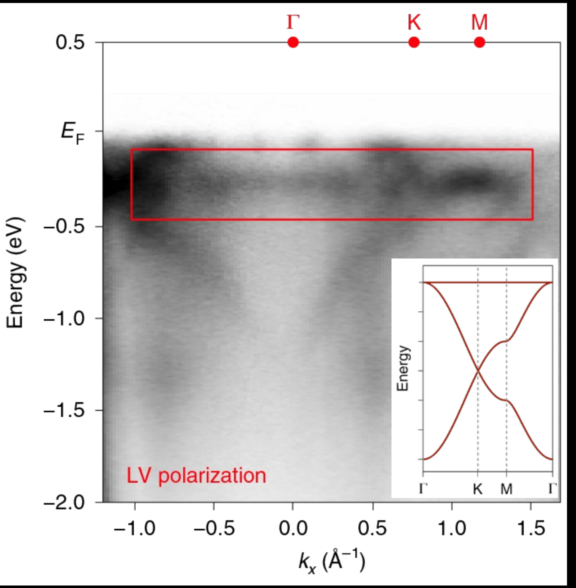
FeGe









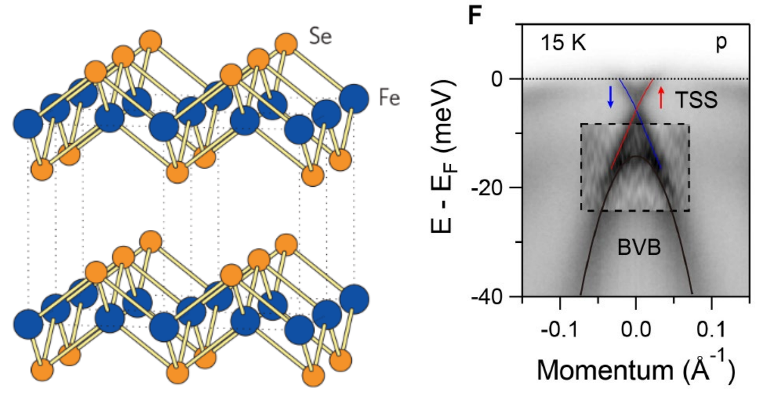


Nature 555, 638 (2018)
Nat. Comm. 10, 4870 (2019)
Nat. Mat. 19, 163 (2019)

Kang *et al.*, Nature Materials 19, 163 (2020)
Teng *et al.*, Nature 609, 490 (2022)

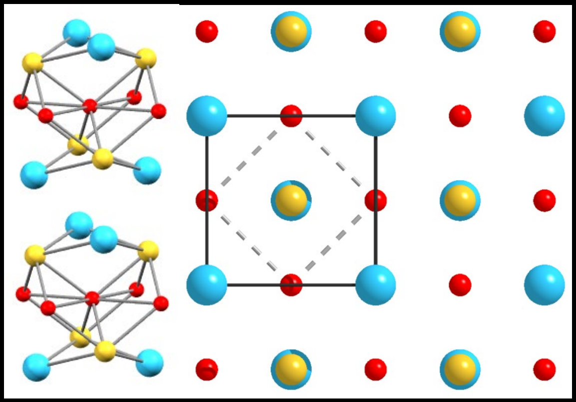
Fe-based high Tc superconductors

Fe(Te,Se)

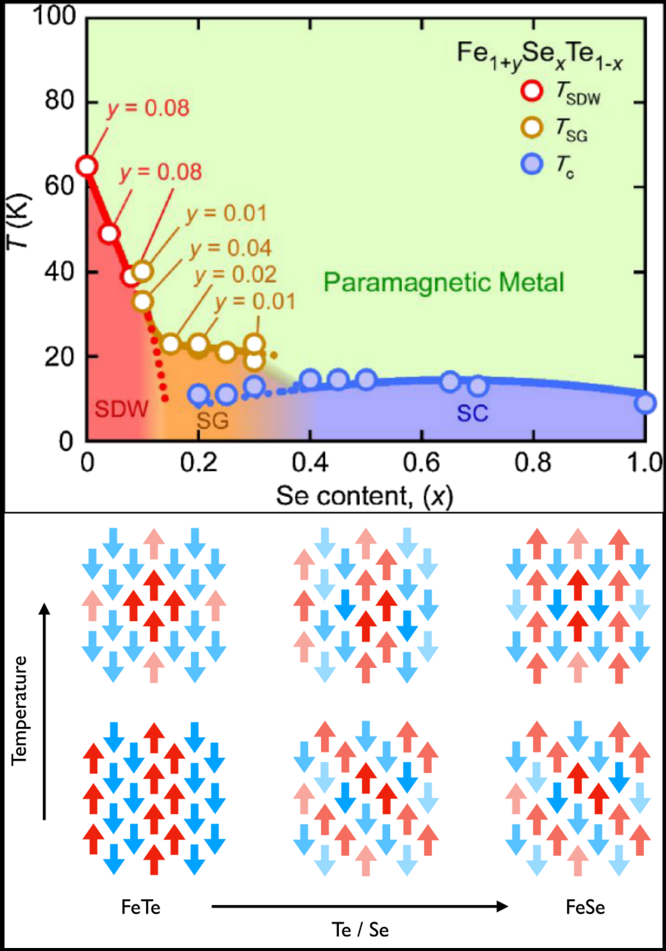


Zhang *et al.*, Science 360, 182 (2018)

Li(Fe,Co)As

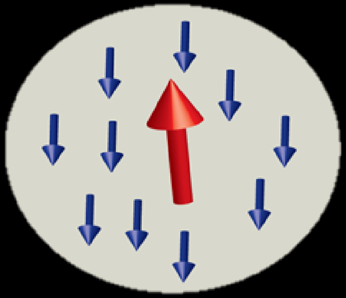


Zhang *et al.*, Nat. Phys. 15, 41 (2019)

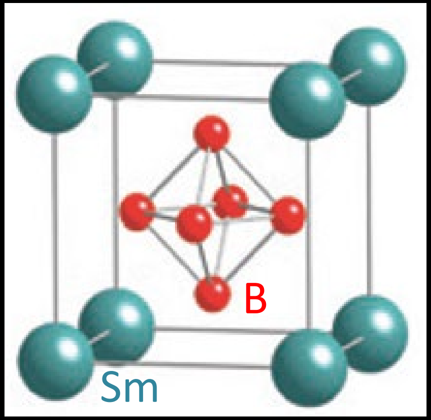


Tranquada *et al* J. Phys.: Condens. Matter 32, 374003 (2020)

Kondo lattice systems

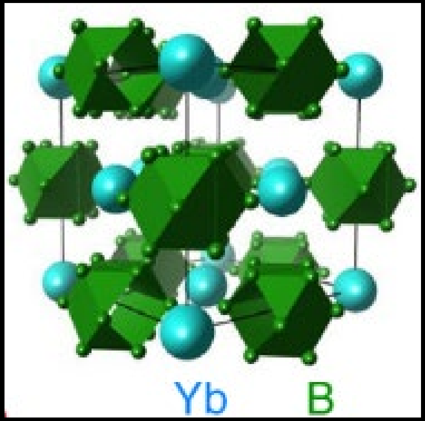


SmB_6



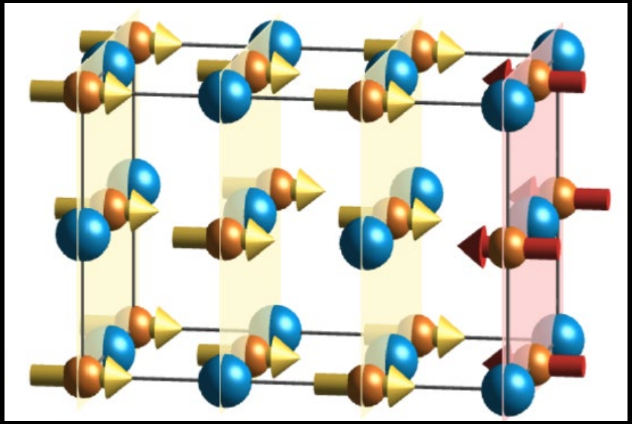
Nat. Mat. 13, 466 (2014)

YbB_{12}



PRL112, 016403 (2014)

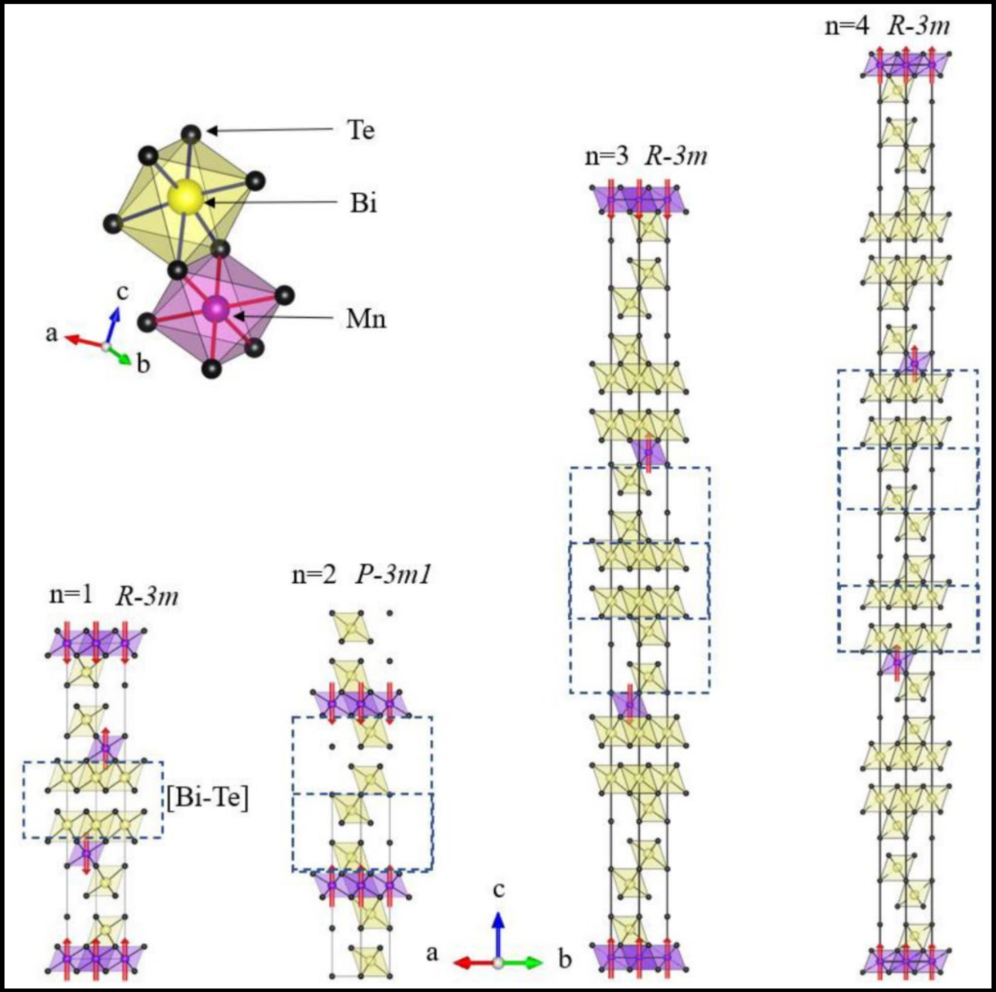
Possible WSM CeBi



PRL 120, 086402 (2018)
PRB 105, 085134 (2022)

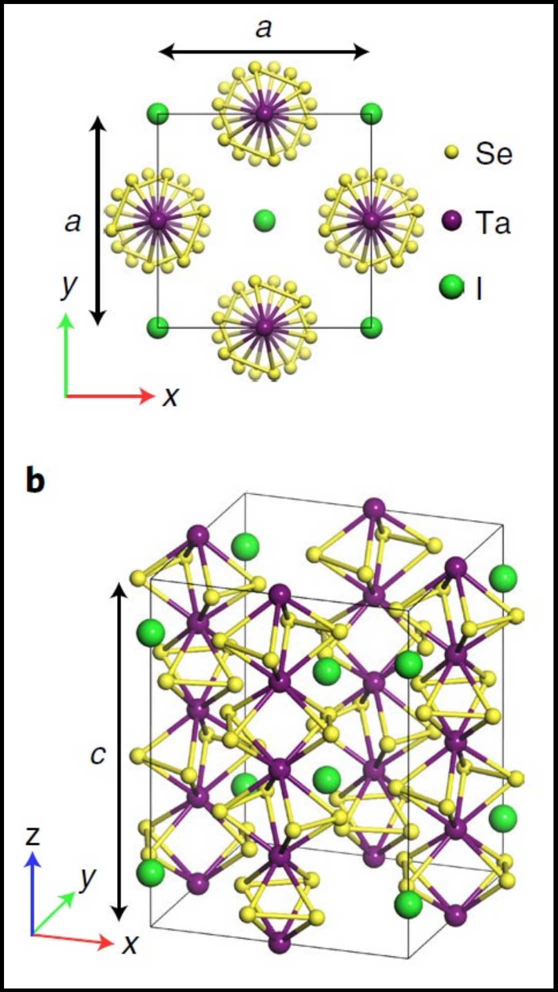
Magnetic semimetals & axion insulators

Intrinsic magnetic TI, $MnBi_{2n}Te_{3n+1}$



Li *et al.*, Sci.Adv. 5, eaaw5685 (2019)
Hu *et al.*, Nat. Comms. 11, 97 (2020)
Liu *et al.*, Nat. Mat. 19, 522 (2020)
Hu *et al.*, Sci. Adv. 6, eaba4275 (2020)

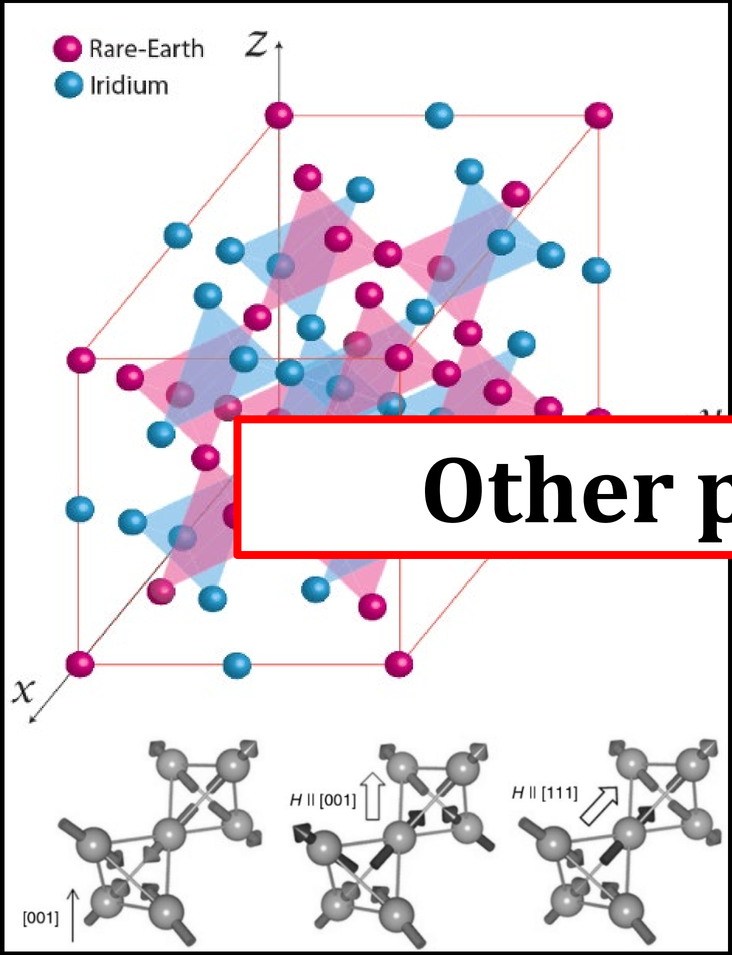
CDW+Weyl in $(TaSe_4)_2I$



Gooth *et al.*, Nature 575, 315 (2019)
Shi *et al.*, Nat. Phys. (2021)

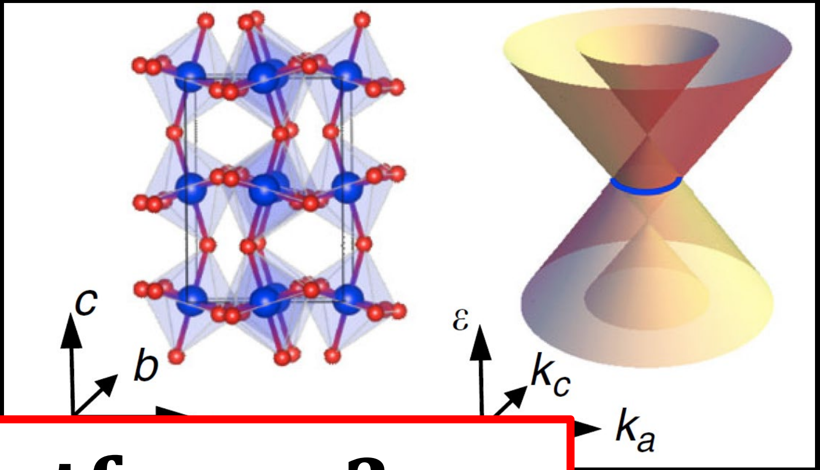
Iridates (5d-TMO)

WSM? pyrochlore $R_2Ir_2O_7$



Wan *et al.*, PRB 83, 205101 (2011)
Ueda *et al.*, Nat. Comm. 8, 15515 (2017)
Ueda *et al.*, Nat. Comm. 9, 3032 (2018)

Dirac line node in perovskite $CaIrO_3$

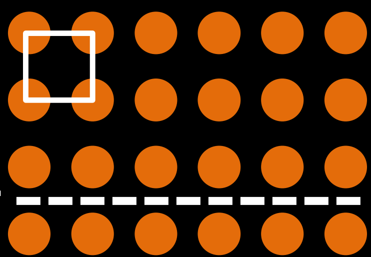


2 (2021)

Other platforms?

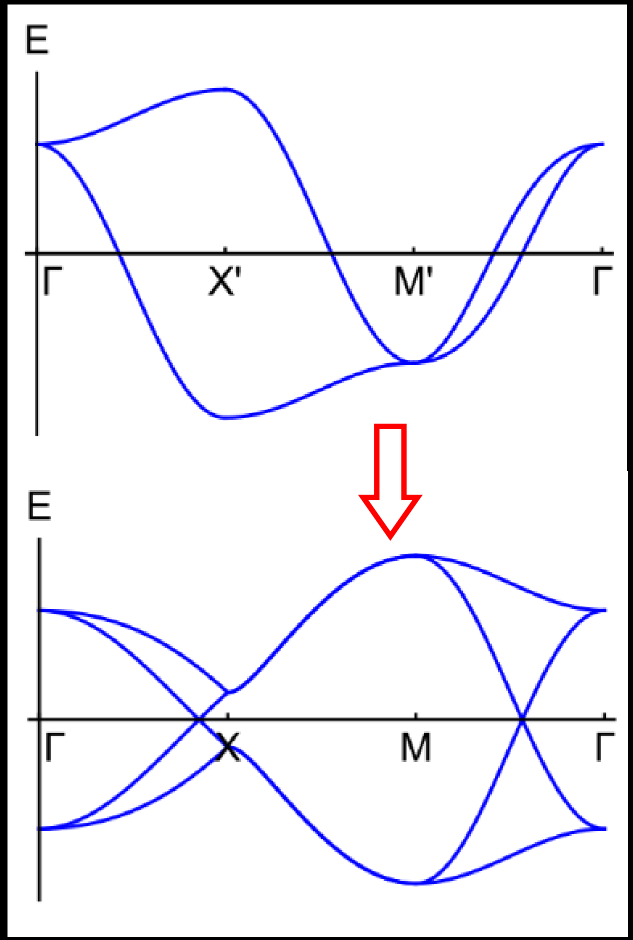
Non-symmorphic Dirac Nodal Line Semimetals, ZrSiS

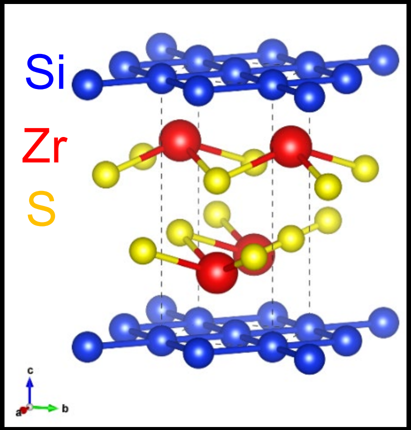
Symmorphic



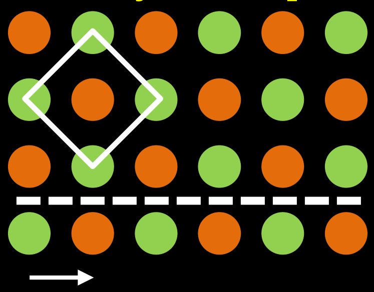
mirror

Banding folding half-filled *p*-orbitals

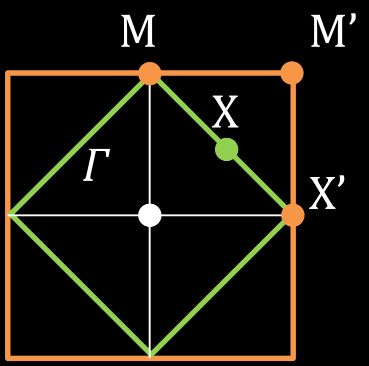




Non-symmorphic

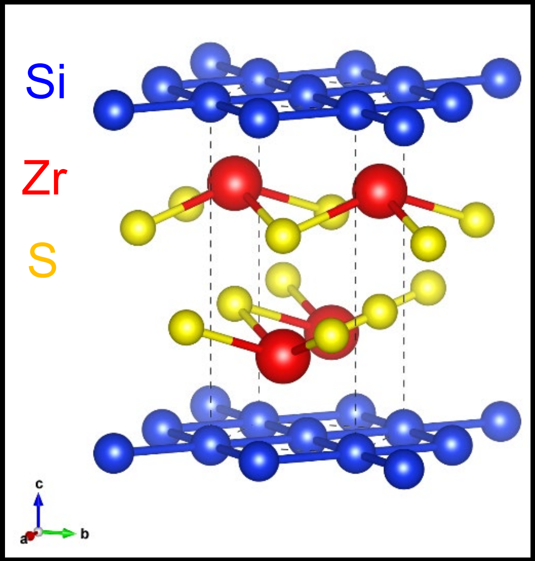


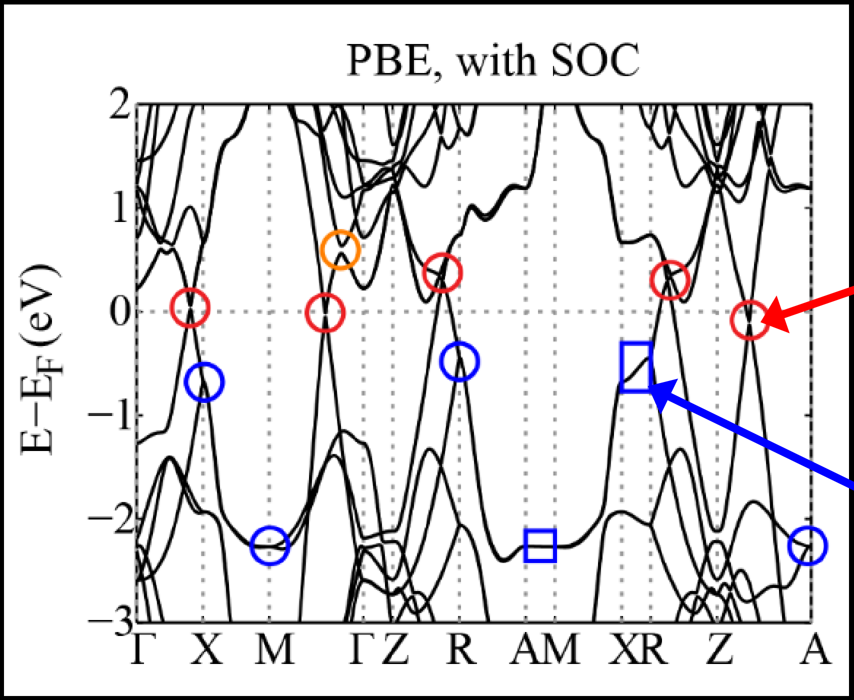
Glide-
mirror



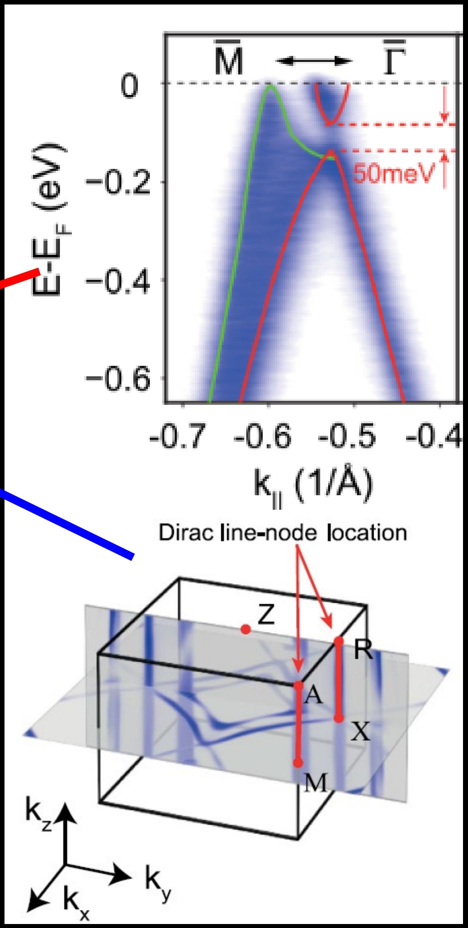
Young & Kane, PRL115, 126803 (2015)
L.M. Schoop *et al.*, Nat Comm. 7, 11696 (2016)

Non-symmorphic Dirac Nodal Line Semimetals, ZrSiS



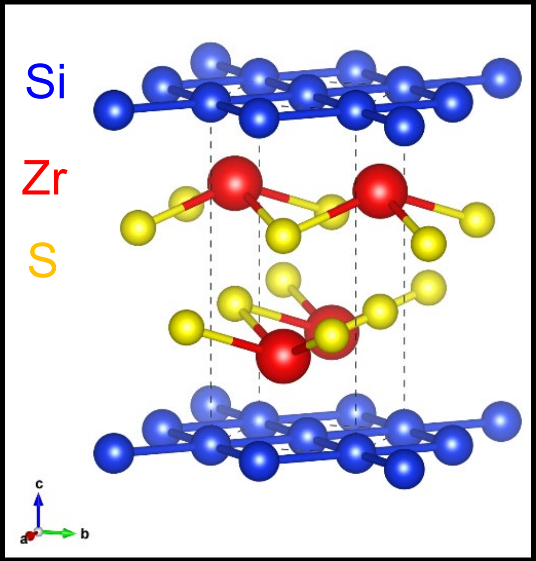


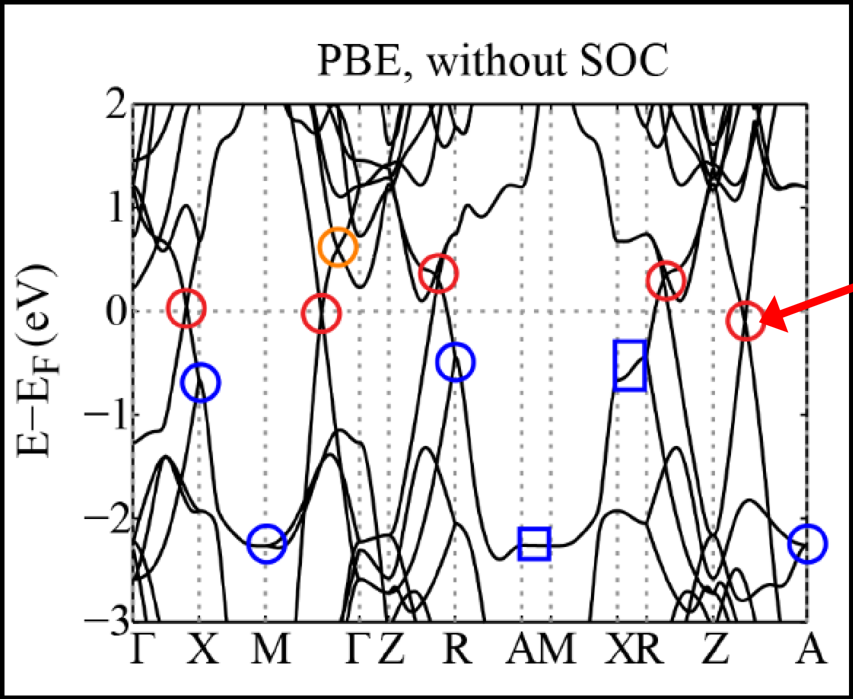
ns-symmetry protected



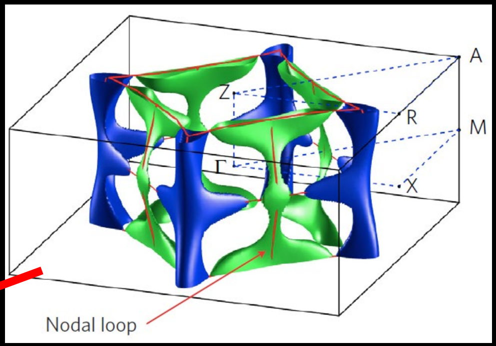
L.M. Schoop *et al.*, Nat Comm. 7, 11696 (2016)
Ali *et al.*, Sci. Adv.2, e1601742 (2016)
C. Chen *et al.*, PRB 95, 125126 (2017)
Su *et al.*, New J. Phys. 20, 103025 (2018)
Pezzini *et al.*, Nat. Phys. 14, 178 (2018)

Non-symmorphic Dirac Nodal Line Semimetals, ZrSiS

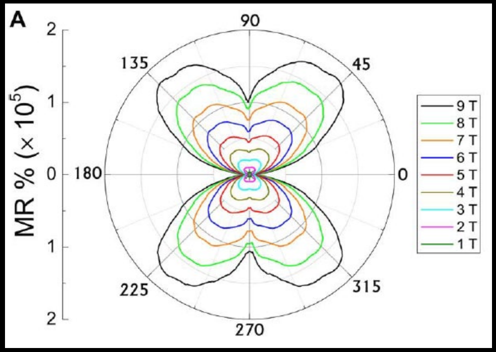




m-symmetry protected



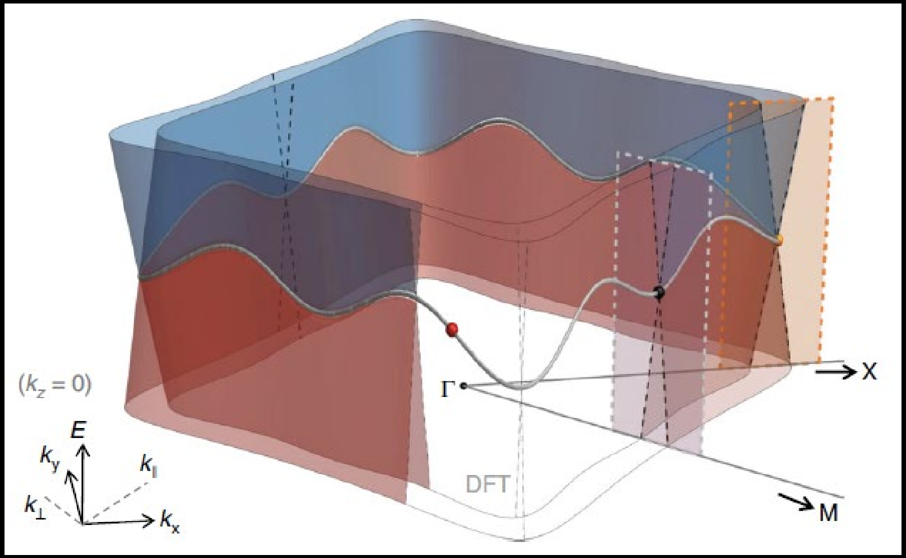
Butterfly AMR

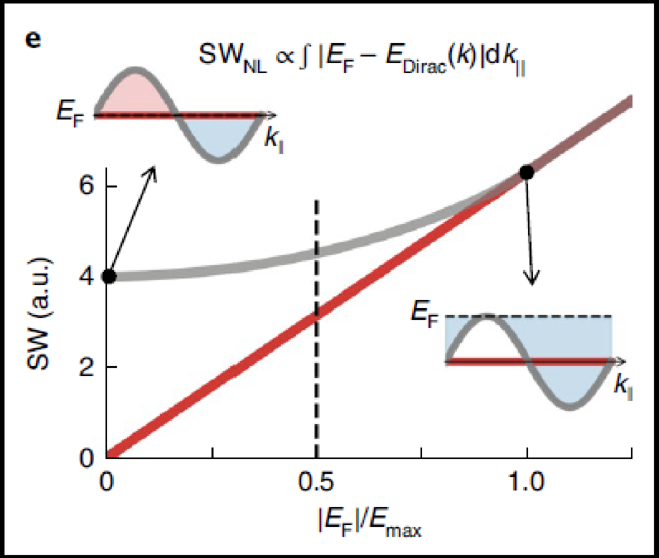


L.M. Schoop *et al.*, Nat Comm. 7, 11696 (2016)
Ali *et al.*, Sci. Adv.2, e1601742 (2016)
C. Chen *et al.*, PRB 95, 125126 (2017)
Su *et al.*, New J. Phys. 20, 103025 (2018)
Pezzini *et al.*, Nat. Phys. 14, 178 (2018)

Electronic correlations in ZrSiS family

Strong reduction of V_F and Drude weight;
Large enhancement in m^*.
Electron correlation due to Dirac nodal line.



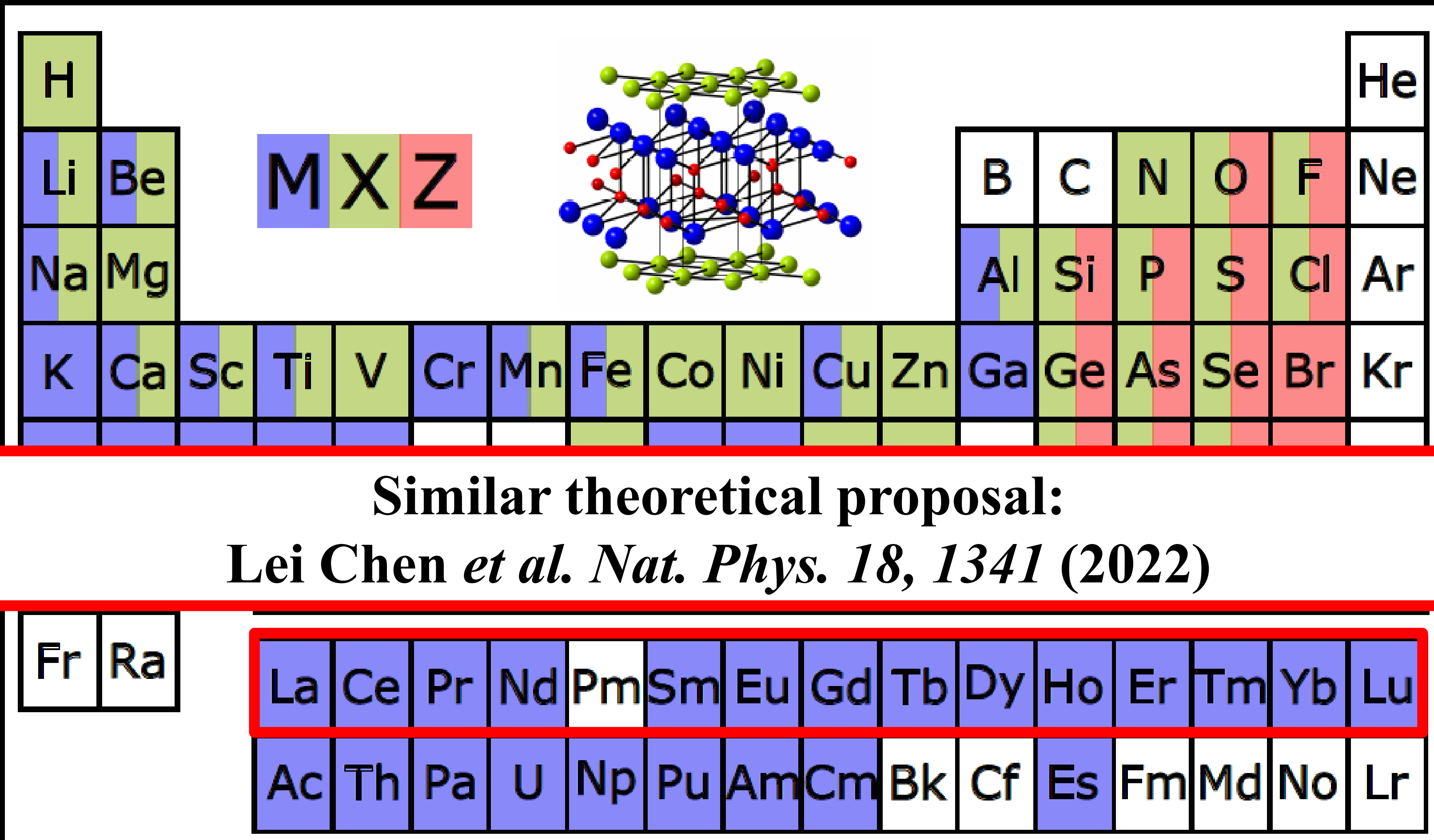


$v_{F,\perp} \sim 4.3eV\text{Å}$ $\quad v_{F,\parallel} \propto \dfrac{\partial \epsilon}{\partial k_{\parallel}} = 0$

Rudenko *et al.*, PRL 120, 216401 (2018)
Pezzini *et al.*, Nat. Phys. 14, 178 (2018)
Shao *et al.*, Nat. Phys. 16, 636 (2020)

The ZrSiS Family

More than 500 known compounds

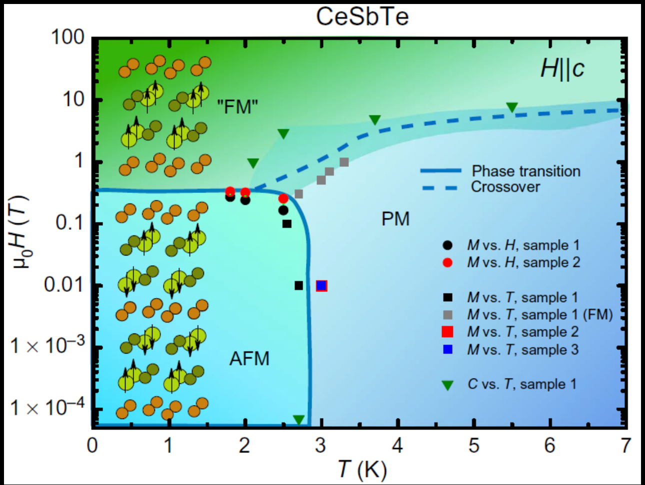


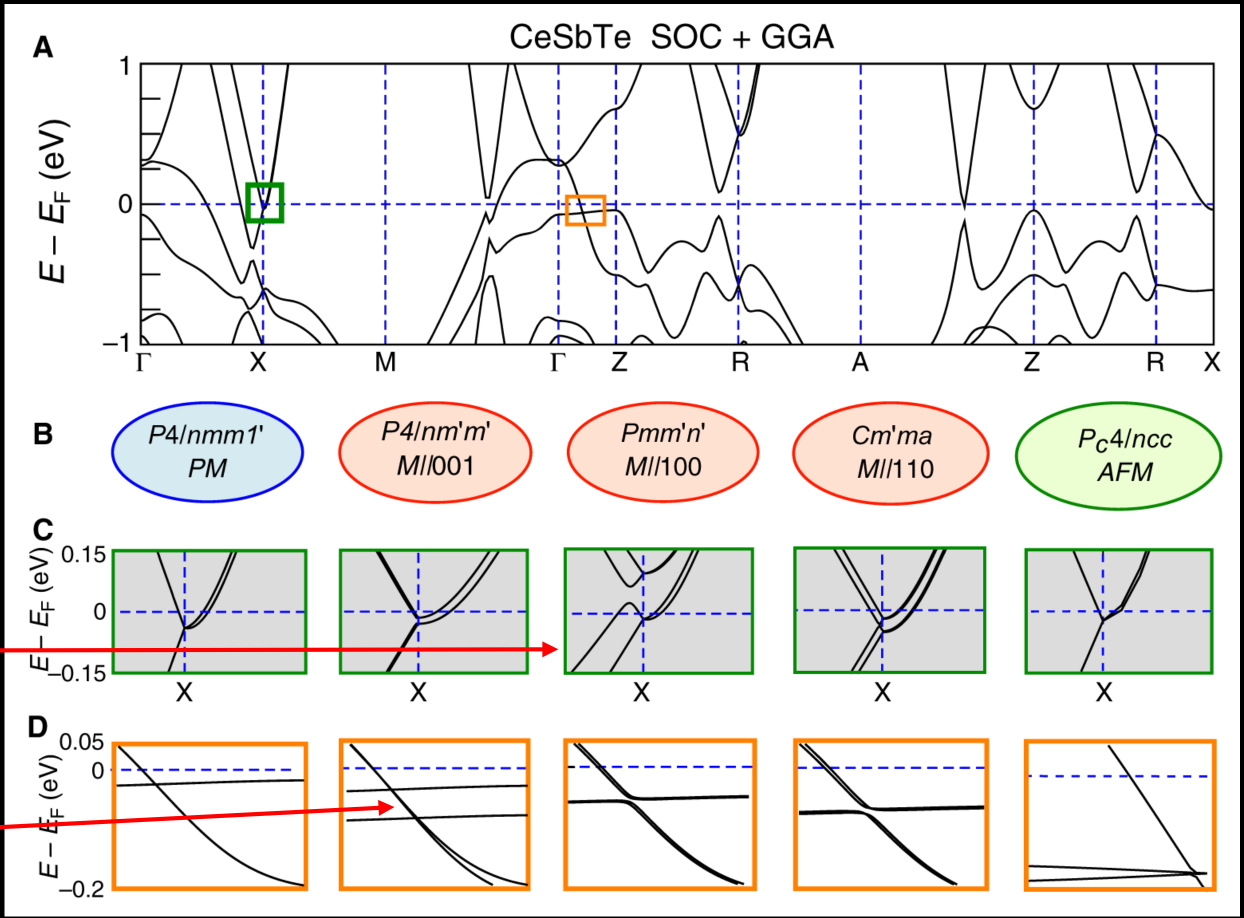
Similar theoretical proposal:
Lei Chen *et al. Nat. Phys. 18, 1341* (2022)

S. Klemenz *et al.*, Annual Reviews of Material Research 49, 185 (2019)

Antiferromagnetic CeSbTe

Tunable Weyl and Dirac states with magnetic order!

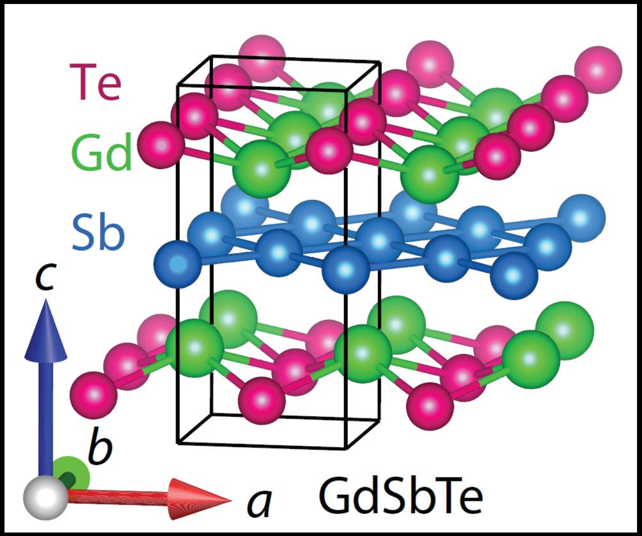


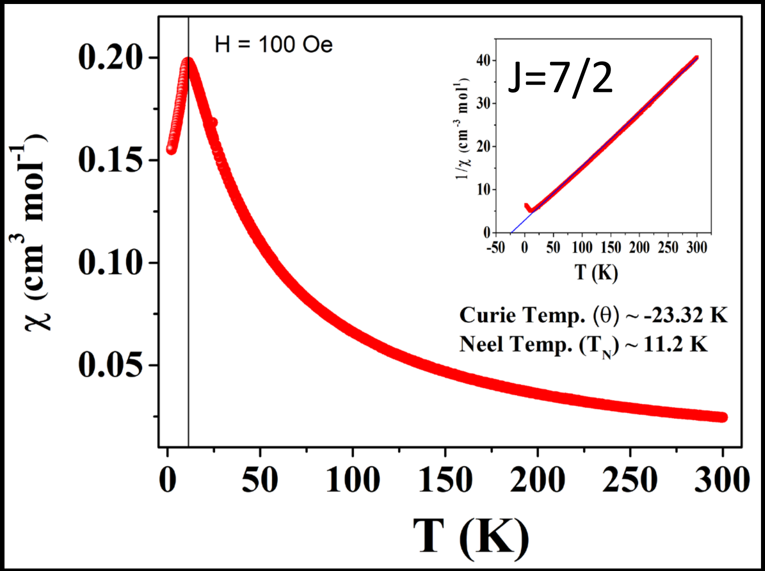


- Two-fold degenerate Weyl points appear close to X.
- Triply degenerate point -> possible double Fermi arcs at surface.

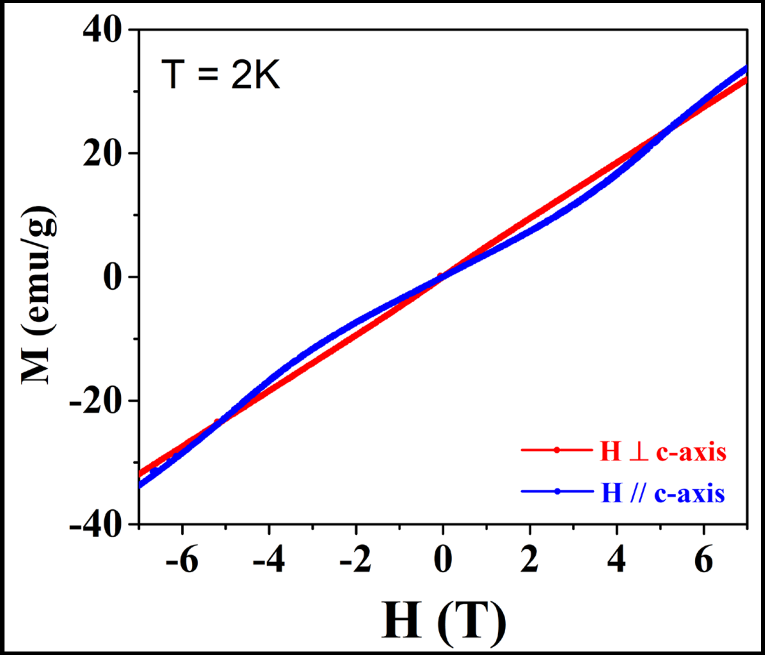
Leslie M. Schoop *et al.*, Sci. Adv. 4, eaar2317 (2018)

Antiferromagnetic $GdSb_xTe_{2-x-\delta}$

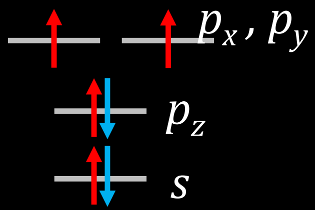




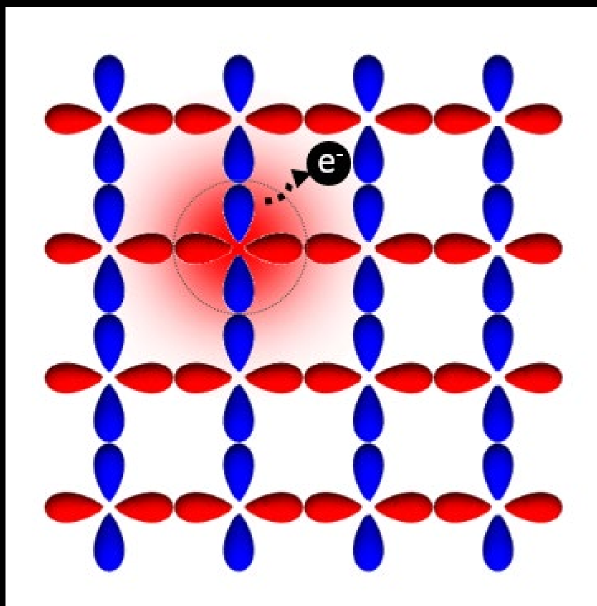
Sankar *et al.*, Inorg. Chem. 58, 11730 (2019)
Lei *et al.*, *Adv. Quantum Technol.* 1900045 (2019)

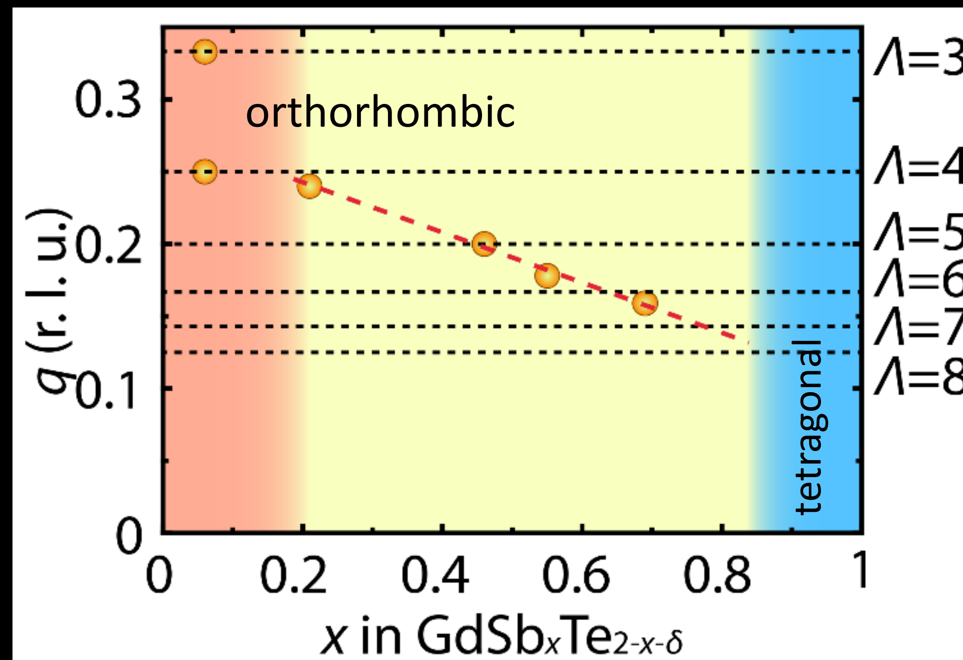


Phase diagram of $GdSb_xTe_{2-x-\delta}$



Half-filled *p*-orbitals
1e/bond to stabilize the lattice (6e/Sb)
Te-doping increases the Peierls instability towards CDW

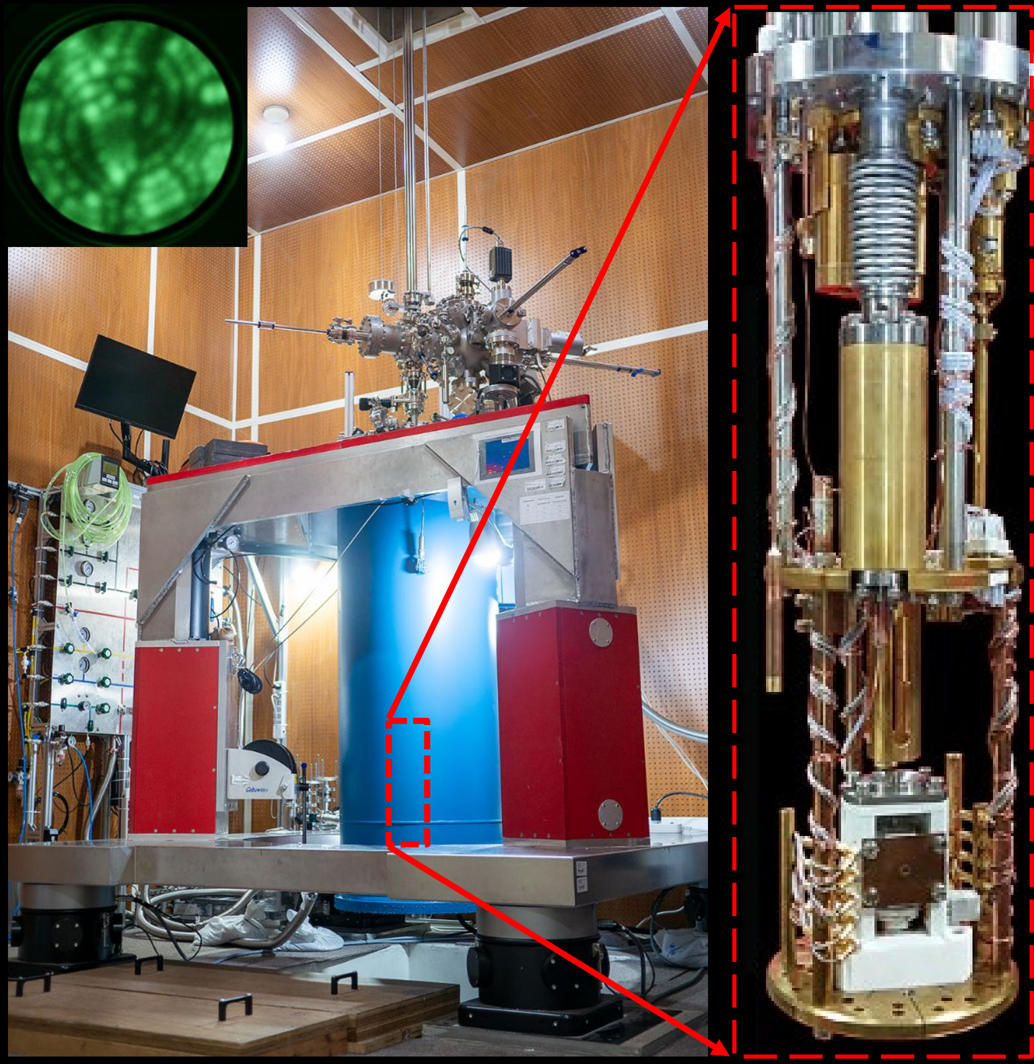


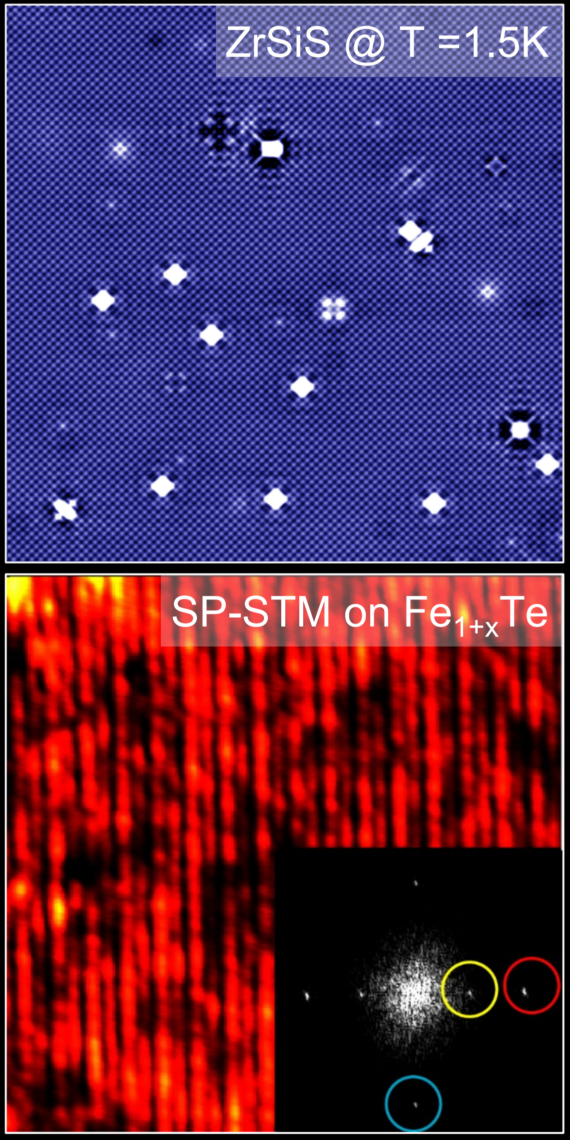


Lei *et al., Adv. Quantum Technol.* 1900045 (2019)
Sebastian Klemenz e*t al.*, JACS 142, 6530 (2020)

Homemade 1K-9T SI-STM

Continuous measurement for ~ 7 days
Active + passive vibration isolation + UHV-FIM



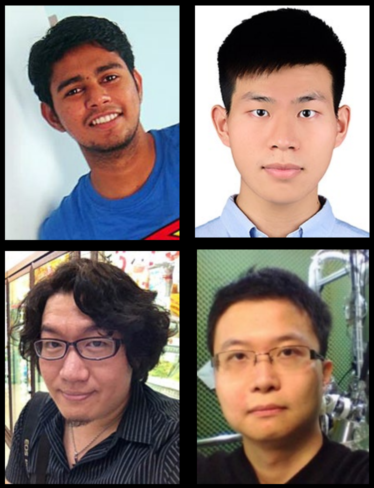


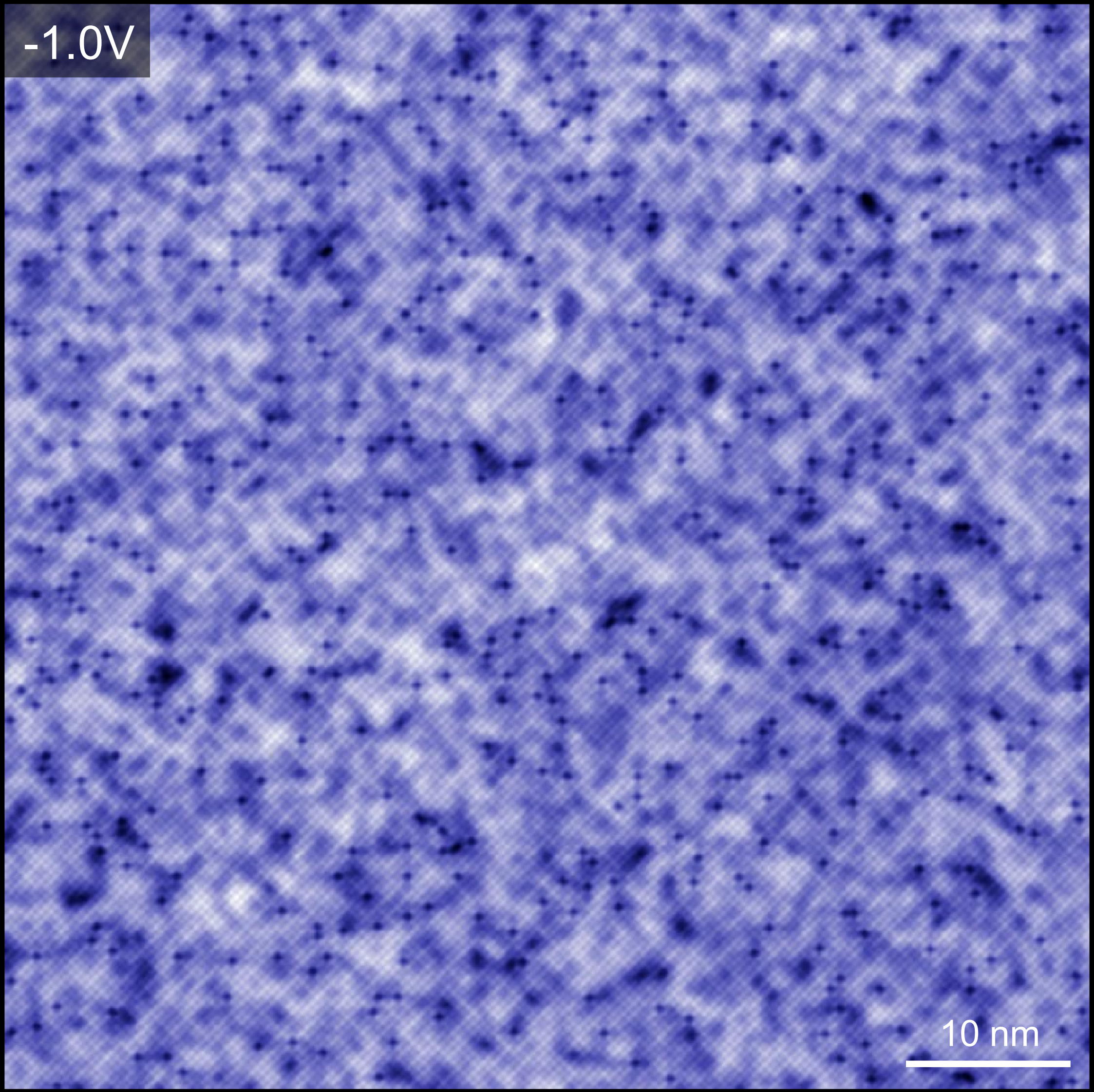
NIC-56 Soundroom

http://www.phys.sinica.edu.tw/~chuangtm

Cleaved surface of $Gd_{1.02}Sb_{0.87}Te_{1.11}$

T = 4.2K

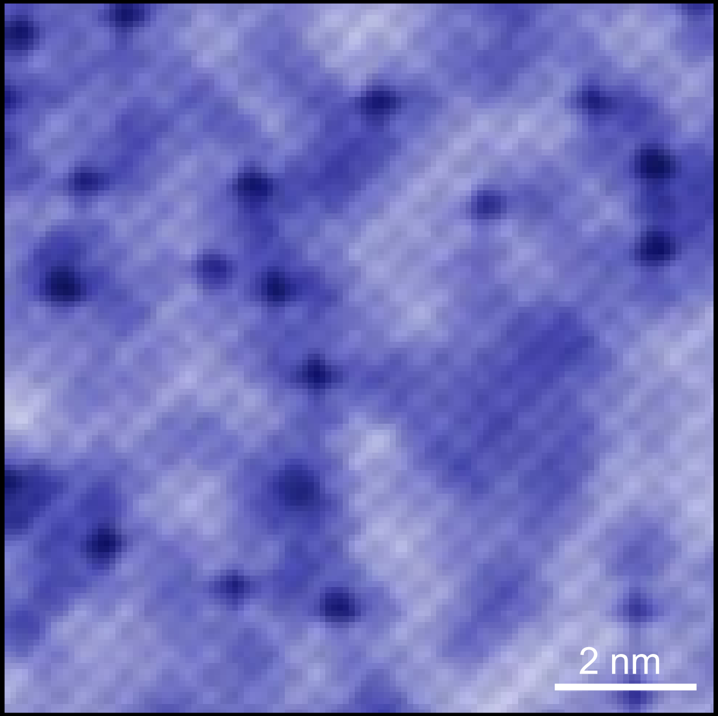




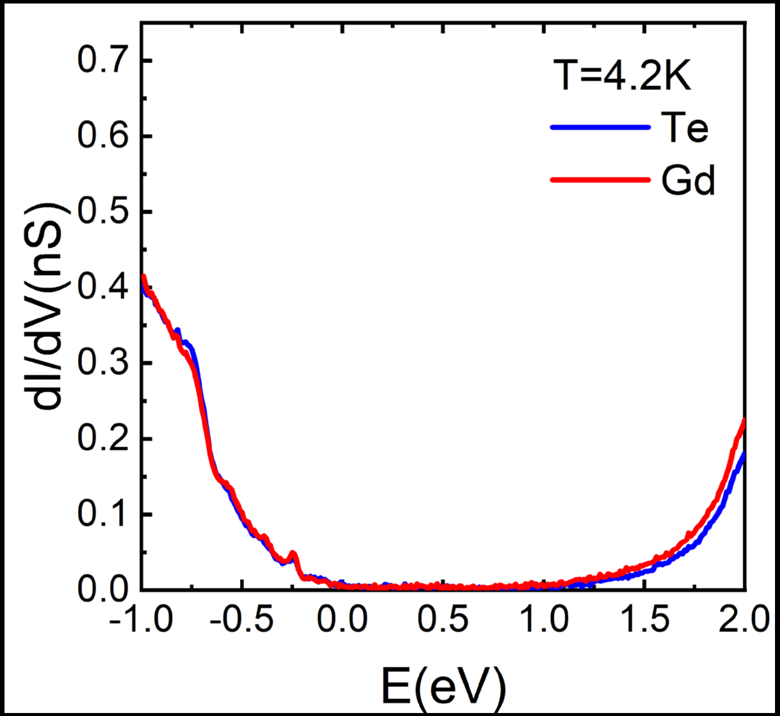
Venkatesan *et al.*, *in preparation*

Cleaved surface of $Gd_{1.02}Sb_{0.87}Te_{1.11}$

z(*r*, E=-1.0V)

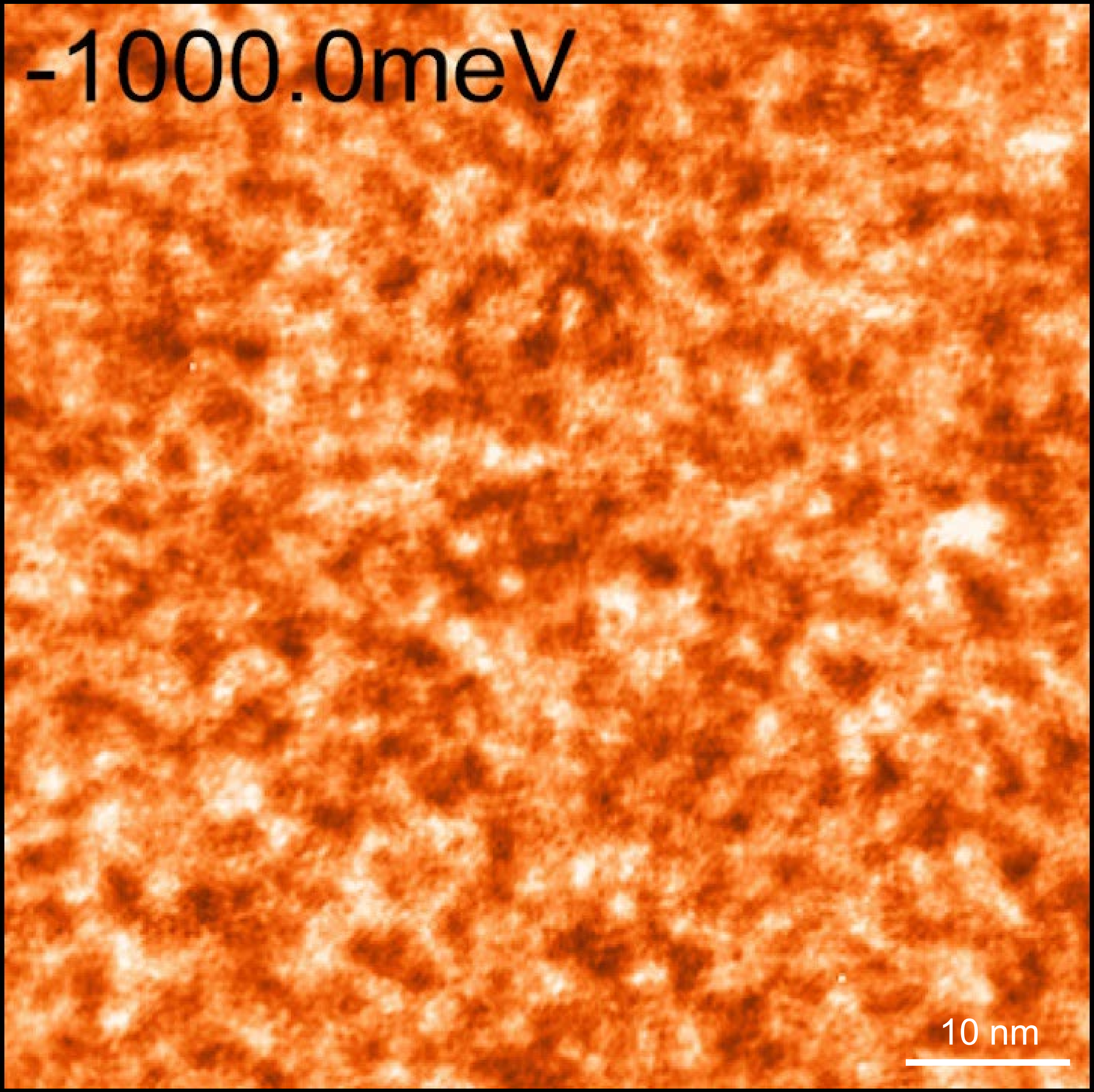


Averaged spectrum



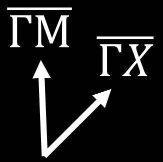
Differential Conductance Map in GdSbTe

dI/dV(r, E) @ T = 4.2K

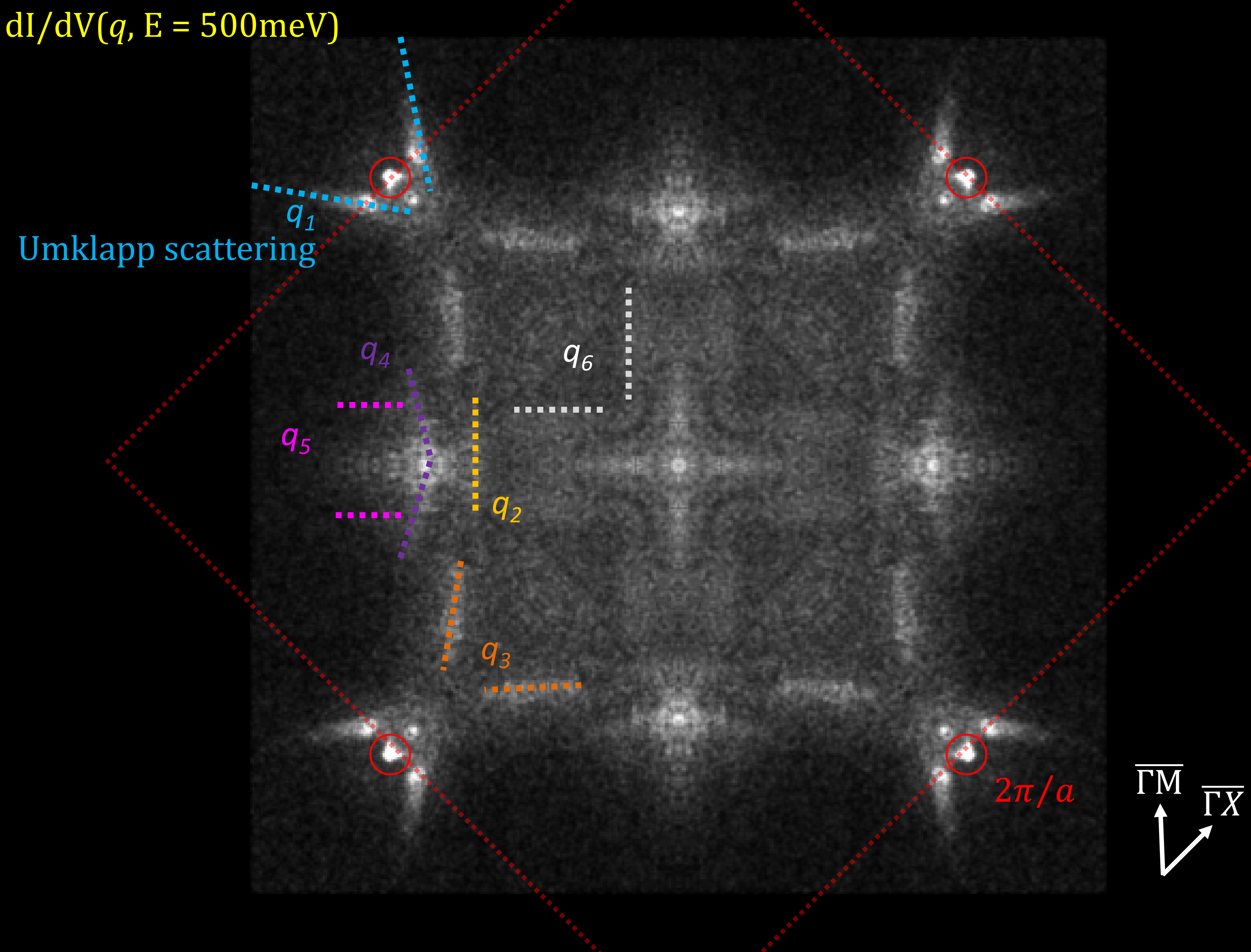


Quasiparticle scattering interference (QPI) imaging

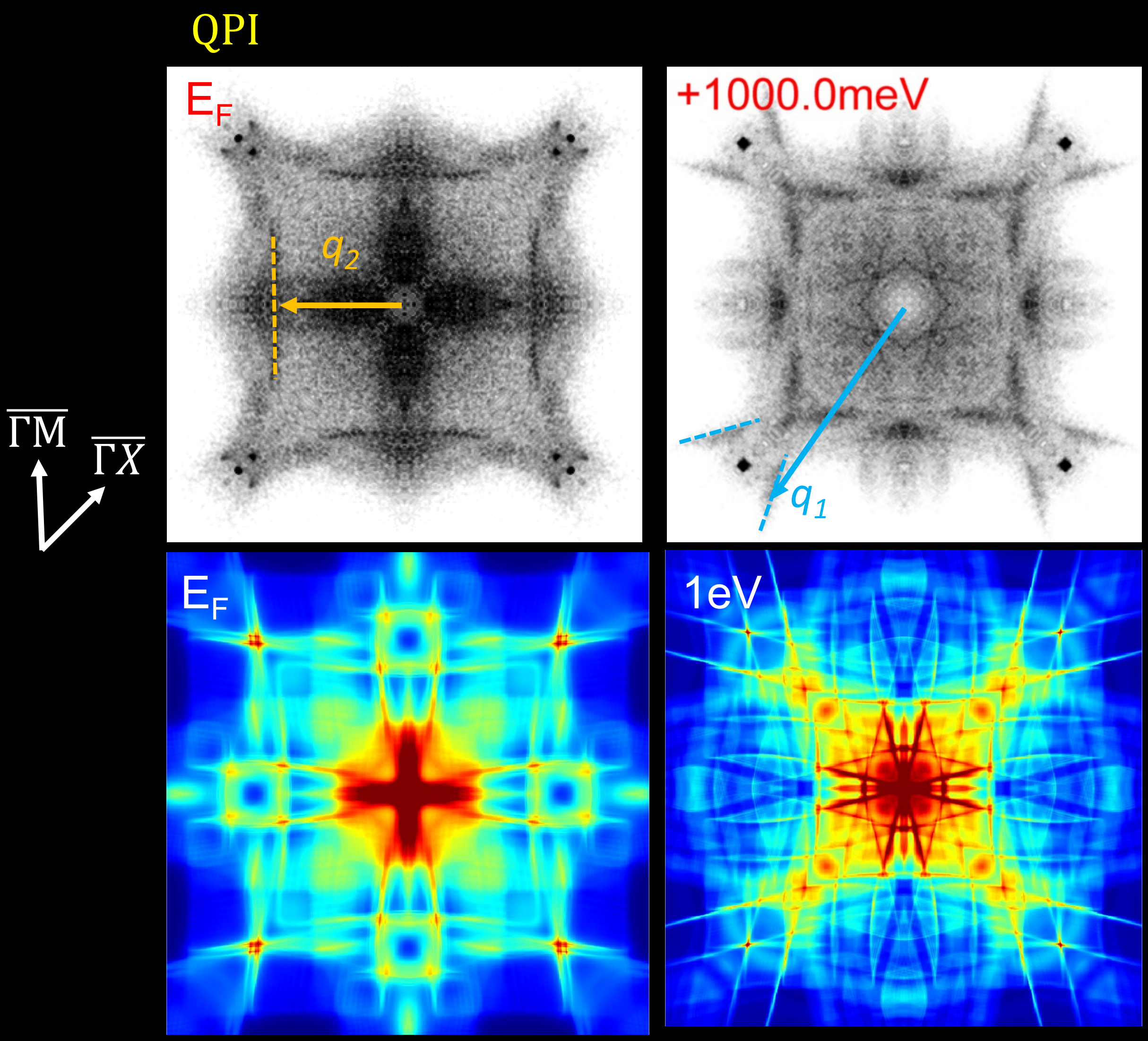
dI/dV(q, E) @ T = 4.2K

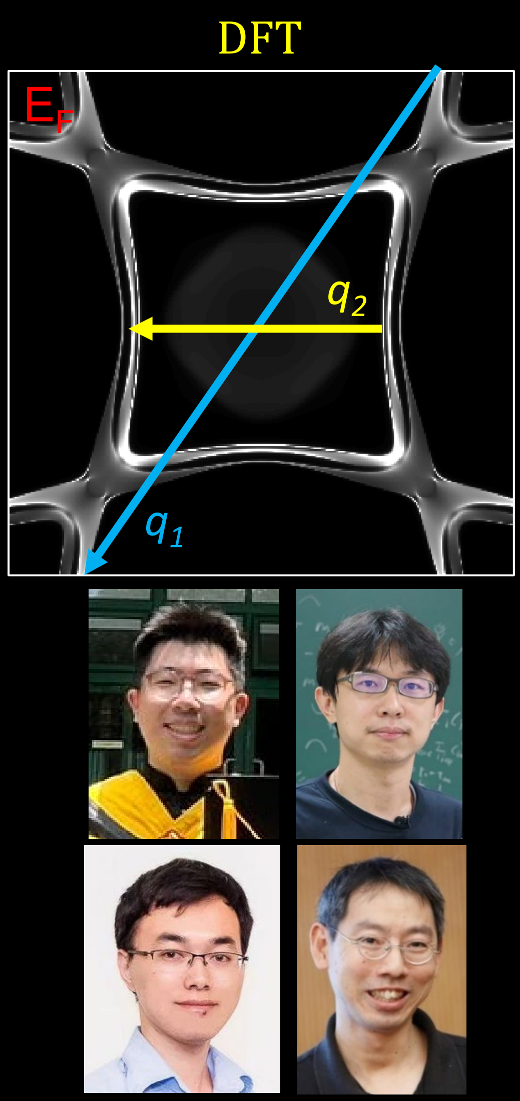


Identification of q-vectors

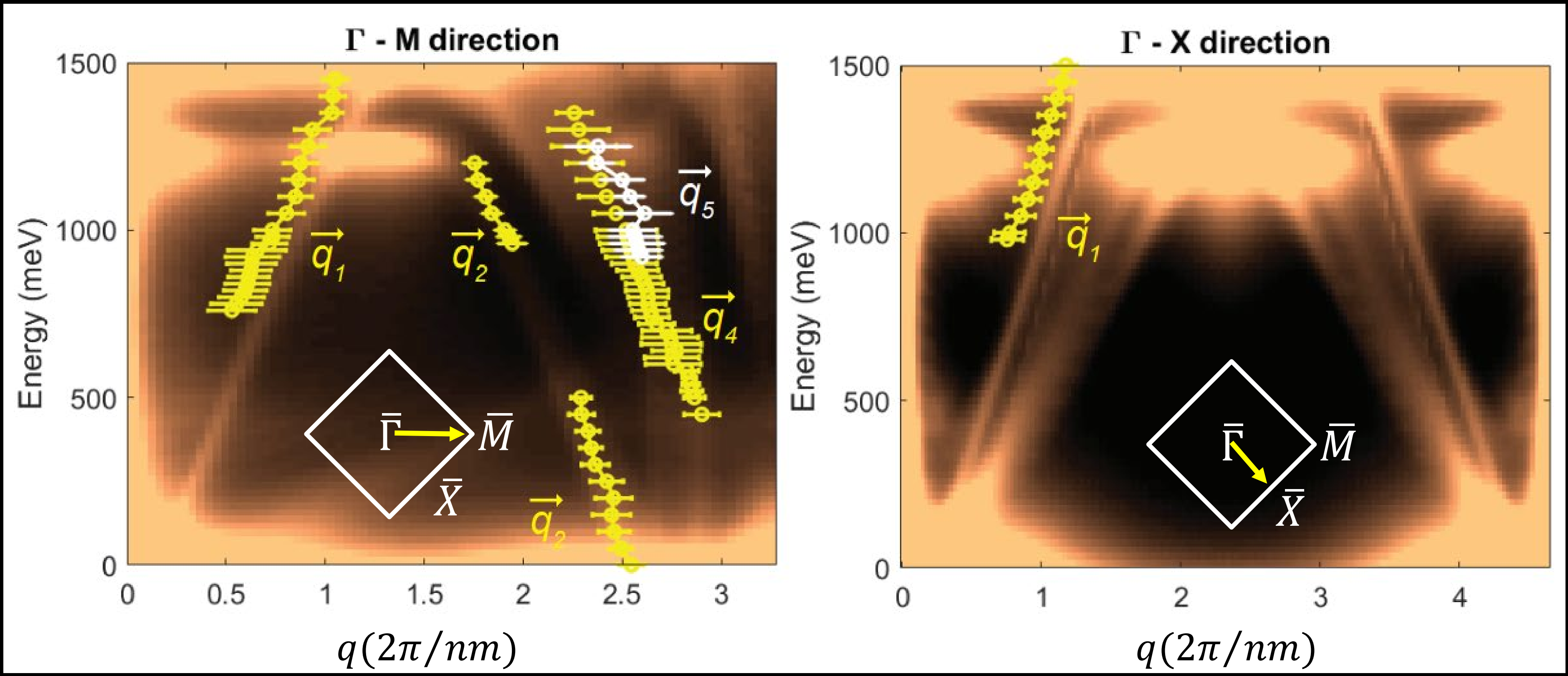


Identification of q-vectors and scattering process



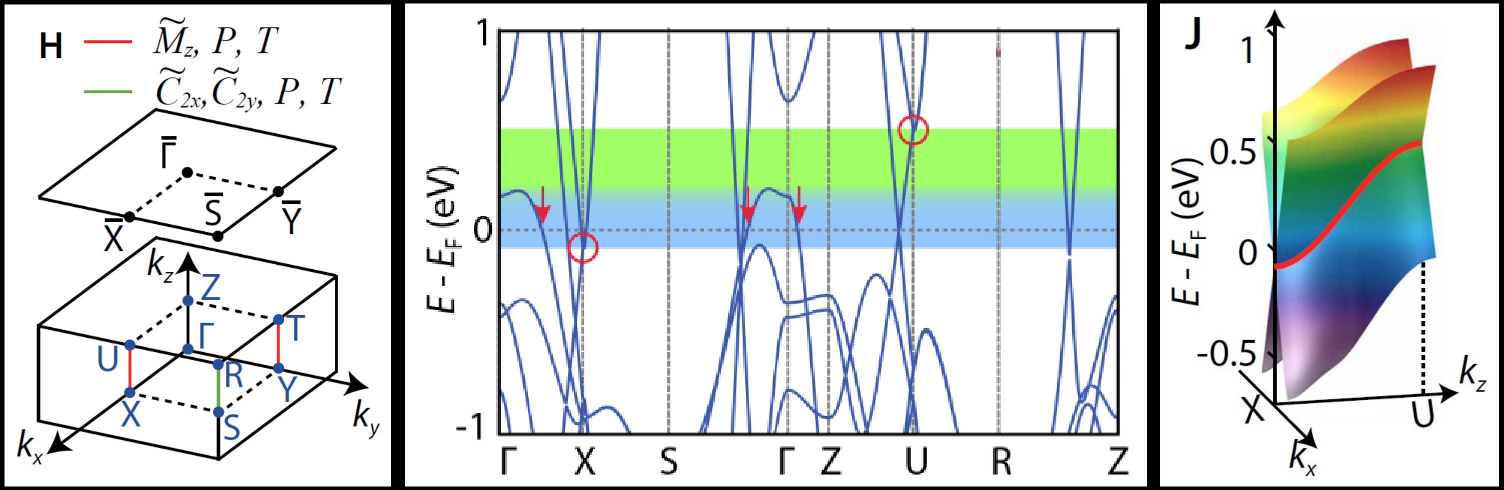


Multiple linear dispersive q-vectors

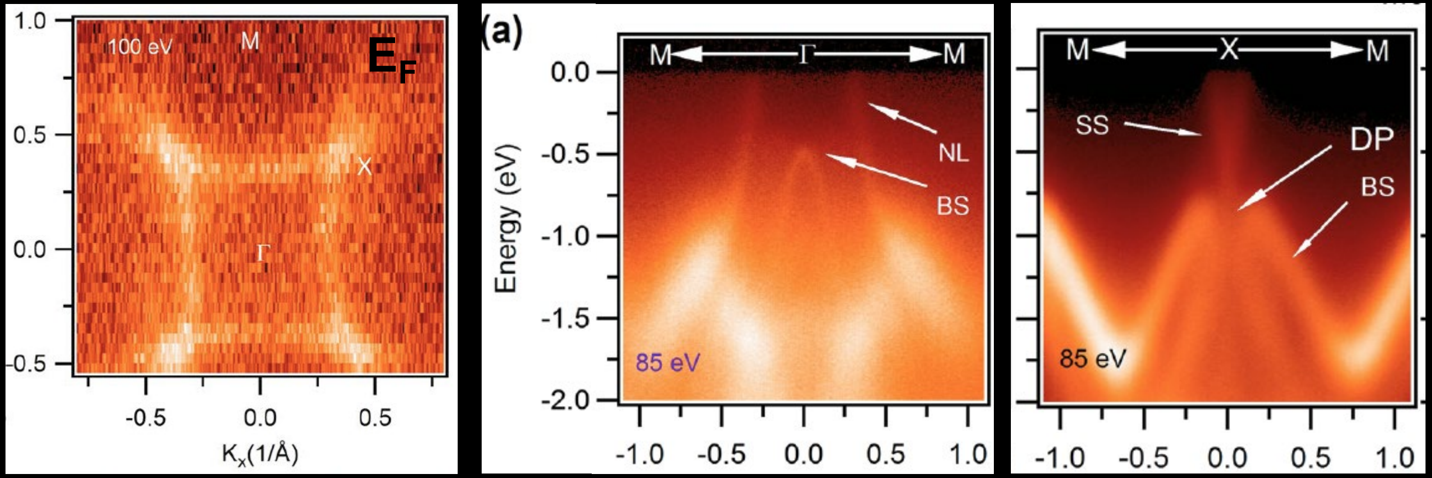


Consistent with ARPES

Non-symmorphic protected-DN

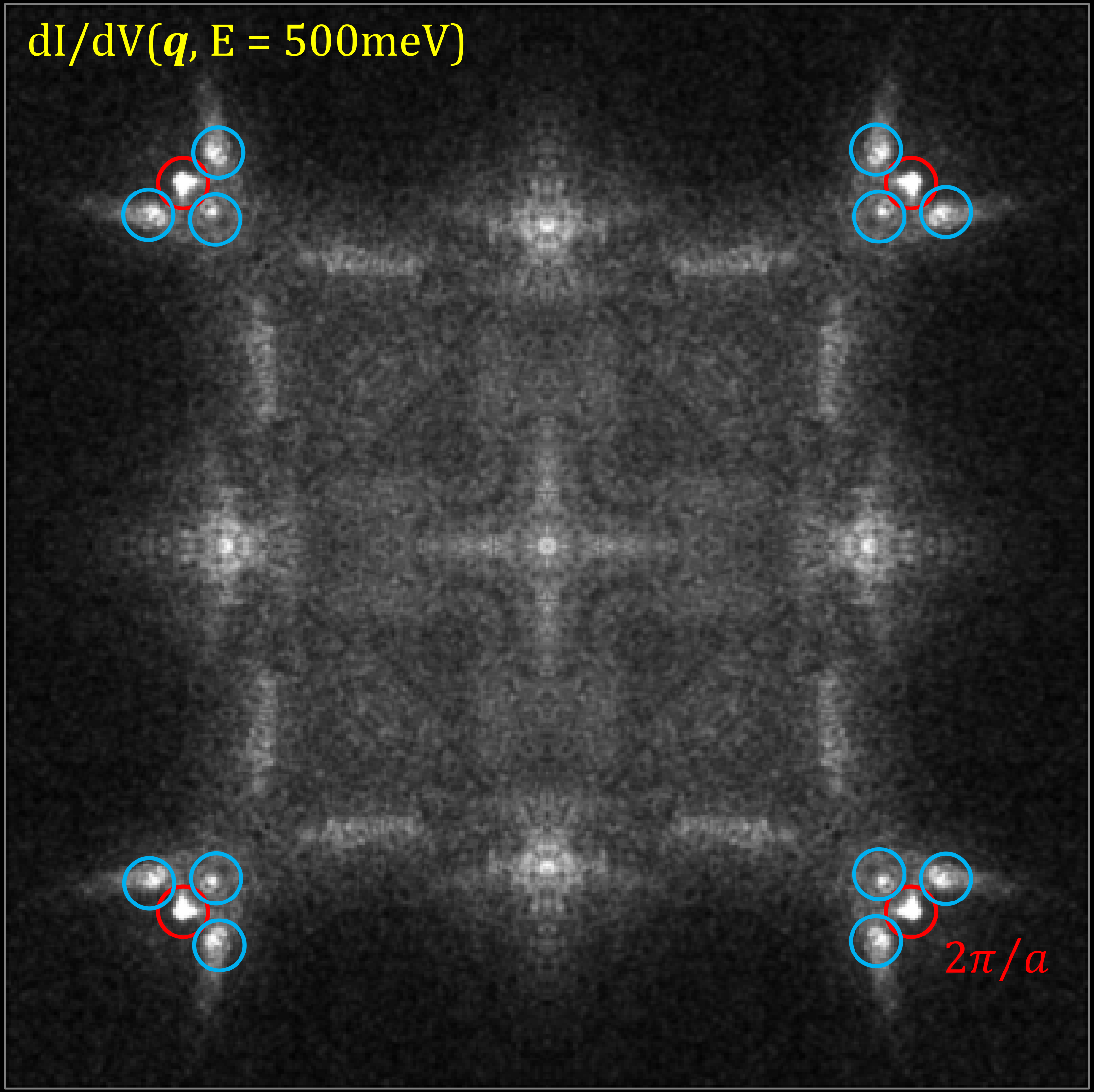


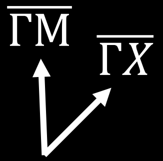
Lei *et al.*, Adv. Mater. 33, 2101591 (2021)



M. M. Hosen *et al.,* Sci. Rep. 8, 13283 (2018)

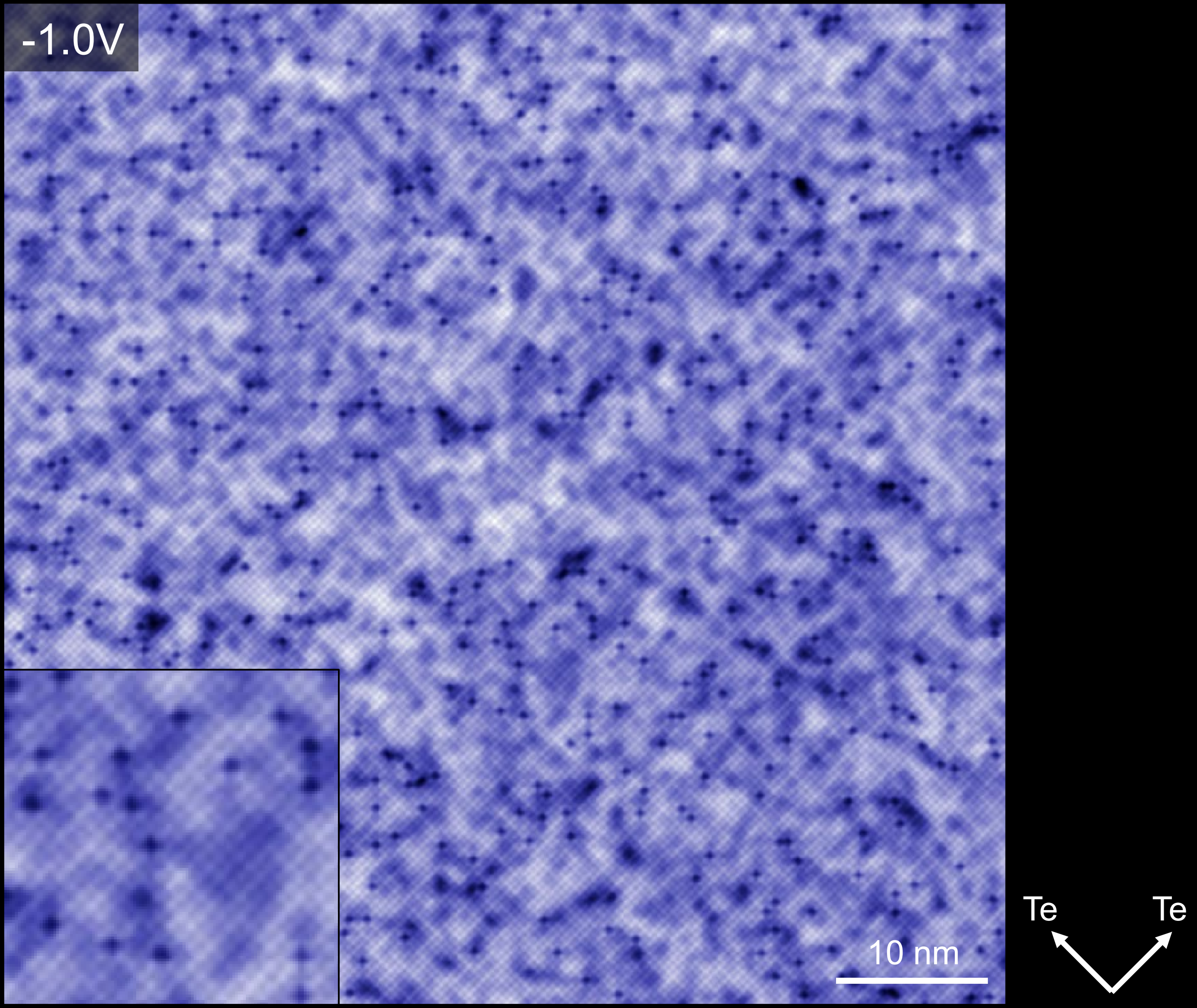
Additional static peaks around Bragg peaks?





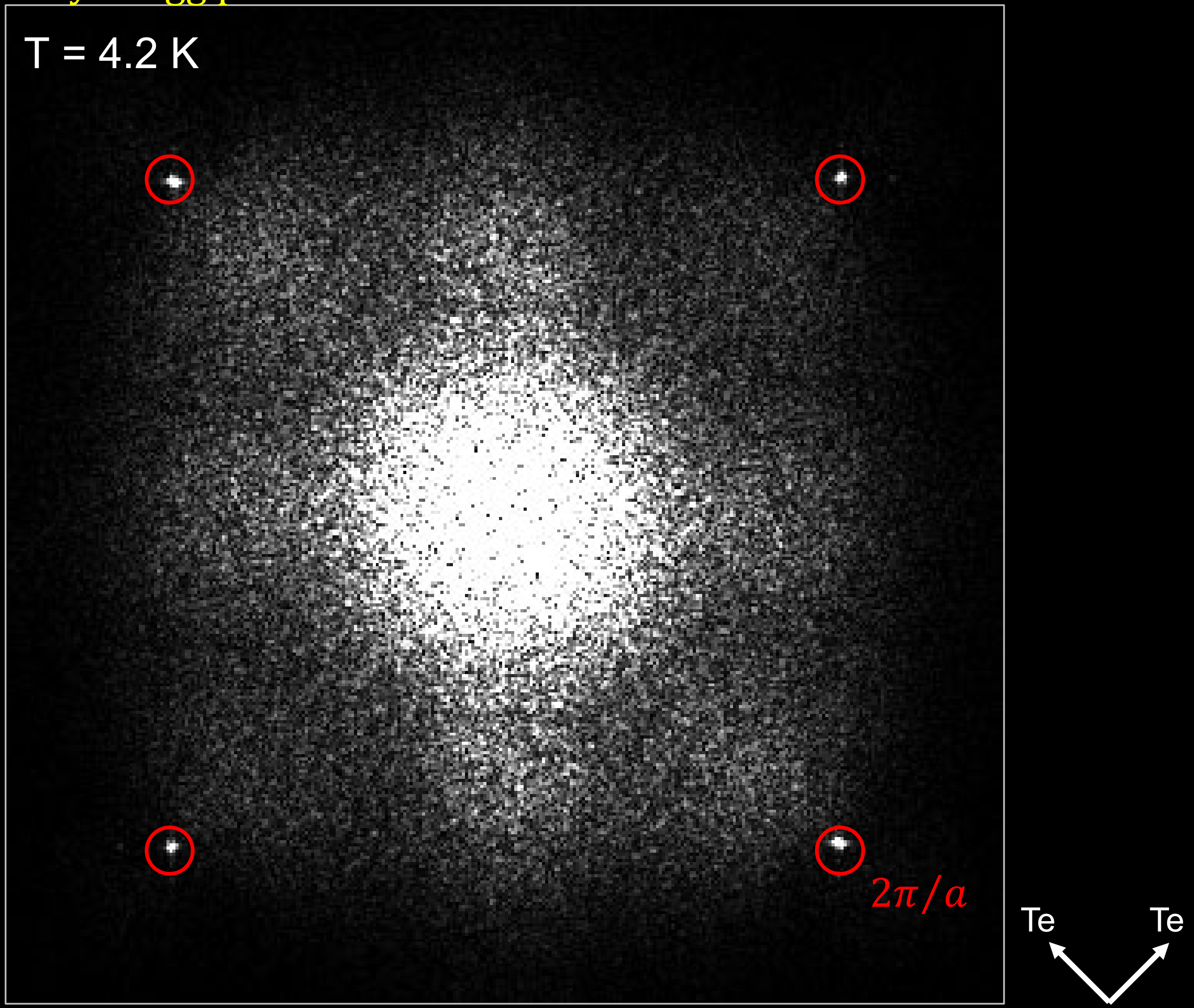
Surface Topograph of $Gd_{1.02}Sb_{0.87}Te_{1.11}$

T = 4.2K



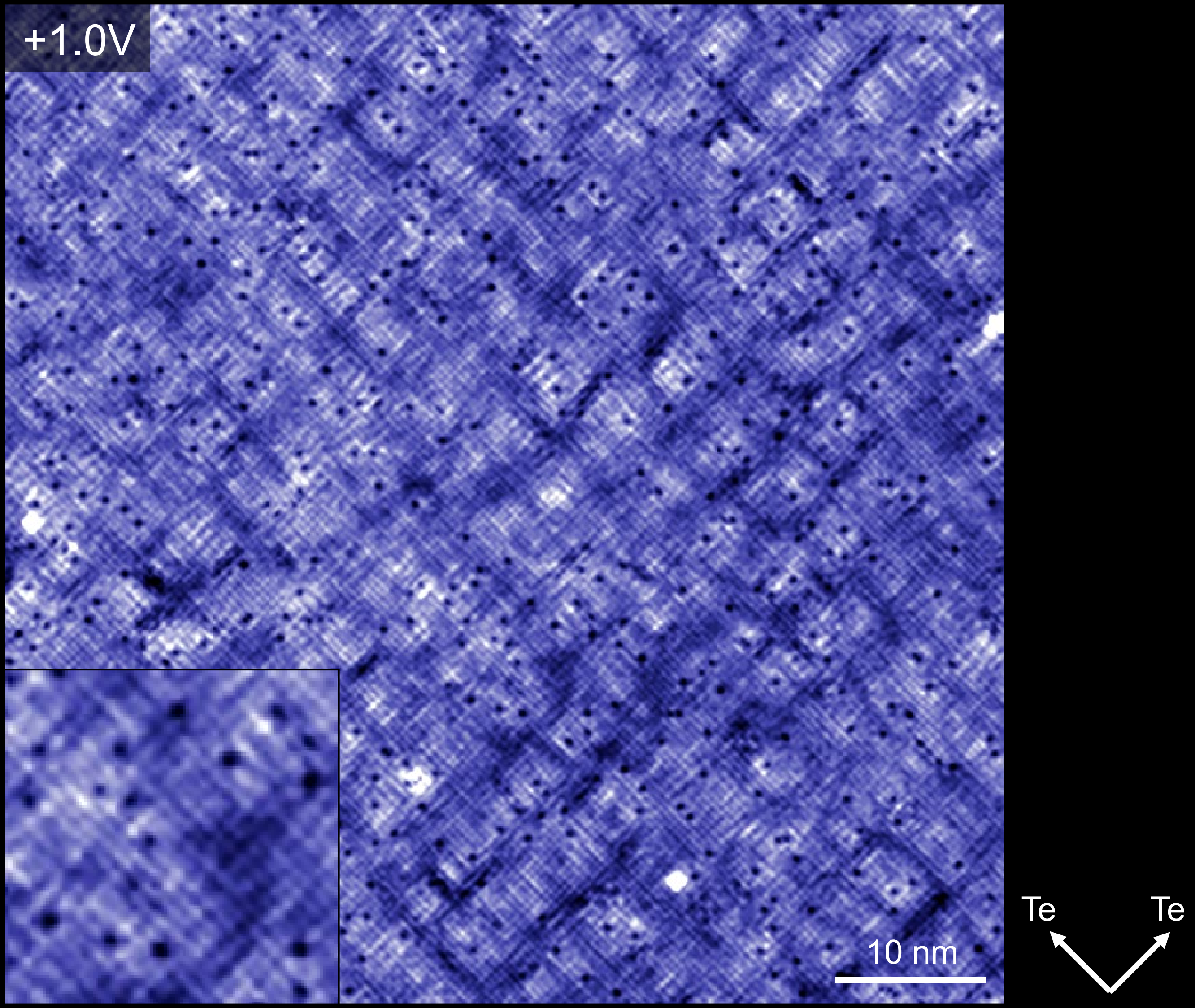
FFT of $z(\boldsymbol{r}, E = -1\text{eV})$

Only Bragg peaks are visible

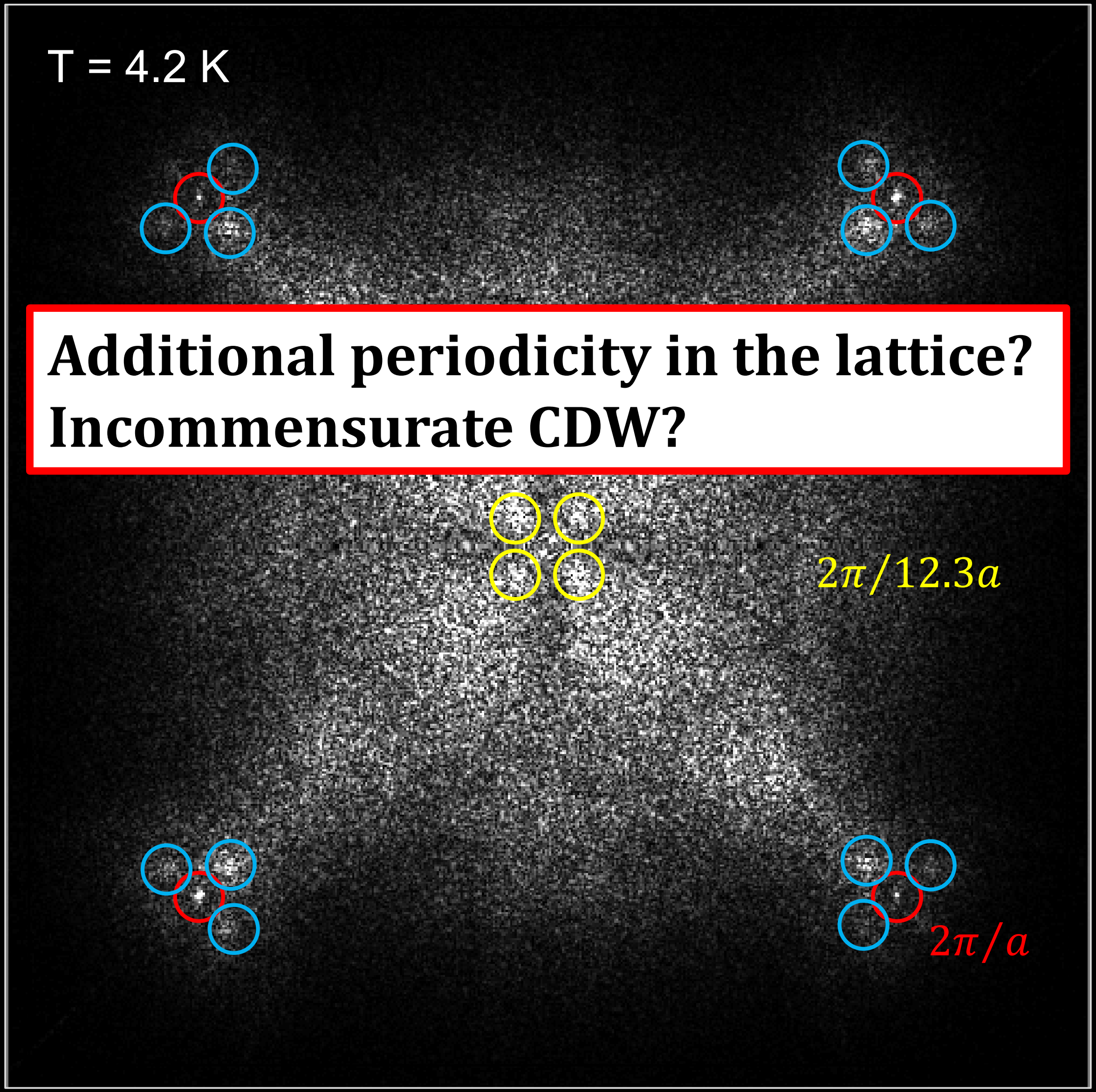


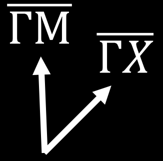
Surface Topograph of $Gd_{1.02}Sb_{0.87}Te_{1.11}$

T = 4.2K



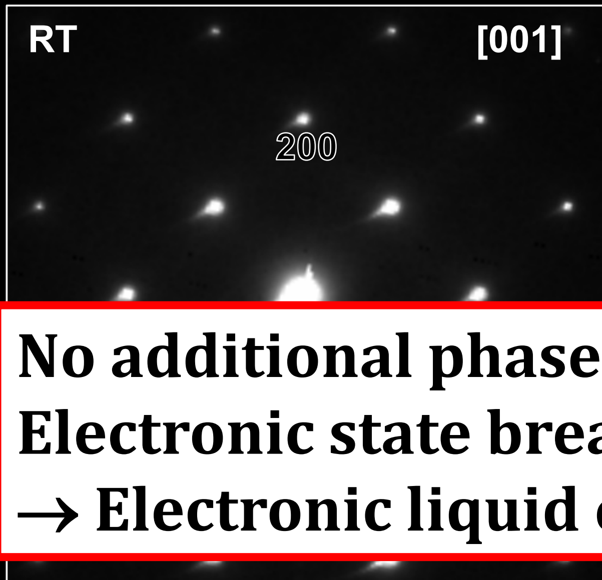
FFT of z($\boldsymbol{r}$, E = +1eV)

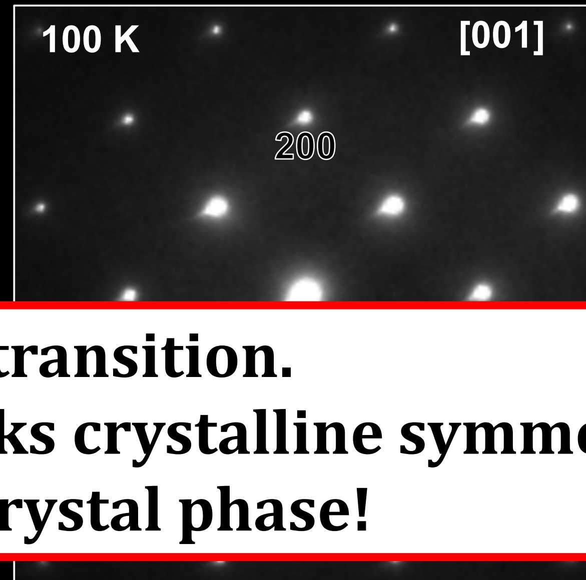




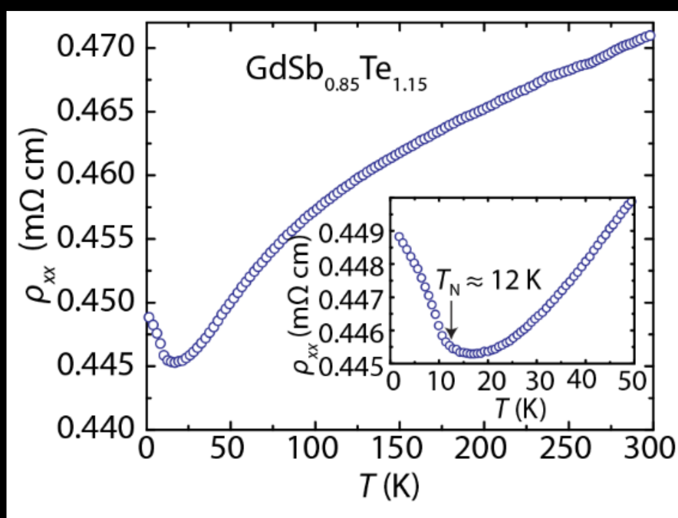
Venkatesan *et al.*, *in preparation*

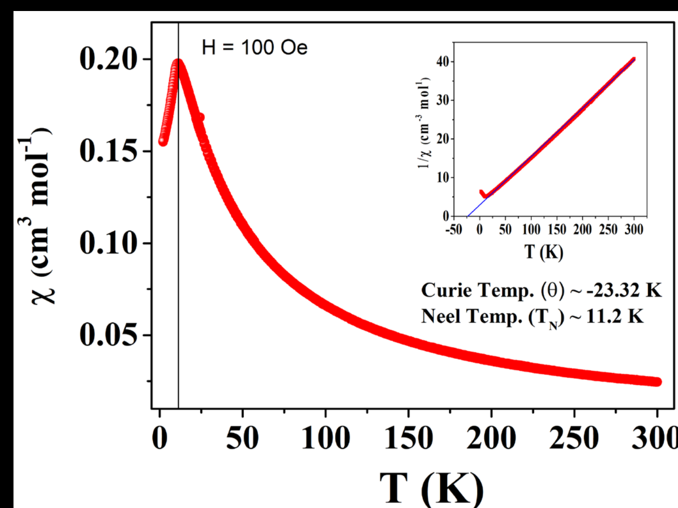
No CDW distortion from bulk measurements





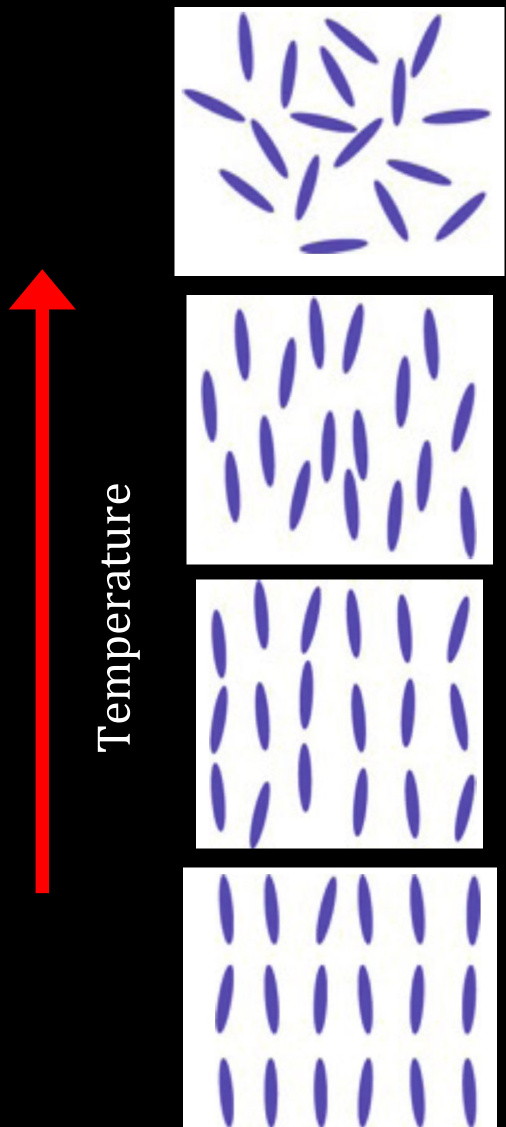
No additional phase transition.
Electronic state breaks crystalline symmetry
→ Electronic liquid crystal phase!





Lei *et al.*, Adv. Mater. 33, 2101591 (2021)

Classical Complex Fluid



Liquid
(Isotropic)

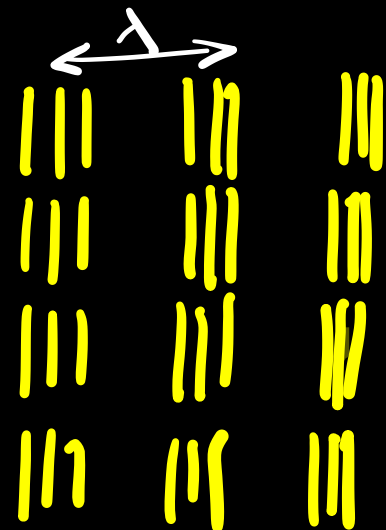
Nematic

Smectic
(stripe)

Crystal

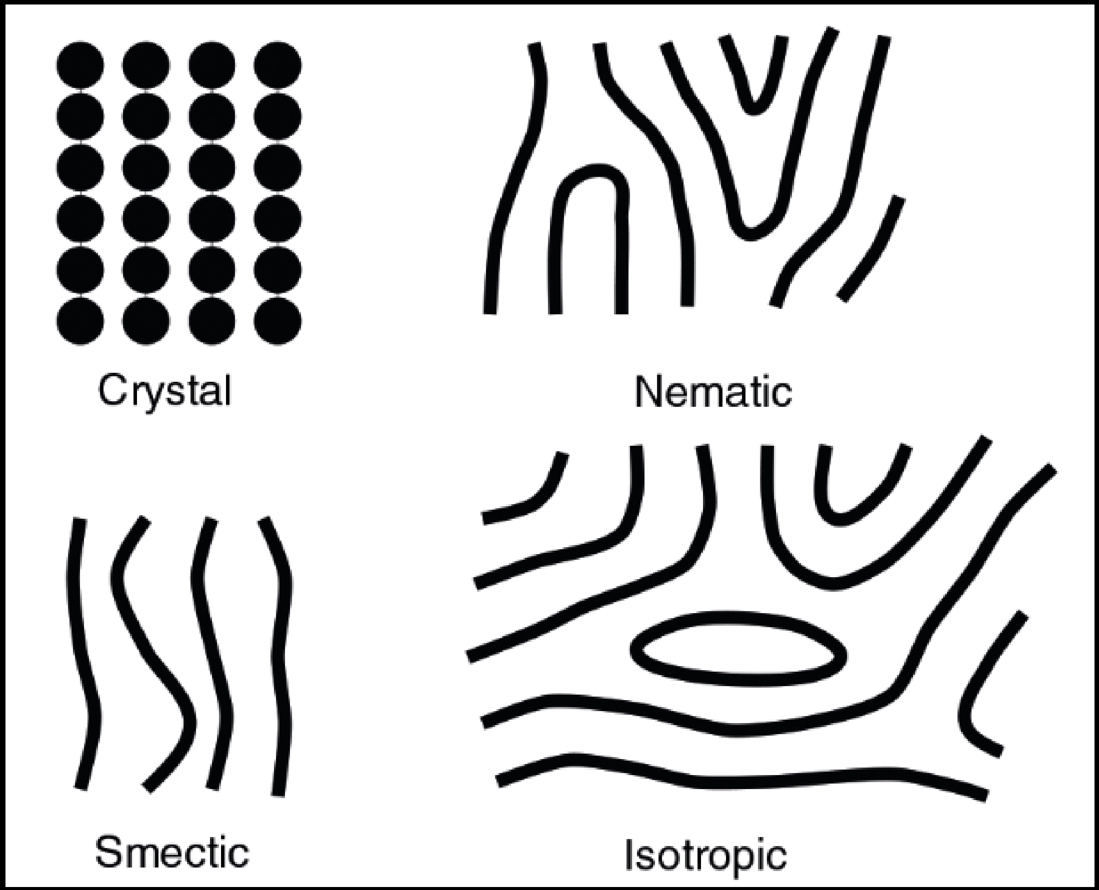
<u>Nematic</u>
breaks rotational symmetry only

<u>Smectic</u>
breaks rotational & translational symmetry

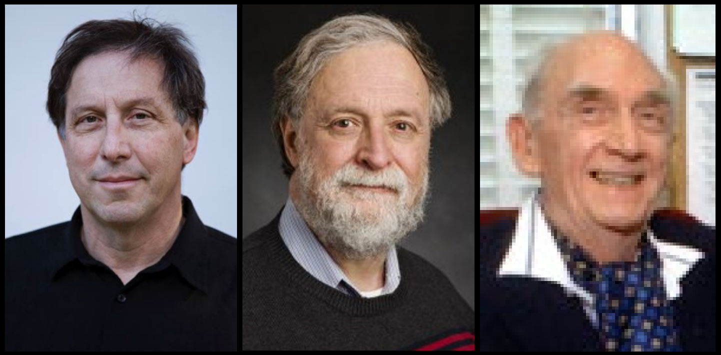


F. Reinitzer, doi:10.1007/BF01516710 (1888)

Electronic liquid-crystal (ELC) Phases

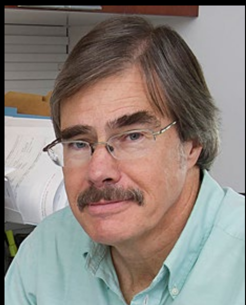


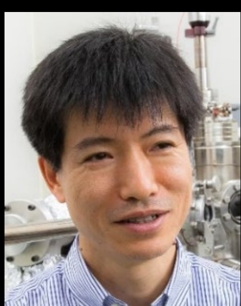
S. A. Kivelson, E. Fradkin & V. J. Emery, Nature 393, 550 (1998)



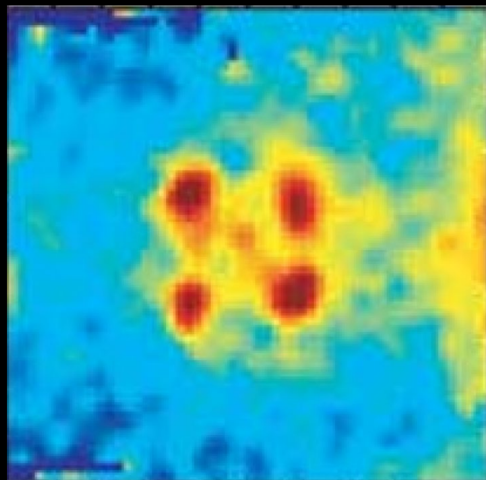
Electronic nematicity with an origin closely related to spin and/or orbital degrees of freedom.

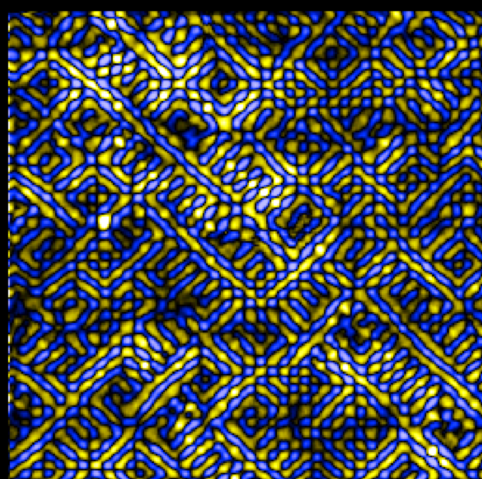
ELC Phases in High Tc Superconductors



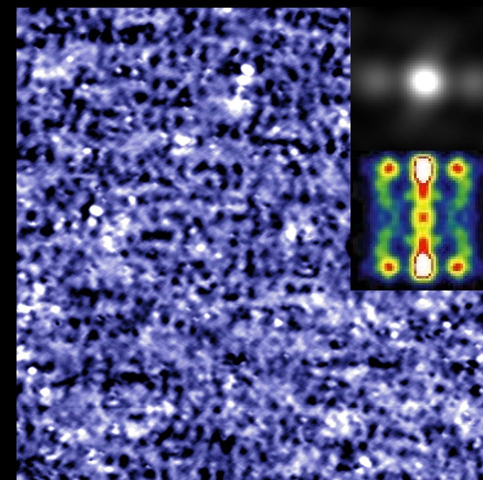


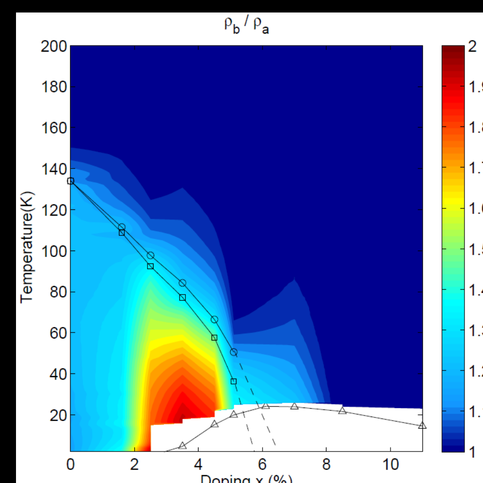
Cuprates



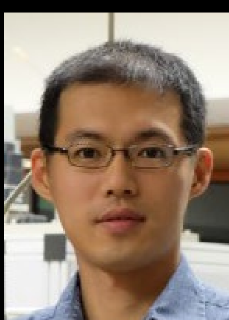


Fe-based SC





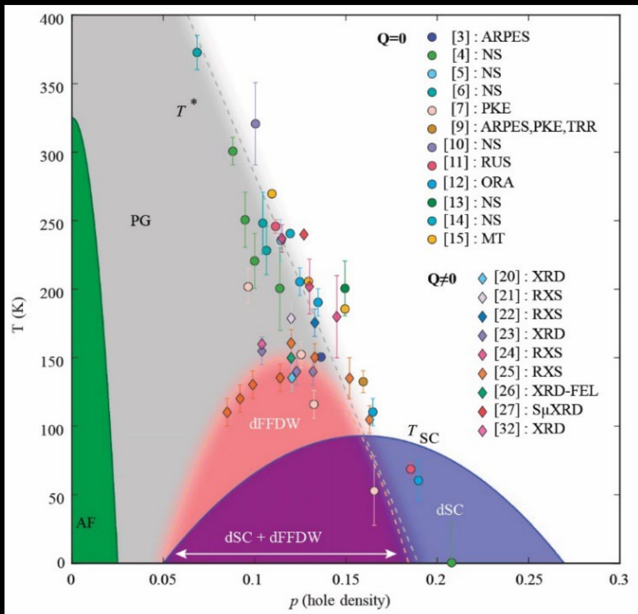


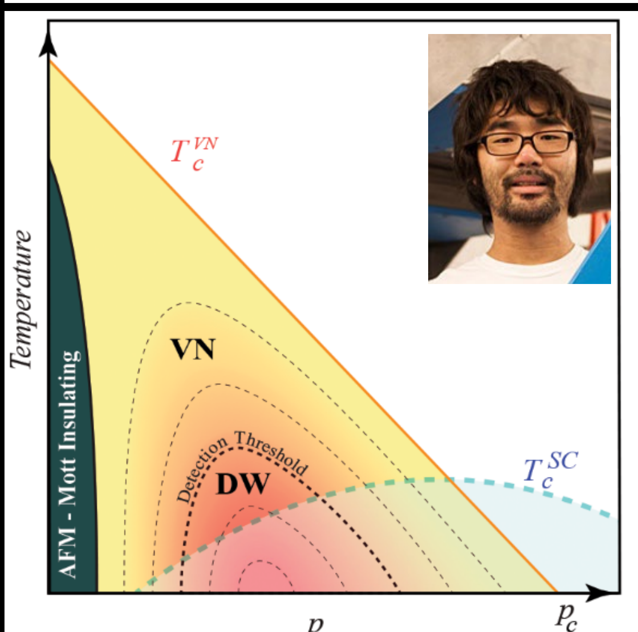


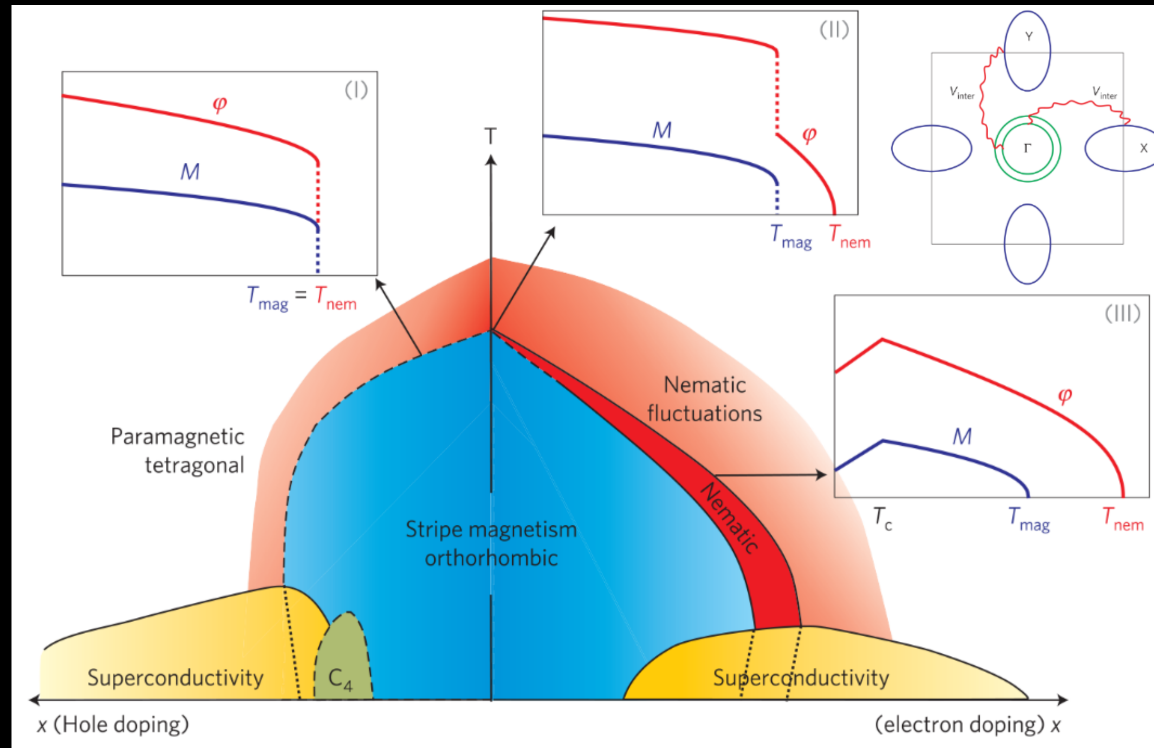
J. M Tranquada *et. al.*, Nature **429**, 534 (2004)
Y. Kohsaka *et al.*, Science 315, 1380 (2007)

T.-M. Chuang *et al.*, Science 327, 181 (2010)
J.H. Chu *et al.*, Science 329, 824 (2010)

ELC Phases in High Tc Superconductors







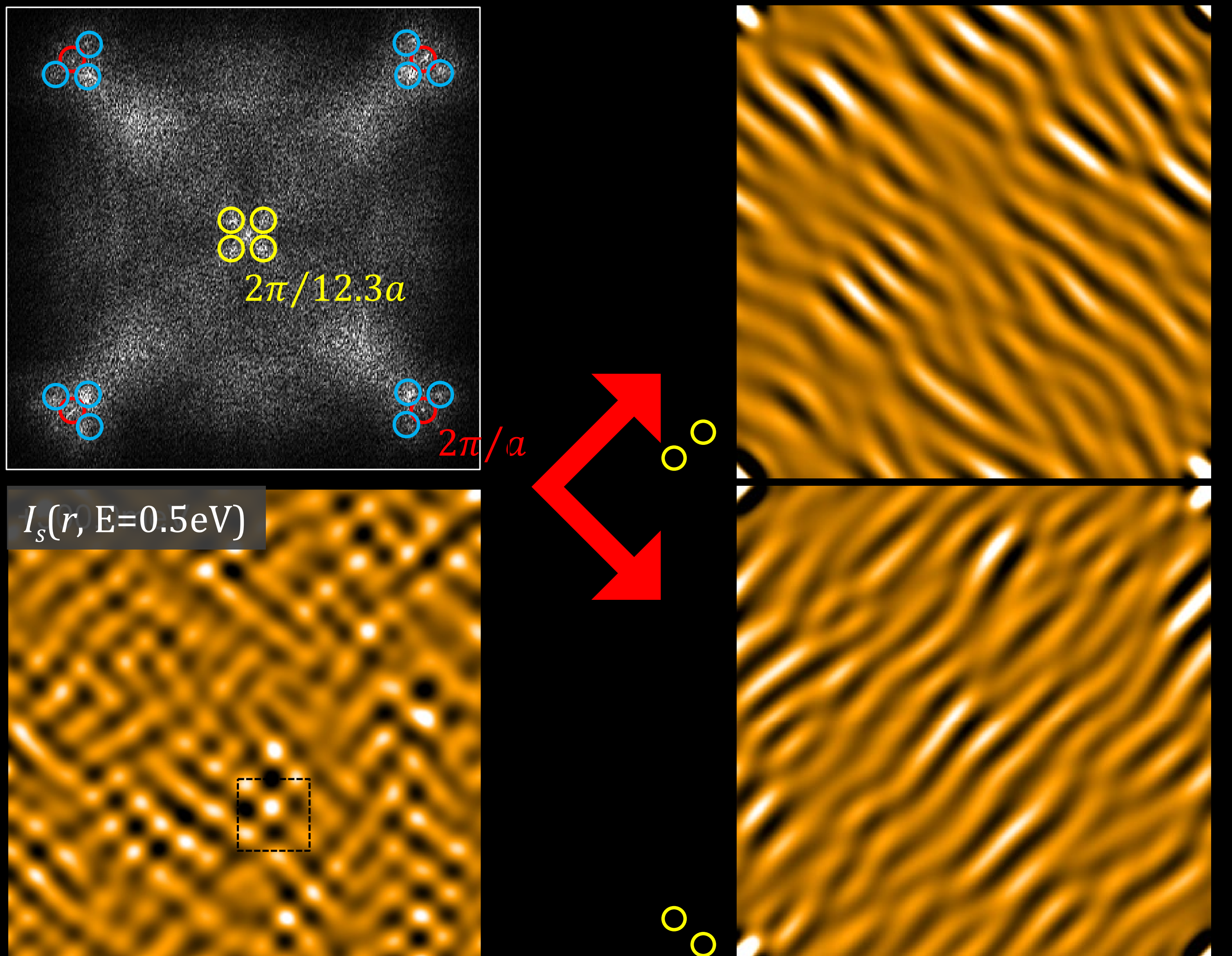
R. M. Fernandes *et al.*, Nature Physics 10, 97 (2014)

S. Mukhopadhyay *et al.*, PNAS 116, 13249 (2019)

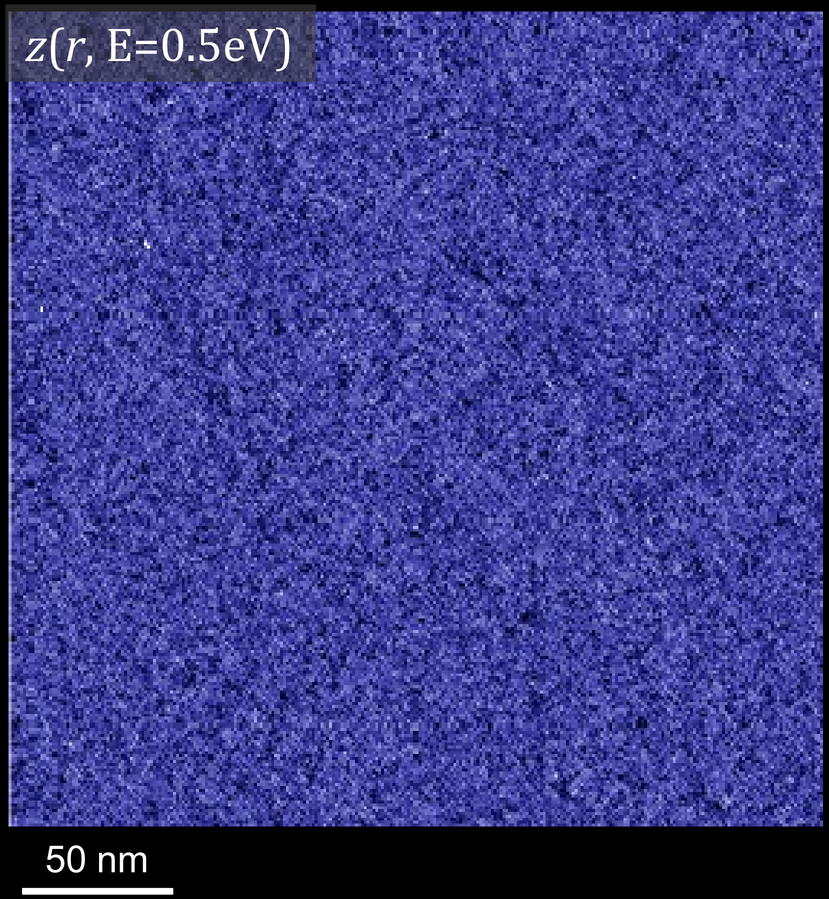
Broken translational symmetry

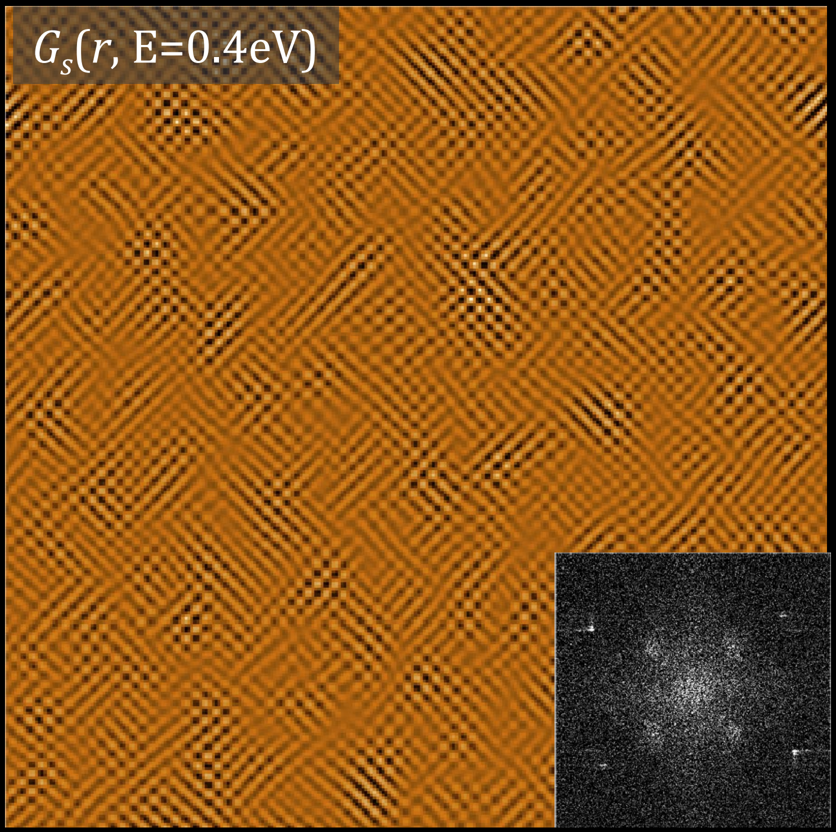
Checkerboard

Orthogonal stripes with q=12.3a



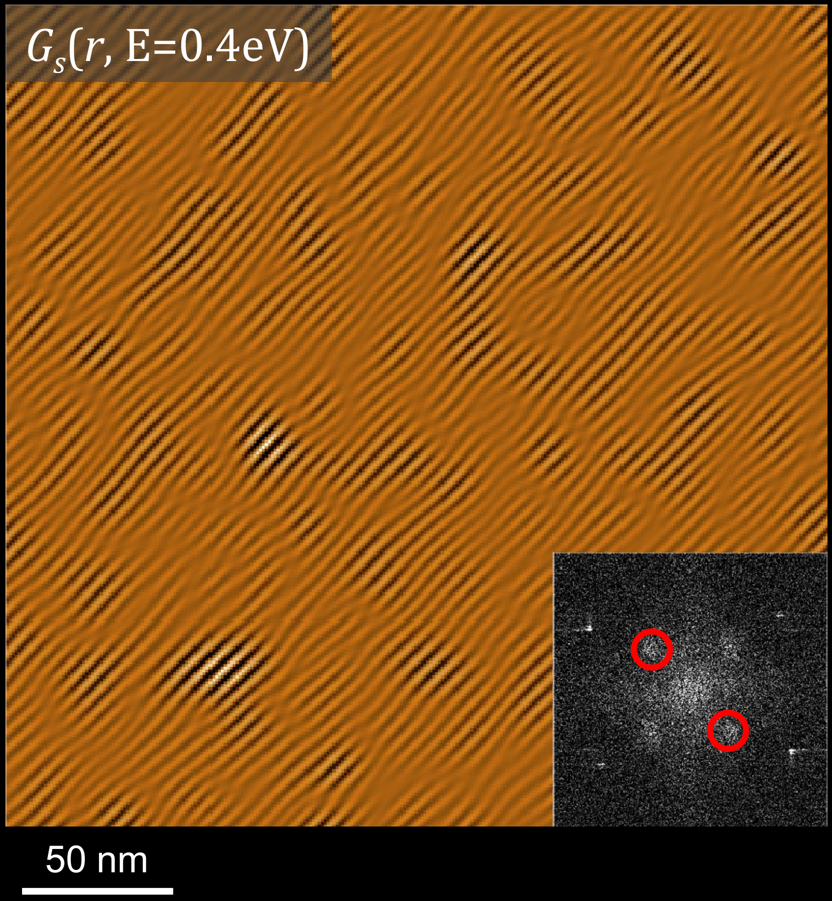
Broken translational symmetry

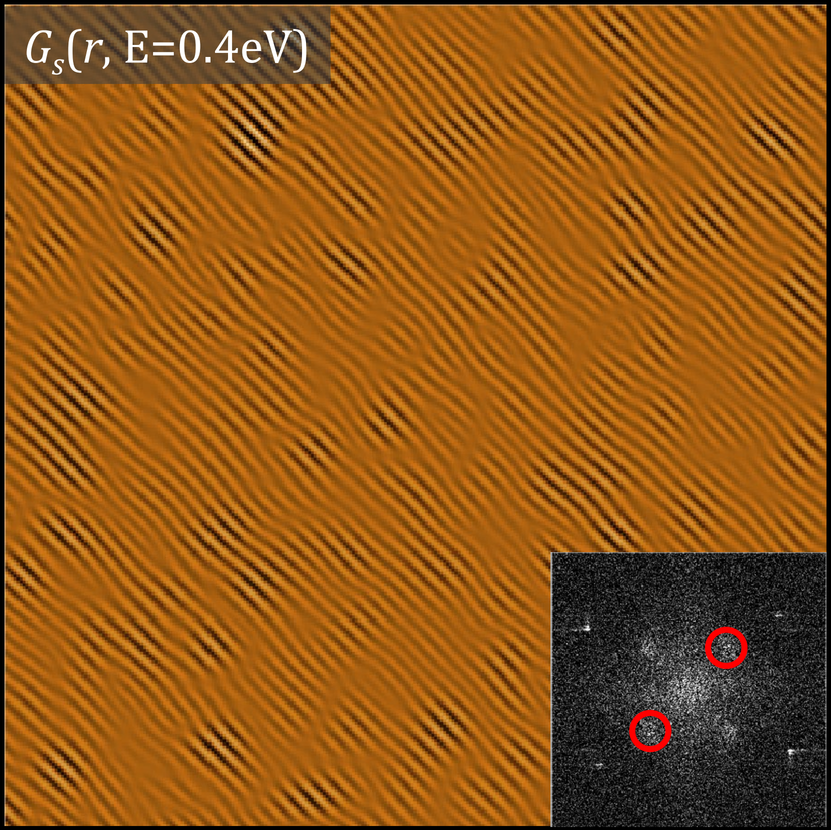




Venkatesan *et al.*, *in preparation*

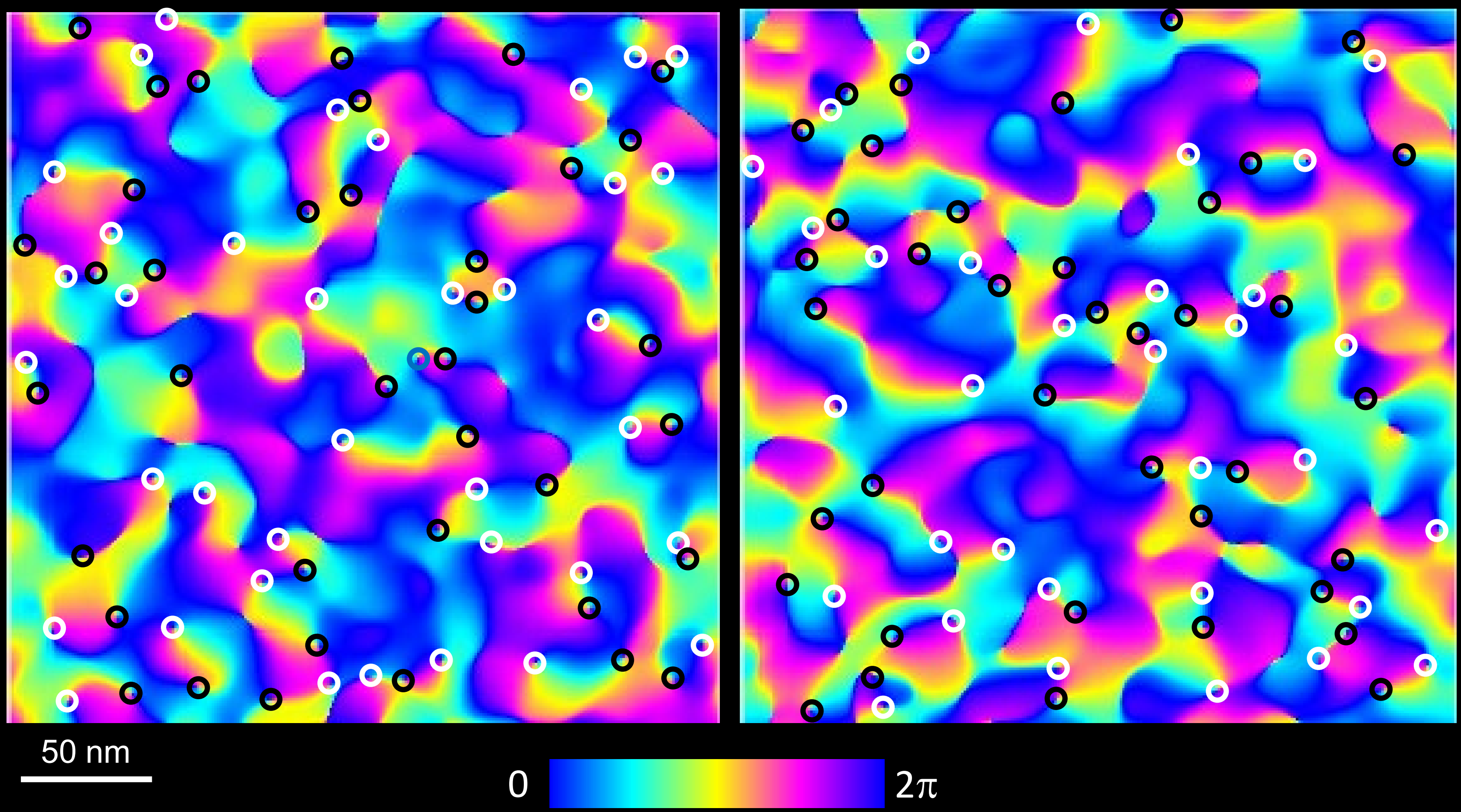
Broken translational symmetry





Venkatesan *et al.*, *in preparation*

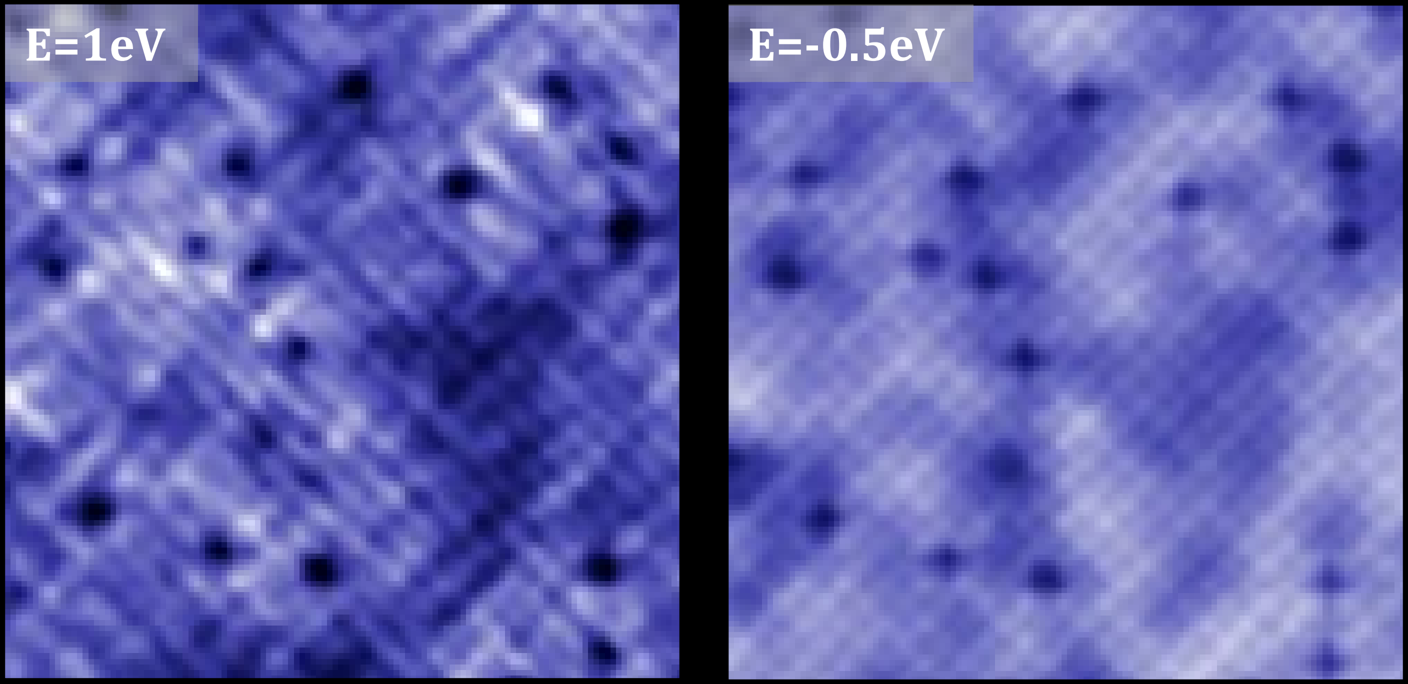
Topological defects in $G_s(r, \mathrm{E}=0.4\mathrm{eV})$

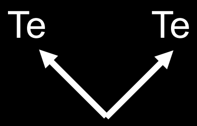


Venkatesan *et al.*, *in preparation*

Broken local rotational symmetry

Local electronic nematic phase

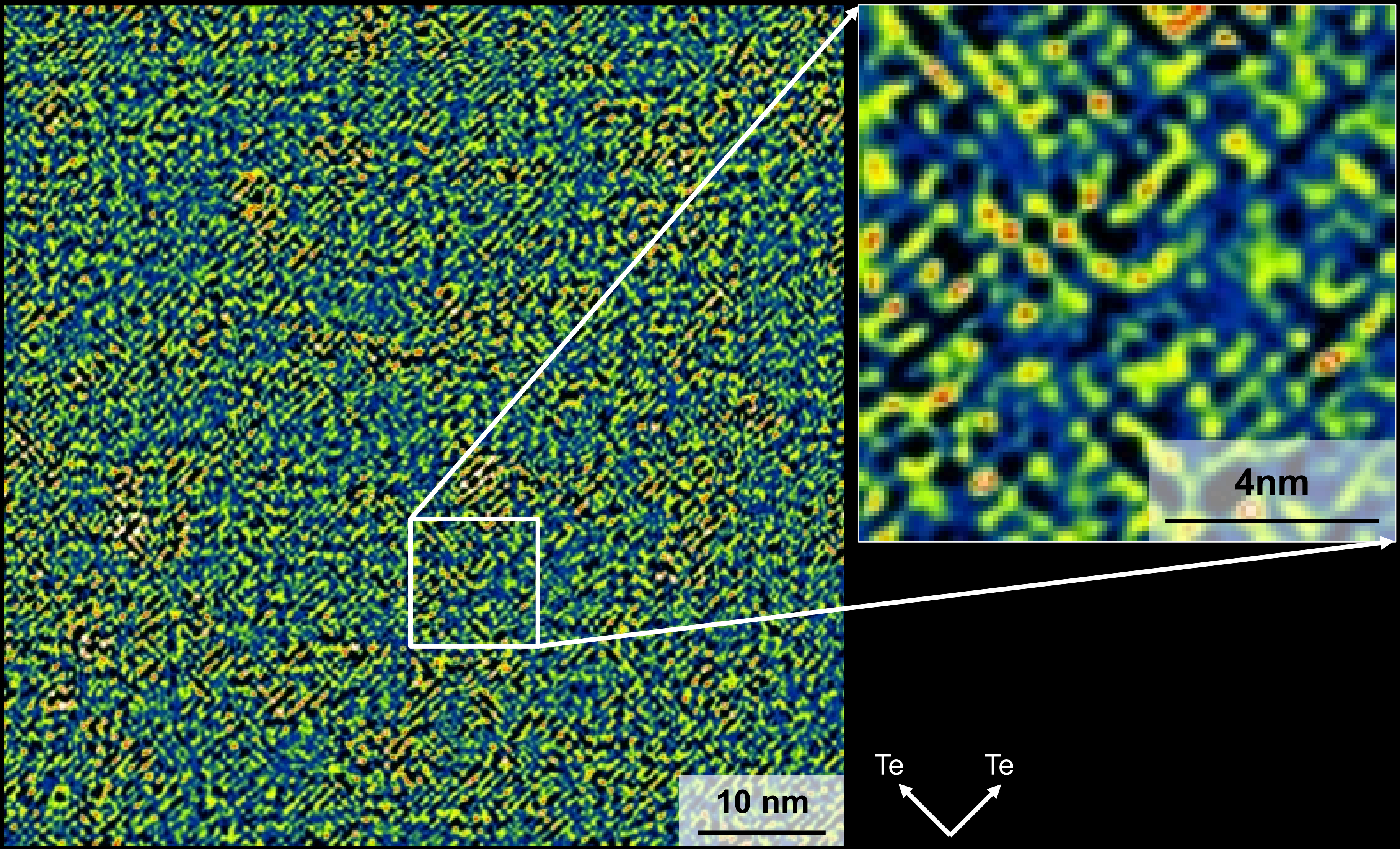




Venkatesan *et al.*, *in preparation*

Local electronic nematic phase

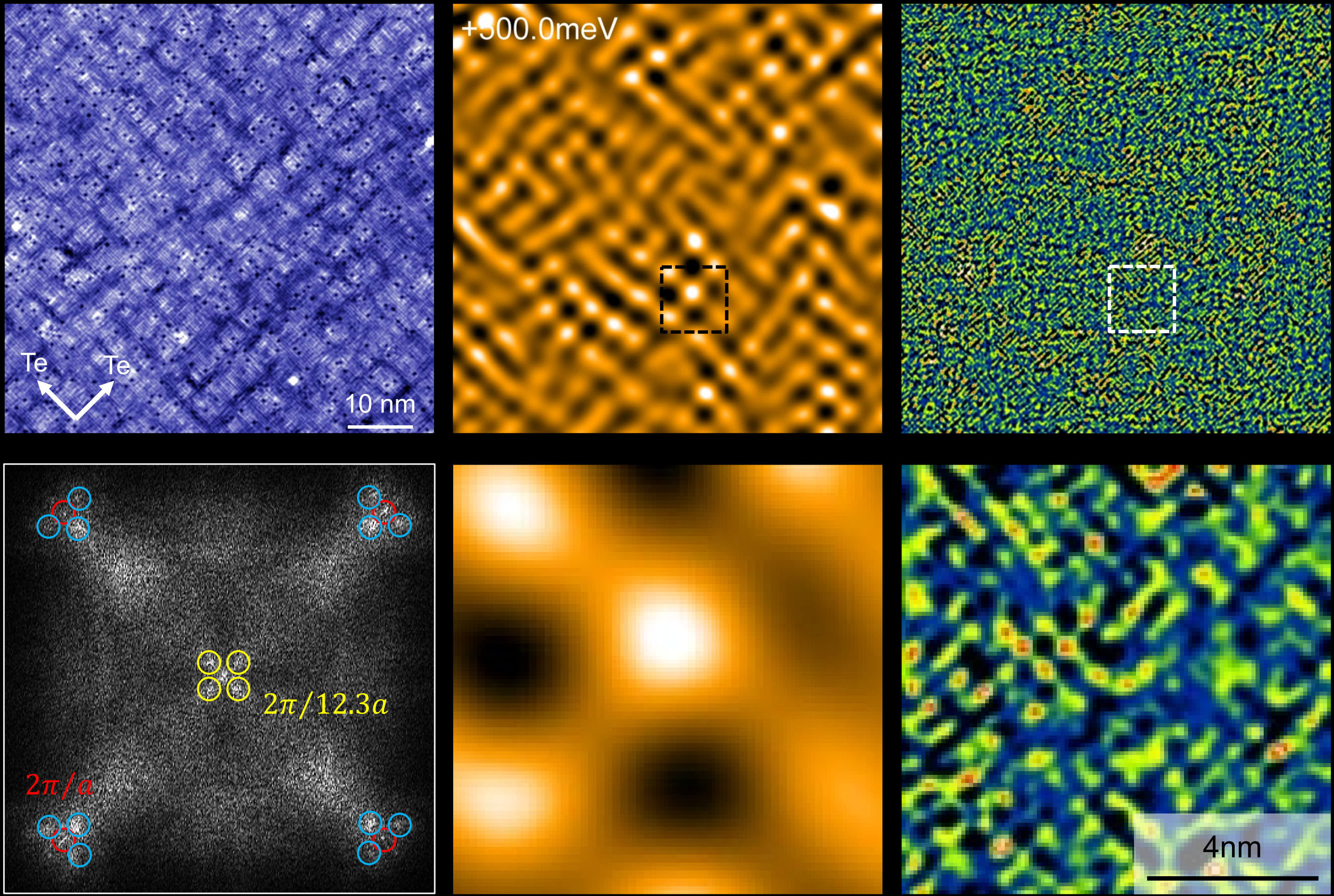
$\nabla^2 I_{nematic}(r,$ E=0.5eV) after FFT-filtering lattice and stripe peaks.



Venkatesan *et al.*, *in preparation*

ELC phases @ the AFM state

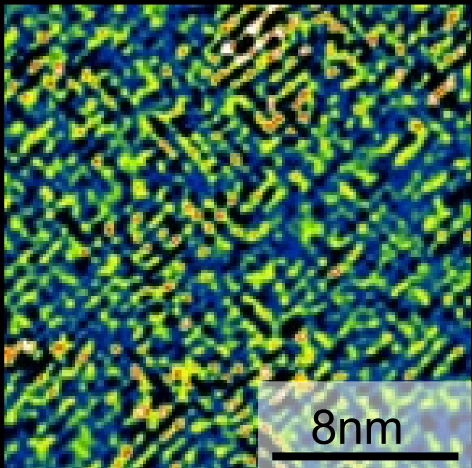
$z(r, \mathrm{E{=}1eV})$ $\quad$ $I_s(r, \mathrm{E{=}0.5eV})$ $\quad$ $\nabla^2 I_{nematic}(r, \mathrm{E{=}0.5eV})$



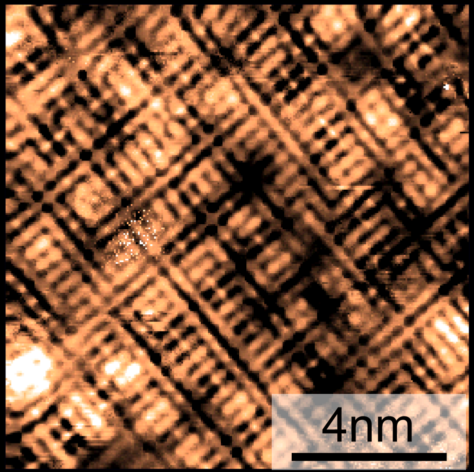
Venkatesan *et al.*, *in preparation*

Resemblance of underdoped Mott insulators

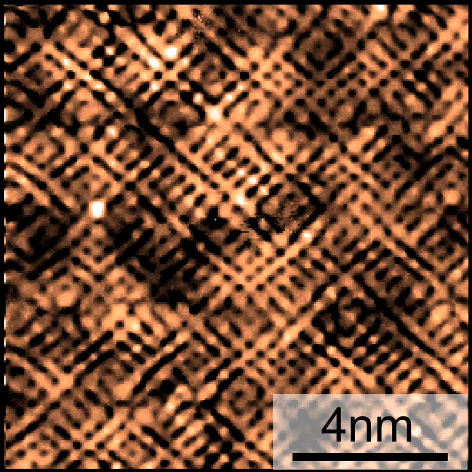
GdSbTe



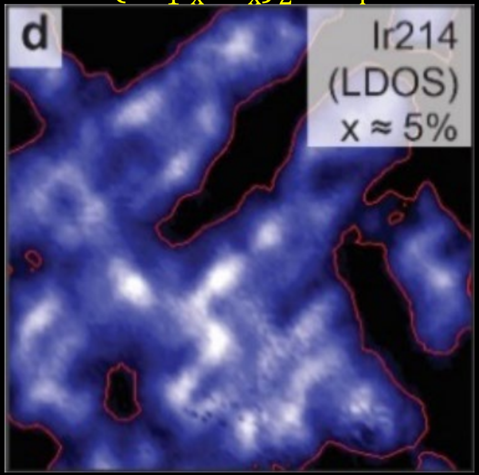
$Ca_{1.90}Na_{0.10}CuO_2Cl_2$

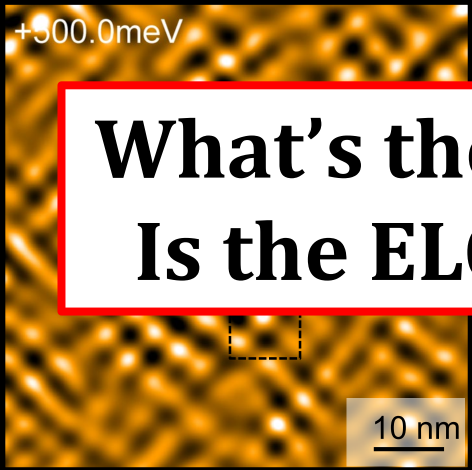


$Bi_{2.2}Sr_{1.8}Ca_{0.8}Dy_{0.2}Cu$



$(Sr_{1-x}La_x)_2IrO_4$



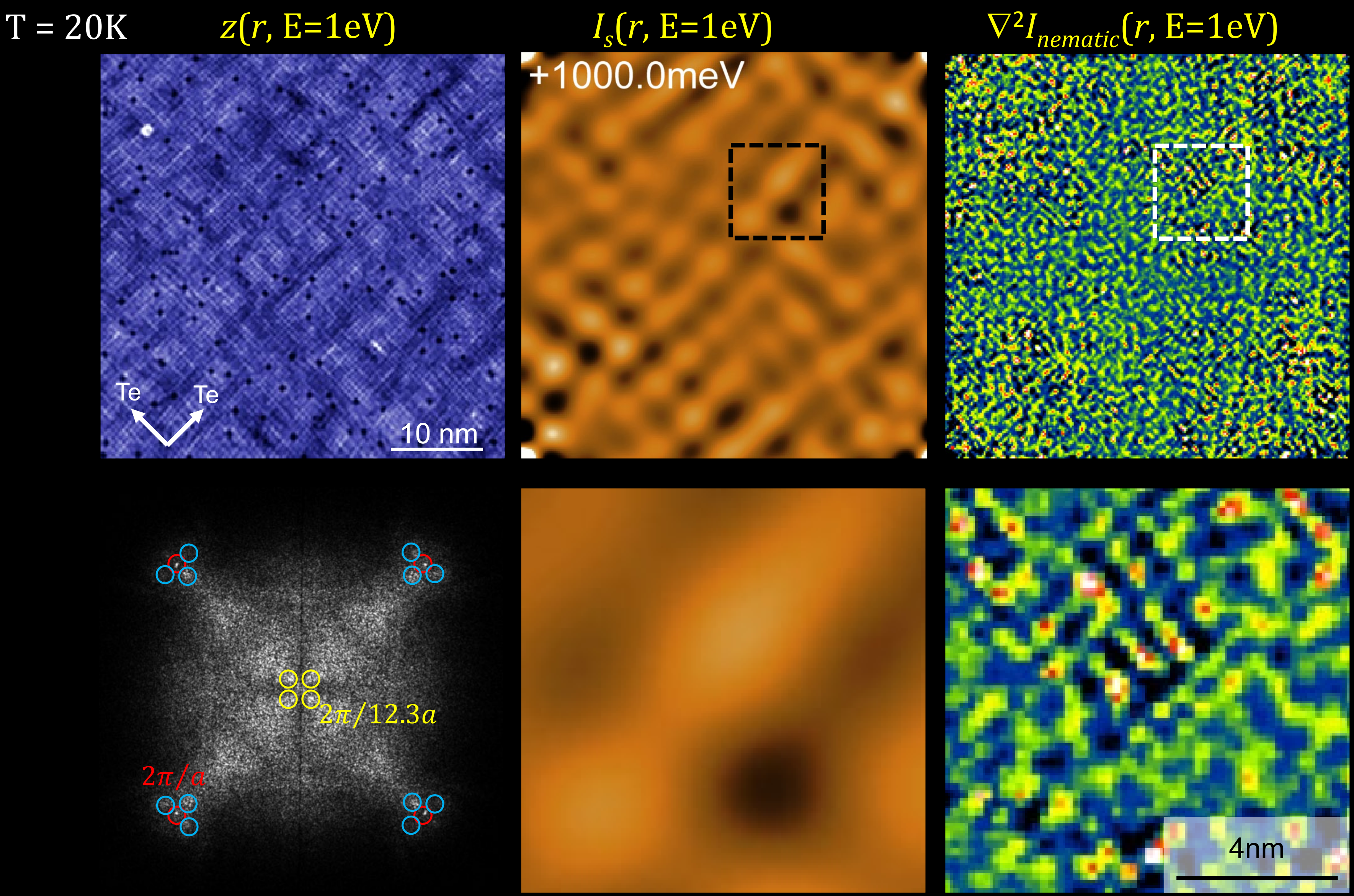


Science 315, 1380 (2007)
PNAS 111, E3026 (2014)

Nat. Phys. 13, 21 (2017)

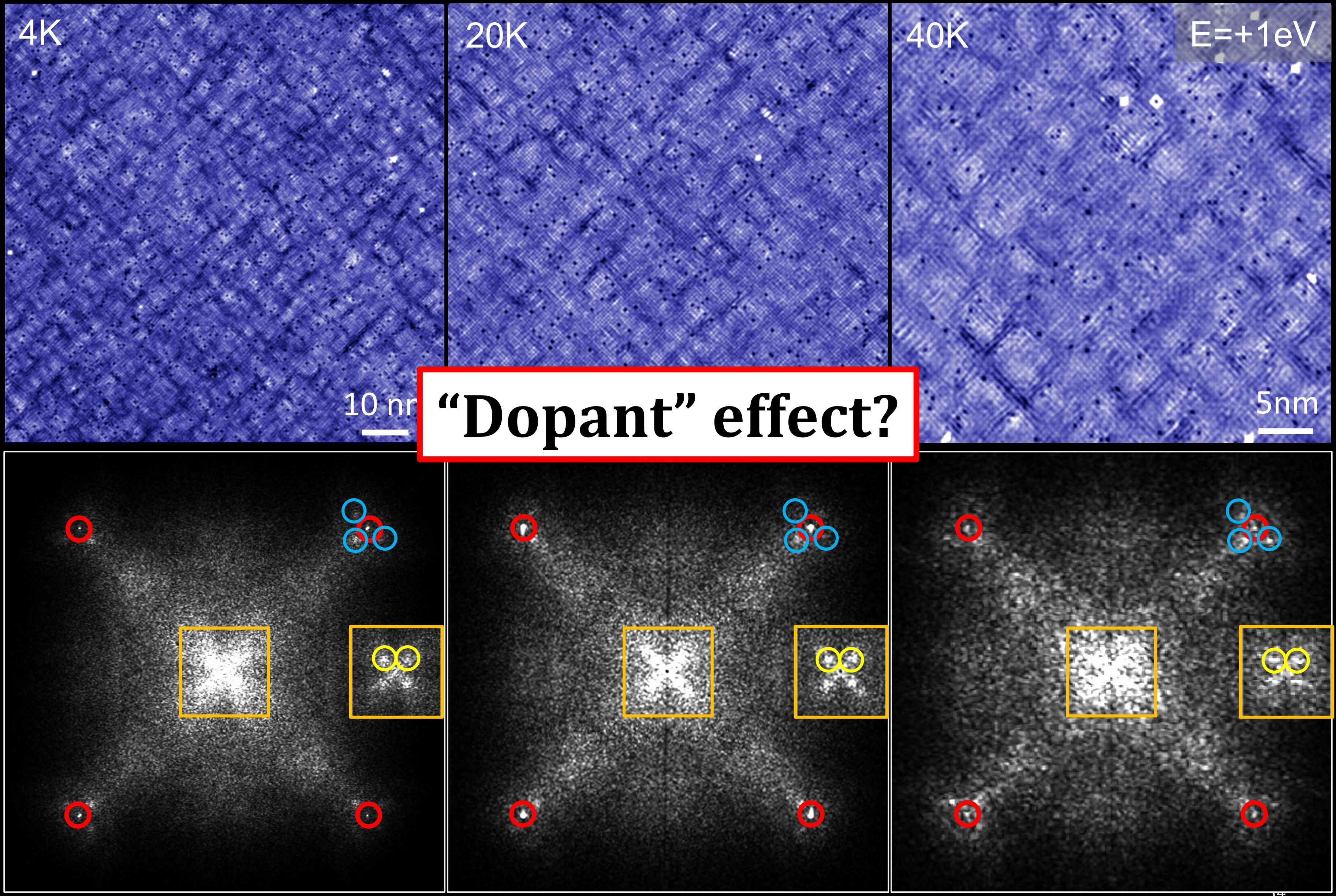
What's the origin of ELC phase in GdSbTe?
Is the ELC phase induced by AFM order?

ELC still exists above T_N



Venkatesan *et al.*, *in preparation*

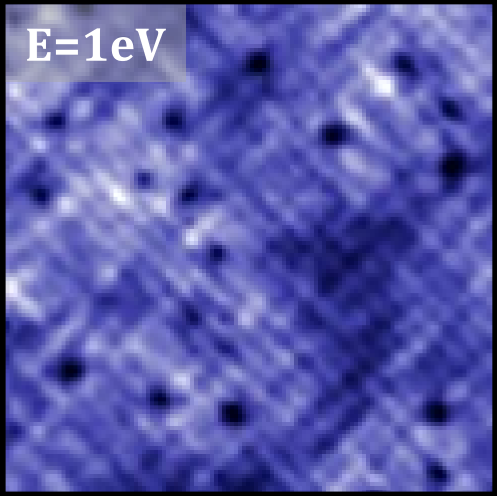
ELC still exists above T_N

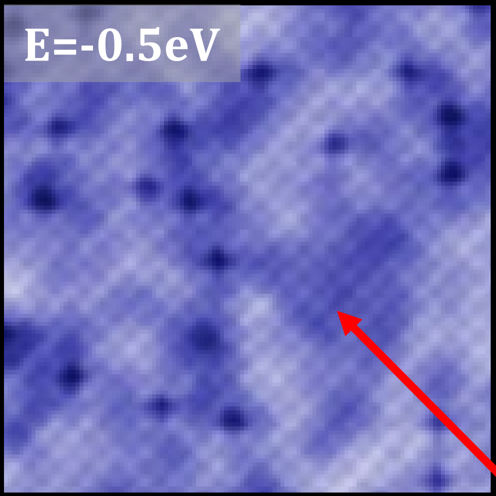


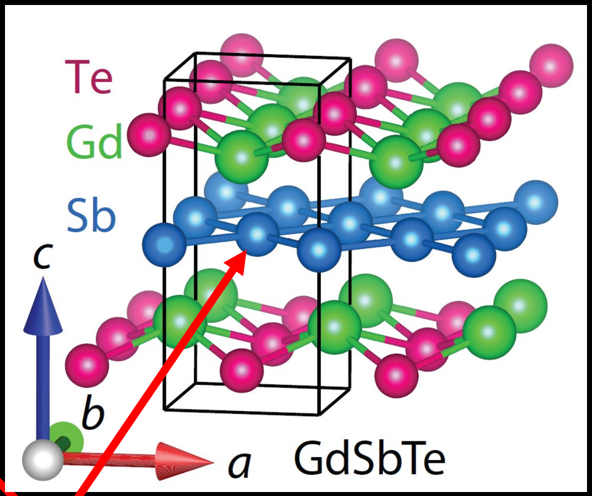
Venkatesan *et al.*, *in preparation*

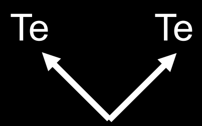
Origin of ELC phases?

1D electronic structure
Broken local rotational symmetry!







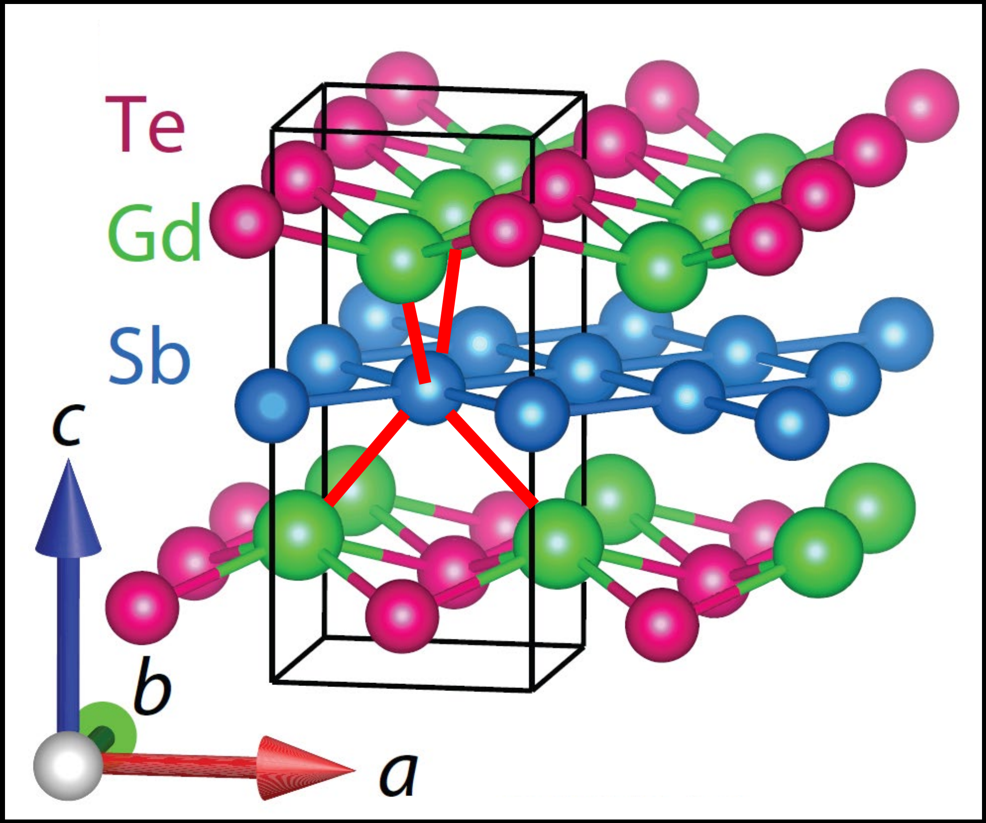


Can these difference in contrast be due to ~12% of Te substitution to the Sb-layer?

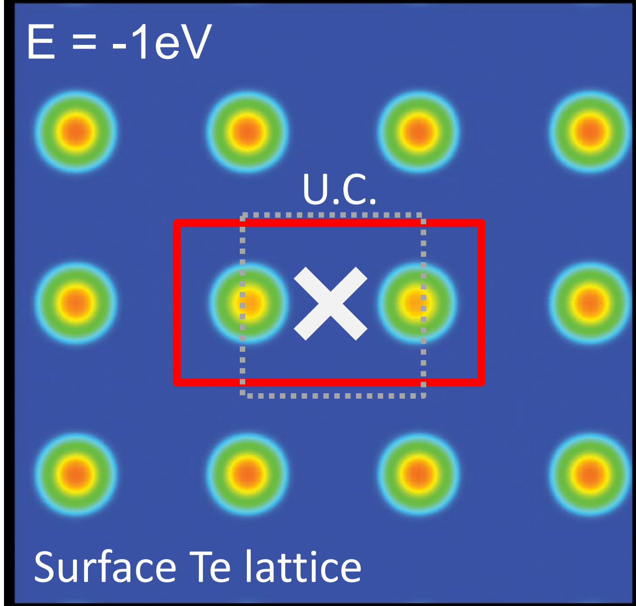
Venkatesan *et al.*, *in preparation*

Anisotropic bond at Sb-sites

- Due to Te substitution to the Sb-layer?
- Te-substitution in Sb-layer creates a C2-symmetric impurity state at Te-surface.



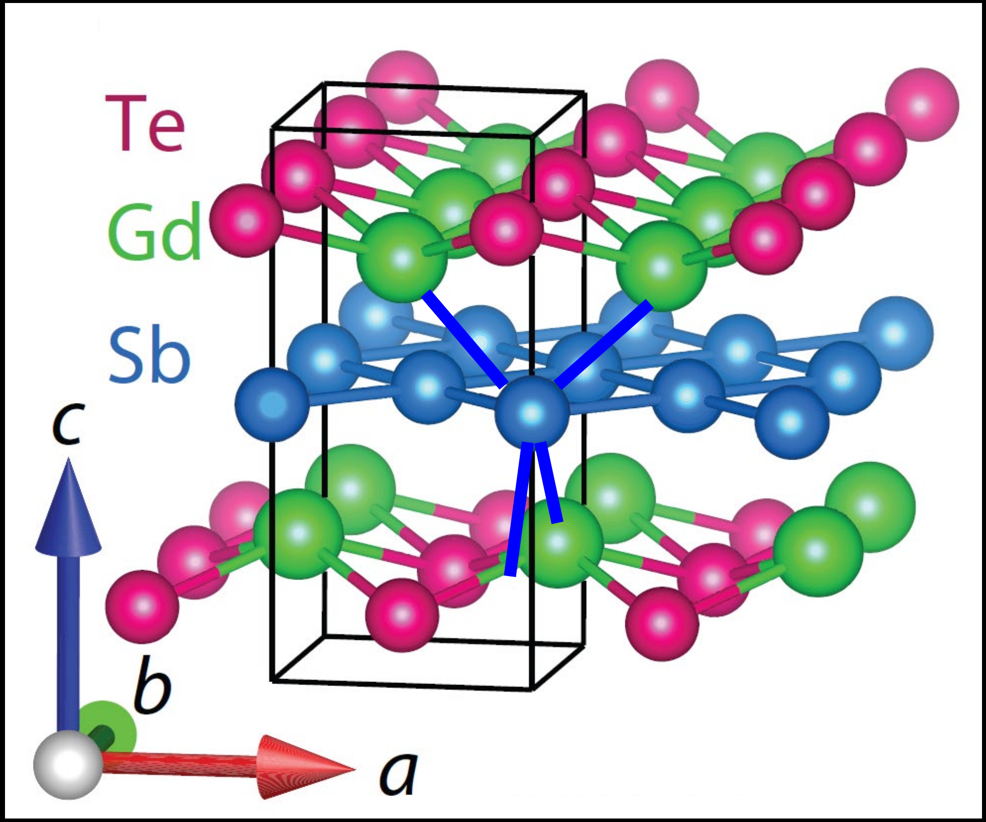
Charge density



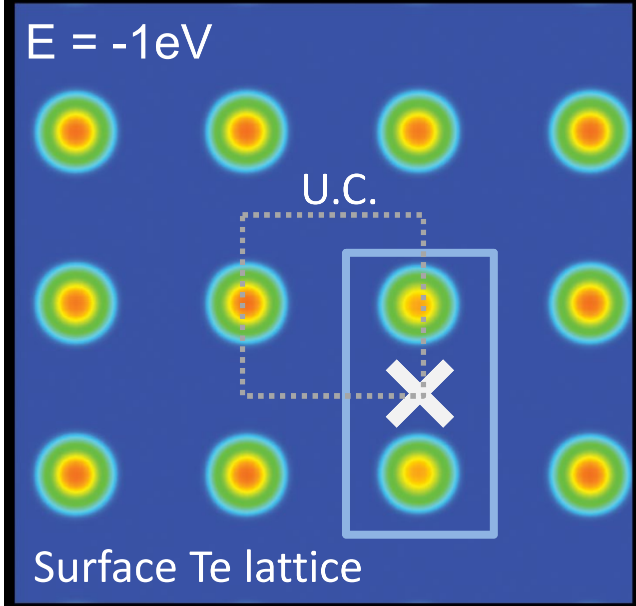
Venkatesan *et al.*, *in preparation*

Anisotropic bond at Sb-sites

- Due to Te substitution to the Sb-layer?
- Te-substitution in Sb-layer creates a C2-symmetric impurity state at Te-surface.



Charge density



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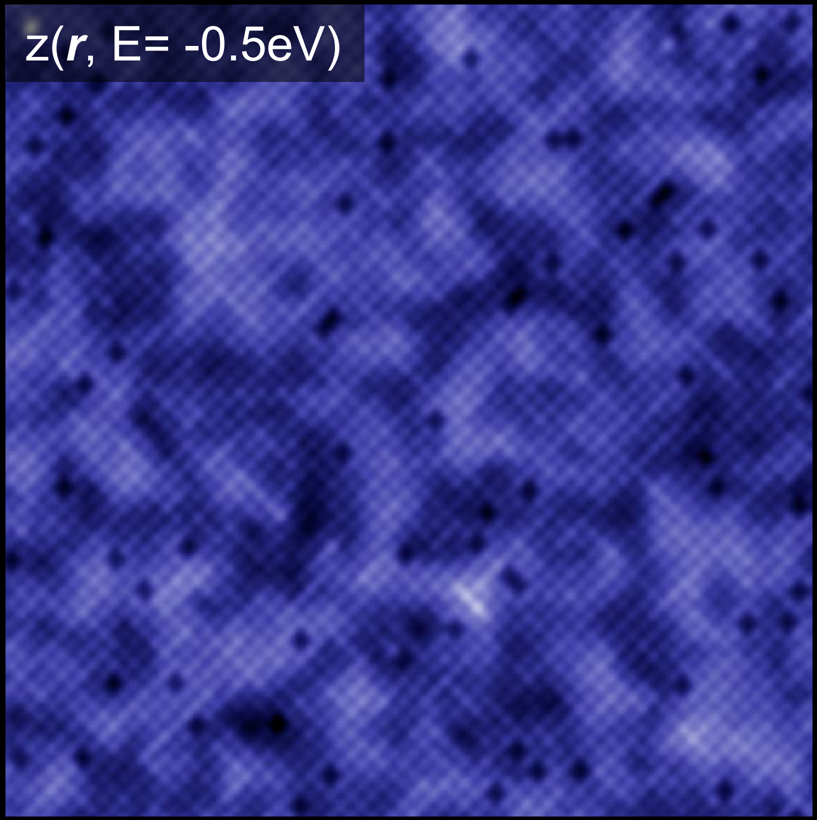
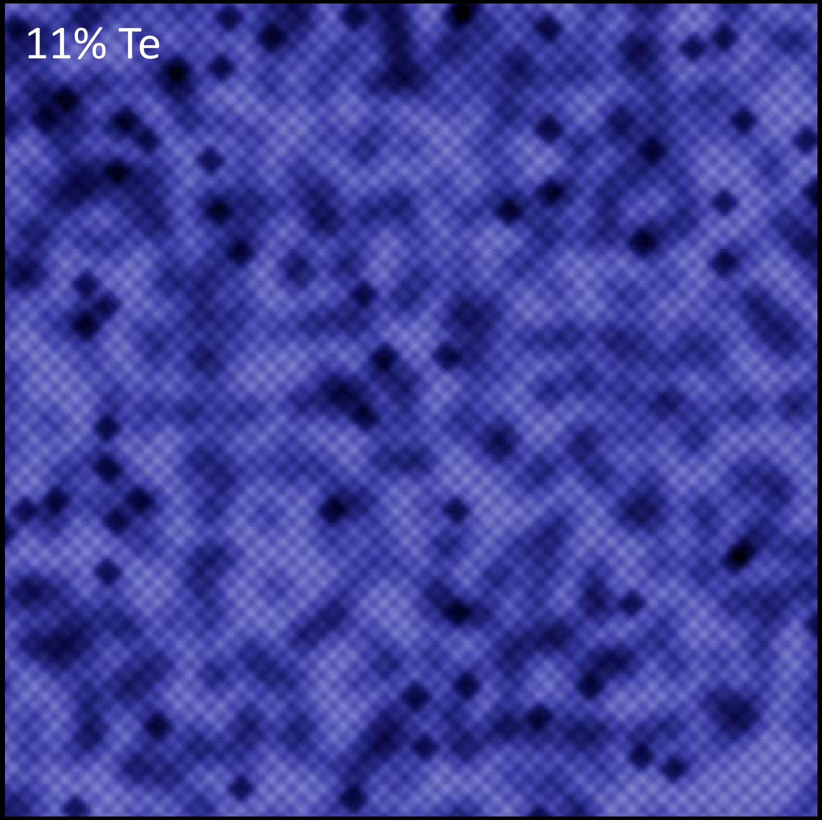
Sb/Te substitution in the Sb layer

STM



24nm

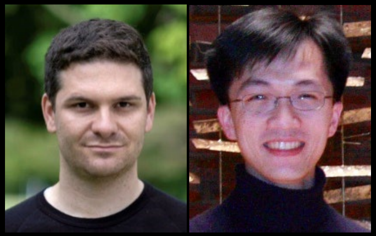
Simulation
(Te/Sb subsitution+ 2% Te vacancy)



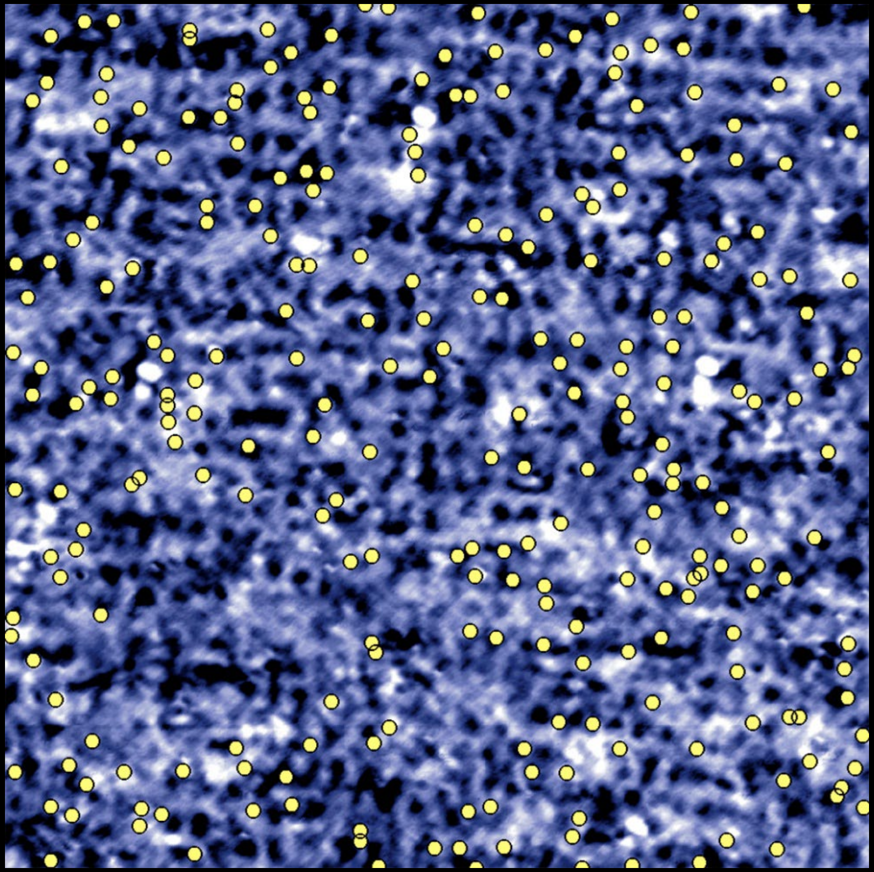
Qualitatively agree with STM topograph

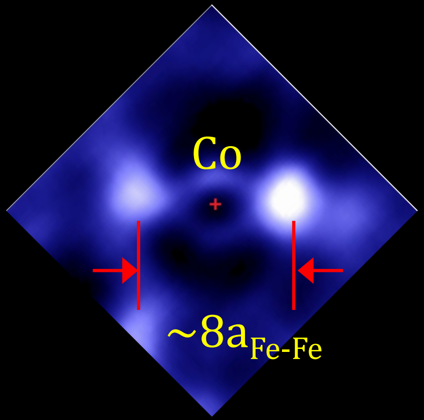
Venkatesan *et al.*, *in preparation*

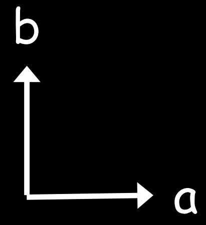
Co Dopants & Nematicity in $Ca(Co_{0.03}Fe_{0.97})_2As_2$



$I(\vec{r},+50mV)$

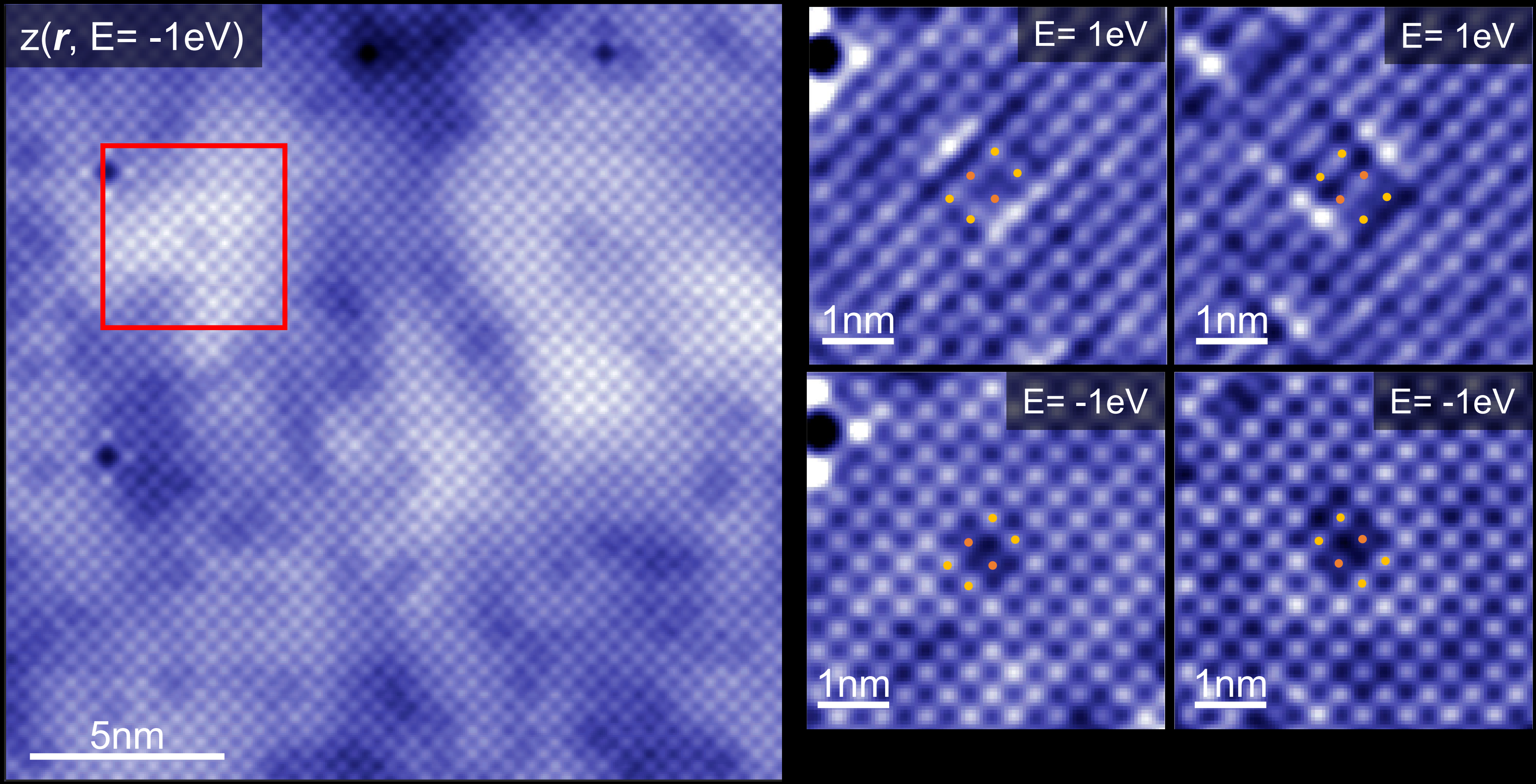






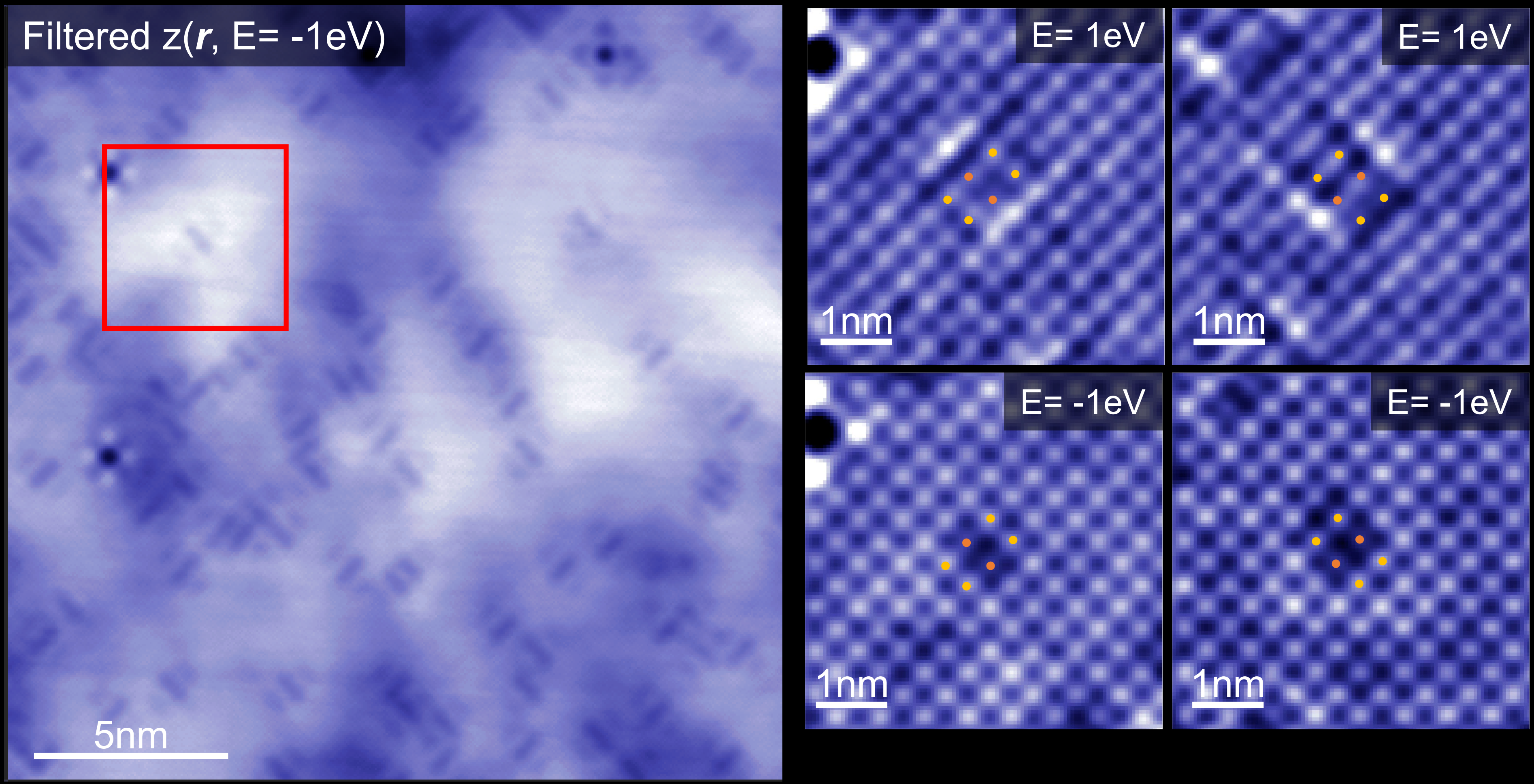
M.P. Allan & T.M. Chuang *et al.,* Nature Phys. 9, 220 (2013)

Isolated C2 impurities in $GdSb_{0.98}Te_{1.02}$



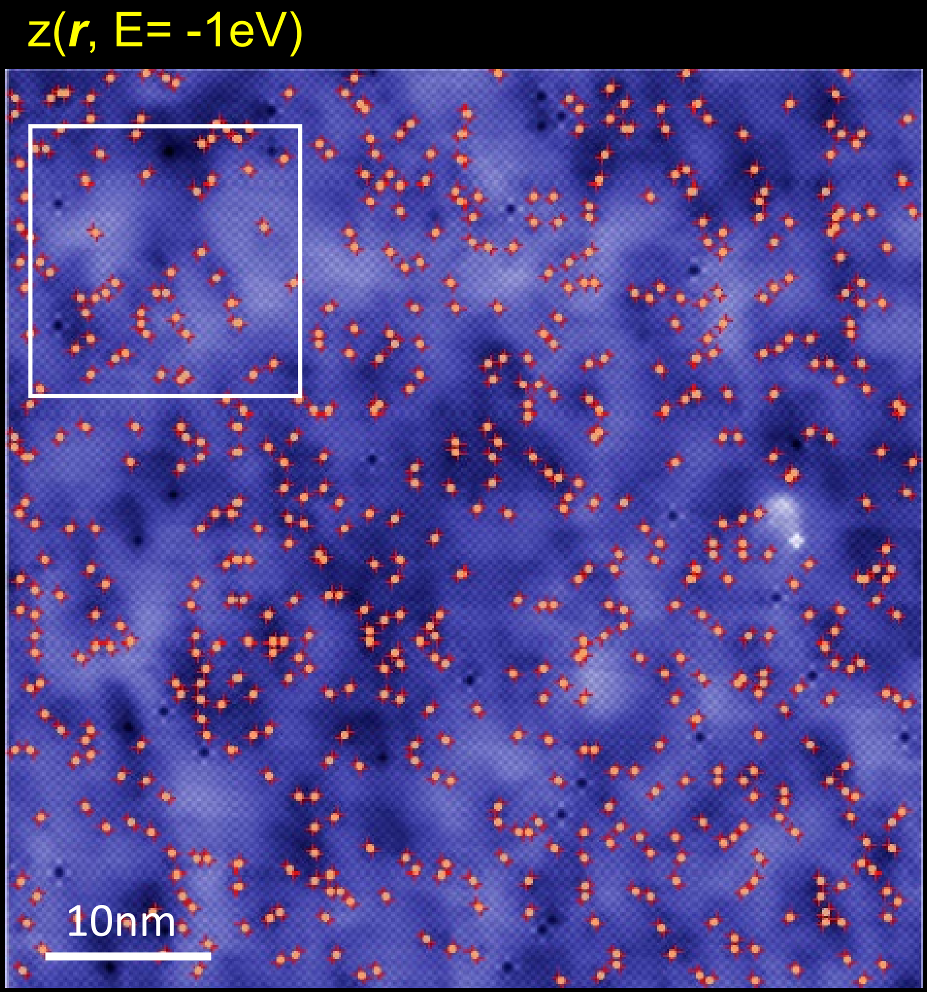
Venkatesan *et al.*, *in preparation*

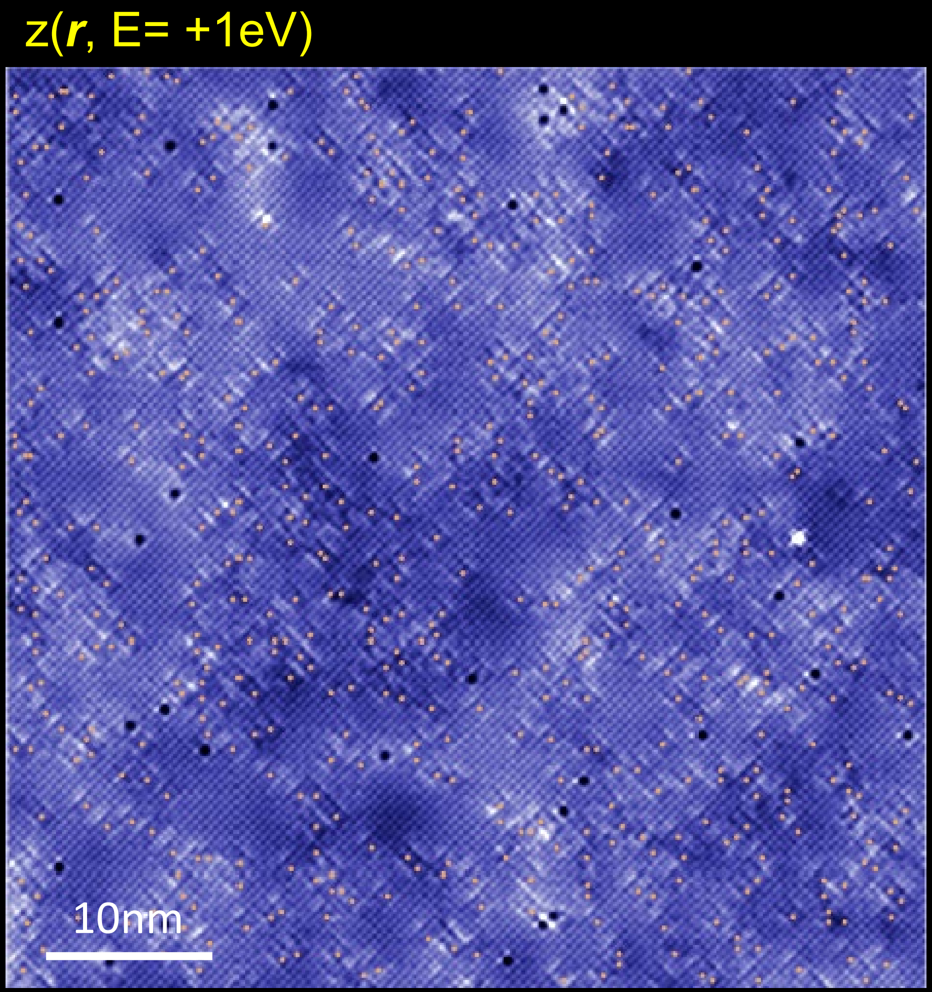
Isolated C2 impurities in $GdSb_{0.98}Te_{1.02}$



Venkatesan *et al.*, *in preparation*

Te-substitution sites correlated with local nematicity

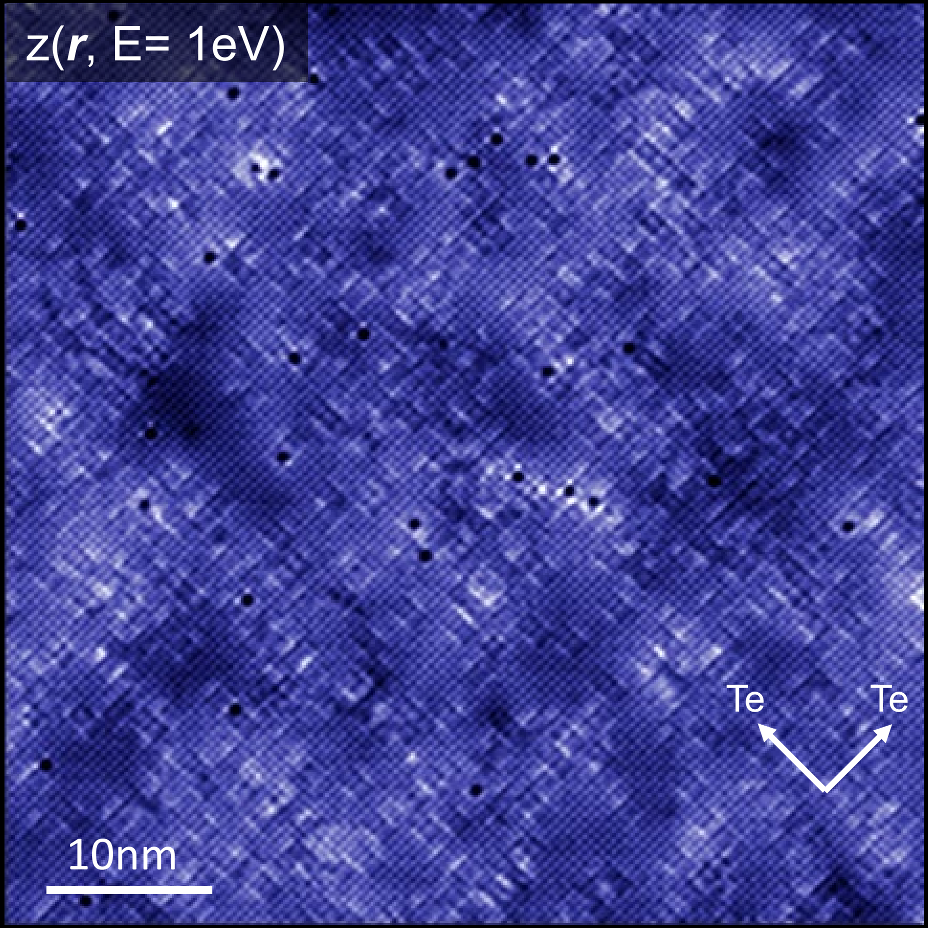


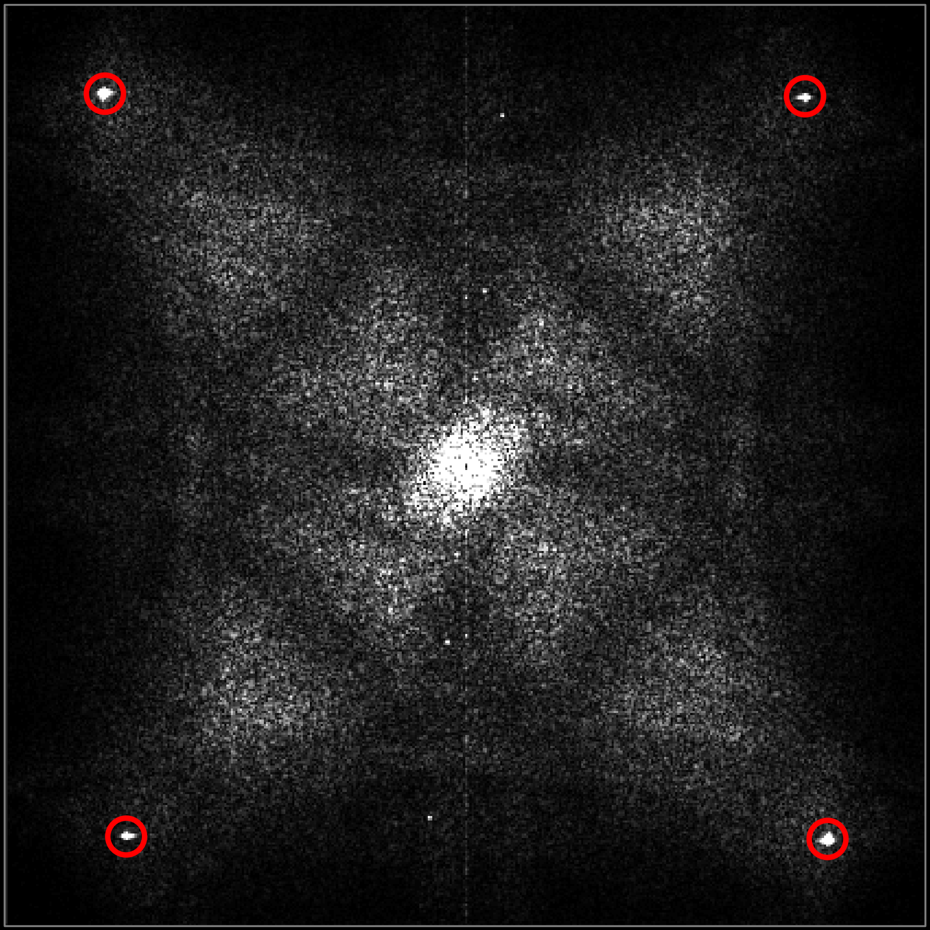


Quench disorder + non-symmorphic symmetry are key to the local nematic phase.

No broken translational symmetry in $GdSb_{0.98}Te_{1.02}$

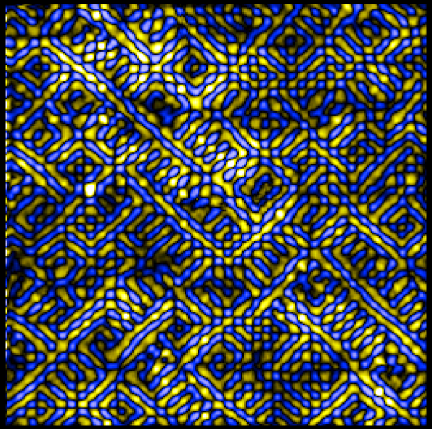
Quench disorder plays a key role for ELC phase!



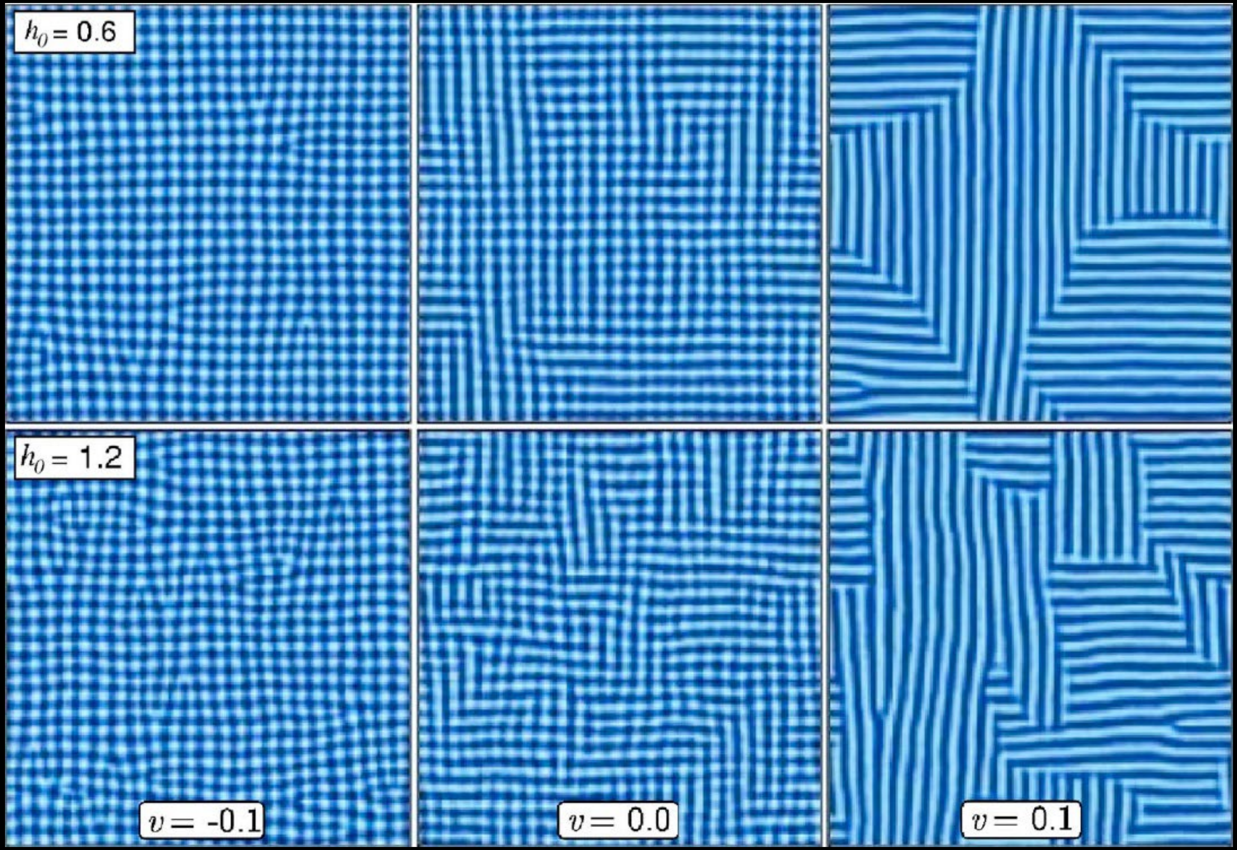


Quenched disorder on the ELC phase in cuprates

- Random electrostatic potential due to charged dopants coupled to an unidirectional CDW.
- Due to disorder, translation symmetry breaking may not occur. Instead, vestigial nematic order survives.

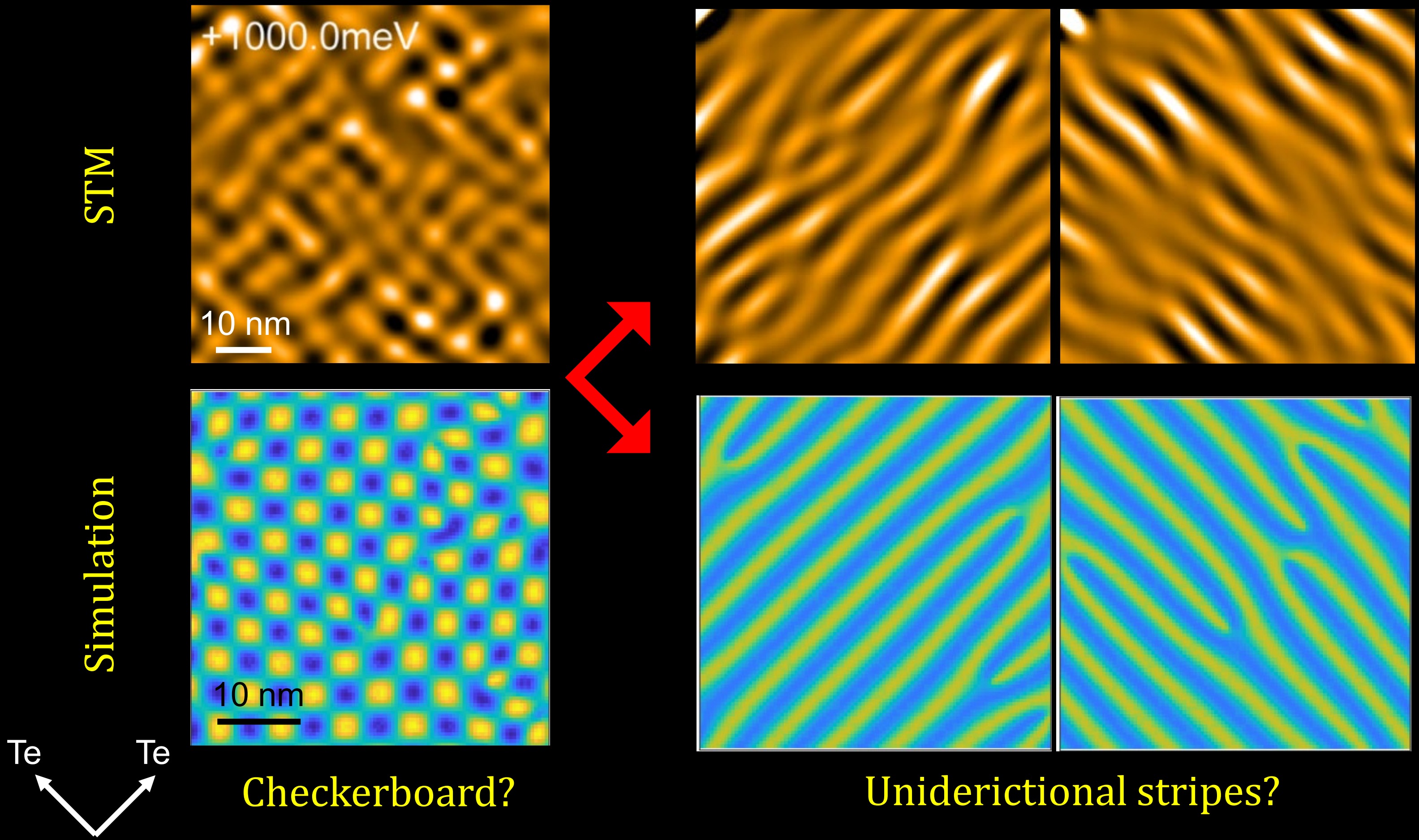


Strength of the random field, h_0
Coupling constant, ν



Adrian Del Maestro *et al.*, PRB 74, 024520 (2006)
J. A. Robertson et al., PRB 74, 134507 (2006)

Te-substitution on the electronic stripes in GdSbTe



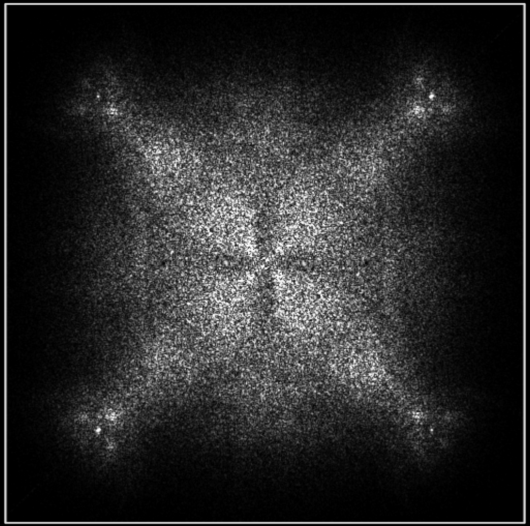
Checkerboard?

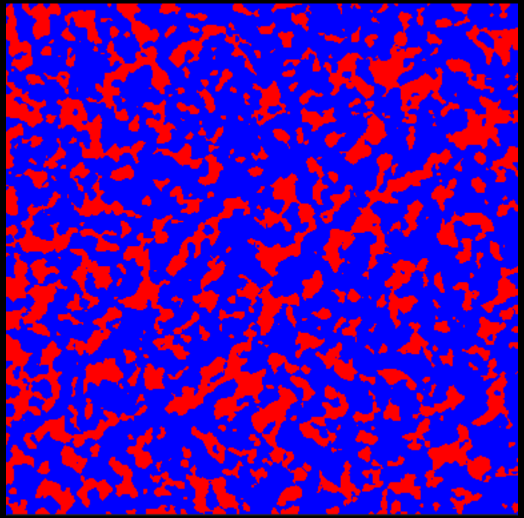
Uniderictional stripes?

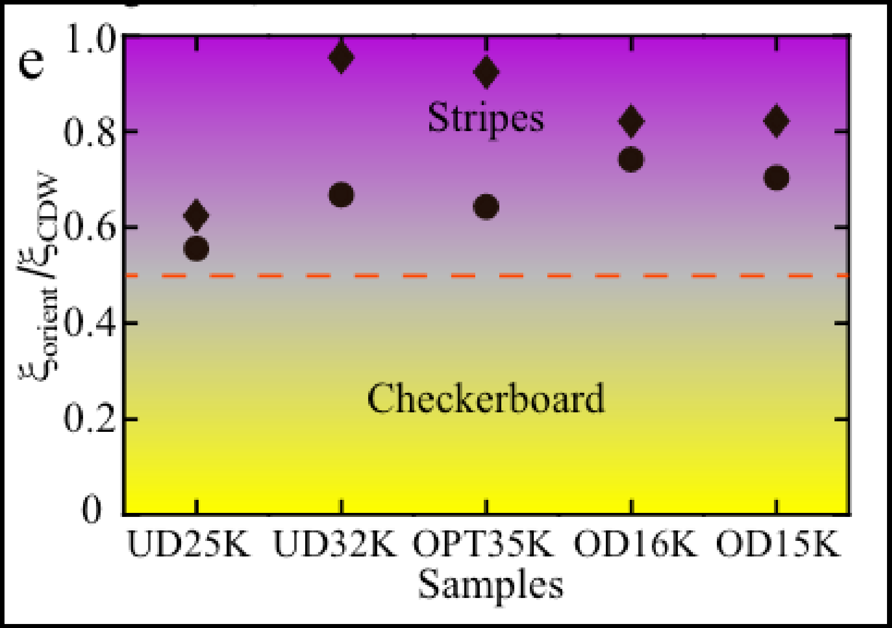
Adrian Del Maestro *et al.*, PRB 74, 024520 (2006)
J. A. Robertson et al., PRB 74, 134507 (2006)

Checkerboard or Stripe?

Criteria for differentiating two phases through local C2 symmetry breaking



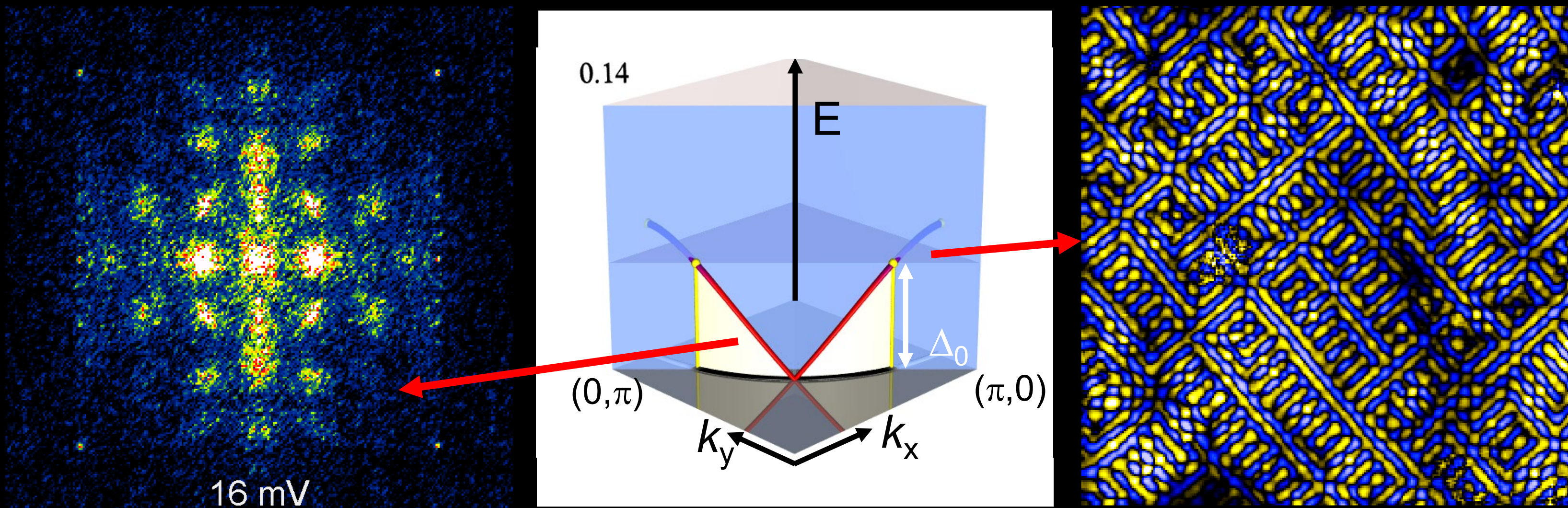




Song, CL. et al. Nat Commun 14, 2622 (2023).

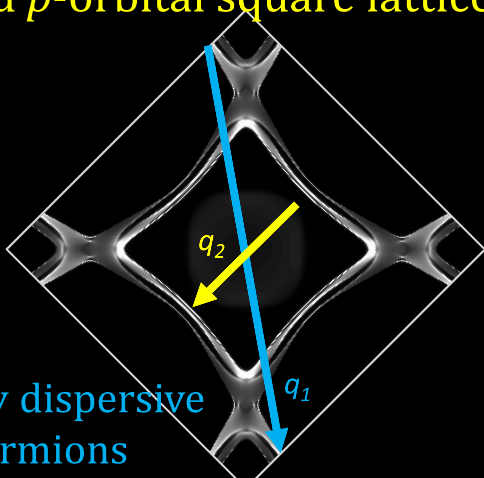
Cuprates vs GdSbTe

Half-filled *d*-orbital square lattice

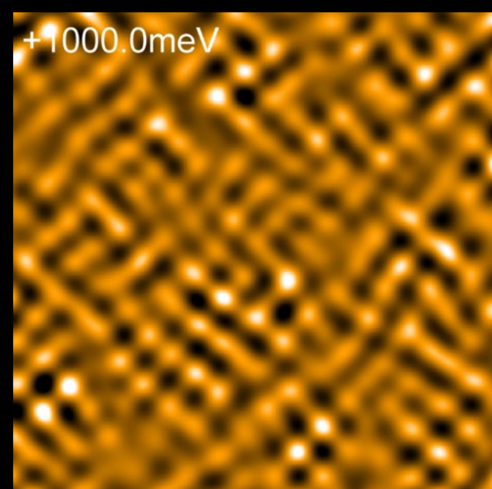


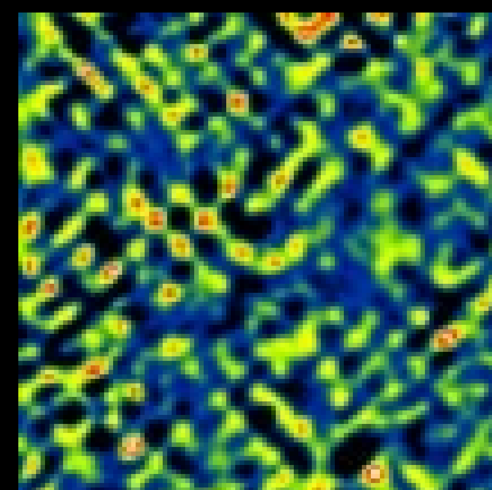
Y. Kohsaka *et al*., Nature 454, 1072 (2008)

Half-filled *p*-orbital square lattice



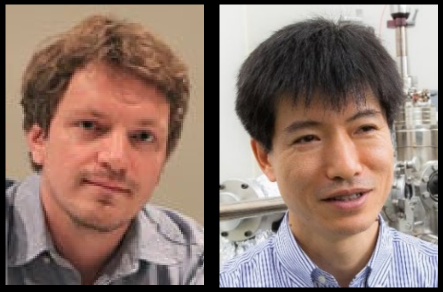
Linearly dispersive
Dirac fermions



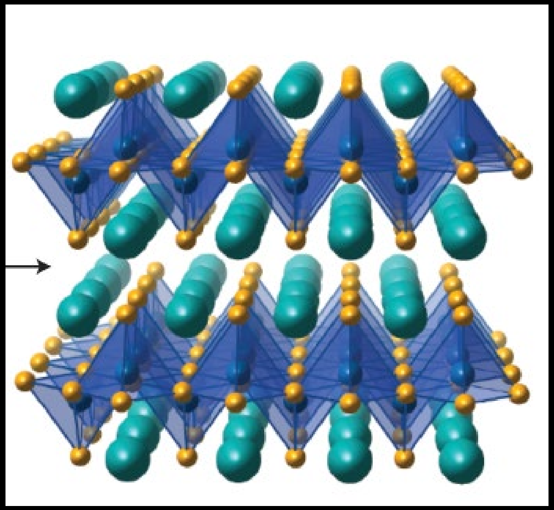


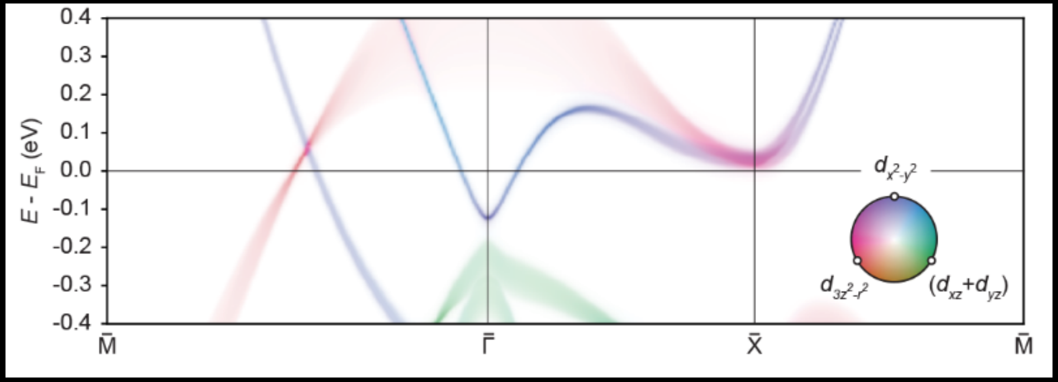
Venkatesan *et al*., *in preparation*

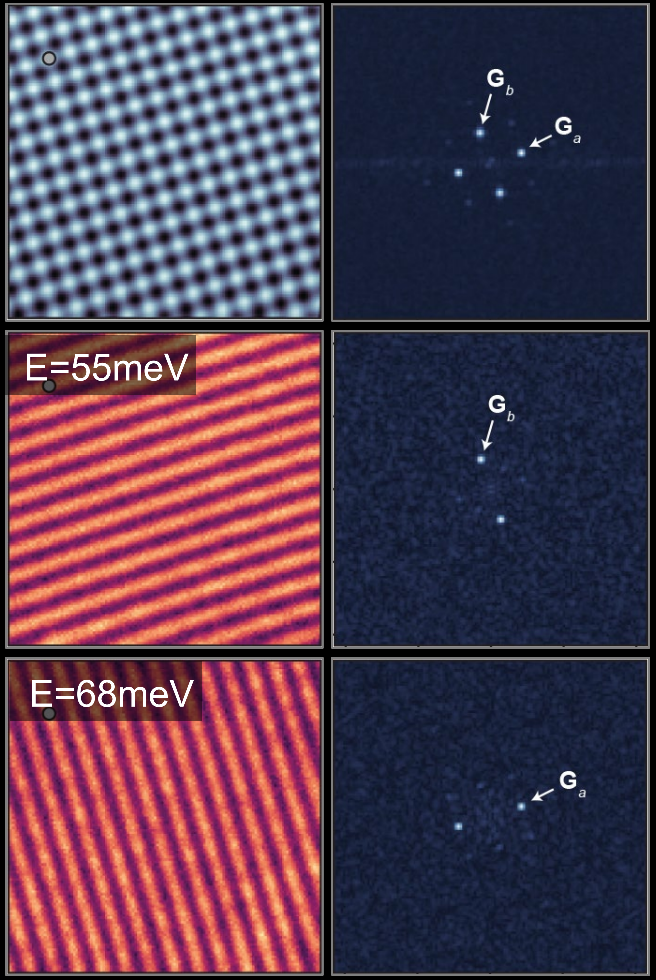
Electronic nematicity in the Dirac semimetal $BaNiS_2$



Surface Ni-square net







C.J. Butler *et al.*, PNAS 119, e2212730119 (2022)

Summary

- Coexistence of ELC and Dirac fermions in correlated DNL GdSbTe.
- Dopants and non-symmorphic symmetry play important roles!
- Further microscopic understanding of ELC phases in other SCESs