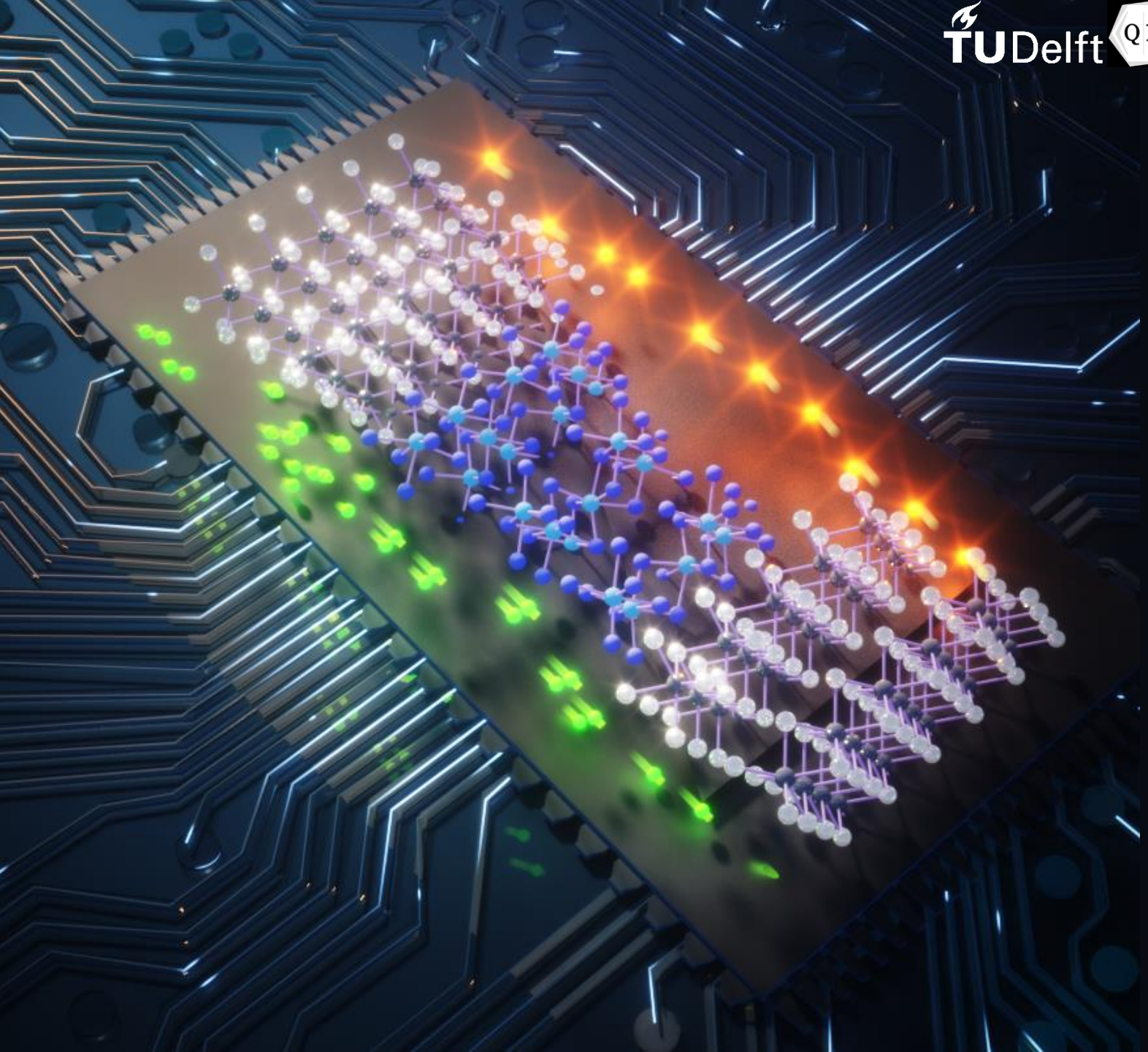


2D Quantum Material Josephson Junctions (QMJJ)

Mazhar N. Ali[1,2,3], H. Wu[1,2], Y. Wang, Michiel Dubbelman et al[1,2]

IMPACT 2024, Institut d'études scientifiques de Cargèse, Corsica

20-08-2024

[1]Delft University of Technology (TU Delft), Netherlands

[2]Kavli Institute of Nanoscience Delft, Netherlands

[3]Material Mind Inc., Fremont, California

Outline

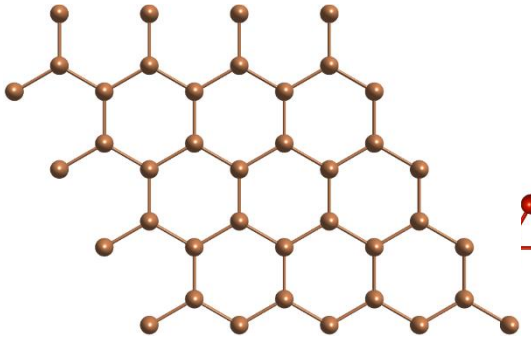
- Background 1: Quantum Materials (Brief)
- Background 2: Josephson Junctions (JJs) (Brief)
  - The Josephson Effects
  - JJs critical to 21st century technologies
- Main: Quantum material (QM) JJs – the next generation JJ
  - Thesis: Use the inherent properties of the QM to modulate JJ behavior (and SC) in new and unexpected ways
    - Strongly correlated insulator (Mott Insulator) JJ – breathing Kagome
    - $Nb_3Cl_8/Br_8/I_8$ and the field-free Josephson diode (*non-reciprocal* superconductivity)

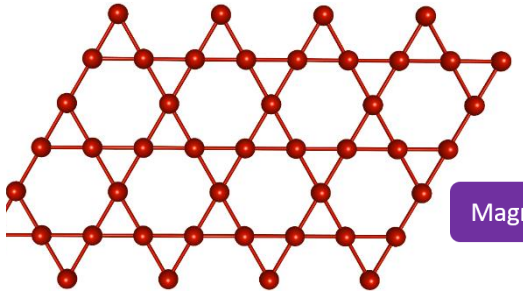
H, Wu., et al, *Nature*, 604, 653-656 (2022) H. Wu et al, *under review at Nature, 2024* M. Dubbelmann et al, *manuscript in preparation 2024*

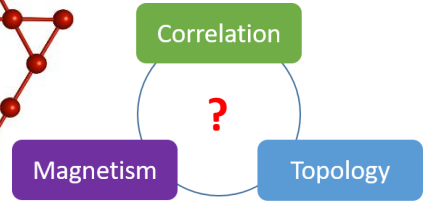
Background 1: Quantum Materials

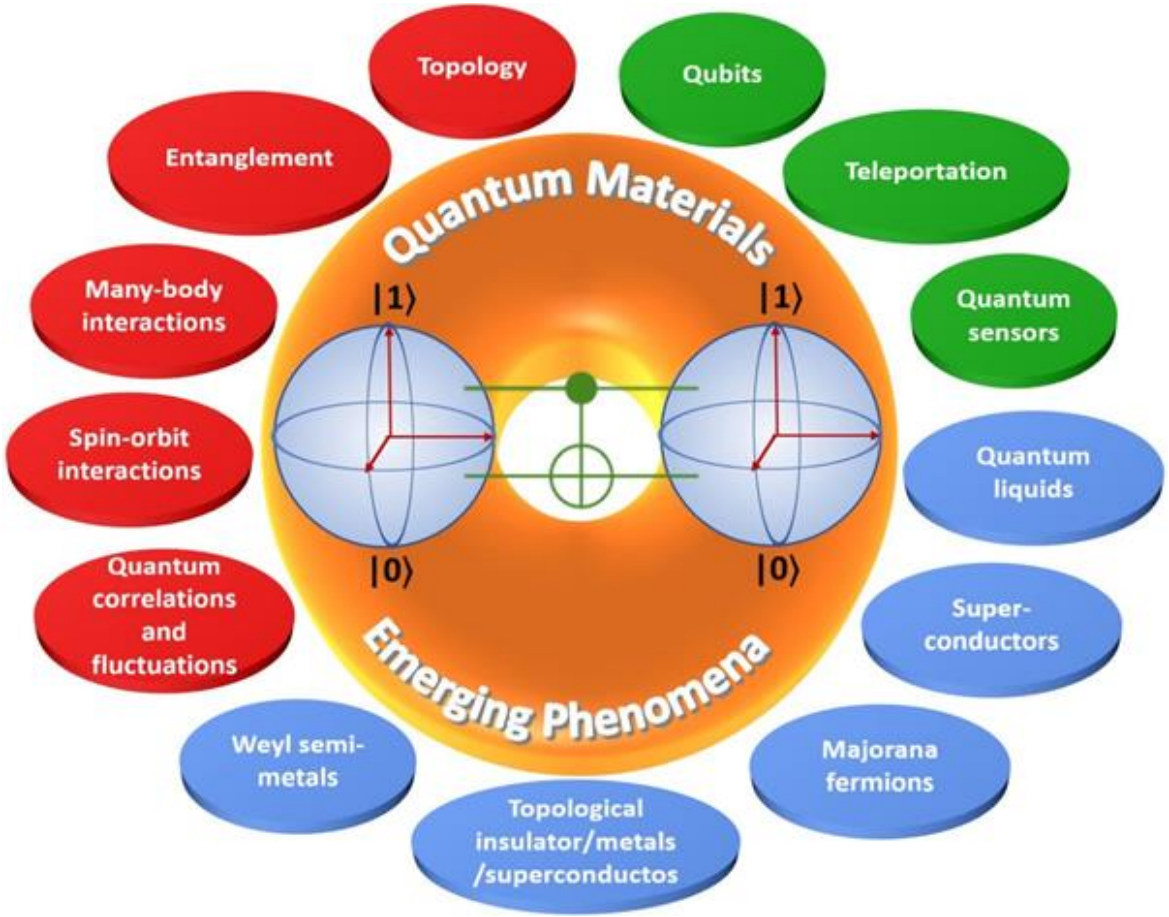
Quantum Materials

Rao, M. S. R., Bhallamudi, V. P., Hammel, C. P., Journal of Physics D: Applied, 51, 2020



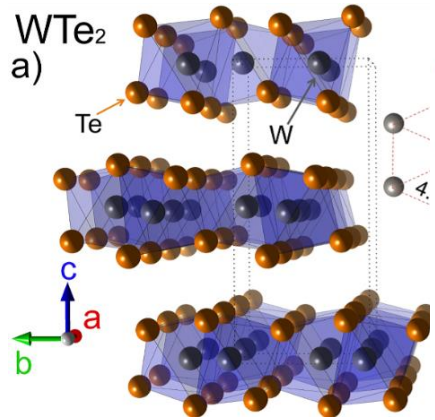


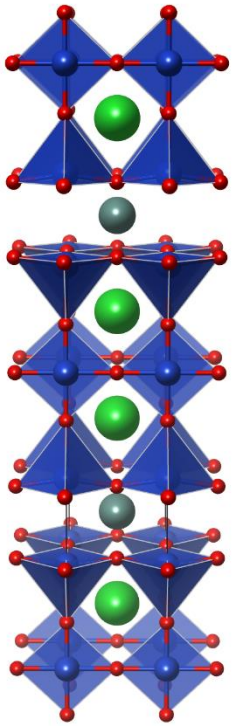




"The simplest of definition might be that a quantum material is a material whose electronic or magnetic properties are not best described using classical particles or calculations that do not take into account the full character of the system."

- Topological materials
- Spin liquids
- Quantum Ferroelectrics
- Quantum Magnetoelectrics
- Exotic magnets
- **Superconductors**
- Many more classes





- **2D ones are especially fun: can easily be made into quantum devices!**

$YBa_2Cu_3O_{7-x}$ (YBCO)

C. Z. Chen, et al, Phys. Rev. B. 98, 075430

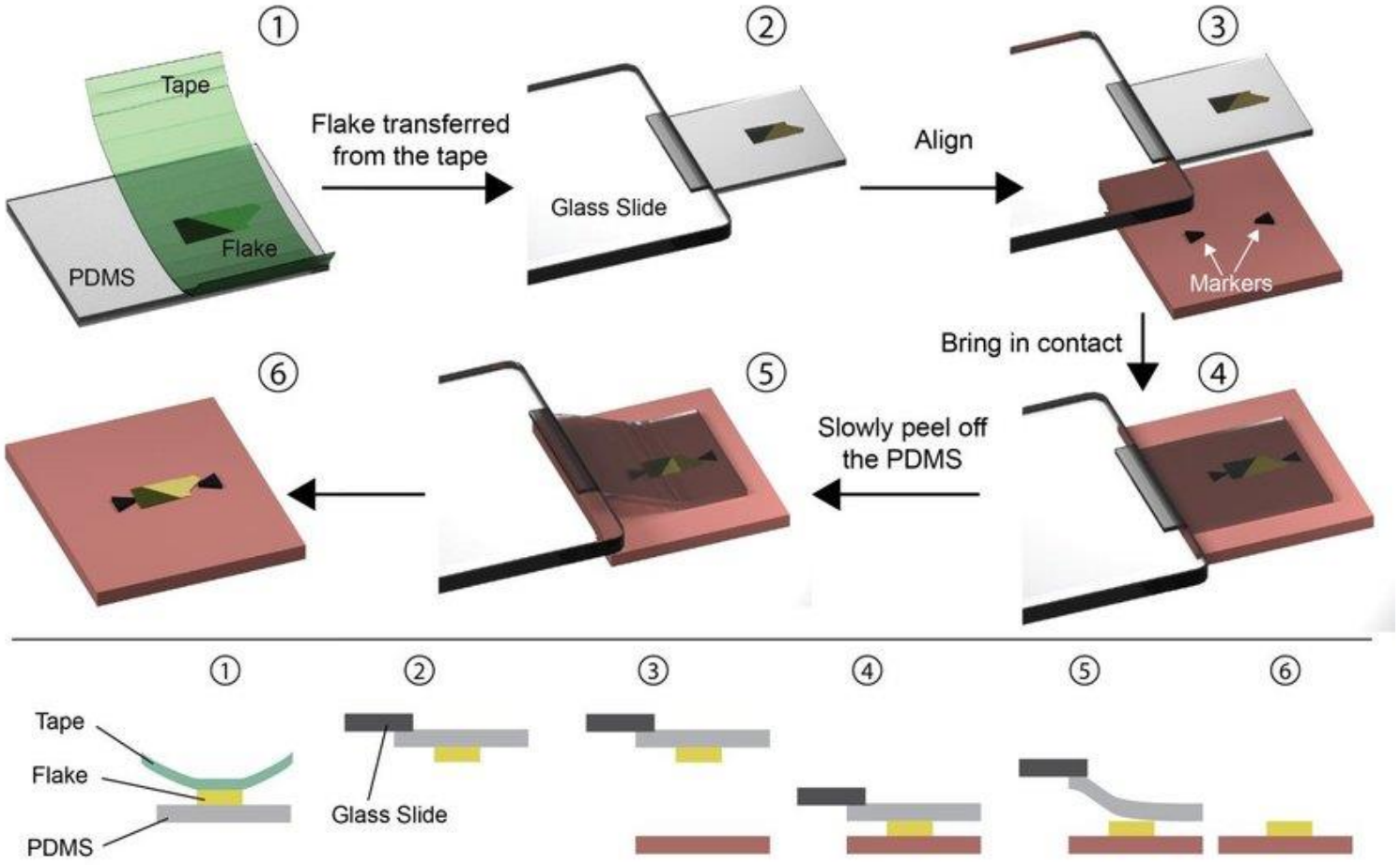
Y. Choi, et al, Nature Materials, 19, 974, 2020

Y. Wang, et al, Nature Physics, doi:10.1038/s41567-021-01190-7, 2021

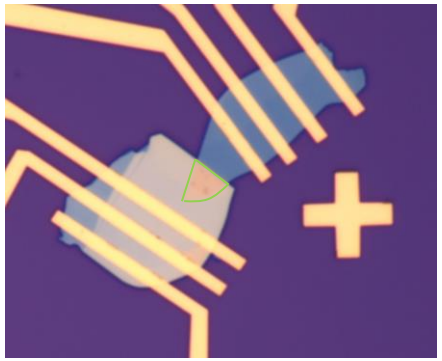
Y. Wang et al, *Science Advances 9, 28,* (2023)

Y. Wang et al, *Nature Reviews Physics, 5, 635–658 (2023)*

2D Quantum Materials can exfoliate/transfer



- Nearly layer by layer construction
  - 2D limit, finite size
- Can make novel heterostructures
  - Non-thermodynamic products
  - Access novel areas of materials phase space



Background 2: Josephson Junctions (JJs)

Brian Josephson and the [illegible]” myth

- 1962 – Brian Josephson (22 y/o) predicted that two superconductors separated by a thin insulating barrier would have a spontaneous DC current.
- Myth: Josephson’s calculation was part of a HOMEWORK assignment of P.W. Anderson’s (Nobel Laureate).
- The truth:

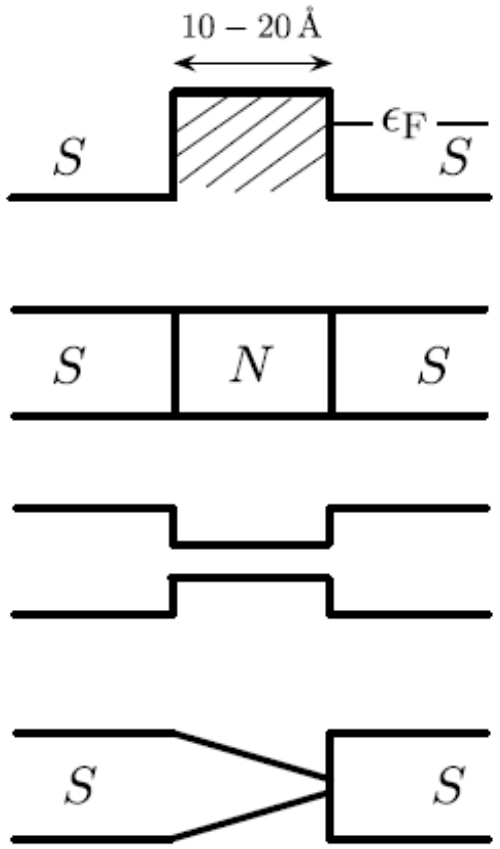
Date: Wed, 10 Jun 2009 09:43:54 +0100
From: Brian Josephson <bdj10@cam.ac.uk>
To: pjh@phys.ufl.edu
Subject: the Josephson myth
Dear Peter,

While browsing I came across your mention of the ’myth’ that I discovered the effect because of a problem set by Anderson. Your correction is not completely correct either! It was Pippard, my supervisor, who drew my attention to Giaevar’s tunnelling expts. and his theory, which started me thinking (especially as to how one could get away without using coherence factors). Anderson on the other hand told me of the Cohen/Falicov/Phillps calculation involving a single superconductor when it came our in PRL, which gave me the idea of how to do the two-sc. case. Previously I had got the broken symmetry idea which was crucial from a number of papers including Anderson’s pseudospin model, and also expounded in his lecture course which I went to.

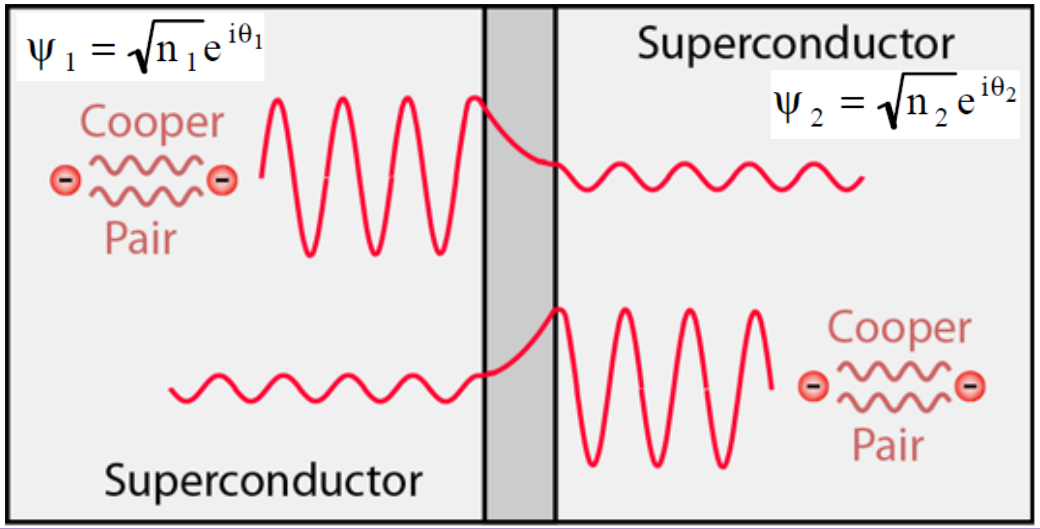
Best regards, Brian J.

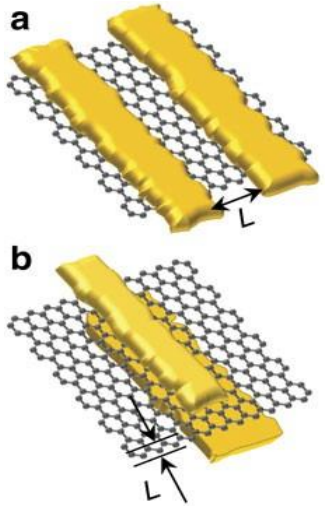
Hyperphysics, http://hyperphysics.phy-astr.gsu.edu/hbase/Solids/coop.html, Peter Hirschfeld, PHZ7427, Josephson

The Josephson Junction – Coherent wavefunctions



- Two superconductors connected via a “weak link”
- Typically a barrier material either Insulating or Normal Metallic





Top: planar JJ schematic Bottom: Vertical JJ schematic.

$$I = I_c \sin \Delta\phi \quad \text{dissipationless current}$$

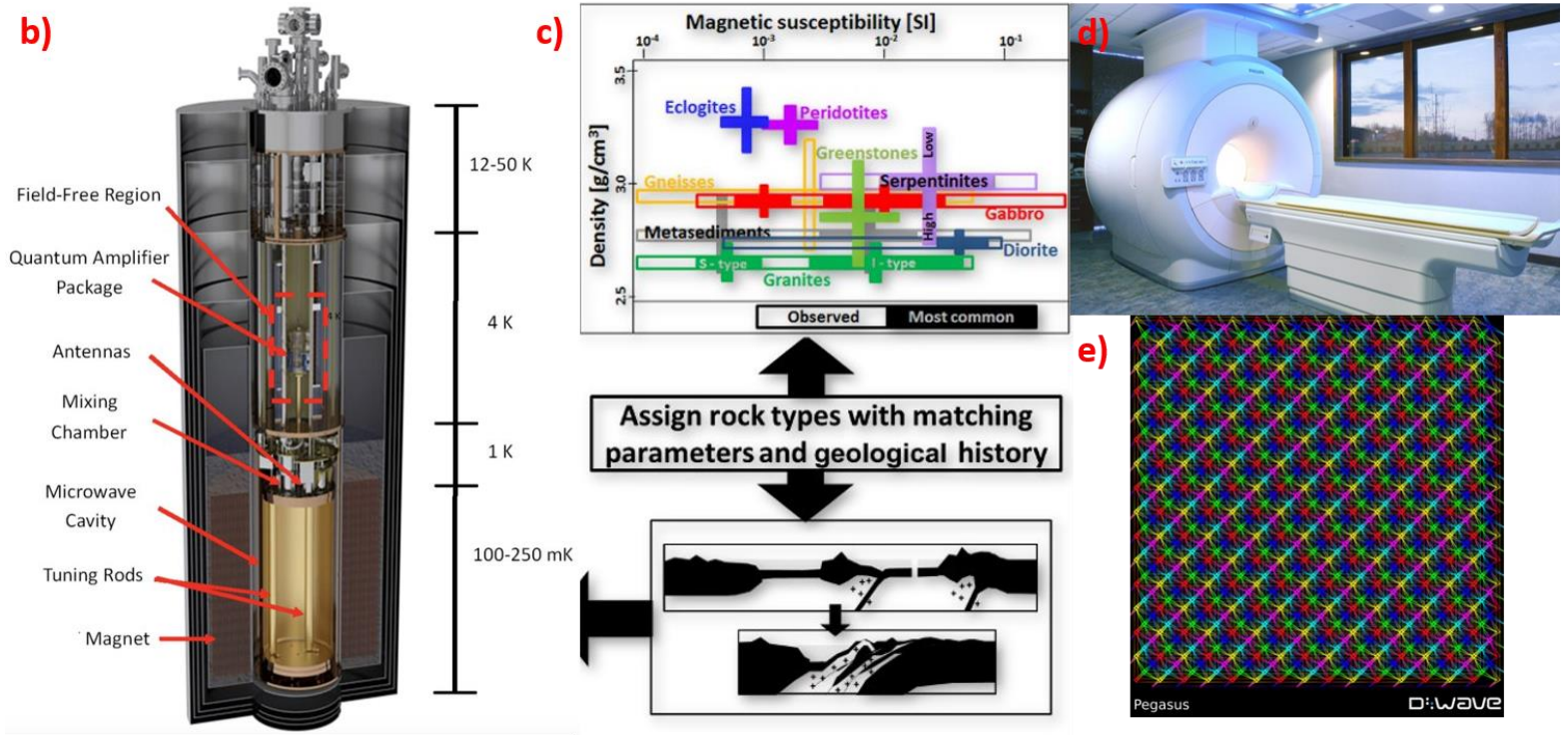
$$\frac{d}{dt}\Delta\phi = \frac{2eV}{\hbar} \quad \text{where } V \text{ is voltage across junction}$$

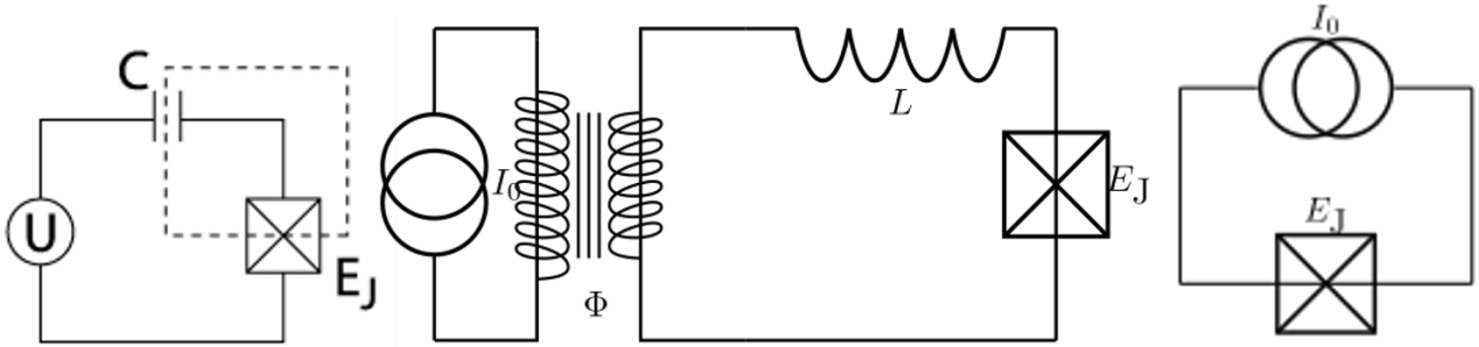
$$I(t) = I_c \sin(2eVt/\hbar) \quad \text{(ac Josephson effect)}$$

PHYS598 A.J.Leggett, Lecture 13 The Josephson Effect

Lee, G. H., et al, Nat. Comm. 6, 6181, 2015

JJs in modern technology – from sensors to computers





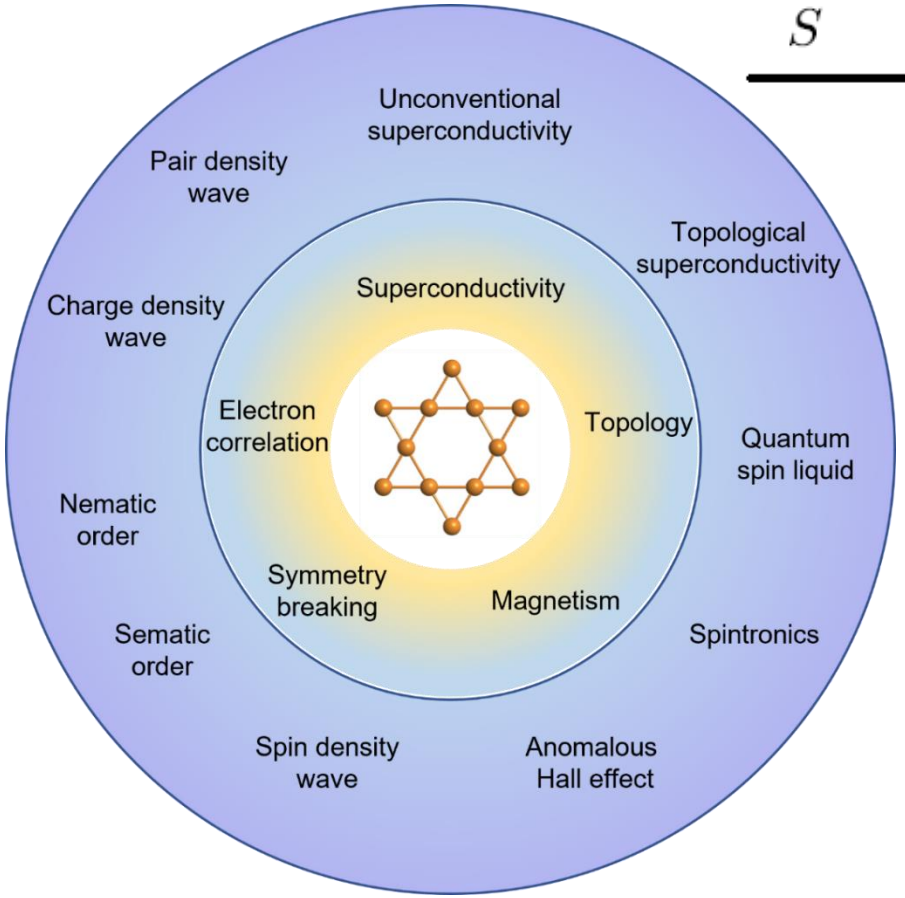
b) Schematic of ADMX (Axion **Dark Matter Experiment**) which uses a SQUID amplifier [5]. c,d) SQUID magnetometer used in **geological analysis and magnetic resonance imaging**. e.) D-Wave Pegasus 16 RSFQ **Computer Chip with 10^6 Josephson Junctions**.

Quantum Computing: $Al/AlO_x/Al$, Basic superconducting Qubit schematics. Left: Charge Qubit; Middle, Flux Qubit, Right, Phase Qubit, **All 3 utilize JJs in their design.**

Aszlatos, S. J., et al, Phys. Rev. Lett. 104, 041301, 2010

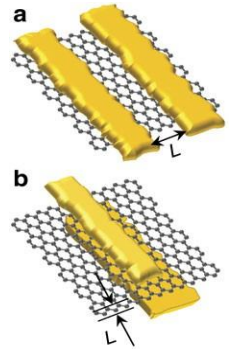
Main: Quantum material (QM) JJs – the next generation JJ

Quantum Materials as the barrier in JJs (QMJJ)



INTERFACE QM phenomena into superconductivity!

- 1.) Topological materials
  - Berry curvature, spatially confined states
- 2.) Spin liquids
  - Magnetic frustration
- 3.) Certain Ferroelectrics
  - Polarization
- 4.) Certain Magnetoelectrics
  - Chern-Simons interaction
- 5.) Non-collinear magnets
  - Spatially varying local magnetic field
- 6.) ***Strongly correlated materials (not SC)***
  - ***Mott-Hubbard Insulators (MI)***
- Much much more



Modulate the SC in ways we could only dream of in bulk!

C. Z. Chen, et al, Phys. Rev. B. 98, 075430

Y. Choi, et al, Nature Materials, 19, 974, 2020

Y. Wang, et al, Nature Physics, doi:10.1038/s41567-021-01190-7, 2021 **Y. Wang et al, *Science Advances 9, 28,* (2023)** **Y. Wang et al, *Nature Reviews Physics, 5, 635–658 (2023)***

Mott insulator

Kinetic Energy α hopping t

double occupation U

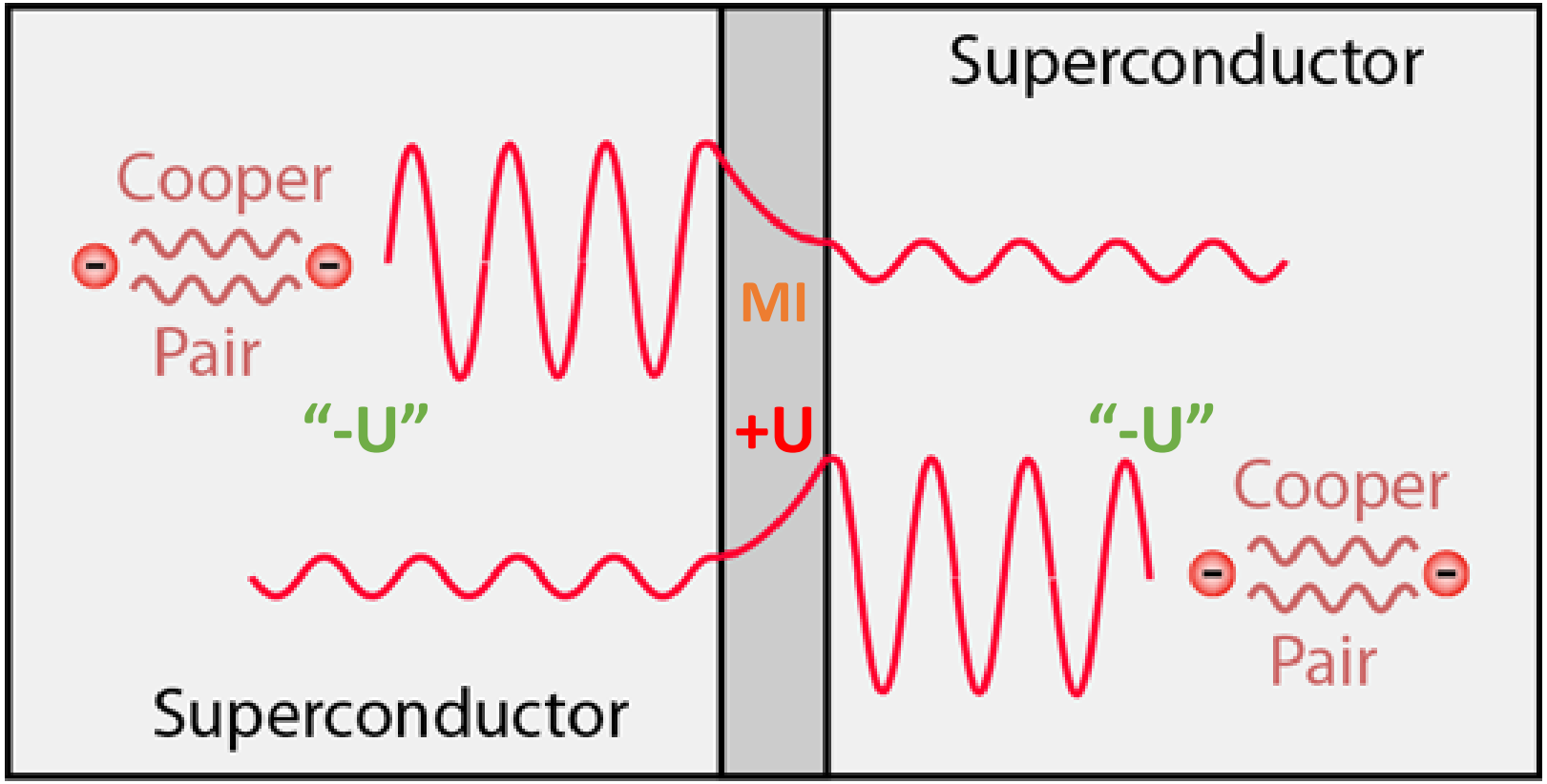
$$H = -t \sum_{l,\sigma} \left(c^{\dagger}_{l,\sigma} c_{l+1,\sigma} + c^{\dagger}_{l+1,\sigma} c_{l,\sigma} \right) + U \sum_{l} n_{l,\uparrow} n_{l,\downarrow}$$

Hubbard model

Competition between electron delocalization and localization.
In ordinary metals t >> U.
In certain substances the hopping amplitude is reduced by a reduced overlap between orbitals. In these cases we can have t ~ U and this competition can drive a transition to a localised state.

Important note: the insulating state in this picture is not driven by magnetic ordering (common misconception). Magnetic ordering occurs at low temperatures but it is not the cause of the insulating state, neither dictates its energy scale.

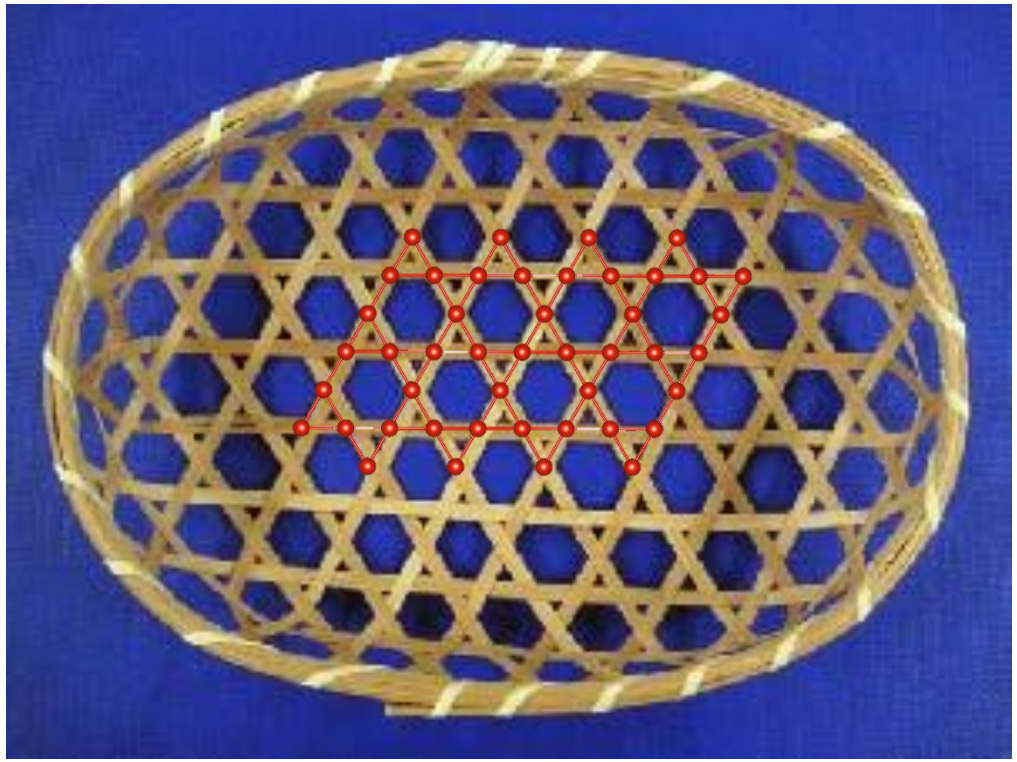
what happens?

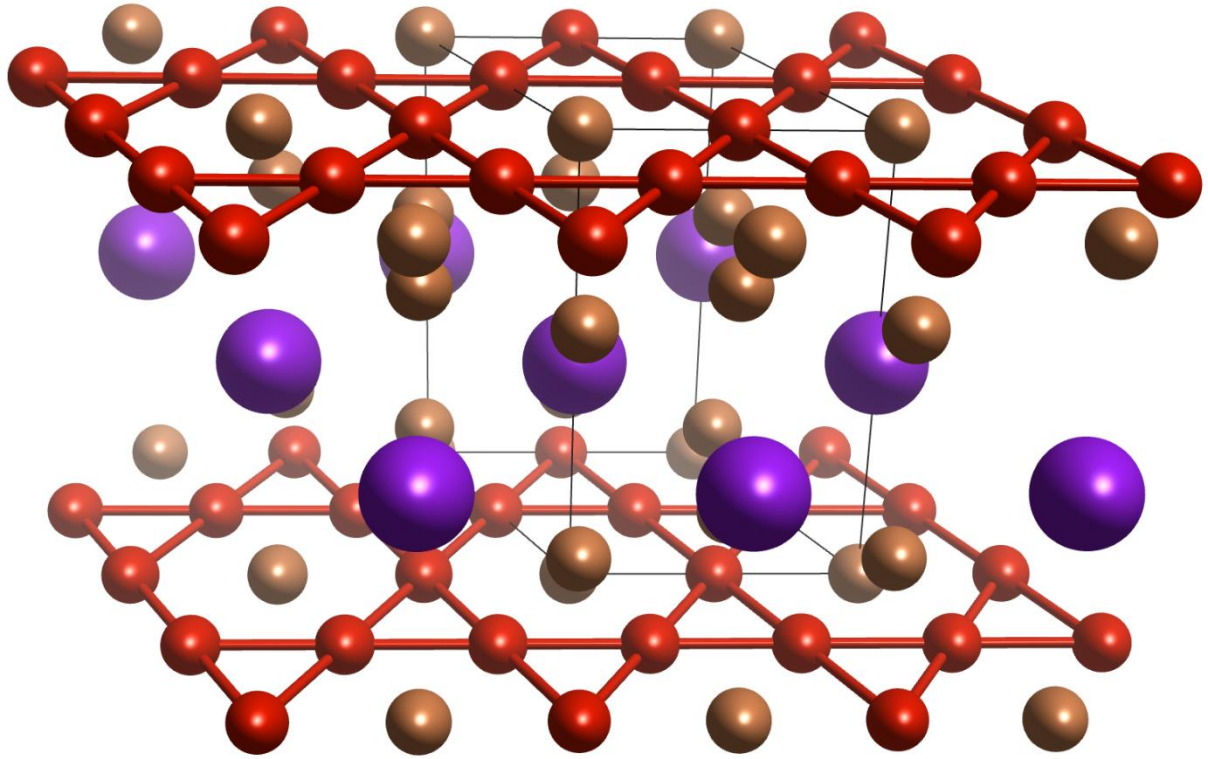


- Mean field, MI barrier is instrinsically antagonistic!
- Harder to couple than normal insulator (given same band gaps and thicknesses)
- BUT…inversion and time reversal symmetries can be broken…what happens then?

T. Morimoto and N. Nagaosa, *Scientific Reports* **volume 8**, Article number: 2973 (2018

So which QM-MI? Kagome – “in a basket…eyes”



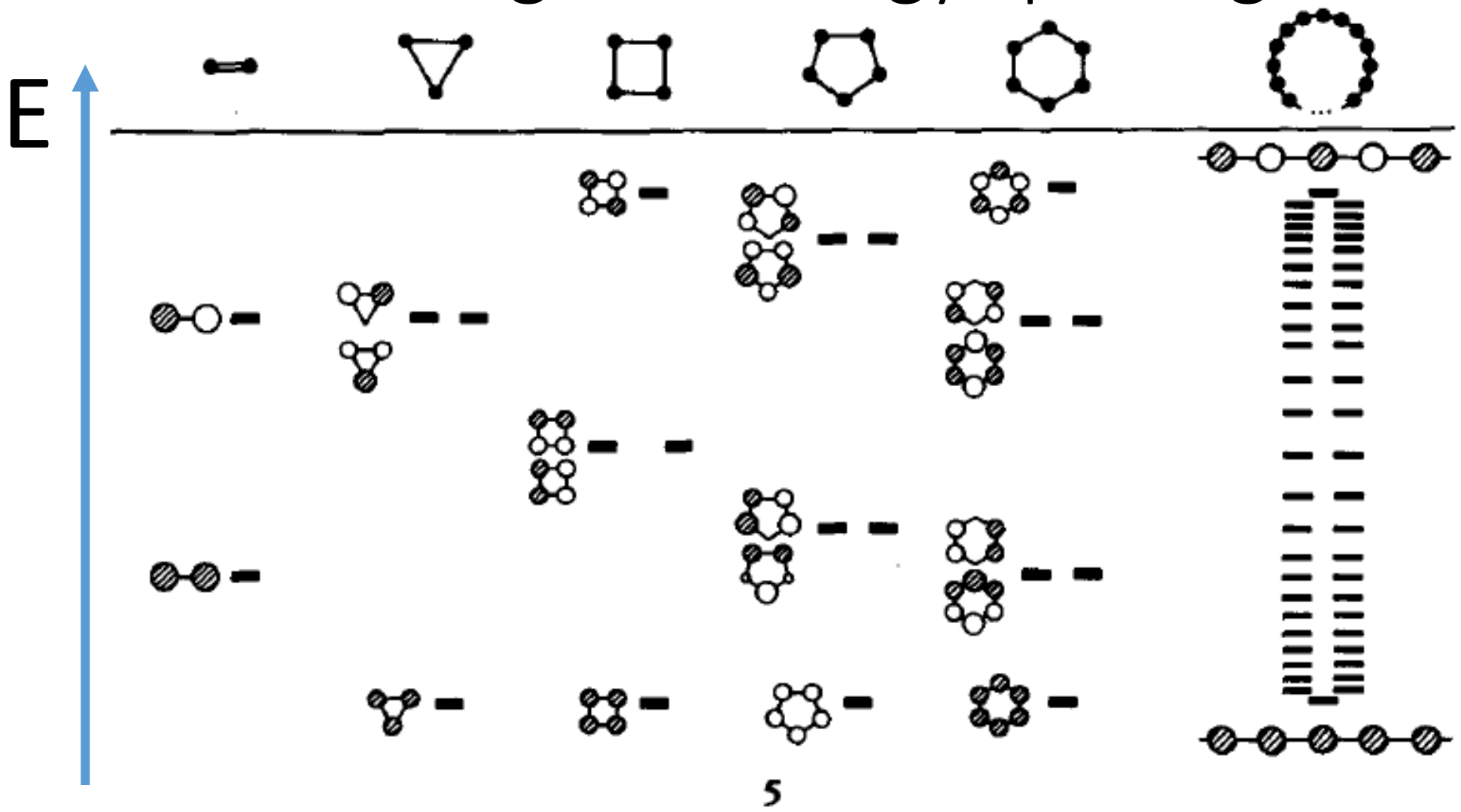


AV_3Sb_5, A = K, Cs, Rb

- Japanese Basket Weaving Pattern -> Real world solid state crystal structure
- “Trihexagonal Tiling” – **4 connected**: each vertex has 4 neighbours
- Hexagons + Triangles

S.Y. Yang, et al. Science Advances (2020): eabb6003.

Recall bonding and energy splitting



Anti bonding **(AB)** – Always the highest energy

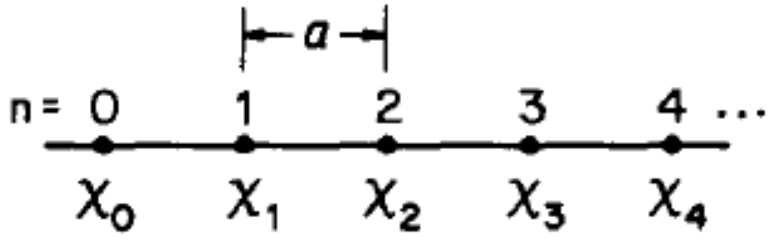
Bonding **(B)** – Always the lowest energy

Equal parts B and AB? – Non-bonding **(NB)**; energy relatively unchanged from free ion levels

A simple model: create “bands” by starting with monomers and adding units

“infinite” polymer: Atomic Orbitals -> Molecular Orbitals -> “bands”

Quick refresher: A chain of hydrogens



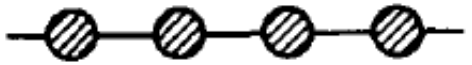
n is the hydrogen position, a is the unit cell size, X_0, etc. are the atomic orbitals of the atoms.

$$\psi_k = \sum_n e^{ikna} \chi_n$$

Bloch function representation of the overall wavefunction: X_n is the "basis set"

$$k = 0 \qquad \psi_0 = \sum_n e^0 \chi_n = \sum_n \chi_n$$

$$= \chi_0 + \chi_1 + \chi_2 + \chi_3 + \cdots$$

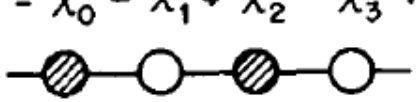


What happens when k = 0? Exponent dies

Chemist: Same phase overlap…bonding, lowest energy

$$k = \frac{\pi}{a} \qquad \psi_{\frac{\pi}{a}} = \sum_n e^{\pi i n} \chi_n = \sum_n (-1)^n \chi_n$$

$$= \chi_0 - \chi_1 + \chi_2 - \chi_3 + \cdots$$



What happens when k = π/a? alternating positive and negative

Chemist: Out of phase…antibonding, highest energy

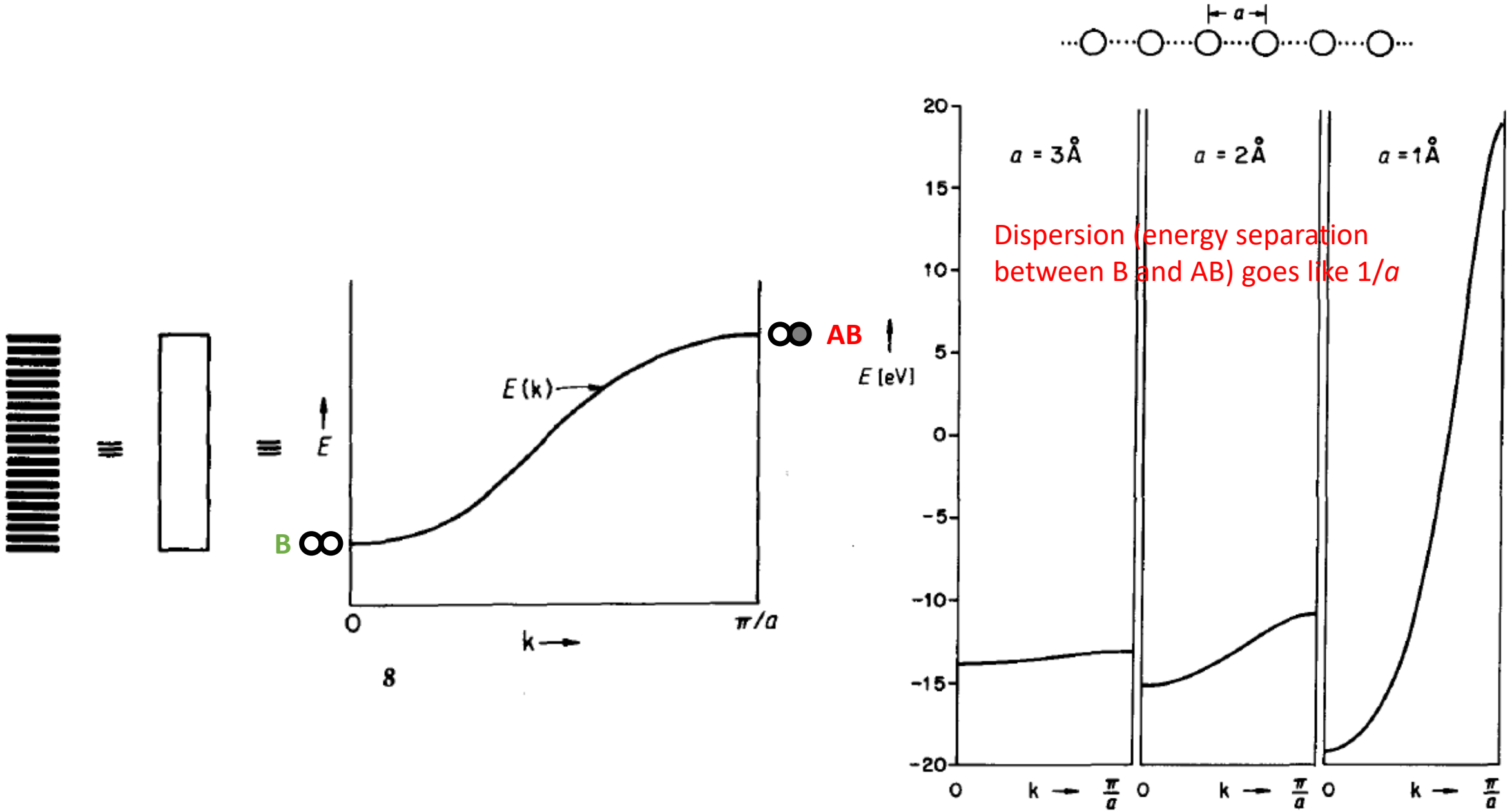
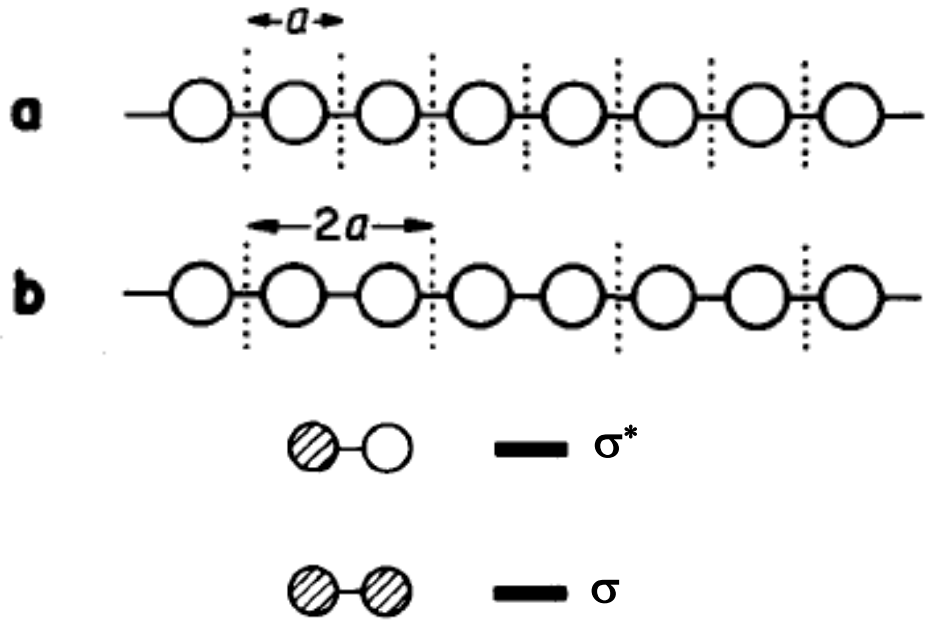
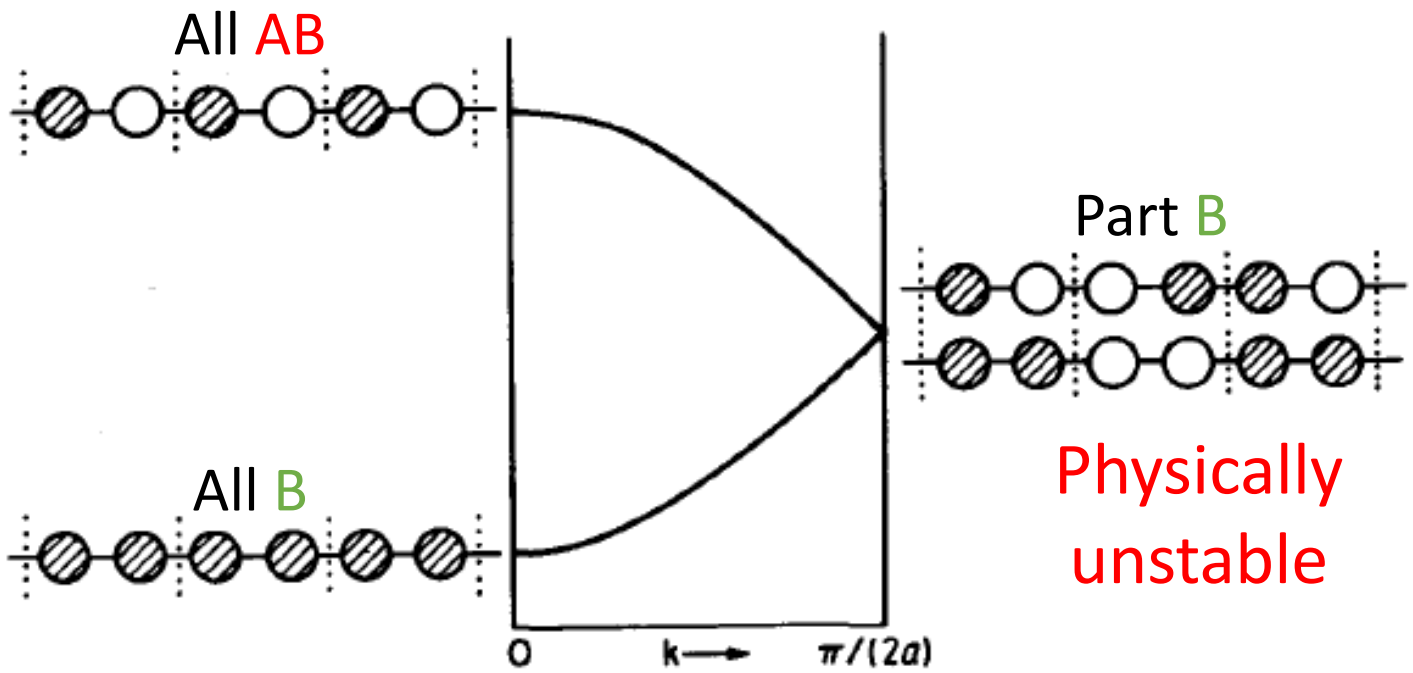


Figure 1 The band structure of a chain of hydrogen atoms spaced 3, 2, and 1 Å apart. The energy of an isolated H atom is −13.6 eV.

What about more than 1 electronic unit in the unit cell?

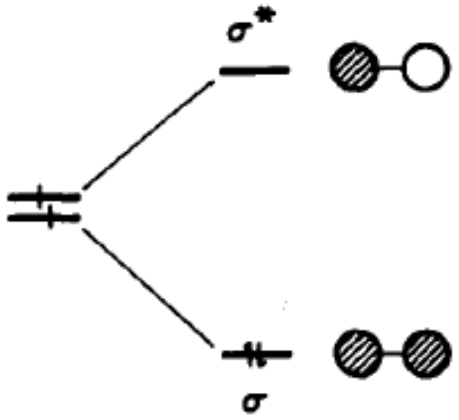
Consider a chain of hydrogen atoms again, but consider doubling the unit cell



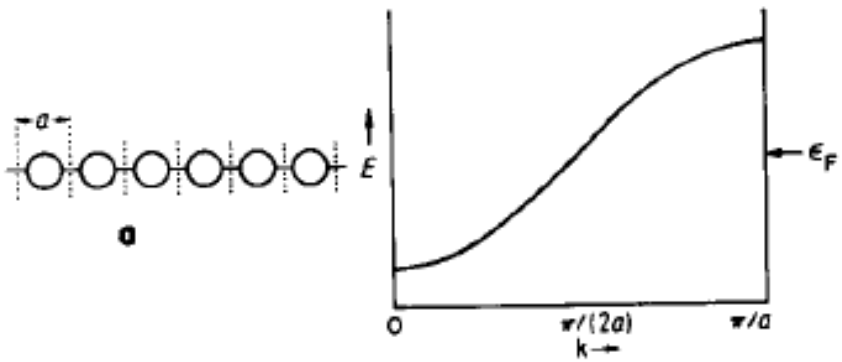


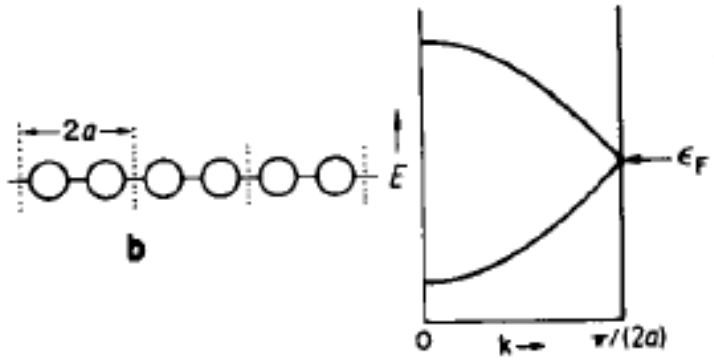
Physically unstable

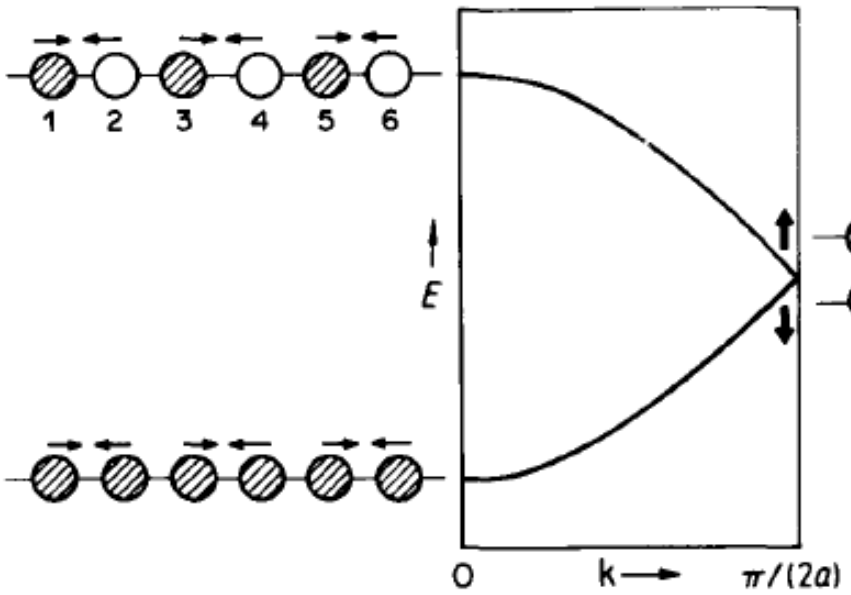
The Peierls Distortion



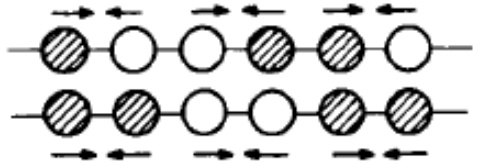
Things WANT to bond in solids…it lowers energy



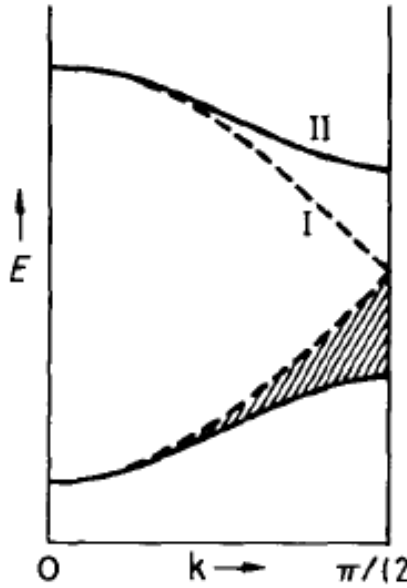


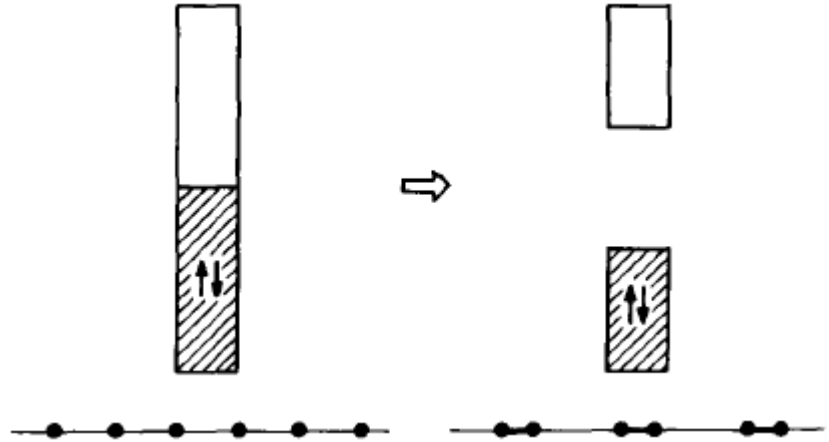


Part B-

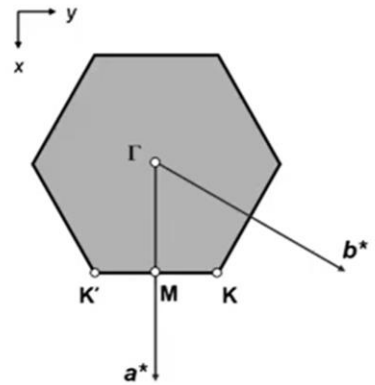


Part B+



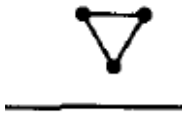


Special Points in a 2D Hexagonal Lattice



label	coordinates
Γ	$0\,a^* + 0\,b^*$
M	$(1/2)\,a^* + 0\,b^*$
K	$(1/3)\,a^* + (1/3)\,b^*$
K'	$(2/3)\,a^* - (1/3)\,b^*$

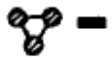
Consider a set of all pz-orbitals
(for now, px/py ignored)

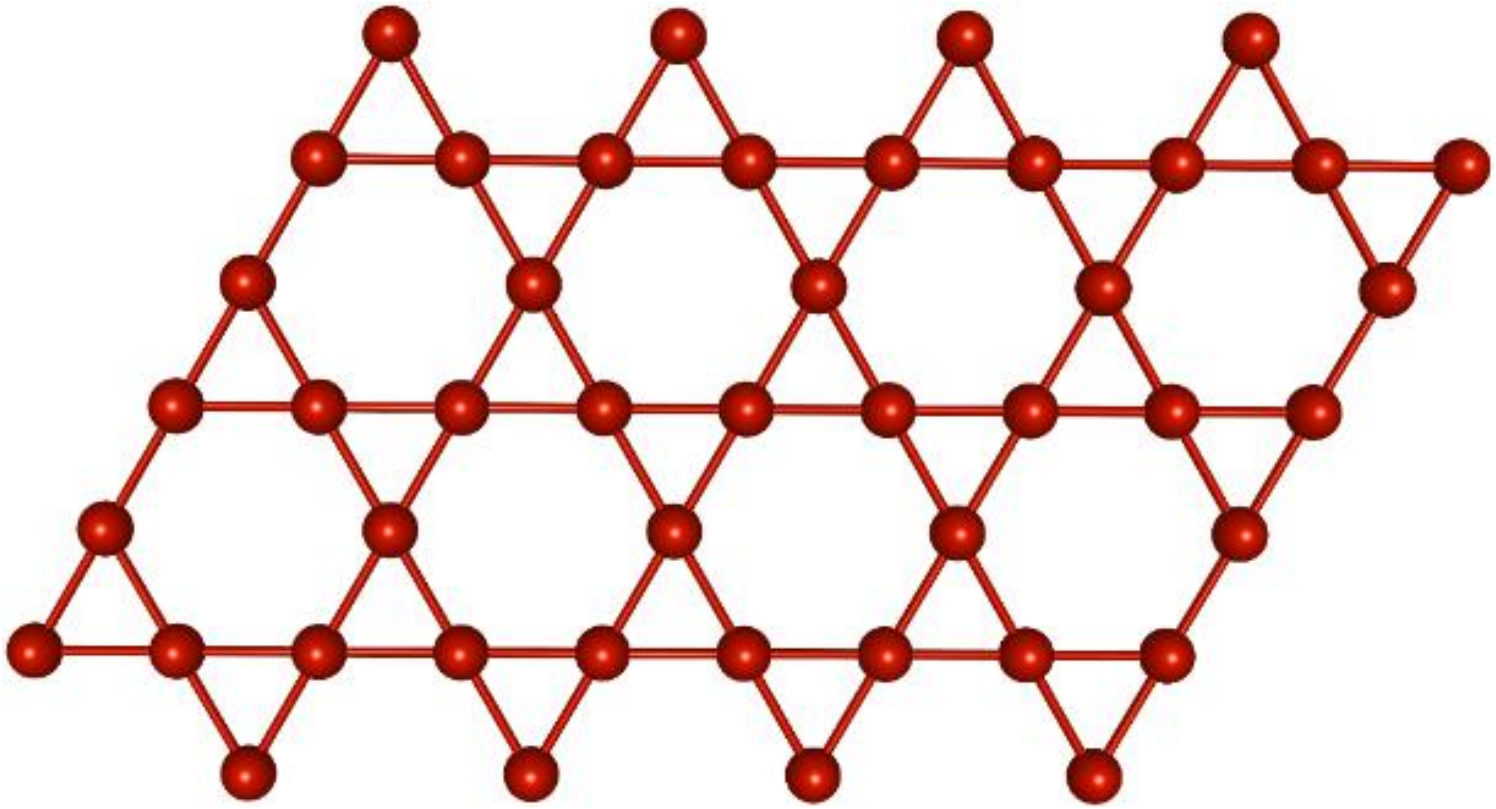


Choice of basis:

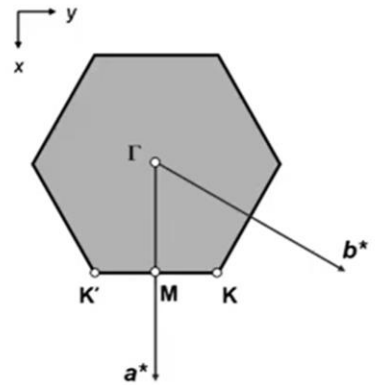
π_2  2x out-of-phase; 1 node,

π_3  2x 50% in-phase; 1 out of phase

π_1  3x in-phase



Special Points in a 2D Hexagonal Lattice



label	coordinates
Γ	$0\,a^* + 0\,b^*$
M	$(1/2)\,a^* + 0\,b^*$
K	$(1/3)\,a^* + (1/3)\,b^*$
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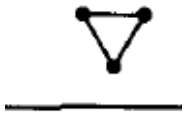
(for now, px/py ignored)



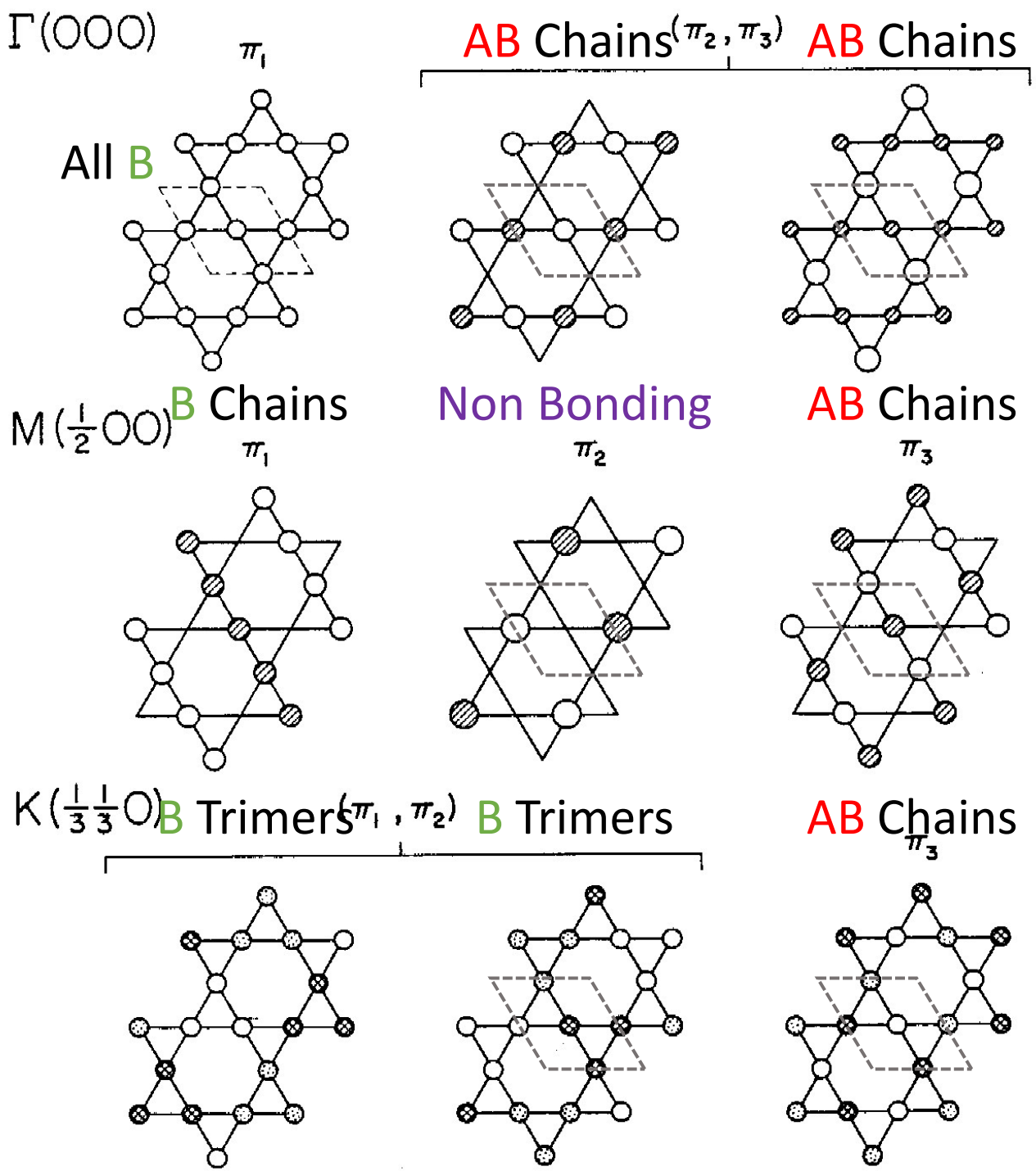
Choice of basis:

π_2  2x out-of-phase; 1 node,

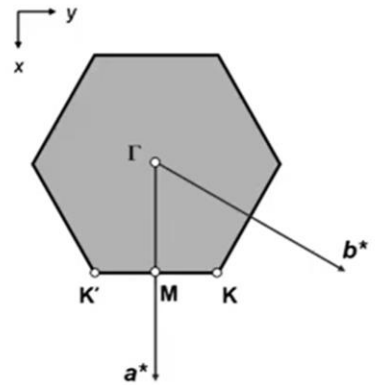
π_3  2x 50% in-phase; 1 out of phase

π_1  3x in-phase

Johnston, R., **Hoffman, R.,** *Polyhedron*, 9, 15, 1990

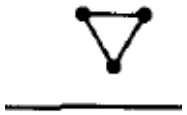


Special Points in a 2D Hexagonal Lattice



label	coordinates
Γ	$0\,a^* + 0\,b^*$
M	$(1/2)\,a^* + 0\,b^*$
K	$(1/3)\,a^* + (1/3)\,b^*$
K'	$(2/3)\,a^* - (1/3)\,b^*$

Consider a set of all pz-orbitals
(for now, px/py ignored)



Choice of basis:

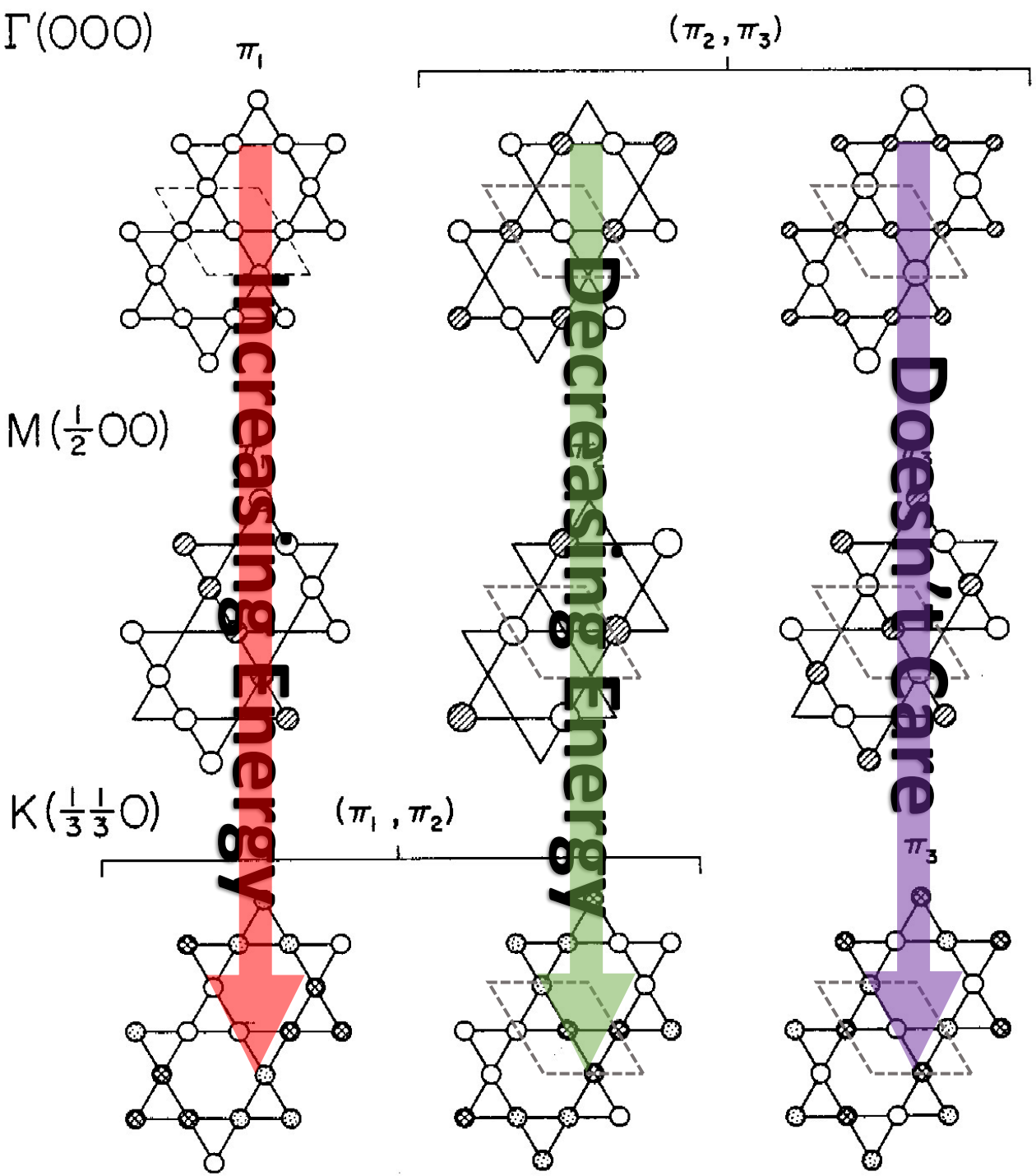
π_2 
π_3

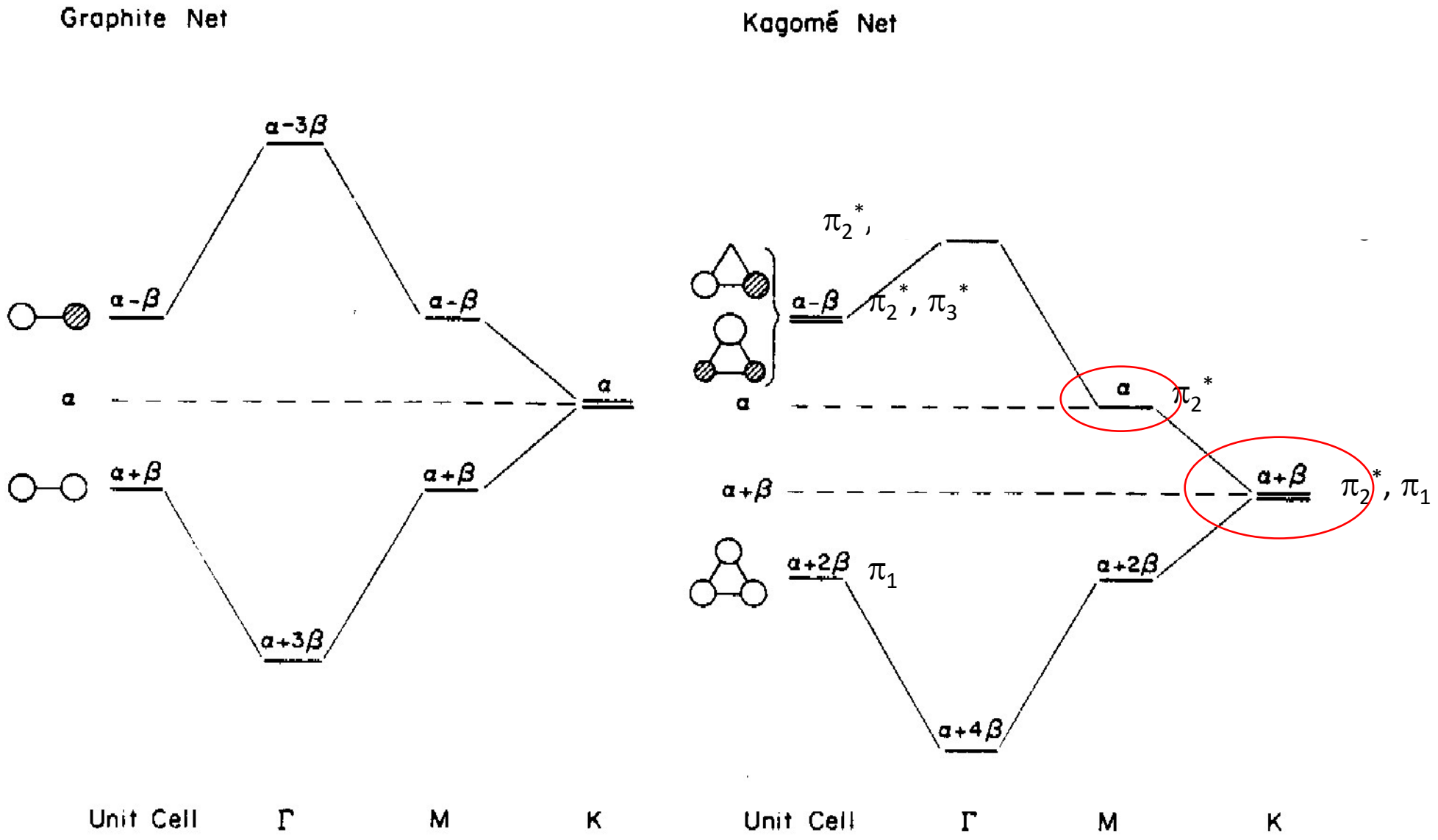
2x out-of-phase; 1 node,
2x 50% in-phase; 1 out of phase

π_1 

3x in-phase

Johnston, R., **Hoffman, R.,** *Polyhedron*, 9, 15, 1990



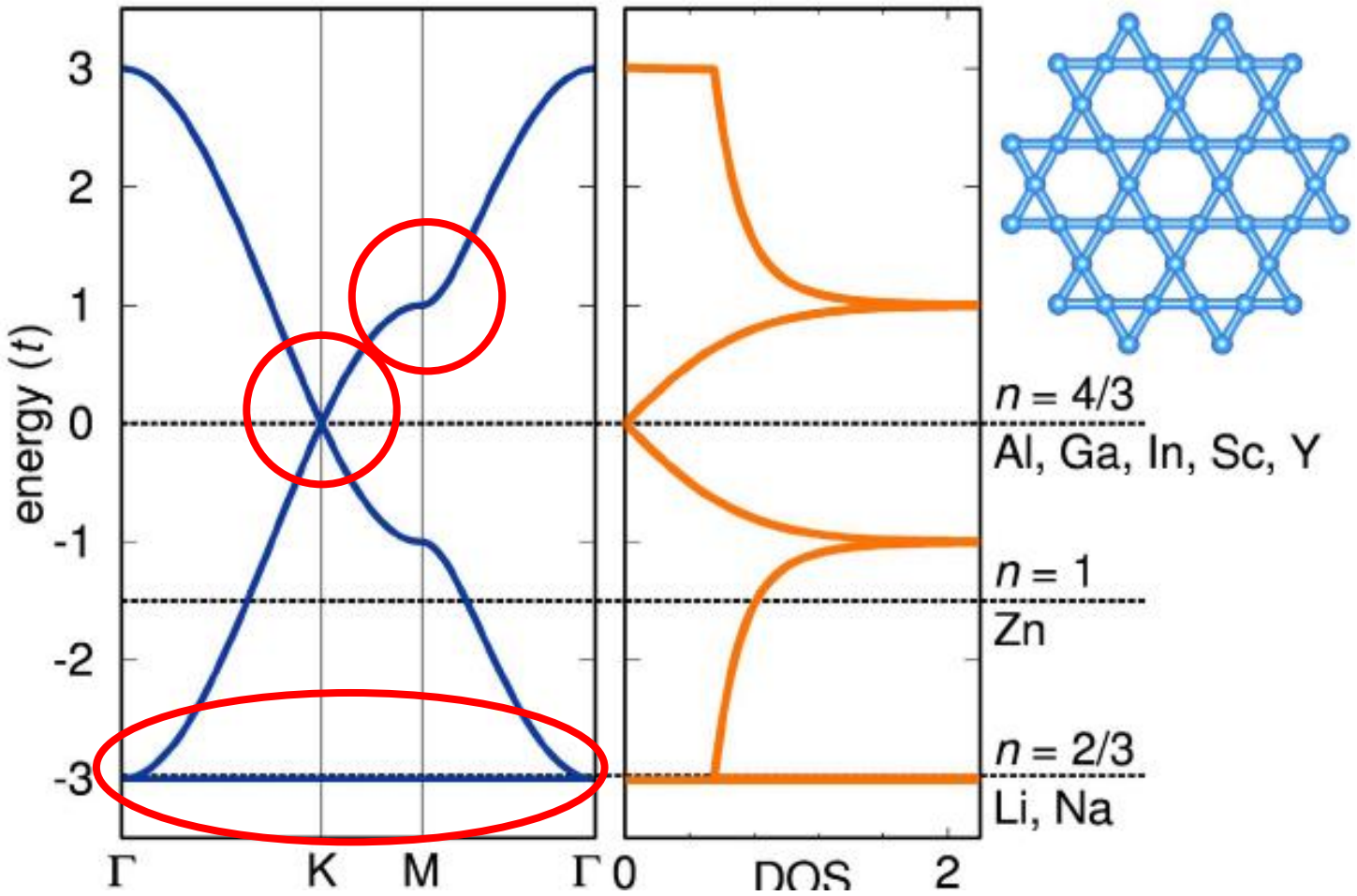


Atomic Orbitals -> Molecular Orbitals -> "bands"

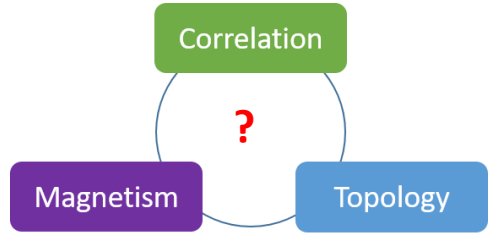
All bands in atomic lattices come from interference…of orbitals

Johnston, R., **Hoffman, R.,** *Polyhedron*, 9, 15, 1990 **Hoffman, R., *"Of Solids and Surfaces"*, Wiley-VCH, 1988**

Ideal Kagome Nets – close but not our MI

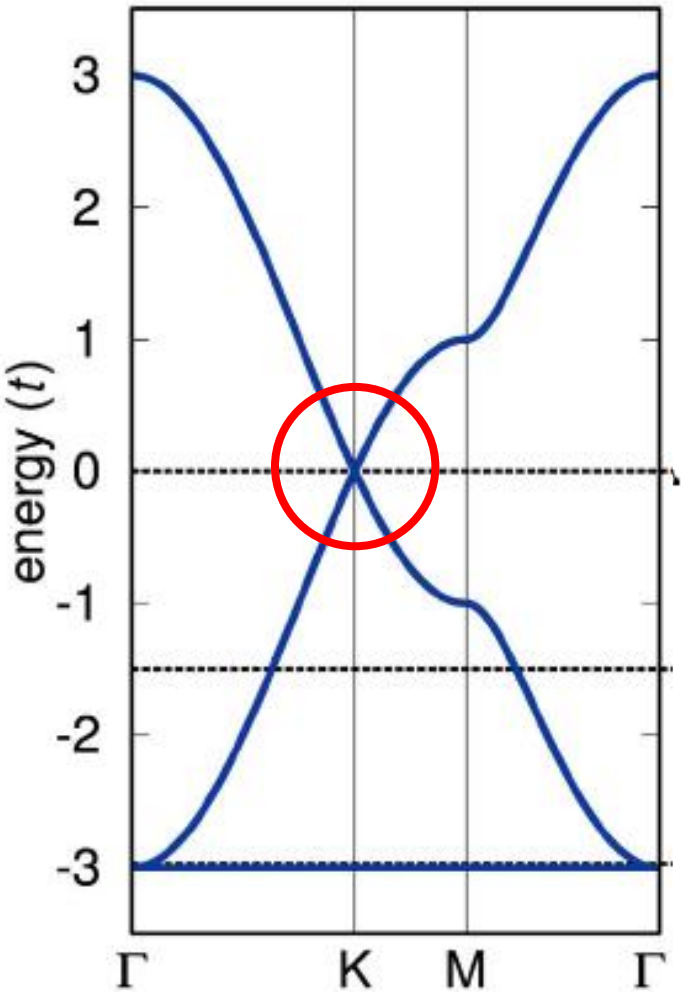


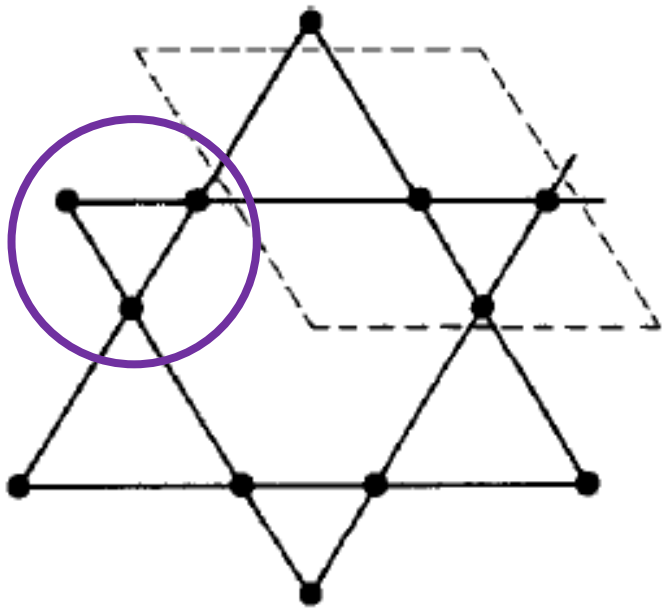
- Dirac Point at K and surface/edge states in SOC gap opening - topology
- Van Hove Singularities – strong correlations
- Flat Band – strong correlations

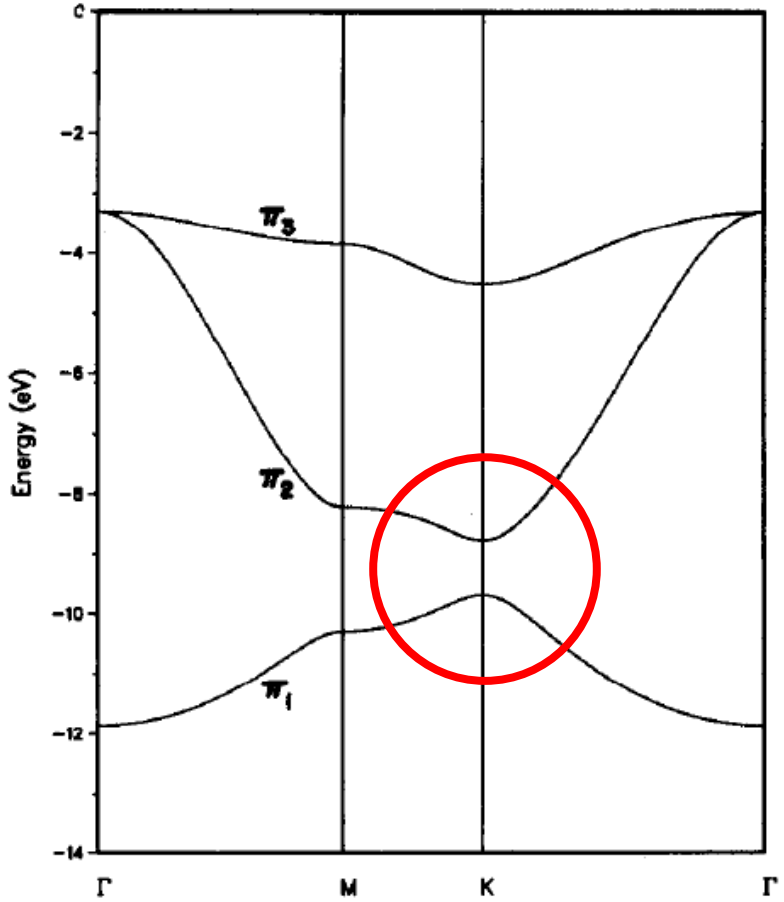


"Quantum states and intertwining phases in kagome materials" Y. Wang et al, *Nature Reviews Physics, 5, 635–658 (2023)*

Trigonal distortion: Kagome *insulator*







Johnston, R., **Hoffman, R.,** *Polyhedron*, 9, 15, 1990

QM of choice: $Nb_3Cl_8/Br_8/I_8$

- Kagome ***Insulator*** (Nb)
- Layered, van der Waals gap
- Trigonally distorted ("breathing mode") Kagome Insulator
- AFMs in bulk (so far)

INORGANIC CHEMISTRY FRONTIERS

RESEARCH ARTICLE

View Article Online

Rearrangement of van der Waals stacking and formation of a singlet state at T = 90 K in a cluster magnet†

John P. Sheckelton, Kemp W. Plumb, Benjamin A. Trump, Collin L. Broholm and Tyrel M. McQueen

Inorganic Chemistry

Article

pubs.acs.org/IC

Magnetic–Nonmagnetic Phase Transition with Interlayer Charge Disproportionation of Nb_3 Trimers in the Cluster Compound Nb_3Cl_8

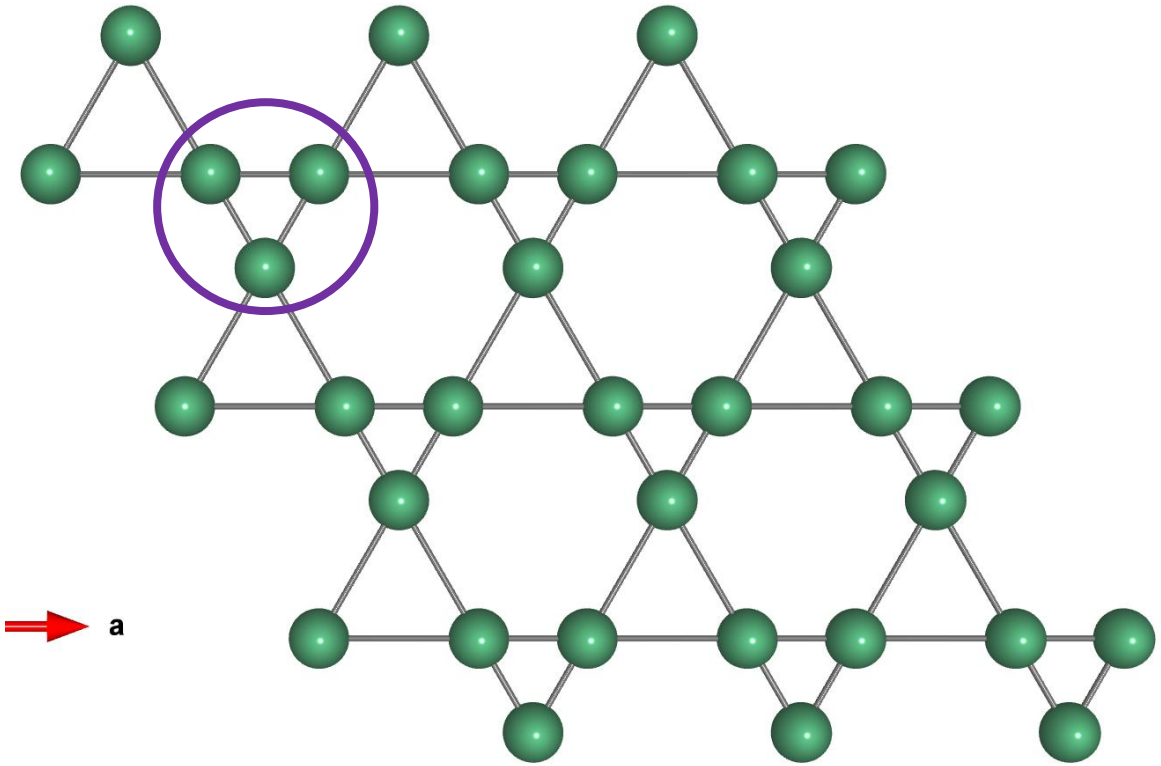
Yuya Haraguchi, Chishiro Michioka, Manabu Ishikawa, Yoshiaki Nakano, Hideki Yamochi, Hiroaki Ueda and Kazuyoshi Yoshimura

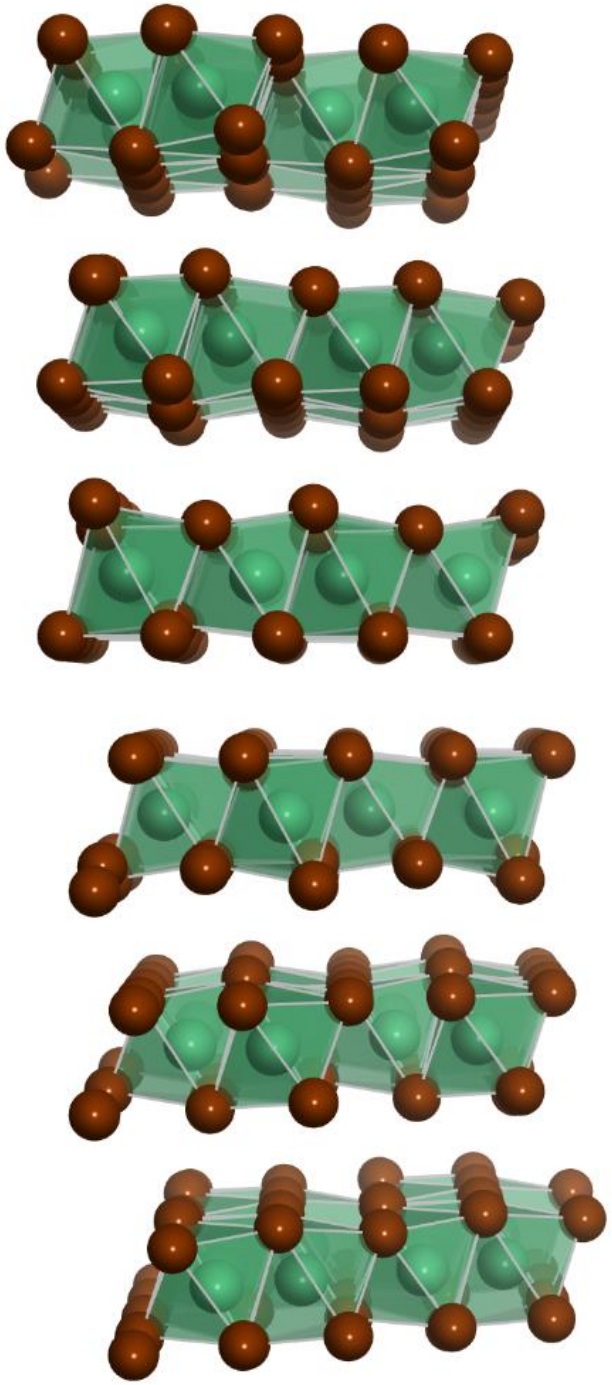
Department of Chemistry, Graduate School of Science, Kyoto University, Kyoto 606-8502, Japan

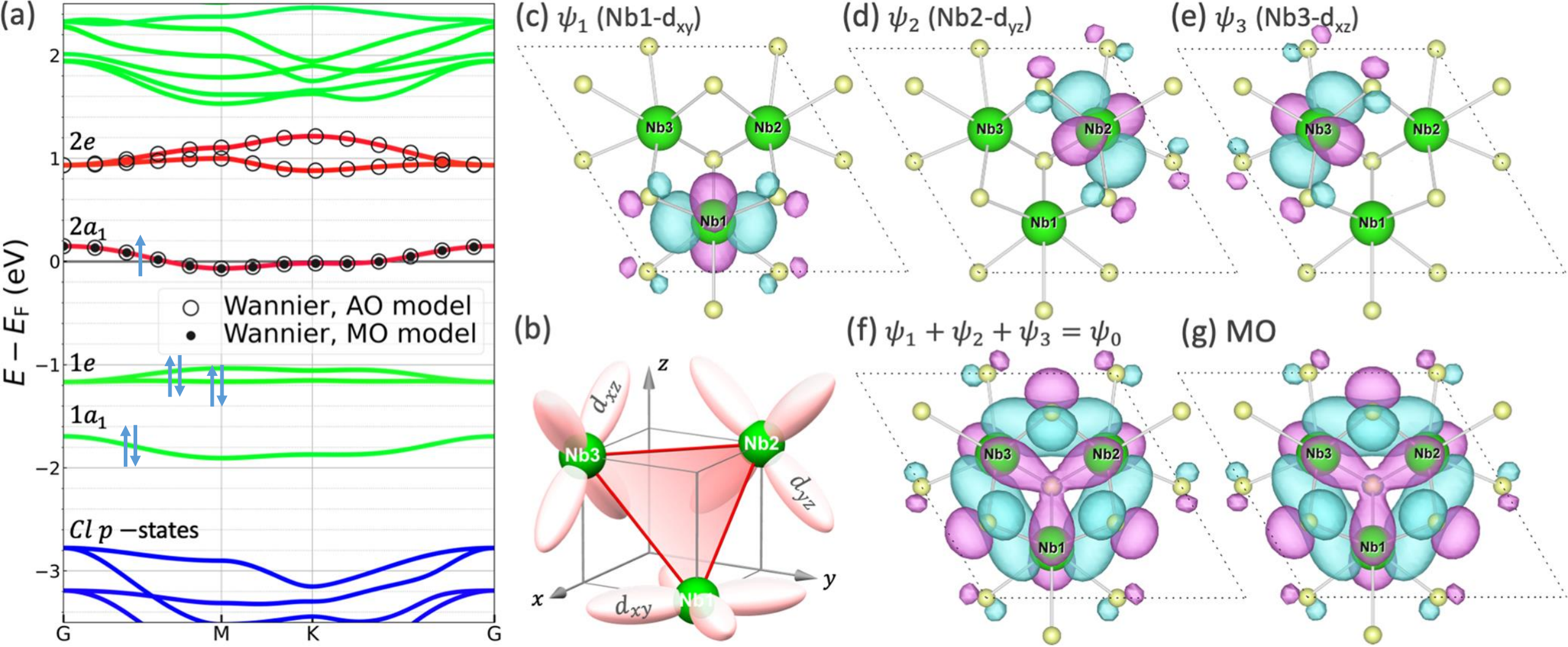
Research Center for Low Temperature and Materials Sciences and Institute for Liberal Arts and Sciences, Kyoto University, Kyoto 606-8501, Japan

Inorg. Chem. Front., 2017, ***4***, 481

Inorg. Chem. 2017, ***56***, 3483−3488

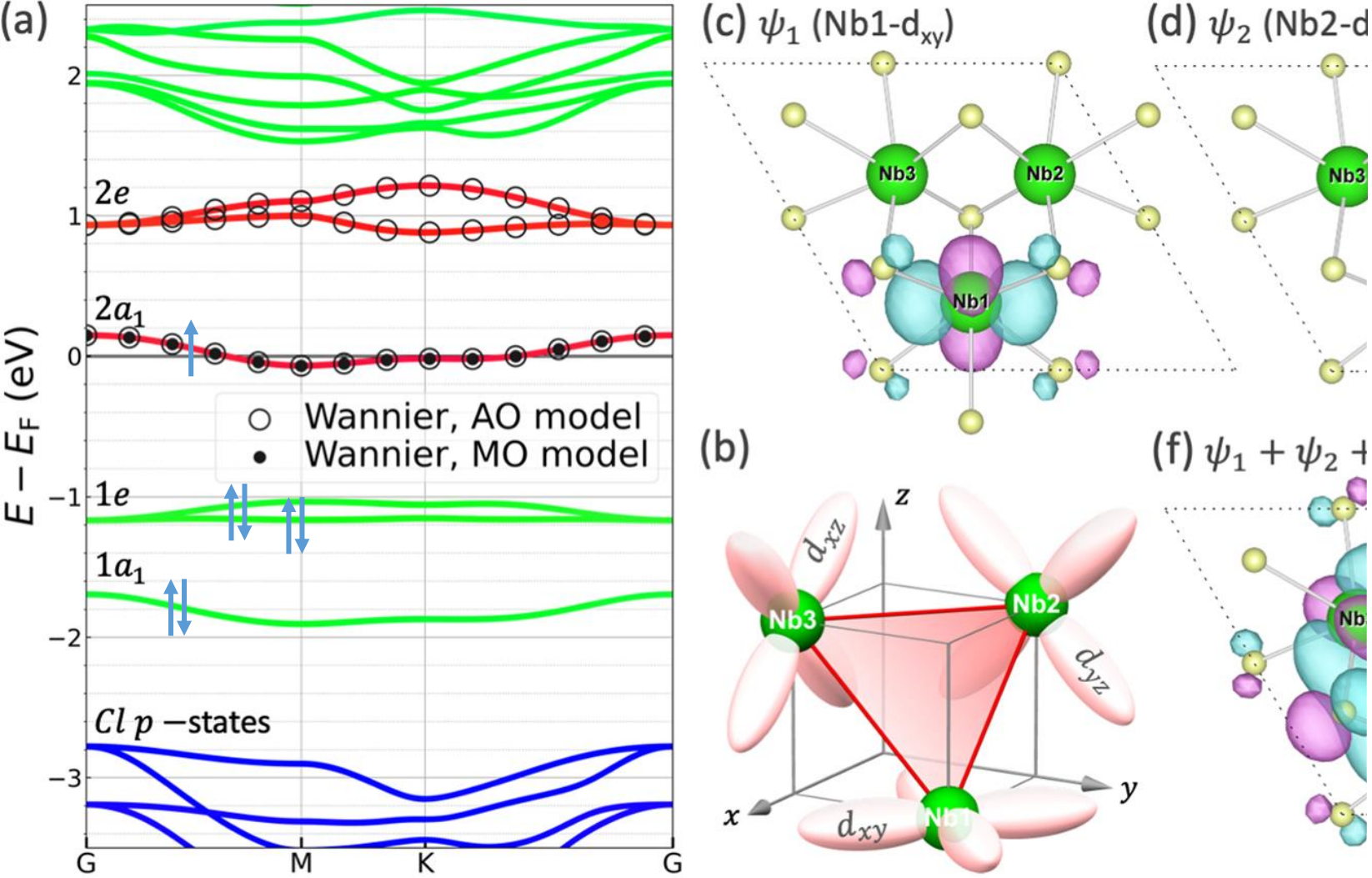






- Formally Nb_3Cl_8: $8e^-$(Cl) / 3 = 2.667+/Nb
- 3^+, 3^+, 2^+ oxidation states – Nb brings 5 electrons so
- $2e^-$ + $2e^-$ + $3e^-$ = $7e^-$ in 3d-p molecular orbitals

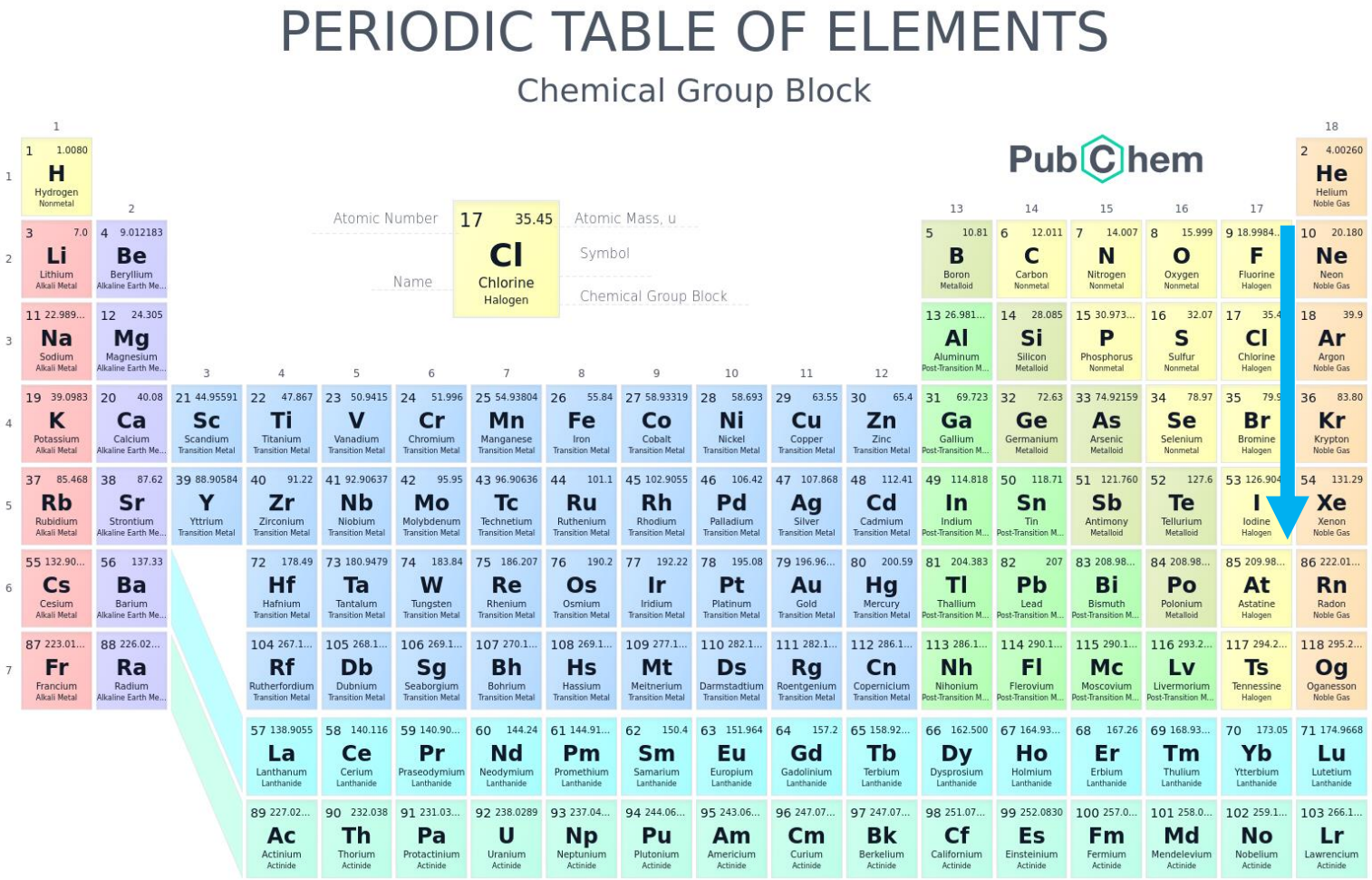
Grytsiuk, R., Roesner, M., *NPJ Quantum Materials*, 9, 8, 2024



- Formally Nb_3Cl_8: $8e^-$(Cl) / 3 = 2.667+/Nb
- 3^+, 3^+, 2^+ oxidation states – Nb brings 5 electrons at Nb^0 so
- $2e^- + 2e^- + 3e^- = 7e^-$ in 4d-p molecular orbitals

Grytsiuk, R., Roesner, M., *NPJ Quantum Materials*, 9, 8, 2024

Nb_3X_8 Series Expectation



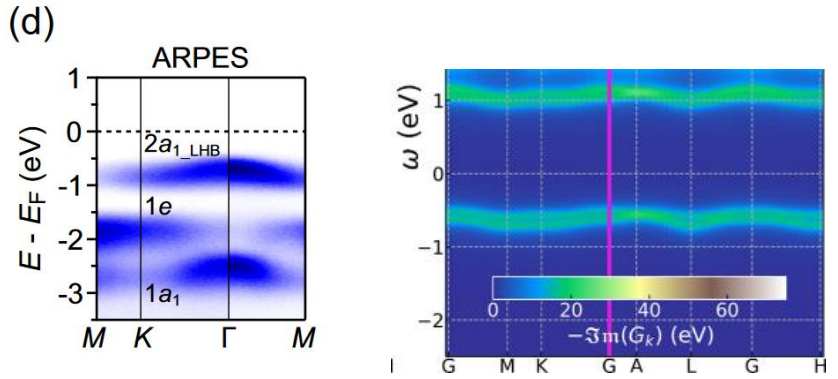
What happens to the "mott insulating" state as a function of F(not yet) -> Cl -> Br -> I?

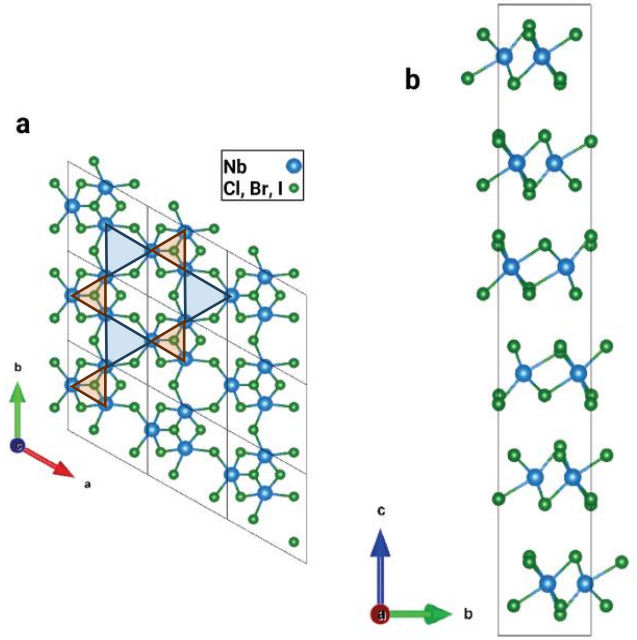
Chemical expectations:

- Larger orbitals, increased overlap
- Increased band dispersion; less flat
- **Decreased magnitude of hubbard U, increased magnitude of hopping, t**
- So *maybe* MI -> Trivial I

Niobium Halides and their “Mottness”

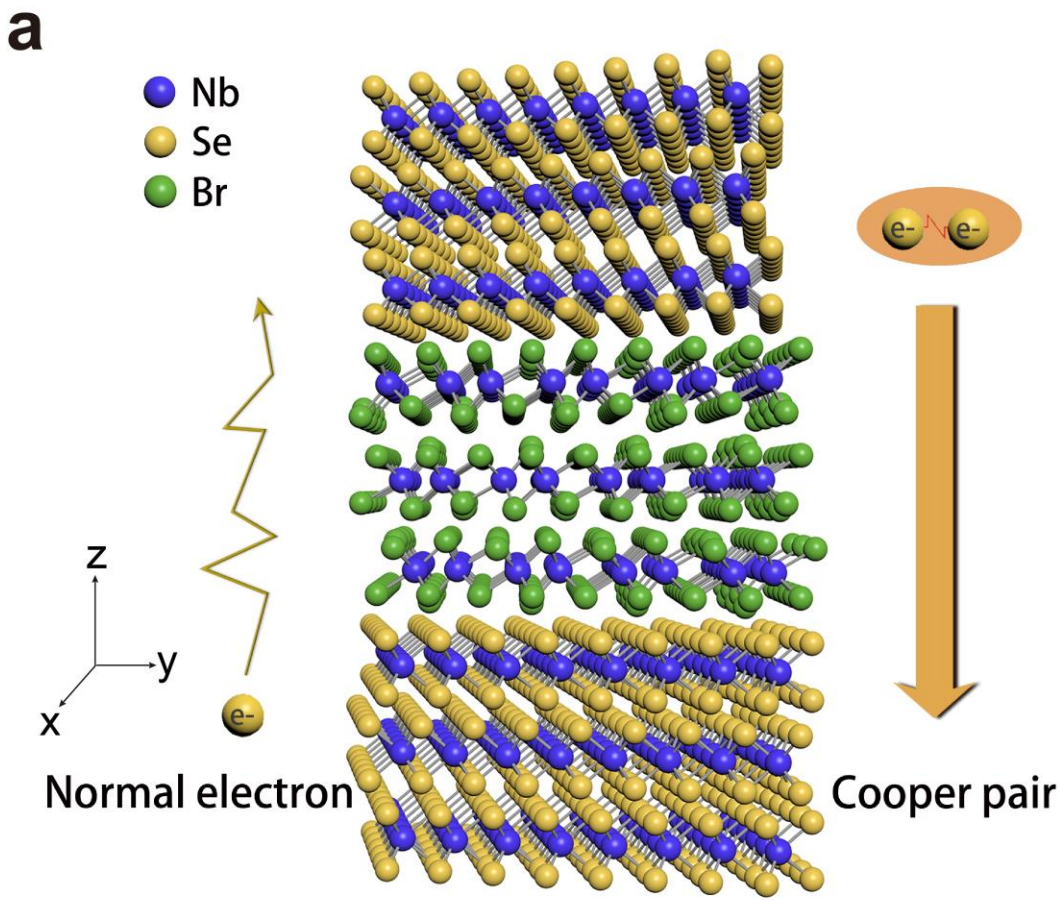
- Nb_3Cl_8
  - Deep Mott Insulator (U >> t)
- Nb_3Br_8
  - OK Mott Insulator (U > t)
- Nb_3I_8
  - Junky MI or trivial insulator (U ~ t)

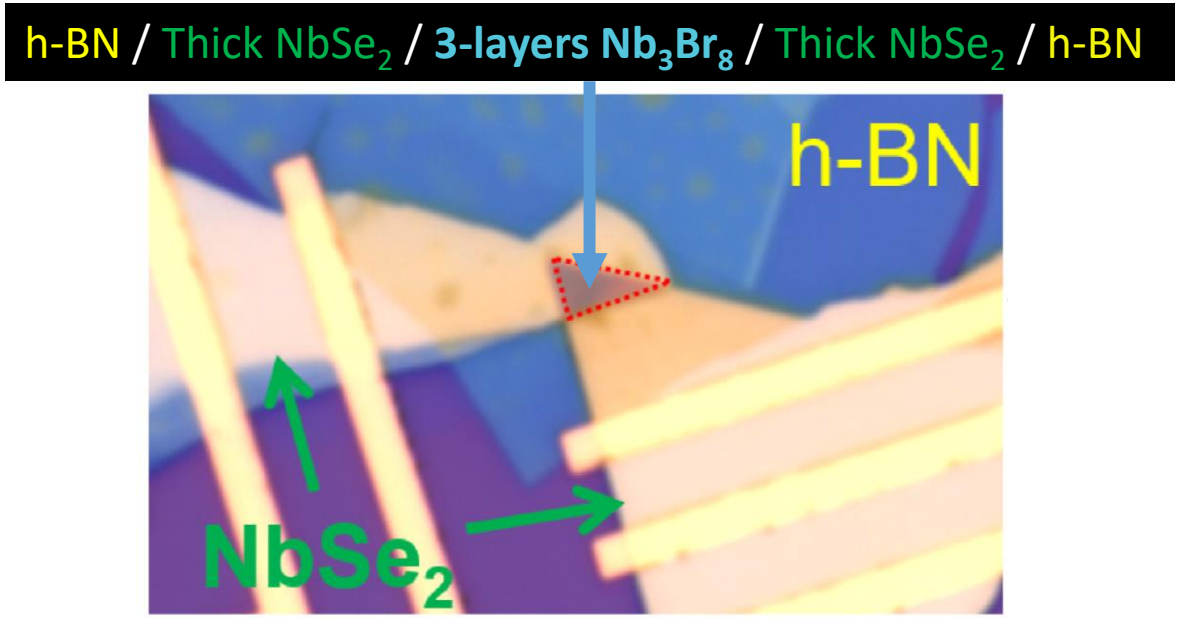




Gao, S. *et al.* Discovery of a Single-Band Mott Insulator in a van der Waals Flat-Band Compound. *Phys. Rev. X* **13**, 041049 (2023).
Grytsiuk, S., Katsnelson, M. I., Loon, E. G. C. P. van & Rösner, M. Nb3Cl8: a prototypical layered Mott-Hubbard insulator. *npj Quantum Materials* **9**, 8 (2024).

Nb_3Cl_8/Br_8 QMJJs



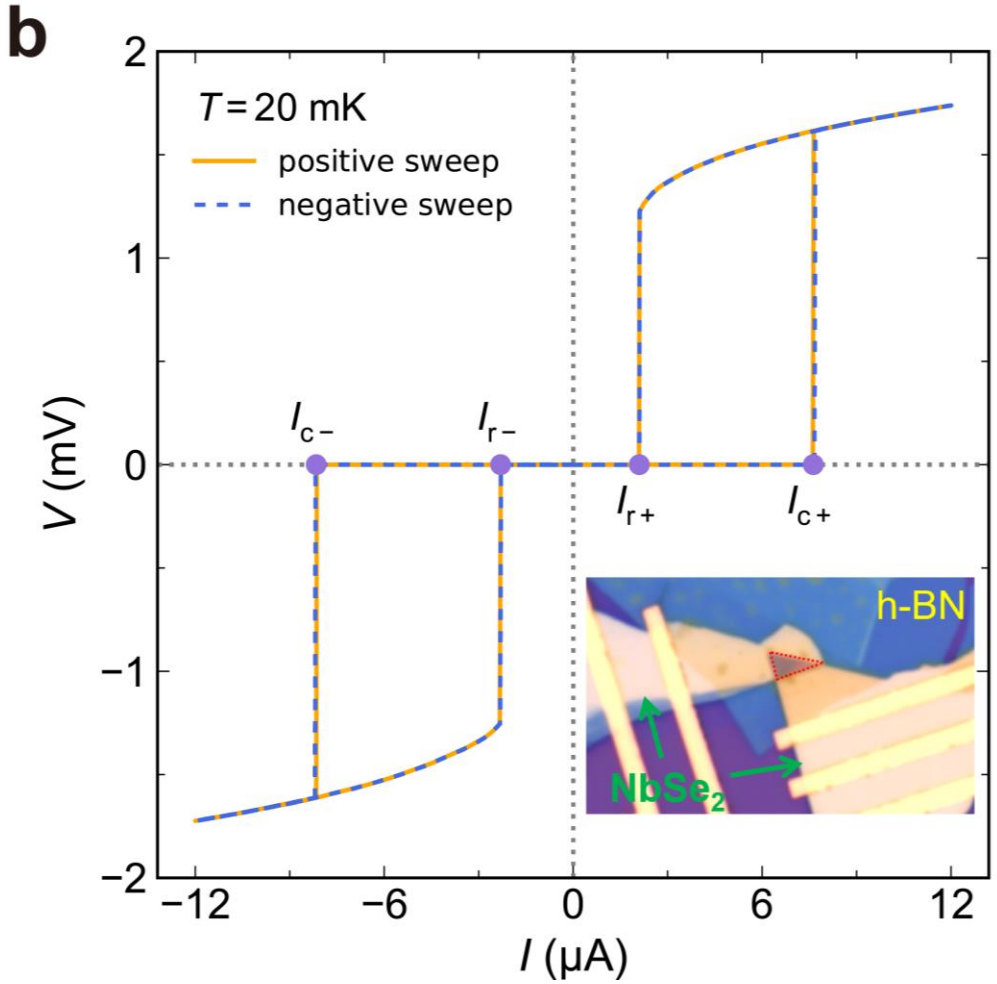


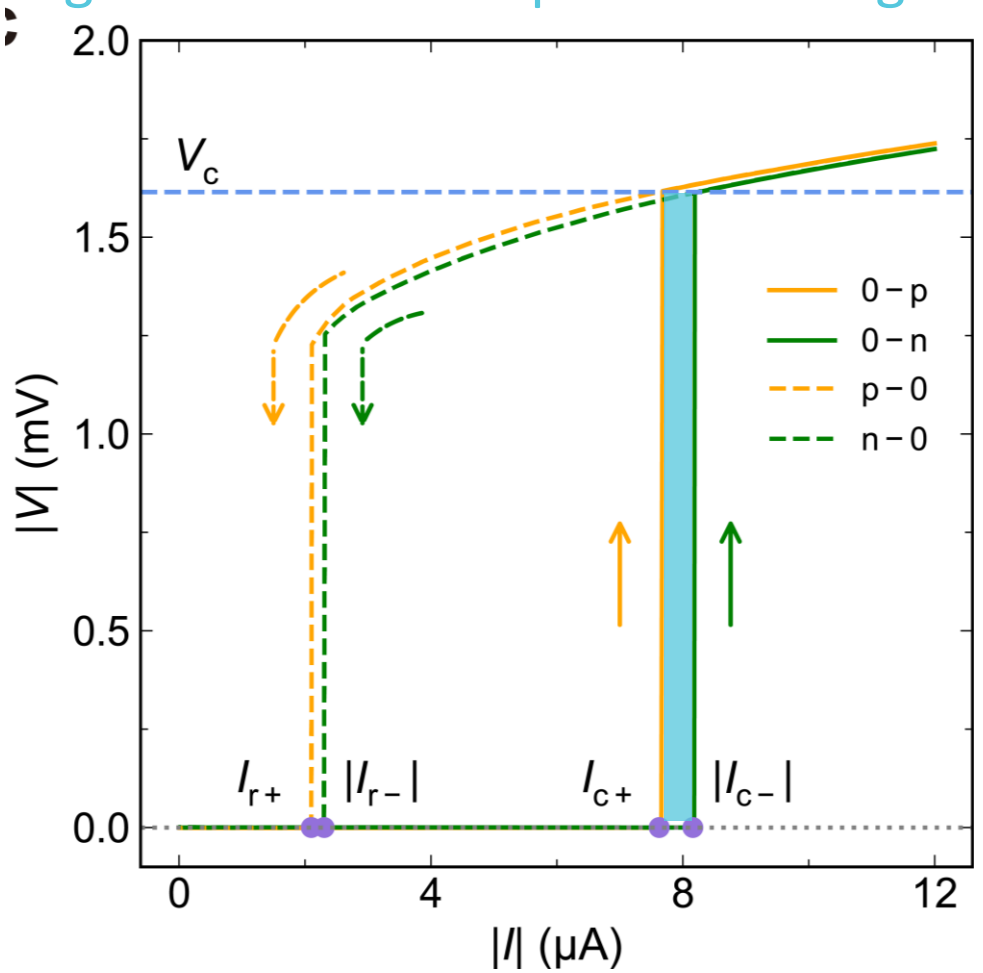
Breaking inversion symmetry: 3 (4,5) layer stack AND arbitrary twist angles of $NbSe_2$ layers

H, Wu., et al, *Nature*, 604, 653-656 (2022)

Nb_3Br_8 Junction

Critical Current with negative voltage is greater than with positive voltage: ΔI_c





H, Wu., et al, *Nature*, 604, 653-656 (2022)

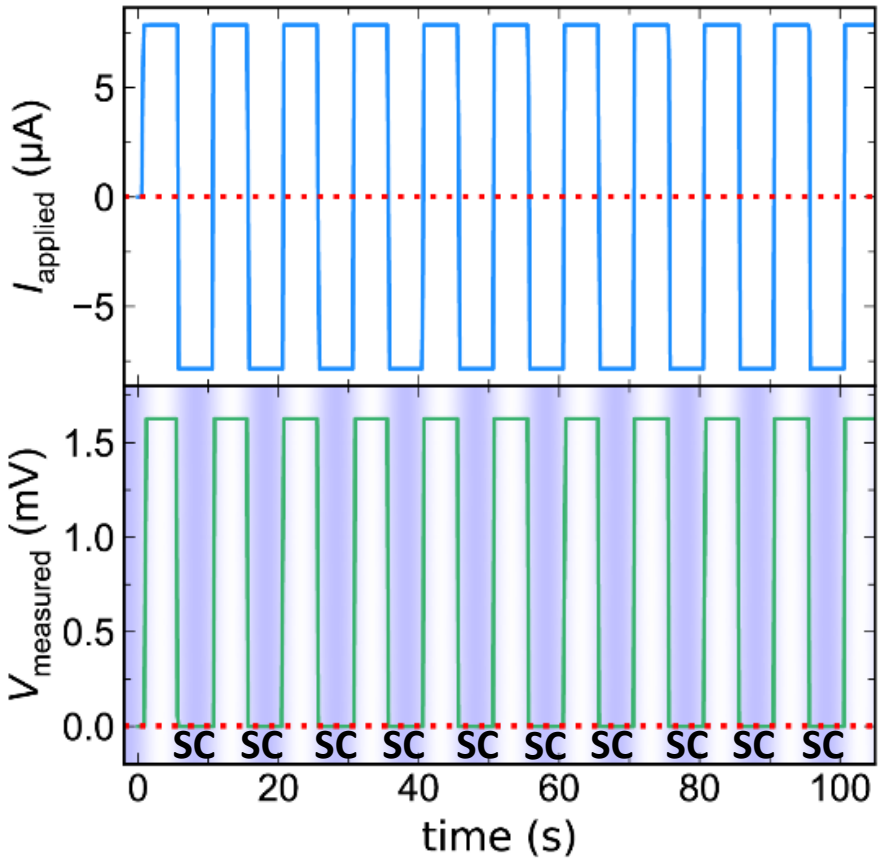
So…If $I_{applied}$ is chosen carefully, Junction should SC in only one direction!

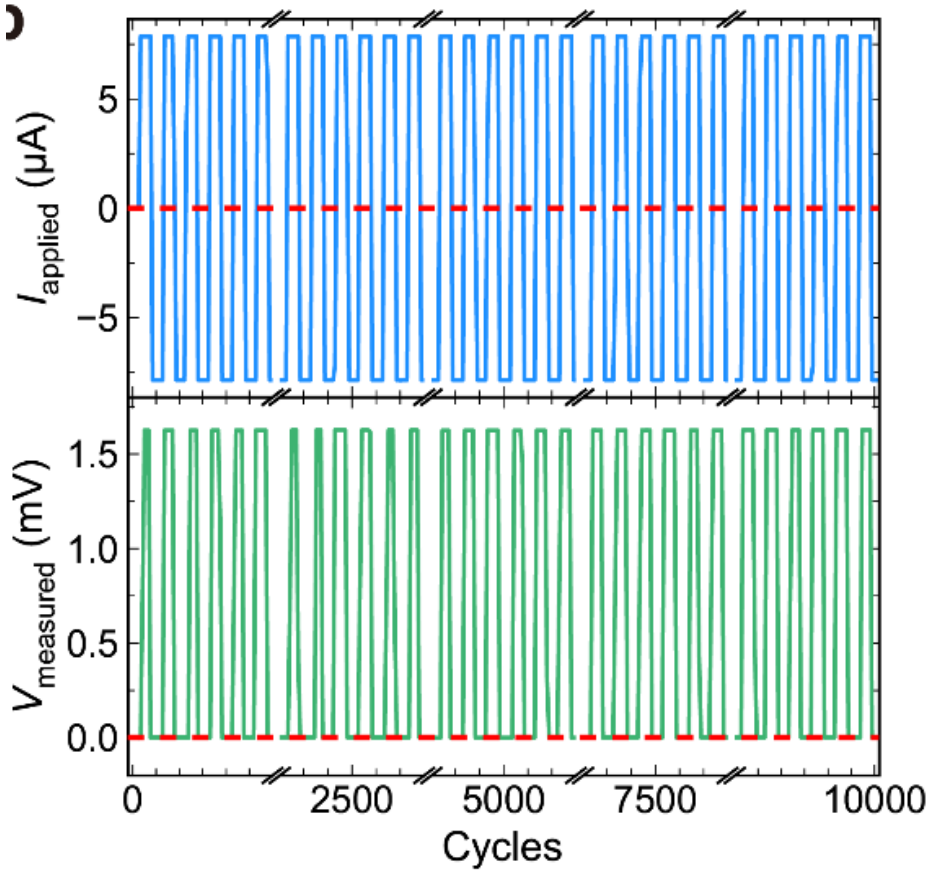
10,000 cycles, 0.5Hz, no punch through error

$I_{applied}$ = +/- 7.9 uA; **in between I_{c+} and $|I_{c-}|$**

T = 20 mK, B = 0, freq = 0.1 Hz

Rectification Ratio >10^4

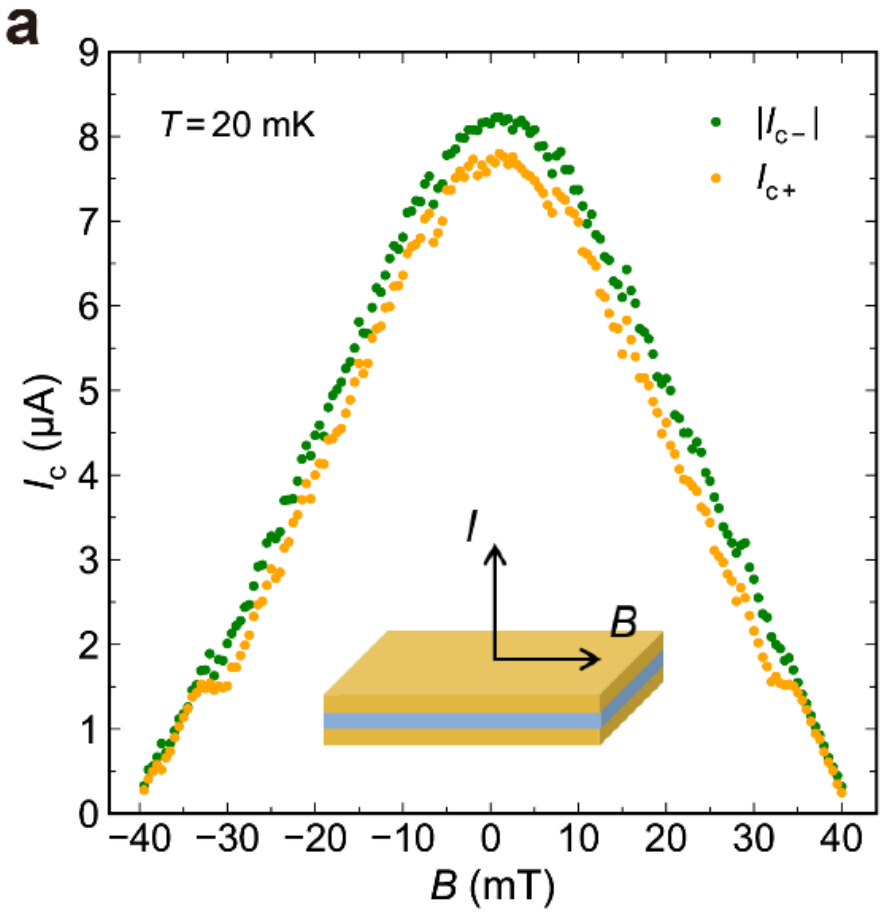




Rectified half the excitation! Josephson DIODE

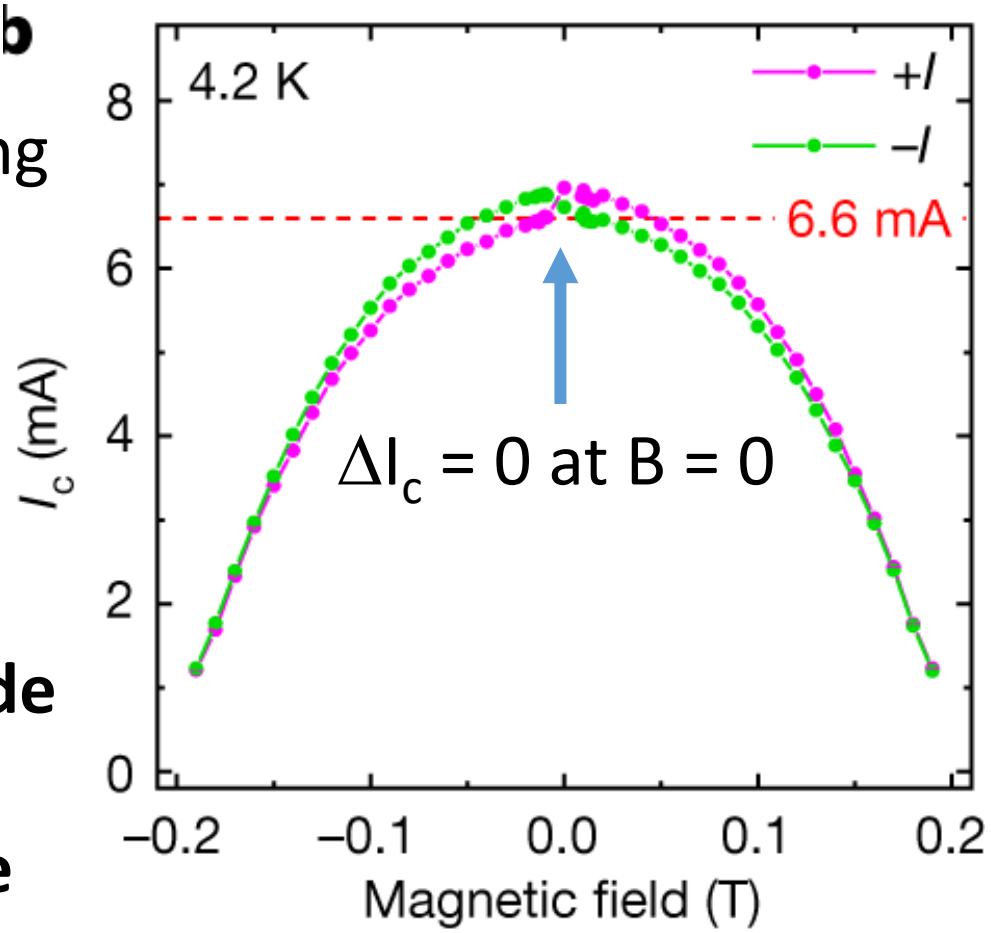
H, Wu., et al, *Nature*, 604, 653-656 (2022)

Does it really work field-free (B = 0)?



Compare with the bulk superconducting diode effect from magnetochiral anisotropy:

The Josephson diode is NOT the same mechanism as the bulk SC diode



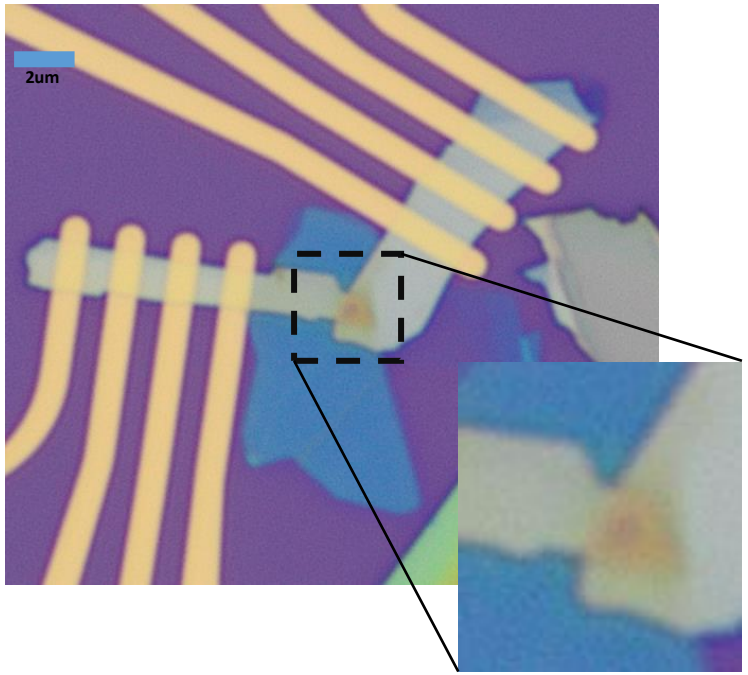
YES! ΔI_c is non-zero at B = 0

H, Wu., et al, *Nature*, 604, 653-656 (2022)

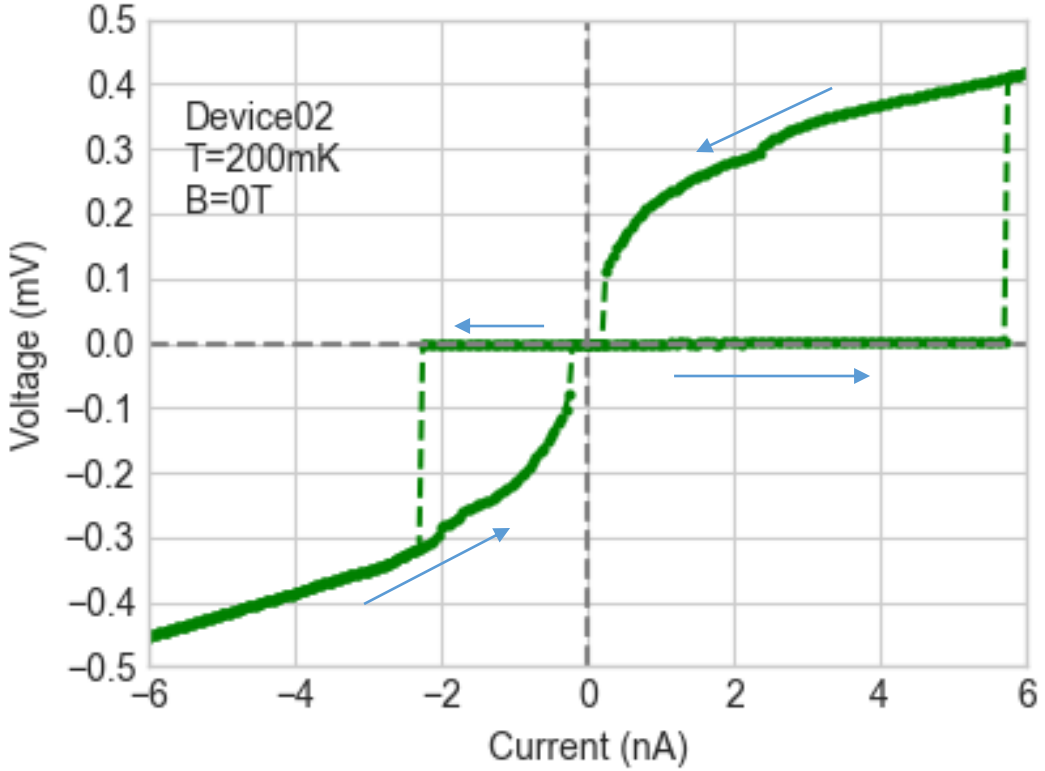
F. Ando, et al, *Nature*, 584, 373, 2020

What about Nb_3Cl_8?

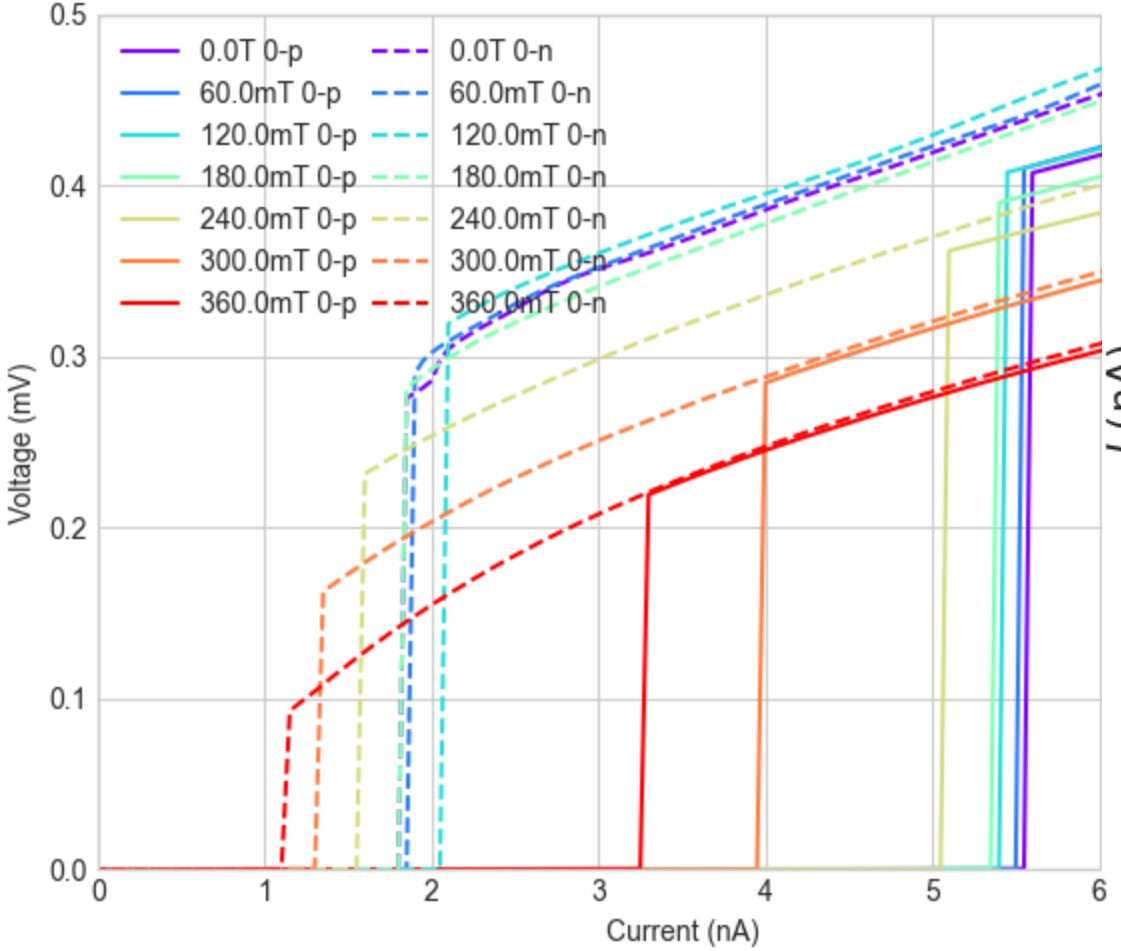
$$J_{c+} \approx 2\text{nA}/\mu\text{m}^2$$

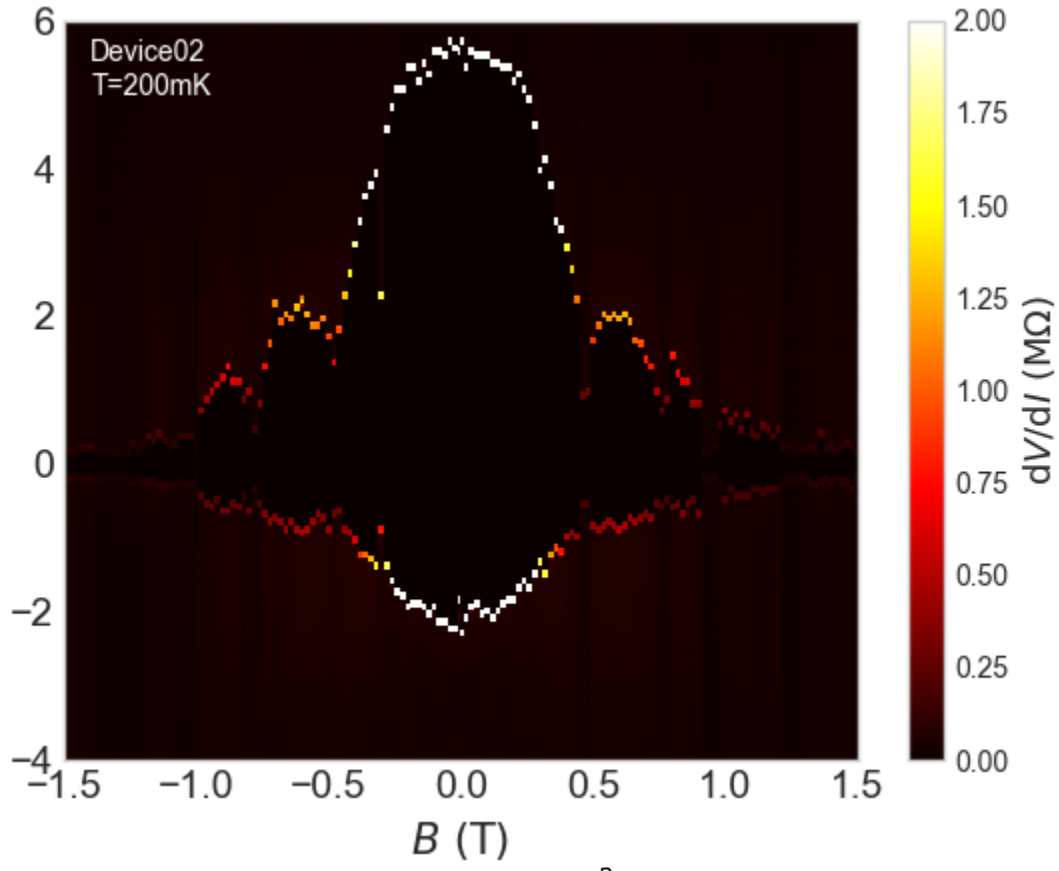


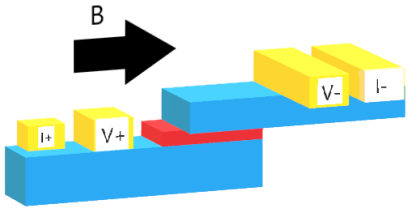
$$\Delta I_c = 3.45\,\text{nA}$$



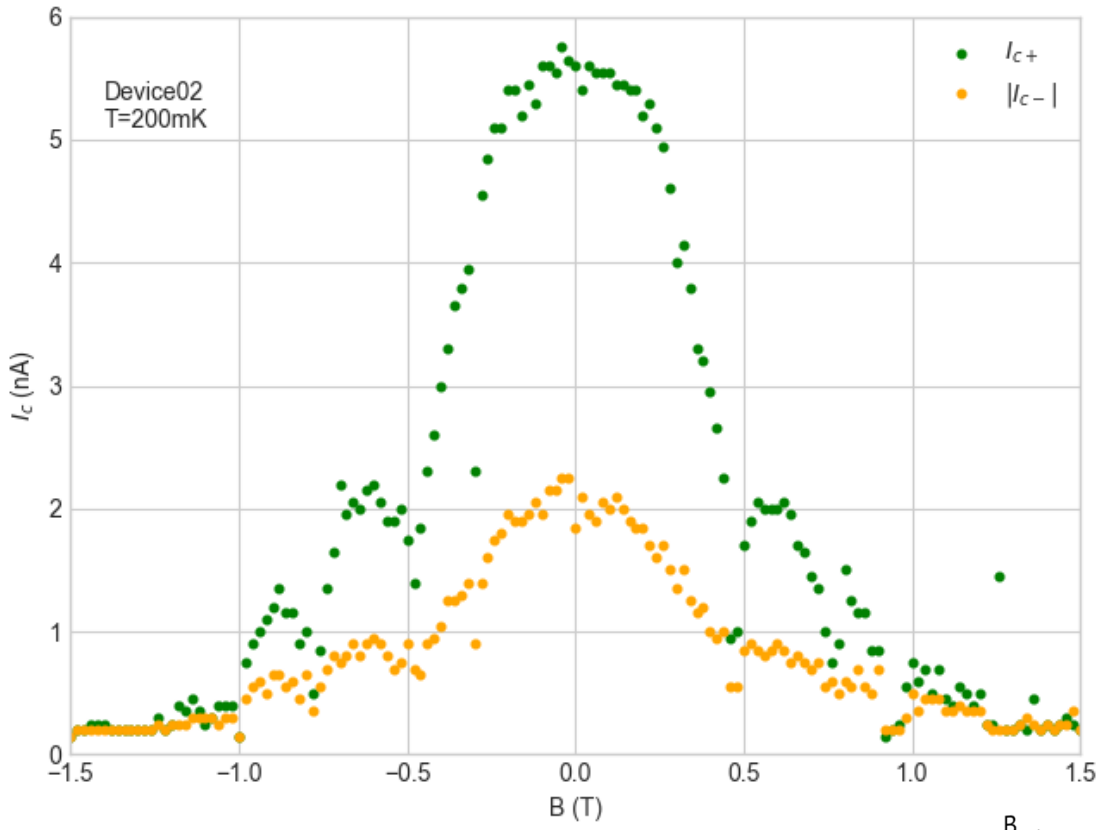
Field Dependence of Nb_3Cl_8 Junction

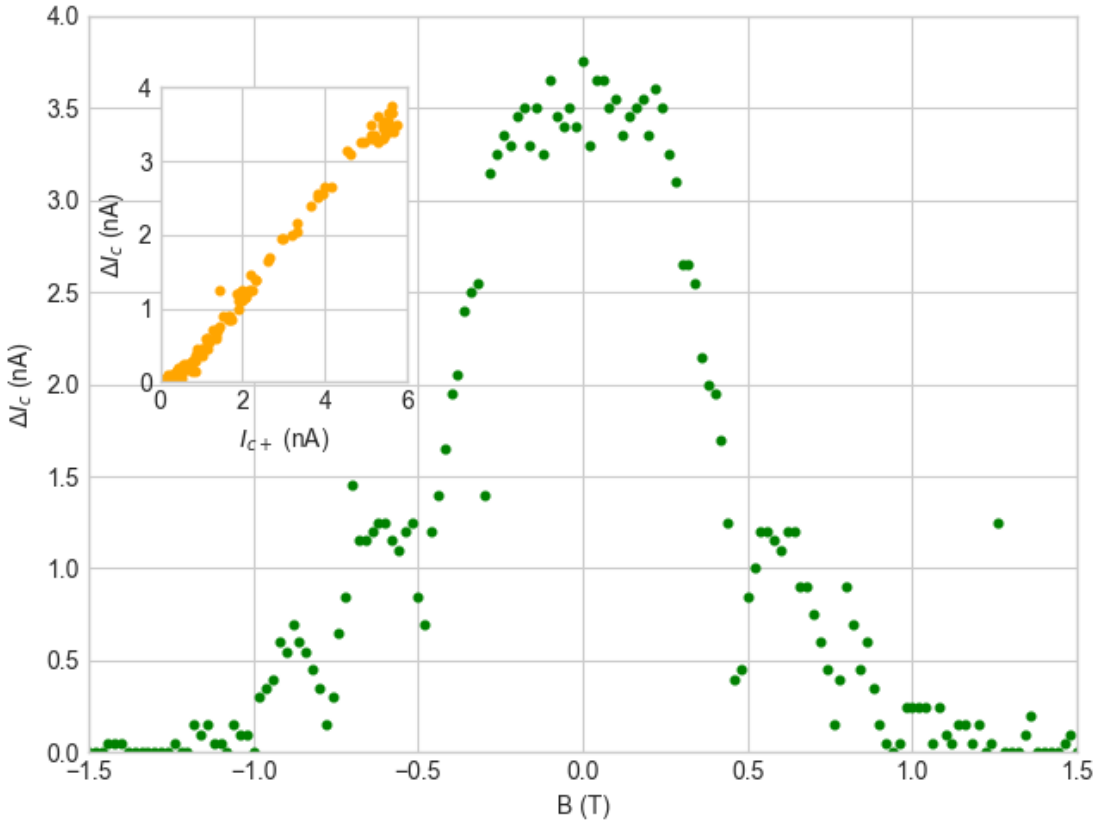


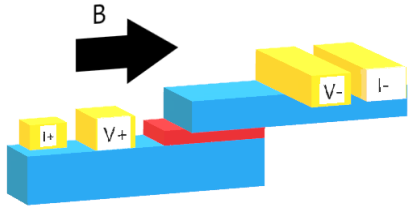




Field Dependence of Nb_3Cl_8 Junction

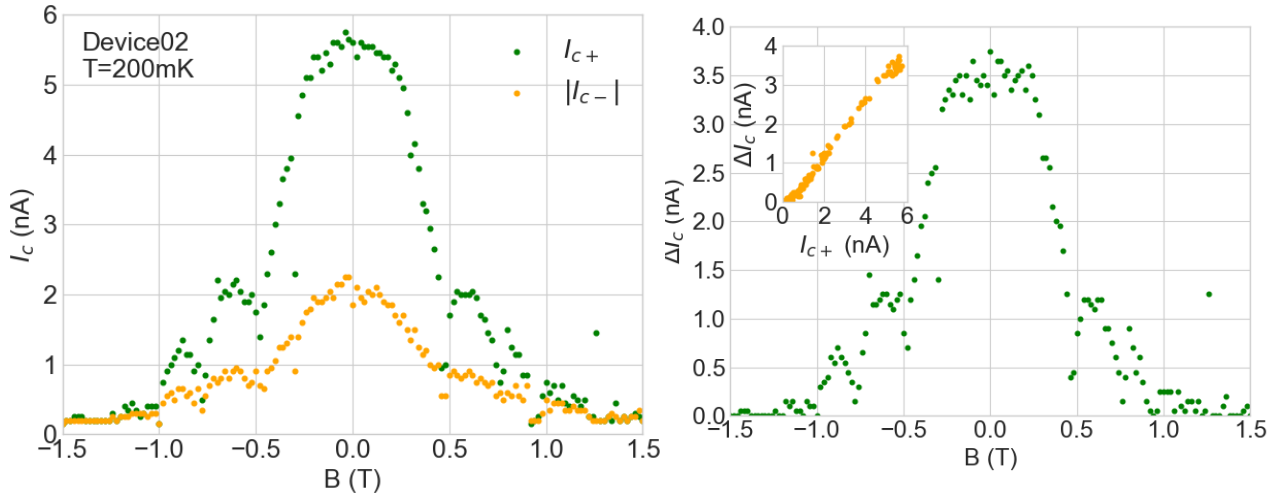




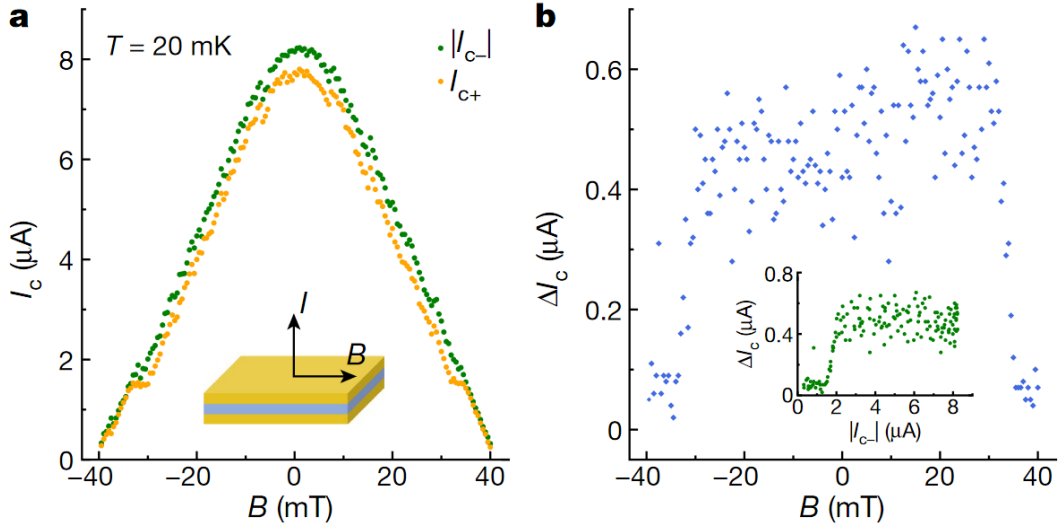


Comparing Field Dependence of Nb_3Cl_8 & Nb_3Br_8

- Nb_3Cl_8 →



- Nb_3Br_8 →

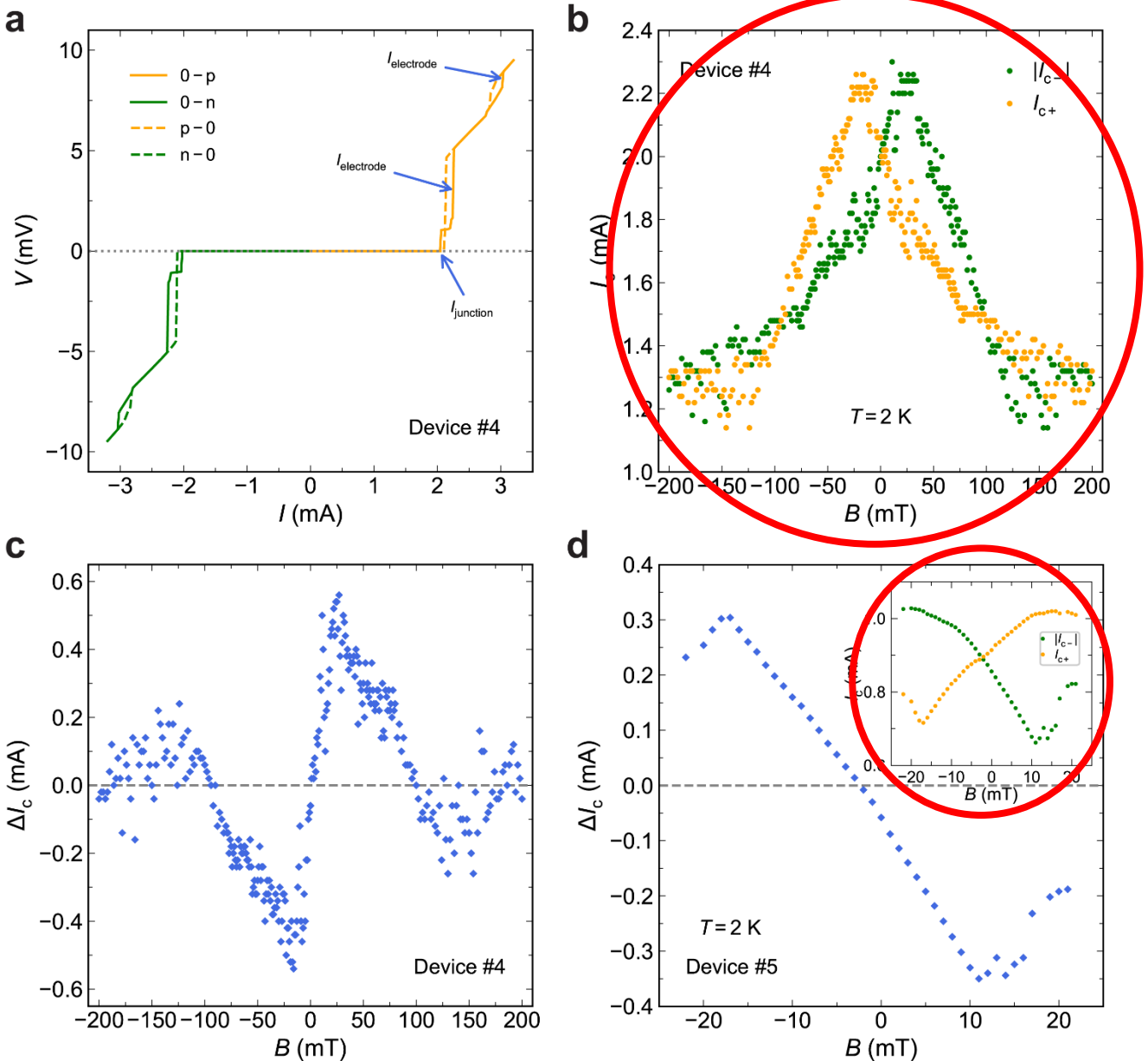


- Wu, H., et.al. (2022). The field-free Josephson diode in a van der Waals heterostructure. *Nature*, *604*(7907), Article 7907.

Is it really the $Nb_3Cl_8Br_8$ barrier?

$NbSe_2/NbSe_2$

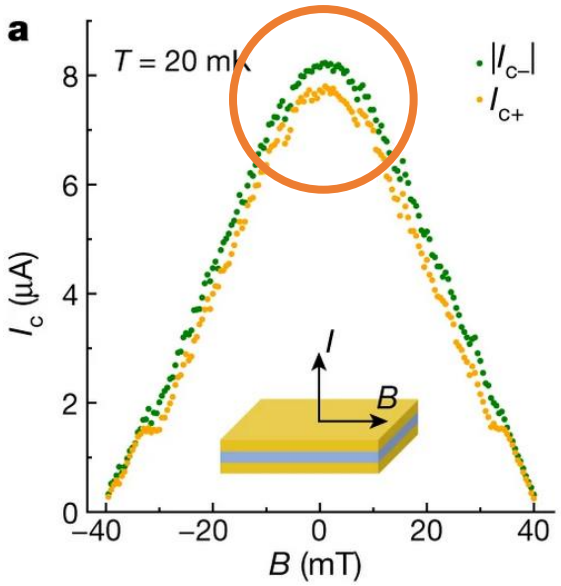
$NbSe_2/FLG/NbSe_2$



H, Wu., et al, *Nature*, 604, 653-656 (2022)

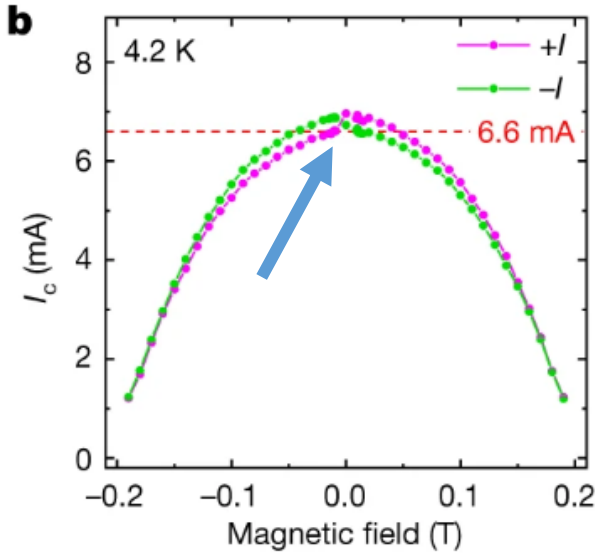
Categorizing Superconduting Diode Effect Devices by Magnetic Field Response

No crossing



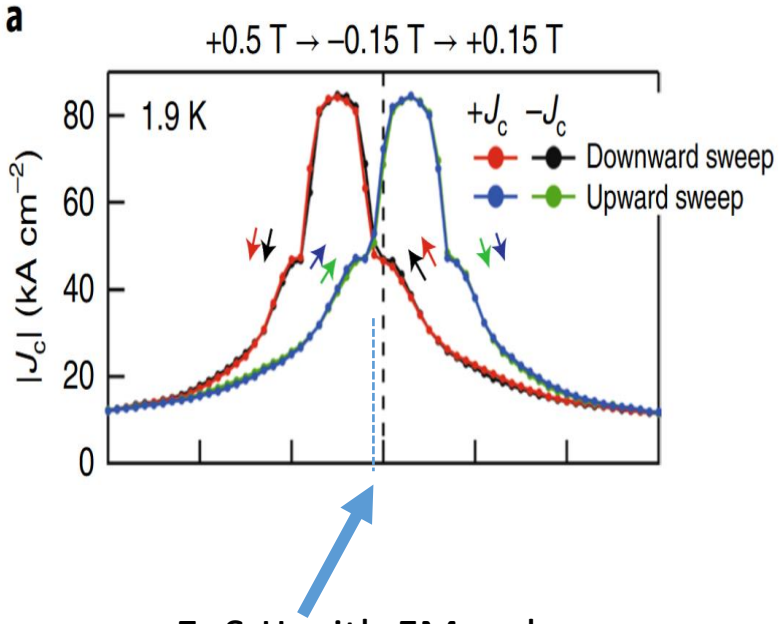
MI JJ

Crossing around zero field



V/Nb/Ta multilayers

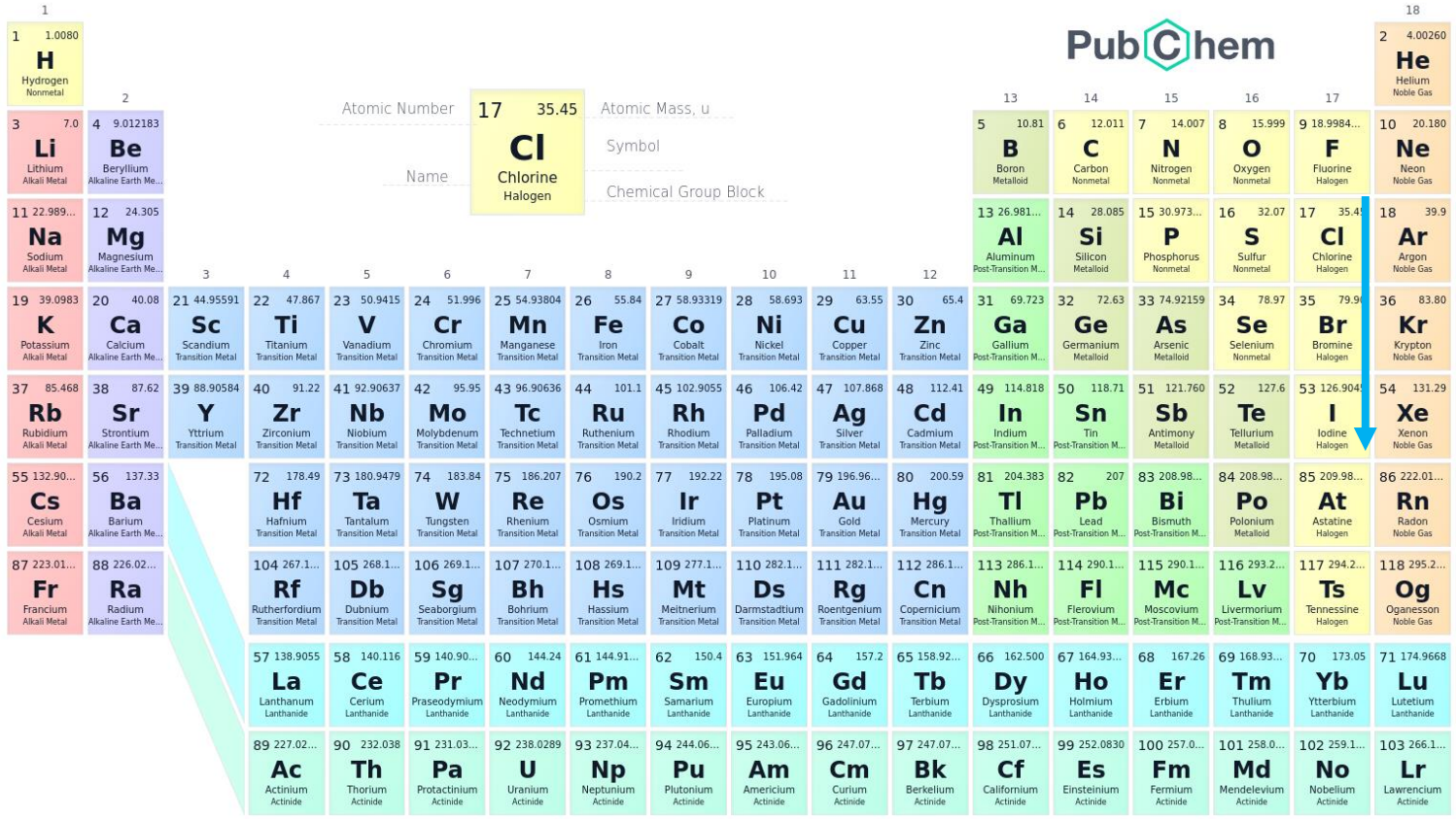
Crossing around finite field



EuS JJ with FM order

- Wu, H., et.al. (2022). The field-free Josephson diode in a van der Waals heterostructure. *Nature*, *604*(7907), Article 7907.
- Ando, F., et.al. (2020). Observation of superconducting diode effect. *Nature*, *584*(7821), Article 7821.
- Narita, H., et.al. (2022). Field-free superconducting diode effect in noncentrosymmetric superconductor/ferromagnet multilayers. *Nature Nanotechnology*, *17*(8), 823–828

Nb_3X_8 Series Josephson Diodes



What happens to the Josephson Diode behaviour as a function of F (not yet) -> Cl -> Br -> I?

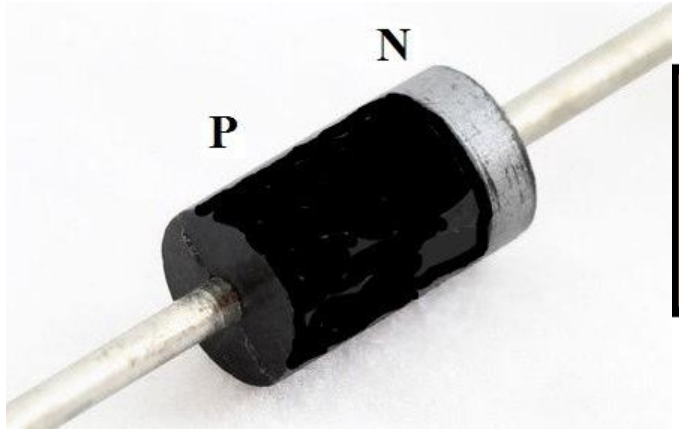
JD behavoir got worse.

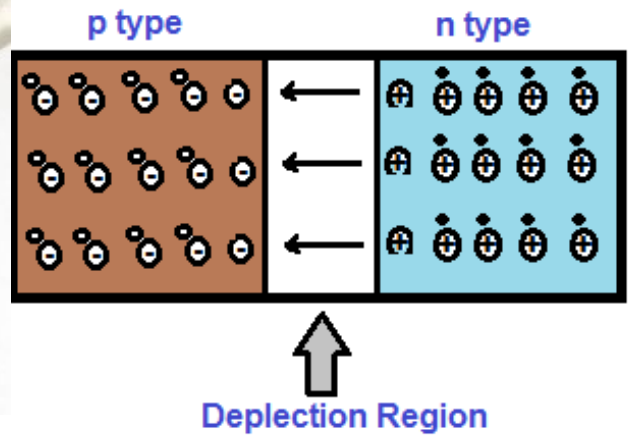
How does magnetism affect it?

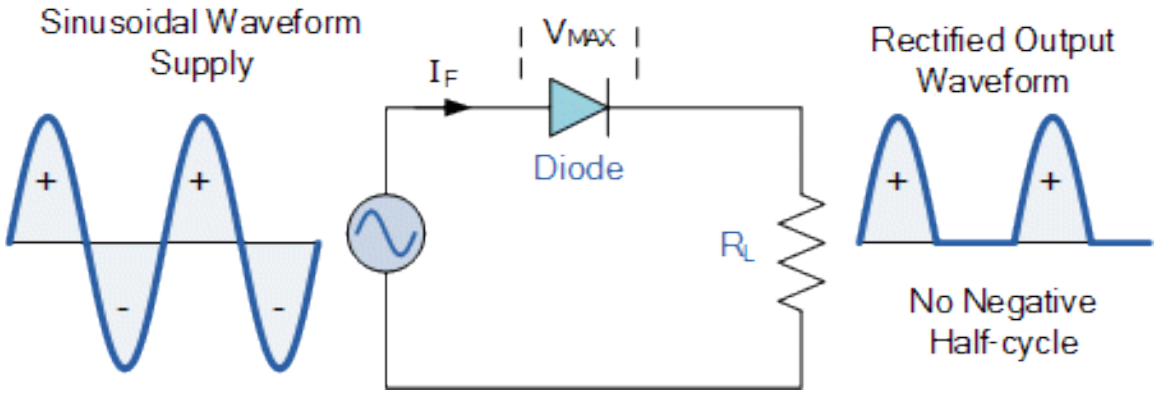
Clearly different than others (e.g. EuS, gated graphene, etc)

	Nb_3Cl_8	Nb_3Br_8	Nb_3I_8
JD Type	FF. Symm	FF. Symm	?
U/t (theory)	~40	~10	~2
J_c	~2nA/μm^2	~2μA/μm^2	?
ΔI_c	~3nA	~700nA	?
$\Delta I_c/I_c$ (%)	~45%	~10%	?

Nonreciprocal (NR) Conduction in general







- Non-Reciprocal – forward and backward flows differ
  - ✓Break inversion symmetry (x,y,z) != (-x, -y, -z)
  - ✓Then need a nonlinear response (E.g. p/n junction, MCA)
  - ✓For a single crystalline system, break time-reversal symmetry (TRS) with **magnetic field** or spatial effect (i.e. **electronic correlation and dissipation**)
  - ✓**Rectification (Diode Effect): very basic demonstration of non-reciprocity**

NR - critical for many components (gyrators, isolators, circulators, active transistors, etc) - important for everything from wireless transmitters to quantum computing!

Nakai, R., et al, Phys. Rev. B 99, 115201 (2019) Morimoto, T. et al, Sci. Rep. 8, 2973, 2018

Nagulu, A., et al, Nature Electronics, doi: 10,1038/s41928-020-0400-5

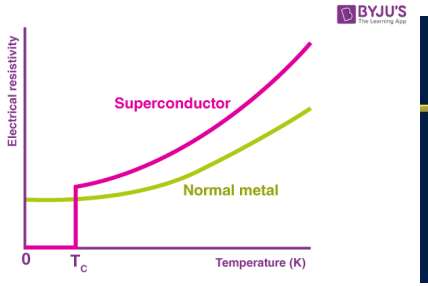
Potential Benefits of Non-Reciprocal SC devices

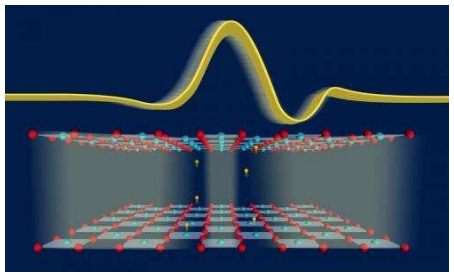
Enables superconducting non-reciprocal circuits and components

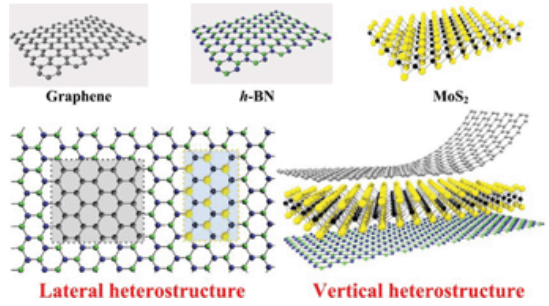
in analogy

to semiconducting non-reciprocal circuits and components!

- ENERGY: Dramatic switching energy reduction
- SPEED: Old IBM studies; material possibilities up to **THz switching**
- SIZE: Quantum Materials, 2D JJs, few nm thick







Dienst, A. *Nature Photonics*, 5, 485, 2011

Wang, H., et al, *Nanoscale*, https://doi.org/10.1039/C4NR03435J

The field-free Josephson diode in a van der Waals heterostructure

Overview of attention for article published in Nature, April 2022

377

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零磁场下的超导半导体：新物理和新器件的开端 知社学术圈49分钟前0跟贴
163.com, 17 May 2022
1911年，荷兰物理学家卡默林·昂纳斯发现了超导性。正常传导中，电子以单粒子的形式运动；在超导体中，它们成对运动，不会损失任何电

物理學家們研發出了長久以來被認為不可能的超導電路
Yahoo! News, 15 May 2022
藉由將一種古典材料替換成具有獨特量子性質的材料，科學家們已製造出一超導電路，能夠達成長久以來被視為不可能的壯舉。這項由德國、荷蘭、以及美國的研究人員所帶來的發現，翻轉了一世紀以來，對於超導電路天性的看法，以及如何能夠調整它們的電流於實際應用上。 過往的侷限...

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Giulia Pacchioni

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Katharina Zeissler

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BY RAHUL RAO | PUBLISHED APR 27, 2022 3:30 PM

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Superconductor breakthrough heralds faster computing

Tom Whipple, Science Editor

Thursday April 28 2022, 12.00am BST, The Times

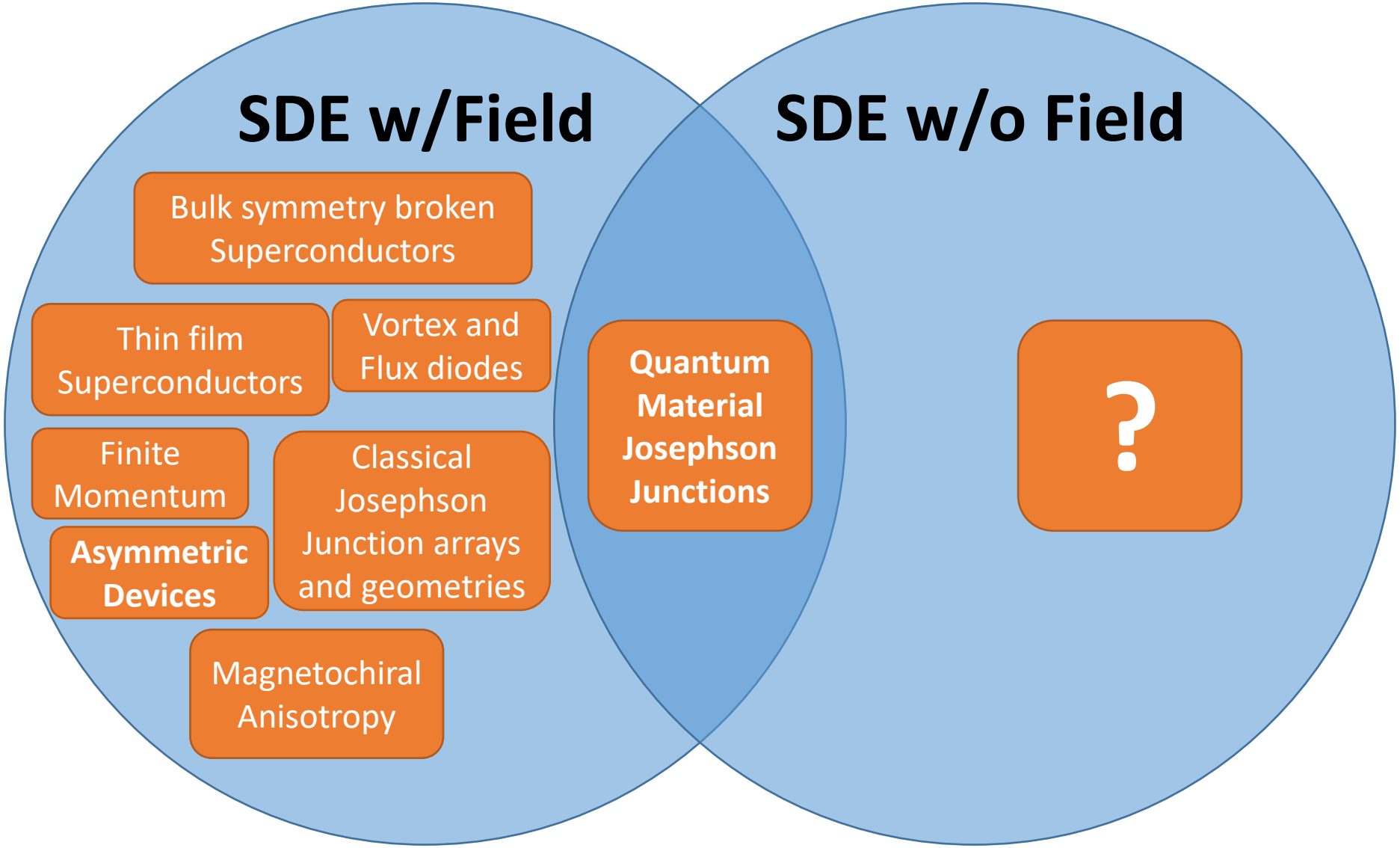
SUPERCONI

Scientists unveil Josephson diode

04 May 2022

An international group of physicists has demonstrated that a very thin layer of quantum-mechanical material sandwiched between two pieces of superconductor can

Superconducting Diode Effects



Non-reciprocal superconductivity via QMJJs

- Explosion of realisations:
  - Topological Insulators
  - Dirac/Weyl Semimetals
  - 2DEGs
  - Twisted Graphene Heterostructures
  - Single atom scale JJs: Pb-Cr-Pb
  - Ferromagnetic JJs

State of the art:

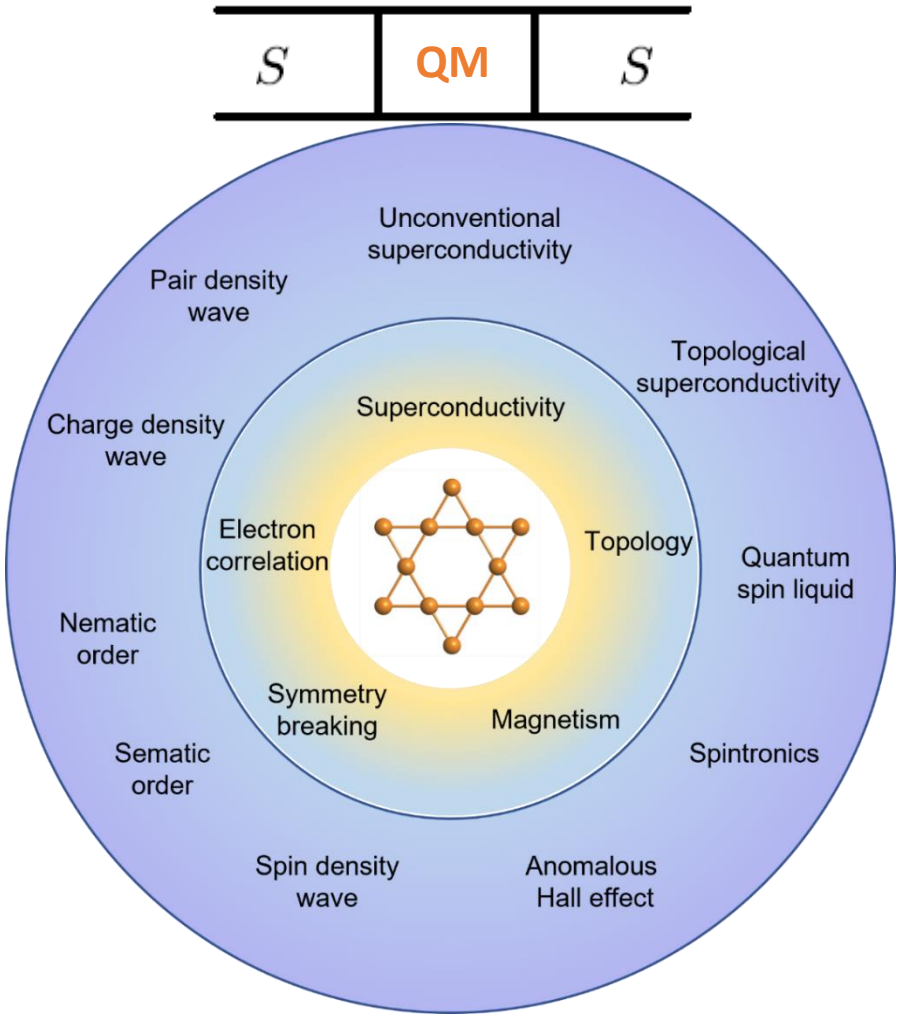
Efficiencies > 50%

Working temperature > 77K

Switching speed > 100KHz

Scalability – Ongoing

QMJJs moving forward

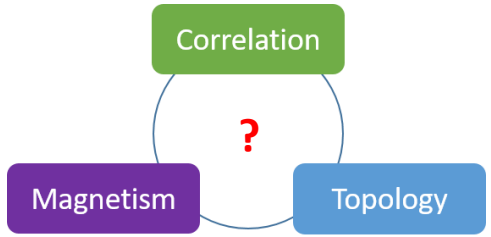


- 1.) Strongly correlated materials (not SC)
  - Mott-Hubbard Insulators
- 2.) Topological materials
  - Berry curvature, spatially confined states
- 3.) Spin liquids
  - Magnetic frustration
- 4.) Certain Ferroelectrics
  - Polarization
- 5.) Certain Magnetoelectrics
  - Chern-Simons interaction
- 6.) Non-collinear magnets
  - Spatially varying local magnetic field
- Much, much more

C. Z. Chen, et al, Phys. Rev. B. 98, 075430
Y. Choi, et al, Nature Materials, 19, 974, 2020
Y. Wang et al, *Nature Reviews Physics, 5, 635–658 (2023)*

Table 1| Properties of Kagome materials

Materials	Low Temperature Magnetism	Topological	Electron Correlation	Phase transitions
AV_3Sb_5 (A=Cs, K, Rb)	No long range order but TRSB reported[78,119,120]	Dirac semimetal[32,62]	Weak e-e correlation[84], vHS[62,63], flat band[60]	Structure distortion[86,87], CDW[69], PDW[29], nematic/stripe orders[28,73], SC[30]
RMn_6Sn_6	Ferrimagnetic: R=Tb, Dy, Ho, Er (conical magnetic order in R= Dy, Ho) [185] Antiferromagnetic: R= Tm[185] Antiferromagnetic, double-flat-spiral: R=Y, Sc, Lu, Er[187–189] Ferromagnetic: R=Li, Mg, Ca[191,192]	Chern phase: R=Tb[35], Gd-Er[202], proposed for R=Y[204] Dirac cone in YMn_6Sn_6[204]	flat band and vHS reported in YMn_6Sn_6	Magnetic transitions
RMn_6Ge_6	Ferromagnetic: R=Nd, Sm[179] Antiferromagnetic: R=Dy-Yb, Sc, Y, Lu, Gd[177,193]	Not reported	Not clear	Magnetic transition
RFe_6Sn_6,RFe_6Ge_6 R=Dy-Yb, Sc, Y, Lu	Mostly antiferromagnetic[177,178]	Not reported	Not clear	Magnetic transitions
RV_6Sn_6	Non-magnetic: R= Y[194] Weak paramagnetic: R=Sc[195] R=Gd: weak, field dependent magnetism[194]	Dirac cone in R=Gd, Ho[201,202]	vHS in R=Gd, Ho[201,202]	Structural and CDW transitions in ScV_6Sn_6[195] Magnetic transition in GdV_6Sn_6[194]
$MoCo_6Ge_6$ $Yb_{0.5}Co_3Ge_3$	Paramagnet[196] Weak magnetism, possible magnetic transition around 20 K[41,42]	Not reported Not reported	Not clear Not clear	Structural transition[196] Structural transition[42]
Nb_3X_8 (X=Cl, Br, I)	X=Cl, Br, paramagnetic to nonmagnetic transition (bulk crystal)[37] Thin film: not clear	Not reported	Strong correlation Flat band[40,223,228] Mott insulator[39,40]	Structural and magnetic transition
FeGe FeSn CoSn	Antiferromagnetic[230] Antiferromagnetic[15] Paramagnetic[16]	Not reported Dirac cone[15] Dirac cone[16]	vHS[230] Flat band[15] Flat band[16,17]	FeGe[230]: Structural, CDW and magnetic transitions
Mn_3Ge,Mn_3Sn	Chiral antiferromagnetic[20,22]	Weyl semimetal[21]	Not clear	Magnetic transition
$Co_3Sn_2S_2$	Ferromagnetic[14]	Weyl semimetal[13,14]	Flat band[235]	Magnetic transition
Fe_3Sn_2	Noncollinear ferromagnetic, skyrmion[18,19]	Massive Dirac point[236]	Flat band[237]	Magnetic transition
RT_3X_2	Mostly weak magnetism[213–215,233,238,239]	Dirac cone proposed[214,234]	Flat band, vHS proposed[214,234]	SC in many compounds, e.g. $LaRu_3Si_2$[213,240], $LaIr_3Ga_2$[214], YRu_3Si_2[215], $LaRh_3B_2$[239], $CeRh_3B_2$[239]



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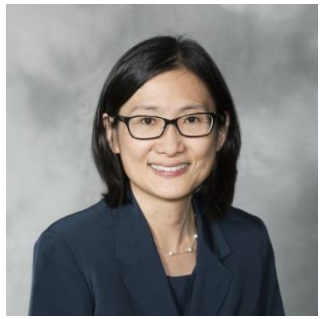
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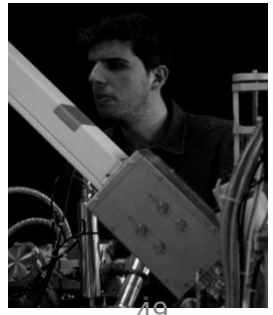
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