SUMMER SCHOOL LECTURE · GDAŃSK – PQChips2006

Physics and Applications of devices based on vdW superconductors

From van der Waals crystals to functional cryogenic devices

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ROADMAP

Lecture outline

01 **Why superconducting electronics, why vdW?**
Motivations

02 **VdW superconductors**
Materials toolbox and main properties

03 **Unconventional pairing and magnetic field resilience**
Ising superconductivity

04 **Topological superconductivity**
Majorana routes in vdW heterostructures

05 **Superconductor/ferromagnet vdW hybrids**
Superspintronics, spin-triplet supercurrents

06 **Diodes, sensors & quantum circuits**
SDE, SQUIDs, JPAs, bolometers, qubits

07 **Scalability & outlook**
Wafer-scale growth, open challenges

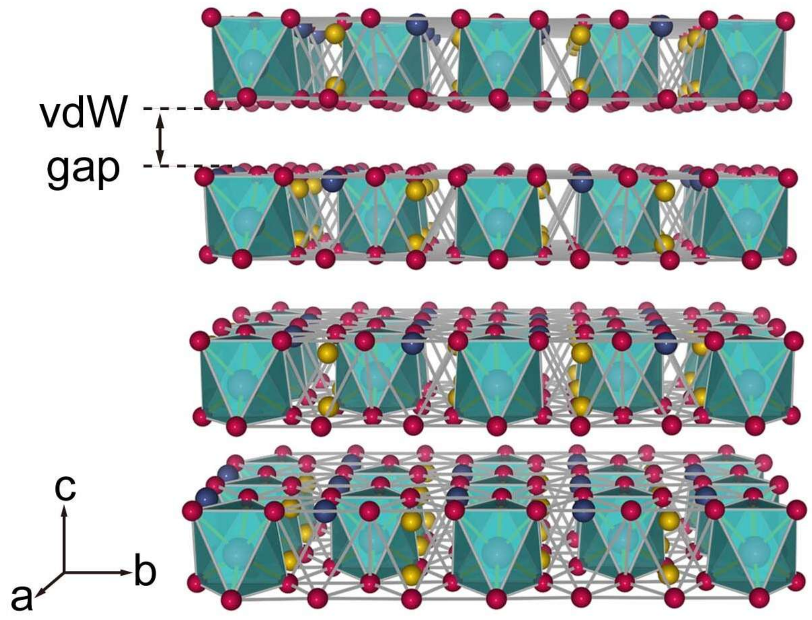
MOTIVATION

Why superconducting electronics?

- Non-resistive state → (virtually) **dissipation-free devices**
- Macroscopic **quantum coherence** → natural platform for qubits, parametric amplifiers, ultra-sensitive detectors
- Josephson junctions give a **nonlinear circuit** element with no normal-conducting analogue
- Already central to **several applications** including magnetometry, energy-efficient digital superconducting logic, superconducting quantum computing, single-photon and THz detection

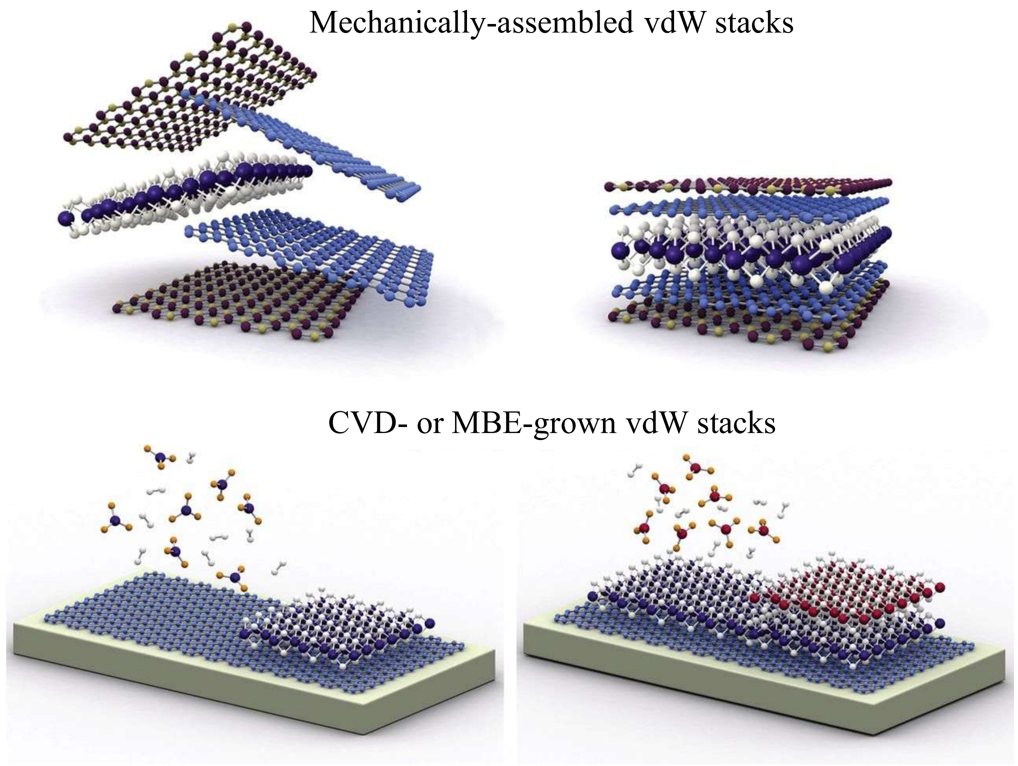
Why van der Waals (vdW) materials?

- Atomically thin, dangling-bond-free surfaces → clean, sharp interfaces without lattice-matching constraints
- **Tunable properties** with layer number, twist angle, electrostatic gating, geometric curvature and strain.
- Physics **absent in 3D thin films** → broken inversion symmetry, strong spin–orbit coupling in the monolayer limit
- Heterostructures assembled "Lego-style" by stacking → opens endless pathways for **new device functionalities**



A SHORT PRIMER

What is a vdW material?



- Layered crystals: strong in-plane covalent bonding, weak out-of-plane van der Waals bonding.

- Individual layers can be mechanically exfoliated down to a monolayer (ML), or grown directly by chemical vapor deposition (CVD)/molecular beam epitaxy (MBE).

- Different layers — metals (e.g., graphene), superconductors (e.g., $NbSe_2$), magnets (e.g., Fe_3GeTe_2), insulators (e.g., hBN) — can be stacked into heterostructures with atomically sharp interfaces.

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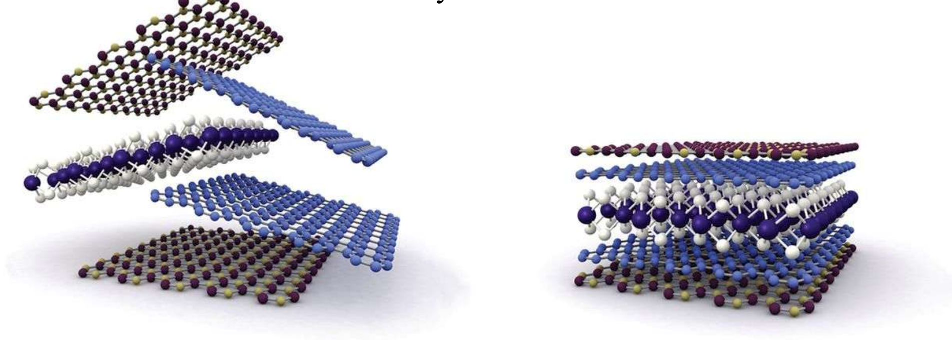
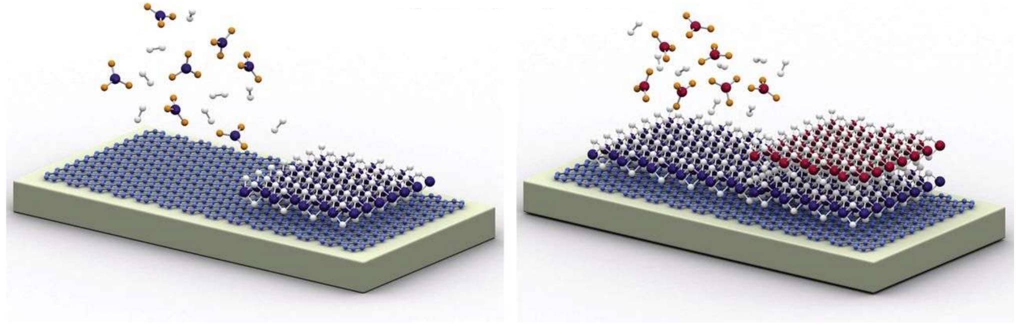
Mechanically-assembled vdW stacks



CVD- or MBE-grown vdW stacks



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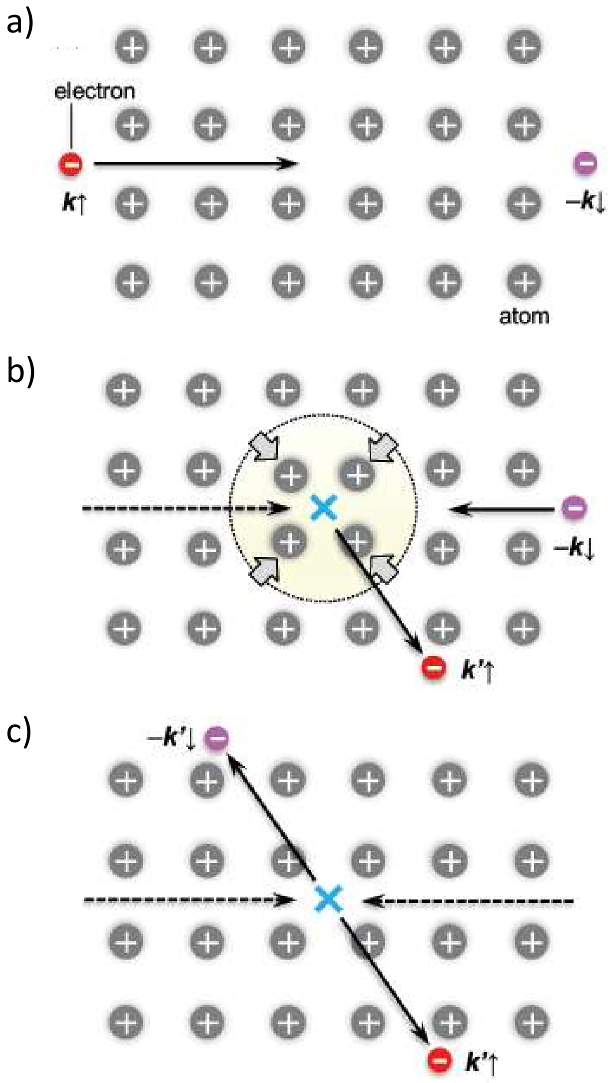
- **This lecture focuses on vdW superconductors (mostly transition-metal dichalcogenides, TMDs) and their heterostructures with other magnetic, insulating and topological vdW materials.**

BACKGROUND

Cooper pairs and the superconducting gap

- Below the superconducting critical temperature (T_c), electrons near the Fermi surface bind into **Cooper pairs** (**CPs**) via an effective attractive interaction – this is phonon-mediated in **Bardeen-Cooper-Schrieffer** (**BCS**) theory.

- In conventional (BCS, spin-singlet, s-wave) pairing, CPs form between electrons with **opposite spin and momentum**, (k↑, –k↓).



https://www.issp.u-tokyo.ac.jp/labs/tosyo/note/

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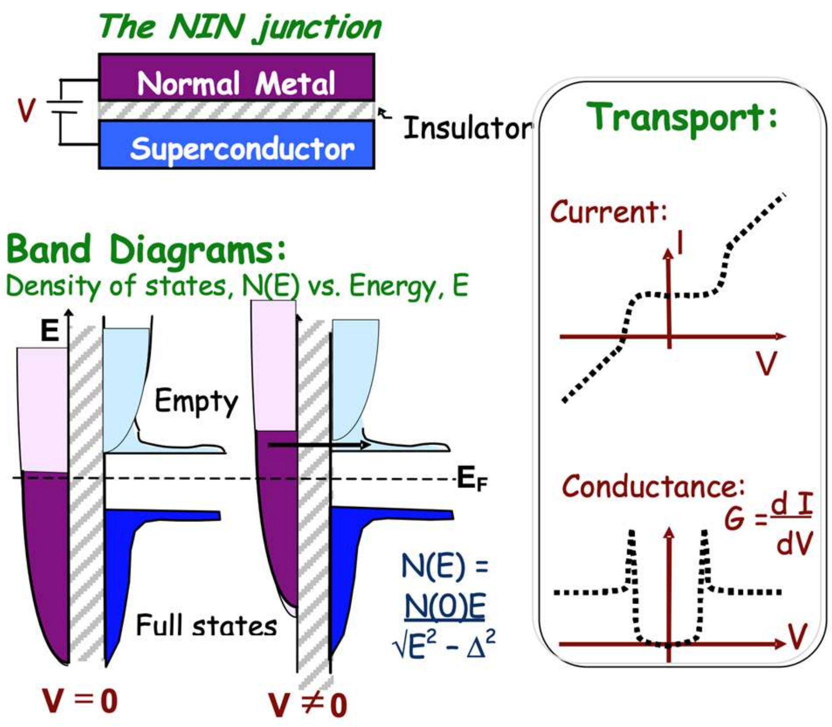
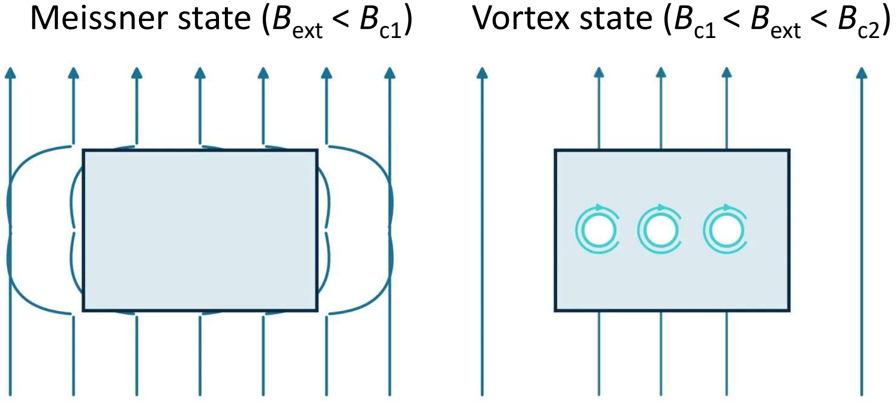
- Pairing opens **an energy gap Δ in the density of states** — measurable, for example, by tunnelling or scanning tunneling spectroscopy (STS)

- **Key idea for today: by changing the symmetry of the electronic bands (via reduced dimensionality, broken inversion symmetry, spin–orbit coupling) different and ”more robust” pairs can form.**



L. H. Greene, *AIP Conf. Proc.* **795**, 70–82 (2005)

Magnetic response

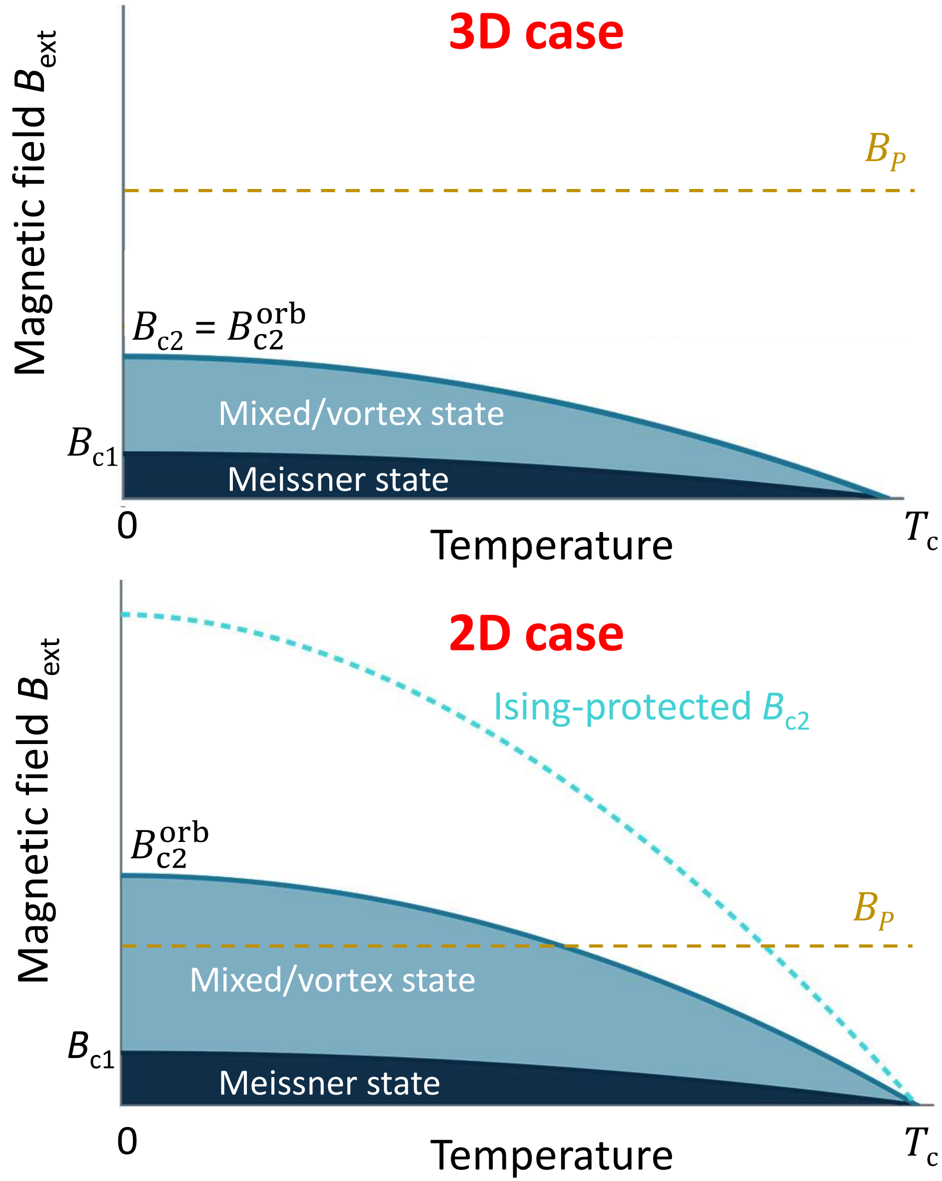


Pauli field

$$B_P(0) = \frac{\Delta_0}{\sqrt{2}\mu_B}$$

In superconductors with thickness *d* << *ξ*

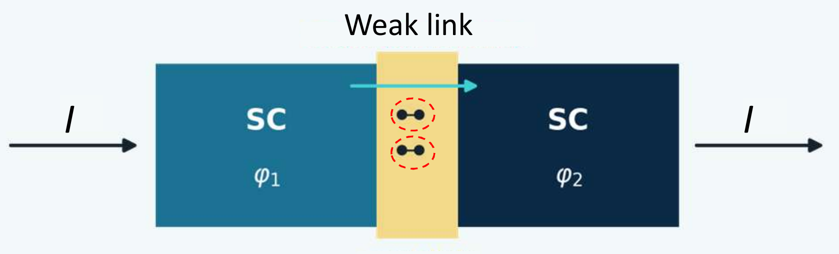
$$B_{c2}^{orb}(0) = \frac{\sqrt{12}\Phi_0}{2\pi\xi(0)d}$$



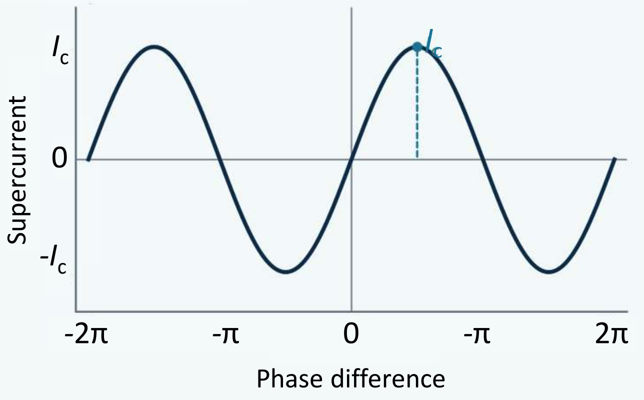
Josephson junctions & the current-phase relation (CPR)

- A Josephson junction (JJ) = two superconductors (SCs) coupled through a weak link (insulator, normal metal, semiconductor, magnet, …)
- A dissipationless supercurrent I flows, set by the phase difference ϕ across the junction: $I(\phi) = I_c \cdot \sin(\phi)$ for a conventional JJ
- I_c = critical current: the maximum supercurrent the junction can sustain
- Two JJs in a circular loop → a superconducting quantum interferometer device (SQUID). Here, I_c oscillates with the magnetic flux through the loop — the basis of the most sensitive magnetometers that exist
- **The shape of $I(\phi)$ — the current-phase relation (CPR) — can give insights into the topology of the weak link**

Josephson junction

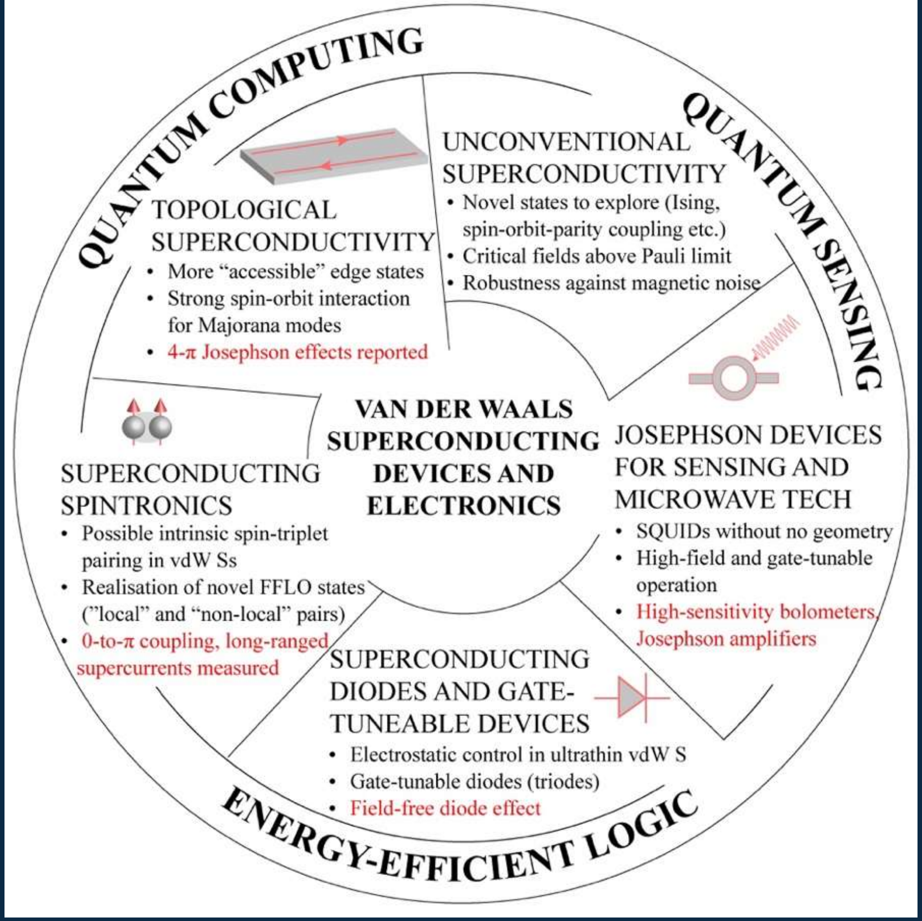


Current-phase relation (CPR)



THE BIG PICTURE

One material platform, five device families



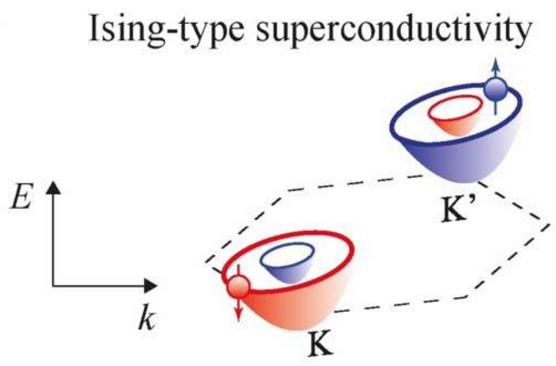
A. Di Bernardo & E. Scheer,
Rep. Prog. Phys. (Under Review)

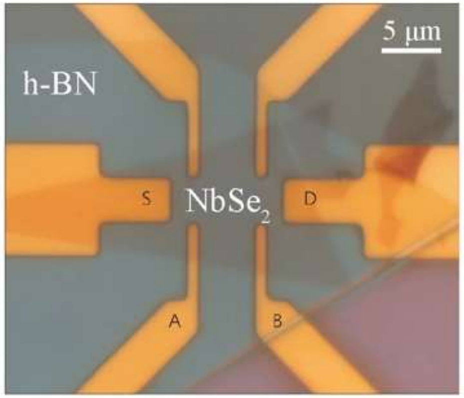
VdW superconductors and other materials at a glance

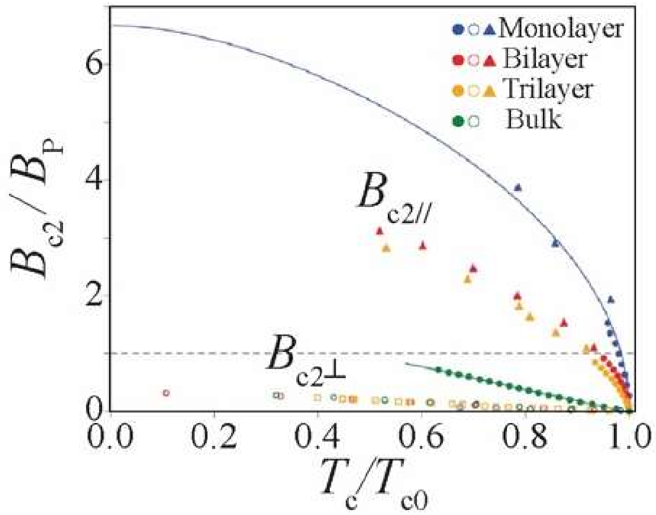
Material/Polytype	Ground state	Why it matters	Used for
$NbSe_2$ (2H)	Non-centrosymmetric SC, Ising pairing	$B_{c2\parallel}$ up to ~6 times B_P; Charge-density wave (CDW) order	Most-used vdW SC electrode; diodes, JJs, sensors
TaS_2 (2H)	Non-centrosymmetric SC	Layer-dependent T_c; CDW competition	SOC-driven B_{c2} studies
1T′-WTe_2 / 2M-WS_2	Centrosymmetric, topological	Band inversion, SOPC, QSH edge states	Topological superconductivity
Fe_3GeTe_2 (FGT)	Itinerant vdW ferromagnet	Strong perpendicular magnetic anisotropy (PMA), tunable T_{Curie}	SC/FM spin valves, spin-triplet studies
$Cr_2Ge_2Te_6$ (CGT)	Soft vdW ferromagnetic insulator	Rich domain texture, small B_{ext} switching	0-to-π junctions, domain-engineered I_c (when combined with a SC)
$NiPS_3$	Antiferromagnet	Non-collinear spin texture	spin-triplet generation (with a SC)
$Cr_{1/3}NbS_2$	Helimagnet	Non-collinear spin texture	lithography-free SQUIDs
hBN	Wide-gap insulator	Atomically flat, ultra-low disorder	Encapsulation, tunnel barriers, dielectrics

Ising superconductivity: pairing protected by spin–orbit coupling

- In monolayer 2H-$NbSe_2$, inversion symmetry is broken — unlike the bulk (ABAB stacking restores it)
- Strong SOC of Nb + broken inversion → spin splitting of bands at finite momentum *k*, locked out-of-plane
- Can be seen as result of an effective field B_{so} (perpendicular to crystal field and electron motion) that pins the electron spins along +z or –z depending on valley (K vs K')
- Cooper pairs form between electrons at K and K' with opposite, out-of-plane-locked spins → "**Ising pairing**"



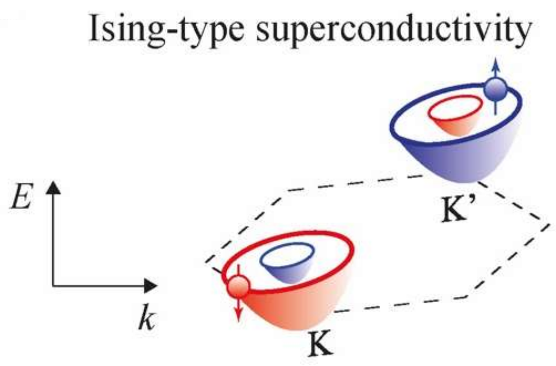


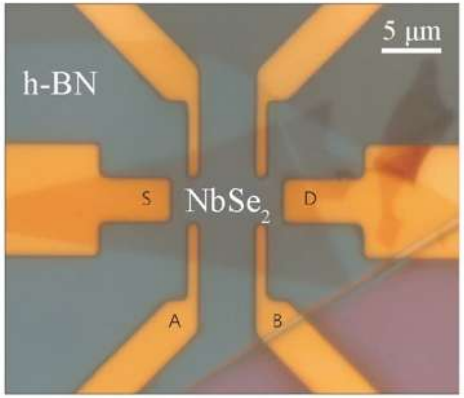


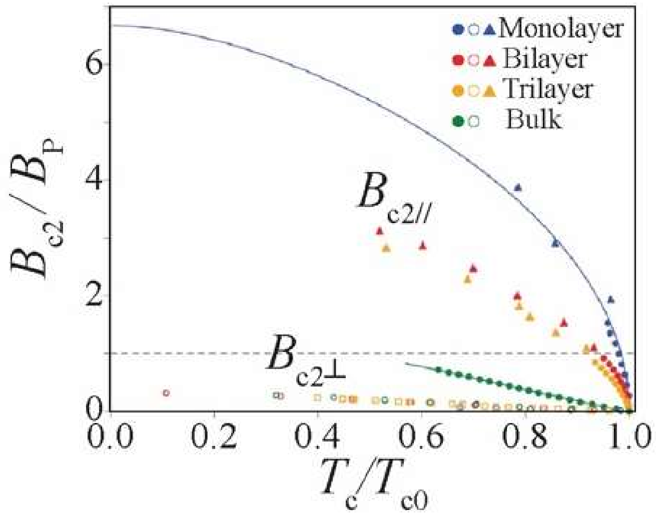
X Xi et al., *Nat. Phys.* **12**, 139–143 (2016)

Ising superconductivity: pairing protected by spin–orbit coupling

- Monolayer $NbSe_2$: measured $B_{c2\|}(0) \approx 6 \times B_P(0)$
- Bilayer, trilayer $NbSe_2$ show progressively smaller enhancement — the effect is intrinsically a monolayer (single-mirror-plane) phenomenon
- **Practical uptake: $NbSe_2$ vdW electrodes/weak links can operate at in-plane fields that would destroy a conventional Al or Nb thin-film device — useful wherever superconducting devices must coexist with strong magnetic fields**





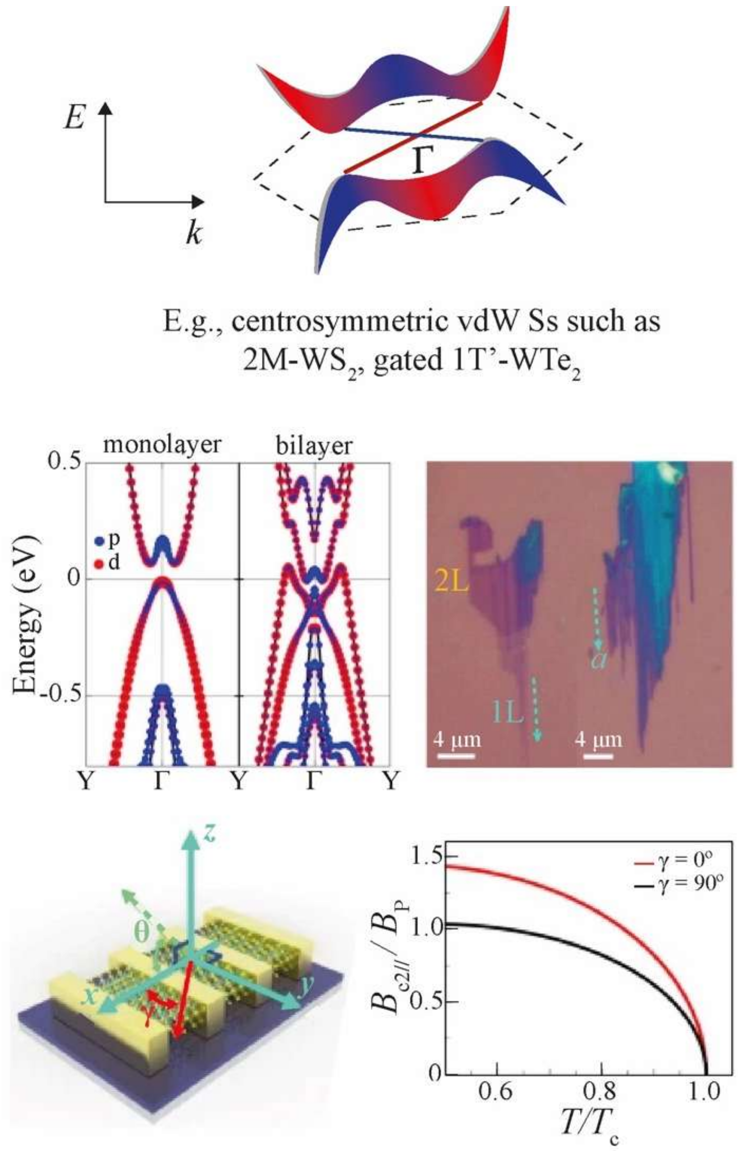


X Xi et al., *Nat. Phys.* **12**, 139–143 (2016)

UNCONVENTIONAL PAIRING (3)

Spin–orbit–parity coupling

- What about centrosymmetric vdW SCs, where inversion symmetry is NOT broken?
- Conventional spin–momentum SOC terms are forbidden by inversion symmetry — so no Ising pairing is possible
- Nonetheless, near momenta where bands of opposite parity invert (band inversion), **spin, momentum AND parity can still couple — spin-orbit-parity coupling (SOPC)**
- Example: few-layer 2M-WS_2 — topological band inversion gives $B_{c2\parallel}(0) \approx 30.5$ T, exceeding B_P, with a clear two-fold in-plane anisotropy
- Same phenomenology (field-resilient pairing) as Ising SC, but with completely different symmetry origin.



E. Zhang et al., *Nat. Phys.* **19** 106–113 (2023)

Concepts: Andreev bound states, YSR states, Majorana zero modes

Andreev bound state (ABS)

Arises from Andreev reflection at a SC/normal metal interface; disperses with phase and B_{ext}; can also merge into a zero-bias peak mimicking a MZM

Yu–Shiba–Rusinov (YSR) state

Bound state at a magnetic impurity on a SC surface; spin-polarised, local; splits linearly in B_{ext} — a common look-alike of a MZM signature

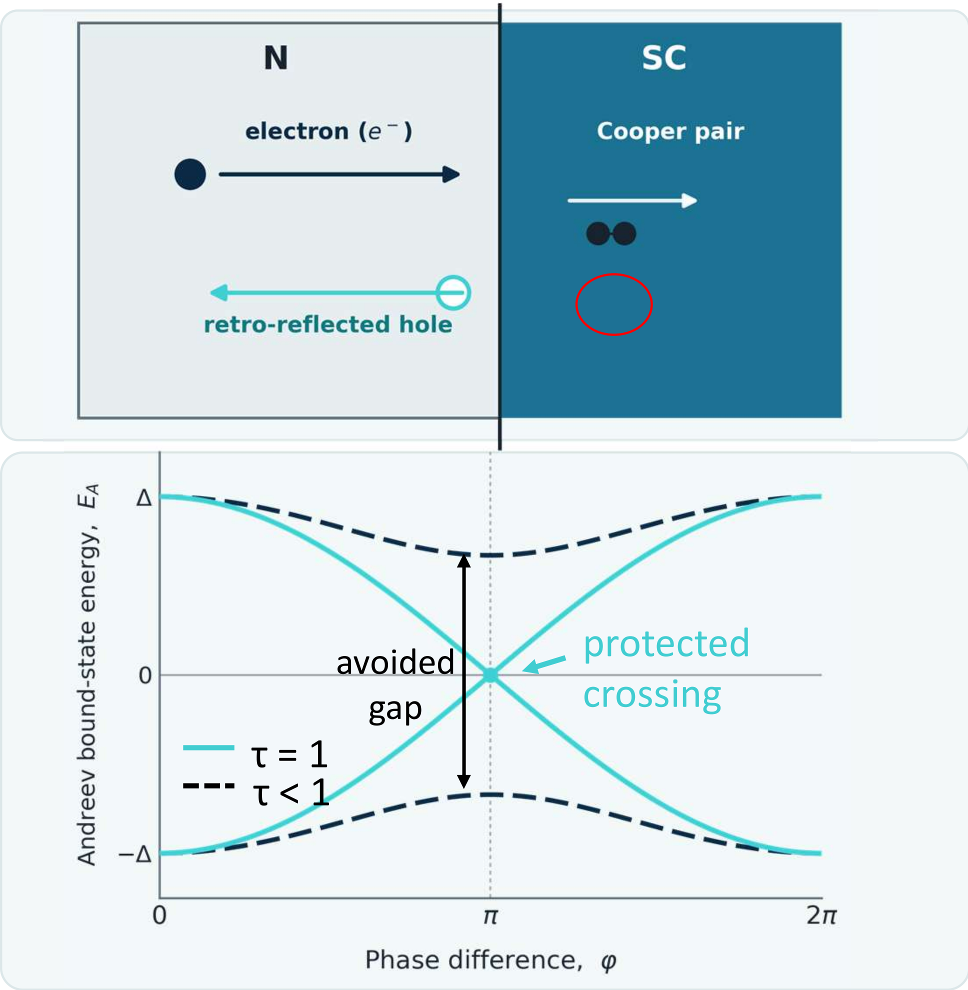
Majorana zero mode (MZM)

Self-conjugate boundary excitation of a topological SC; protected by the bulk gap; non-Abelian exchange statistics → route to fault-tolerant qubits

- **Two experimental fingerprints commonly sought for MZMs:**
  - a zero-bias conductance peak (ZBCP) in tunnelling spectroscopy, ideally quantised at $2e^2/h$
  - a 4π-periodic (rather than 2π) Josephson effect in a topological weak link
- **The catch: YSR states and ABSs can BOTH produce a ZBCP that looks superficially like a MZM — careful, non-local measurements are needed to tell them apart**

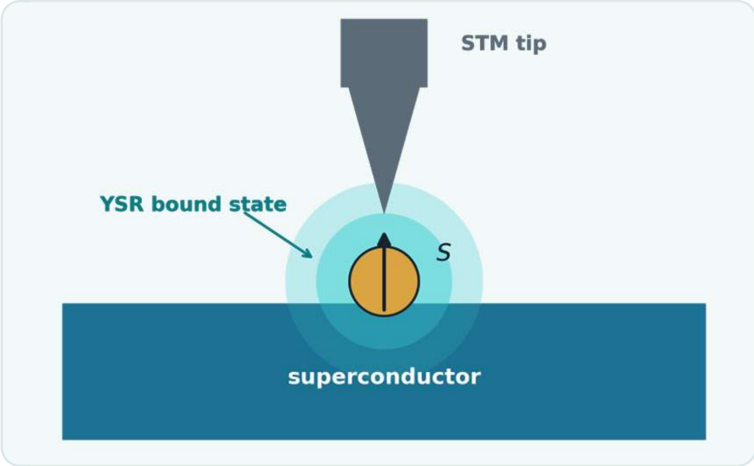
Andreev reflection and Andreev bound states

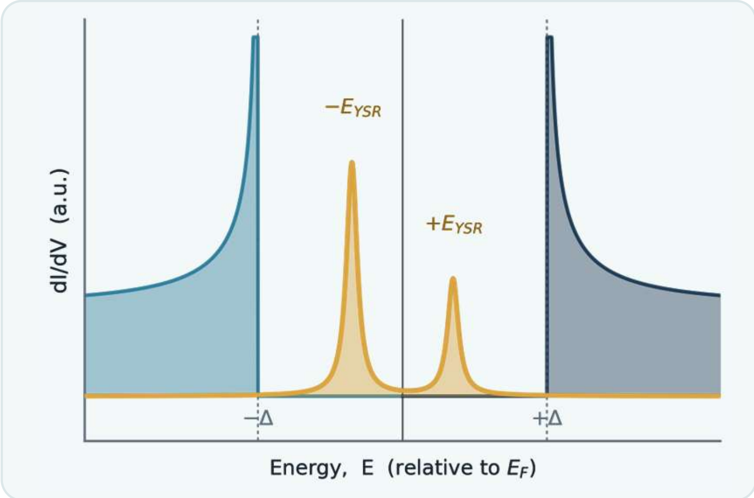
- At a normal-metal/superconductor (N/SC) interface, an electron with energy below the gap ($|E| < \Delta$) cannot enter the SC as a single quasiparticle — there is no state accessible for it there.
- **Instead, the electron is retro-reflected as a hole, retracing the electron's original path, while a Cooper pair is transmitted into the condensate — this is known as an Andreev reflection**
- In a short weak link between two superconductors, multiple Andreev reflections confine discrete, phase-dependent states inside the gap: the Andreev bound states (ABS)
- **For a single, perfectly transmitting channel ($\tau = 1$), the two ABS branches cross zero energy at $\phi = \pi$ — a protected crossing that survives all local perturbations**
- Any backscattering ($\tau < 1$) opens an avoided gap at $\phi = \pi$ — the crossing is only protected in a topological weak link, which is exactly why it matters for Majorana physics



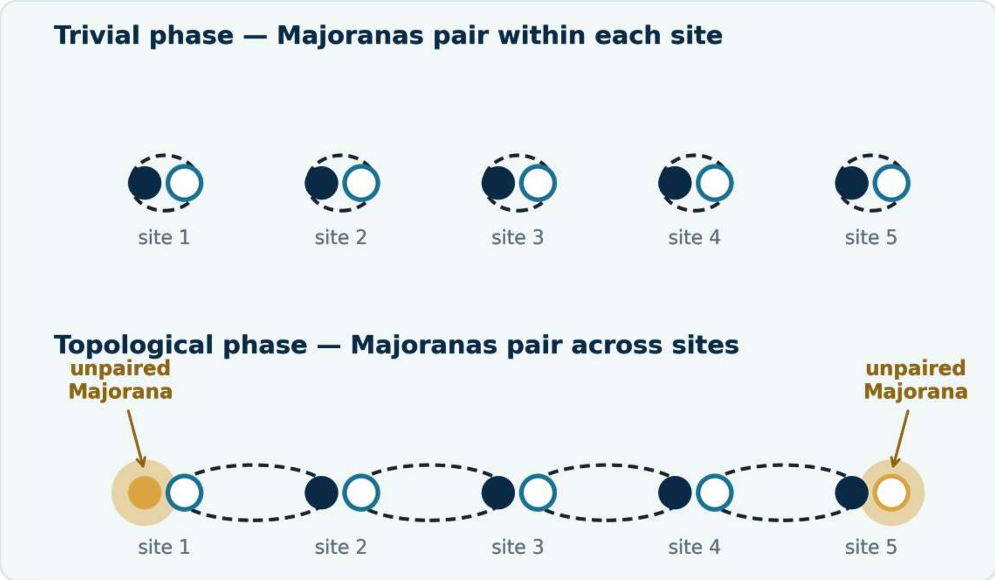
Yu–Shiba–Rusinov states: magnetic impurities

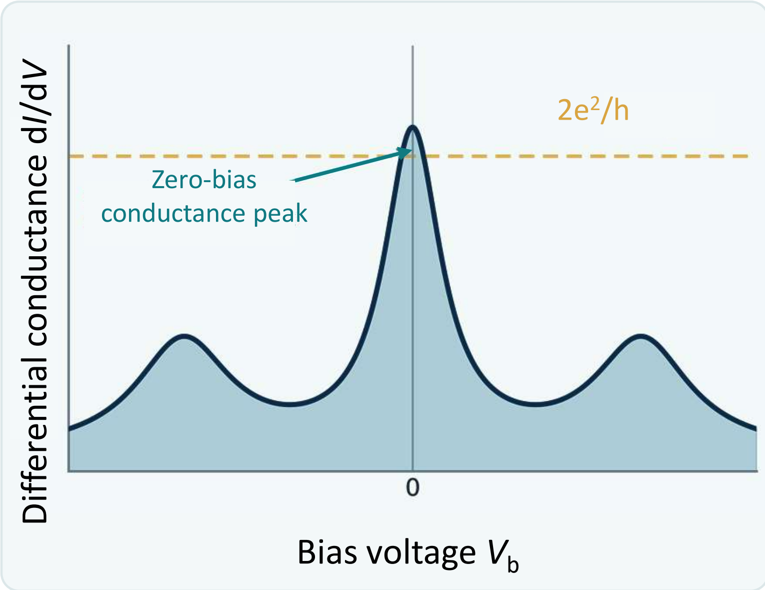
- A magnetic impurity (adatom, molecule) on a superconducting surface locally breaks time-reversal symmetry via exchange coupling to the quasiparticles
- This pulls a pair of spin-polarised bound states in from the gap edge to a sub-gap energy $\pm E_{YSR}$ - **the Yu–Shiba–Rusinov (YSR) state**, predicted independently by Yu, Shiba and Rusinov in the late 1960s
- Tunnelling spectroscopy sees two sharp, particle–hole asymmetric resonances inside the coherence-peak gap, rather than the featureless Δ-gap of a clean surface
- As the exchange coupling increases, E_{YSR} moves toward mid-gap and can cross zero energy.
- **A a YSR state pinned near zero energy therefore produces a zero-bias peak that can look just like a Majorana signature**





Majorana zero modes at a topological edge





- **Every electron operator can be split into two Majorana fermions, γA and γB — each its own antiparticle. In the Kitaev-chain toy model (a 1D p-wave superconductor), these can pair up in two distinct ways**
  - Trivial phase: γ_A and γ_B of the SAME site pair up — an ordinary, fully gapped chain with no special end states
  - Topological phase (hopping and pairing dominating over on-site chemical potential): γ_B of one site pairs with γ_A of the NEXT site — leaving one γ unpaired at each end. The two end Majoranas together form a **single, spatially separated fermionic state** at exactly zero energy: the MZM
- Signature: a zero-bias conductance peak (ZBCP), ideally quantised at $2e^2/h$ — but YSR and ABS physics can mimic this without any topology!

Why vdW materials for topological superconductivity?

Compared to 3D superconducting equivalents

- **Edges of vdW stacks**, where MZMs should arise, can be engineered to be not buried (e.g., via proper arrangements of vdW flakes)

- This aspect should also **facilitate the study and manipulation of topological edge states** in vdW systems under electrical or optical stimuli.

Some vdW materials are also per se candidates for topological superconductivity or are topological insulators that can be proximitized to vdW SCs.

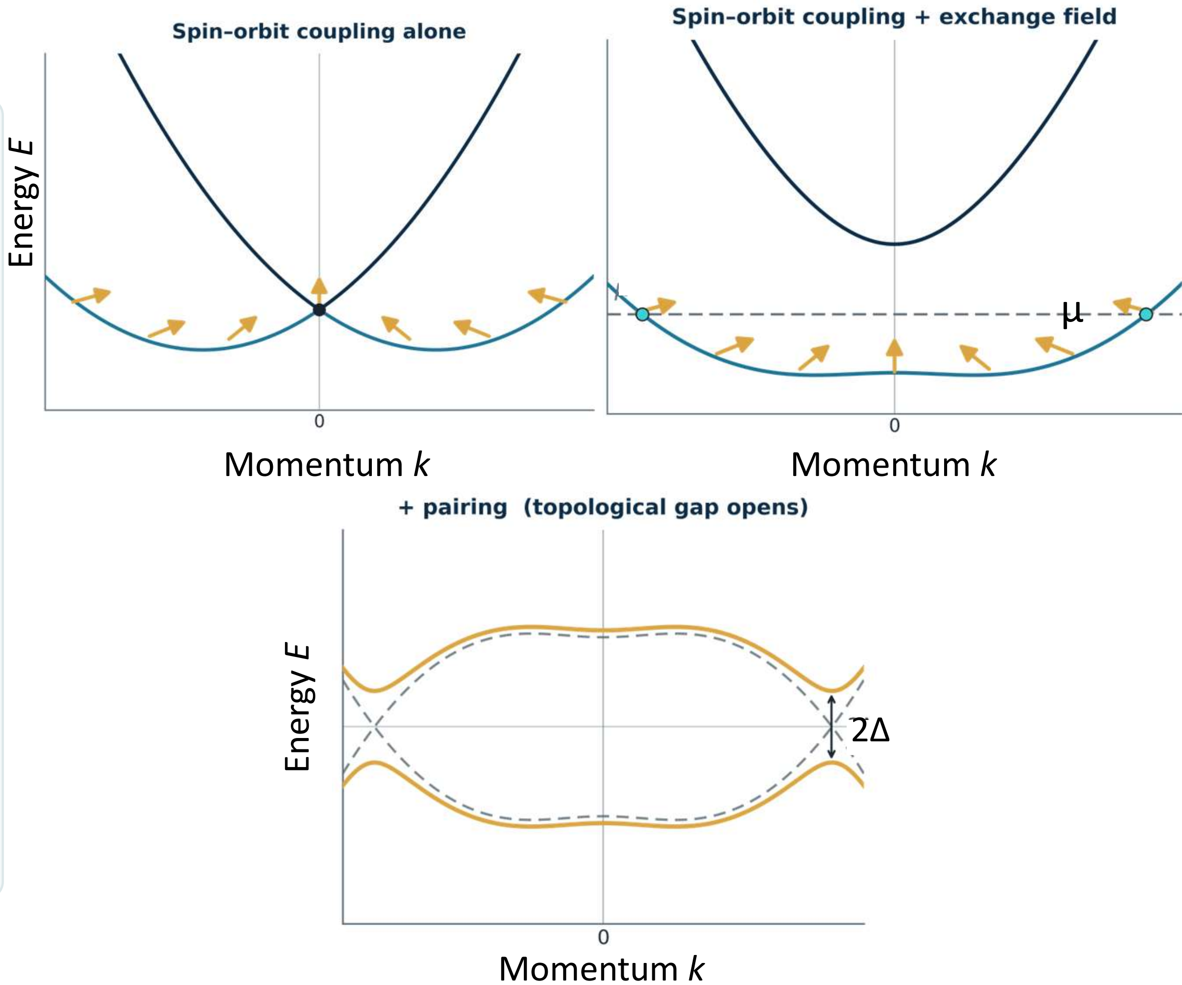
Two routes to topological superconductivity in vdW stacks

Route 1 — Magnetic proximity

- FI/SC or AFI/SC stack, e.g. $CrBr_3/NbSe_2$, $CrI_2/NbSe_2$

  (FI = ferromagnetic insulator;

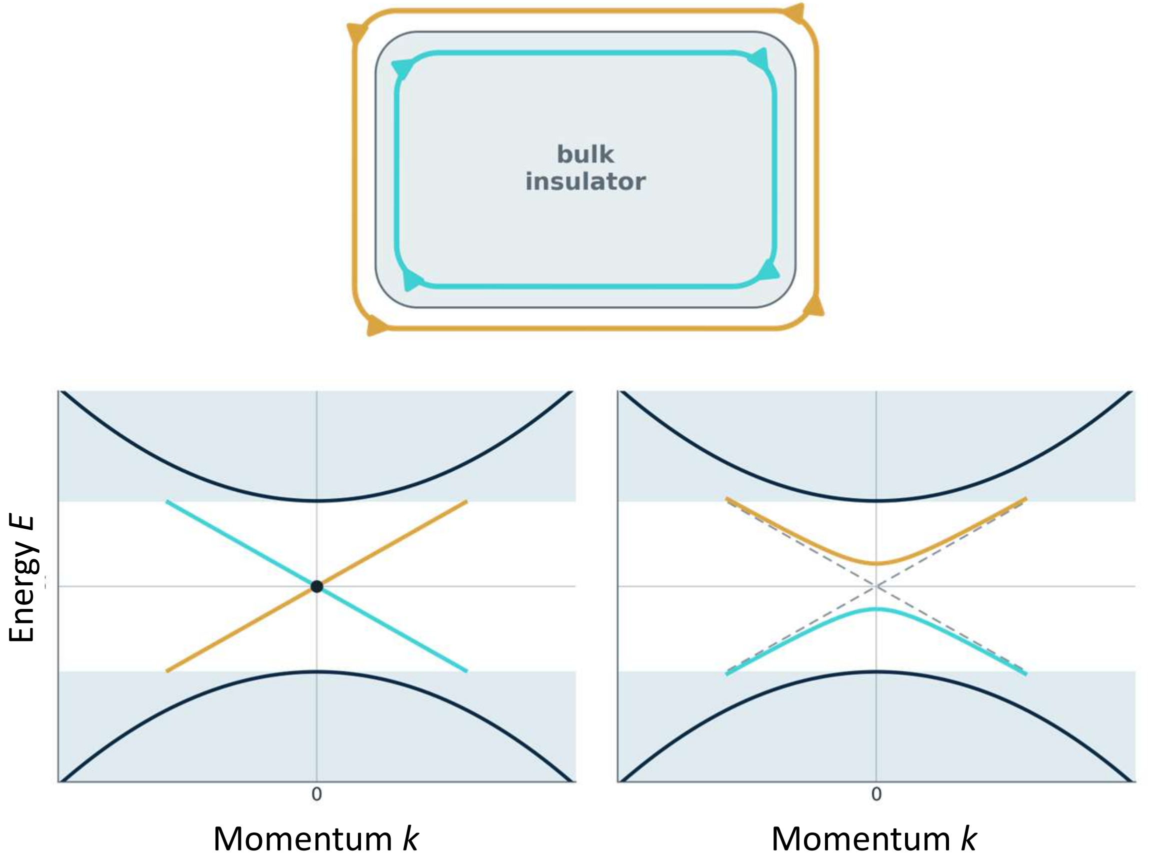
  AFI = antiferromagnetic insulator)
- Needs three ingredients together: s-wave pairing + exchange field h_{ex} (breaks TRS) + spin–orbit coupling
- Topological when h_{ex} exceeds a critical value set by Δ and μ
- **Experimentally contested: same ZBCP signatures reinterpreted as trivial YSR states in several follow-up studies**



Two routes to topological superconductivity in vdW stacks

Route 2 — Band topology

- Induce superconductivity via proximity in an already-topological vdW material, e.g. monolayer 1T′-WTe_2 (quantum spin Hall insulator) on $NbSe_2$
- Spin-momentum-locked helical edge states + s-wave pairing → effective p-wave superconductivity, no h_{ex} or B_{ext} needed
- Symmetry class DIII → helical Majorana Kramers pairs
- **Evidence from low-T STM appears more robust: coexistence with QSH edge state, resilient to B_{ext} and disorder**



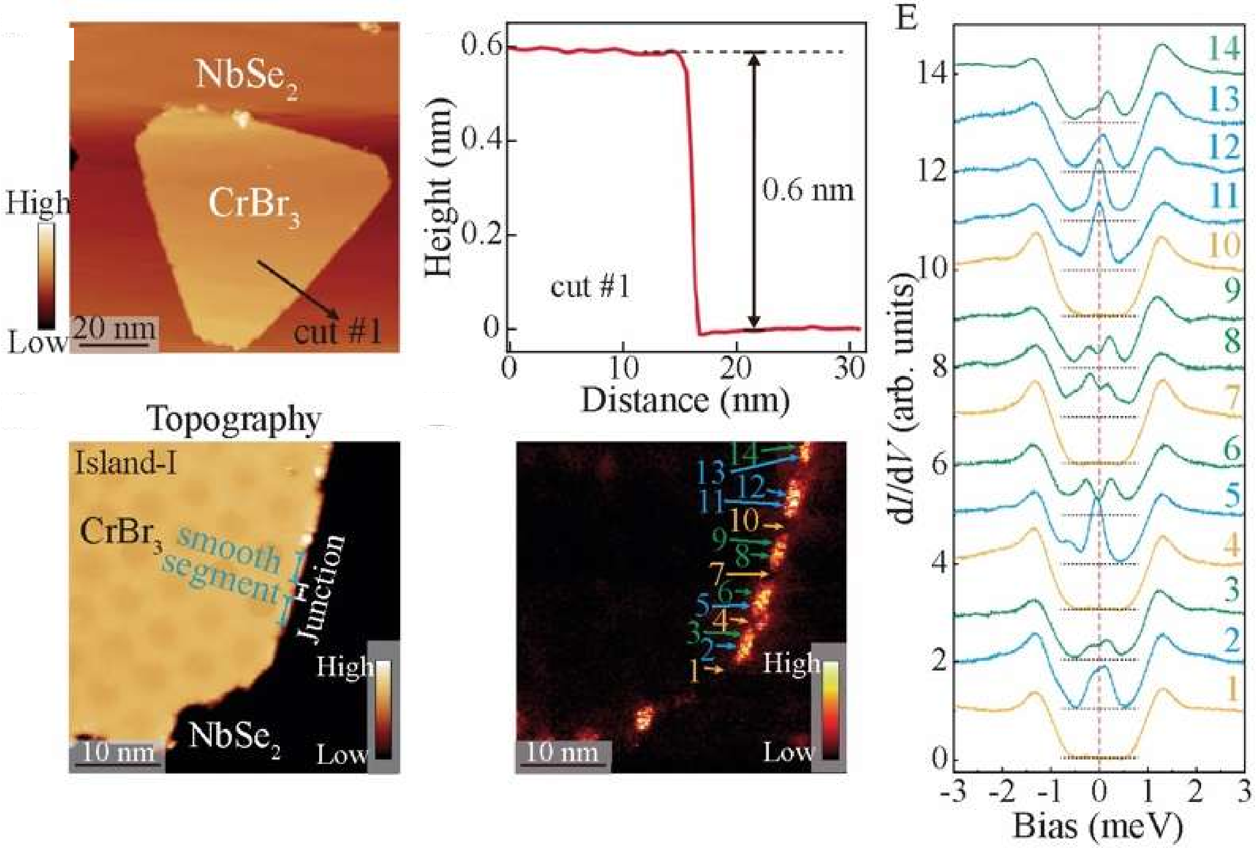
Evidence I: $CrBr_3/NbSe_2$ edge states — MZM or YSR?

- Kezilebieke and co-authors: ZBCPs at $CrBr_3$ island edges on $NbSe_2$ — originally interpreted as chiral MZMs.

Later studies painted a different picture:

- STM on $CrBr_3/NbSe_2$ (right picture) resolved two distinct edge-state types, consistent with YSR states from lattice reconstruction rather than MZMs
- Shot-noise STM and DFT-supported studies on $CrCl_3/NbSe_2$ found no topological signature — just edge-localised YSR states

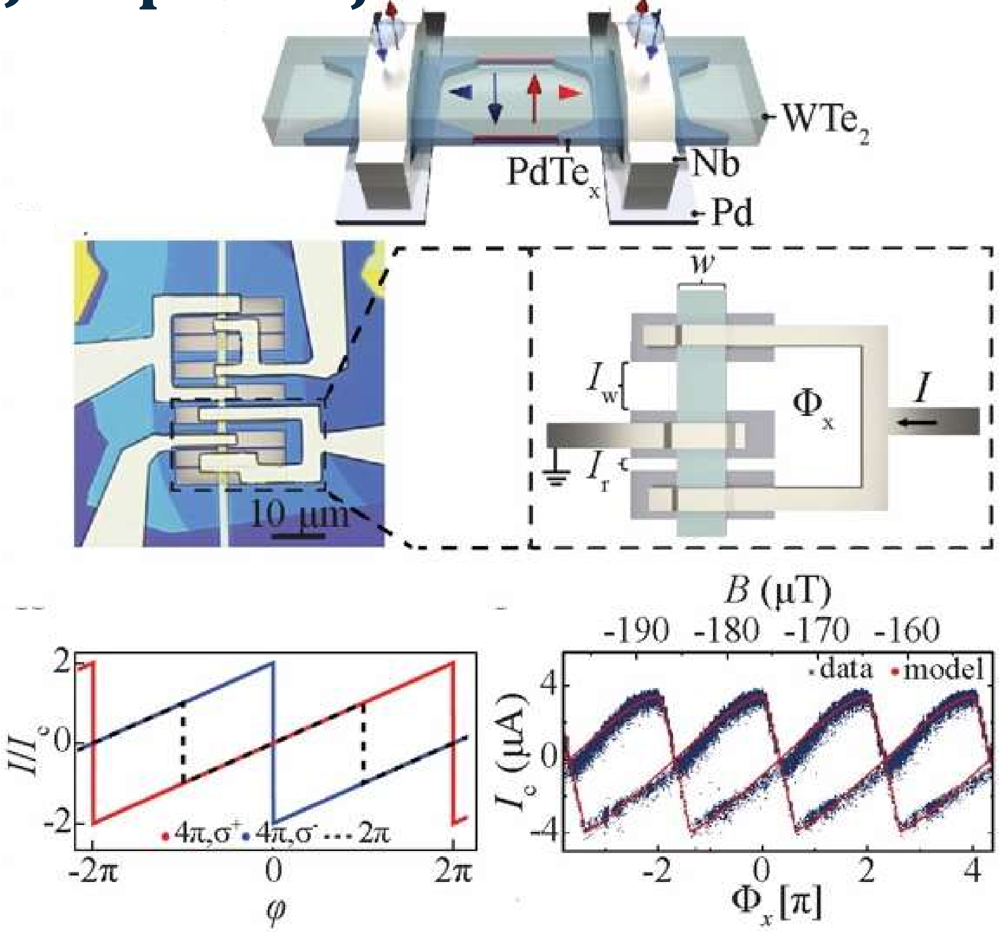
- Possible reconciliation: a moiré superstructure (from lattice mismatch) may stabilise a topological phase only for specific, well-defined growth conditions



Y. Li et al., *Nat. Commun.* **15**, 10121 (2024)

Evidence II: WTe_2 topological Josephson junctions

- WTe_2 weak link between 3D SC electrodes (Pd, Nb): unusual current-phase relation with 4π-periodicity — hallmark of perfect Andreev reflection in a topological weak link
- Caveat: the same CPR can also arise trivially from extra junctions forming where Pd interdiffuses into WTe_2
- Stronger evidence from low-T STM: proximity-induced superconductivity coexists with the quantum-spin-Hall edge state of monolayer 1T′-WTe_2 on $NbSe_2$, with features consistent with 1D topological SC robust to disorder and in-plane B_{ext}
- **Missing experiment: a fully vdW JJ (WTe_2 weak link + vdW SC electrodes) in an asymmetric SQUID geometry — would give phase-sensitive proof of the 4π-periodic contribution**

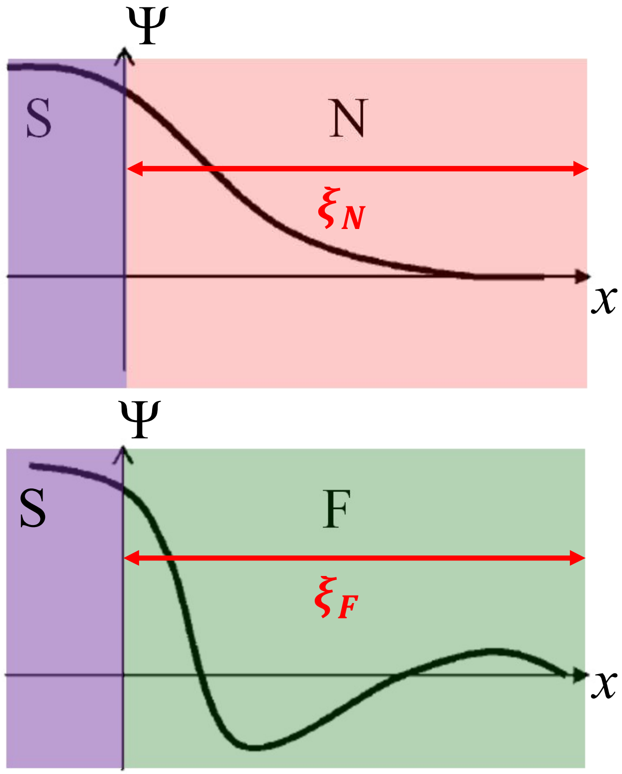


M. Endres et al., *Phys. Rev. Mater.* **6** L081201 (2022)

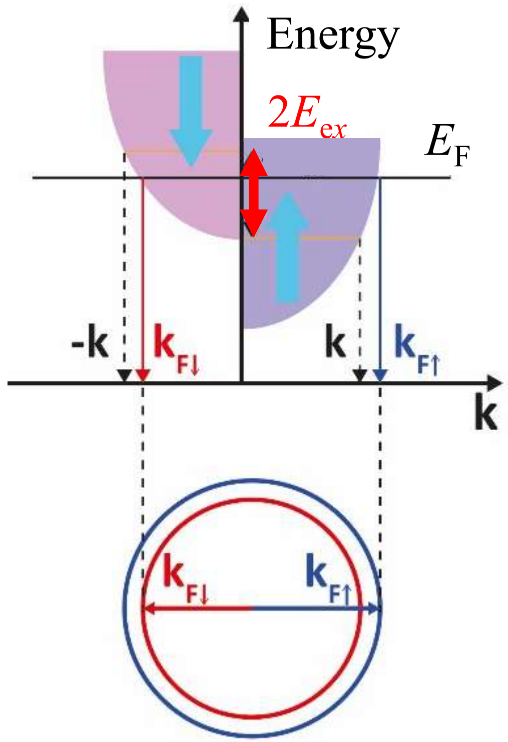
What's still missing?

- **A decisive non-local measurement**
  - correlated end-to-end conductance, or a perturb-one-end / measure-the-other protocol — the only way to unambiguously rule out YSR/ABS look-alikes
  - vdW edges are lithographically accessible, making this realistic in the near term
- **Fully-vdW topological Josephson junctions**
  - replace 3D metal electrodes (Pd, Nb) with vdW superconducting electrodes — removes interdiffusion artefacts
  - New candidate weak links: $NiTe_2$ and $PtTe_2$ (type-II Dirac semimetals, superconducting diode effect via finite-momentum pairing), and 2M-WS_2 as a single-material topological SC

Basics of superconducting proximity effects



A. Buzdin, *Rev. Mod. Phys*. **77**, 935–976 (2005)
Larkin & Ovchinnikov, Sov. Phys. JET*P* **20**, 762 (1965)
Fulde & Ferrell, *Phys. Rev.* **135**, A550 (1964)



Cooper pairs gain non-null momentum ***Q*** at a S/F interface

$\boldsymbol{k}_{\uparrow} \Rightarrow \boldsymbol{k}_{\uparrow} = \boldsymbol{k}_{\mathrm{Ferm}} + \boldsymbol{q}$

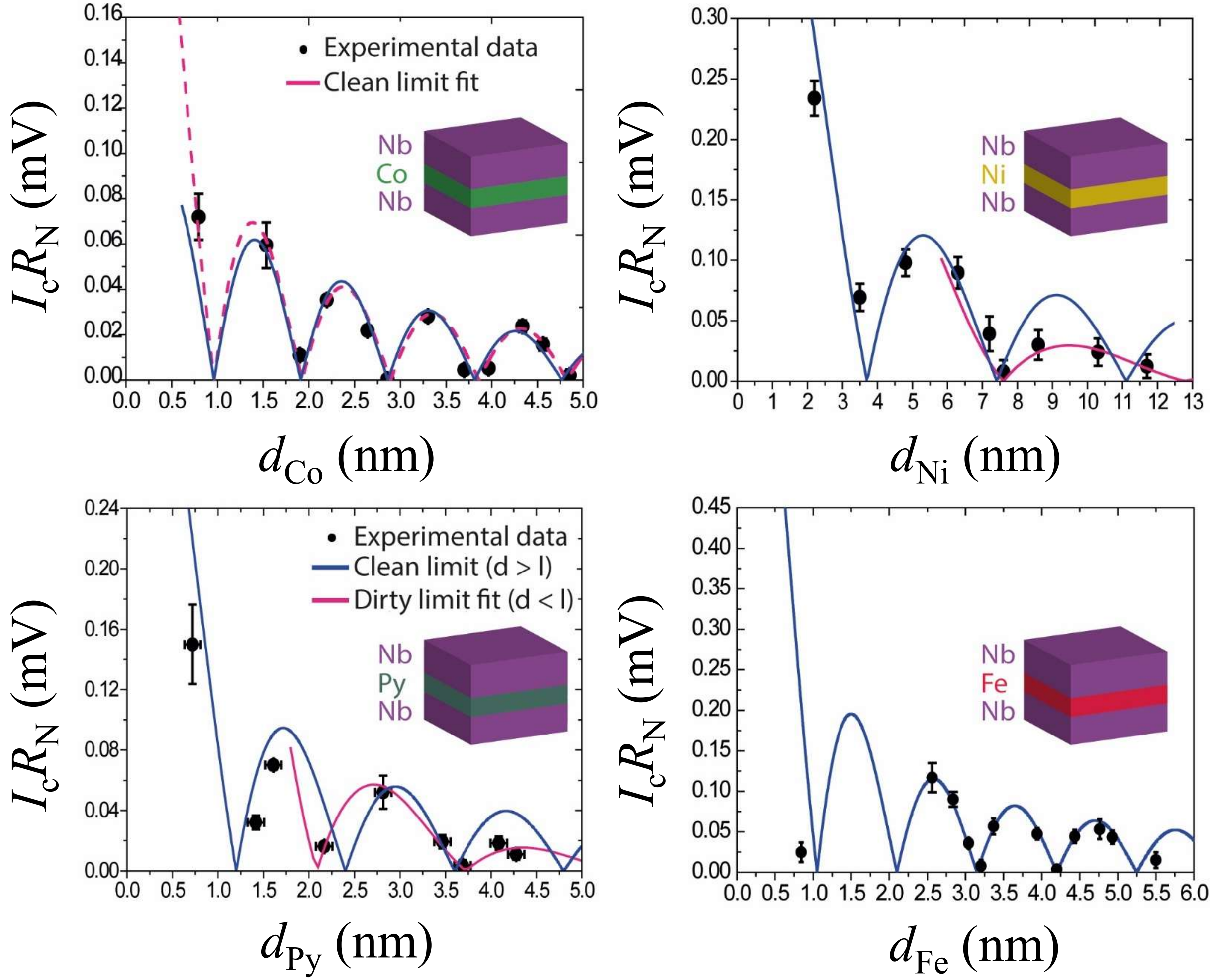
$\boldsymbol{k}_{\downarrow} \Rightarrow \boldsymbol{k}_{\downarrow} = \boldsymbol{k}_{\mathrm{Fermi}} - \boldsymbol{q}$

$$\boldsymbol{Q} = 2\boldsymbol{q} = 2E_{ex}/\boldsymbol{v}_{\mathbf{F}}$$

Decay (coherence) lengths in N and F

$$\xi_N \propto \sqrt{\frac{\hbar D_N}{k_B T}} \qquad \xi_F \propto \sqrt{\frac{D_F}{E_{ex}}}$$

SC/F/SC junctions with a strong F



$$I_c R_N \propto \frac{\left|\sin\left(2E_{ex}d_F/\hbar v_F\right)\right|}{2E_{ex}d_F/\hbar v_F}$$

J. W. A. Robinson et al., *Phys. Rev. Lett.* **97**, 177003 (2006)

J. W. A. Robinson et al., *Phys. Rev. B* **76**, 094552 (2007)

Long-ranged spin-triplet generation

$$|\psi\rangle = \sqrt{\frac{1}{2}}\left(|\uparrow\rangle_{\boldsymbol{k}}|\downarrow\rangle_{-\boldsymbol{k}} - |\downarrow\rangle_{\boldsymbol{k}}|\uparrow\rangle_{-\boldsymbol{k}}\right)$$

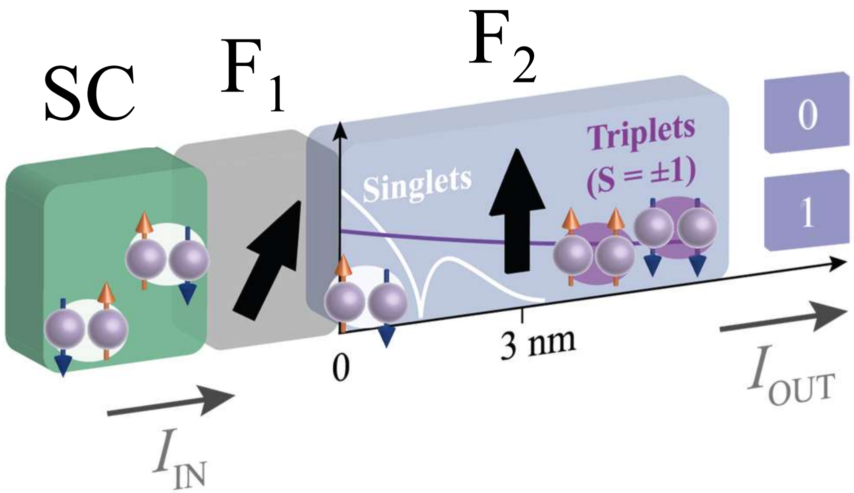
Spin-singlets

At a SC/F interface

Spin-singlets

$$|\psi\rangle = \sqrt{\frac{1}{2}}\left(\left(|\uparrow\rangle_{\boldsymbol{k}}|\downarrow\rangle_{-\boldsymbol{k}} - |\downarrow\rangle_{\boldsymbol{k}}|\uparrow\rangle_{-\boldsymbol{k}}\right)\cos(\Delta\theta) + i\left(|\uparrow\rangle_{\boldsymbol{k}}|\downarrow\rangle_{-\boldsymbol{k}} + |\downarrow\rangle_{\boldsymbol{k}}|\uparrow\rangle_{-\boldsymbol{k}}\right)\sin(\Delta\theta)\right)$$

Spin-triplets (S = 0)



F. S. Bergeret et al., *Phys. Rev. Lett*. **86**, 4096 (2001)
M. Eschrig, *Phys. Today* **64**, 43 (2011)
A. I. Buzdin, *Rev. Mod. Phys.* **77**, 935 (2005)

$S = \pm 1$ triplets

- Long-ranged inside F_2
- Carry a net spin
- Can be used for spintronics with low dissipation

Superspintronics: spin transport without dissipation

- Combine a SC with a F → generate Cooper pairs with parallel-aligned spins (spin-triplet pairs)
- Spin-triplet pairs are NOT killed by the h_{ex} of F → can propagate over long distances inside it
- This enables "spintronics in the superconducting state" — spin transport and logic with (almost) no energy dissipation.

Why vdW materials can help here:

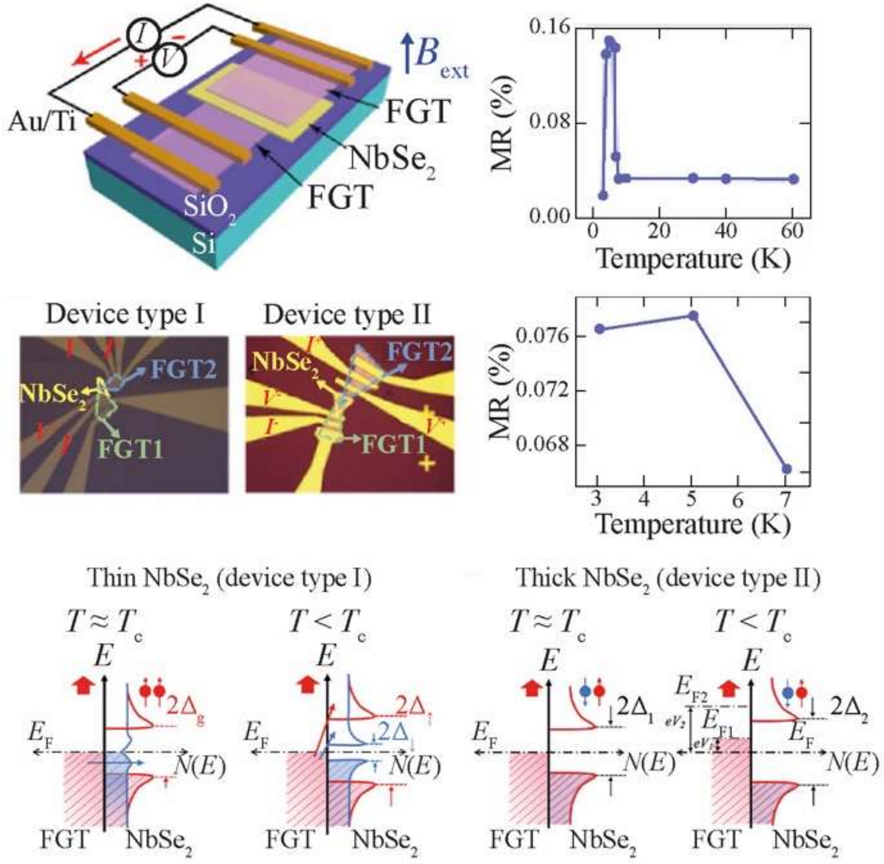
– atomically sharp SC/F interfaces without high-temperature growth

– large combinations of materials possible (more functionalities) whilst preserving crystallinity

– small magnetic volume in a few-layer F flake → easier to demonstrate spin-transfer torque switching by a supercurrent

F/SC/F vdW superconducting spin valve

- FGT/$NbSe_2$/FGT vdW pseudo-spin valve: proximity effect from FGT spin-splits the density of states in thin $NbSe_2$ into $\Delta_{\uparrow}$ and $\Delta_{\downarrow}$
- Result: a 17-fold magnetoresistance enhancement below a $NbSe_2$ thickness of ∼ 25 nm ("type I" regime), set by the relative alignment of the two FGT layers' magnetizations
- Thicker $NbSe_2$ ("type II"): proximity effect too weak to split the gap — MR becomes voltage-governed instead of T-governed.



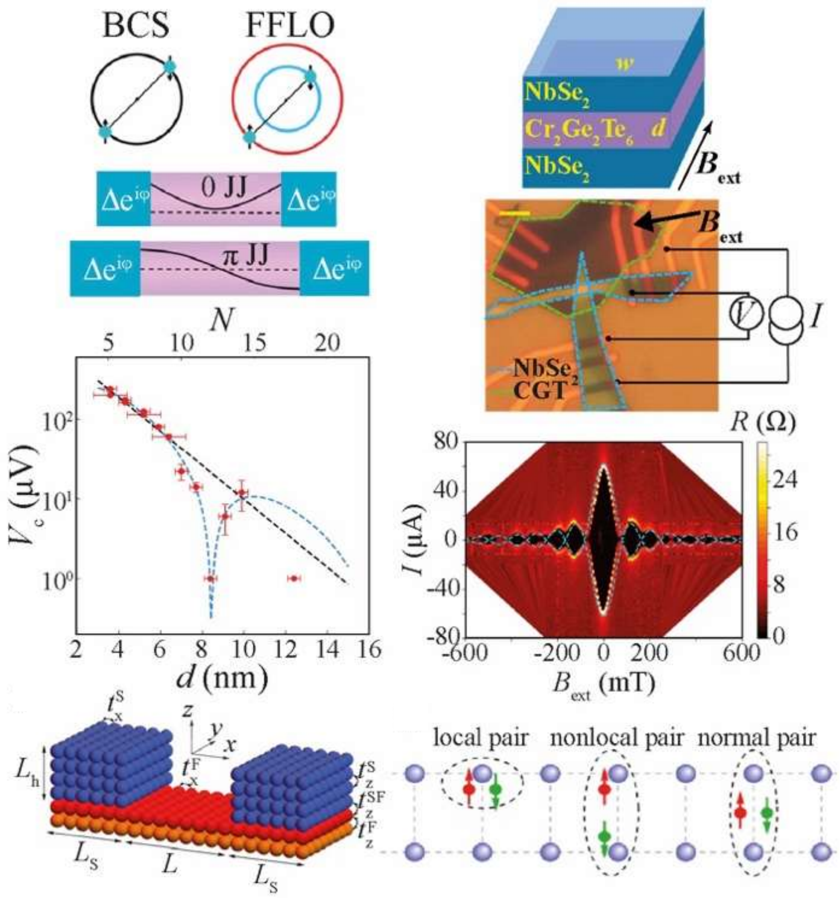
X Zeng et al., *ACS Appl. Mater. Interfaces* **15** 57397–57405 (2023)

Domain-engineered supercurrents: 0-to-π junctions

- **$NbSe_2$/CGT/$NbSe_2$ JJs: as the CGT (ferromagnetic insulator)** thickness d_F is tuned, I_c passes through TWO zeros — signature of an **FFLO-like sign change of the order parameter** (0-to-π transition) inside the weak link.

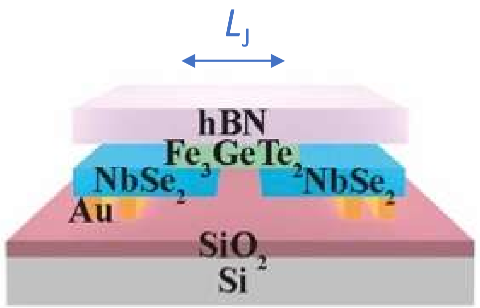
- SQUIDs embedding $NbSe_2$/CGT/$NbSe_2$ junctions show an arbitrary phase shift (~149°) rather than a clean 0 or π state — attributed to coexisting 0- and π-phase regions set by the $Cr_2Ge_2Te_6$ (CGT) domain configuration (additional knob).

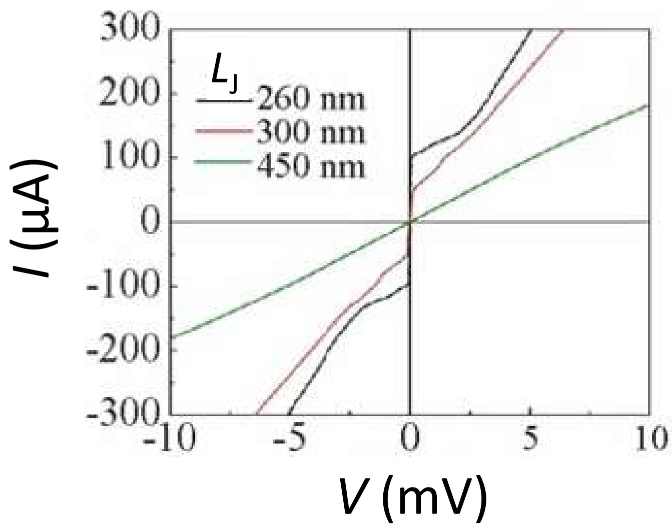
- Predicted the formation of local Cooper pairs or split pairs in a SC/F vdW system (F being a vdW bilayer). This can lead to Josephson junctions with gate voltage- (V_G-) tuneable 0-to-π switching.



Long-ranged spin-triplet supercurrents

- Lateral $NbSe_2$/FGT/$NbSe_2$ junctions: measurable Josephson **coupling up to ~300 nm separation** — far beyond the ~3.5 nm spin-singlet coherence length in FGT
- Candidate origin: non-coplanar (frustrated triangular-lattice) spin texture in FGT, which can generate odd-frequency spin-triplet pairs
- Alternative explanation: 2D interface superconductivity at the $NbSe_2$/FGT interface — still an open question





G. Hu et al., *Nat. Commun.* **14** 1779 (2023)

Long-ranged spin-triplet supercurrents

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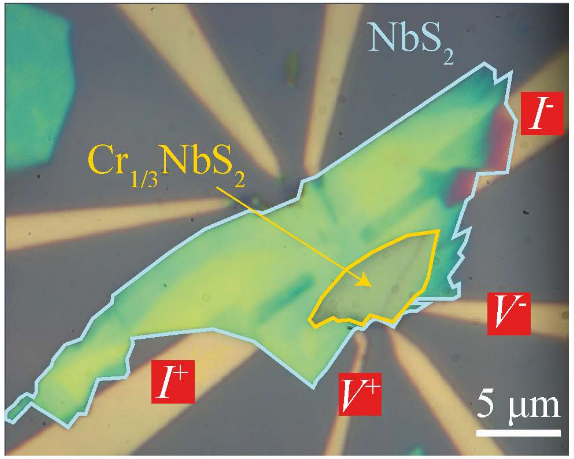
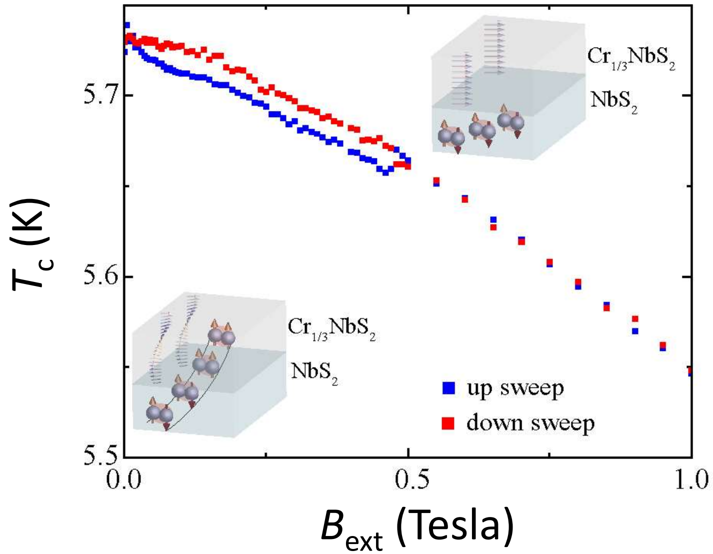
- Alternative explanation: 2D interface superconductivity at the $NbSe_2$/FGT interface — still an open question
- Independent evidence: $Cr_{1/3}NbS_2$/NbS_2 stacks — T_c rises when the helimagnet is turned by B_{ext} into a homogeneous (ferromagnetic) state, consistent with suppression of triplet generation and less pair-breaking

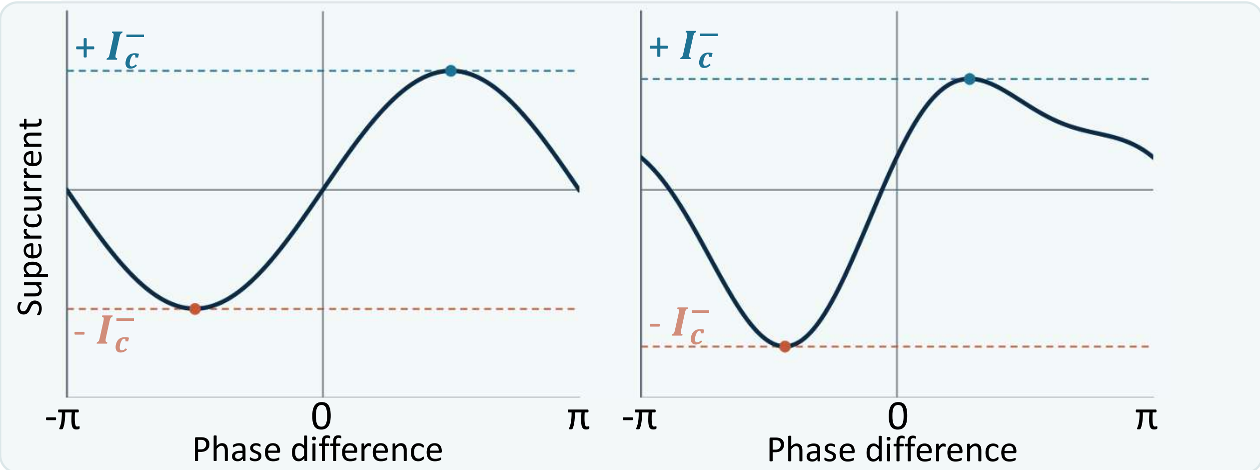


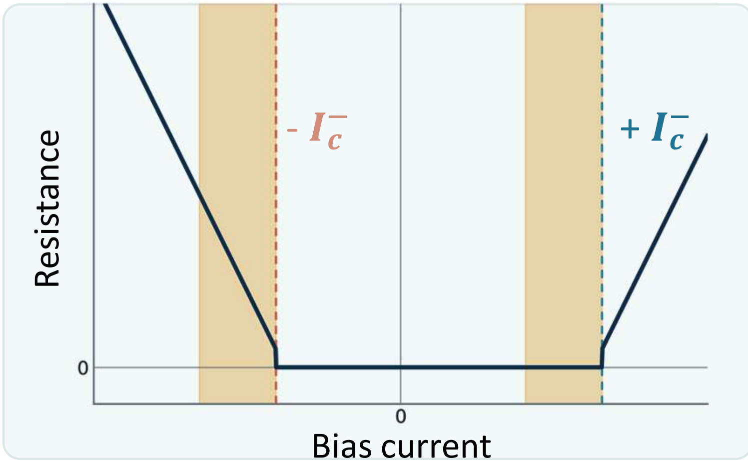


A. Spuri et al., *Phys. Rev. Res.* **6** L012046 (2024)

The superconducting diode effect (SDE)

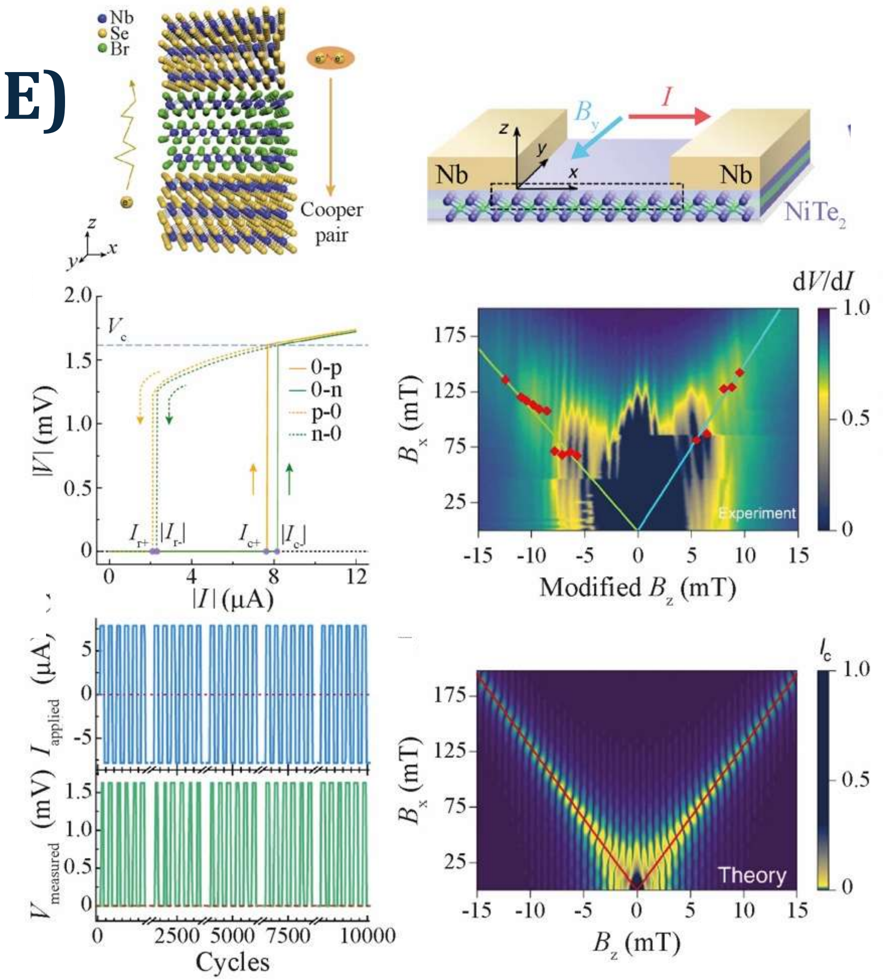
- **SDE: the critical current is asymmetric, $I_c^+ \neq |I_c^-|$ supercurrent flows more easily in one direction than the other**
- Extra harmonics appear in the CPR whenever both inversion symmetry AND time-reversal symmetry are broken together, shifting the positive and negative maxima of $I(\phi)$ to unequal heights
- **This is NOT like an ordinary semiconductor diode: below its own threshold, current in EITHER direction is still fully dissipationless — the asymmetry is only in where each direction's threshold sits**
- The measurable signature: bias with a current whose magnitude sits between $|I_c^-|$ and I_c^+ — one polarity stays superconducting (R = 0), the other is already resistive (R > 0).
- **Figure of merit - diode efficiency: η = (I_c^+ − |I_c^-|) / (I_c^+ + |I_c^-|)**





The superconducting diode effect (SDE)

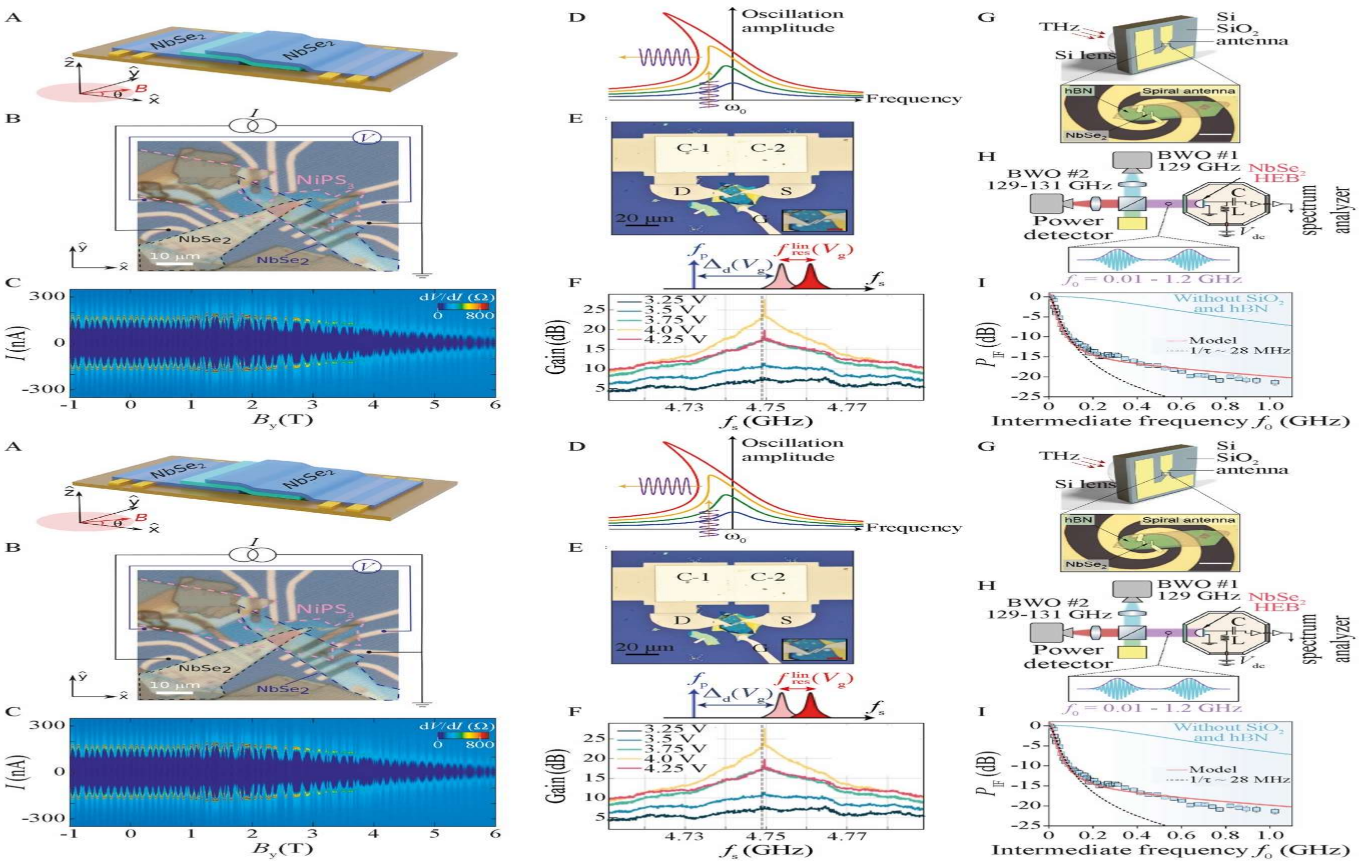
- **vdW platforms give several routes to a B_{ext}-free SDE:**
  - NbSe$_2$/Nb$_3$Br$_8$/NbSe$_2$ vertical JJ — obstructed-atomic-insulator weak link with an intrinsic non-magnetic singlet ground state
  - Nb/NiTe$_2$ lateral JJ — finite-momentum Cooper pairing in a topological semimetal weak link sets the SDE polarity
- **Why it matters: rectifiers, non-reciprocal logic elements and read-out circuits with no dissipation and no external B_{ext} needed**
- In principle, possibility of combining SDE with V_G control (thanks to gate tunability of vdW materials). Useful for logics?



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

B. Pal et al., *Nat. Phys.* **18**, 1228-1233 (2022)

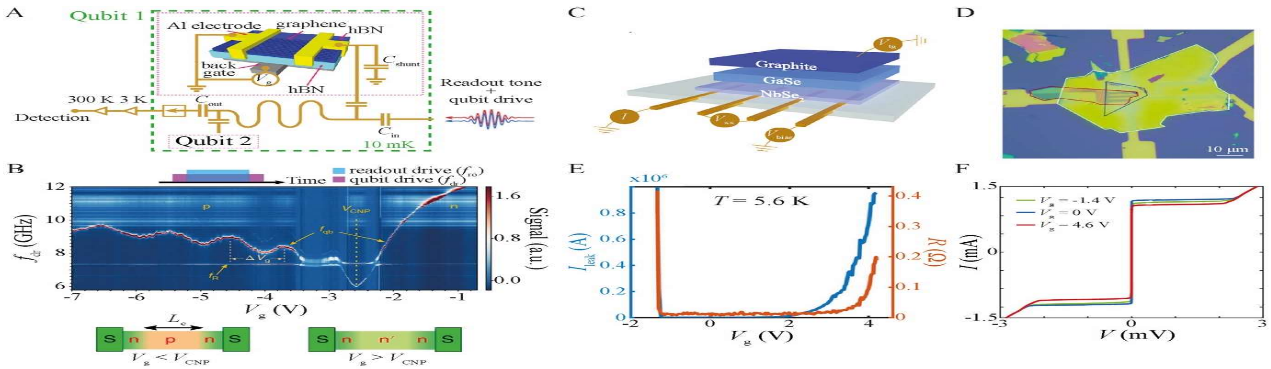
SQUIDs, parametric amplifiers and bolometers

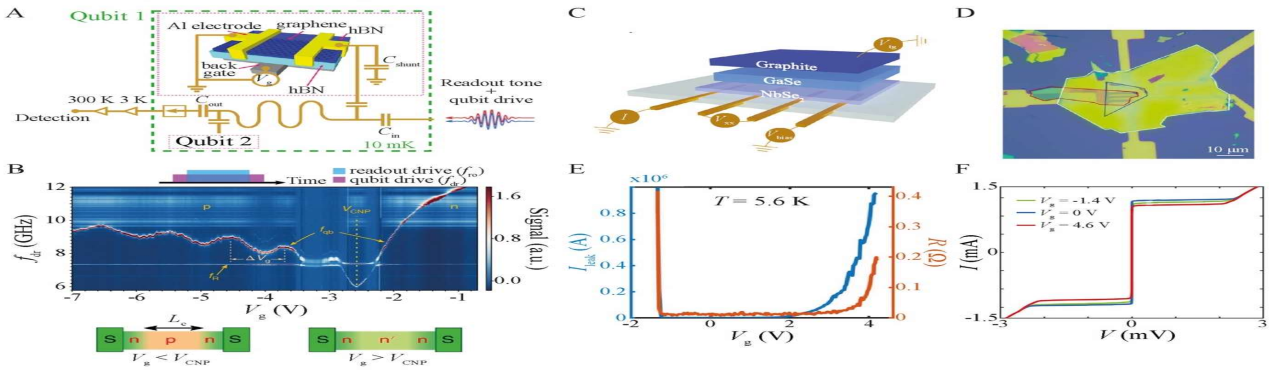


- $NbSe_2$/$NiPS_3$-based vdW SQUID: antiferromagnetic weak link gives interference patterns **with no need for a geometric loop area** — compact, planar SQUIDs
- Graphene-based Duffing-oscillator Josephson parametric amplifier: gate-tunable resonance frequency via a graphene JJ — low-noise amplification for qubit readout
- $NbSe_2$ antenna-coupled bolometer: hot-electron thermal response used for sub-mm/THz radiation detection with high sensitivity and fast thermal recovery

C González-Sánchez, *Adv. Mater.* e202521250 (2026) J Sarkar et al., *Nat. Nanotechn*. **17**, 1147-1152 (2022) K Shein et al., *Nano Lett.* **24** 2282–2288 (2024)

Gate-tunable vdW devices





I-J Wang et al., *Nat. Nanotechnol.* **14** 120–125 (2019) Y Ding et al., *ACS Nano* **19**, 1295-1301 (2025)

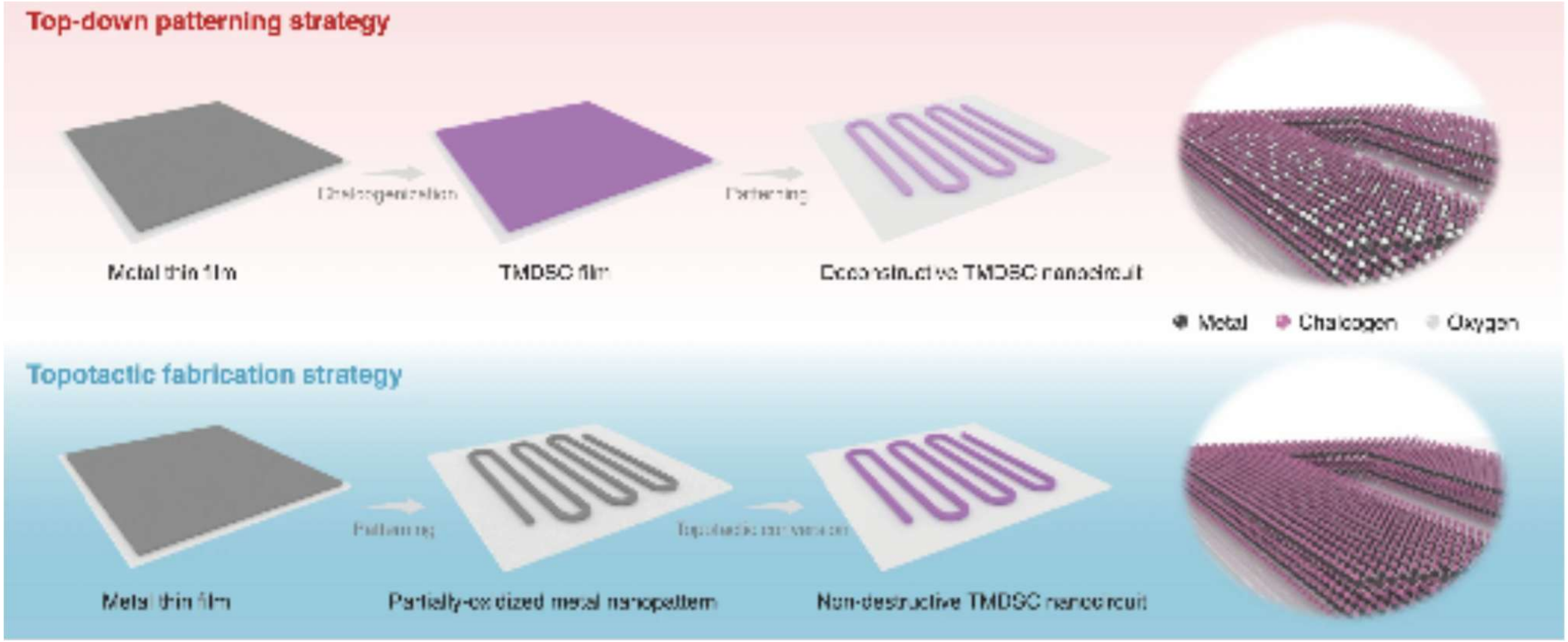
Electric-field gating of vdW SCs can suppress the critical current, shift the qubit spectrum, or even switch superconductivity on/off in ionic-liquid-gated MoS_2 or WS_2

(more discussed in tomorrow's lecture)

vdW building blocks inside superconducting quantum circuits

- **Graphene-based gatemon qubits: Al/graphene/Al JJs embedded in cQED architectures — qubit frequency tuned electrostatically instead of by flux**
- Twisted-bilayer-graphene and twisted-cuprate JJs proposed as qubits exploiting intrinsically unconventional pairing
- hBN as the vdW “workhorse” dielectric: ultra-low-loss tunnel barriers and encapsulation for qubit coherence
- Miniaturised transmons using vdW capacitor dielectrics — smaller footprint than bulk-oxide capacitors
- **Common challenge across all these: interfacing delicate vdW elements with standard superconducting circuit fabrication (wiring, packaging, cryogenic reliability) without degrading coherence**

vdW building blocks inside superconducting quantum circuits



V E Manucharyan, Science **326** 113–116 (2009)

LOOKING AHEAD

Future directions

1

Materials & growth

- Wafer-scale, reproducible growth (CVD/MBE/topotactic routes)
- Cleaner interfaces: cryogenic dry-transfer to reduce PDMS/polymer residues
- New candidates: $NiTe_2$, $PtTe_2$, 2M-WS_2 for topological SC

2

Physics questions

- Decisive non-local proof of Majorana modes
- Origin of long-range triplet supercurrents in FGT
- Gate-tuneable FFLO states → purely electrical 0-to-π switching

3

Devices & circuits

- Fully-vdW topological JJs in asymmetric SQUIDs
- Field-free diodes and non-volatile vdW memories
- Deeper integration into scalable quantum circuits

Take-home messages

- Dimensionality + broken symmetries + strong SOC give vdW superconductors properties (huge $B_{c2\parallel}$, gate tunability, accessible edges) that 3D thin films don't easily offer
- The SAME material toolbox ($NbSe_2$, WTe_2, FGT, CGT, hBN, …) recombines into very different devices: topological JJs, spin valves, diodes, SQUIDs, qubits
- Several "textbook" 3D superconducting-electronics concepts (0-to-π junctions, proximity effect, Josephson coupling) get a genuinely new twist in the 2D limit — not just a smaller version of the same physics
- Interpretation matters as much as data: the $CrBr_3/NbSe_2$ story is a reminder that a single spectroscopic signature (ZBCP) rarely settles a topological claim
- The main bottleneck to real applications is not physics but materials engineering — wafer-scale growth and clean, reproducible interfaces

Thank you

Questions & discussion welcome

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adibernardo@unisa.it

Further reading

A. Di Bernardo, E. Scheer, “Van der Waals superconducting electronics: materials, devices and circuit integration”, https://arxiv.org/abs/2601.07018