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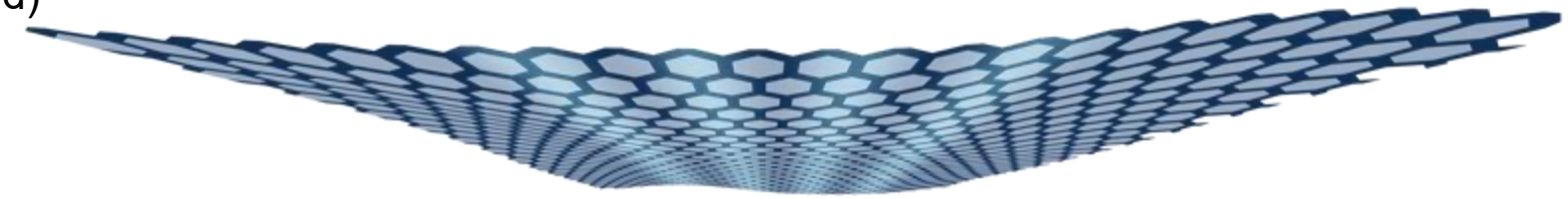
SW Quantum Matter for Quantum Technologies
Ingelheim am Rhein 2024



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Ensslin Group

ETH zürich

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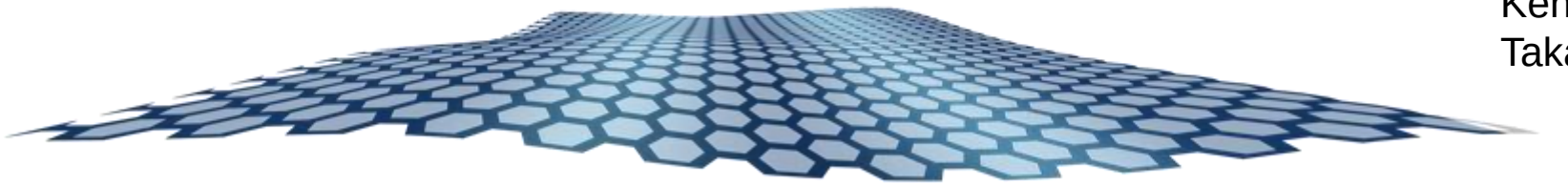

Bilayer Graphene – a Tunable 2D Semiconductor For Novel Types of Qubits

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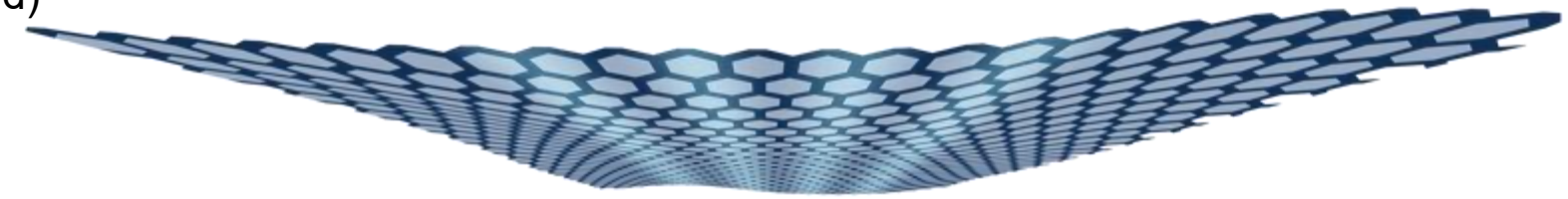

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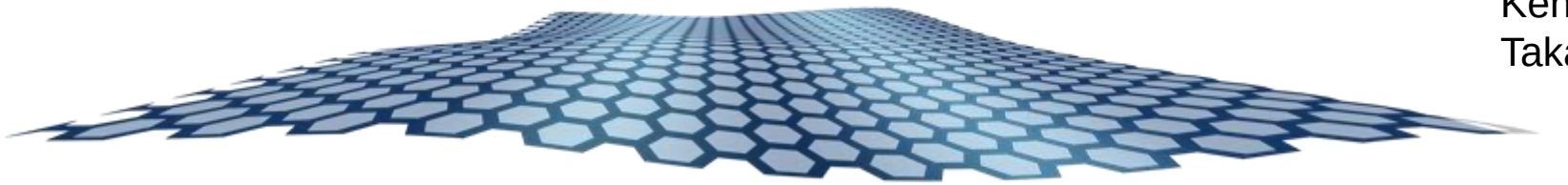

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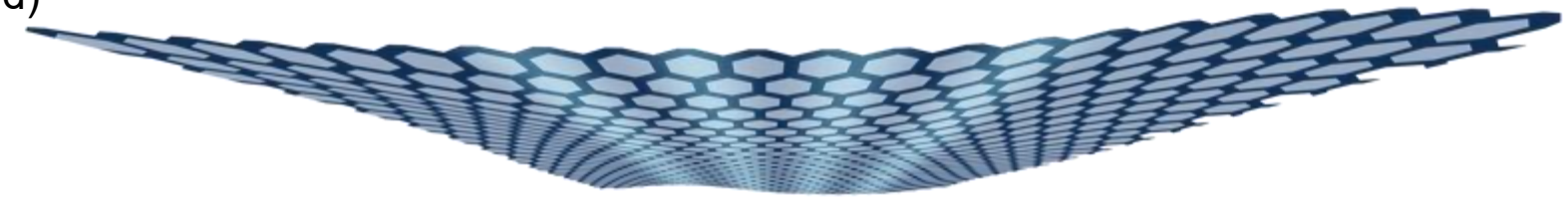

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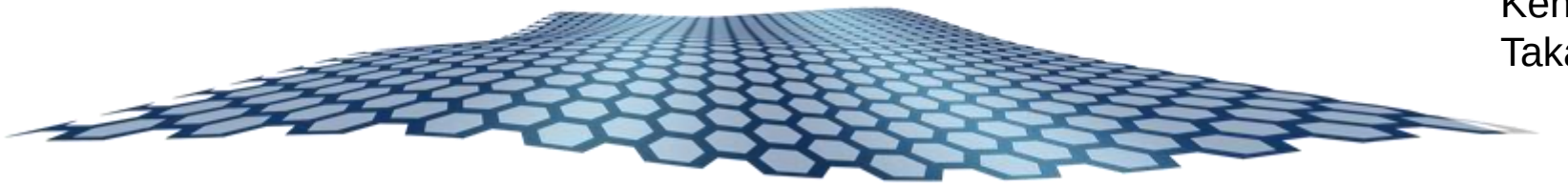
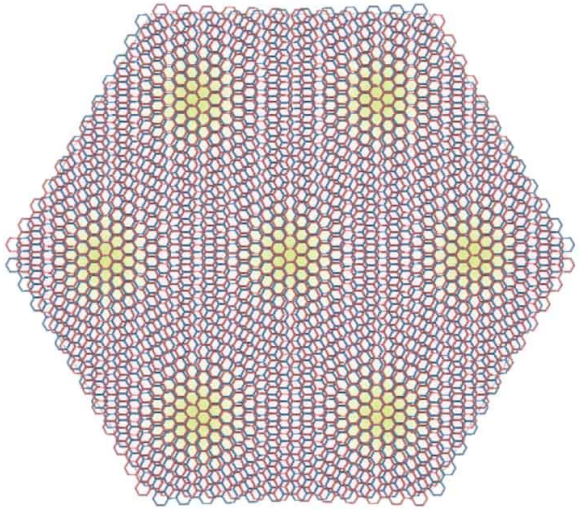


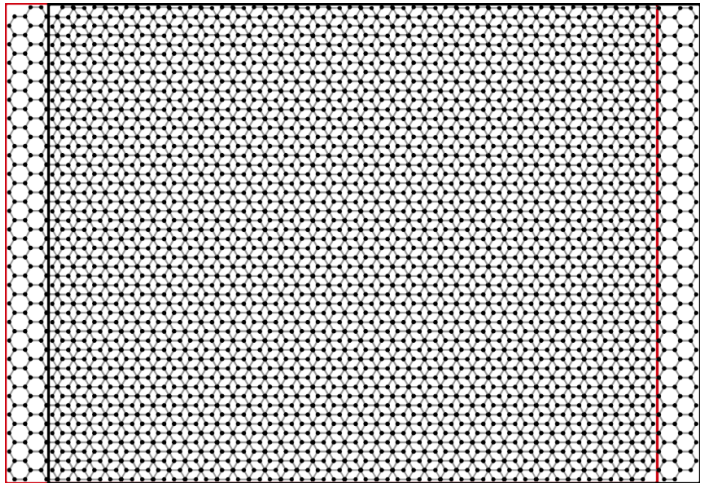
Bilayer Graphene – a Tunable 2D Semiconductor For Novel Types of Qubits

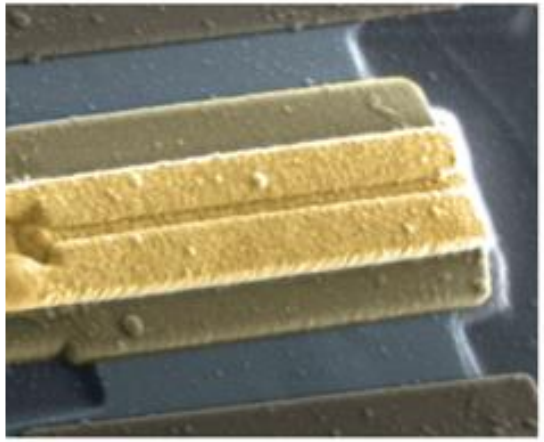
Quantum Graphene Devices in The Ensslin Nanophysics Group

Twisted graphene

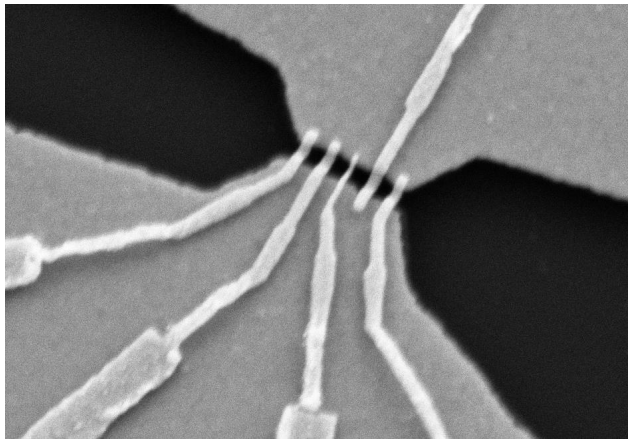


Bernal graphene





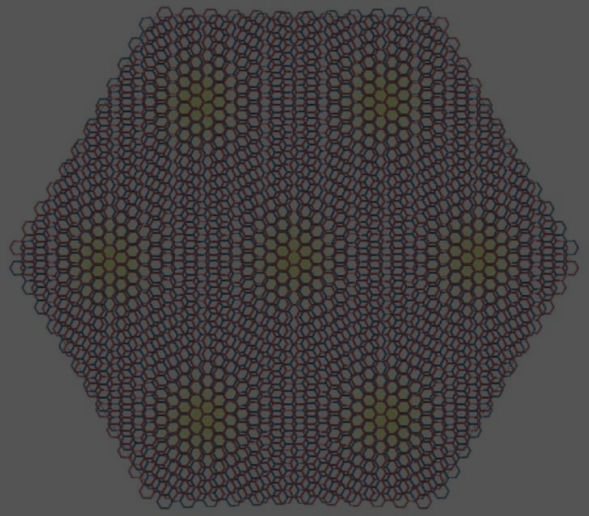
Josephson Junctions
SQUIDs
Rings
Cooper-Pair Box..
Gatemons...

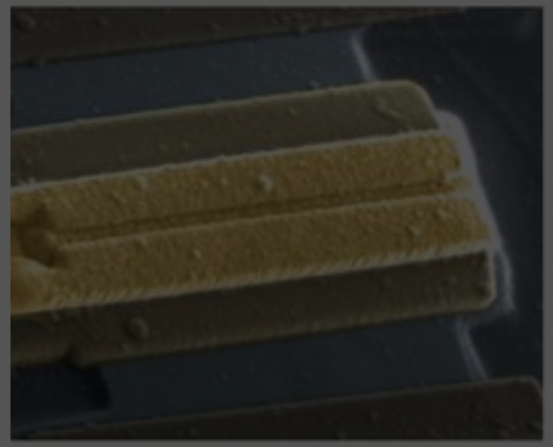


QPCs
Quantum dots

Quantum Graphene Devices in The Ensslin Nanophysics Group

Twisted graphene





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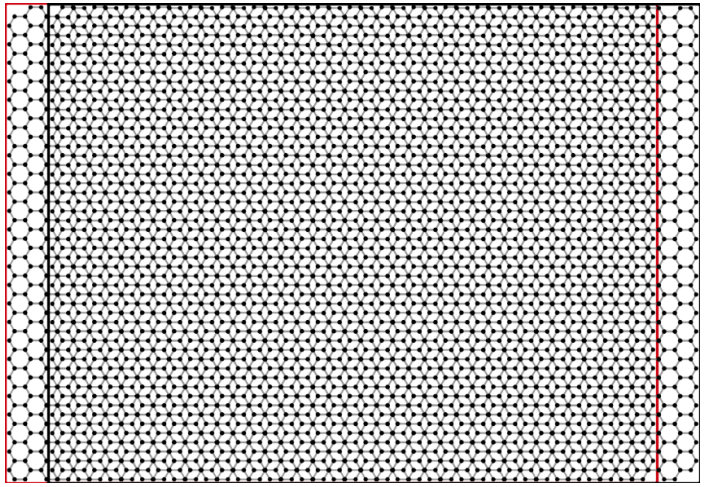
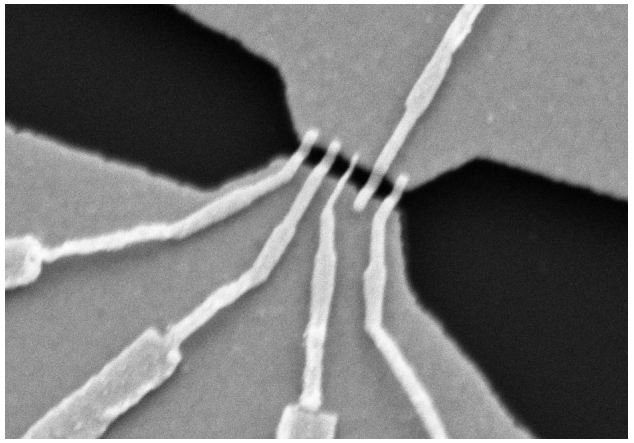
Bernal graphene

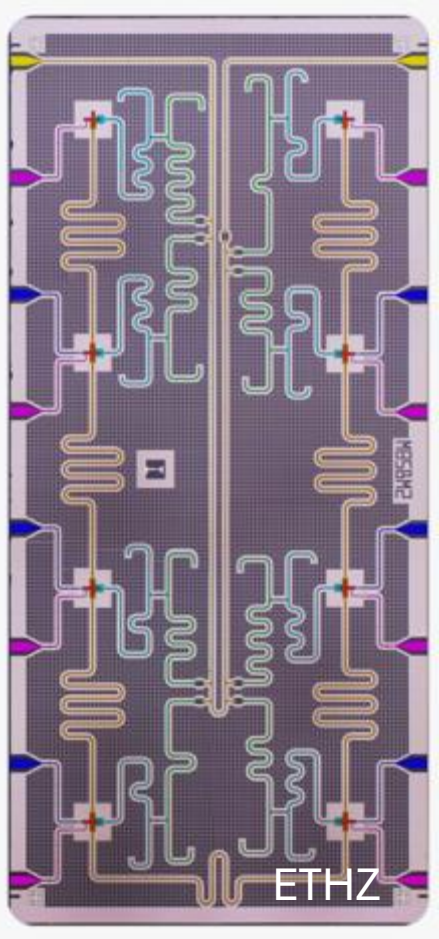




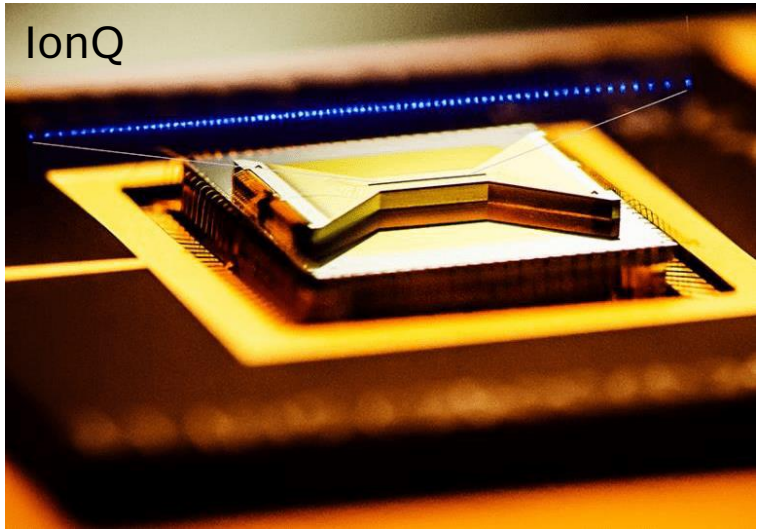
QPCs
Quantum dots

Who Has The Best Qubit?

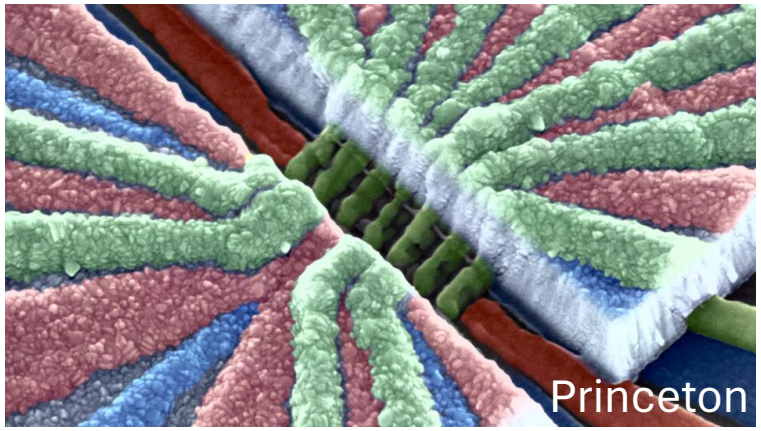
Superconducting circuits



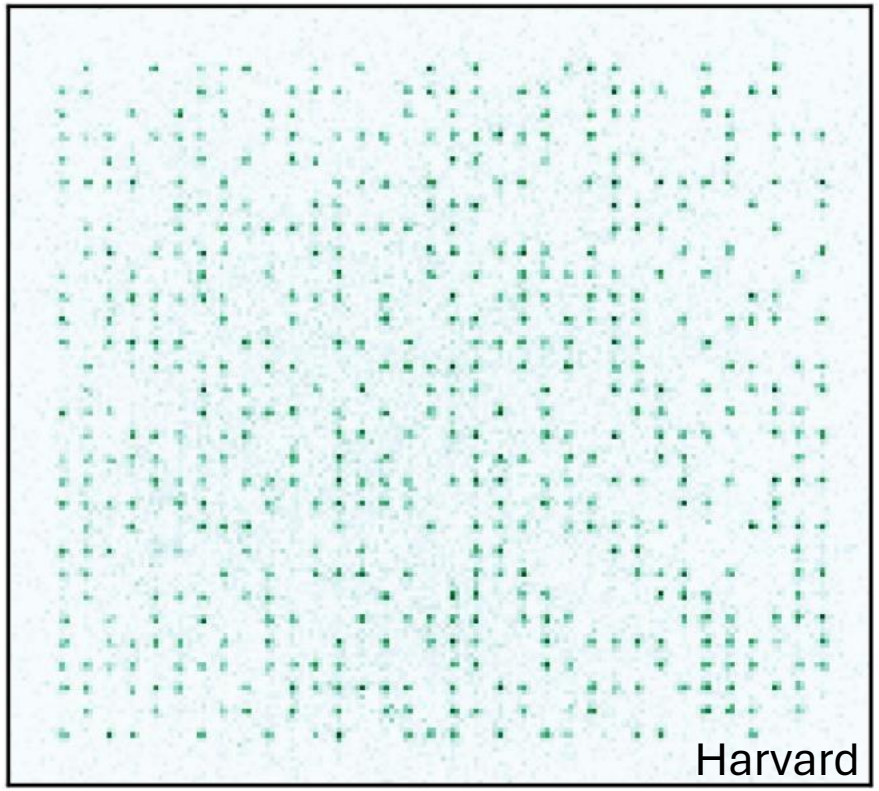
Ion traps



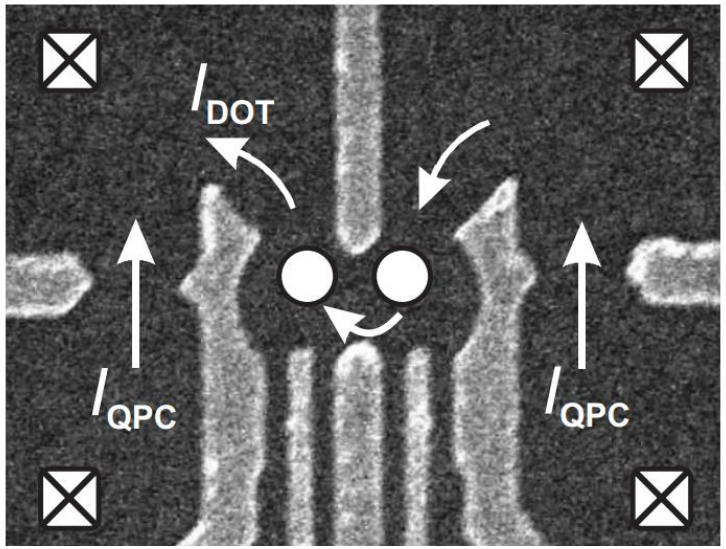
Quantum dots



Cold atoms

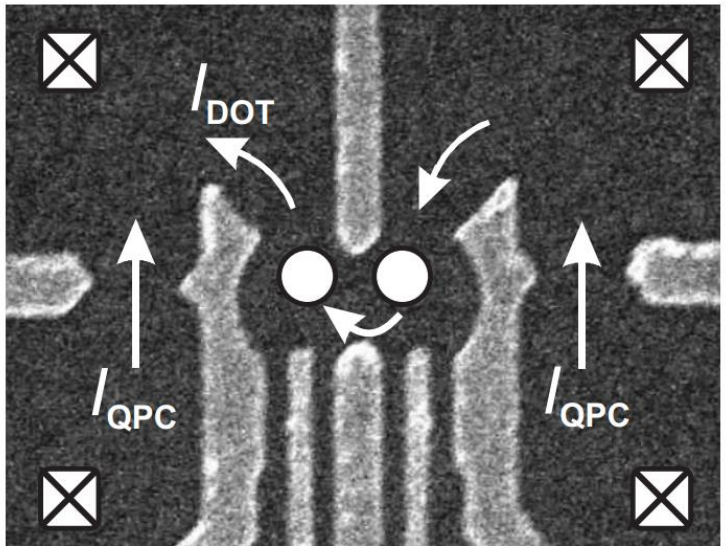


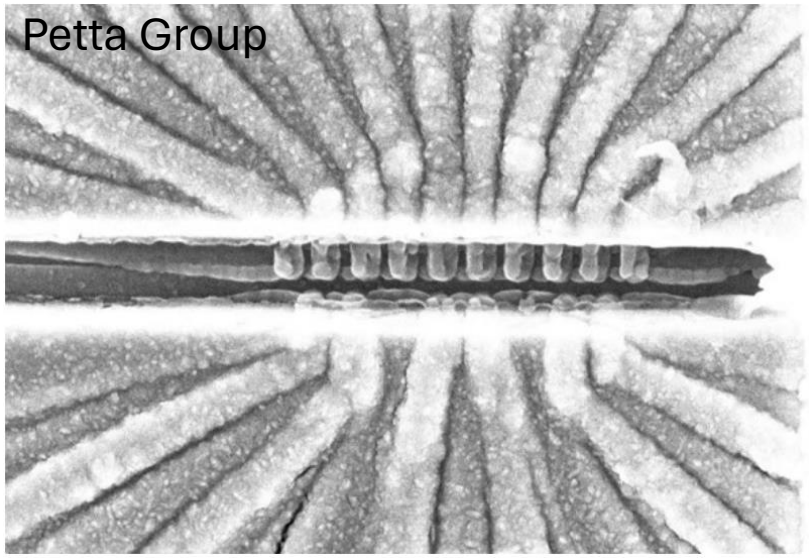
Quantum Dots (Spin and Charge Qubits)



GaAs: the pioneer

Quantum Dots (Spin and Charge Qubits)

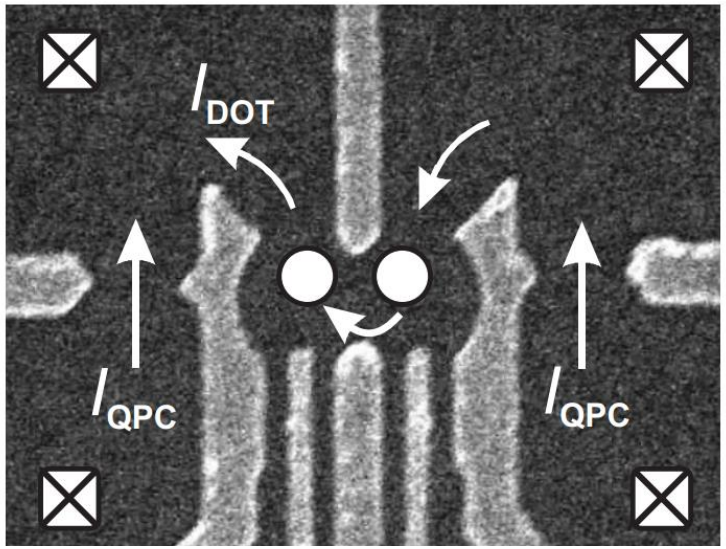


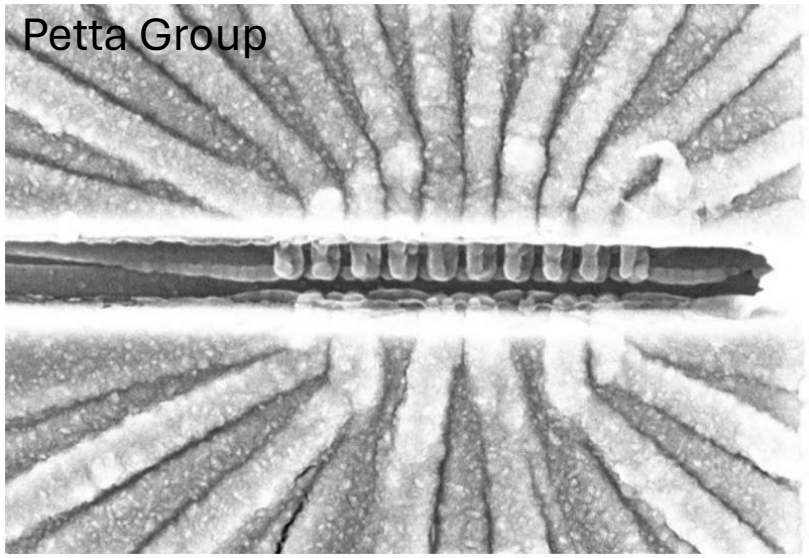


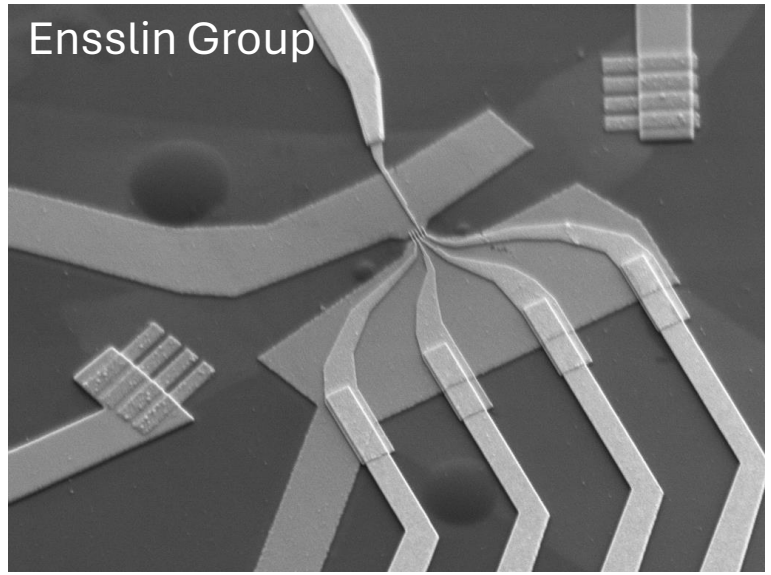
GaAs: the pioneer

Si: the workhorse

Quantum Dots (Spin and Charge Qubits)







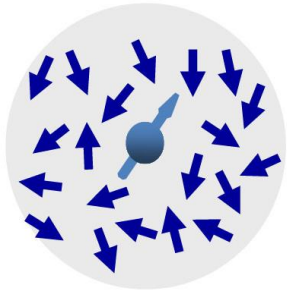
GaAs: the pioneer

Si: the workhorse

Graphene: the future

Why Carbon?

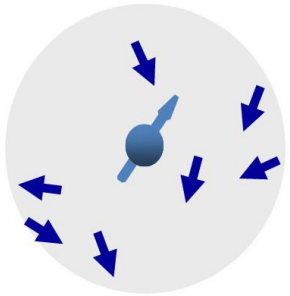
GaAs



$T_2^* \approx 10$ ns

Petta *et al.*, Science 2005

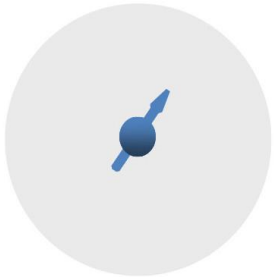
Si



$T_2^* \approx 1$ µs

Kawakami, Scarlino *et al.*, Nat. Nano 2014

^{28}Si



$T_2^* \approx 100$-250 µs

Veldhorst *et al.*, Nat. Nano 2014

^{12}C

$T_2^* \approx ???$

- **Low magnetic noise**:

Naturally only 1.01% nuclear spinful C^{13}
→ weak hyperfine interaction

- **Low electrical noise:**

Low mass
→ weak spin-orbit coupling

- **High mobility**

→ high quality easy-to-tune QDs

- **Low effective mass**

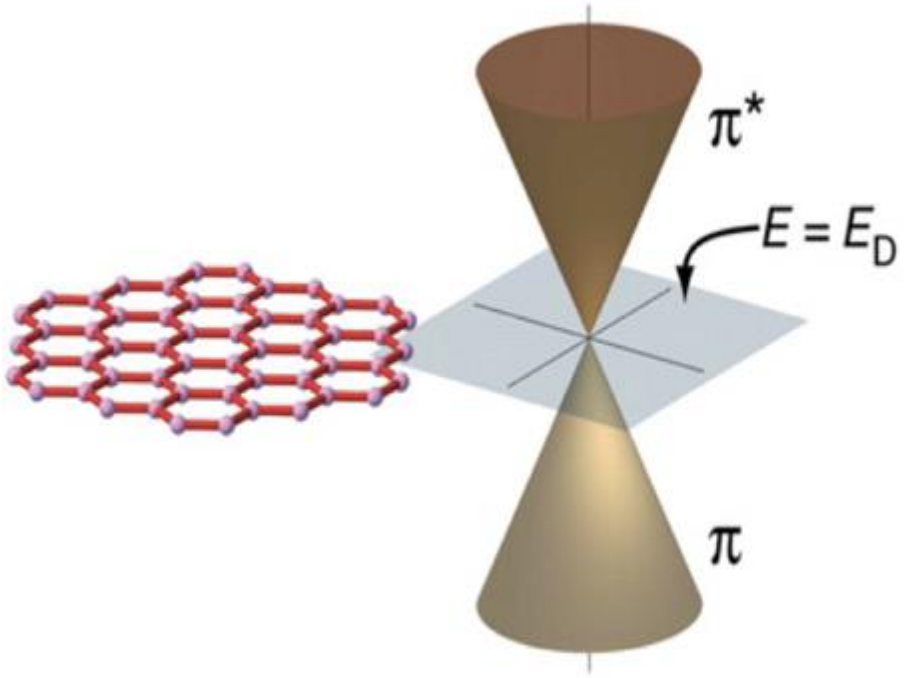
→ bigger gate footprint

- **Robust in-plane valley degree of freedom**

→ immunity to interface disorder
→ new types of long-lived qubits (valley and spin-valley)

Bandstructures and Energy Gaps

single layer **Graphene**



linear dispersion

No gap!

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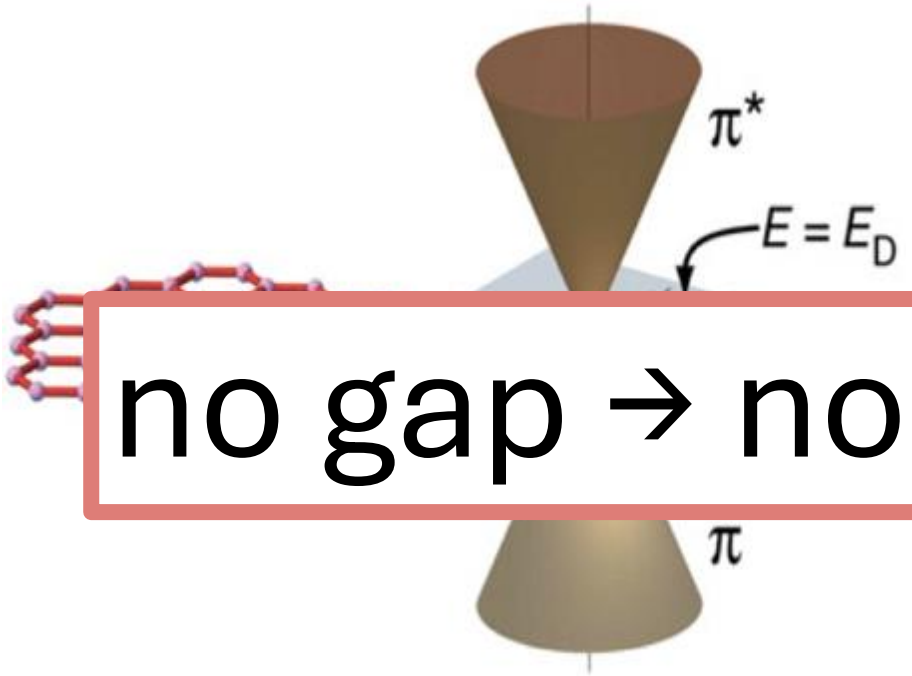

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no gap → no dot → no qubit

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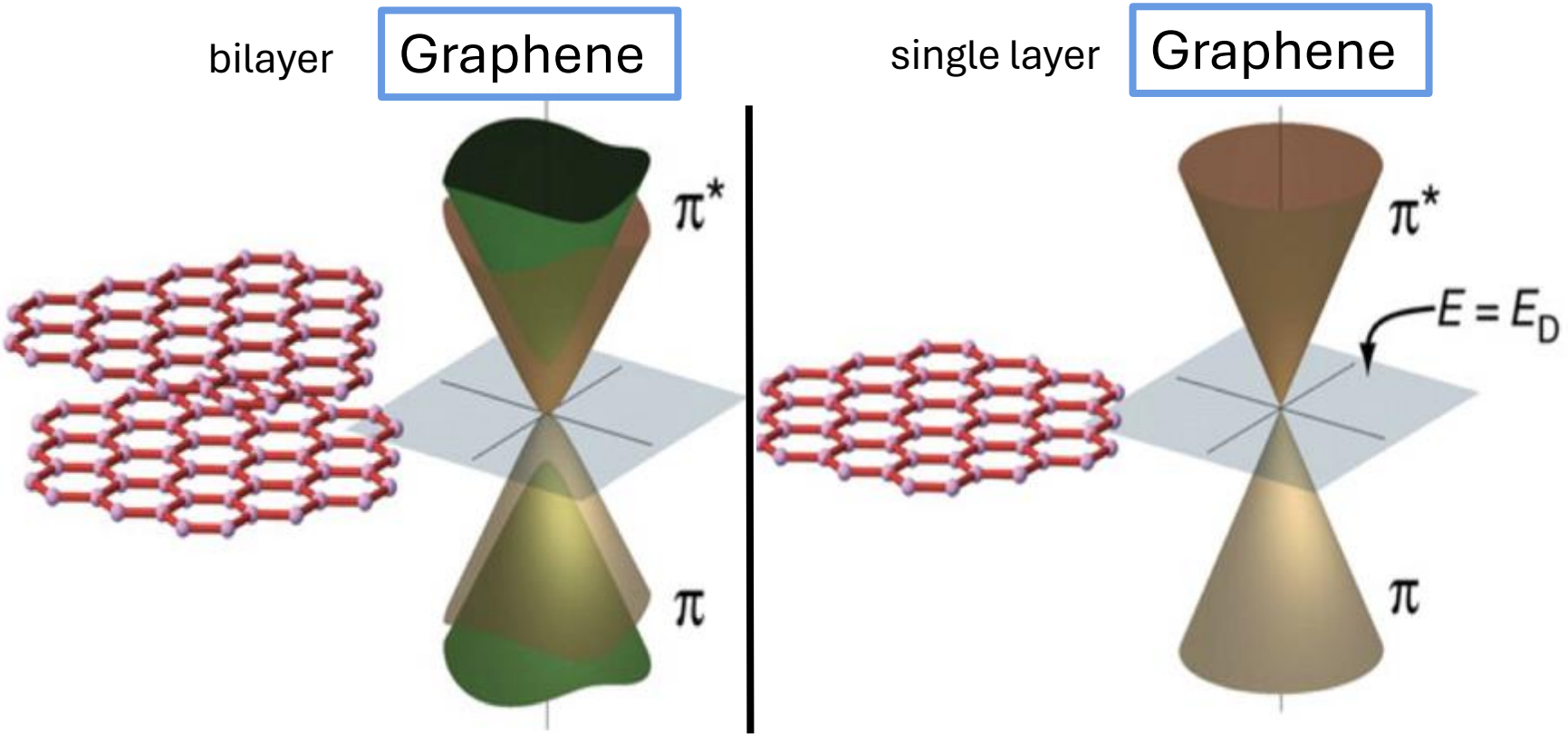
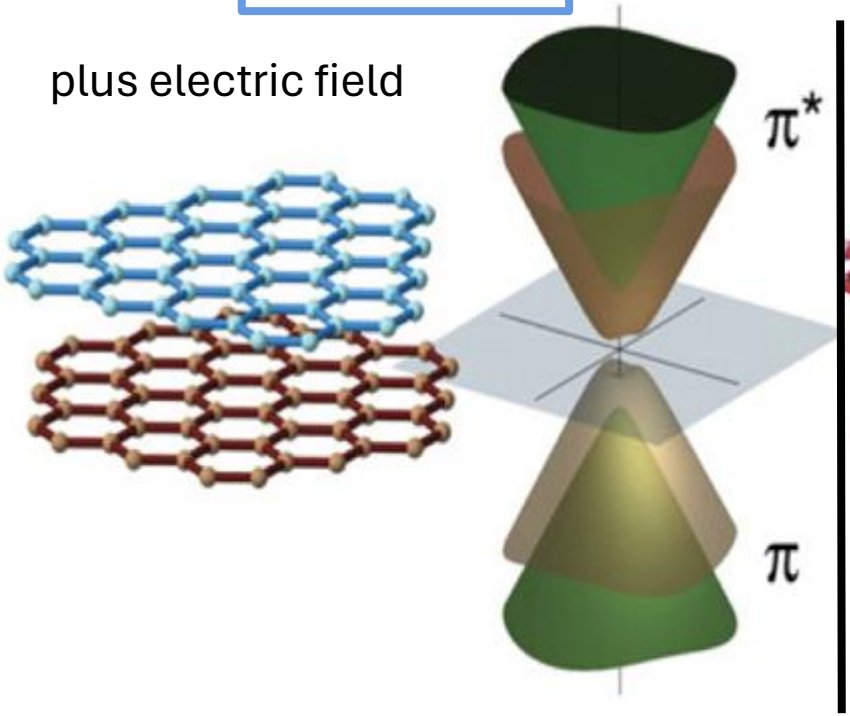
Bandstructures and Energy Gaps



Bandstructures and Energy Gaps

bilayer Graphene

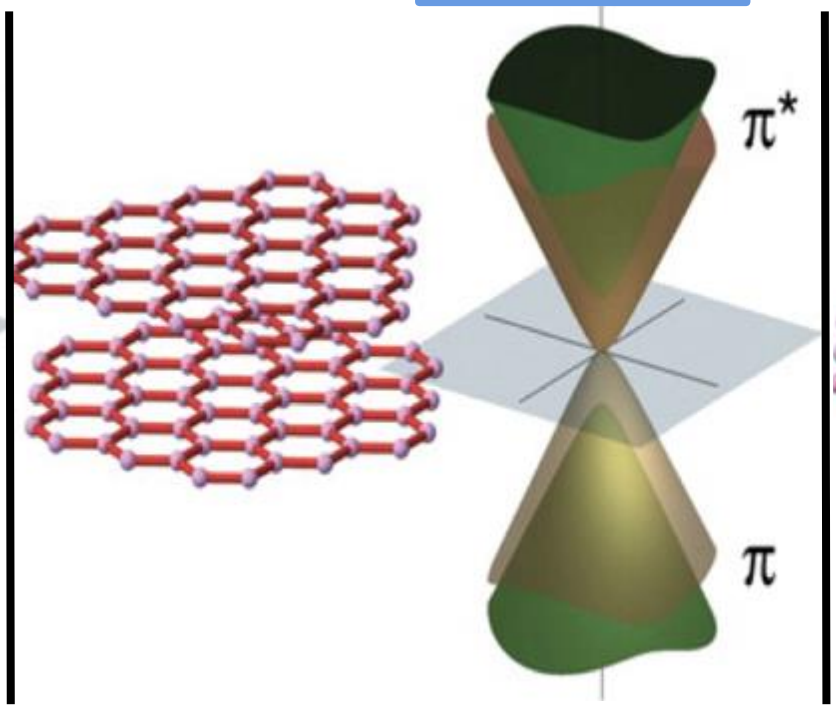
plus electric field



Higgs (sombrero) dispersion!

GAP!

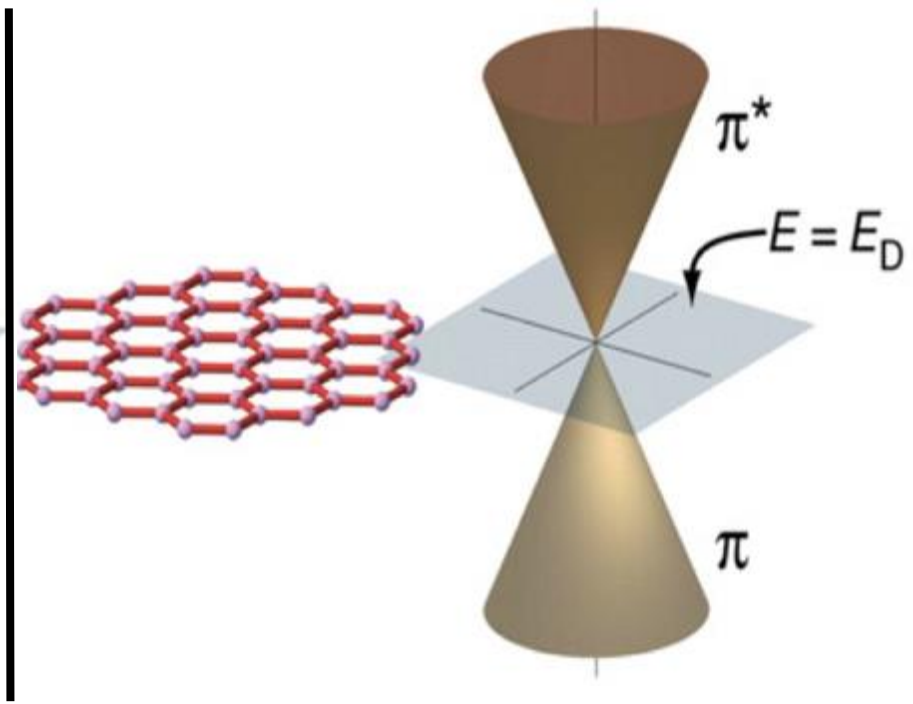
bilayer Graphene



parabolic dispersion

No gap!

single layer Graphene



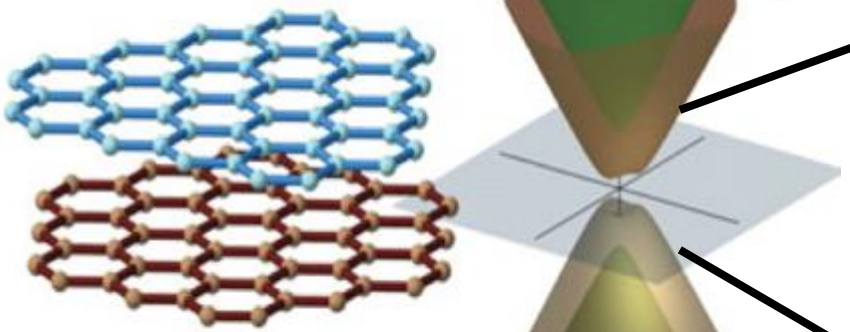
linear dispersion

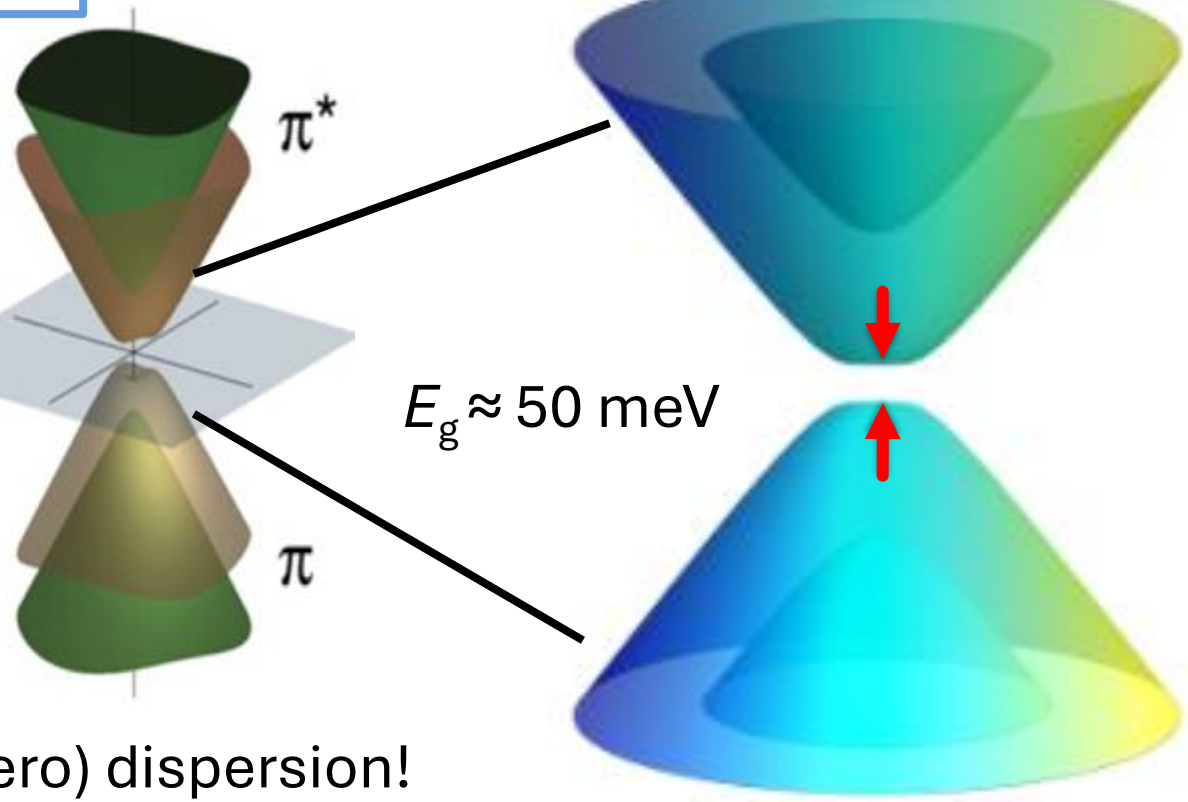
No gap!

Bandstructures and Energy Gaps

bilayer **Graphene**

plus electric field





electric field: ≈ V/nm

$E_g \approx 50$ meV

Higgs (sombrero) dispersion!

GAP!

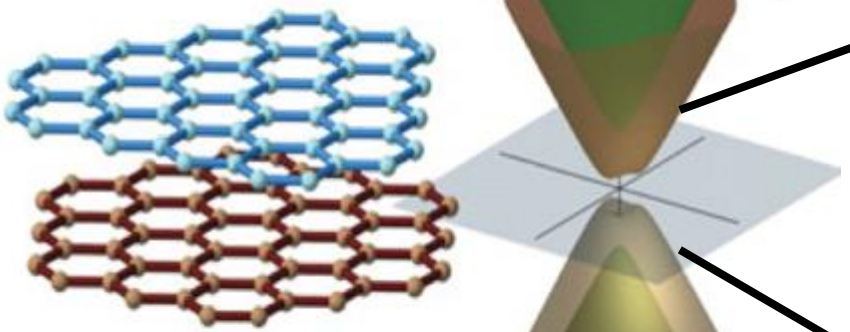
Theory:
Min *et al.*, PRB 2007

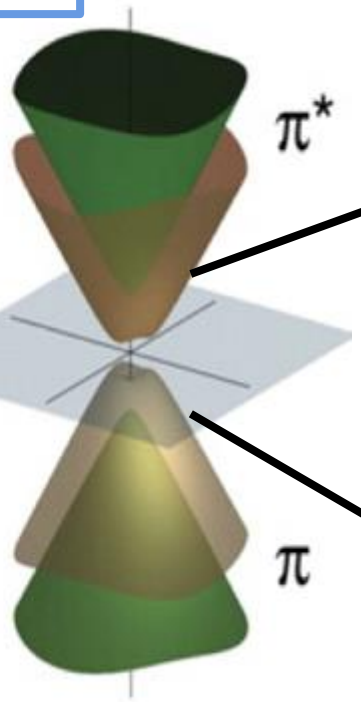
Experiment:
Oostinga *et al.*, Nature Materials 2008

Bandstructures and Energy Gaps

bilayer **Graphene**

plus electric field





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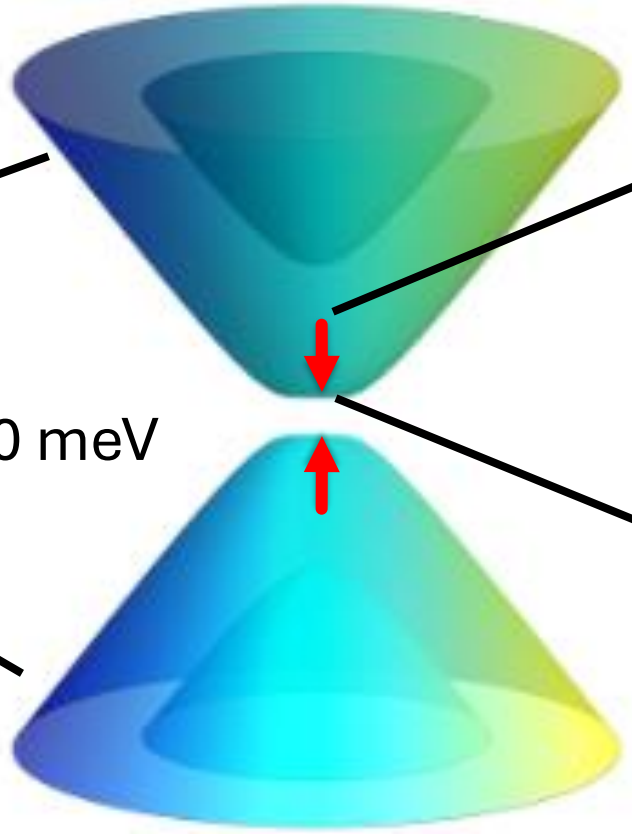

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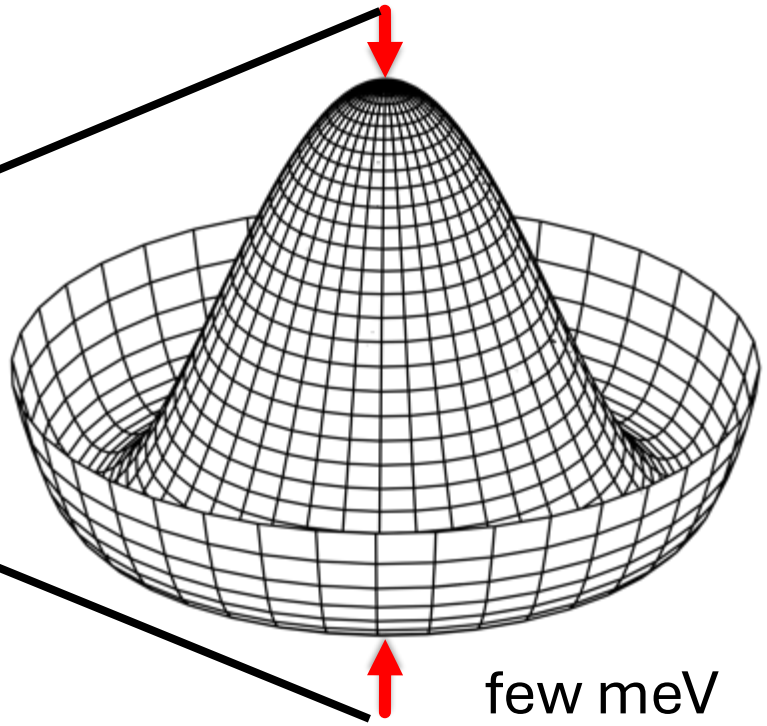
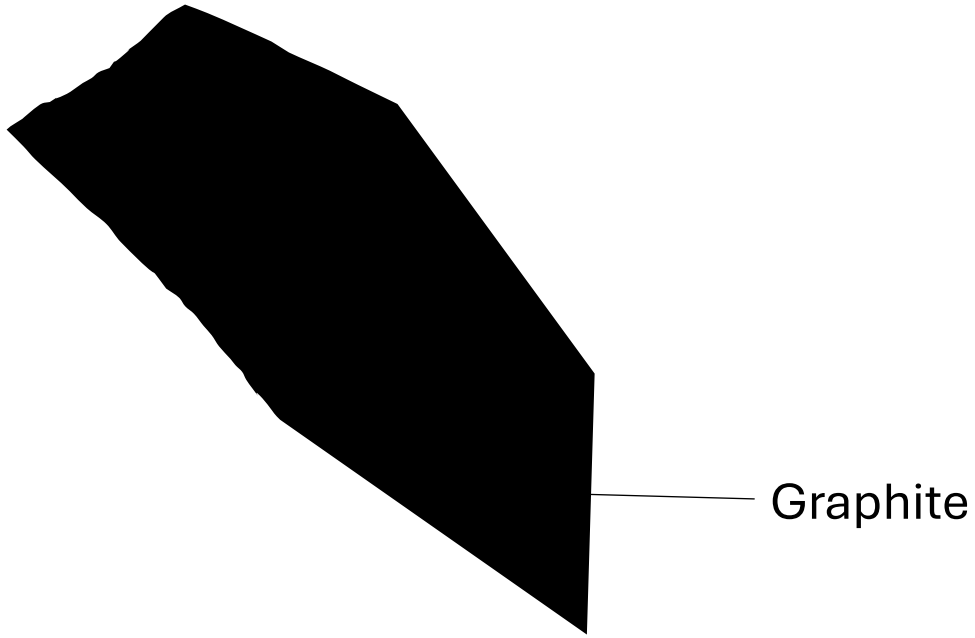


few meV

Higgs (sombrero) dispersion!

GAP!

Bilayer Graphene: Sample Design



Cr/Au

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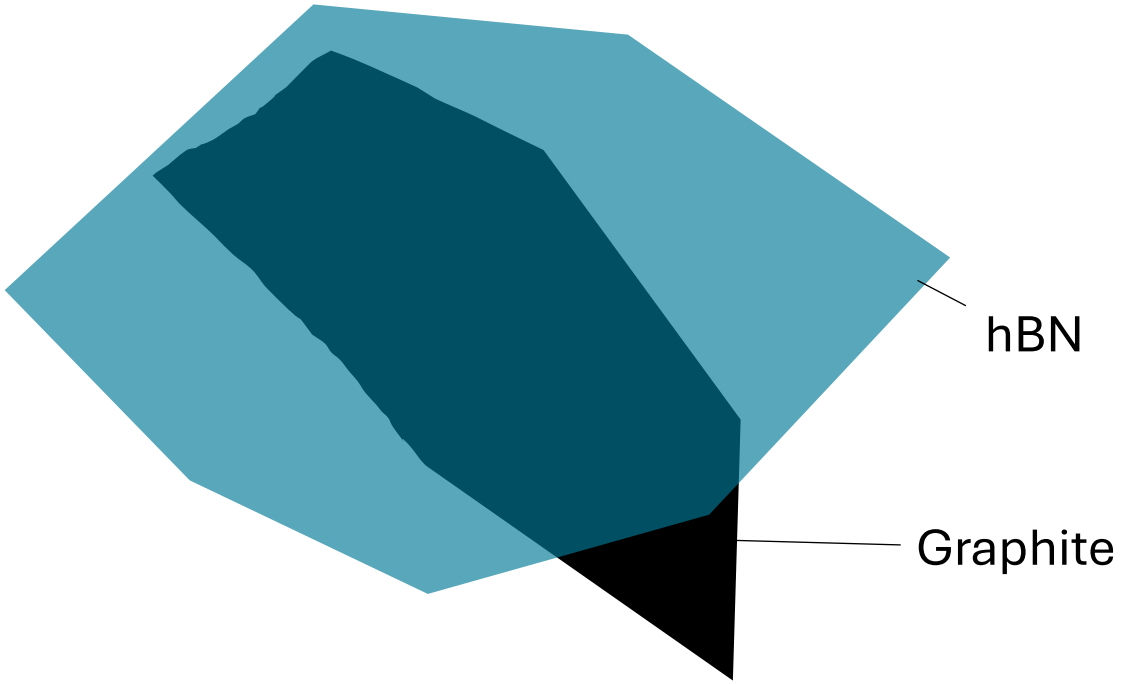

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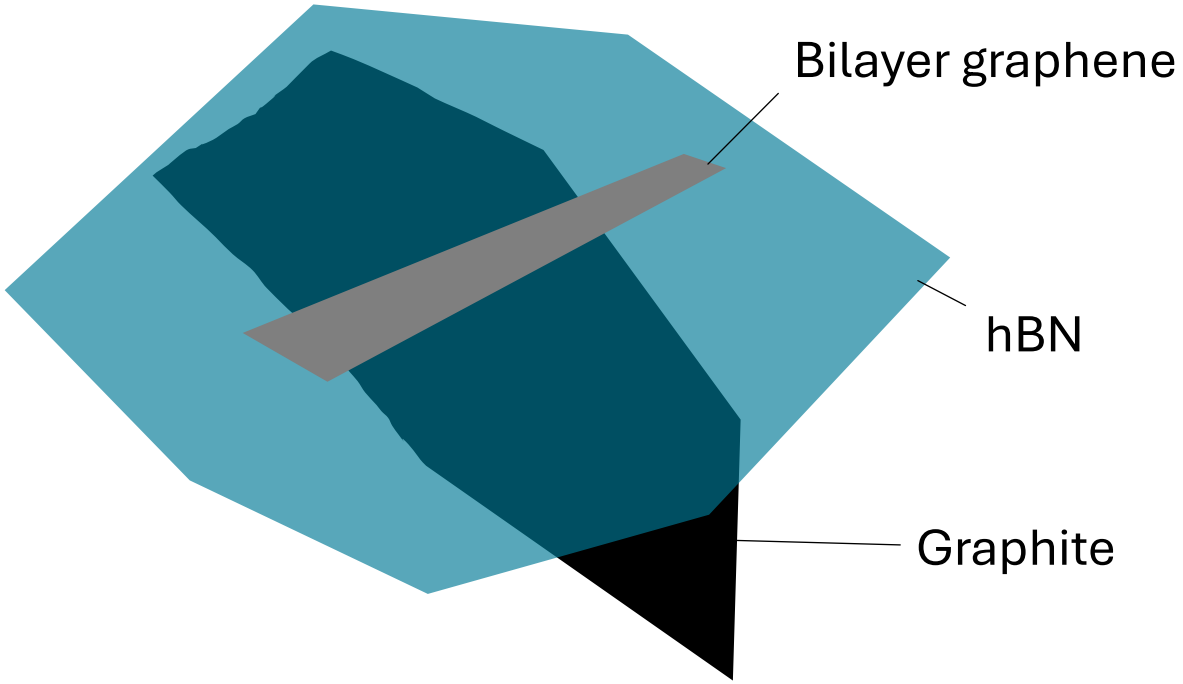

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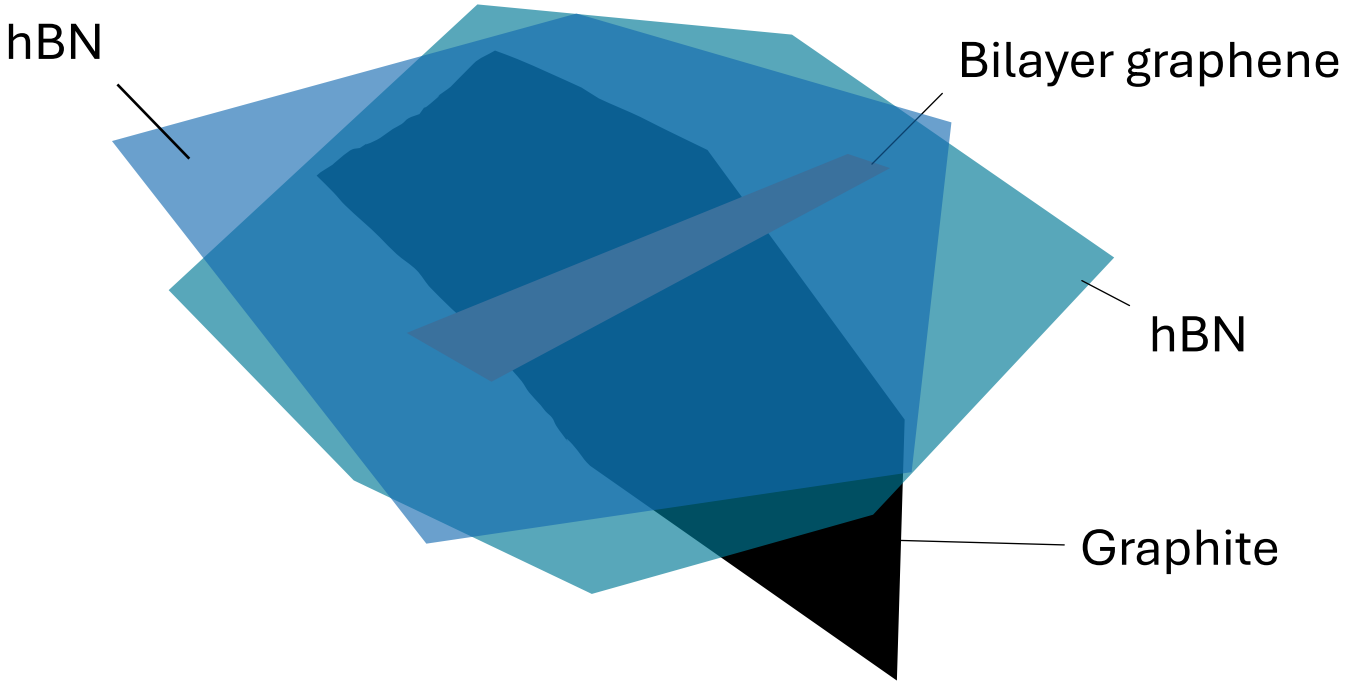

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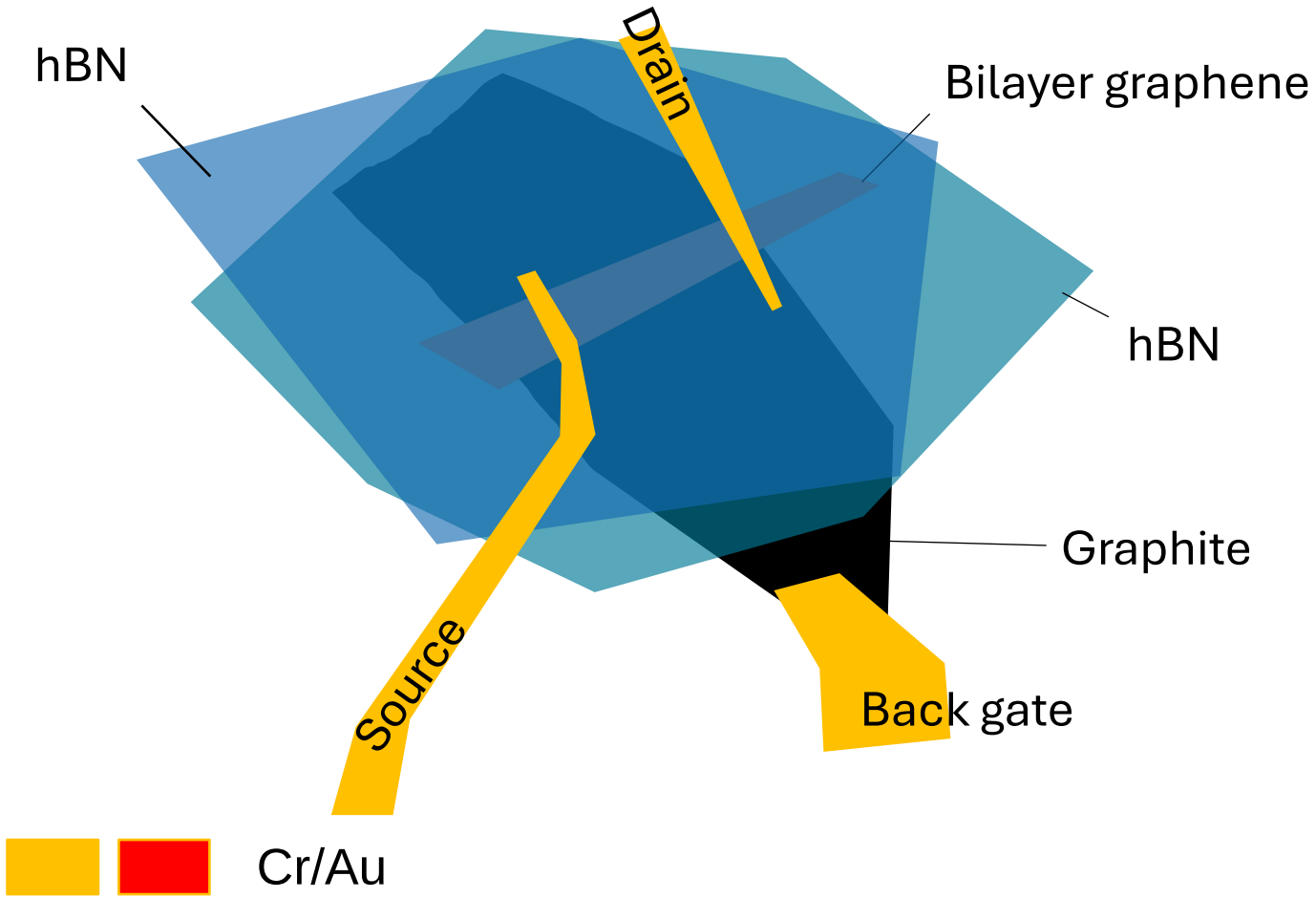

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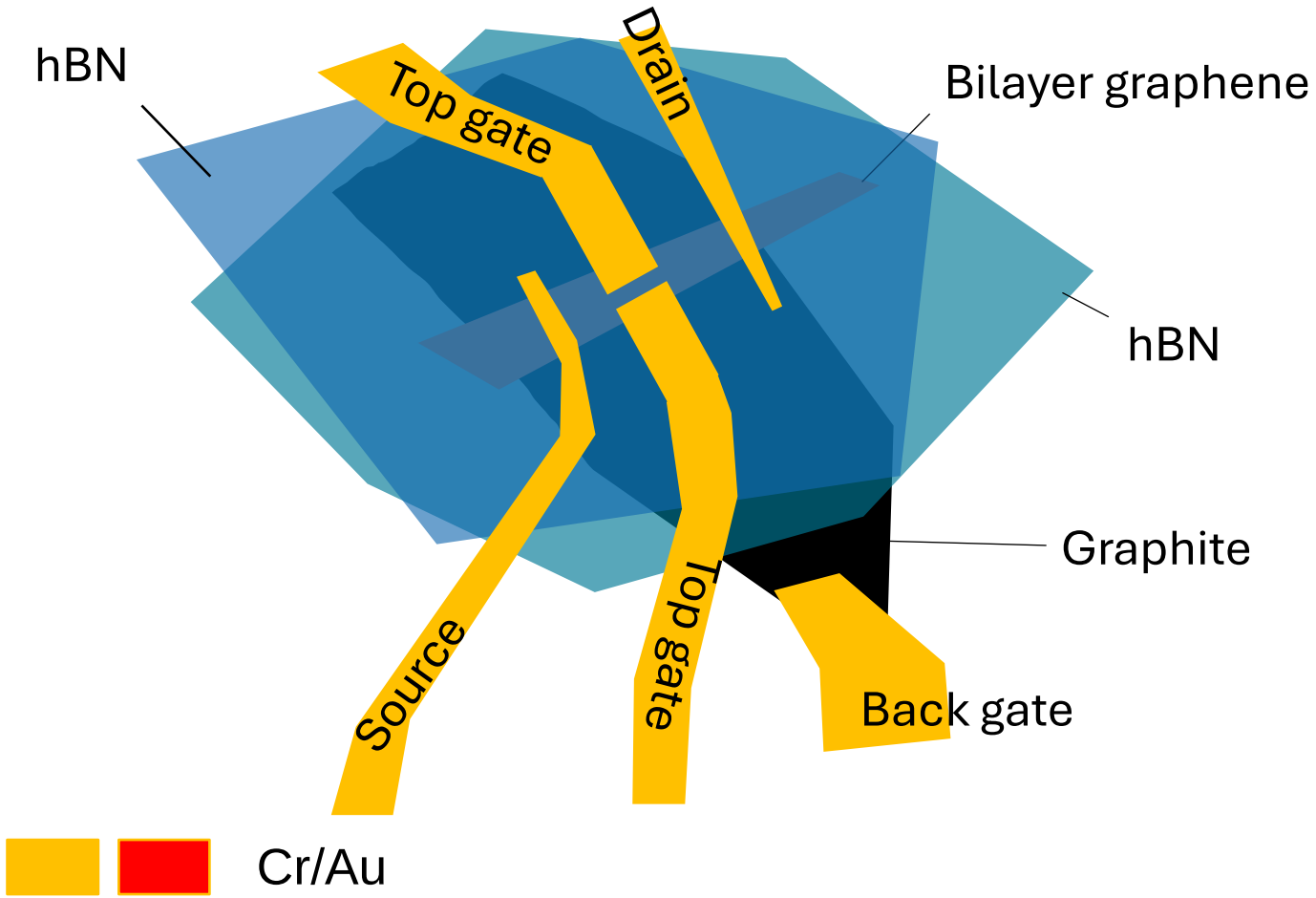

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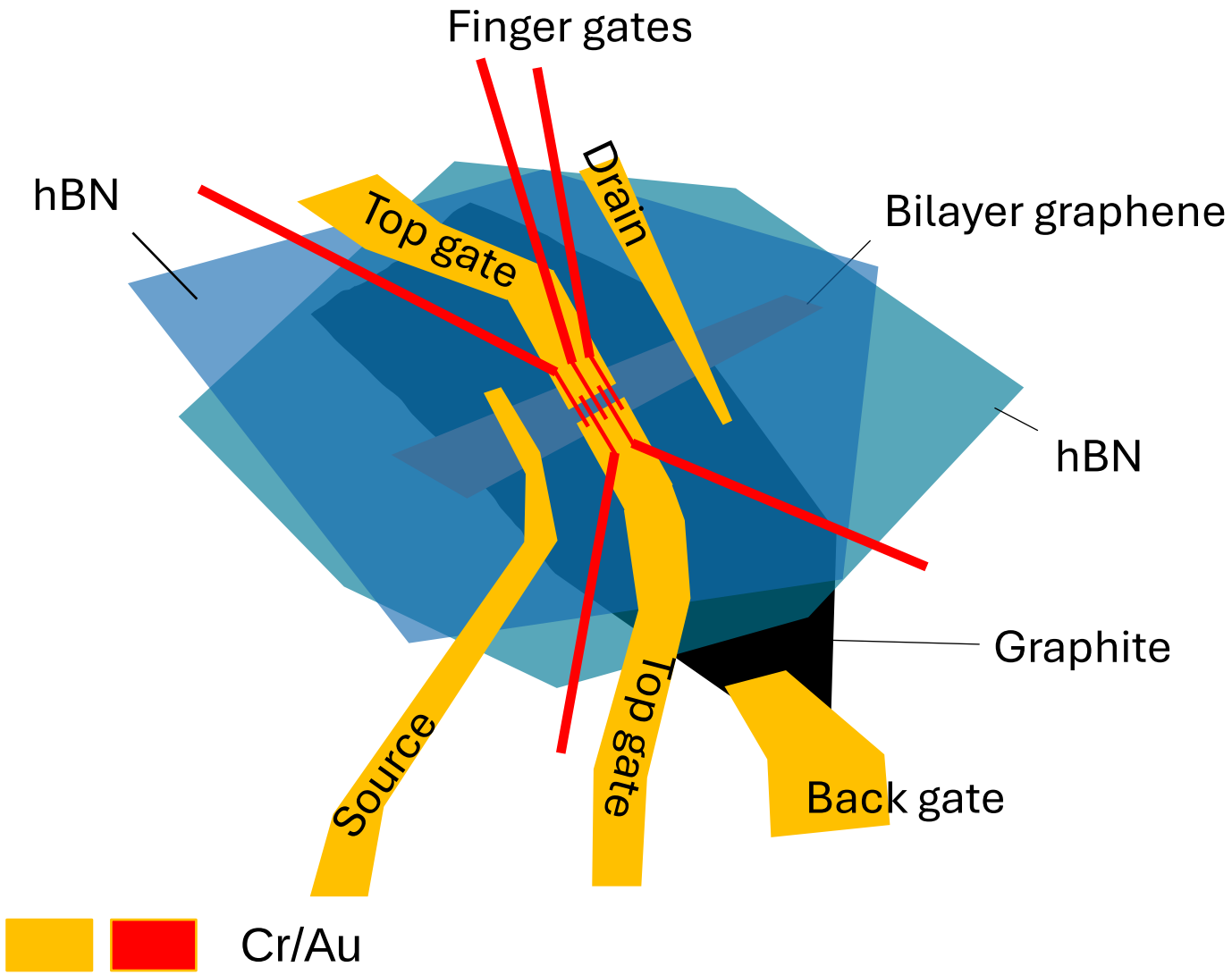

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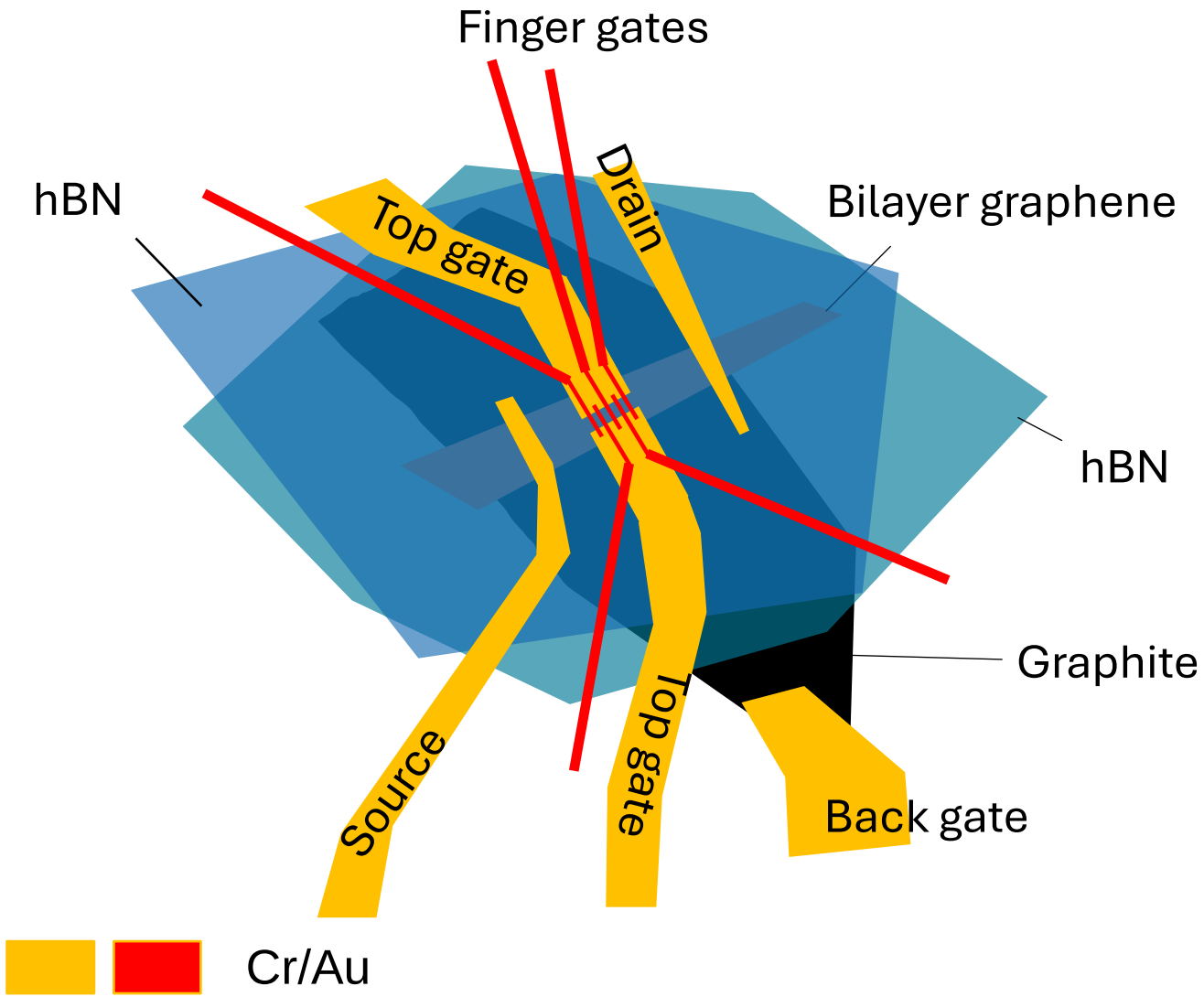
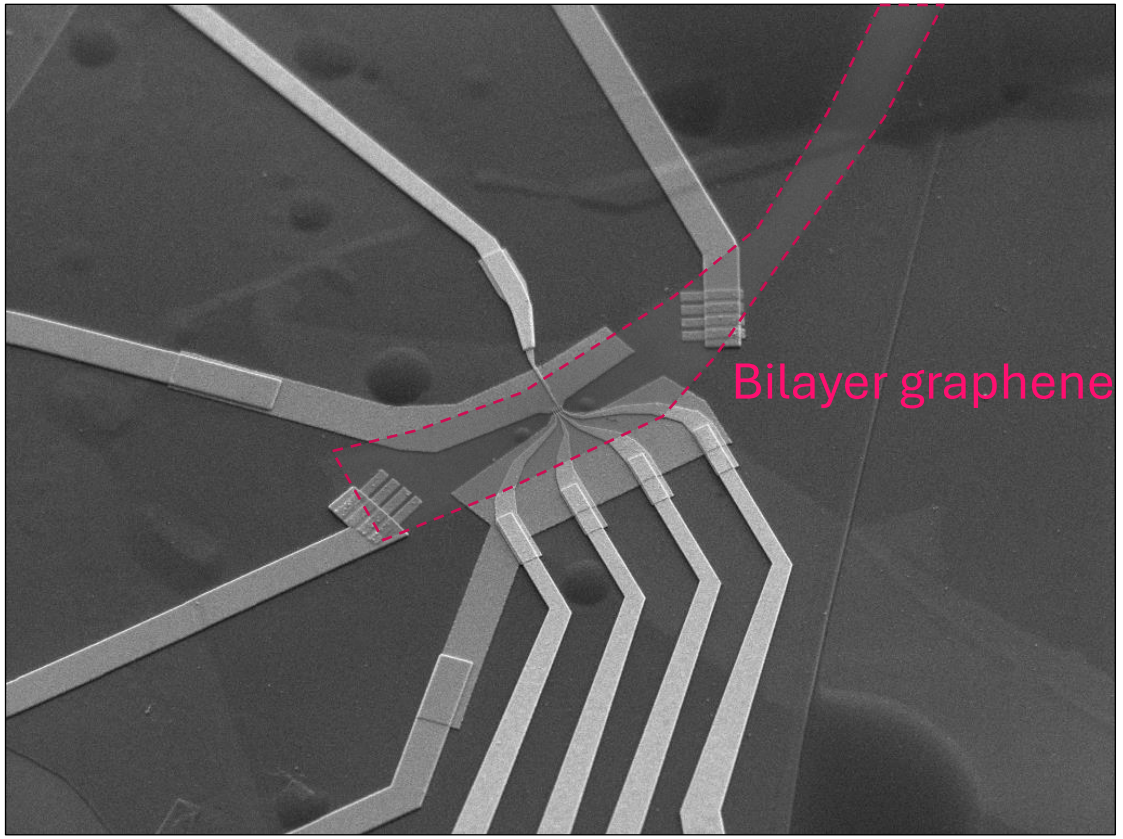
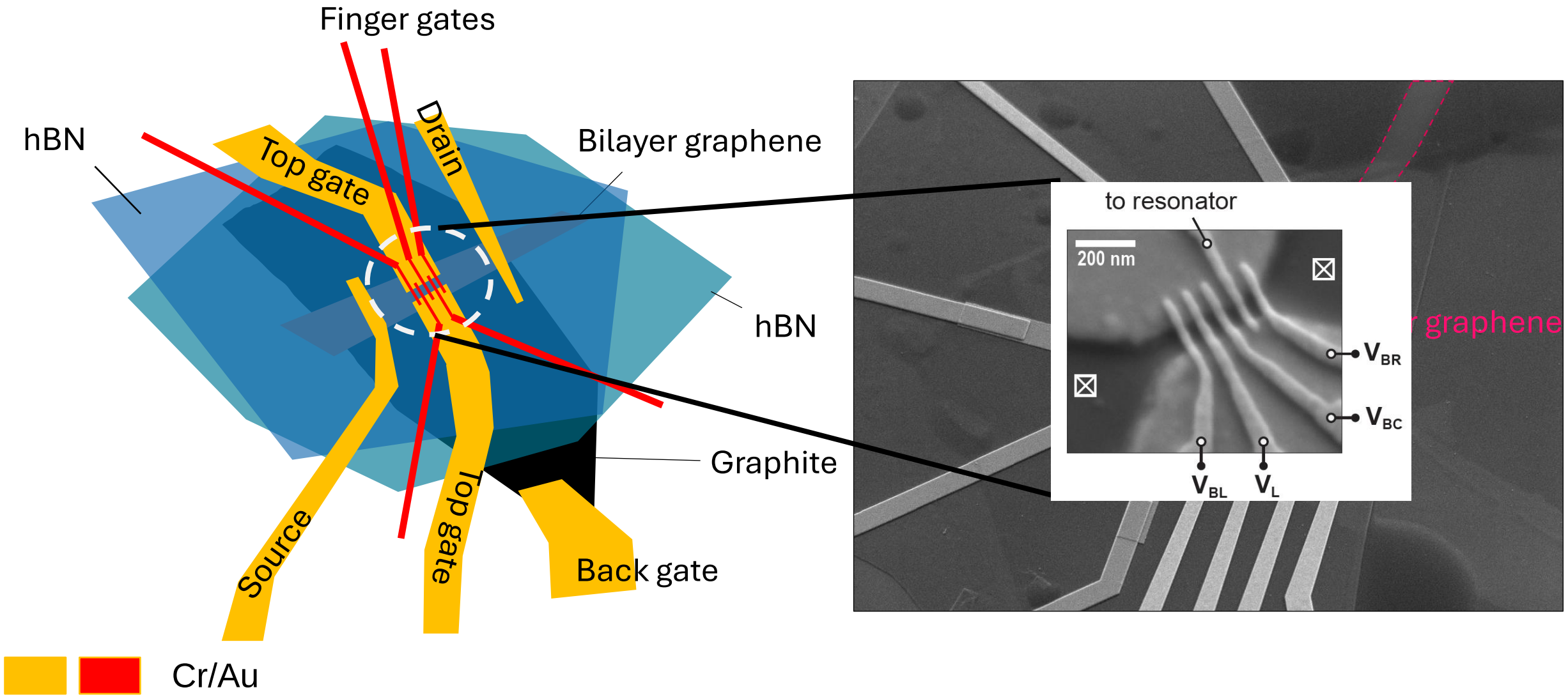
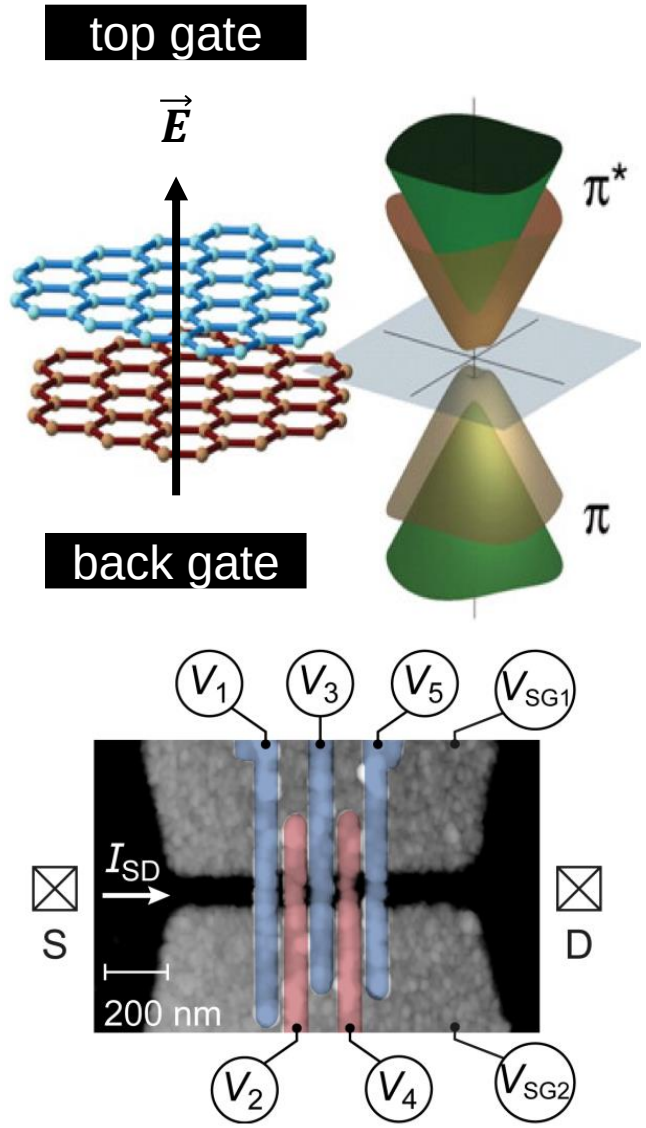




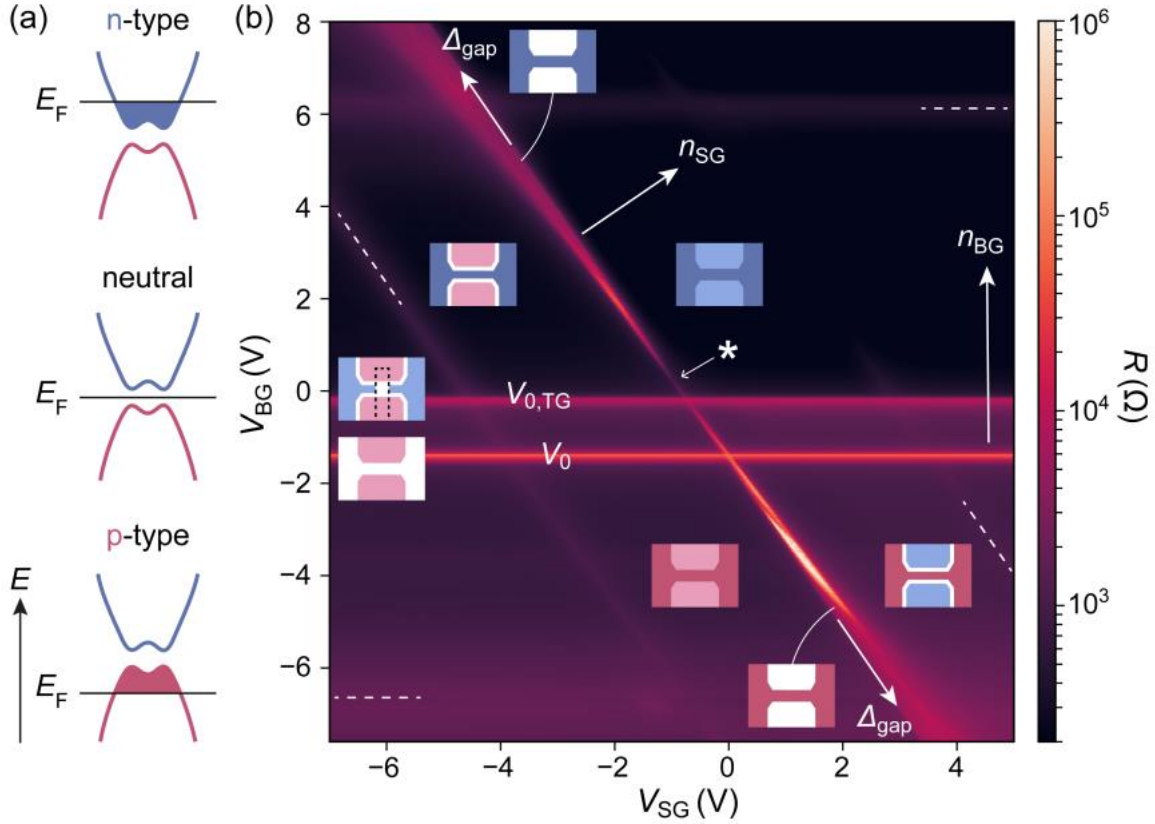
Bilayer Graphene: Sample Design



Bandgap Opening in BLG by Dual Gating



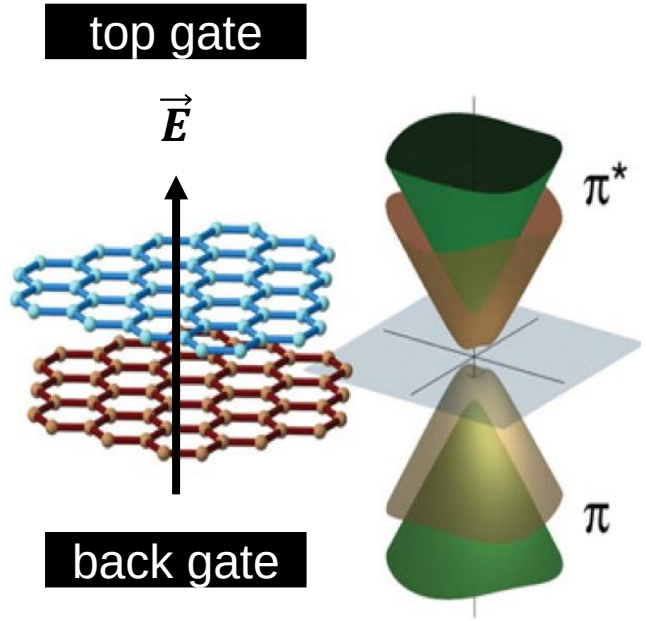
Chuyao Tong., PhD Thesis 2023

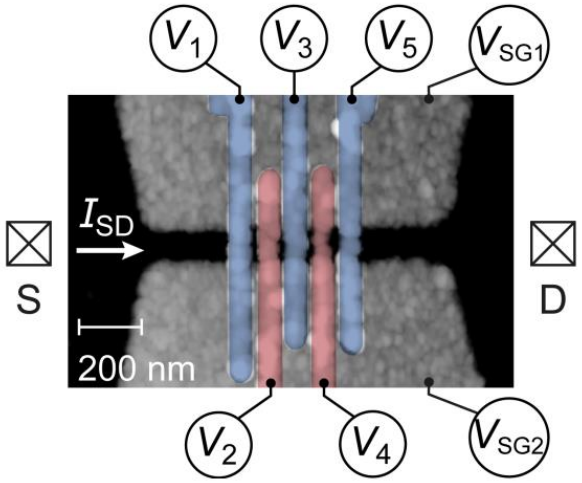


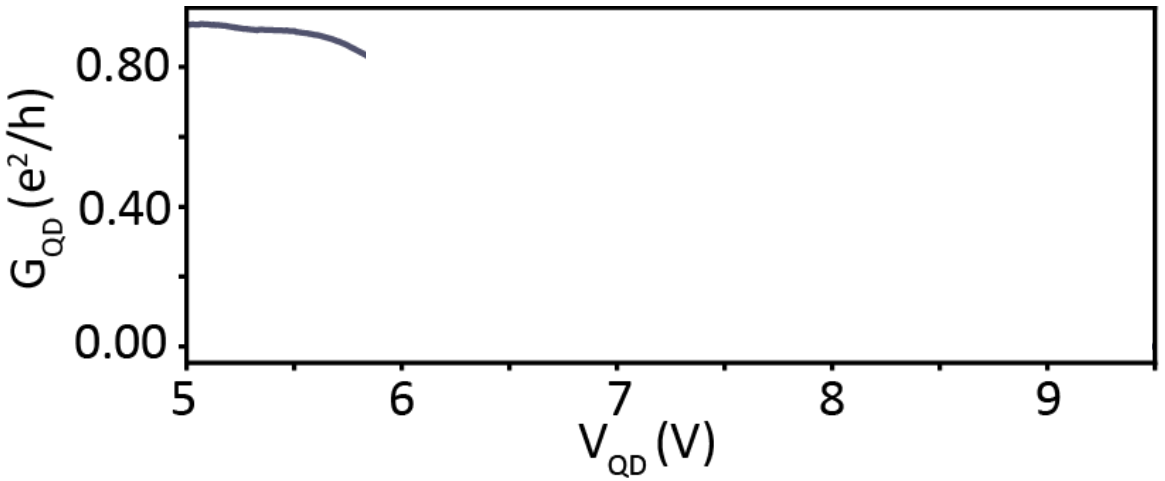
Simultaneous control:

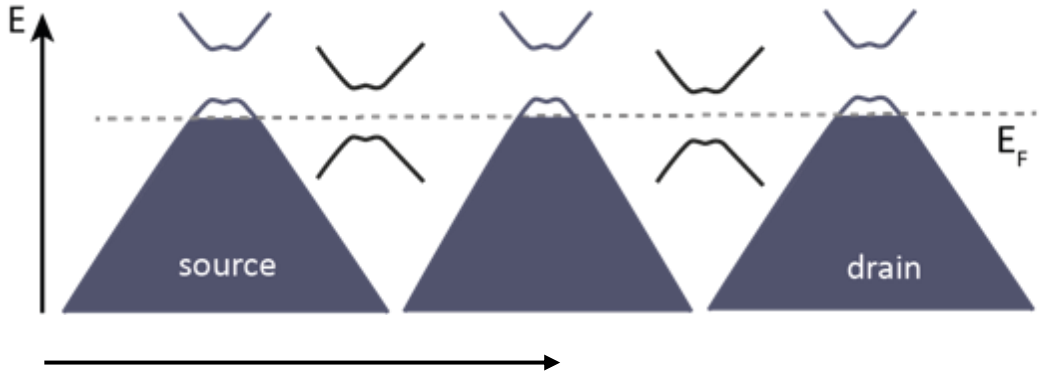
- Δ_{gap} ($\vec{E}$ ($|V_{TG} - V_{BG}|$)
  $\sim 10 - 100$ meV
- E_F ($V_{TG} + V_{BG}$)
  i.e. doping

Forming a Quantum Dot



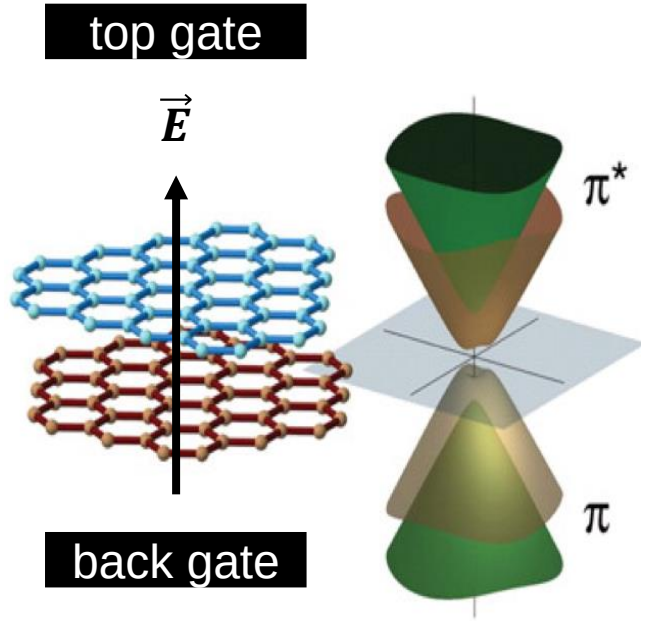


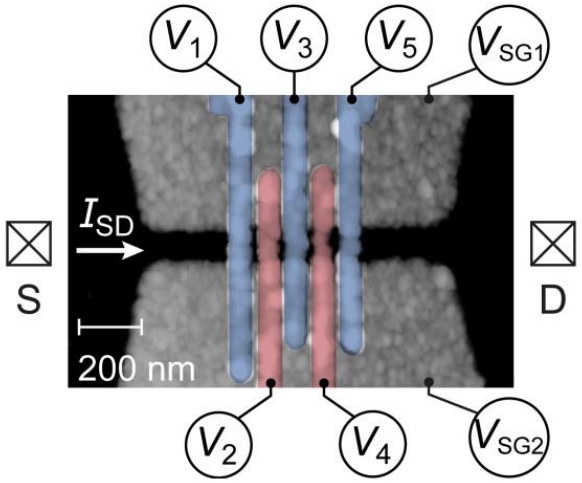


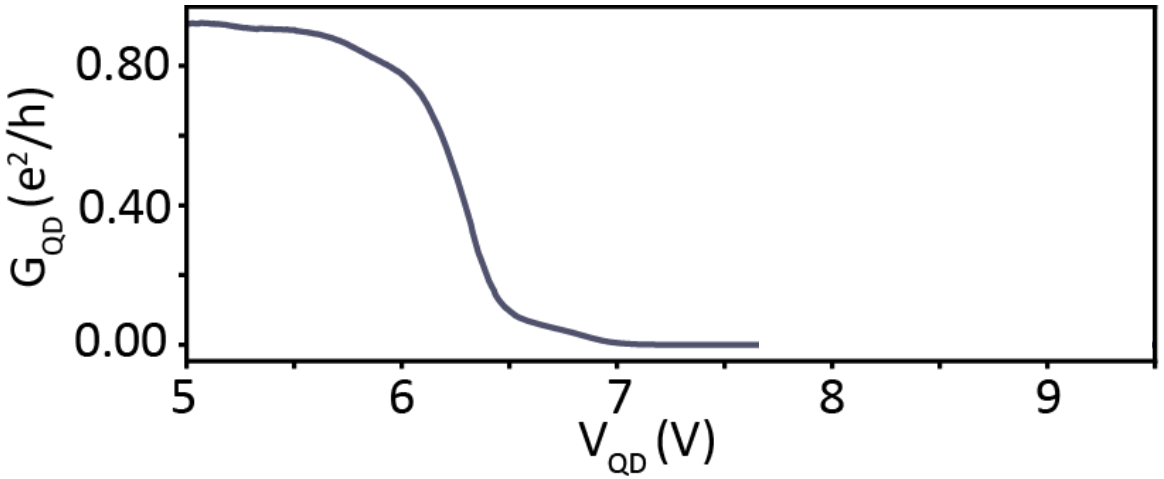


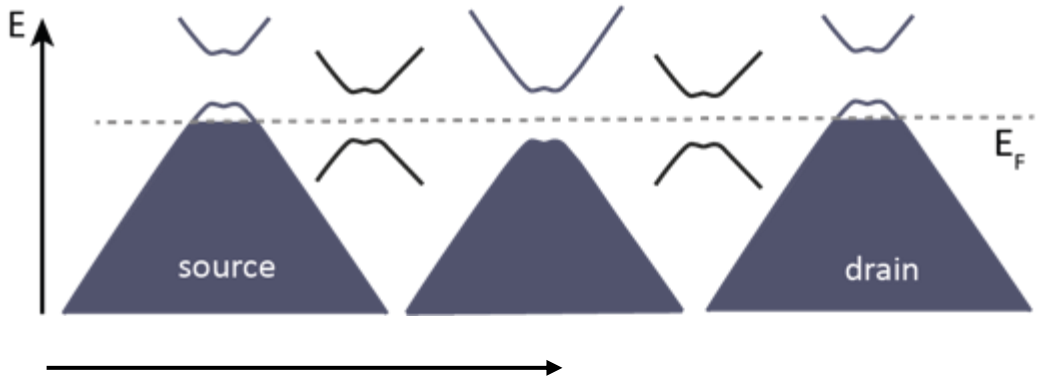
Cut along the channel

Forming a Quantum Dot









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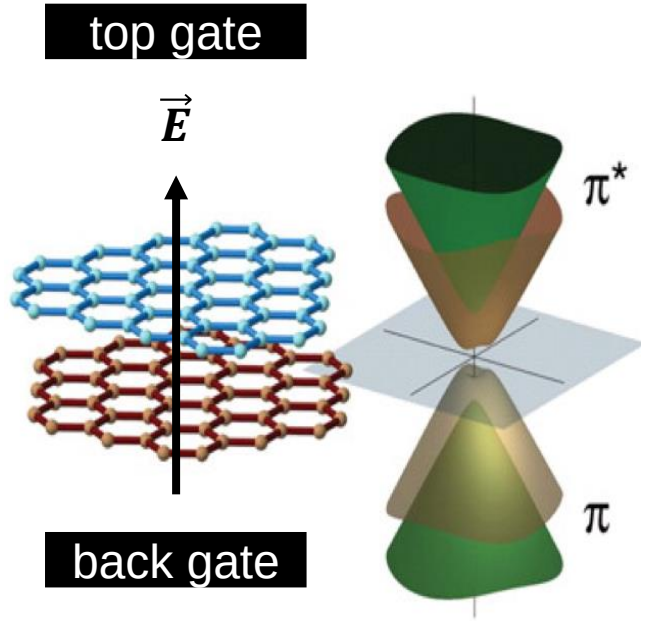
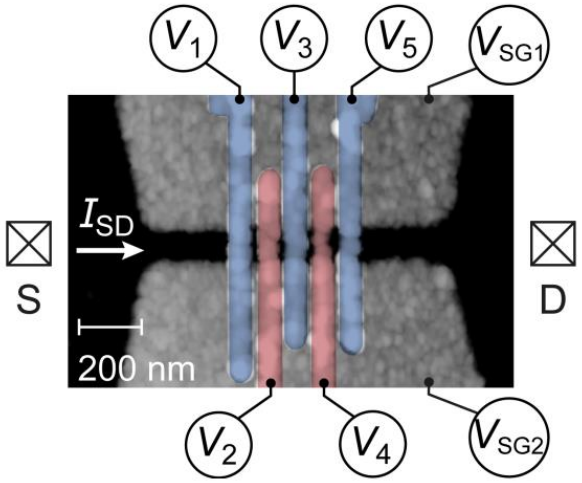
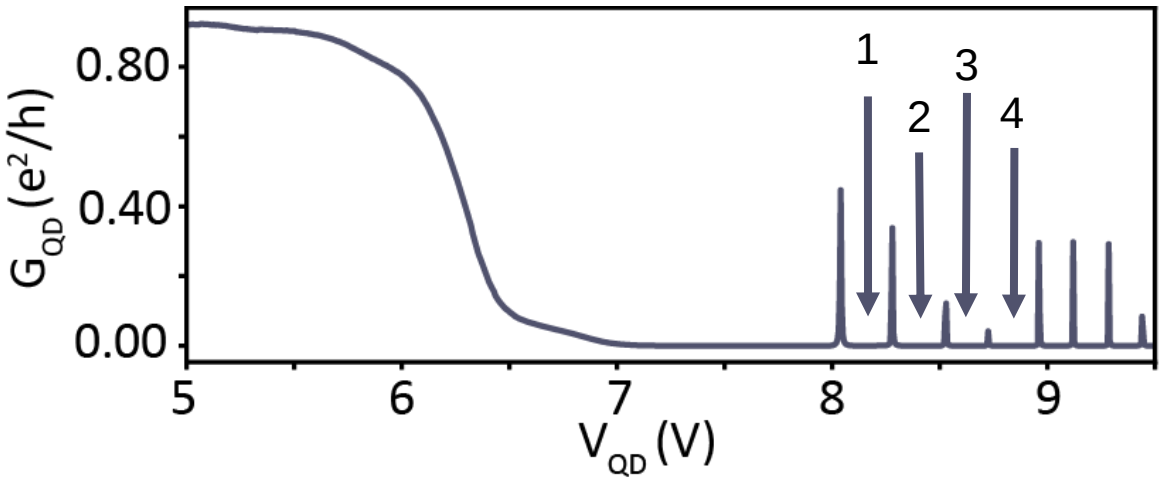
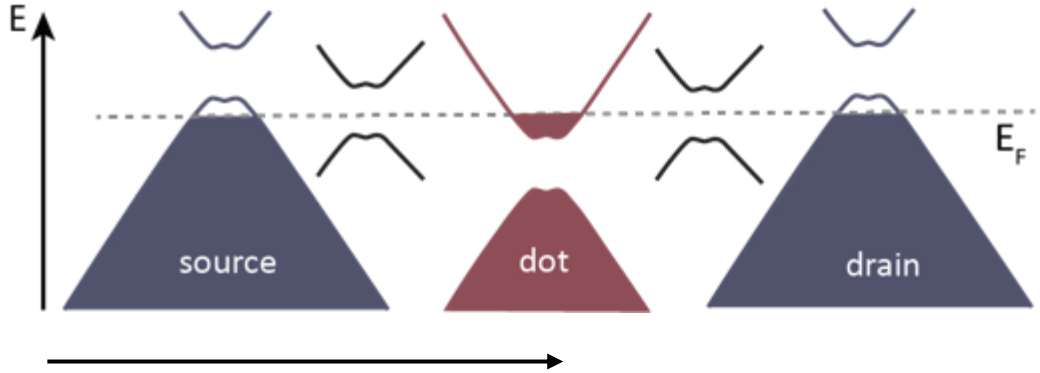
Forming a Quantum Dot









Cut along the channel

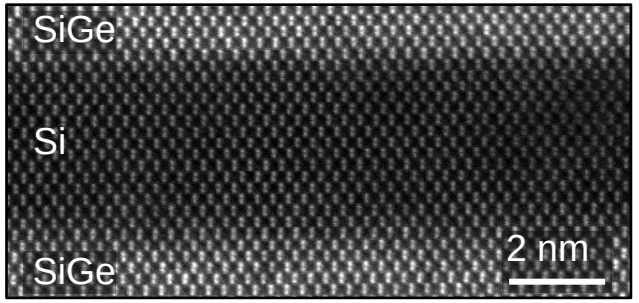
Valleys in BLG

Real space

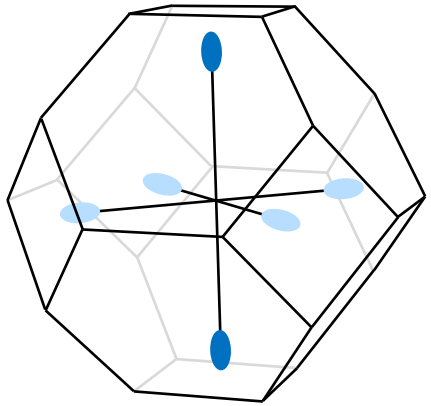
Reciprocal space

SiGe/Si/SiGe

hBN/BLG/hBN



Borjans *et al.*, PRApplied 2022



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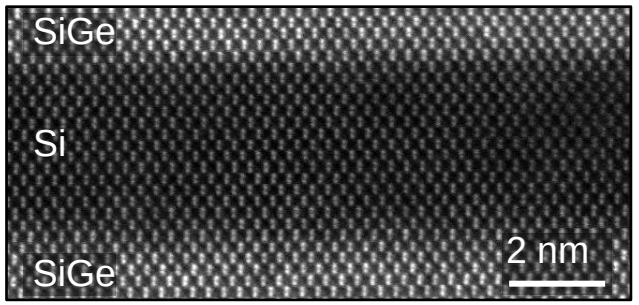
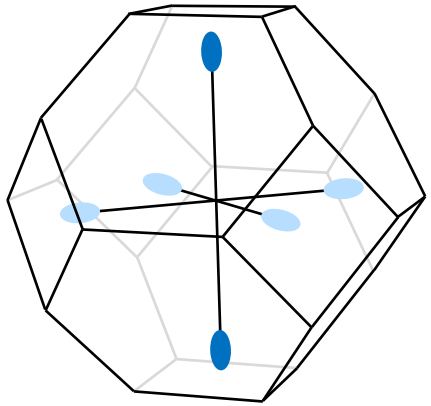
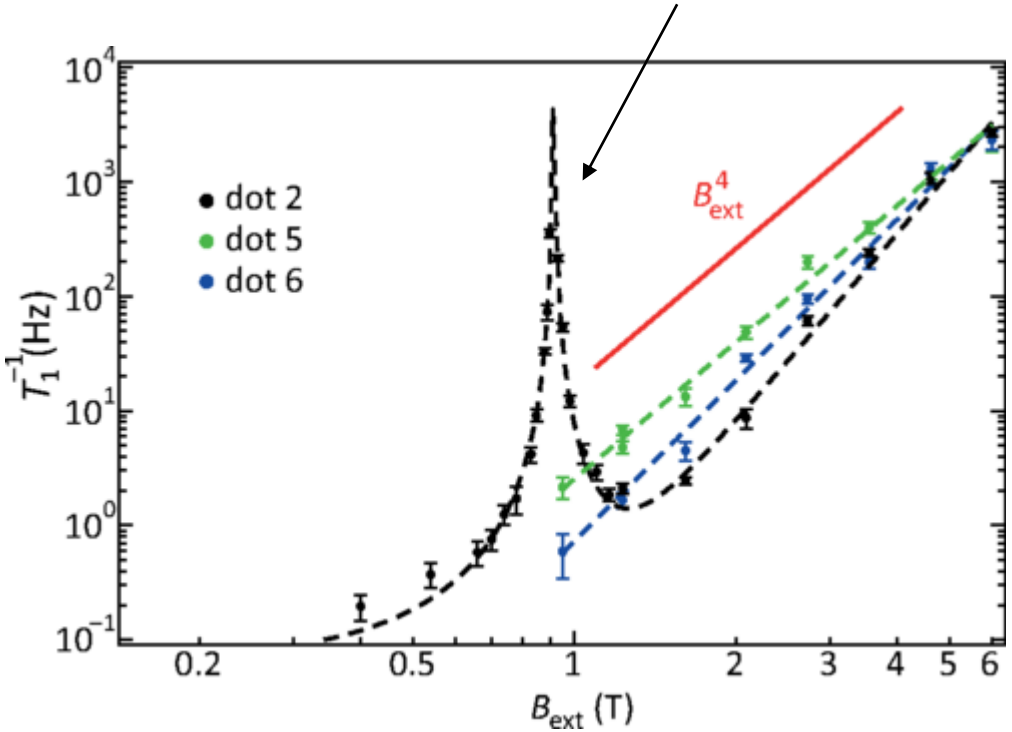


Borjans *et al.*, PRApplied 2022



Spin-valley hot-spot



Borjans *et al.*, PRApplied 2019

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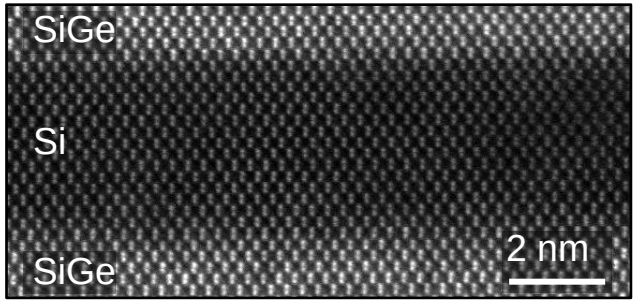
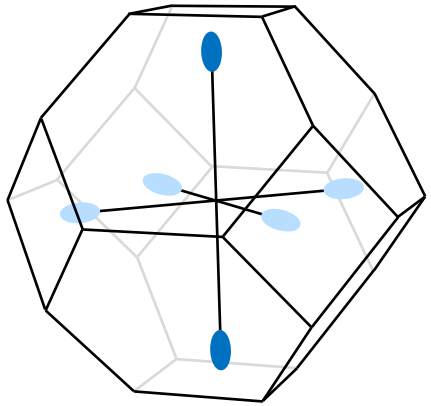
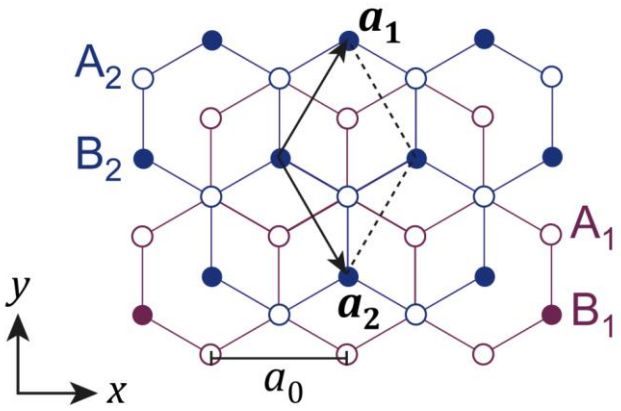


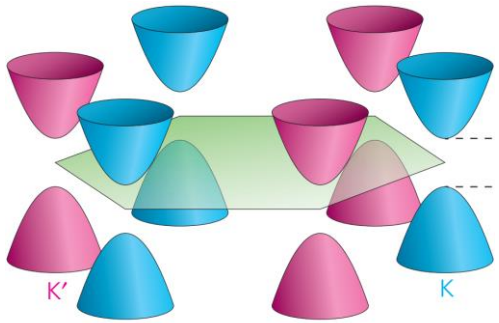
Borjans *et al.*, PRApplied 2022



Valley is bad quantum number!

hBN/BLG/hBN





Shimazaki *et al.*, Nat.Phys. 2015

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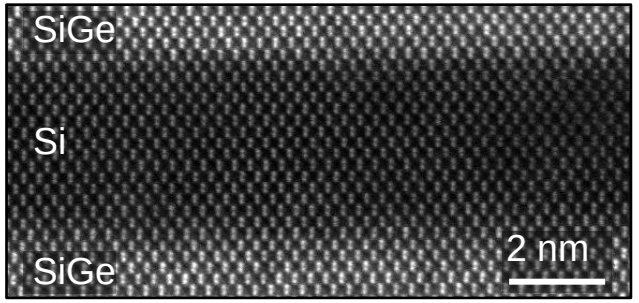
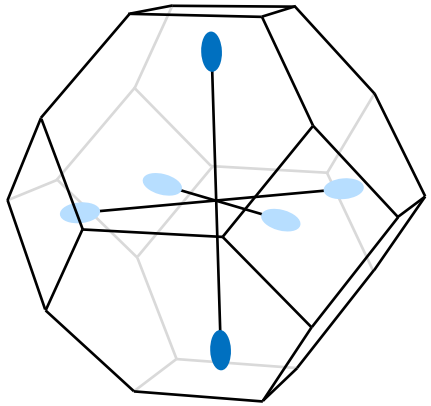


Borjans *et al.*, PRApplied 2022



Valley is bad quantum number!

Inter-valley scattering events require:

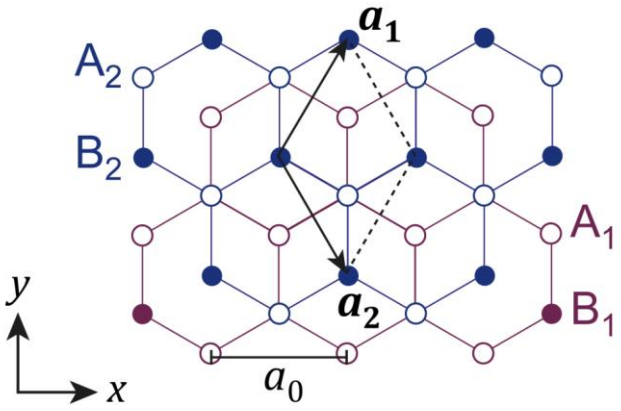
Large momentum δk

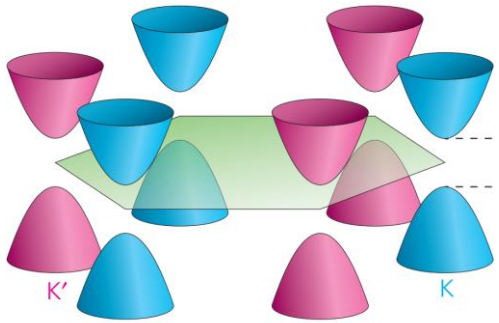
↕

Small distance δr (atomic scale)

→ Atomic defects?
→ Sharp potential boundary?
→ Phonons?

hBN/BLG/hBN





Shimazaki *et al.*, Nat.Phys. 2015

2D valleys protected from defects at interface!

Valley is a robust quantum number!

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Valleys in BLG

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Reciprocal space

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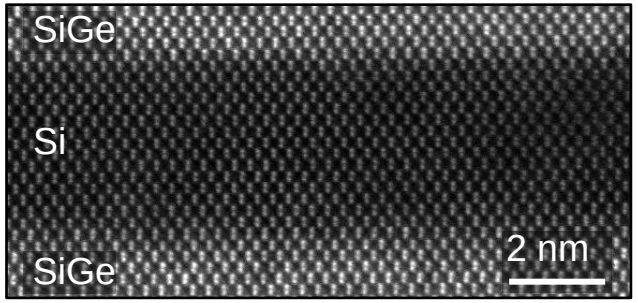
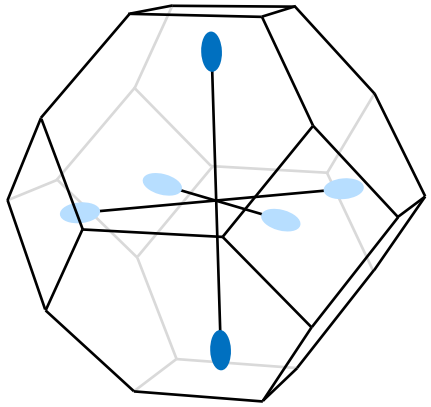


Borjans *et al.*, PRApplied 2022



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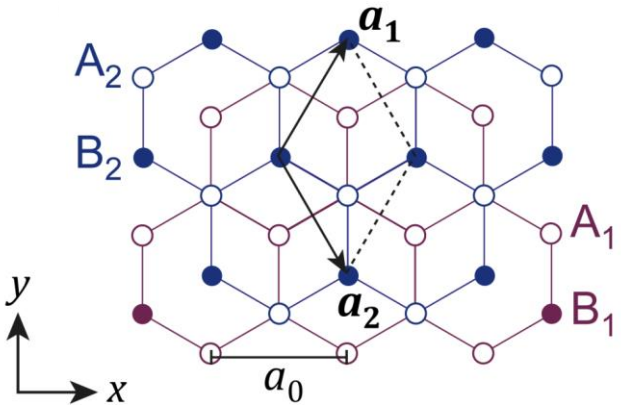

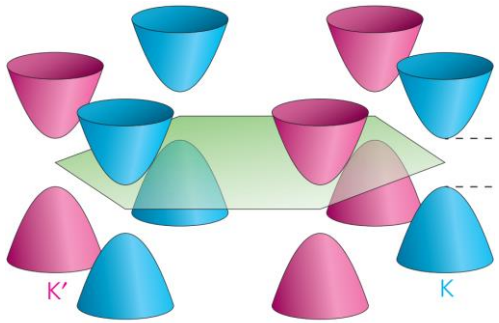

Shimazaki *et al.*, Nat.Phys. 2015

2D valleys protected from defects at interface!

Valley is a robust quantum number!

Singlet-Triplet $T_1^{\text{valley}} \approx 800$ ms $T_1^{\text{spin}} \approx 50$ ms

Garreis, Tong *et al.*, Nature Physics 2024

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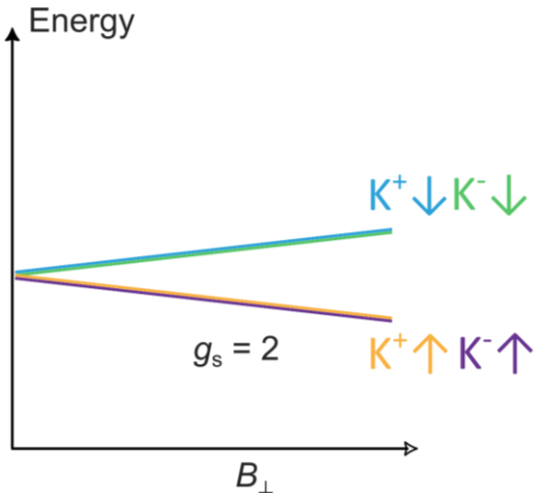
Single-Carrier Spectrum in BLG Quantum Dot

- **Two well defined quantum numbers:**

→ 4-fold degeneracy $|K^+\uparrow\rangle$ $|K^+\downarrow\rangle$ $|K^-\uparrow\rangle$ $|K^-\downarrow\rangle$



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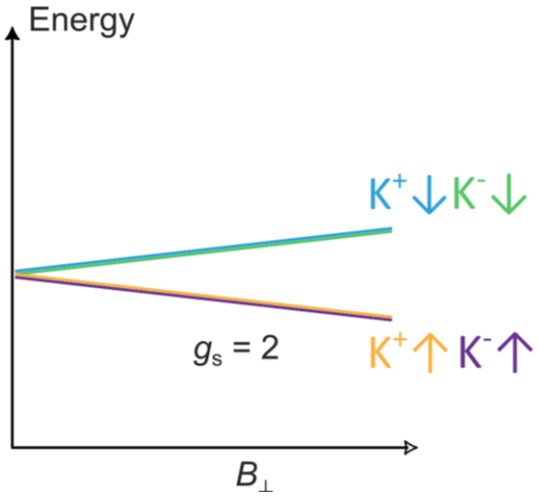
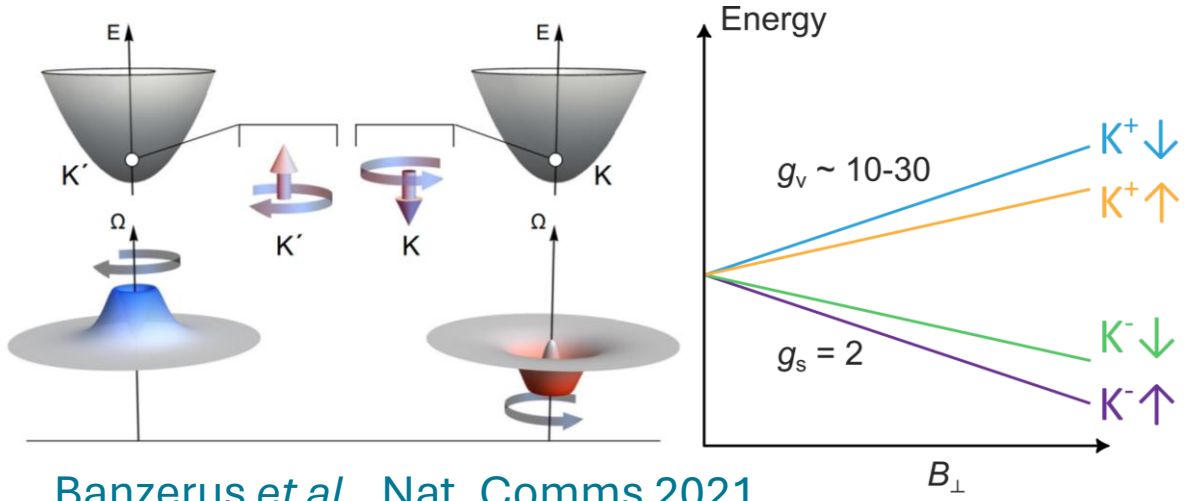


- **Non-trivial Berry curvature:** A. Knothe *et al.*, PRB 2018

→ large orbital valley magnetic moment g_V-factor



Banzerus *et al.*, Nat. Comms 2021

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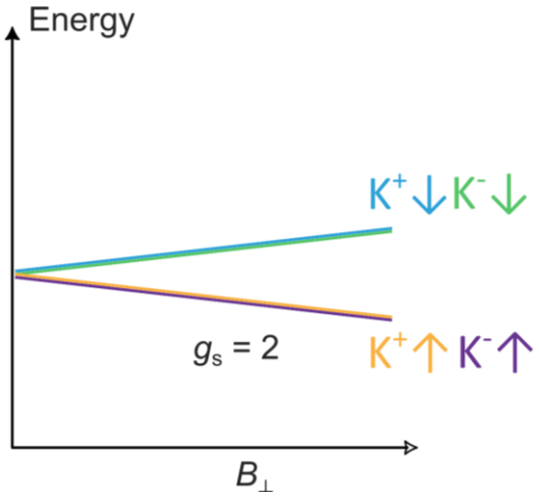

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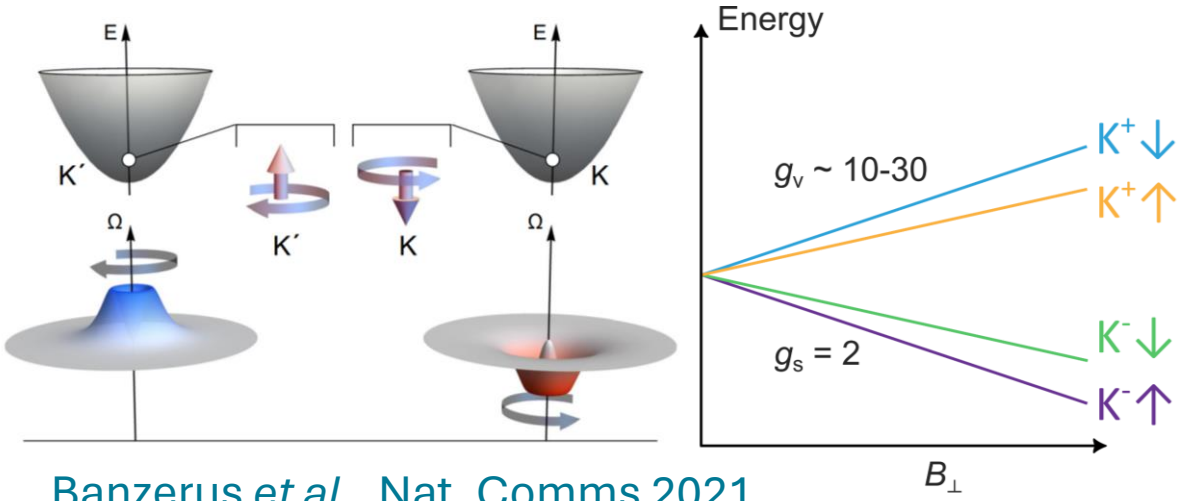


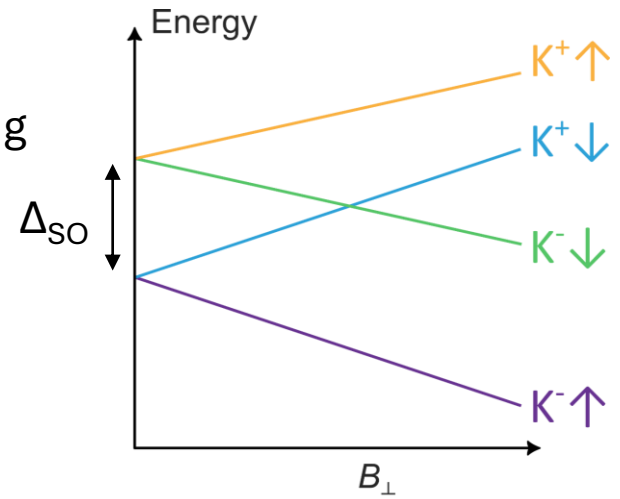
Banzerus *et al.*, Nat. Comms 2021

- **Intrinsic Kane-Mele Spin-Orbit coupling**

→ zero-field, momentum-independent splitting of Kramers pairs: $(K^+\uparrow\rangle\ |K^-\downarrow\rangle)$ and $(K^-\uparrow\rangle\ |K^+\downarrow\rangle)$

$$\hat{H}_{\mathrm{SO}} = \frac{1}{2}\Delta_{\mathrm{SO}}\hat{\sigma}^z\hat{\tau}^z$$

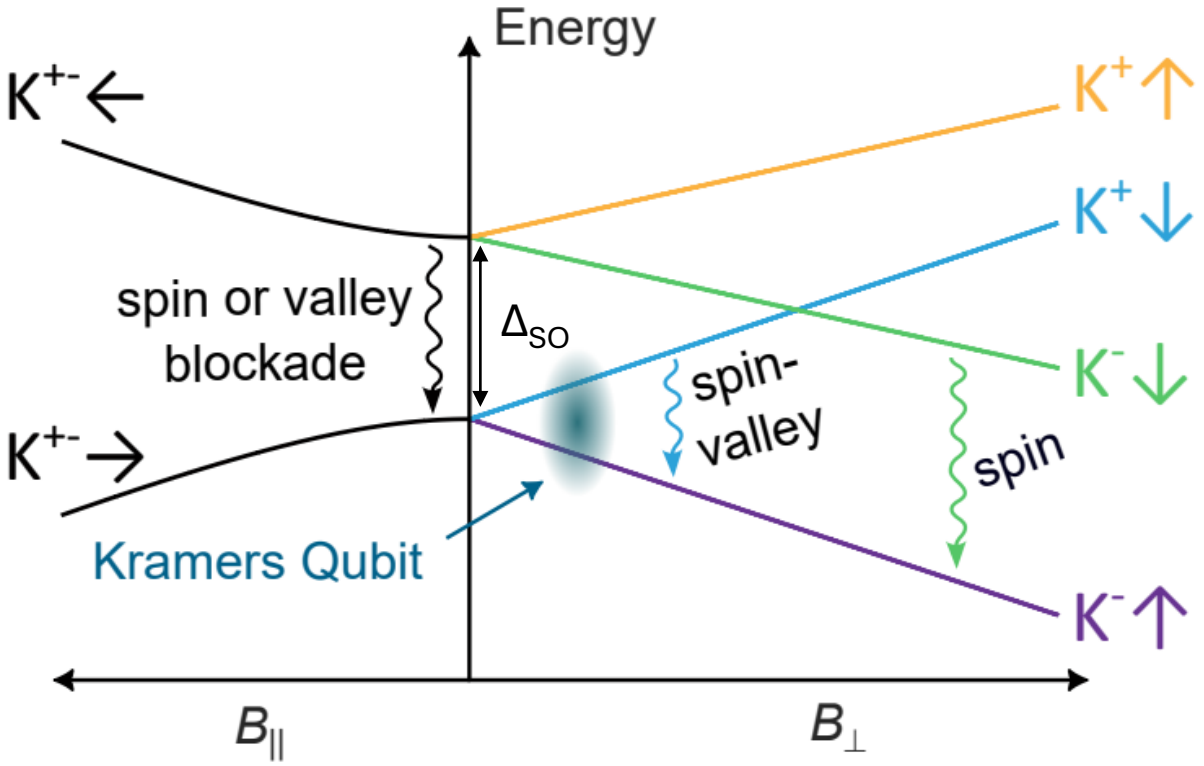
Kane and Mele *et al.*, PRL 2005

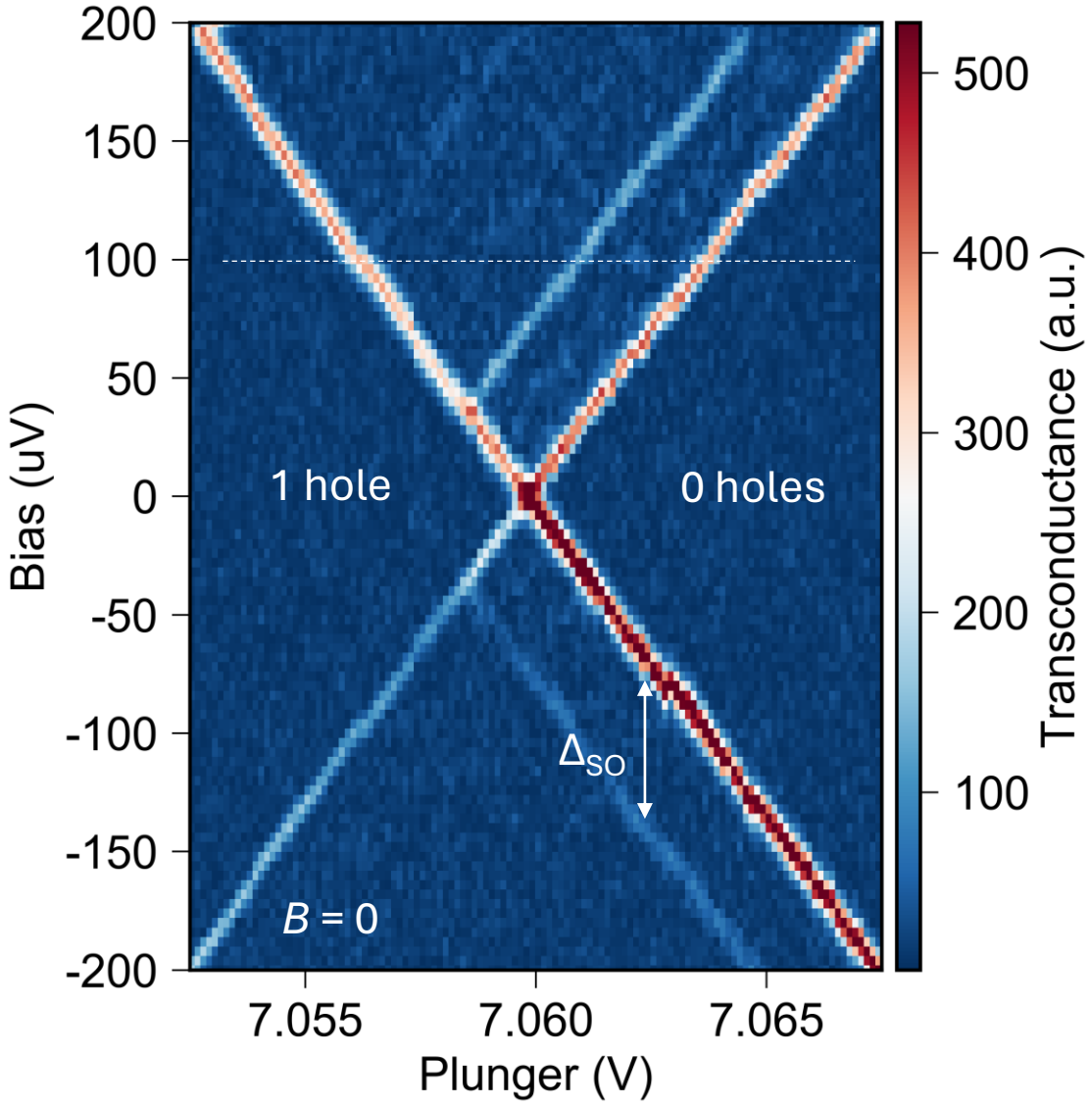


$$\Delta_{\mathrm{SO}} = 60\text{–}80\ \mu\mathrm{eV}$$

Kurzmann *et al.*, Nat. Com. 2021
Banzerus *et al.*, Nat. Com. 2021
Banzerus *et al.*, Nat.Com. 2022
Duprez *et al.*, arXiv:2311.12949
Denisov *et al.*, arXiv:2403.08143

Experimental Single-Carrier Spectrum in BLG QD





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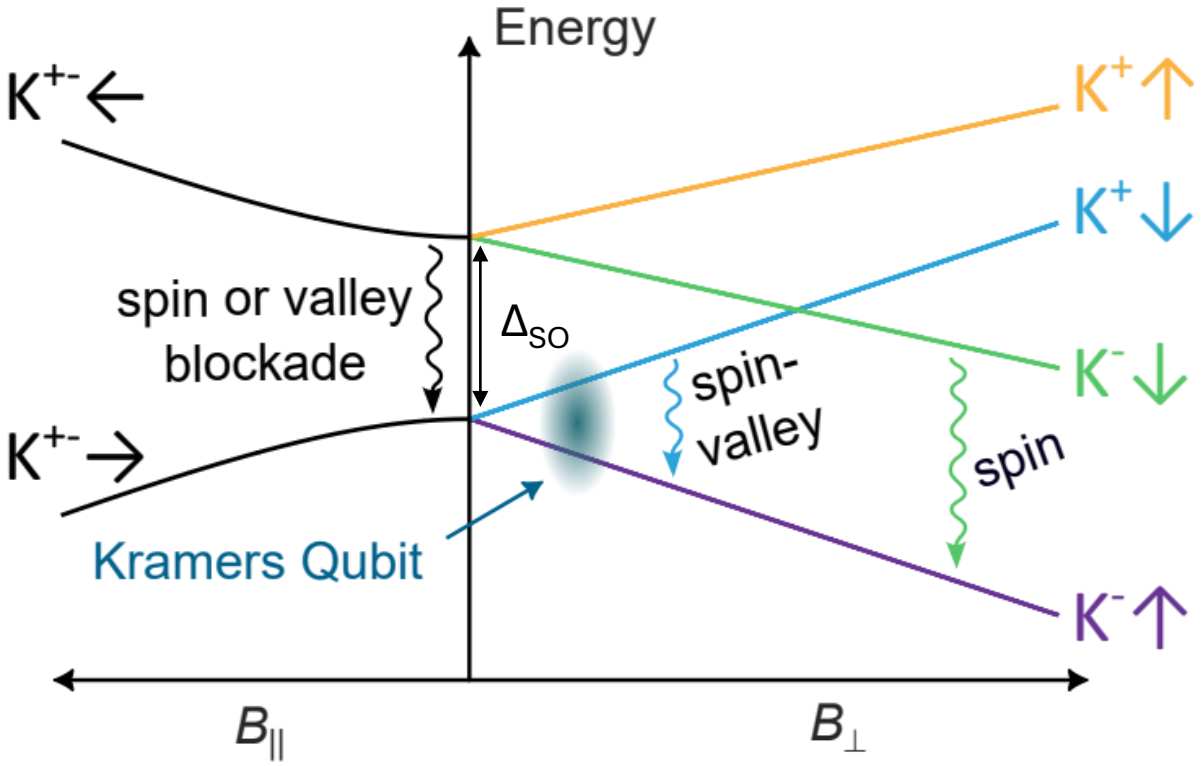

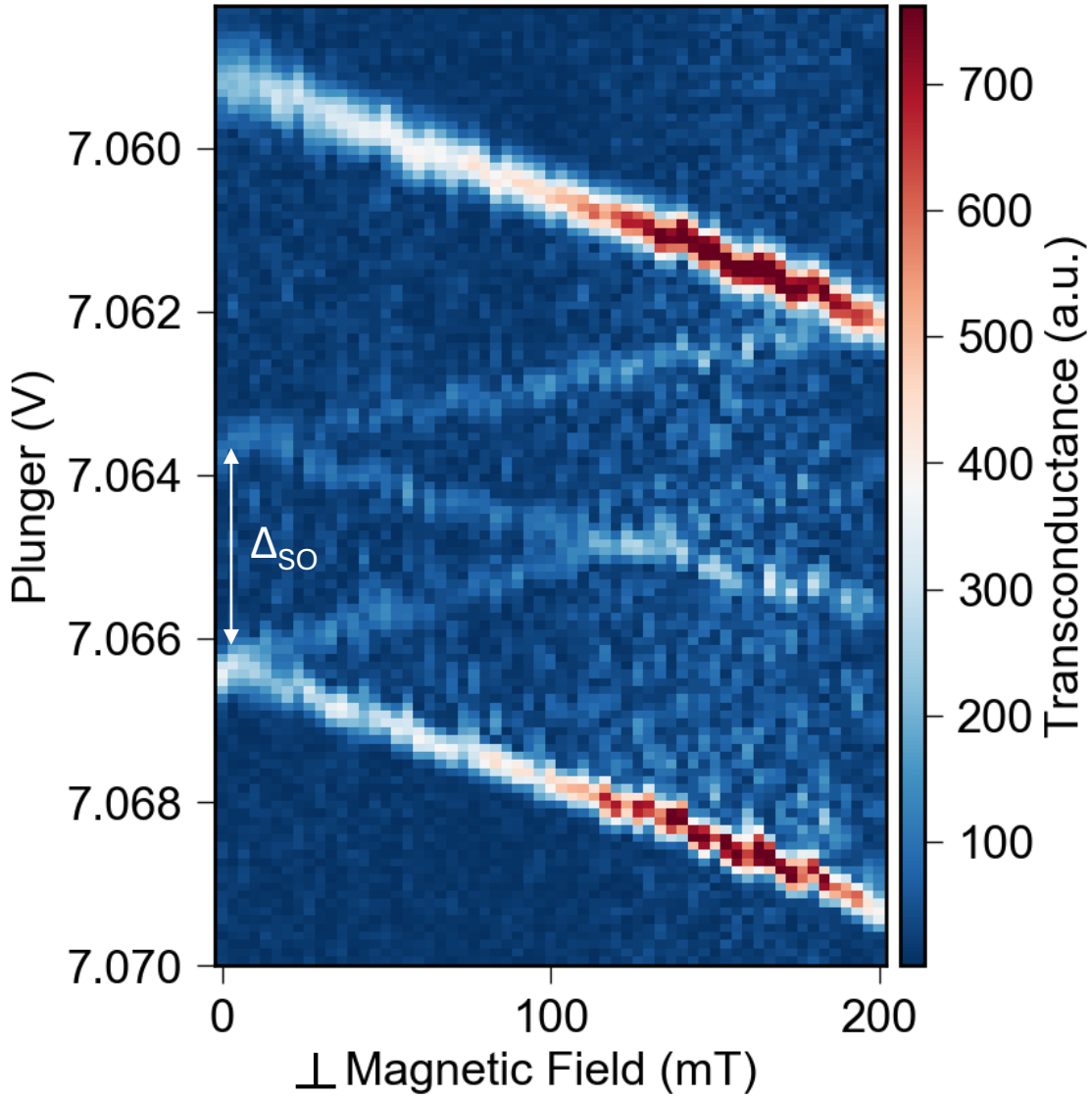

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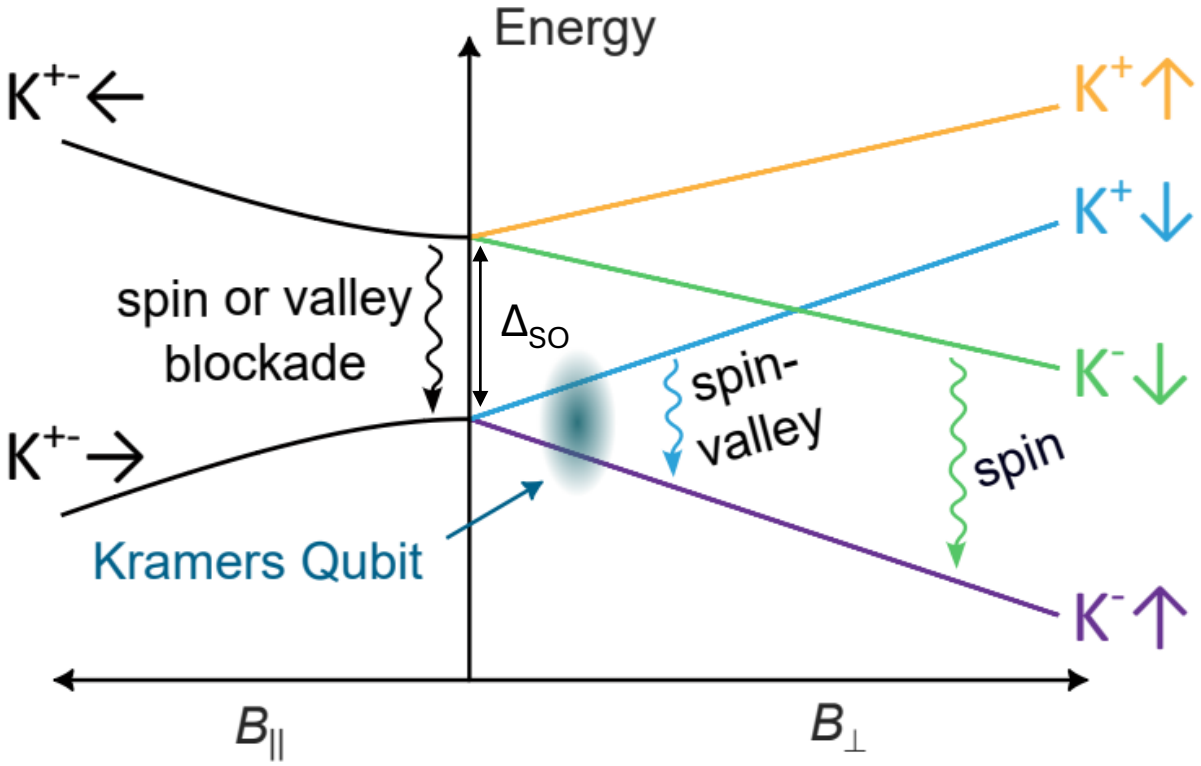
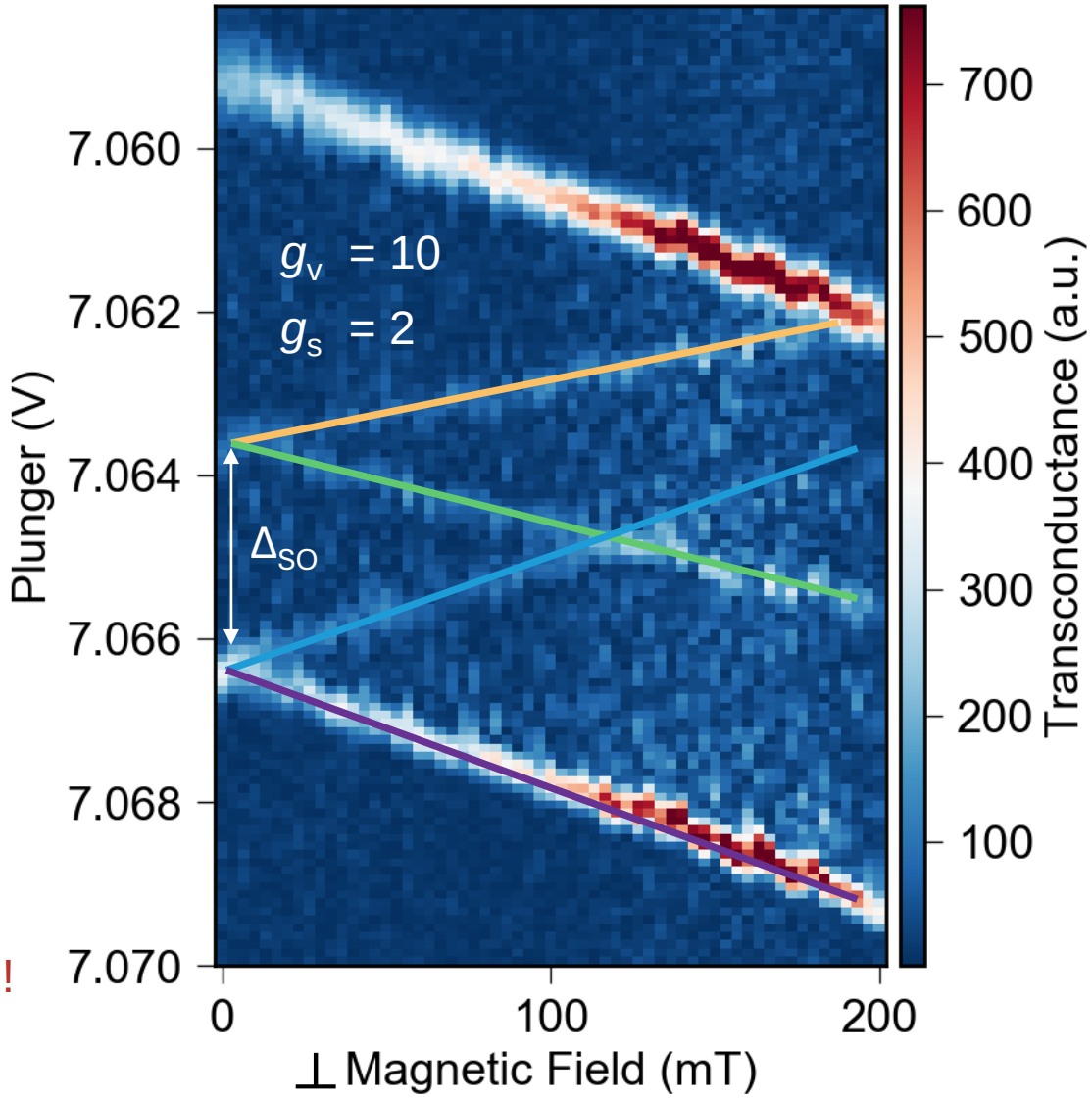
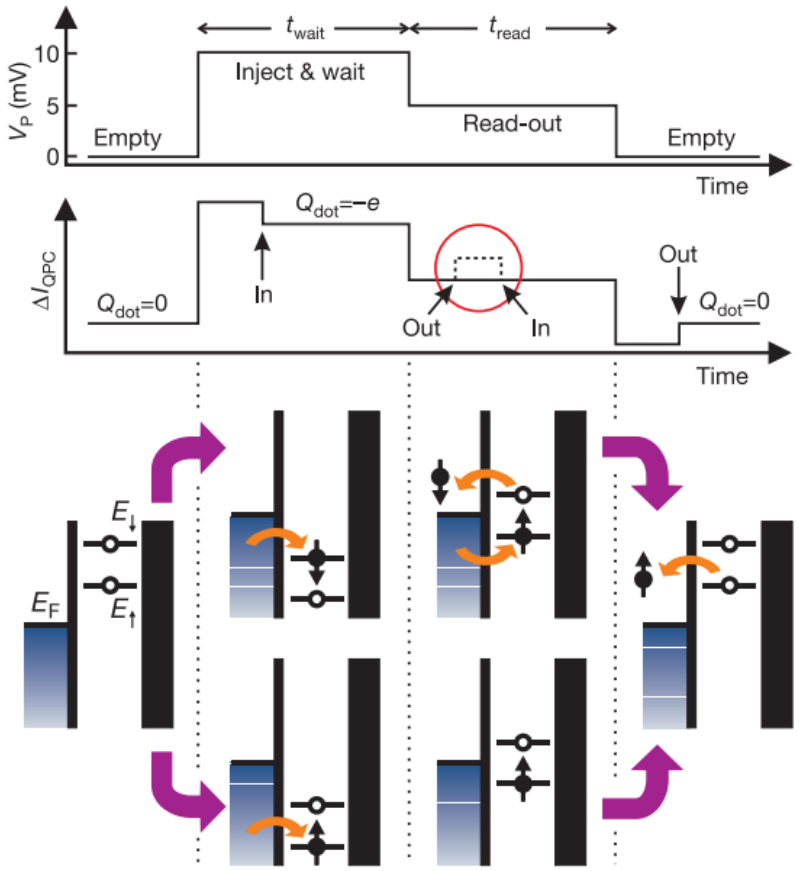


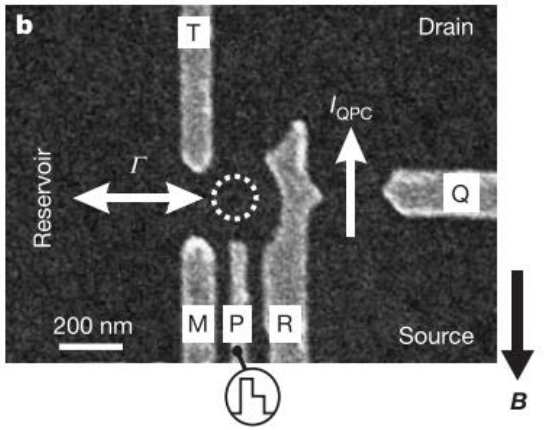


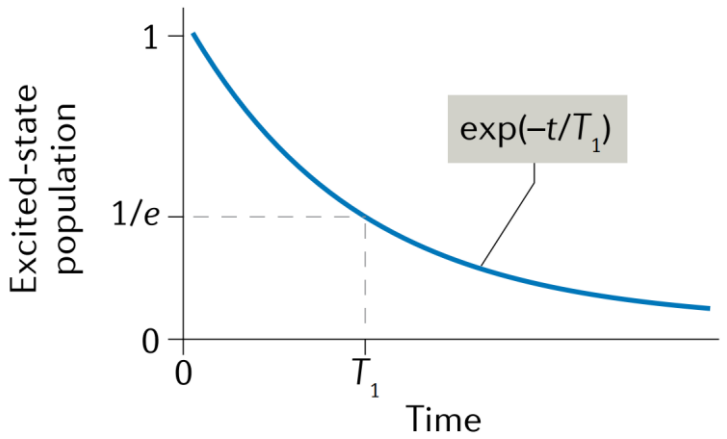
Flipping both quantum numbers is a rare second-order process!
Extreme spin-valley coherence and life-time?

Measuring the lifetime: Single-Shot Elzerman Readout



Elzerman *et al.*, Nature 2004

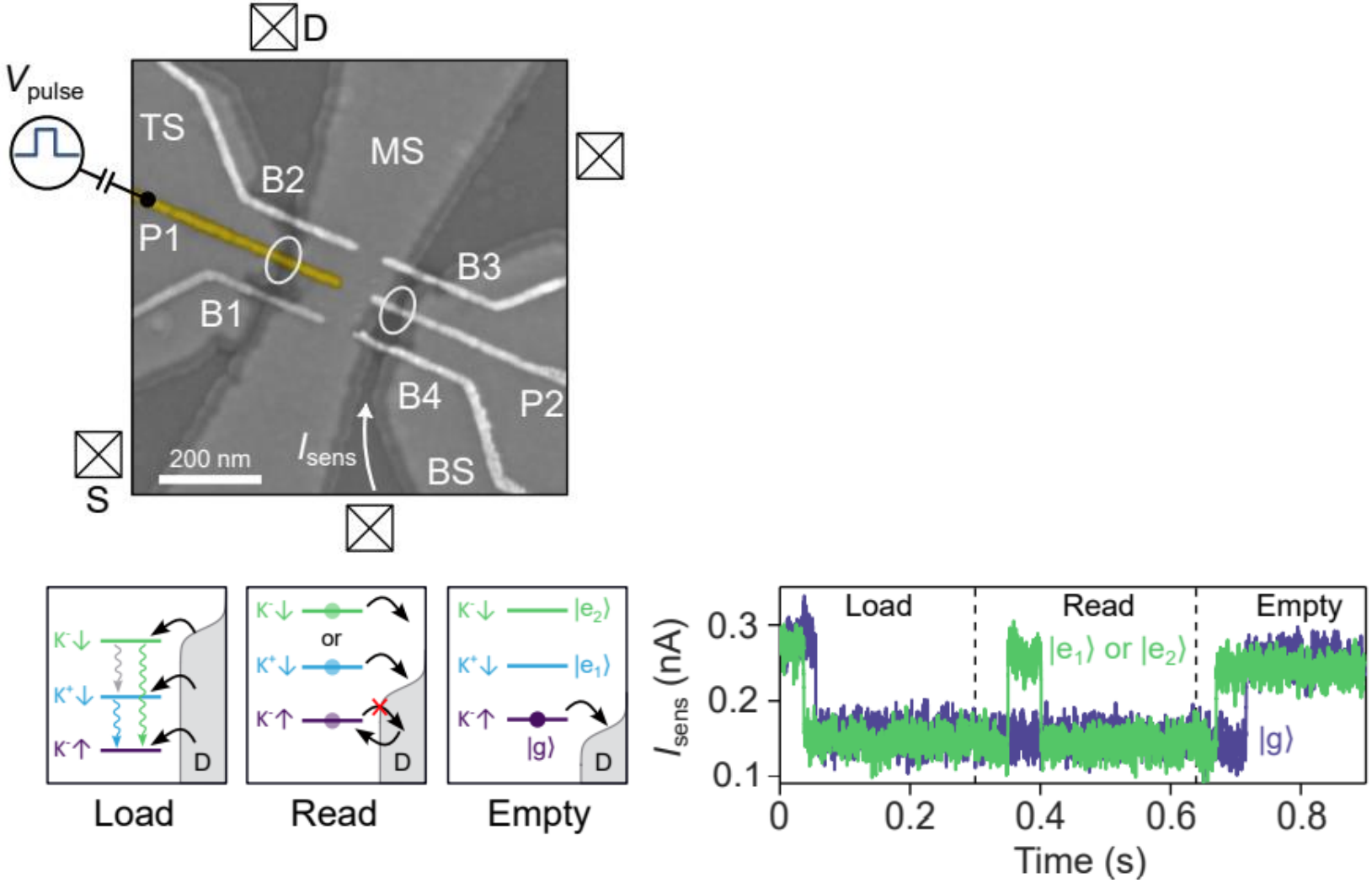




Stano and Loss *et al.*, Nat. Rev. Phys. 2022

Single-Shot Elzerman readout in BLG

Denisov *et al.*, arXiv:2403.08143



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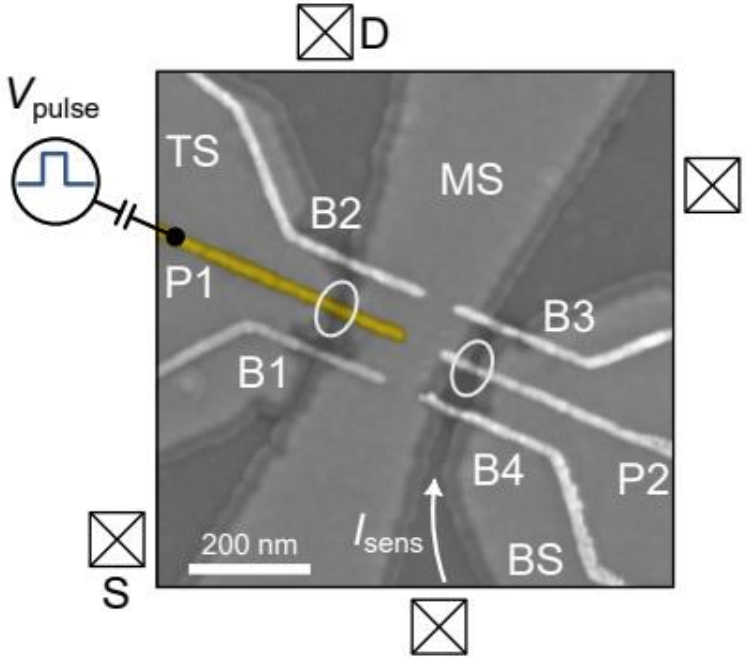
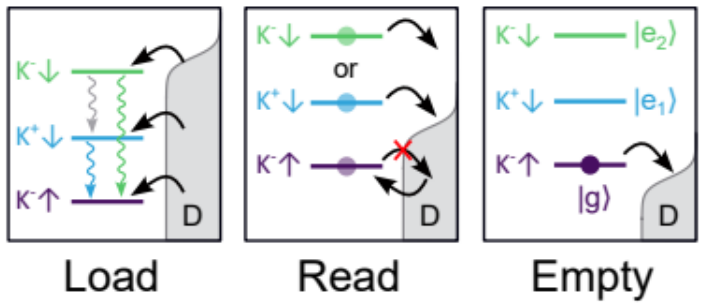
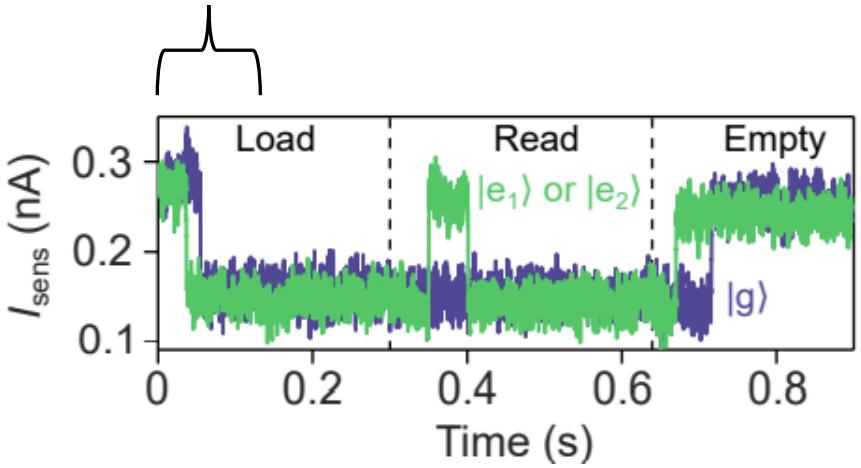




Low tunneling rates ~ 20 Hz

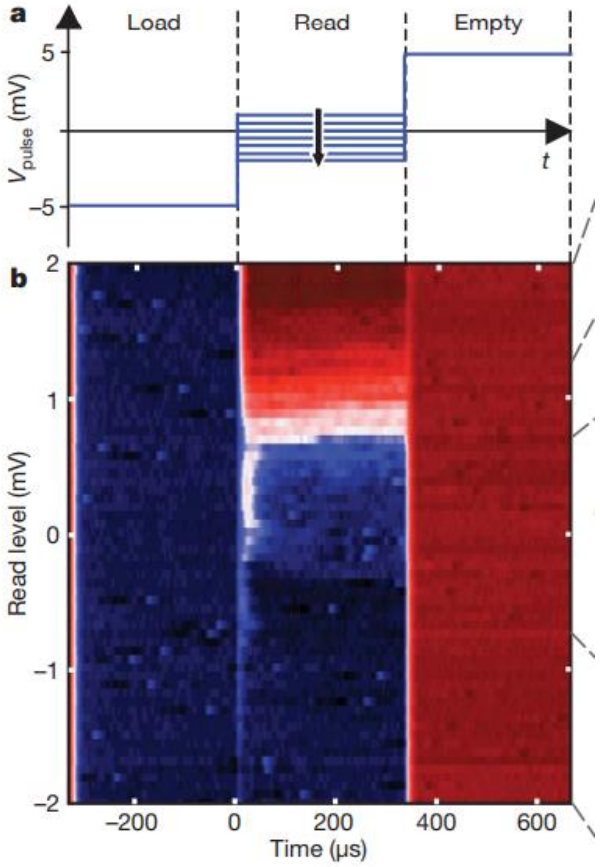
→ QD is highly decoupled from leads!

→ How to measure spectrum?

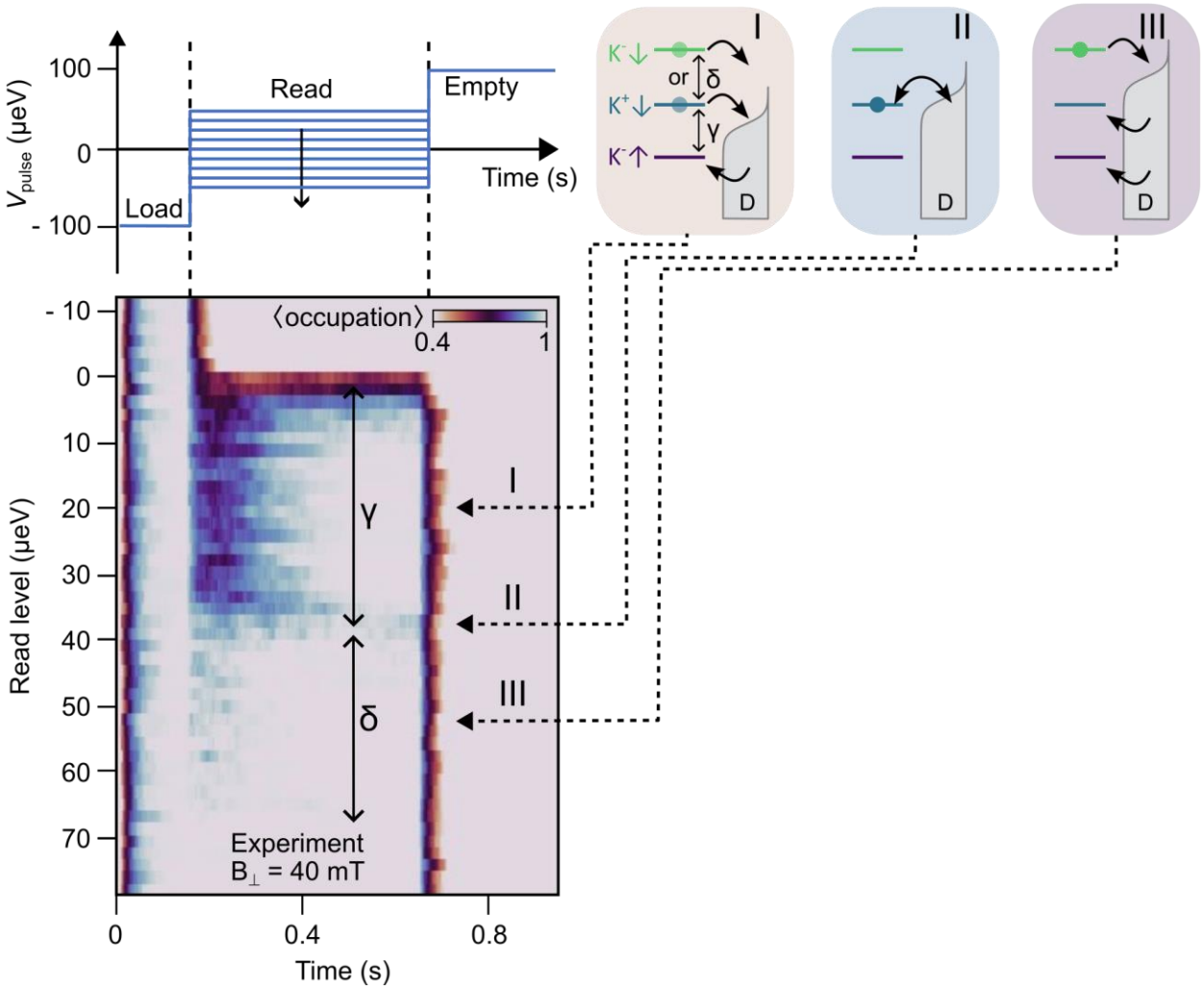


Single-Shot Spectroscopy of The Highly Decoupled QD

Read-out level calibration

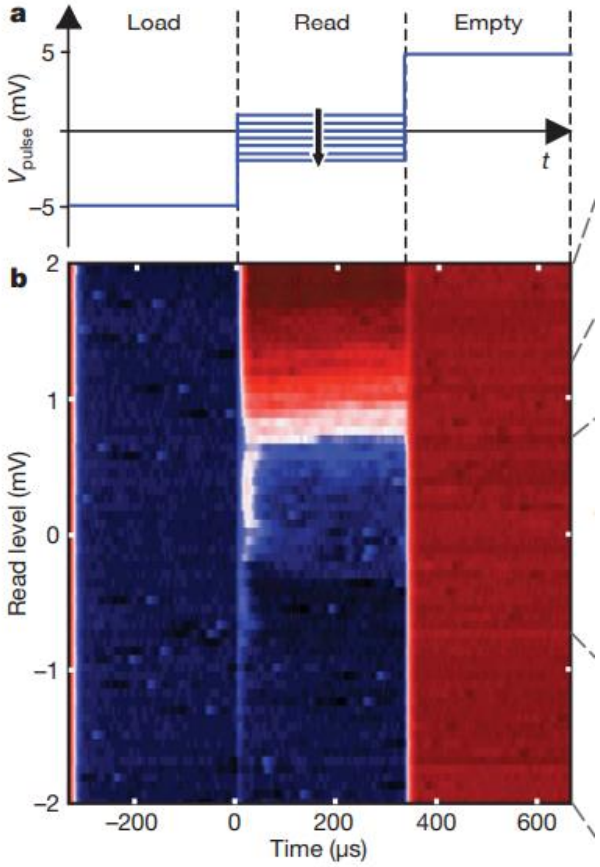


Morello *et al.*, Nature 2010



Single-Shot Spectroscopy of The Highly Decoupled QD

Read-out level calibration



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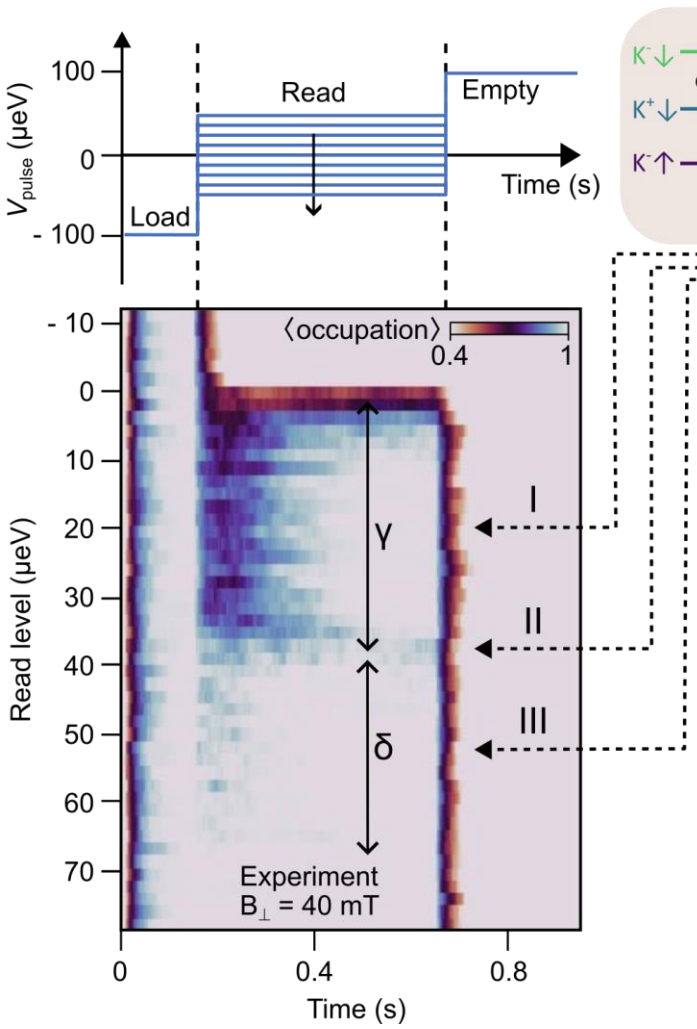
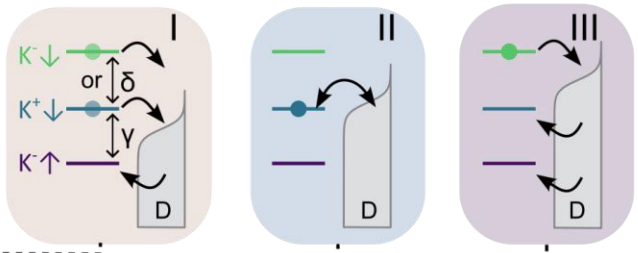
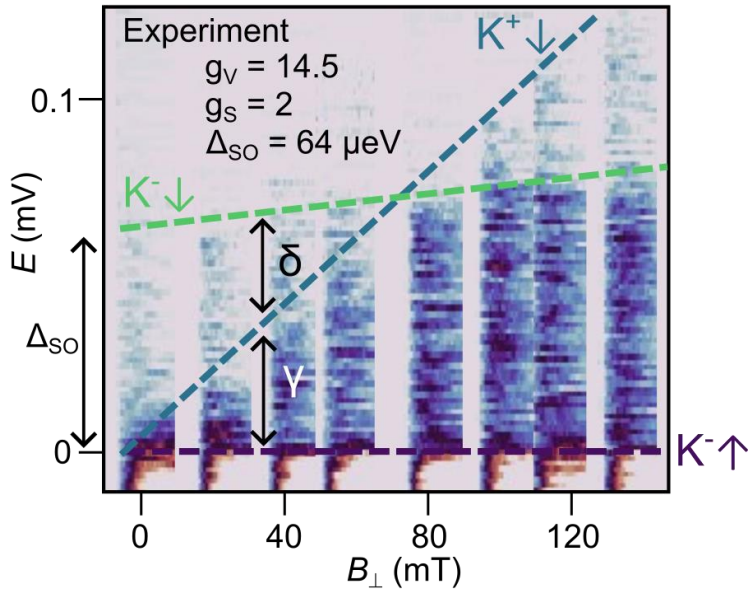
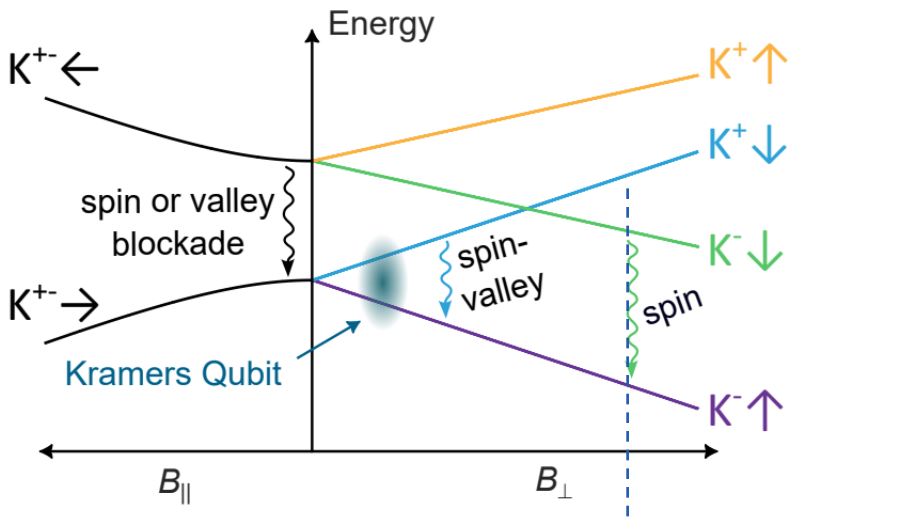


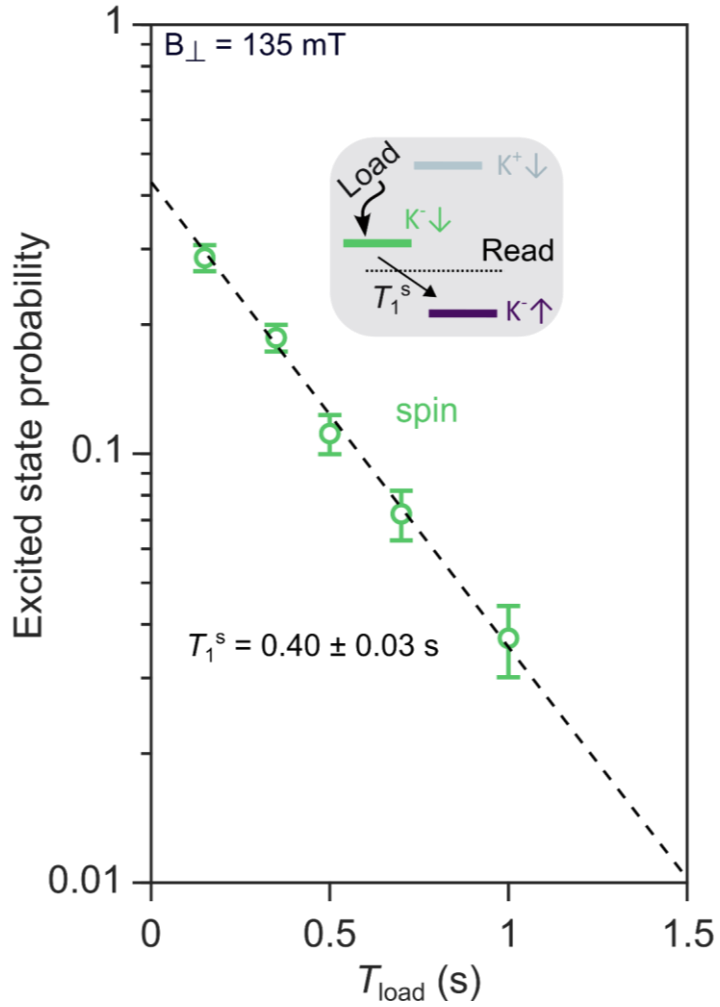




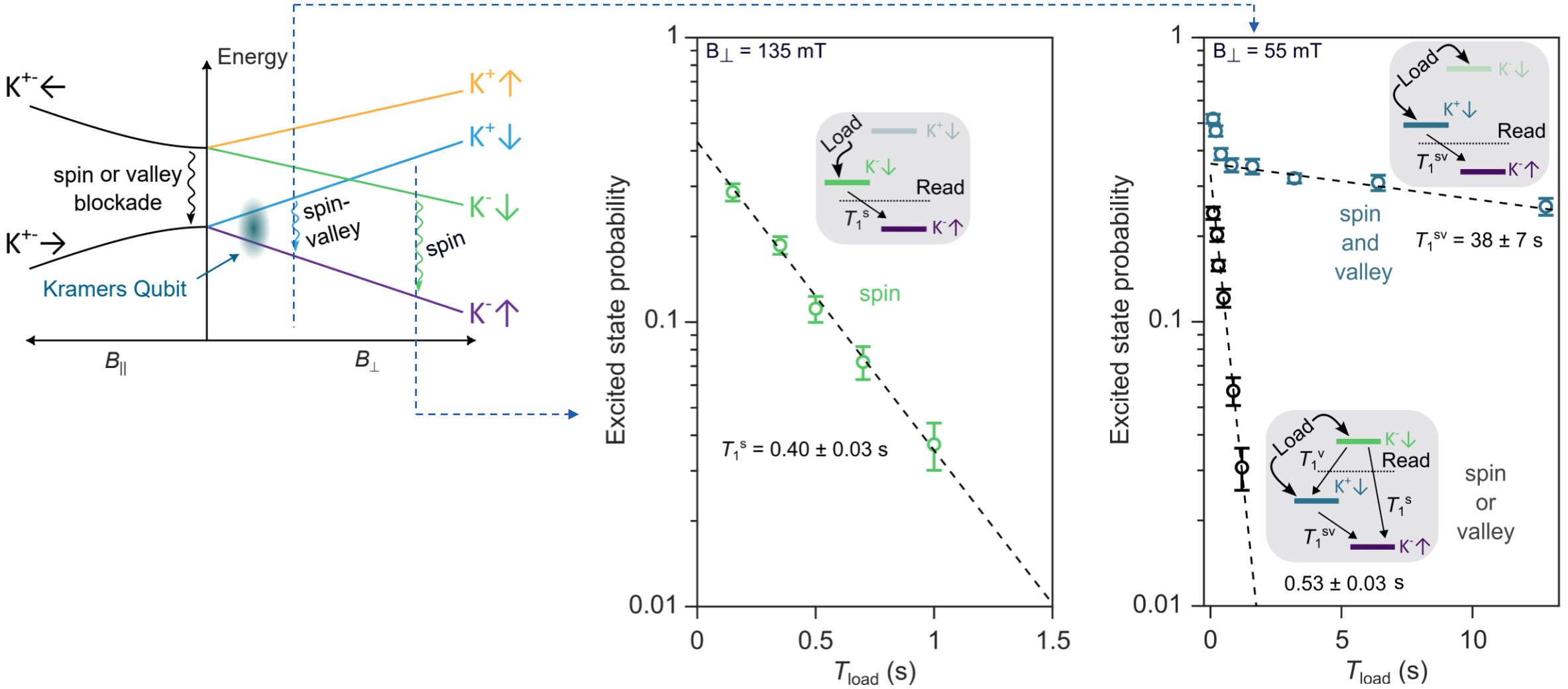
Spectrum reconstructed

T_1 Measurements



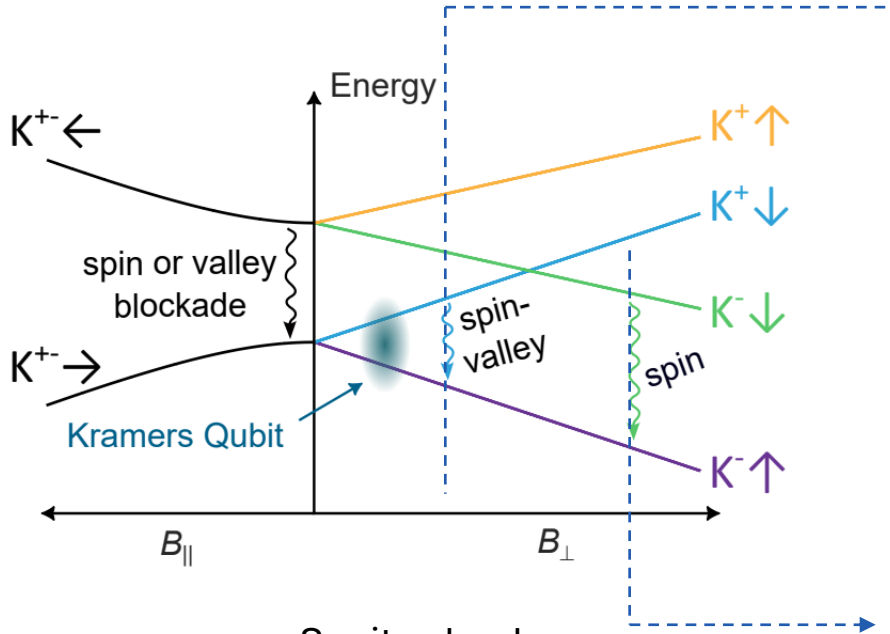


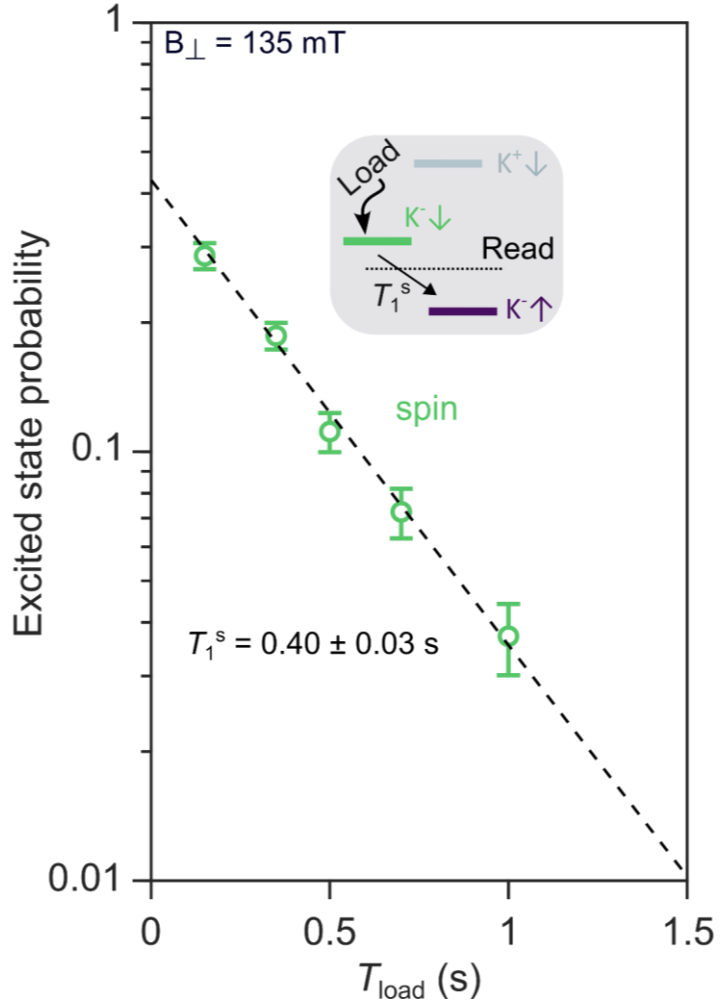
T_1 Measurements

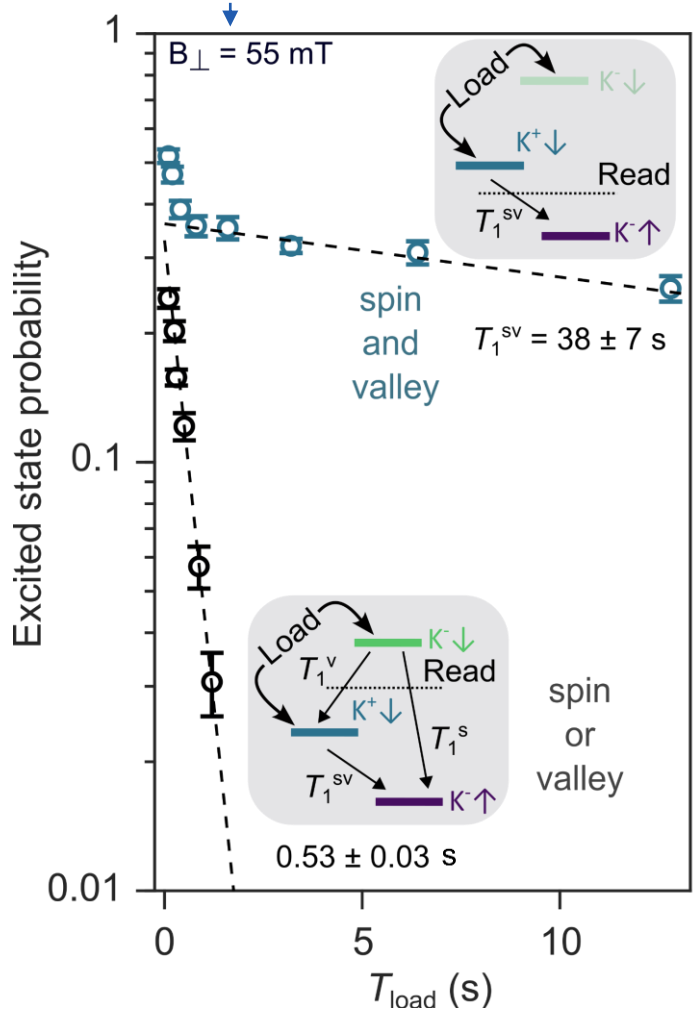


Denisov *et al.*, arXiv:2403.08143

T_1 Measurements





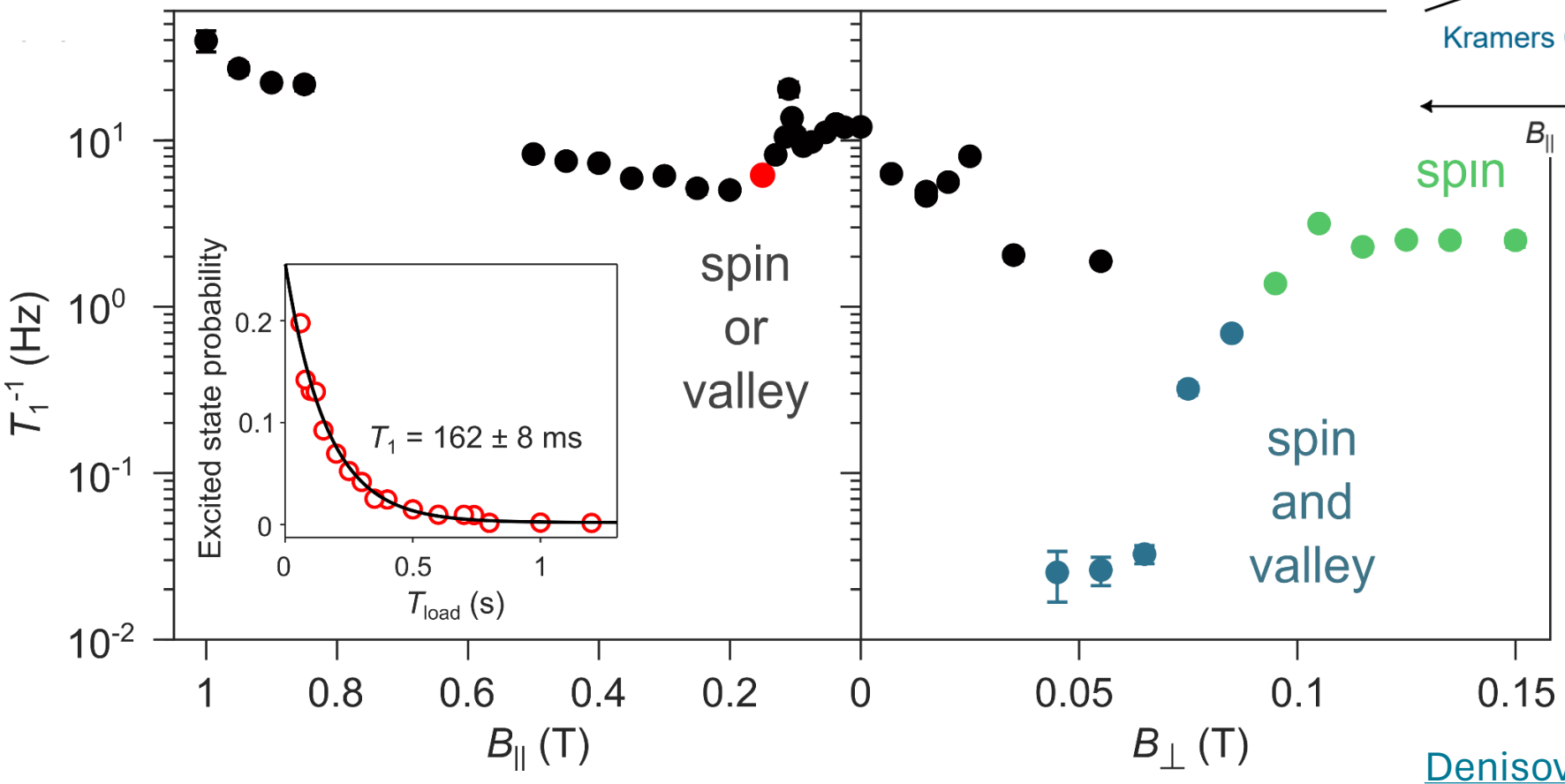


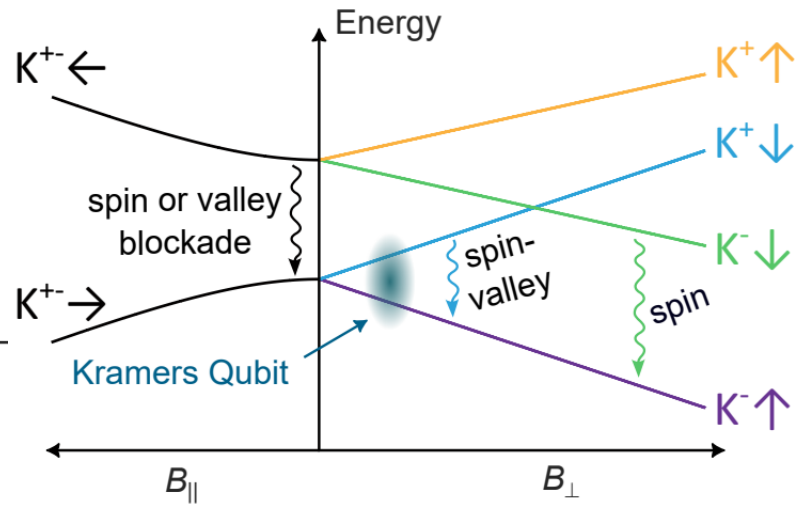
Time	Coherence	Qubit	Material	Host	Date
57 s	T_1	LD/e	GaAs/AlGaAs	2D	2018-08
30 s	T_1	LD/i	Si:P	imp	2017-03
10 s	T_1	LD/e	GaAs/AlGaAs	2D	2017-10
9.8 s	T_1	LD/i	Si:P	imp	2019-05
9.3 s	T_1	LD/i	Si:P	imp	2018-03
9 s	T_1	LD/e	Si/SiO_2	1D	2021-03
6 s	T_1	LD/i	Si:P	imp	2010-09

Denisov *et al.*, arXiv:2403.08143

Stano and Loss *et al.*, Nat. Rev. Phys. 2022

Magnetic Field Dependence of T_1





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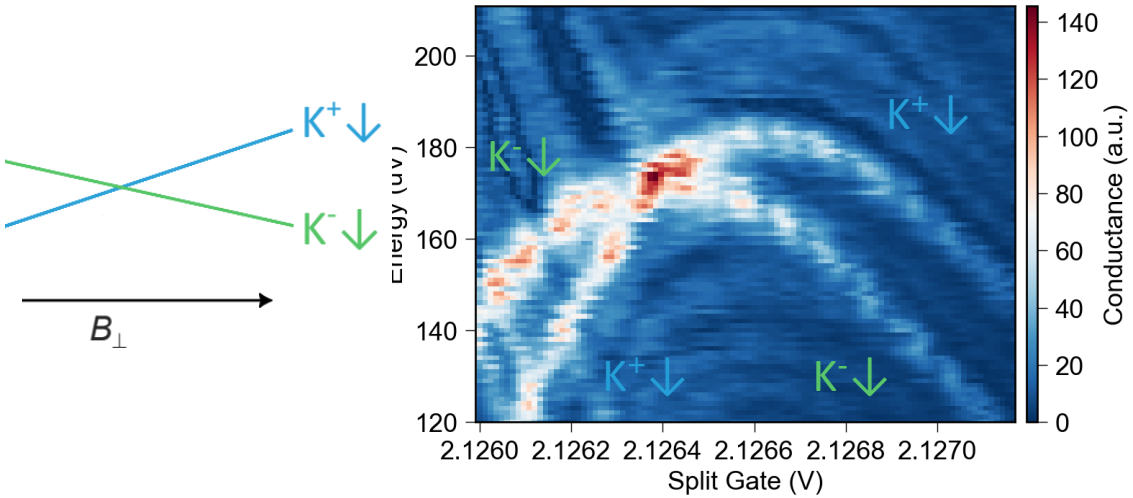
Outlook: Spin/Valley Qubits in BLG

- **How to flip valley or spin-valley controllably ?**

→ electrically tunable g_v-factor (Tong *et al.*, Nano Letters 2021)

→ curving the QD (Laird *et al.*, Nat. Nano. 2013)

→ atomic defects



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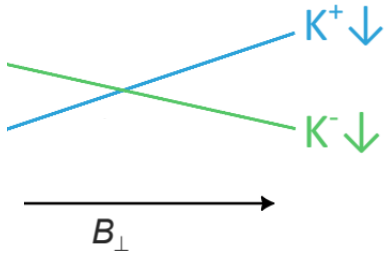
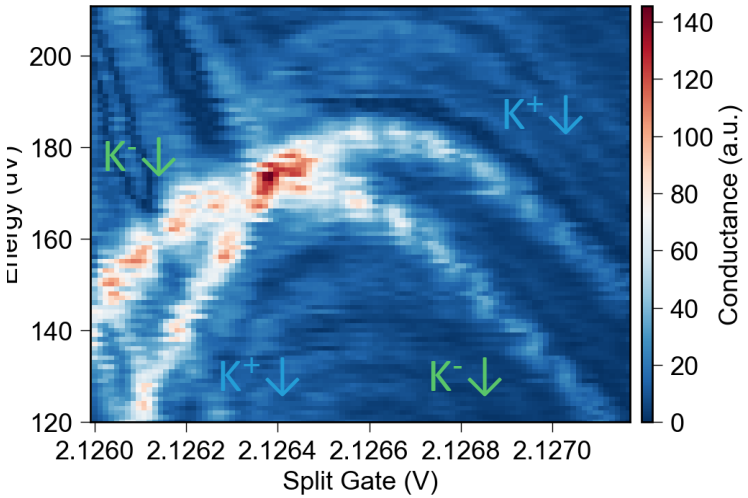
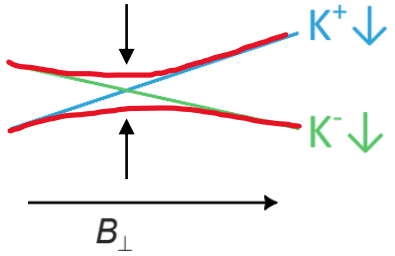




- **Valley qubit and valley mixing term**

→ how low is the valley intermixing term $\Delta_{K+K-} < 2$ neV ?

Garreis, Tong *et al.*, Nature Physics 2024



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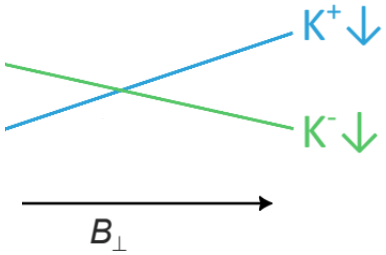

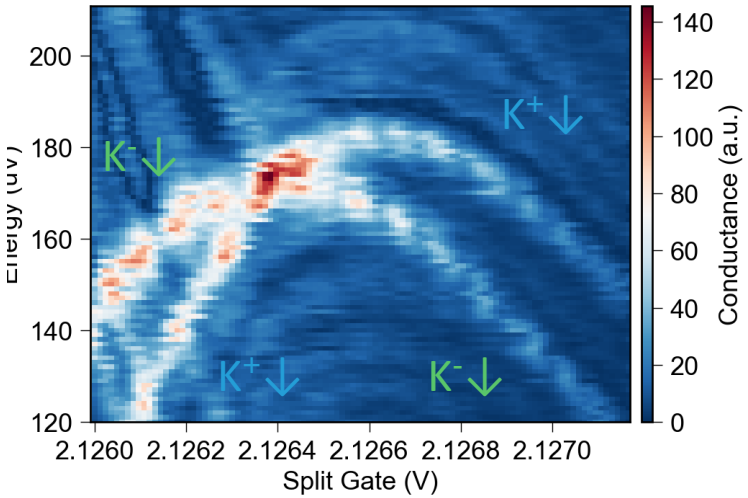

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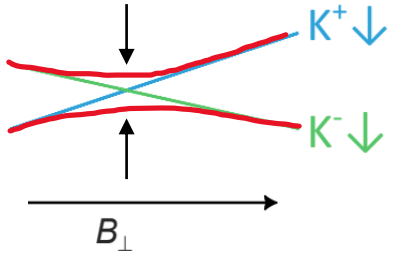
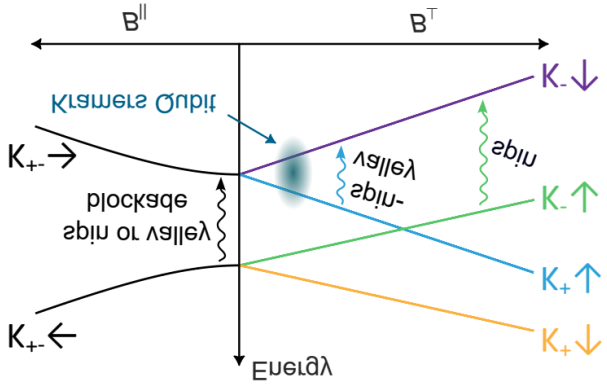


- **3-carrier dot:**

→ Inverted spectrum

→ Realistic EDSR frequency



$$\Delta_{\mathrm{SO}} \approx 40 - 80\,\mu\mathrm{eV} \mathrel{\widehat{=}} 10 - 20\,\mathrm{GHz}$$

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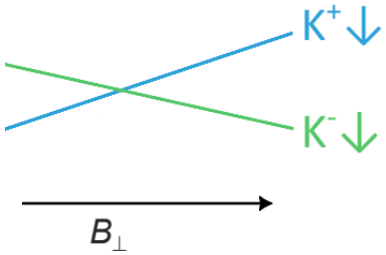

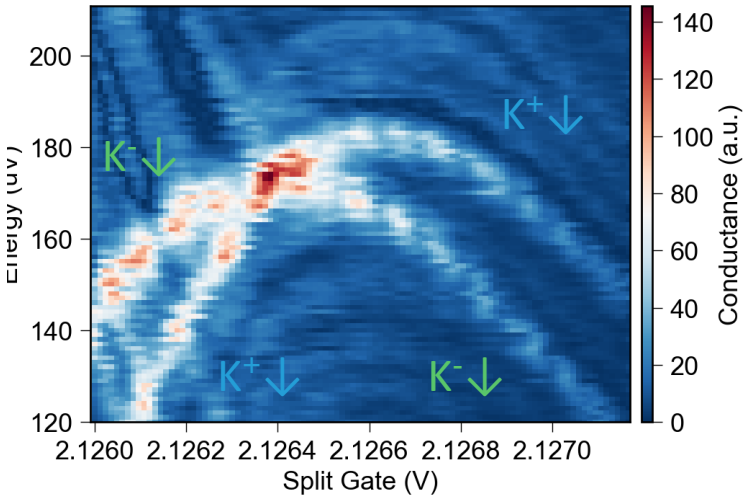

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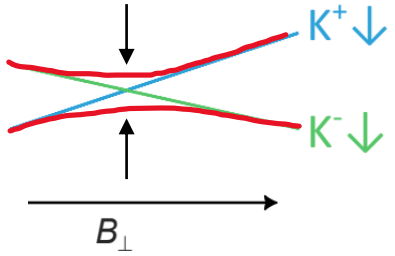

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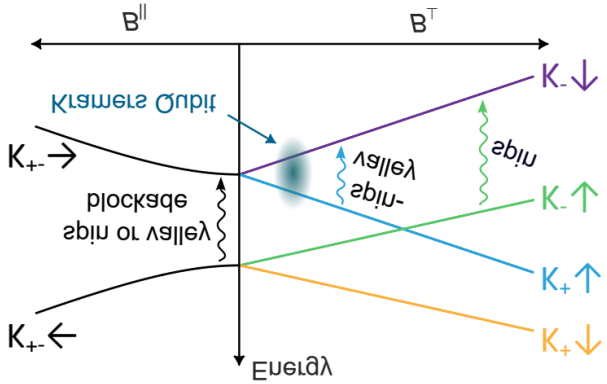


$$\Delta_{\mathrm{SO}} \approx 40 - 80\,\mu\mathrm{eV} \mathrel{\widehat{=}} 10 - 20\,\mathrm{GHz}$$

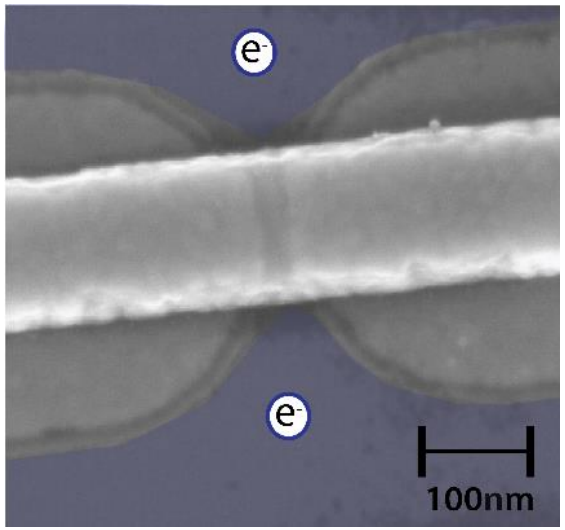
- **Zero-magnetic field spin/valley qubit**

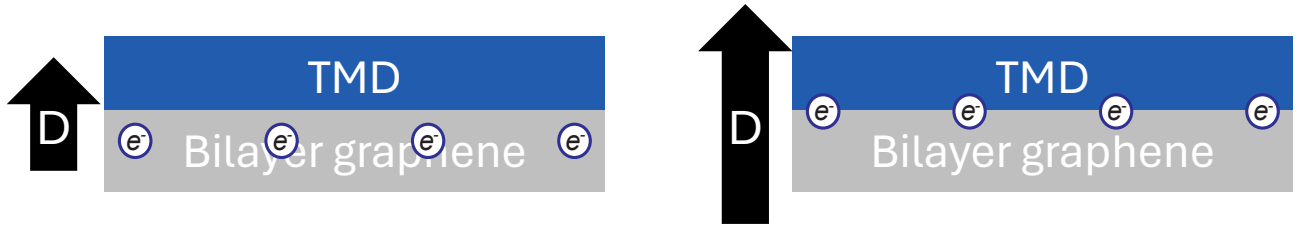
- **Kramers exchange qubit**

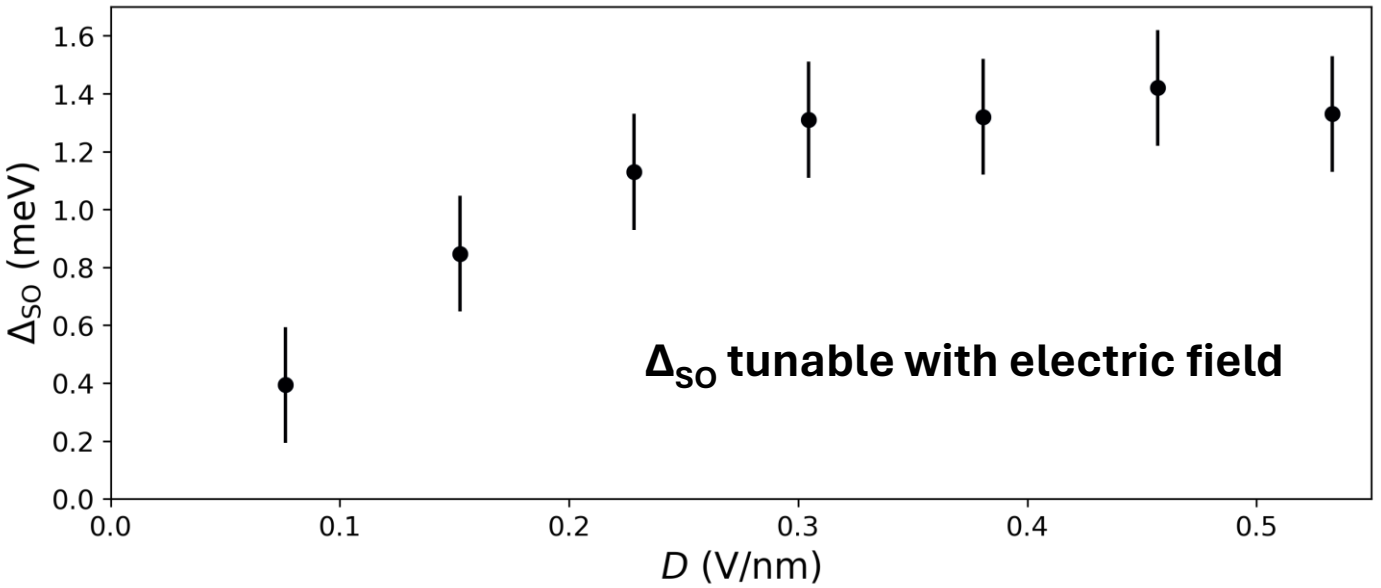
→ Two-qubit gates

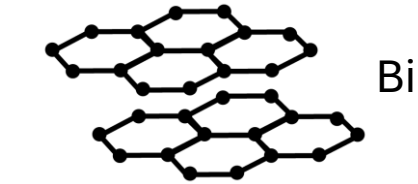
Outlook: Enhancing SOI via TMD (WS_2, WTe_2) proximity

Device by Jonas Gerber







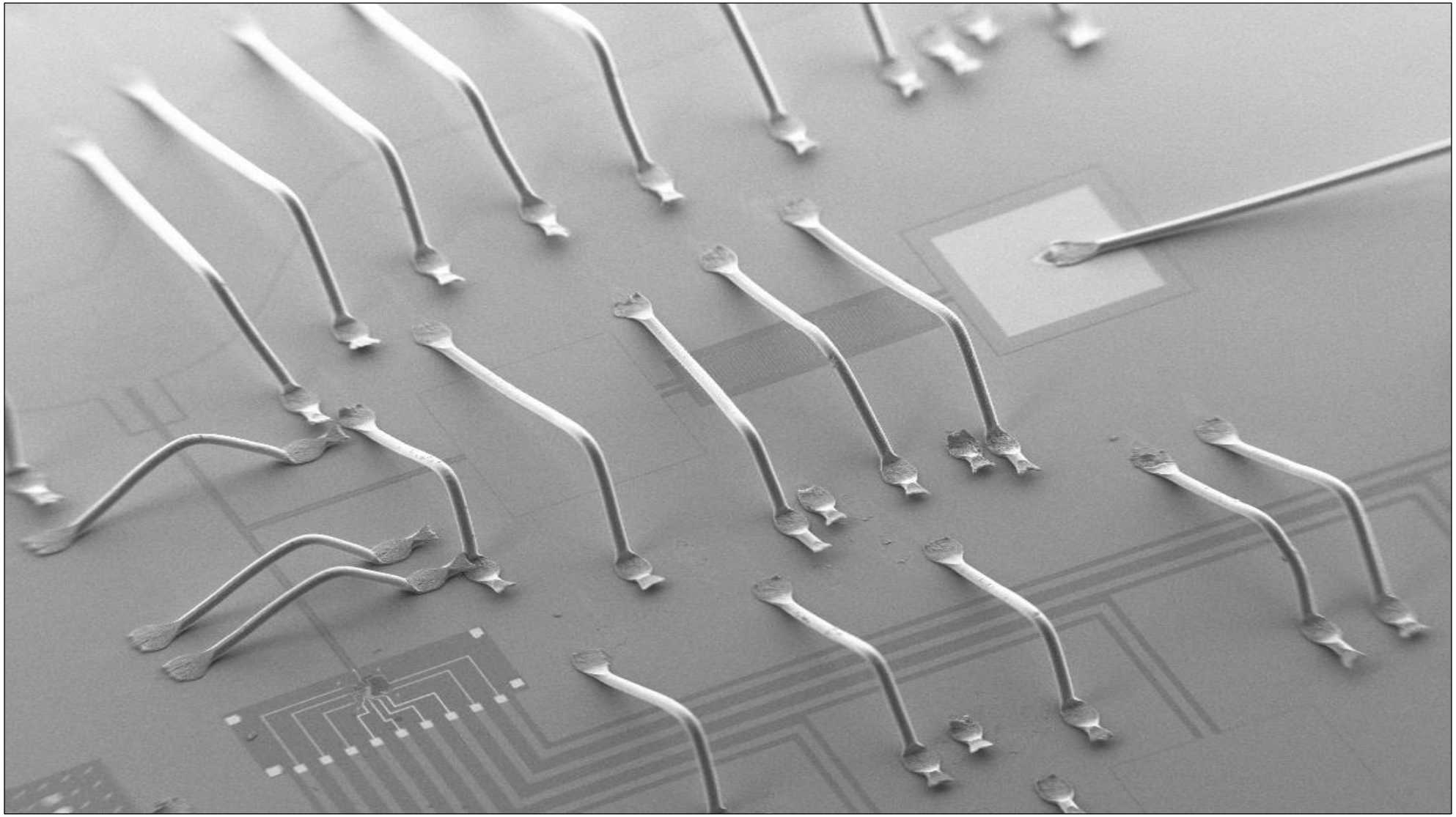


Bilayer graphene

WTe2

Outlook: cQED with BLG Quantum Dots

Device by Max Ruckriegel



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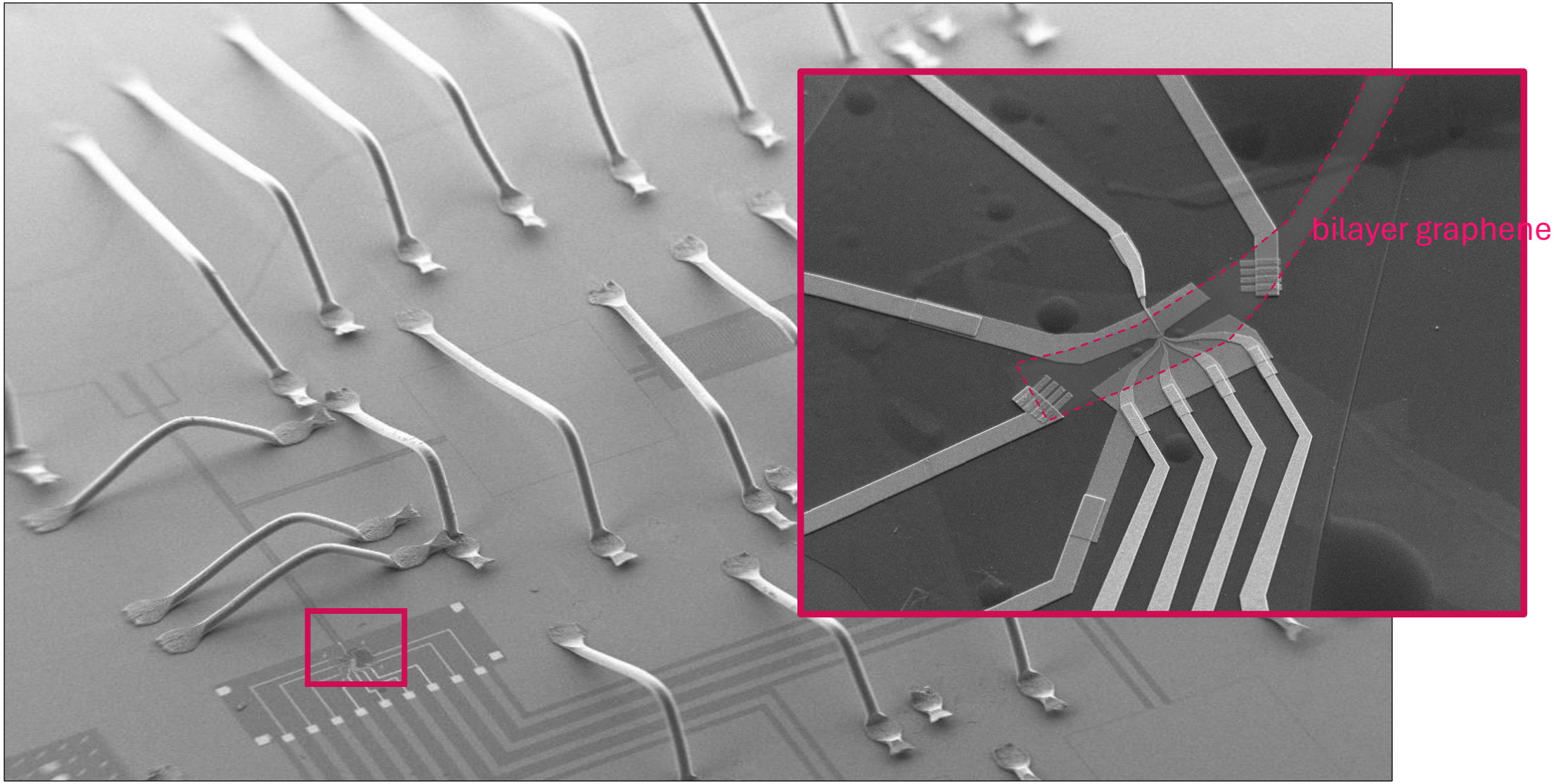
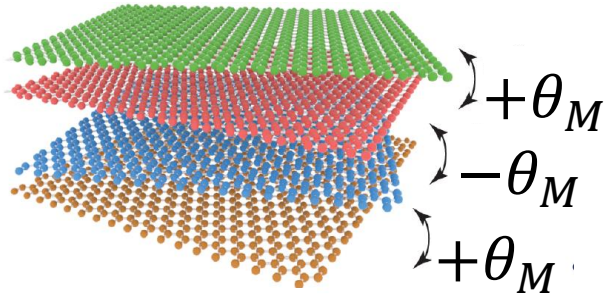


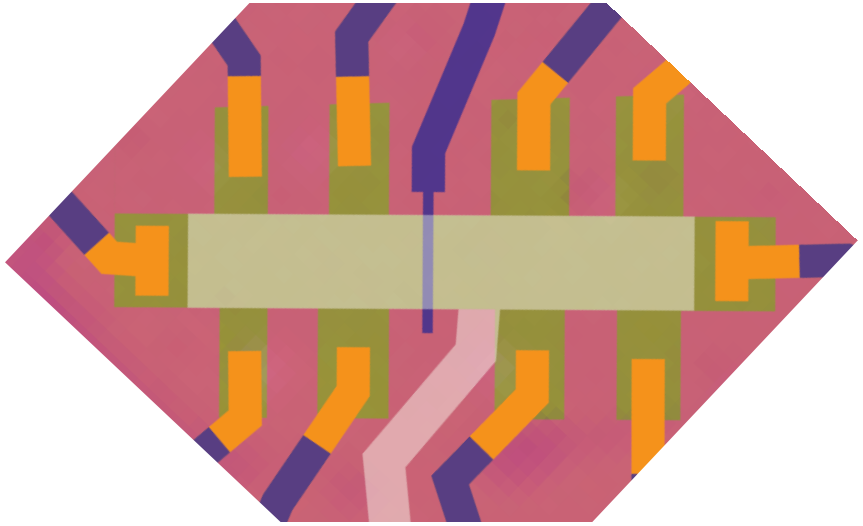
- **Charge/spin/valley-photon coupling**

Outlook: Magic Angle Twisted 4-layers Graphene

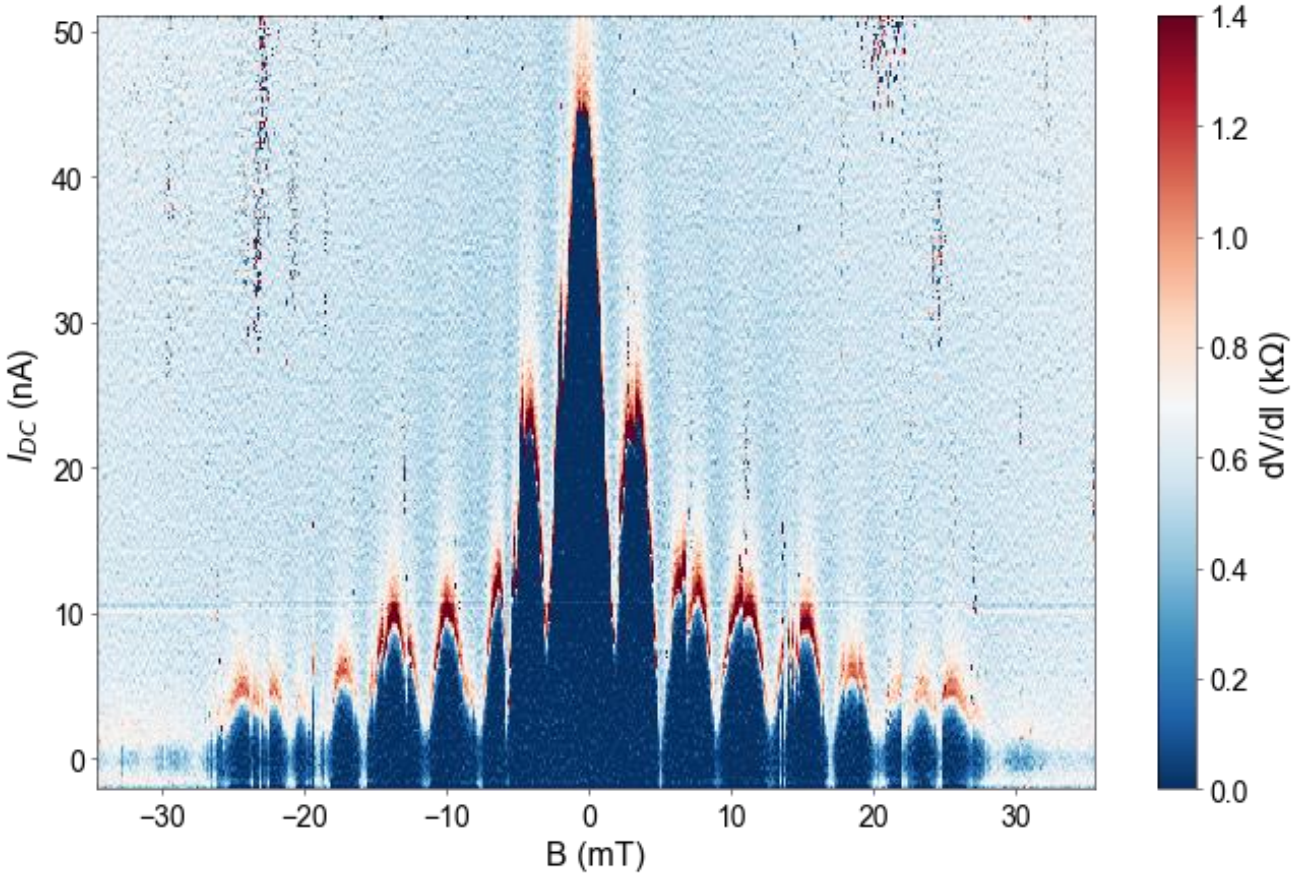
Device by Marta Perego



- Aleternating twist angle
- $\theta_M = 1.77°$

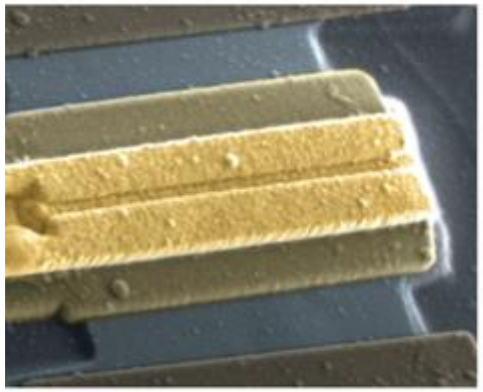


- **Andreev reflection, MAR and Hard gap?**
- **Andreev bound states?**
- **How MATBLG proximitizes normal graphene?**
- **Vortices?**



Graphene Dreams

Josephson Junctions



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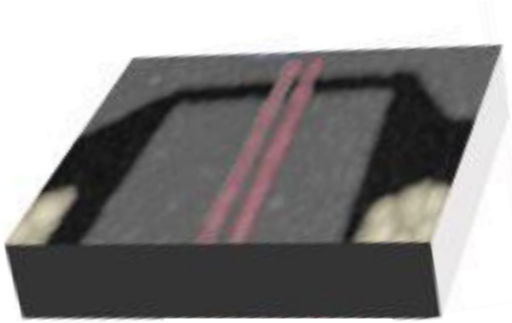
Quantum Dots



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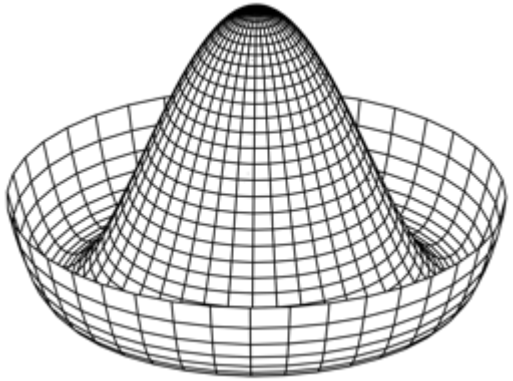
Topology



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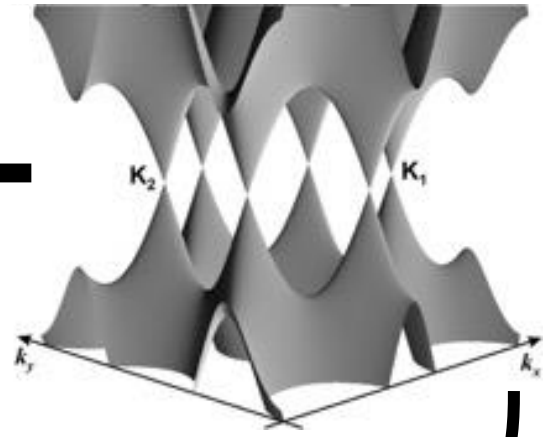
Valleys



Hybrid quantum systems in the very same material
Physical properties controlled by gate voltages

Thank you!

Schweizerischer Nationalfonds
Fonds national suisse
Fondo nazionale svizzero
Swiss National Science Foundation

FQXi
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FNSNF
SWISS NATIONAL SCIENCE FOUNDATION

QuESTech
Innovative Training Network (ITN)

Quantum e-leaps

erc

GRAPHENE FLAGSHIP

QSIT Quantum Science and Technology

Artem Denisov adenisov@phys.ethz.ch