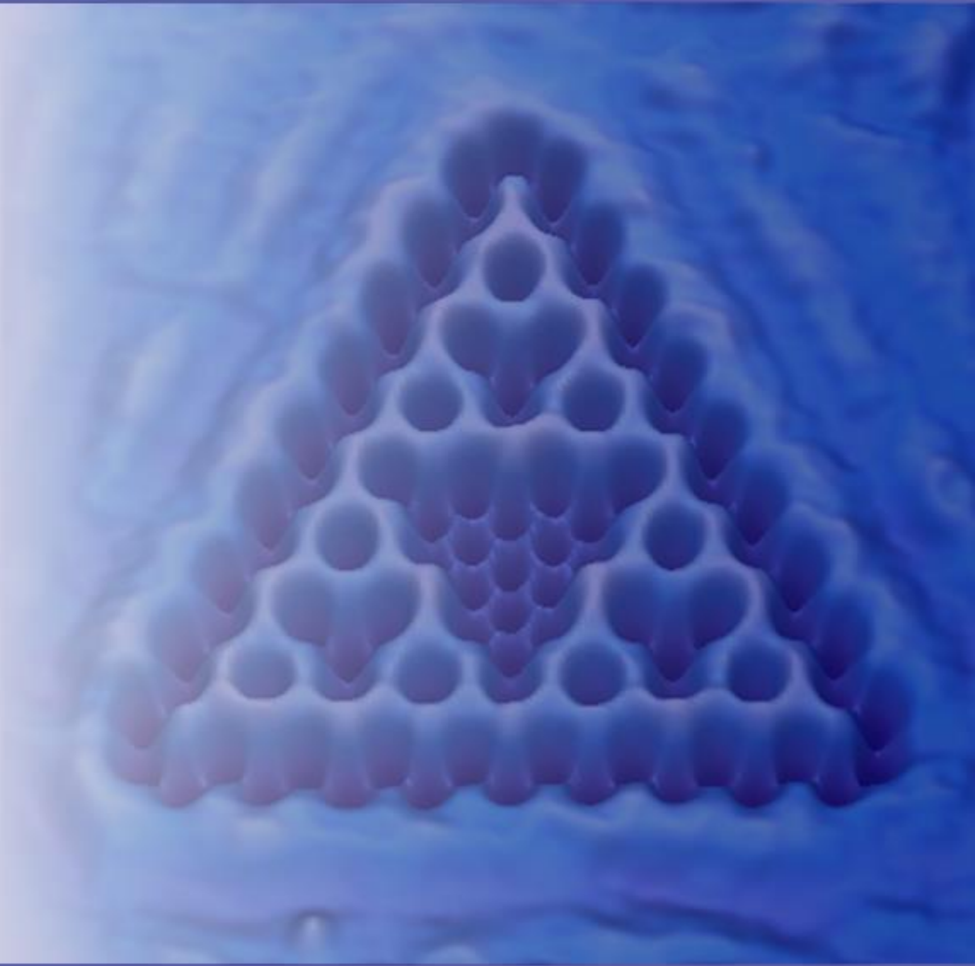
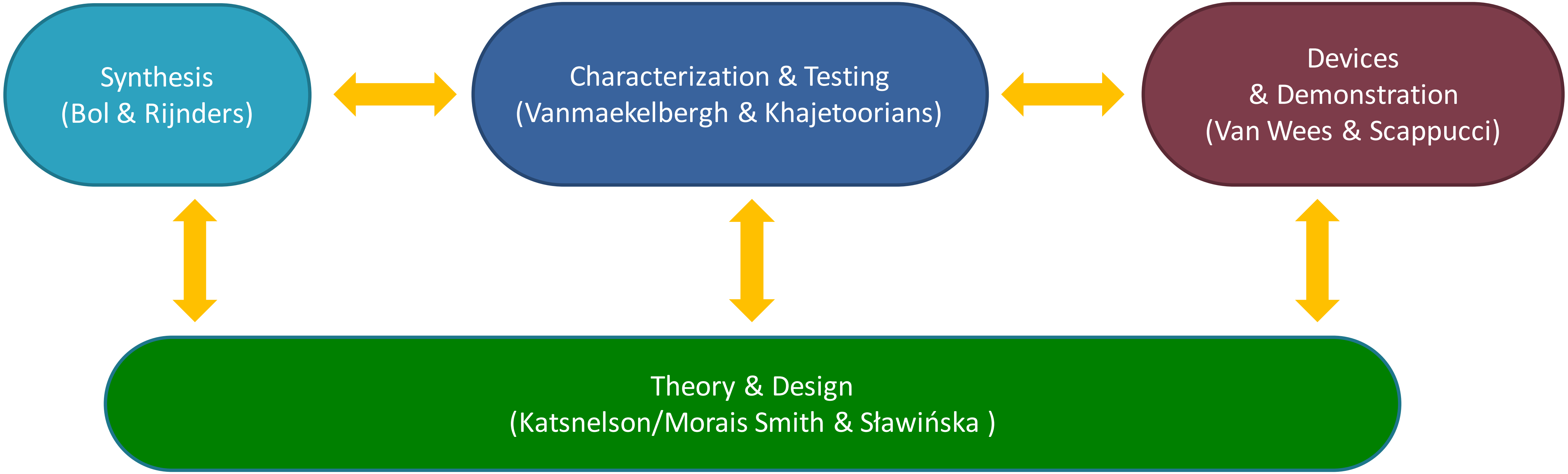
Characterization & Testing



Ingmar Swart

Utrecht University
www.swartlab.eu

In QuMat there are pillars, as well as four ‘Methods & Techniques’



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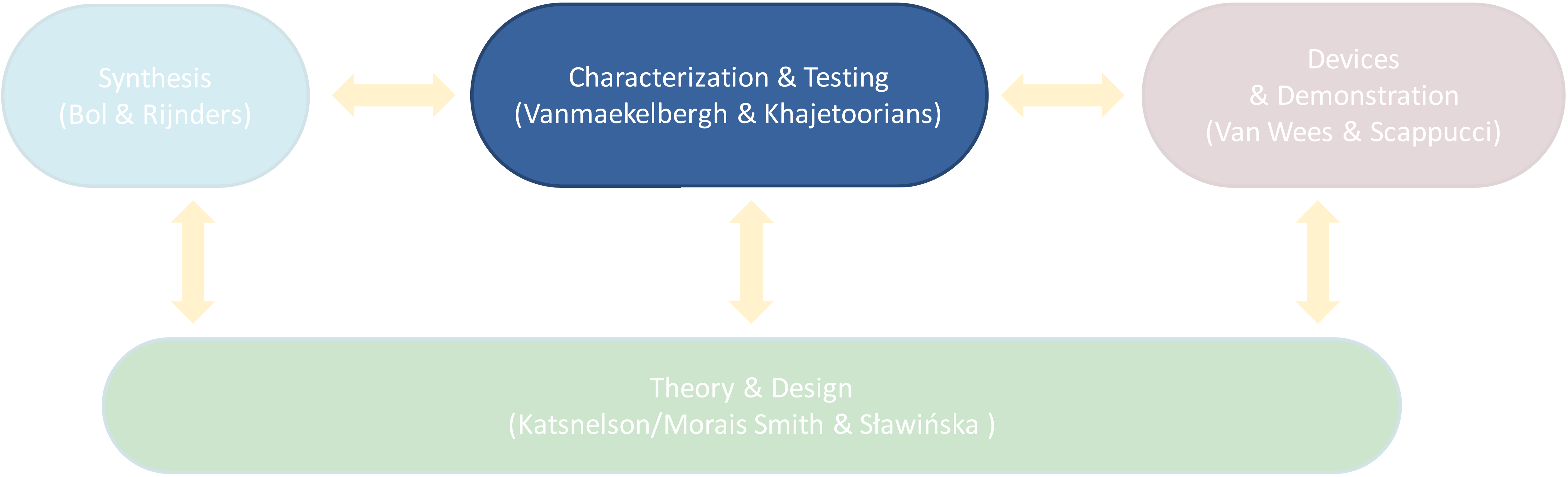


Characterization & Testing

Many characterization techniques are available in the consortium:

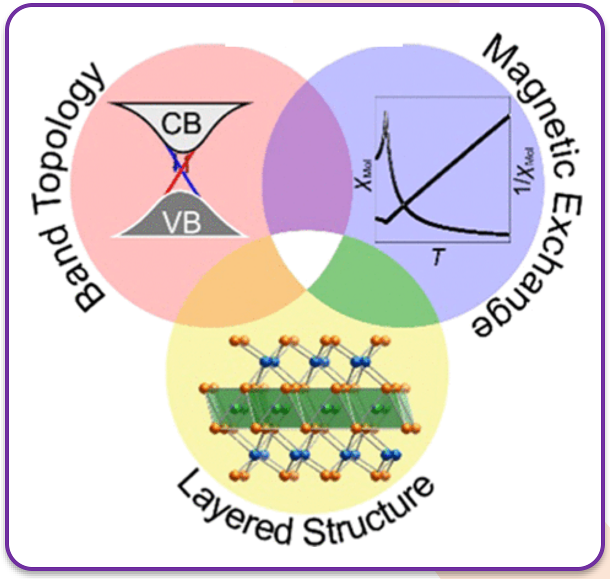
- ARPES (Amsterdam, Groningen)
- Scanning probe microscopy and spectroscopy (Delft, Nijmegen, Twente, Utrecht)
- Scanning SQUID Magnetic Microscopy (Twente)

- Transport measurements
- Far-field and near-field optical spectroscopy, from XUV to THz, static to time-resolved

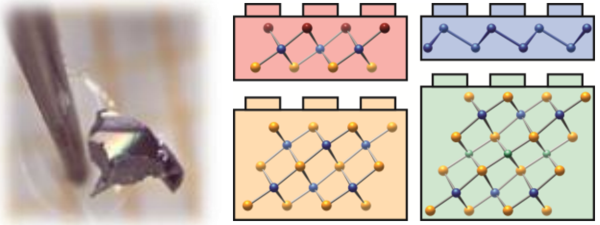
ARPES

Characterising edge states in k-space

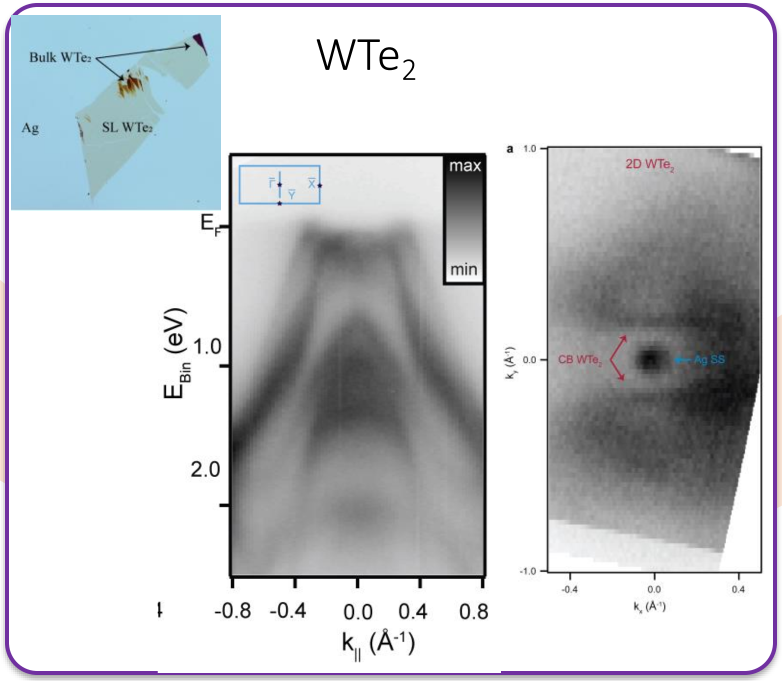
QuMat



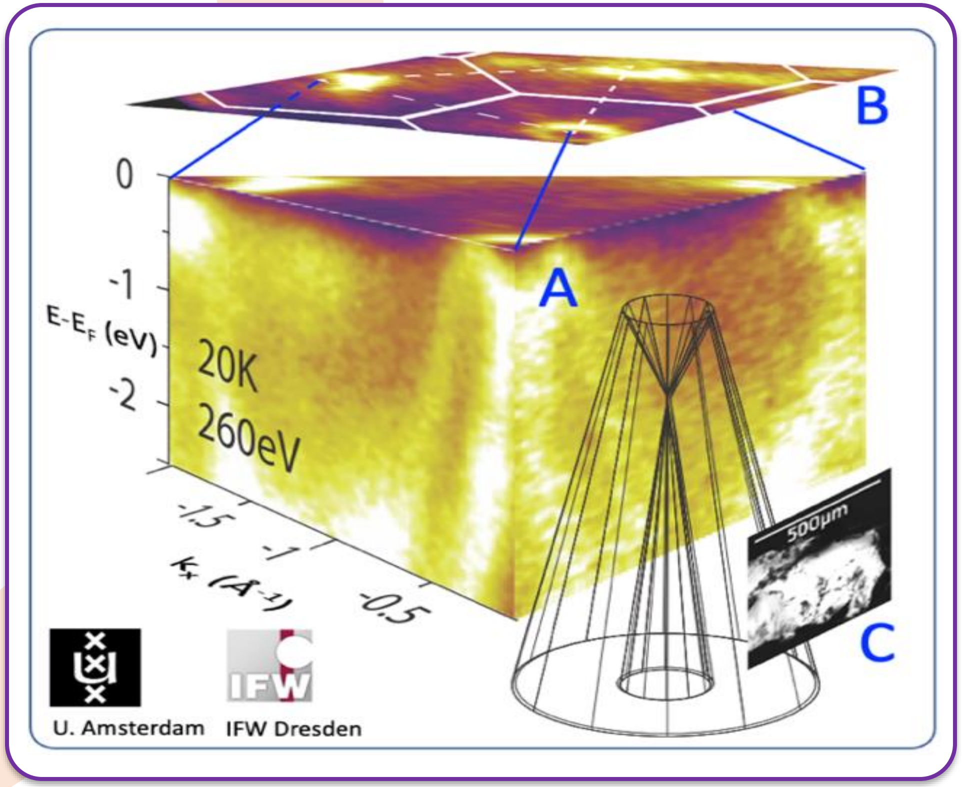
Designer MTI bulk crystals
$(MnBi_2Te_4)(Bi_2Te_3)_n$, n = 0-4,
doped by Sb, Fe, V, Cr
Magnetic nodal-line semimetals REBiTe,
RE = Gd, Nd, Ce



Our Challenge: surface electronic structure of magnetic topo materials



t-resolved ARPES
e.g. $MnSb_2Te_4$ single crystal
In-situ exfoliation in vacuum
single layer WTe_2



High resolution ARPES
e.g. $MnSb_2Te_4$ single crystal
→ μARPES of exfoliated / transferred systems
germanene from UT

ARPES capabilities in Amsterdam

QuMat

- $T_{min.}$ 13K
- 2D k-scanning (±15°)
- ΔE <5meV | <2 meV for laserARPES
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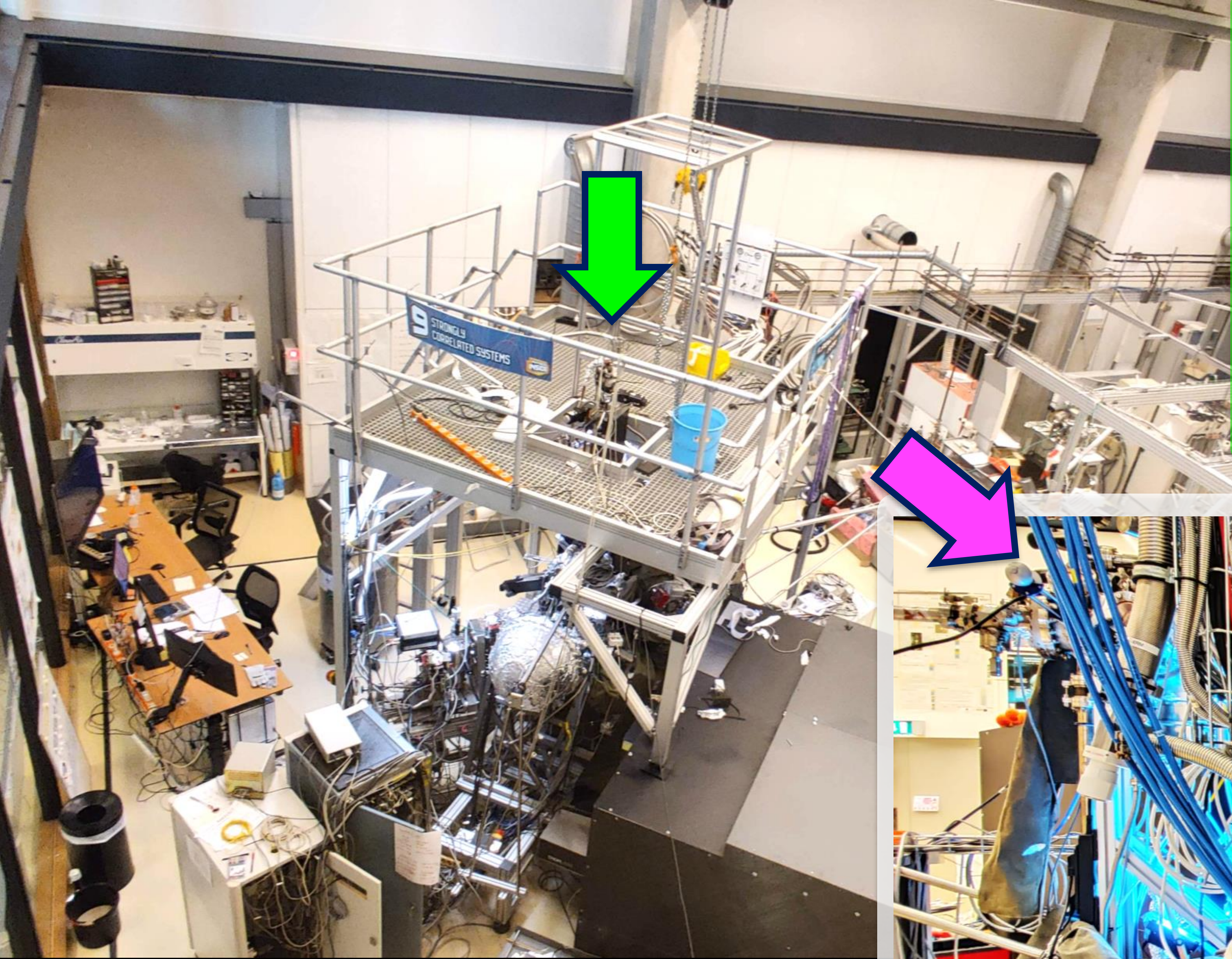
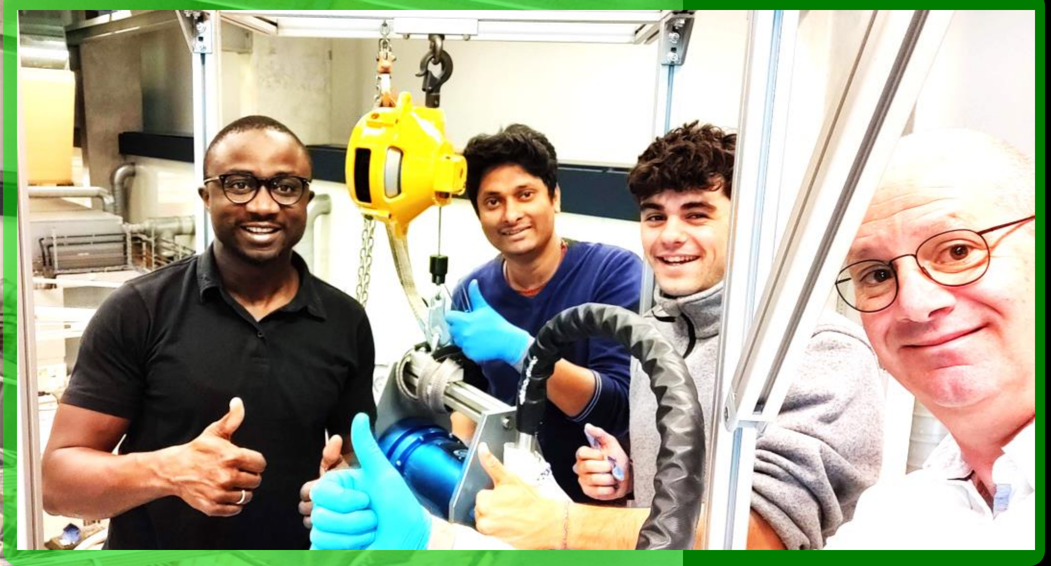
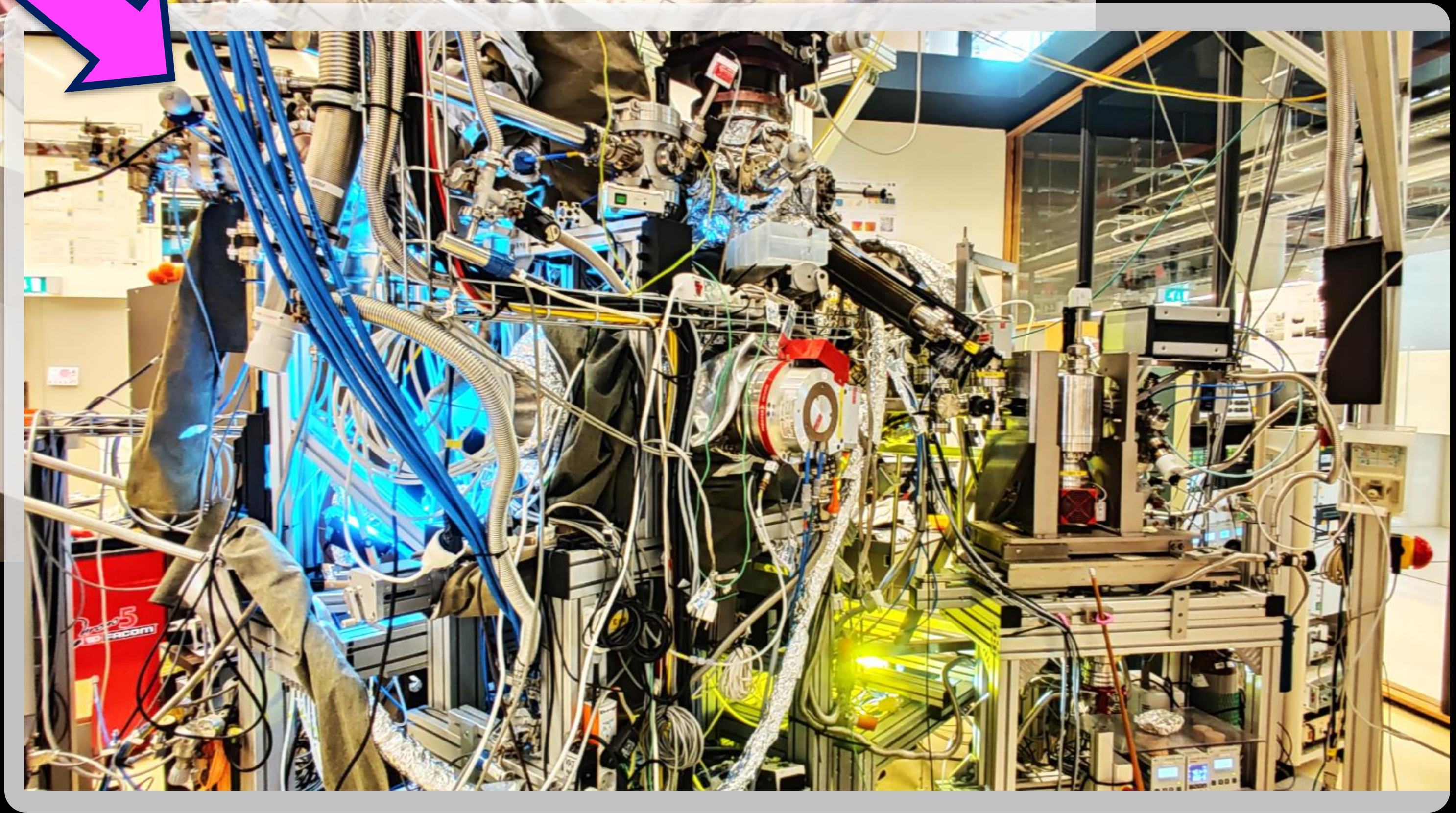
strongly correlated and topological

Quantum Materials Amsterdam



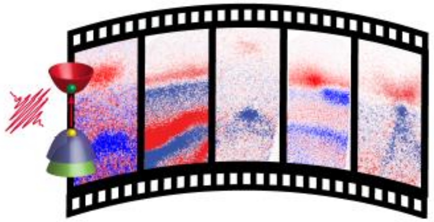




Quantum Materials
Amsterdam

ARPES capabilities in Groningen

- Lab will be set up in the new Feringa building
- 2D k-scanning (±15°)
- High harmonic based – energy up to ≈ 35 eV
- Spot-size <100 μm
- Time resolution on 100 fs scale
- Tunable pump energy: visible to IR range



- synchrotron ARPES, XSW, XPD & time resolved ARPES, XPS & XPD @ FELs

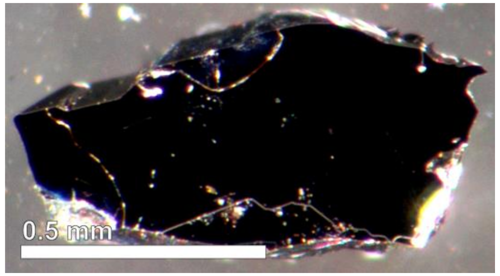
ASTRID2 (DK), DIAMOND (UK), SOLEIL (FR), MAX-IV & BALTAZAR (SE), ELETTRA (IT), FLASH (DE), UBC & CLS (CD)

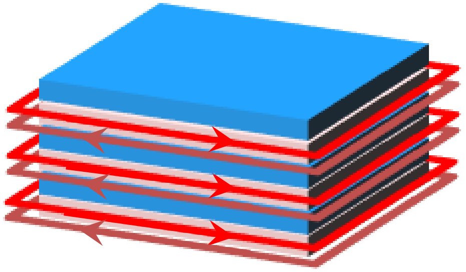
two-dimensional and topological

Materials portfolio in Amsterdam

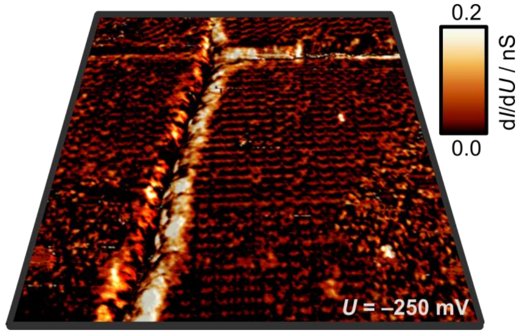
QuMat

- 3D weak topological insulators: $Bi_{14}Rh_3I_9$, Bi_2TeI, Bi_2TeBr

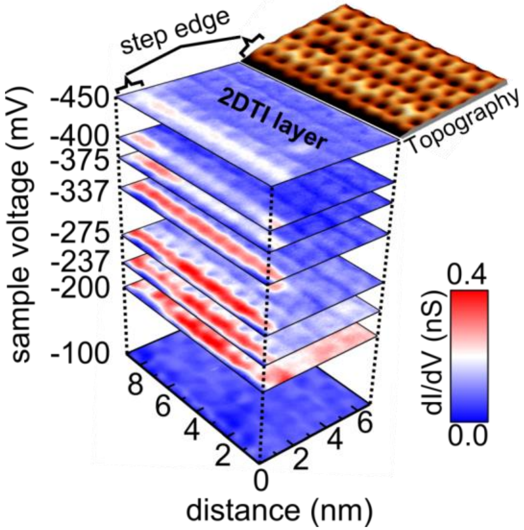




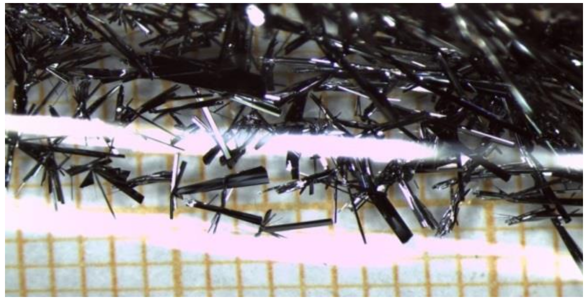
B. Rasche, A. Isaeva et al. *Nature Mater.* 12, 422 (2013)



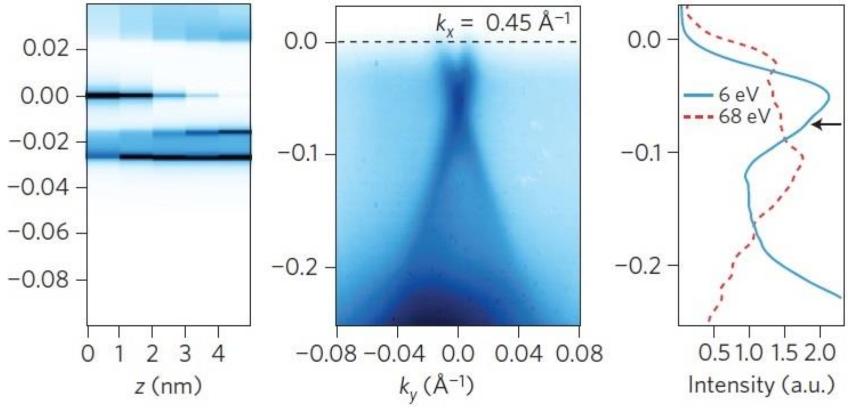
C. Pauly et al. *Nature Phys.* 11, 338 (2015)



- Dual topological insulators: Bi_2TeI, Bi_4I_4



G. Autès, A. Isaeva, et al. *Nature Chem.* 15, 154 (2016)



- Materials by design on demand…

Delft: ESR-STM, 300 mK, 2D vector magnetic field

STM: single spins, but limited energy resolution
ESR: high energy resolution, but ensemble technique

Key idea: apply a time-dependent electric field between tip and sample to drive coherent spin excitations (E-field modulate parameters in spin Hamiltonian). Monitor current as a function of frequency

Image taken from ottelab.tudelft.nl

SPIN PHYSICS

Free coherent evolution of a coupled atomic spin system initialized by electron scattering

Lukas M. Veldman[1], Laëtitia Farinacci[1], Rasa Rejali[1], Rik Broekhoven[1], Jérémie Gobeil[1], David Coffey[1], Markus Ternes[2,3], Alexander F. Otte[1]*

Full insight into the dynamics of a coupled quantum system depends on the ability to follow the effect of a local excitation in real-time. Here, we trace the free coherent evolution of a pair of coupled atomic spins by means of scanning tunneling microscopy. Rather than using microwave pulses, we use a direct-current pump-probe scheme to detect the local magnetization after a current-induced excitation performed on one of the spins. By making use of magnetic interaction with the probe tip, we are able to tune the relative precession of the spins. We show that only if their Larmor frequencies match, the two spins can entangle, causing angular momentum to be swapped back and forth. These results provide insight into the locality of electron spin scattering and set the stage for controlled migration of a quantum state through an extended spin lattice.

Science **372**, 964 (2021)

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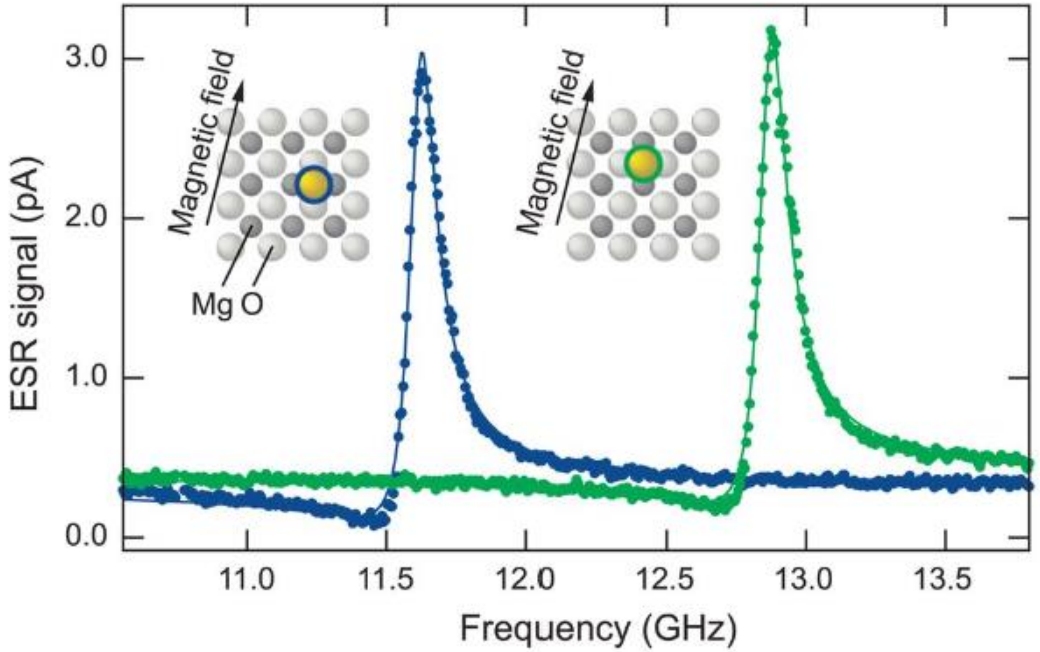
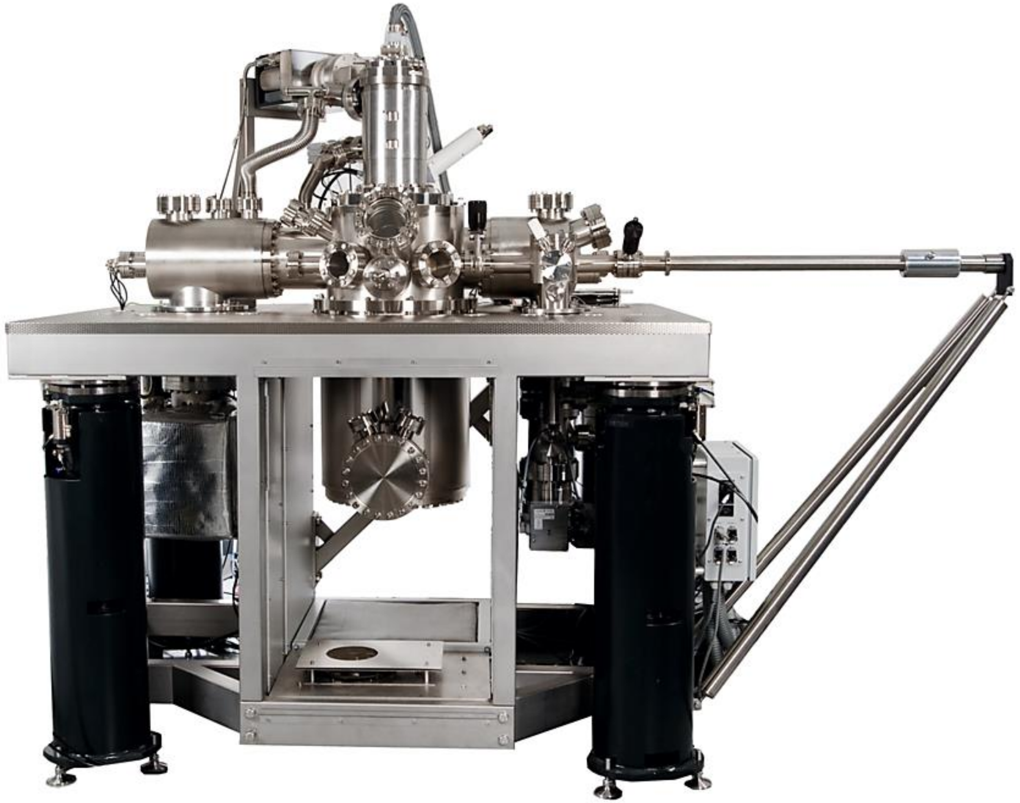
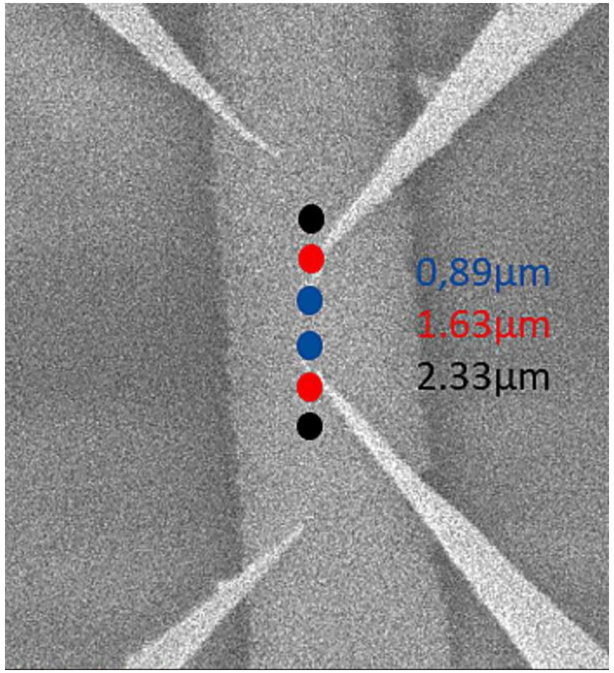


72, 964 (2021)

Twente: 4-probe STM, 4K





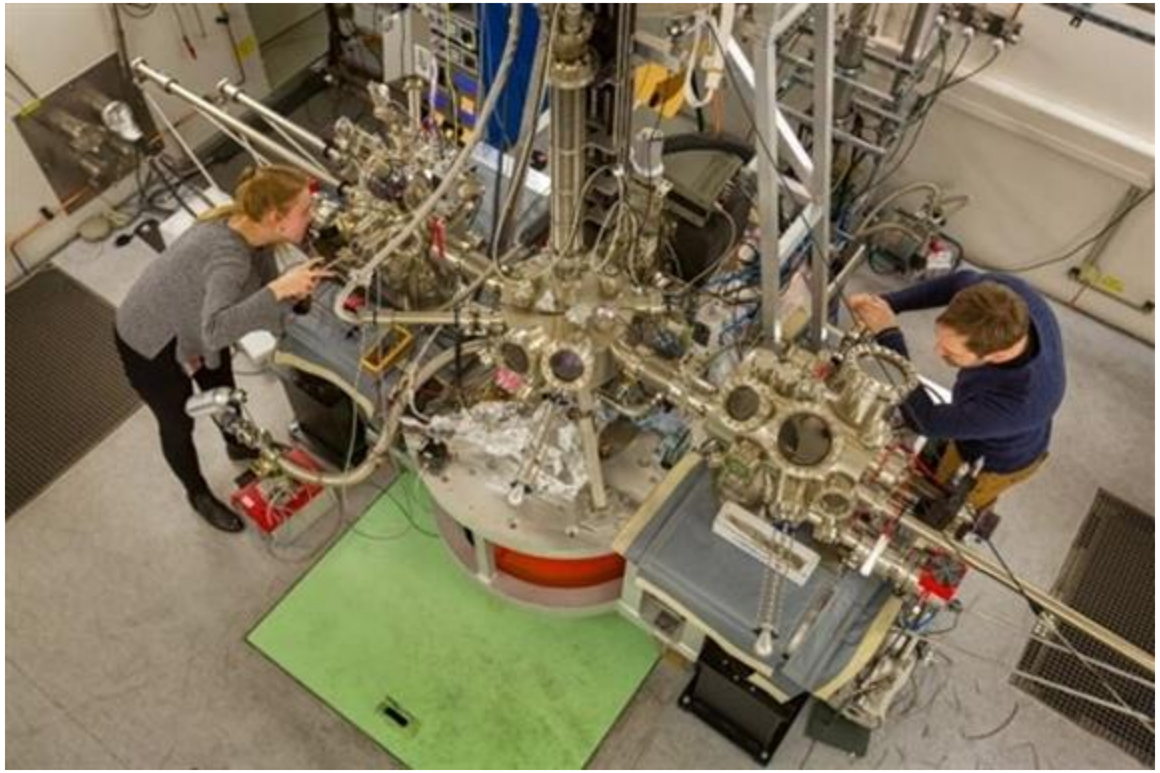
Images taken from www.scientaomicron.com

Nijmegen: Ultra-low temperatures, ESR, 2D vector magnetic fields

<u>State-of-the-art</u>:

- 30 mK
- 9/4T 2D vector magnet
- ESR-STM
- Connected to two MBE chambers

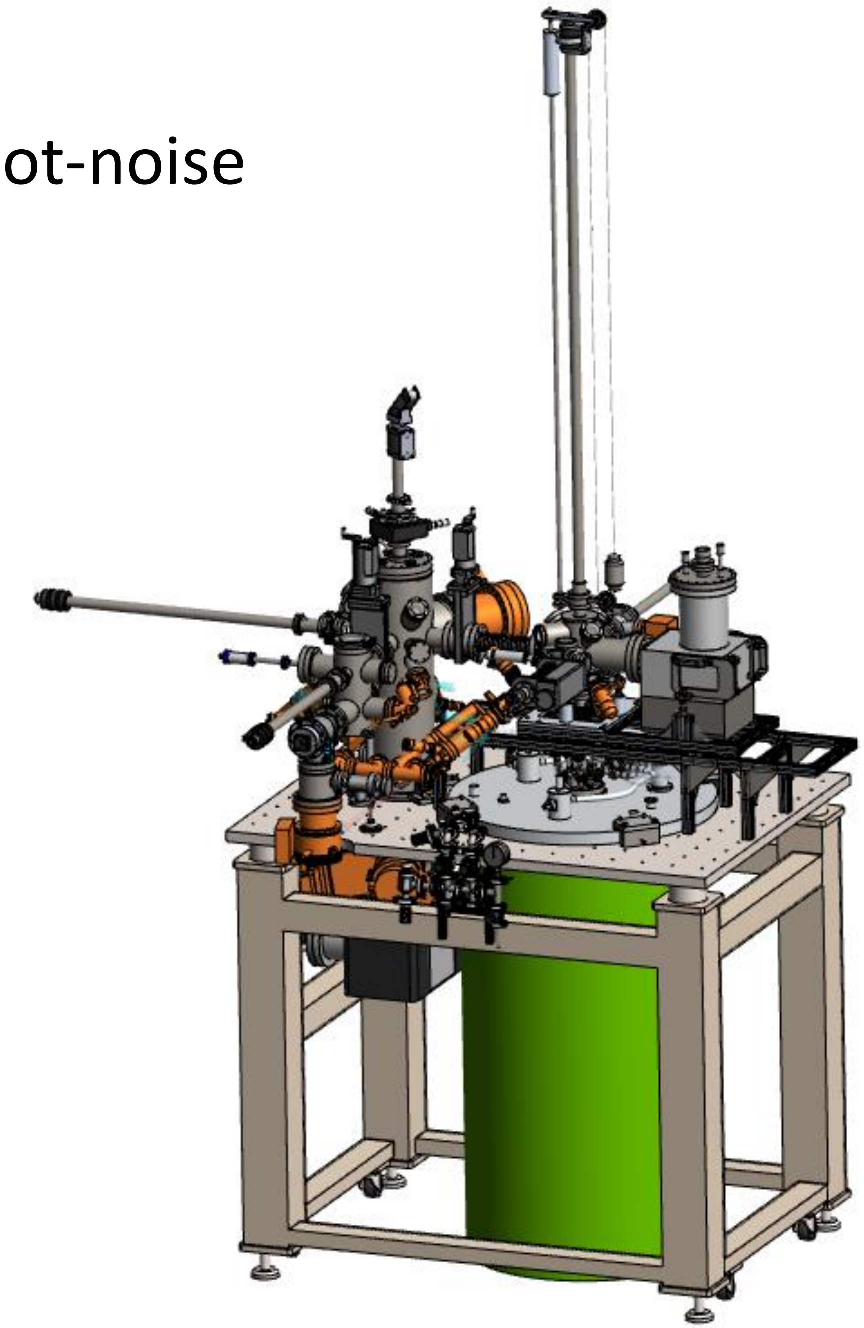
<u>Under development</u>: 6mK-9/4T SP-STM



Images taken from www.ru.nl/spm

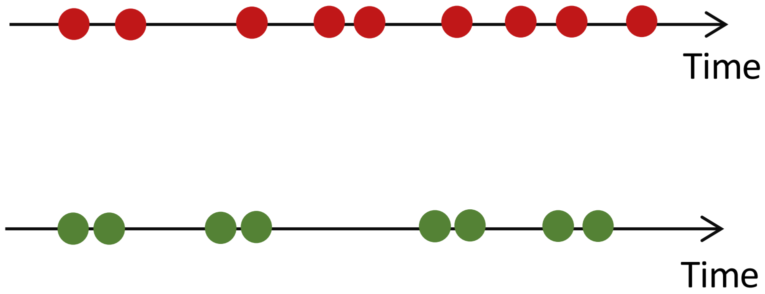
Utrecht: 300 mK, 3D vector magnet, STM & AFM, shot-noise

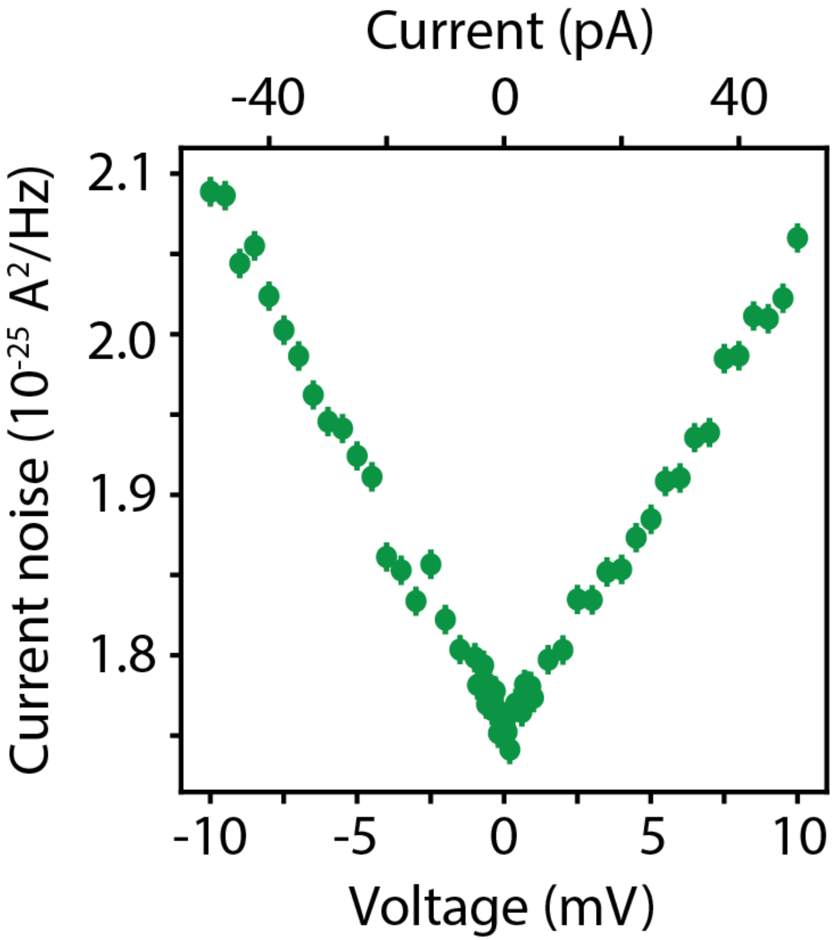
- Base temperature: 0.32K (single shot hold time >70h)
- 3D vector magnetic field: 2/2/9T
- STM and AFM
- 6 Additional contacts for backgate/transport measurements
- Cold cleaving stage, evaporation onto cold sample
- MBE chamber, LEED
- High-frequency preamplifier for shot-noise measurements



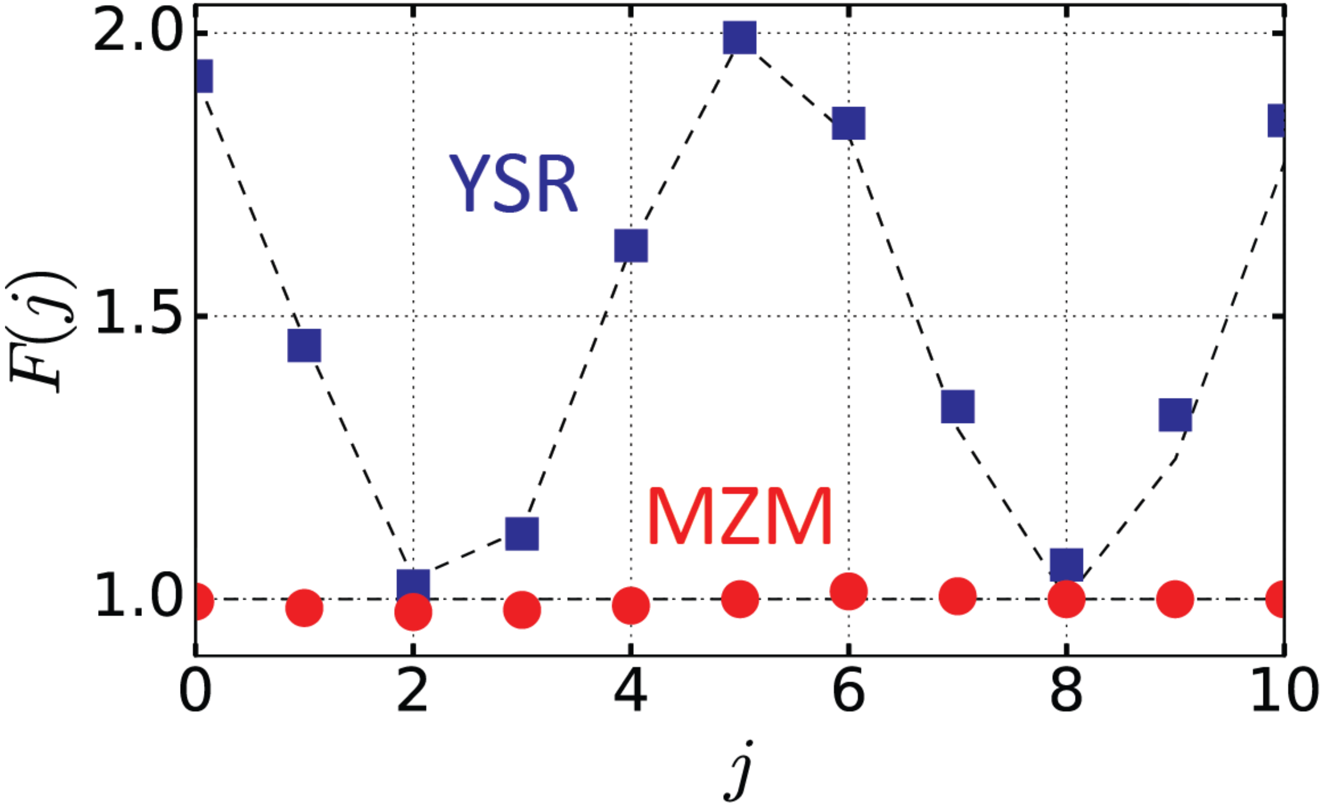
Preliminary result

Discreteness of charge leads to noise: $S_P(V) = 2\ q\ |I|$





Use shot-noise to identity zero-energy states



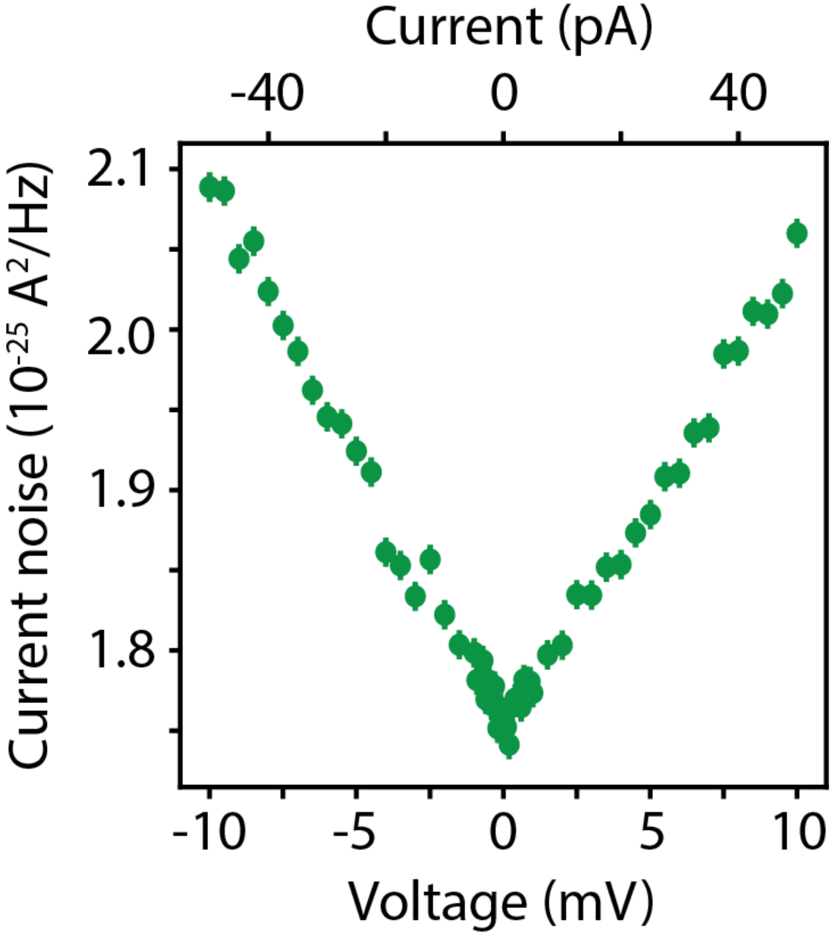
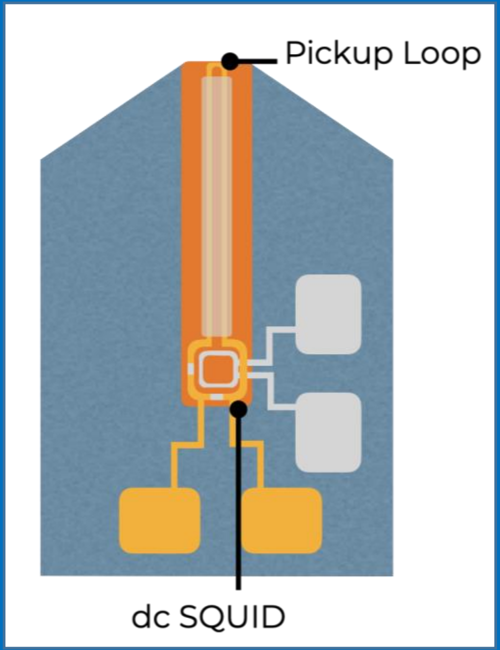
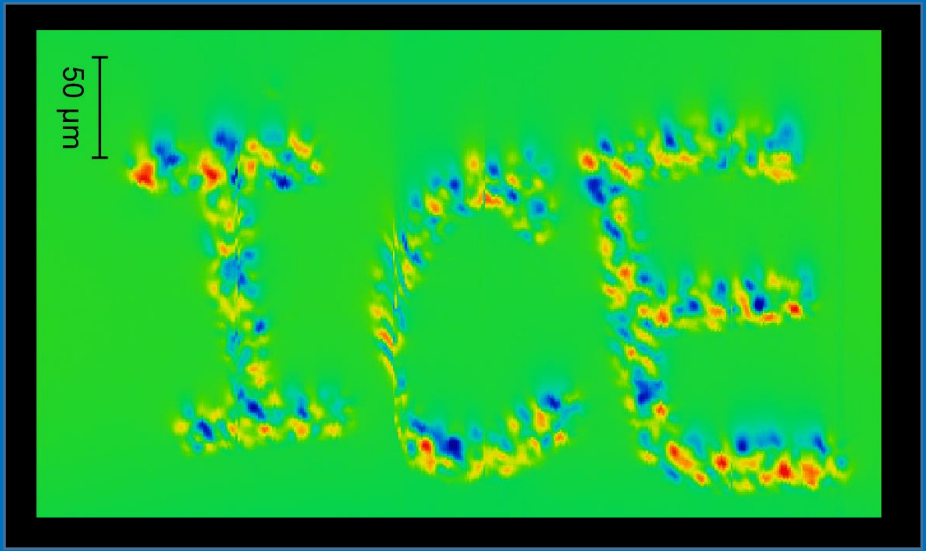


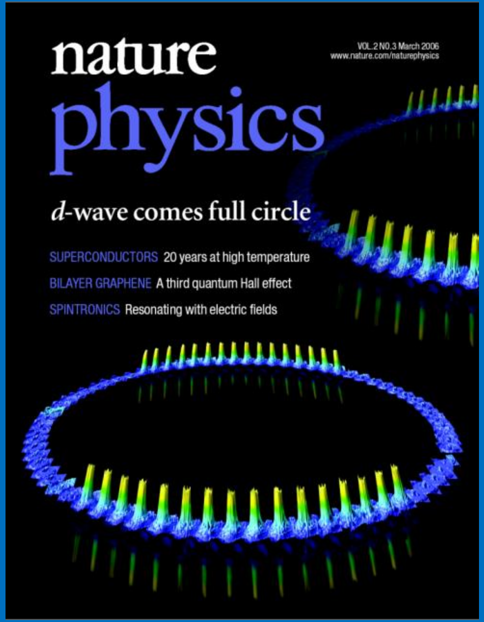
Image adapted from Phys. Rev. B **104**, L121406 (2021)

SCANNING SQUID MAGNETIC MICROSCOPY

Scanning SQUID Magnetic Microscopy



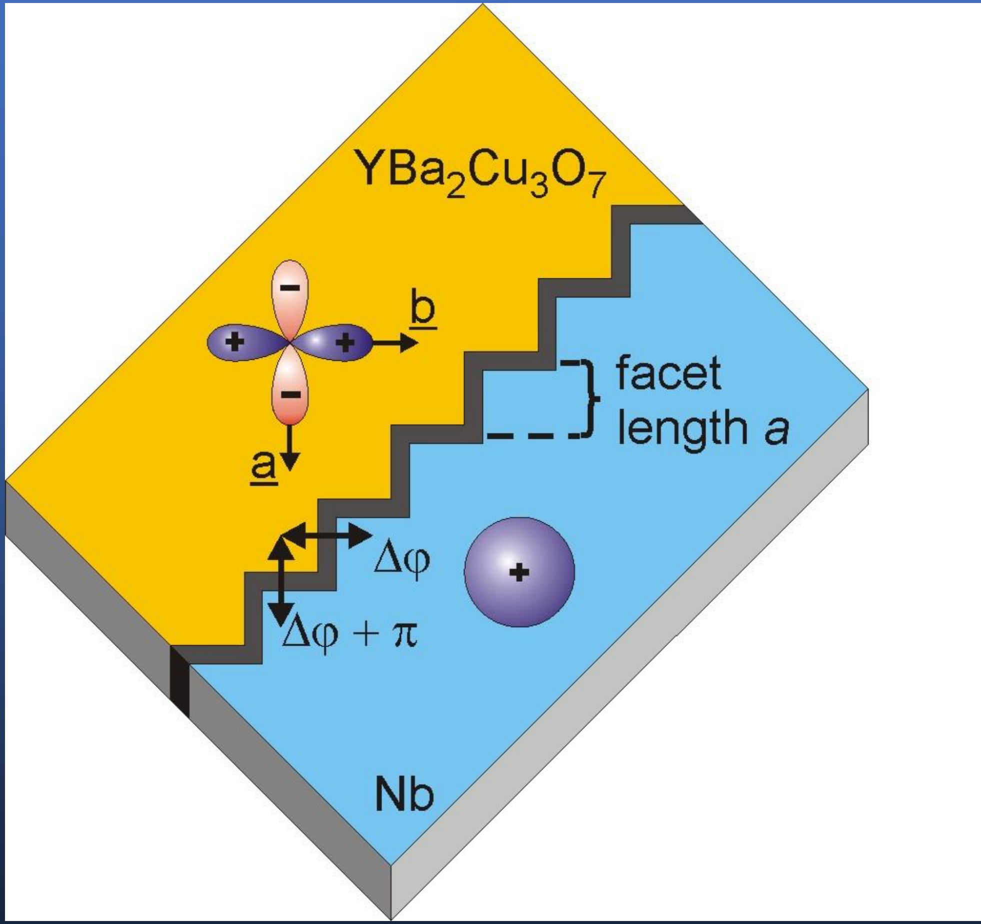


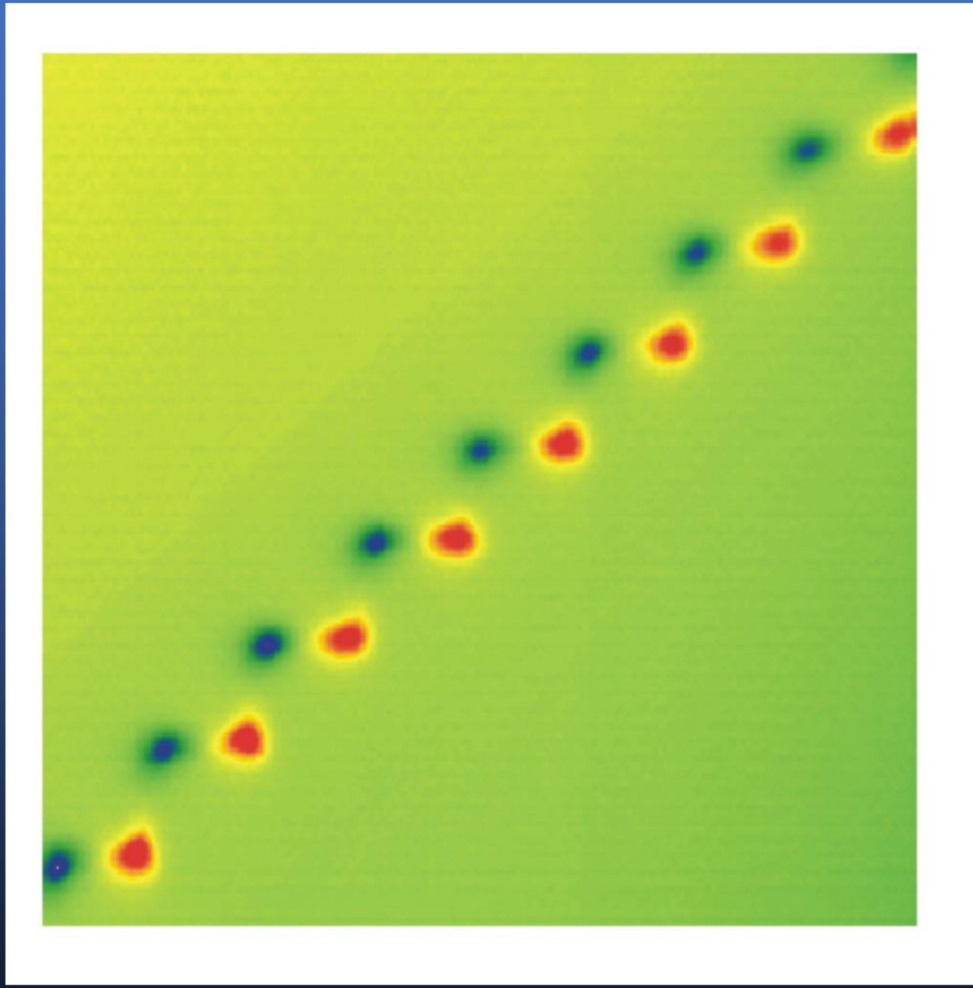


Hans Hilgenkamp
MESA+ Institute for Nanotechnology
University of Twente

QuMat PhD, from Jan.: Thijs Roskamp

Antiferromagnetically ordered array of spontaneously generated half flux quanta in YBCO-Au-Nb Zigzag array

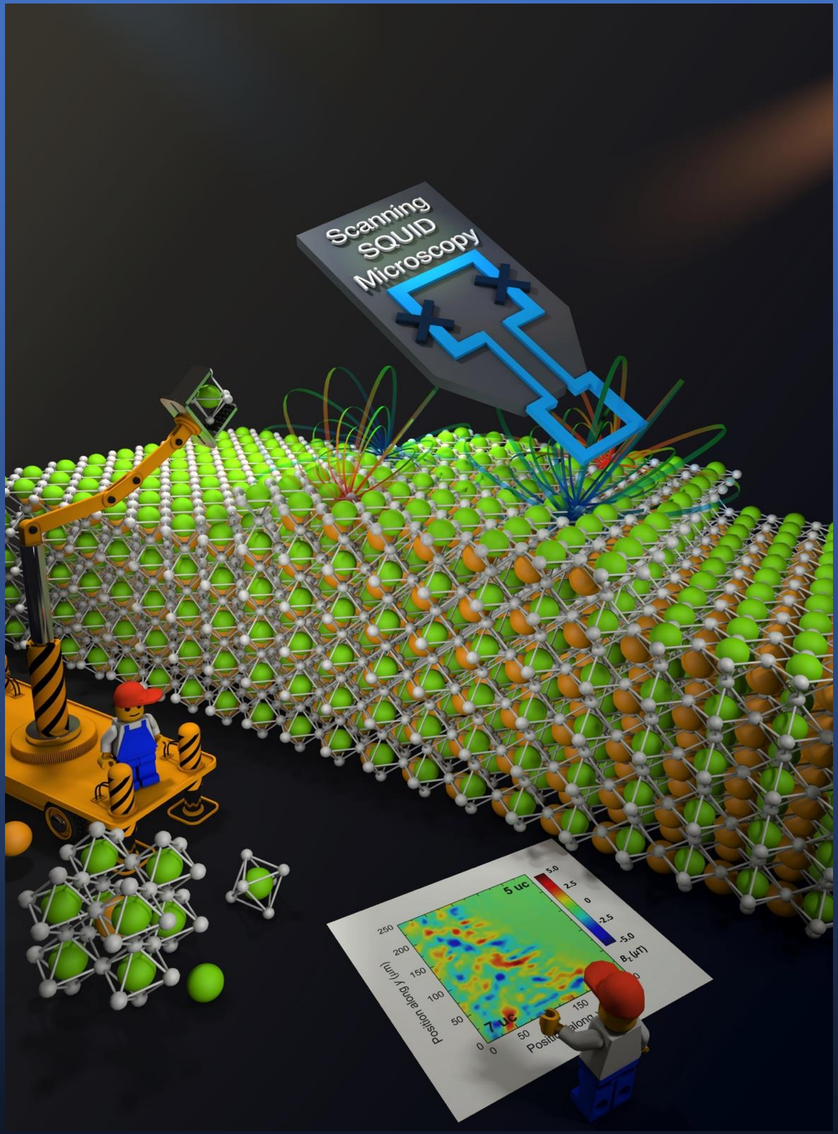


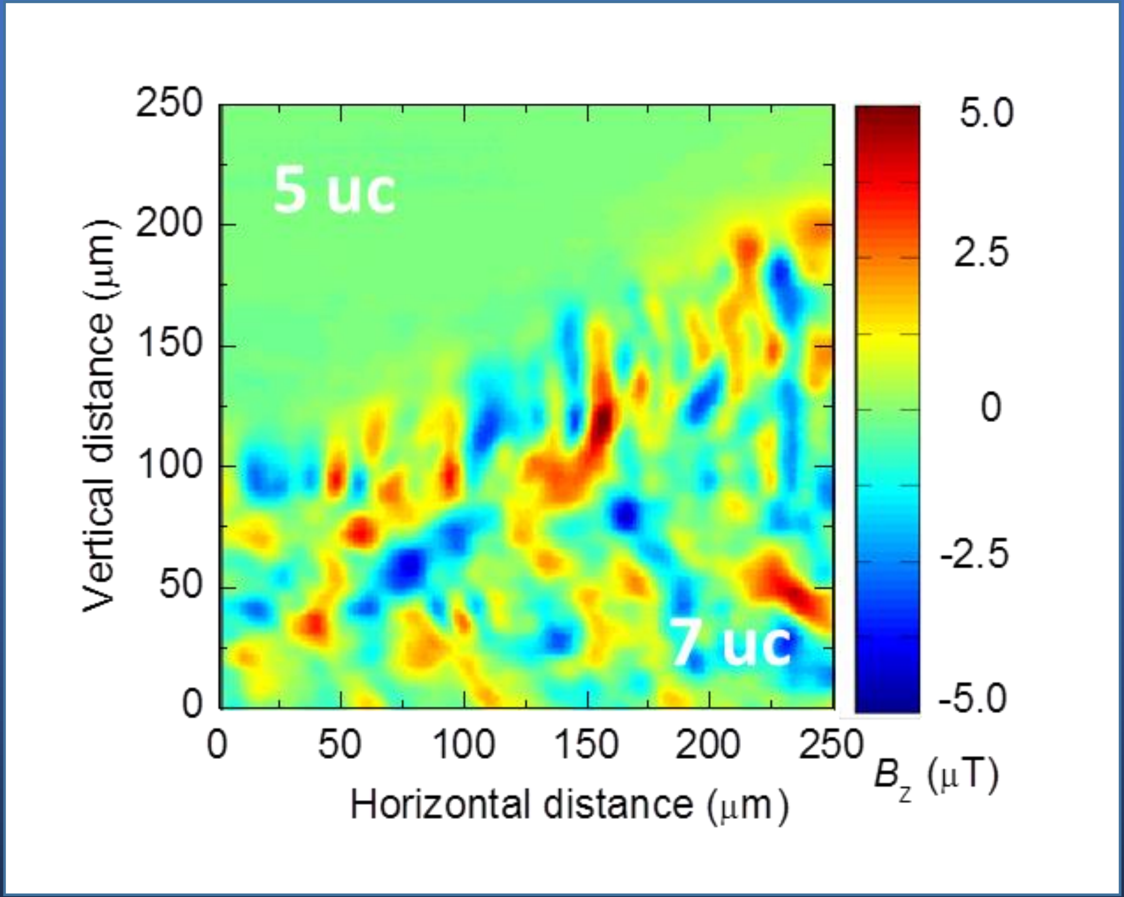


a = 40 μm

Hilgenkamp, Ariando, Smilde, Blank, Rijnders, Rogalla, Kirtley & Tsuei, *Nature* 422, 50-53 (2003)

Critical thickness for a magnetic transition in $LaMnO_3$





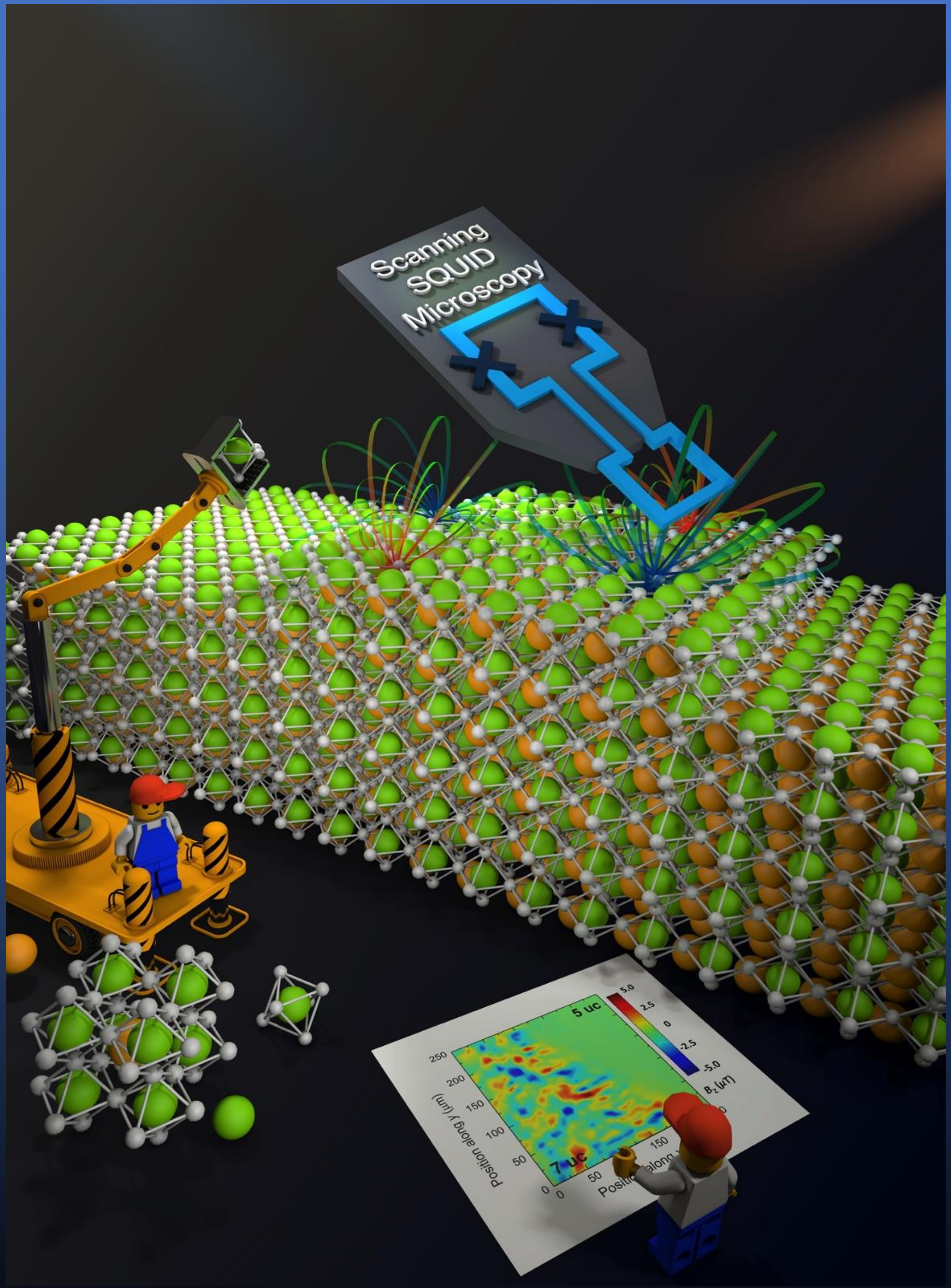
X. Renshaw Wang et al., *Science* 349, 716 (2015)

Critical thickness for a magnetic transition in a perovskite heterostructure

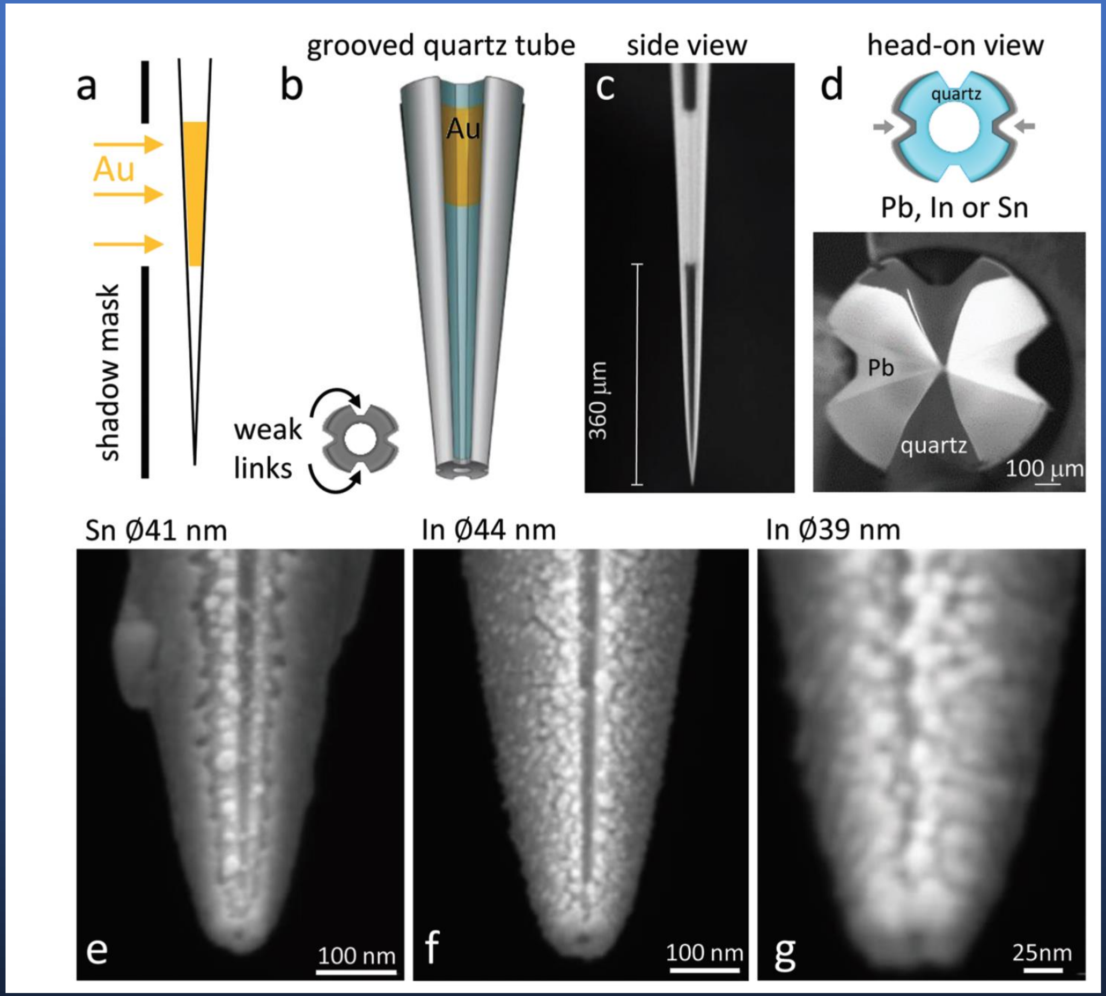
X. Renshaw Wang, C.J. Li, W.M. Lü, T.R. Paudel, D.P. Leusink, M. Hoek, N. Poccia, A. Vailionis, T. Venkatesan, J.M.D. Coey, E.Y. Tsymbal, Ariando, and H. Hilgenkamp

University of Twente, NUS Singapore, Univ. of Nebraska, Stanford Univ., Trinity College Dublin

X. Renshaw Wang et al.,
Science 349, 716 (2015)



Scanning SQUID Microscopy using ’SQUID-on-tip’ devices

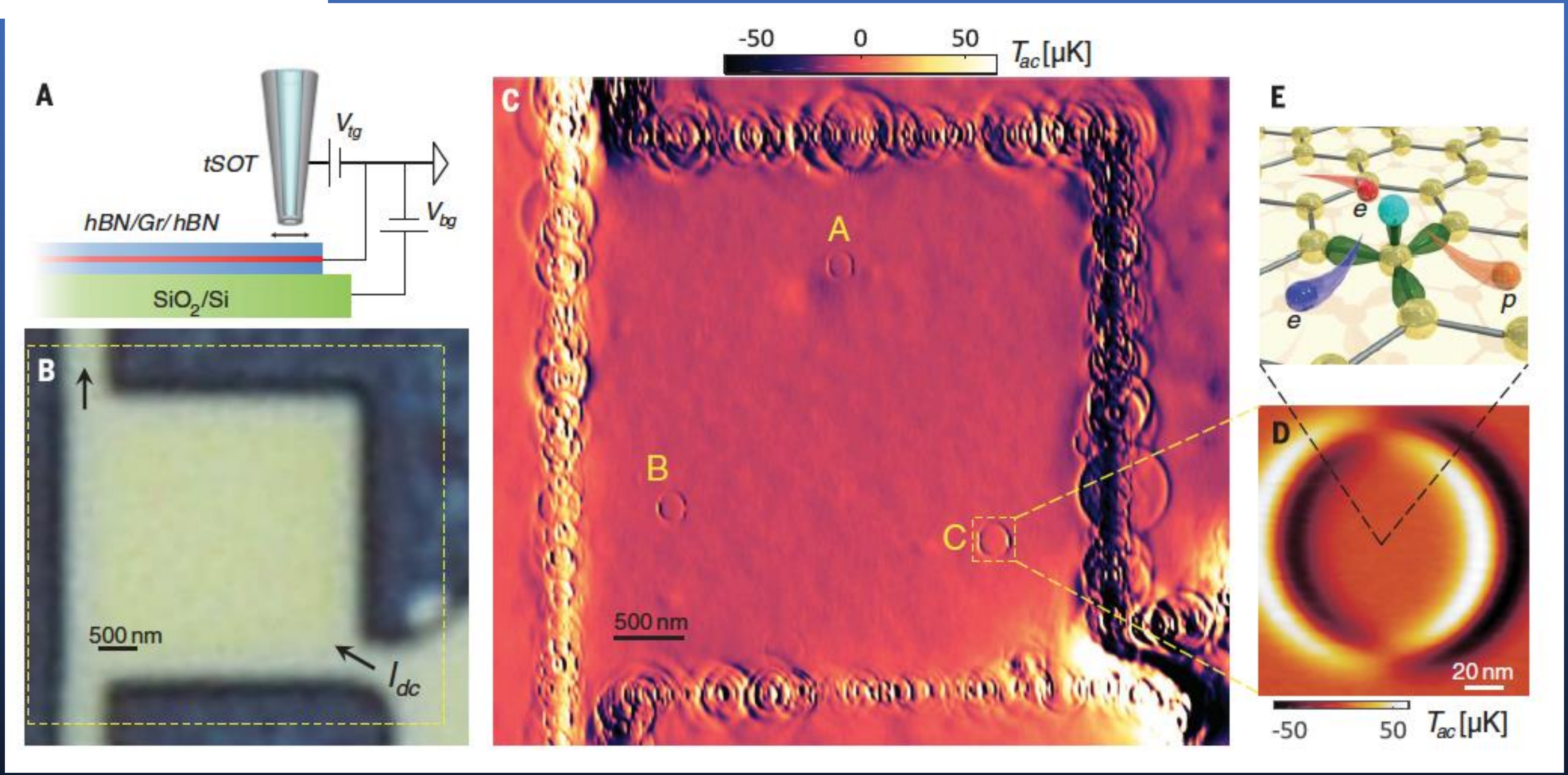


Y. Anahory, ..., E. Zeldov, ’*SQUID-on-tip with single electron spin sensitivity for high-field and ultra-low temperature nanomagnetic imaging*, Nanoscale 12, 3174 (2020)

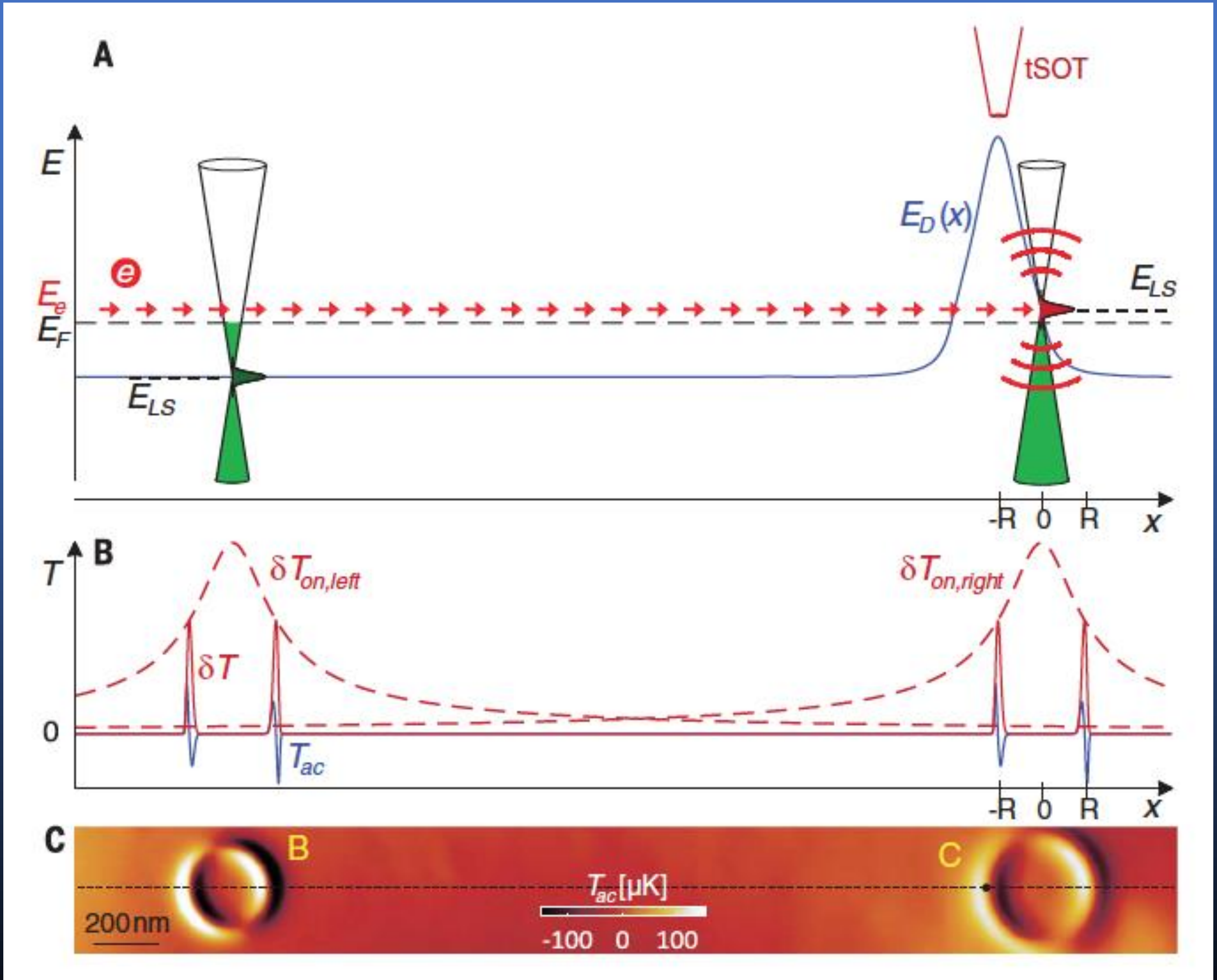
GRAPHENE

Imaging resonant dissipation from individual atomic defects in graphene

Dorri Halbertal,[1]* Moshe Ben Shalom,[2]* Aviram Uri,[1] Kousik Bagani,[1] Alexander Y. Meltzer,[1] Ido Marcus,[1] Yuri Myasoedov,[1] John Birkbeck,[2] Leonid S. Levitov,[3] Andre K. Geim,[2] Eli Zeldov[1]*



D. Halbertal et al,
Science 358, 1303 (2017)



D. Halbertal et al,
Science 358, 1303 (2017)

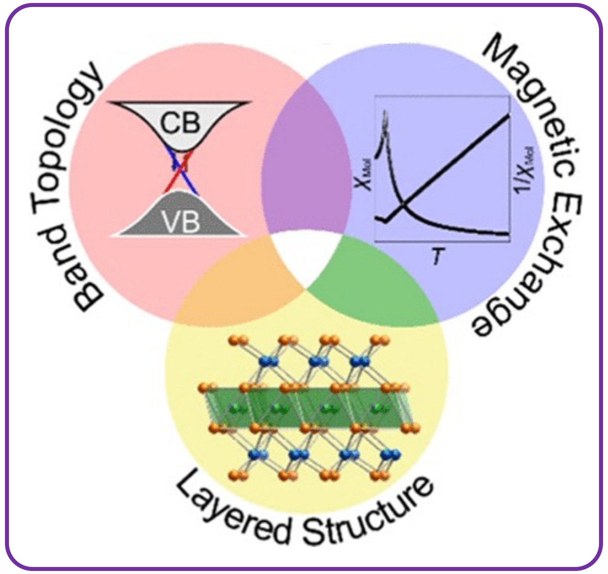
Conclusions

- Wide variety of state-of-the-art equipment available in our consortium
- Electronic, magnetic properties, real- and reciprocal space, static and time-domain
- But: we need a clear overview of available methods & techniques

Call-to-action for PIs: we need to collect relevant information about the techniques and expertise available in our labs and distribute this information

Characterising edge states in k-space

QuMat



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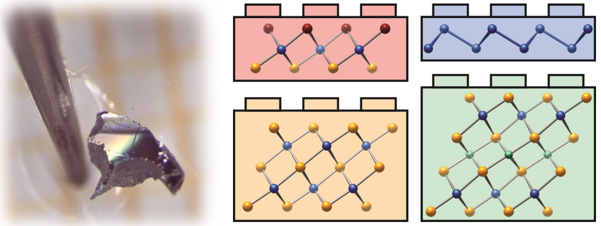
Magnetic nodal-line semimetals REBiTe, RE = Gd, Nd, Ce



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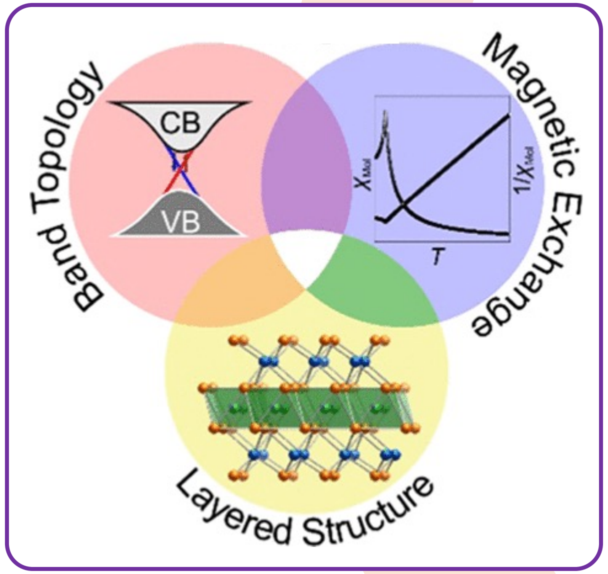

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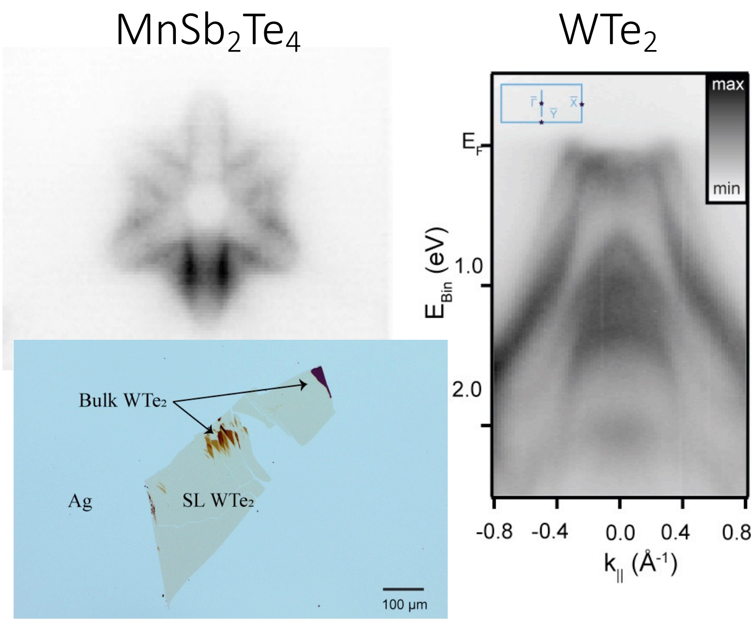

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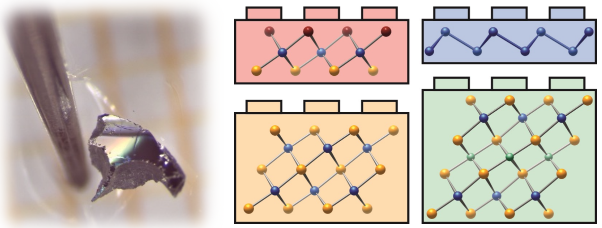

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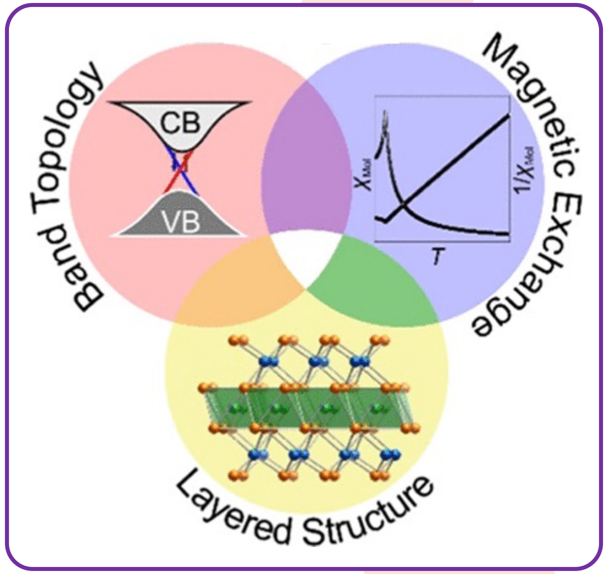
QuMat



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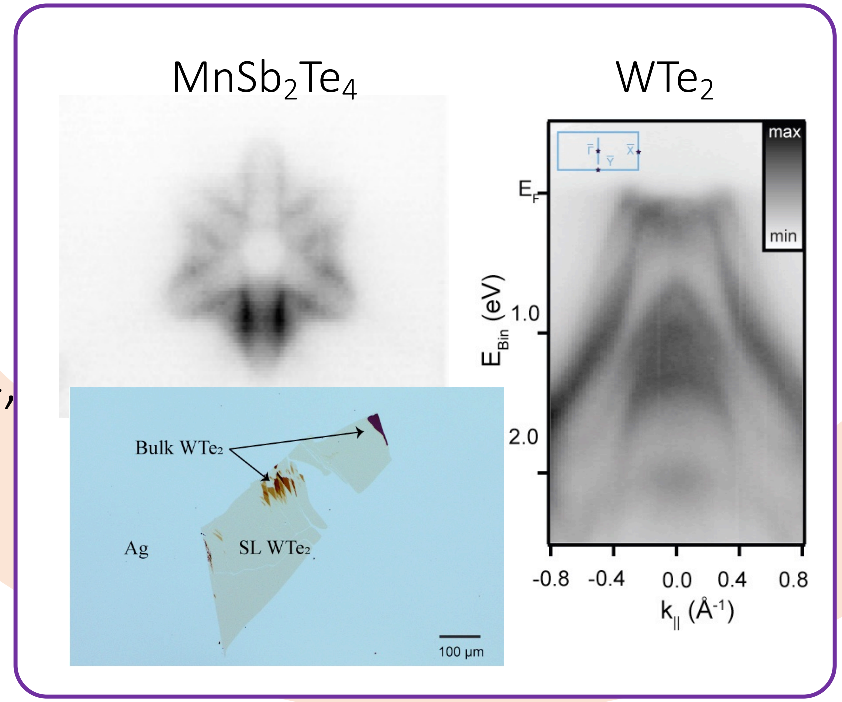

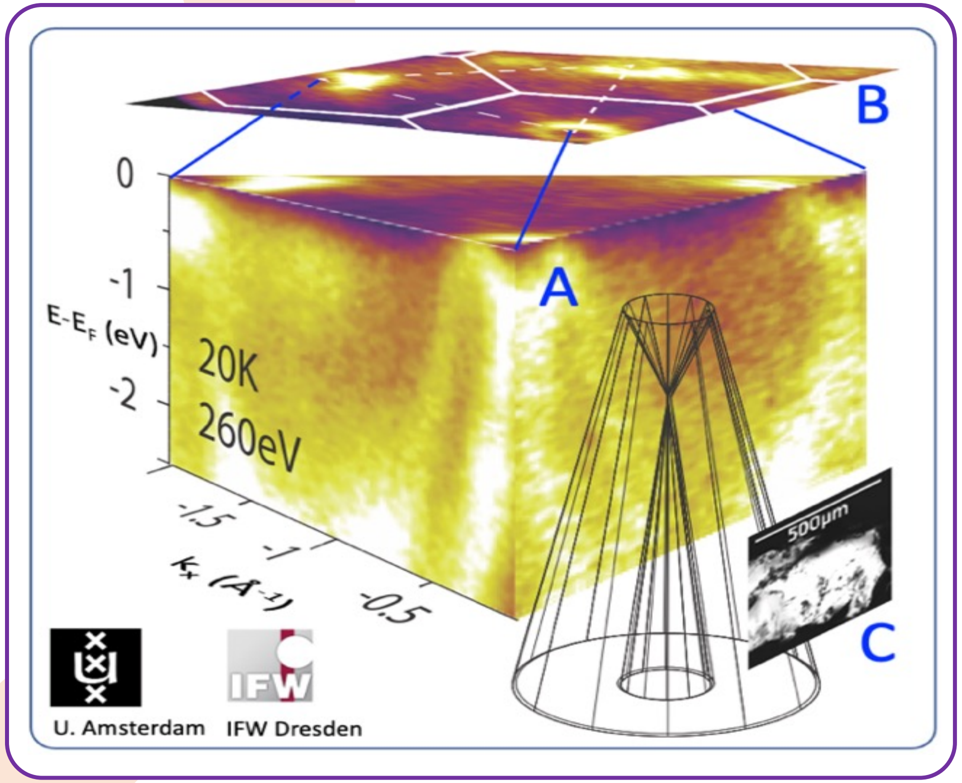

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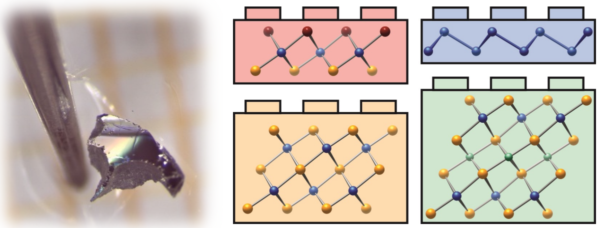

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single layer WTe_2

High resolution ARPES
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germanene from UT

ARPES capabilities in Amsterdam

QuMat

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Quantum Materials Amsterdam

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QuMat

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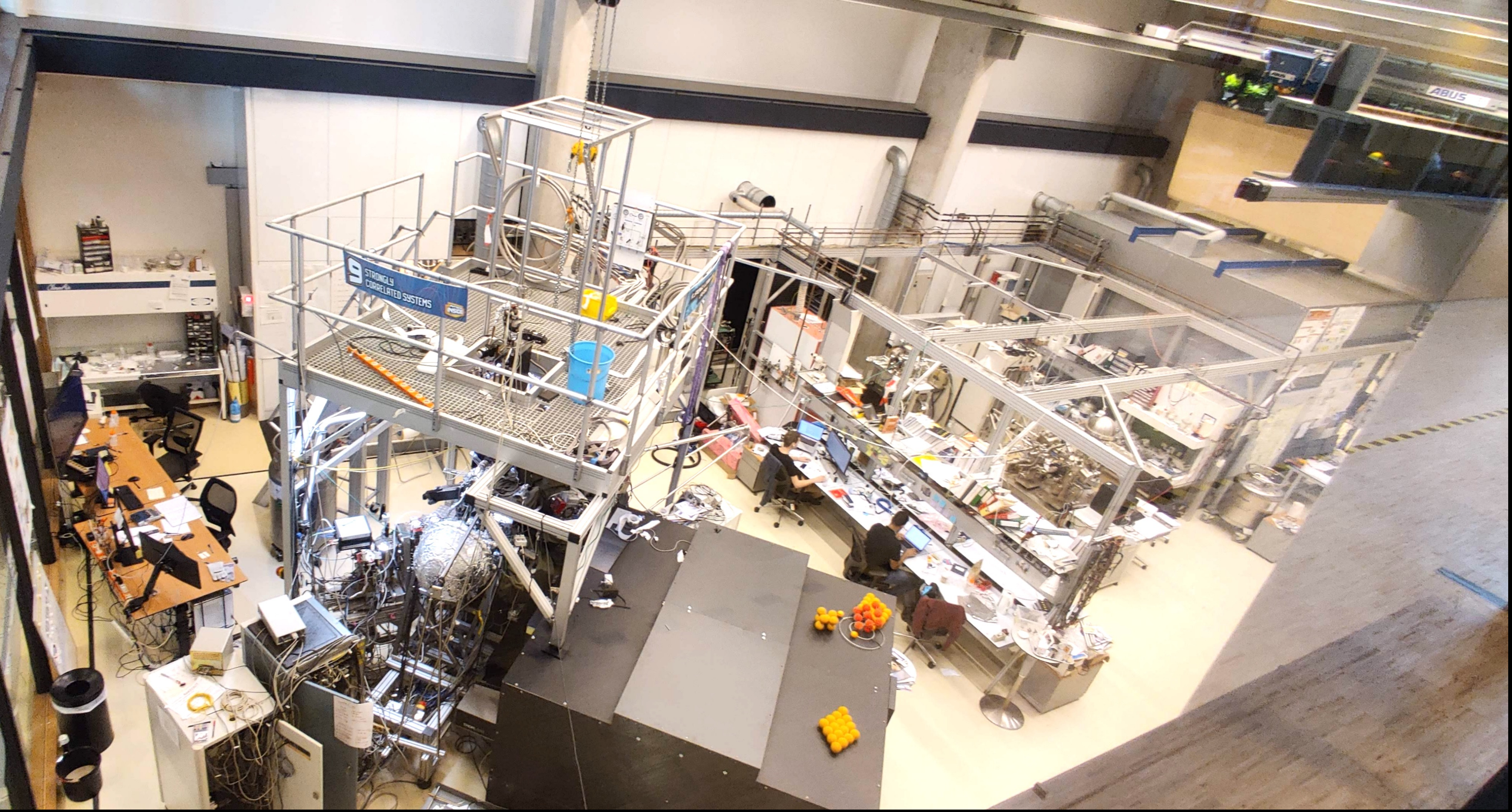
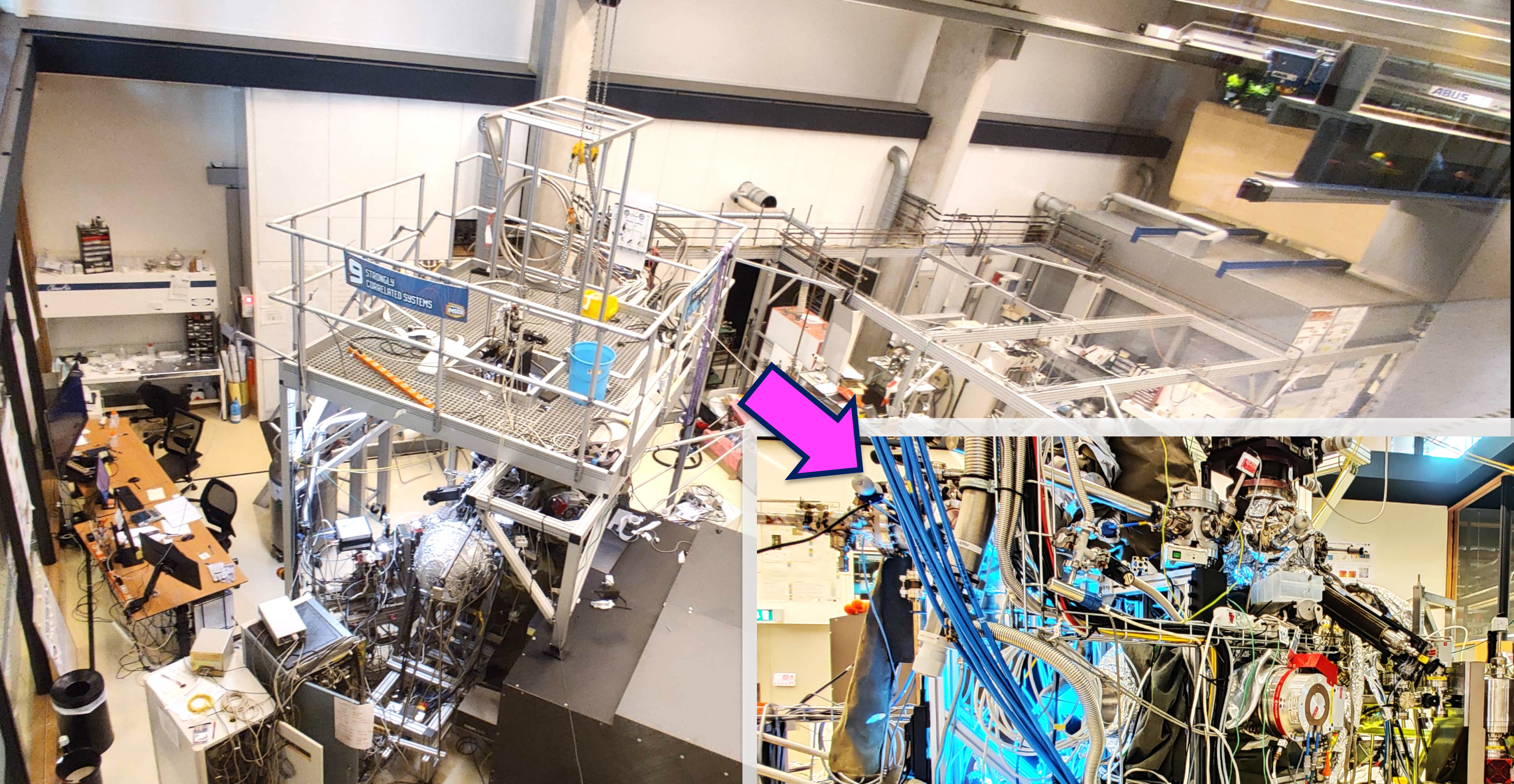
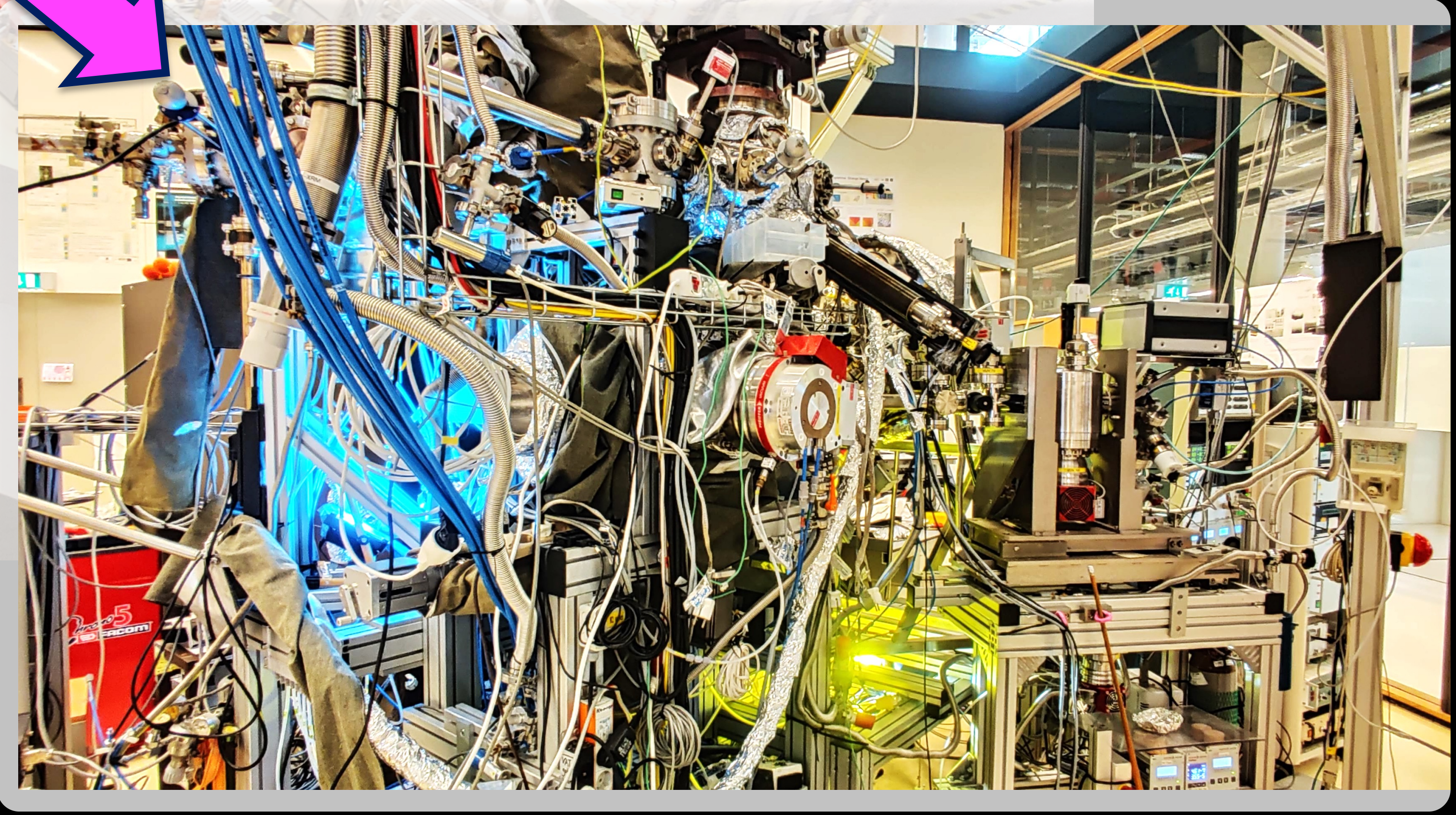
Quantum Materials Amsterdam



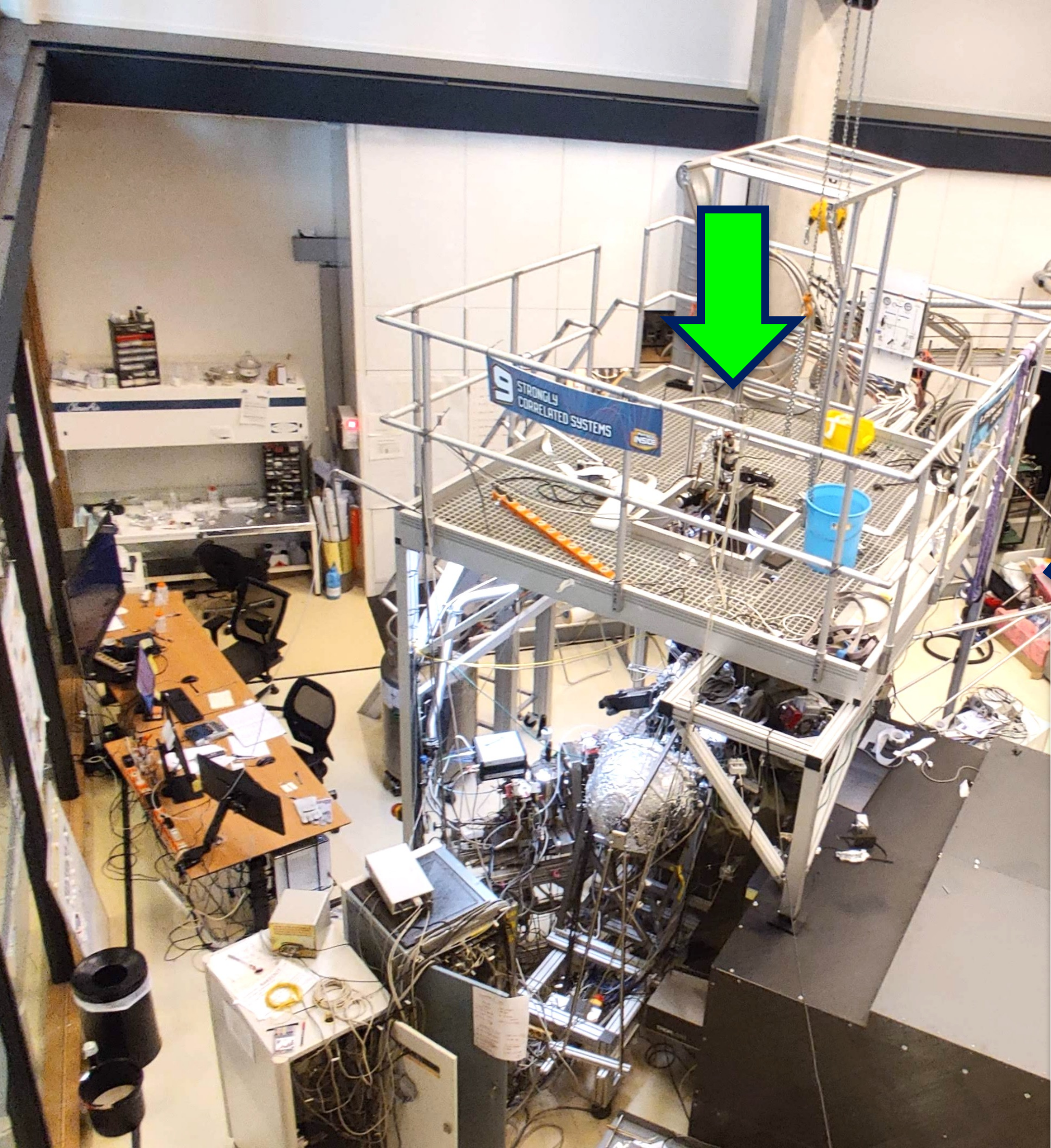
Quantum Materials

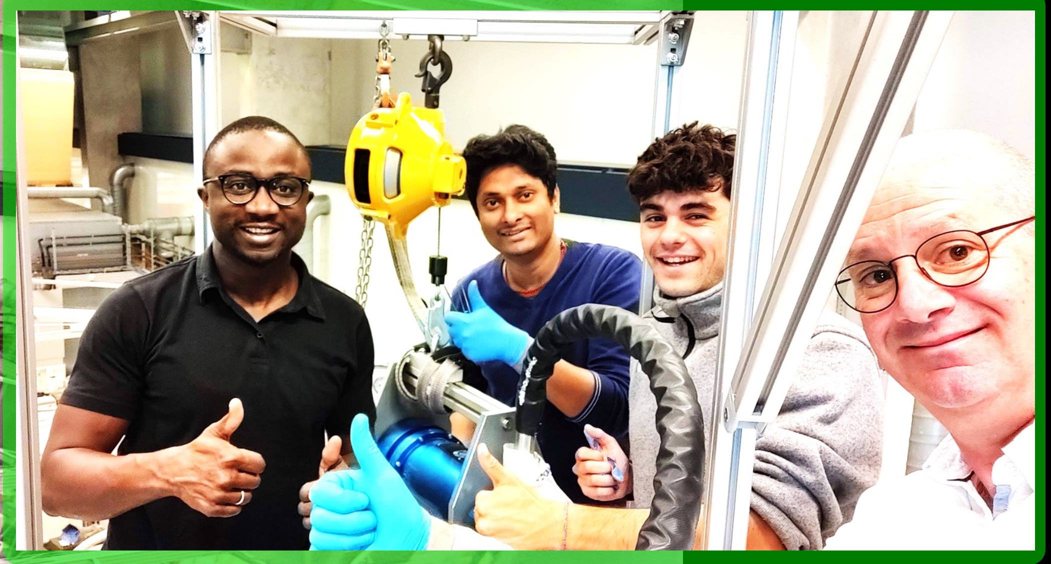
Amsterdam

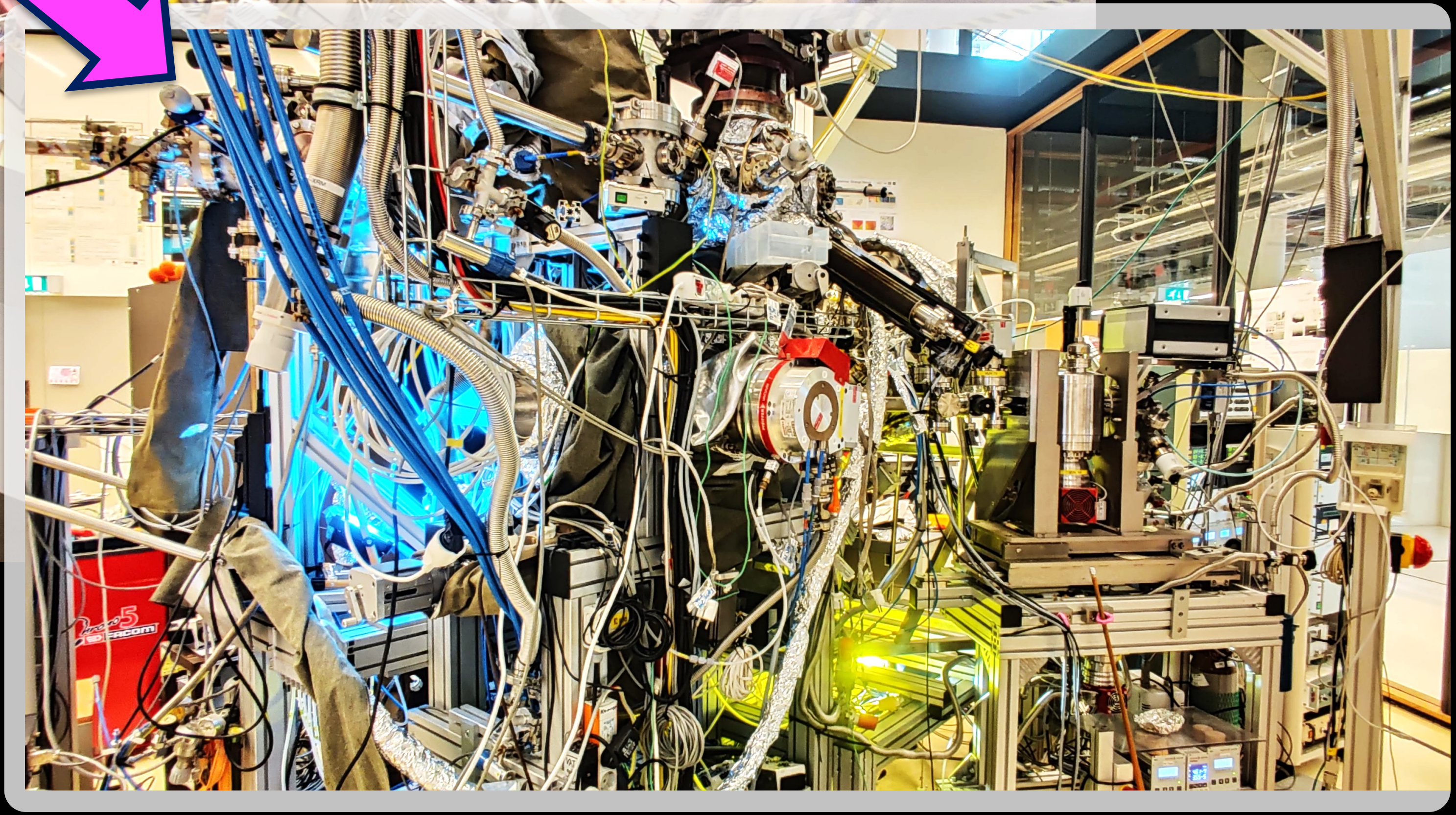




Quantum Materials
Amsterdam







Quantum Materials

Amsterdam

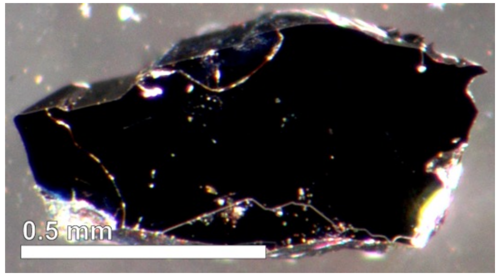
Materials portfolio in Amsterdam

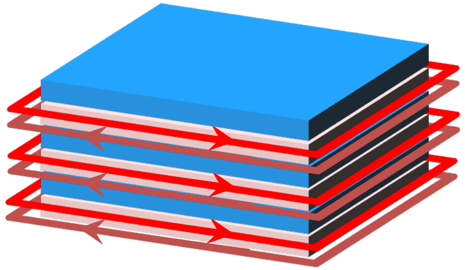
QuMat

Materials portfolio in Amsterdam

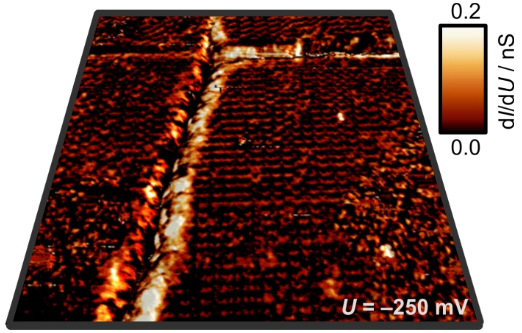
QuMat

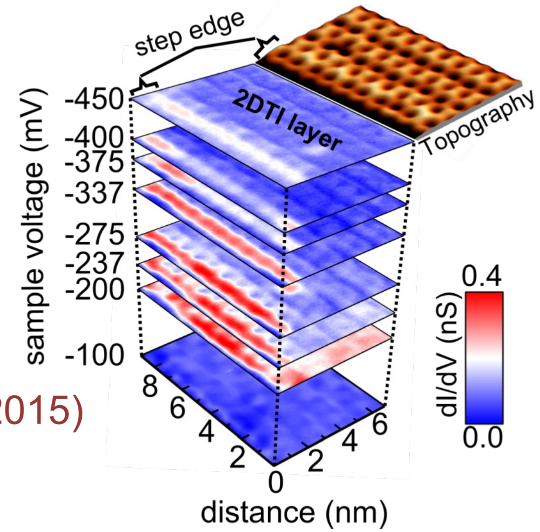
- 3D weak topological insulators: $Bi_{14}Rh_3I_9$, Bi_2TeI, Bi_2TeBr





B. Rasche, A. Isaeva et al. *Nature Mater.* 12, 422 (2013)





C. Pauly et al. *Nature Phys.* 11, 338 (2015)

Materials portfolio in Amsterdam

QuMat

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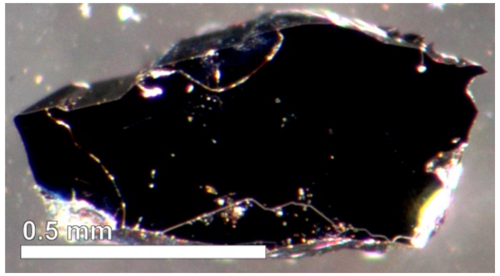

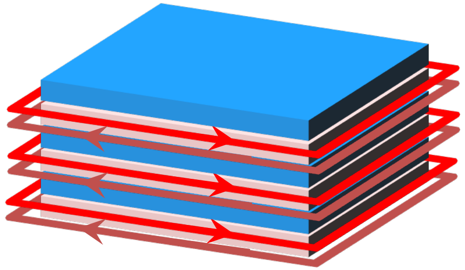

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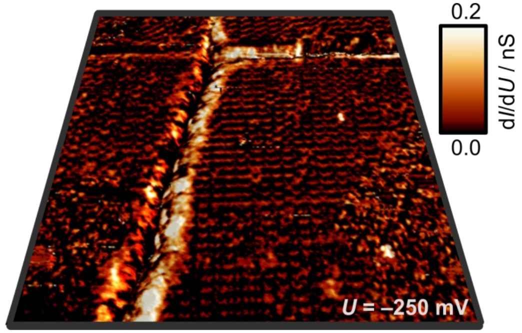

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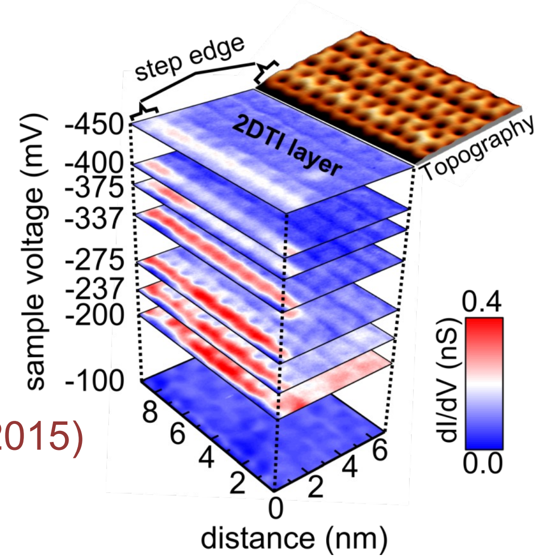
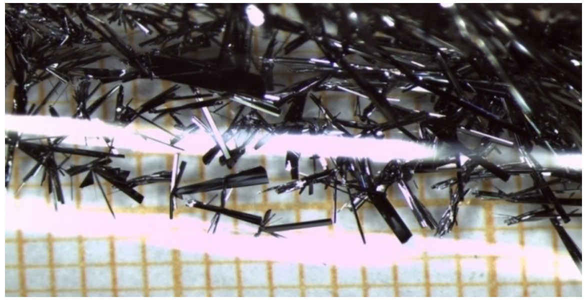
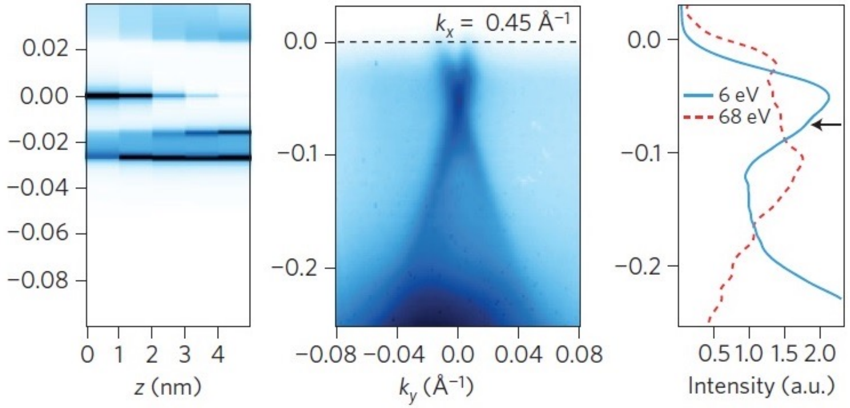


- Dual topological insulators: Bi_2TeI, Bi_4I_4



G. Autès, A. Isaeva, et al. *Nature Chem.* 15, 154 (2016)



Materials portfolio in Amsterdam

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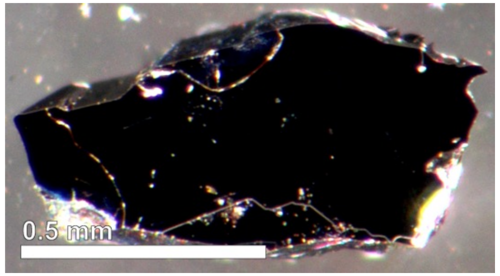

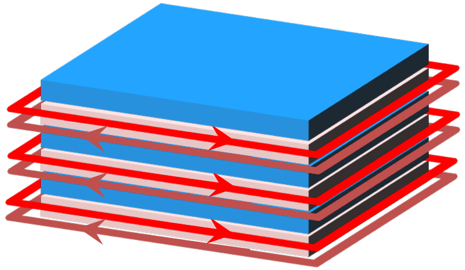

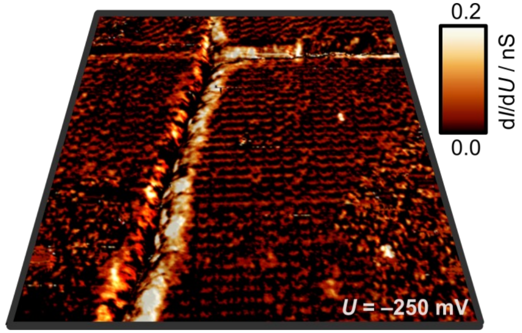

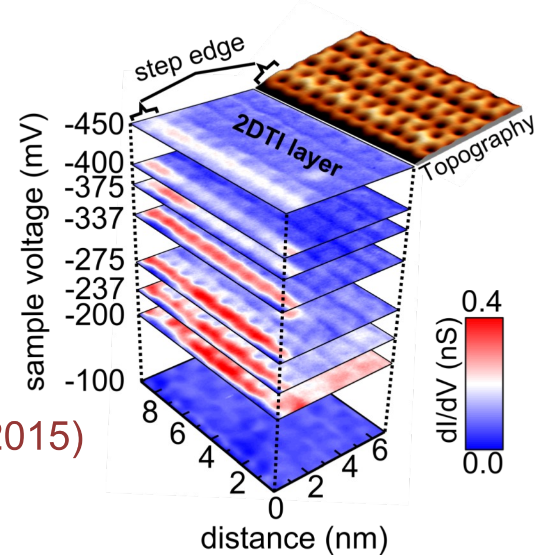

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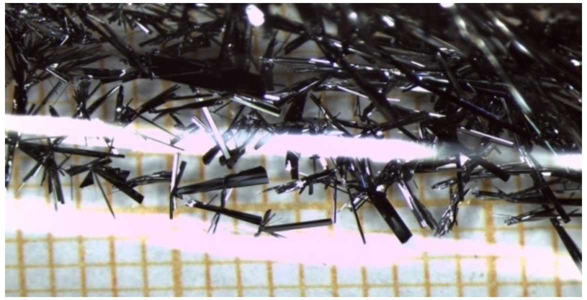

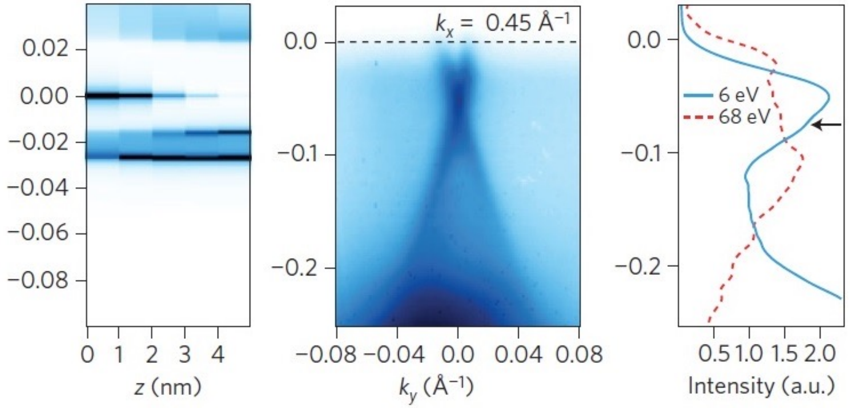

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- Materials by design on demand…