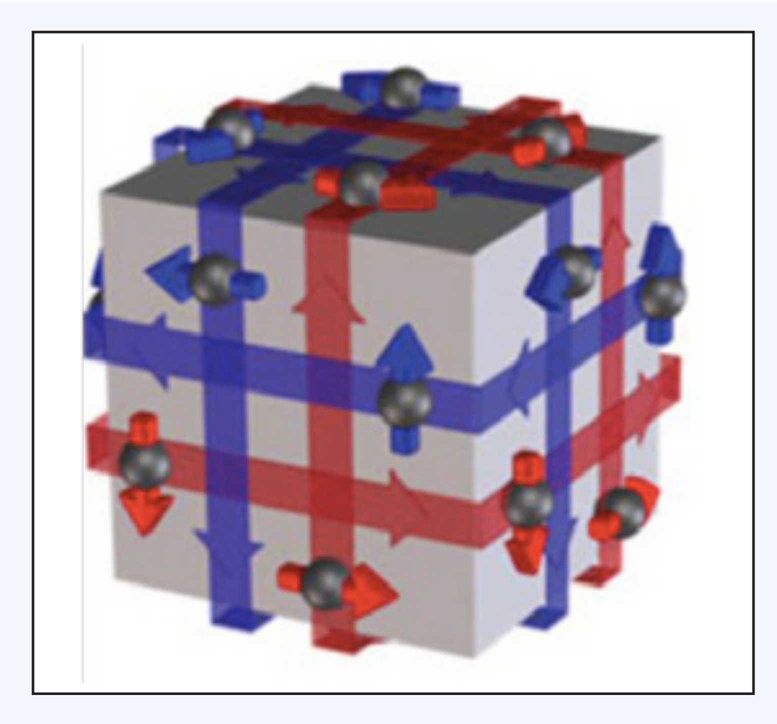
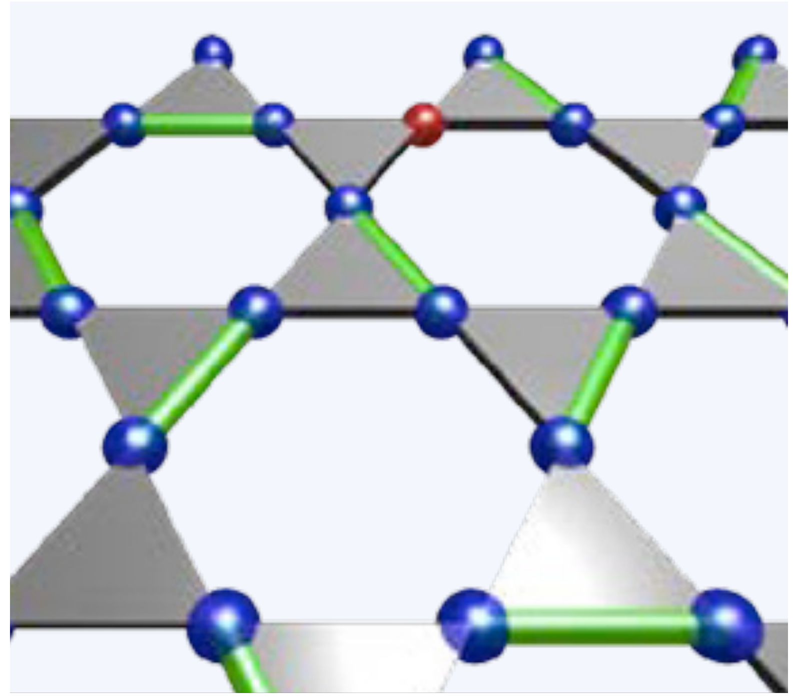
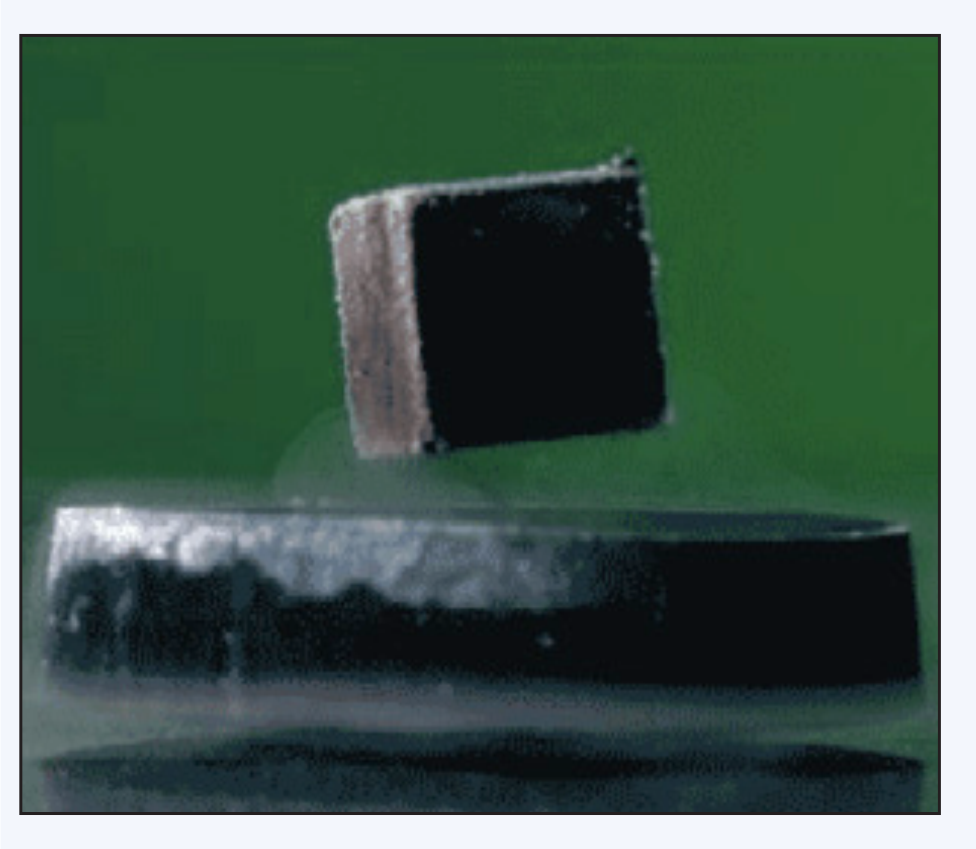
PennState

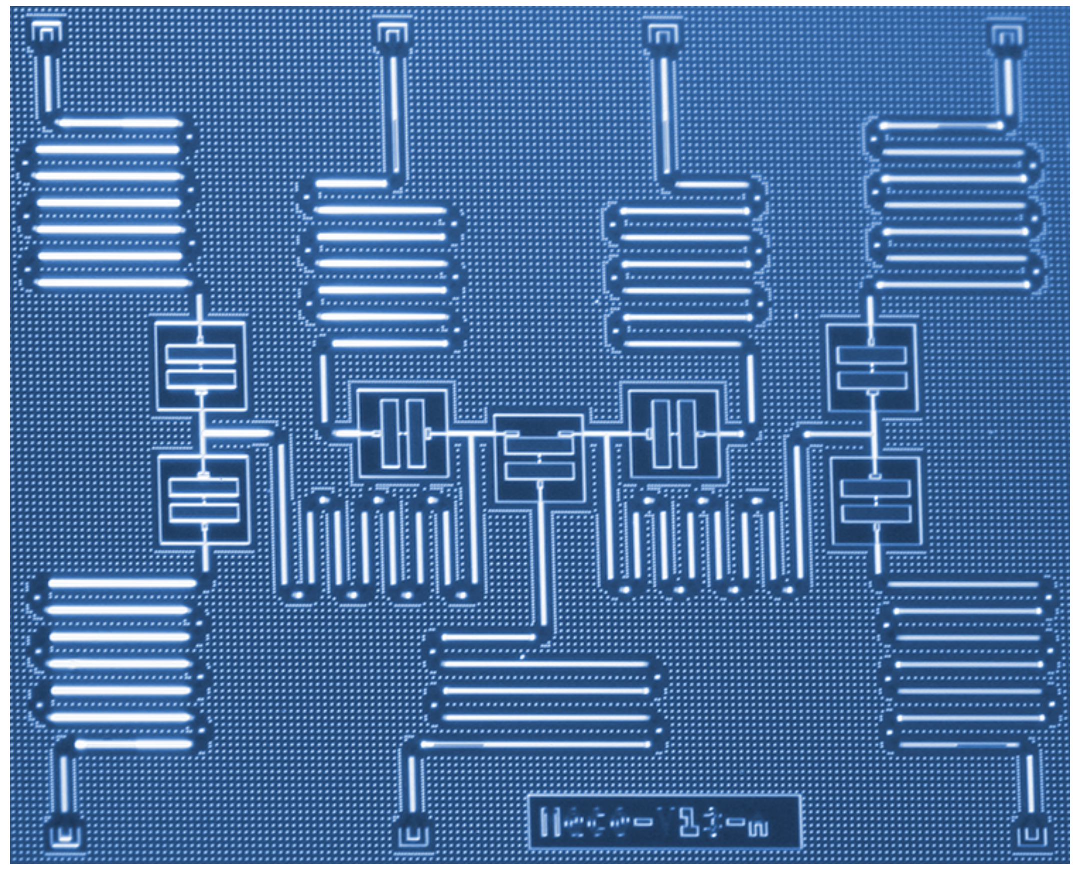
Quantum Materials & Quantum Technologies: Challenges & Opportunities

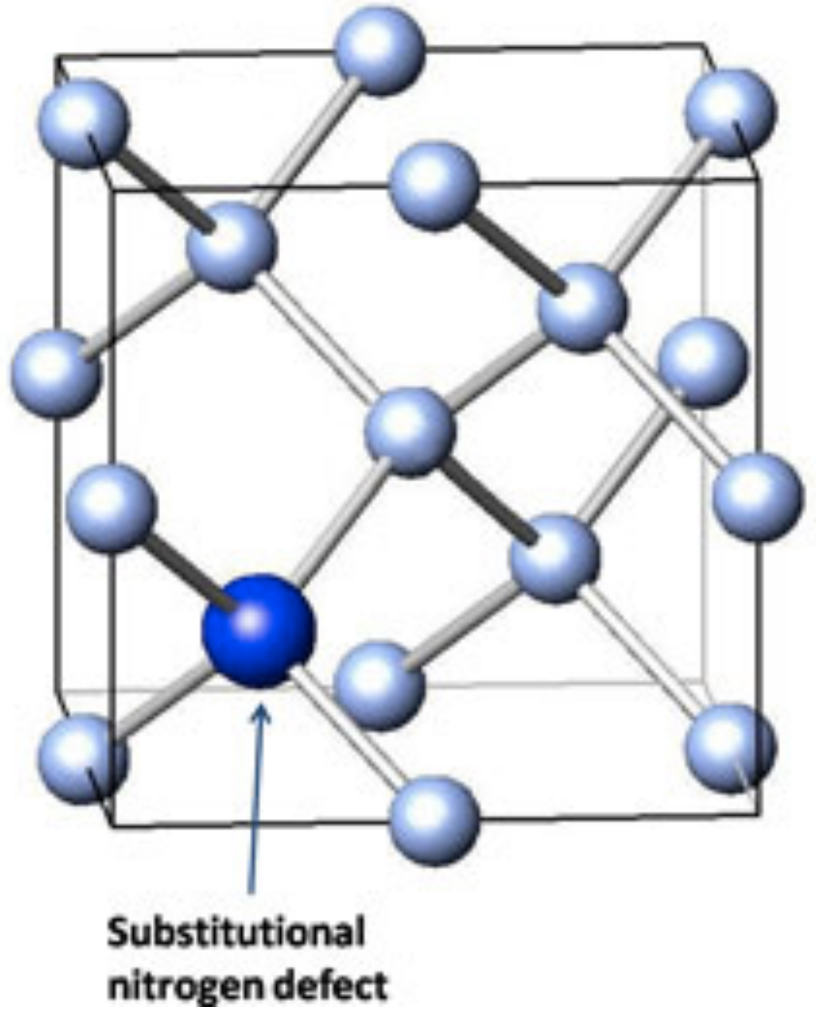
Nitin Samarth, Dept. of Physics











Outline

- Introduction to quantum materials
- Quantum materials: impact on “first generation” quantum technologies
- Quantum materials: what is needed for the “next generation” of quantum technologies & quantum networks?
- “Hybrid” quantum materials — potential for quantum networks

Useful Resources:

https://science.energy.gov/bes/community-resources/reports/

https://www.nature.com/collections/ydsxkfvwws/

Quantum materials

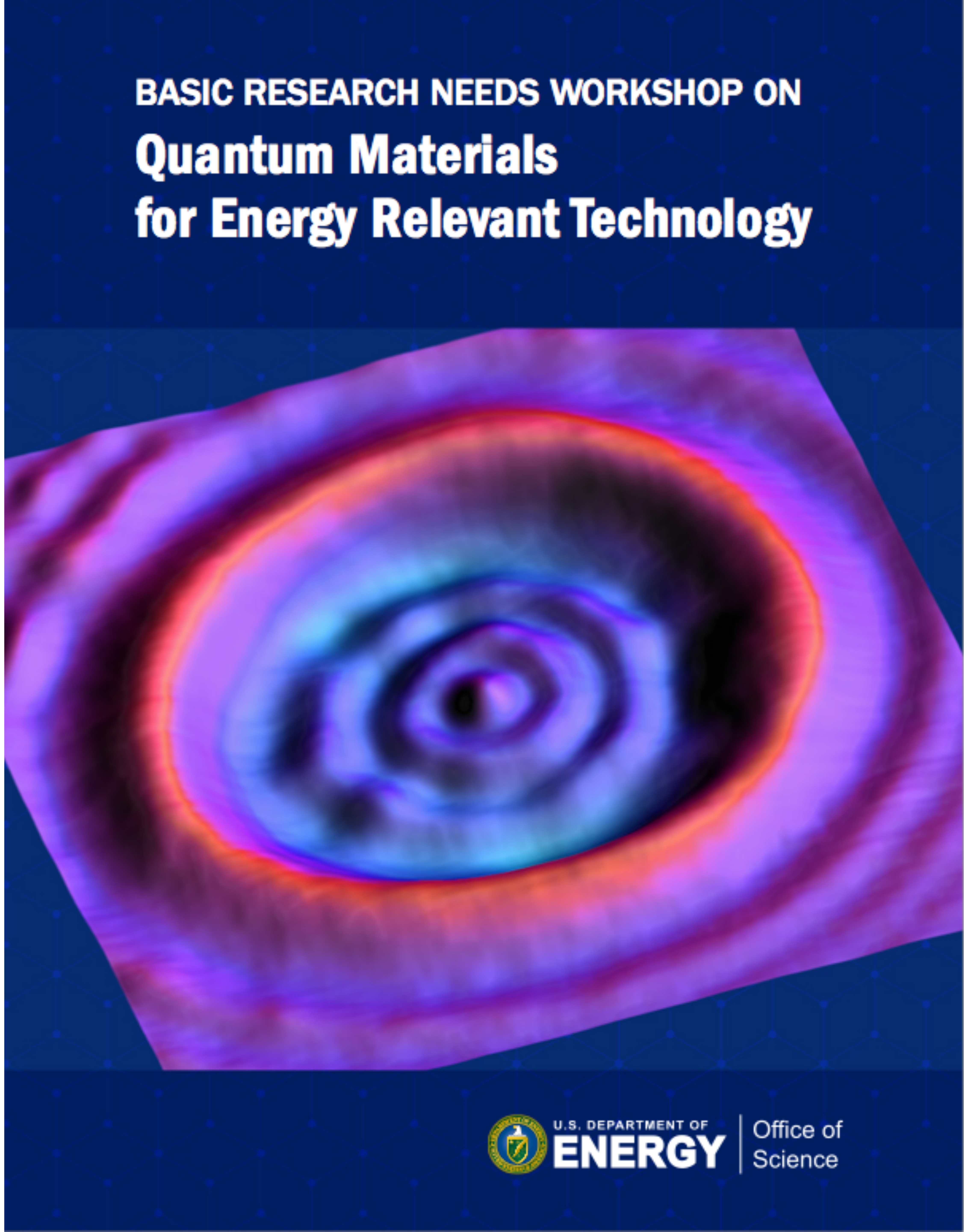
- "Quantum materials are solids with exotic physical properties, arising from the quantum mechanical properties of their constituent electrons; such materials have great scientific and/or technological potential."

- Key concepts: quantum confinement, quantum fluctuations, quantum entanglement, quantum coherence, topology.

- Semiconductor & magnetic nanostructures, superconductors, correlated electron systems, topological materials (topological insulators, Weyl semimetals, Dirac semimetals), quantum spin liquids, ferro/ferri/antiferromagnets, multiferroics, 2D materials.

- Rich fundamental physics & materials science

- What is the technological impact, current and potential?



Quantum materials & ‘first-generation’ quantum technologies

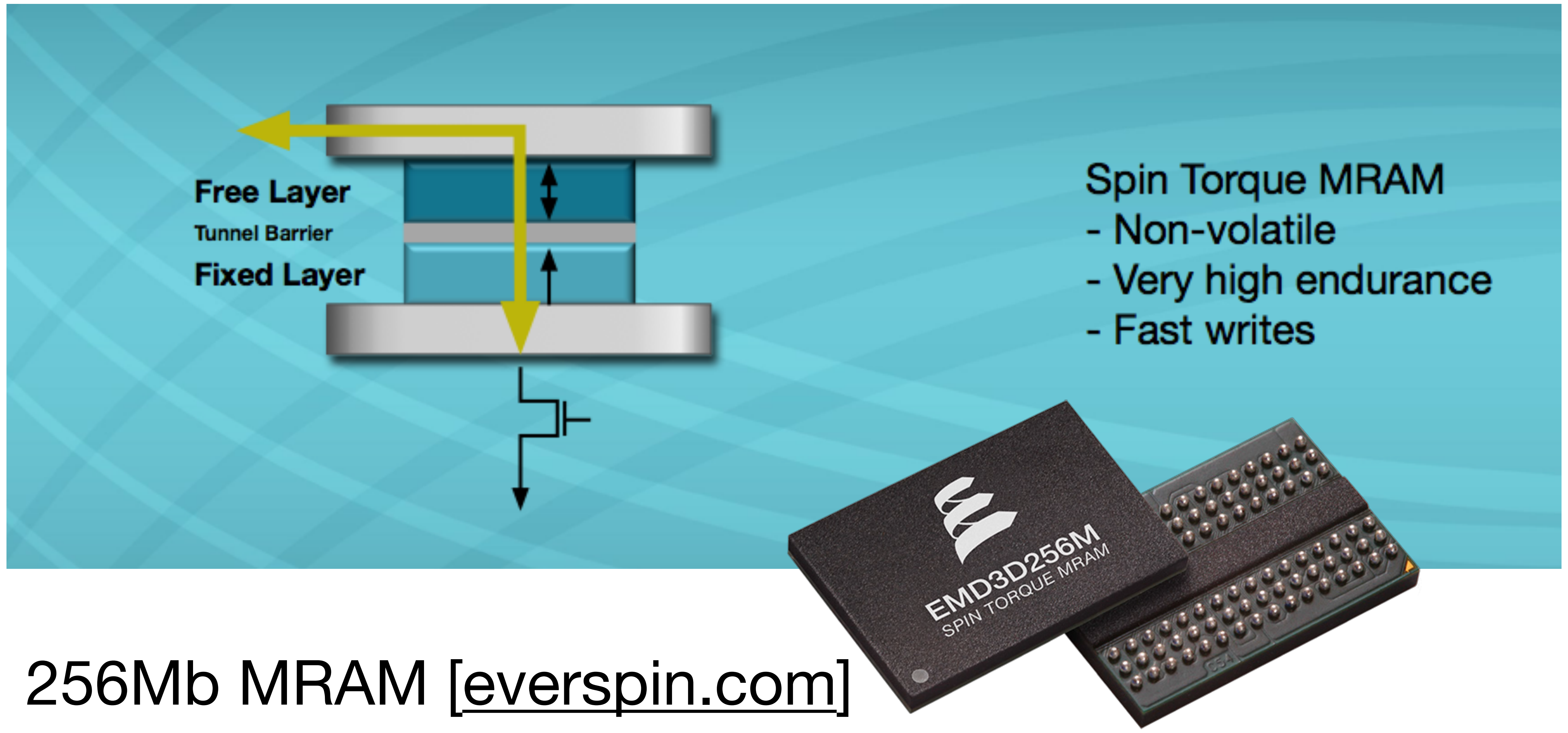
- Over 50 years of fundamental research into the quantum description of semiconductors, superconductors, and magnetic materials has led to diverse technological applications, most of which rely on control over the wave function amplitude.

- Examples:

  - Semiconductor hetero- and nano-structures for light emitters/detectors (quantum well lasers, quantum cascade lasers, quantum dot LEDs, photodetectors) and high-frequency transistors (HEMTs in mobile phones).

  - Magnetic multilayers for memory (MTJ read heads in disk drives; non-volatile MRAM chips).

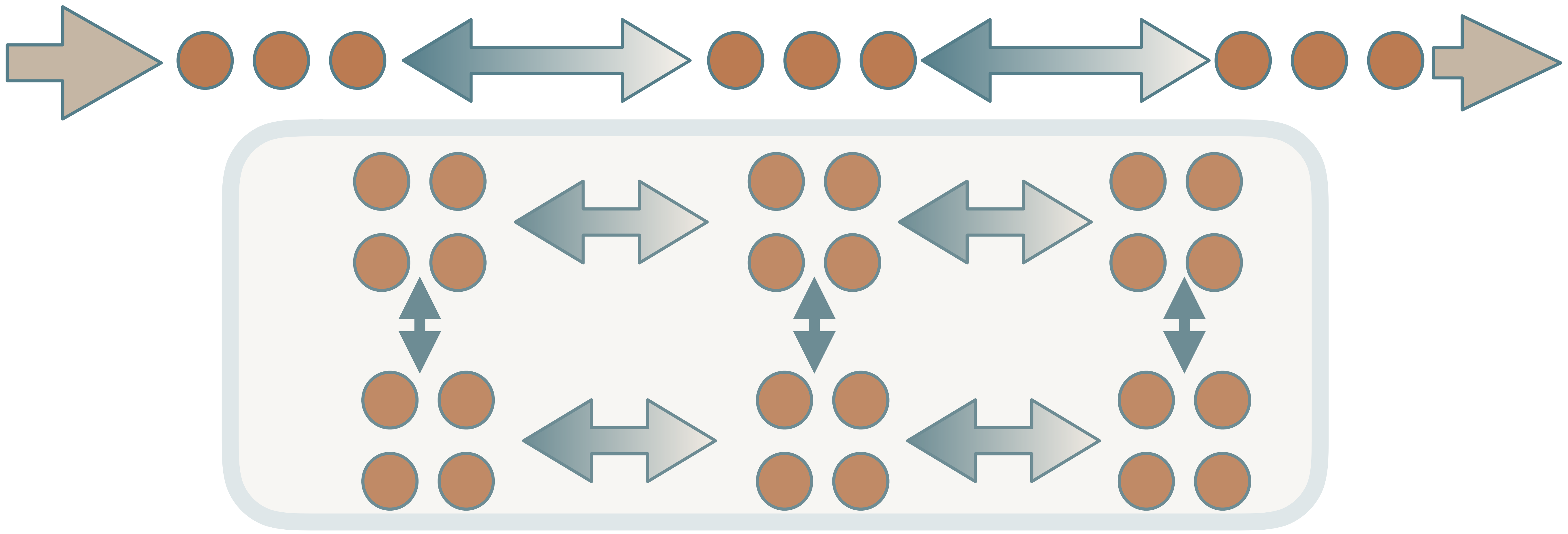
[nanosys.com]



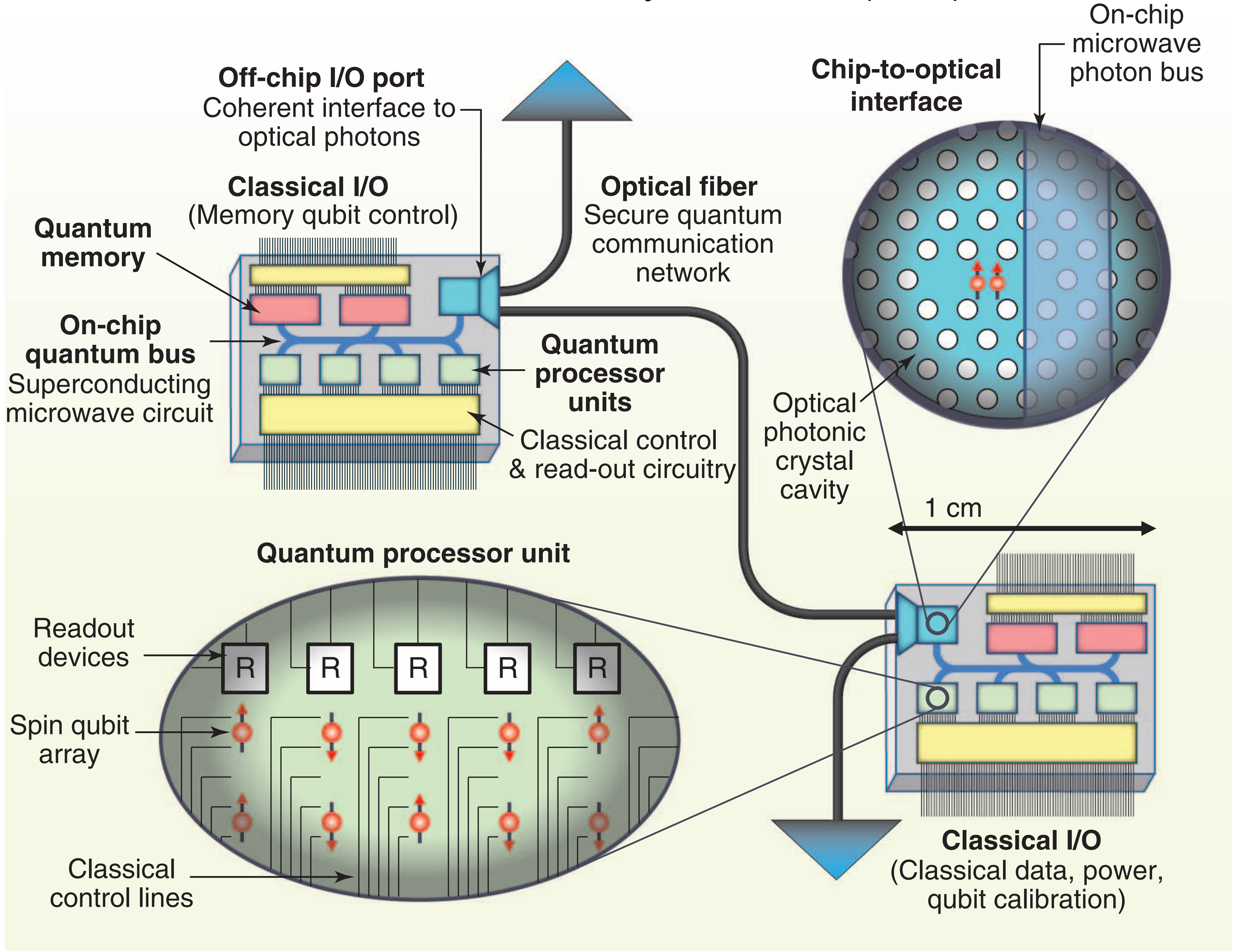
256Mb MRAM [everspin.com]

Quantum materials & ‘next-generation’ quantum technologies

- Next-generation quantum technologies such as quantum networks exploit all aspects of the quantum mechanical wave function (amplitude, phase, non-locality, entanglement)
- Quantum architectures & networks require exchanging quantum information coherently between nodes (qubits) and channels (flying qubits) — demonstrated first in cold atoms & trapped ions
- Most advanced scalable solid state quantum architectures: Josephson junction arrays (Al/Al_2O_3)
- Few qubit demos: spin qubits in semiconductor quantum dots & quantum defects [single donors, nitrogen vacancy (NV) centers, C-Si-divacancies, etc.]
- Futuristic: semiconductor nanowires + superconductivity, topological superconductors (Majorana)



cf. Duan & Monroe, *Rev. Mod. Phys.* **82**, 1209 (2010)



Awschalom *et al*., *Science* **339**, 1174-1179 (2013)

Quantum networks: examples of advances

Heralded entanglement between distant stationary qubits using **photons**:

- Trapped ions [e.g. *Phys. Rev. Lett.* **100**, 150404 (2008)]
- Cold atoms [e.g. *Science* **316**, 1316 (2007)]
- Nitrogen-vacancy (NV) defect centers [*Nature* **497**, 86 (2013)]
- Semiconductor quantum dots [*Nature Physics* **12**, 218–223 (2016)]
- Superconducting qubits [*Phys. Rev. X* **6**, 031036 (2016)]

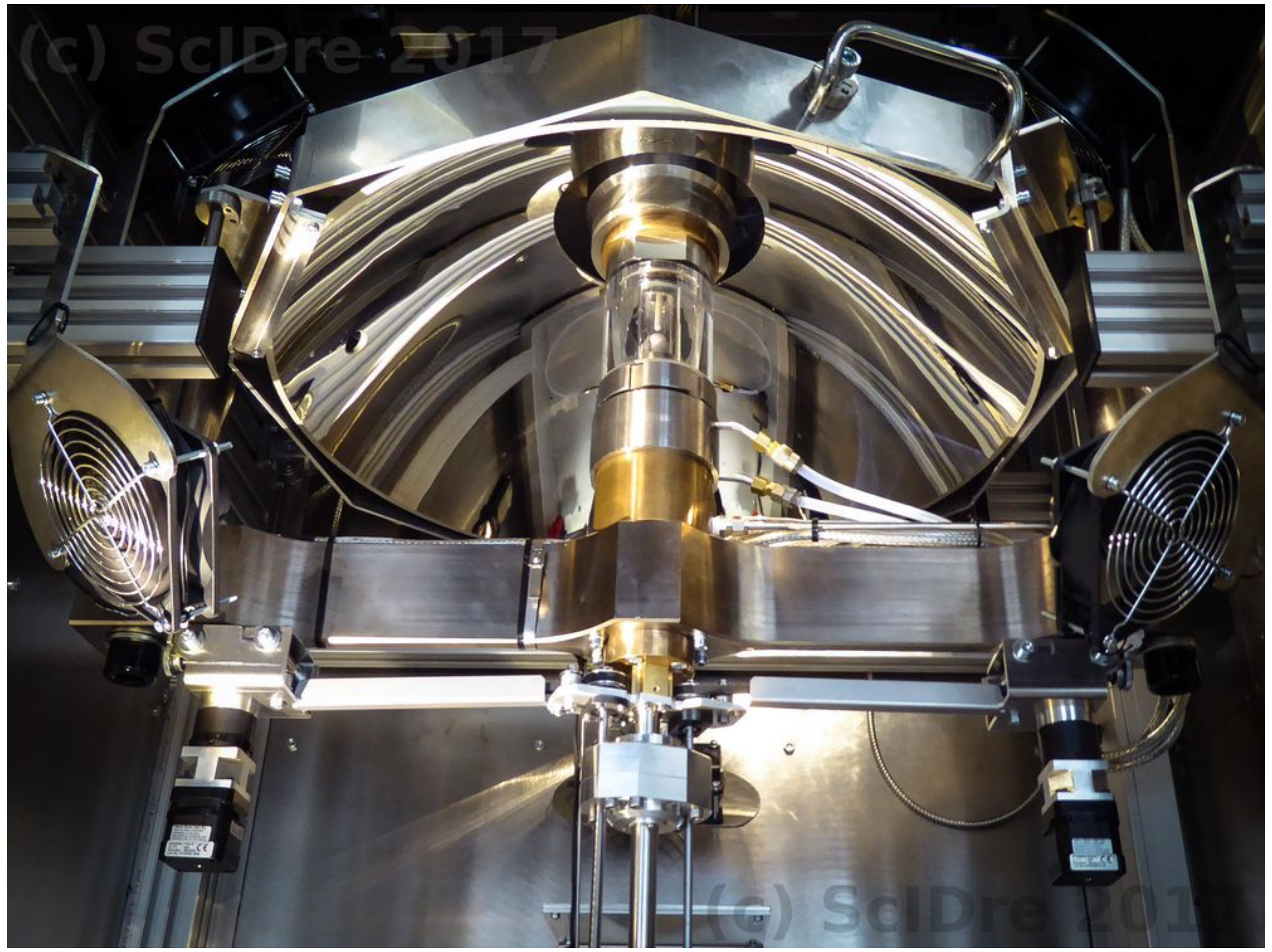
Challenges for materials synthesis

- What materials aspects need to be controlled for enhancing quantum coherence times?
- What do we need for scaling solid state platforms?
- Can we develop hybrid systems that demonstrate ‘entanglement-on-a-chip’ using modes other than photons?

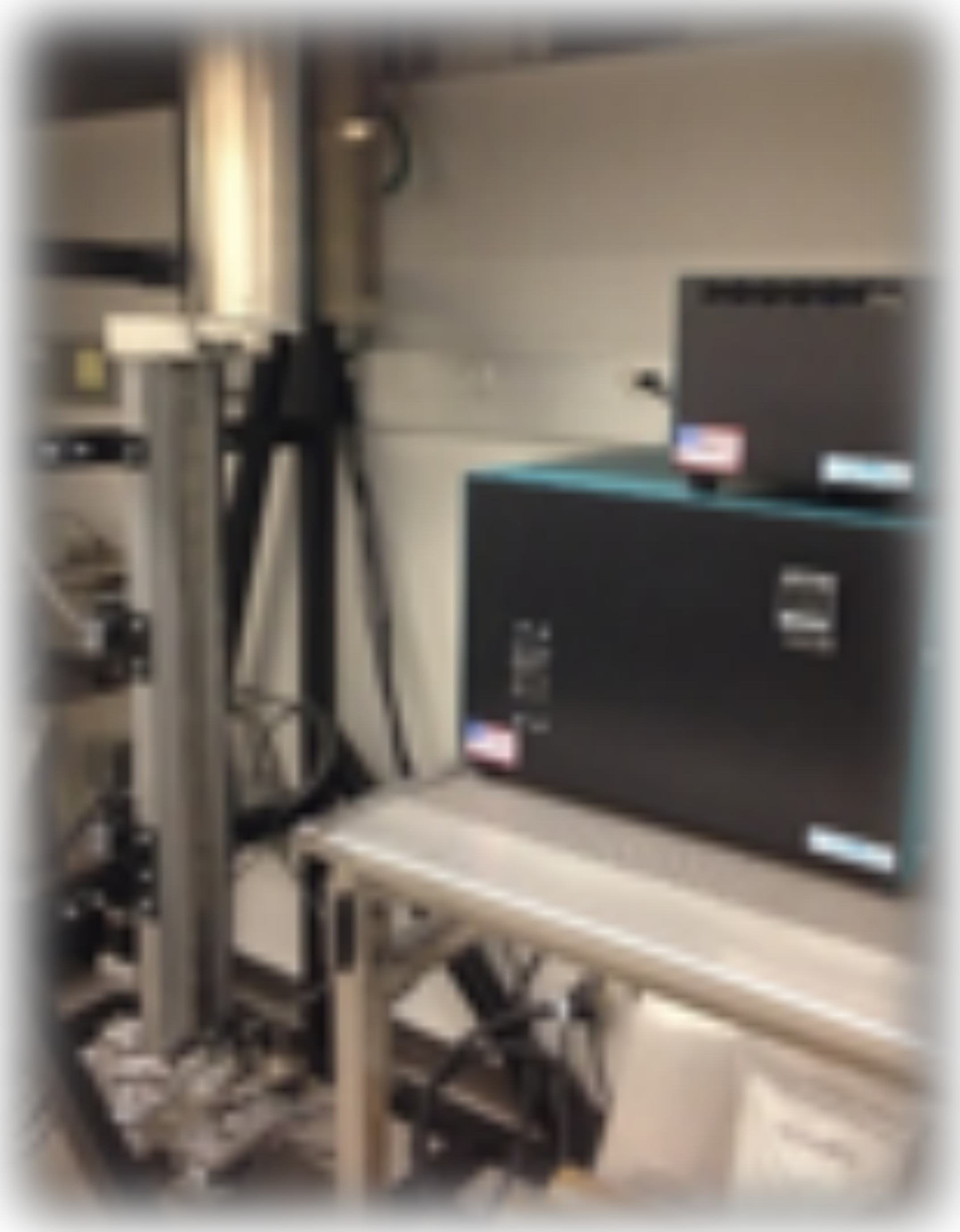
Quantum materials:
synthesis of bulk crystals

Exotic superconductor Sr_2RuO_4
[Mao, Penn State]

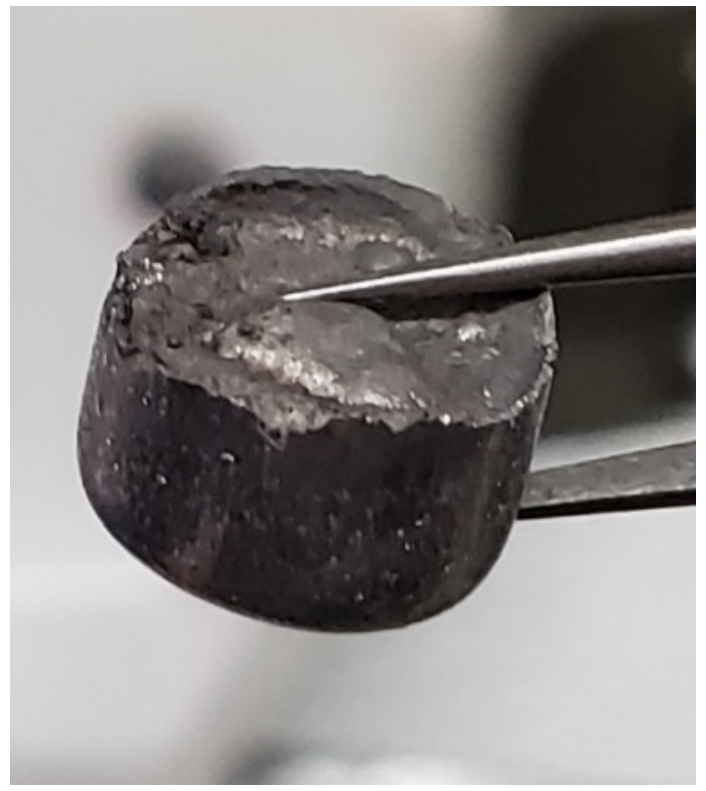
Bulk crystal growth continues to provide quantum material specimens of high crystalline quality

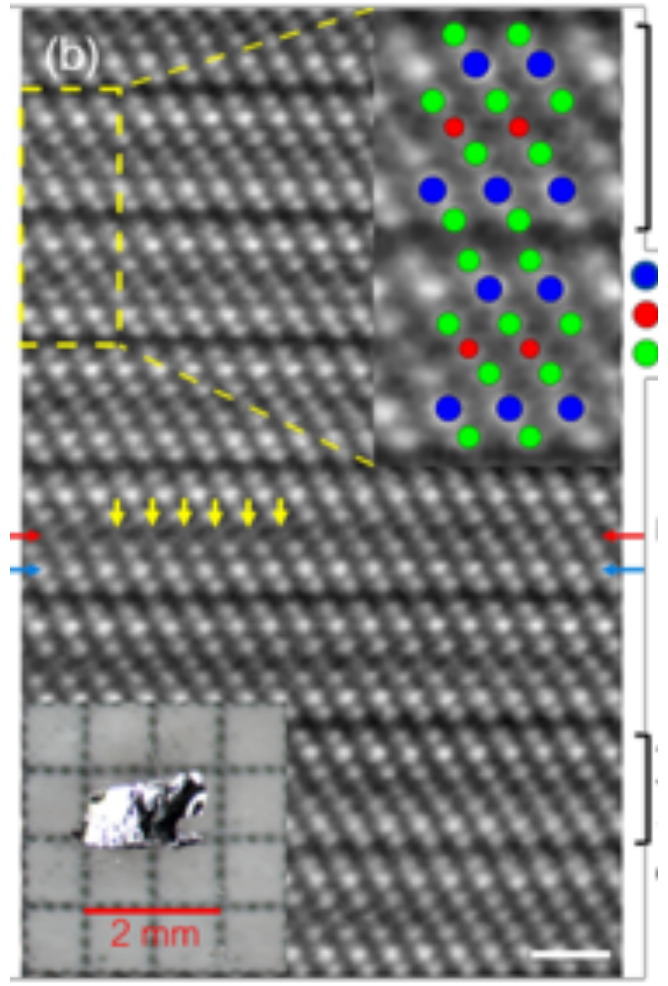


High pressure floating zone furnace
[Mcqueen, Johns Hopkins]



Vertical Bridgman
[2DCC, Penn State]





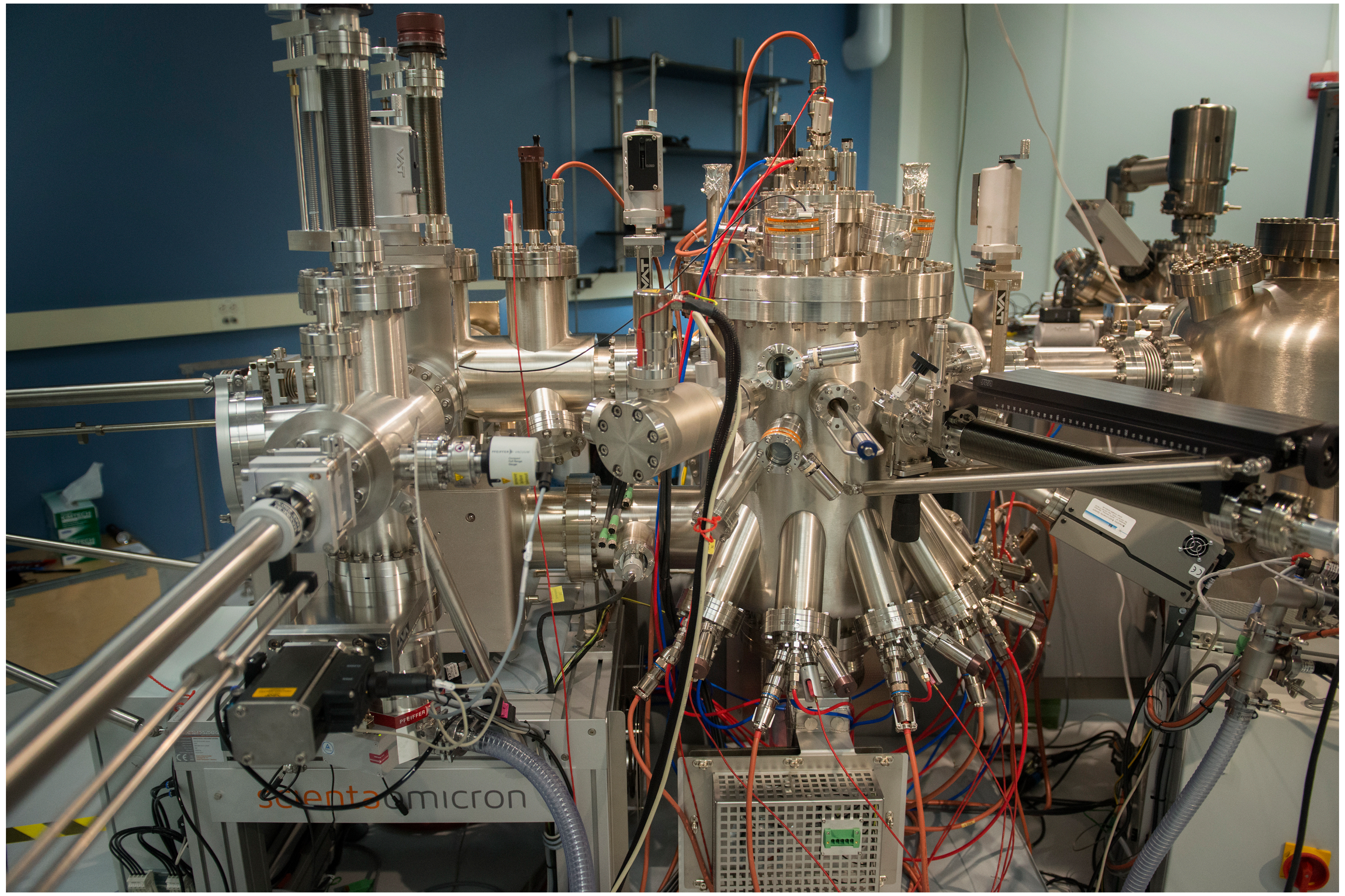
Antiferromagnetic topological insulator $BiMn_2Te_4$
[Mao, Penn State]

Quantum materials: synthesis of thin films & heterostructures

2D Crystal Consortium
NSF Materials Innovation Platform

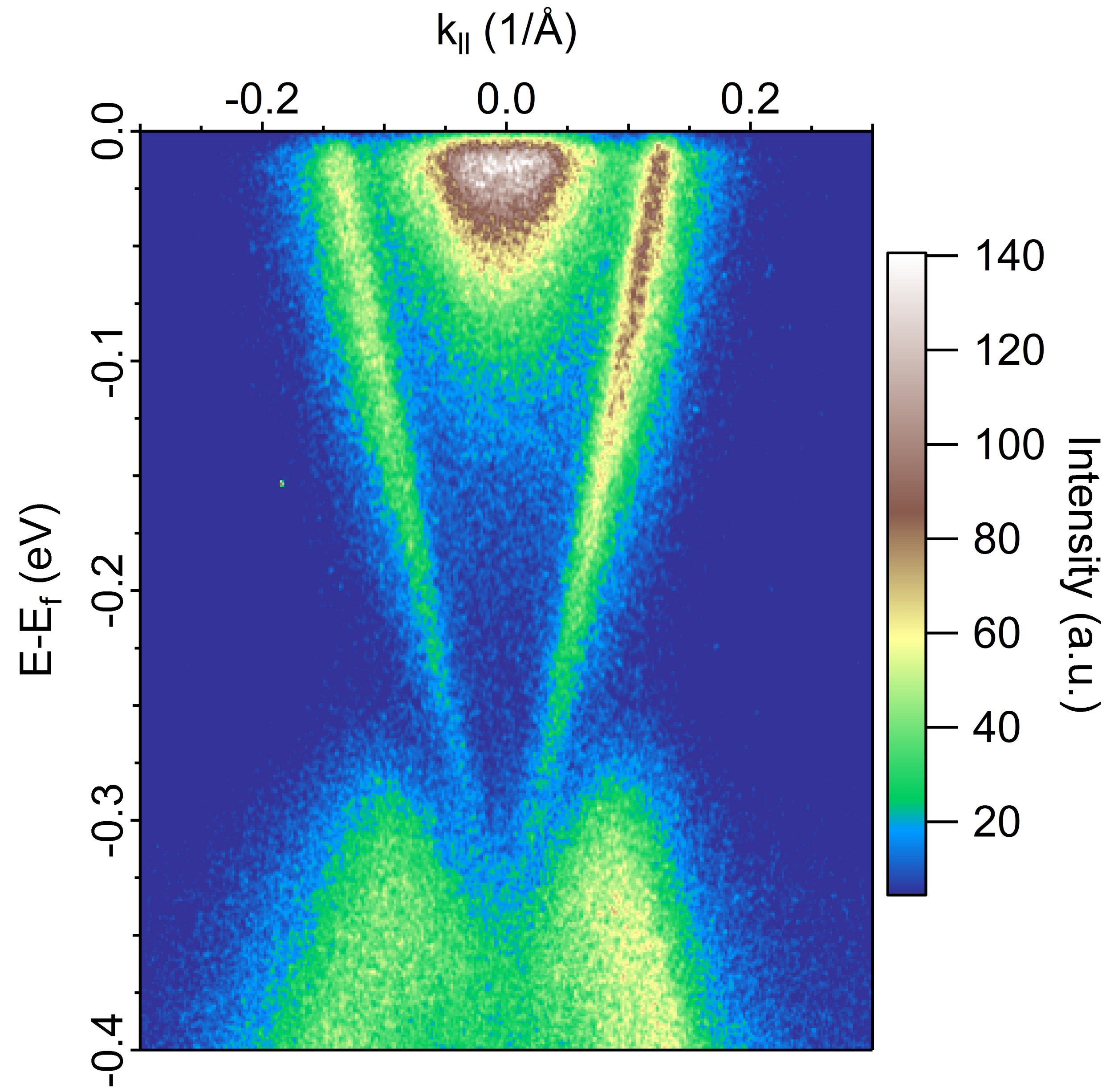
PennState

Epitaxial growth of thin films allows one to tune many parameters such as strain, interfaces, order parameters and is crucial for potential applications

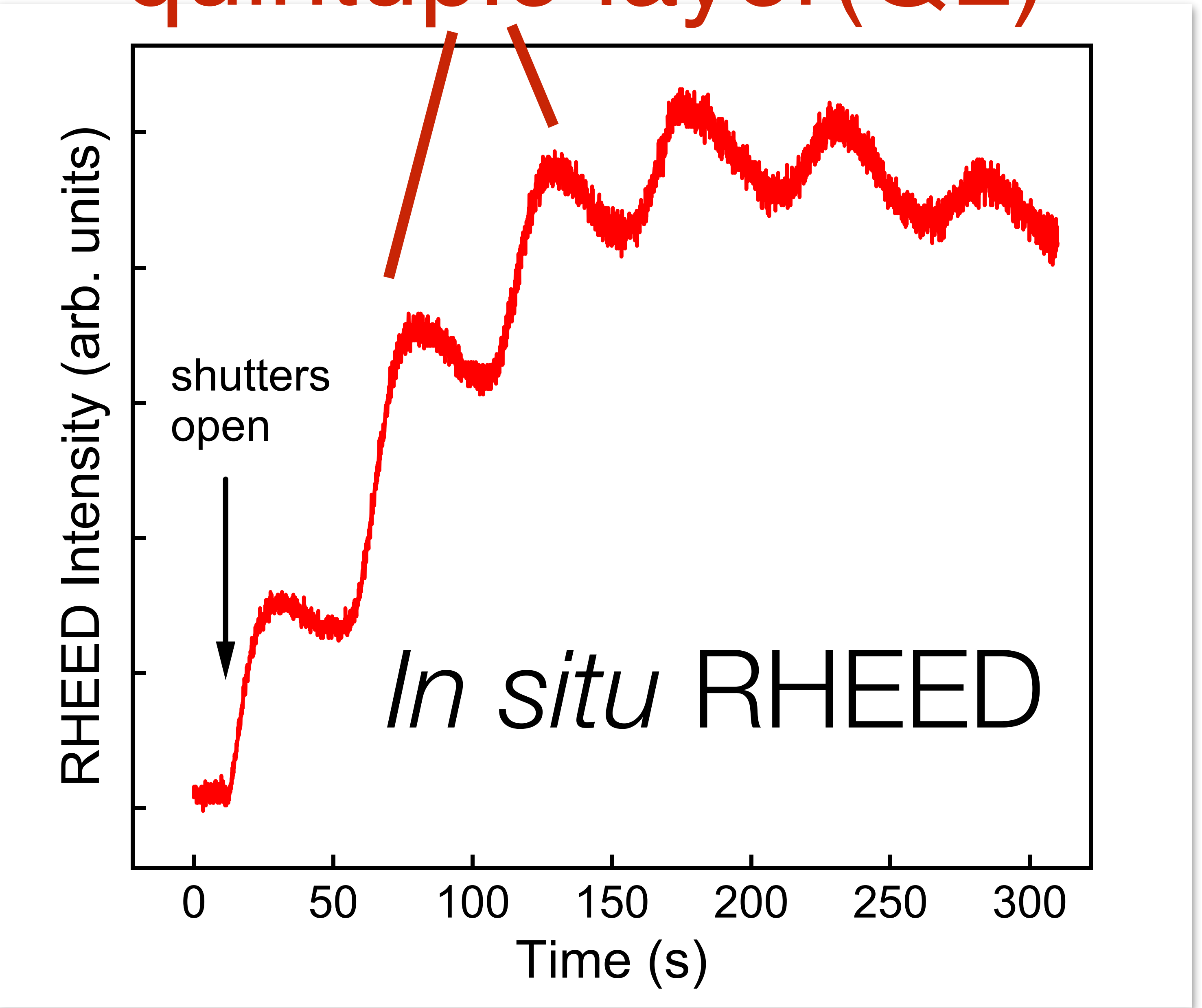


Molecular Beam Epitaxy

In vacuo ARPES

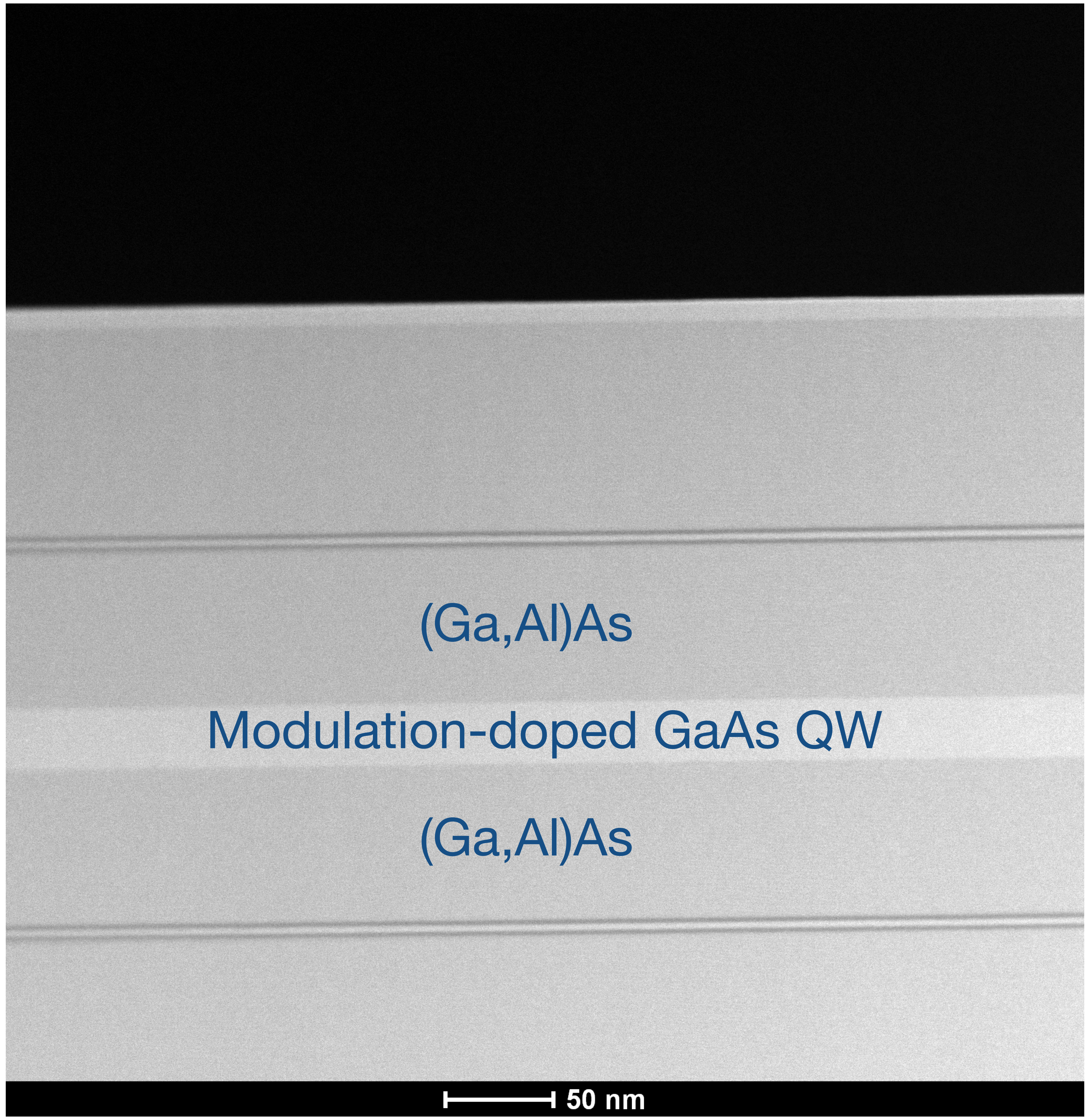


quintuple layer(QL)



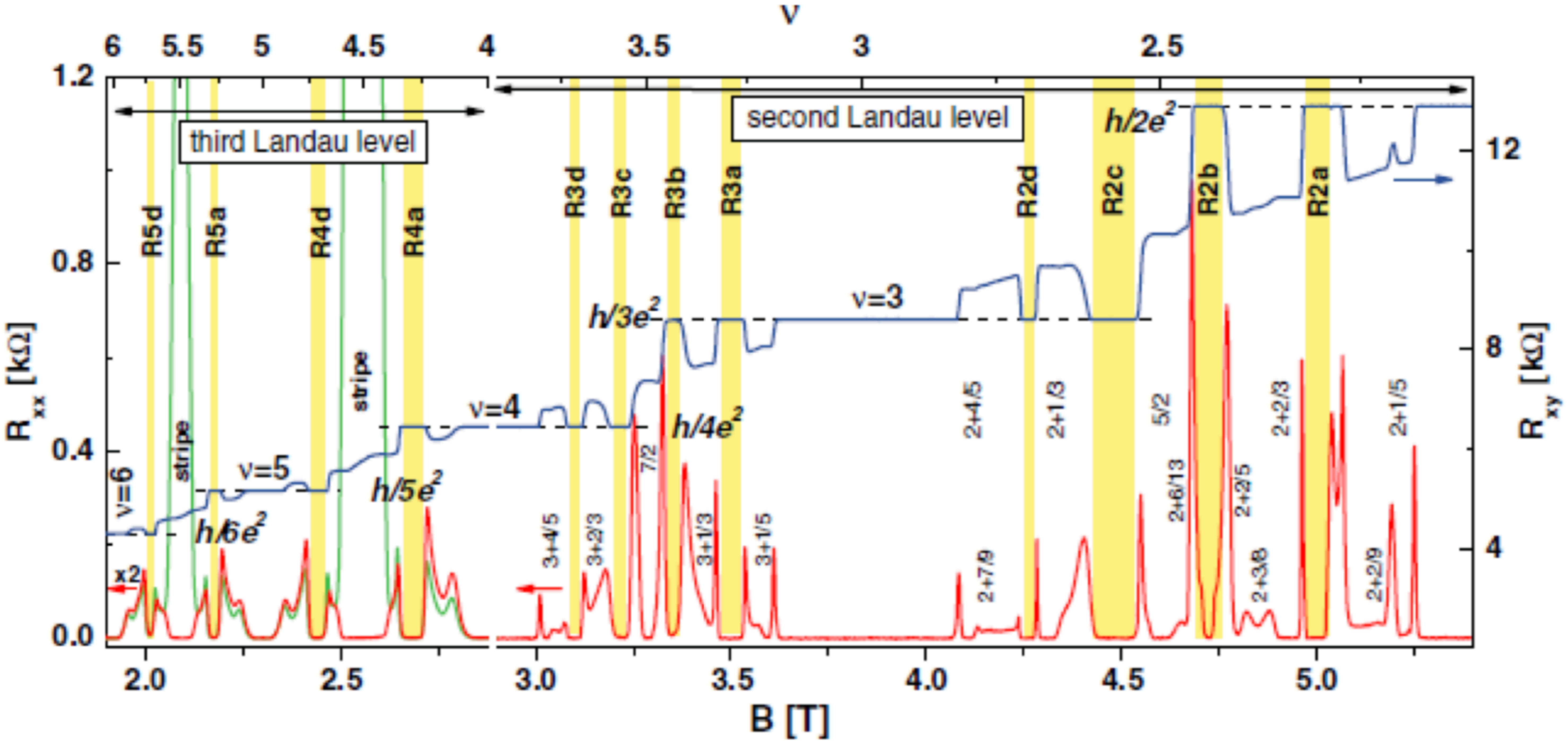
The quintessential topological quantum material

[Purdue]



Sample courtesy: Manfra, Purdue
TEM: Samarth & Kally, Penn State

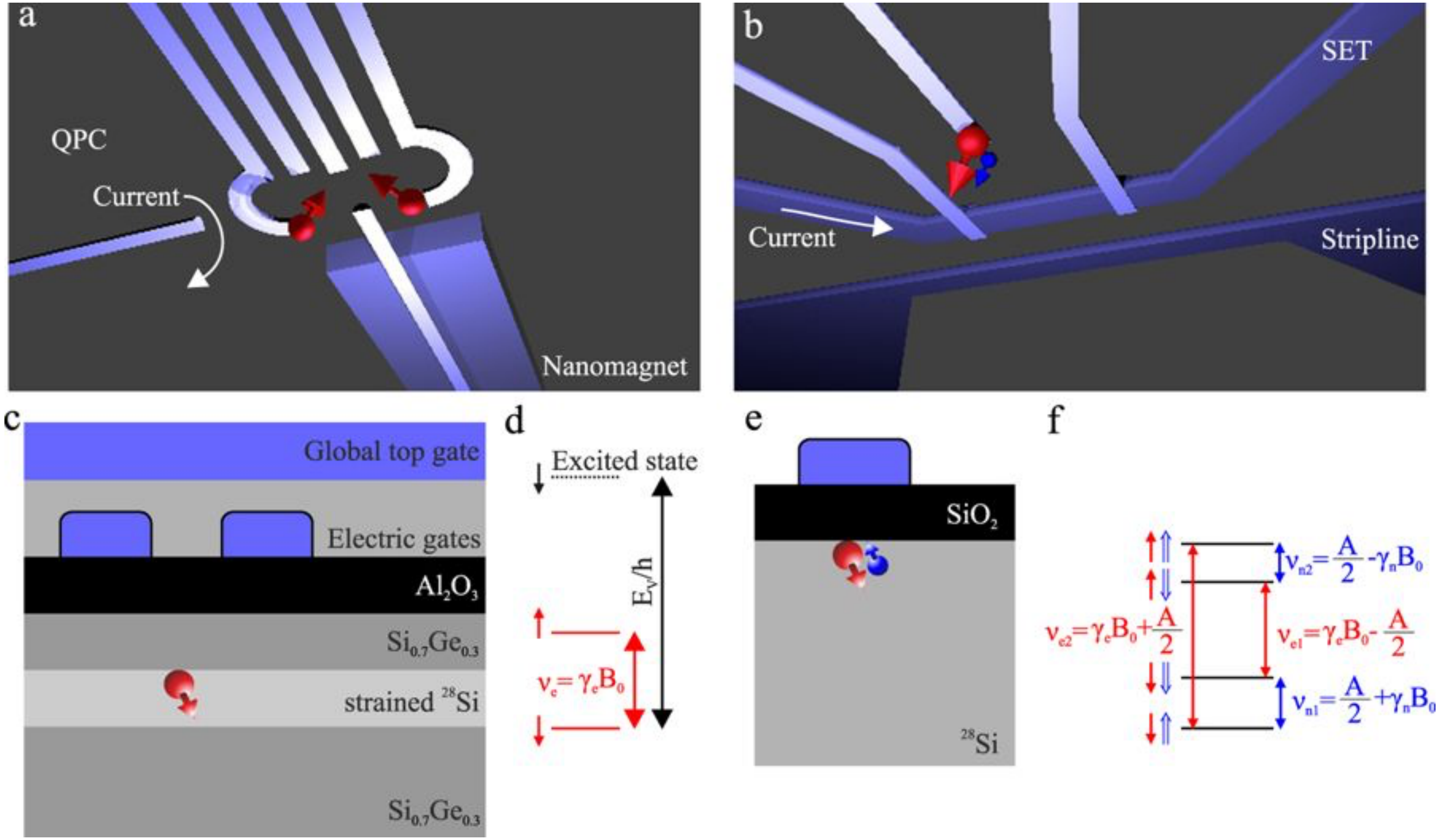
Graphic: Manfra, Ann. Rev. CMP (2013)



2D electron gas formed in a modulation-doped GaAs quantum well is the ideal quantum material — structurally perfect crystals, highest known mobility of any material (~35 x 10^6 cm^2/V.s), host of emergent phenomena such as composite fermions, bubble/stripe phases, excitonic superconductivity, possibly **non-Abelian states for topological quantum computing**

Semiconductor spin qubits

Vandersypen *et al*., *npj Quantum Information* **3**, 34 (2017) **[Delft]**



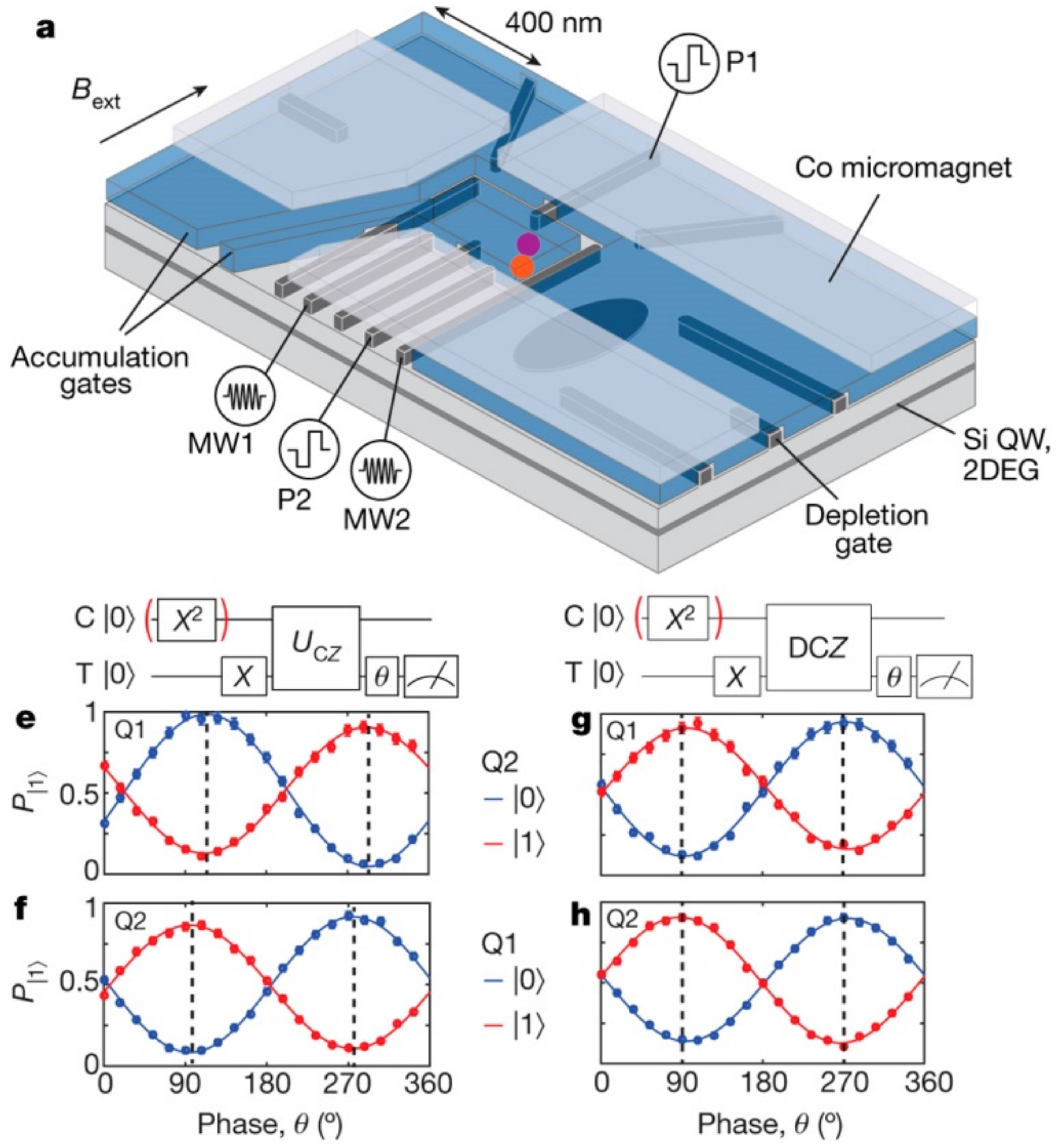
Essential idea is to trap, probe, and manipulate a single electron.

Quantum dot in an electrically gated 2DEG [Si/SiGe, GaAs/GaAlAs].

Single donor atom coupled to an electrostatic gate [P-doped Si].

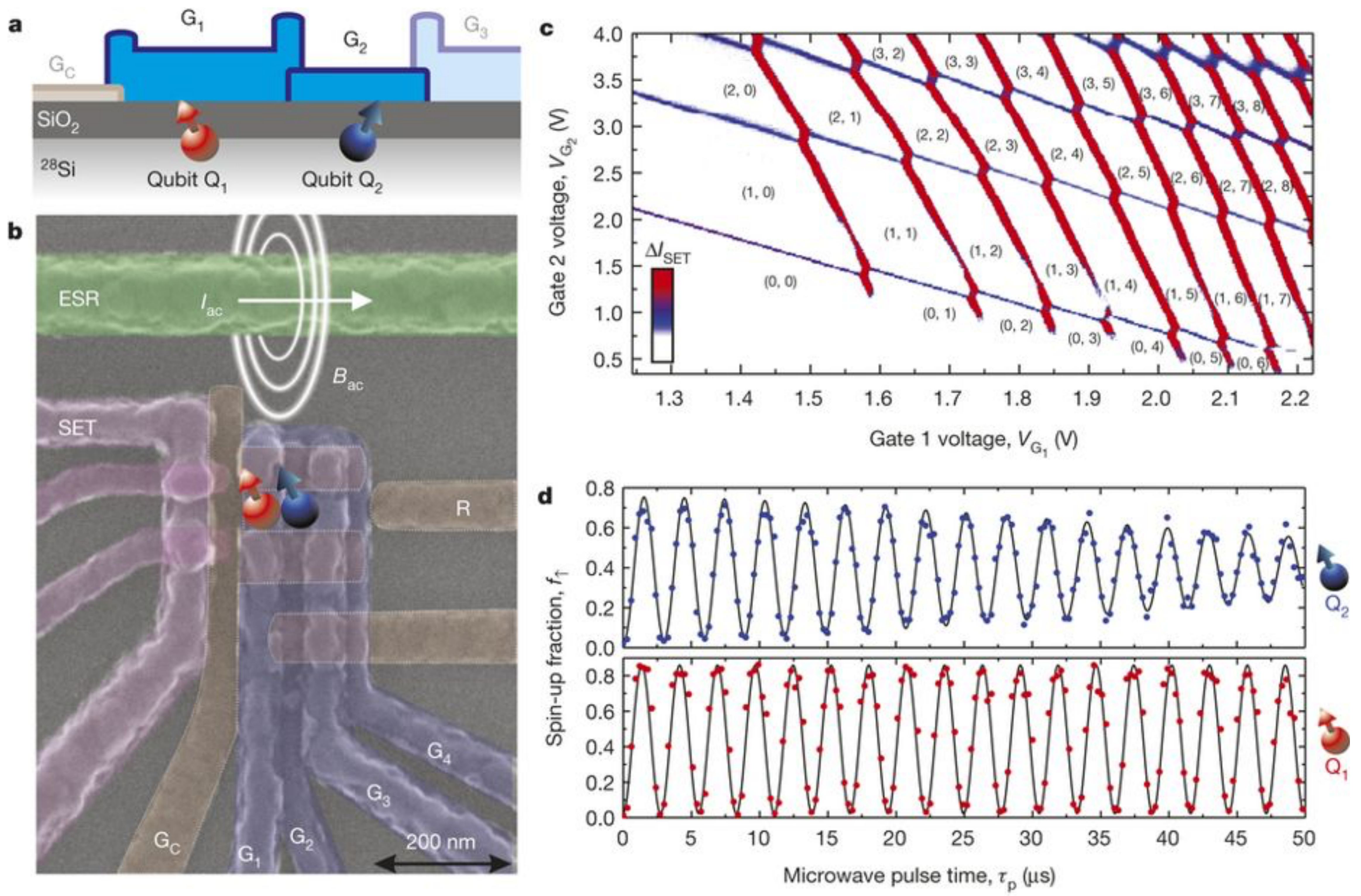
The two level Zeeman-split spin states of these single confined electrons define the qubit.

Spin qubits in semiconductors



Watson *et al*., *Nature* **555**, 633 (2018)

2-qubit quantum processors demonstrated in both Si/SiGe quantum dots & P-doped Si.

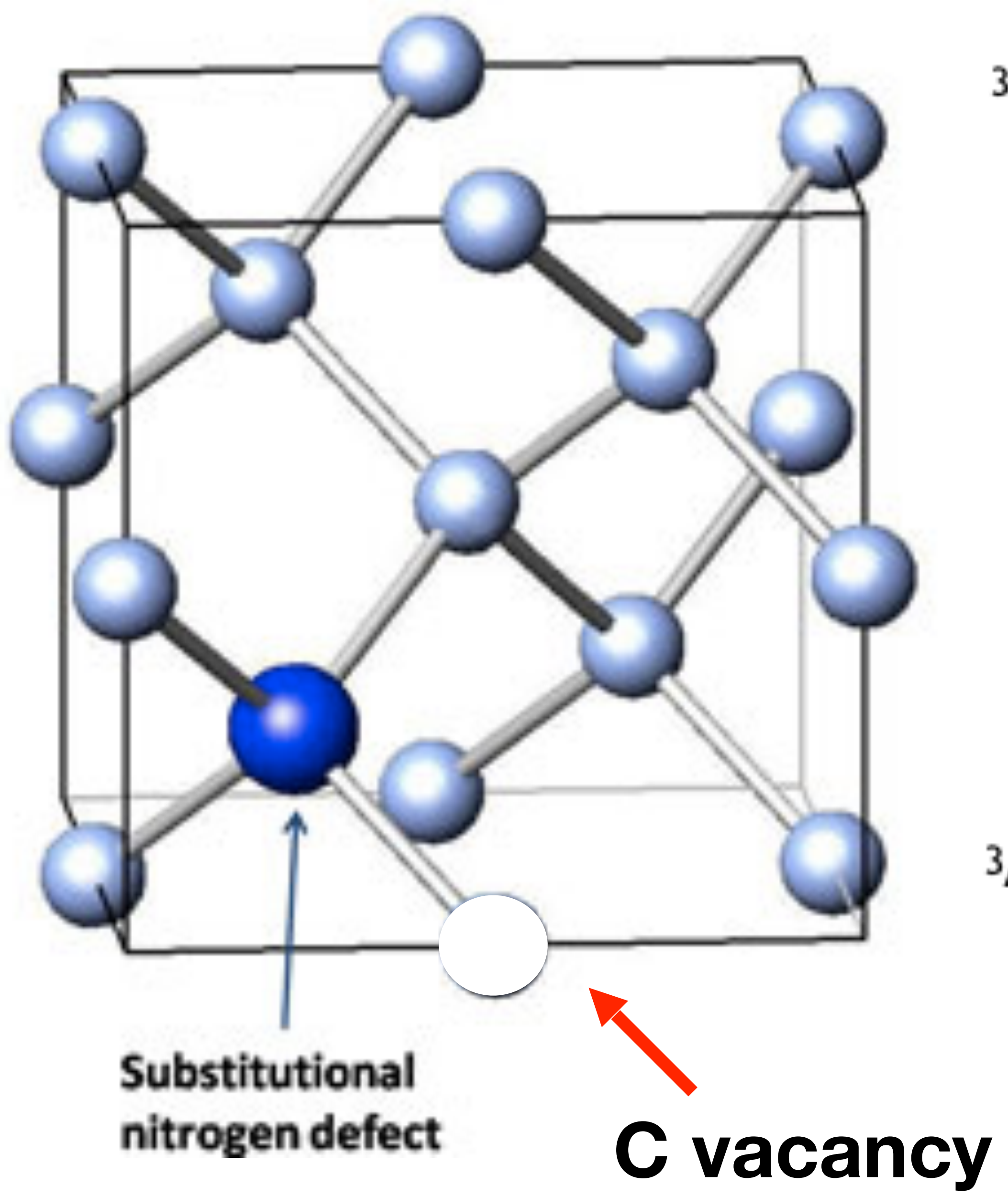


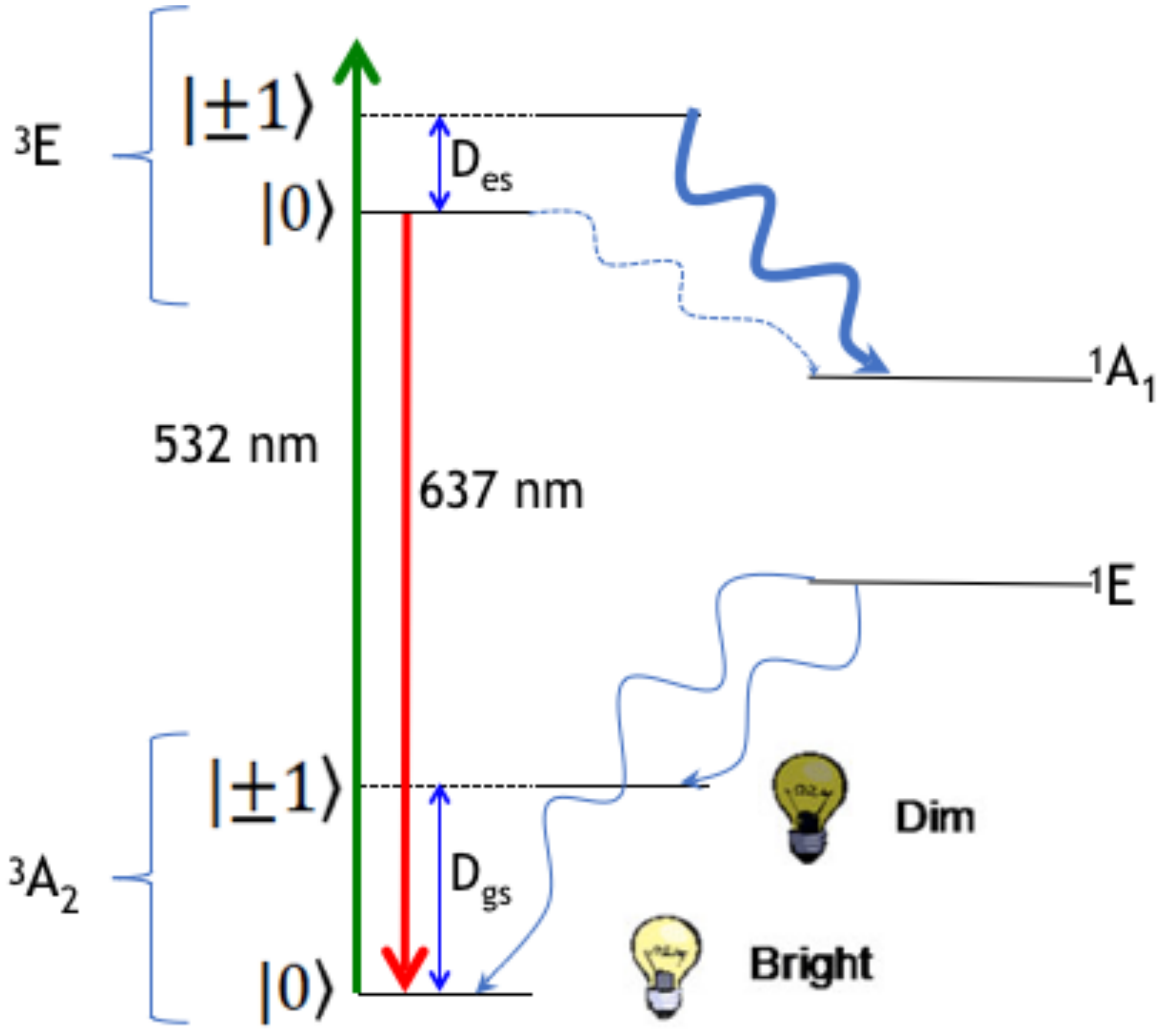
Watson *et al*., *Nature* **526**, 410 (2015)

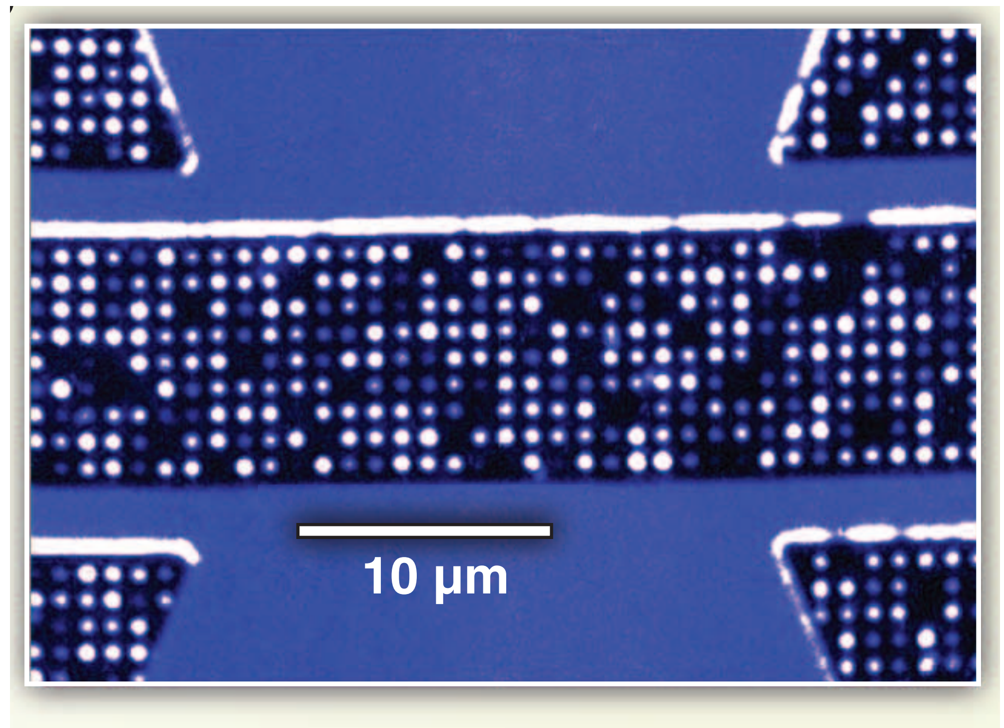
[Delft]

Single spin defects & quantum information

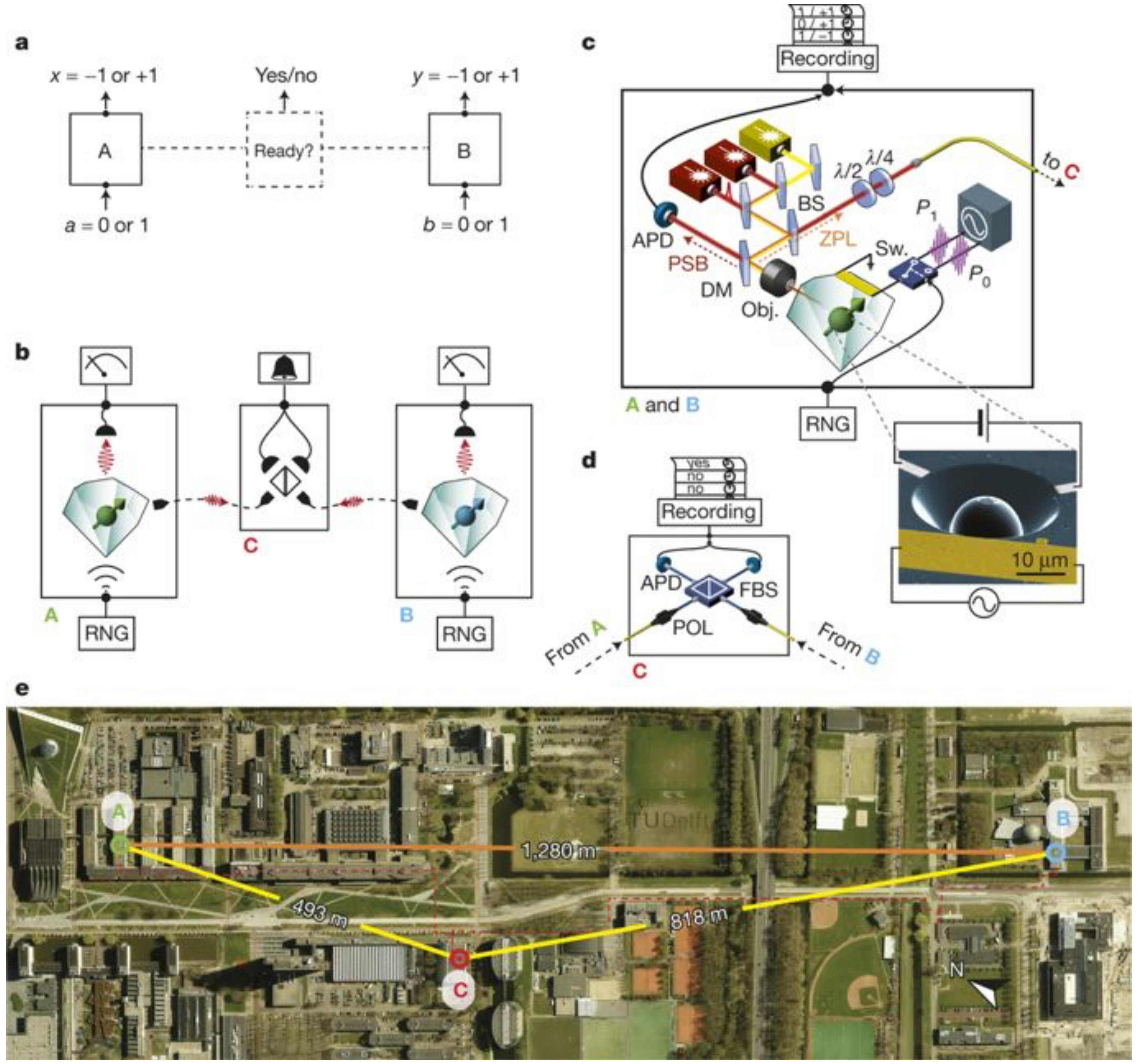
NV-center: diamond







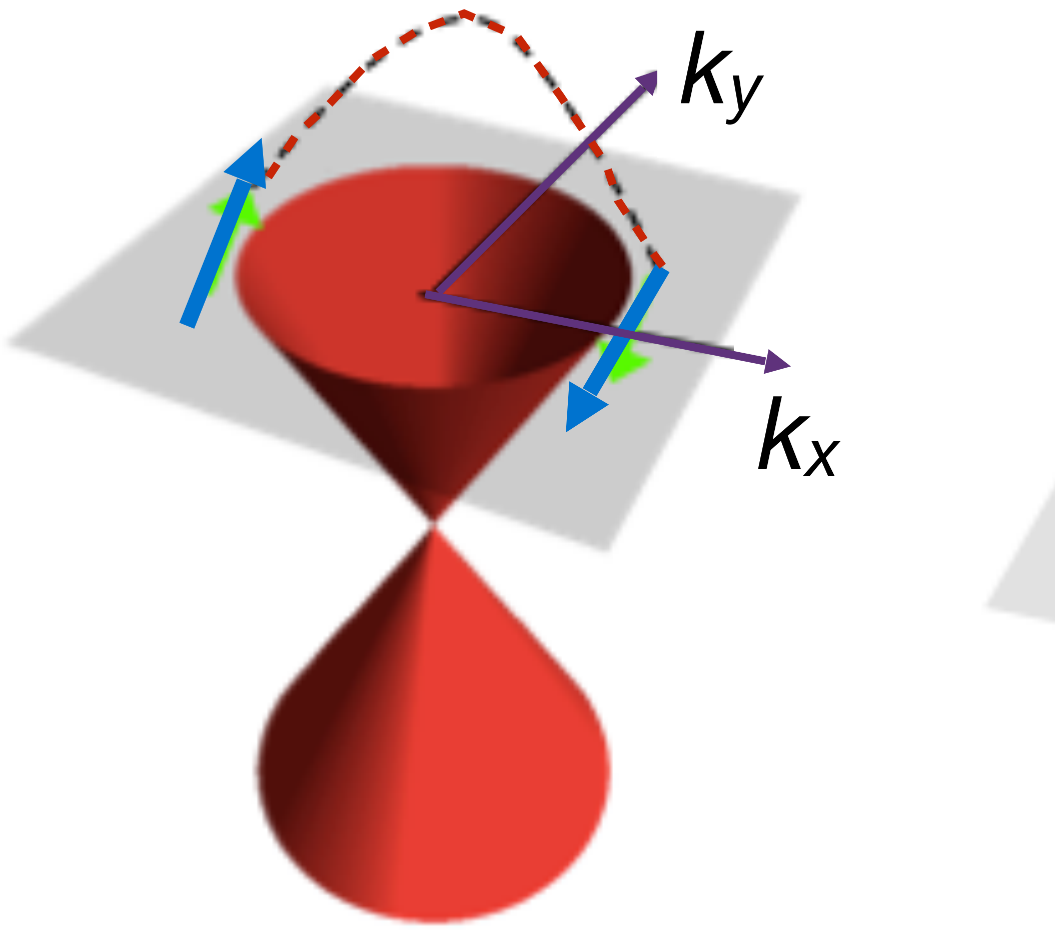
Chip scale nano fabrication of single spin arrays in diamond. D. M. Toyli *et al.*, *Nano Lett.* **10**, 3168 (2010). **[Awschalom, Chicago]**

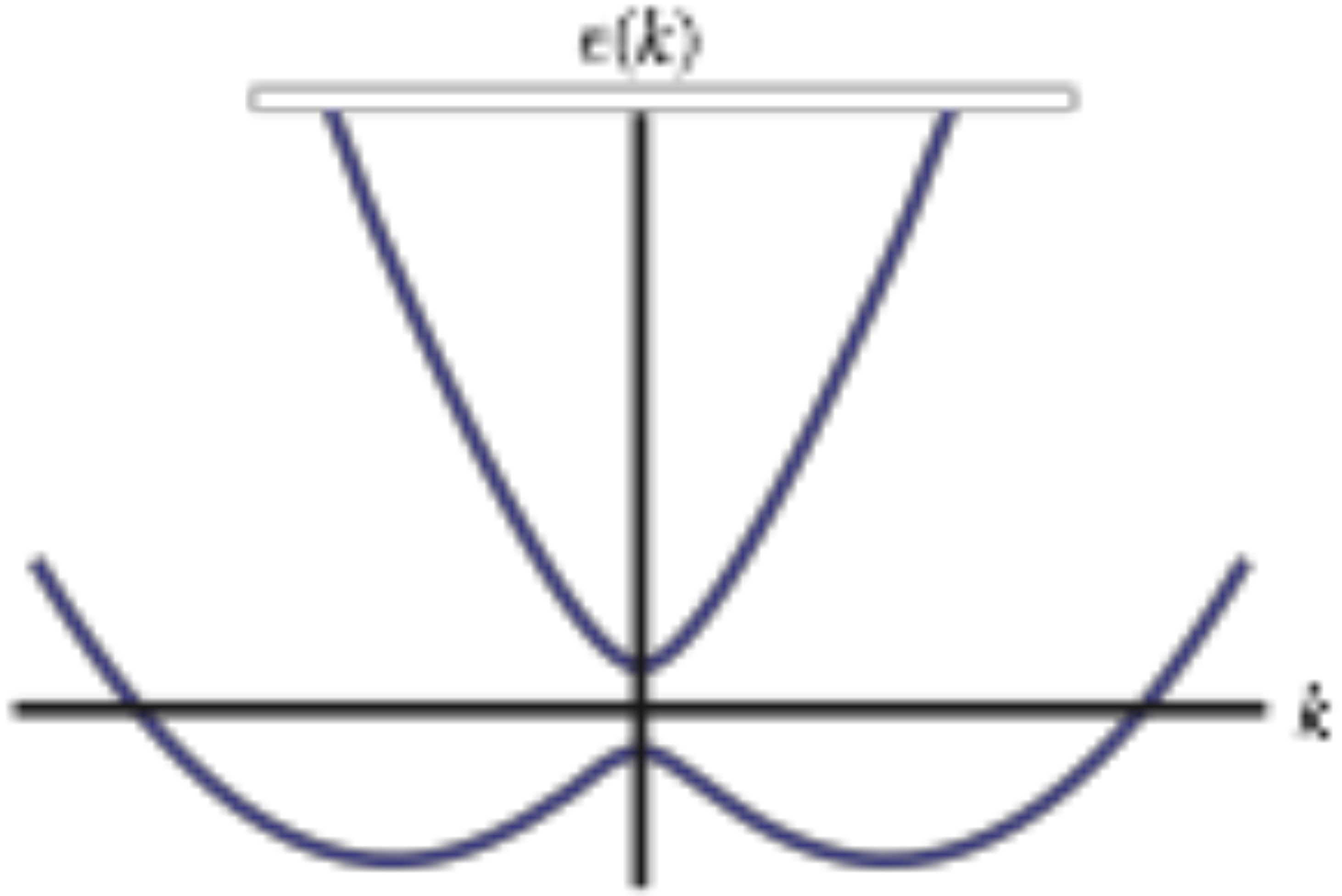


Loophole-free Bell inequality violation using electron spins separated by 1.3 kilometres. Hensen *et al.*, *Nature* **526**, 682–686 (2015). [Hanson, Delft]

Topological quantum computing with Majorana fermions

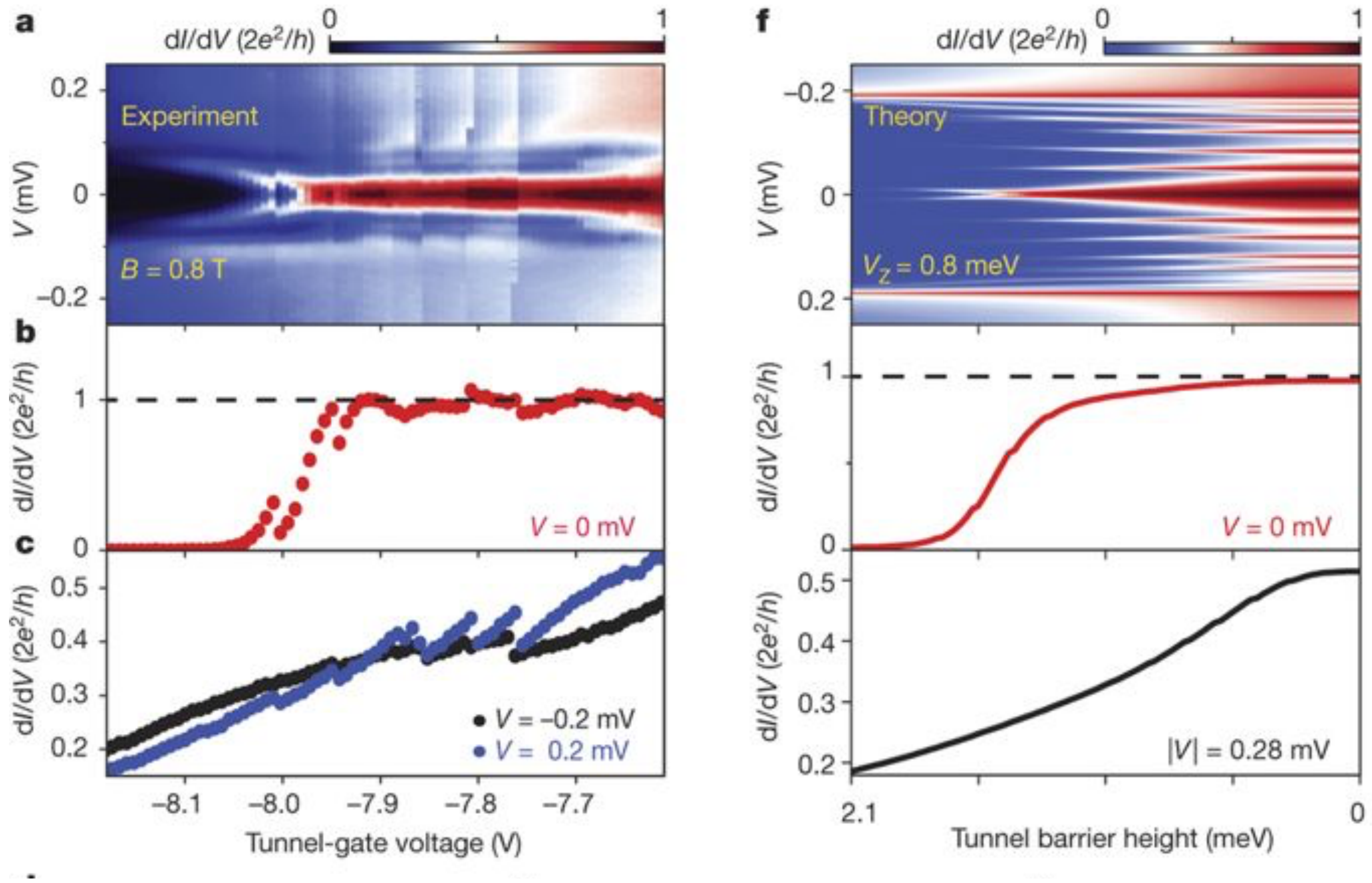
- Topological quantum computing: a fault tolerant approach to quantum computing that uses the ‘braiding’ of non-abelian topological quantum objects
- Simplest possible realization is the ‘Majorana zero mode’ (MZM)
    - Fermionic operator
    - Self-adjoint $\gamma^2 = 1$
    - Commutes with the Hamiltonian $[H, \gamma] = 0$
- MZMs predicted in:
    - 'Topological superconductors’ — pairing in ‘spin-momentum locked’ states
    - ‘Synthetic topological superconductors’ — semiconductor nanowire + strong spin-orbit coupling + proximity induced superconductivity



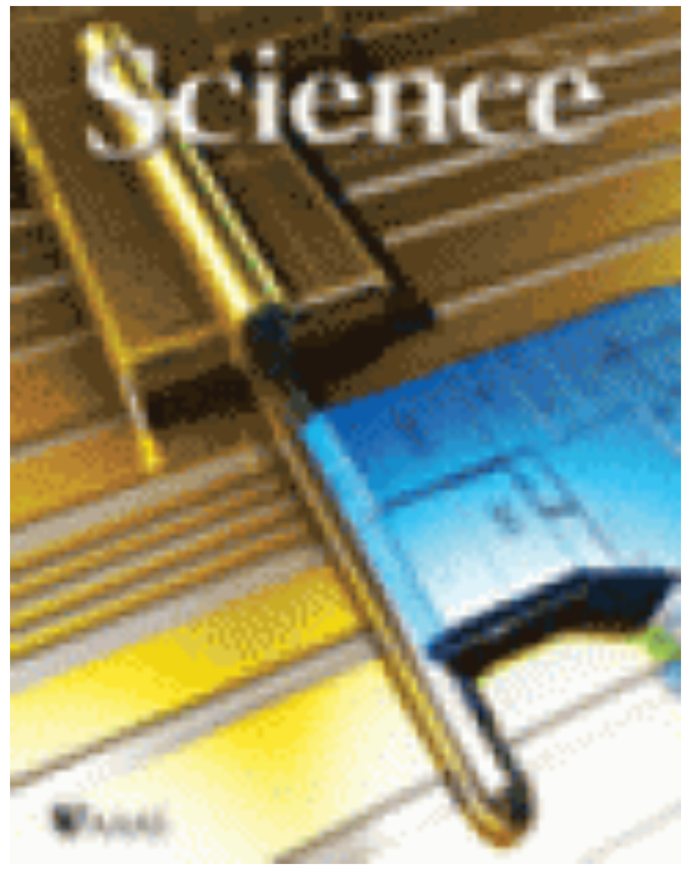


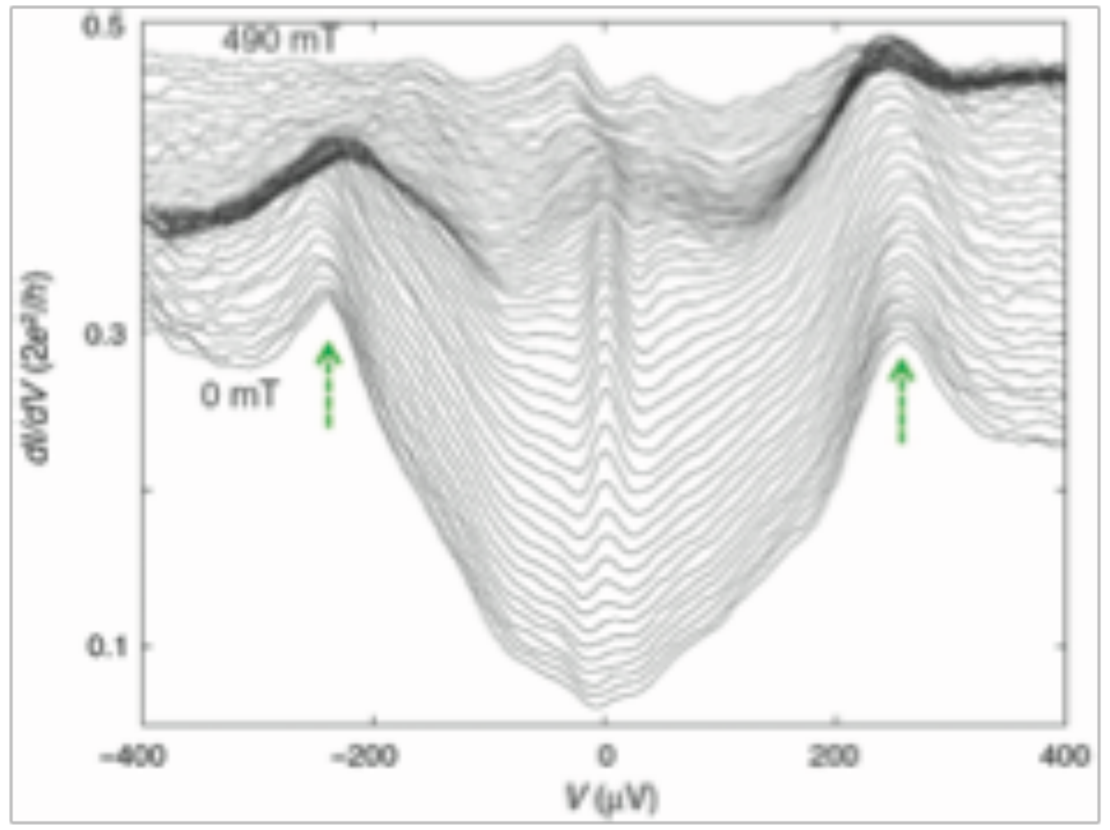
Majorana fermions: state-of-the-art

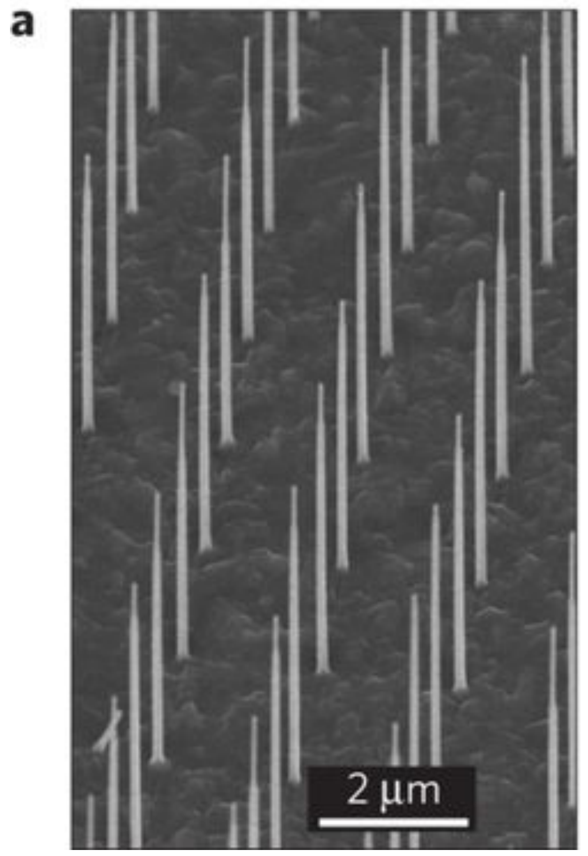
Quantized Majorana conductance in InSb/Al nanowires
(Zhang *et al*, *Nature* **556** , 74 (2018))

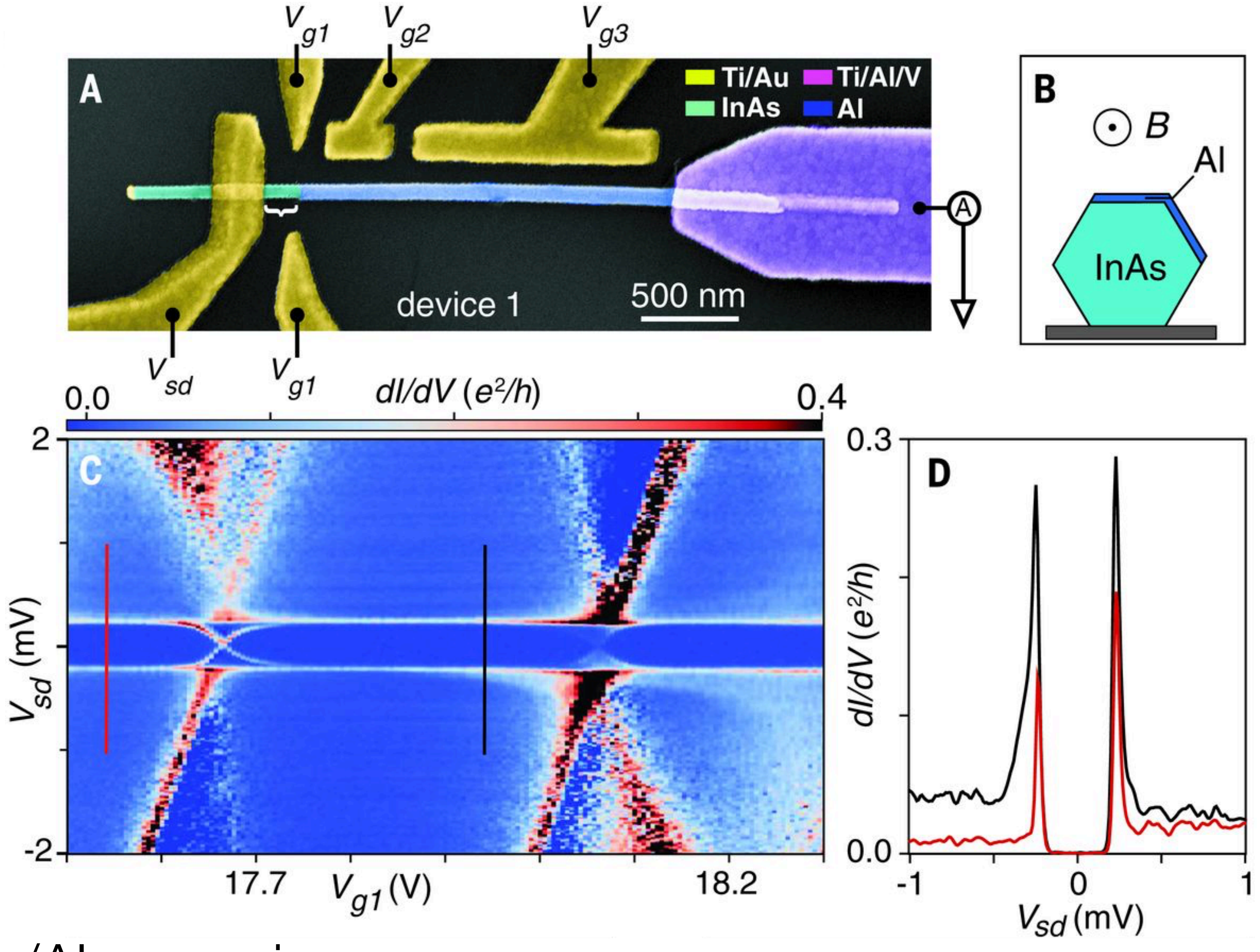


MZM in InSb/Al nanowires
(Mourik *et al*, *Science* **336** , 1003 (2012)









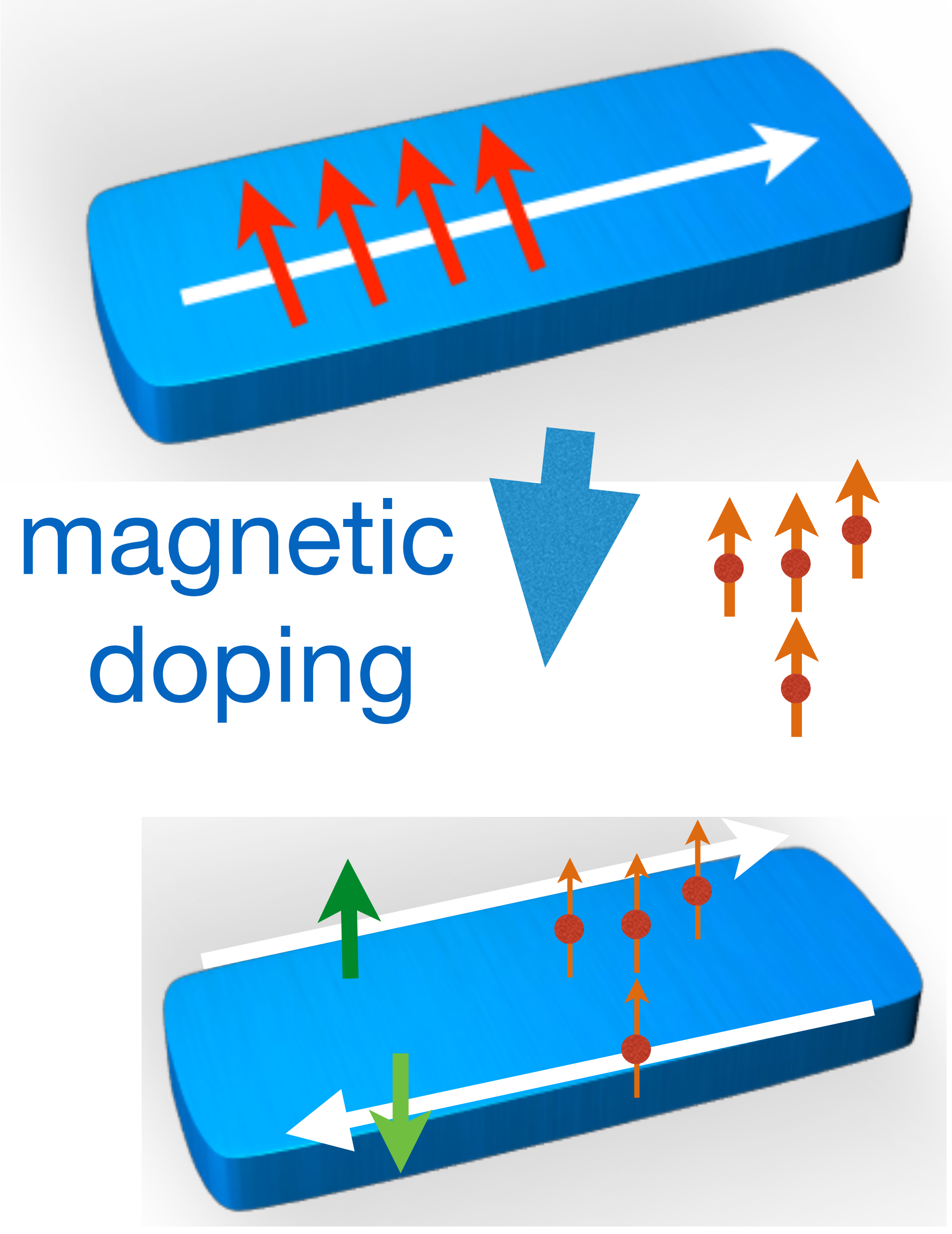
Epitaxial InAs/Al nanowires
(Krogstrup *et al*, *Nature Materials* **14**, 400 (2015)
Deng *et al*, *Science* **354**, 1557 (2016)

[Delft, Copenhagen]

- Two leading efforts seeking Majorana zero modes in InAs & InSb nanowire interfaced with superconductors report evidence MZM.
- Interpretations still debated & definitive proof (braiding) is needed.

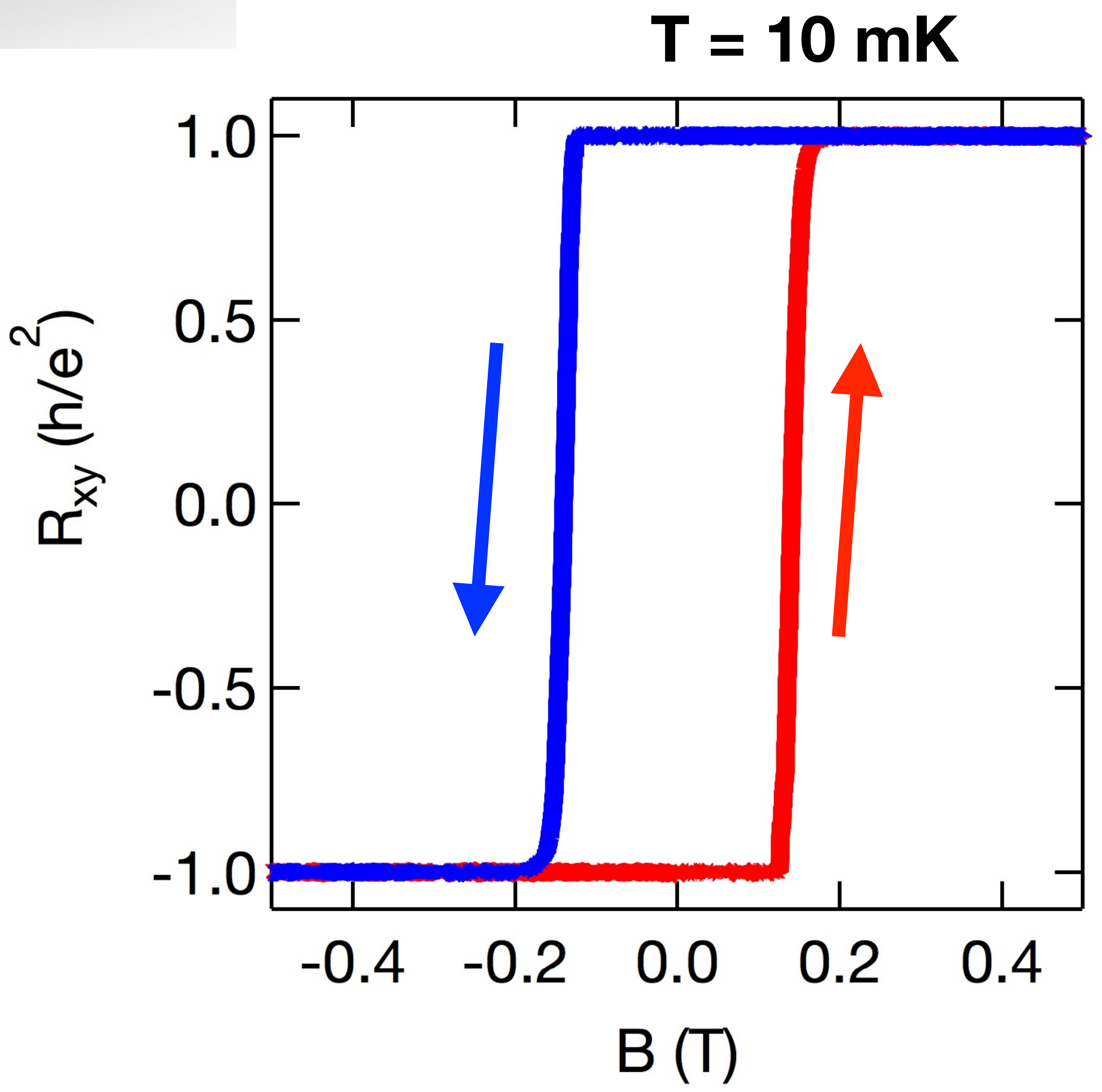
Hybrid quantum materials: topology + magnetism

- Making a topological insulator ferromagnetic breaks time-reversal symmetry
- Helical Dirac surface states converted into dissipation-less chiral edge states in the zero field remnant state of the ferromagnet
- “Quantum anomalous Hall insulator” — quantization precise to 1 part on 10^6
- Possible application in JJ-based quantum architectures: zero field edge plasmons could be exploited in on-chip zero magnetic field microwave circulator [*Nature Comm*. **8**, 1836 (2017) — Sydney/Stanford/UCLA]



Chang *et al.*, *Science* 340, 167 (2013)
Chang *et al.*, *Nature Materials* **14**, 473 (2015)
Bestwick *et al.*, *Phys. Rev. Lett.* **114**, 187201 (2015)
Kandala *et al.*, *Nature Communications*,**6**, 7434 (2015).
Kou *et al.*, *Nature Communications*, **6**, 8474 (2015)

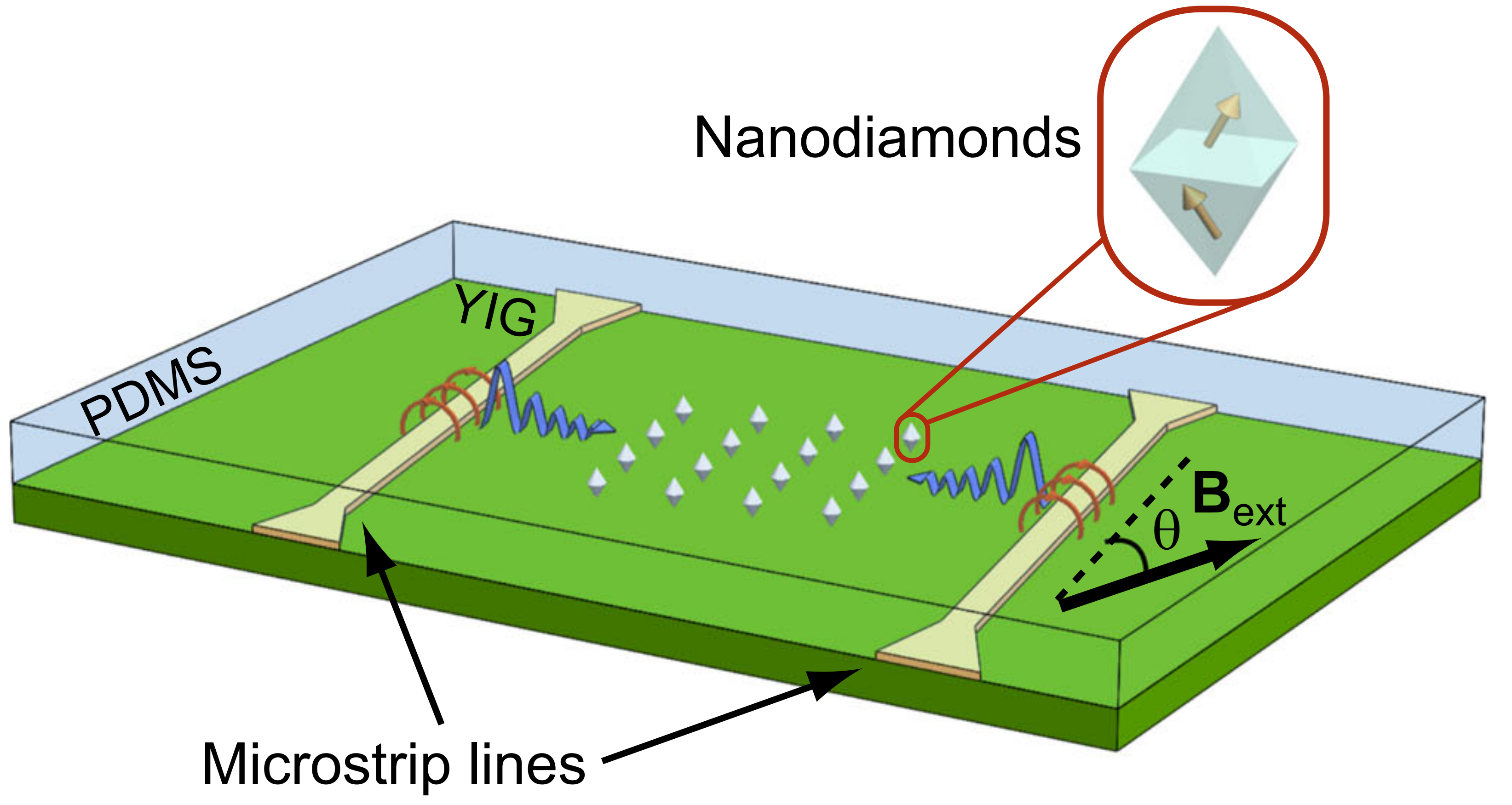
[Tsinghua/IOP, Penn State, Tokyo, Wurzburg, Stanford, UCLA]

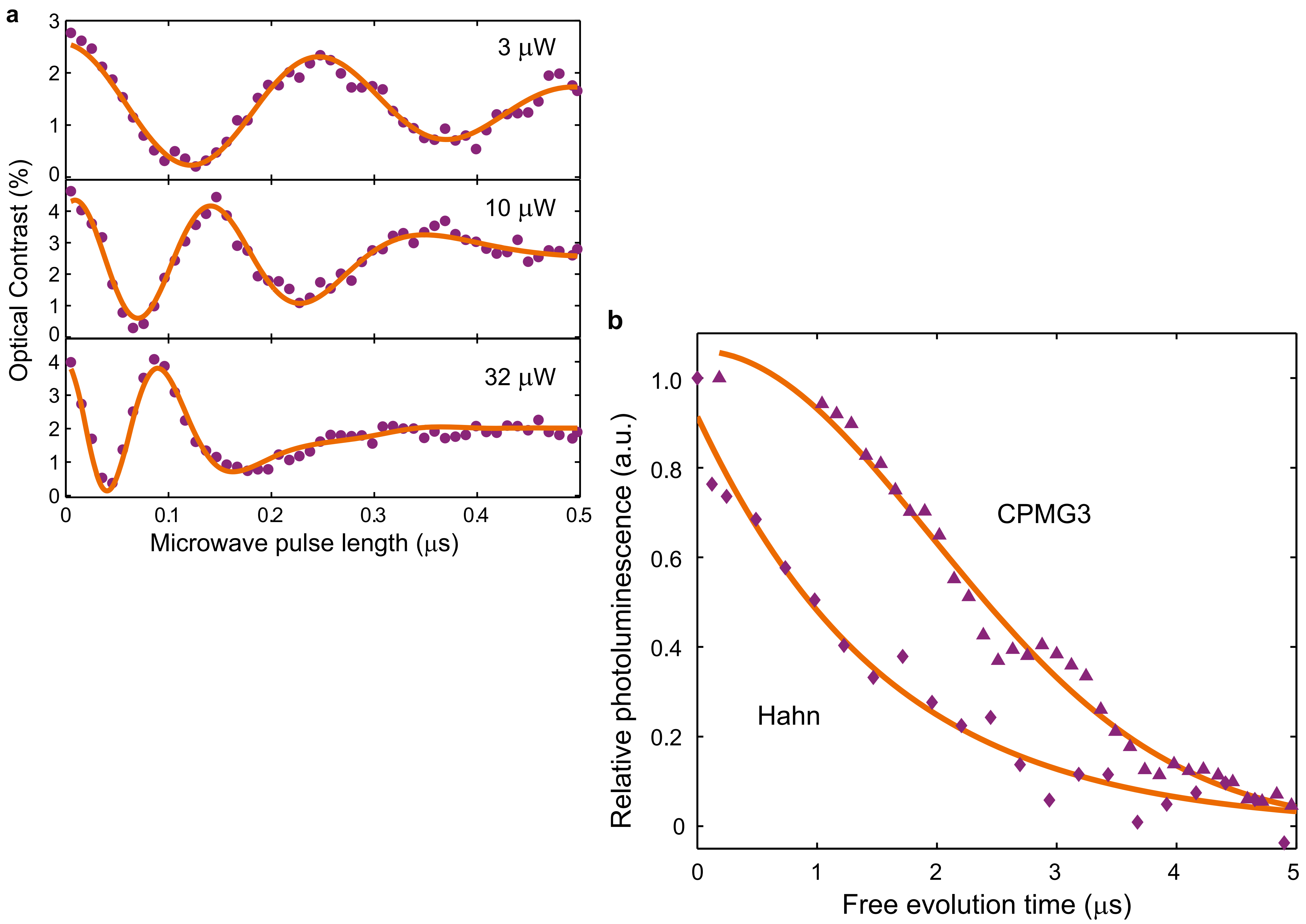


Liu, *et al*, *Science Advances* **2**, e1600167 (2016)

Hybrid quantum materials: quantum defects + magnons

- Hybrid architectures have been demonstrated that combine NV centers in diamond with spin waves (magnons) in the low damping ferrimagnet yttrium iron garnet (YIG).
- Surface confined magnons excited in the ferromagnet amplify the interactions between a microwave source and the NV centers.
- Coherent interactions between magnons and NV centers allow magnon-mediated coherent control of spin qubits over distances ~100 μm.

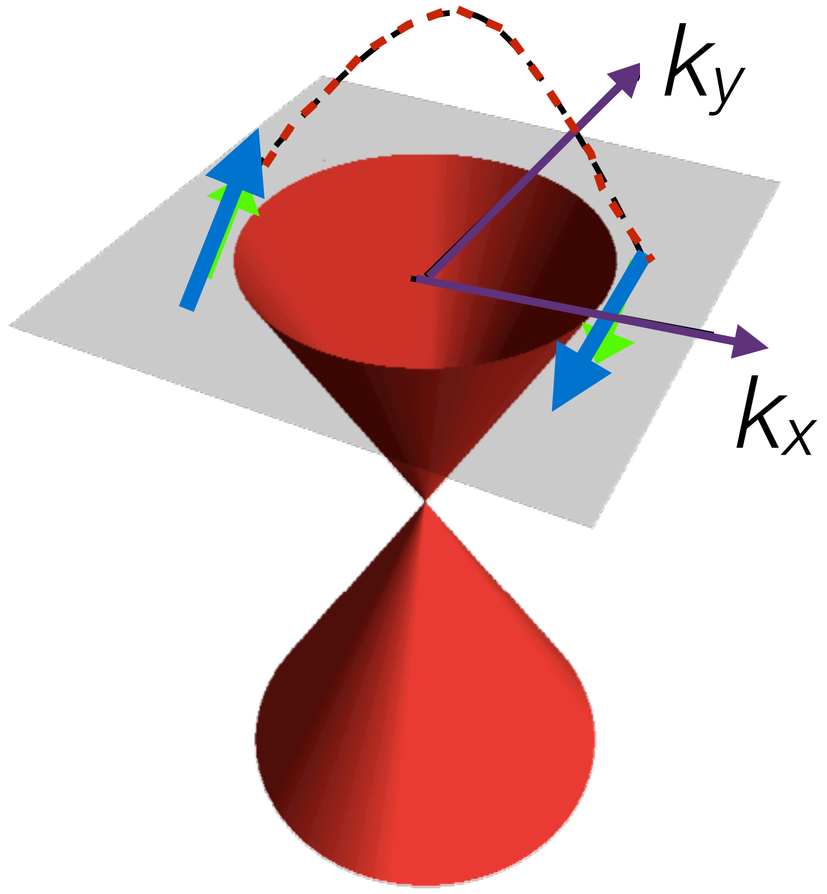


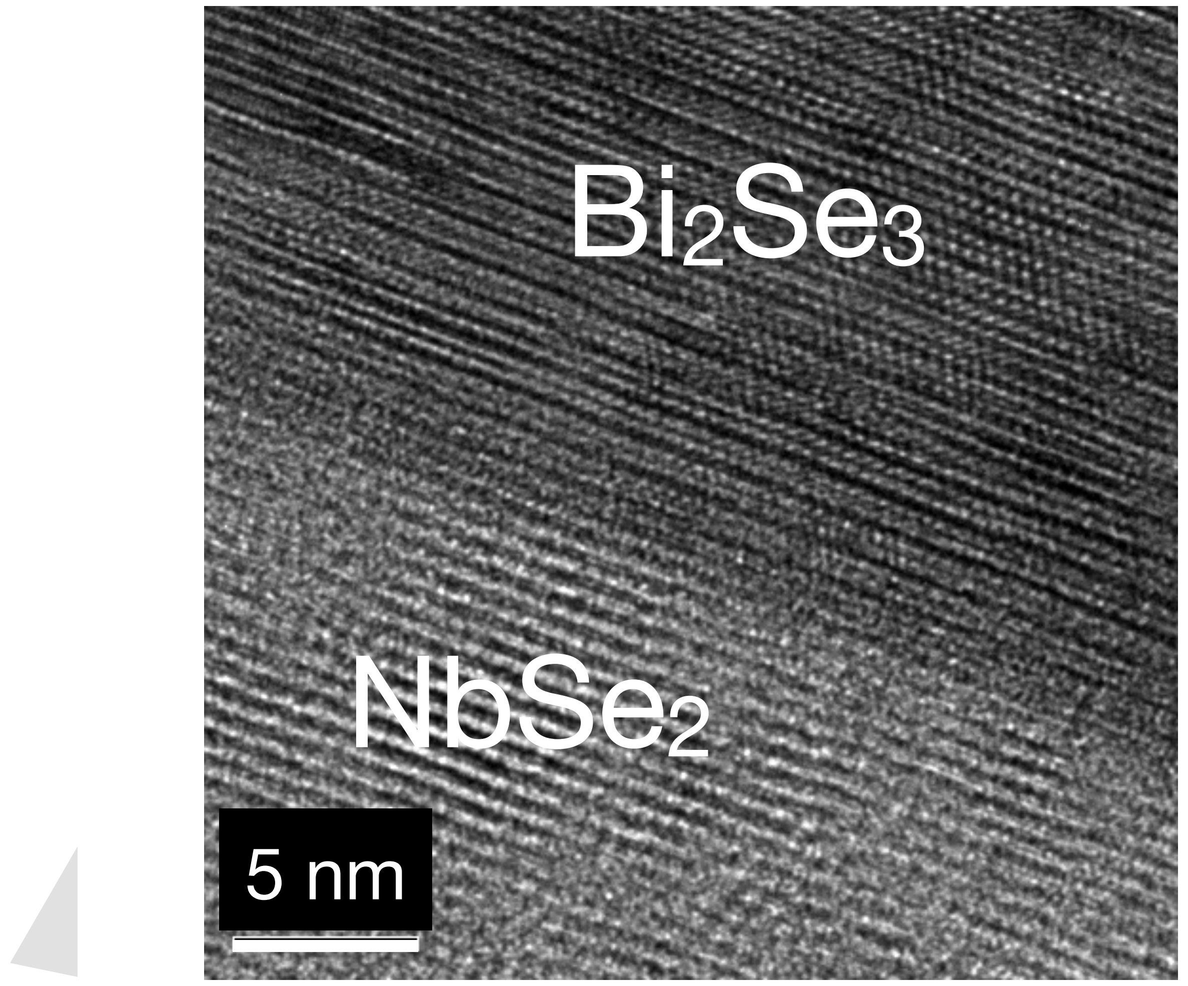


Andrich *et al.*, *npj Quantum Information* **3**:28 (2017)
[Awschalom group, Chicago]

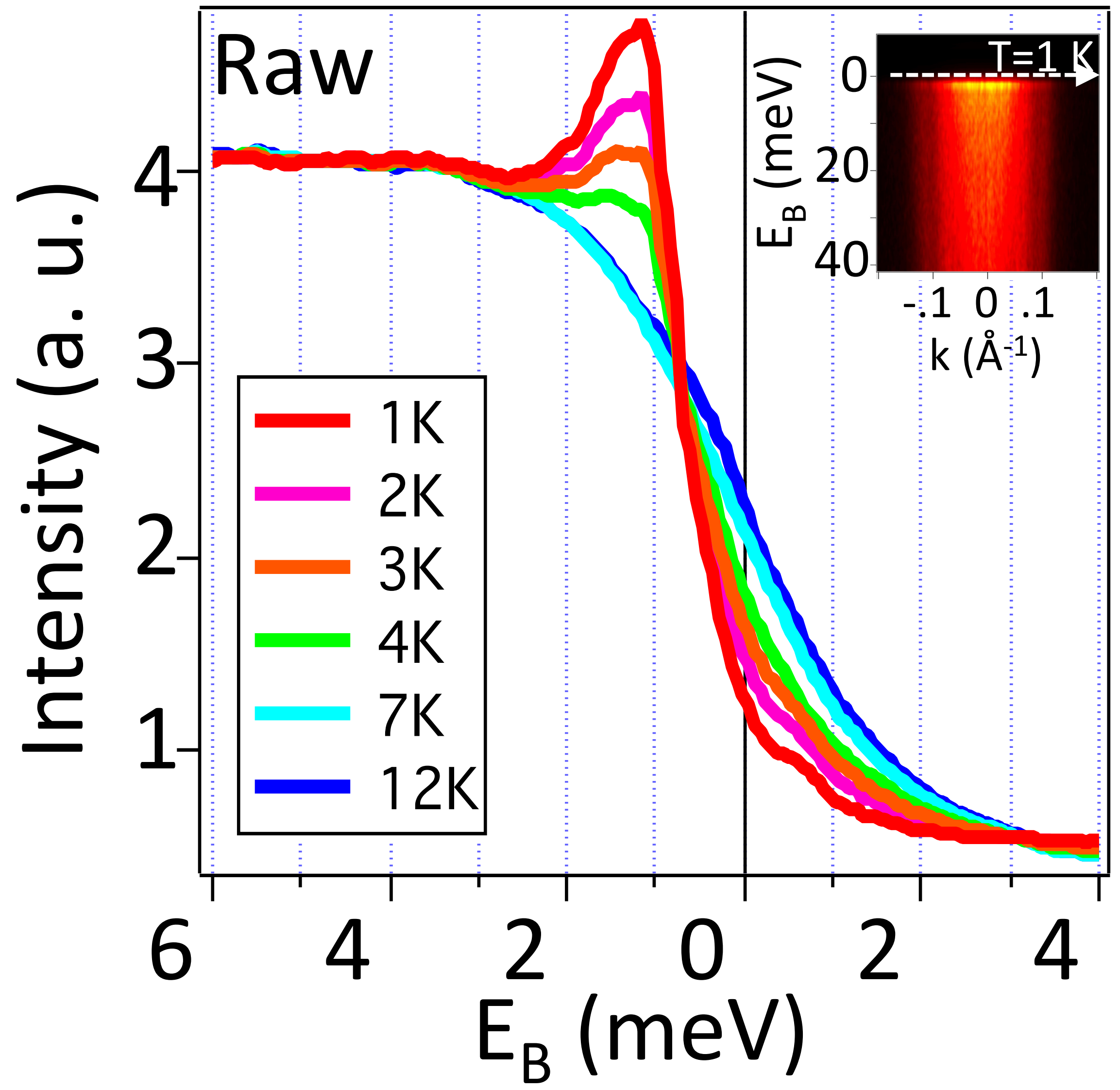
Hybrid quantum materials: topological insulator + superconductivity

- Heteroepitaxial synthesis of chalcogenide topological insulator (Bi_2Se_3) on a conventional s-wave superconductor ($NbSe_2$) as a route toward a topological superconductor & Majorana modes.
- Angle-resolved photoemission shows the development of a pairing gap in the helical Dirac surface states.
- Modes of a topological superconductor could serve as novel quantum conduit if they can be entangled with proximal qubits.





k = k_1 (Surface)



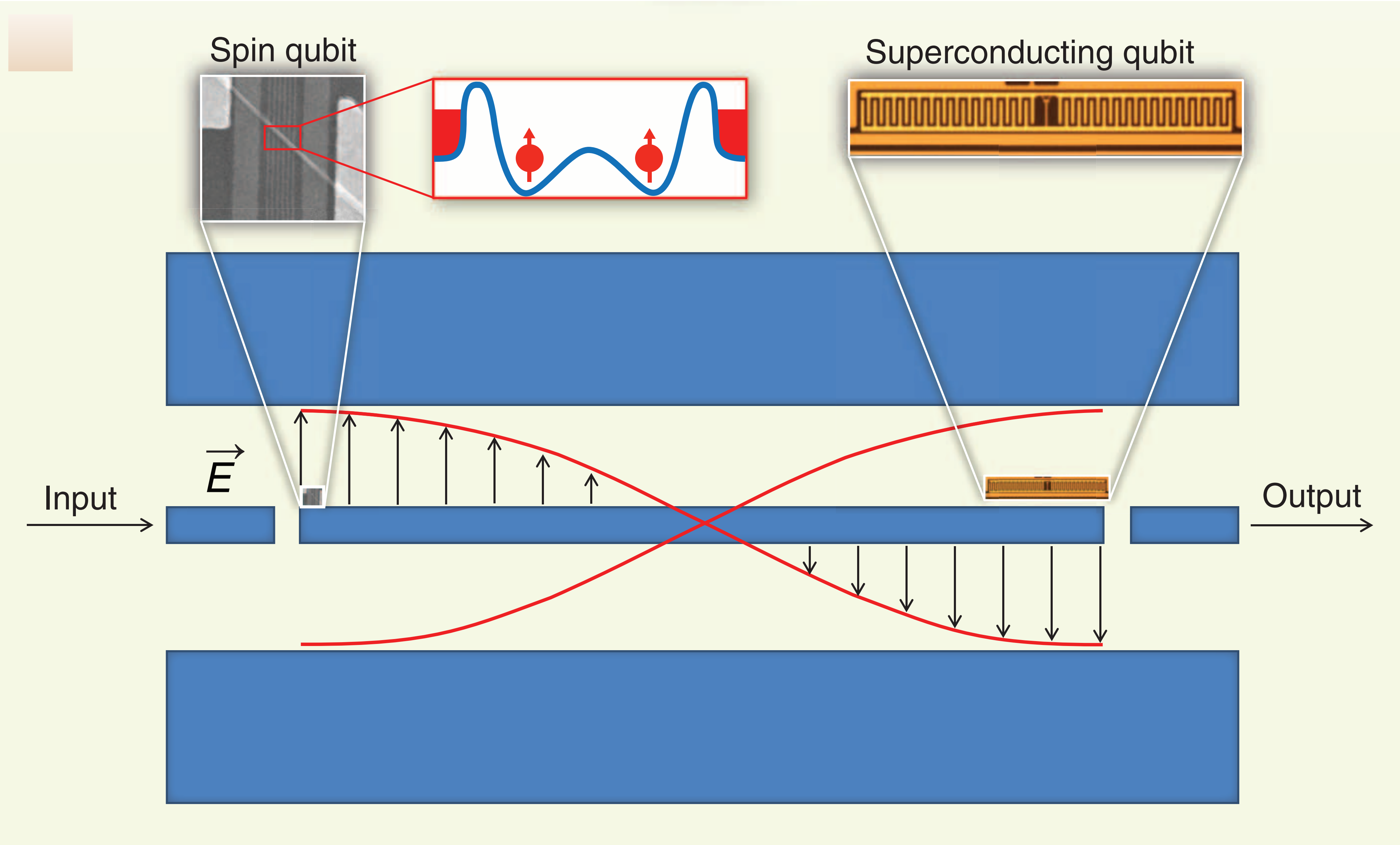
S.-Y. Xu *et al.*, *Nat. Phys.* **10**, 943 (2014)
[Princeton/Penn State]

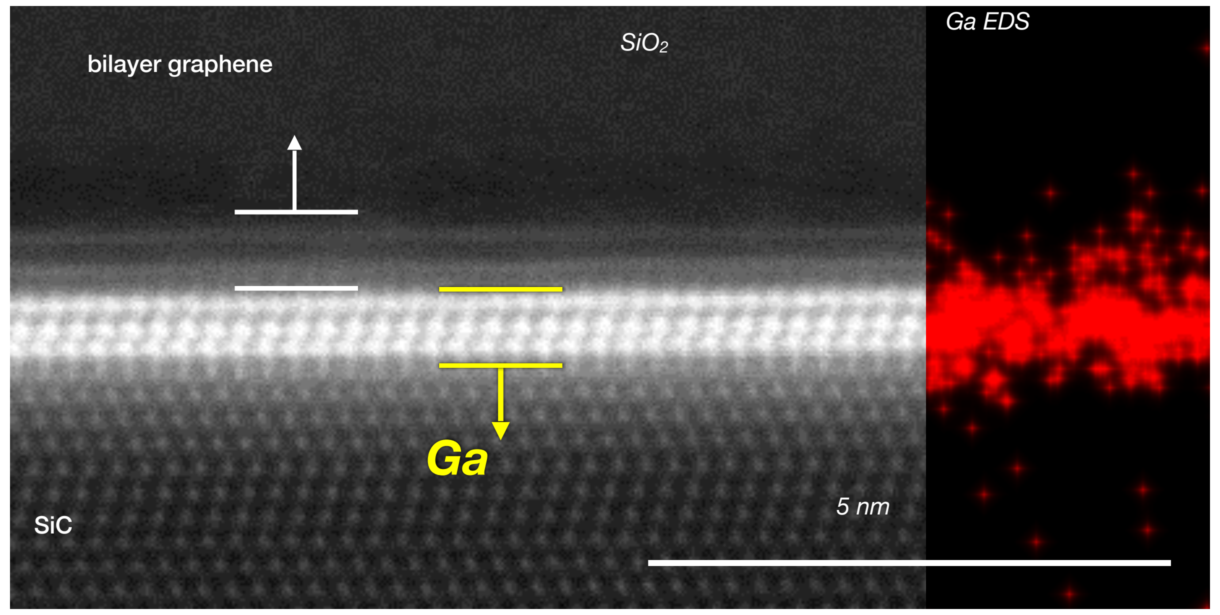
Hybrid quantum materials: coupling defect spin qubits to superconductor

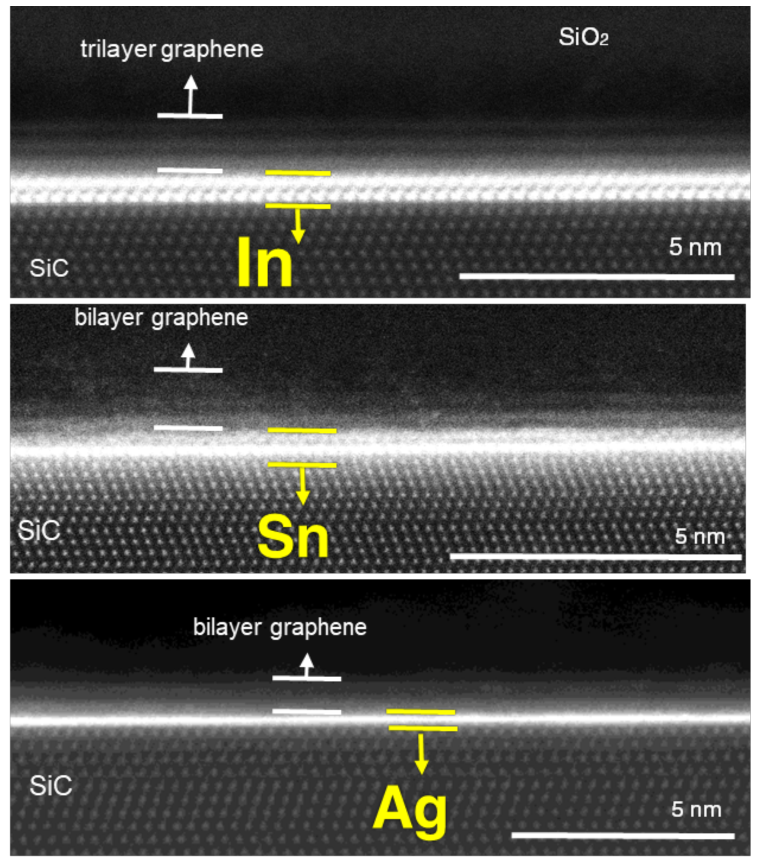
- New synthesis strategies for combining diverse quantum materials (topological, 2D, magnets, superconductors) are desirable
- Confinement heteroepitaxy: a route that enable synthesis of ultra thin metals in between graphene/SiC interface [Robinson, Penn State/2DCC-MIP]
- Demonstrated integration of single crystal 2D superconductors with SiC/graphene, allowing coupling to topological insulator overlayers.
- Couple the single crystal superconductor to divacancy quantum defects in SiC?

Awschalom *et al*., *Science* **339**, 1174-1179 (2013)

Coupling between spin and SC qubit via cavity mode







“Confinement Heteroepitaxy”: route toward integrating single crystal superconductors with variety of quantum materials — topological insulators, quantum defects, etc. [Josh Robinson, Penn State]

Summary

- Materials synthesis & characterization played a critical role in the first generation of quantum technologies by designing materials that tailored quantum wave function amplitudes through quantum confinement and band structure engineering.

- The current generation of quantum technologies demands new approaches for materials design that incorporates quantum coherence & quantum entanglement.

- Quantum technologies based on superconducting JJ arrays rapidly progressing; opportunities for semiconductor nanostructure qubits and single spin defect qubits to scale beyond few qubits

  - Can we develop hybrid quantum materials to entangle solid state qubits (e.g. single spin defects) with modes other than photons (e.g. chiral edge states, magnons, Cooper pairs)?

  - What aspects of materials are important? How do we develop deterministic control over the placement and 'quality' of quantum defects?

  - How should we invest in training of a highly technically skilled 'quantum materials' workforce? Example: NSF Materials Innovation Platforms — user facilities for training in advanced materials synthesis.

2D Crystal Consortium

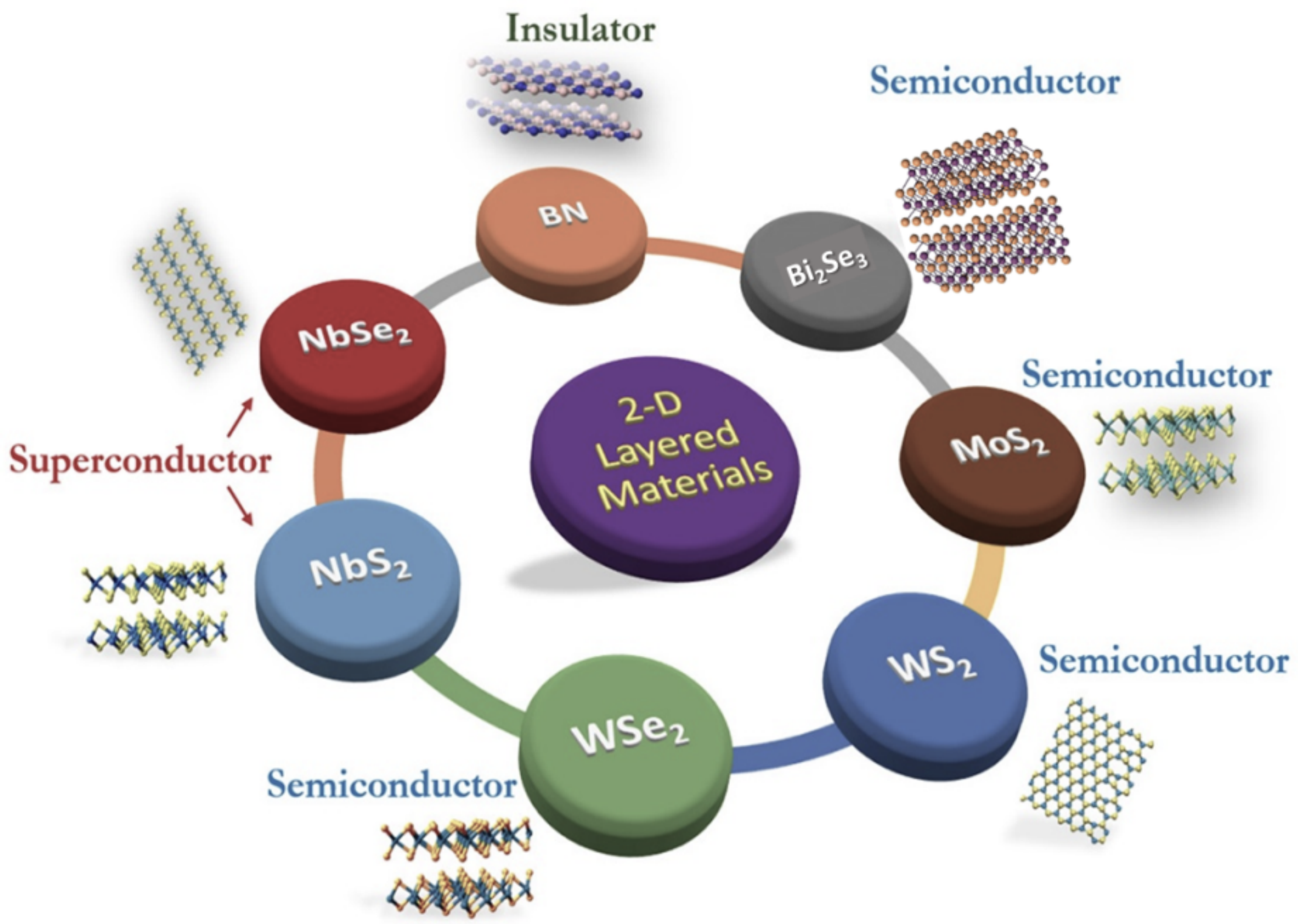
NSF Materials Innovation Platform

An NSF **user facility** with broad access

mip.psu.edu

A new paradigm for developing a community in quantum materials.
NSF funded 2 Materials Innovation Platform sites at Cornell & Penn State.
Users submit proposals for on site visits & sample only requests.
No user fees for academic or government use.

- Open calls for user proposals,
- Access to a team of local experts
- Community knowledge-base of synthetic protocols
- Webinars, Workshops, Website resources



Hybrid MBE
Chalcogenide MOCVD
CVT, Bridgman, floating zone

in situ measurement

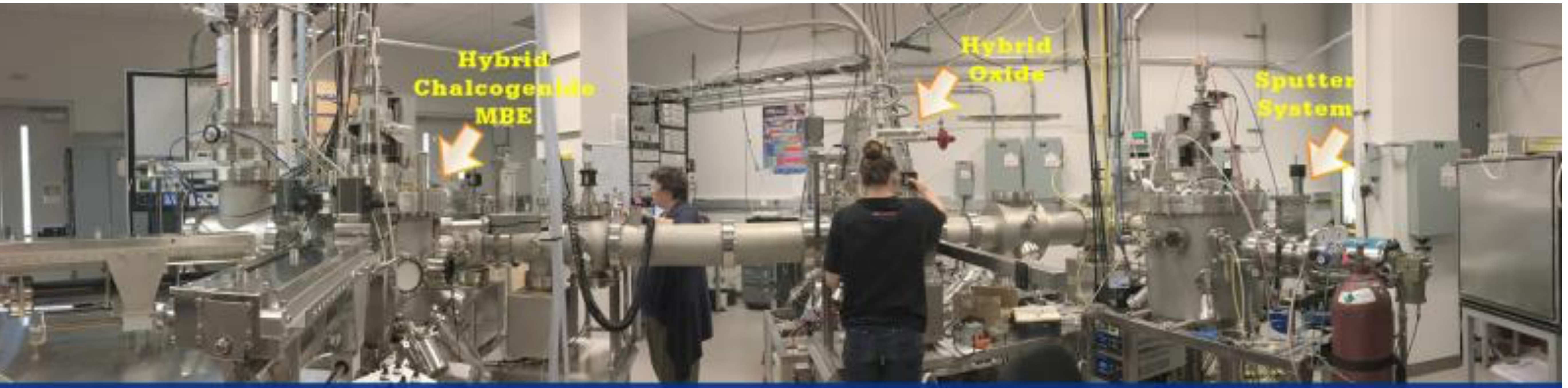
insights into growth

STM/AFM
ARPES
4-probe
Raman, PL

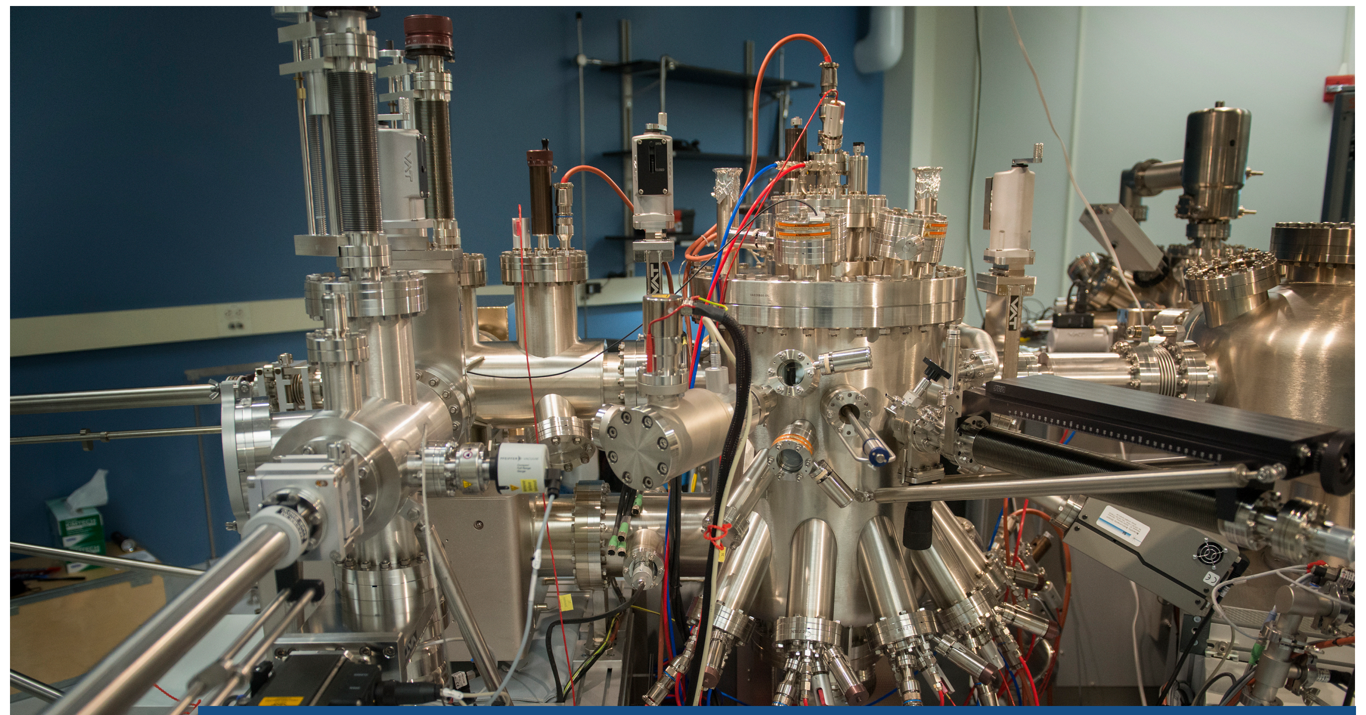
characterization & interpretation

DFT
Reactive FF
Monte Carlo
Phase field

Broad access to compelling synthetic tools with integrated theory support



Hybrid Chalcogenide MBE, Hybrid Oxide MBE and Sputter System



MBE + STM + ARPES