

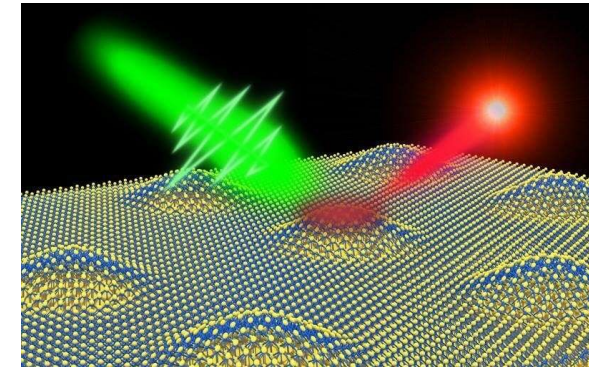
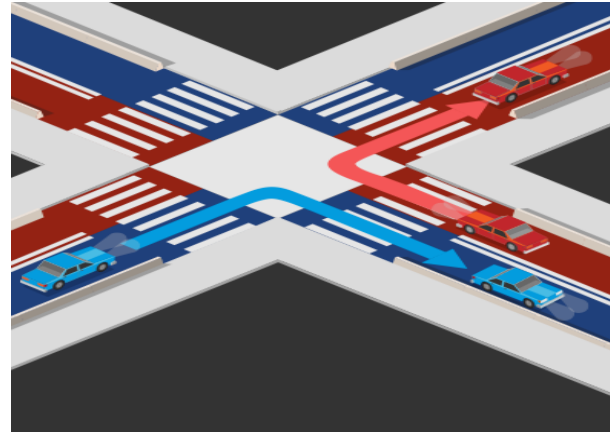
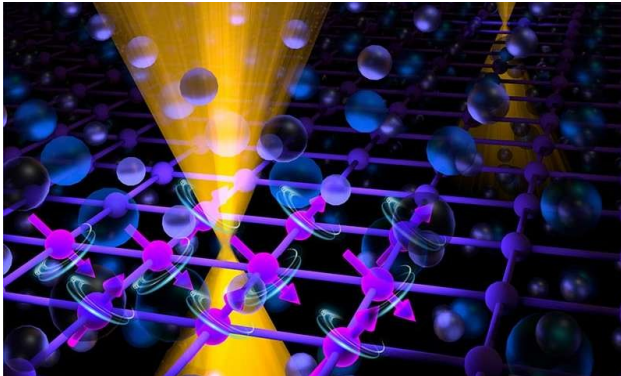


Quantum Materials and Devices: The case of exemplary “lane-discipline”



<http://cnqt-group.org>

<https://twitter.com/quantumtranspo1>



Bhaskaran Muralidharan
Dept. of Electrical Engineering,
Indian institute of technology Bombay
First International Quantum Conclave

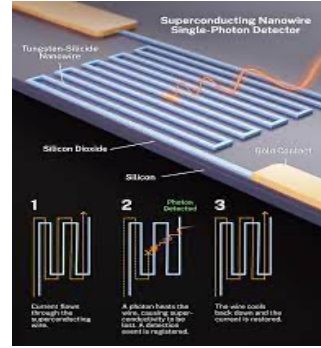


27/03/2023

Quantum Technologies

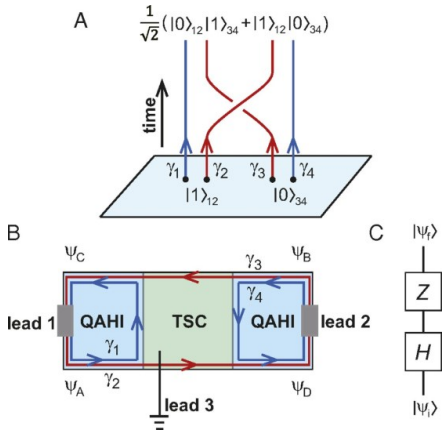
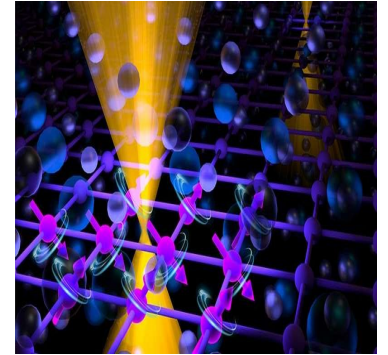
Quantum Sensors

Quantum Metrology, Optical Metrology, Quantum Gyroscopes, Magnetometers, Clocks, Accelerometers, etc.



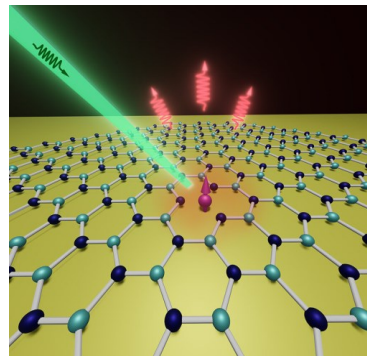
Quantum Enhanced Technologies

Quantum Heat Engines, Refrigerators, Batteries, Quantum Inspired Algorithms, Quantum Imaging, Quantum Machine learning etc.



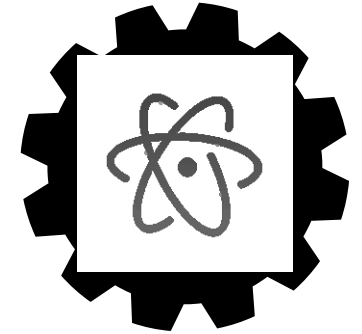
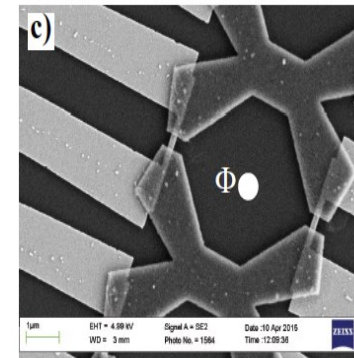
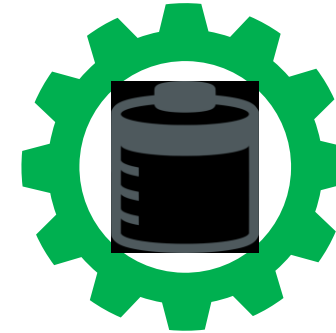
Quantum Computation

Quantum Algorithms, Coherent Architectures for QC, NISQ Devices, Quantum Cryptography, Quantum Chemistry on Quantum Computers etc.



Quantum Communication

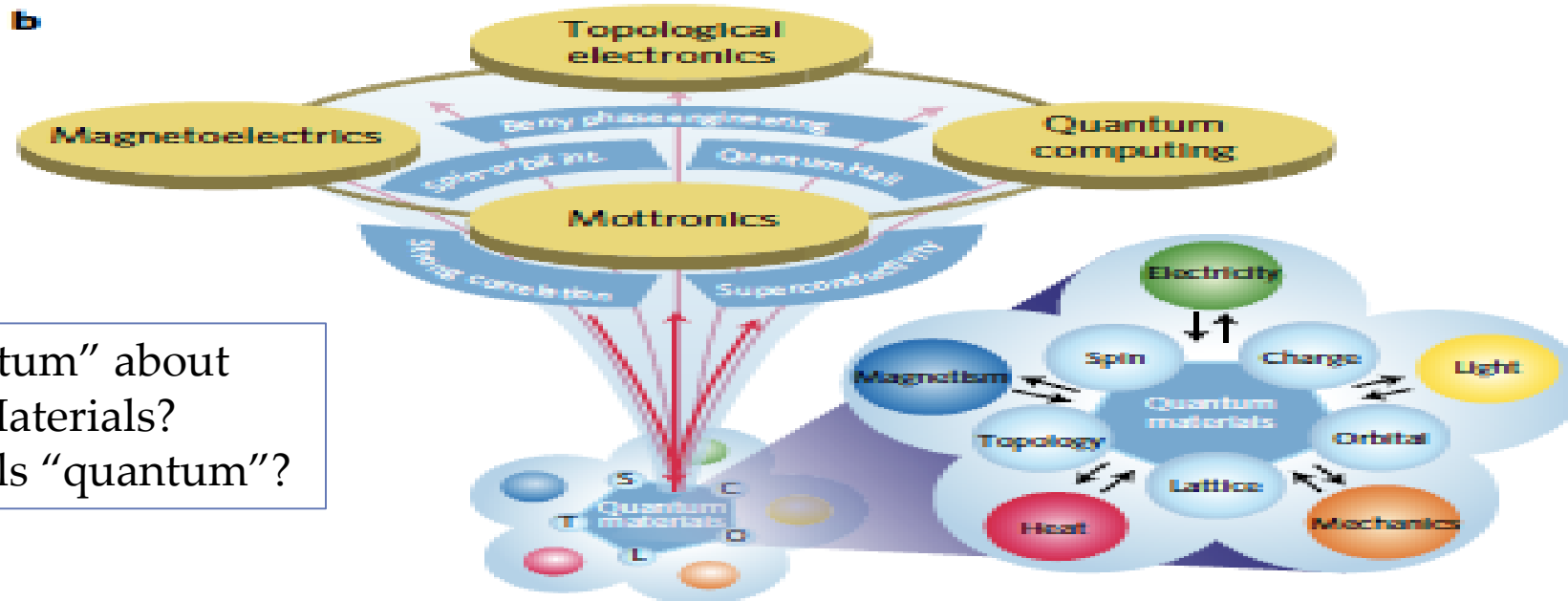
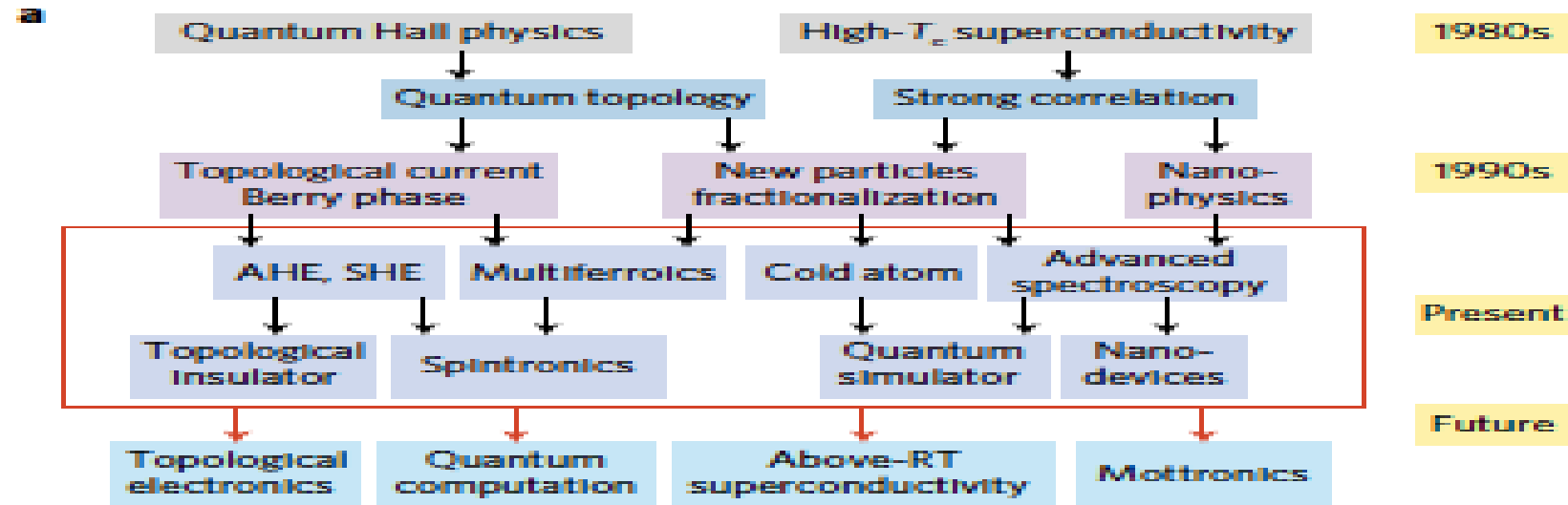
Quantum Secure Key Distribution, Communication Theory, Quantum Satellite Communication, etc.



Quantum Materials

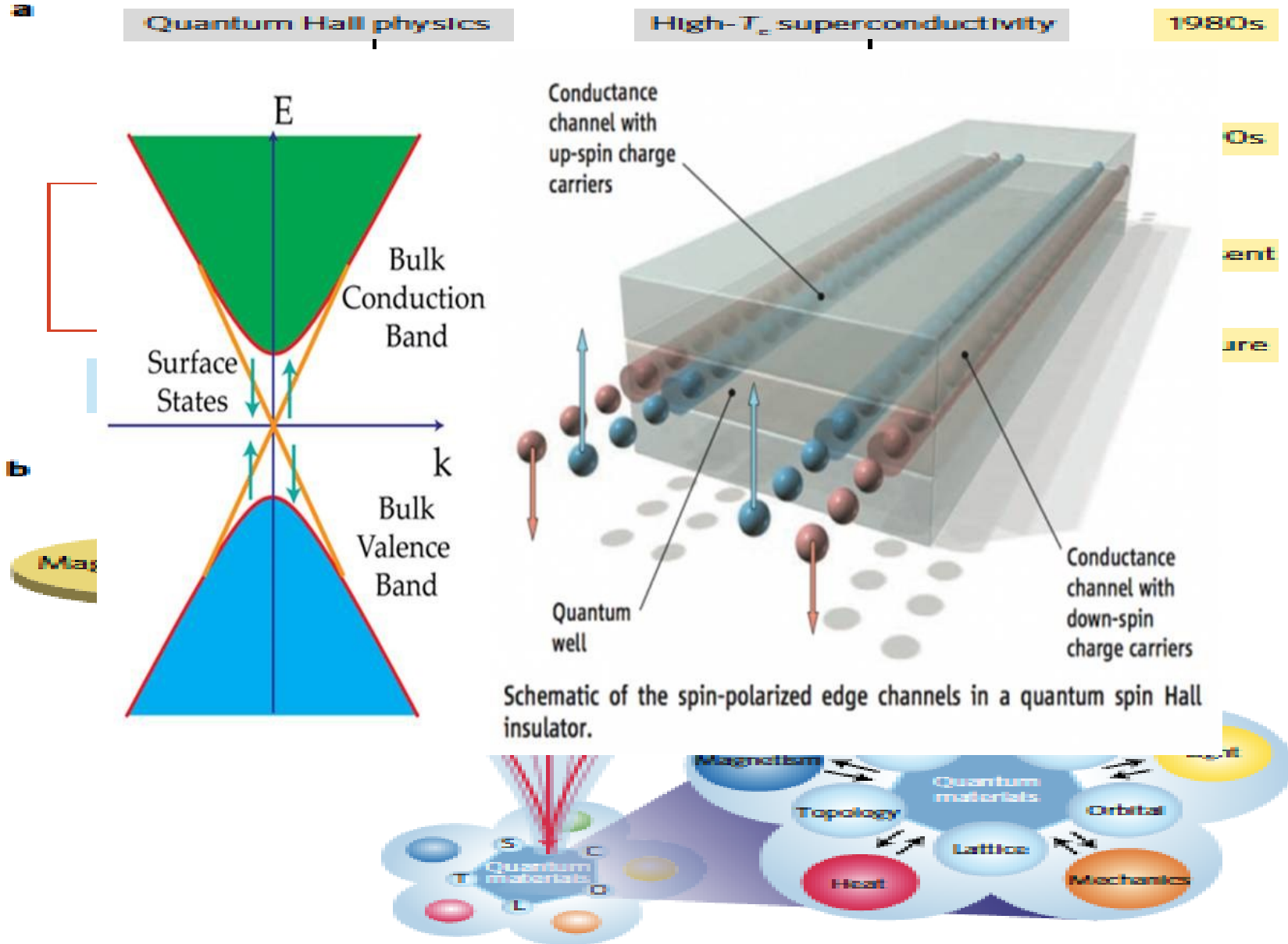
Quantum materials for QC, Topological Materials, Weyl, Dirac & Majorana, Quantum Liquids, etc.

World of Quantum Materials

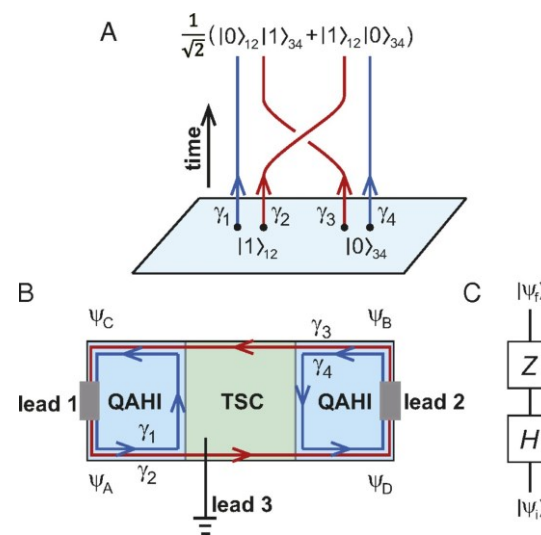
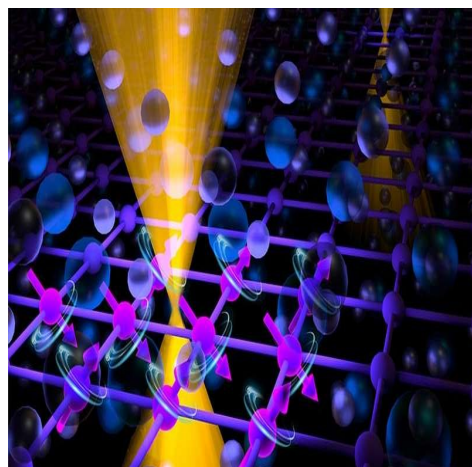
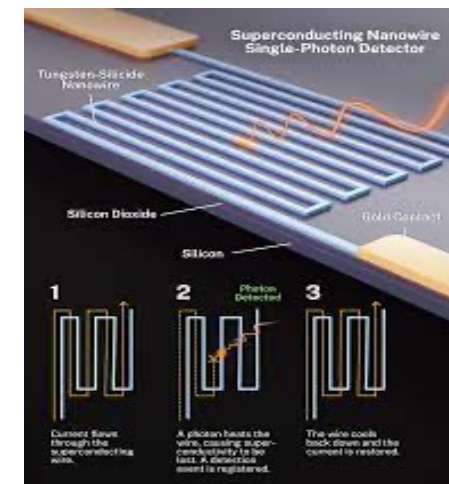
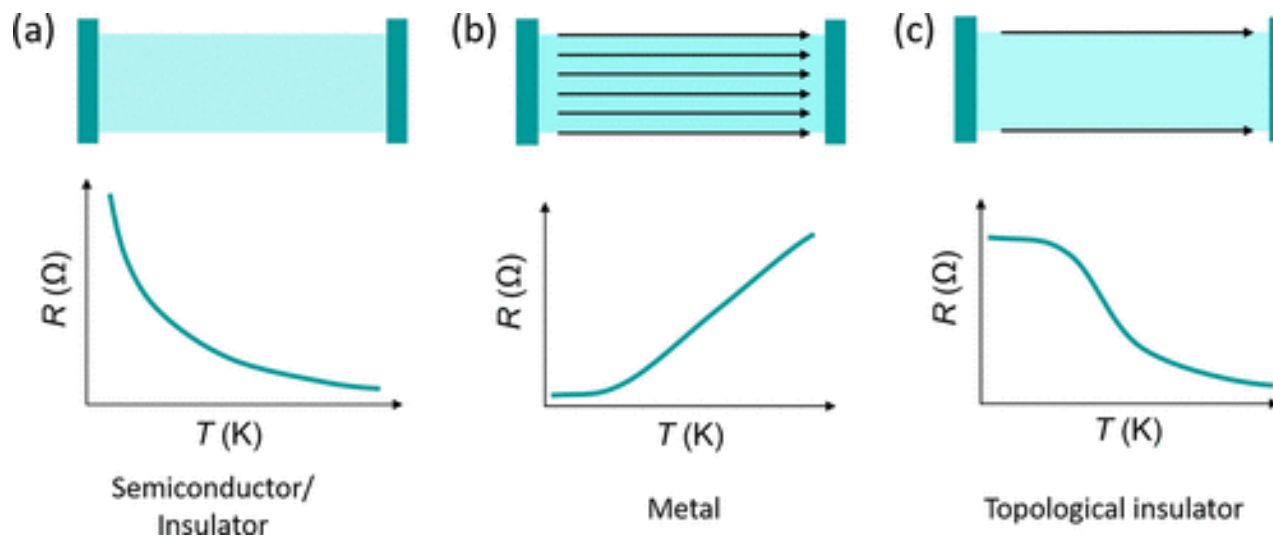
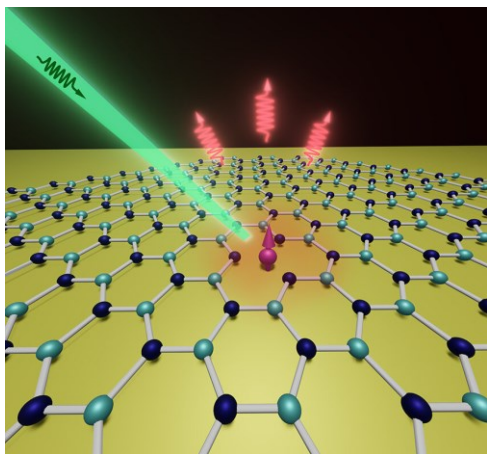


What is “quantum” about Quantum Materials?
Aren’t all materials “quantum”?

In this Keynote--- Only the “tip” of the Iceberg!

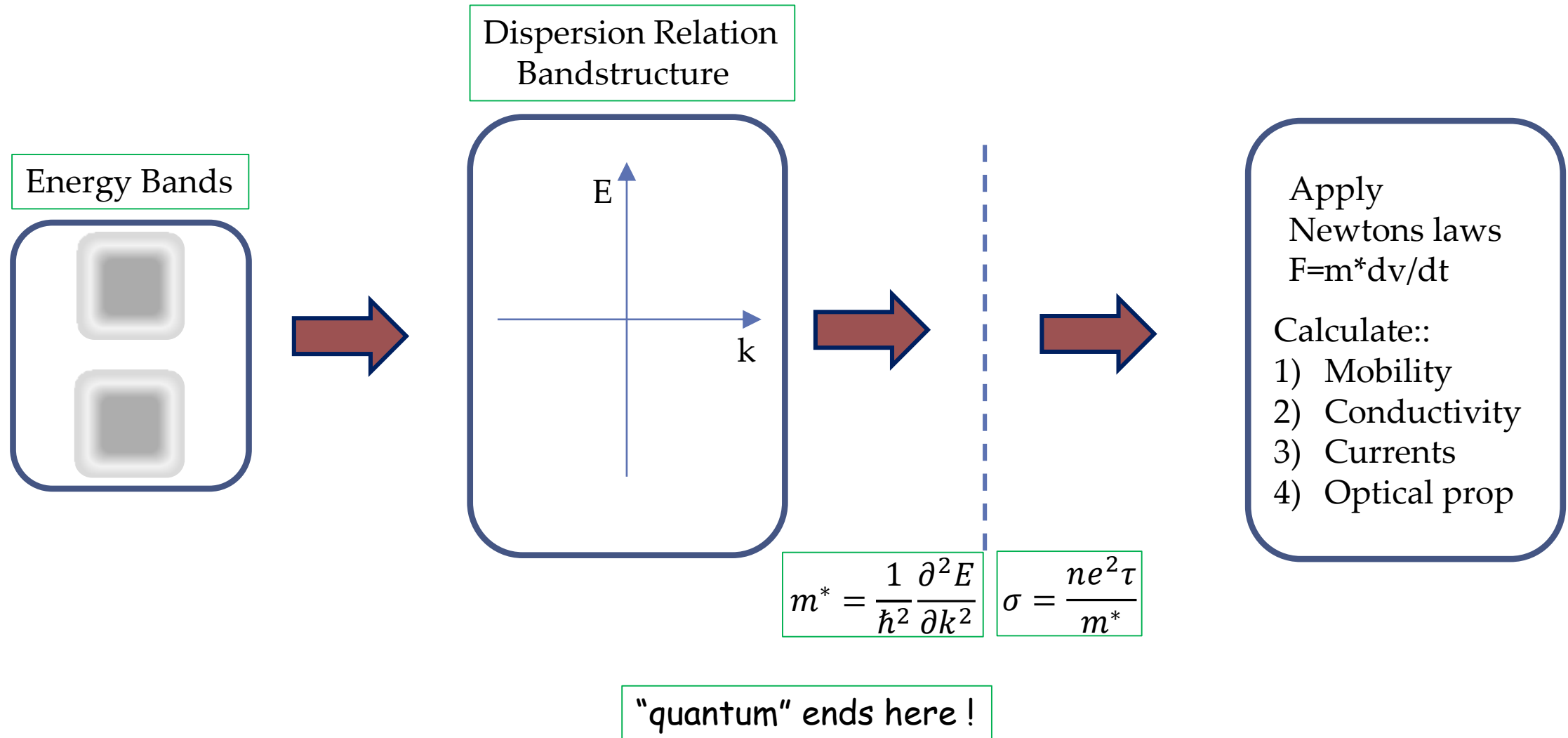


Quantum Materials: Topological Insulators



What is “quantum” about Quantum Materials?
Aren't all materials “quantum”?

Standard Materials – Low-level QM!



Topological Quantum Materials?



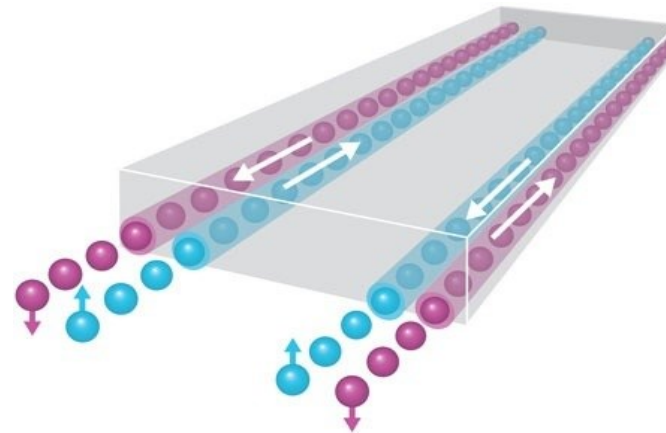
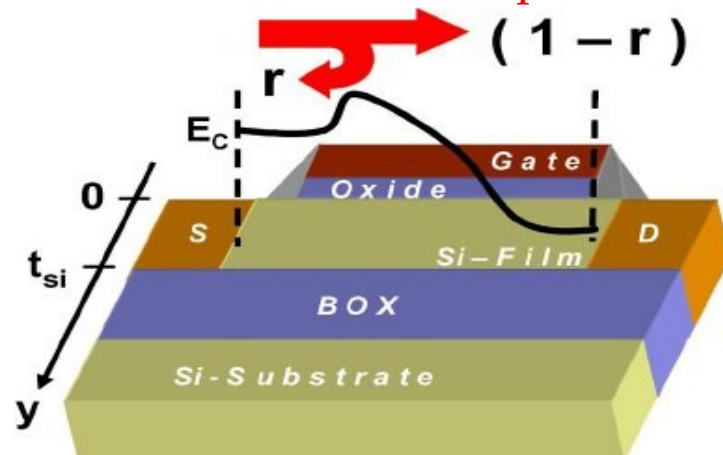
← Conventional Materials

Topological Materials →



Beyond Moore: Binary and non-binary Logic

ISSUE: Power Dissipation



We need to "dig" into QM at a "higher" level

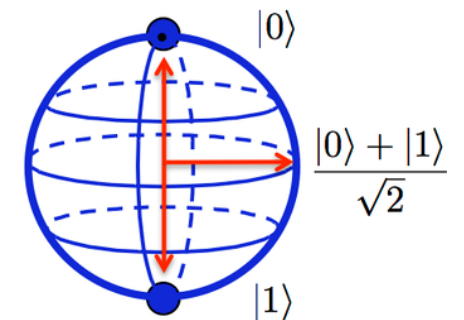
Beyond Moore: Quantum Computation

ISSUE: Qubit stability (Decoherence)

● 0

● 1

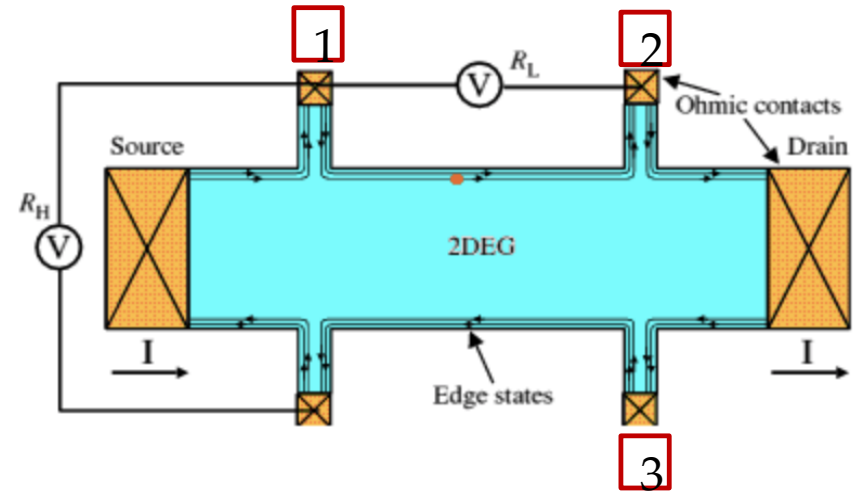
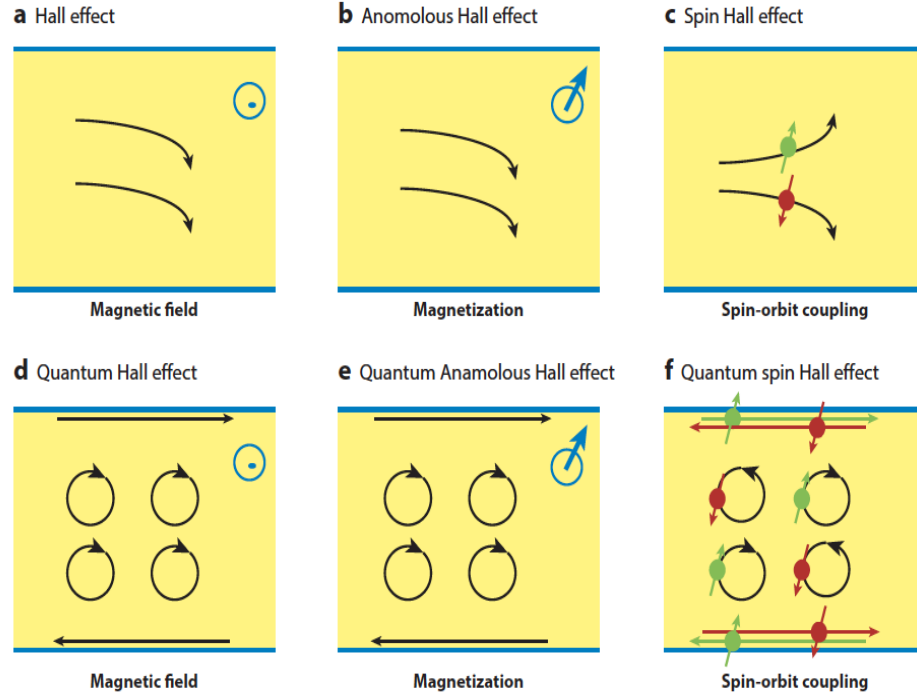
Classical Bit



Qubit

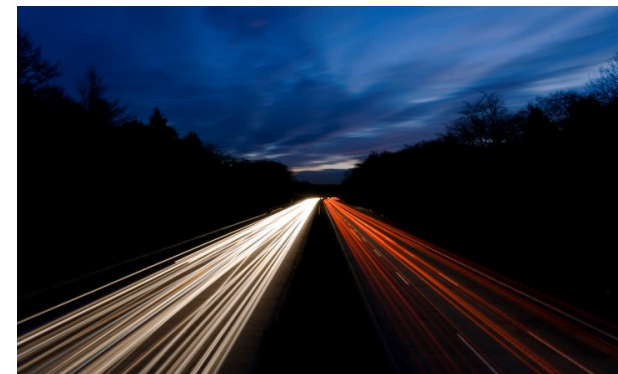
Quantum Effects “visible” at Macroscale!

Family of Quantum Hall Effects :: Starting point of topological stability



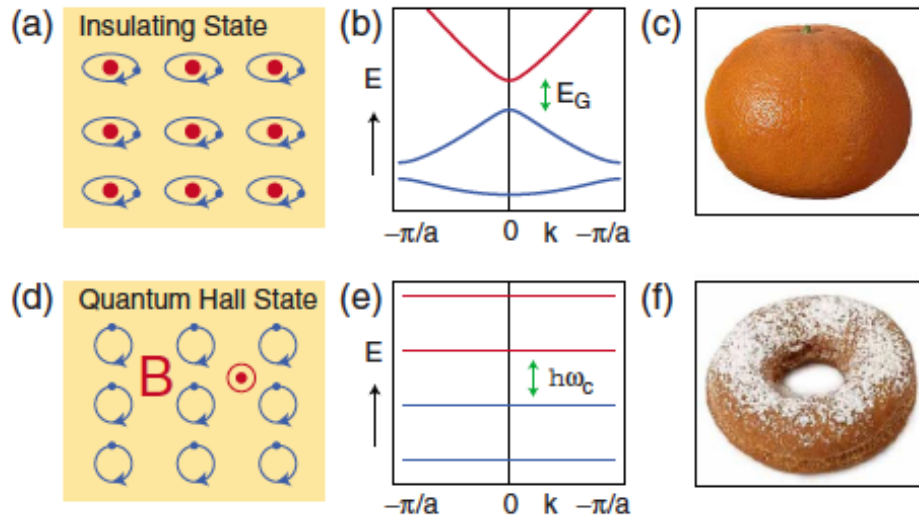
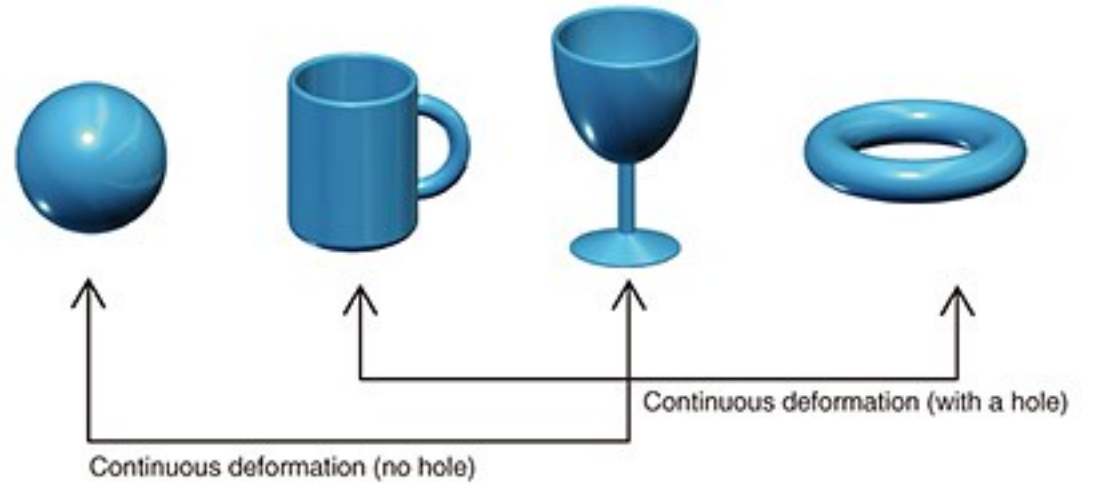
Recurring theme in topological quantum materials

Bulk ☹️



Edges 😊

Topology- a way to classify - Quantum robustness



The Nobel Prize in Physics 2016



Ill: N. Elmehed. © Nobel Media 2016
David J. Thouless
 Prize share: 1/2

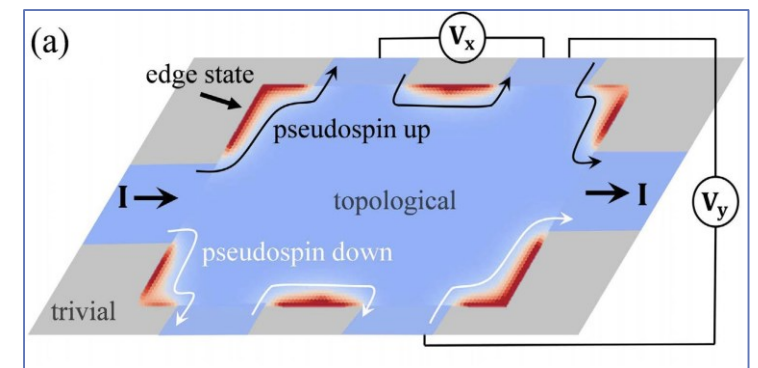
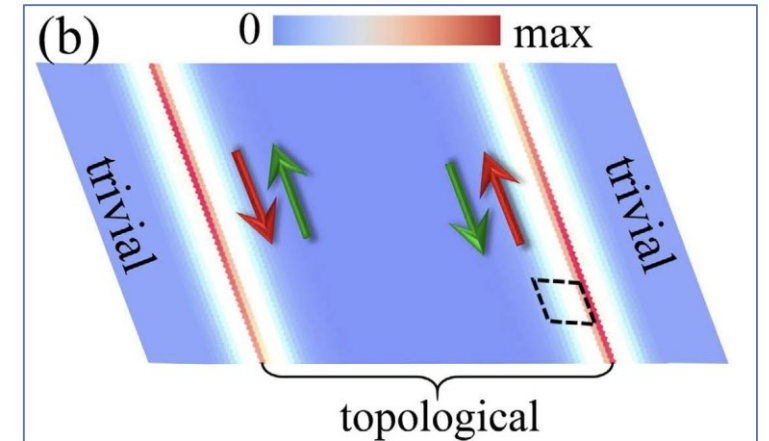
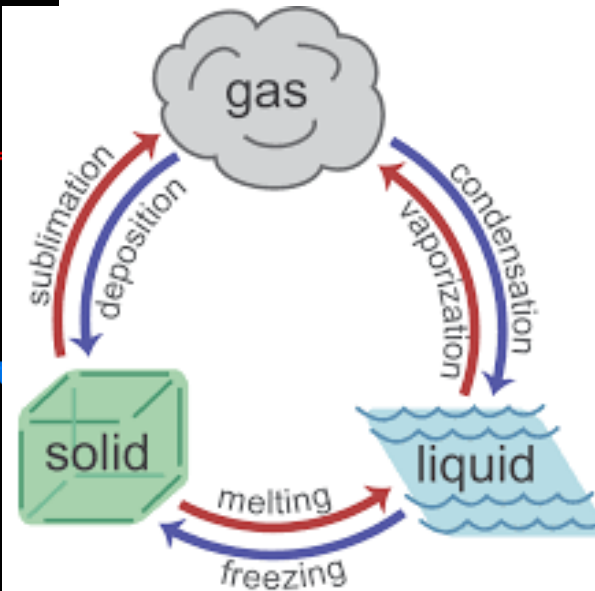
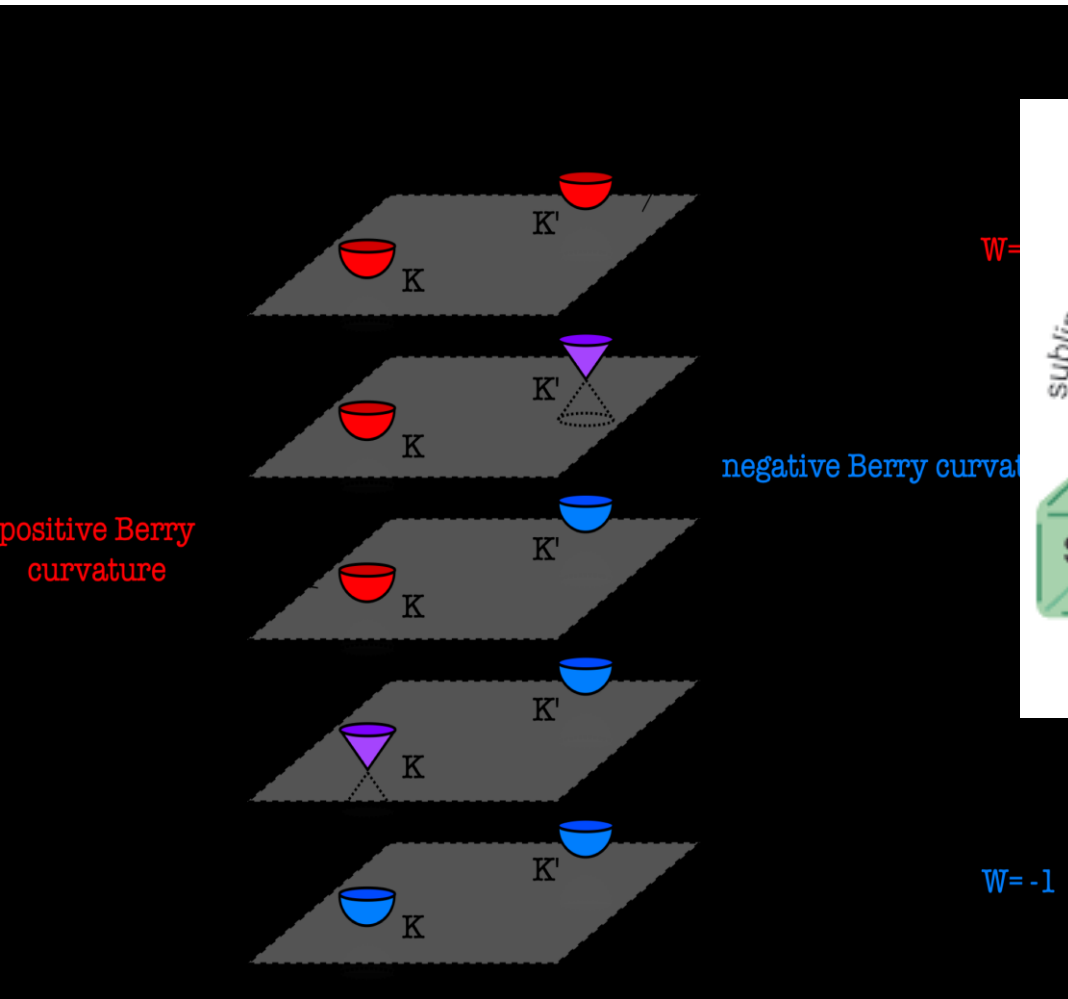


Ill: N. Elmehed. © Nobel Media 2016
F. Duncan M. Haldane
 Prize share: 1/4



Ill: N. Elmehed. © Nobel Media 2016
J. Michael Kosterlitz
 Prize share: 1/4

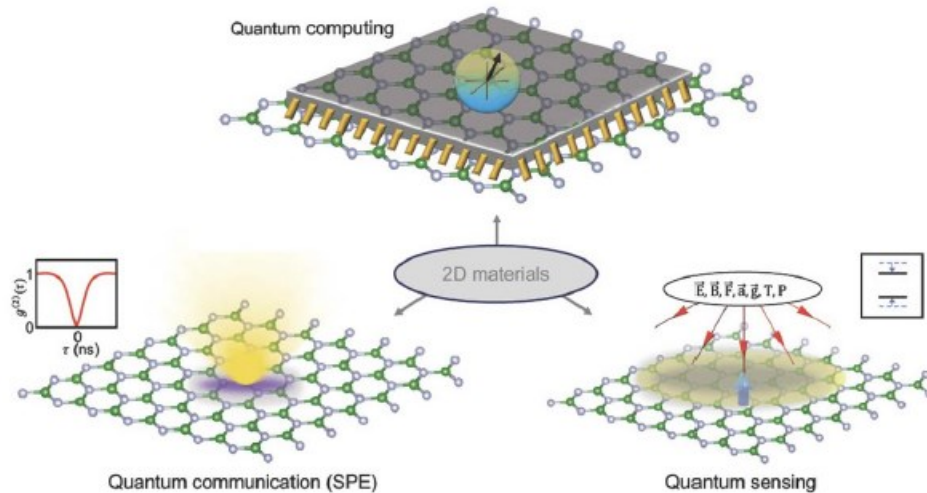
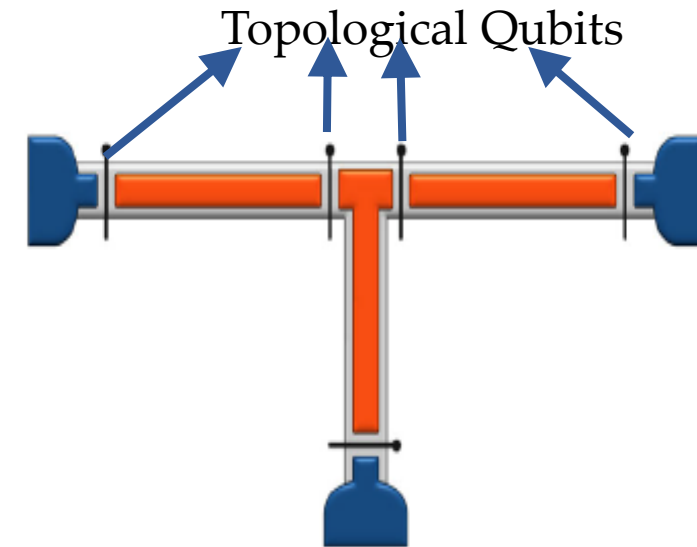
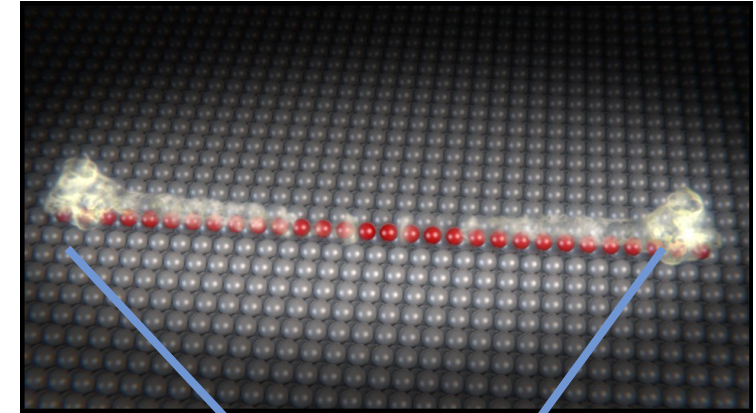
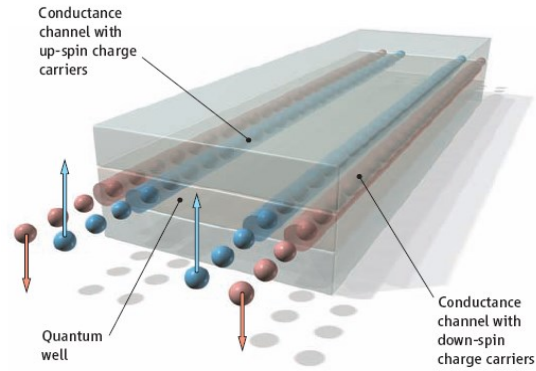
How to exploit topology?



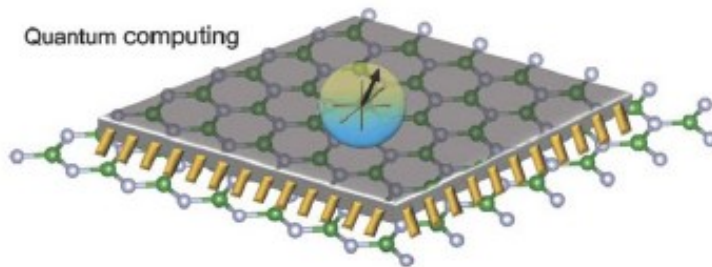
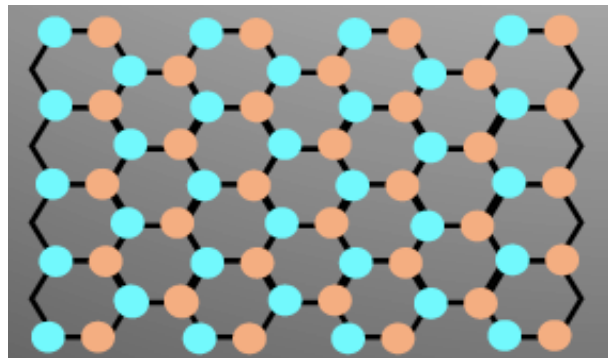
- 1) Harness the Phase transitions
- 2) Harness the robustness!

<https://topocondmat.org>

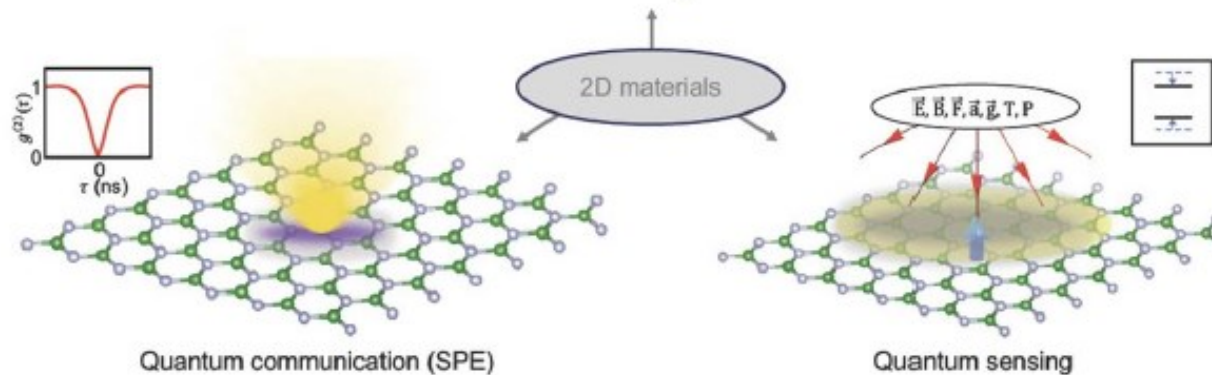
“Topo”-tronics -> Topological Electronics → Topological QM to devices



A tale of two "valleys"

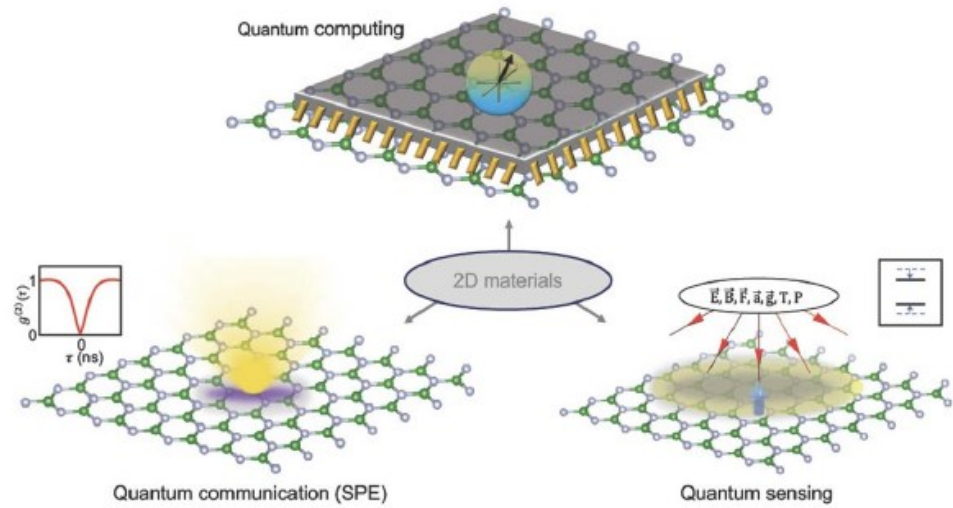


Three internal degrees of freedom
Spin
Valley index
Sublattice pseudospin



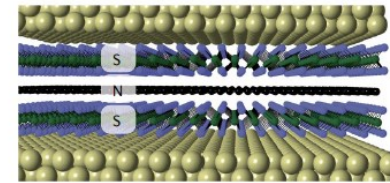
2D Quantum Materials
Spin-valley Qubits
Single photon emitters

The vast “flatland” frontier

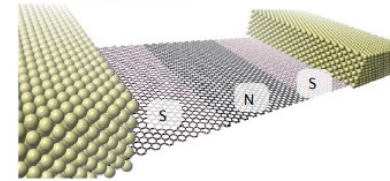


a Bottom-up heterostructures

2D vertical heterostructures

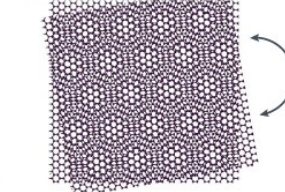


2D lateral heterostructures

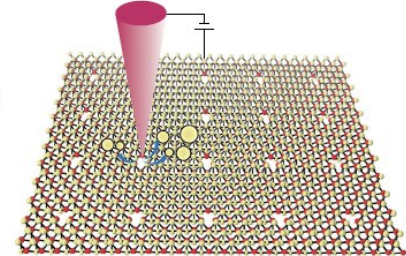


b Controlled fabrication

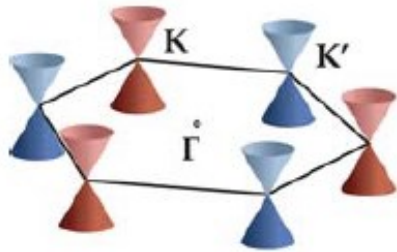
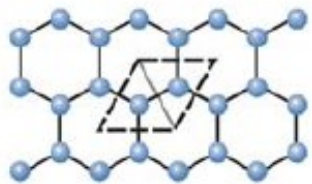
Tunable twist angle



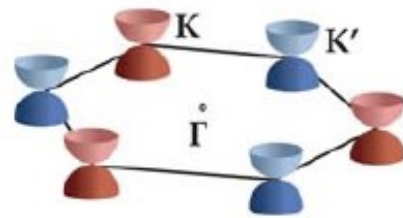
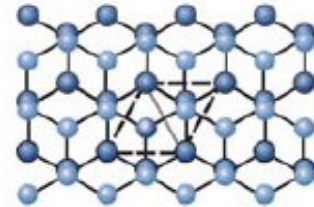
Creation of single-photon emitters



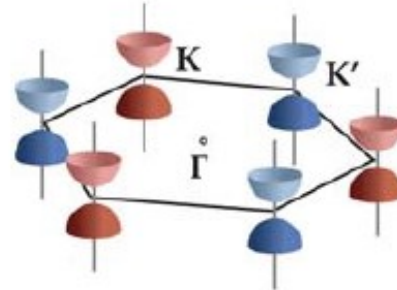
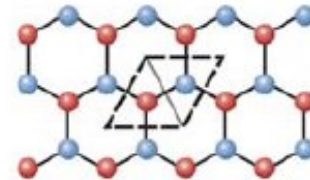
a Monolayer graphene



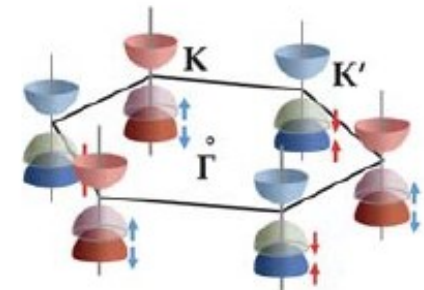
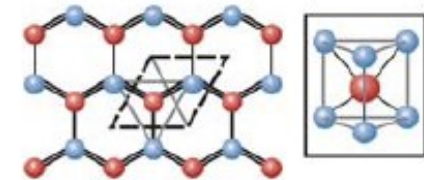
b Bilayer graphene



c Hexagonal boron nitride

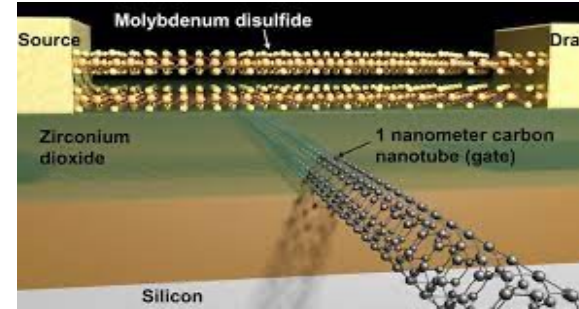


d TMD (MX₂)



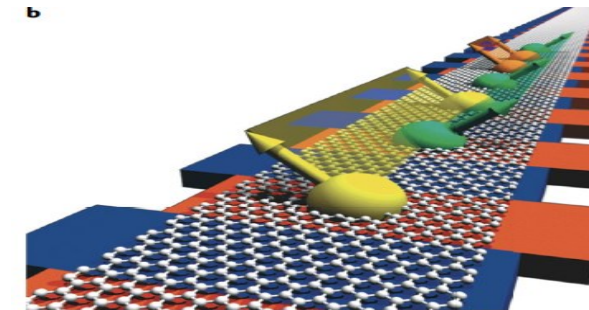
Quantum Devices: Building Blocks

Classical
Computing



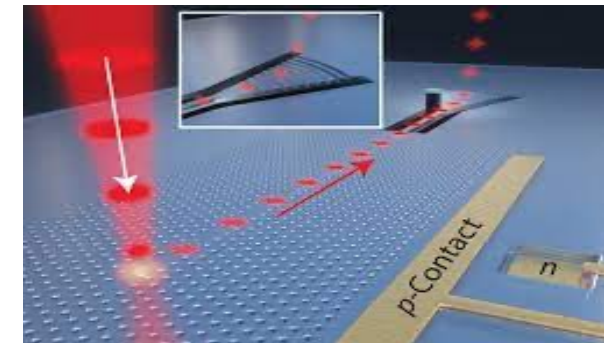
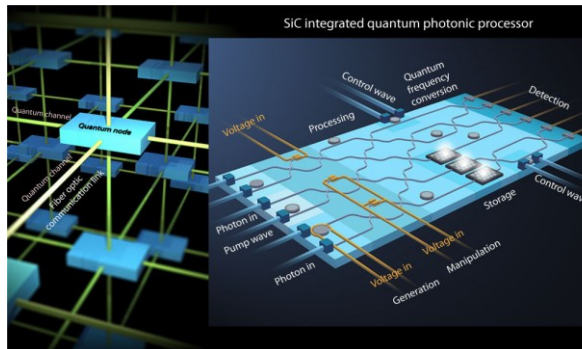
Classical
Bits
Transistor
Various platforms

Quantum
Computing



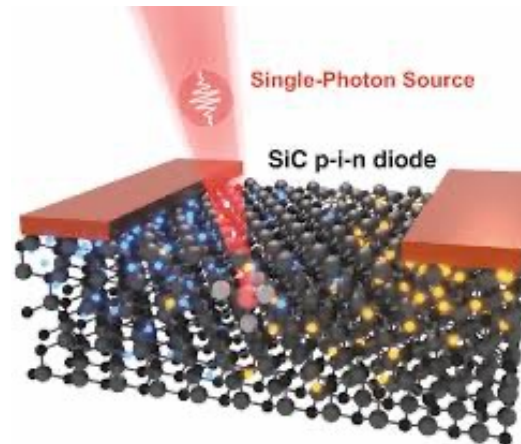
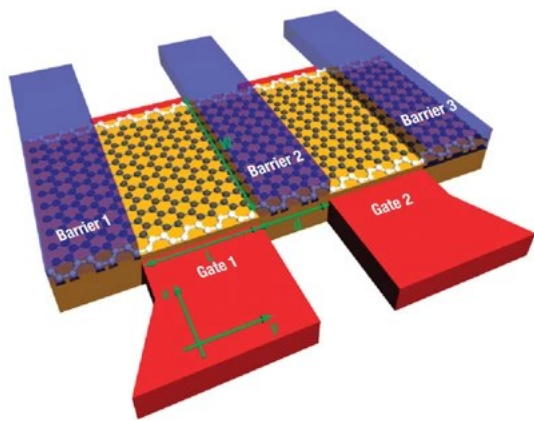
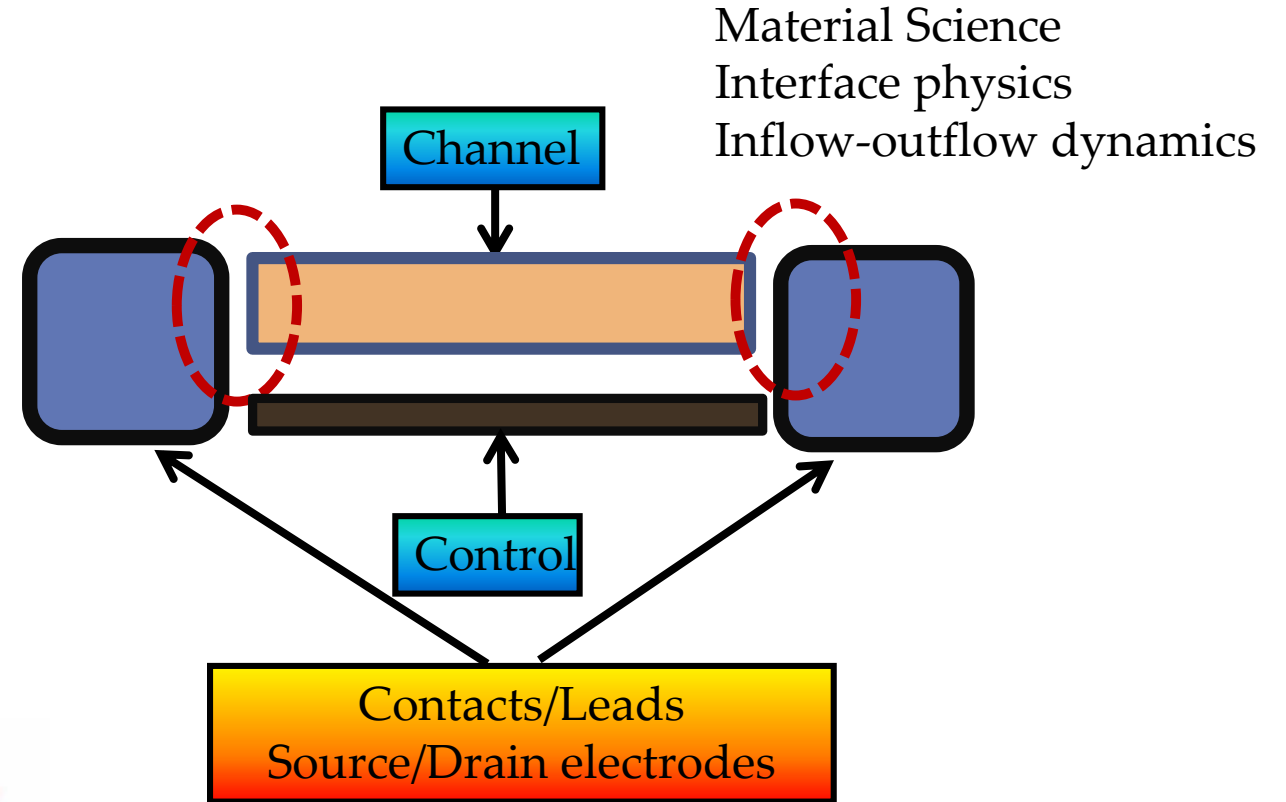
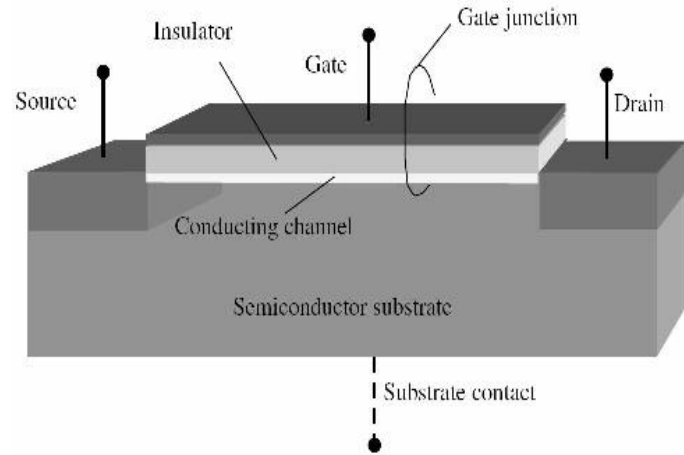
Qubit
Various platforms

Quantum
Communications



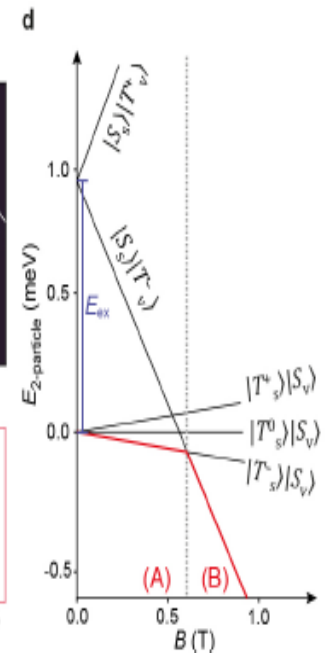
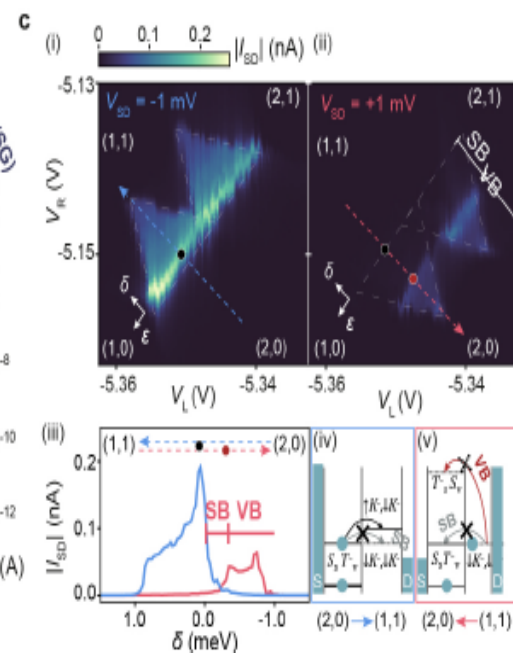
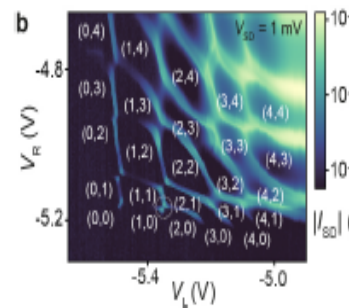
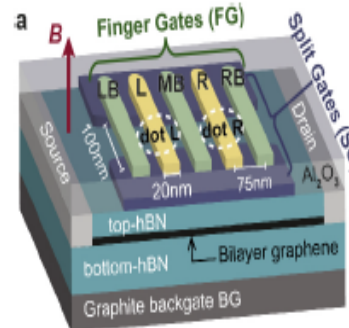
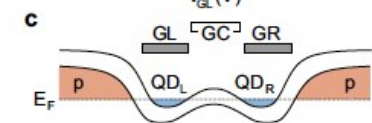
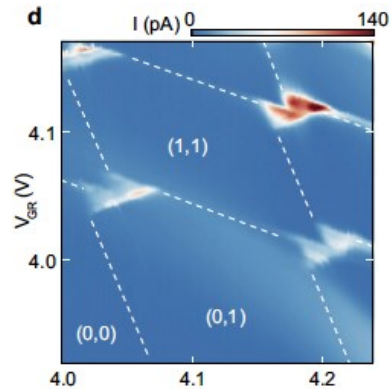
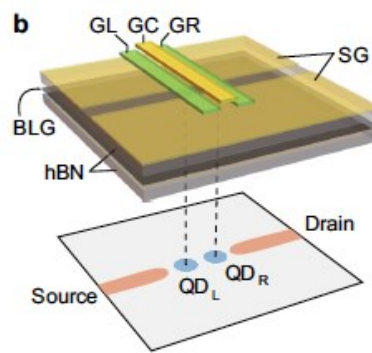
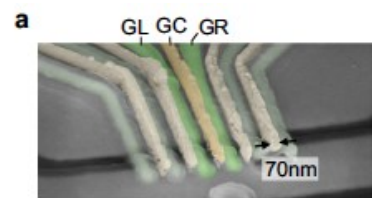
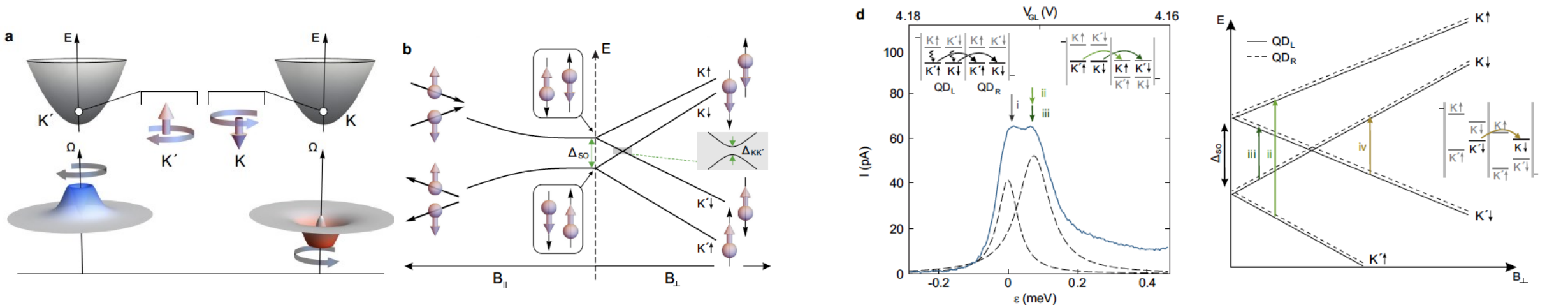
Single photon Emitters
Various platforms

Anatomy of a Building Block

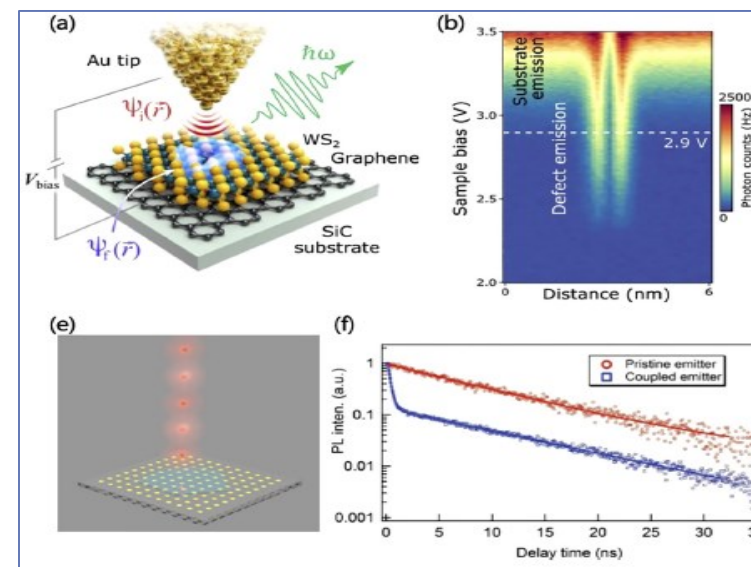
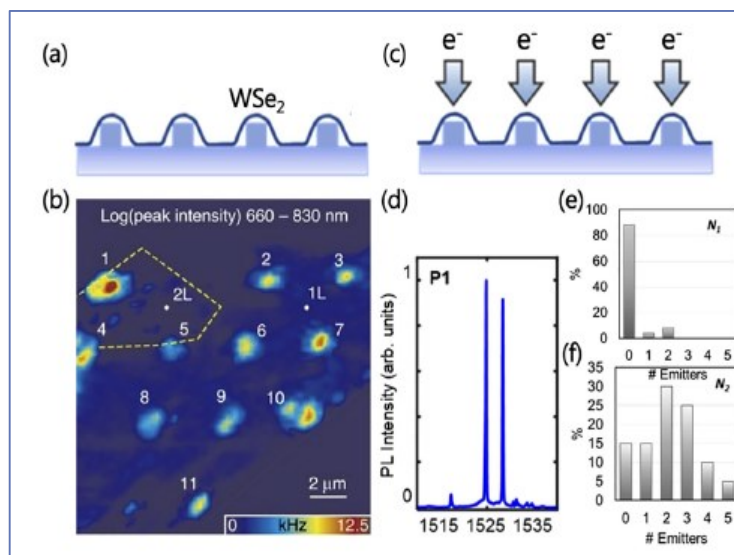
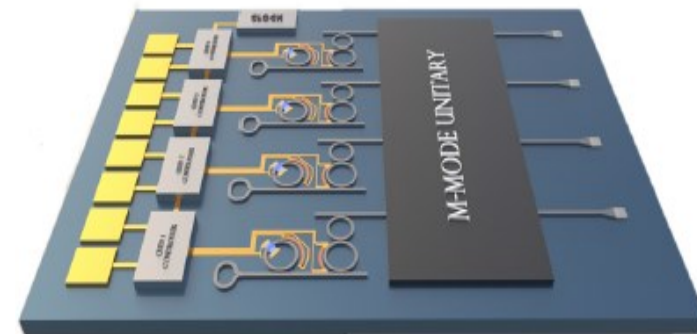
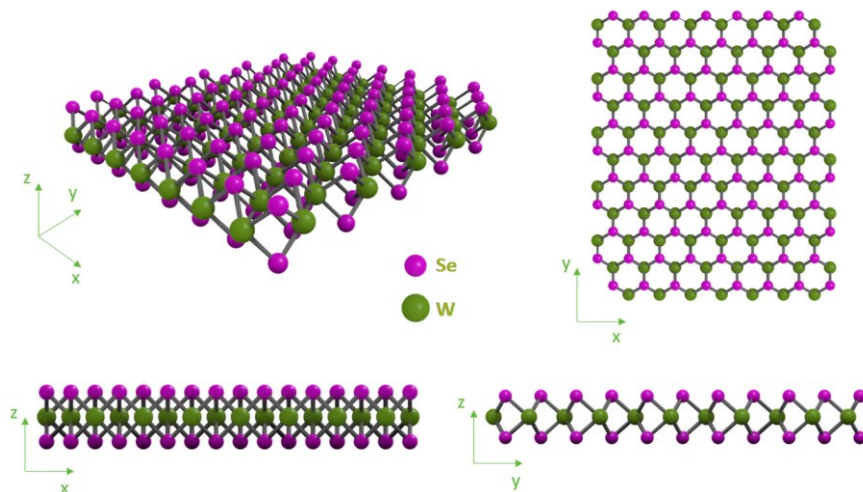
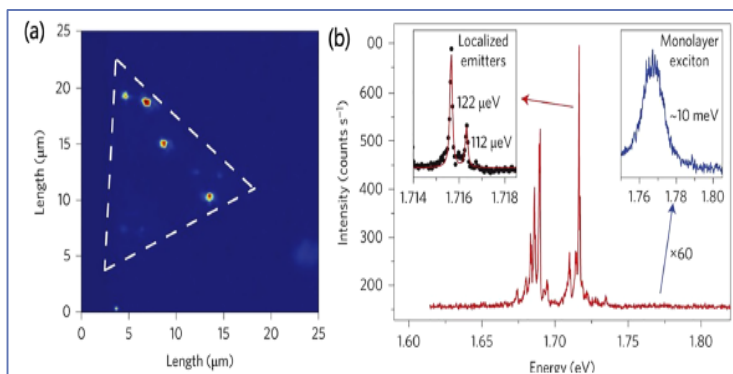


Datta, Lessons from Nanoelectronics, (2012)
Feynman, Lectures on Computation, (1998)

Graphene based qubits

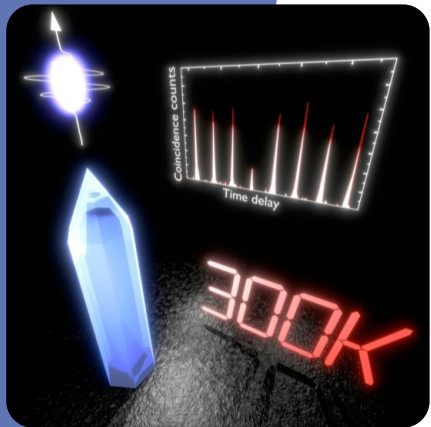


Single Photon Emitters - TMDC





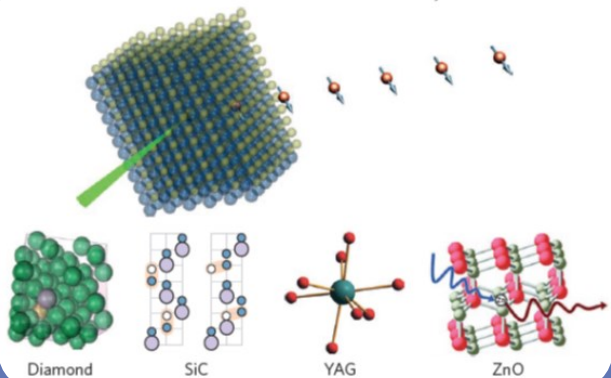
SINGLE PHOTON SOURCE



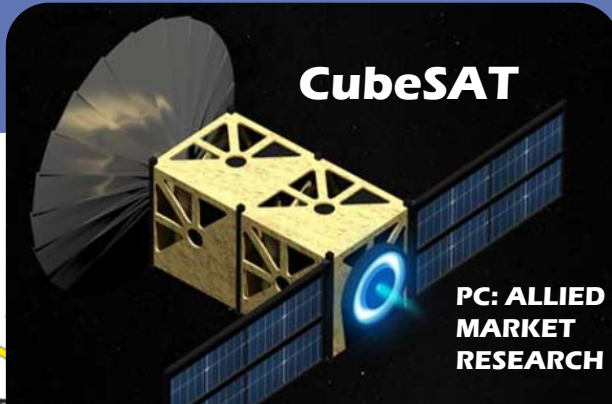
GaN QD-Based Single Photon Source

D Saha and A...

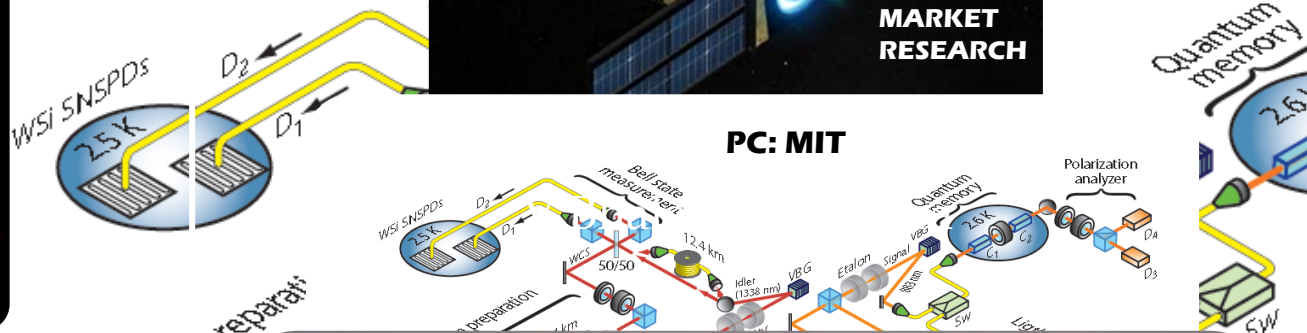
Colour centres in bulk 3D hosts and nanocrystals



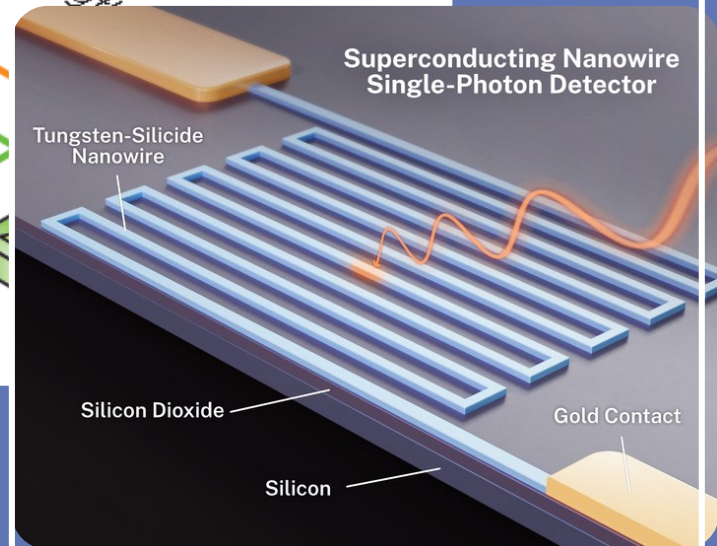
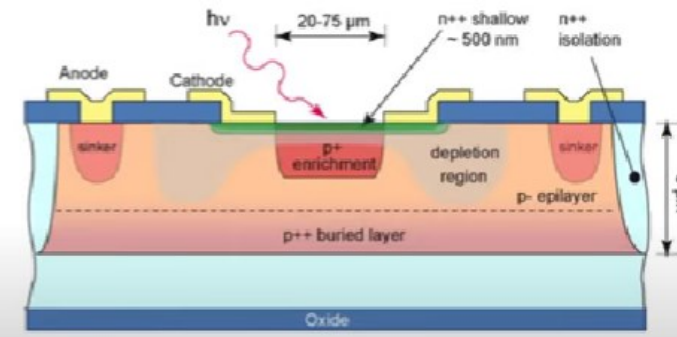
DEFECTS IN 3D CRYSTALS, NATURE PHOTONICS, 10 (2016)



PC: MIT



SINGLE PHOTON DETECTOR



PC: NIST

- Silicon 10G Modulators**
driven with on-chip circuitry
highest quality signal
low loss, low power consumption
- Flip-chip bonded lasers**
wavelength 1550nm
passive alignment
non-modulated = low cost/reliable
- Silicon Optical Filters - DWDM**
electrically tunable
integrated w/ control circuitry
enables >100Gb in single mode fiber

Complete 10G Receive Path
Ge photodetectors
trans-impedance amplifiers
output driver circuitry

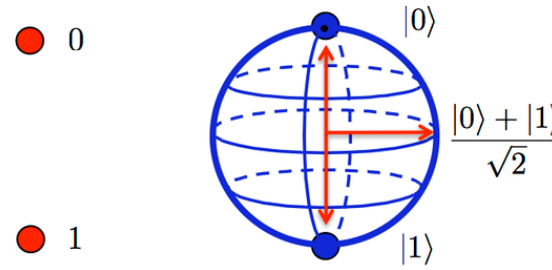
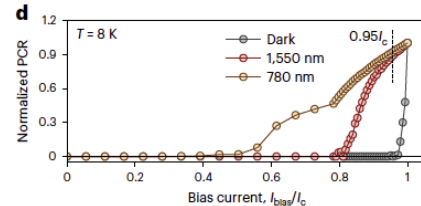
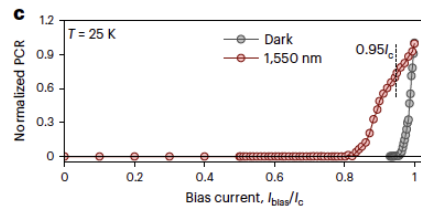
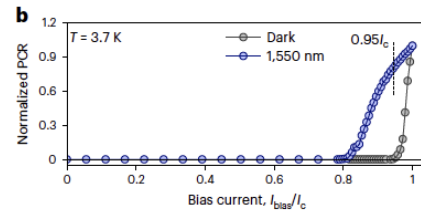
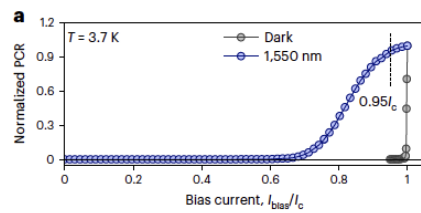
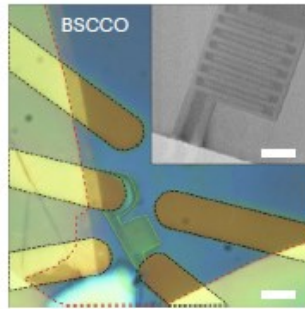
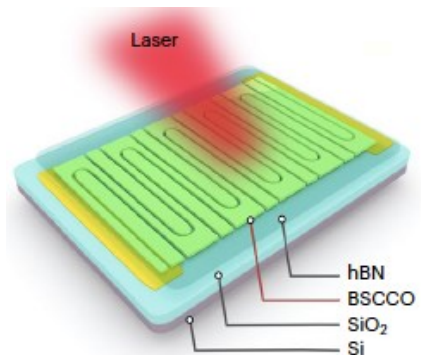
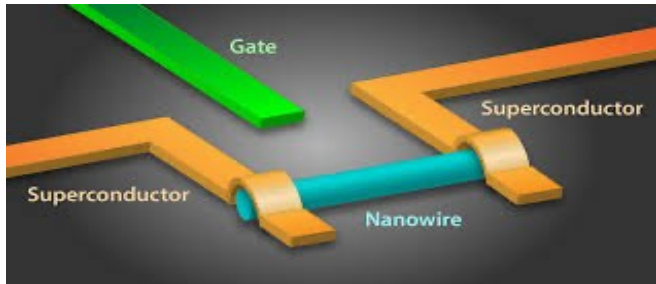
Integrated Silicon Photonics

K Saha, Various groups

Fiber cable plugs here

Ceramic Package

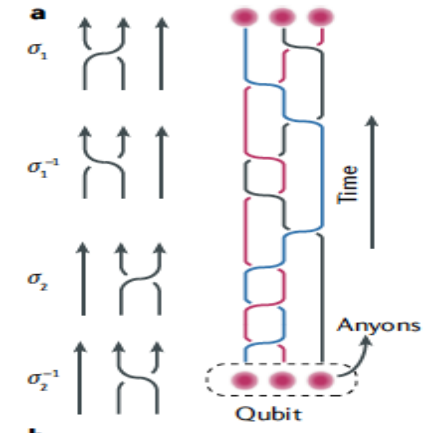
Superconducting Hybrid Systems



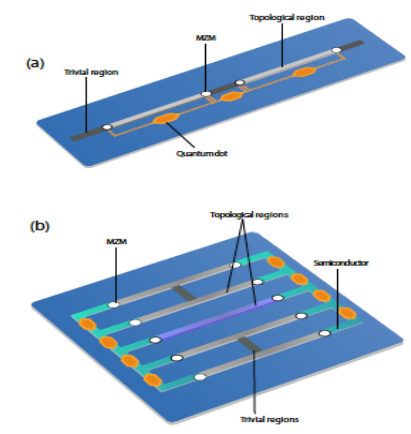
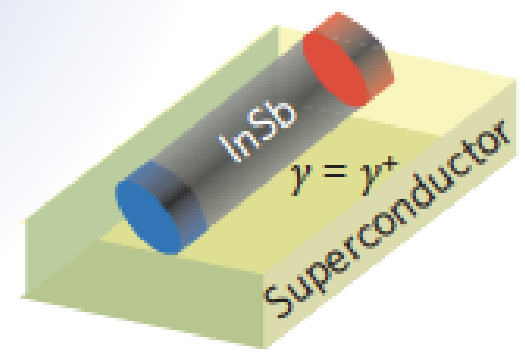
Classical Bit

Qubit

Topological QP



Majorana fermions



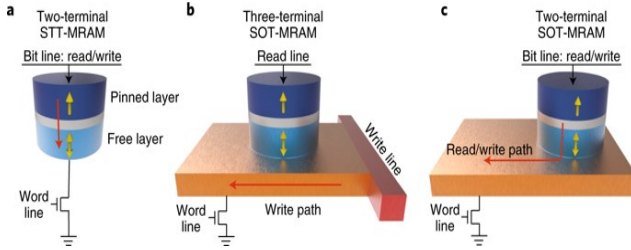
I. Charaev et.al., Nat. Nano., (2023).

Das Sarma et.al., npj quant. Inf., 1, 15001, (2015)

"Beyond Moore" Device Research Highlights



Spintronics: MRAM



Recent Publications

IEEE Trans. Elec Dev., 63, 4527-4563, (2016).
 Phys. Rev. Applied, 8, 064014, (2017).
 Appl. Phys. Lett., 112, 192404, (2018).
 Phys. Rev. Applied, 12, 024038, (2019).
 IEEE Trans. Nano., 19, 469, (2020).

- Spin filtering devices
- STT-MRAM
- Toward Neuromorphic

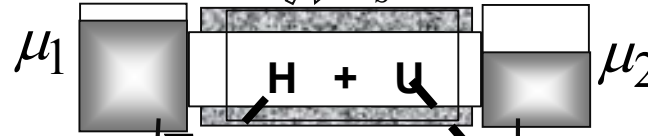
- 2D topological spintronics
- Materials -> Devices -> Functionalities

Recent Publications

Phys. Rev. B, 98, 125417, (2018).
 Phys. Rev B, 100, 155431, (2019)
 Phys. Rev. Research 2, 043430, (2020).
 Phys. Rev B, 103, 165432, (2021).
 Phys Rev B, 105, L161403, (2022)
 Comms Phys. (2023)

Dissipative aspects

Scatterers



Material aspects

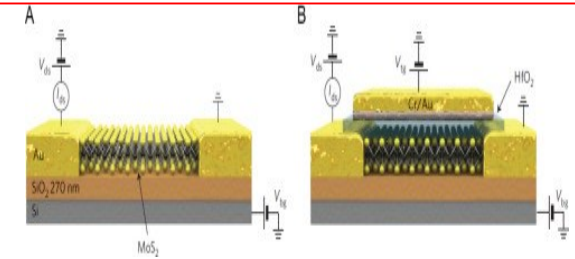
Interface aspects

Control aspects

Unified Quantum Device
Simulation Platform

Topological hybrid quantum systems

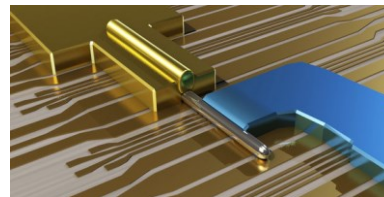
2D Quantum Materials and Devices



Recent Publications

Phys. Rev. Applied, 10, 014022, (2018).
 Phys. Rev. B, 99, 075415, (2019).
 Phys. Rev. B (Rapid Comm), 100, 081403, (2019).
 Phys. Rev. Materials, 3, 124005, (2019).
 Phys. Rev. Research, 2, 043041, (2020)
 npj 2D materials., 6, 19, (2022)

- Quantum Hall hybrid systems
- Straintronics
- Topotronics



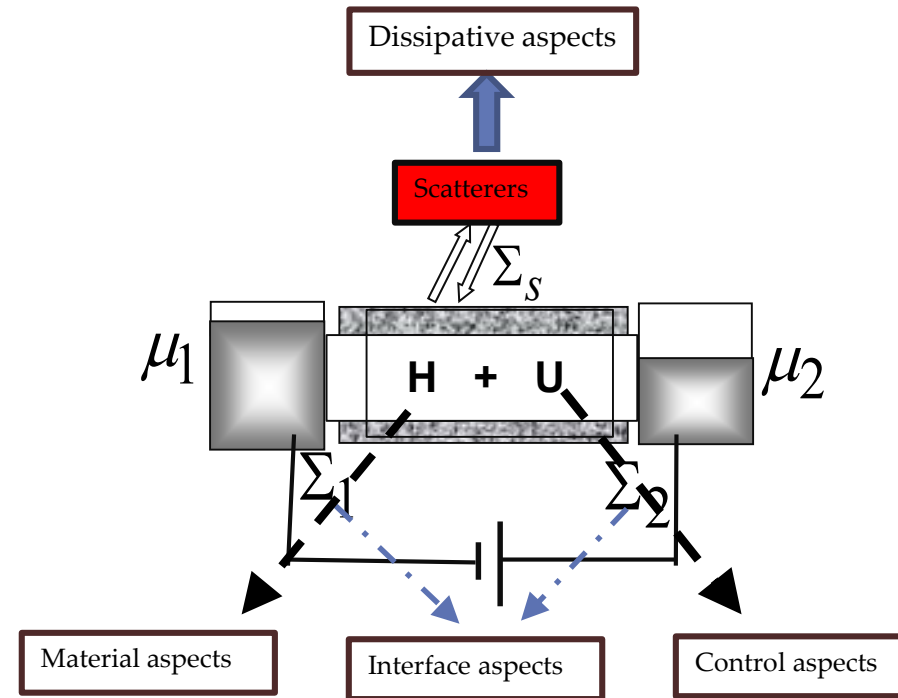
- 1-D Majorana devices
- Topological vs trivial
- Entropic signatures
- Magnetic insulator hybrids



Computational Nanoelectronics and Quantum Transport (CNQT@IITB)

<http://cnqt-group.org>

<https://twitter.com/quantumtranspo1>



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