STC for Integrated Quantum Materials

NSF Grant DMR 1231319

http://CIQM.Harvard.edu

Harvard University – PI Robert Westervelt

Howard University – co-PI Gary Harris

Massachusetts Institute of Technology – co-PI Ray Ashoori

Museum of Science, Boston – co-PI Carol Lynn Alpert

Contents

- STC for Integrated Quantum Materials
  - Vision
  - Research Areas
  - Science and Education Community
- Center for Nanoscale Systems at Harvard
  - Shared facilities for materials growth, nanofabrication, and electron microscopy
  - Multi-institution and multi-disciplinary users.

Quantum Engineering

quantum electronics & photonics with atomic-scale devices

electrons

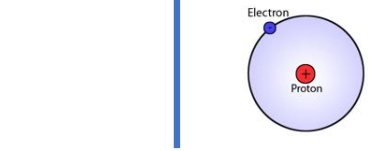
energy — size

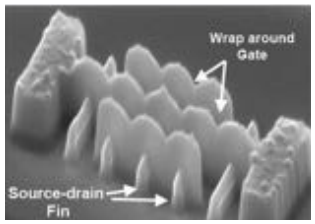
0.001 eV — 10 nm

300 K

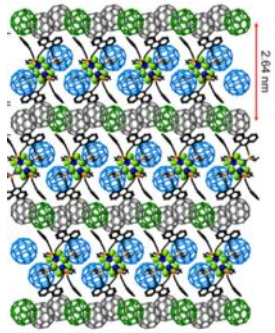
0.1 eV — 1 nm

10 eV — 0.1 nm

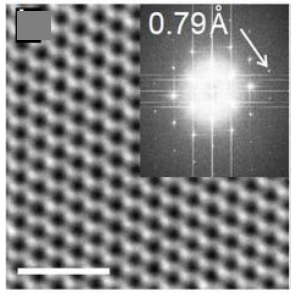




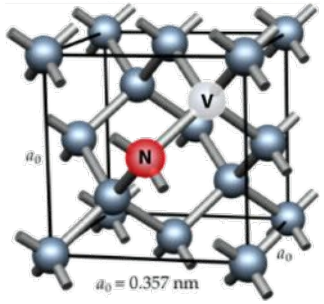
22 nm CMOS



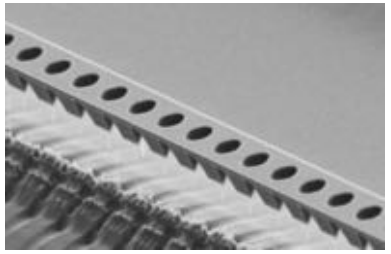
vdW hetero-structures



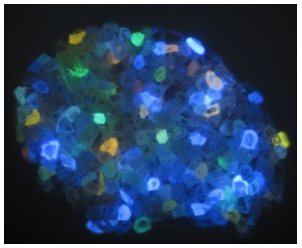
atomic layer graphene



atomic NV center



diamond photonics



color center diamond

light

10 μm

1 μm

0.1 μm

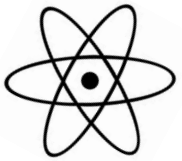
New Particles in Quantum Materials

electrons & photons | Bloch waves in solids | **new quantum particles**

electron

photon

atom



vacuum

---

e & h with m*

slower photon

phonon

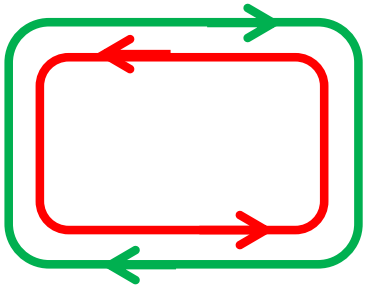
solids

---

e & h, massless
no energy gap

graphene

topological edge
states for B = 0



topological
insulators

300 K
qubit

diamond
NV centers

quantum
materials

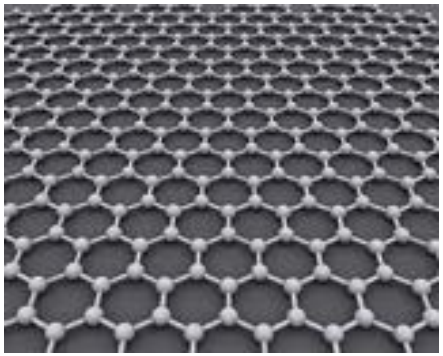
Quantum Information Science & Technology

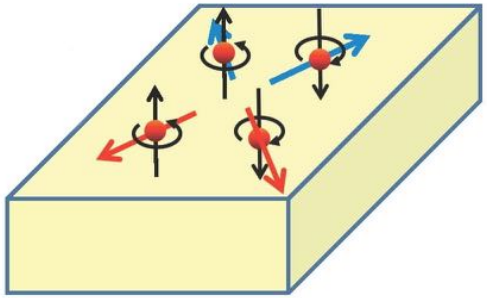
Create atomic-scale devices and systems based on **quantum materials** for **quantum sensors**, **quantum communication** and **quantum computers**.

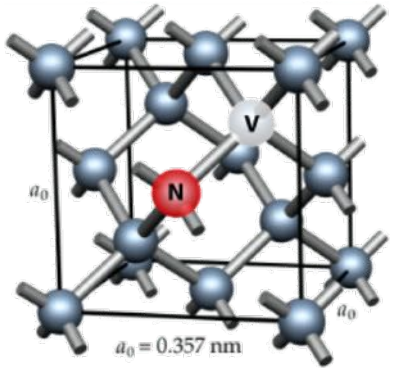
Atomic Layers: Graphene, BN, MoS_2 – *atomic scale devices*

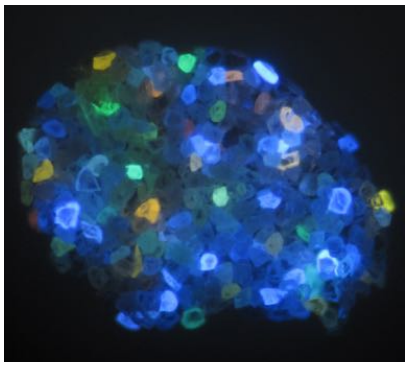
Topological Insulators – *topologically protected data channels*

NV Center Diamond – *1 atom memory sites, quantum sensors*

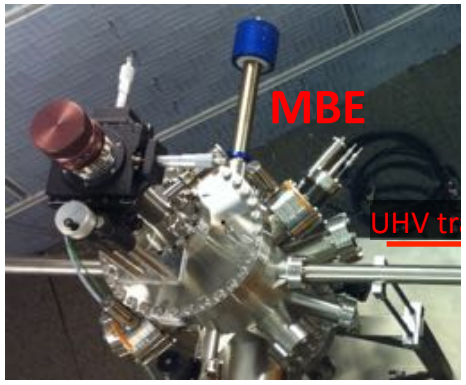








Materials & Device Innovation Cycle



MBE & CVD
Materials
Growth

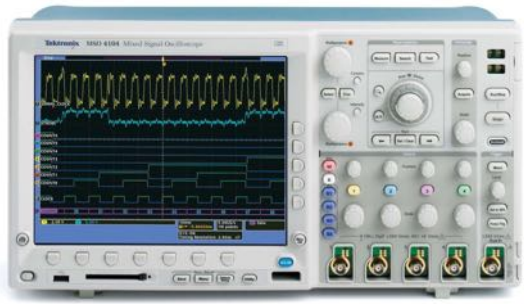
JEOL
HR STEM
CNS
Imaging

Growth & Processing

Device Fabrication & Characterization

Atomic Modeling & Understanding

Theory



Experimental
Test Data

Novel vdW Heterostructures
Philip Kim (Harvard) - leader
Ray Ashoori (MIT)
Tina Brower-Thomas (Howard)
Donhee Ham (Harvard)
Eric Heller (Harvard)
Efthimios Kaxiras (Harvard)
Jing Kong (MIT)
Tomas Palacios (MIT)
Steven Richardson (Howard)
Robert Westervelt (Harvard)

Discovery of Topological Crystals
Joe Checkelsky (MIT) – leader
Alan Aspuru-Guzik (Harvard)
David Bell (Harvard)
Liang Fu (MIT)
Nuh Gedik (MIT)
Bertrand I Halperin (Harvard)
Jenny Hoffman (Harvard)
Tito Huber (Howard)
Efthimios Kaxiras (Harvard)
Jagadeesh Moodera (MIT)
Thomas Searles (Howard)

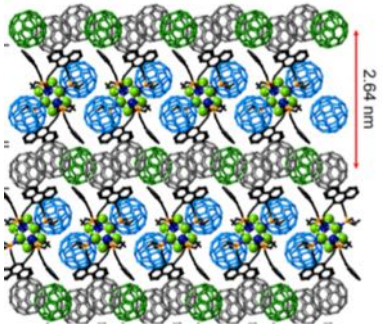
Research Faculty

Topologically Protected Qubits
Amir Yacoby (Harvard) - leader
Pratibha Dev (Howard)
Liang Fu (MIT)
Nuh Gedik (MIT)
Bertrand I. Halperin (Harvard)
Pablo Jarillo-Herrero (MIT)
Philip Kim (Harvard)
Leonid Levitov (MIT)
Jagadeesh Moodera (MIT)

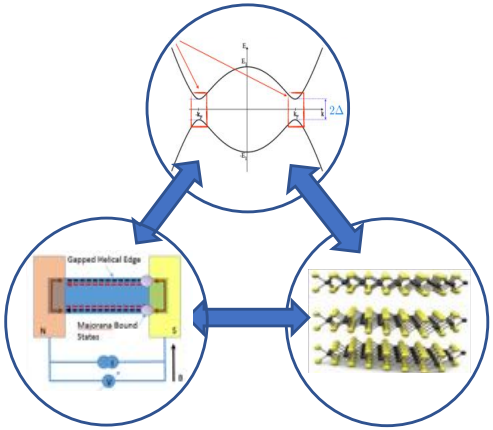
Quantum Networks
Marko Loncar (Harvard) - leader
Pratibha Dev (Howard)
Dirk Englund (MIT)
Gary Harris (Howard)
Evelyn Hu (Harvard)
Efthimios Kaxiras (Harvard)
Jing Kong (MIT)
Tomas Palacios (MIT)

Mission – 4 Research Areas

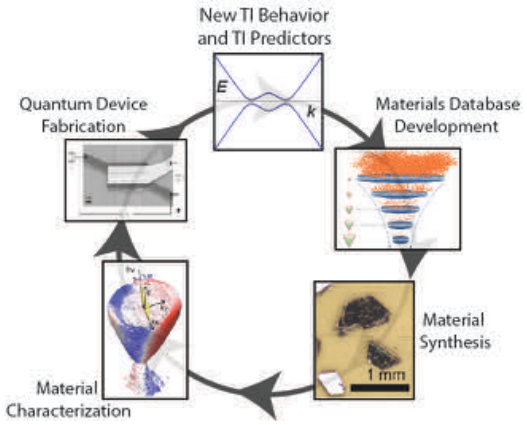
RA1 **Novel vdW Heterostructures**
Philip Kim - Quantum Sensors



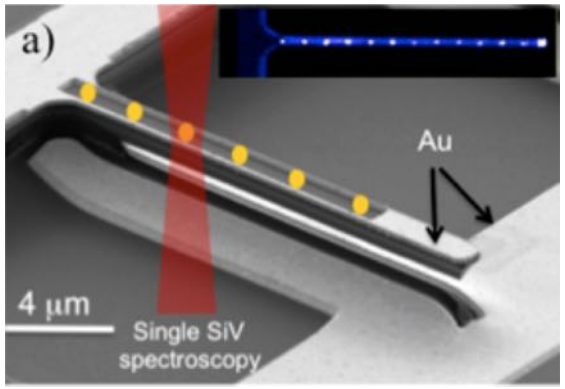
RA3 **Topologically Protected Qubits**
Amir Yacoby – Quantum Computers



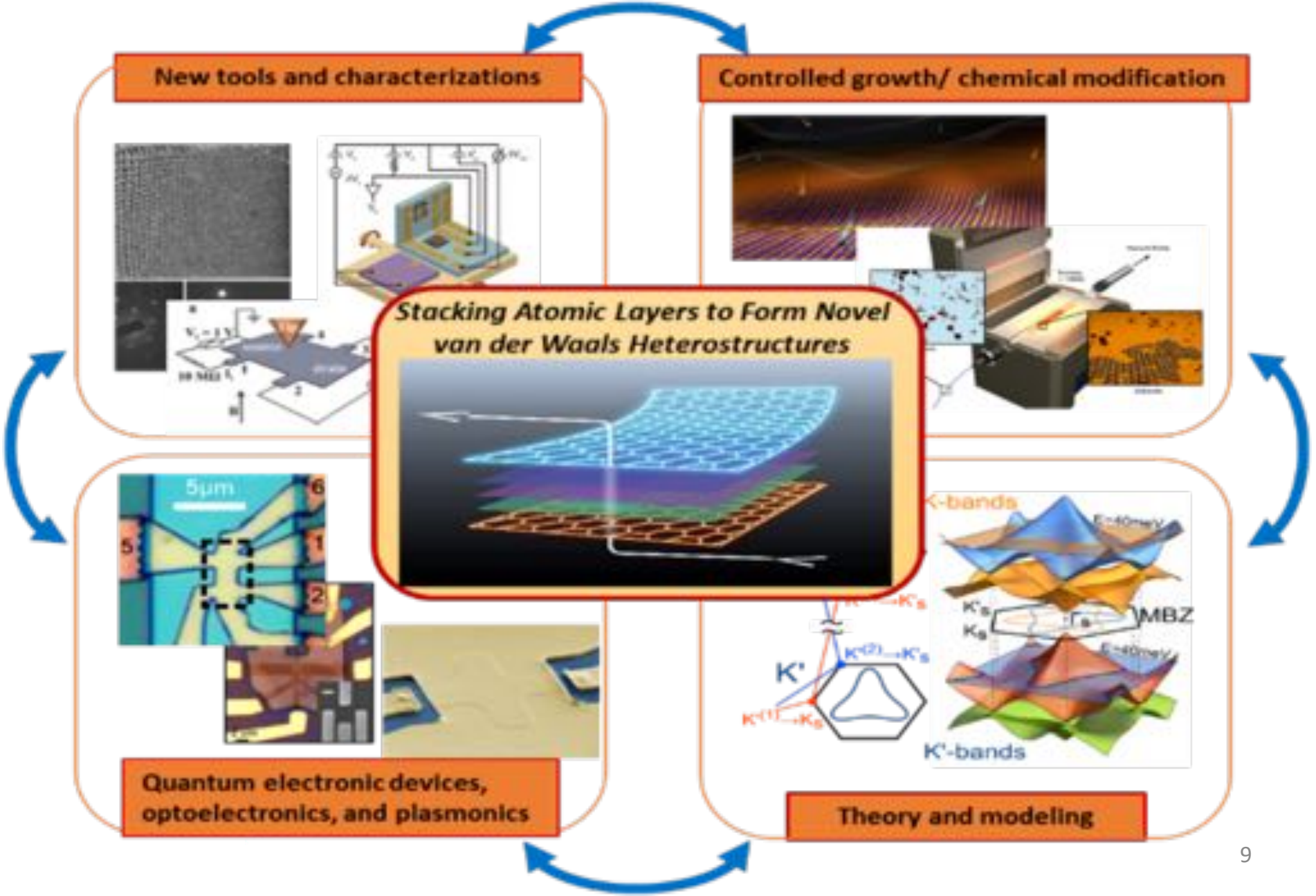
RA2 **Discovery of New Topological Crystals J. Checkelsky** – Quantum Networks & Computers



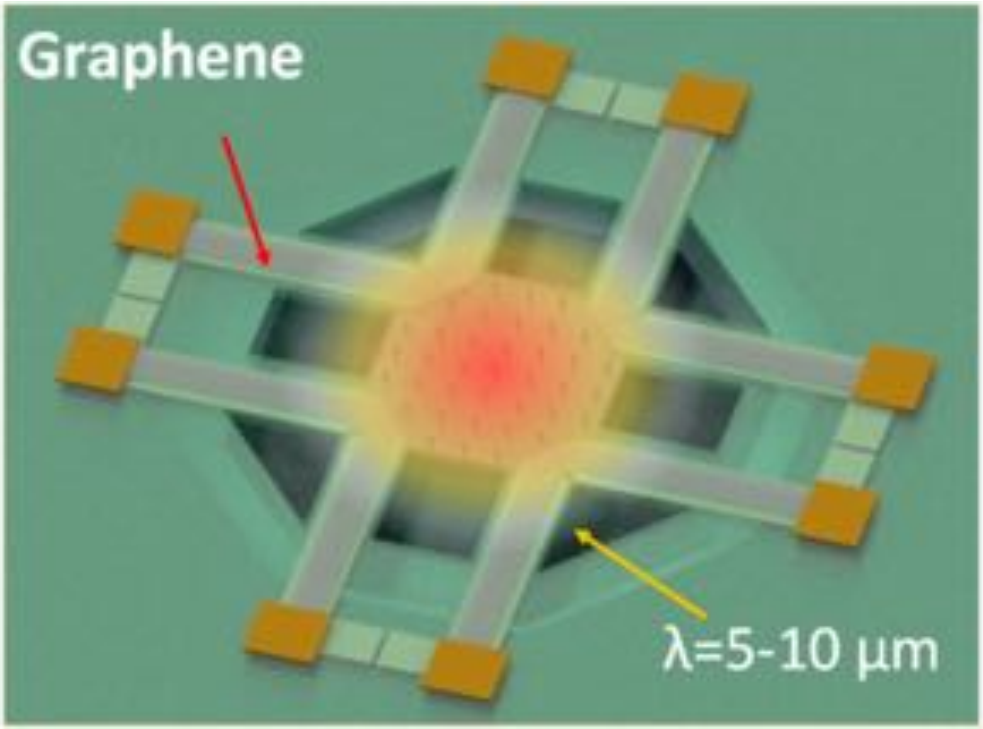
RA4 **Quantum Networks with Solid State Quantum Emitters**
Marko Loncar – Quantum Networks

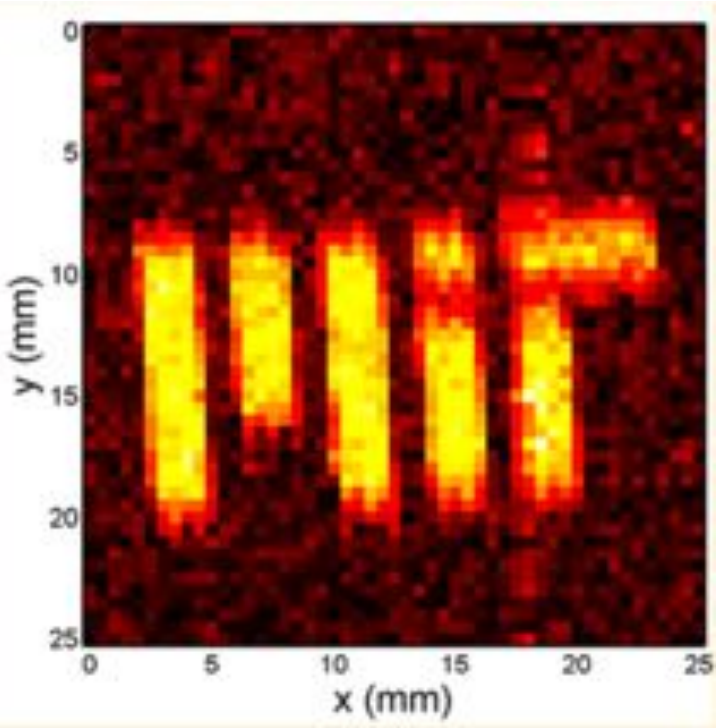


Research Area 1: Novel van der Waals Heterostructures led by Philip Kim



Graphene Thermopile
Kong, Palacios, Jarillo-Herrero

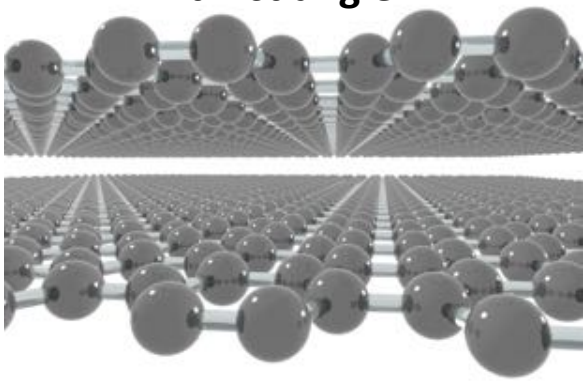


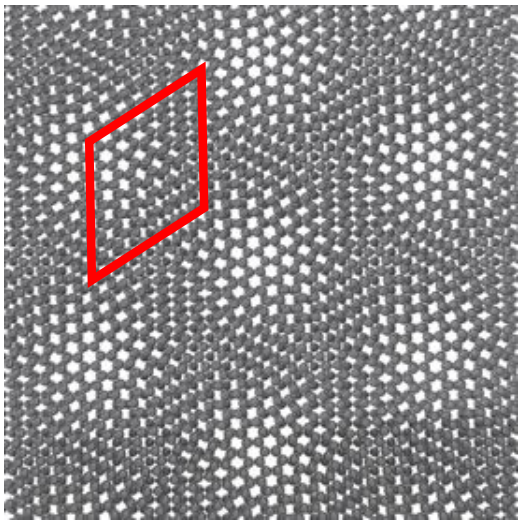


Hsu et al. Nano Lett. (2015)

Engineering band gaps in twisted bilayer graphene

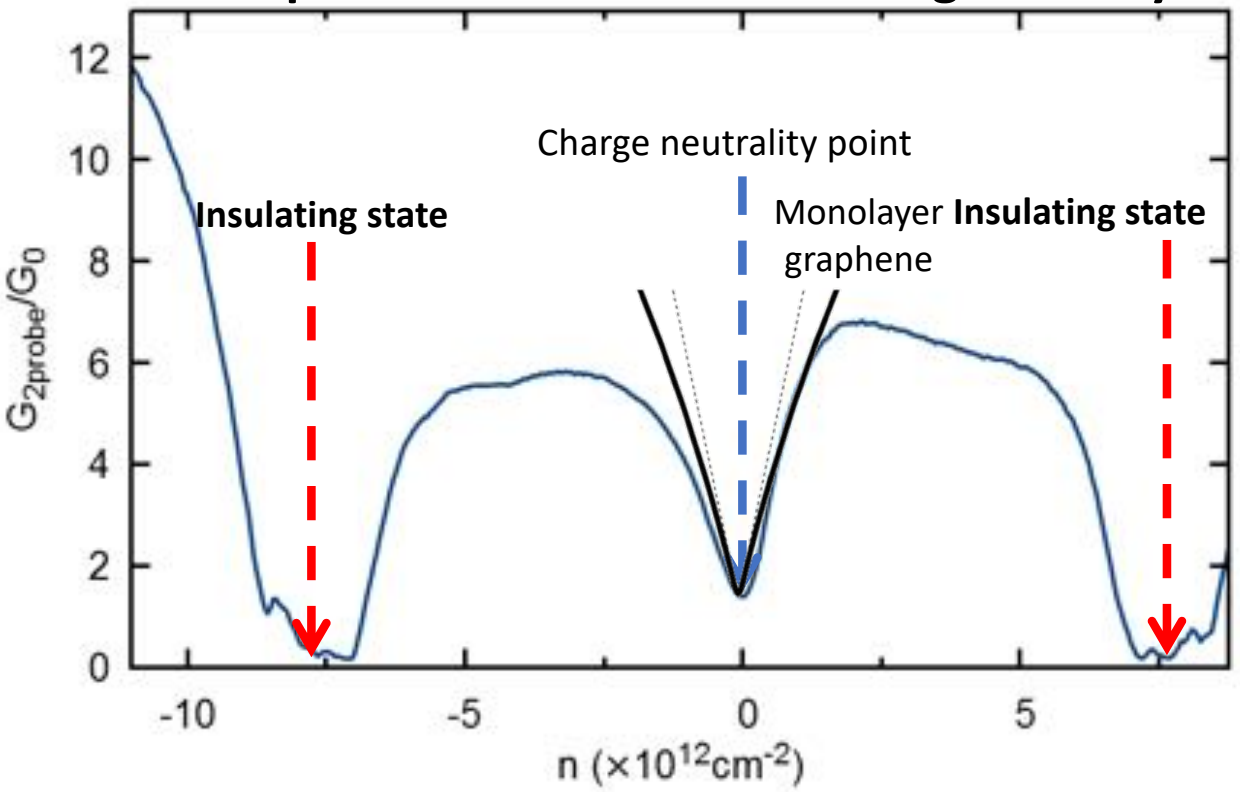
G/G heterostructure with 1.8° twist angle





Emergent moiré pattern with $\lambda = 7.8$ nm

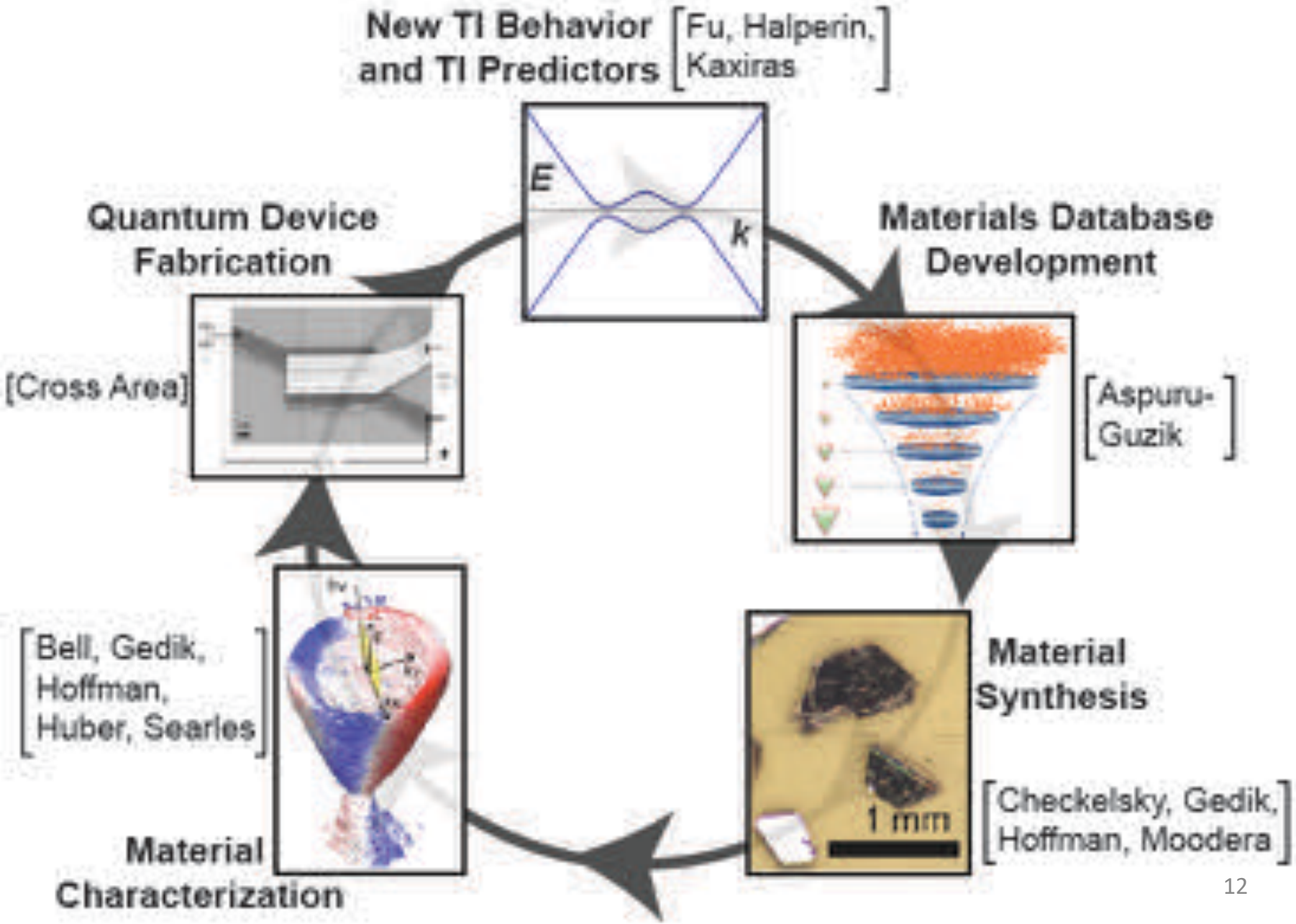
Two probe conductance vs. charge density



Insulating states observed at high number densities!

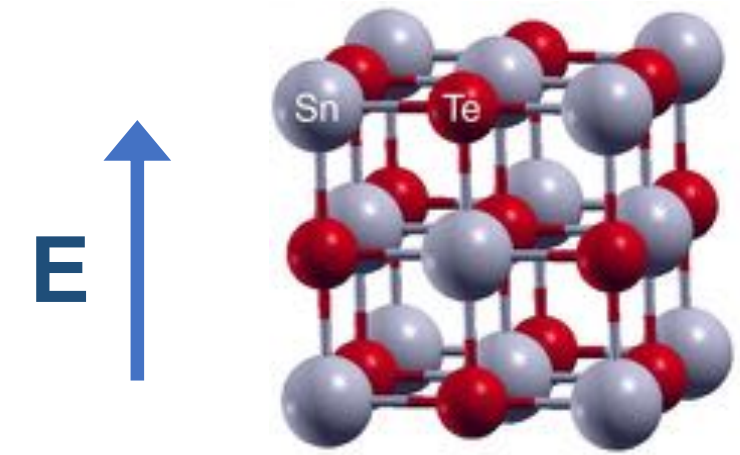
Cao et al. PRL (2016)

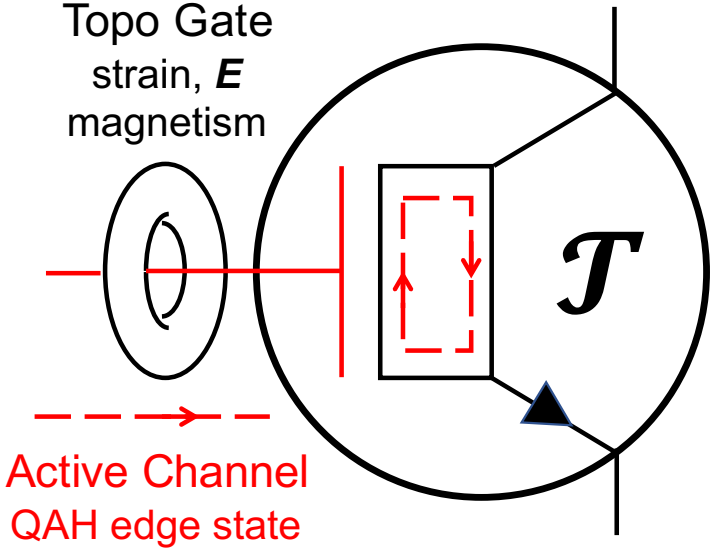
Research Area 2: Discovery of New Topological Crystals led by Joe Checkelsky

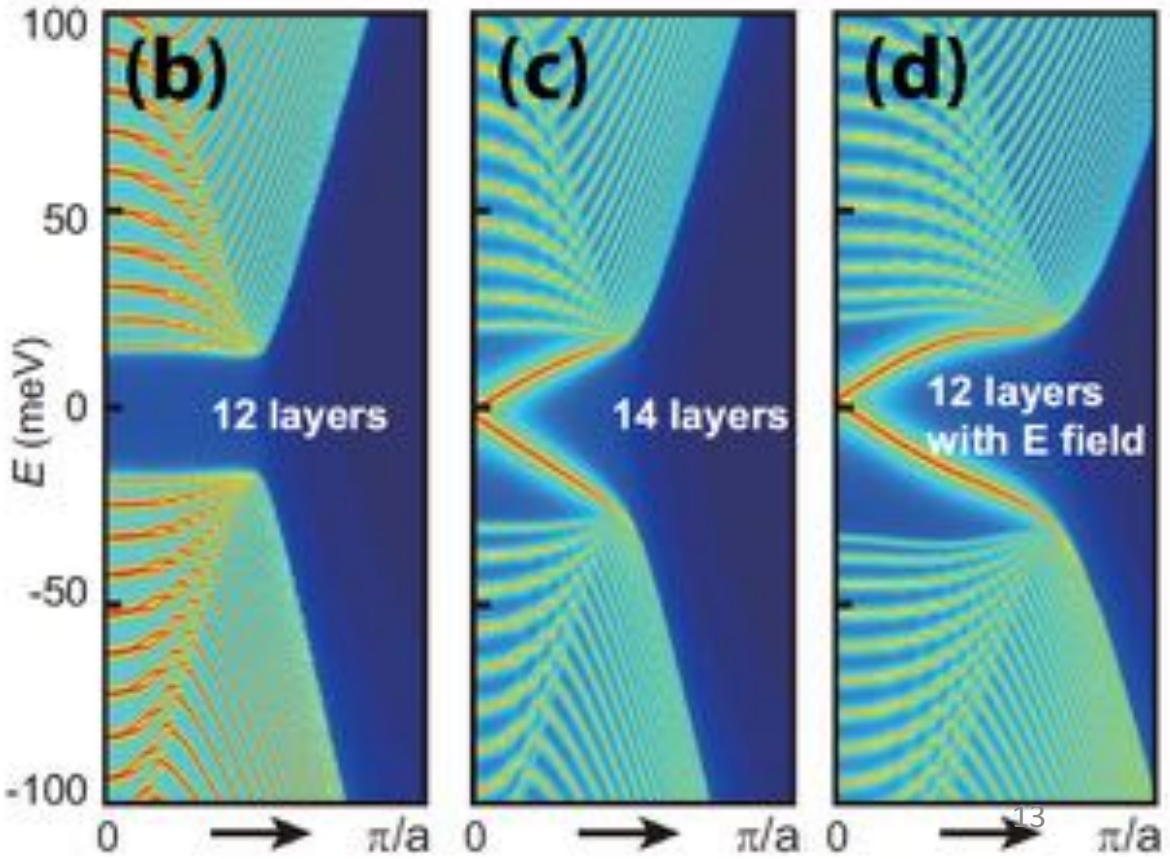


Topological Transistor

Liang Fu

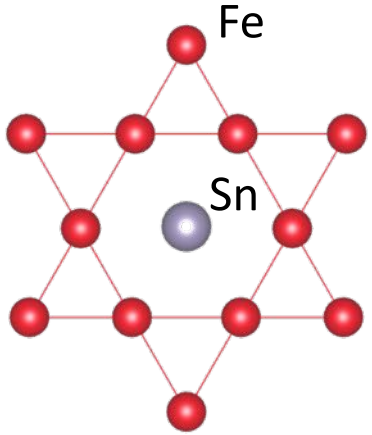


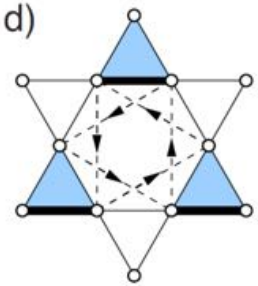


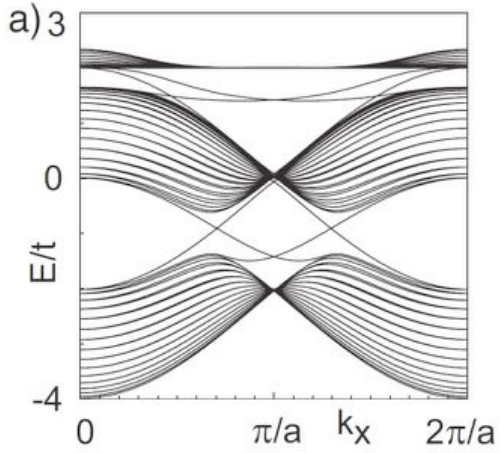


Liang Fu PRB (2015)

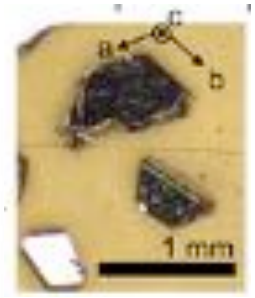
Theoretically Predicted Kagome Crystal







F. von Cube and D. Bell



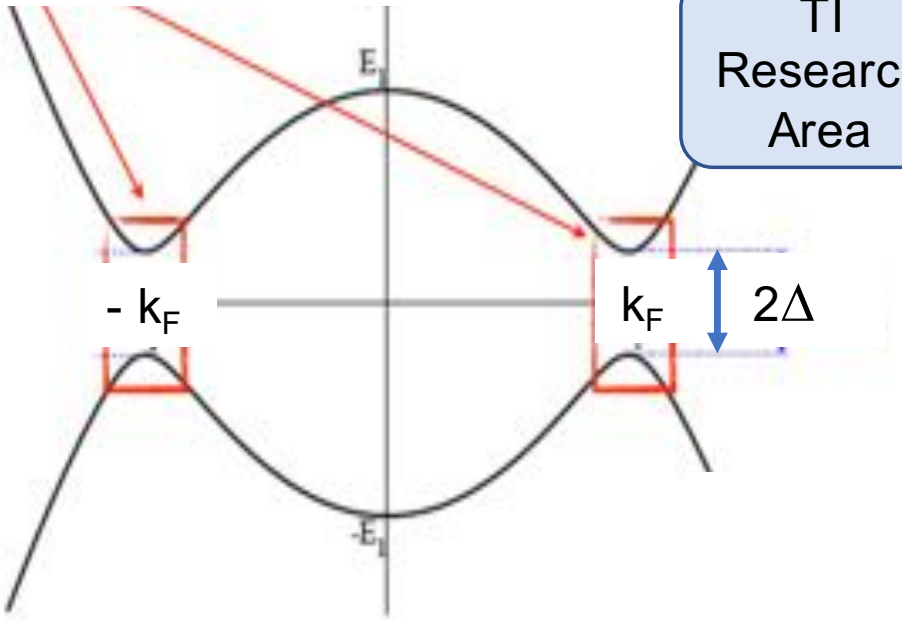
PHYSICAL REVIEW B **80**, 113102 (2009)
H.-M. Guo and M. Franz

Bulk Single Crystals
Fe_3Sn_2 – Ferromagnetic Kagome Metal

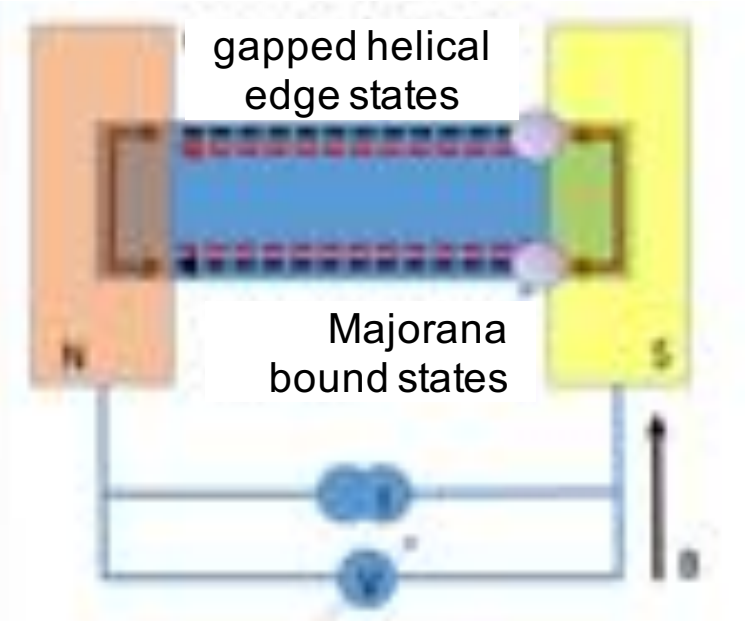
Ye, Bell, Fu, Comin, JGC et al

Research Area 3 Topologically Protected Qubits led by Amir Yacoby

Modeling hybrid devices & materials

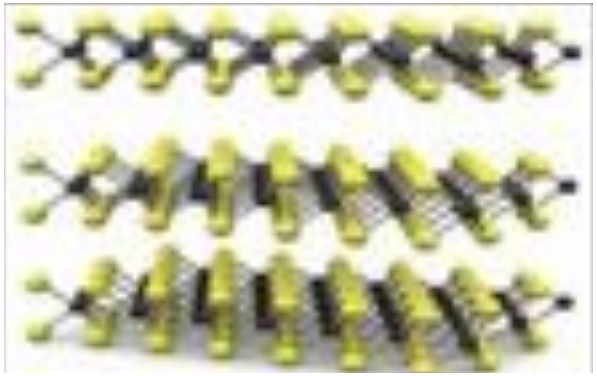


TI Research Area



Testing Topological Superconductivity

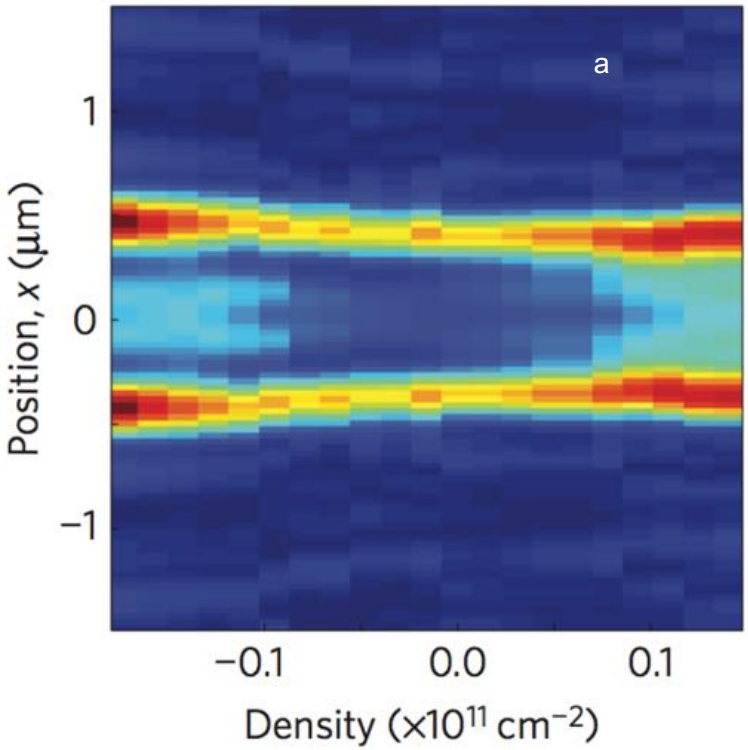
vdW Materials Research Area

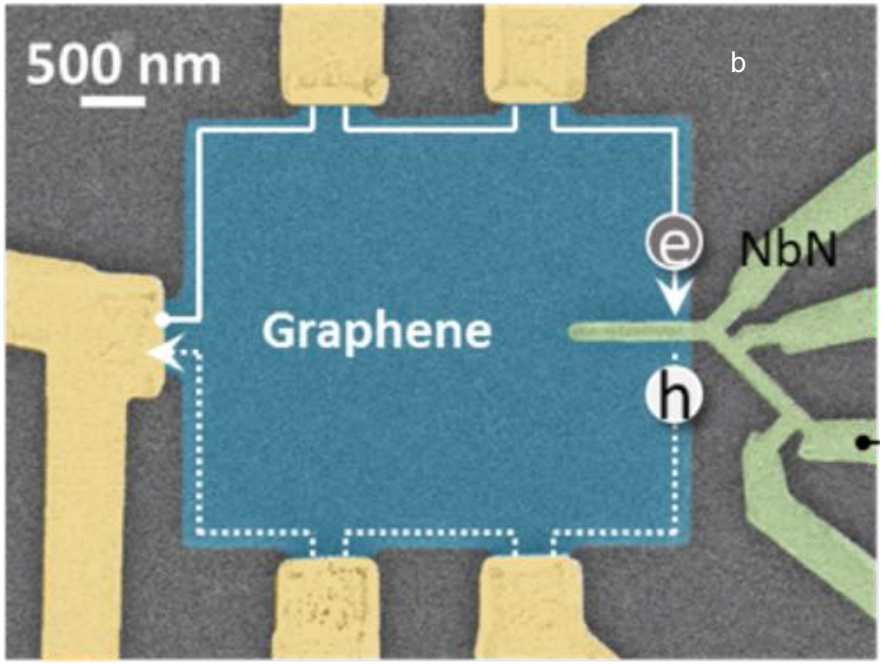


Building blocks: Synthesis and characterization

Coherent Edge States in Graphene

Kim & Yacoby, Research Areas 1 & 3

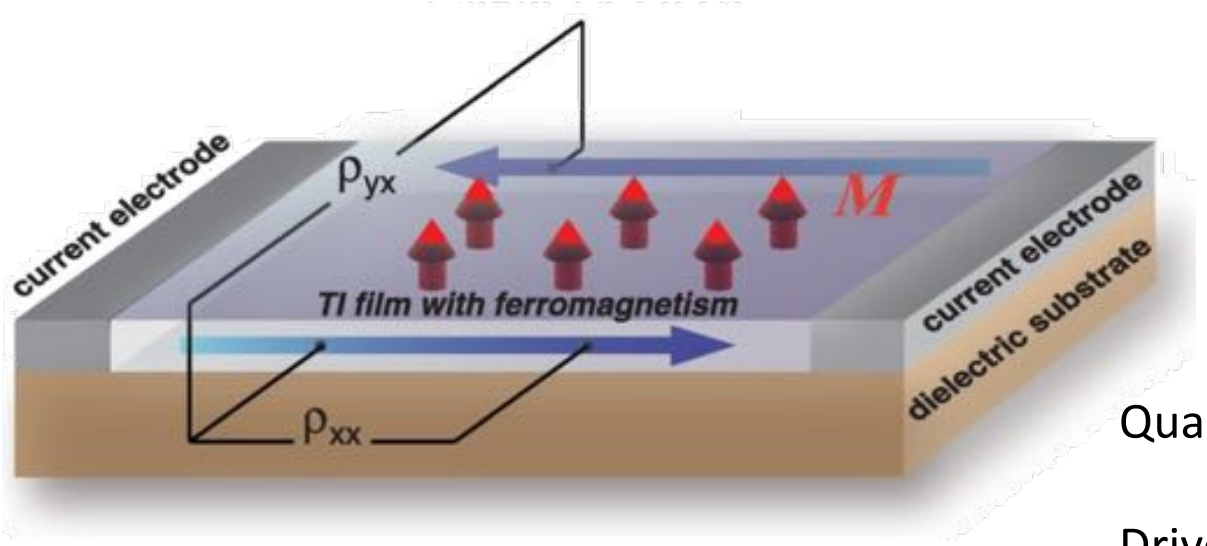




(a) Current positions *vs*. electron density, from superconducting interferometry in a graphene Josephson junction. [Allen ... Jarillo-Herrero, Levitov, Yacoby, Nature Phys (2016)]

(b) Graphene device with a narrow superconducting contact that transmits correlated eh pairs *via* crossed Andreev reflection. [Lee ... Yacoby, Kim Nature Physics (2017)]

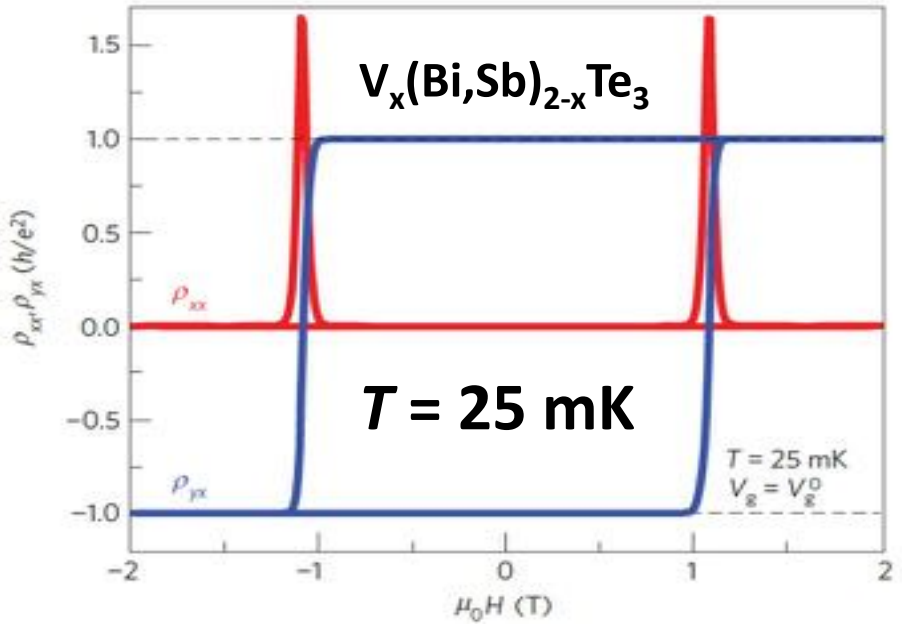
Quantum Anomalous Hall Effect

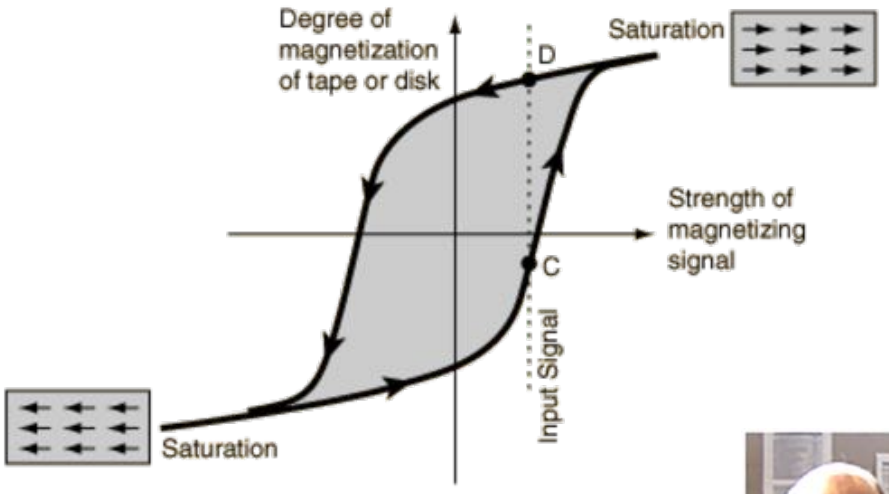


Improved QAH phase from original report by Chang, Xue et al (2013)

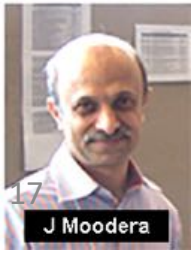
Quantum Hall Effect at Zero Magnetic Field

Driven by Ferromagnetism

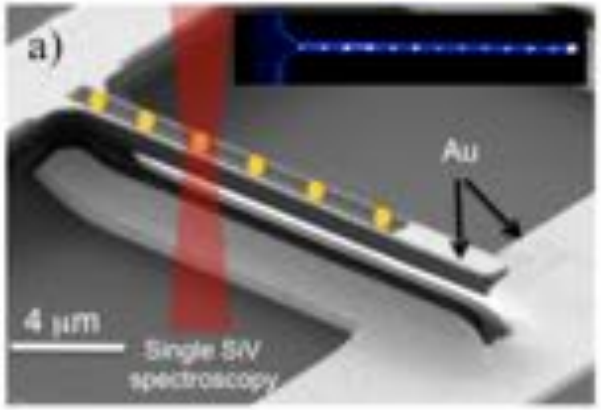


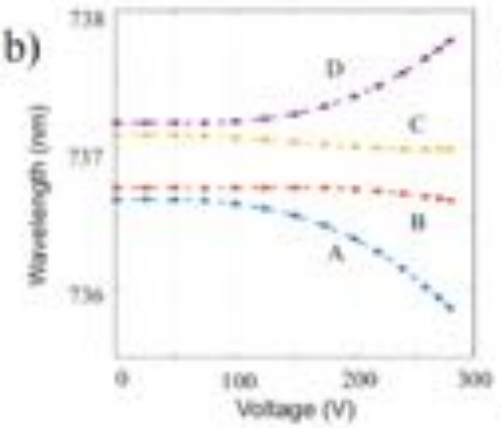


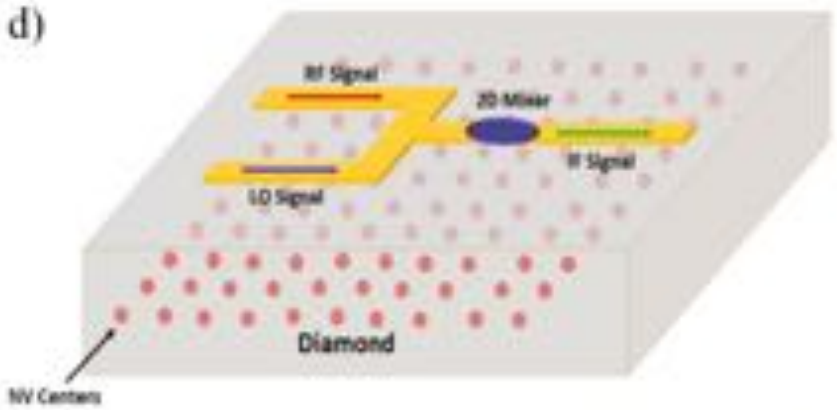
Chang, Moodera, et al, Nat Mat (2015)

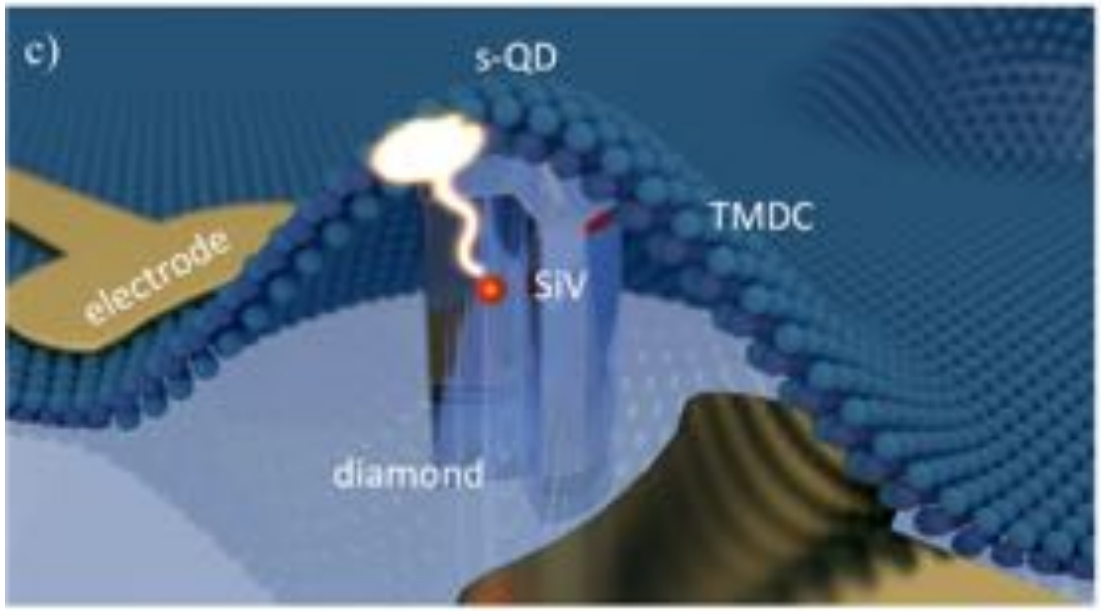


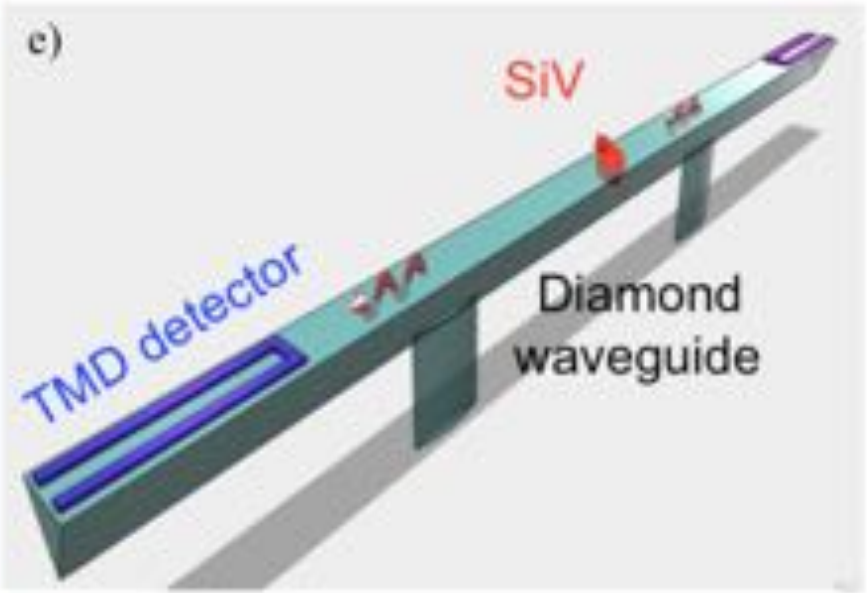
Research Area 4: Quantum Networks with Solid State Quantum Emitters led by Marko Loncar



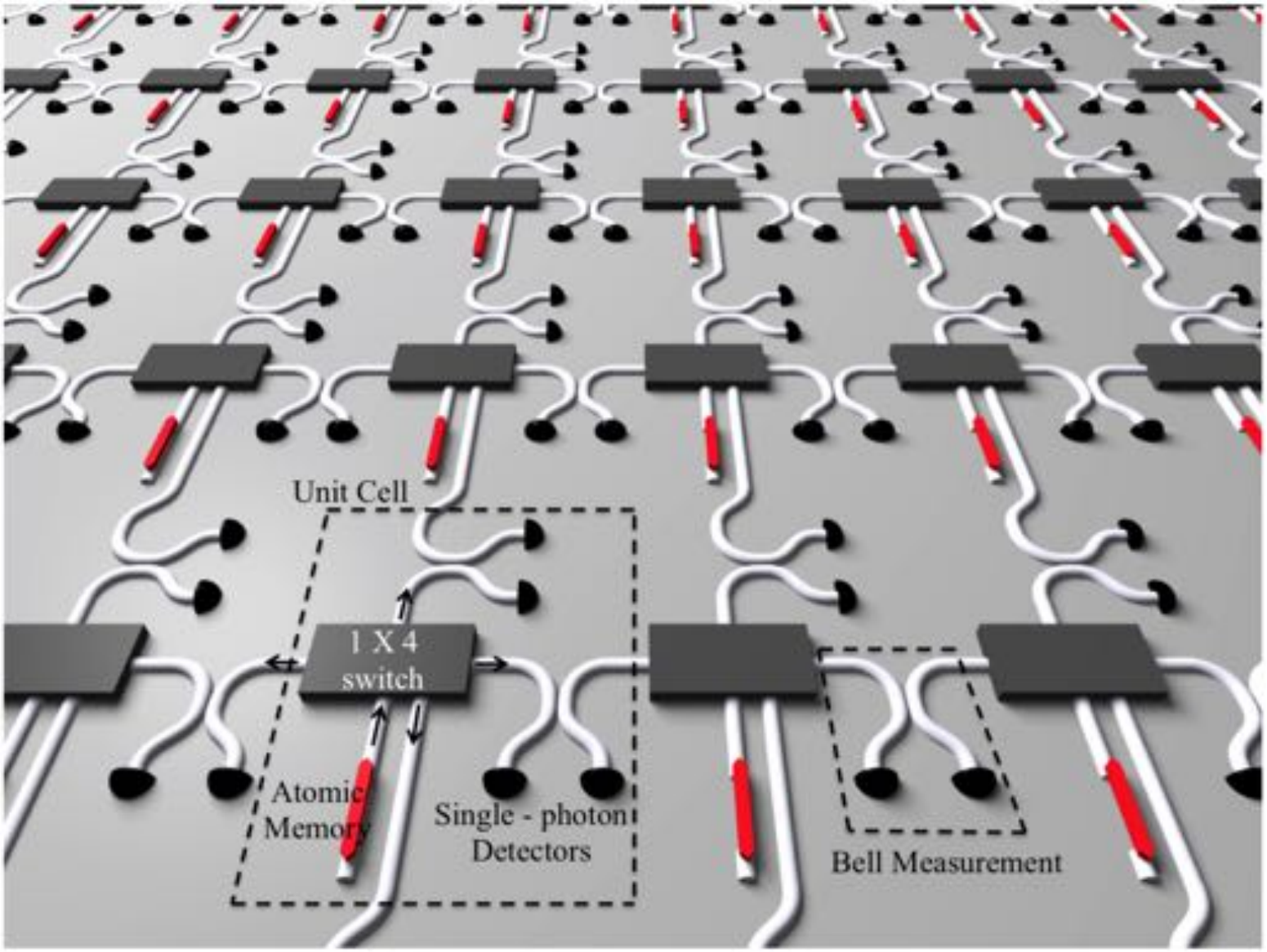








Quantum Networks with Solid State Quantum Emitters – Marko Loncar

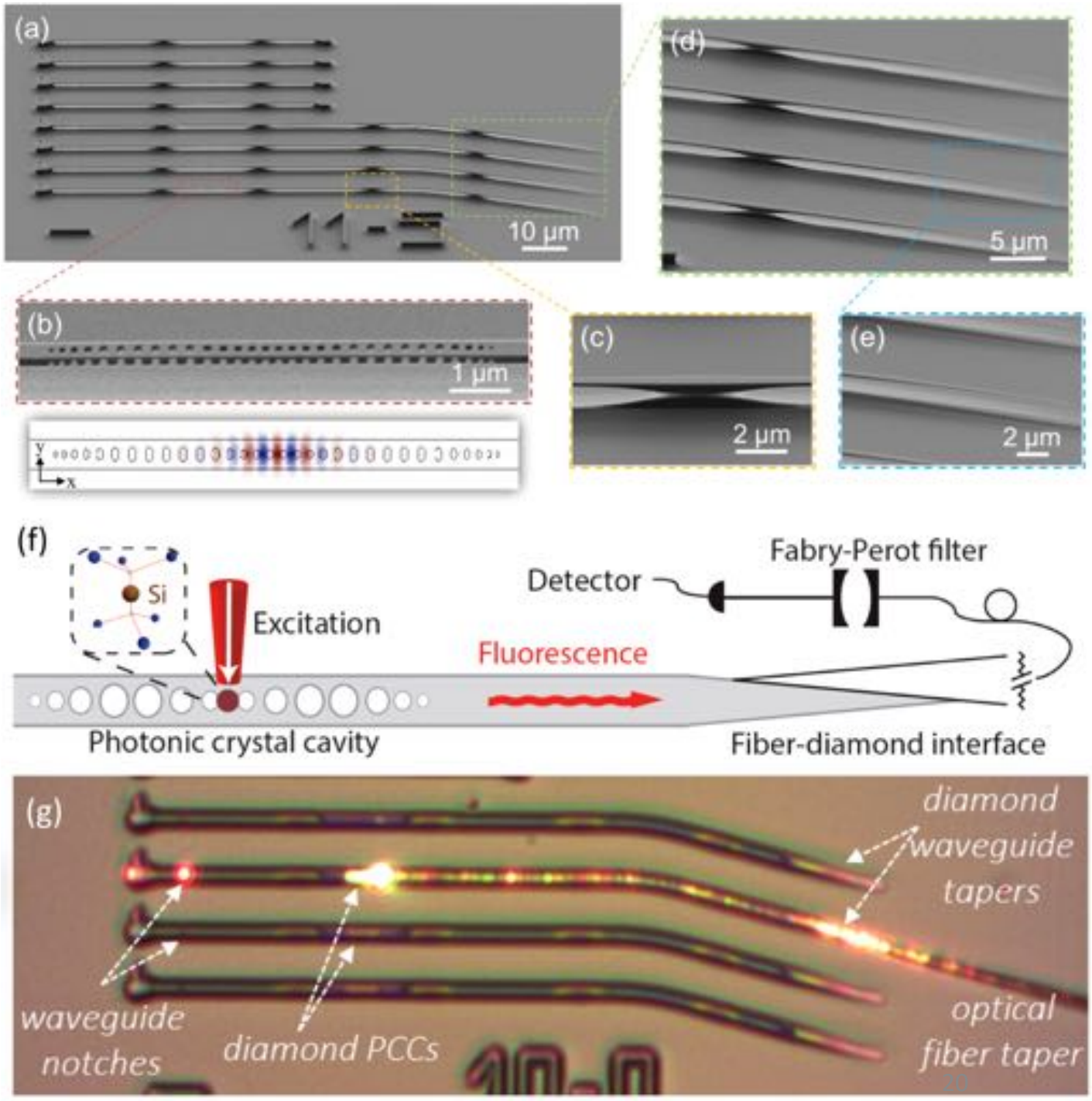


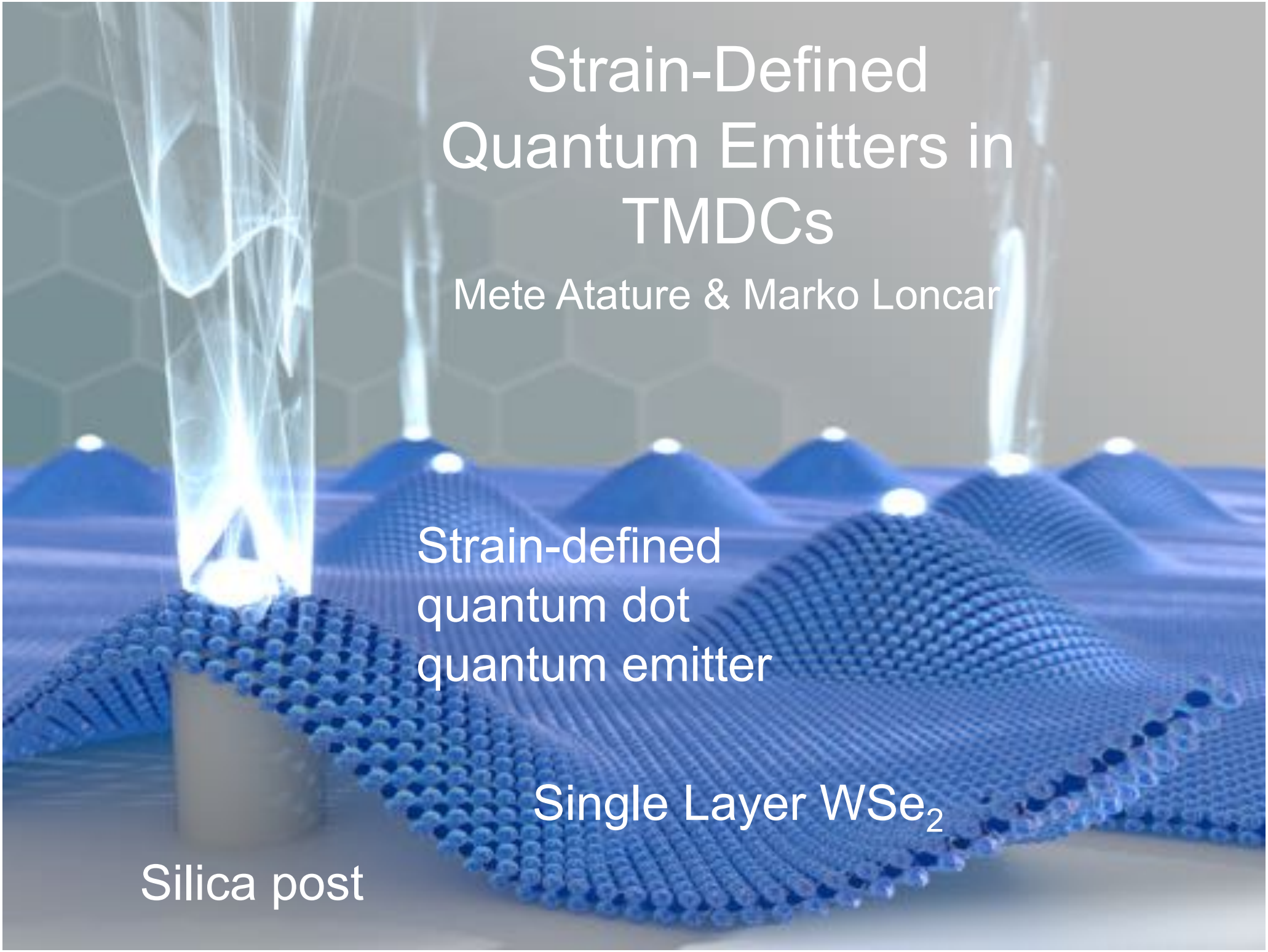
Blueprint: M. Pant, H. Choi, et al, arXiv:1704.07292 (2017)
Hybrid integration: S. Mouradian, T. Schröder et al. Phys. Rev. X (2015)

On-chip Diamond Nanophotonic Network

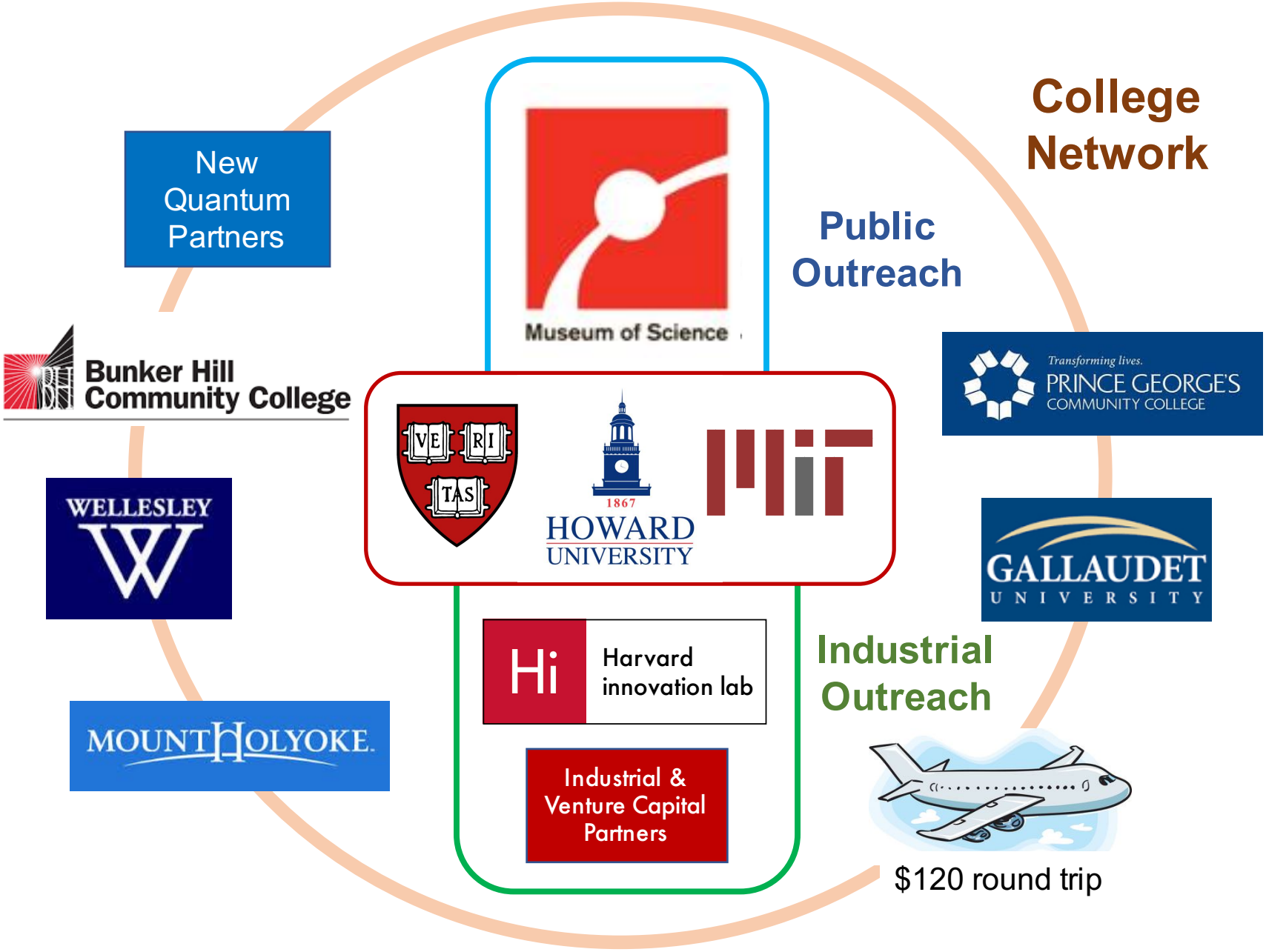
Lukin & Loncar

SEM images: (a) resonator array with key parts (b) diamond nanobeam photonic cavities with SiV color centers (c) waveguide support (d, e) diamond tapers for >98% fiber-coupling. (f) SiV fluorescence in the diamond waveguide is collected by optical fiber. (g) Optical fiber taper in contact with a diamond waveguide taper. [Burek ... Nature Comm. (2014)]




Strain-Defined
Quantum Emitters in
TMDCs
Mete Atature & Marko Loncar
Strain-defined
quantum dot
quantum emitter
Single Layer WSe_2
Silica post

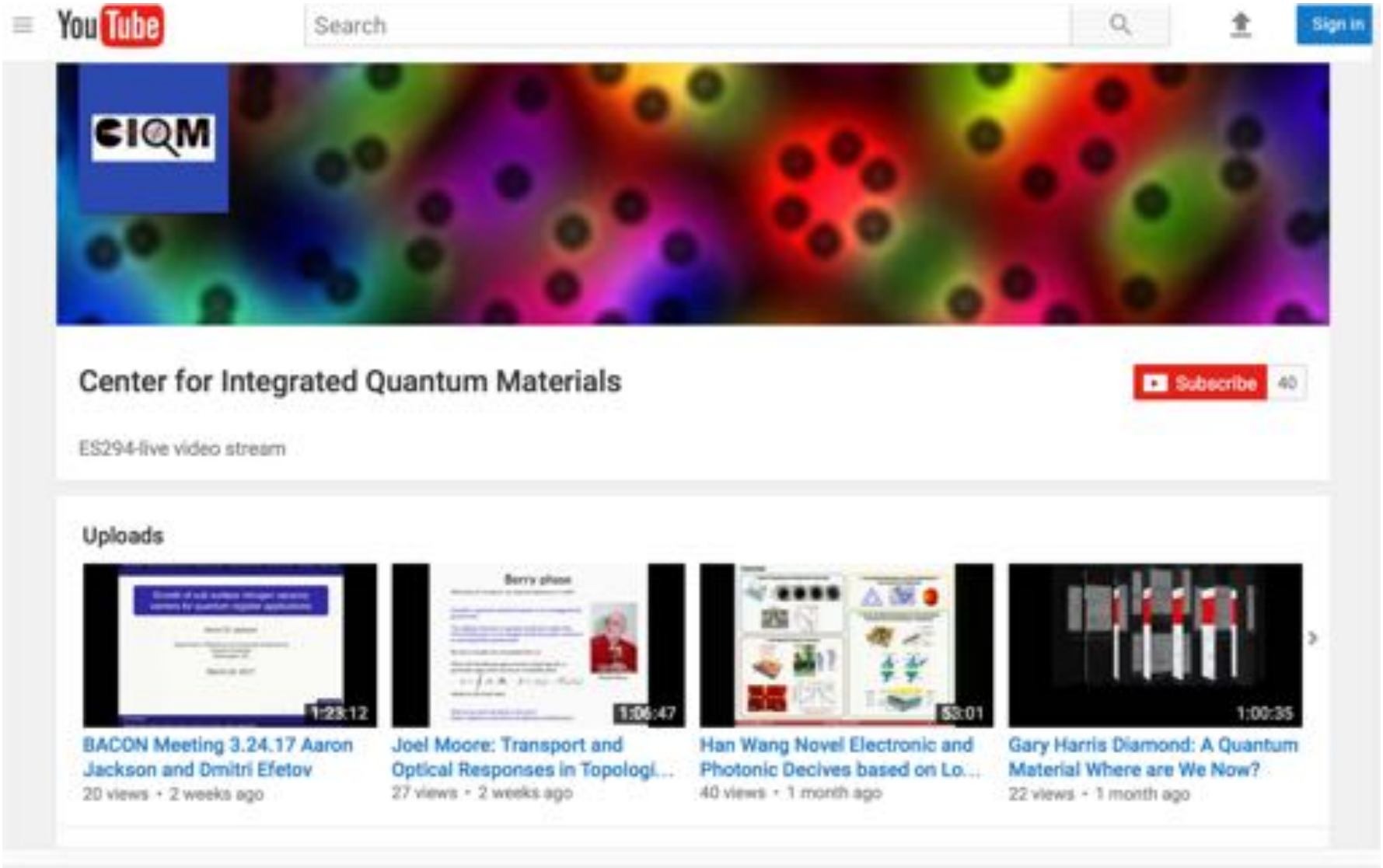
Science & Education Community



NanoDays 2017

Pablo Jarillo-Herrero (MIT)
"Welcome to Flatland! 2-D Materials in the Quantum Age"

CIQM YouTube Channel



College Network Activities

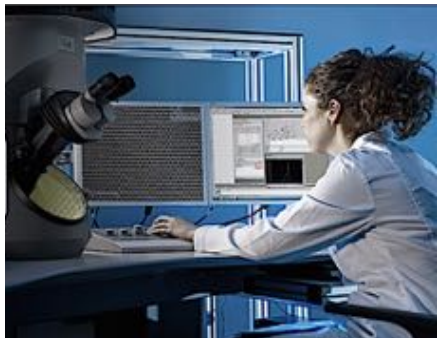
DHH Gallaudet students **Mandy Houghton** and **Brandt Marceaux** visit **Horace Mann School for the Deaf and Hard of Hearing** to talk about their summer internships in quantum materials with **Evelyn Hu**.

Science demonstrator Daniel Rosenberg and **Horace Mann students** make liquid nitrogen ice cream at Harvard.

Success Stories in Technology Transfer

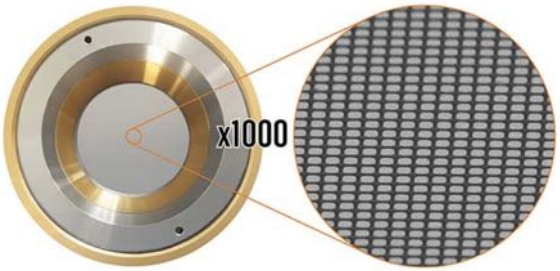
Graphenea

Graphene applications
Jesus De la Fuente (CEO Graphenea)
Tomas Palacios (MIT)



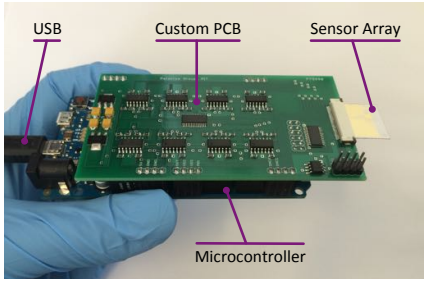
elementsix

Sculpted diamond
Daniel Twitchen (Element Six)
Marko Loncar (Harvard)



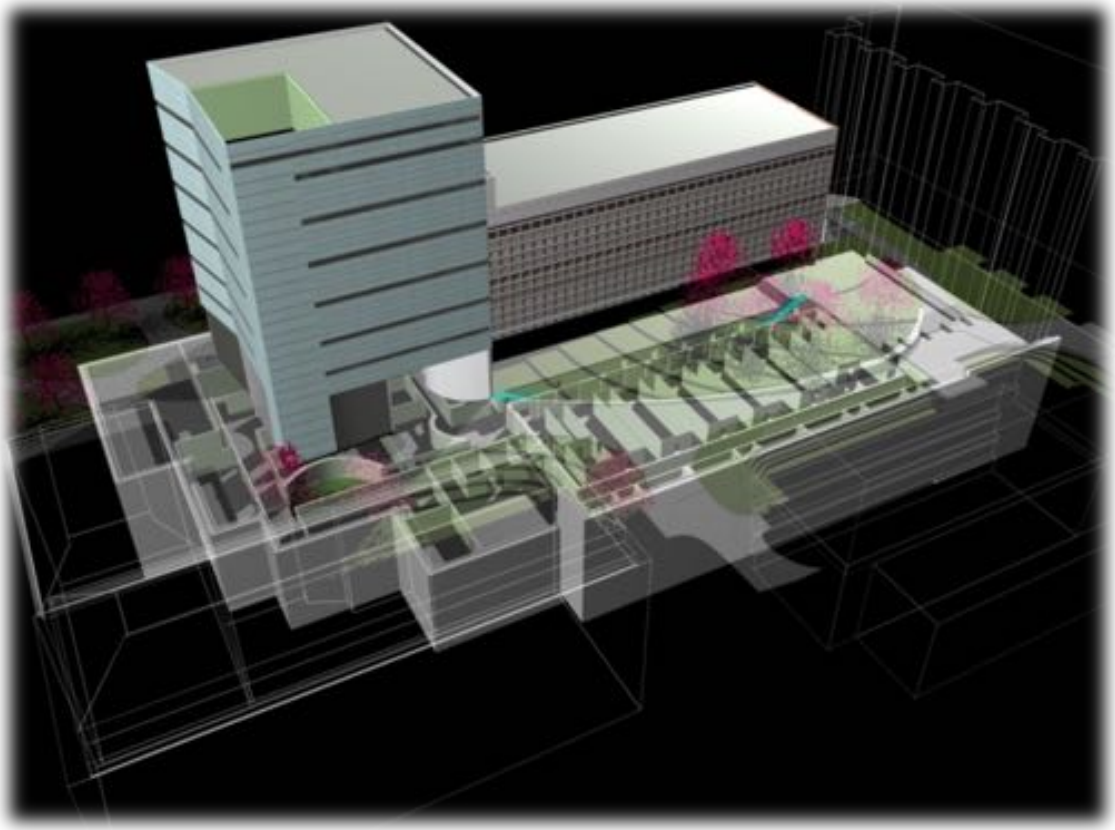
NGX technologies

Charles Mackin (NGX)
Tomas Palacios (MIT)



NSF CIQM

Epicenter for Nanoresearch at Harvard:
CENTER FOR NANOSCALE SYSTEMS



Robert Westervelt
Director

William L. Wilson
Executive Director

Thank you!