2018 NSF/DOE/AFOSR Quantum Science Summer School
June 22, 2018

QS^3 2018 School Summary

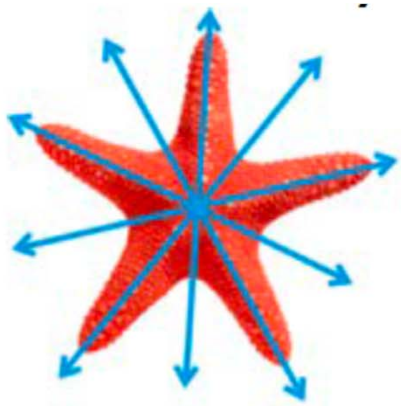
Kyle Shen (Cornell)

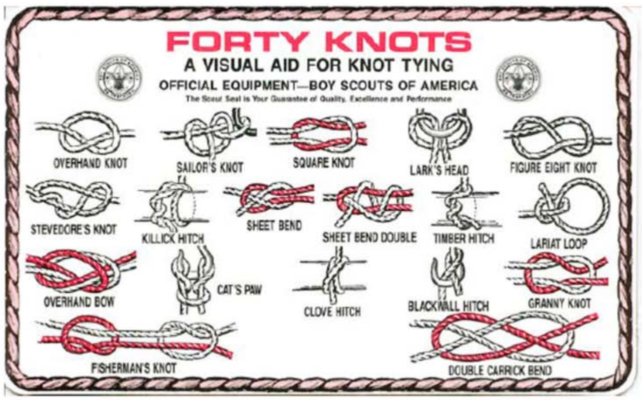
Some Thank yous!

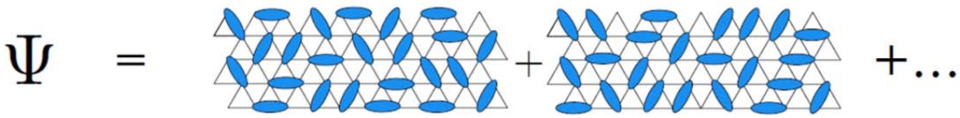
- **A Big Thanks to Caroline Brockner!!!**
- Also to our fantastic speakers!
- Kavli Institute @ Cornell & David Muller for weekend outing
- NSF, DOE, AFOSR

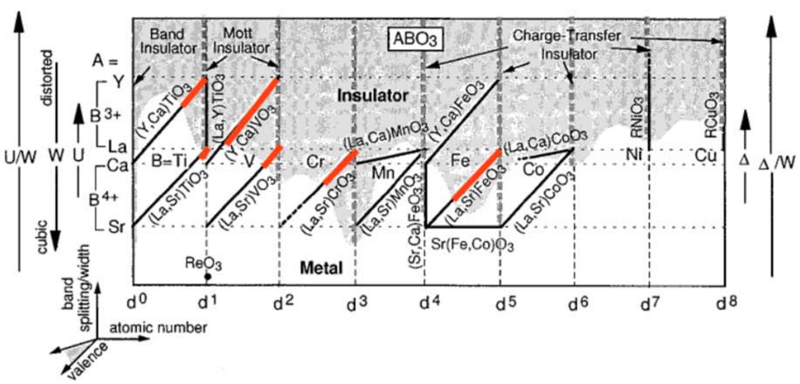
Balents: Overview of Quantum Materials

- Order
- Topology
- Entanglement
- Correlations









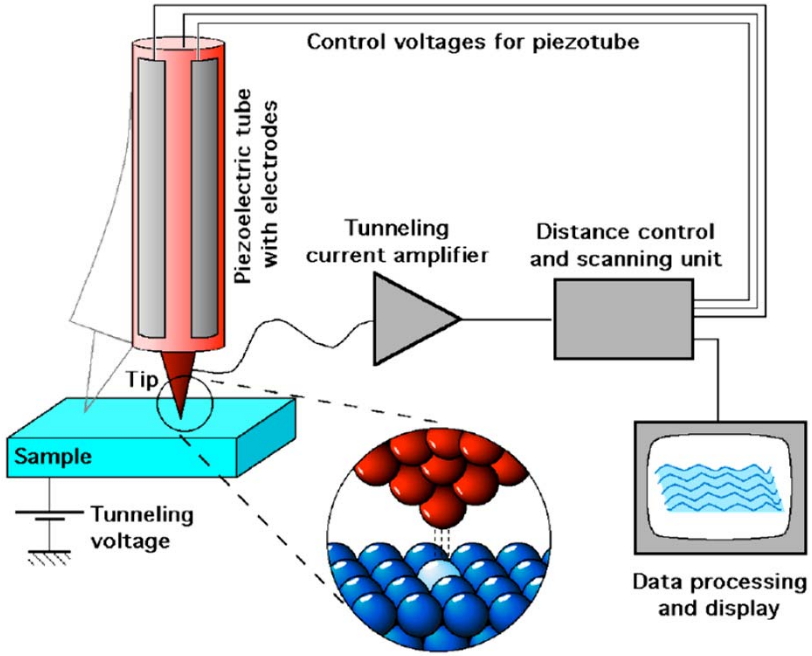
Giustino: Density Functional Theory

$$\left[-\sum_i \frac{\nabla_i^2}{2} + \sum_i V_{\mathrm{n}}(\mathbf{r}_i) + \frac{1}{2}\sum_{i\neq j}\frac{1}{|\mathbf{r}_i - \mathbf{r}_j|}\right]\Psi = E\,\Psi$$

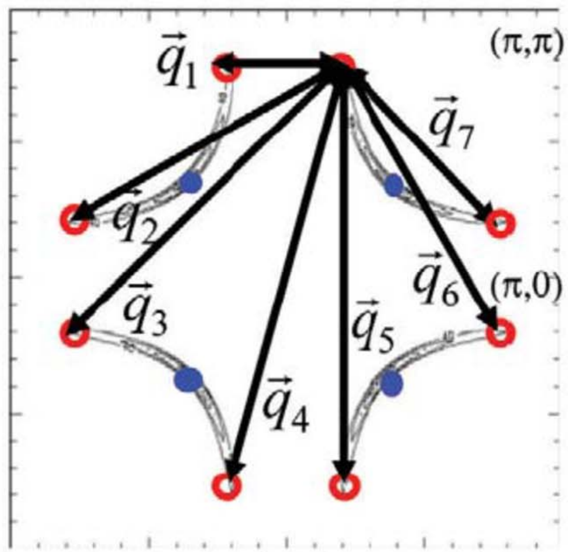
Electronic structure theory in a nutshell

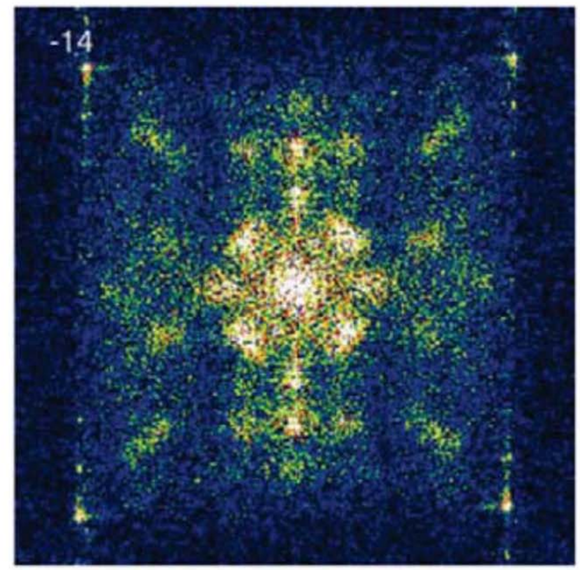
Powerful technique, very broadly applied, has shortcomings, continuously being improved

Davis: STM of Quantum Materials



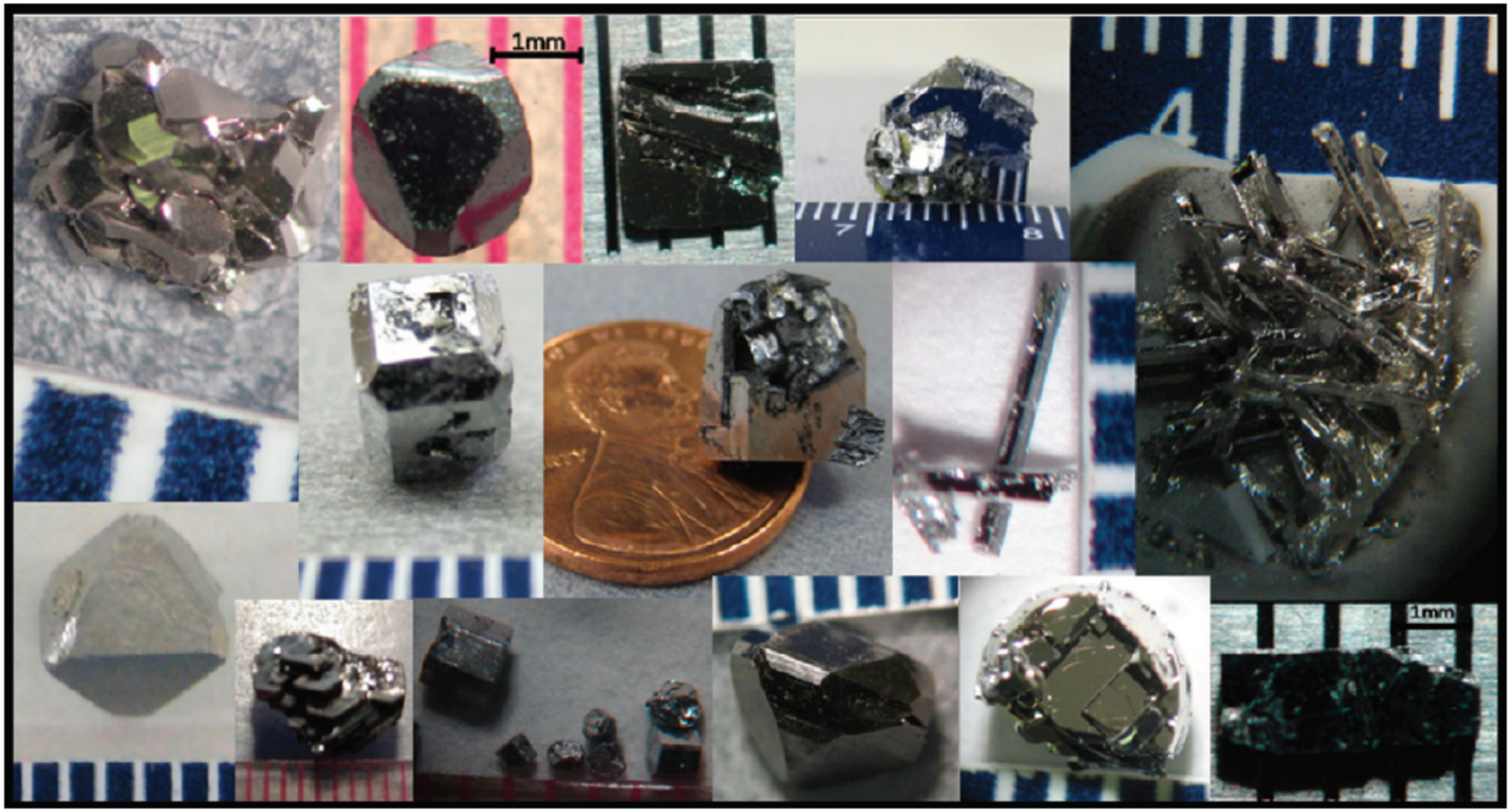
Stephen Edkins PhD Thesis





Topography, local density of states, quasi-particle interference

Chan: Bulk Synthesis of Quantum Materials

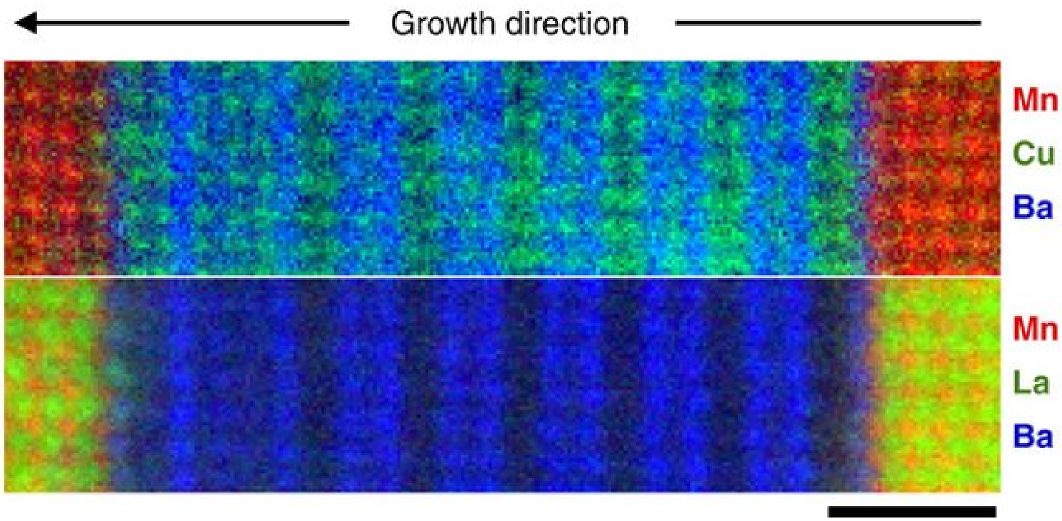


Many different methods

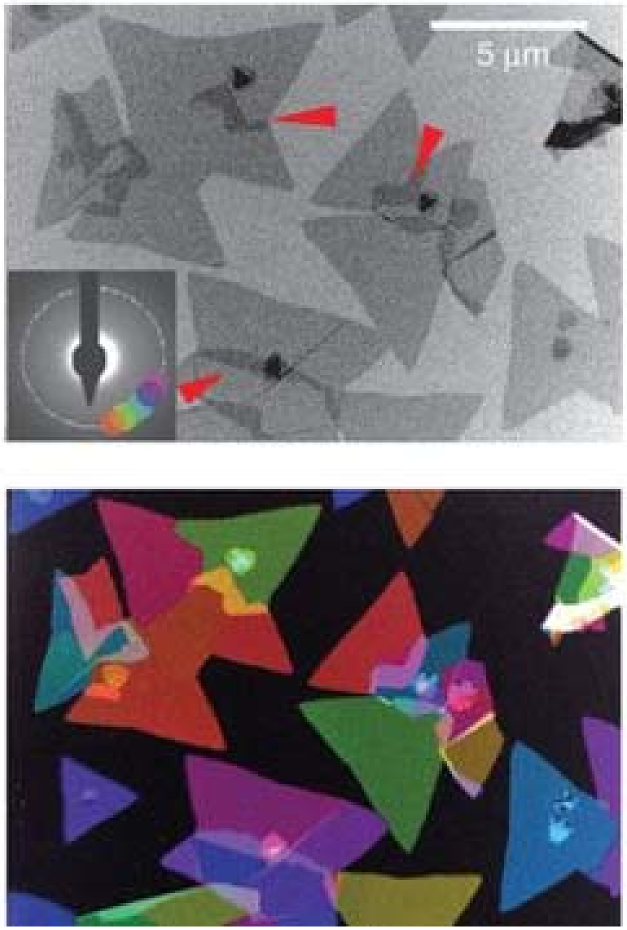
Relies on experience and materials knowledge

Phelan, W.A.; Menard, M.C.; Kangas, M.J.; McCandless, G.T.; Drake, B.; Chan, J.Y. "Adventures in Crystal Growth: Synthesis and Characterization of Single Crystals of Complex Intermetallic Compounds" Chem. Mater., 2012, 24, 409 – 420.

Muller: Electron Microscopy of Quantum Materials



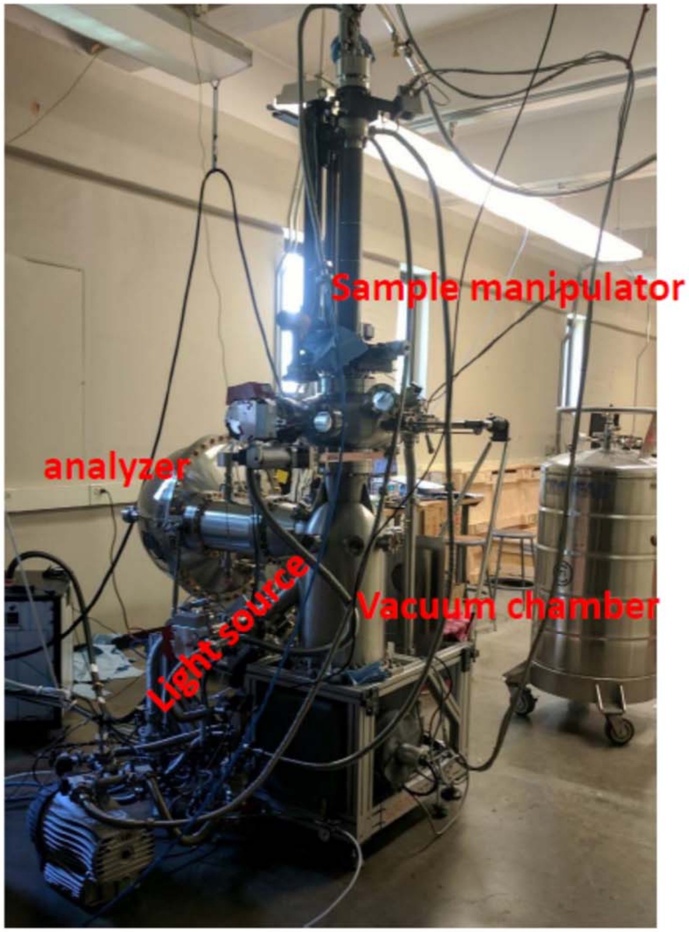
Chien *et al*., Nat Comm 4, 2336 (2013)



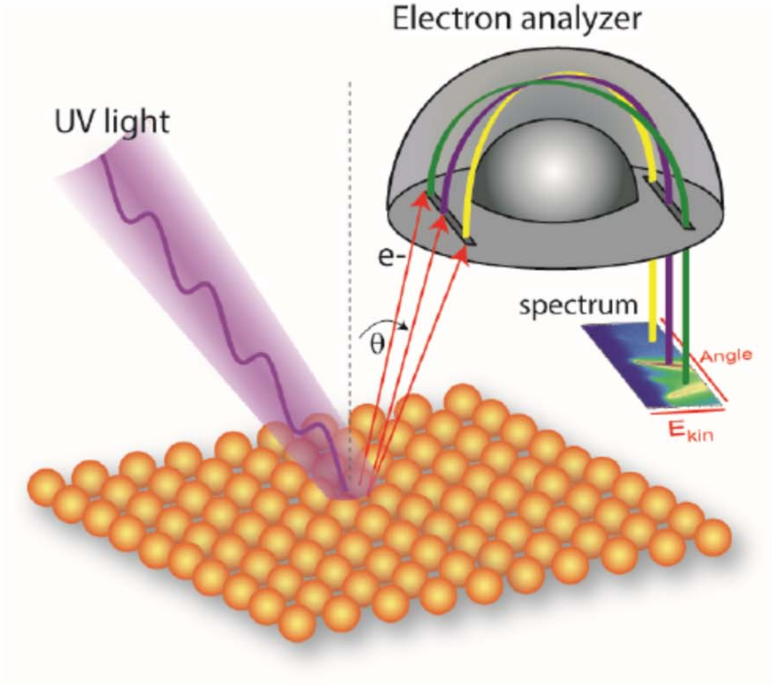
Van der Zande *et al*., Nat Mat 12, 554 (2013)

Can probe structure, composition, magnetic order, and more!

Vishik: ARPES of Quantum Materials



Important tool for electronic band structure

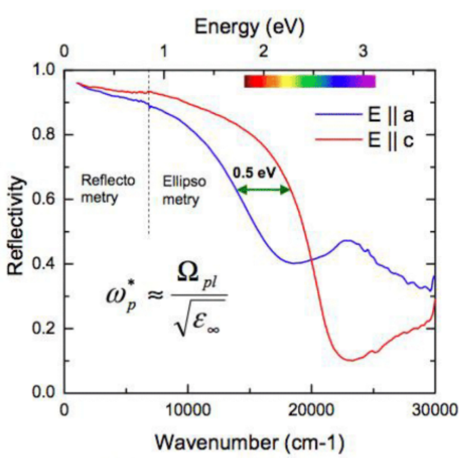


Armitage: Optical & THz spectroscopy of Quantum Materials

A tool to study electrodynamic properties of conducting electrons

Plasma frequency, scattering rate, effective mass of charge carriers for free or weakly interacting electron gas in metals

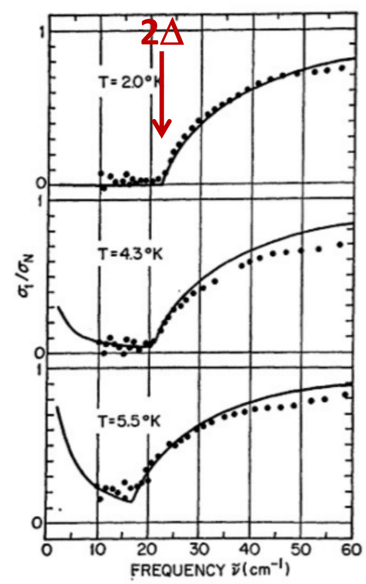
The two colors of MgB_2



Guritanu *et al.* PRB **73**, 104509 (2006)

Size of superconducting gap

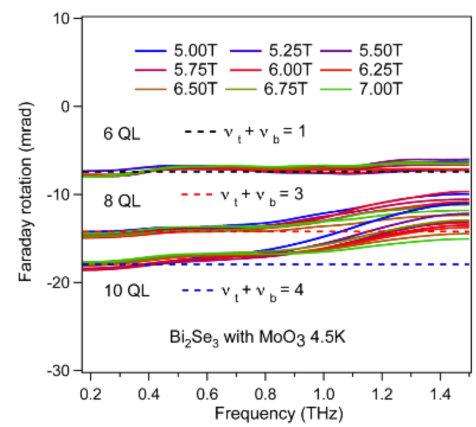
Pb, thin films



Topological properties

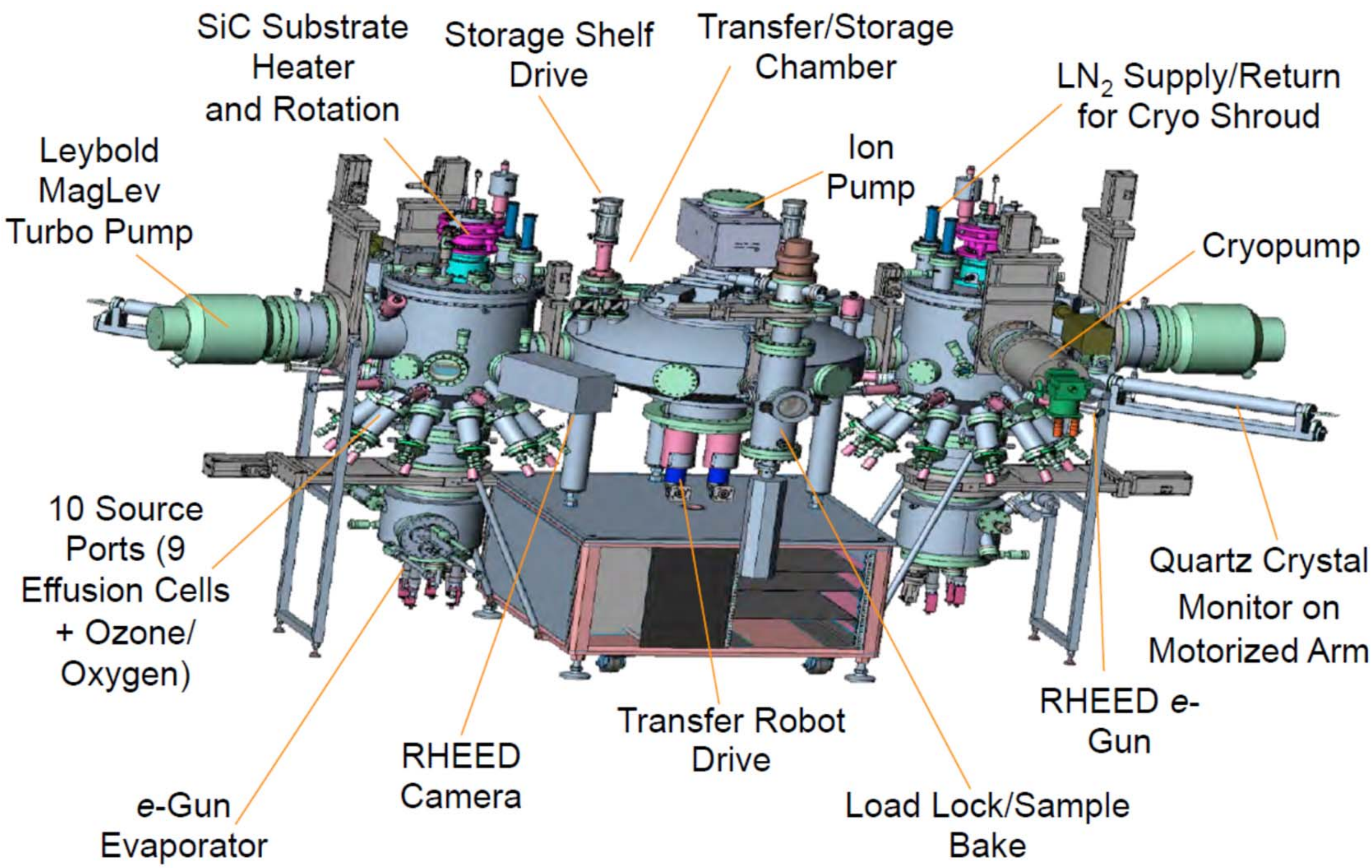
Quantized Faraday rotation

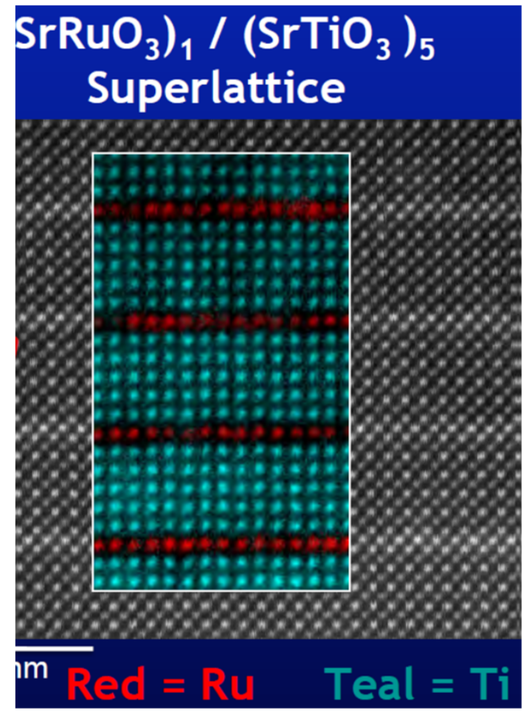
topological insulator Bi2Se3 films



$$\tan(\phi_F) = \frac{2\alpha}{1+n}(N_t + \frac{1}{2} + N_b + \frac{1}{2}),$$

Schlom: Molecular Beam Epitaxy of Quantum Materials



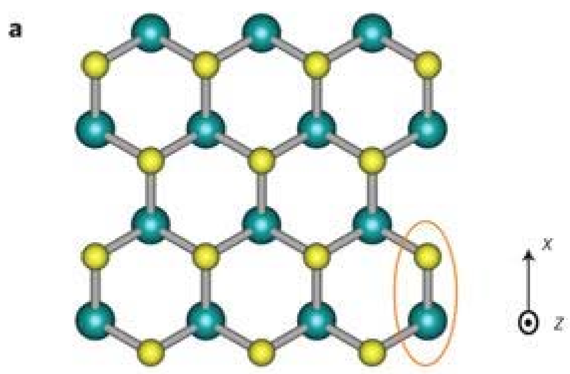


Equipment Intensive, material exquisite control

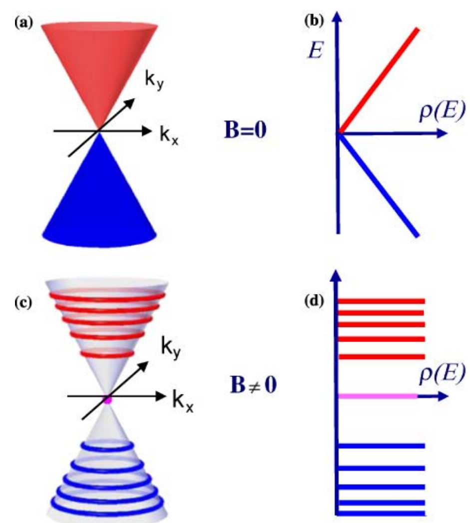
Shan: Two-Dimensional Quantum Materials

Single layer materials:
graphene, MoS_2 , WS_2, etc

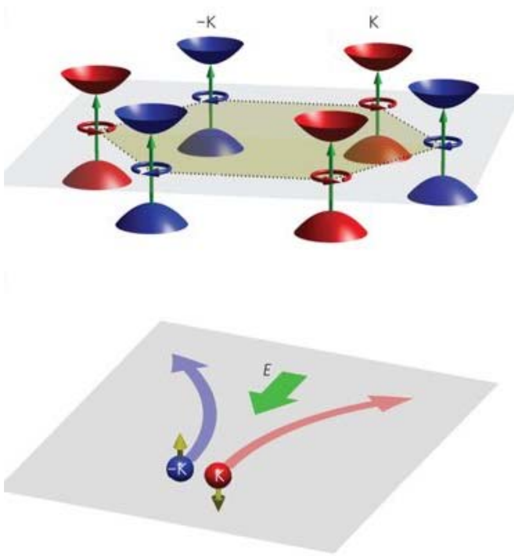
quantum confinement effects
due to a single layer



Measurements of Berry phase
in graphene



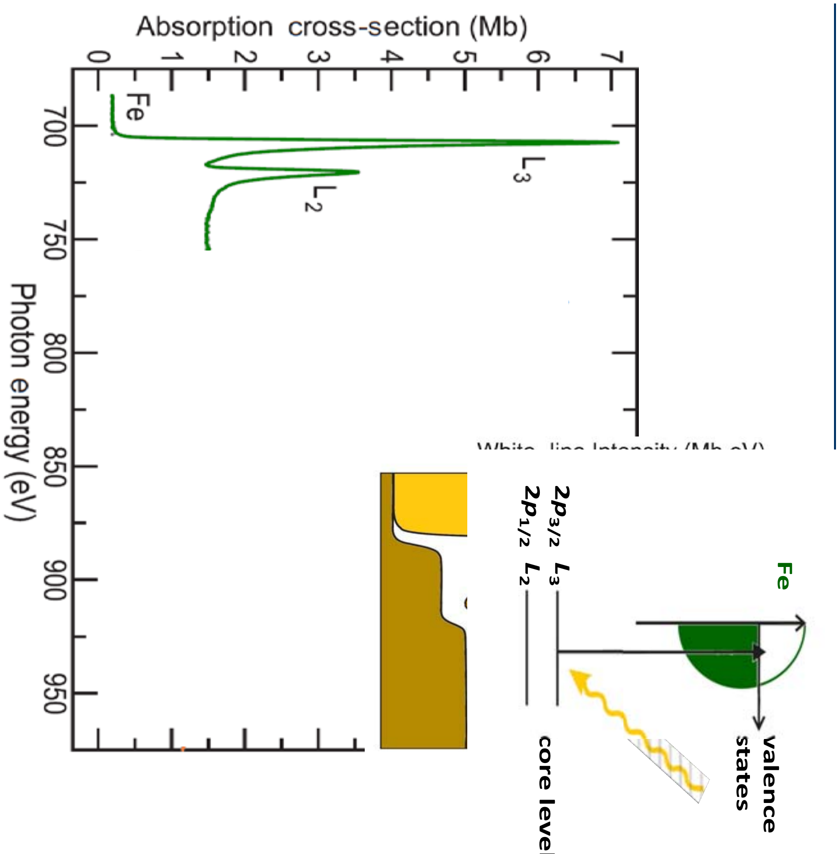
Valley hall effect



N2

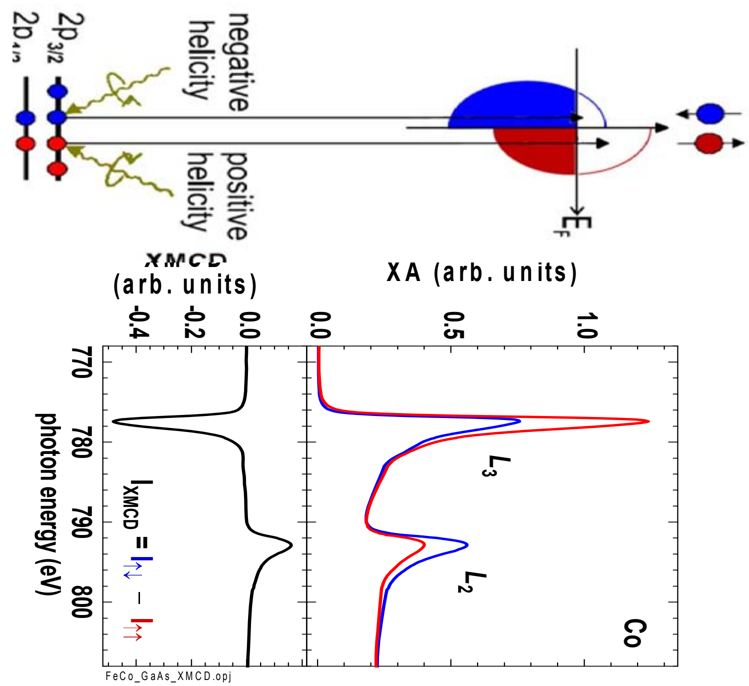
Ruff: X-Ray Scattering on Quantum Materials

X-ray absorption: “White line”



Credit: Elke Arenholz, LBNL

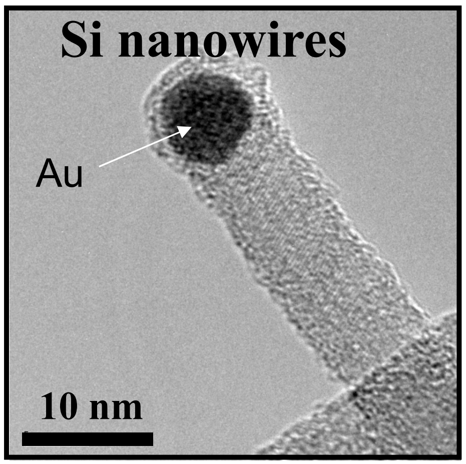
Probing magnetism with x-ray magnetic circular dichroism (XMCD)

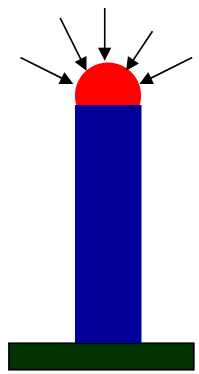


Elastic scattering, absorption and emission spectroscopy
resonance elastic scattering, resonant inelastic scattering,
x-ray magnetic circular dichroism

Cha: Nanoscale Quantum Materials

Vapor-Liquid-solid growth of nanowires

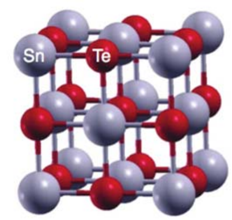


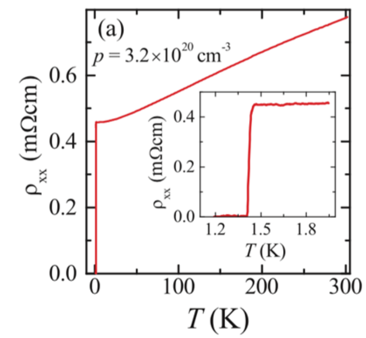


Growth

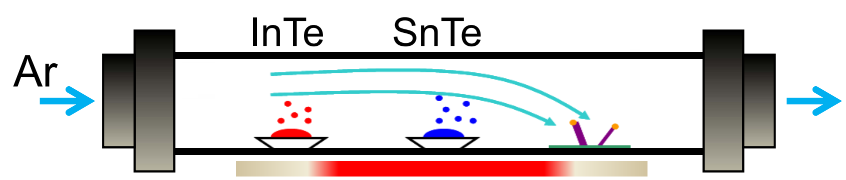
Cui and Lieber, *App. Phys. Lett. 78*, Page 2214-2216 (2001).

Nanostructure approach to study topological Insulators and topological superconductors





In-doped SnTe

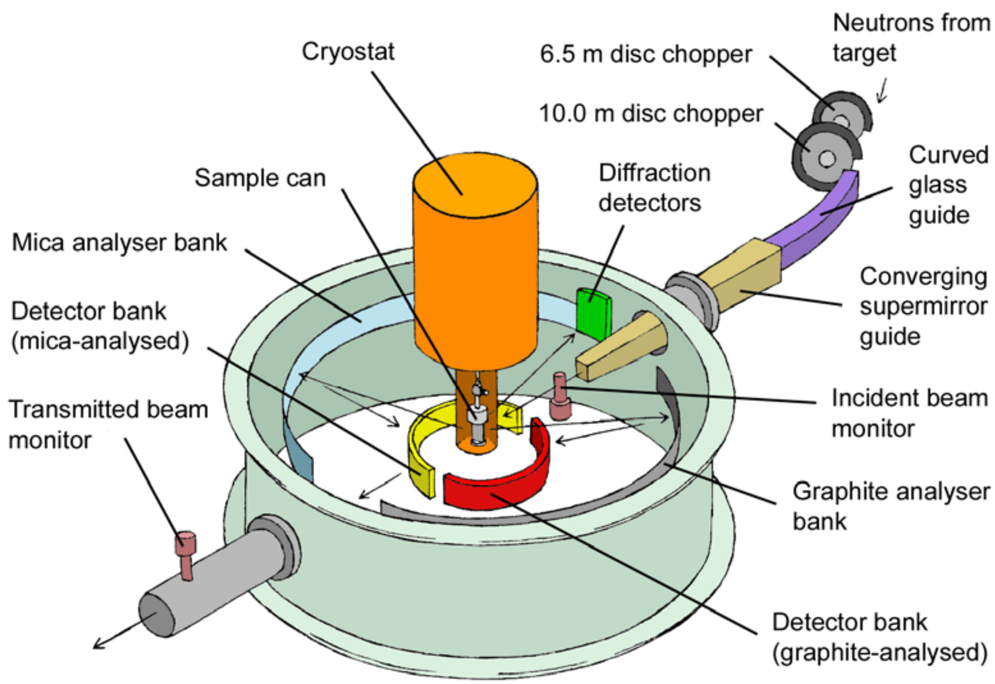


(111) In-doped SnTe Nanoplate

Nano Lett. 15 p.3827 – 3832 (2015)

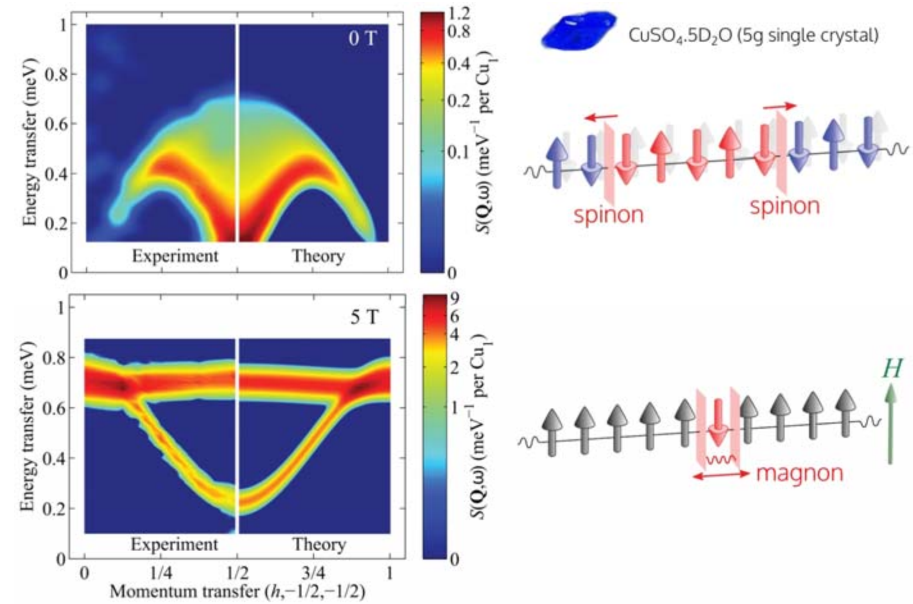
PRB 88, 140502 (2013), PRL 109, 217004 (2012), PRL 110, 206804 (2013), PRB 93, 024520 (2016), …

Tranquada: Neutron Scattering on Quantum Materials



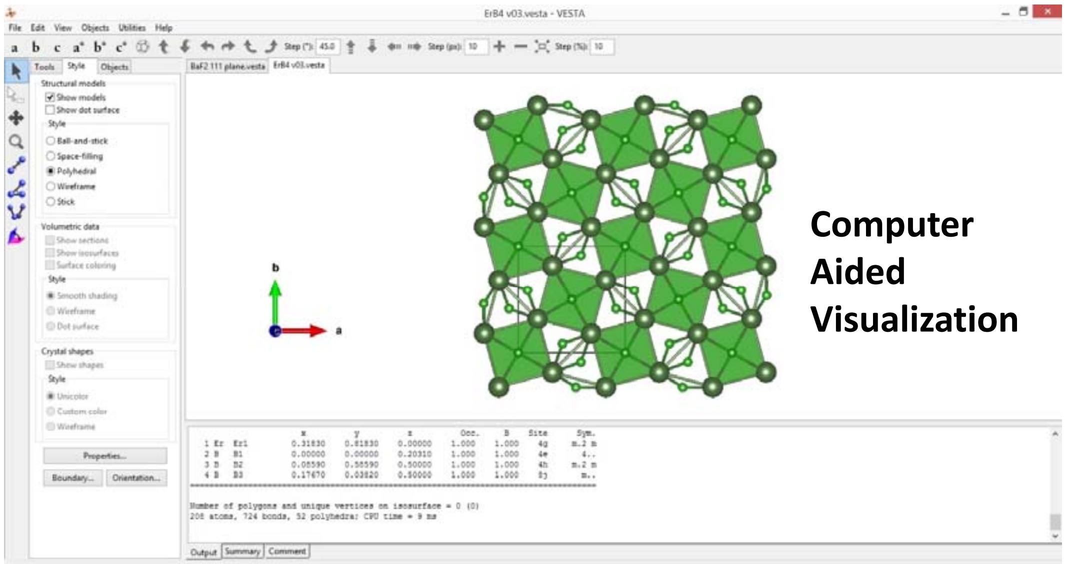
High Resolution Spectrometer at ISIS

Elastic and Inelastic scattering
Probe of structure, magnetism, and more!

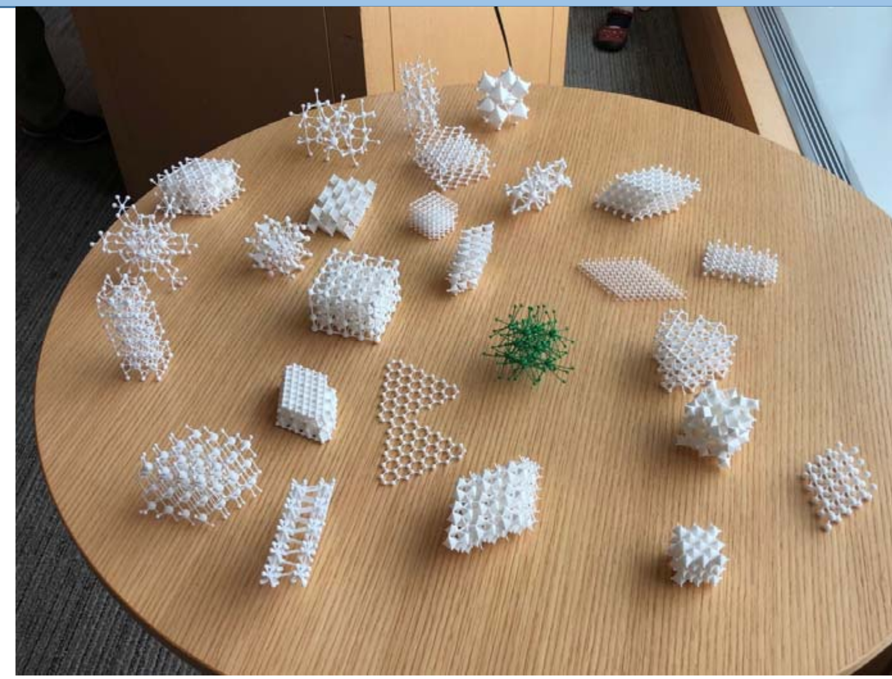


M. Mourigal *et al*., Nat Phys 9, 435 (2013)

Modeling Quantum Materials



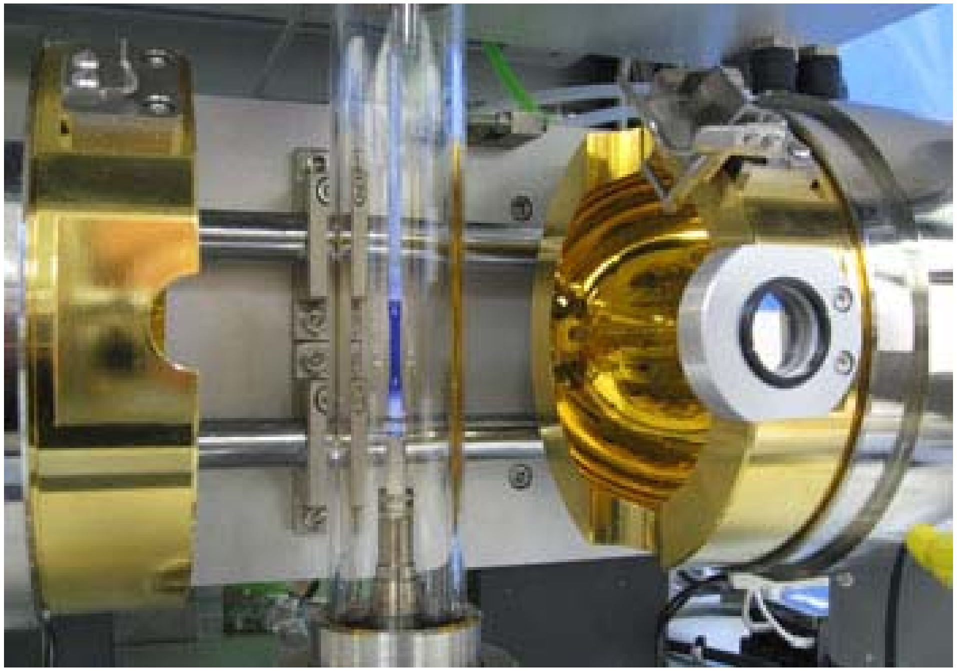
Computer Aided Visualization



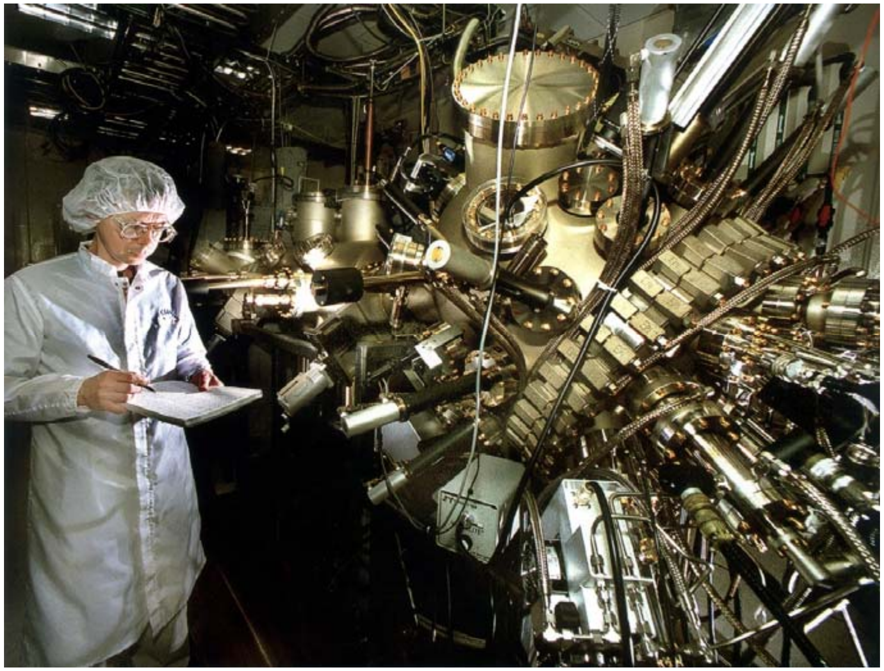
3D printing of structures

VR modeling

Synthesis Methods

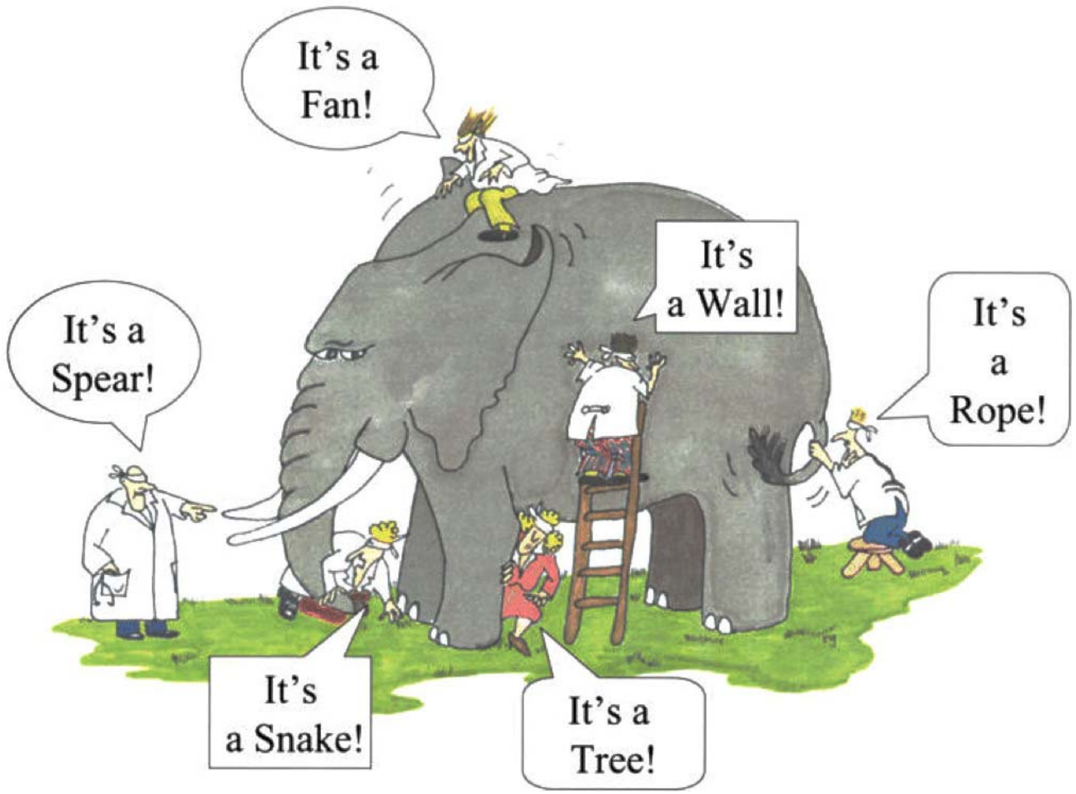


Bulk Growth



Thin Film Growth

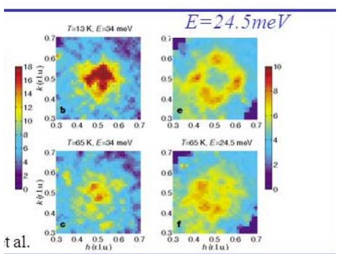
Characterization Methods



Characterization Methods

Spectroscopic bulk methods

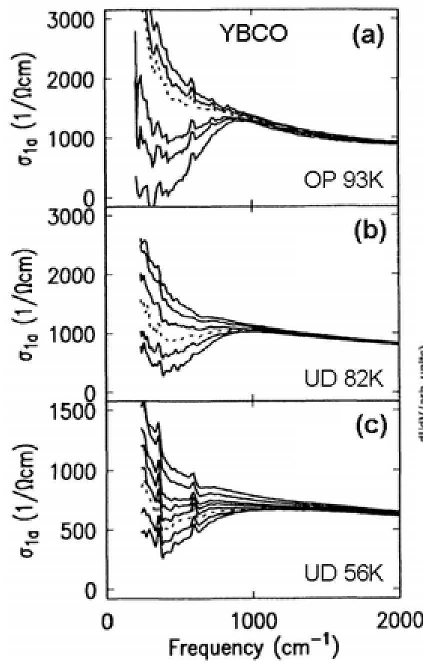
Optical/IR spectroscopy
Neutron scattering
X-ray scattering
EELS (to some extend)
ARPES (to some extend)



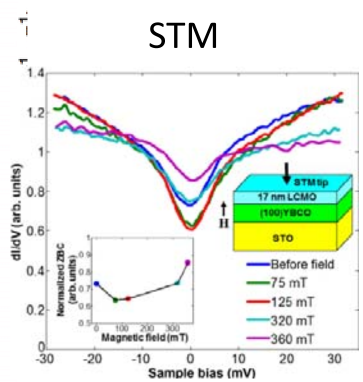
Dynamic stripes in YBCO by neutron scattering

Superconducting gap in YBCO

Optical spectroscopy

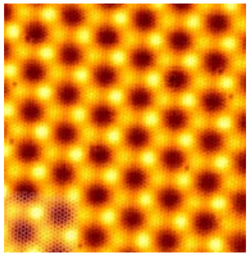


STM

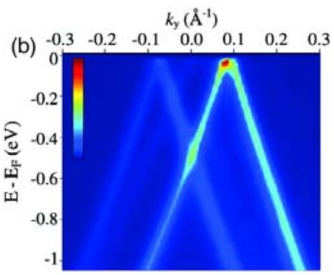


Surface methods

STM
STEM
ARPES

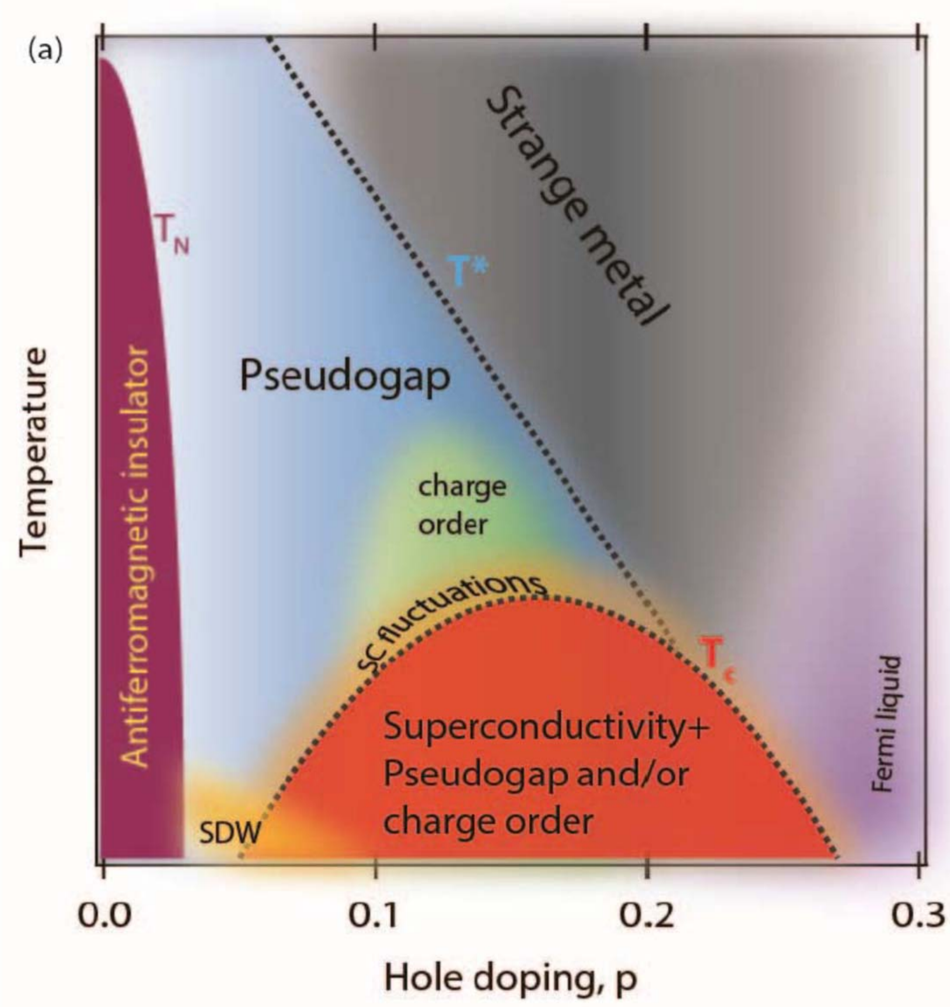


STM image of graphene



ARPES of graphene

High Temperature Superconductors

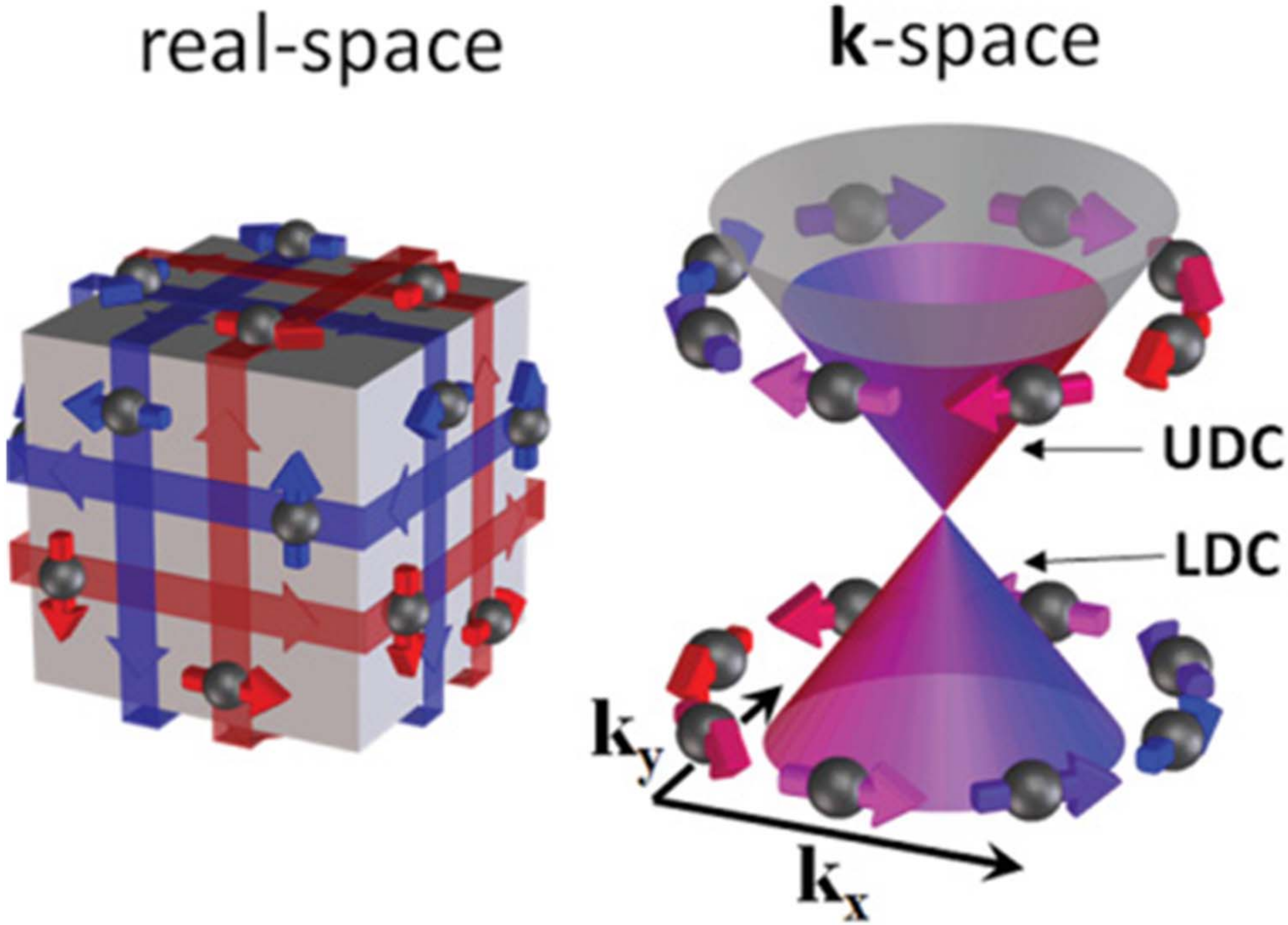


Continues to be one of the most important problems in quantum materials

Pathways to higher T_C?

Vishik, ROPP 81, 062501 (2018)

Topological Materials



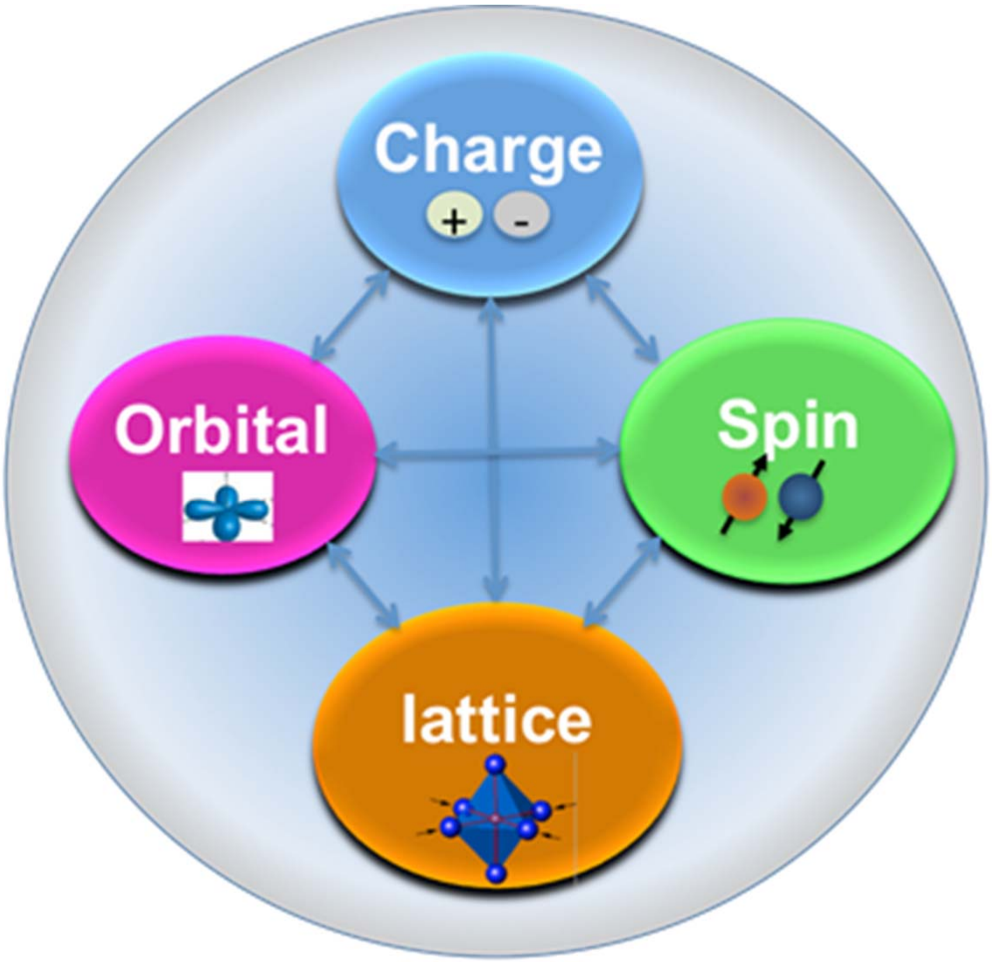
Protected
Boundary modes

New class of materials (10 years old) overlooked in band theory

Useful?

Lanzara Group

Correlated Materials



Coupling of multiple degrees of freedom

→ Emergent Behavior

→ New Phases

→ Technologically useful functionalities?

QS3 2019 : Quantum Devices

Location: Penn State
Organizers: The same
Time: **June 2019**

Please provide feedback
➔ Form sent Wednesday

Approval from NSF/DOE to have up to 1/5 returning students

➔ Please apply if interested!