Materials by Design and Condensed Matter Connections to High Energy Physics

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December 8, 2014

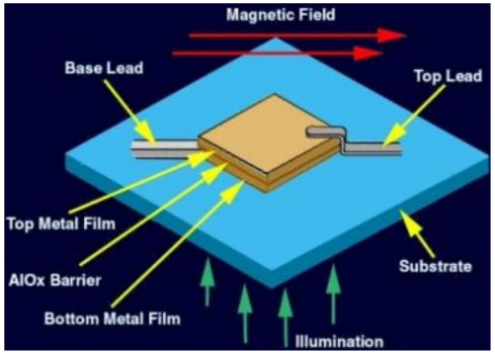
Outline

1. Low Temperature Superconducting Detectors (TES, etc.)
2. Superconducting RF Cavities, Magnets & Undulators
3. Wide Band Gap γ-ray Detectors
4. Monopoles, Anapoles, Skyrmions, Majoranas & Higgs
5. AdS/CFT and Tensor Networks

with special thanks to Val Novosad (TES), Thomas Proslier & Mike Pellin (SRF), Mercouri Kanatzidis (wide band gap), Wai Kwok & Ulrich Welp (SC wires & magnets)

Low Temperature Detectors (Joel Ullom, NIST, Aug. 2012 BES Workshop)

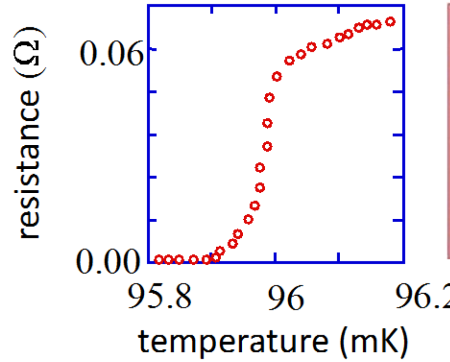
Superconducting Tunnel Junctions (STJs)

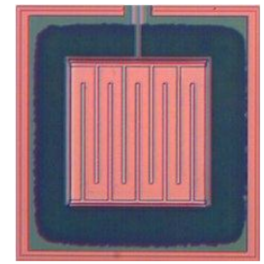


- absorption of photon breaks Cooper pairs: Δ ~ 1 meV
- junction formed from pair of superconducting electrodes separated by an insulator
- signal = electronic tunneling across junction
- ~40 pixel measurements from LLNL group, 100 pixels at AIST

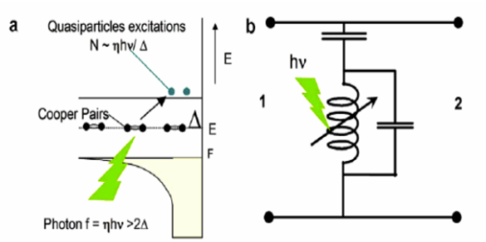
Transition Edge Sensors (TESs)

Thermal sensors





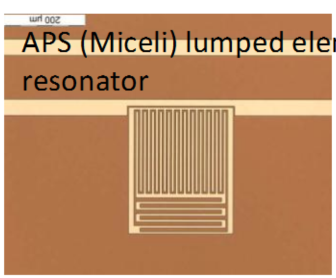
Microwave Kinetic Inductance Detectors (MKIDs)



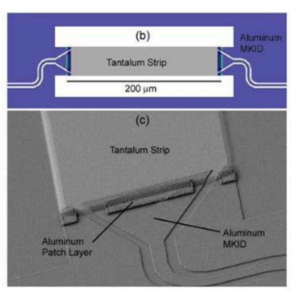
-pair breaking changes surface impedance of superconductor

-film embedded in μwave resonator

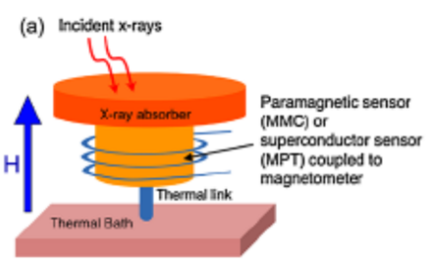
APS (Miceli) lumped element resonator

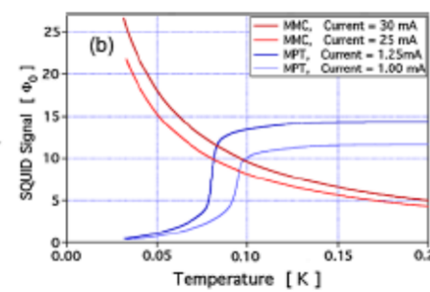


UCSB (Mazin) separate absorber



Magnetic MicroCalorimeters (MMCs)

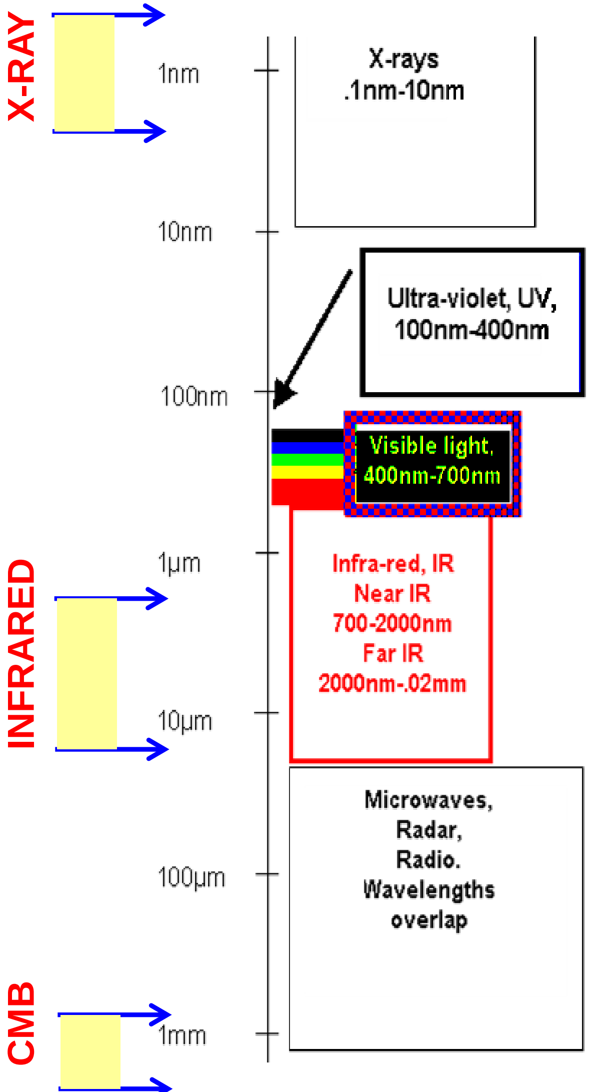




- Deposited energy changes paramagnetic or diamagnetic response
- SQUID sensor sees this as change in flux
- No Johnson noise

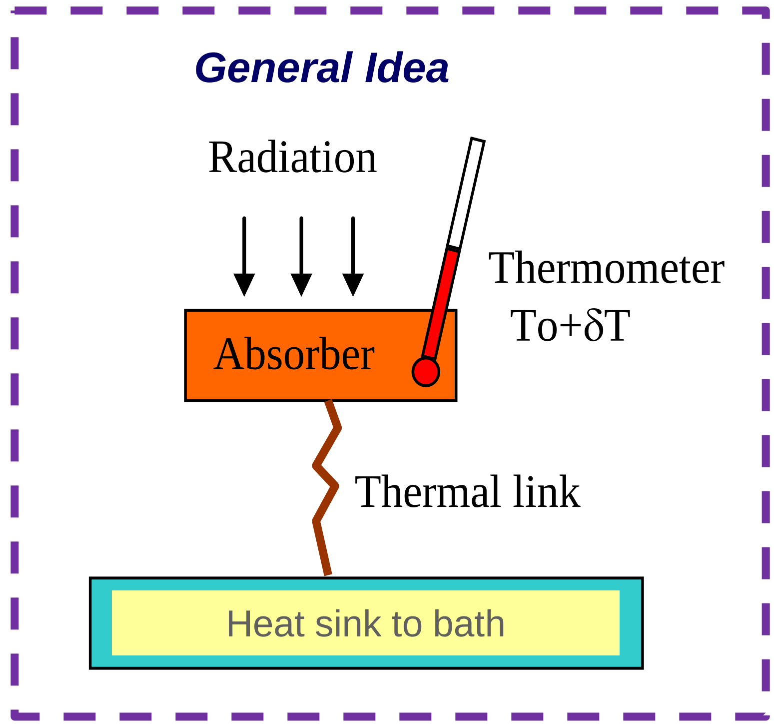
Bolometric detector - thermal detector

EM Radiation → Temperature Change → Electrical signal



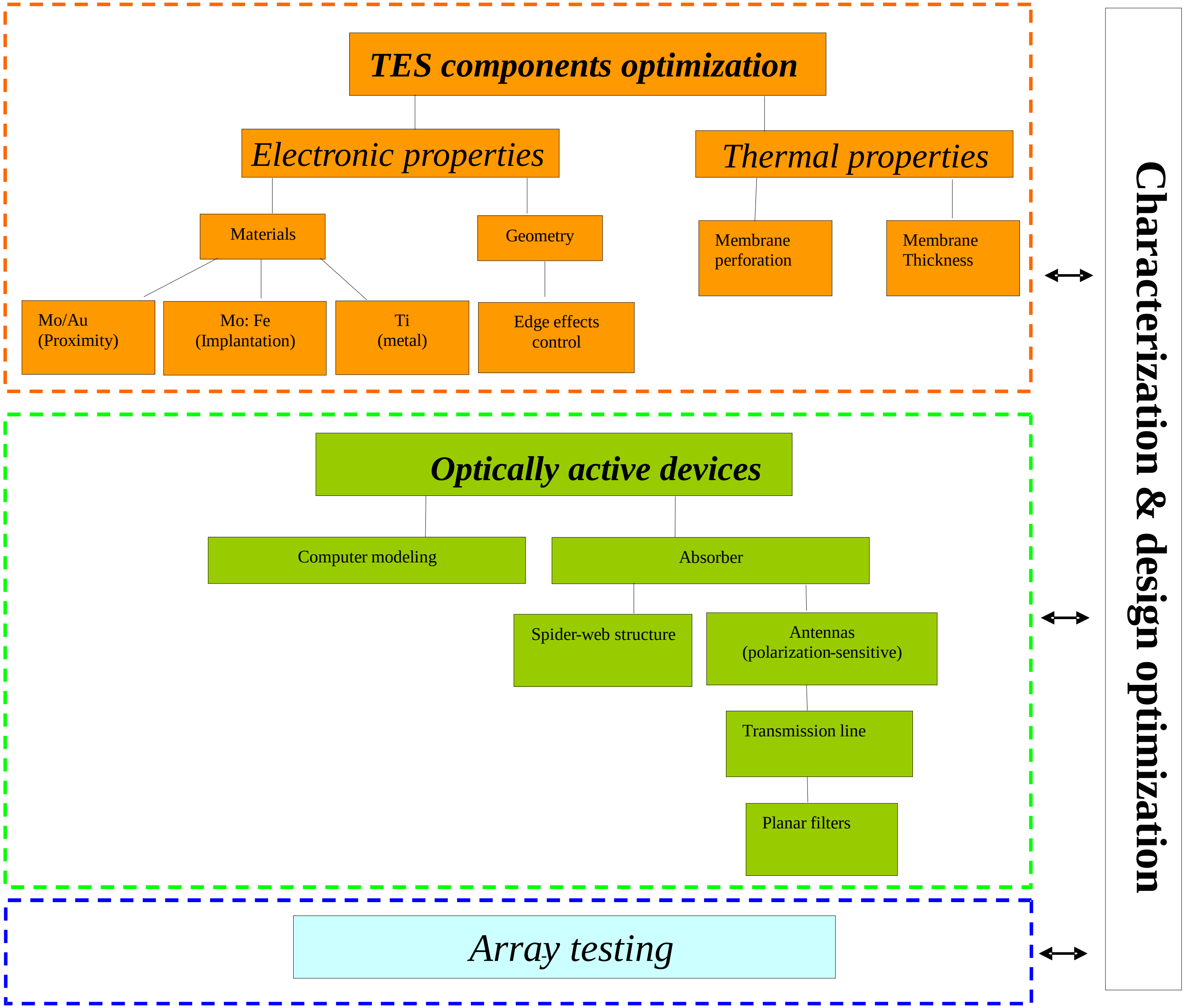
Spectral range is defined by the absorber

an opportunity for broad-band imaging



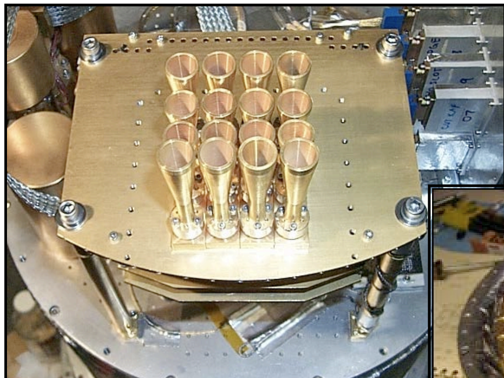
***COMPONENTS*:** Absorber, Thermometer, Thermal link

It takes time & expertise to make a deployable device



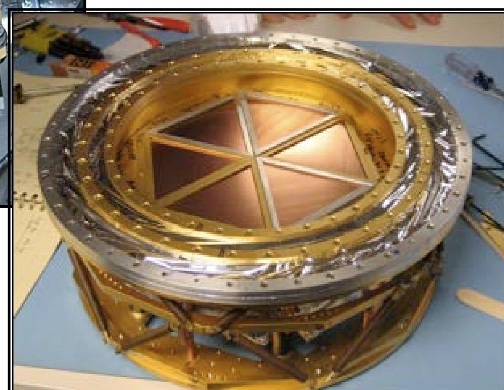
Evolution of CMB TES detectors

2001: ACBAR
16 detectors



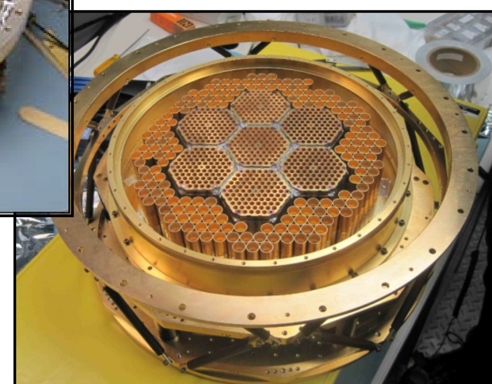
50x improvement

2007: SPT
960 detectors



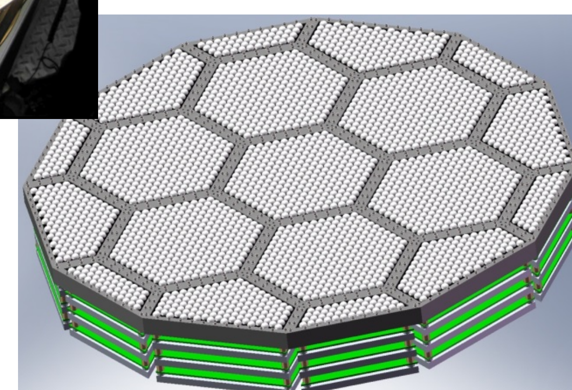
Add polarization

2012: SPTpol
1536 detectors



10x improvement

2016: SPT-3G
15,324 detectors

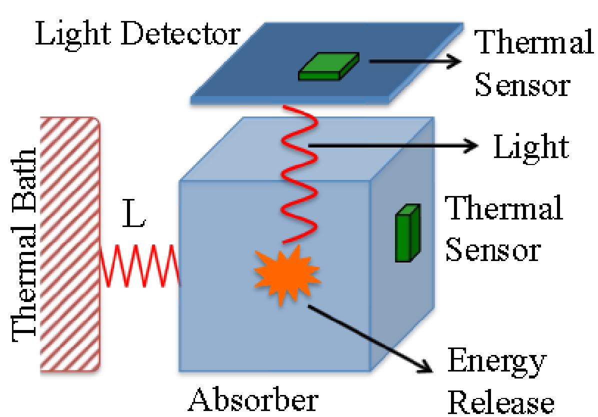


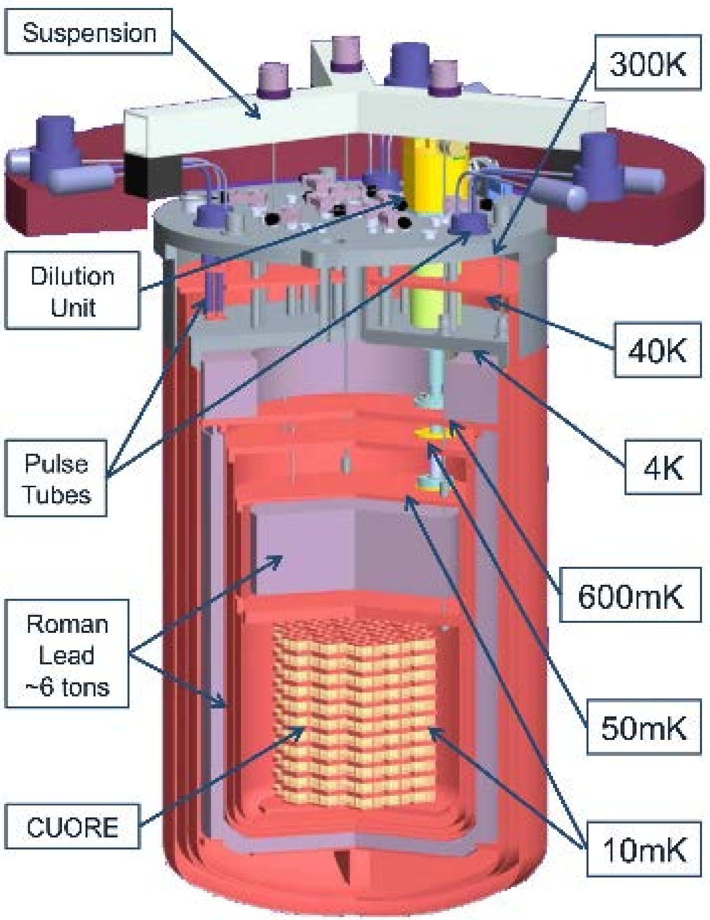
Requires new approach for higher focal plane density

Neutrinoless double beta decay with CUORE

(The Cryogenic Underground Observatory for Rare Events)

- CUORE is funded by the US (DOE and NSF) and EU (INFN)
- 988 x 750 gram crystals of natural TeO_2 with thermistors
- **Future R&D:** Better background suppression and particle identification
- "Thermal" + "light" detectors to distinguish between $0\nu\beta\beta$ events and α particles
- **SC detectors as a candidate technology:** ultimate energy resolution, scalable, multiplexing with SQUIDs, thermal and/or optical sensitivity
- **Materials with T_c 10-15 mK are needed**

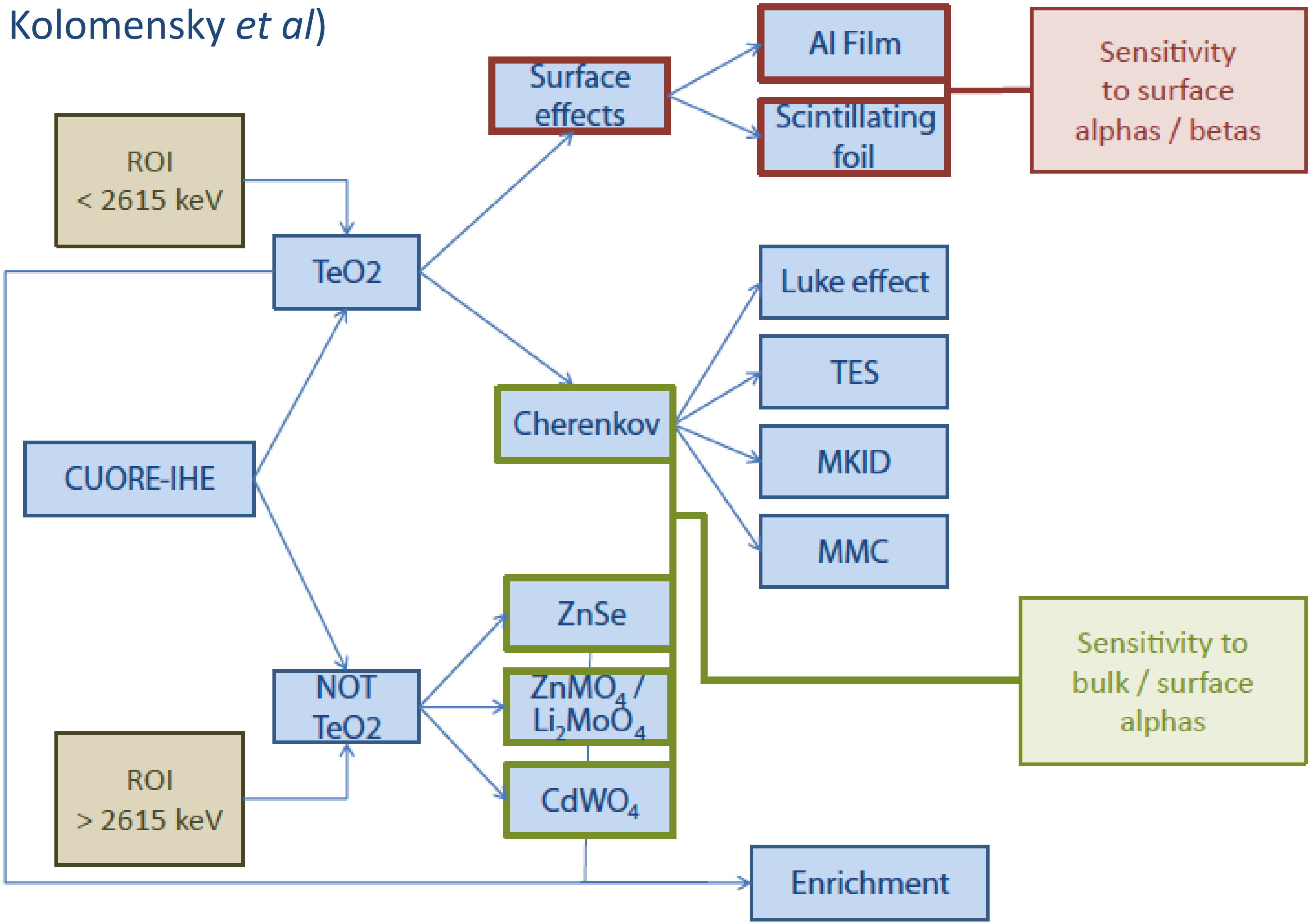




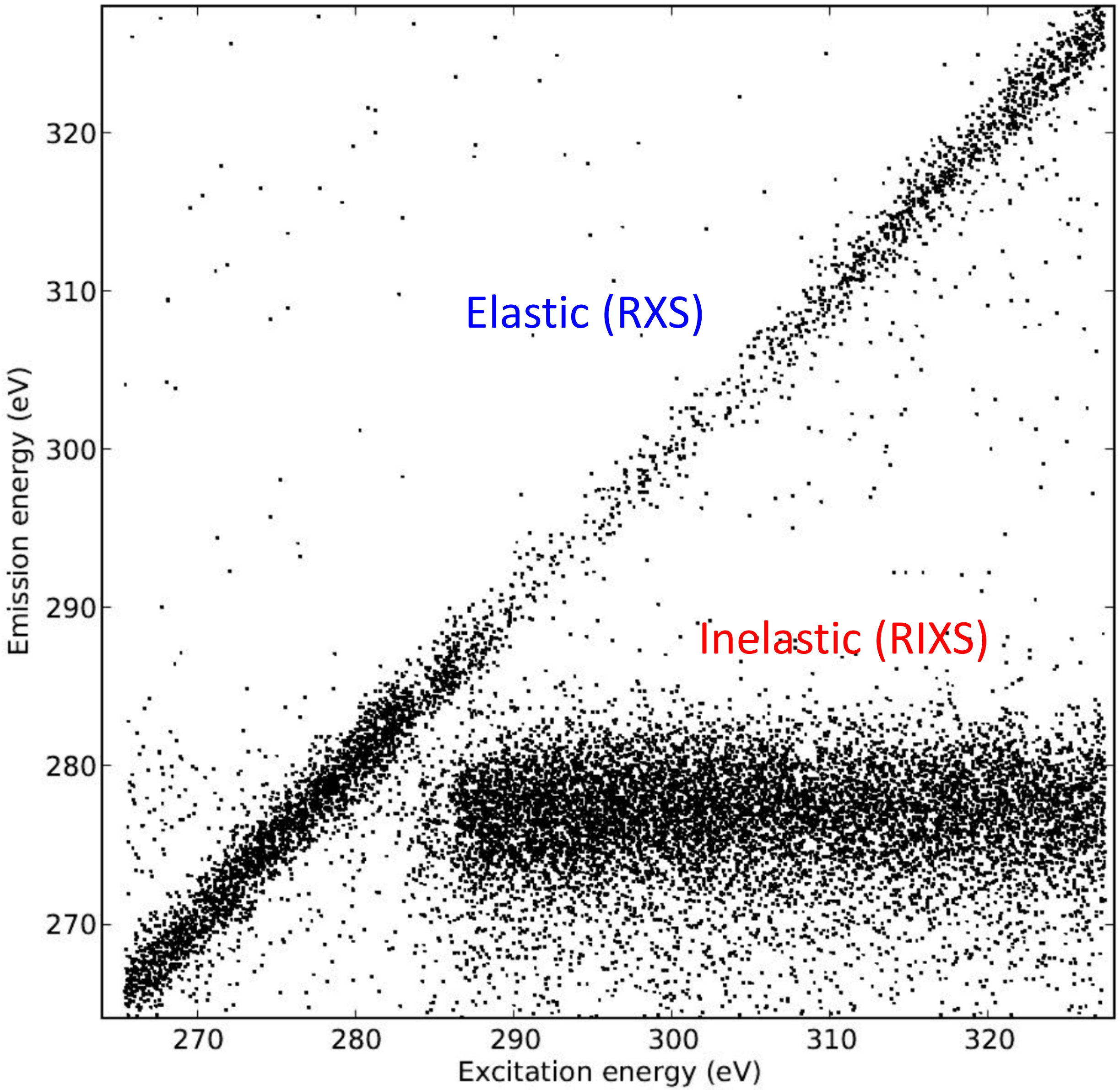
D. R. Artusa *et al.*, http://arxiv.org/abs/1407.1094

Scheme of R & D detector activities for CUORE-IHE

(Y. G. Kolomensky *et al*)



Energy discrimination with TES for X-ray scattering

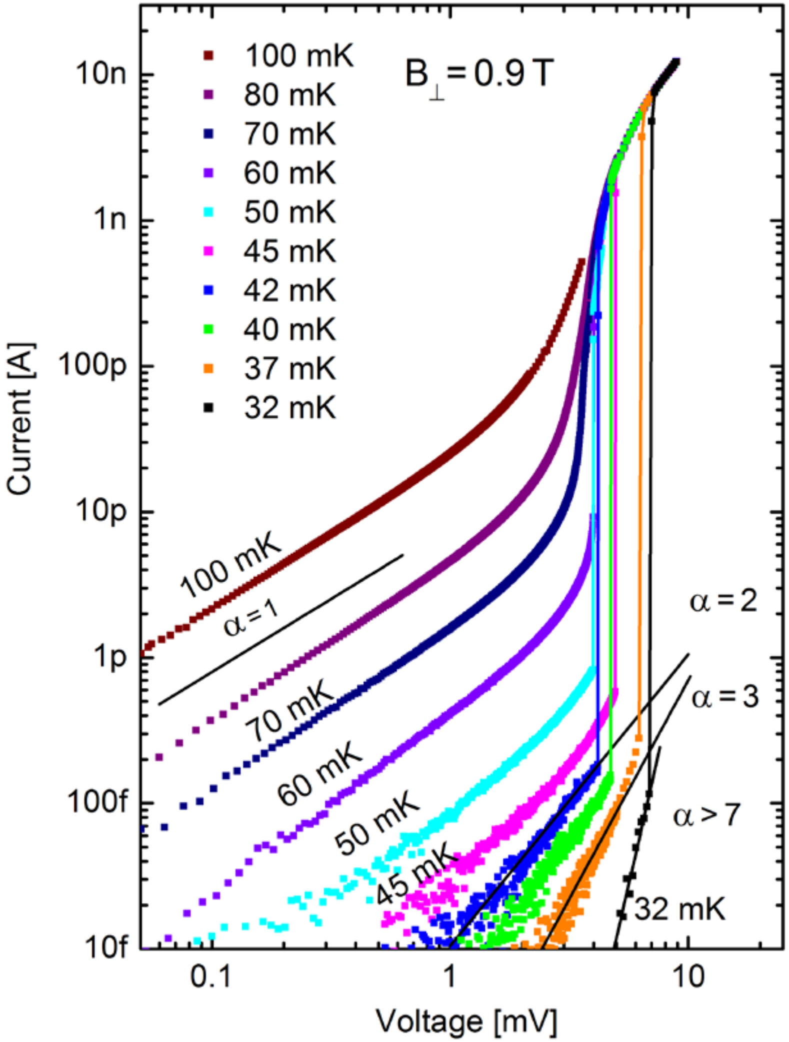


Joel Ullom, NIST,
Aug. 2012 BES Workshop

Will allow for a 100 fold improvement in signal to noise ratio

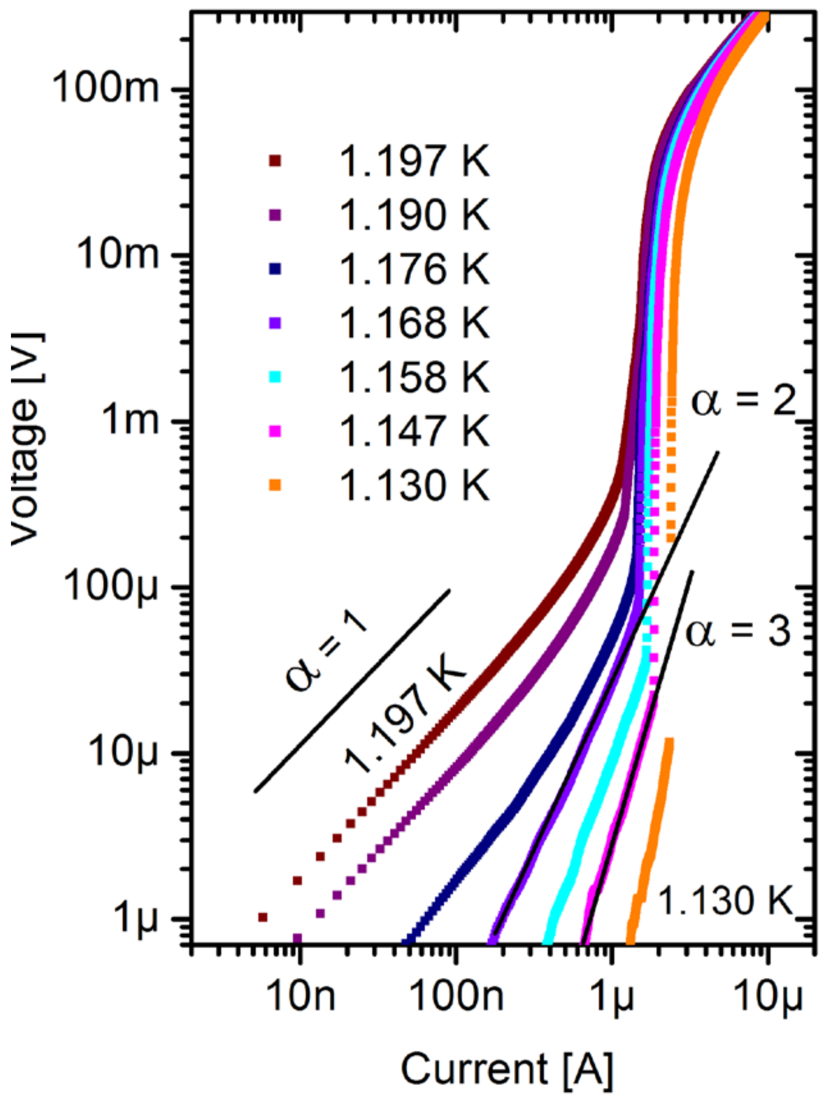
Improved resolution from superconductor-insulator transition?

transition to superinsulating state (TiN)

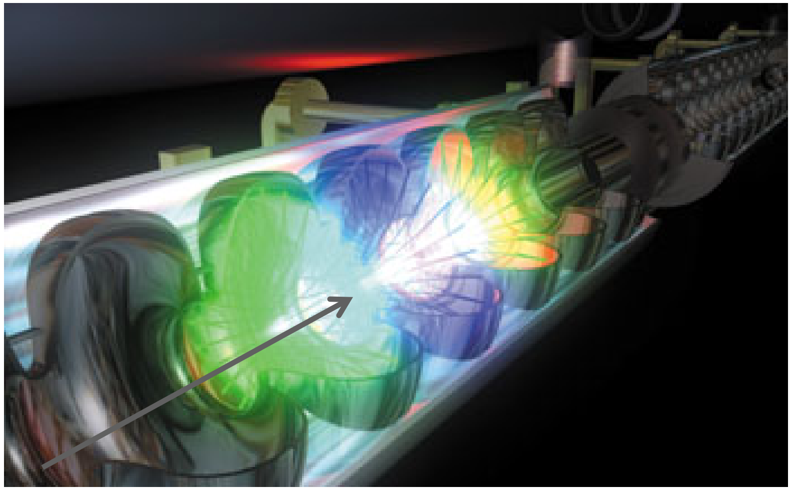


Baturina *et al*, EPL (2012)

transition to superconducting state (TiN)



Superconducting Radio-Frequency (SRF) Cavities



SRF Cavity Needs:

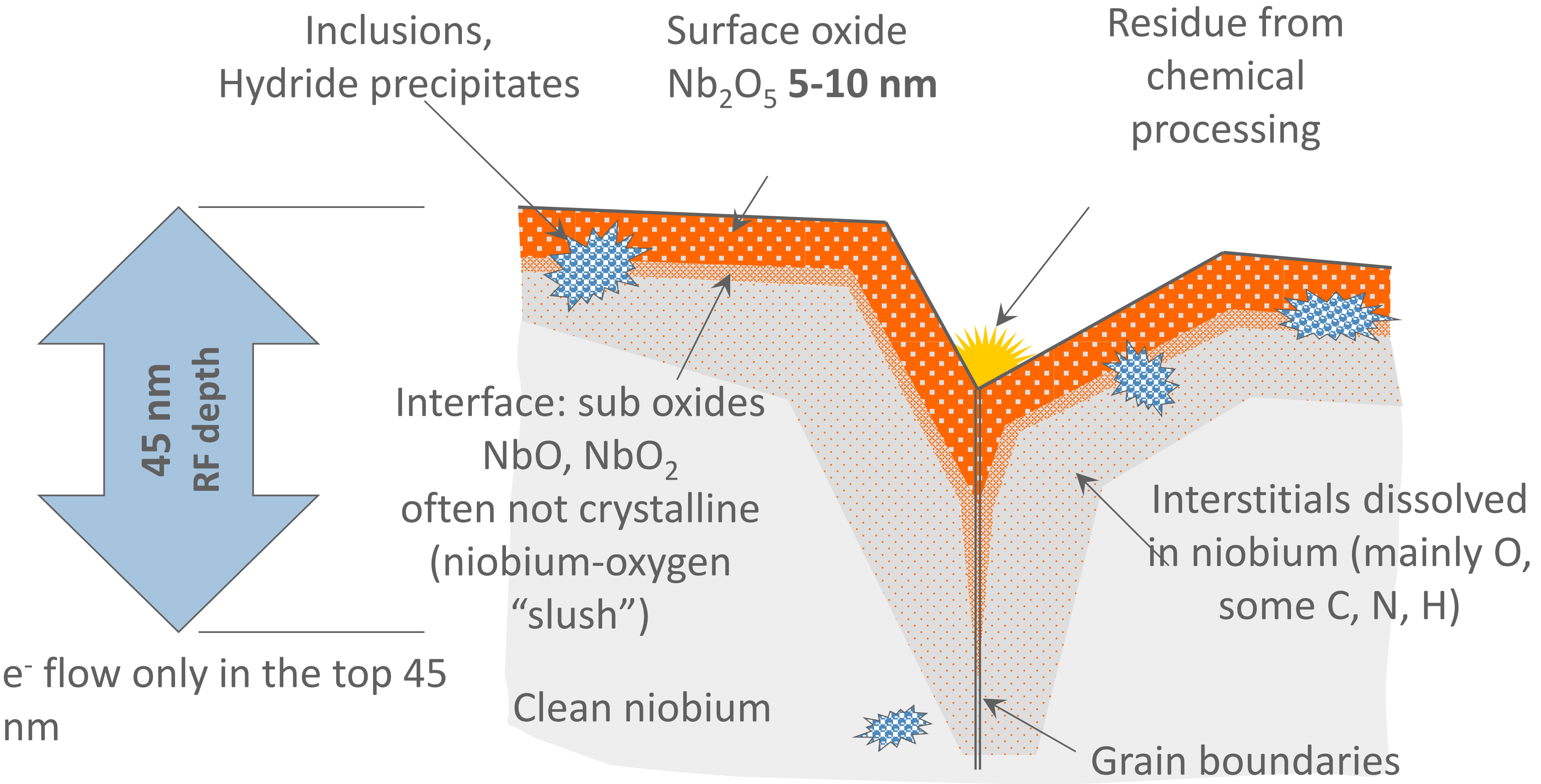
- Higher Gradients, Currents
- Lower operational costs
  - Operating Temperature
  - Dissipation
- Lower Capital Costs – Nb, fabrication, etc.

RF electromagnetic field inside the cavity:

screening currents -> dissipation
-> performance

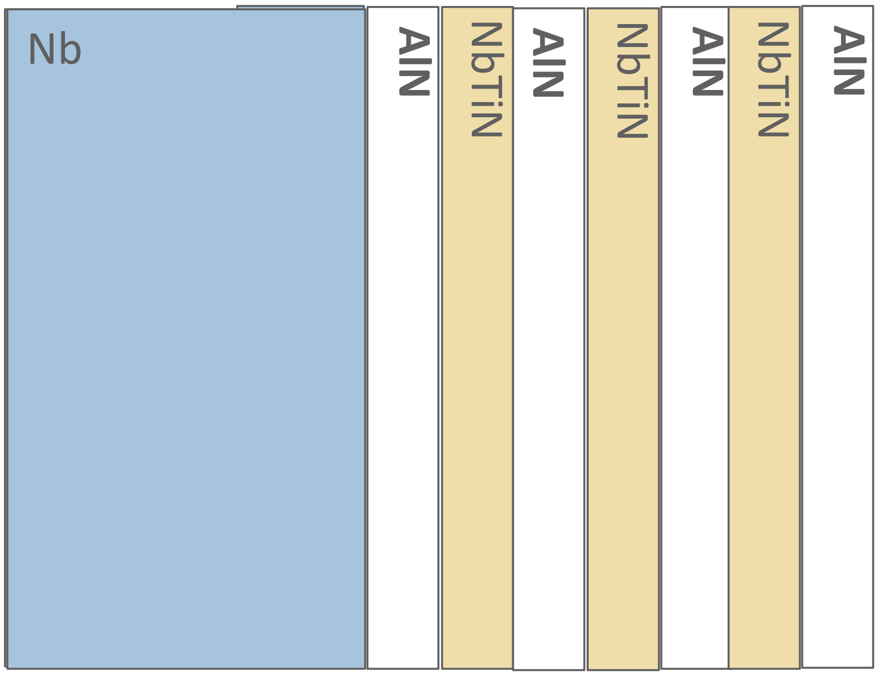
- Performance limitations: fundamental understanding of dissipation mechanisms
- Atomic Layer Deposition: synthesizing new materials and application to RF cavities

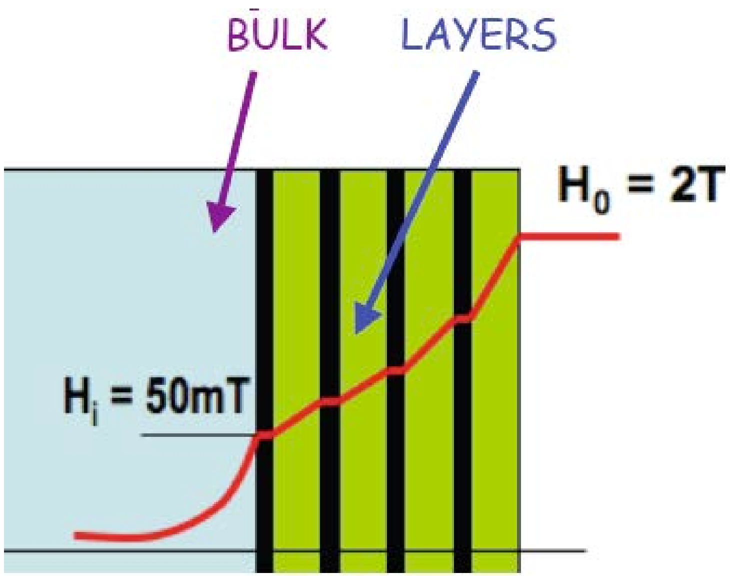
Niobium surfaces are complex and poorly controlled at the nanometer scale



Probe the surface superconductivity (by tunneling, etc.)

A basis to build new cavity layered structures that might allow for transformationally higher field gradients





Gurvevich, Appl. Phys. Lett. (2006)

- Layered structures raise the critical magnetic field at which vortex losses form.
- ALD allows fabrication with atomic scale precision without regard to the aspect ratio.
- We need to develop ALD synthetic chemistries for superconducting material growth.

Synergy

Jlab

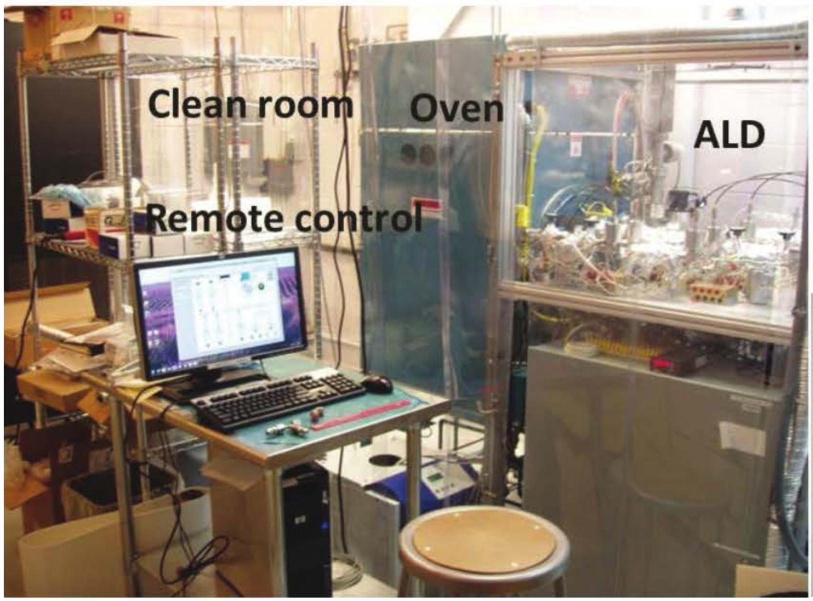
Single Cell Nb Cavities Testing

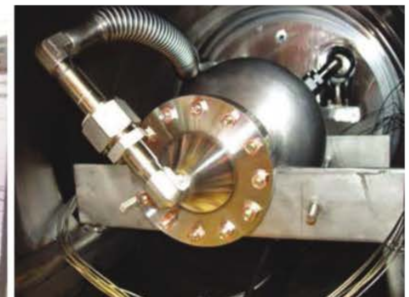
FNAL

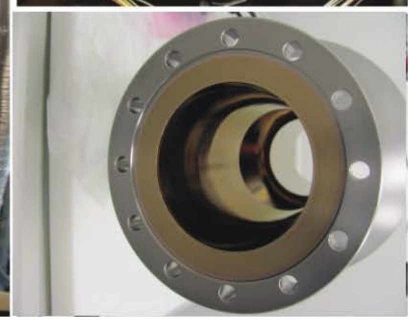
Single Cell Nb Cavities

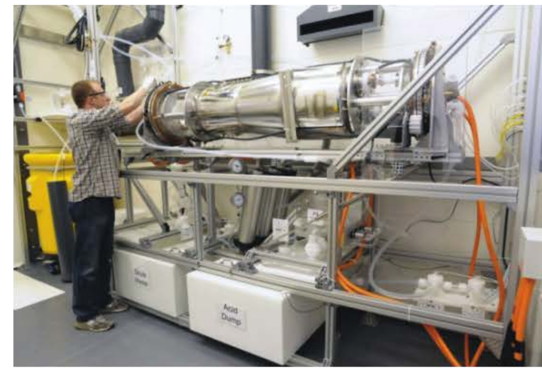
MSD/HEP

PHYS/APS/HEP









Material science fundamentals

Surface treatments
RF testing

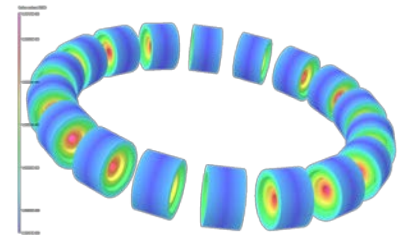
Superconductors at Work

Medical
MRI

Motors, Generators
& Wind turbines

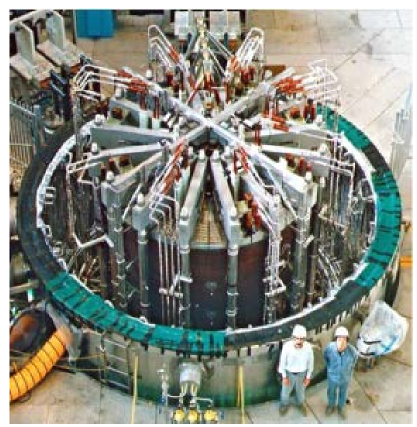
Transportation
MagLev

Magnetic
Energy Storage

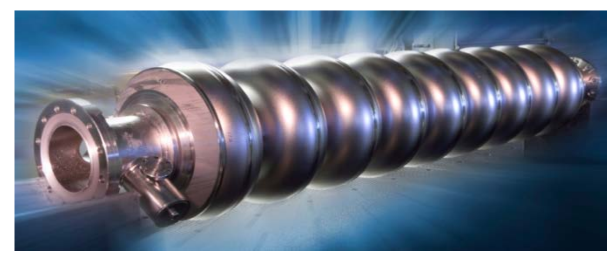


Power Cables, Electric Grid

Fusion Energy



Superconducting RF cavities



Envisioned specifications for technical applications

Application	Operating Field (Tesla)	Operating Temp. (K)	Key requirements	Wire needed per device (kA-m)
Cables	0.01 to 0.1 (ac) 0.1 to 1 (DC)	70 to 77	Low ac losses (ac) High currents (dc)	40,000 to 2,500,000
Wind/Off-shore Generators	1 to 3	30 to 65	In-field I_c	2,000 to 10,000
Transformers	0.1	65 to 77	Low ac losses	2,000 to 3,000
Fault current limiters	0.1	65 to 77	Thermal recovery High volts/cm	500 to 10,000
SMES	2 to 30 T	4 to 50	In-field I_c	2,000 to 3,000
Automotive motors	2 to 5	30 to 65	Low ac losses In-field I_c	500 to 1,000
Aerospace	2 to 5	30 to 50	Light weight In-field I_c	1,000 to 2,000
Magnets/coils	5 to 30	4.2 to 40	In-field I_c	200 to 2,000
MRI, NMR, HEP, Fusion reactors	**5 to 30**	**4.2 K to 30**	**In-field I_c** **Long lengths** **Persistent joints**	**2000 - 100,000+**

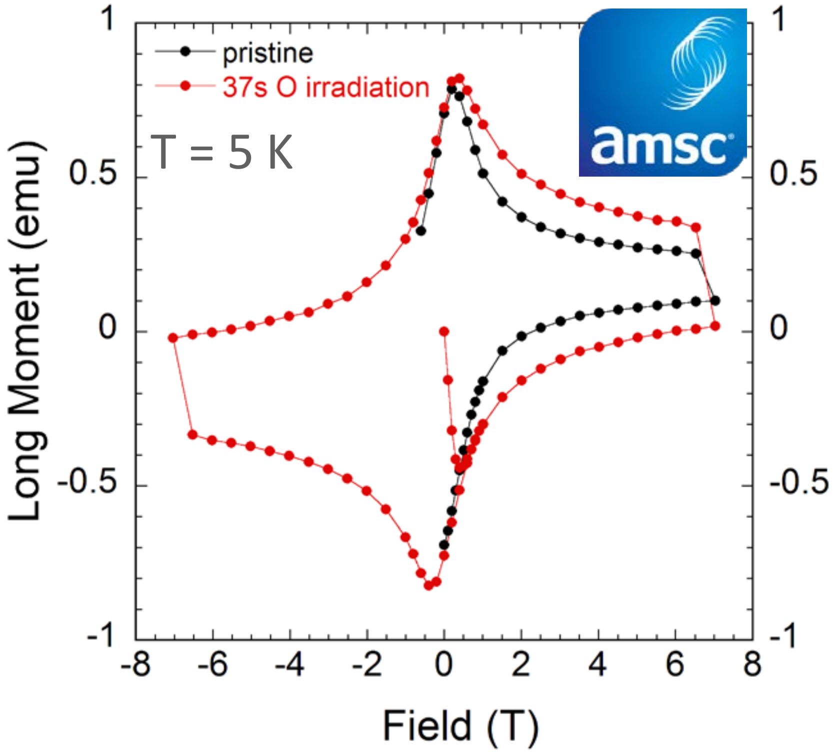
Typical operational parameters in various superconductor applications

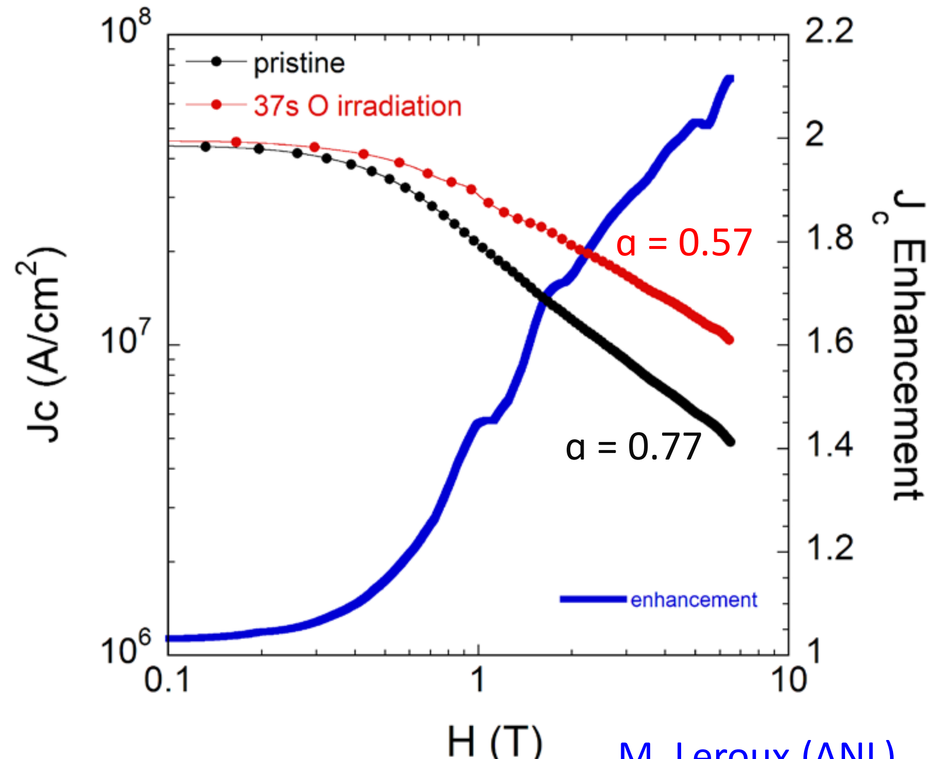
V. Selvamanickam, HTS4 Fusion Workshop, May 26-27, 2011, Karlsruhe, Germany

TARGET 'Sweet spot' for rotating machines and high field magnets
10 MA/cm^2 at T ~ 30K in several H = 2 – 30 Teslas

Doubling J_c in a Few Seconds with Oxygen Irradiation

2500 fold increase in defect creation: $1x10^{13}$ O^{2+}/cm^2





M. Leroux (ANL)
A. Kayani (WMU)

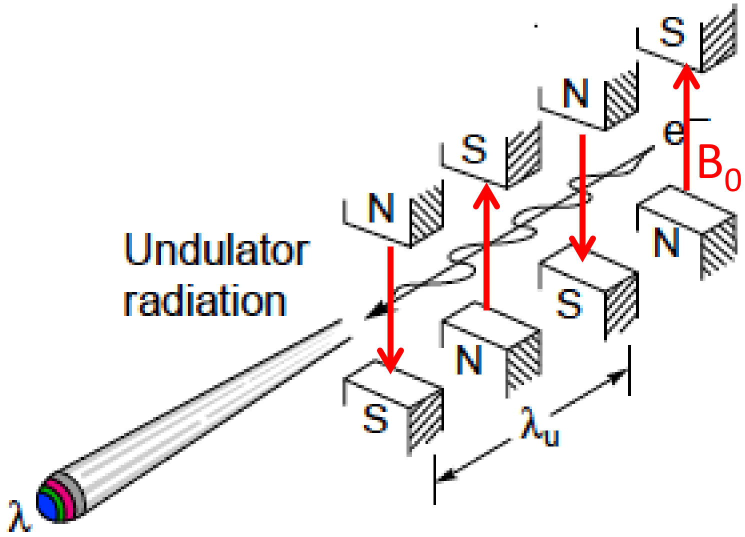
- **No reduction in T_c**
- **Doubling of J_c after 37 sec with a 17 nA beam current**
- **Largest enhancement in high fields: rotating machinery, transformers, magnets**

Viable reel-to-reel manufacturing process

Undulators

Undulators: sources of partially coherent, tunable X-rays
commonly used in linear accelerators and storage rings

Based on deflection of relativistic electrons in a periodic magnetic structure



Magnetic deflection parameter K

$$K = 0.93 B_0 [T] \lambda_u [cm]$$

Emitted wavelength

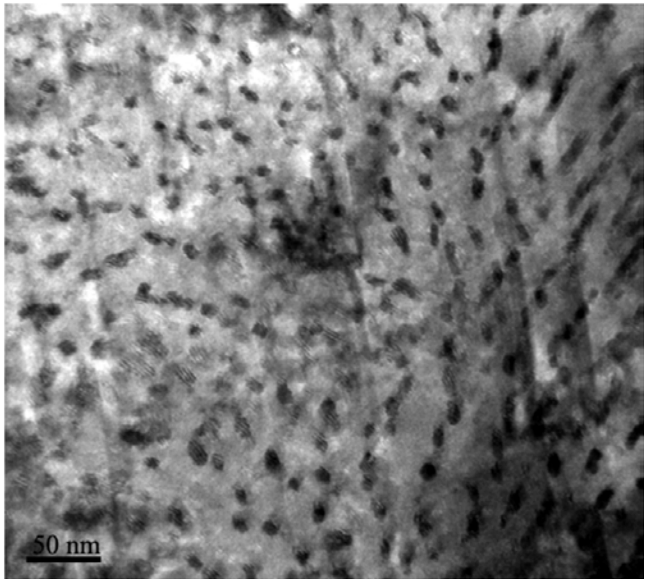
$$\lambda = \frac{\lambda_u}{2\gamma}\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right)$$

After: D. T. Attwood, http://ast.coe.berkeley.edu/sxreuv/

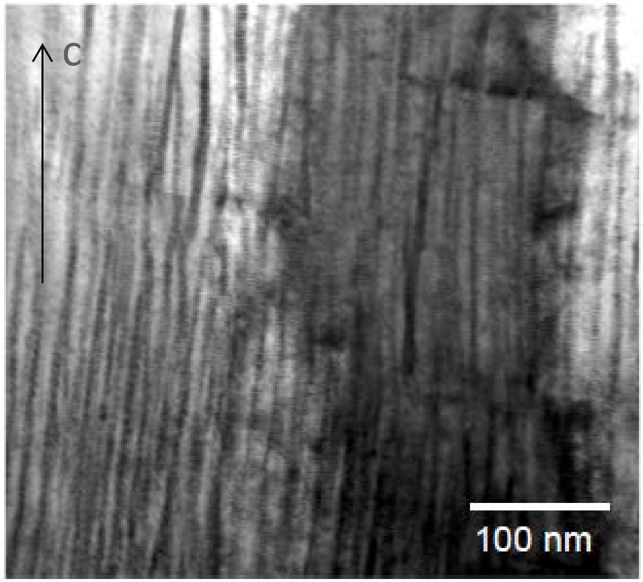
Range of tunability, brilliance of X-ray beam increase with K

Highest possible on-axis magnetic field B_0

Addition of 15% zirconium to MOCVD grown YBCO: Dense array of self-assembled $BaZrO_3$ nano-rods



Plane-view



Cross-section

V. Selvamanickam (Univ. Houston)

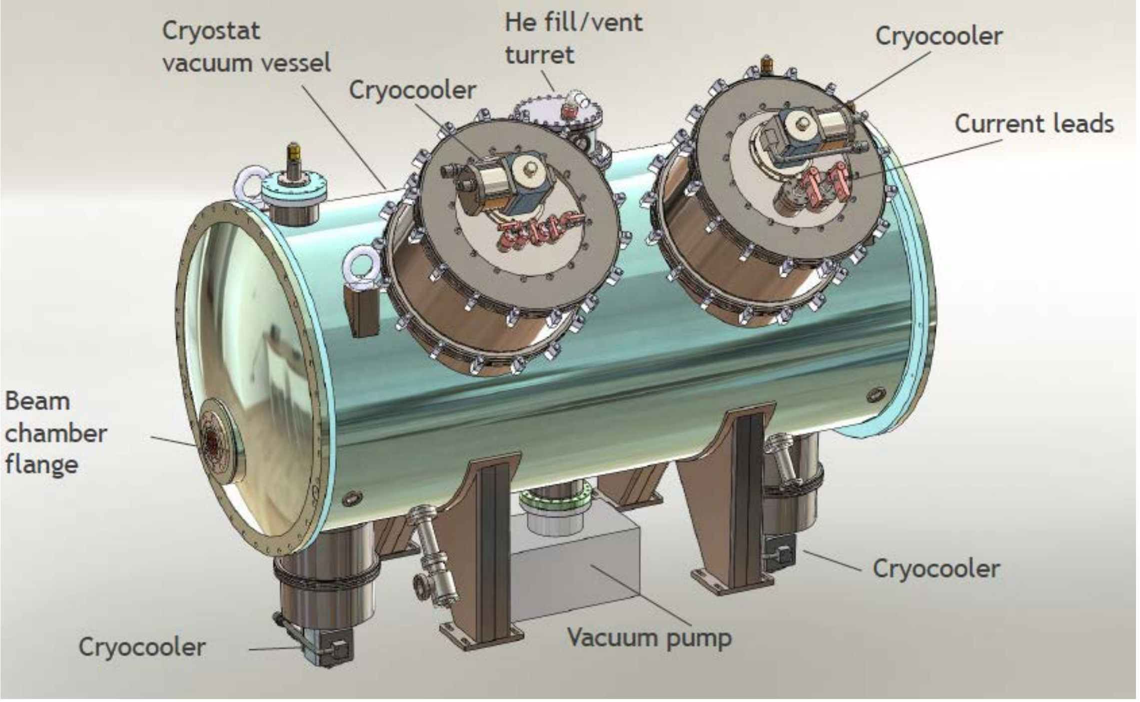
effective pinning of extended vortex sections

~ 17 nm spacing, ~ 5 nm diameter

Research samples reach the requirements for undulators

Possible operation of HTSC at temperatures above 4.2 K

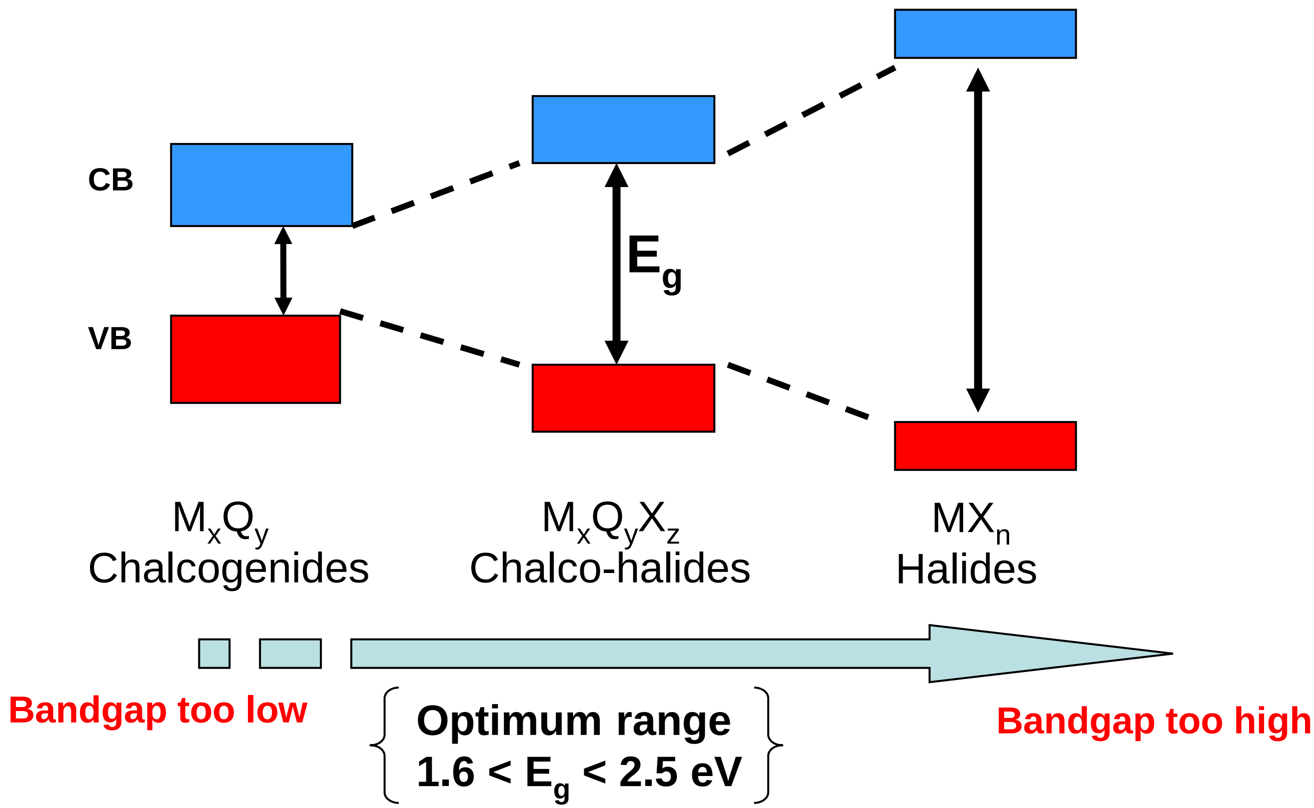
Complex, expensive cryogenics for current NbTi-undulators



Y. Ivanyushenkov (ANL)

~ 10 K: higher cooling power, simpler and cheaper operation

Metal chalcogenide - metal halide hybrid: high density wide band gap materials for γ-ray detection



For example:

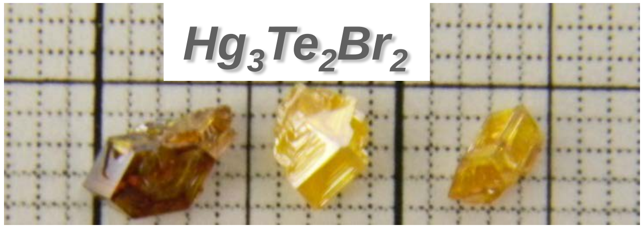
$BiBr_3$ (E_g ~ 2.2 eV) + Bi_2S_3 (E_g ~ 1.1 eV) → 2BiSBr (E_g ~ 1.95 eV)

BiSBr has a high density of 6.7 g/cm^3 and a band gap of 1.95 eV

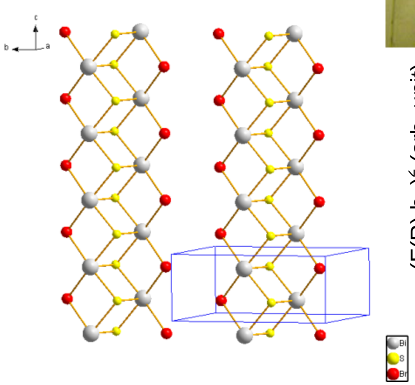
Kanatzidis & Chung (ANL)

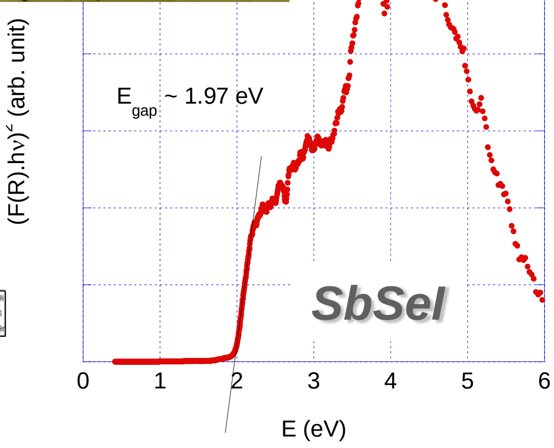
Accomplishments – crystal growth and characterization

- Initiated synthesis and growth experiments in the SbSeX and $Hg_3Q_2X_2$ (Q = S, Se, Te; X = Cl, Br, I) family of promising materials.
- $Hg_3Te_2Br_2$ phase possess the highest density in the $Hg_3Q_2X_2$ family of 7.78 g/cm^3 and an optical band gap of 2.5 eV.
- Single crystal growth of SbSeI: - 8 mm x 10 mm in dimensions.
- Single crystal growth for $Hg_3Te_2Br_2$ - up to 3 x 3 x 2 mm^3 in dimensions.

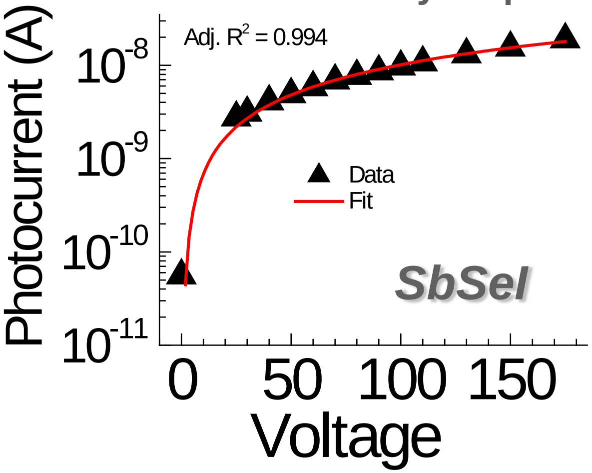


Single crystals of $Hg_3Te_2Br_2$ grown by vapor transport (grid is 1 mm)



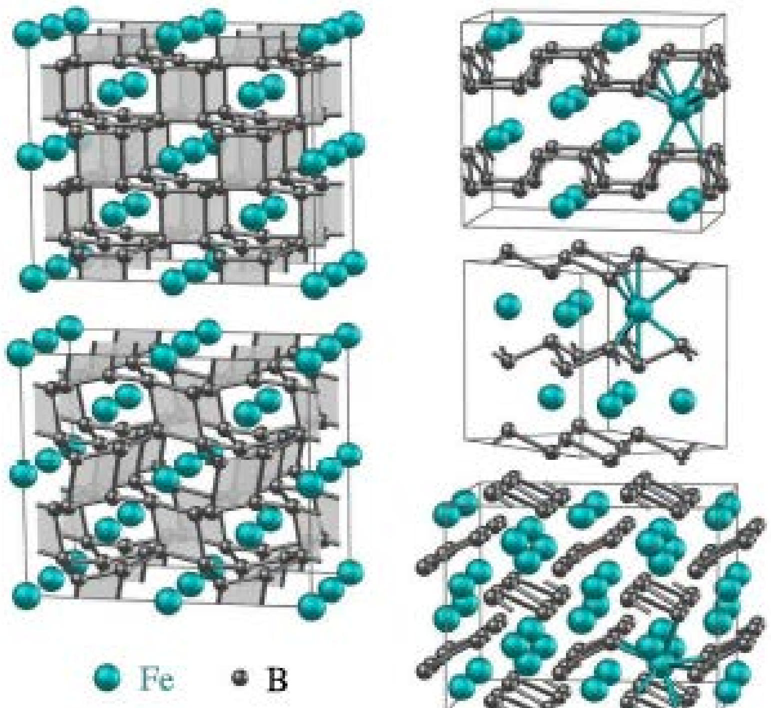


Photoconductivity response



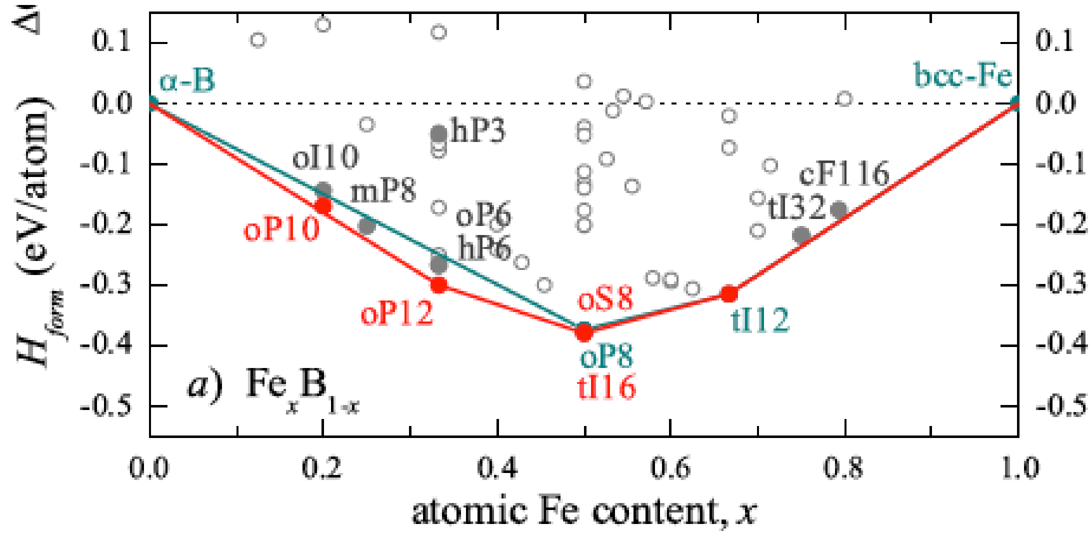
Kanatzidis & Chung (ANL)

Evolutionary search for new superconductors (FeB series)

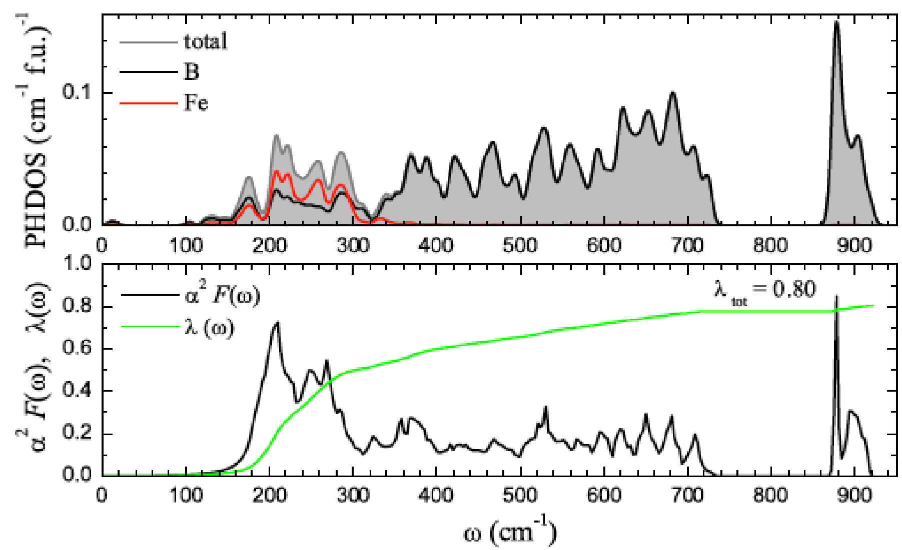


$oI10\text{-}FeB_4$
$oP10\text{-}FeB_4$ (new)

$oP6\text{-}FeB_2$
$hP6\text{-}FeB_2$
$oP12\text{-}FeB_2$ (new)

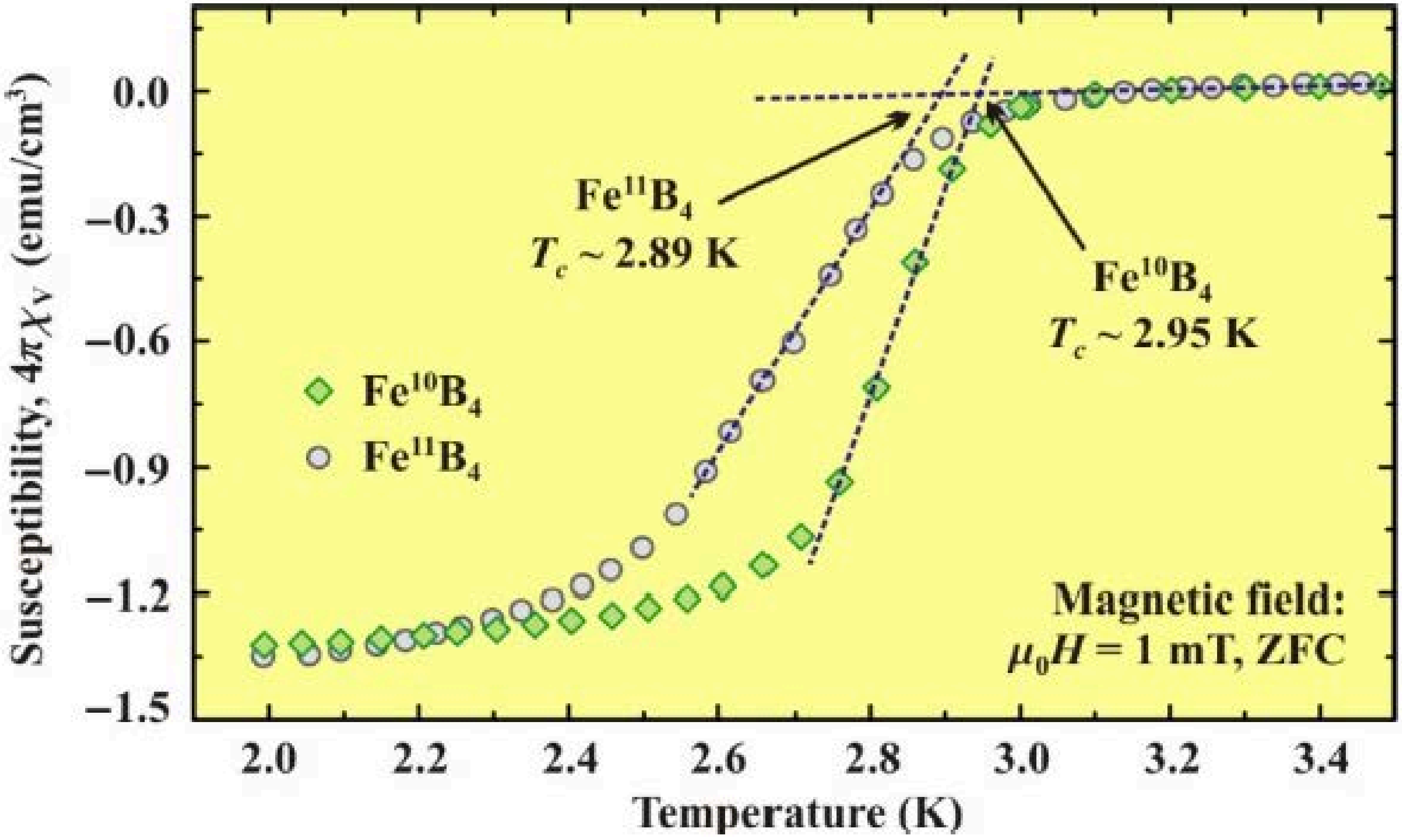


Predicted Superconductivity in *oP*10-FeB_4 (15-20K)



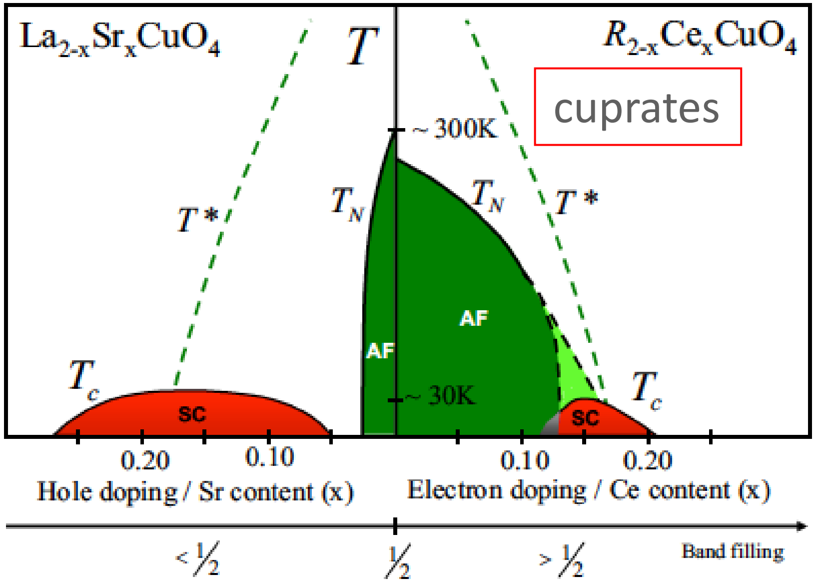
Kolmorgorov *et al*, PRL (2010)

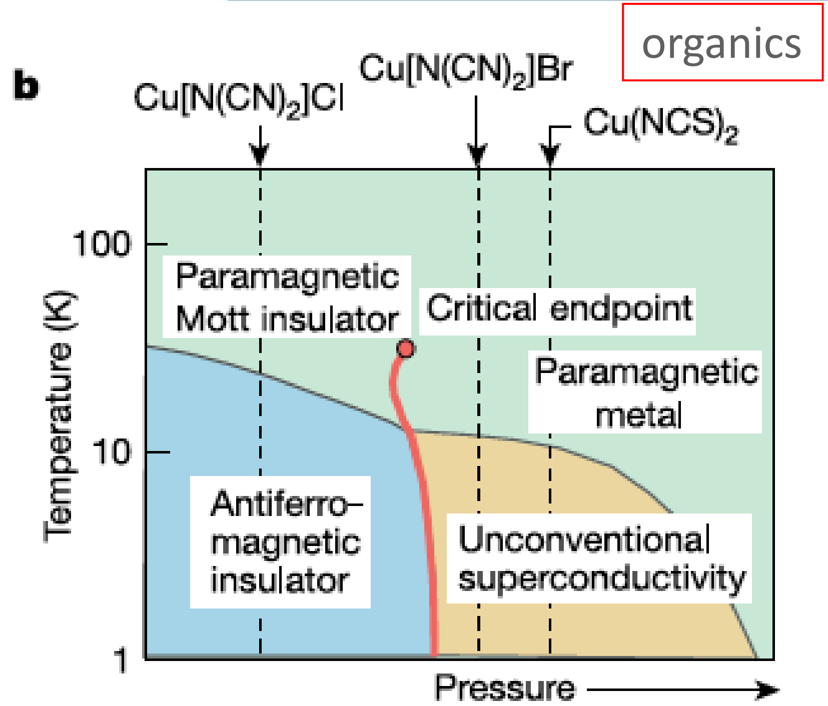
Synthesized and found to have a T_c of 3K
(only known “hit” from a materials genome approach)

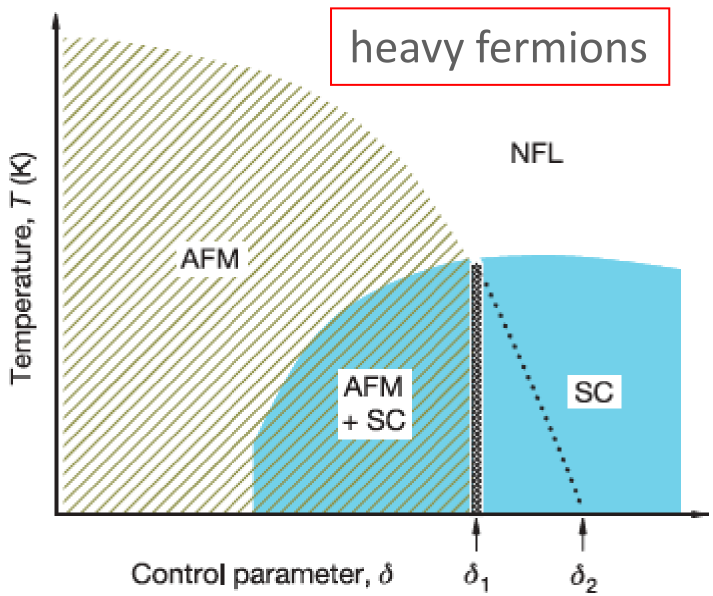


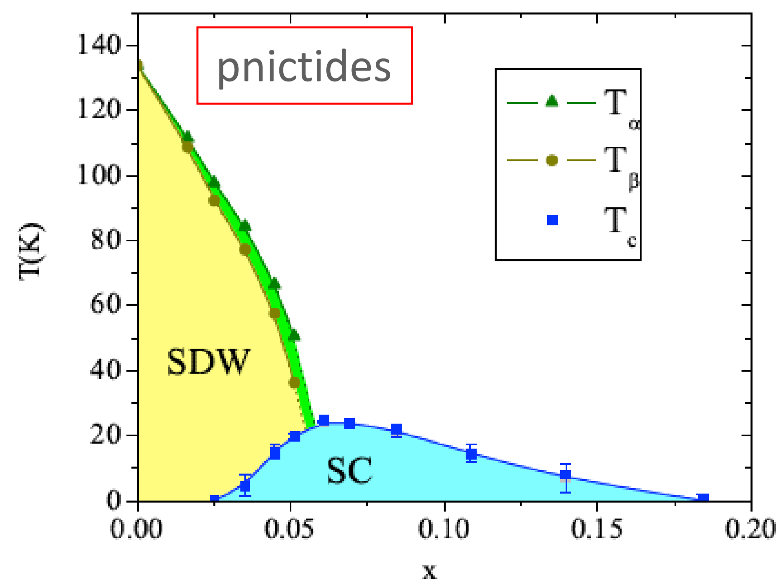
Gou *et al*, PRL (2013)

Similarity of SC Phase Diagrams



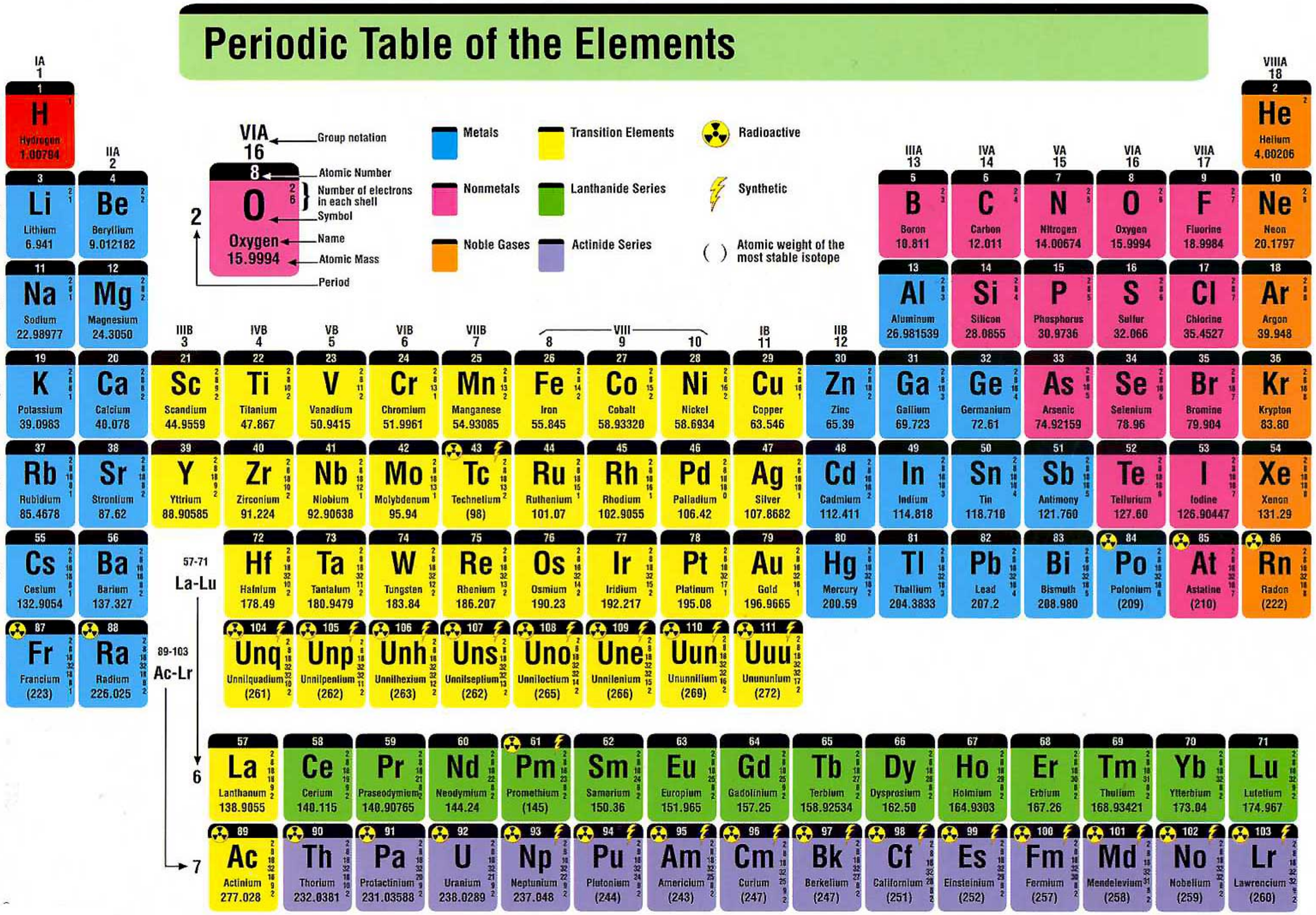






A possible search strategy for new superconductors

Yellow – the "metal", Red – the "ligand", Blue, Green – the "spacer"



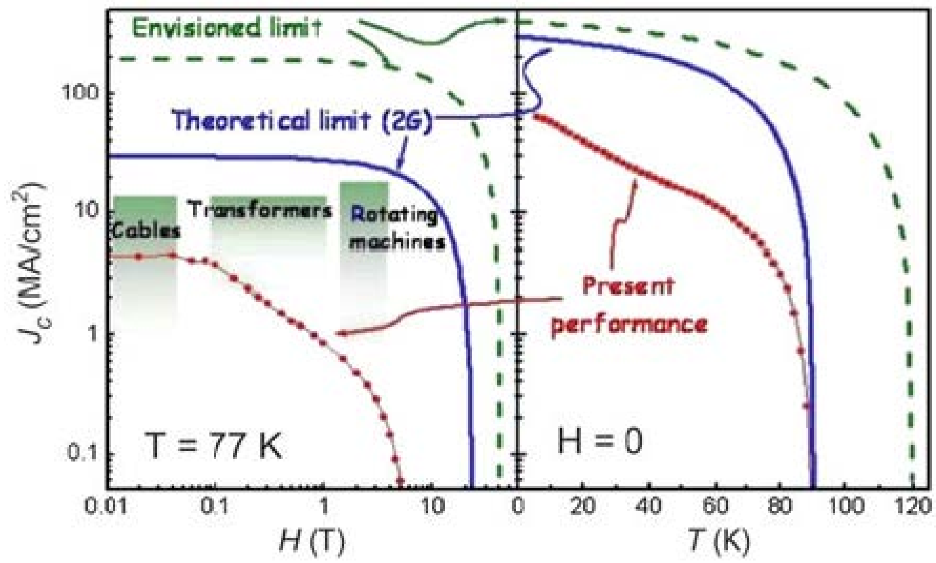
But an increased T_c leads to a reduced phase stiffness

$$\frac{T_\phi}{T_p} \propto \frac{n_s^* v_F}{\gamma T_p^2}$$

$$T_c = \min\{T_\varphi, T_p\}$$

$$J_c \propto n_s^* T_p$$

$$\gamma = \sqrt{\frac{M}{m}}$$



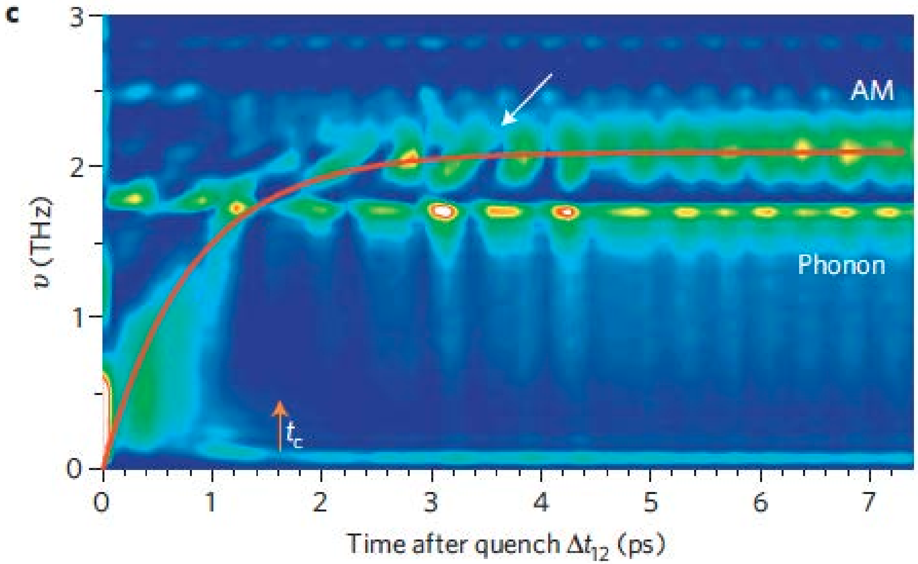
Decreasing Anisotropy & Increasing Pair Density (Cumulative) →

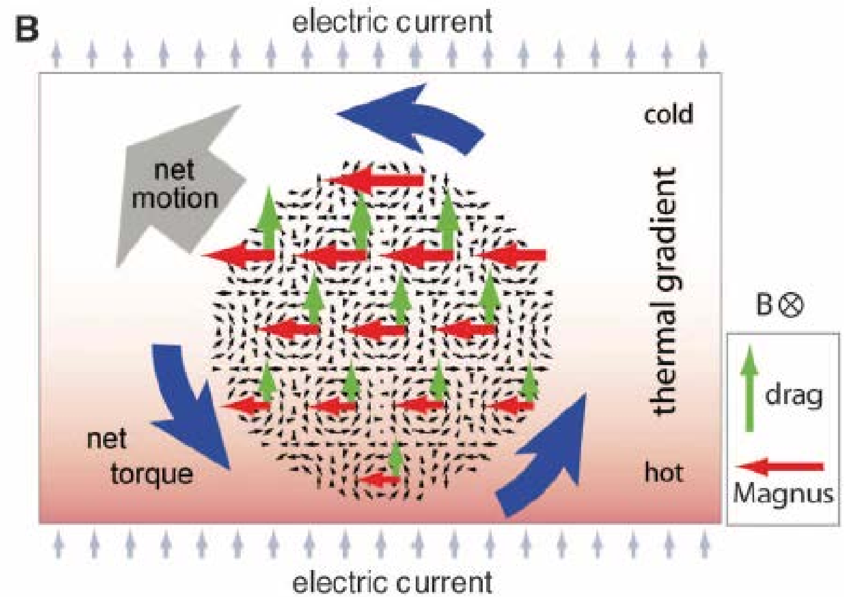
Increasing Pairing Interaction - T_p ↓

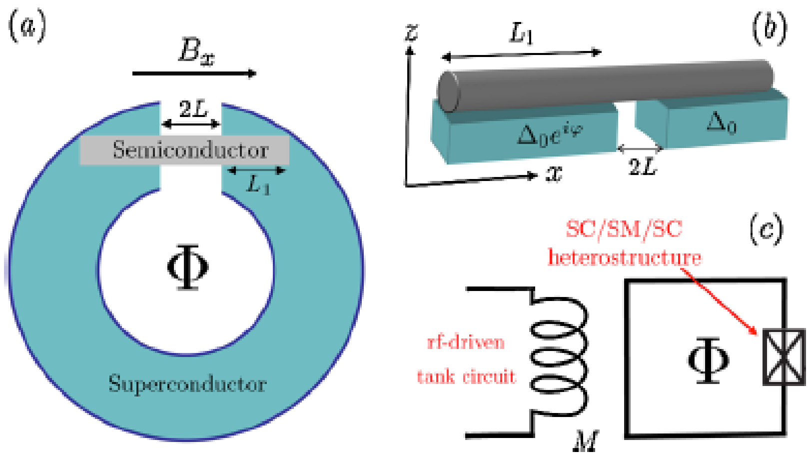
T_p	T_c $\frac{J_c}{J_c^{YBCO}}$	$\gamma \to 1$	n_s^* X 2	n_s^* X 10
90 K (YBCO)	90 K 1	90 K 1	90 K 2	90 K 10
180 K	72 K 2	180 K 2	180 K 4	180 K 20
270 K	54 K 3	270 K 3	270 K 6	270 K 30
360 K	36 K 4	180 K 4	360 K 8	360 K 40

Beasley, MRS Bulletin (2011)

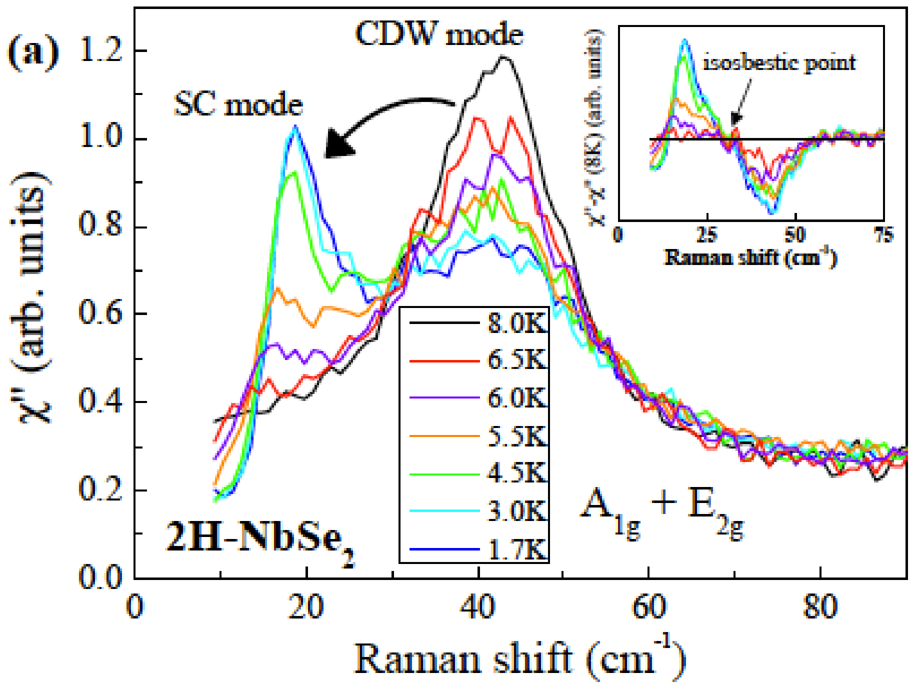
Monopoles, Anapoles, Skyrmions, Majoranas and Higgs
Welcome to the New World of Condensed Matter Physics





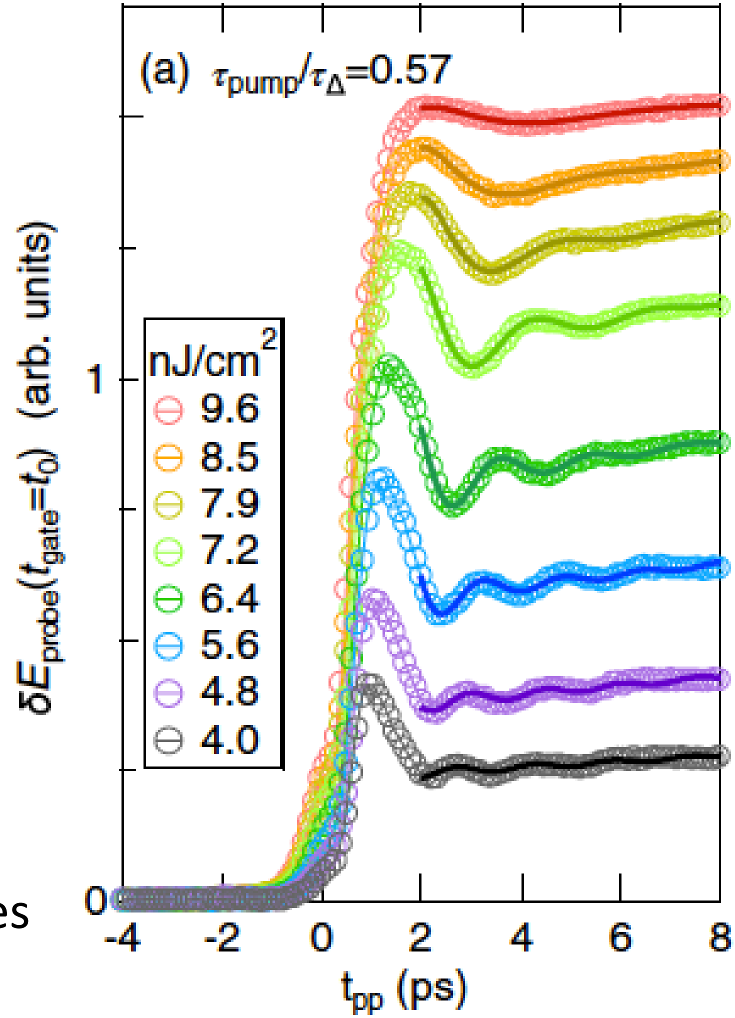


Higgs modes in superconductors and charge density waves



Transfer of weight from SC to CDW Higgs modes with decreasing T in $NbSe_2$ (Raman scattering)

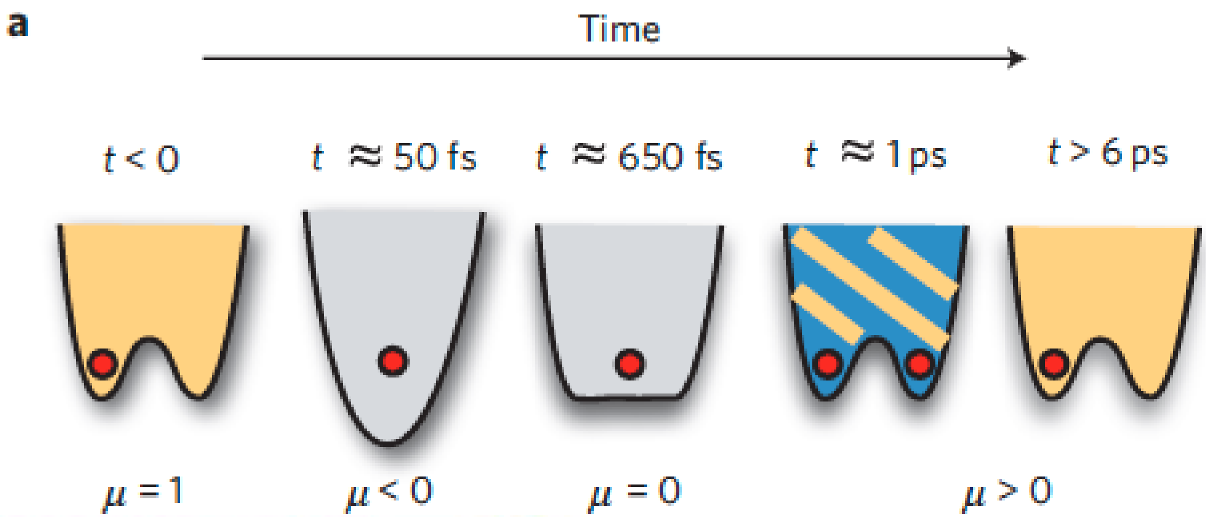
Measson *et al*, PRB (2014)

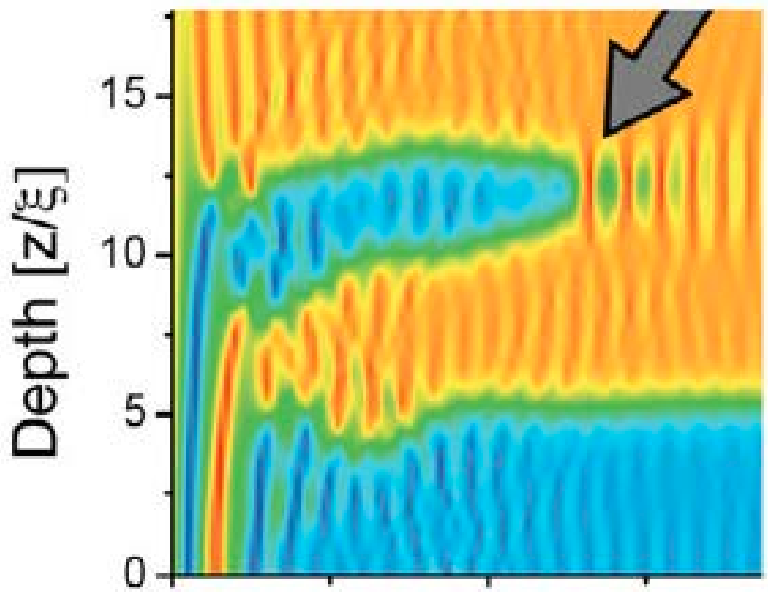


SC Higgs oscillations seen in THz pump-probe studies of NbTiN

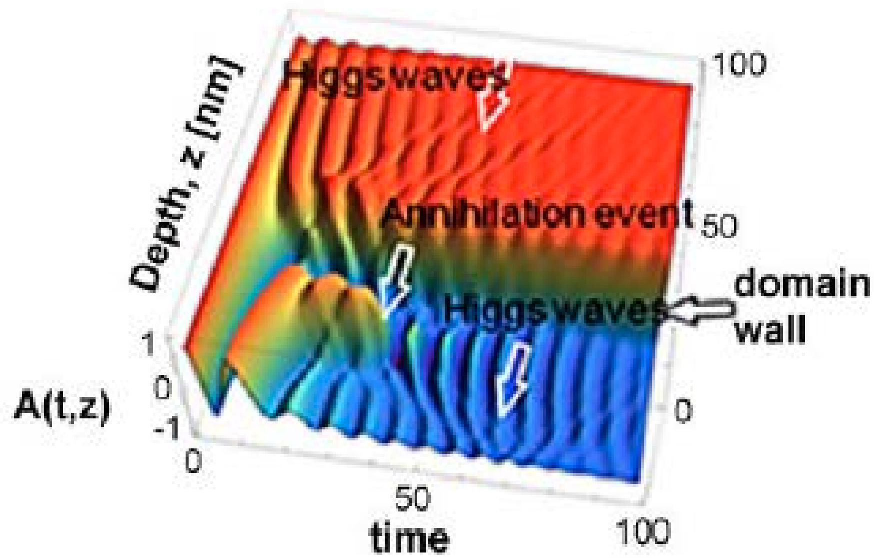
Matsunaga *et al*, PRL (2013)

CDW order parameter domain creation and annihilation in $TbTe_3$ as revealed by pump-probe studies (Kibble-Zurek mechanism)





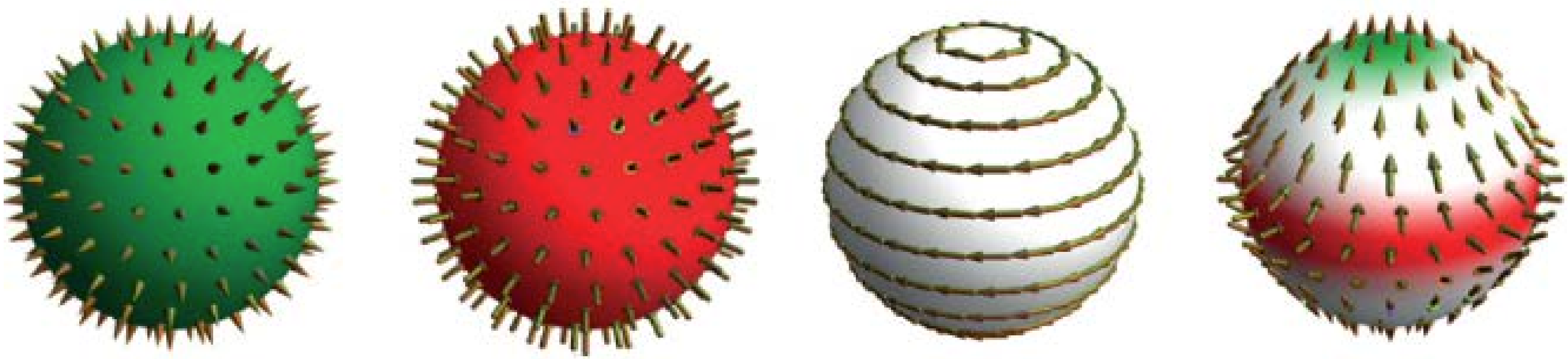
pump-probe delay (ps)



Yusupov *et al.*, Nat. Phys. (2010)

Multipole expansion of magnetic free energy in a solid where m is the magnetic dipole moment; a the magnetic monopole; t the toroidal (anapole) moment; q the magnetic quadrupole

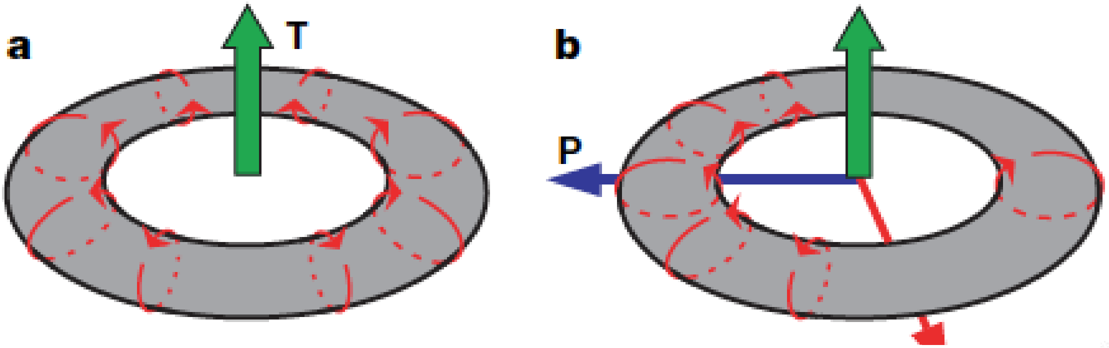
$$H_{\mathrm{int}} = -\boldsymbol{m} \cdot \boldsymbol{H}(0) - a(\nabla \cdot \boldsymbol{H})_{r=0} - \boldsymbol{t} \cdot [\nabla \times \boldsymbol{H}]_{r=0} - q_{ij}(\partial_i H_j + \partial_j H_i)_{r=0} - \dots .$$

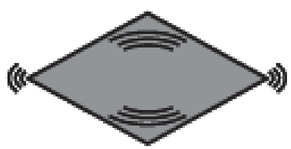
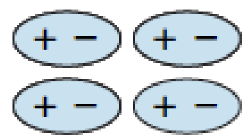
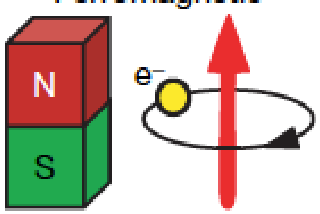
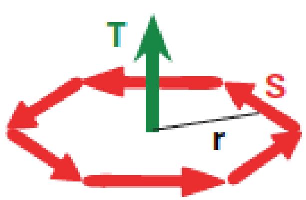


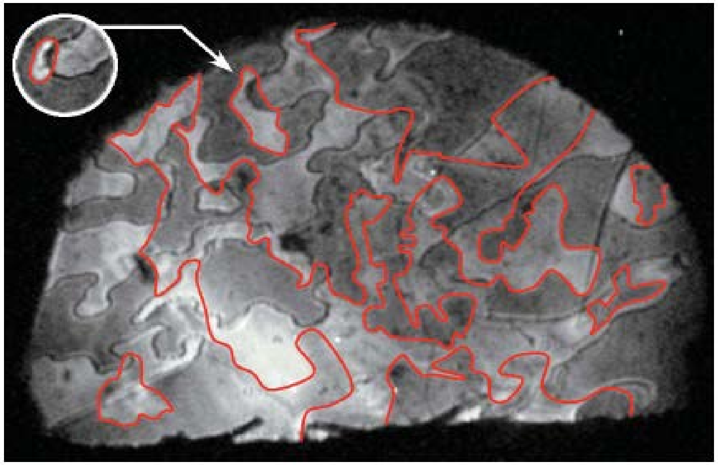
+ monopole   - monopole   z anapole z^2 quadrupole

Dubrovik & Tugushev, Phys Rep (2000)
Di Matteo, J Phys D (2012)
Spaldin *et al*, PRB (2013)

Toroidal moments have been observed in $LiCoPO_4$ (used as a cathode in Li-ion batteries!) by optical second harmonic generation



Time \ Space	Invariant	Change
Invariant	Ferroelastic 	Ferroelectric 
Change	Ferromagnetic 	Ferrotoroidic 



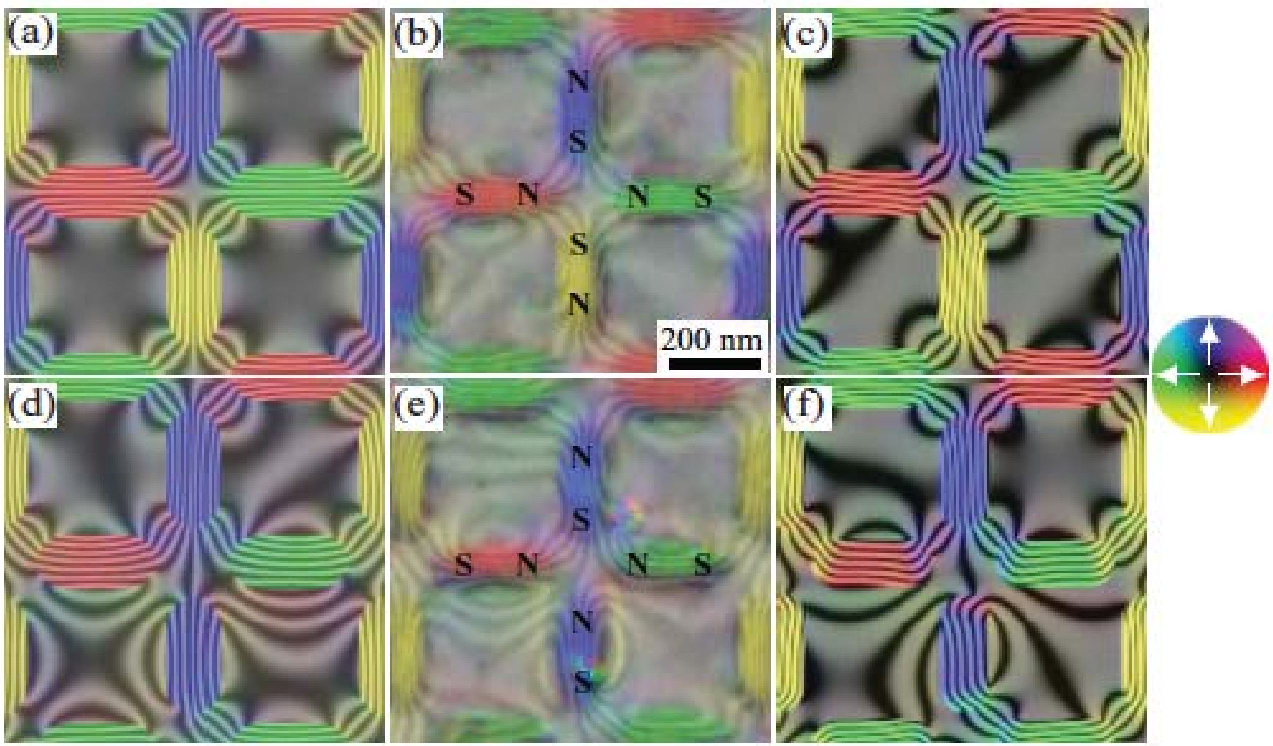
Van Aken *et al.*, Nature (2007)

Magnetic Monopoles in Spin Ice

Leonard: Are you really going to be on NPR?

Sheldon: Yes, they're interviewing me by phone from my office regarding the recent so-called discovery of magnetic monopoles in spin-ices. It's pledge week and they're trying to goose the ratings with a little controversy.

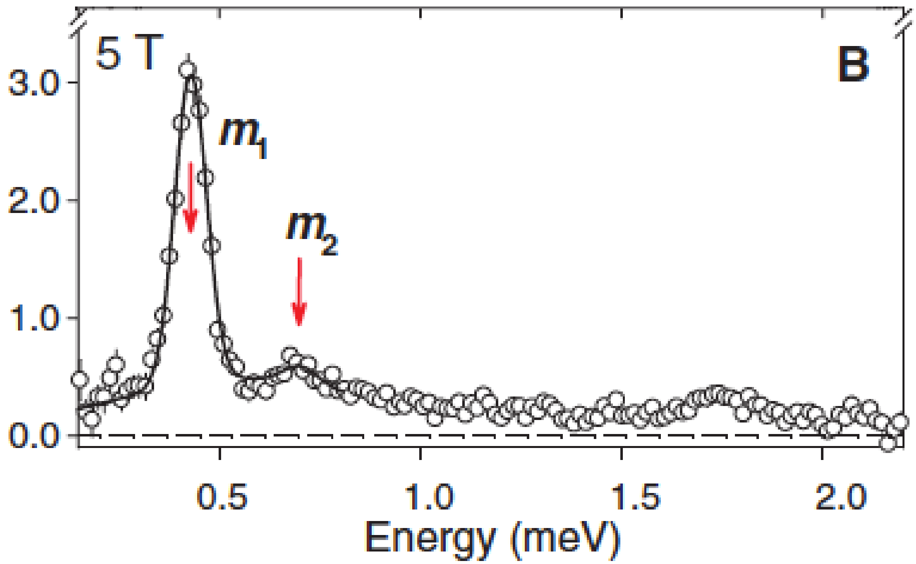
Magnetic Monopole Defects in Artificial Spin Ice imaged with Lorentz TEM

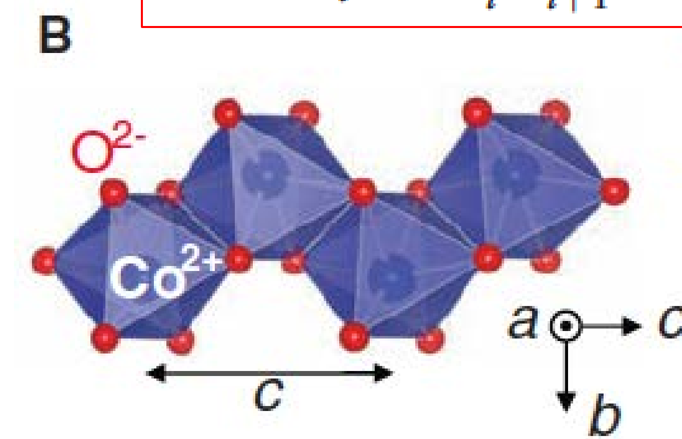


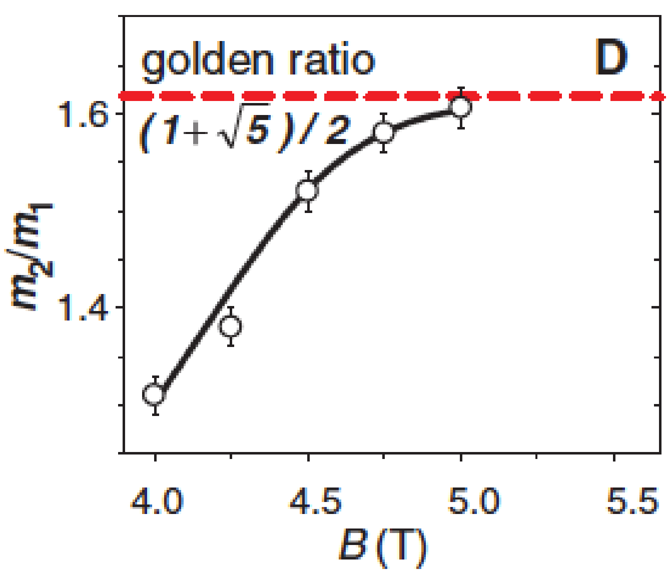
Phatak *et al*, PRB (2011)

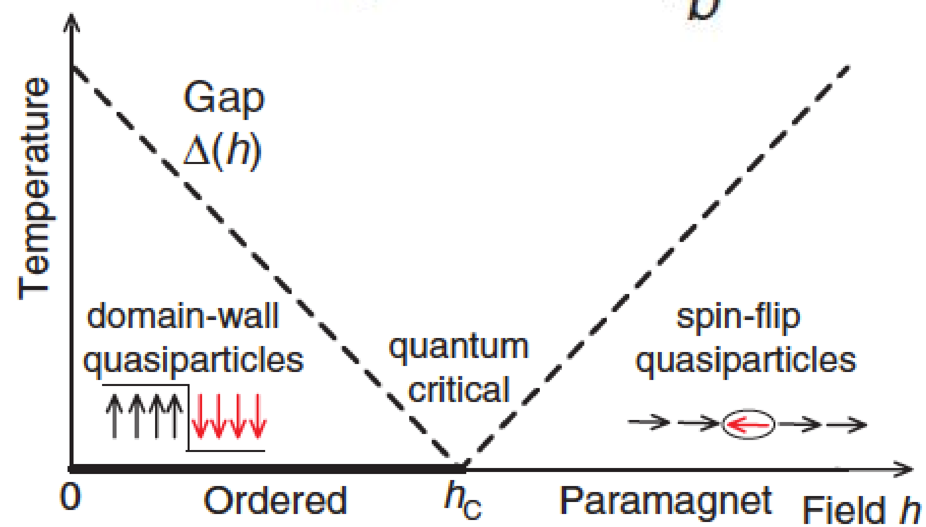
Emergent E_8 Symmetry in an Ising Spin Chain ($CoNb_2O_6$)

$$H = \Sigma_i - J S_i^z S_{i+1}^z - h S_i^x$$



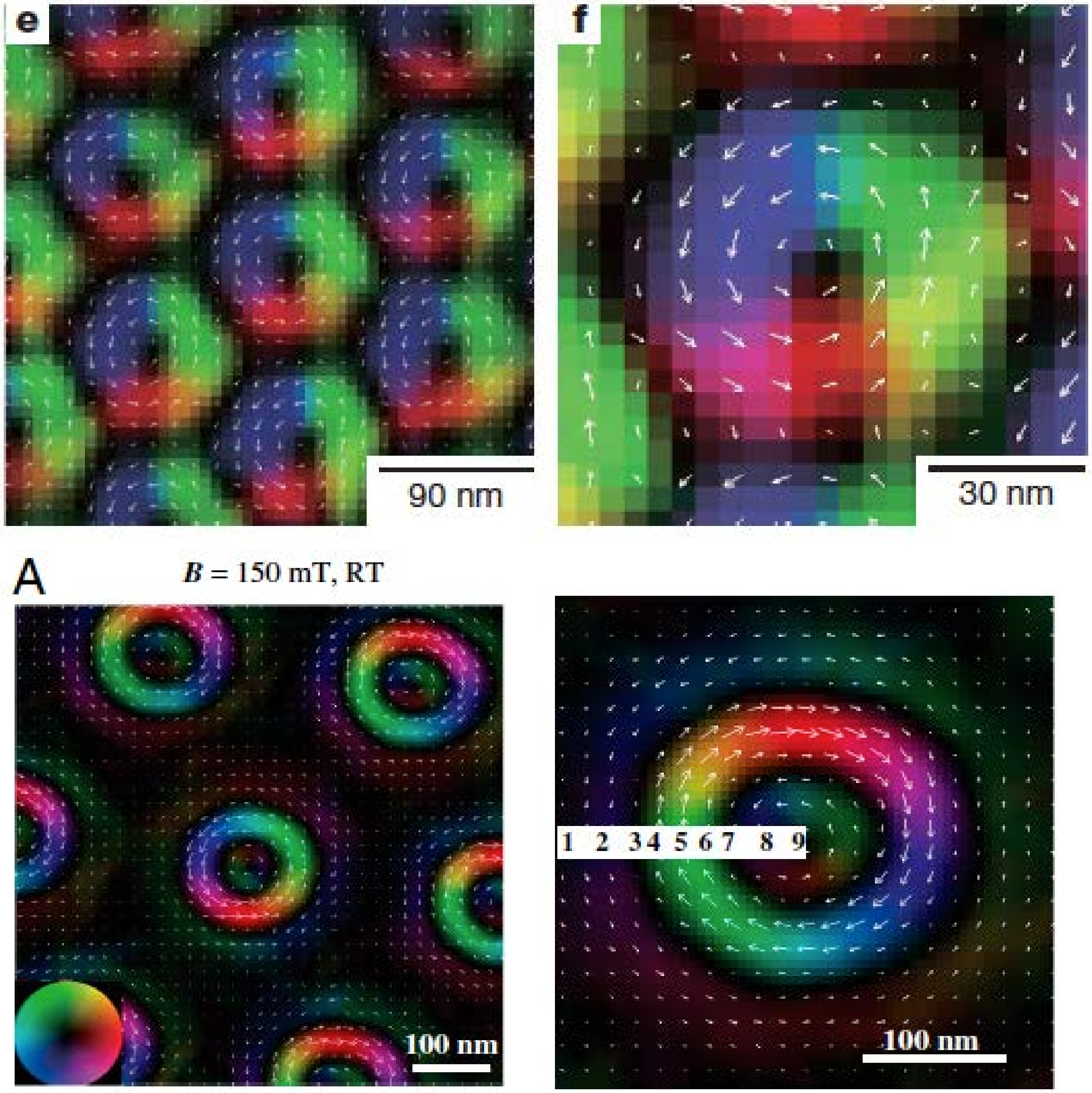






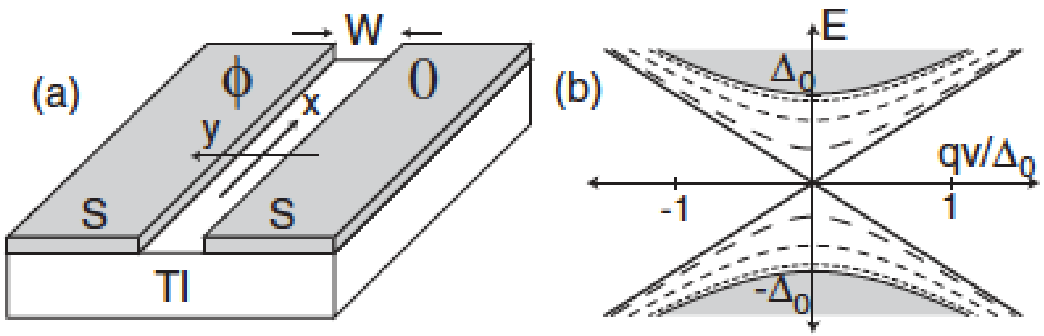
Zamolodchikov, IJMPA (1989)
Coldea *et al*, Science (2010)

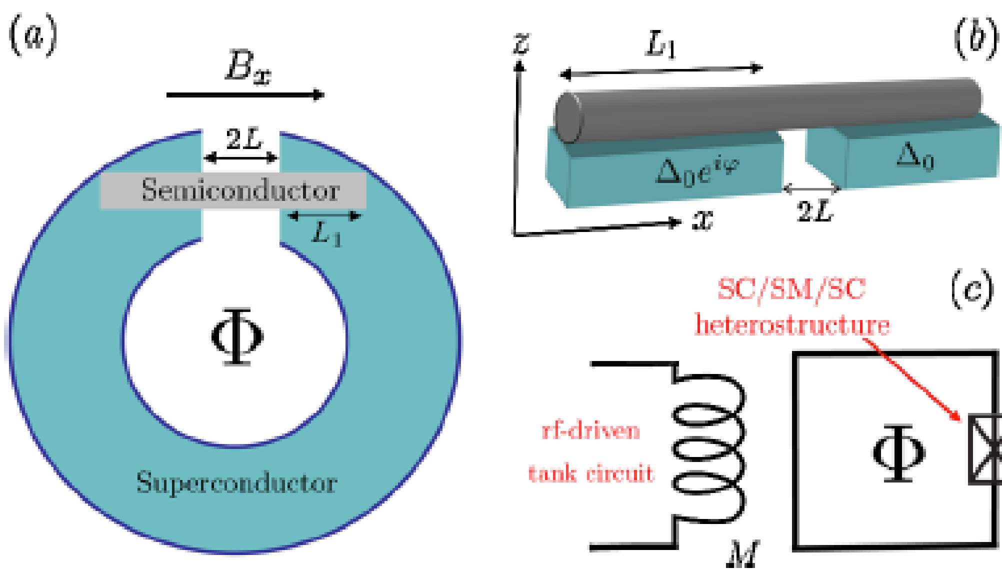
Skyrmions in Co doped FeSi (top) and Sc doped Ba ferrite (bottom) imaged by Lorentz TEM



Yu *et al*, Nature (2010)
Yu *et al*, PNAS (2012)

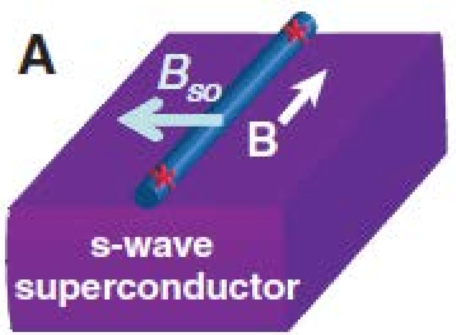
A junction between a topological insulator (or a wire with strong spin-orbit coupling) and a superconductor might localize a Majorana mode at their junction

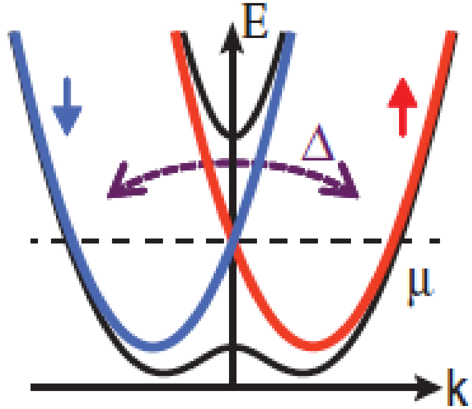


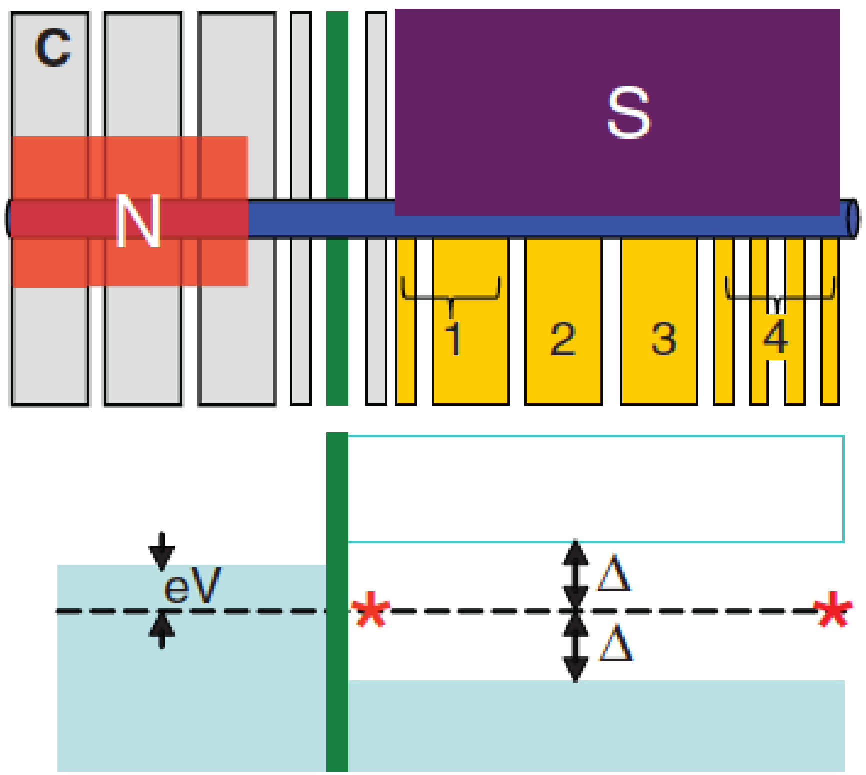


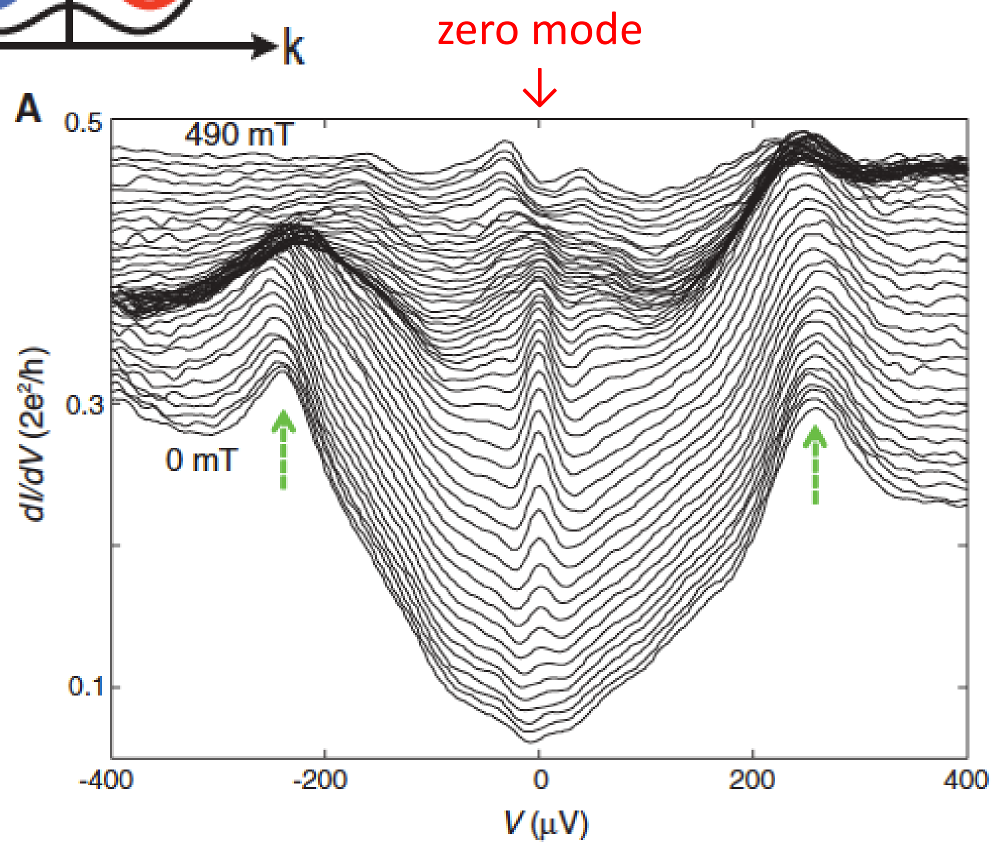
Kitaev, Phys Usp (2001)
Fu & Kane, PRL (2008)
Lutchyn *et al*, PRL (2010)
Oreg *et al*, PRL (2010)

Majorana Fermions in an InSb nanowire on NbTiN ?



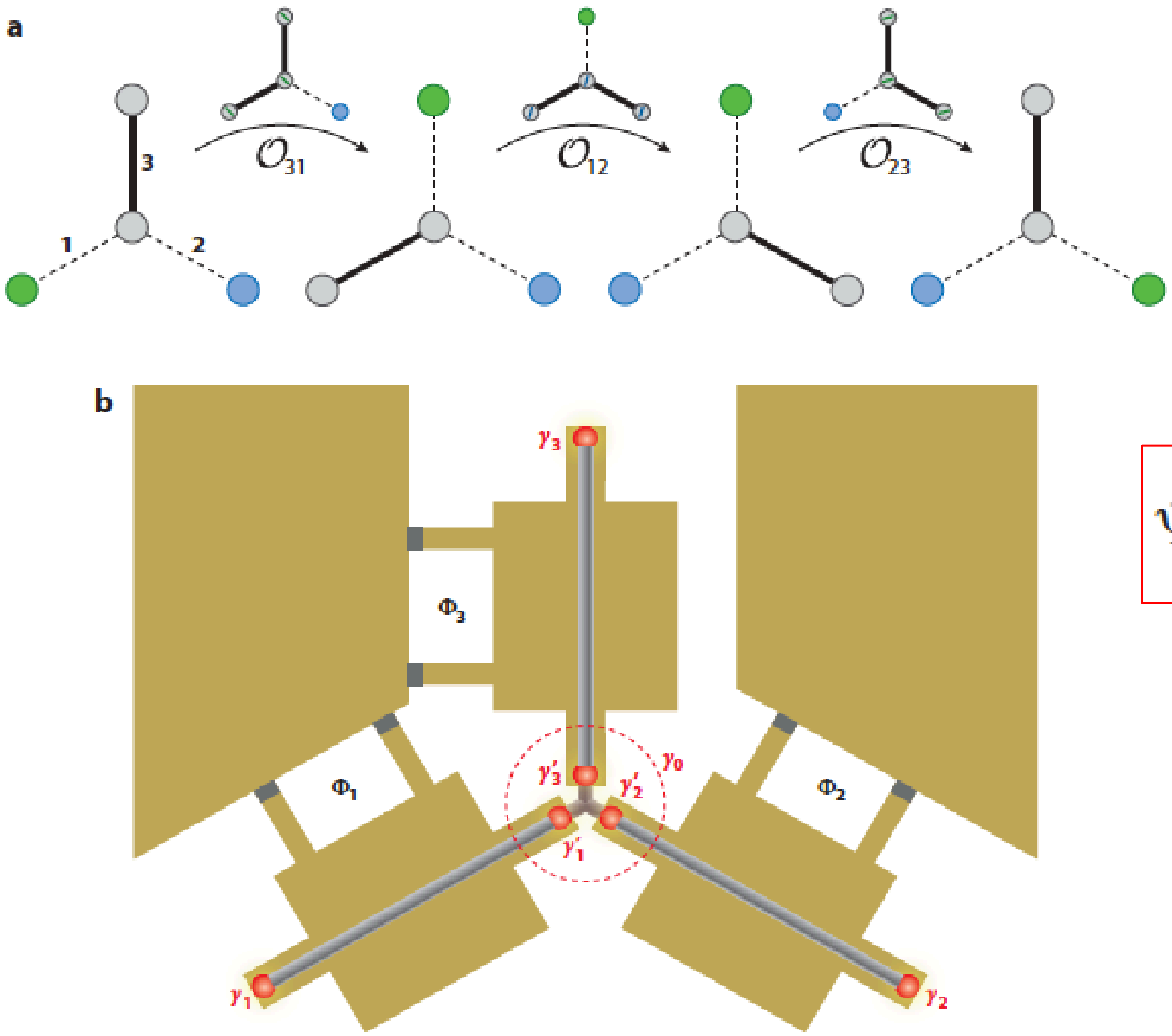






Mourik *et al*, Science (2012)

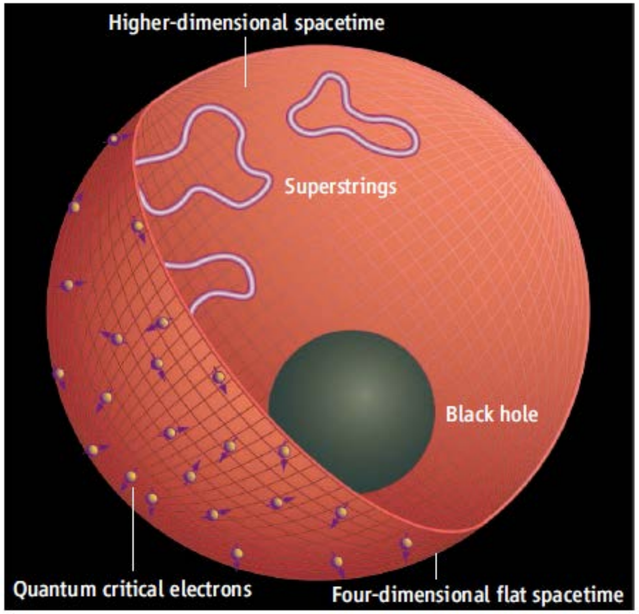
Topological Quantum Computing by Braiding Majorana Fermions



$$\Psi \mapsto \exp\left(i\frac{\pi}{4}\sigma_z\right)\Psi$$

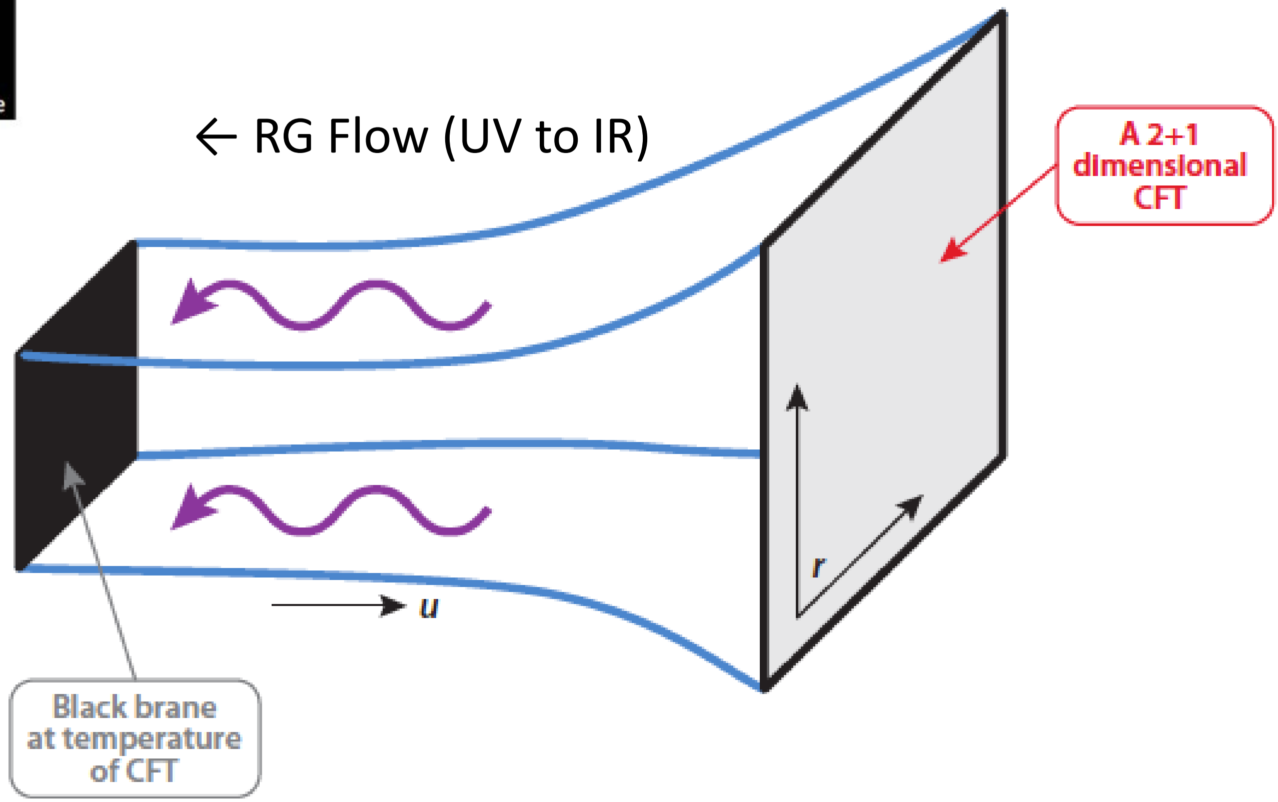
Kitaev, Phys Usp (2001)
Nayak *et al*, RMP (2008)
Alicea, RPP (2012)
Beenakker, ARCMP (2013)

Holographic Approach - AdS/CFT



Map a strong coupling QFT on the boundary of an AdS_4 space-time to a weak coupling gravity dual in the interior with μ and T determined by a "black brane" at the center

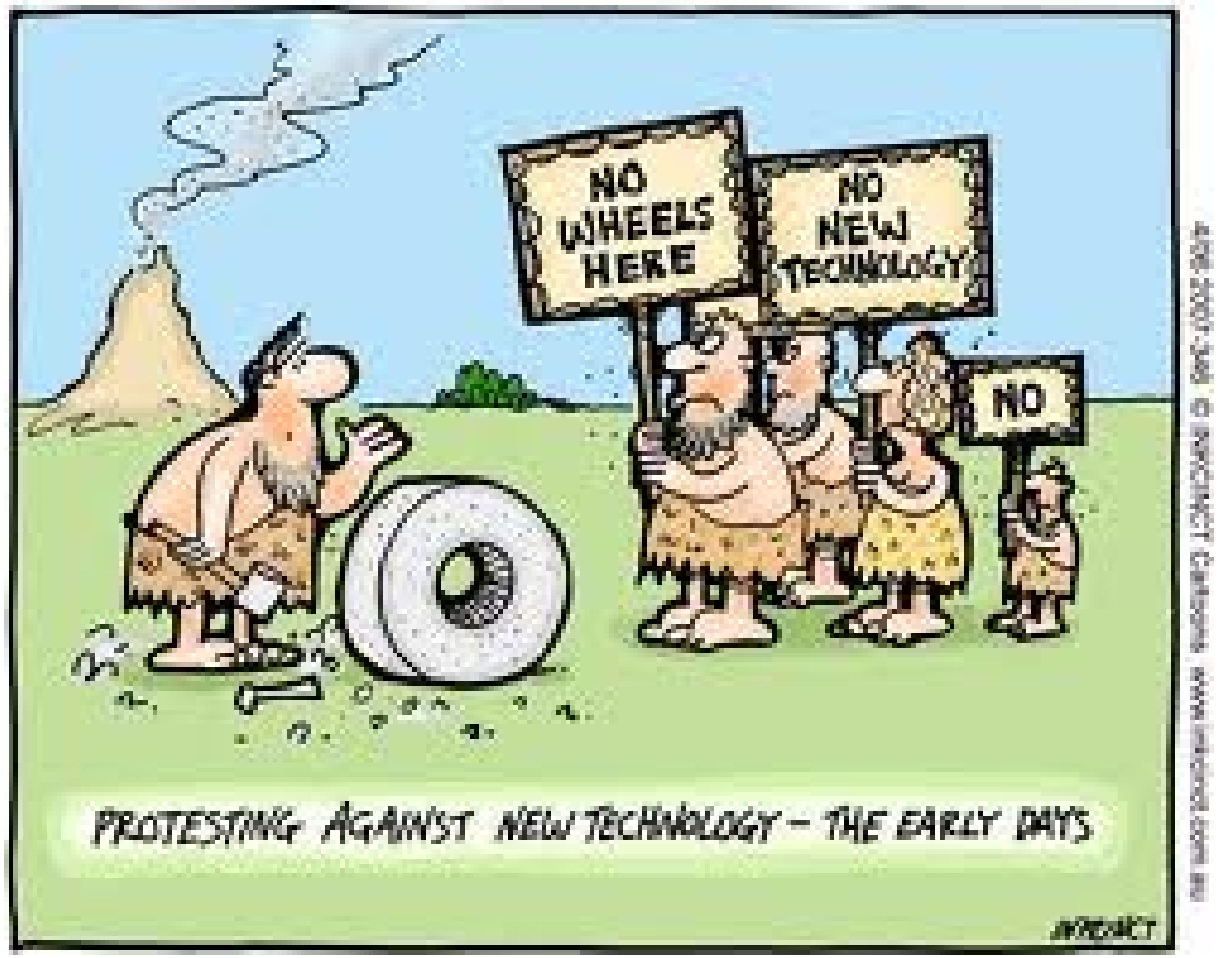
$AdS_2 \rightarrow CFT_1$



Hartnoll, Science (2008); Sachdev, ARCMP (2012)

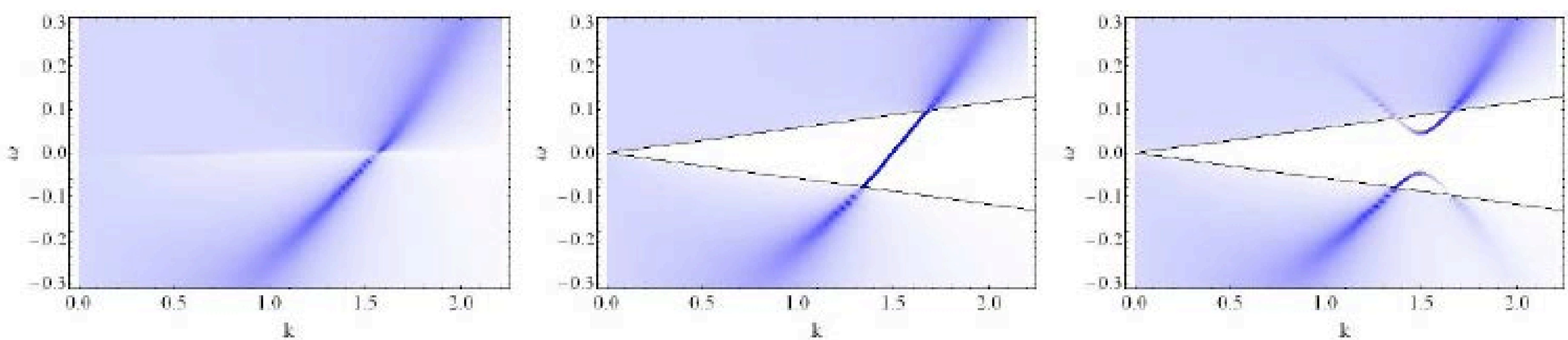
Applications to Condensed Matter Physics (?)

(well, there have always been those resistant to change!)

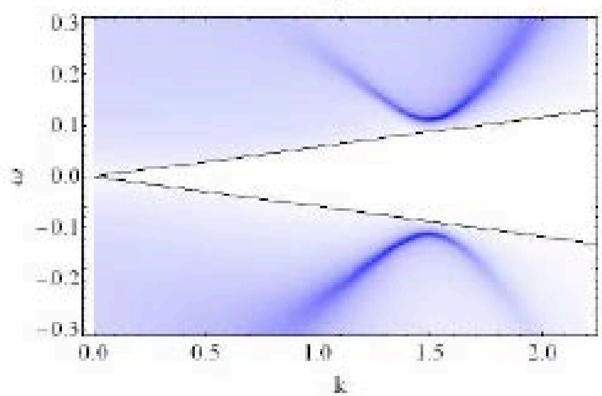


Scalar fields near the “black brane” can condense (holographic superconductivity) leading to a change from $AdS_2 \times R^2 \rightarrow AdS_4$

This change in geometry causes the “light cone” for spinors to open up (plot 2) giving rise to quasiparticles, with a Majorana coupling of the spinors to the scalar opening up a Bogoliubov gap (plots 3 and 4)



Energy vs momentum



Faulkner *et al*, JHEP (2010)

Can AdS/CFT help with condensed matter gauge theories?

(slave bosons for Kondo lattice, RVB for cuprates, etc.)

1. AdS/CFT large N limit is different from a typical condensed matter physics large N limit

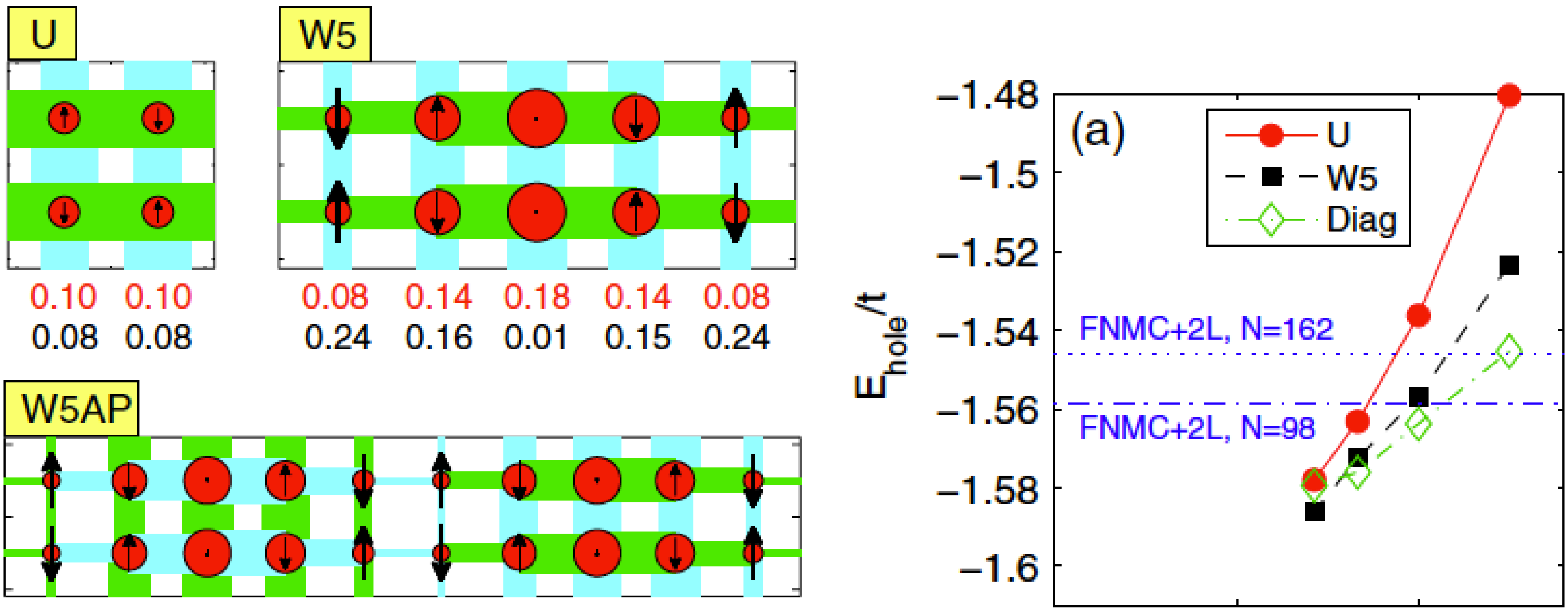
2. Condensed matter gauge fields are typically constraint fields

   In particular, they do not have a "kinetic" energy
   (that is, one is at "infinite" coupling)

3. Can we find an AdS dual to such theories?

Nayak, Phys Rev Lett (2000)
Lee, Nagaosa, Wen, Rev Mod Phys (2006)

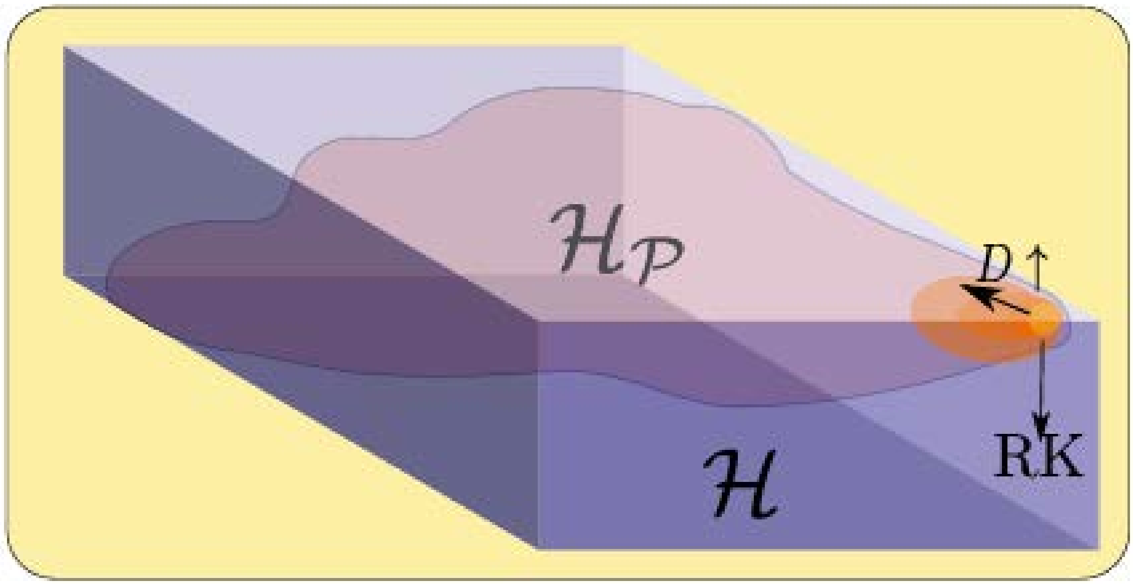
iPEPS simulations of t-J model for doped cuprates (lower variational free energy than fixed node QMC)



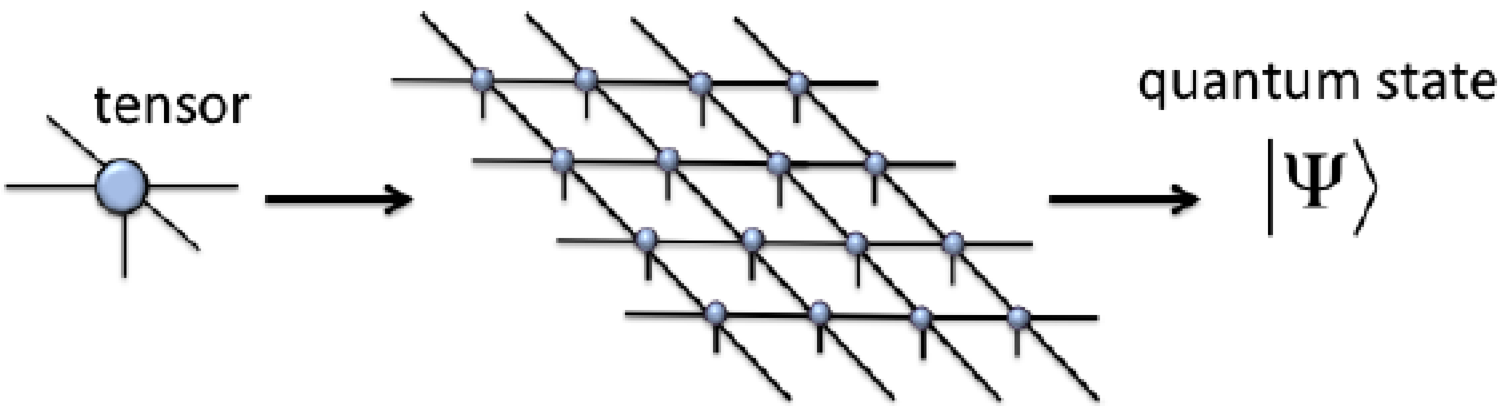
U – uniform antiferromagnet (AF) + d-wave superconductor (dSC)
W5 – modulated AF + dSC + charge density wave (CDW)
W5AP – modulated AF + antiphase dSC + CDW

Corboz *et al*, PRL (2014)

Tensor Networks for Lattice Gauge Theories



H – Hilbert space
H_P – physical Hilbert space
D – low energy sector
(area law for entanglement)



Tagliacozzo *et al*, PRX (2014); Rico *et al*, PRL (2014);
Buyens *et al*, PRL (2014); Banuls *et al*, JHEP & PoS (2013)