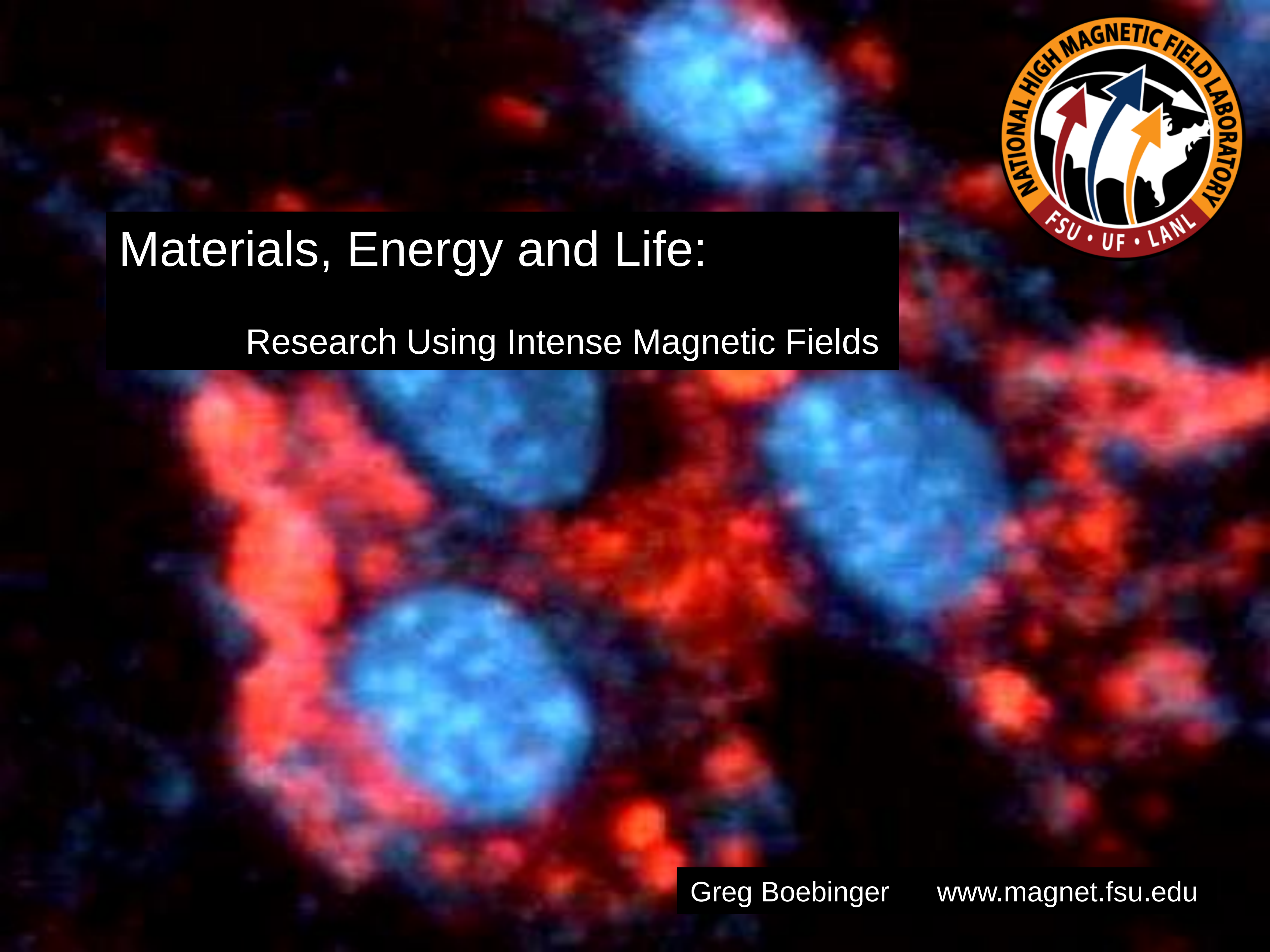


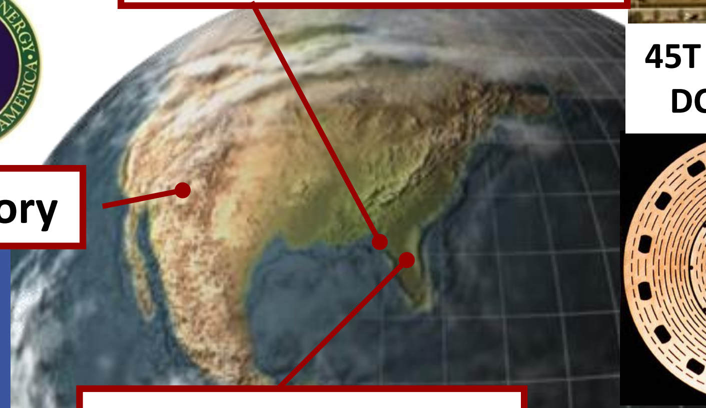
Materials, Energy and Life:

Research Using Intense Magnetic Fields

Greg Boebinger www.magnet.fsu.edu

National High Magnetic Field Laboratory

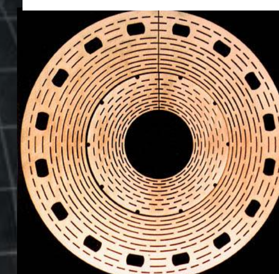
Florida State University

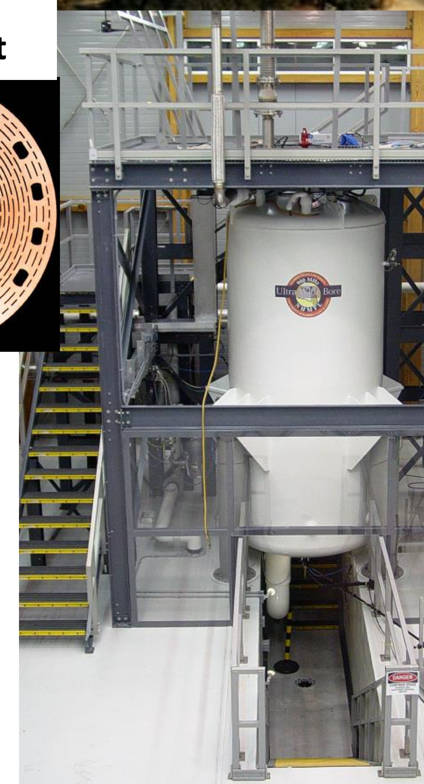


Los Alamos National Laboratory

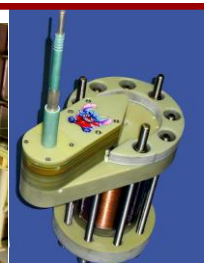
University of Florida

45T Hybrid DC Magnet





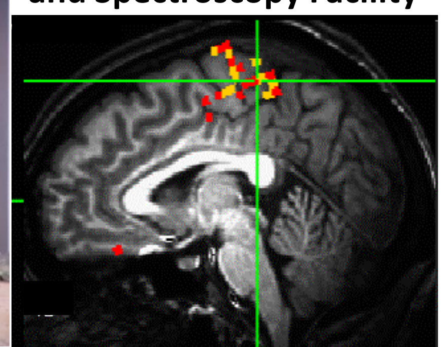
900MHz, 105mm bore
21T NMR/MRI Magnet

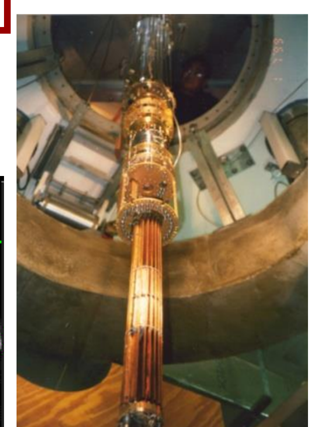


101T Pulse Magnet
15mm bore

11.4T MRI Magnet
400mm warm bore

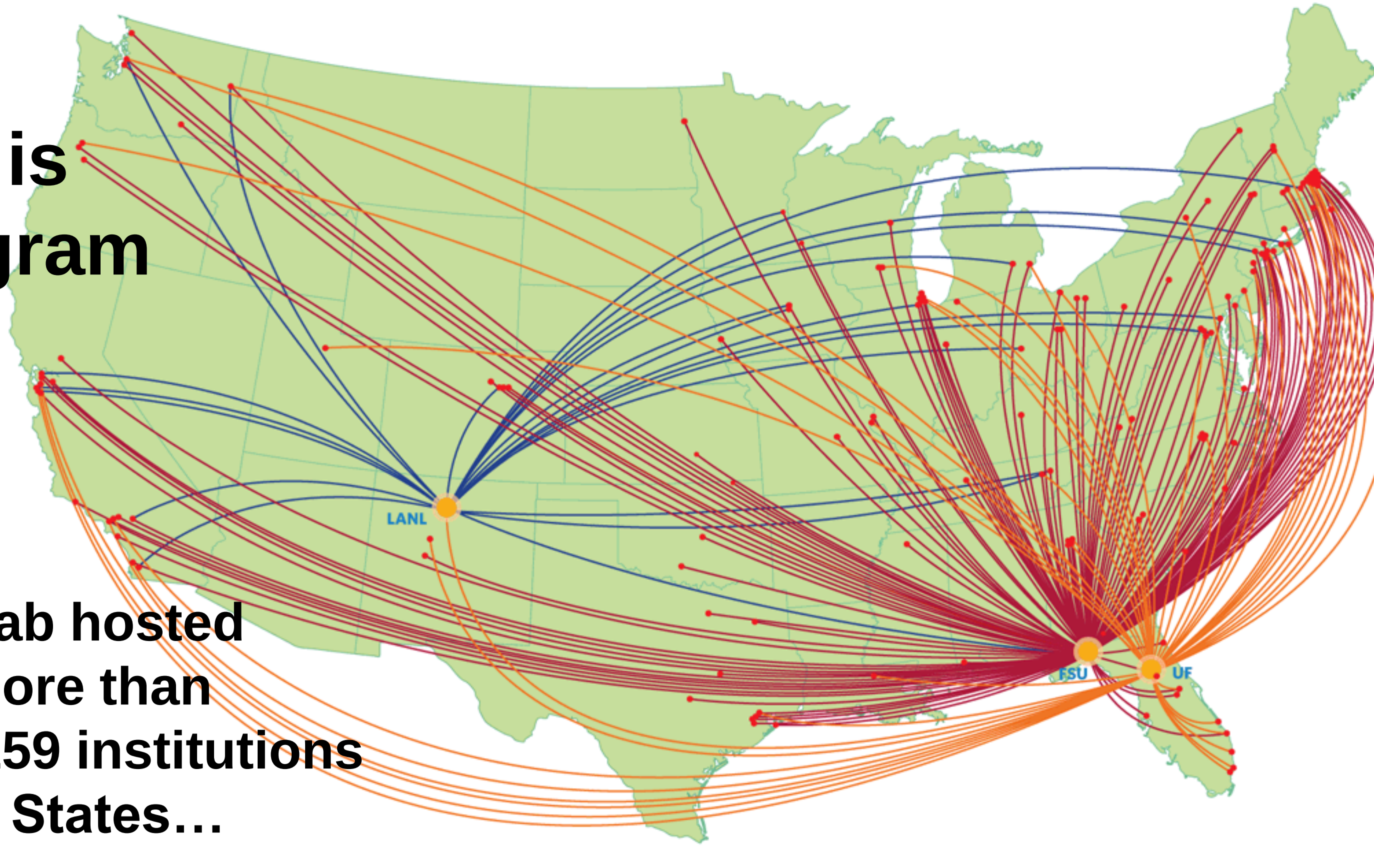
Advanced Magnetic Resonance Imaging and Spectroscopy Facility





High B/T Facility
17T, 6weeks at 1mK

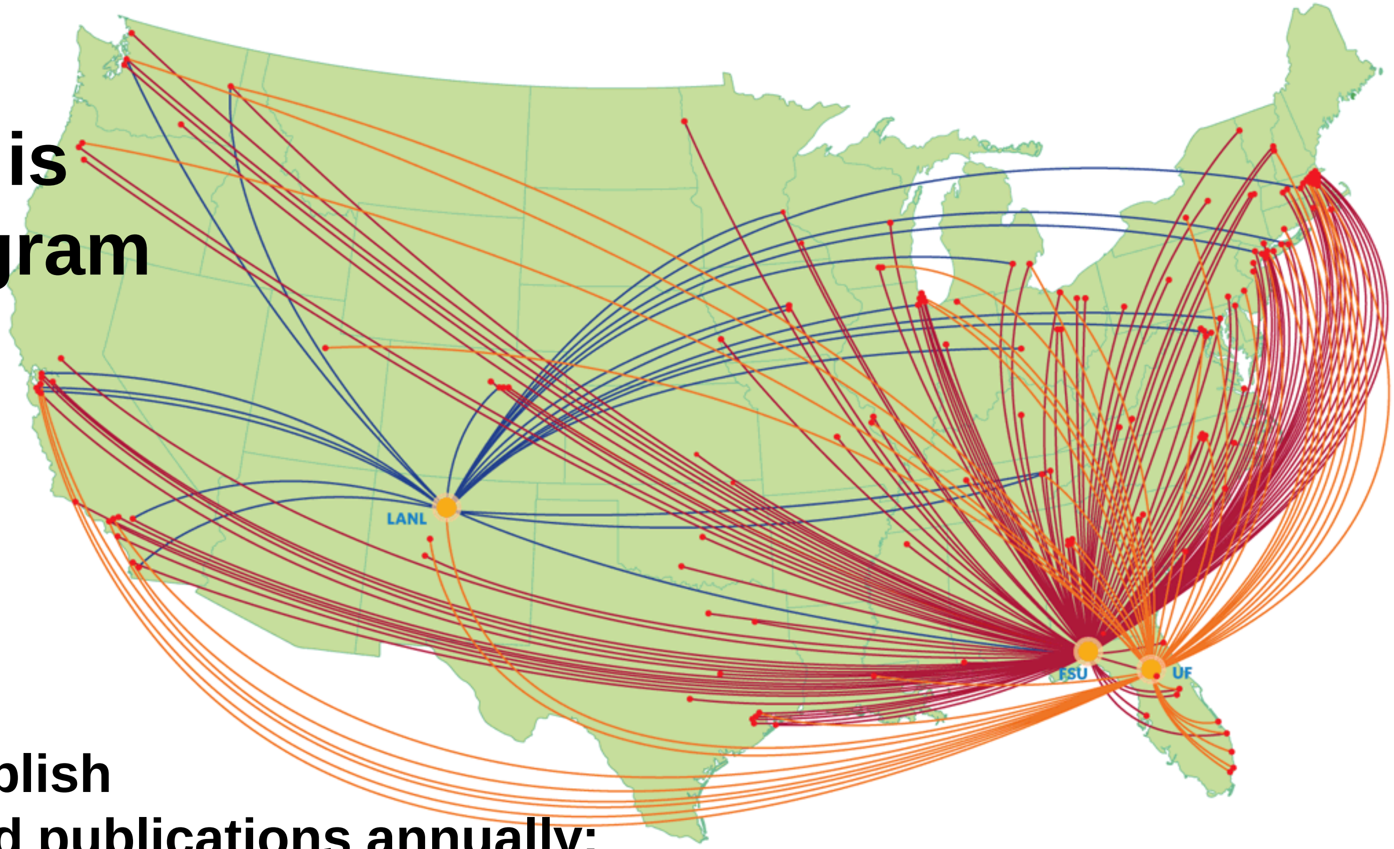
The MagLab is its User Program



In 2012, the MagLab hosted experiments by more than 1350 users from 159 institutions across the United States…

…and a total of 277 institutions throughout the world.

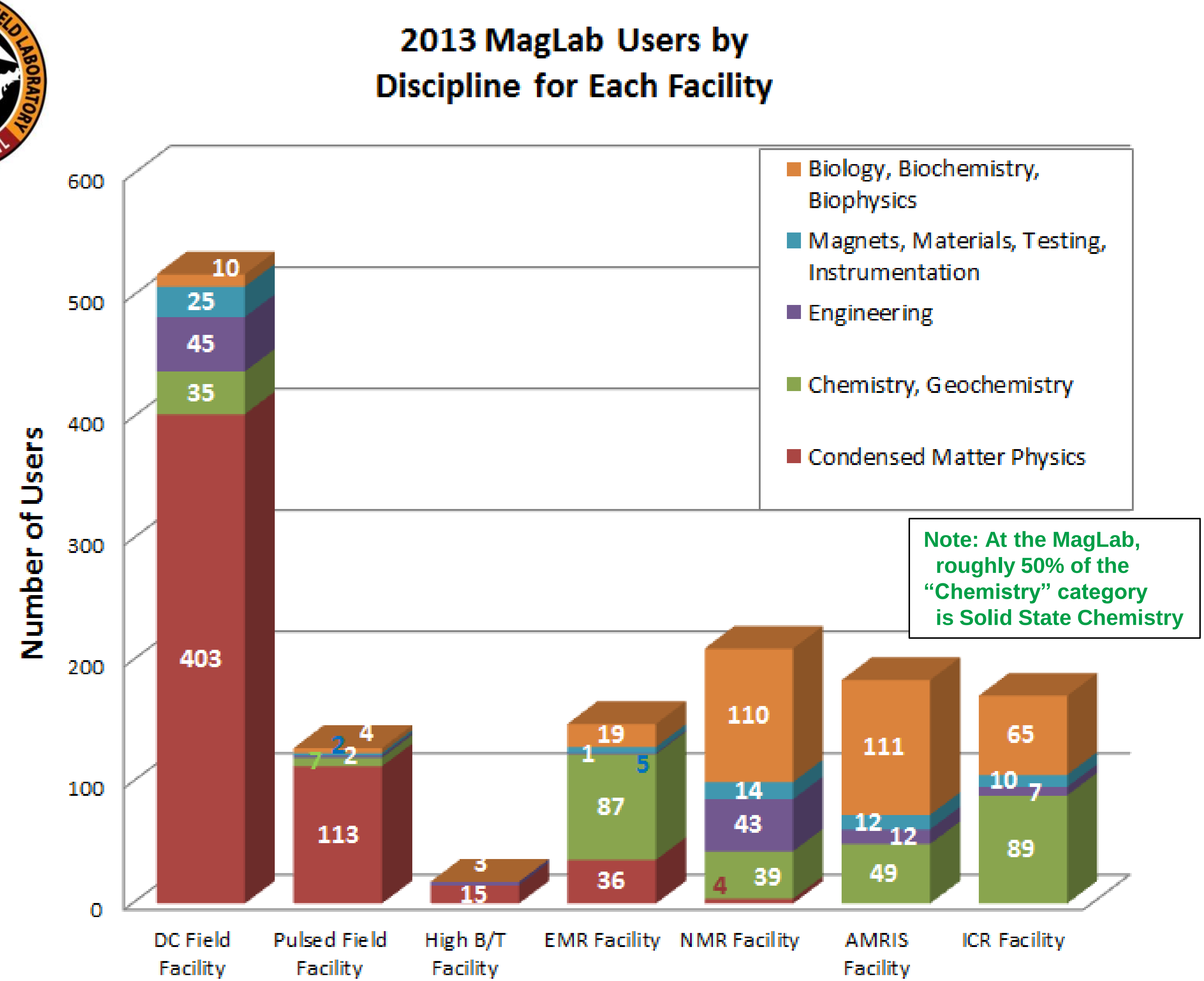
The MagLab is its User Program



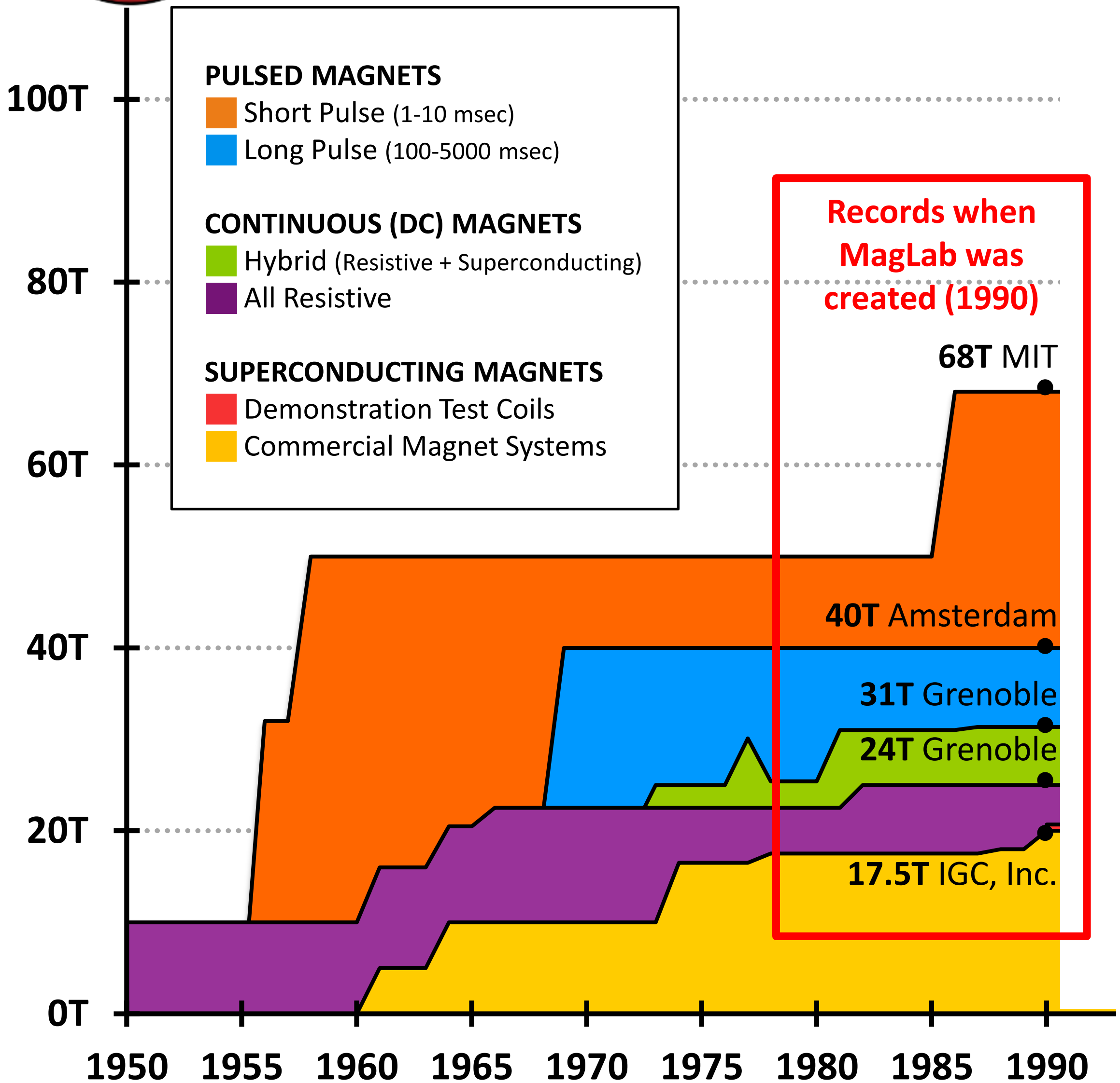
MagLab users publish about 440 refereed publications annually:

<u>**2009-2013 Publications**</u>

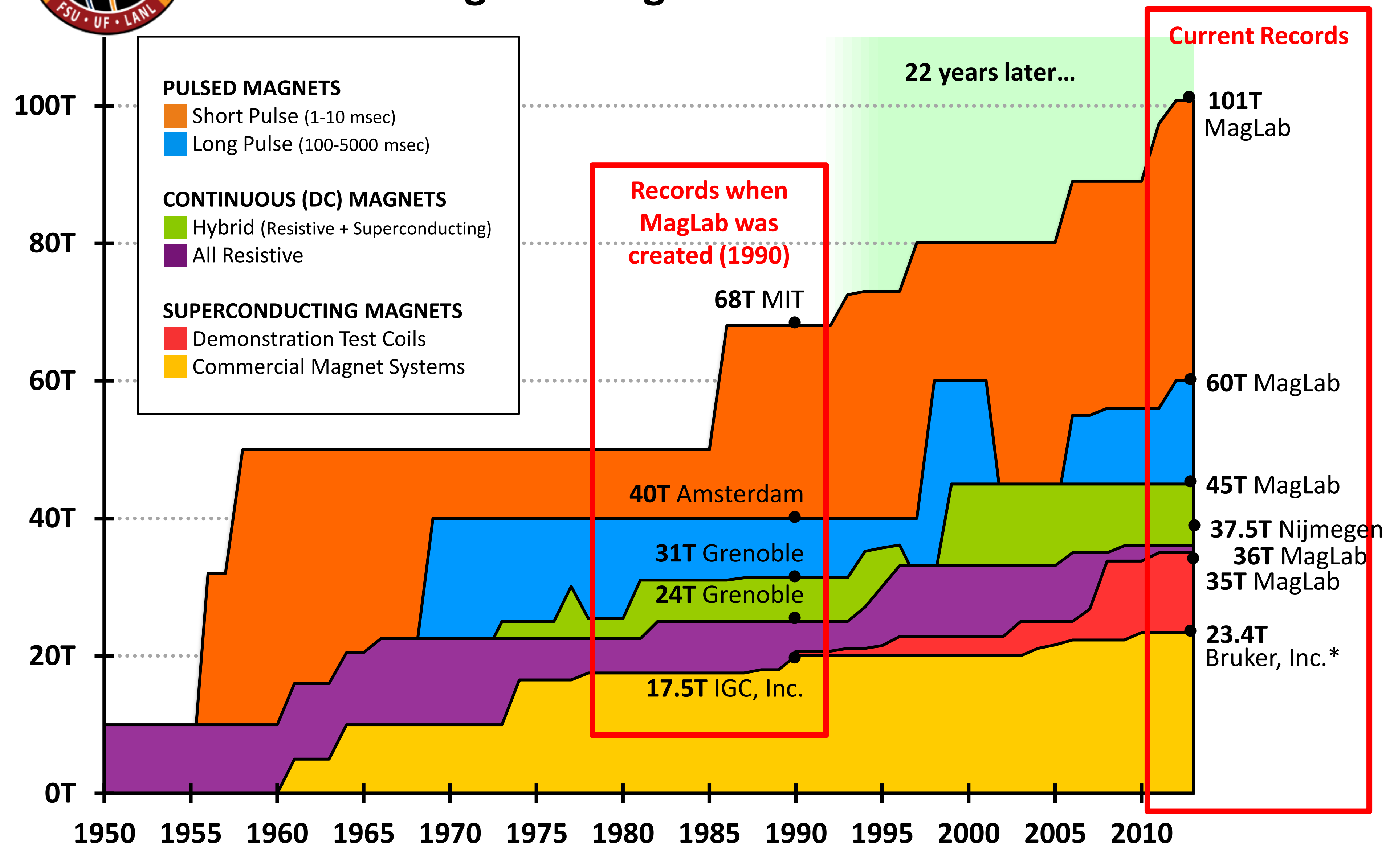
2200	**Total Publications**
28	***PNAS***
63	***Nature Journals***
147	***Physical Review Letters***
318	***Physical Review B***
47	***PRB (Rapid Comm)***
59	***JACS***


2013 MagLab Users by Discipline for Each Facility
Number of Users
600
500
400
300
200
100
0
Biology, Biochemistry, Biophysics
Magnets, Materials, Testing, Instrumentation
Engineering
Chemistry, Geochemistry
Condensed Matter Physics
Note: At the MagLab, roughly 50% of the "Chemistry" category is Solid State Chemistry
10
25
45
35
403
4
2
2
7
113
3
15
19
1
5
87
36
110
14
43
4
39
111
12
12
49
65
10
7
89
DC Field Facility
Pulsed Field Facility
High B/T Facility
EMR Facility
NMR Facility
AMRIS Facility
ICR Facility

MagLab Technology Leads the World for Highest Magnetic Fields Achieved

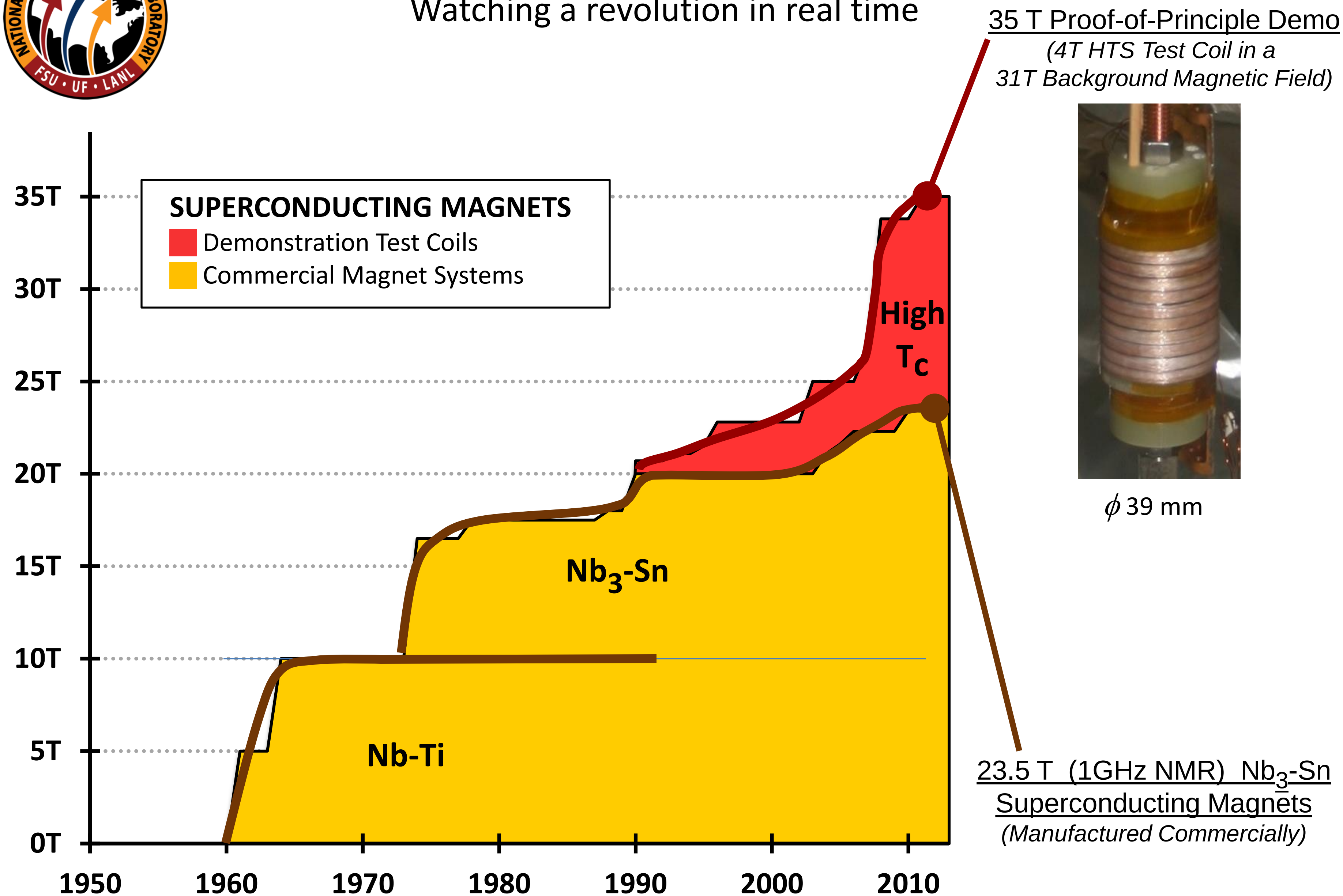


MagLab Technology Leads the World for Highest Magnetic Fields Achieved

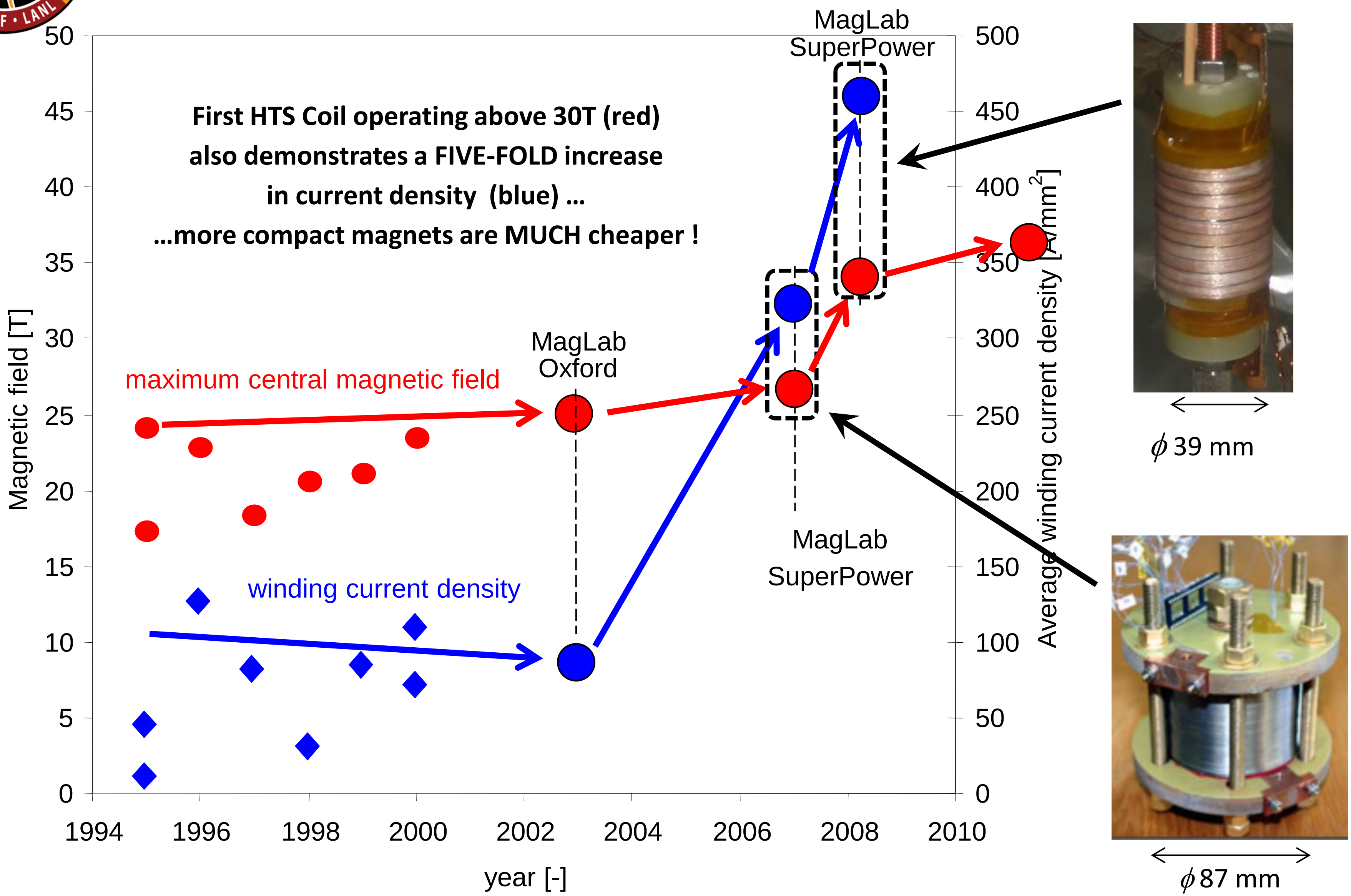


Superconducting Magnet Technology

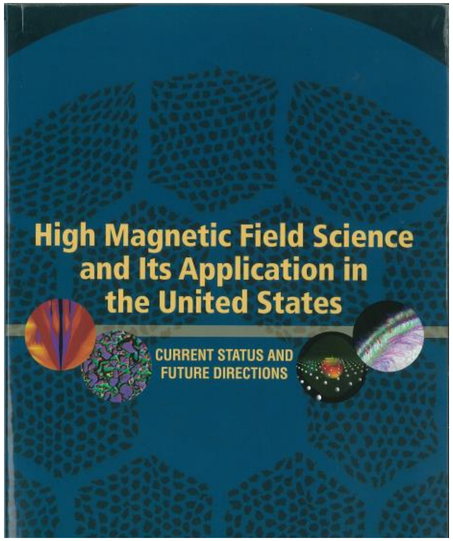
Watching a revolution in real time



A Decade of MagLab Collaborations on High-Tc Test Coils



The 2013 National Research Council "MagSci" Report is extremely supportive of the MagLab



EXECUTIVE SUMMARY:

Continued advancement in high-magnetic-field science requires substantial investments in magnets with enhanced capabilities.

The NHMFL in the United States is presently considered to be the world leader in both advancing magnet technology and high-field science.

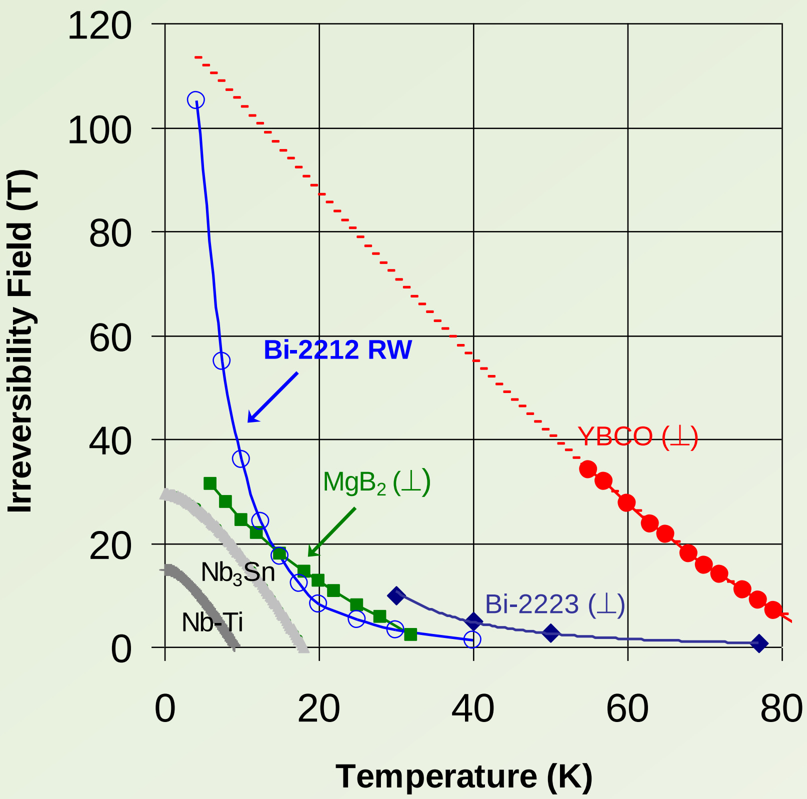
Magnet projects must include materials development and magnet component test-bed facilities

Most MagSci magnets require HTS materials and technology development

MagSci Recommended Magnet Projects
1: 30-37 T (1.3 – 1.6 GHz) NMR Magnet
2: 150 T (msec) pulse for thermal transport & optical experiments
3a: 40 T pulse, 30 sec rep rate for neutrons and/or x-rays 3b: 40 T HTS SC magnet for neutrons (and/or x-rays) 3c: 25-35T Series Connect Hybrid for neutrons and/or x-rays
4: Regional 32 T – 40T SC facilities (including at the MagLab)
5: 60 T hybrid magnet
6: 20 T large-animal & human MRI
7: Axion & other detectors, fusion, particle accelerators, radiotherapy.

An important sidebar……

- Higher T_c superconducting magnets are a persistent dream of the condensed matter community……
- Cuprates can superconduct up to 130 K
  - Applications in liquid nitrogen at 77 K are still very rare
  - More than 95% of all superconductor sold is still Nb-Ti with T_c of 9 K
- Applications are determined by high J_c, J_e and H_{irr} rather than by high T_c
- Conductors of exotic materials are difficult!



The dream: escape from bottom left corner to the upper and the right……

ITER has made tonnage breakout for Nb_3Sn – both CERN and the MagLab are assisting ITER

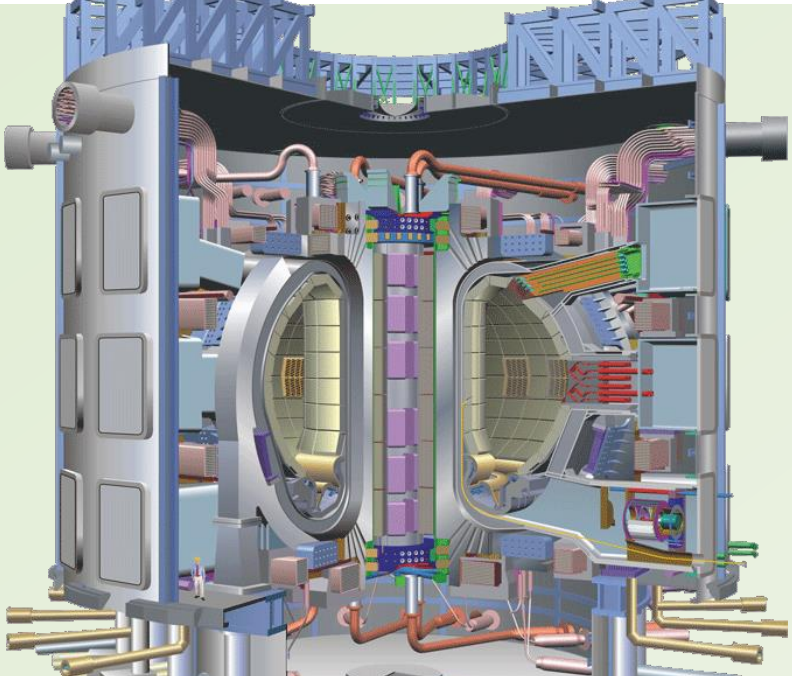
SUPERCONDUCTIVITY IN Nb_3Sn AT HIGH CURRENT DENSITY IN A MAGNETIC FIELD OF 88 kgauss

J. E. Kunzler, E. Buehler, F. S. L. Hsu, and J. H. Wernick
Bell Telephone Laboratories, Murray Hill, New Jersey
(Received January 9, 1961)

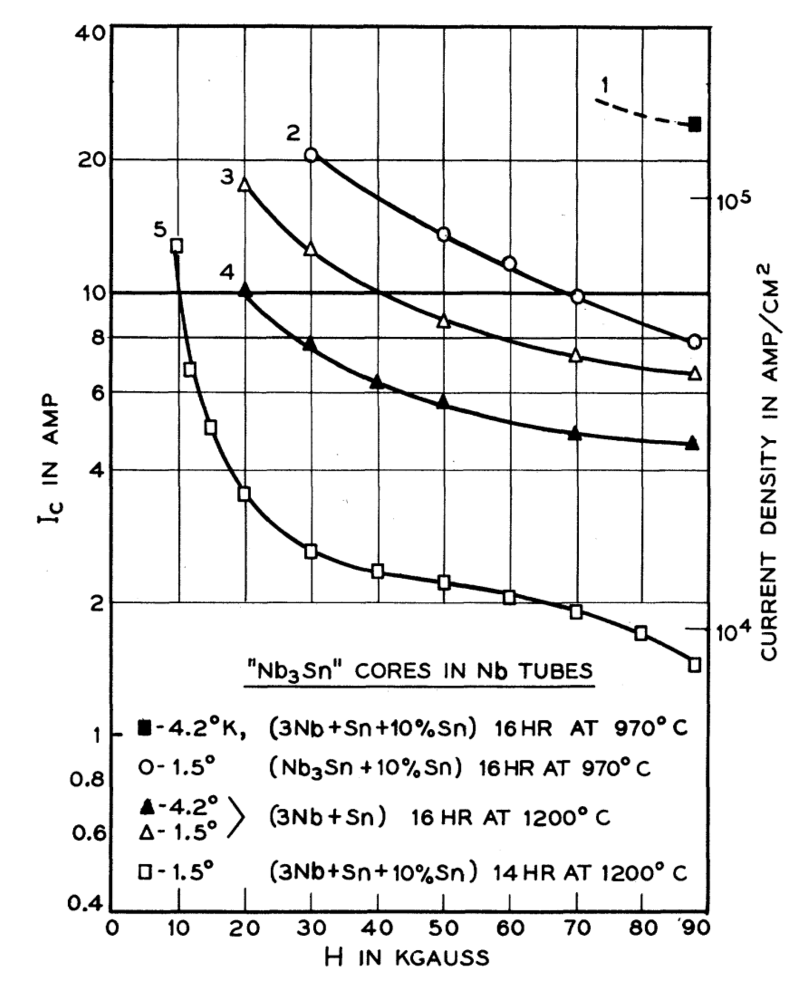
We have observed superconductivity in Nb_3Sn at average current densities exceeding 100 000 amperes/cm² in magnetic fields as large as 88 kgauss. The nature of the variation of the critical current (the maximum current at a given field for which there is no energy dissipation) with magnetic field shows that superconductivity extends to still higher fields. Existing theory does not account for these observations. In addition to some remarkable implications concerning superconductivity, these observations suggest the feasibility of constructing superconducting solenoid magnets capable of fields approaching 100 kgauss, such as are desired as laboratory facilities and for containing plasmas for nuclear fusion reactions.[1,2]

The highest values of critical magnetic fields previously reported for high current densities

89

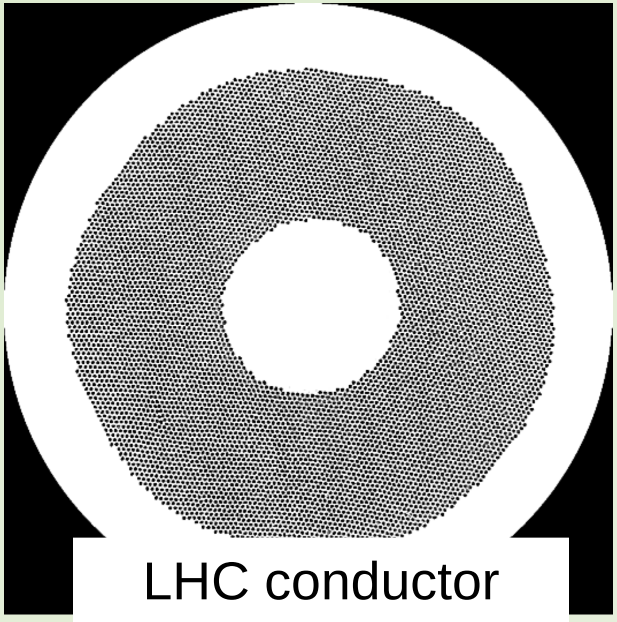


ITER uses 600 tonnes of Nb_3Sn

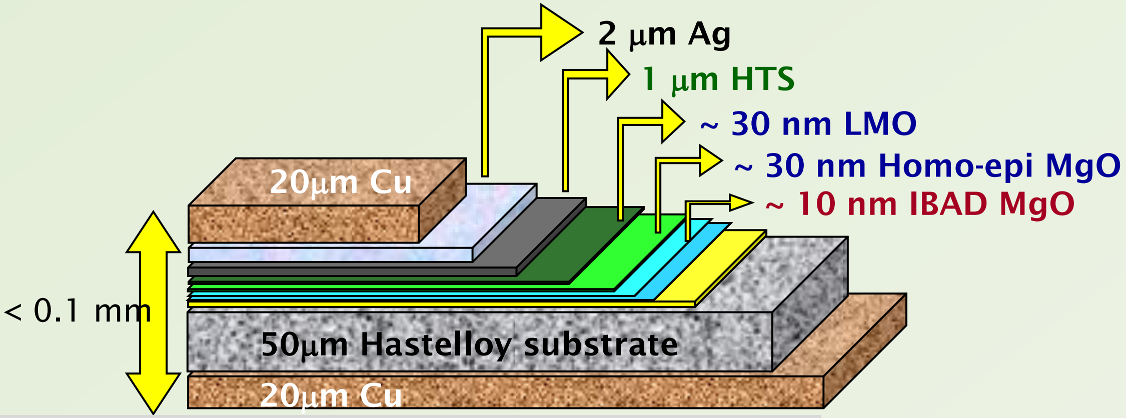


Phys Rev Letts **6**, 89 (1961), submitted **January 9, 1961**, published **February 1, 1961**!

HTS Magnet Conductors in 2012



Nb47Ti conductor- thousands of 8 μm diameter Nb47Ti filaments in pure Cu (0.8 mm dia.), easily cabled to operate at 10-100 kA

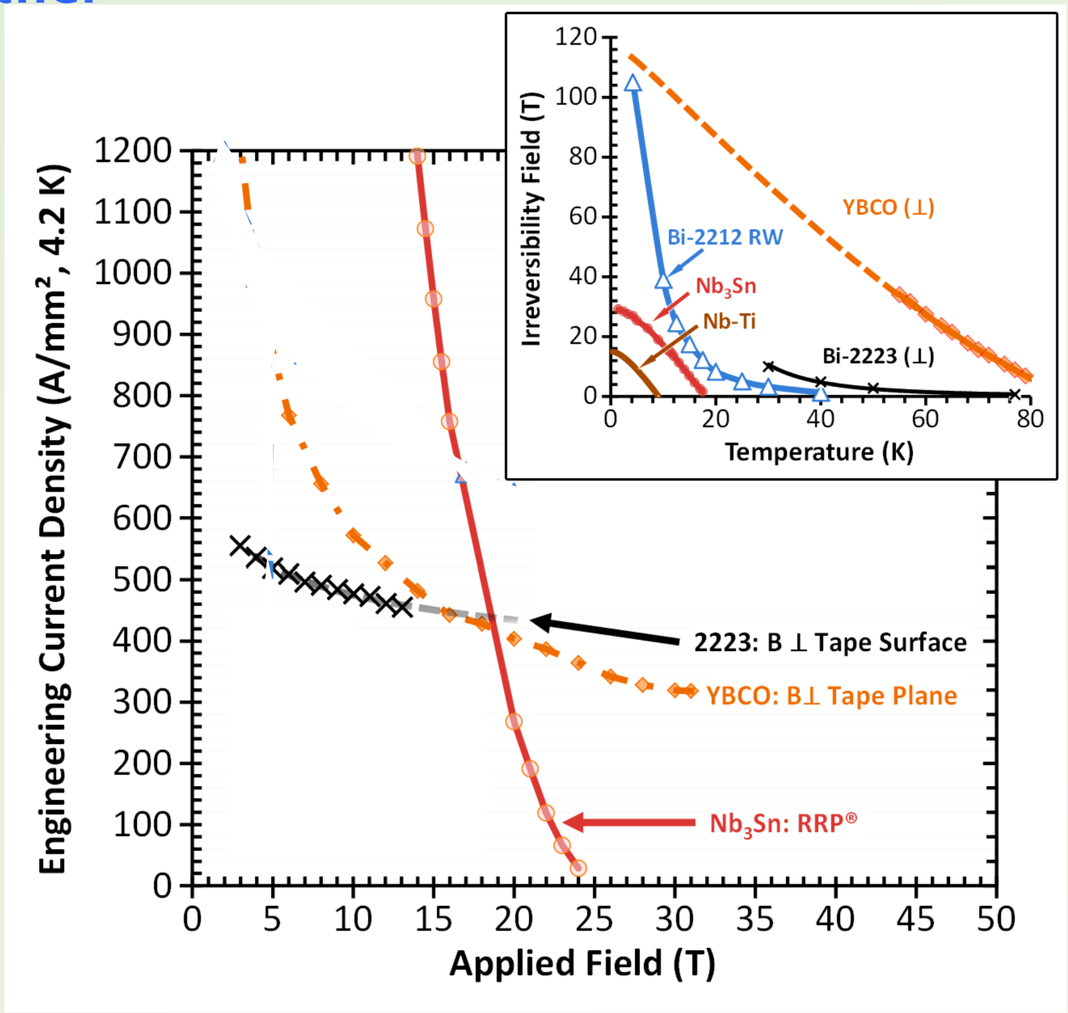


2. REBCO coated conductor – extreme texture (single crystal by the mile) – for maximum GB transparency (2007)

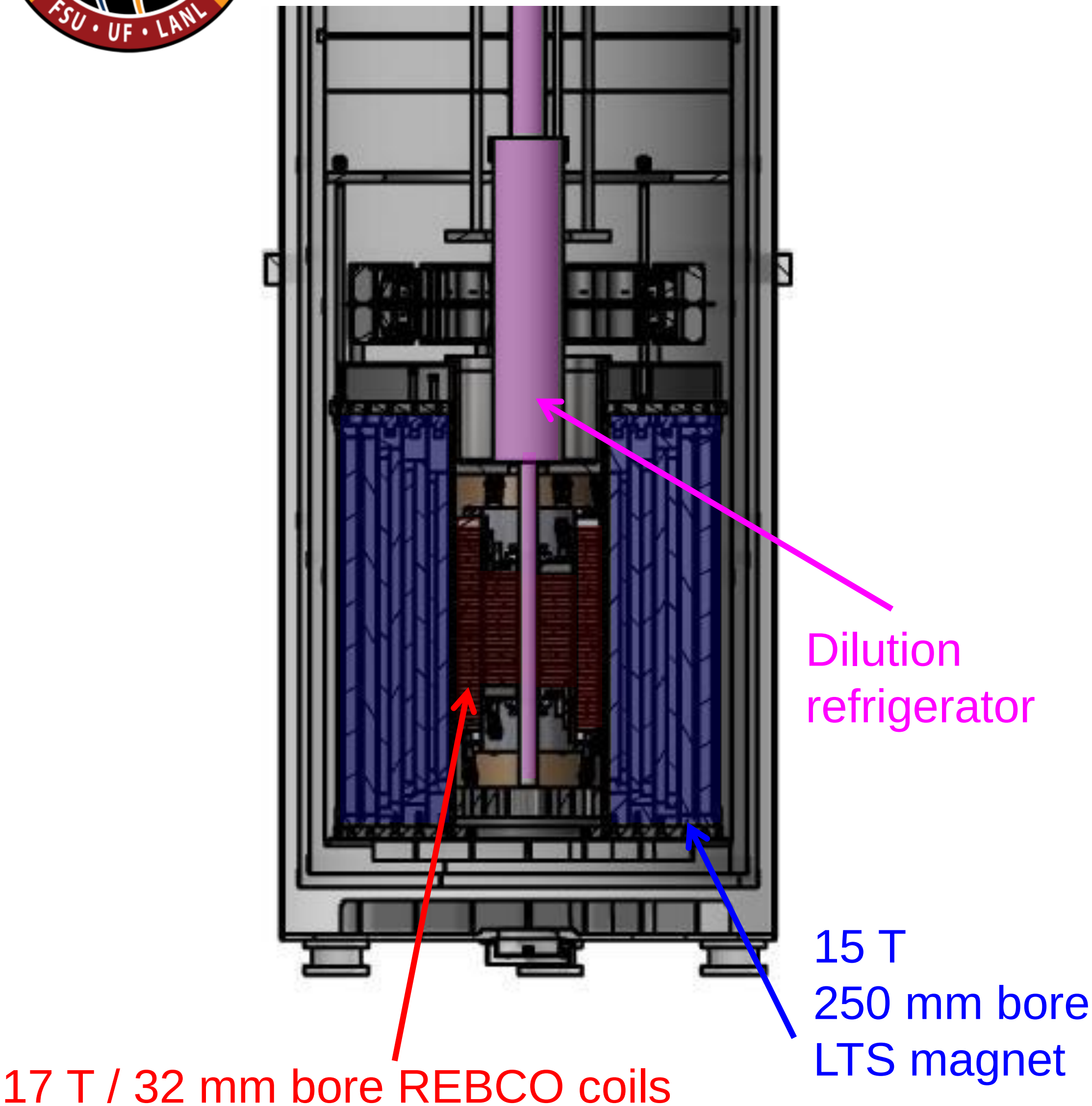
1. Bi-2223 – the first HTS conductor – uniaxial texture developed by deformation and reaction (1995- today)

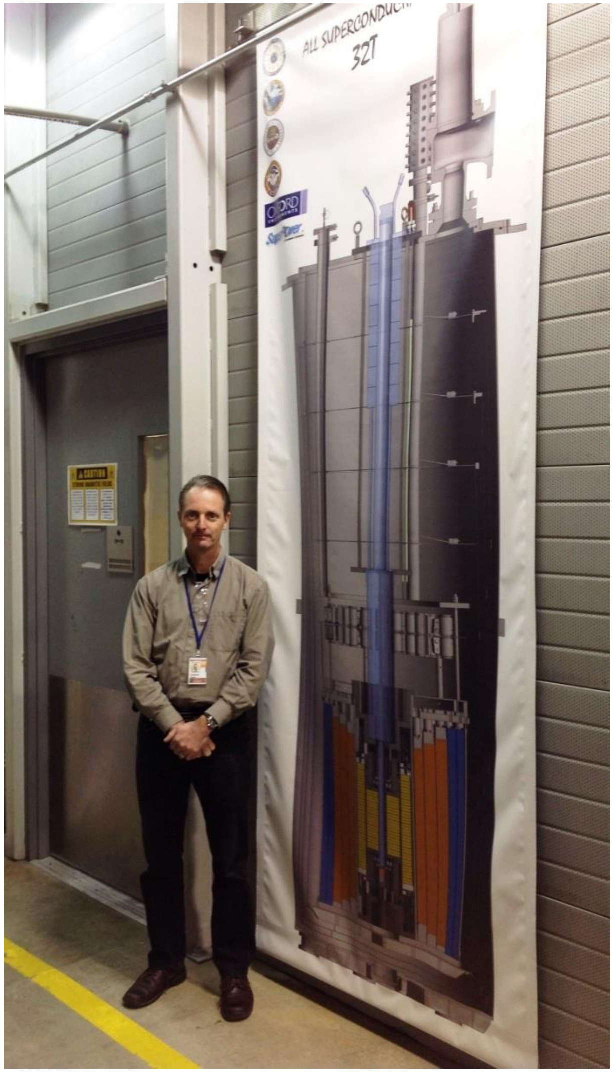
An important sidebar……

- Applications are determined by high J_c, J_e and H_{irr} rather than by high T_c
- Conductors of exotic materials are difficult!

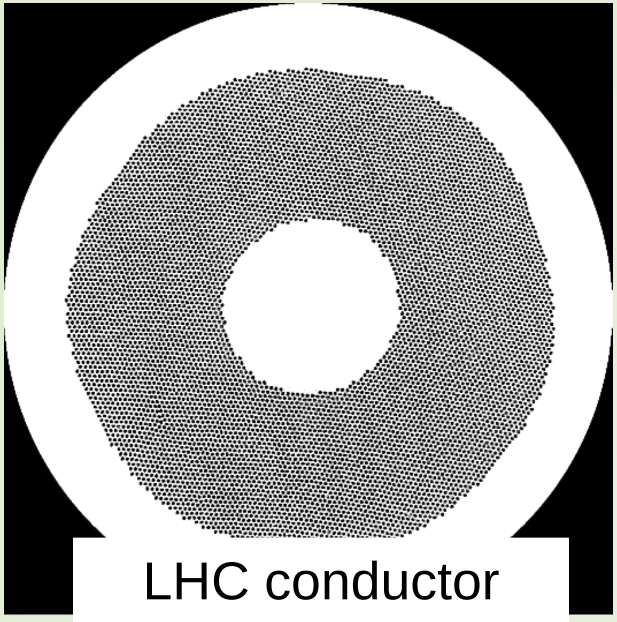


High-Tc Superconducting Magnet Technology: Building a 32T All-Superconducting REBCO Magnet

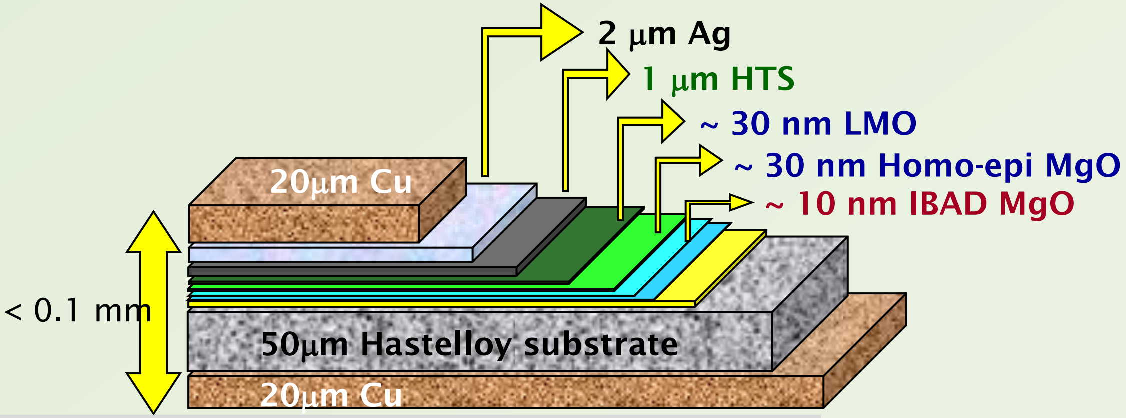




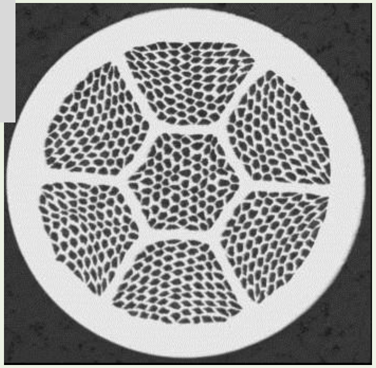
HTS Magnet Conductors Now



Nb47Ti conductor- thousands of 8 μm diameter Nb47Ti filaments in pure Cu (0.8 mm dia.), easily cabled to operate at 10-100 kA



4. REBCO coated conductor – extreme texture (single crystal by the mile) – for maximum GB transparency (2007)

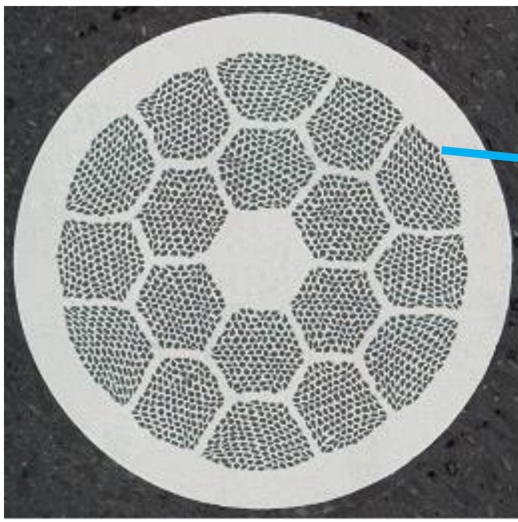


3. Bi-2212 – high J_c without macroscopic texture (2012)!

1. Bi-2223 – the first HTS conductor – uniaxial texture developed by deformation and reaction (1995- today)

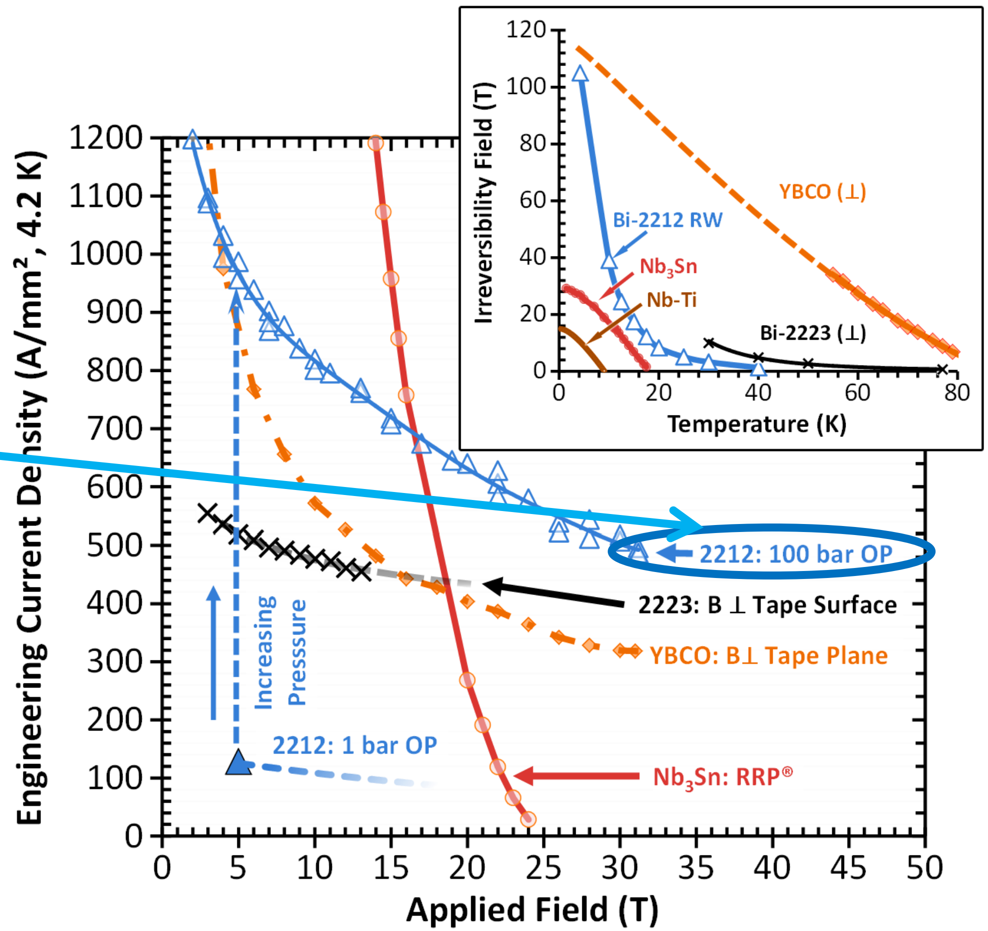
Bi-2212 –developed by NHMFL, DOE-HEP labs and Oxford Superconducting Technology (OST) – twisted, round, filamentary conductor fully competitive with any other HTS in J_E

- Fine filament twisted conductor is ideal for high homogeneity NMR and accelerator magnets



From the cover of the MagSci report

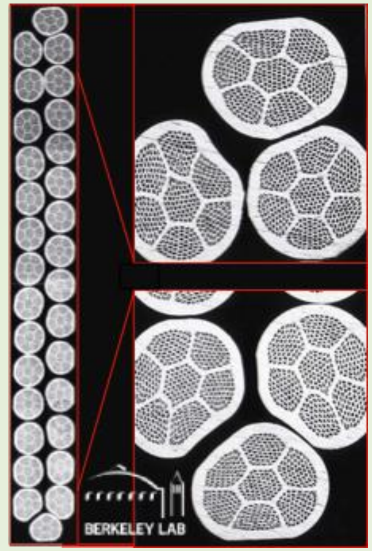
(DCL et al. arXiv 1305.1269 – to appear Nature Materials 2014)

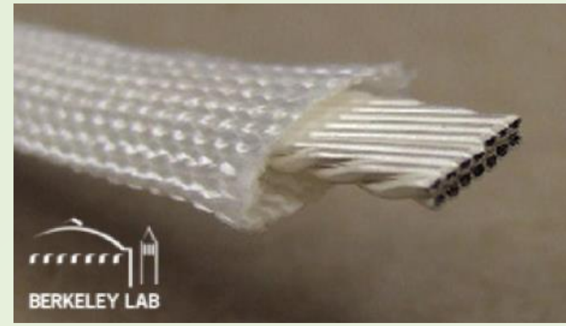


Bi-2212 conductor support by DOE–OHEP: an outcome of Bismuth Strand and Cable Collaboration (BSCCo)

Large magnets are better protected when cabled:
Substantial R&D required to develop HTS cabling technologies

- Cables vital for 60 T hybrid at the NHMFL, an LHC energy upgrade and a neutrino machine based on a Muon Collider at Fermilab
- Easy path to 2212 cables through the standard Rutherford cable





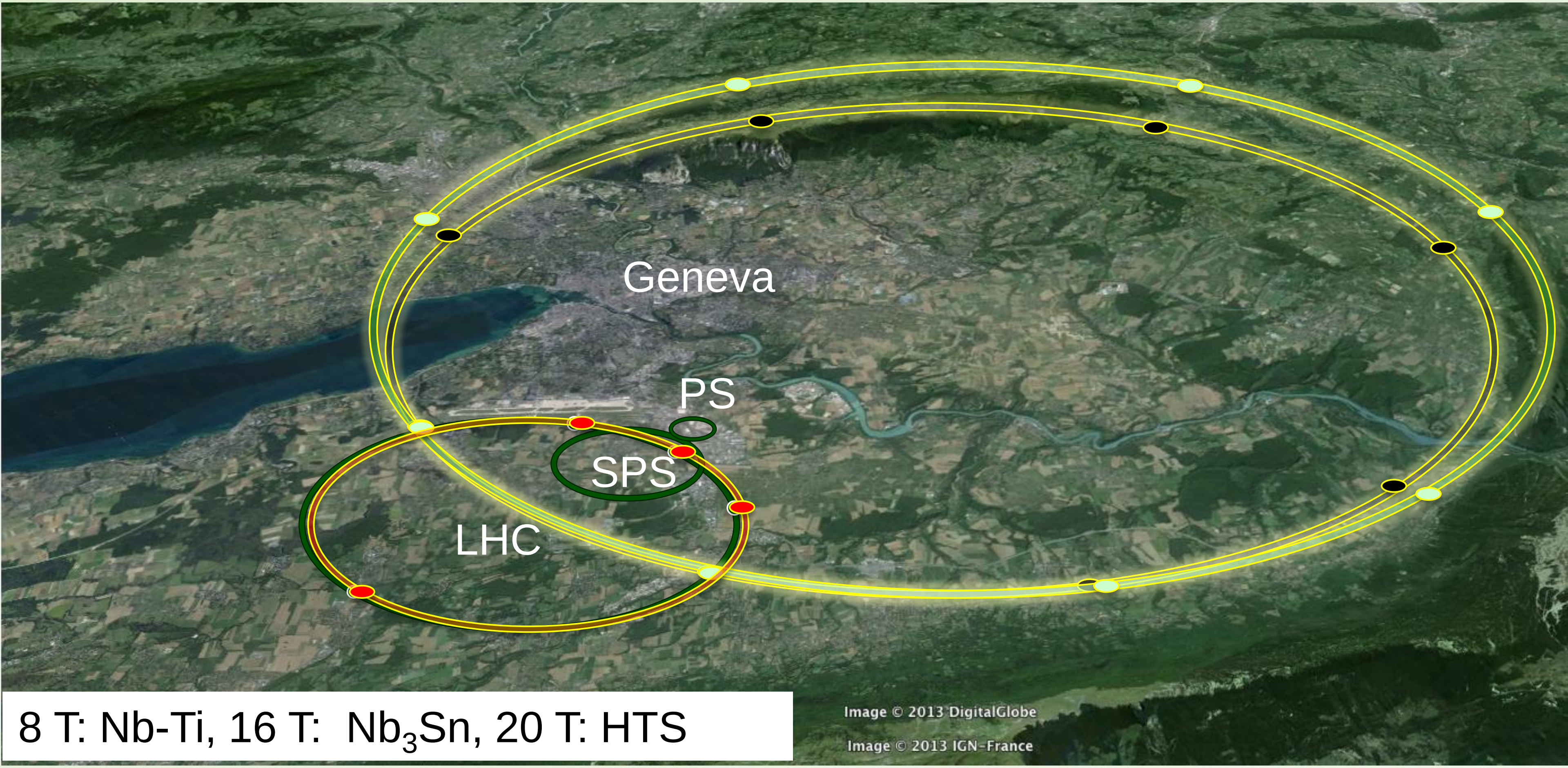
Bi-2212 Rutherford cables (Arno Godeke LBNL) with mullite insulation sleeve

REBCO coated conductor cable wound in many layers helically on a round form

Other variants too: e.g. Roebel cable

- REBCO cables are harder (Coated Conductor is a single filament) – but possible (IRL, KIT, CORC, twisted stack (MIT)

Size and field trade off for the LHC



8 T: Nb-Ti, 16 T: Nb_3Sn, 20 T: HTS

LHC	HE-LHC	VHE-LHC	VHE-LHC
27 km, 8.33 T	27 km, **20 T**	80 km, **20 T**	100 km, **16 T**
14 TeV (c.o.m.)	33 TeV (c.o.m.)	100 TeV (c.o.m.)	100 TeV (c.o.m.)

Luca Bottura (CERN) – MT23 talk

High Magnetic Fields and Materials

National High Magnetic Field Laboratory

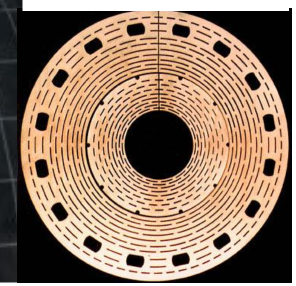
1.4 GW Generator

Los Alamos National Laboratory

101T Pulse Magnet
10mm bore

Florida State University

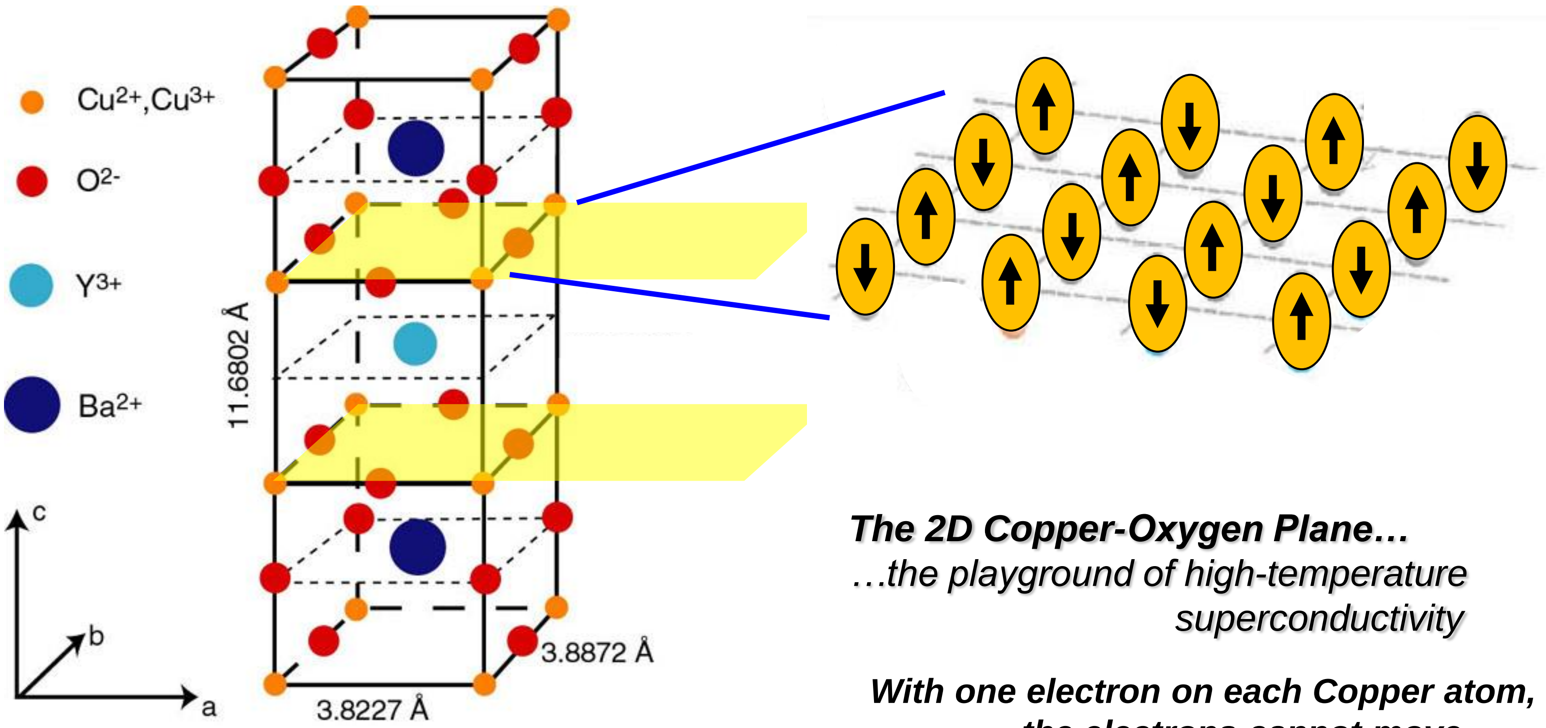
45T Hybrid
DC Magnet



Graphene, Fe-based superconductors,
Quantum oscillations in cuprate superconductors,
Topological insulators, Molecular magnets,
Model magnetic systems, Frustrated magnets,
Magnetic Bose-Einstein Condensates, Qubits,
Energy-related materials, Petroleum, Natural Products,
Bio-macromolecular complexes and the Brain

First Key Ingredient for ('Cuprate') High-Temperature Superconductors:

the Copper – Oxygen Plane

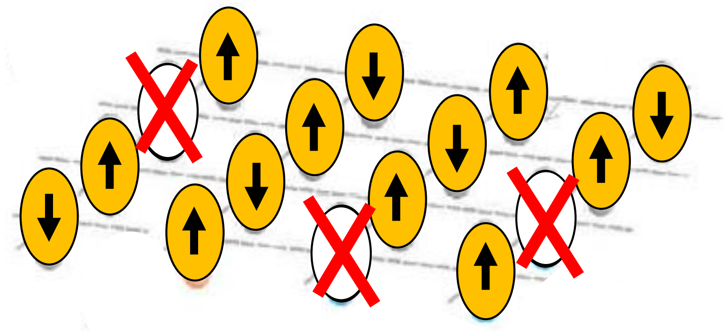


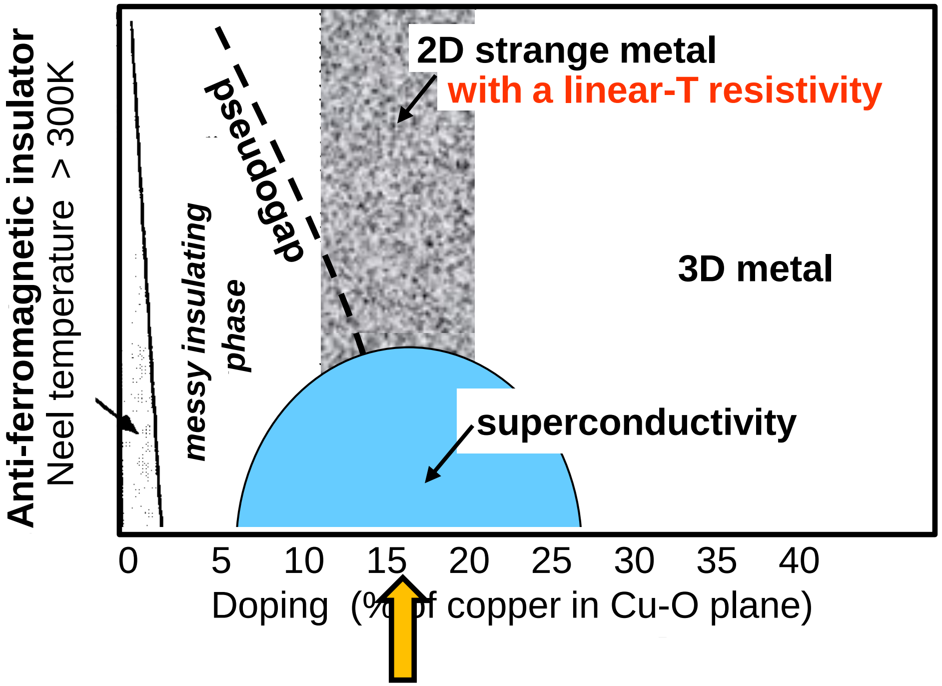
The 2D Copper-Oxygen Plane…
…the playground of high-temperature superconductivity

With one electron on each Copper atom, the electrons cannot move …and you have an insulator

Second Key Ingredient for ('Cuprate') High-Temperature Superconductors:

Removing electrons from the Copper – Oxygen Plane





Remove ~5% to ~27% of the electrons…

<u>…and you have a HIGH-TEMPERATURE SUPERCONDUCTOR</u>

For more than a dozen different materials, the <u>*same*</u> 16% doping

…optimizes superconductivity (highest transition temperature)

Large Fermi Surface in Tl-2201 in the overdoped regime

Original measurement using Angle-Dependent Magneto-resistance Oscillations:
N.E. Hussey, M. Abdel-Jawad, A. Carrington, A.P. Mackenzie, L. Balicas,
"A coherent three-dimensional Fermi surface in a high-transition-temperature superconductor" **Nature 425, 814 (2003)**

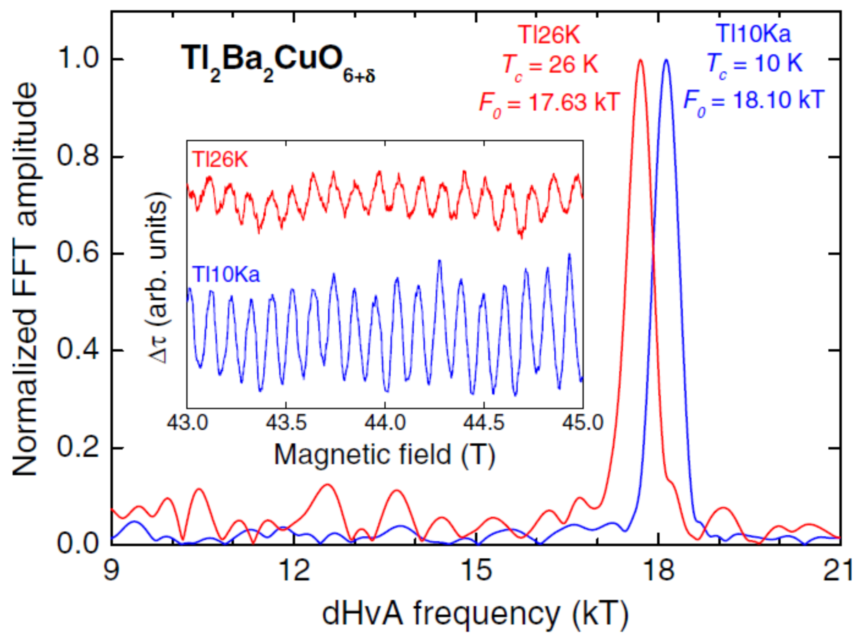
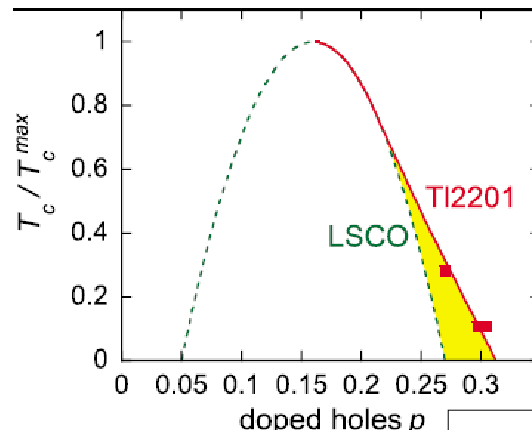
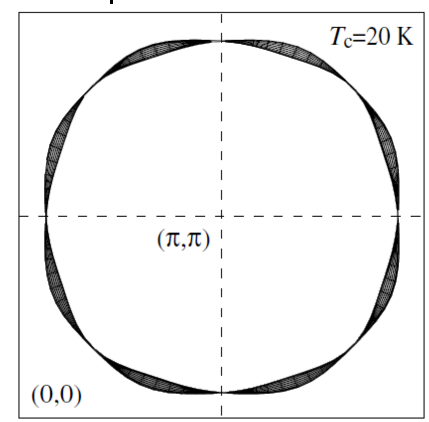


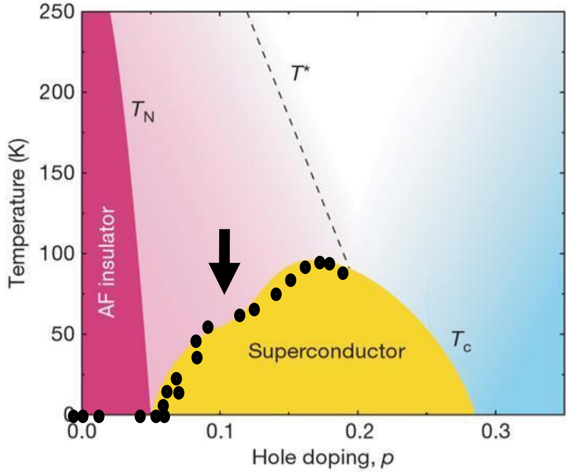
FIG. 1. (Color online) Fast Fourier transform of torque data between 38 and 45 T for Tl26K (red) and Tl10Ka (blue) samples. The data were taken at T=0.35 K. The inset shows the raw data for the two samples.





A.F. Bangura, P.M.C. Rourke, T.M. Benseman, M. Matusiak, J.R. Cooper, N.E. Hussey, and A. Carrington
Fermiology and electronic homogeneity of the superconducting overdoped cuprate $Tl_2Ba_2CuO_{6+delta}$ revealed by quantum oscillations **Phys. Rev. B 82, 140501(R) (2010)**

2007: Small Fermi Surface in the Underdoped YBCO – The Pseudogap State Looks like an Ordinary Fermi Liquid !

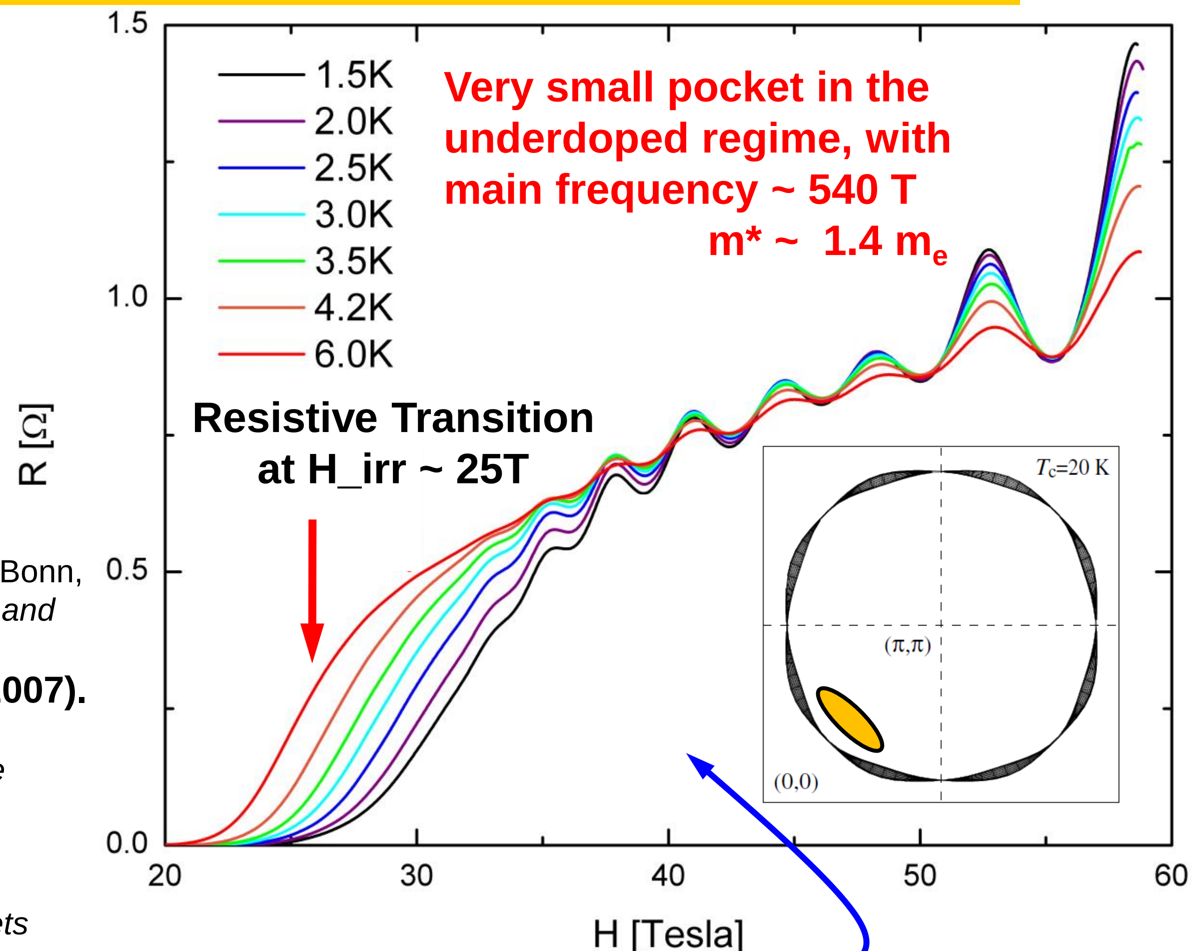


N. Doiron-Leyraud, C. Proust, D. LeBoeuf, J. Levallois, J-B Bonnemaison, R. Liang, D.A. Bonn, W.N. Hardy, L. Taillefer, "*Quantum oscillations and the Fermi surface in an underdoped high-Tc superconductor.*" **Nature 447, 565-568 (2007).**

Yelland, E. A. *et al. Quantum oscillations in the underdoped cuprate YBa2Cu4O8.* **Phys. Rev. Lett. 100, 047003 (2008).**

Bangura A. F. *et al. Small Fermi surface pockets in underdoped high temperature superconductors: observation of Shubnikov-de Haas oscillations in YBa2Cu4O8.* **Phys. Rev. Lett. 100, 047004 (2008).**

Jaudet C. *et al., de Haas–van Alphen oscillations in the underdoped high-temperature superconductor YBa2Cu3O6.5.* **Phys. Rev. Lett. 100, 187005 (2008).**

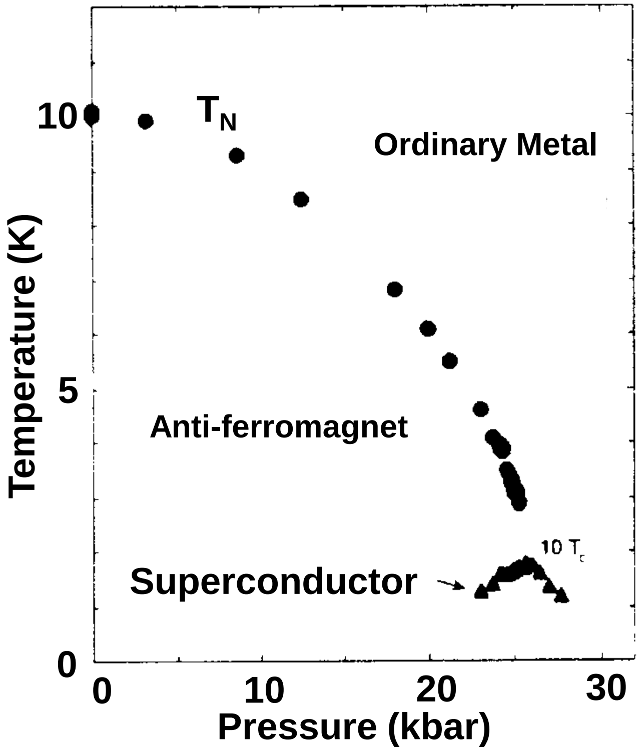


B.J.Ramshaw, B. Vignolle, J. Day, R. Liang, W.N. Hardy, C. Proust, D.A. Bonn, *Angle dependence of quantum oscillations in YBa2Cu3O6.59 shows free spin behavior of quasiparticles* **Nature Physics 7, 234 (2010)**

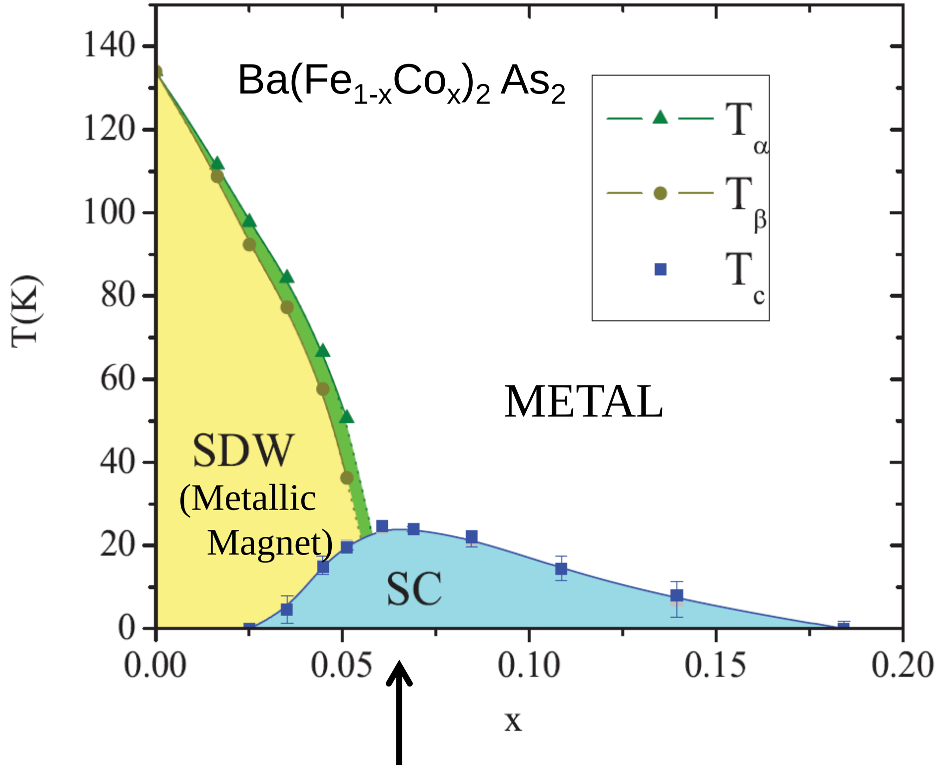
Suchitra E. Sebastian *et al. A multi-component Fermi surface in the vortex state of an underdoped high-Tc superconductor.* **Nature 454 200 (2008)**

Superconductivity is Stabilized Near Quantum Critical Points, ***but no one knows why.***

N.D. Mathur et al., Nature **394**, 39 (1998)



$CeIn_3$
a Heavy Fermion Compound
with Superconducting Tc < 1 K

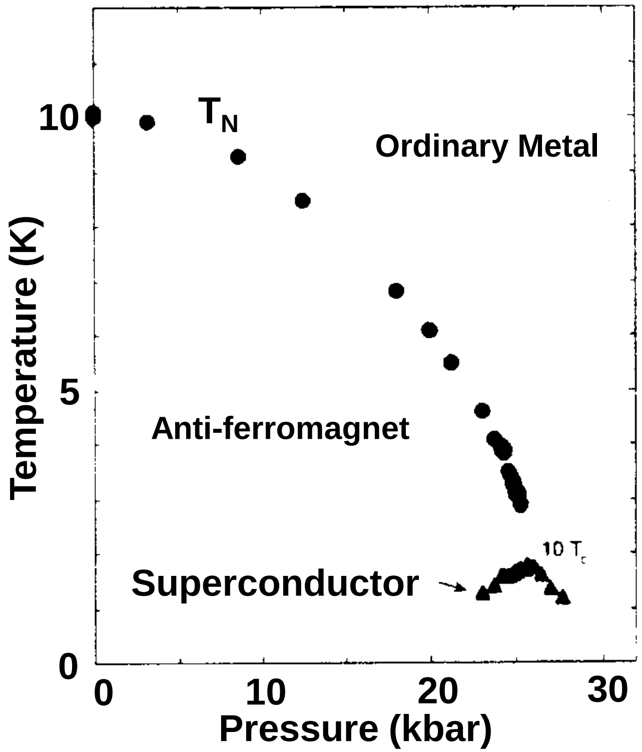


doping=0.13

Jiun-Haw Chu, James G. Analytis, Chris Kucharczyk,
Ian R. Fisher, Phys. Rev. **B 79**, 014506 (2009)
Determination of the phase diagram of the electron doped superconductor $Ba(Fe_{1-x}Co_x)_2 As_2$

Superconductivity is Stabilized Near Quantum Critical Points, ***but no one knows why.***

N.D. Mathur et al., Nature **394**, 39 (1998)



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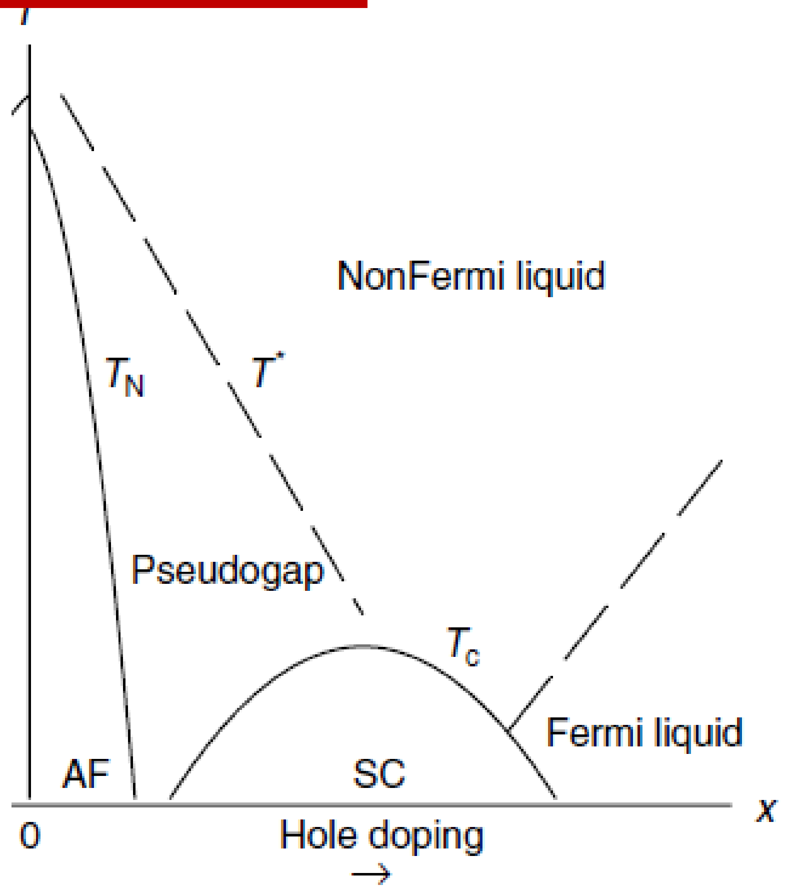


Hole-doped High-Temperature Superconducting Cuprate
Maximum Tc ~ 40-150K

National High Magnetic Field Laboratory

1.4 GW Generator

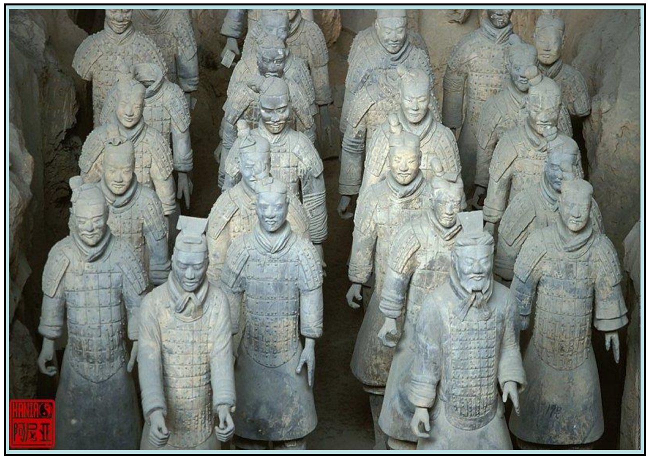
Los Alamos National Laboratory

101T Pulse Magnet
10mm bore

Graphene, Fe-based superconductors,
Quantum oscillations in cuprate superconductors,
Topological insulators, Molecular magnets,
Model magnetic systems, Frustrated magnets,
Magnetic Bose-Einstein Condensates, Qubits,
Energy-related materials, Petroleum, Natural Products,
Bio-macromolecular complexes and the Brain

Materials Research on Chinese Terracotta Warriors (479-221 BC)
Saving Lives for more than 2000 Years

Terracotta Army to protect the emperor in the afterlife…instead of the real army



Calcite - $CaCO_3$
Bone White - $Ca_5(CO_3)_2(OH)_2$
White Lead – $2Pb(CO_3)_2 \cdot Pb(OH)_2$

Soot - carbon black

Han Purple* - $BaCuSi_2O_6$**

Cinnabar - HgS
Hematite - Fe_2O_3
Red Lead – Pb_3O_4

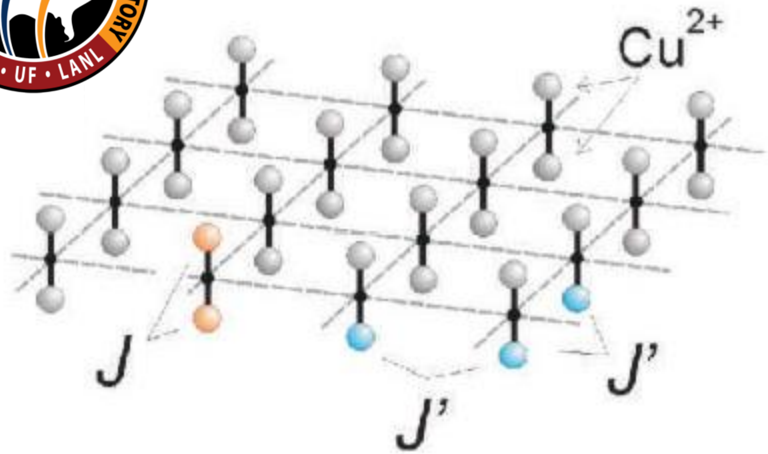
Malachite – $Cu_2CO_3(OH)_2$

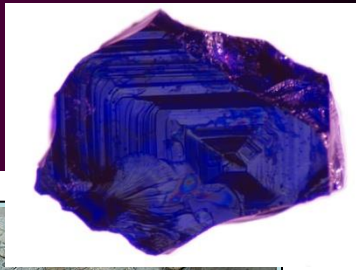
Han Blue* – $BaCuSi_4O_{10}$**

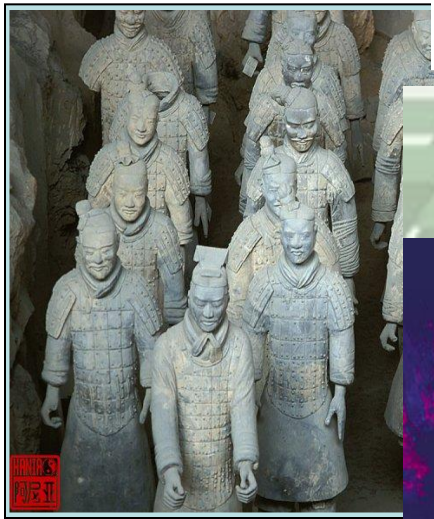
***** man-made pigments**

J. Zuo et al., *J. Raman Spectrosc.* ***34****, 121 (2003)*
H. Langhals & D. Bathelt, *Angew. Chem. Int. Ed.* **42**, 5676 (2003)

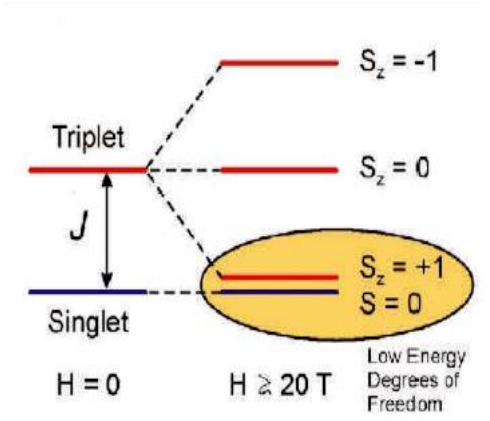
2500 Years of Materials Research on $BaCuSi_2O_6$



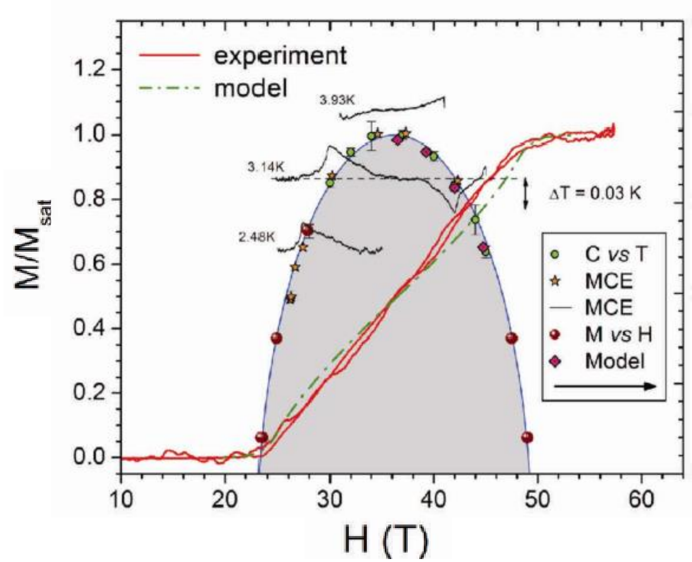




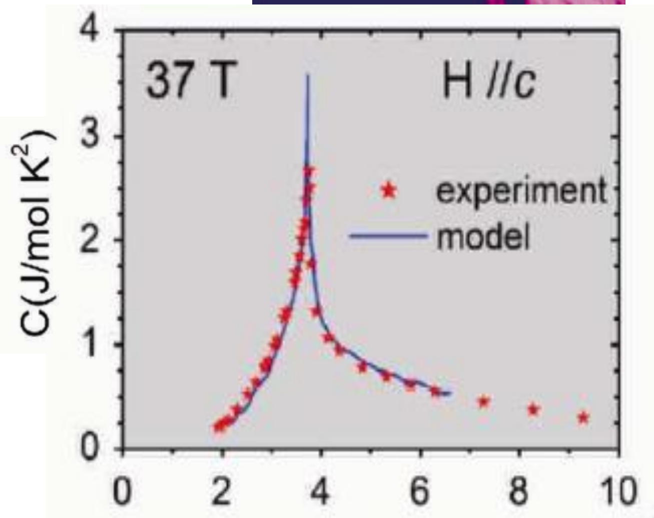
$BaCuSi_2O_6$: A quasi-2D magnetic insulator with a gapped spin dimer ground state



Magnetic fields create a gas of bosonic spin triplet excitations, called triplons



Slow increase in MAGNETIZATION is evidence of electron spin correlations.

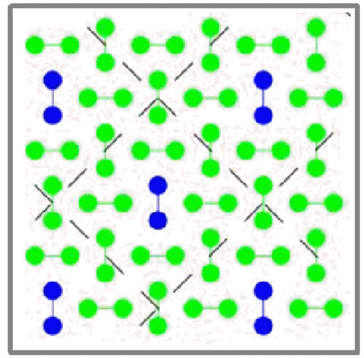


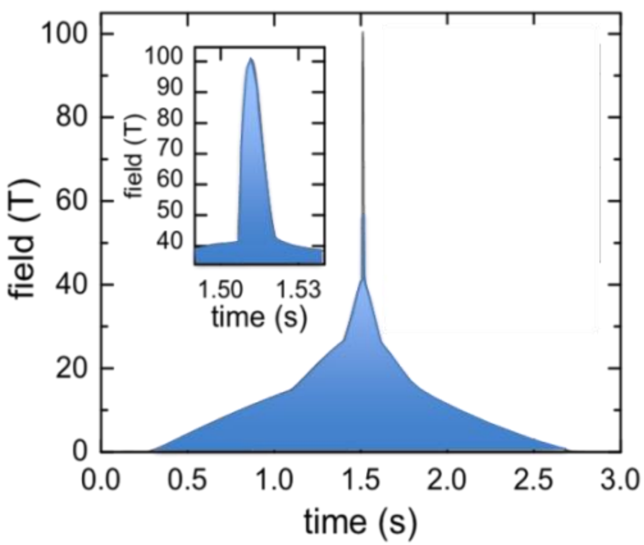
Lambda transition in SPECIFIC HEAT due to Bose condensation of triplons

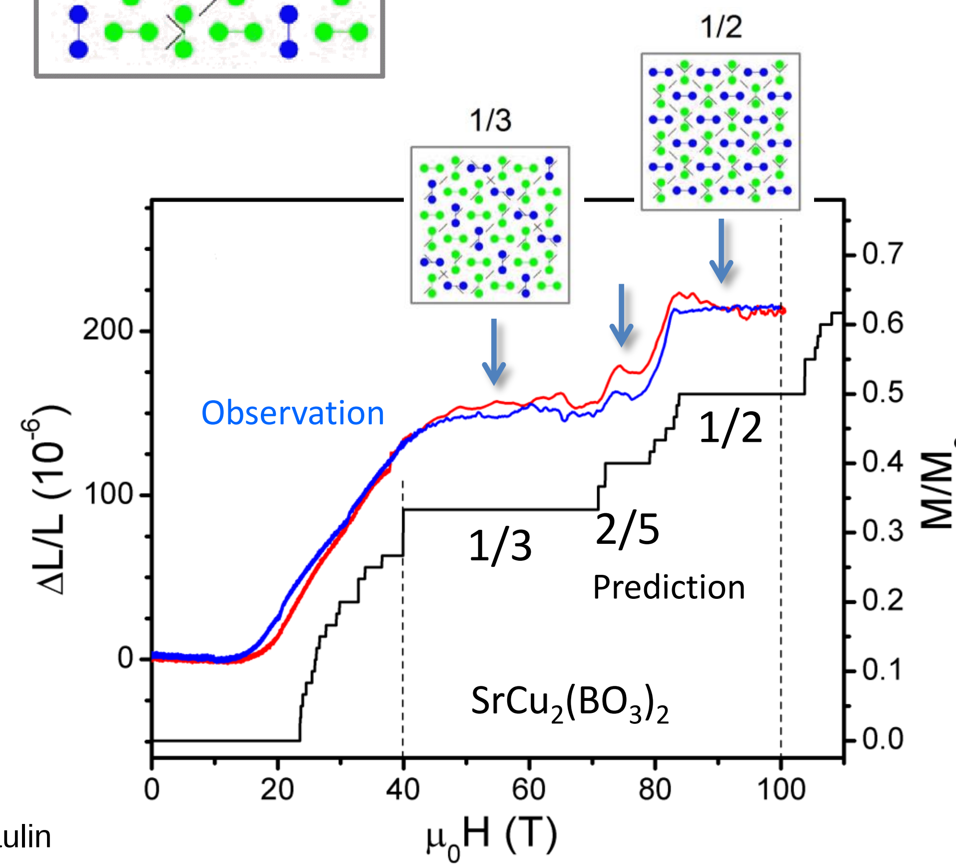
Crystalline spin transitions at 75T and 82T: New Magnetic Spin Textures revealed at ultrahigh magnetic fields

MPI-CPfS, Dresden, Univ. of Wyoming, LANL, McMaster University, NHMFL

- $SrCu_2(BO_3)_2$ realizes the "Shastry-Sutherland Model": *Orthogonal spin dimers on square lattice*
- Dimers are *coupled;* magnetization increases in a complex series of plateaus as *stable magnetic textures* are formed







Marcelo Jaime, Ramzy Daou, Scott A. Crooker, Franziska Weickert, Atsuko Uchida, Adrian E. Feiguin, Cristian D. Batista, Hanna A. Dabkowska, and Bruce D. Gaulin
PNAS, (July 2012)

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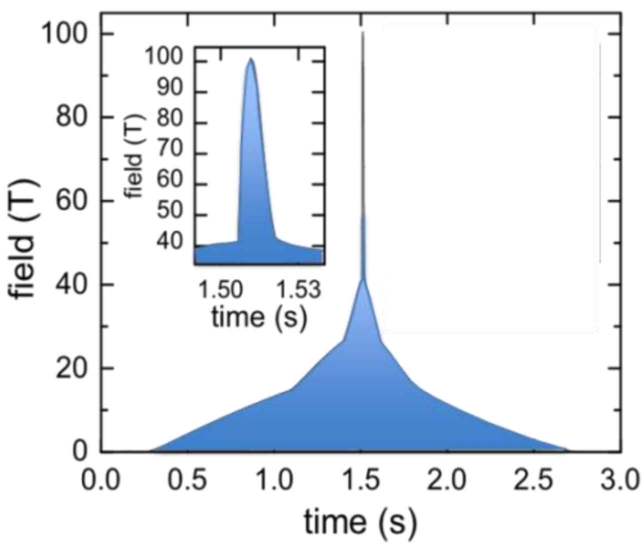

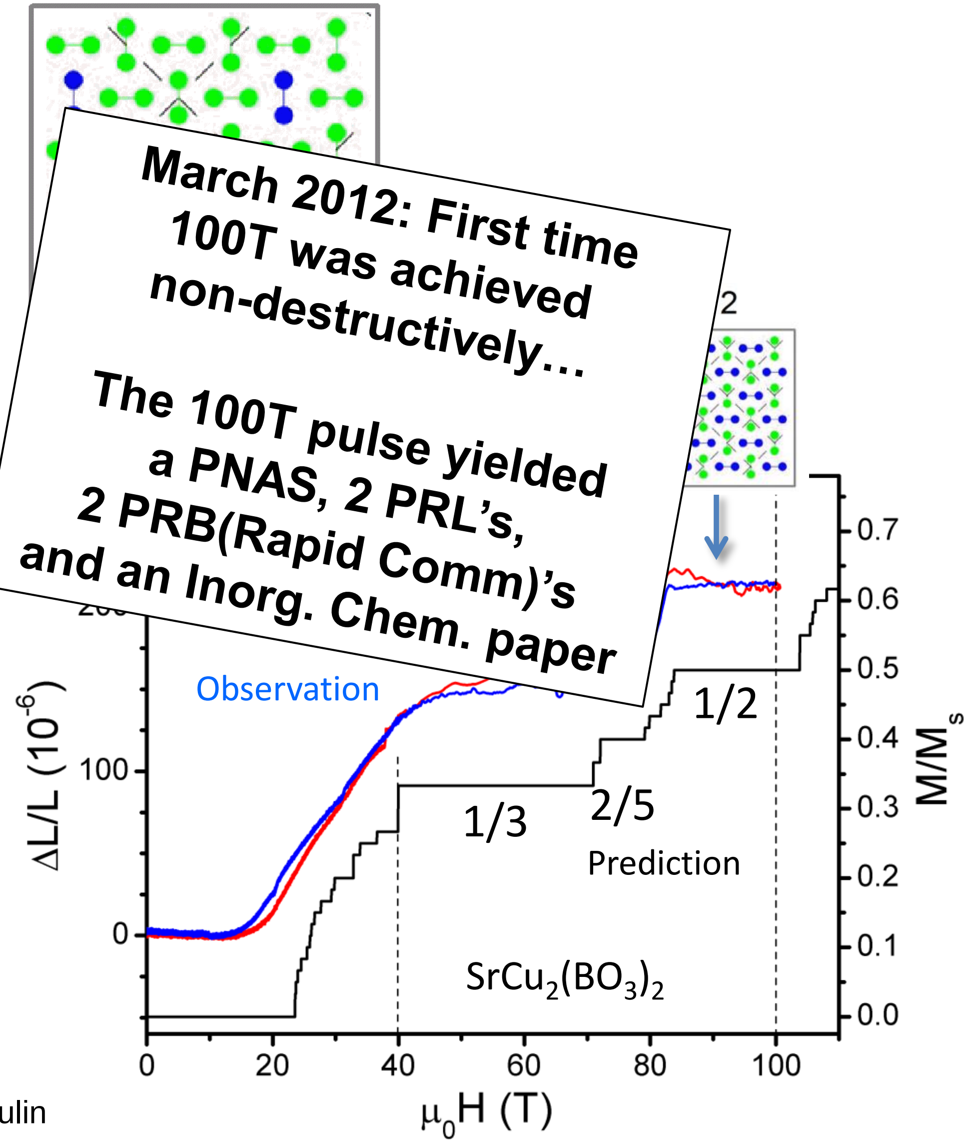

March 2012: First time 100T was achieved non-destructively…

The 100T pulse yielded a PNAS, 2 PRL's, 2 PRB(Rapid Comm)'s and an Inorg. Chem. paper

Marcelo Jaime, Ramzy Daou, Scott A. Crooker, Franziska Weickert, Atsuko Uchida, Adrian E. Feiguin, Cristian D. Batista, Hanna A. Dabkowska, and Bruce D. Gaulin
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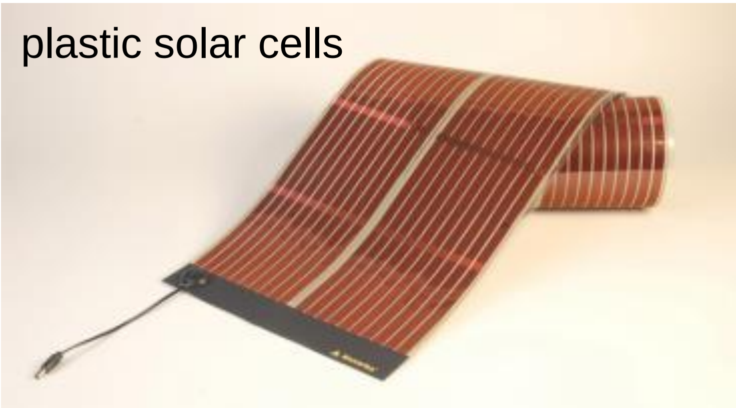
High Magnetic Fields and Energy

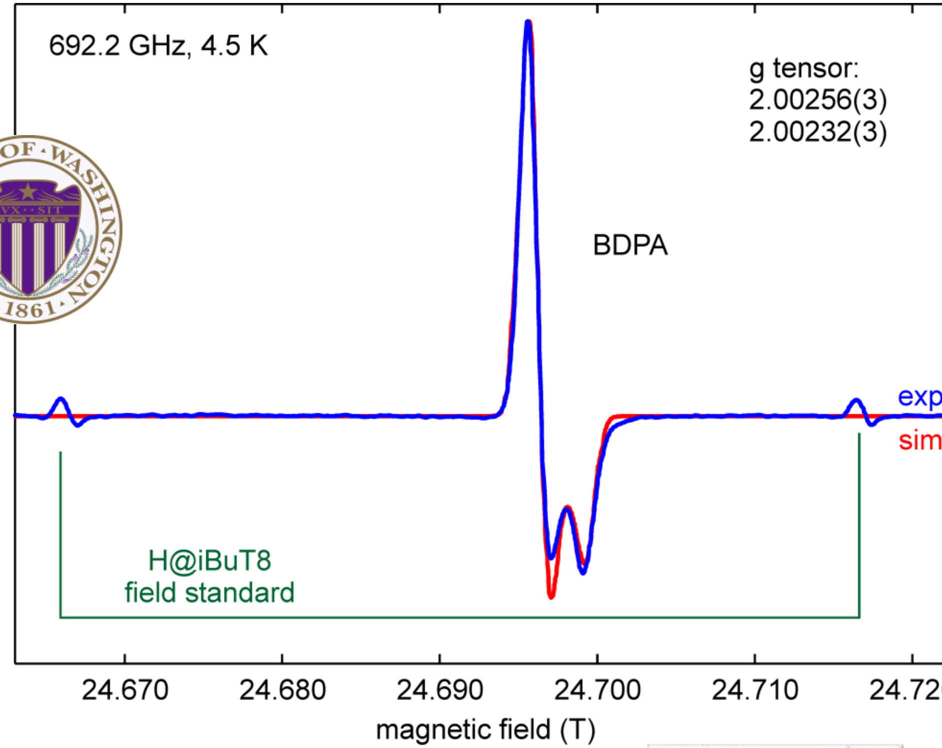
National High Magnetic Field Laboratory

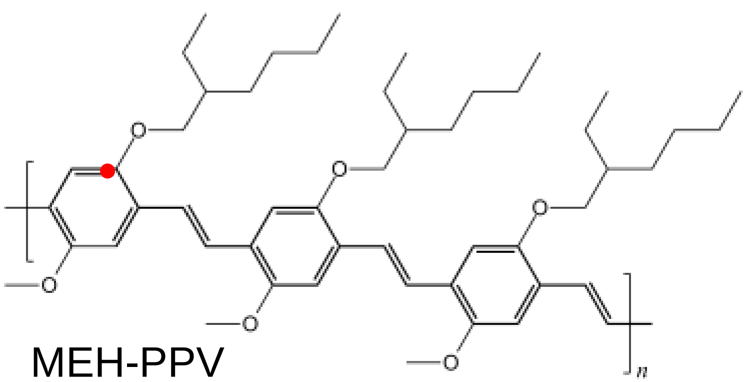
Graphene, Fe-based superconductors,
Quantum oscillations in cuprate superconductors,
Topological insulators, Molecular magnets,
Model magnetic systems, Frustrated magnets,
Magnetic Bose-Einstein Condensates, Qubits,
Energy-related materials, Petroleum, Natural Products,
Bio-macromolecular complexes and the Brain

High-field EPR probes charge carriers in plastic solar cells



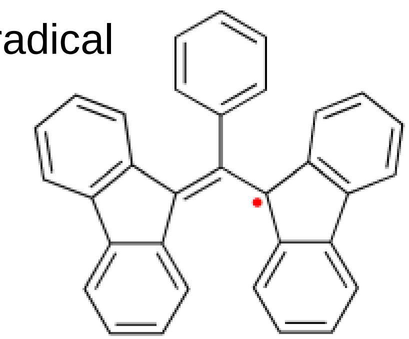
If the unpaired electron is delocalized over a large volume, its g factor is nearly that of a free electron (2.0023 and isotropic). As such, high magnetic fields are required to measure the g-tensor in carbon-centered radicals in organic photovoltaics.

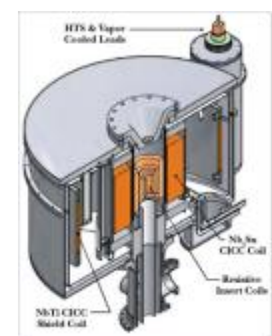




MEH-PPV
carbon-centered radical

BDPA
model radical





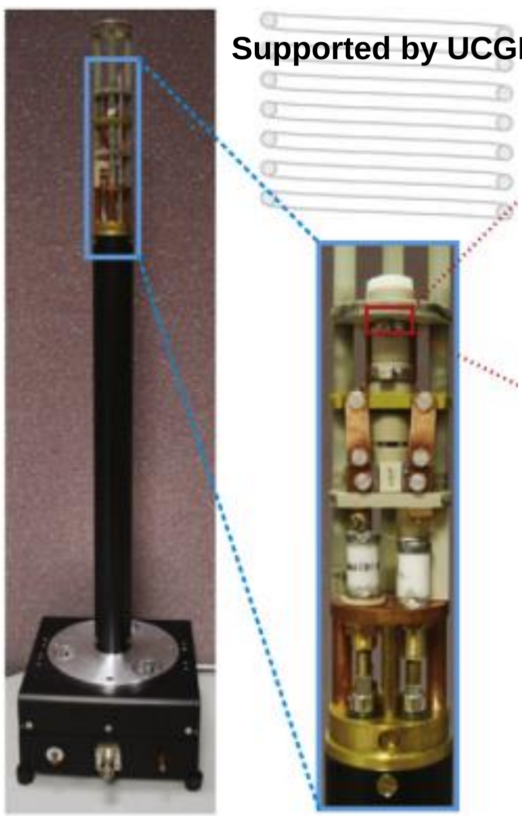
SCH will provide even greater g resolution

In Situ ^{7}Li NMR Stray Field Imaging (STRAFI) in a Half-Cell Battery

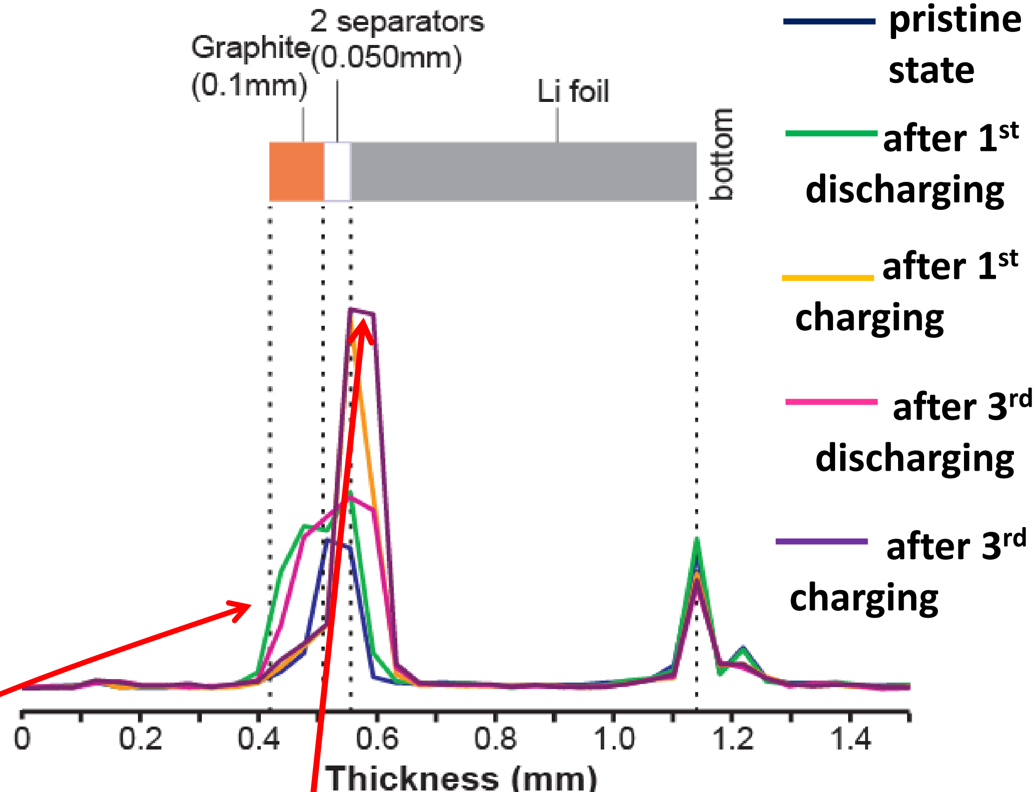
Yong Yang at Xiamen University, Jim Zheng at FSU, Riqiang Fu at NHMFL

A STRAFI probe was designed to image solid and liquid materials containing quadrupolar nuclei using the fringe field of a superconducting magnet.

Supported by UCGP



Imaging Li^{+} ion transfer between electrodes



Reveals formation and changes of irreversible microstructures of the Li components in the interface between electrolyte and electrodes

Reveals a non-uniform Li-ion distribution in the graphite for the first time

Facilities: NMR/MRI Facility (19.6 Tesla Magnet)

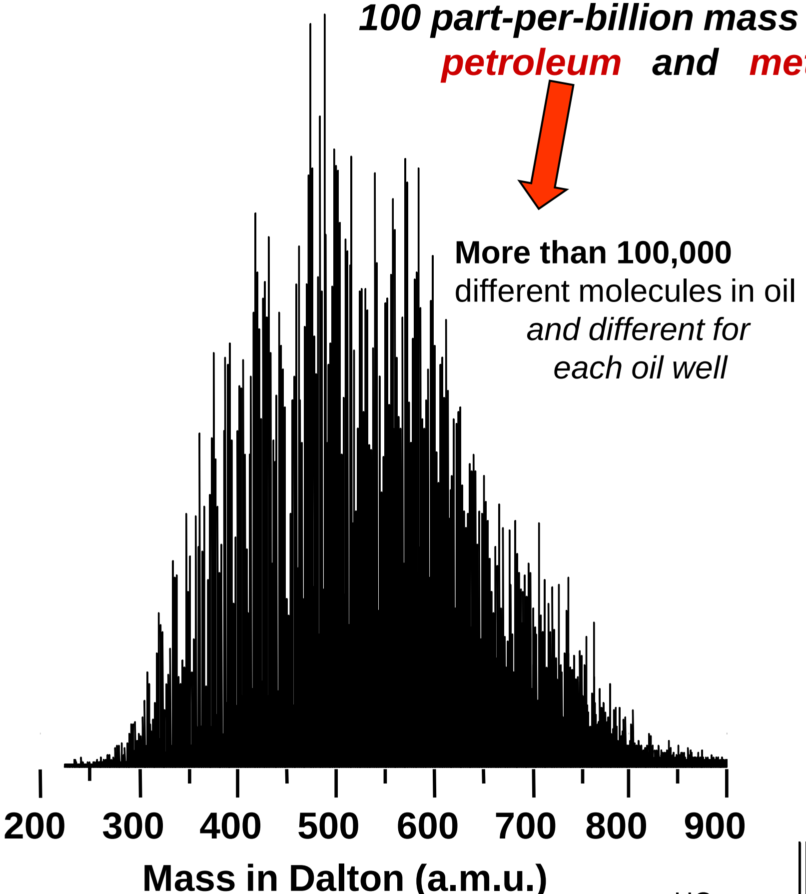
Citation: ***Non-Destructive Monitoring of Charge-Discharge Cycles on Lithium Ion Batteries Using 7Li Stray-Field Imaging,*** Joel A. Tang, Sneha Dugar, Guiming Zhong, Naresh S. Dalal, Jim P. Zheng, Yong Yang, & Riqiang Fu, **Scientific Reports 3:2596, 1-6 (2013);** ***Solid-State STRAFI NMR Probe for Material Imaging of Quadrupolar Nuclei,*** Joel A. Tang, Guiming Zhong, Sneha Dugar, Jason Kitchen, Yong Yang, & Riqiang Fu, **J. Magn. Reson. 225:93-101 (2012).**

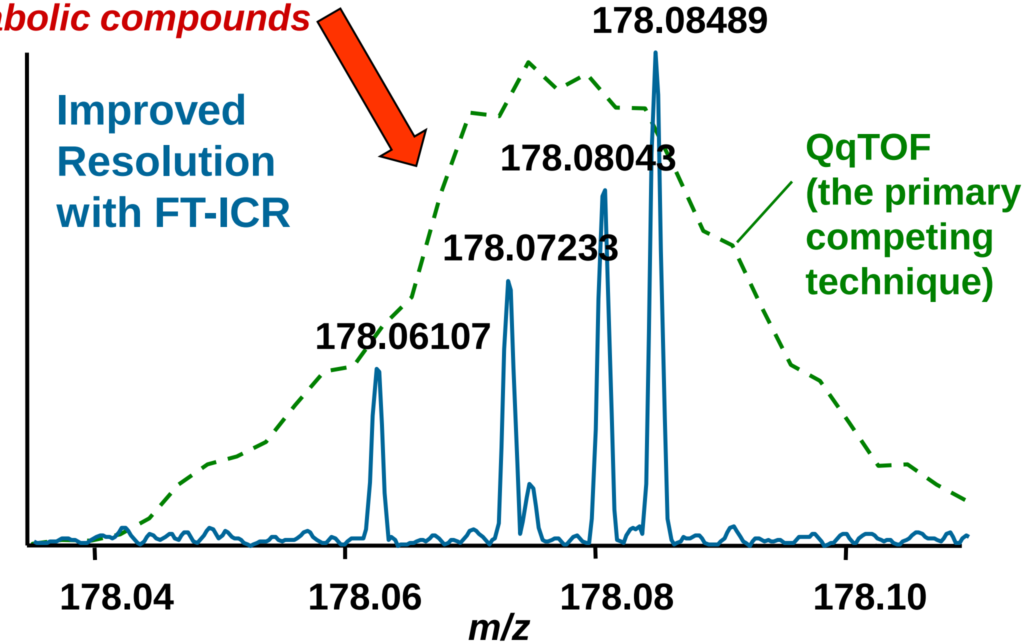
National High Magnetic Field Laboratory

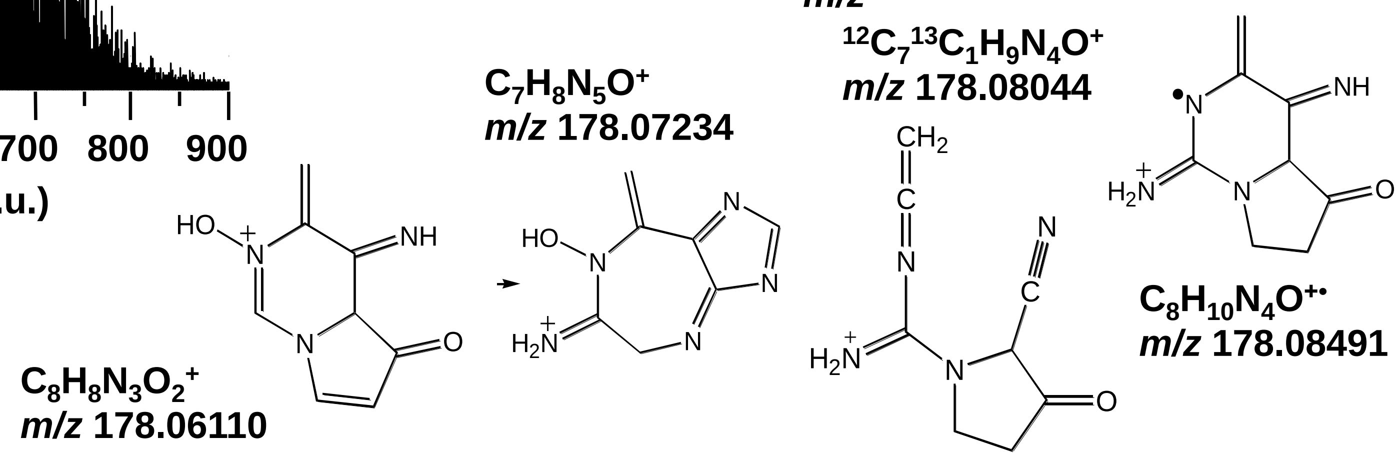
Graphene, Fe-based superconductors,
Quantum oscillations in cuprate superconductors,
Topological insulators, Molecular magnets,
Model magnetic systems, Frustrated magnets,
Magnetic Bose-Einstein Condensates, Qubits,
Energy-related materials, **Petroleum,** Natural Products,
Bio-macromolecular complexes and the Brain

Ion Cyclotron Resonance: Mass Spectroscopy

With a 14 T high-homogeneity wide-bore magnet, 100 part-per-billion mass resolution and accuracy to analyze petroleum and metabolic compounds



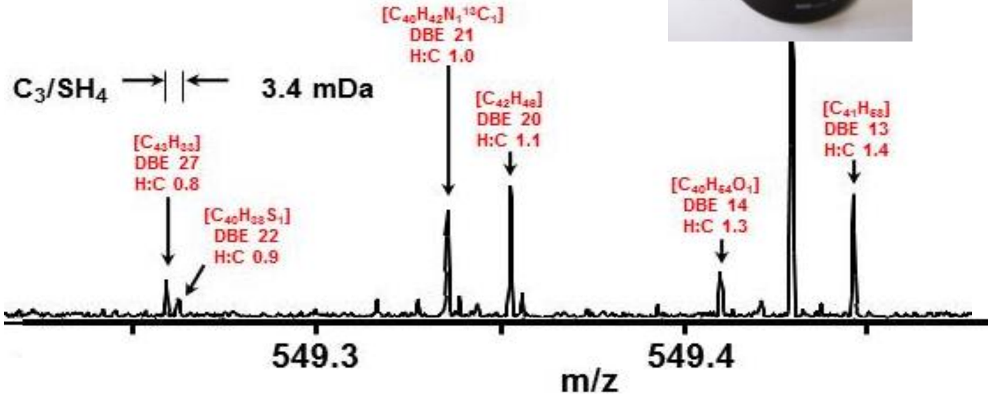




Petroleum Analysis with Ion Cyclotron Resonance

Woods Hole Oceanographic Institute and National High Magnetic Field Laboratory

Deepwater Horizon Petroleum



Ion Cyclotron Resonance (ICR) can develop a “fingerprint” of the Deepwater Horizon oil by identifying 10,000’s of compounds in each sample.

The MagLab’s 9.4T ICR magnet can resolve 0.003 mDa and therefore can distinguish C_3 from SH_4 (greater than one part in 100,000 resolution) to allow for sulfur differentiation from pure hydrocarbons….the ability that launches “PETROLEOMICS”

Facilities: NHMFL Ion Cyclotron Resonance Facility

Citation: *Expansion of the Analytical Window for Oil Spill Characterization by Ultrahigh Resolution Mass Spectrometry: Beyond Gas Chromatography*; McKenna, A.M.; Nelson, R.K.; Reddy, C.M.; Savory, J.J.; Kaiser, N.K.; Fitzsimmons, J.E.; Marshall, A.G. and Rodgers, R.P.; **Environmental Science & Technology, 47, 7530-7539 (2013)**

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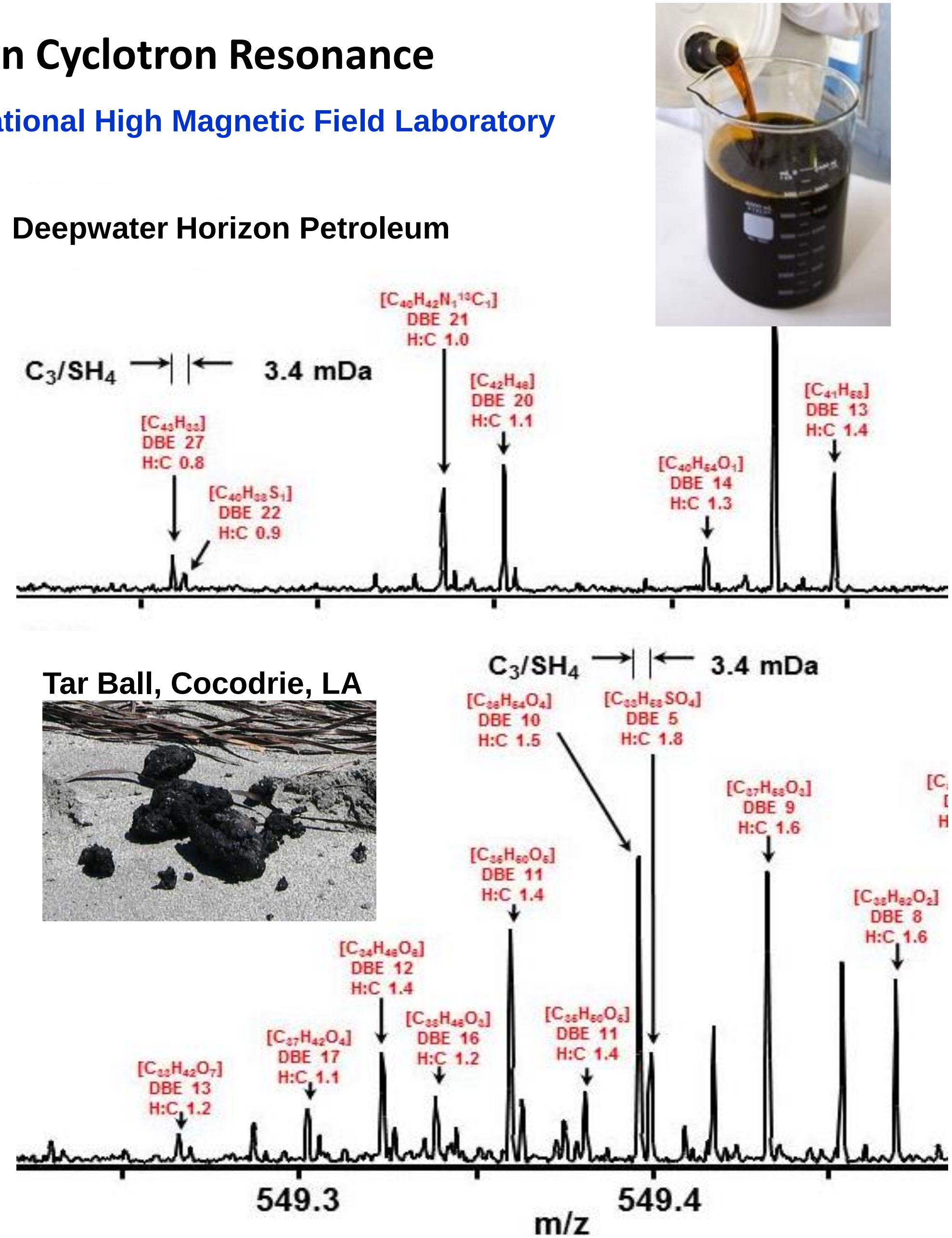
One might have expected to see fewer compounds in a weathered tar ball, because all volatile compounds would have evaporated.

Instead there are three times as many compounds, because bacteria and sunlight have led to the oxidization of many compounds.

High magnetic fields provide unique opportunities to probe the environmental fate of spilled oil, toxicology, and molecular modeling of biotic/abiotic weathering.



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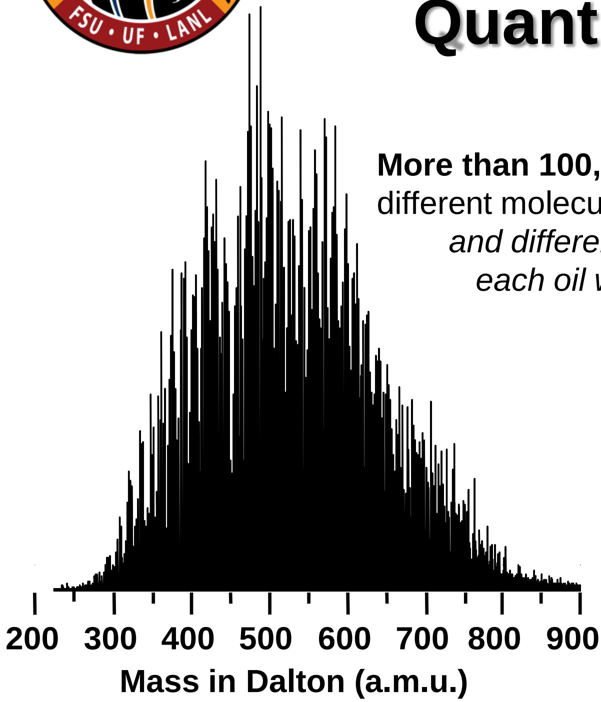
Inventing ‘Petroleomics’: Quantitative Analysis of Petroleum



More than 100,000
different molecules in oil
and different for each oil well

…what is in the crud that clogs the oil pipelines ?
(costing $10,000,000 a day)

NOT polymerization…
rather a physical entanglement of relatively small molecules

…how do we make useful fuel from this low grade crude?
(we have enough of this stuff to achieve energy independence)

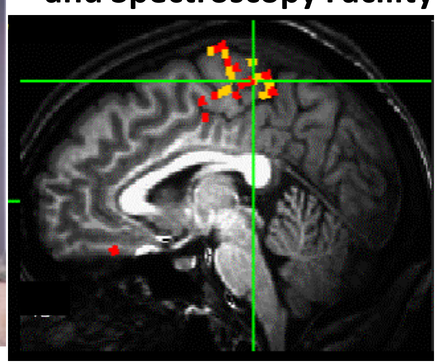
…what cyclic compounds are in this “residue”?
…and sulfur ligands / acids / <insert word here>
(individualize refinement and mitigate pollution)

High Magnetic Fields and Life

National High Magnetic Field Laboratory

11.4T MRI Magnet 400mm warm bore

Advanced Magnetic Resonance Imaging and Spectroscopy Facility



Graphene, Fe-based superconductors,
Quantum oscillations in cuprate superconductors,
Topological insulators, Molecular magnets,
Model magnetic systems, Frustrated magnets,
Magnetic Bose-Einstein Condensates, Qubits,
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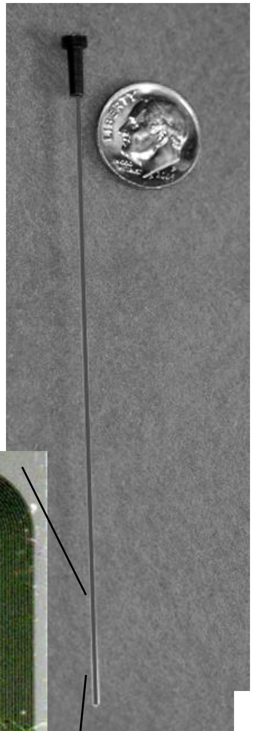
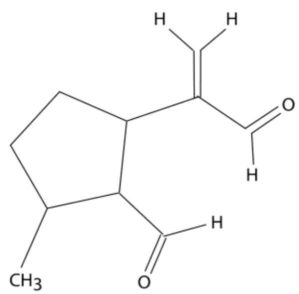
Chemical Warfare in the Natural World:
Solving Molecular Structures of Ultra-Small Samples

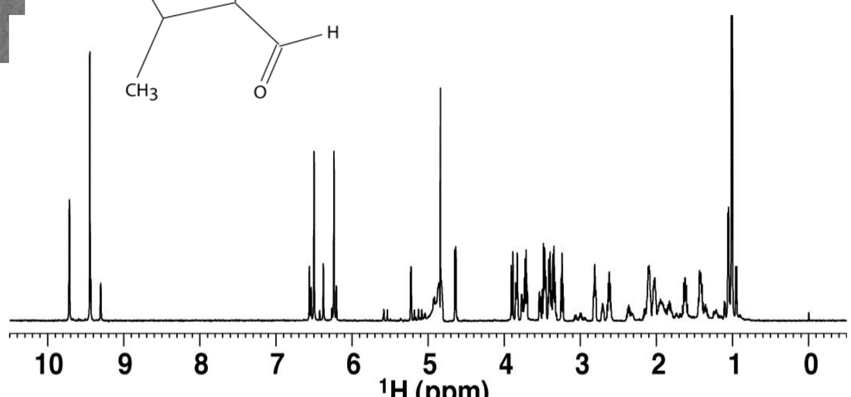


YBCO
rf coil

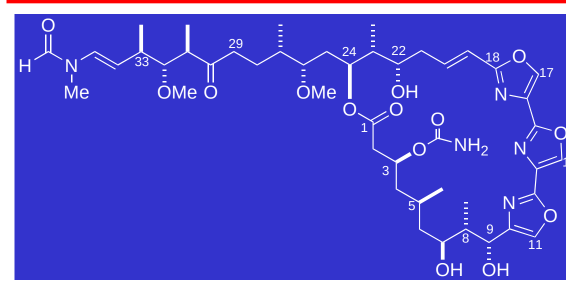
- **High Quality NMR Spectrum**
  from a single milking of a single walking stick…
  no purification…10nL sample $(0.1mm)^3$

Anisomorphal





and from an unusual shell-less mollusk on the coral reef…



National High Magnetic Field Laboratory

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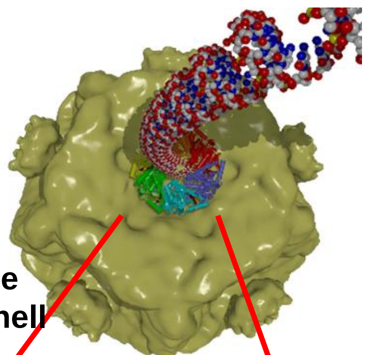
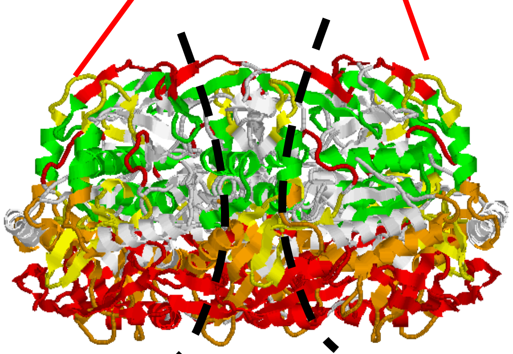
Fighting Viruses: Plugging the RNA Channels

Structure of Macro-bio-assemblies: too big for X-rays alone to solve

Ion Cyclotron Resonance weighs the pieces of the RNA channel to detect how much deuterium (heavy hydrogen) has exchanged with the hydrogen

HIV, with its RNA passing through the protective shell





RNA Channel (side view) mass increase rates when fully exposed to deuterium

WHICH surface is the EXTERIOR of the virus ?

Hydrogen/Deuterium Exchange Rate reveals which side of the RNA channel is on the virus exterior

> 100 h^{-1} FAST

10 h^{-1} - 100 h^{-1}

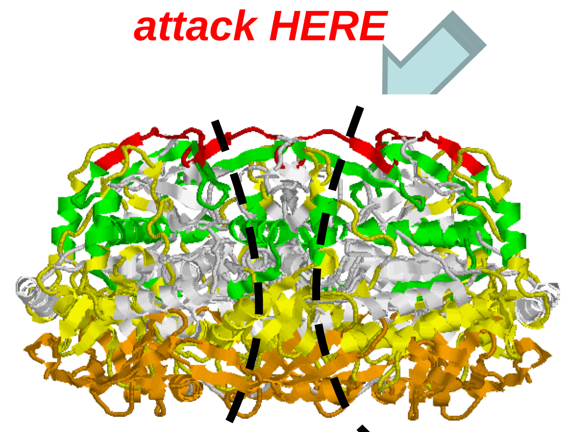
1 h^{-1} - 10 h^{-1}

0.1 h^{-1} - 1 h^{-1}

< 0.1 h^{-1} SLOW

This is the EXTERIOR…

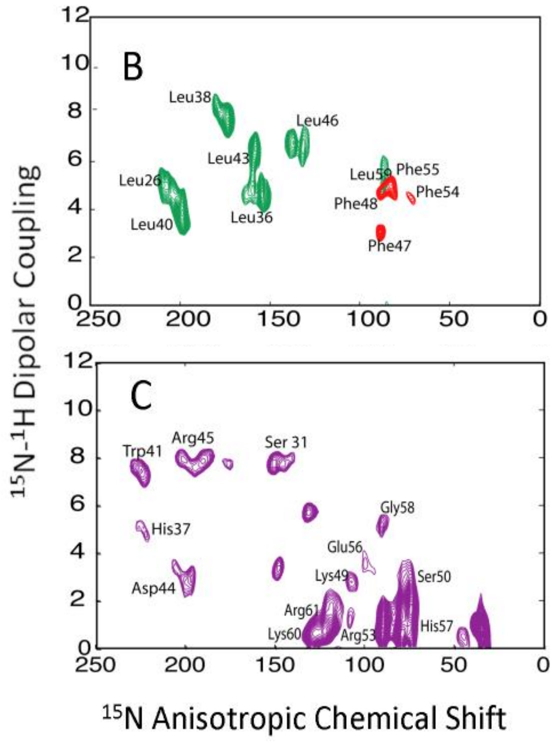
…design a drug to attack HERE

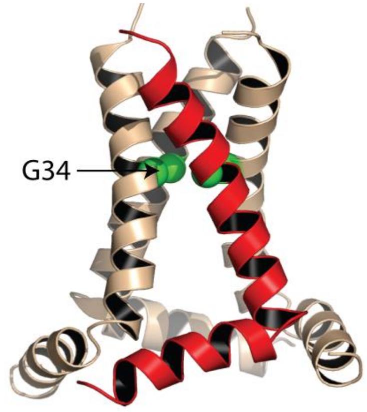


RNA Channel mass increase rates when attached to Procapsid

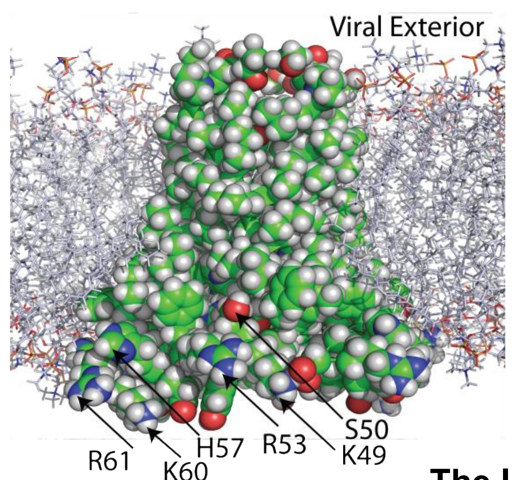
First Fully Functional Membrane Protein Structure Measured in a Native-Like Membrane Environment

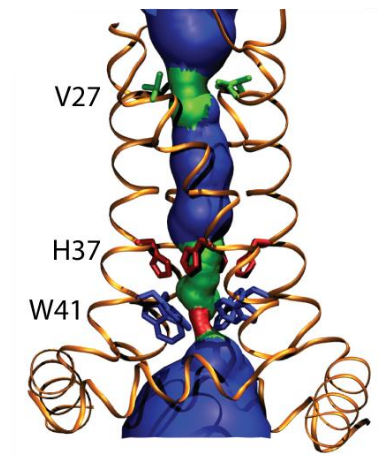
900 UWB Data





- **M2 Protein (22-62) from Influenza A**
- **Structure determined in uniformly aligned liquid-crystalline lipid bilayers**





The largest structure solved by ssNMR (20 kDa)

A collaboration:
D. Busath, Dept. of Physiology and Developmental Biology, BYU;
H.-X. Zhou, Dept. of Physics, FSU

Sharma et al., 2010 **Science**

This would not be possible without the highest fields <u>and Low-E probes</u>.

Quadrupolar Nuclei: the REST of the Periodic Table

Quadrupolar Nuclei: the REST of the Periodic Table

Elements with:

Only I =1/2 nuclear spins

Quadrupolar nuclei (i.e. I > 1/2)

H 2																	*He*
Li 6,7	**Be 9**											**B 10, 11**	*C*	**N 14**	**O 17**	*F*	**Ne 21**
Na 23	**Mg 25**											**Al 27**	*Si*	*P*	**S 33**	**Cl 35, 37**	Ar
K 39, 41	**Ca 43**	**Sc 45**	**Ti 47, 49**	**V 50, 51**	**Cr 53**	**Mn 55**	*Fe*	**Co 59**	**Ni 61**	**Cu 63, 65**	**Zn 67**	**Ga 69, 71**	**Ge 73**	**As 75**	*Se*	**Br 79, 81**	**Kr 83**
Rb 85, 87	**Sr 87**	*Y*	**Zr 91**	**Nb 93**	**Mo 97**	Tc	**Ru 99, 101**	*Rh*	**Pd 105**	*Ag*	*Cd*	**In 113, 115**	*Sn*	**Sb 121 123**	*Te*	**I 127**	**Xe 129 131**
Cs 133	**Ba 135 137**	**La 138 139**	**Hf 177 179**	**Ta 181**	*W*	**Re 185 187**	**Os 187 189**	**Ir 191 193**	*Pt*	**Au 197**	**Hg 201**	*Tl*	*Pb*	*Bi*	Po	At	Rn
Fr	Ra	Ac															

Ce	**Pr 141**	**Nd 143 145**	Pm	**Sm 147 149**	**Eu 151 153**	**Gd 155 157**	**Tb 159**	**Dy 161 163**	**Ho 165**	**Er 167**	*Tm*	**Yb 173**	**Lu 175 176**
Th	Pa	**U 235**	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

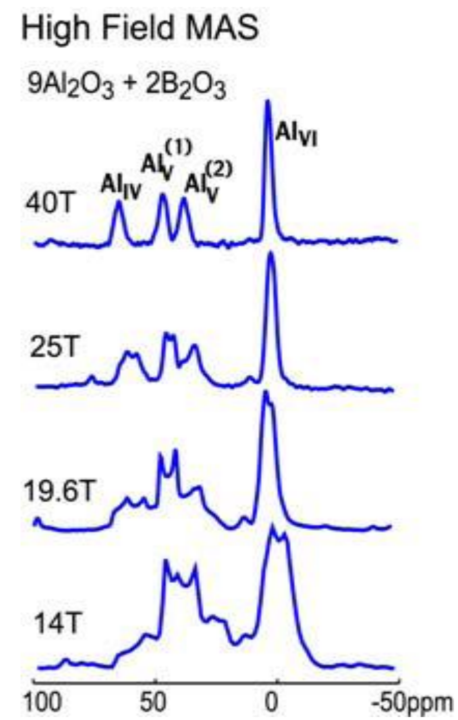
NMR of New Materials in DC Powered Magnets

I = 1 ^{2}H, ^{6}Li, ^{14}N

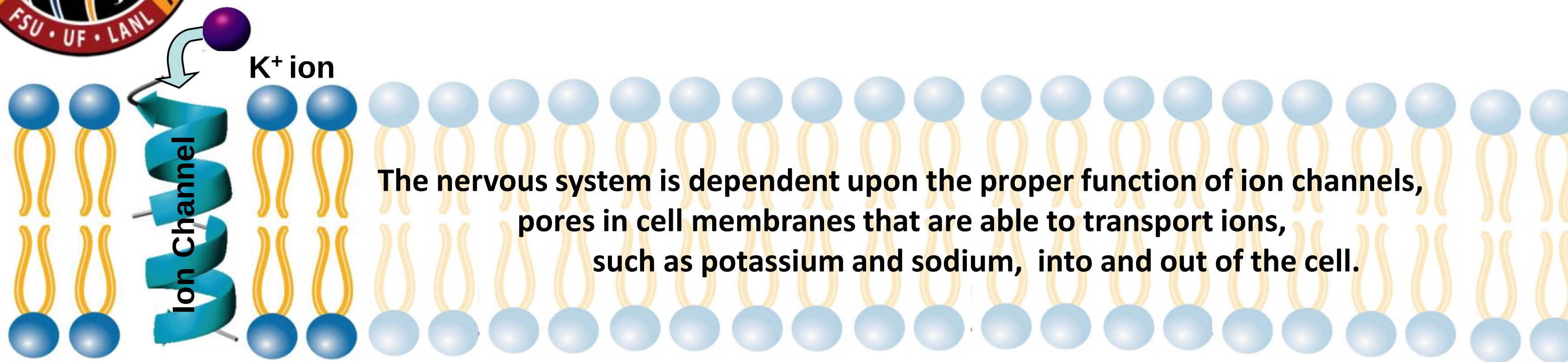
I = 3/2 ^{7}Li, ^{11}B, ^{23}Na, $^{69,71}Ga$, ^{87}Rb…

I = 5/2 ^{17}O, ^{25}Mg, ^{27}Al, ^{47}Ti, ^{67}Zn…

- **Catalysts: surface chemistry**
- **Porous materials: clays and zeolites**
- **Batteries and fuel cells: ion transport**

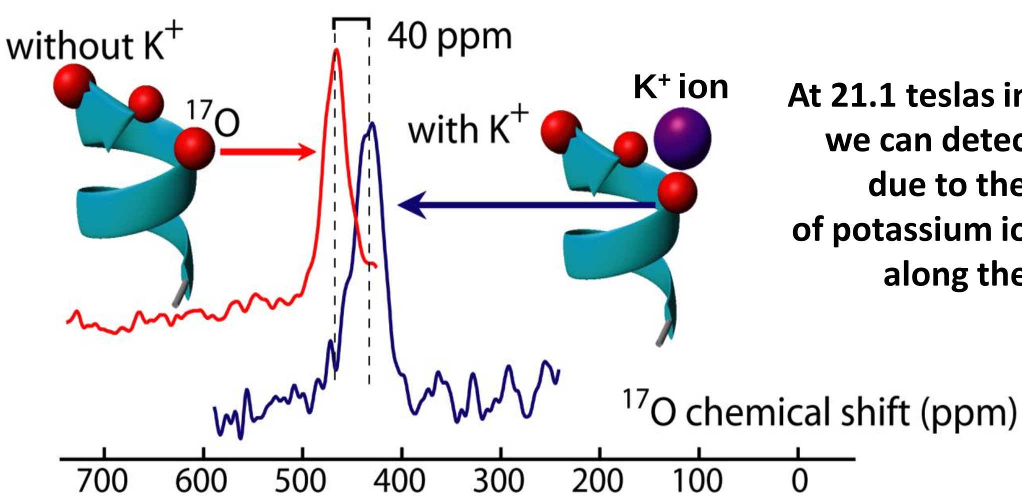


Quadrupolar NMR: Oxygen-17 NMR Spectroscopy



The nervous system is dependent upon the proper function of ion channels, pores in cell membranes that are able to transport ions, such as potassium and sodium, into and out of the cell.

Because ^{17}O is a quadrupolar nucleus, it is a very sensitive indicator of the electric fields of nearby ions.



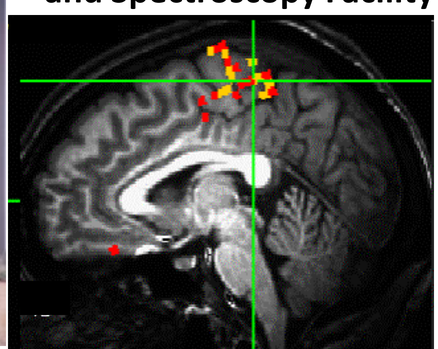
The shift in the ^{17}O NMR signal upon detecting the electric field from a nearby potassium ion (K^+).

At 21.1 teslas in the 900MHz magnet we can detect NMR line shifts due to the electric fields of potassium ions at particular sites along the ion channel

National High Magnetic Field Laboratory

11.4T MRI Magnet
400mm warm bore

Advanced Magnetic Resonance Imaging and Spectroscopy Facility



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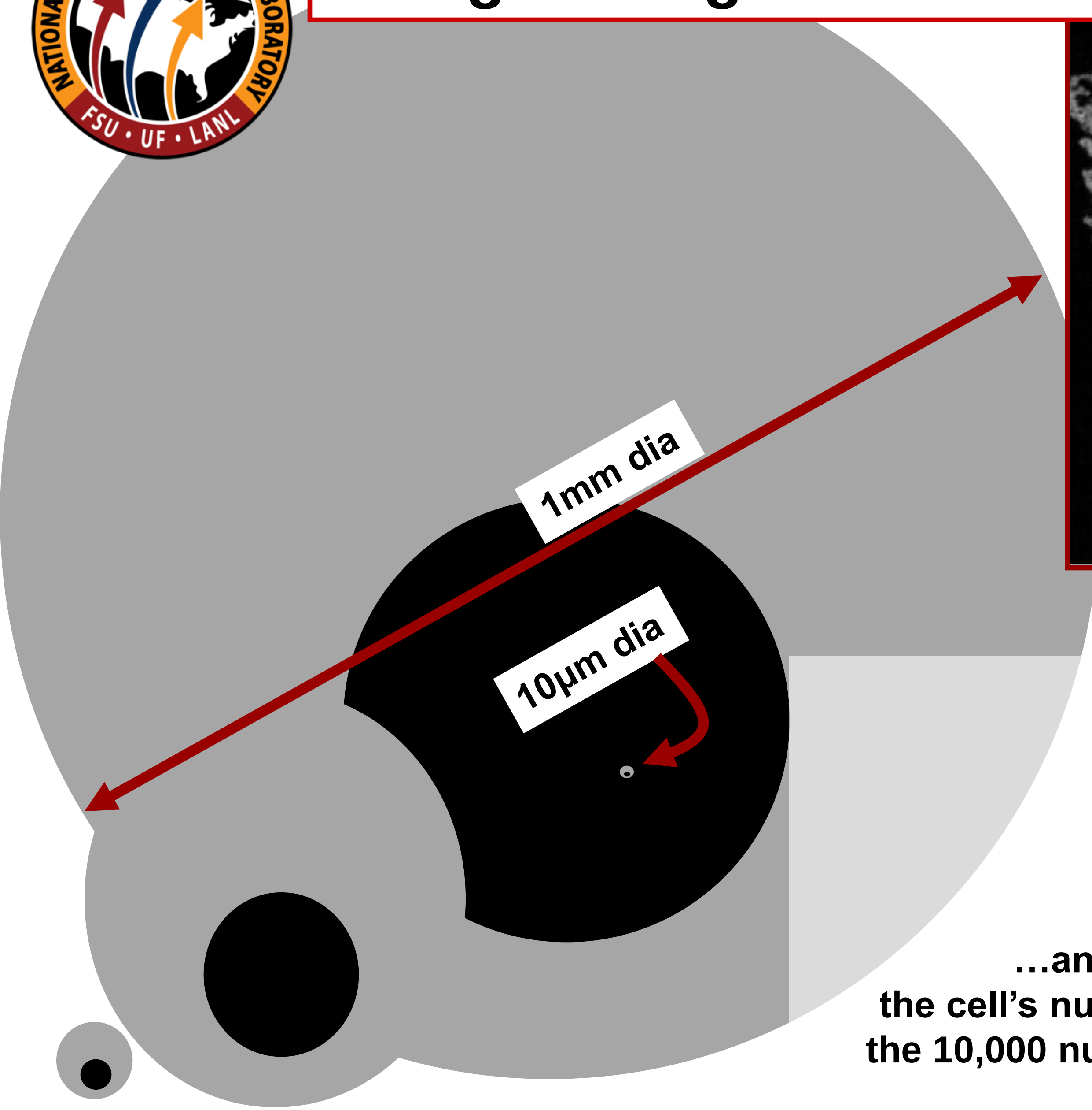
MRI goes High-Definition



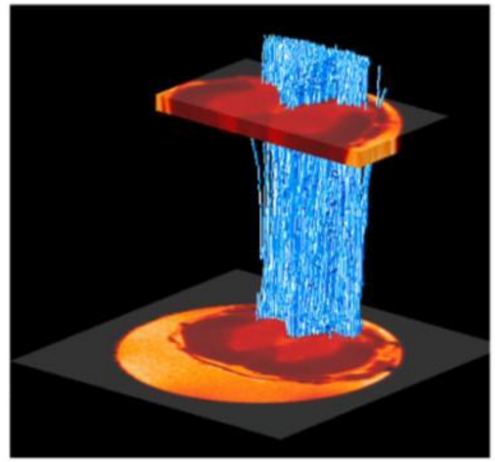
Imaging has improved from frog ovum to rat neuron in 20 years (10^6 : 1 volume ratio)

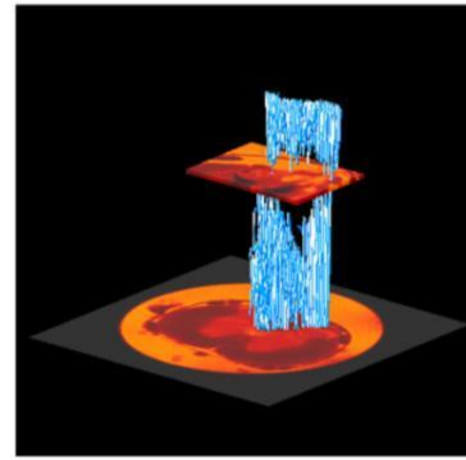
…and now sub-cellular structures: the cell's nucleus…and starting to resolve the 10,000 nucleoi *inside* the cell's nucleus

Tracking Water Pathways in the Spinal Cord and Brain:

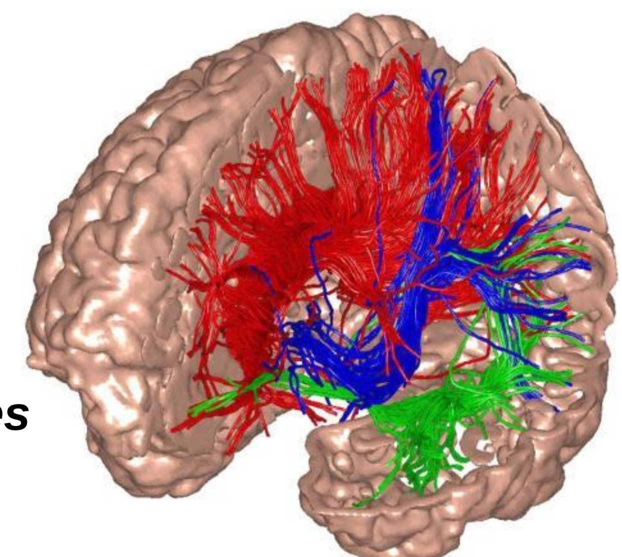
Mapping the Water Diffusion Tensor from MRI

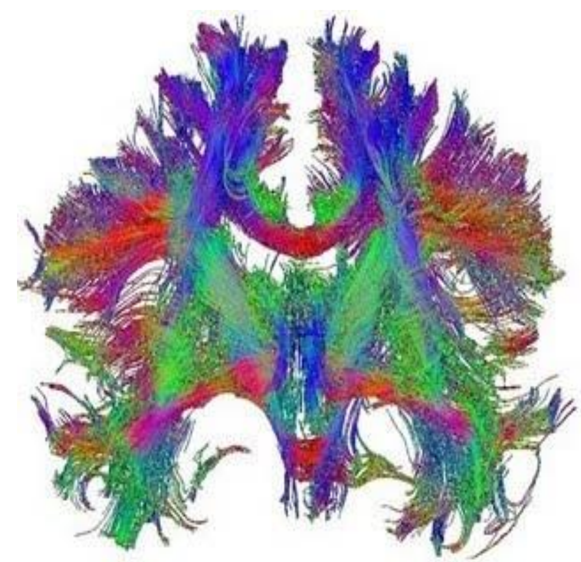
Water diffusion is easy along nerves, difficult between nerves.





Healthy (left) and Damaged (right MOUSE SPINAL CORDS





Water pathways in the HUMAN BRAIN can now resolve bundles as small as 100 axons

Quadrupolar Nuclei Revisited for MRI

I = 1 ^{2}H, ^{14}N…
I = 3/2 ^{11}B, ^{23}Na…
I = 5/2 ^{17}O…

Elements with:
Only I =1/2 nuclear spins (white)
Quadrupolar nuclei (cyan)
(i.e. I > 1/2)

H 2																	*He*
Li 6,7	**Be 9**											**B 10, 11**	*C*	**N 14**	**O 17**	*F*	**Ne 21**
Na 23	**Mg 25**											**Al 27**	*Si*	*P*	**S 33**	**Cl 35, 37**	Ar
K 39, 41	**Ca 43**	**Sc 45**	**Ti 47, 49**	**V 50, 51**	**Cr 53**	**Mn 55**	*Fe*	**Co 59**	**Ni 61**	**Cu 63, 65**	**Zn 67**	**Ga 69, 71**	**Ge 73**	**As 75**	*Se*	**Br 79, 81**	**Kr 83**
Rb 85, 87	**Sr 87**	*Y*	**Zr 91**	**Nb 93**	**Mo 97**	Tc	**Ru 99, 101**	*Rh*	**Pd 105**	*Ag*	*Cd*	**In 113 -5**	*Sn*	**Sb 121 -3**	*Te*	**I 127**	**Xe 129 -31**
Cs 133	**Ba 135 -7**	**La 138 -9**	**Hf 177 -9**	**Ta 181**	*W*	**Re 185 -7**	**Os 187 -9**	**Ir 191 -3**	*Pt*	**Au 197**	**Hg 201**	*Tl*	*Pb*	*Bi*	Po	At	Rn
Fr	Ra	Ac															

Ce	**Pr 141**	**Nd 143 -5**	Pm	**Sm 147 -9**	**Eu 151 -3**	**Gd 155 -7**	**Tb 159**	**Dy 161 -3**	**Ho 165**	**Er 167**	*Tm*	**Yb 173**	**Lu 175 -6**
Th	Pa	**U 235**	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

Second Generation MRI:
because you're not just water and fat

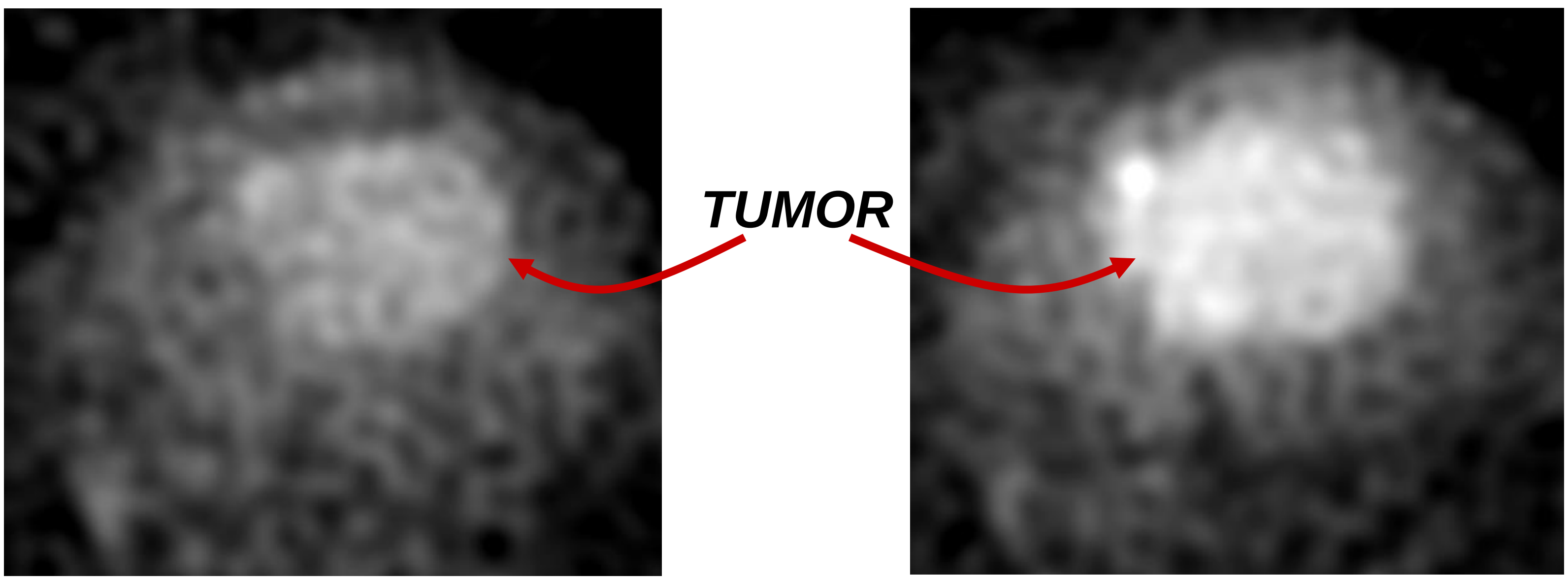
Rapid Assessment of Chemotherapy *using Sodium MRI*

In vivo **^{23}Na Images of mouse brain**

Sodium MRI is *thousands of times more difficult* than ordinary Hydrogen MRI

Sodium (^{23}Na) inside the cells is a biomarker for imminent cell death.

Before Therapy ***4 Days after Therapy***

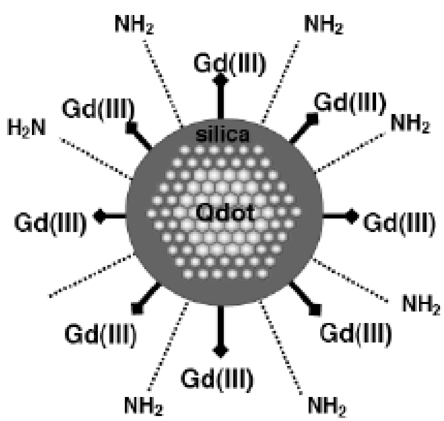


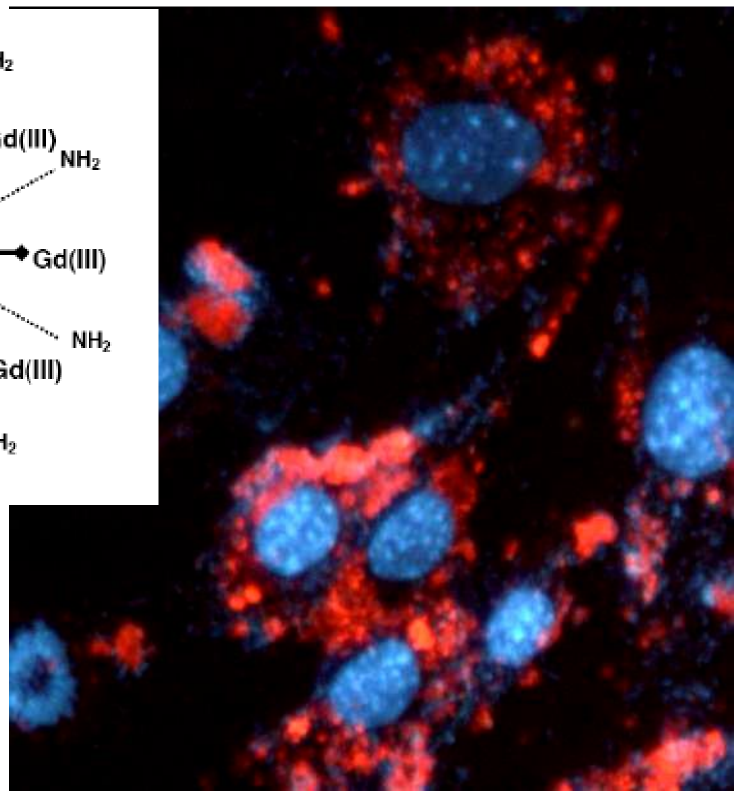
We learn that the chemotherapy is working even BEFORE the tumor cells die.

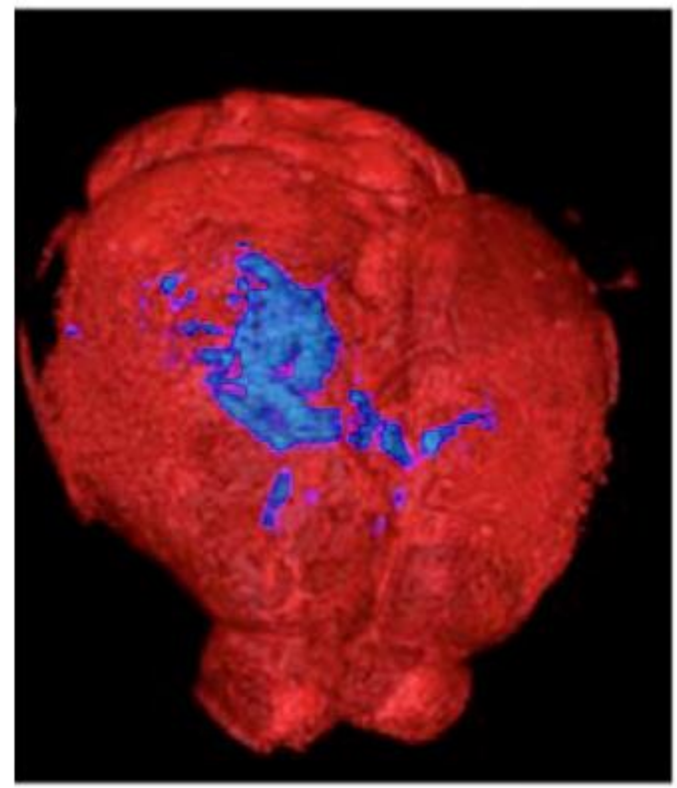
Magnetic Quantum Dots for Live Stem Cell Tracking

Living stem cells, labeled with bio-compatible Gadolinium nanoparticles…

tracked *in vivo* using Magnetic Resonance Imaging in a mouse brain as they respond to brain damage resulting from hypoxia.







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