New Physics
from
New Materials

or

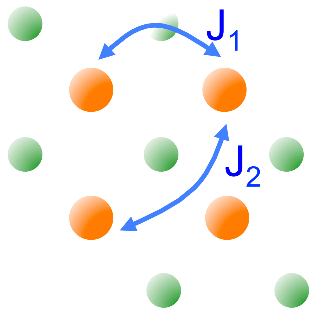
Controlling dimensionality and interactions

or

Many-body (emergent) phenomena through strong correlations

What we do….

Interactions (J_i) between magnetic ions in a (crystalline) solid



Specific heat capacity

$$C = -T\frac{\partial^2 F}{\partial T^2}$$

Resistivity $\rho = \sum nM_{ij}$

Thermopower $S \propto \pm 1/E_F$

$$H = \sum J_i S_i S_{i+1}$$

Hamiltonian

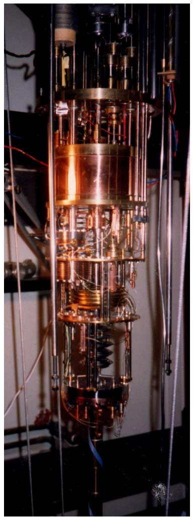
$$F = kT \ln \sum_s e^{-H/kT}$$

Partition function

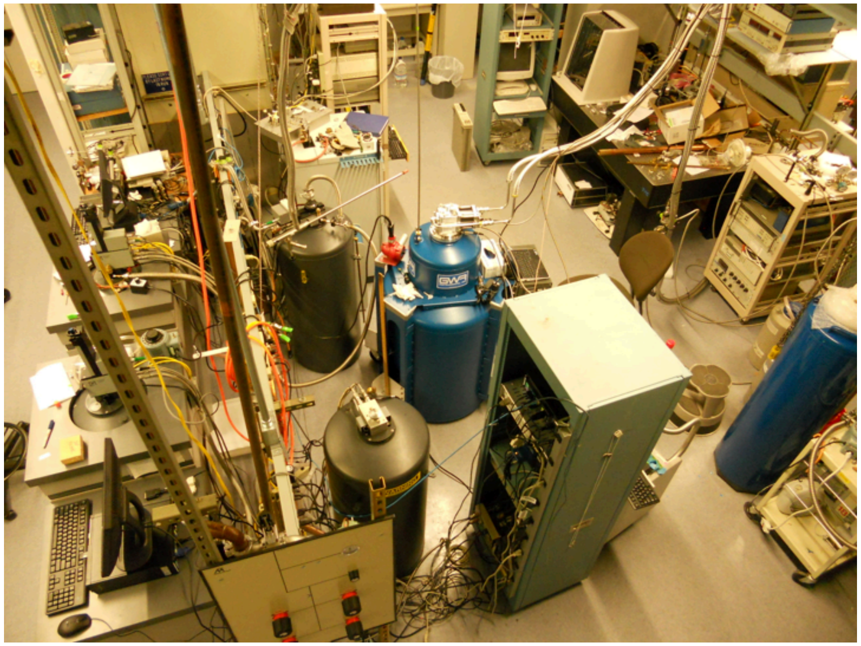
Theory (High fields, low T)

$$\chi = -\frac{\partial^2 F}{\partial H^2}$$

Magnetic susceptibility



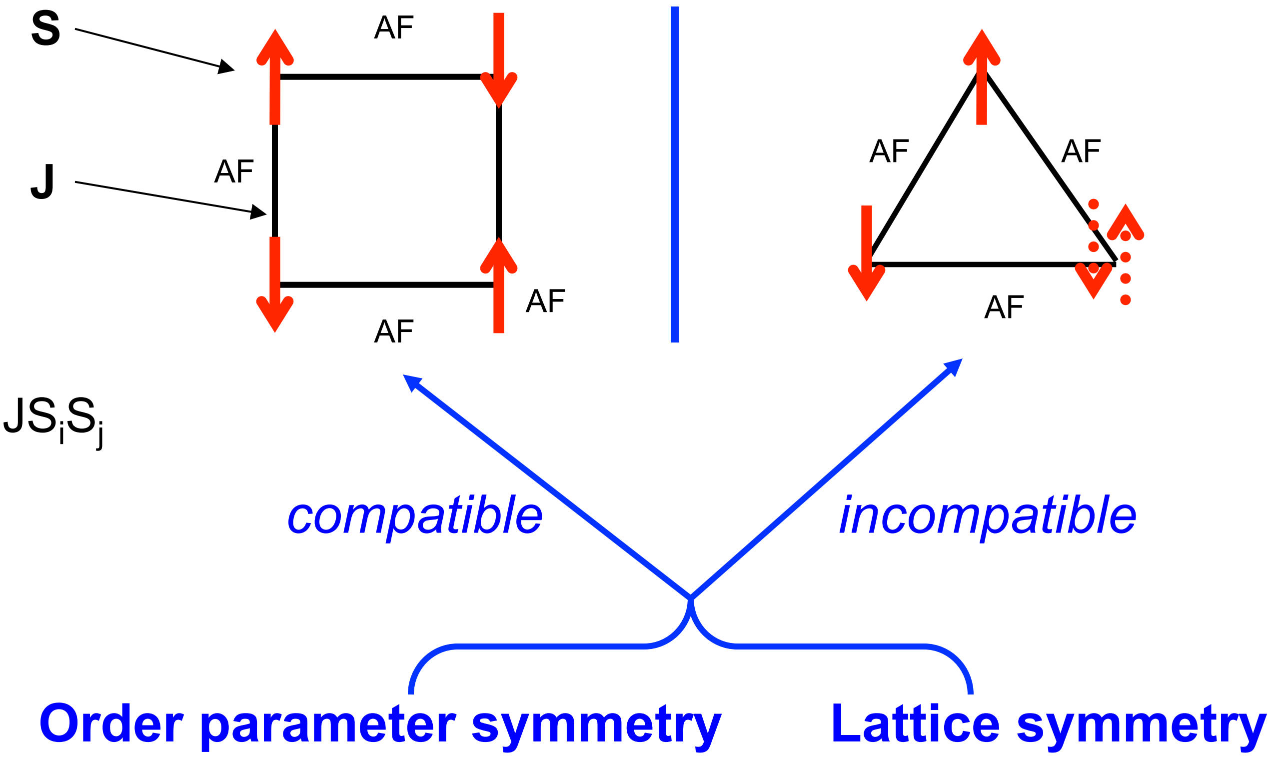
^{3}He/^{4}He dilution refrigerator



My Lab at 2300 Delaware

Degrees of freedom live on crystalline lattices

Unfrustrated and Frustrated Spins



$H = \Sigma_{ij} J S_i S_j$

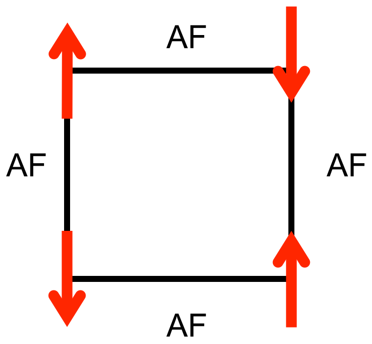
compatible

incompatible

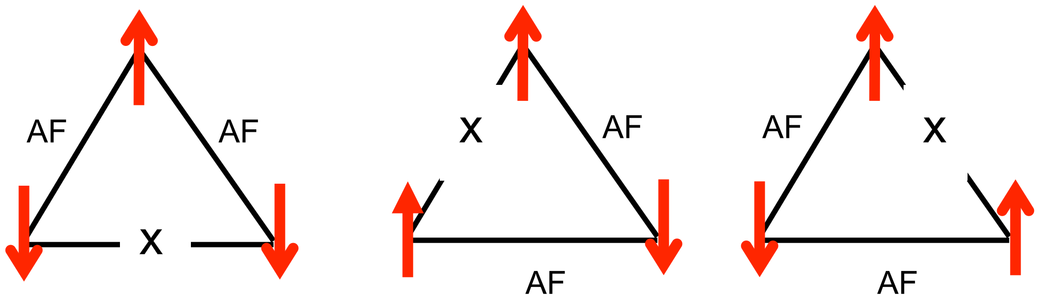
Order parameter symmetry

Lattice symmetry

Geometrical Frustration *is* spectral weight downshift



Long range order occurs at $T_c = \theta \sim JzS^2$



Frustrated situation – Long range order doesn't necessarily occur

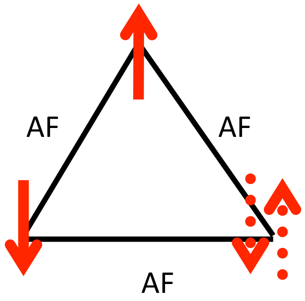
Symmetry incompatibility → degeneracy

Geometrical Frustration – Materials Considerations

Frustration →

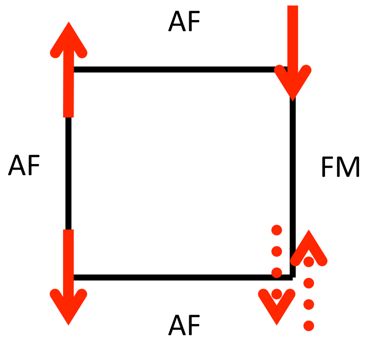
Disorder ↓

Antiferromagnetism Ferromagnetism Metamagnetism Ferrimagnetism	Geometrical Frustration
percolation, random fields	Spin glass



Symmetry incompatibility

$$H=\Sigma S_i \bullet S_j$$



Frustrated Materials

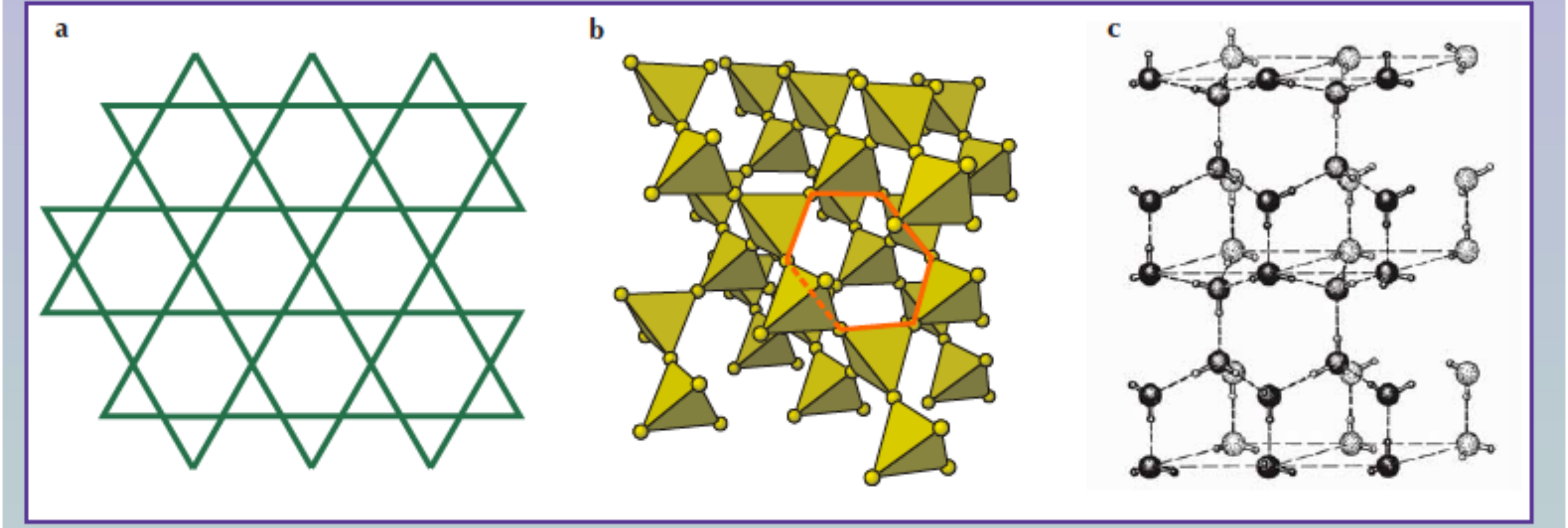
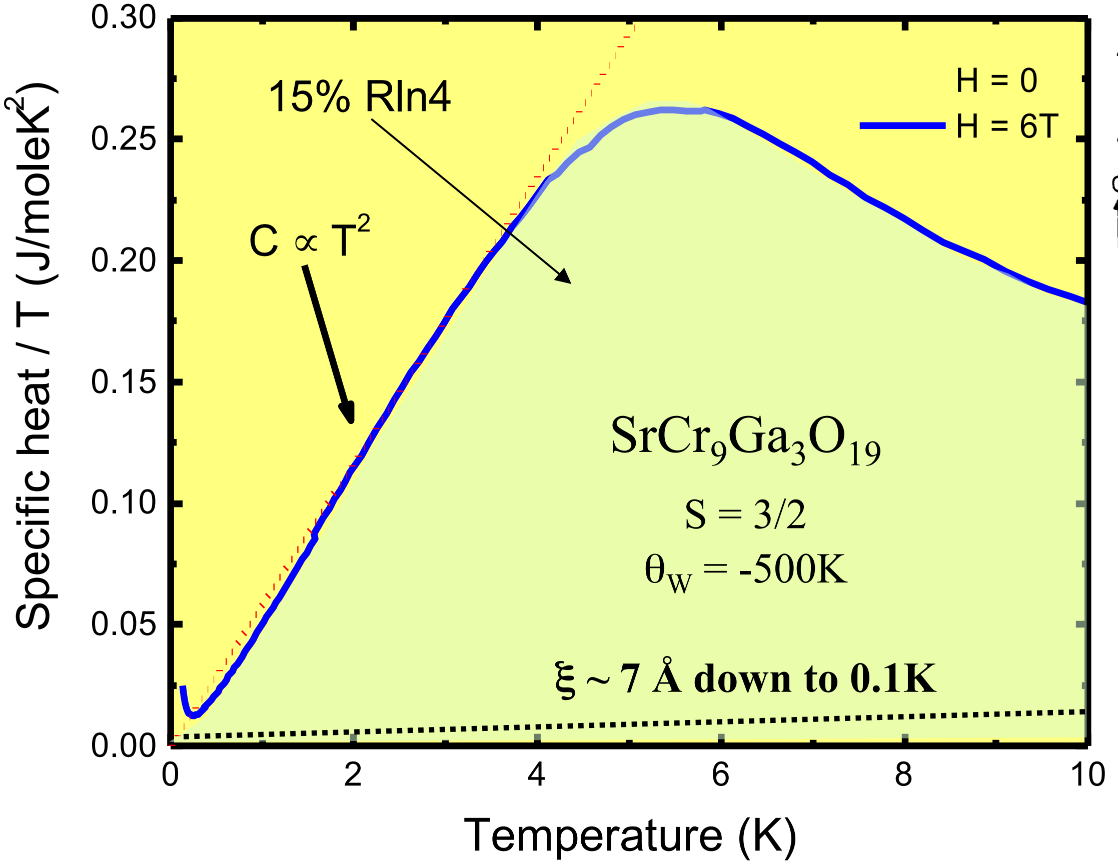
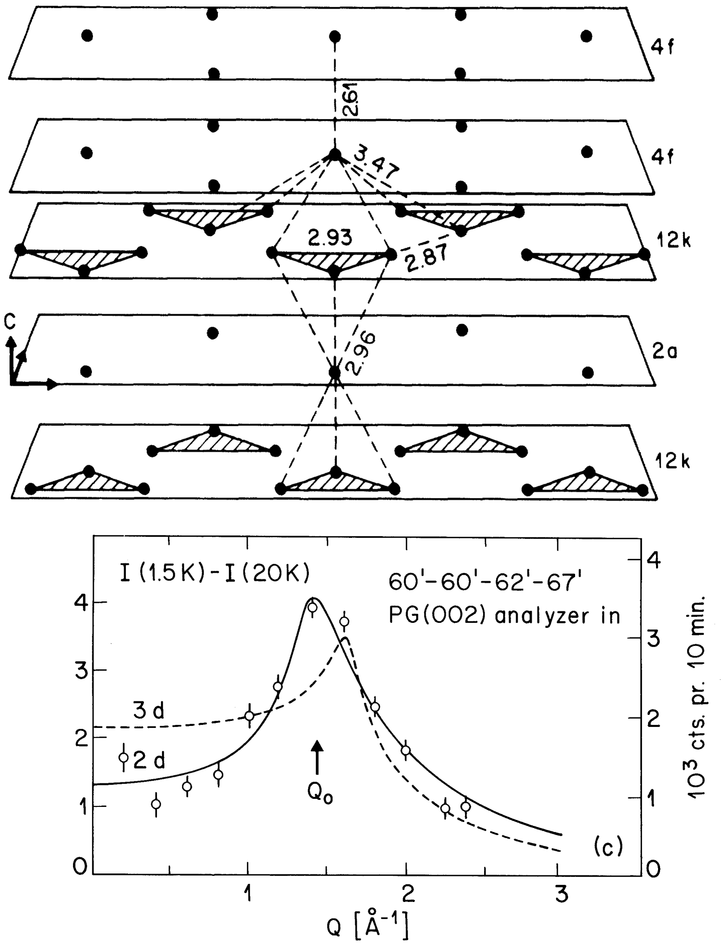


Figure 2. Frustrated lattices. **(a)** The kagome lattice consists of vertex-sharing triangles. **(b)** The pyrochlore lattice is a network of vertex-sharing tetrahedra. The orange hexagonal loop is discussed in figure 4. **(c)** Hexagonal ice consists of protons (small spheres) that reside on the bonds between two oxygen atoms (large spheres). The positions of the oxygens are uniquely determined, but there are exponentially many allowed proton configurations.

Spectral weight downshift in the kagome magnet $SrCr_9Ga_3O_{19}$



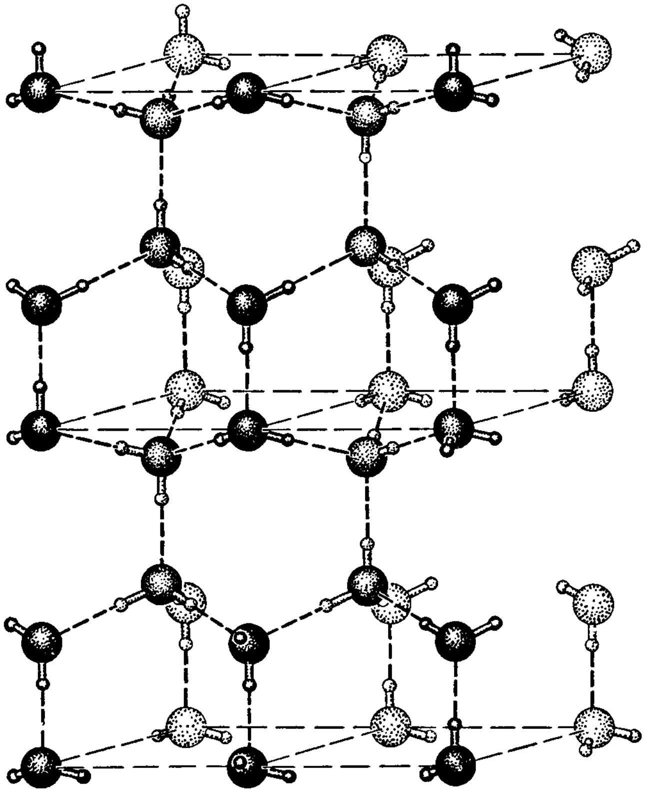
APR et al., PRL, **64**, 2070 (1990)



Broholm, Aeppli et al

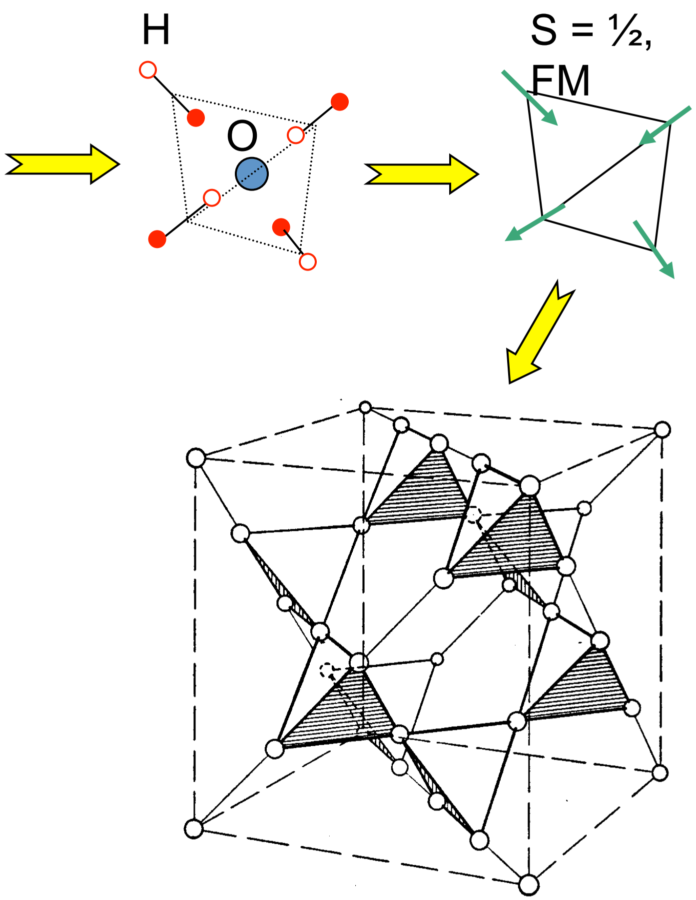
Neutron scattering – liquid like structure factor

Ice & Spin Ice



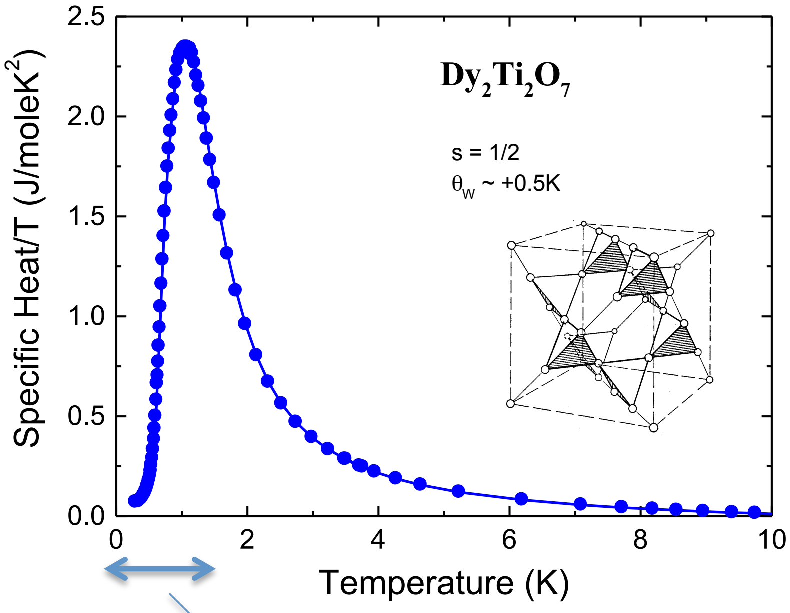
Pauling, The Nature of the Chemical Bond

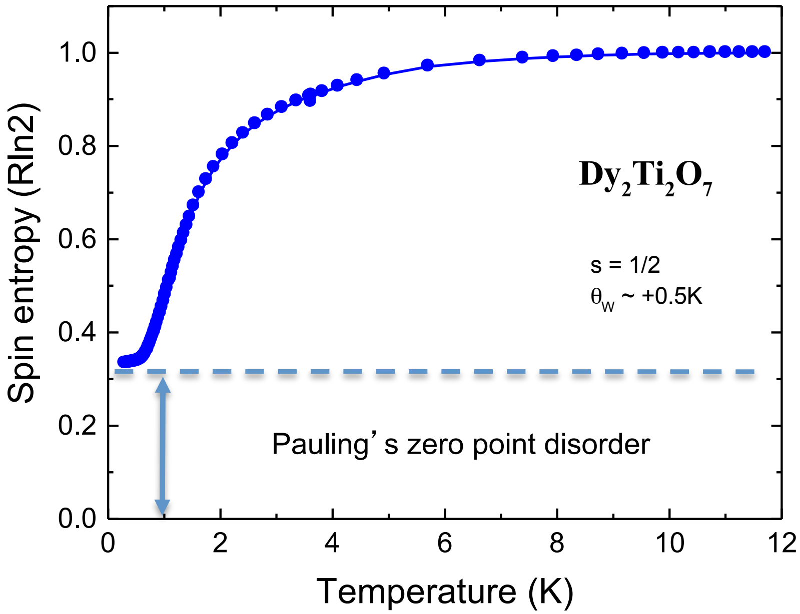
S_0 = Rln3/2

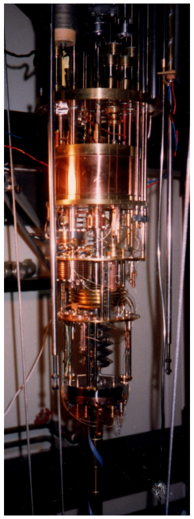


B-spinel, or pyrochlore

Observation of Zero Point disorder in *Spin Ice* - $Dy_2Ti_2O_7$

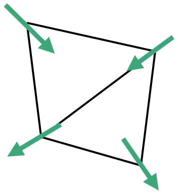




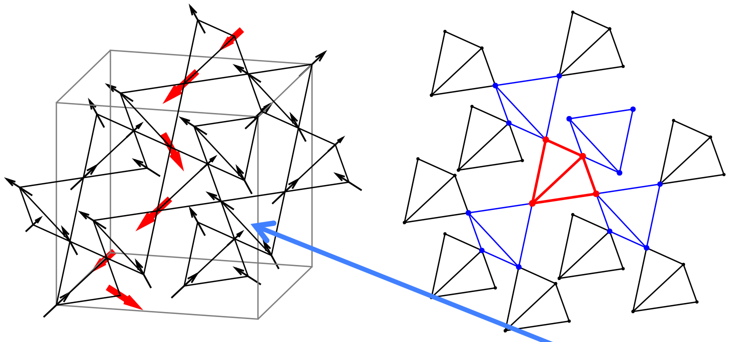


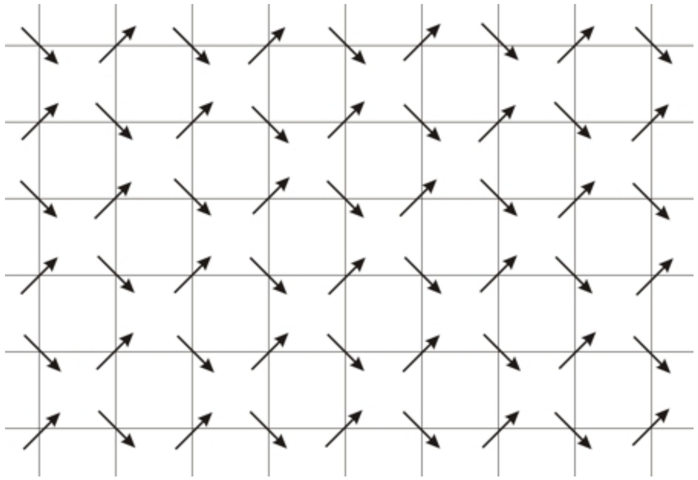
A. Ramirez et al, *Nature* (1999)

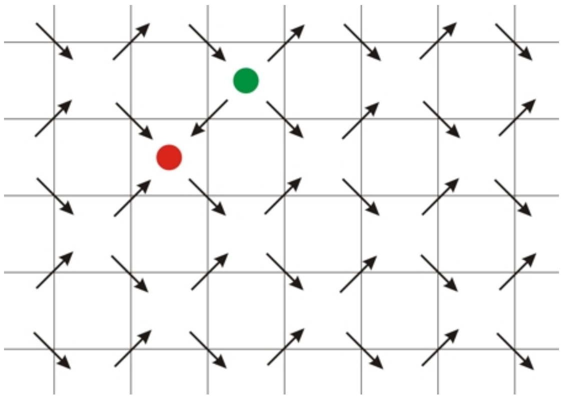
Electrostatics of *Spin Ice* – Emergence of Monopoles

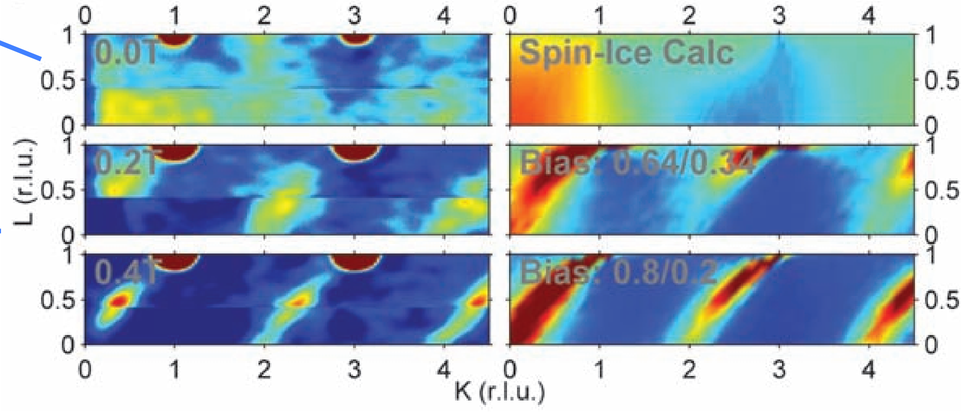


$$\Rightarrow \quad \vec{\nabla}\cdot\vec{S}=0$$









Morris et al, Science, 2009

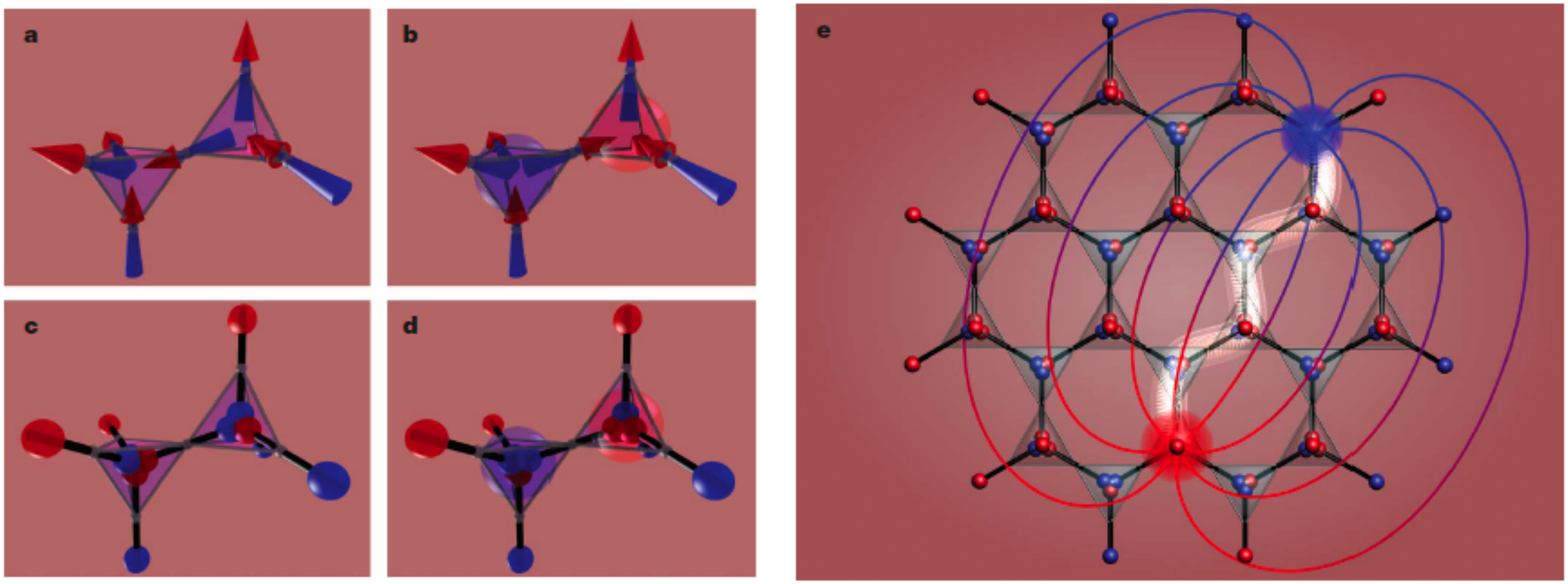
Castelnovo, Moessner, Sondhi, Nature 2008

nature Vol 451|3 January 2008|doi:10.1038/nature06433

LETTERS

Magnetic monopoles in spin ice

C. Castelnovo[1], R. Moessner[1,2] & S. L. Sondhi[3]



PHYSICAL REVIEW B **84**, 094437 (2011)

Higgs transitions of spin ice

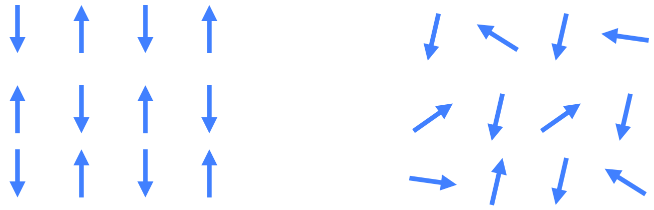
Stephen Powell
Joint Quantum Institute and Condensed Matter Theory Center, Department of Physics, University of Maryland,
College Park, Maryland 20742, USA

(Received 5 July 2011; published 22 September 2011)

When the lattice positions are the degrees of freedom

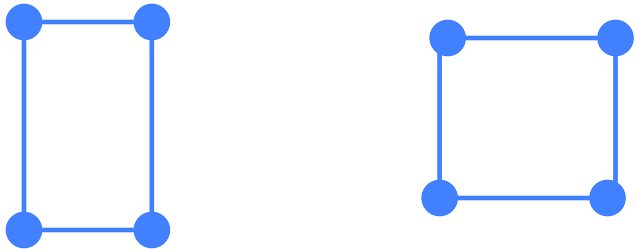
Compare Magnetic vs. Structural Transitions

Generic Magnetic Transition – Order-Disorder

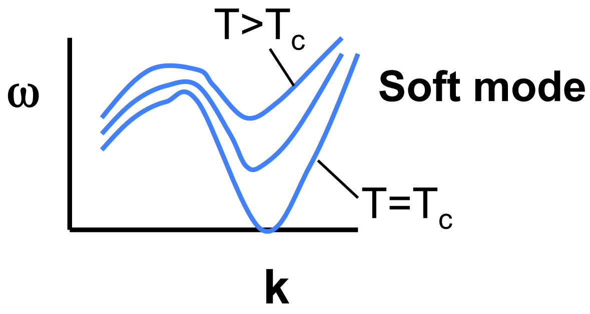


below T_c above T_c

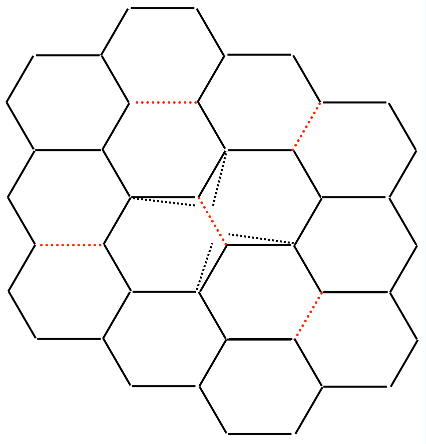
Generic Structural Transition – Displacive



below T_c above T_c

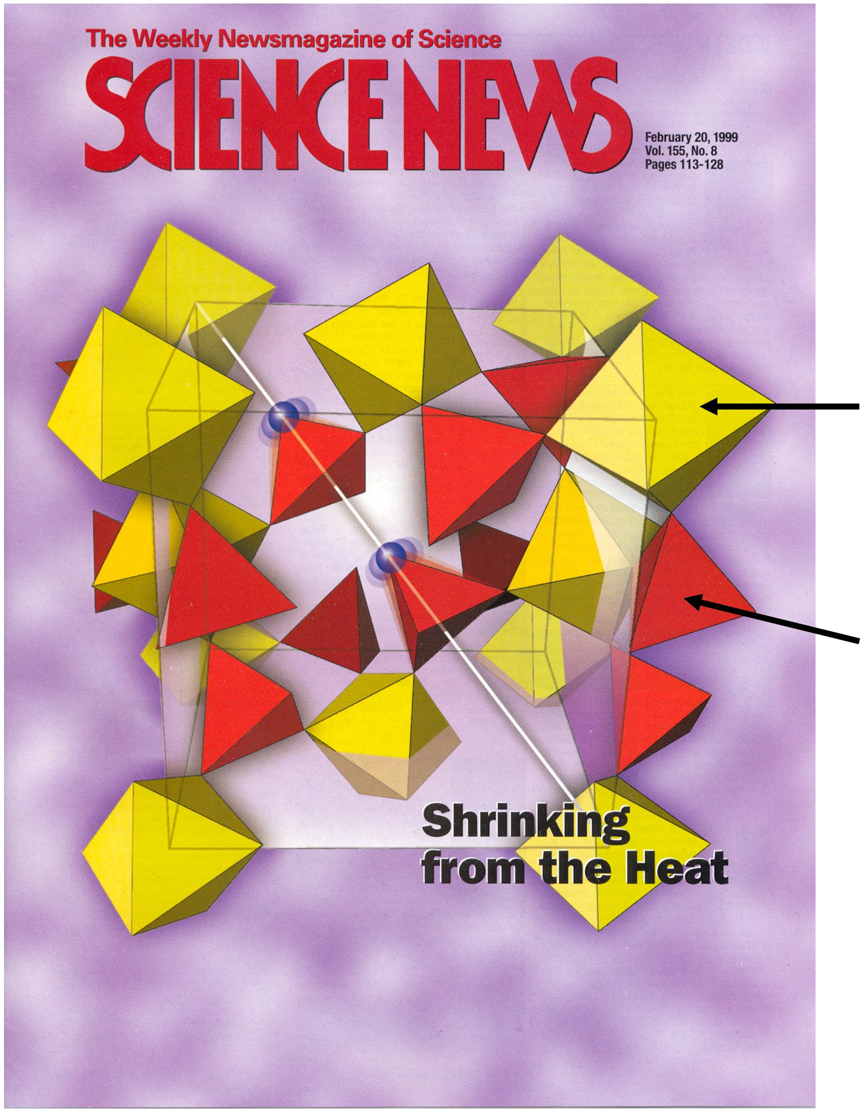


Frustrated Honeycomb



e.g. can’t tile 2-space with pentagons, so certain soft modes would be frustrated

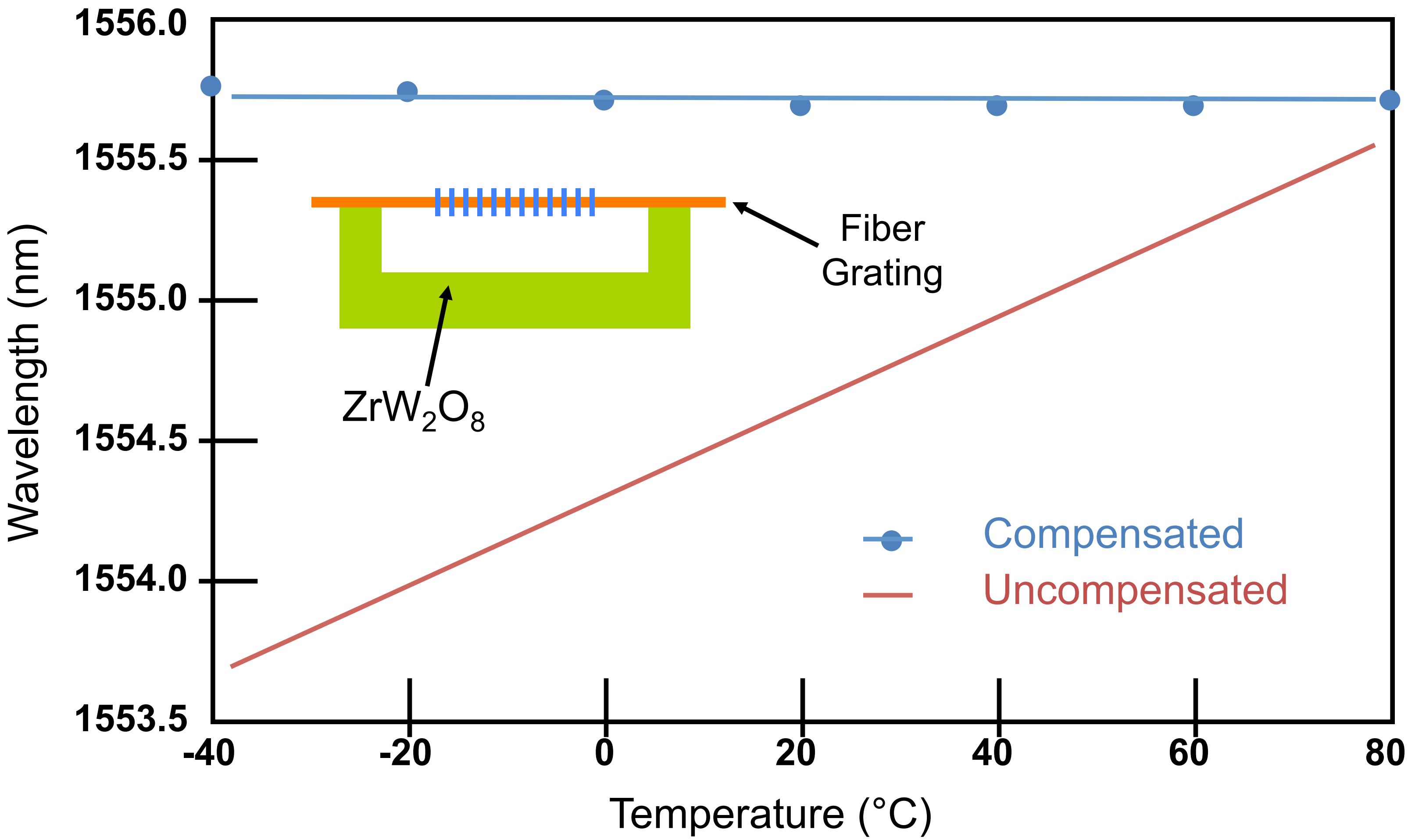
Frustrated In Nonmagnetic Systems: Negative Thermal Expansion in ZrW_2O_8



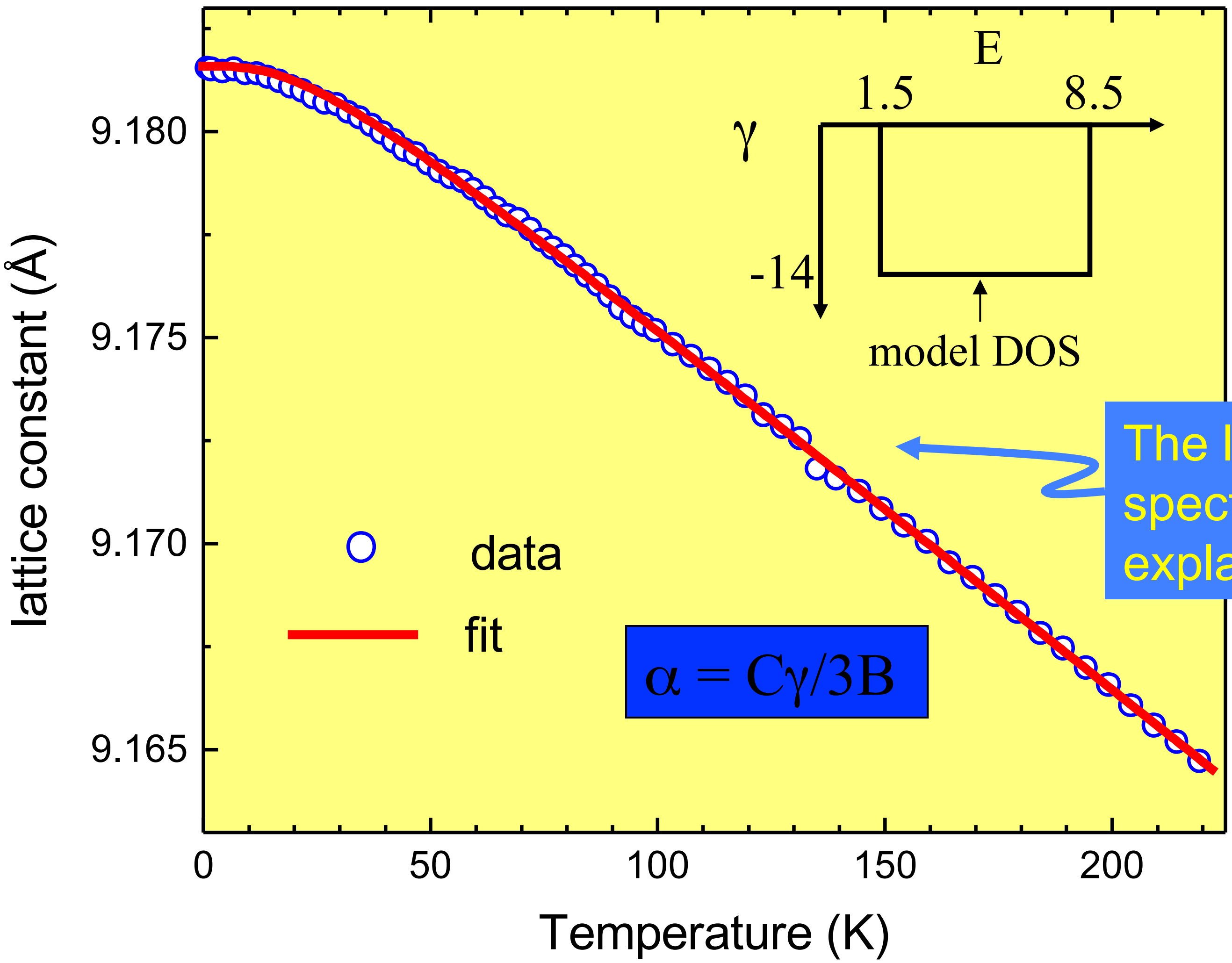
ZrO_6

WO_4

Solution to problem - bond FBG to ZrW_2O_8/ZrO_2 composite



Low-energy modes in ZrW_2O_8 and NTE

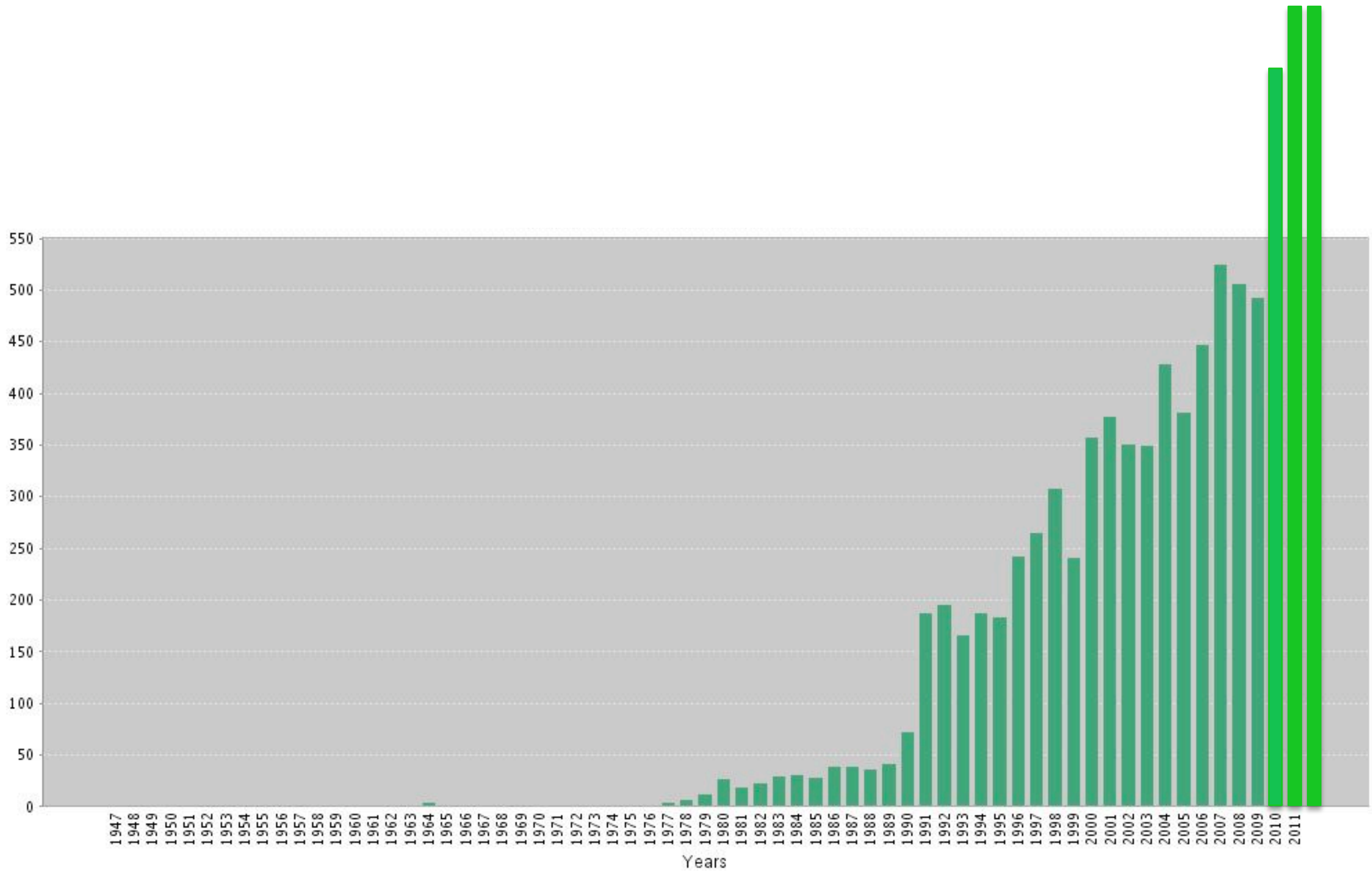


$\alpha = C\gamma/3B$

The low energy spectral weight explains NTE

Nature **396**, 147 (1998)

Papers with key word "frustration"



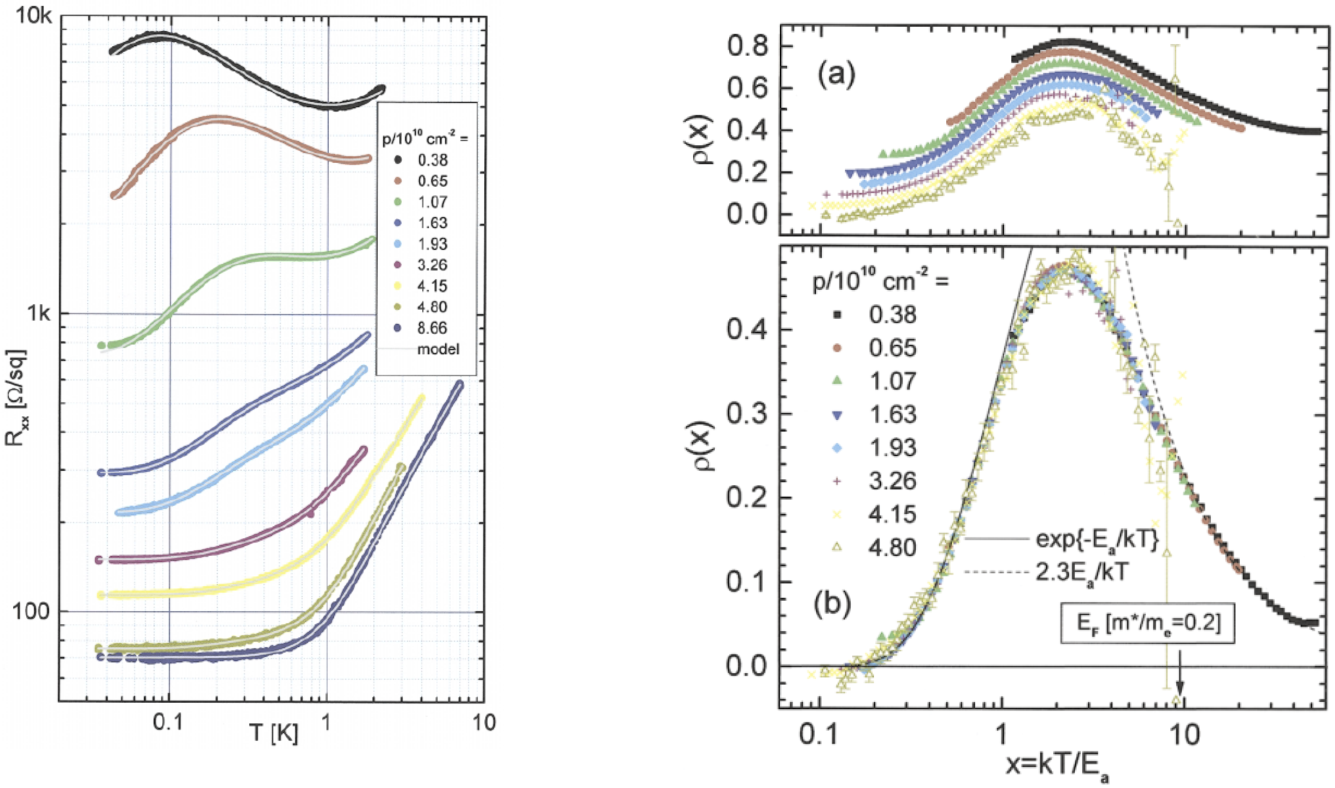
Source: ISI Web of Science

Can work in Reduced Dimensions

Metallic state induced by interactions in 2D

Nonmonotonic Temperature-Dependent Resistance in Low Density 2D Hole Gases

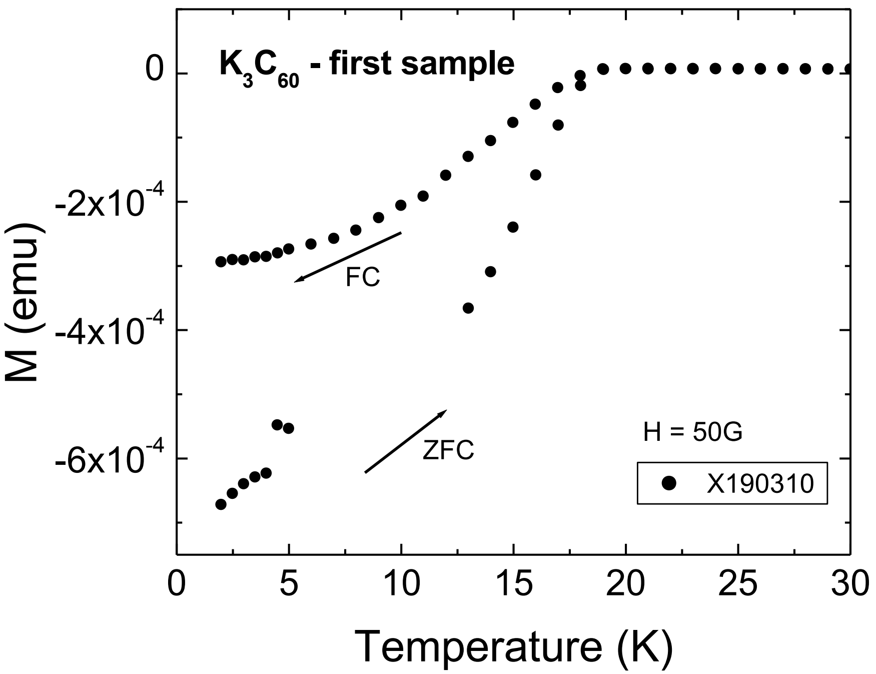
A. P. Mills, Jr., A. P. Ramirez, L. N. Pfeiffer, and K. W. West
Bell Labs, Lucent Technologies, 600 Mountain Avenue, Murray Hill, New Jersey 07974
(Received 12 April 1999)

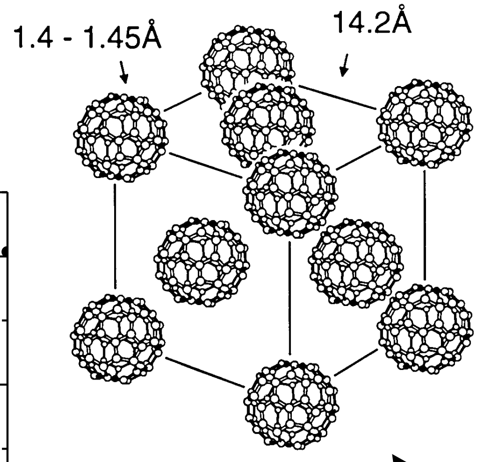


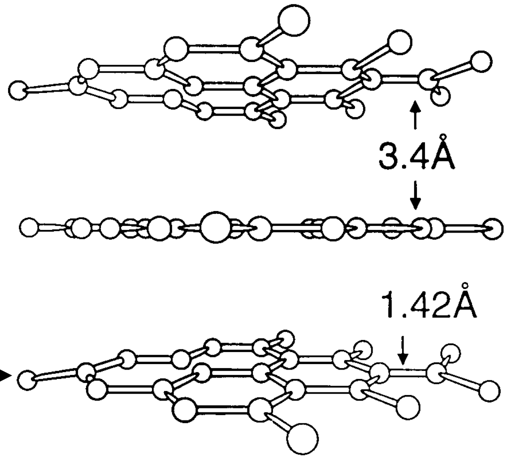
Physics from Zero Dimensions

Molecular Superconductors – The Higgs mechanism in soot!

A_3C_{60}







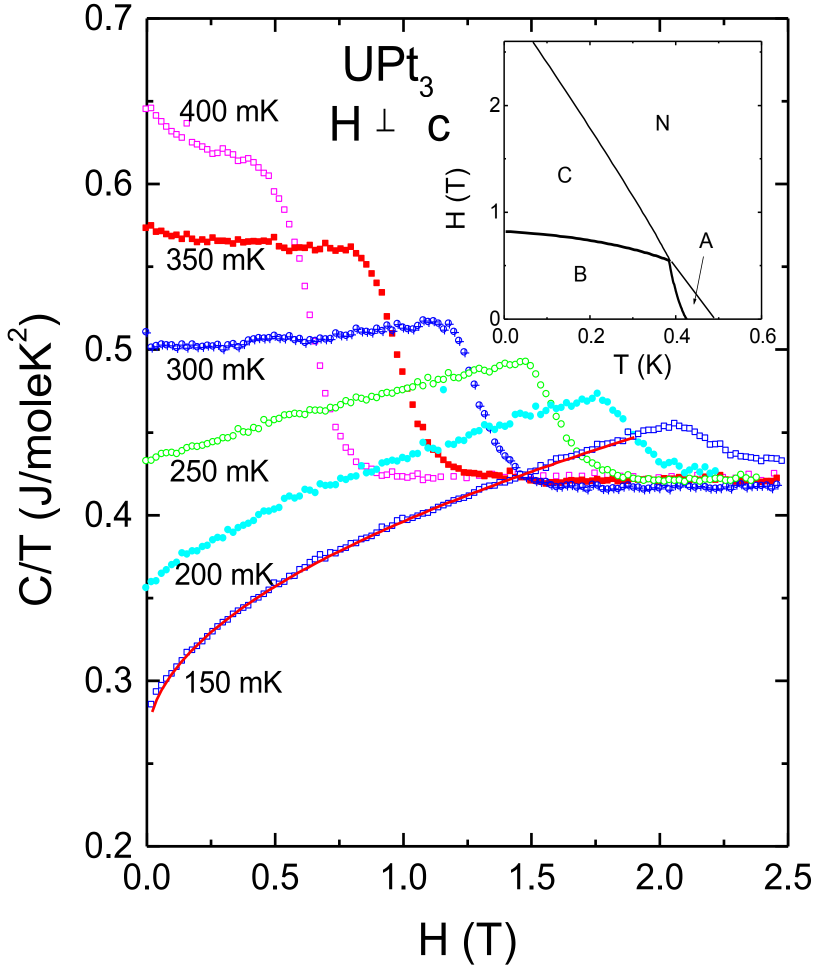
A_3C_{60} : T_c = 30K

AC_8 : T_c = 0.5K

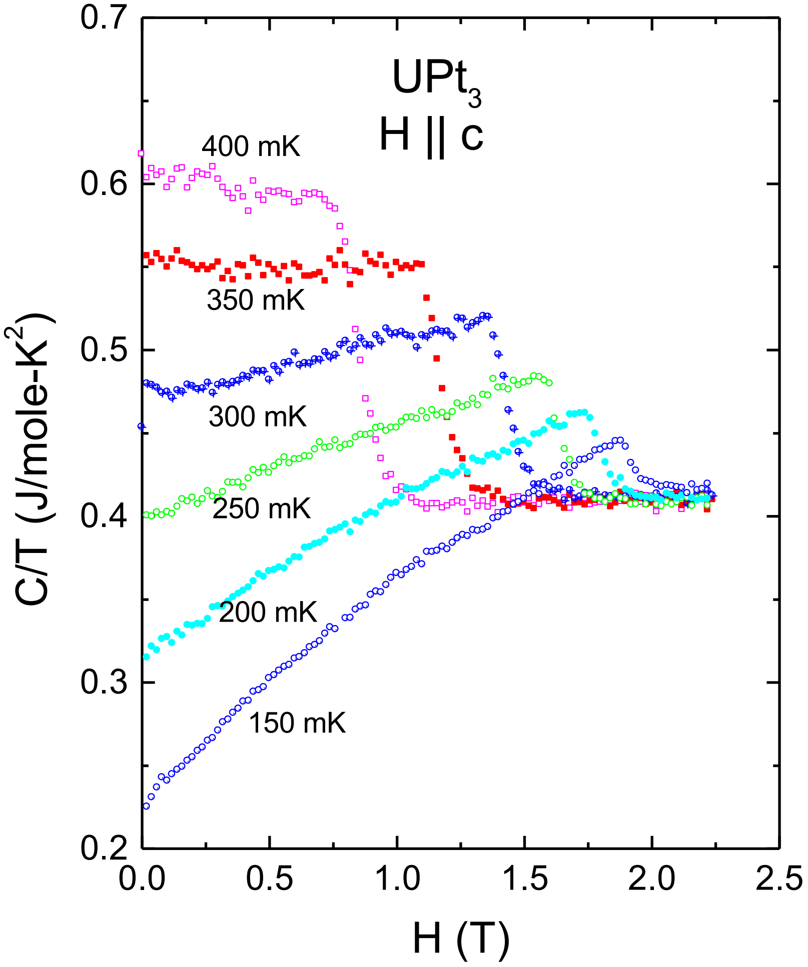
Graphite

A. Hebard et al., *Nature* (1991)

Anisotropic Superconducting State from Strong Correlations in a “heavy Fermion”

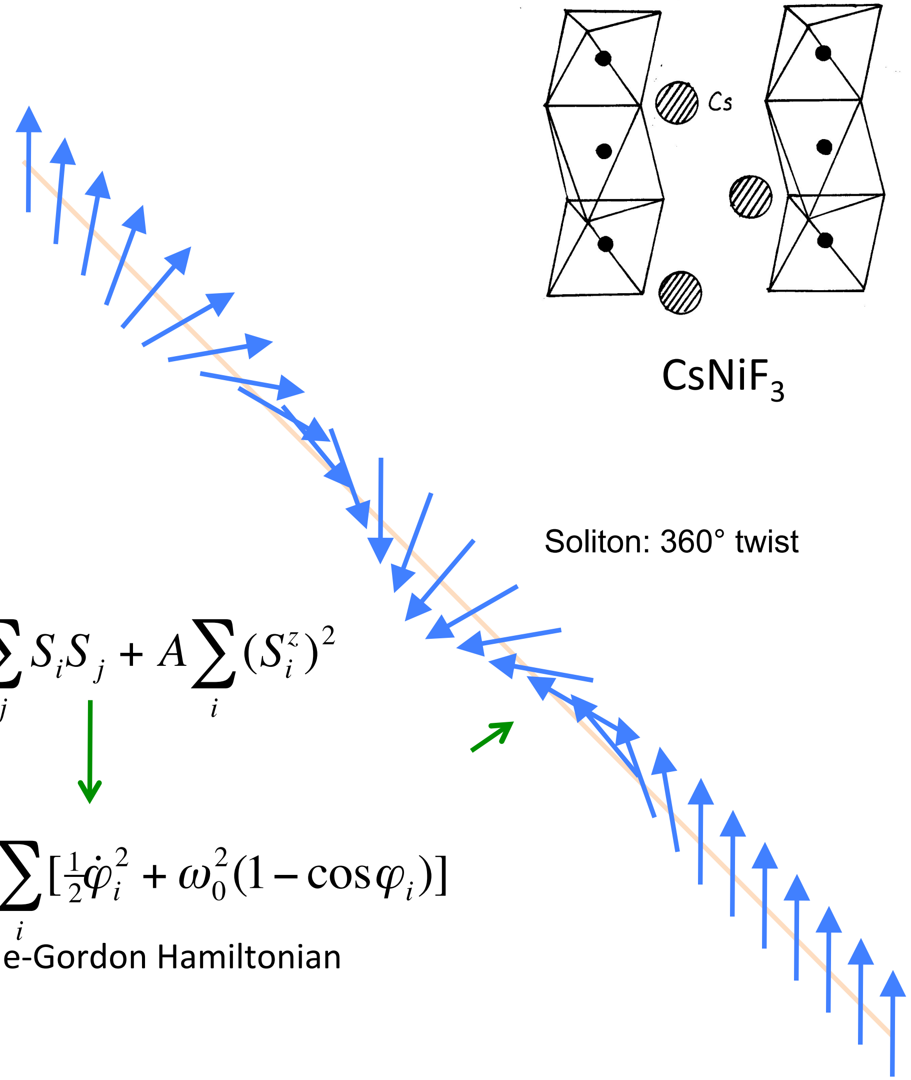


f1vgrph

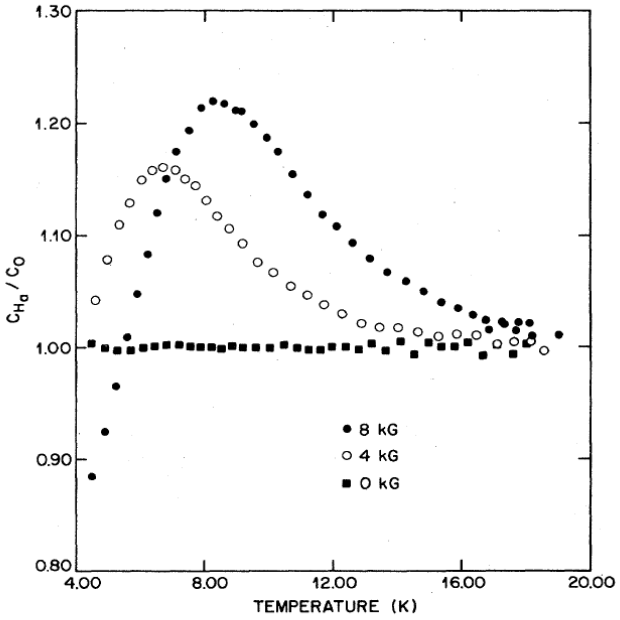


f2vgrph

A Quasi 1-D System



CsNiF$_3$



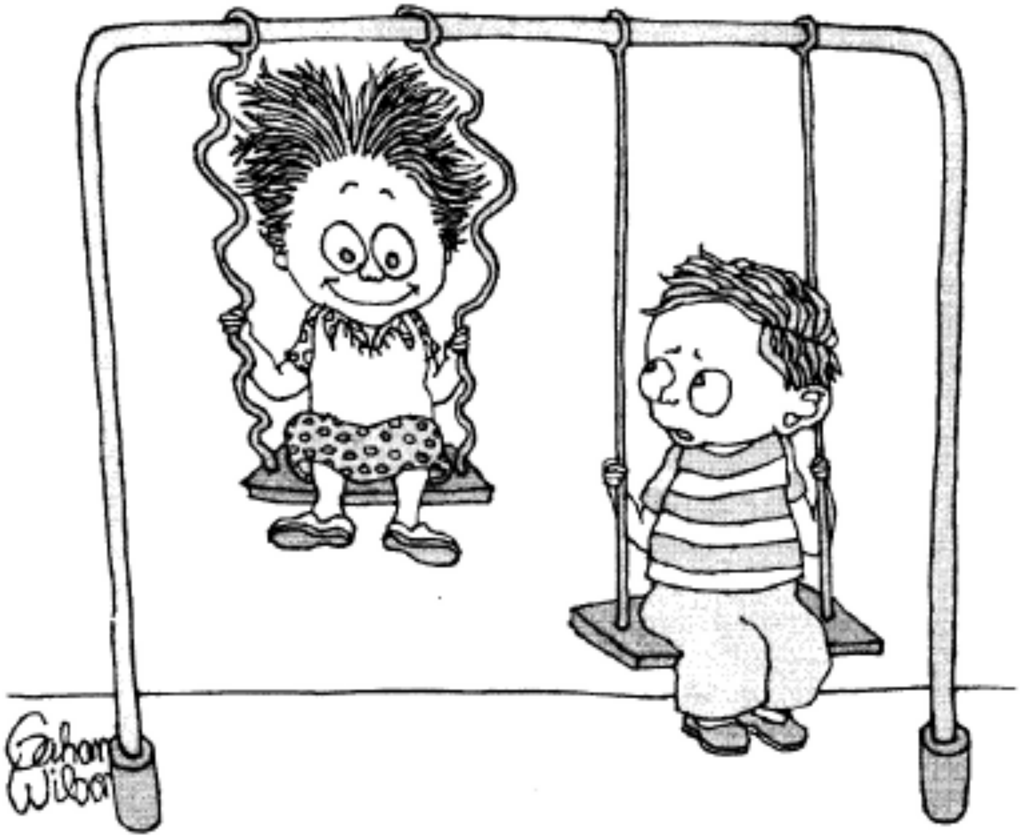
Soliton: 360° twist

$$H = J\sum_{ij} S_i S_j + A\sum_i (S_i^z)^2$$

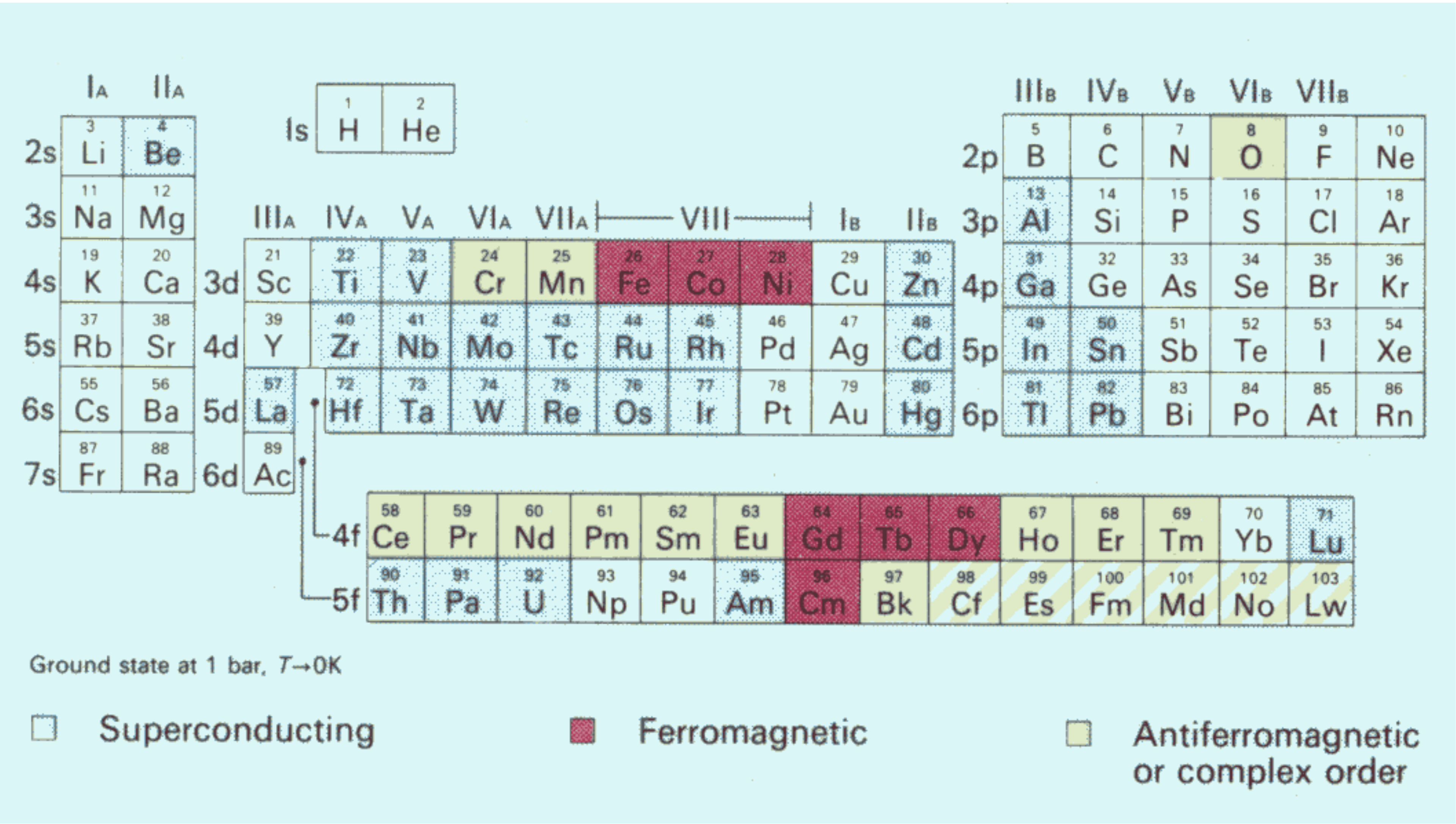
$$\downarrow$$

$$H = a\sum_i [\tfrac{1}{2}\dot{\varphi}_i^2 + \omega_0^2(1-\cos\varphi_i)]$$

Sine-Gordon Hamiltonian



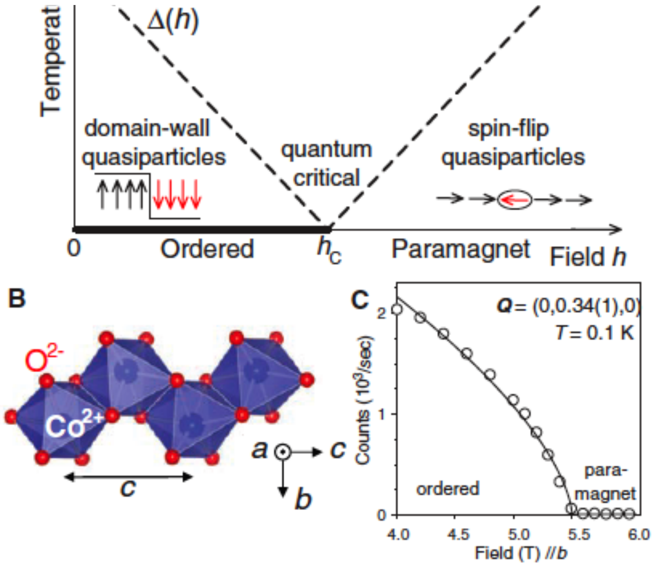
"Forward and backward, not up and down!"

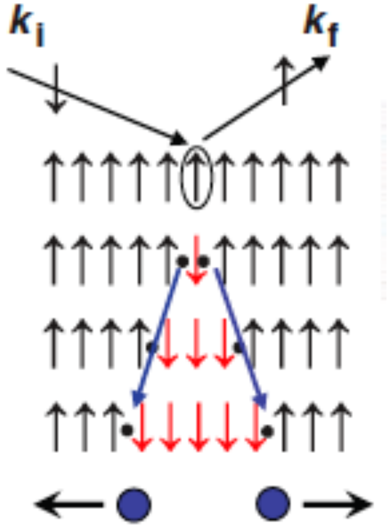
IA IIA
1s 1 H 2 He
IIIB IVB VB VIB VIIB
2s 3 Li 4 Be
2p 5 B 6 C 7 N 8 O 9 F 10 Ne
3s 11 Na 12 Mg
IIIA IVA VA VIA VIIA VIII IB IIB
3p 13 Al 14 Si 15 P 16 S 17 Cl 18 Ar
4s 19 K 20 Ca 3d 21 Sc 22 Ti 23 V 24 Cr 25 Mn 26 Fe 27 Co 28 Ni 29 Cu 30 Zn 4p 31 Ga 32 Ge 33 As 34 Se 35 Br 36 Kr
5s 37 Rb 38 Sr 4d 39 Y 40 Zr 41 Nb 42 Mo 43 Tc 44 Ru 45 Rh 46 Pd 47 Ag 48 Cd 5p 49 In 50 Sn 51 Sb 52 Te 53 I 54 Xe
6s 55 Cs 56 Ba 5d 57 La 72 Hf 73 Ta 74 W 75 Re 76 Os 77 Ir 78 Pt 79 Au 80 Hg 6p 81 Tl 82 Pb 83 Bi 84 Po 85 At 86 Rn
7s 87 Fr 88 Ra 6d 89 Ac
4f 58 Ce 59 Pr 60 Nd 61 Pm 62 Sm 63 Eu 64 Gd 65 Tb 66 Dy 67 Ho 68 Er 69 Tm 70 Yb 71 Lu
5f 90 Th 91 Pa 92 U 93 Np 94 Pu 95 Am 96 Cm 97 Bk 98 Cf 99 Es 100 Fm 101 Md 102 No 103 Lw
Ground state at 1 bar, T→0K
Superconducting
Ferromagnetic
Antiferromagnetic or complex order

Quantum Criticality in an Ising Chain: Experimental Evidence for Emergent E_8 Symmetry

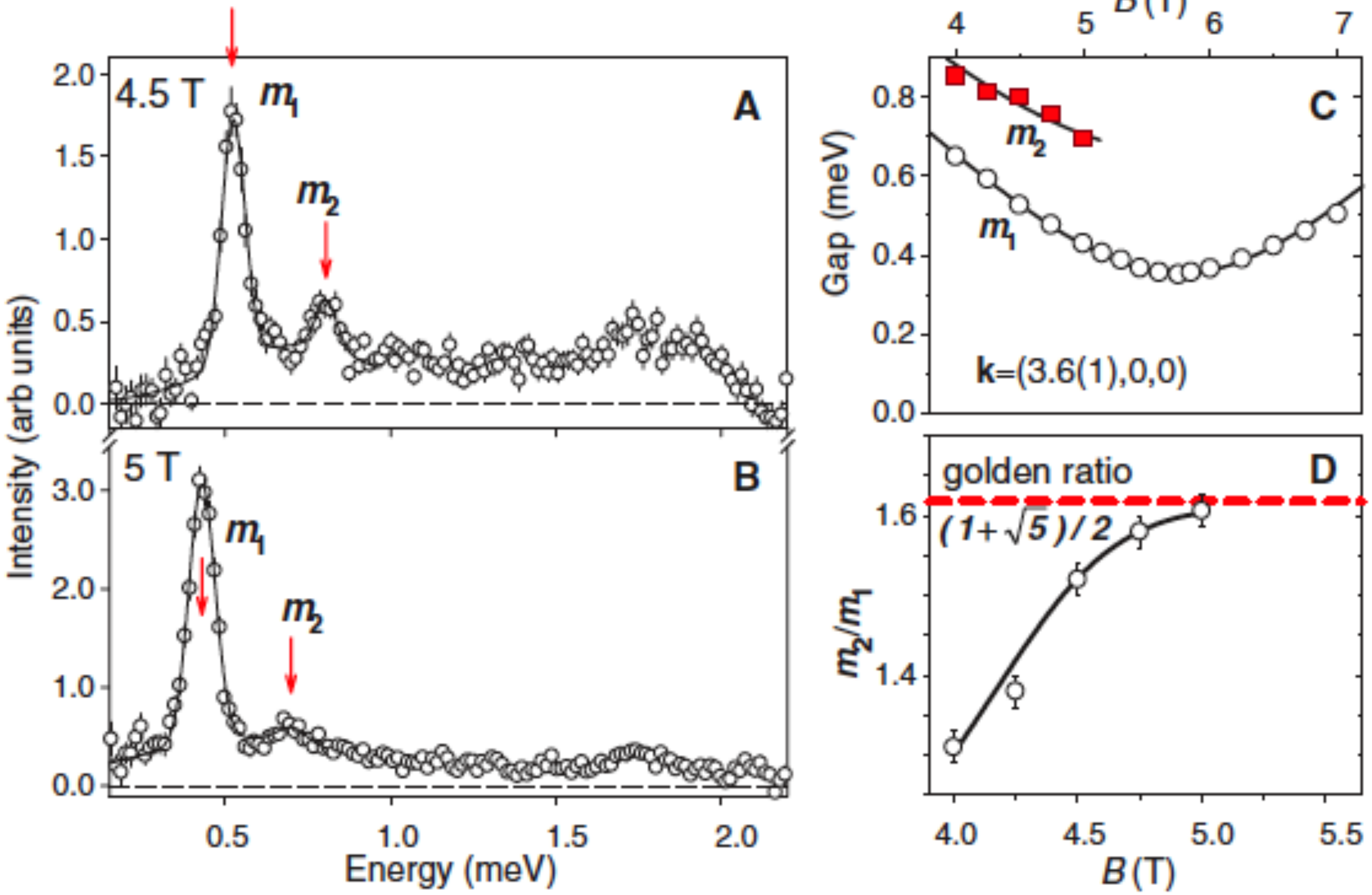
R. Coldea,[1]* D. A. Tennant,[2] E. M. Wheeler,[1]† E. Wawrzynska,[3] D. Prabhakaran,[1]
M. Telling,[4] K. Habicht,[2] P. Smeibidl,[2] K. Kiefer[2]

Quantum phase transitions take place between distinct phases of matter at zero temperature. Near the transition point, exotic quantum symmetries can emerge that govern the excitation spectrum of the system. A symmetry described by the E_8 Lie group with a spectrum of eight particles was long predicted to appear near the critical point of an Ising chain. We realize this system experimentally by using strong transverse magnetic fields to tune the quasi–one-dimensional Ising ferromagnet $CoNb_2O_6$ (cobalt niobate) through its critical point. Spin excitations are observed to change character from pairs of kinks in the ordered phase to spin-flips in the paramagnetic phase. Just below the critical field, the spin dynamics shows a fine structure with two sharp modes at low energies, in a ratio that approaches the golden mean predicted for the first two meson particles of the E_8 spectrum. Our results demonstrate the power of symmetry t m behaviors.





Energy spectrum in $CoNb_2O_6$



The Rise of Topological Insulators

History:

1)Quantum Hall Effect and edge states (~1980)

2)Chern number topology (~1983)

3)QHE intrinsically (Haldanium) (~1987)

4)Projecting into 3D (~1990)

5)Spitting the bands with spin orbit (~2004)

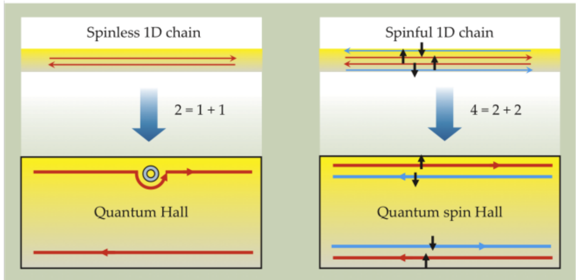
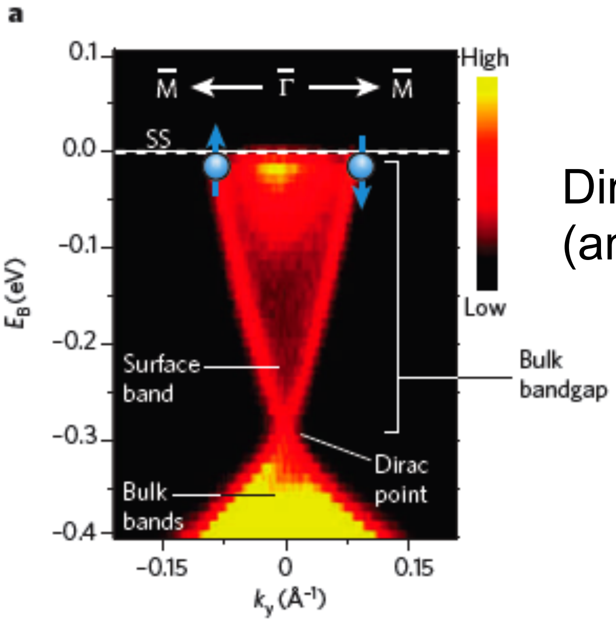
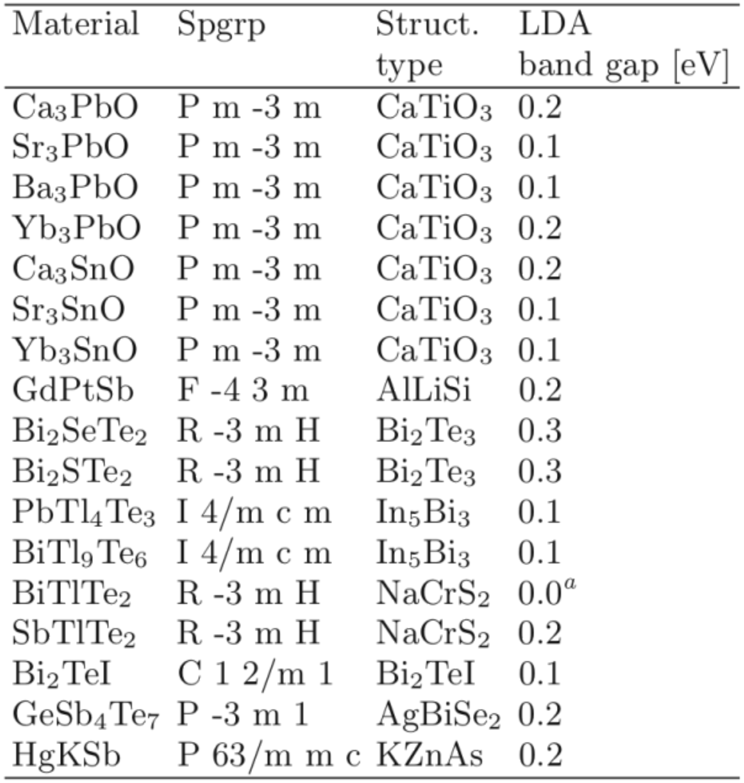


Figure 1. Spatial separation is at the heart of both the quantum Hall (QH) and the quantum spin Hall (QSH) effects. **(a)** A spinless one-dimensional system has both a forward and a backward mover. Those two basic degrees of freedom are spatially separated in a QH bar, as illustrated by the symbolic equation "2 = 1 + 1." The upper edge contains only a forward mover and the lower edge has only a backward mover. The states are robust: They will go around an impurity without scattering. **(b)** A spinful 1D system has four basic channels, which are spatially separated in a QSH bar: The upper edge contains a forward mover with up spin and a backward mover with down spin, and conversely for the lower edge. That separation is illustrated by the symbolic equation "4 = 2 + 2."



Dirac spectrum in Bi_2Se_3
(analogies to graphene)

The Rise of Topological Insulators



Material	Spgrp	Struct. type	LDA band gap [eV]
Ca_3PbO	P m -3 m	$CaTiO_3$	0.2
Sr_3PbO	P m -3 m	$CaTiO_3$	0.1
Ba_3PbO	P m -3 m	$CaTiO_3$	0.1
Yb_3PbO	P m -3 m	$CaTiO_3$	0.2
Ca_3SnO	P m -3 m	$CaTiO_3$	0.2
Sr_3SnO	P m -3 m	$CaTiO_3$	0.1
Yb_3SnO	P m -3 m	$CaTiO_3$	0.1
GdPtSb	F -4 3 m	AlLiSi	0.2
Bi_2SeTe_2	R -3 m H	Bi_2Te_3	0.3
Bi_2STe_2	R -3 m H	Bi_2Te_3	0.3
$PbTl_4Te_3$	I 4/m c m	In_5Bi_3	0.1
$BiTl_9Te_6$	I 4/m c m	In_5Bi_3	0.1
$BiTlTe_2$	R -3 m H	$NaCrS_2$	0.0^a
$SbTlTe_2$	R -3 m H	$NaCrS_2$	0.2
Bi_2TeI	C 1 2/m 1	Bi_2TeI	0.1
$GeSb_4Te_7$	P -3 m 1	$AgBiSe_2$	0.2
HgKSb	P 63/m m c	KZnAs	0.2

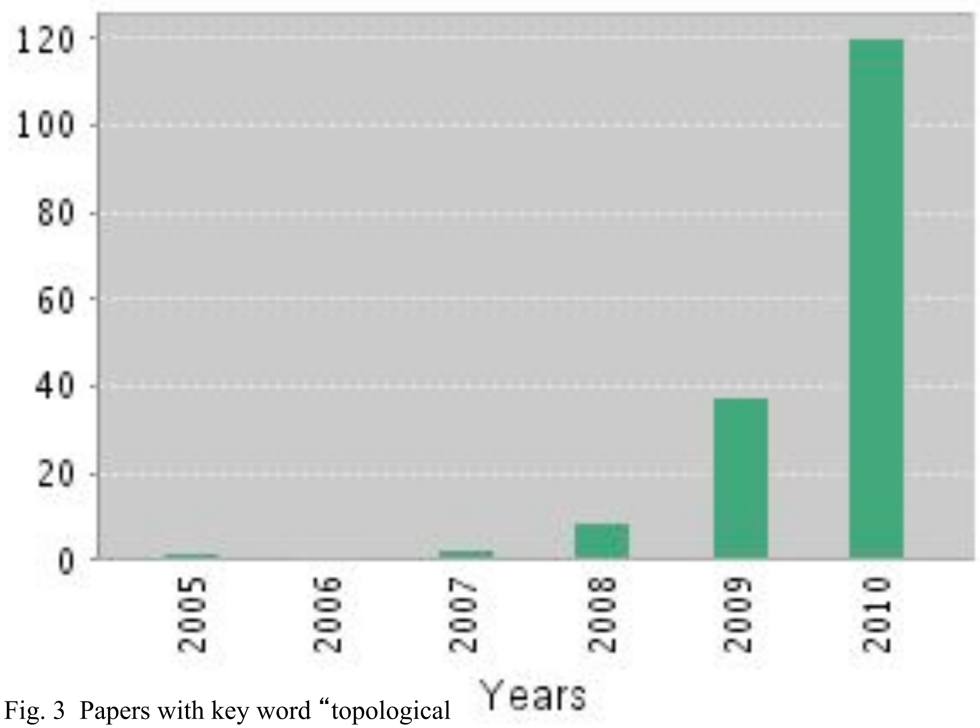


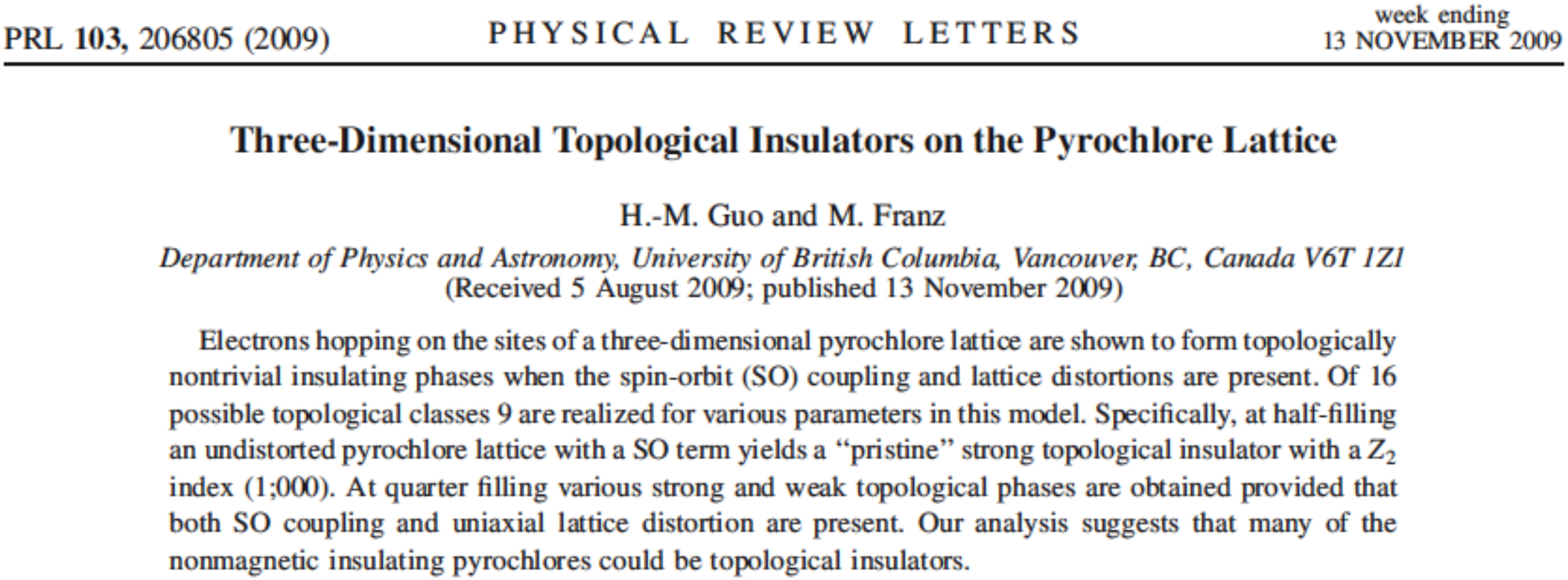
Fig. 3 Papers with key word “topological insulator”. ISI, Nov 2010

2012 Buckley Prize awarded for Topological Insulator Discovery (Kane, Mollenkamp, Zhang)

Other aspects of Topological Insulators

- Predictions of EB axion term in interior of TIs
- Monopoles
- Majorana Fermions
- Spintronics

Connection between Geometrical Frustration and Topological Insulators !



PRL **103,** 206805 (2009) PHYSICAL REVIEW LETTERS week ending 13 NOVEMBER 2009

Three-Dimensional Topological Insulators on the Pyrochlore Lattice

H.-M. Guo and M. Franz

Department of Physics and Astronomy, University of British Columbia, Vancouver, BC, Canada V6T 1Z1

(Received 5 August 2009; published 13 November 2009)

Electrons hopping on the sites of a three-dimensional pyrochlore lattice are shown to form topologically nontrivial insulating phases when the spin-orbit (SO) coupling and lattice distortions are present. Of 16 possible topological classes 9 are realized for various parameters in this model. Specifically, at half-filling an undistorted pyrochlore lattice with a SO term yields a “pristine” strong topological insulator with a Z_2 index (1;000). At quarter filling various strong and weak topological phases are obtained provided that both SO coupling and uniaxial lattice distortion are present. Our analysis suggests that many of the nonmagnetic insulating pyrochlores could be topological insulators.

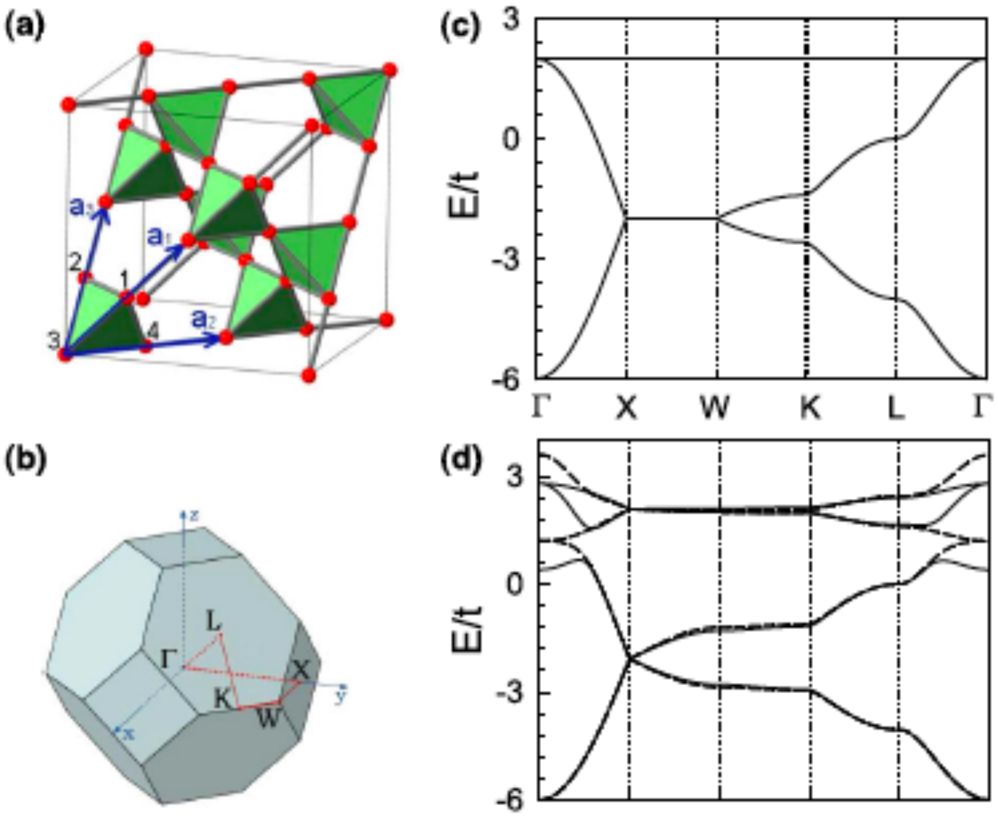
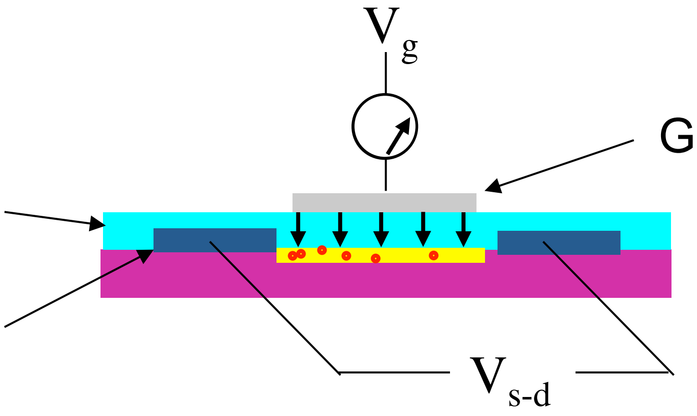


FIG. 1 (color online). (a) Pyrochlore lattice is a face-centered cubic Bravais lattice with a 4-point basis forming a shaded tetrahedron. (b) The first Brillouin zone of the fcc lattice with high-symmetry lines and points indicated. (c) Band structure of the tight-binding model Eq. (1). (d) Band structure with spin-orbit coupling Eq. (3) for $\lambda = -0.1t$ (solid line) and $\lambda = 0.1t$ (dashed line).

New materials from devices

How does a field-effect transistor work?

Rutgers method, Podzorov, Gershenson
2003

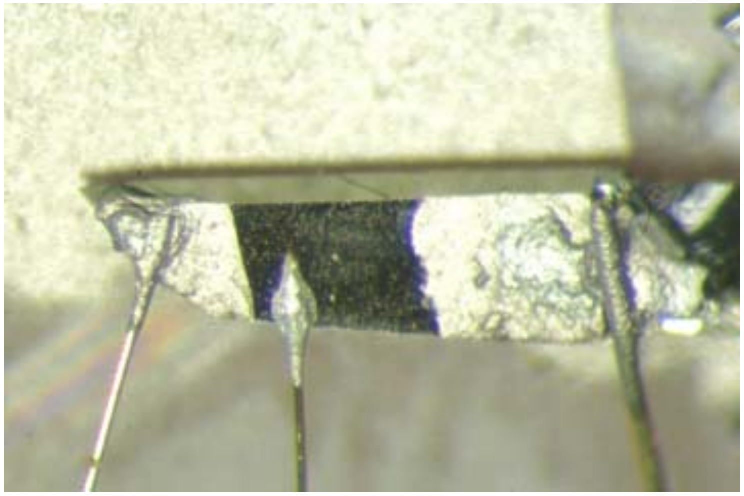


Insulating
gate
barrier

Gate electrode

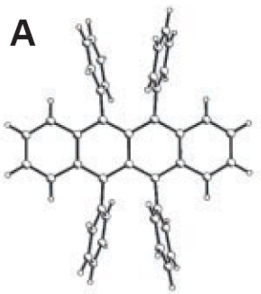
semiconductor

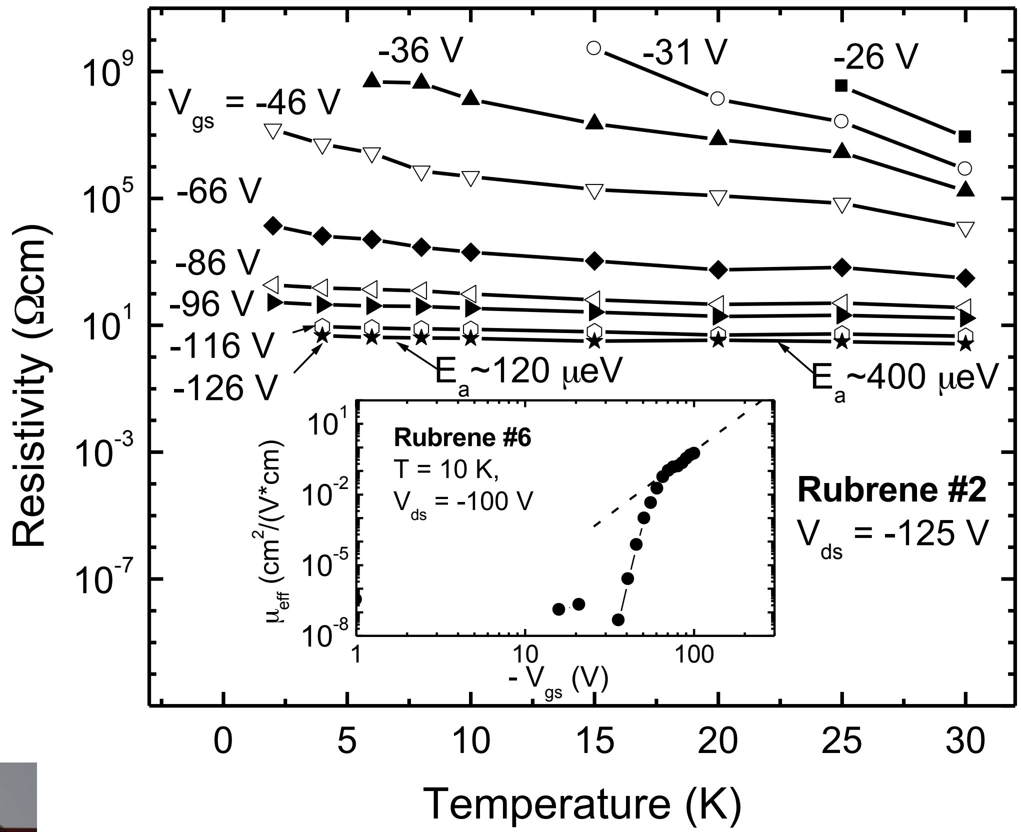
source and drain
electrodes



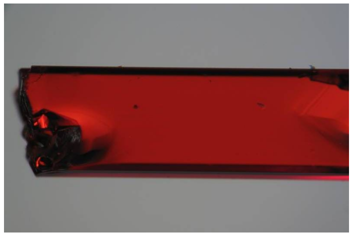
R. Zeis, C. Kloc, X. Chi

Low-temperature behavior of a Rubrene FET

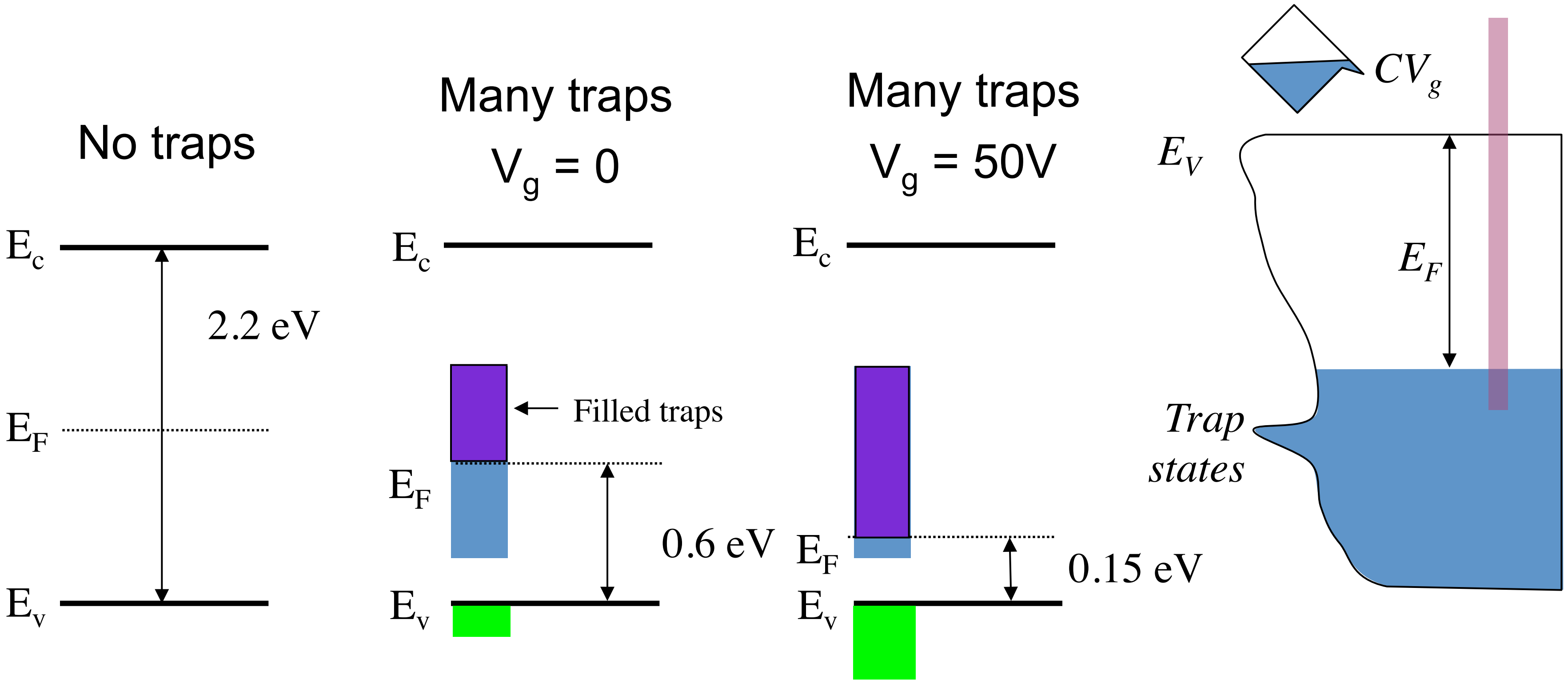




$\mu_{eff} = (dI_d/dV_{gs})Ld_{par}/(WV_{ds}\varepsilon\varepsilon_0)$,



Estimating trap density from Activation Energy

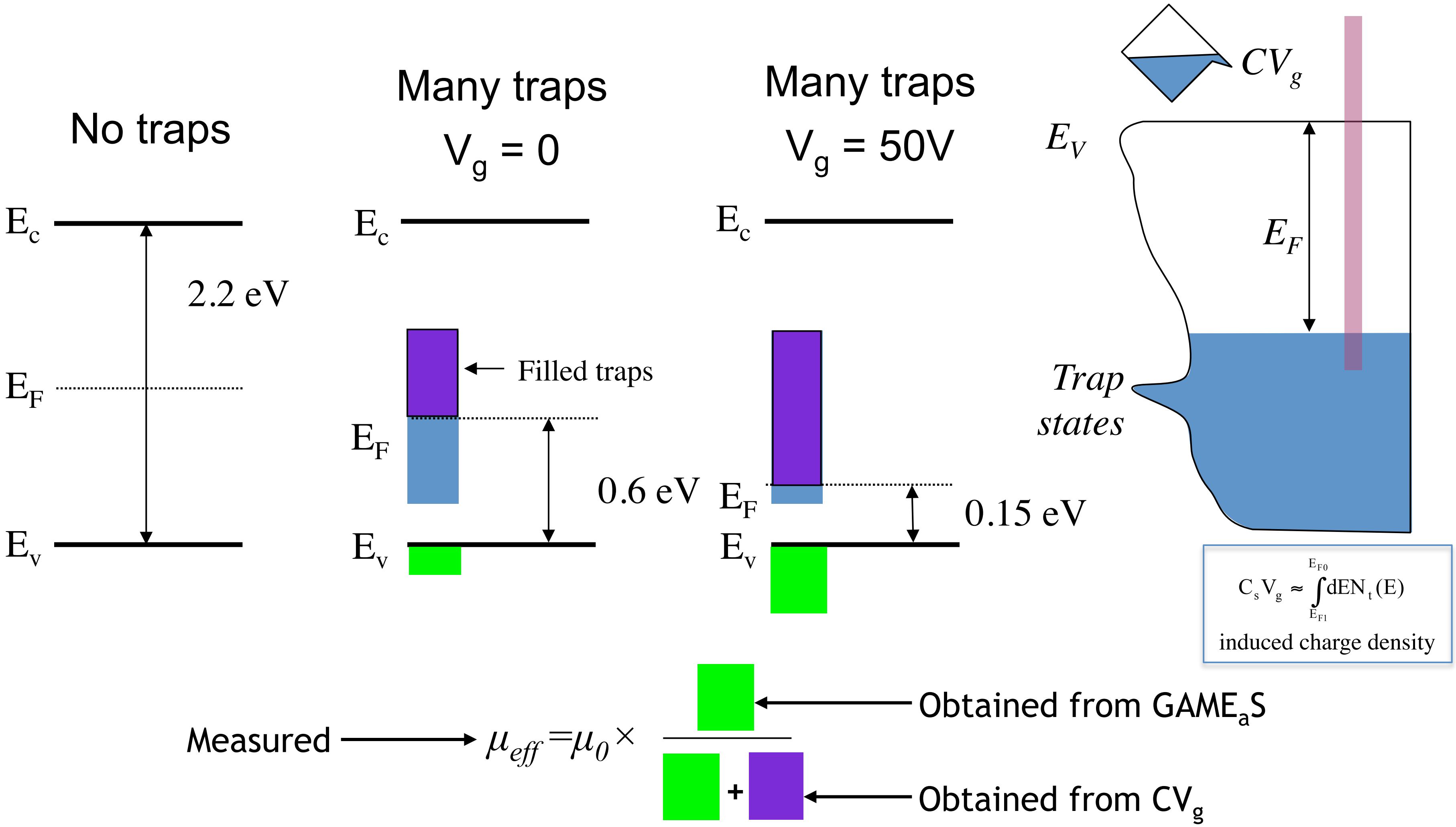


induced charge density

$$C_s V_g \approx \int_{E_{F1}}^{E_{F0}} dE N_t(E)$$

$$\mu_{eff} = \mu_0 \times \frac{\text{🟩}}{\text{🟩} + \text{🟪}}$$

Estimating μ_0 from GAME$_a$S



No traps

Many traps $V_g = 0$

Many traps $V_g = 50V$

E_c

E_F

E_v

2.2 eV

Filled traps

0.6 eV

0.15 eV

CV_g

E_V

E_F

Trap states

$$C_s V_g \approx \int_{E_{F1}}^{E_{F0}} dE N_t(E)$$

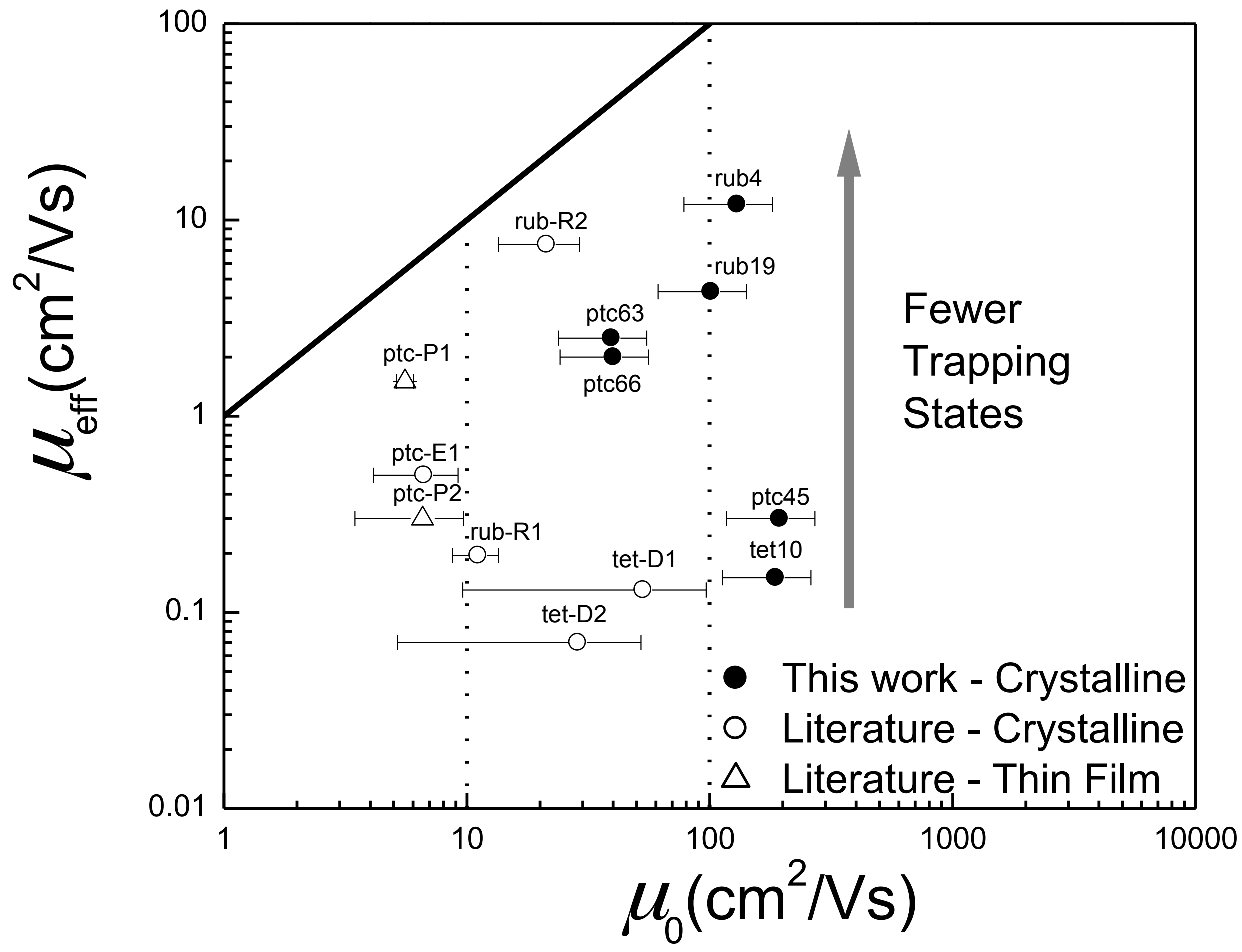
induced charge density

Measured → $\mu_{eff} = \mu_0 \times$ 🟩 / (🟩 + 🟪)

Obtained from GAME$_a$S

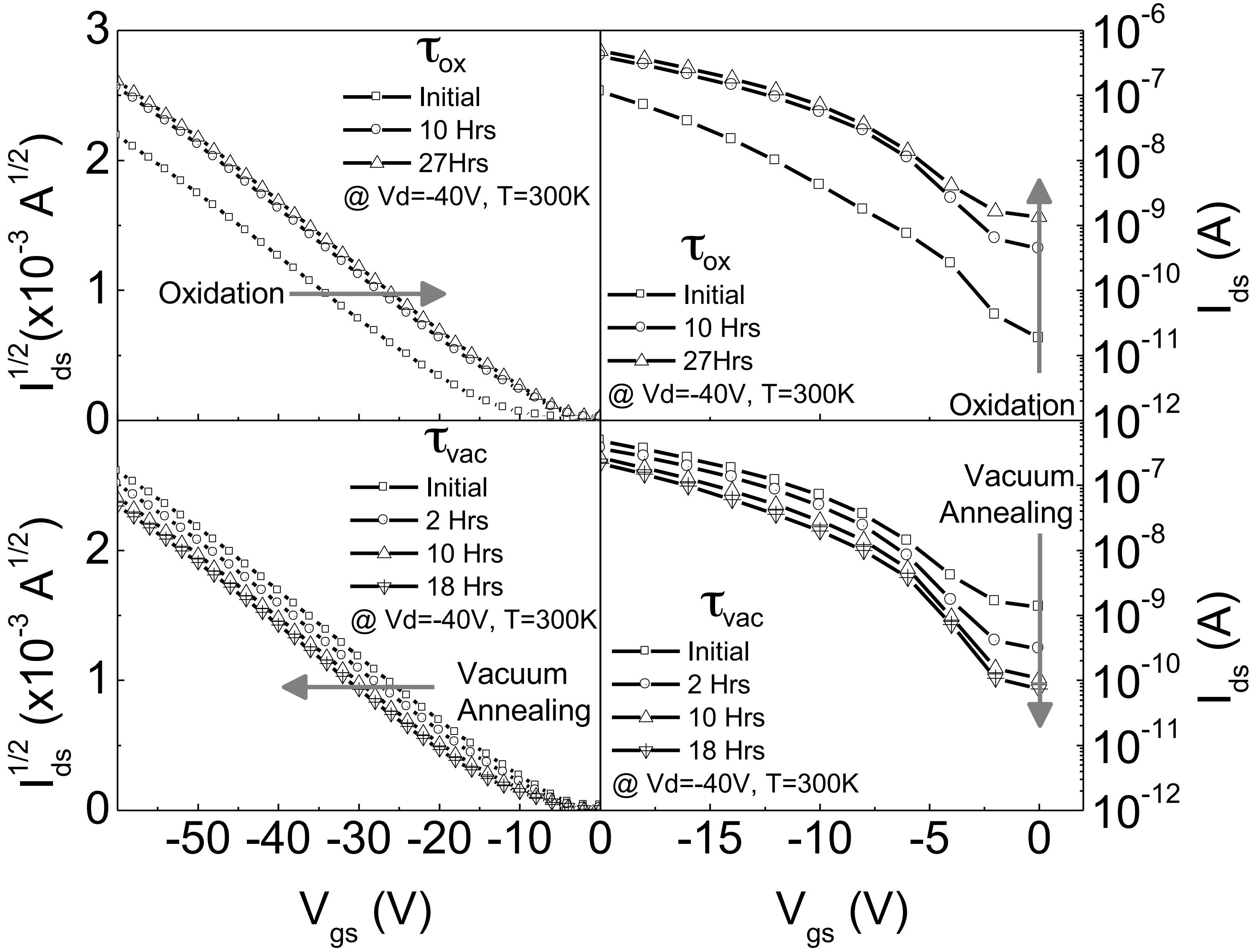
Obtained from CV$_g$

Limits on intrinsic mobility



- Intrinsic mobility might reach 200 cm^2/Vs if trap states are removed

Can also use device to modify material



US007821000B2

(12) **United States Patent**
Kloc et al.

(10) **Patent No.:** **US 7,821,000 B2**
(45) **Date of Patent:** **Oct. 26, 2010**

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(54) **METHOD OF DOPING ORGANIC SEMICONDUCTORS**

(75) Inventors: **Christian Leo Kloc**, Constance (DE); **Arthur Penn Ramirez**, Summit, NJ (US); **Woo-Young So**, New Providence, NJ (US)

(73) Assignees: **Alcatel-Lucent USA Inc.**, Murray Hill, NJ (US); **The Trustees of Columbia University**, New York, NY (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 89 days.

(21) Appl. No.: **12/024,484**

(22) Filed: **Feb. 1, 2008**

(65) **Prior Publication Data**

US 2009/0194762 A1 Aug. 6, 2009

(51) **Int. Cl.**
H01L 51/40 (2006.01)
H01L 21/00 (2006.01)

(52) **U.S. Cl.** **257/40**; 257/E51.001; 257/E21.001; 438/99

(58) **Field of Classification Search** 257/40, 257/E51.001, E21.001; 438/99
See application file for complete search history.

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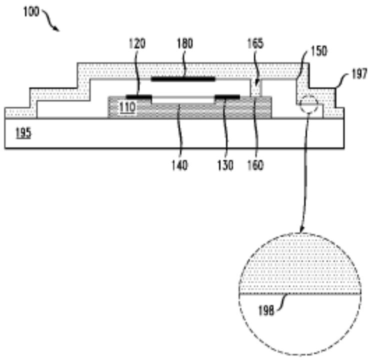
(Continued)

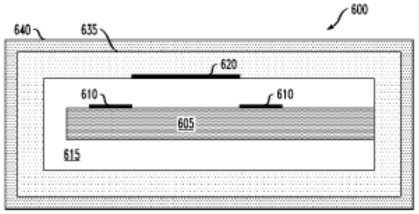
Primary Examiner—Victor A Mandala
Assistant Examiner—Whitney Moore
(74) *Attorney, Agent, or Firm*—Hitt Gaines, PC

(57) **ABSTRACT**

An apparatus has a crystalline organic semiconducting region that includes polyaromatic molecules. A source electrode and a drain electrode of a field-effect transistor are both in contact with the crystalline organic semiconducting region. A gate electrode of the field-effect transistor is located to affect the conductivity of the crystalline organic semiconducting region between the source and drain electrodes. A dielectric layer of a first dielectric that is substantially impermeable to oxygen is in contact with the crystalline organic semiconducting region. The crystalline organic semiconducting region is located between the dielectric layer and a substrate. The gate electrode is located on the dielectric layer. A portion of the crystalline organic semiconducting region is in contact with a second dielectric via an opening in the dielectric layer. A physical interface is located between the second dielectric and the first dielectric.

13 Claims, 10 Drawing Sheets





New Physics
from
New Materials

or

Controlling dimensionality and interactions

or

Many-body (emergent) phenomena through strong correlations

Thanks!