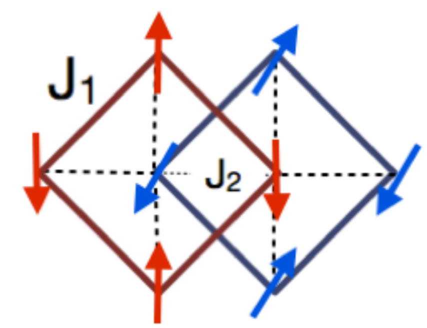
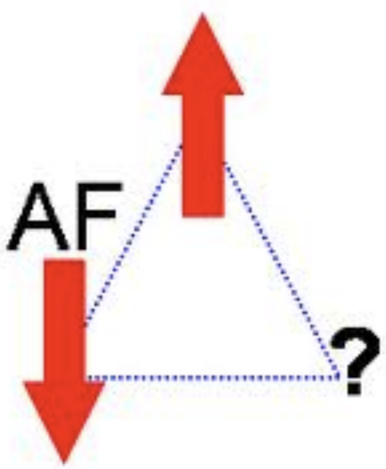
Spin Models = “Economy” Strongly Correlated Systems

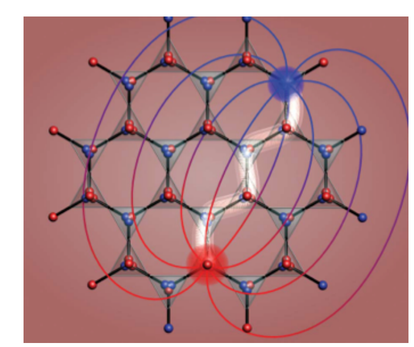
Frustration ⟶ Ordering

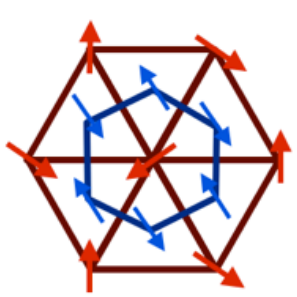


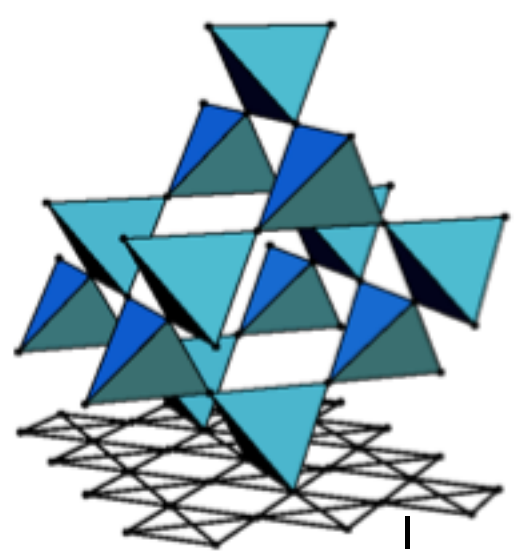


Spin Ice, Fractionalization and Topology

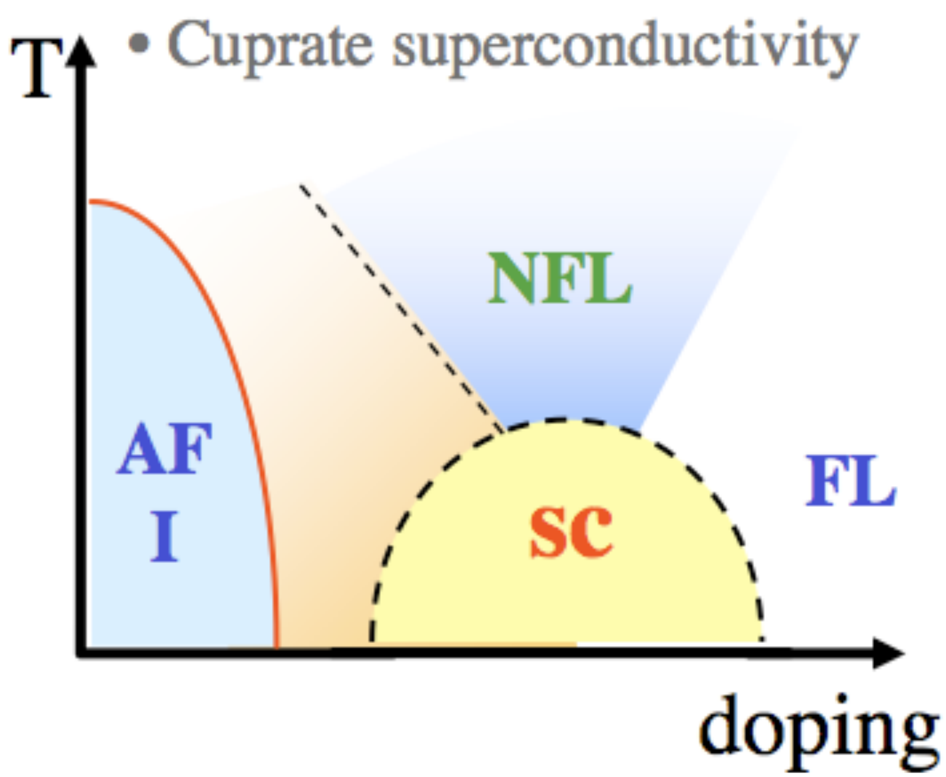
My Fifteen Minute Presentation:
“Quantum Annealed Criticality”

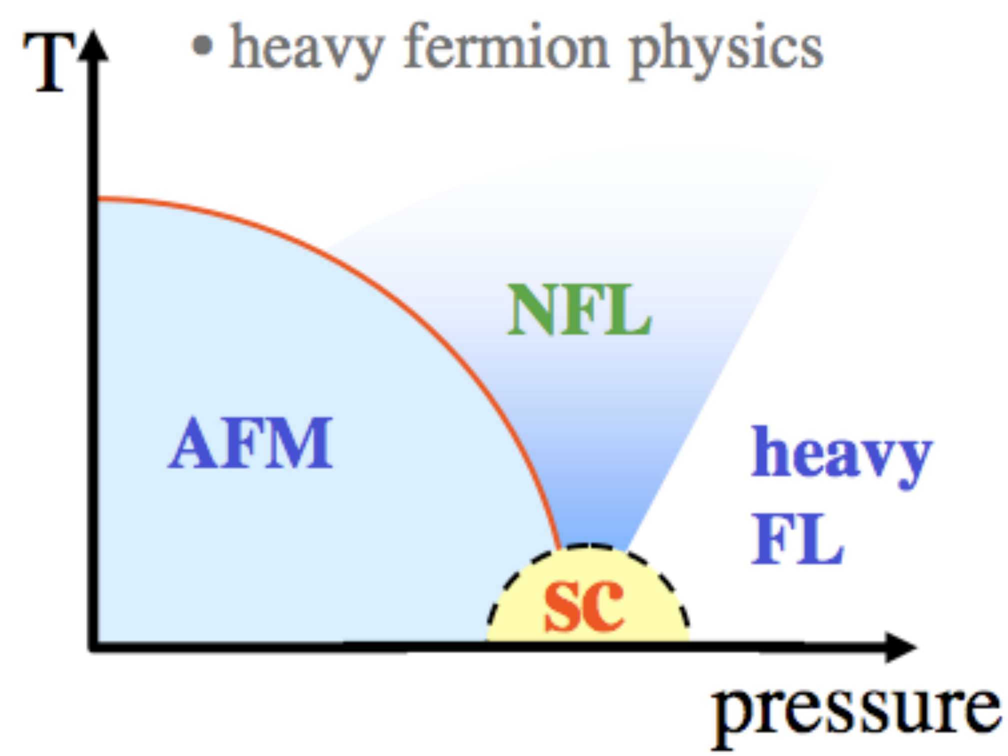


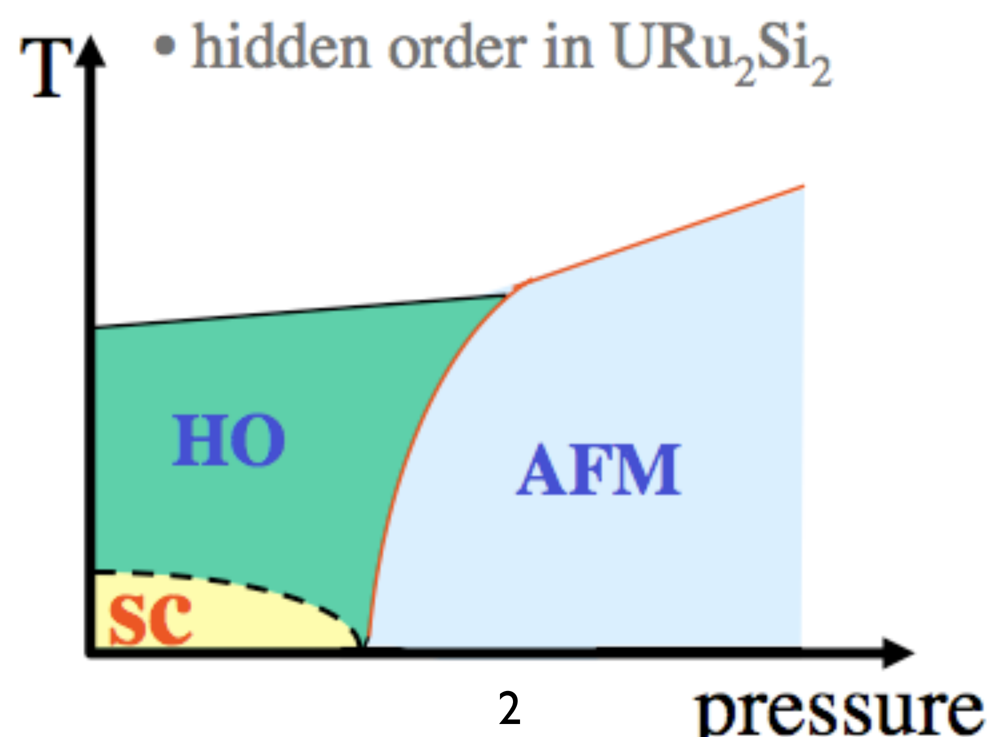




Motivation: Novel Materials with Competing Interactions and Exotic Phases



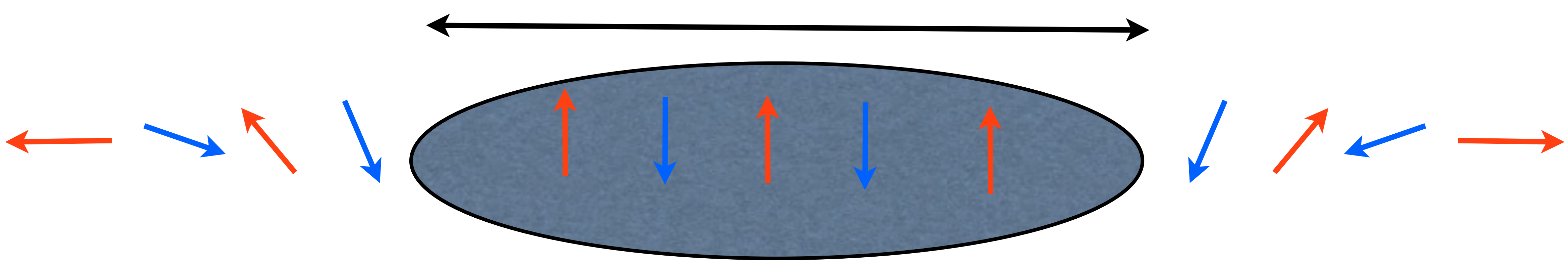




2D Heisenberg Antiferromagnets at Finite Temperature

Hohenberg-Mermin-Wagner Theorem (1966) $\longrightarrow$ No Long-Range Order at Finite Temperatures

$$\xi \sim a\ e^{\frac{2\pi J S^2}{kT}}$$



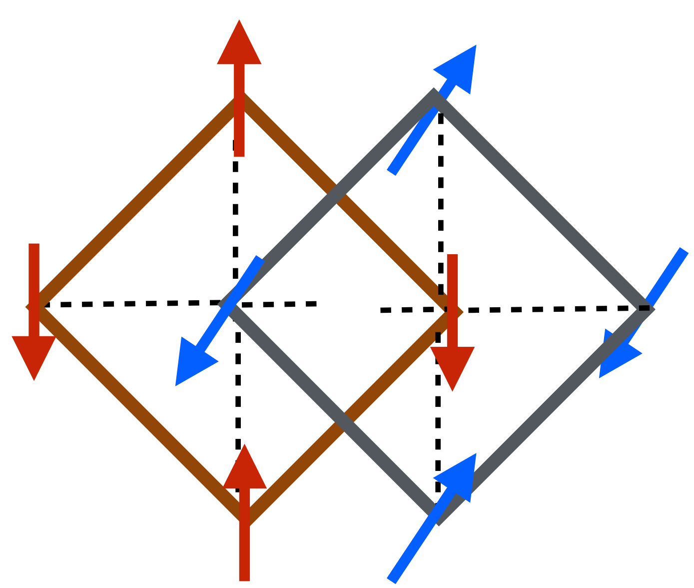
Frustration $\longrightarrow$ Discrete Symmetry-Breaking at Finite Temperatures

Thermal Fluctuation-Selected Order: A Simple Example

$$H = J_1 \sum_{\langle i,j \rangle} S_i \cdot S_j + J_2 \sum_{\langle\langle i,j \rangle\rangle} S_i \cdot S_j$$

$$(J_2 >> J_1)$$

Sublattices classically decoupled



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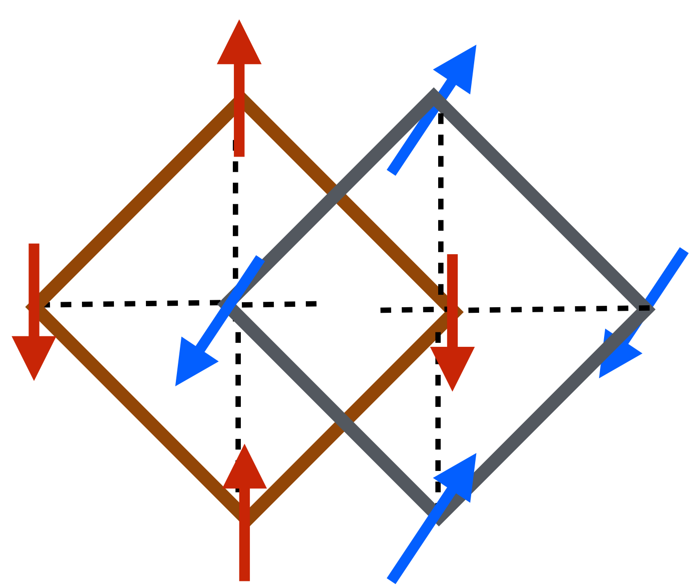
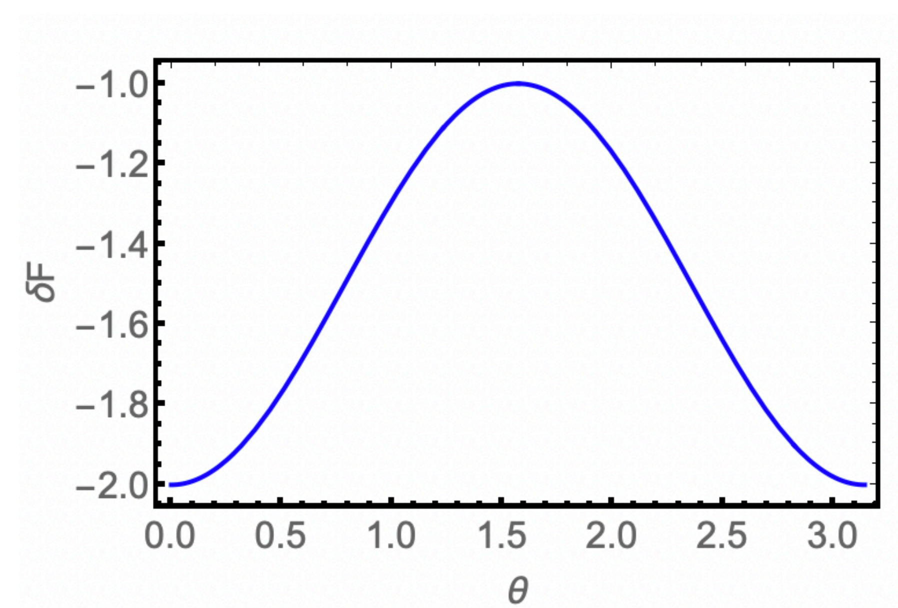


Fluctuation Free Energy



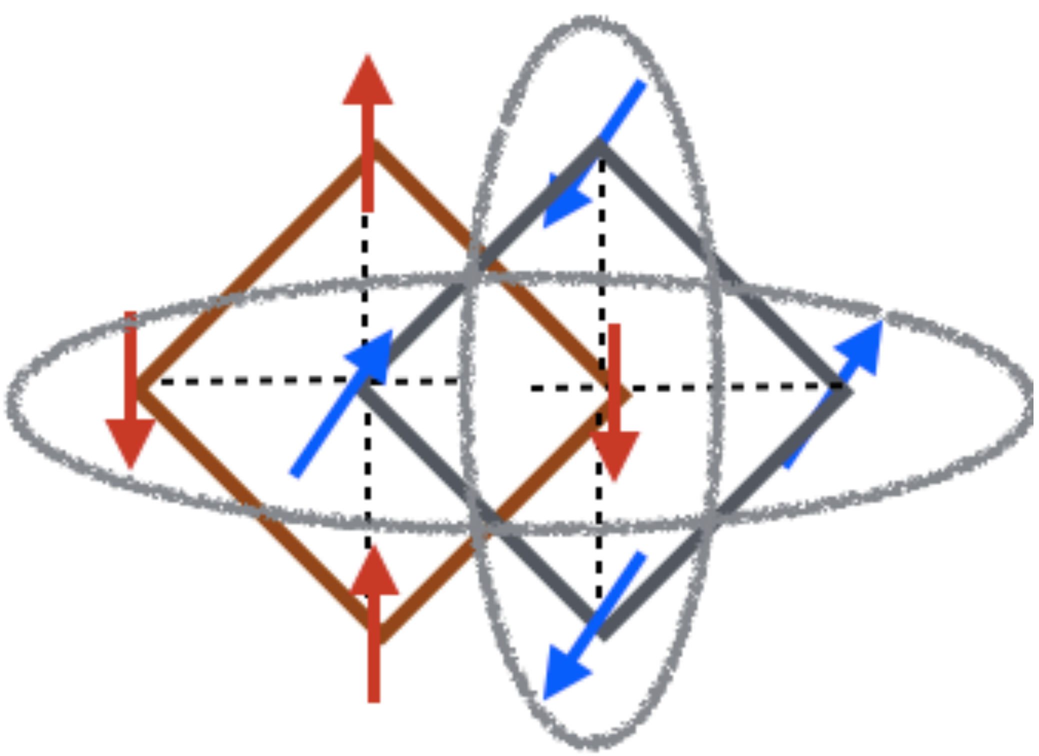
Collinear States Selected

Thermally Fluctuation-Selected Order: A Simple Example

$$H = J_1 \sum_{\langle i,j \rangle} S_i \cdot S_j + J_2 \sum_{\langle\langle i,j \rangle\rangle} S_i \cdot S_j$$

$(J_2 >> J_1)$

"Order from Disorder"
(Villain 1977, Shender 1982, Henley 1989)



Discrete Z_2 Relative Degree of Freedom

$$\vec{M}_1 \cdot \vec{M}_2 = \sigma = \pm 1$$

Thermally Fluctuation-Selected Order: A Simple Example

$$H = J_1 \sum_{\langle i,j \rangle} S_i \cdot S_j + J_2 \sum_{\langle\langle i,j \rangle\rangle} S_i \cdot S_j$$

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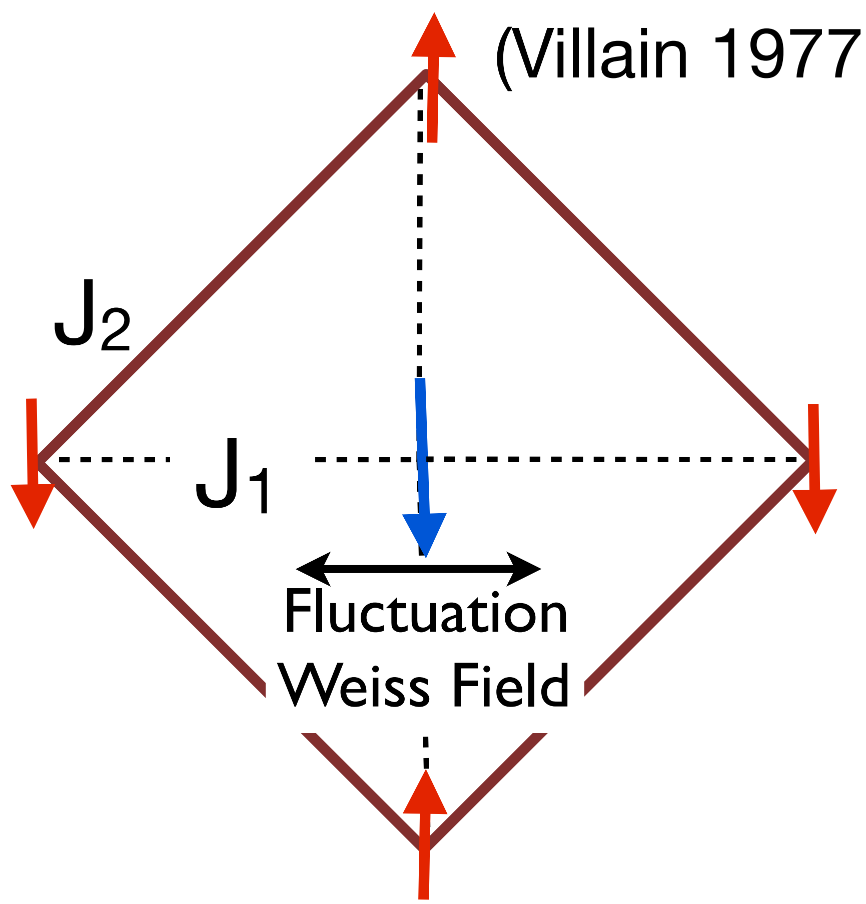
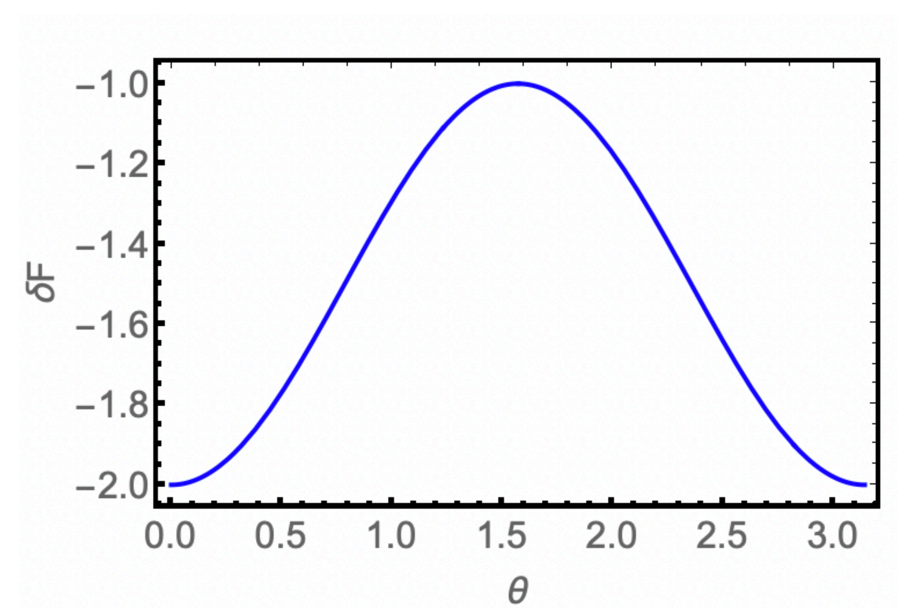


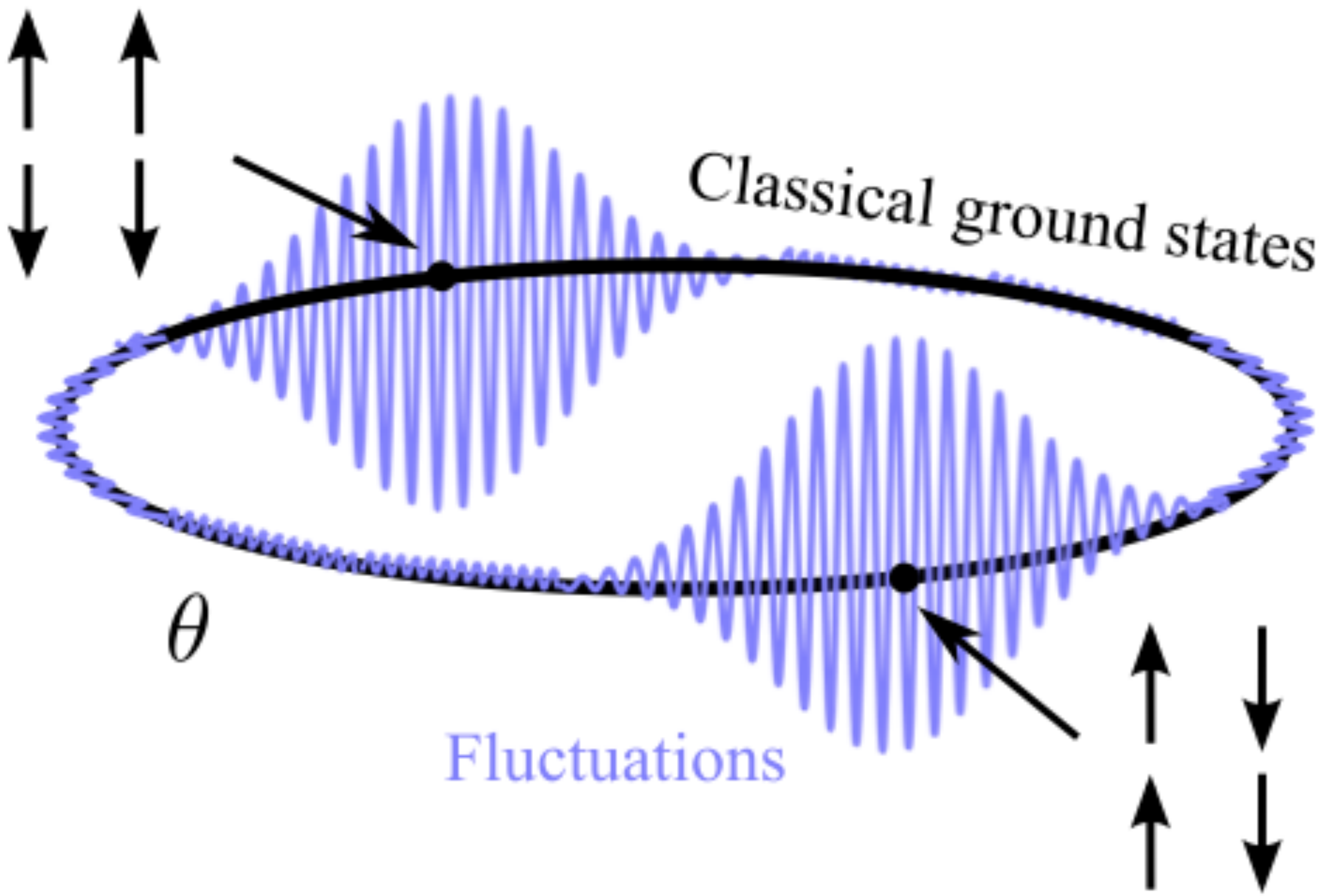
Fluctuation Free Energy



Collinear States Selected

Spins like to align the **fluctuation** Weiss field to their "easy plane" (Henley 1989).

Order From Disorder



Fluctuations Select "Soft" States from Degenerate Ground-State Manifold

(courtesy, R. Flint)

(Villain 80, Shender 82, Henley 89)

First Theory-Experiment Agreement on "Order from Disorder"

EUROPHYSICS LETTERS 1 September 1988

Europhys. Lett., 7 (1), pp. 83-86 (1988)

Quantum Exchange Magnon Gap in an Antiferromagnet with Dynamically Interacting Spin Subsystems.

A. G. GUKASOV (*), TH. BRÜCKEL (**), B. DORNER (**), V. P. PLAKHTY (*)
W. PRANDL (***), E. F. SHENDER (*) and O. P. SMIRNOV (*)

(*) *Leningrad Nuclear Physics Institute, Gatchina, Leningrad 188350, USSR*
(**) *Institut Laue-Langevin, 156X, 38042 Grenoble Cedex, France*
(***) *Institut für Kristallographie der Universität Tübingen*
Charlottenstr. 33, D-7400 Tübingen, BRD

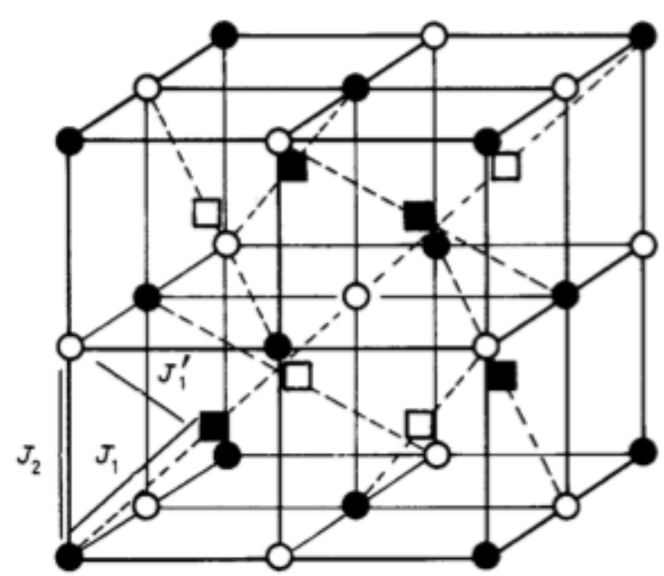
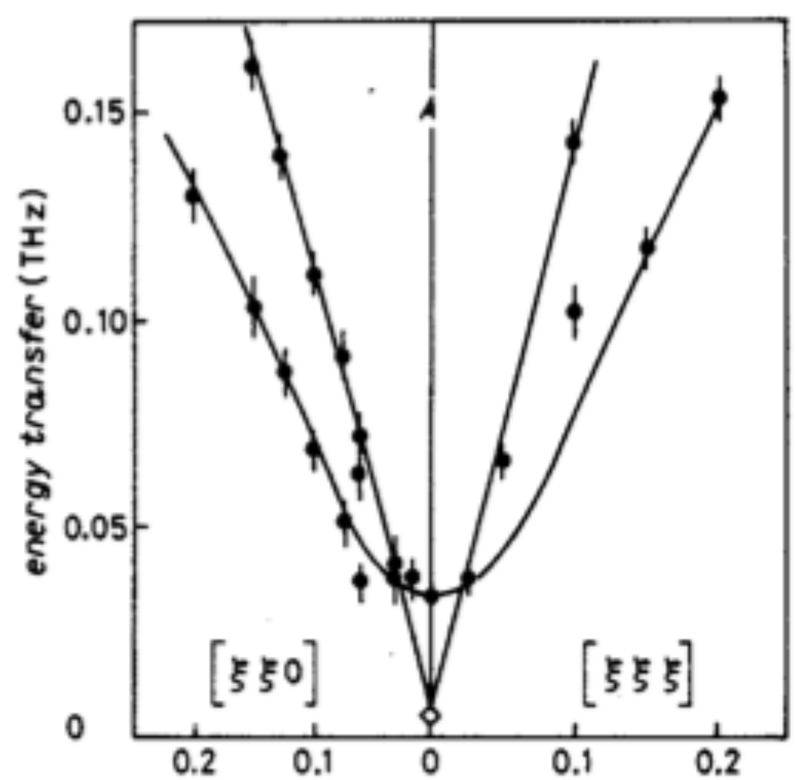


Fig. 1. – The magnetic structure of $Fe_2Ca_3(GeO_4)_3$. Open symbols indicate spin down, full symbols spin up. The two subsystems mentioned in the text are distinguished by squares and circles, respectively. Dashed lines indicate the threefold axis.



More Recent Theory-Experiment Agreement on "Order from Disorder"

PRL **109**, 077204 (2012) PHYSICAL REVIEW LETTERS week ending 17 AUGUST 2012

Quantum Order by Disorder and Accidental Soft Mode in $Er_2Ti_2O_7$

M. E. Zhitomirsky,[1] M. V. Gvozdikova,[1] P. C. W. Holdsworth,[2] and R. Moessner[3]

[1] *Service de Physique Statistique, Magnétisme et Supraconductivité, UMR-E9001 CEA-INAC/UJF, 17 rue des Martyrs, 38054 Grenoble Cedex 9, France*

[2] *Laboratoire de Physique, École Normale Supérieure de Lyon, CNRS 69364 Lyon Cedex 07, France*

[3] *Max-Planck-Institut für Physik komplexer Systeme, 01187 Dresden, Germany*

(Received 2 April 2012; published 16 August 2012)

PRL **109**, 167201 (2012) PHYSICAL REVIEW LETTERS week ending 19 OCTOBER 2012

Order by Quantum Disorder in $Er_2Ti_2O_7$

Lucile Savary,[1] Kate A. Ross,[2] Bruce D. Gaulin,[2,3,4] Jacob P. C. Ruff,[2,5] and Leon Balents[6]

[1] *Department of Physics, University of California, Santa Barbara, California 93106-9530, USA*

[2] *Department of Physics and Astronomy, McMaster University, Hamilton, Ontario L8S 4M1, Canada*

[3] *Canadian Institute for Advanced Research, Toronto, Ontario M5G 1Z8, Canada*

[4] *Brockhouse Institute for Materials Research, McMaster University, Hamilton, Ontario L8S 4M1, Canada*

[5] *The Advanced Photon Source, Argonne National Laboratory, Argonne, Illinois 60439, USA*

[6] *Kavli Institute for Theoretical Physics, University of California, Santa Barbara, California 93106-4030, USA*

(Received 5 April 2012; published 15 October 2012)

(xy Pyrochlore spin system)

Thermally Fluctuation-Selected Order: A Simple Example

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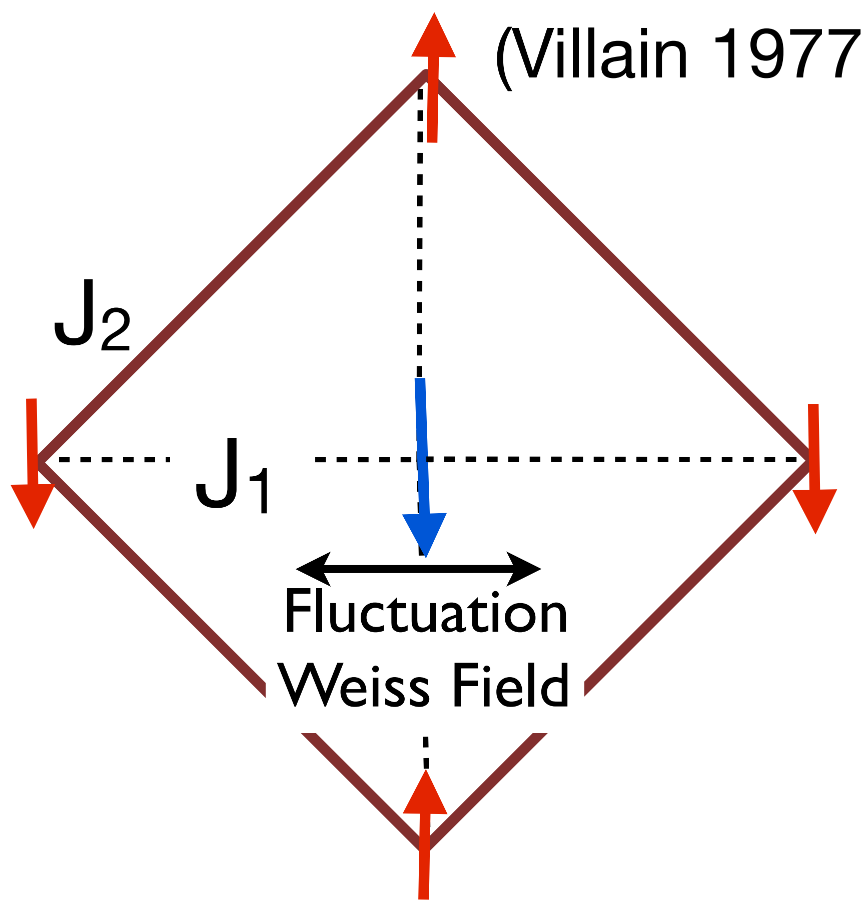
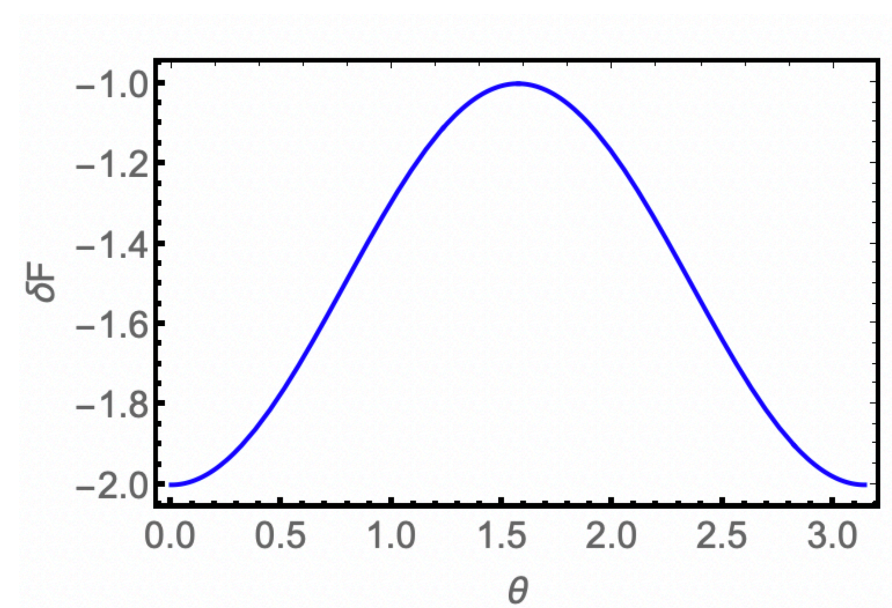
$(J_2 >> J_1)$

"Order from Disorder"
(Villain 1977, Shender 1982, Henley 1989)



Fluctuation Free Energy



Collinear States Selected

Spins like to align the **fluctuation** Weiss field to their "easy plane" (Henley 1989)

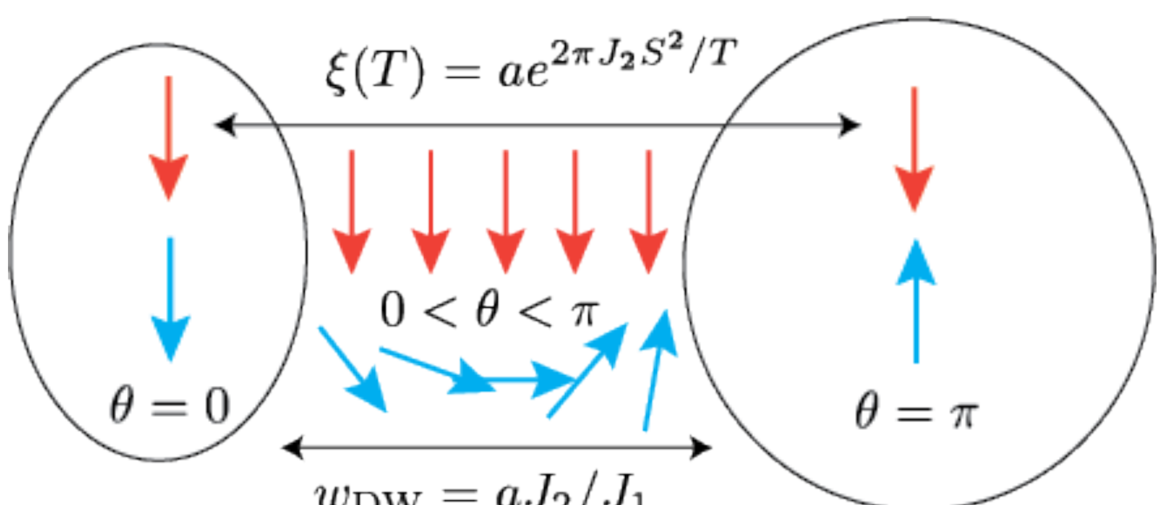
Phase Diagram

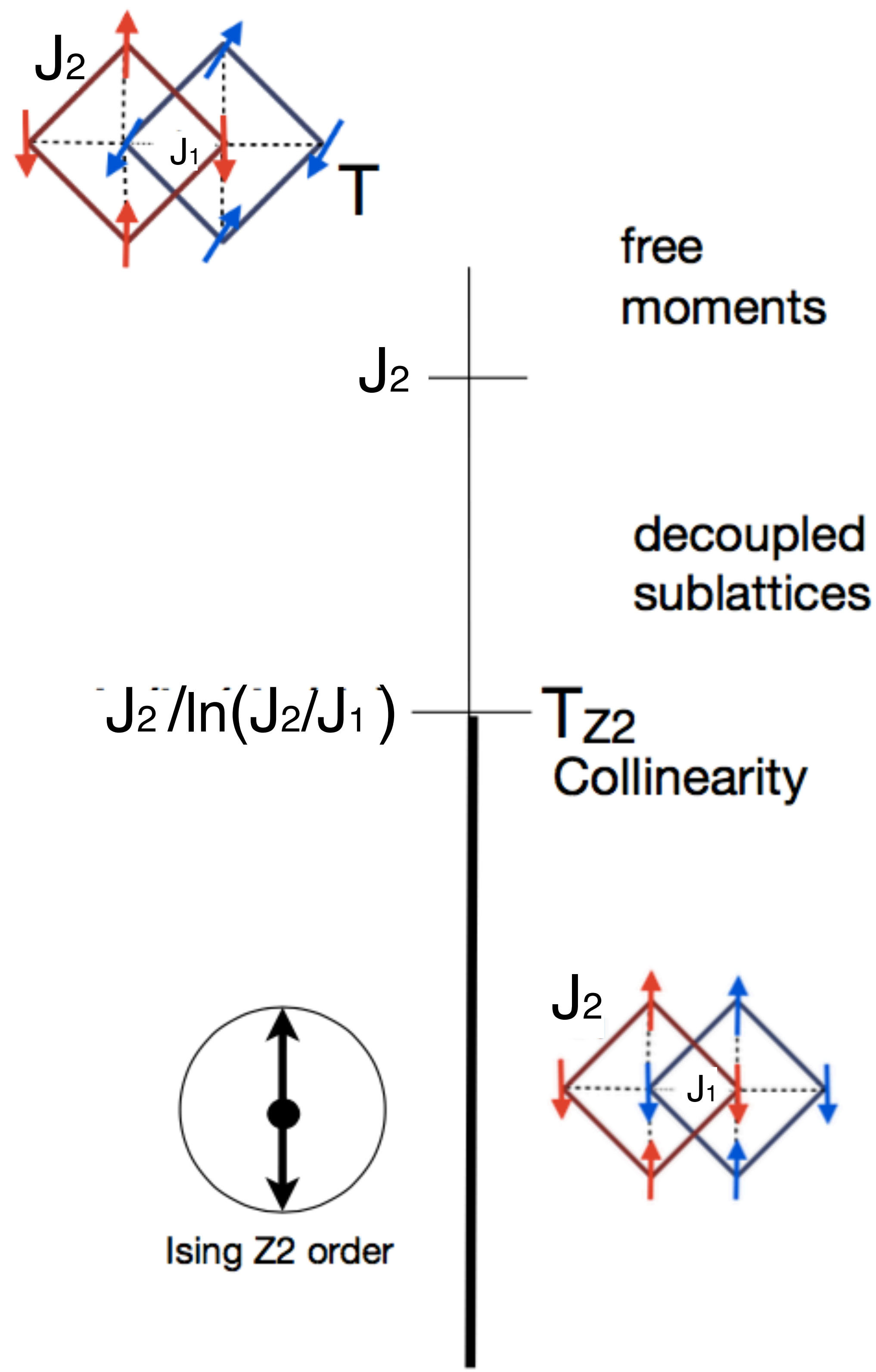
$$S = \frac{1}{2}\int_x \sum_i K(\partial_\mu \boldsymbol{n}_i)^2 - \frac{\gamma}{a^2}\int_x (\boldsymbol{n}_1 \cdot \boldsymbol{n}_2)^2$$

Ising Transition Temperature $T_c = J_2/\ln(J_2/J_1)$

Intuitive Argument: Z_2 domains defined if Heisenberg correlation length is longer than the domain wall thickness

$$\xi(T) = ae^{2\pi J_2 S^2/T} > w_{\rm DW} \propto aJ_2/J_1$$

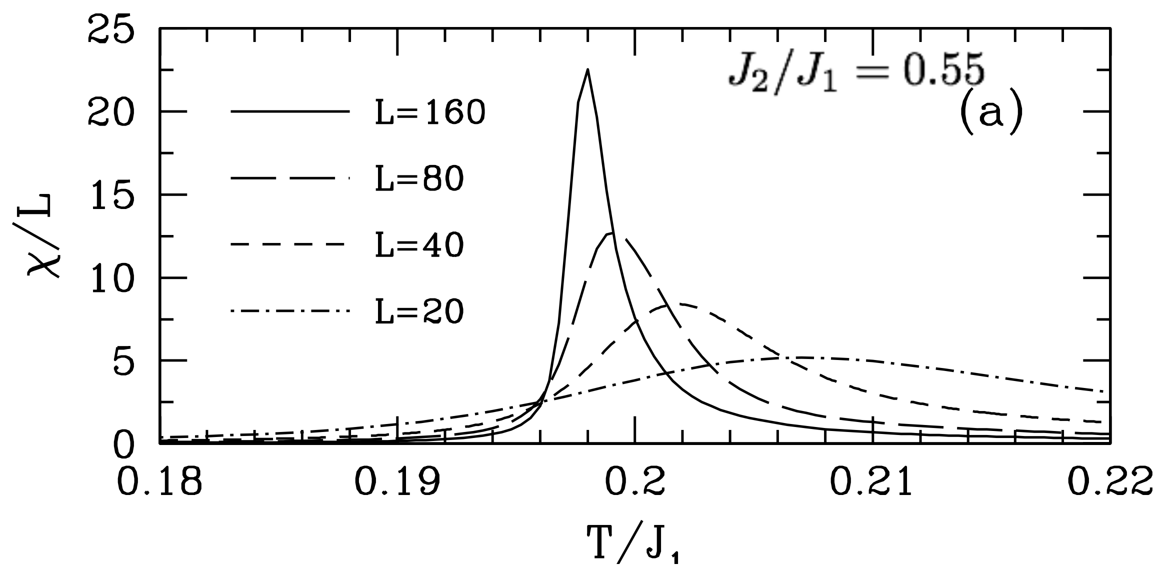




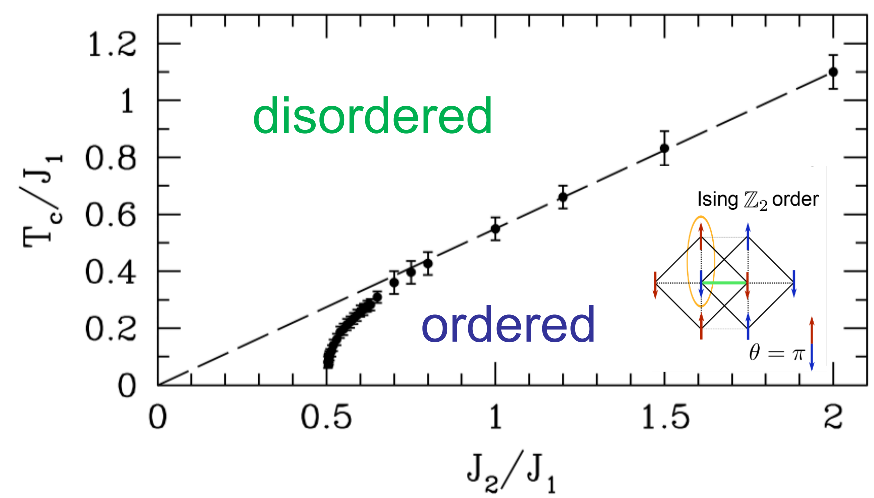
PC, Coleman and Larkin (90)

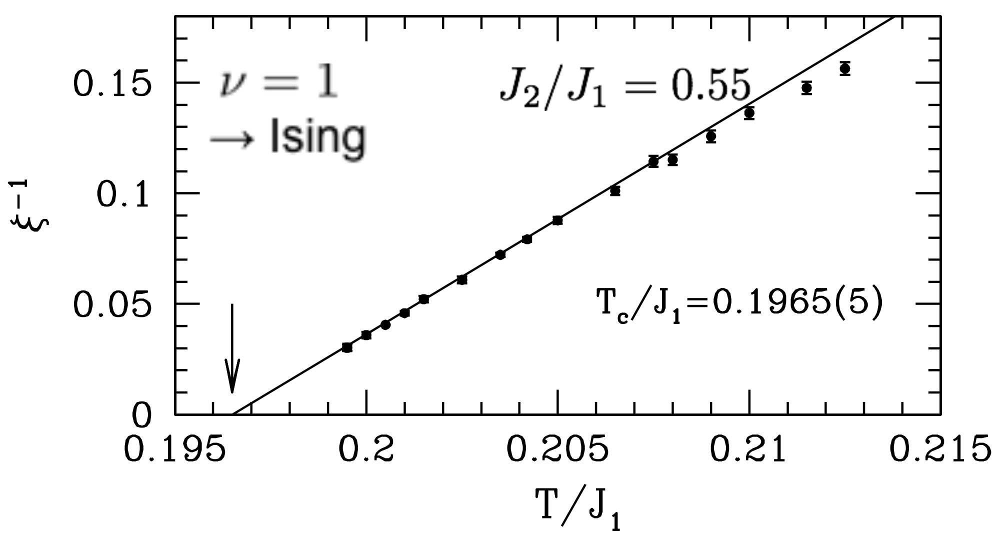
Finite Temperature Ising Transition

Long Wavelength Analysis Confirmed by Classical Monte Carlo



MC phase diagram:





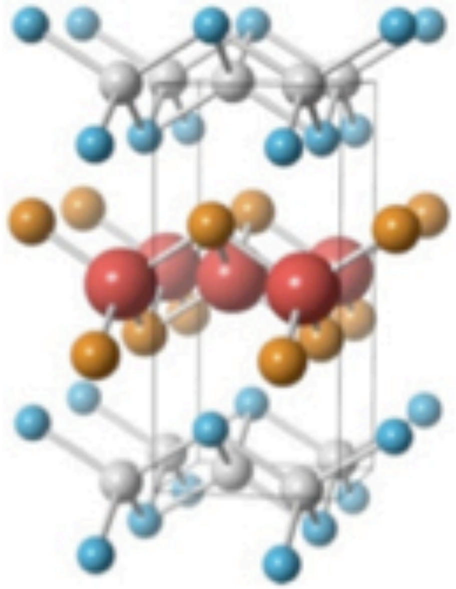
Weber et al (03)

Also confirmed for the S=1/2 case

Any link with Experiment ??

Discovery of New High-T_C Superconductors

Hideo Hosono

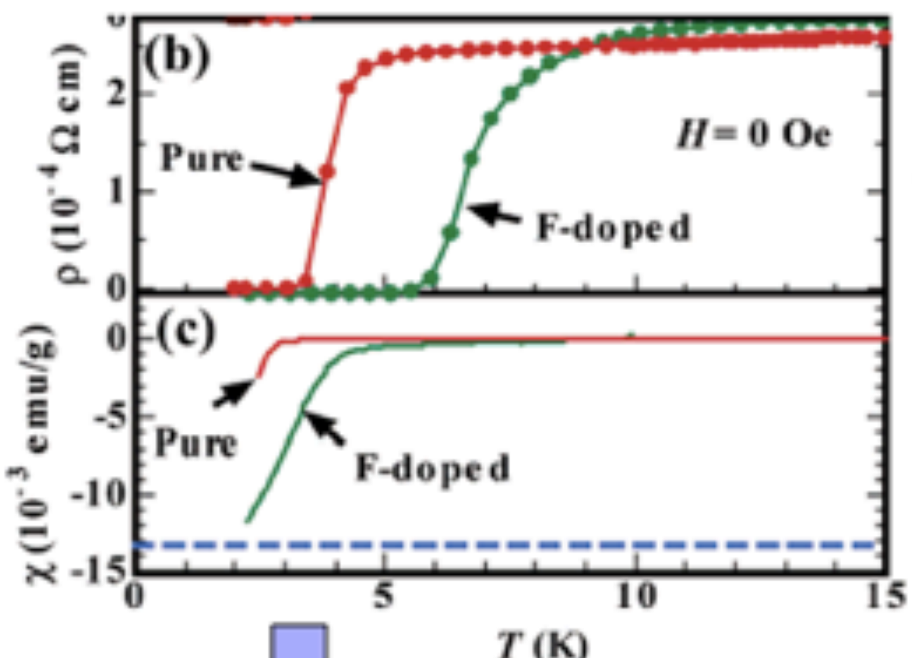


LaCuSO

$(LaO)^{+}(Cu^{+}S^{2-})$

$(LaO)^{+}(Fe^{2+}P^{3-})$ — **LaFePO**

$(LaO)^{+}(Fe^{2+}As^{3-})$ — **LaFeAsO**



Pure

F substitution

F substitution

Feb. 18 $LaFeAsO_{1-x}F_x$

T_C~26 K

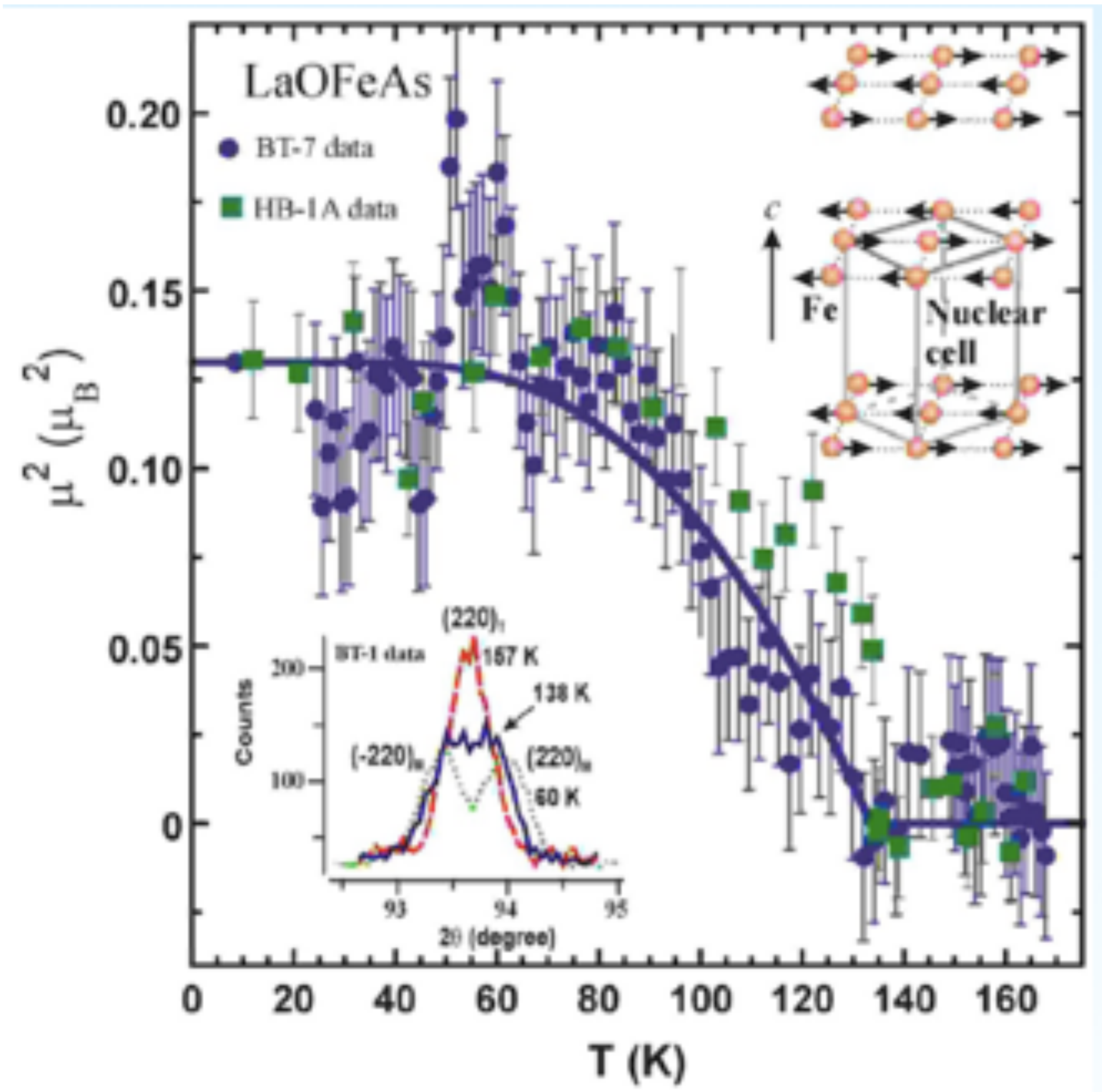
2007

2008

Rutgers
Center for Materials Theory

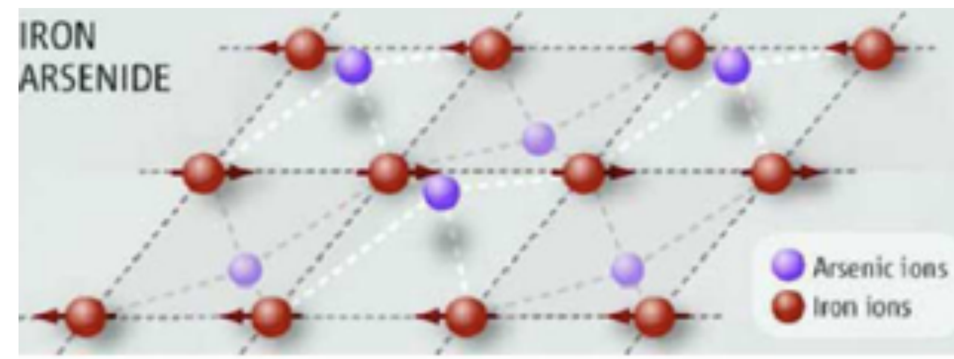
The Iron Age of Superconductivity has Begun !

Spin Structure from Neutron Scattering



Cruz et al (08)

Familiar Spin Pattern !!



Frustration in the Pnictides (J1-J2 Model)

Yildirim (08)

Si and Abrahams (08)

P. Coleman (Rutgers)
M. Continentino (CBPF)
G. Lonzarich (Cambridge)

Quantum Annealed Criticality

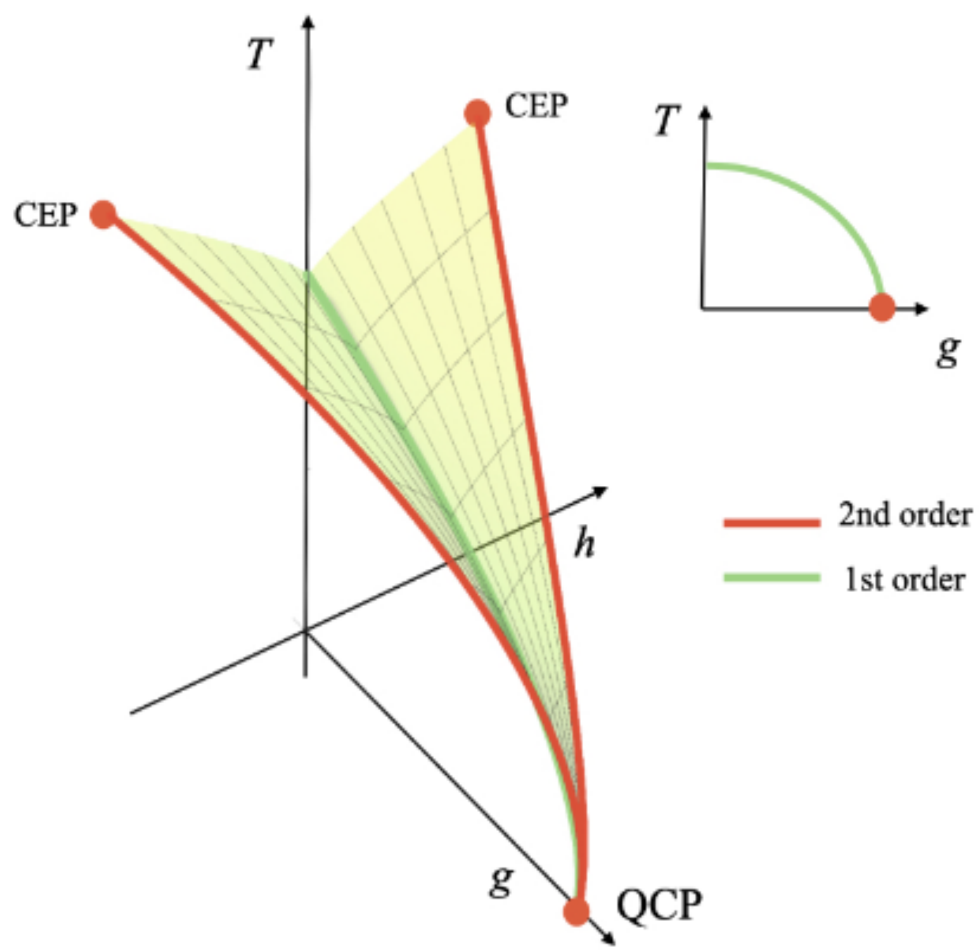
P. Chandra (Rutgers)

How can systems that have classical first-order transitions display quantum criticality ??

Phys. Rev. Research 2, 043440 (2020)

P. Coleman (Rutgers)
M. Continentino (CBPF)
G. Lonzarich (Cambridge)

Quantum Annealed Criticality



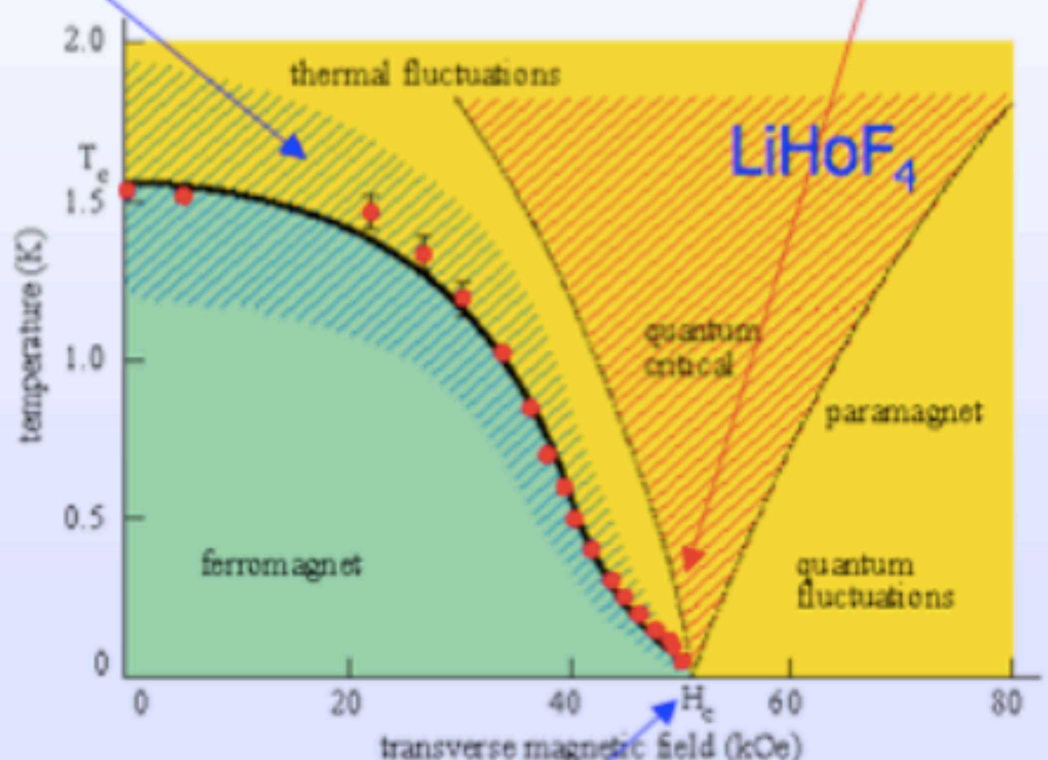
Classical and Quantum Phase Transitions

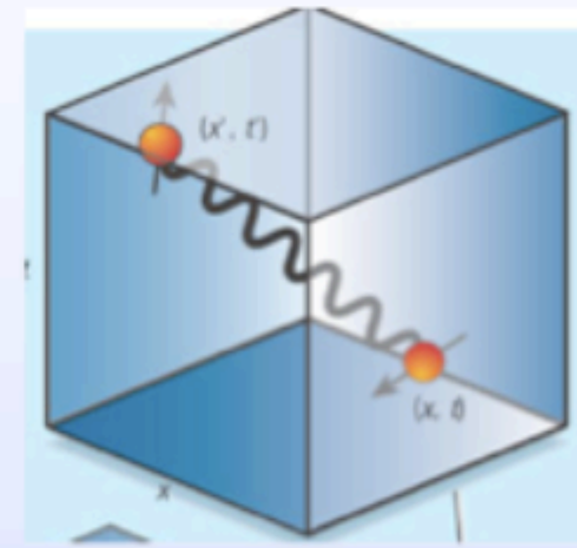
classical phase transition

$$\xi \propto (T - T_c)^{-\nu_c} \quad (T >> J)$$

quantum critical regime

$$\xi(T) \propto T^{-\frac{1}{z}} \quad (T << J)$$





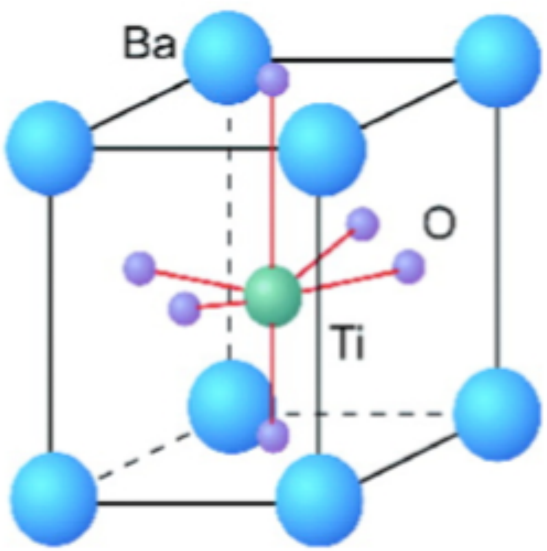
$$d_{eff} = d + z$$

D. Bitko et al., Phys. Rev. Lett. **77**, 940 (1996)

2nd order quantum phase transition

$$\xi(T = 0) \propto (g - g_c)^{-\nu}$$

Experimental Motivation: Ferroelectrics



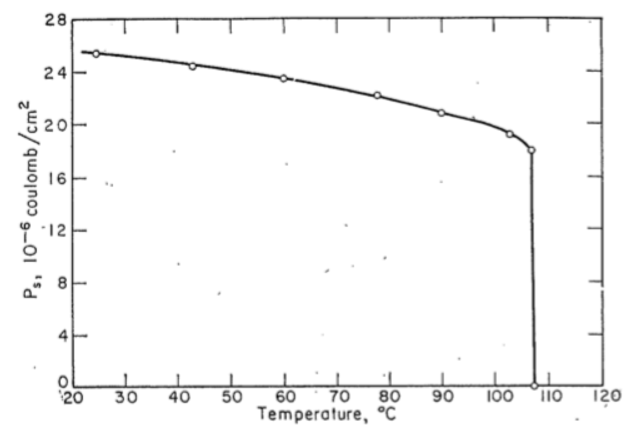
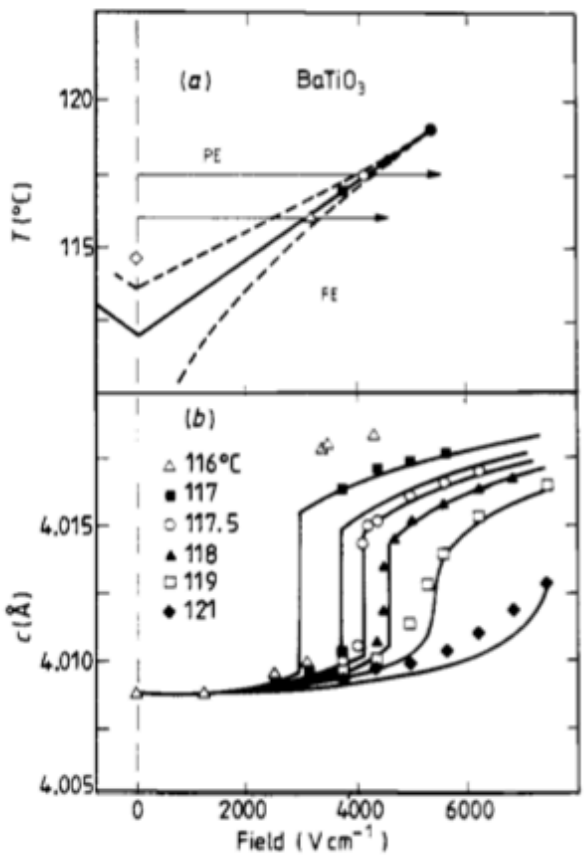


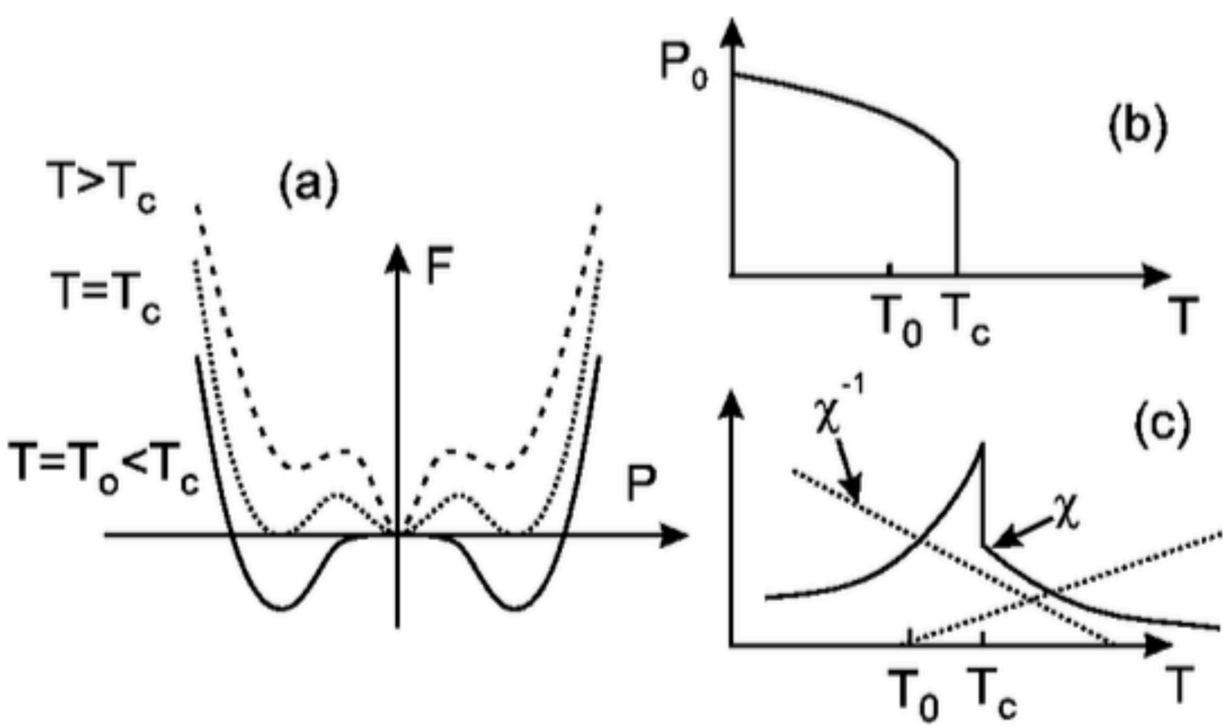
FIG. IV-7. Spontaneous polarization of tetragonal $BaTiO_3$ as a function of temperature (according to Merz (M 2)).

Jona and Shirane, FE Crystals (1962)



McWhan et al., J.Phys. C (1985)

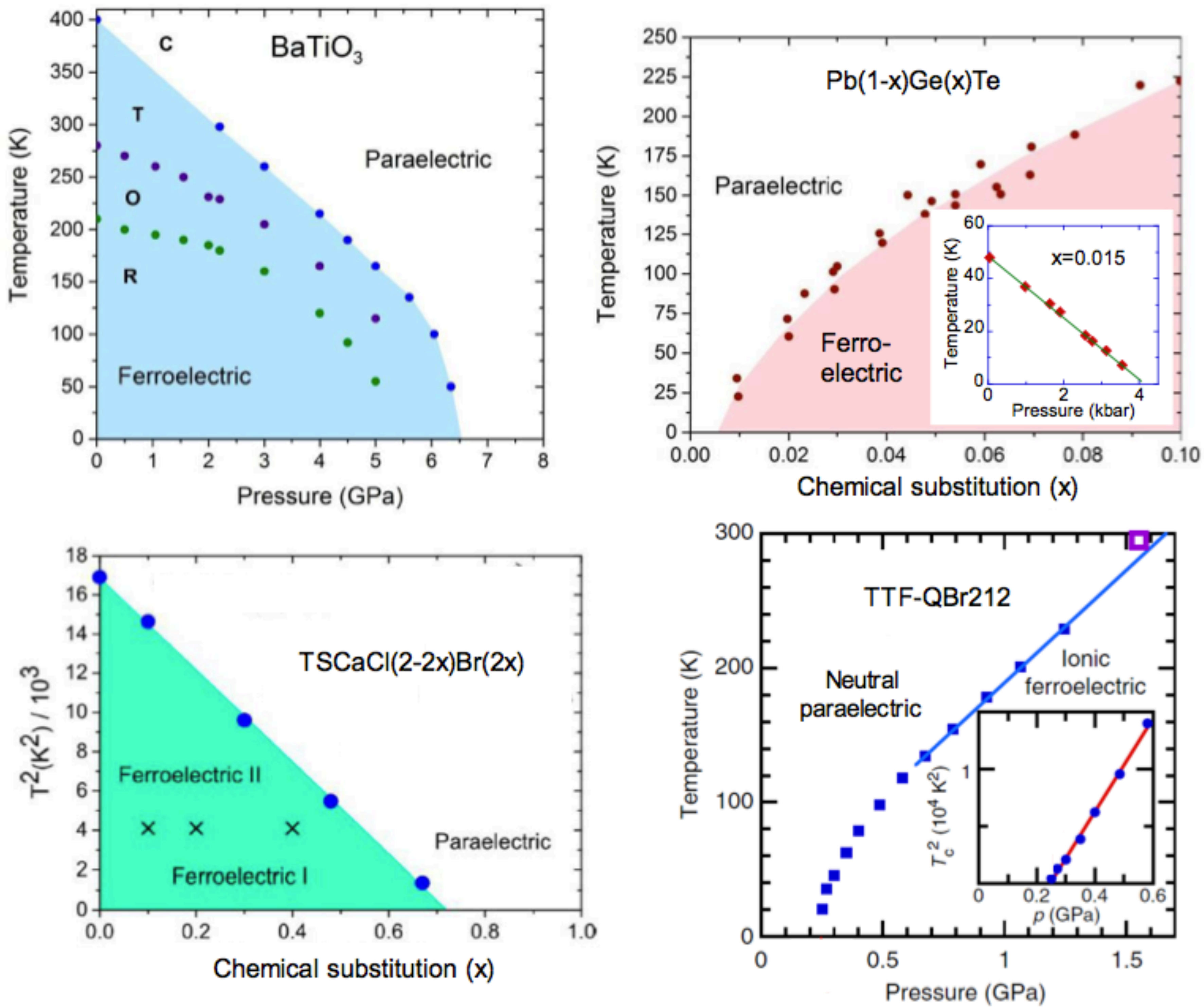
Figure 1. (*a*) Phase diagram of $BaTiO_3$ showing line of first-order transitions terminating at a critical point (full circle). (*b*) Lattice constant against electric field at different temperatures. Full and broken curves in 1(*a*) and 1(*b*) are calculated by minimising the free energy and they correspond to the equilibrium and spinodal boundaries.



Classically First-Order !


Actuator
Piezoelectricity
Thermal infrared switch
Electro-optical activity
DRAM storage capacitor
High permittivity
Piezoelectric
Pyroelectric
Ferroelectric
Pyroelectricity
Polarizability
Infrared sensors
NVFRAM memory cell

Quantum Criticality with Classical First-Order Transitions !



PC, Lonzarich, Rowley and Scott, ROPP (2017)

(Classical) Larkin-Pikin Mechanism

(A. I. Larkin and S. Pikin, Sov. Phys. JETP 29, 891 (1969))

Interaction of strain with fluctuating critical order parameter

Diverging Specific Heat in a Clamped System

↓

1st Order Transition in the Unclamped System

LP Criterion for 1st Order Transition

$$\kappa < \frac{\Delta C_V}{T_c}\left(\frac{dT_c}{d\ln V}\right)^2$$

$$\kappa^{-1} = K^{-1} - (K + \frac{4}{3}\mu)^{-1} \qquad \kappa \sim K\frac{c_L^2}{c_T^2}$$

Shear Strain Crucial

Coupling of the uniform strain to the energy density

↓

Macroscopic Instability of the Critical Point

↓

Discontinuous Phase Transition

Generalization for the Quantum Case ???

Generalization for the Quantum Case ???

Rewrite in terms of correlation functions (energy fluctuations)

Include dynamics and quantum tuning parameter

$(\tilde{\kappa} = \kappa - \Delta\kappa)$ $\tilde{\kappa} < 0$ 1st Order Transition

A Flavor for the Quantum Case

$$\lim_{T \to 0} \Delta\kappa \propto \int dq\ d\nu\ q^{d-1}\ \chi^2(q, i\nu)$$

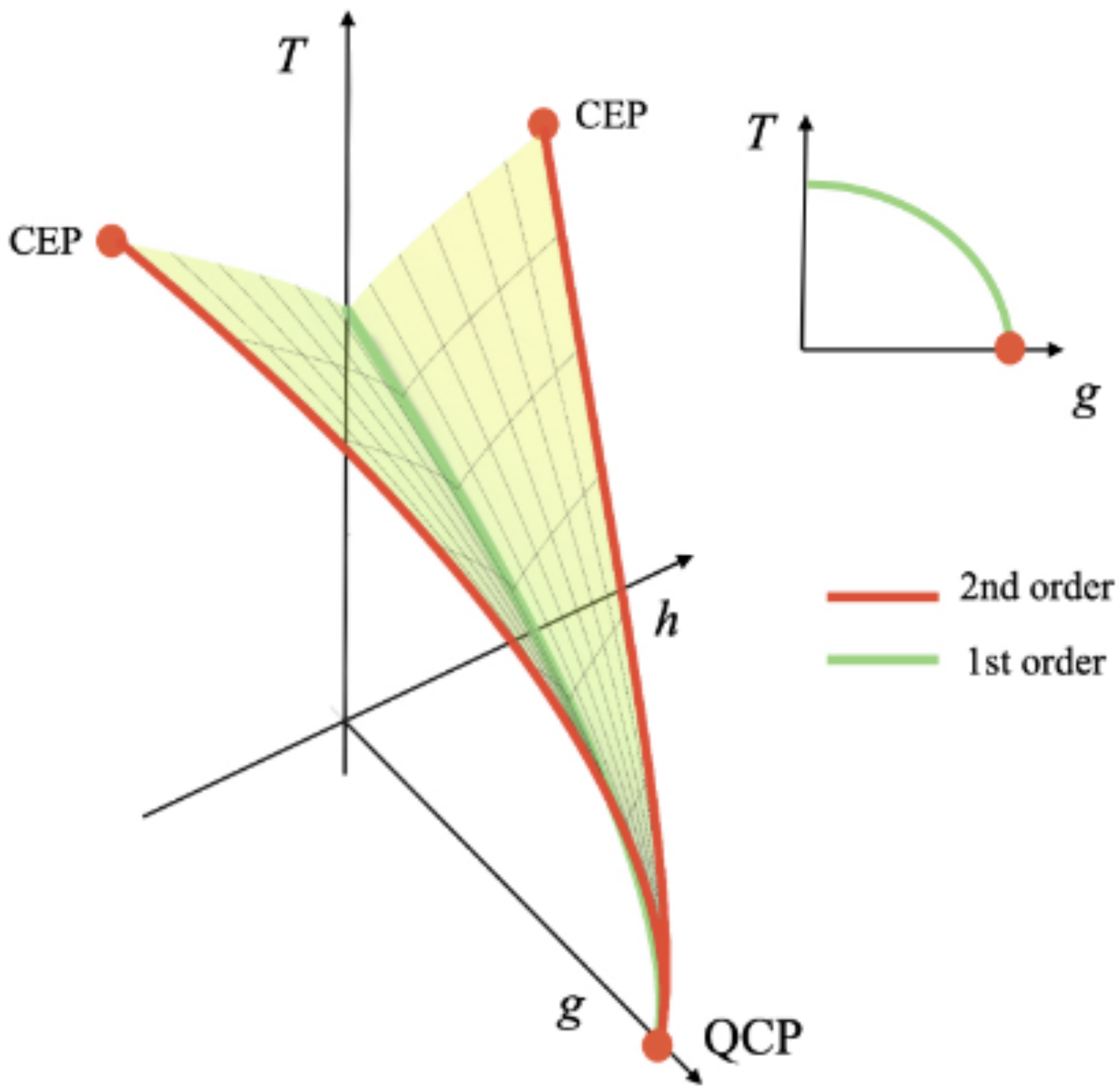
$$[\chi] = \left[\frac{1}{q^2}\right]$$

$$[\nu] = [q^z]$$

$$\lim_{T \to 0} [\Delta\kappa] = \frac{[q^{d+z}]}{[q^4]}$$

Non-Singular for d + z > 4 !!

Generalized Larkin-Pikin Results



Experimental Signatures

New Lattice-Sensitive

Settings for Exploration

of Exotic Quantum Phases

Elastic Anisotropy ??
Domain Dynamics??
Disorder ??
Metallic Systems ??

PC, P. Coleman, M.A. Continentino and G.G. Lonzarich,
Phys. Rev. Research 2, 043440 (2020).


thank you
danke
謝謝
teşekkür ederim
gracias
merci
obrigado
bedankt
dziękuję
go raibh maith agat
mochchakkeram
sukriya
kop khun krap
terima kasih
grazie
arigatō
takk
dakujem
tapadh leat
спасибо
Баярлалаа
рахмат
dank je
hvala
mauruuru
sagolun
taiku
мерси
감사합니다
ありがとう
ευχαριστώ
хвала
faafetai lava
blagodaram
dhanyavad
dankie
enkosi
asante
obrigada
chnorakaloutioun
gracies
sobodi
dekuji
mesi
shukriya
trugarez
najis tuke
dhanyavadagalu
diolch
rahmet
tanemirt
paldies
misaotra
mahalo
tack
mersi
barka
welalin