Unconventional Phenomena on the Border of Itinerant-Electron Magnetism

KITP-UCSB October 2011

Gilbert Lonzarich & Quantum Matter Group
Cavendish Laboratory

University of
Cambridge

Ferroelectrics

SE Rowley, LJ Spalek, MPM Dean, S Haines

& SS Saxena

Magnetic Materials

LA Sibley, JR Wensley, C Liu & E Pugh

PL Alireza, YTC Ko, SK Goh, & M Sutherland

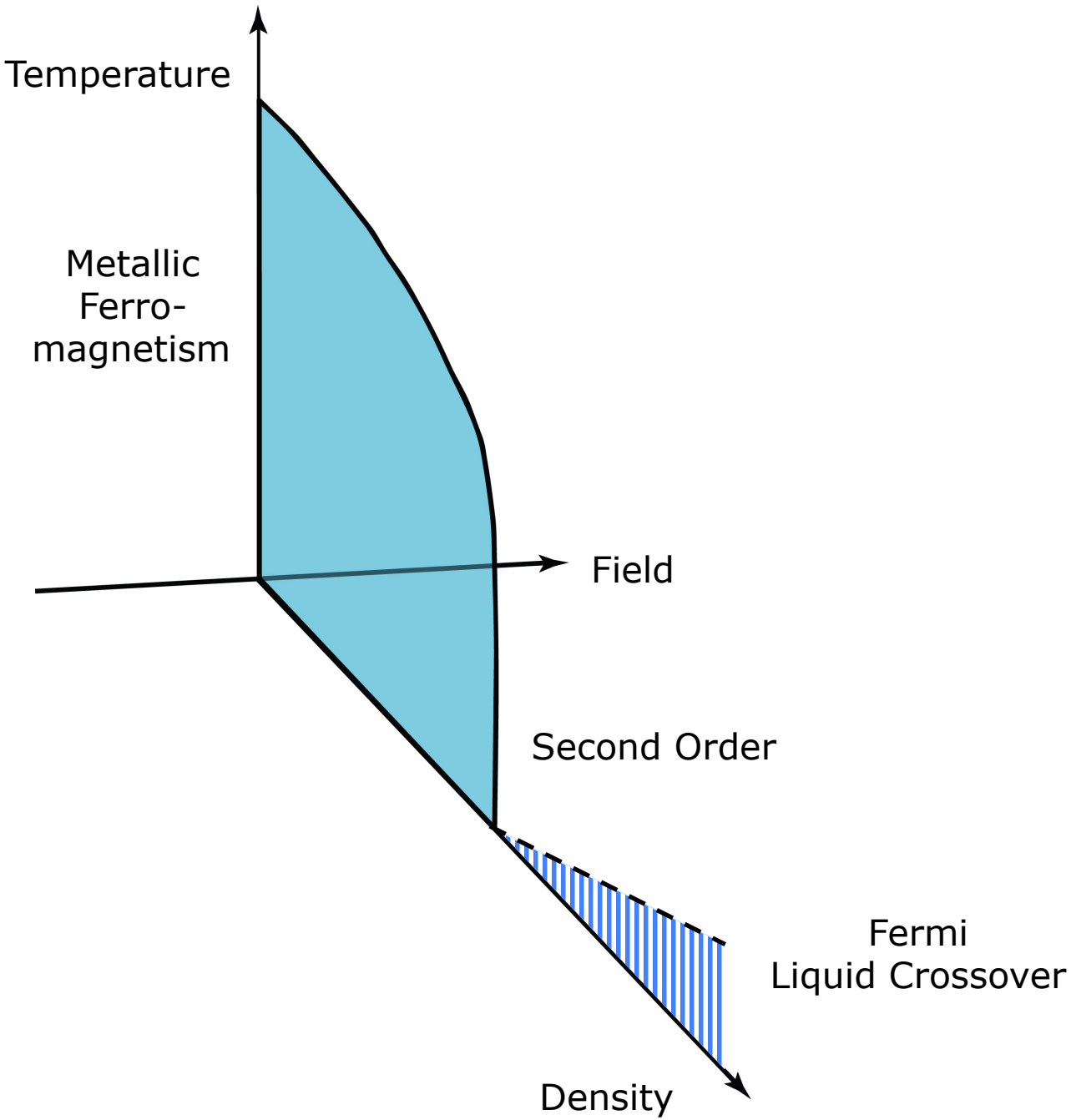
RP Smith, SE Rowley & SS Saxena

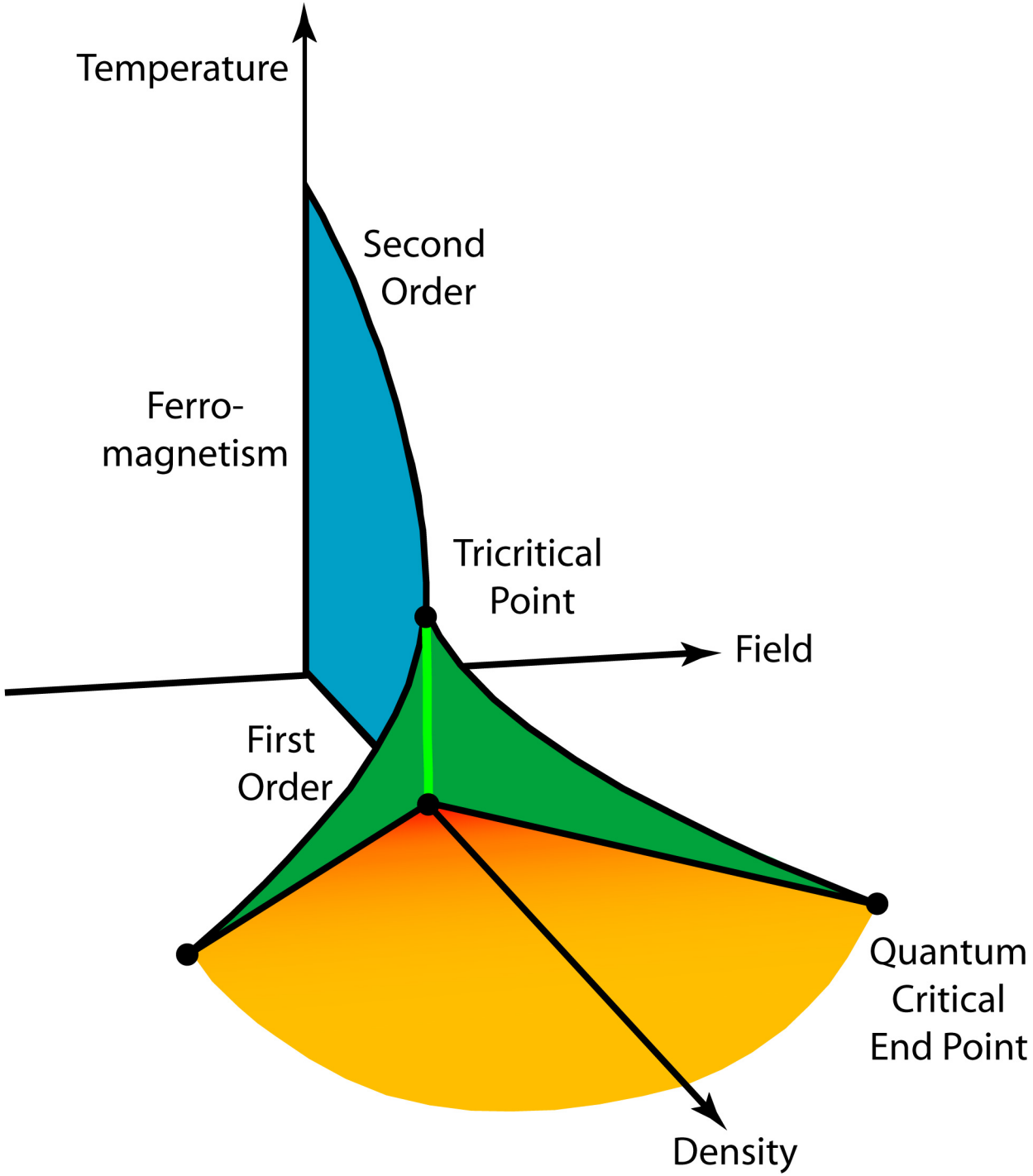
High Purity Specimens

N Kimura (Sendai), S Takashima, M Nohara & H Takagi (Tokyo)

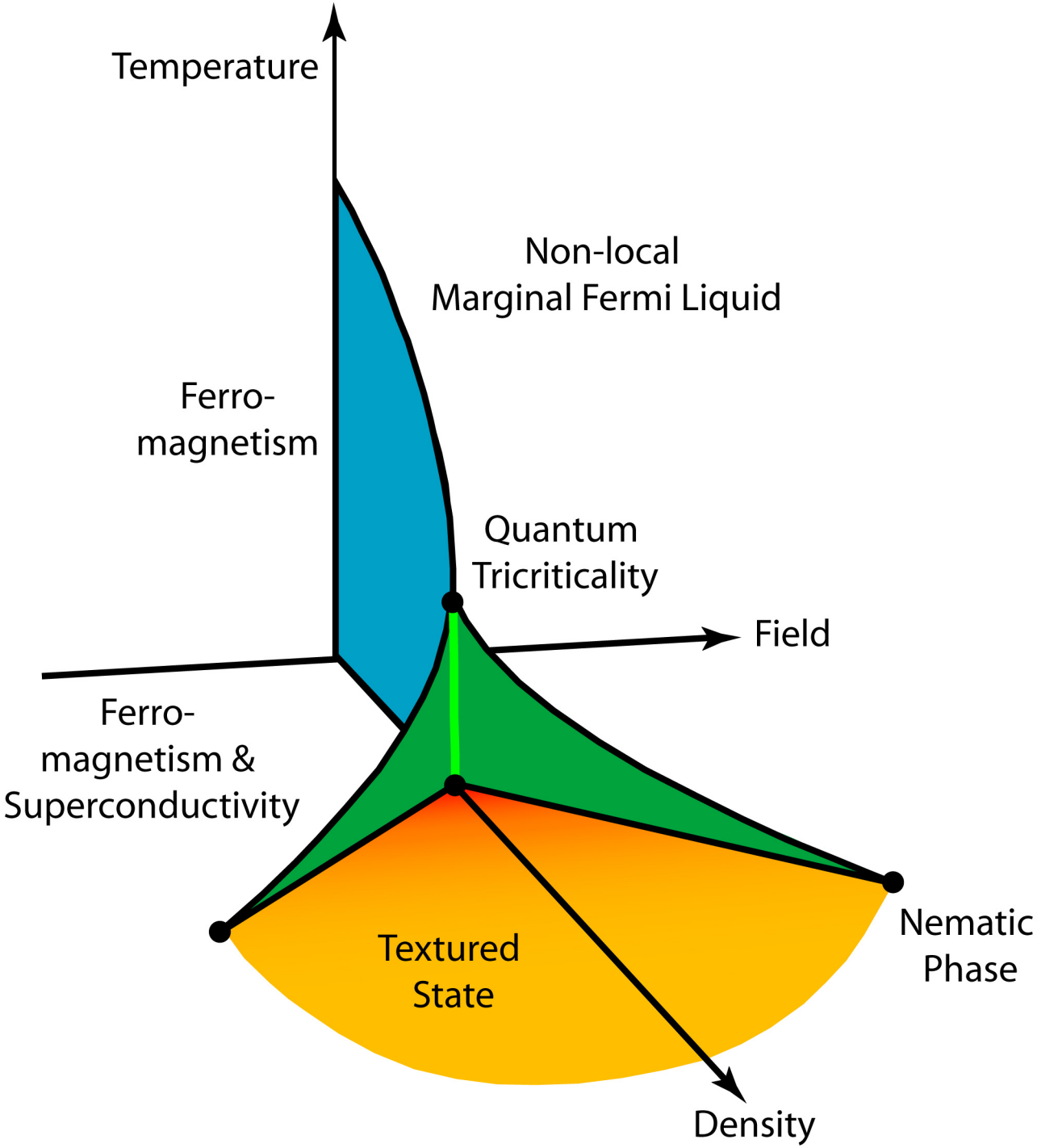
F Nakamura (Hiroshima), Y Maeno (Kyoto) & S Nakatsuji (Tokyo)

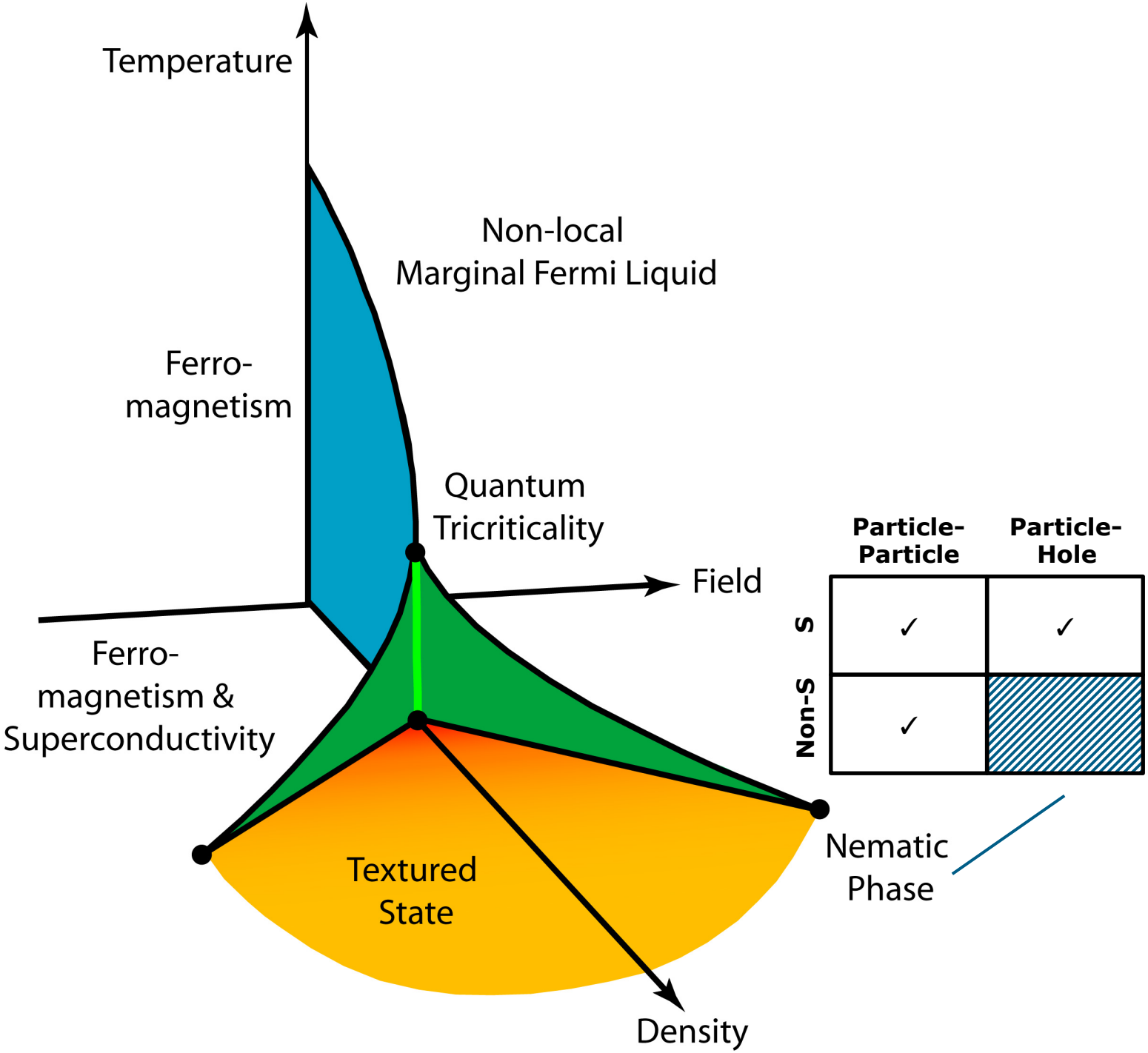
J Scott (Cambridge)


Temperature
Metallic
Ferro-
magnetism
Field
Second Order
Fermi
Liquid Crossover
Density



C Pfleiderer, SR Julian & GGL, *Nature* (2001);
D Belitz, TR Kirkpatrick & J Rollbuhler, *PRL* (2005);
M Imada *et al.*, *J Phys: Cond Mat* (2010)


Temperature
Non-local
Marginal Fermi Liquid
Ferro-
magnetism
Quantum
Tricriticality
Field
Ferro-
magnetism &
Superconductivity
Textured
State
Nematic
Phase
Density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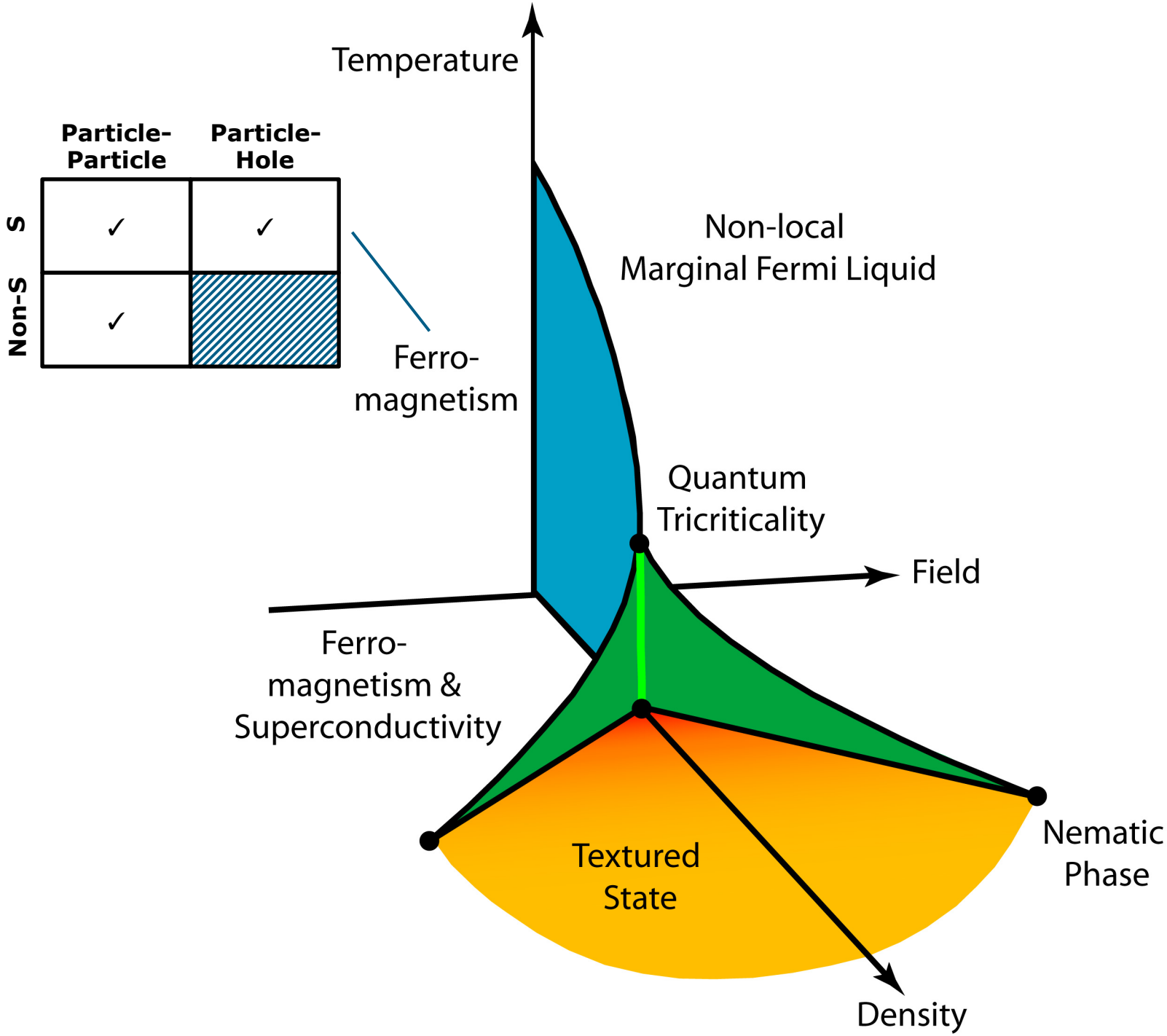
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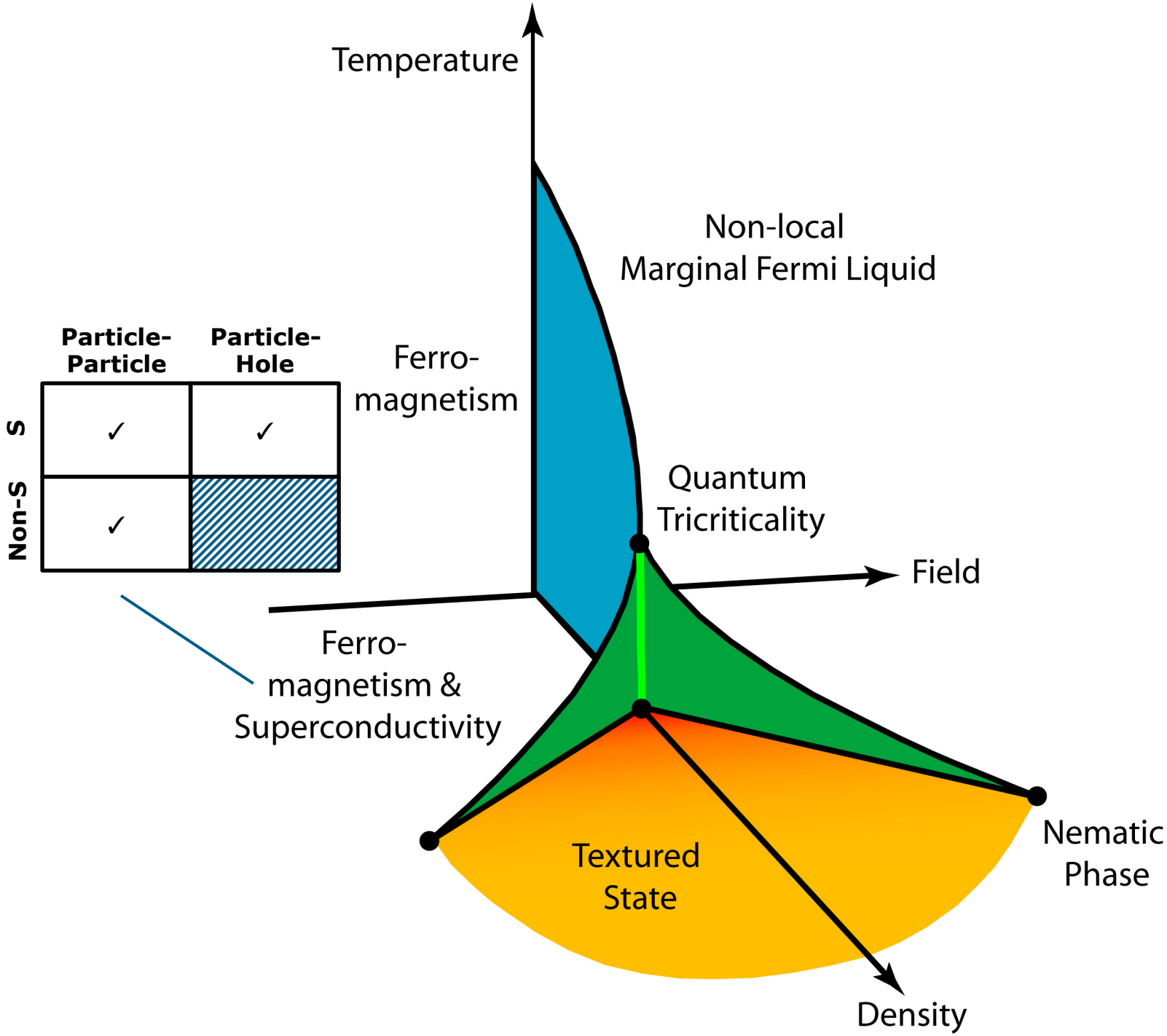
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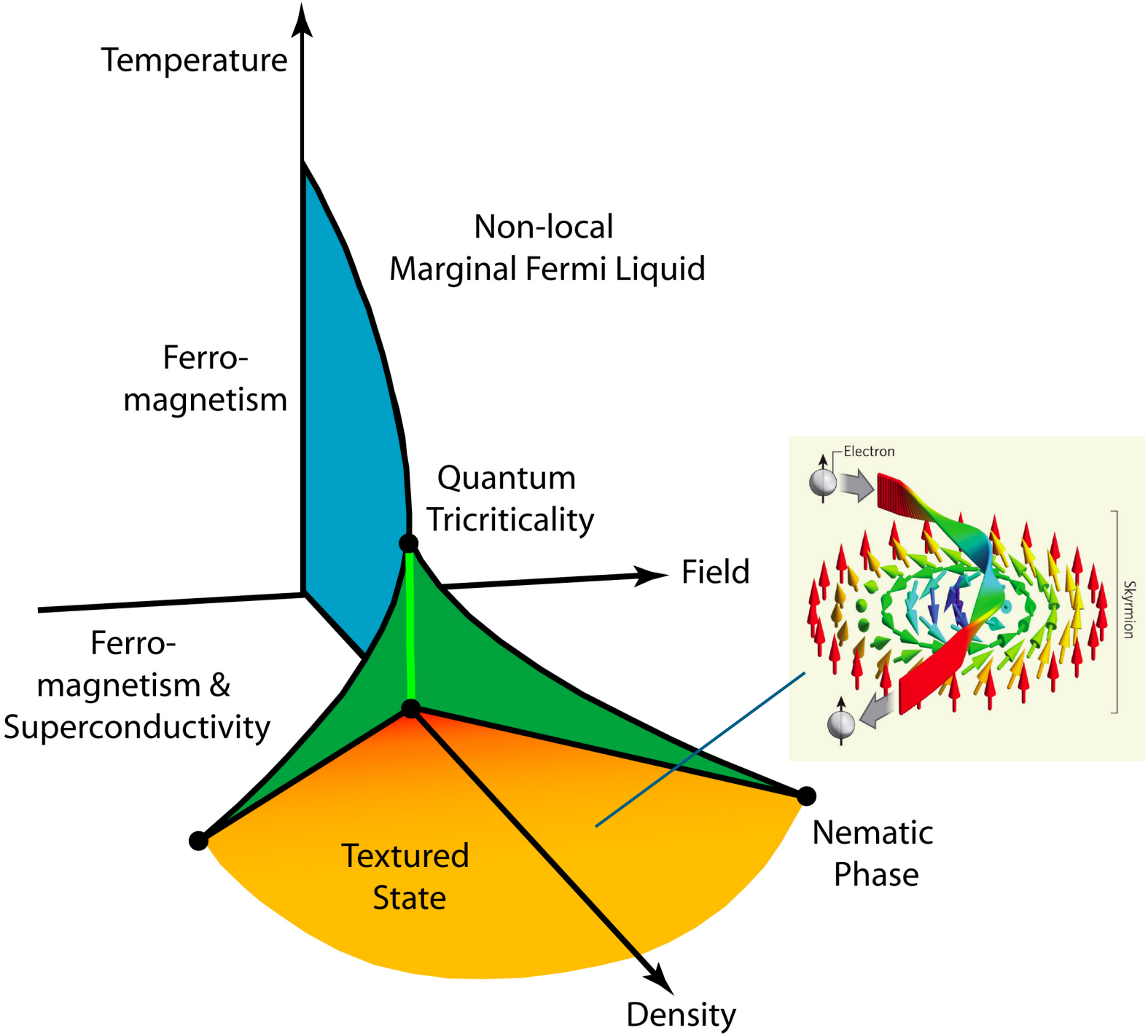
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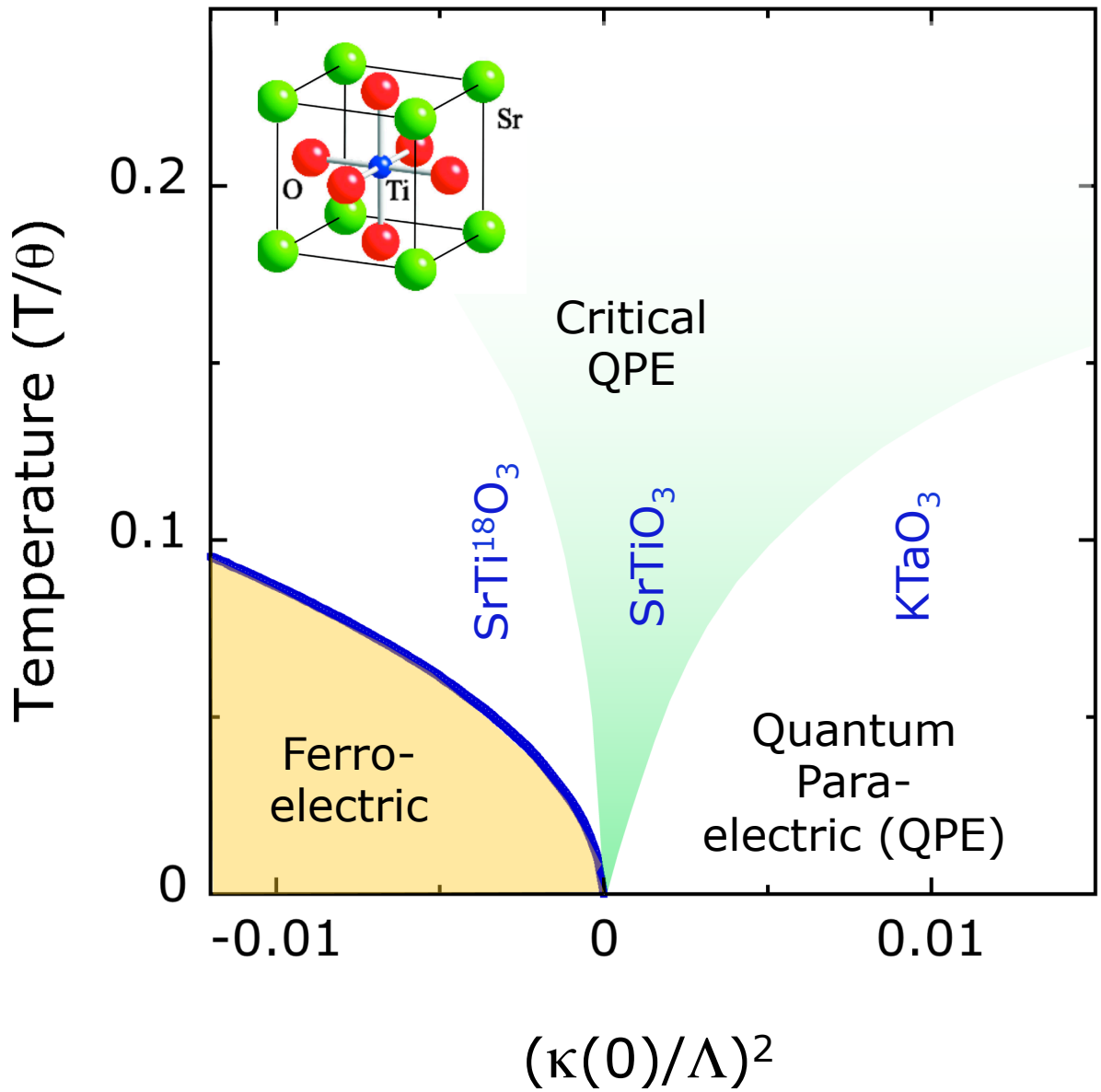
Border of Displacive Ferroelectricity

SE Rowley *et al.* (2011);
L Palova, P Chandra & P Coleman, *PRB* (2009);
R Roussev & AJ Millis, *PRB* (2003)



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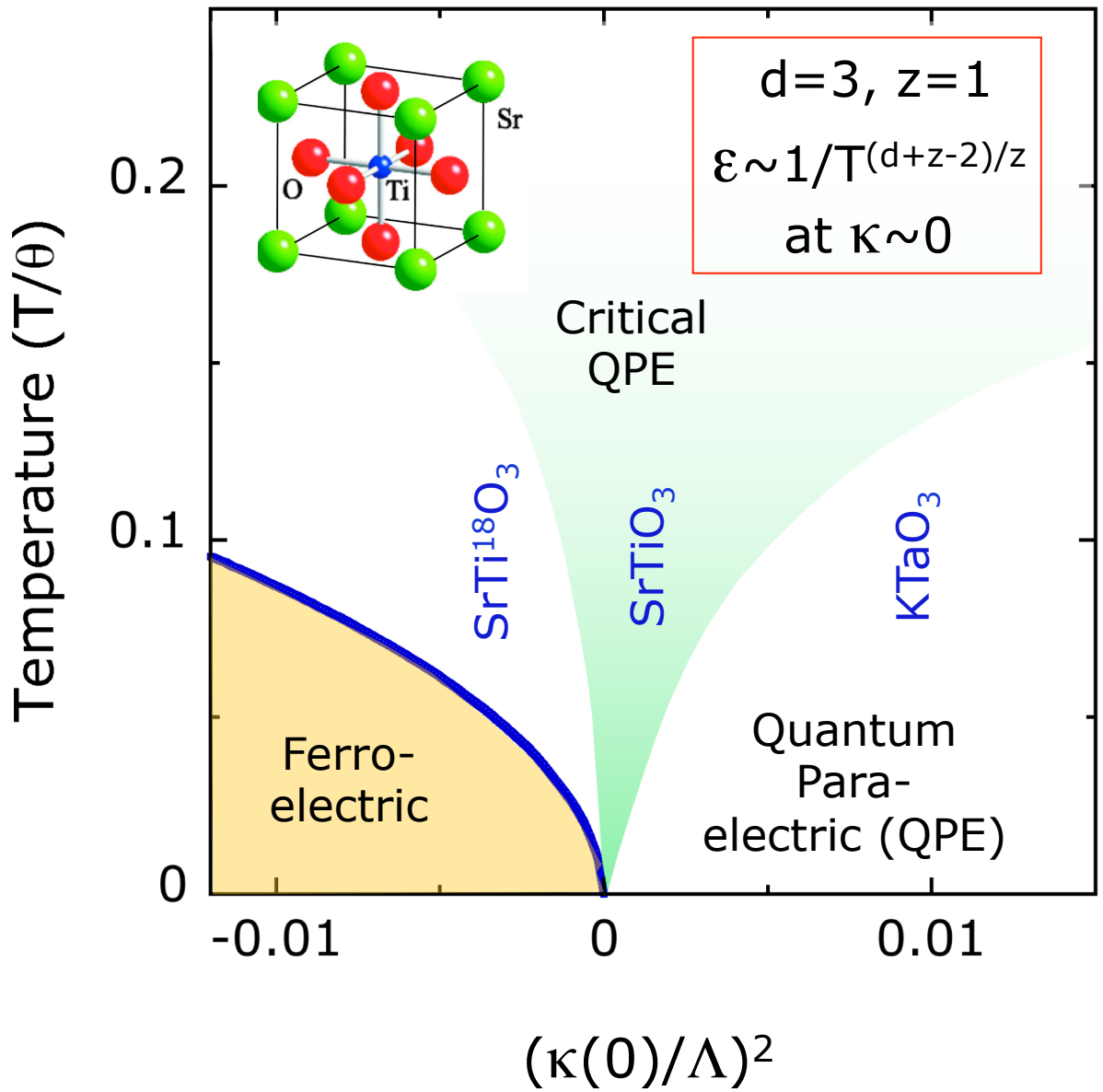
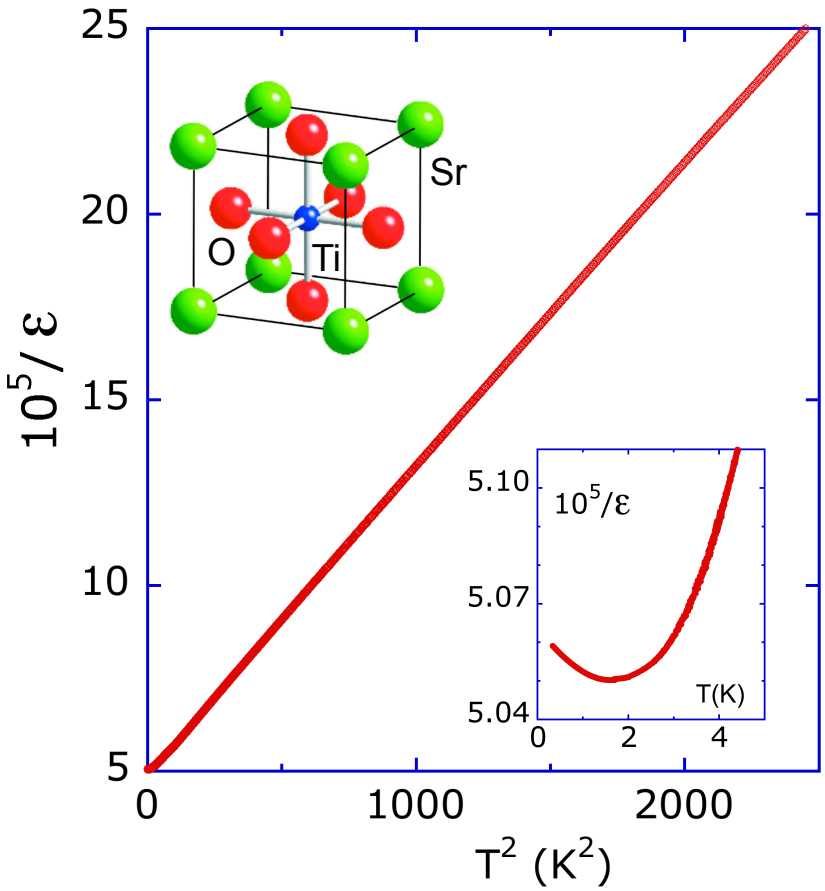


Polar Mode

$\omega^2 \sim \kappa^2 + q^2$

$\omega \rightarrow q$ as $\kappa \rightarrow 0$

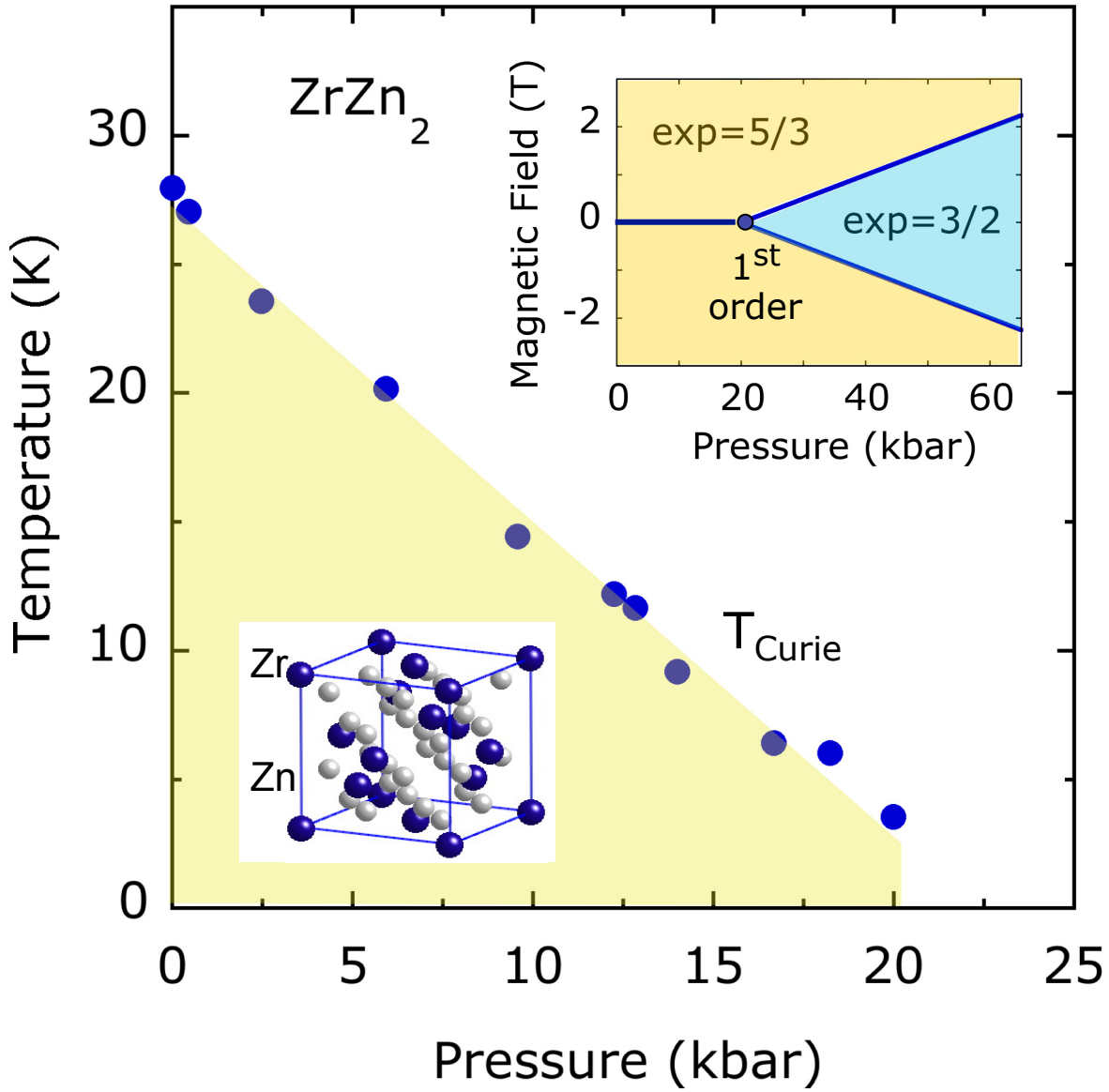
Border of Displacive Ferroelectricity
$SrTiO_3$: T^2 Divergence of Dielectric Function



SE Rowley, LJ Spalek, RP Smith, MPM Dean, GGL, JF Scott & SS Saxena (2011)

Border of Metallic Ferromagnetism
$ZrZn_2$: First Order Transition & $T^{5/3}$ to $T^{3/2}$ Resistivity

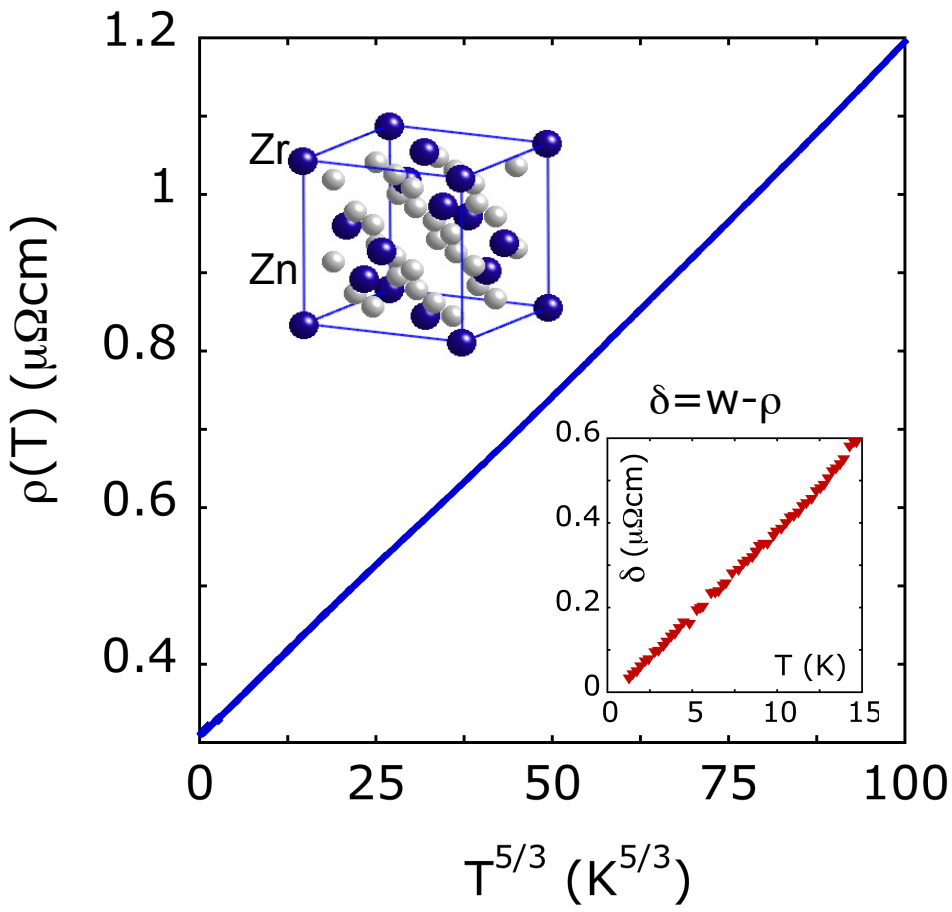
LA Sibley,
JR Wensley,
E Pugh
C Liu, GGL,
N Kimura,
S Takashima,
M Nohara
& H Takagi
(2011)



$\Delta\rho \sim T^{exp}$
0.5K to 5K

Border of Metallic Ferromagnetism

$ZrZn_2$: Electrical Resistivity ρ & Thermal Resistivity $w = L_0T/\kappa$



RP Smith, M Sutherland, GGL, SS Saxena,
N Kimura, S Takashima, M Nohara & H Takagi, *Nature* (2008)

Border of Metallic Ferromagnetism

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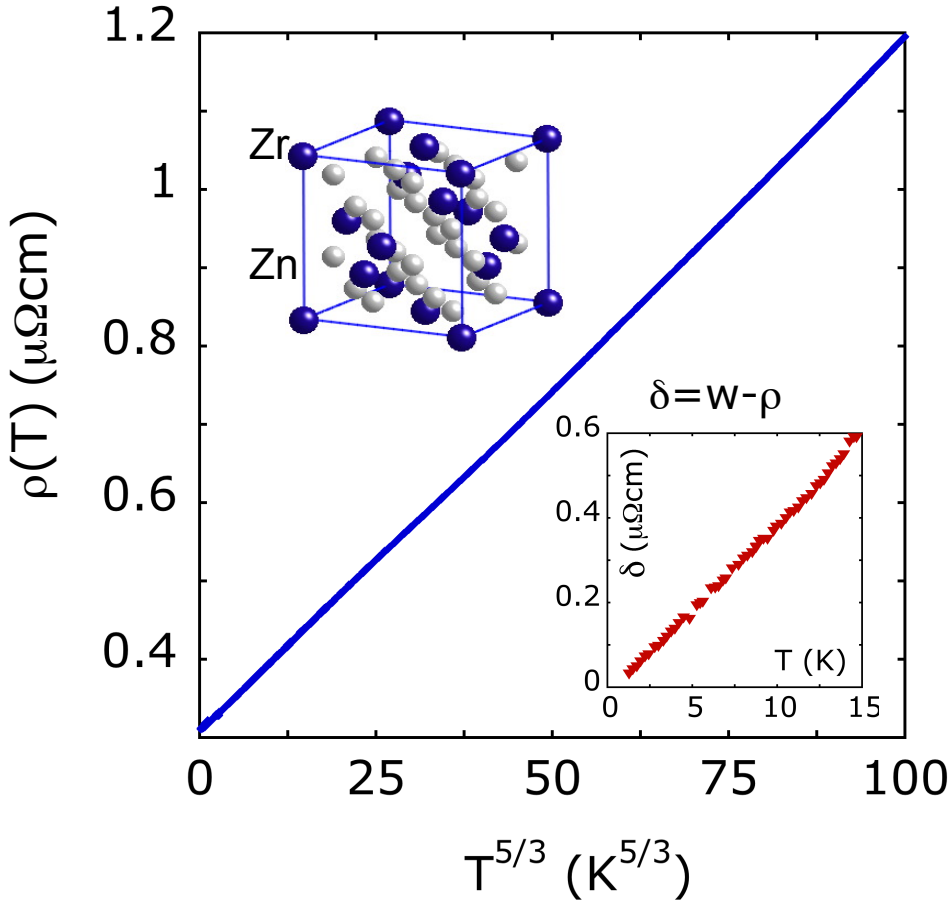

$d=3,\ z=3$

$w \sim T^{d/z}$

$\rho \sim T^{(d+2)/z}$

at $\kappa \sim 0$

Paramagnons

$\Gamma \sim q(\kappa^2+q^2)$

$\Gamma \rightarrow q^3$ as $\kappa \rightarrow 0$

RP Smith, M Sutherland, GGL, SS Saxena,
N Kimura, S Takashima, M Nohara & H Takagi, *Nature* (2008)

Border of Metallic Ferromagnetism
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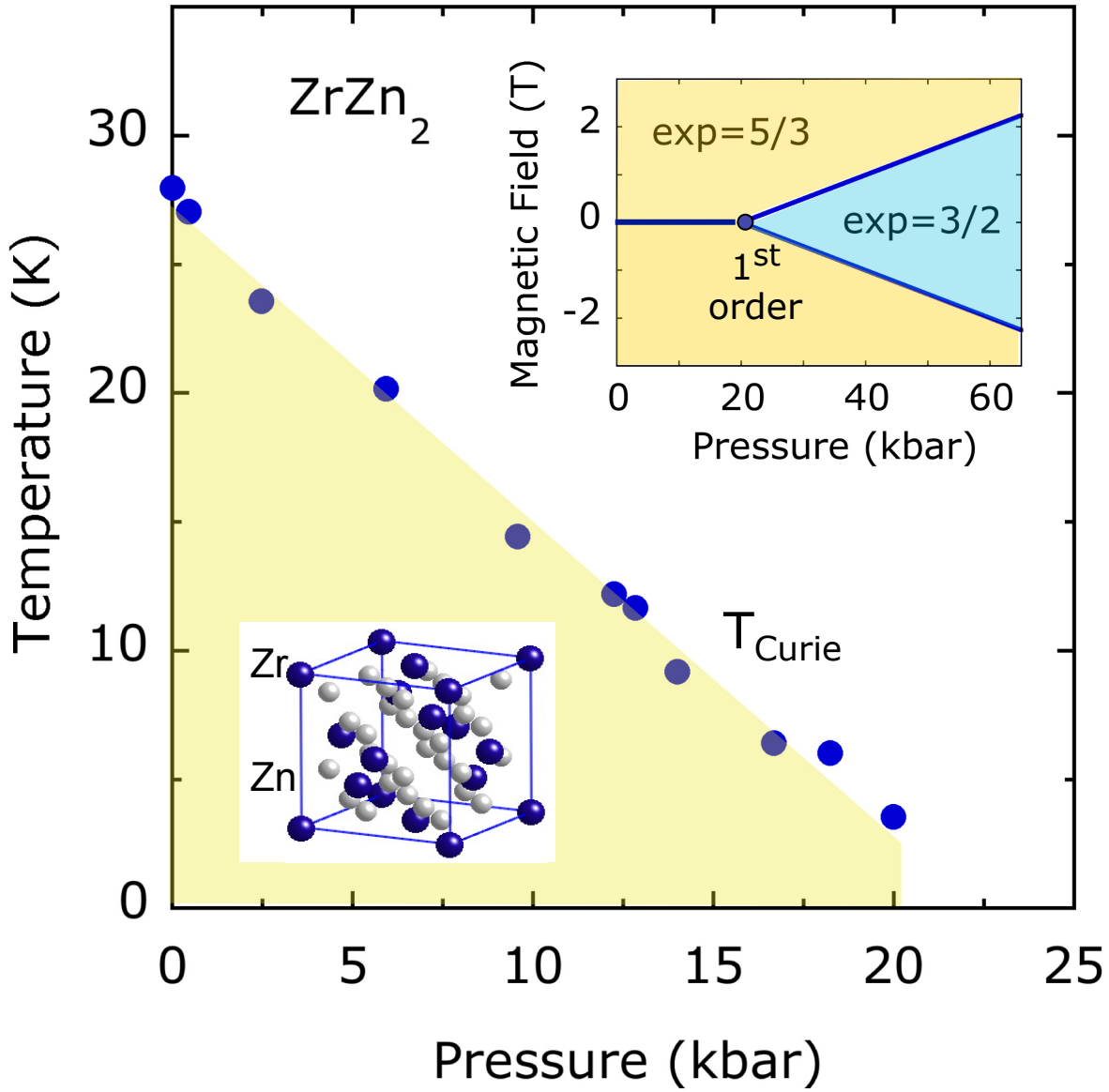
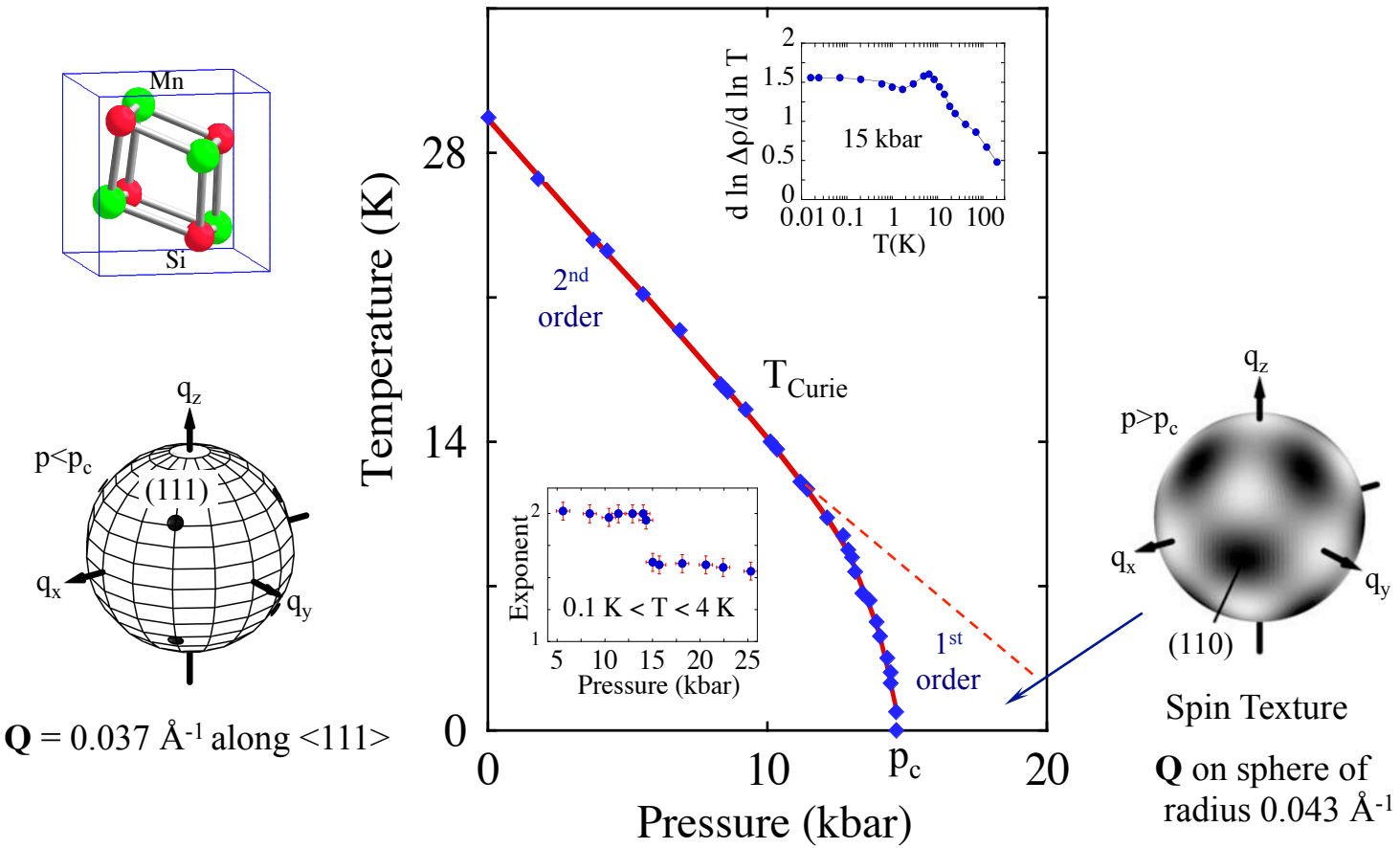
LA Sibley,
JR Wensley,
E Pugh
C Liu, GGL,
N Kimura,
S Takashima,
M Nohara
& H Takagi
(2011)



$\Delta\rho \sim T^{exp}$
0.5K to 5K

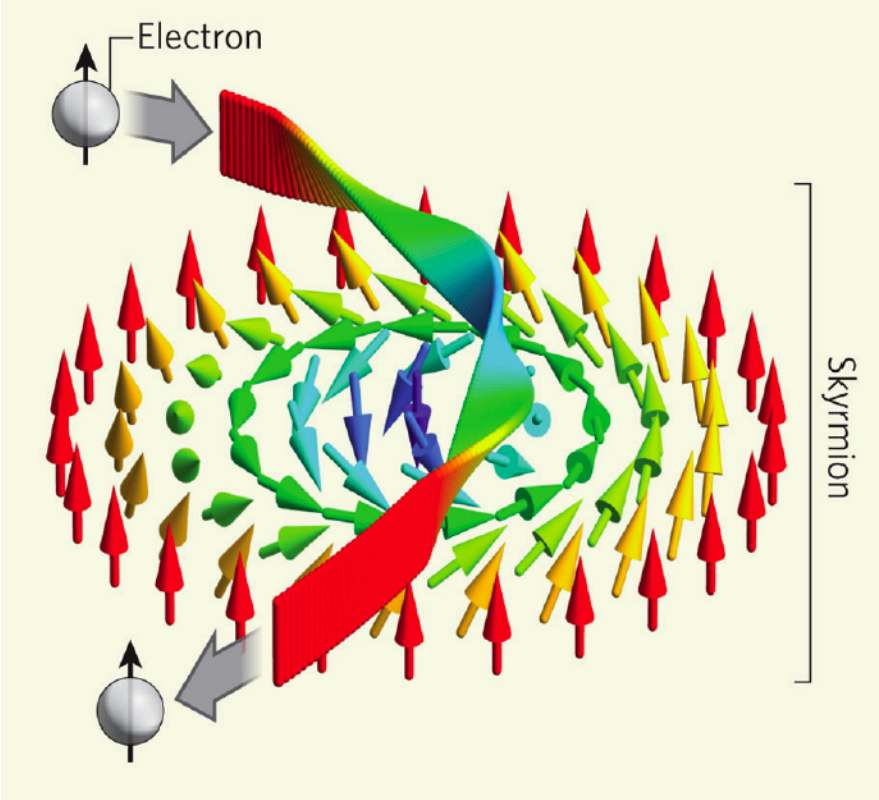
MnSi: Temperature-Pressure Phase Diagram



C Pfleiderer *et al.*, *Nature* (2001) & (2004); N Doiron-Leyraud *et al.*, *Nature* (2003); C Pfleiderer, SR Julian, GJ McMullan & GGL, *PRB* (1997); C Thessieu, C Pfleiderer, AN Stepanov & J Flouquet, *J Phys: Cond Mat* (1997); JD Thompson, Z Fisk & GGL, *Physica B* (1989);

W Yu *et al.*, *PRL* (2004); Y Uemura *et al.*, *Nature* (2006); P Pedrazzini, *et al.*, *Physica B* (2006) & *PRL* (2007); …

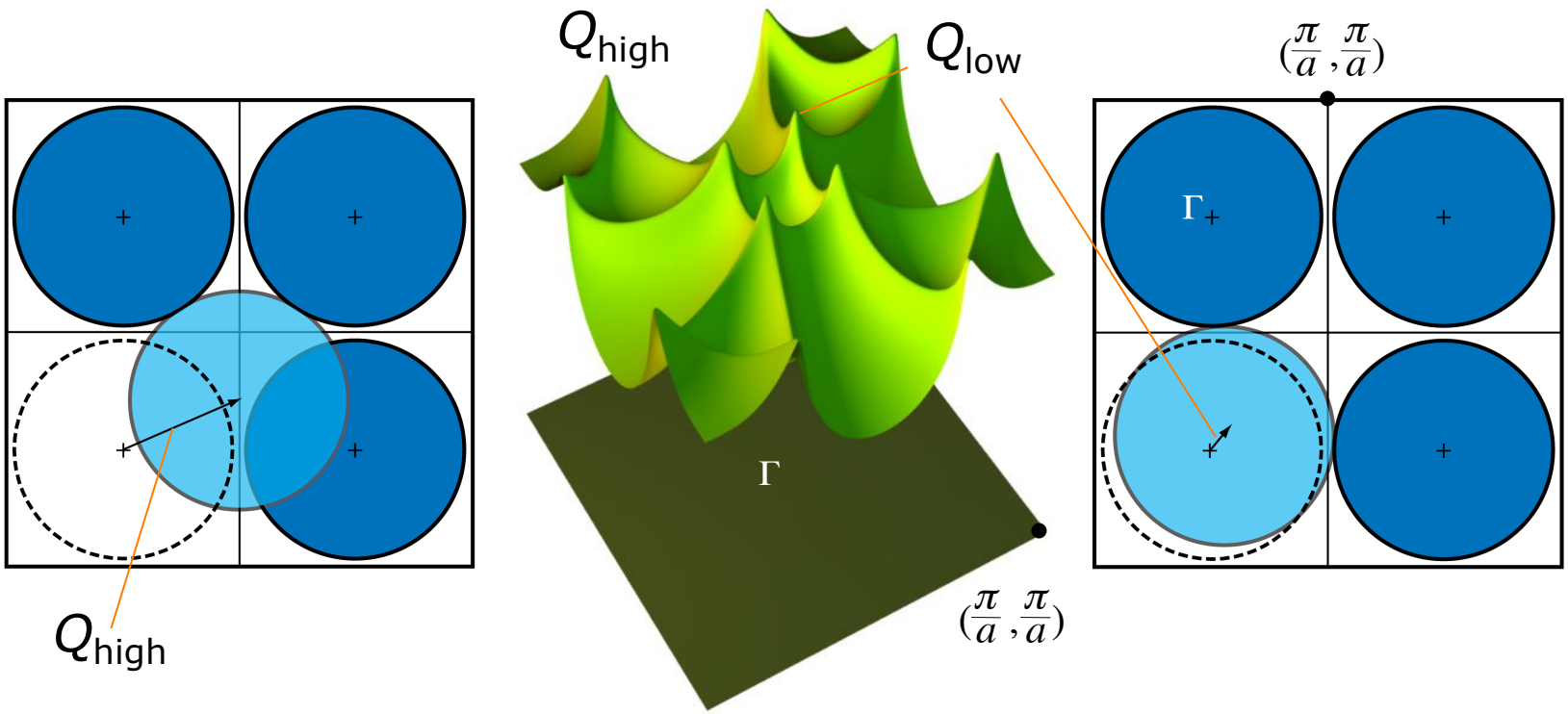
Spin Texture as Coherent Superposition of Spin Spirals



C Pfleiderer & A Rosch, *Nature* (2010)

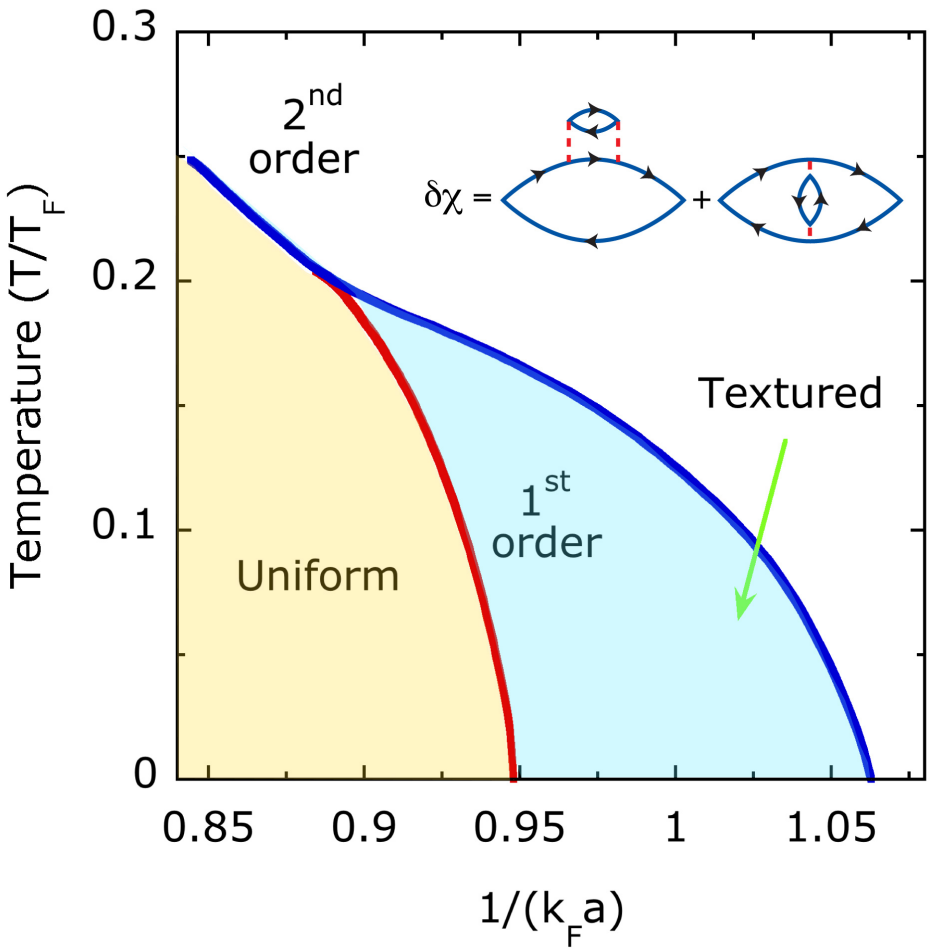
Spin Spirals from the Dzyaloshinky-Moriya
Interaction in Lattices without Space Inversion Symmetry

Spin Spirals from Fermi Surface Nesting:
Fermi Surface and Lindhard Function for d_{xy} Band of Sr_2RuO_4



AP Mackenzie, SR Julian, *et al.*, *PRL* (1996)
C Bergemann, SR Julian, AP Mackenzie, *et al.*, *PRL* (2000)
C Bergemann; P Monthoux

Spin Spirals from Non-Analytic Corrections to Fermi Liquid Theory: Intrinsic Spin Texture on the Border of Metallic Ferromagnetism

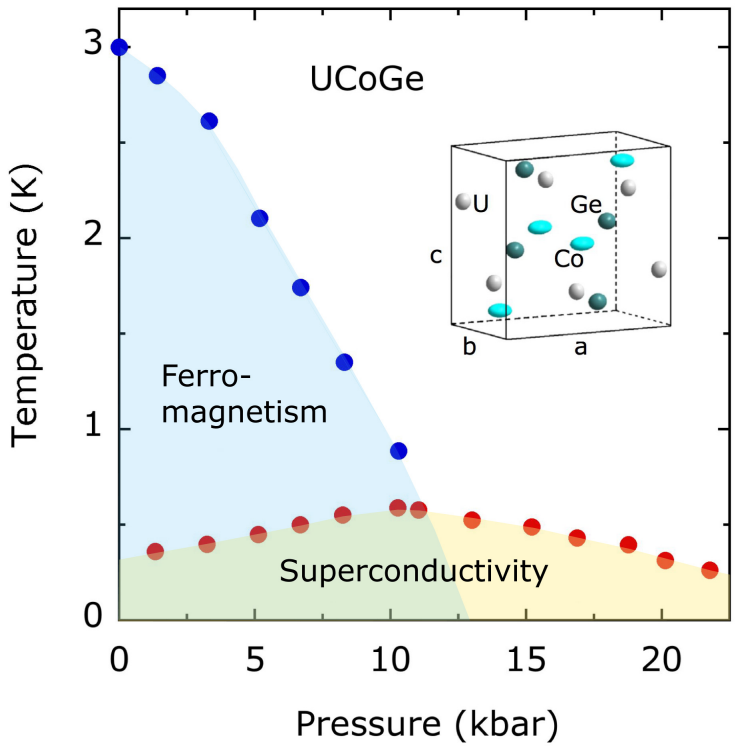


a = scattering length

GJ Conduit, AG Green & BD Simon, *PRL* (2009);
AV Chubukov, DL Maslov & AJ Millis, *PRB* (2006); GY Chitov & AJ Millis, *PRB* (2001)
D Belitz, TR Kirkpatrick & T Vojta, *PRB* (1997), …

Superconductivity on Border of Itinerant-Electron Ferromagnetism

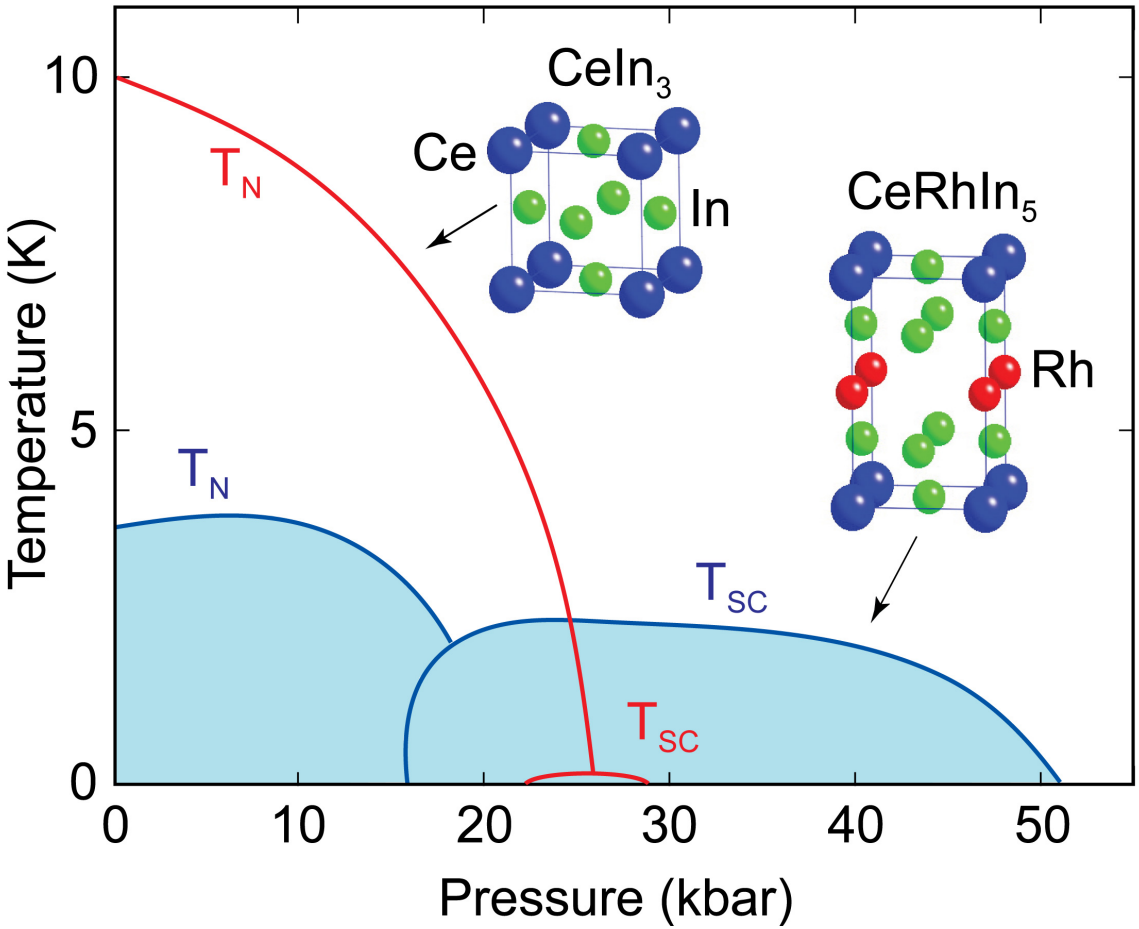
Uniaxial Ferromagnet



UCoGe: A Gasparini *et al., J Low Temp Phys* (2010)
UIr: T Akazawa *et al. JPSJ* (2006)
URhGe: AD Huxley, *et al.*, *JPSJ* (2007); D Aoki *et al., Nature* (2001); AD Huxley, *et al.*, *J Phys: Cond Mat* (2003)
UGe_2: SS Saxena *et al., Nature* (2000), …

NQR Studies: T Ohta, *et al., JPSJ* (2010); T Hatton *et al., Physica C* (2010); Y Kitaoka, *et al., JPSJ* (2005); …

Superconductivity on the Border of Antiferromagnetism in Related Cubic and Tetragonal Systems

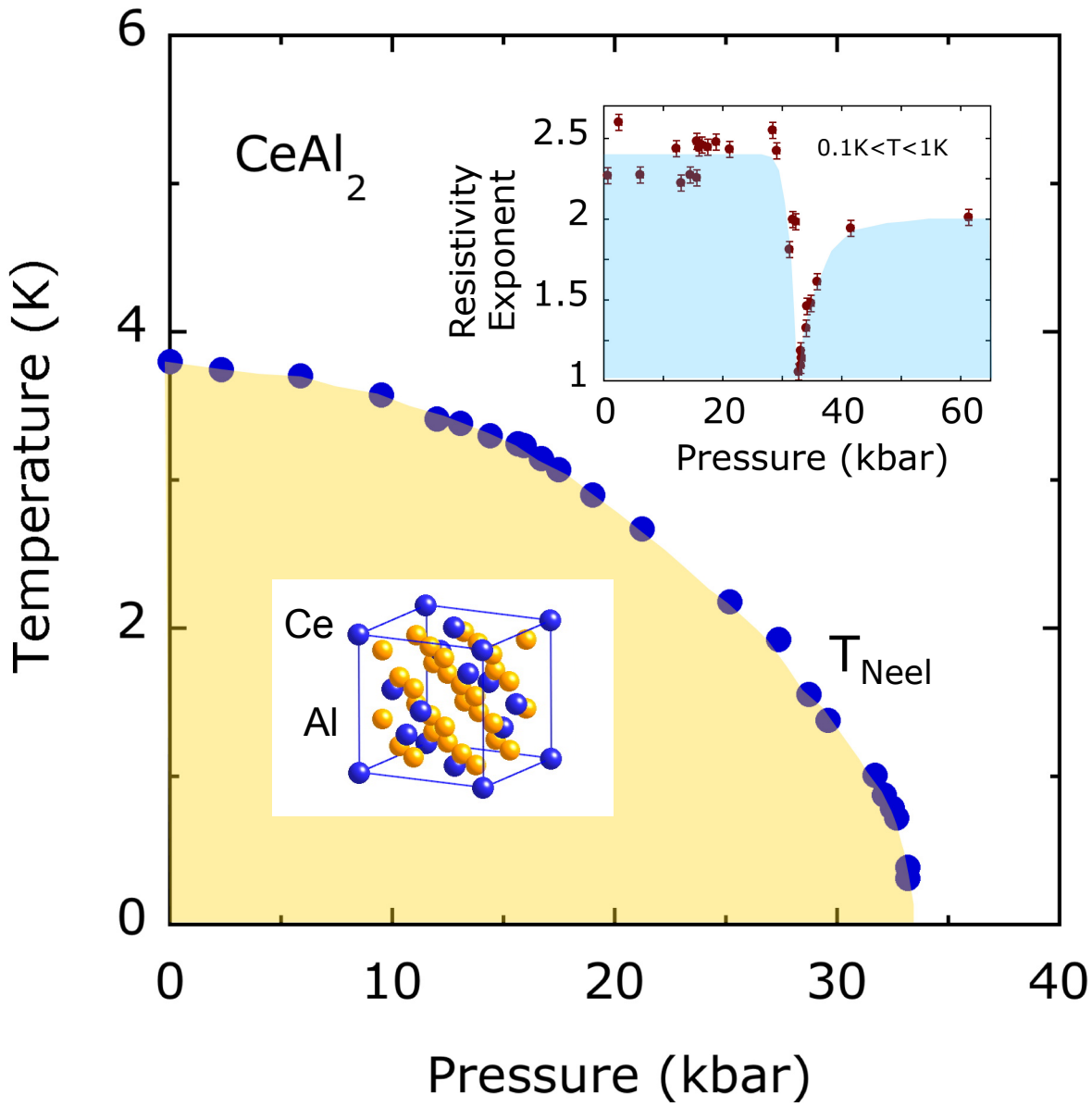


$CeIn_3$: IR Walker, FM Grosche, DM Freye & GGL (1997); …

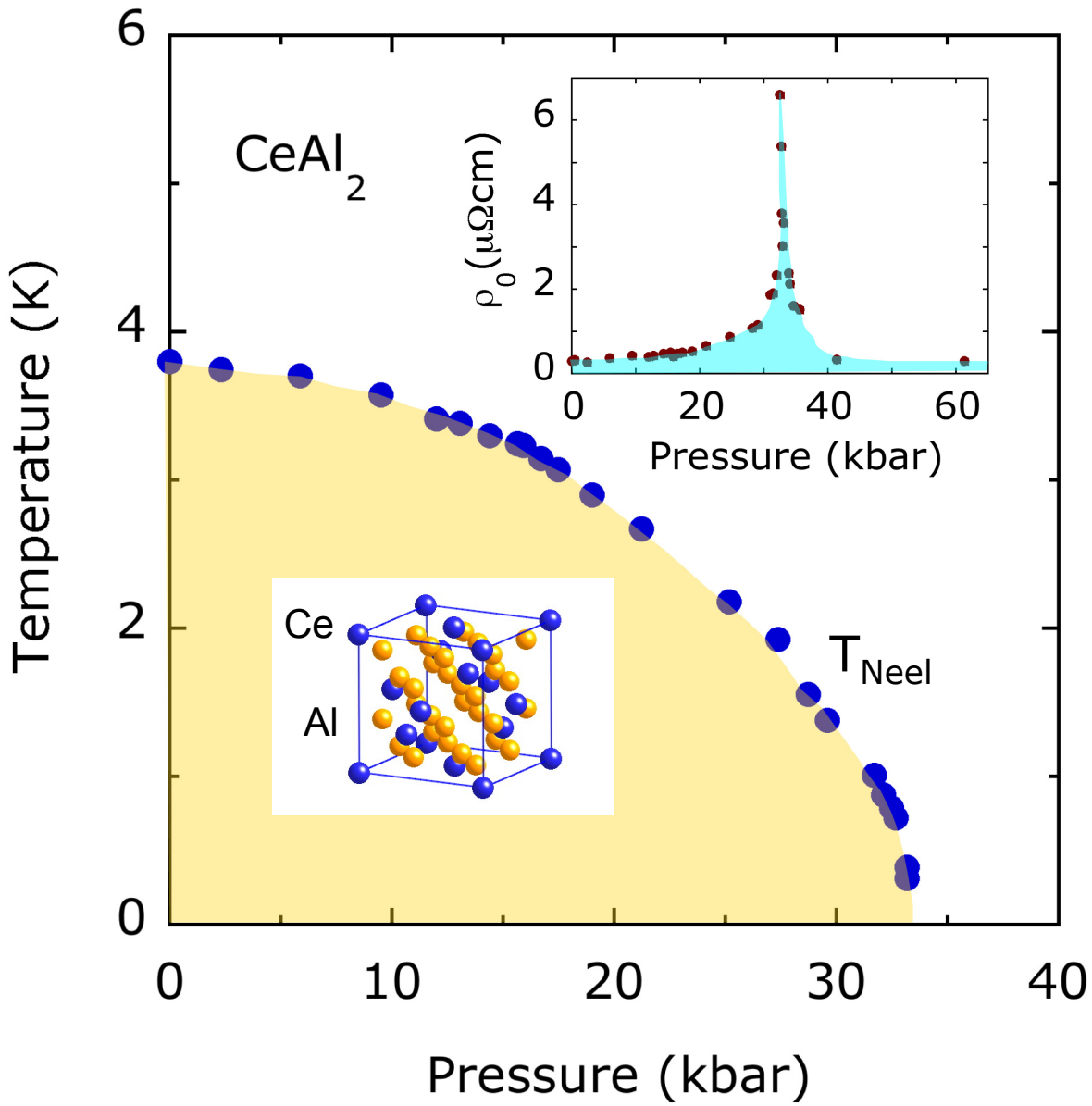
$CePd_2Si_2$: N Mathur *et al.* (1998); FM Grosche *et al.* (2001); …

$CeMIn_5$ (M = Co, Rh, Ir): H Hegger *et al.* (2000); JL Sarrao *et al.* (2001); …

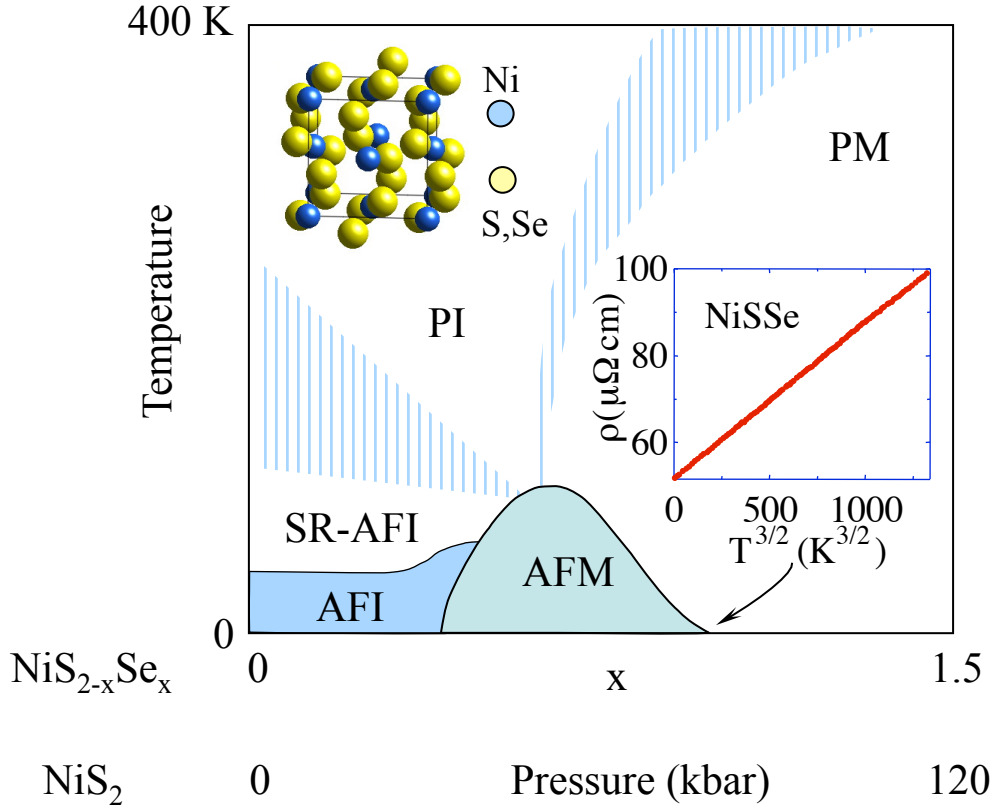
JR Wensley,
LA Sibley,
C Liu,
E Pugh
& GGL
(2011)

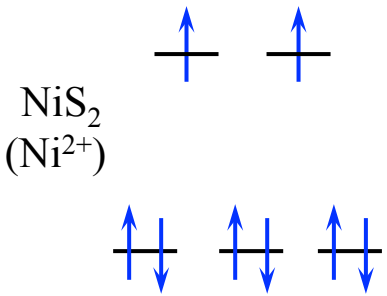


JR Wensley,
LA Sibley,
C Liu,
E Pugh
& GGL
(2011)



Border of Antiferromagnetism in Cubic Dichalcogenide: NiS_2





JA Wilson (1985);
T Takimoto, T Hotta &
K Ueda, *PRB* (2004)

AFI (M) = Spin-1 Antiferromagnetic Insulator (Metal)

PI (M) = Paramagnetic Insulator (Metal)

S Miyasaka *et al.*, *JPSJ* (2000); P Niklowitz *et al. PRB* (2008); H Takagi *et al.* (2008)

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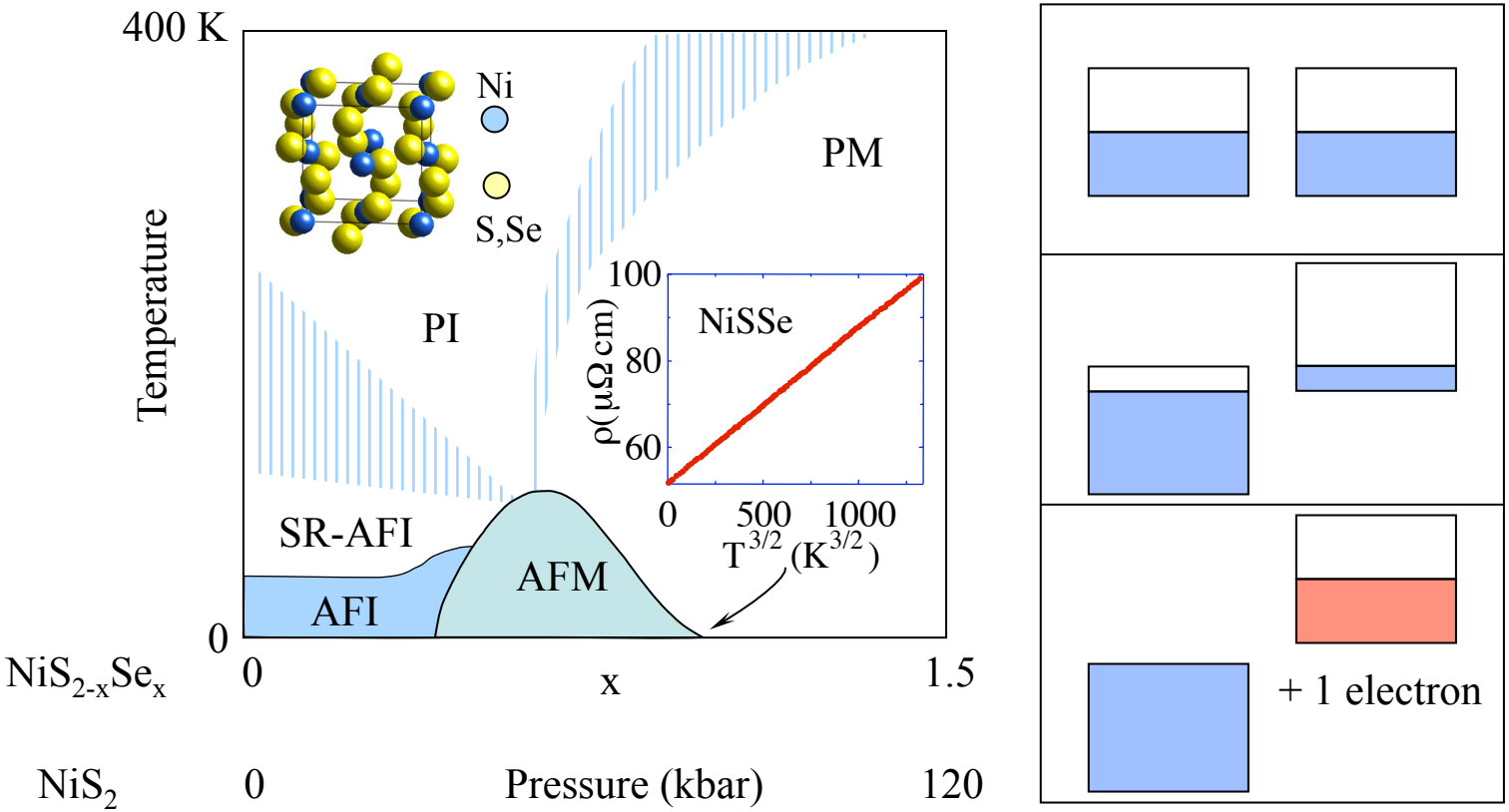

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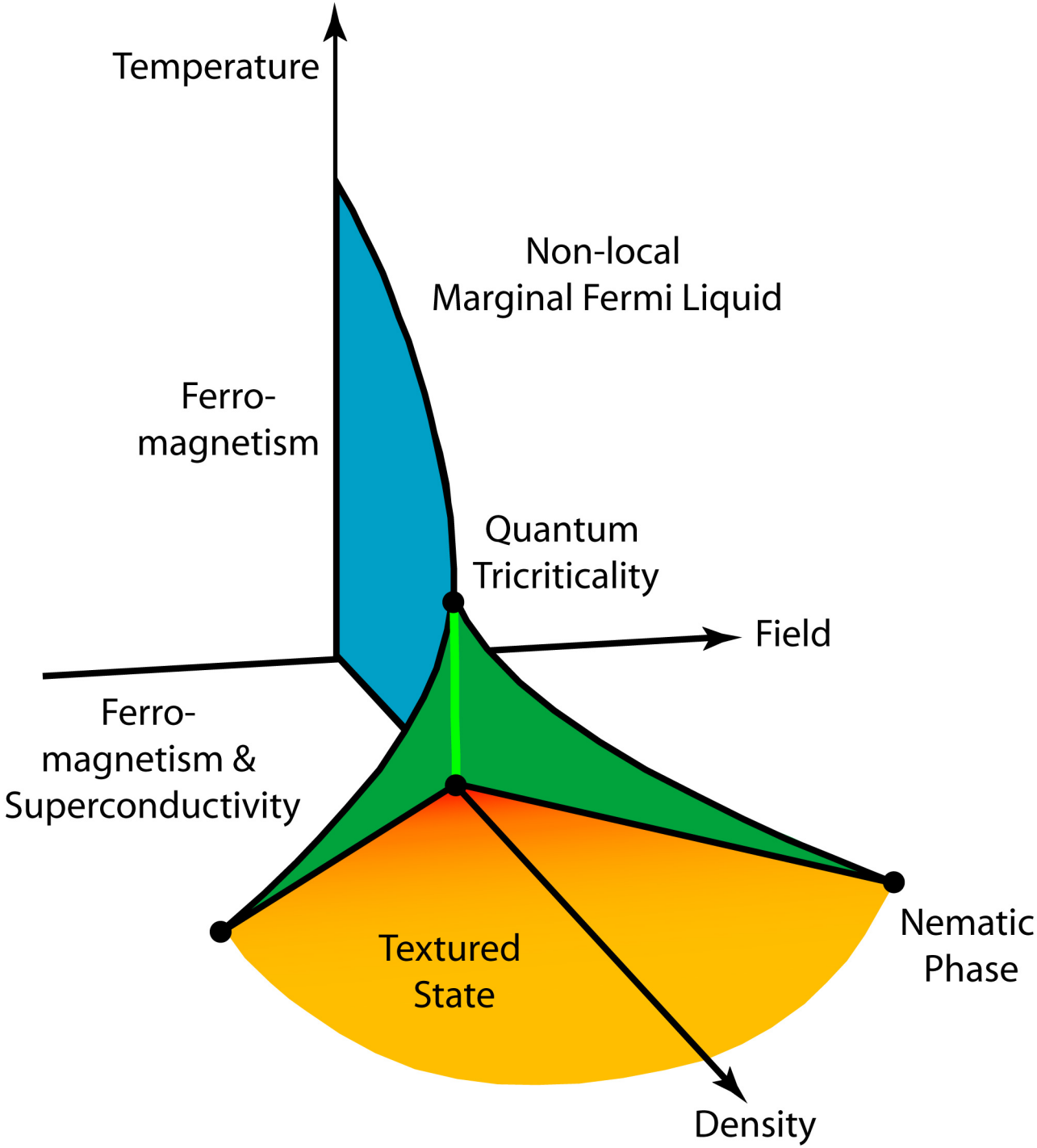
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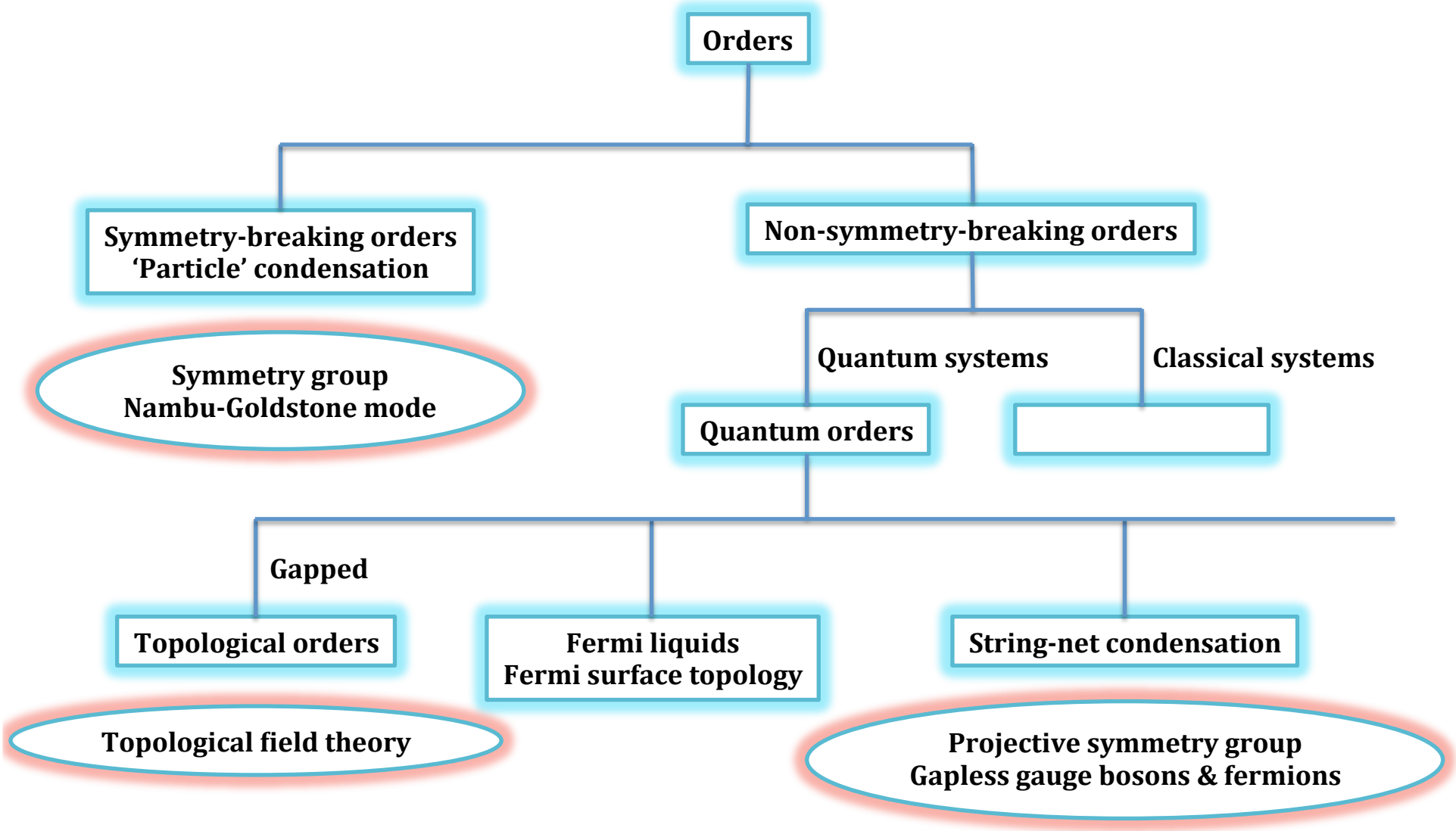
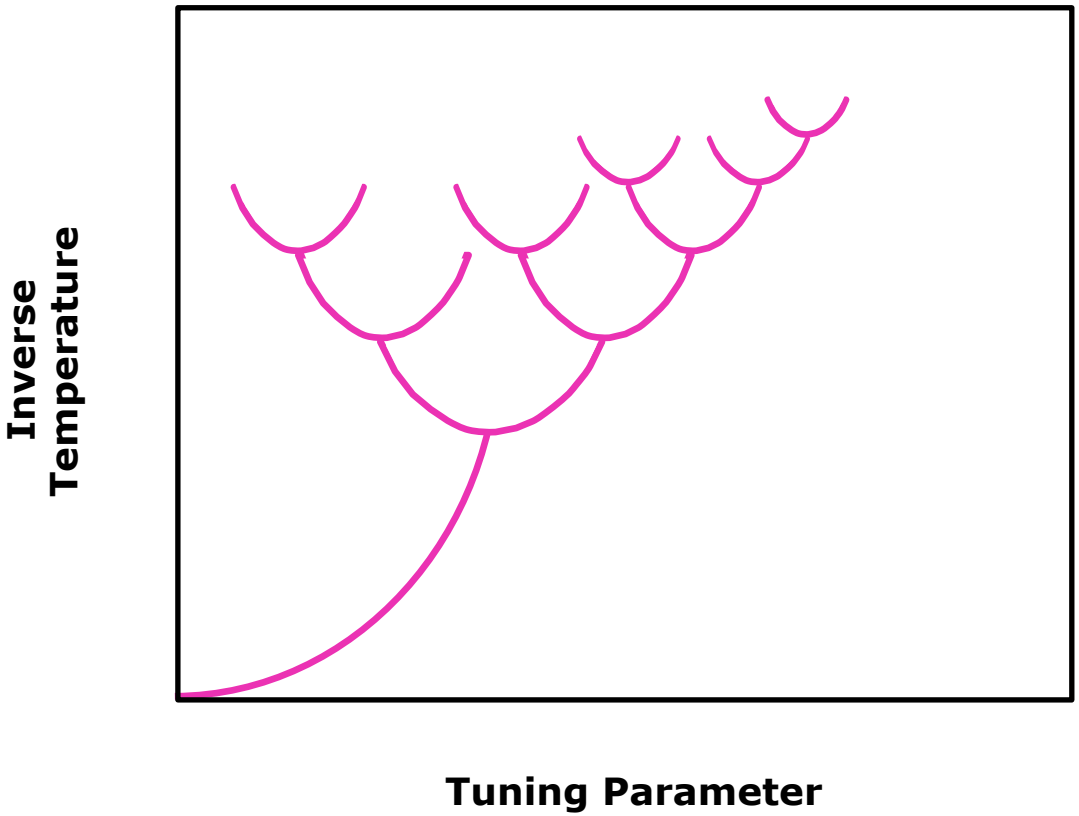
A classification of different orders in matter (and in a vacuum)



After: X-G Wen, Quantum Field Theory of Many-Body Systems, Oxford, 2004

Possible Hierarchy of Instabilities in Ideally Clean Limit



The End