Superconductivity and Magnetism in Topological Half-Heusler Semimetals

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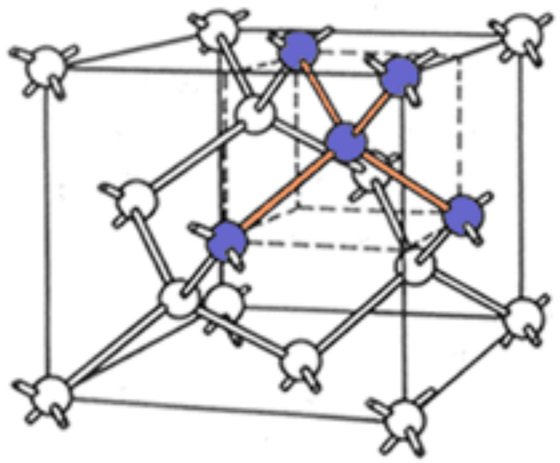
Sci. Adv. **1**, e1500242

Outline

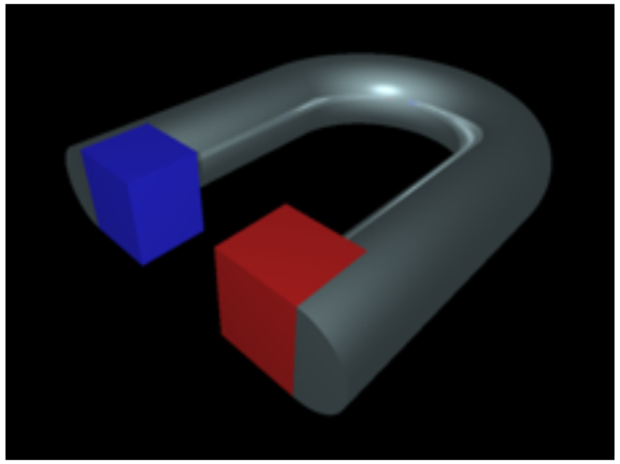
- Introduction:
  - Topological insulator: a new quantum state of matter
  - Half Heusler semimetal RPdBi:
    promising candidate for a topological material
- Experimental Results for RPdBi:
  - Magnetic susceptibility: Localized f electrons
  - Neutron diffraction: Antiferromagnetism
  - Charge transport and magnetic measurements:
    Superconductivity
- Discussion:
  - Realization of peculiar superconductivity:
    Singlet-triplet mixing, Magnetic SC, BCS-BEC crossover
- Summary

Topological Insulator

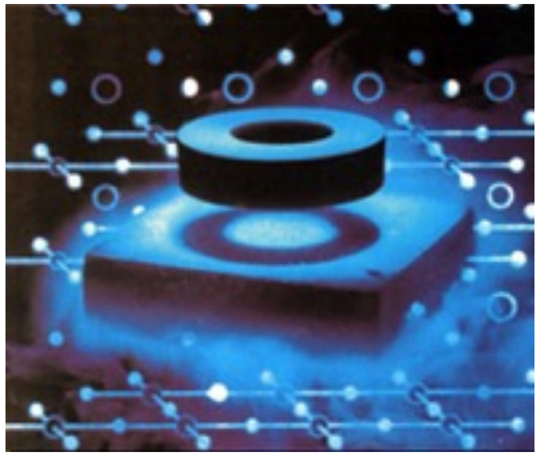
Phase transition **Breaking symmetry**



Crystal: Broken translational symmetry



Magnet: Broken rotational symmetry



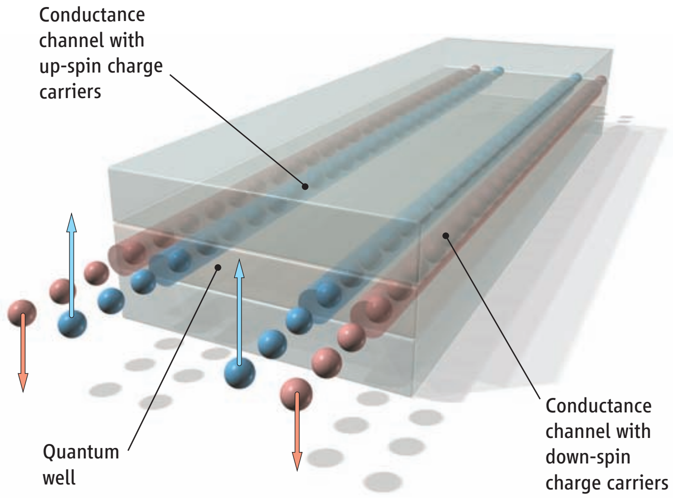
Superconductor: Broken gauge symmetry

Topological insulator New quantum phase of matter

absence of symmetry breaking

e.g. Quantum spin Hall state
2D topological insulator

chiral boundary state



Schematic of the spin-polarized edge channels in a quantum spin Hall insulator.

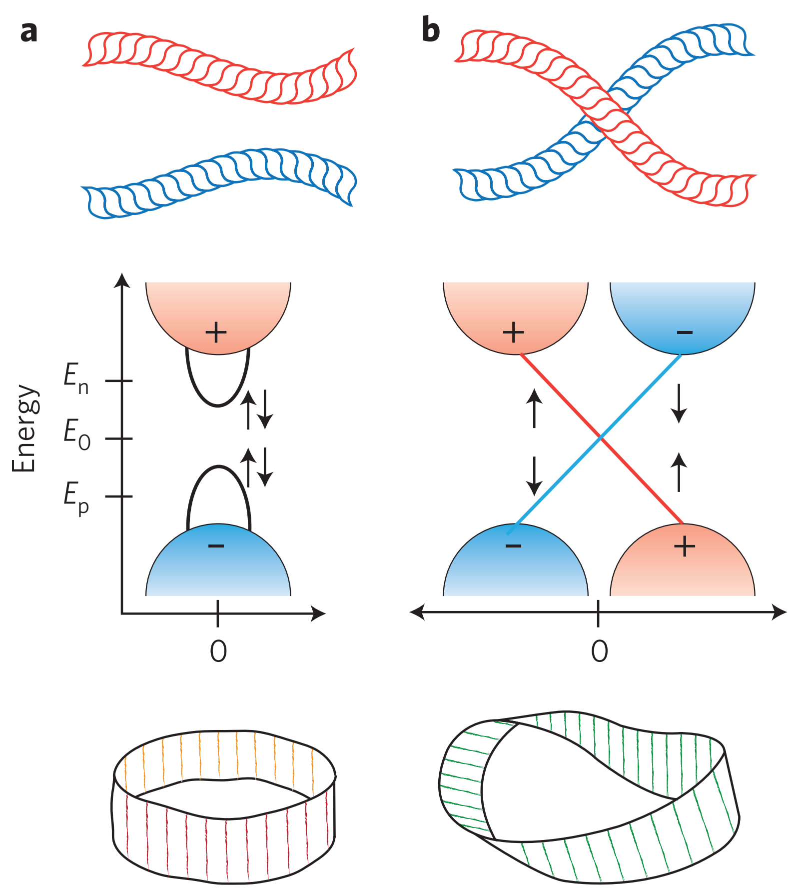
M. Konig *et al.* Science (2007)

Topological Insulator

3D Topological insulator L. Fu *et al.* Phys. Rev. Lett. (2007)

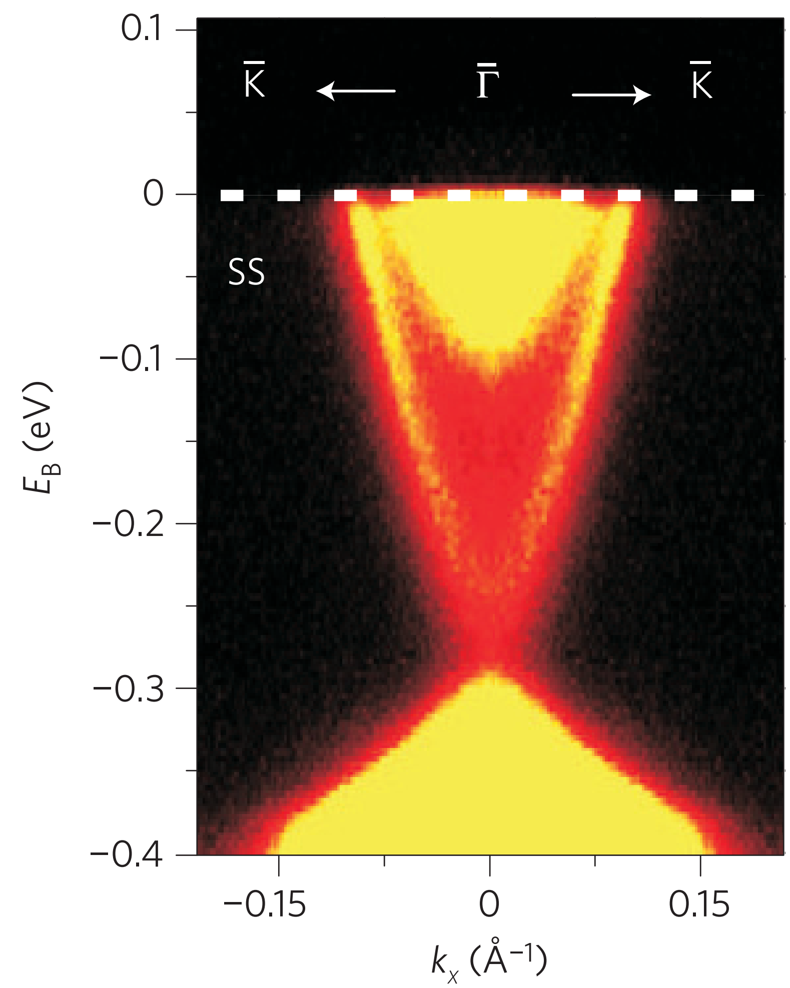
Metallic surface state protected against time reversal invariant perturbations

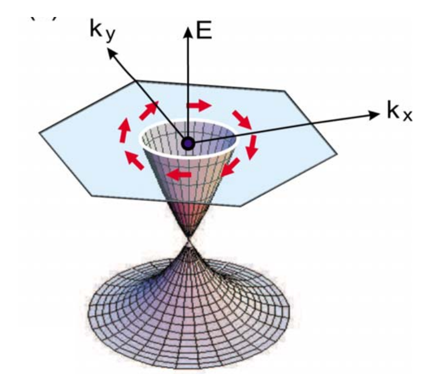
Trivial **Topological**



H.C. Manoharan *et al.* Nat. Nano (2010)

Bi_2Se_3





Y. Xia *et al.* Nat. Phys. (2009)

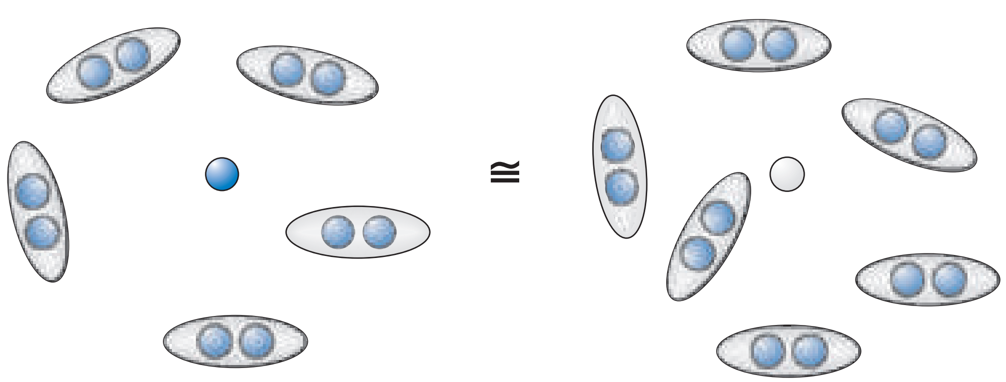
Topological order with symmetry breaking

Unusual collective modes predicted in particle physics

Majorana fermion

Charge neutral

$$\hat{c}^\dagger = \hat{c}$$



F. Wilczek *et al.* Nat. Phys. (2009)

Topological order
+
Superconductivity

Axion

Anomalous magnetoelectric effect

$$\mathbf{M} = -(e^2/4\pi\hbar c)\theta\mathbf{E}$$

$$\theta : \text{axion field}$$

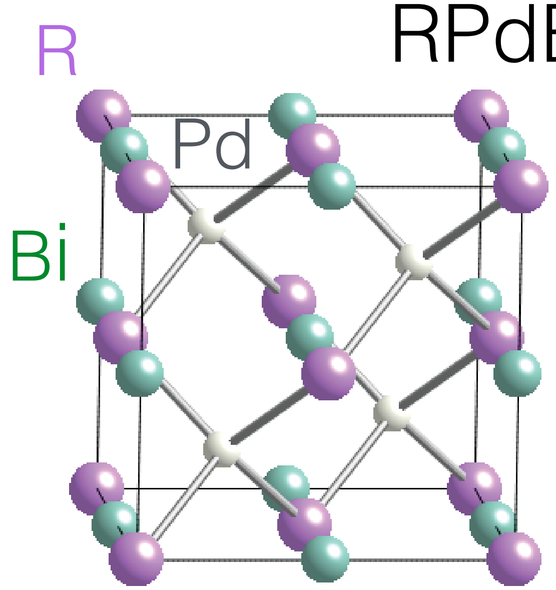
R. Li *et al.* Nat. Phys. (2010)

Topological order
+
Magnetism

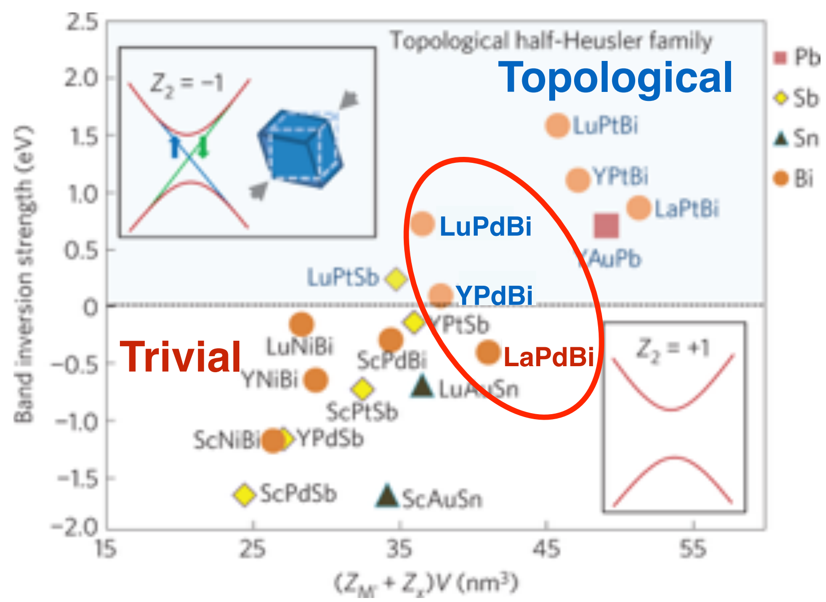
Half Heulser semimetals

Cubic MgAgAs type

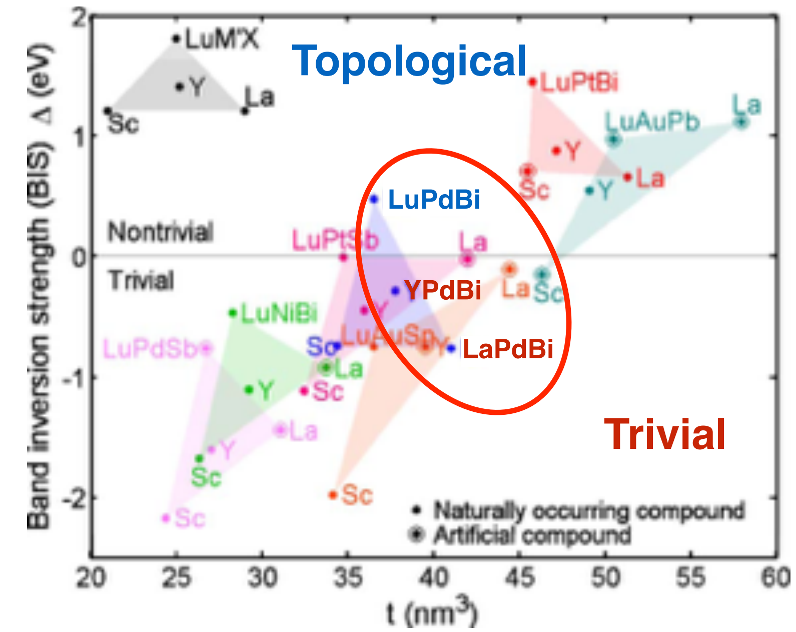
RPdBi



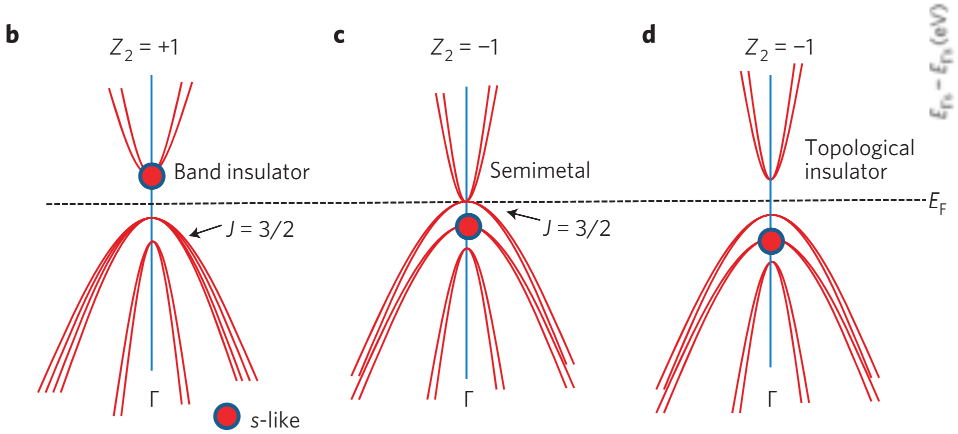
Lack of inversion symmetry



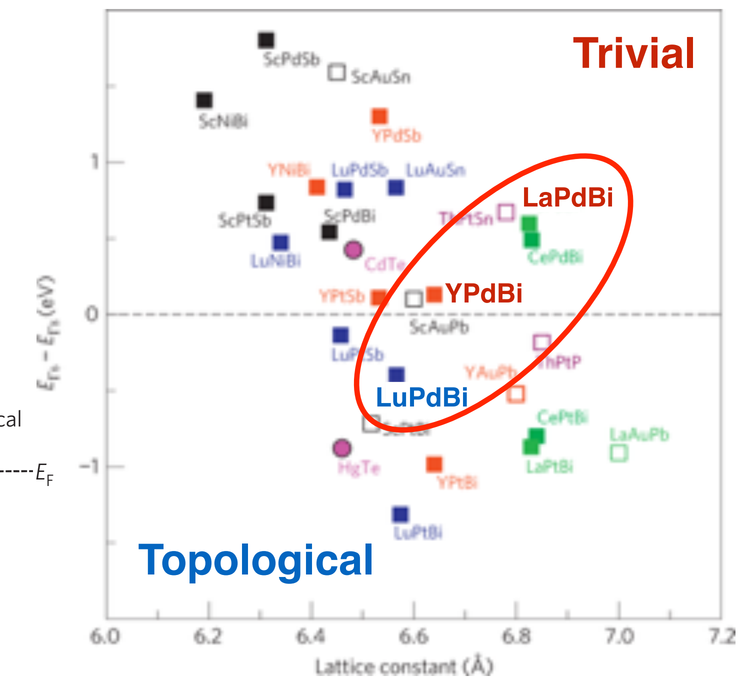
Lin *et al.* Nat. Mat. (2010)

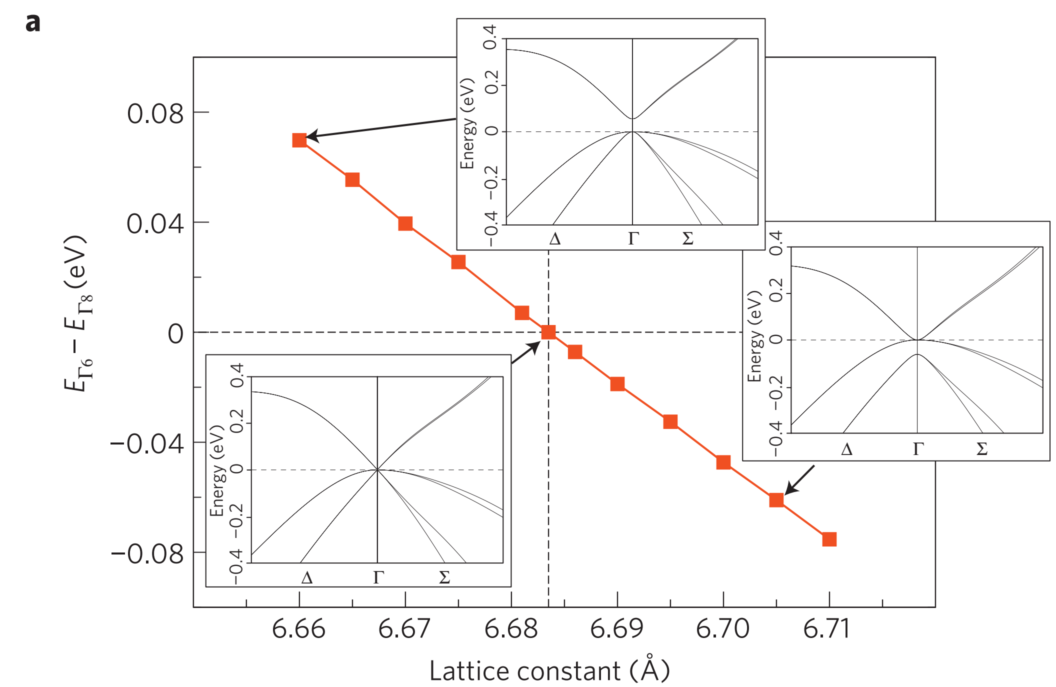


Al-Sawai *et al.* PRB (2010)



Lin *et al.* Nature material (2010)





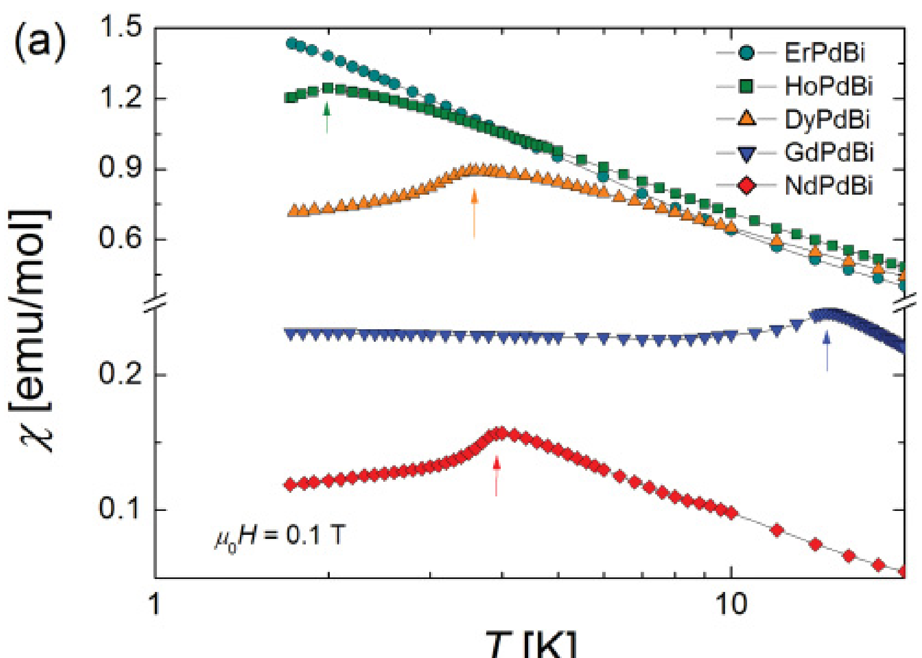
S. Chadov *et al.* Nature Material (2010)

At the border between trivial and topological states

Rare earth based RPdBi

RPdBi: Promising tunable topological materials with (multi-)symmetry breaking

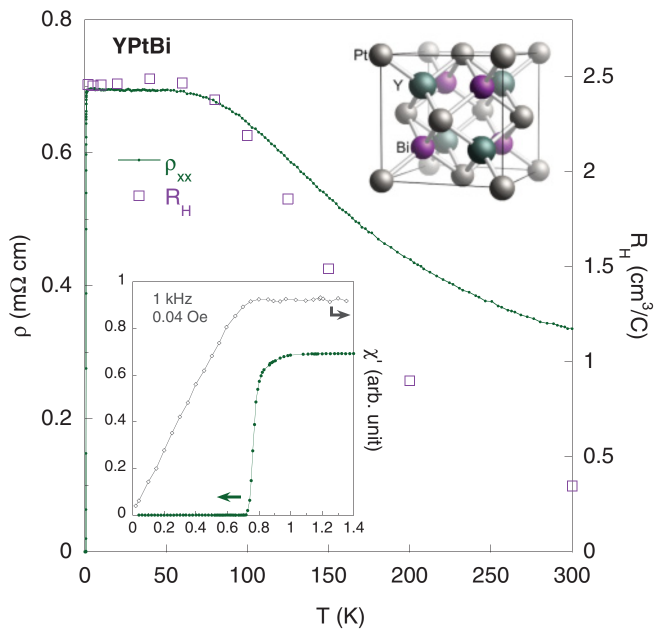
Antiferromagnetism



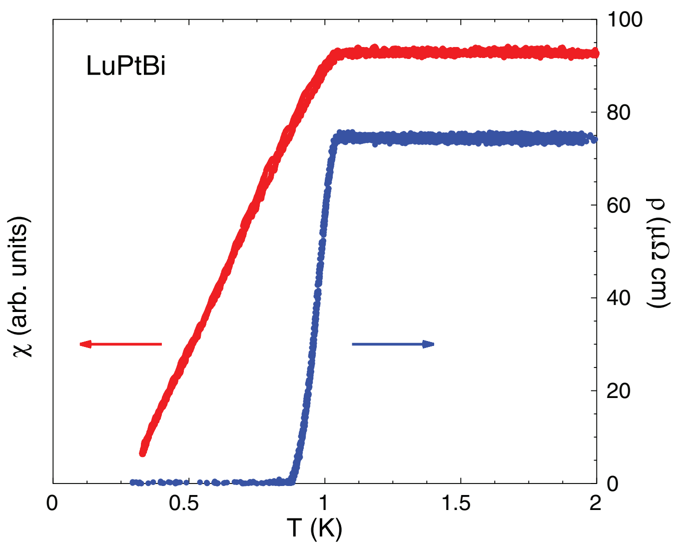
K. Gofryk *et al. PRB* (2011)

Superconductivity

YPtBi



LuPtBi



N. Butch *et al. PRB* (2011)

F. Tafti *et al. PRB* (2013)

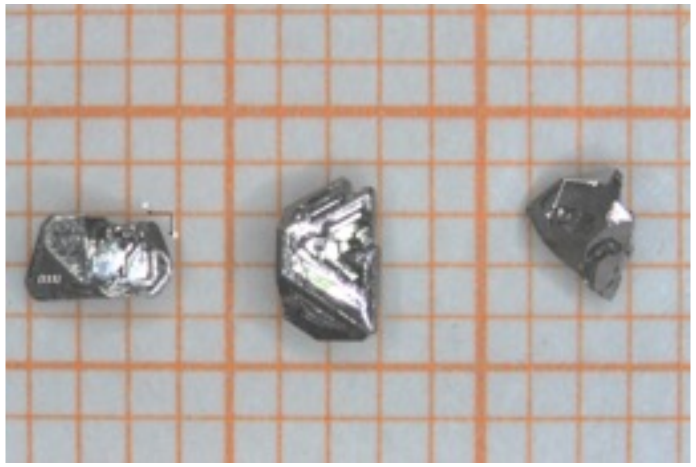
RPdBi
polycrystalline samples

RPtBi
single crystal

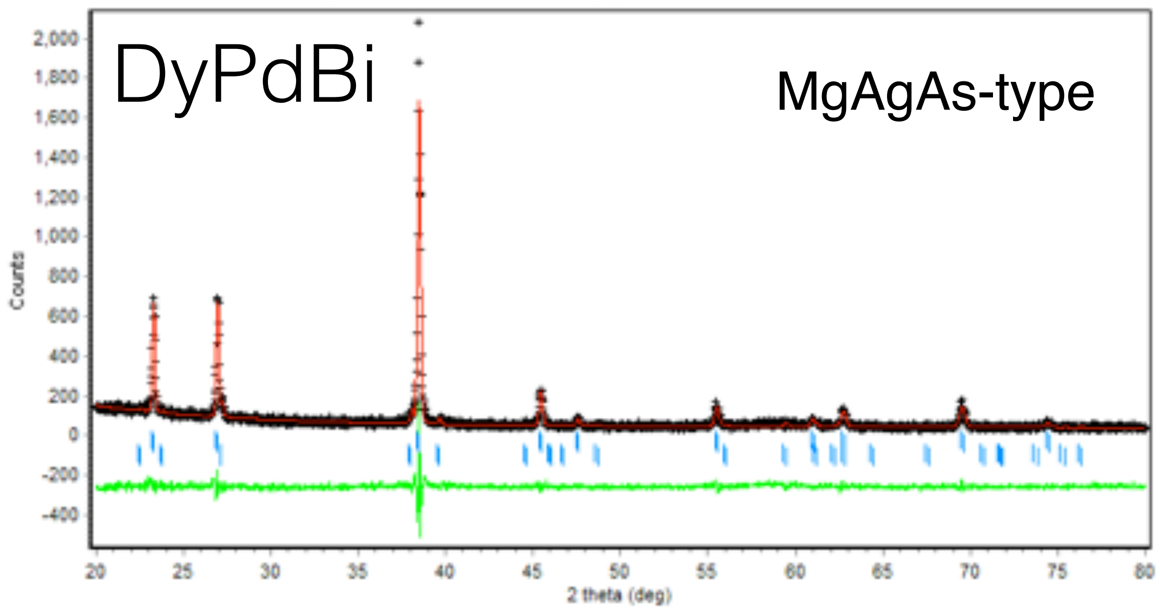
Sample preparation

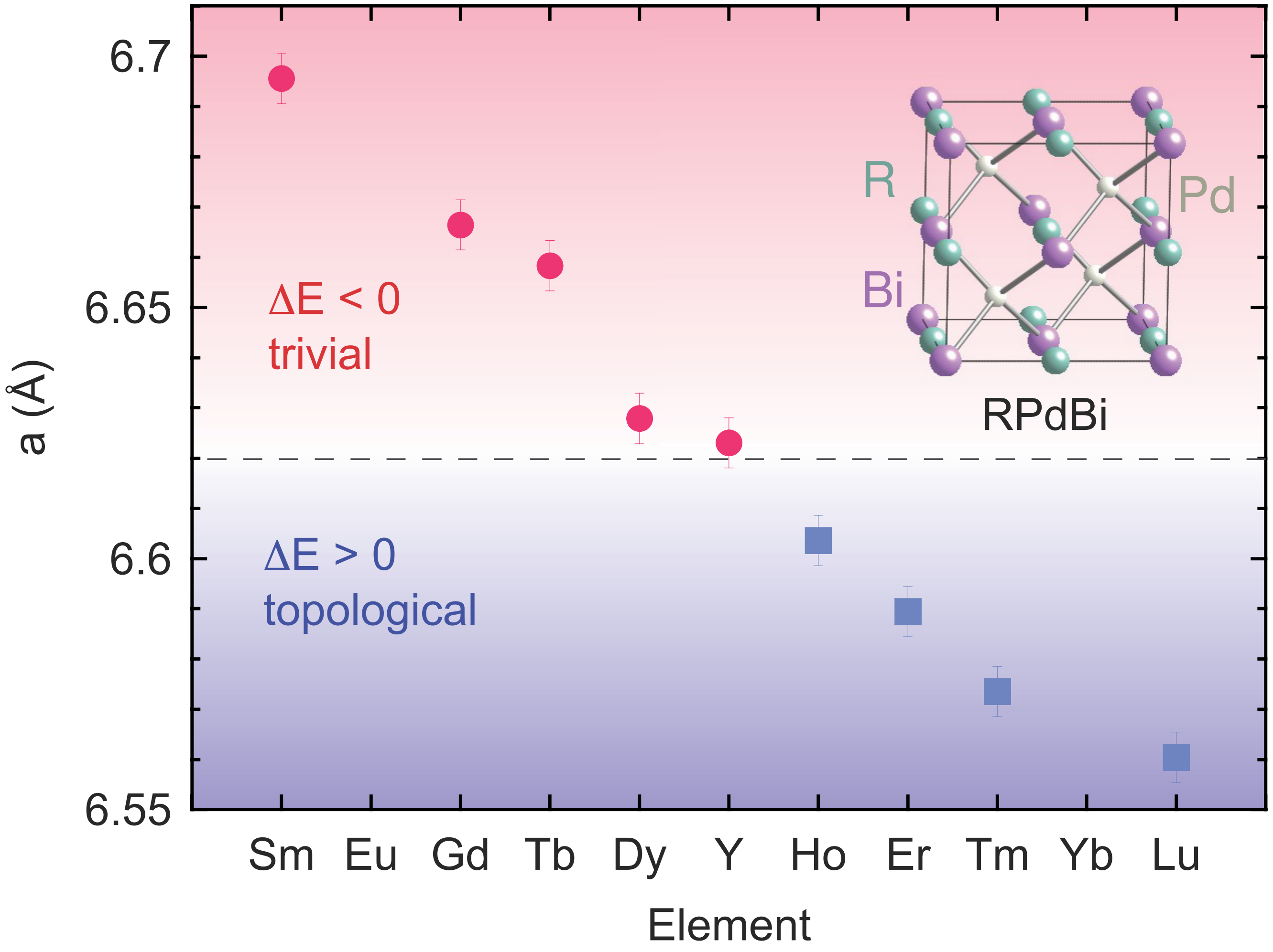
Single crystal

Self-flux method   R : Pd : Bi = 1 : 1 : 5 -10



1 mm

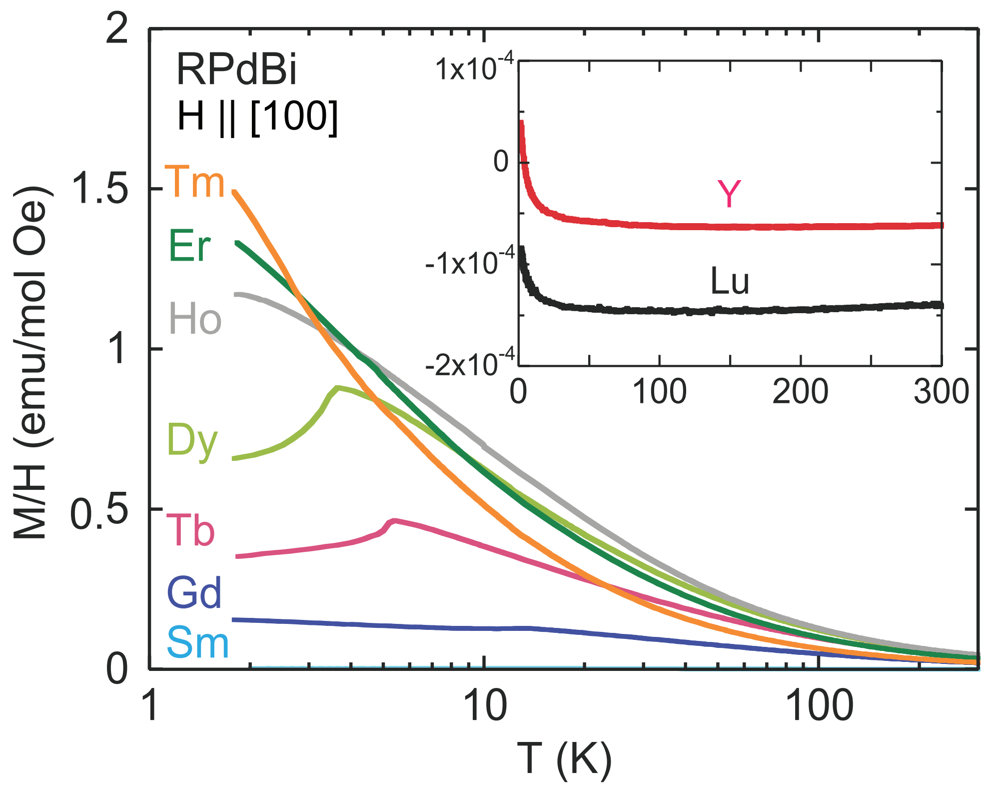


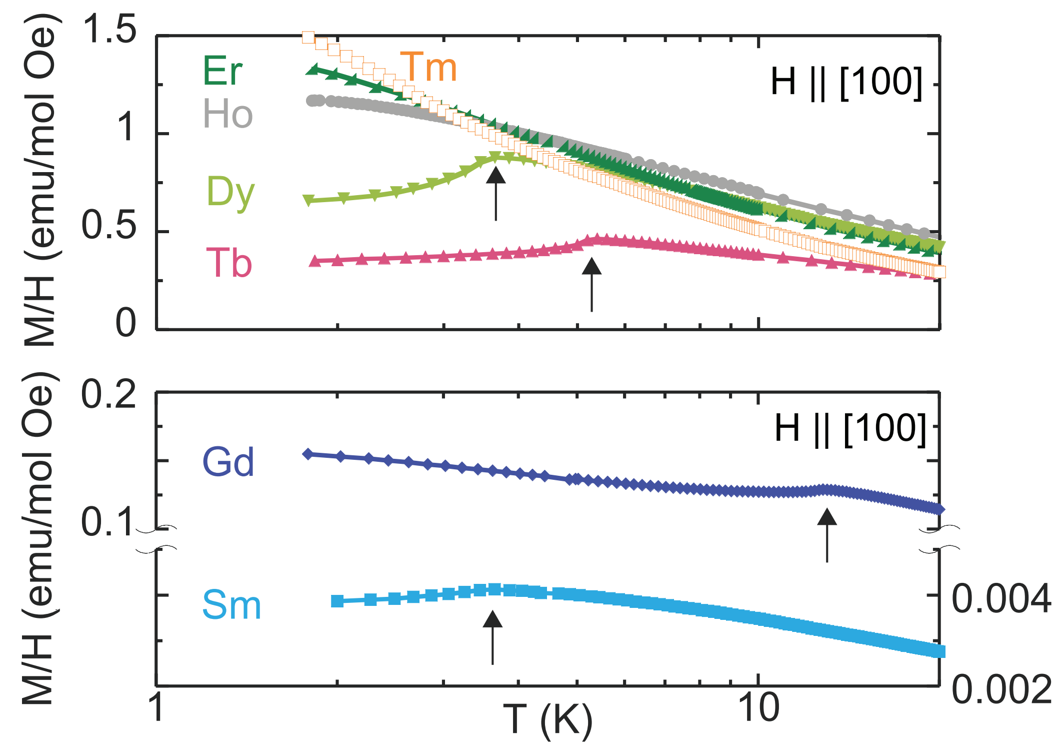


$a_c = 6.62$ Å

S. Chadov *et al.* Nat. Mat. (2010)

Magnetic susceptibility





R	T_N (K)	Θ_W (K)	μ_{eff} (μ_B)	μ_{free} (μ_B)
Sm	3.4	-258	1.9	0.85
Gd	13.2	-49.6	7.66	7.94
Tb	5.1	-28.9	9.79	9.72
Dy	2.7	-14.3	10.58	10.65
Ho	1.9	-9.4	10.6	10.6
Er	1.0	-4.8	9.18	9.58
Tm	<0.4	-1.7	7.32	7.56

Currie-Weiss behavior $\frac{M}{H} = \frac{C}{T - \Theta_W}$

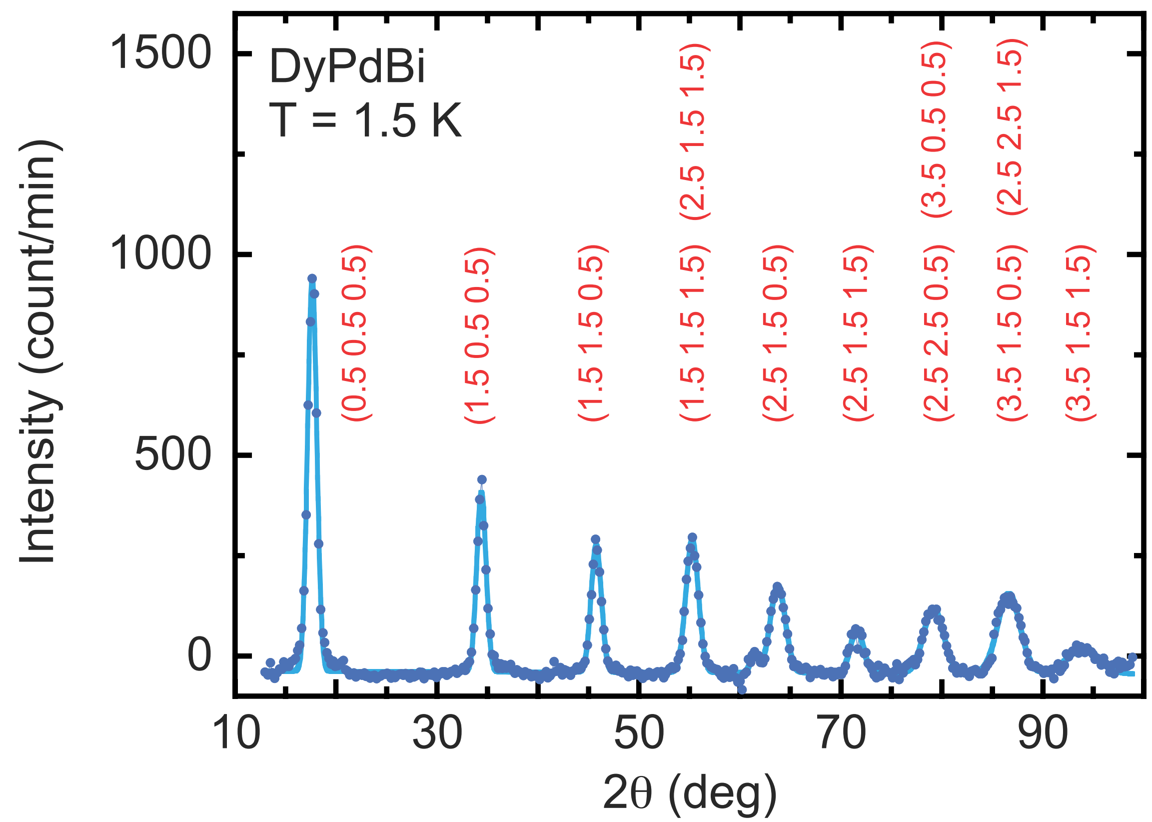
Θ_W: Weiss temperature

f electrons: well-localized

Low temperature anomaly associated with AFM

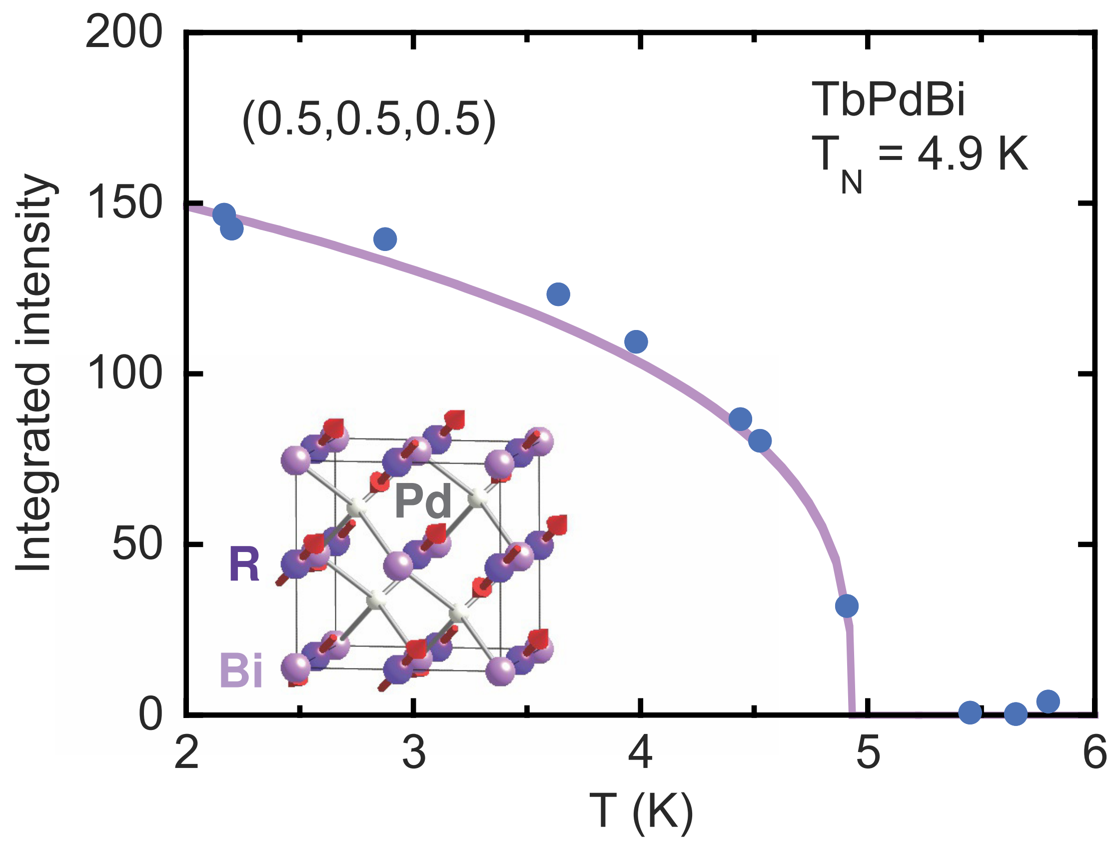
Neutron diffraction

Magnetic Brag peak



fcc type-II AFM

Order parameter

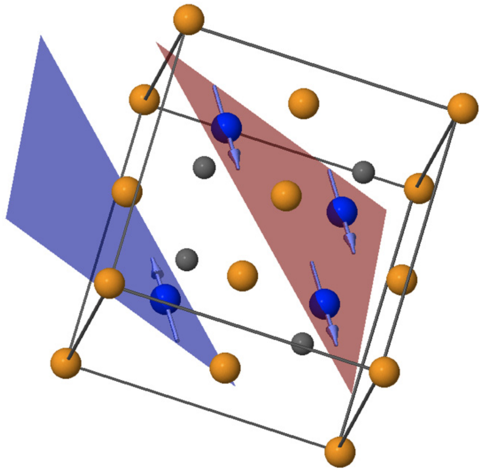


Q = (1/2,1/2,1/2)

Topological AF insulator?

R. Mong *et al.* *PRB* (2010)

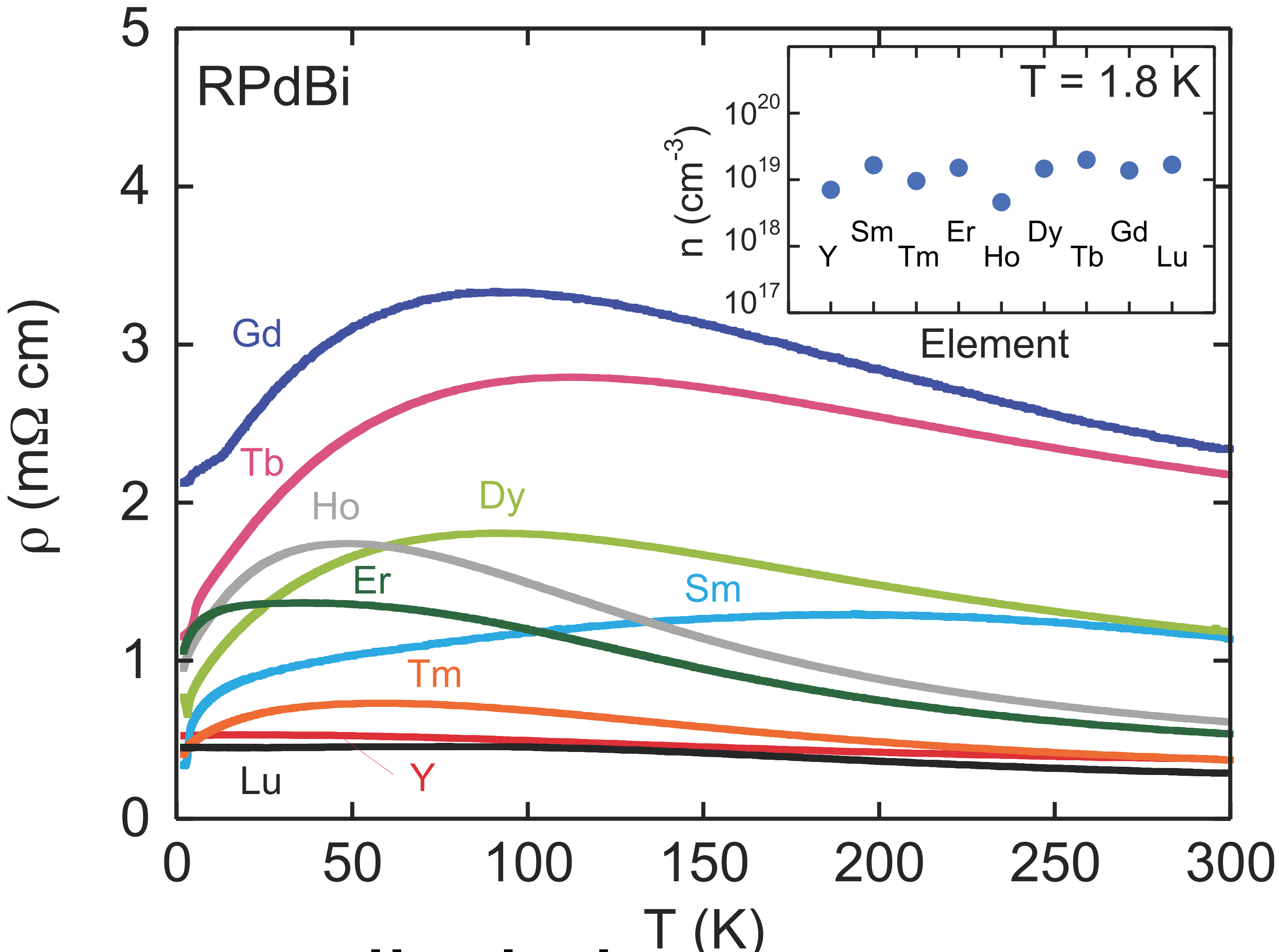
R. Muller *et al.* *PRB* (2014)



Ho, Tb

the same magnetic structure

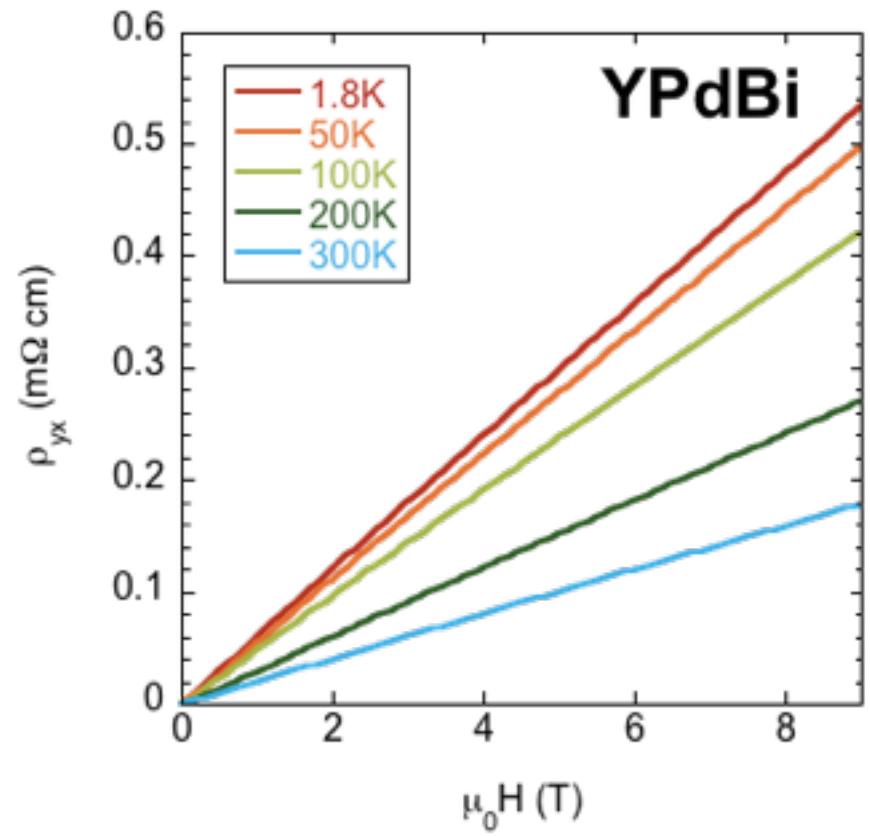
Charge transport



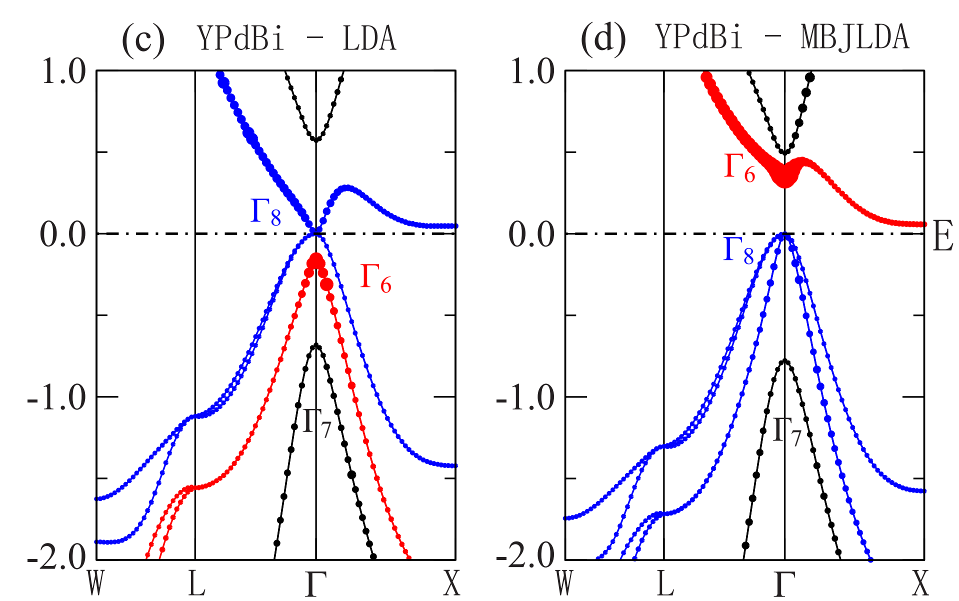
Semi-metallic behavior

$n \sim 10^{19}$ cm^{-3}

Consistent with band calculations



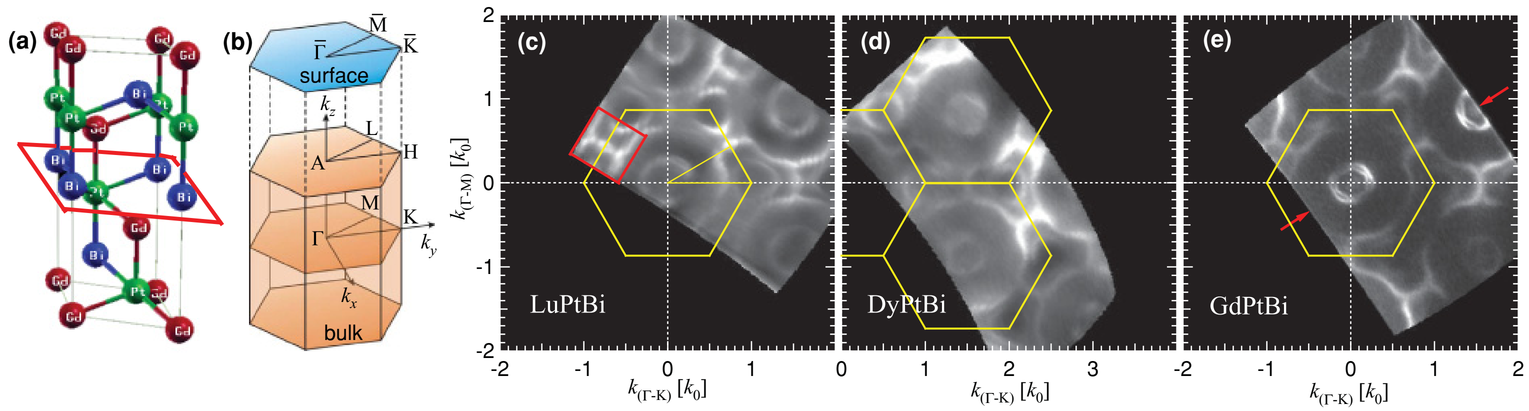
Carrier: Hole



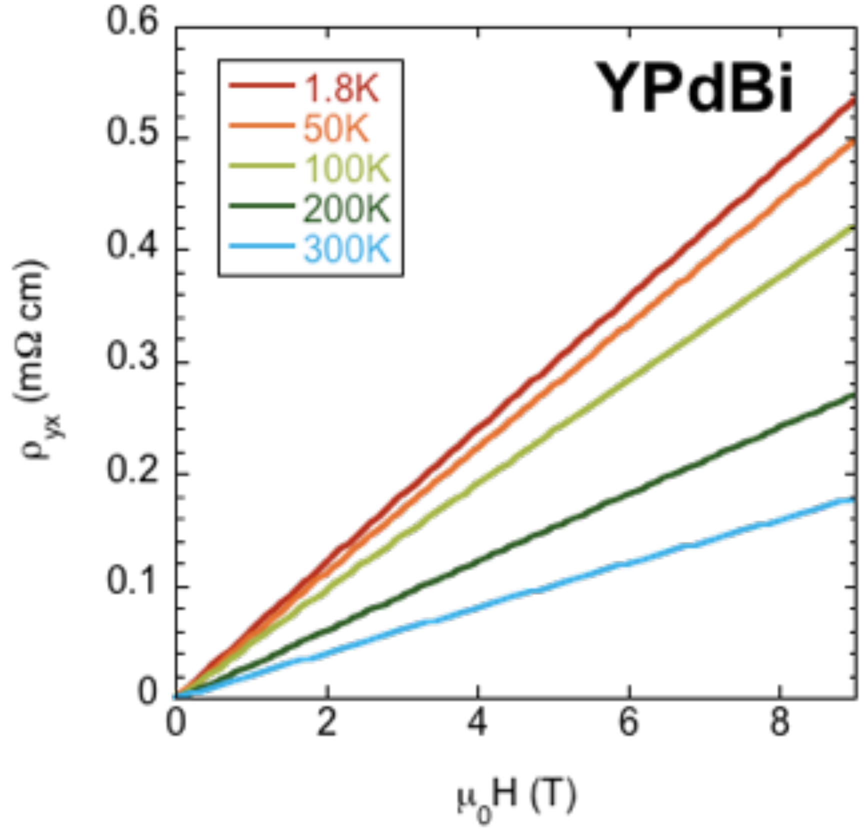
Feng *et al.* PRB (2010)

Charge transport

Surface Fermi surface in RPtBi



C. Liu *et al.* PRB (2011)



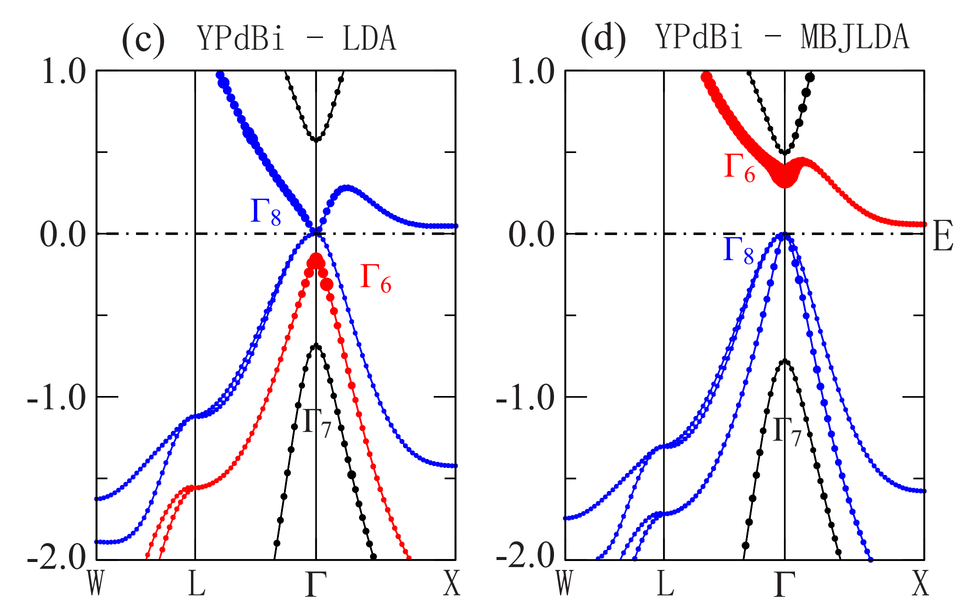
not inconsistent with TI properties

Carrier: Hole

Semi-metallic behavior

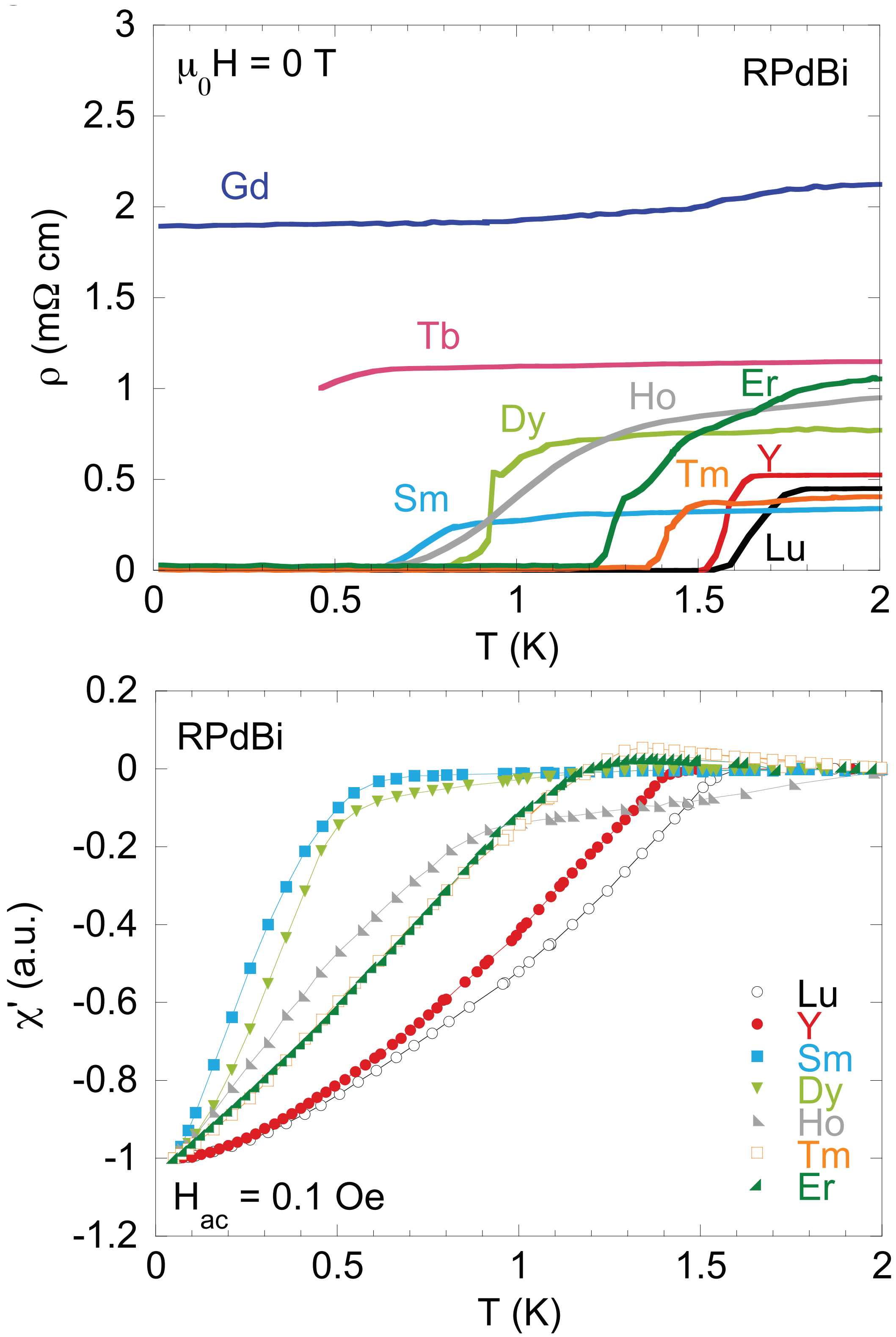
n ~ 10^{19} cm^{-3}

Consistent with band calculations



Feng *et al.* PRB (2010)

Superconductivity



Low temperature

Superconductivity except for Gd

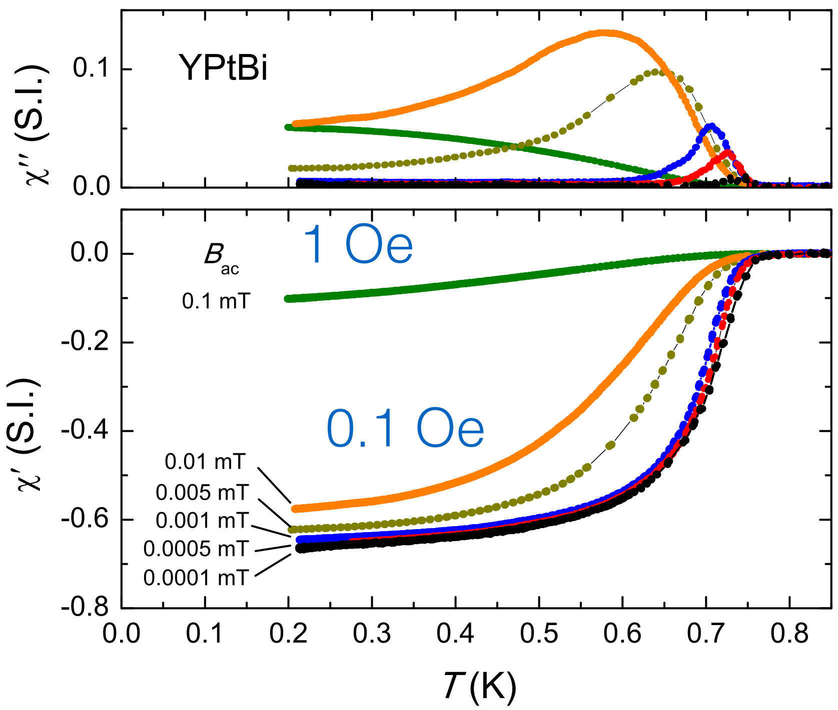
Large but non-saturating screening

Extremely small H_{c1}

Extremely long penetration depth due to low carrier density

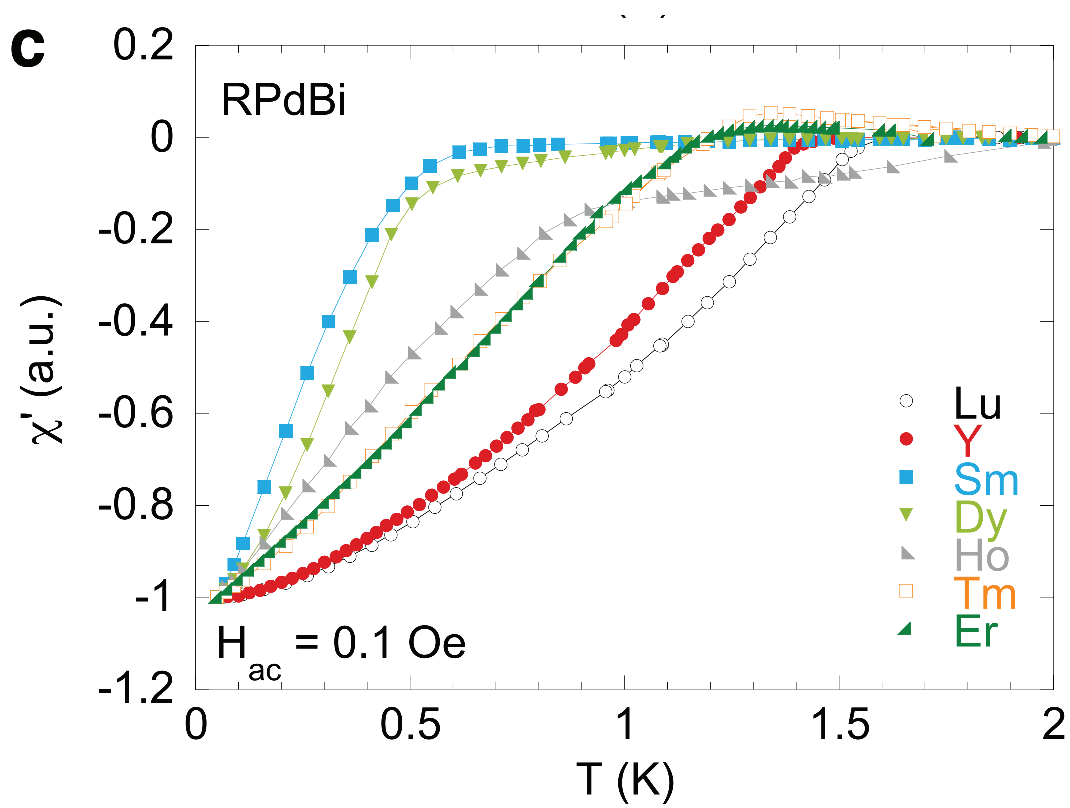
$$H_{c1} \propto \lambda^{-2} \qquad \lambda \propto \sqrt{\frac{m}{n}}$$

Superconductivity



Huge field dependence of magnetic susceptibility

T.V. Bay *et al.* Solid State Commun. (2014)



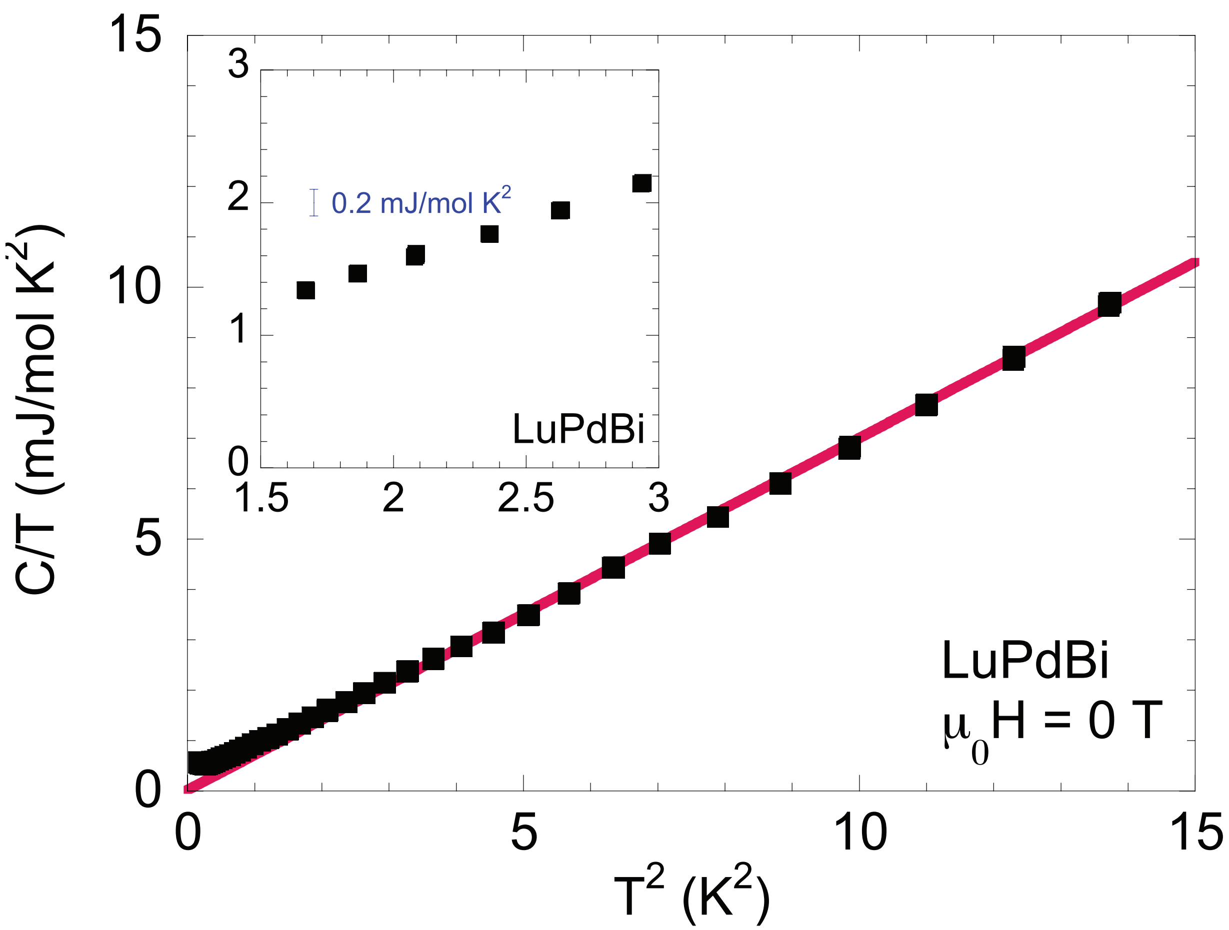
Large but non-saturating screening

Extremely small H_{c1}

Extremely long penetration depth due to the low carrier density

$$H_{c1} \propto \lambda^{-2} \quad \lambda \propto \sqrt{\frac{m}{n}}$$

Lack of heat capacity jump



$$C/T = \gamma_n + \beta T^2$$

$$\gamma_n = 0.0 \pm 0.5 \text{ mJ/mol K}^2$$

Low carrier density

$$n \sim 10^{19} \ cm^{-3}$$

$$m^* \sim 0.09 m_e$$

W. Wang *et al.* Sci. Rep. (2013)

$$\Delta C/\gamma_n T_c = 1.43$$

$$\Delta C/T < 0.2 \text{ mJ/mol K}^2$$

beyond the resolution

Dominant triplet pairing?

A1 phase of superfluid ^{3}He

D.Vollhardt and P.Wolfle,
The Super fluid Phases of Helium 3 (1990)

Non-centrosymmetric SC

Superconducting paring function

$$\Psi_{\sigma\sigma'}(\mathbf{k}) = g(\mathbf{k})\chi(\sigma, \sigma')$$

orbital spin

exchange electrons

$$\Psi_{\sigma'\sigma}(-\mathbf{k}) = -\Psi_{\sigma\sigma'}(\mathbf{k})$$

antisymmetric

$$\text{Singlet}: g(-\mathbf{k}) = g(\mathbf{k}), \chi(\sigma', \sigma) = -\chi(\sigma, \sigma')$$

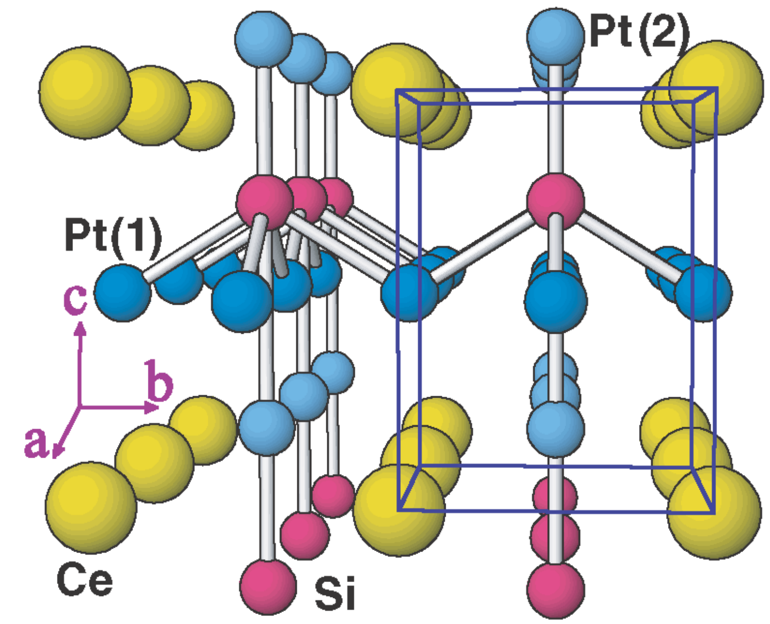
$$\text{Triplet}: \mathbf{g}(-\mathbf{k}) = -\mathbf{g}(\mathbf{k}), \chi(\sigma', \sigma) = \chi(\sigma, \sigma')$$

Lack of inversion symmetry

No restriction of spin parity

Admixture of singlet and triplet

c.f. heavy fermion SC $CePt_3Si$

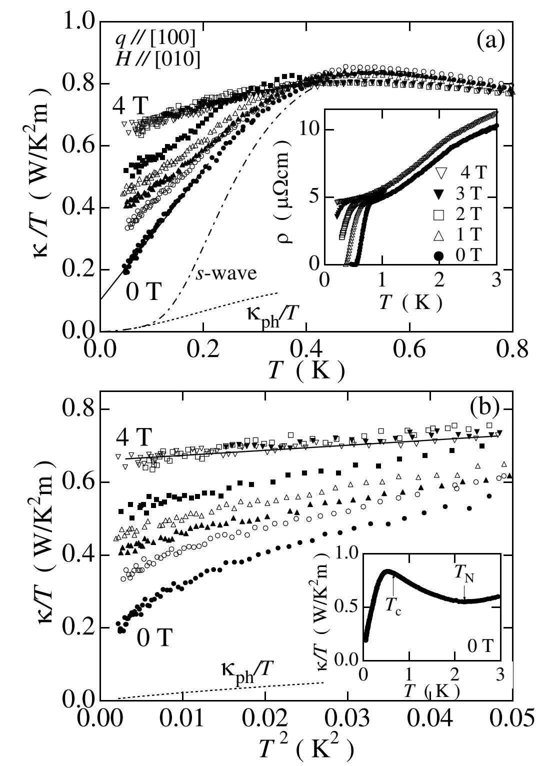


E. Bauer *et al.* PRL (2004)

$$\kappa/T \sim N(E_F)v_F\ell$$

$$\kappa/T \propto T$$

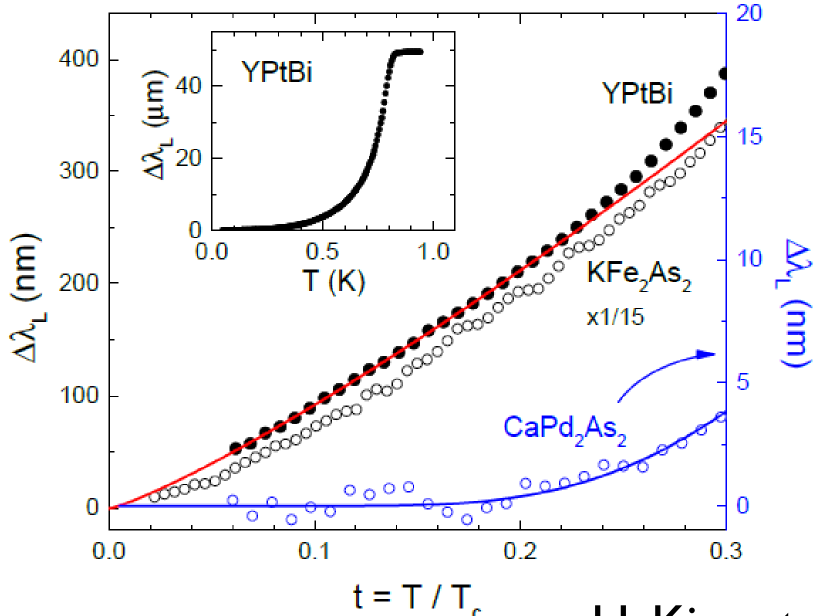
Nodal SC



K. Izawa *et al.* PRL (2005)

Nodal SC in half Heusler

Penetration depth



H. Kim et al., unpublished

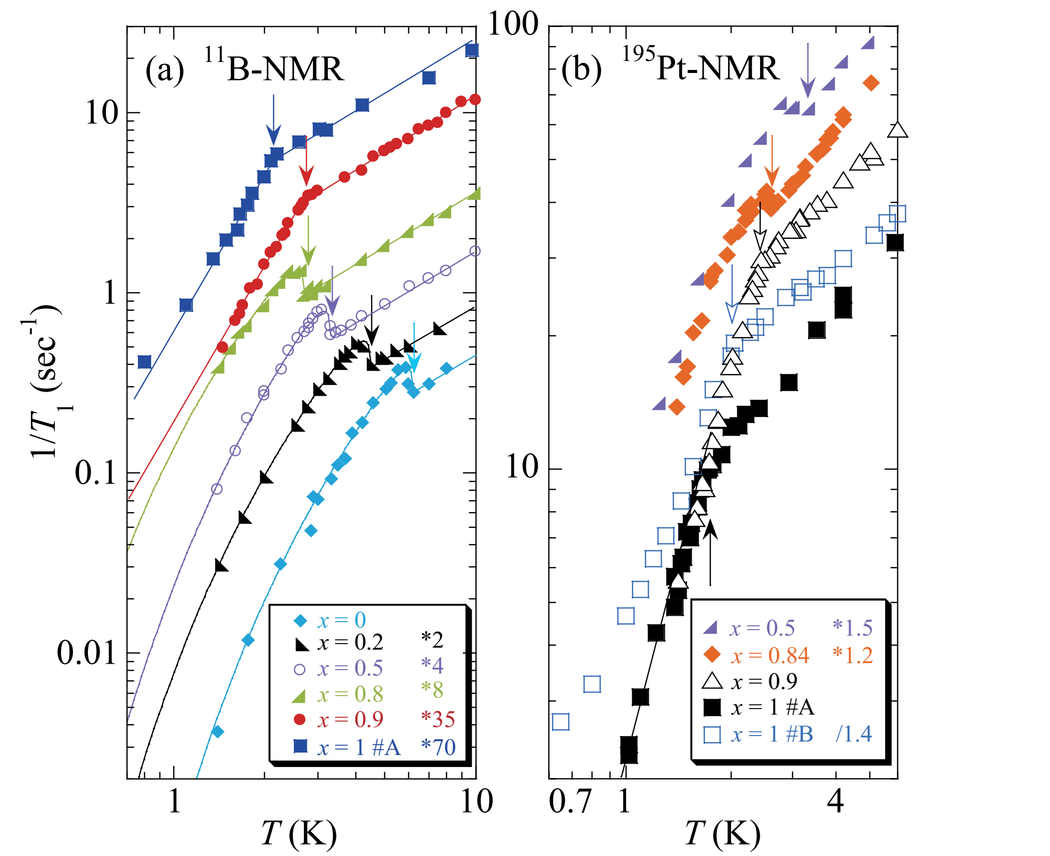
$$\Delta\lambda_L \propto T^{1.2}$$

Nodal SC

YPtBi

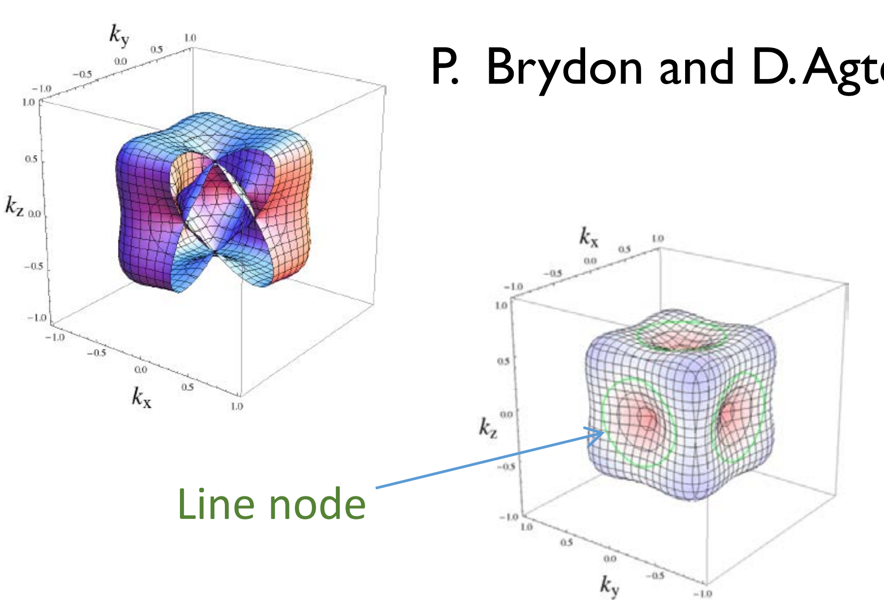
Tuning dominant contribution of singlet/triplet paring states

c.f. $Li(Pd,Pt)_2B_3$ S.Harada *et al.* PRB (2012)



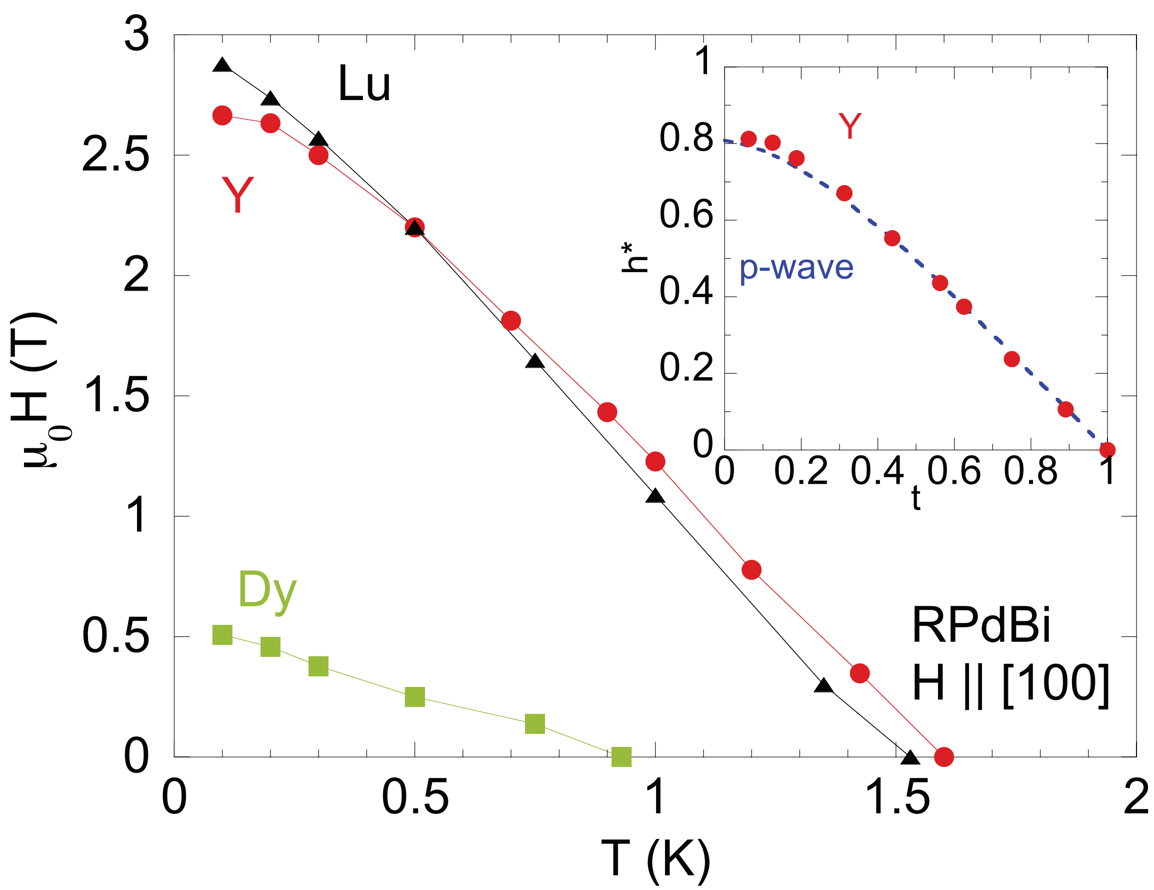
Theoretical Fermi surface

P. Brydon and D. Agterberg, unpublished



UNIVERSITY OF MARYLAND

Finite triplet component



WHH theory N. Werthamer *et al.* PR (1966)

$$H_{c2}(0) = -\alpha T_c \left.\frac{dH_{c2}}{dT}\right|_{T=T_c}$$

$\alpha = 0.69$ dirty SC

$\alpha = 0.74$ clean SC

exceeding of orbital depairing field

YPdBi: $\mu_0 H_{c2}(0)$ = 2.7 T, α = 0.82

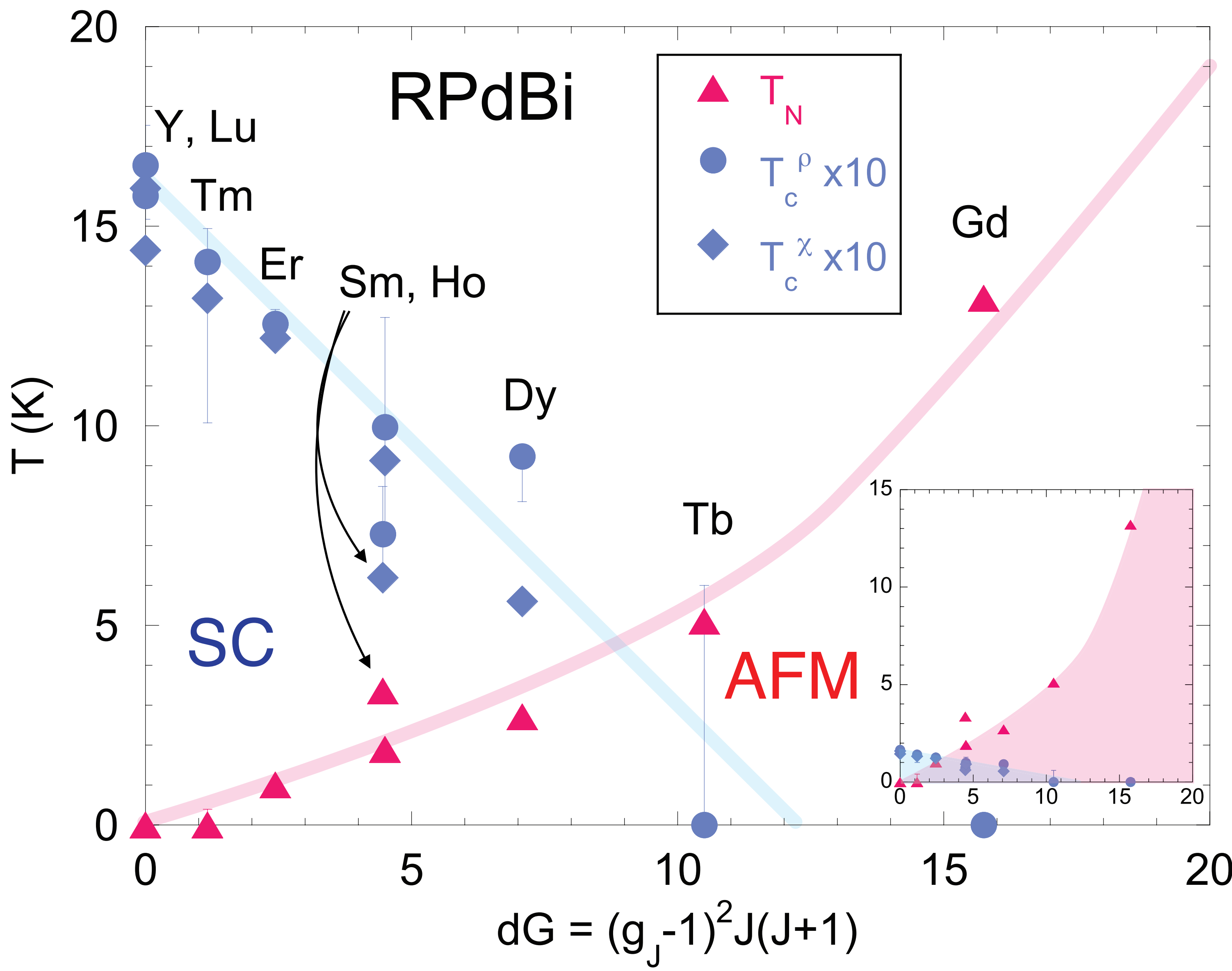
LuPdBi: = 2.9 T, α = 0.91

DyPdBi: = 0.7 T, α = 0.93

Finite triplet component?

Magnetic superconductivity

Anticorrelation between T_C and T_N, well-scaled by de Gennes factor



SC is suppressed by magnetic scattering due to local moments of f electrons

AFM is induced by RKKY interaction

Another canonical material for magnetic superconductor

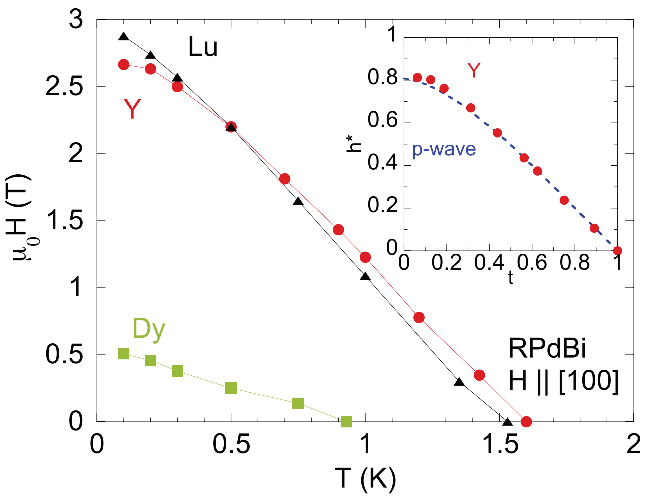
c.f. Borocarbide

H. Müller *et al.* Rep. Prog. Phys. (2001)

Chevrel phases

Φ. Fischer *et al.* Appl. Phys. (1978)

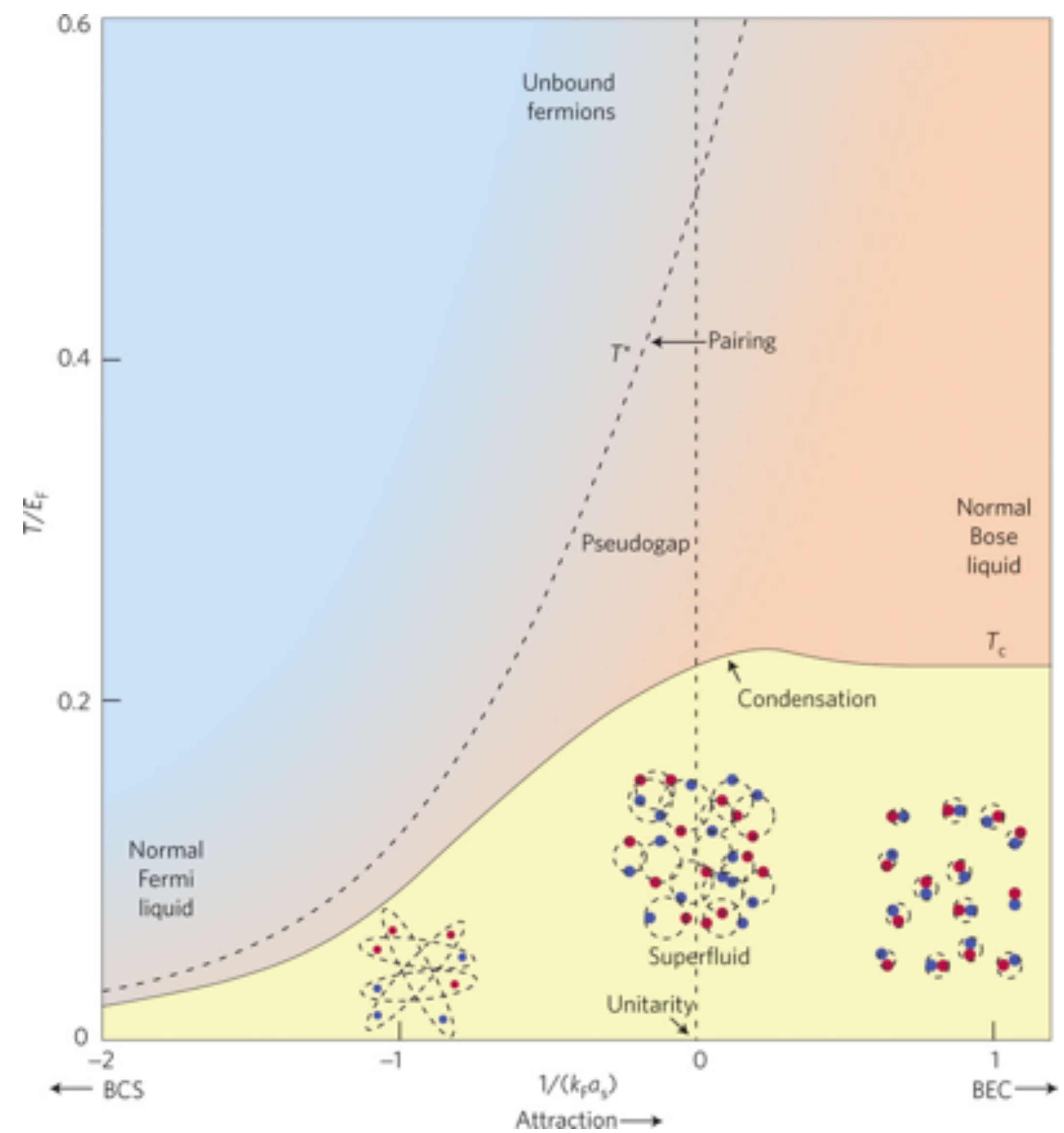
BCS-BEC crossover?



$$H_{c2}(0) = \frac{\phi_0}{2\pi\xi^2}$$

ϕ_0: flux quantum

$\xi \gg d_{e-e}$ $\xi \ll d_{e-e}$



Coherence length

$\xi \sim 10$ nm YPdBi

Average inter-electron distance

$$d_{e-e} \sim n^{-1/3} \sim 5 \text{ nm}$$

$$n \sim 10^{19} \text{cm}^{-3}$$

$$\xi \sim d_{e-e}$$

Exotic superconducting state?

M. Randeria *et al.* Nature Physics (2010)

Summary

We have studied superconductivity and magnetism in the topological half semimetal RPdBi.

- fcc type II AFM with Q = (1/2, 1/2, 1/2)
- Anticorrelation between T_c and T_N, well-scaled by de Gennes factor
- Anomalous SC: Triplet dominant? BCS-BEC crossover?

Strong candidate for tunable topological materials with multi-symmetry breaking

Combination of topological and symmetry-breaking order

	SC	AFM	Topo
Y	✓	✗	✗
Lu	✓	✗	✓
Tm	✓	✓(?)	✓
Er	✓	✓	✓
Sm	✓	✓	✗
Ho	✓	✓	✓
Dy	✓	✓	✗
Tb	✓(?)	✓	✗
Gd	✗	✓	✗