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Thermodynamic and transport experiments on the ground state of strongly correlated electron systems

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Gandia, April 2024

Thanks to my group and collaborators

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Complexity and Topology in Quantum Matter

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Research group

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erc
CoG

TU Dresden Technical University

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Population 580 000

Our research

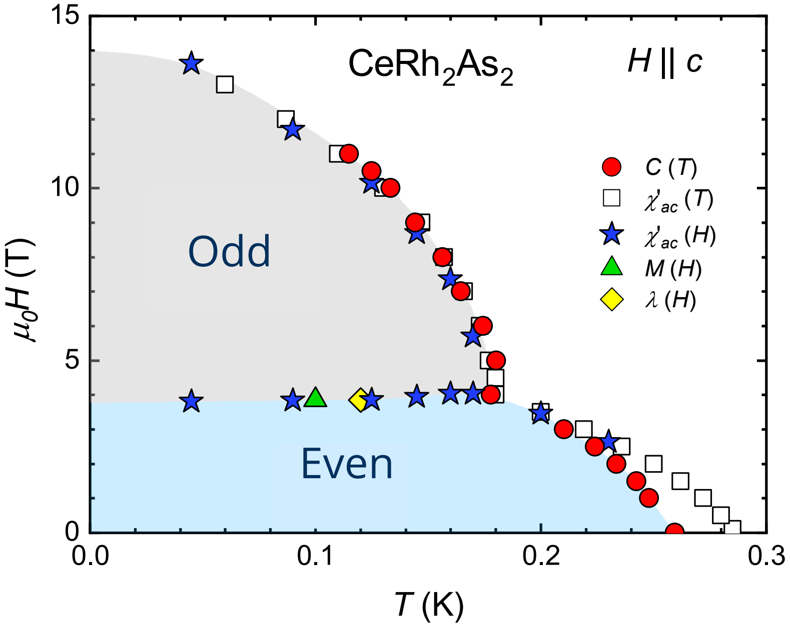
Research goal

Find and explore exotic states in bulk crystals

Unconventional metals, magnets and superconductors

Topological states

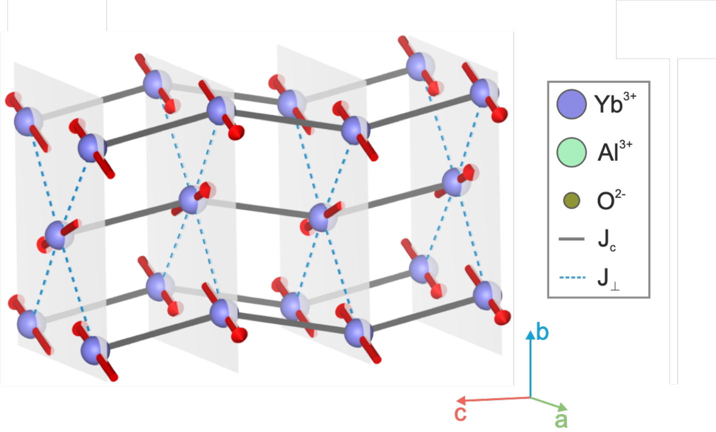
2 Postdoc positions in December!



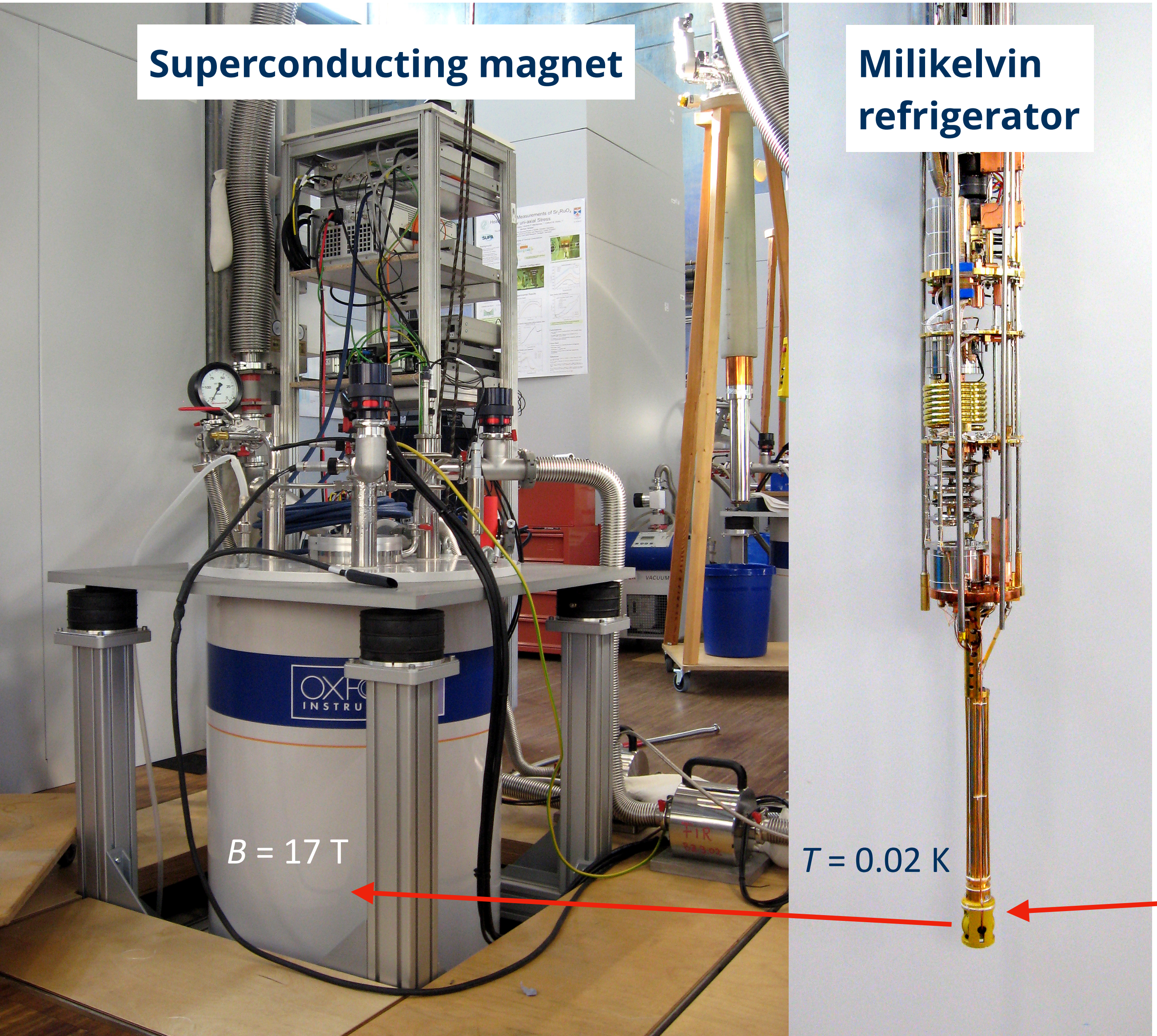
S. Khim, J. Landaeta, ..., E. Hassinger, Science (2021)

YbAlO$_3$

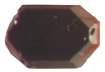
Quasi- 1D spin chain



Experimental techniques



Sample



0.5 mm

High sensitivity bulk techniques

Magnetic ac-susceptibility χ (20 mK - 300 K, 18 T)

Electrical transport ρ (20 mK - 300 K, 18 T)

Thermal transport κ (30 mK - 300 K, 8 T)

Quantum oscillations

In extreme conditions

Low temperature

0.02 K - 300 K

High magnetic field

17 T + high-field labs

High pressure

Piston cylinder technique, 3 GPa (ρ,χ)

Uniaxial pressure (ρ,χ)

Why study strongly correlated electron systems?

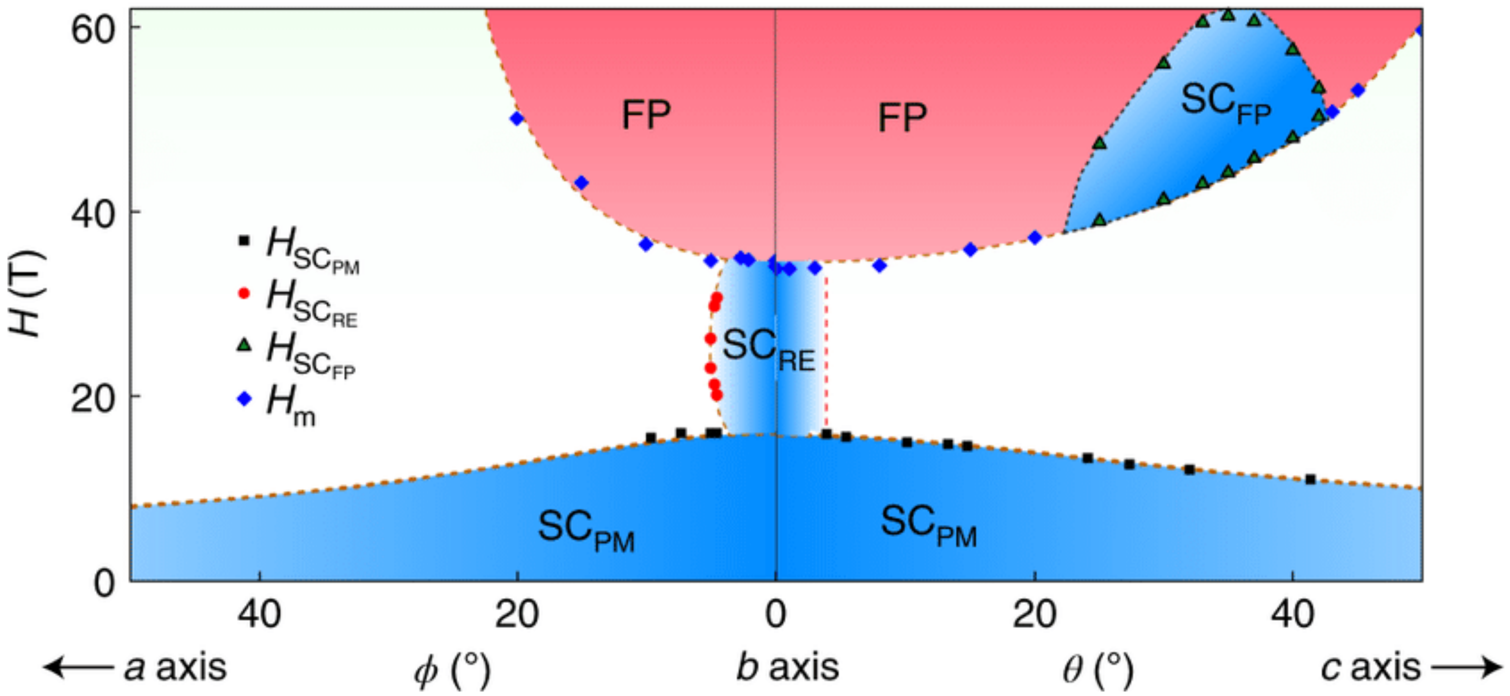
Present highly interesting unconventional properties:

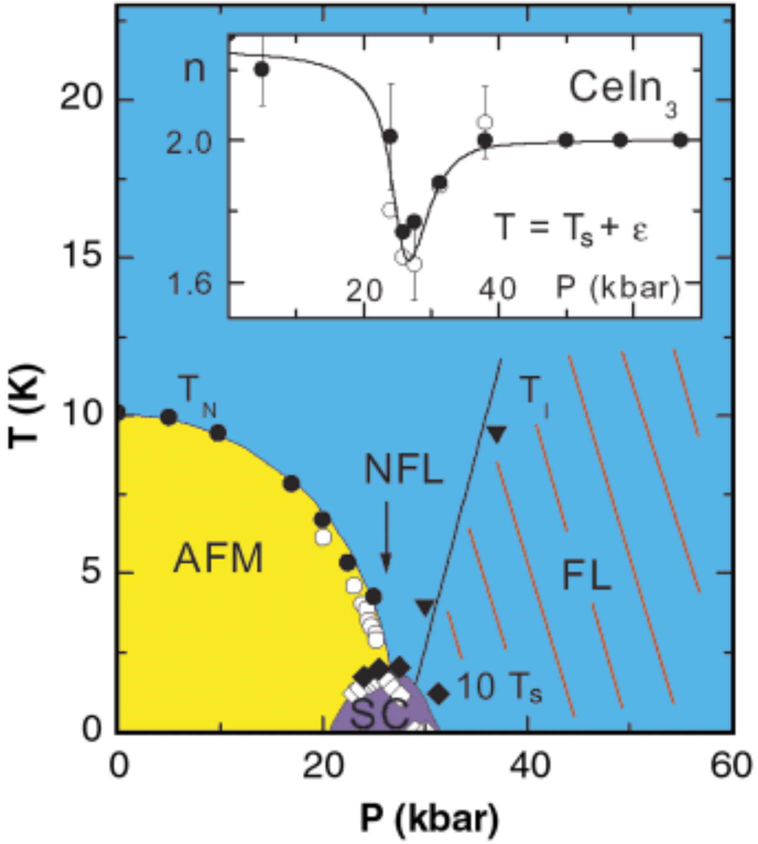
Superconductivity at the border of magnetic phases

Non-Fermi liquid behaviour near quantum critical points

Odd-parity (possibly topological) unconventional superconductivity

Recently discovered examples: UTe$_2$, CeRh$_2$As$_2$





Knebel et al. PRB 2001

Ran et al. Nat. Phys. 2019

Outline

Underlying question: What can we learn from thermodynamic and transport experiments about the ground state of correlated electron systems?

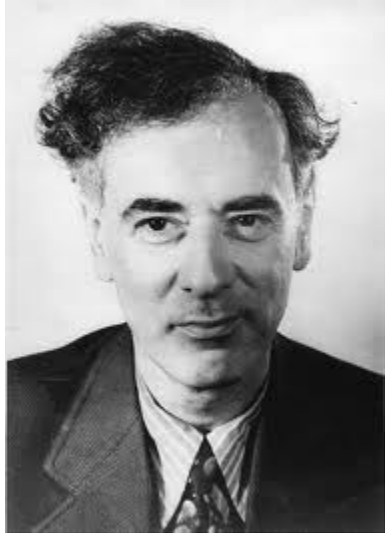
1. Basics on Fermi liquids
2. Extreme case of strong interactions: Heavy-fermion systems, prototype materials to study quantum criticality, example $CeRh_2As_2$
3. Superconductivity in a locally non-centrosymmetric system, example $CeRh_2As_2$

Learning outcomes

After hearing this lecture, you will be able to

- Interpret experimental results from some of the macroscopic experimental techniques
- Explain the competition of Kondo effect and RKKY interaction
- Relate the thermodynamic and transport properties to the ground state
- Recognise properties of locally non-centrosymmetric superconductors

Fermi liquid theory



- Lev Davidovich Landau 1956
- Observation: ^{3}He behave like a free fermion gas
- Interactions are taken into account by introduction of an effective mass
- Quasiparticles are N-particle excitations with same charge and spin as free particles
- Describes normal state of most metals at low temperature

Free electron gas

$$c_V = \frac{\pi^2}{3} k_B^2 N\left(\varepsilon_F\right) T = \gamma_0 T.$$

Fermi liquid: specific heat

$$\frac{C}{T} = \gamma_0 \frac{m^*}{m}. \qquad \frac{m^*}{m} = 1 + \frac{1}{3} F_1^s$$

Magnetic susceptibility

$$\chi = \chi_0 \frac{m^*}{m} (1/(1 + F_0^a))$$

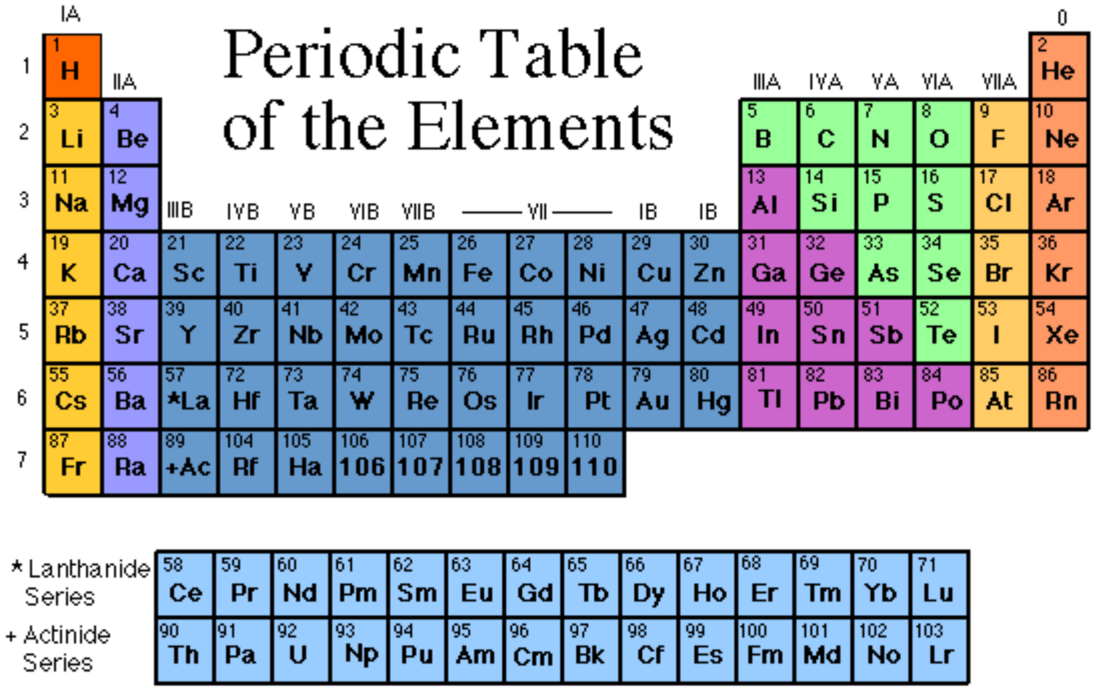
Pauli susceptibility

Fermi temperature is lowered

$$T_{\mathrm{F}} \propto \frac{1}{m^*}$$

Heavy Fermion systems

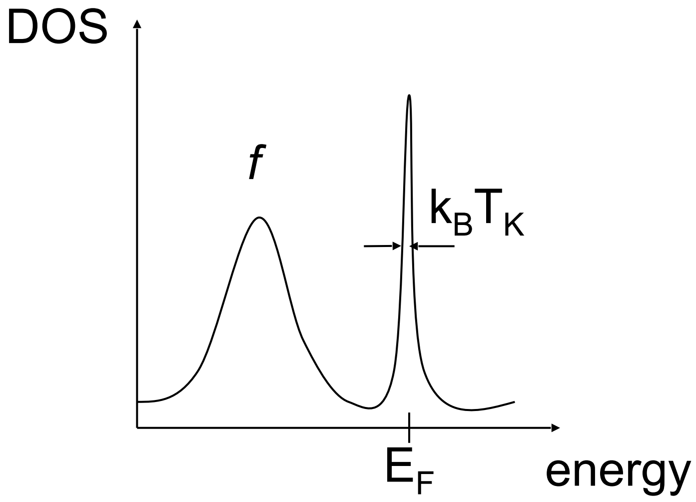
- Typically Ce or Yb intermetallic compounds (discovered 1975 $CeAl_3$)
- 4f shell is partly filled => local magnetic moments
- Strong interaction between f electrons and conduction electrons via Kondo effect => hybridization => large density of states at the Fermi level
- Extreme examples of Fermi liquids, effective masses of 1000 times the free electron mass
- Enhanced specific heat and magnetic susceptibility



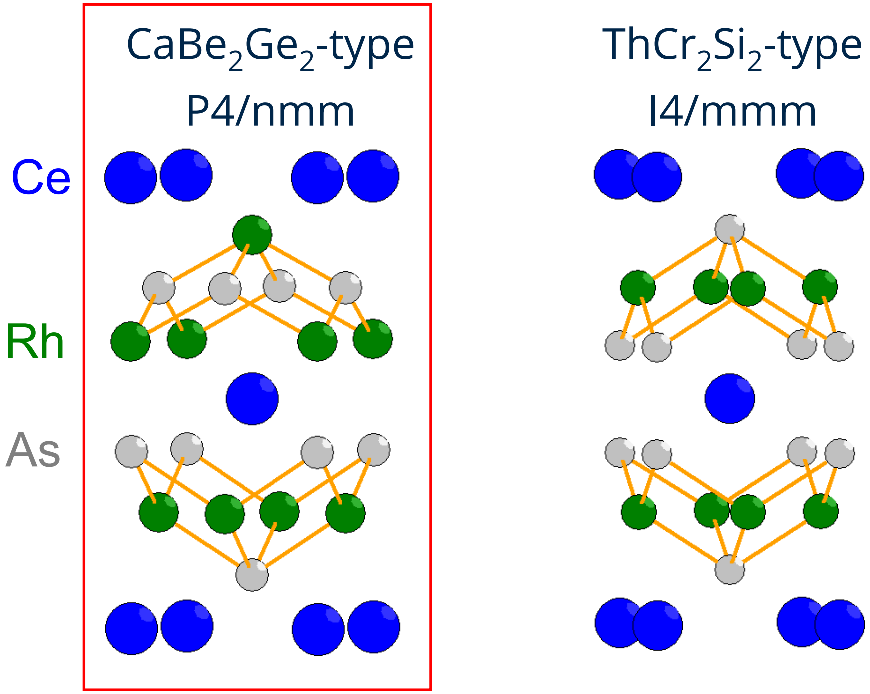
Periodic Table of the Elements

	IA	IIA	IIIB	IVB	VB	VIB	VIIB	——	VII	——	IB	IB	IIIA	IVA	VA	VIA	VIIA	0
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	57 *La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89 +Ac	104 Rf	105 Ha	106 106	107 107	108 108	109 109	110 110								

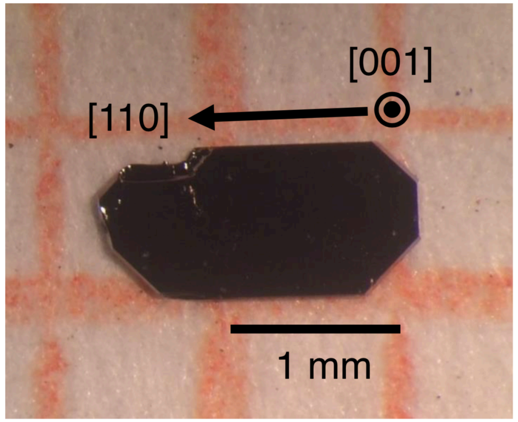
* Lanthanide Series	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
+ Actinide Series	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr



Example material $CeRh_2As_2$


$CaBe_2Ge_2$-type
P4/nmm

$ThCr_2Si_2$-type
I4/mmm



Grown by Seunghyun Khim
using Bi flux

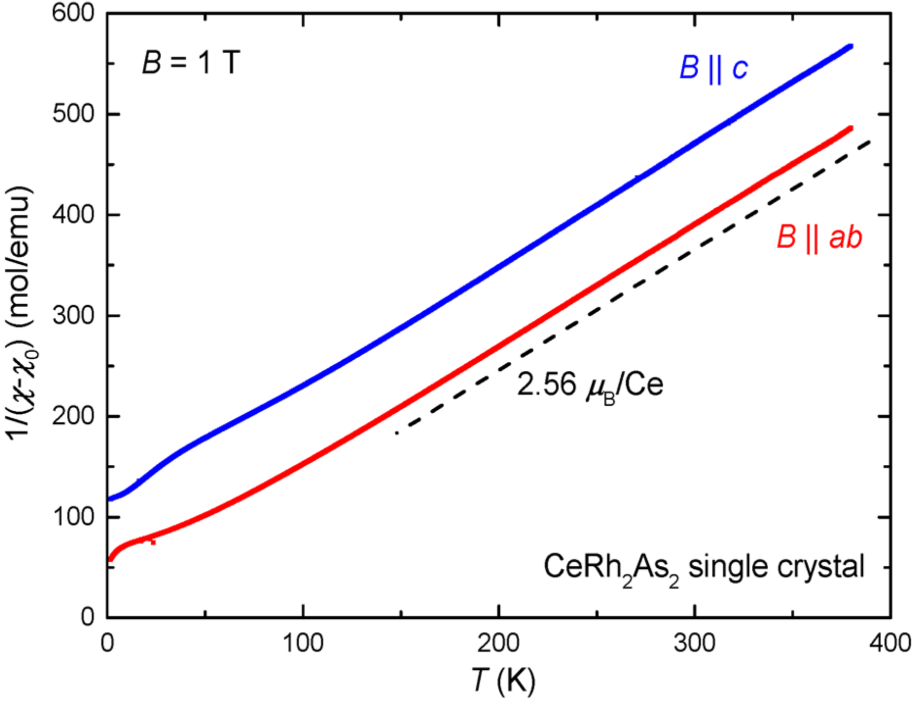
Typical sample dimensions, but
smaller is possible

The structure is not relevant for the explanation of the heavy-fermion behaviour, but for superconductivity

First report by R. Madar *et al.*, J. Less-Common Metals (1987)

Basic properties: Magnetic susceptibility

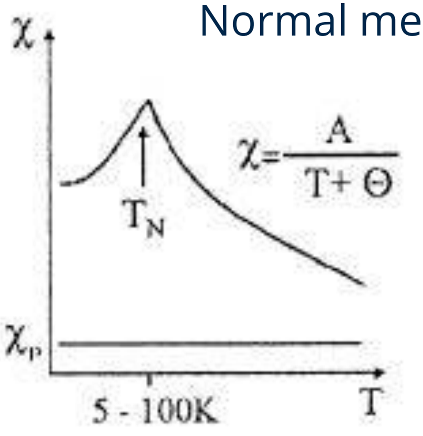
Inverse susceptibility along c and basal-plane



- Ce: 1 electron in the f shell (L = 3, S = 1/2 => J = 5/2)
- for T > 50 K, weakly interacting moments, Curie Weiss
- effective moment very close to Ce^{3+} value
- *f*-electron localised at high temperature as in free atom
- at low T: no evidence for magnetic order, moments are screened by Kondo interaction

→ trivalent Ce system with sizeable *c-f* hybridization

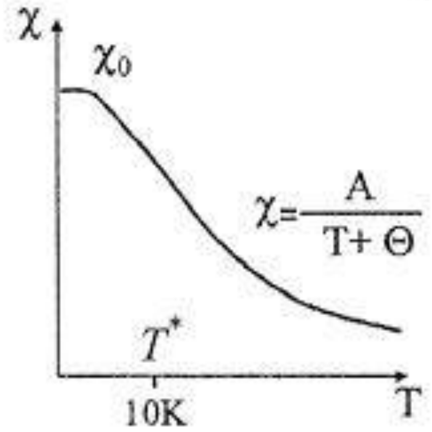
Normal metallic magnet



For antiferromagnets the Curie-Weiss law holds

Néel temperature T_N

$$\chi_{Pauli} = \mu_0 \mu_B^2 N(E_F)$$



Here: No magnetic order

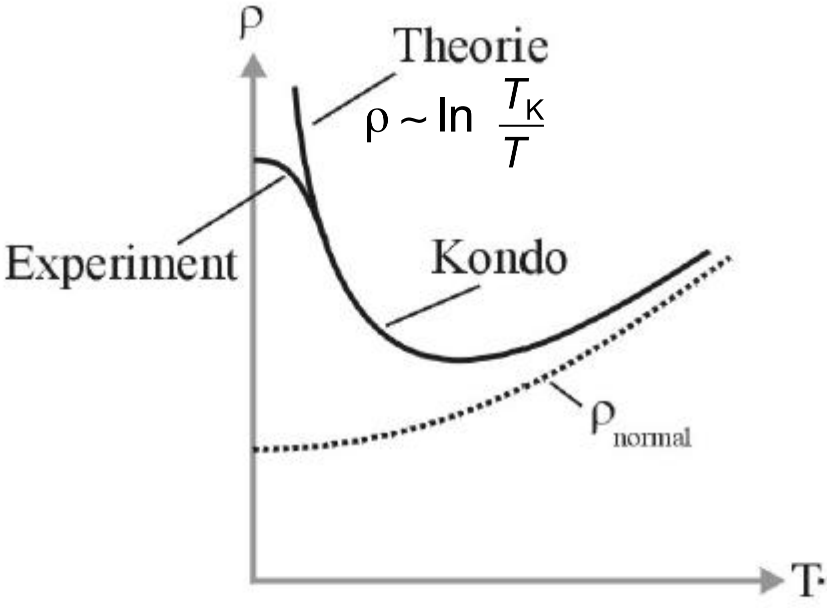
For $T < T^*$: Flat temperature response with high value, Pauli susceptibility of conduction electrons with large density of states at E_F

$$\chi = \chi_0 \frac{m^*}{m} (1/(1 + F_0^a))$$

Kondo Effect

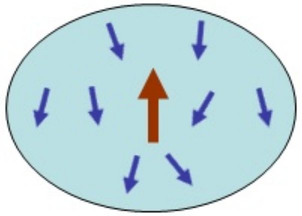
Experimental resistance

(Au with Fe impurities)



Jun Kondo ‘63

explanation



polarization
cloud

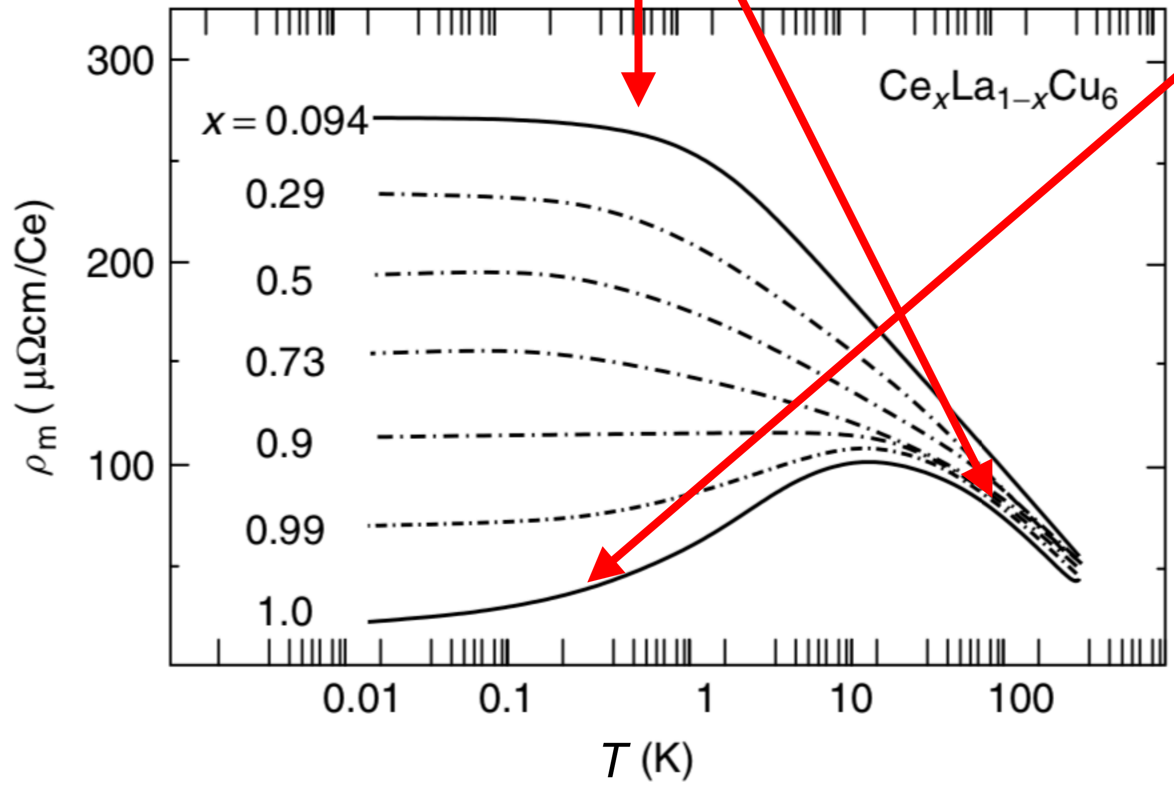
Conduction electrons form screening cloud around magnetic impurity
Local moments are screened
Non-magnetic ground state

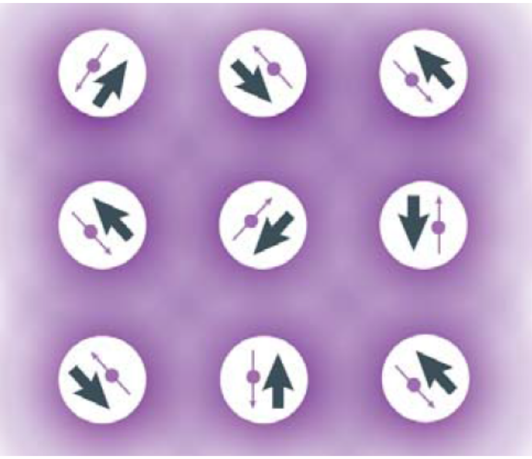
$T_K \sim D \exp(-1/JD(E_F))$

T_K Kondo temperature, below which singlets are formed

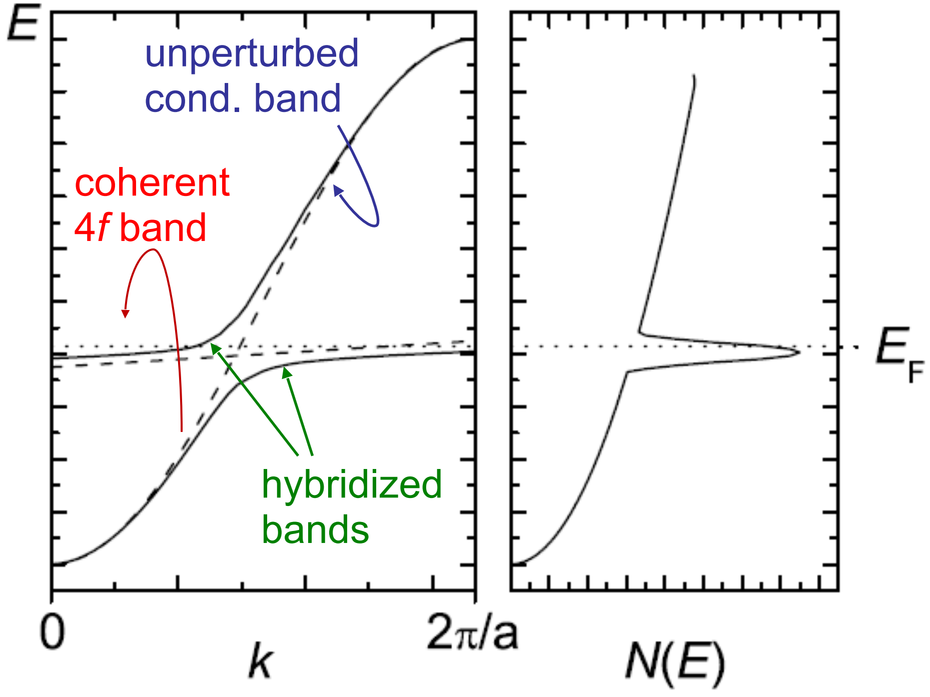
From Kondo impurity to Kondo lattice

Single magnetic impurity
For high T or low impurity density



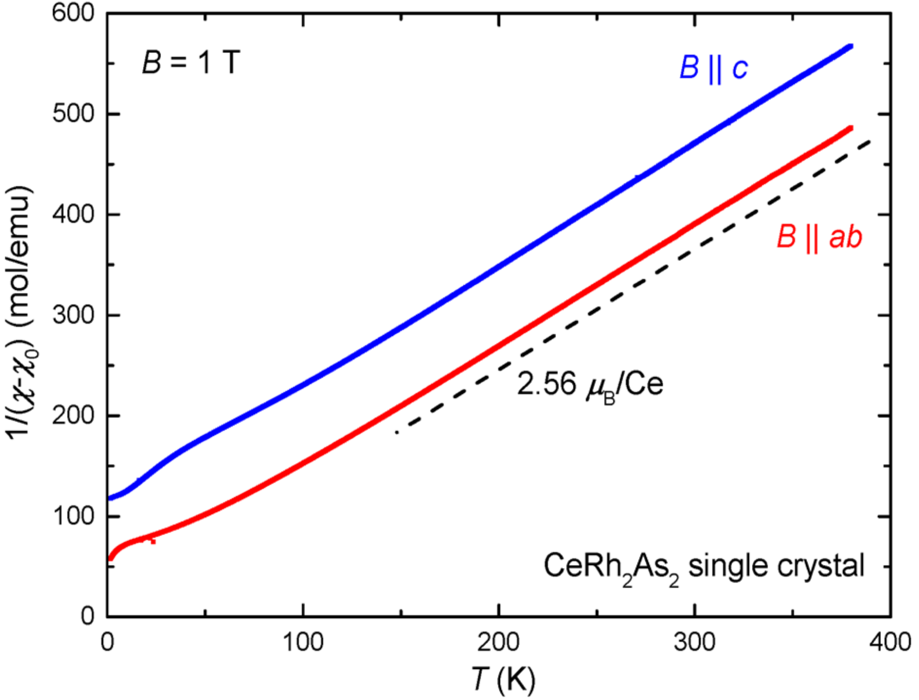


Magnetic ions
on every lattice
site
↓
Kondo-lattice



Basic properties: Magnetic susceptibility

Inverse susceptibility along c and basal-plane



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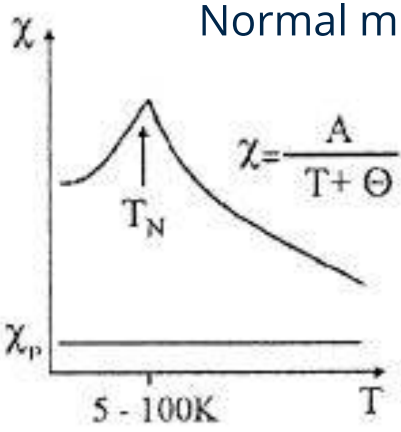

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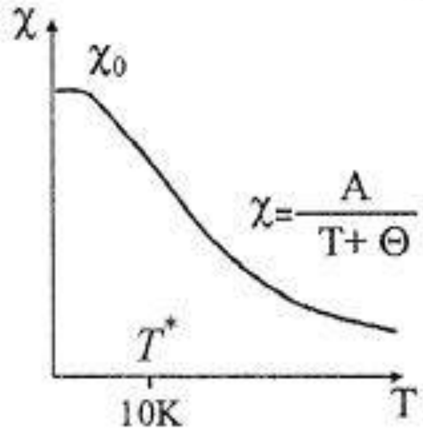


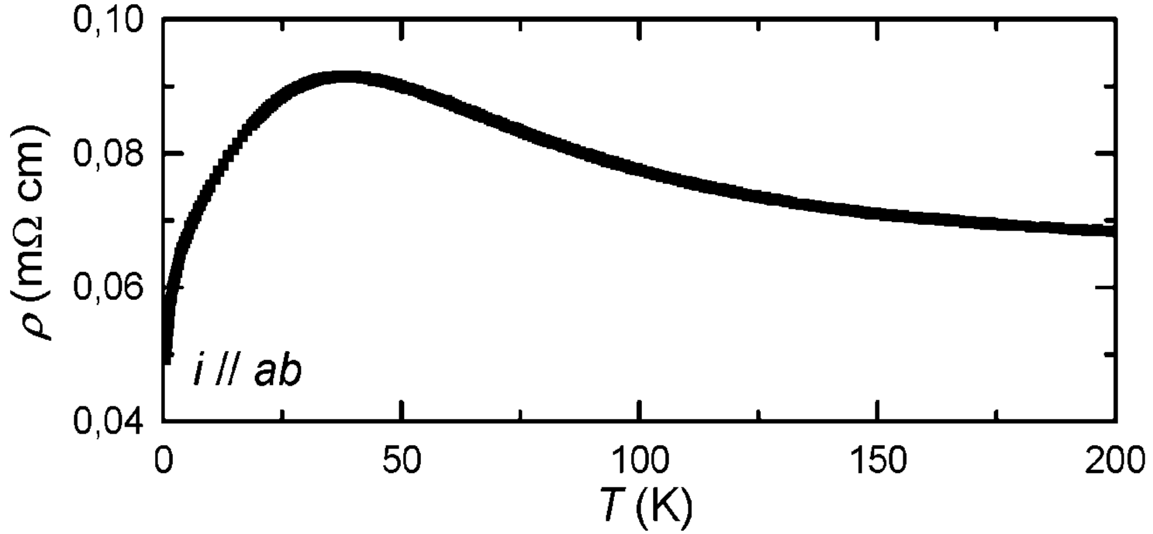
Here: No magnetic order

For *T* < *T**: Flat temperature response with high value, Pauli susceptibility of conduction electrons with large density of states at E_F

$$\chi = \chi_0 \frac{m^*}{m}(1/(1+F_0^a))$$

Electrical resistivity

Resistivity of $CeRh_2As_2$



Resistivity

- T dependence typical for Kondo lattice systems
  - for T > 50 K: increase with decreasing T

→ Incoherent Kondo scattering (Kondo impurity model)

  - For T < 20 K: pronounced drop

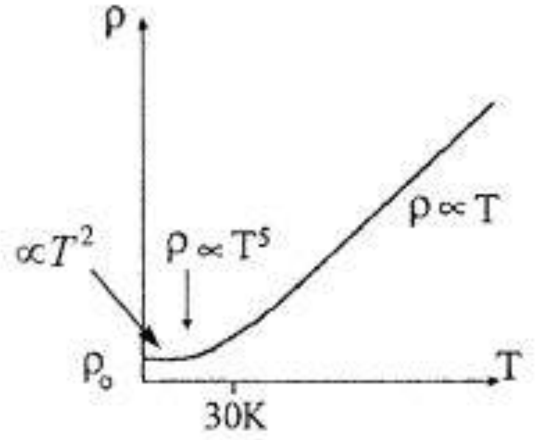
→ formation of coherent Kondo lattice

However: Different to standard Fermi liquid at low T

  - no T^2 above superconducting transition

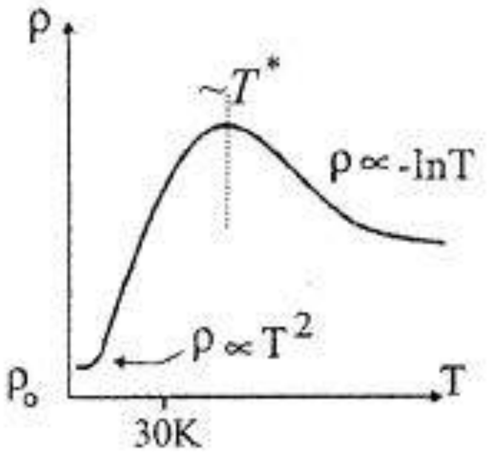
→ Non-Fermi liquid behaviour

Normal metal



$\rho \sim T$ phonon scattering
$\rho \sim T^5$ for $T \ll \theta$
$\rho \sim T^2$ low temperature and very clean samples electron-electron scattering

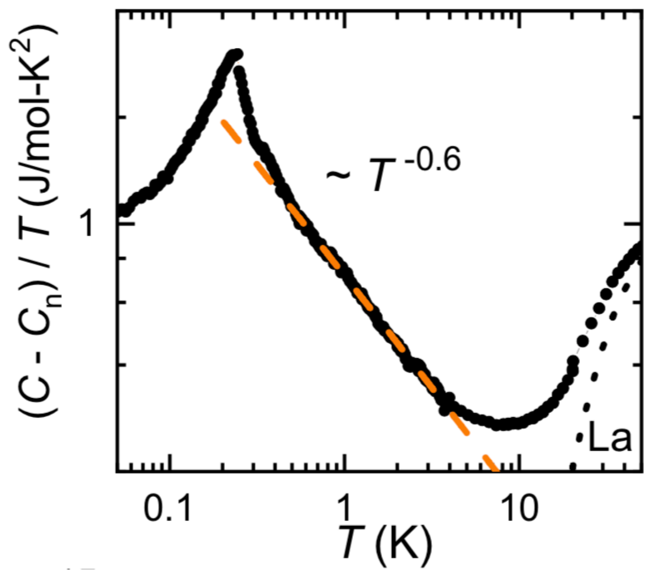
Typical heavy fermion system



For $T > T^*$ ρ big and weakly T-dependent
For $T \sim T^*$ maximum
For $T \ll T^*$ $\rho = \rho_0 + AT^2$
$A \sim \gamma^2$ is large: scattering of heavy quasiparticles

Specific heat

Specific heat C/T

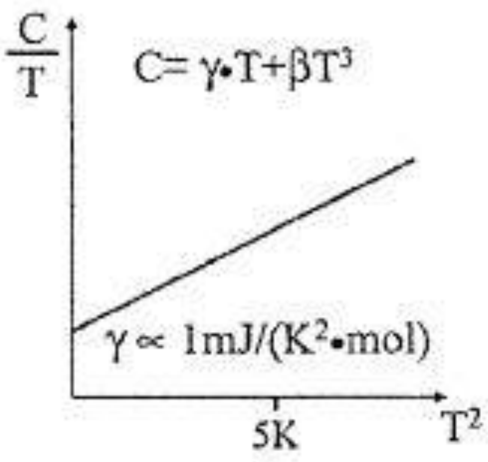


- Large, but smooth increase in C/T
- Large values of C/T → heavy fermions
- However: Different to standard Fermi liquid at low T: No saturation => non-Fermi liquid behaviour

→ evidence for large critical fluctuations

→ Proximity to a QCP

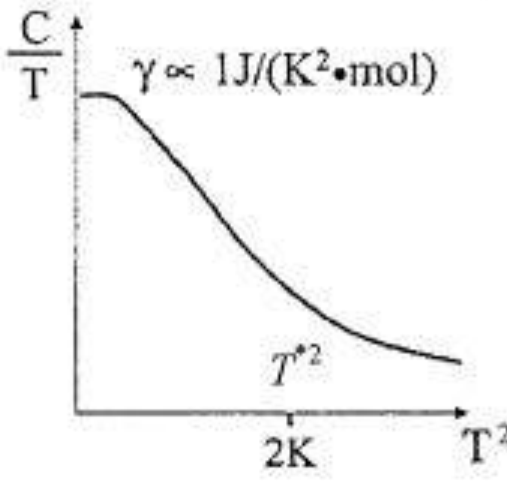
Normal metal



γ electronic, β phononic contribution

$$c_V = \frac{\pi^2}{3} k_B^2 N(\varepsilon_F) T = \gamma_0 T.$$

Typical heavy fermion system



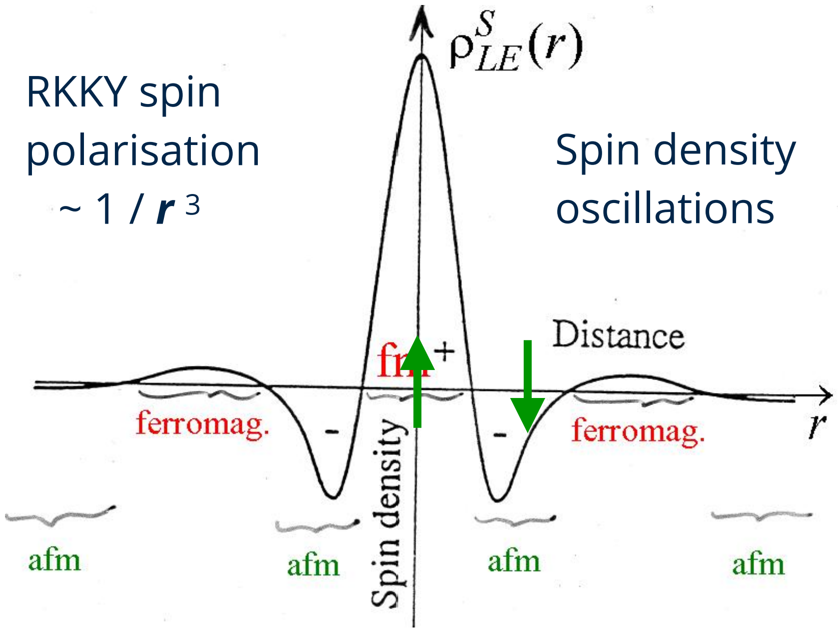
For $T > T^*$ γ rises because of rising density of states

For $T < T^*$

Flat temperature response with high value, large density of states at E_F

$$\frac{C}{T} = \gamma_0 \frac{m^*}{m}.$$

Another interaction: RKKY



RKKY spin polarisation
~ 1 / $\boldsymbol{r}^3$

Spin density oscillations

RKKY interaction
Magnetic interaction between *f* moments via conduction electrons
magnetic ground state
$T_{RKKY} \sim J^2 D(E_F)\cos(k_F r)/k_F r$

Rudermann, Kittel, Kasuya, Yosida

Local magnetic moment at x – 0, causes Friedel oscillations of the spin density of the electron gas (same coupling as Kondo), this polarises another local moment.

Weak type of exchange interaction, low transition temperatures

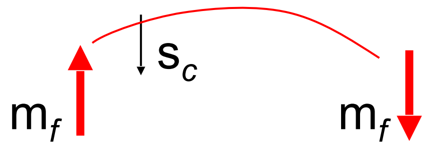
Heavy Fermion systems under pressure

RKKY interaction

Magnetic interaction between *f* moments via conduction electrons

magnetic ground state

$T_{RKKY} \sim J^2 D(E_F) \cos(k_F r)/k_F r$

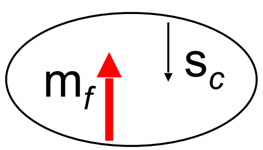


Kondo effect

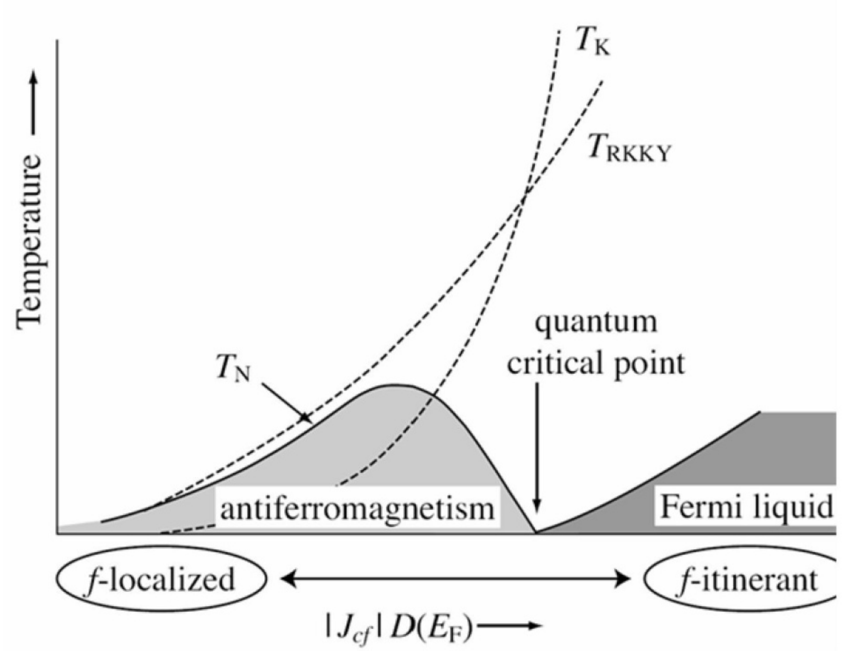
Conduction electrons screen *f* moment

Non-magnetic ground state

$T_K \sim D \exp(-1/JD(E_F))$

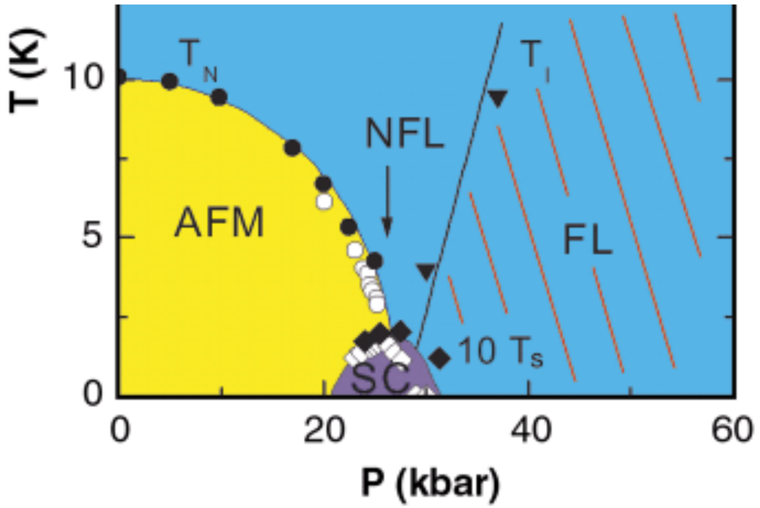


Total moment =0

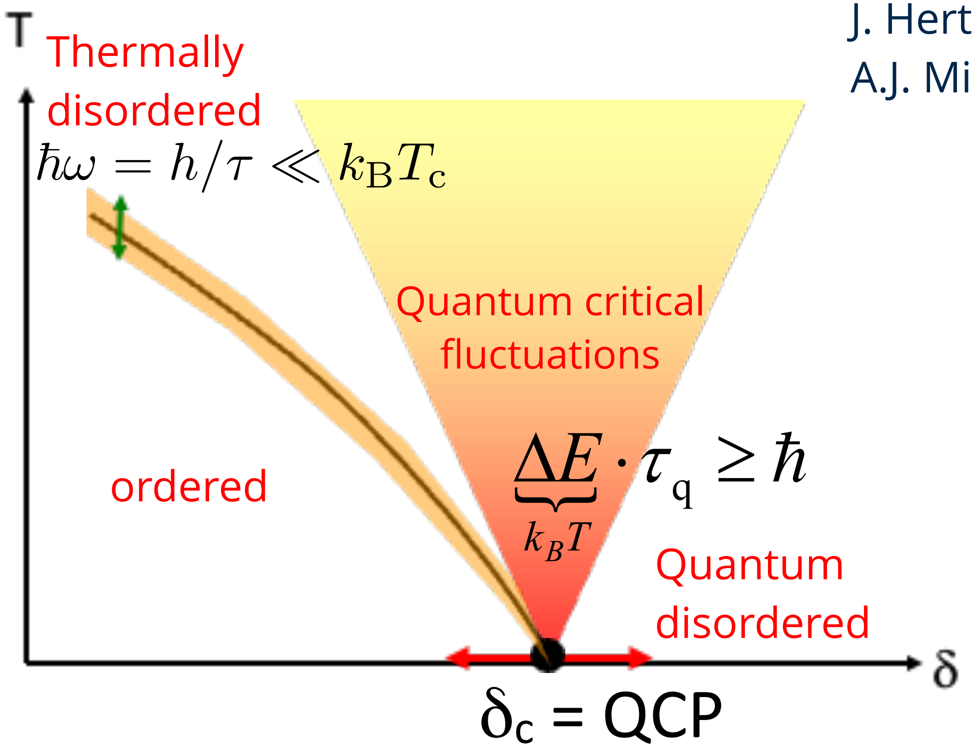


Doniach 1977

Pressure tunes J => suppression of order at quantum critical point



Classical and quantum phase transitions



J. Hertz 1976,
A.J. Millis 1993

- Correlation time τ ->∞ at 2nd order phase transitions
- energy of temporal OP fluctuations $\hbar\omega = h/\tau \ll k_B T_c$ can be neglected close to T_c
- However, if $T_c = 0$, inequality never holds in approach of the transition!
- Quantum critical regime: temporal OP fluctuations matter
- Criticality in effective dimension $d_{eff}=d+z$ with z: dynamical critical exponent
- New universality classes, different types of criticality with many unusual novel properties

- Experimental realisations: need material that displays different ground states dependent on the tuning of a non-thermal “control parameter” δ (e.g. chemical substitution or doping, application of pressure, magnetic field, …)
- Prime example: heavy-fermion metals

Slide P. Gegenwart

Experimental signatures of quantum criticality

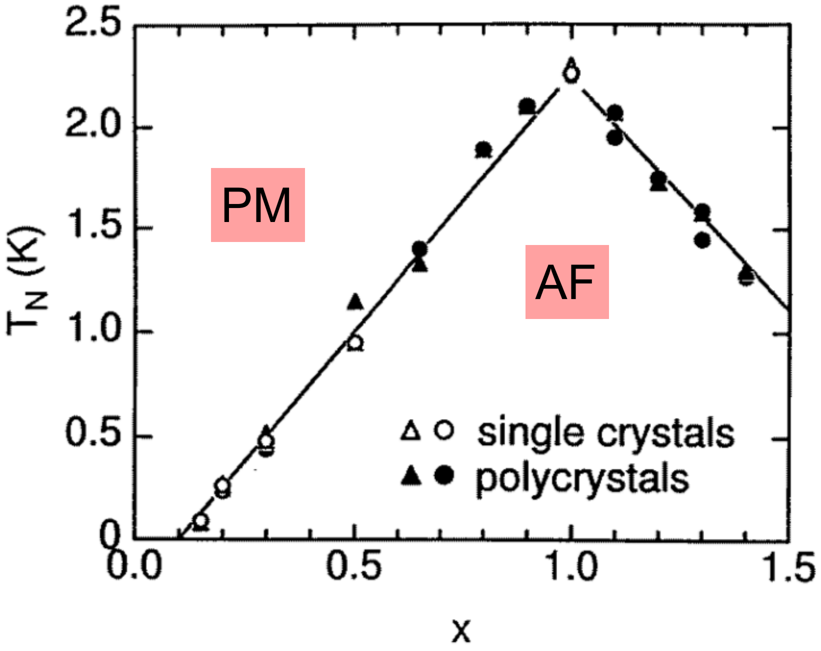
Fermi-liquid: specific heat: $C/T = \gamma_0$

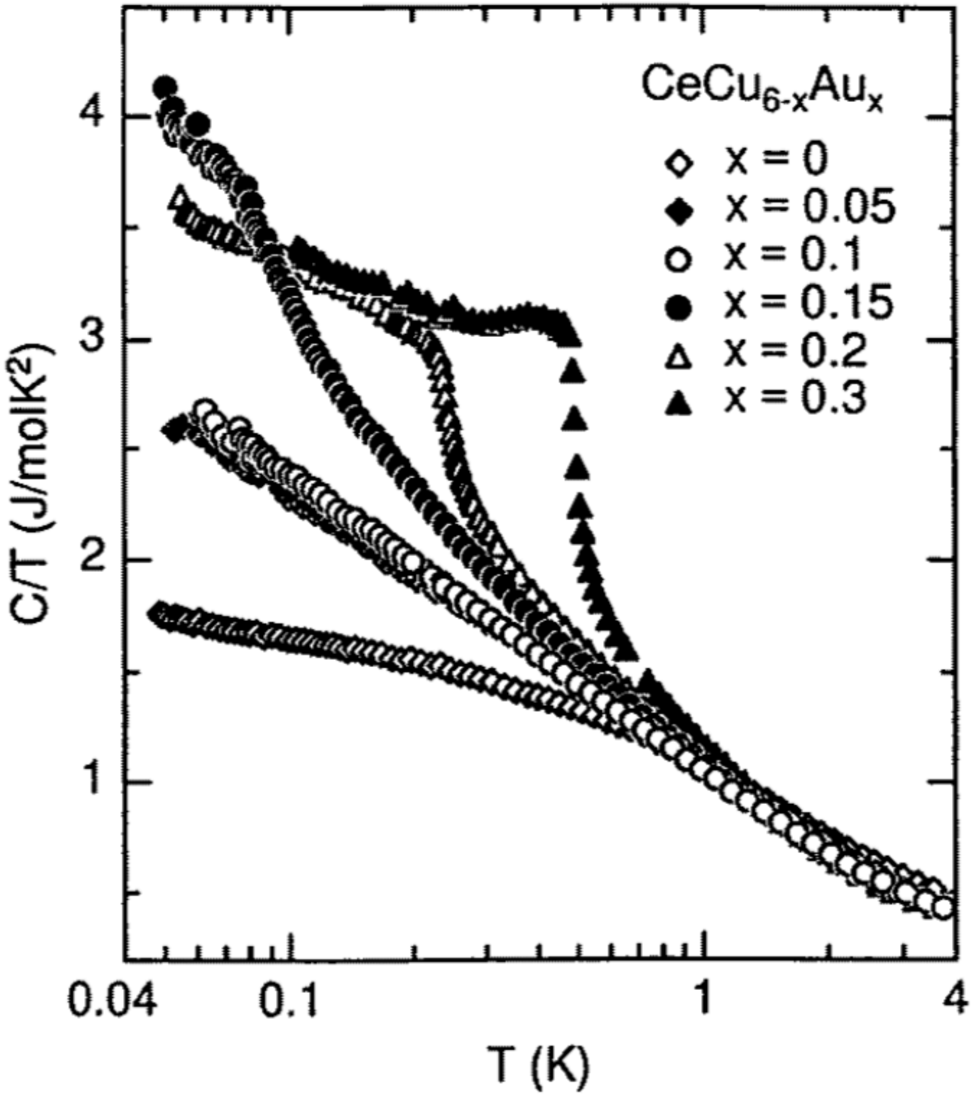
electr. resistance: $\rho - \rho_0 = AT^2$

Non-Fermi liquid: $C/T \sim \log(T_0/T)$, or weak power law divergence

$\rho - \rho_0 \sim T$, or exponent below 2

v. Löhneysen et al., 1996





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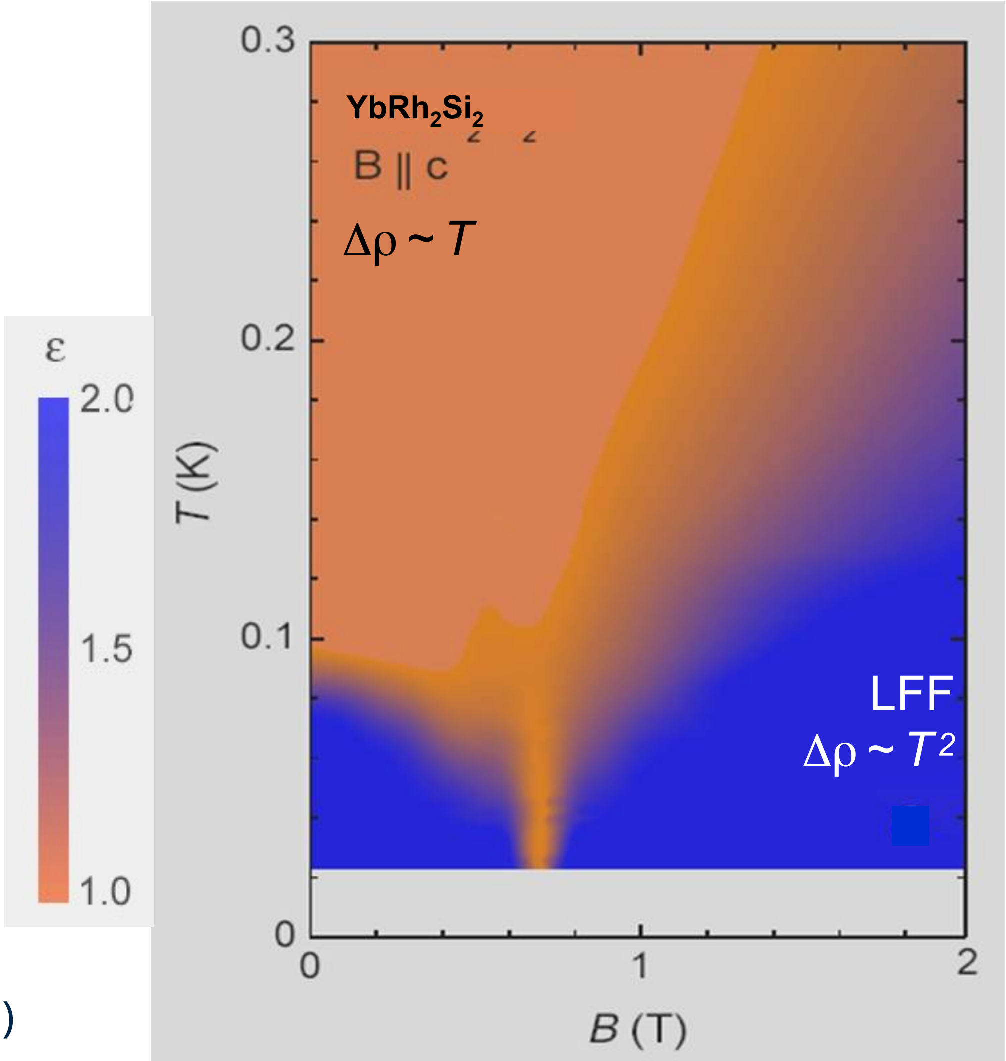
Non-Fermi liquid: $C/T \sim \log(T_0/T)$, or weak power law divergence

$\rho - \rho_0 \sim T$, or exponent below 2

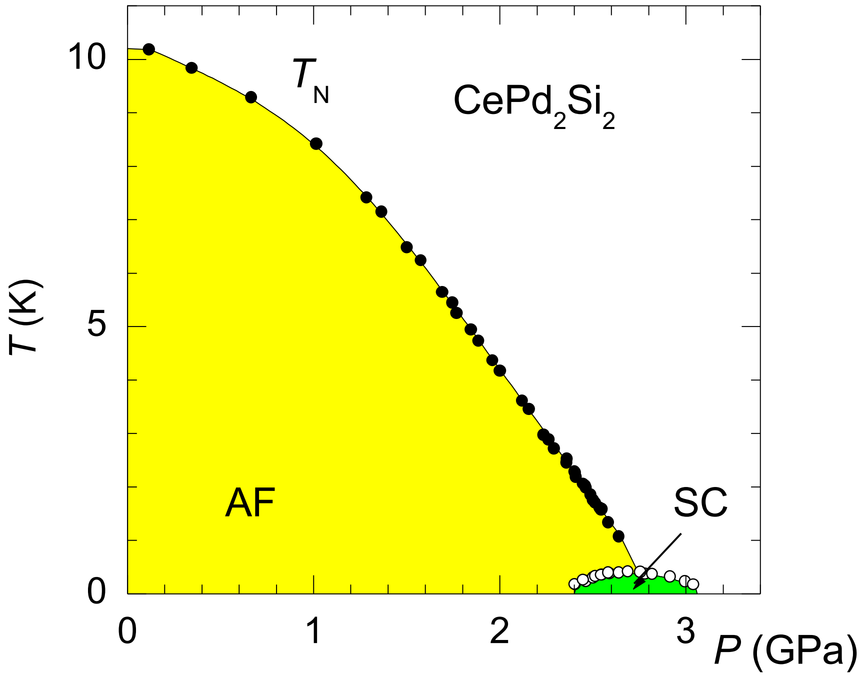
Color is exponent of *T*-dependence of resistivity

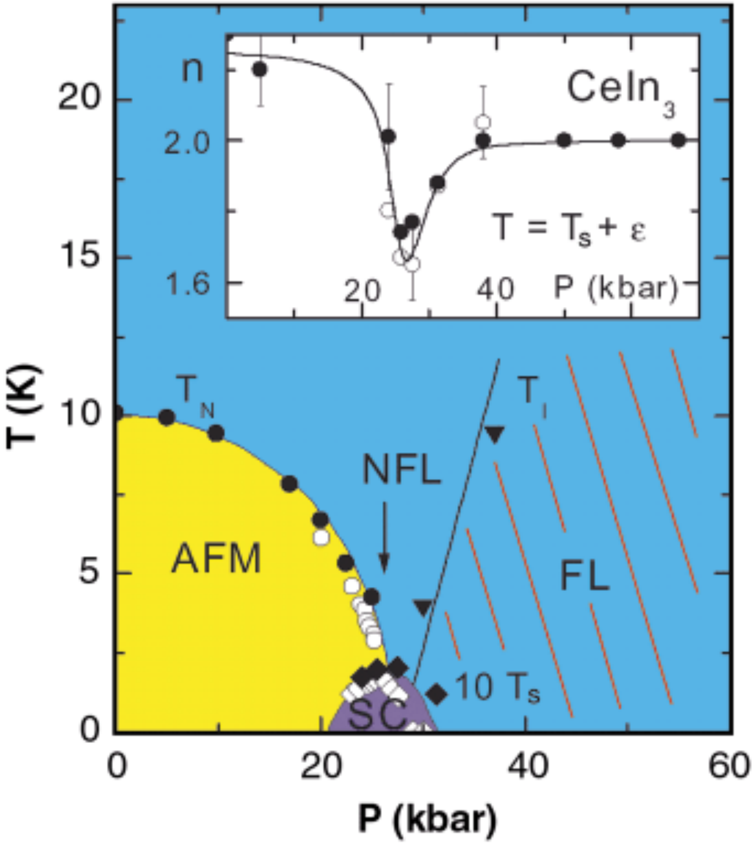
$$\rho(T)=\rho_0 + AT^n$$



P. Gegenwart, Q. Si, F. Steglich, Nature Phys. (2008)

Unconventional superconductivity near a quantum critical point





Mathur et al. Nature 1998

Knebel et al. PRB 2001

Possible origin of non-Fermi liquid behavior

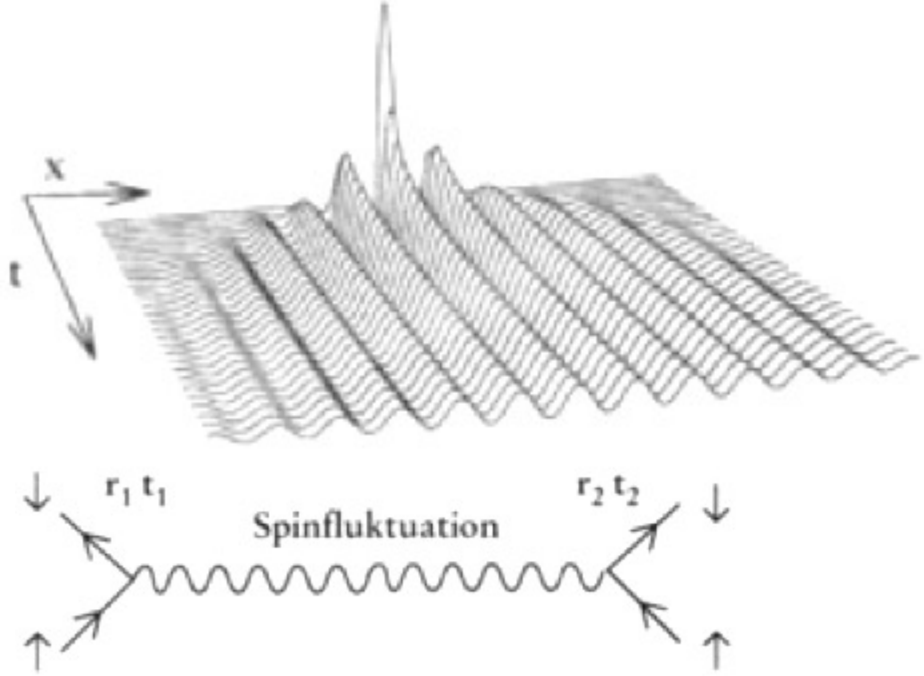
Experiments: divergence of *C/T*, electrical resistance $\Delta\rho \sim T^{\varepsilon}$ with $\varepsilon<2$, different theoretical ideas:

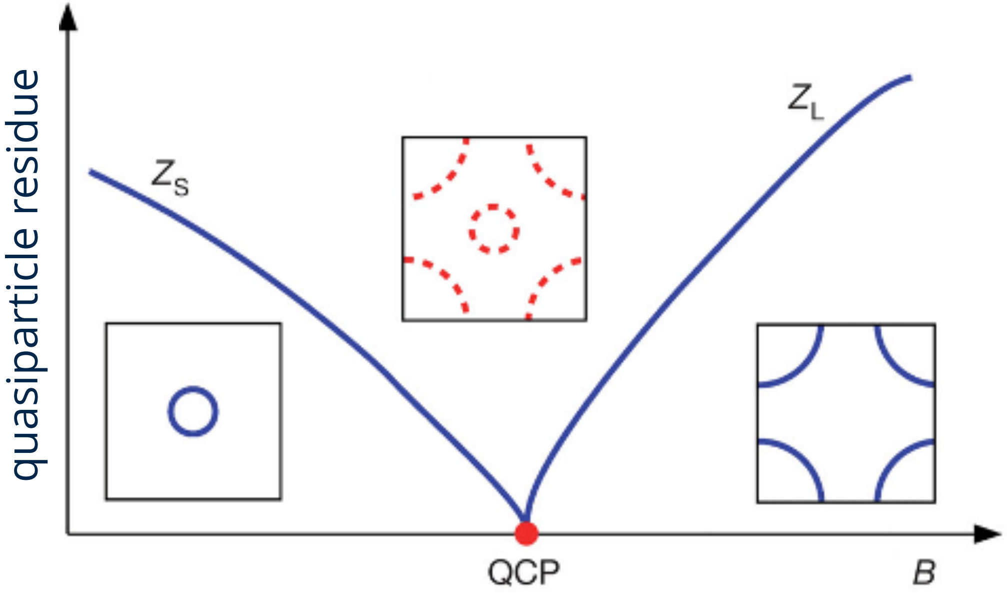
a) Magnetic correlations decay slowly near QCP, become strong

-> Quasiparticles undergo anomalous scattering & superconductivity mediated by spin fluctuations

b) Quasiparticles disintegrate because f-electrons localize

-> mass divergence, change of Fermi surface from small (f-el localized) to large (f-el contribute)





A. Rosch: Physik unserer Zeit 30 (1999) 119.

H. Pfau et al., Nature 484, 493 (2012).

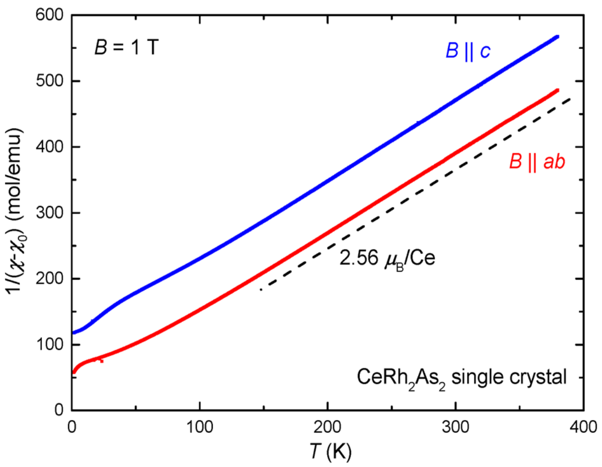
Slide P. Gegenwart

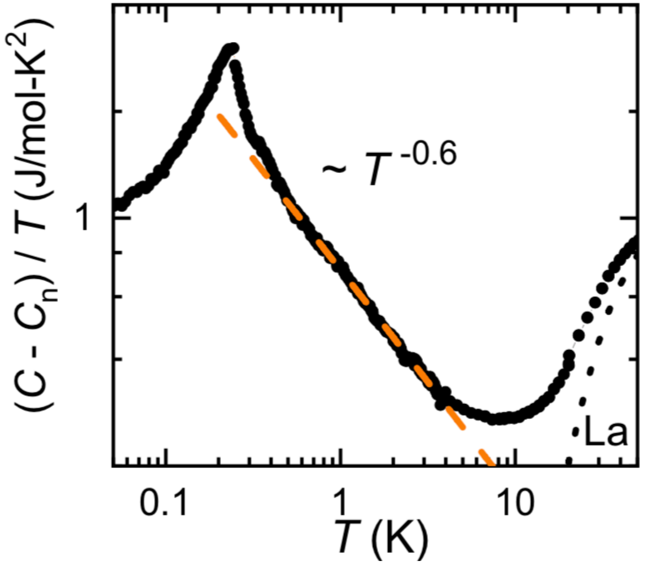
CeRh$_2$As$_2$

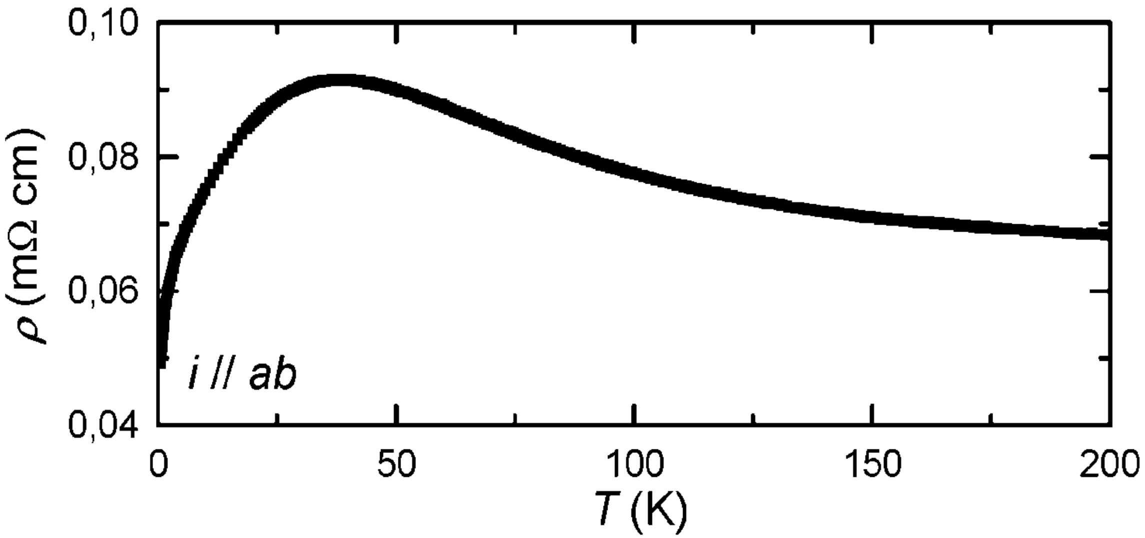
Ac susceptibility, specific heat and resistivity of CeRh$_2$As$_2$ at high temperature

1. Kondo-lattice system
2. No order down to 0.5 K
3. Non-Fermi liquid behavior at low temperature

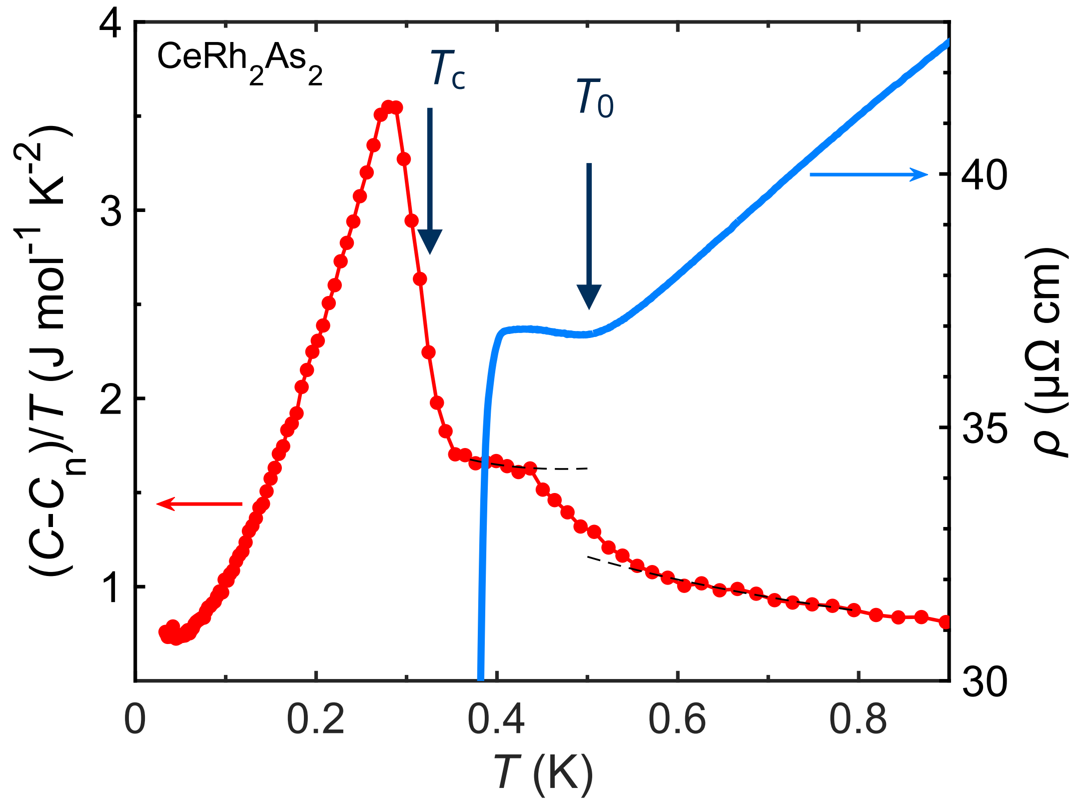
-> Proximity to a quantum critical point (might be important for superconducting pairing mechanism)







Interesting ordered states at low temperature



K. Semeniuk *et al.*, PRB (2023)

T_0 order (Phase I), non-magnetic or weakly magnetic

T_0 ~ 0.5 K

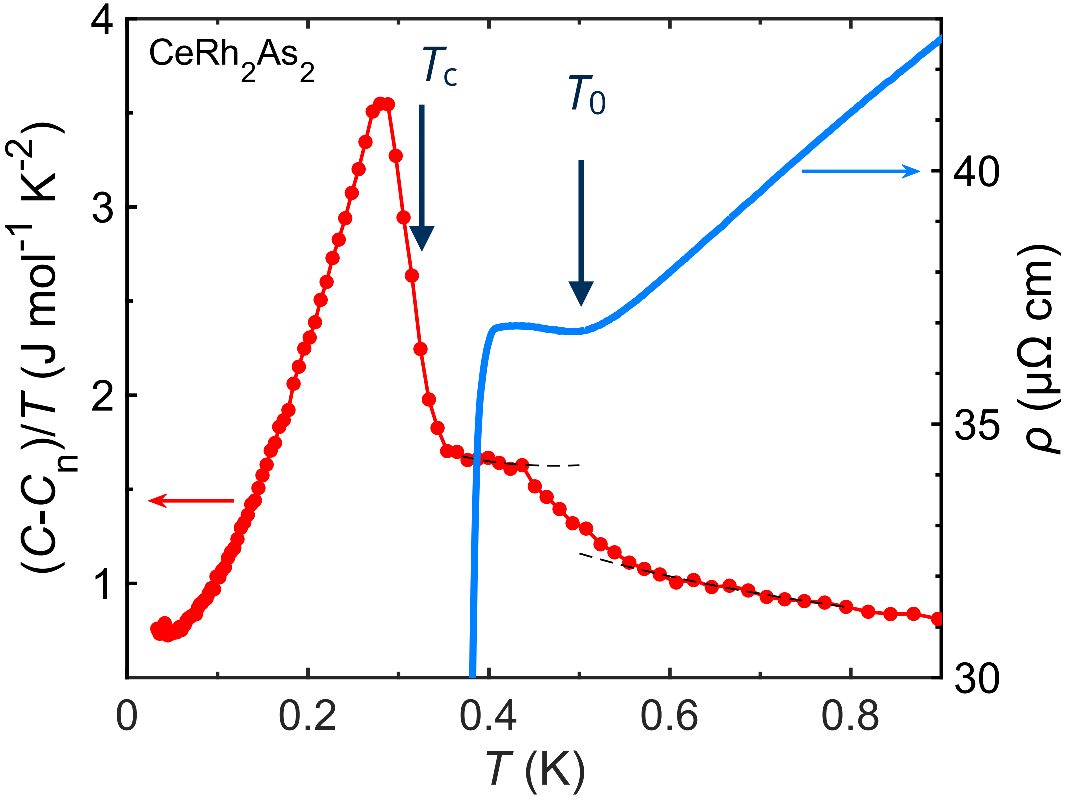
Heavy-fermion superconductivity
Large jump in specific heat
=> f electrons involved

T_c ~ 0.35 K

Buzz groups

- How can you recognise a heavy-fermion system from magnetic susceptibility/ resistivity/ specific heat? How do you explain their temperature dependence?
- How does the competition of Kondo interaction and RKKY interaction lead to quantum criticality in heavy-fermion systems?
- Which extraordinary phenomena can be observed near a quantum critical point?

Interesting ordered states at low temperature



T_0 order (Phase I), non-magnetic or weakly magnetic

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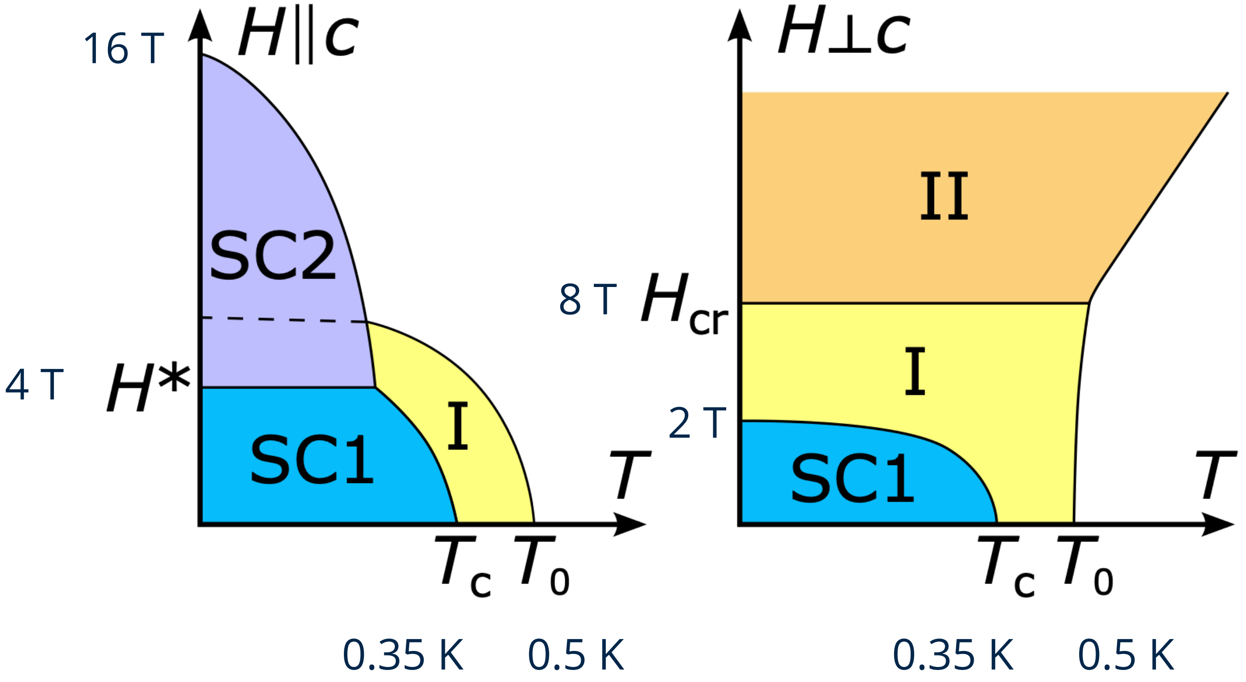
Heavy-fermion superconductivity
Large jump => f electrons involved

T_c ~ 0.35 K

K. Semeniuk *et al.*, PRB (2023)

$CeRh_2As_2$ - a unique material



Superconductivity at $T_c = 0.35$ K

Anisotropic in magnetic field

Switch from **SC1** to **SC2** only for H || c, large critical fields strongly exceeding Pauli limit

Phase I at $T_0 = 0.5$ K

Unknown origin

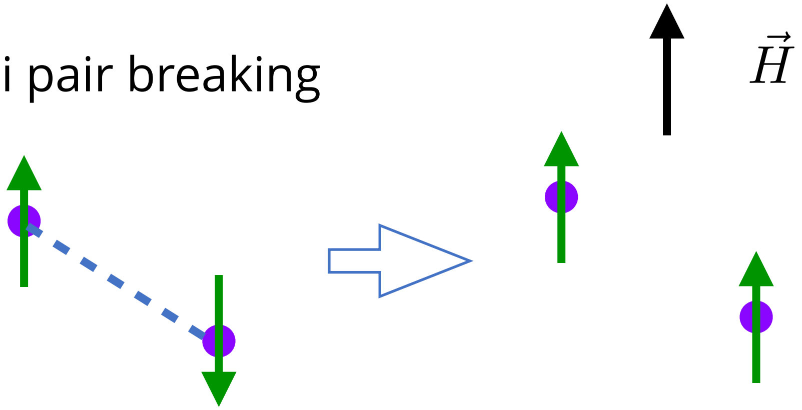
Anisotropic in magnetic field

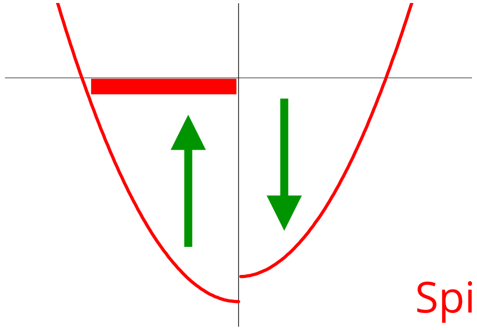
Switch to **Phase II** at 8 T

1. Superconductivity

Pair breaking by magnetic field

- Pauli pair breaking

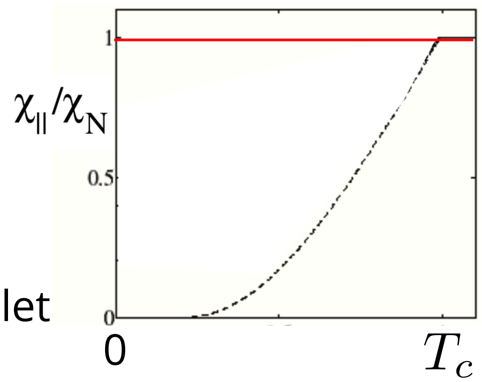




Magnetic energy

$$\frac{\chi_N}{2} H_p^2 \sim E_{\mathrm{cond}}$$

$$H_p = \frac{\sqrt{2}\Delta}{g\mu_{\mathrm{B}}} \approx 1.84\, T_c$$

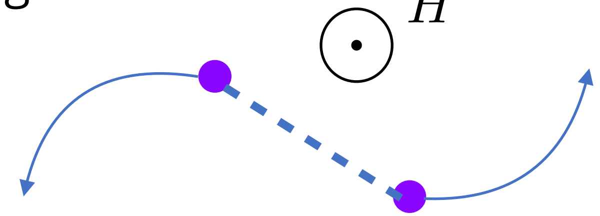


Spin triplet
No Pauli limit
for T = 0

Spin singlet

- Orbital pair breaking

By Lorentz force



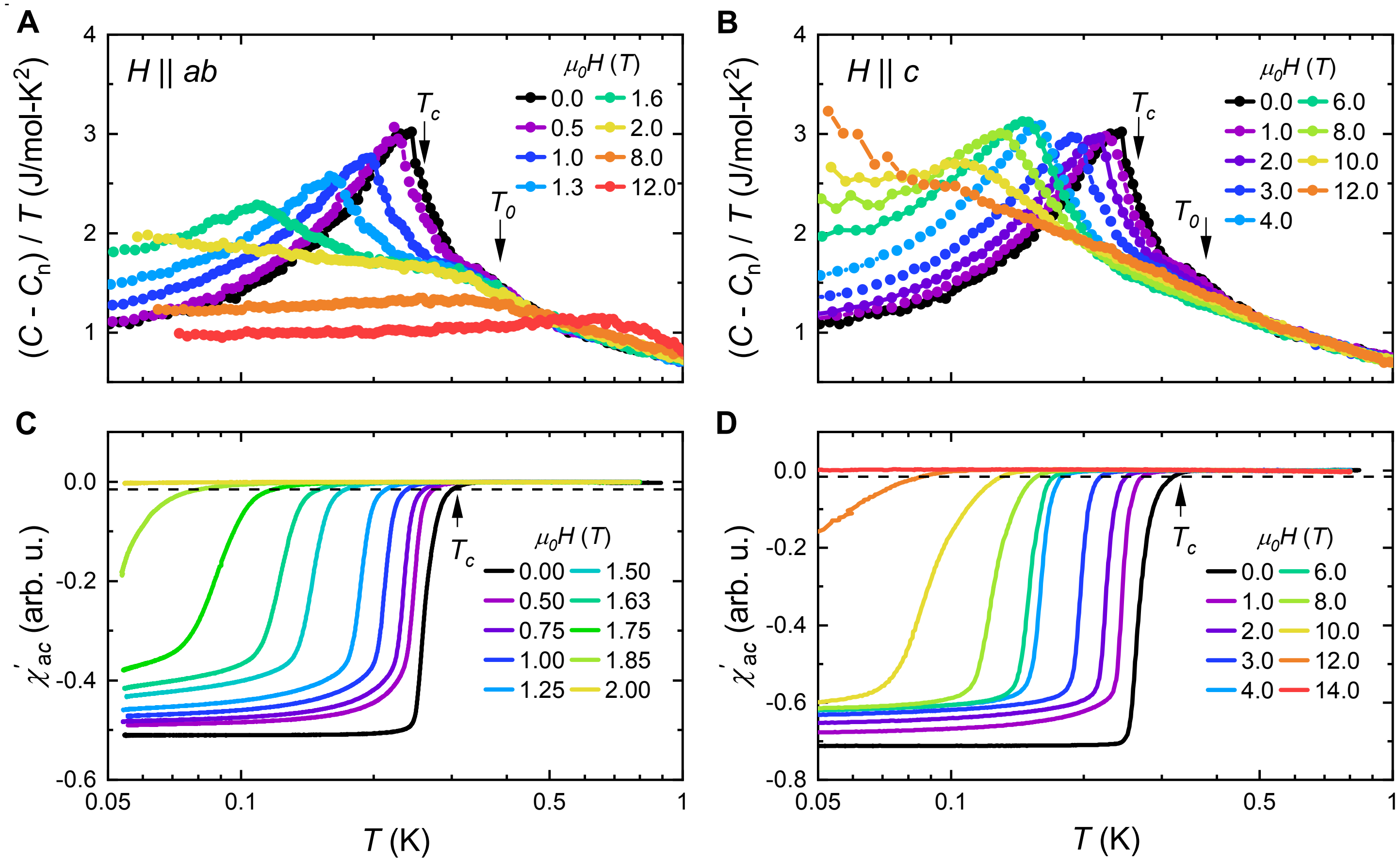
$$H_{orb} = \frac{\Phi_0}{2\pi\xi_0^2}$$

$$\xi_0 \propto v_{\mathrm{F}} \;\Rightarrow H_{orb} \propto m^{*2}$$

$$H_{orb} = 0.69\, T_c \left.\frac{dH_{c2}}{dT}\right|_{T_c}$$

Field suppression of superconductivity

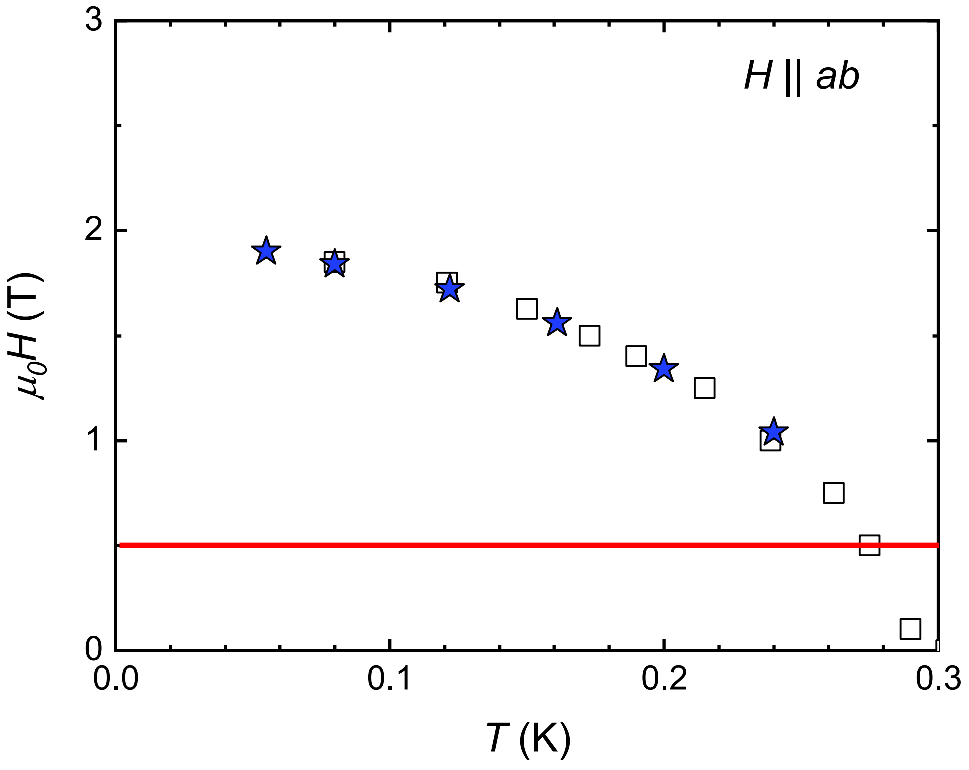
H | | ab   *H* | | c



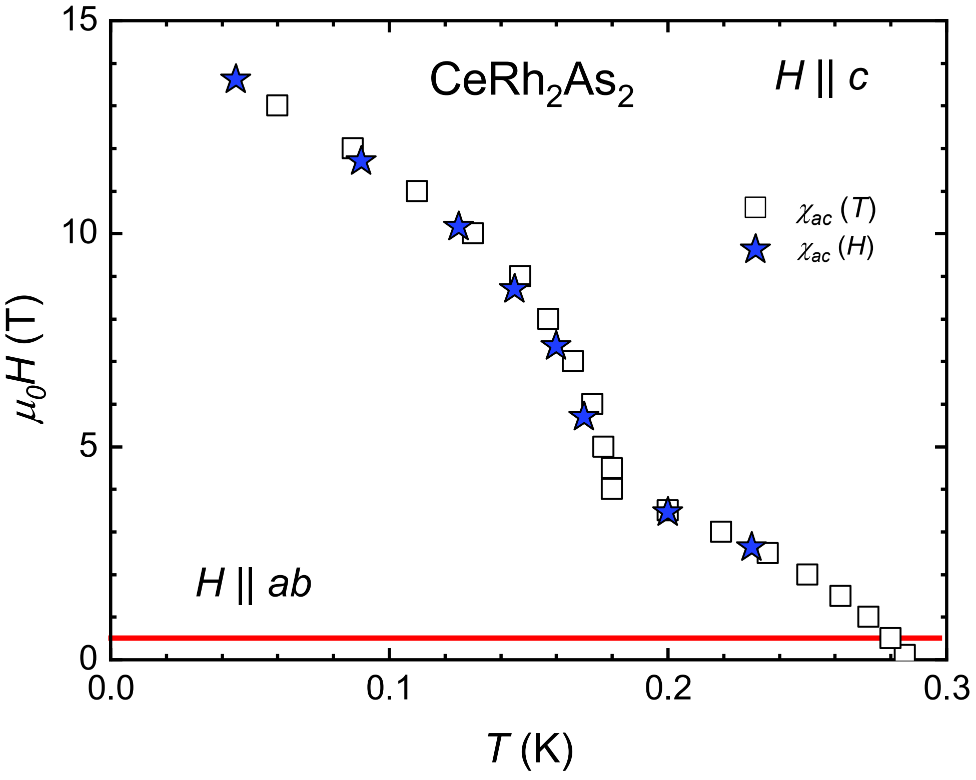
T_c suppressed at 2 T T_c suppressed at 14 T

Unusual critical fields

$H \,||\, ab$



$H \,||\, c$

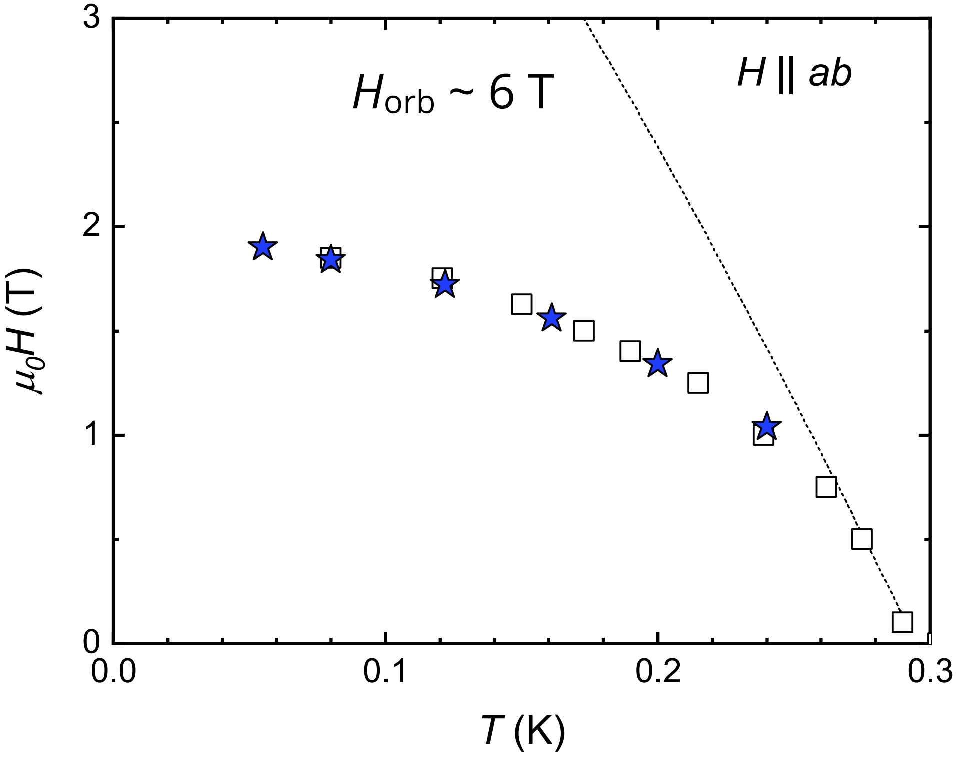


- Kink
- Huge H_{c2}/T_c
- Strong anisotropy

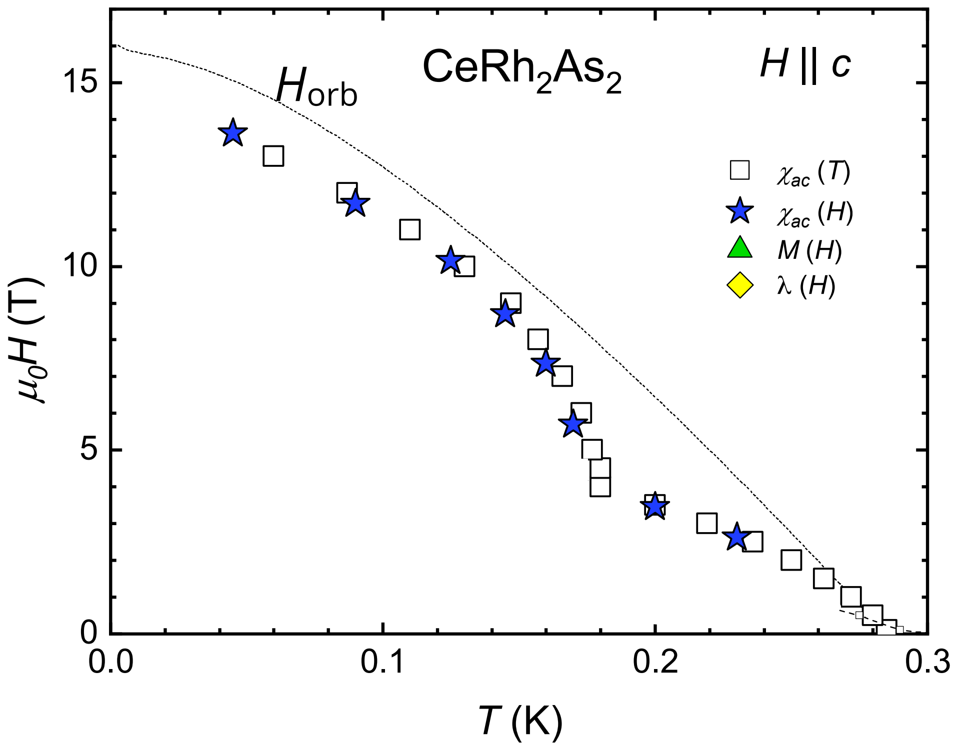
$H_P = 1.84\ T_c = 0.5$ T

Orbital limit

H | | ab



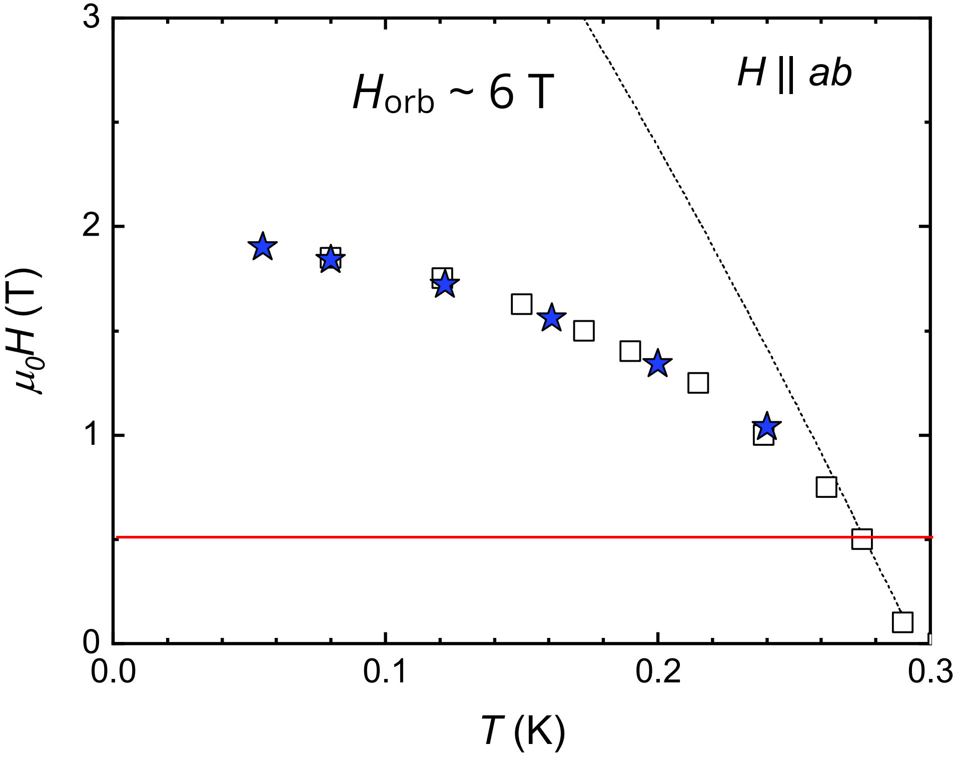
H | | c



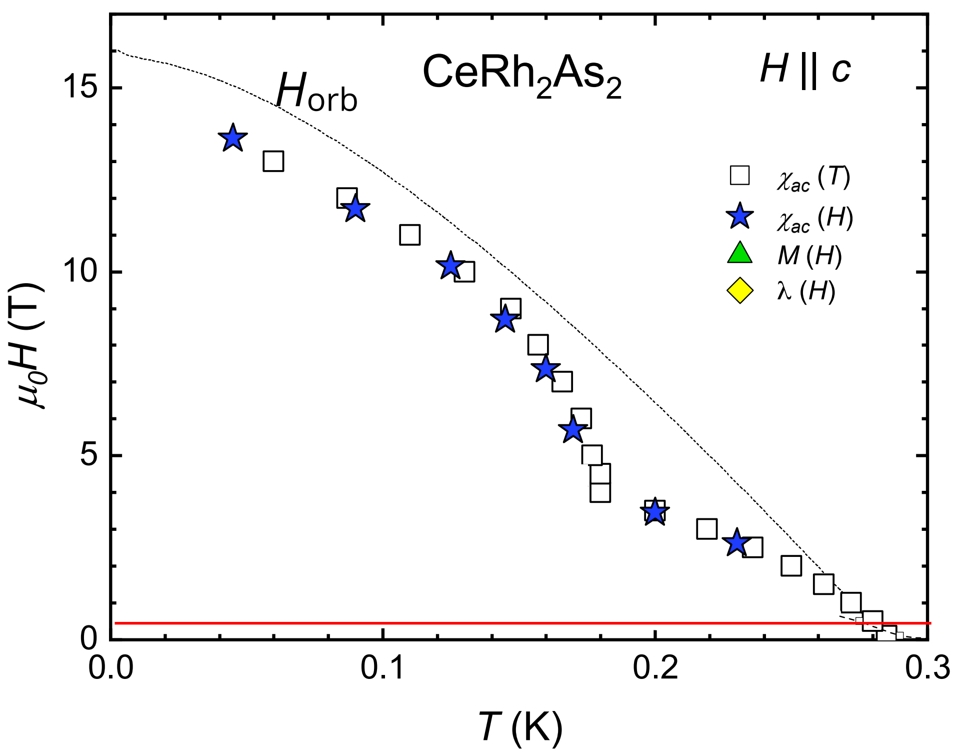
Above kink orbitally limited

Pauli limit

H | | ab



H | | c

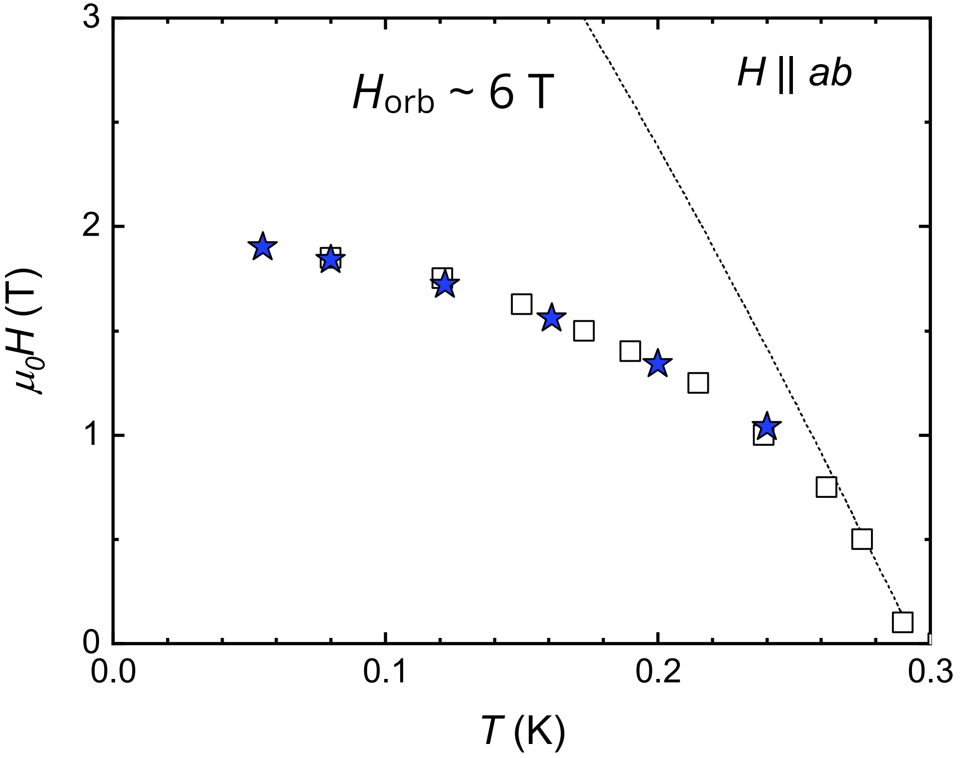


$H_P = 1.84\ T_c = 0.5$ T

Enhanced Pauli limit

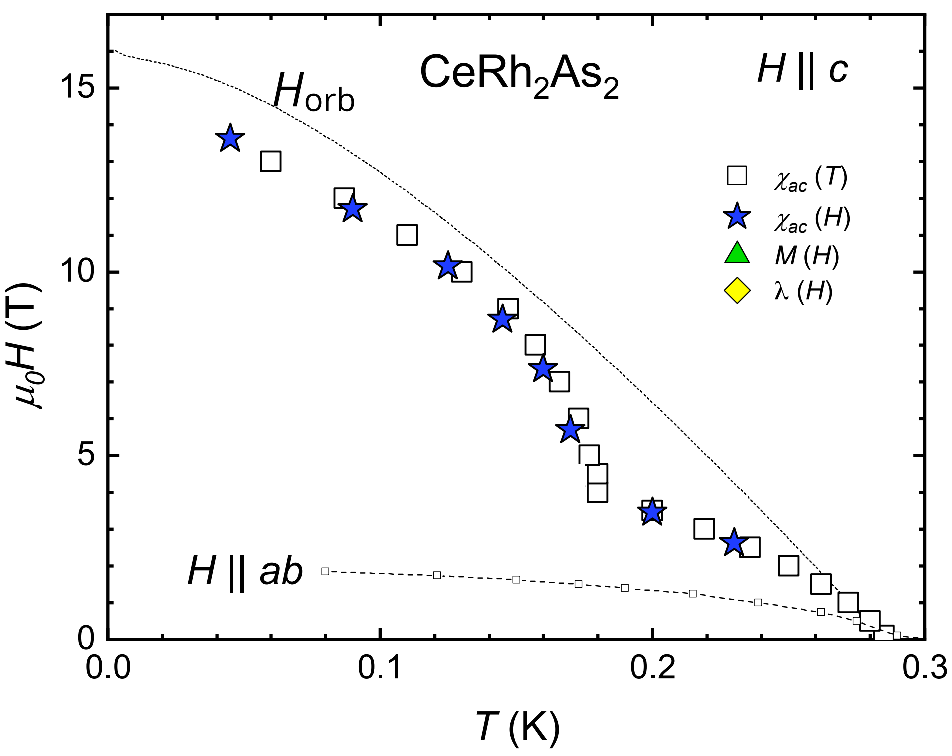
Anisotropy

H || ab



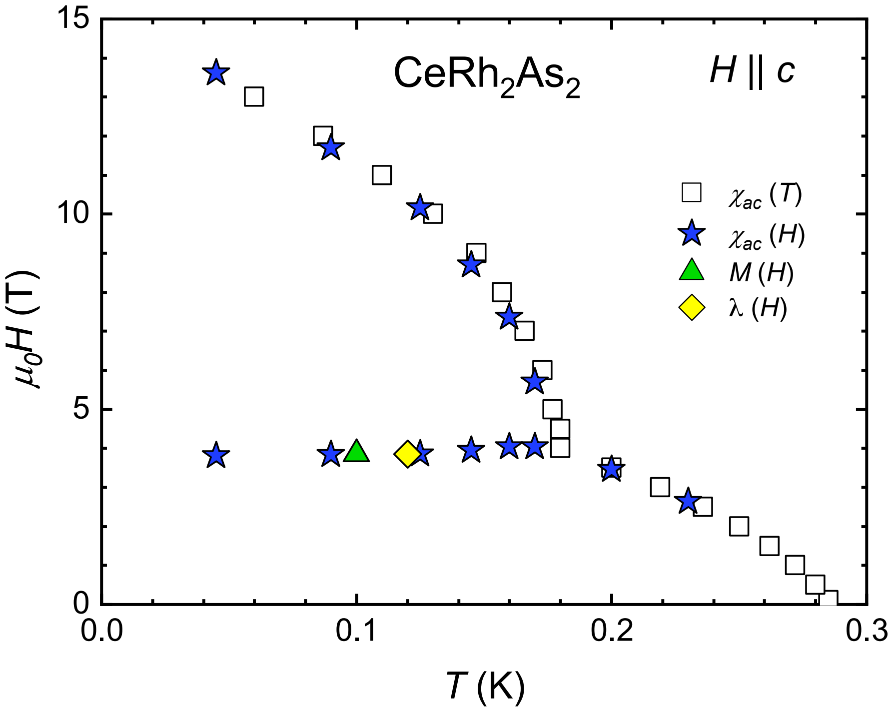
Enhanced Pauli limit

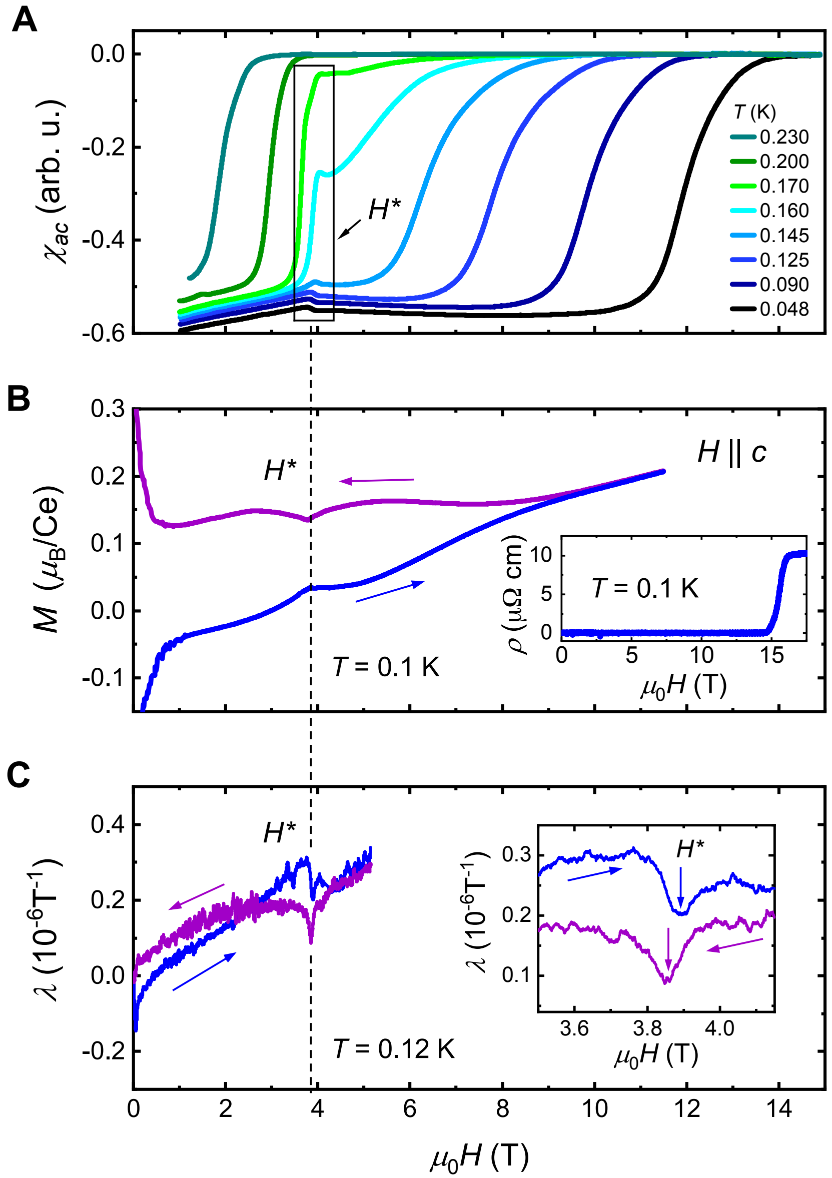
H || c



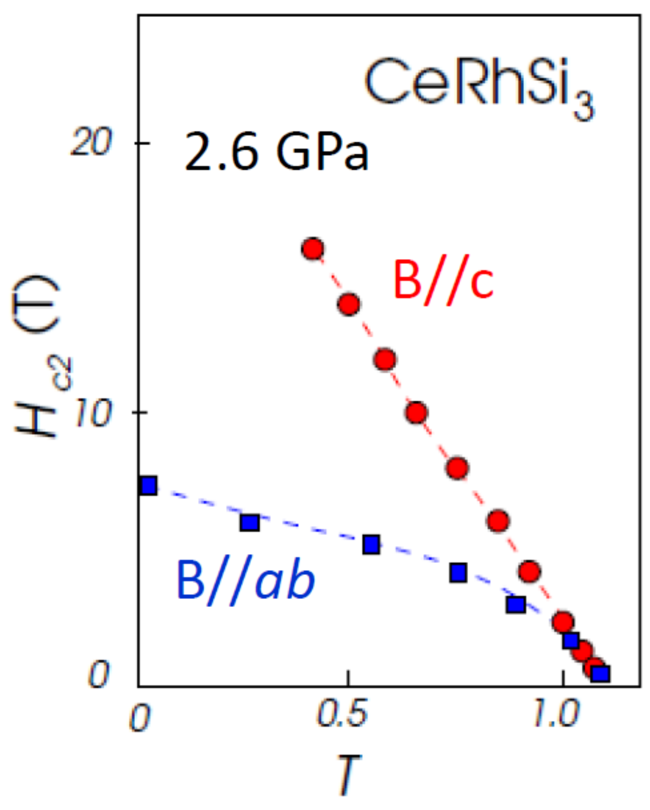
Larger enhanced Pauli limit
factor of 3 difference in the low-field region

Two superconducting states

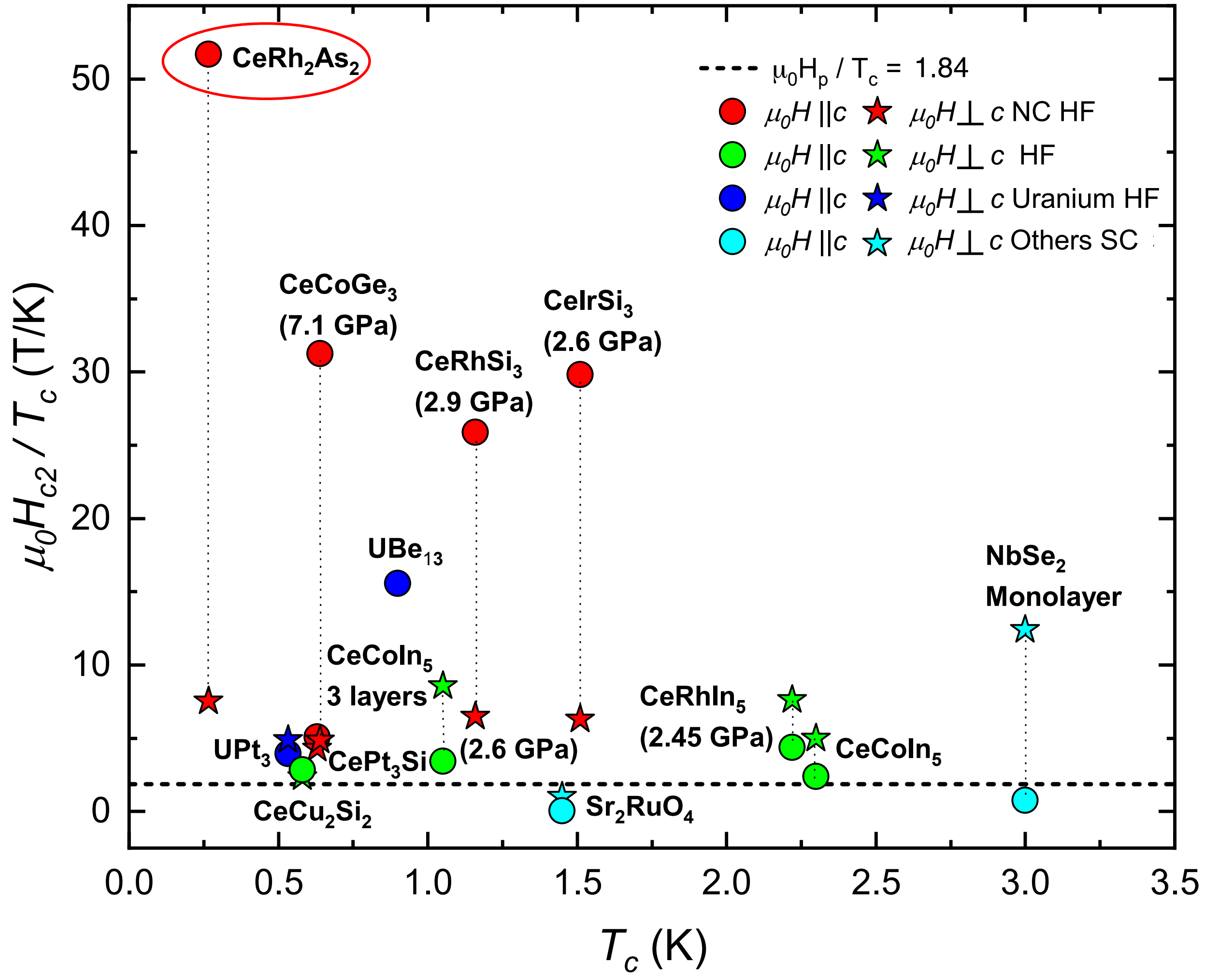




Comparison with non-centrosymmetric superconductors



N. Kimura et al., PRL (2007)
M. Sigrist, AIP conf. Proceed. (2005)

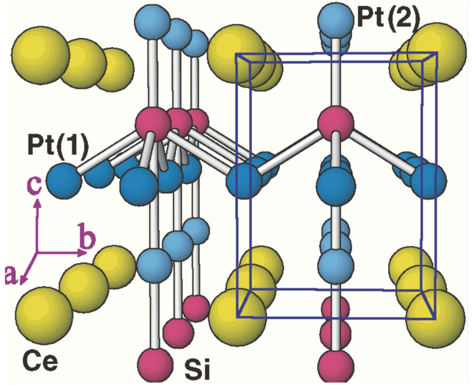


Local symmetry (non centrosymmetric) has strong impact on SC

Non-centrosymmetric systems

Electric field
=> Effective magnetic field
In the plane

CePt$_3$Si



Bauer et al. PRL (2004)

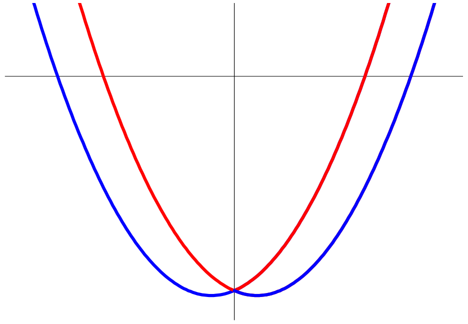
$$\vec{B} = -\frac{\vec{v}}{c} \times \vec{E} = \frac{E}{mc}(\vec{k} \times \hat{z})$$

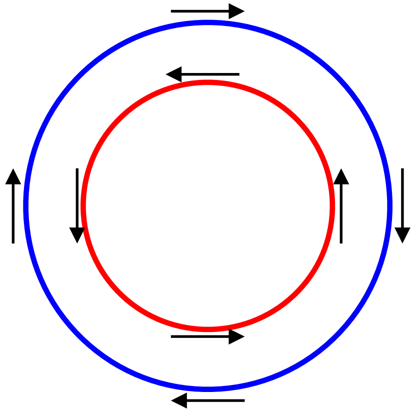
Rashba spin-orbit coupling

$$\sum \alpha_R \, \vec{g}(\vec{k}) \cdot \vec{\sigma}_{ss'} c^{\dagger}_{\vec{k}s} c_{\vec{k}s'}$$

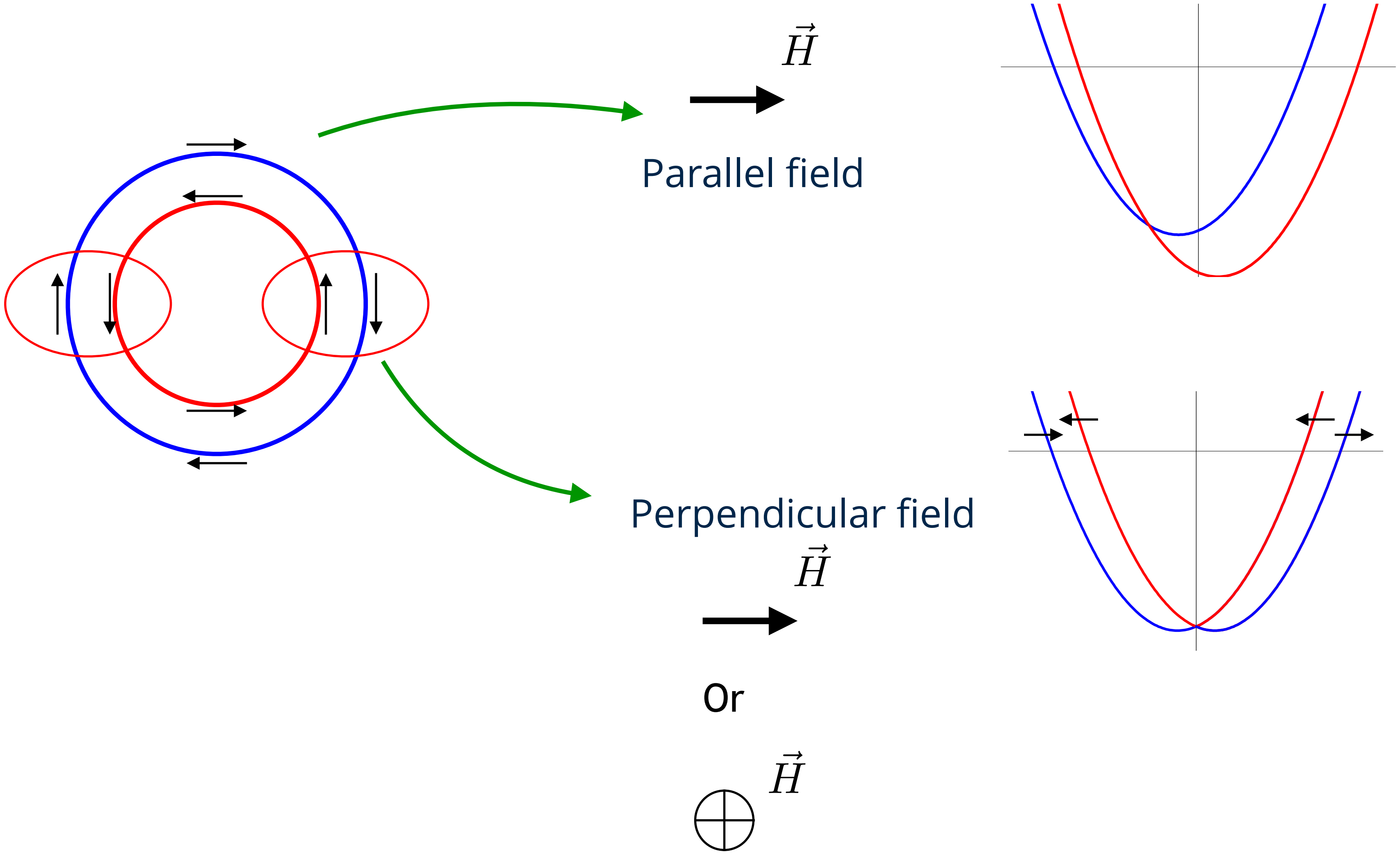
$$\vec{g}(\vec{k}) = k_x \hat{y} - k_y \hat{x}$$

Bands split





Non-centrosymmetric metals in a magnetic field


$\vec{H}$

Parallel field

Perpendicular field

$\vec{H}$

Or

$\vec{H}$

Bands shift

Pauli susceptibility

χ_P

Bands mix

Van Vleck susceptibility

χ_{vV}

$$\chi_{ab} = \frac{1}{2}(\chi_P + \chi_{vV})$$

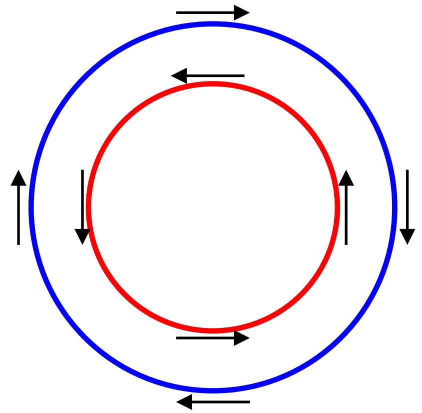
$$\chi_c = \chi_{vV}$$

For large Rashba

Superconductivity in non-centrosymmetric systems

Absence of inversion symmetry
=> Parity is not well defined
Even and odd functions mix
=> Singlet and triplet mixing possible

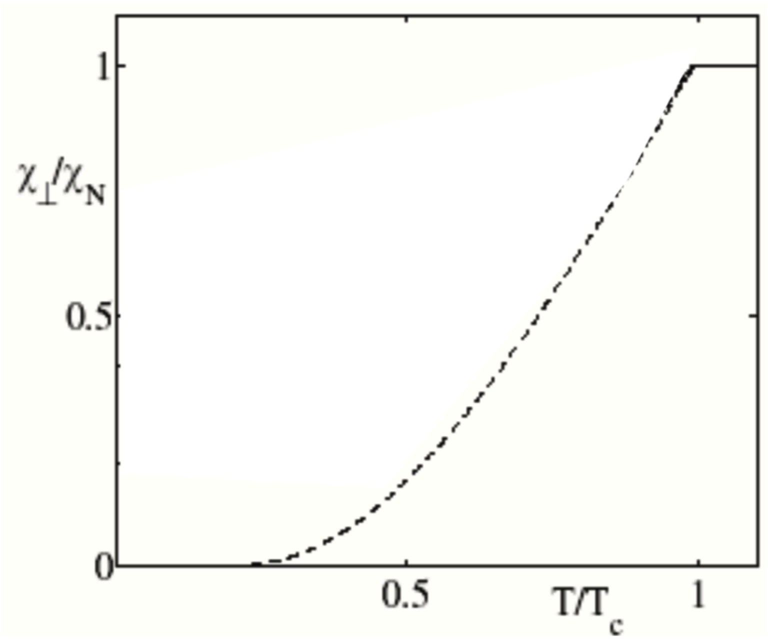
Gap equations of singlet and triplet are coupled,
Since coupling is of order α_R/ E_F channels can be studied separately



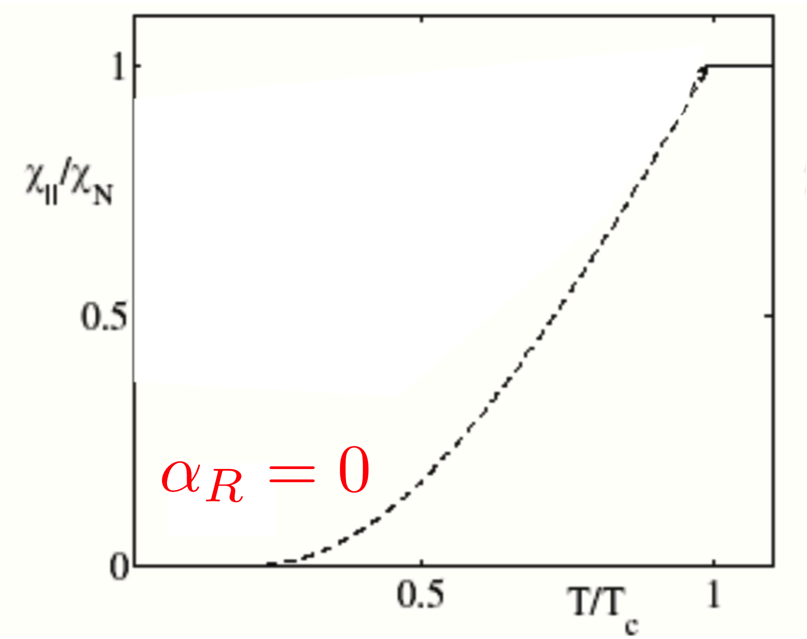
Bauer and Sigrist, Non-centrosymmetric superconductors, Lecture notes in Physics 2012

Spin susceptibility in singlet superconductor

H || ab



H || c



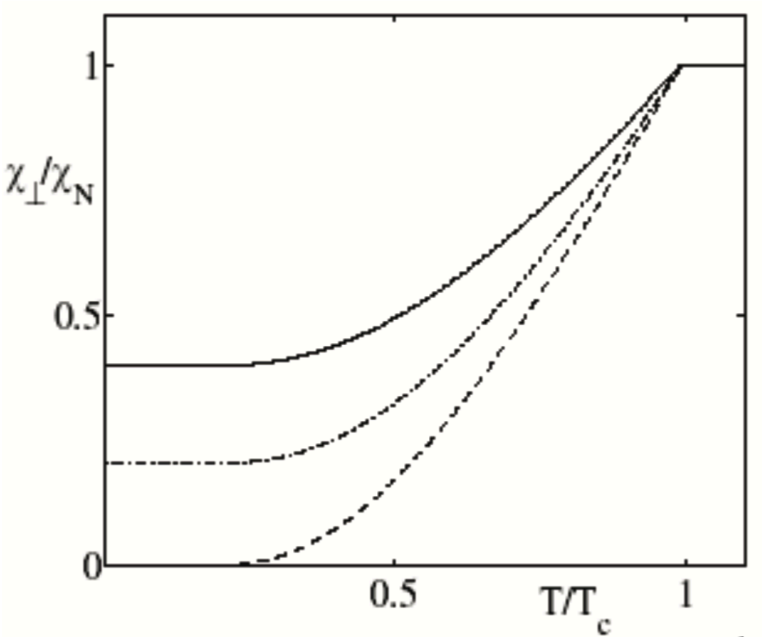
Singlet superconducting state

Frigeri et al. NJP 2004

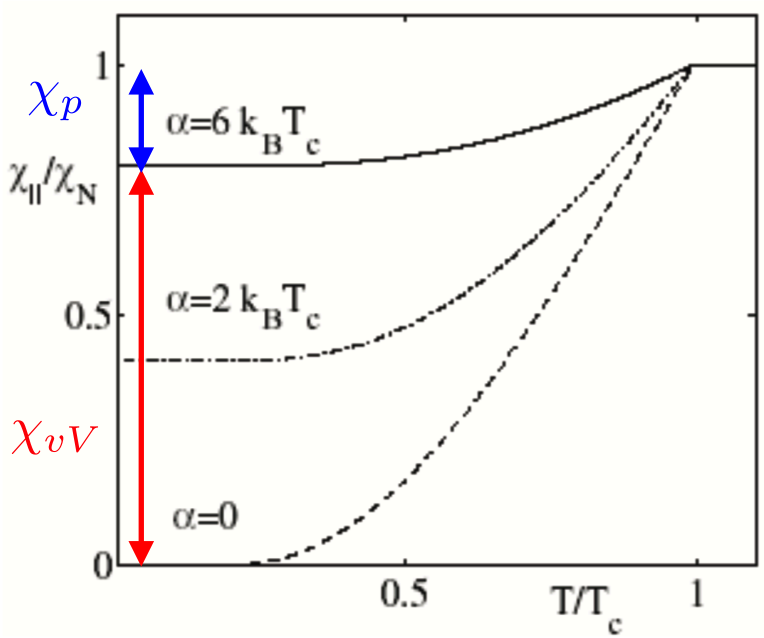
Pauli susceptibility vanishes in SC state

Spin susceptibility in singlet superconductor + Rashba

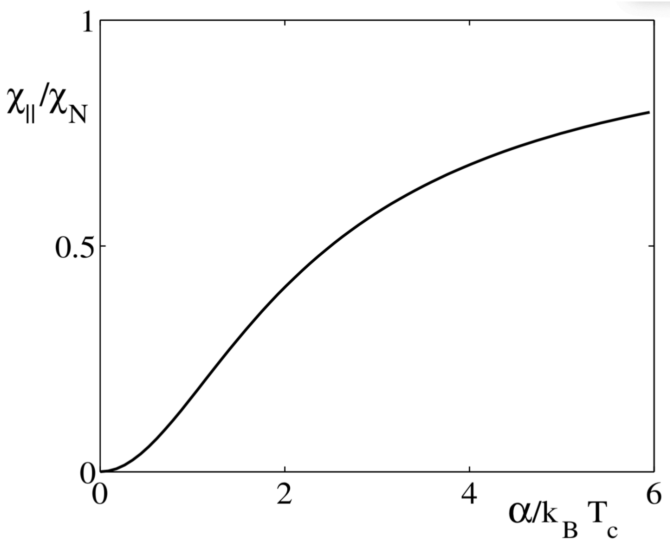
H || ab



H || c



H || c



$$\chi_{ab} = \frac{1}{2}(\chi_P + \chi_{vV})$$

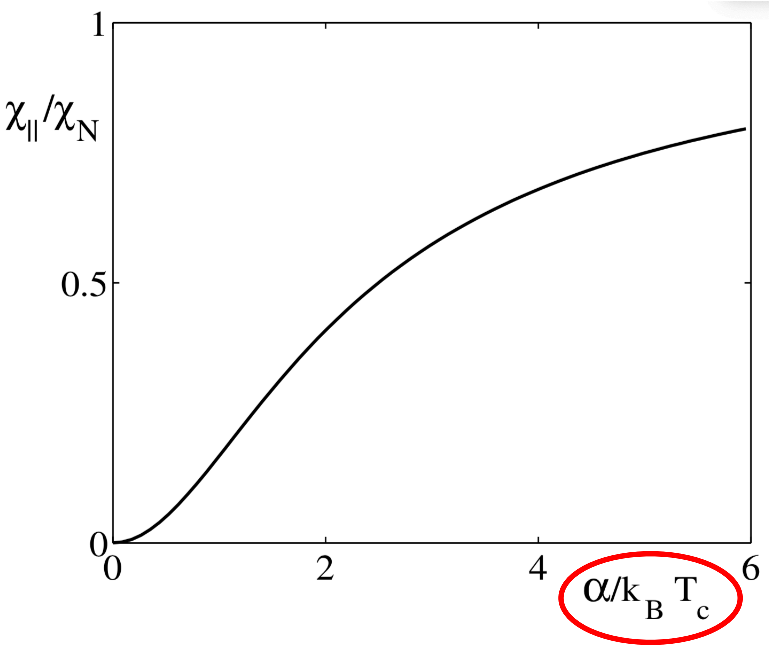
$$\chi_c = \chi_{vV}$$

Frigeri et al. NJP 2004

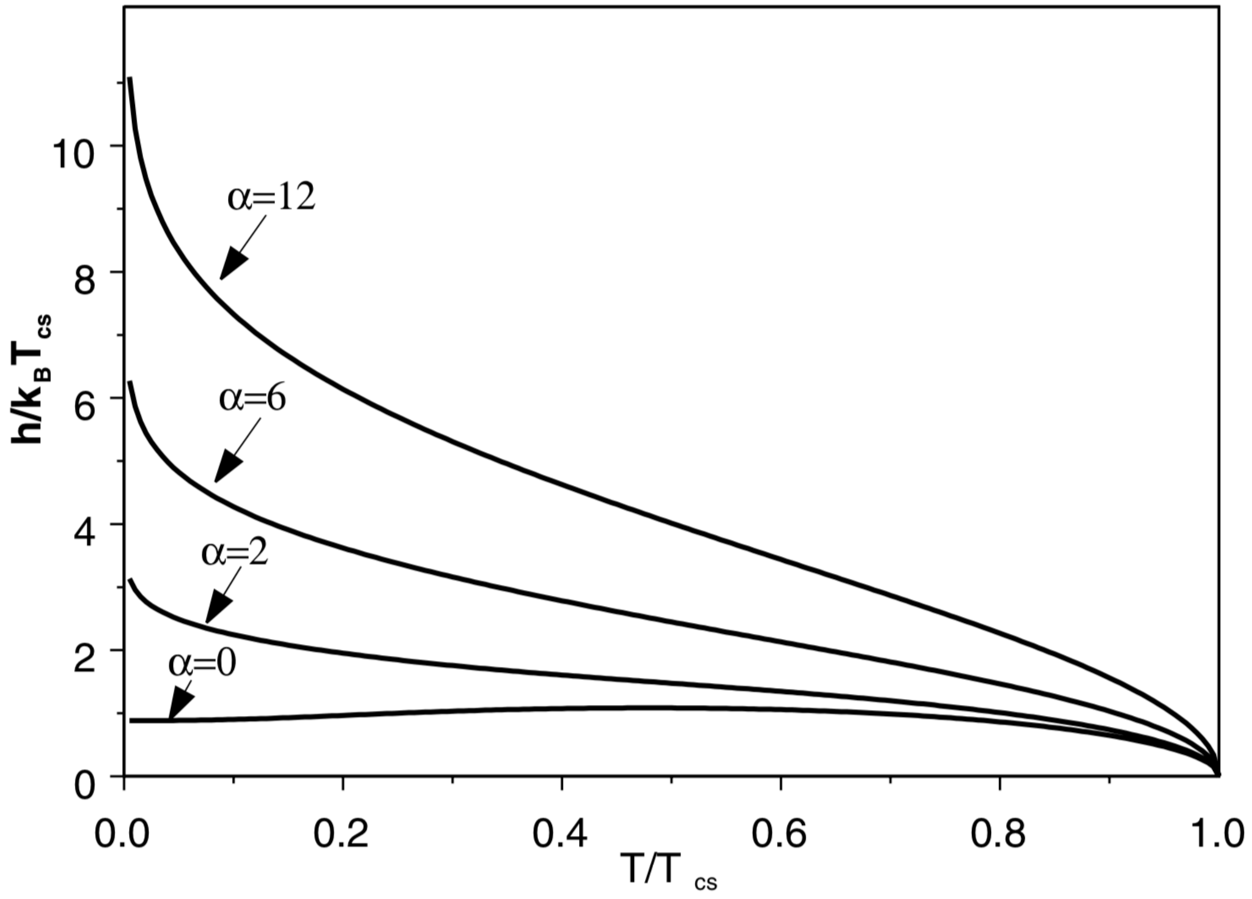
Pauli susceptibility vanishes in SC state
Van Vleck susceptibility not influenced by SC state

Pauli limit in singlet superconductor + Rashba

$$H_P \propto \frac{T_c}{g\sqrt{1-\chi_s/\chi_n}}$$

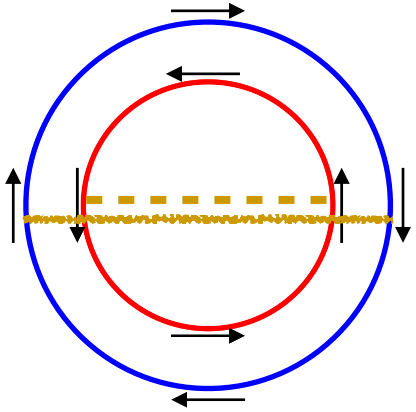


> 10 ...1000



Frigeri et al. PRL (2004)

Non-centrosymmetric superconductors versus $CeRh_2As_2$



Non-centrosymmetric superconductors

- Enhanced Pauli limit ("spin locking")
- Anisotropic Pauli limit with larger Pauli limit for H||c

But:

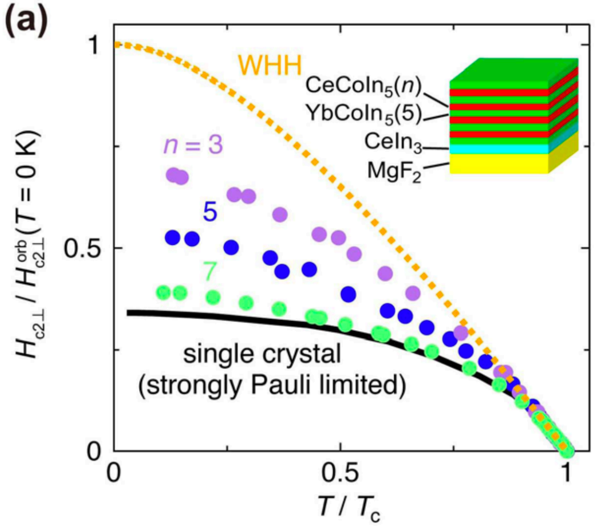
Kink not observed in non-centrosymmetric systems

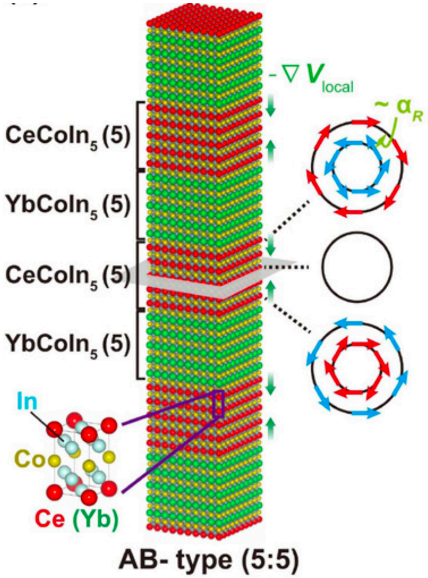
How about locally non-centrosymmetric system?

Locally non-centrosymmetric superconductors

Large critical fields in layered superconductors

S. Goh, et. al. PRL (2012)
Shimozawa, et. al., Rep. Prog. Phys. (2016)





Locally non-centrosymmetric superconductors

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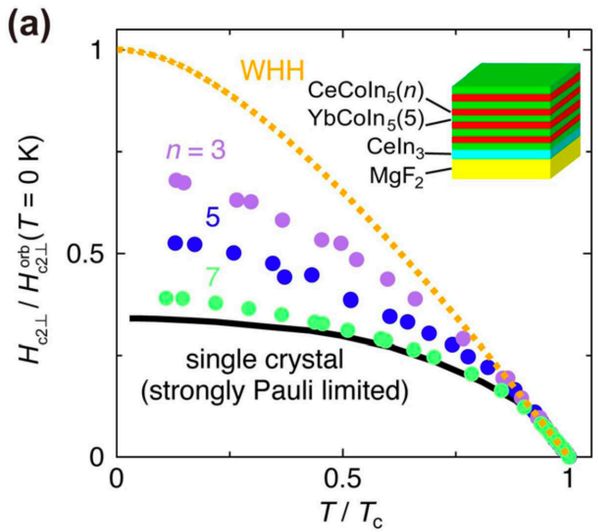
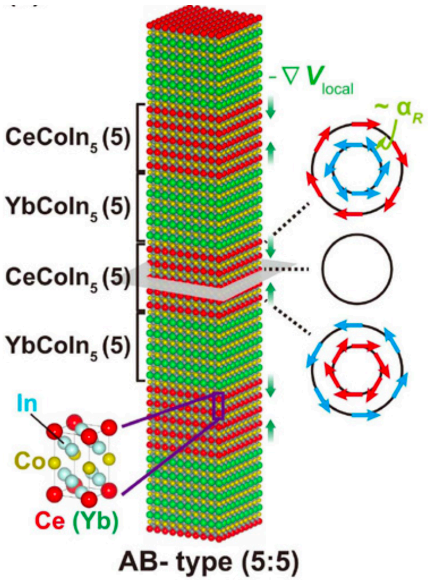
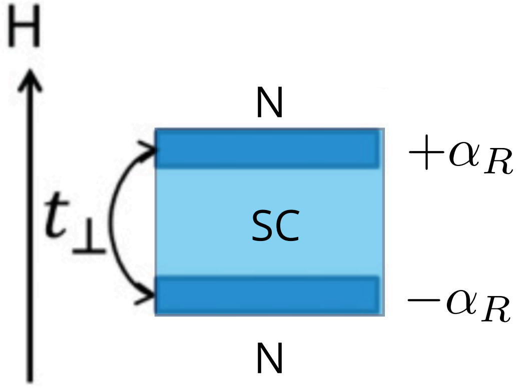


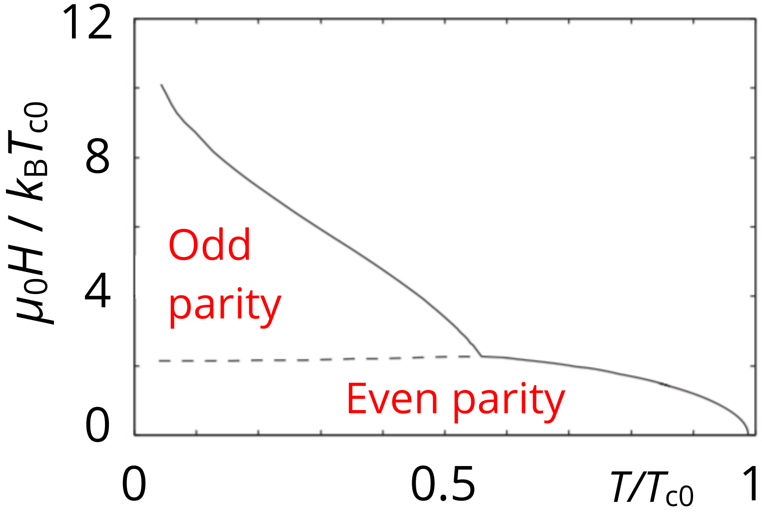




Two superconducting states

Even parity	Odd parity
Δ	$-\Delta$
Δ	Δ

Parity is well defined, no mixing



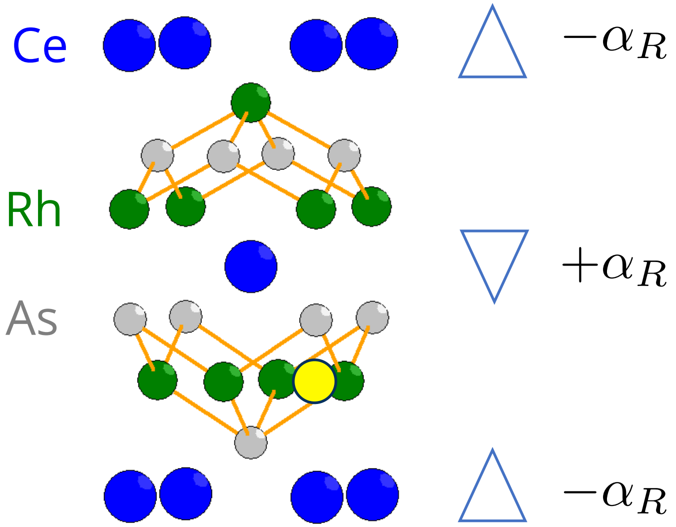
For intermediate

$$\frac{\alpha_R}{t_\perp}$$

Yoshida, Sigrist, Yanase, PRB (2012)

Crystal structure

$CaBe_2Ge_2$-type
P4/nmm



Local C_{4v} point group
Overall centrosymmetric

R. Madar et al., J. Less-Common Metals (1987)

Locally non-centrosymmetric at Ce position

Two Ce atoms per unit cell

Alternating Ce environment

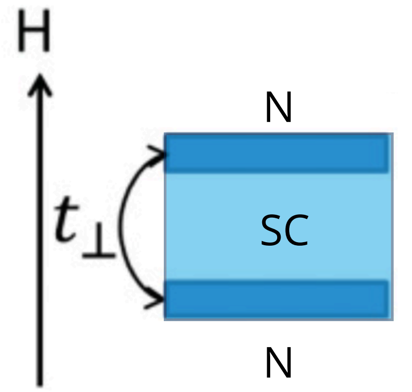
Alternating Rashba interaction

Globally inversion symmetric

=> Parity is well defined, no mixing

Locally non-centrosymmetric superconductors

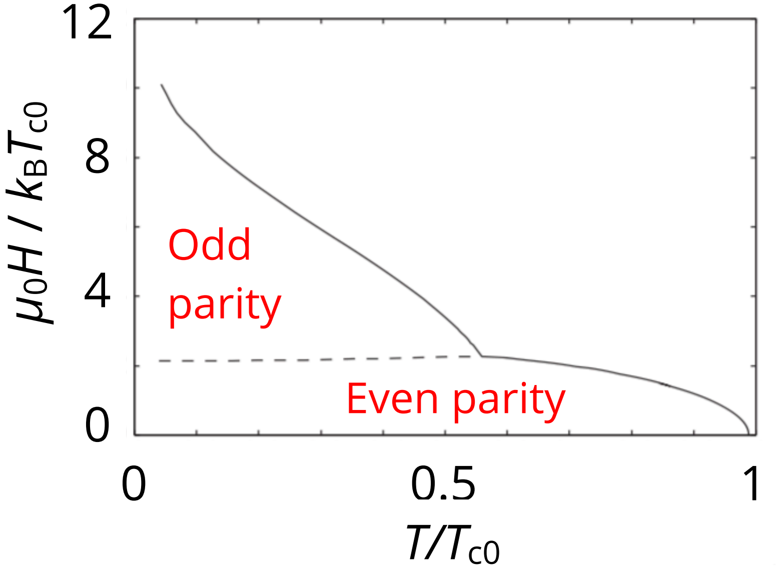
Two superconducting states

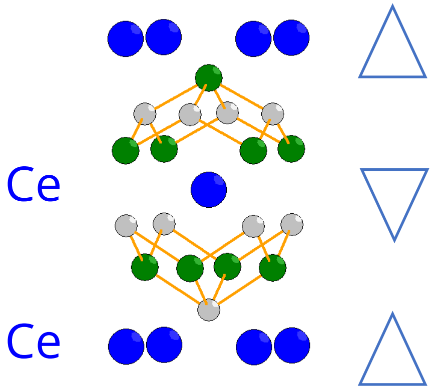


	Even parity	Odd parity
$+\alpha_R$	Δ	$-\Delta$
$-\alpha_R$	Δ	Δ

Yoshida, Sigrist, Yanase, PRB (2012)

Parity is well defined, no mixing

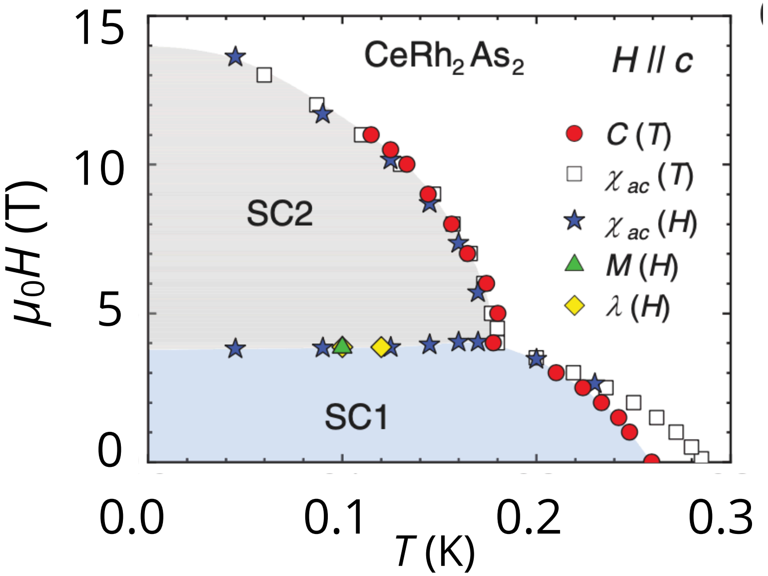




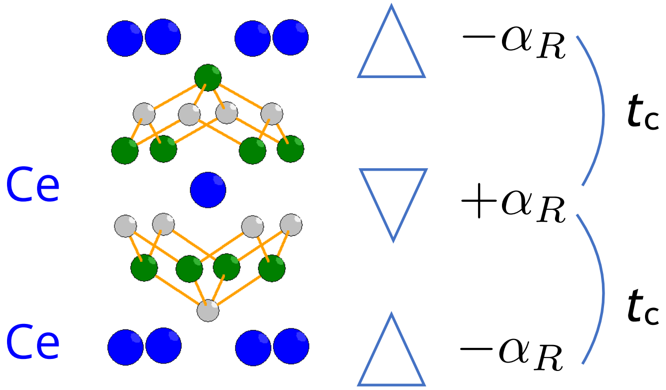
$-\alpha_R$	Δ	$-\Delta$
$+\alpha_R$	Δ	Δ
$-\alpha_R$	Δ	$-\Delta$

t_c

t_c



Model



In-plane hopping

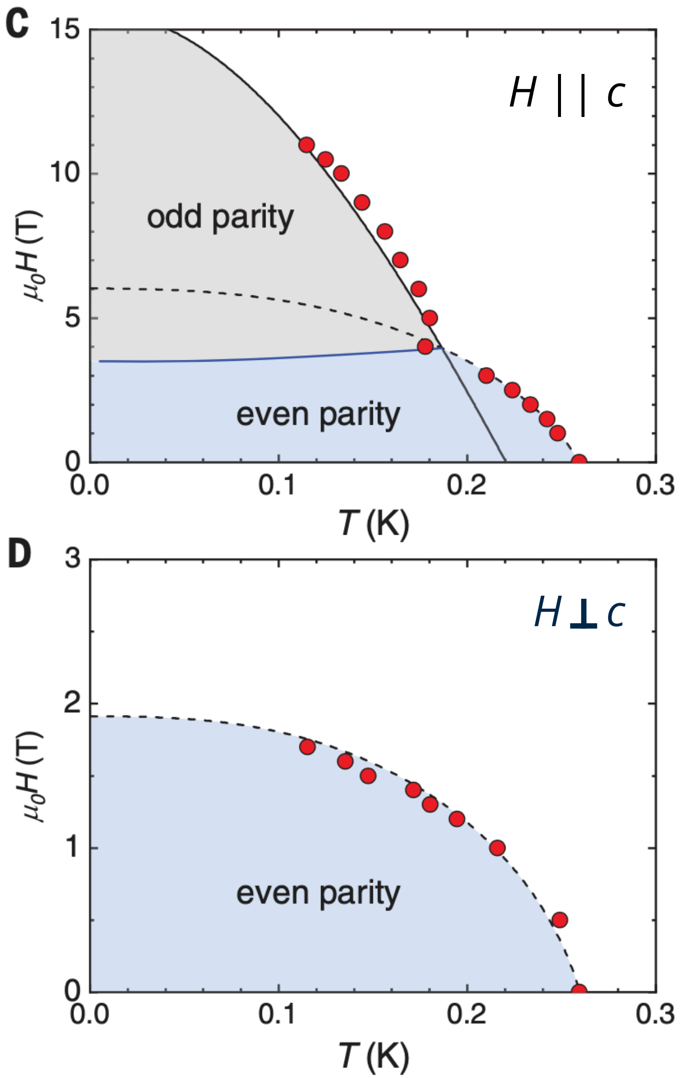
Rashba SO term

$$
\begin{aligned}
H_N = \quad & t_1[\cos(k_x)+\cos(k_y)] - \mu + \alpha_R \tau_z [\sin(k_x)\sigma_y - \sin(k_y)\sigma_x] \\
& + t_{c,1}\tau_x \cos(\frac{k_z}{2})\cos(\frac{k_x}{2})\cos(\frac{k_y}{2}) + t_{c,2}\tau_y \sin(\frac{k_z}{2})\cos(\frac{k_x}{2})\cos(\frac{k_y}{2}) \\
& + \lambda \tau_z \sigma_z \sin k_z (\cos k_x - \cos k_y) \sin k_x \sin k_y .
\end{aligned}
$$

Inter-layer hopping

Ising-like SO term
(much smaller than Rashba) => set to 0

Even- to odd-parity transition

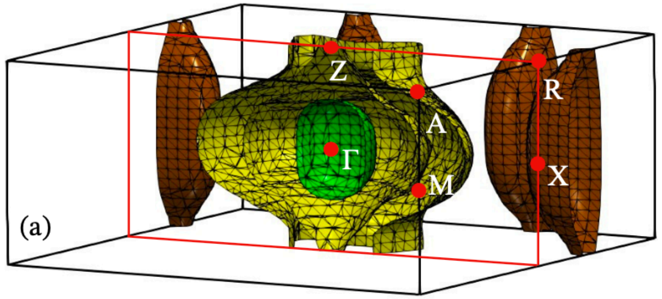


Phase transition from even-parity to odd-parity superconductivity

SC1 Pauli limited with enhanced Pauli limit
Anisotropy given by ratio $\alpha_{\mathrm{R}}/t_{\mathrm{c}}$

Cavanagh *et al.*, PRR (2021)
Large ratio from non-symmorphicity

Nogaki *et al.*, PRR (2021)
Odd-parity state predicted to be **topological crystalline superconducting state**



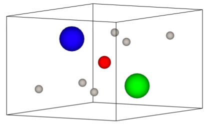
Hafner *et al.* PRX (2022)

Local inversion symmetry breaking

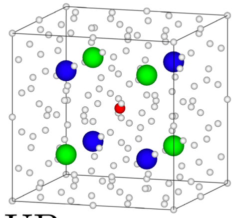
A common motif

Inversion partner atoms

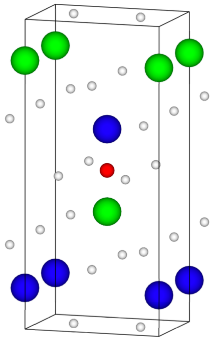
Sublattice degree of freedom



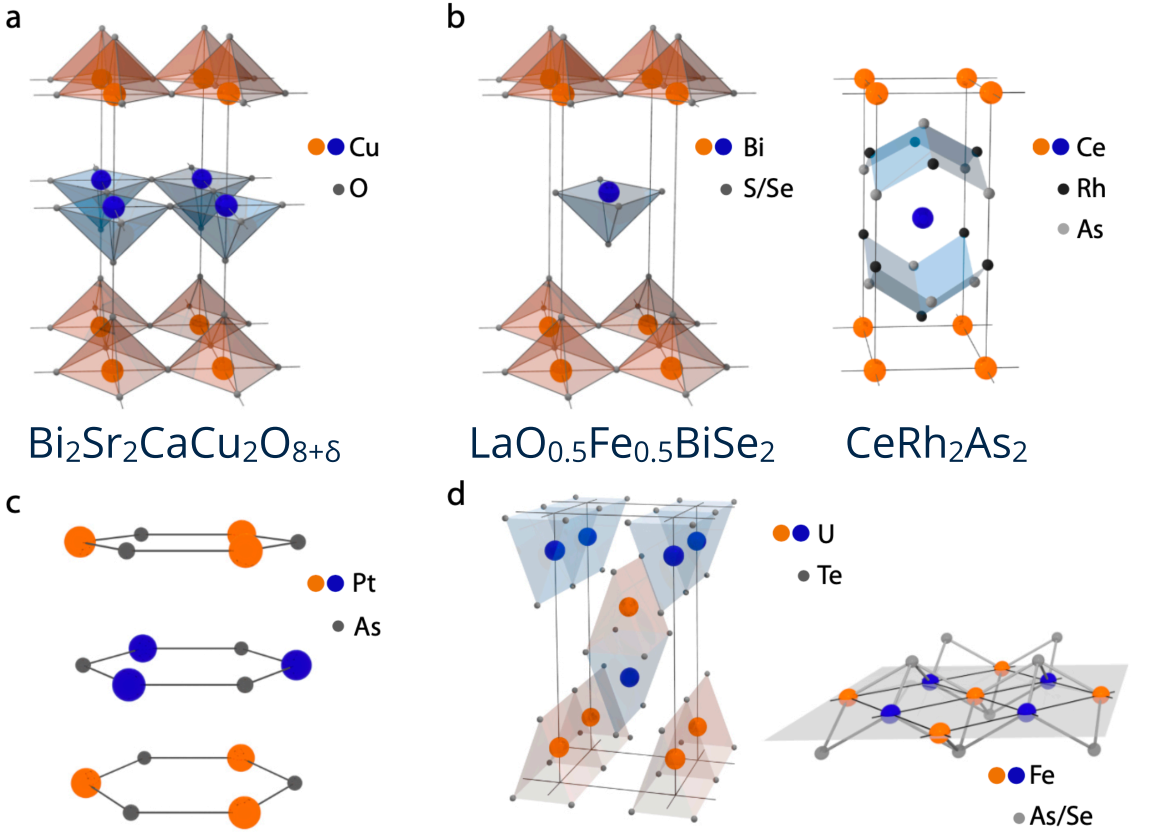
$\mathrm{UPt_3}$



$\mathrm{UBe_{13}}$



$\mathrm{UTe_2}$



$\mathrm{Bi_2Sr_2CaCu_2O_{8+\delta}}$

$\mathrm{LaO_{0.5}Fe_{0.5}BiSe_2}$

$\mathrm{CeRh_2As_2}$

SrPtAs

$\mathrm{UTe_2}$

Single-layer Fe SC

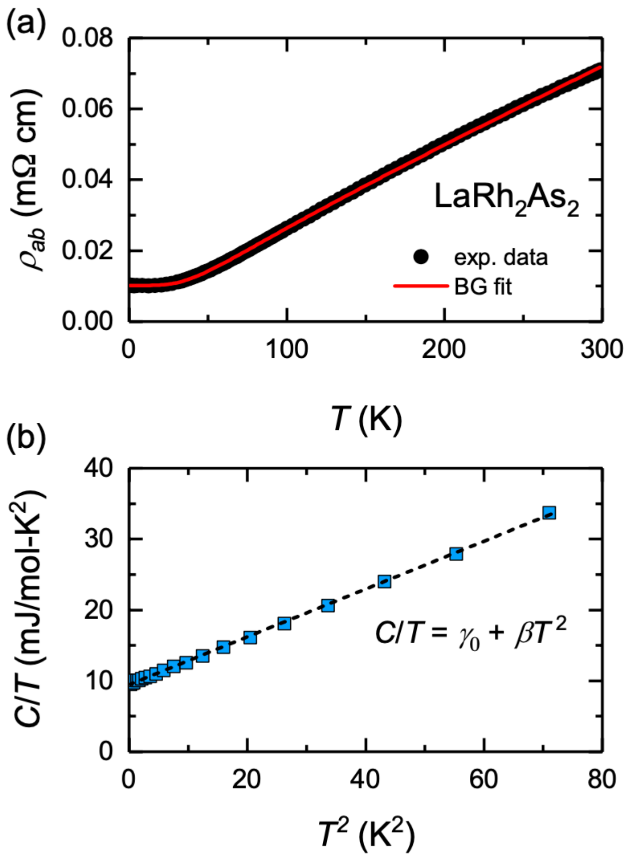
Anderson, PRB (1984)

Appel and Hertel, PRB (1987)

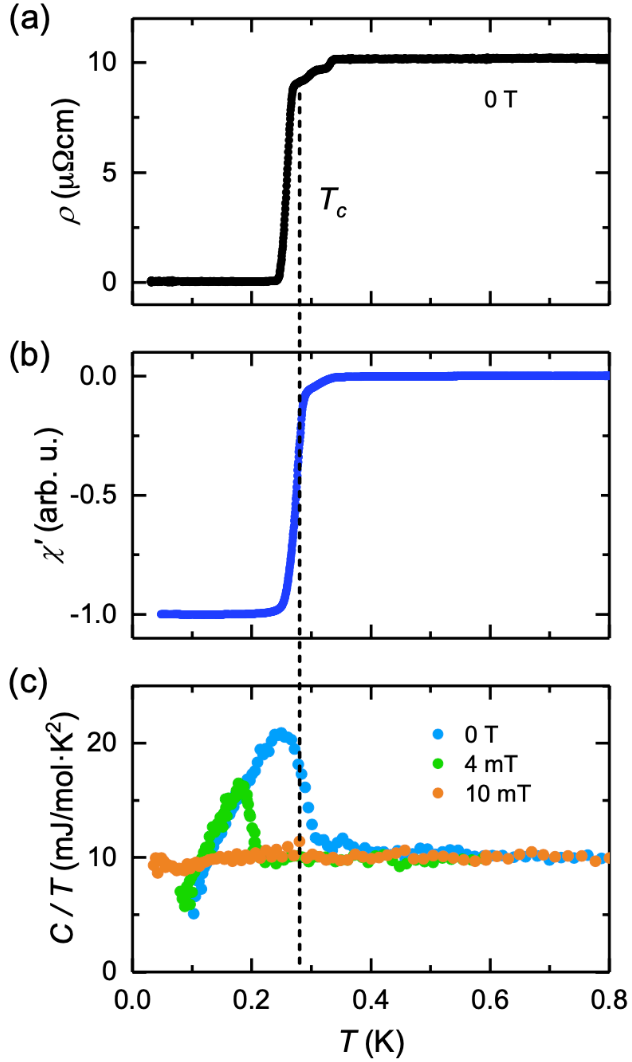
Hazra and Coleman, PRL (2023)

Fischer *et al*., Ann. Rev. Cond. Mat. (2023). <— Review paper on locally non-centrosymmetric superconductors

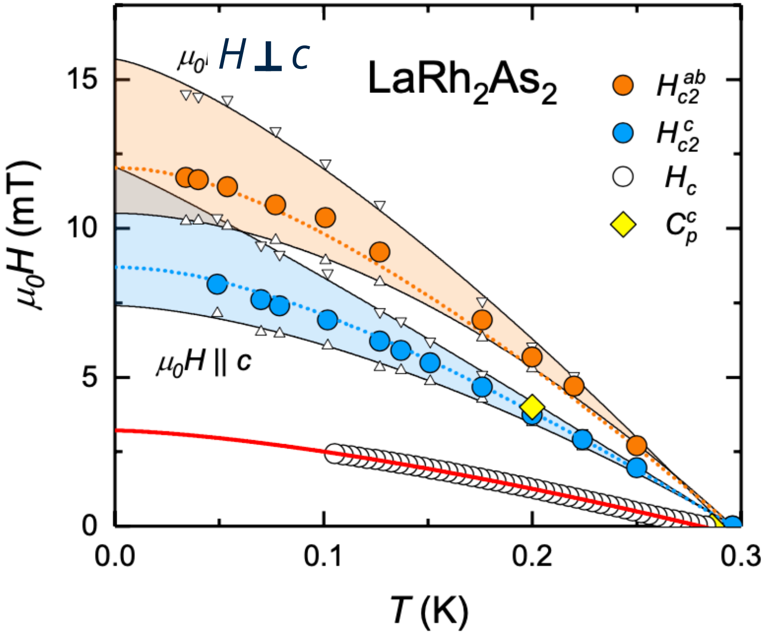
Symmetry is not everything
The case of $LaRh_2As_2$



- Same structure
- Weak correlations



- Same T_c
- Conventional Phonon coupling
- Low critical fields (orbitally limited)
- Correlations are needed!



Landaeta et al. PRB (2022)

2. Relation of superconductivity with Phase I

Pressure experiments

Pressure tuning

Pressure effective tuning parameter for quantum materials

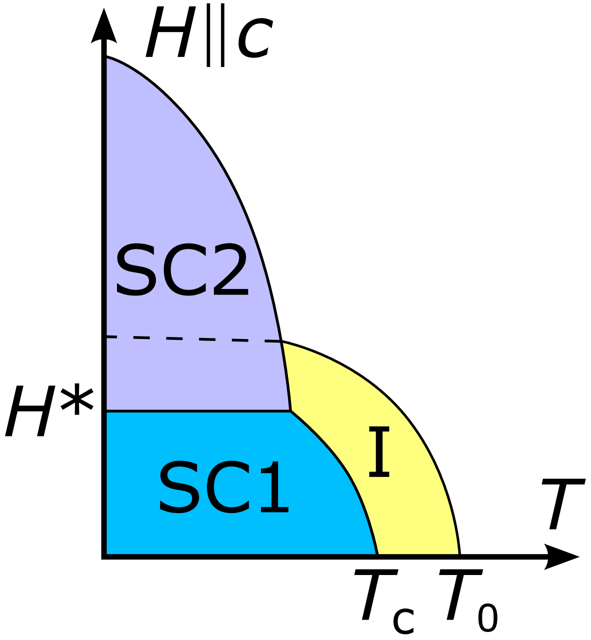
What stabilises two-phase superconductivity?

Proximity to quantum critical point?

Resistivity and specific heat

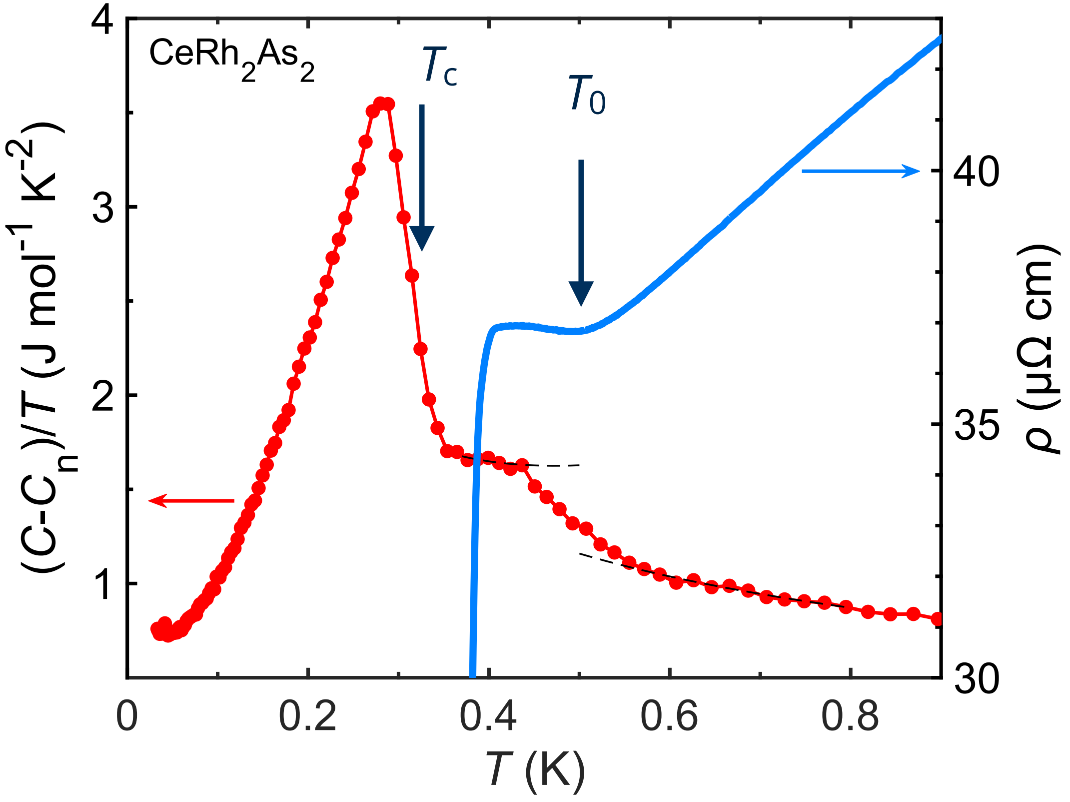
P up to 2.67 GPa in piston cylinder pressure cell

Information on both normal and superconducting state properties



M. Pfeiffer, K. Semeniuk, J. Landaeta, R. Borth, C. Geibel, M. Nicklas, M. Brando, S. Khim, E. Hassinger, arXiv:2312.09728 (2023)
K. Semeniuk, M. Pfeiffer, J. Landaeta, M. Nicklas, C. Geibel, M. Brando, S. Khim, E. Hassinger, arXiv:2312.09729 (2023)

Proximity to a quantum critical point



Specific heat

Huge Sommerfeld coefficient
=> Large effective mass

Non-Fermi liquid behaviour

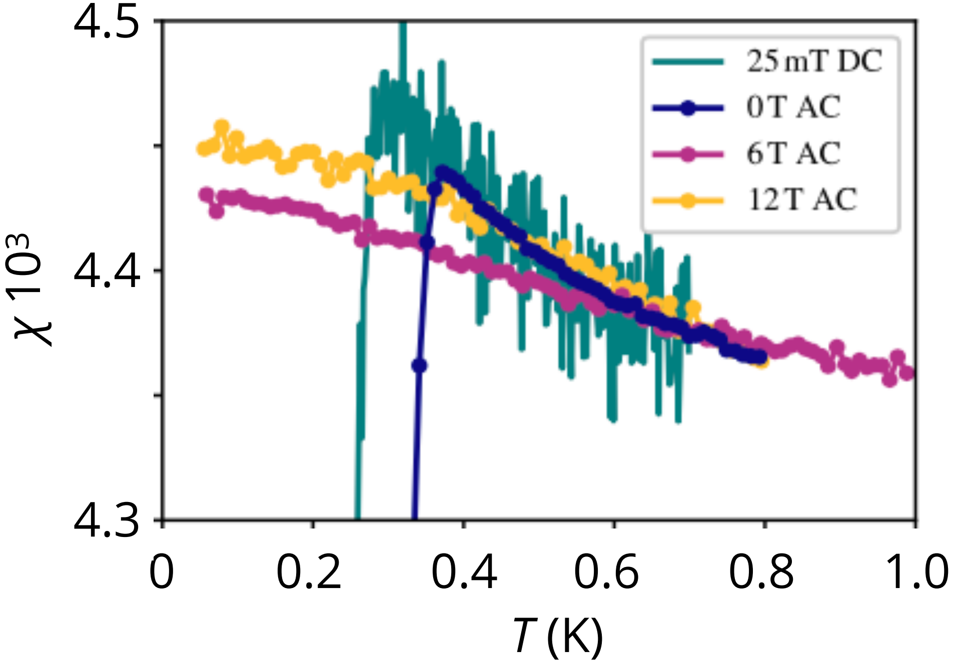
Resistivity

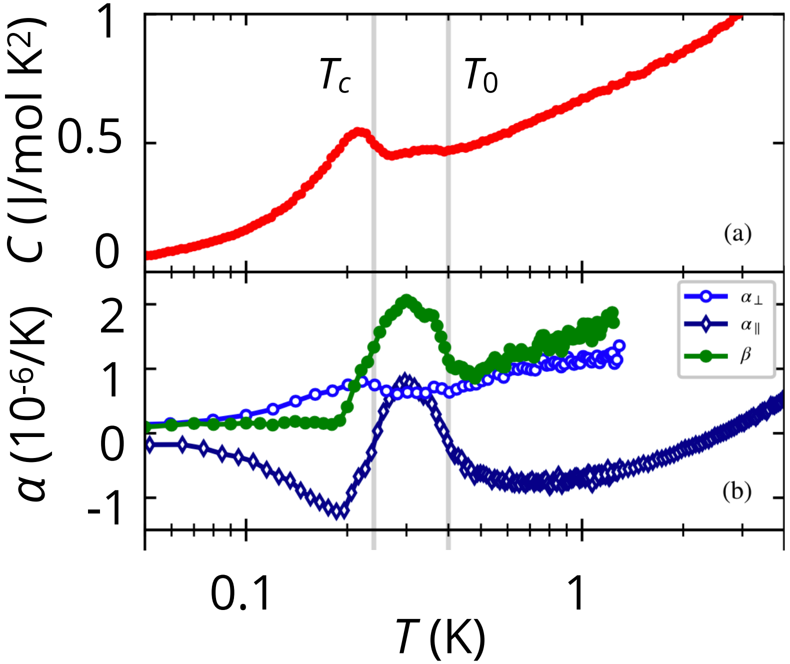
~ $T^{0.5}$

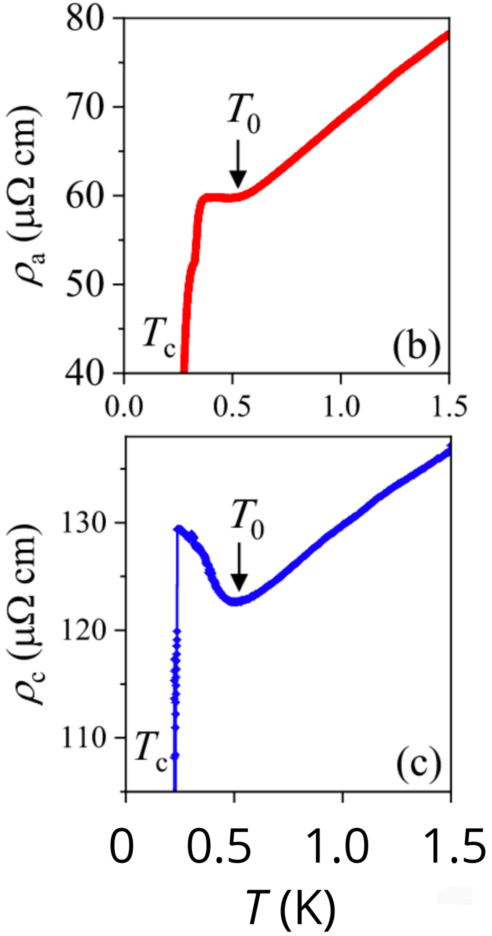
Low ordering temperature T_0
Phase I QCP?

Is superconductivity stabilised by quantum fluctuations of Phase I?

Experimental signatures of the transition at T_0







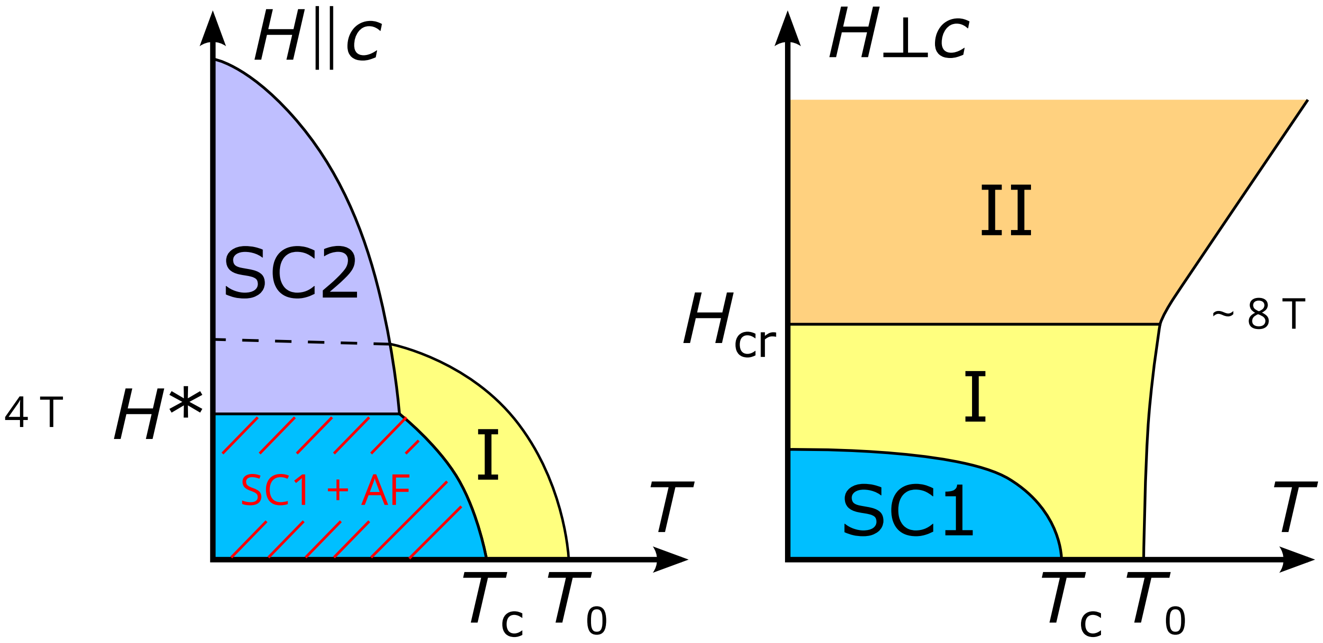
No anomaly observed at T_0 in susceptibility and magnetization

Weak magnetic or non-magnetic order

Microscopic information missing

Mishra *et al.*, PRB (2022)
D. Hafner *et al.*, PRX (2022)

Anisotropy of T_0 in field with strong enhancement for $H \perp c$



Hafner, *et al.*, PRX (2022)
K. Semeniuk, et al., PRB (2023)

Kibune et al. PRL (2022)
Ogata et al. PRL (2023)
Machida, PRB (2022)
Schmidt and Thalmeier, arxiv (2024)

Strong increase of T_0 for inplane fields not expected for AF order

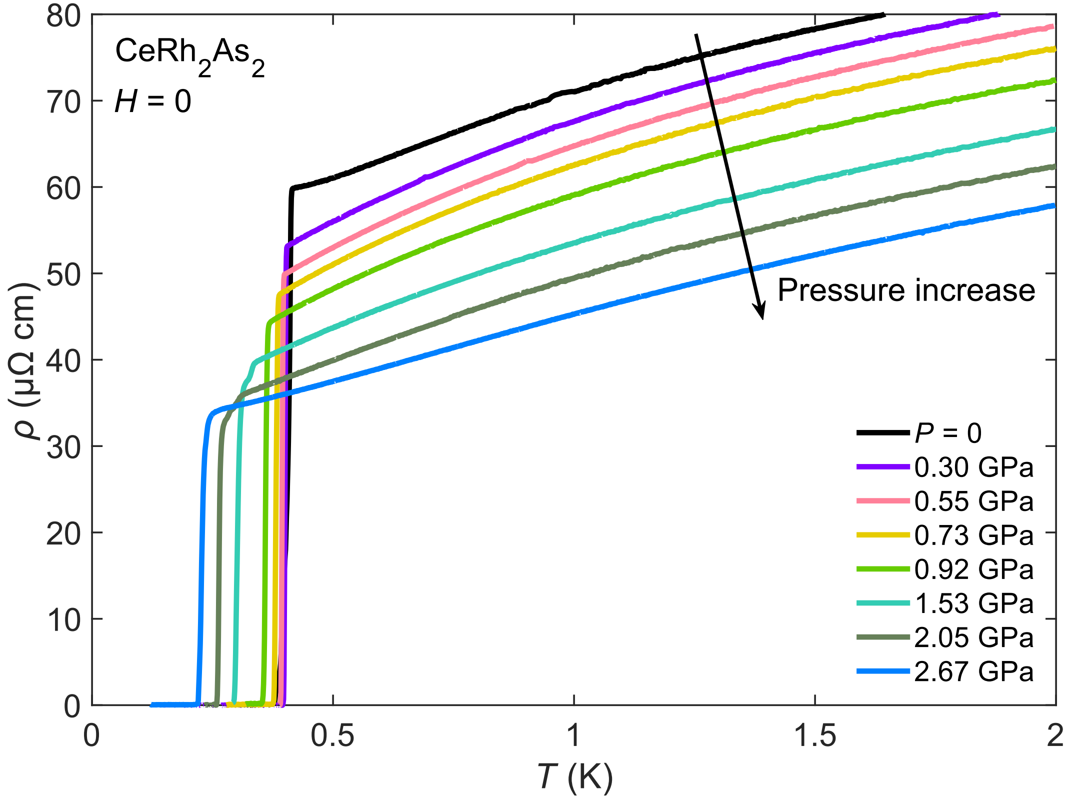
NQR/NMR
Onset of AF order below 0.25 K
= bulk T_c of that sample

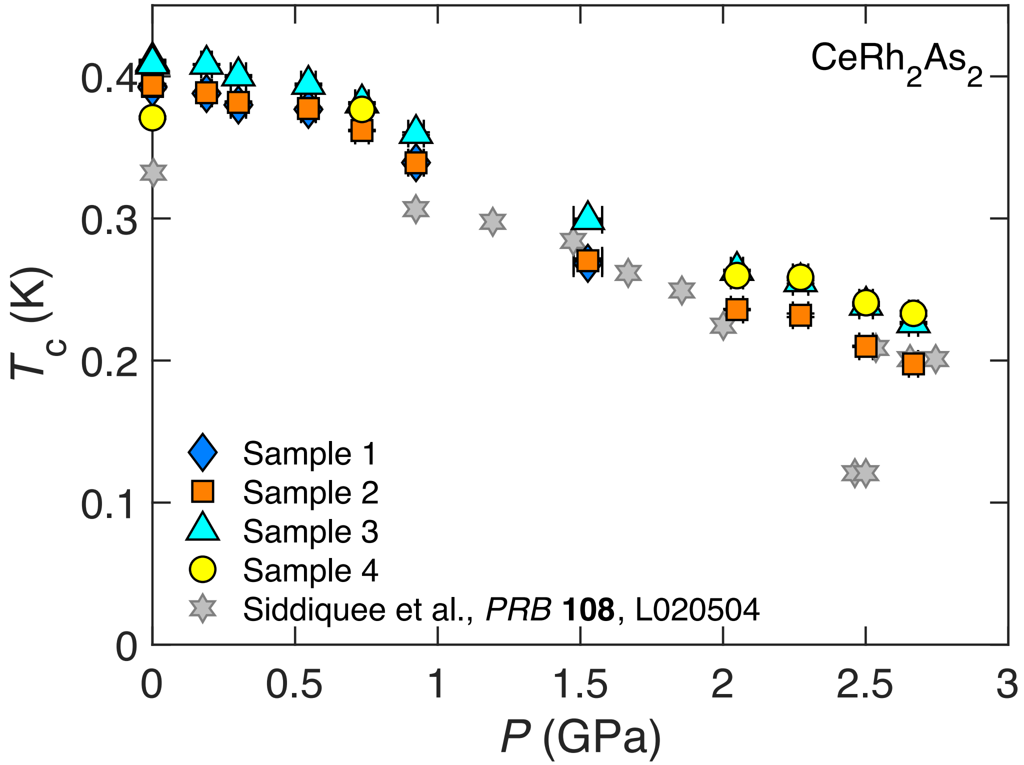
Third order parameter? Accidentally same critical temperature as SC?

Possibility that H* is a magnetic transition???

Here, we focus on T_c and T_0
no evidence for extra AF state in our measurements.

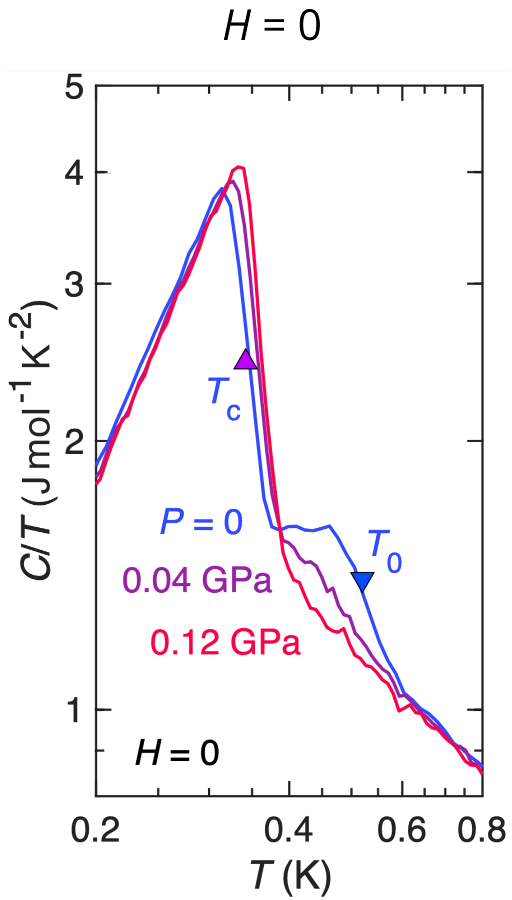
Suppression of T_c

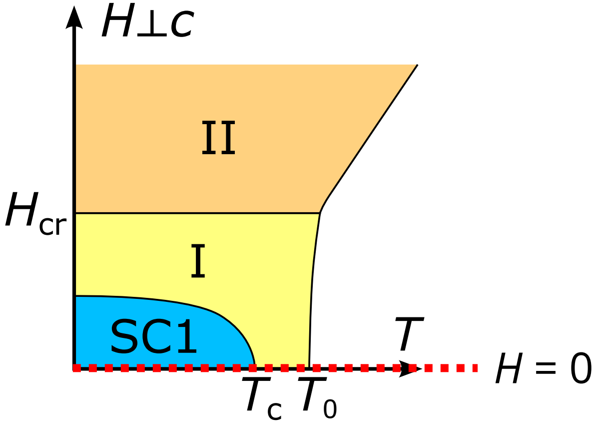




Monotonous decrease of T_c
by factor of 2

T_0 suppressed by pressure

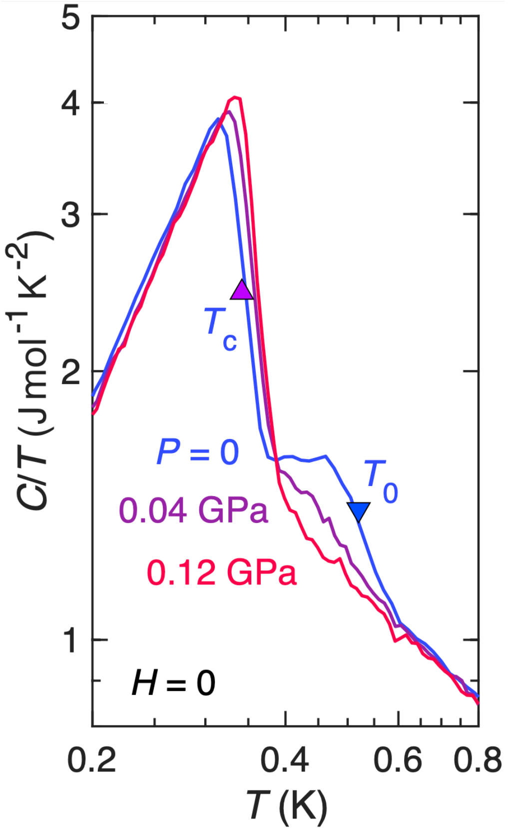




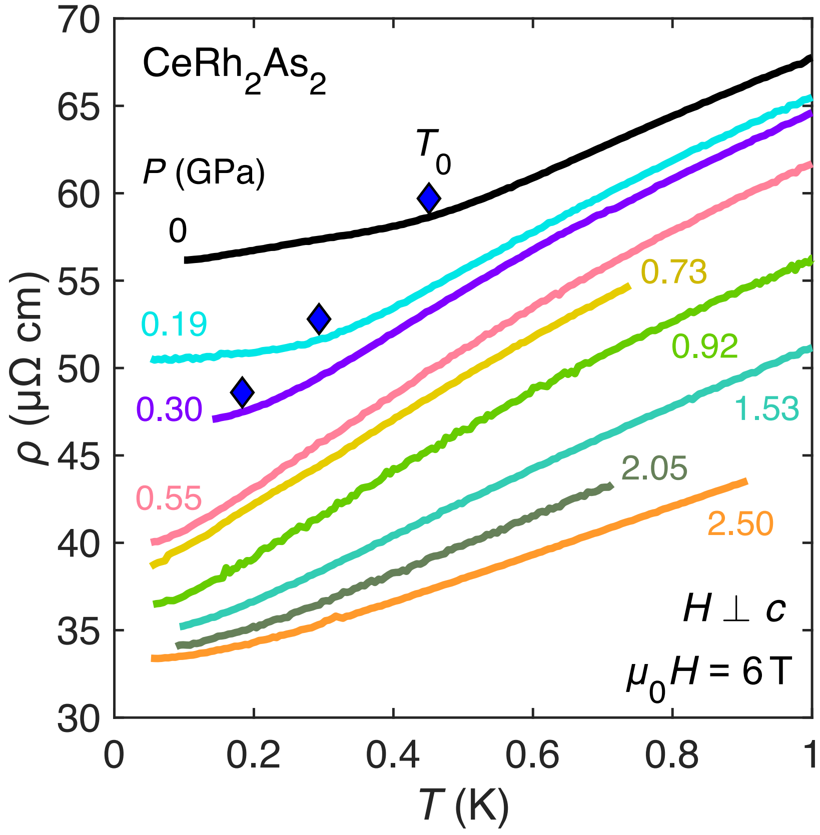
Suppression of T_0

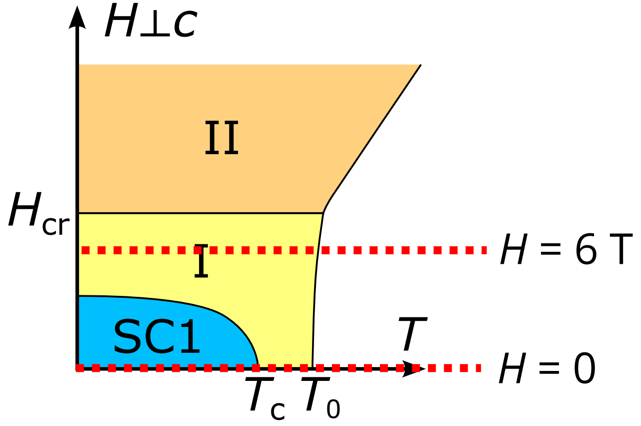
T_0 suppressed by pressure

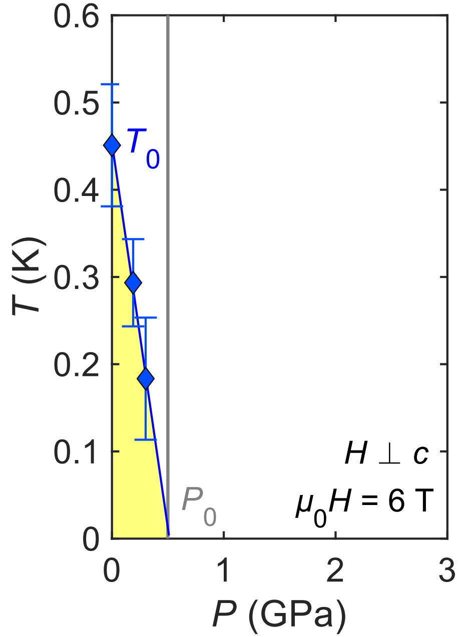
$H = 0$



$H = 6$ T

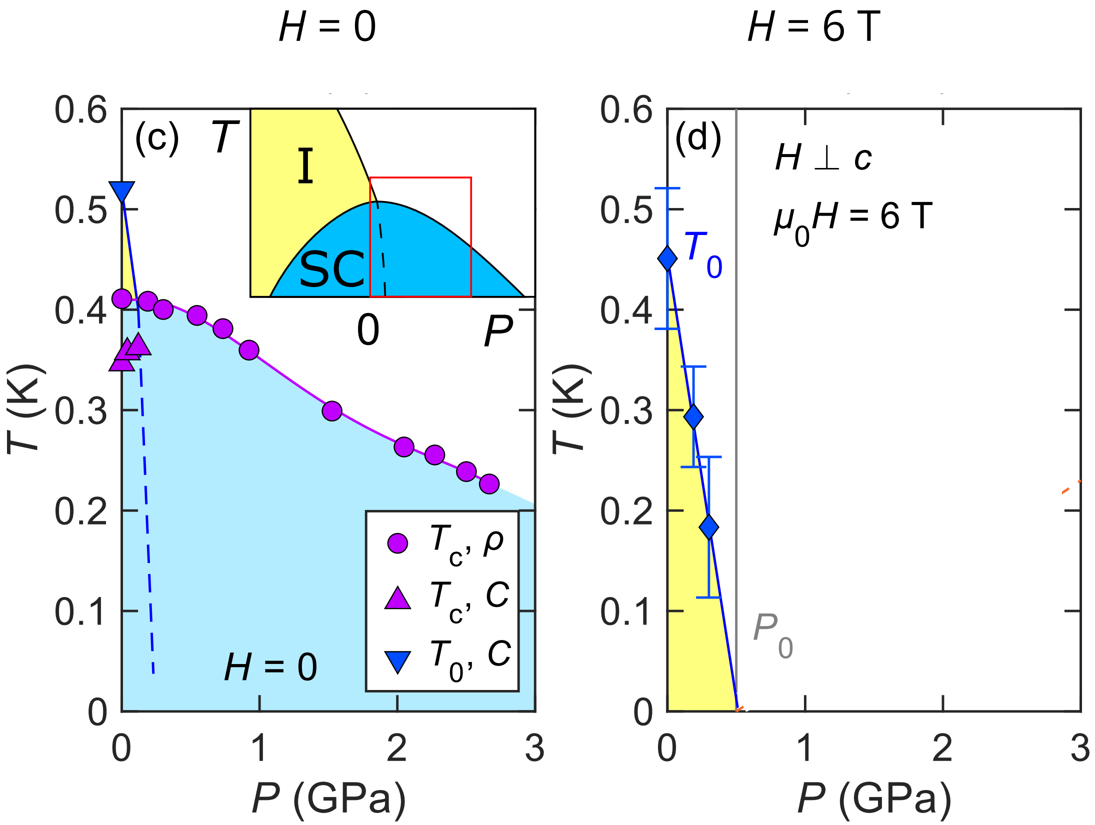






Suppression of T_0 in zero field and also at 6 T

Quantum critical point of Phase I and superconducting dome



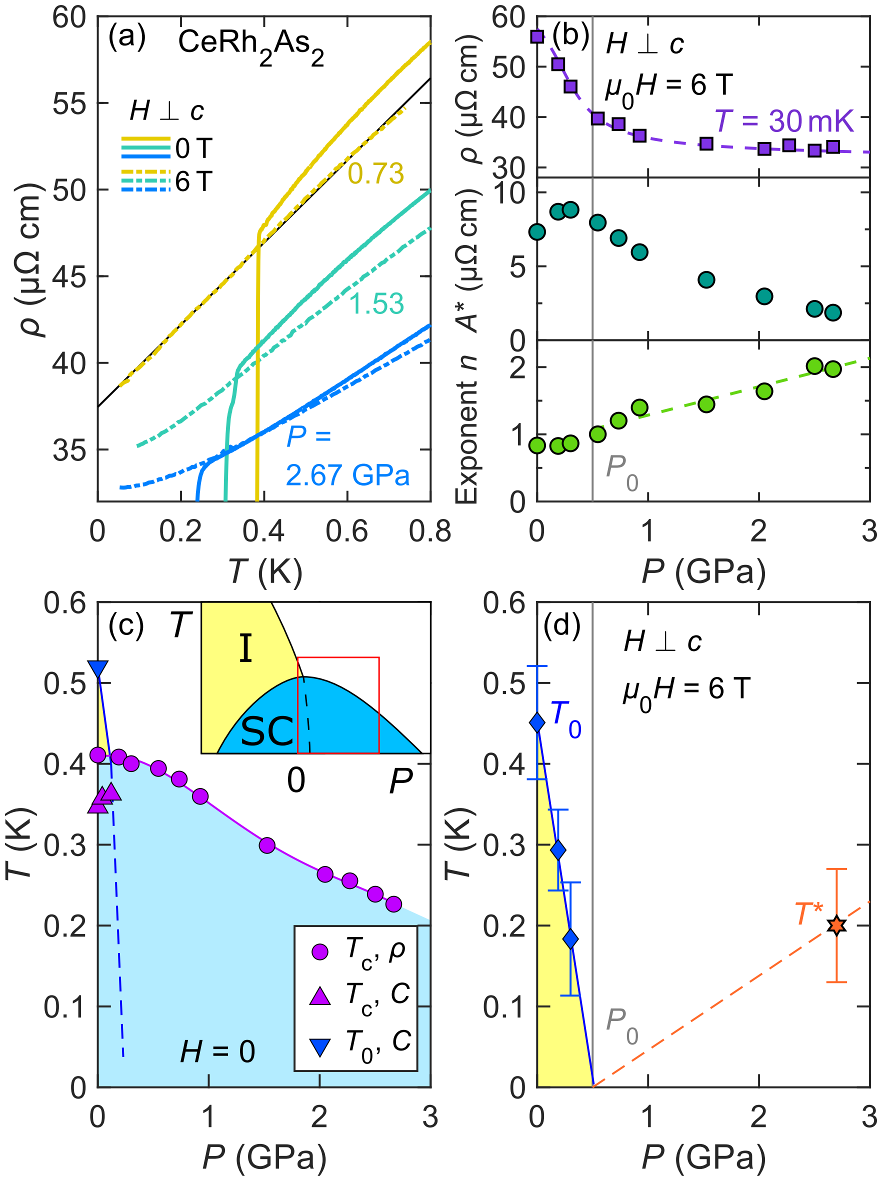
Quantum critical point of Phase I

P_0 = 0.5 GPa

Dome of superconductivity around P_0

Quantum critical fluctuations of Phase I are driving superconductivity

Temperature dependence of resistivity



Power-law analysis

$$\rho(T) = \rho_0 + A^*(T/T_{\mathrm{ref}})^n, \text{ with } T_{\mathrm{ref}} = 0.3\,\mathrm{K}$$

Increase of exponent to n = 2 at 2.67 GPa

=> Recovery of Fermi liquid behavior below T^* = 0.2 K at 2.67 GPa

A* coefficient decreases for $P > P_0$

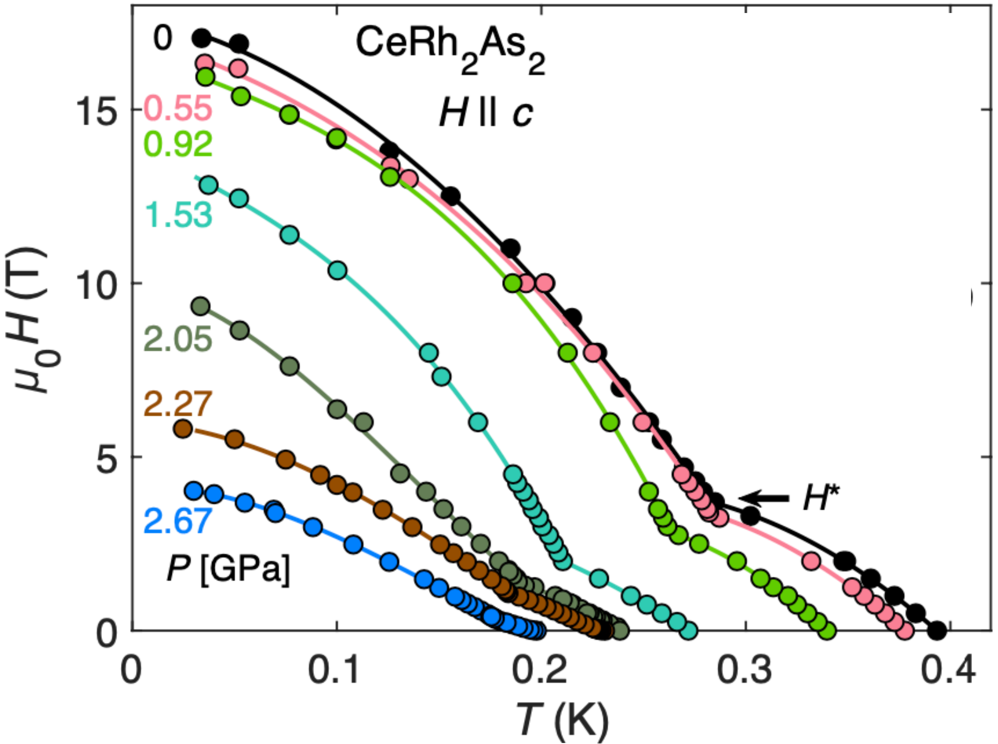
Corresponds to $\rho(T_{ref}) - \rho(T=0)$

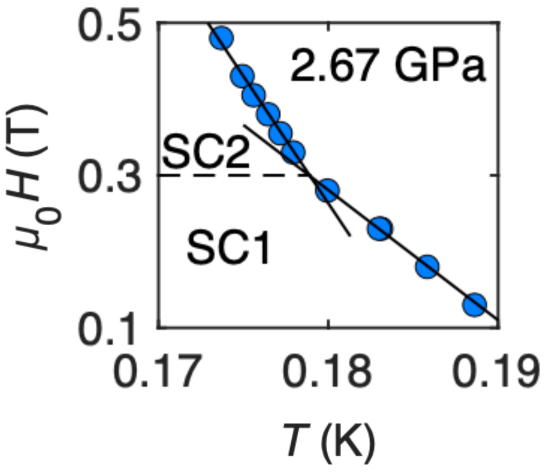
When T_{ref} = const

=> Decrease of correlations with pressure ($A \sim m^{*2}$)

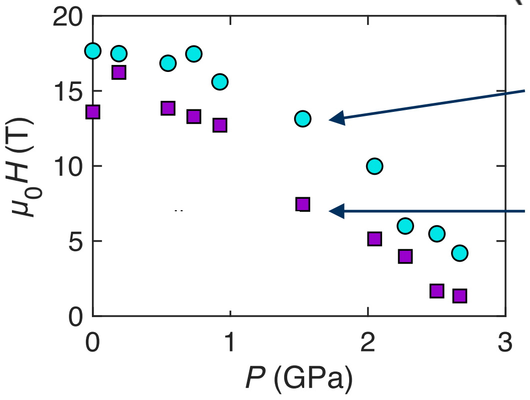
Confirmation of quantum critical behavior!

Critical field *H* | | *c*





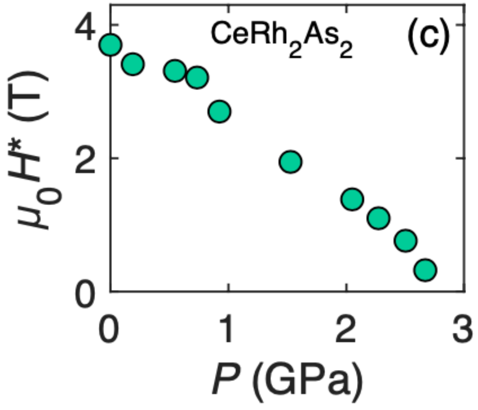
Two superconducting states survive up to 2.67 GPa



Monotonous decrease of H_{c2}

Due to decrease of orbital limit (slope near T_c)

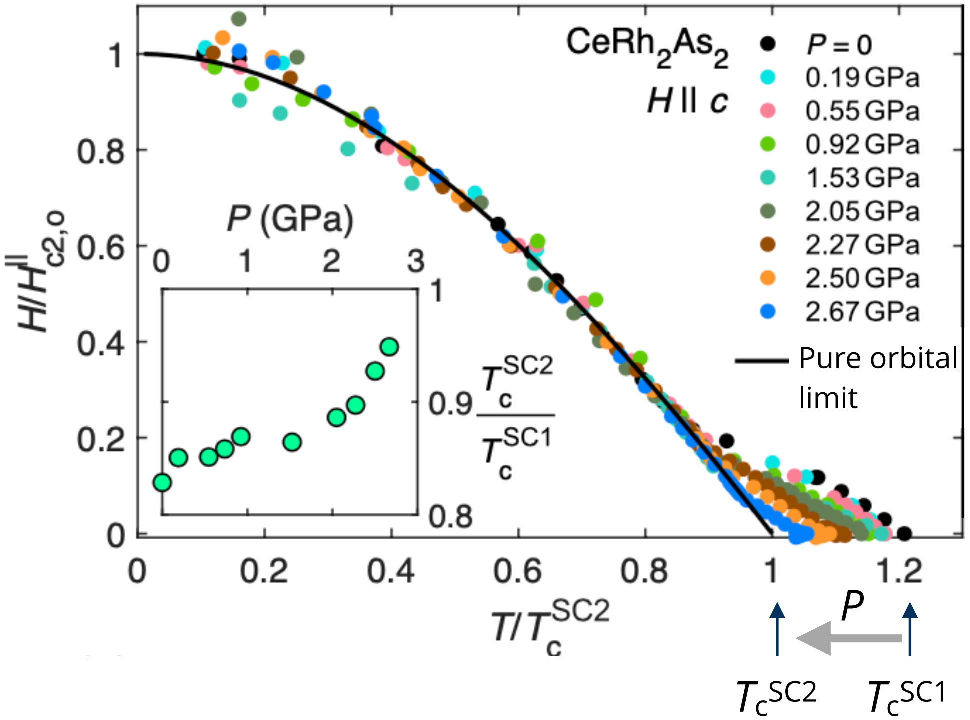
Due to decrease of effective mass when going away from QCP



Strong decrease of *H**

What does that mean for model?

Critical field *H* || *c* : comparison with model

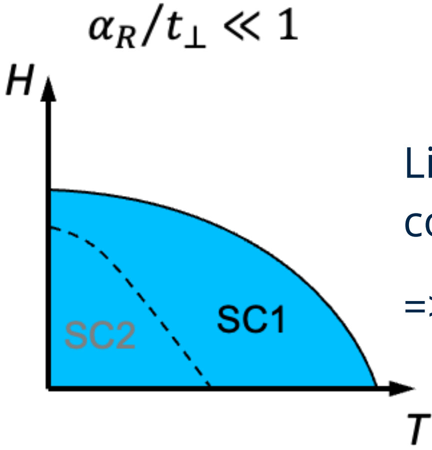


T_c (SC2) approaches T_c (SC1)

Strong pressure dependence is quite interesting.

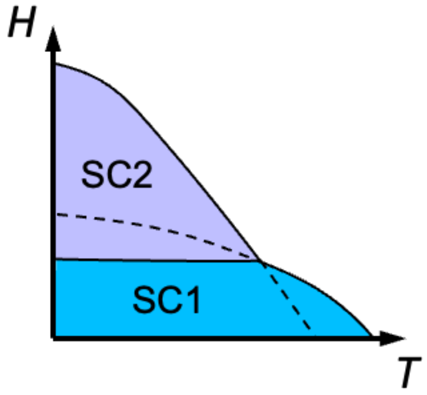
How can this be explained?

Critical field *H* || *c* : Model expectations



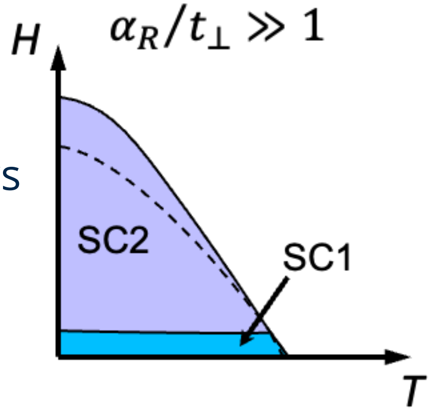
Limit of strongly coupled layers

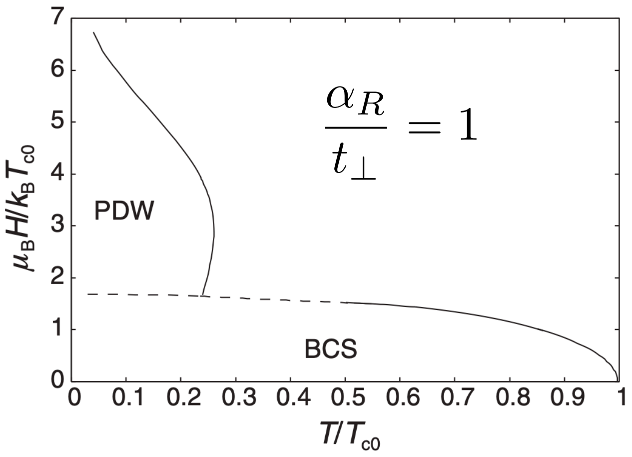
=> centrosymmetric

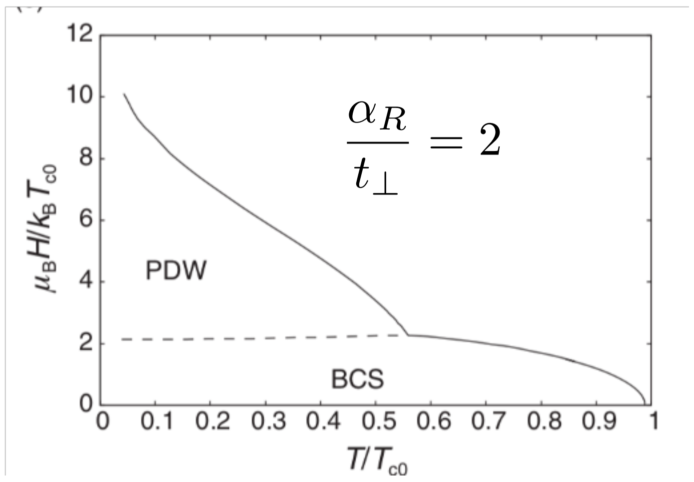


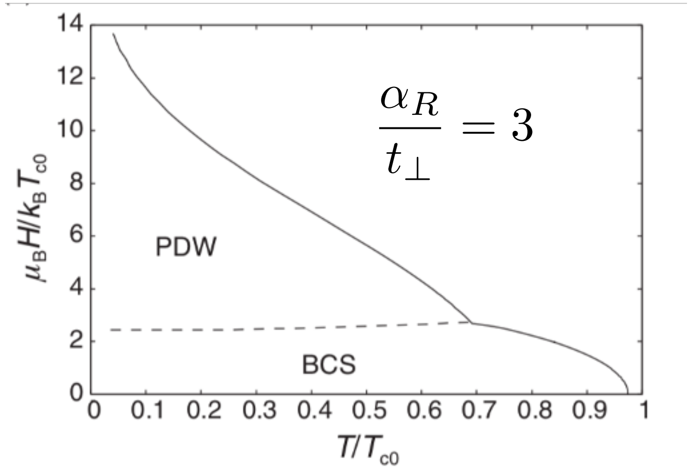
Limit of independent layers

=> non-centrosymmetric







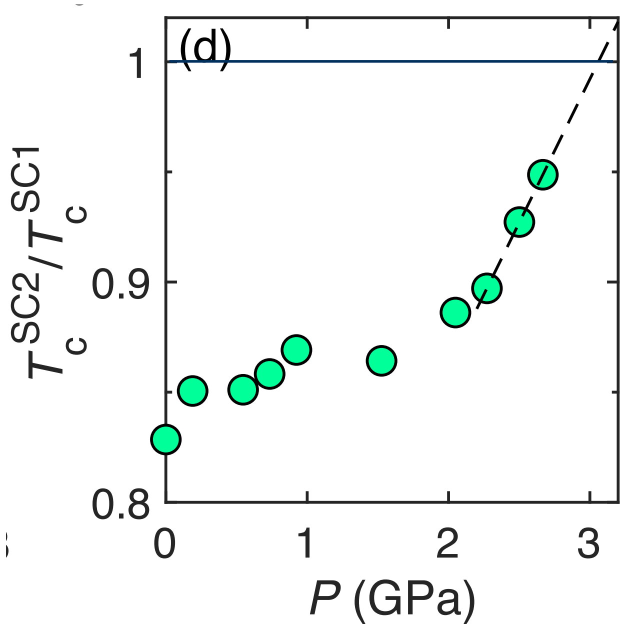


Yoshida, Sigrist, Yanase, PRB (2012)

Pressure tunes $\frac{\alpha_R}{t_\perp}$ effectively in CeRh$_2$As$_2$

Possible if Fermi surface at zone boundary is tuned by pressure

Critical field *H* || *c* : comparison with model



Extrapolation: T_c (SC2) will become equal to T_c (SC1) very quickly at 3 GPa

T_c (SC2) > T_c (SC1) is impossible within current model

Extension of current theory

1. Odd parity interaction becomes stronger with pressure, phase transition in zero field as a function of pressure from even-parity to odd-parity state

To be tested…

Pressure dependence - summary

Rather traditional pressure phase diagram with

Quantum critical point of Phase I at 0.5 GPa (but unknown order)

Superconducting dome

Two-phase superconductivity

*T*c suppressed but two states survive

Odd-parity superconductivity is stabilised by pressure

Prospect for odd-parity superconductivity in zero field?

Beyond the current theoretical understanding.

For more microscopic understanding, direct measurements of the order parameter of Phase I and of the Fermi surface (and its changes with pressure) are necessary.