Superconductivity in Non-Centrosymmetric Materials: Discovery in $LaRhGe_3$ and Normal-State Electron-Phonon Interactions

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TRIUMF

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Outline

- Superconductivity
- Superconductivity in Non-Centrosymmetric Materials
- Properties of the Weyl Semimetal $LaRhGe_3$
- Superconductivity in $LaRhGe_3$
- *e-ph* Interactions in the Normal State of $LaRhGe_3$

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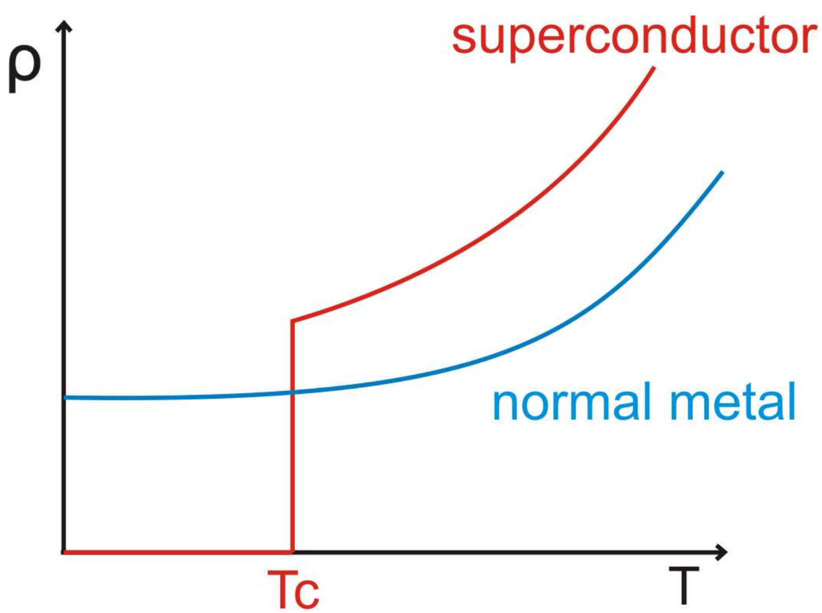
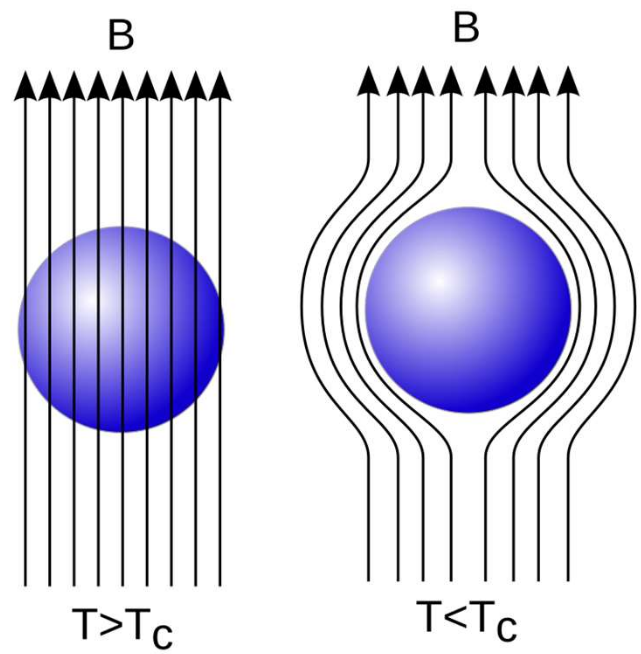
Superconductivity – The Phenomena

Zero resistance below a temperature T_c



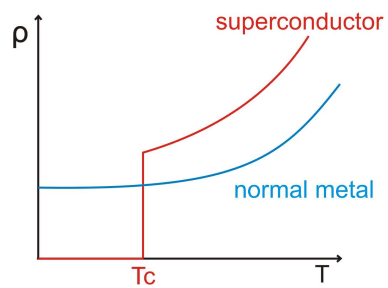
Expulsion of magnetic field below T_c

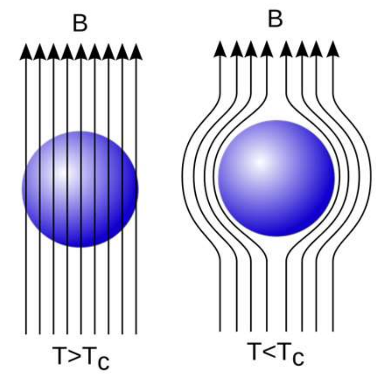


https://simpliphy.wordpress.com/2012/05/06/superconductivity/

https://en.wikipedia.org/wiki/Meissner_effect

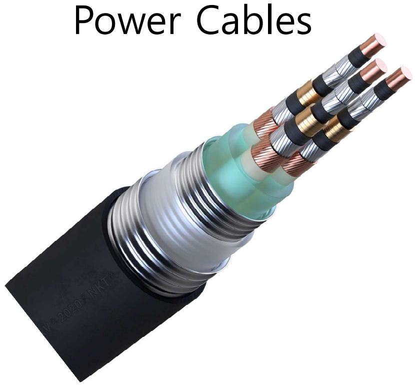
Superconductivity – Applications



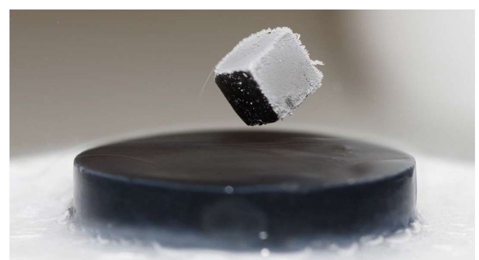


MRI

Power Cables



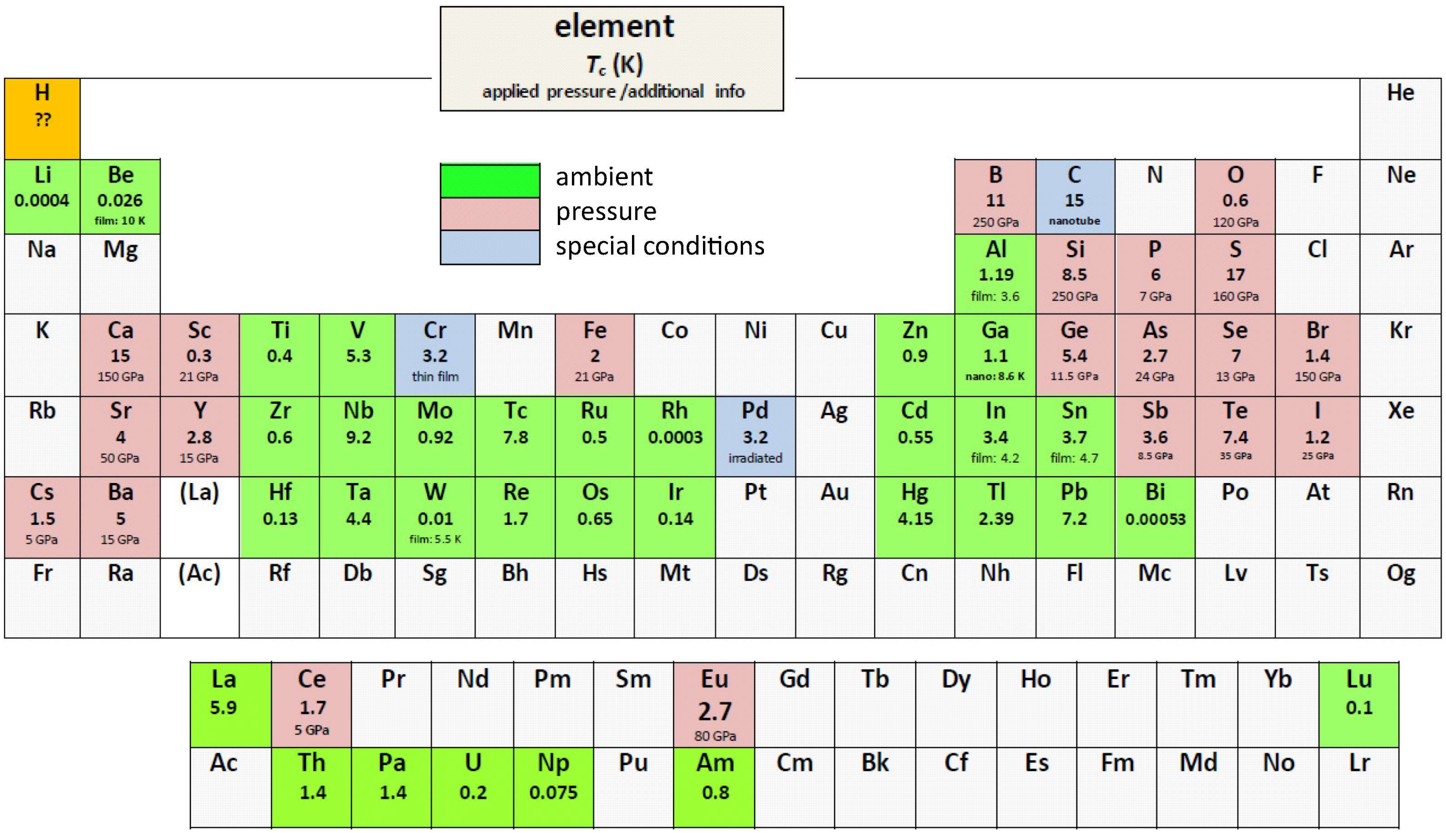
Levitating Objects



MagLev Trains

https://simpliphy.wordpress.com/2012/05/06/superconductivity/ https://en.wikipedia.org/wiki/Meissner_effect

Superconductivity in the elements

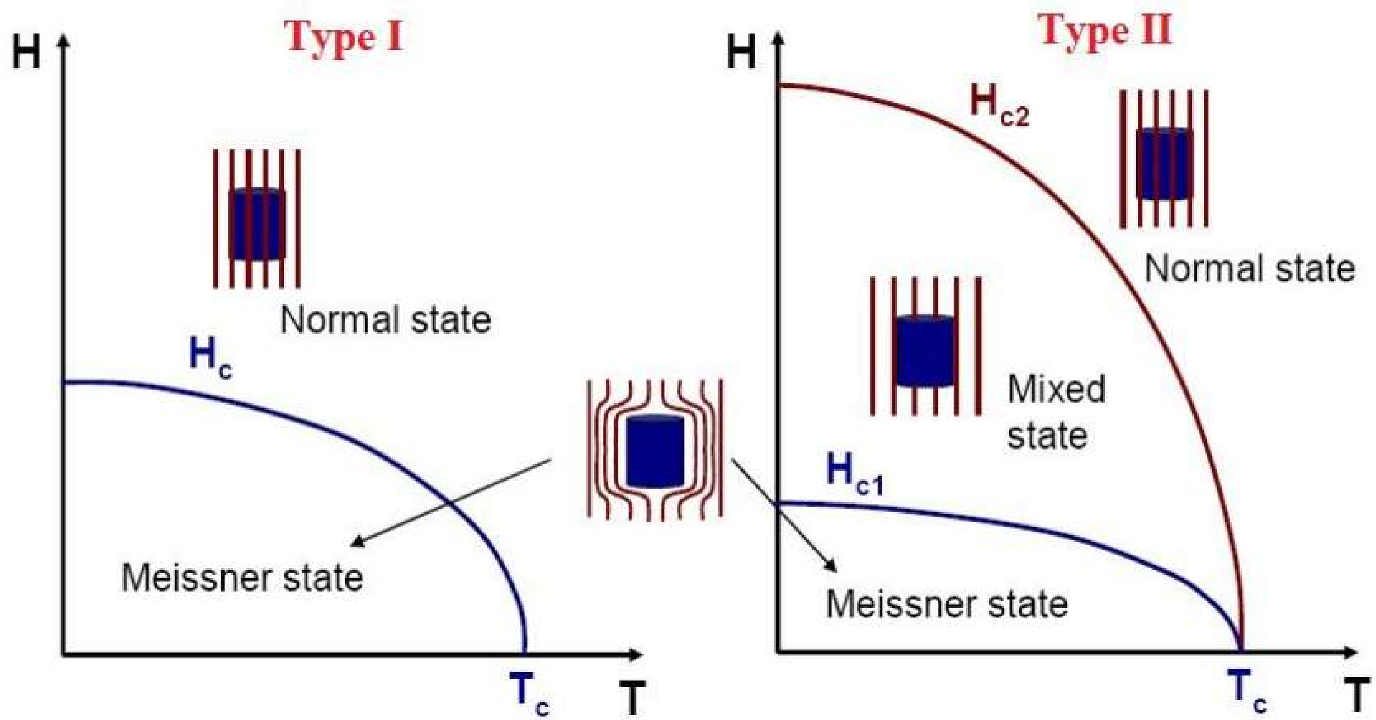


https://doi.org/10.3390/met12020337

Superconductivity – Type I vs. Type II

Typically elemental superconductor
s

Typically binary and ternary superconductors



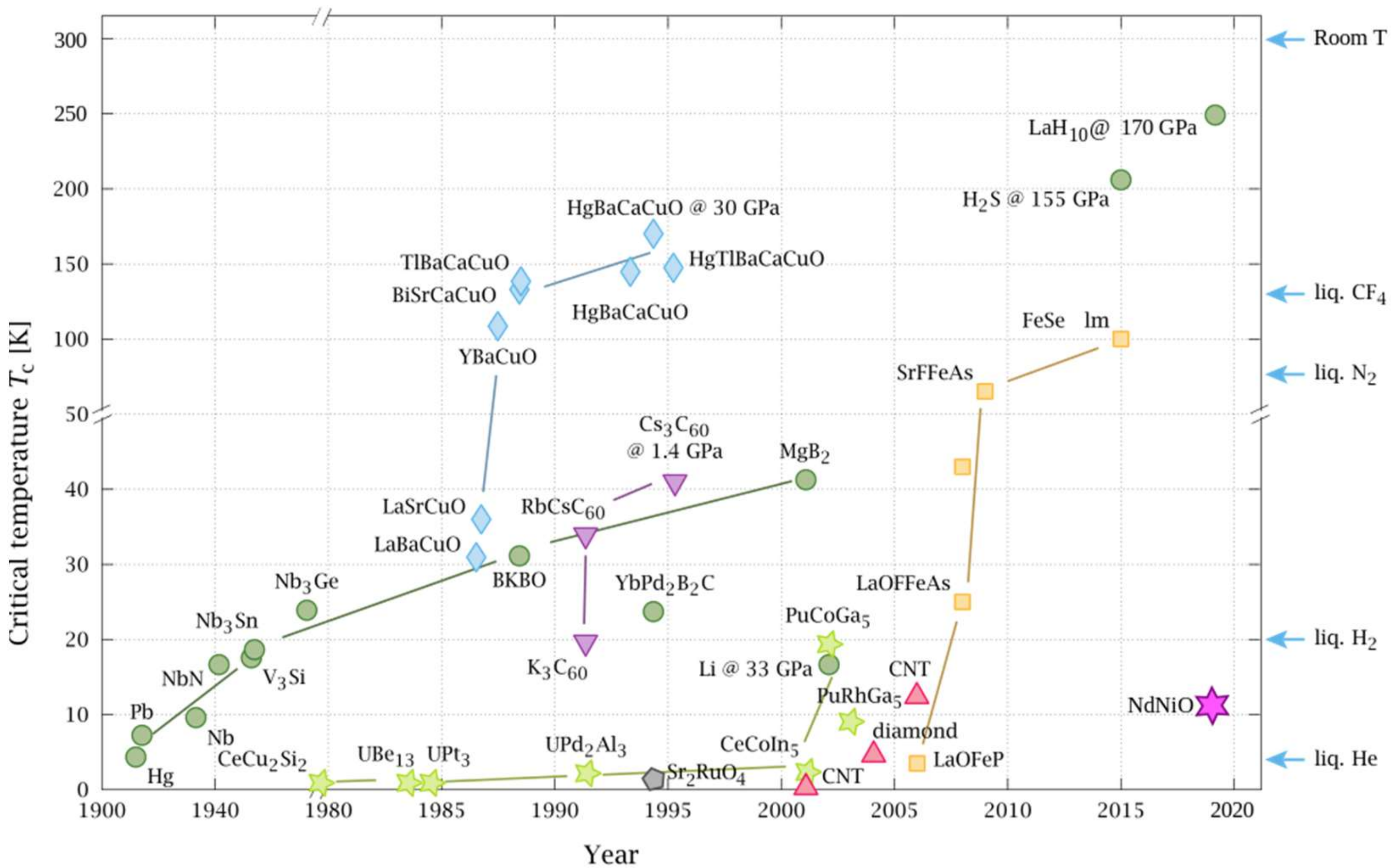
Superconducting T_c in Materials

First discovered in Hg in 1911

T_c in intermetallic superconductors explored after the discovery

High T_c discovered in the copper oxides in 1986

Exotic states in low T_c superconductors important for future applications



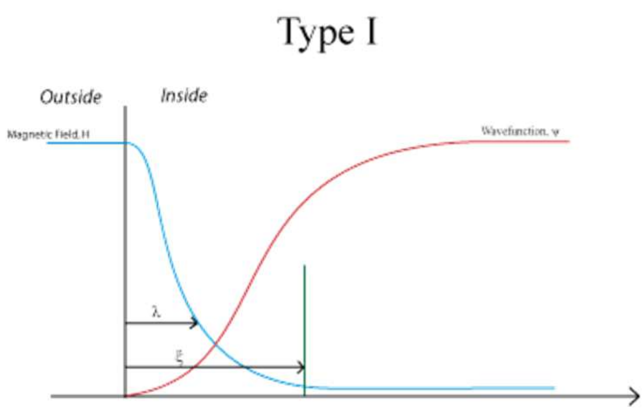
https://en.wikipedia.org/wiki/High-temperature_superconductivity

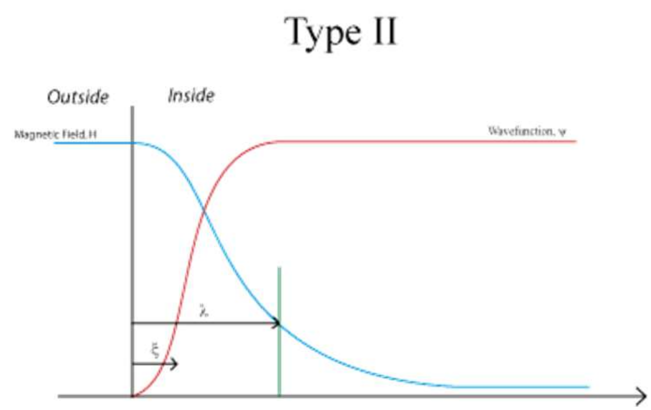
Superconductivity – Cooper Pairing

Singlet & Triplet cooper pairing possible on degenerate Fermi surface

Ratio of coherence length ξ and penetration depth λ determine type-I/II nature

Ginzburg-Landau constant $\kappa_{GL} = \xi/\lambda = 1/\sqrt{2}$ is the border between type-I/II





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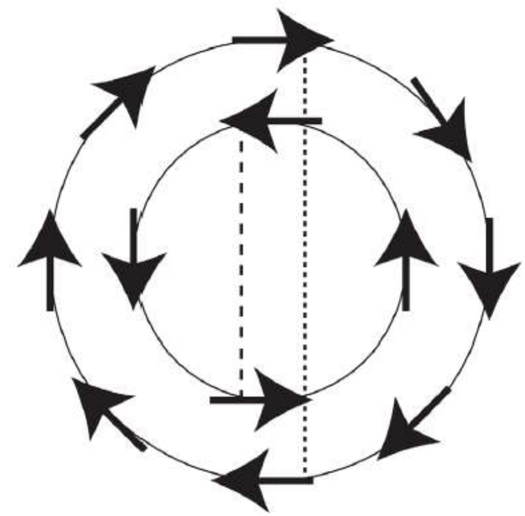
Superconductivity in Non-centrosymmetric Materials

- Non-centrosymmetric space group *I4mm* and spin-orbit-coupling (SOC) leads to splitting of spin-up and spin-down bands, which is termed Antisymmetric SOC (ASOC).
- Spin-singlet pairing is unaffected, but one of the three triplet pairings possible is promoted!
- This results in a mixture of singlet-triplet pairings possible in non-centrosymmetric superconductors.

Rashba Split
Fermi Surface



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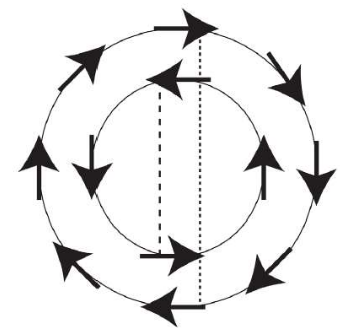
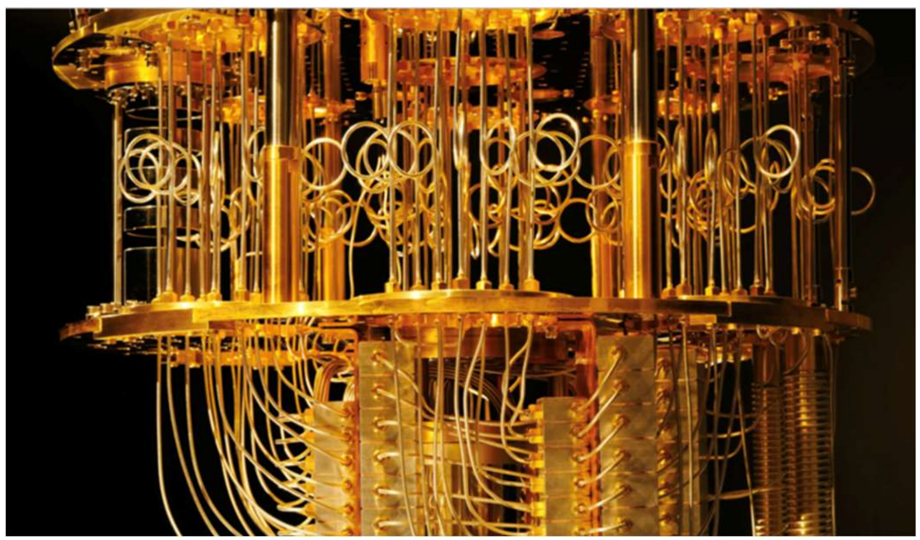


Spin	Pairing	Possibility
↑↓-↓↑	Singlet	O
↑↑	Triplet	X
↓↓	Triplet	X
↑↓+↓↑	Triplet	O

Rep. Prog. Phys. **80**, 036501 (2017)

Superconductivity in Non-centrosymmetric Materials – Applications

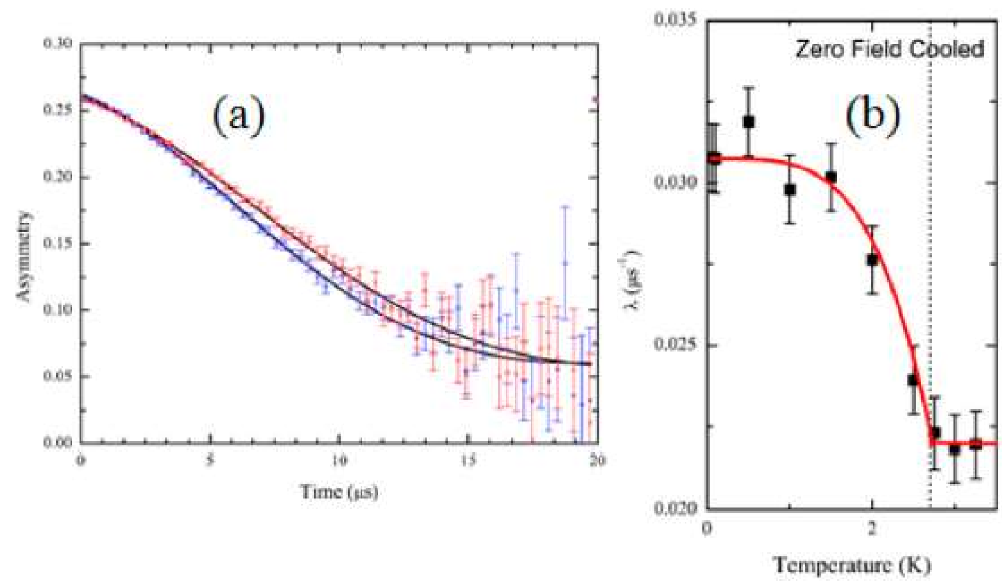
- Triplet pairing in a superconductor can allow for Majorana bound state
- Majorana bound states can be manipulated for quantum computing
- Even a low T_c superconductor with triplet pairing can allow for novel application



Superconductivity in Non-centrosymmetric Materials

- In non-centrosymmetric superconductors you may realize time reversal symmetry breaking (TRSB).
- Such TRSB can be seen in experiments, such as muon spin relaxation (μSR).

$LaNiC_2$



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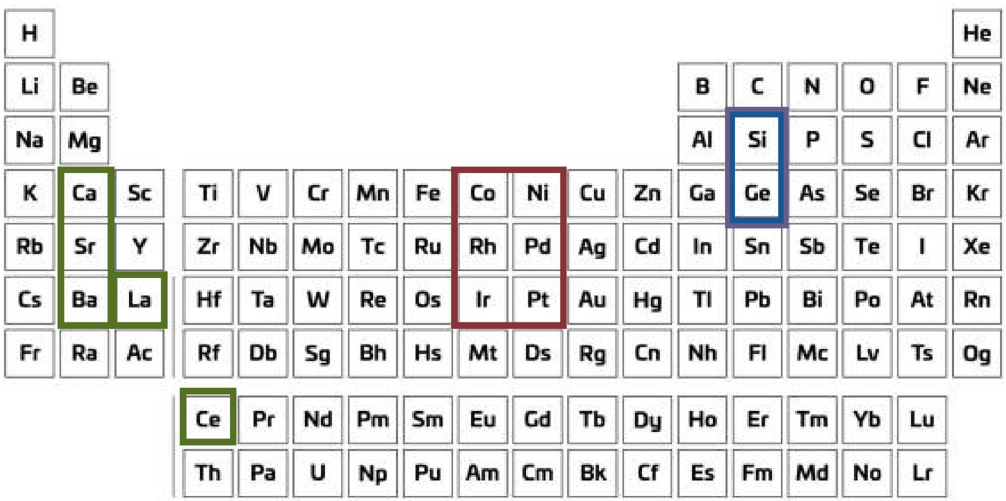
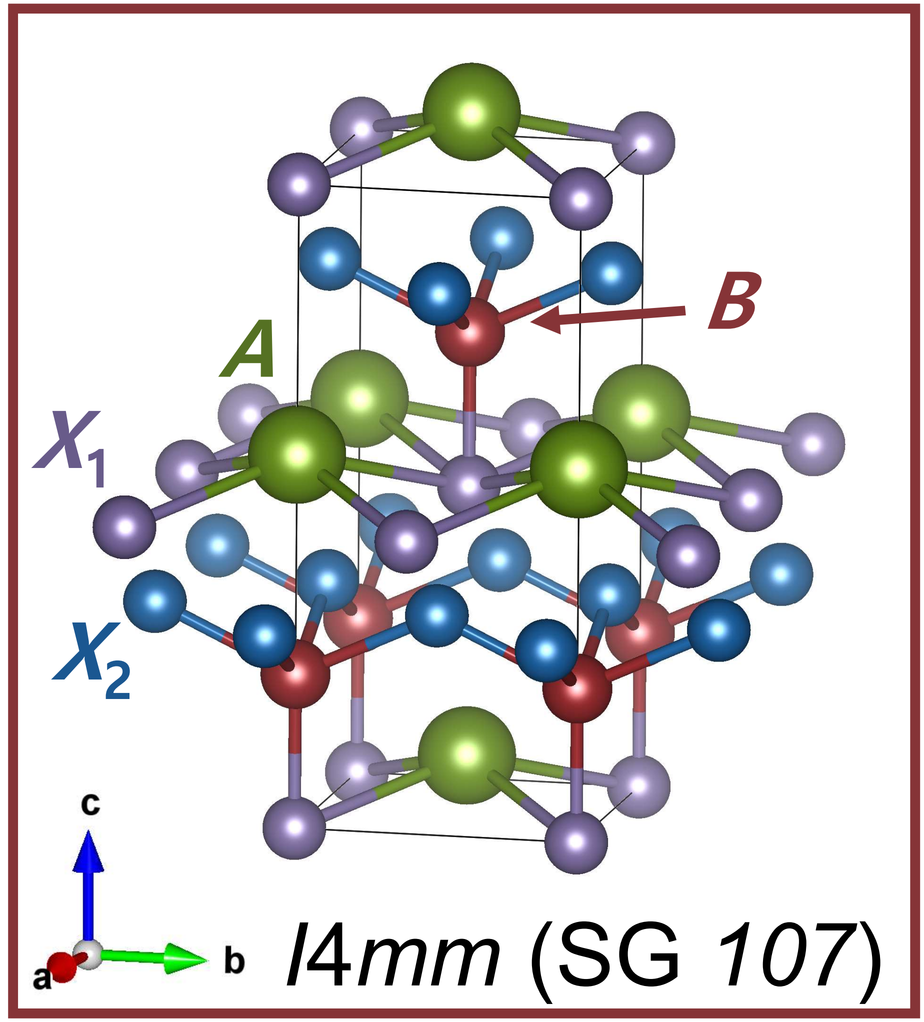
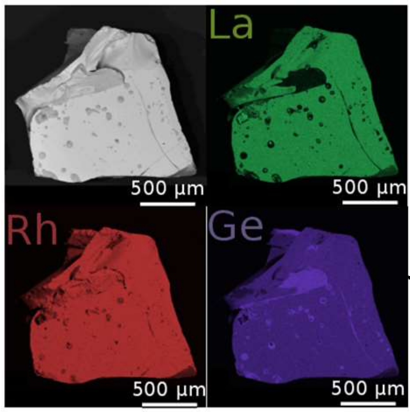
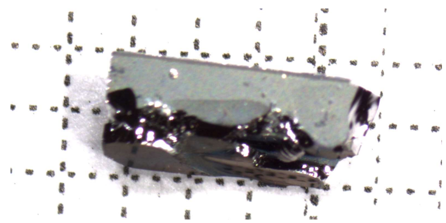
ABX_3 in *I4mm* Crystal Structure

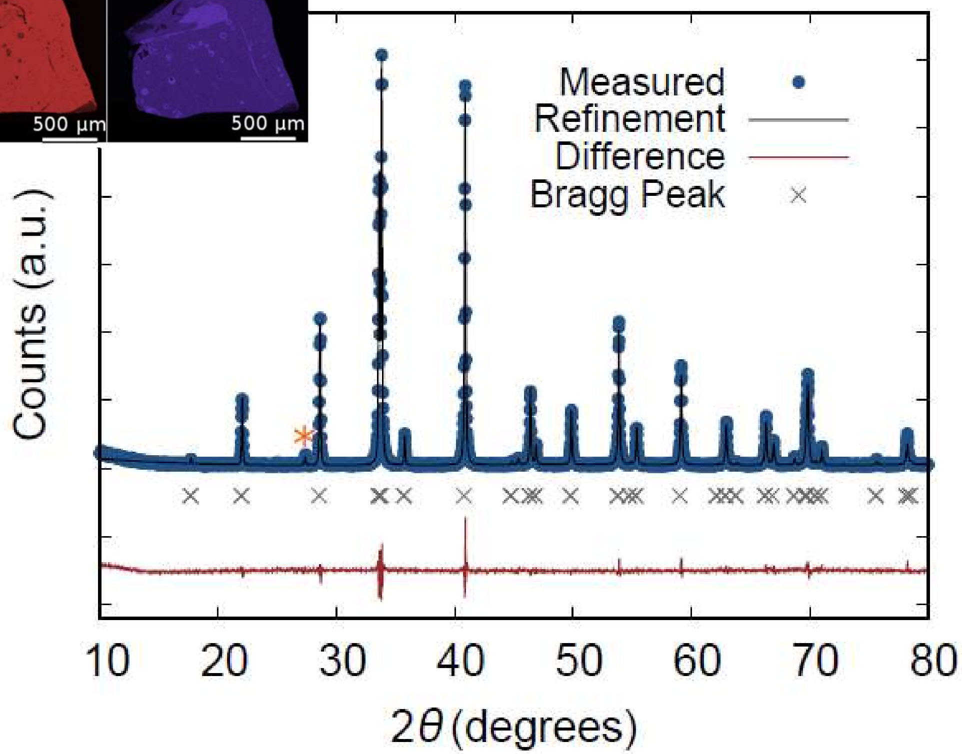


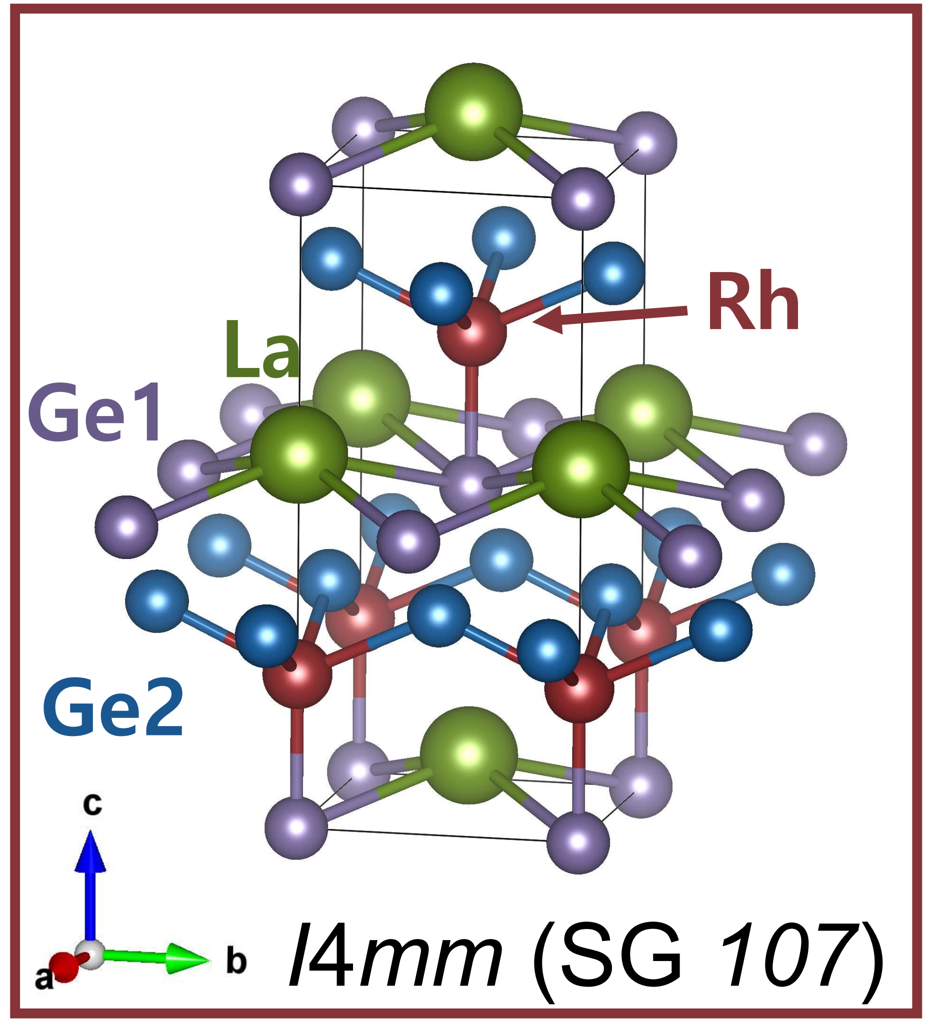


Self-Flux Grown $LaRhGe_3$ Crystals



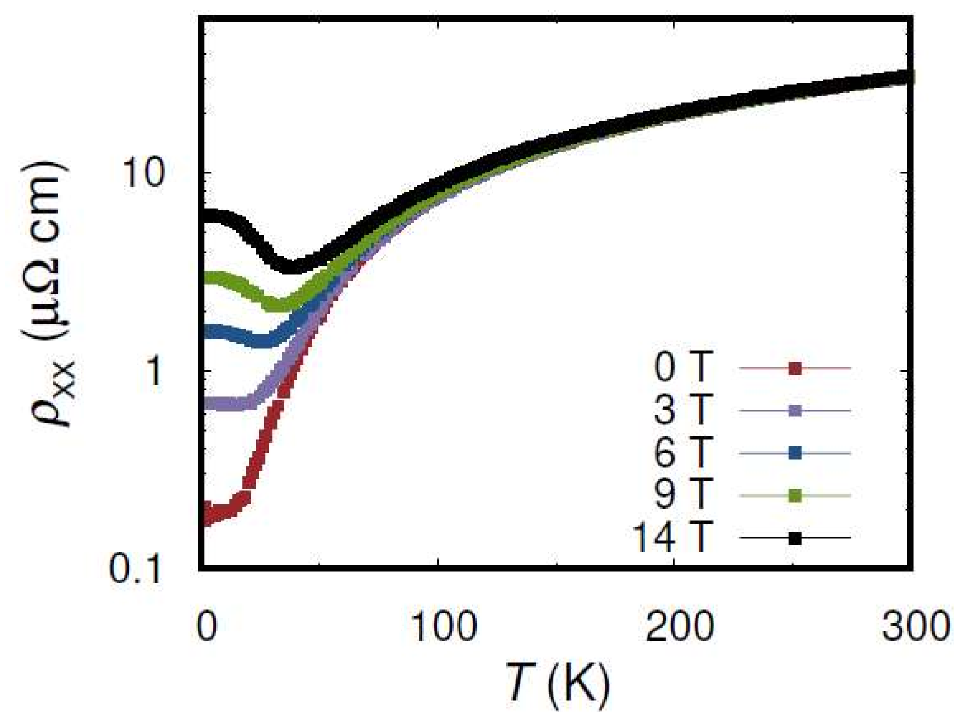






$LaRhGe_3$ Transport – ρ *vs.* T

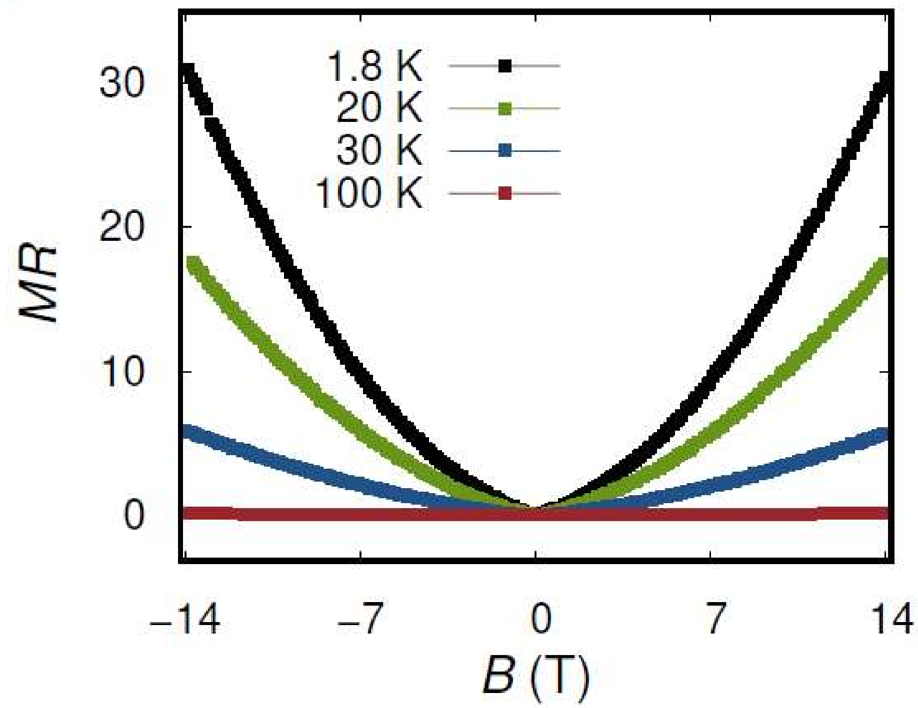
- Transport in zero-field shows metallic behavior
- Upturn at low temperature in measurements under magnetic field of >6 T



$LaRhGe_3$ Transport – Magnetoresistance

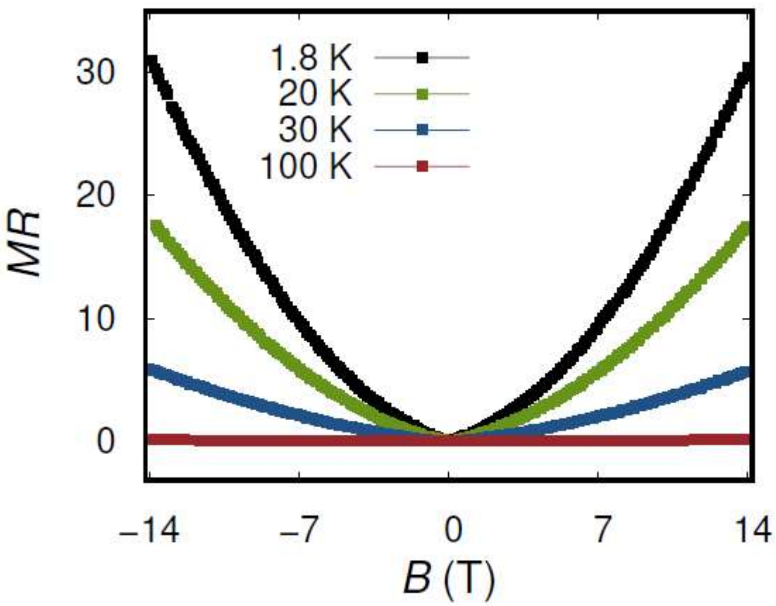
- Non-saturating magnetoresistance up to 14 T at low *T*

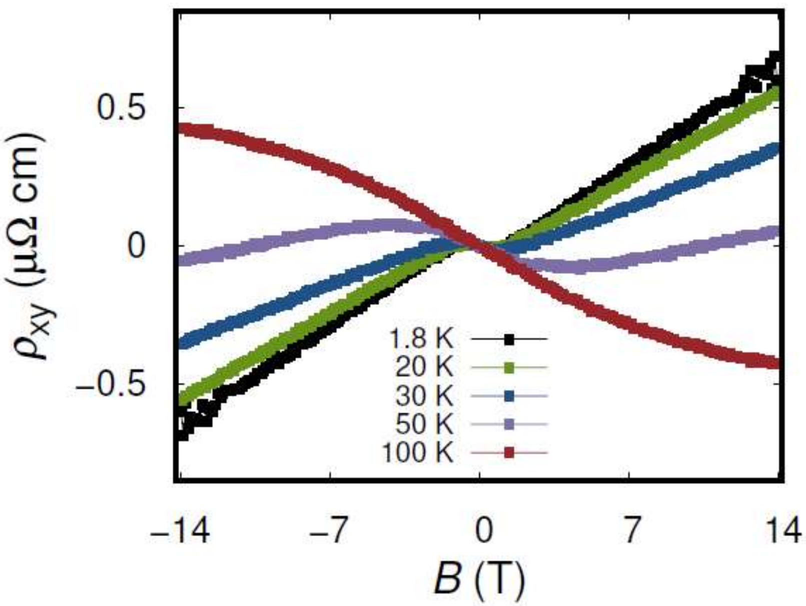
- Increase in magnetoresistance appears below 50 K



LaRhGe$_3$ Transport – Hall Measurement

Simultaneous measurements of Hall resistivity (ρ_{xy}) and magnetoresistance (ρ_{xx}) allows us to use a two-band model to extract *e* and *h* concentration and mobility





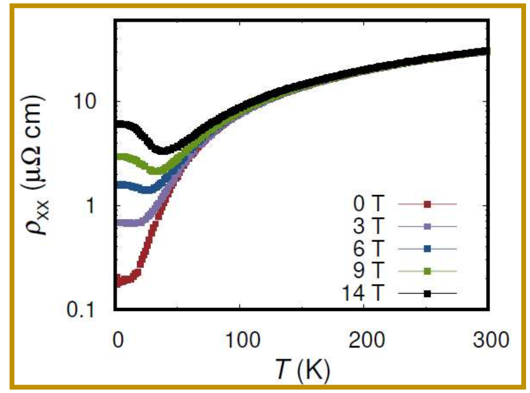
$$\rho_{\mathrm{xx}} = \frac{1}{e}\frac{(n_{\mathrm{h}}\mu_{\mathrm{h}} + n_{\mathrm{e}}\mu_{\mathrm{e}}) + (n_{\mathrm{h}}\mu_{\mathrm{e}} + n_{\mathrm{e}}\mu_{\mathrm{h}})\mu_{\mathrm{h}}\mu_{\mathrm{e}}B^2}{(n_{\mathrm{h}}\mu_{\mathrm{h}} + n_{\mathrm{e}}\mu_{\mathrm{e}})^2 + (n_{\mathrm{h}} - n_{\mathrm{e}})^2\mu_{\mathrm{h}}^2\mu_{\mathrm{e}}^2B^2}$$

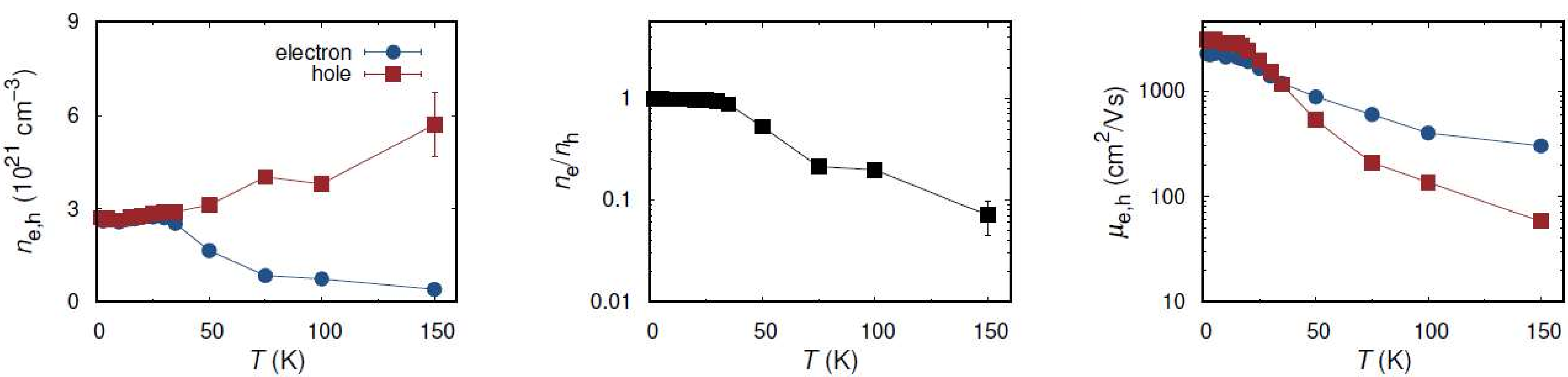
$$\rho_{\mathrm{xy}} = \frac{B}{e}\frac{n_{\mathrm{h}}\mu_{\mathrm{h}}^2 - n_{\mathrm{e}}\mu_{\mathrm{e}}^2 + (n_{\mathrm{h}} - n_{\mathrm{e}})\mu_{\mathrm{h}}^2\mu_{\mathrm{e}}^2B^2}{(n_{\mathrm{h}}\mu_{\mathrm{h}} + n_{\mathrm{e}}\mu_{\mathrm{e}})^2 + (n_{\mathrm{h}} - n_{\mathrm{e}})^2\mu_{\mathrm{h}}^2\mu_{\mathrm{e}}^2B^2}$$

LaRhGe$_3$ Transport – *e-h* compensation

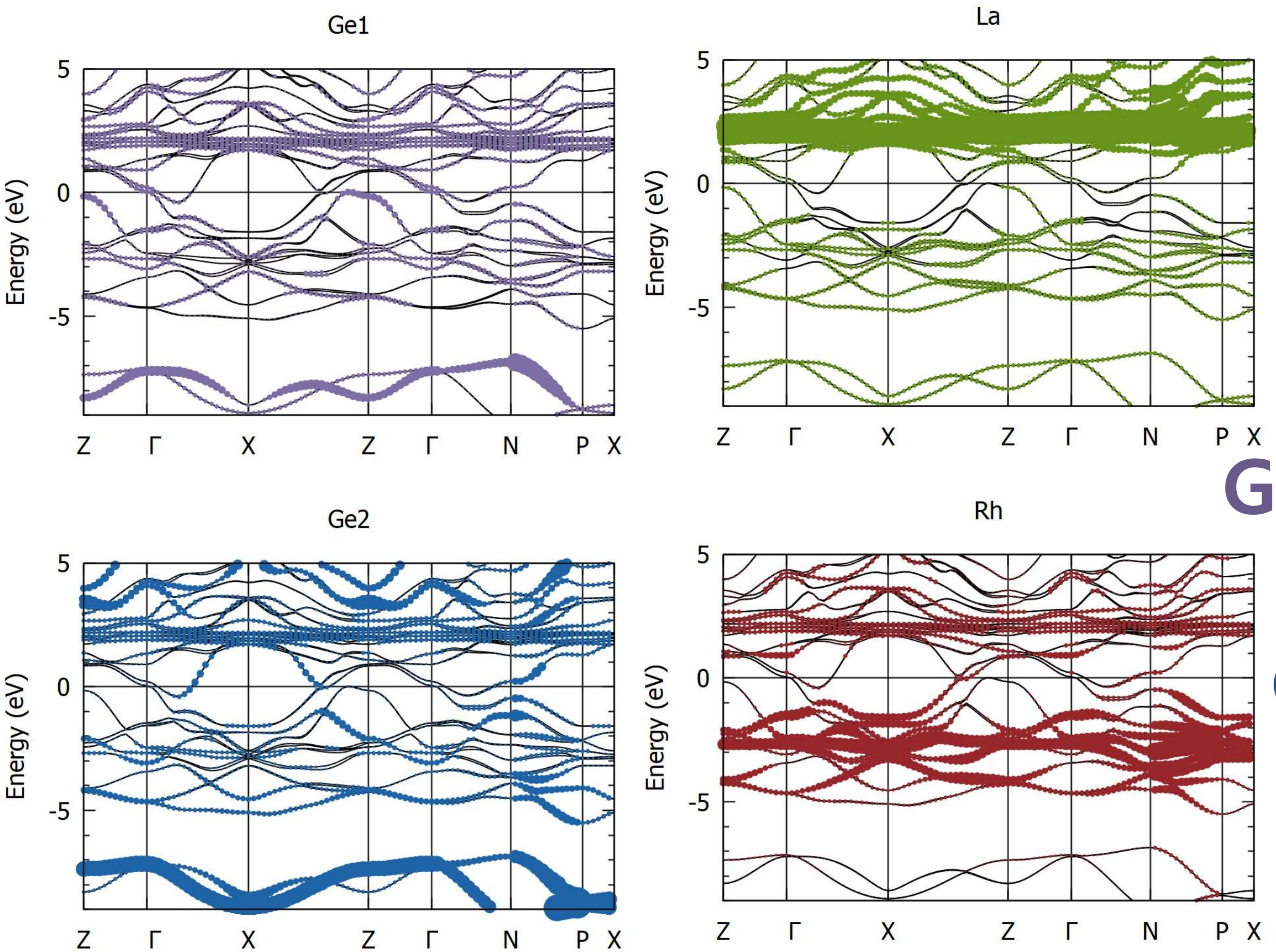
- Carrier concentration shows compensation of n_h and n_e at low T, in the region where upturn is seen in ρ_{xx}

- High mobility consistent with semimetallic character of LaRhGe$_3$

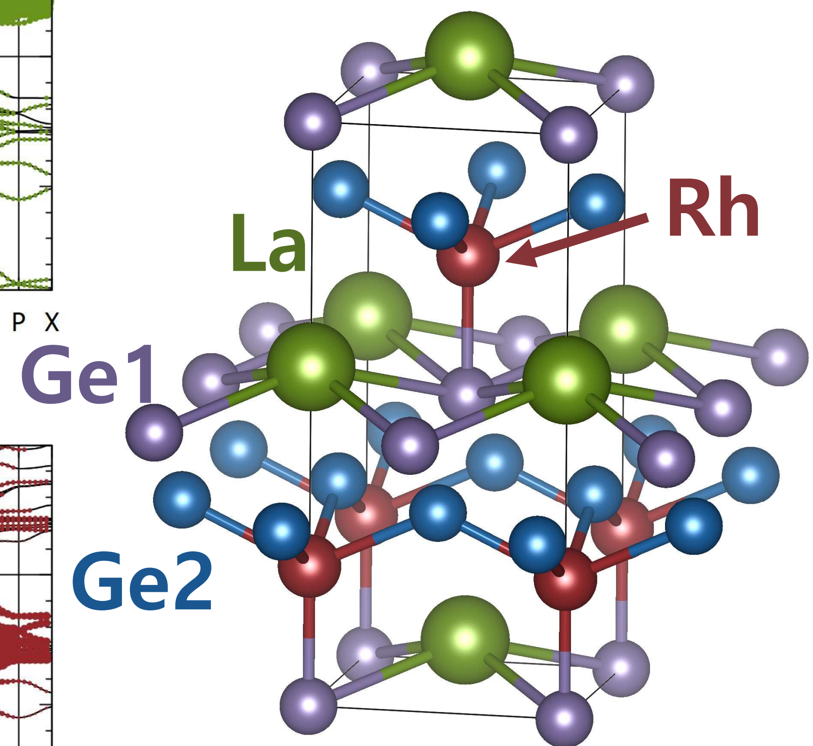




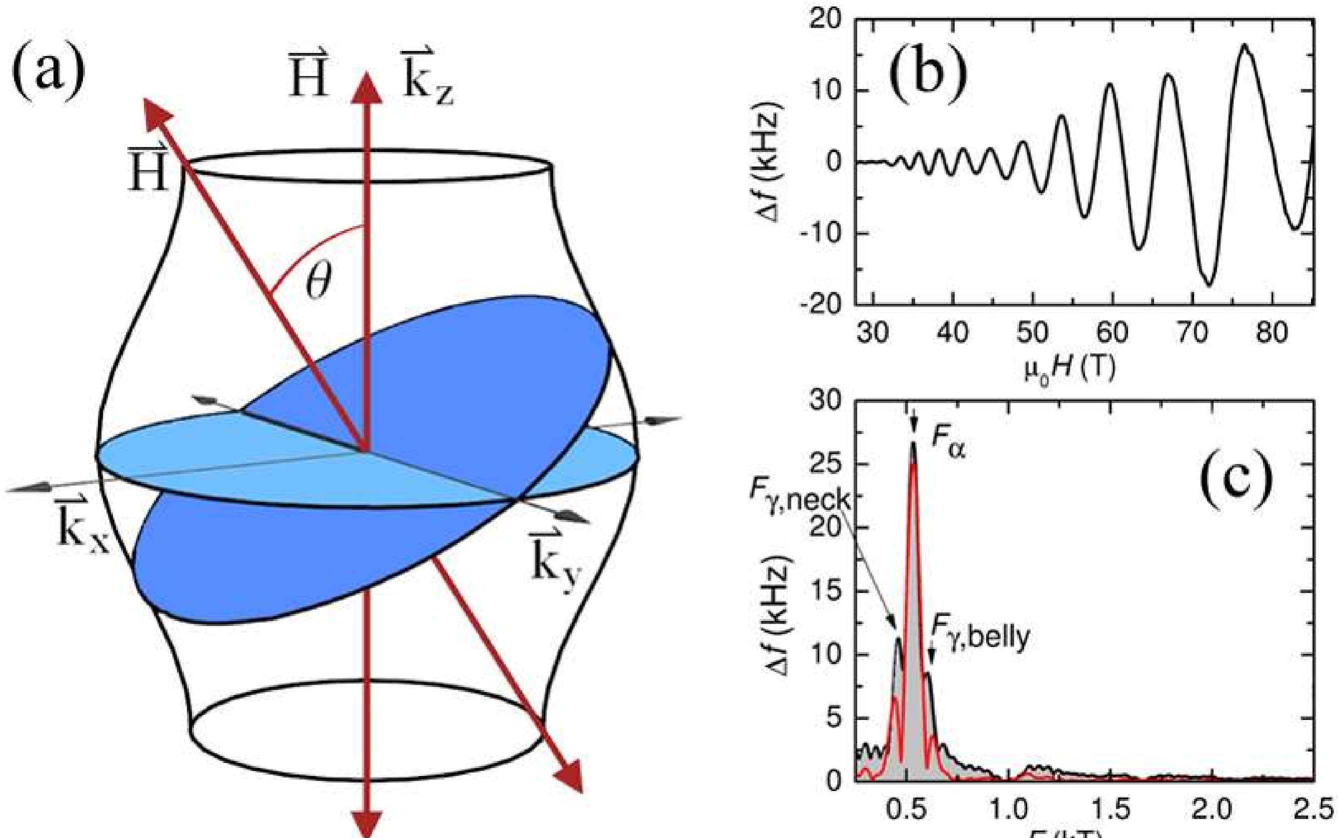
LaRhGe$_3$ Band Calculation – Element Contribution



Two degenerate hole bands and one degenerate electron band

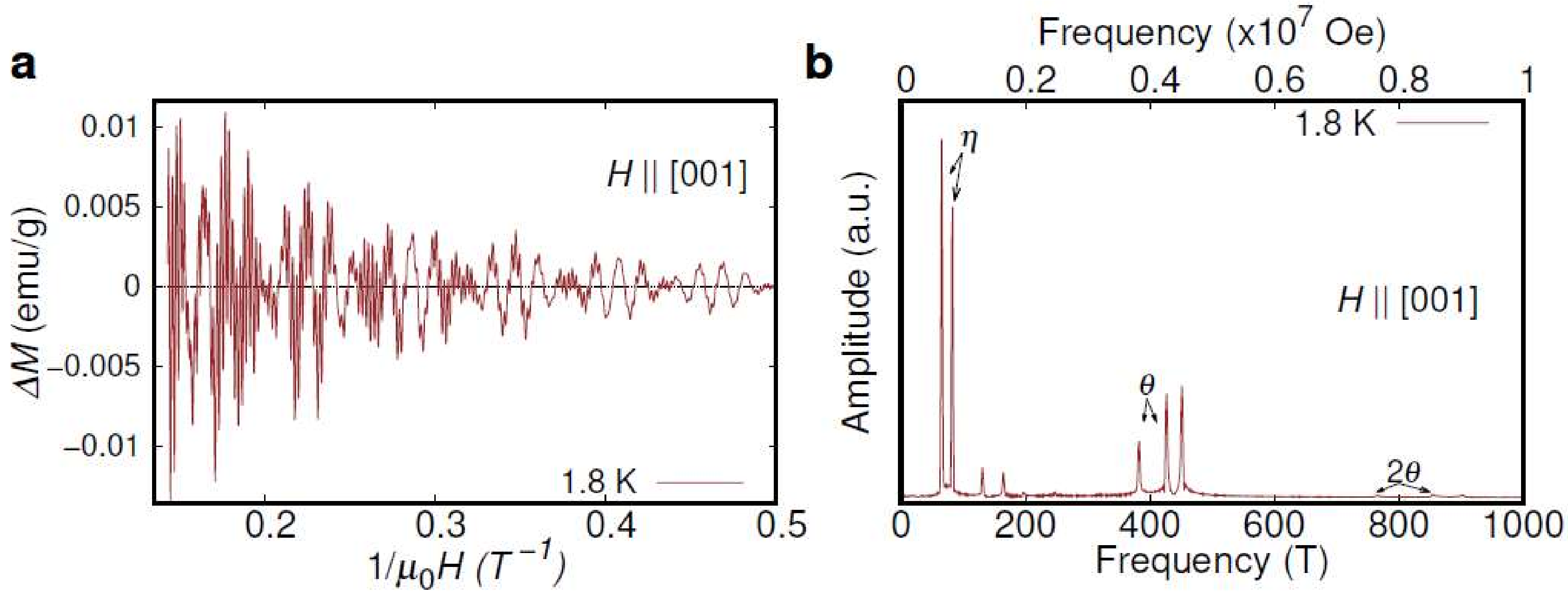


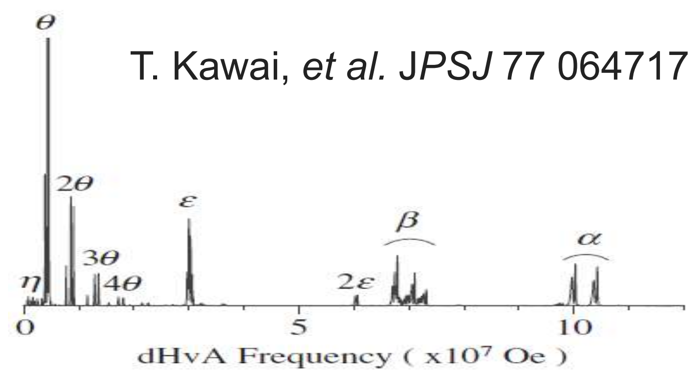
Quantum Oscillations



https://physics.aps.org/articles/v3/86

$LaRhGe_3$ Magnetization – dHvA FFT $H//c$ vs. Literature



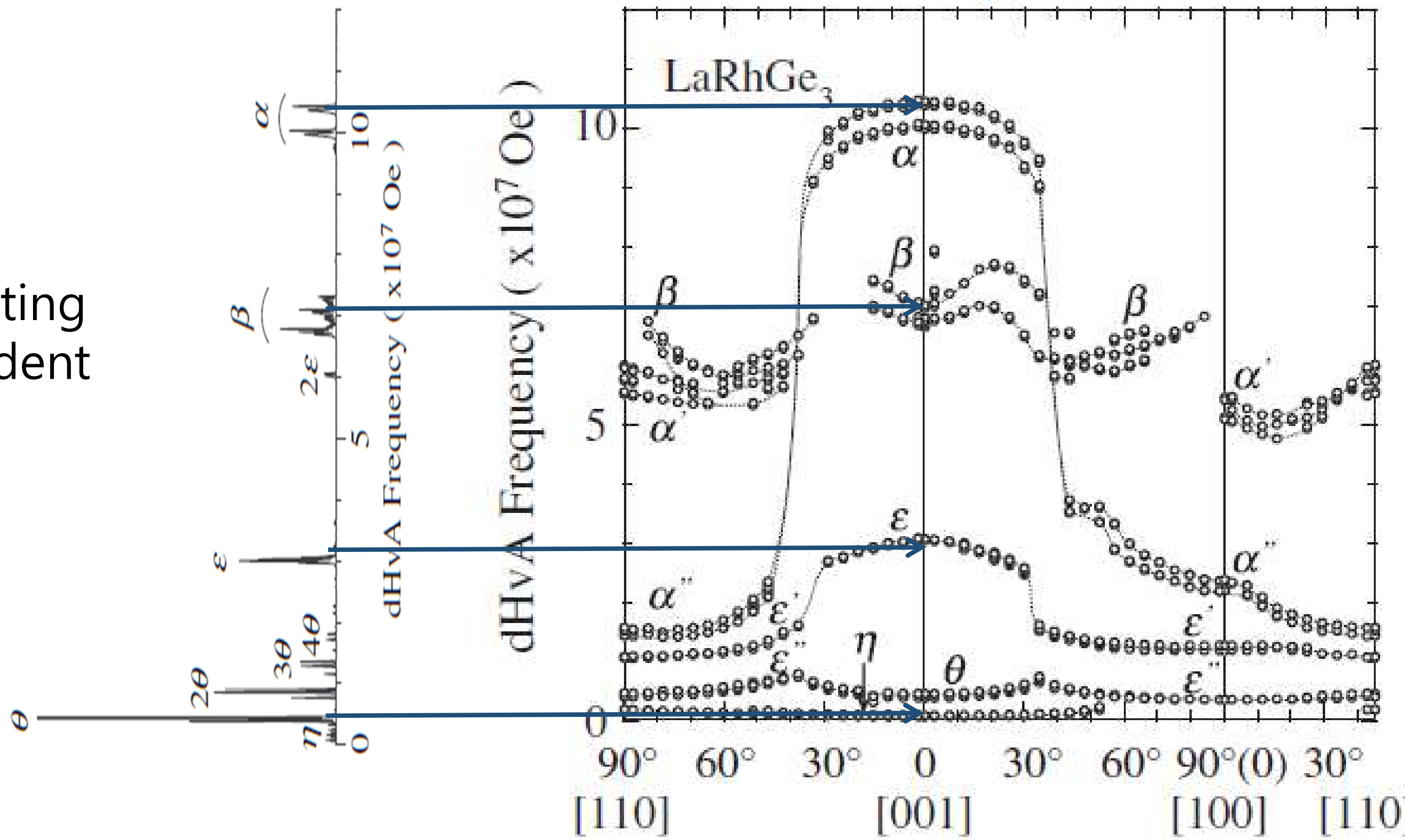


T. Kawai, *et al.* J*PSJ* 77 064717 (2008).

Splitting in oscillating frequency in $LaRhGe_3$ consistent with previous report

$LaRhGe_3$ Literature: Angle-Dependence of dHvA

Frequency splitting
is angle-dependent



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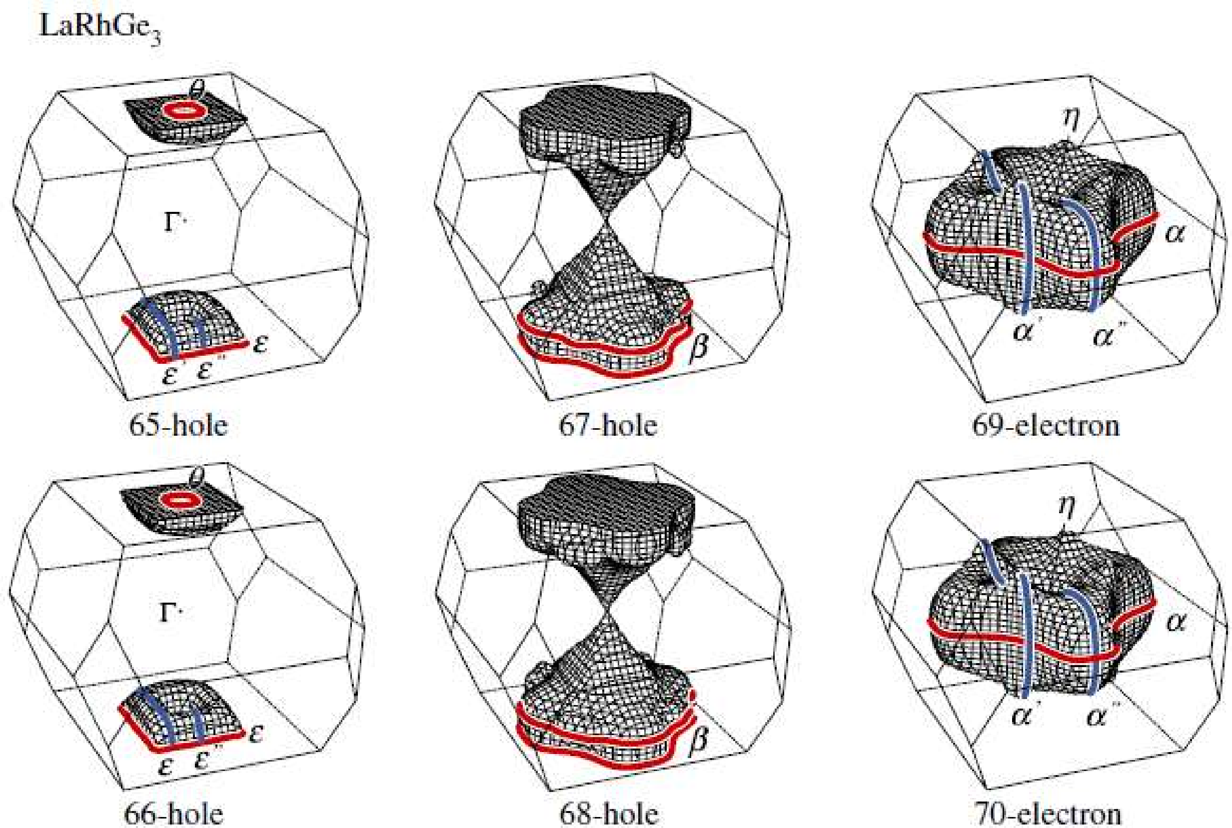
LaRhGe$_3$ Literature: Fermi Surface



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RTGe_3 Literature: Effective Mass and ASOC

Non-centrosymmetric space group I4*mm* results in ASOC in La$RhGe_3$, with Rh contributing to SOC

Replacing Ge with Si has little affect in other members of LaMX_3 family

6 Bands and ASOC in La$RhGe_3$

Experiment			Theory		
Branch	F ($\times 10^7$ Oe)	m_c^* (m_0)	Branch	F_b ($\times 10^7$ Oe)	m_b (m_0)
			$H \parallel [001]$		
α	10.4	1.04	α band 69	10.5	1.11
	10.0	1.04	band 70	10.1	1.12
β	6.98	0.83	β band 68	7.82	1.24
	6.77	1.89	band 68	7.24	0.91
	6.77	0.85	band 67	7.11	2.01
			band 67	6.89	0.88
ε	3.06	0.74	ε band 66	3.13	0.68
	3.04	0.73	band 65	3.01	0.69
θ	0.44	0.44	θ band 65	0.33	0.31
	0.38	0.51	band 66	0.28	0.24
η	0.08	0.22	η band 70	0.03	0.27
	0.06	0.23	band 69	0.03	0.26

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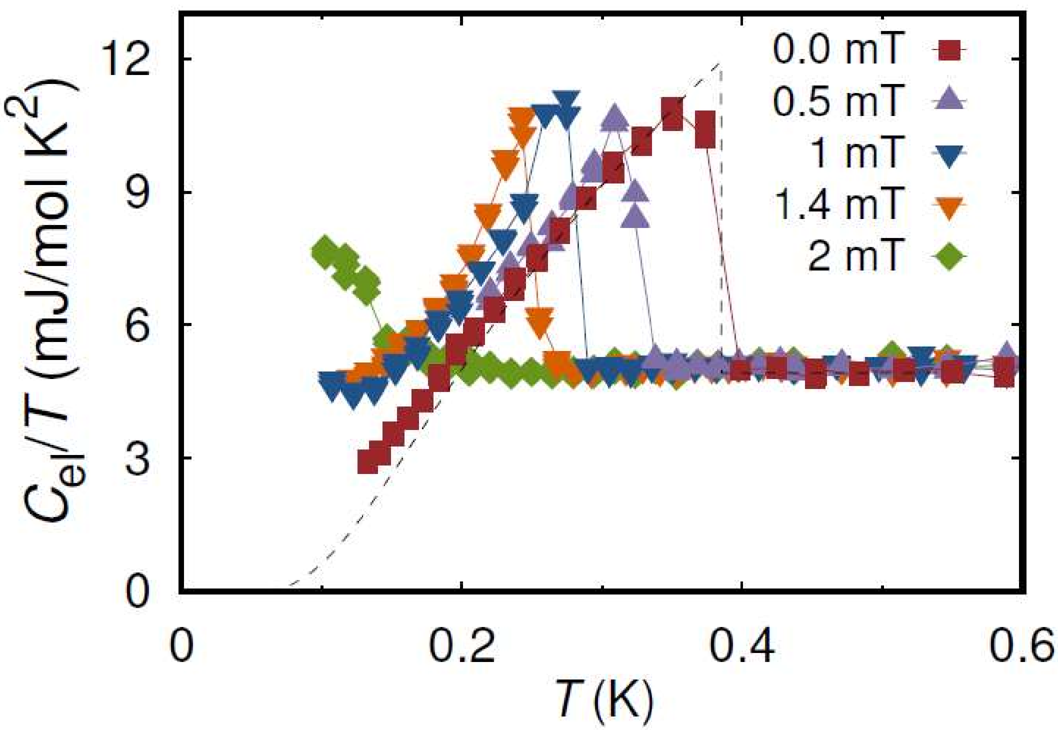
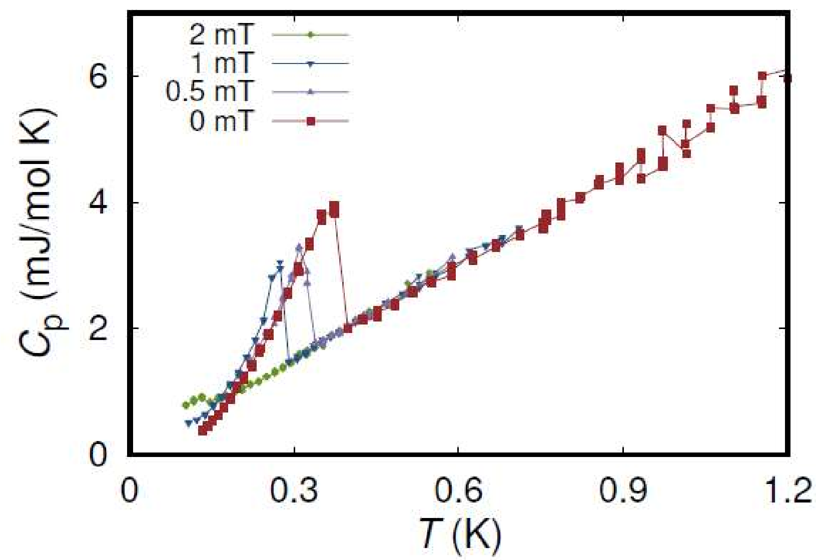
$LaRhGe_3$ Specific Heat – Superconductivity

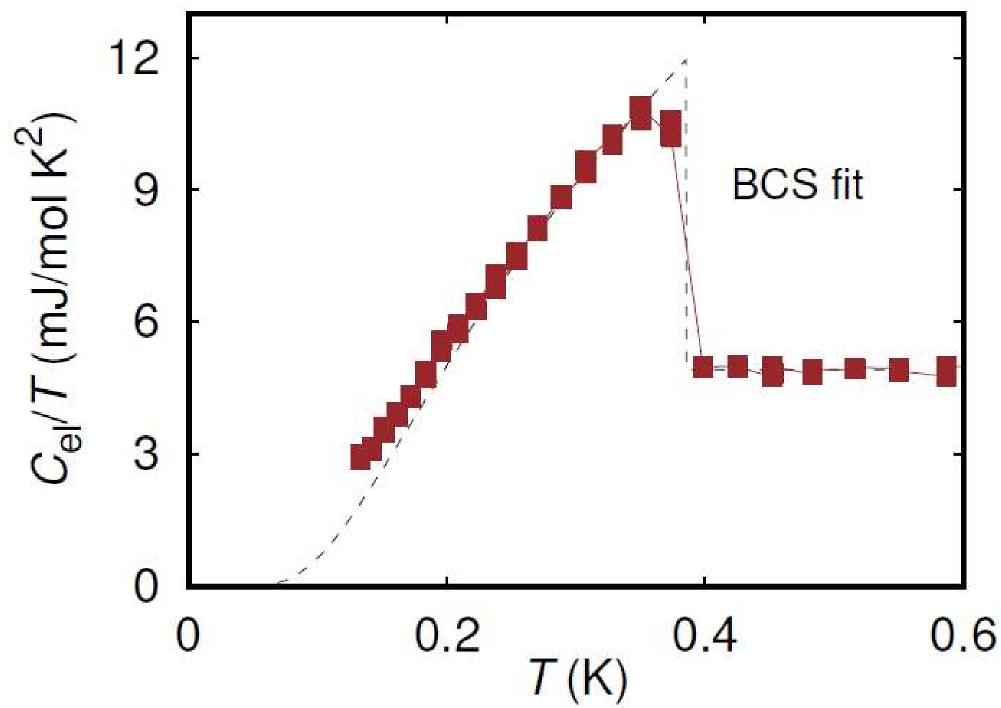
Jump at T_c ~ 0.39 K, and transition is pushed to lower T with increasing field H





LaRhGe$_3$ Specific Heat – Superconductivity

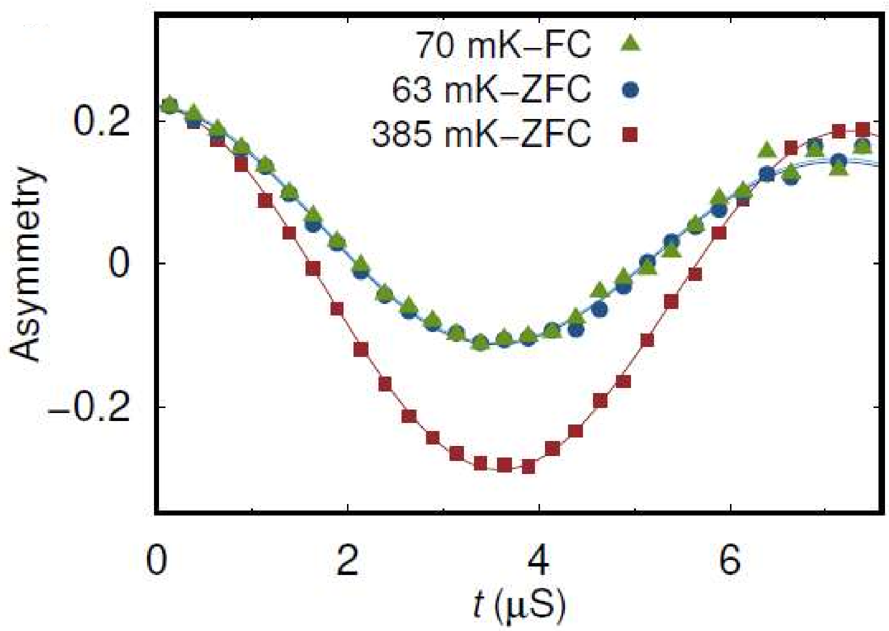
- Jump at T_c similar to expectation based on weak-coupling BCS.
- Low temperature experimental data is not low enough to suggest any gap symmetry

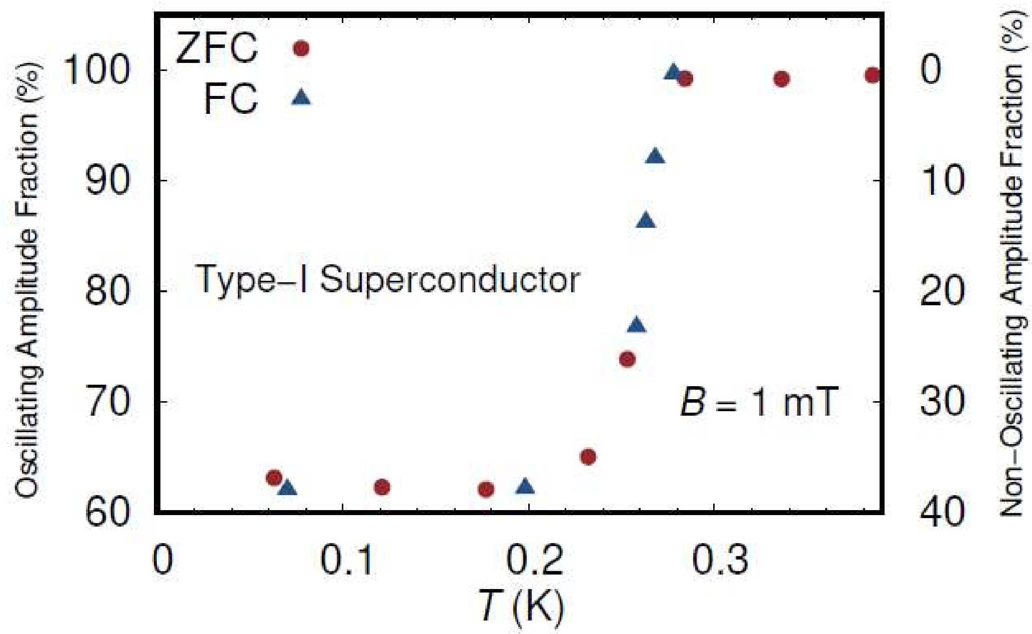


LaRhGe$_3$ μSR – Type I Superconductivity

Fitted to Simple Gaussian form

T_c~0.28 K

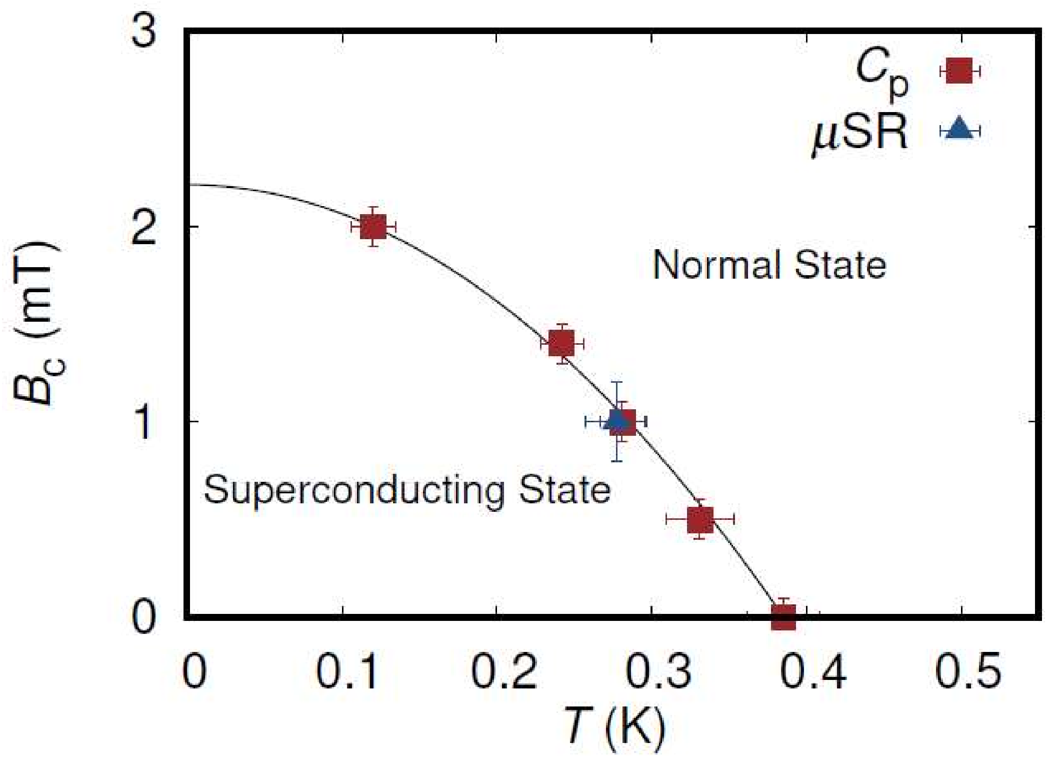




$LaRhGe_3$ Phase Diagram – Superconductivity

T_c from µSR and C_p match well!

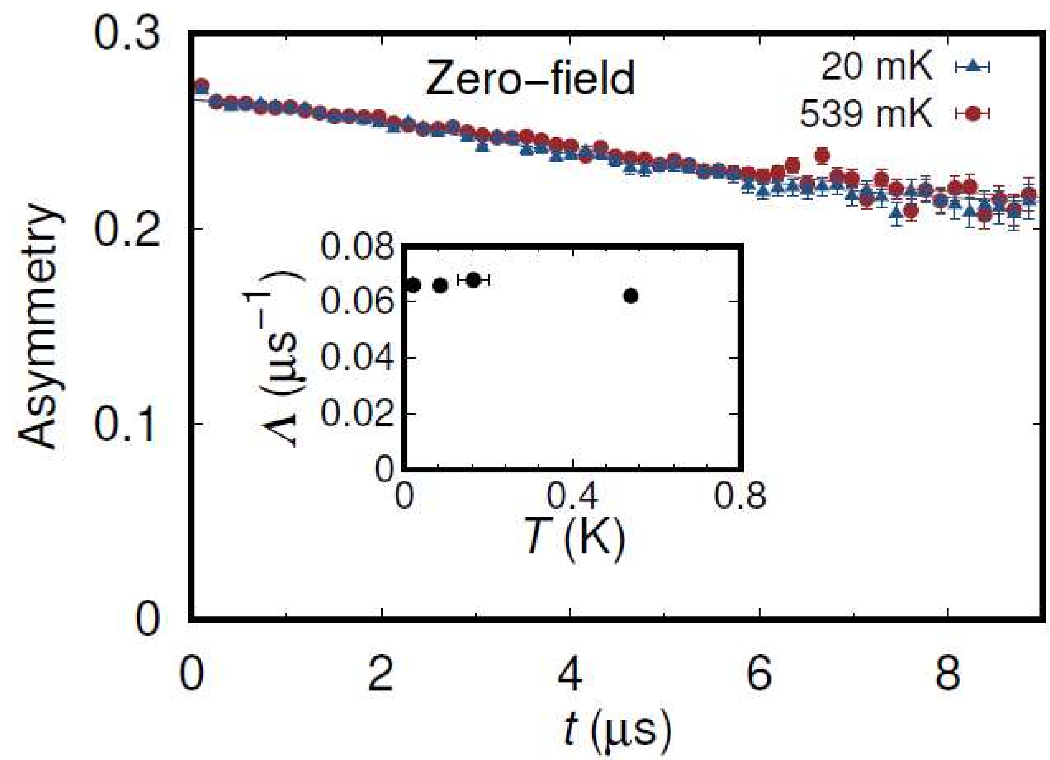
Parameter	Value	Units
T_c	0.39(1)	K
$B_c(0)$	2.2(1)	mT
γ_n	4.92(4)	mJ mol^{-1} K^{-2}
β	0.25(1)	mJ mol^{-1} K^{-4}
θ_D	341(10)	K
λ_{ep}	0.34(2)	-



LaRhGe$_3$ μSR – Zero-Field

No sign of significant TRSB

Fitted Gaussian Kubo-Toyabe form



$LaRhGe_3$ vs. Other *I4mm* Superconductors

Comparing $LaRhGe_3$ with other non-centrosymmetric superconductors in the space group *I4mm*

Compound	T_c (K)	γ_n (mJ mol^{-1} K^{-2})	$B_{c2}(0)$ (T)
$Ba(Pt,Pd)Si_3$	2.3–2.8	4.9–5.7	0.05–0.10
$La(Rh,Pt Pd,Ir)Si_3$	0.7–2.7	4.4–6	Type I/0.053
$Ca(Pt,Ir)Si_3$	2.3–3.6	4.0–5.8	0.15–0.27
$Sr(Ni,Pd,Pt)Si_3$	1.0–3.0	3.9–5.3	0.039–0.174
$Sr(Pd,Pt)Ge_3$	1.0–1.5	4.0–5.0	0.03–0.05
$LaRhGe_3$	0.39(1)	4.92(4)	Type I/0.0021(1)

Lowest Critical Field!

Lowest T_c!

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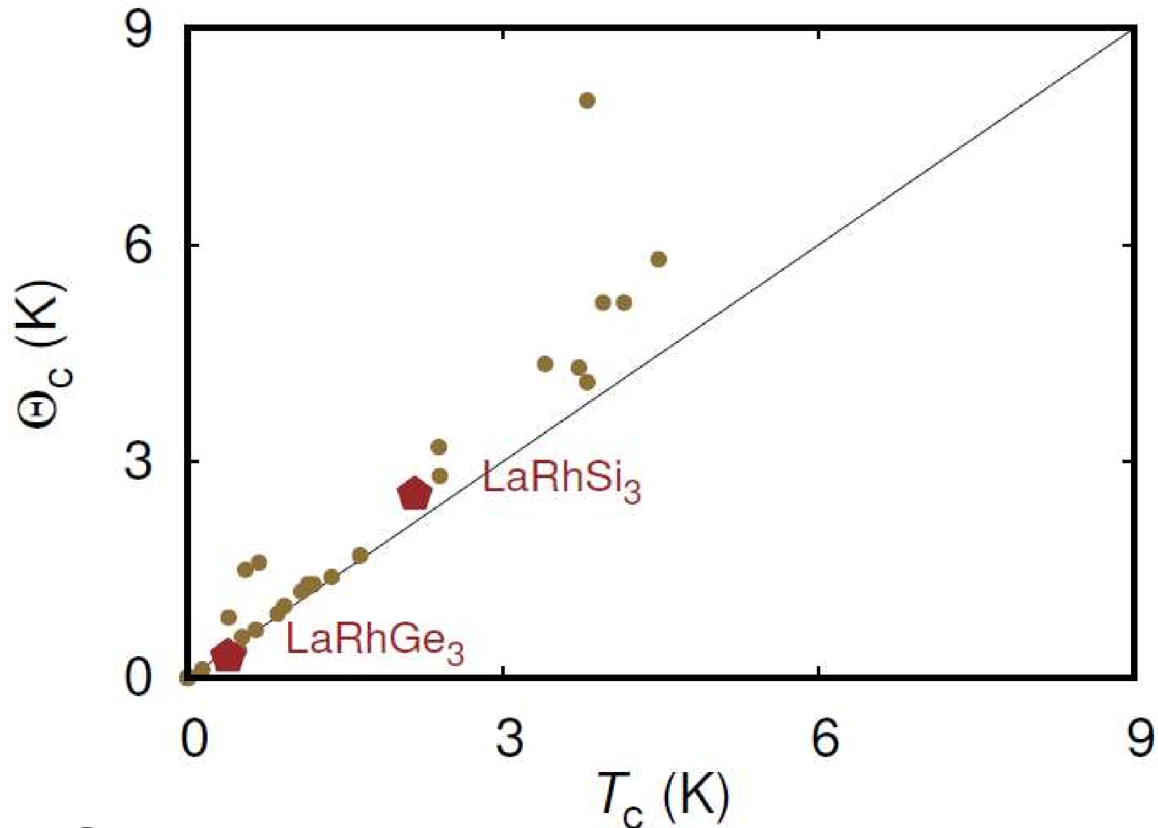
$LaRhGe_3$ vs. Other Type-I Elemental Superconductors

Plotting θ_C vs. T_c of
various type-I superconductors

$$\Theta_c = 2\mu_0 H_c(0)/\sqrt{1.43\gamma_n\mu_0}$$

Another confirmation that $LaRhGe_3$ is a **weakly-coupled superconductor**!



μSR→ no sign of significant TRSB

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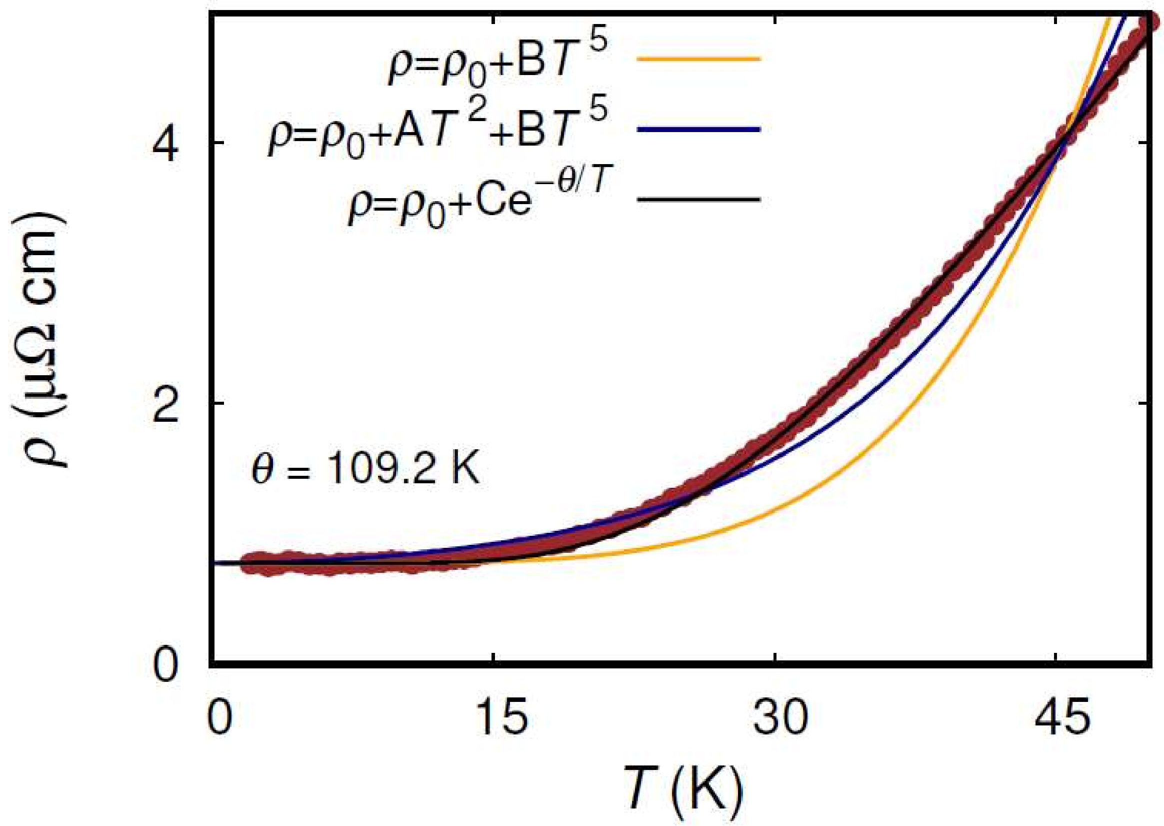
$LaRhGe_3$ Transport – *ρ vs. T* in Zero-Field

Low *T* region of resistivity is poorly fitted with a quadratic *T* term.

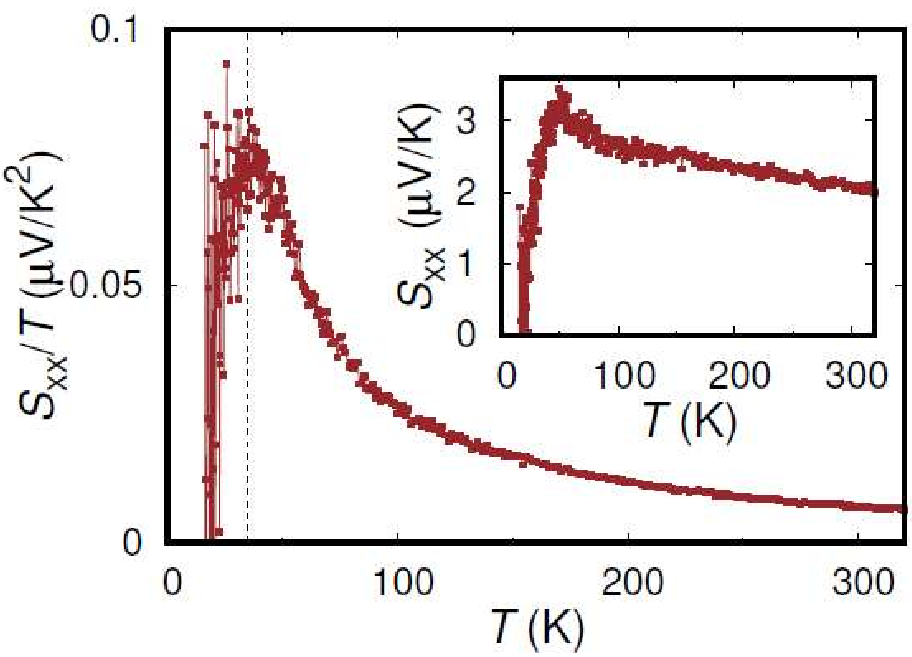
Low temperature regions fits well to an exponential term!

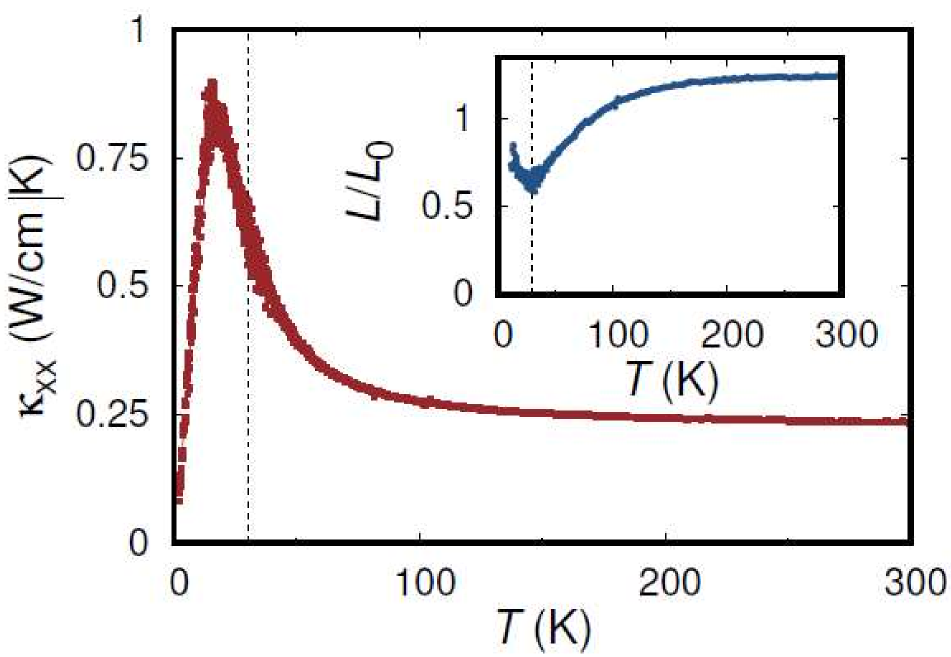
Perhaps associated with unusual electrons with phonons interactions at low *T* in the normal state…



$LaRhGe_3$ – Seebeck and Thermal Conductivity Measurement

We find a peak at low *T* in the Seebeck and thermal conductivity measurements on $LaRhGe_3$, suggestive of enhanced *e-ph* interactions

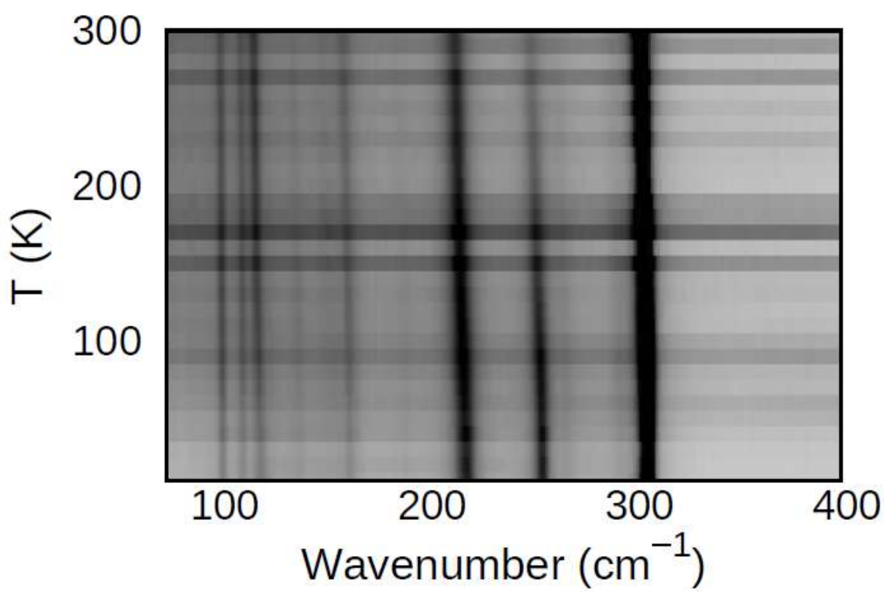


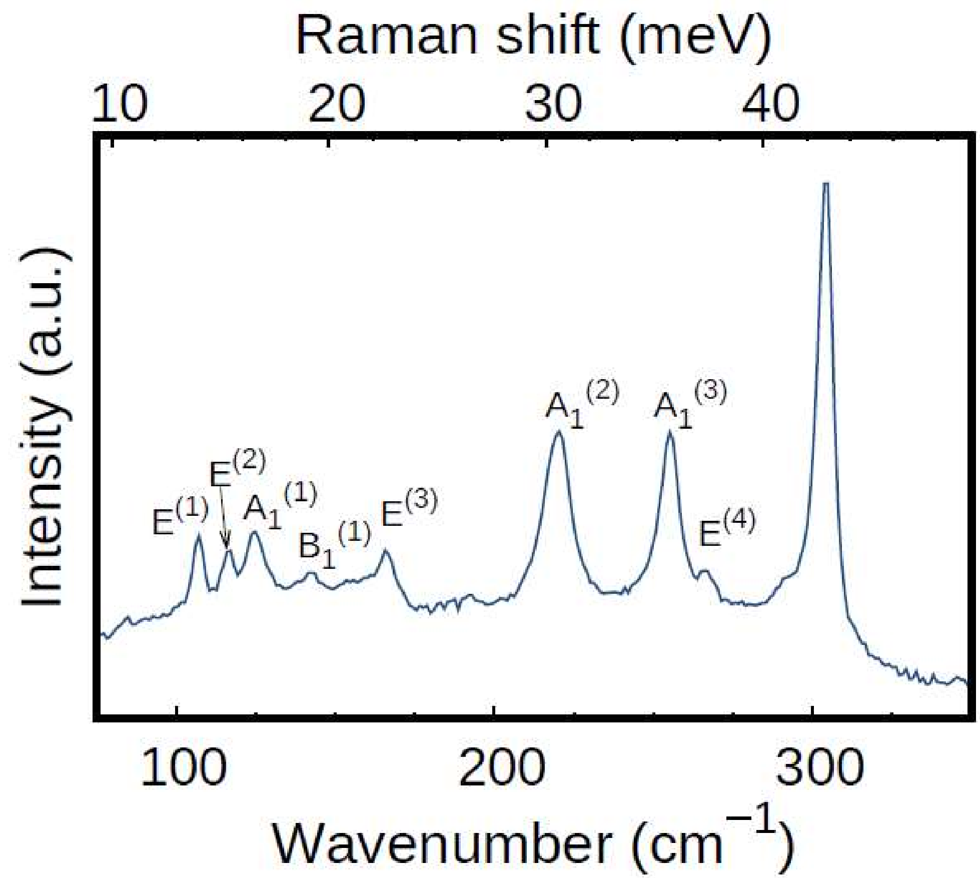


LaRhGe$_3$ Phonons – Raman Spectroscopy

Raman spectra reveals multiple phonons

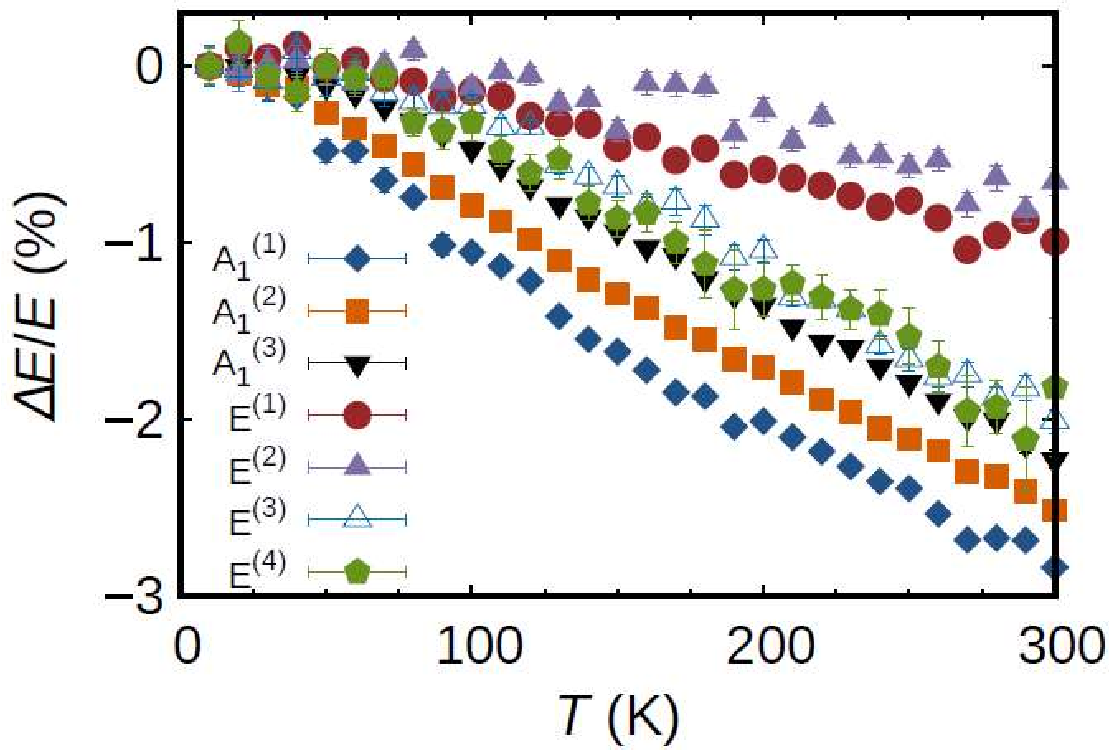
Measuring Raman at low *T*.....





$LaRhGe_3$ Phonons – Low *T* Raman Spectroscopy

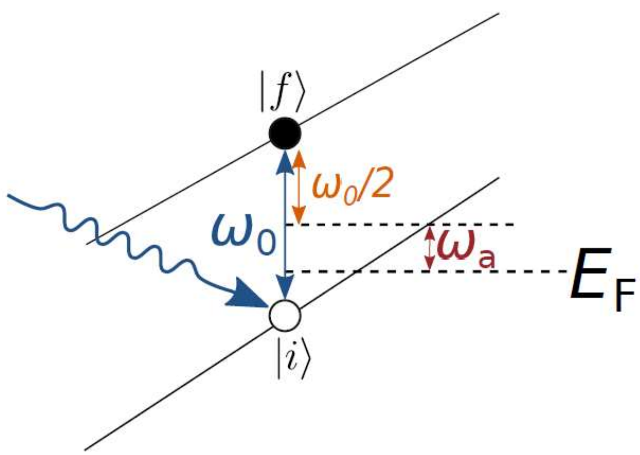
- Large relative change in *E* of the lowest $A_1^{(1)}$ mode
- The other modes with large relative change in *E* are $A_1^{(2)}$ and $A_1^{(3)}$
- *e-ph* interactions effect the linewidth of the Raman modes, but not the *E*

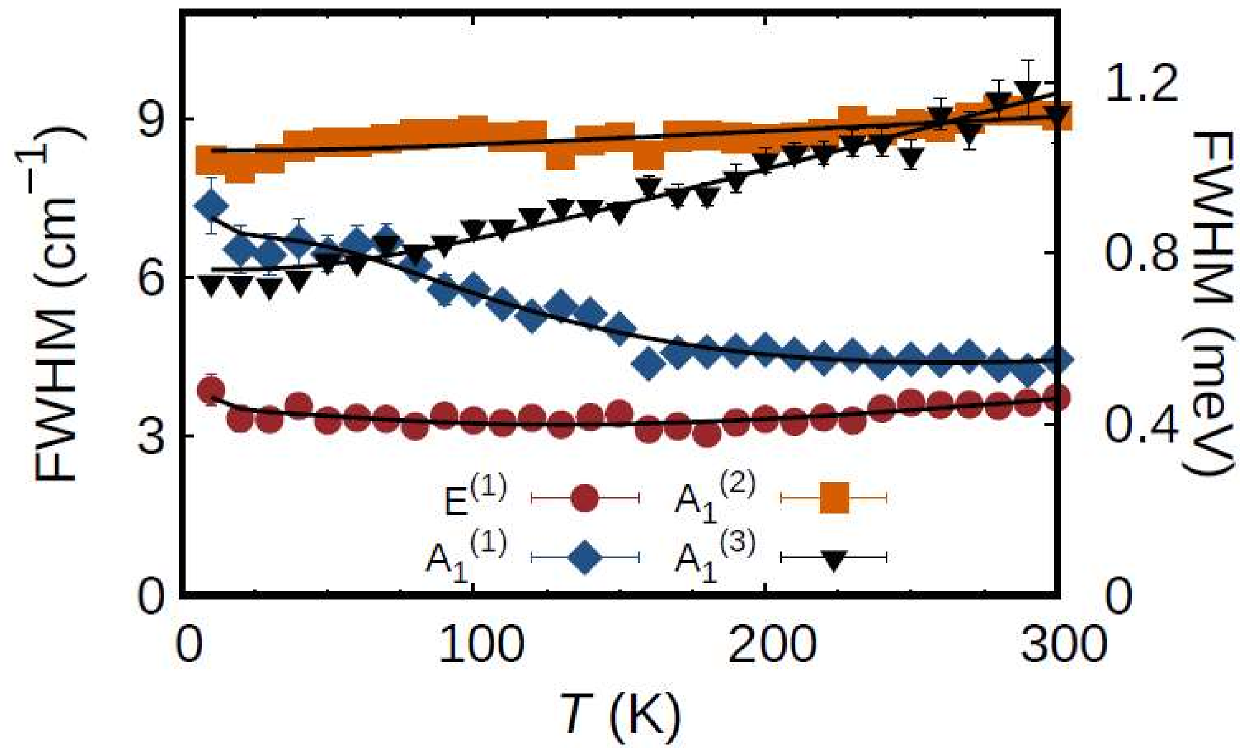


$$\omega(T) = \omega_0 e^{-3\gamma_G \alpha_0 T} - \omega_{3p}[1 + n(\omega_1, T) + n(\omega_0 - \omega_1, T)]$$

LaRhGe$_3$ Phonons – Low T Raman Spectroscopy

- The FWHM of the A_1 modes show anomalous behavior
- Can be explained with a model that suggest strong *e-ph* interactions





$$\gamma(T) = \gamma_0 + \gamma_{3p}[1 + n(\omega_1, T) + n(\omega_0 - \omega_1, T)] \\ + \gamma_{ep}[f(\omega_a - \omega_0/2) - f(\omega_a + \omega_0/2)]$$

Summary

- Normal State Properties of Semimetallic $LaRhGe_3$
  Compensated carriers ($10^{21}/cm^3$) & non-saturating magnetoresistance
- Superconductivity in Non-Centrosymmetric Materials
  ASOC in $LaRhGe_3$ due to Rh allows for mixing of singlet-triplet pairing
- Superconducting Properties of $LaRhGe_3$
  Evidence for weak coupling superconductivity from C_p, type-I superconductivity from TF μSR, T_c~0.385 K, H_c~2.1 mT and no significant triplet pairing in zero-field μSR
- *e-ph* Interactions in the Normal State
  Unusual T-dependence of ρ_{xx}, Evidence from peak at ~30 K in S_{xx} and κ_{xx}
  Raman spectra at low T reveal unusual FWHM of $A_1^{(1)}$ mode

Thank You!

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