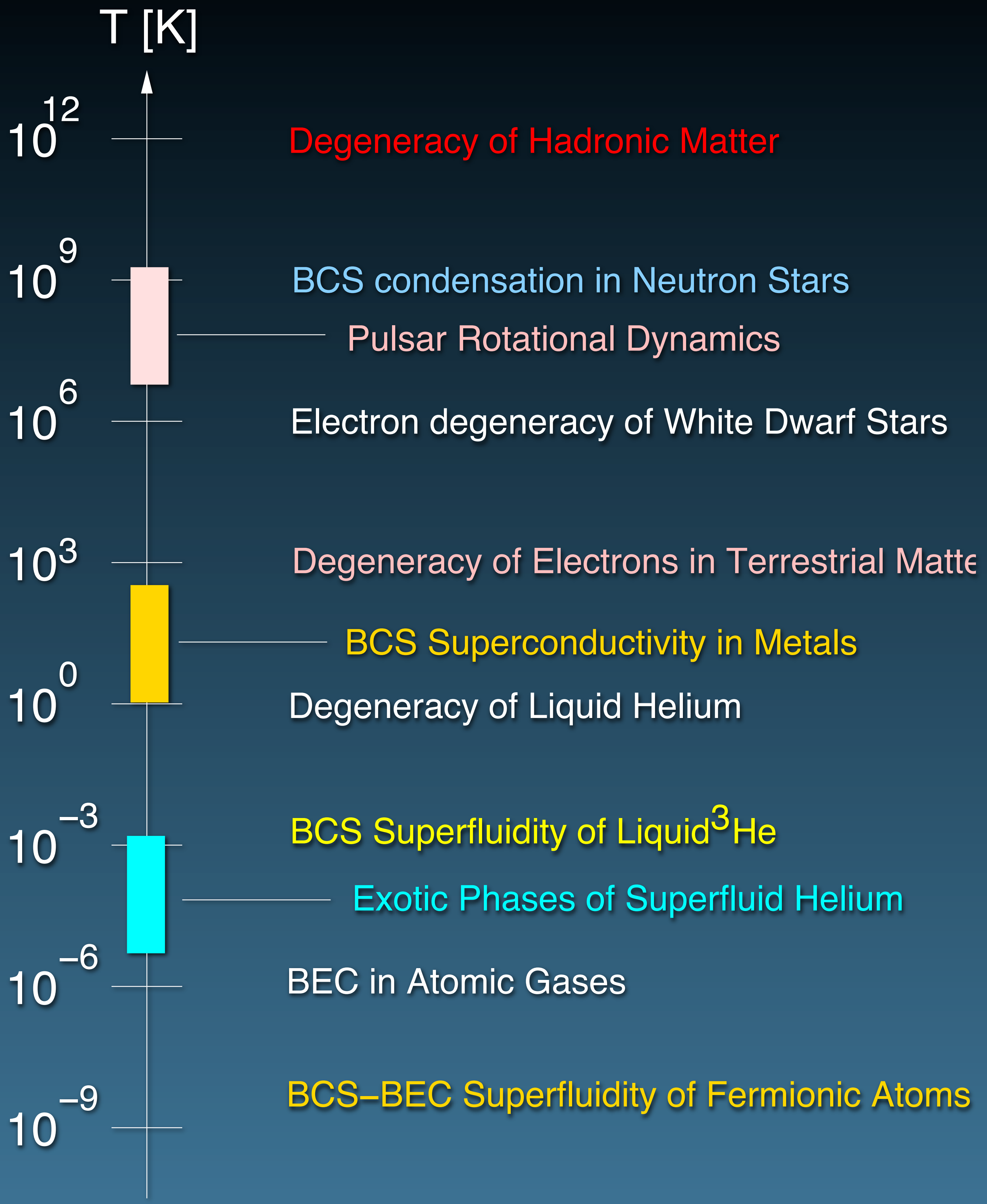
BCS Pairing from 10^{-9} to 10^{+9} K



T [K]

10^{12} Degeneracy of Hadronic Matter

10^{9} BCS condensation in Neutron Stars

Pulsar Rotational Dynamics

10^{6} Electron degeneracy of White Dwarf Stars

10^{3} Degeneracy of Electrons in Terrestrial Matte

BCS Superconductivity in Metals

10^{0} Degeneracy of Liquid Helium

10^{-3} BCS Superfluidity of Liquid ^{3}He

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10^{-6} BEC in Atomic Gases

BCS–BEC Superfluidity of Fermionic Atoms

10^{-9}

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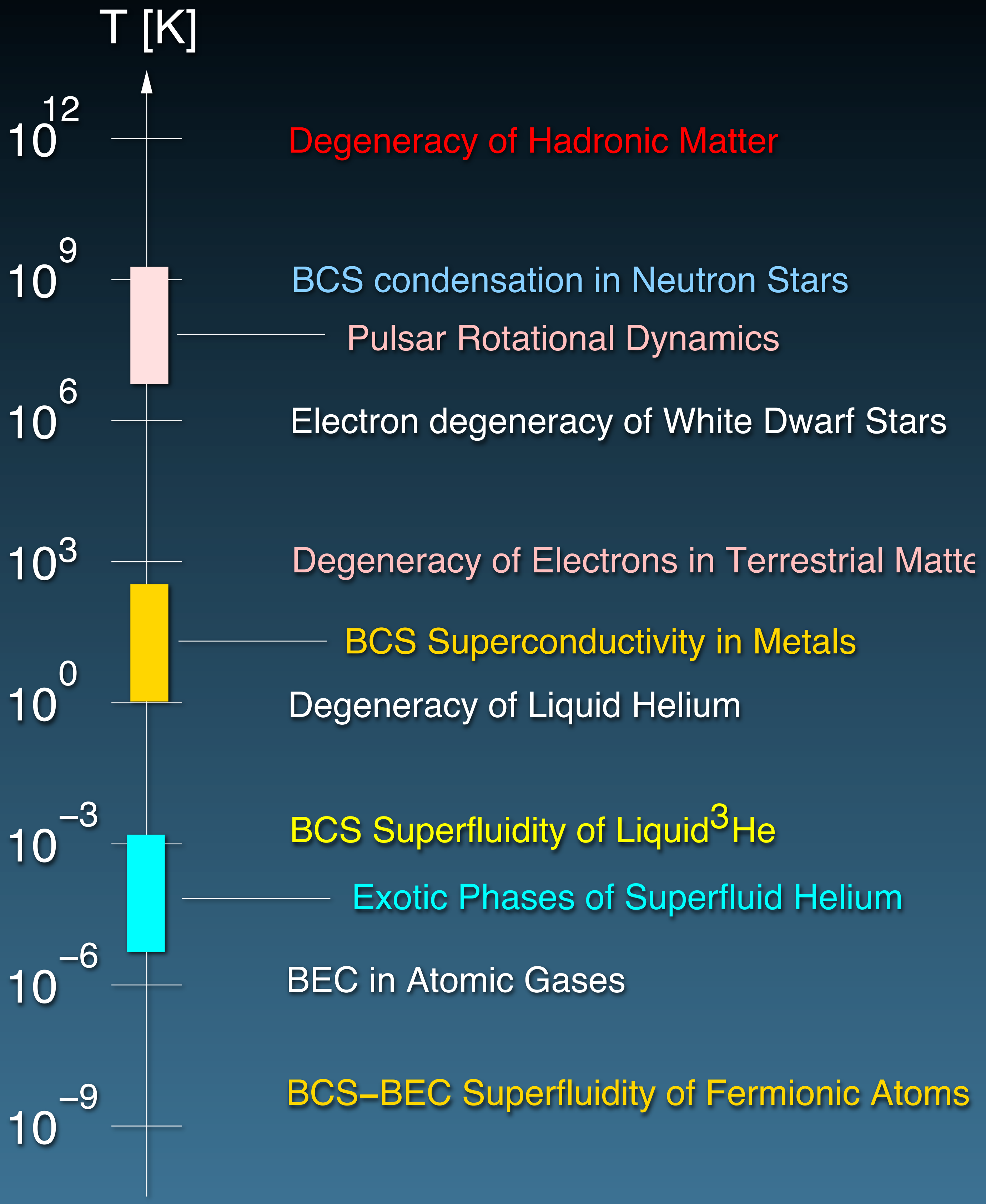

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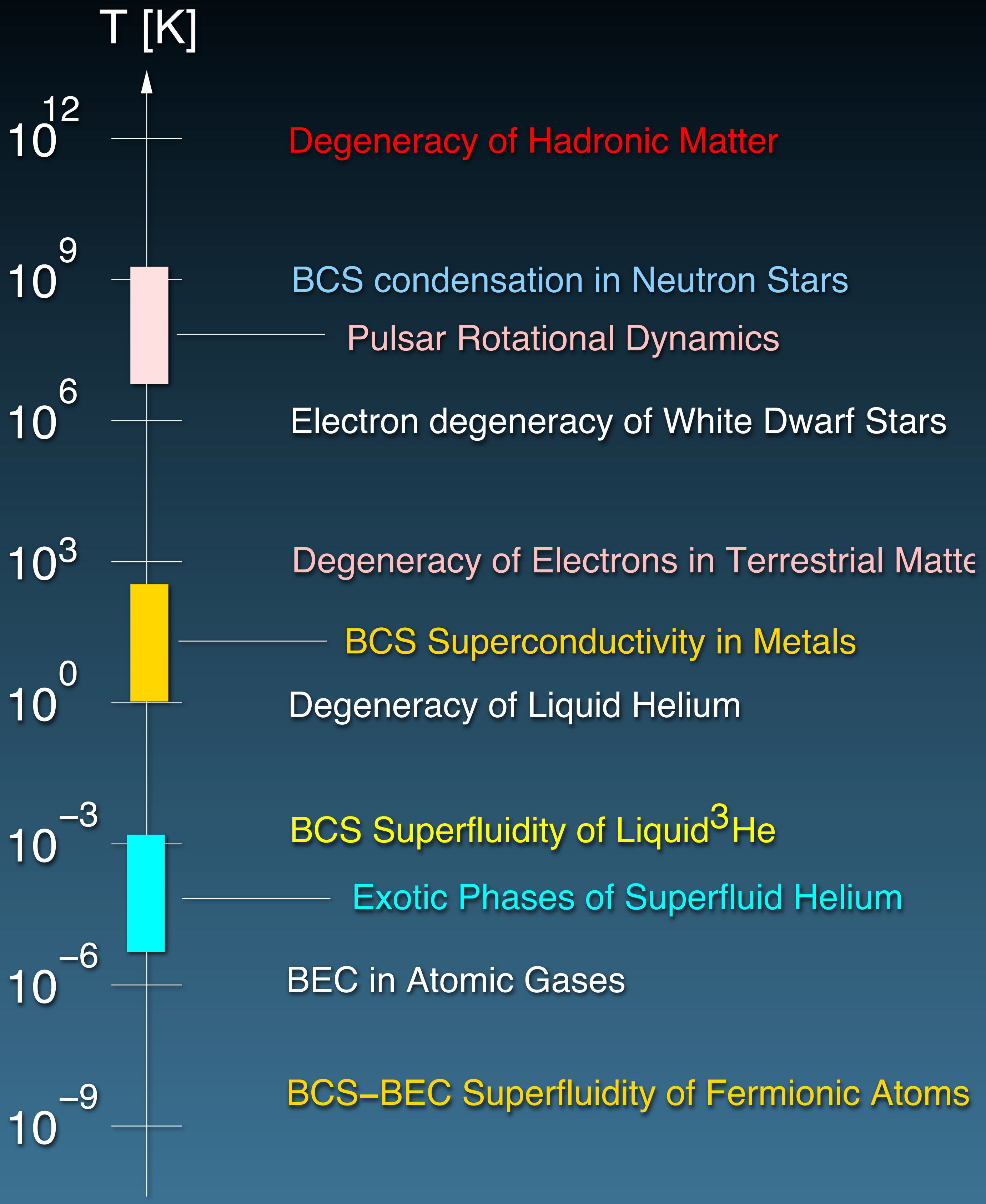

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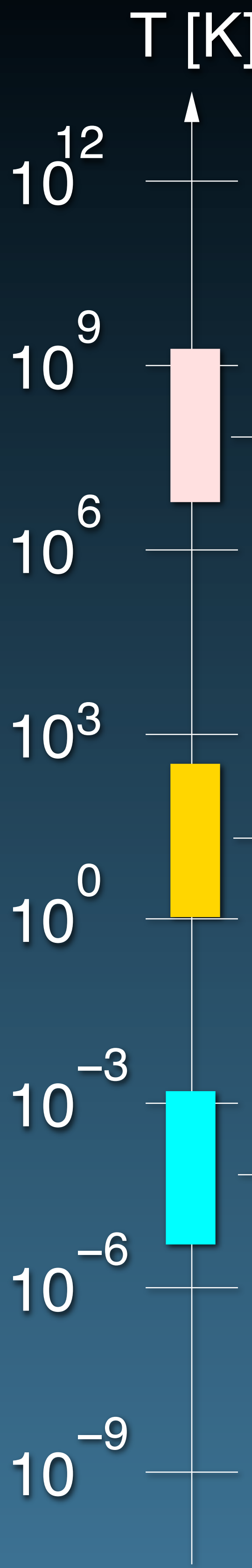

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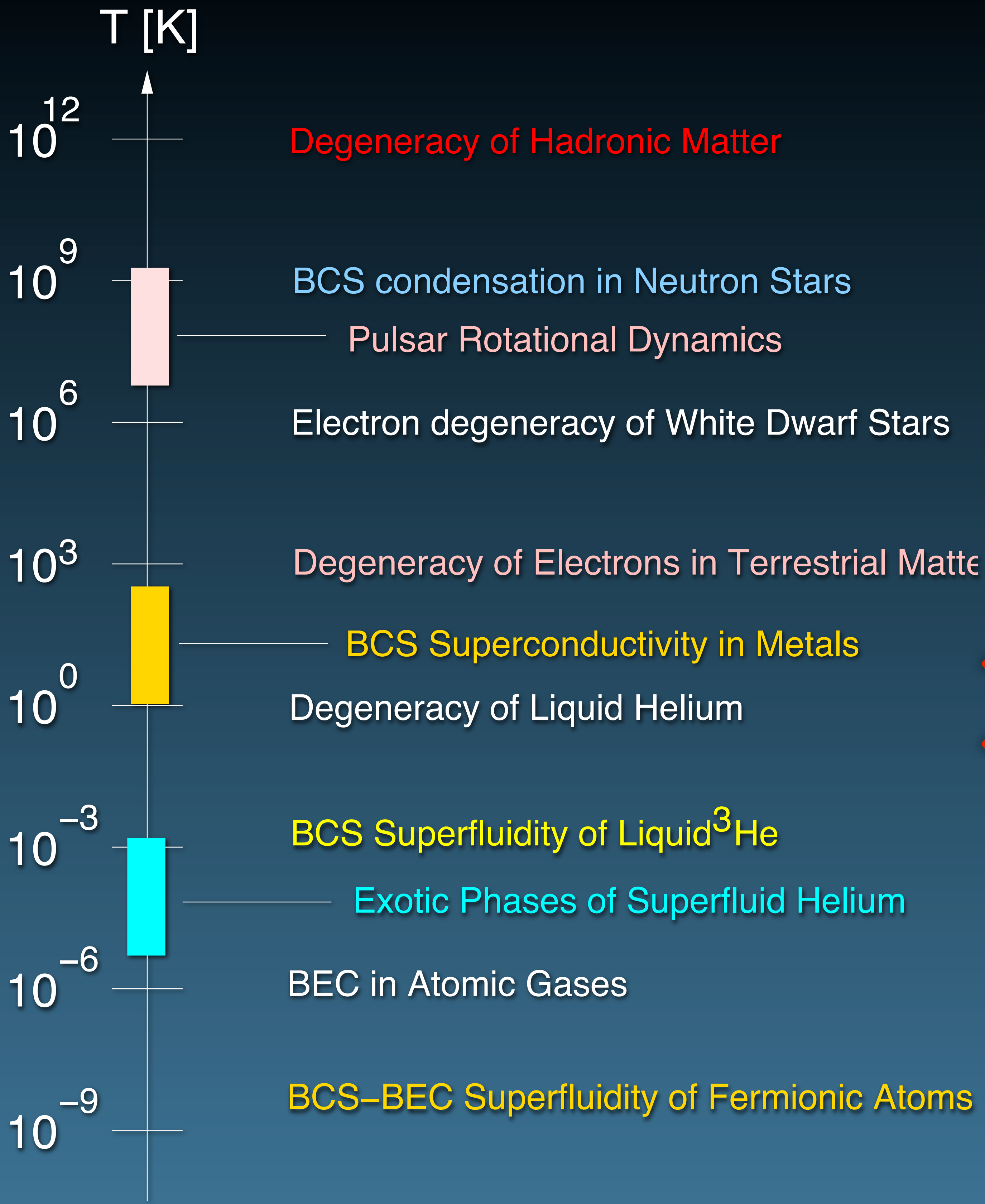

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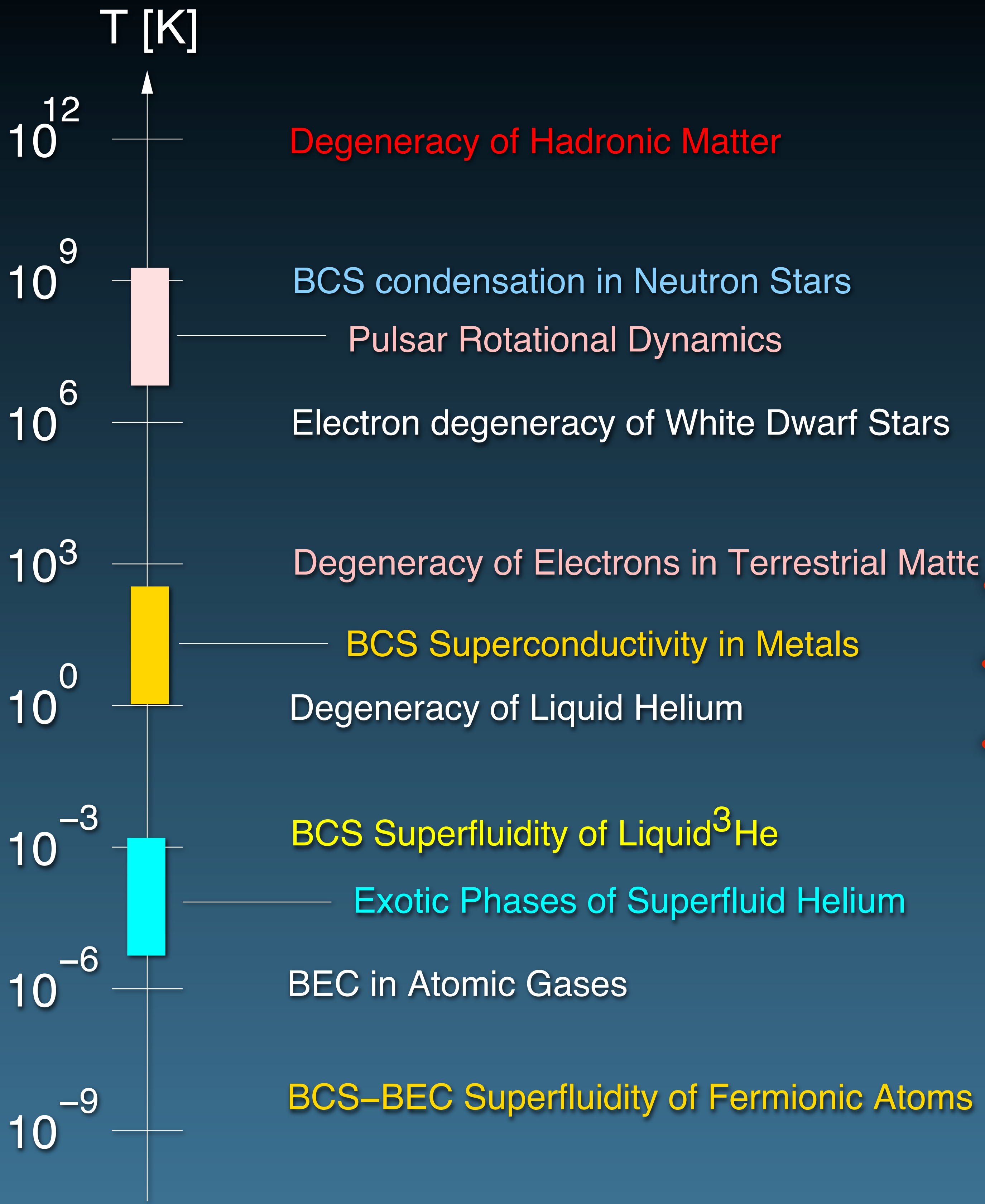

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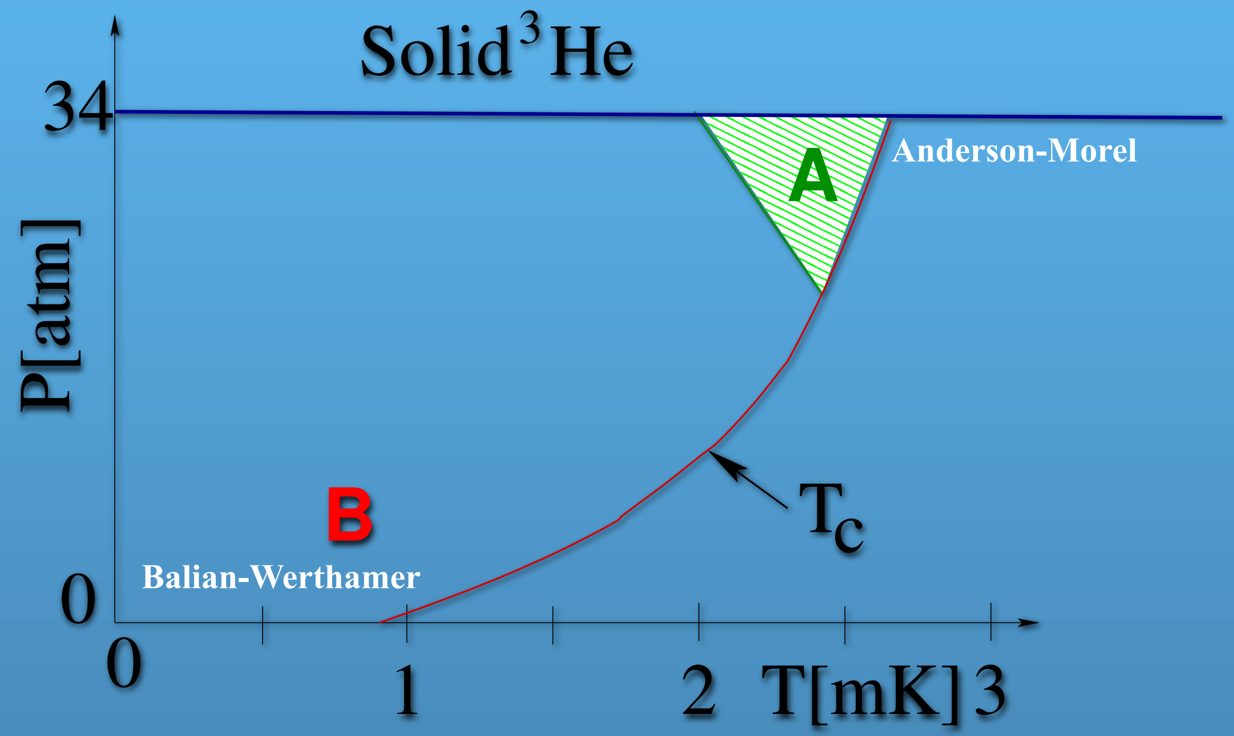

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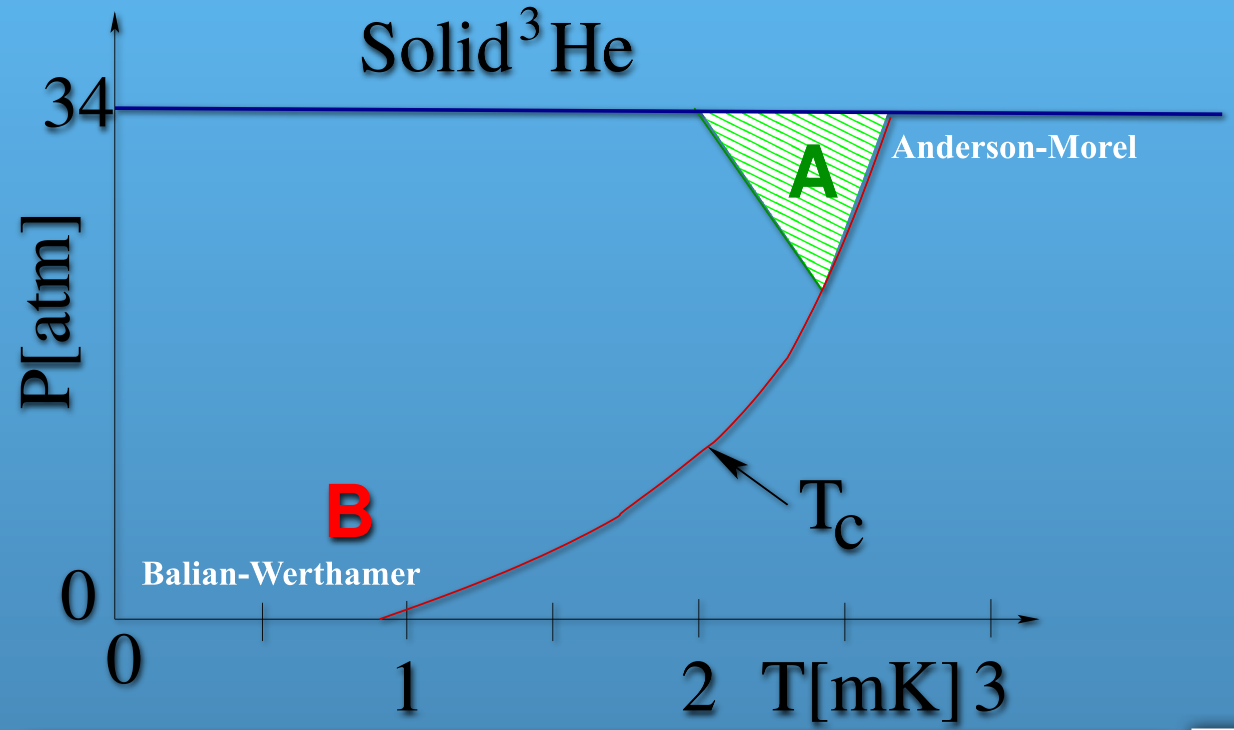

$G = SO(3)_{orbit} \times SO(3)_{spin} \times U(1)_{gauge} \times P \times T \times C$

^{3}He

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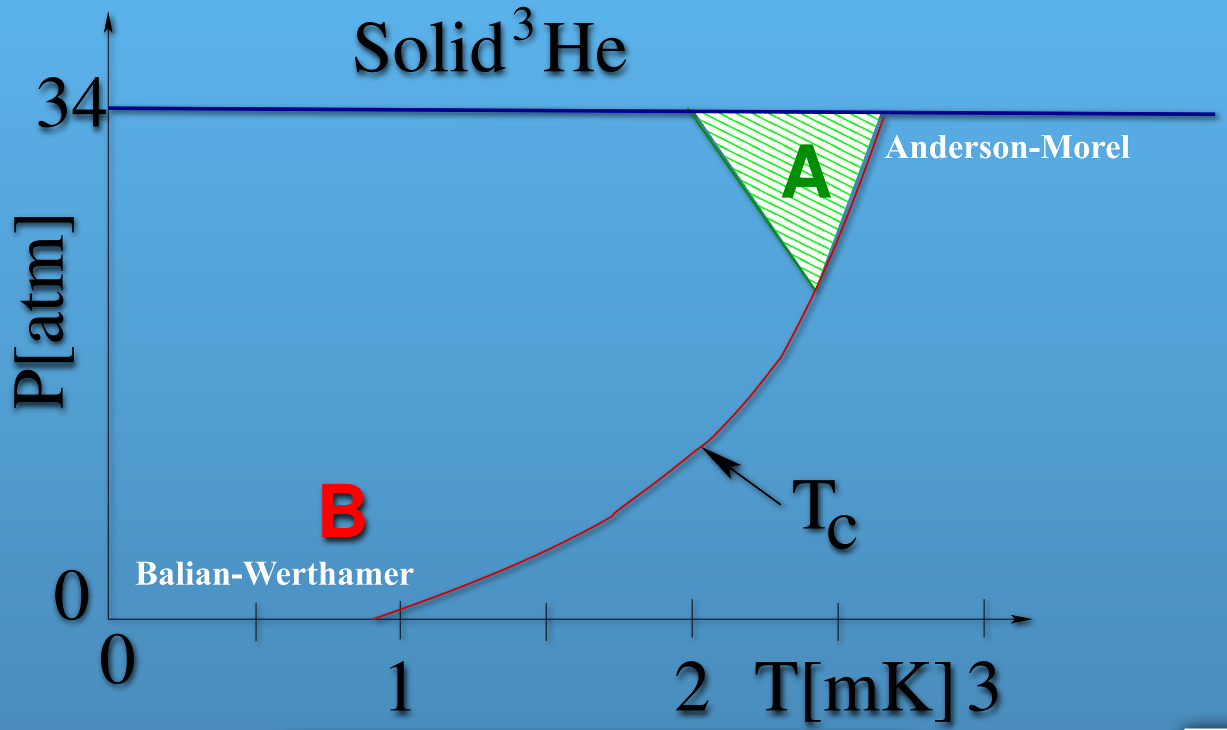

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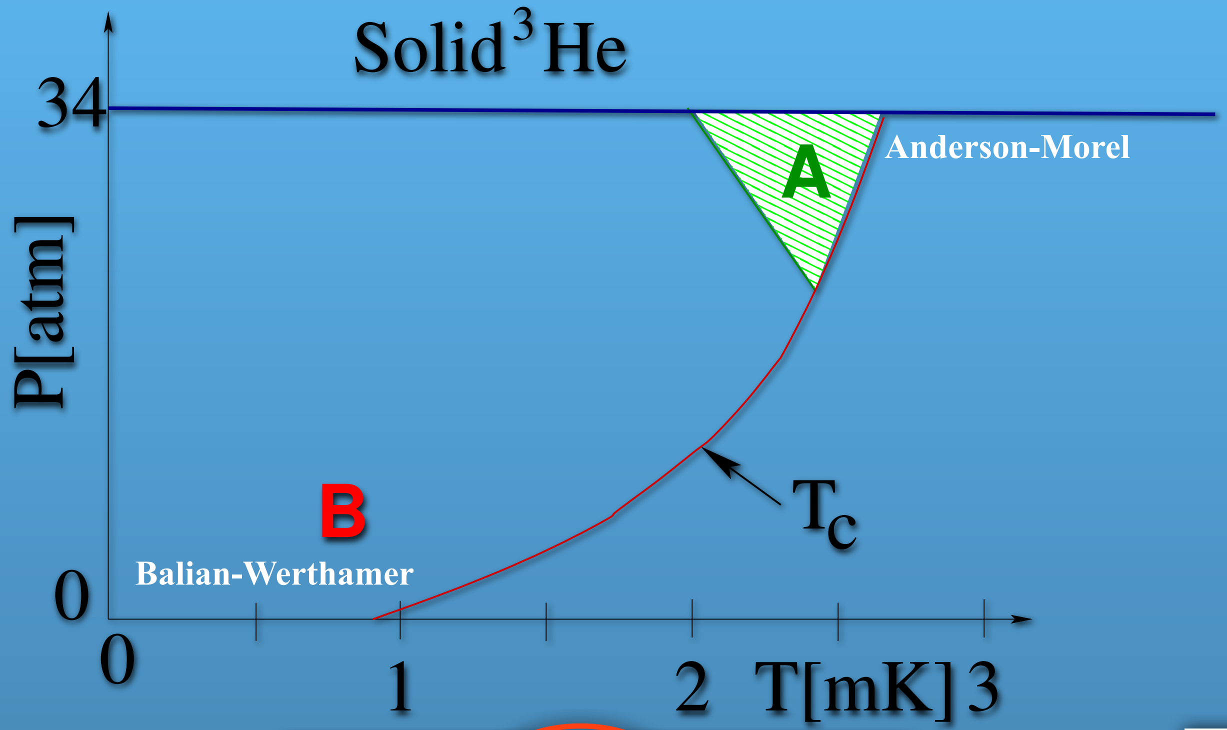

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^{3}He

$$V = V_1 \left(\varphi^\dagger_{+1} \varphi_{+1} + \varphi^\dagger_{-1} \varphi_{-1} \right)$$

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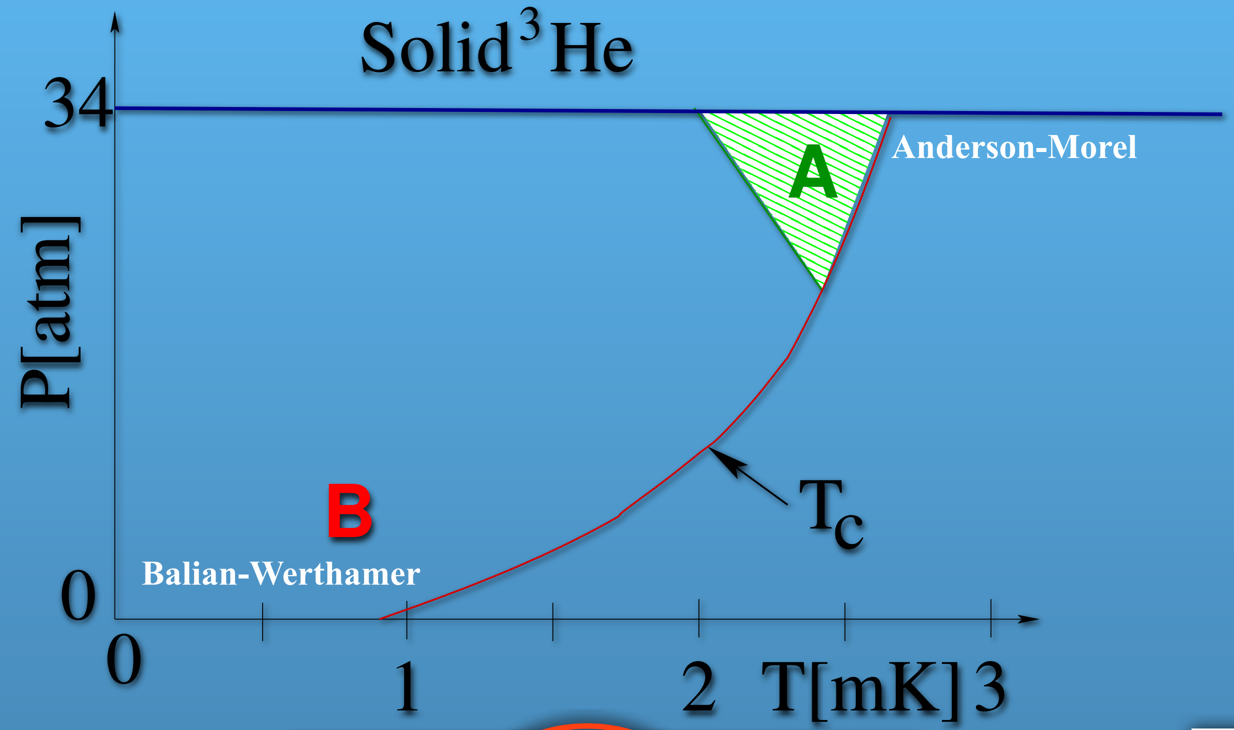

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^{3}He

- Symmetry Breaking Field = Nuclear Zeeman Energy

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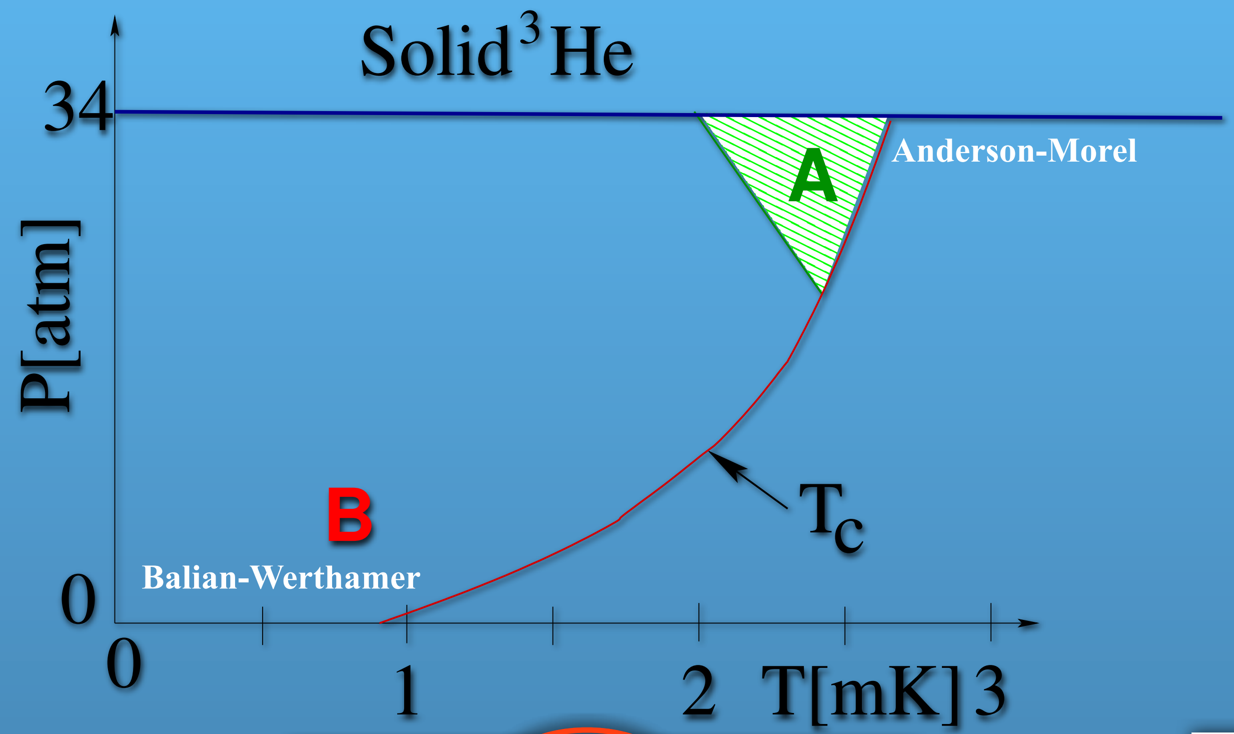

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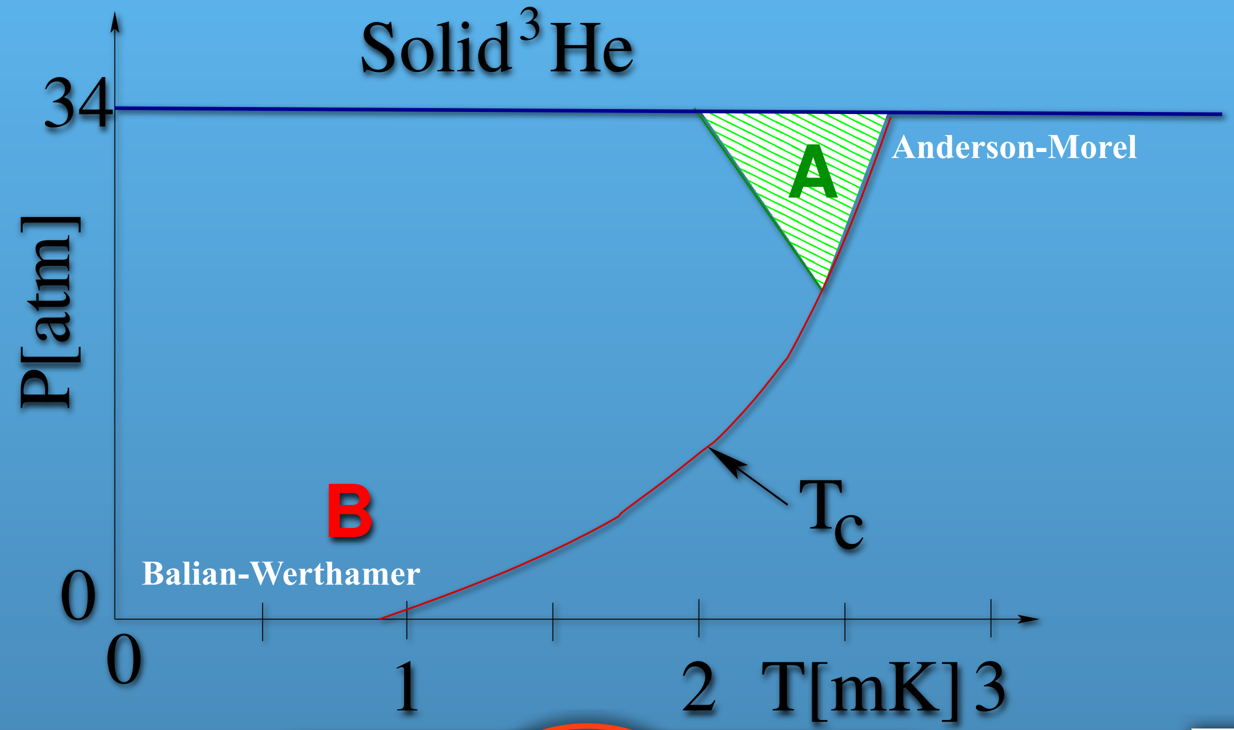

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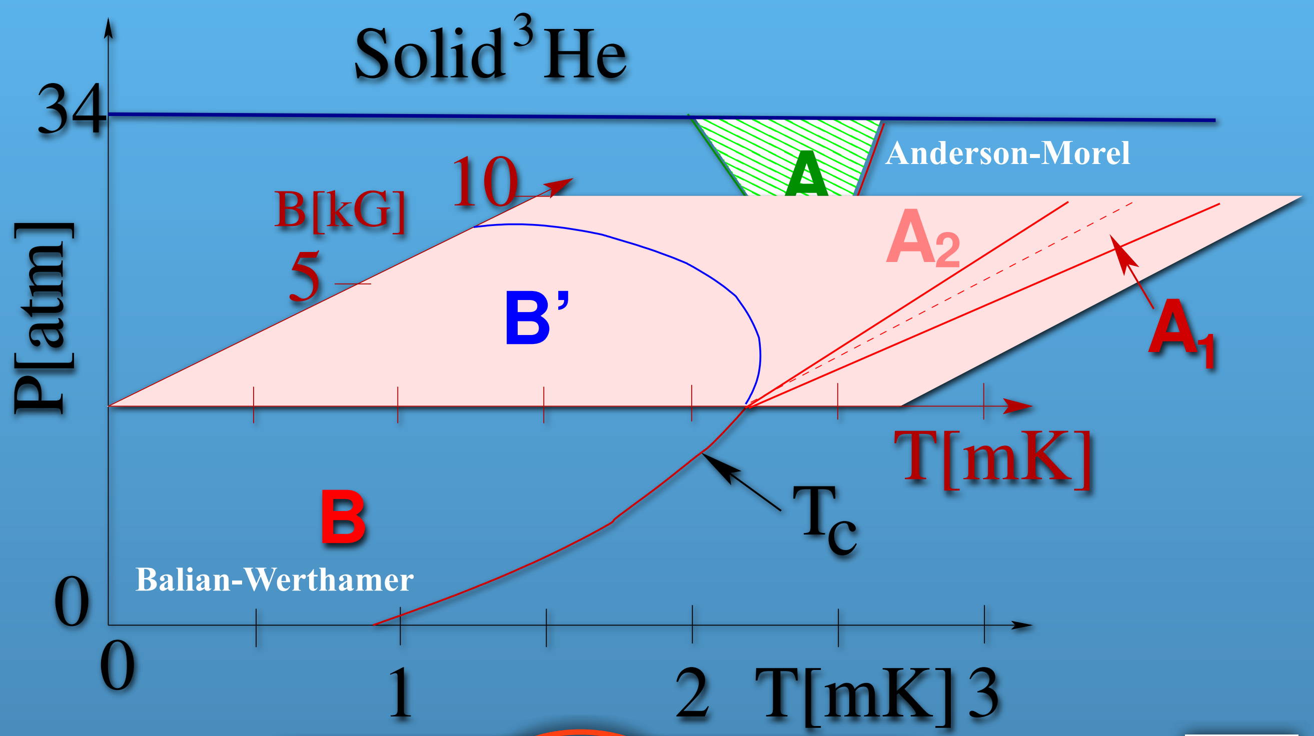

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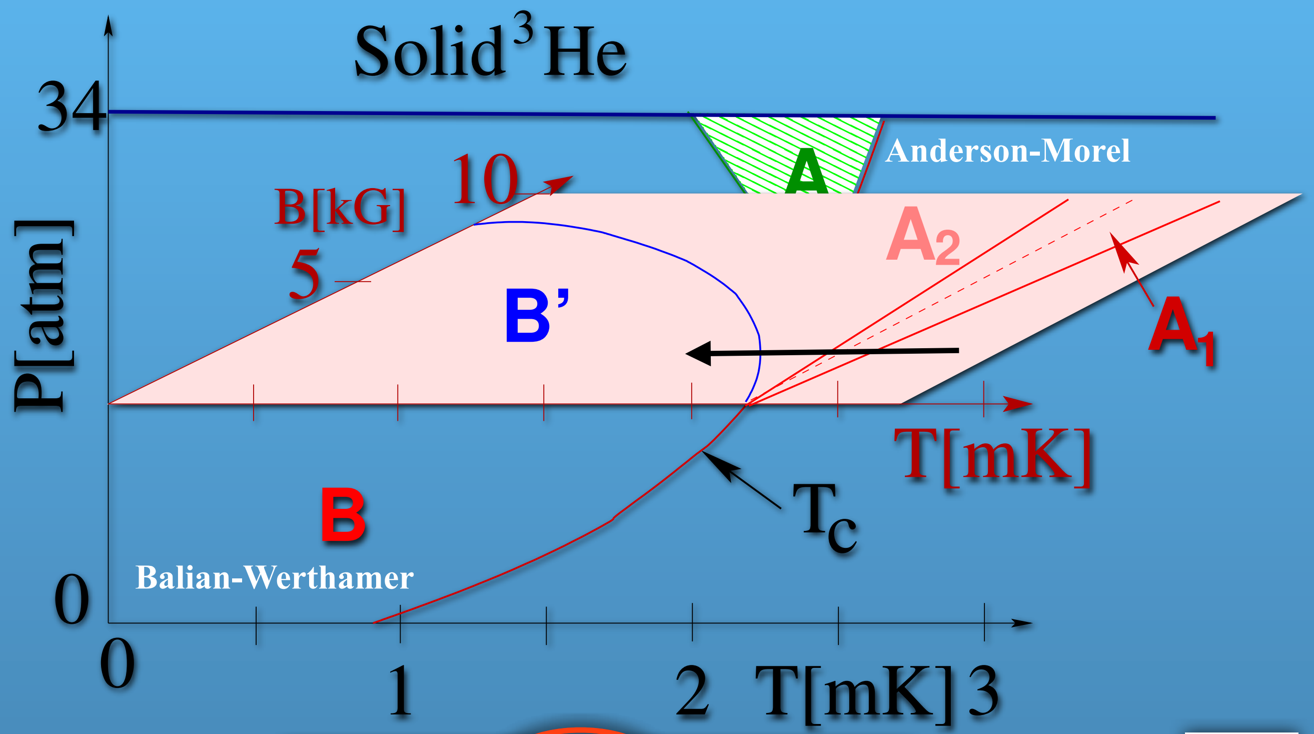

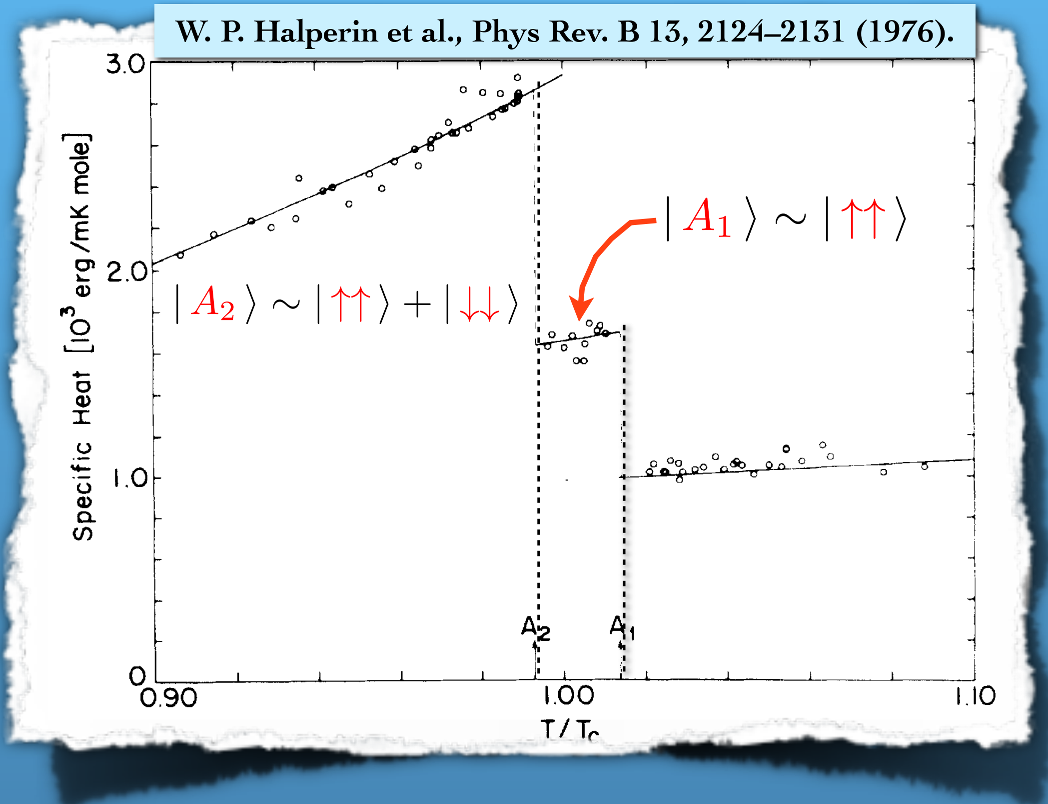
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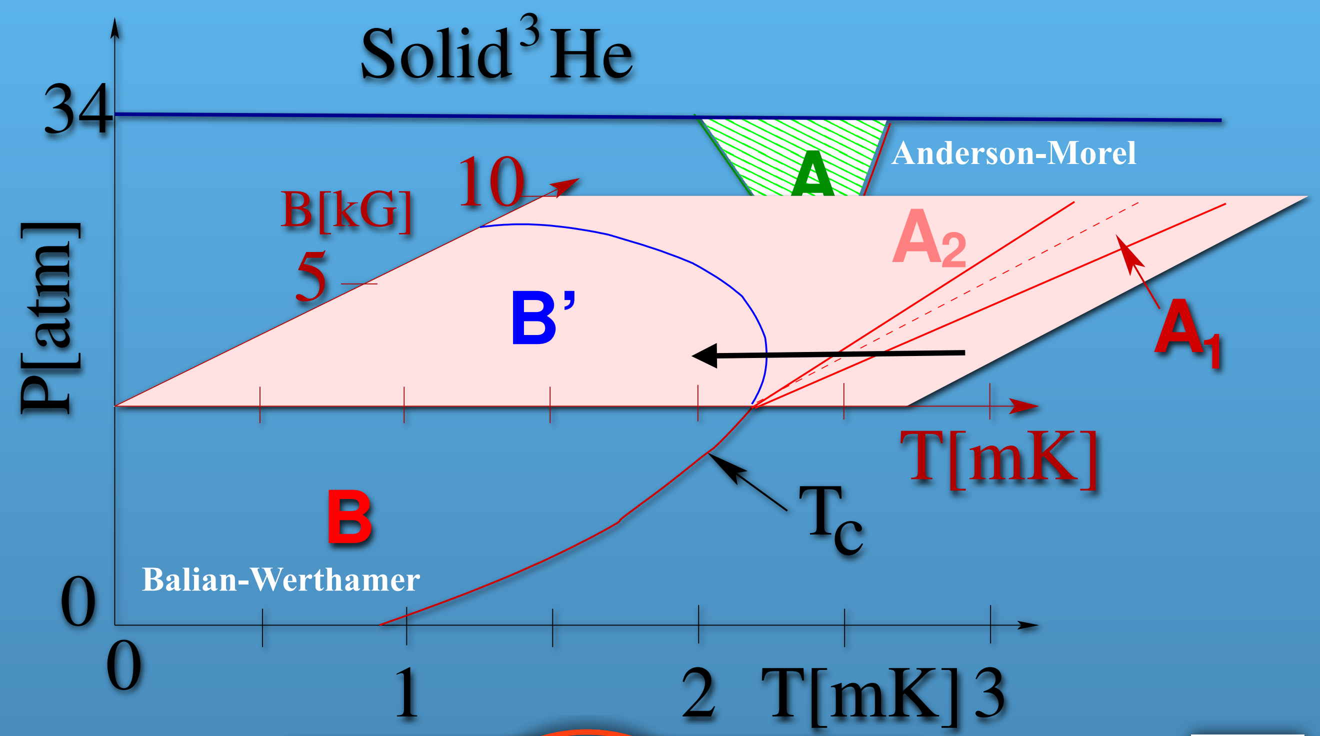

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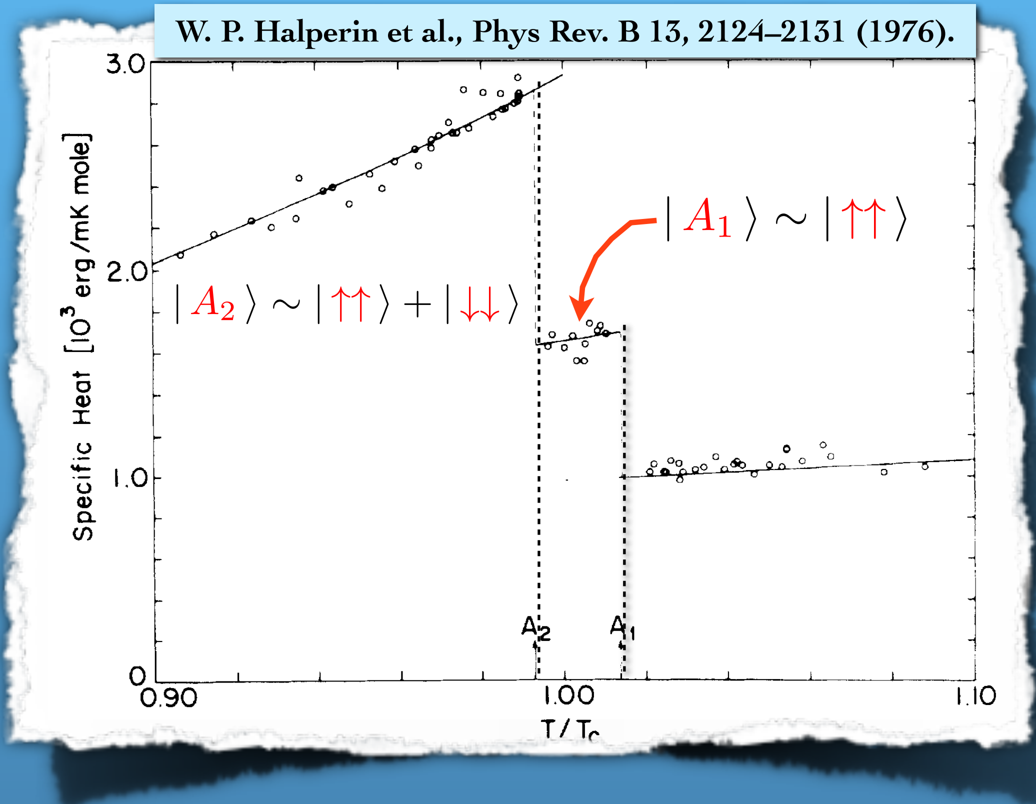

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UPt$_3$

$G = D_{6h} \times U(1)_{\mathrm{gauge}} \times T$

$$V(\mathbf{p},\mathbf{p}') = V_E \left(\phi_1^\dagger(\mathbf{p})\phi_1(\mathbf{p}') + \phi_2^\dagger(\mathbf{p})\phi_2(\mathbf{p}') \right)$$

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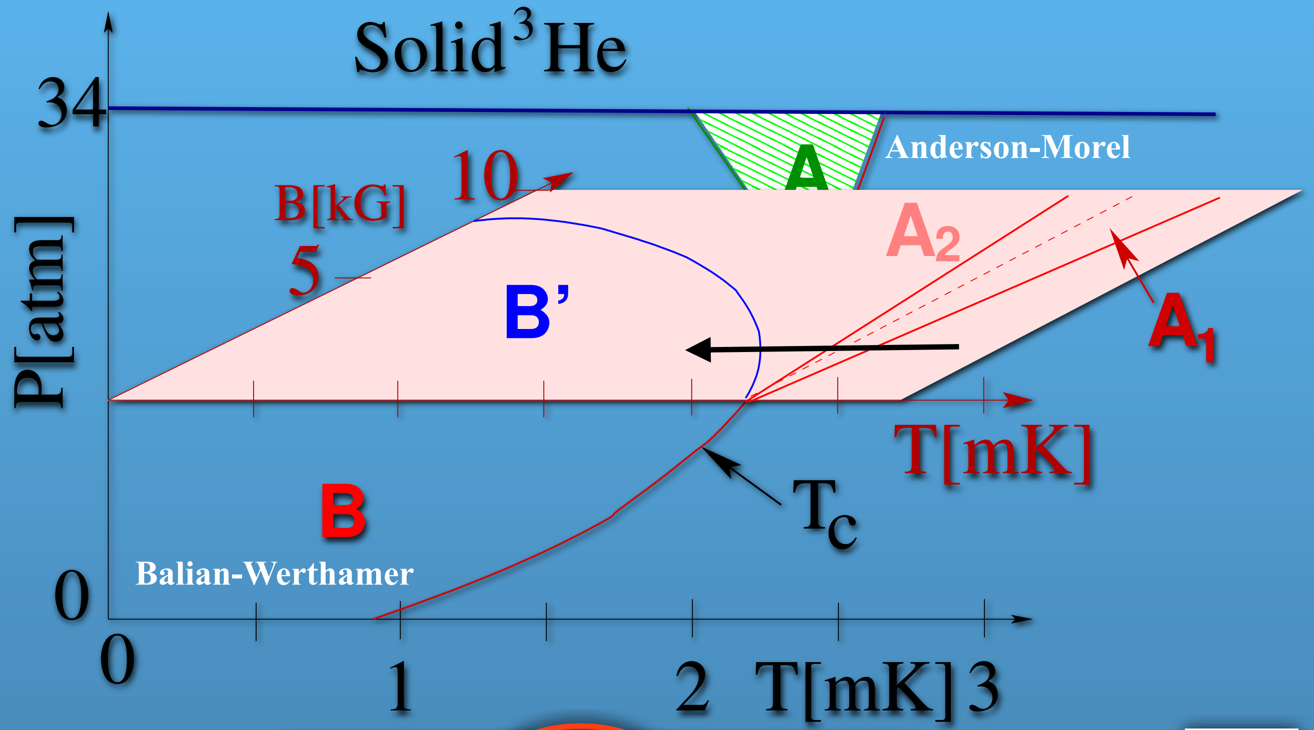

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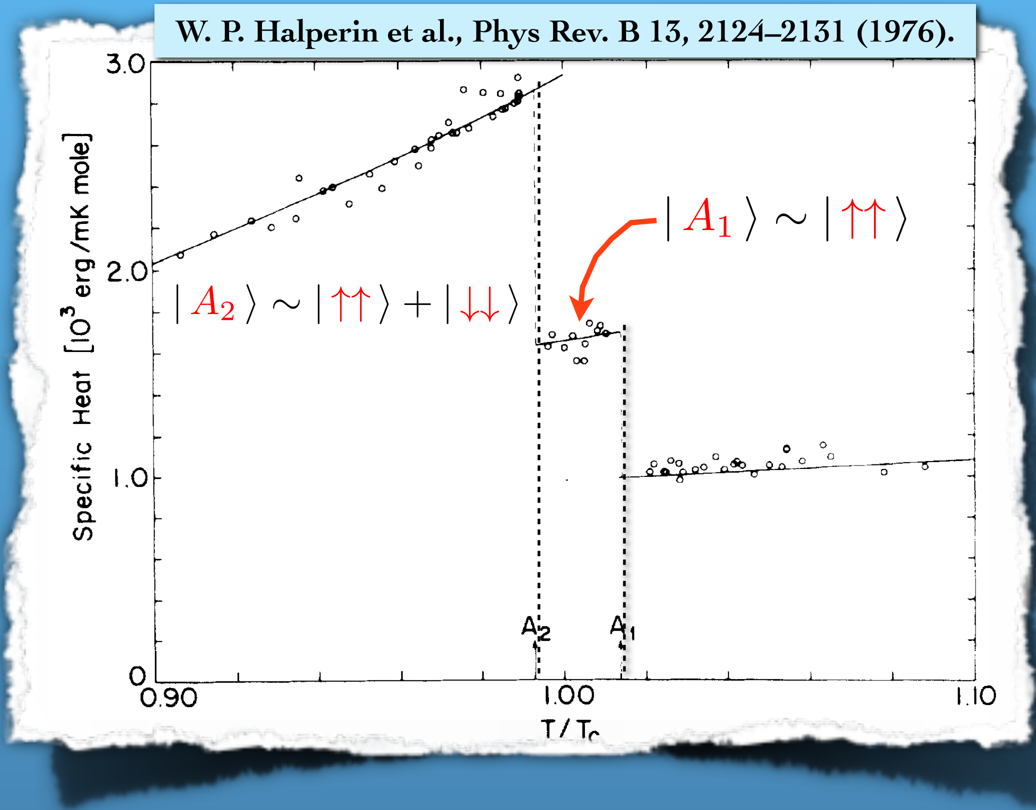

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UPt$_3$

$$G_B = C_{6-N}$$

$$V(\mathbf{p}, \mathbf{p}') = V_E \left(\phi_1^\dagger(\mathbf{p}) \phi_1(\mathbf{p}') + \phi_2^\dagger(\mathbf{p}) \phi_2(\mathbf{p}') \right)$$

$$\rightarrow \mathbf{\Delta}(\mathbf{p}) = \eta_1 \phi_1(\mathbf{p}) + \eta_2 \phi_2(\mathbf{p})$$

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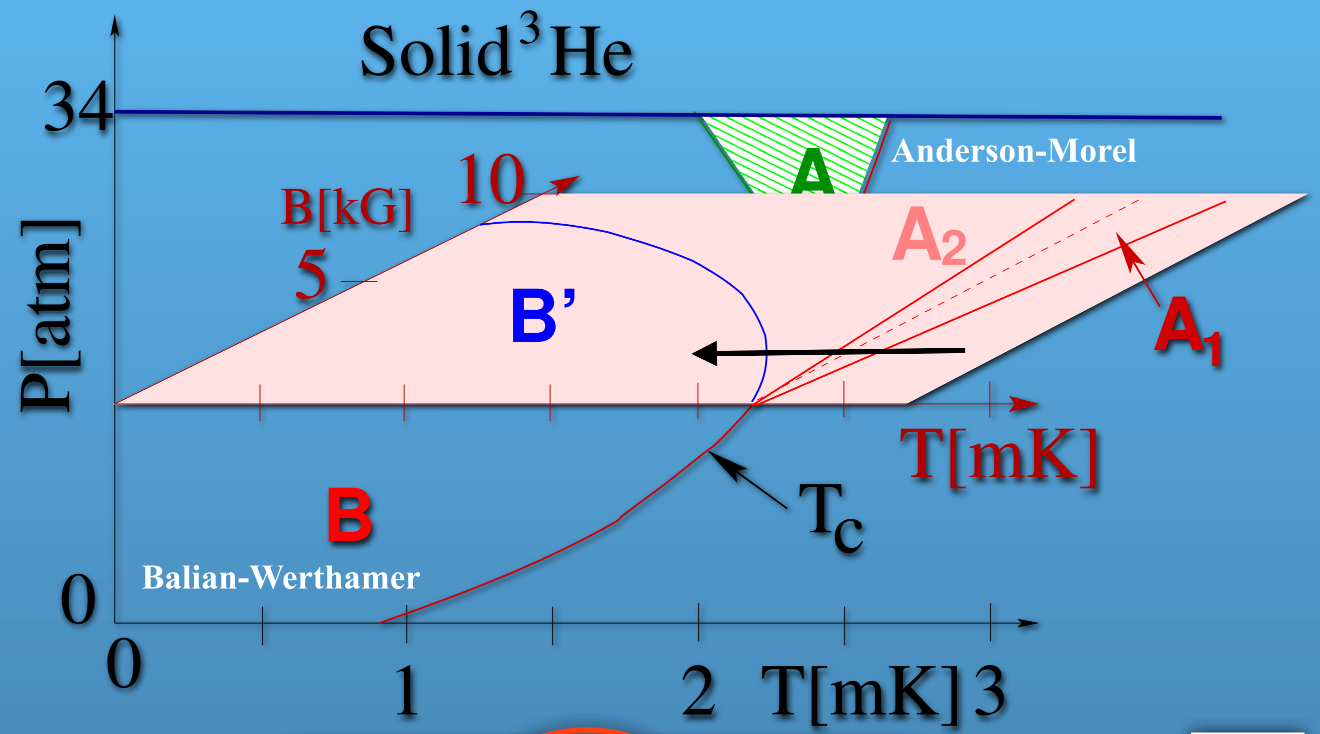

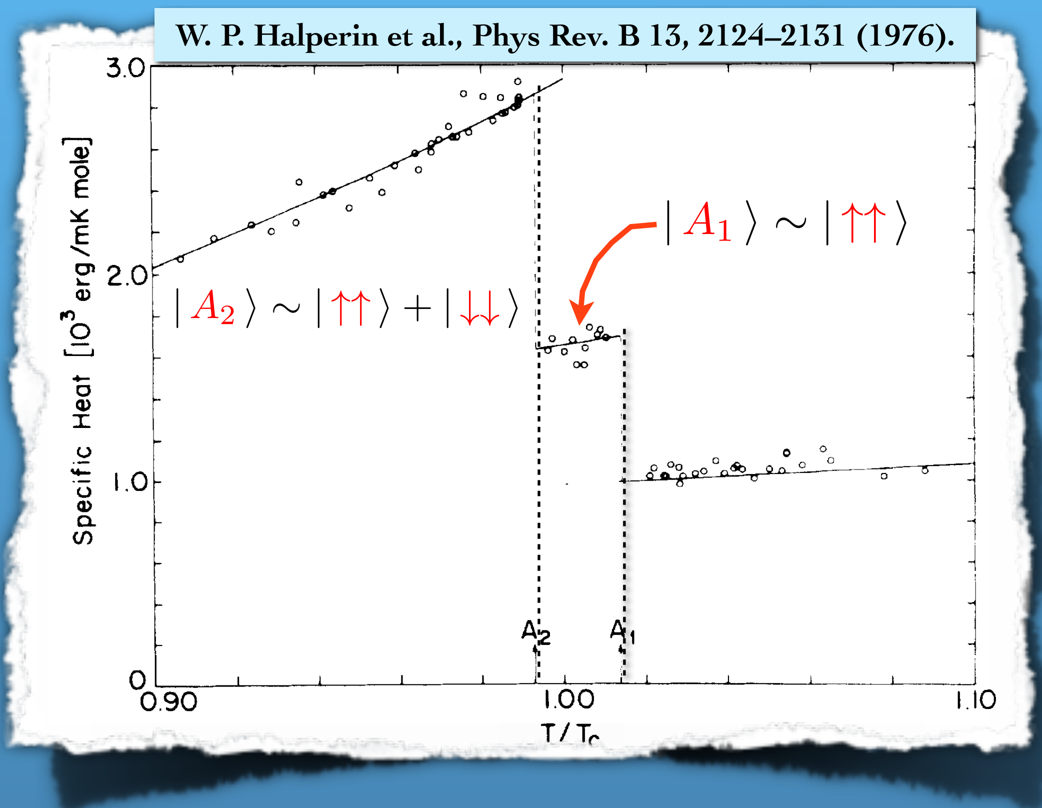
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- ❖ Competing Orders - SC & AFM + Strain (T > Tc)
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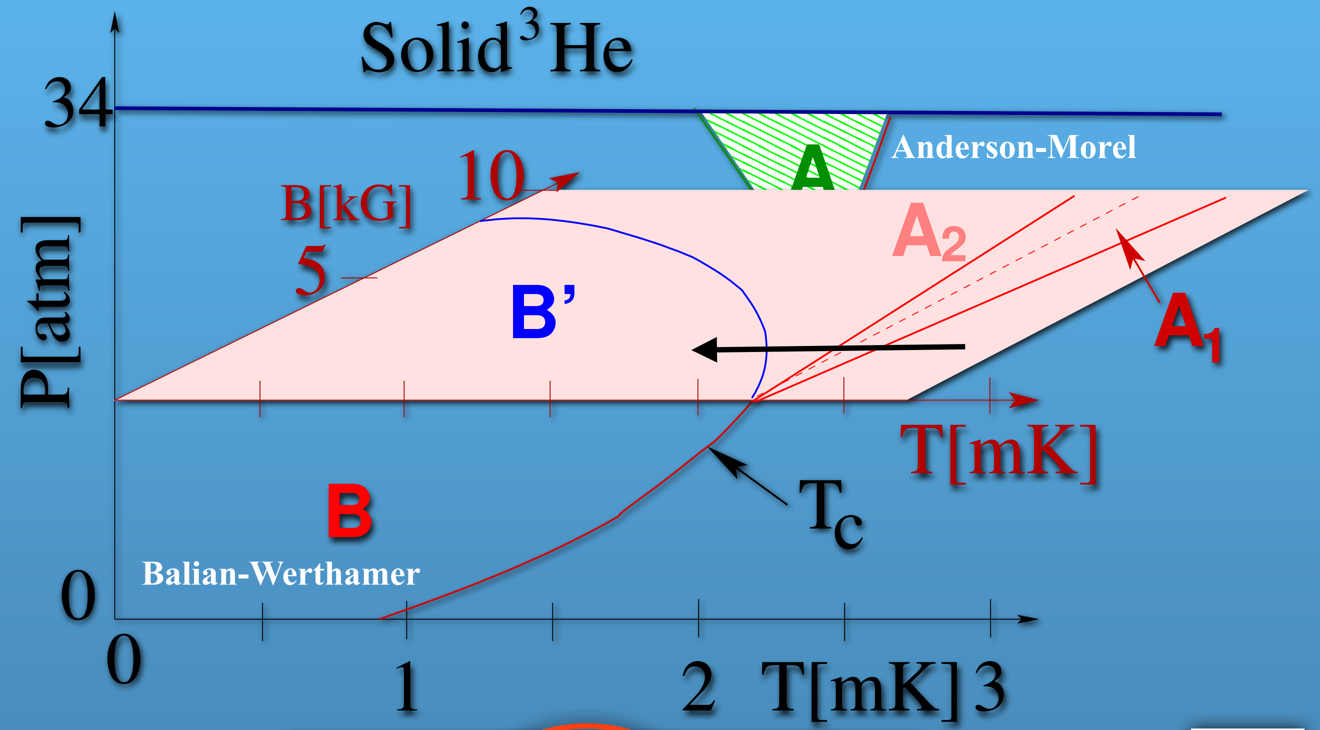

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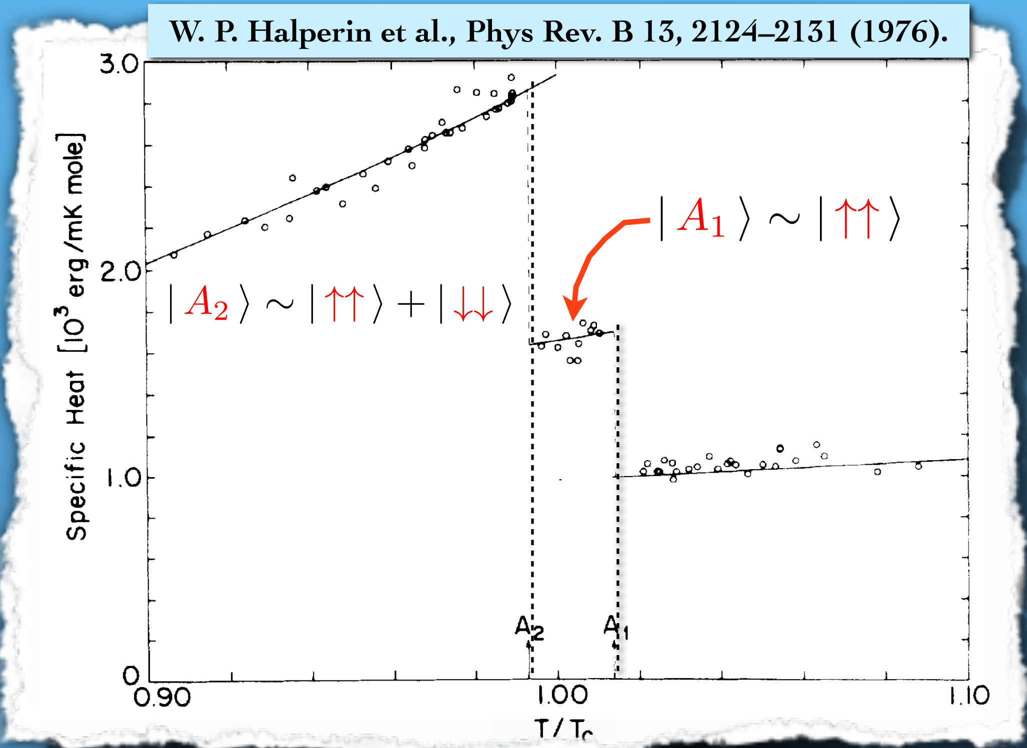
$$T_{c_1}\ |A\rangle = \begin{pmatrix}\phi_1\\ 0\end{pmatrix} \qquad T < T_{c_2} < T_{c_1}\ |B\rangle = \begin{pmatrix}\phi_1\\ i\phi_2\end{pmatrix}$$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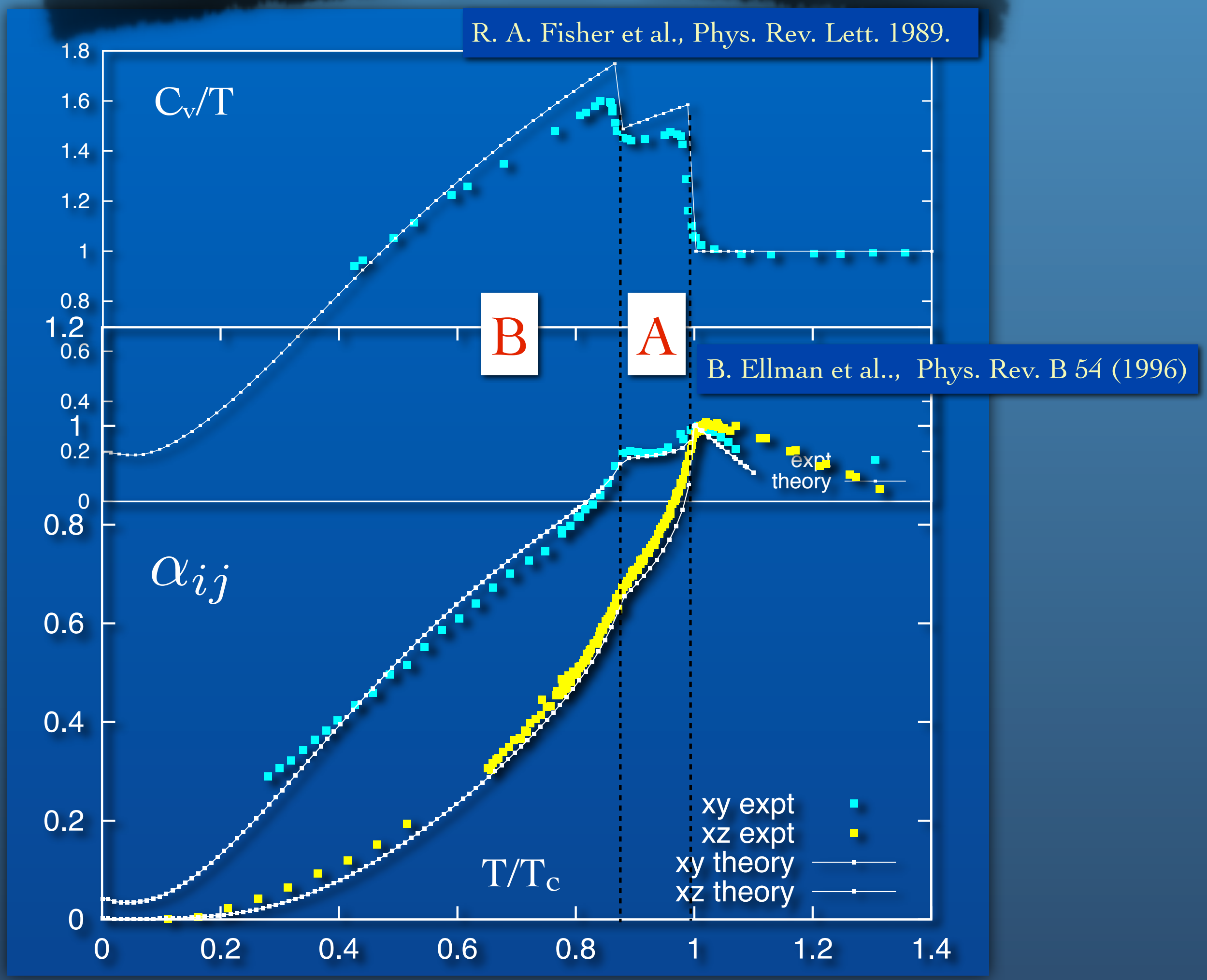
R. A. Fisher et al., Phys. Rev. Lett. 1989.

B. Ellman et al.., Phys. Rev B 54 (1996)

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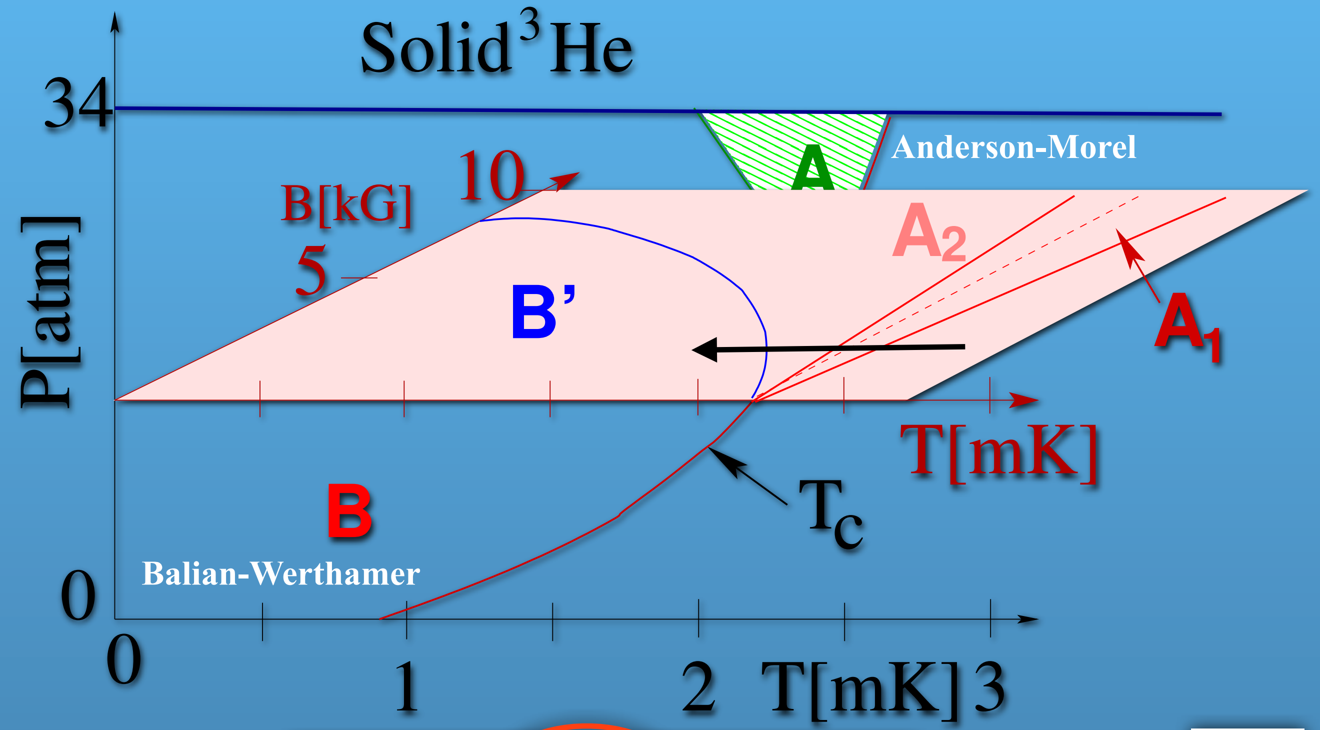

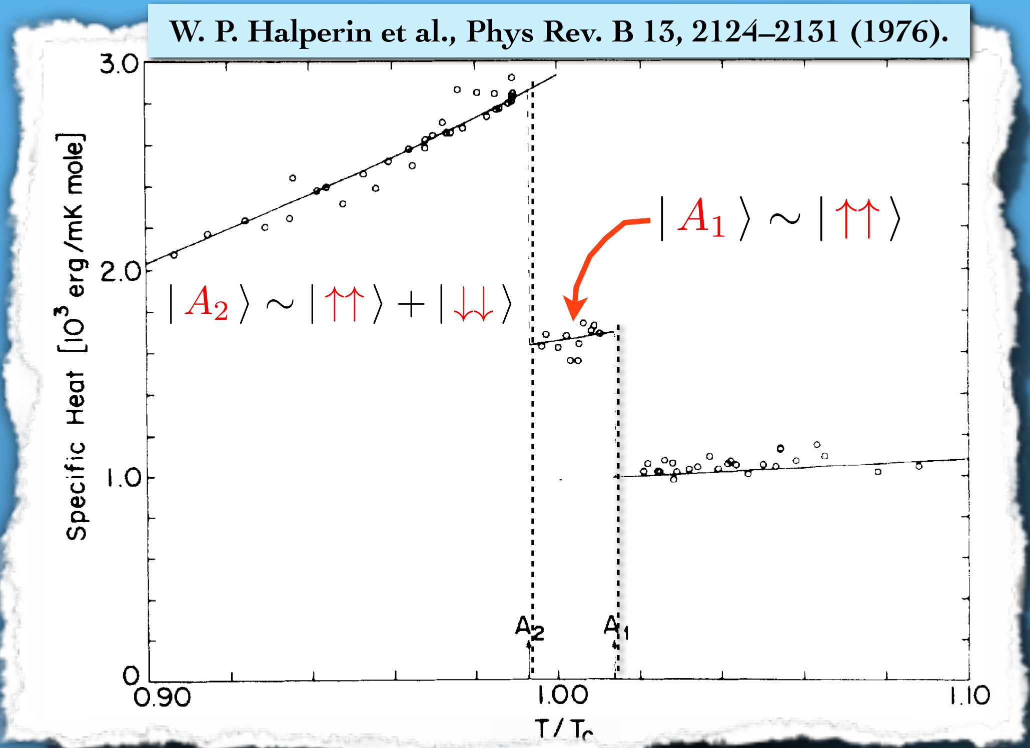
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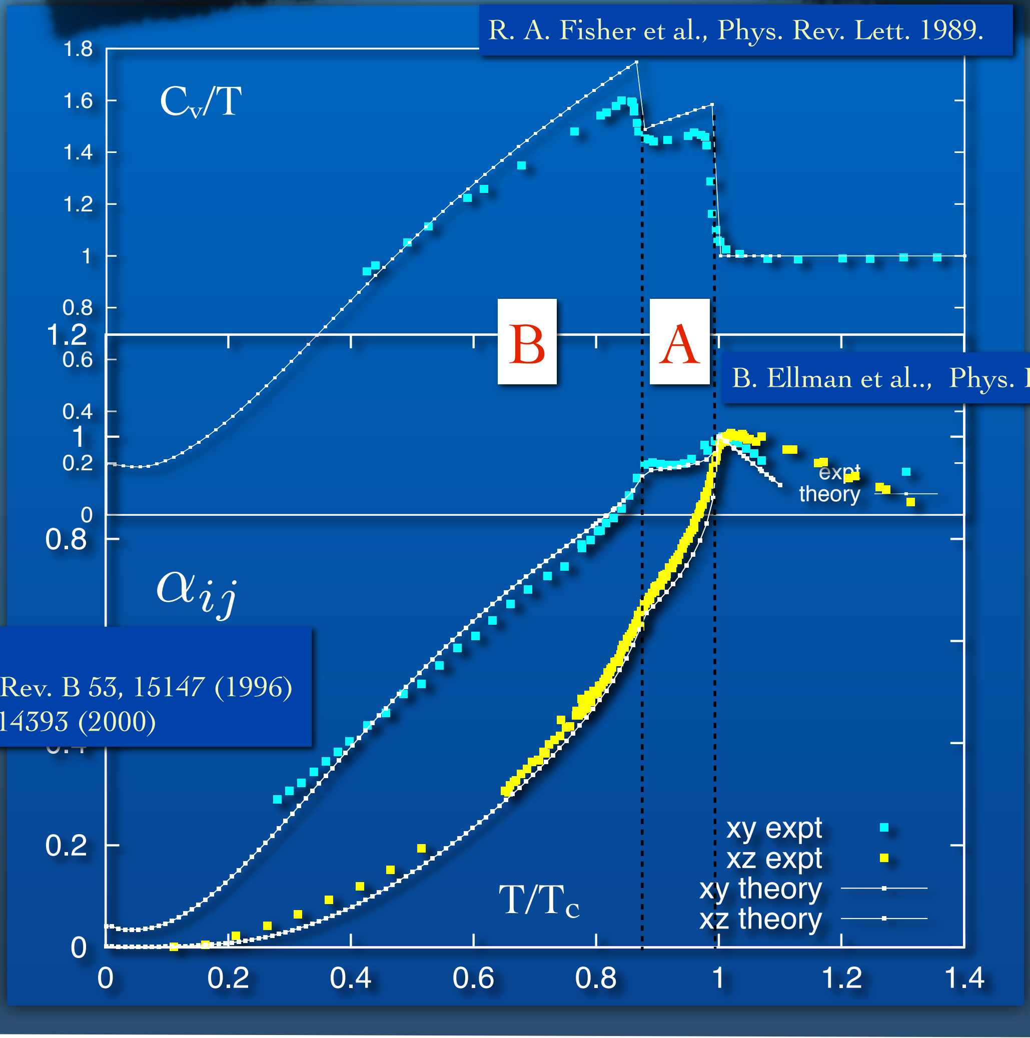
UPt$_3$

$G_B = \cancel{C_{6-N}}$

$$V(\mathbf{p}, \mathbf{p}') = V_E \left(\phi^\dagger_1(\mathbf{p}) \phi_1(\mathbf{p}') + \phi^\dagger_2(\mathbf{p}) \phi_2(\mathbf{p}') \right)$$

$$\rightarrow \boldsymbol{\Delta}(\mathbf{p}) = \eta_1 \phi_1(\mathbf{p}) + \eta_2 \phi_2(\mathbf{p})$$

Theory:
M. Graf, S-K Yip, D. Rainer & JAS., Phys. Rev. B 53, 15147 (1996)
M. Graf, S-K Yip & JAS., Phys. Rev. B 62, 14393 (2000)


R. A. Fisher et al., Phys. Rev. Lett. 1989.

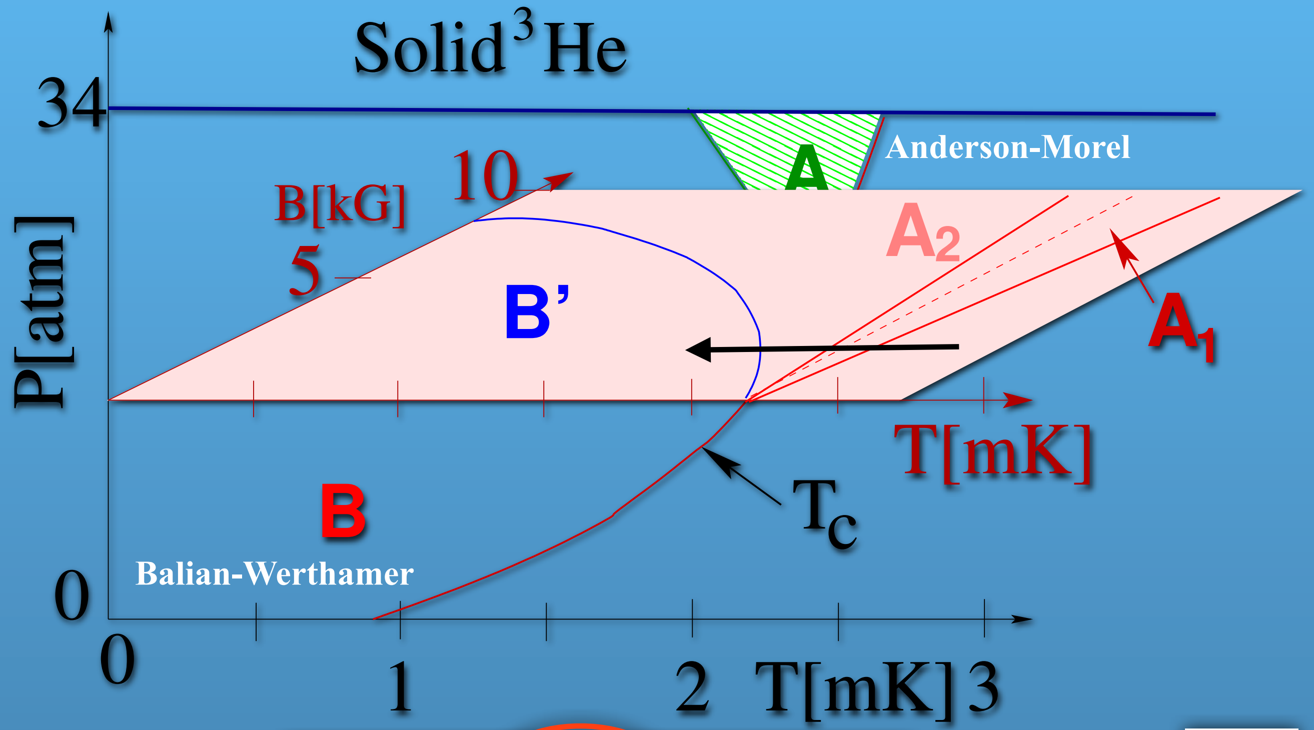
B. Ellman et al.., Phys. Rev. B 54 (1996)

- Competing Orders - SC & AFM + Strain (T > Tc)
- Lifts degeneracy of a 2D E - representation of **G**

$$T_{c_1}\ |A\rangle = \begin{pmatrix} \phi_1 \\ 0 \end{pmatrix} \quad T < T_{c_2} < T_{c_1}\ |B\rangle = \begin{pmatrix} \phi_1 \\ i\phi_2 \end{pmatrix}$$

Symmetry Breaking Fields & Multi-Component Unconventional Superconductivity

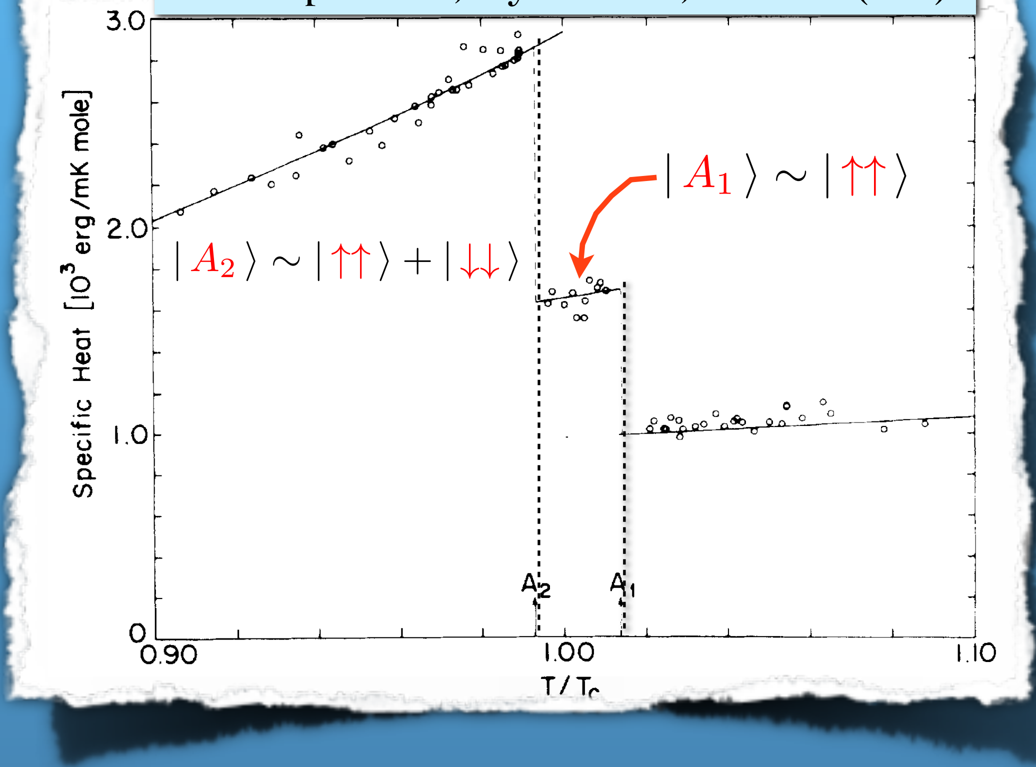
D. W. Hess, T. Tokuyasu & JAS, J. Phys. Cond.. Mat. l, 8135-4314 (1989).



$G_{ABM} = SO(2)_{S_z} \times U(1)_{N-L_z}$

^{3}He

W. P. Halperin et al., Phys Rev. B 13, 2124–2131 (1976).



- Symmetry Breaking Field = **Nuclear Zeeman Energy**
- Splitting of the Thermodynamic Transition

$$\xrightarrow{B} V = \left(V_+\varphi^\dagger_{+1}\varphi_{+1} + V_-\varphi^\dagger_{-1}\varphi_{-1}\right)$$

$$V_+ - V_- = -\lambda\, B \qquad \Delta T_c/T_c = \tilde{\lambda} B$$

UPt$_3$

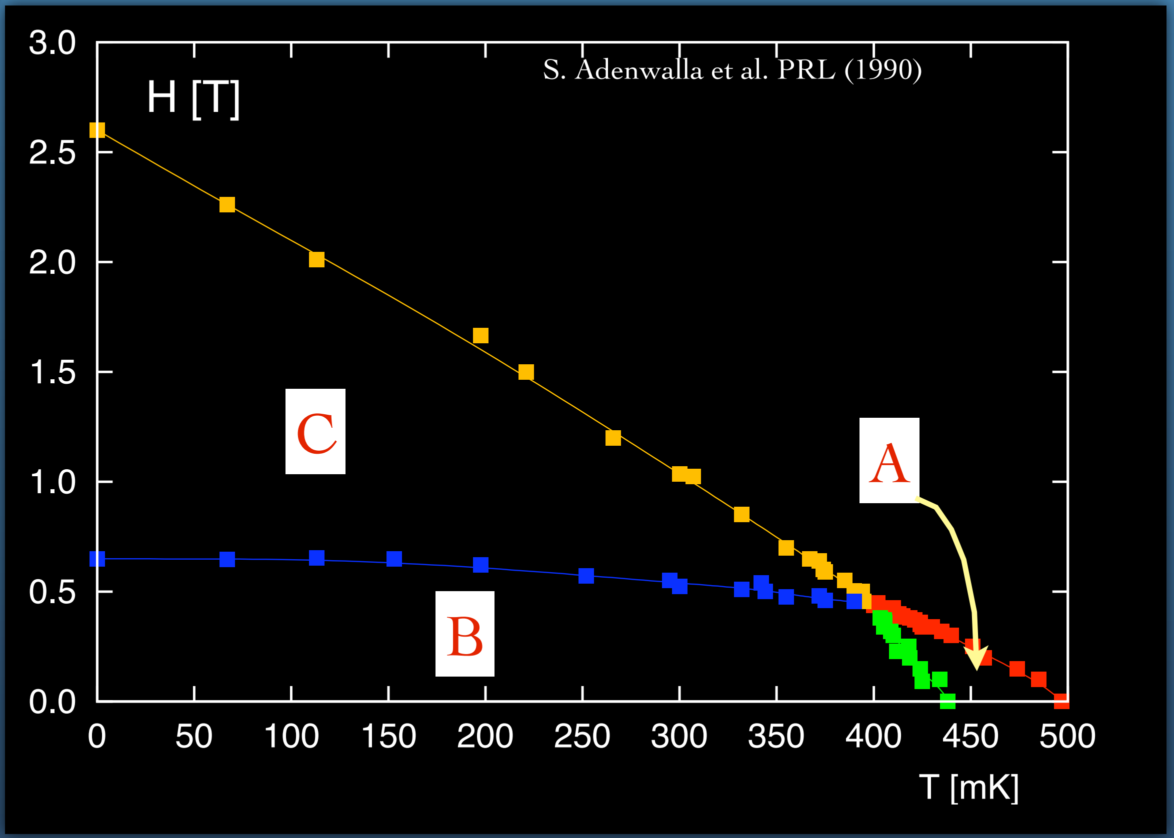
$G_B \cancel{= C_{6-N}}$

$$V(\mathbf{p},\mathbf{p}') = V_E\left(\phi^\dagger_1(\mathbf{p})\phi_1(\mathbf{p}') + \phi^\dagger_2(\mathbf{p})\phi_2(\mathbf{p}')\right)$$

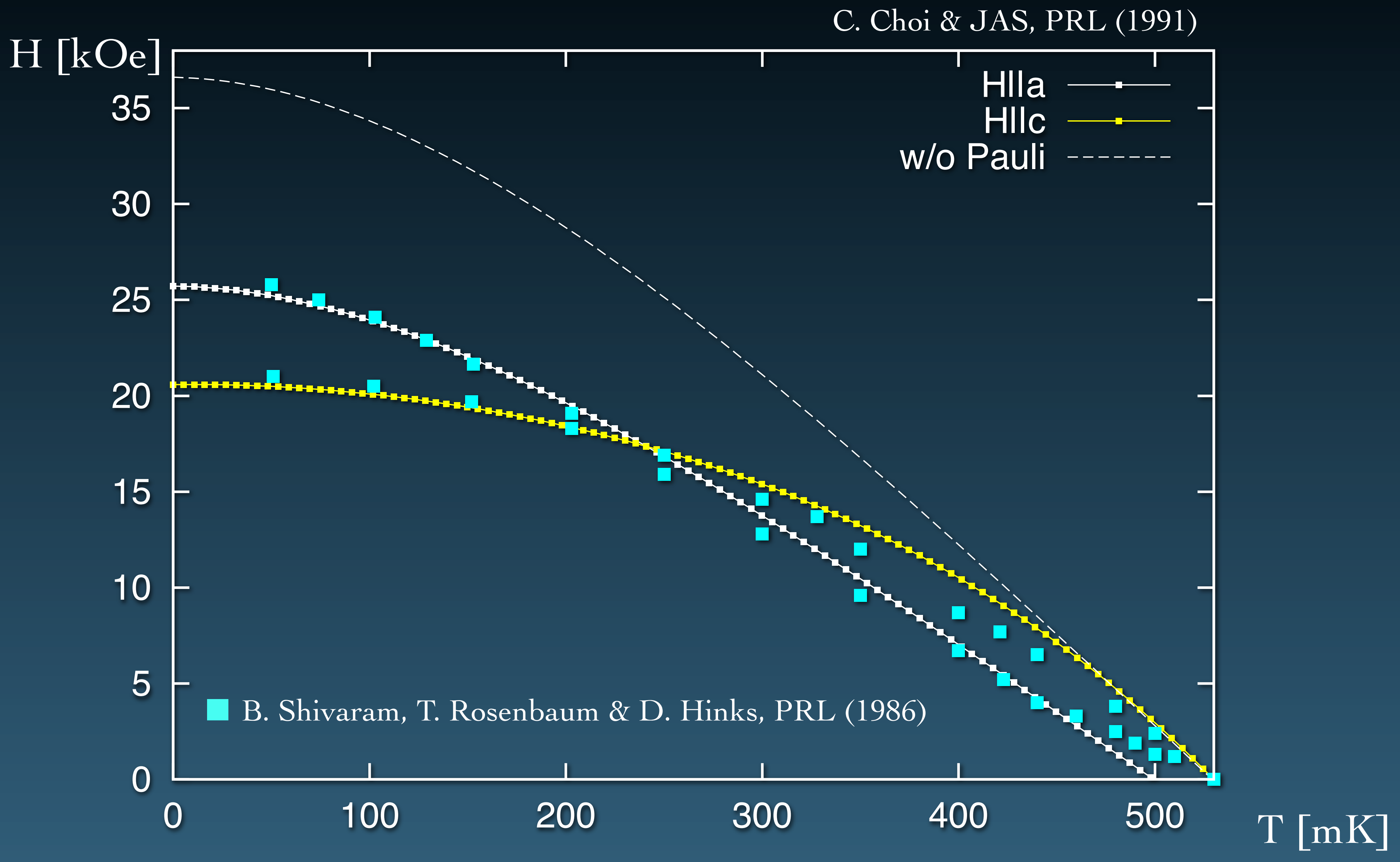
$$\rightarrow \boldsymbol{\Delta}(\mathbf{p}) = \eta_1\phi_1(\mathbf{p}) + \eta_2\phi_2(\mathbf{p})$$

- Competing Orders - SC & **AFM + Strain (T > Tc)**
- Lifts degeneracy of a 2D E - representation of **G**

$$T_{c_1}\ |A\rangle = \begin{pmatrix}\phi_1\\ 0\end{pmatrix} \qquad T < T_{c_2} < T_{c_1}\ |B\rangle = \begin{pmatrix}\phi_1\\ i\phi_2\end{pmatrix}$$

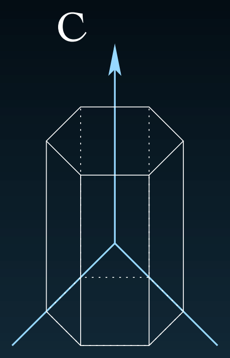

S. Adenwalla et al. PRL (1990)

Anisotropic Pauli limiting & Spin-Triplet Superconductivity

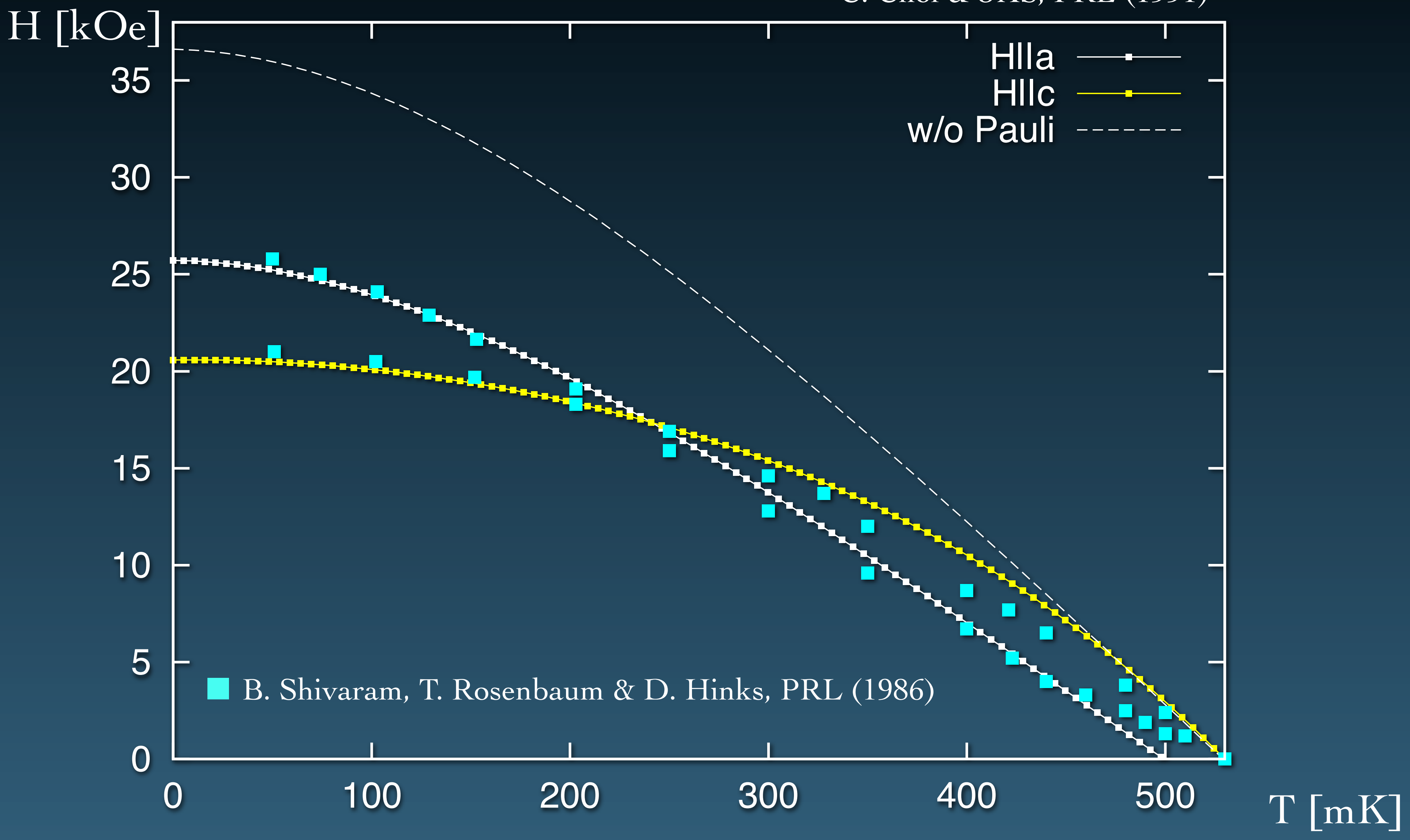


C. Choi & JAS, PRL (1991)

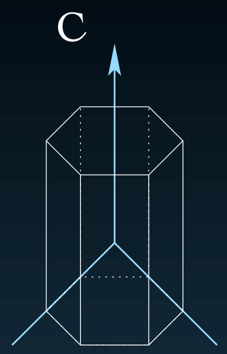
■ B. Shivaram, T. Rosenbaum & D. Hinks, PRL (1986)



Anisotropic Pauli limiting & Spin-Triplet Superconductivity

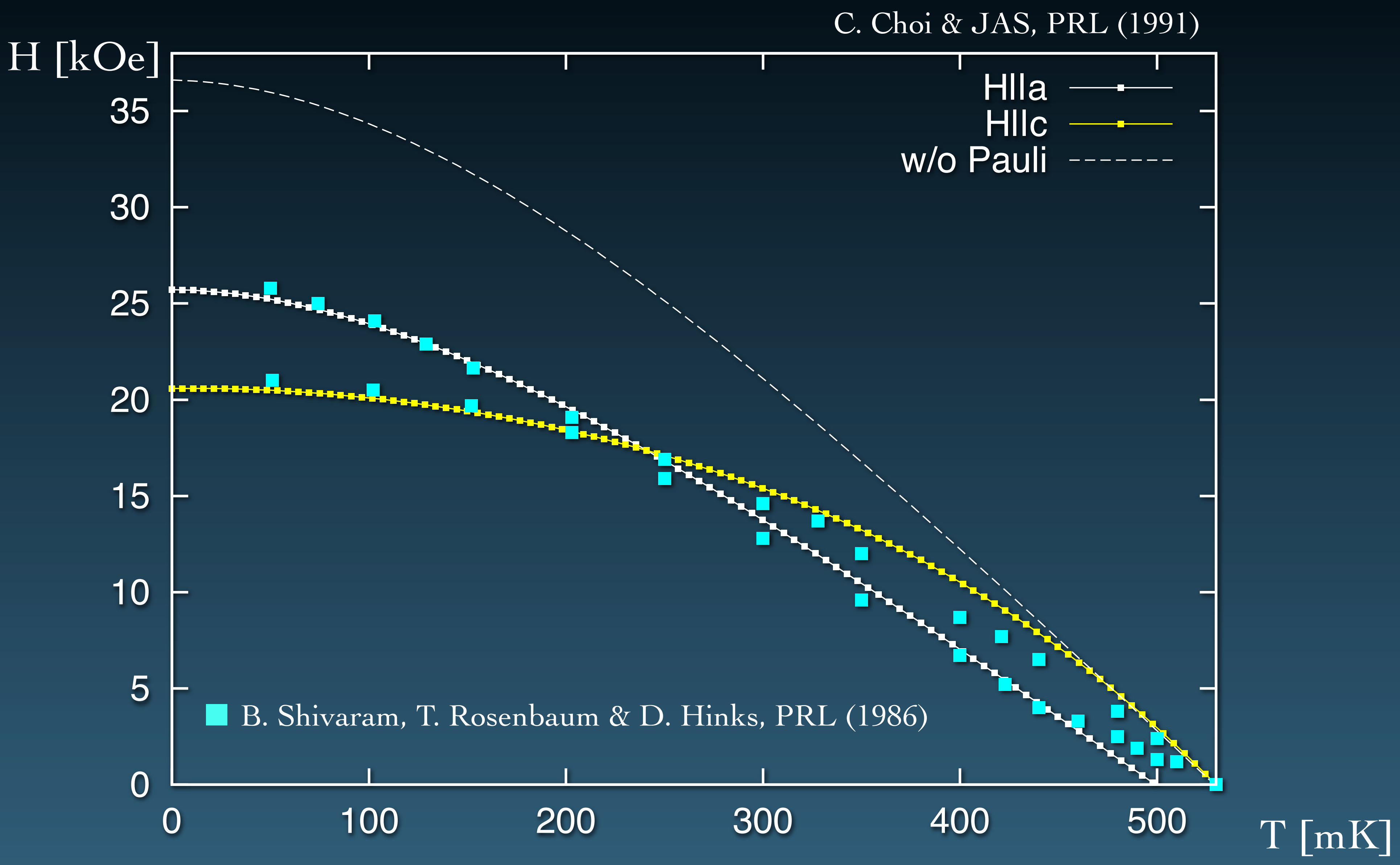


C. Choi & JAS, PRL (1991)



$\vec{\mathbf{d}}||\hat{\mathbf{c}}$ $|\uparrow\downarrow + \downarrow\uparrow\rangle$

Anisotropic Pauli limiting & Spin-Triplet Superconductivity



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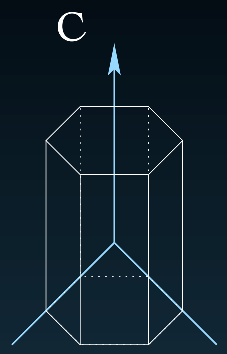
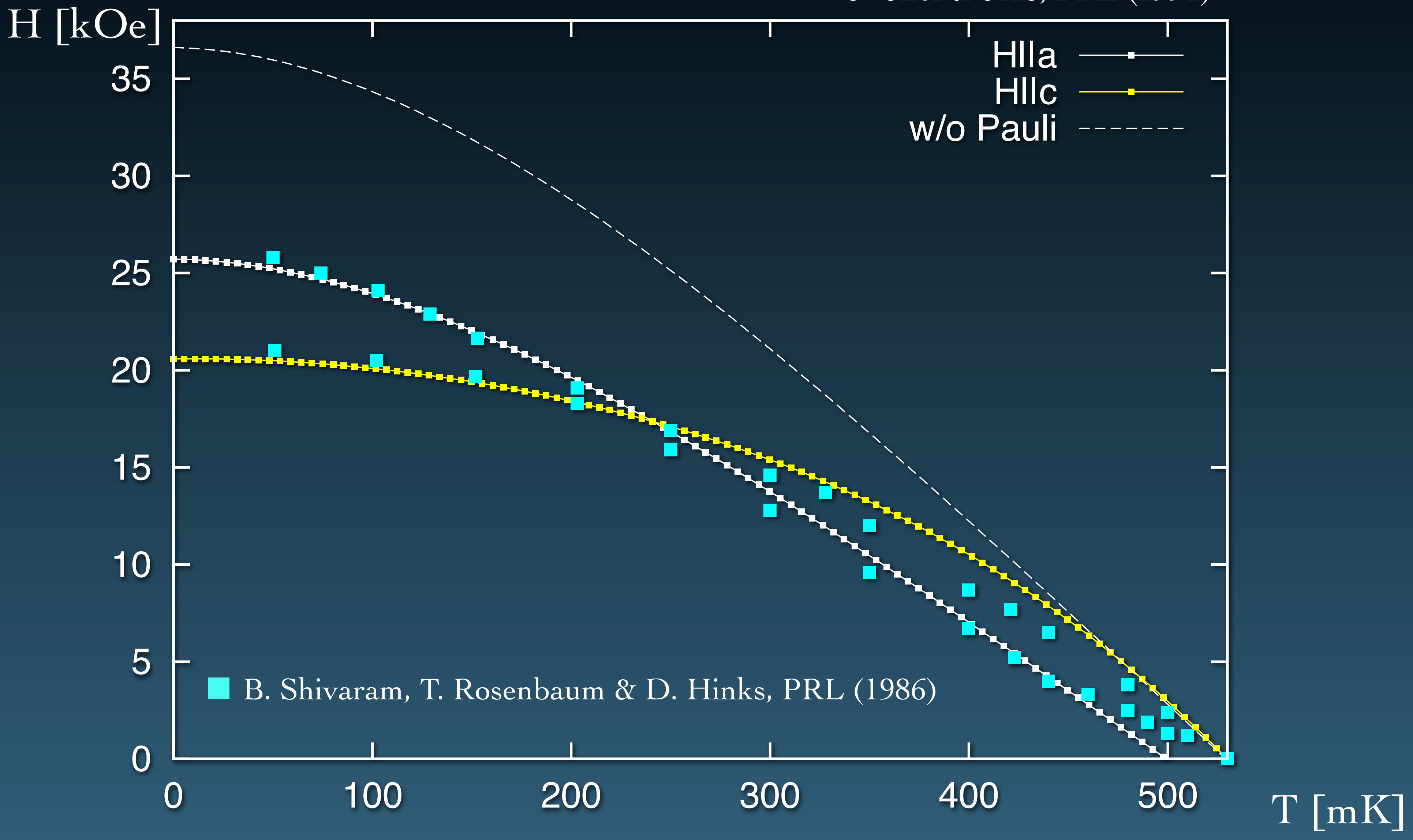


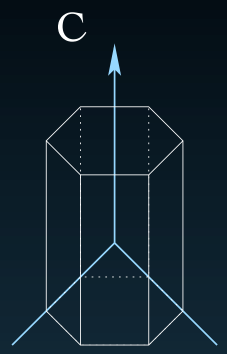
$$\vec{\mathbf{d}}||\hat{\mathbf{c}} \qquad |\uparrow\downarrow+\downarrow\uparrow\rangle$$

$$= \; |\rightrightarrows\rangle + |\leftleftarrows\rangle$$

Anisotropic Pauli limiting & Spin-Triplet Superconductivity

C. Choi & JAS, PRL (1991)





$$\vec{\mathbf{d}}||\hat{\mathbf{c}} \qquad |\uparrow\downarrow + \downarrow\uparrow\rangle$$

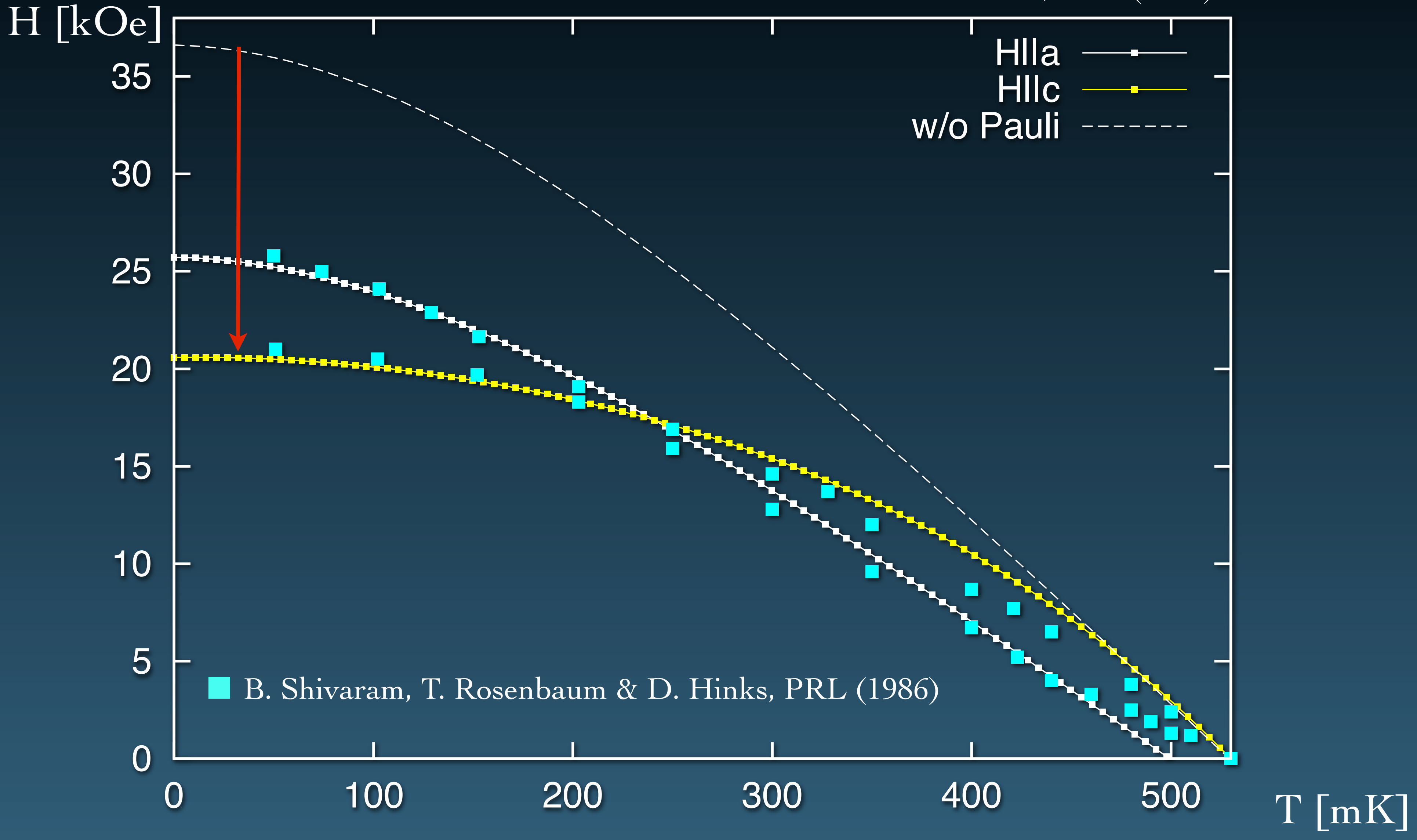
$$= |\rightrightarrows\rangle + |\leftleftarrows\rangle \qquad \mathbf{H}\perp\vec{\mathbf{d}}$$

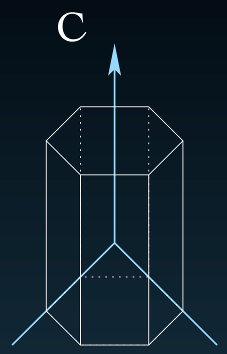
No pair breaking

$$\longrightarrow (1+\eta H)|\rightrightarrows\rangle + (1-\eta H)|\leftleftarrows\rangle$$

Anisotropic Pauli limiting & Spin-Triplet Superconductivity

C. Choi & JAS, PRL (1991)





$\vec{d}||\hat{c}$ $\quad |\uparrow\downarrow + \downarrow\uparrow\rangle$

$= \quad |\rightrightarrows\rangle + |\leftleftarrows\rangle$

$\longrightarrow \quad (1+\eta H)|\rightrightarrows\rangle + (1-\eta H)|\leftleftarrows\rangle$

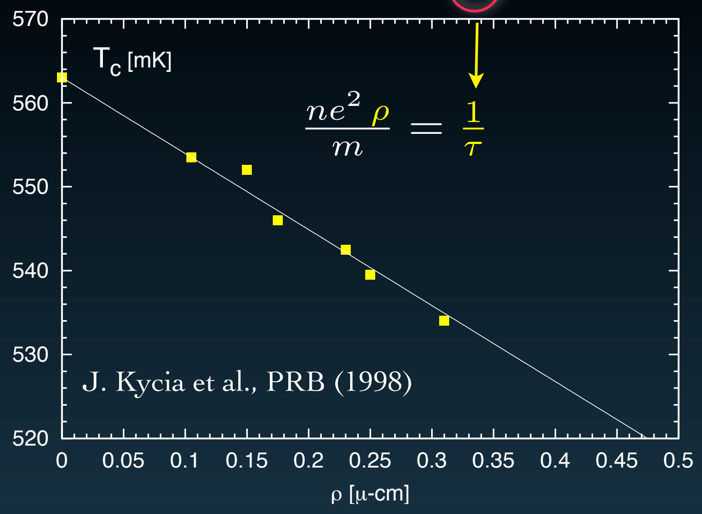
$\mathbf{H}||\vec{d}$ **pair breaking**

$\mathbf{H} \perp \vec{d}$ **No pair breaking**

➡ Spin-Triplet & strong Spin-Orbit Coupling - E_{1u} or E_{2u}

L. Gorkov (1987)

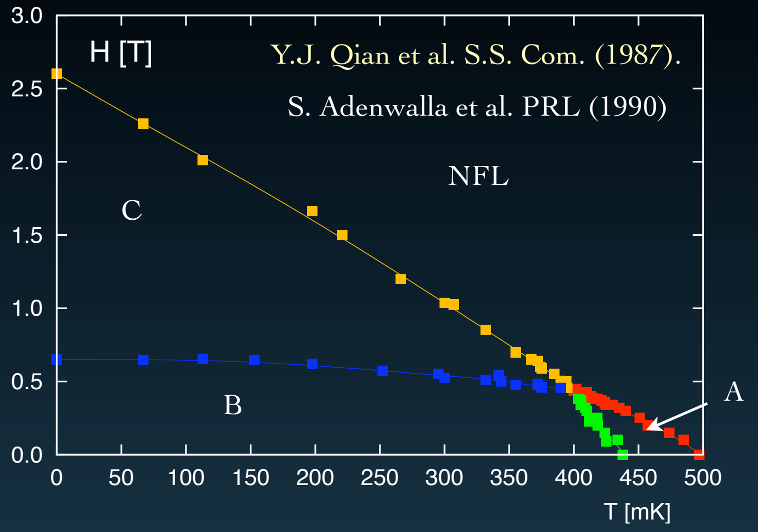
$$T_c = T_{c0} - \frac{\pi}{8}\frac{\hbar/k_B}{\boxed{\tau}}$$



$$\frac{ne^2\rho}{m} = \frac{1}{\tau}$$

J. Kycia et al., PRB (1998)

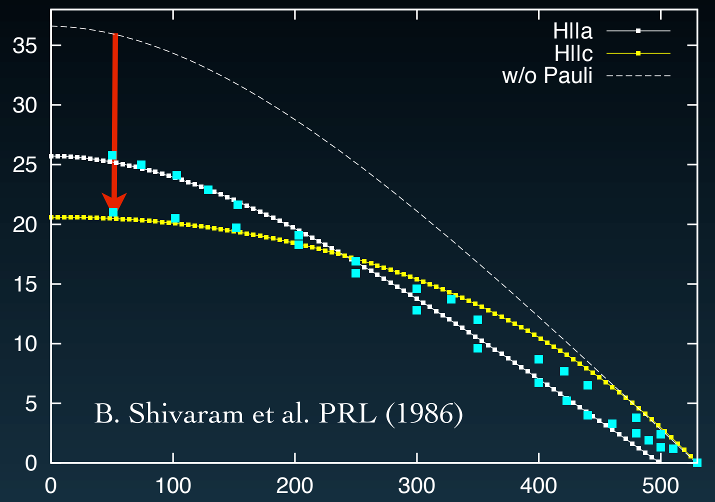
H-T phase diagram J. A. Sauls, Adv. Phys. (1994).



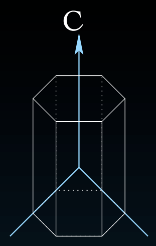
Y.J. Qian et al. S.S. Com. (1987).

S. Adenwalla et al. PRL (1990)

Anisotropic Pauli limiting C. Choi & JAS, PRL (1991)



B. Shivaram et al. PRL (1986)



- P. Anderson
- L. Gor'kov
- P. Hirschfeld
- R. Joynt
- R. Klemm
- K. Machida
- V. Mineev
- M. Norman
- M. Sigrist
- K. Ueda
- C. Varma
- G. Volovik
- P. Wolfle
- ....

$\vec{\mathbf{d}}||\hat{\mathbf{c}}$ $\quad|\uparrow\downarrow + \downarrow\uparrow\rangle$ $\mathbf{H}||\vec{\mathbf{d}}$ *pair breaking*

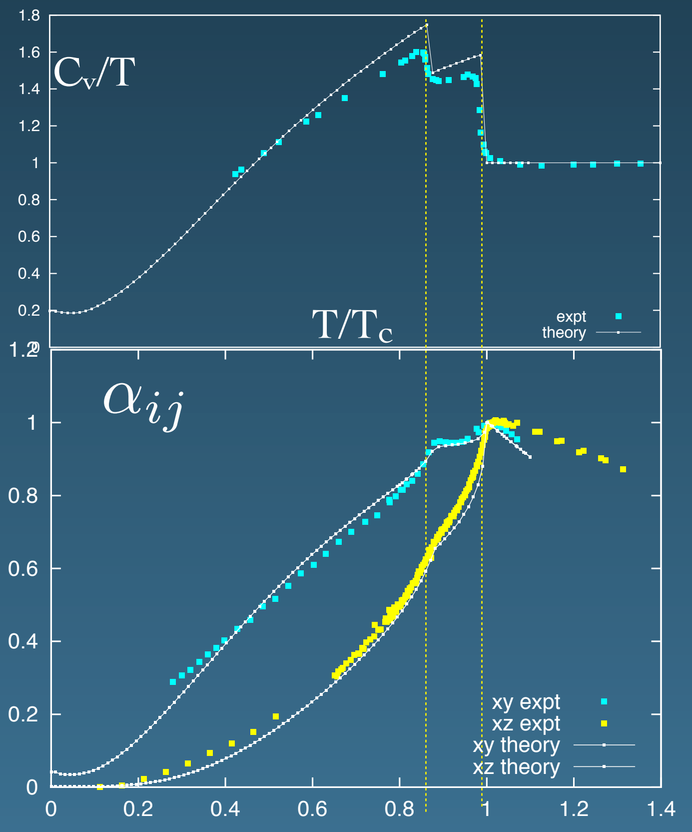
$= |\rightrightarrows\rangle + |\leftrightarrows\rangle$ $\mathbf{H}\perp\vec{\mathbf{d}}$ ***No pair breaking***

$$(1+\eta H)|\rightrightarrows\rangle + (1-\eta H)|\leftrightarrows\rangle$$

➡ Spin-Triplet, E_{1u} or E_{2u}, & strong Spin-Orbit Coupling

Splitting of the SC Transition

R. A. Fisher et al., Phys. Rev. Lett. 1989.

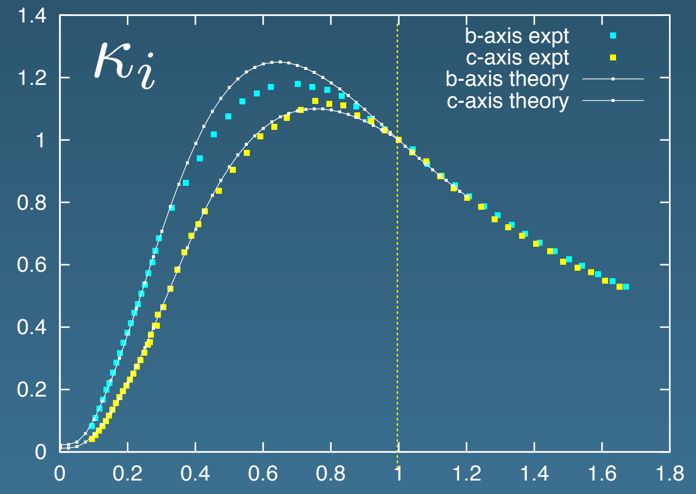


B. Ellman et al., Phys. Rev. B 54 (1996)

✓Heat Capacity Anomalies
✓Anisotropy Transverse Sound
✓Anistropic Thermal Conductivity

M. Graf, S.K. Yip & JAS, PRB (1996)

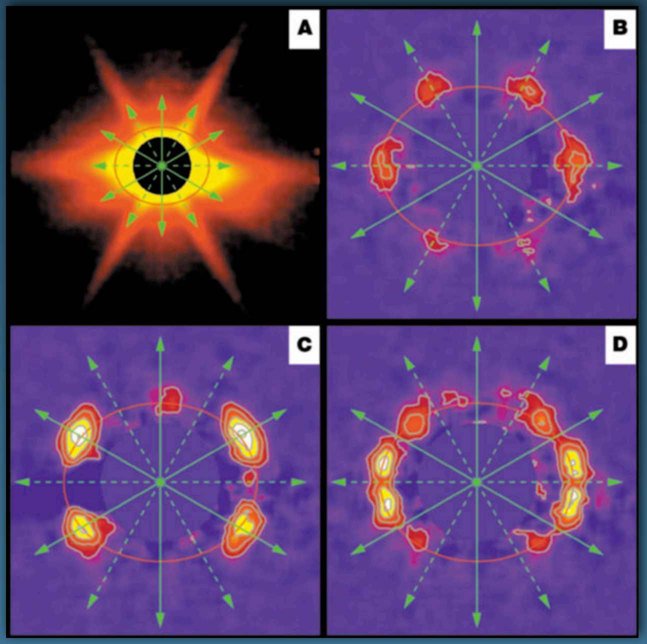
➡ E_{2u} symmetry



B. Lussier et al., Phys. Rev. B 53 (1996)

Realignment of the flux-line lattice in UPt_3 ➡ E_{2u} symmetry

A. Huxley et al. Nature (2000). T. Champel & V. Mineev, PRL (2001)



Josephson Current-Phase Relations for Complex Ground States

Geshkenbein, V. B. and Larkin, A. I. Sov. Phys. JETP Lett., 43, 395, 1986.
Rainer, D. and Sauls, J. A. Jpn. J. Appl. Phys., 26, pp. 1804, 1987.
Millis, A., Rainer, D. and Sauls, J. Phys. Rev., B38, 4504, 1988.

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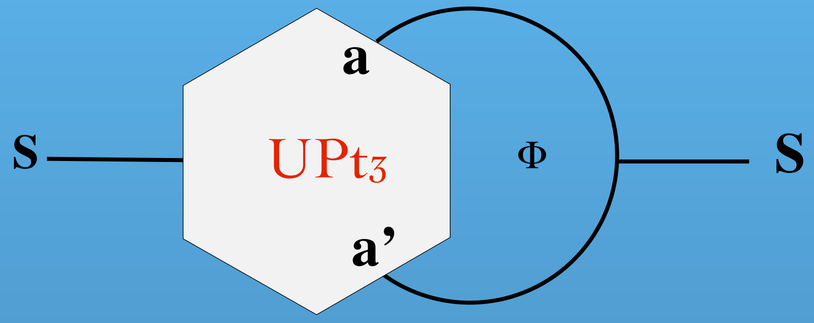

Fig. 3 SQUID geometry for UPt$_3$/S junctions. JAS, Adv. Phys. (1994).

$$I_a(\varphi_u - \varphi_s) = I_{a'}(\varphi_u - \varphi_s + n\,\frac{2\pi}{3})$$

$$n = 1 \text{ for } E_1$$
$$n = 2 \text{ for } E_2$$

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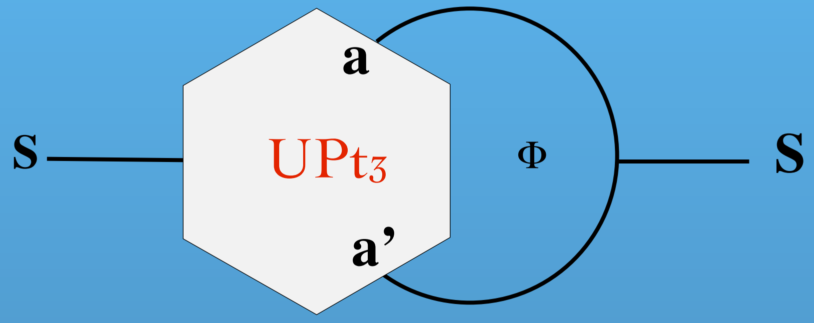

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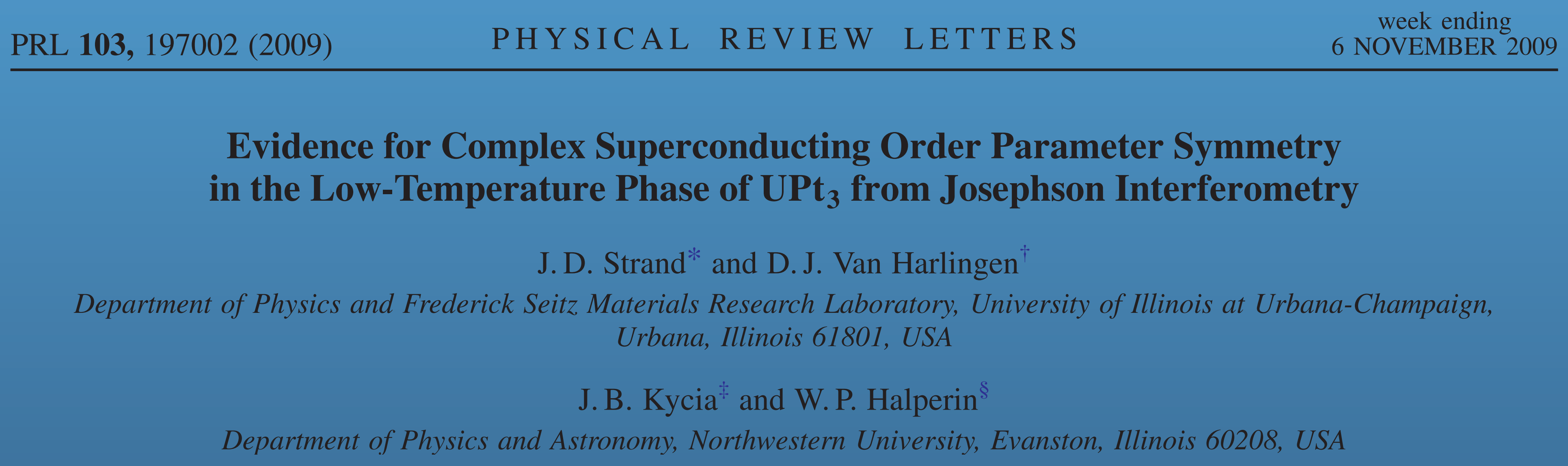


PRL **103,** 197002 (2009) PHYSICAL REVIEW LETTERS week ending 6 NOVEMBER 2009

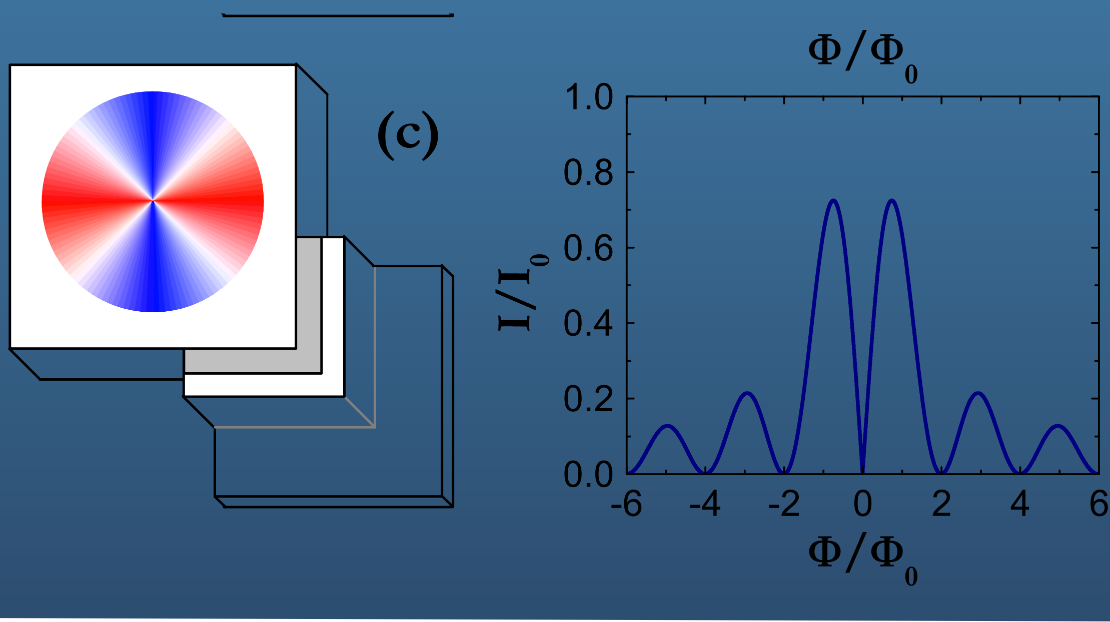
Evidence for Complex Superconducting Order Parameter Symmetry in the Low-Temperature Phase of UPt_3 from Josephson Interferometry

J. D. Strand* and D. J. Van Harlingen†

Department of Physics and Frederick Seitz Materials Research Laboratory, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801, USA

J. B. Kycia‡ and W. P. Halperin§

Department of Physics and Astronomy, Northwestern University, Evanston, Illinois 60208, USA



J. D. Strand *et al.* *Science* **328**, 1368 (2010)

Phase-Sensitive Heat Transport through a Josephson Junction

Maki & Griffin, PRL 15, 921 (1965).

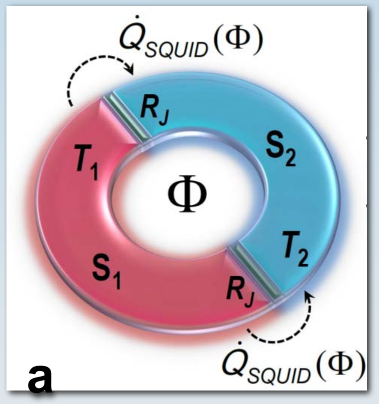
Phase-Sensitive Heat Transport through a Josephson Junction

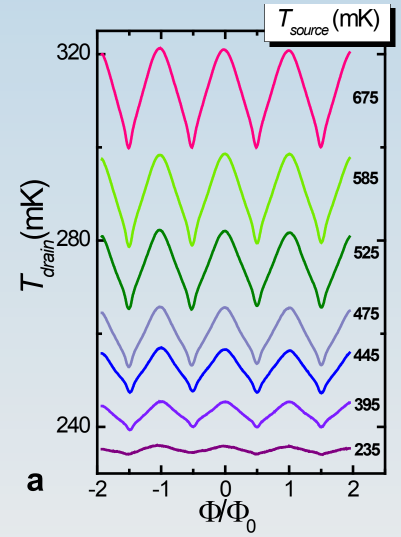
Maki & Griffin, PRL 15, 921 (1965).

The Josephson heat interferometer

arXiv:1205.3353v1 **(2012)**

F. Giazotto* and M. J. Martínez-Pérez
NEST, Istituto Nanoscienze-CNR and Scuola Normale Superiore, I-56127 Pisa, Italy





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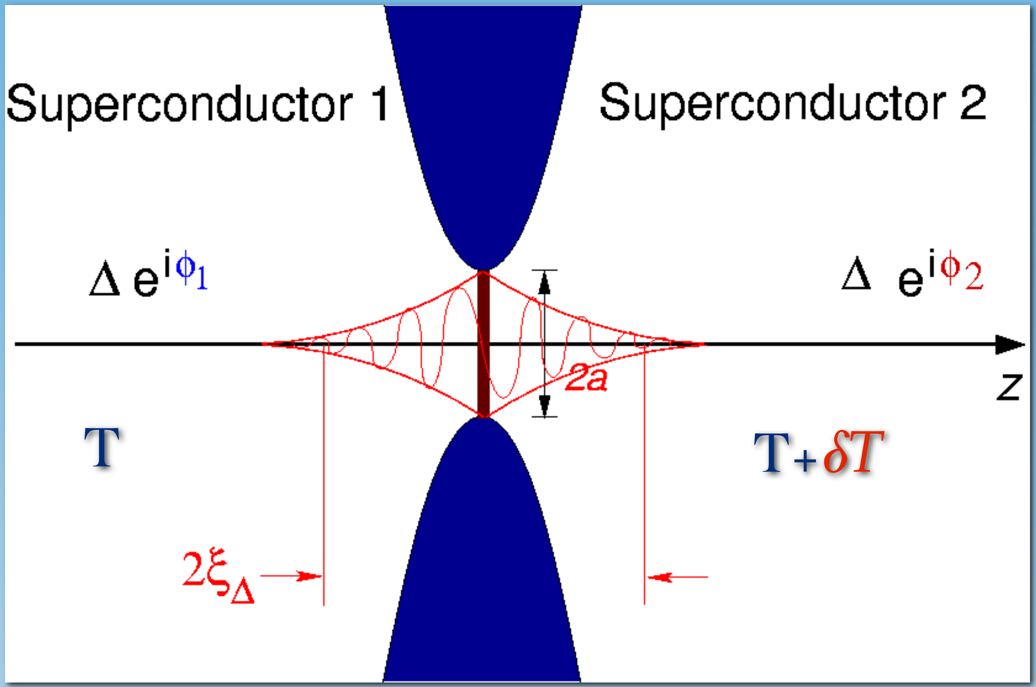
E. Zhao, T. Lowfander, JAS, Phys. Rev. B. 69, 134503 (2004).



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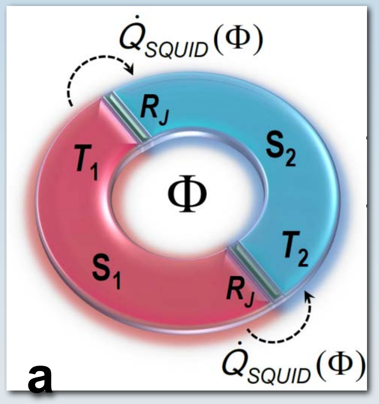

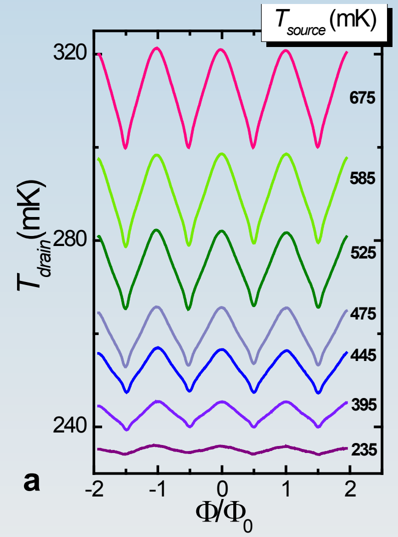

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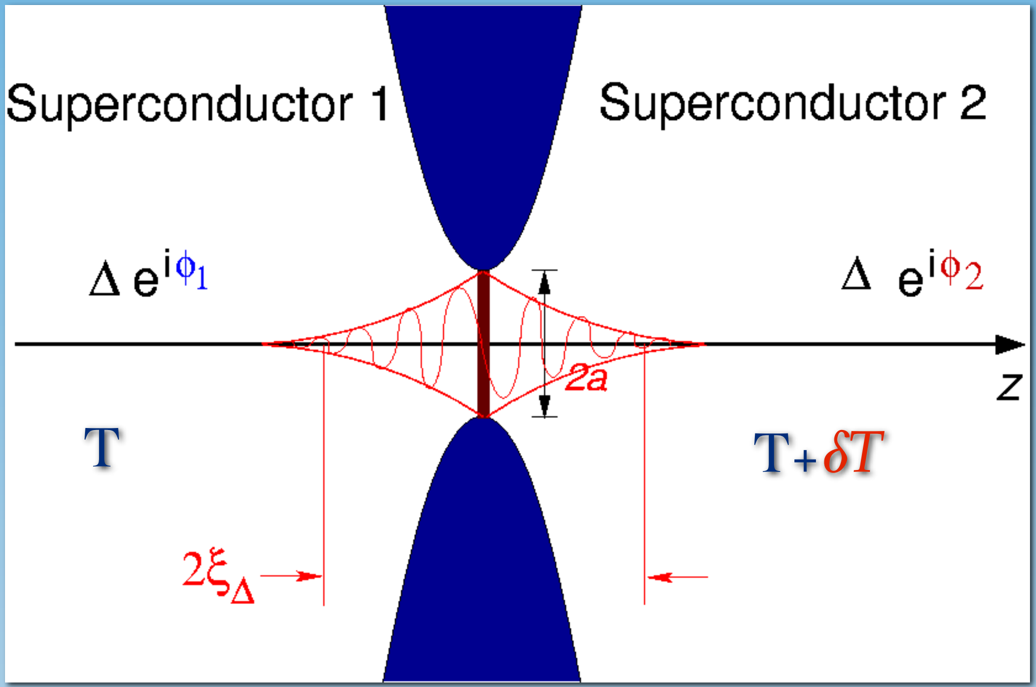

Andreev Bound
State Formation

The Josephson heat interferometer

arXiv:1205.3353v1 **(2012)**

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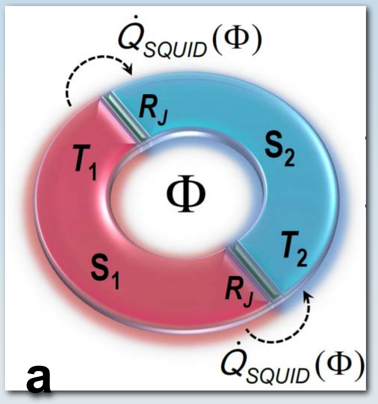

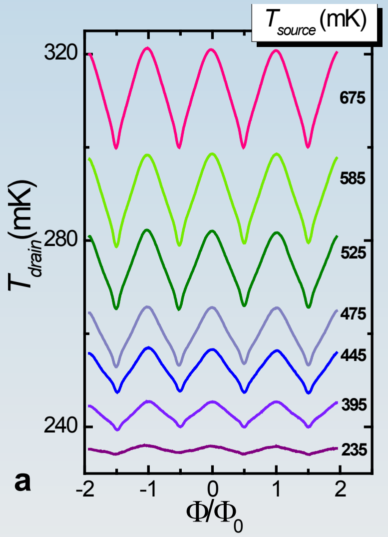

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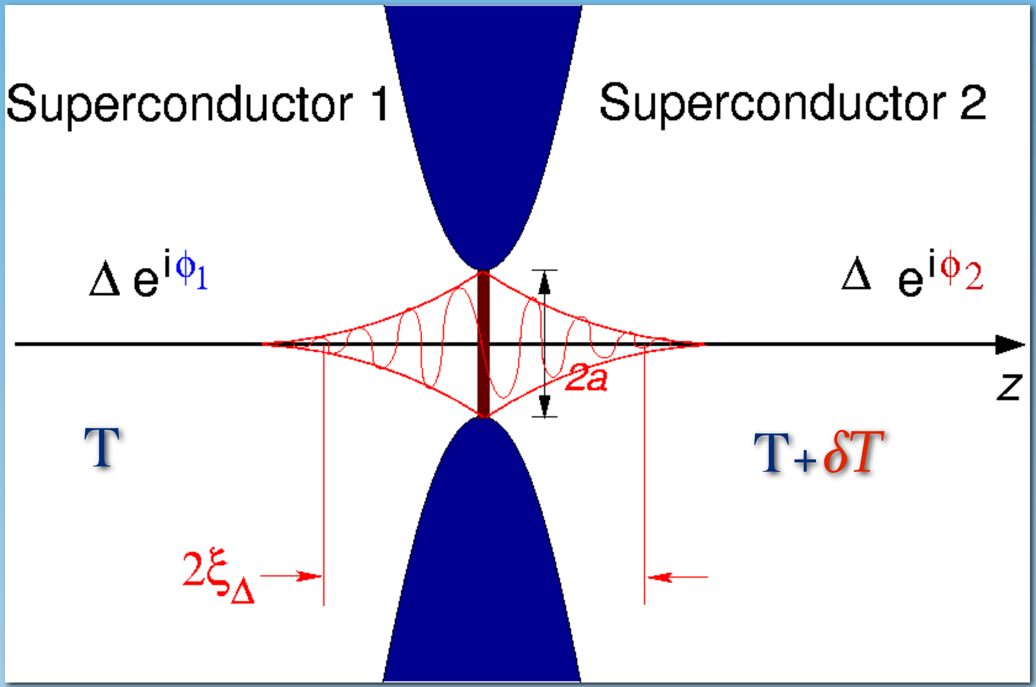
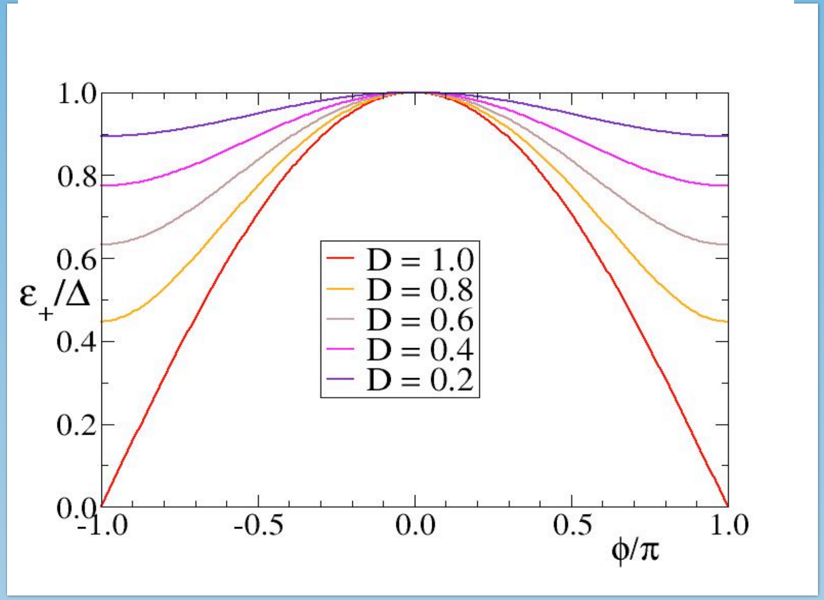


$$\varepsilon_{\pm}(D,\phi) = \pm|\Delta|\sqrt{1-D\sin^2\left(\frac{\phi}{2}\right)}$$



Andreev Bound
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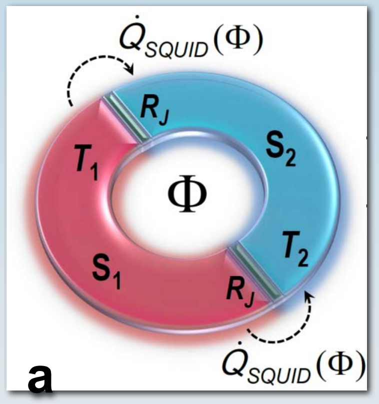

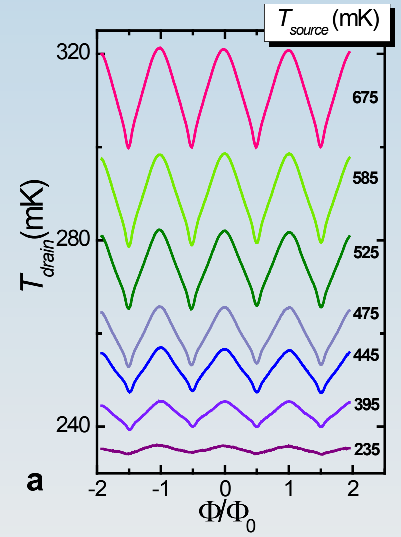

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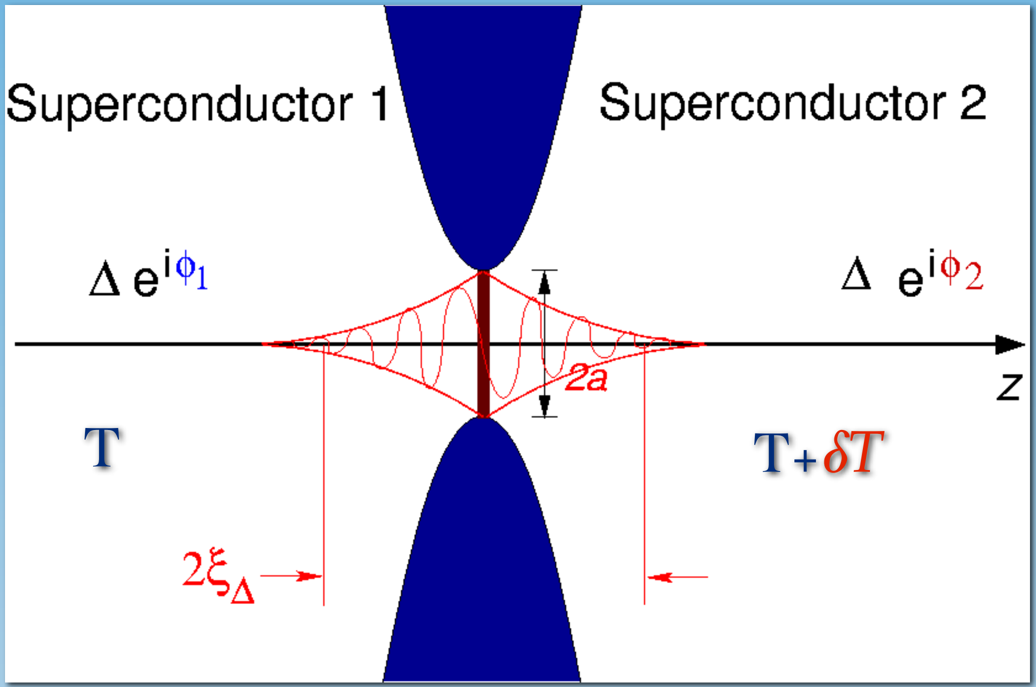

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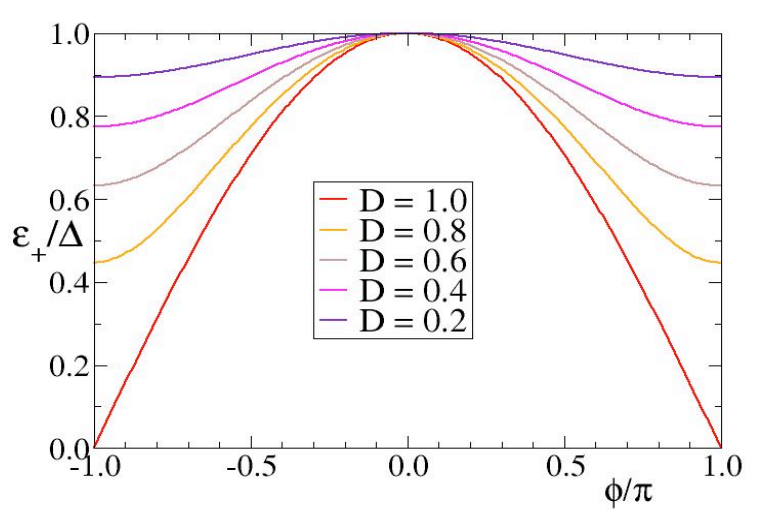

Andreev Bound
State Formation

Thermal Conductance

$$\kappa(\phi,T) = A\int_\Delta^\infty d\varepsilon\, N_{\mathrm{bulk}}(\varepsilon)\left[\varepsilon v_g(\varepsilon)\right] D(\varepsilon,\phi)\left(\frac{\partial f}{\partial T}\right)$$

Bogoliubov Quasiparticle

Transmission Probability

Andreev's ``Demon"
controls heat flow
through the junction

The Josephson heat interferometer

arXiv:1205.3353v1 **(2012)**

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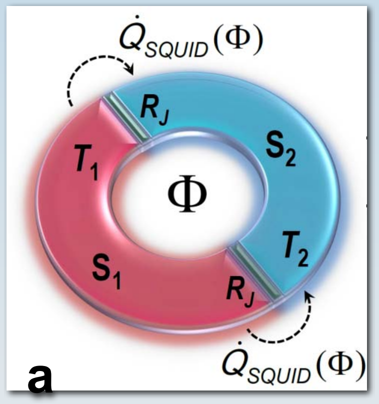

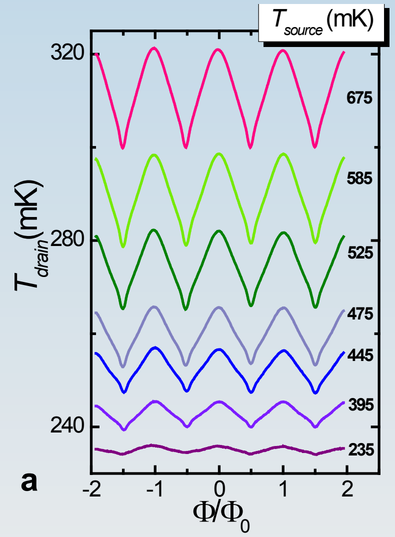

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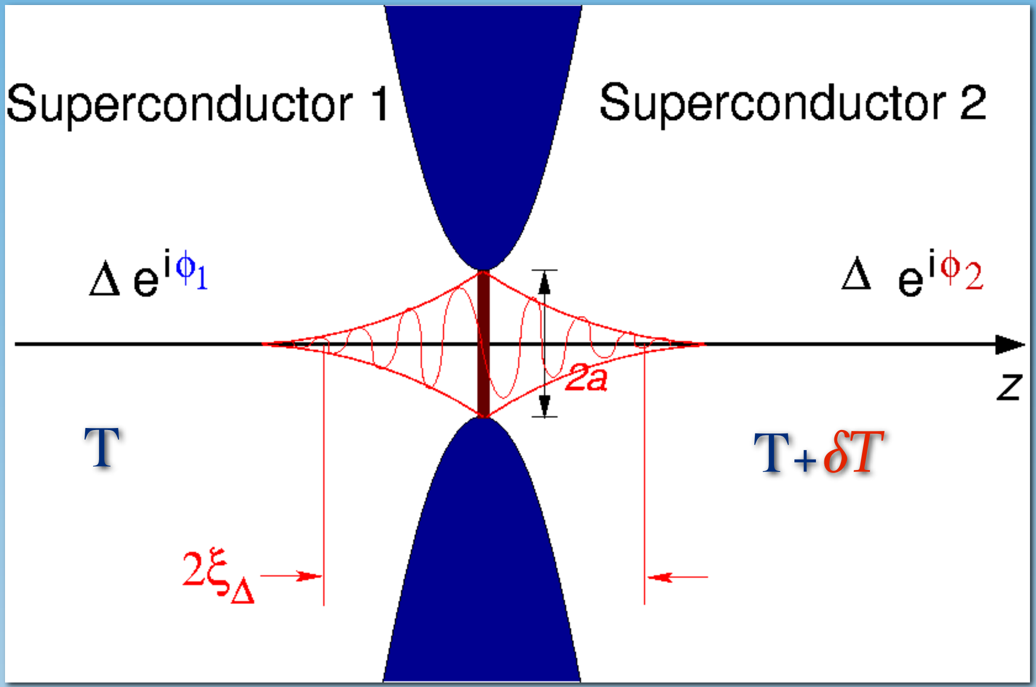
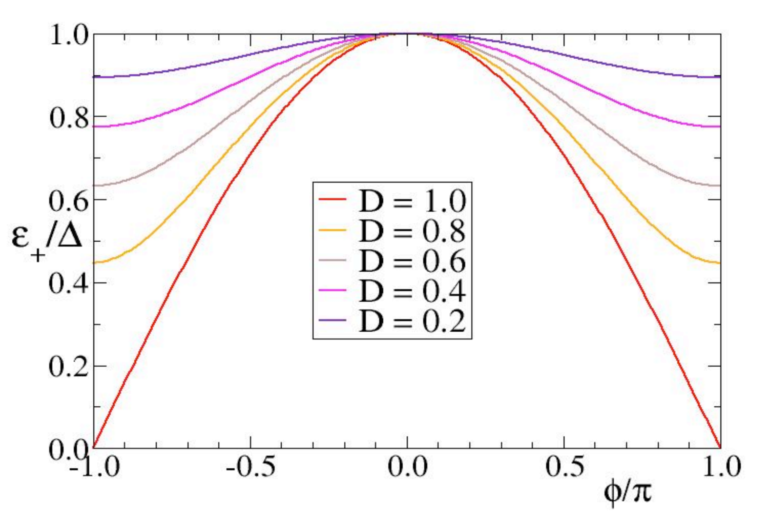


$$\varepsilon_\pm(D,\phi) = \pm|\Delta|\sqrt{1 - D\sin^2\left(\frac{\phi}{2}\right)}$$



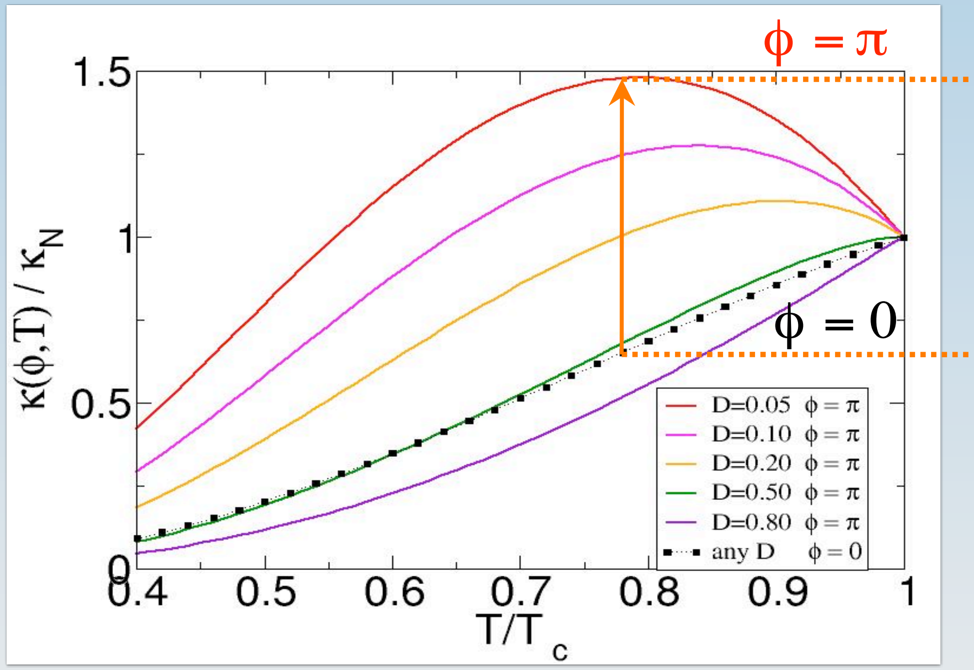
Andreev Bound State Formation

Thermal Conductance

$$\kappa(\phi,T) = A\int_\Delta^\infty d\varepsilon\, N_{\text{bulk}}(\varepsilon)\left[\varepsilon v_g(\varepsilon)\right] D(\varepsilon,\phi)\left(\frac{\partial f}{\partial T}\right)$$

Bogoliubov Quasiparticle Transmission Probability

Andreev's "Demon" controls heat flow through the junction



The Josephson heat interferometer

arXiv:1205.3353v1 **(2012)**

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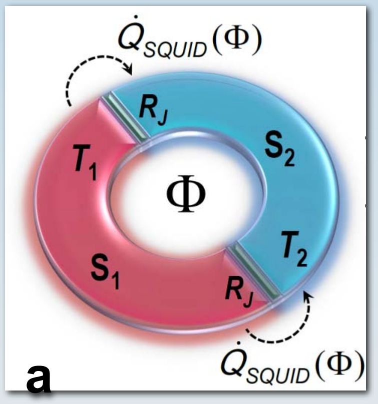

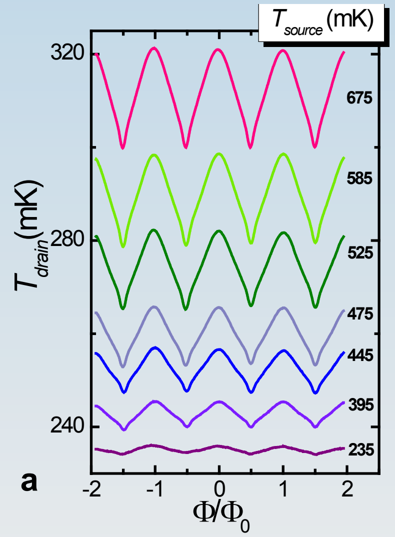

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