Spinors, Strings and Superconductors

P. Coleman
CMT, Rutgers, USA &
HTC, Royal Holloway, UK

U. Victoria, BC
Mar 30, 2016

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Royal Holloway University of London

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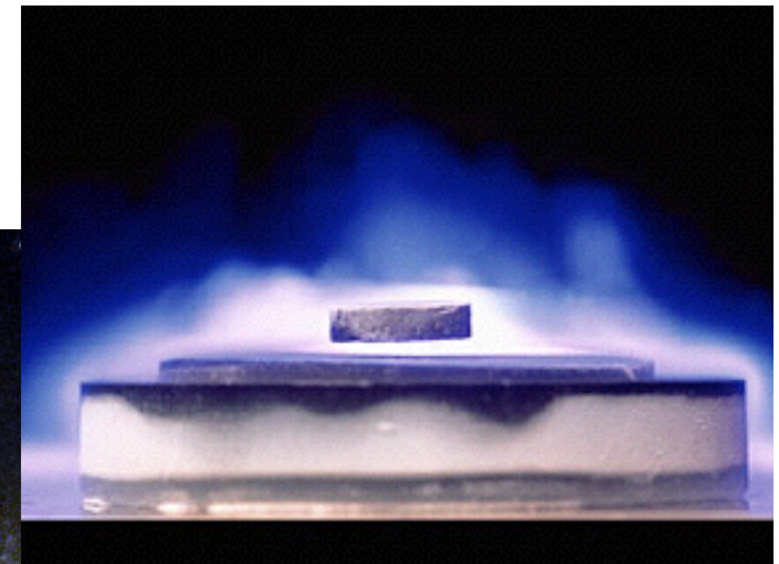

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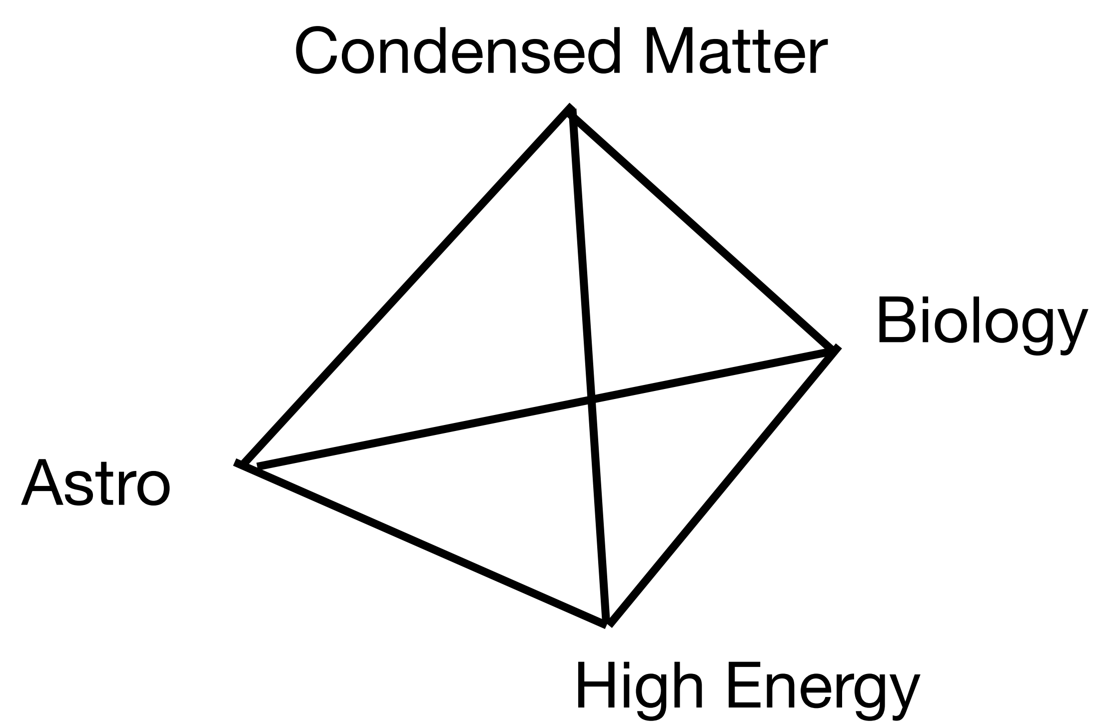
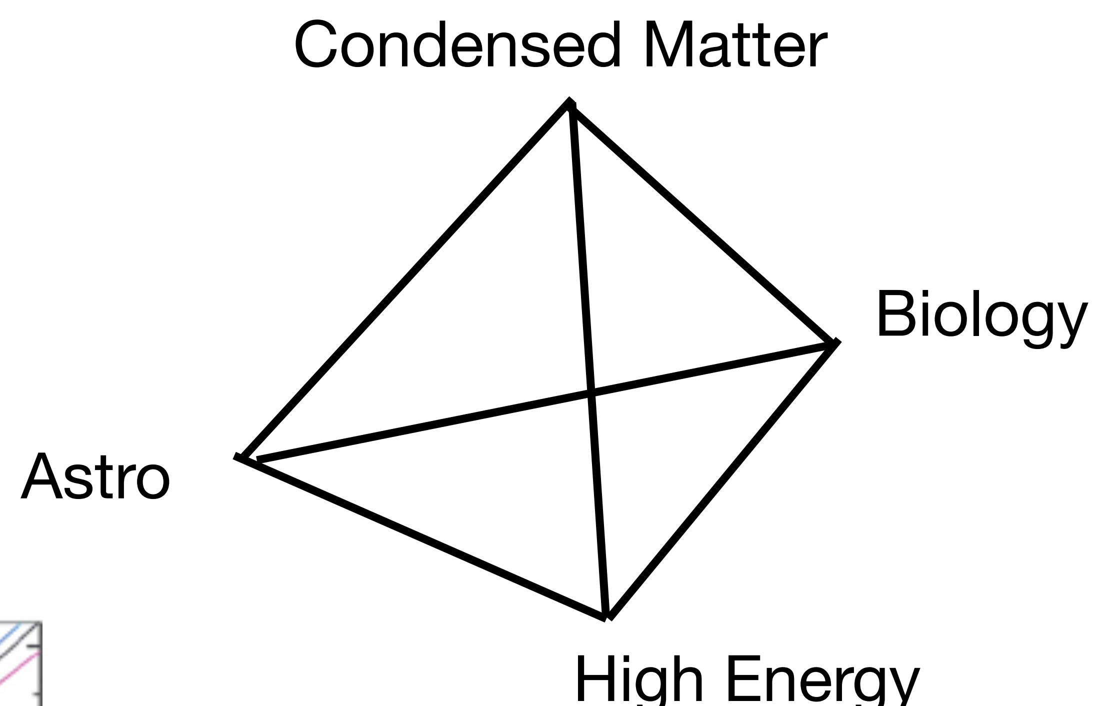
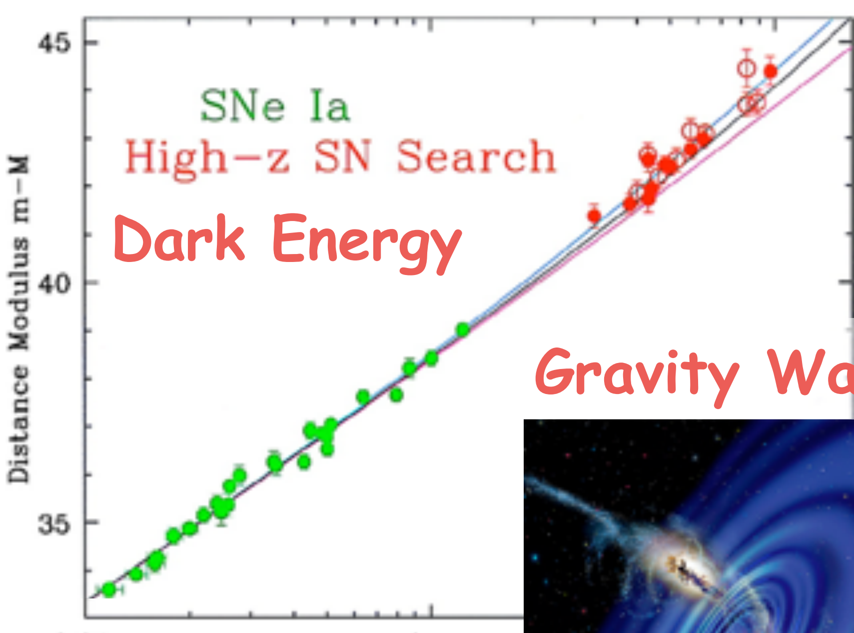
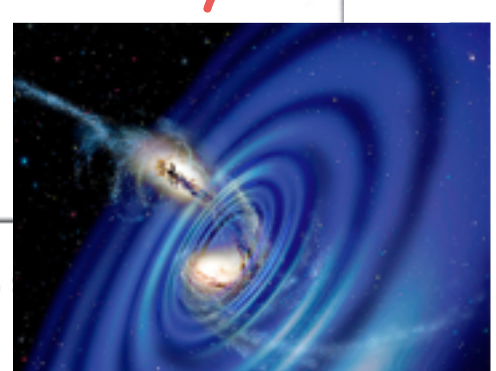
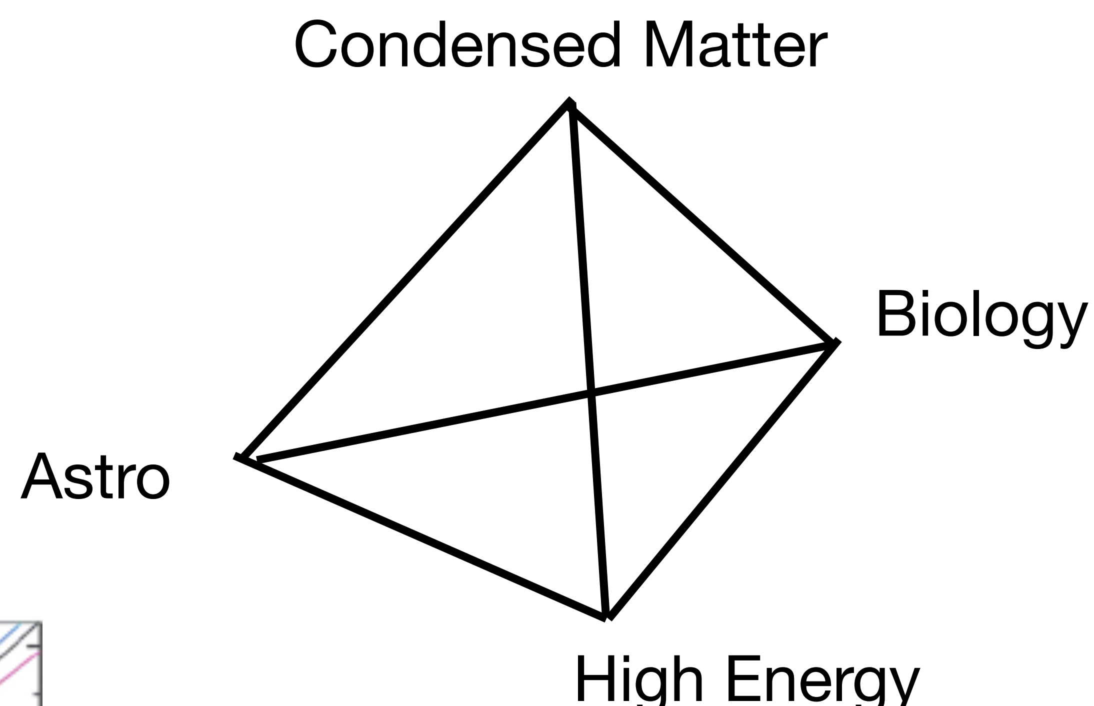

Condensed Matter
Biology
Astro
High Energy





Gravity Waves

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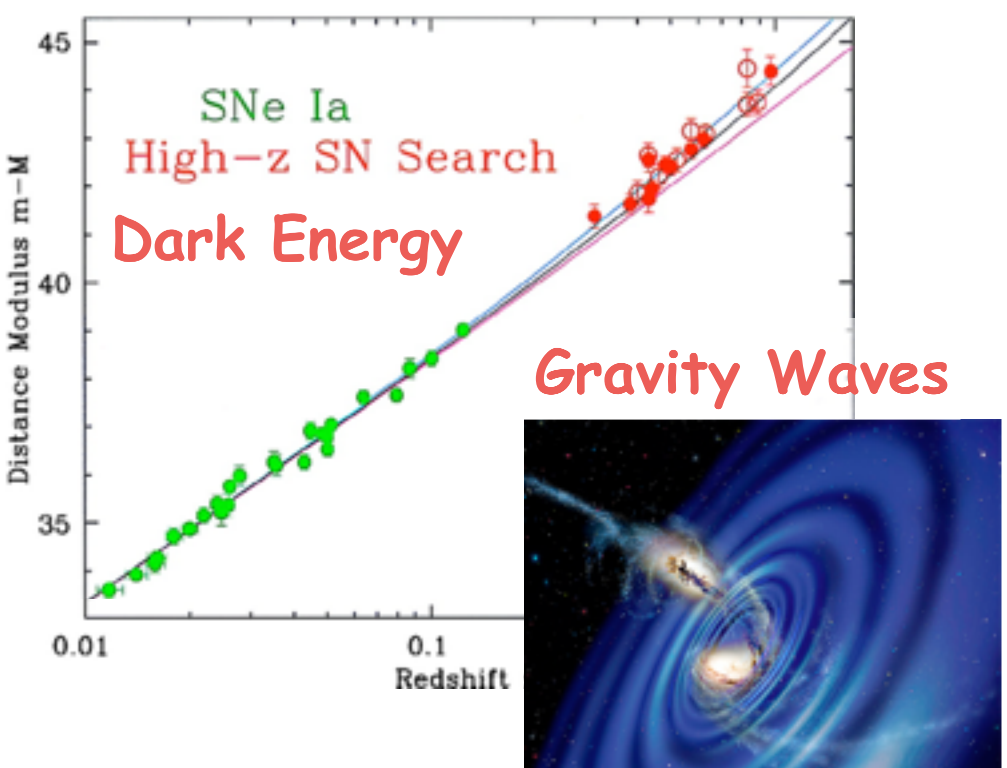
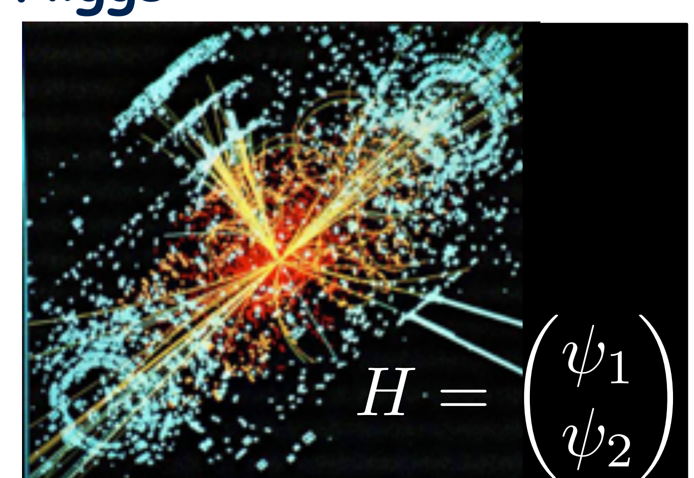
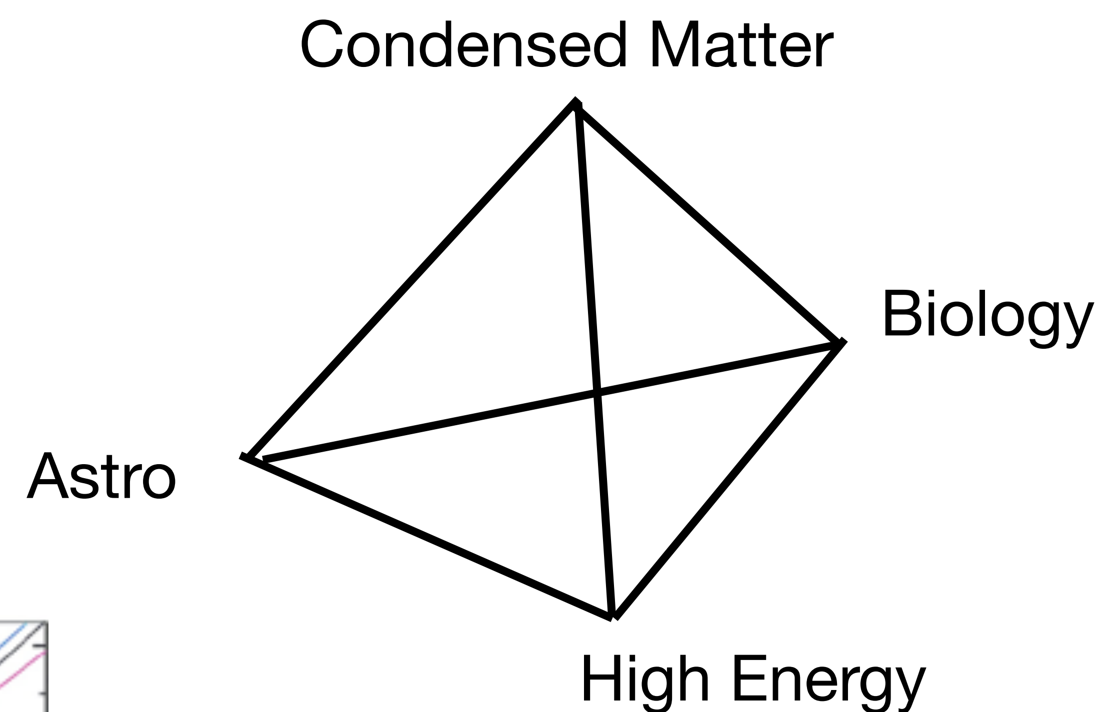
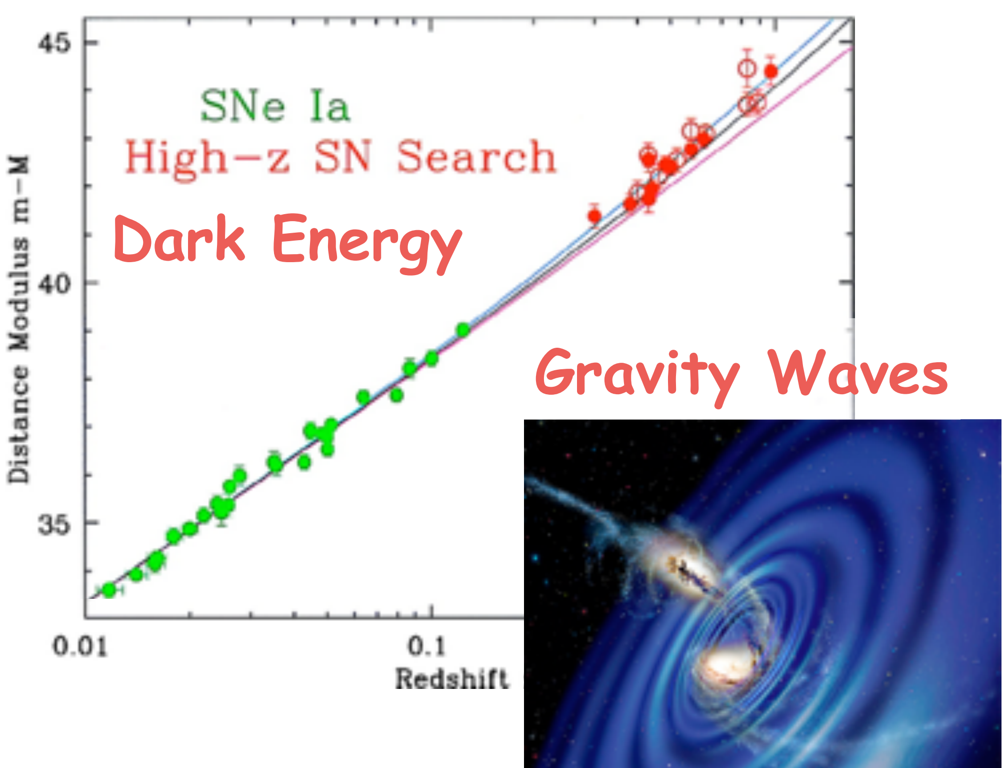
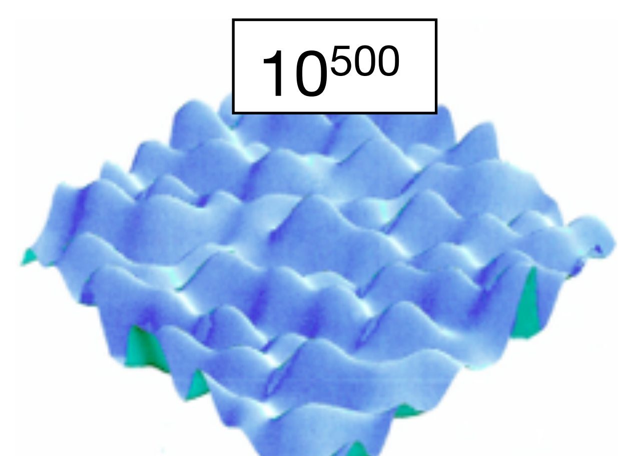

SNe Ia
High−z SN Search
Dark Energy
Distance Modulus m−M
45
40
35
0.01
0.1
Redshift
Gravity Waves

Higgs


$H = \begin{pmatrix} \psi_1 \\ \psi_2 \end{pmatrix}$

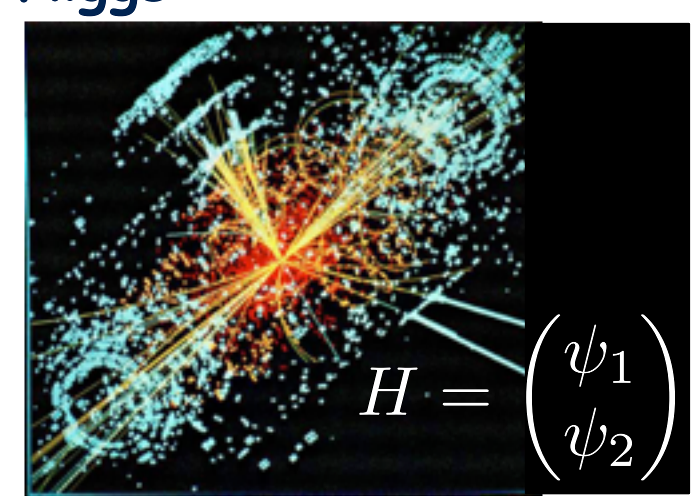


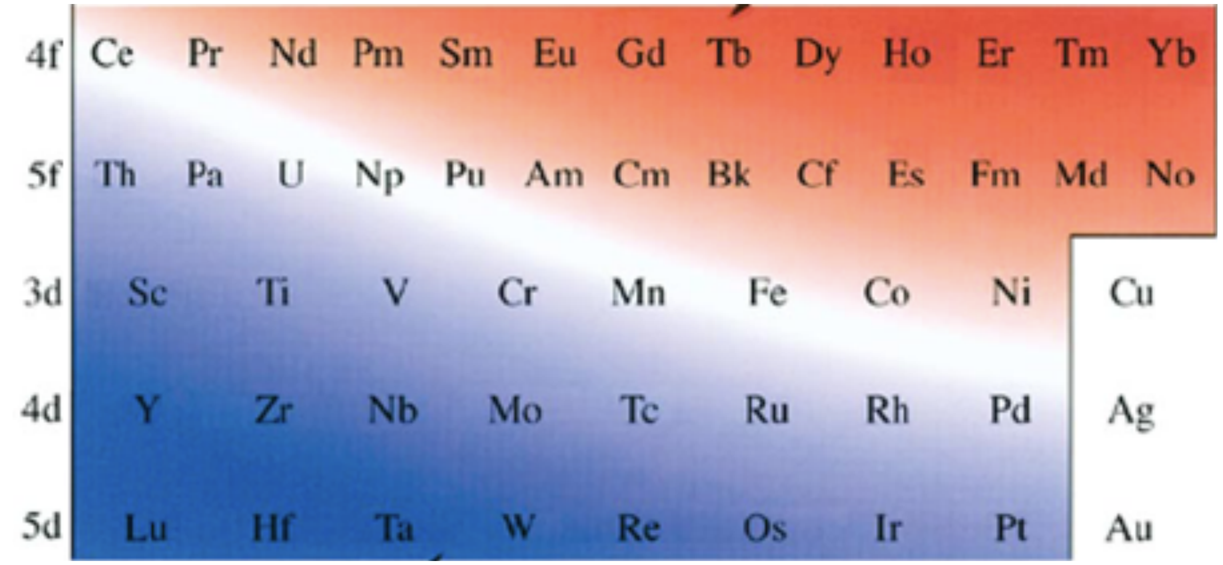


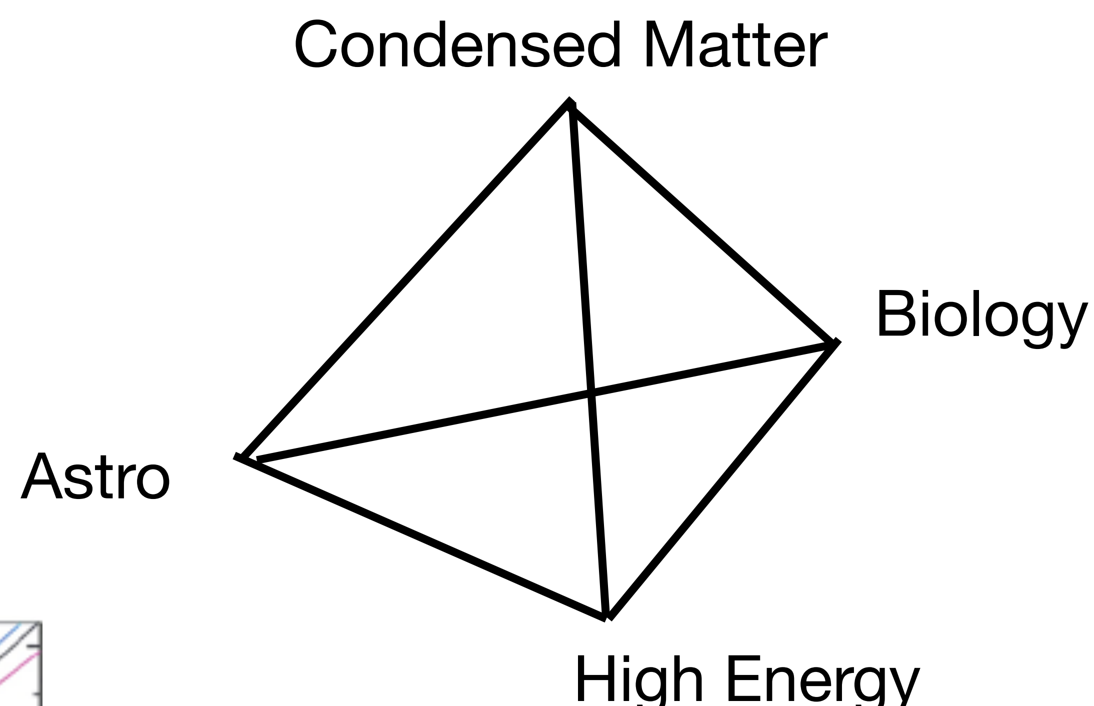


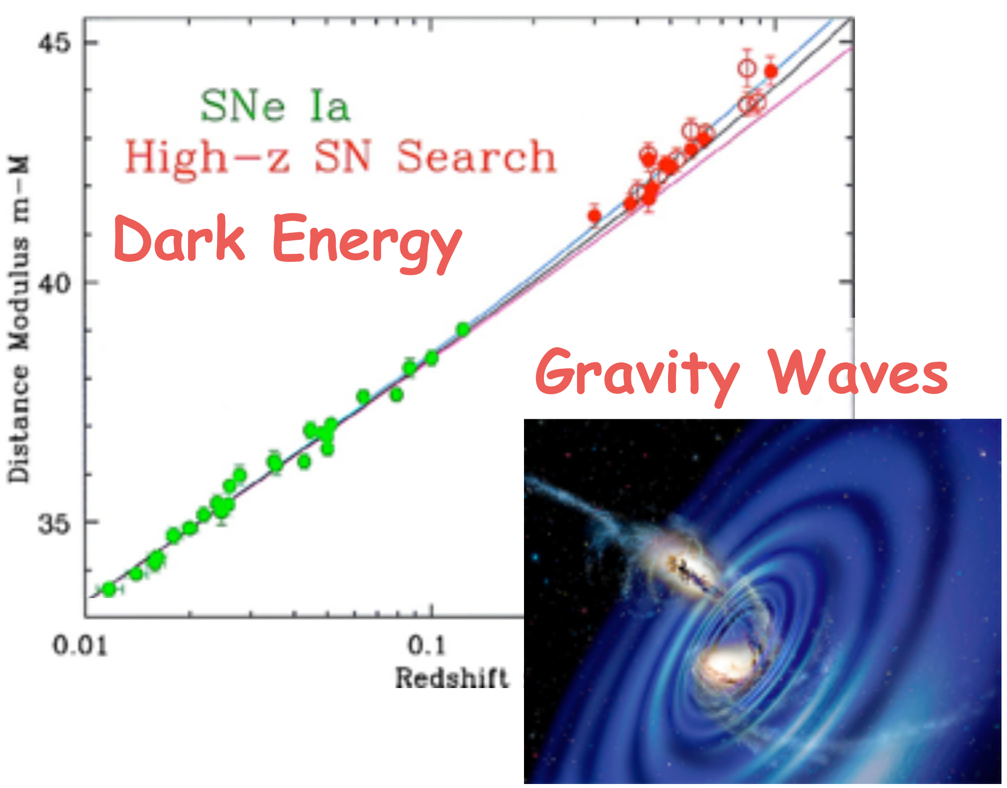
String Multiverse

Higgs

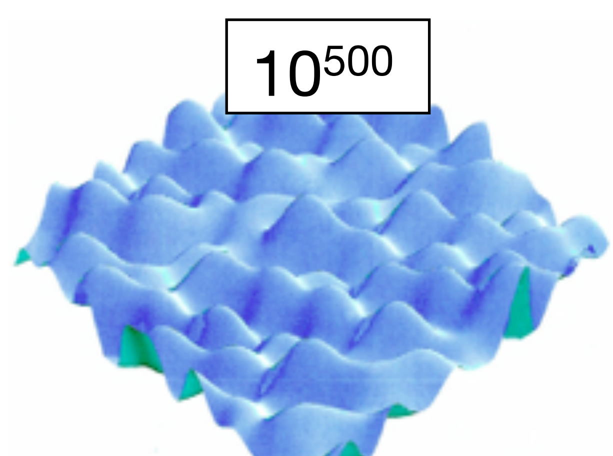






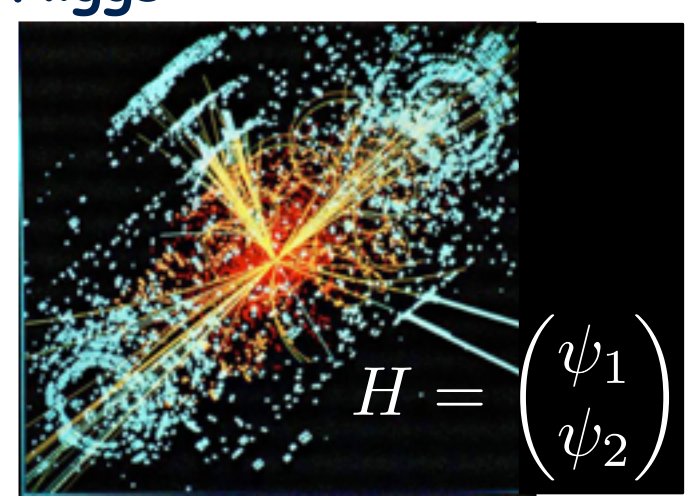


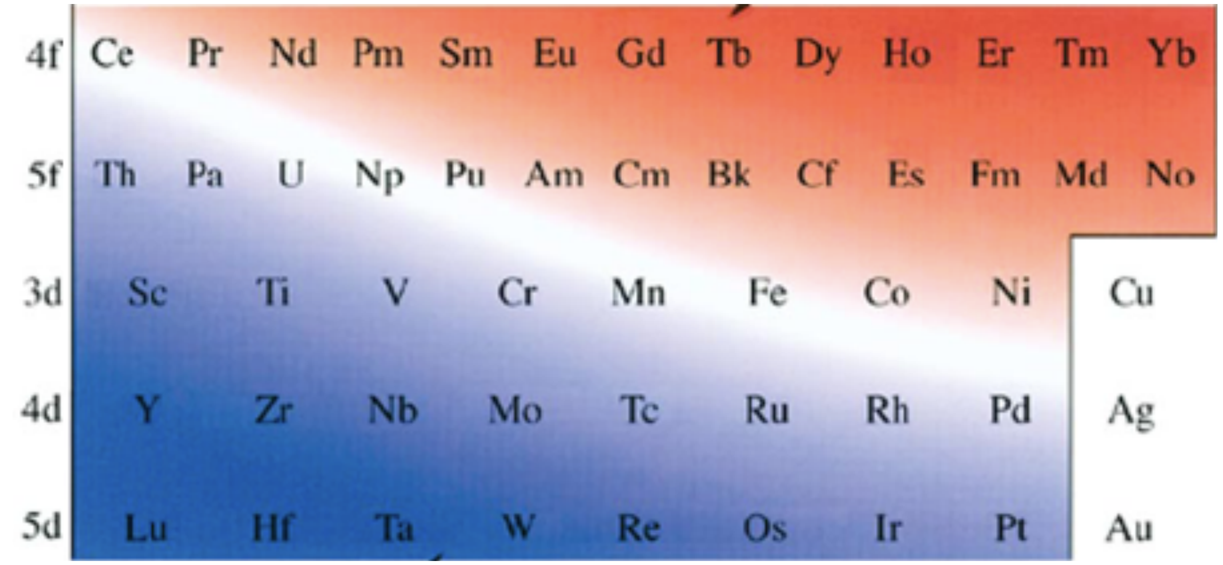
Gravity Waves



String Multiverse

Higgs

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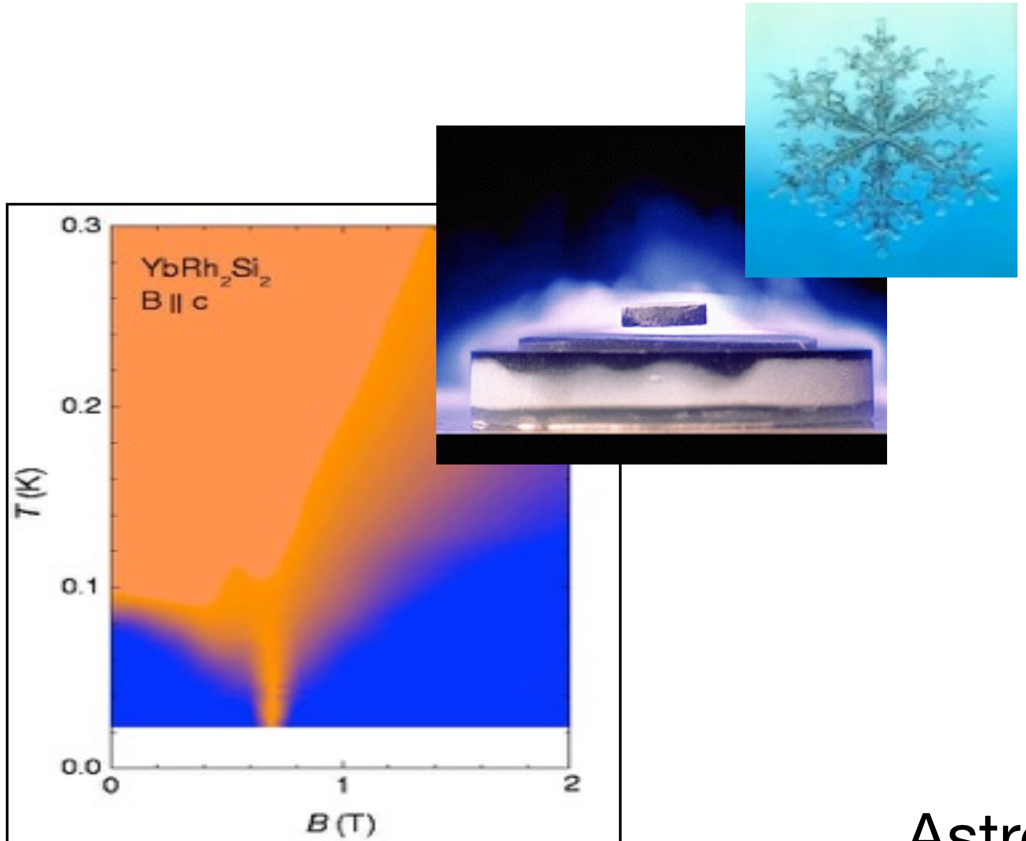
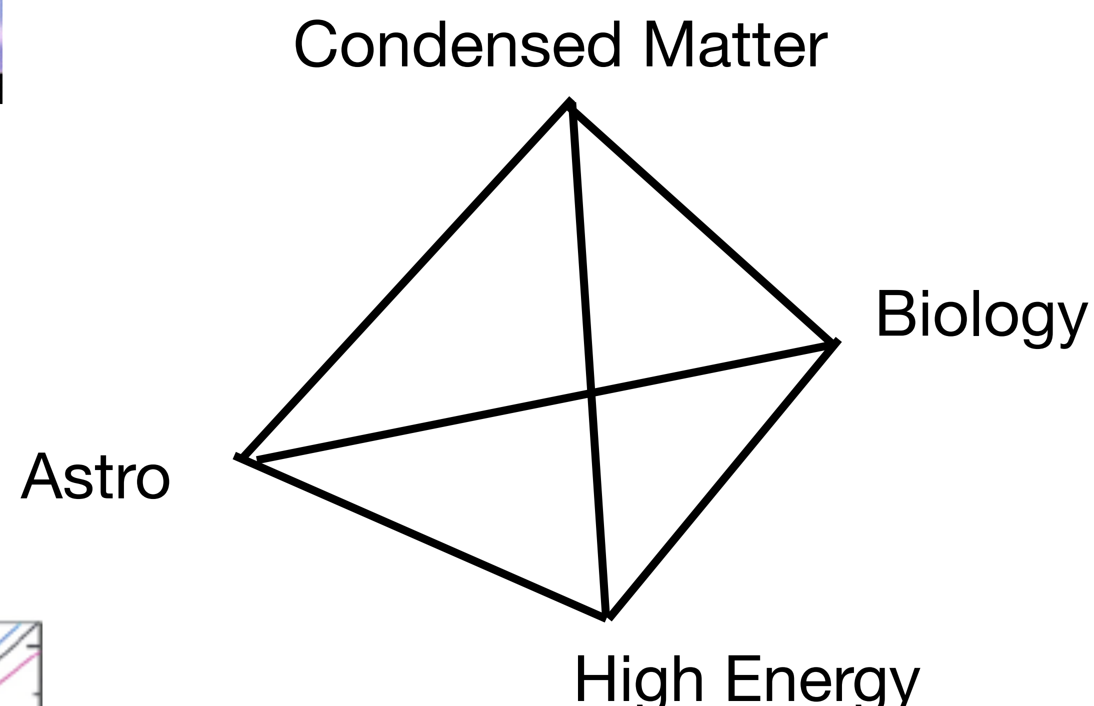
5f Th Pa U Np Pu Am Cm Bk Cf Es Fm Md No
3d Sc Ti V Cr Mn Fe Co Ni Cu
4d Y Zr Nb Mo Tc Ru Rh Pd Ag
5d Lu Hf Ta W Re Os Ir Pt Au


YbRh$_2$Si$_2$
B || c
0.3
0.2
0.1
0.0
T (K)
0
1
2
B (T)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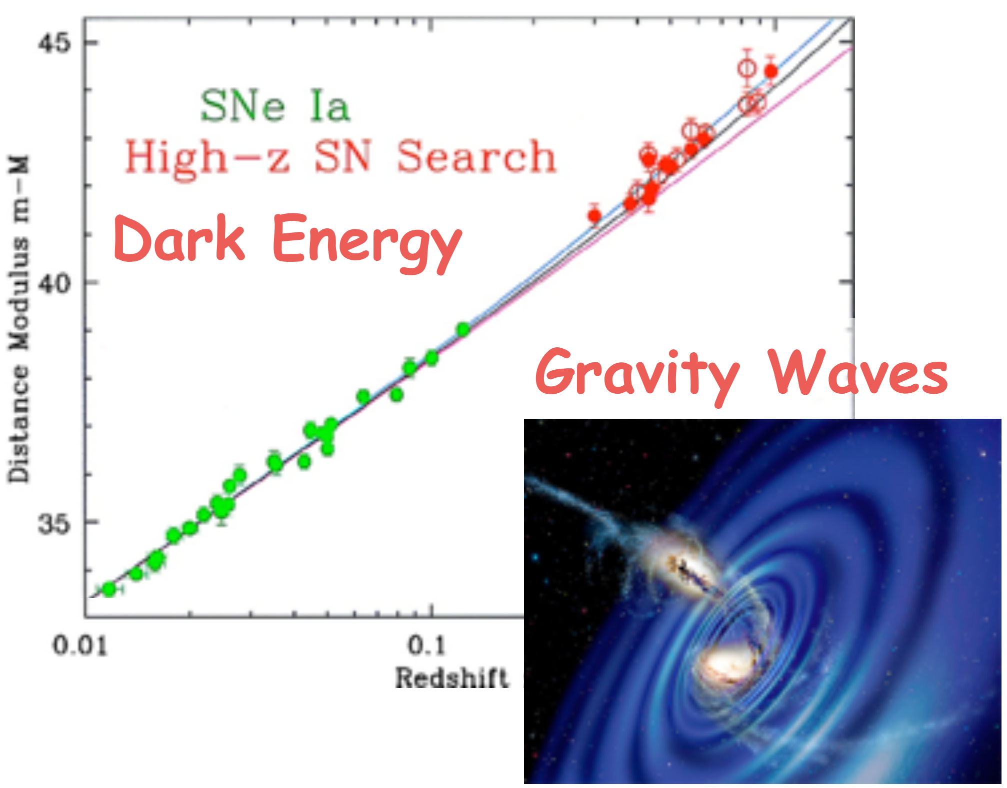
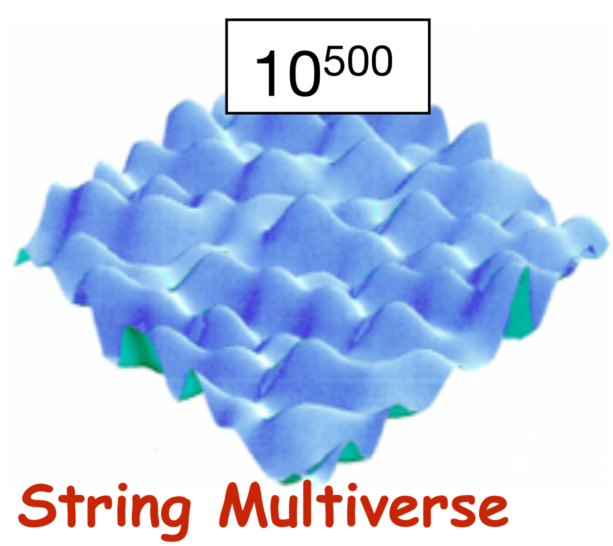
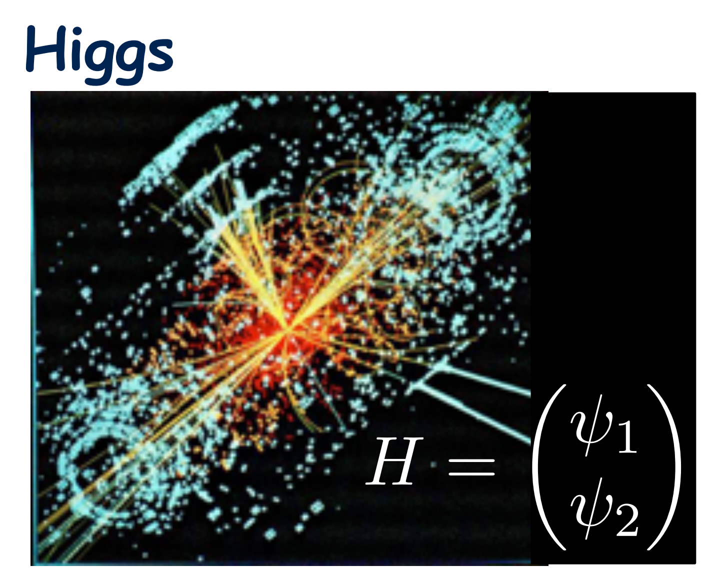
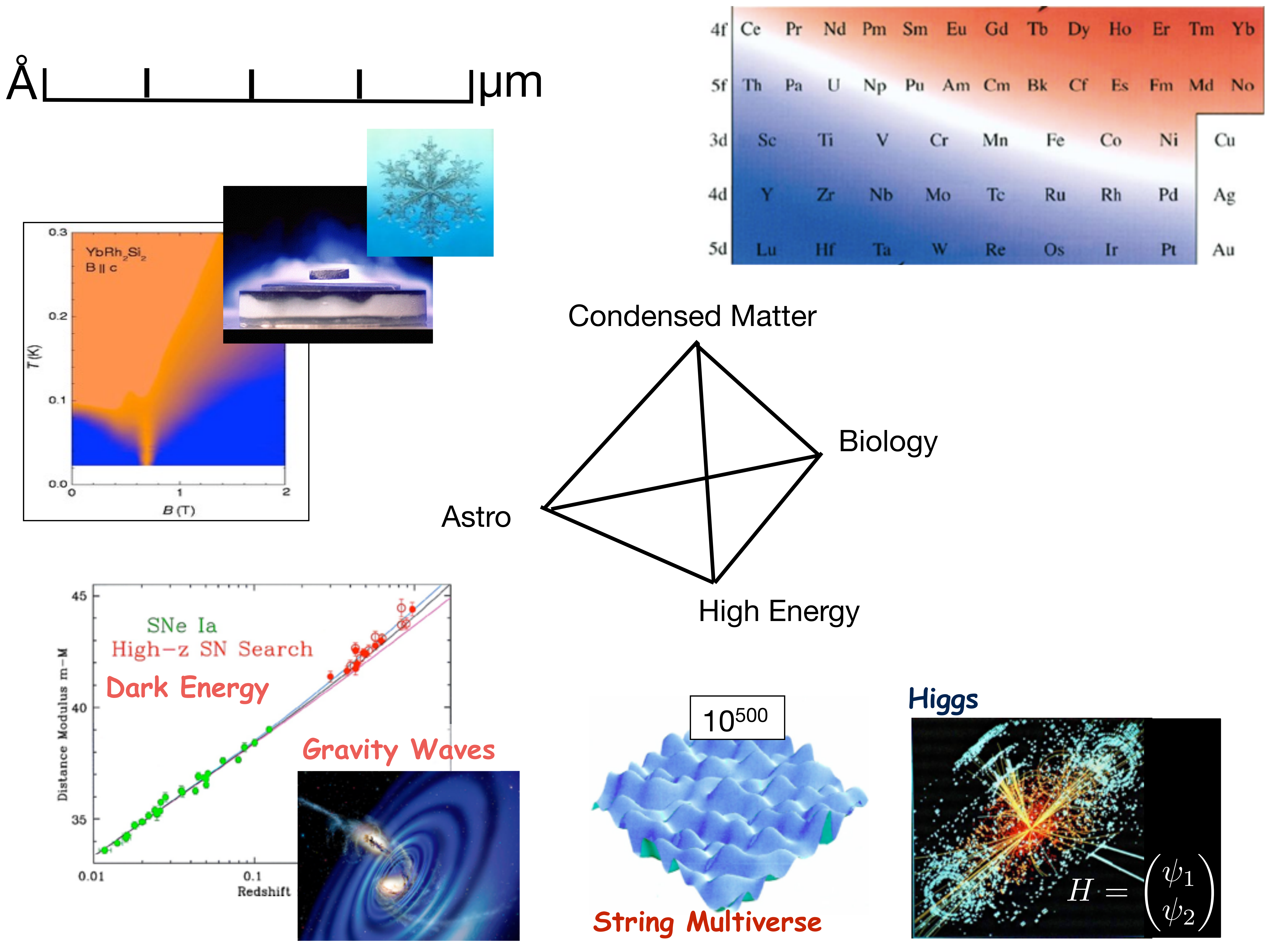
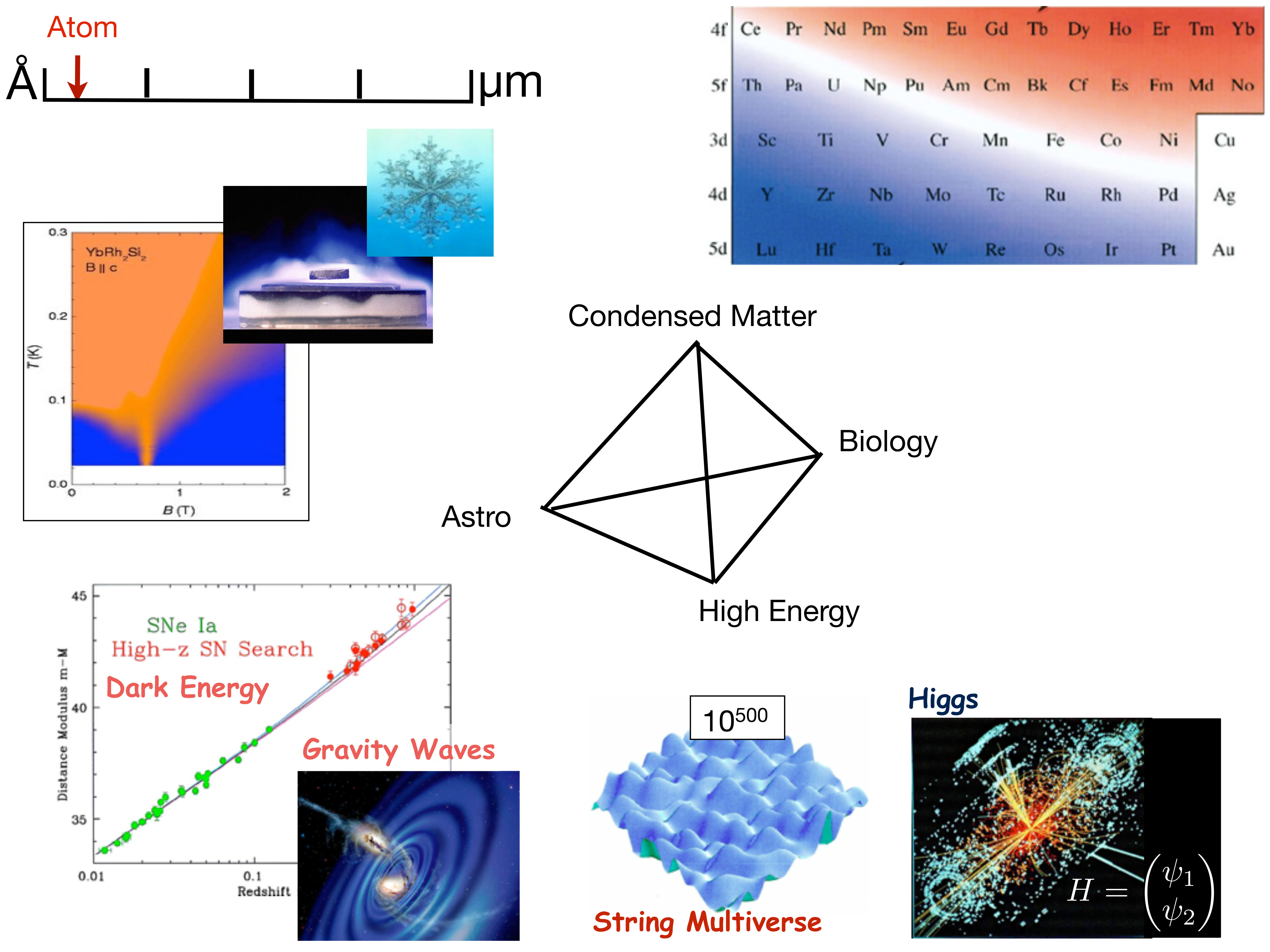

SNe Ia
High−z SN Search
Dark Energy
Gravity Waves
45
40
35
Distance Modulus m−M
0.01
0.1
Redshift


10^{500}
String Multiverse


Higgs
$H = \begin{pmatrix} \psi_1 \\ \psi_2 \end{pmatrix}$



Å
μm
4f Ce Pr Nd Pm Sm Eu Gd Tb Dy Ho Er Tm Yb
5f Th Pa U Np Pu Am Cm Bk Cf Es Fm Md No
3d Sc Ti V Cr Mn Fe Co Ni Cu
4d Y Zr Nb Mo Tc Ru Rh Pd Ag
5d Lu Hf Ta W Re Os Ir Pt Au
YbRh2Si2
B || c
T (K)
B (T)
Condensed Matter
Biology
Astro
High Energy
SNe Ia
High−z SN Search
Dark Energy
Distance Modulus m−M
Redshift
Gravity Waves
10^500
String Multiverse
Higgs
H = (ψ1 ψ2)



Atom
Å
µm
4f Ce Pr Nd Pm Sm Eu Gd Tb Dy Ho Er Tm Yb
5f Th Pa U Np Pu Am Cm Bk Cf Es Fm Md No
3d Sc Ti V Cr Mn Fe Co Ni Cu
4d Y Zr Nb Mo Tc Ru Rh Pd Ag
5d Lu Hf Ta W Re Os Ir Pt Au
$YbRh_2Si_2$
B ∥ c
T (K)
B (T)
Condensed Matter
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Higgs
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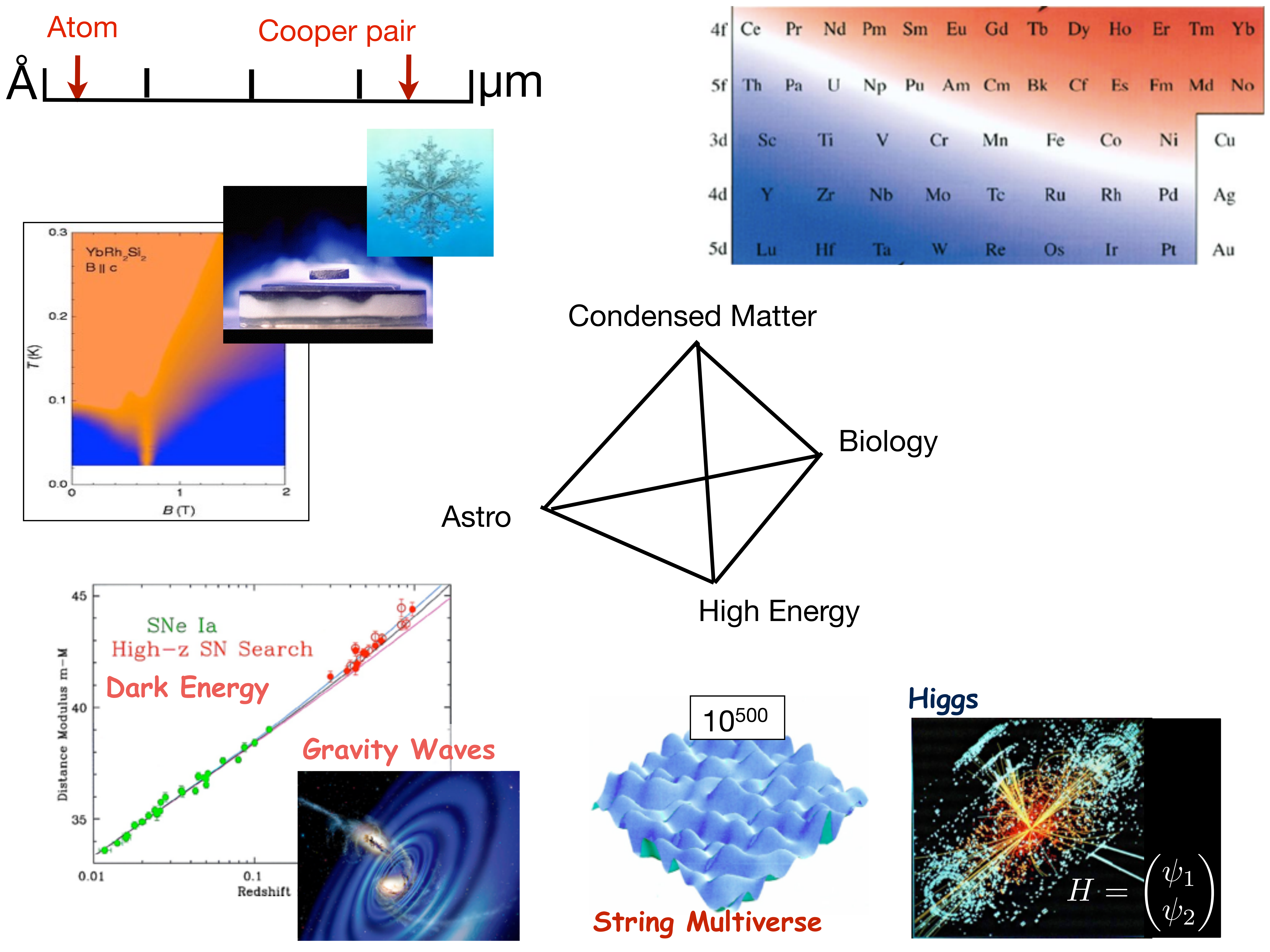

Atom
Cooper pair
Å
µm
4f Ce Pr Nd Pm Sm Eu Gd Tb Dy Ho Er Tm Yb
5f Th Pa U Np Pu Am Cm Bk Cf Es Fm Md No
3d Sc Ti V Cr Mn Fe Co Ni Cu
4d Y Zr Nb Mo Tc Ru Rh Pd Ag
5d Lu Hf Ta W Re Os Ir Pt Au
YbRh$_2$Si$_2$
B ∥ c
T (K)
B (T)
Condensed Matter
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SNe Ia
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Distance Modulus m−M
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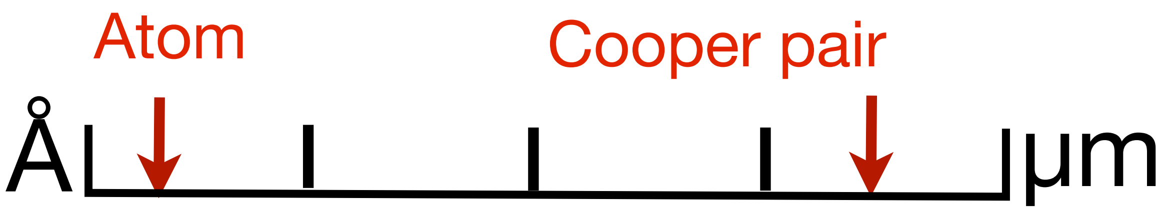
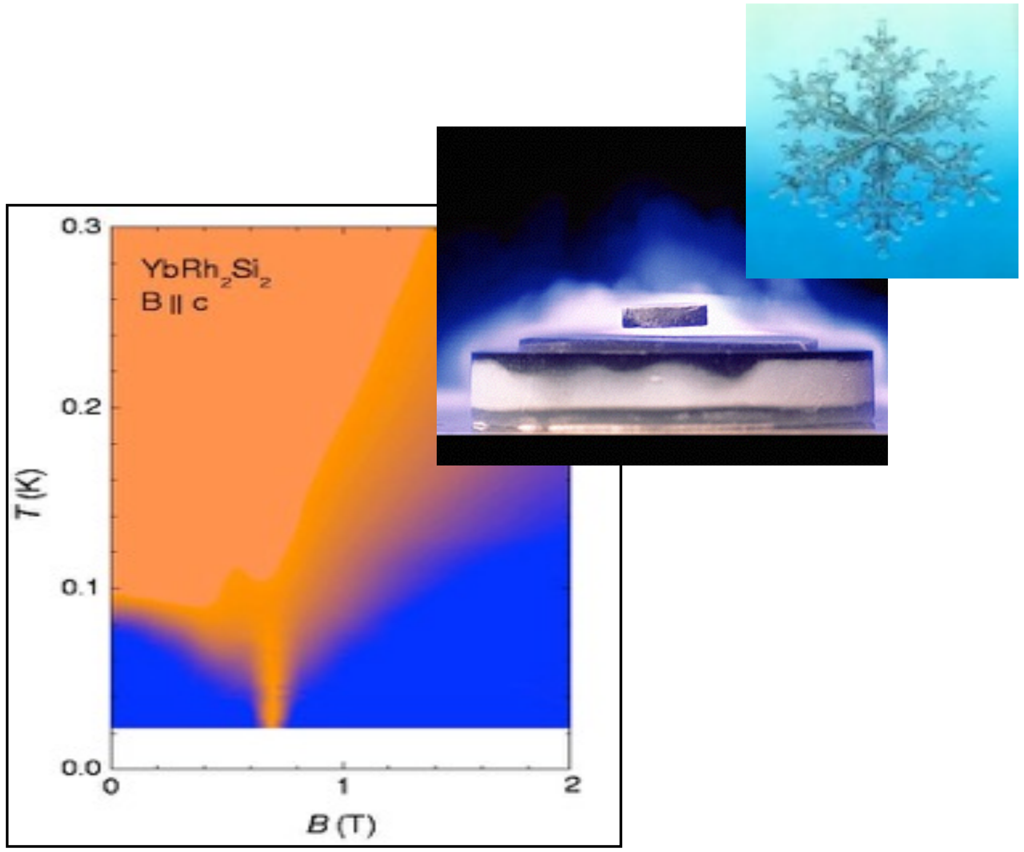
Higgs
$H = \begin{pmatrix} \psi_1 \\ \psi_2 \end{pmatrix}$


Atom
Cooper pair
Å
μm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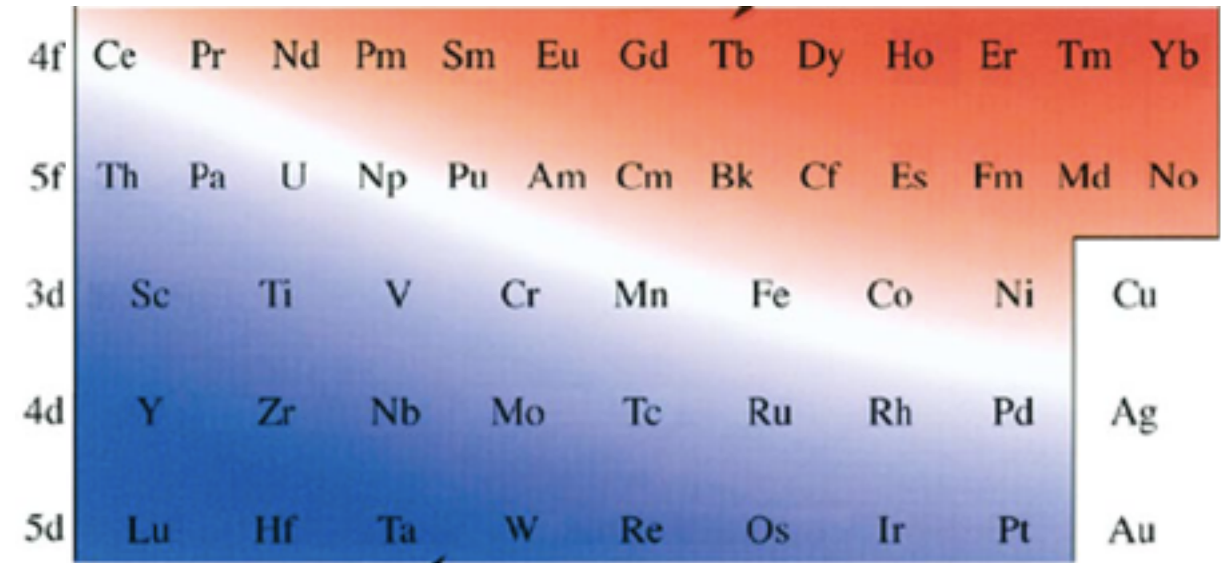
B || c
0.3
0.2
0.1
0.0
T (K)
0
1
2
B (T)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5f Th Pa U Np Pu Am Cm Bk Cf Es Fm Md No
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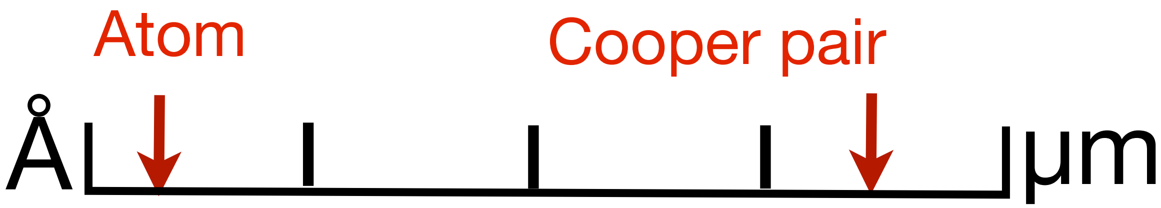
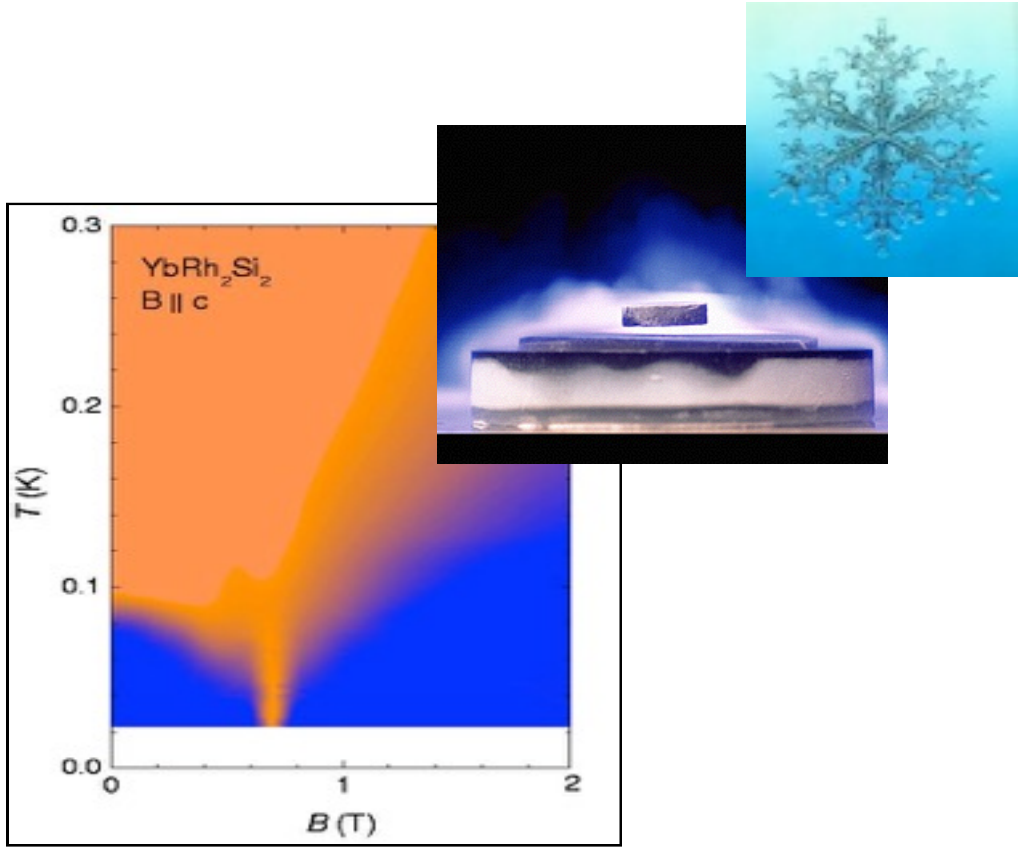
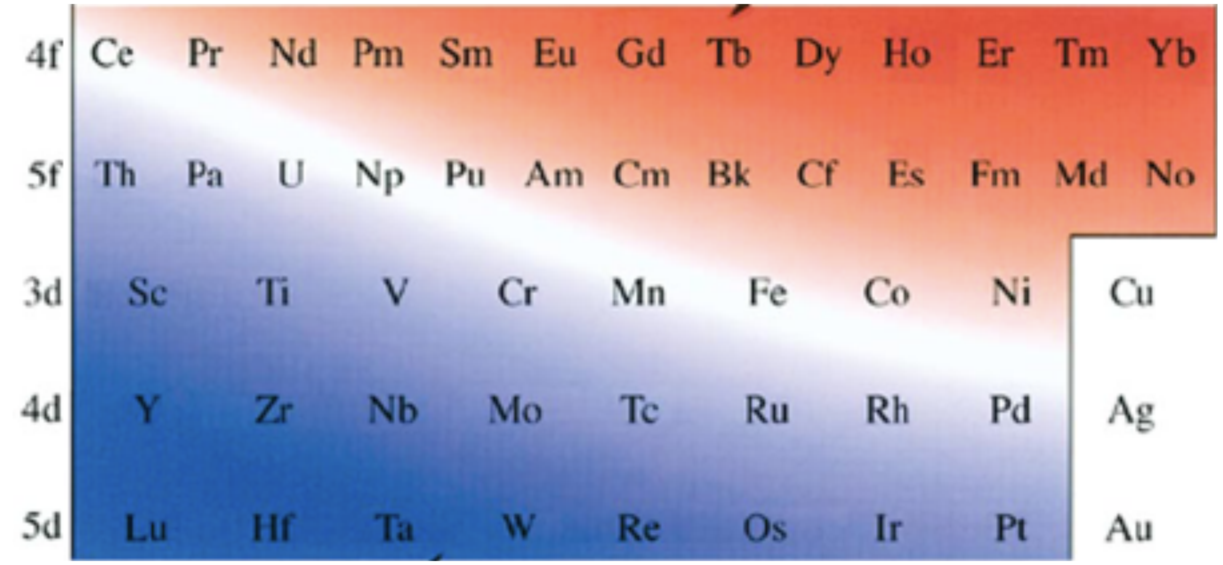
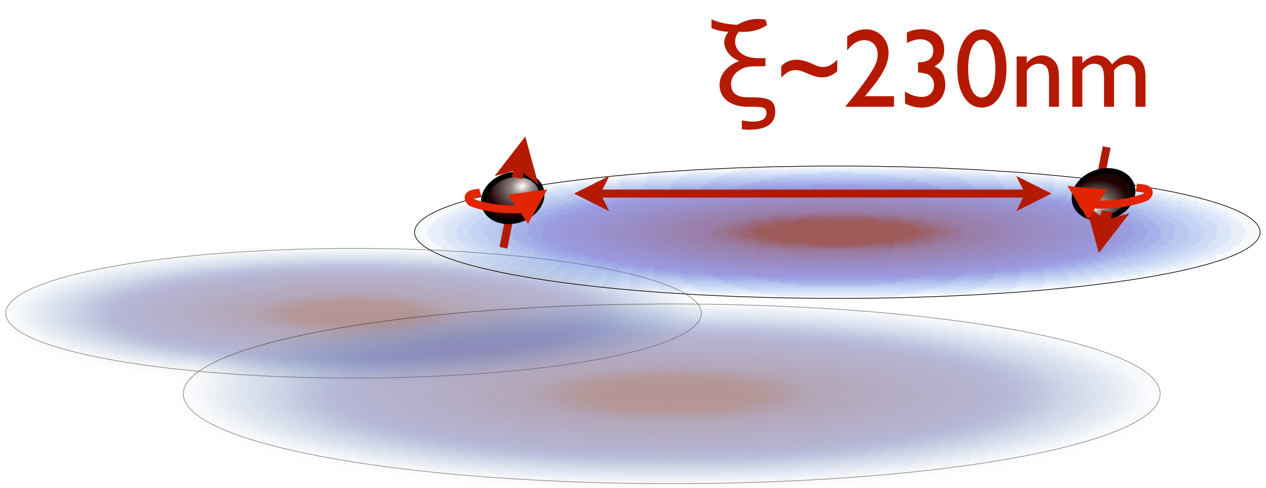
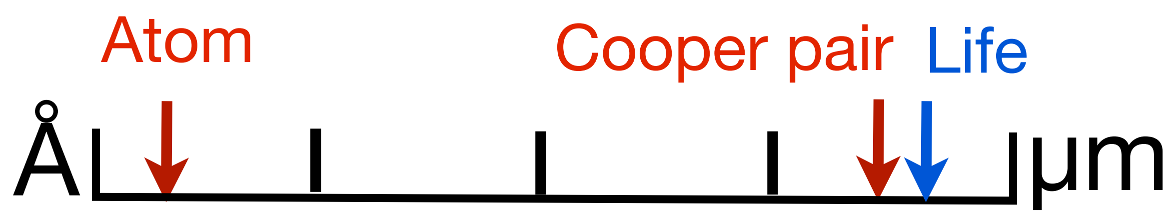


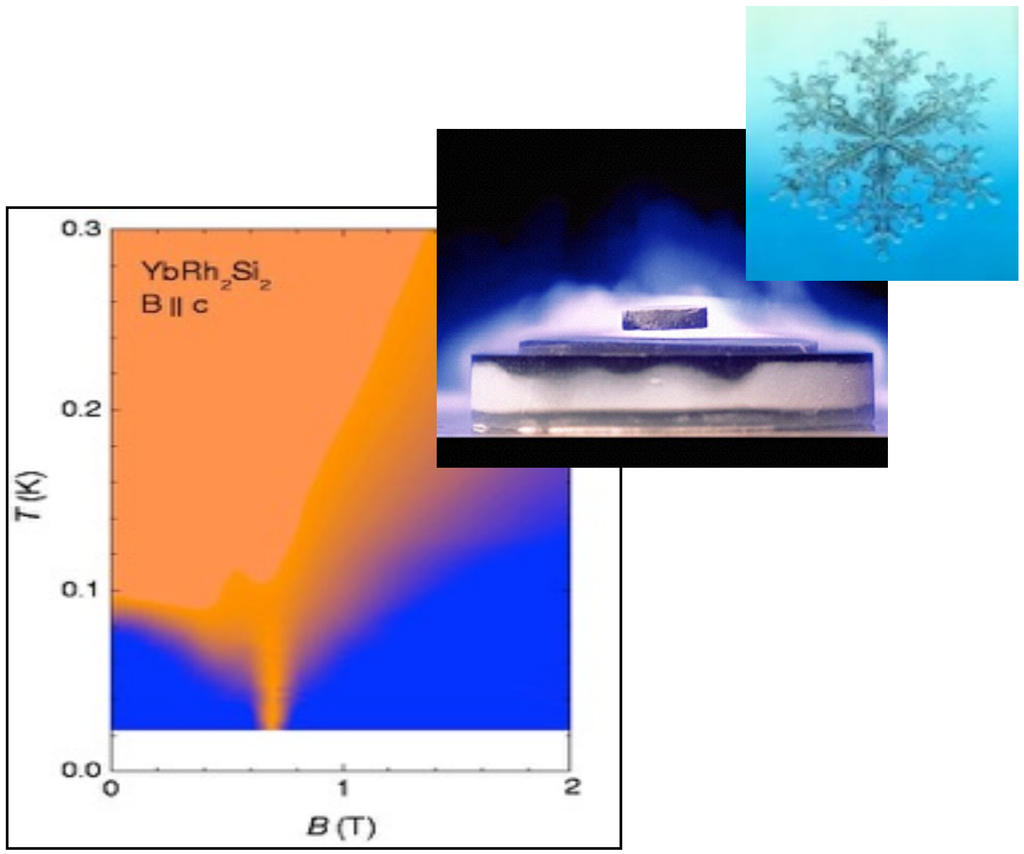




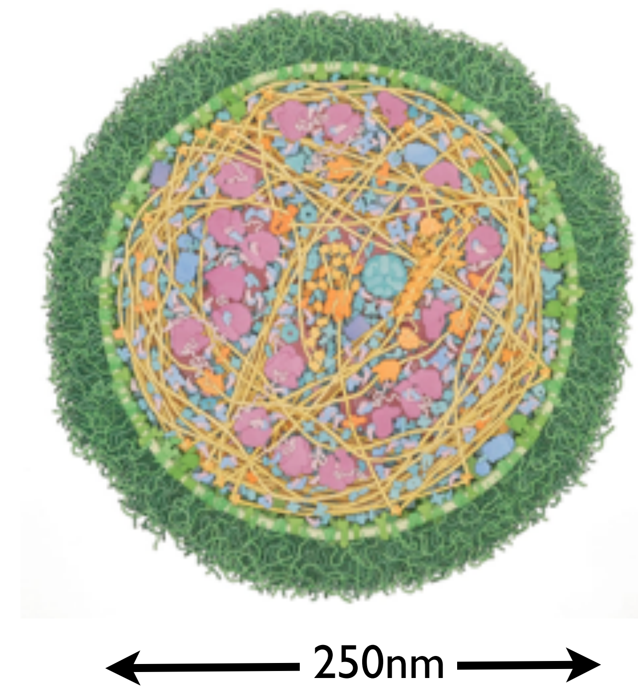


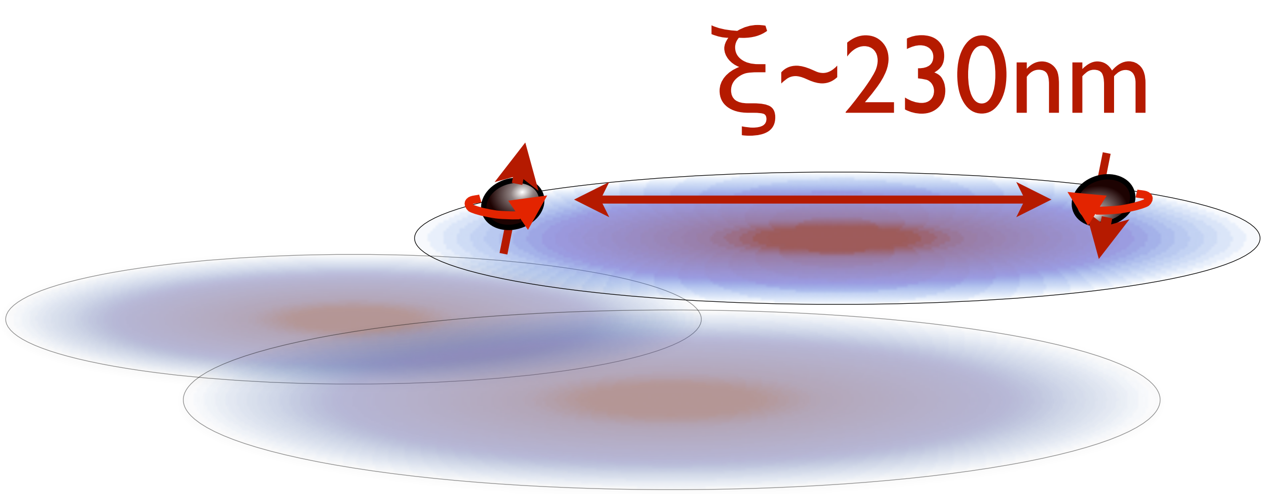
Cooper Pair in Sn



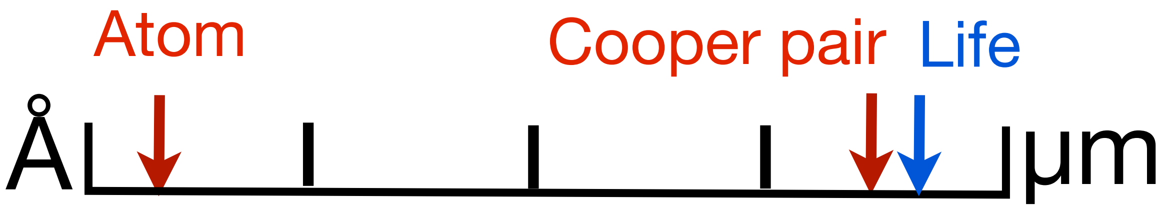


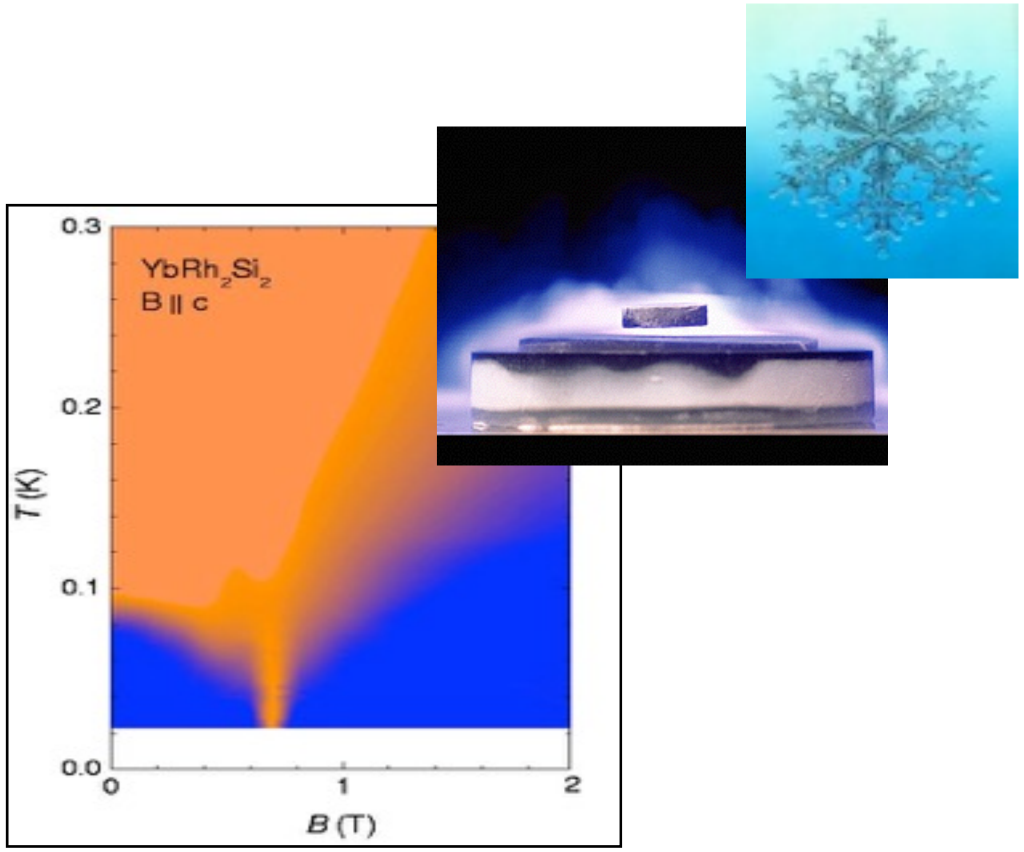
Mycoplasma mycoides





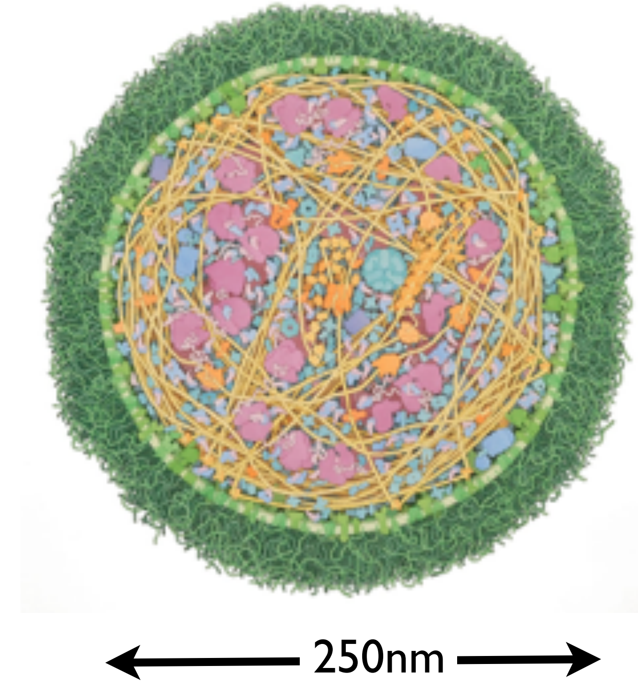
Cooper Pair in Sn

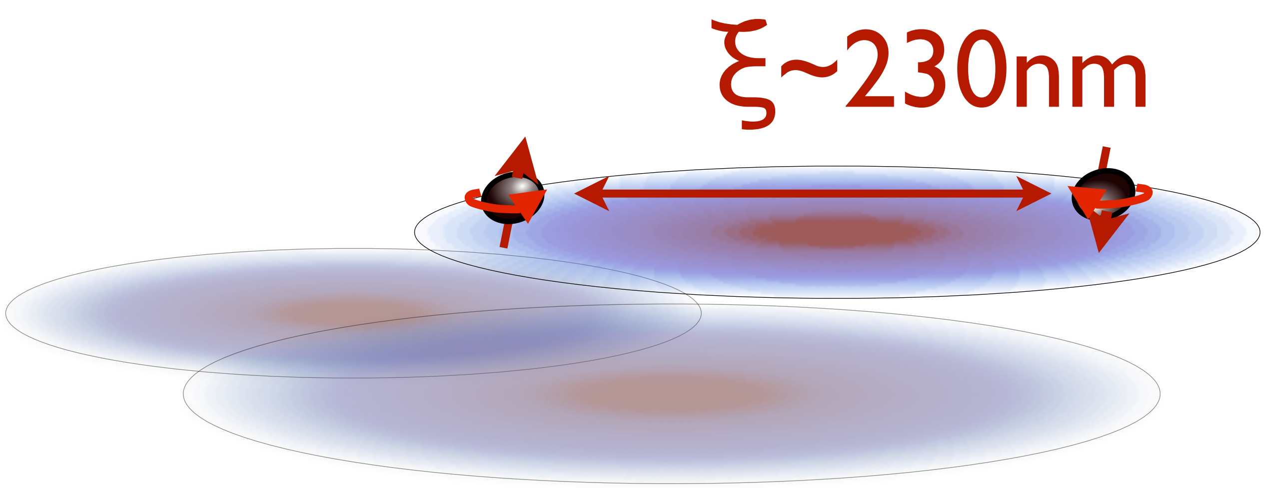




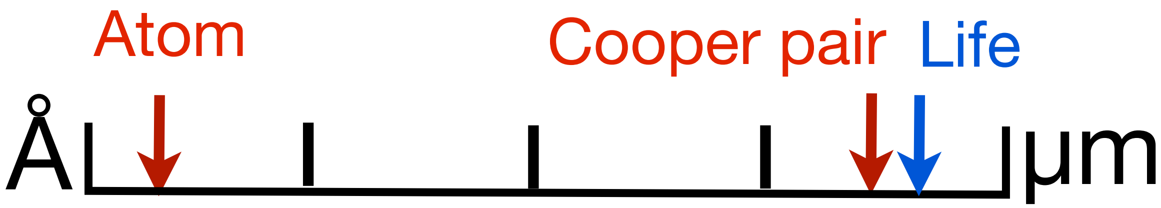
"Emergence"

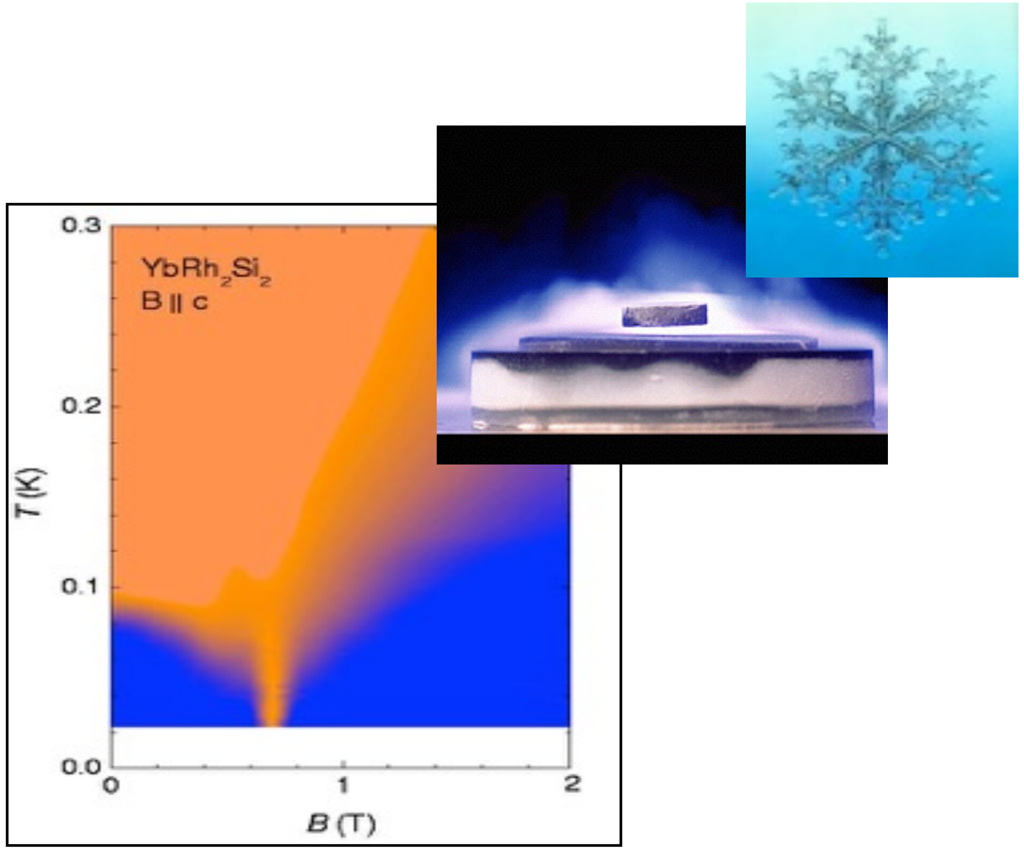
Mycoplasma mycoides





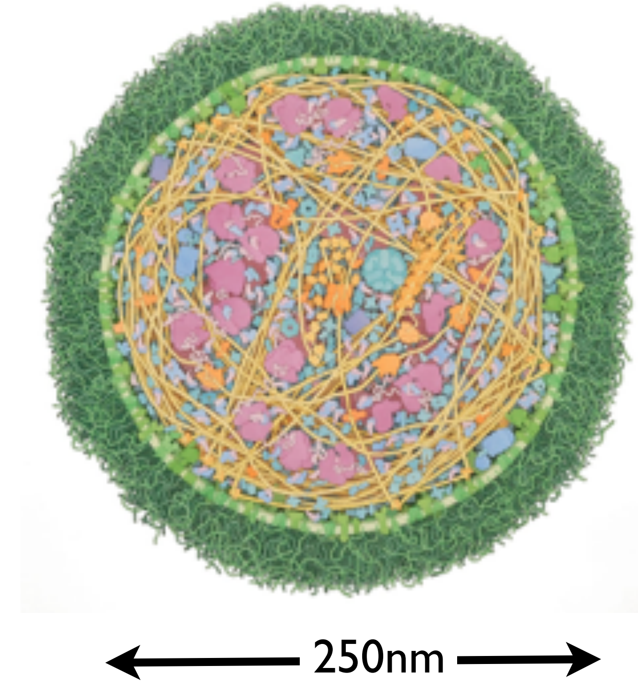
Cooper Pair in Sn

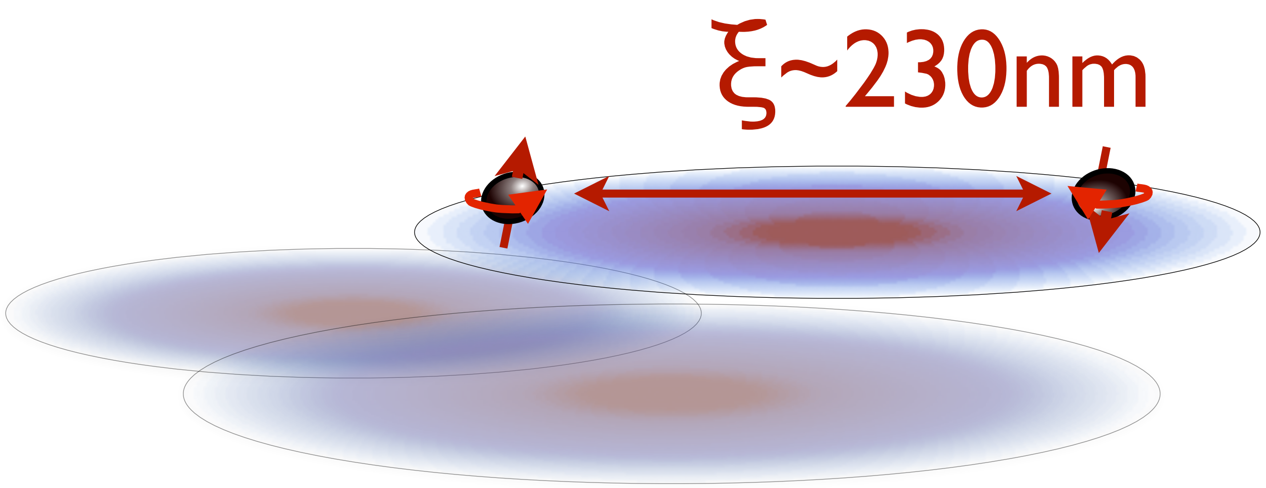




"Emergence"

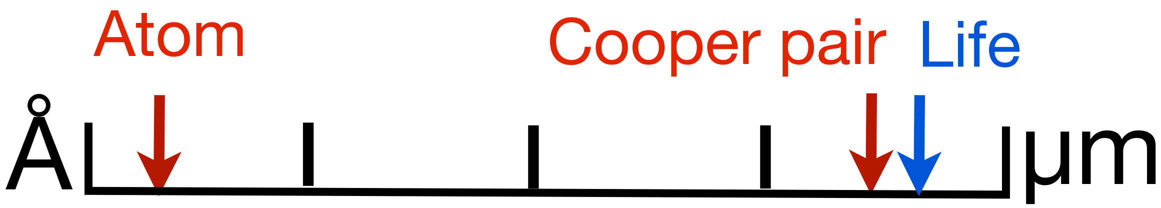
Mycoplasma mycoides





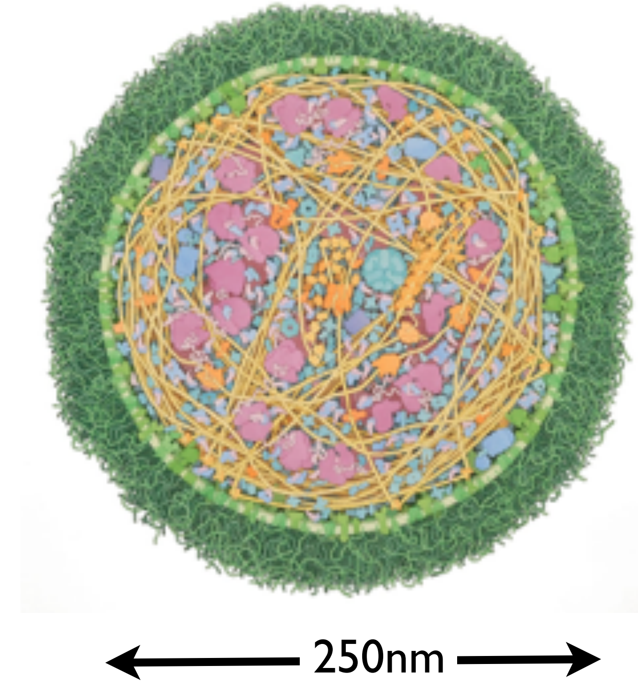
Cooper Pair in Sn

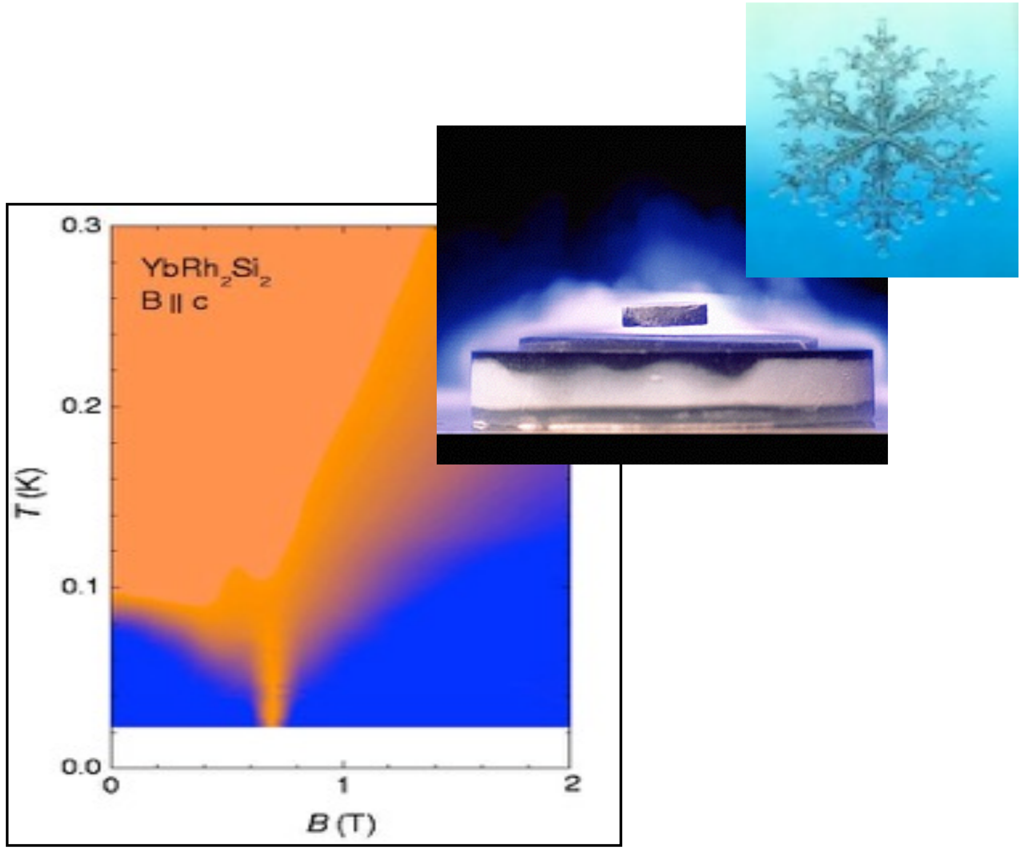
What are the principles that govern the emergence of collective behavior in matter between the Angstrom and the Micron?

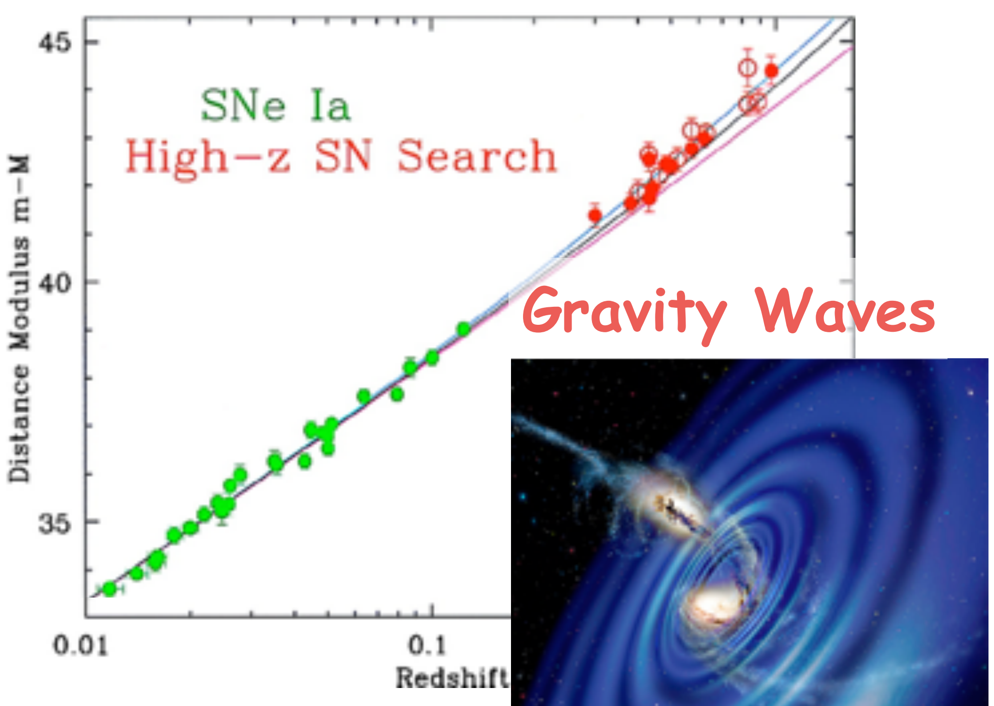


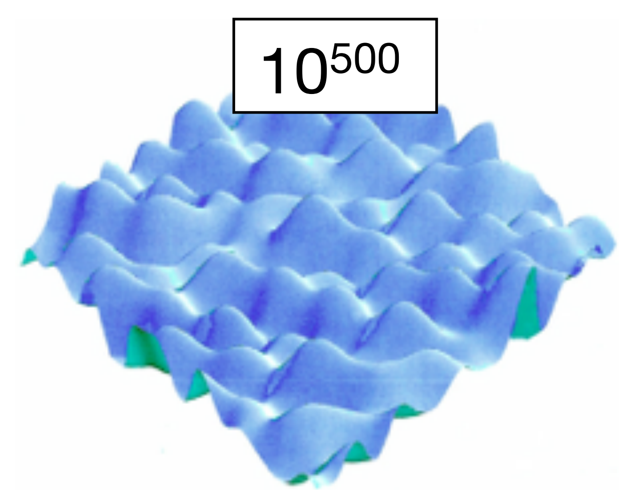
“Emergence”

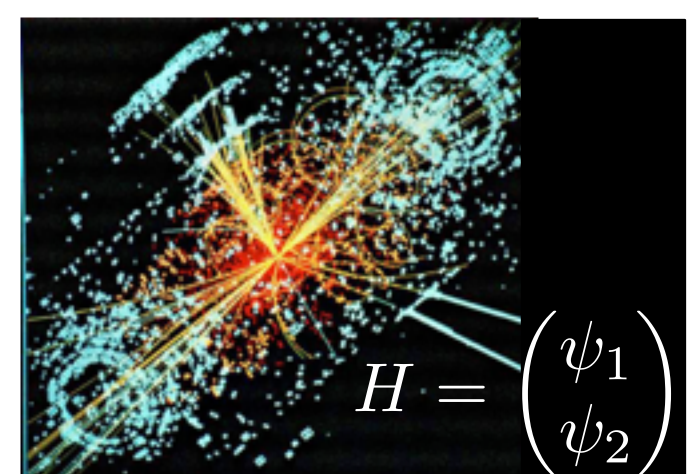
Mycoplasma mycoides

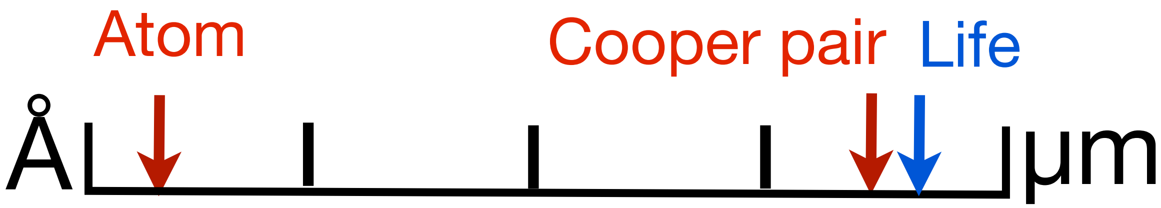


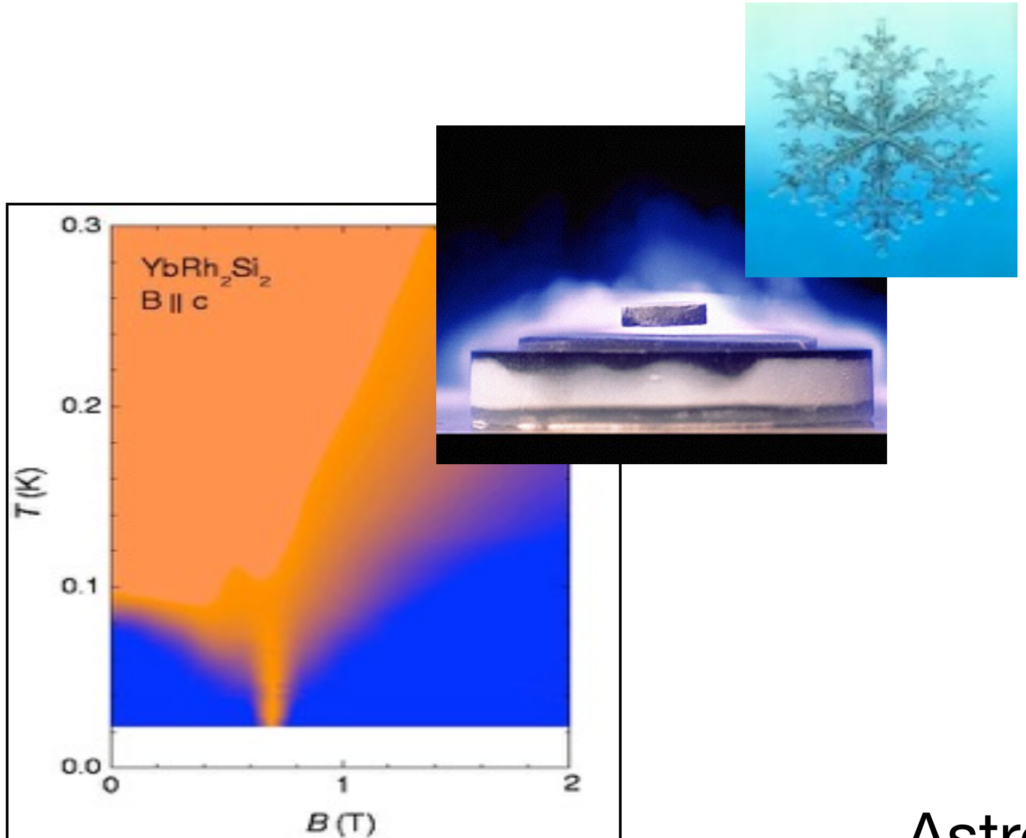






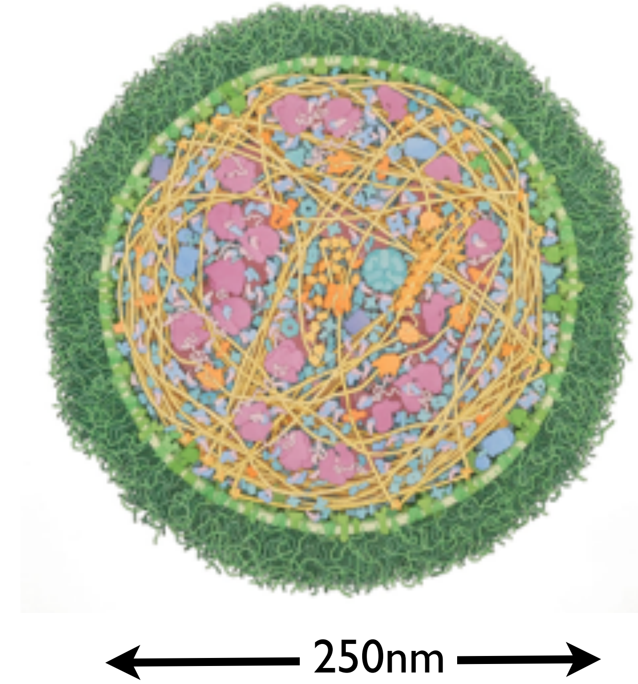


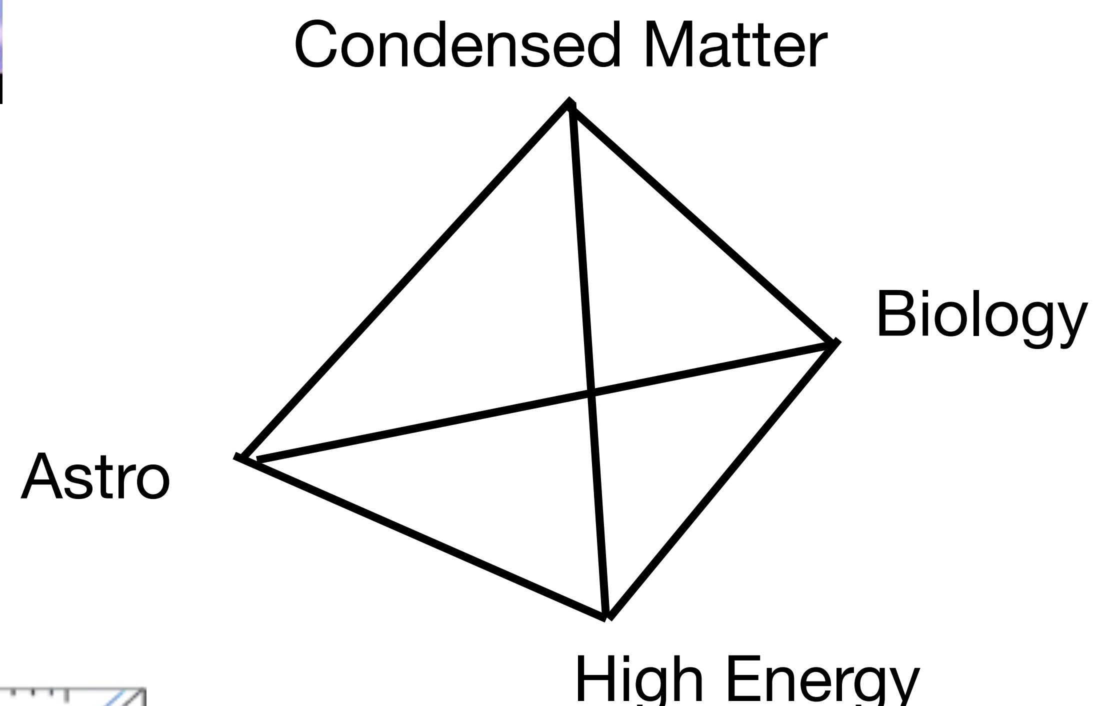


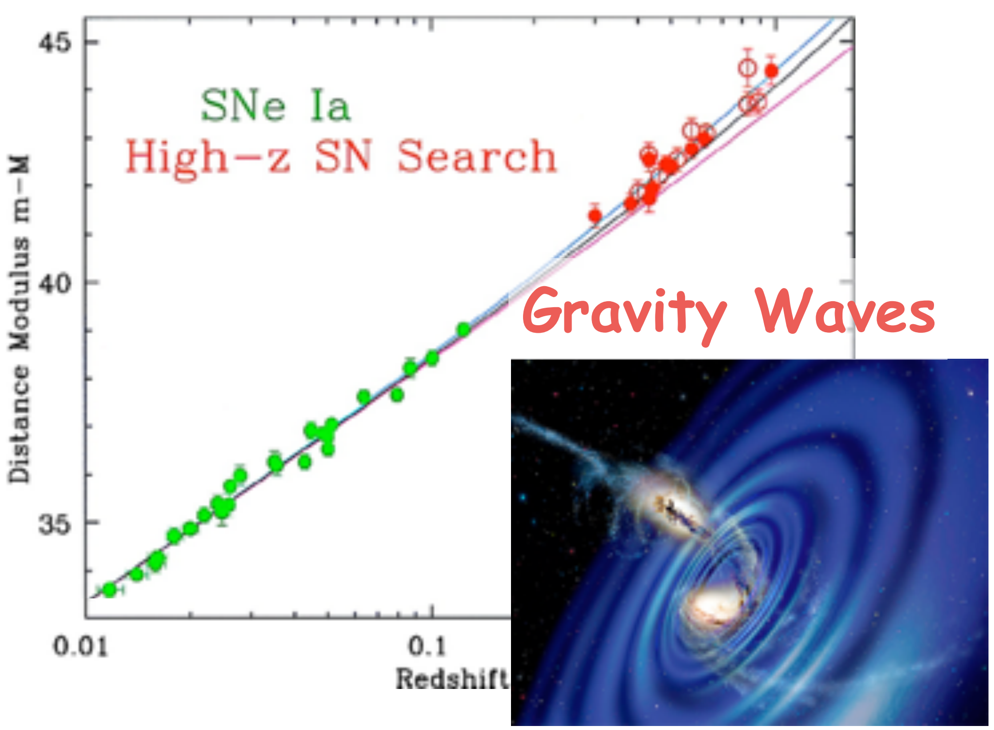


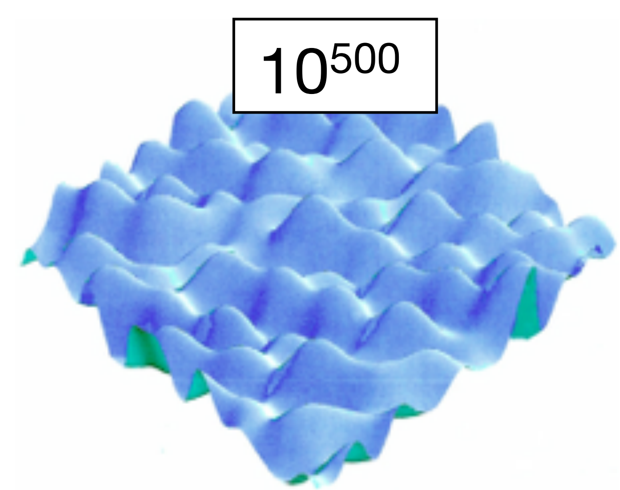
"Emergence"

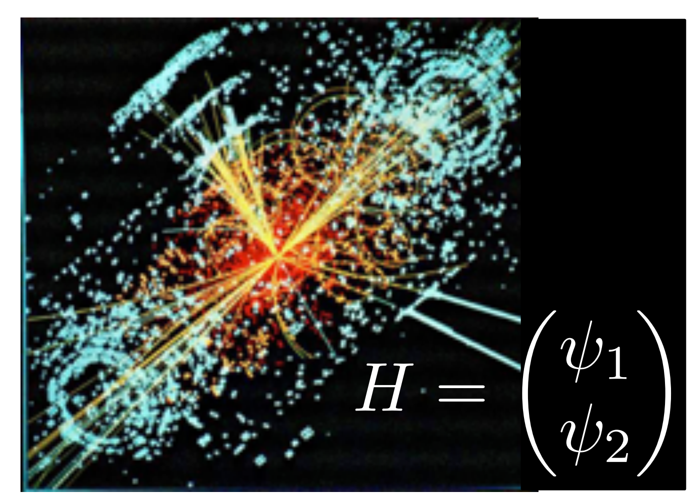
Mycoplasma mycoides

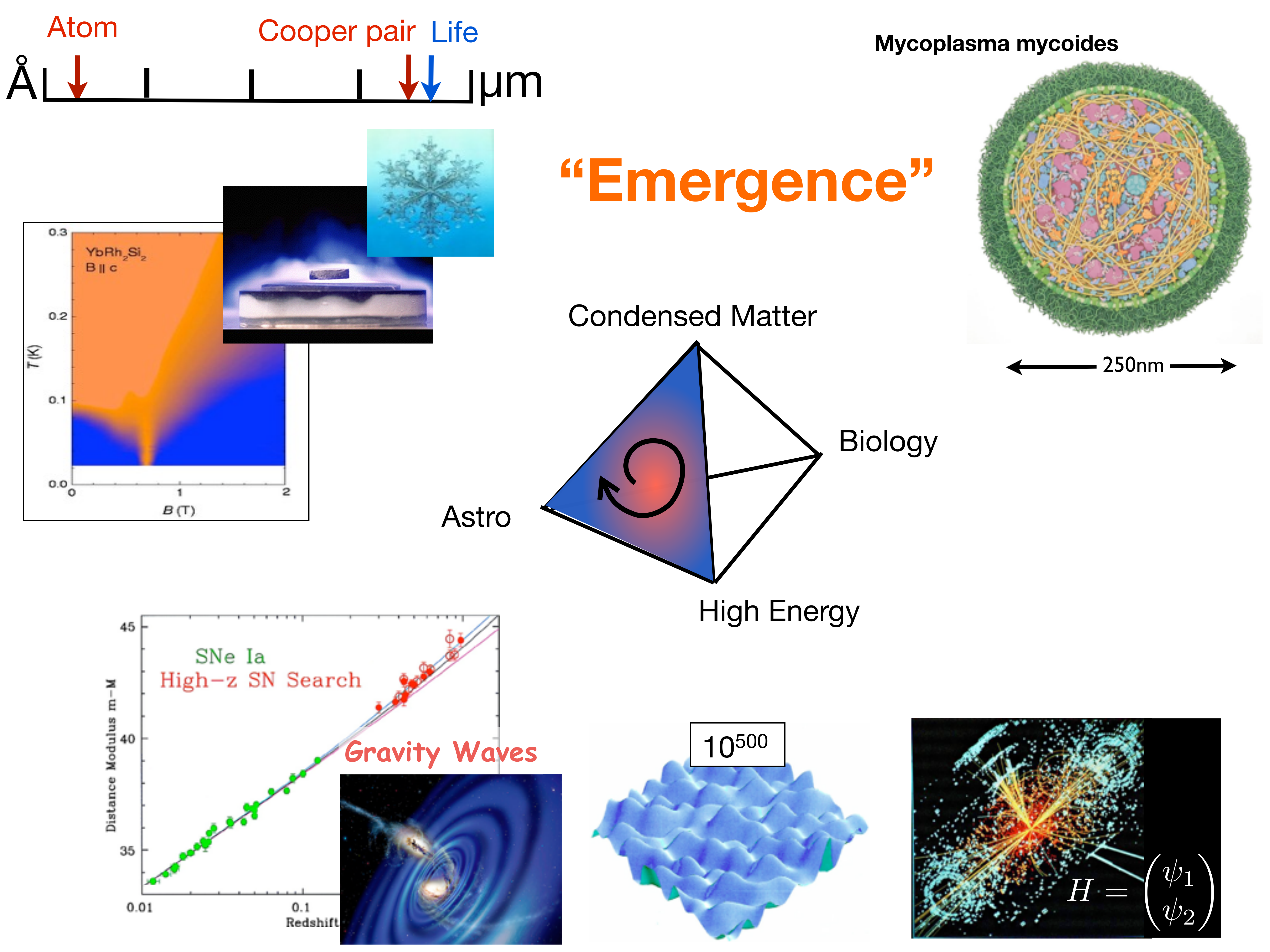












Atom
Cooper pair
Life
Å
μm
Mycoplasma mycoides
250nm
"Emergence"
YbRh2Si2
B || c
T (K)
B (T)
Condensed Matter
Biology
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High Energy
SNe Ia
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Distance Modulus m−M
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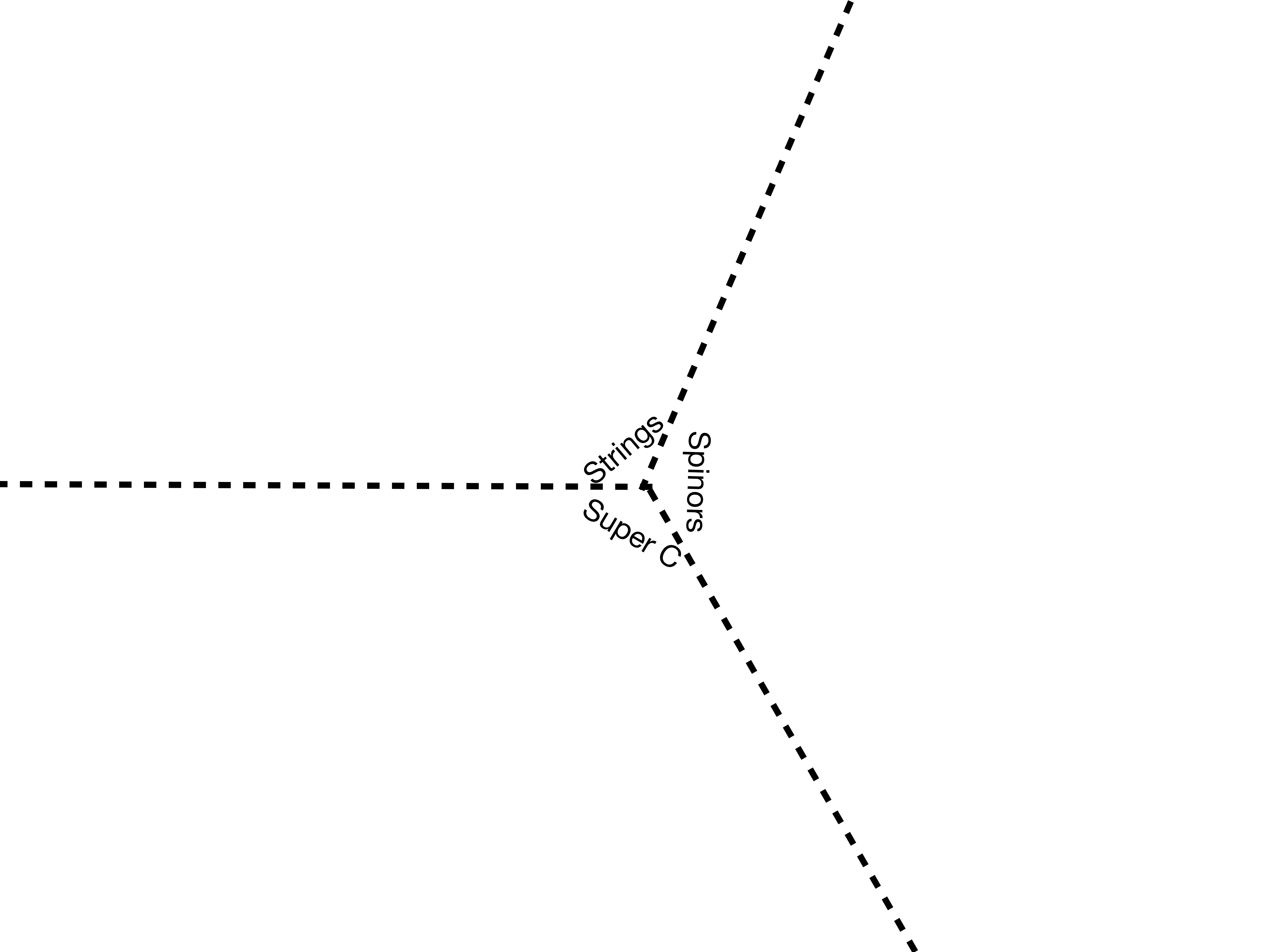
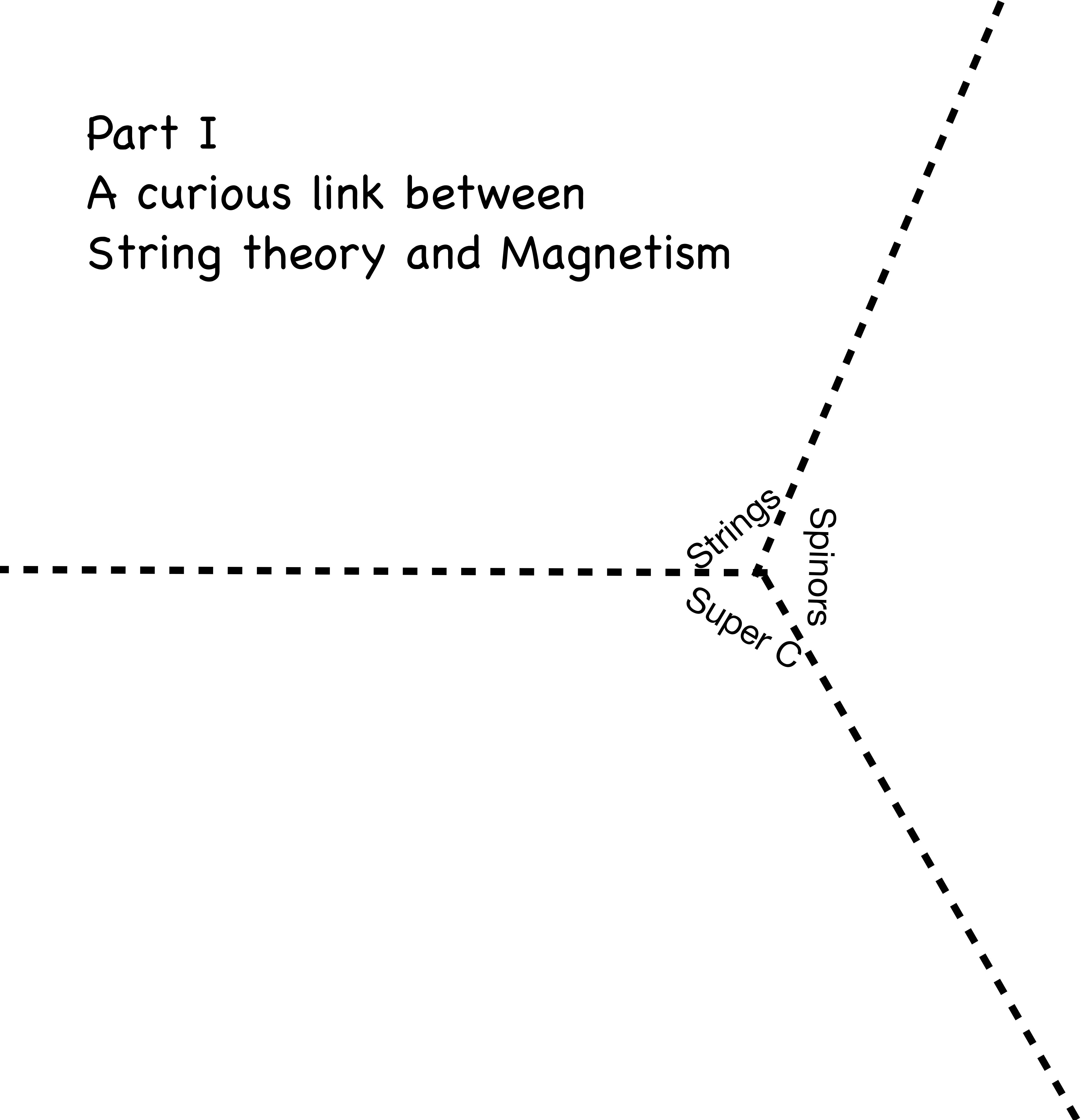
Gravity Waves
10^500
$H = \begin{pmatrix}\psi_1 \\ \psi_2\end{pmatrix}$


Strings
Spinors
Super C

Part I

A curious link between
String theory and Magnetism



Part I
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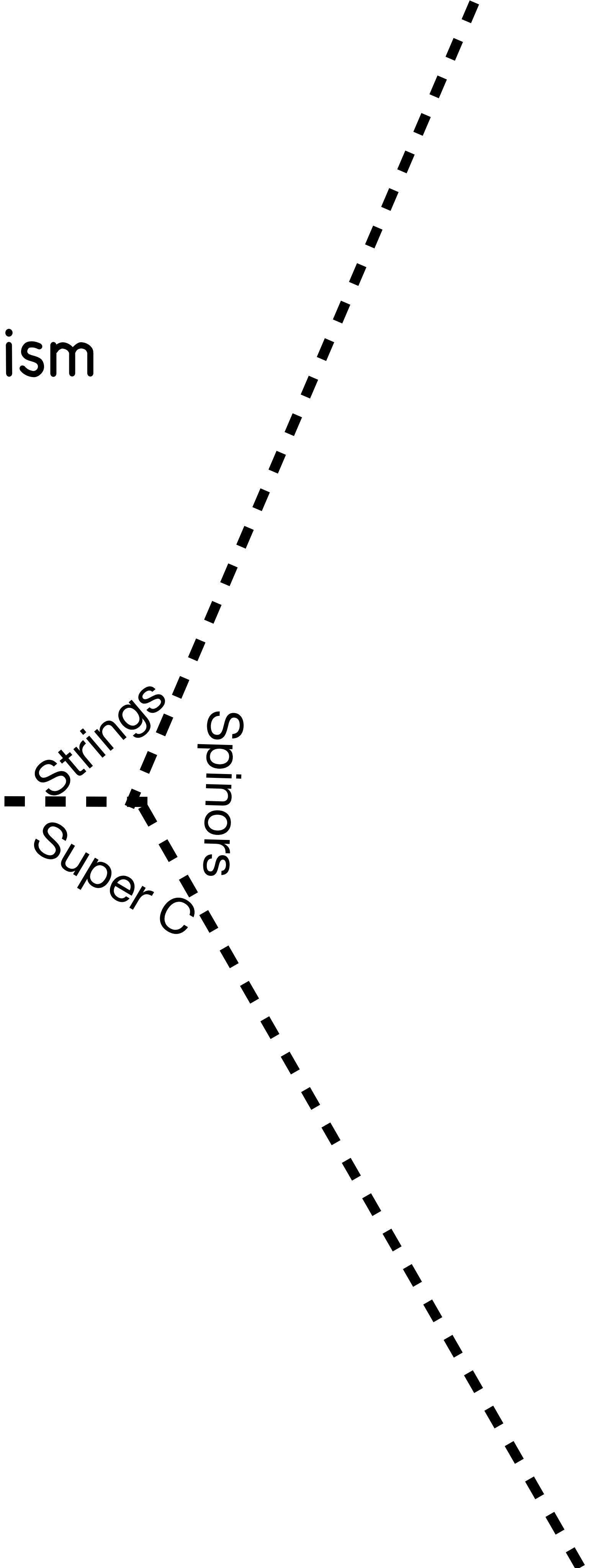
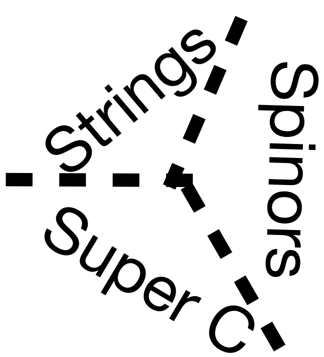


Part II

How a chance conversation with a particle physicist colleague led to a new idea about superconductivity.

Part I

A curious link between
String theory and Magnetism

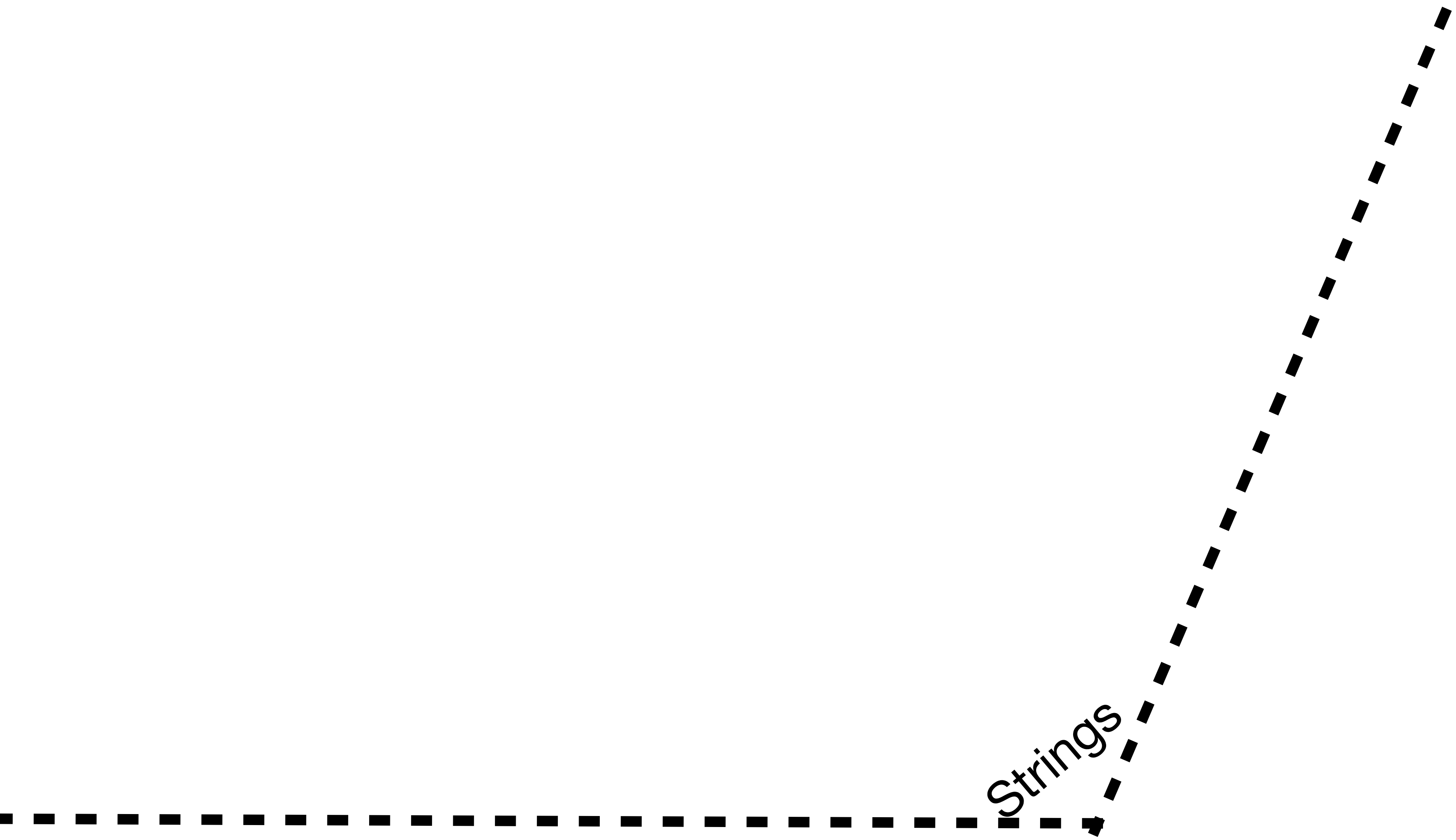


Part III

The discovery of Ising
electrons
suggests “spinor” order.

Part II

How a chance
conversation with a
particle physicist
colleague led to a
new idea about
superconductivity.



Bhilahari Jeevanesan (KIT)
Peter Orth (U. Minnesota)
Premi Chandra (Rutgers CMT)
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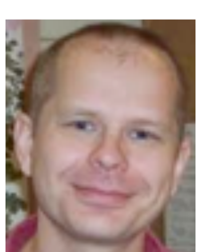
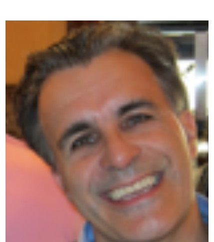

discussions +
Daniel Friedan

Part I
A curious link between String theory and Magnetism

Phys.Rev. Lett. 109, 237205 (2012),
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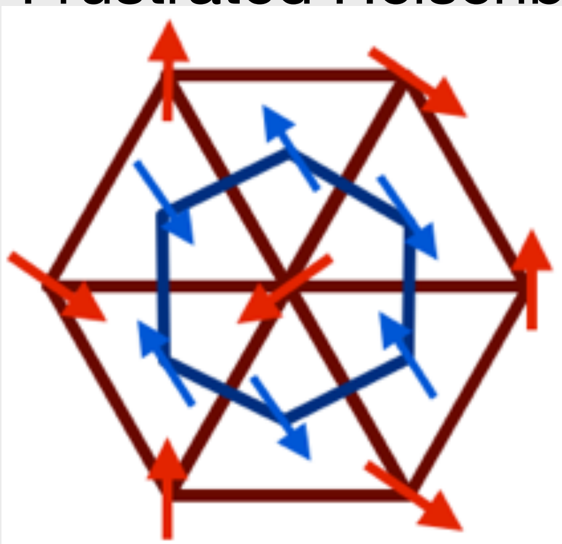
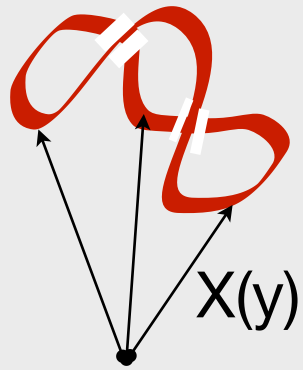
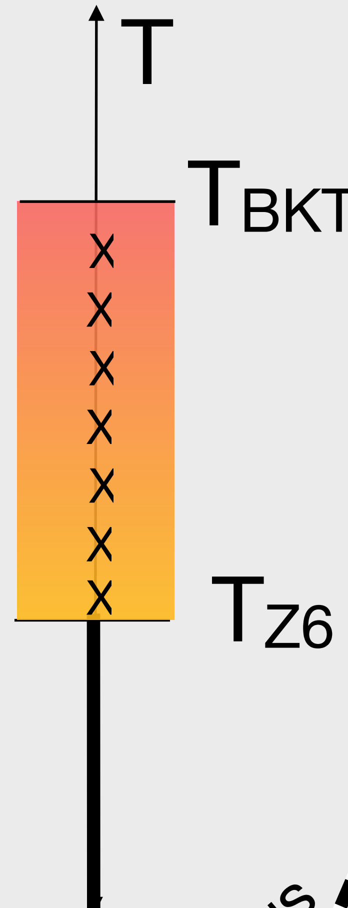
Frustrated Heisenberg AFM







$$\frac{dg^{ab}}{dl} = -\frac{1}{2\pi} R^{ab}$$

Friedan '80, Hamilton '81, Perelmann '06

Strings

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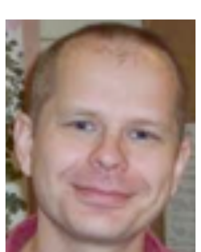


discussions + Daniel Friedan

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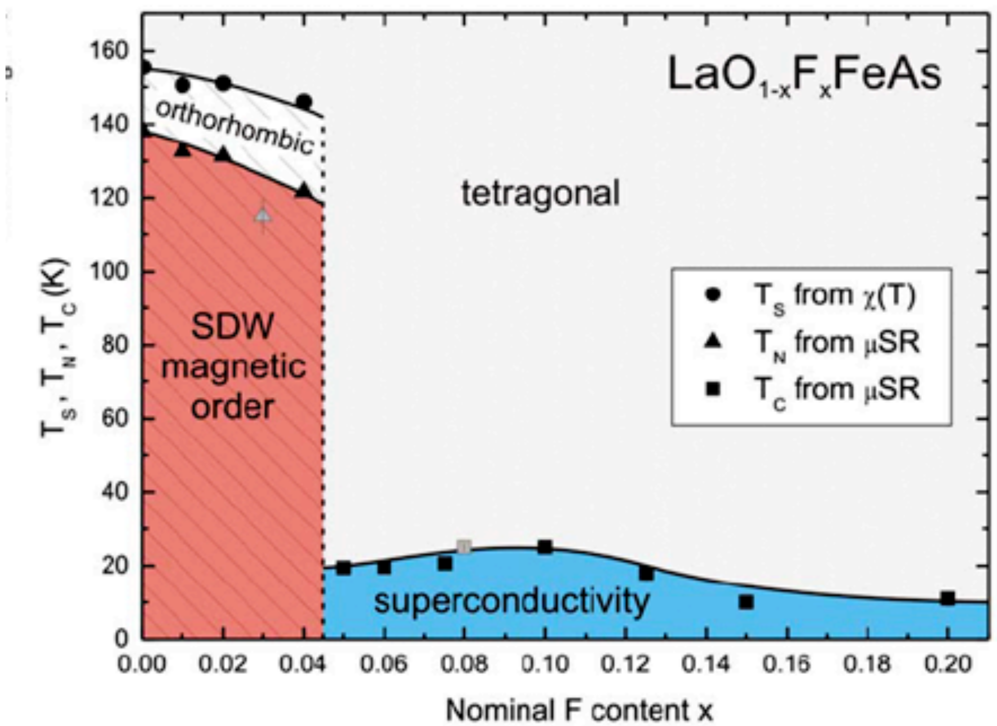
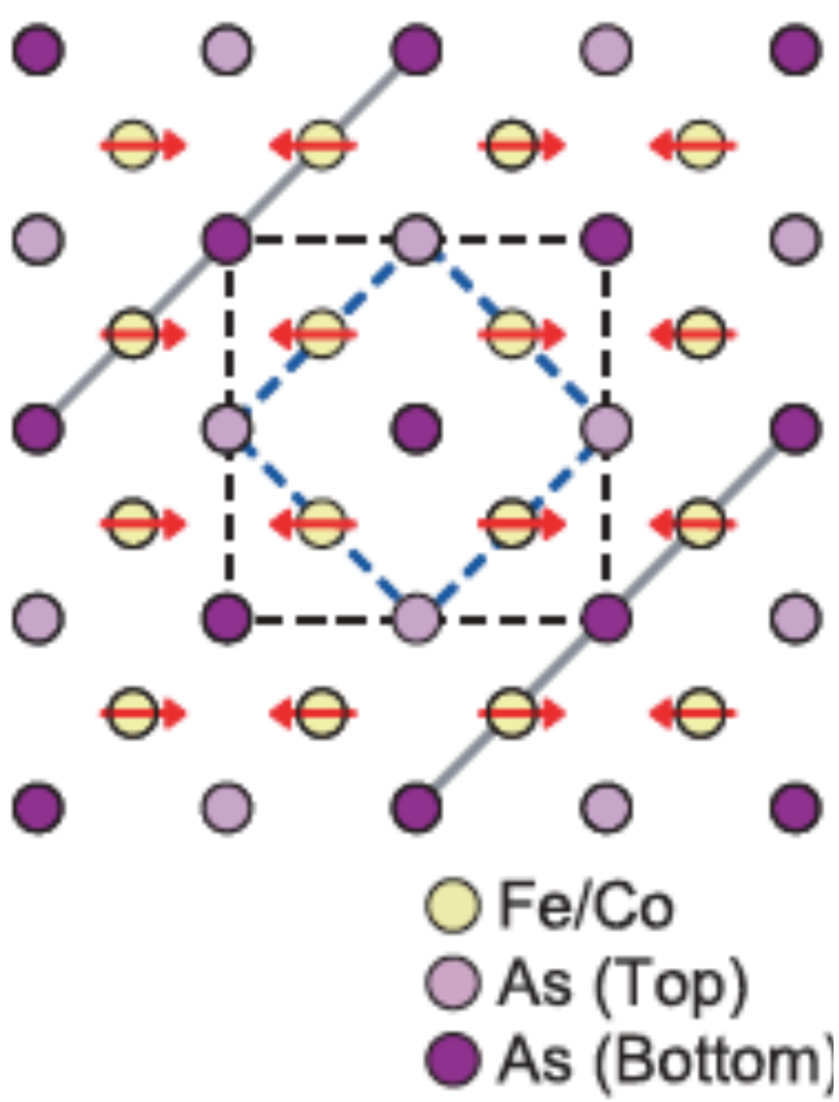
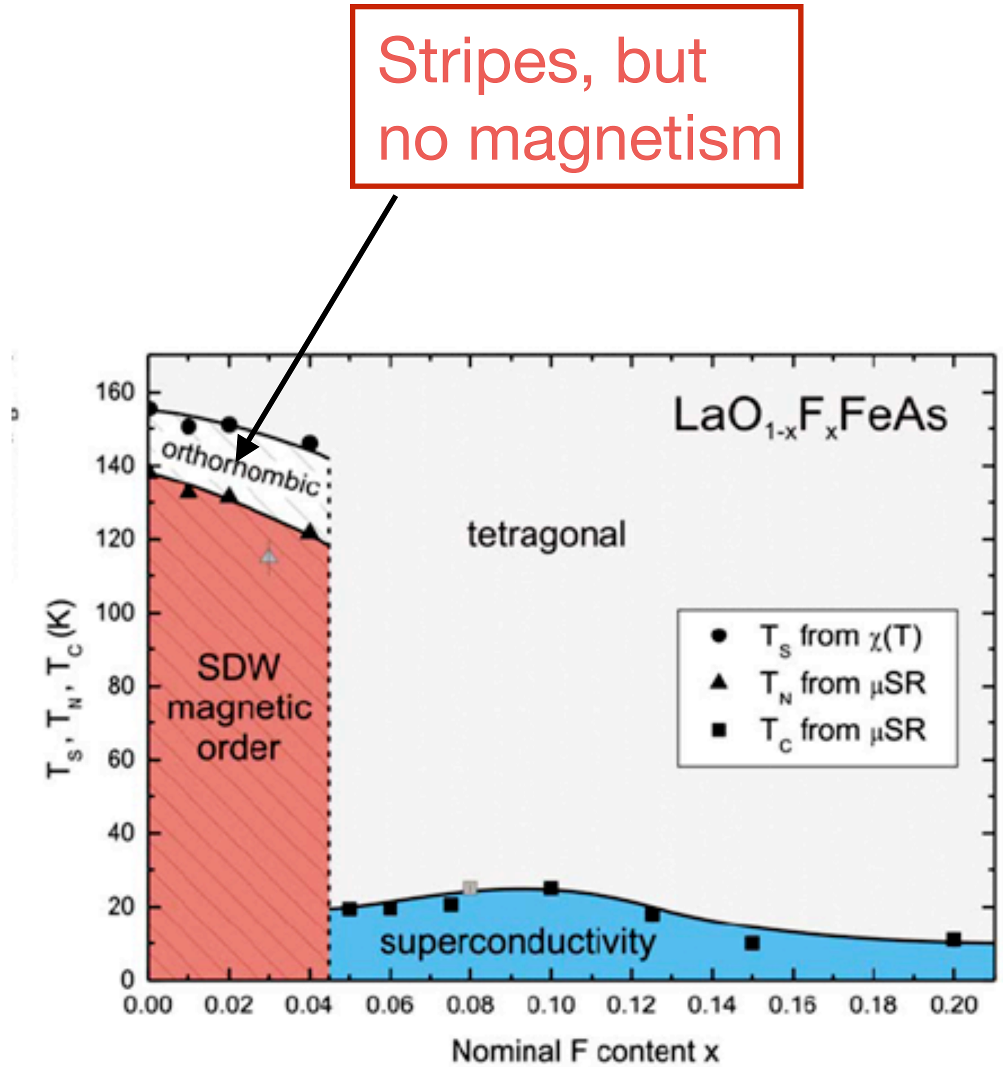


Iron based superconductors (Hosono 2008).





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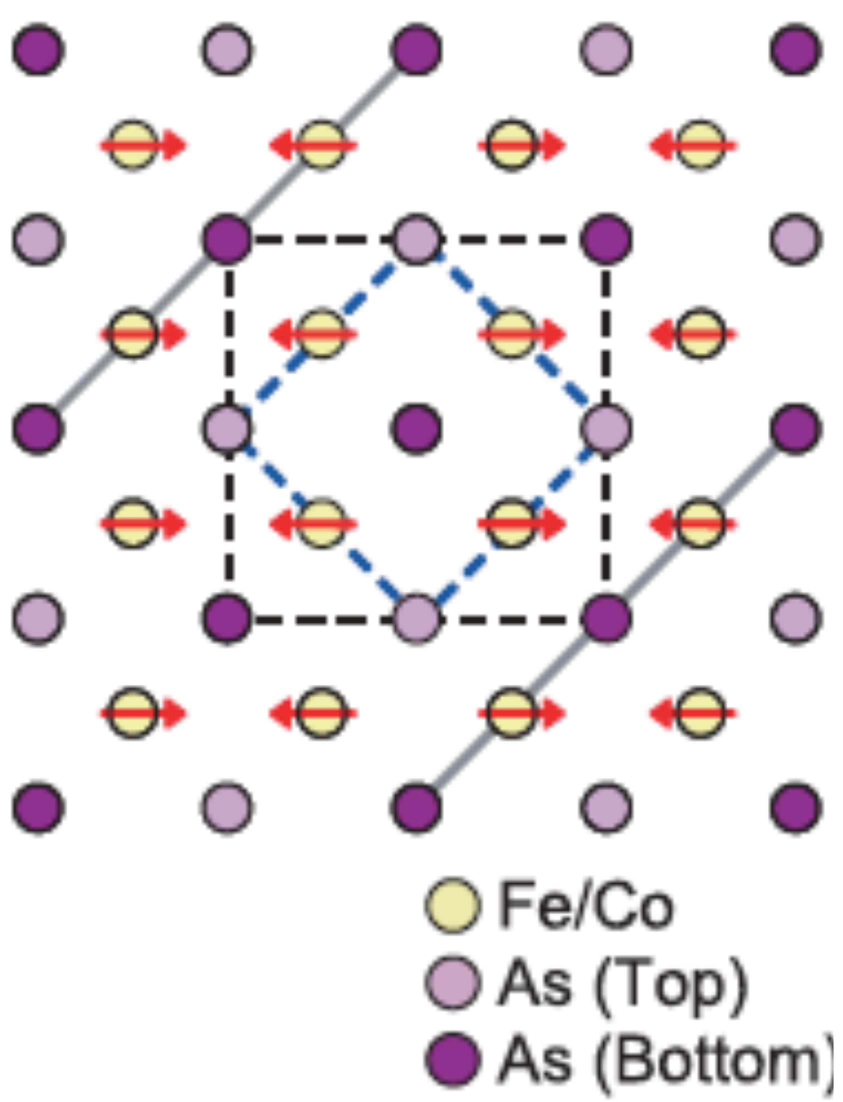
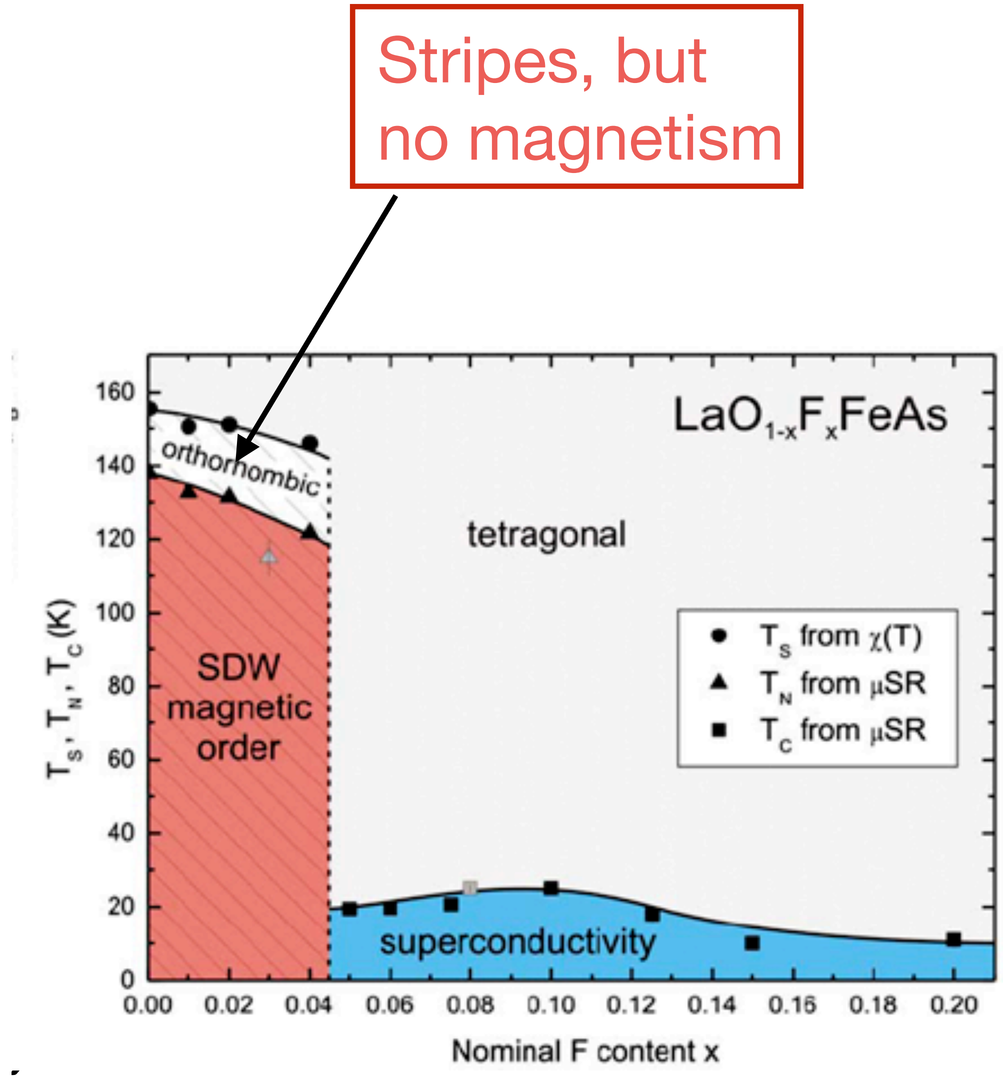
2D Heisenberg Antiferromagnets at Finite Temperature





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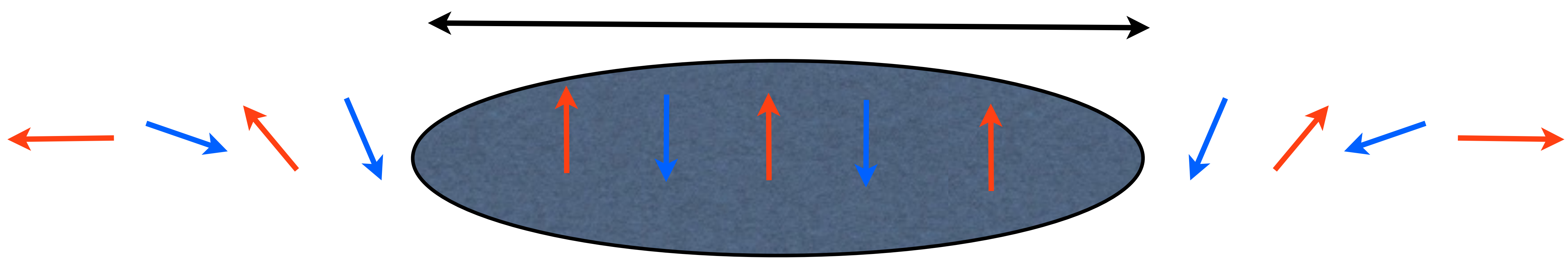

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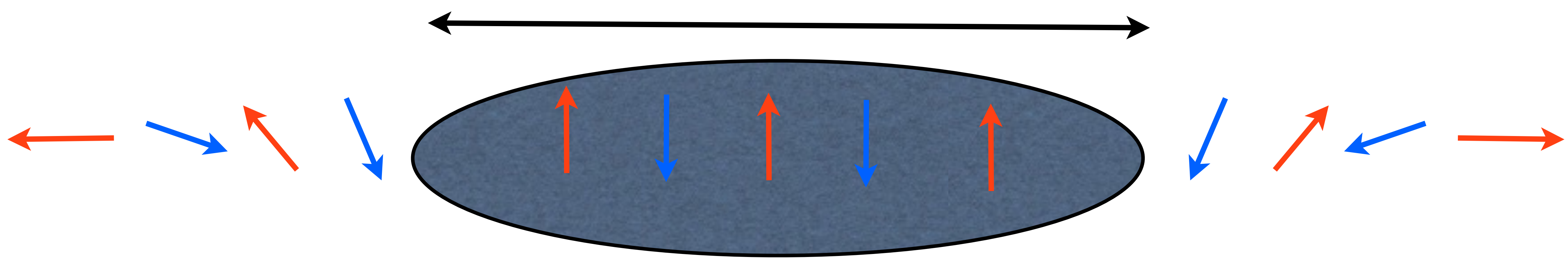

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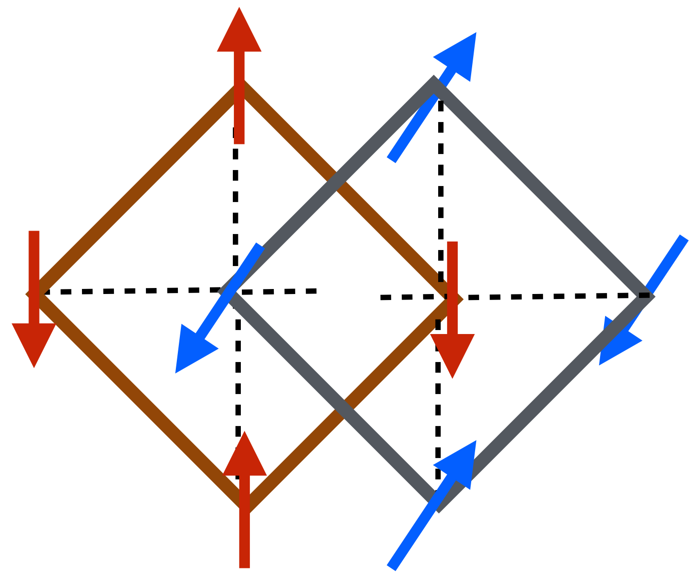

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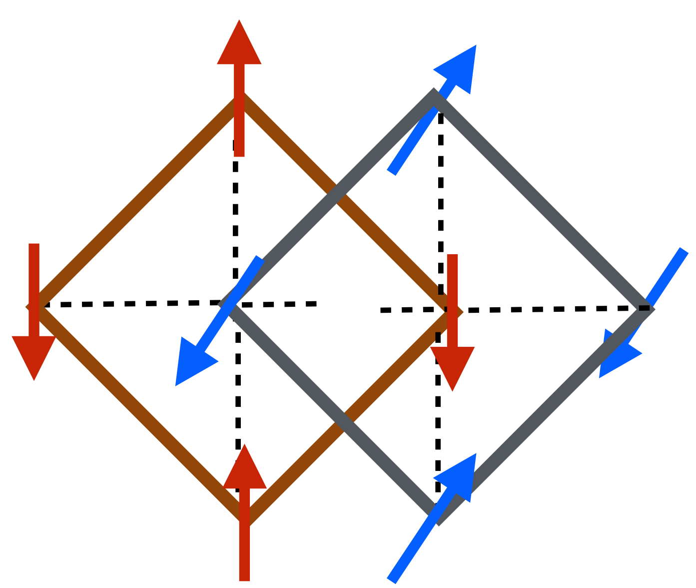
Sublattices classically decoupled



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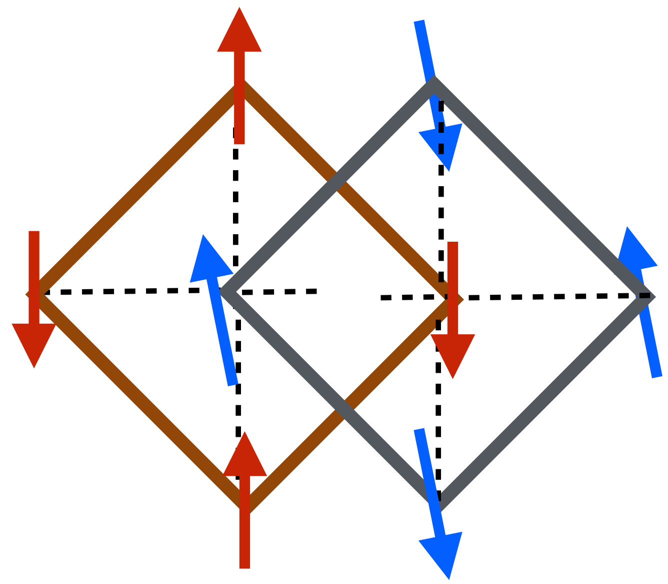

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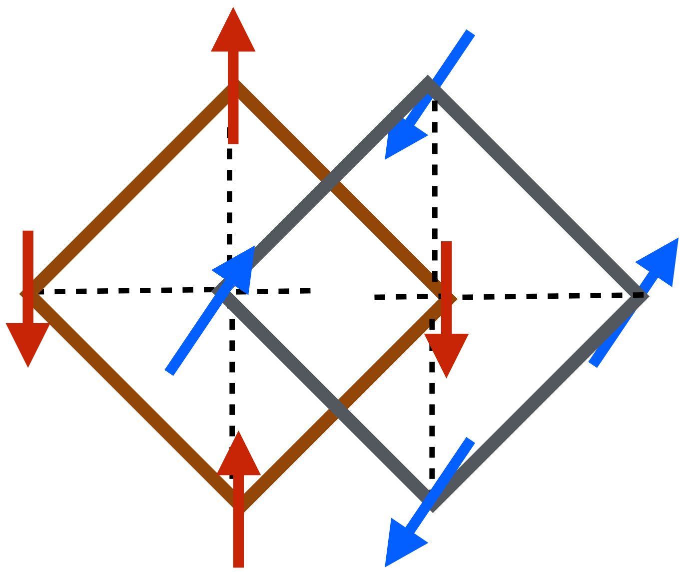

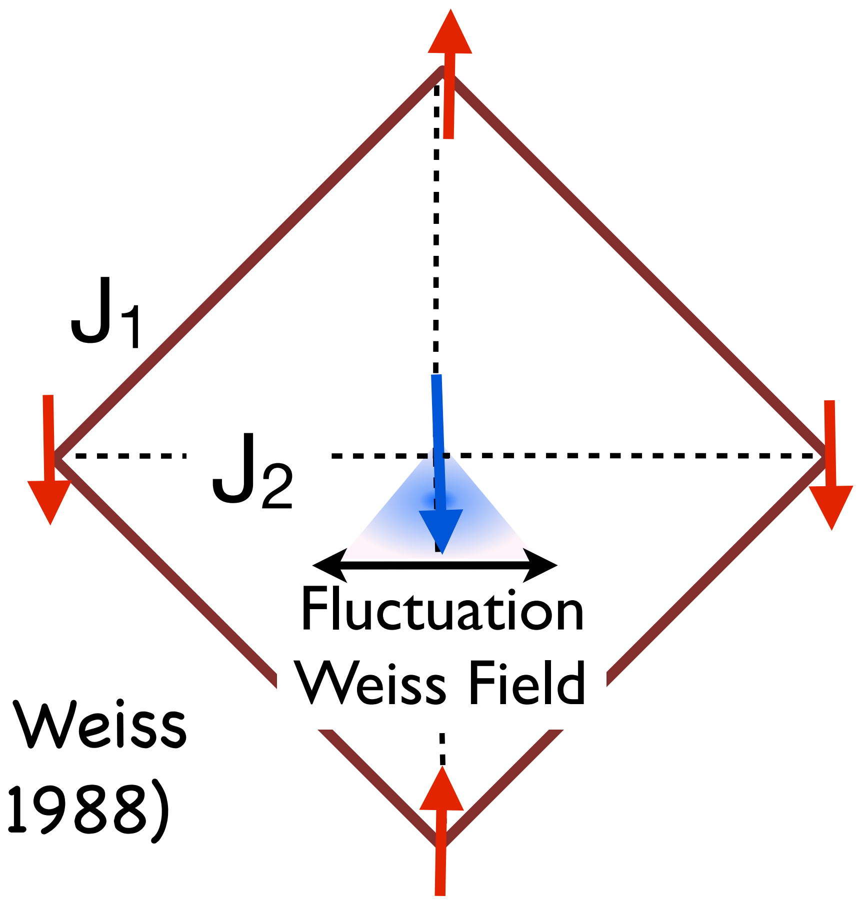

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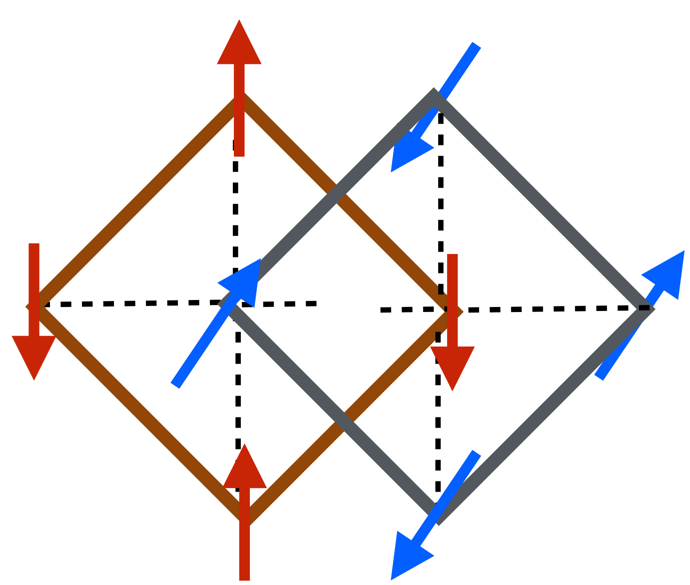
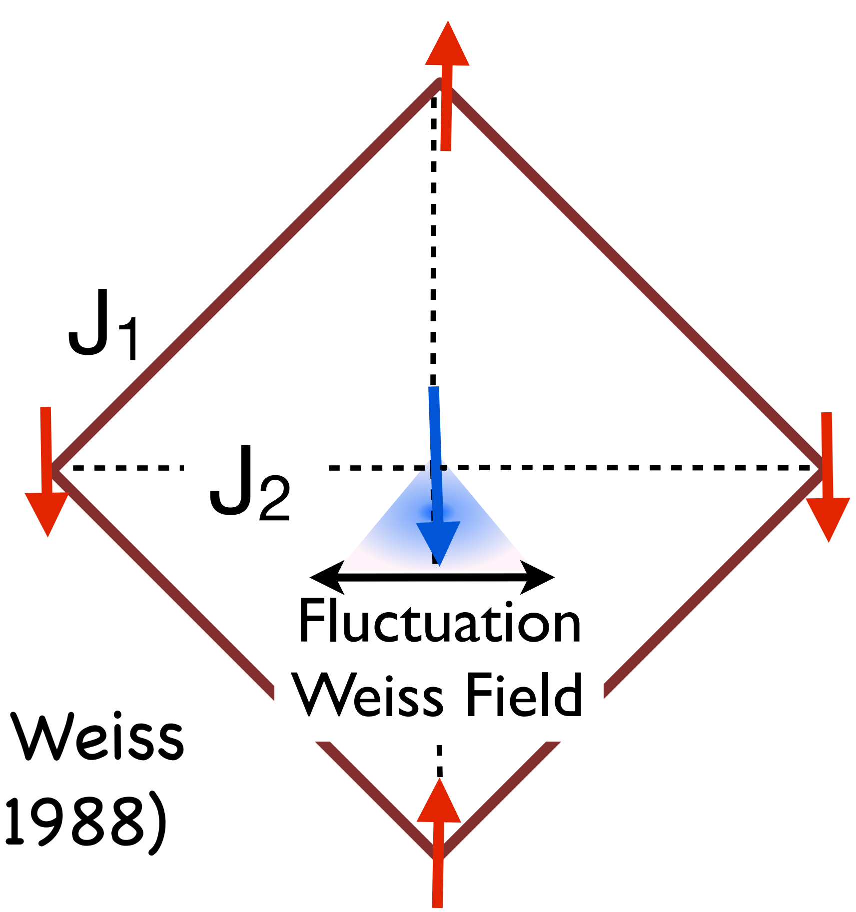


"Order from Disorder" (Villain 1985)



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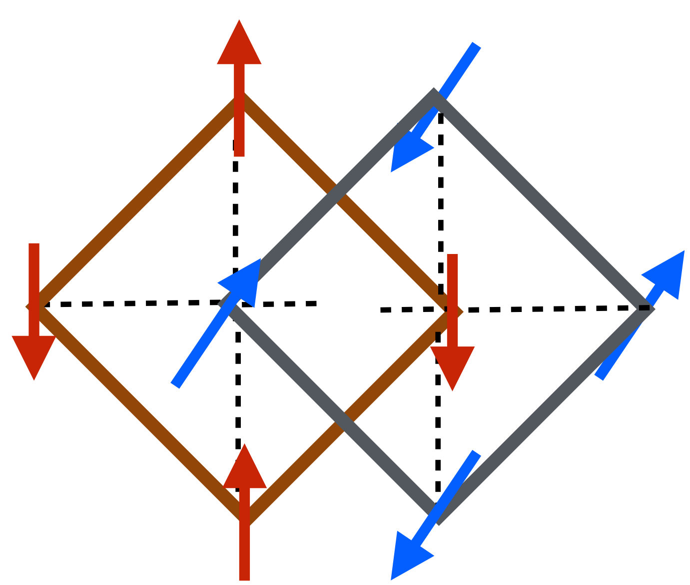

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Discrete Z_2 Relative Degree of Freedom

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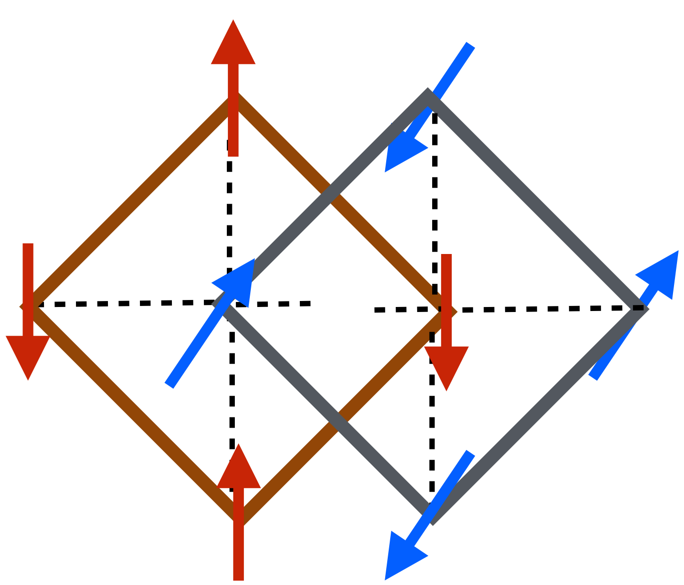

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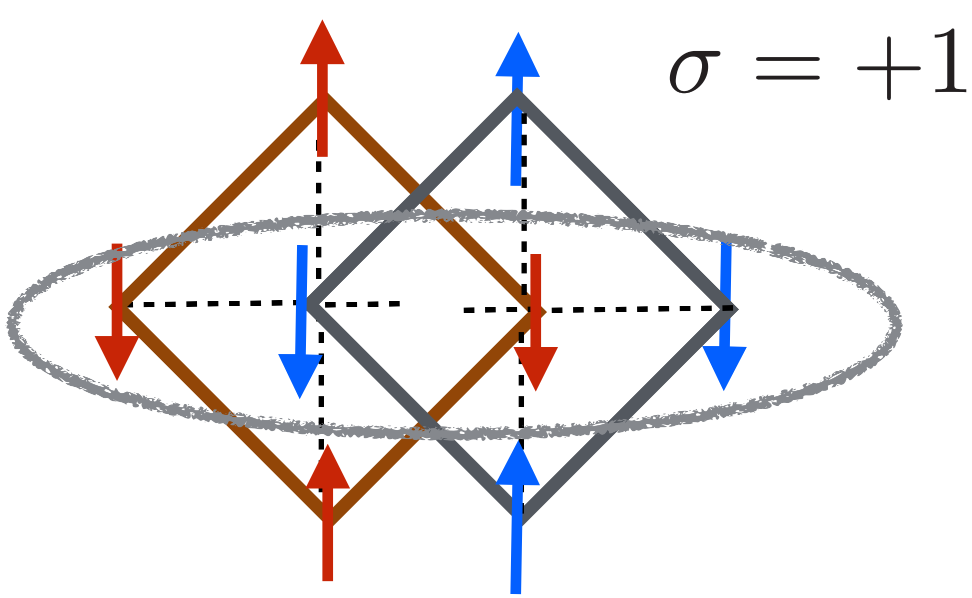

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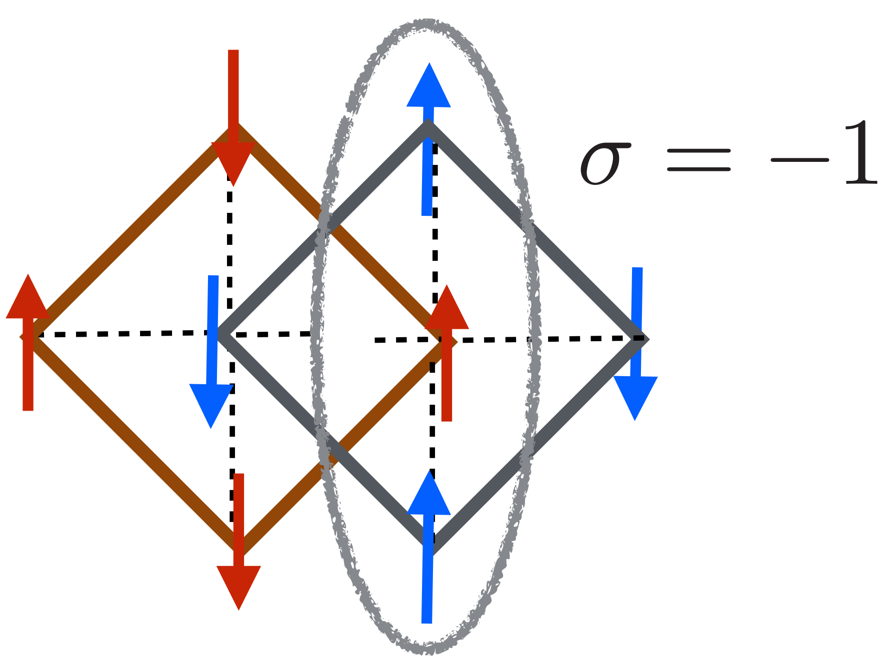

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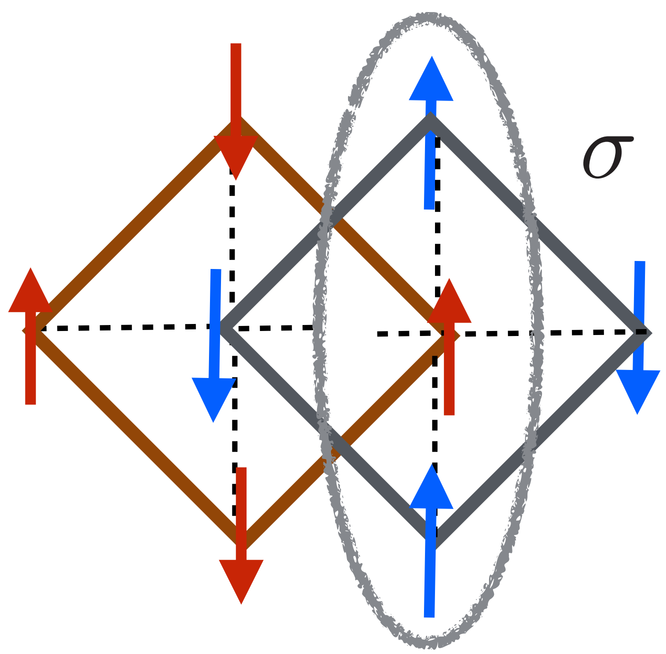

$\sigma = -1$

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$\xi_{Z_2} \to \infty$ $\quad T_{Z_2}$ Chandra, Coleman and Larkin (90)

Despite the absence of magnetization

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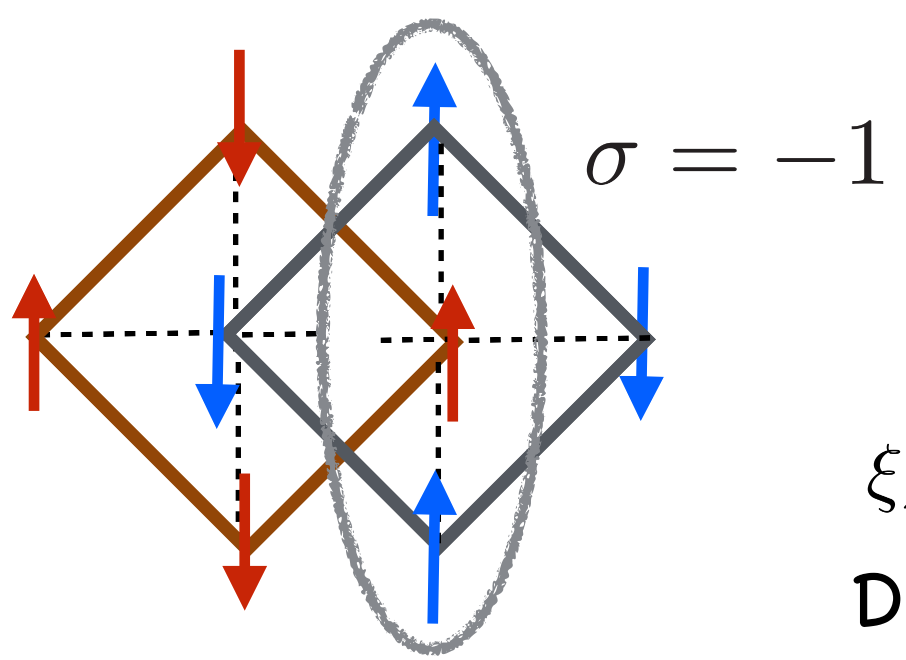

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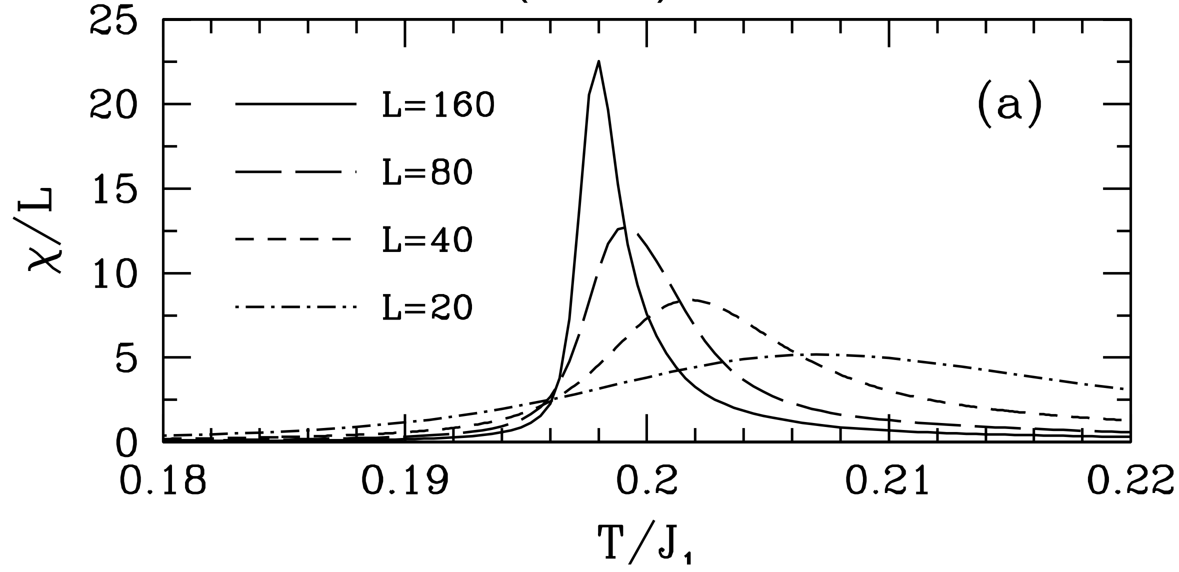
Emergent Z_2 Phase Transition in a disordered Heisenberg System.

Weber et al (2003)



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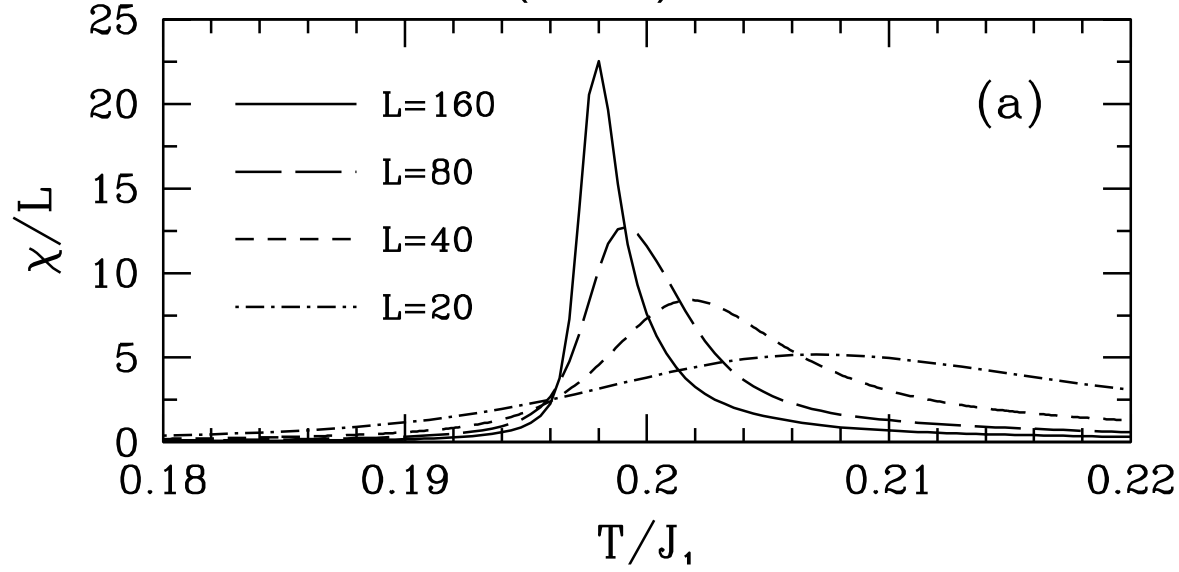

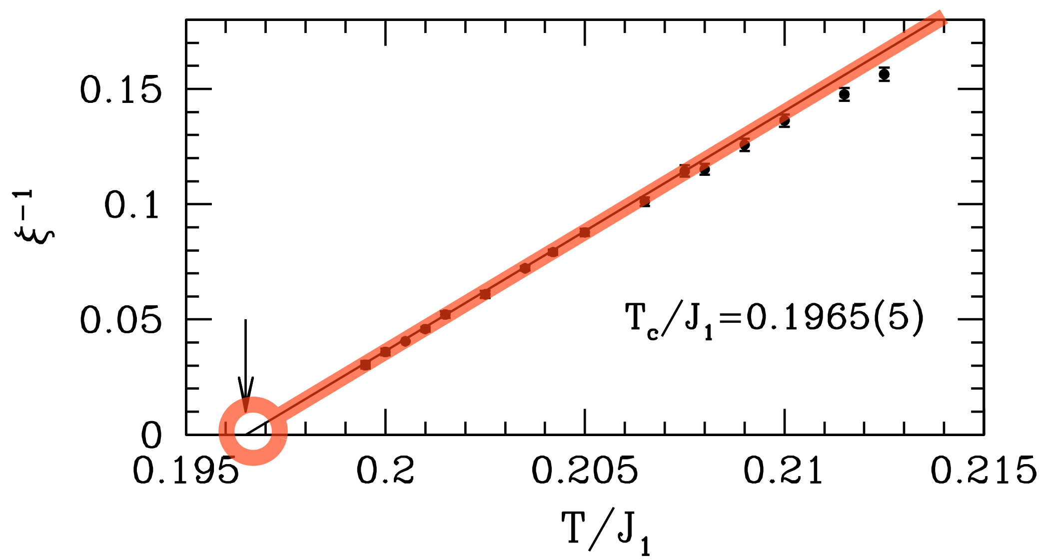

$$\color{red}{\vec{M}_1} \cdot \color{blue}{\vec{M}_2} = \sigma = \pm 1$$

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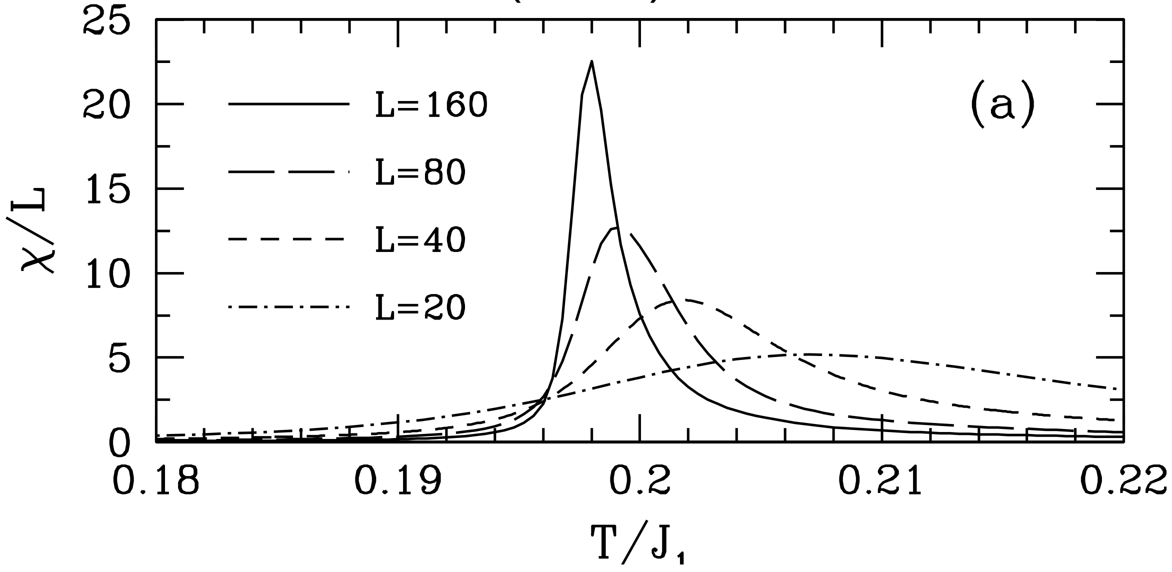

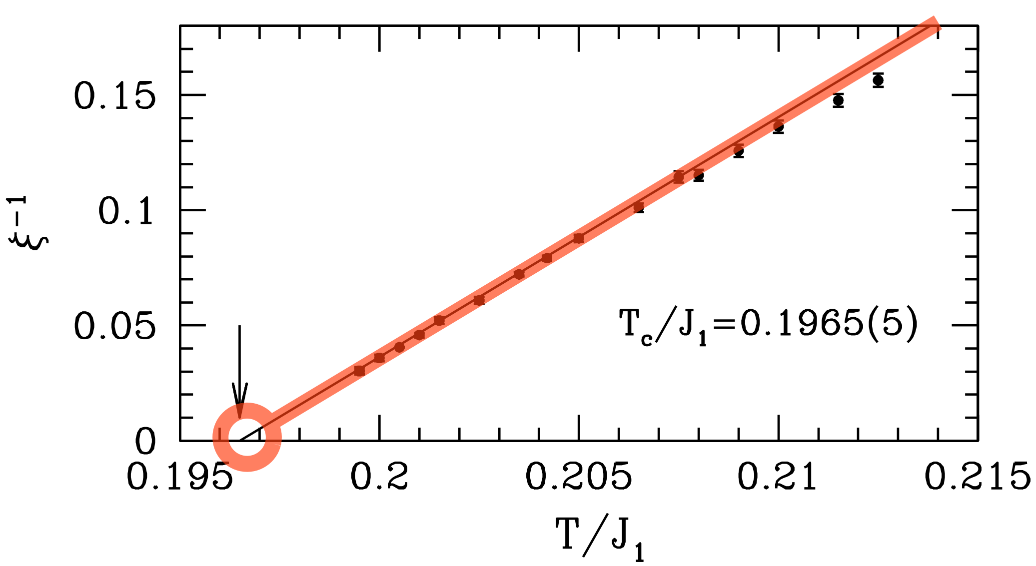

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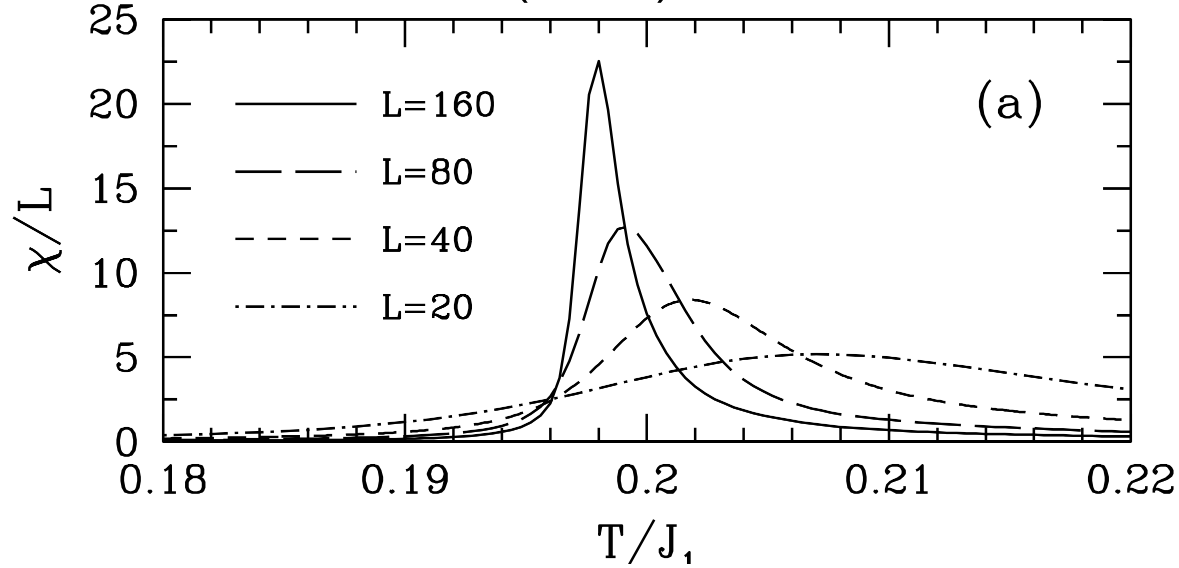

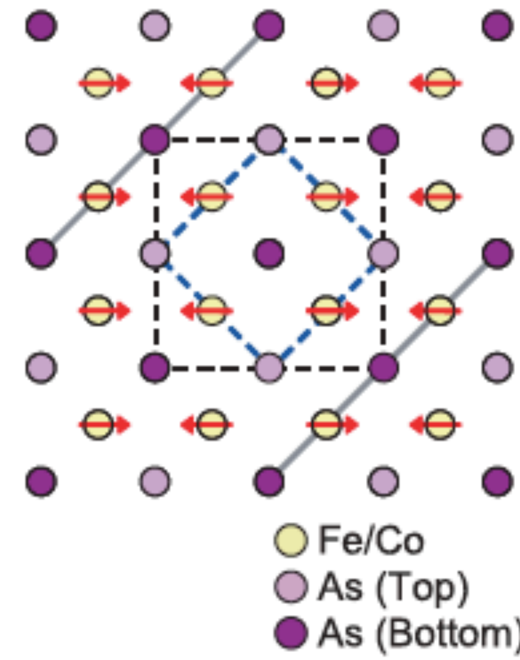

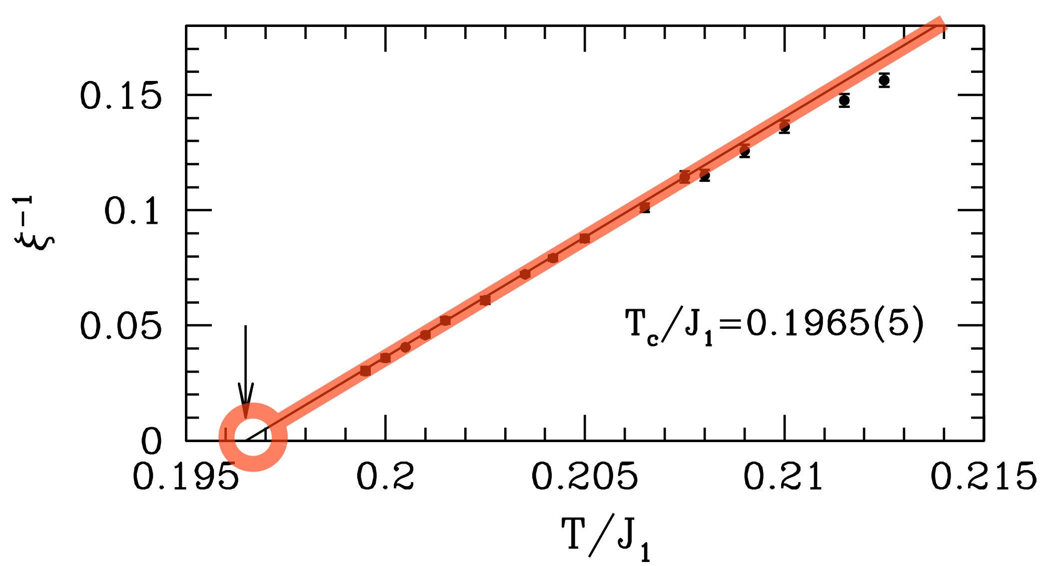

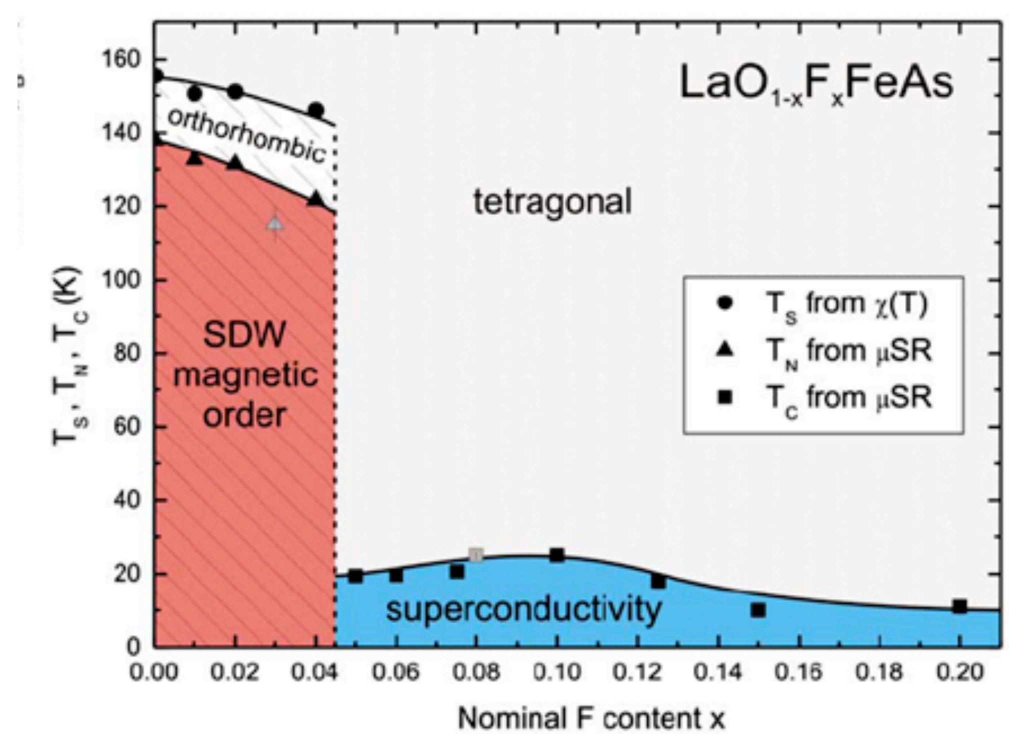

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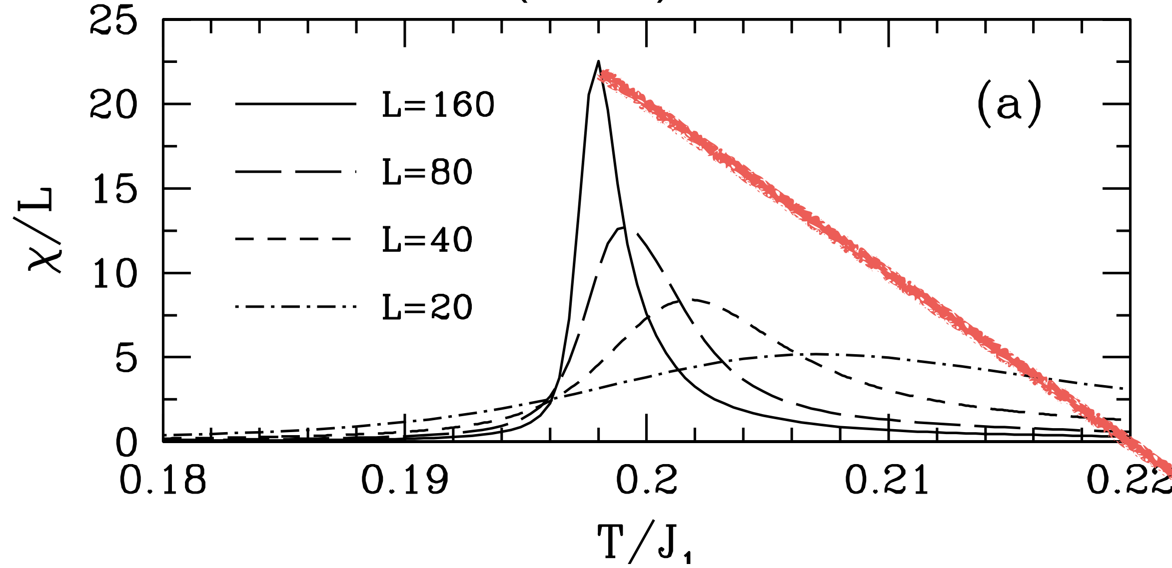

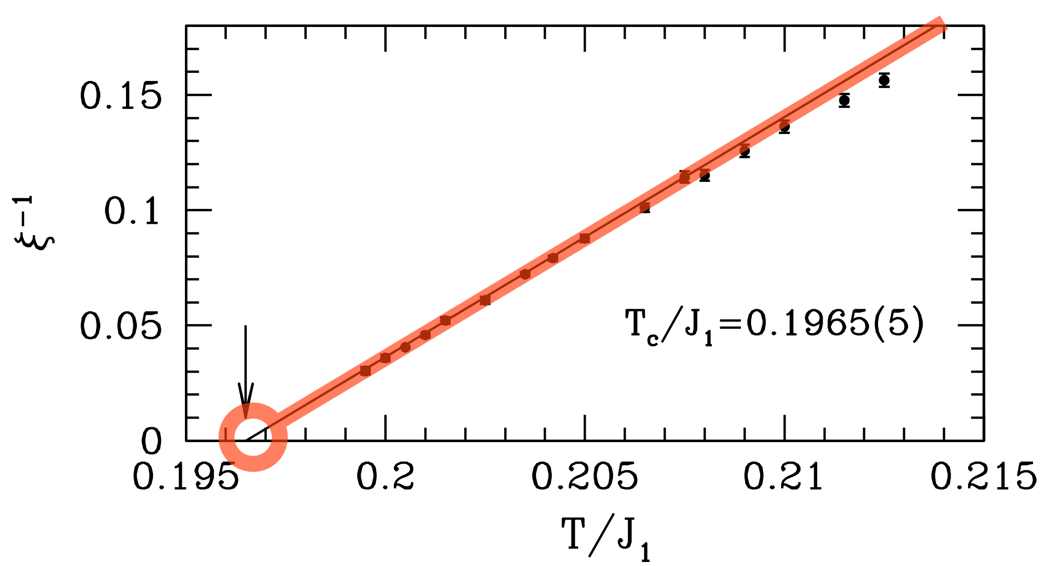

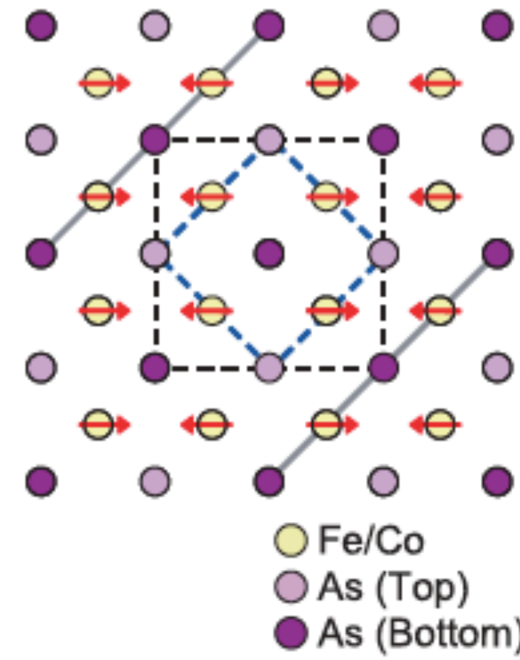

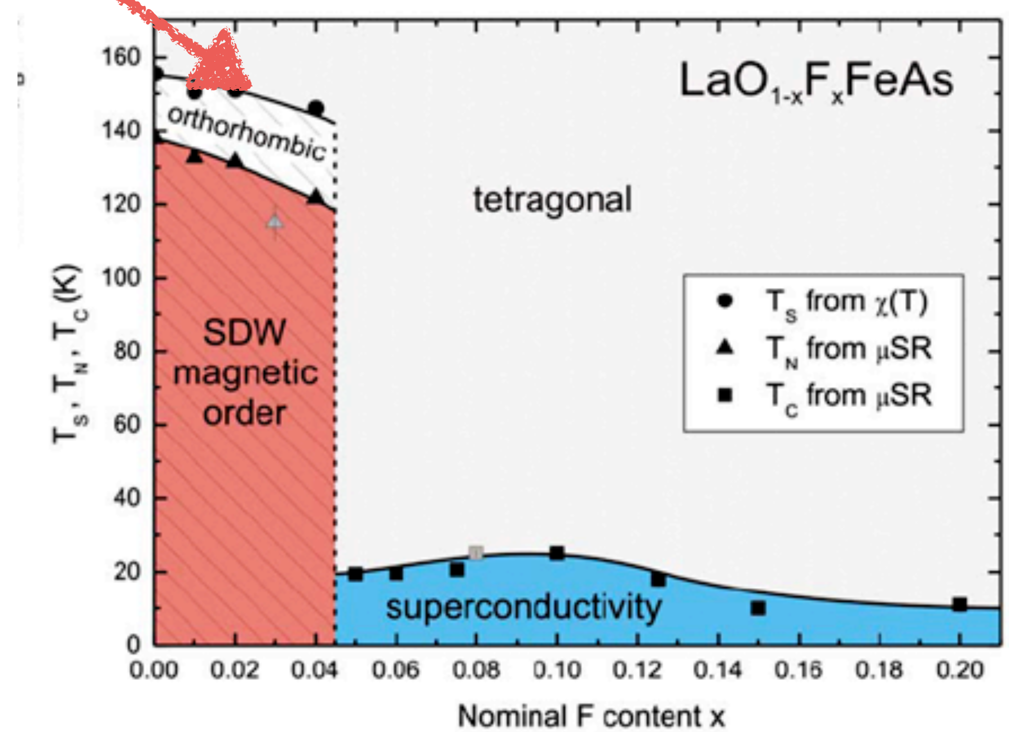

Z_2 generalized to Z_p ??

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$p \geq 5$ → **p-fold anisotropy becomes irrelevant**

Jose et al (77) Kosterlitz-Thouless Transition

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Can we find a 2D Frustrated Heisenberg model that has an emergent critical phase? (even though its underlying spin degrees of freedom have a finite correlation length?)

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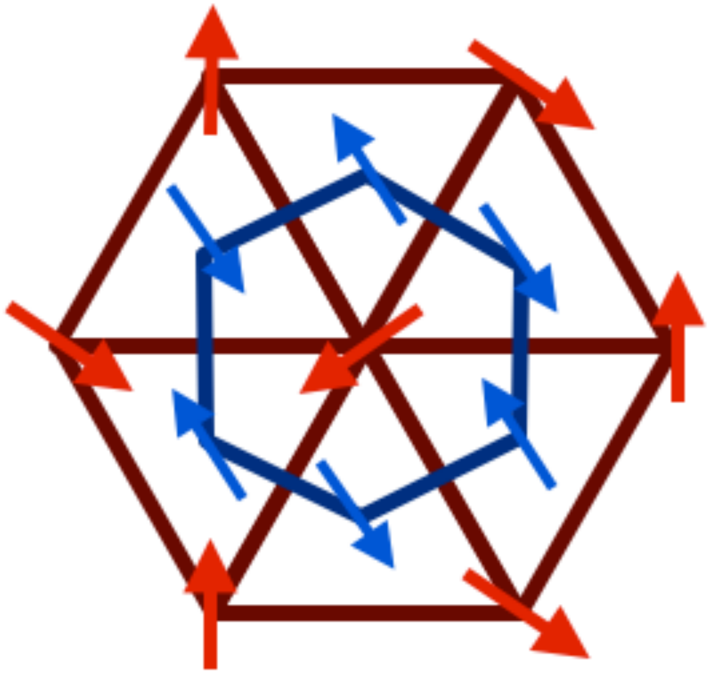
(Polyakov Conjecture: A. M. Polyakov, Phys. Lett. 59B, 79 (1975)).

2D Heisenberg Windmill Model



Windmill in Strangnaes (Sweden)

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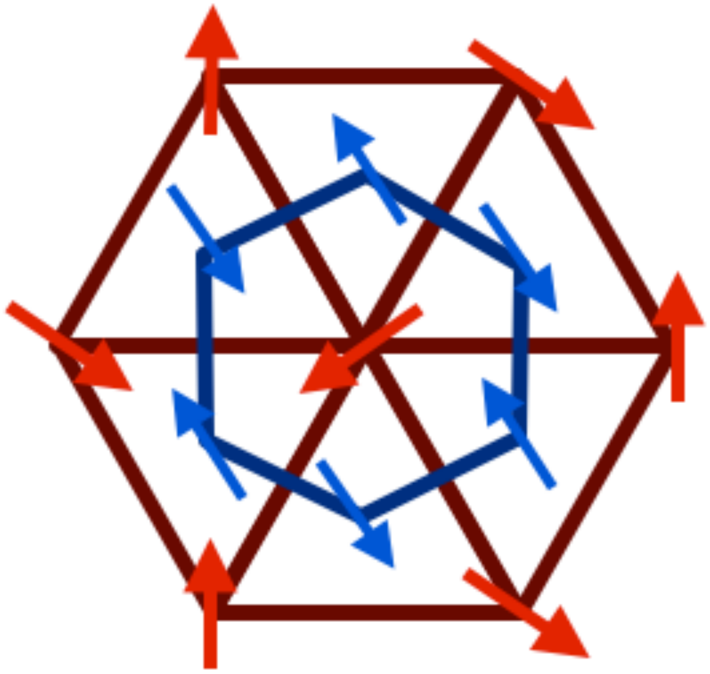

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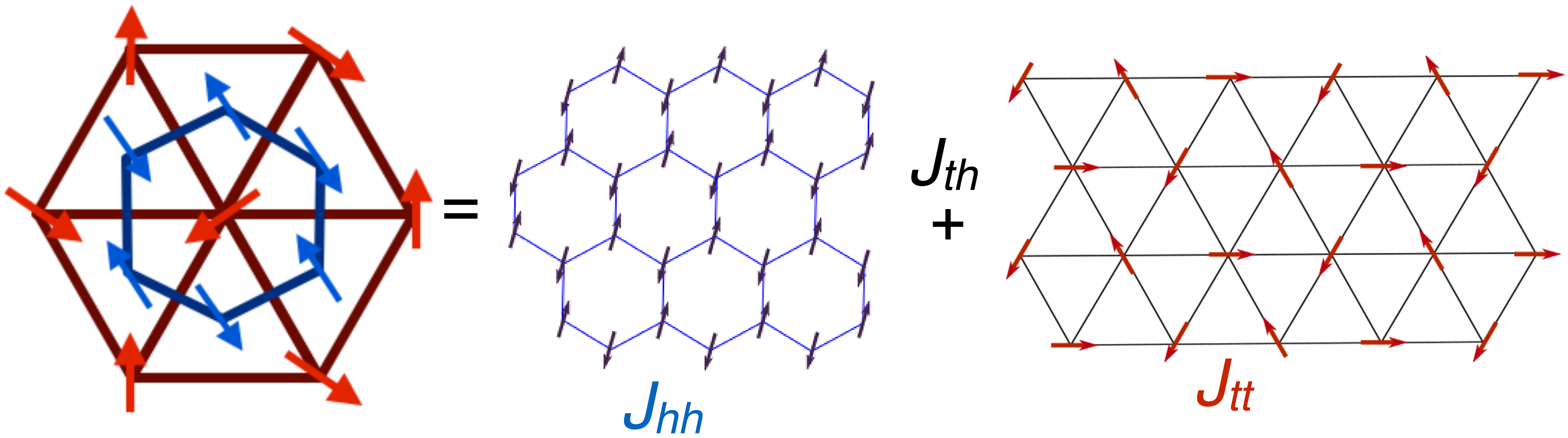

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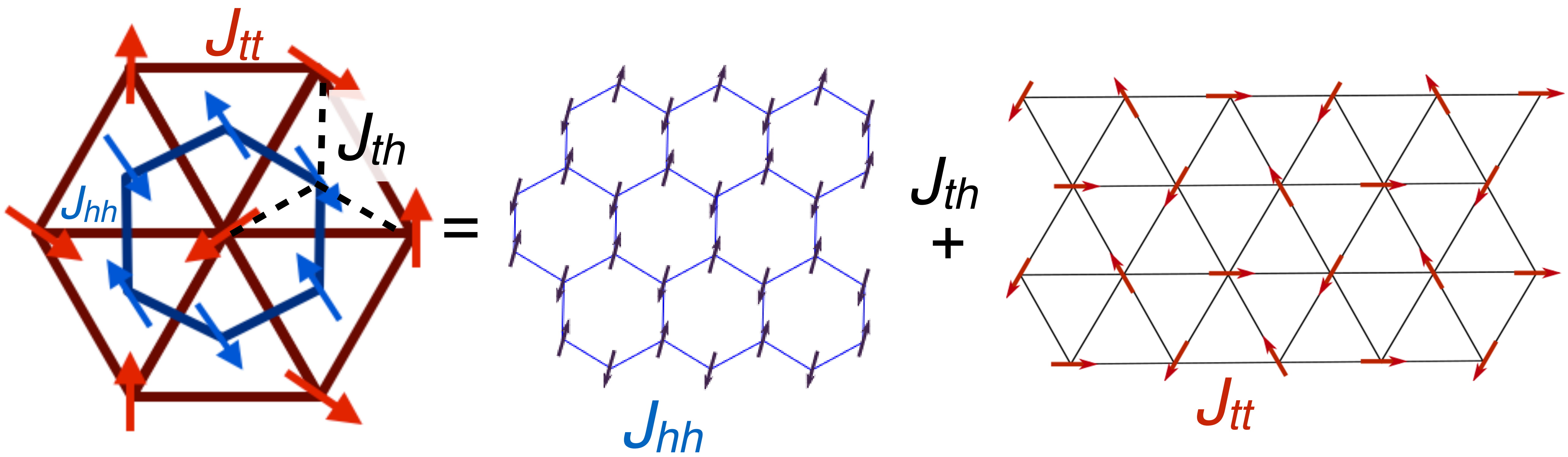

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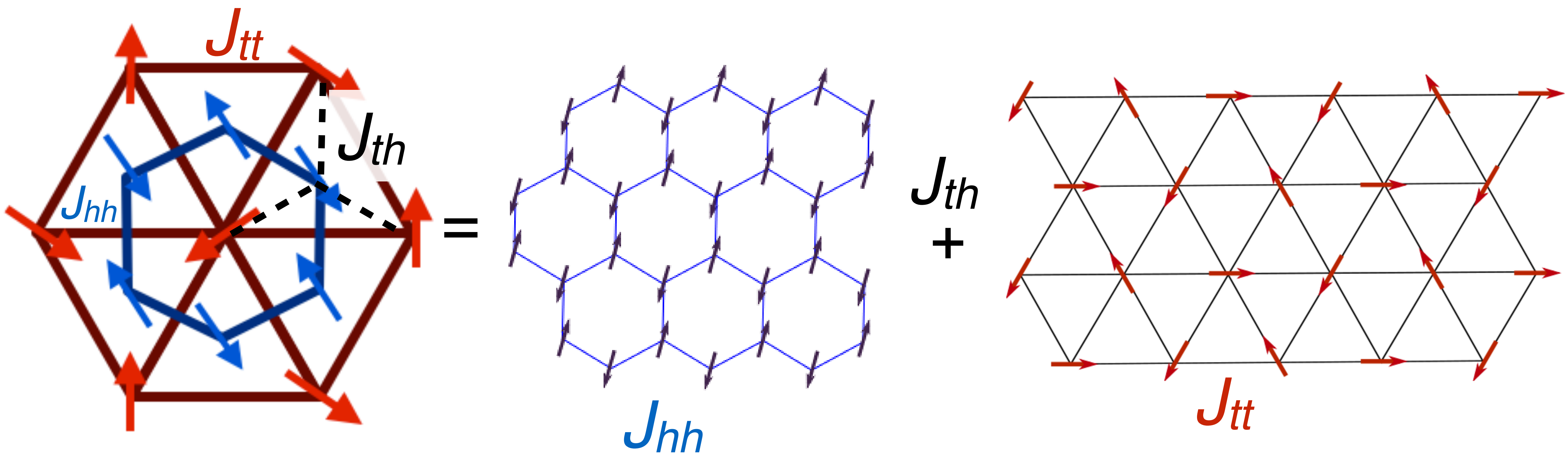

$$H = H_{hh} + H_{tt} + H_{th}$$

$$H_{\alpha\beta} = J_{\alpha\beta} \sum_{j=1}^{N_L} \sum_{\delta_{\alpha\beta}} S_\alpha(j) S_\beta(j + \delta_{\alpha\beta})$$

$\alpha, \beta \in \{t, A, B\}$

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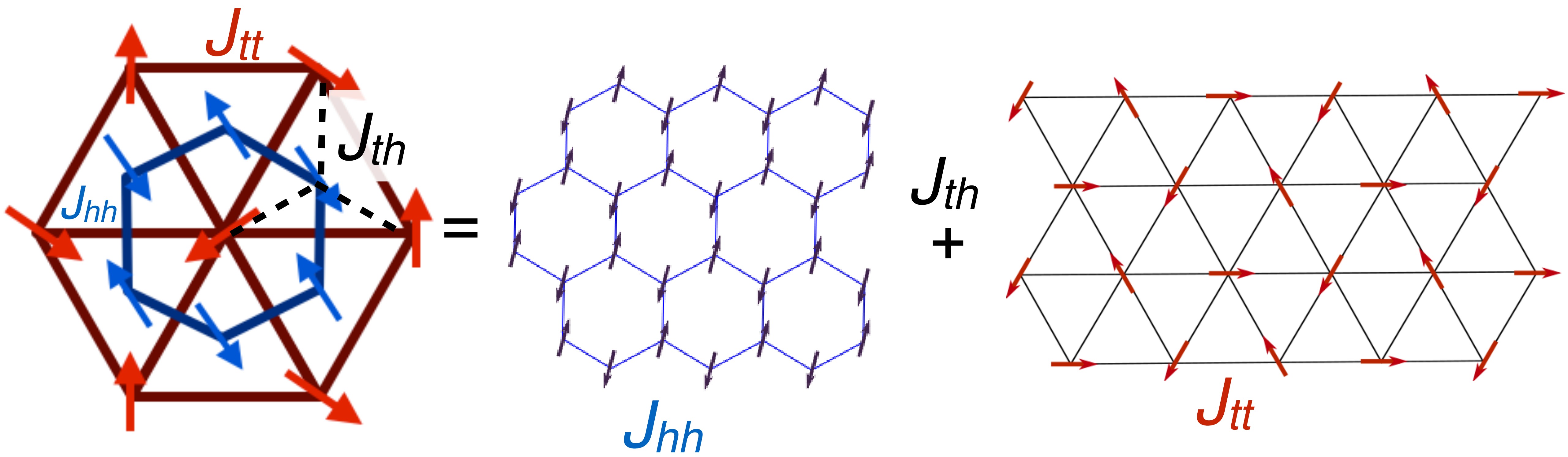
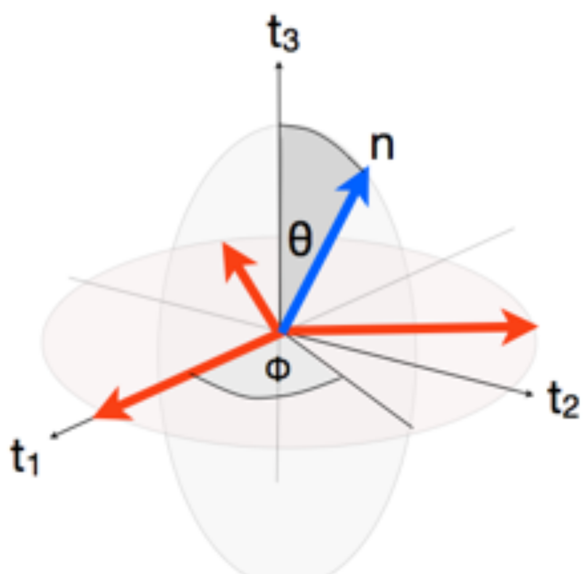


Classically: two decoupled sublattices.



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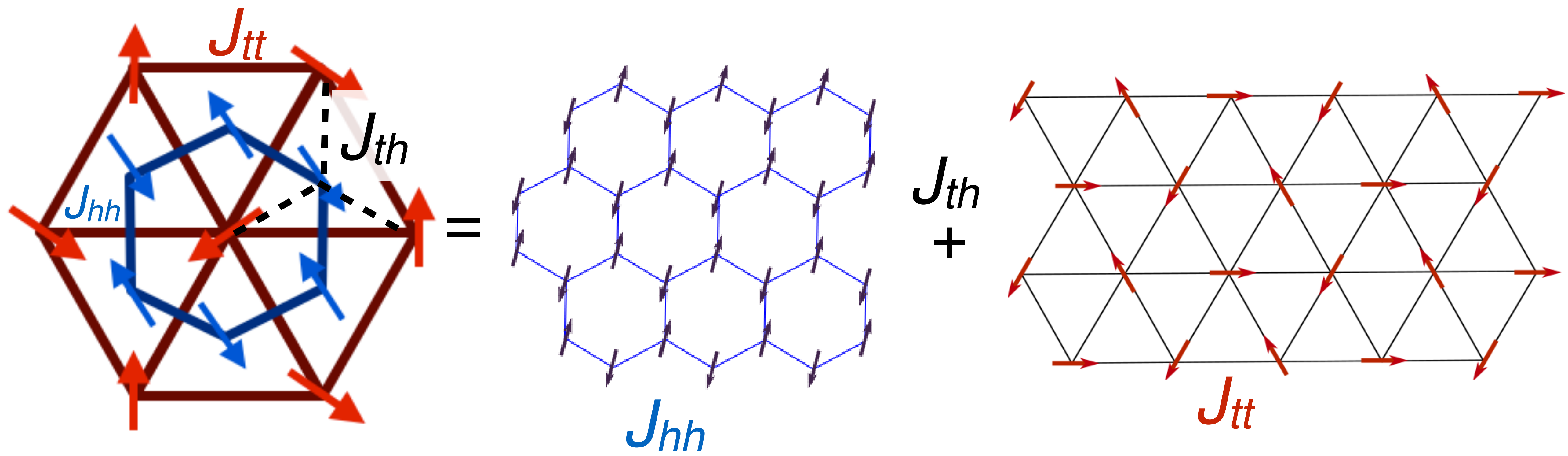

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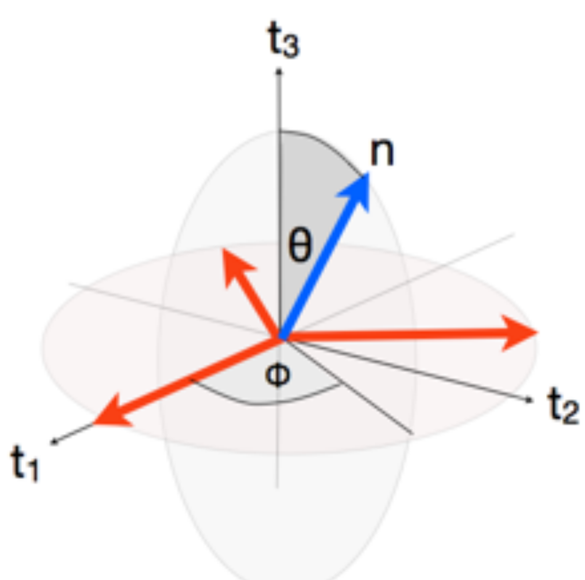
Order from disorder drives coplanarity introducing a Z_6 anisotropy



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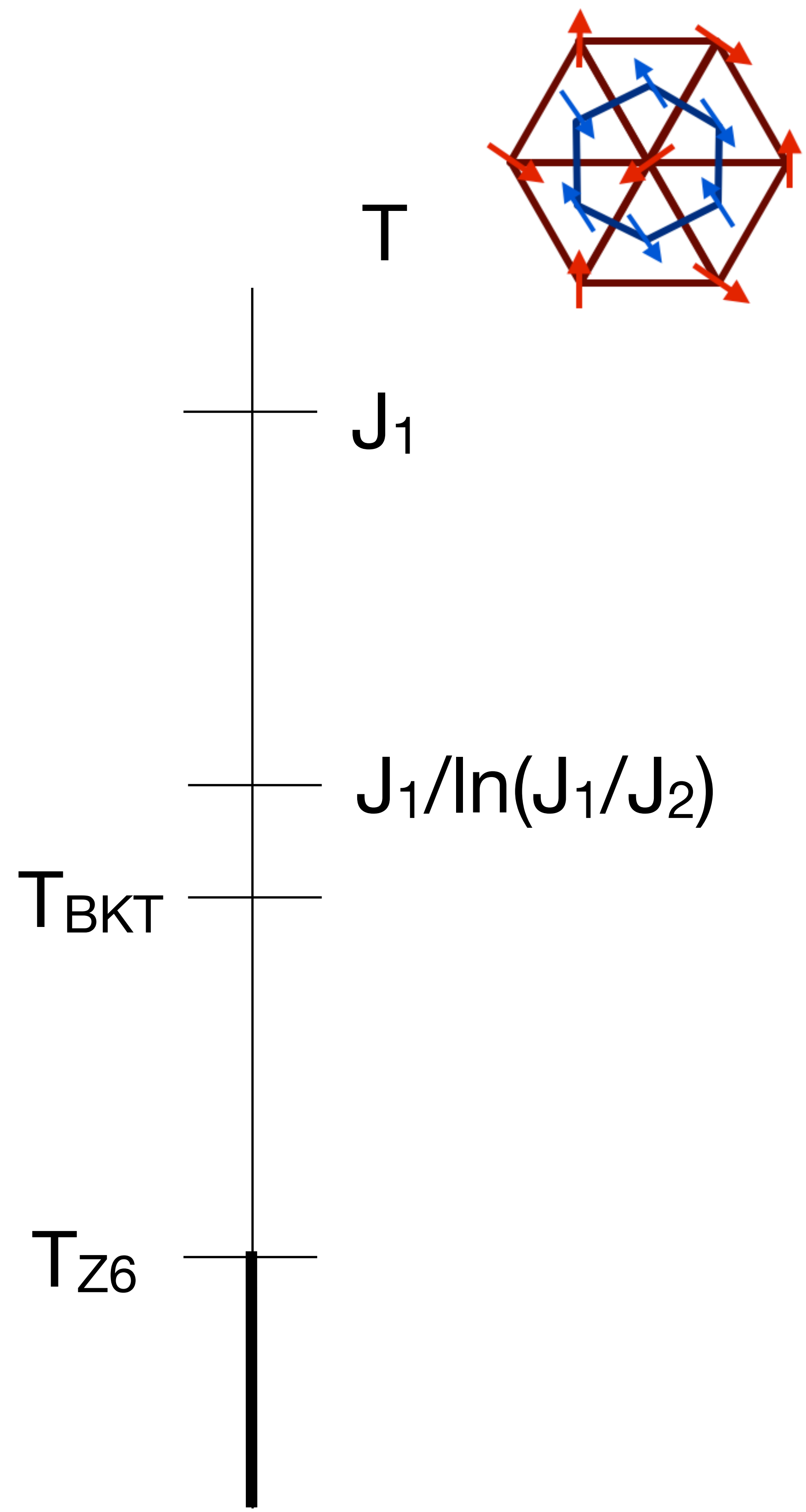
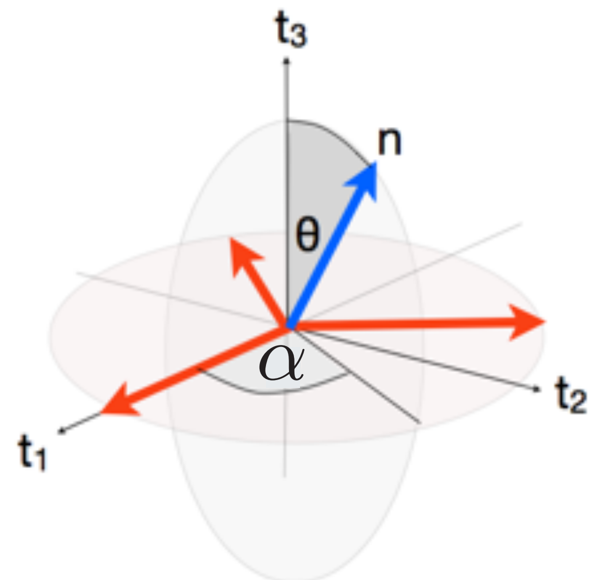
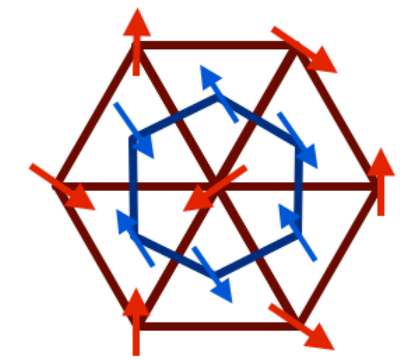

T
J1
J1/ln(J1/J2)
TBKT
TZ6

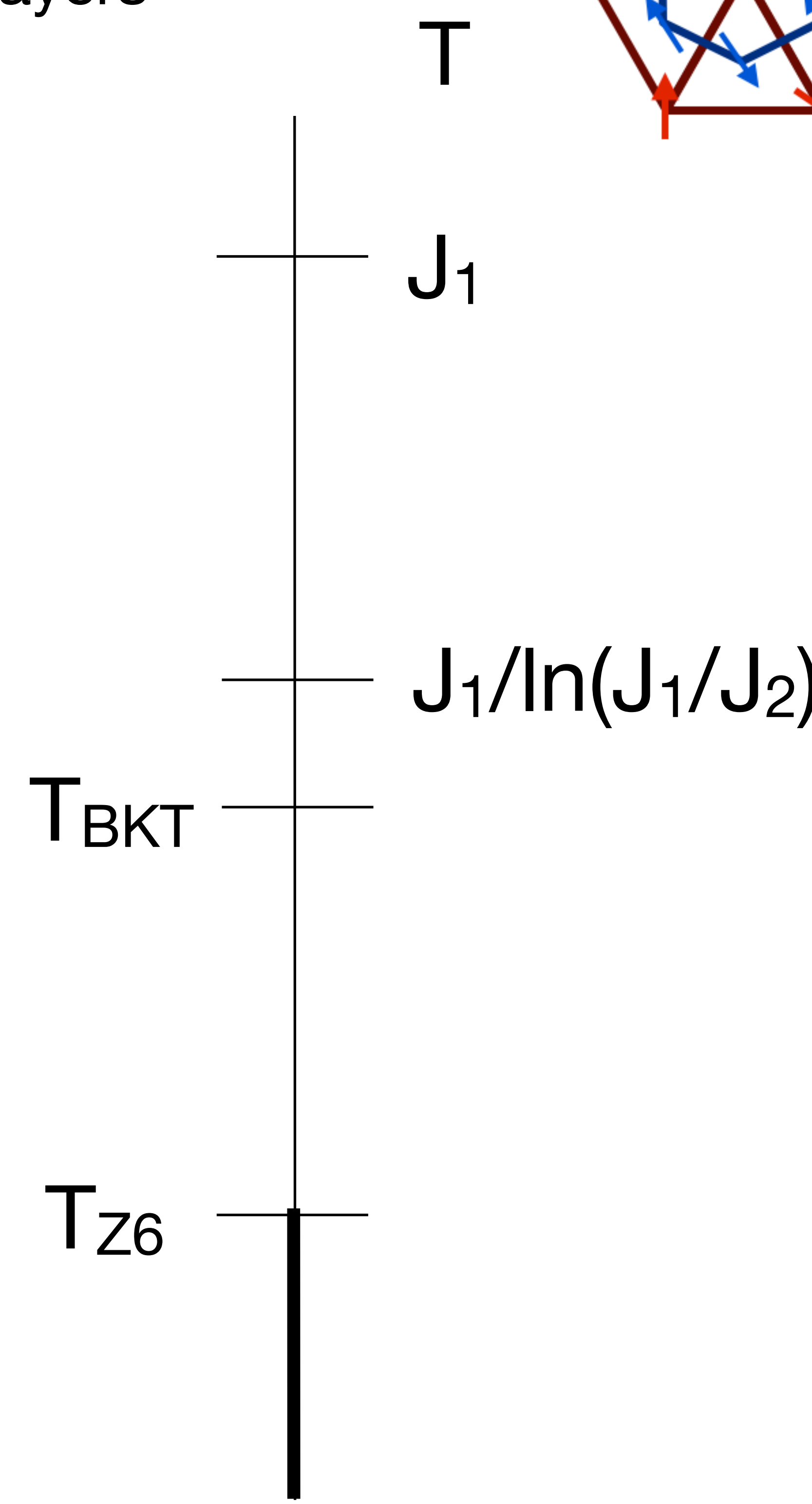
α =relative in-plane angle of magnetization on top and bottom layers

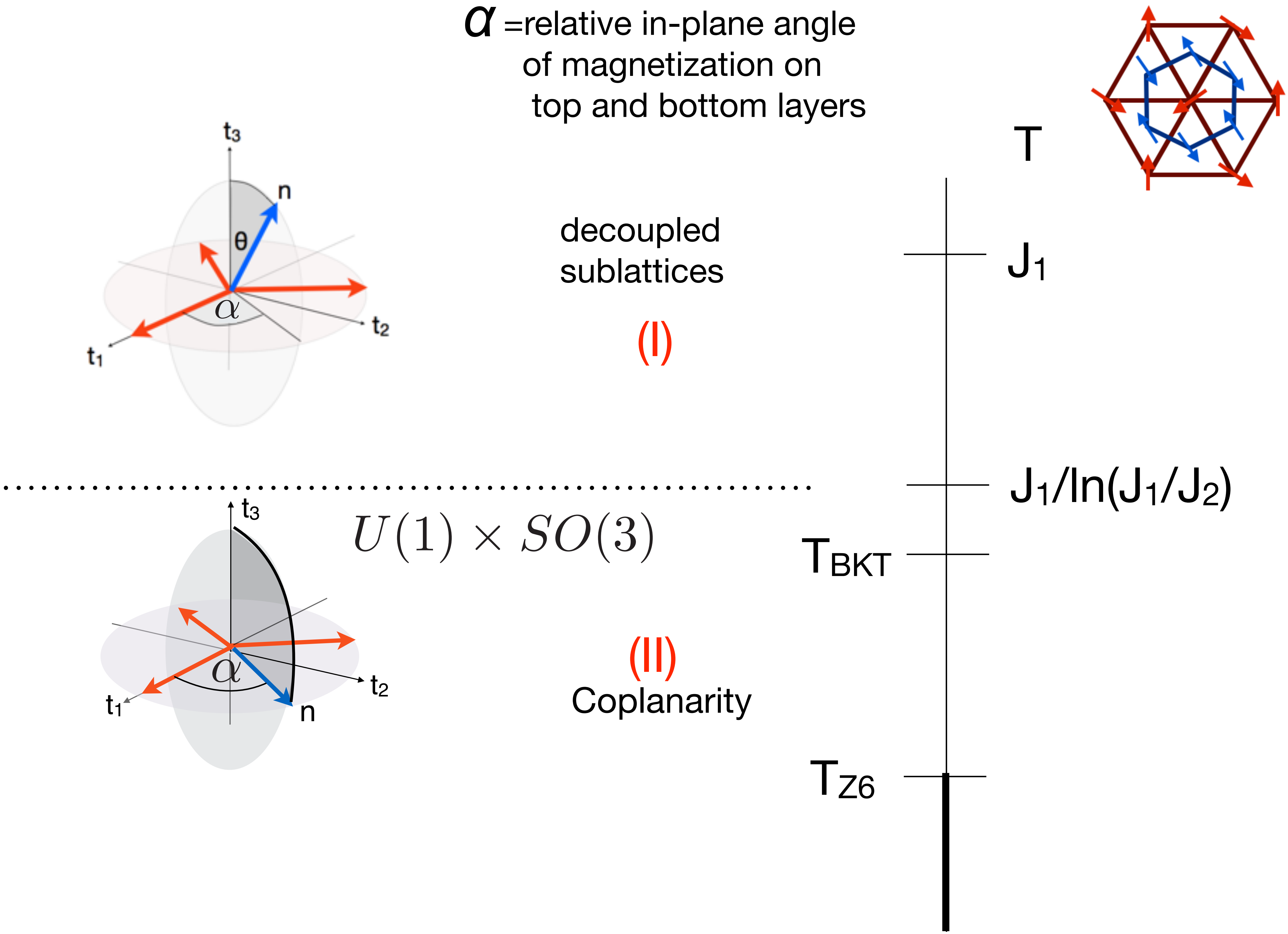




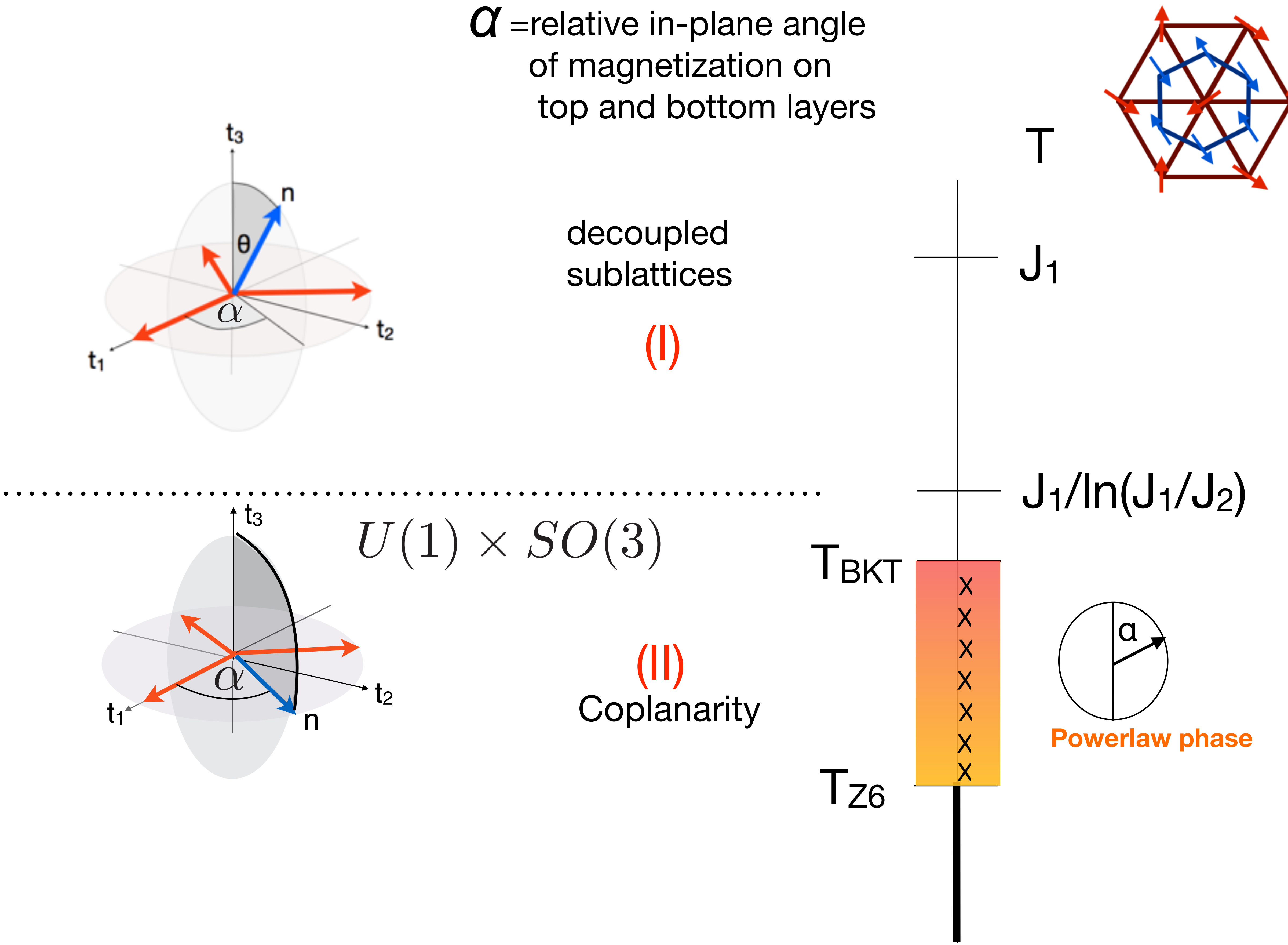
decoupled sublattices

(I)

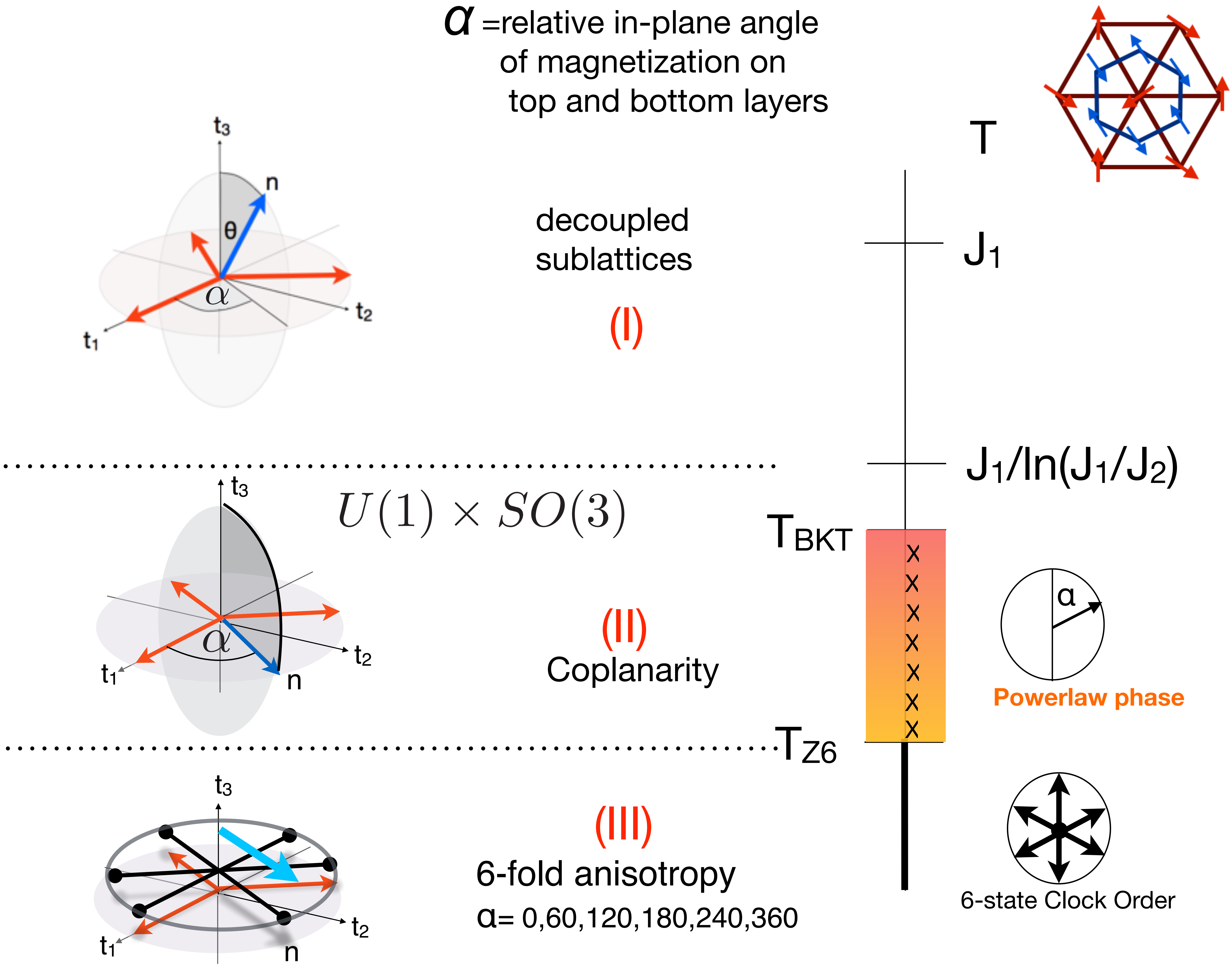




α =relative in-plane angle
of magnetization on
top and bottom layers
T
t3
n
θ
α
t1
t2
decoupled
sublattices
(I)
J1
J1/ln(J1/J2)
$U(1) \times SO(3)$
TBKT
t3
α
t1
t2
n
(II)
Coplanarity
TZ6



α =relative in-plane angle
of magnetization on
top and bottom layers
T
J1
J1/ln(J1/J2)
decoupled
sublattices
(I)
t3
n
θ
α
t2
t1
U(1) × SO(3)
(II)
Coplanarity
TBKT
TZ6
α
Powerlaw phase

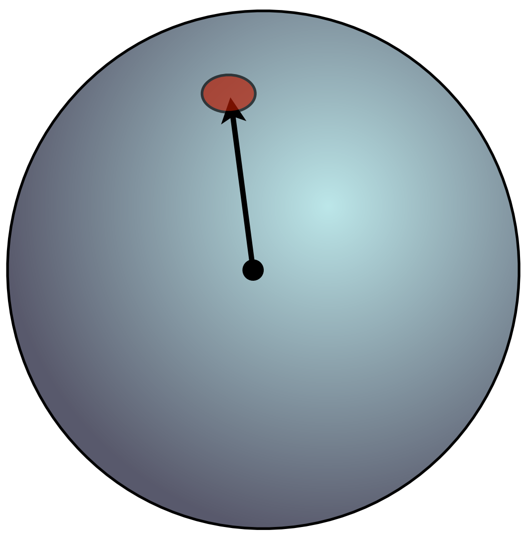


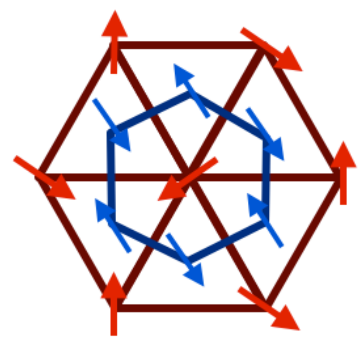
α =relative in-plane angle of magnetization on top and bottom layers
T
decoupled sublattices
(I)
J1
J1/ln(J1/J2)
U(1) × SO(3)
TBKT
(II)
Coplanarity
α
Powerlaw phase
TZ6
(III)
6-fold anisotropy
α= 0,60,120,180,240,360
6-state Clock Order
t1
t2
t3
n
θ

Magnetism, Gravity and String Theory.

Magnetism, Gravity and String Theory.

$$X(x, y) = (\phi, \theta, \psi, \alpha)$$





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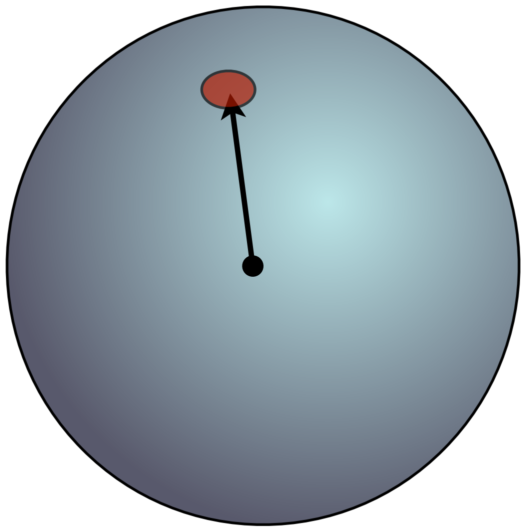

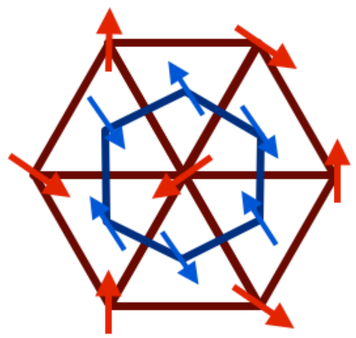

Magnetization = 4D vector

Magnetism, Gravity and String Theory.

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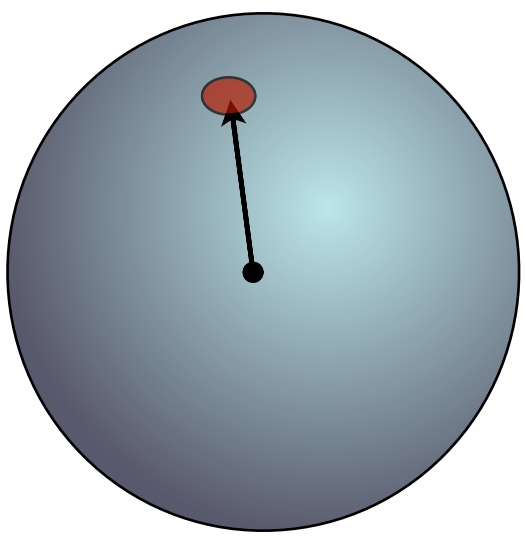
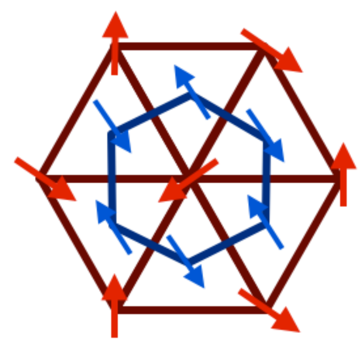
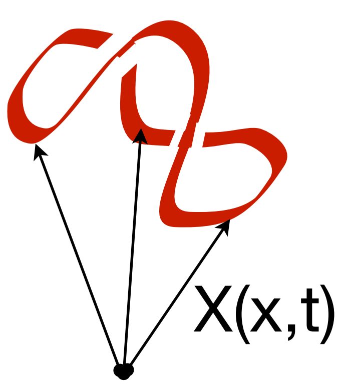




Magnetization = 4D vector

Regarding (x,y)= (x,t), then X(x,t) defines
a string moving in a 4D “target” space.

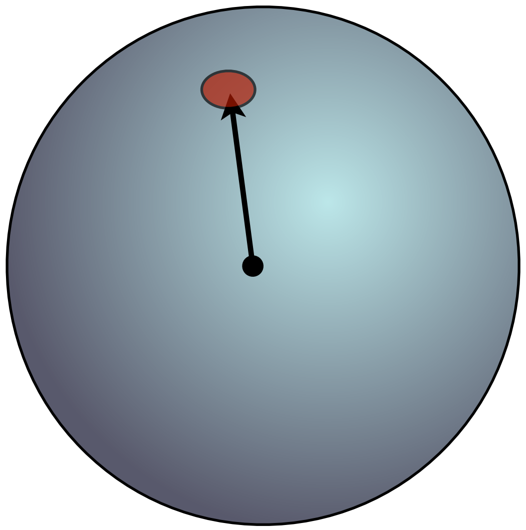


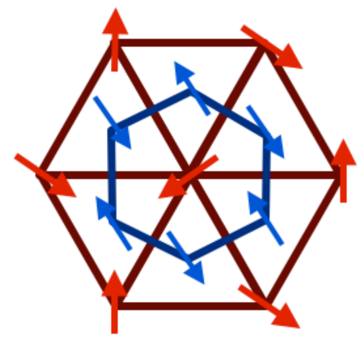
Magnetism, Gravity and String Theory.

$$X(x,y) = (\phi, \theta, \psi, \alpha)$$

$$S = \frac{1}{2}\int d^2 x g_{ij}(X(x))\partial_\mu X^i \partial_\mu X^j$$

Long-wavelength action = 4D string theory.





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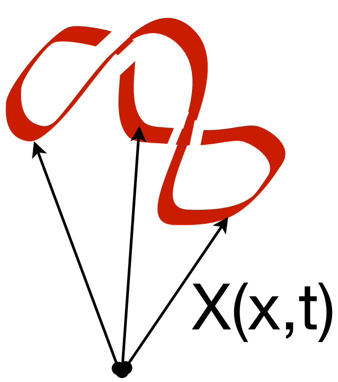

Magnetism, Gravity and String Theory.

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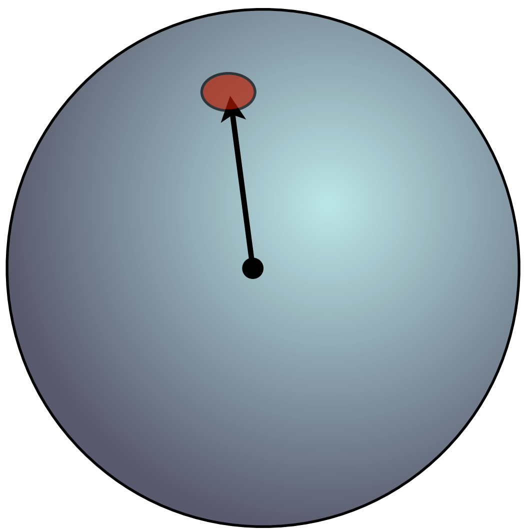

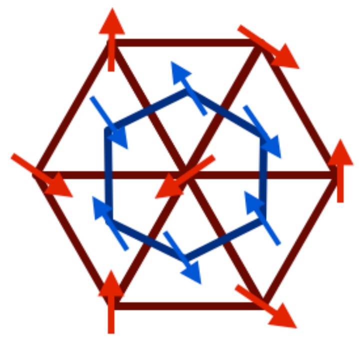

Magnetization = 4D vector

$$S = \frac{1}{2}\int d^2x g_{ij}(X(x))\partial_\mu X^i \partial_\mu X^j$$

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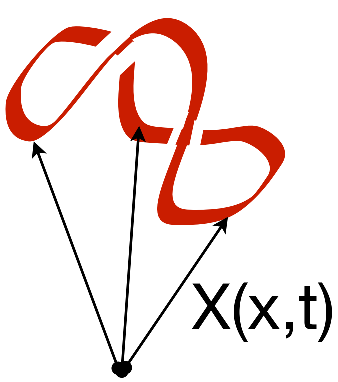

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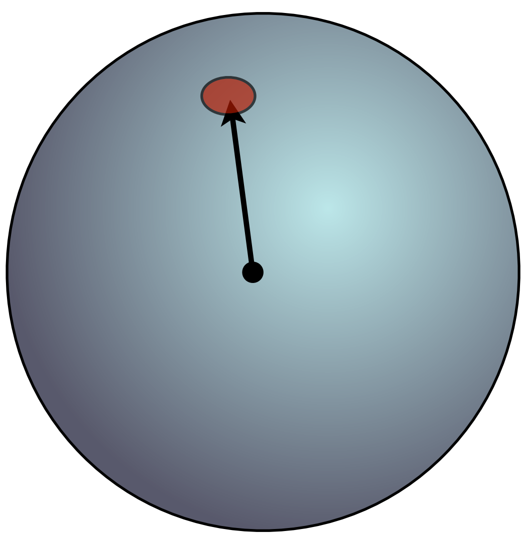
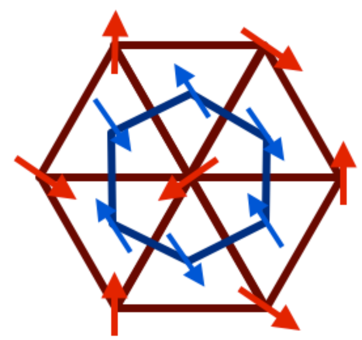




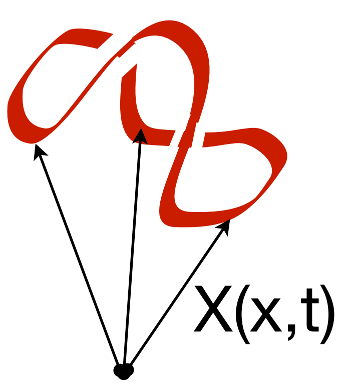
Magnetization = 4D vector

Covariance of the action under co-ordinate transformations in target space means that the scaling equations must also be covariant.

$$ds^2 = g_{ij}(X)\, dX^i dX^j$$

Spinwave stiffness = metric tensor

Regarding (x,y)= (x,t), then X(x,t) defines a string moving in a 4D “target” space.



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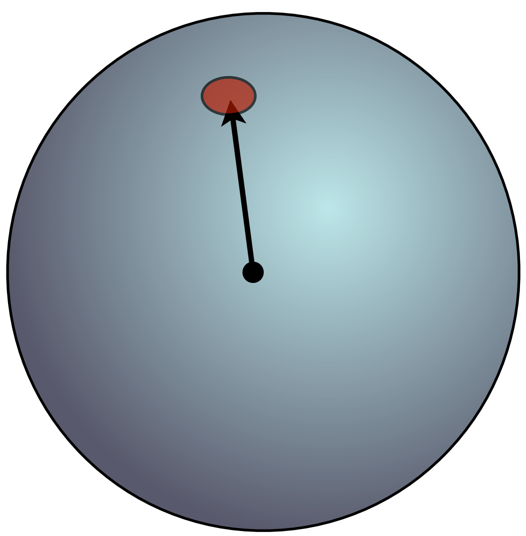

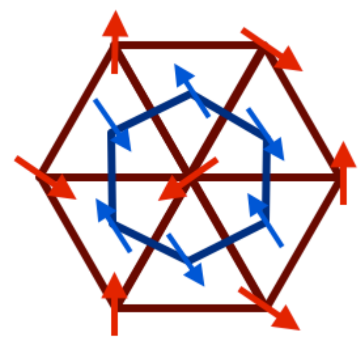

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$$\frac{dg^{ab}}{dl} = -\frac{1}{2\pi} R^{ab}$$

Friedan '80, Hamilton '81, Perelmann '06

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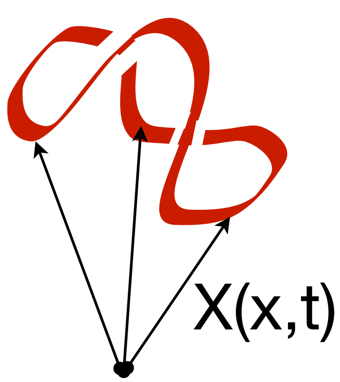

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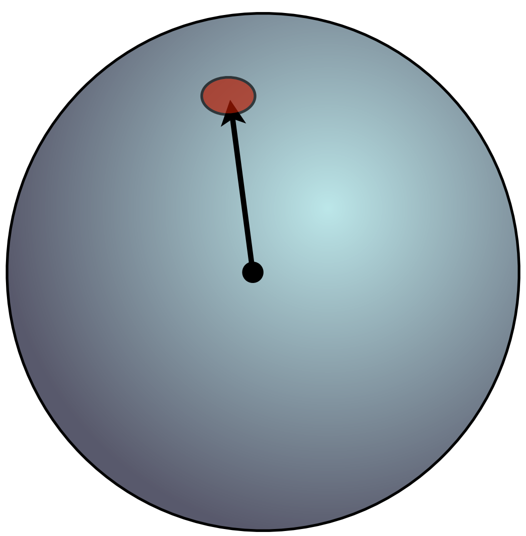

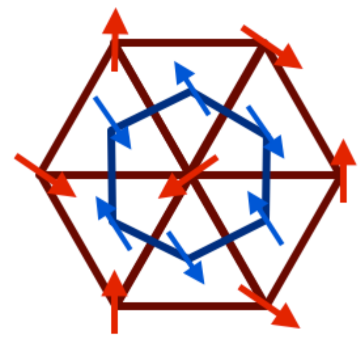

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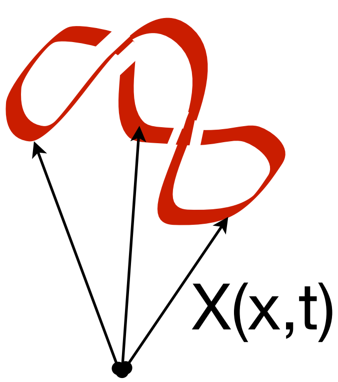

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"Ricci Flow"

Friedan '80, Hamilton '81, Perelmann '06

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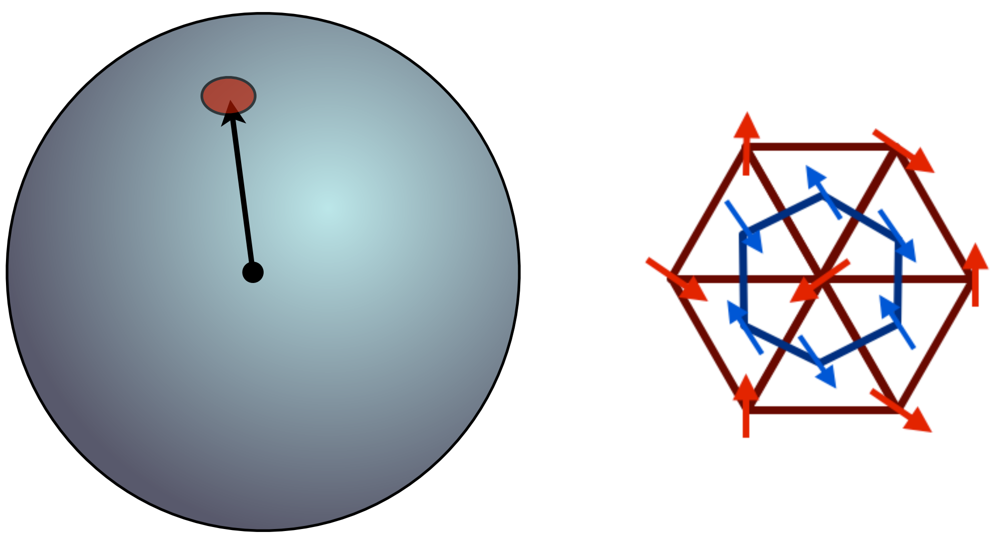

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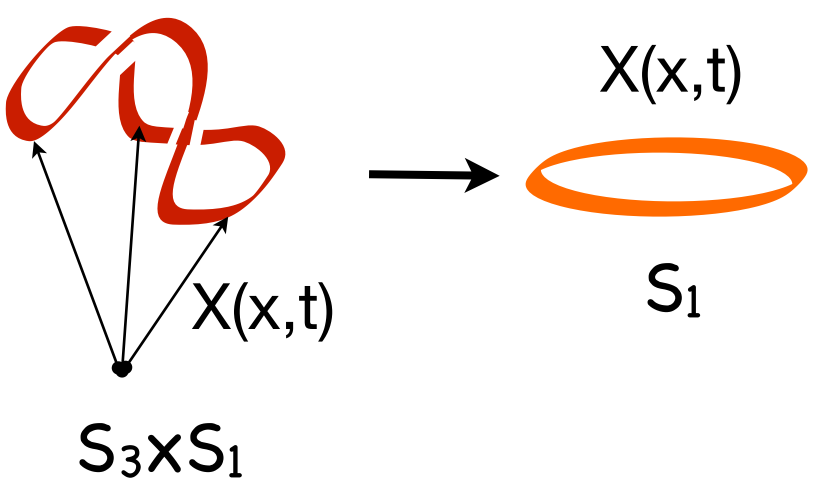

The decoupling of the U(1) degrees of freedom from the SO(3) degrees of freedom is a kind of compactification from a four to a one dimensional universe.

Scaling details.

Scaling details.

$$
\begin{aligned}
S = &- \frac{1}{2}\int d^2x \left(I_1 \Omega_{\mu,1}^2 + I_2 \Omega_{\mu,1}^2 + I_3 \Omega_{\mu,1}^2 \right) \\
&+ \frac{I_\alpha}{2}\int d^2x (\partial_\mu \alpha)^2 + \frac{\kappa}{2}\int d^2x \partial_\mu \alpha \Omega_{\mu,3}
\end{aligned}
$$

Scaling details.

$$S = -\frac{1}{2}\int d^2x\left(I_1\Omega^2_{\mu,1} + I_2\Omega^2_{\mu,1} + I_3\Omega^2_{\mu,1}\right) + \frac{I_\alpha}{2}\int d^2x(\partial_\mu\alpha)^2 + \frac{\kappa}{2}\int d^2x\partial_\mu\alpha\Omega_{\mu,3}$$

$$\longrightarrow \quad S = \frac{1}{2}\int d^2x \; g_{ij}\left[\nabla_\mu X^i \nabla_\mu X^j\right]$$

Scaling details.

$$S = -\frac{1}{2}\int d^2x \left(I_1 \Omega^2_{\mu,1} + I_2 \Omega^2_{\mu,1} + I_3 \Omega^2_{\mu,1} \right) \longrightarrow S = \frac{1}{2}\int d^2x \; g_{ij} \left[\nabla_\mu X^i \nabla_\mu X^j \right]$$

$$+ \frac{I_\alpha}{2}\int d^2x (\partial_\mu \alpha)^2 + \frac{\kappa}{2}\int d^2x \partial_\mu \alpha \Omega_{\mu,3}$$

$$\frac{dg_{ij}}{dl} = -\frac{1}{2\pi} R_{ij}$$

Scaling details.

$$S = -\frac{1}{2}\int d^2x\left(I_1\Omega^2_{\mu,1} + I_2\Omega^2_{\mu,1} + I_3\Omega^2_{\mu,1}\right) \longrightarrow S = \frac{1}{2}\int d^2x\ g_{ij}\left[\nabla_\mu X^i \nabla_\mu X^j\right]$$

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$$\frac{dg_{ij}}{dl} = -\frac{1}{2\pi}R_{ij}$$

15 line mathematica code for Ricci tensor

Input Metric Tensor

$$\mathrm{gl} = \begin{pmatrix} \sin^2(\theta)\left(\mathrm{I1}\sin^2(\psi) + \mathrm{I2}\cos^2(\psi)\right) + \mathrm{I3}\cos^2(\theta) & \sin(\theta)(\mathrm{I1}-\mathrm{I2})\sin(\psi)\cos(\psi) & \mathrm{I3}\cos(\theta) & \frac{1}{2}\kappa\cos(\theta) \\ \sin(\theta)(\mathrm{I1}-\mathrm{I2})\sin(\psi)\cos(\psi) & \mathrm{I1}\cos^2(\psi) + \mathrm{I2}\sin^2(\psi) & 0 & 0 \\ \mathrm{I3}\cos(\theta) & 0 & \mathrm{I3} & \frac{\kappa}{2} \\ \frac{1}{2}\kappa\cos(\theta) & 0 & \frac{\kappa}{2} & \mathrm{I}\varphi \end{pmatrix};$$

Compute Cristoffel Symbol

$$(\Gamma^i)_{kl} = \frac{1}{2} g^{ij} \left(\nabla_l g_{jk} + \nabla_k g_{jl} - \nabla_j g_{kl}\right)$$

$$\frac{dg_{ij}}{dl} = -\frac{1}{2\pi} R_{ij}$$

15 line mathematica code for Ricci tensor

Input Metric Tensor

$$gl = \begin{pmatrix} \sin^2(\theta)\left(I1\sin^2(\psi) + I2\cos^2(\psi)\right) + I3\cos^2(\theta) & \sin(\theta)\,(I1 - I2)\sin(\psi)\cos(\psi) & I3\cos(\theta) & \frac{1}{2}\kappa\cos(\theta) \\ \sin(\theta)\,(I1 - I2)\sin(\psi)\cos(\psi) & I1\cos^2(\psi) + I2\sin^2(\psi) & 0 & 0 \\ I3\cos(\theta) & 0 & I3 & \frac{\kappa}{2} \\ \frac{1}{2}\kappa\cos(\theta) & 0 & \frac{\kappa}{2} & I\varphi \end{pmatrix};$$

```
For[i = 1, i ≤ 4, i++,
 For[k = 1, k ≤ 4, k++,
  For[l = 1, l ≤ 4, l++,
   Γ[[i, k, l]] =
    Sum[1/2 * gu[[i, j]] *
      (D[gl[[j, k]], x[[l]]] + D[gl[[j, l]], x[[k]]] -
       D[gl[[k, l]], x[[j]]]), {j, 1, 4}]]]]
```

Compute Cristoffel Symbol

$$(\Gamma^{i})_{kl} = \frac{1}{2} g^{ij} \left(\nabla_{l} g_{jk} + \nabla_{k} g_{jl} - \nabla_{j} g_{kl}\right)$$

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15 line mathematica code for Ricci tensor

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Compute Ricci Tensor

$$R^k{}_{ijl} = \Gamma^k{}_{il,j} - \Gamma^k{}_{ij,l} + \Gamma^k{}_{jn}\Gamma^n{}_{li} - \Gamma^k{}_{ln}\Gamma^n{}_{ij}$$

$$R_{ij} = R^k{}_{ikj}$$

$$\frac{dg_{ij}}{dl} = -\frac{1}{2\pi} R_{ij}$$

15 line mathematica code for Ricci tensor

Input Metric Tensor

$$gl = \begin{pmatrix} \sin^2(\theta)\left(I1\sin^2(\psi) + I2\cos^2(\psi)\right) + I3\cos^2(\theta) & \sin(\theta)\,(I1 - I2)\sin(\psi)\cos(\psi) & I3\cos(\theta) & \frac{1}{2}\kappa\cos(\theta) \\ \sin(\theta)\,(I1 - I2)\sin(\psi)\cos(\psi) & I1\cos^2(\psi) + I2\sin^2(\psi) & 0 & 0 \\ I3\cos(\theta) & 0 & I3 & \frac{\kappa}{2} \\ \frac{1}{2}\kappa\cos(\theta) & 0 & \frac{\kappa}{2} & I\varphi \end{pmatrix};$$

```
For[i = 1, i ≤ 4, i++,
  For[k = 1, k ≤ 4, k++,
   Riccill[[i, k]] =
    Sum[(D[Γ[[l, i, k]], x[[l]]] - D[Γ[[l, i, l]], x[[k]]] +
       Sum[(Γ[[m, l, m]] * Γ[[l, i, k]] - Γ[[m, i, l]] * Γ[[l, k, m]]), {m, 1, 4}]), {l, 1, 4}]]];
```

Compute Ricci Tensor

$$R^{k}{}_{ijl} = \Gamma^{k}{}_{il,j} - \Gamma^{k}{}_{ij,l} + \Gamma^{k}{}_{jn}\Gamma^{n}{}_{li} - \Gamma^{k}{}_{ln}\Gamma^{n}{}_{ij}$$

$$R_{ij} = R^{k}{}_{ikj}$$

$$\frac{dg_{ij}}{dl} = -\frac{1}{2\pi}R_{ij}$$

15 line mathematica code for Ricci tensor

Input Metric Tensor

$$gl = \begin{pmatrix} \sin^2(\theta)\left(I1\sin^2(\psi) + I2\cos^2(\psi)\right) + I3\cos^2(\theta) & \sin(\theta)(I1 - I2)\sin(\psi)\cos(\psi) & I3\cos(\theta) & \frac{1}{2}\kappa\cos(\theta) \\ \sin(\theta)(I1 - I2)\sin(\psi)\cos(\psi) & I1\cos^2(\psi) + I2\sin^2(\psi) & 0 & 0 \\ I3\cos(\theta) & 0 & I3 & \frac{\kappa}{2} \\ \frac{1}{2}\kappa\cos(\theta) & 0 & \frac{\kappa}{2} & I\varphi \end{pmatrix};$$

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```
For[i = 1, i ≤ 4, i++,
  For[k = 1, k ≤ 4, k++,
   Riccil[[i, k]] =
    Sum[(D[Γ[[l, i, k]], x[[l]]] - D[Γ[[l, i, l]], x[[k]]] +
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```

$$R^k{}_{ijl} = \Gamma^k{}_{il,j} - \Gamma^k{}_{ij,l} + \Gamma^k{}_{jn}\Gamma^n{}_{li} - \Gamma^k{}_{ln}\Gamma^n{}_{ij}$$

$$R_{ij} = R^k{}_{ikj}$$

$$\frac{dg_{ij}}{dl} = -\frac{1}{2\pi}R_{ij}$$

15 line mathematica code for Ricci tensor

This is the renormalization of I3

```
-FullSimplify[1/(2 π) Riccil[[3, 3]]]
```

$$-\frac{I3^2 - (I1 - I2)^2}{4\pi\, I1\, I2}$$

Input Metric Tensor

$$gl = \begin{pmatrix} \sin^2(\theta)\left(I1\sin^2(\psi) + I2\cos^2(\psi)\right) + I3\cos^2(\theta) & \sin(\theta)(I1 - I2)\sin(\psi)\cos(\psi) & I3\cos(\theta) & \frac{1}{2}\kappa\cos(\theta) \\ \sin(\theta)(I1 - I2)\sin(\psi)\cos(\psi) & I1\cos^2(\psi) + I2\sin^2(\psi) & 0 & 0 \\ I3\cos(\theta) & 0 & I3 & \frac{\kappa}{2} \\ \frac{1}{2}\kappa\cos(\theta) & 0 & \frac{\kappa}{2} & I\varphi \end{pmatrix};$$

Compute Ricci Tensor

```
For[i = 1, i ≤ 4, i++,
 For[k = 1, k ≤ 4, k++,
  Riccill[[i, k]] =
   Sum[D[Γ[[l, i, k]], x[[l]]] - D[Γ[[l, i, l]], x[[k]]] +
     Sum[(Γ[[m, l, m]] * Γ[[l, i, k]] - Γ[[m, i, l]] * Γ[[l, k, m]]), {m, 1, 4}], {l, 1, 4}]]];
```

$$R^k{}_{ijl} = \Gamma^k{}_{il,j} - \Gamma^k{}_{ij,l} + \Gamma^k{}_{jn}\Gamma^n{}_{li} - \Gamma^k{}_{ln}\Gamma^n{}_{ij}$$

$$R_{ij} = R^k{}_{ikj}$$

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15 line mathematica code for Ricci tensor

This is the renormalization of I3

```
-FullSimplify[1/(2 π) Riccill[[3, 3]]]
```

$$-\frac{I3^2 - (I1 - I2)^2}{4\pi\, I1\, I2}$$

```
For[i = 1, i ≤ 4, i++,
  For[k = 1, k ≤ 4, k++,
   Riccill[[i, k]] =
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```

Compute Ricci Tensor

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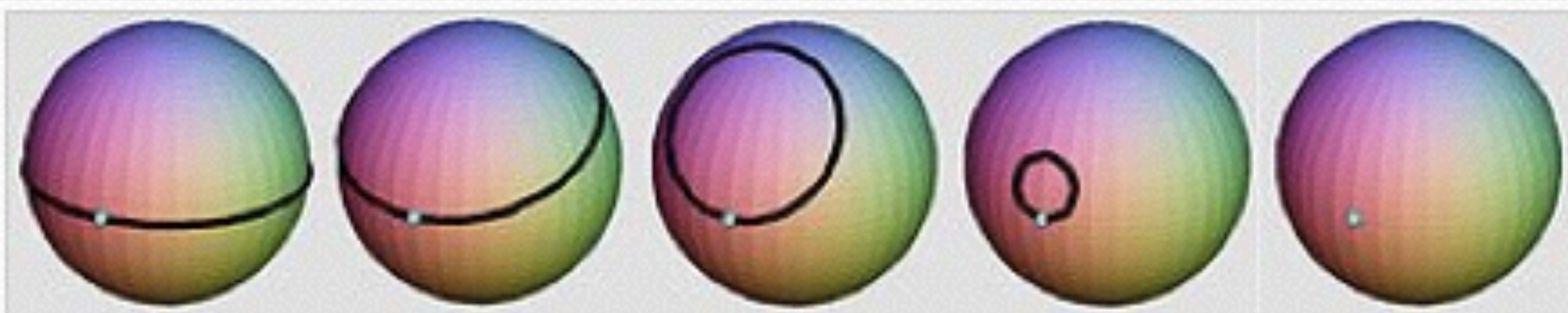
Detailed Analysis: Decoupling of U(1) Degrees of Freedom for all flows.

Poincare Conjecture

Every simply connected, closed 3-manifold is homeomorphic to the 3-sphere.



For compact 2-dimensional surfaces without boundary, if every loop can be continuously tightened to a point, then the surface is topologically homeomorphic to a 2-sphere (usually just called a sphere). The Poincaré conjecture asserts that the same is true for 3-dimensional spaces.

$$\frac{\delta S}{\delta g^{ab}} = 0 = \dot{g}_{ab} - \frac{1}{2\pi} R_{ab}$$

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Friedan '80, Hamilton '81, Perelmann '06

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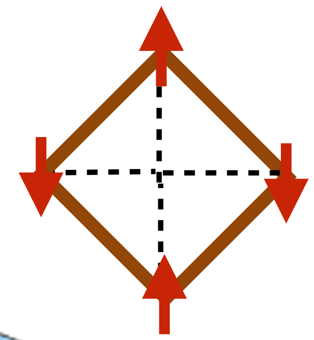
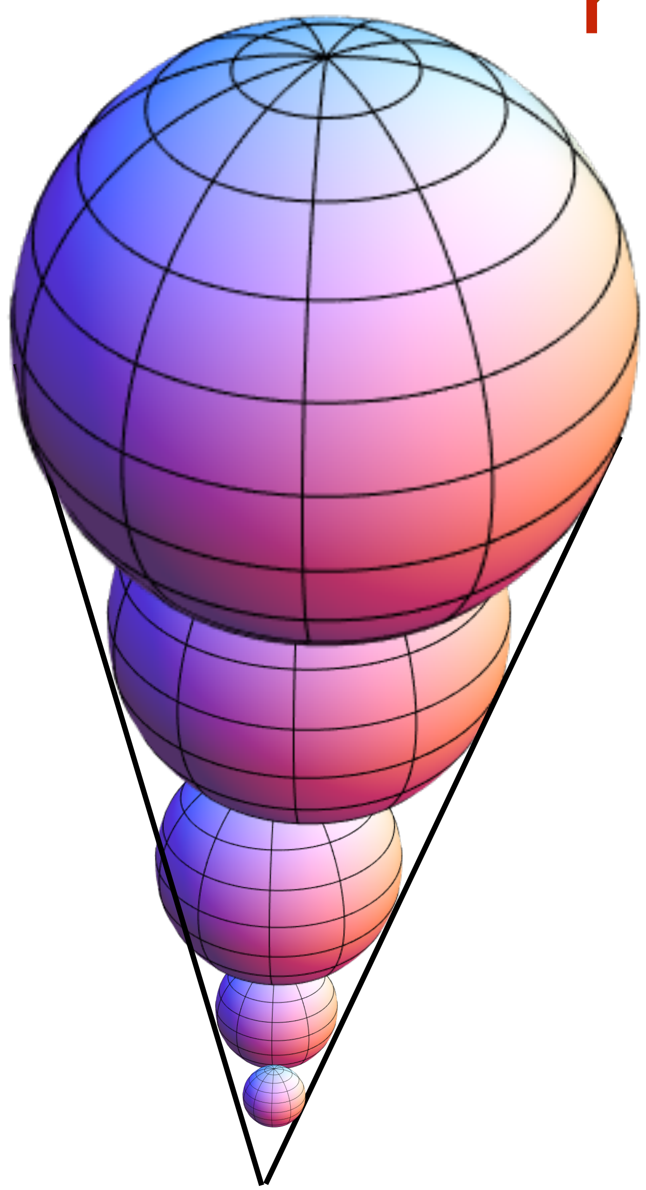
2D Heisenberg





Trivially connected: Polyakov collapse of stiffness to Zero

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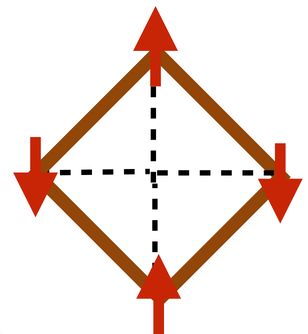
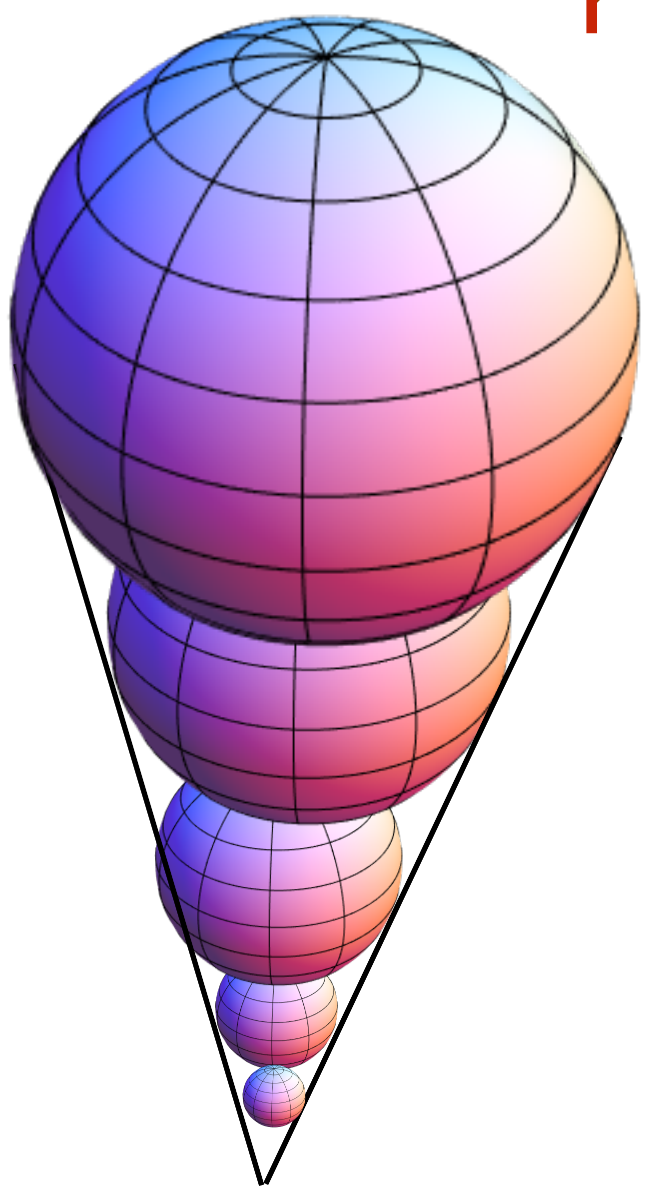
Friedan '80, Hamilton '81, Perelmann '06

2D Heisenberg





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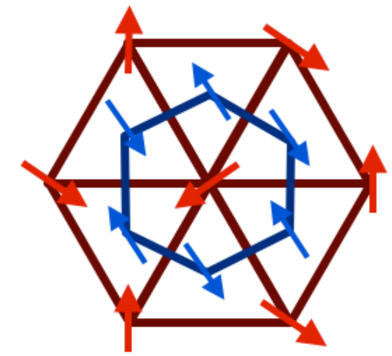
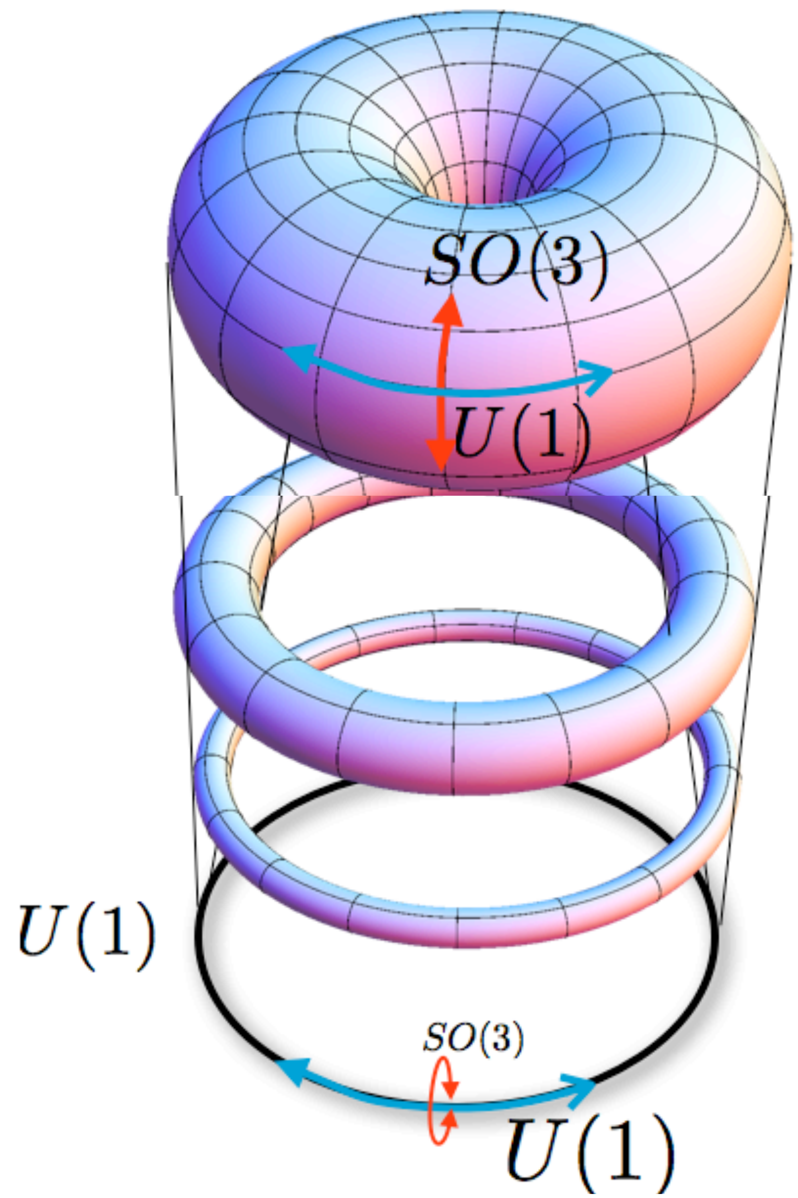
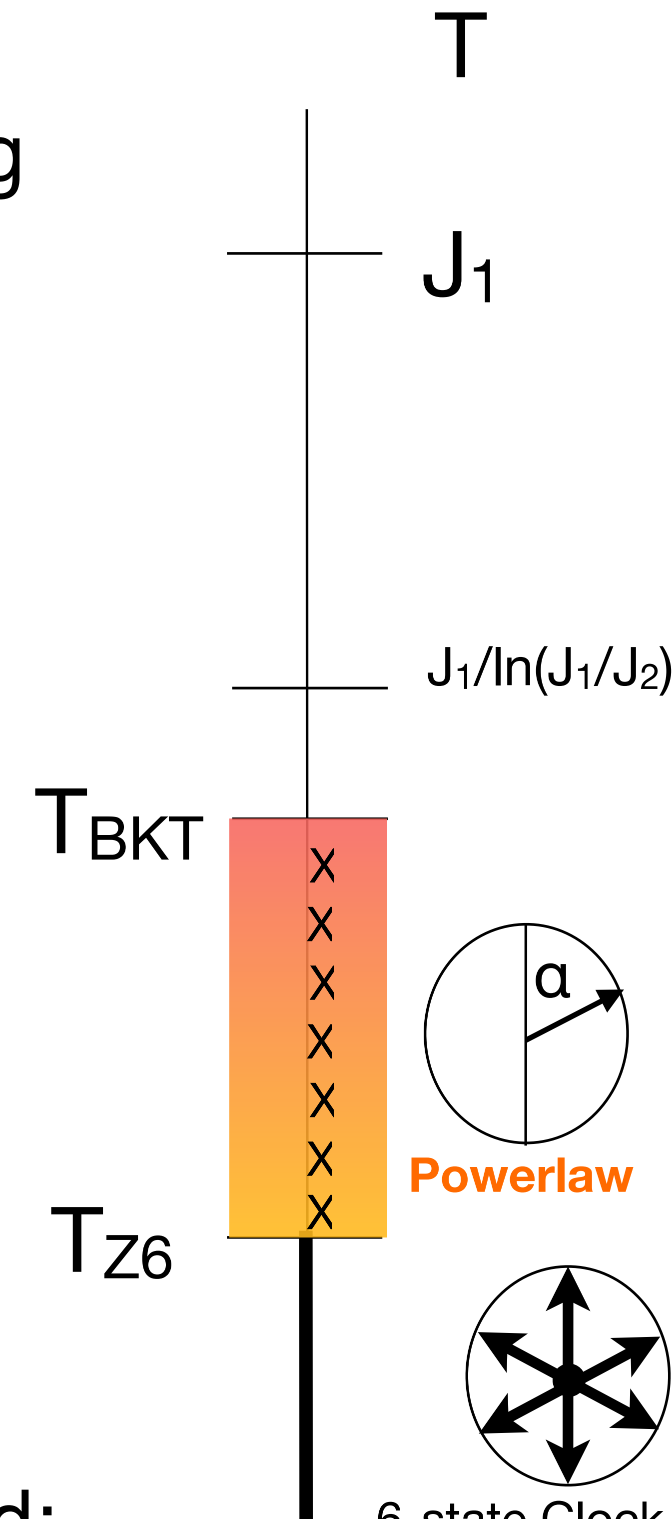


Windmill Heisenberg



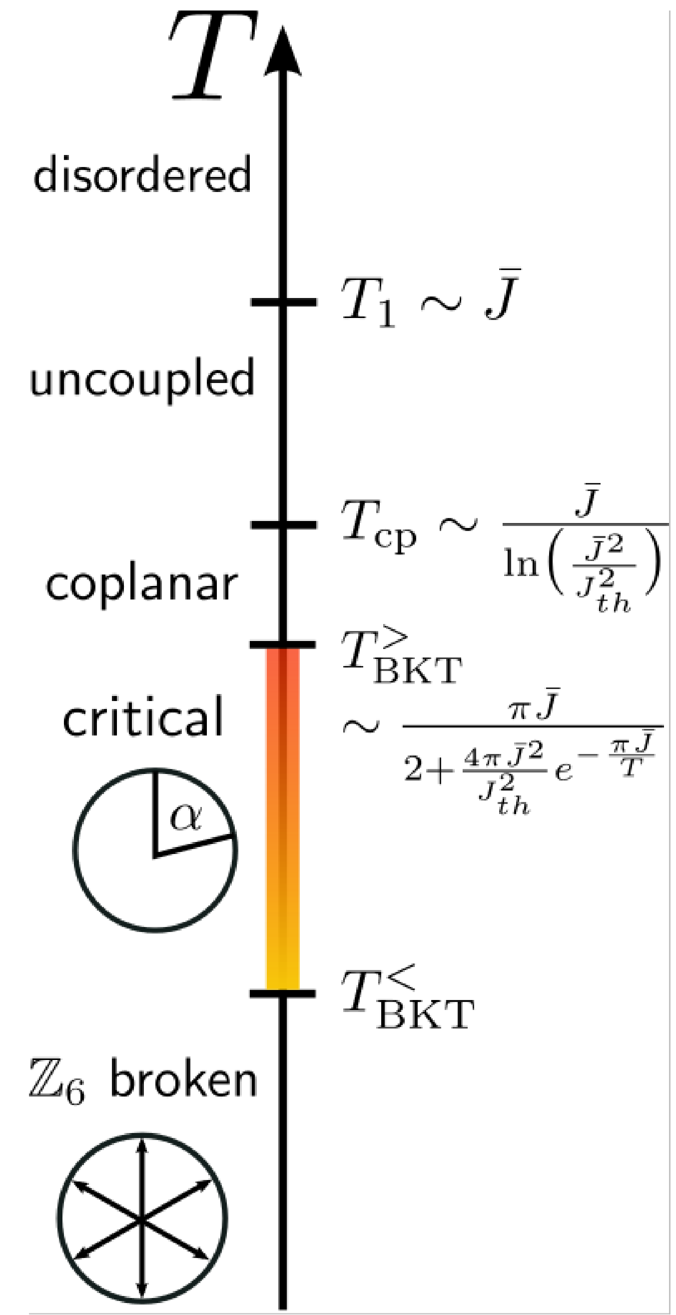
Non-trivially connected: U(1) stiffness survives.



Monte-Carlo simulations

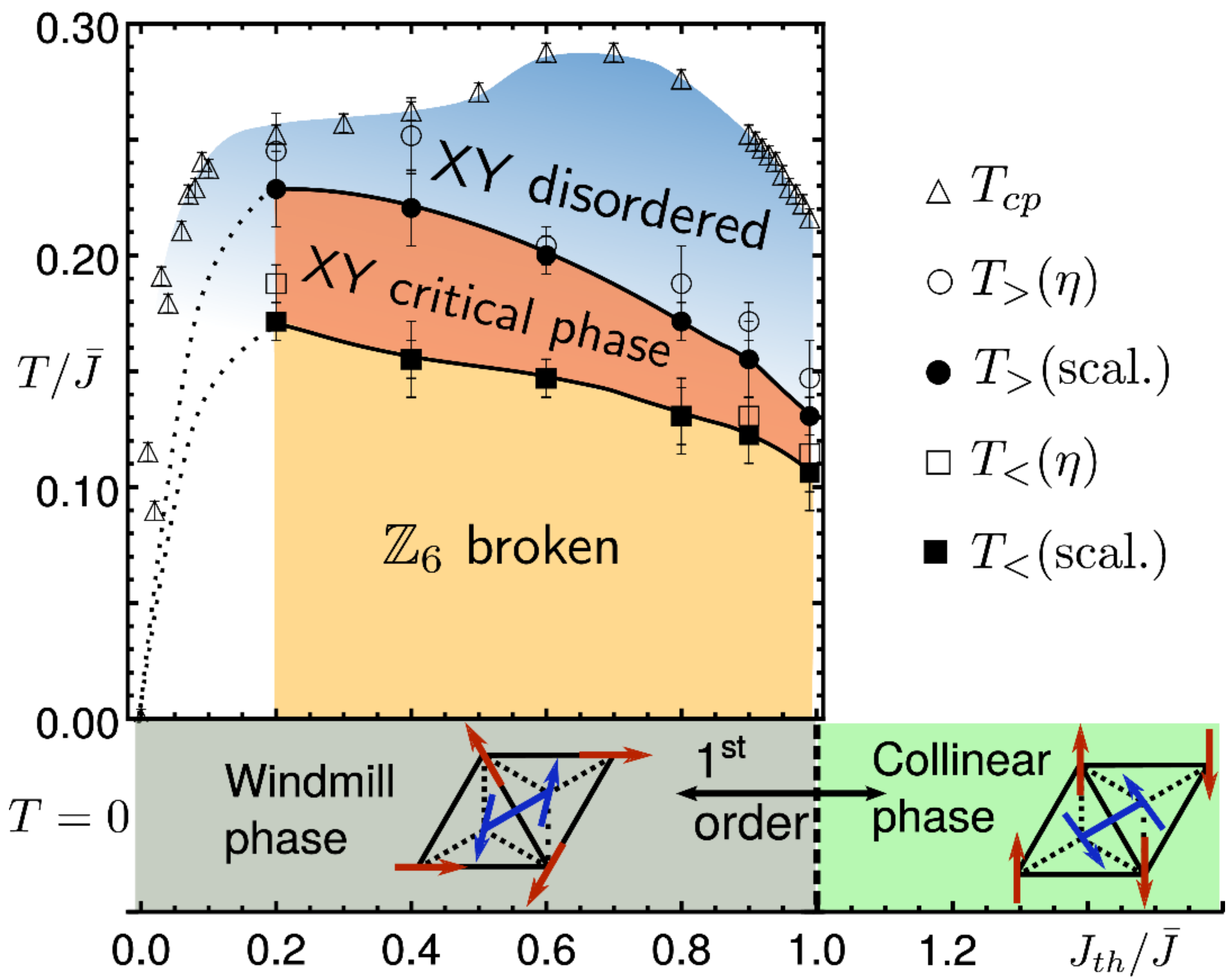
B. Jeevanesan, P. Chandra, P. Coleman, P. Orth
Phys. Rev. Lett. 115, 177201 (2015) .

RG phase diagram



Phase diagram

Monte-Carlo phase diagram



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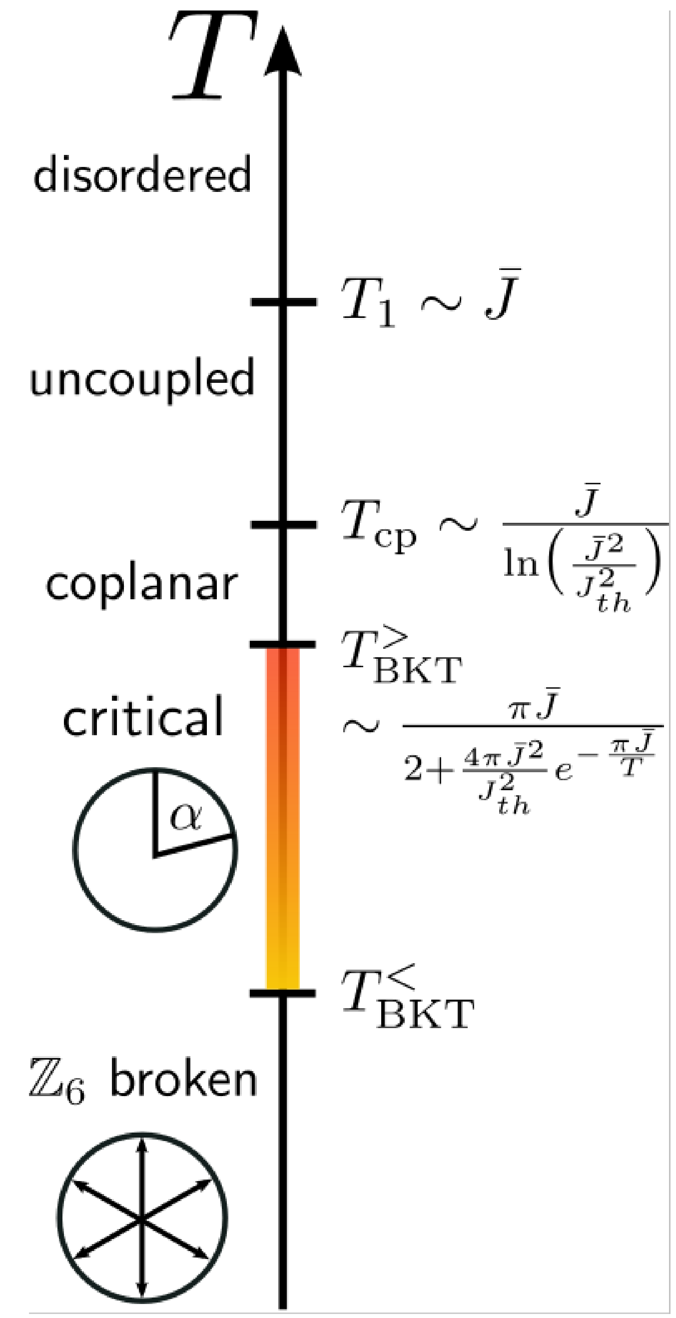

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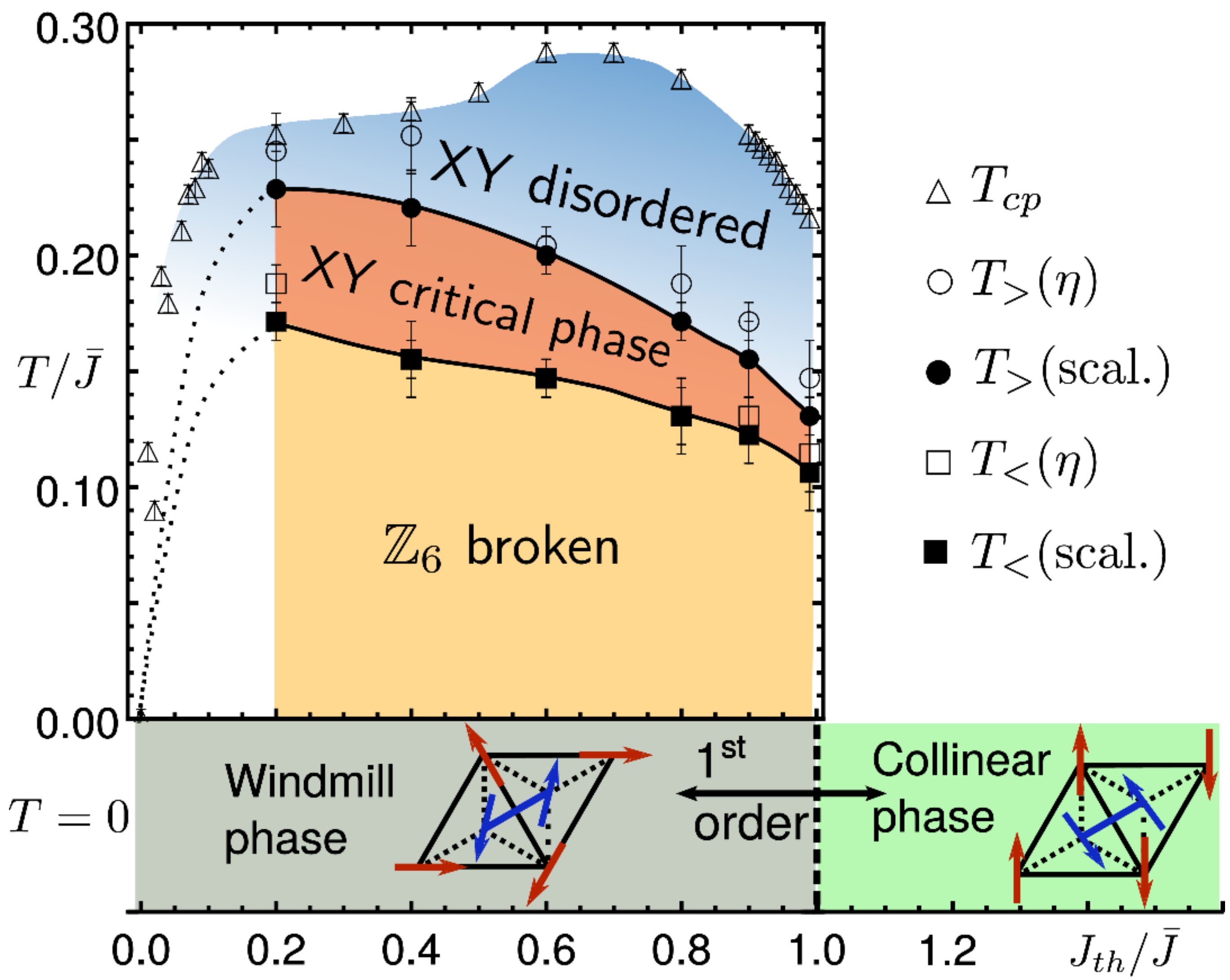

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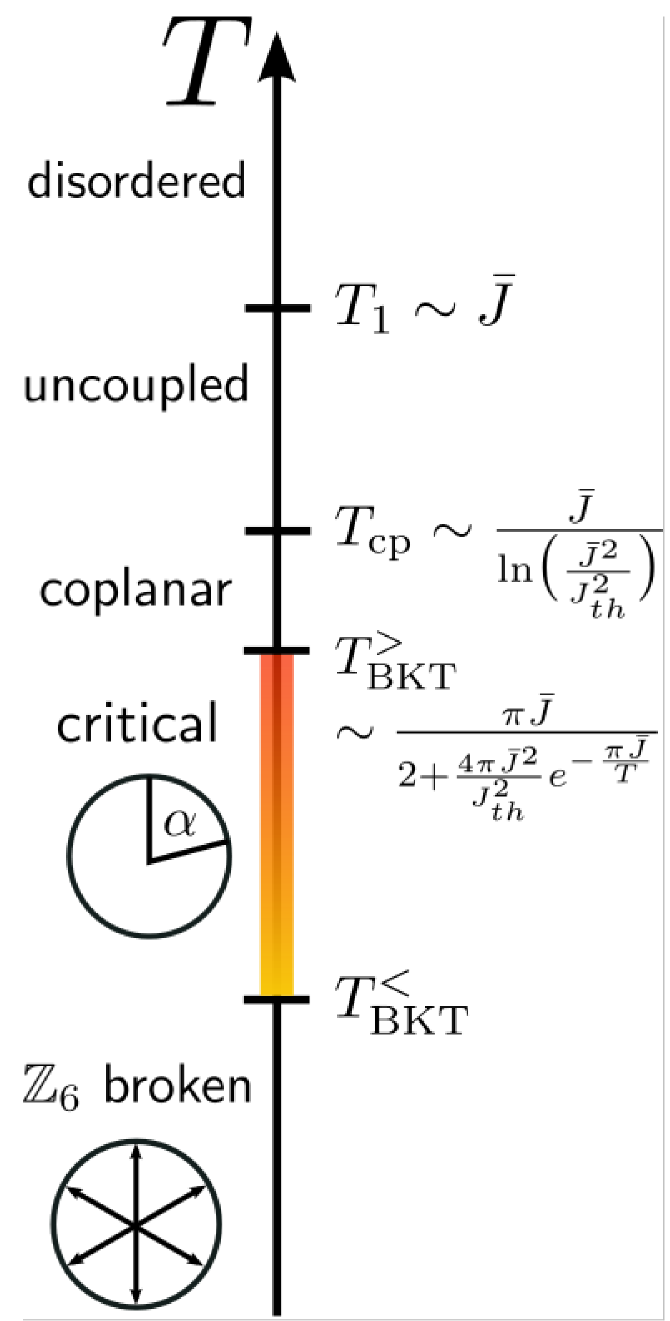
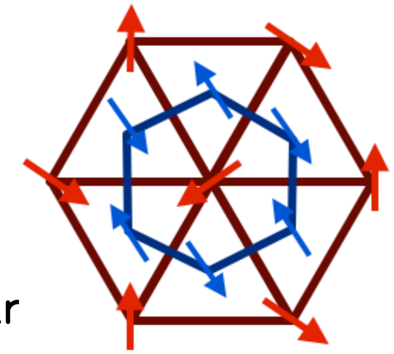
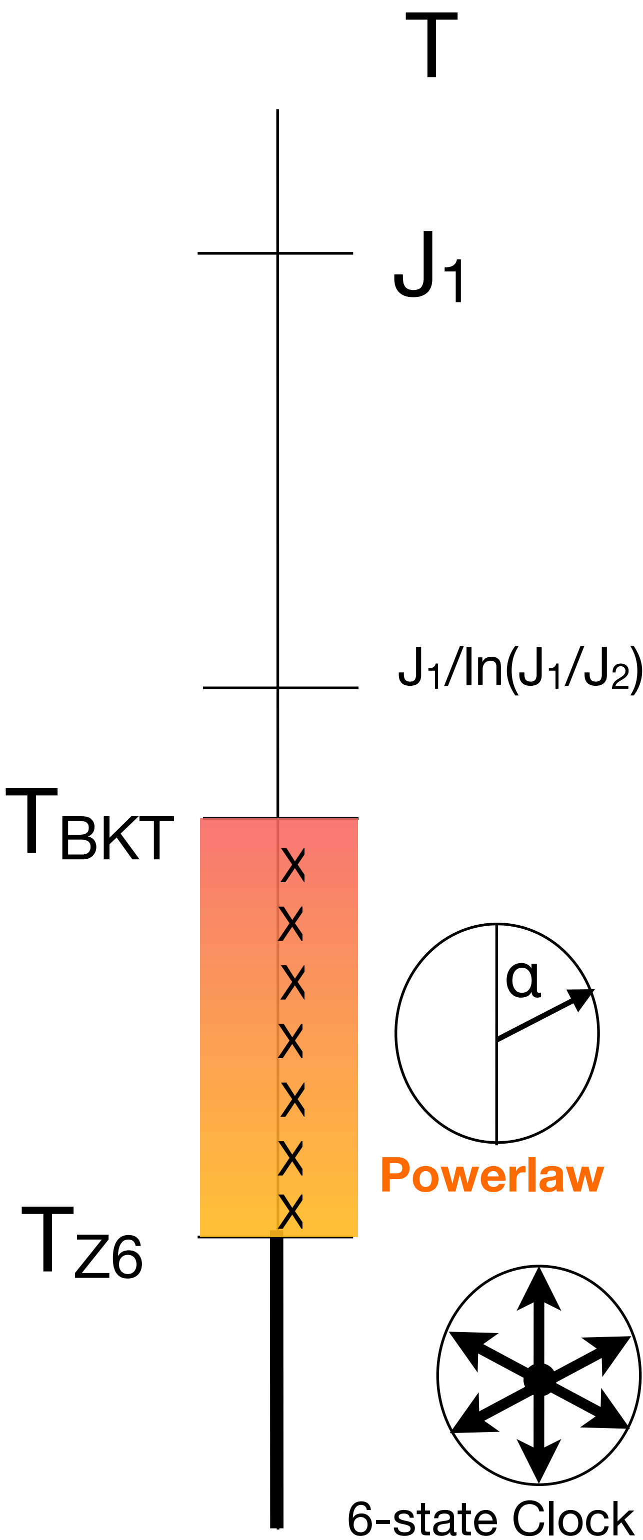


- Monte-Carlo simulations provide unbiased verification of long-wavelength picture.

$$\frac{dg^{ab}}{dl} = -\frac{1}{2\pi}R^{ab}$$

Friedan '80, Hamilton '81, Perelmar





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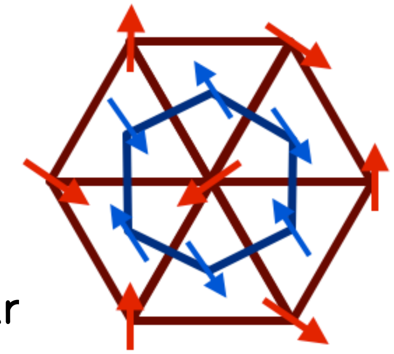

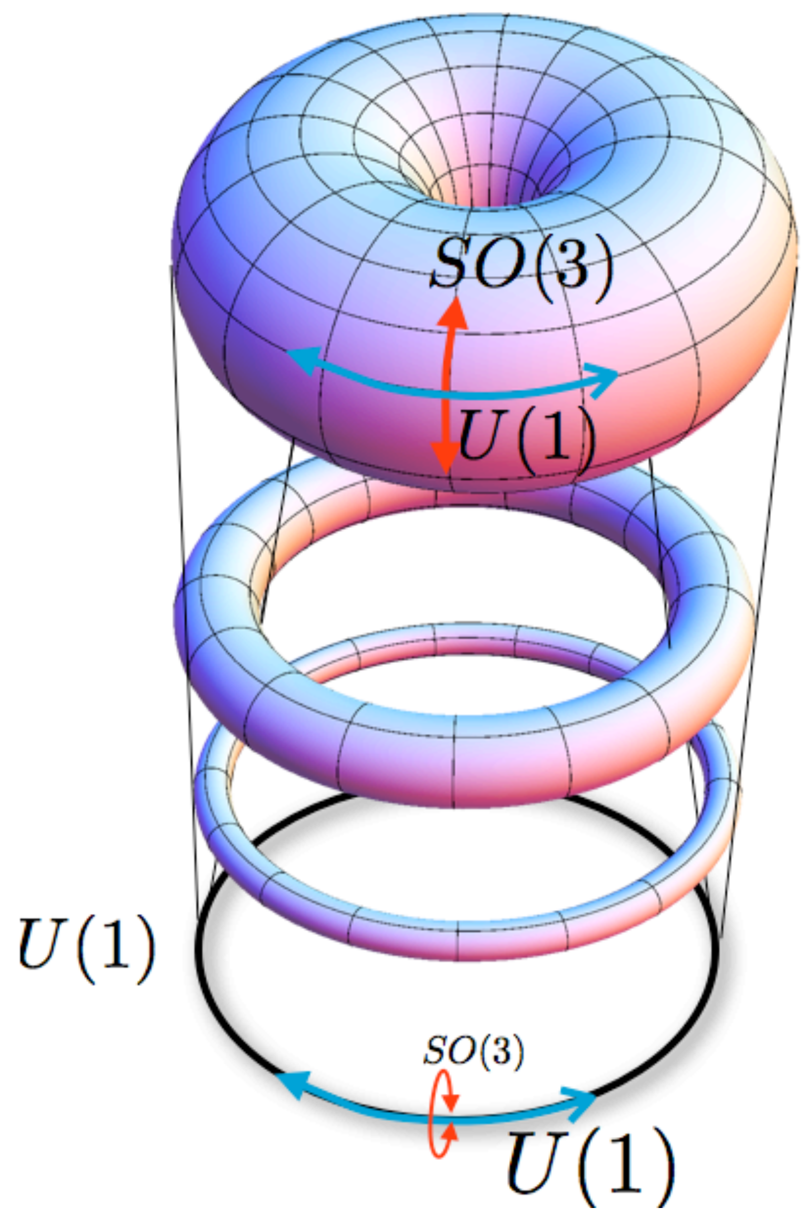

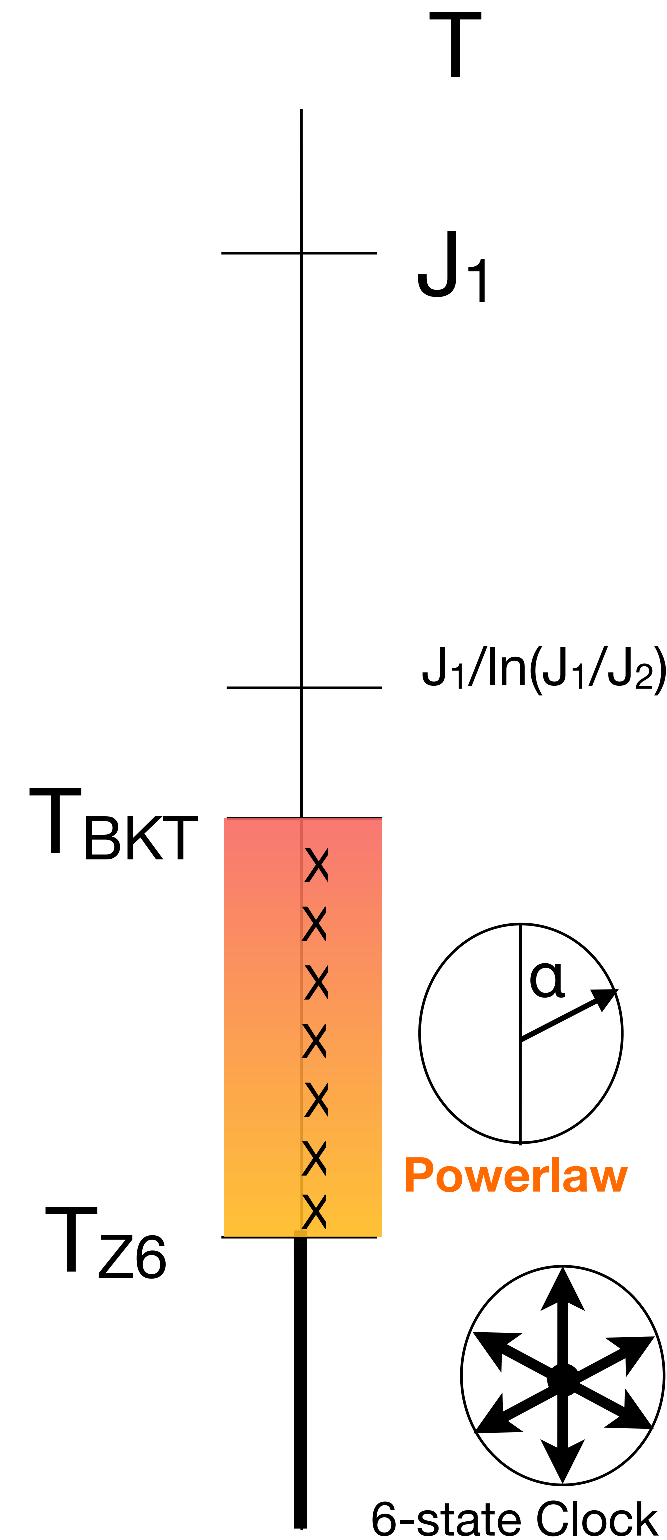

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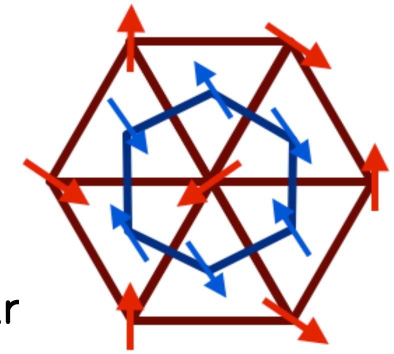

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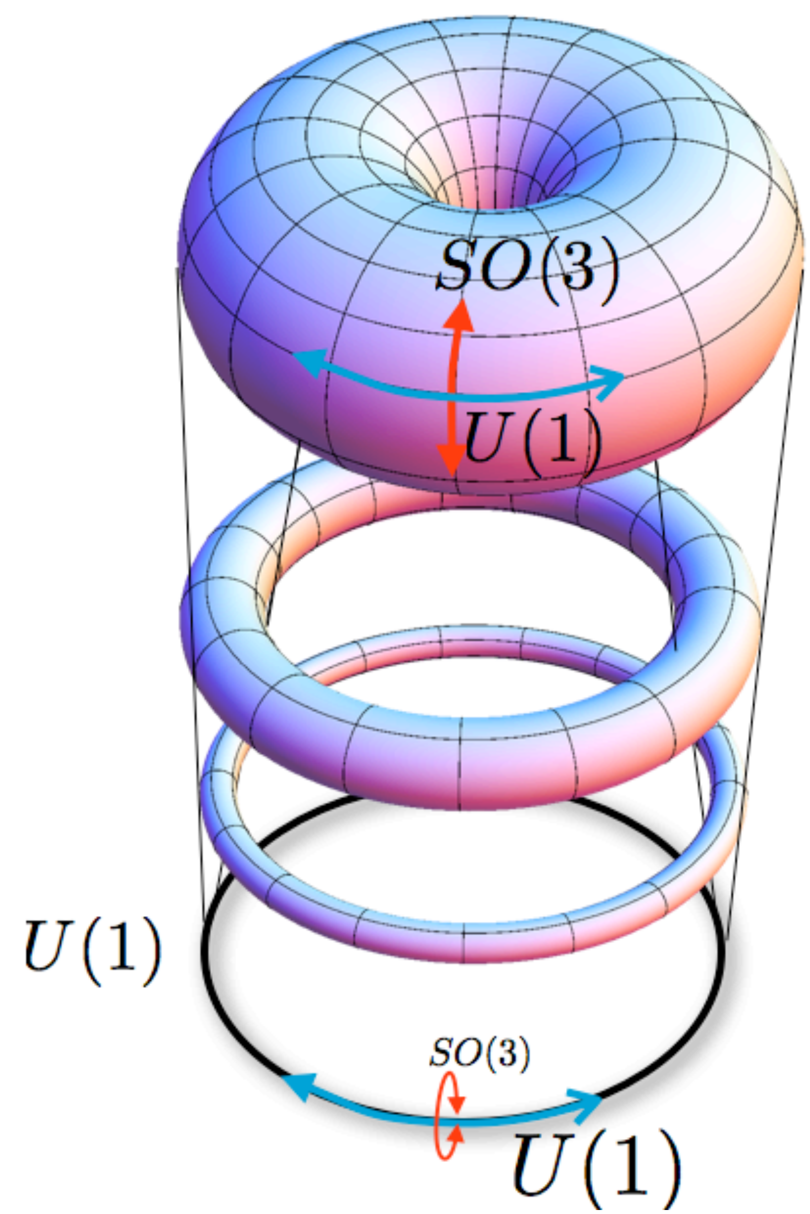

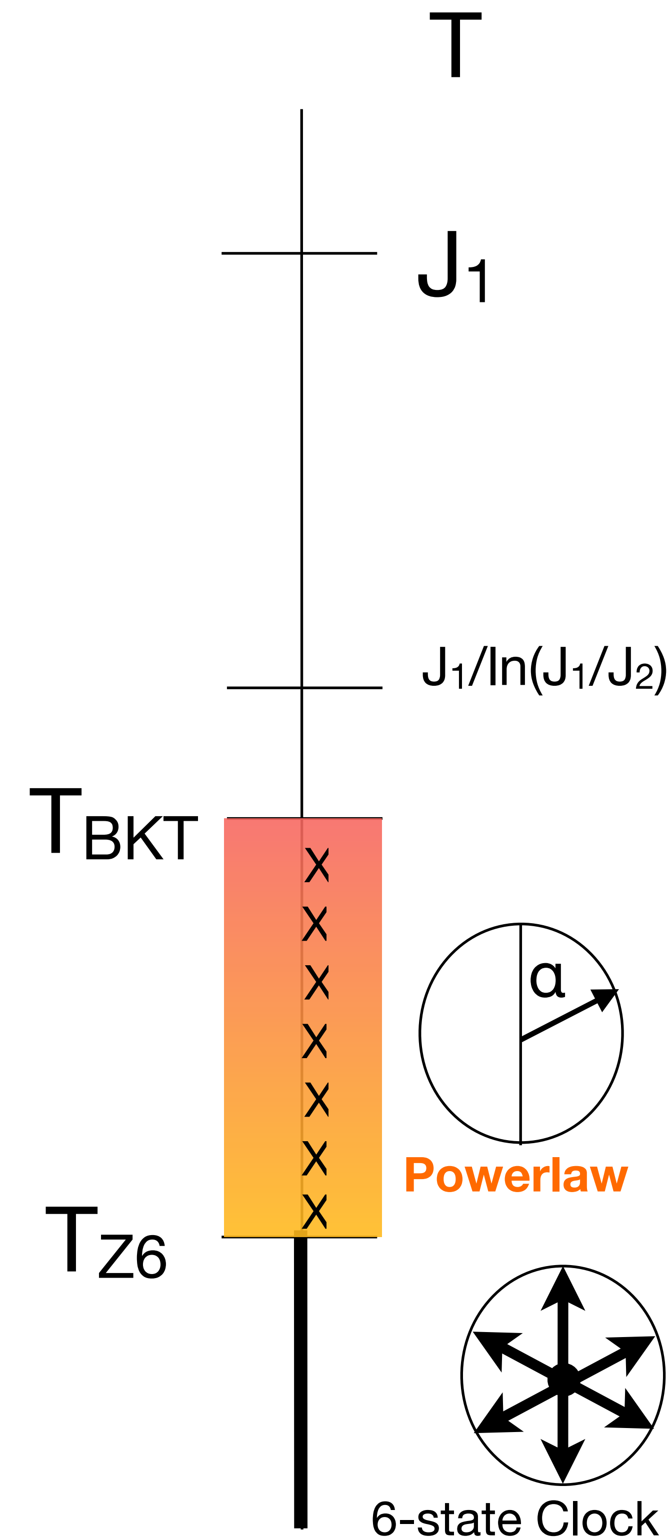

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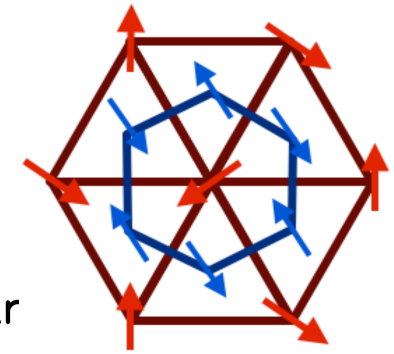

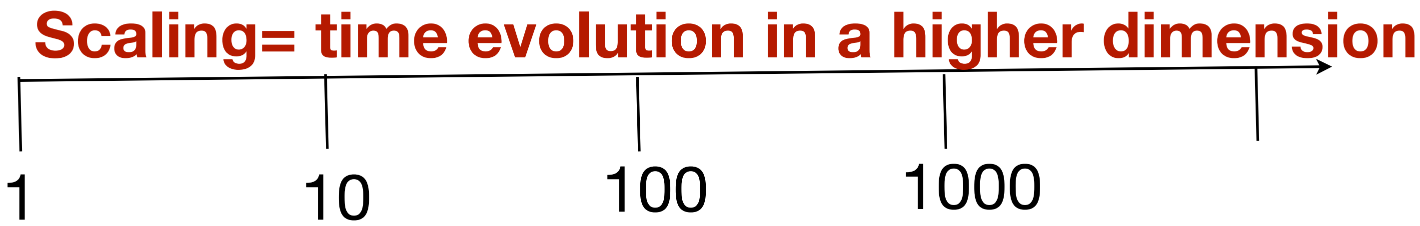

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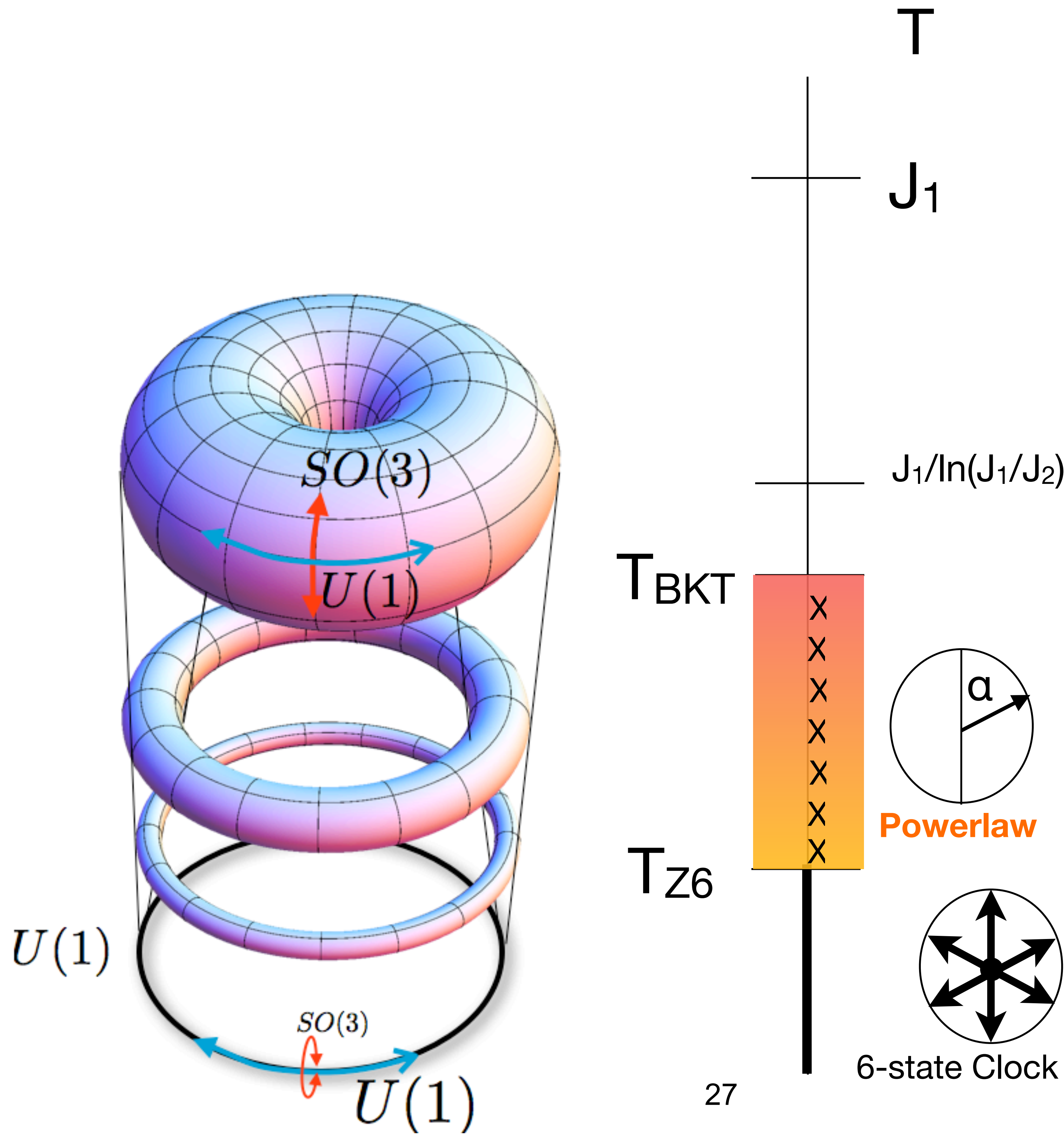
- Realization of mapping of RG into time. (cf AdSCFT)



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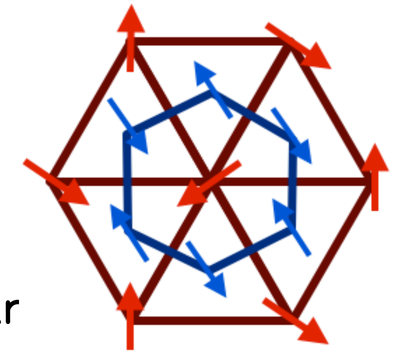
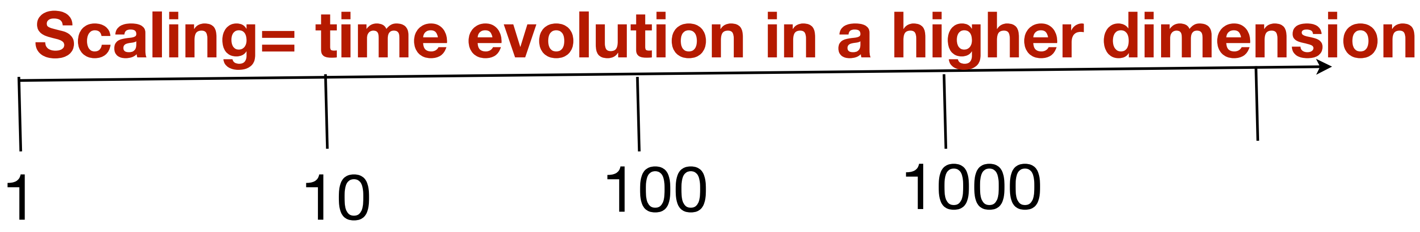
Friedan '80, Hamilton '81, Perelmar





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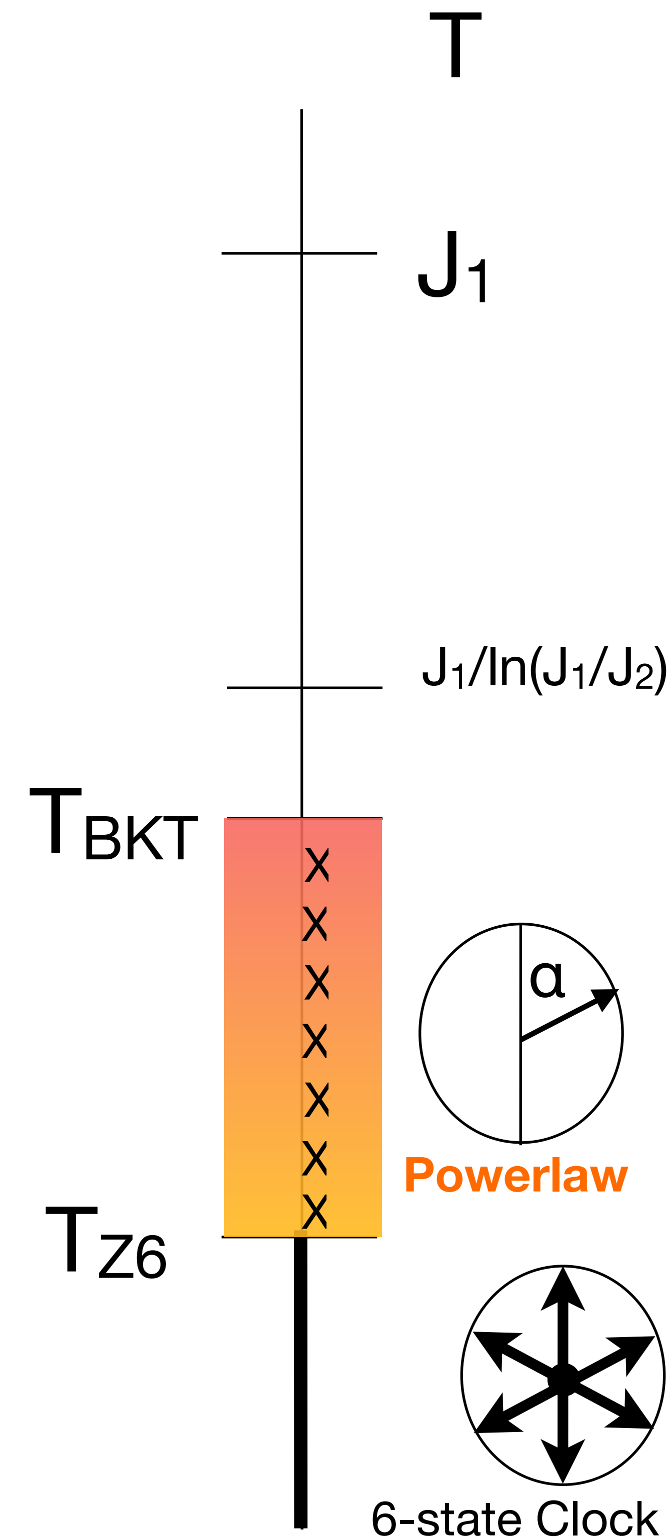
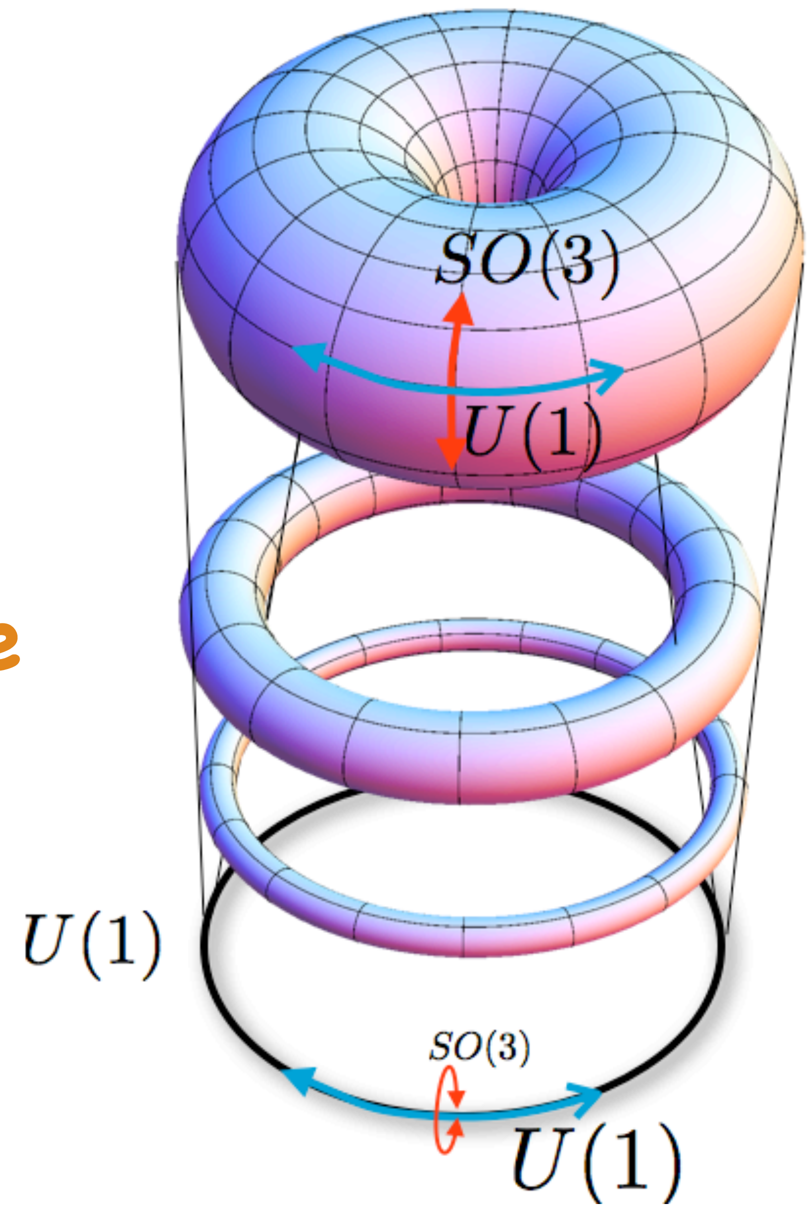




Can this mapping of renormalization onto time be generalized?

Part II

Part II:
COMPOSITE PAIRS

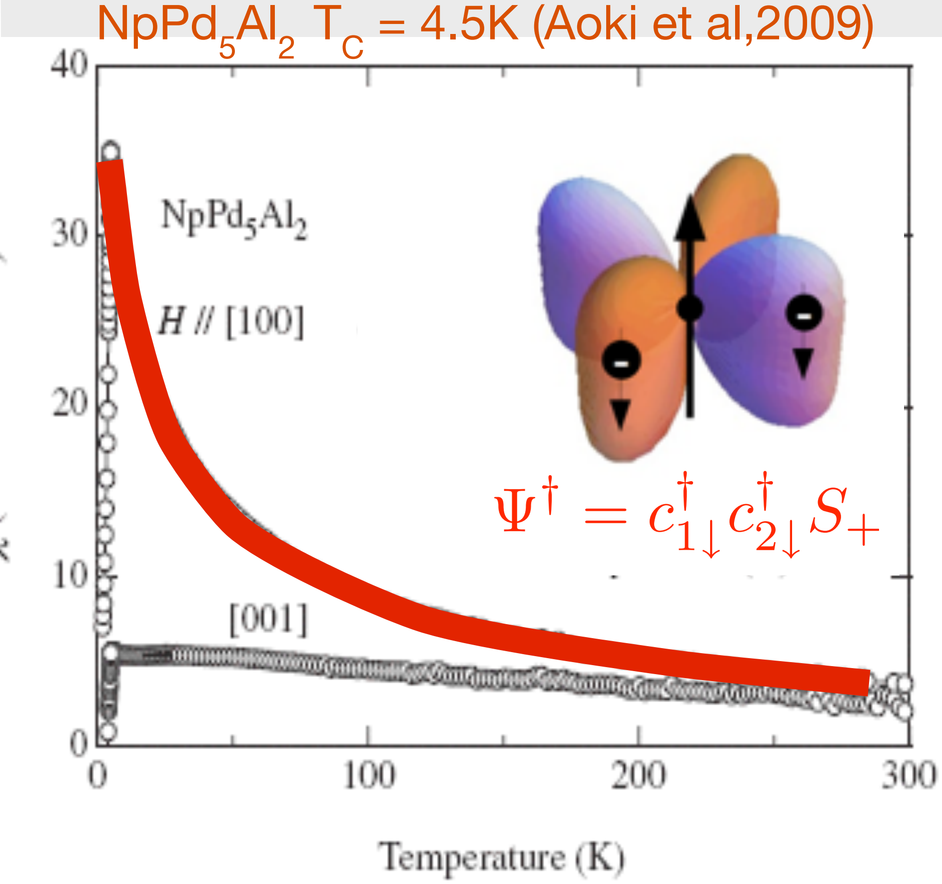
How a chance conversation with a particle physicist colleague led to a new idea about superconductivity.

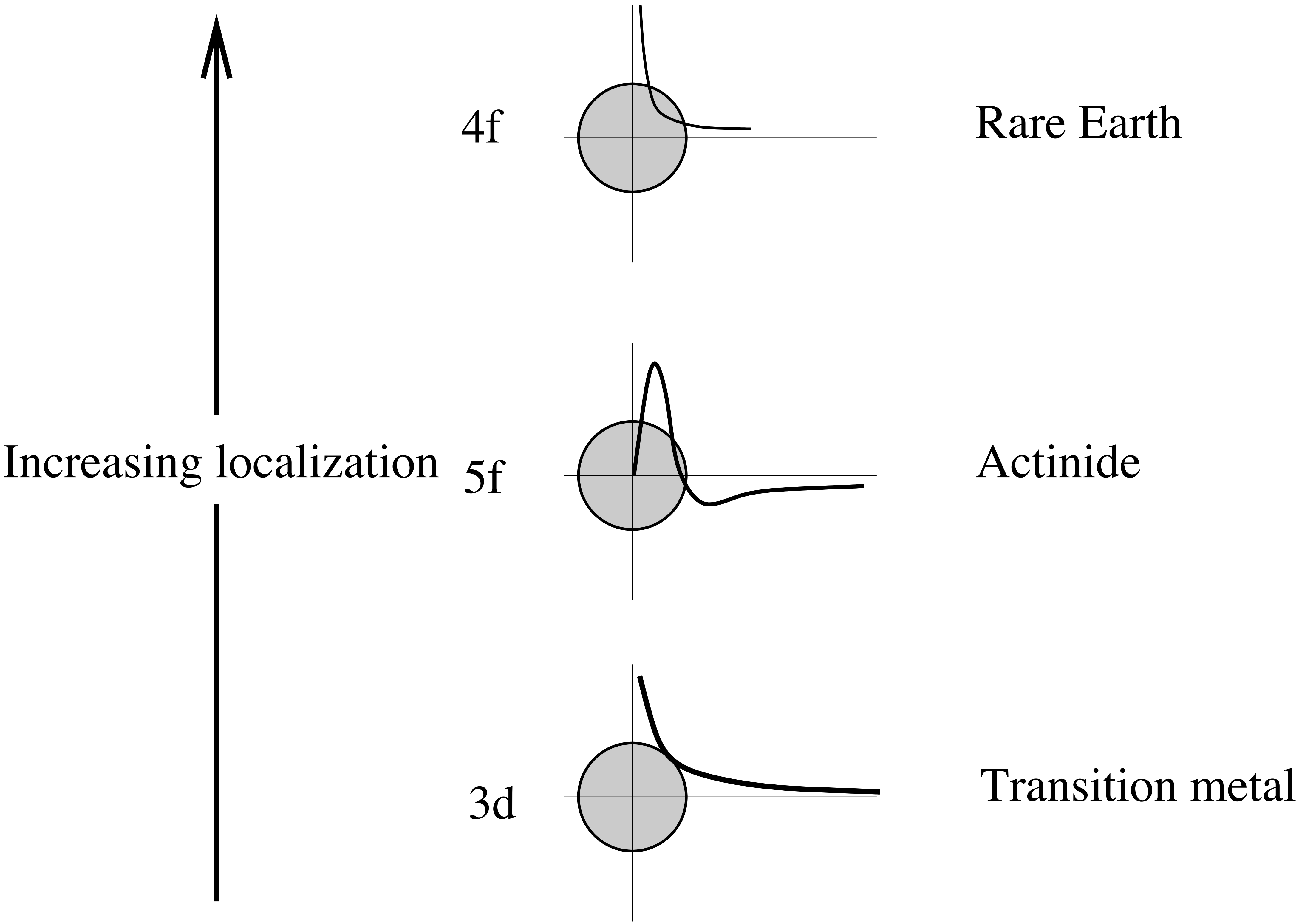
Onur Erten	Rutgers
Rebecca Flint	Iowa State.
Maxim Dzero	Kent State
Andriy Nevidomskyy	Rice
Alexei Tsvelik	Brookhaven NL
Hai Young Kee	U. Toronto
Natan Andrei	Rutgers

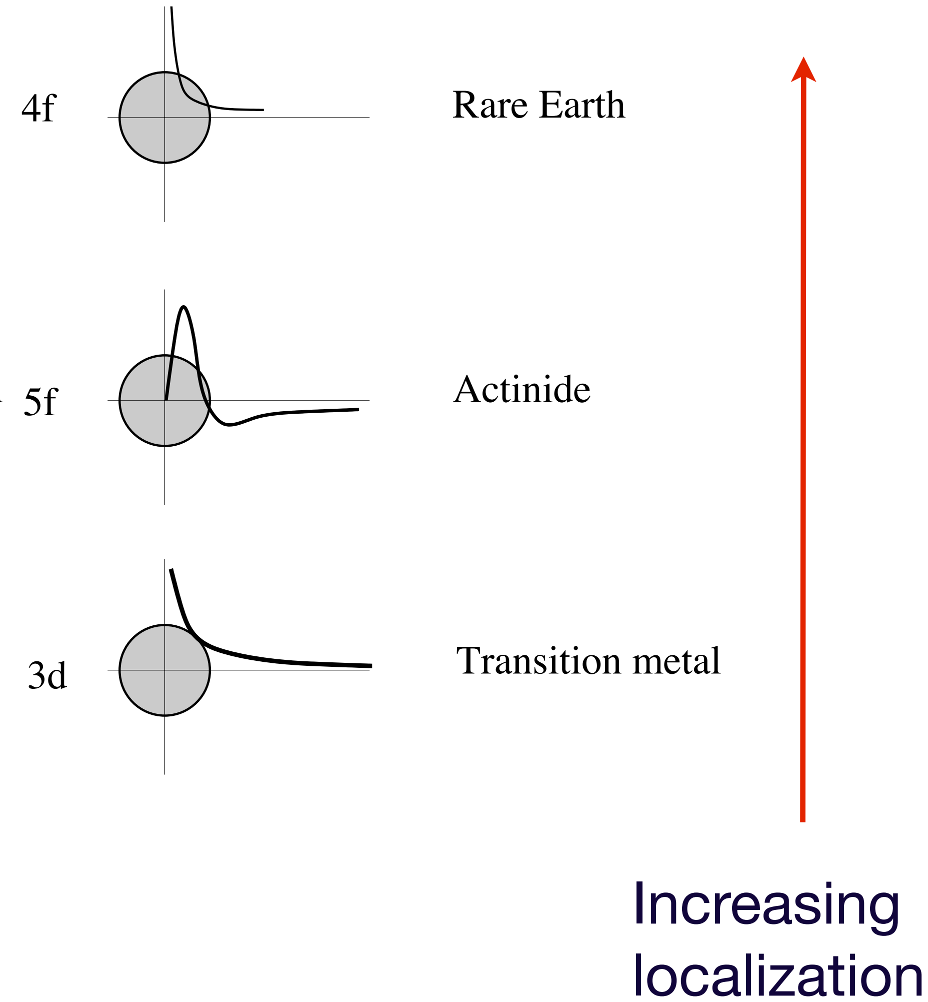
Strings

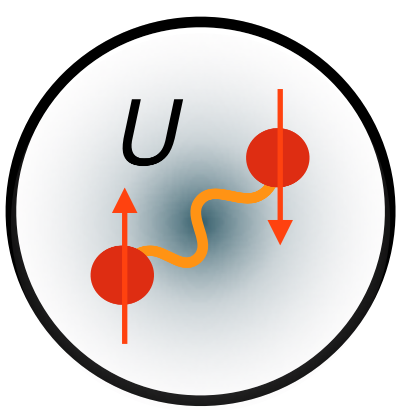
Super C

$NpPd_5Al_2$ T_C = 4.5K (Aoki et al,2009)



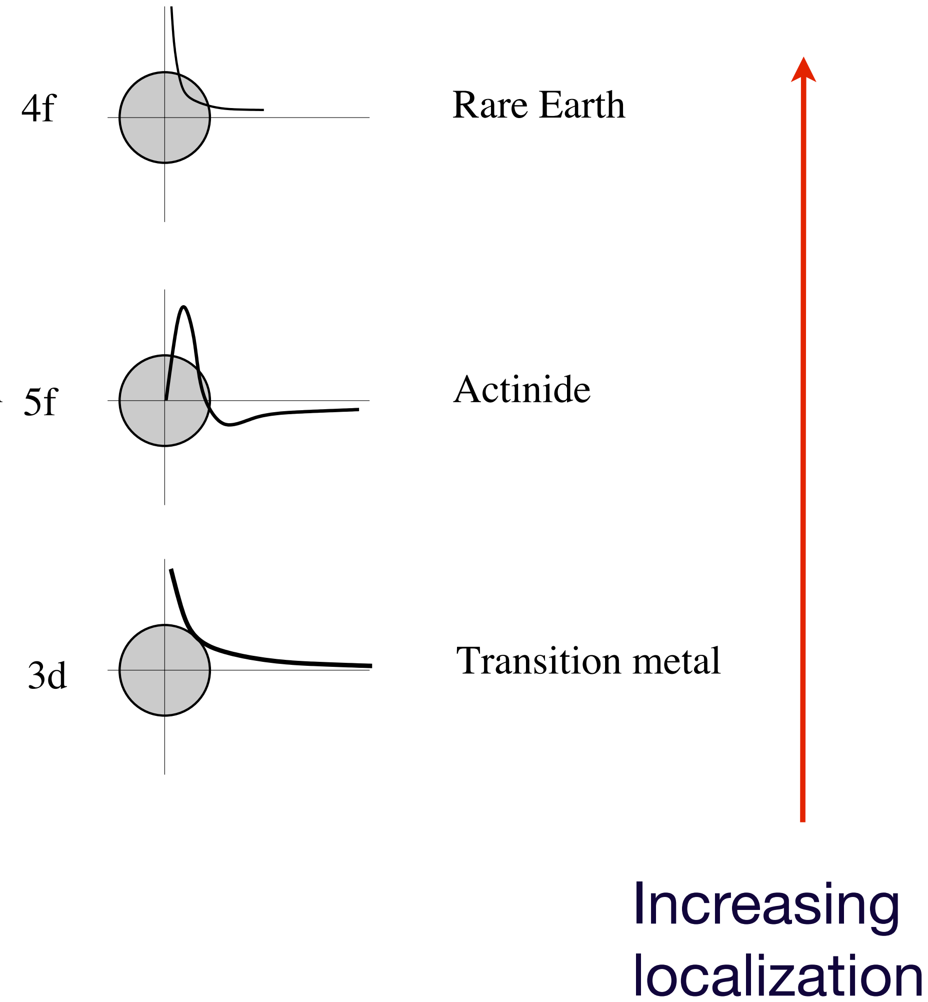

Increasing localization
4f
Rare Earth
5f
Actinide
3d
Transition metal

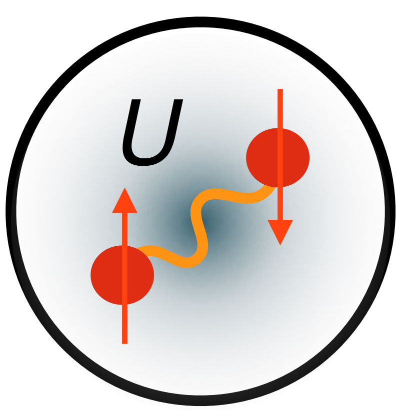




Mott Mechanism.

Anderson U (Anderson 1959)





- No double occupancy: strongly correlated

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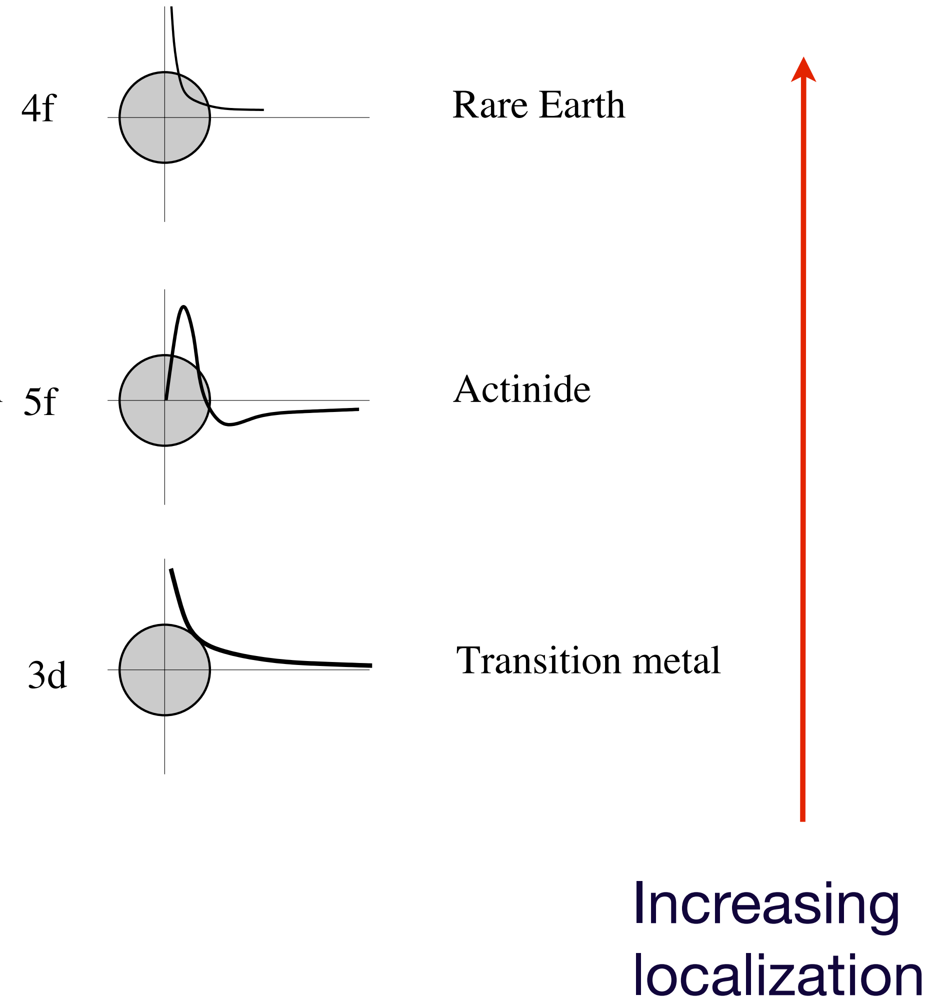

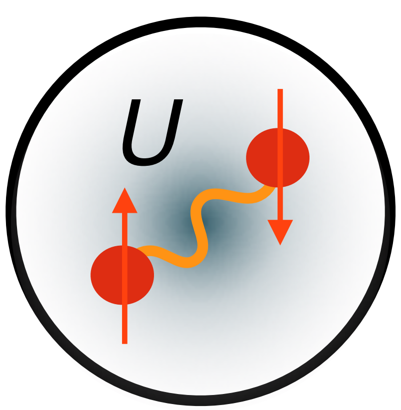

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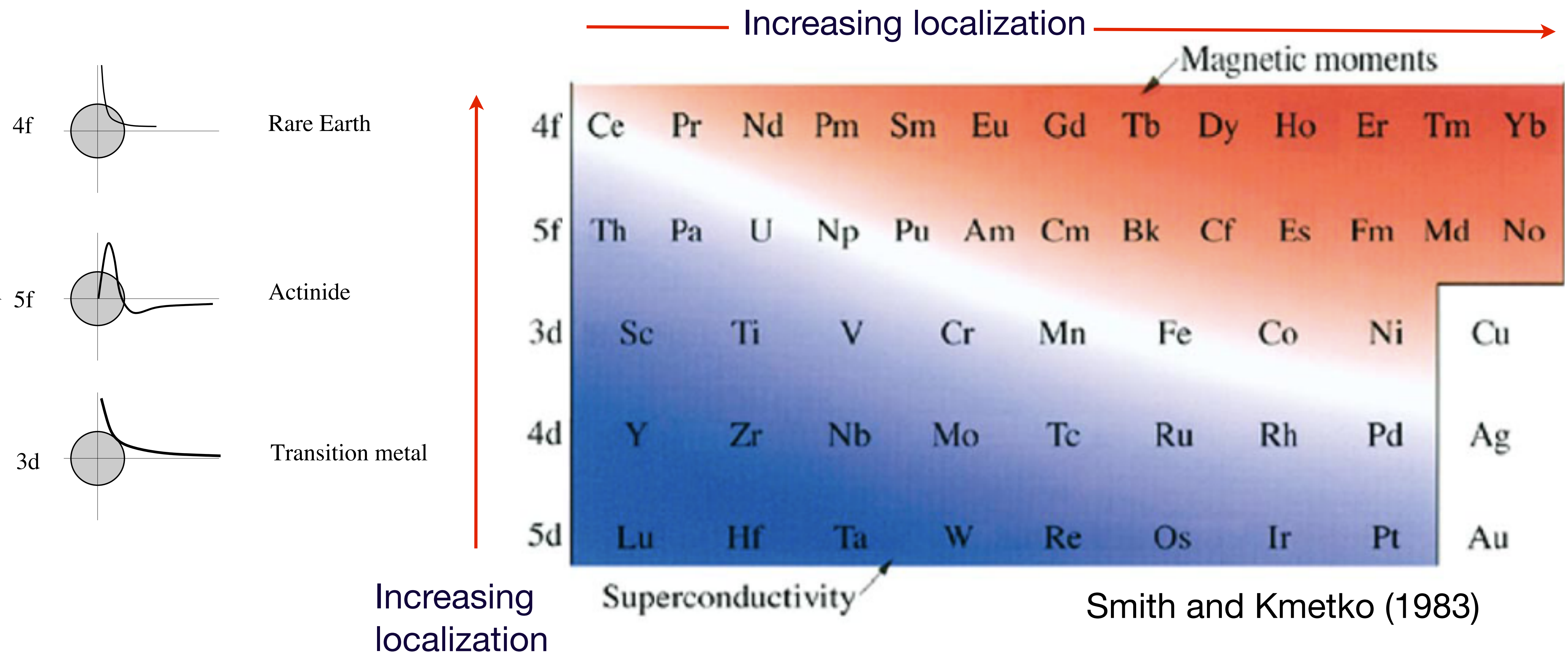

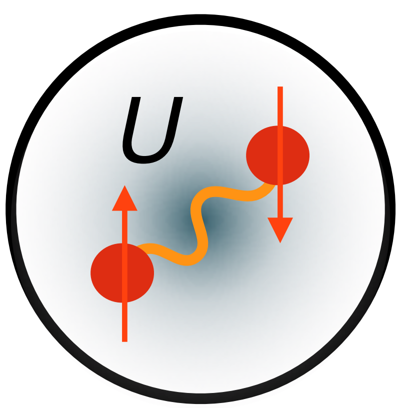

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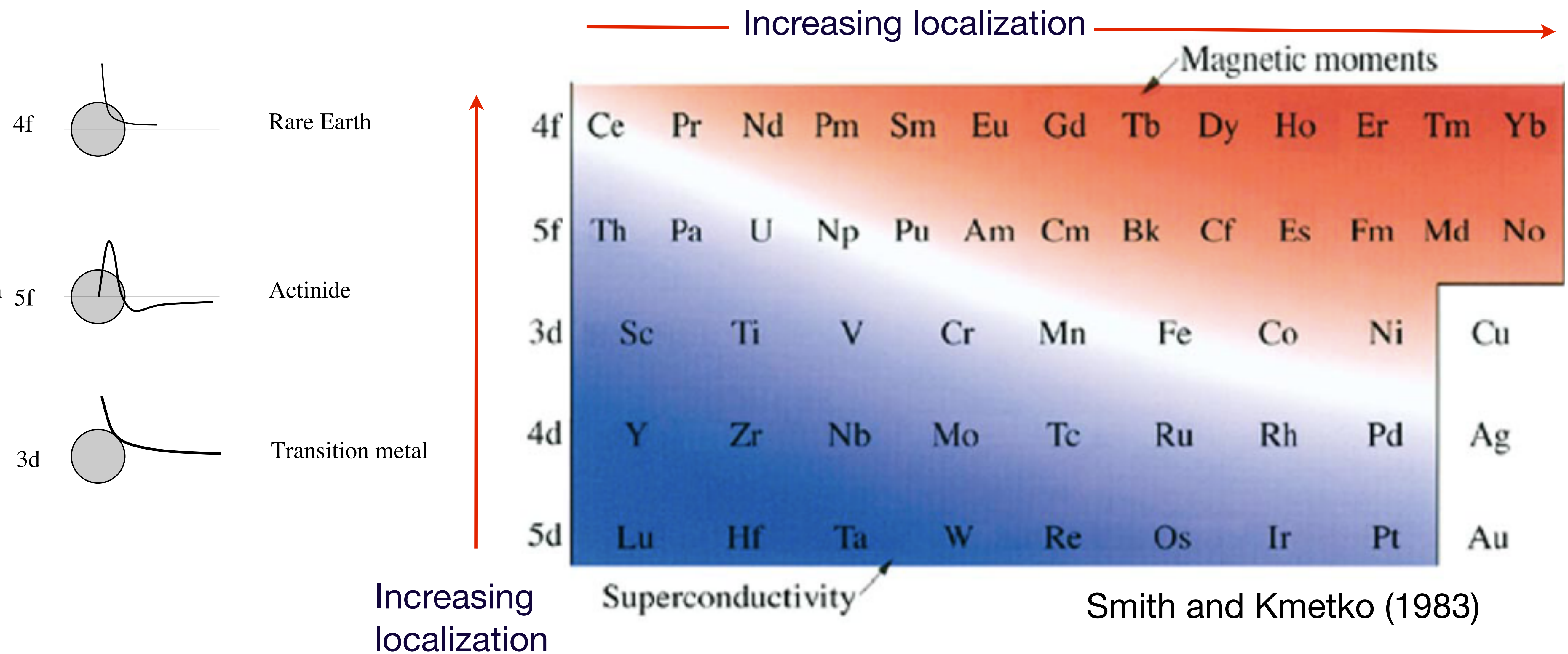
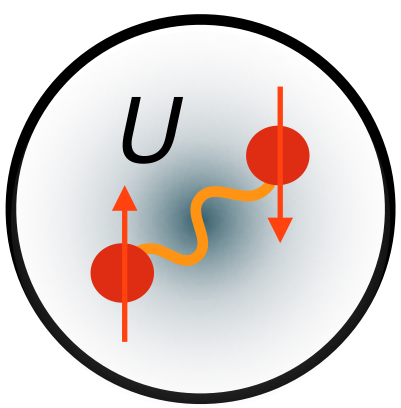


Smith and Kmetko (1983)



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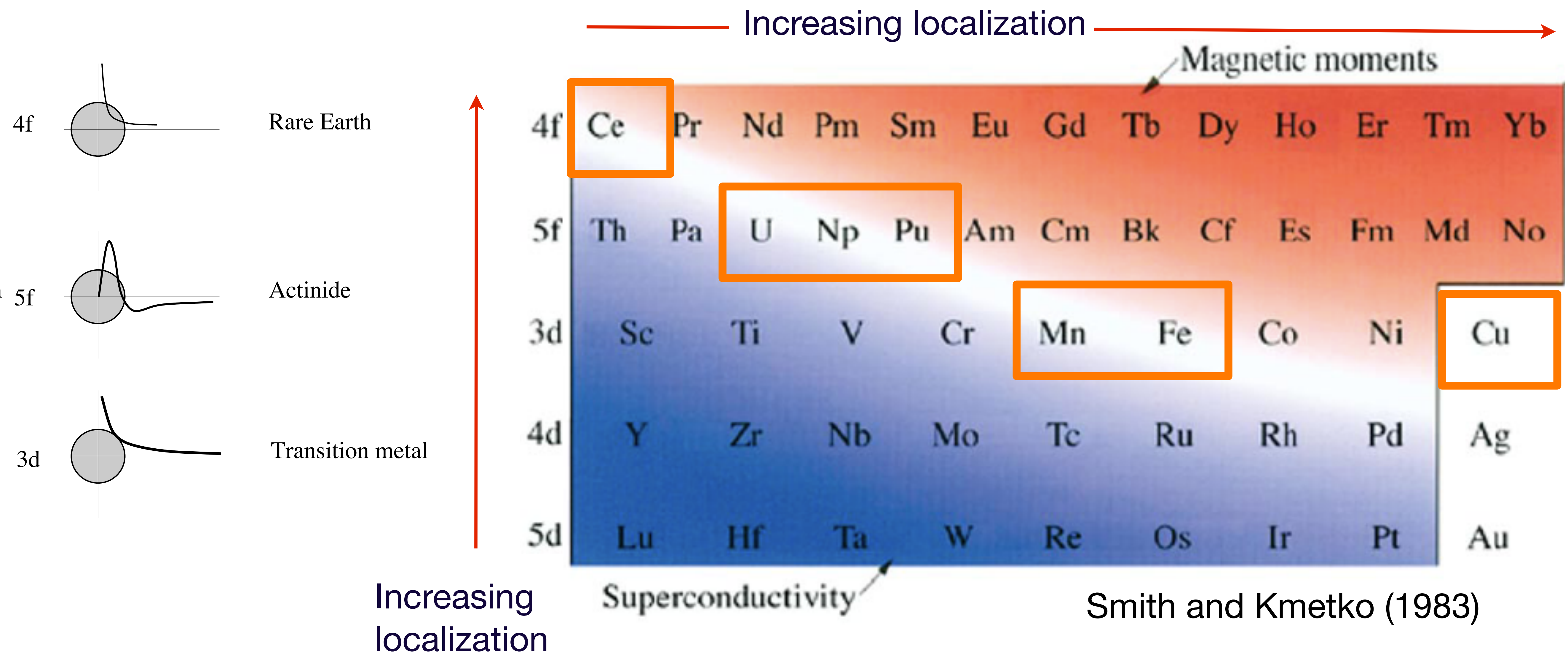

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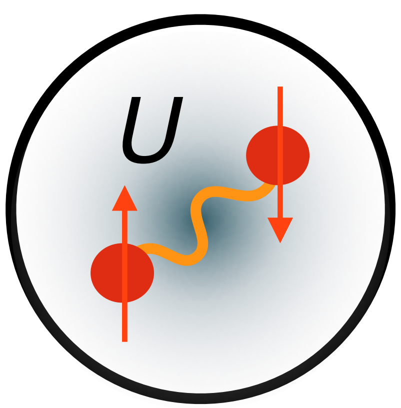

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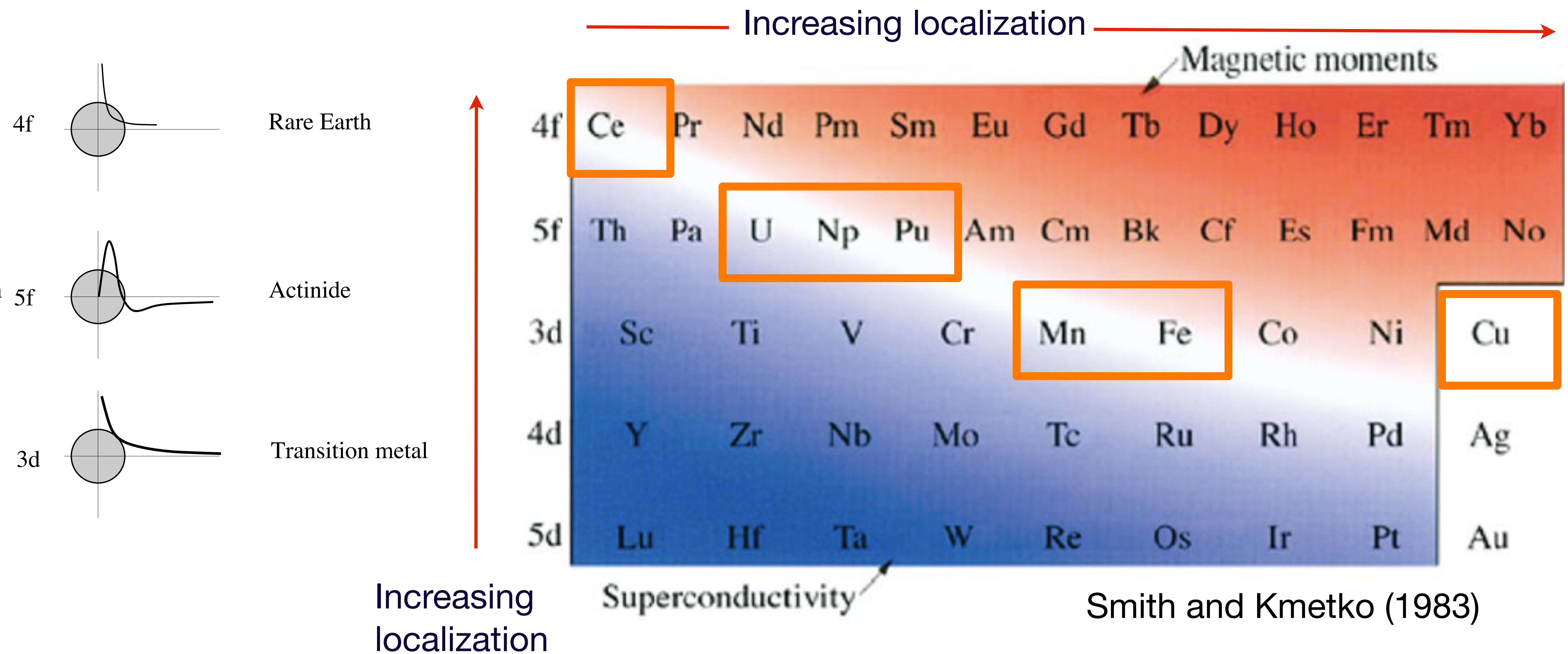

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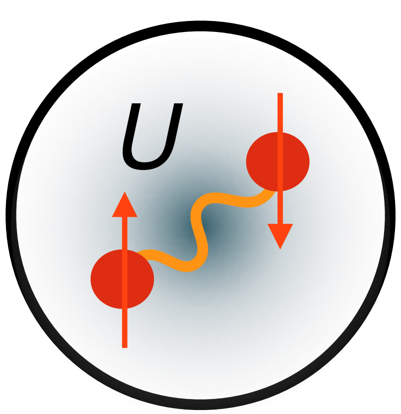
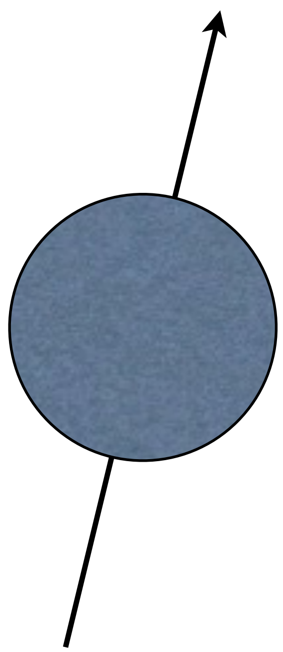


Many things are possible at the brink of magnetism.

Mott Mechanism.

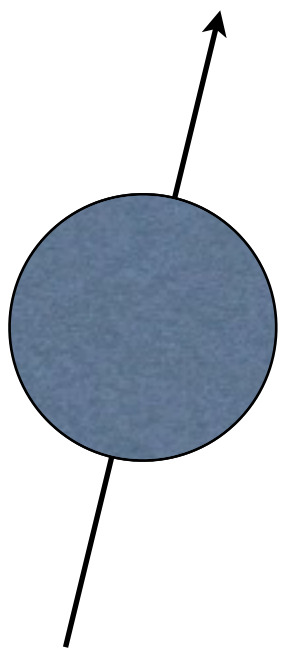
Anderson U (Anderson 1959)

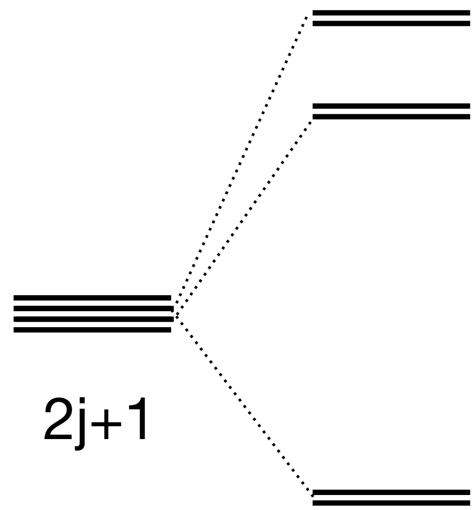
Heavy Fermions + Kondo



Spin (4f,5f): “Quark”of
heavy electron physics.

Heavy Fermions + Kondo





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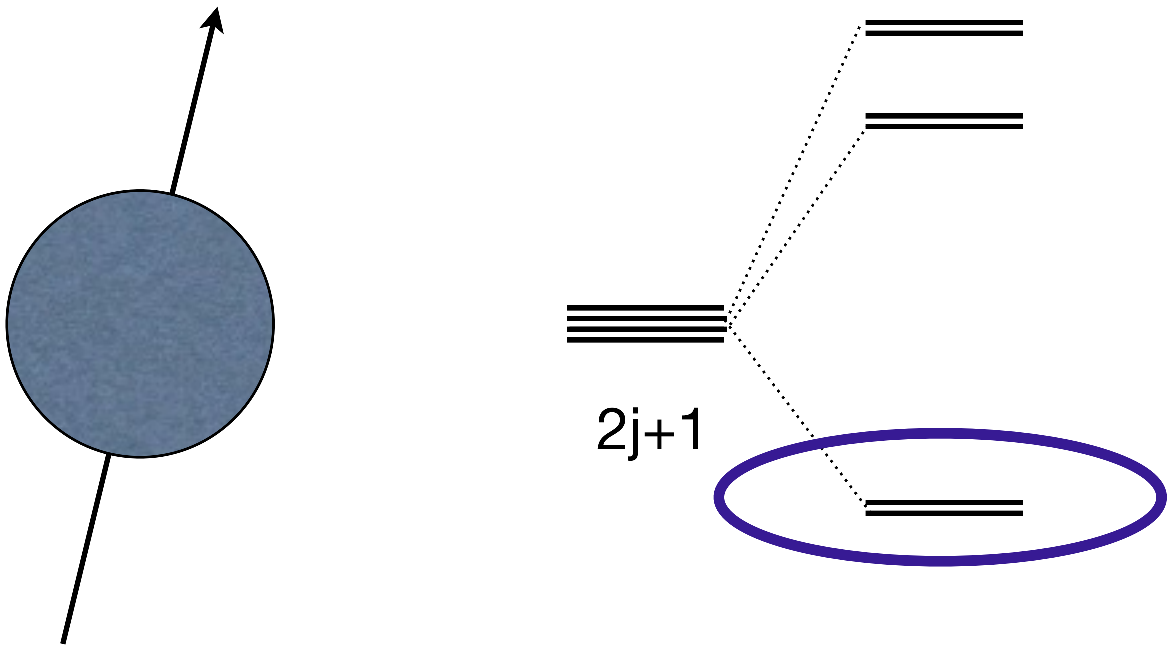

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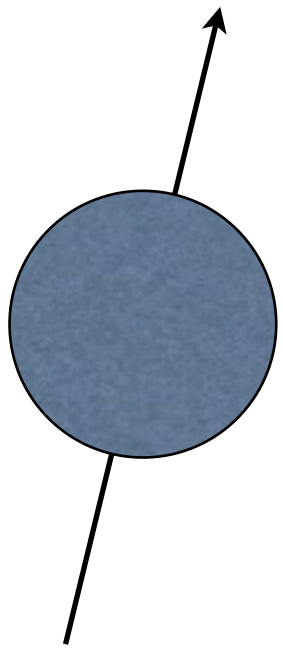
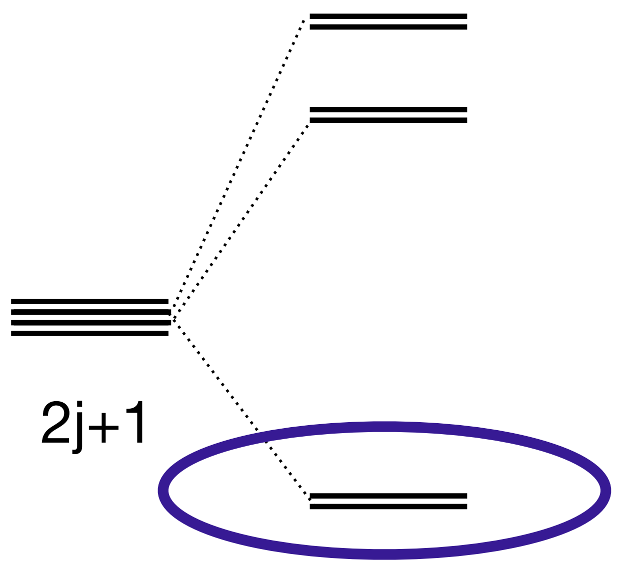
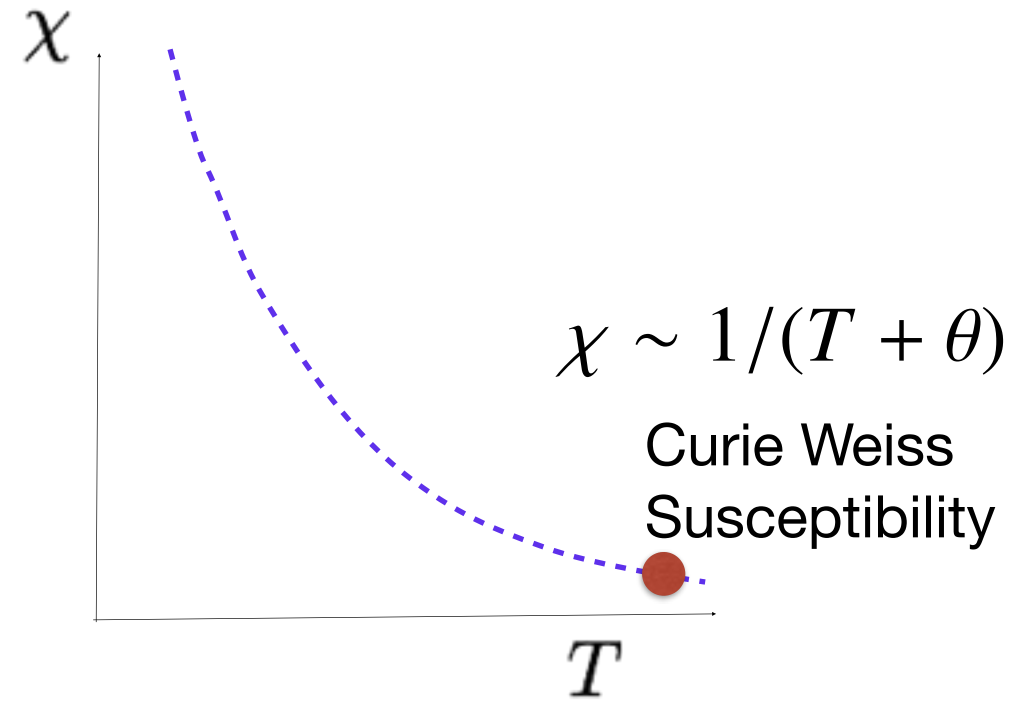
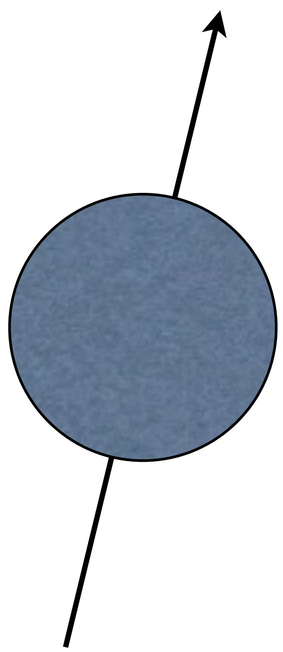






Spin (4f,5f): “Quark”of
heavy electron physics.

Heavy Fermions + Kondo



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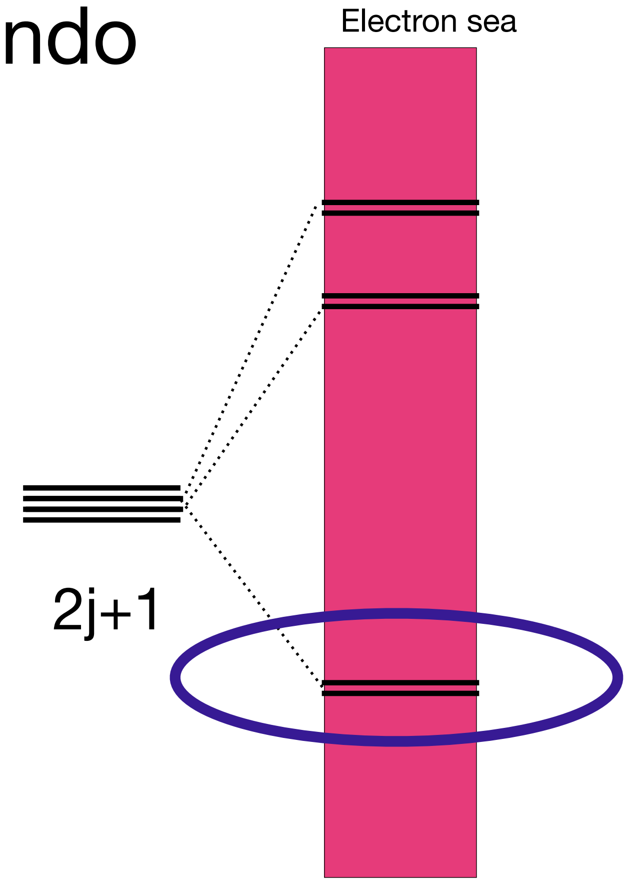

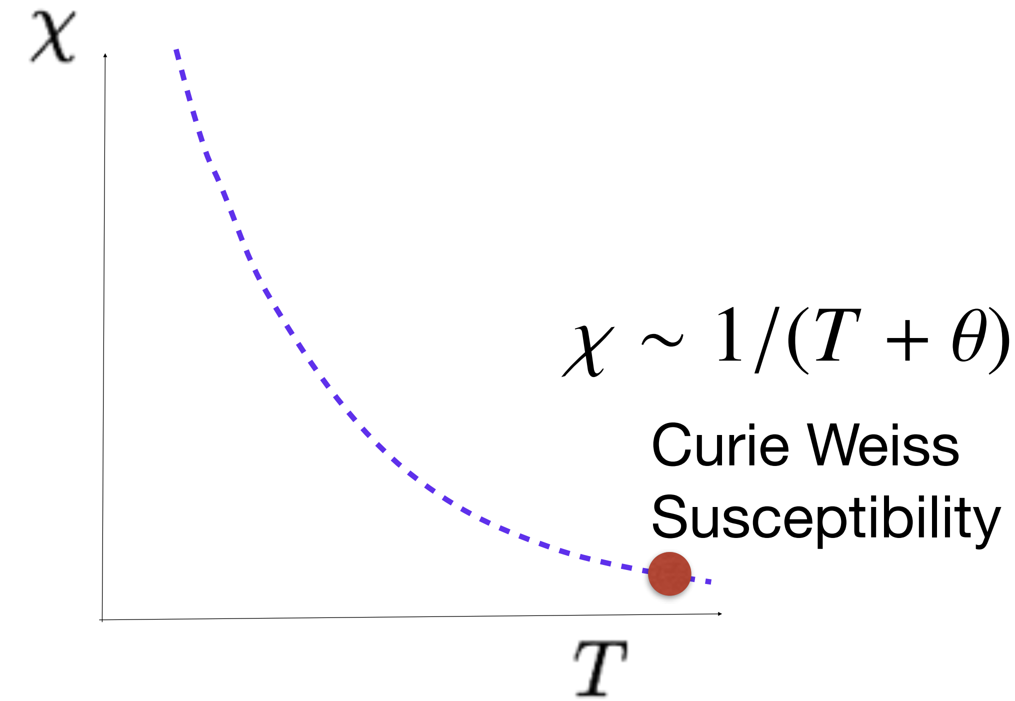

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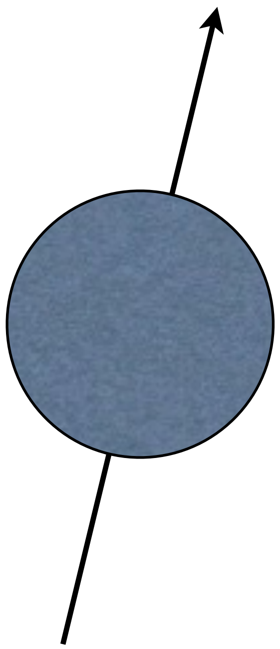
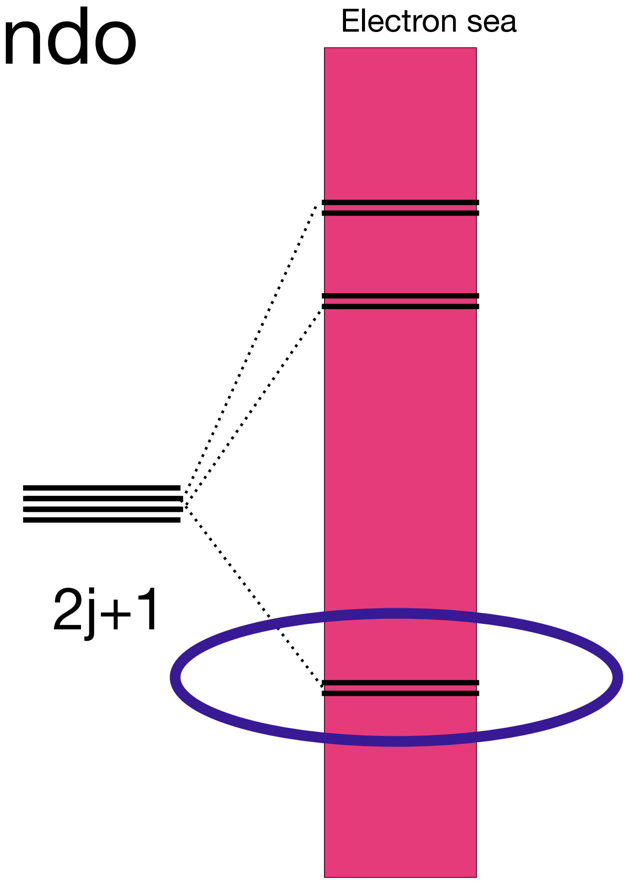
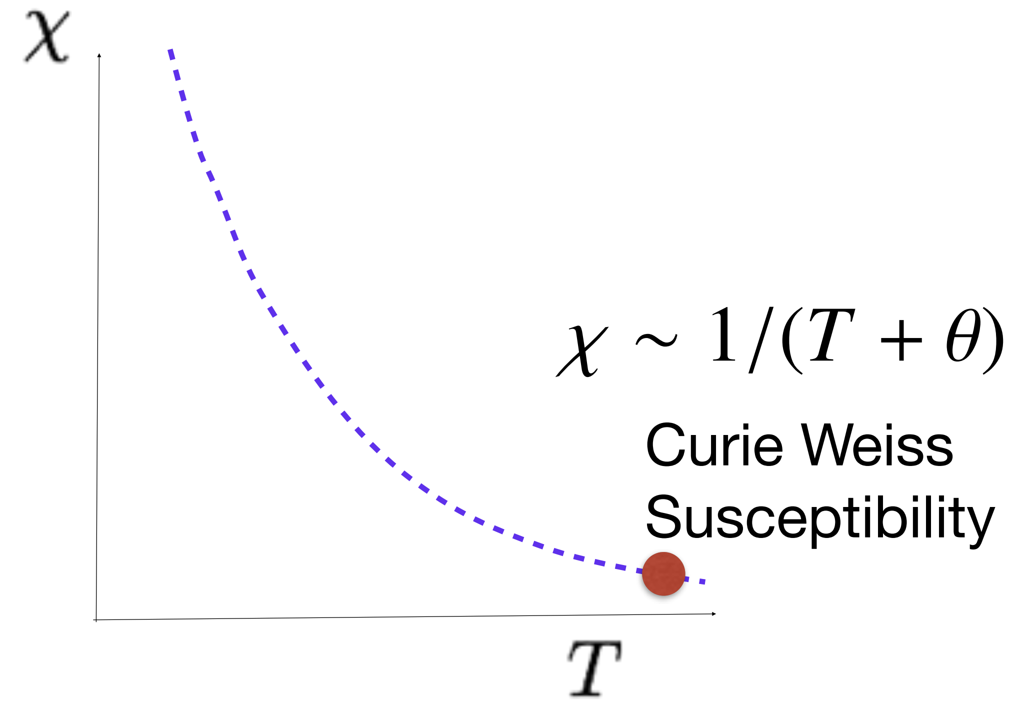
J. Kondo, 1962

Heavy Fermions + Kondo







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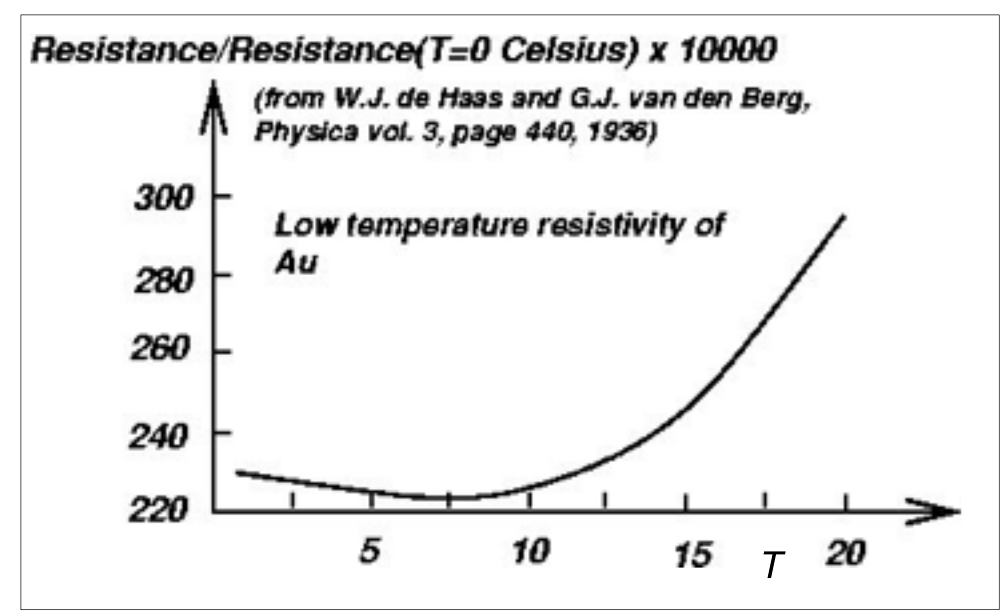

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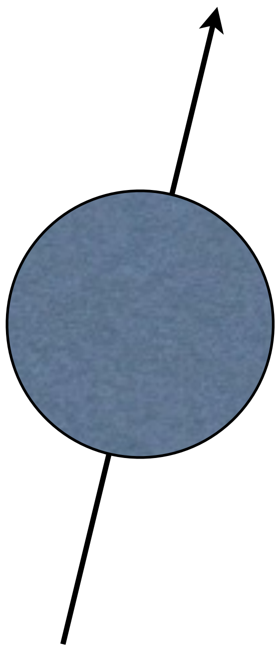

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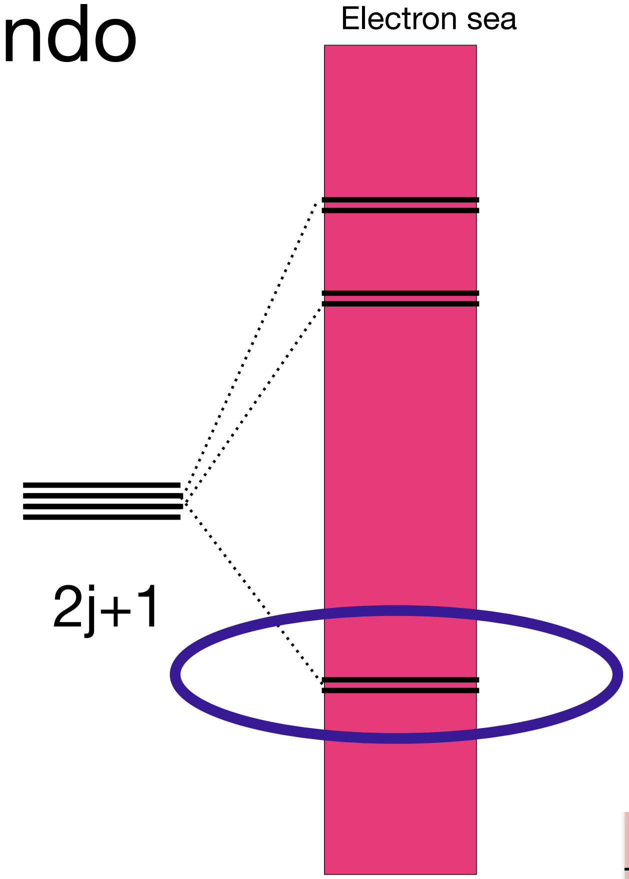

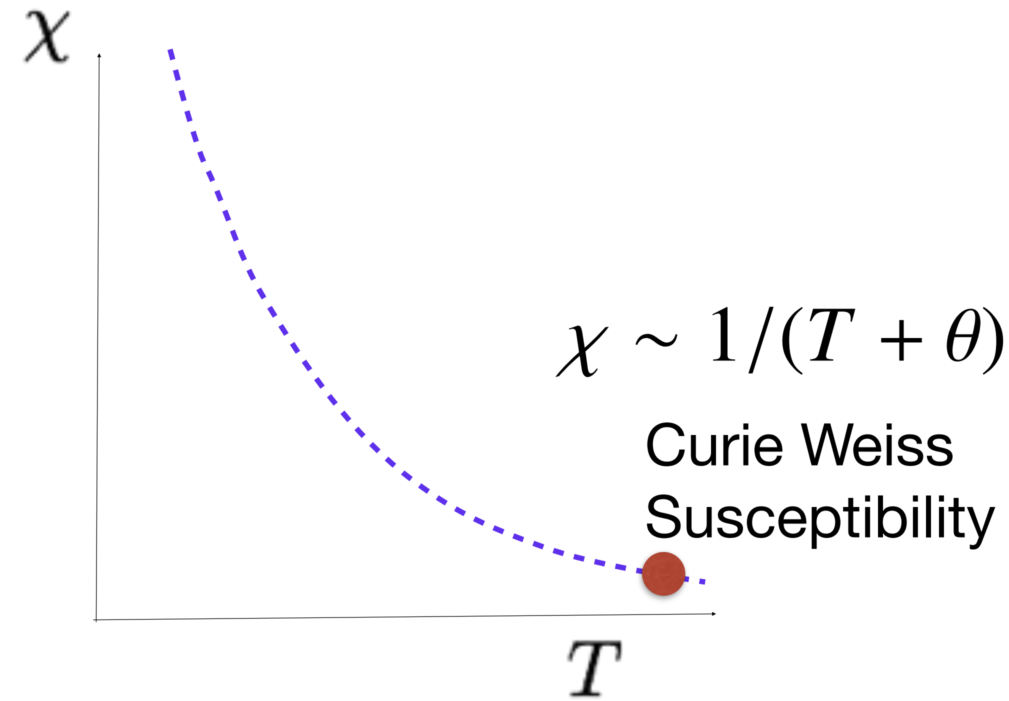

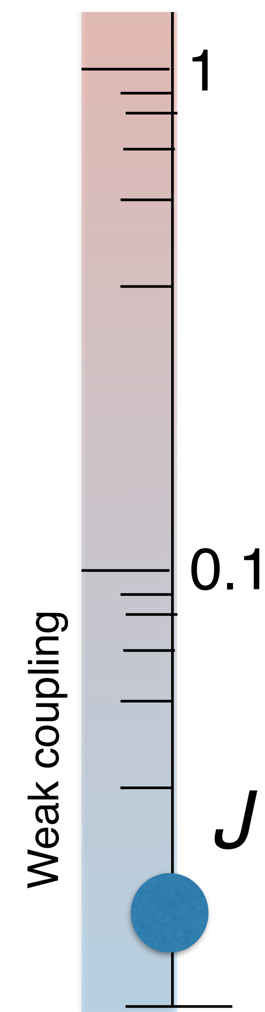

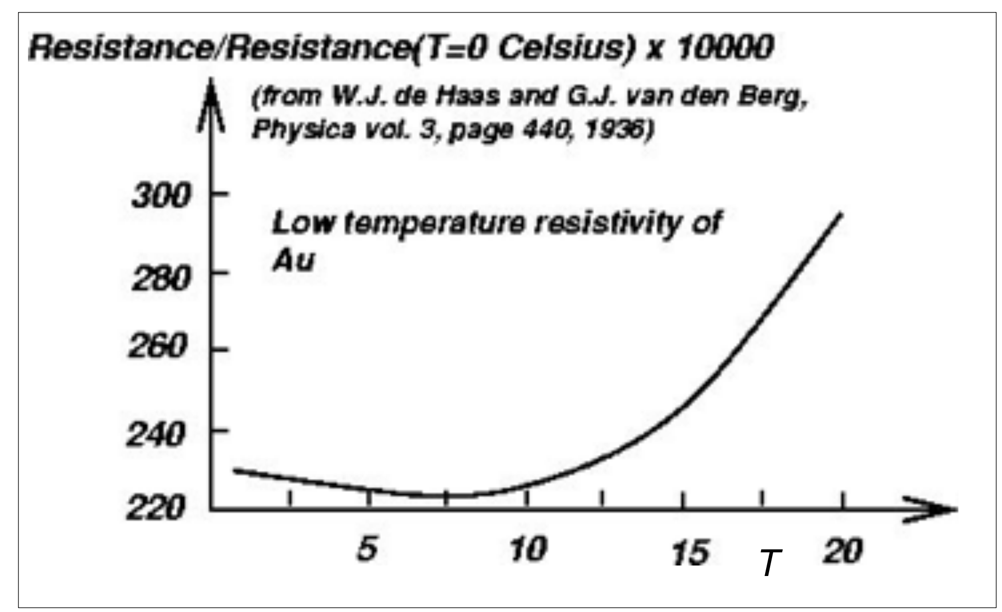

Scales to
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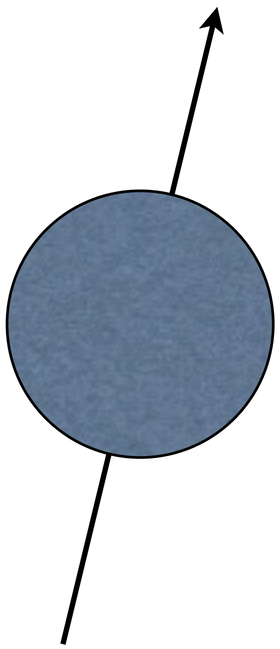

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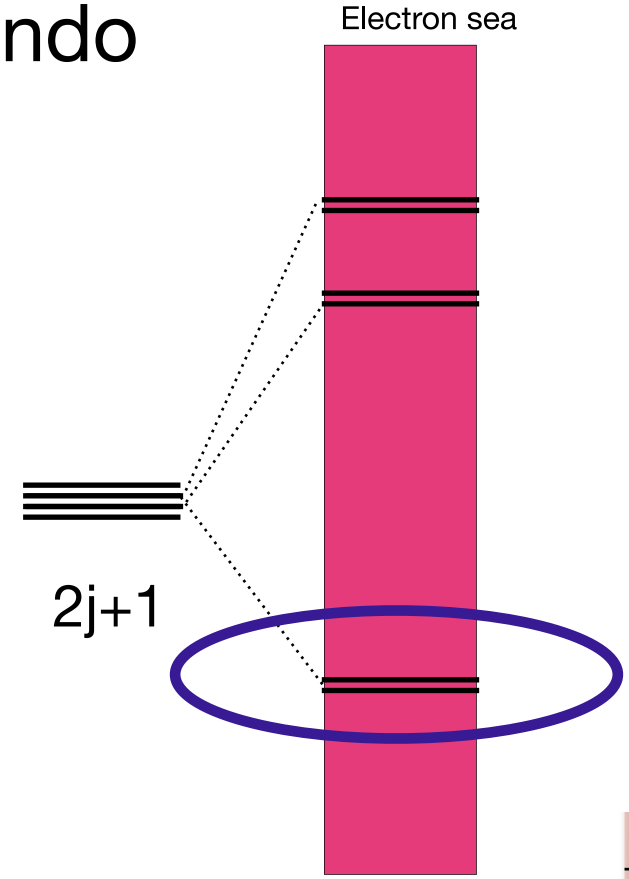
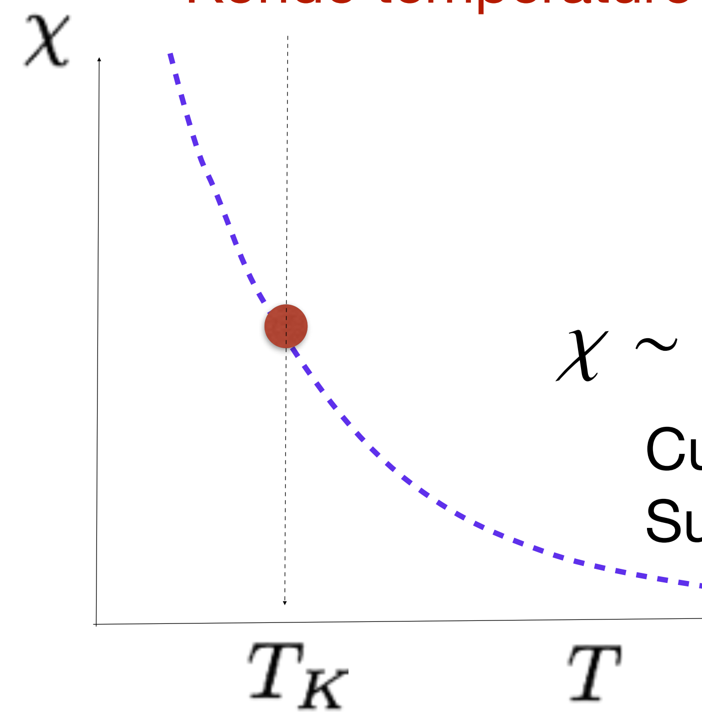


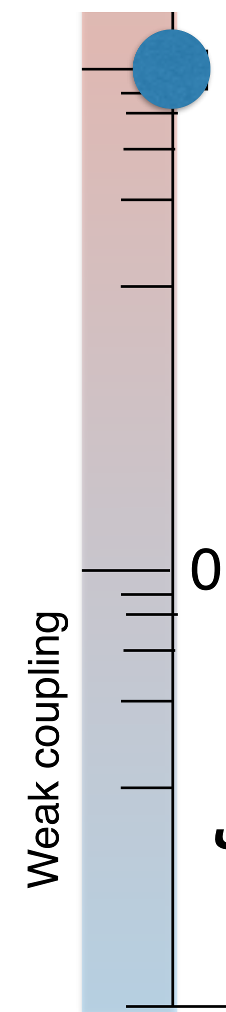
“Kondo temperature”

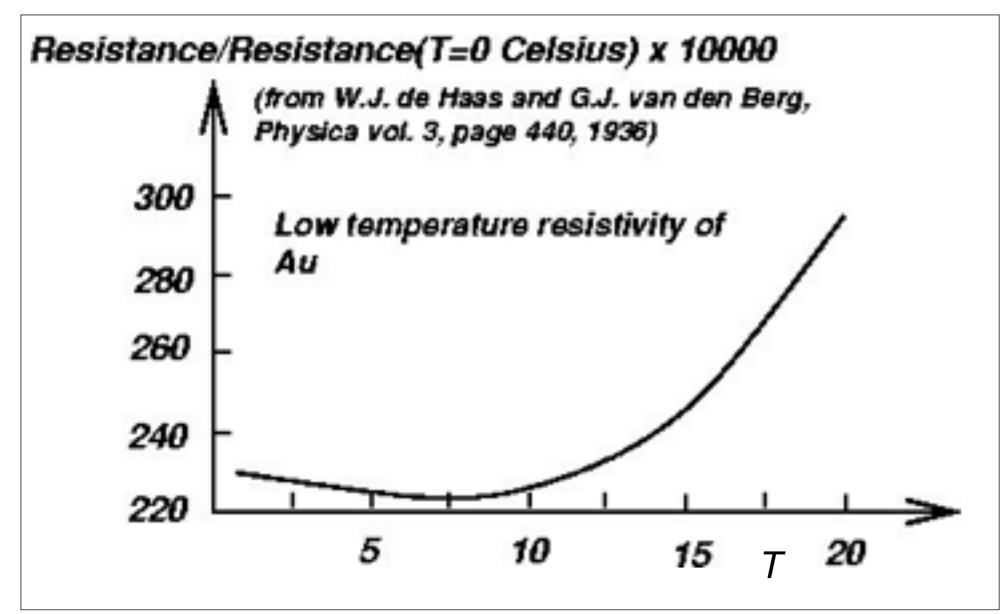


$\chi \sim 1/(T+\theta)$

Curie Weiss Susceptibility

$$T_K = W\sqrt{J\rho}\,e^{-\frac{1}{2J\rho}}$$





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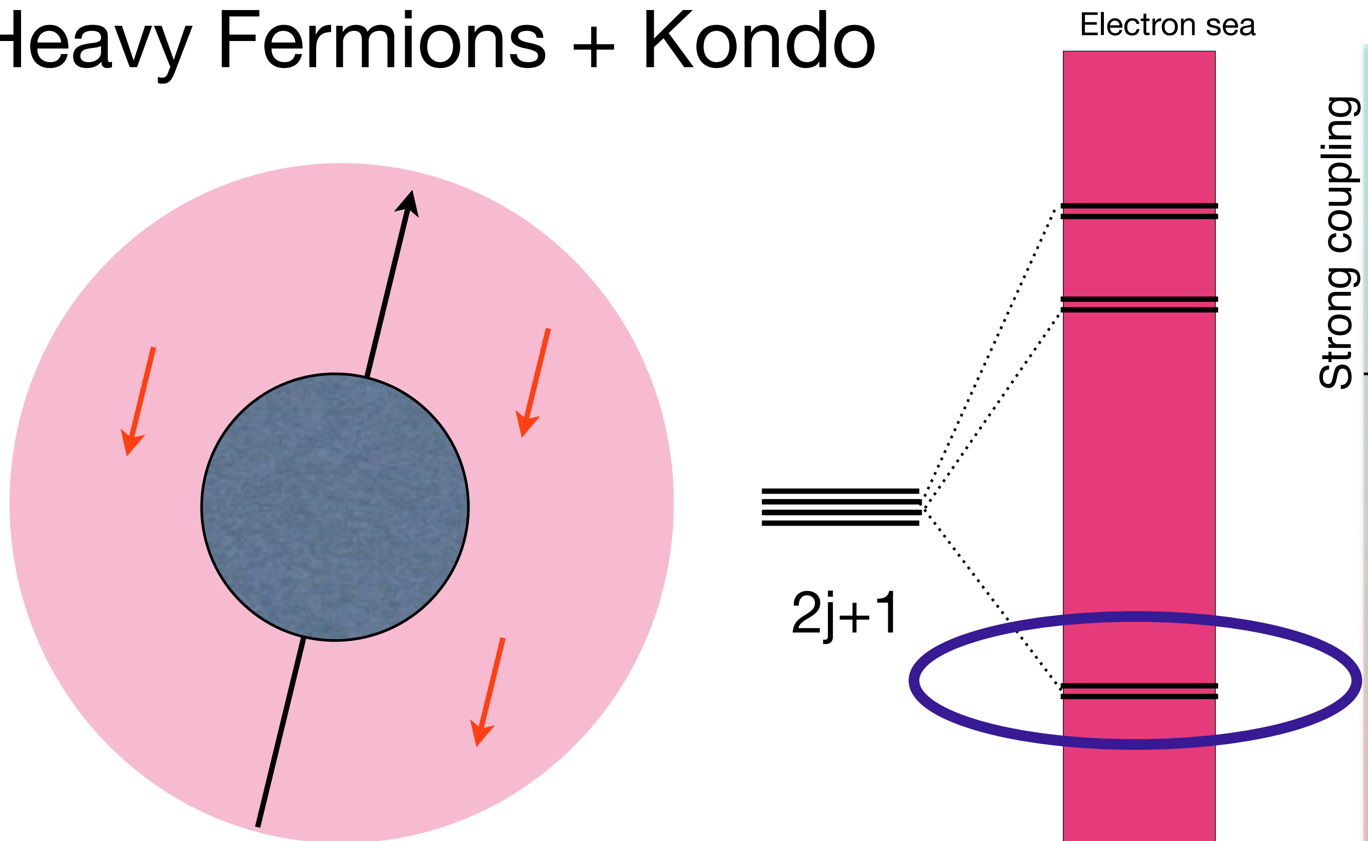

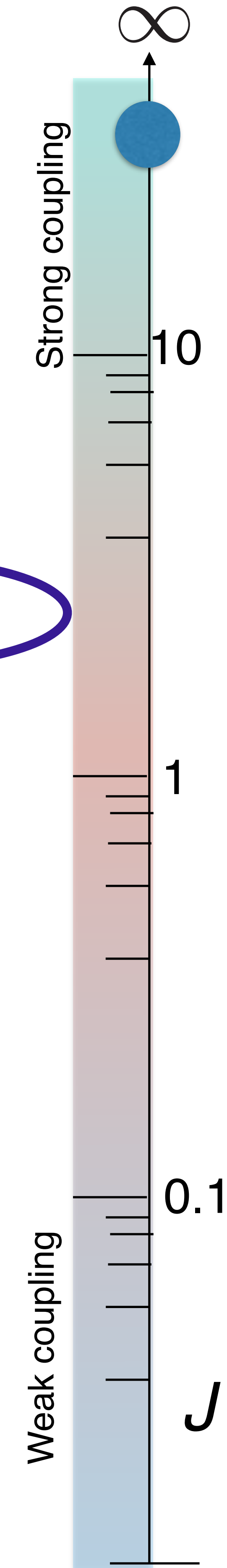

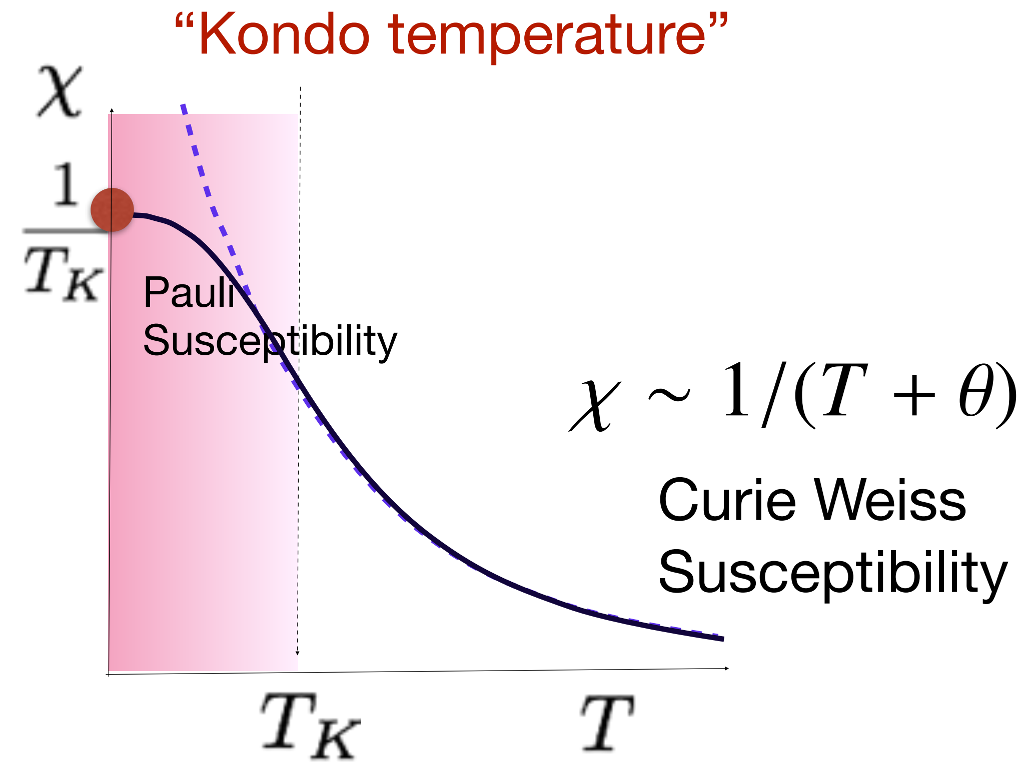

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Kondo Effect: Spin screened by conduction electrons: entangled

$$\uparrow\downarrow - \downarrow\uparrow$$

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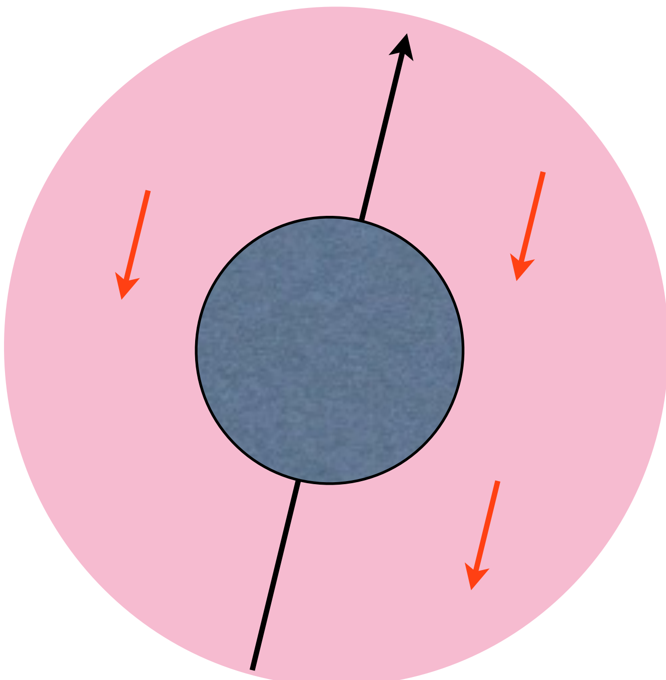
Dense Systems.



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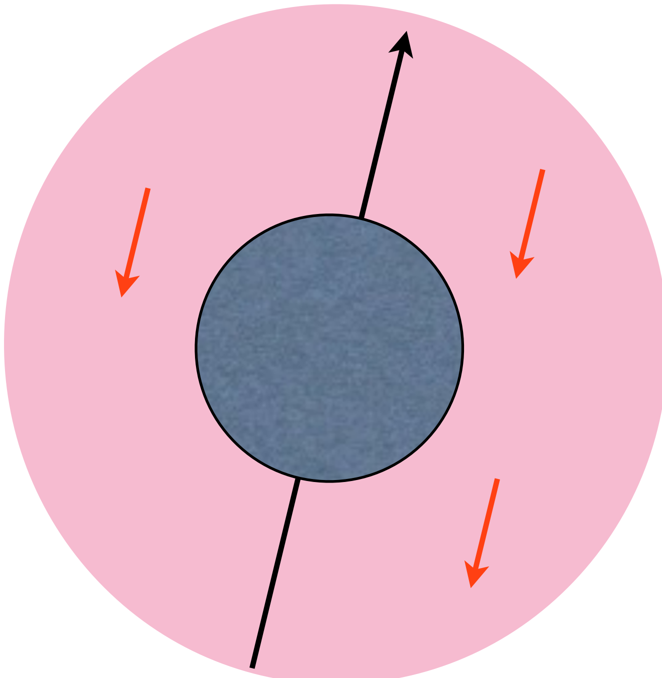
Spin entanglement entropy

Dense Systems.



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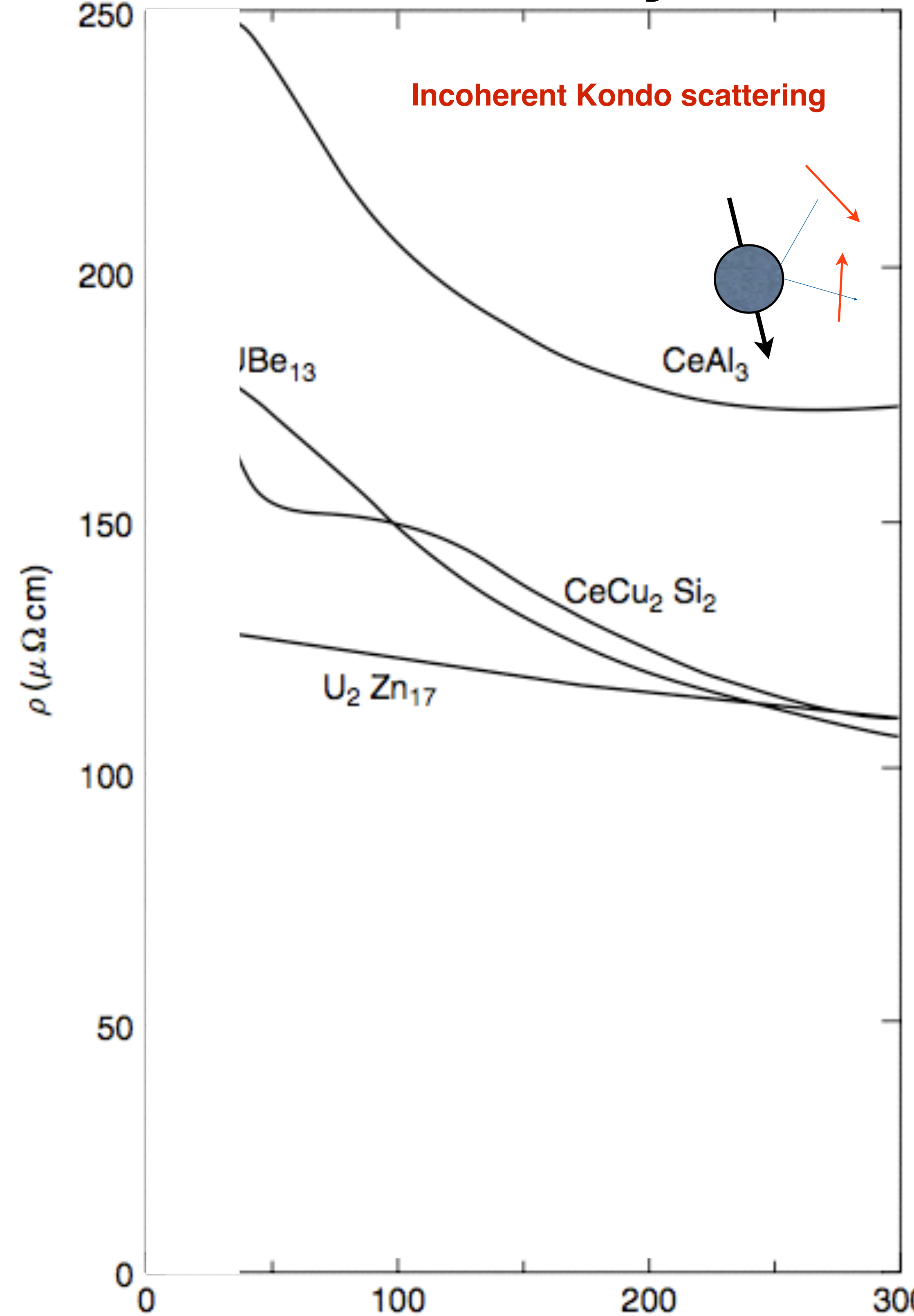

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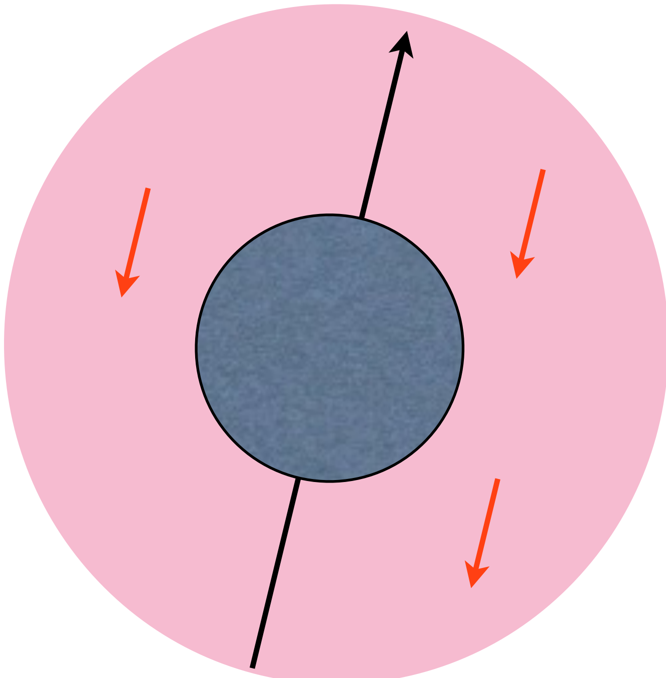

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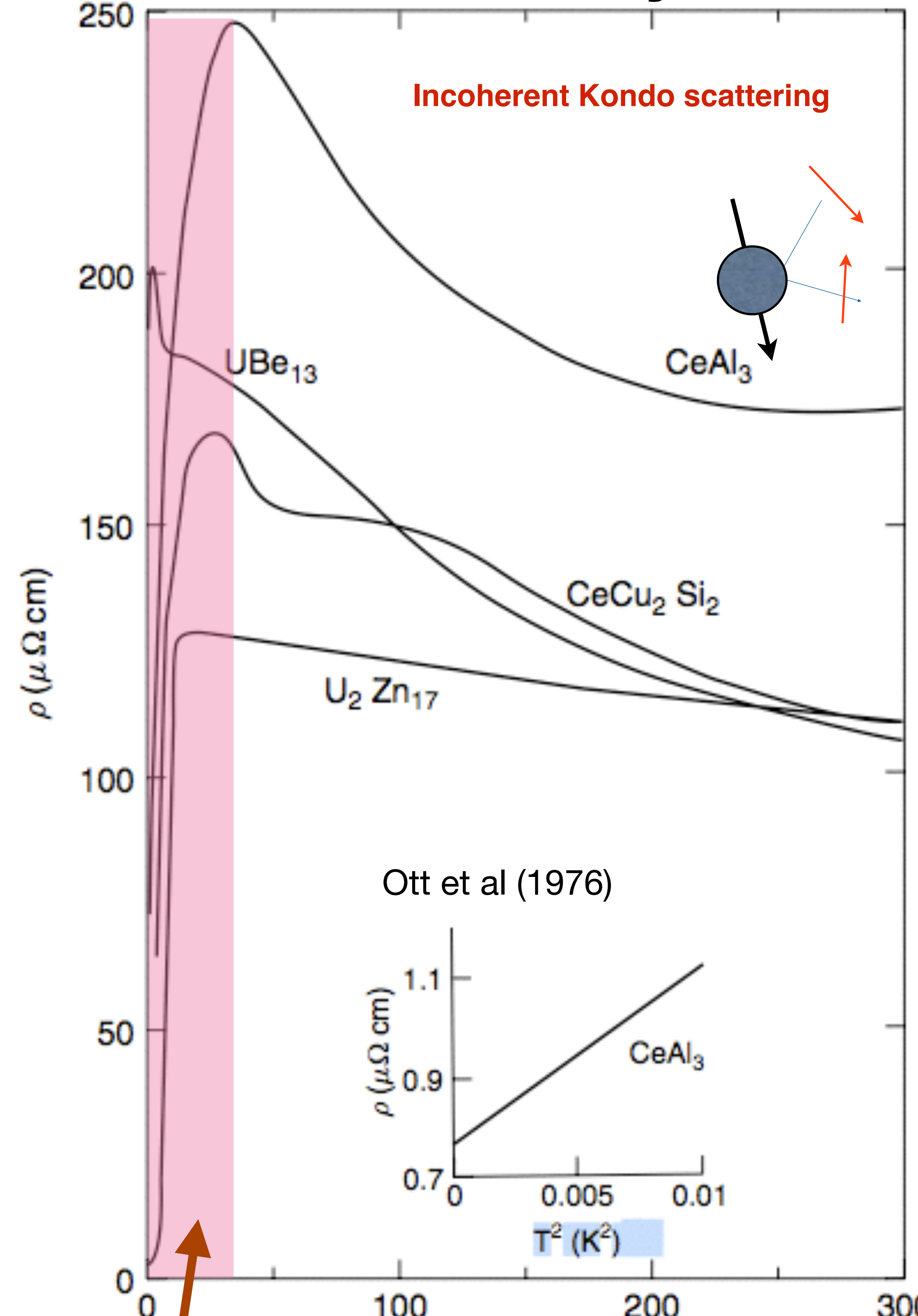
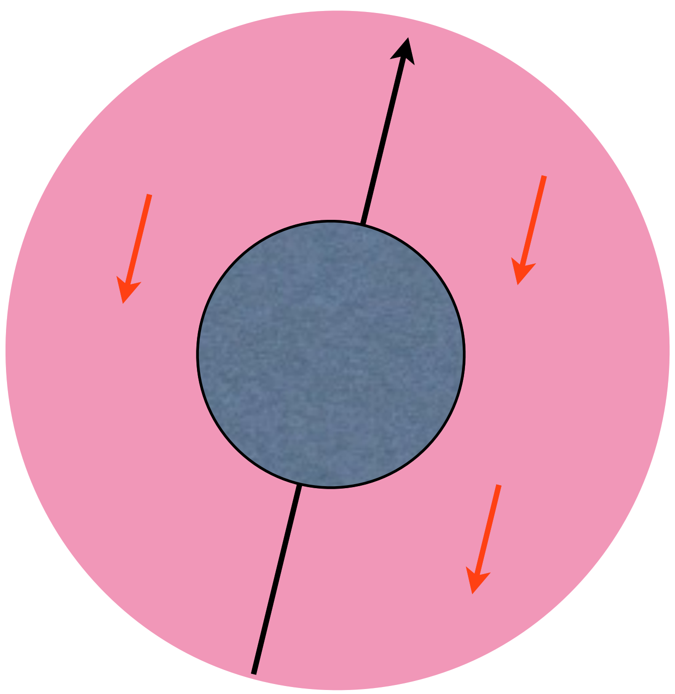


$$\rho(T) = \rho_0 + AT^2$$

Coherent Heavy Fermions

Dense Systems.



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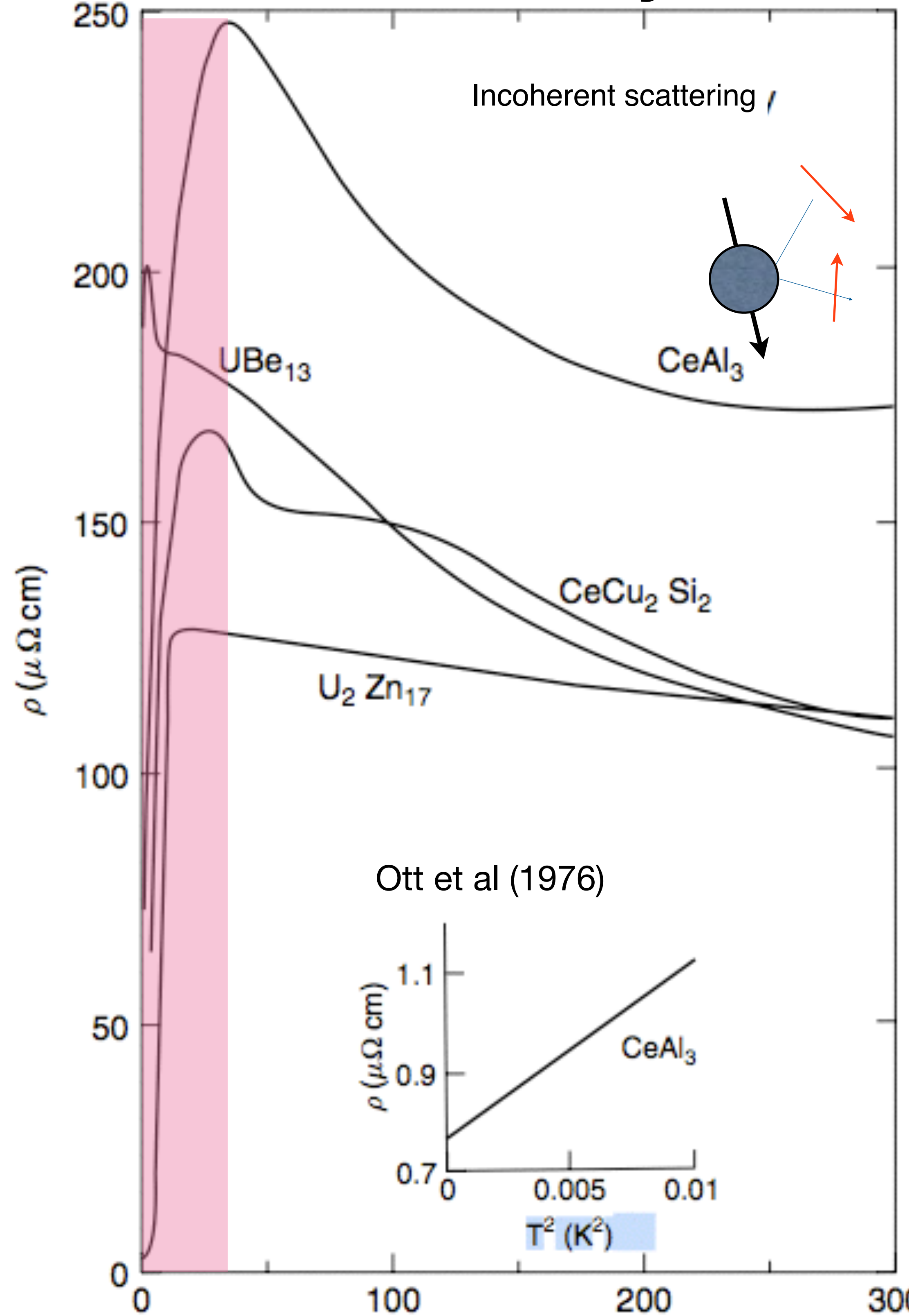

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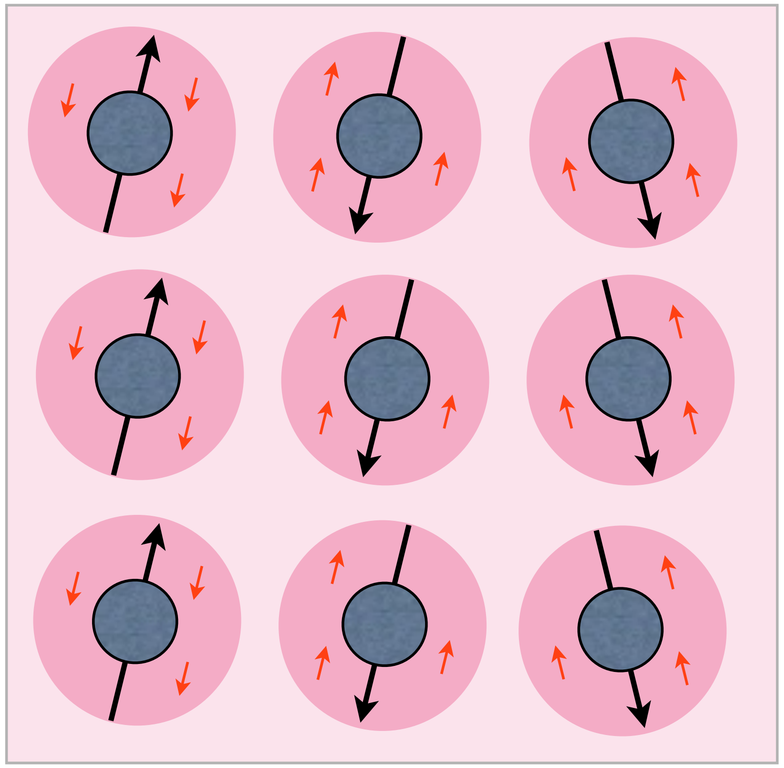
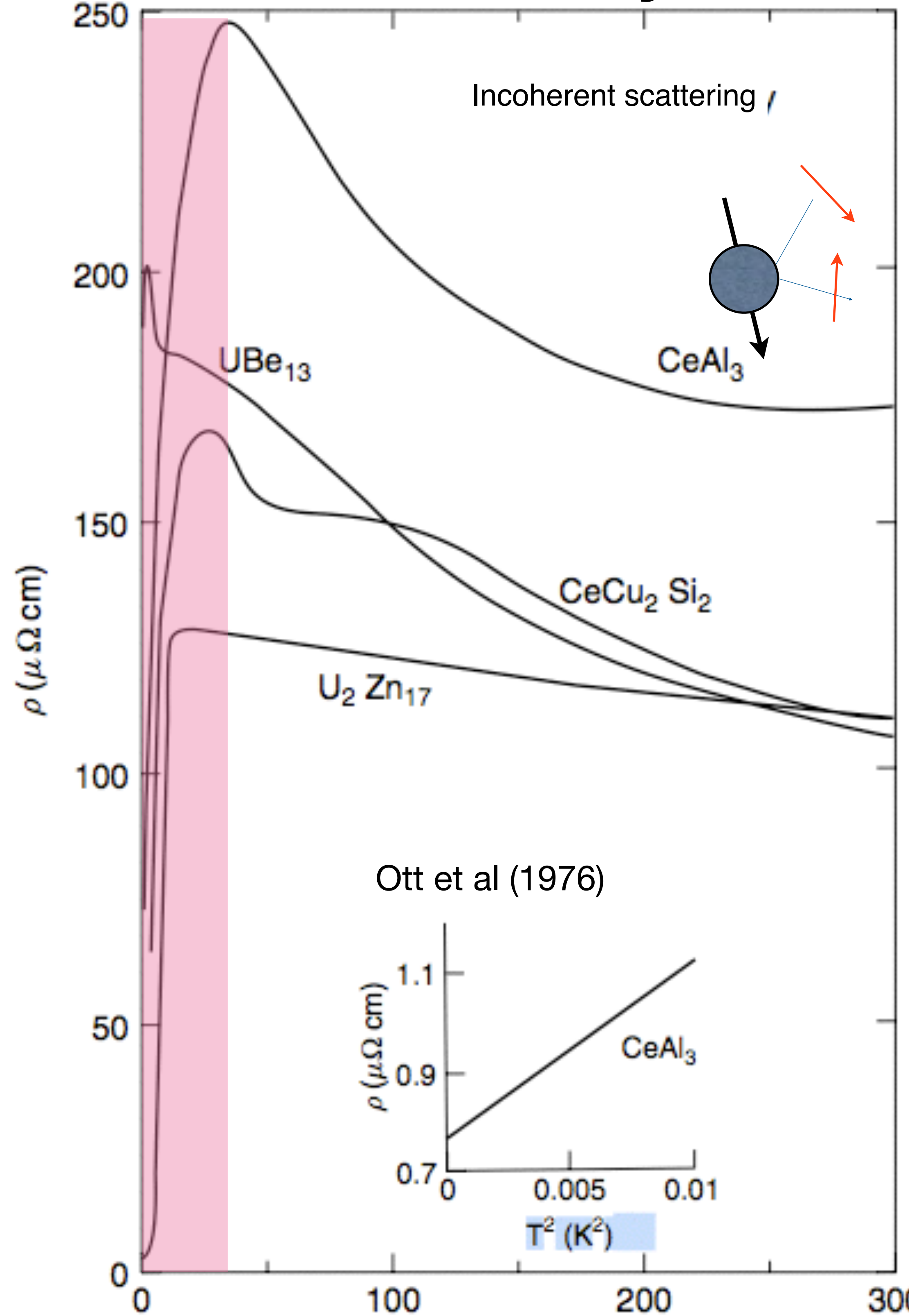


"Kondo Lattice (Doniach 1978)"



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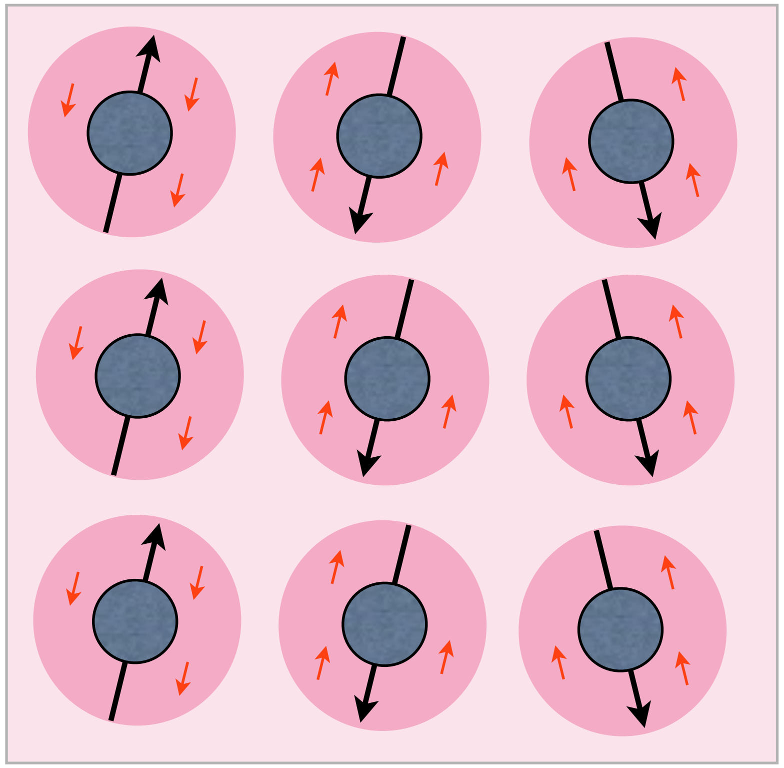

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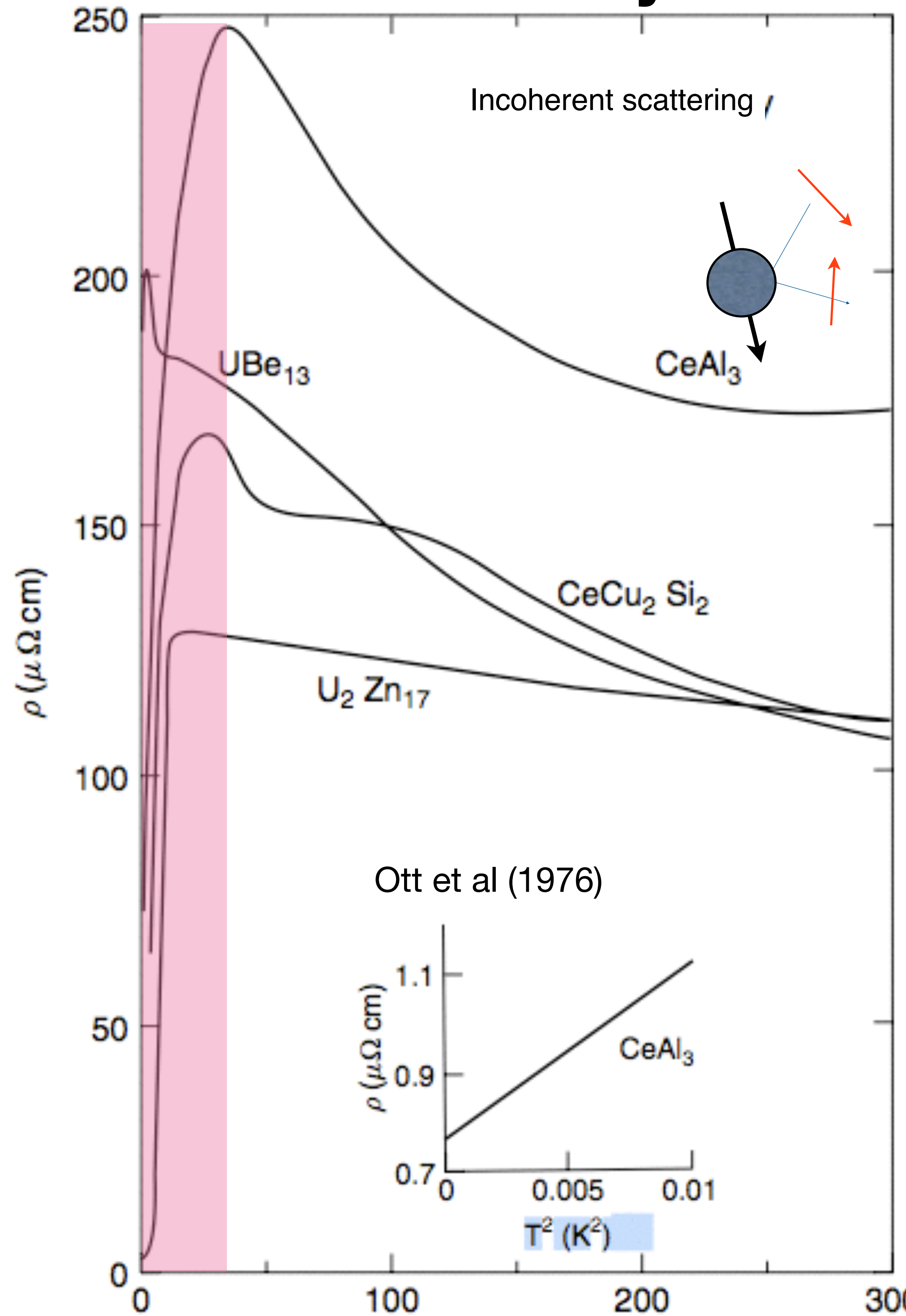

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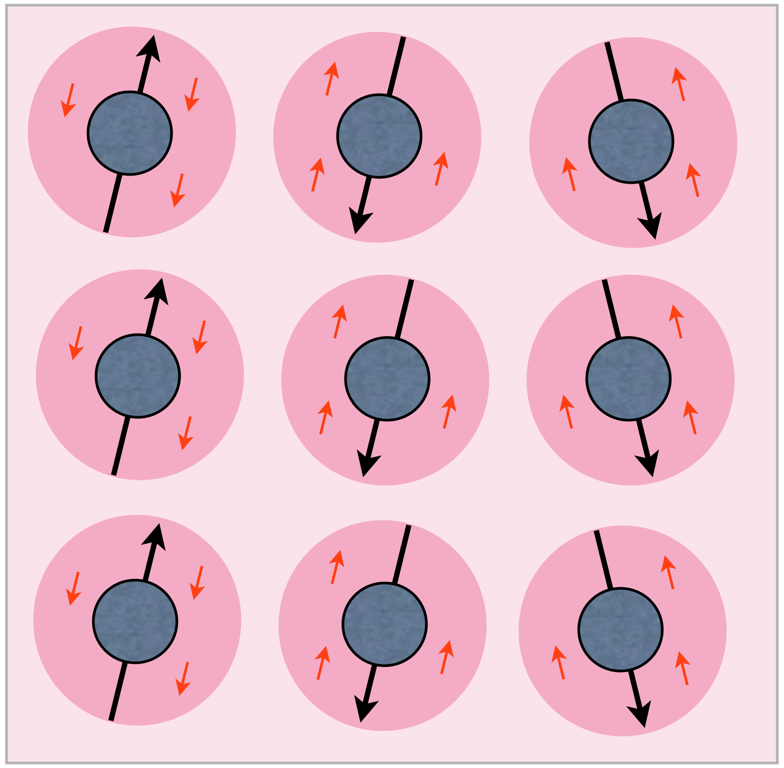

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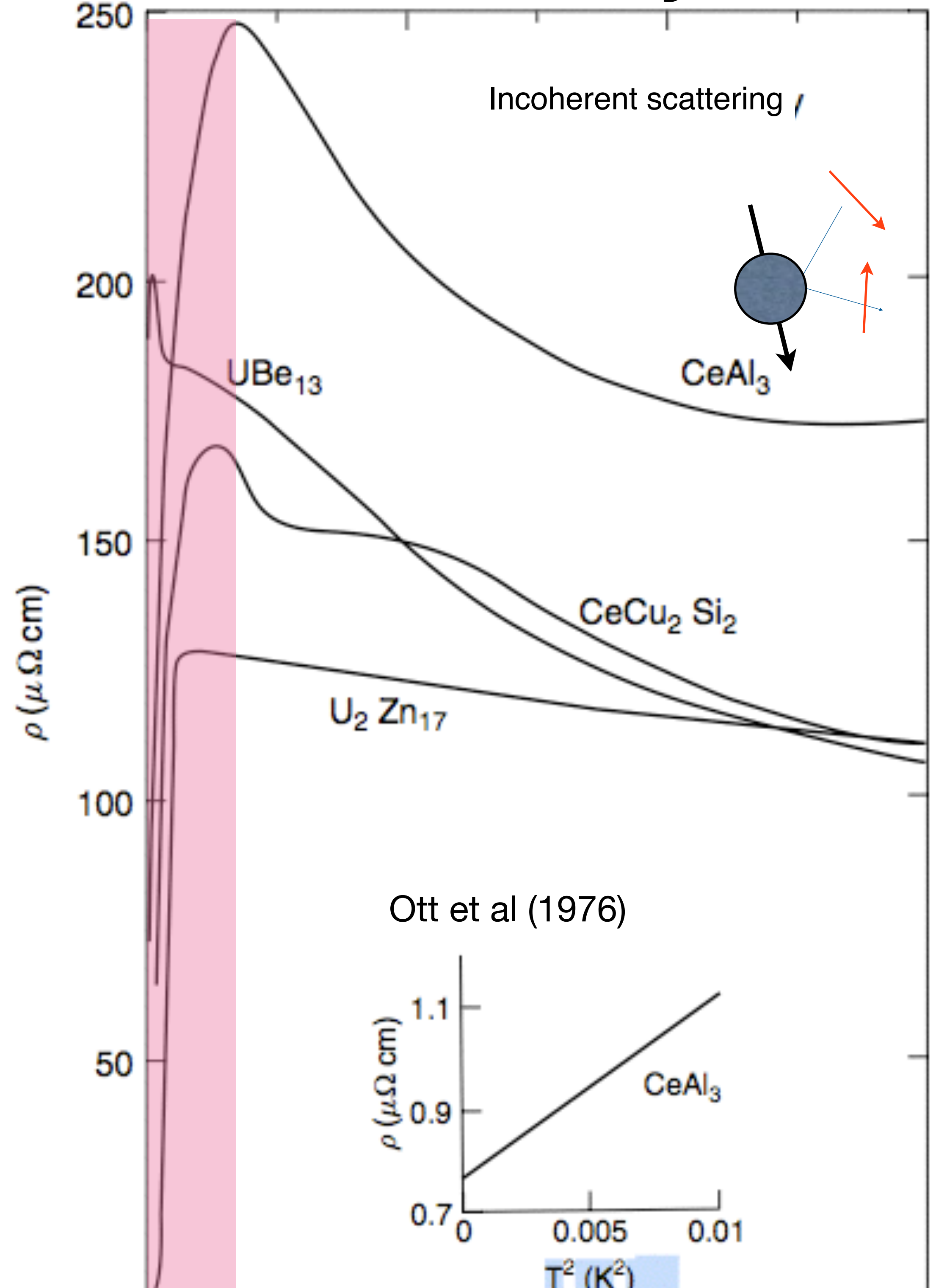
Entangled spins and electrons



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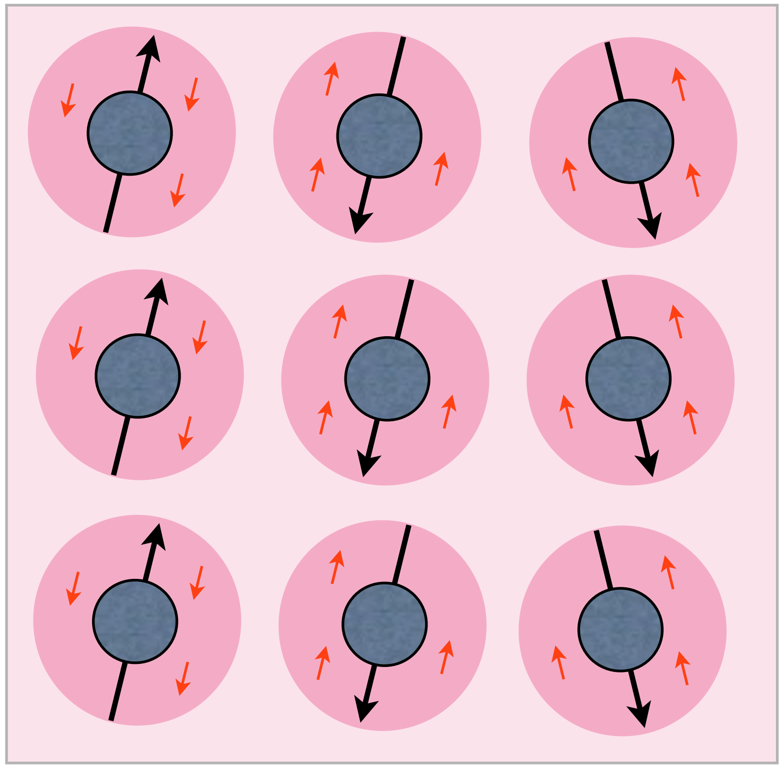

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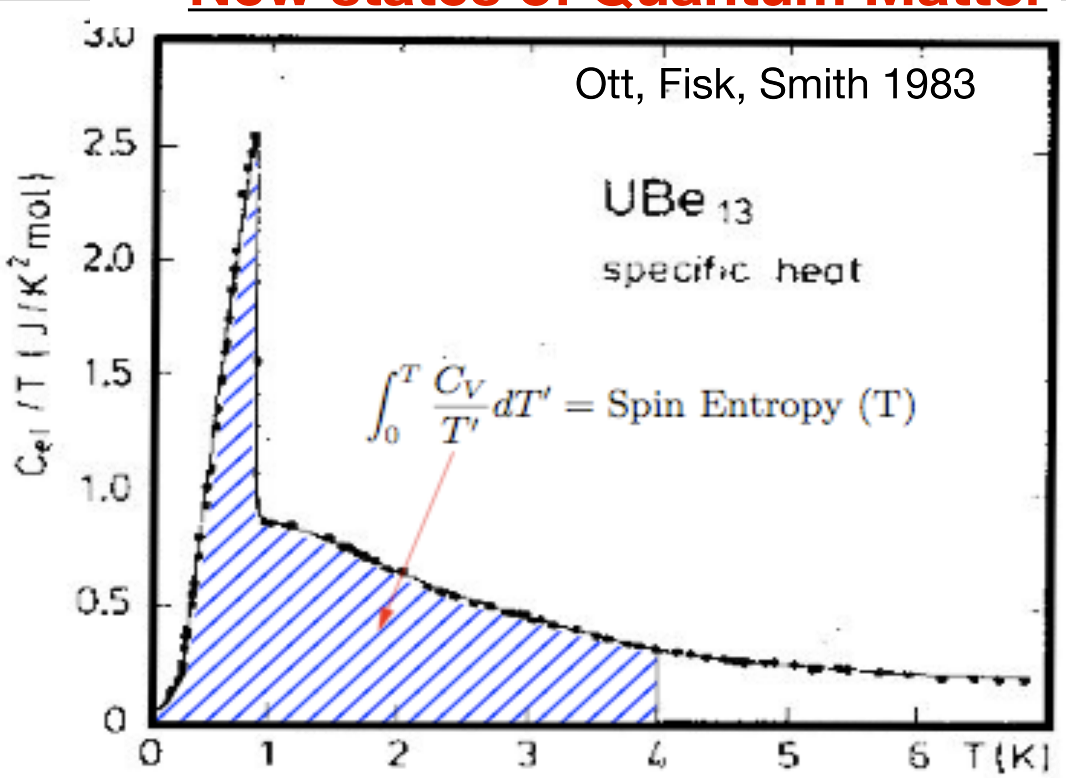
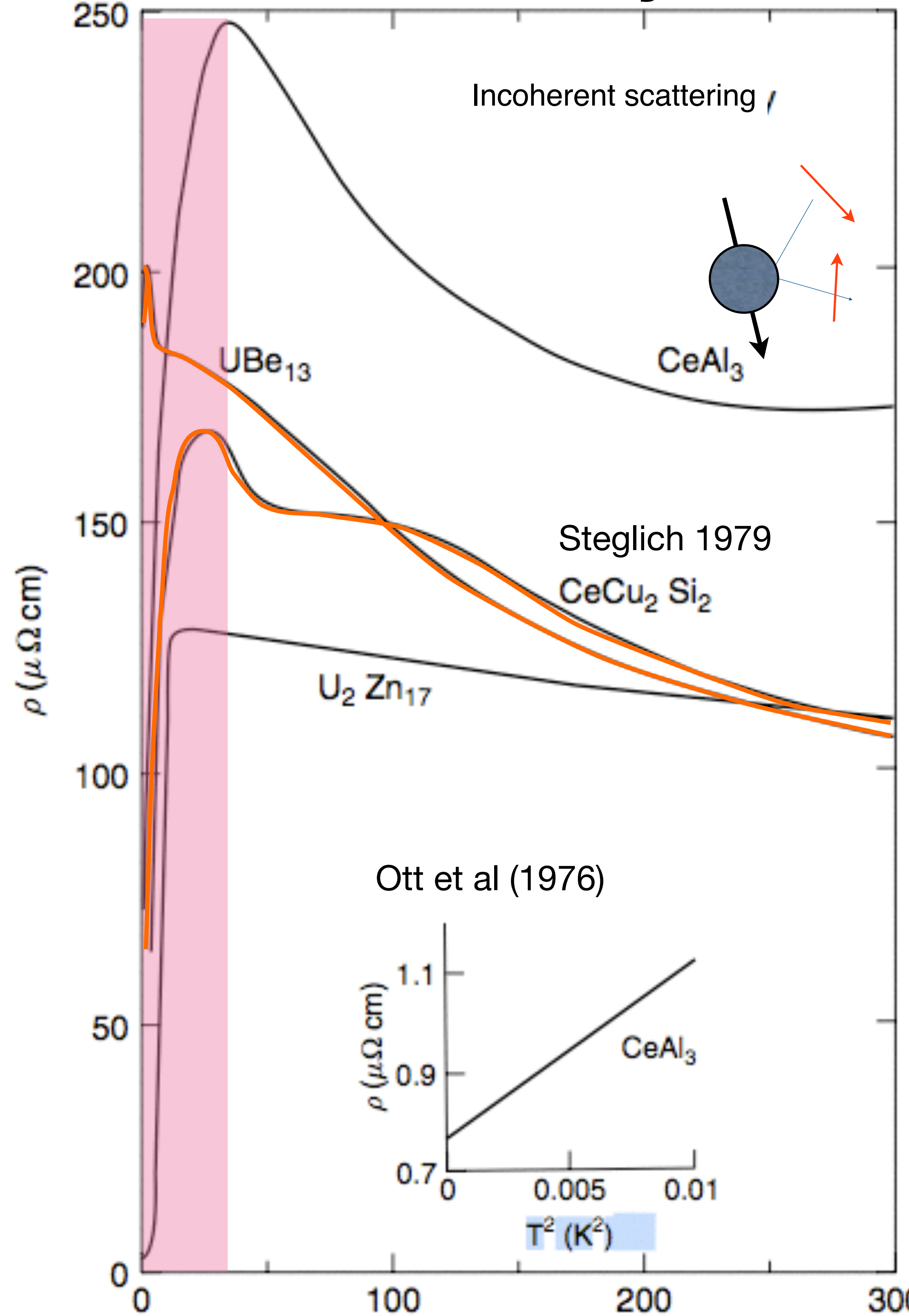
Entangled spins and electrons

→ **New states of Quantum Matter**





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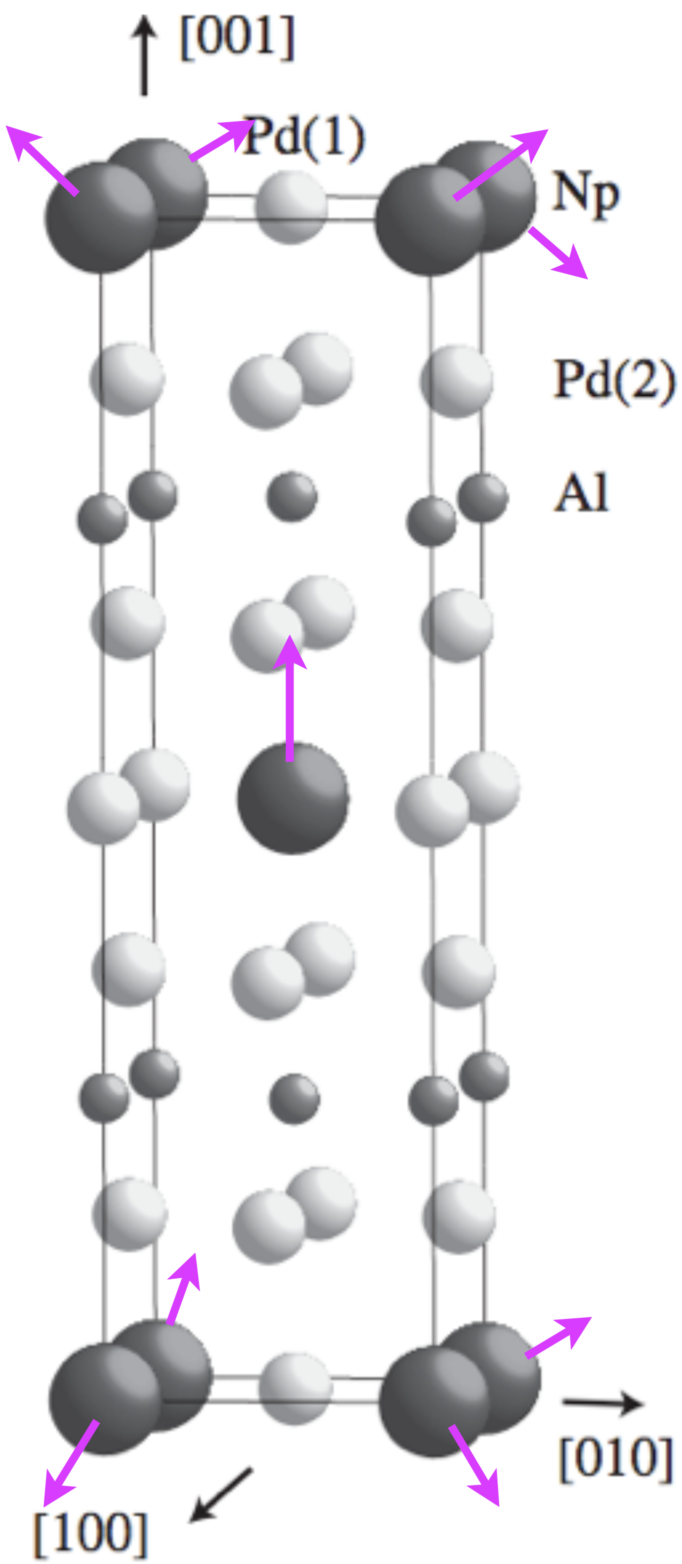
Coherent Heavy Fermions

The remarkable case of $NpPd_5Al_2$



4.5K Heavy Fermion S.C

$NpAl_2Pd_5$

Aoki et al 2007

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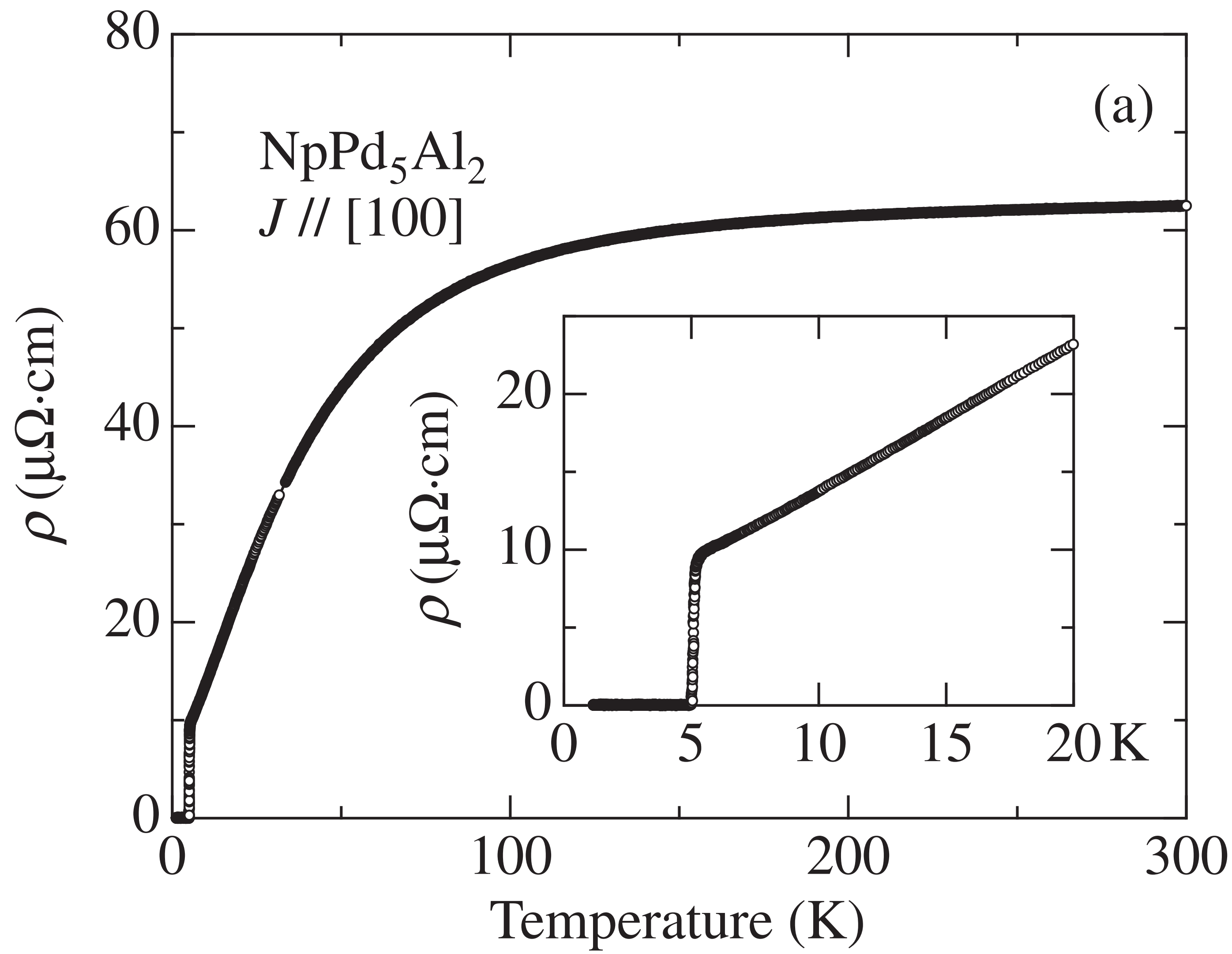

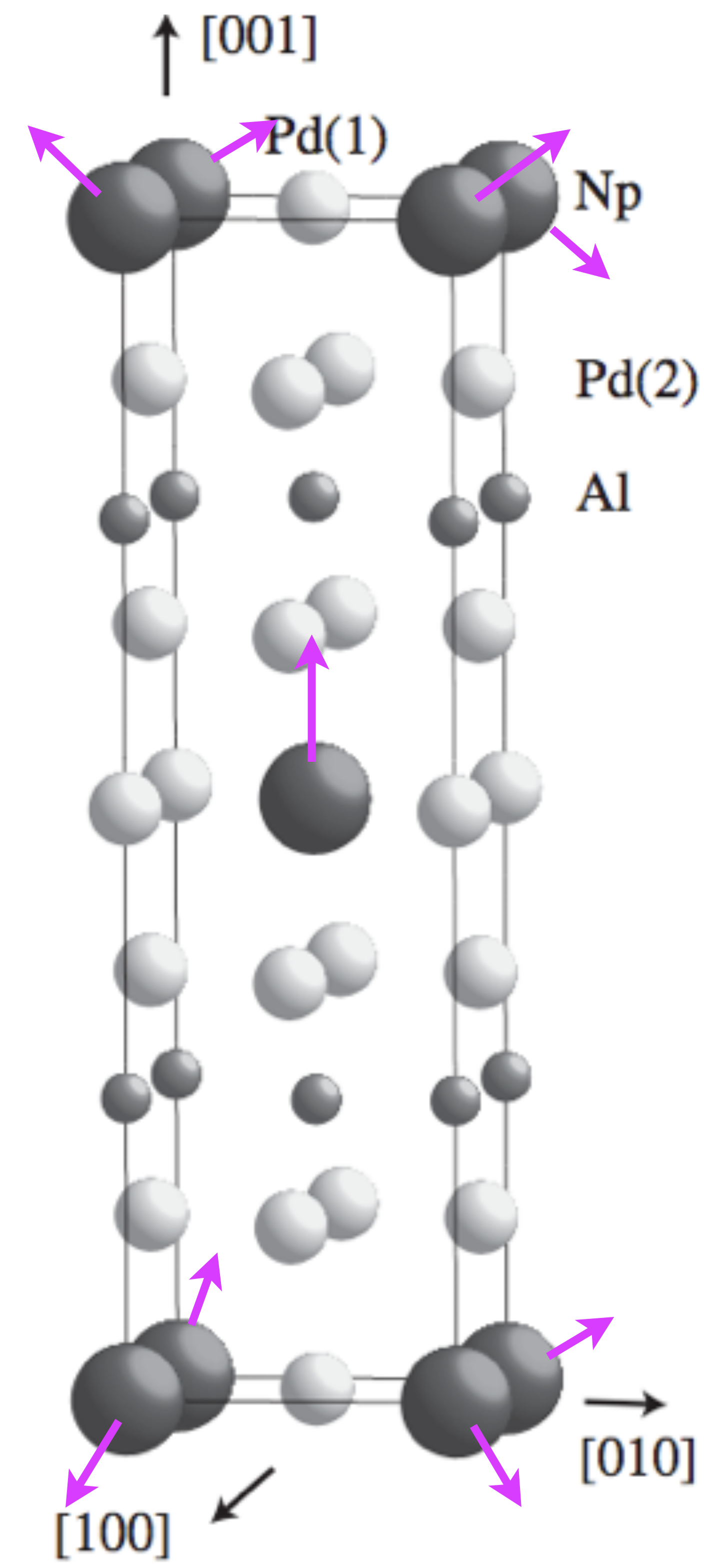

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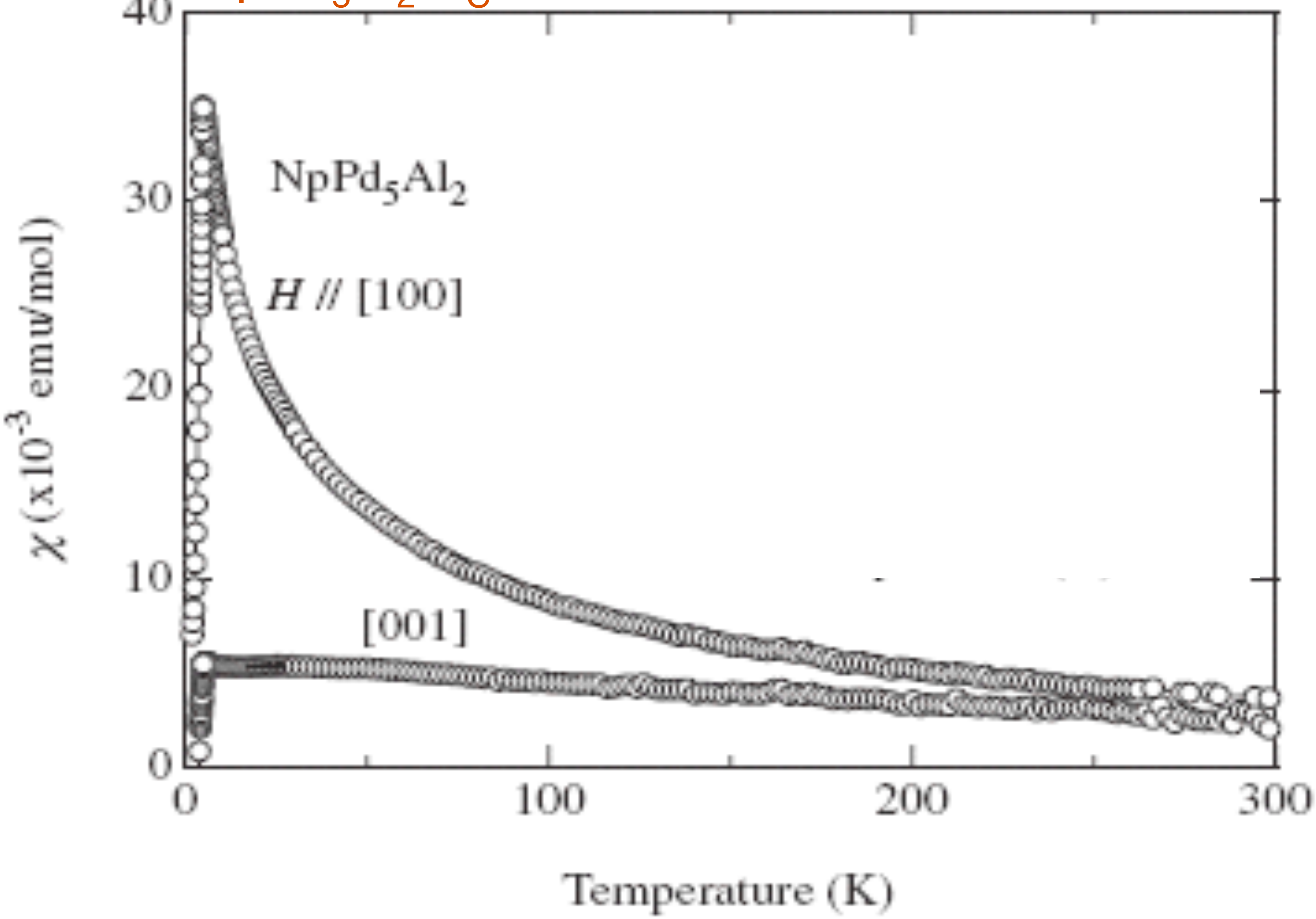
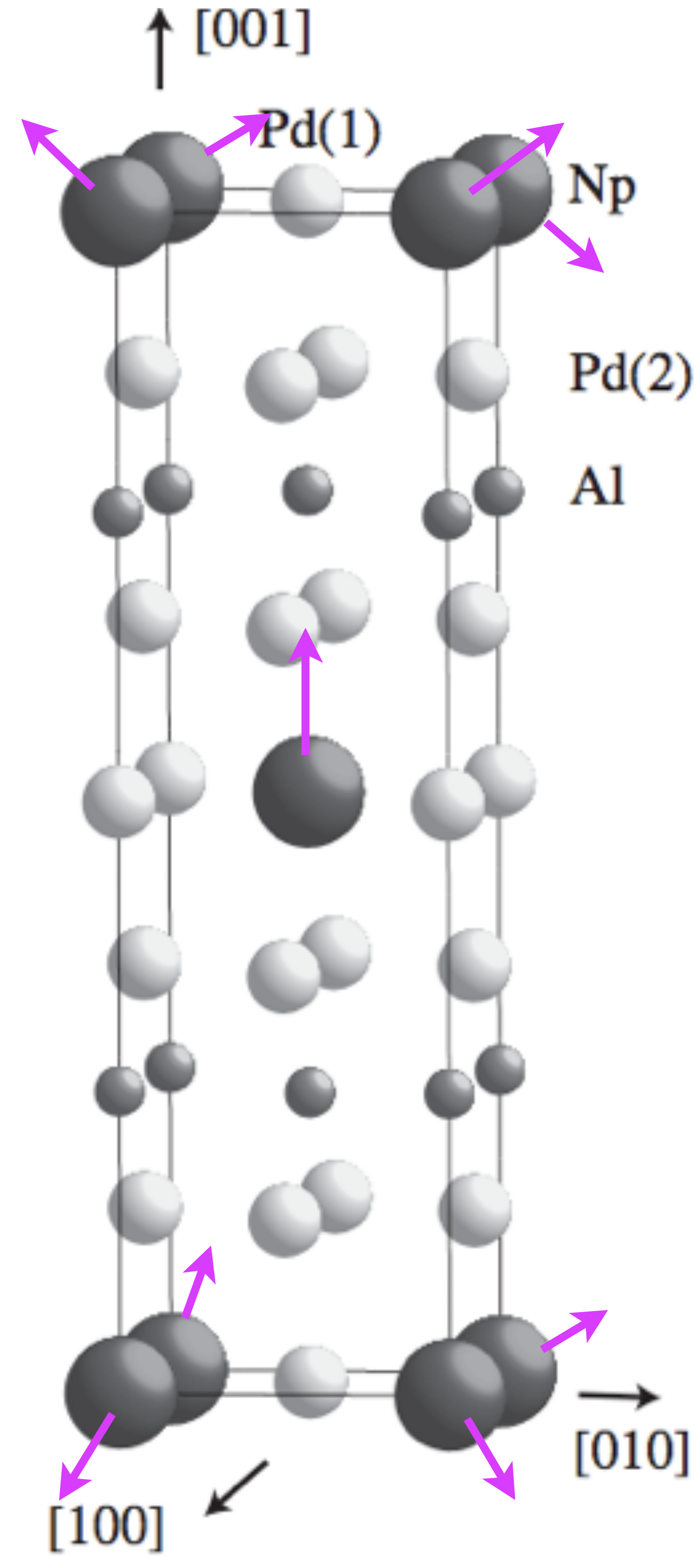
$NpPd_5Al_2$ $T_C = 4.5K$





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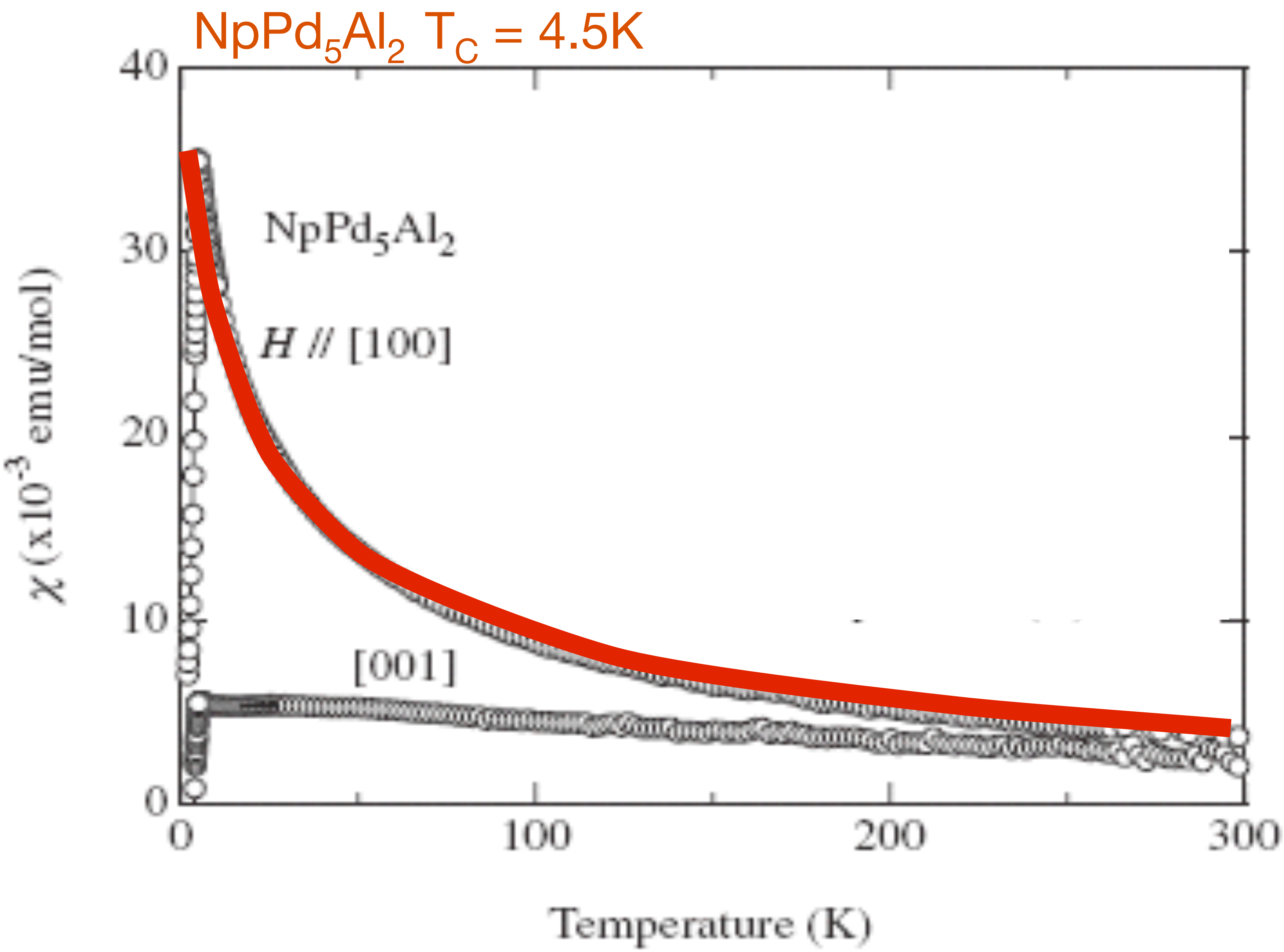

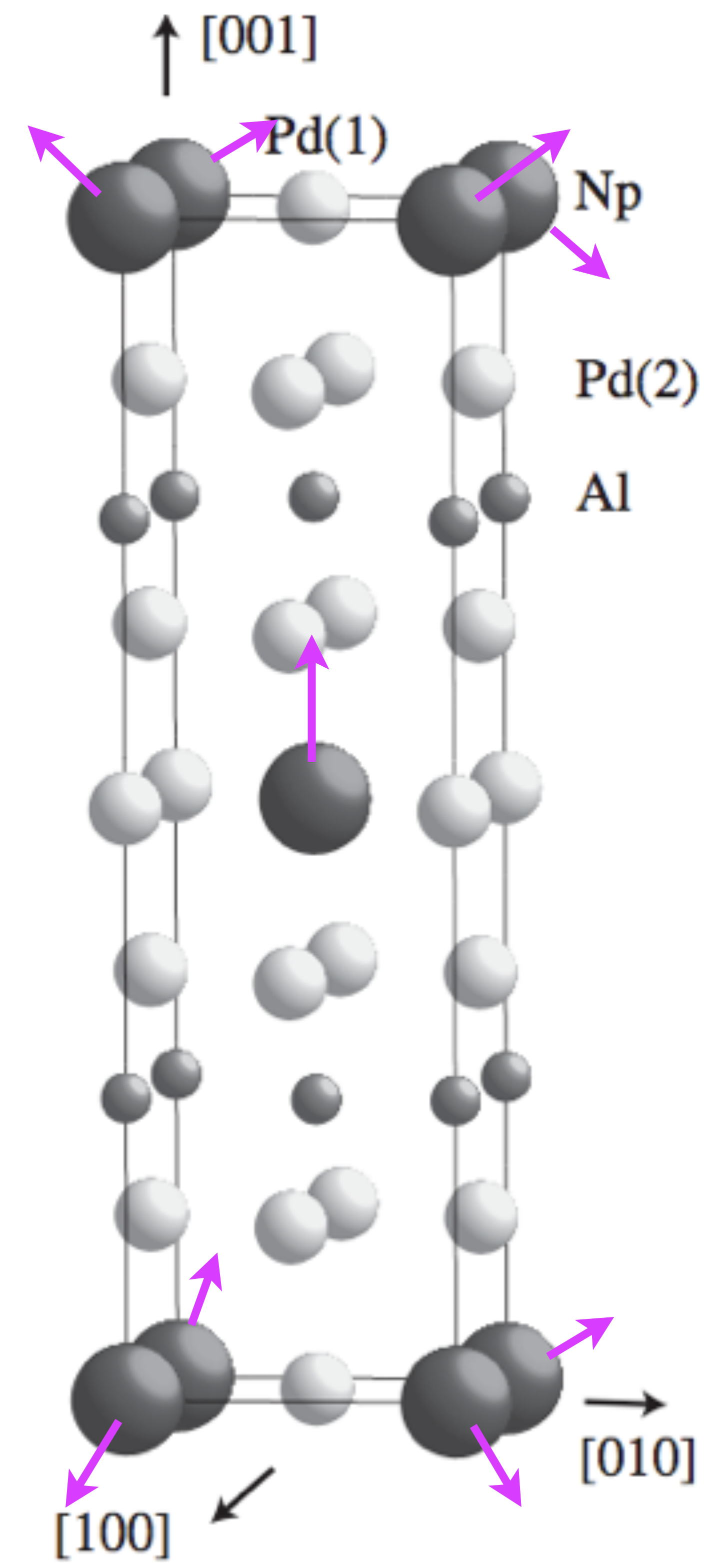

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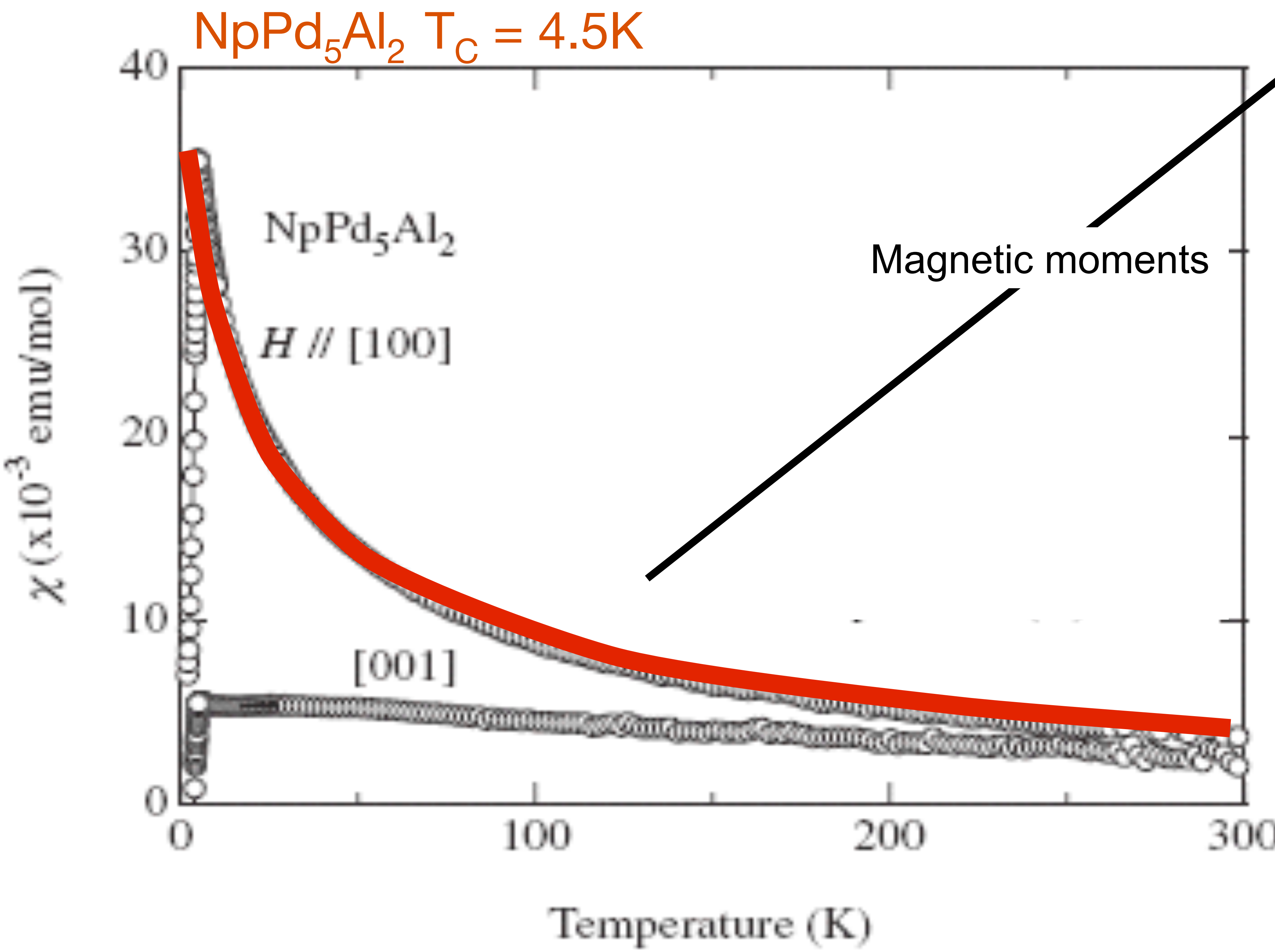

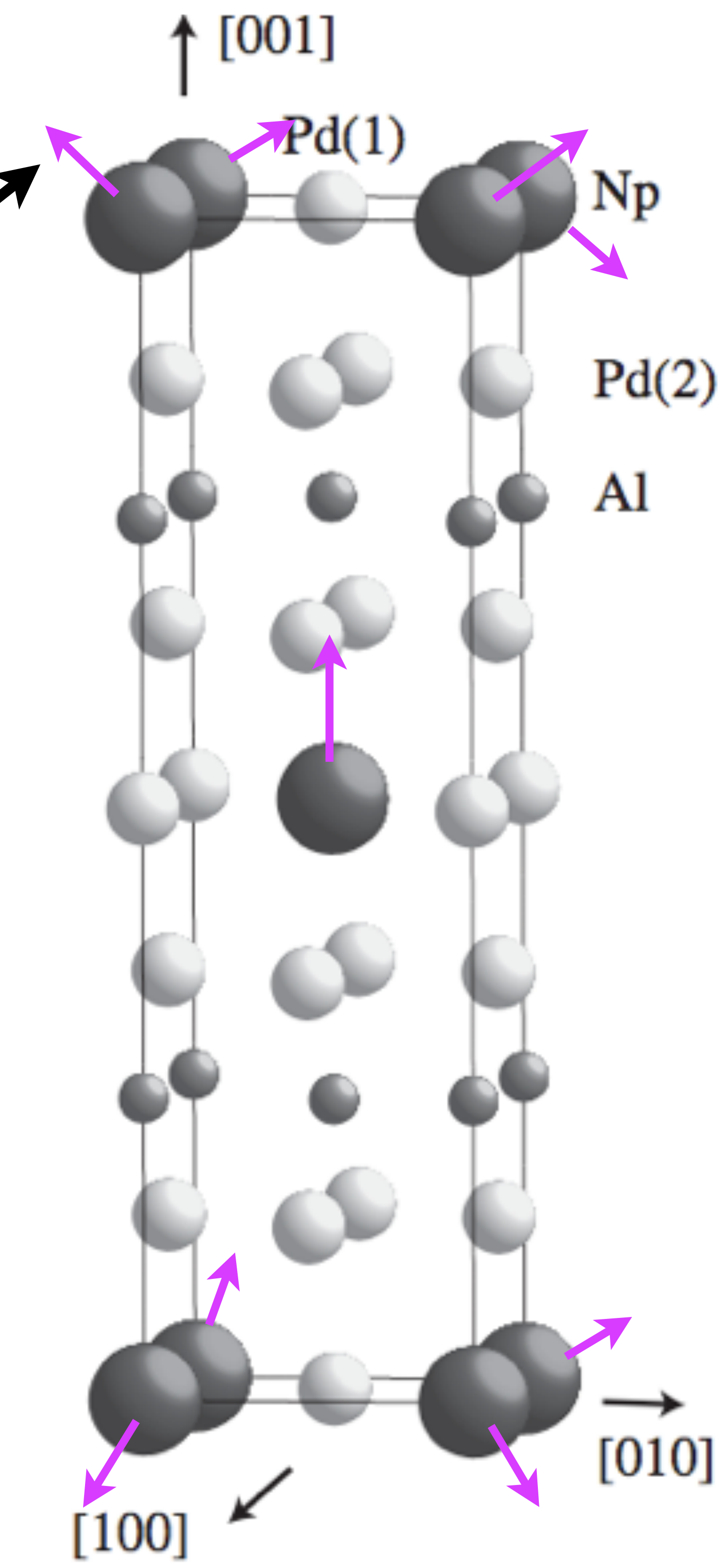

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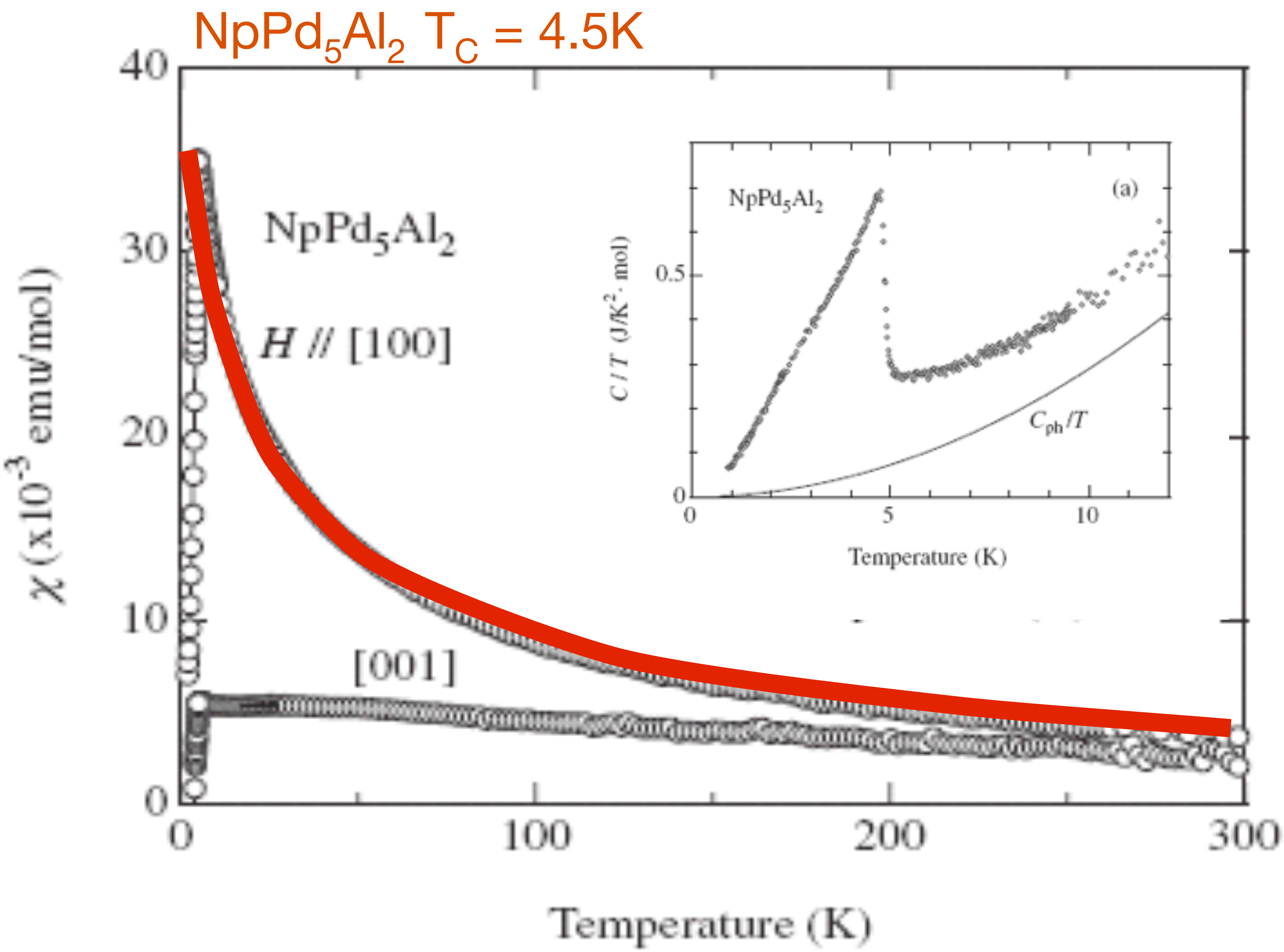

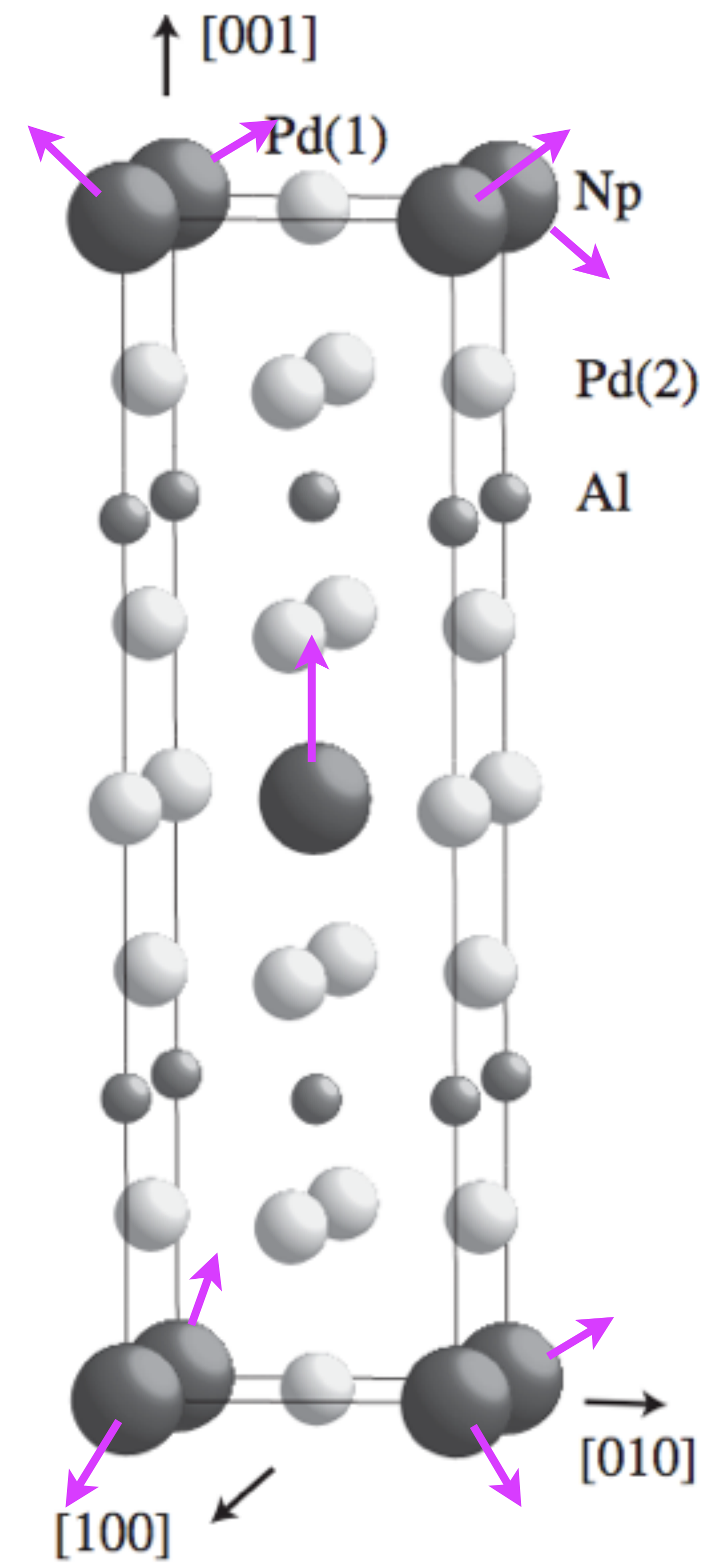

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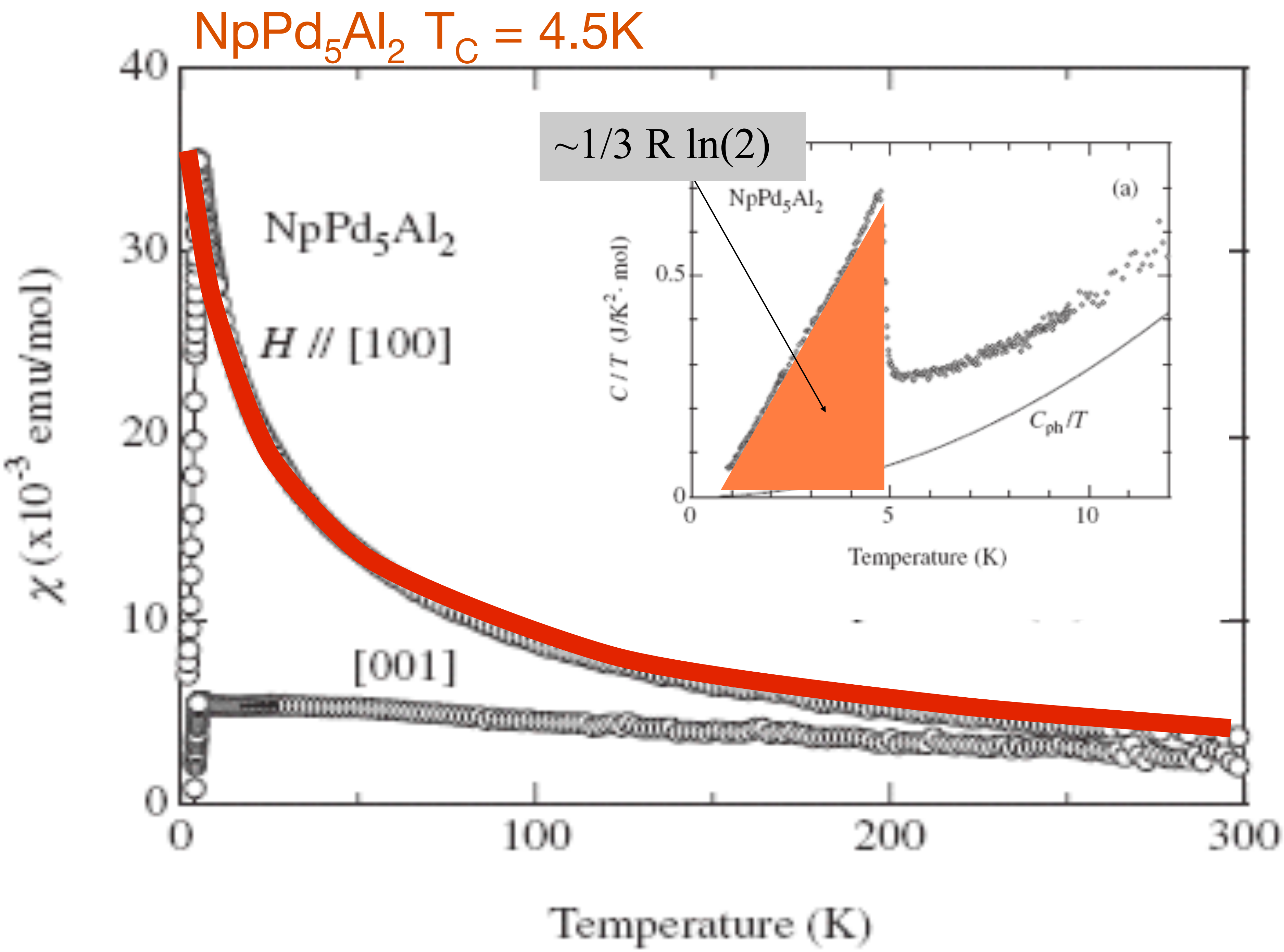

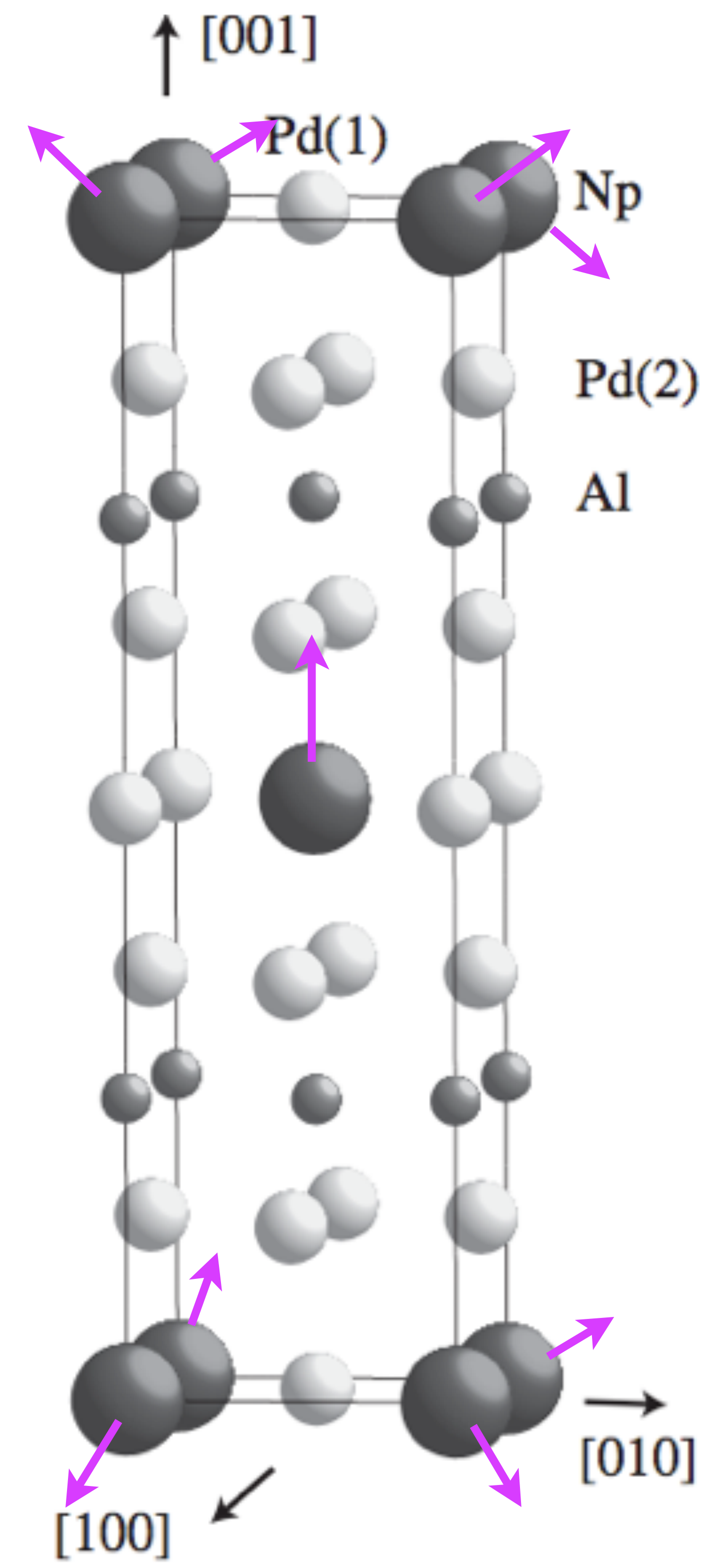

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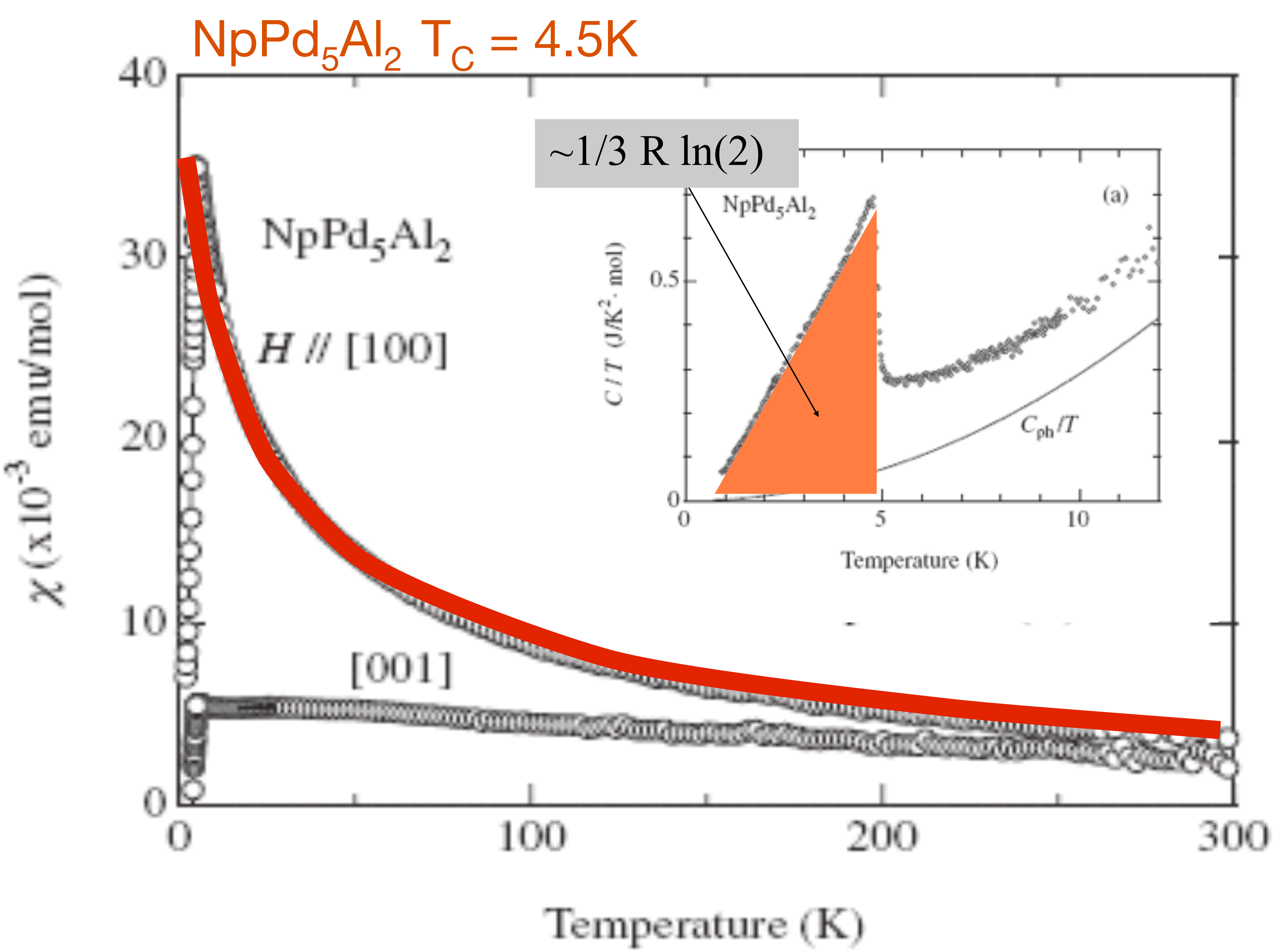

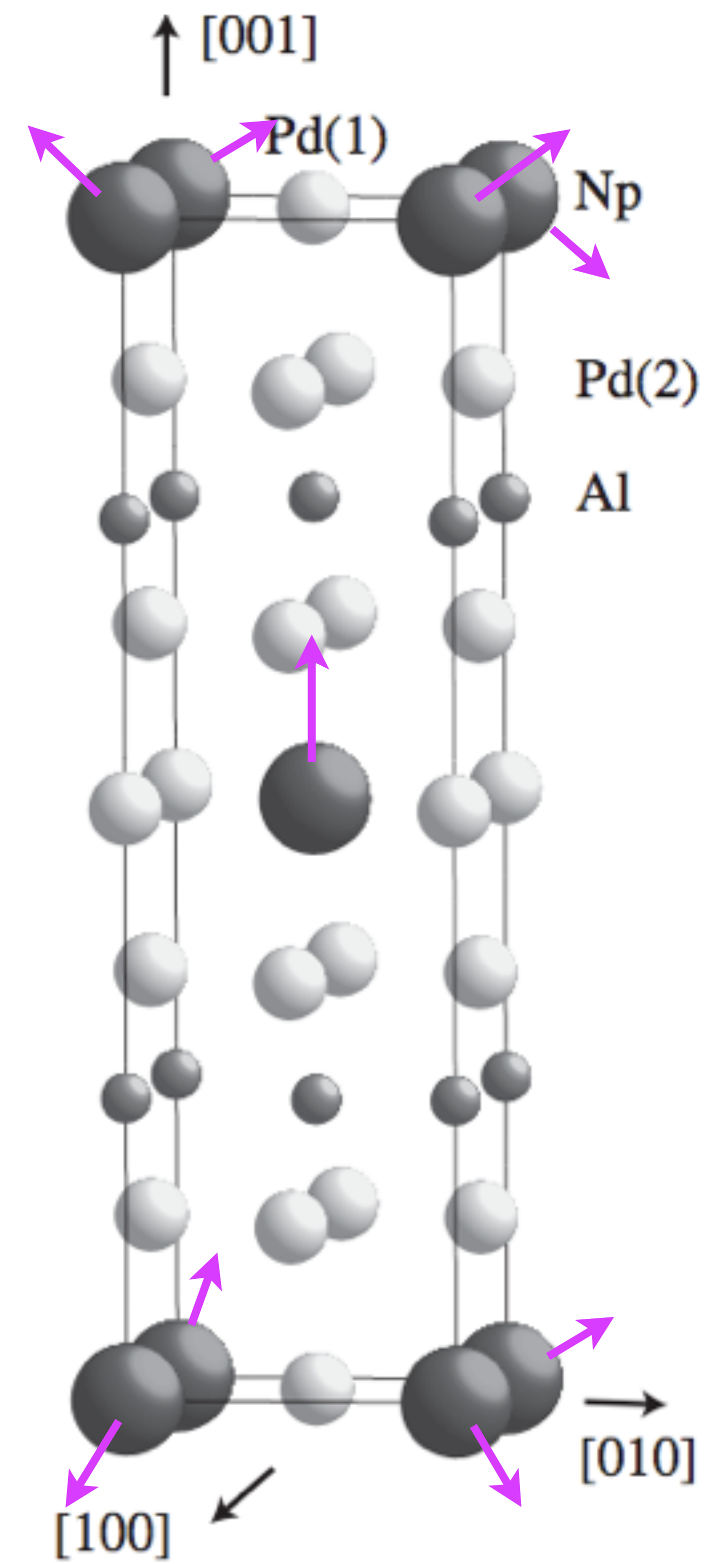

How does the spin form the condensate?

4.5K Heavy Fermion S.C
$NpAl_2Pd_5$
Aoki et al 2007

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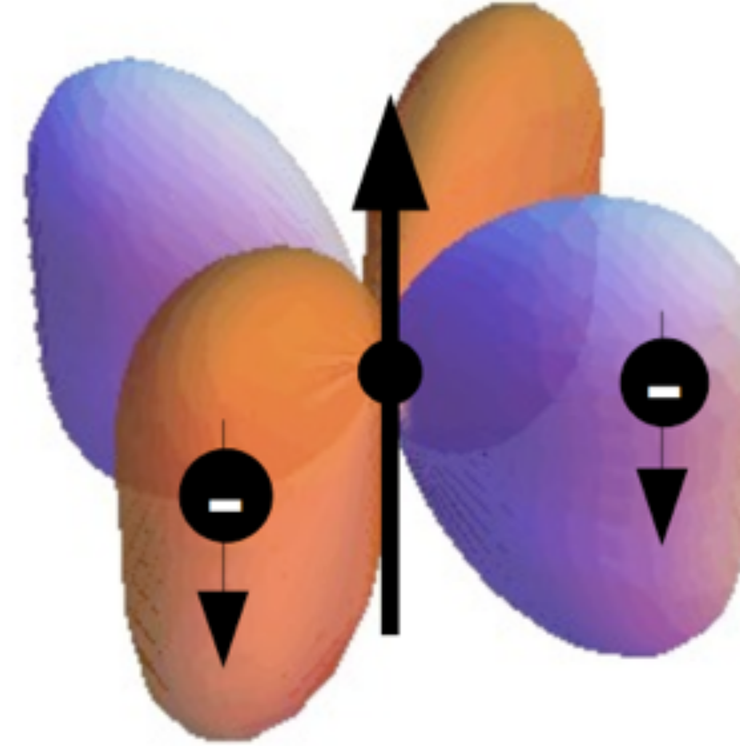
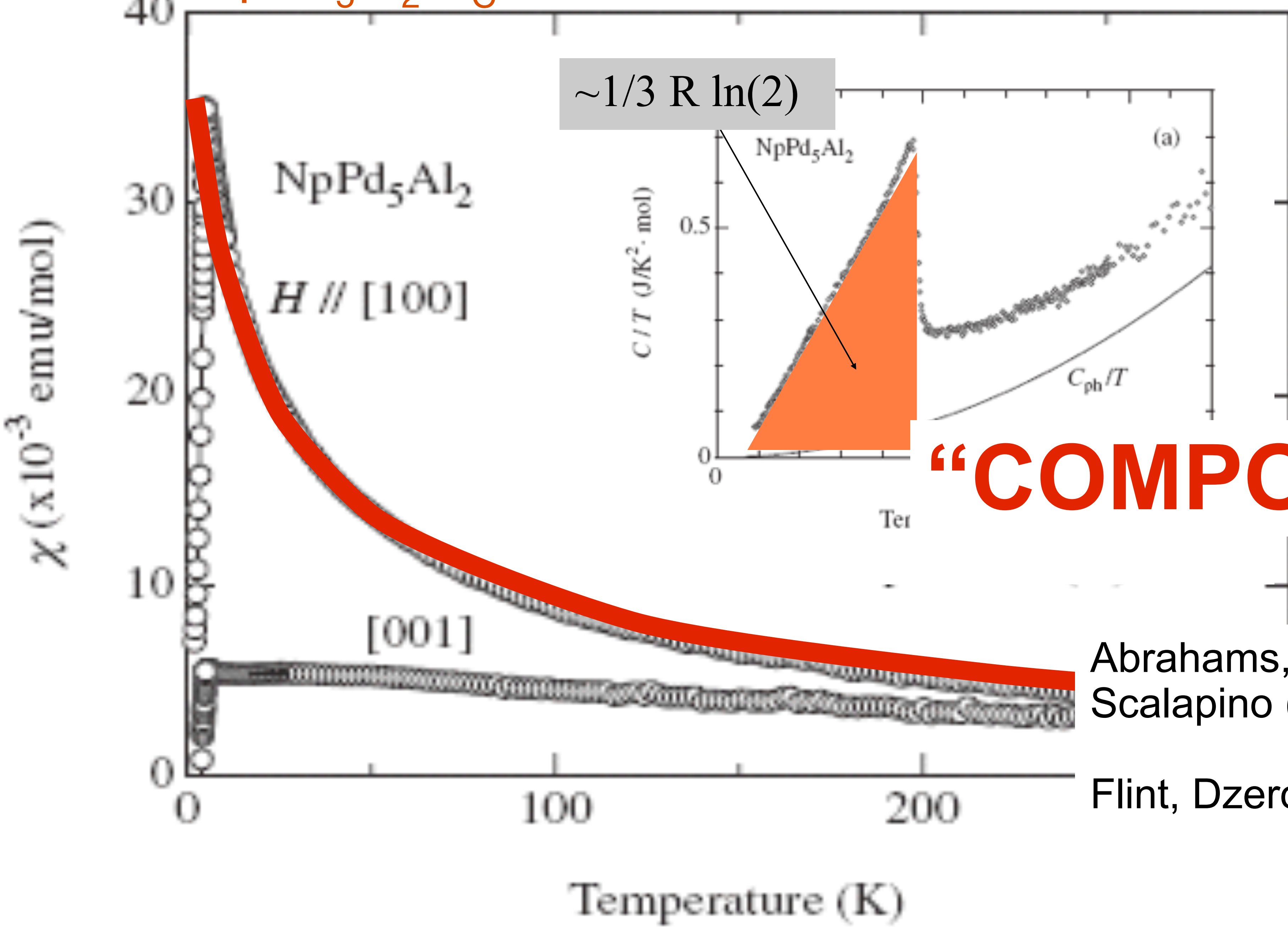


$NpPd_5Al_2$ T_C = 4.5K



"COMPOSITE PAIR"

Abrahams, Balatsky, Schrieffer and Scalapino (1994)

Flint, Dzero, Coleman (2008)

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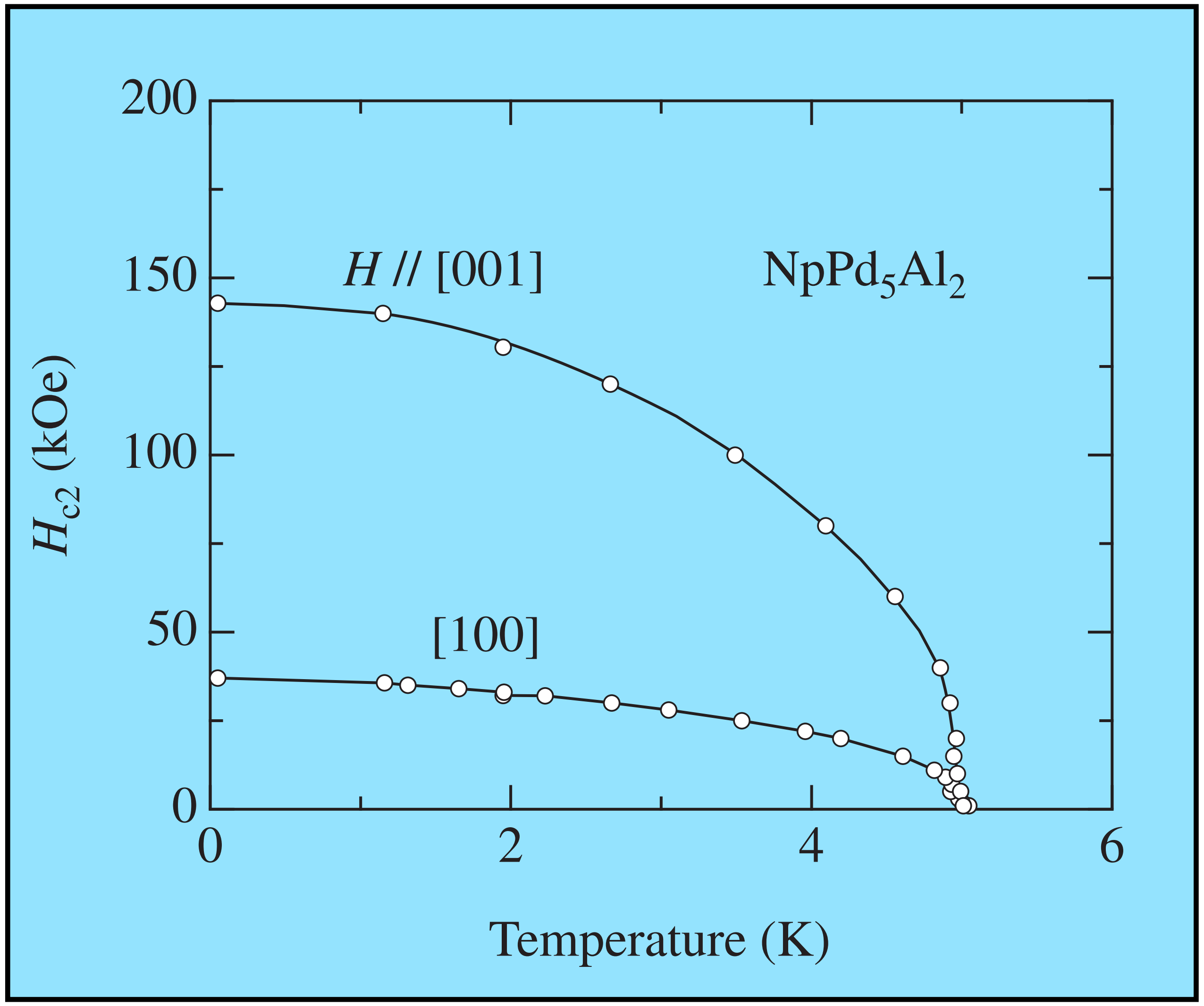
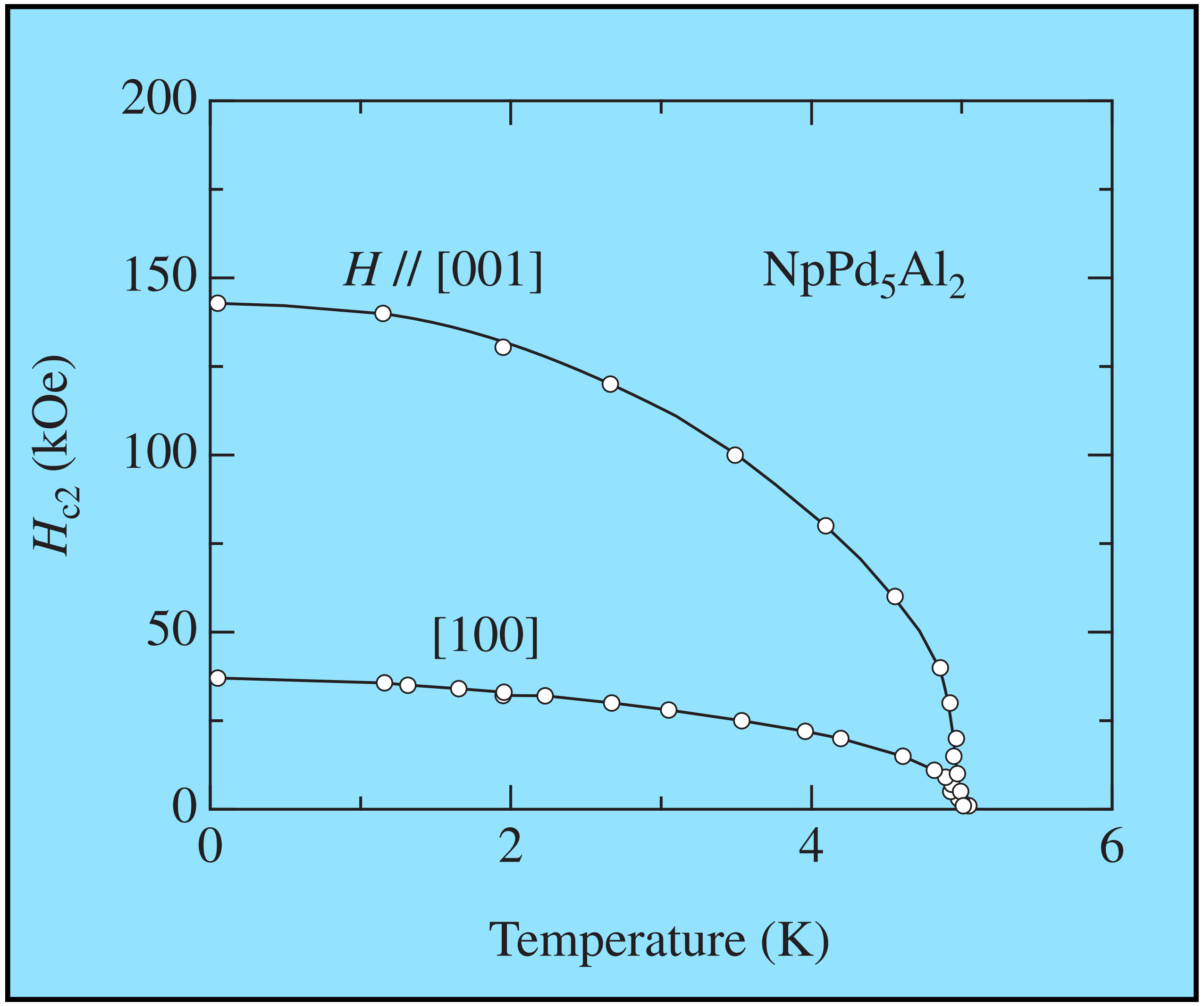
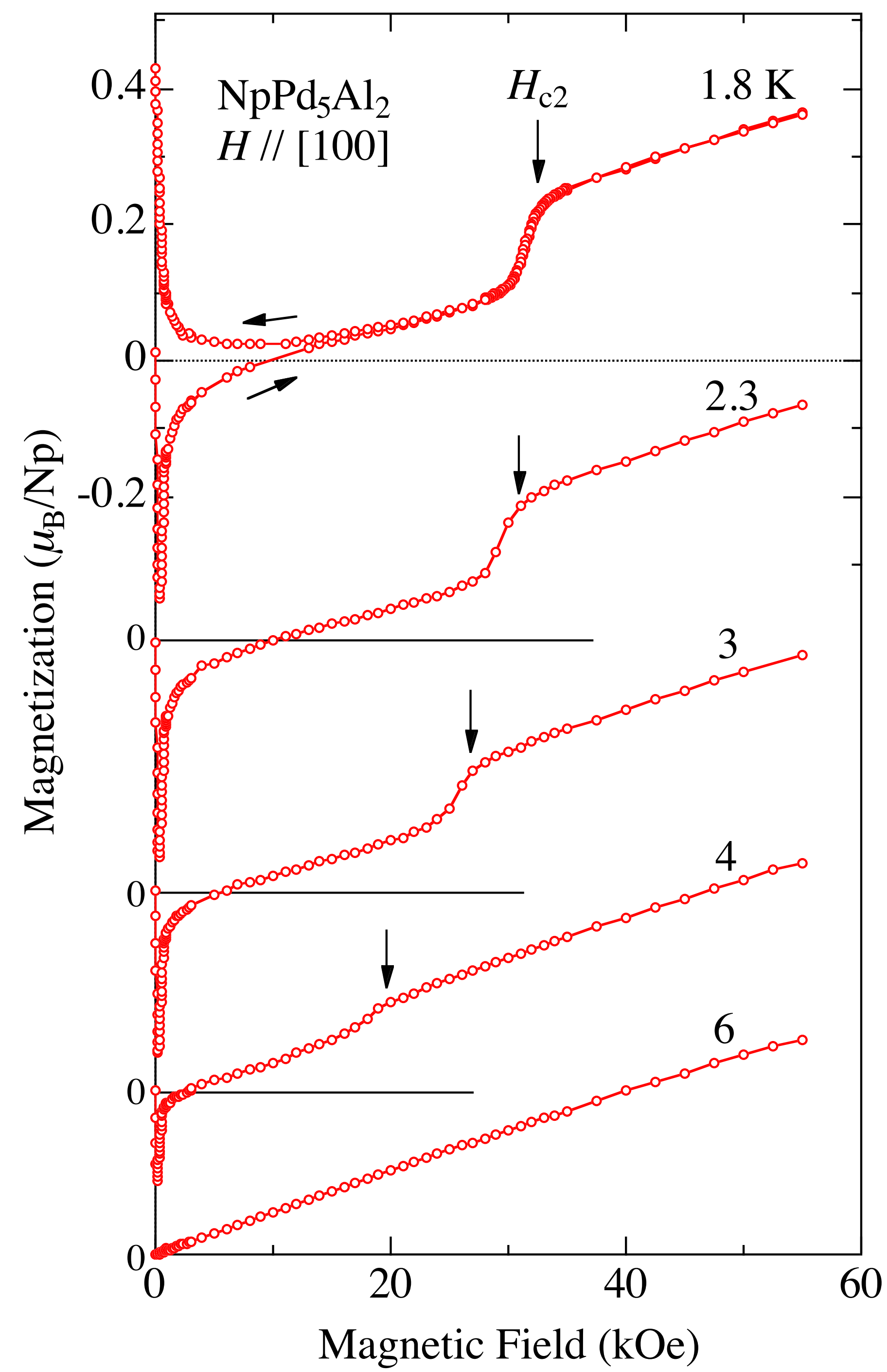
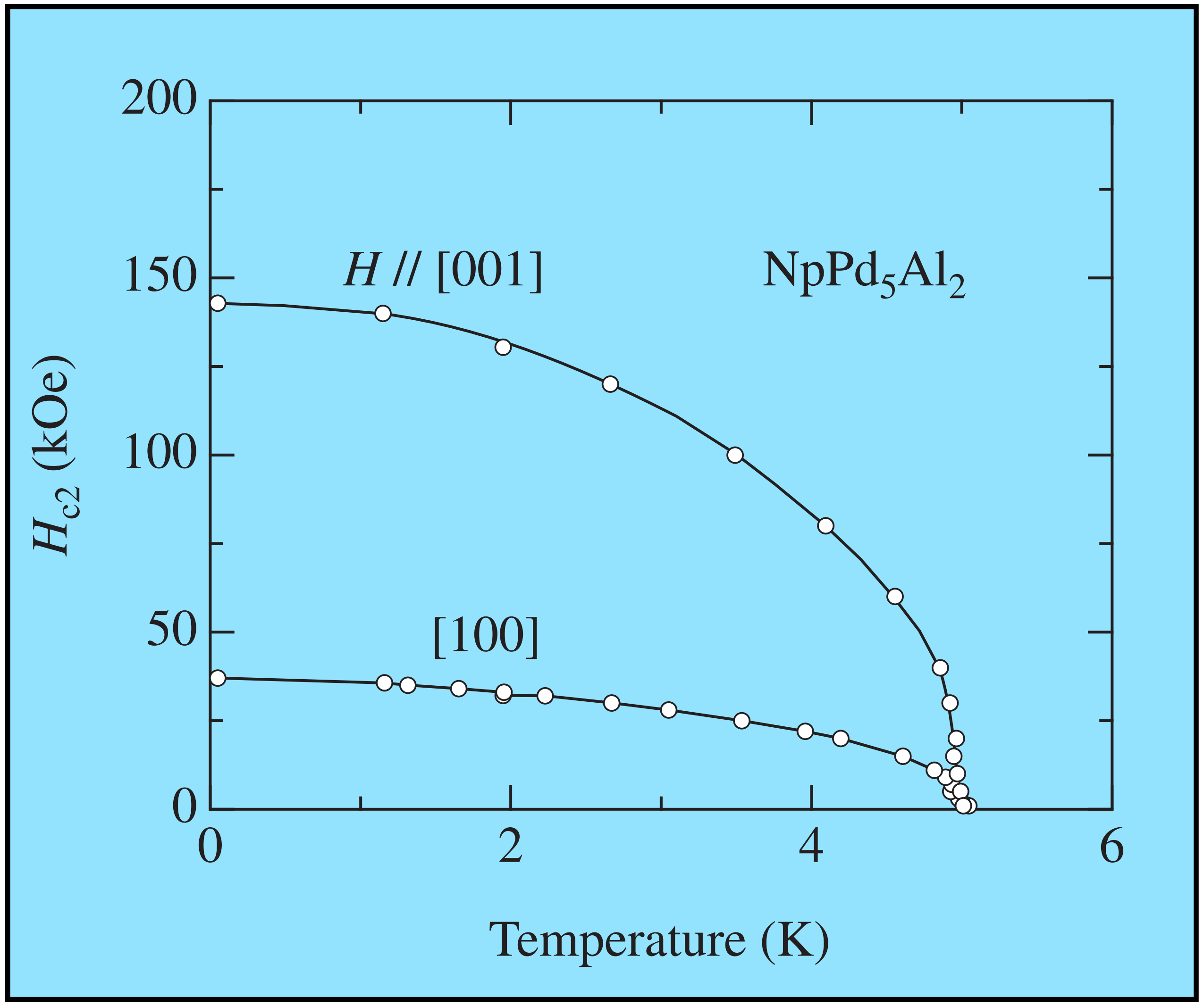


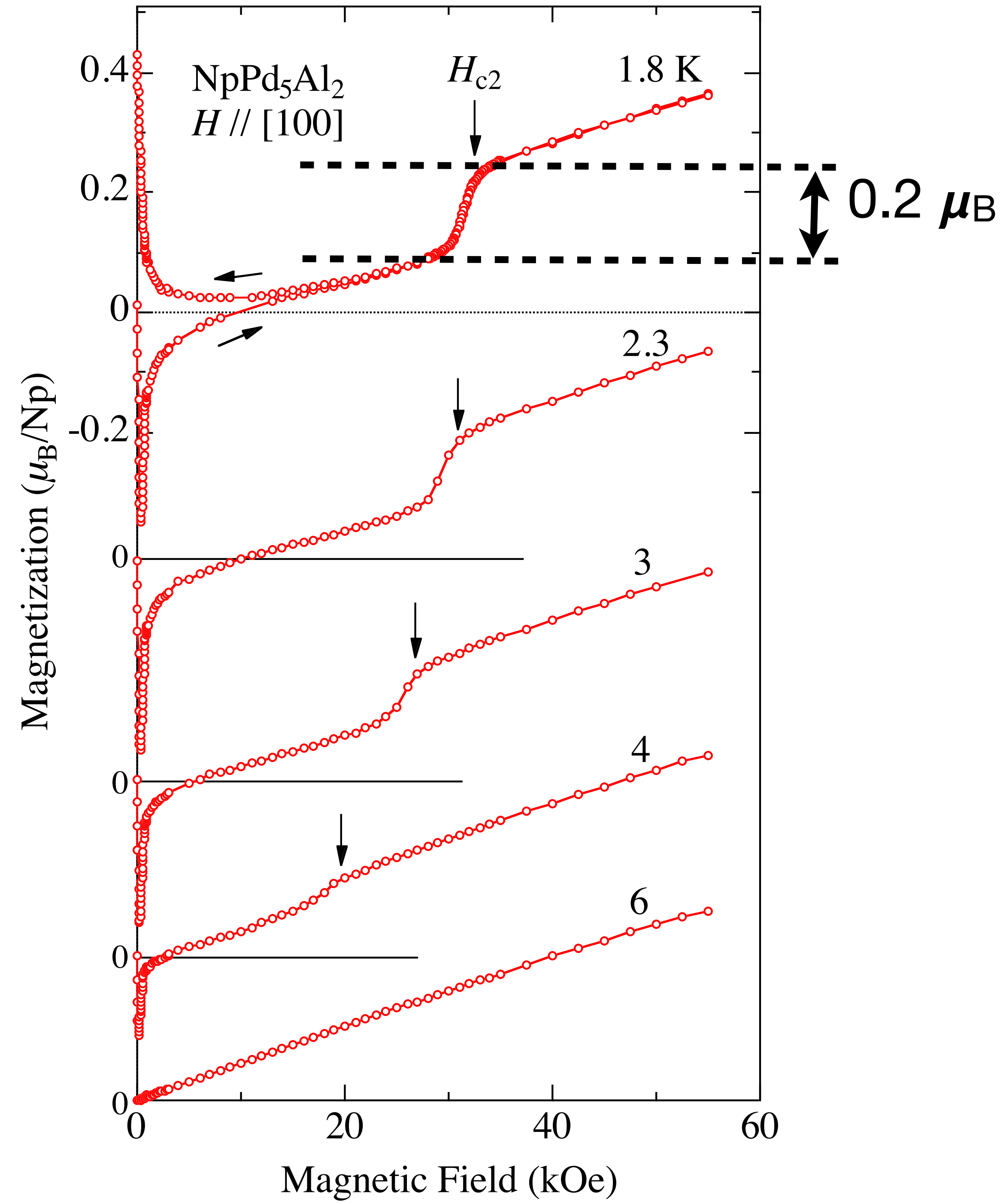
200
150
100
50
0
H_{c2} (kOe)
H // [001]
$NpPd_5Al_2$
[100]
0
2
4
6
Temperature (K)





D. Aoki et al., J. Phys. Soc. Jpn. **76** (2007) 063701.





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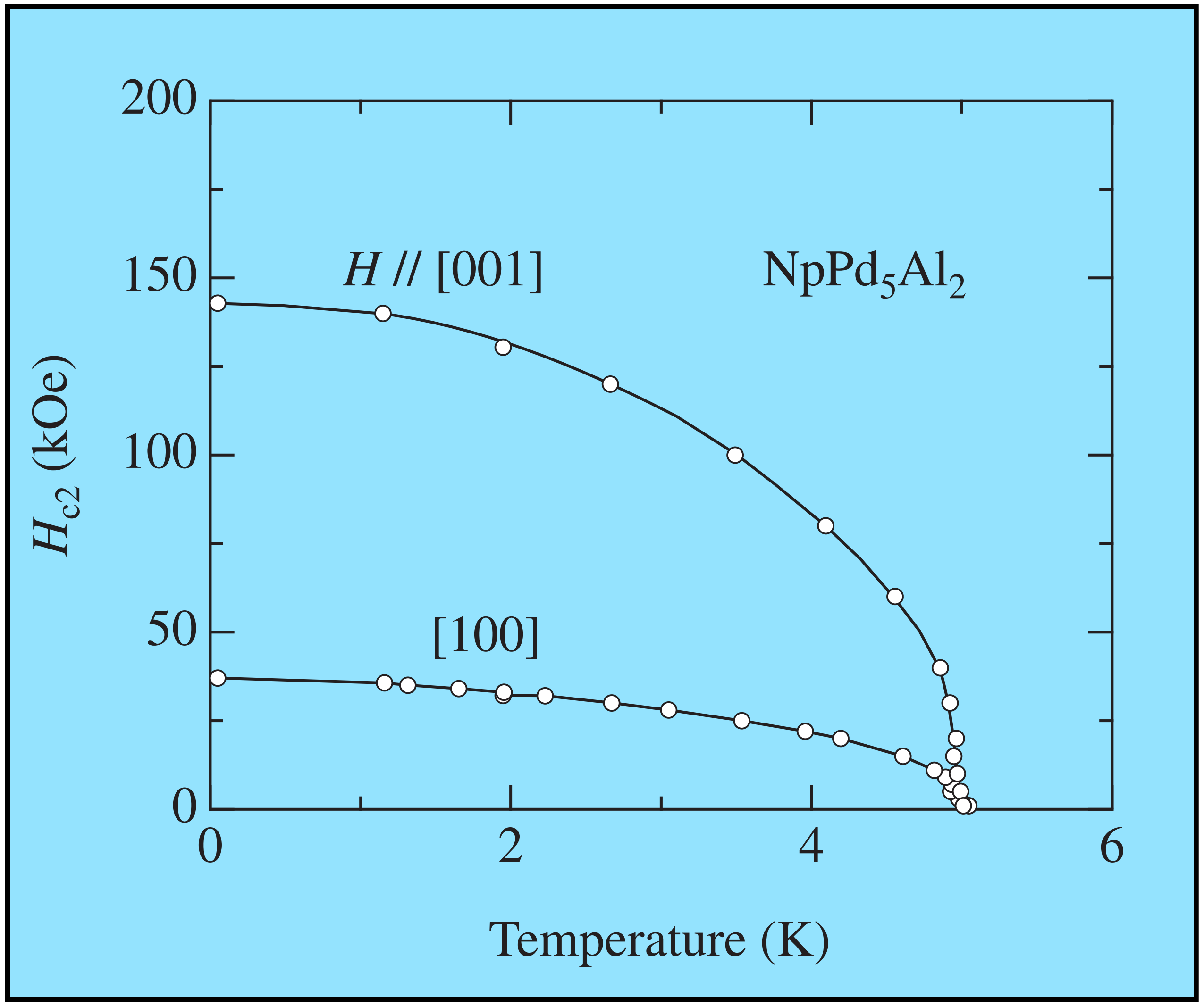
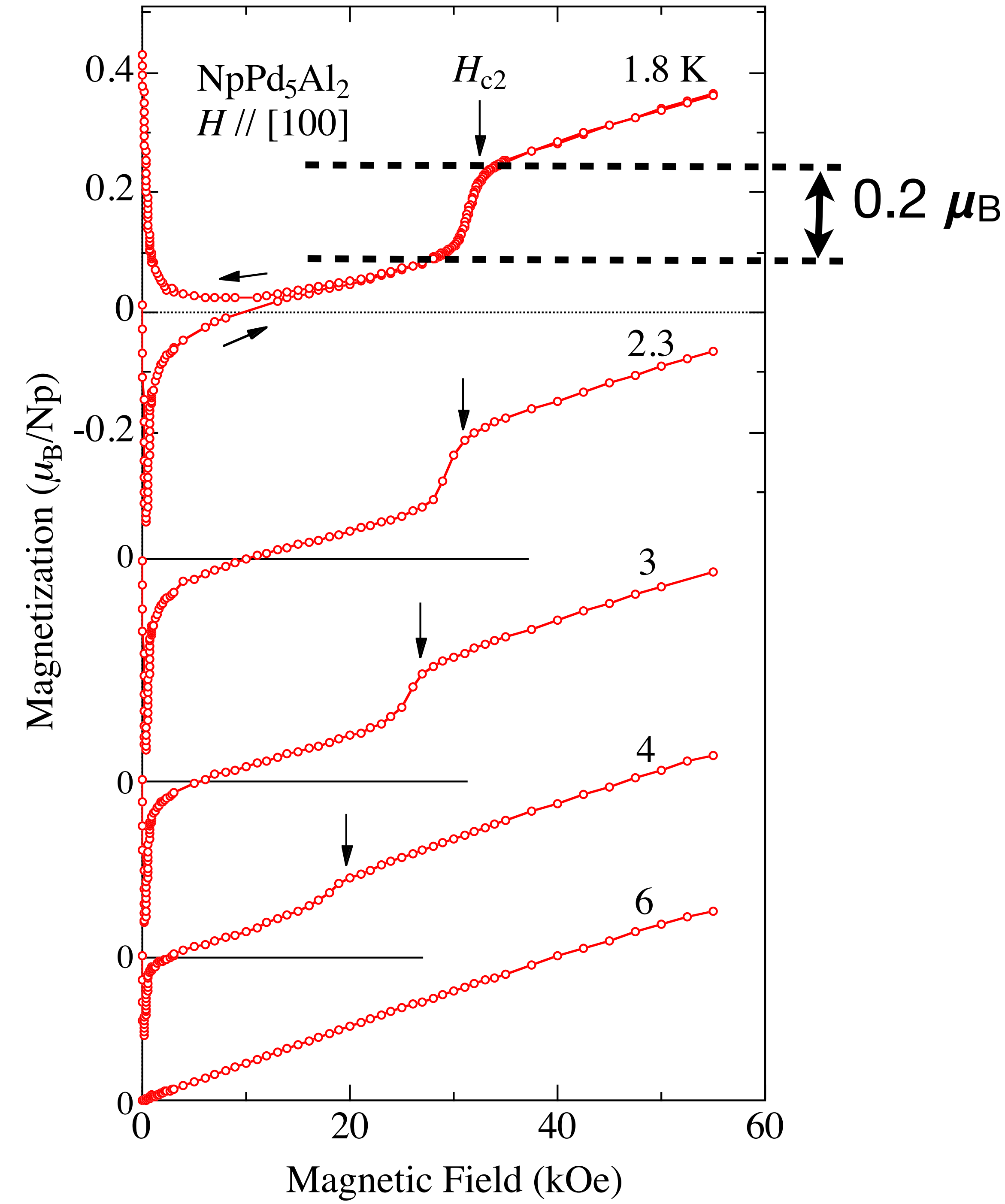
Large first order jump in magnetization at H_{c2}.





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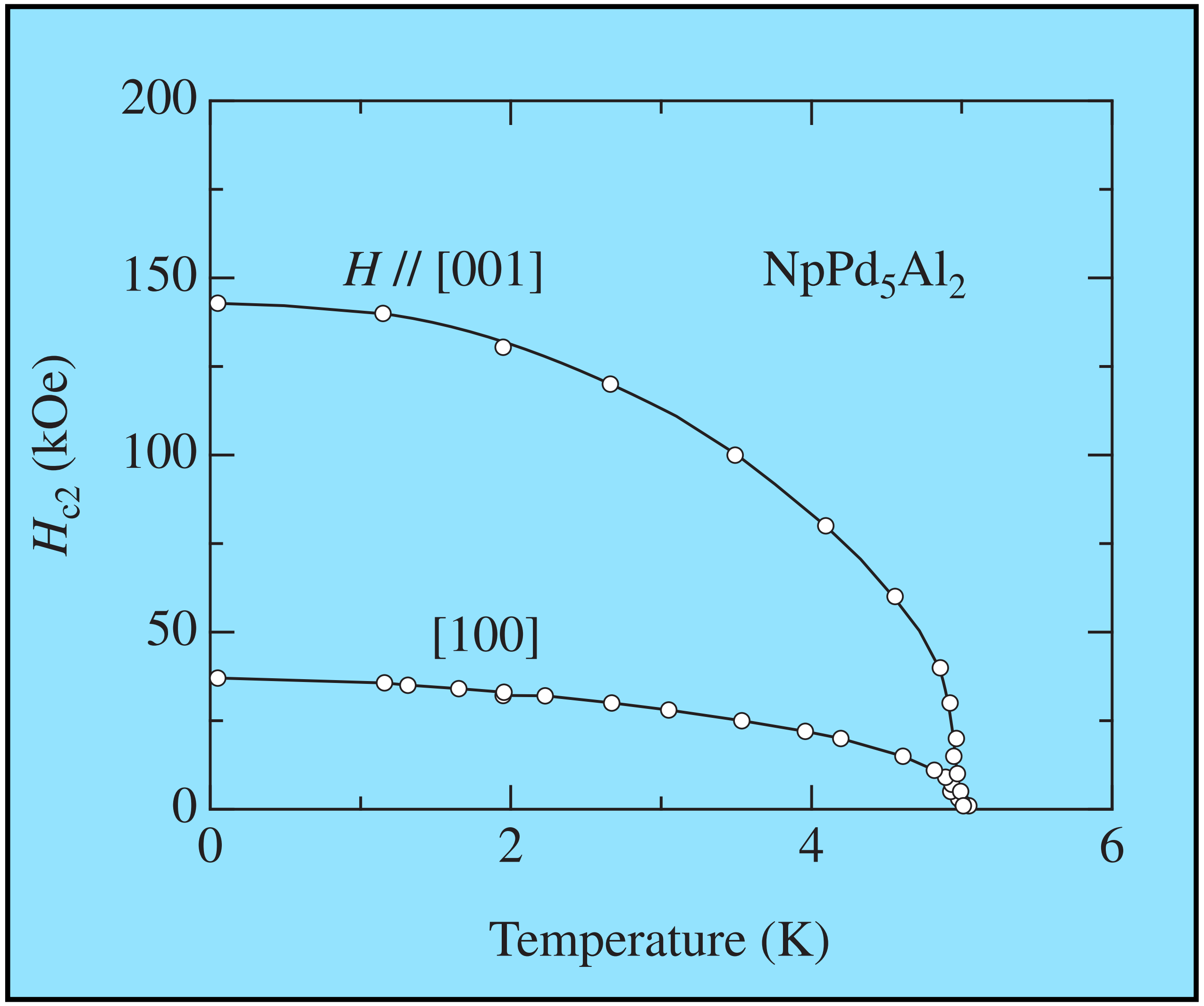

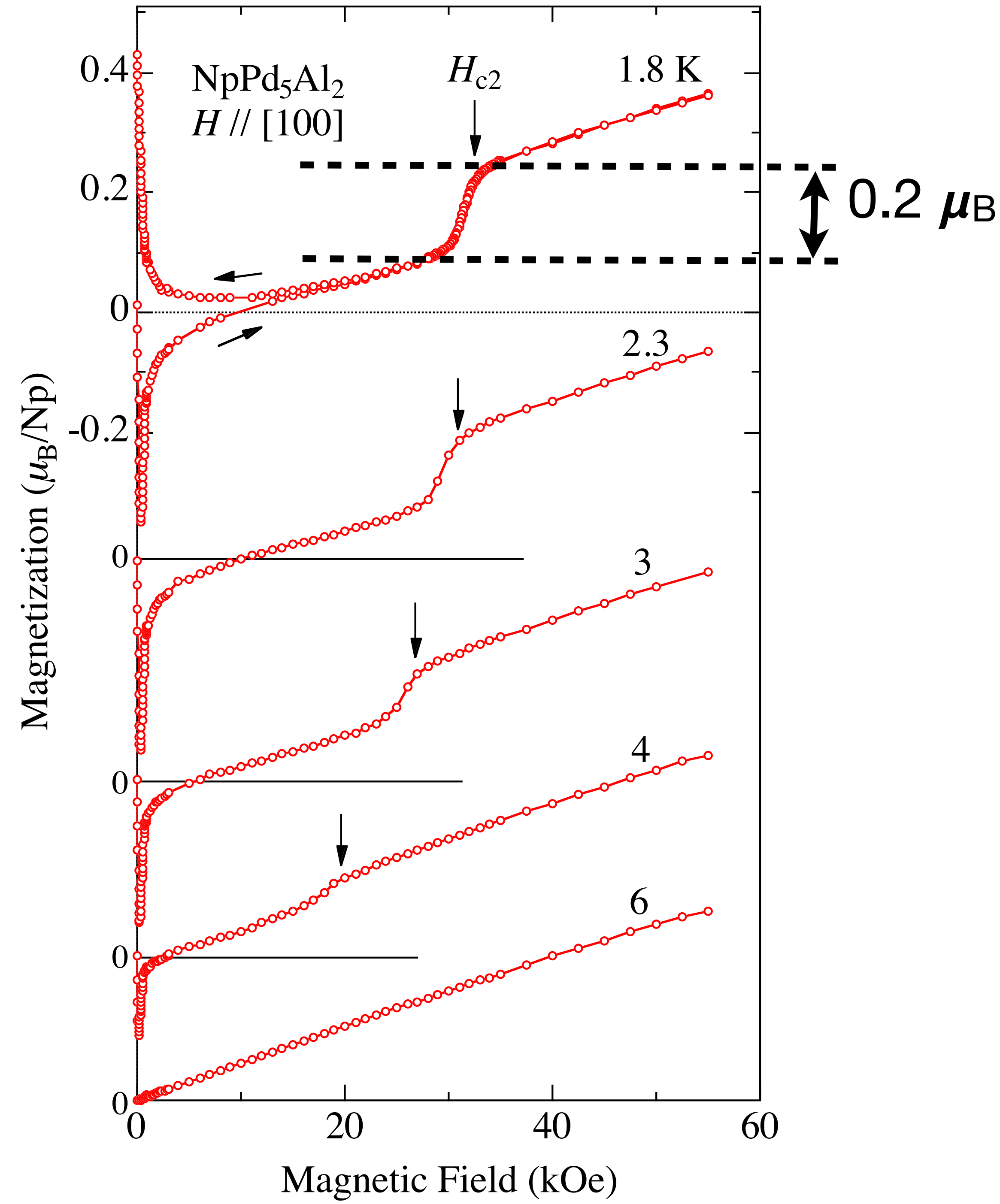

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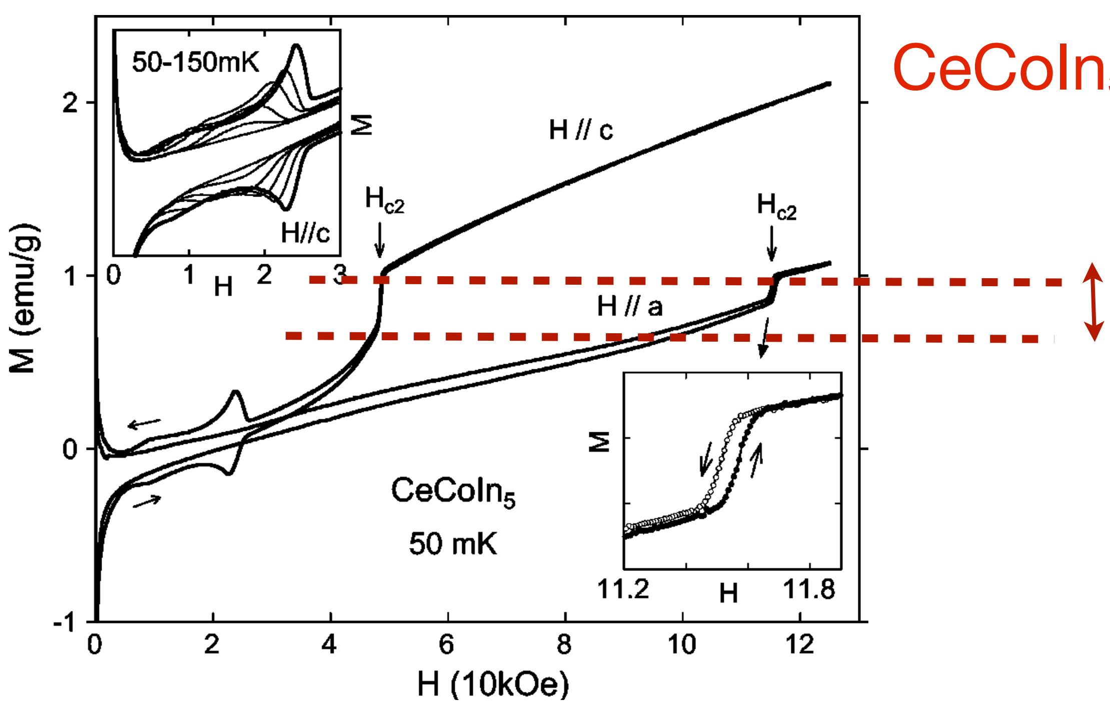


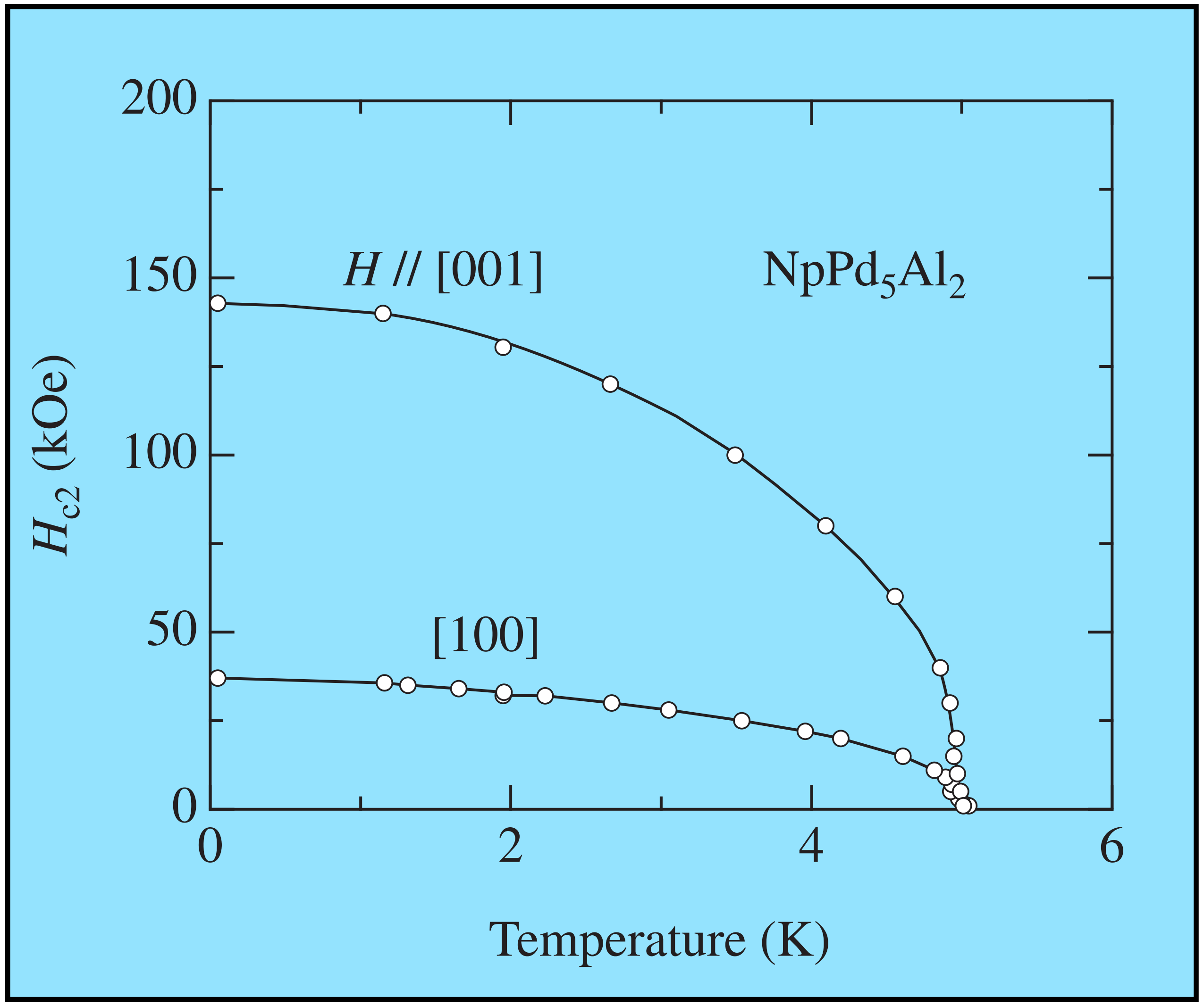
$CeCoIn_5$

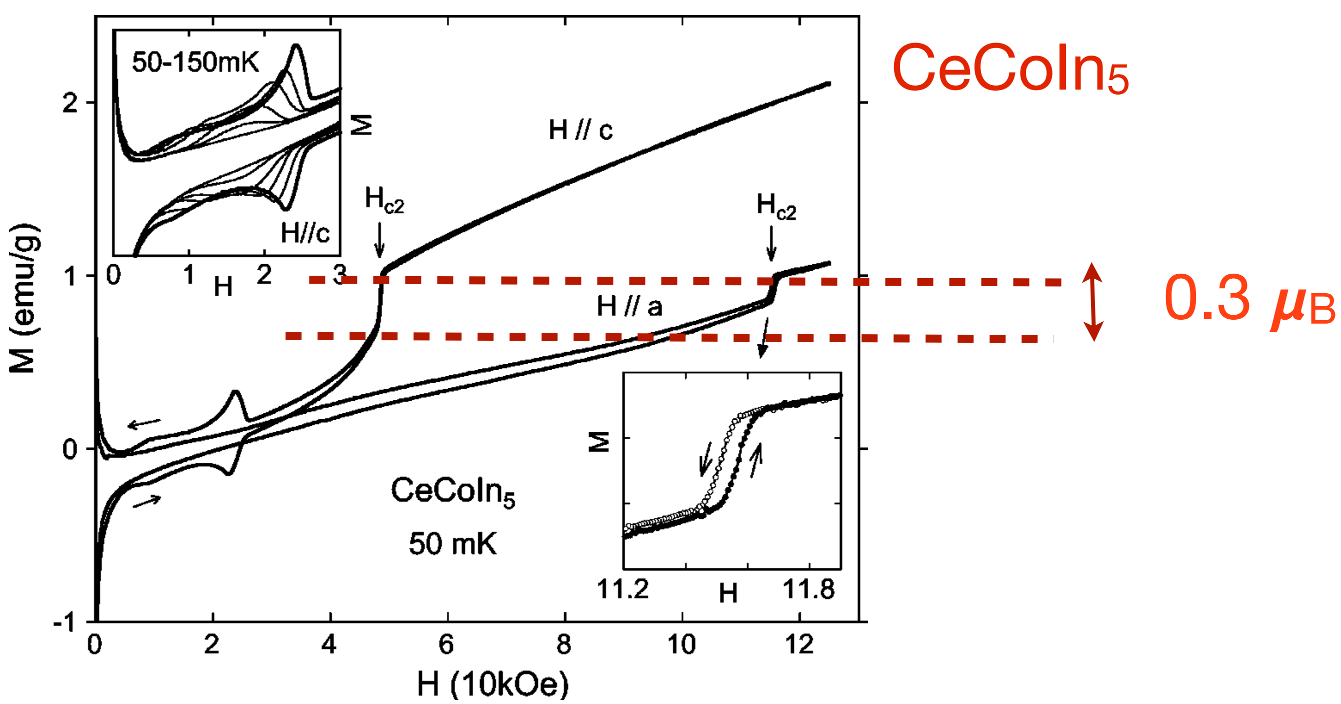
0.3 μ_B

T. Tayama et al., RPB **65**, 180504R (2002)

Large first order jump in magnetization at H_{c2}.

Signals a release of the local moment from the condensate.





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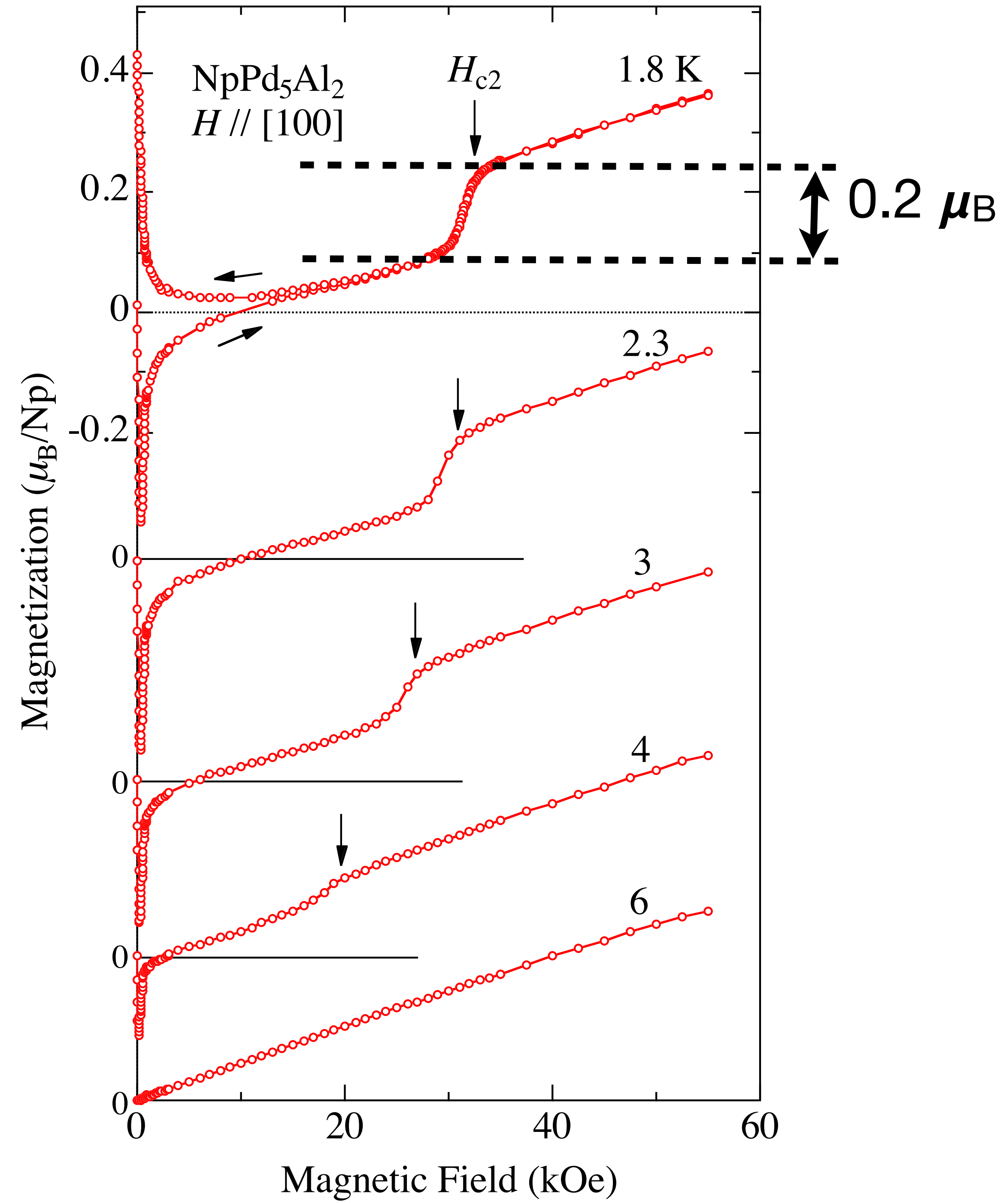

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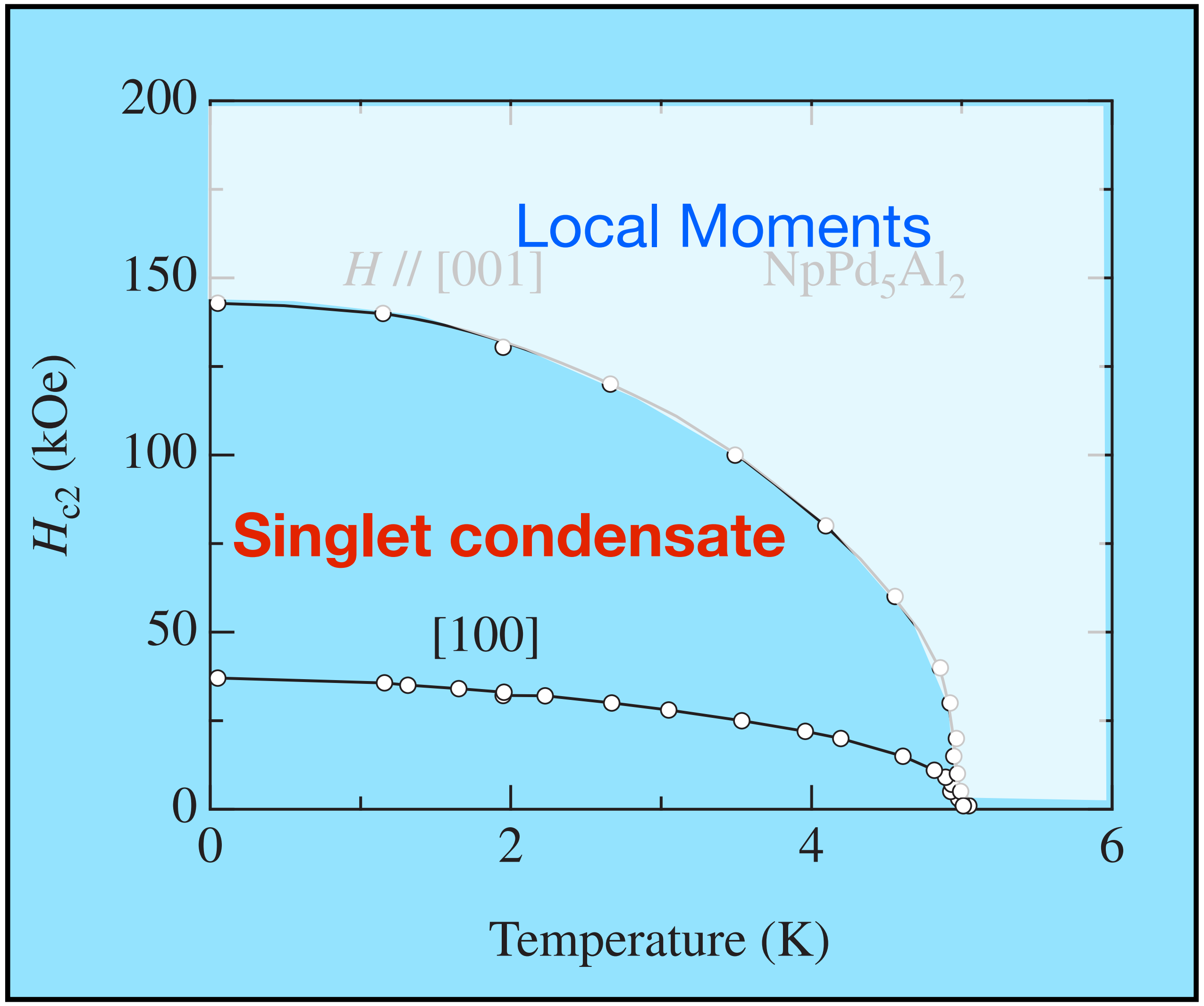

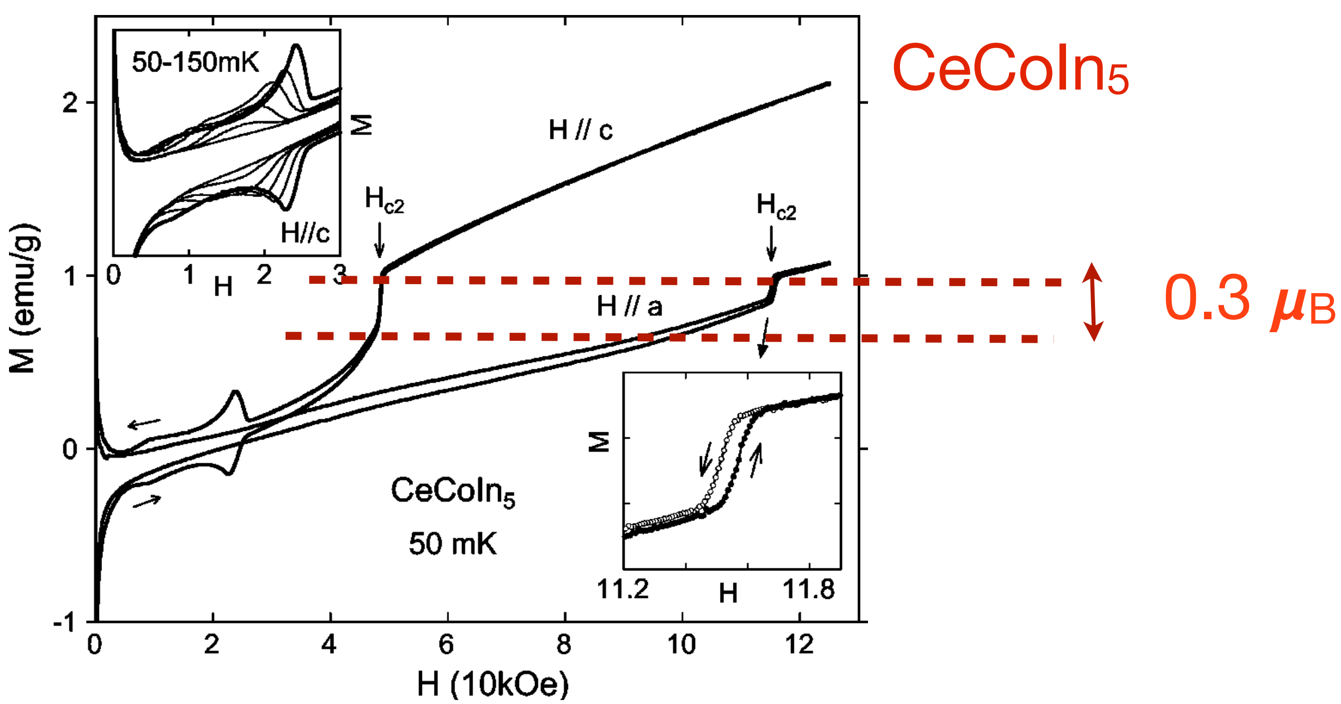

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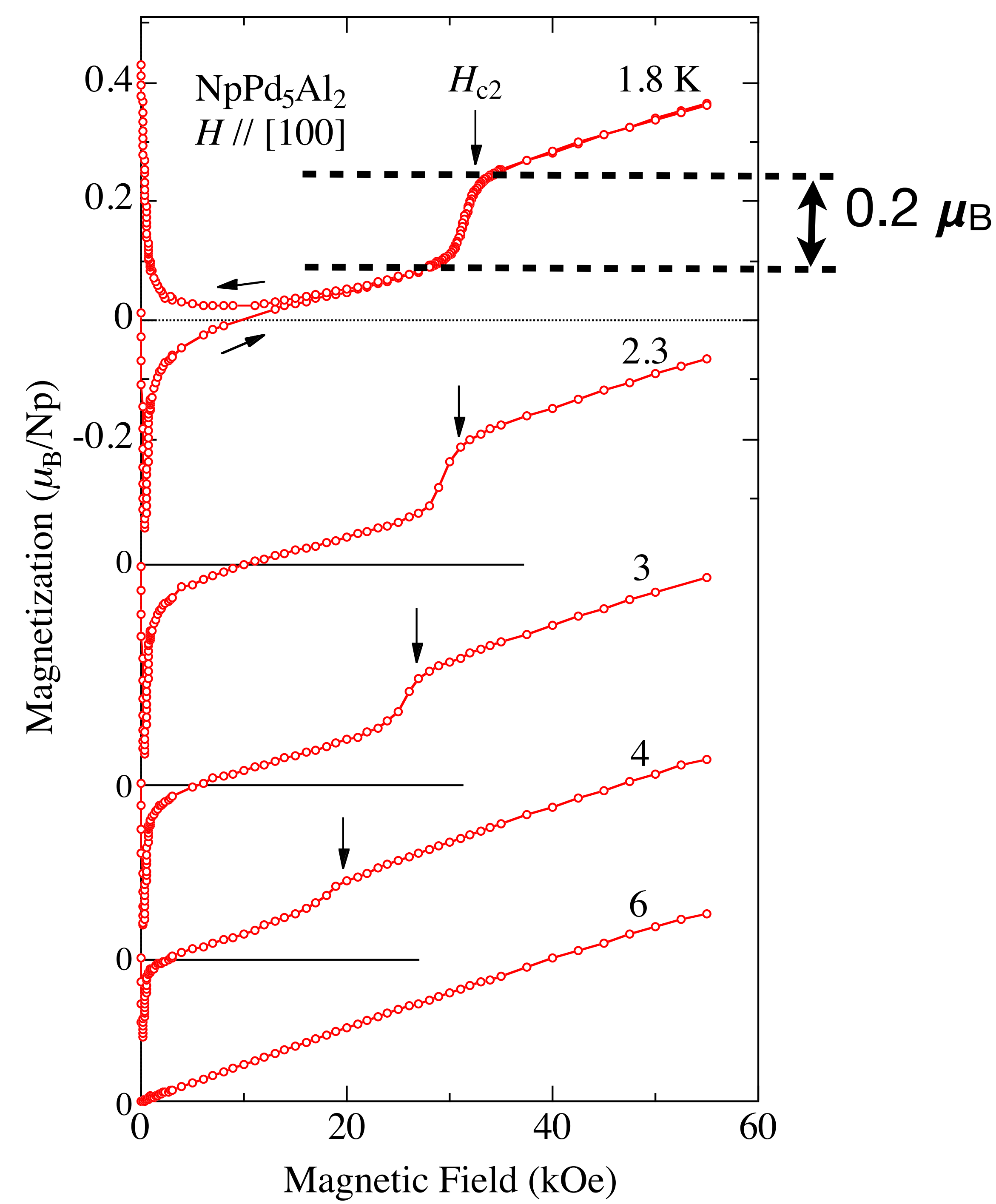

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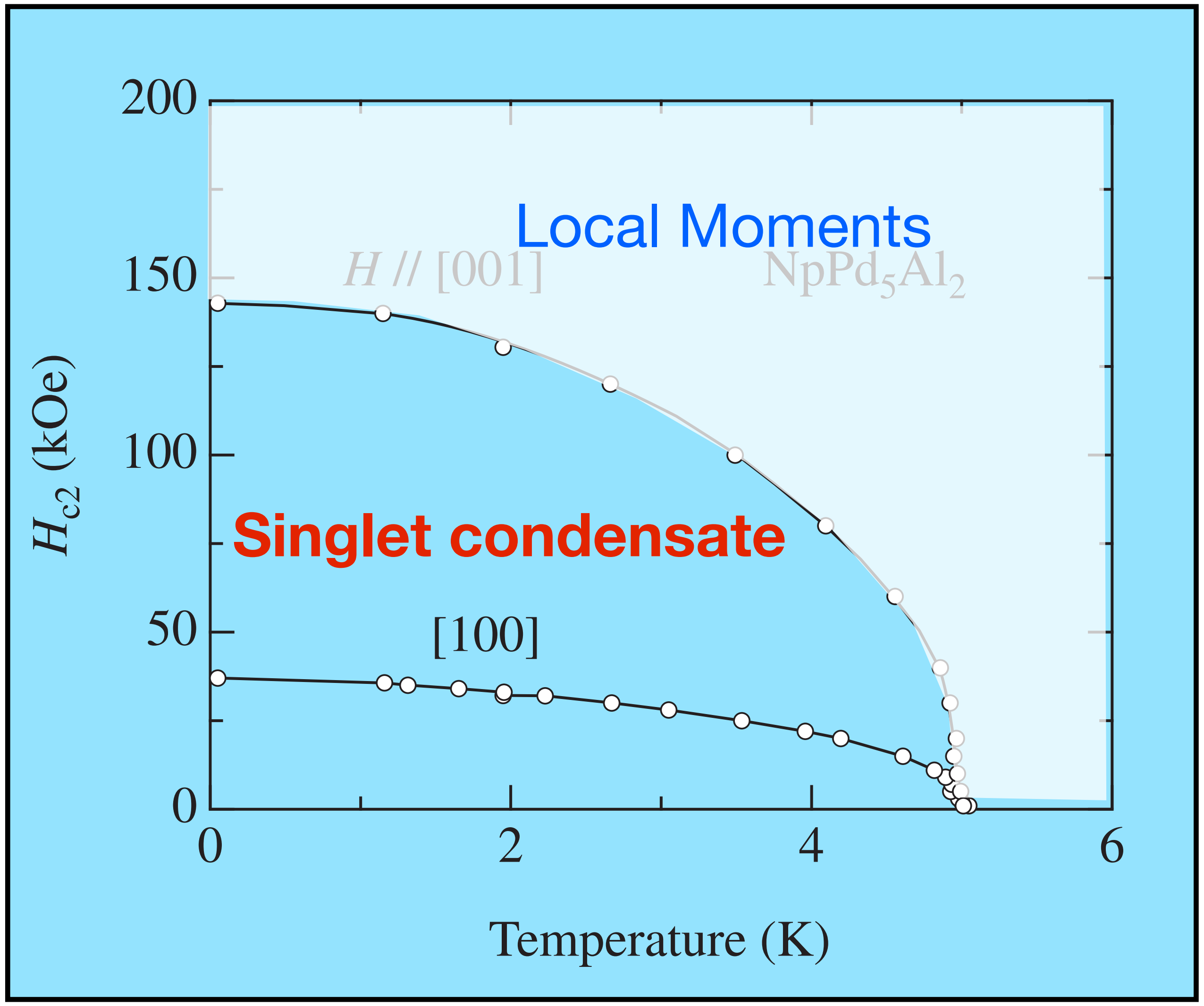

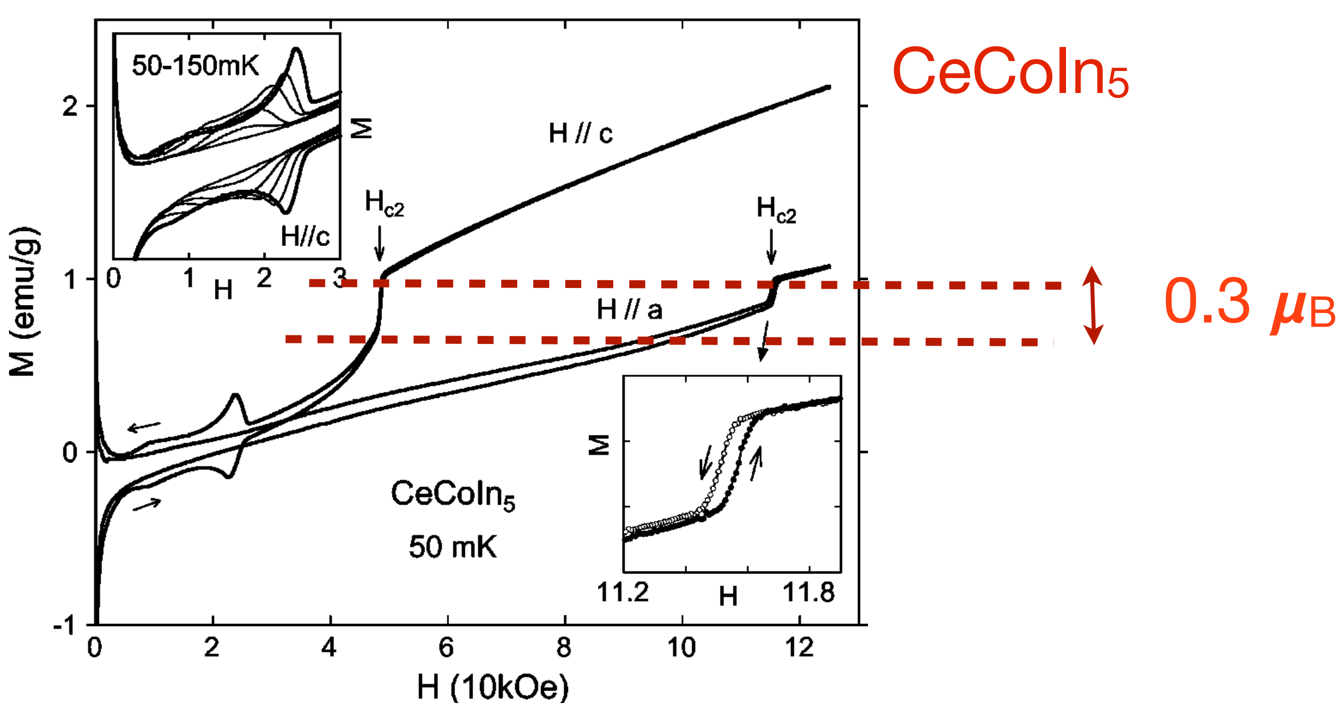

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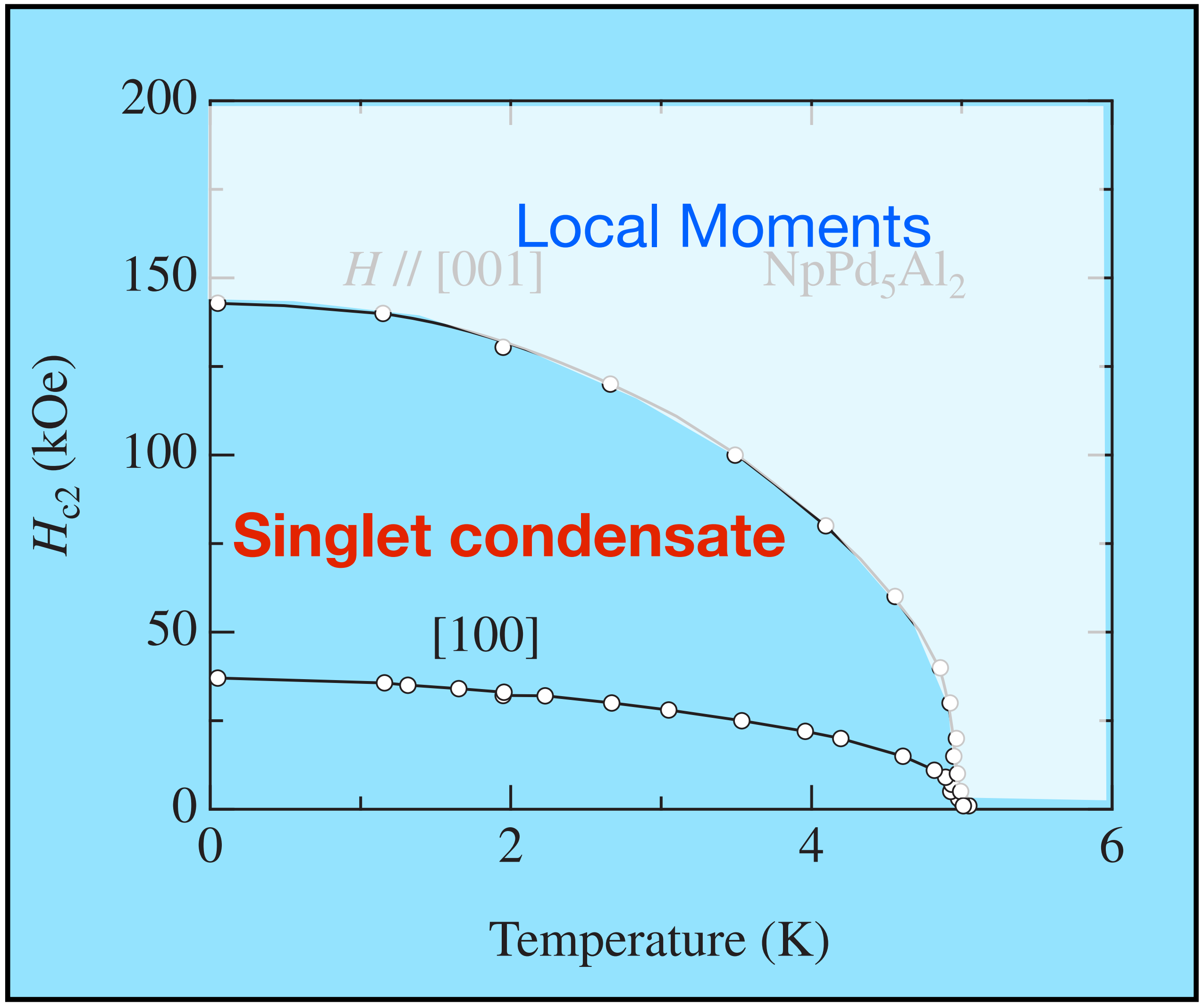

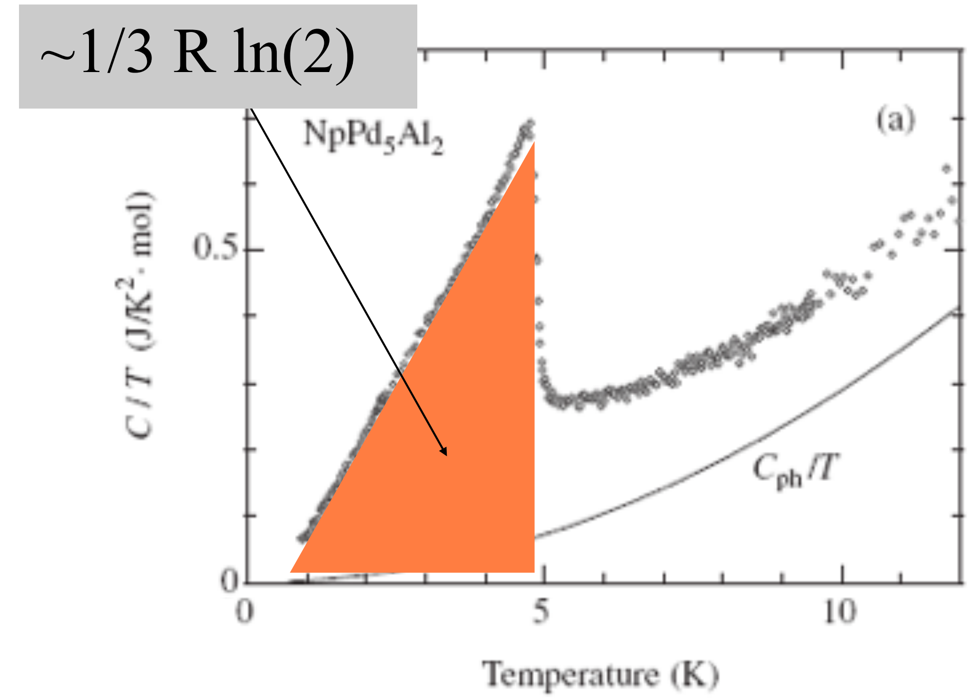

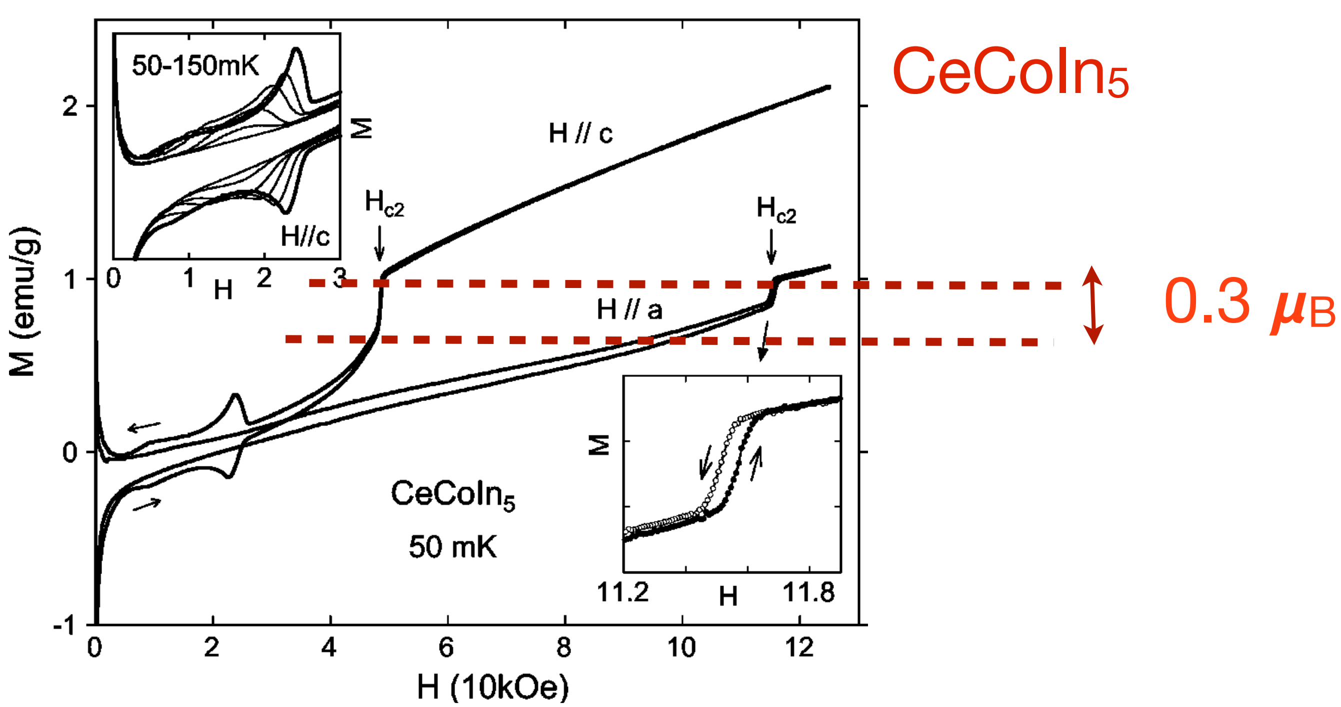

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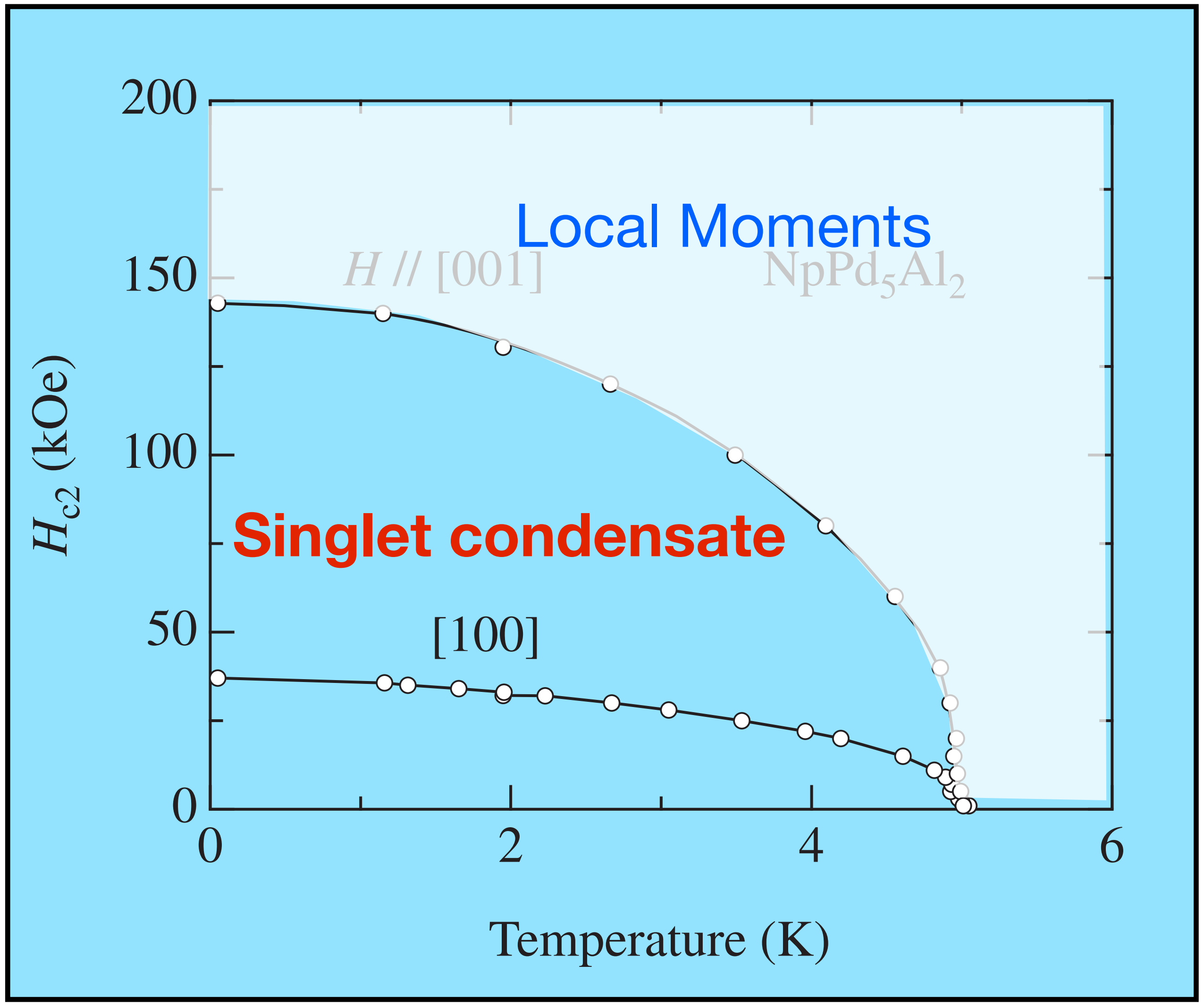
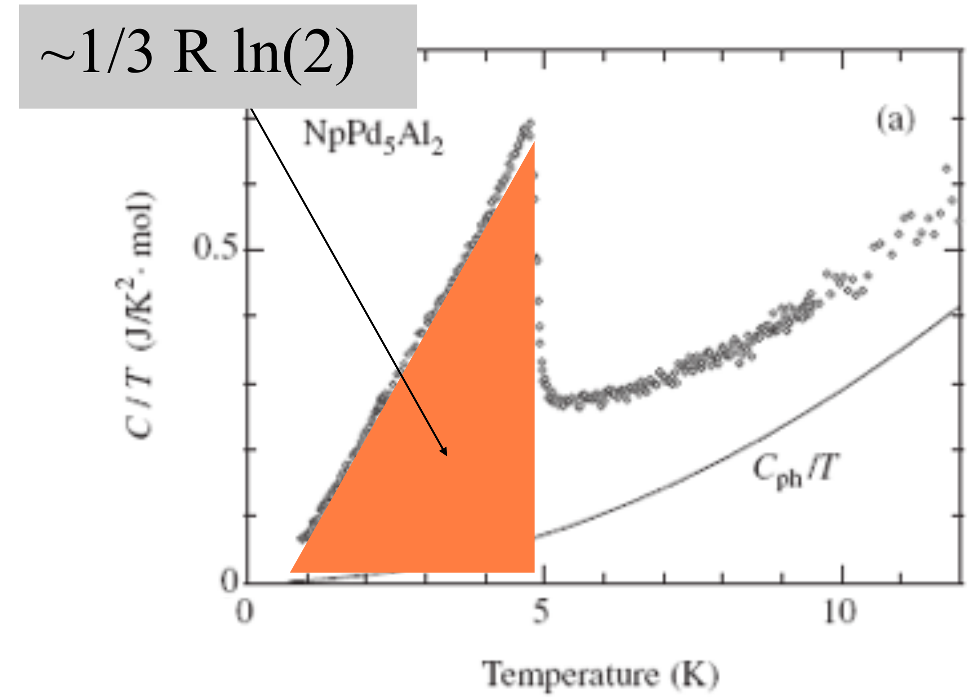
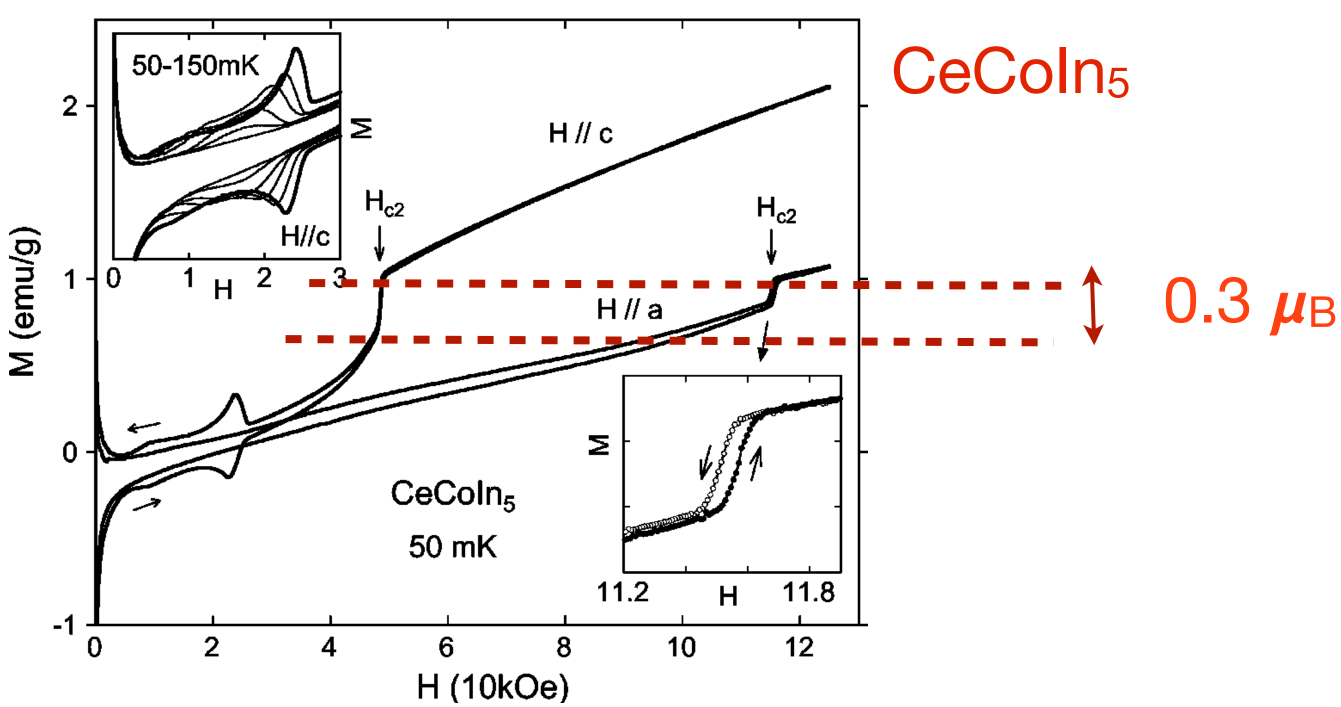




Paradox:

How can a neutral magnetic moments form a charged superconducting condensate?



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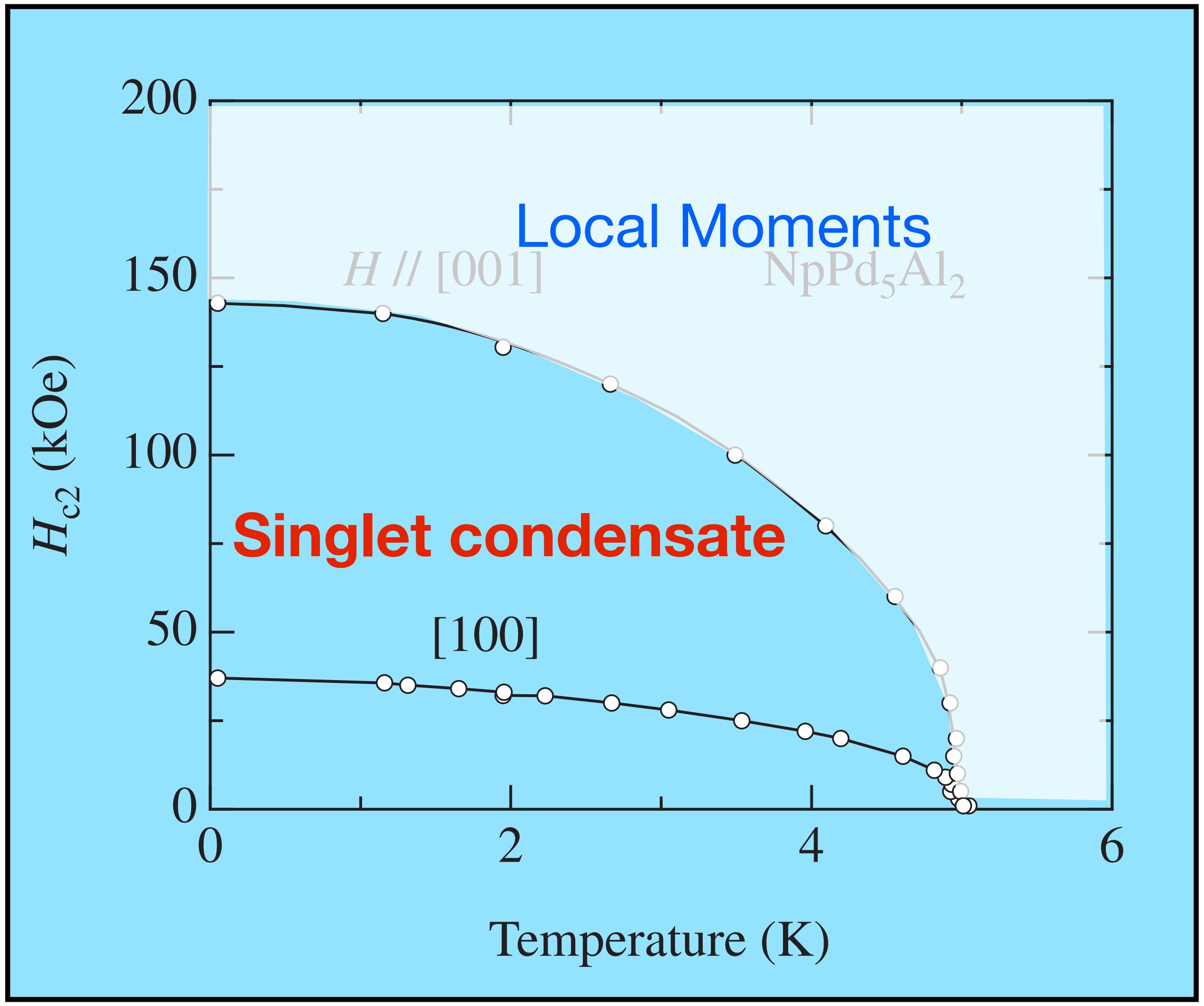

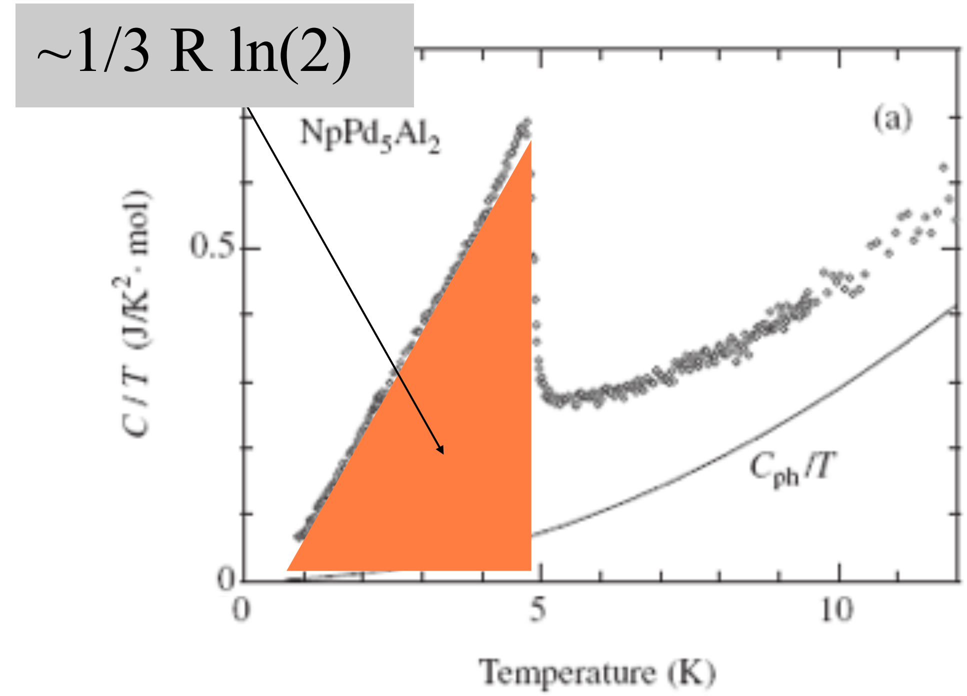

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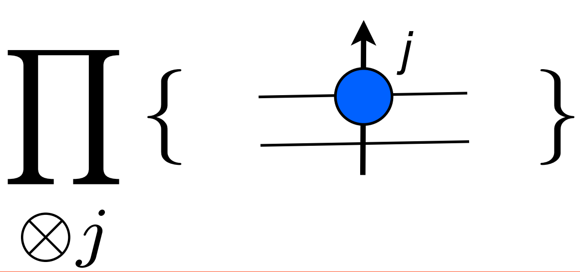
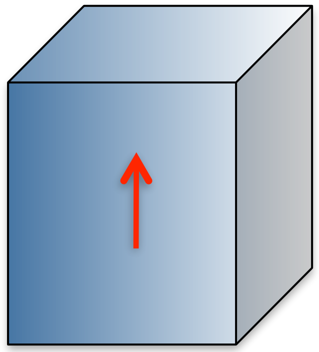


$\otimes$ Charge = Condensate Hilbert Space

Composite pairing Hypothesis.

Coherence and composite fermions



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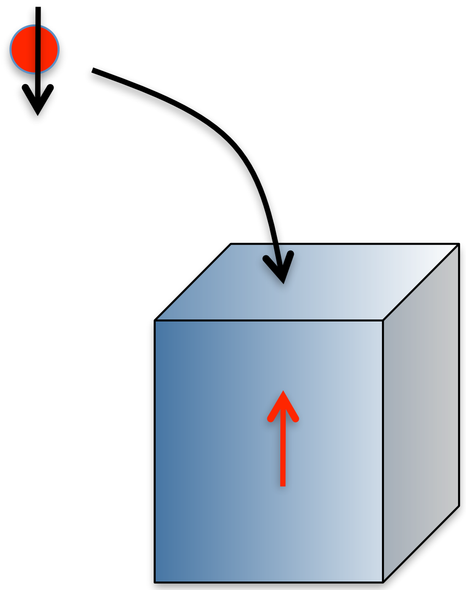

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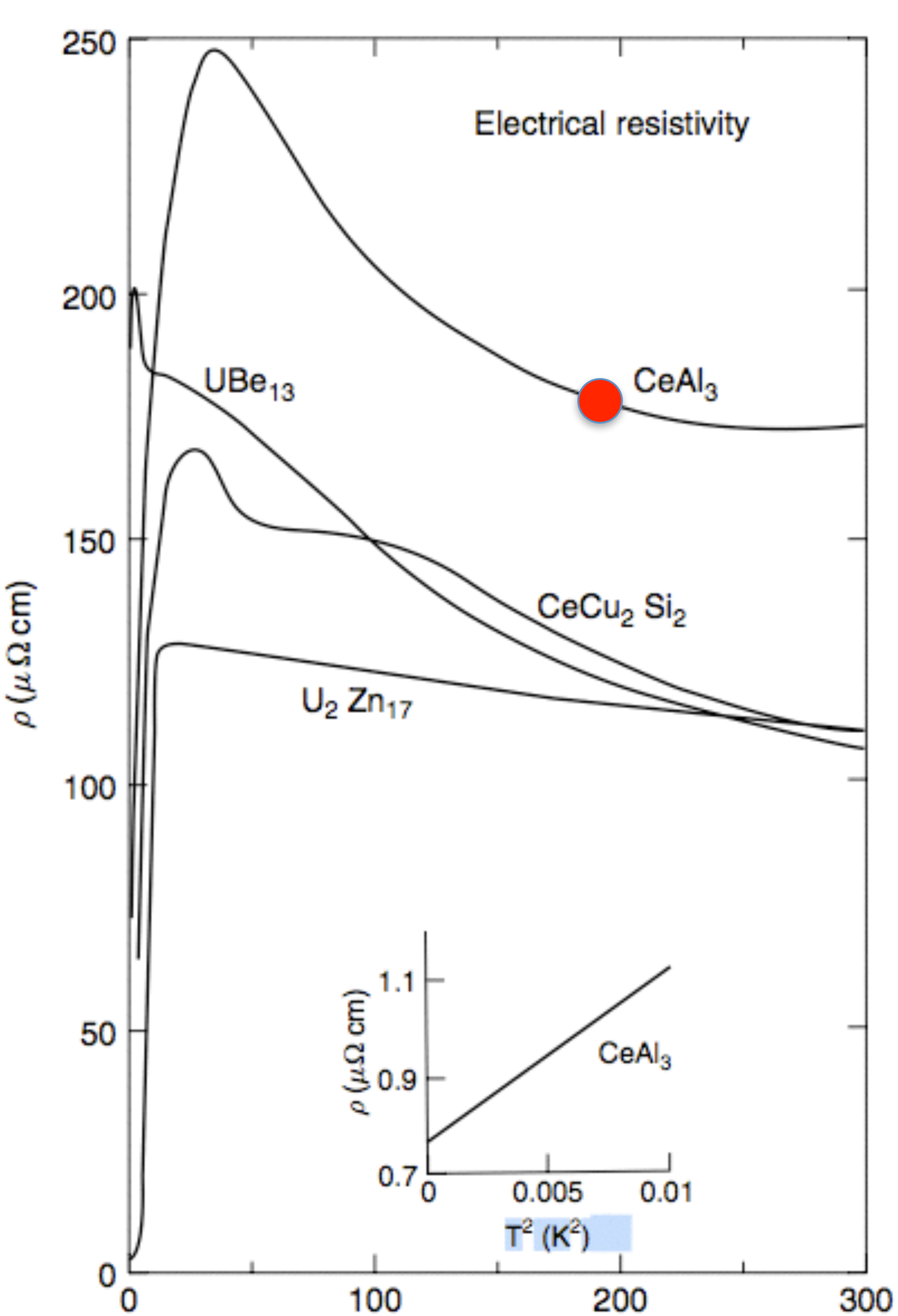

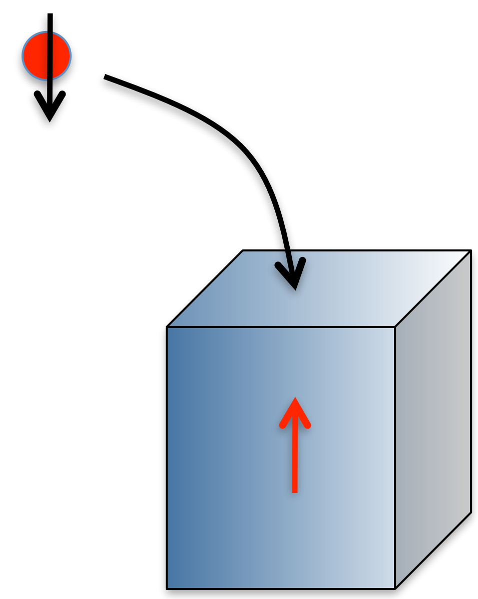

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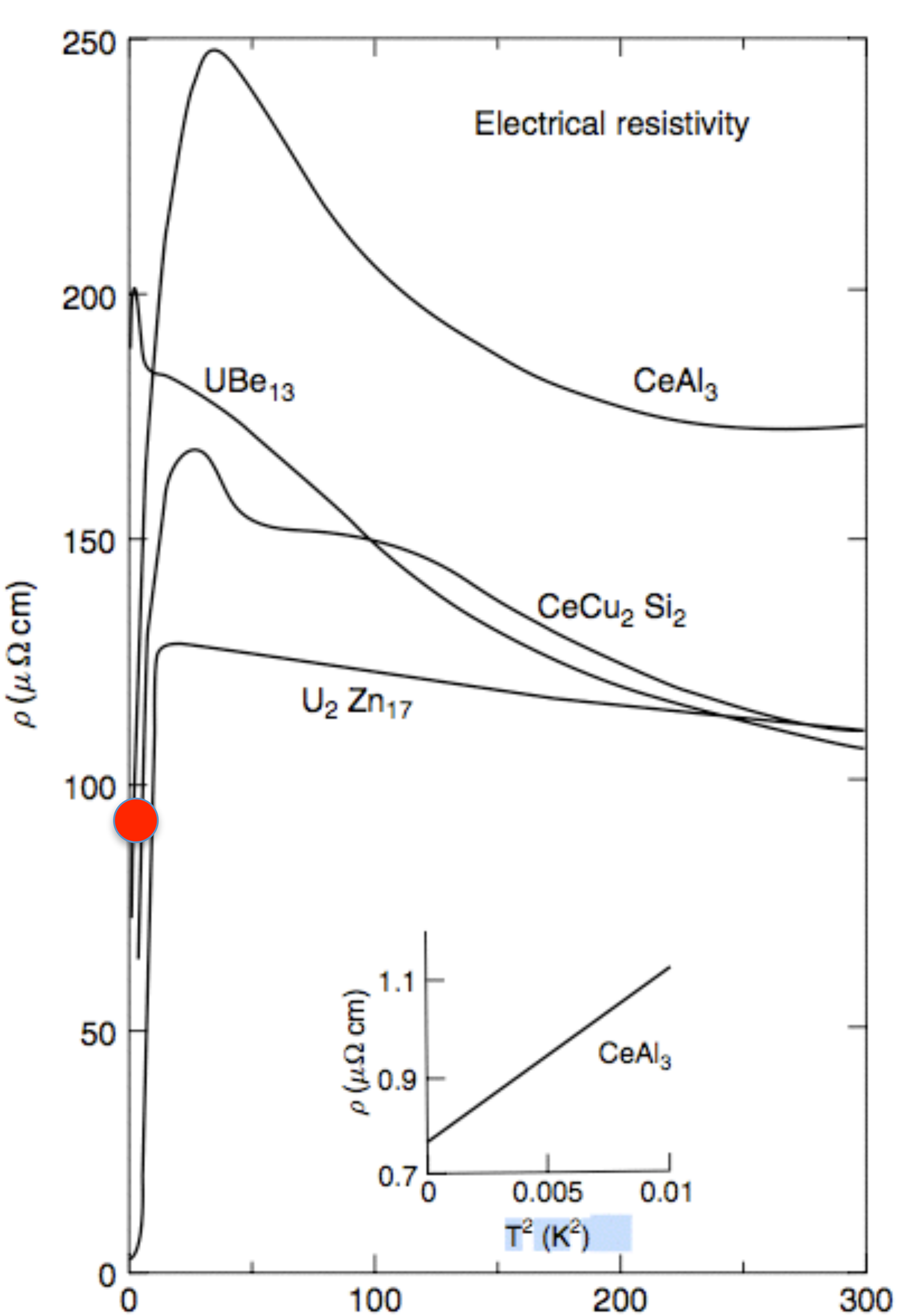

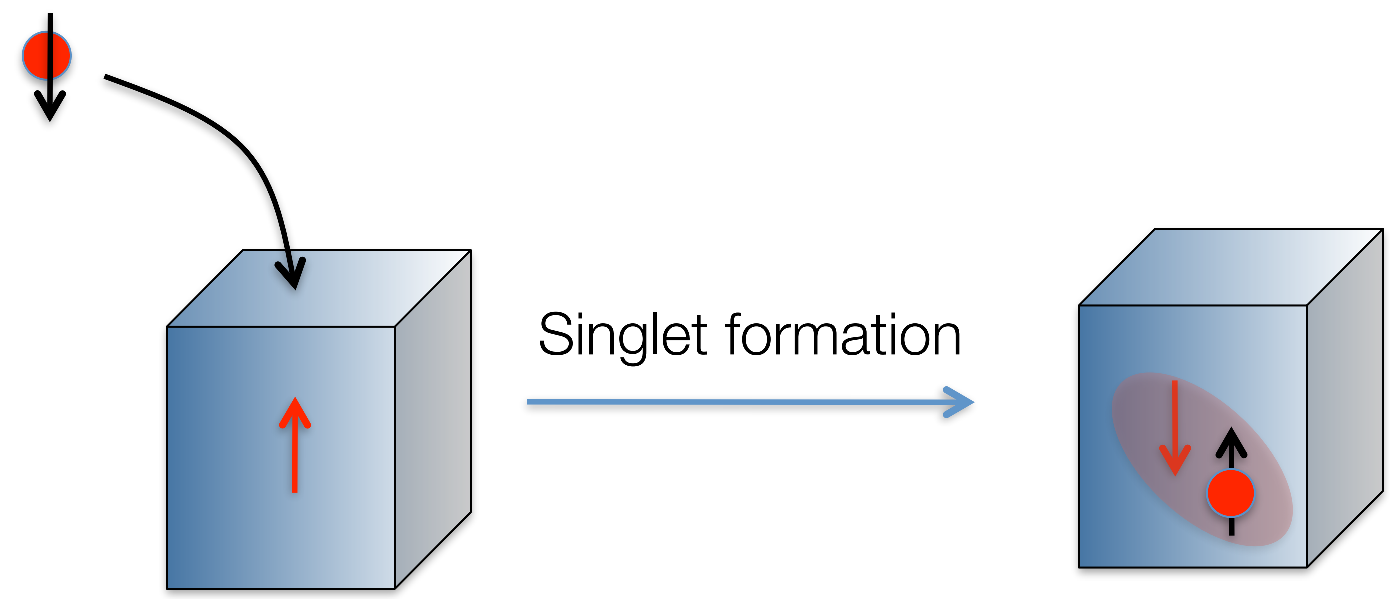

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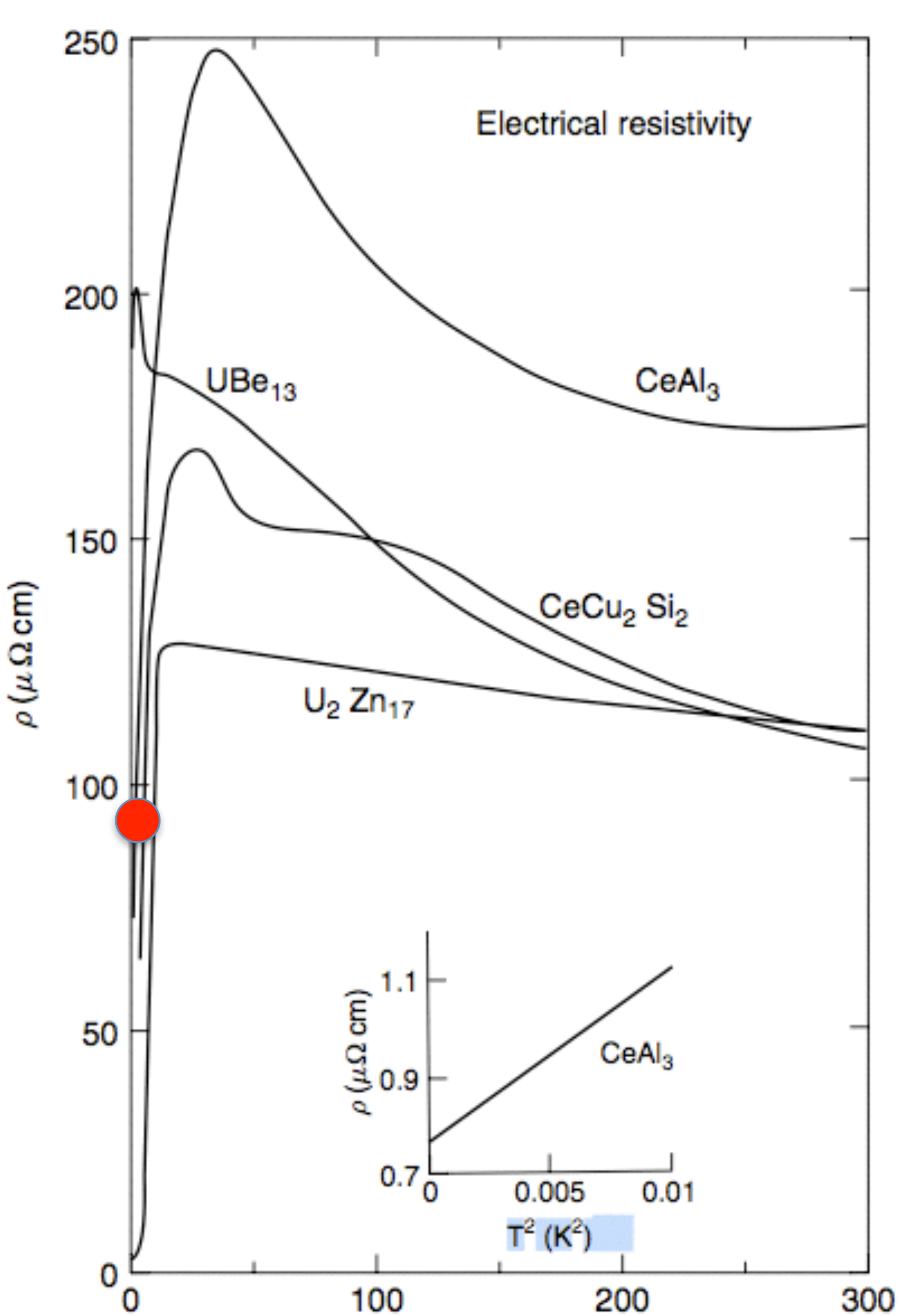
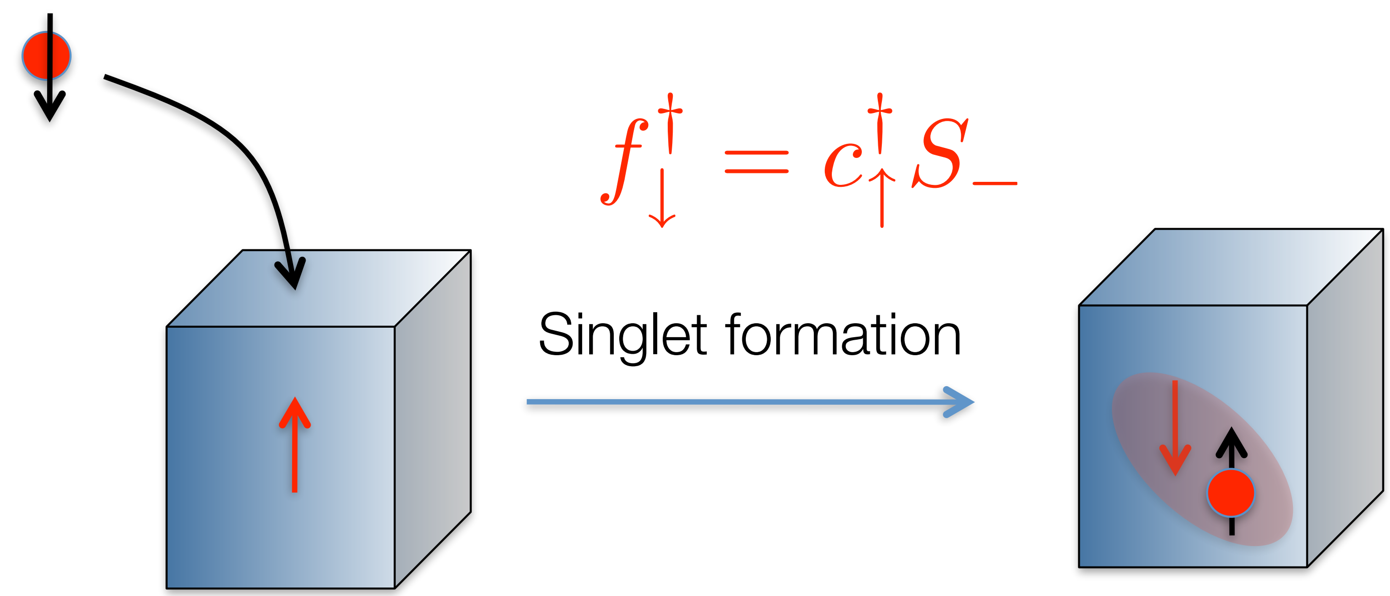
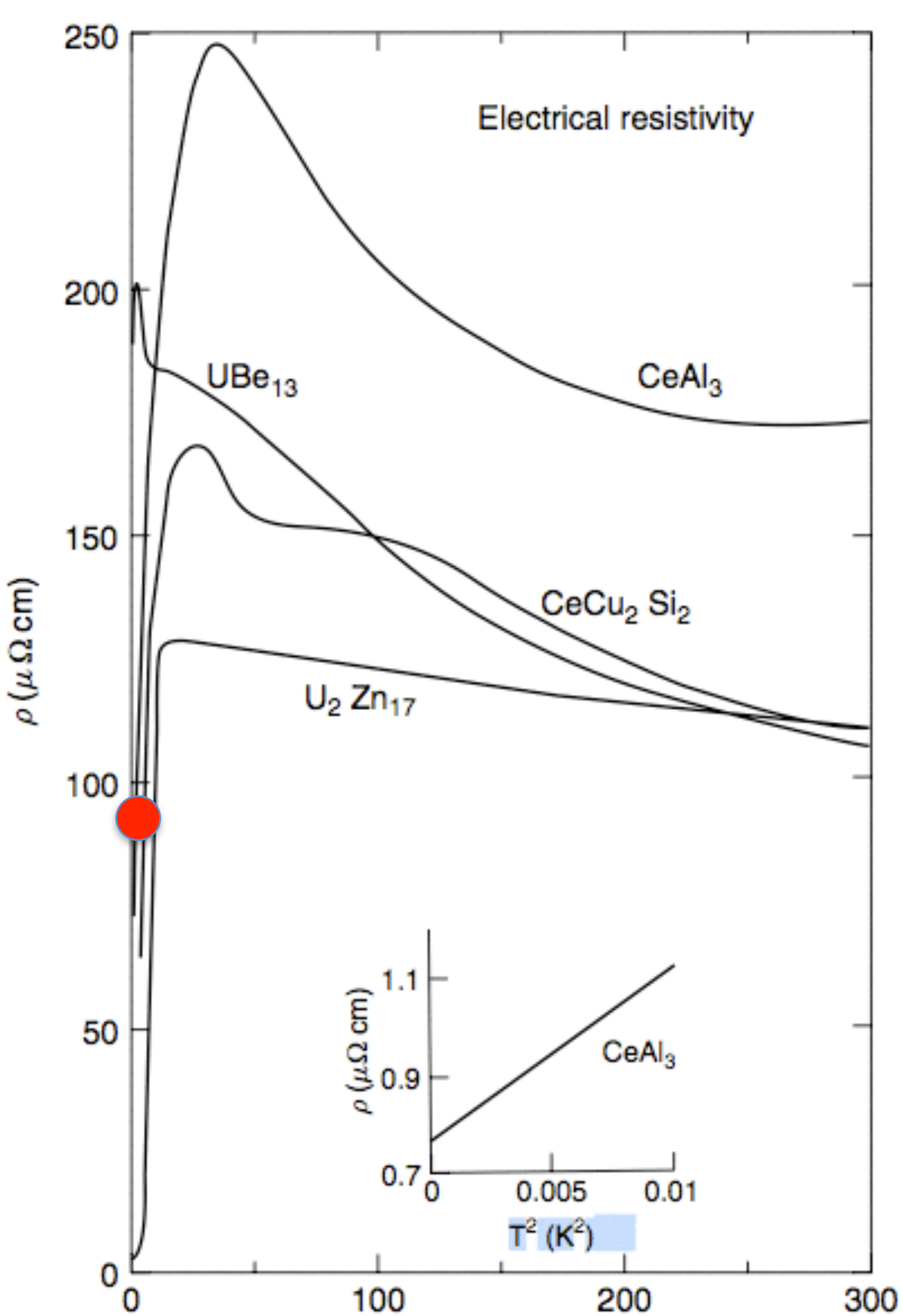


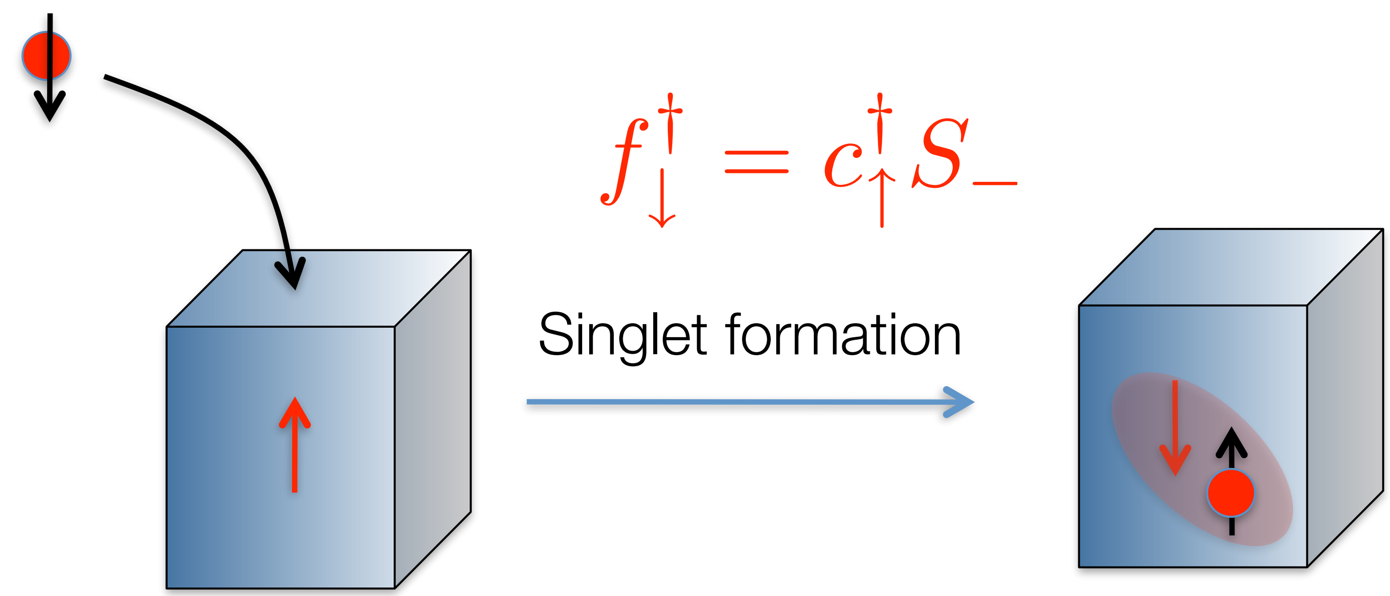


$$f^\dagger_\downarrow = c^\dagger_\uparrow S_-$$

Heavy electron = (electron x spinflip)

Coherence and composite fermions





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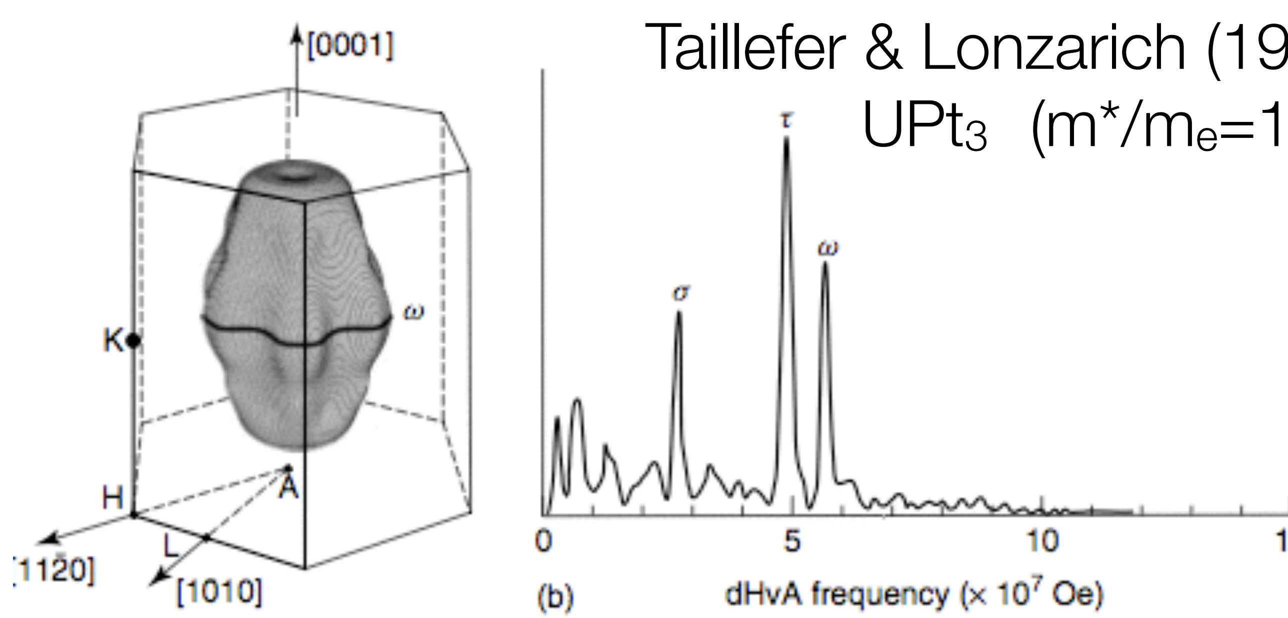
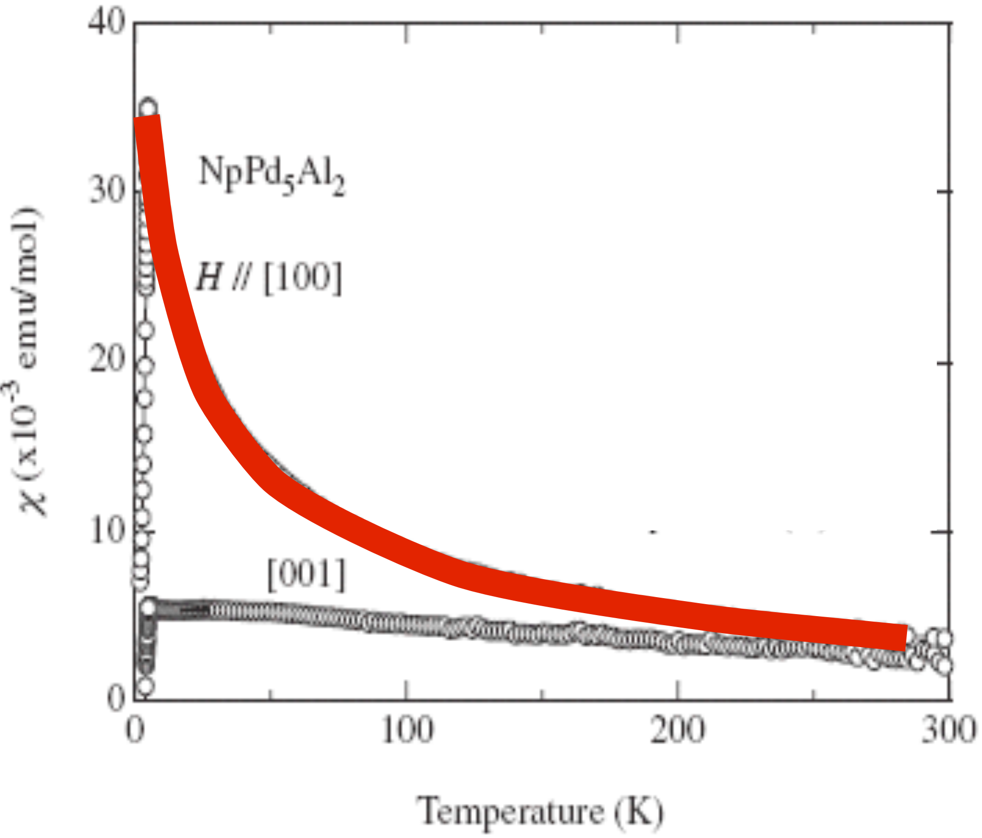


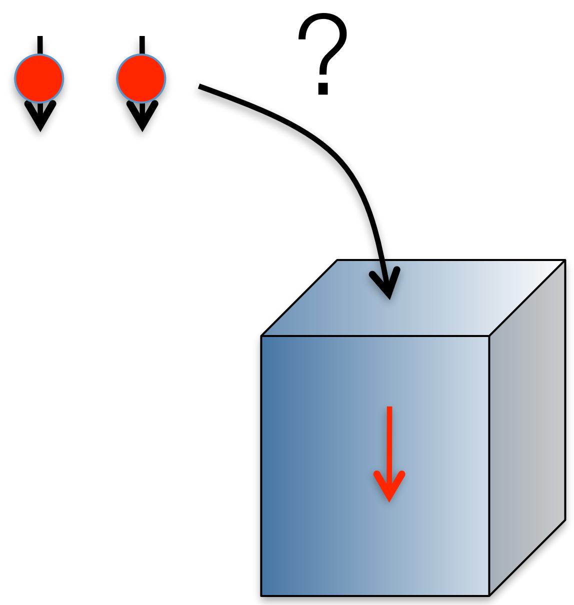
Taillefer & Lonzarich (1985)

UPt_3 $(m^*/m_e=120)$

Composite pairing

$NpPd_5Al_2$ $T_C = 4.5K$





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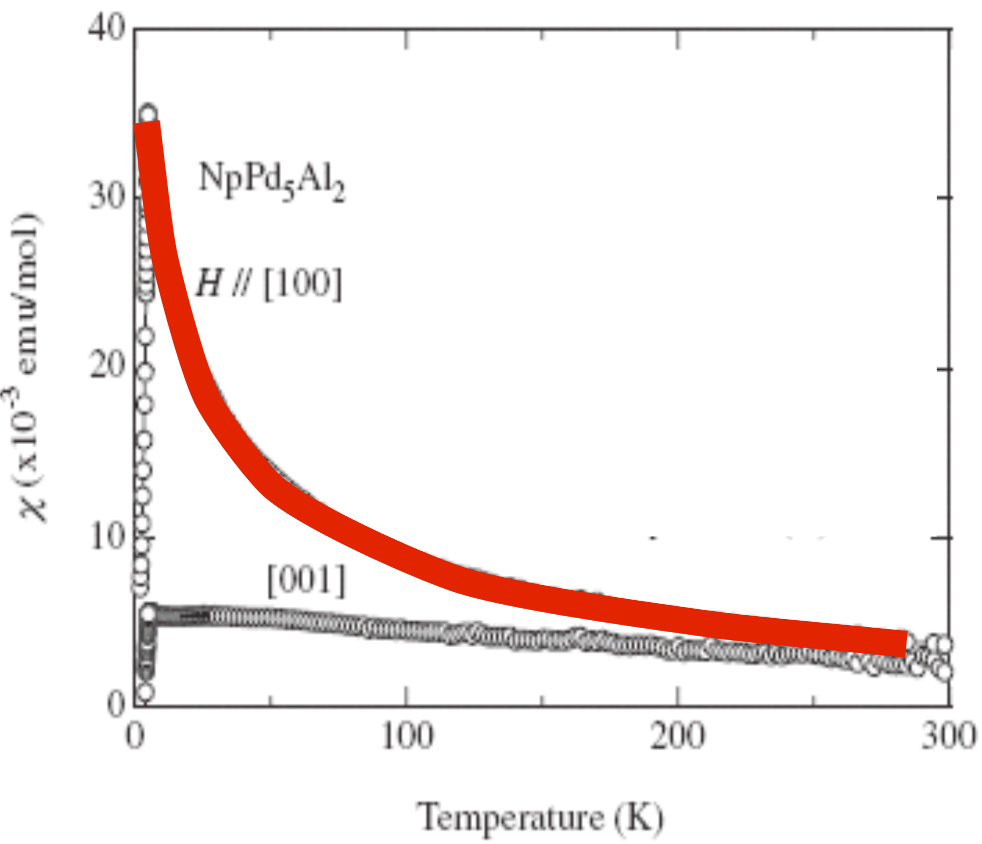

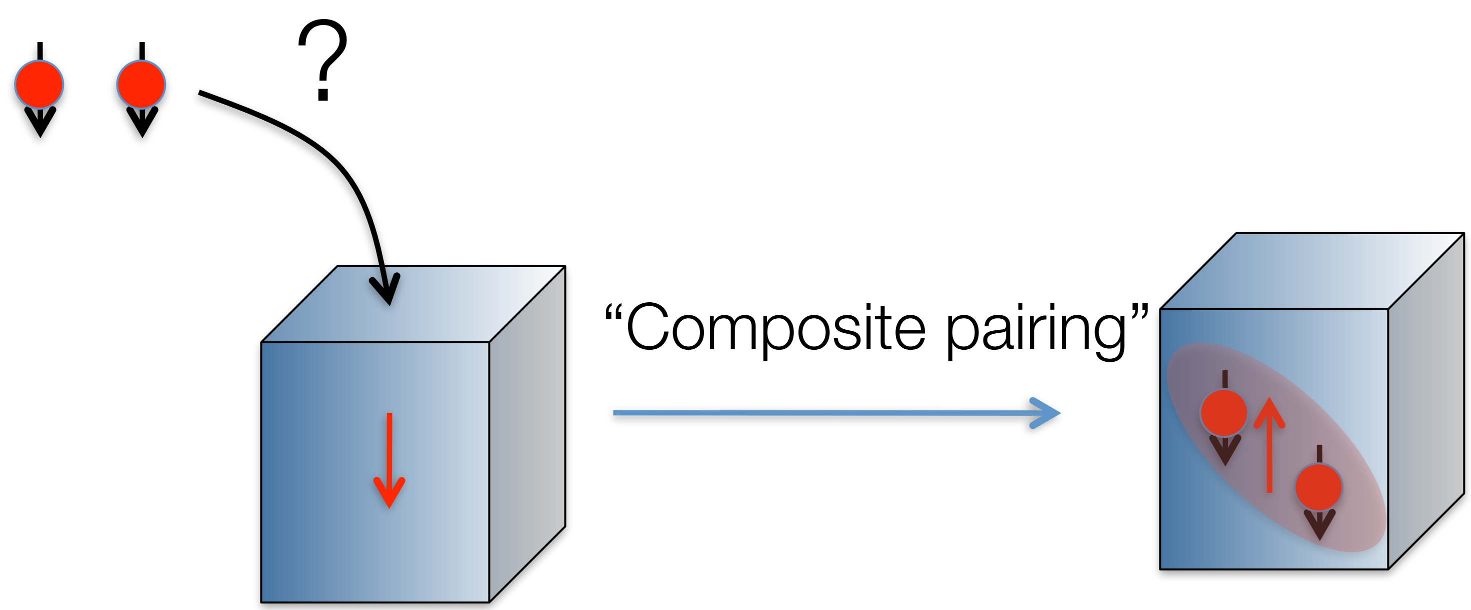

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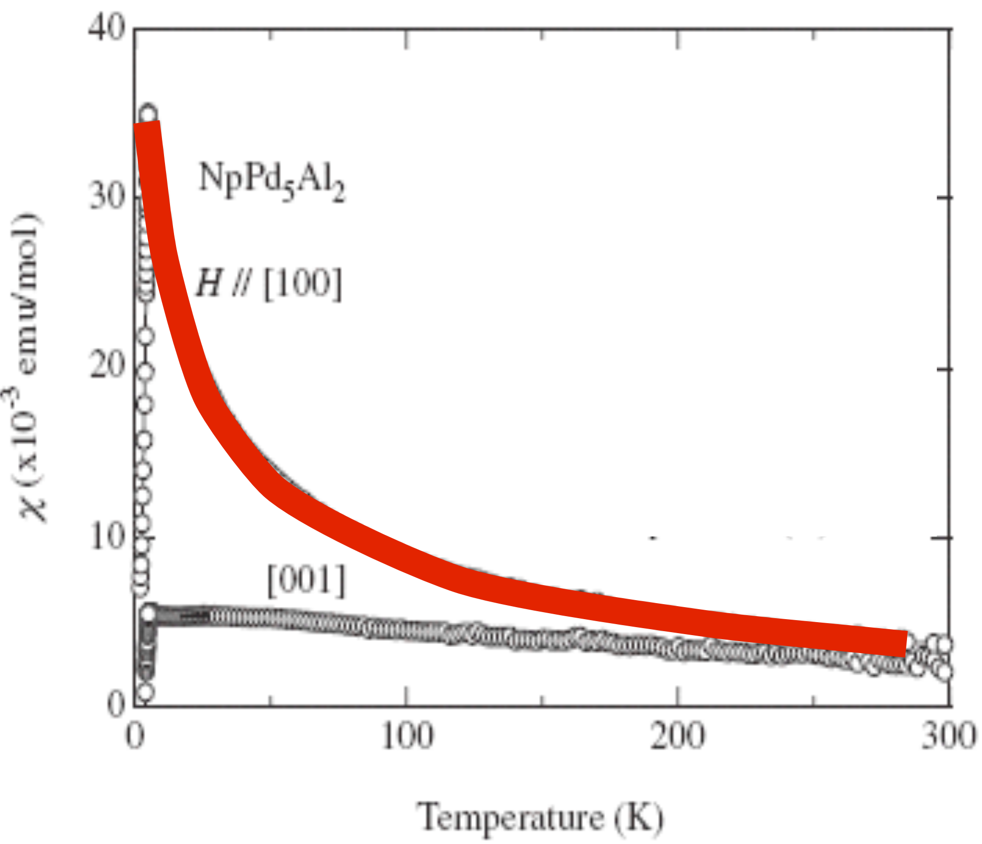
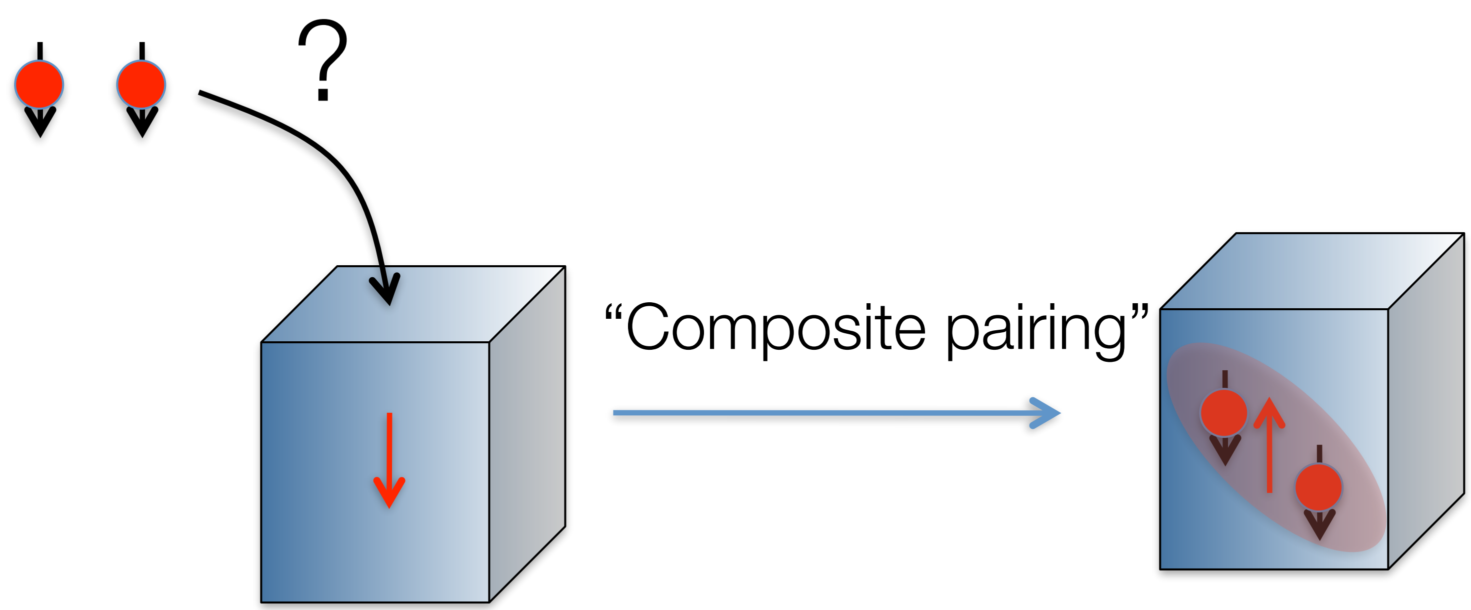
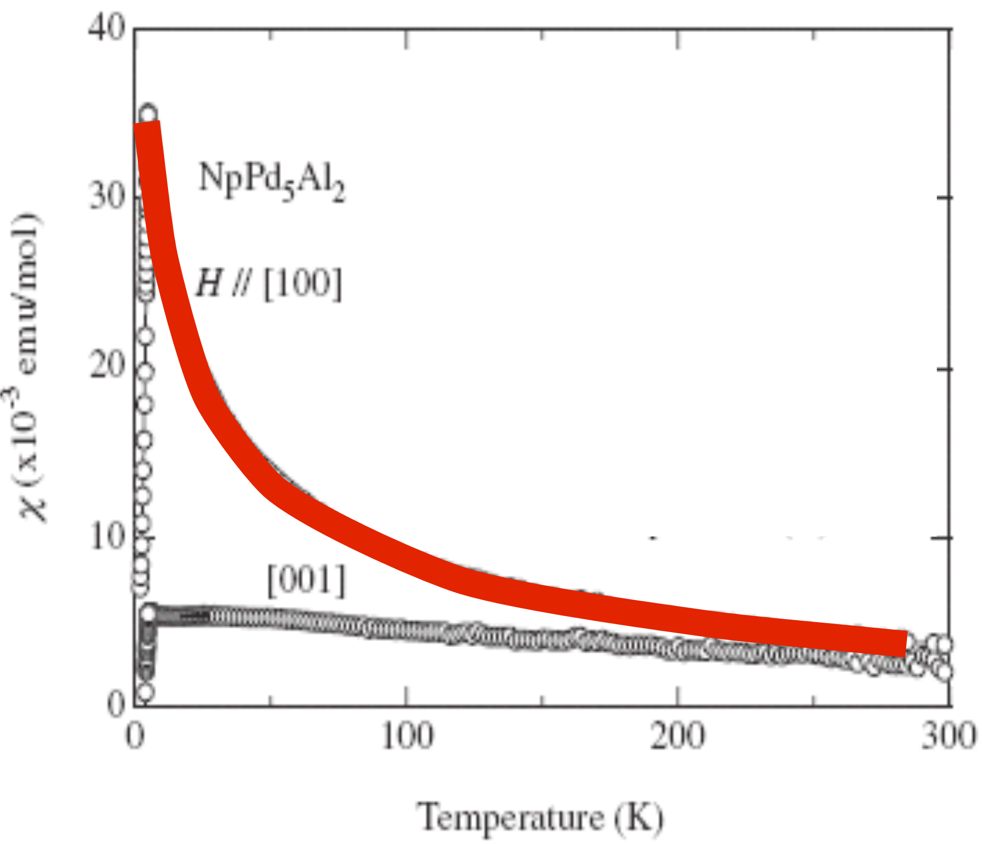


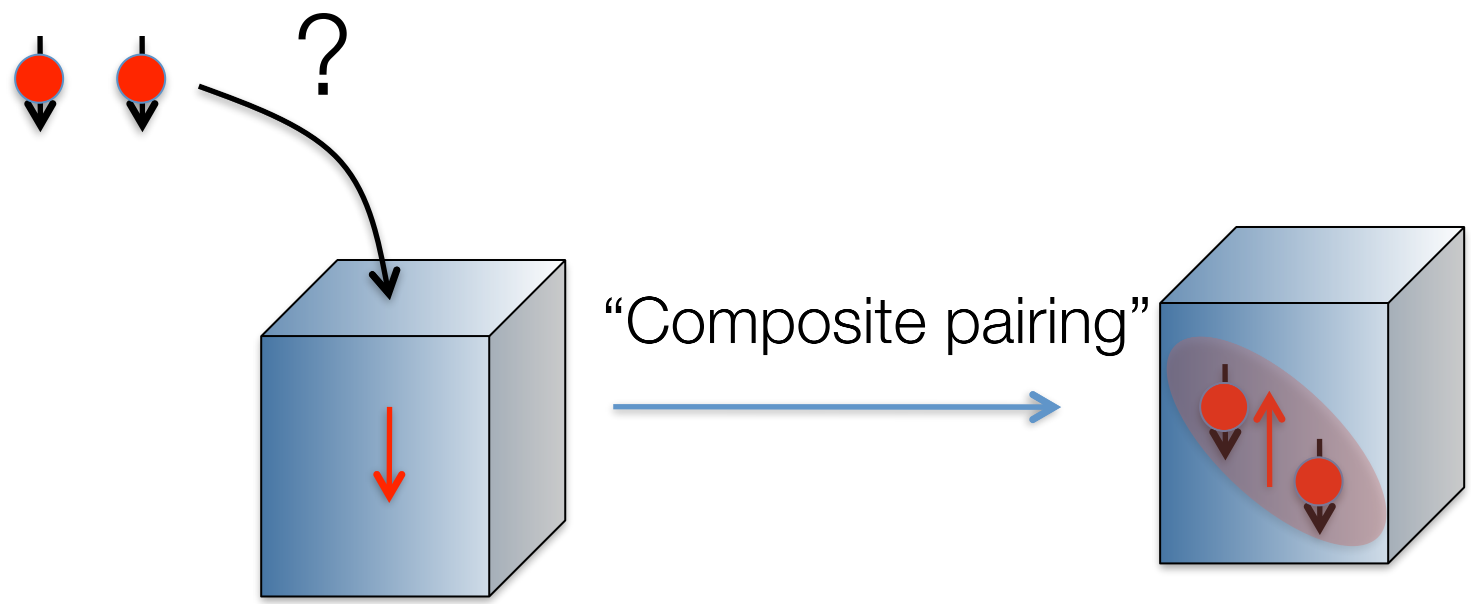


Heavy Cooper pair = (pair x spinflip)

Composite pairing

$NpPd_5Al_2$ $T_C = 4.5K$





Heavy Cooper pair = (pair x spinflip)

$$\Psi^\dagger = c^\dagger_{1\downarrow} c^\dagger_{2\downarrow} S_+$$

Composite pairing

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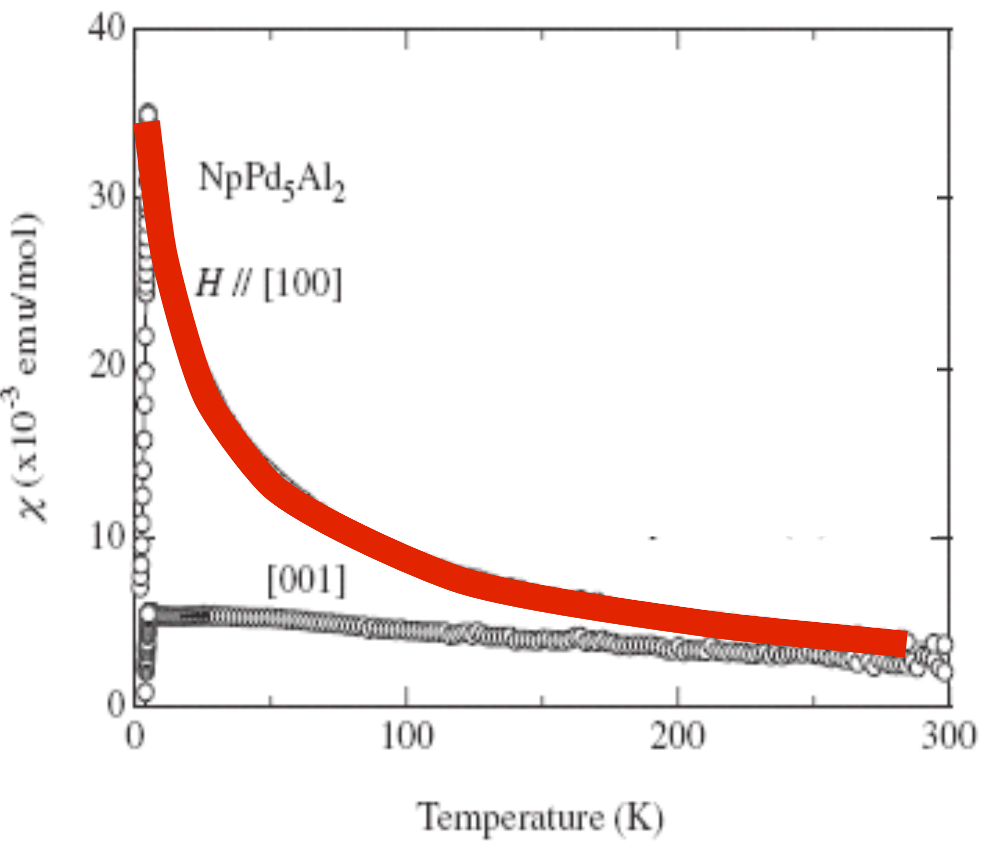

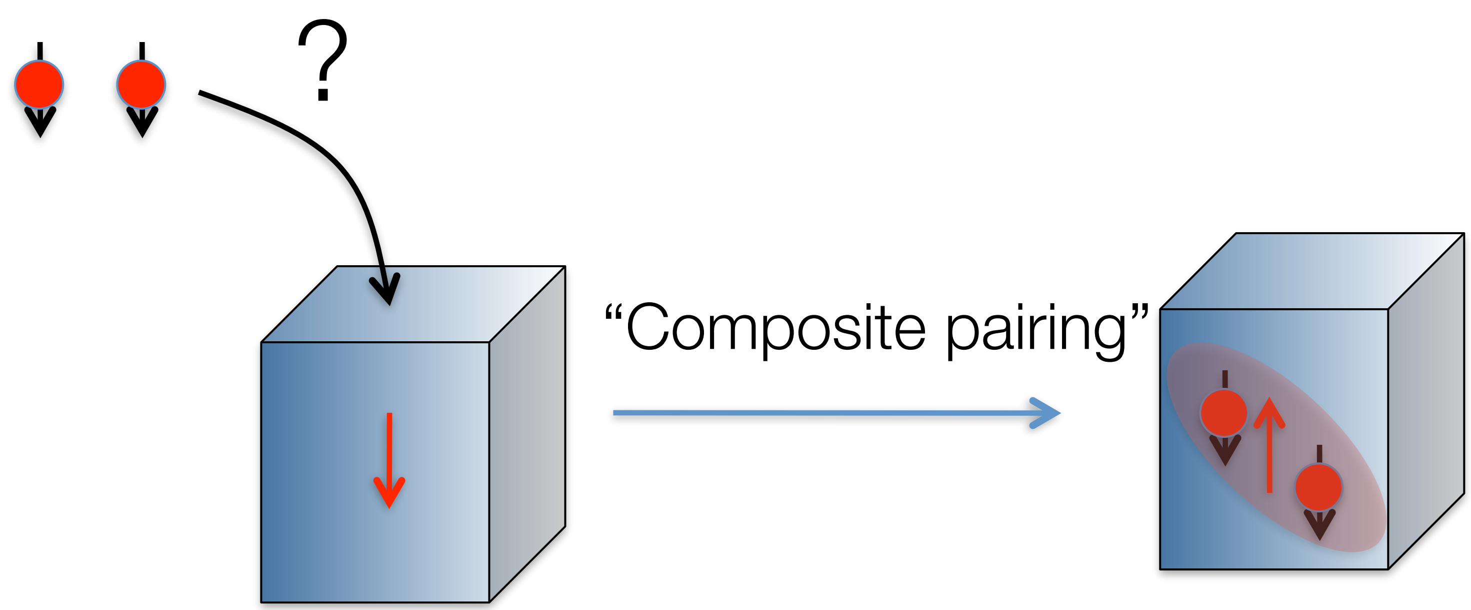

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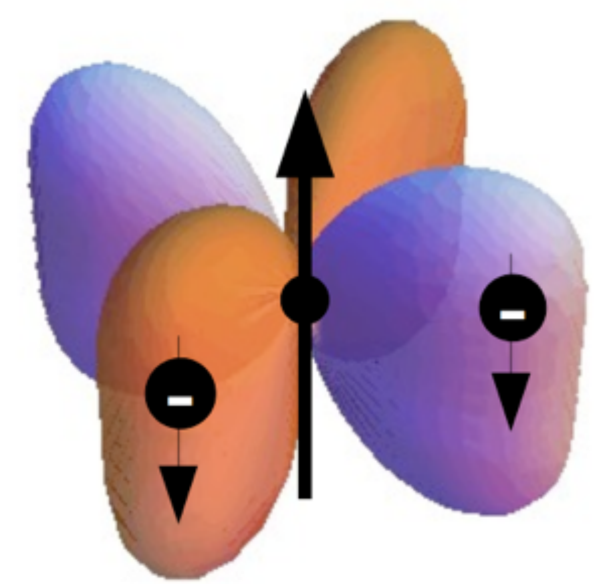


Abrahams, Balatsky, Scalapino, Schrieffer 1995

$$H = \sum_{k} \epsilon_{\mathbf{k}} c^{\dagger}_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} + \frac{1}{N} \sum_{\mathbf{k},\mathbf{k}'} \left(J_1 \psi^{\dagger}_{1a}(j)\psi_{1b}(j) + J_2 \psi^{\dagger}_{2a}(j)\psi_{2b}(j) \right) S^{ba}(j)$$

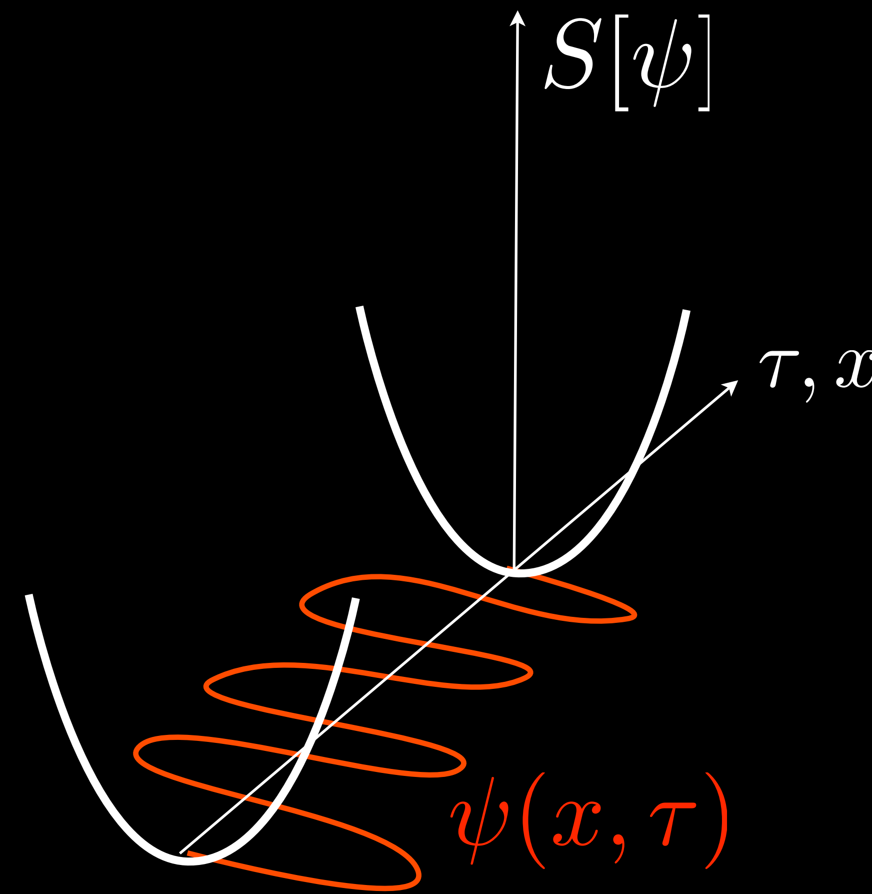
Single FS, two channels.

$$\psi_{\Gamma}(j) = \frac{1}{\sqrt{V}} \sum_{\mathbf{k}} \gamma_{\Gamma\mathbf{k}} \; c_{\mathbf{k}} e^{i\mathbf{k}\cdot\mathbf{x}_j}$$

cf Cox, Pang, Jarell (96)
PC, Kee, Andrei, Tsvelik (98)

$$Z = \int_{\text{Fields}} e^{- \quad S[\psi]}$$

Path Integral



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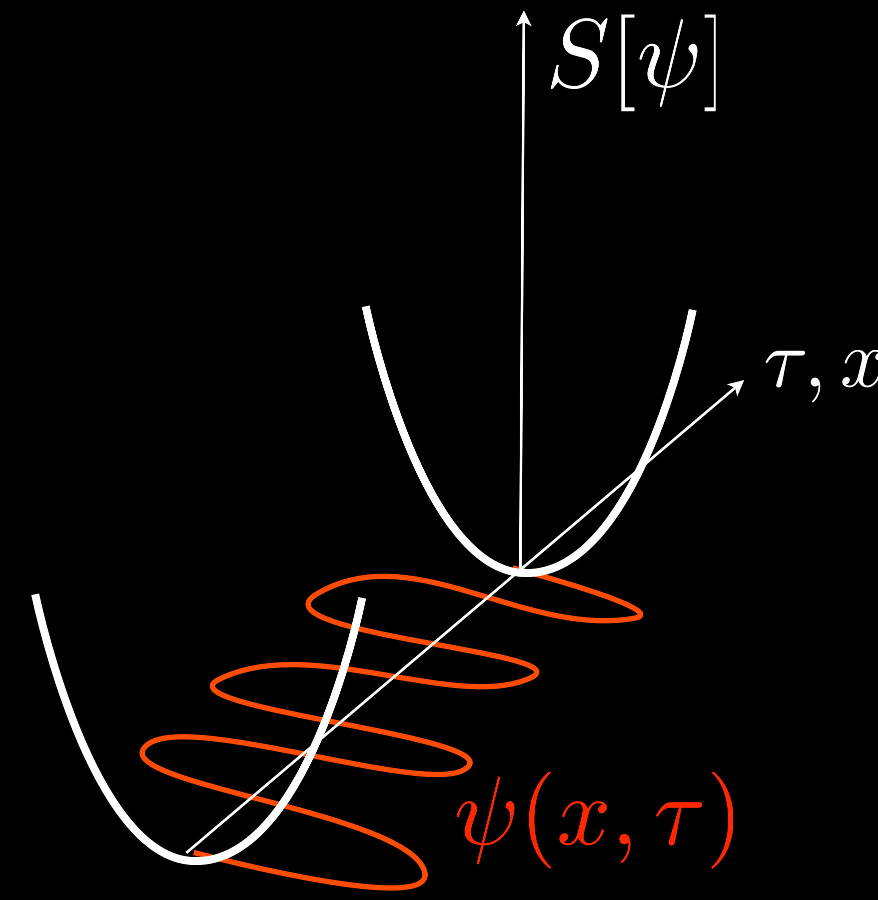

Wild quantum fluctuations!

$$H = \sum_k \epsilon_{\mathbf{k}} c^\dagger_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} + \frac{1}{N}\sum_{\mathbf{k},\mathbf{k}'} \left(J_1 \psi^\dagger_{1a}(j)\psi_{1b}(j) + J_2 \psi^\dagger_{2a}(j)\psi_{2b}(j) \right) S^{ba}(j)$$

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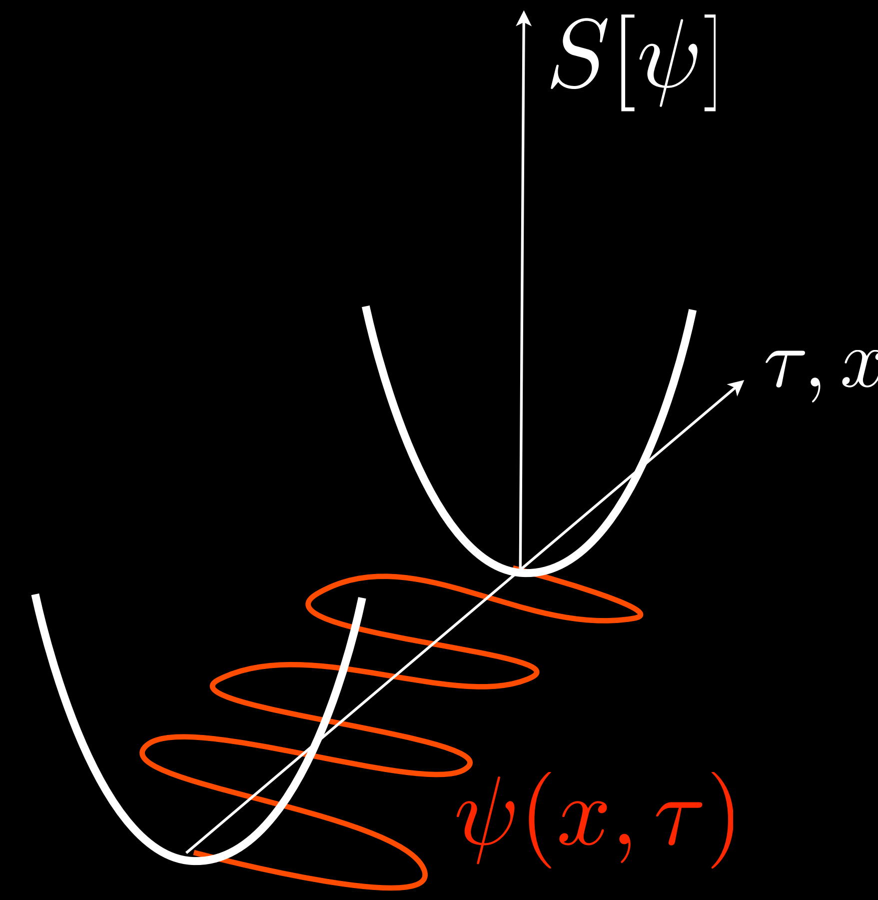
How can we tame the wild Quantum fluctuations?

Path Integral

$$Z = \int_{\text{Fields}} e^{-S[\psi]}$$



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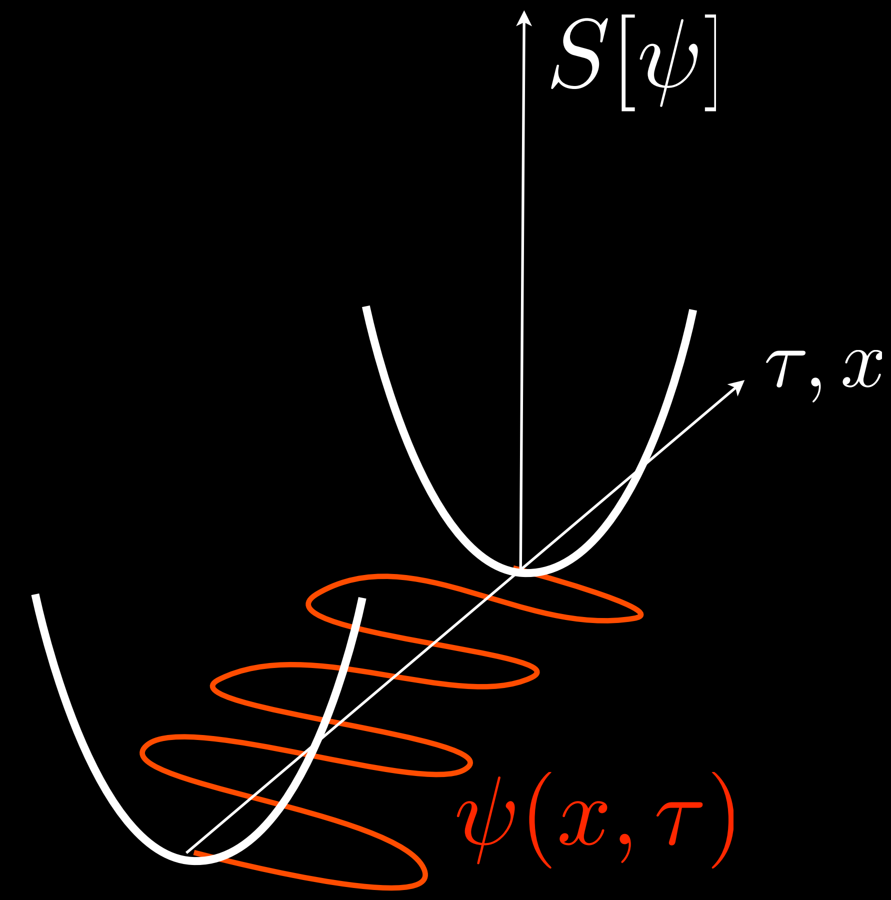
Large *N* expansion.

Path Integral

$$Z = \int_{\rm Fields} e^{-S[\psi]}$$



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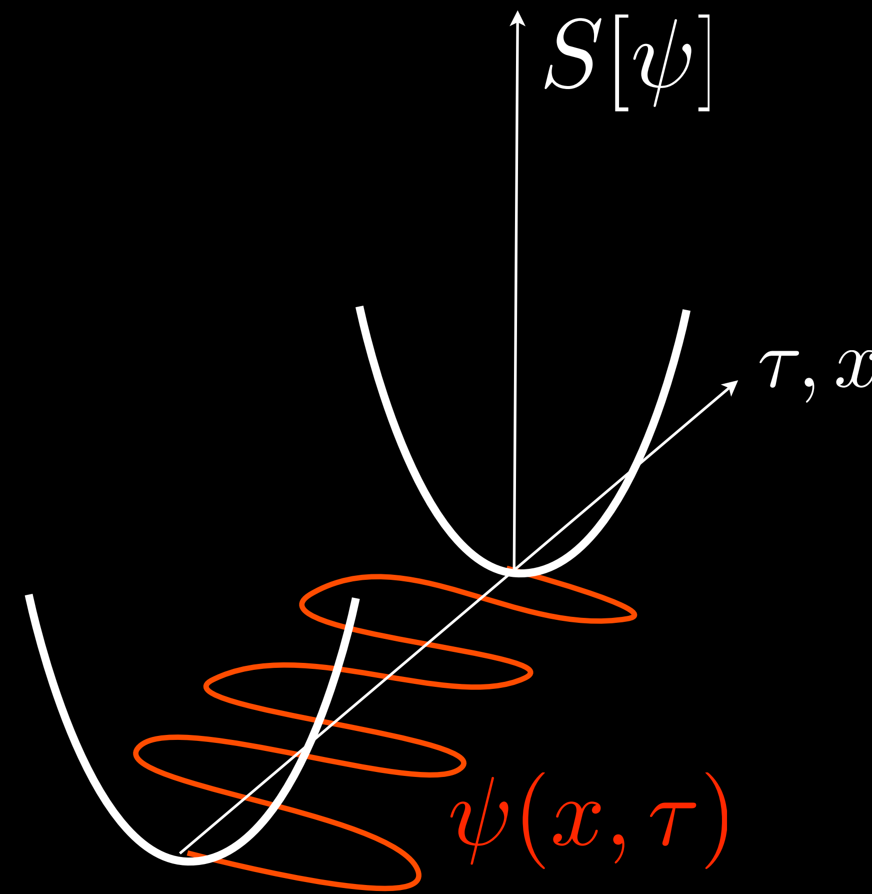

$$\sigma \in \left(-\frac{1}{2}, \frac{1}{2}\right) \longrightarrow \left(-\frac{N}{2}, \frac{N}{2}\right)$$

$$H = \sum_k \epsilon_{\mathbf{k}} c^\dagger_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} + \frac{1}{N} \sum_{\mathbf{k},\mathbf{k}'} \left(J_1 \psi^\dagger_{1a}(j)\psi_{1b}(j) + J_2 \psi^\dagger_{2a}(j)\psi_{2b}(j) \right) S^{ba}(j)$$

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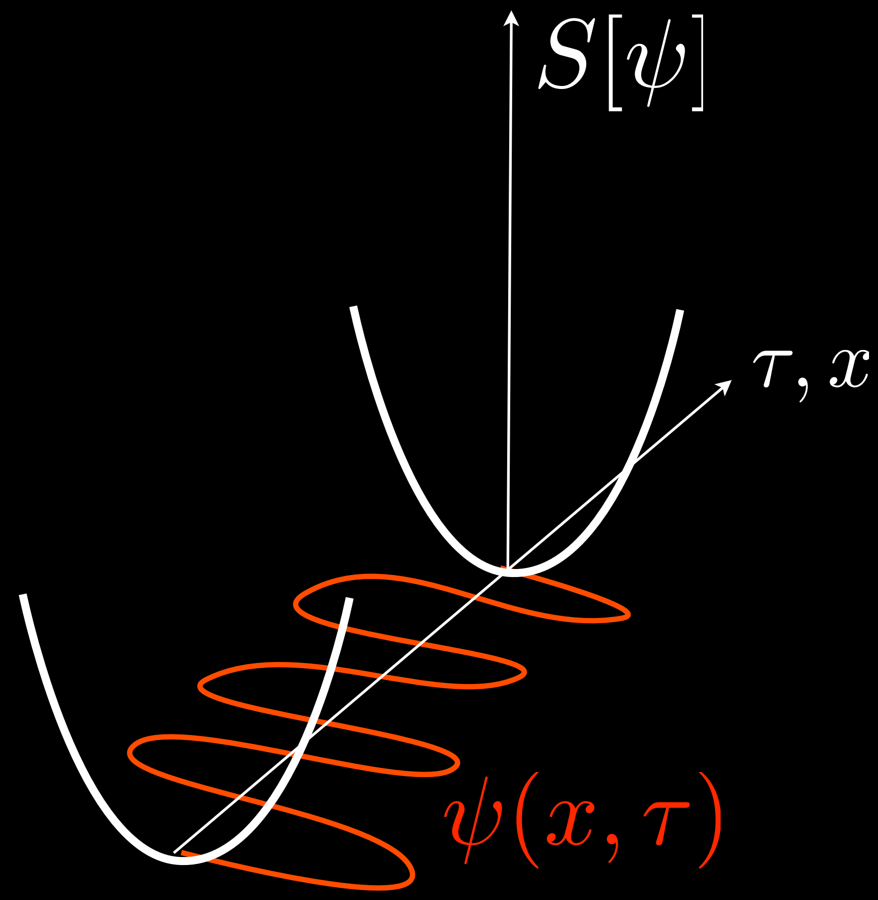
Large *N* expansion.

$$Z = \int_{\text{Fields}} e^{-NS[\psi]}$$



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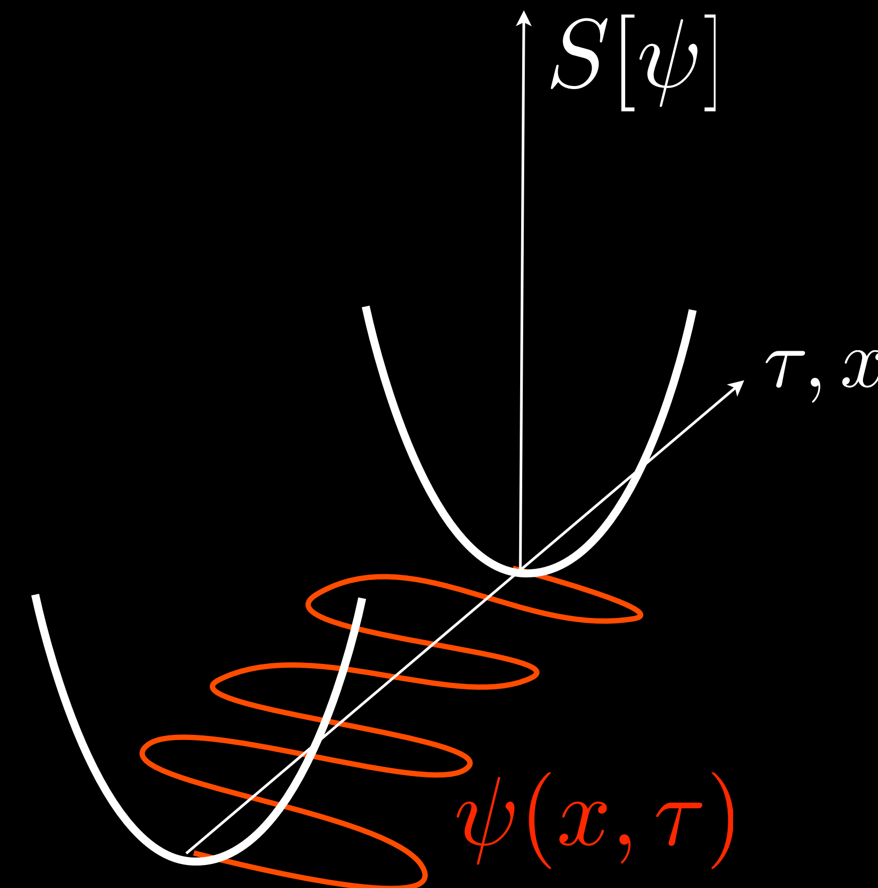
Large *N* expansion.

$$Z = \int_{\mathrm{Fields}} e^{-\frac{S[\psi]}{1/N}}$$



$$\sigma \in \left(-\frac{1}{2}, \frac{1}{2}\right) \longrightarrow \left(-\frac{N}{2}, \frac{N}{2}\right)$$

$$H = \sum_{k} \epsilon_{\mathbf{k}} c^{\dagger}_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} + \frac{1}{N} \sum_{\mathbf{k},\mathbf{k}'} \Big(J_1 \psi^{\dagger}_{1a}(j)\psi_{1b}(j) + J_2 \psi^{\dagger}_{2a}(j)\psi_{2b}(j) \Big) S^{ba}(j)$$

Single FS, two channels.

$$\psi_{\Gamma}(j) = \frac{1}{\sqrt{V}} \sum_{\mathbf{k}} \gamma_{\Gamma\mathbf{k}} \; c_{\mathbf{k}} e^{i\mathbf{k}\cdot\mathbf{x}_j}$$

cf Cox, Pang, Jarell (96)
PC, Kee, Andrei, Tsvelik (98)

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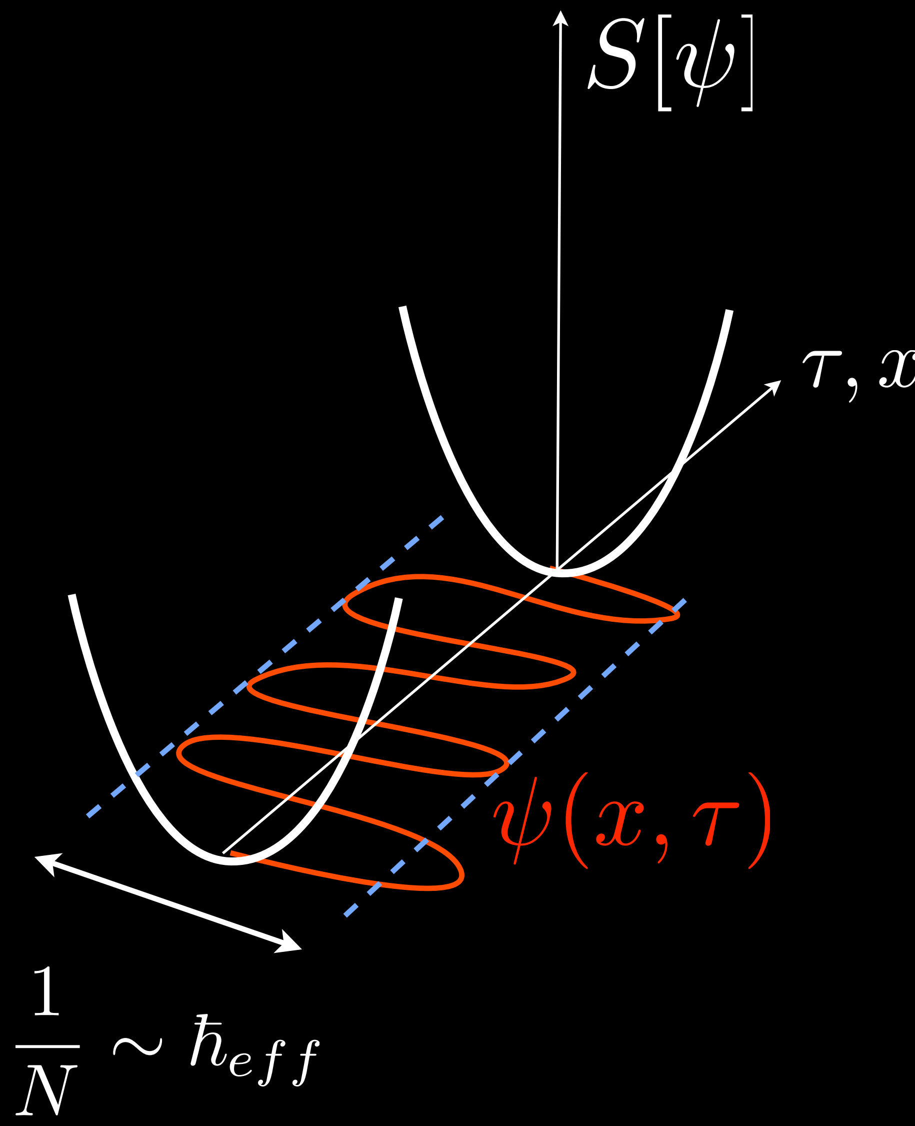

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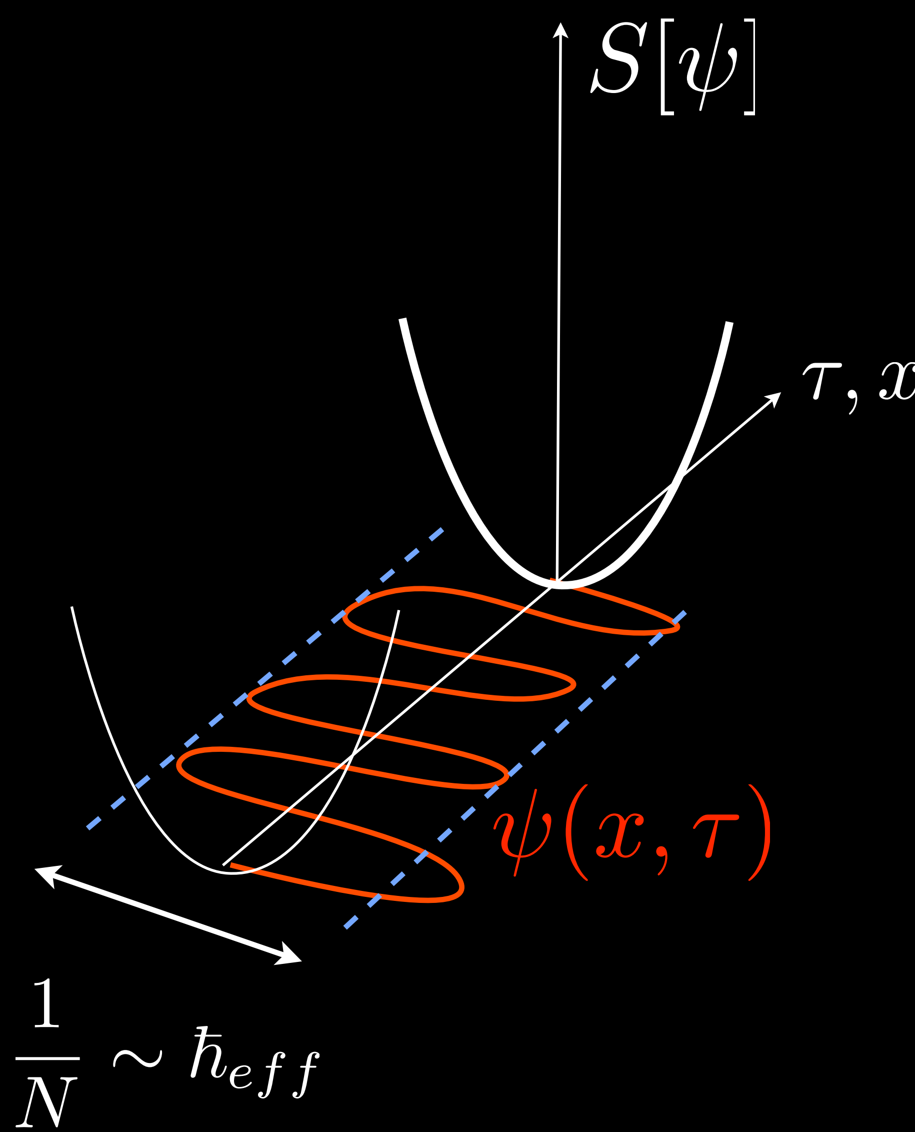
$$N \longrightarrow \infty$$



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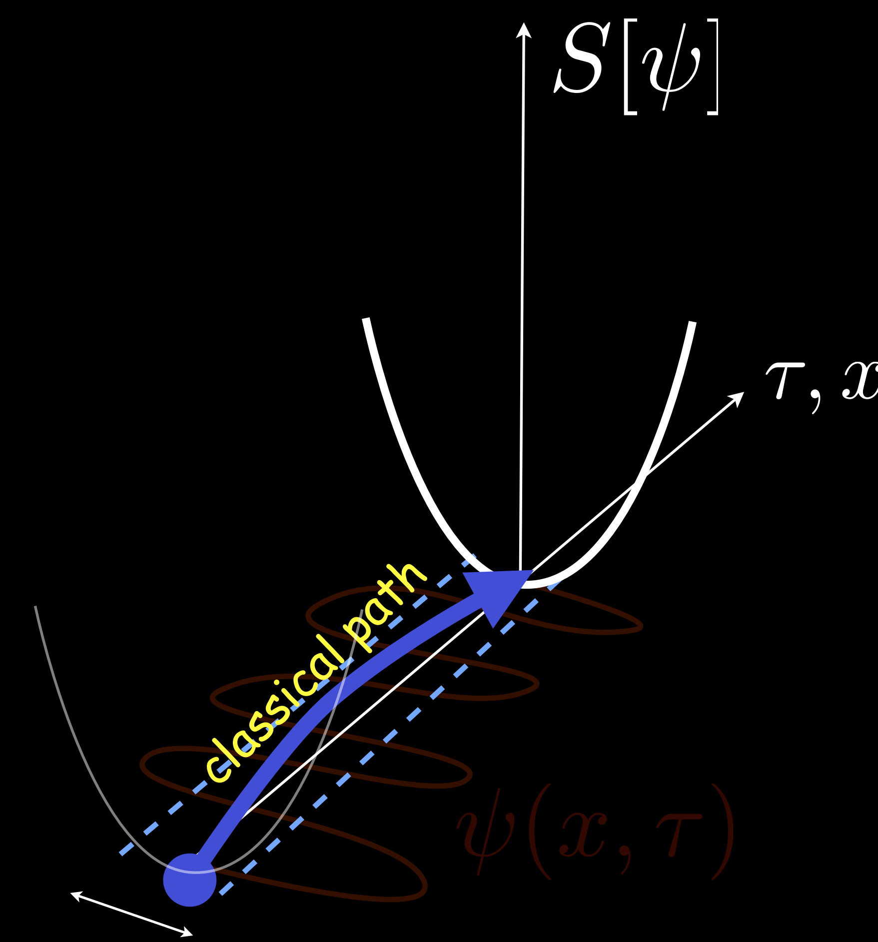

$$\frac{1}{N} \sim \hbar_{eff}$$

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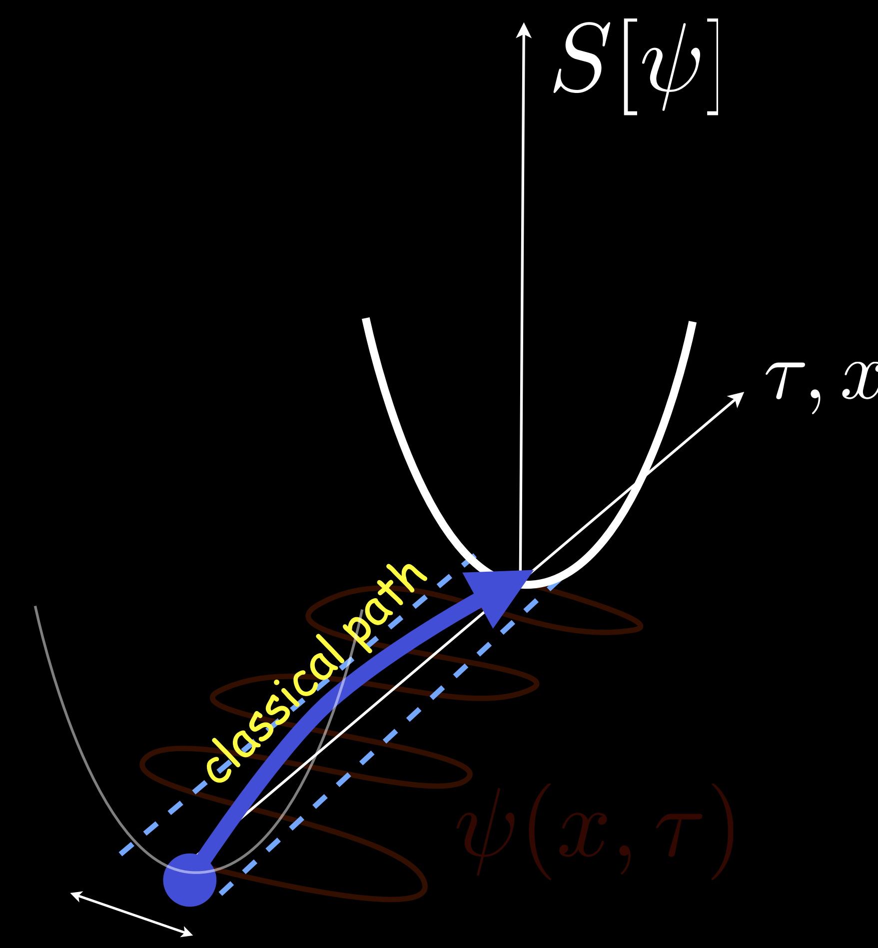

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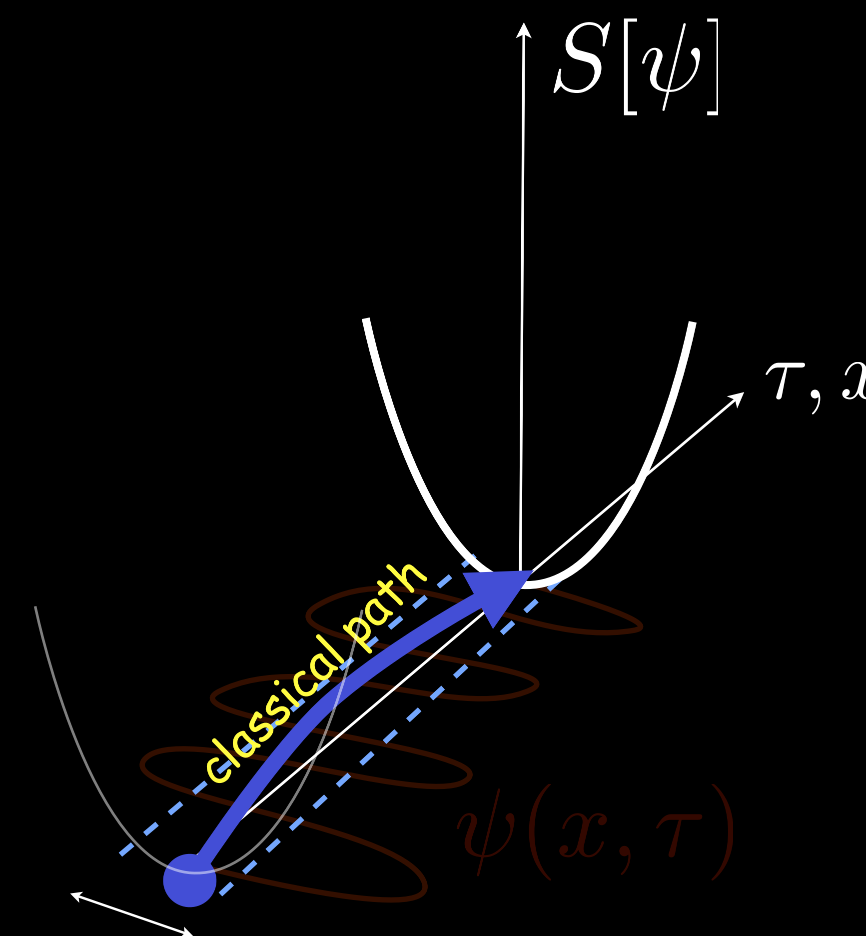
Scott Thomas,
Rutgers NHETC.

PC: why don't you ever use the group SP(N)?



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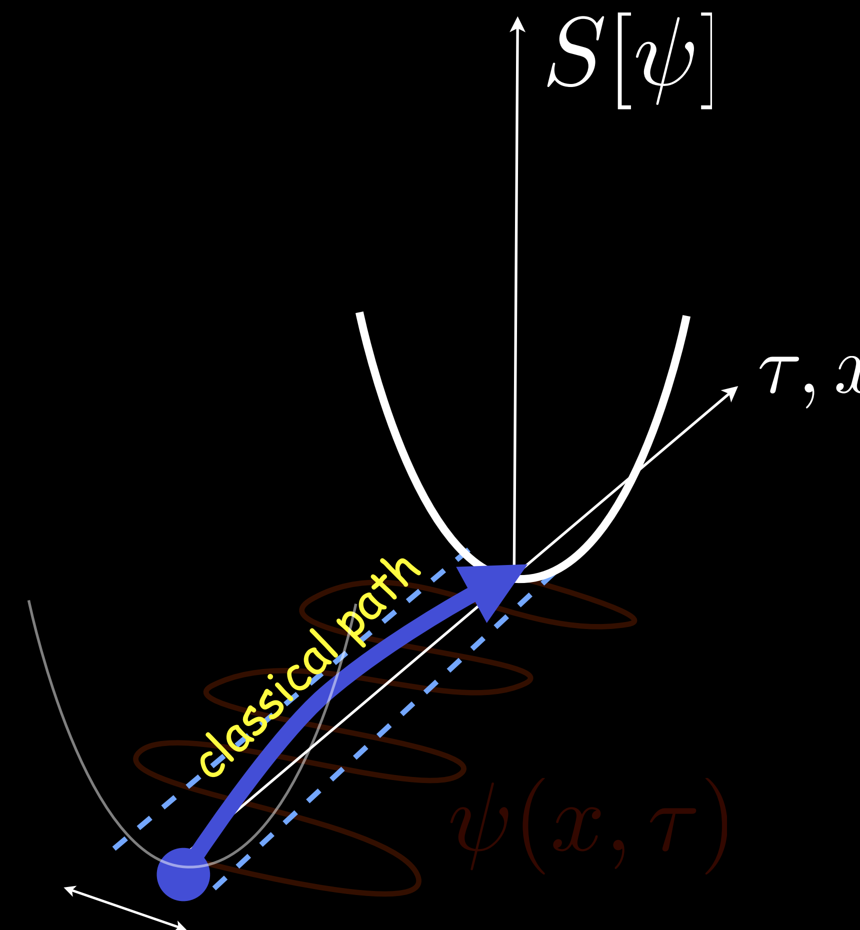

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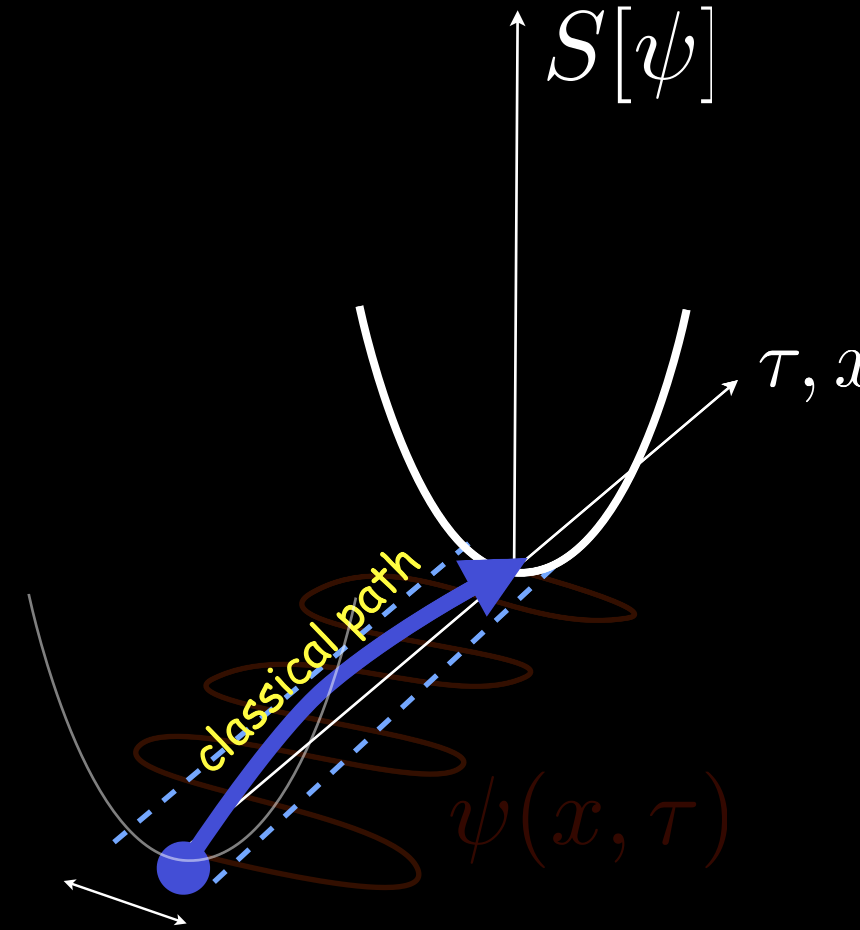

SU(N): *Mesons* *Baryons*

$\bar{q}q$ $q_1 q_2 \ldots q_N$

$$\frac{1}{N} \sim \hbar_{eff}$$

?

$$H = \sum_k \epsilon_{\mathbf{k}} c^\dagger_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} + \frac{1}{N} \sum_{\mathbf{k},\mathbf{k}'} \left(J_1 \psi^\dagger_{1a}(j)\psi_{1b}(j) + J_2 \psi^\dagger_{2a}(j)\psi_{2b}(j) \right) S^{ba}(j)$$

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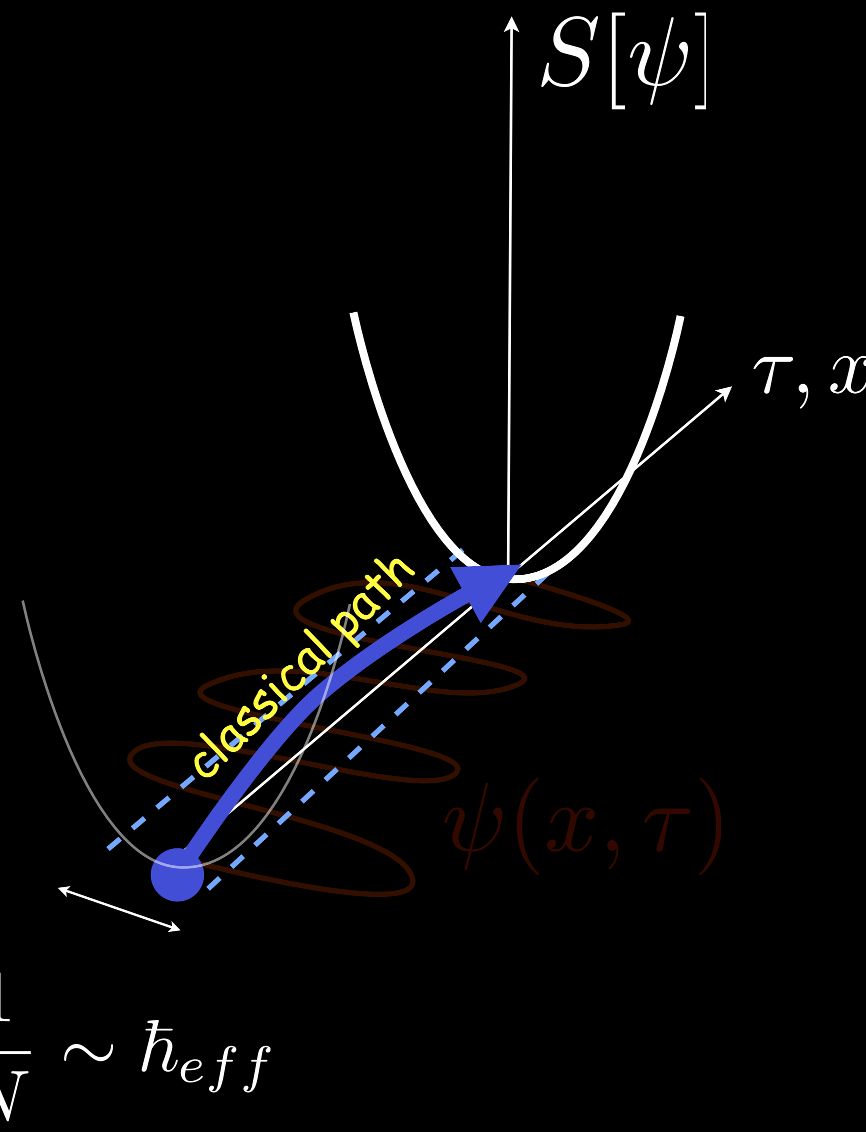

	Mesons	Baryons
SU(N):	$\bar{q}q$	$q_1 q_2 \cdots q_N$
		Cooper pairs
SP(N):	$\bar{q}q$	$q_a q_{-a}$

?

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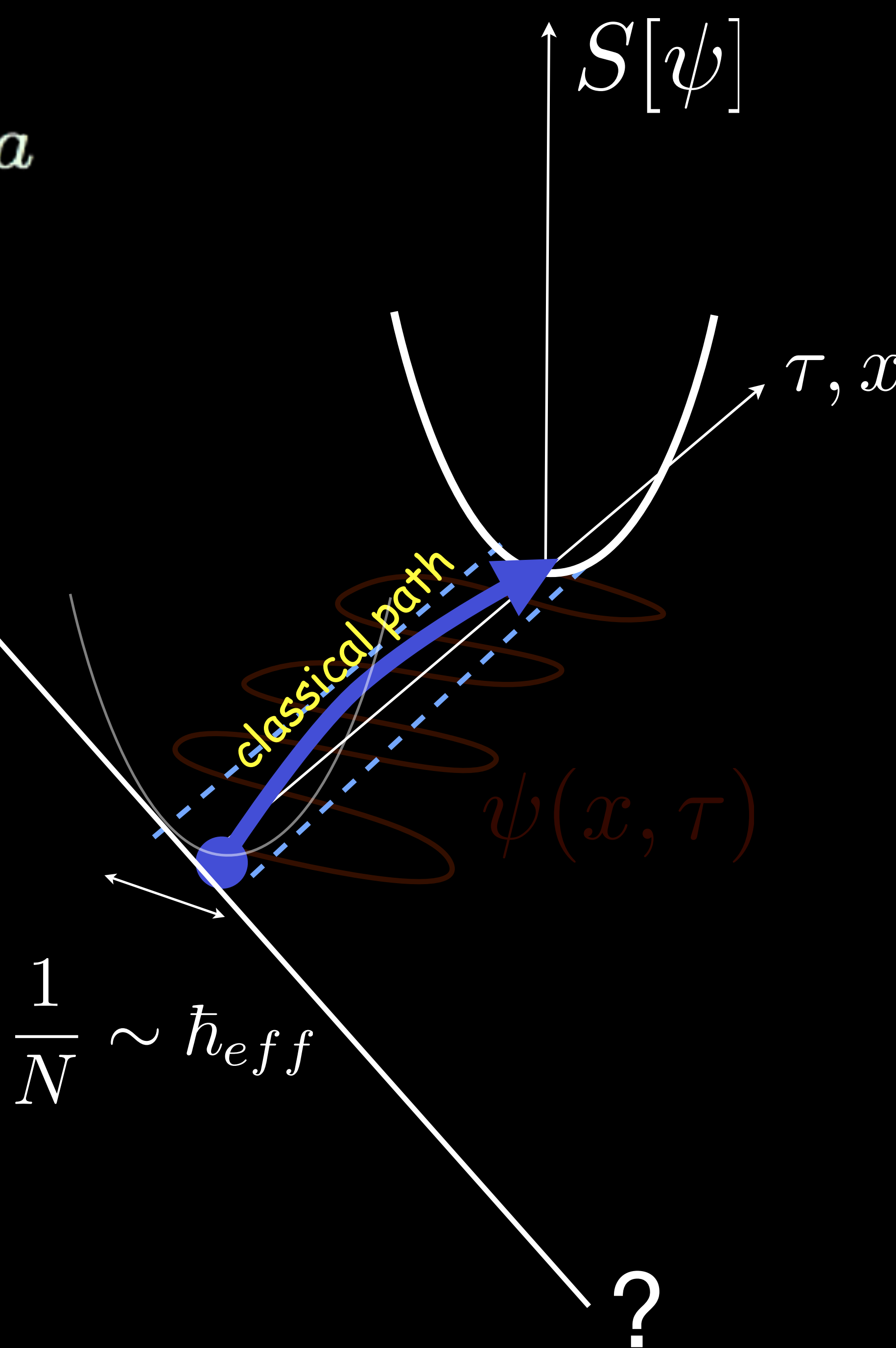
$N \rightarrow \infty$

"Symplectic Large N" R. Flint and PC '08

$$S^{ba} = f_b^\dagger f_a - \text{sgn}(a)\text{sgn}(b) f^\dagger_{-b} f_{-a}$$



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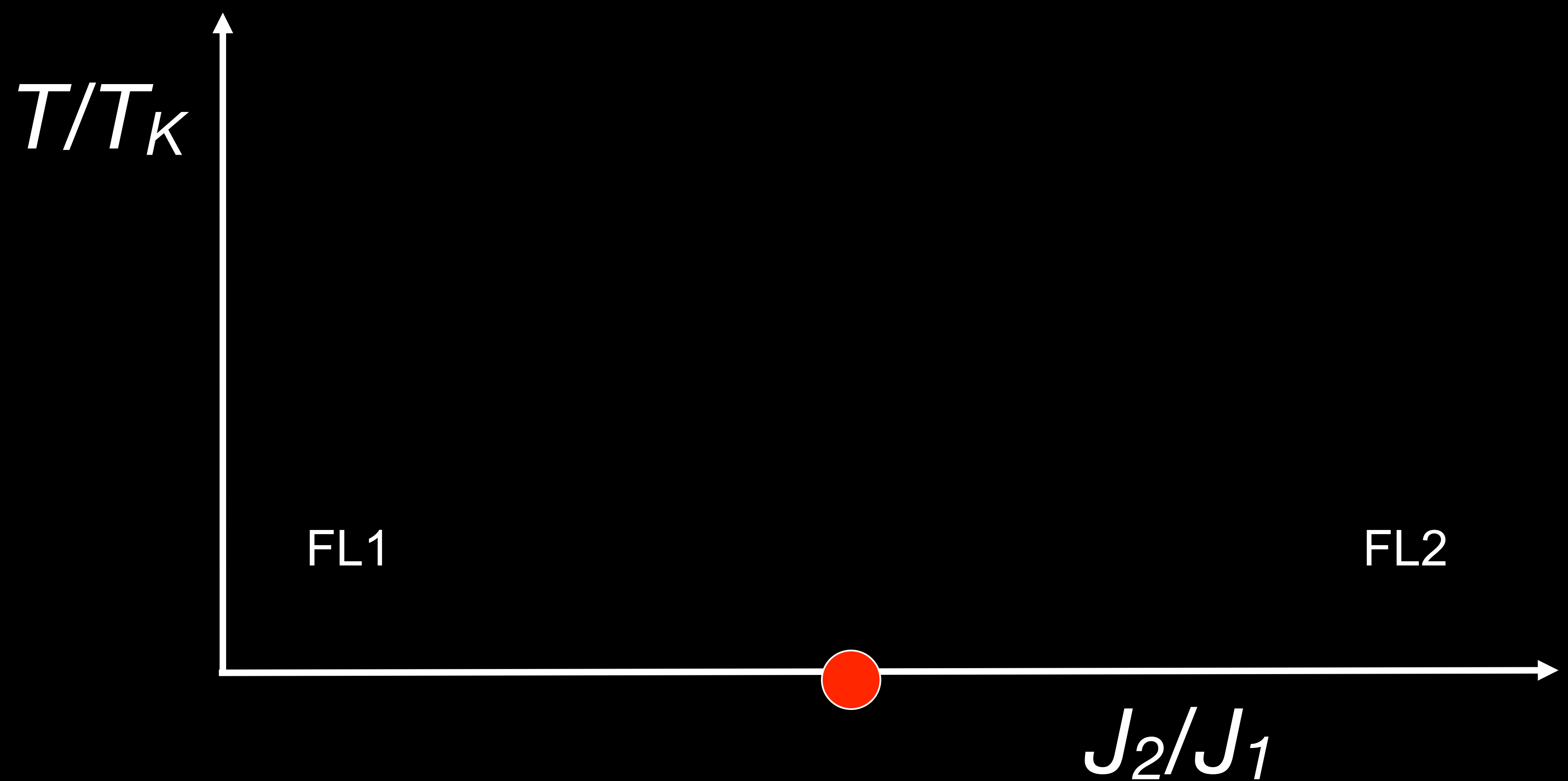
Impurity: quantum critical point for $J_1 = J_2$

Nozieres and Blandin 1980



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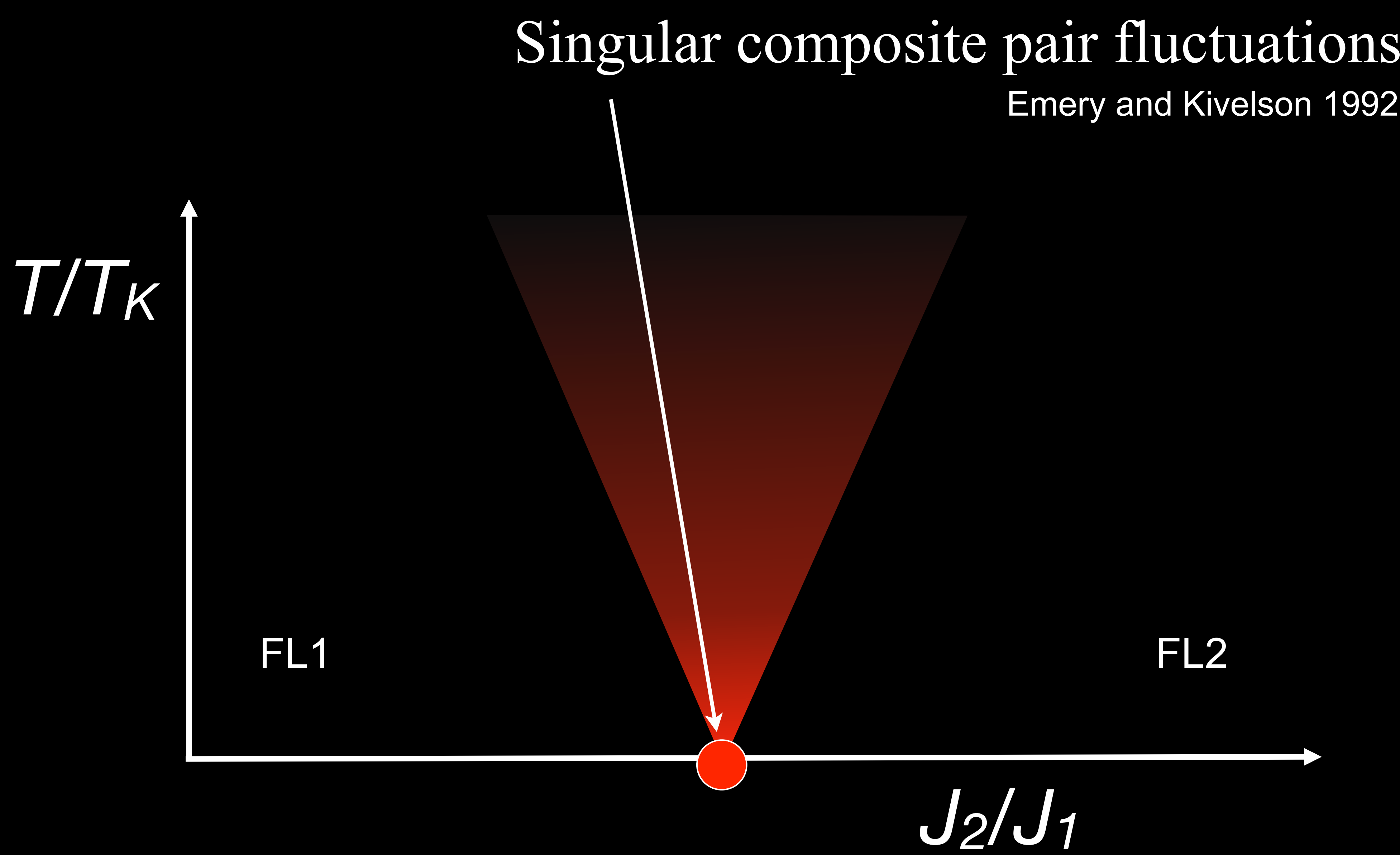

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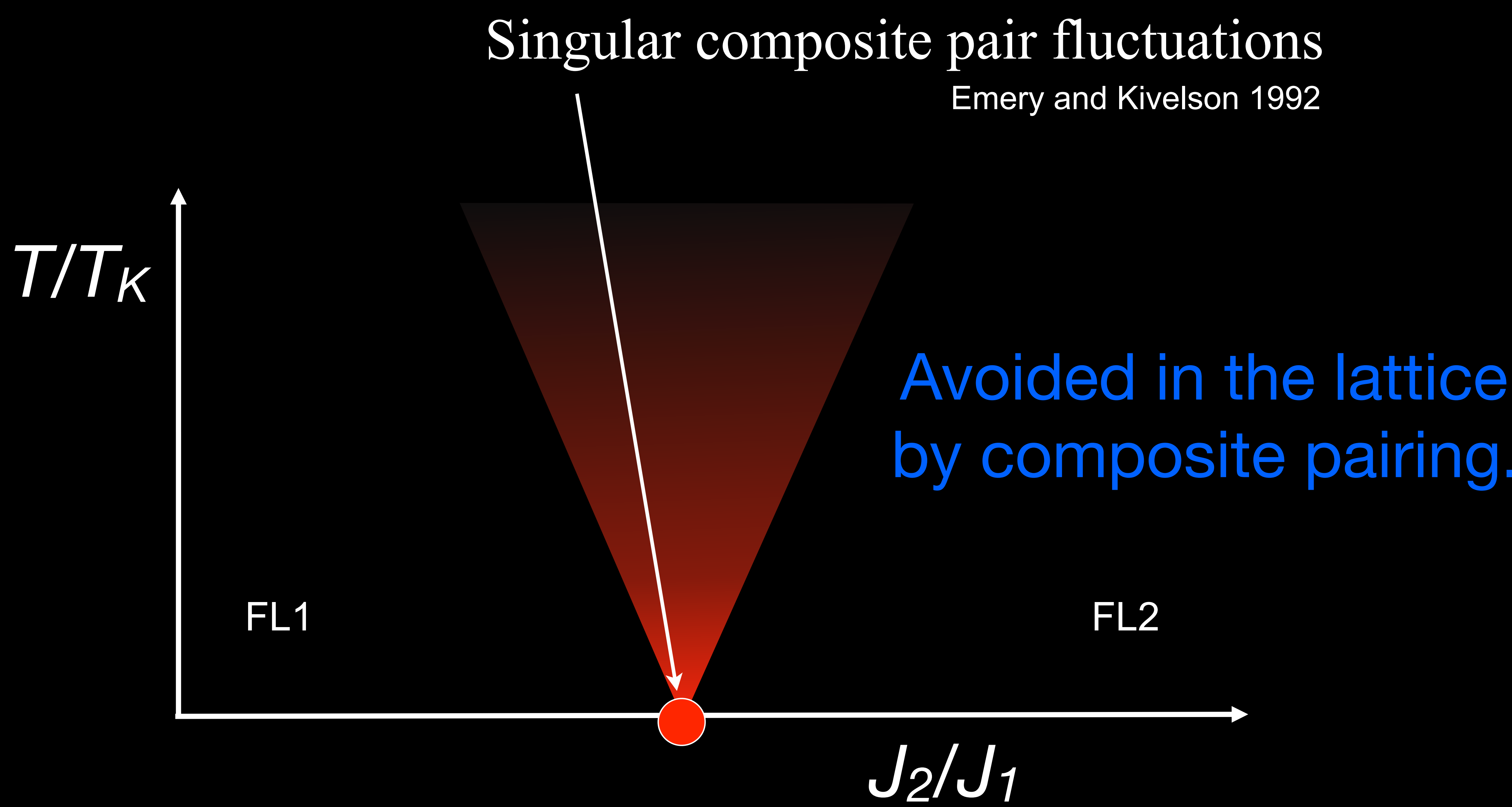

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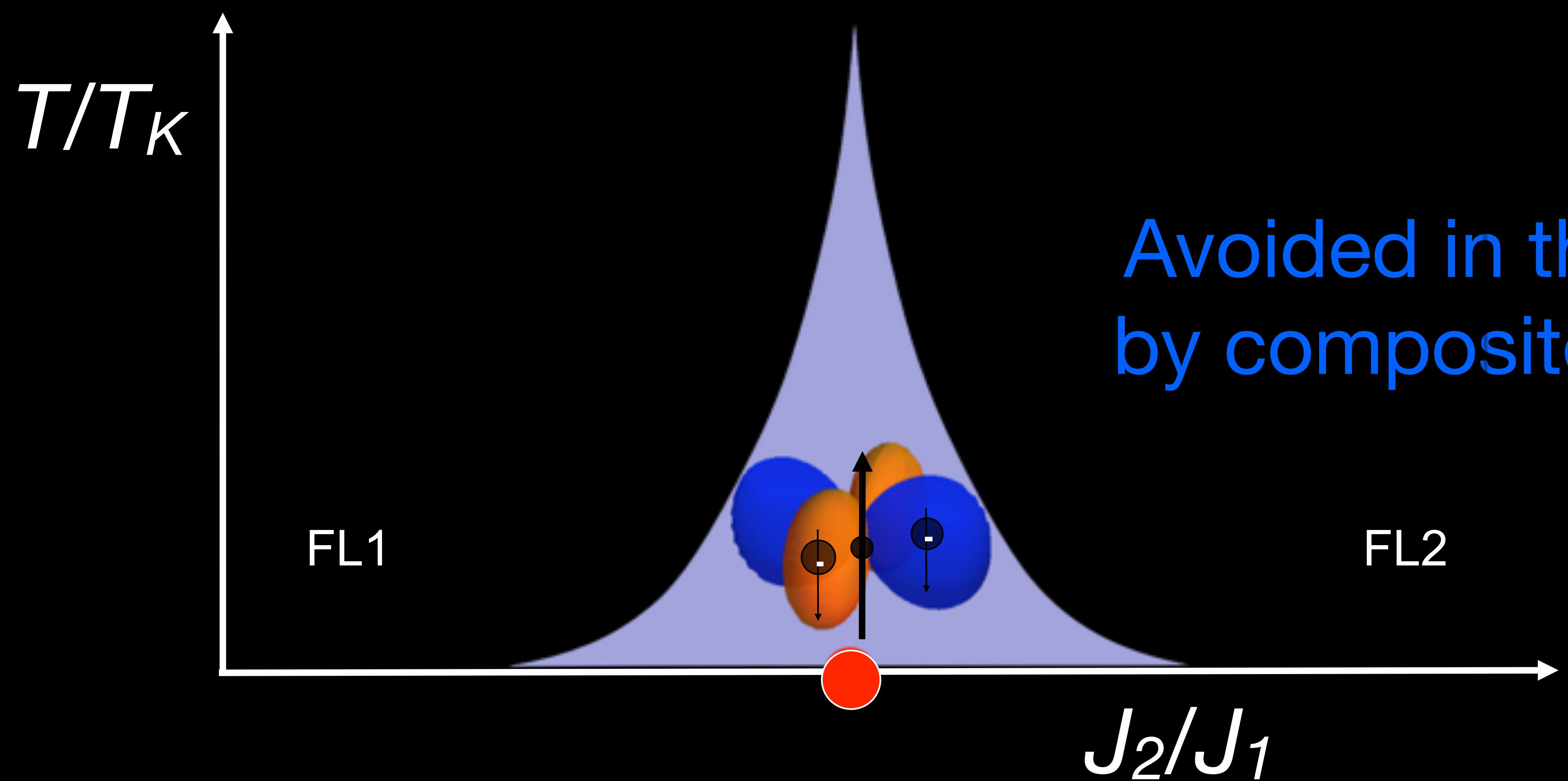
Impurity: quantum critical point for $J_1 = J_2$

Nozieres and Blandin 1980

Singular composite pair fluctuations

Emery and Kivelson 1992



Avoided in the lattice by composite pairing.

$$H = \sum_k \epsilon_{\mathbf{k}} c^\dagger_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} + \frac{1}{N} \sum_{\mathbf{k},\mathbf{k}'} \left(J_1 \psi^\dagger_{1a}(j)\psi_{1b}(j) + J_2 \psi^\dagger_{2a}(j)\psi_{2b}(j) \right) S^{ba}(j)$$

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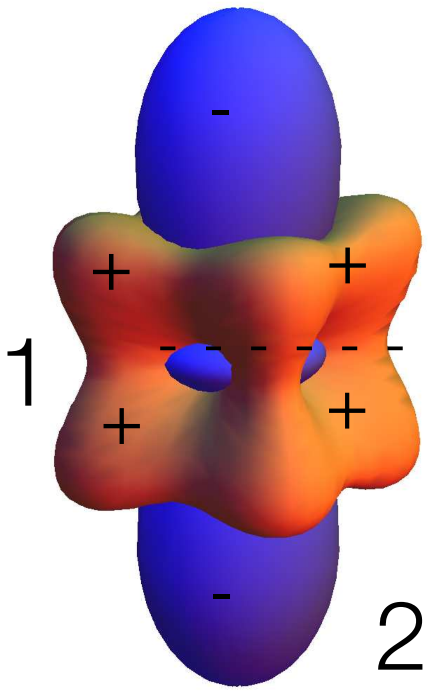
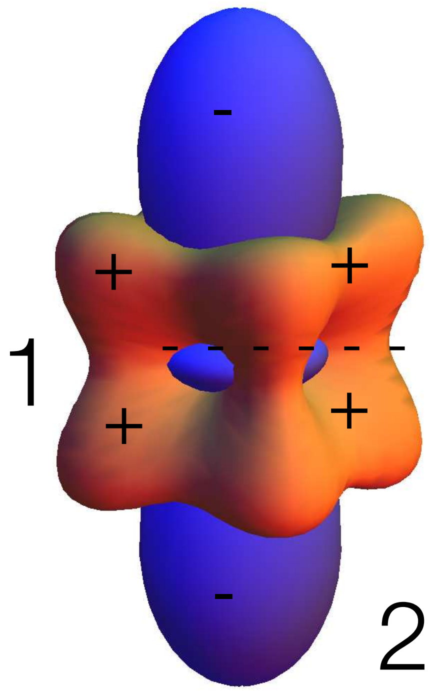


$$\Psi^\dagger = c^\dagger_{1\downarrow} c^\dagger_{2\downarrow} S_+$$



$$\Psi^\dagger = c^\dagger_{1\downarrow} c^\dagger_{2\downarrow} S_+$$

$$Q_{zz} \propto \Psi_C^2$$

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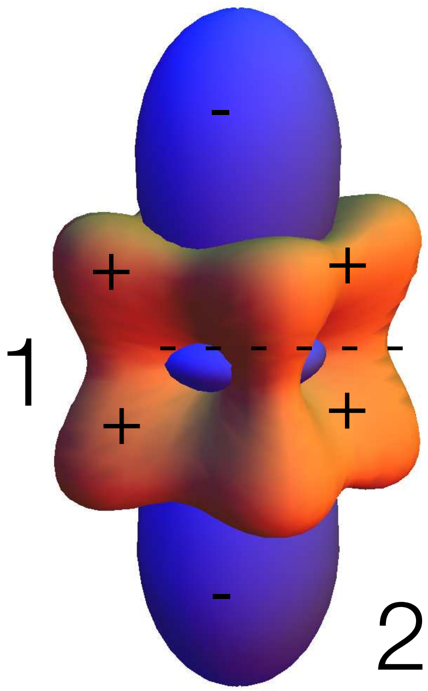

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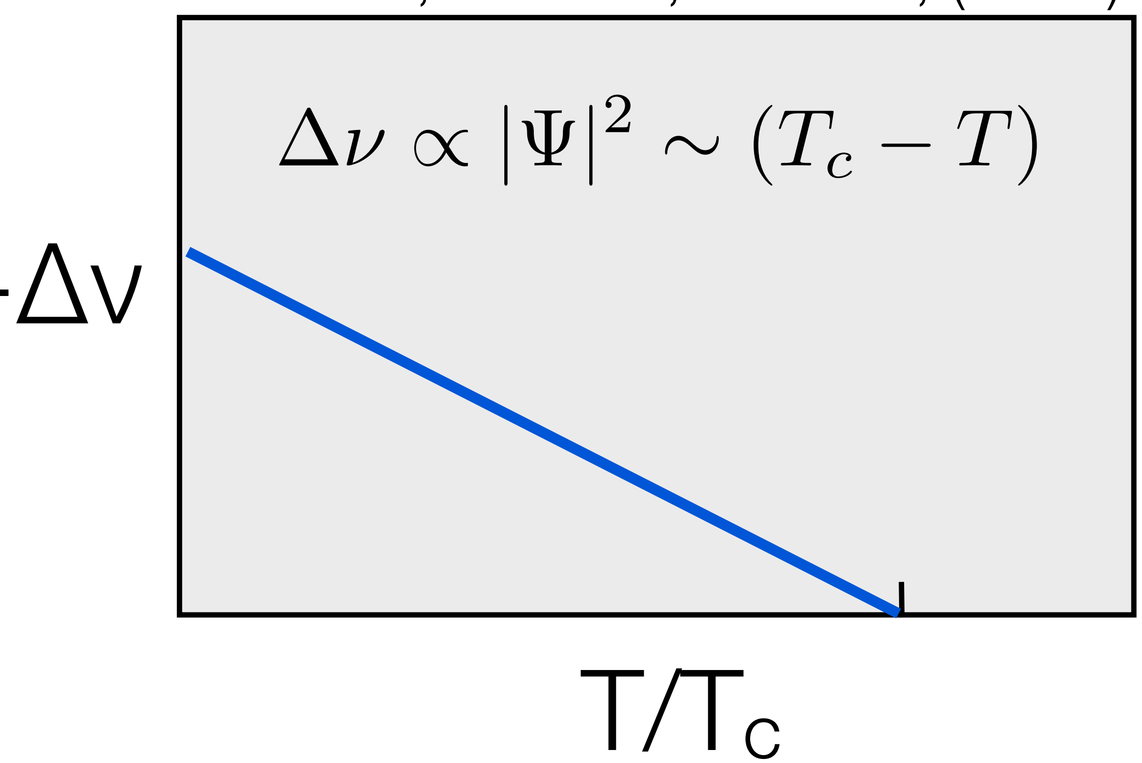
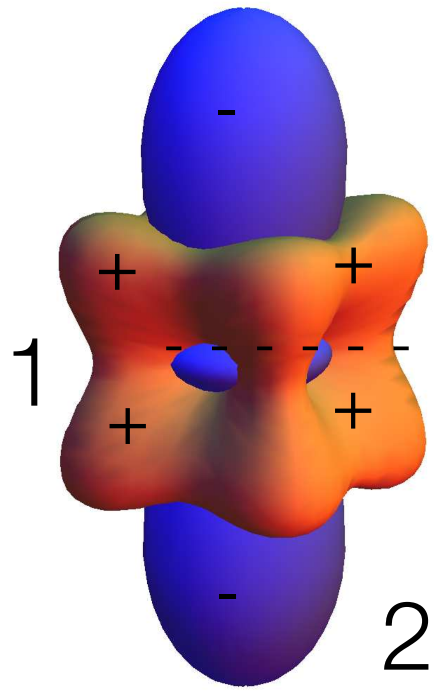
Flint et al, PRB 84, 064054, (2011)





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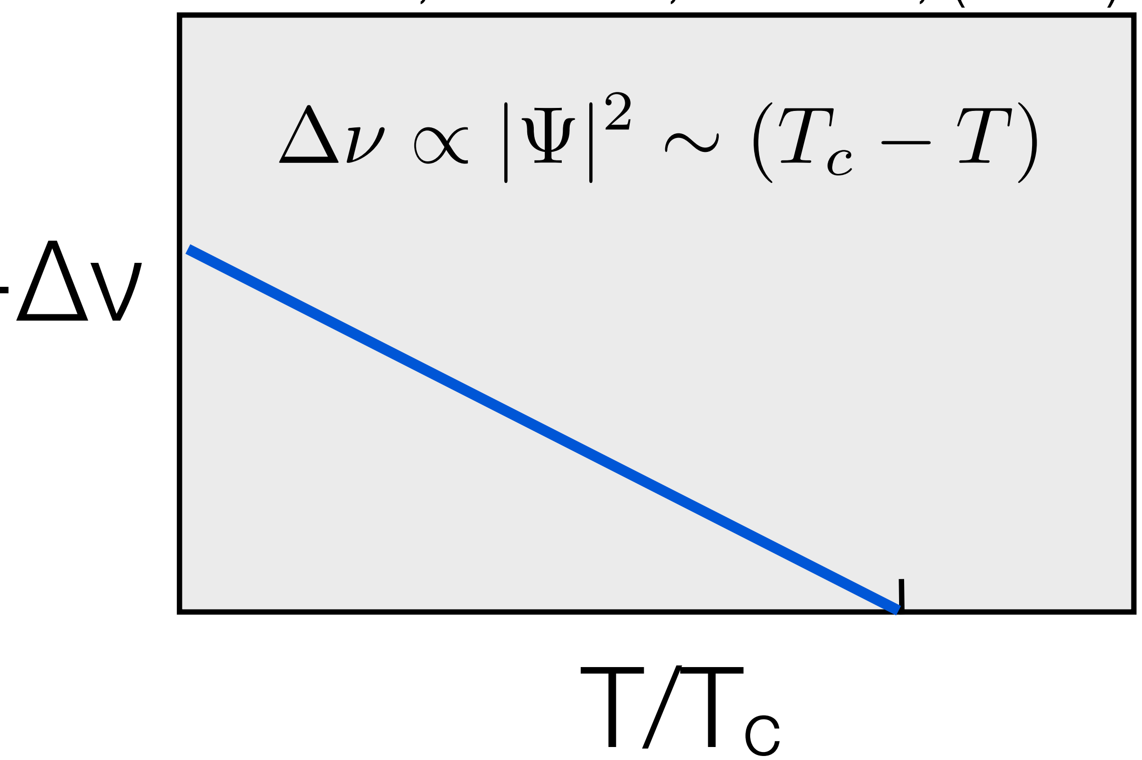
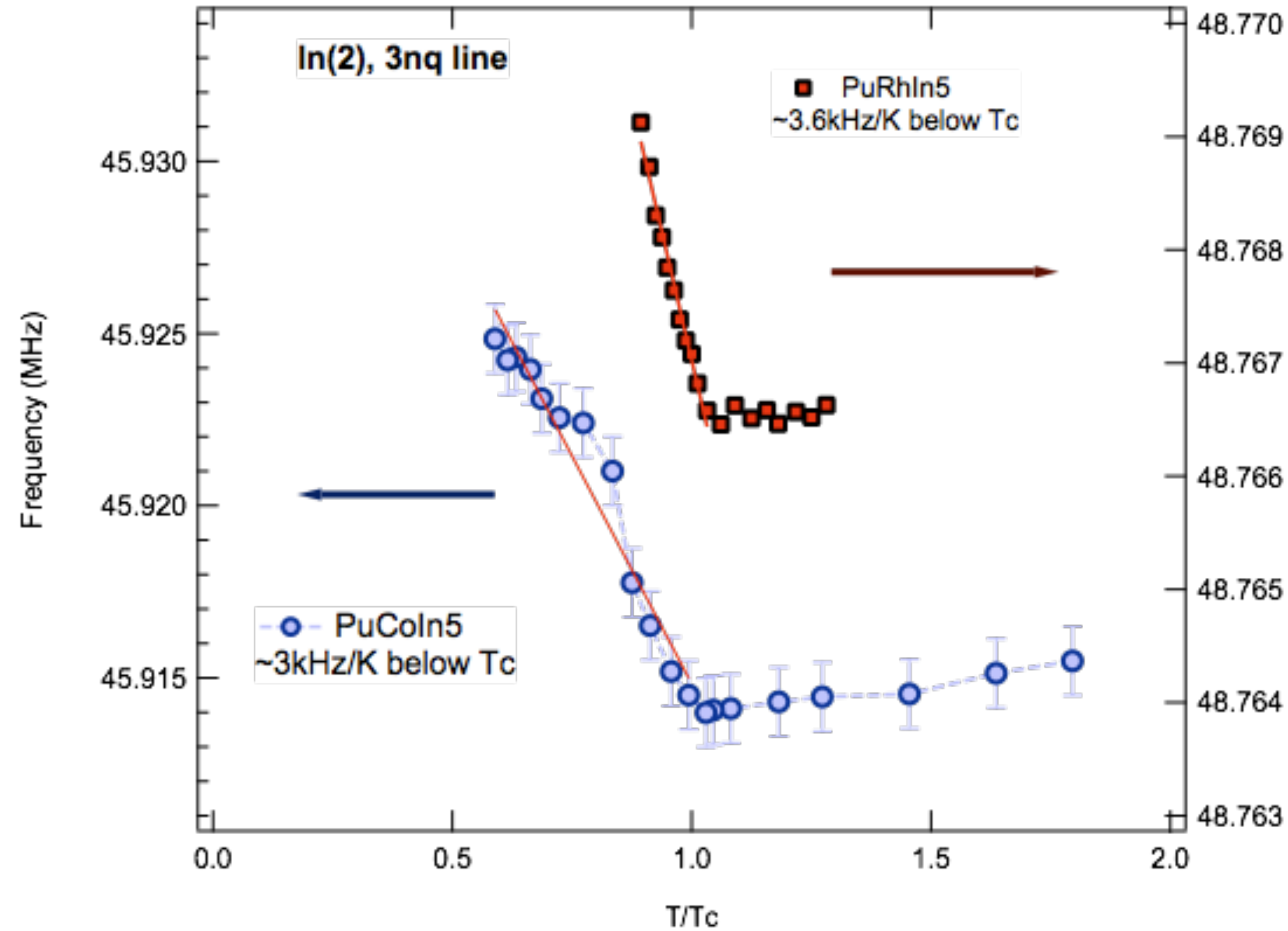
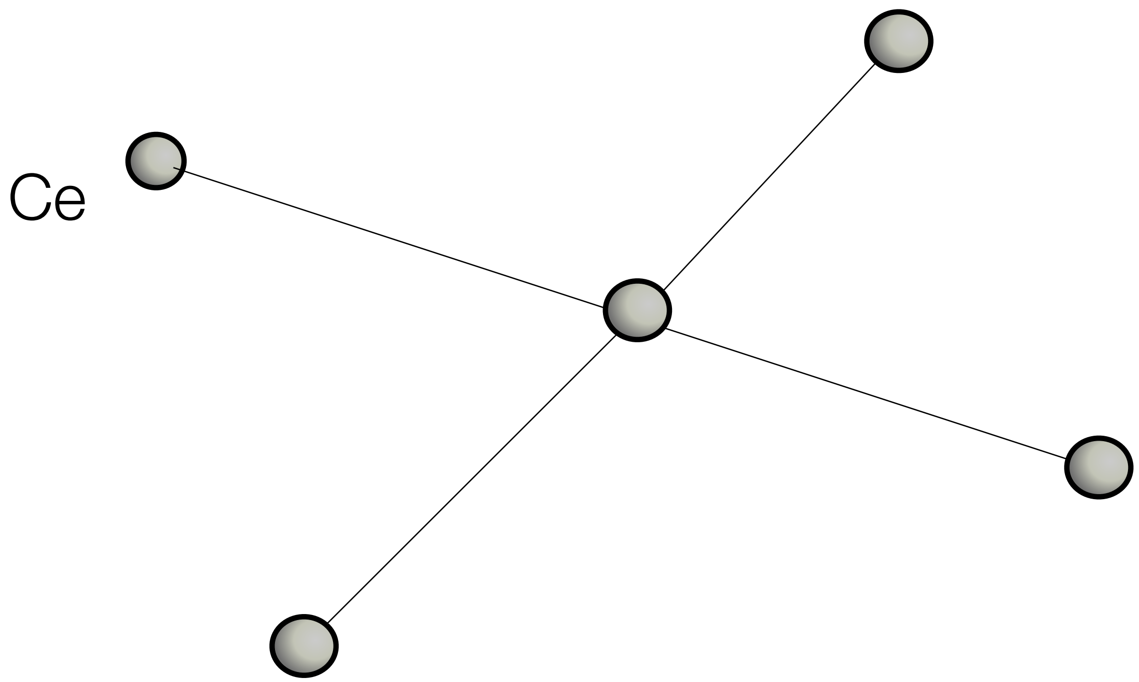


Bauer, G. Koutroulakis, Yasuoka, (2014)



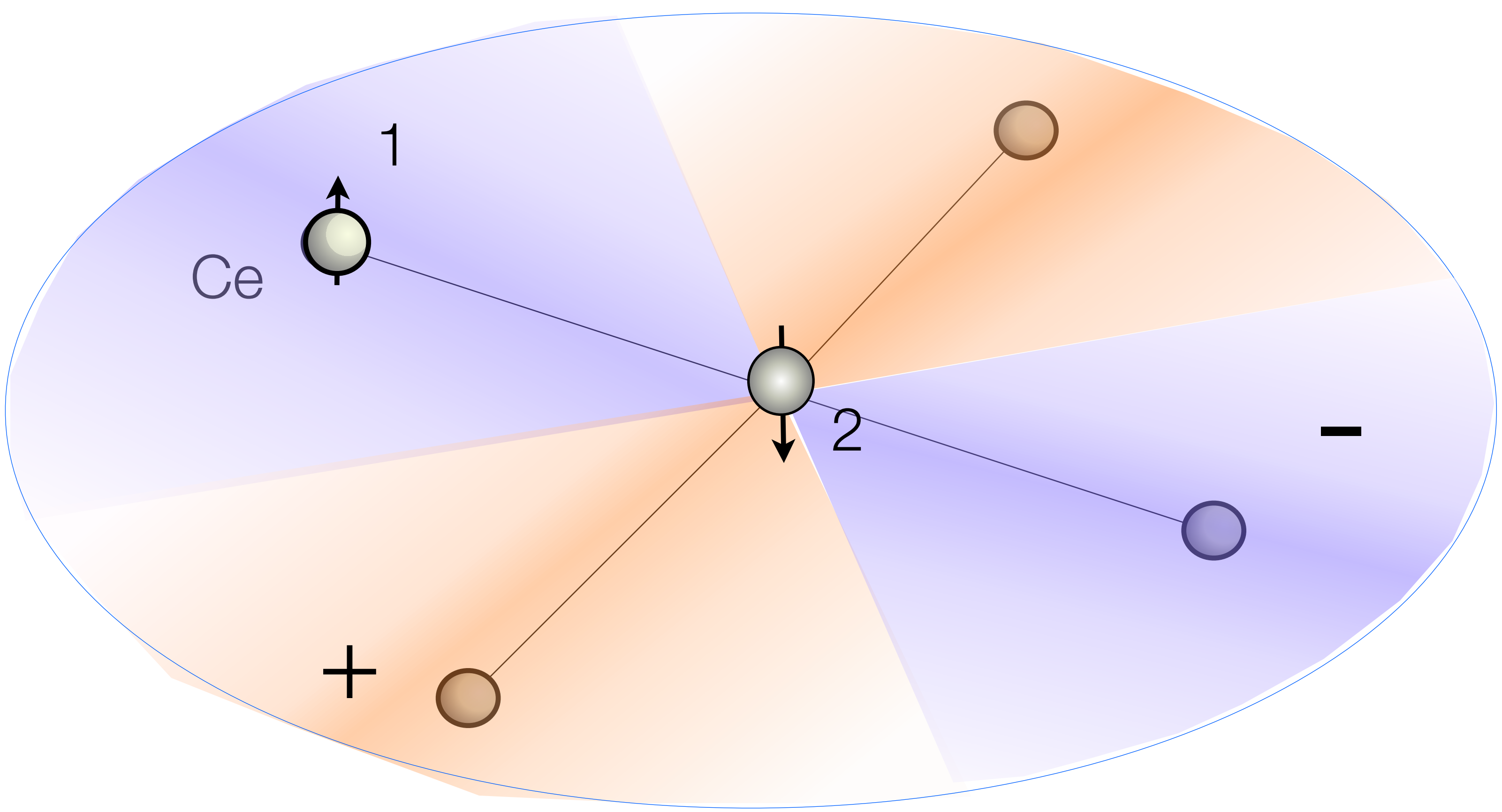
Real-space structure of pair



Real-space structure of pair

Magnetic pair: intercell

$$\Psi_M^\dagger = \Delta_d(1-2) f_\uparrow^\dagger(1) f_\downarrow^\dagger(2)$$



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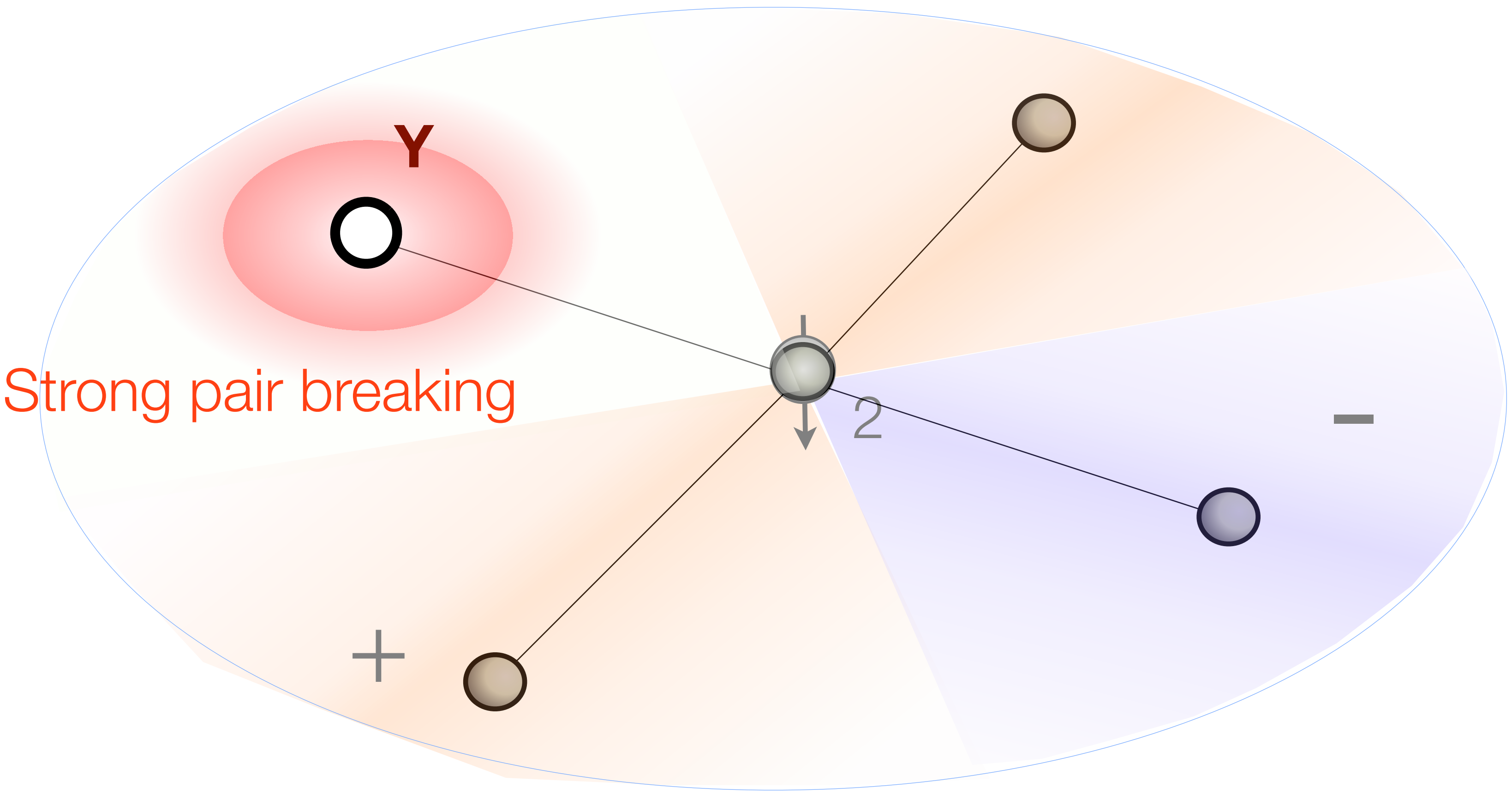

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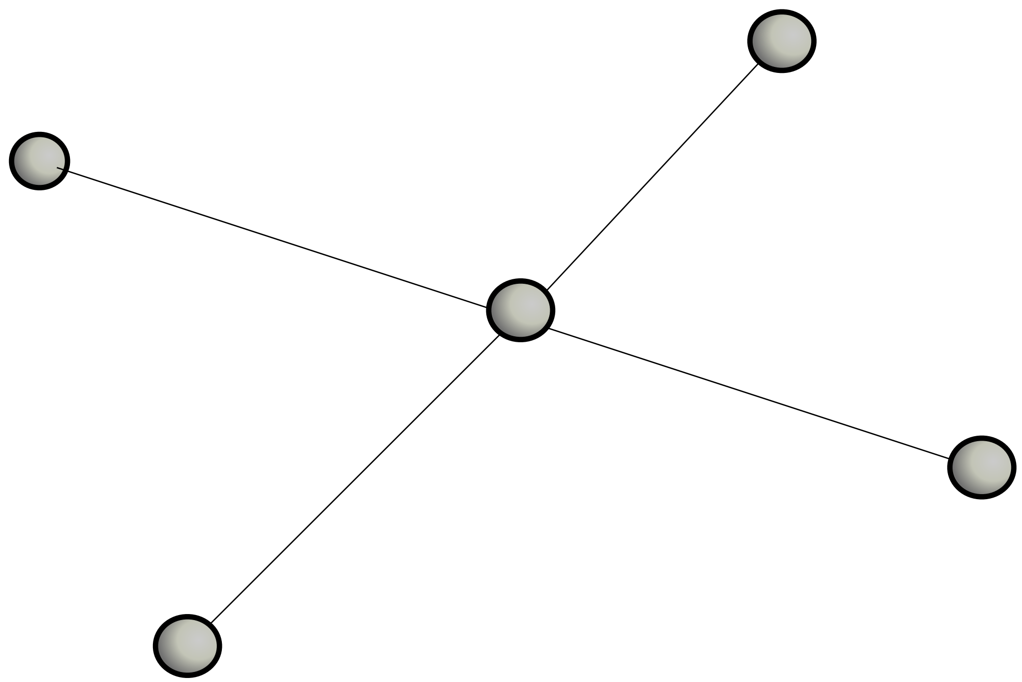

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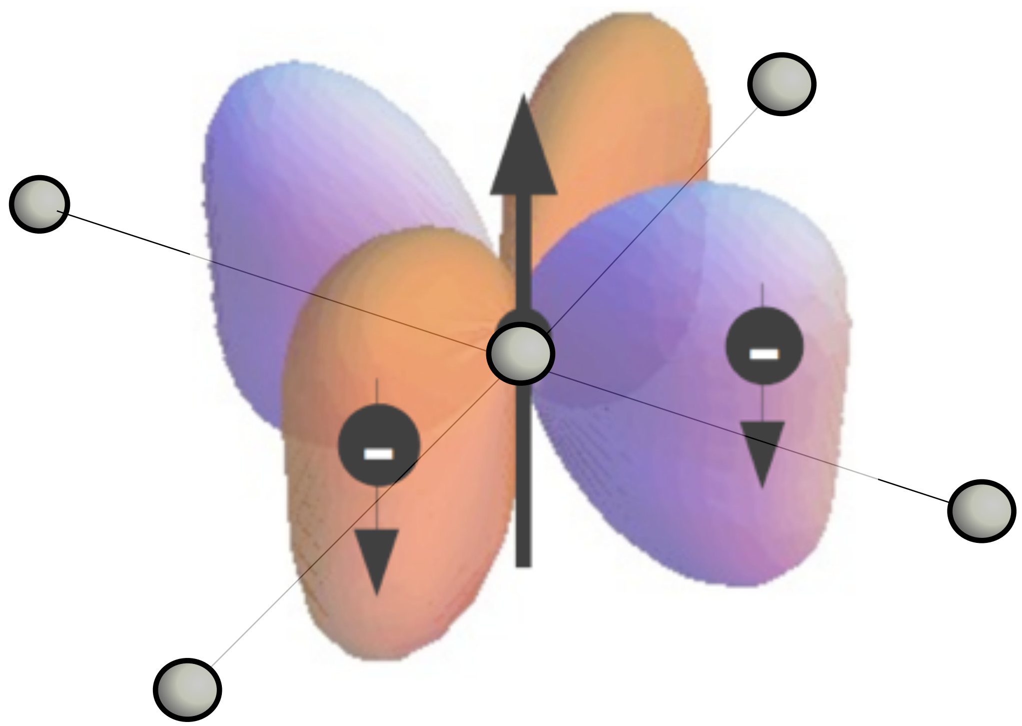

Composite pair

$$\Psi^\dagger_C = c^\dagger_{1\downarrow} c^\dagger_{2\downarrow} S_+$$

Real-space structure of pair

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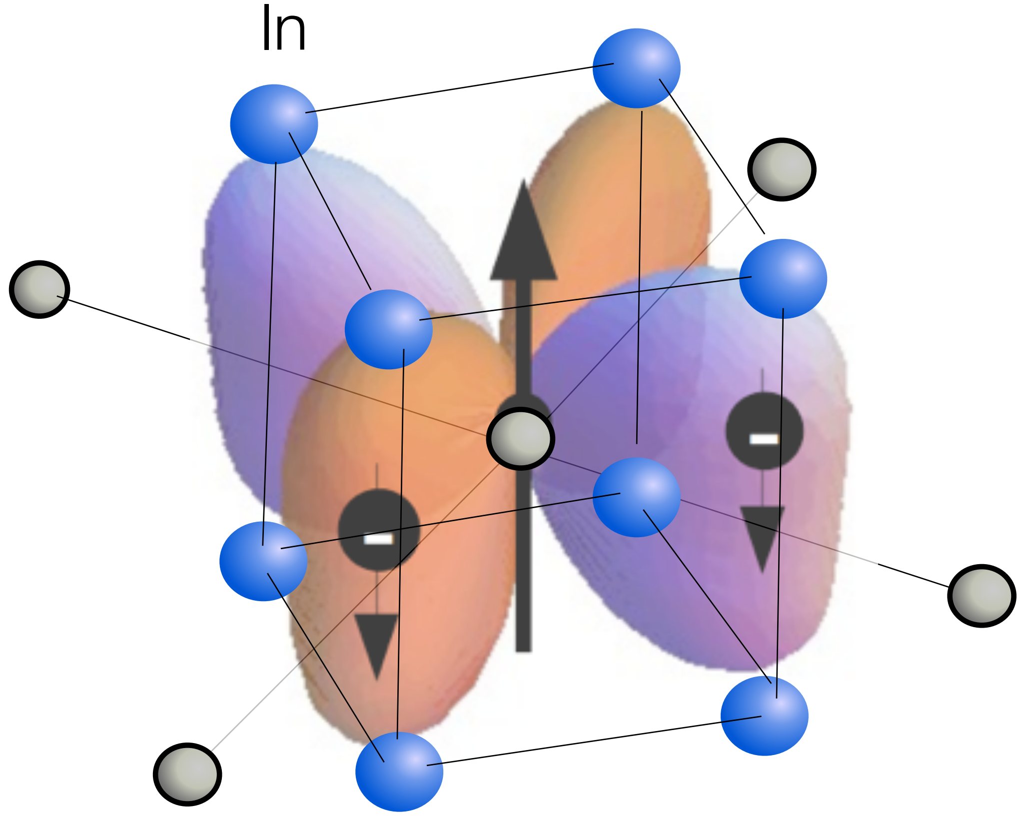


Composite pair**: intra-cell boson**

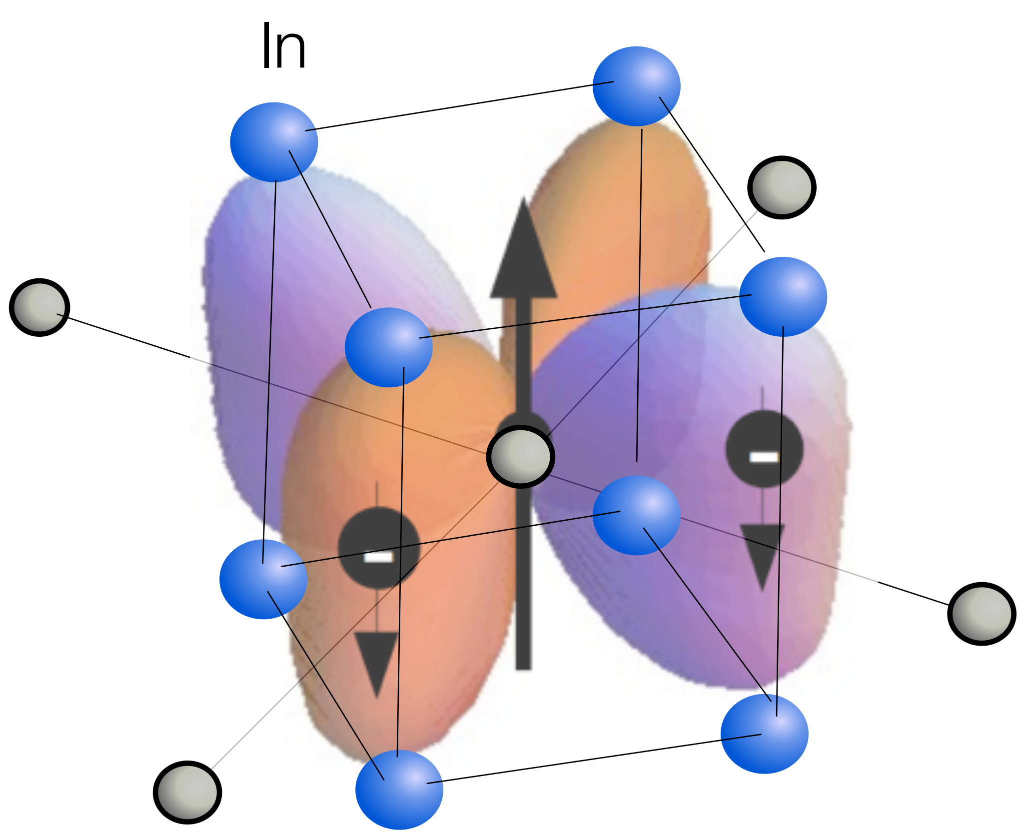
$$\Psi_C^\dagger = c_{1\downarrow}^\dagger c_{2\downarrow}^\dagger S_+$$

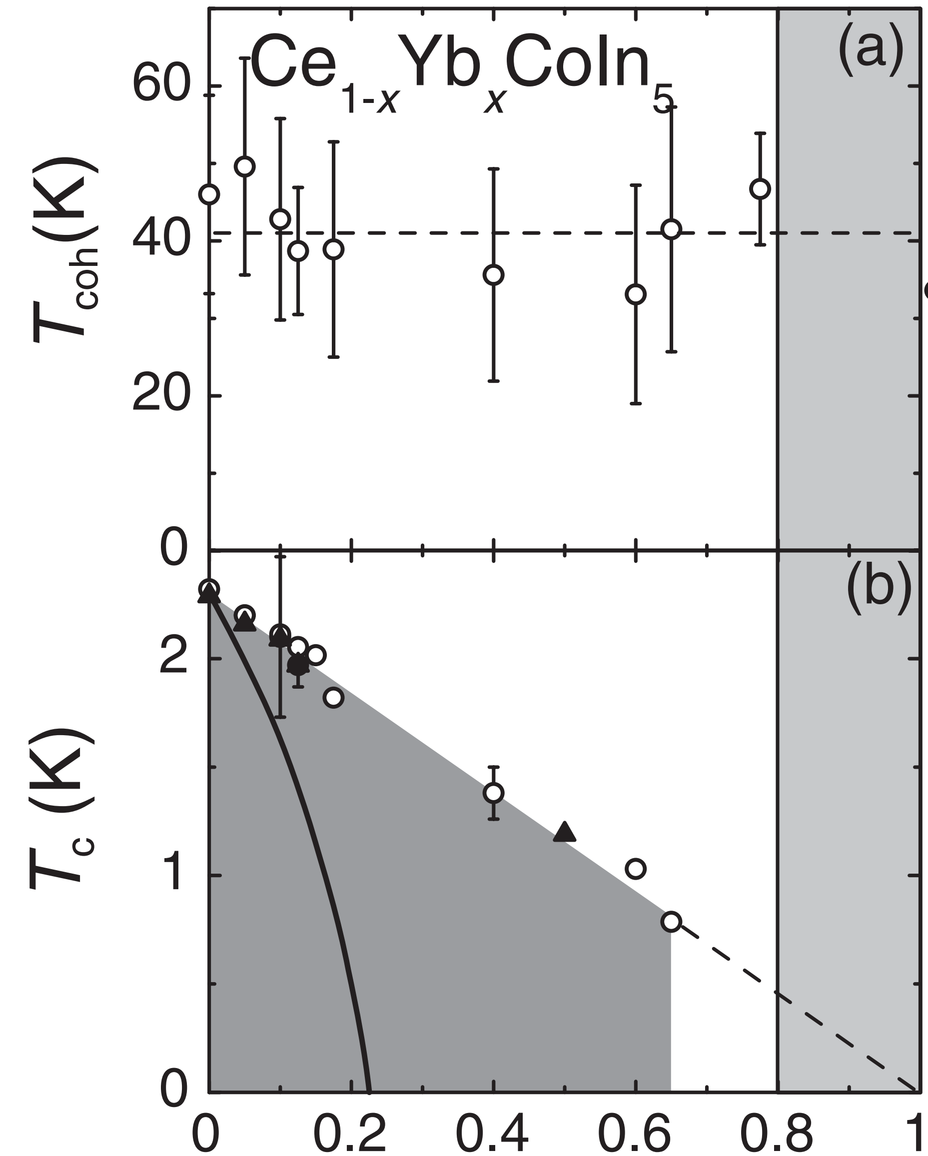
Real-space structure of pair

Extreme Resilience to doping on Ce site.

Magnetic pair: intercell

$$\Psi^\dagger_M = \Delta_d(1-2) f^\dagger_\uparrow(1) f^\dagger_\downarrow(2)$$





Composite pair**: intra-cell boson**

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Lei Shu et al, PRL, (2011)

Real-space structure of pair

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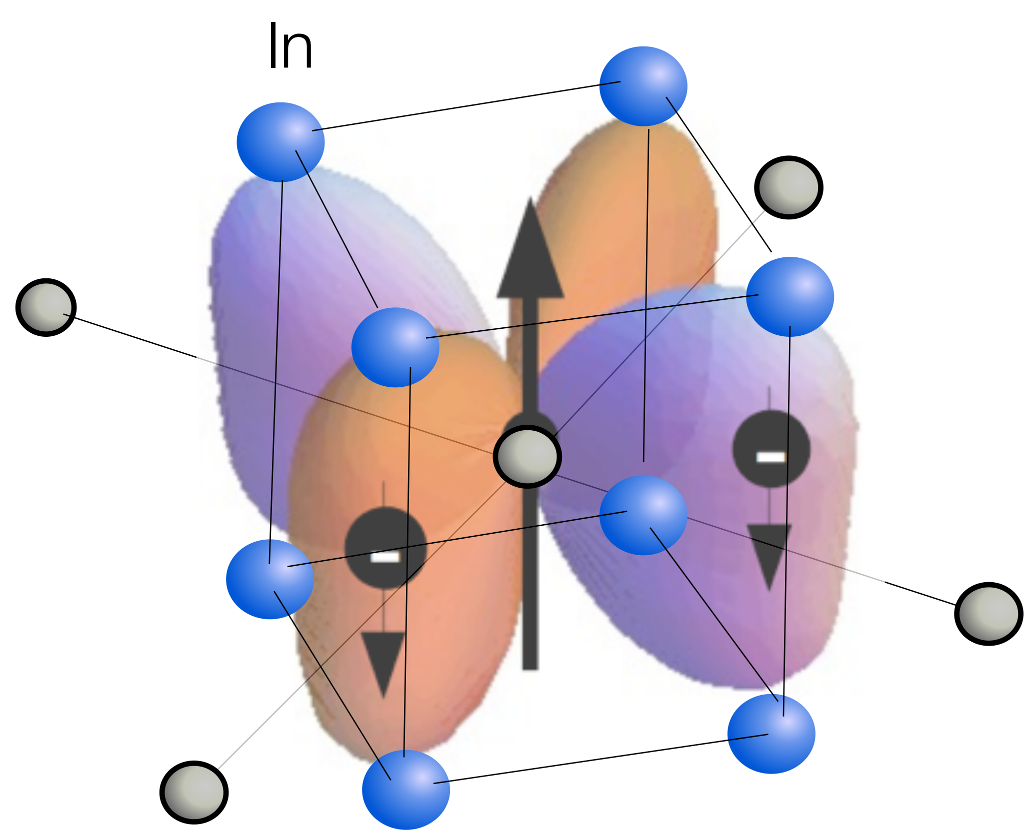

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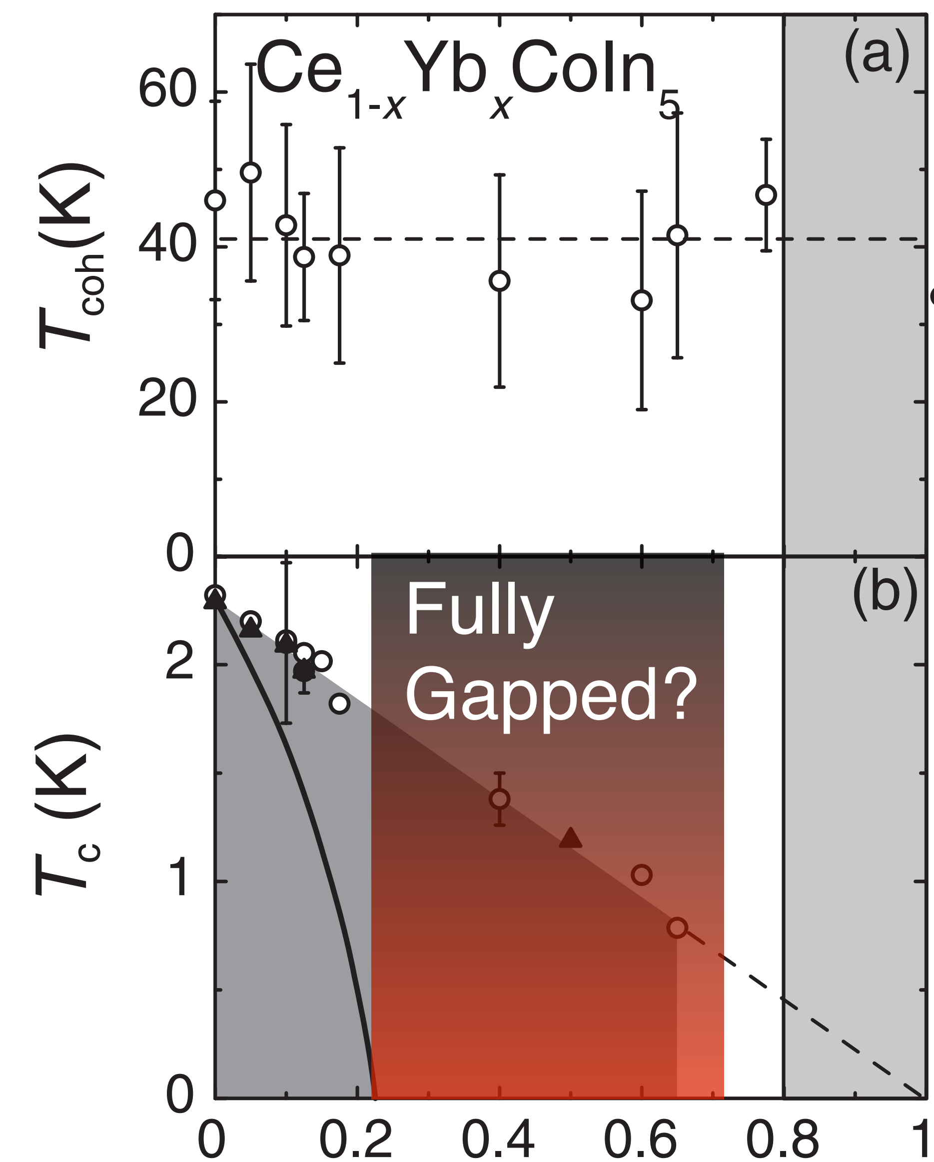


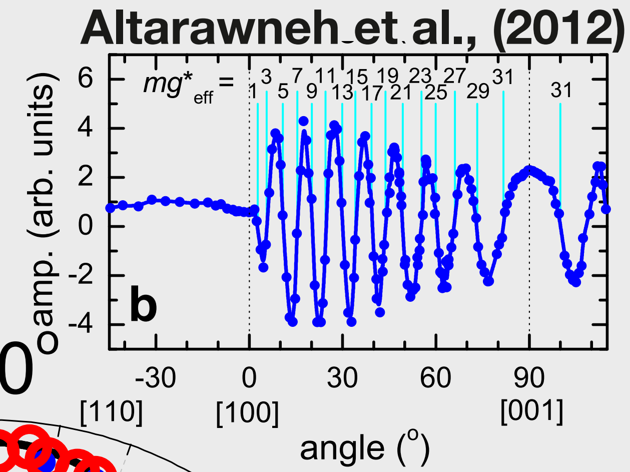
Lei Shu et al, PRL, (2011)

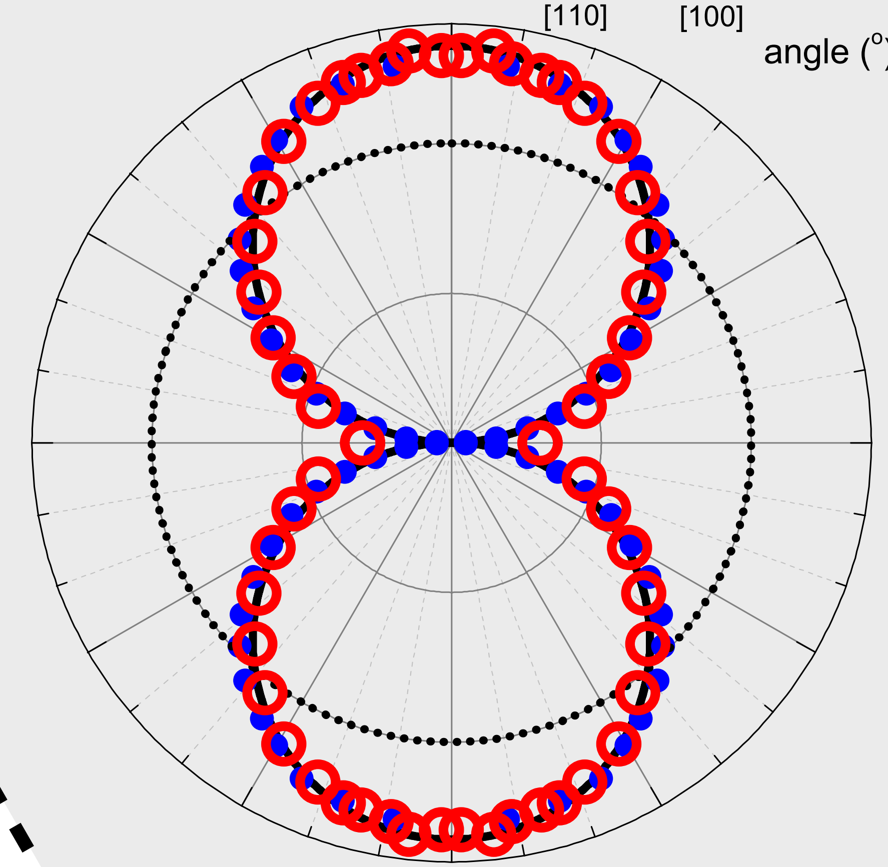
H. Kim et al PRL (2014)
Erten, Flint and PC PRL (2014)

Part III

How an Ising anisotropy in the electrons Suggests a new kind of spinor order.

Spinors





$$\Psi = \begin{pmatrix} \langle \Psi_\uparrow \rangle \\ \langle \Psi_\downarrow \rangle \end{pmatrix}$$

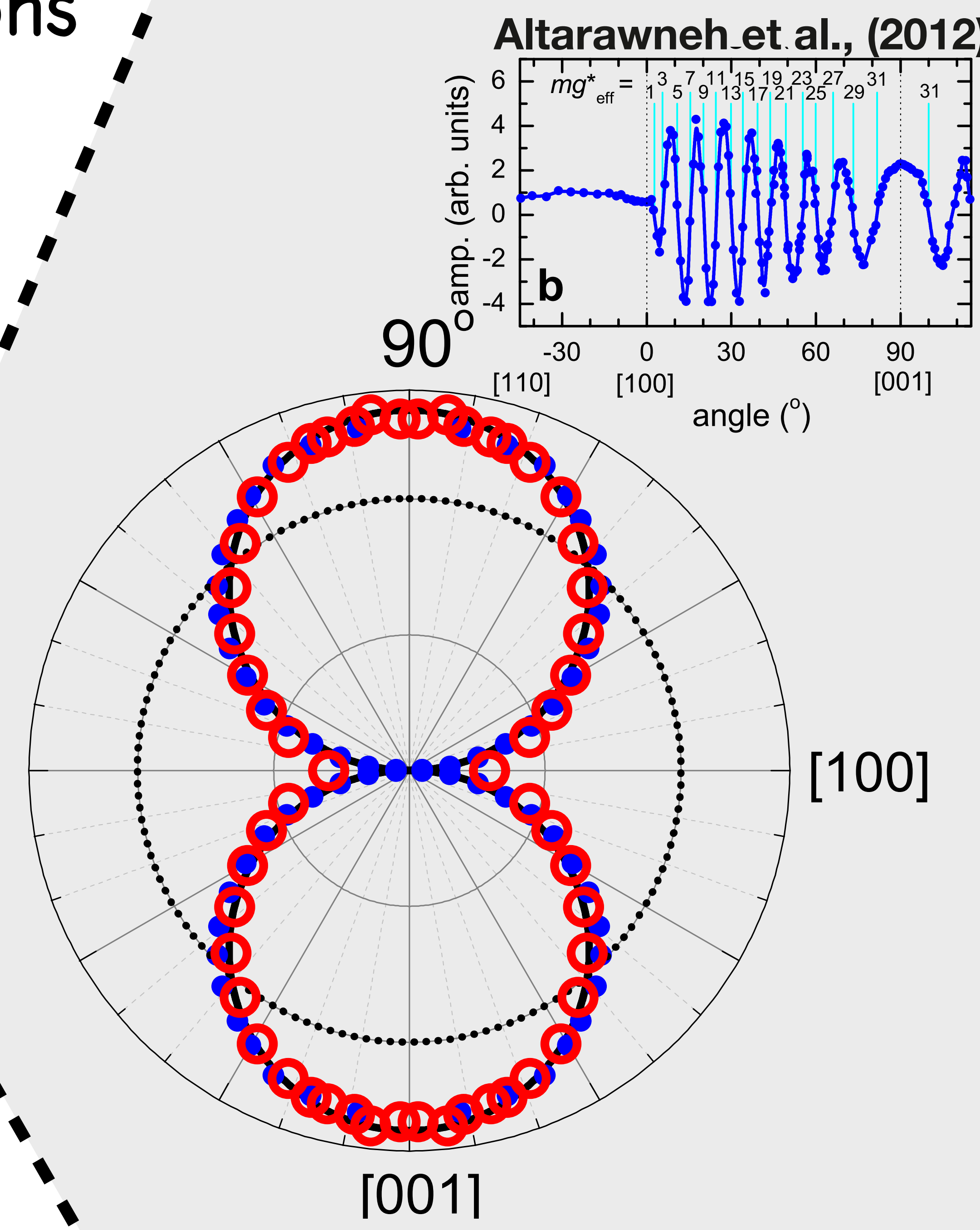
Hasta: Spear (Latin)

Part III

How an Ising anisotropy in the electrons
Suggests a new kind of spinor order.

Rebecca Flint (Iowa St.)

Premi Chandra (Rutgers)



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Hastatic order in the heavy-fermion compound URu_2Si_2

Premala Chandra[1], Piers Coleman[1,2] & Rebecca Flint[3]

Hasta: Spear (Latin)

doi:10.1038/nature11820

Part III

How an Ising anisotropy in the electrons Suggests a new kind of spinor order.

Can order parameters Fractionalize?

Rebecca Flint (Iowa St.)   Premi Chandra (Rutgers)

Hastatic order in the heavy-fermion compound URu_2Si_2

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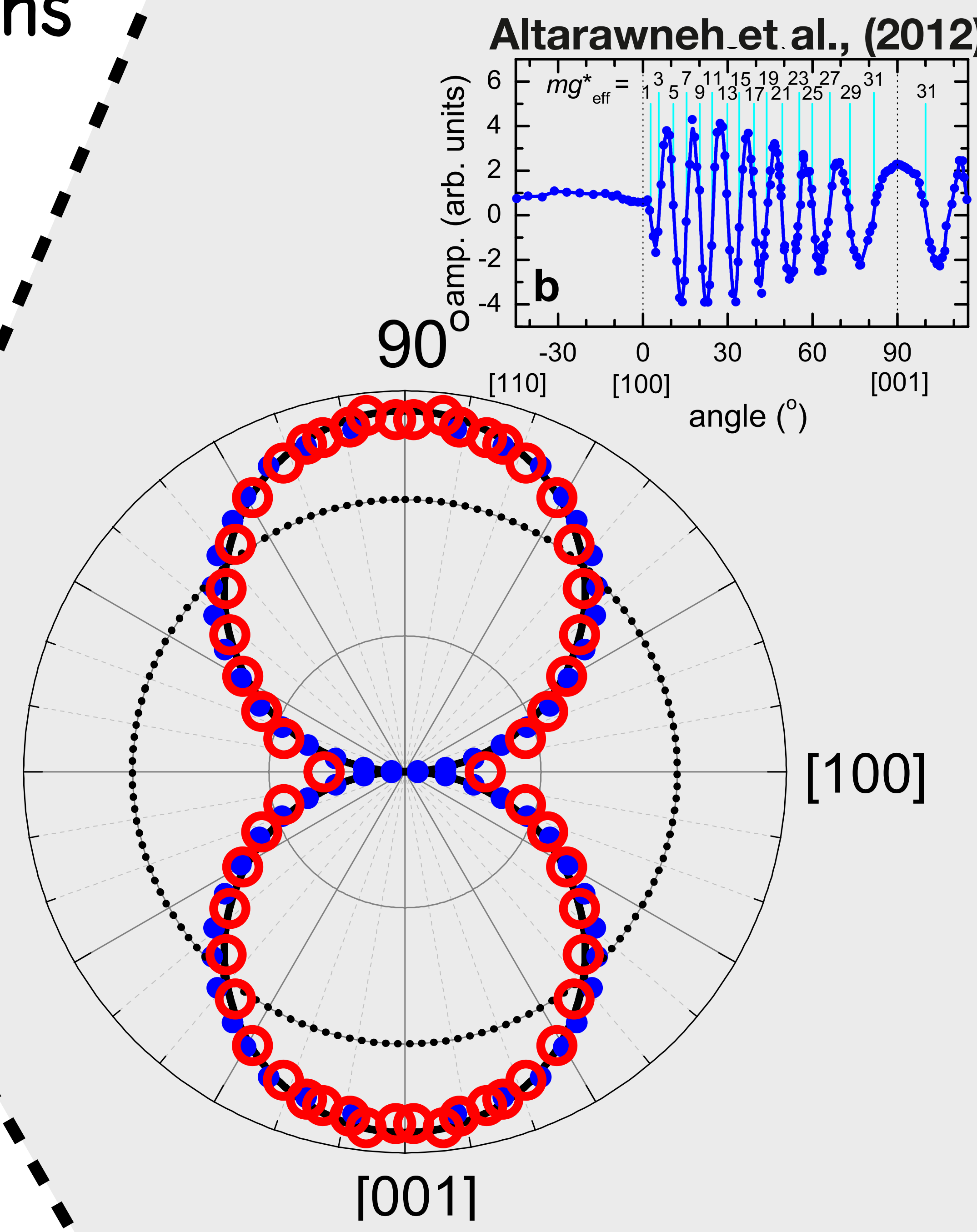

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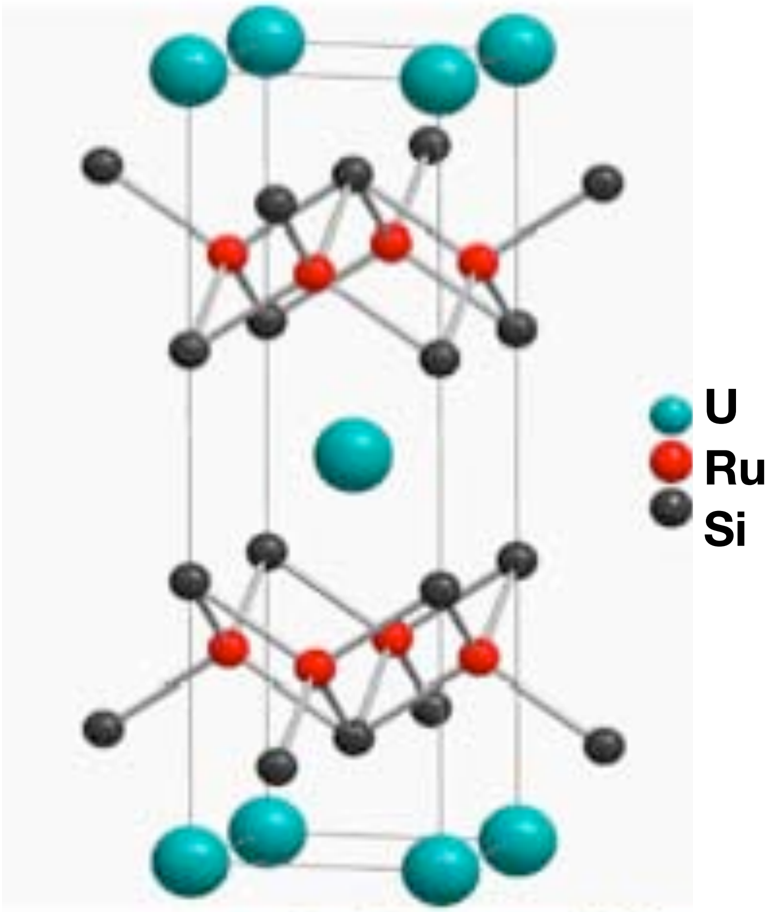
Hidden Order in URu_2Si_2



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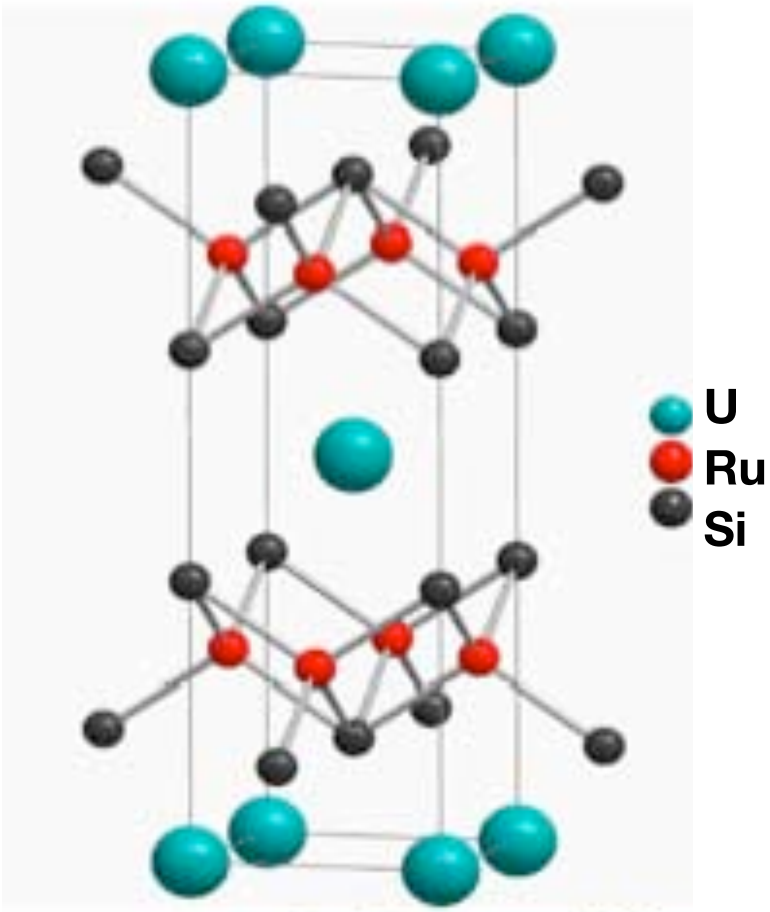

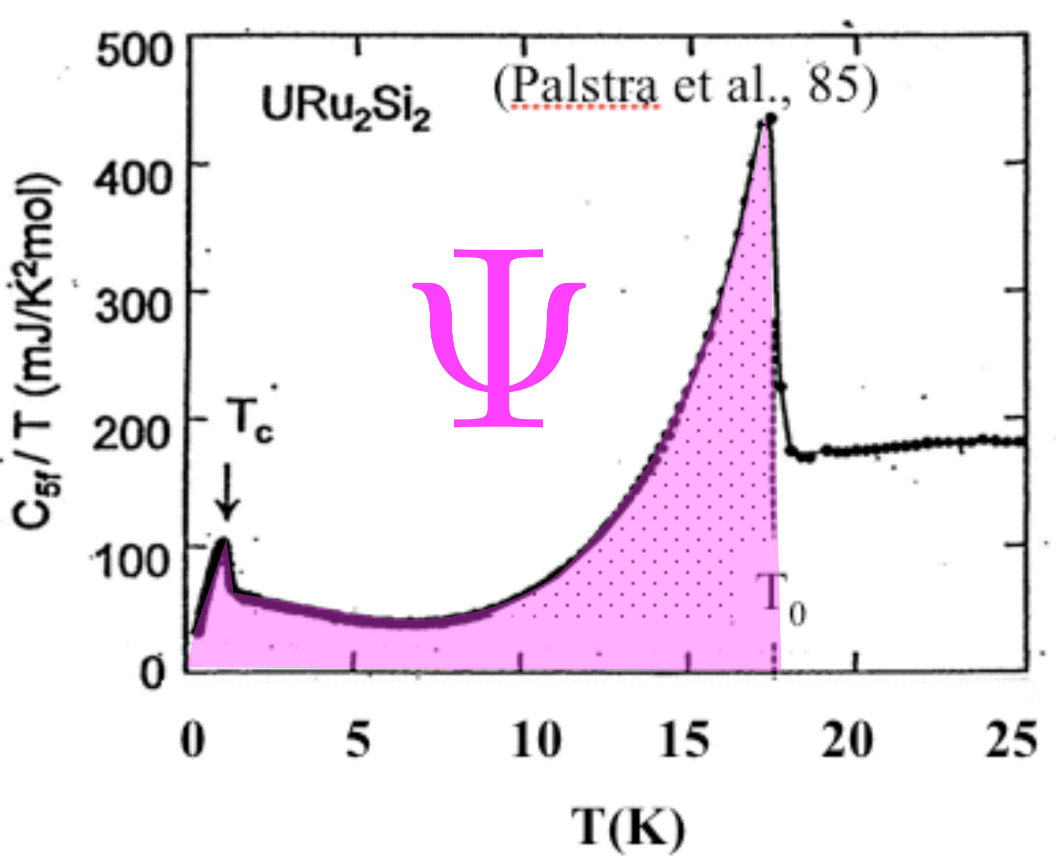

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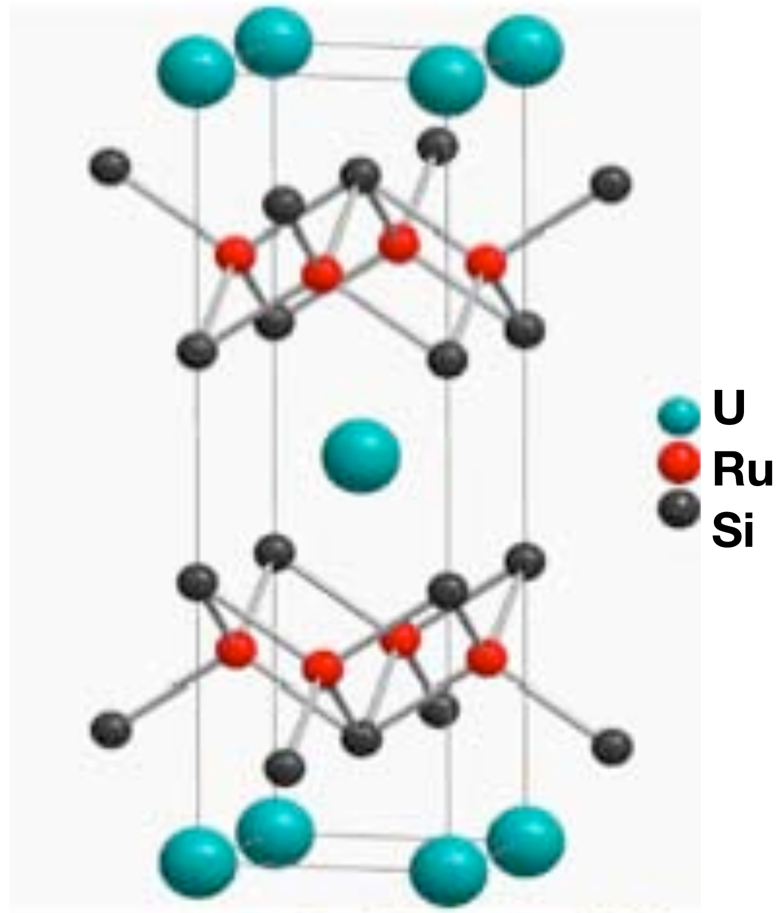
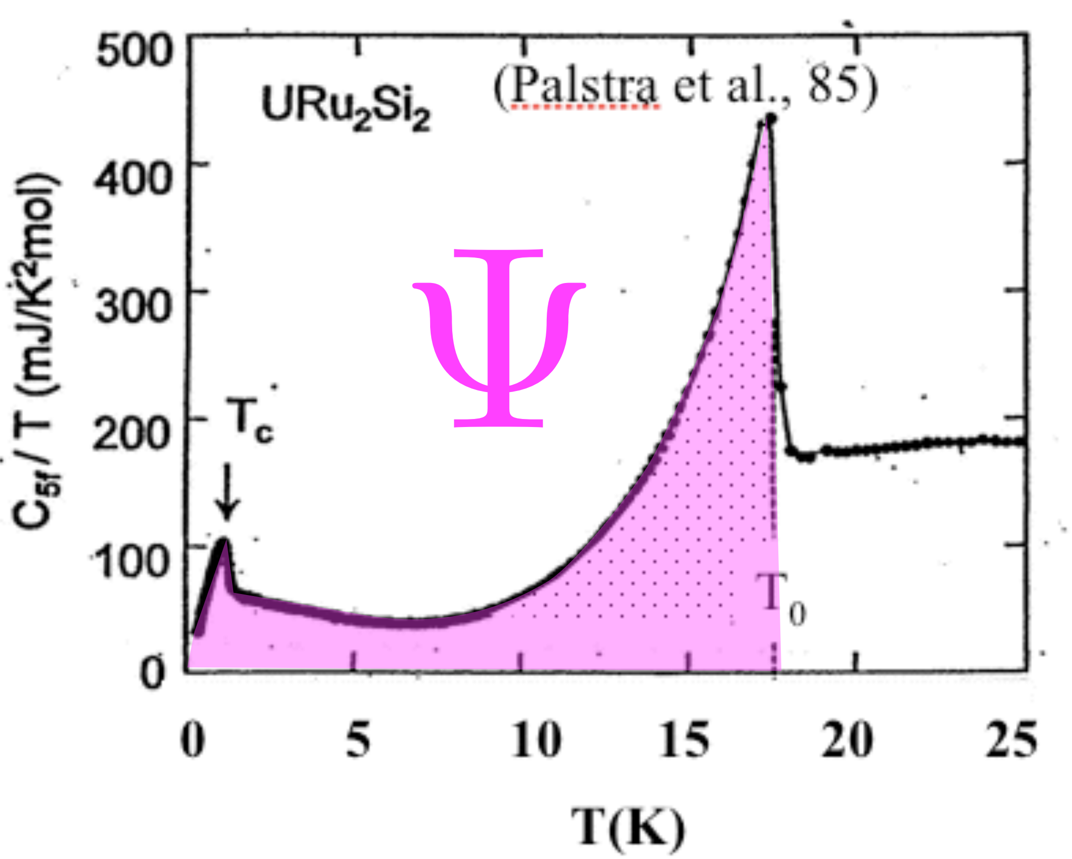
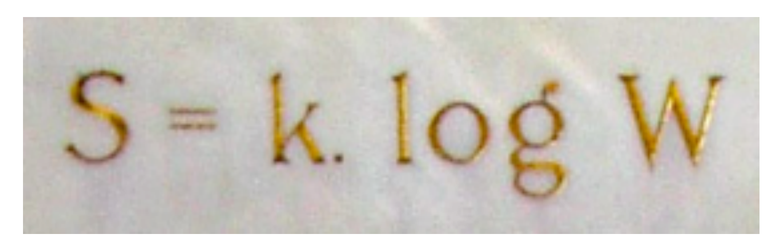




L. Boltzmann



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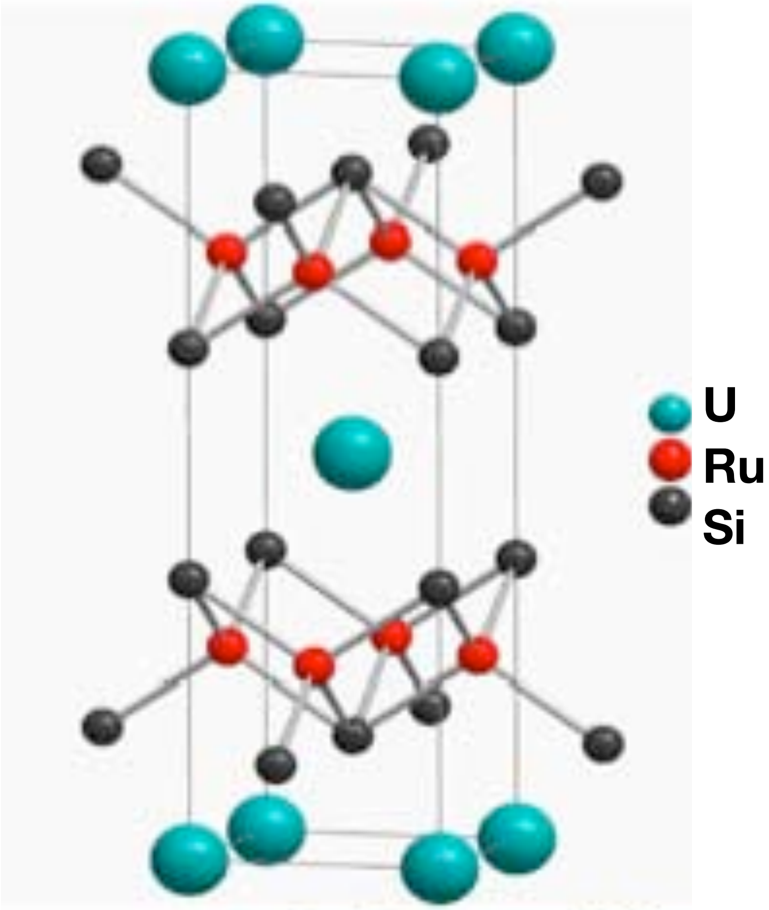

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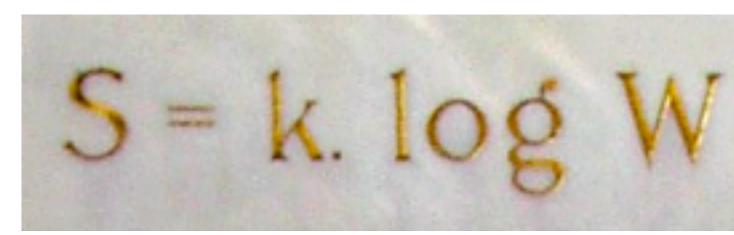
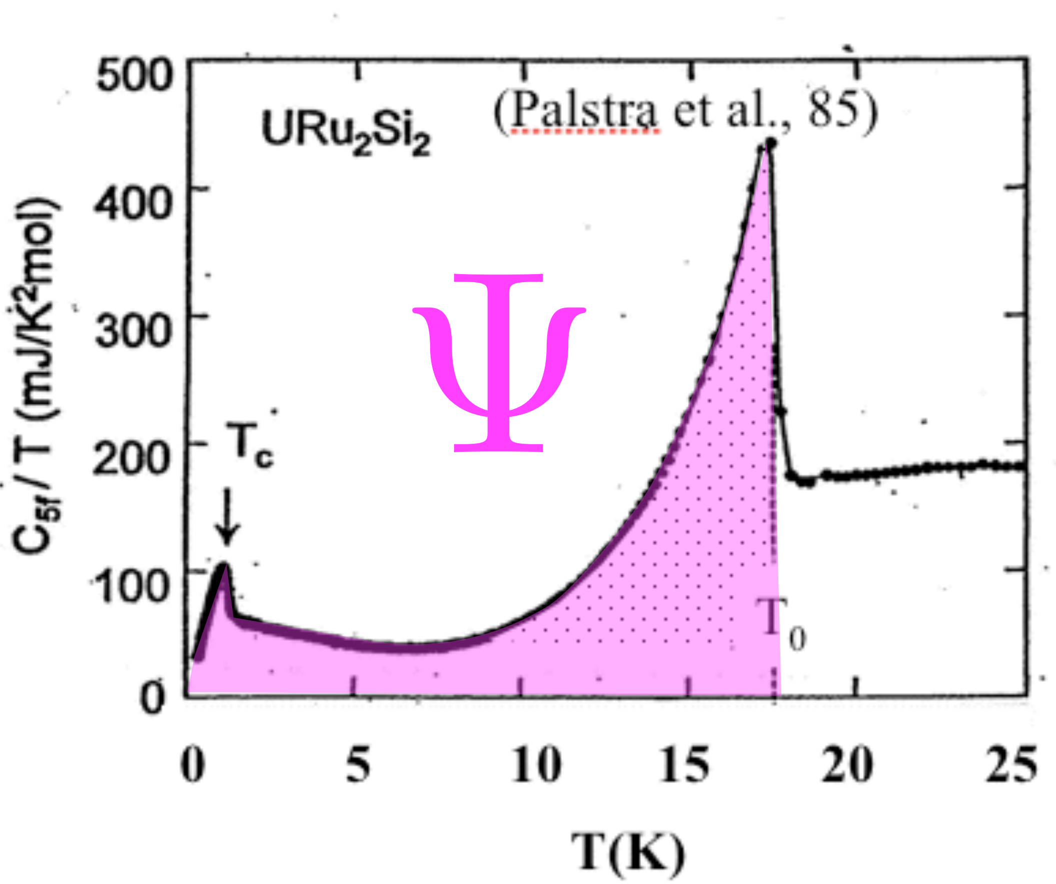
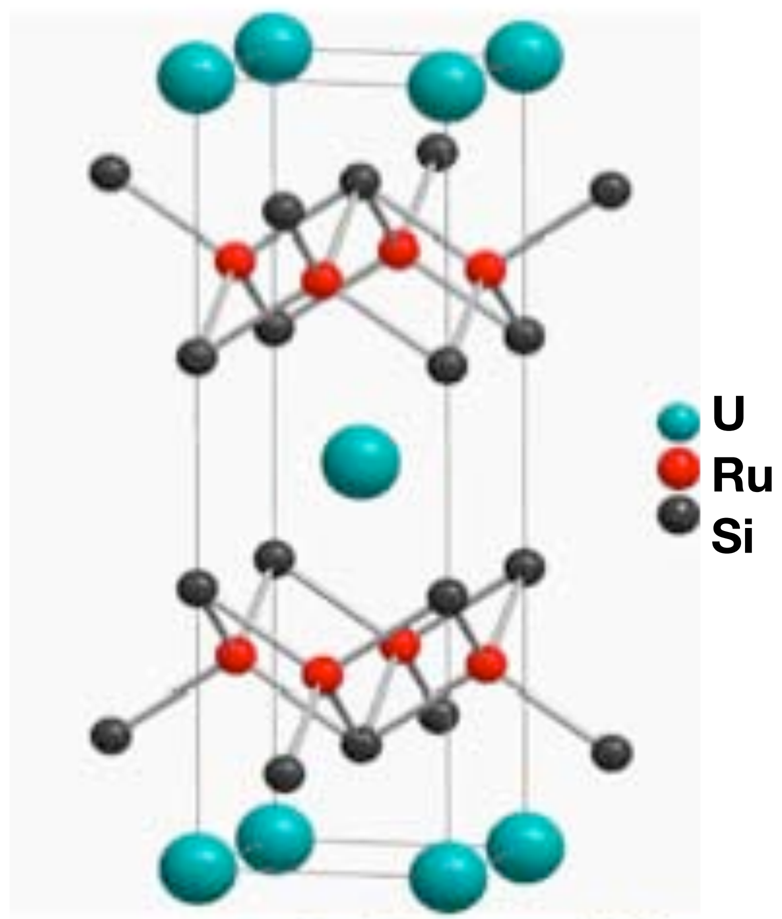




Heat lost on cooling = k log W

= amount of entanglement

Hidden Order in URu_2Si_2



$$\Delta S = \int_0^{T_0} \frac{C_V}{T} dT$$

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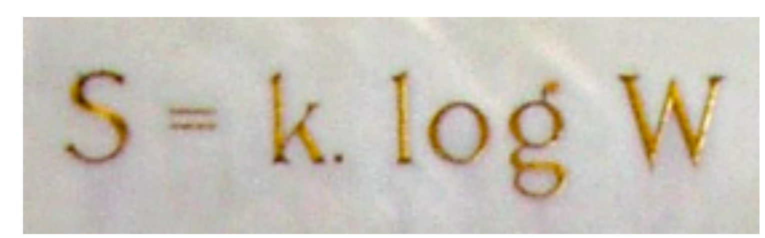

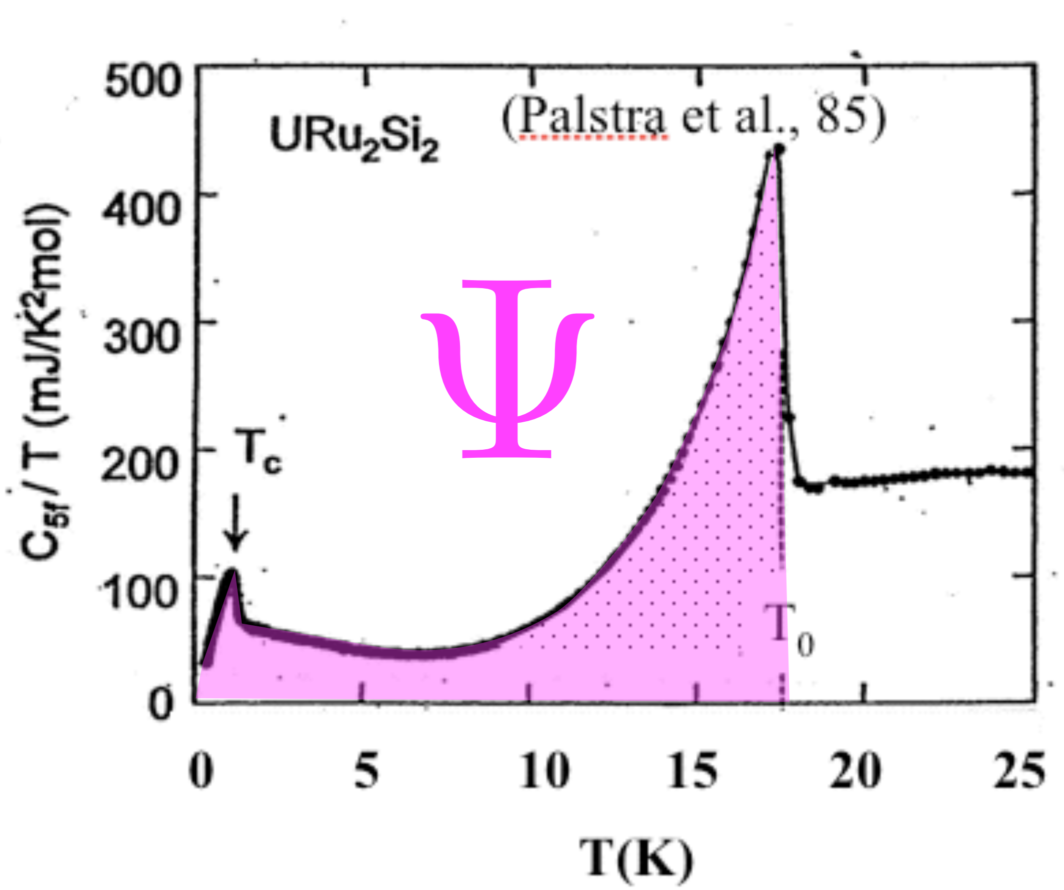

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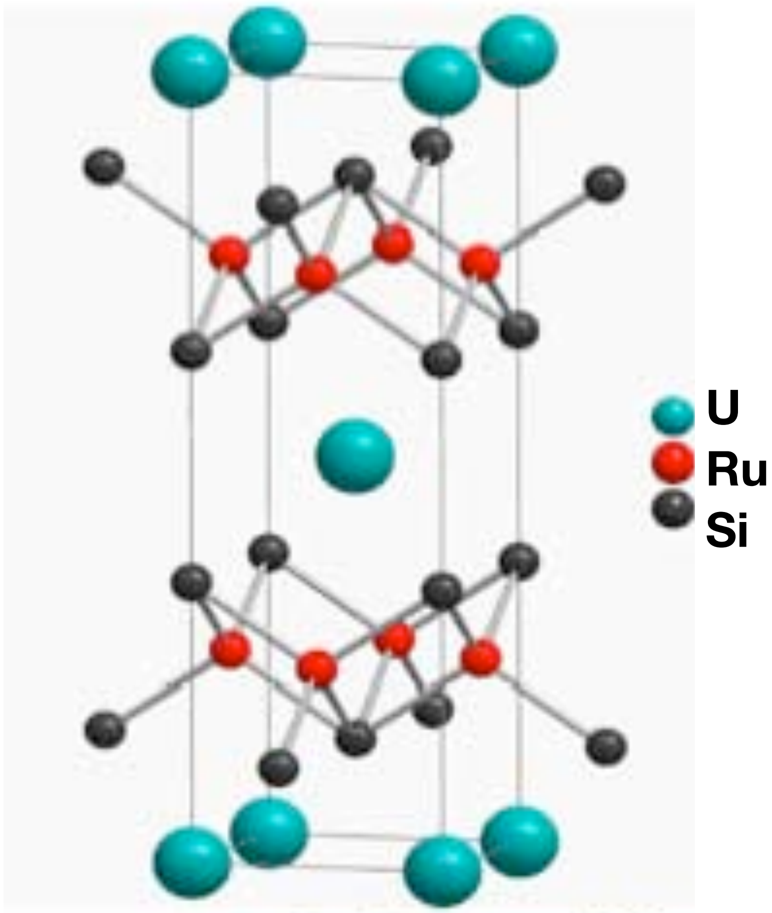

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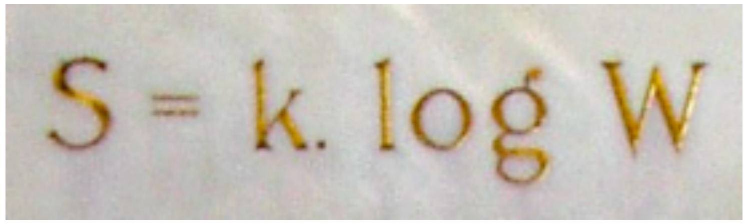

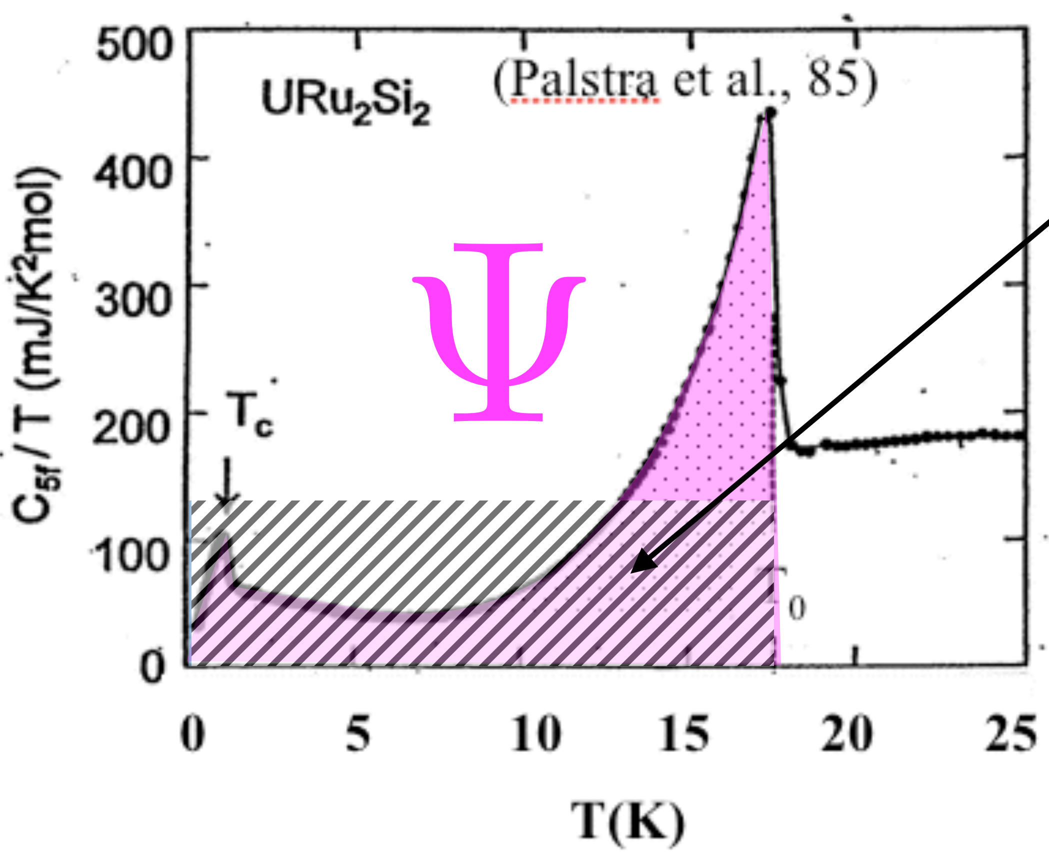

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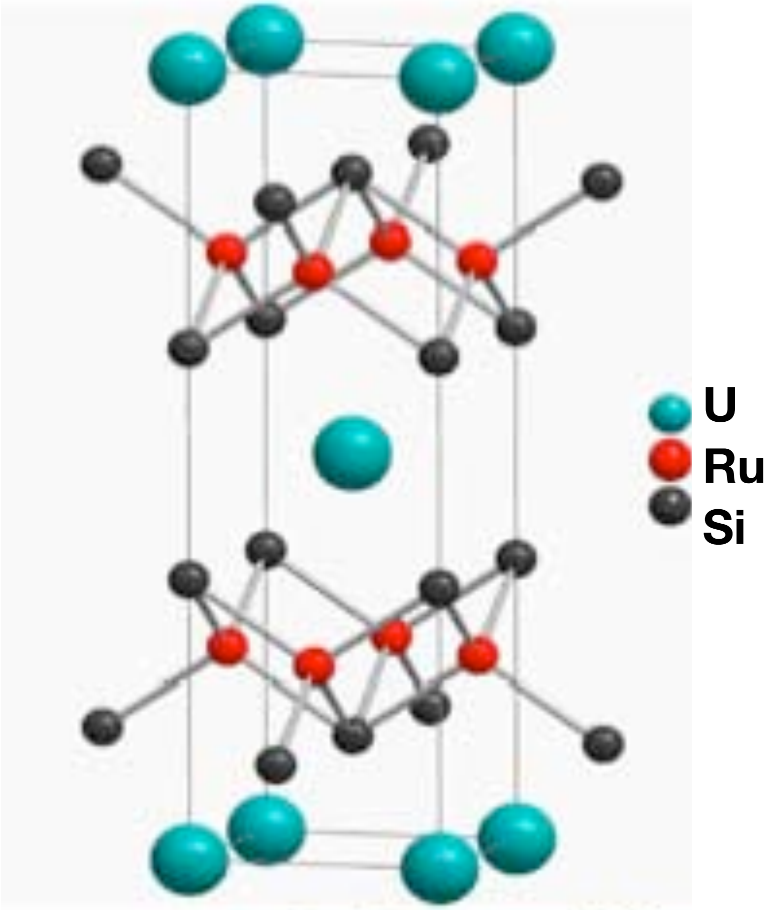

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=0.14 x 17.5 K
=2.45 J/mol/K
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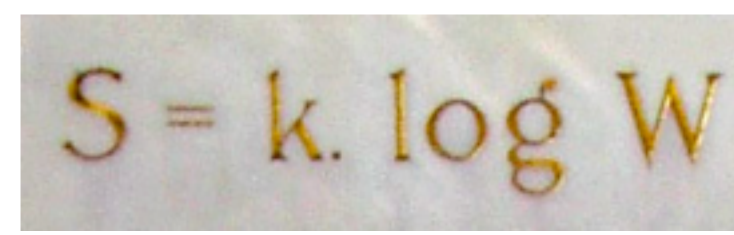

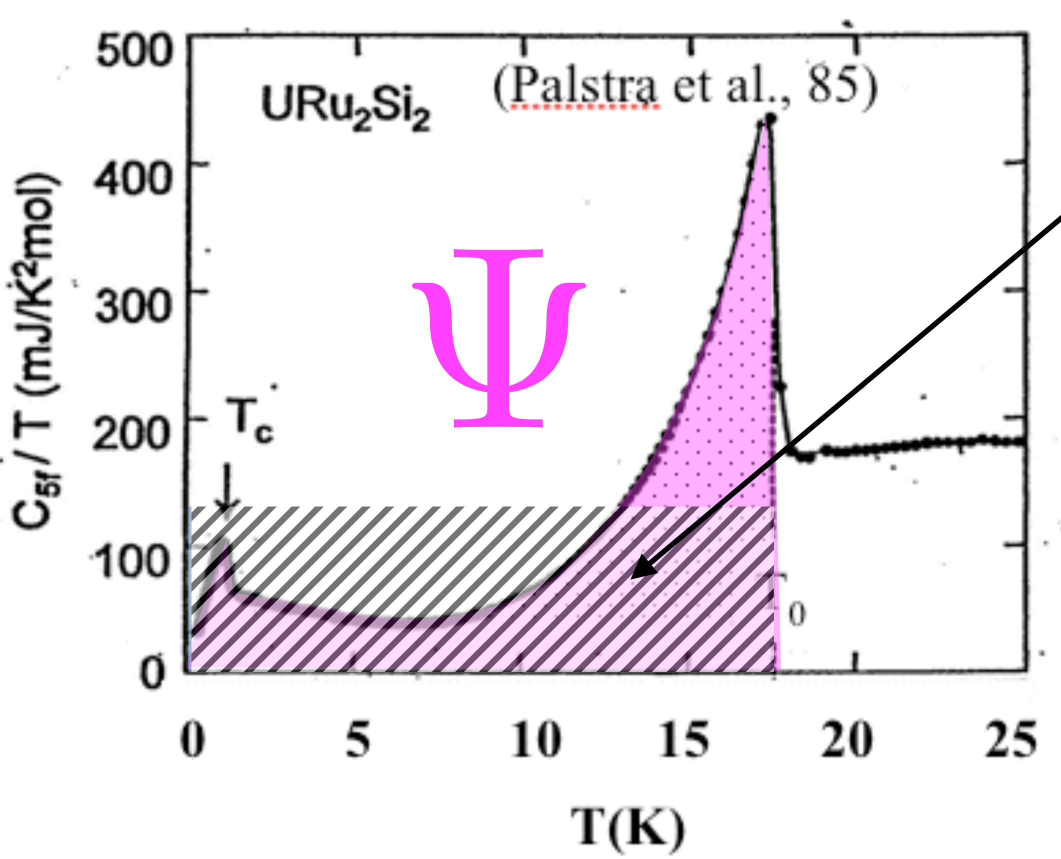

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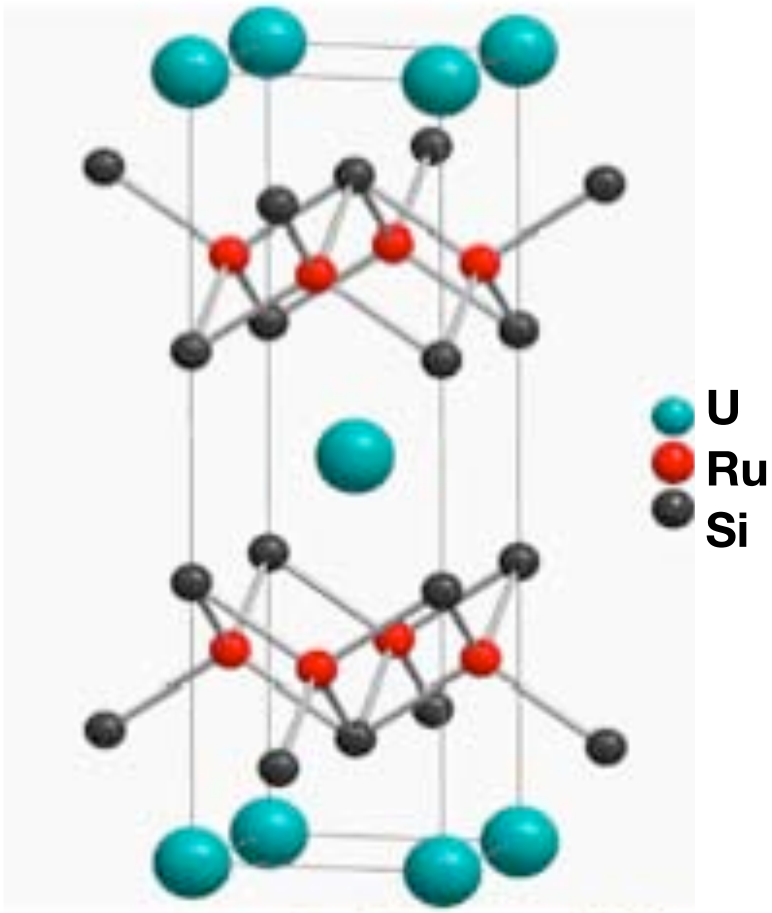

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Huge entropy
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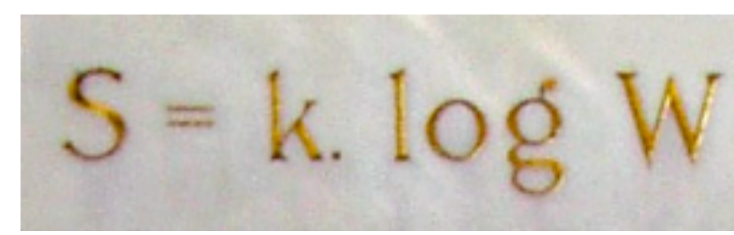

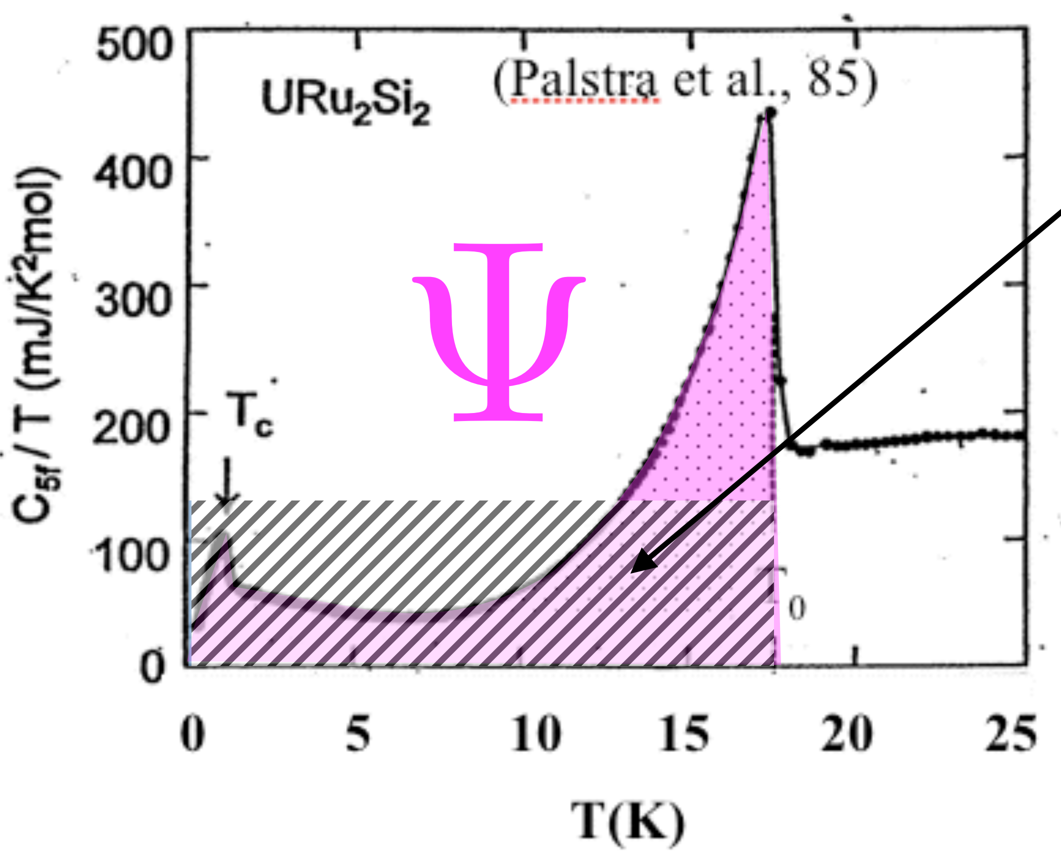

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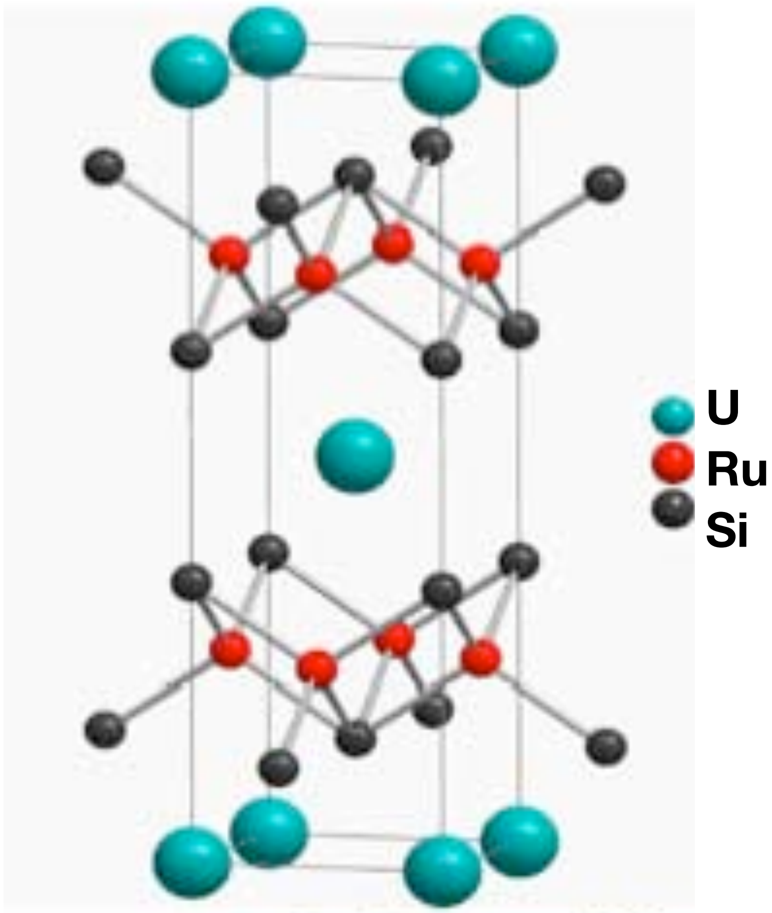

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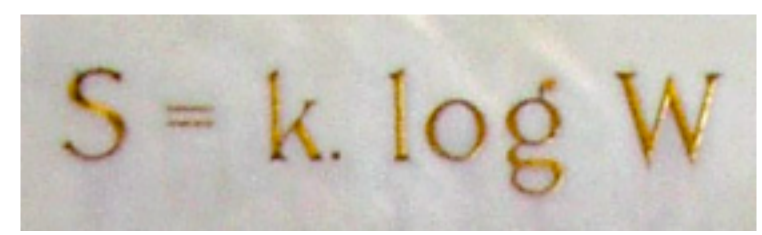

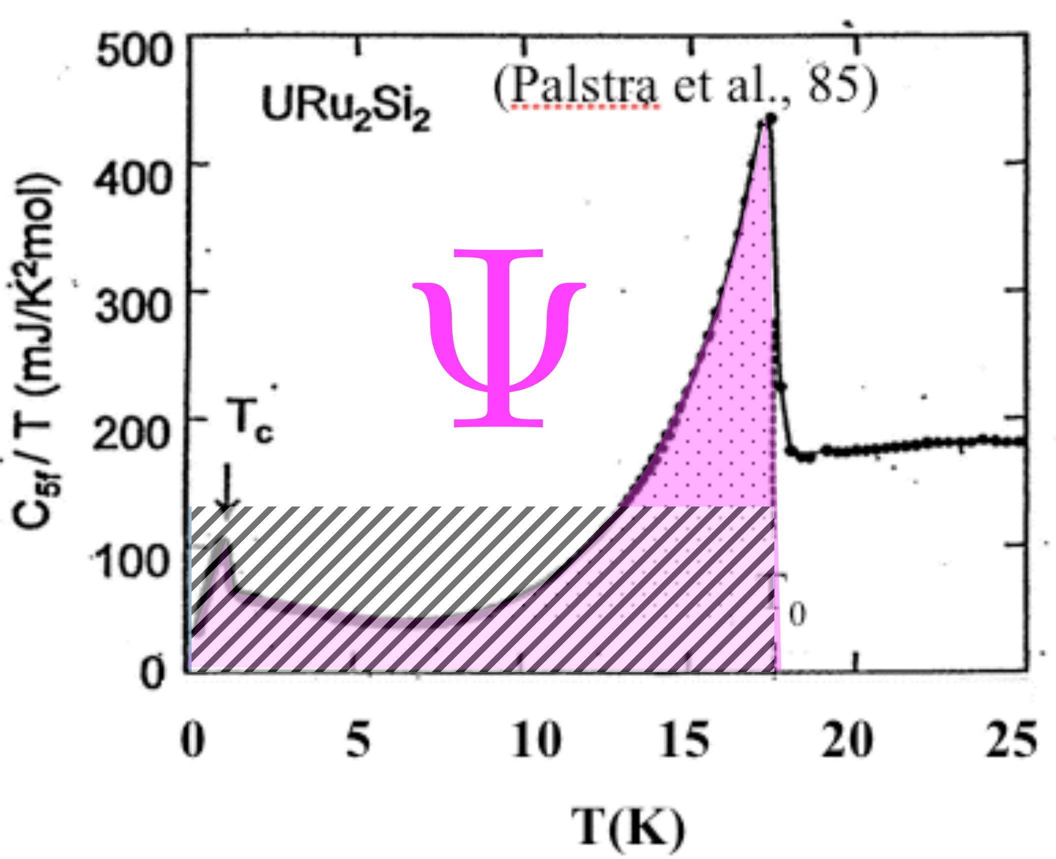

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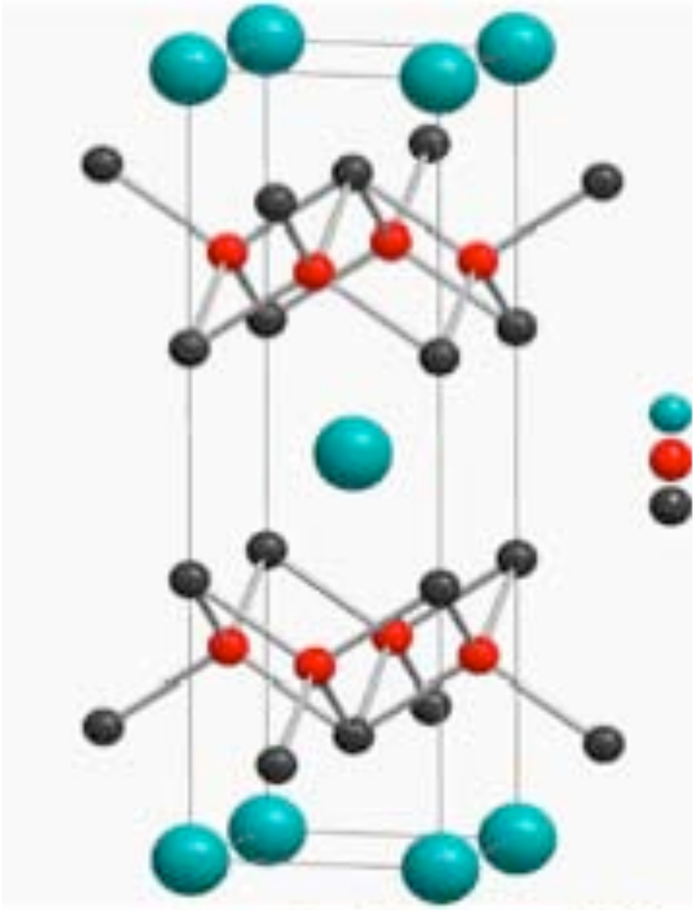

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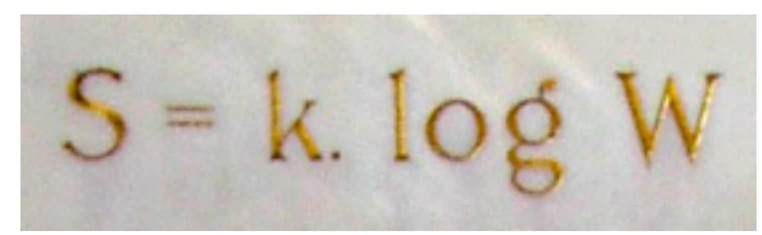

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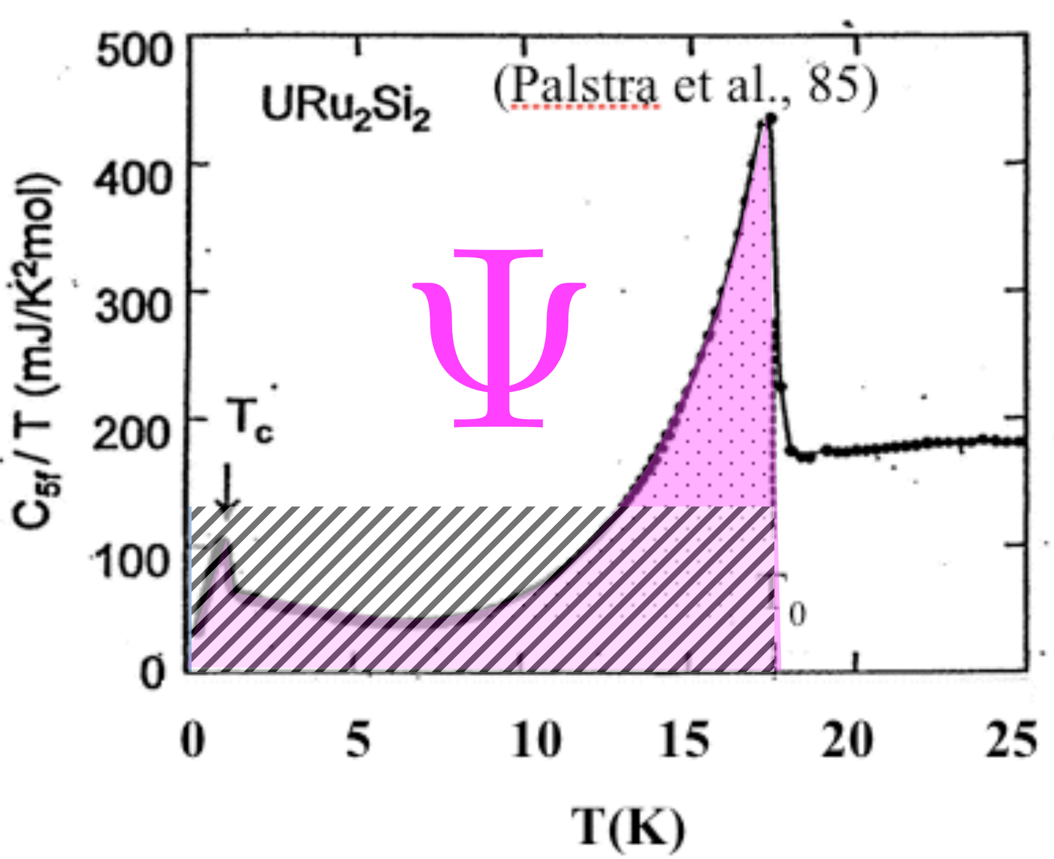
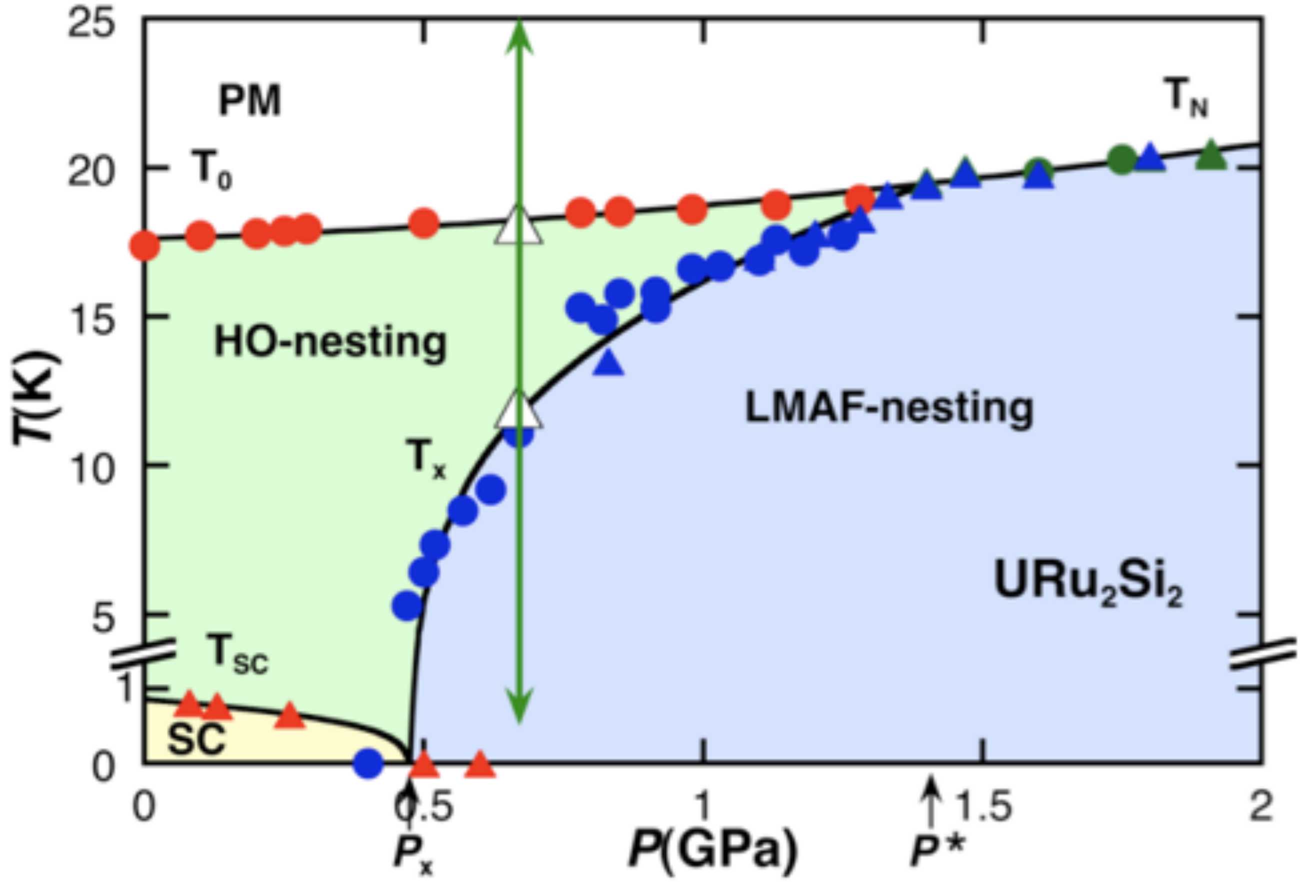
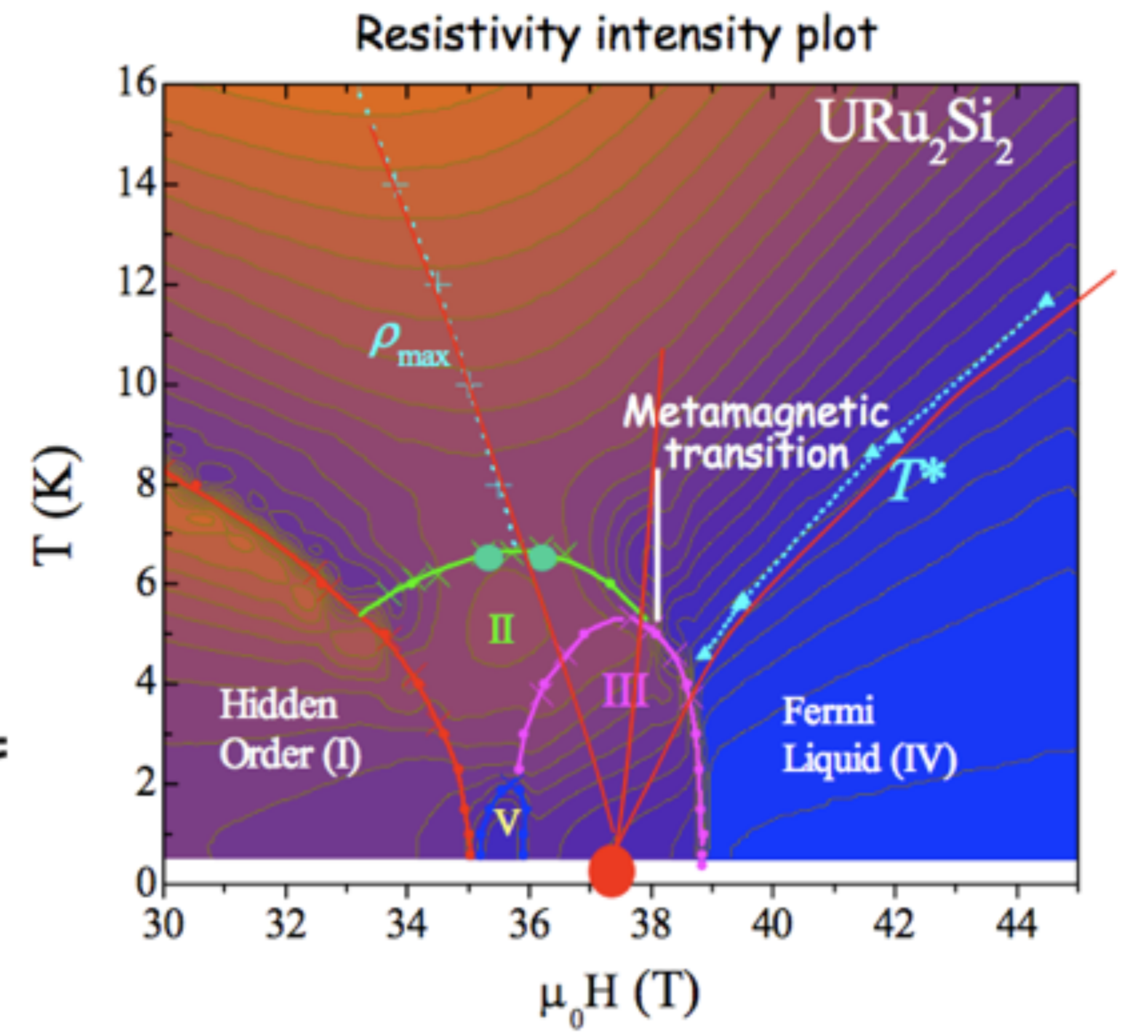


What is the nature of the hidden order?

High pressures, high fields

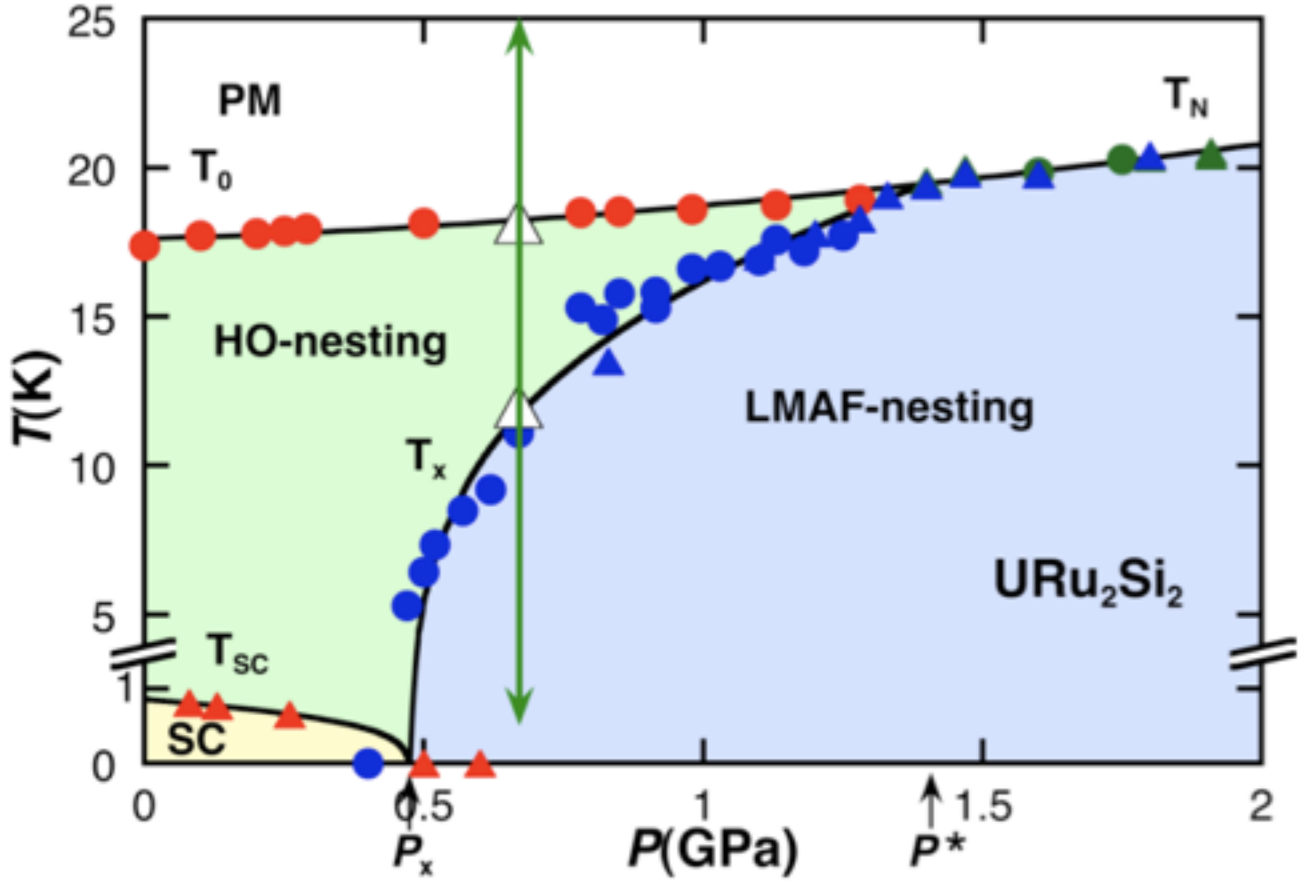


Villaume et al. (08)



Kim et al (03)

High pressures, high fields



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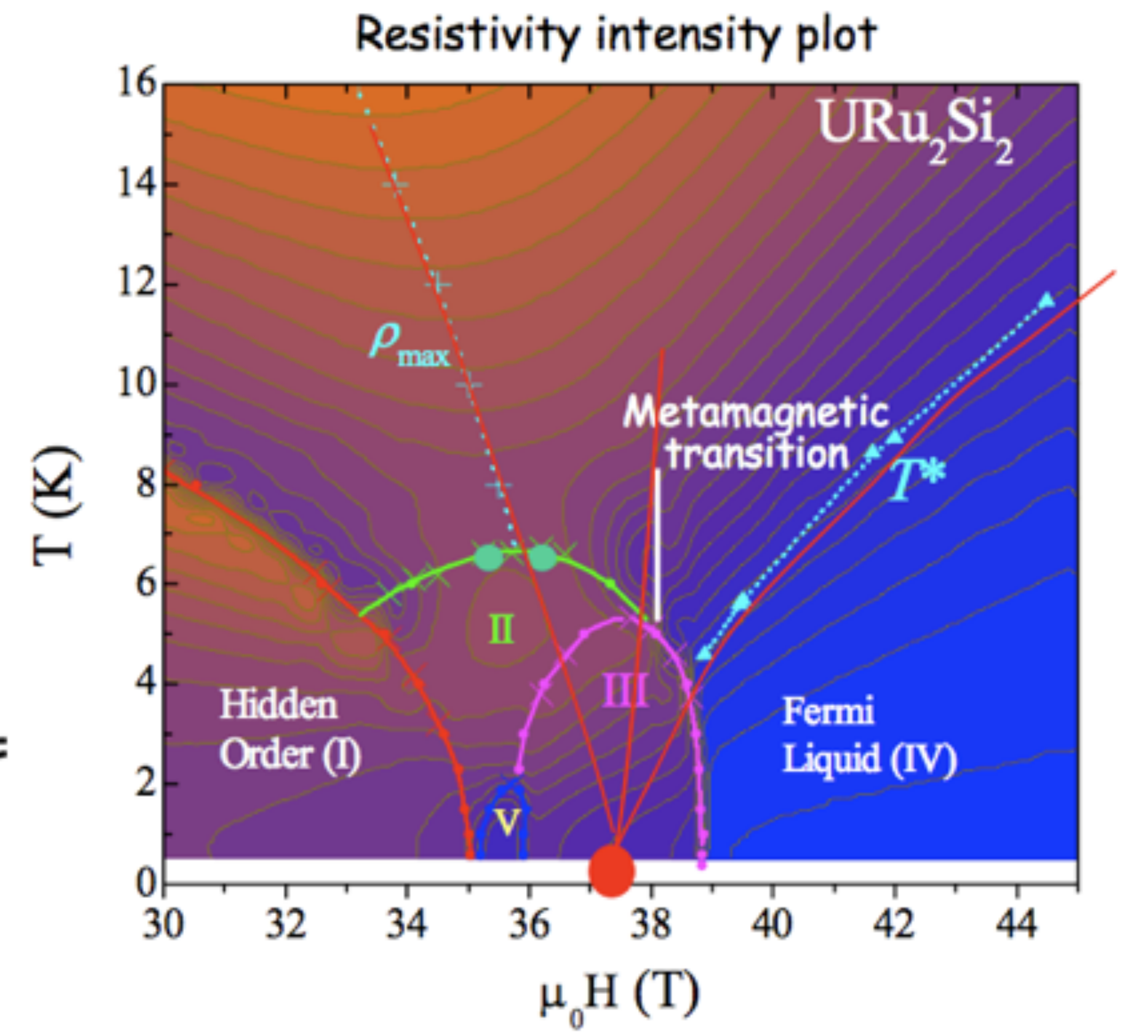


Kim et al (03)

Ising order, present in LMAF, vanishes in the hidden order state. (NMR,MuSR).

25 Years of Theoretical Proposals

Local

Barzykin & Gorkov, '93 (three-spin correlation)
Santini & Amoretti, '94, Santini ('98) (Quadrupole order)

Amitsuka & Sakihabara (Γ_5, Quadrupolar doublet, '94)
Kasuya, '97 (U dimerization)
Kiss and Fazekas '04, (octupolar order)
Haule and Kotliar '09 (hexa-decapolar)

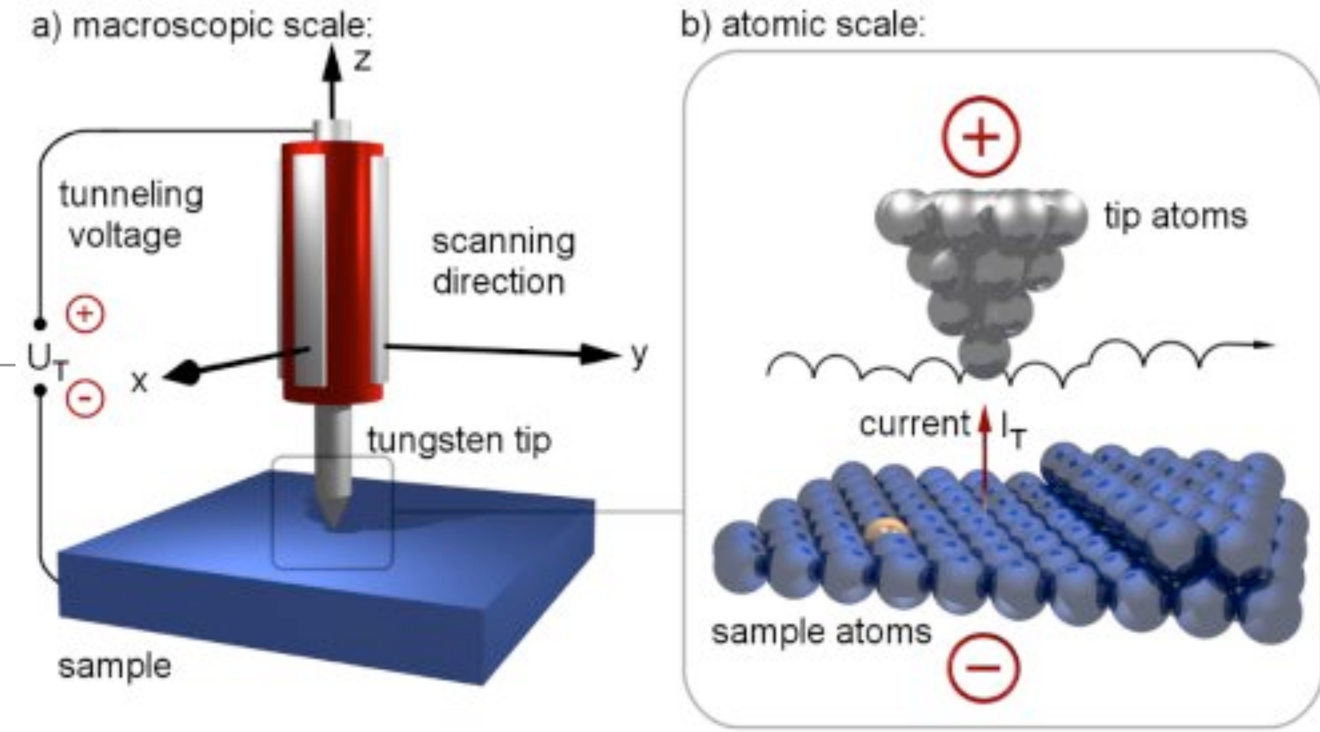
Landau Theory

Shah et al. ('00) "Hidden Order",

Itinerant

Ramirez et al, '92 (quadrupolar SDW)
Ikeda and Ohashi '98 (d-density wave)
Okuno and Miyake '98 (composite)
Tripathi, Chandra, PC and Mydosh, '02 (orbital afm)
Dori and Maki, '03 (unconventional SDW)
Mineev and Zhitomirsky, '04 (SDW)
Varma and Zhu, '05 (spin-nematic)
Ezgar et al '06 (Dynamic symmetry breaking)
Pepin et al '10 (Spin liquid/Kondo Lattice)
Dubi and Balatsky, '10 (Hybridization density wave)
Fujimoto, 2011 (spin-nematic)
Rau and Kee 2012 (Rank 5 pseudo-spin vector)

Cause Célèbre: state of the art spectroscopies



Scanning Tunneling Microscopy

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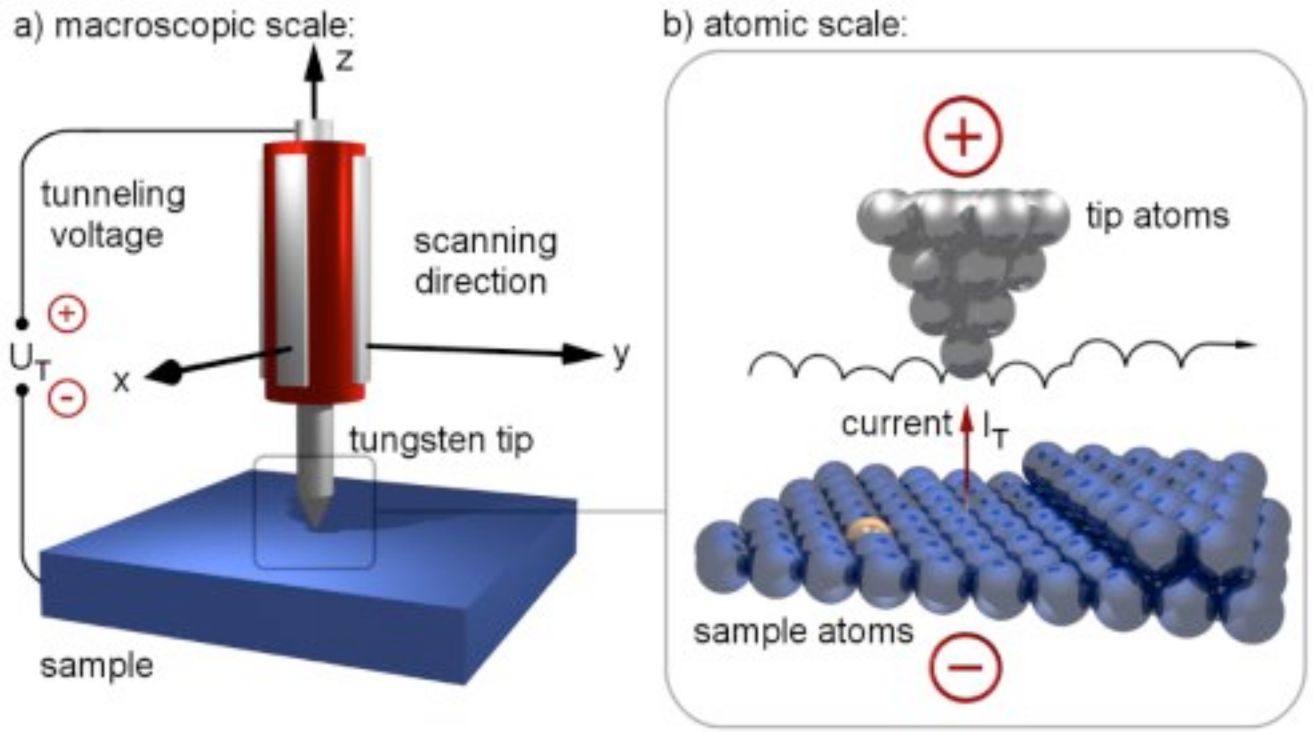
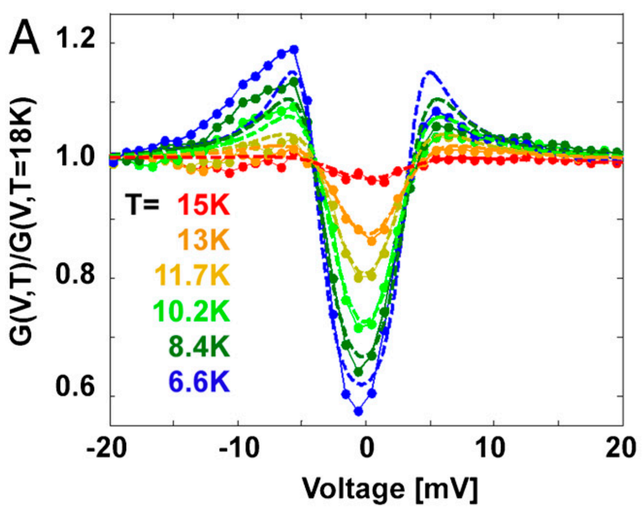
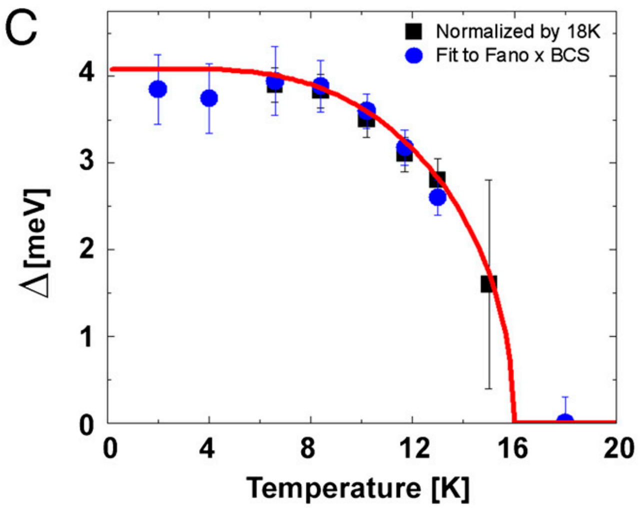


Scanning Tunneling Microscopy

Pegor Aynajian et al, PNAS (2010)





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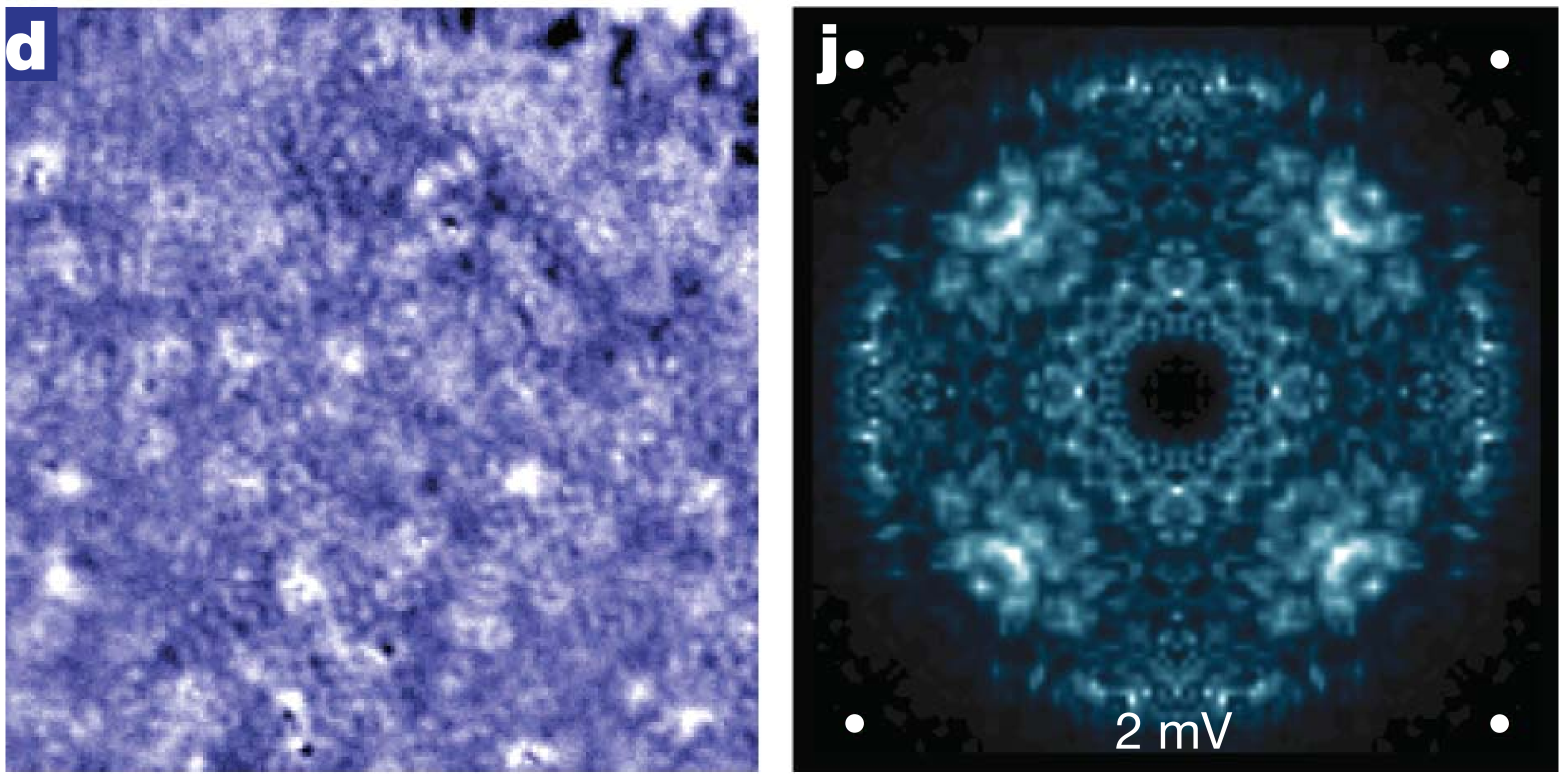

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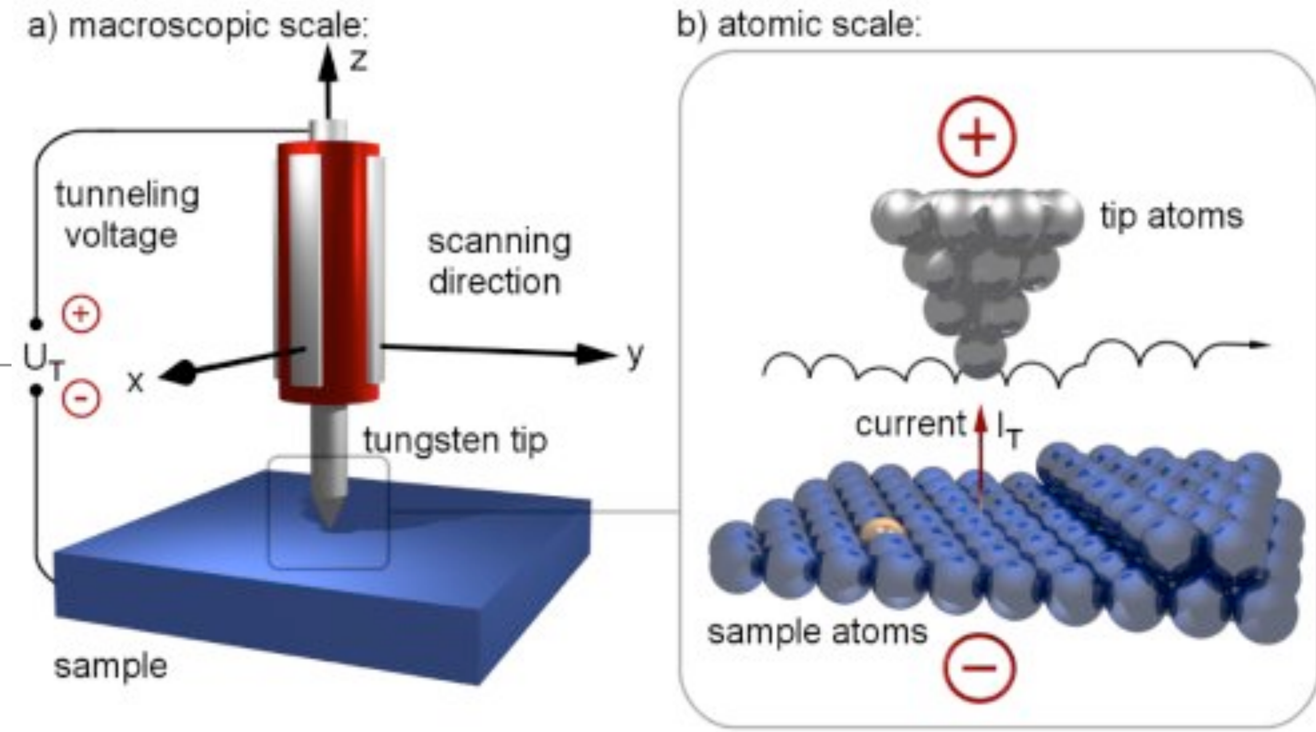

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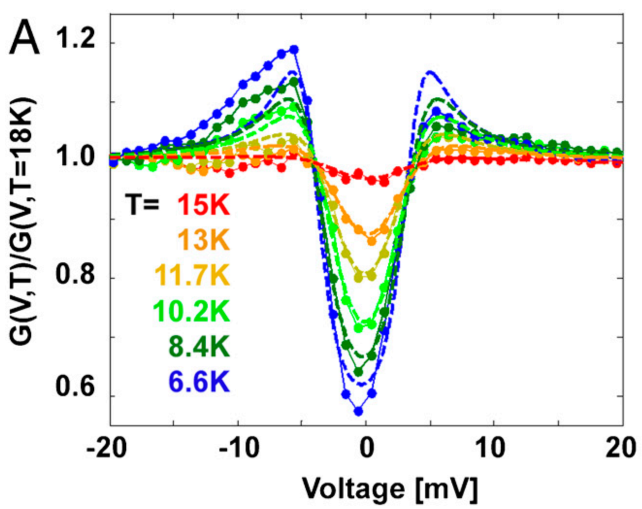

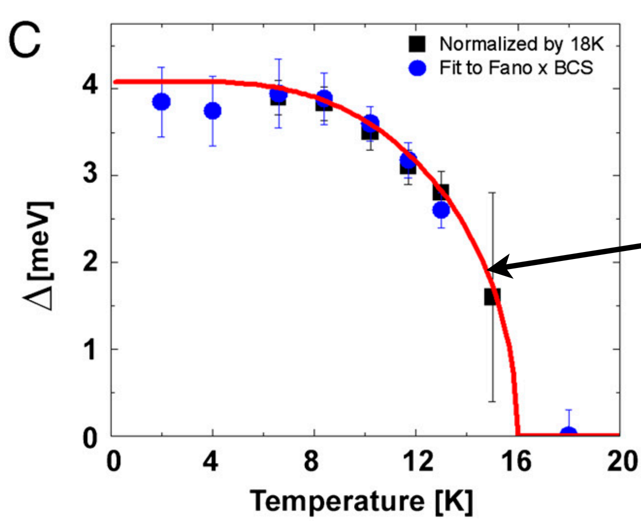

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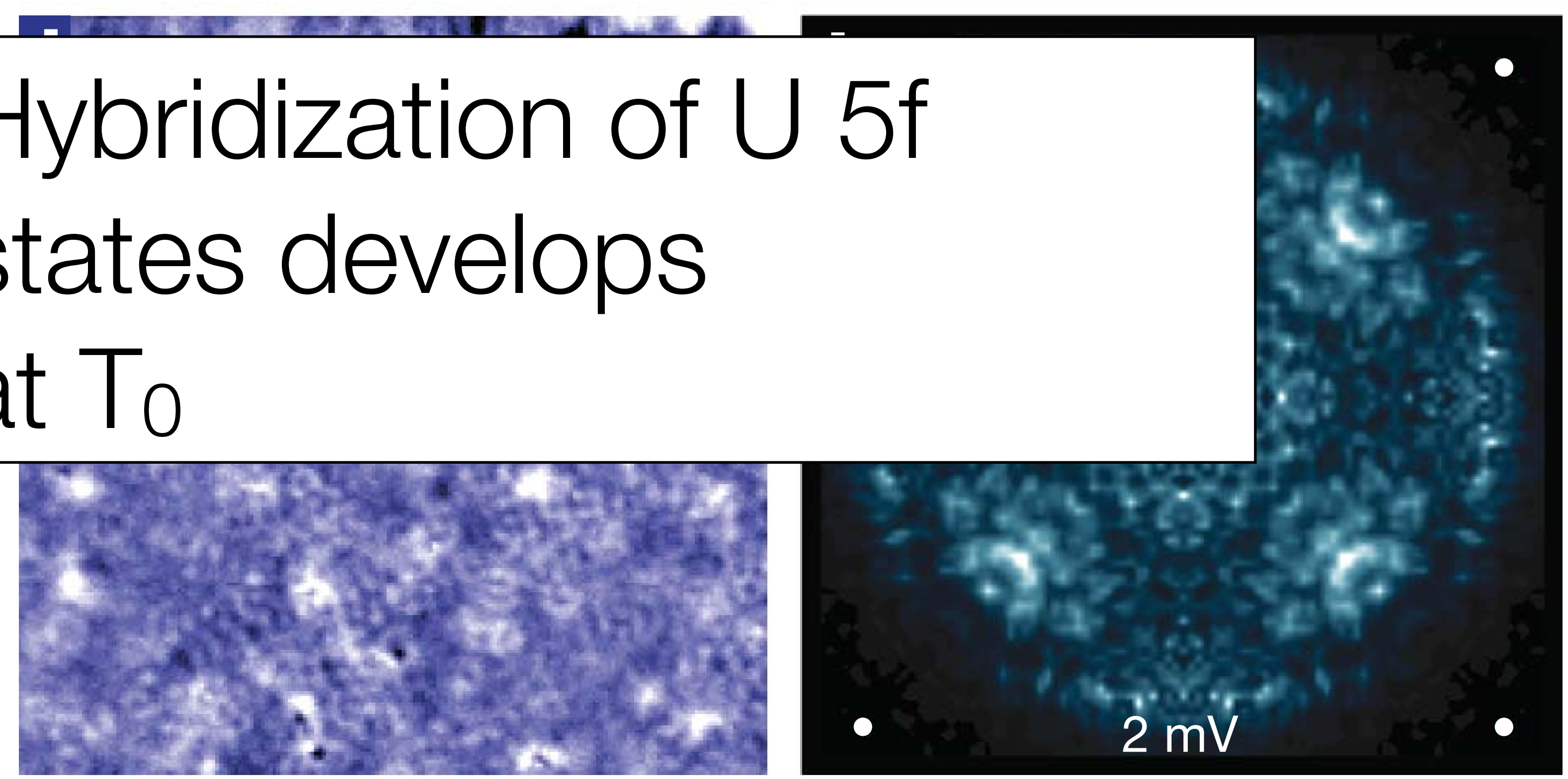

Hybridization of U 5f states develops at T_0

Quantum Oscillations: Giant Ising Anisotropy

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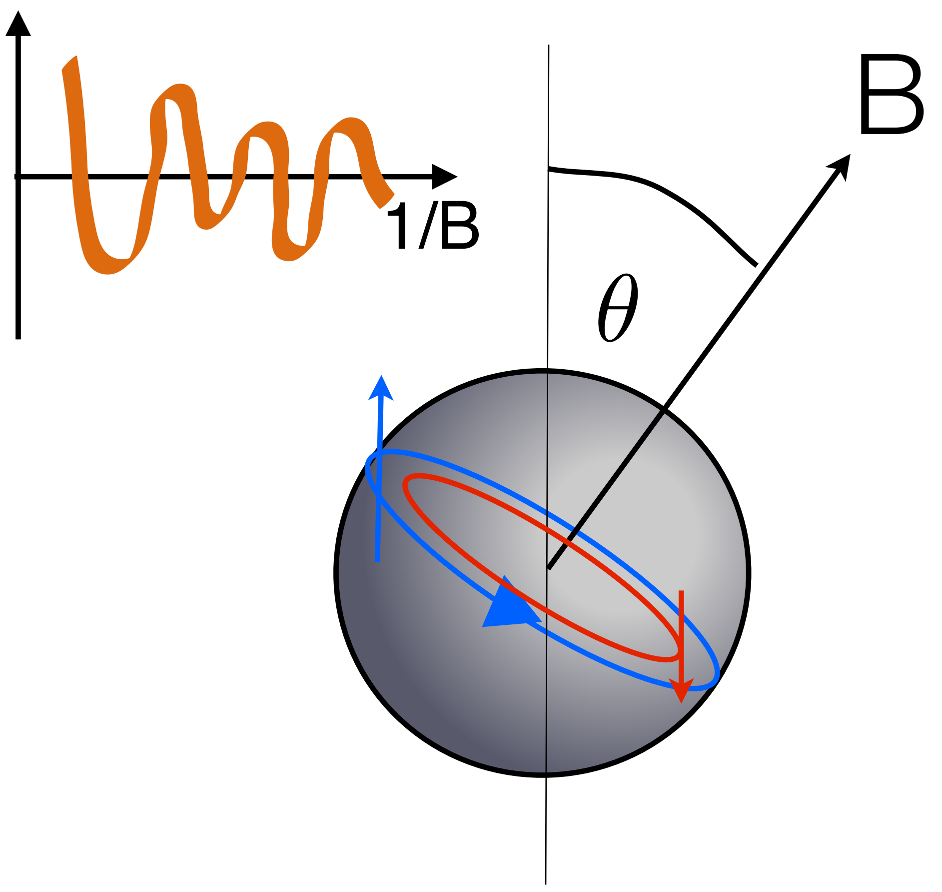

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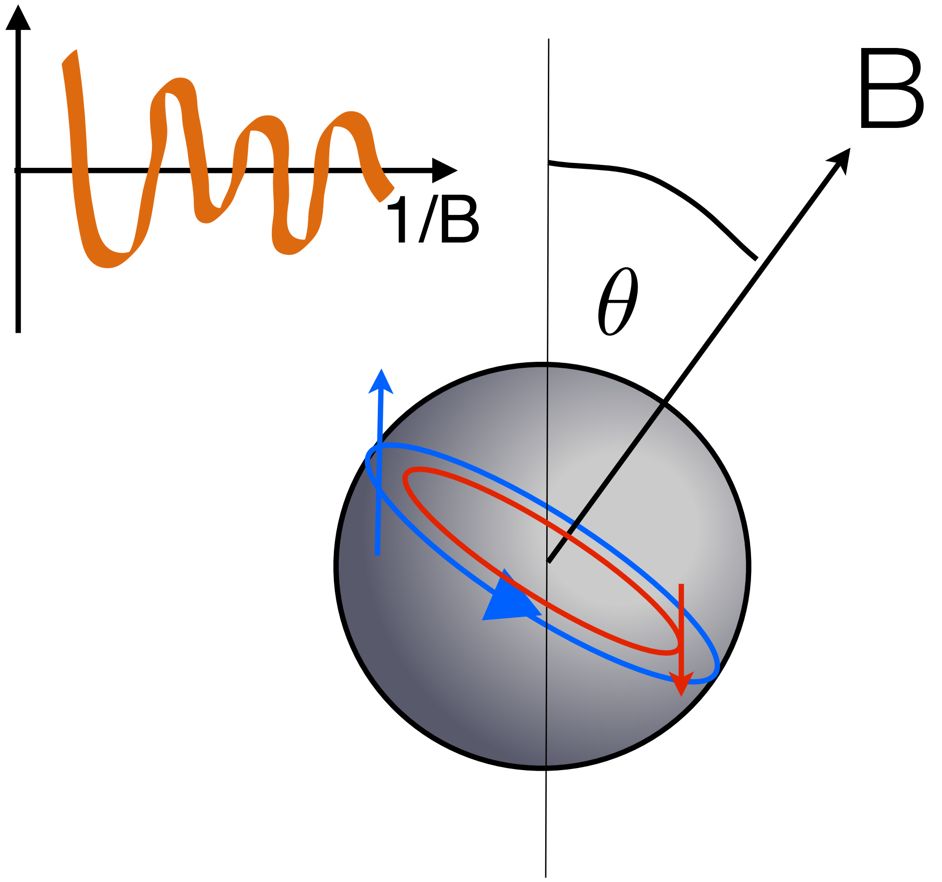
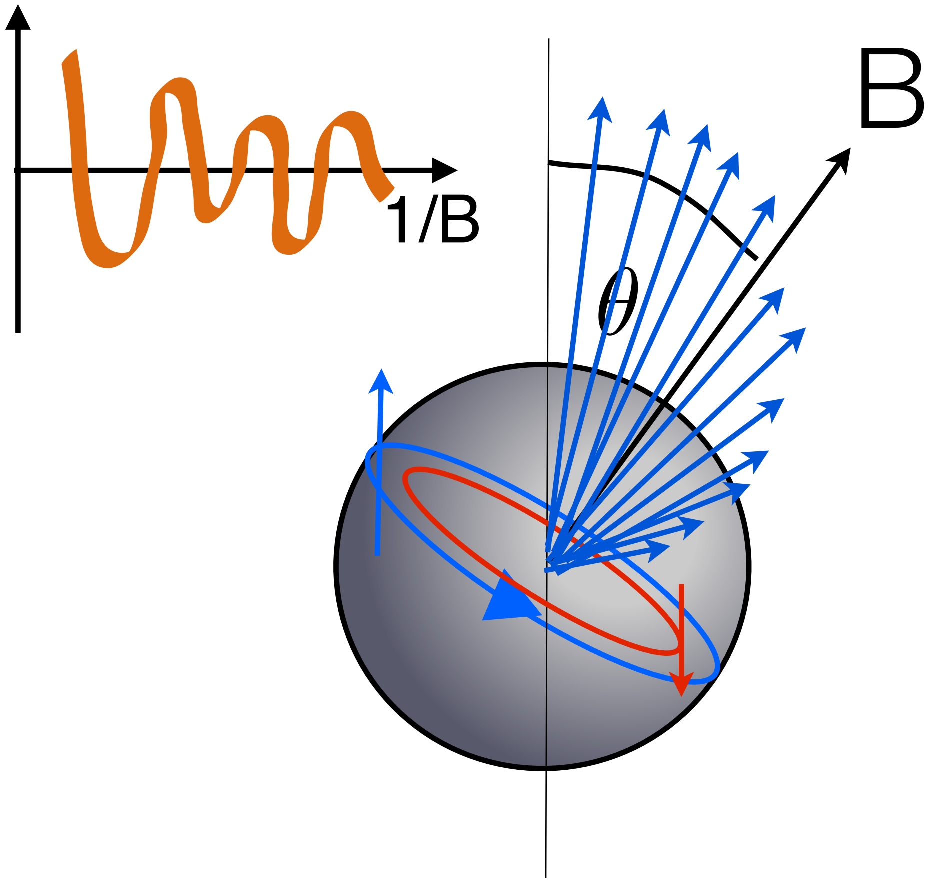


$$M \propto \cos\left[2\pi \frac{\text{Zeeman}}{\text{cyclotron}}\right]$$

$$\frac{m^*}{m_e} g(\theta) = 2n + 1$$

Spin Zero condition

Quantum Oscillations: Giant Ising Anisotropy



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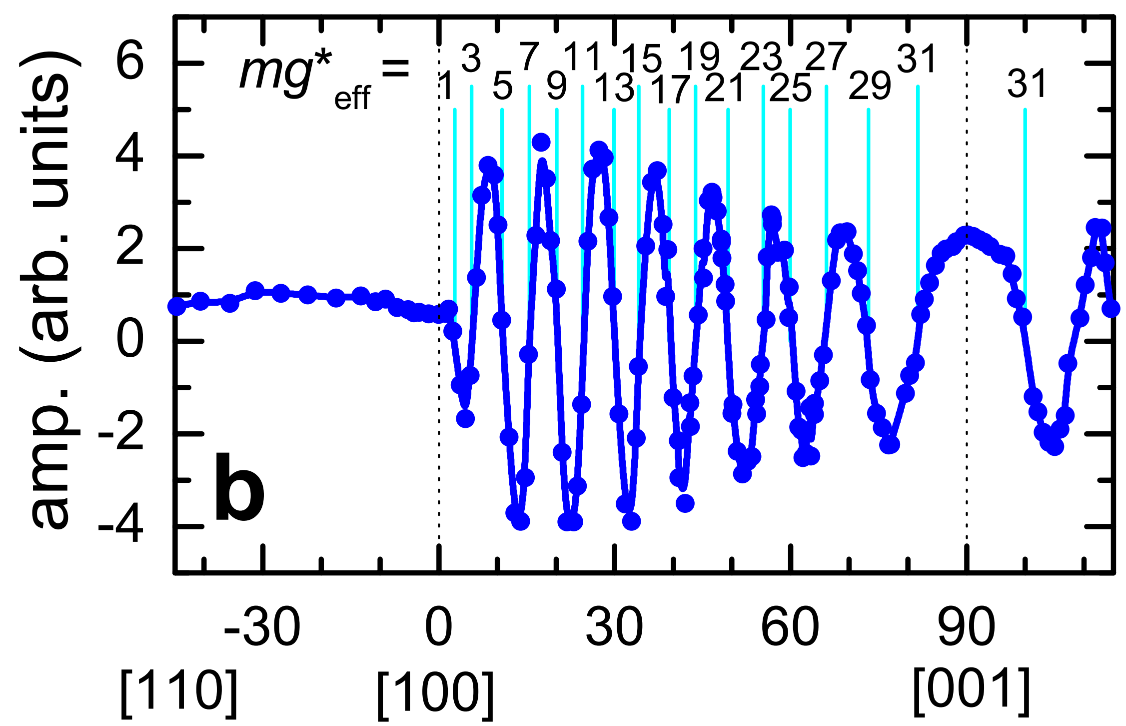
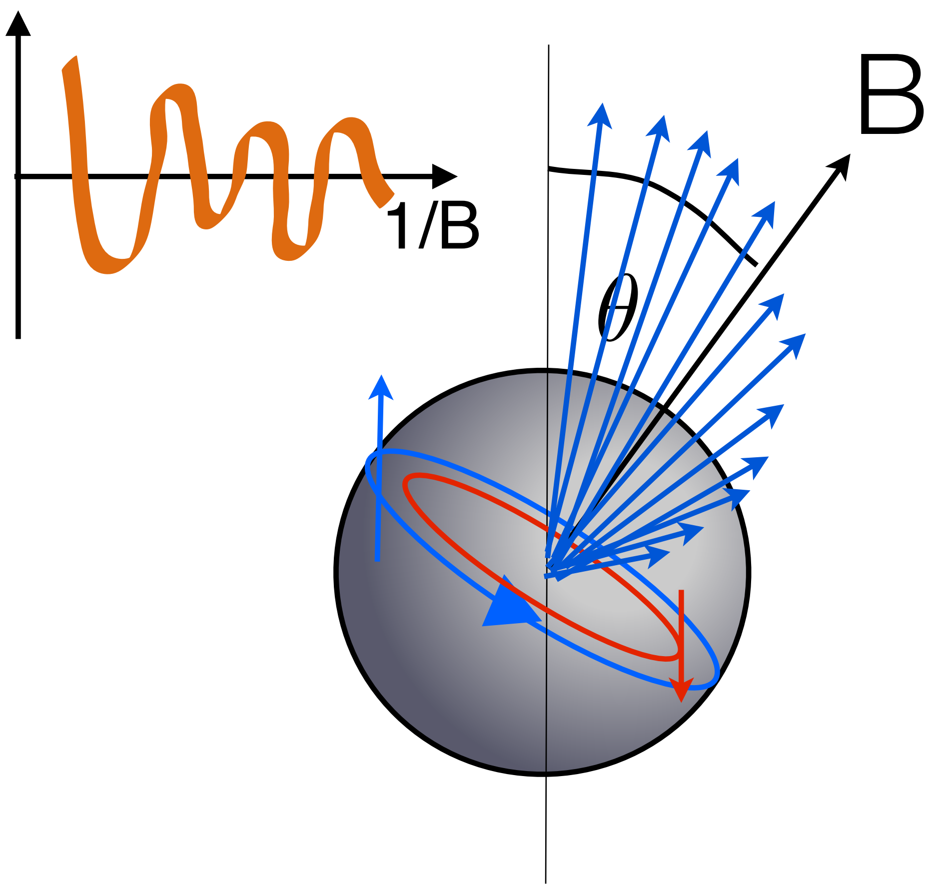
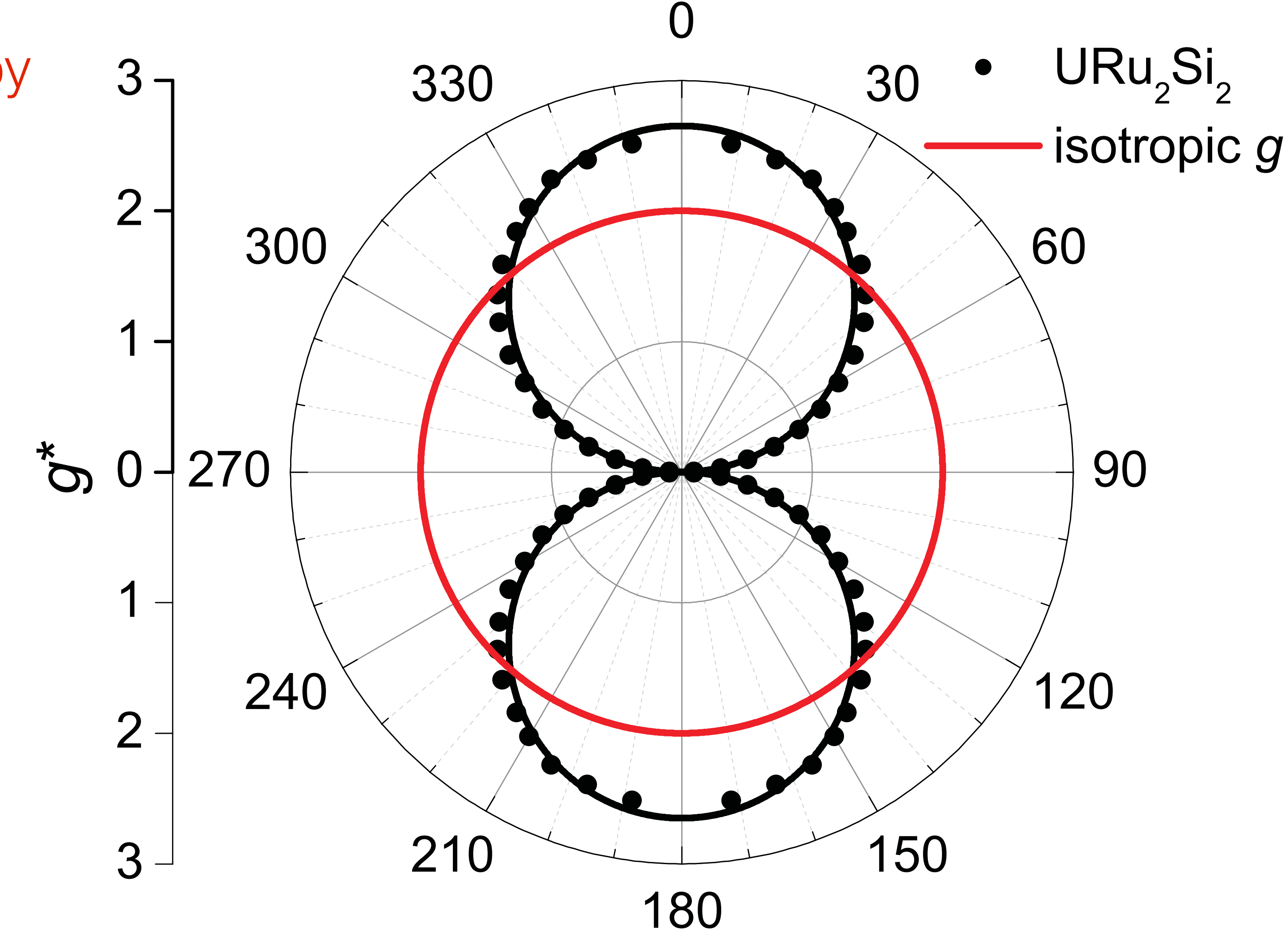


17 spin zeros!

Quantum Oscillations: Giant Ising Anisotropy





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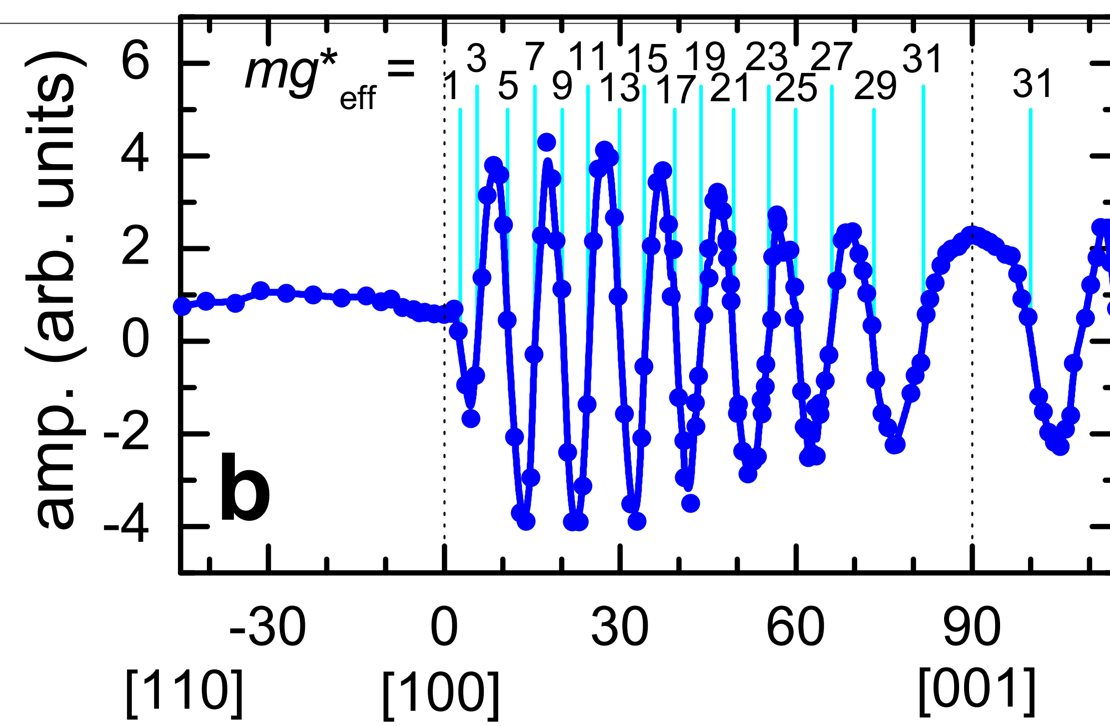

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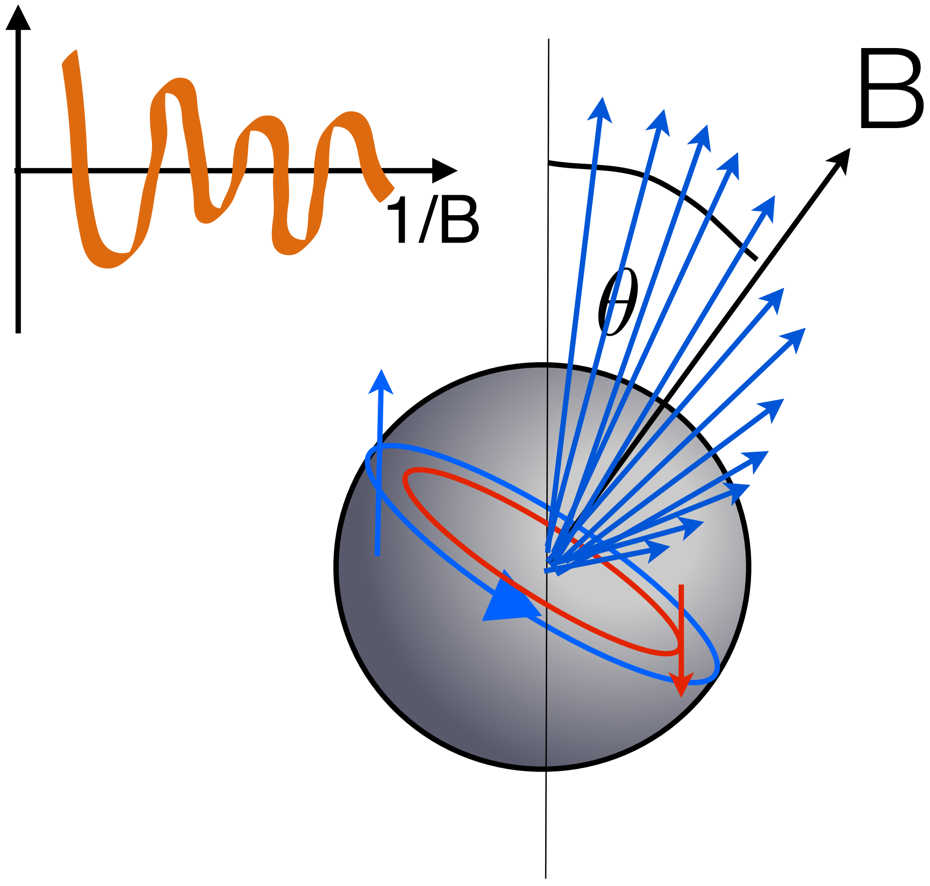

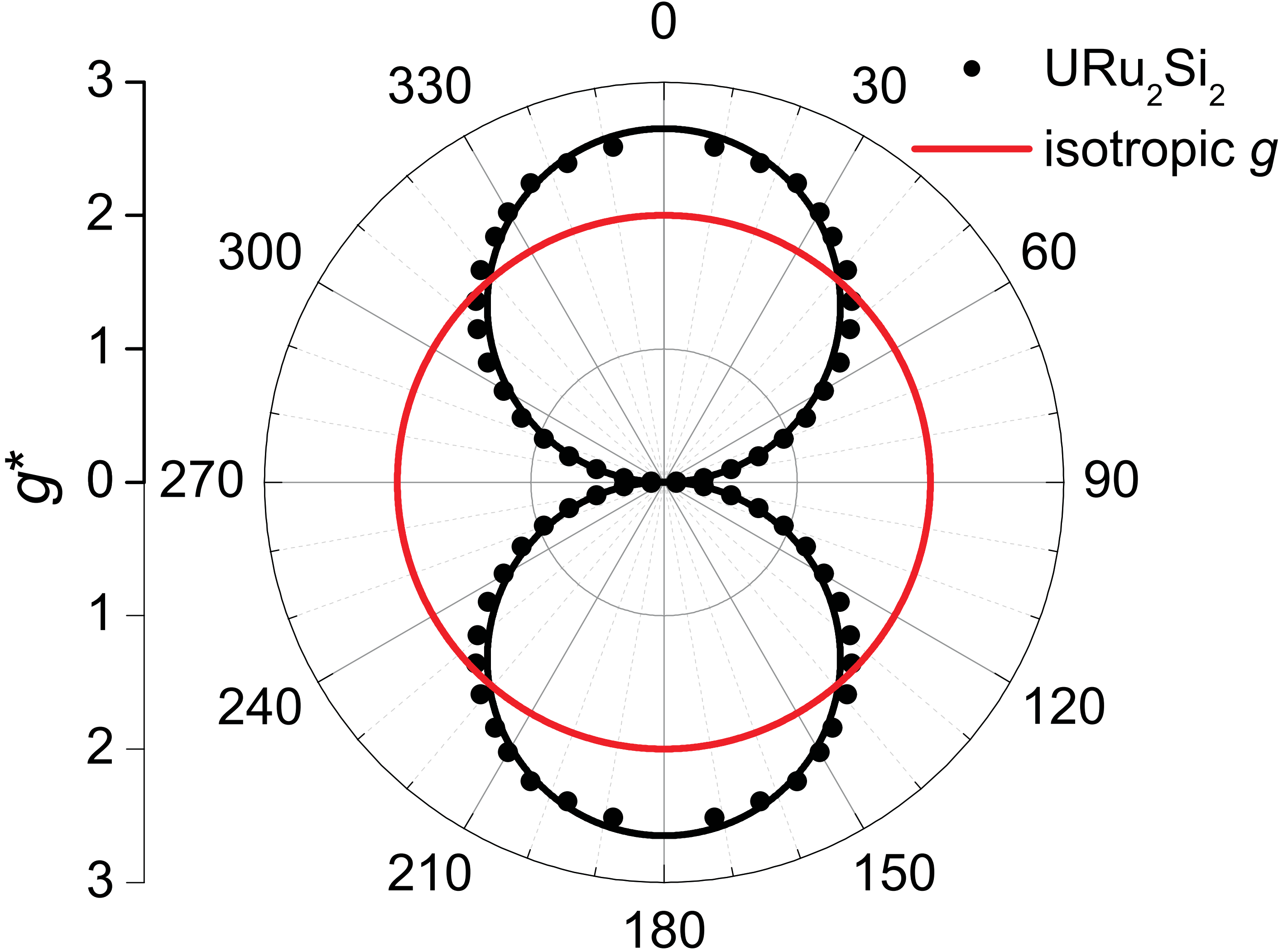

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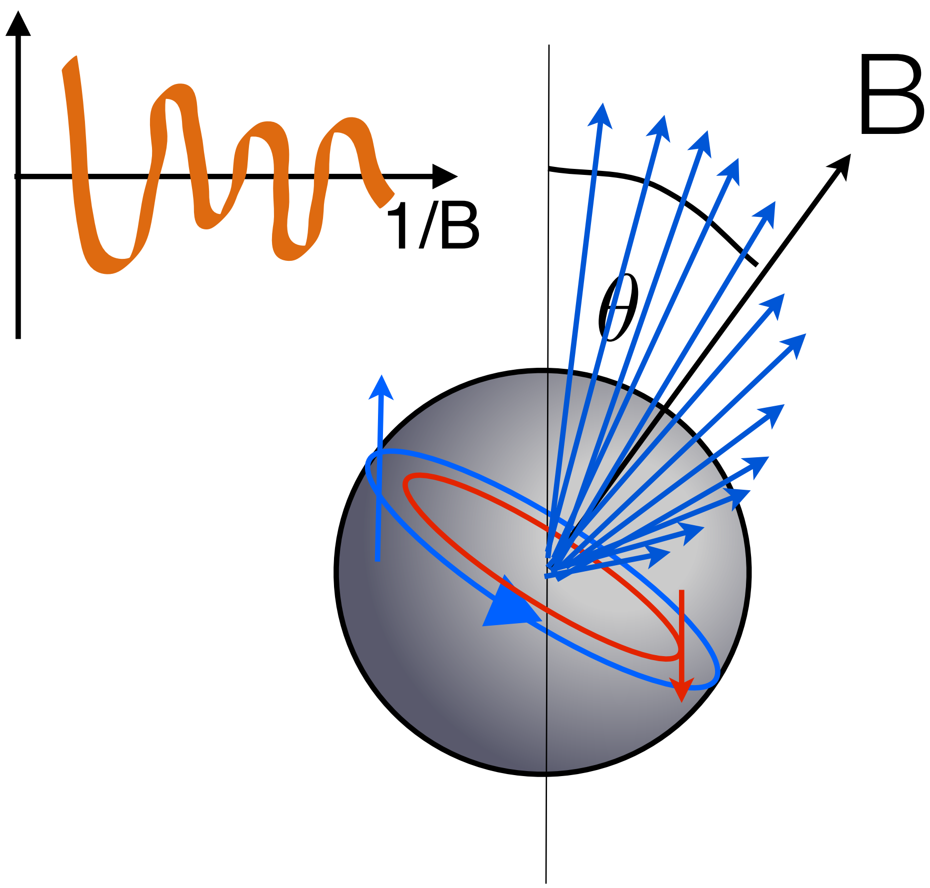
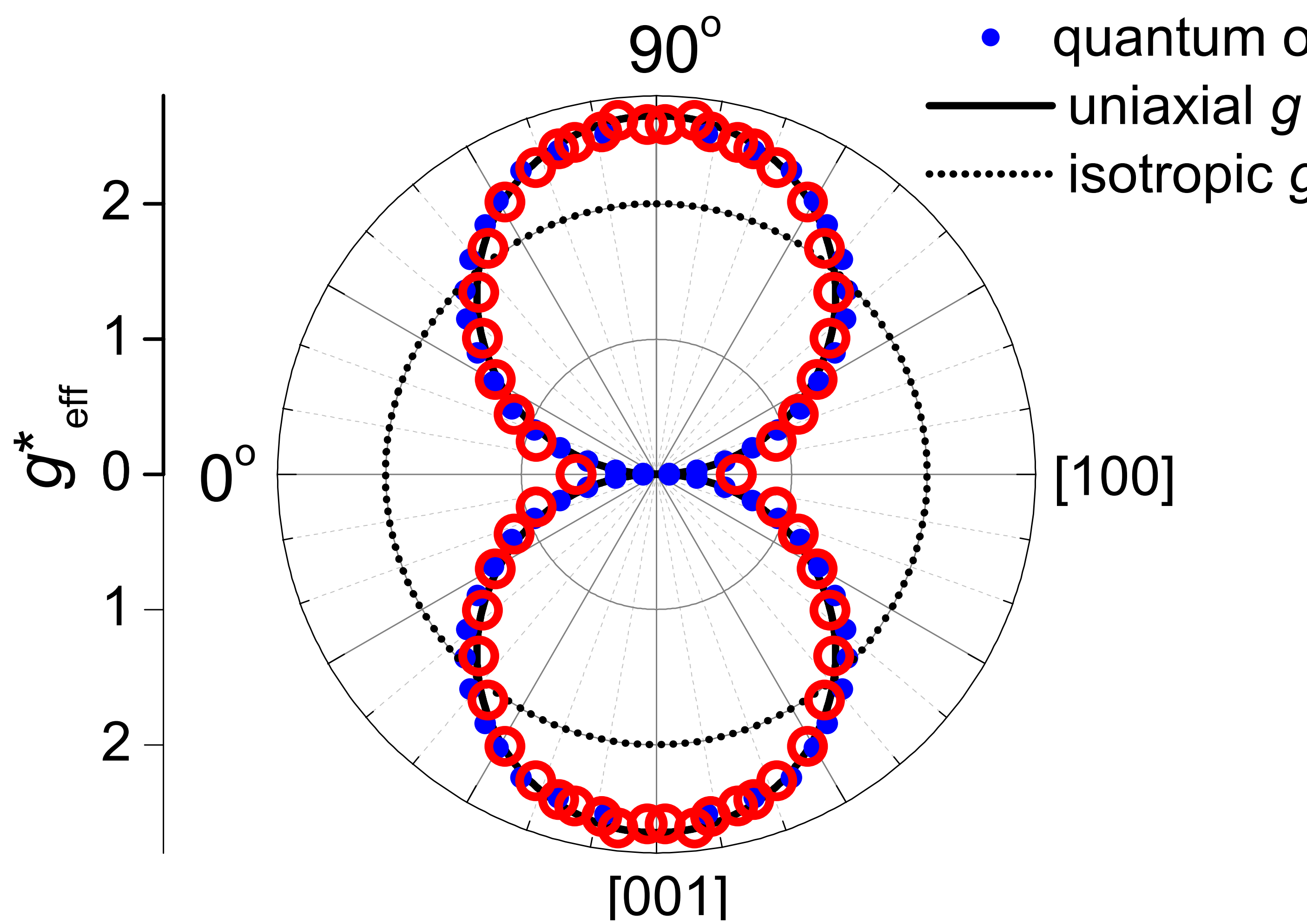
Spin Zero condition

Ising *quasiparticle* with giant anisotropy > 30.
Pauli susceptibility anisotropy > 900

17 spin zeros!

Quantum Oscillations: Giant Ising Anisotropy





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Pauli susceptibility anisotropy > 900

Confirmed from upper critical field measurements

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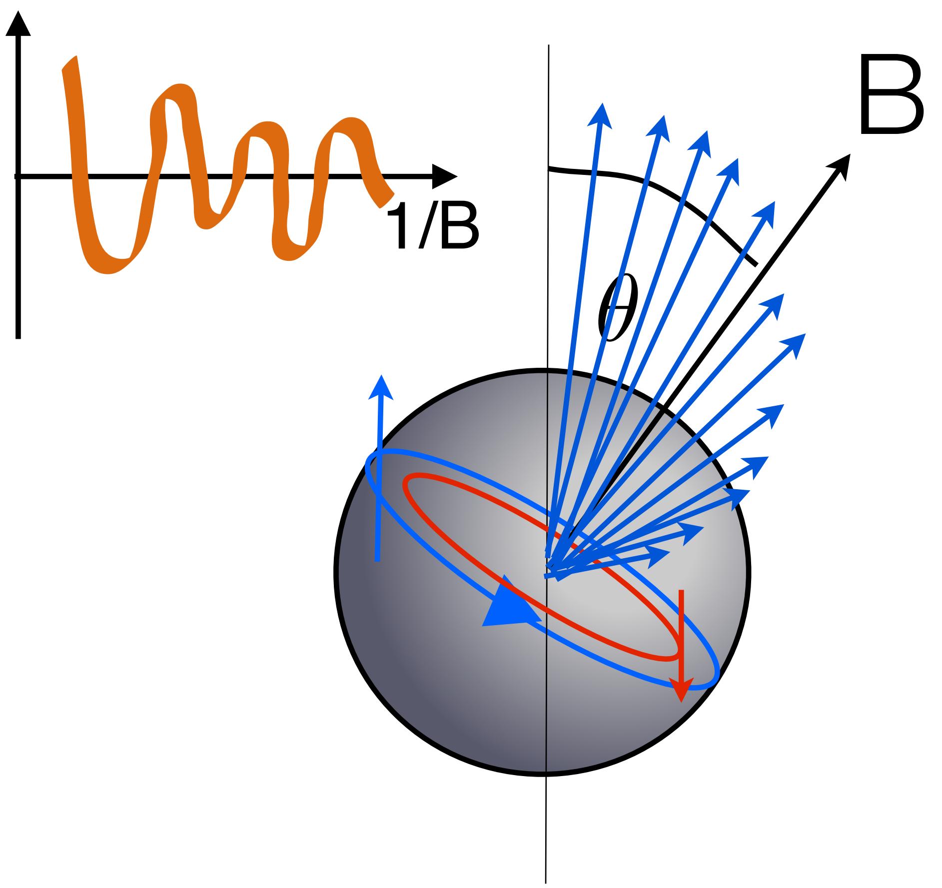

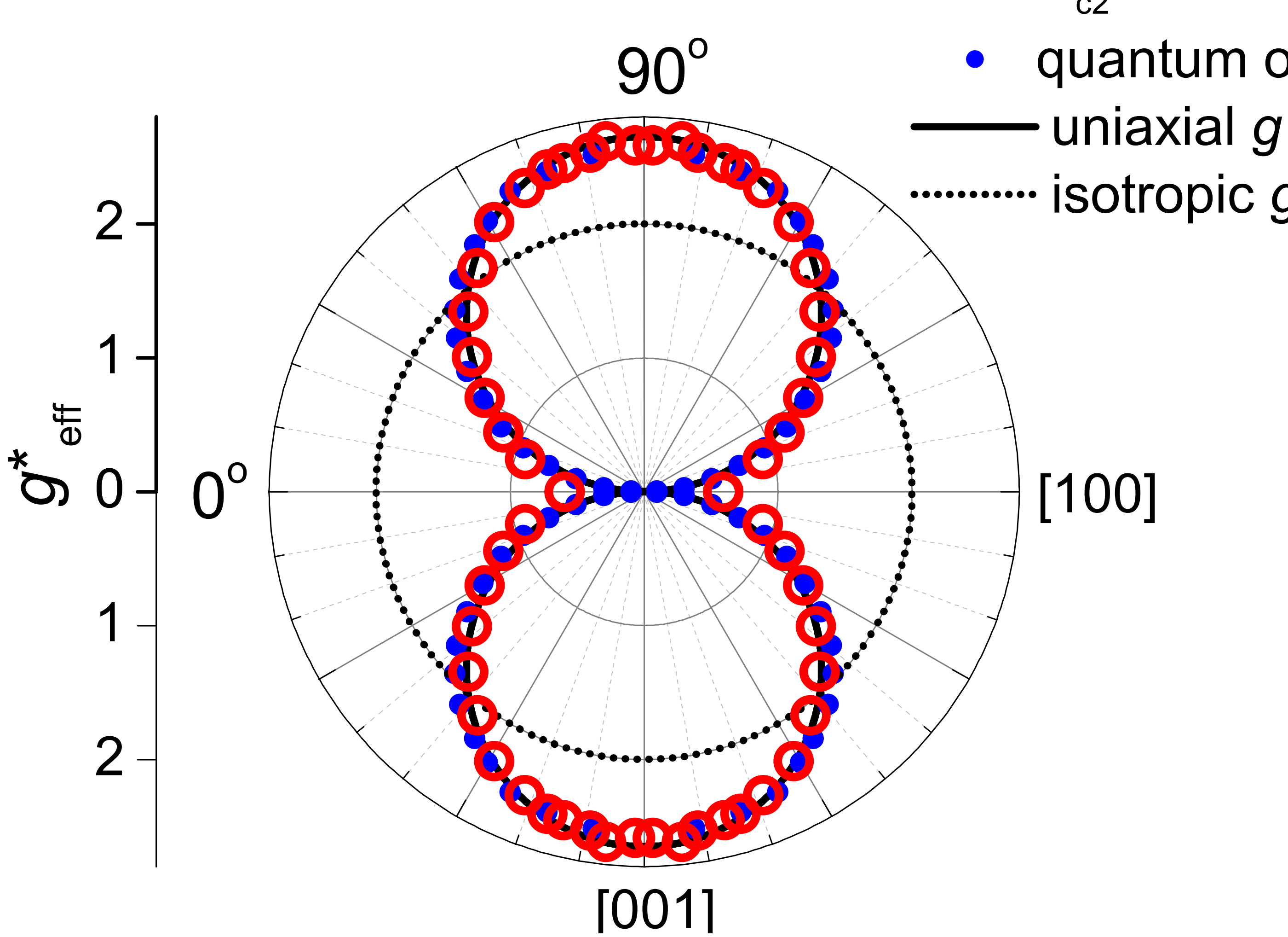

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H. Ohkuni *et al*., Phil. Mag. B 79, 1045 (1999).

$$M \propto \cos\left[2\pi\frac{\text{Zeeman}}{\text{cyclotron}}\right]$$

$$\frac{m^*}{m_e}g(\theta) = 2n+1$$

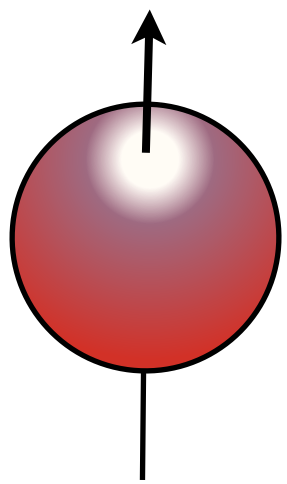
Spin Zero condition

Ising *quasiparticle* with giant anisotropy > 30.
Pauli susceptibility anisotropy > 900

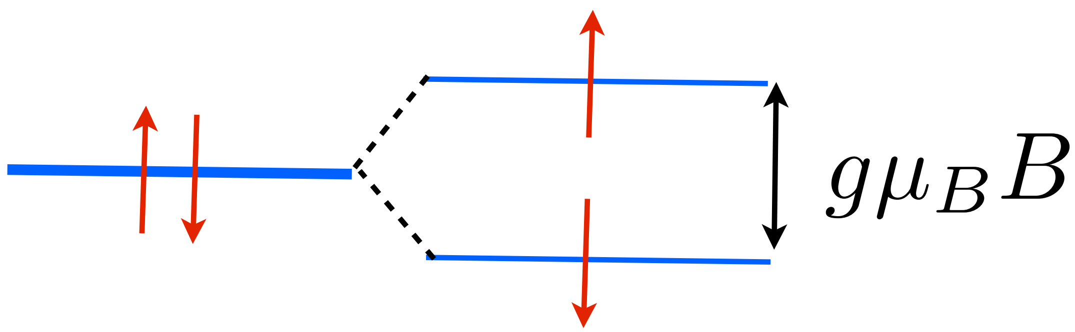
Confirmed from upper critical field measurements

Electrons hybridize with Ising 5f state to form Heavy Ising quasiparticles.

Strange electron spin of URu_2Si_2



electron spin



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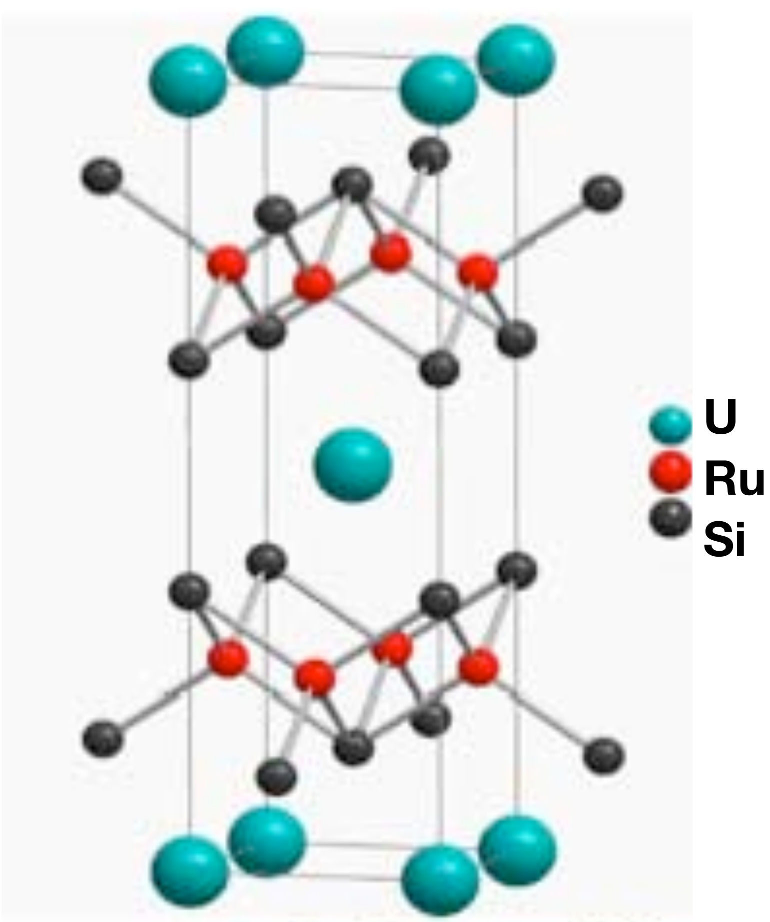

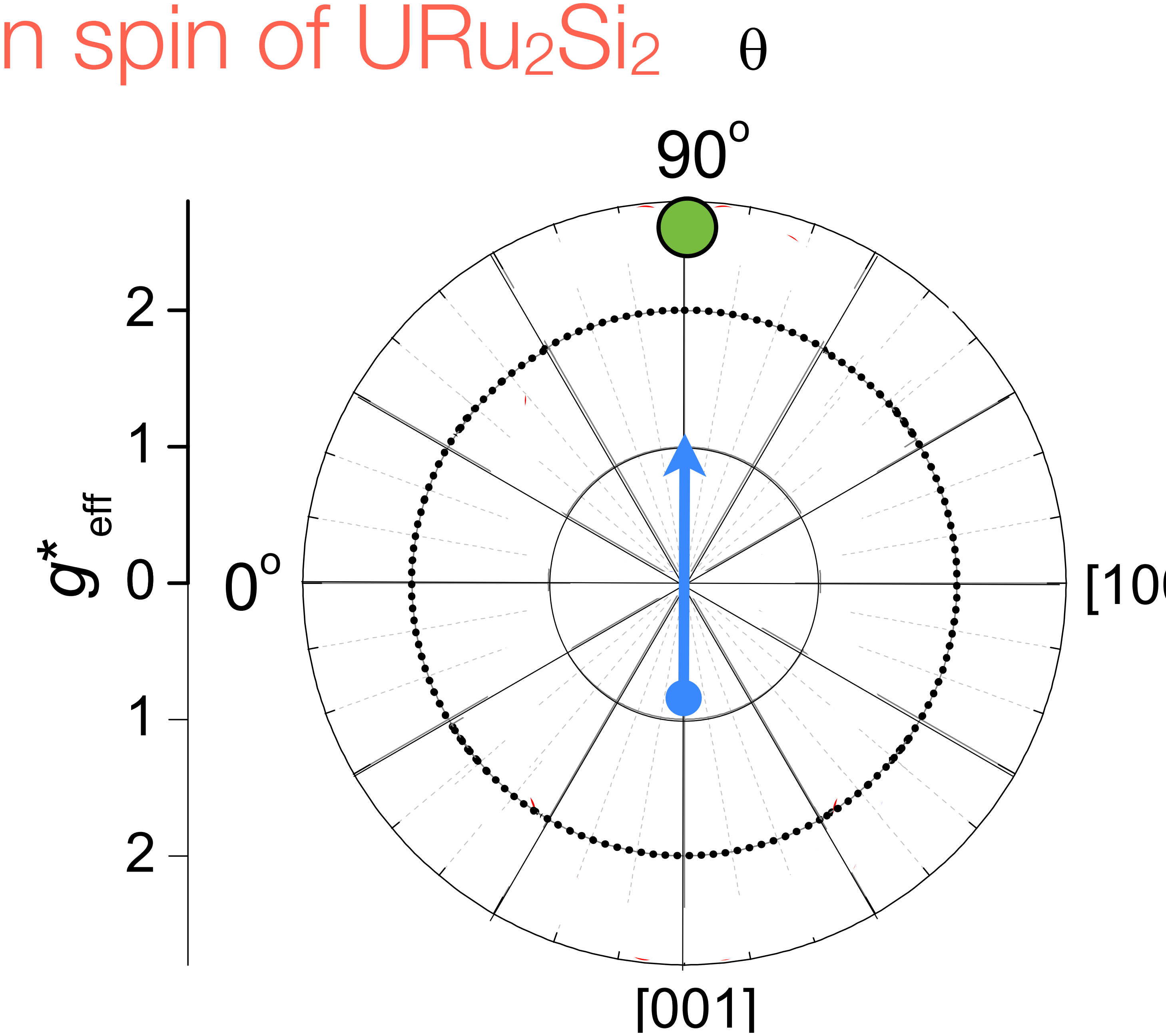

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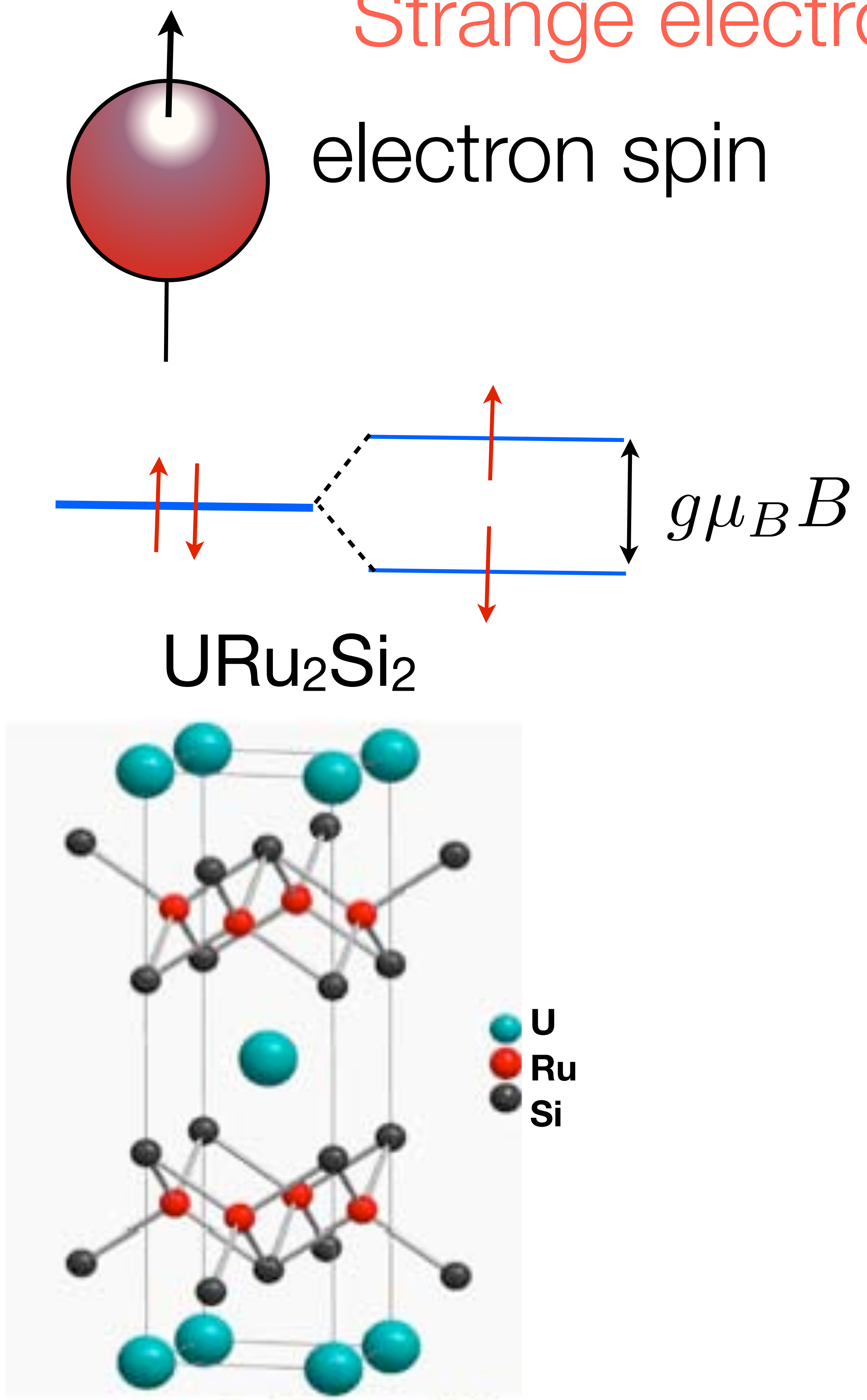

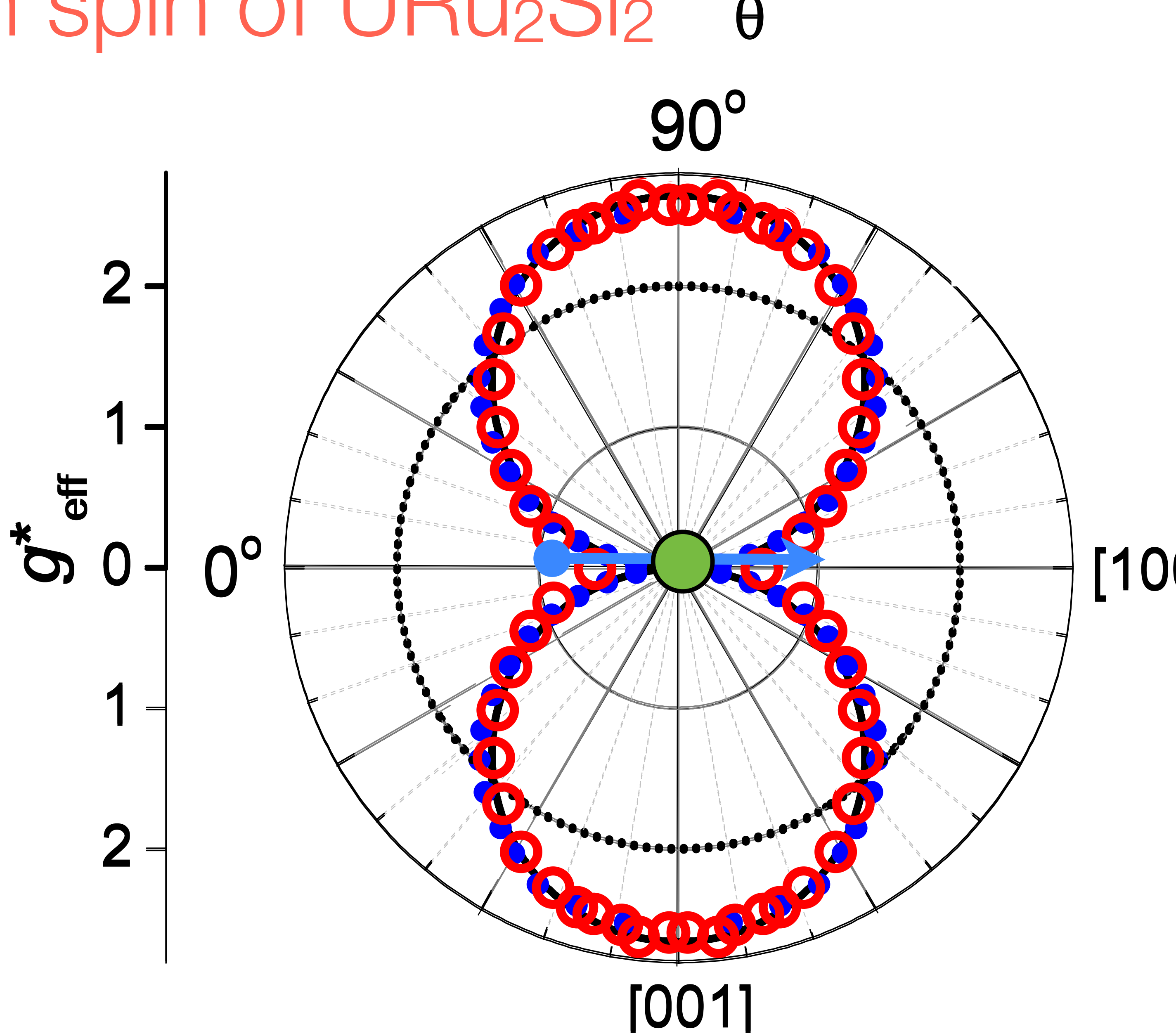

No splitting in transverse direction

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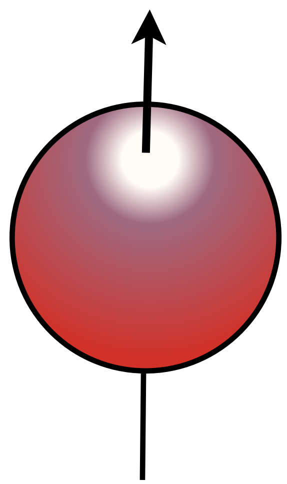

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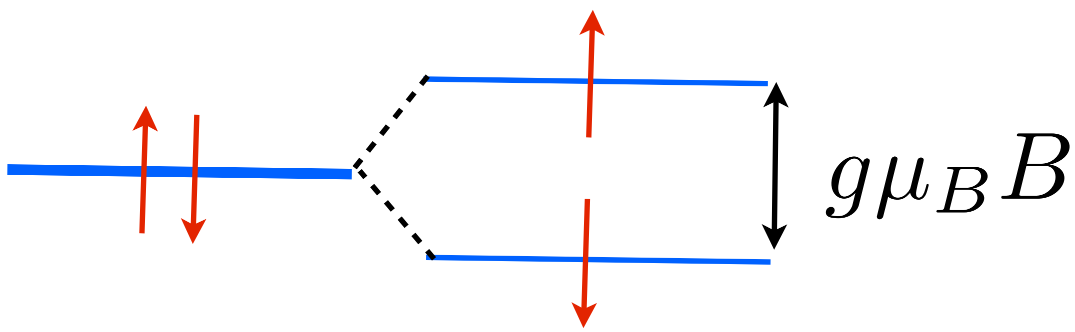

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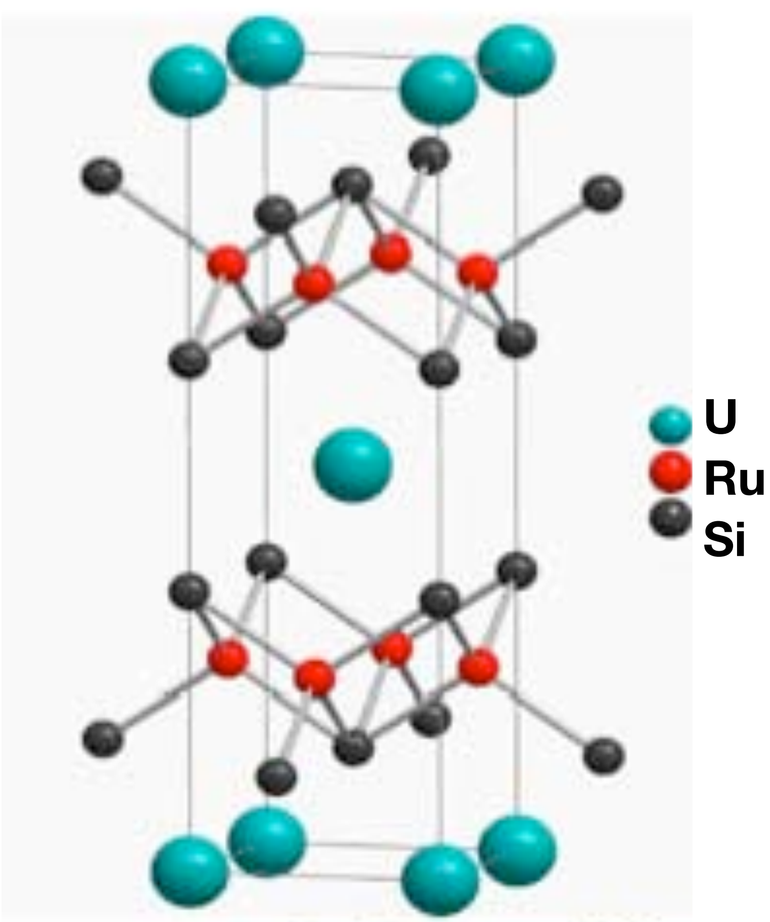
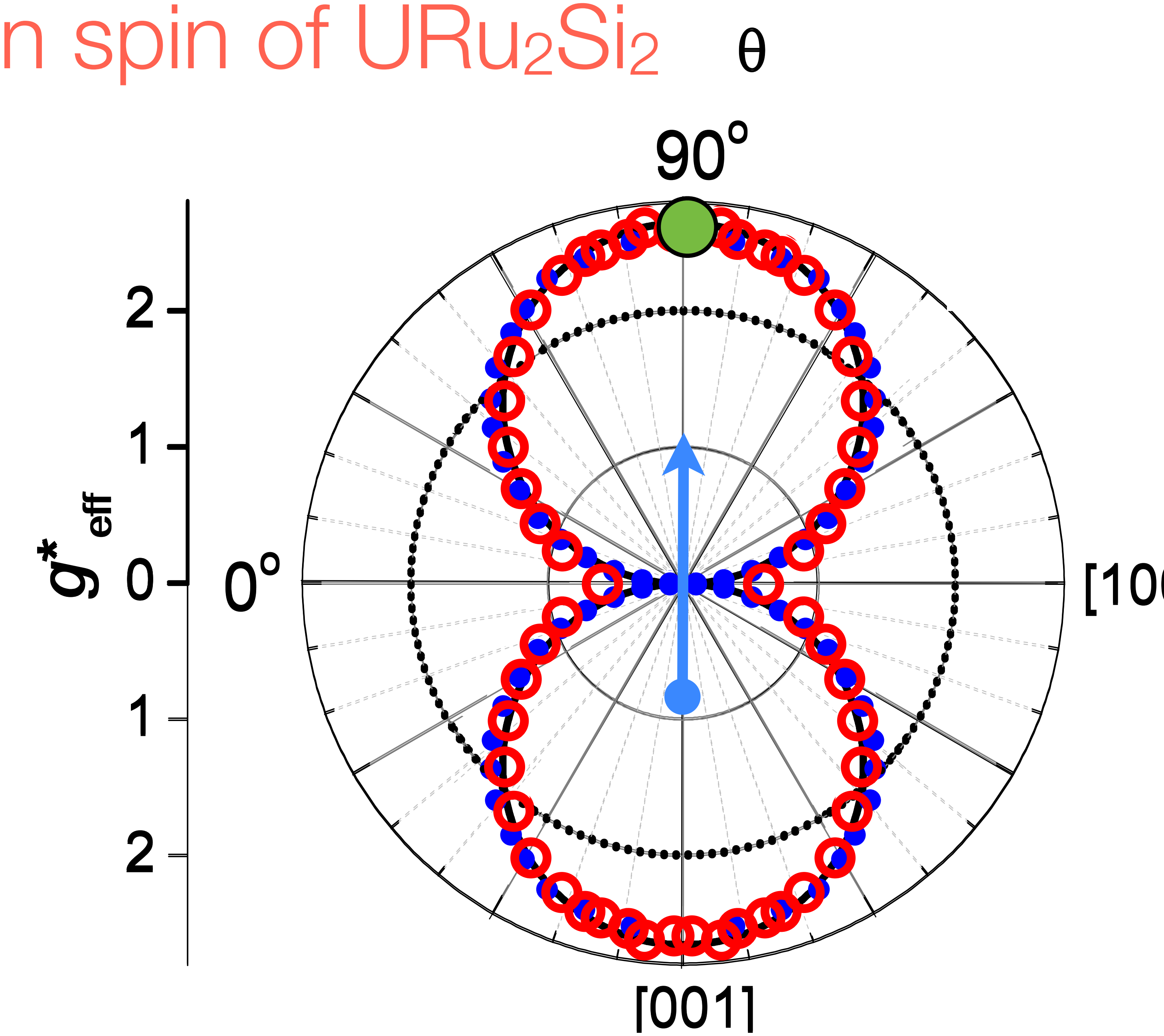


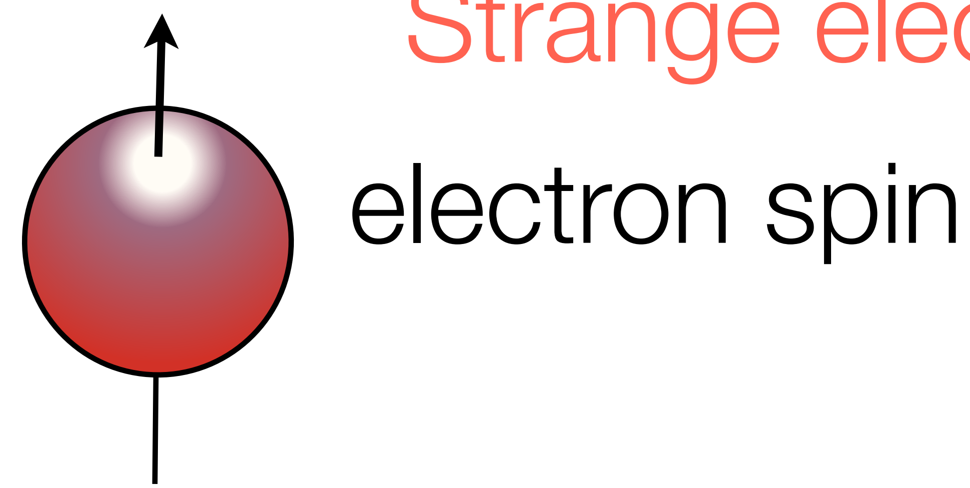


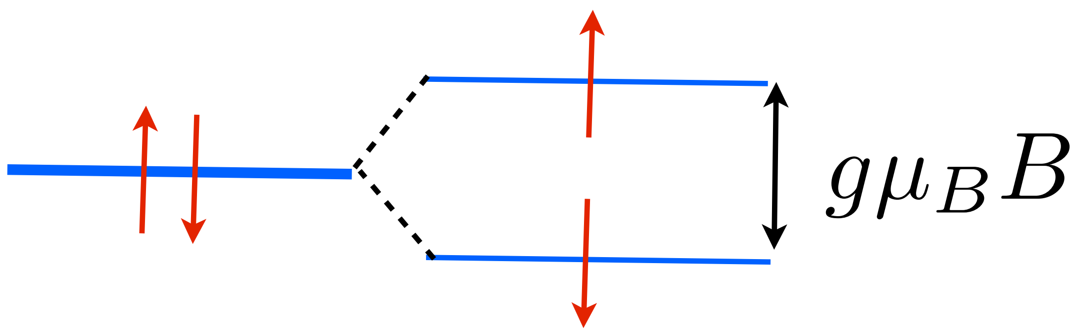
No splitting in transverse direction

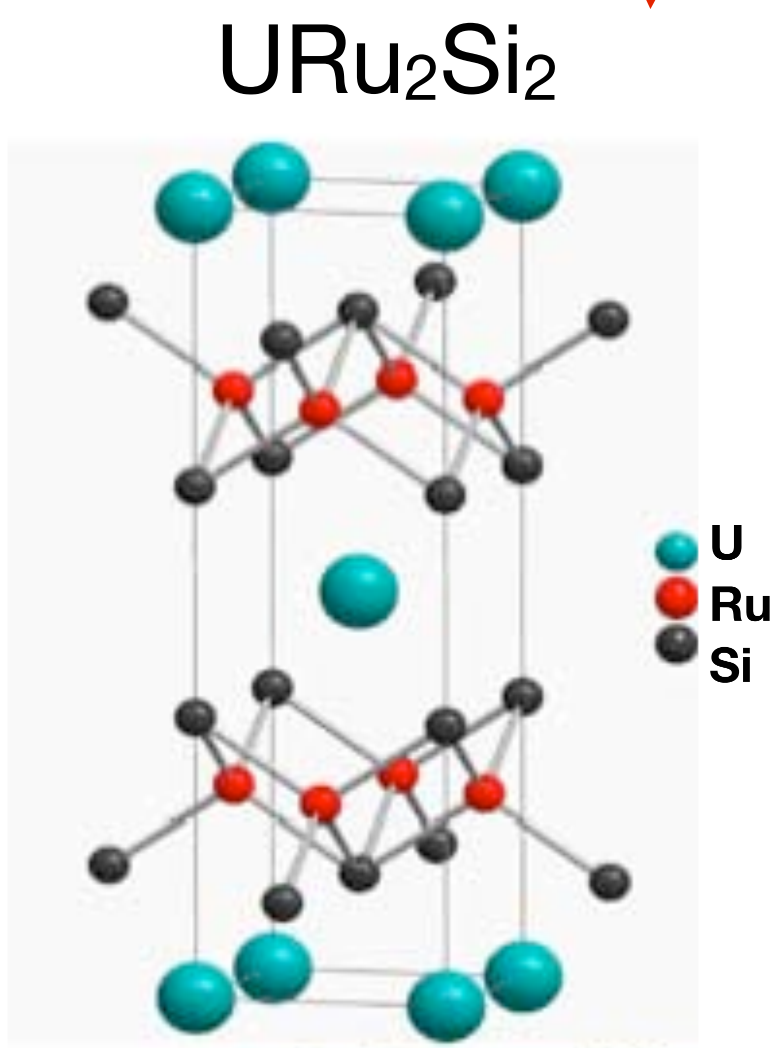
$$M = g\mu_B \cos\theta = M_z$$

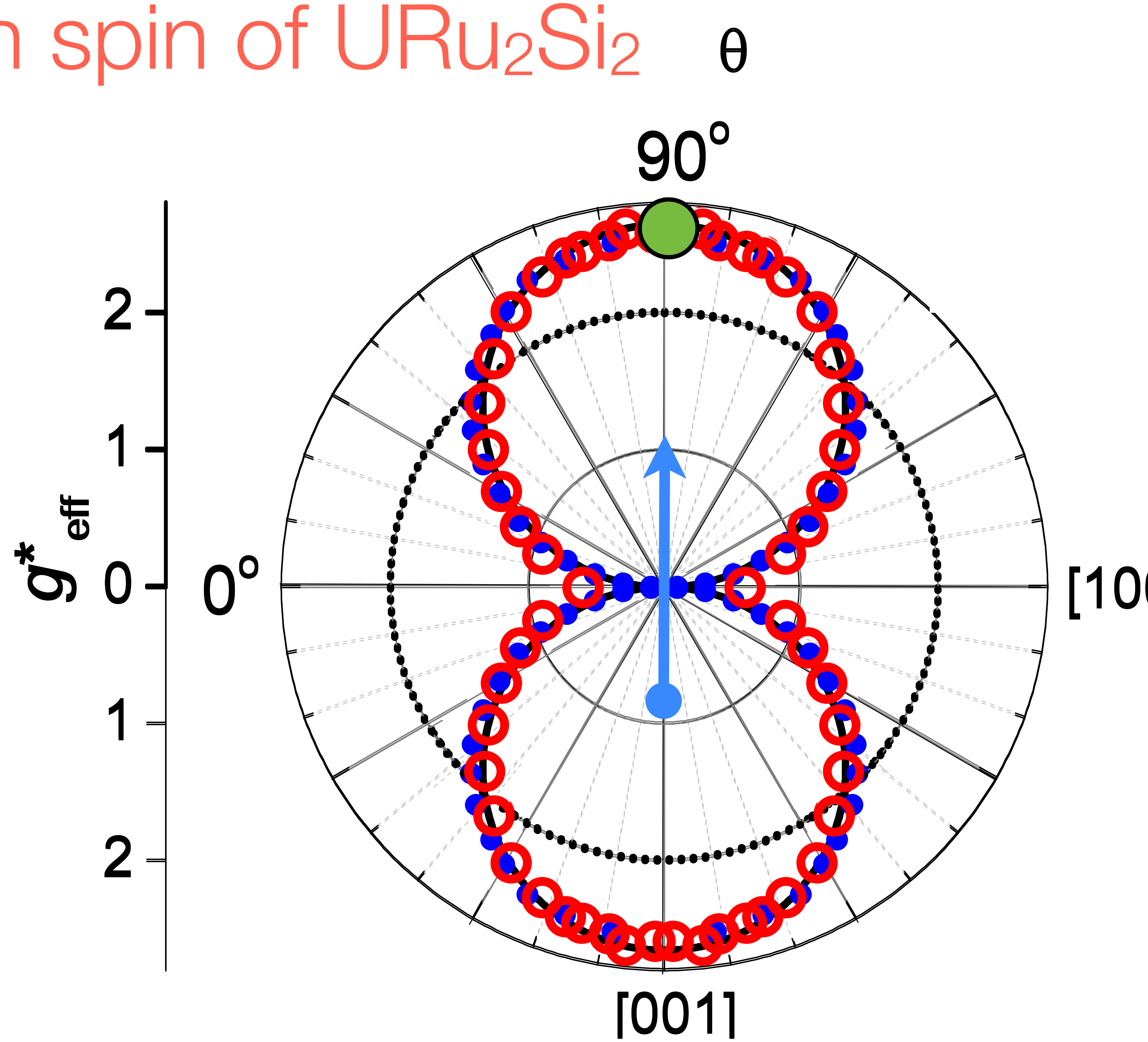
Magnetic moment only along z-axis

Strange electron spin of URu_2Si_2









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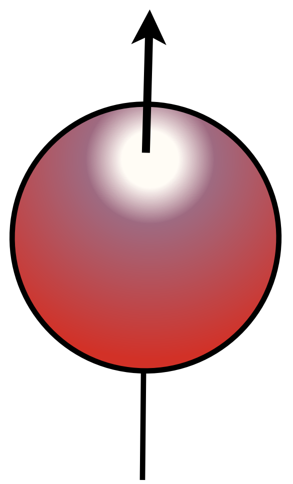

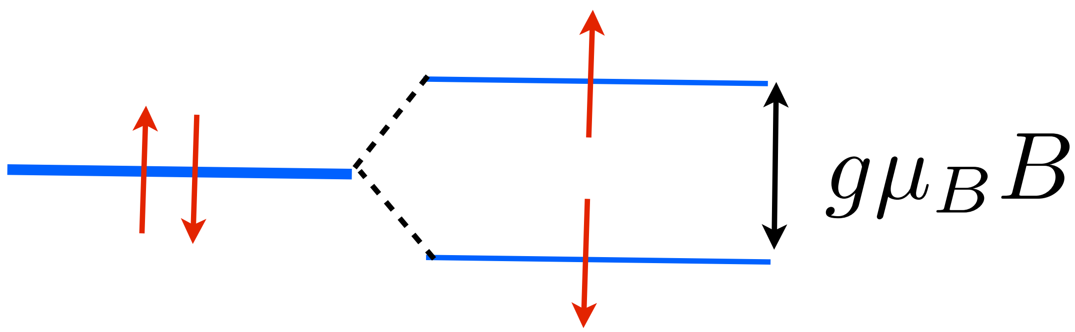

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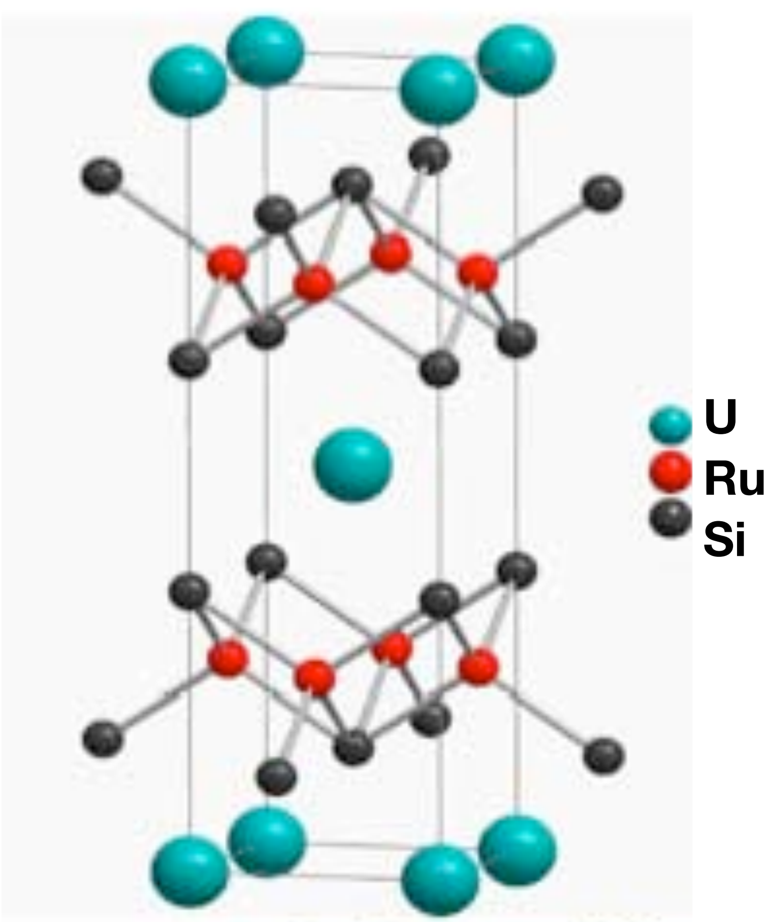

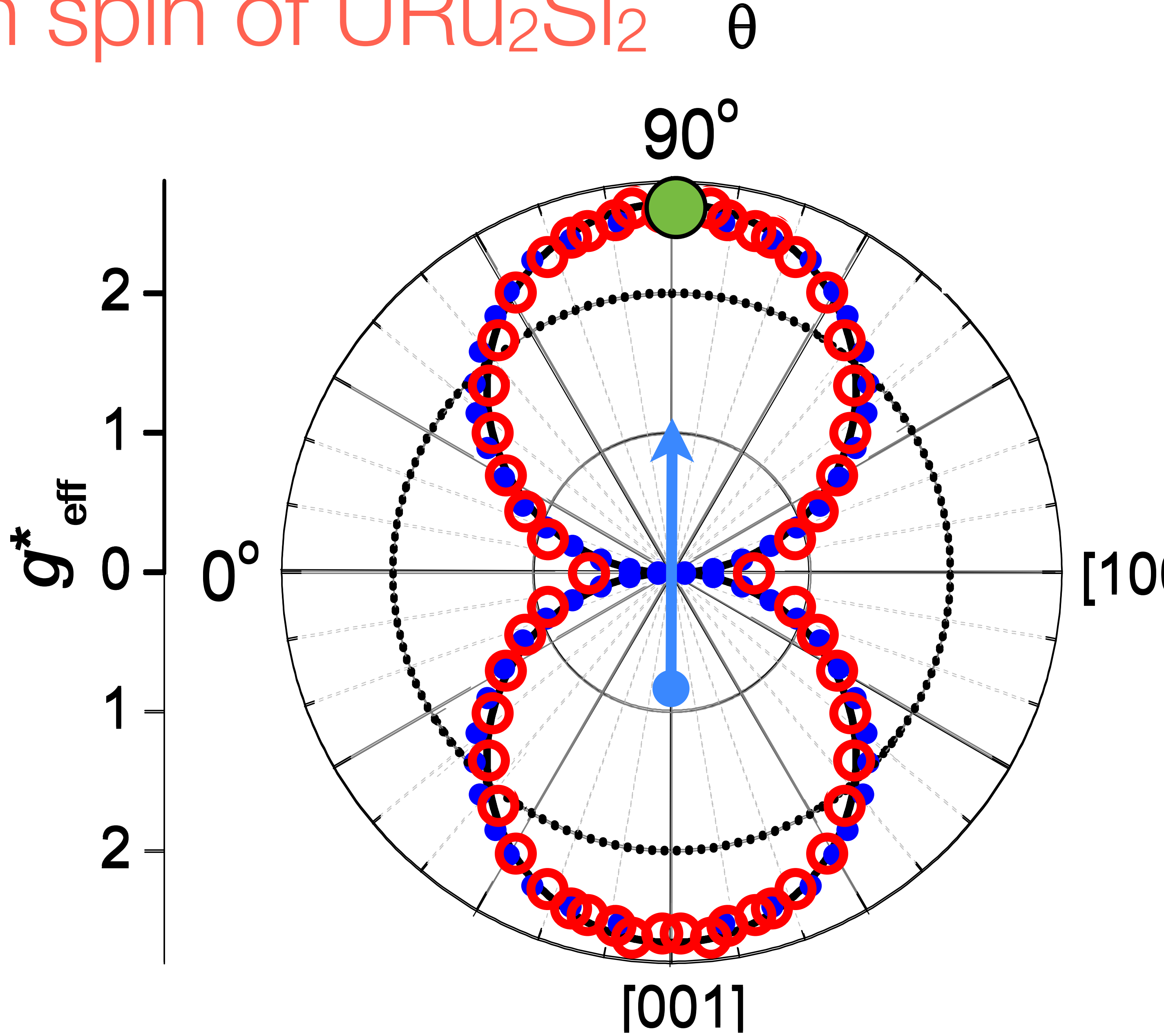

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S~integer?

URu_2Si_2: Electronic Polaroid

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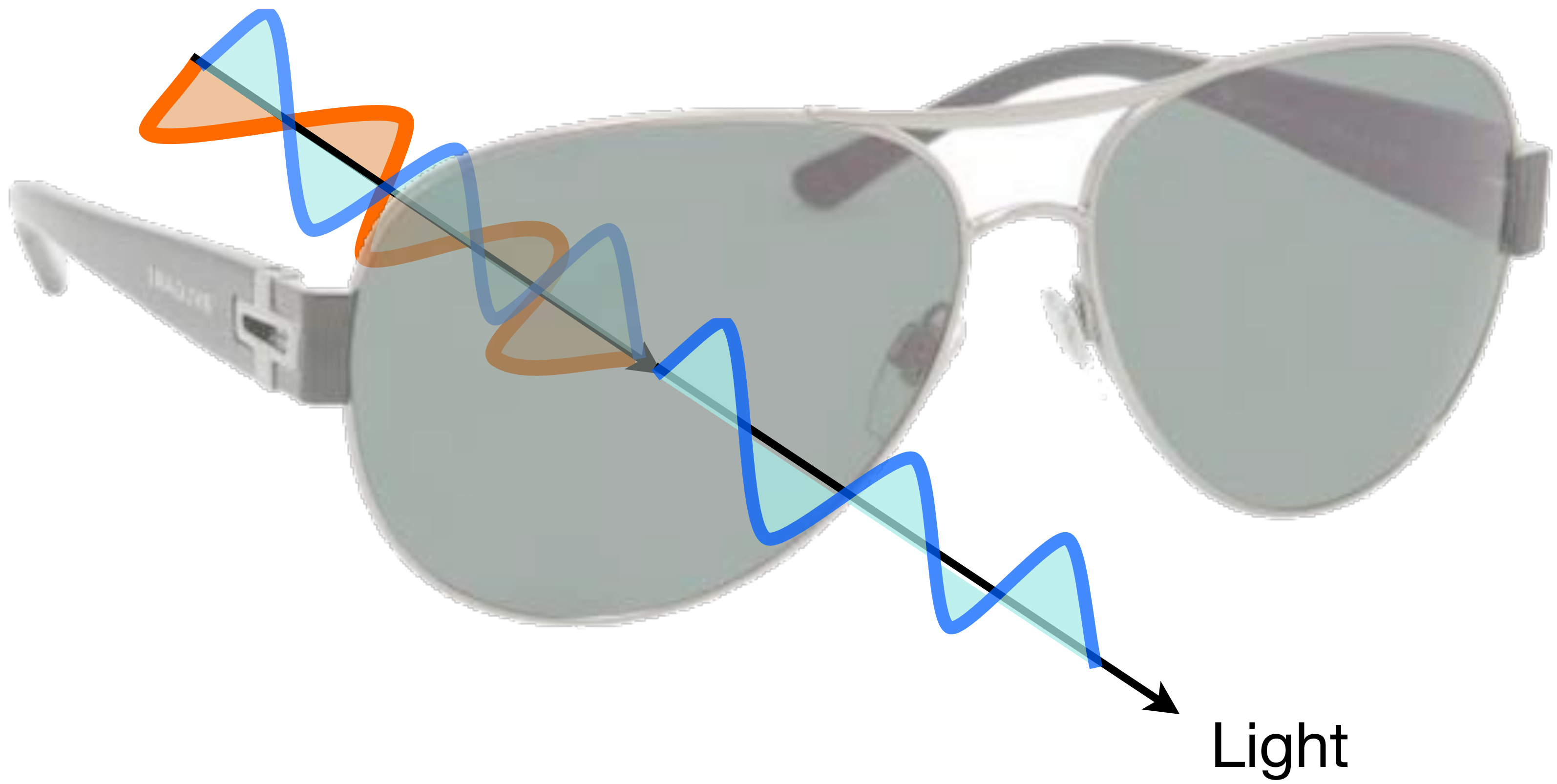

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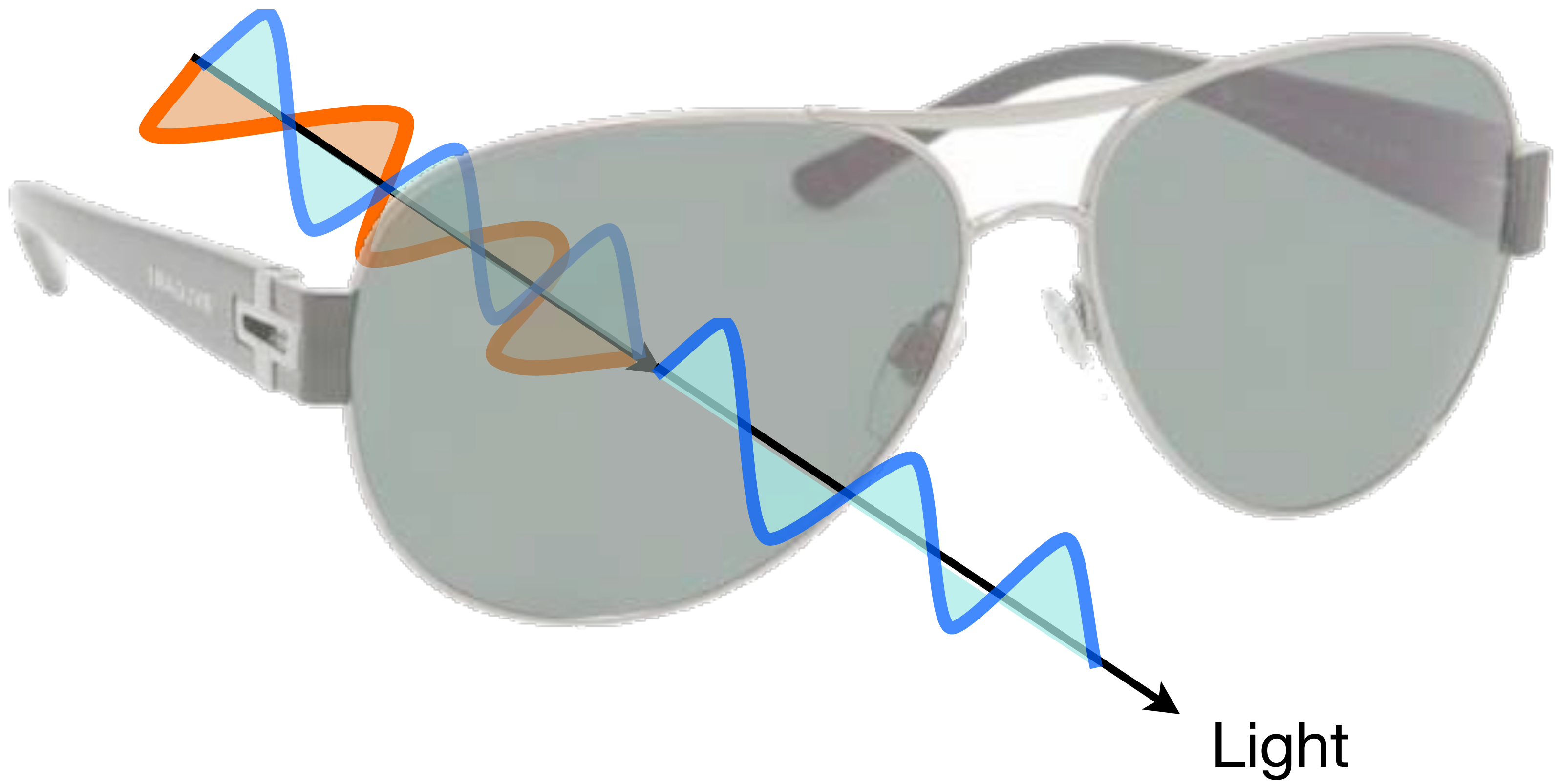

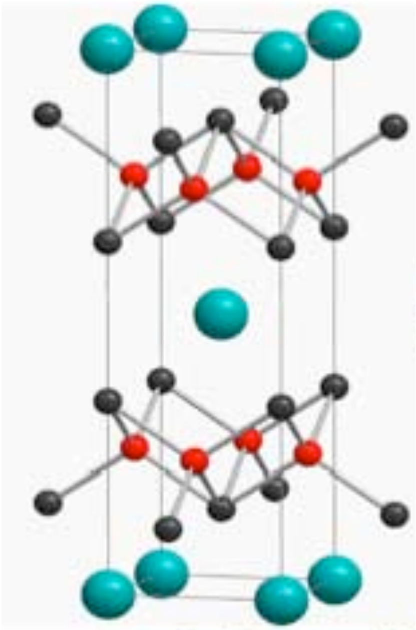

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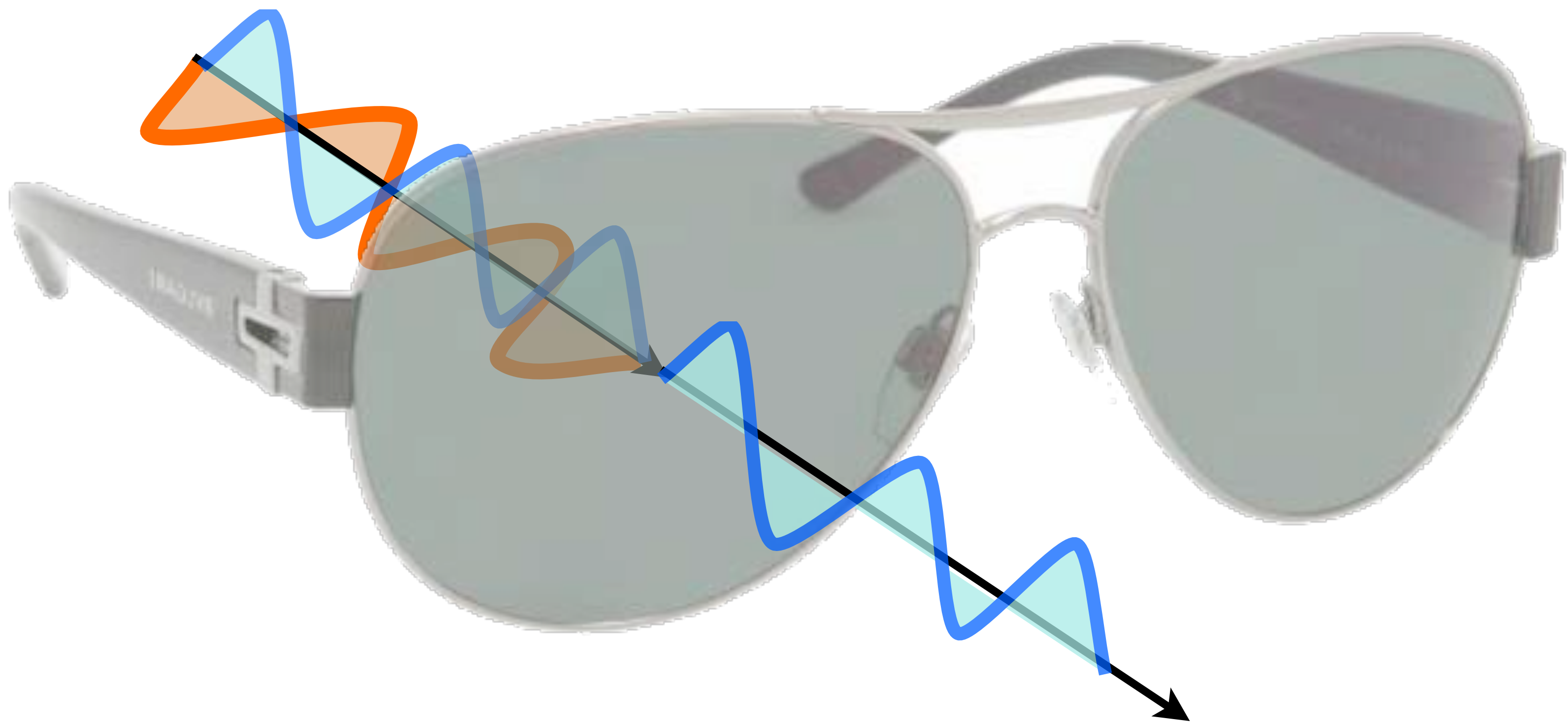

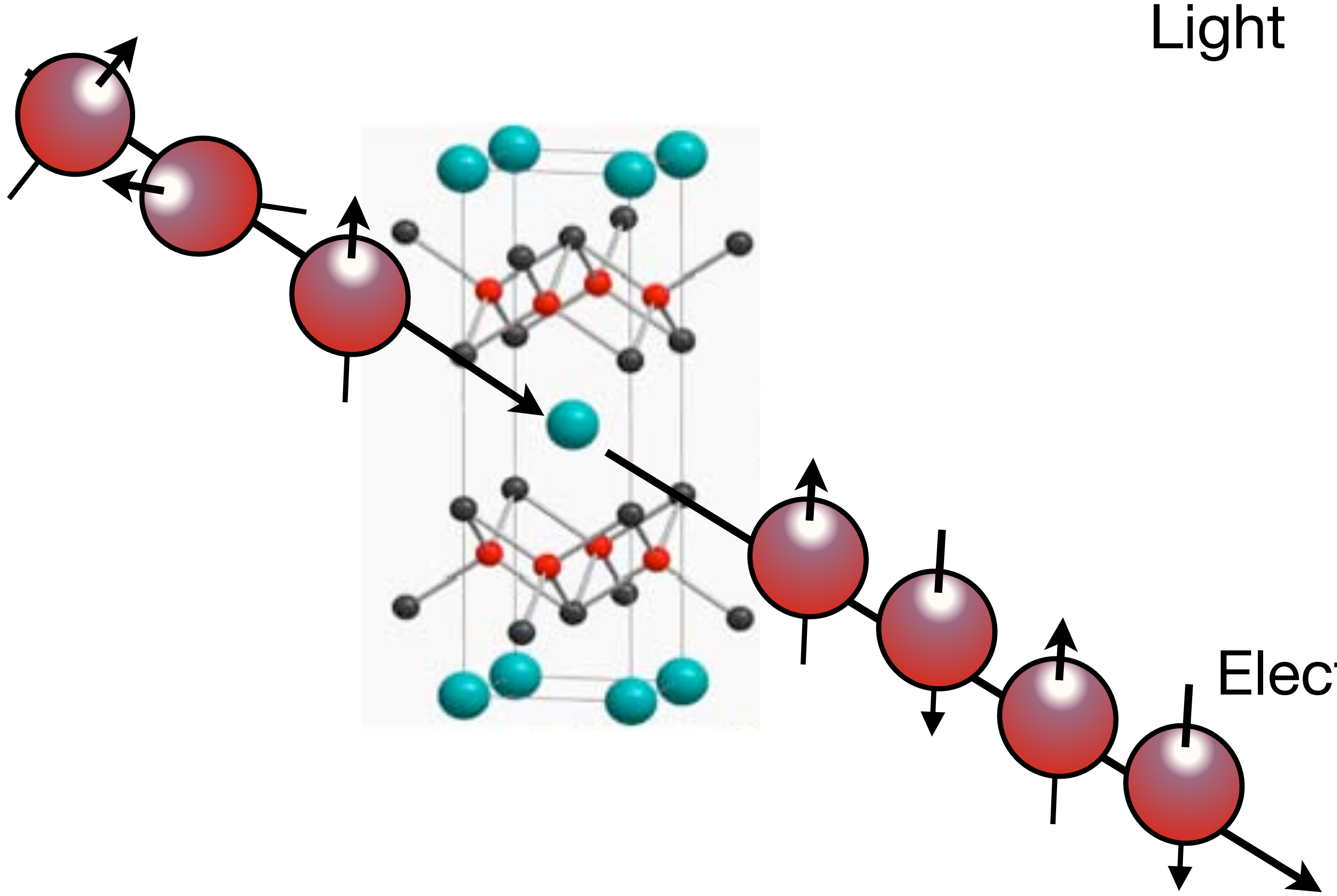

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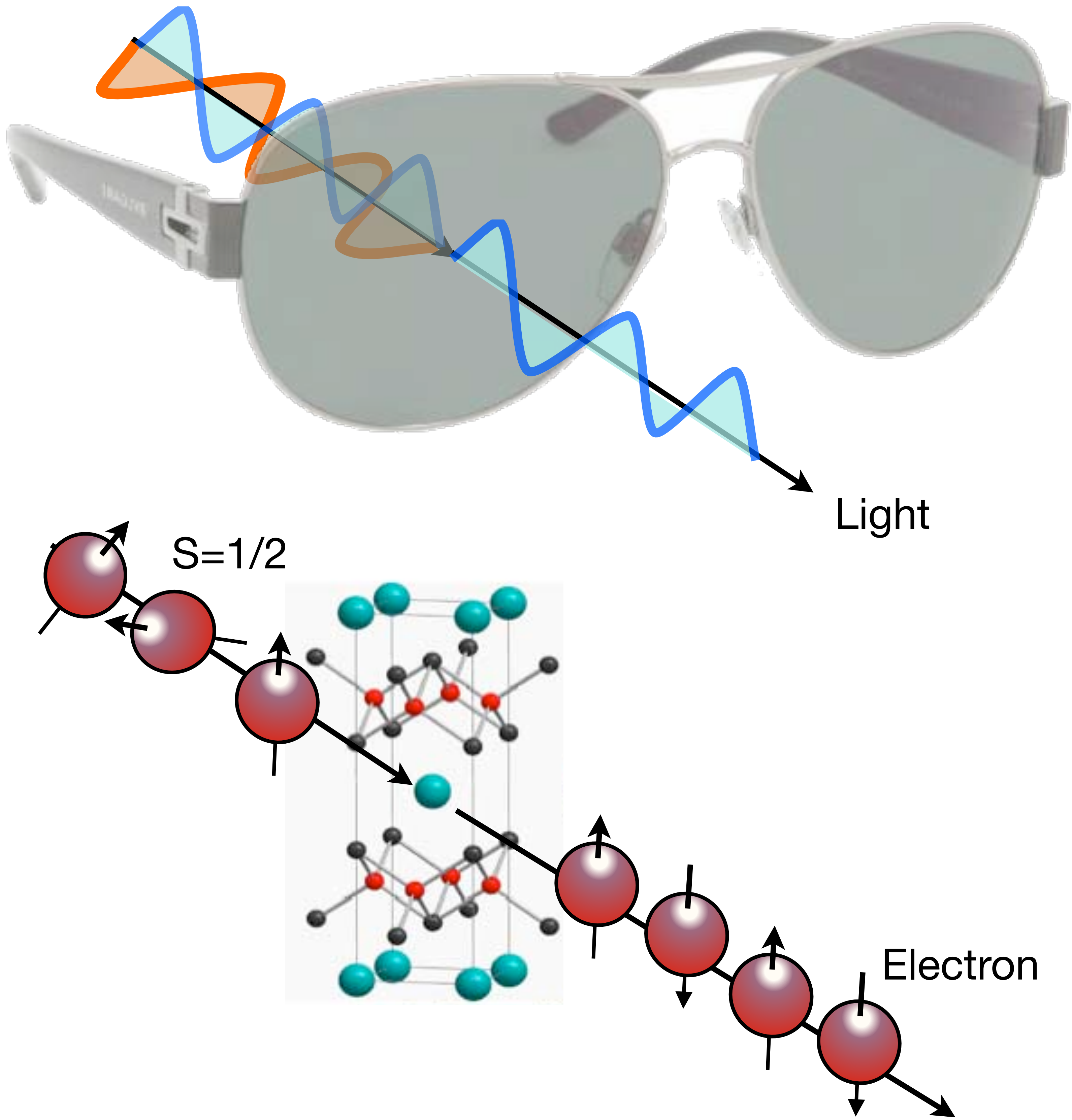

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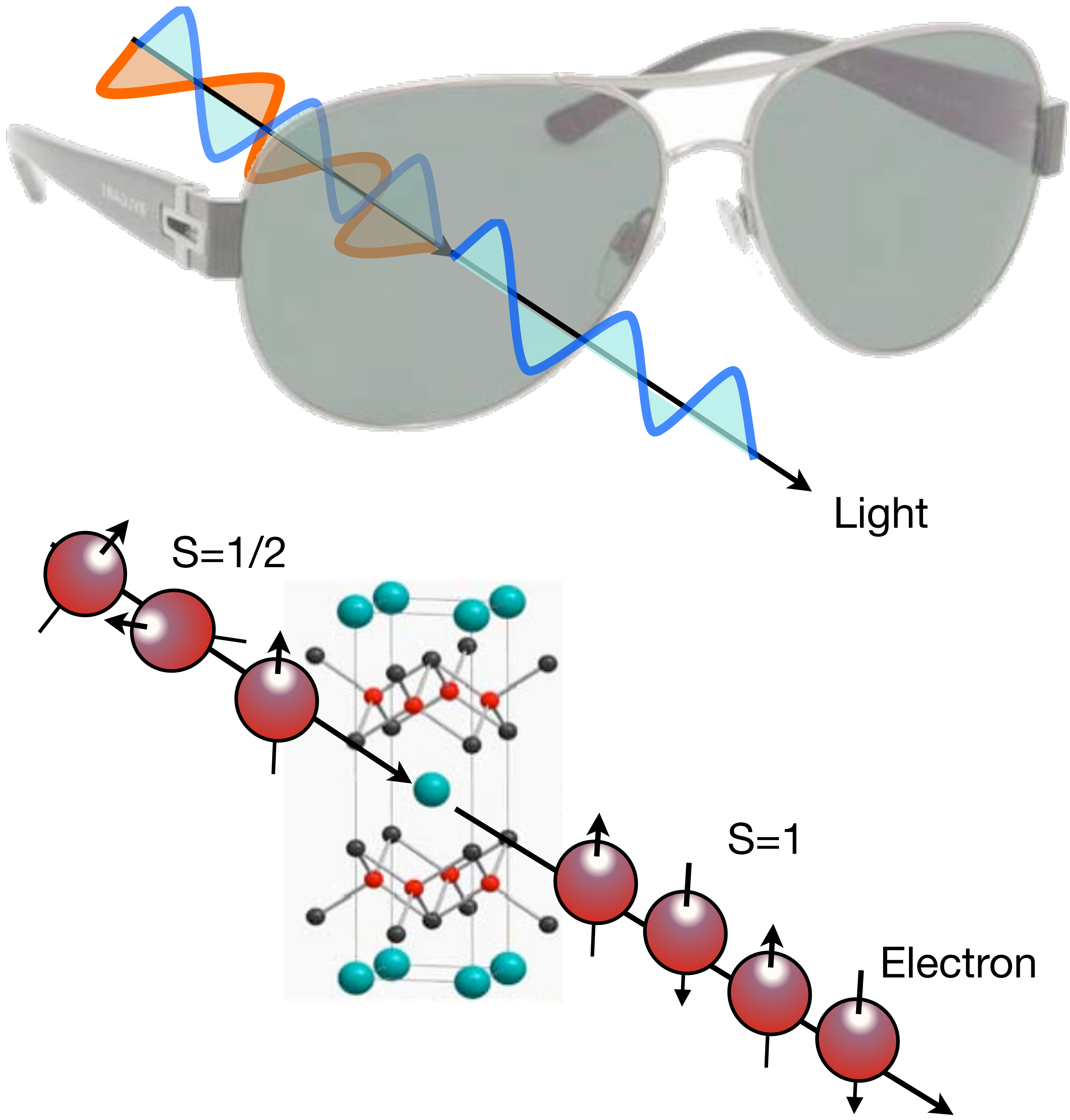

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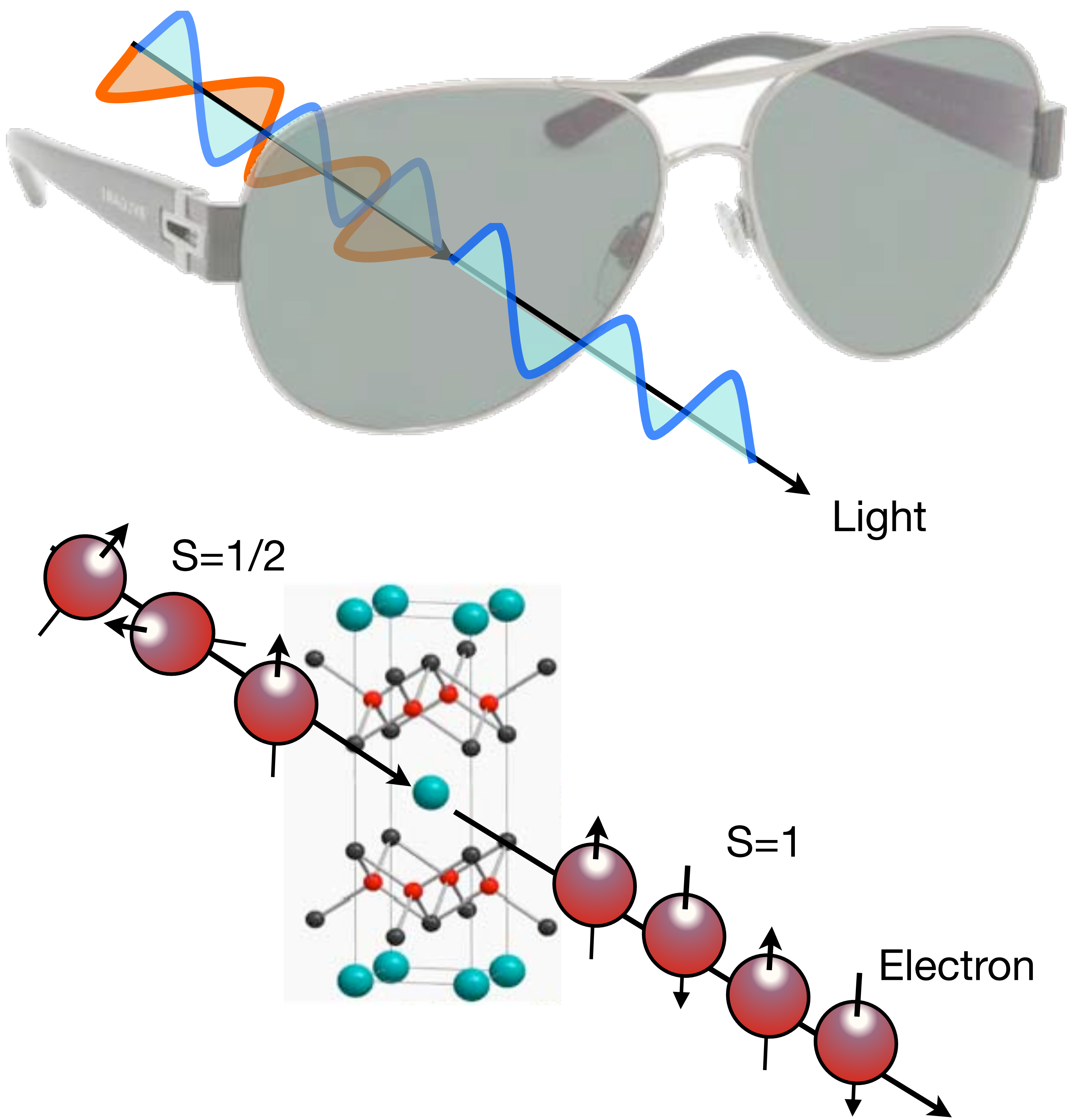

Ψ

Order parameter carries half-integer spin

“Spinor”

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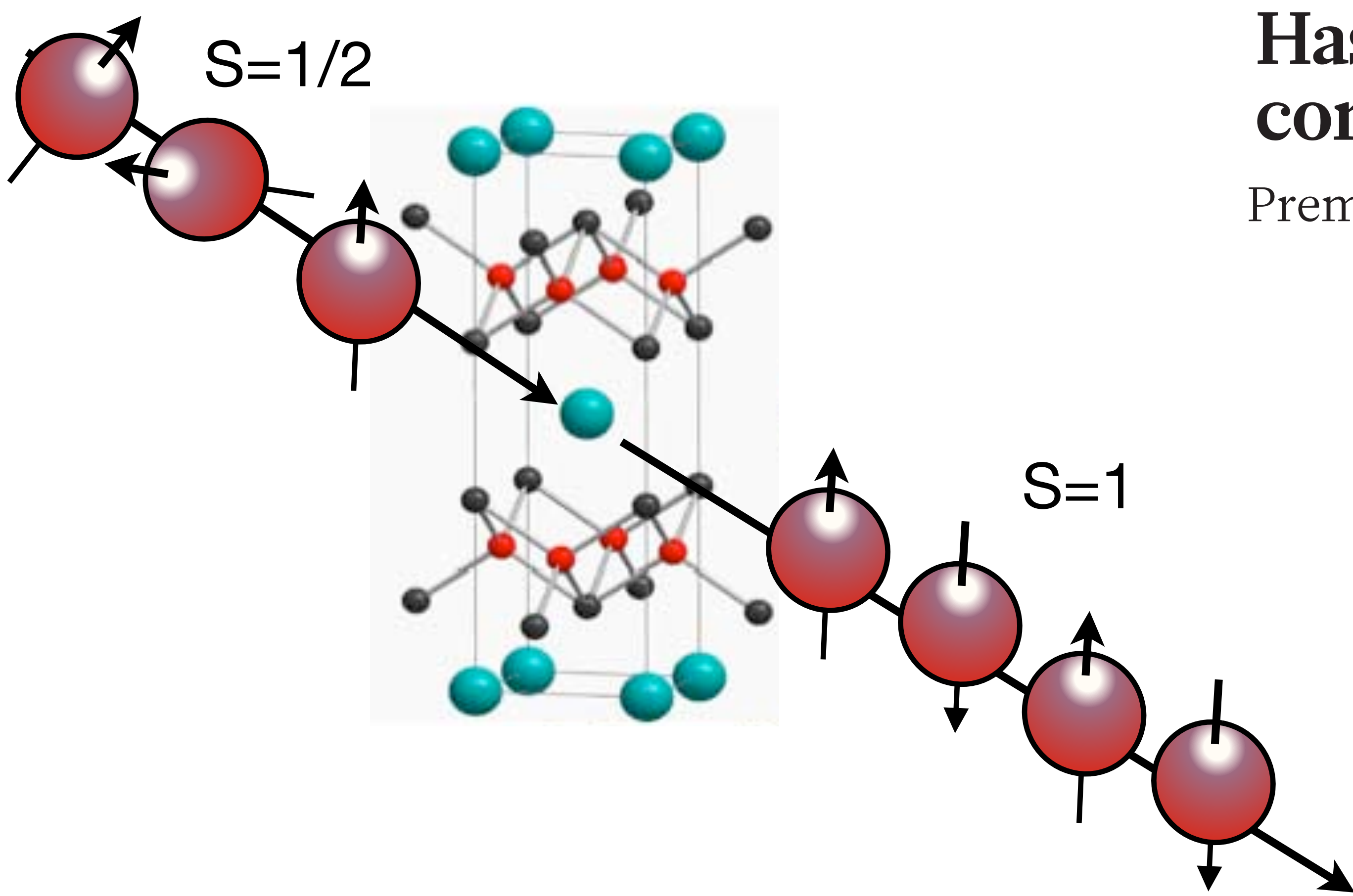

doi:10.1038/nature11820

Hastatic order in the heavy-fermion compound URu_2Si_2

Premala Chandra[1], Piers Coleman[1,2] & Rebecca Flint[3]

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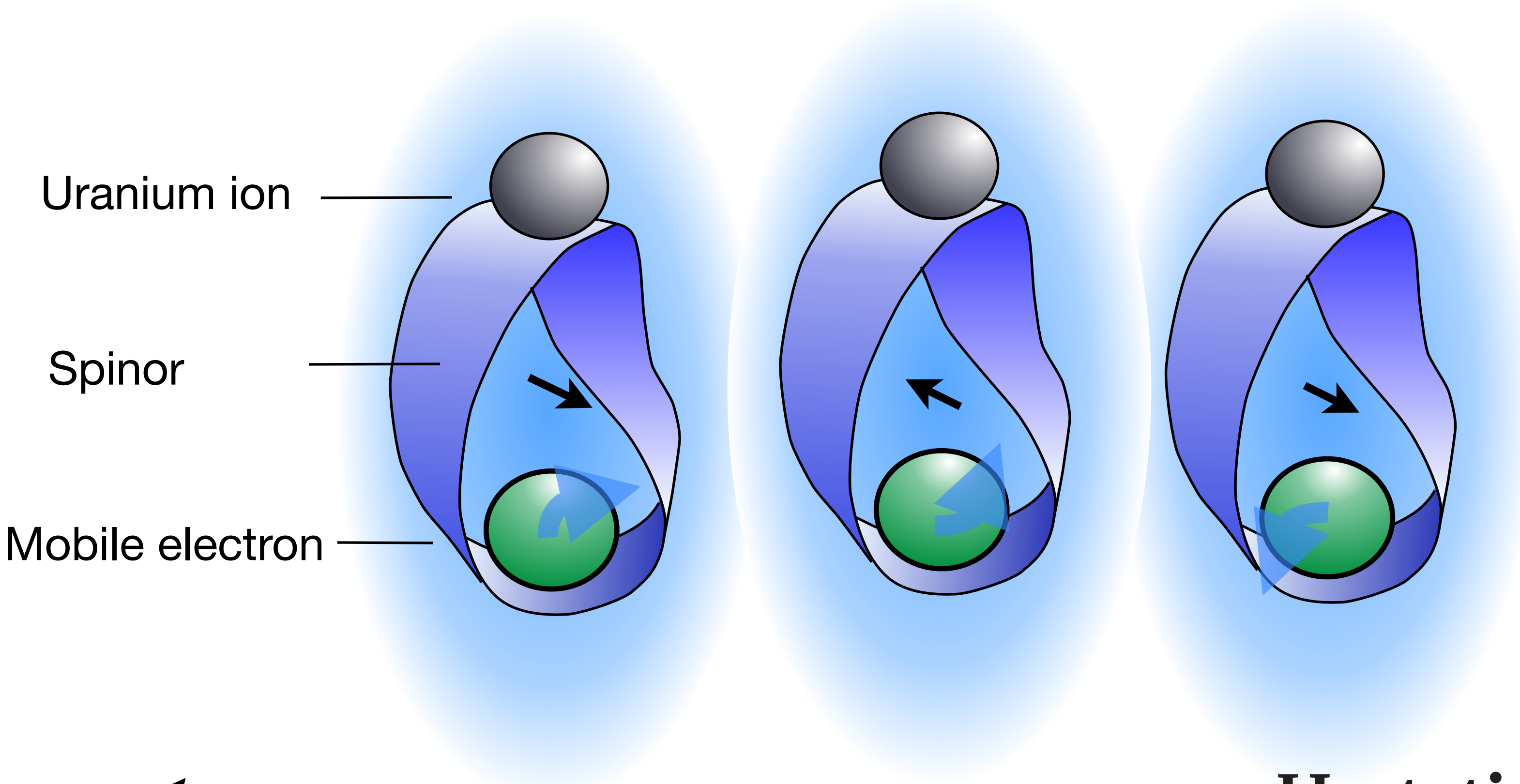

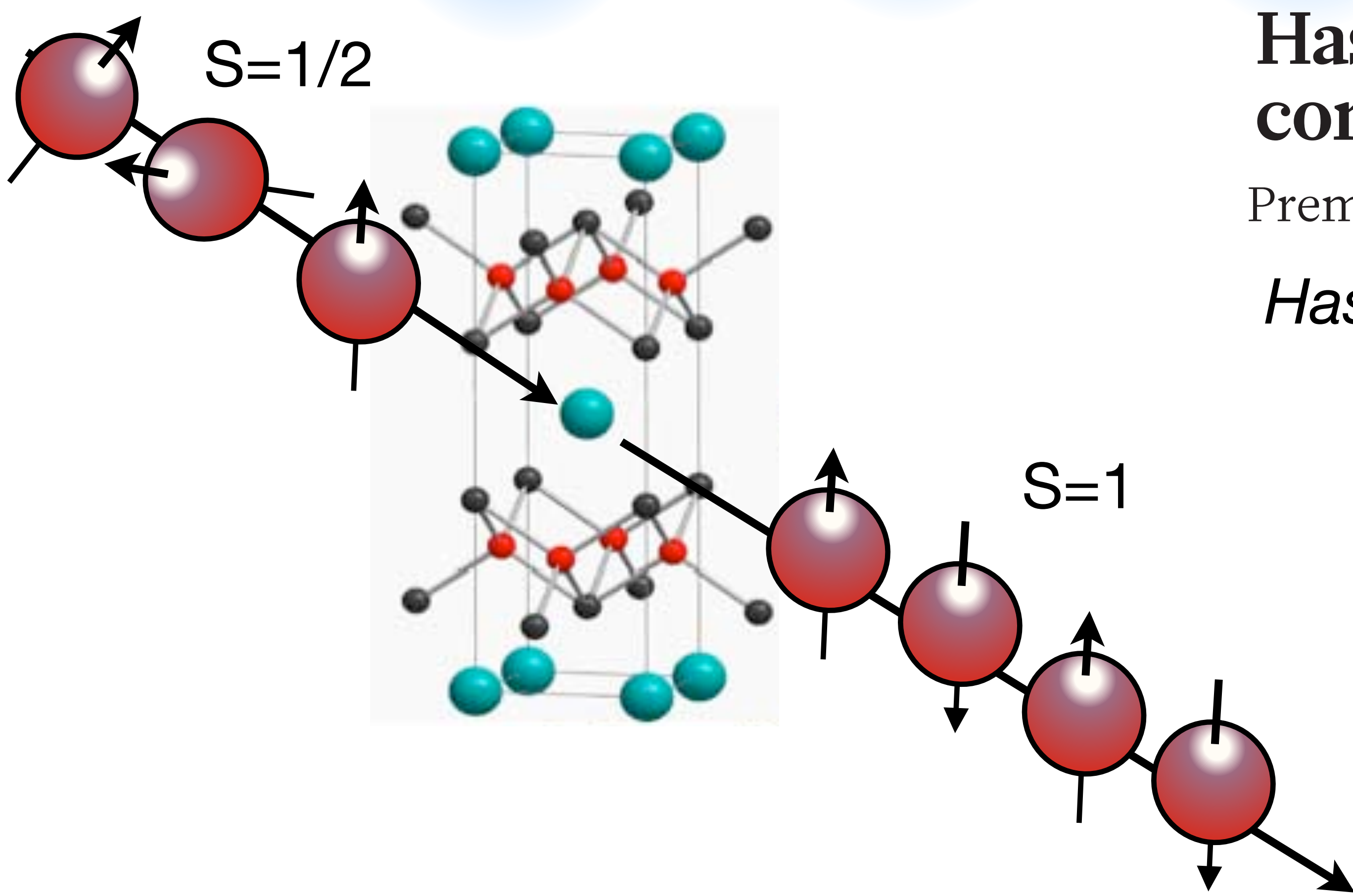

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Hasta: Spear (Latin)

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A curious link between
String theory and Magnetism

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Spinors

Super C

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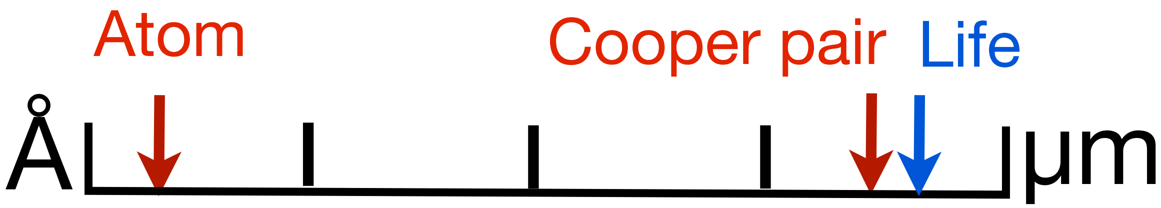
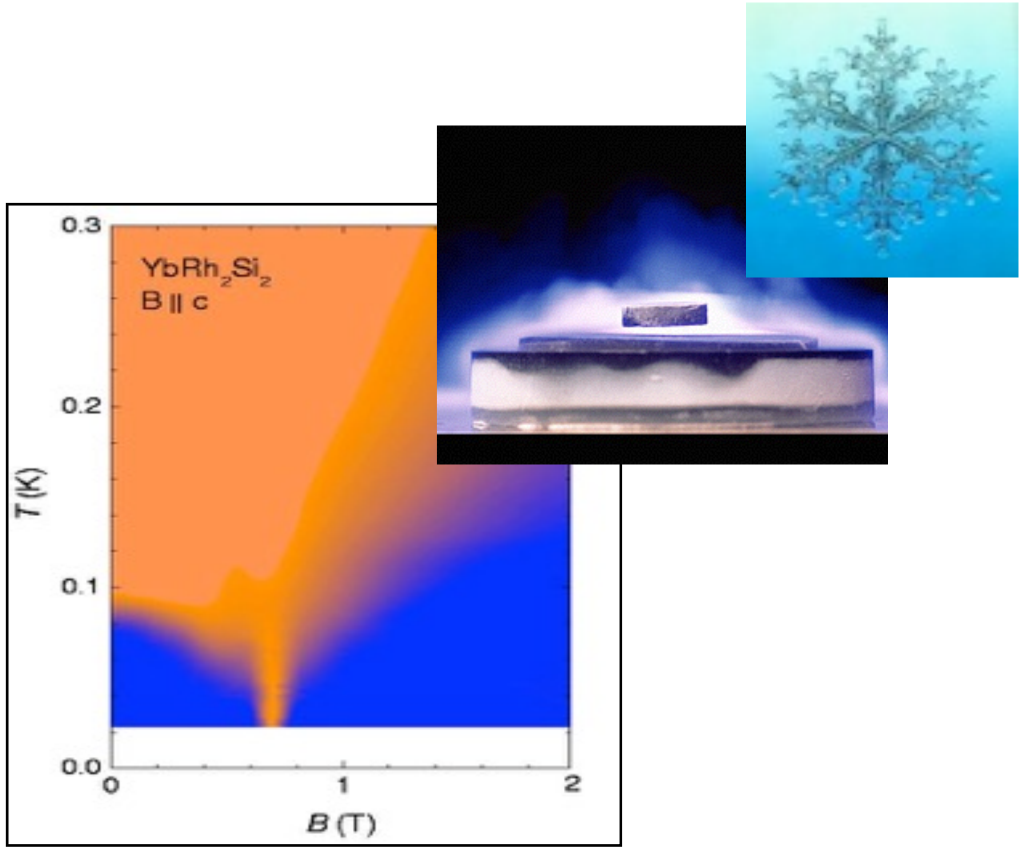
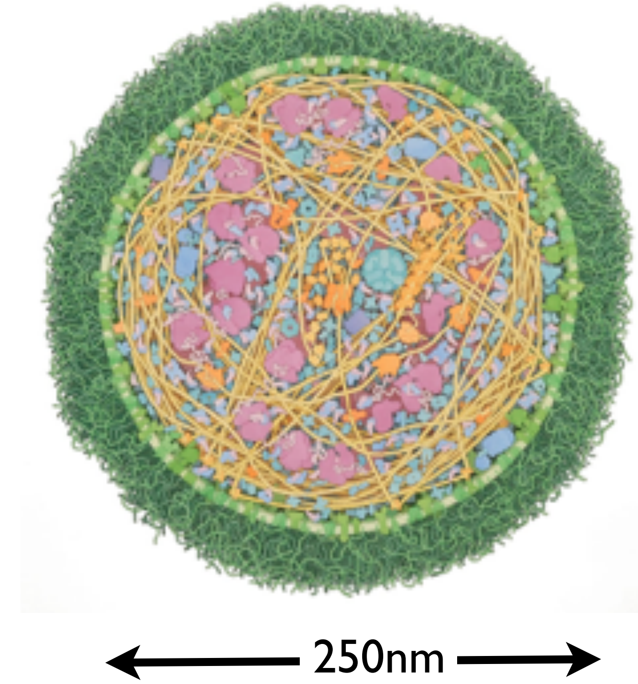
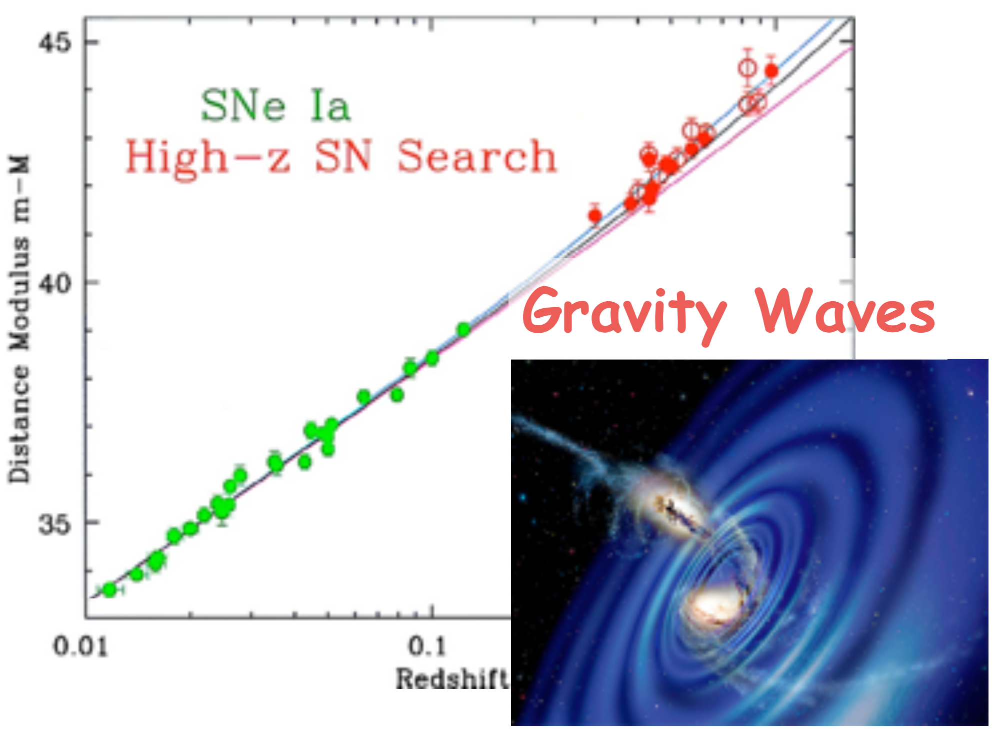


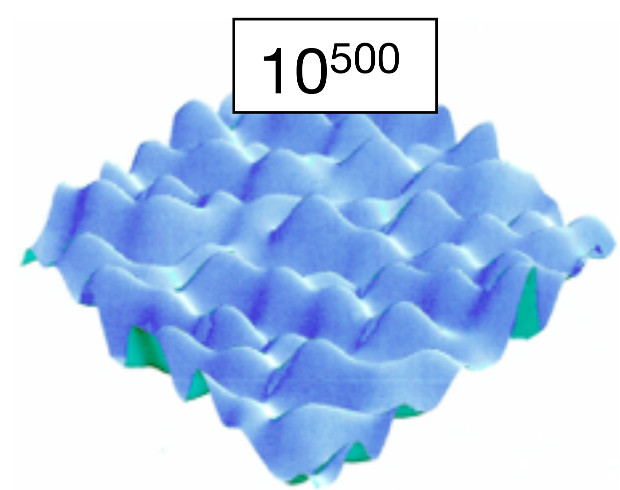
“Emergence”

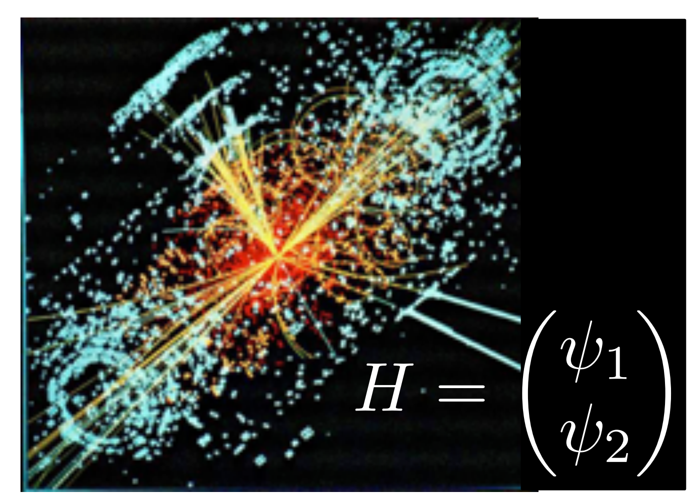


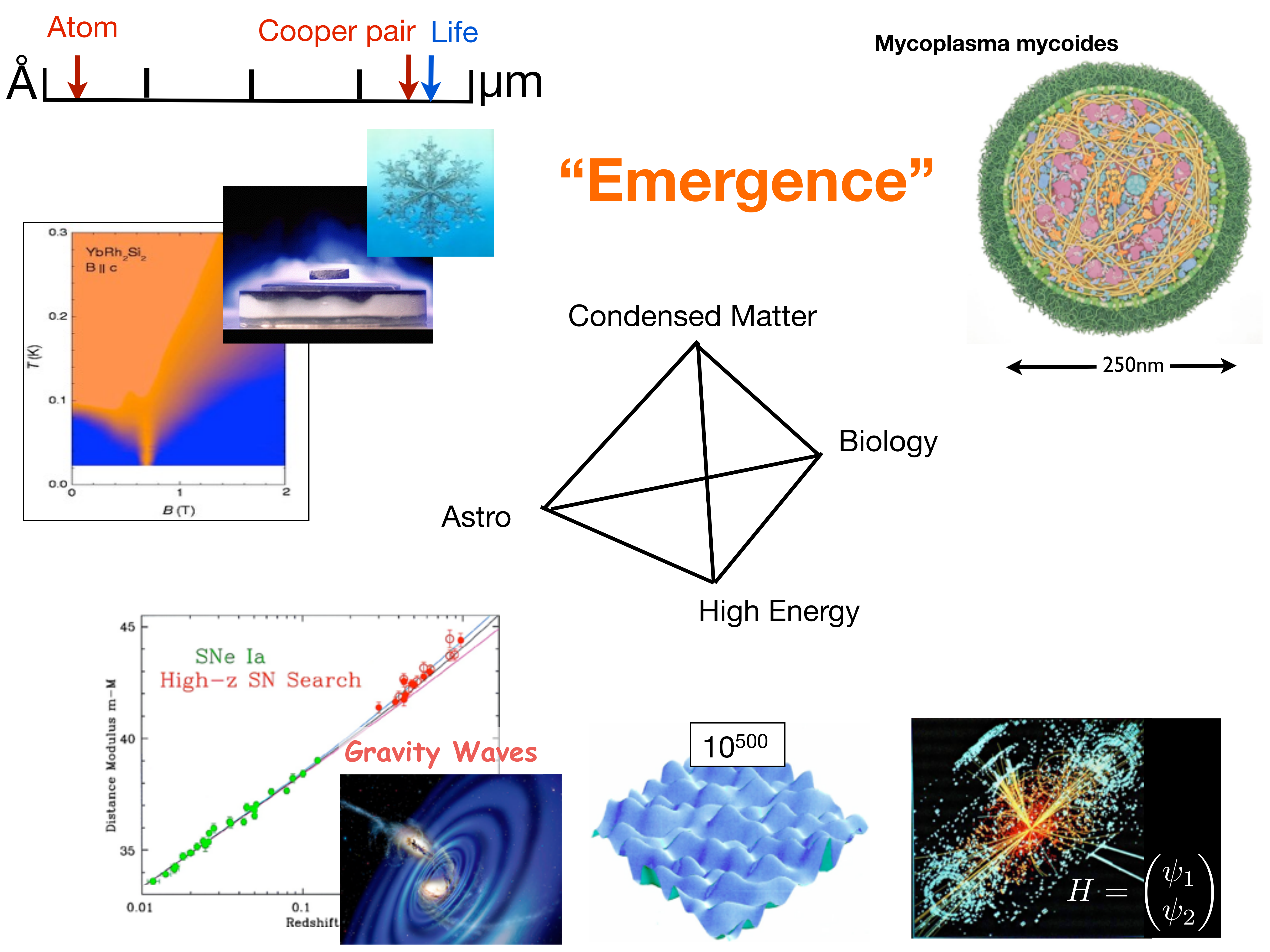
Mycoplasma mycoides











Atom
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Life
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μm
Mycoplasma mycoides
“Emergence”
YbRh2Si2
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0.2
0.1
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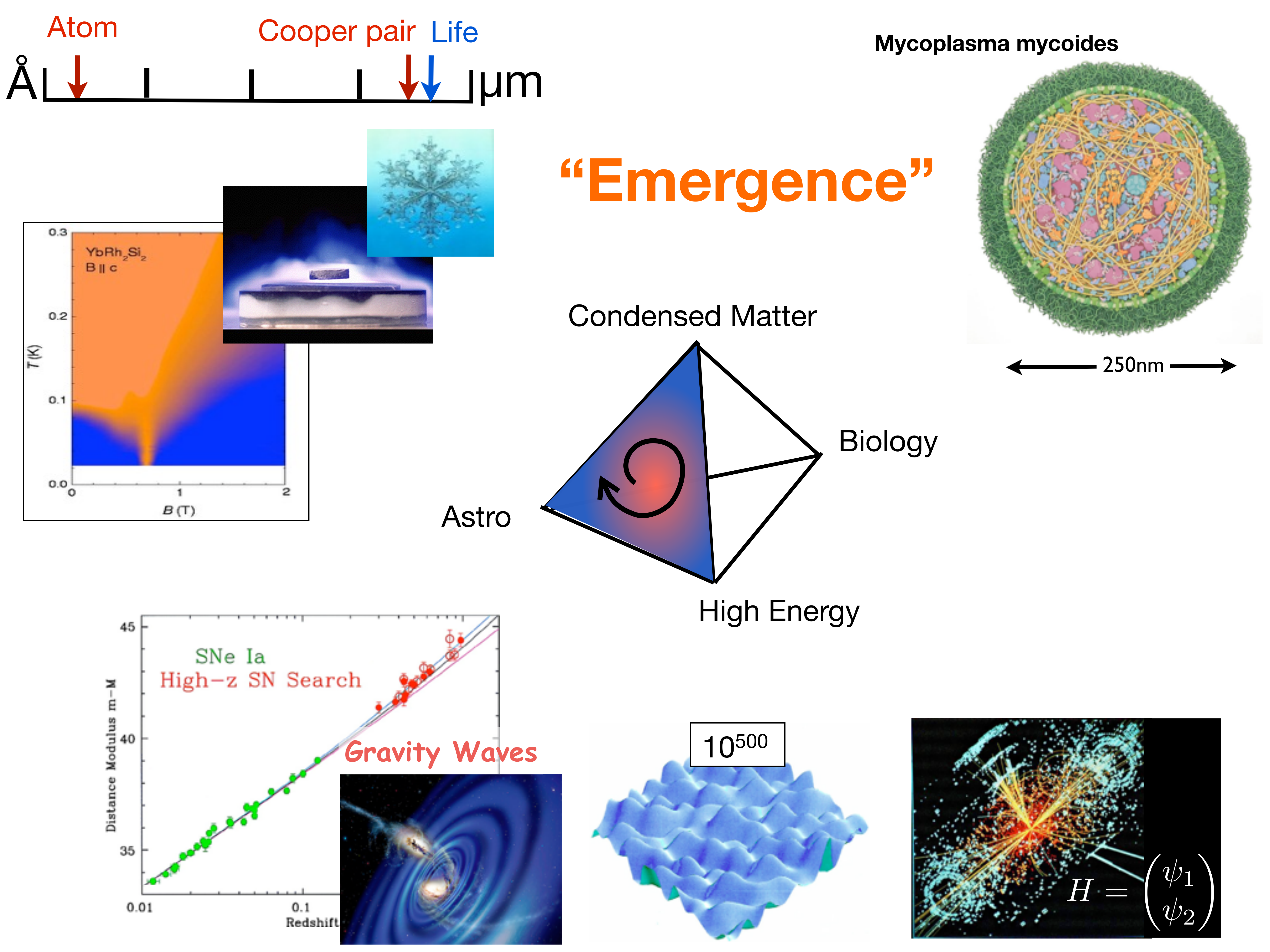
B (T)
Condensed Matter
Biology
Astro
High Energy
250nm
45
40
35
Distance Modulus m−M
SNe Ia
High−z SN Search
0.01
0.1
Redshift
Gravity Waves
10500
H = (ψ1 ψ2)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Thank You.