A Holographic Model of the Kondo Effect

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Credits

Work in progress with:

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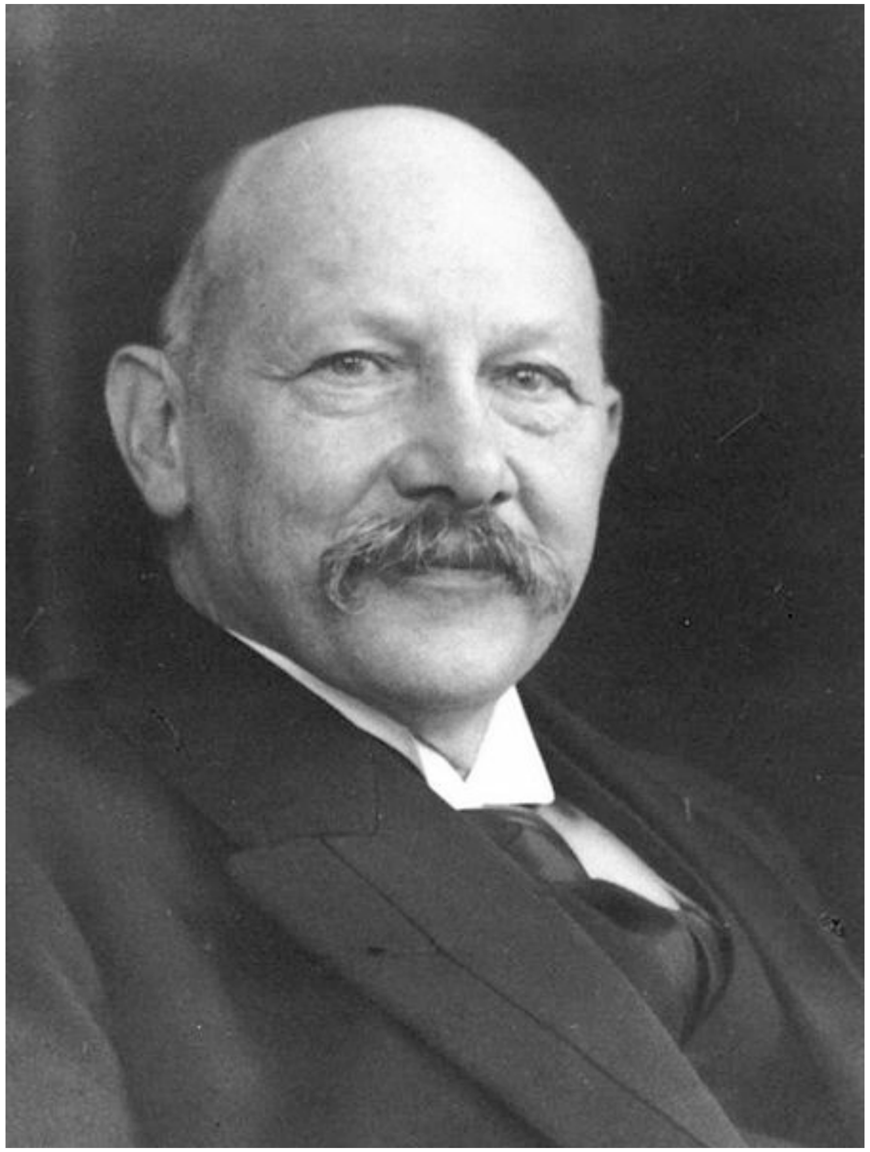
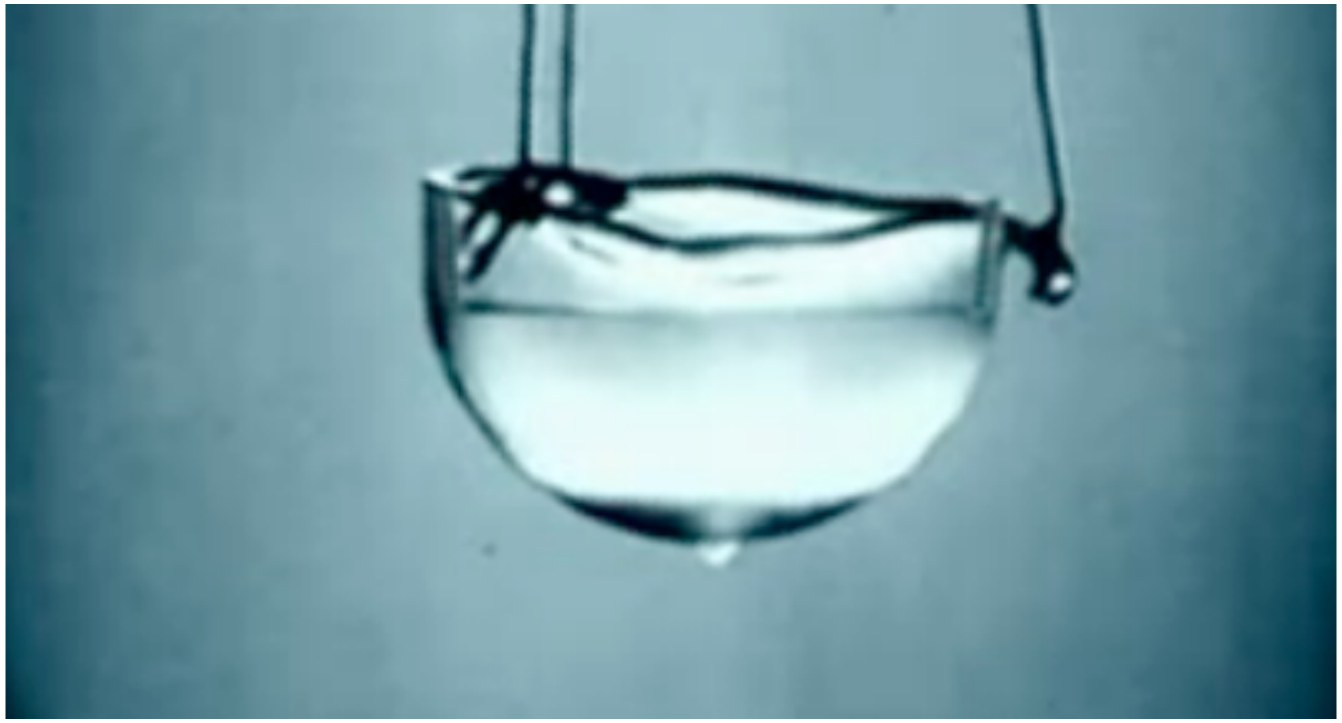
Outline:

- The Kondo Effect
- The CFT Approach
- A Top-Down Holographic Model
- A Bottom-Up Holographic Model
- Summary and Outlook

July 10, 1908

Leiden, the Netherlands



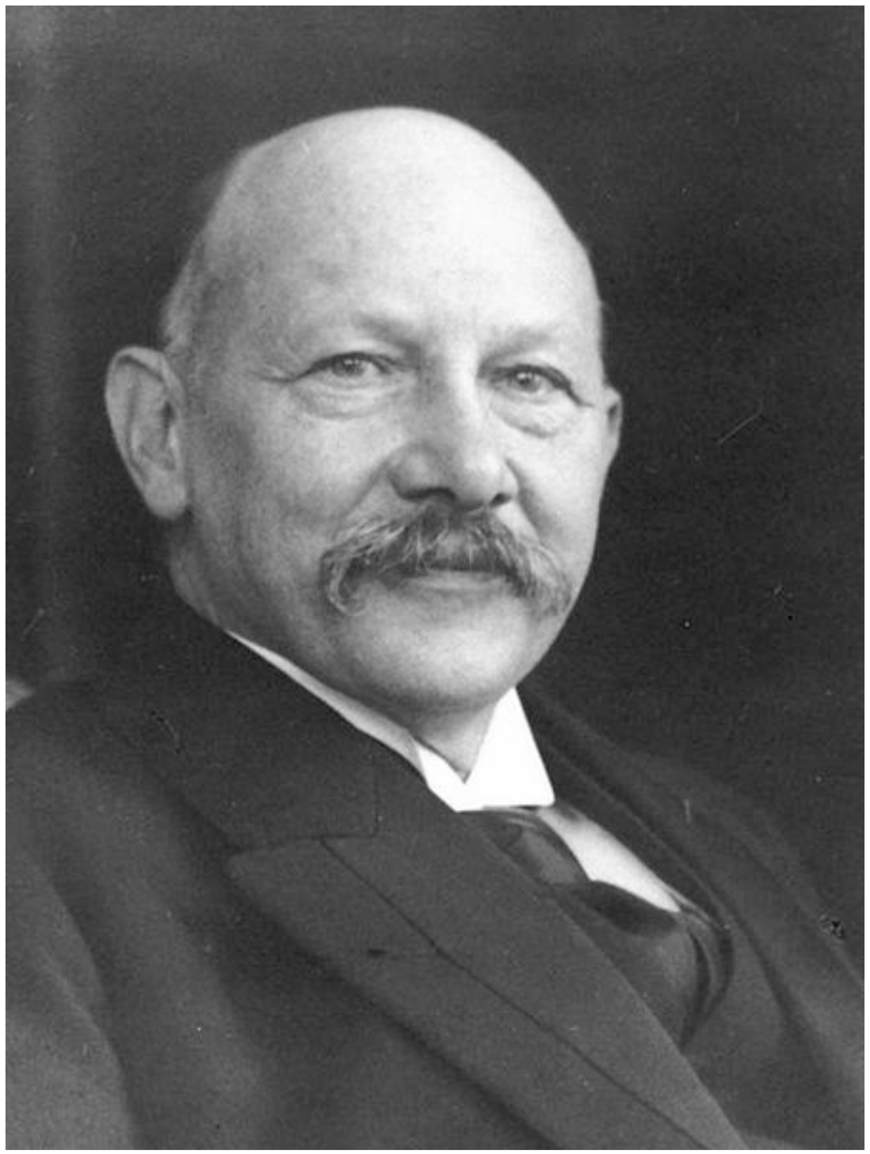


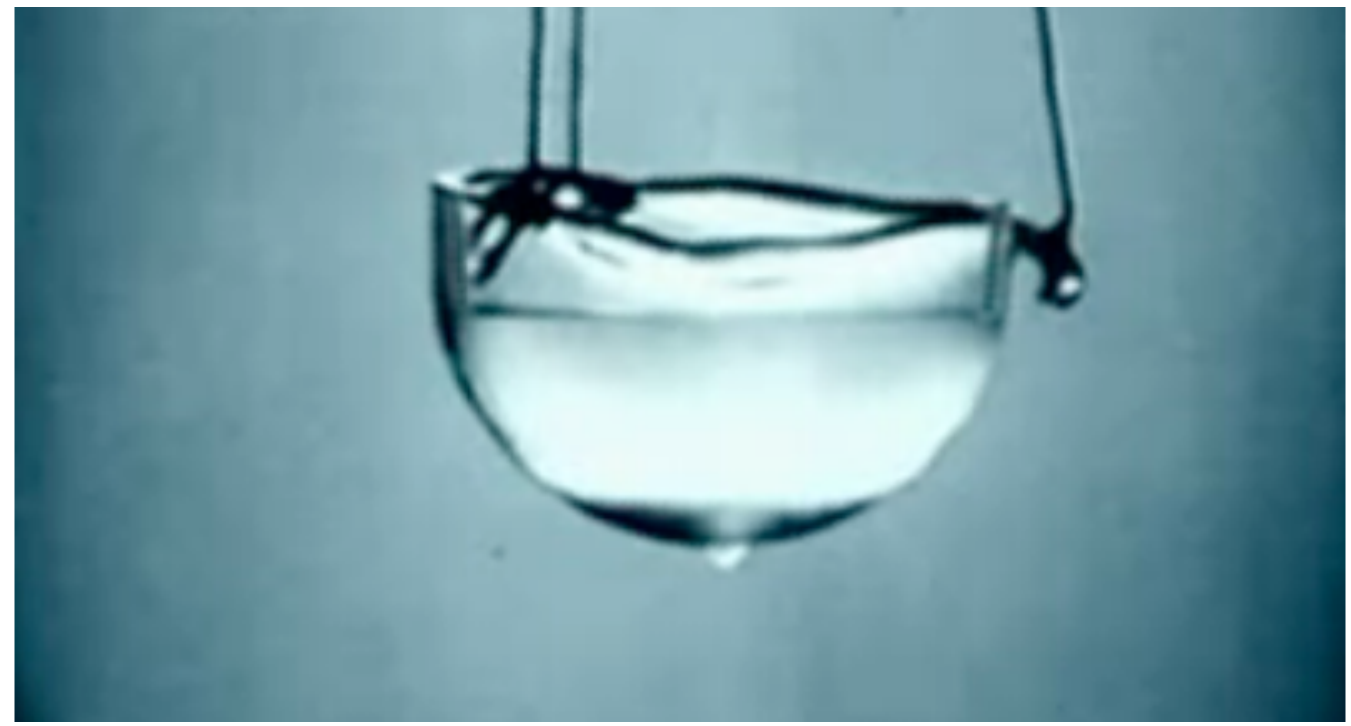
Heike Kamerlingh Onnes liquifies helium

$$T \approx 4.2\ \mathrm{K} \quad (1\ \mathrm{atm})$$

Shortly Thereafter

Leiden, the Netherlands





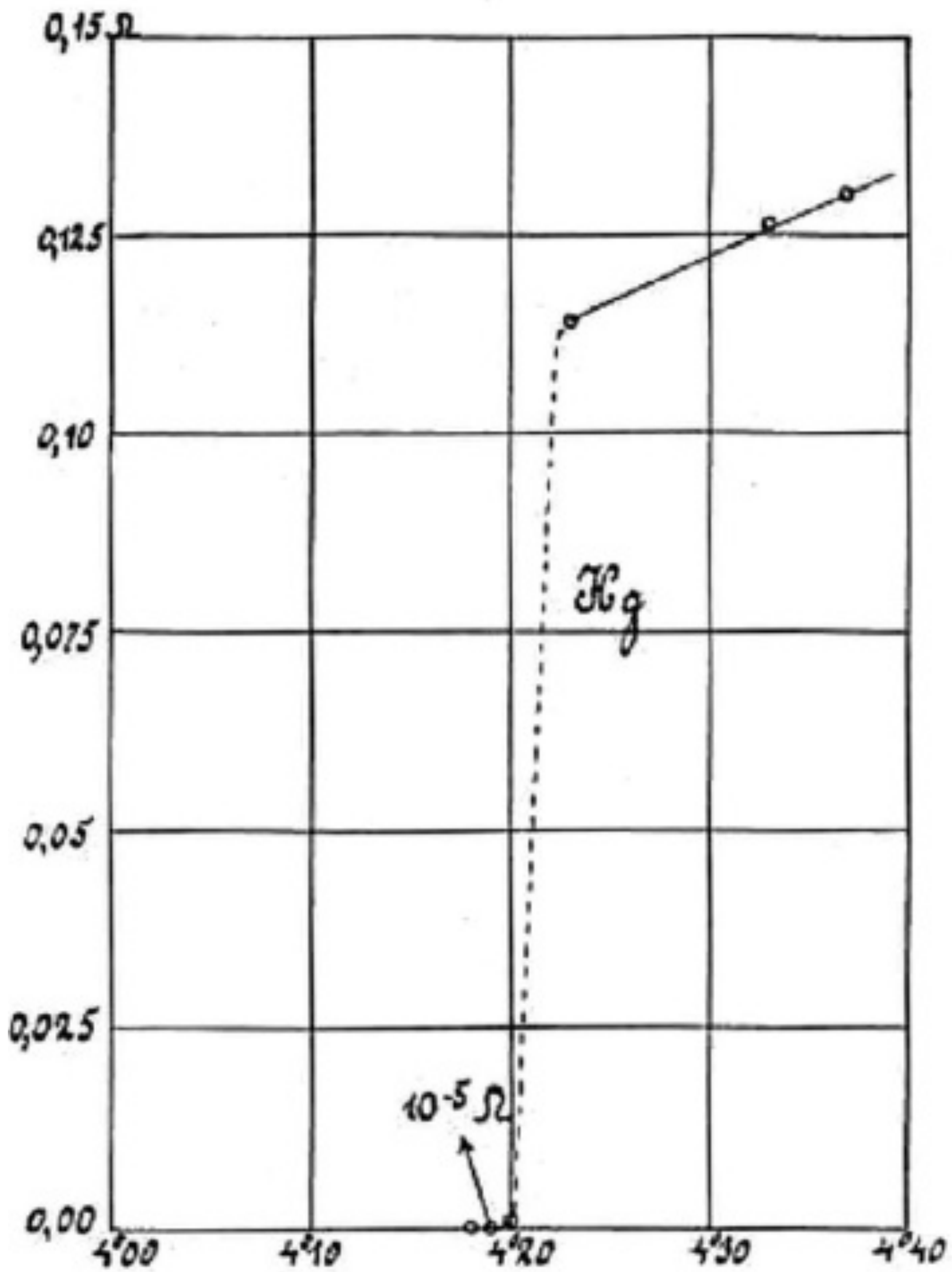
Begins studying low-temperature properties of metals

$$T \approx 1 \text{ to } 10\ K$$

April 8, 1911

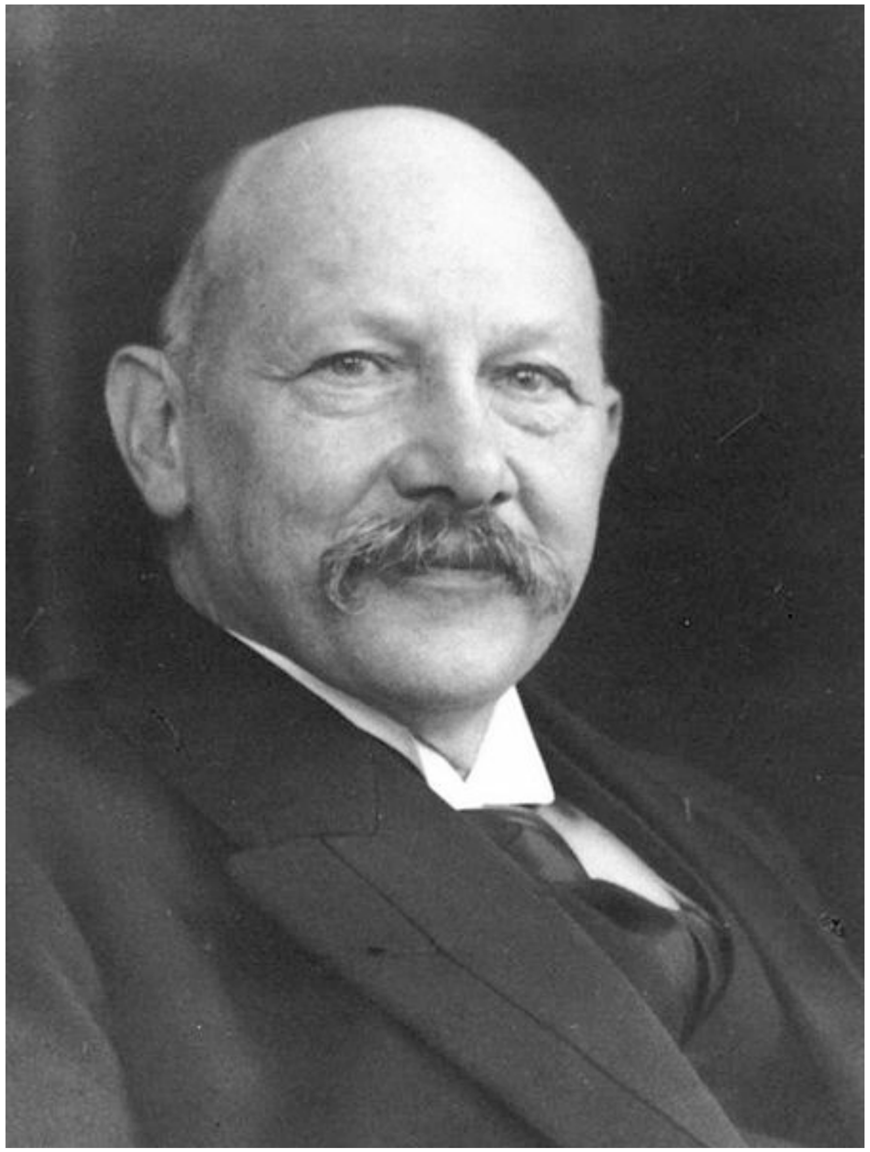
Heike Kamerlingh Onnes discovers superconductivity

R

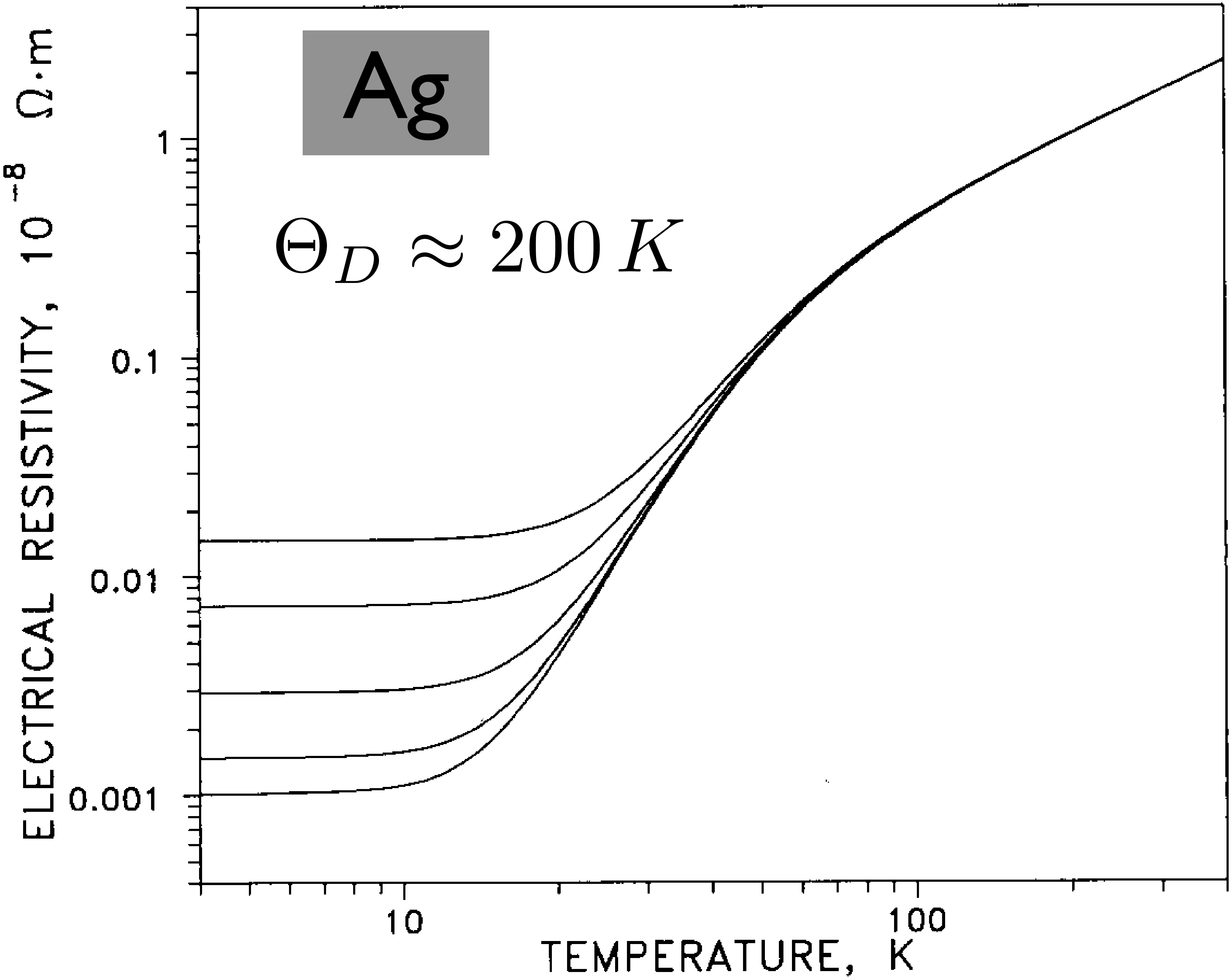


1913

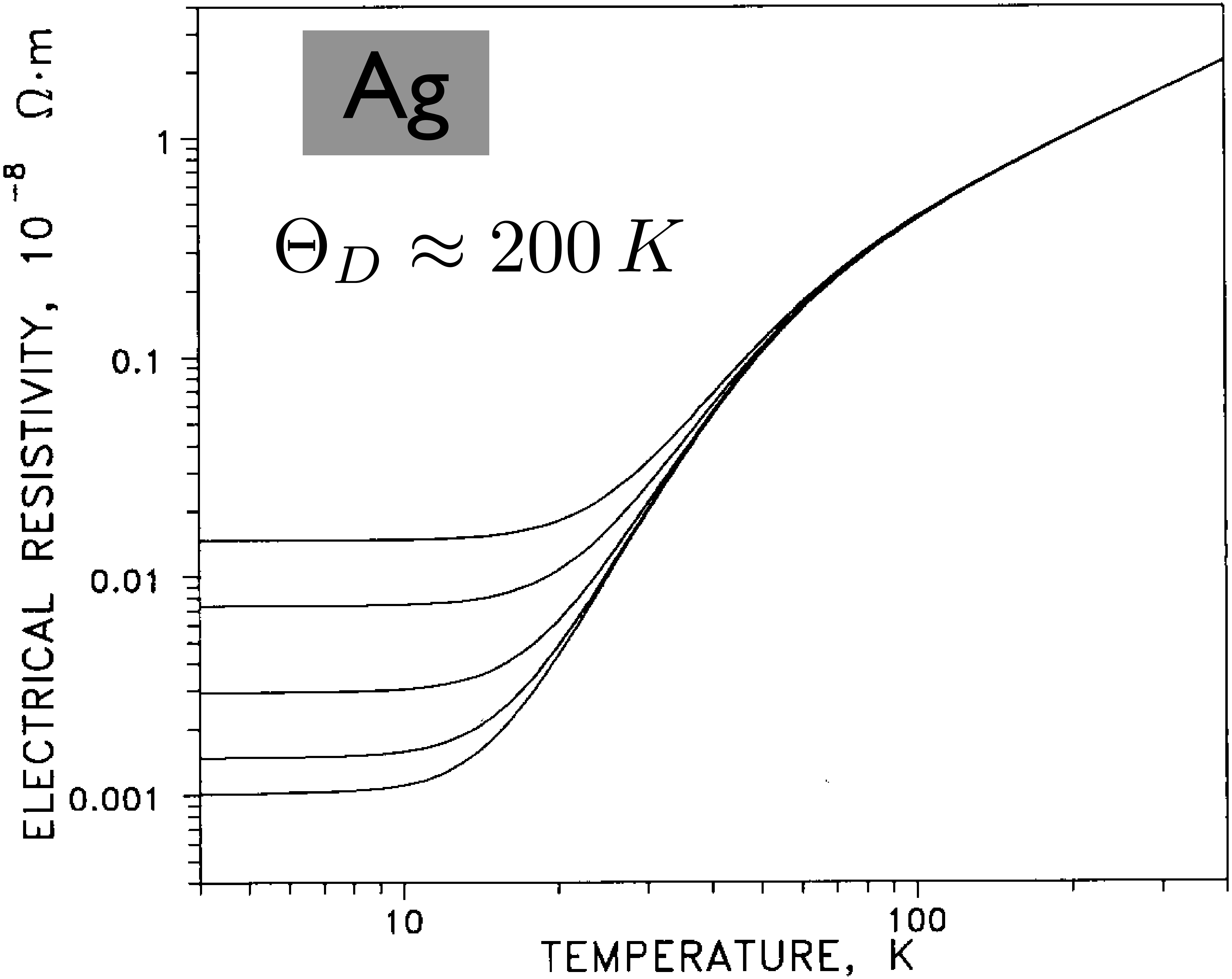
Onnes receives the Nobel Prize in Physics



"for his investigations on the properties of matter at low temperatures which led, *inter alia*, to the production of liquid helium"



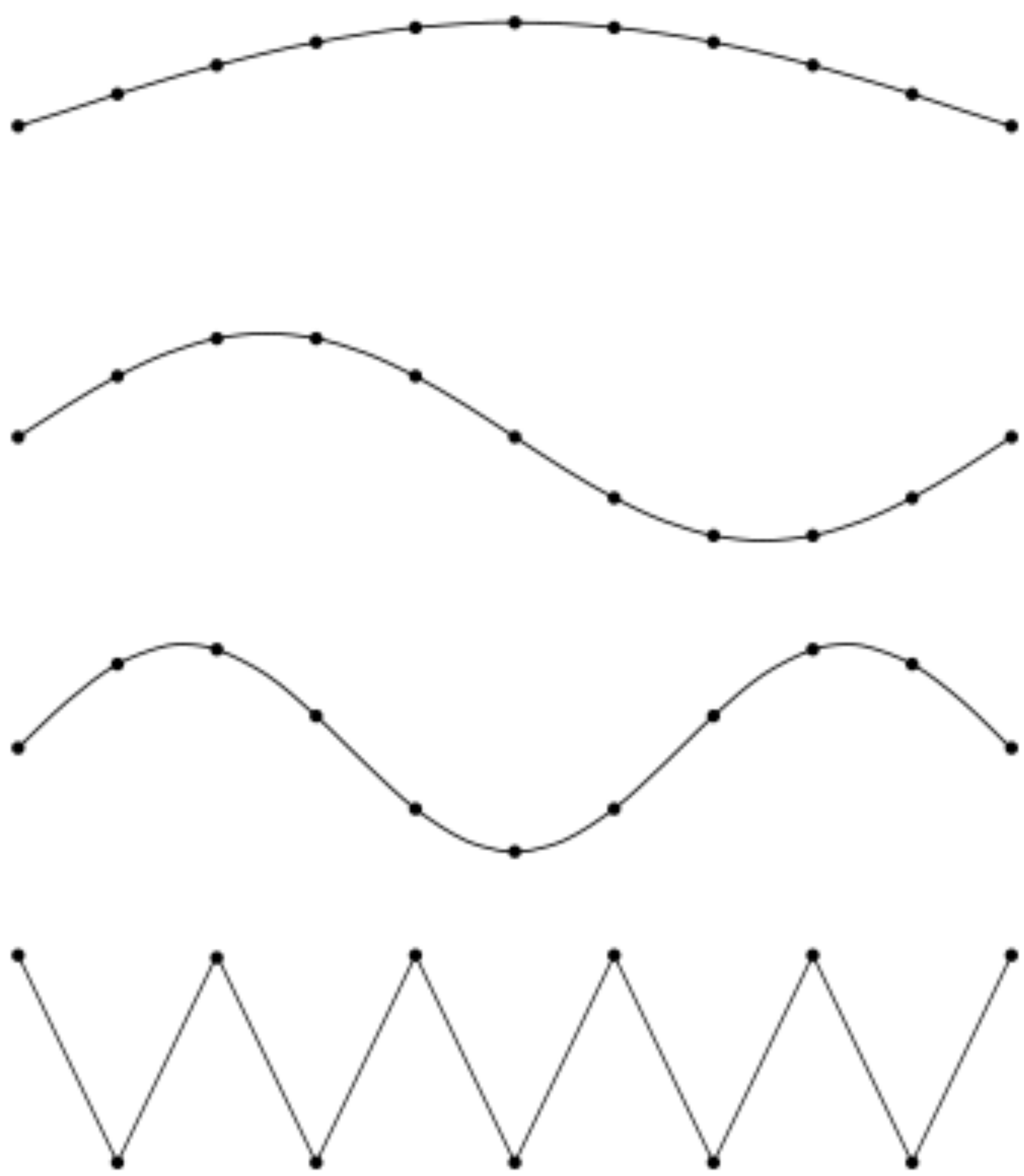
Smith and Fickett, J. Res. NIST, 100, 119 (1995)



Resistivity measures electron scattering cross section

Debye Temperature

Quantized vibrational modes of a solid = Phonons

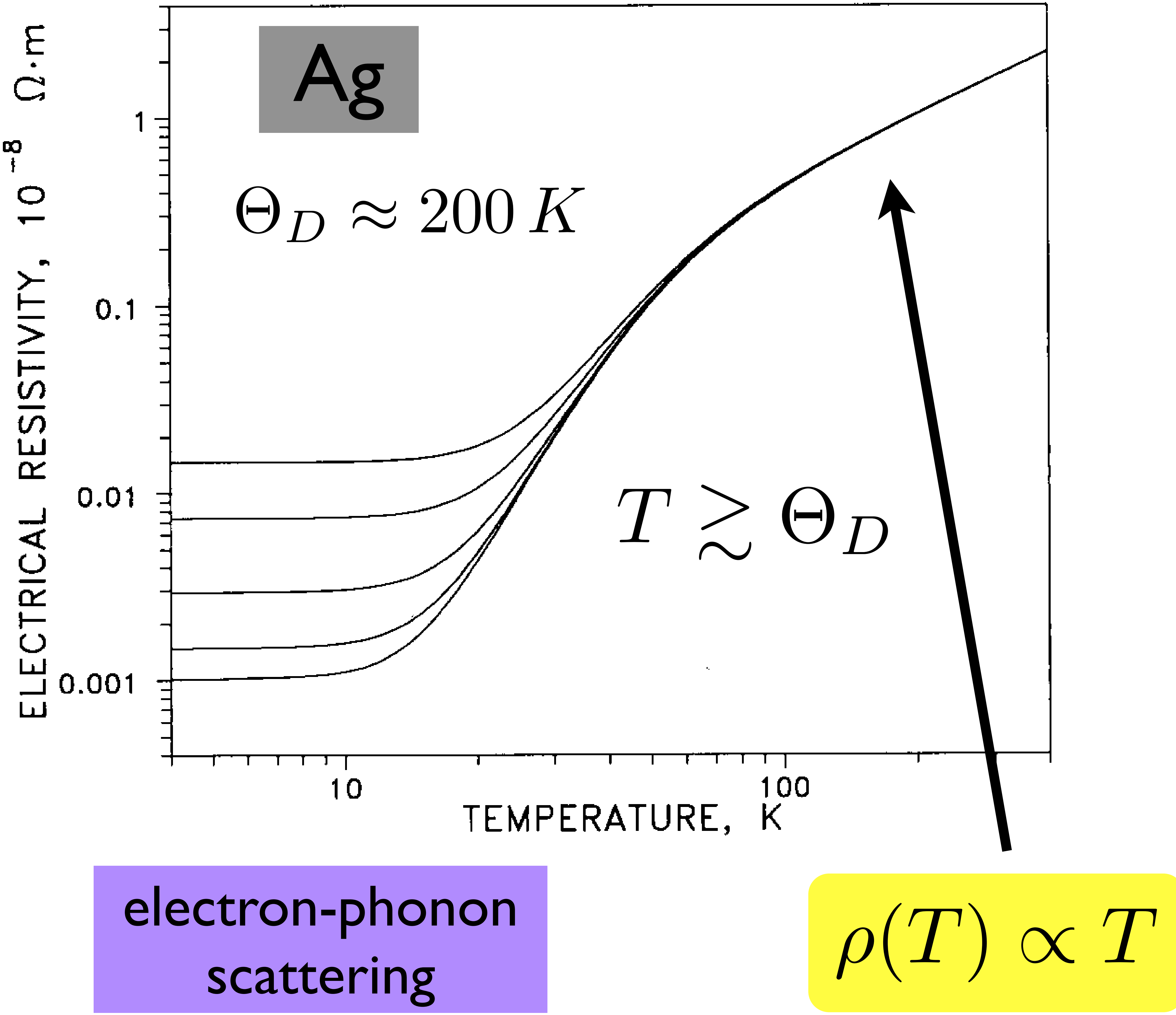


Minimum wavelength: 2 x (lattice spacing)

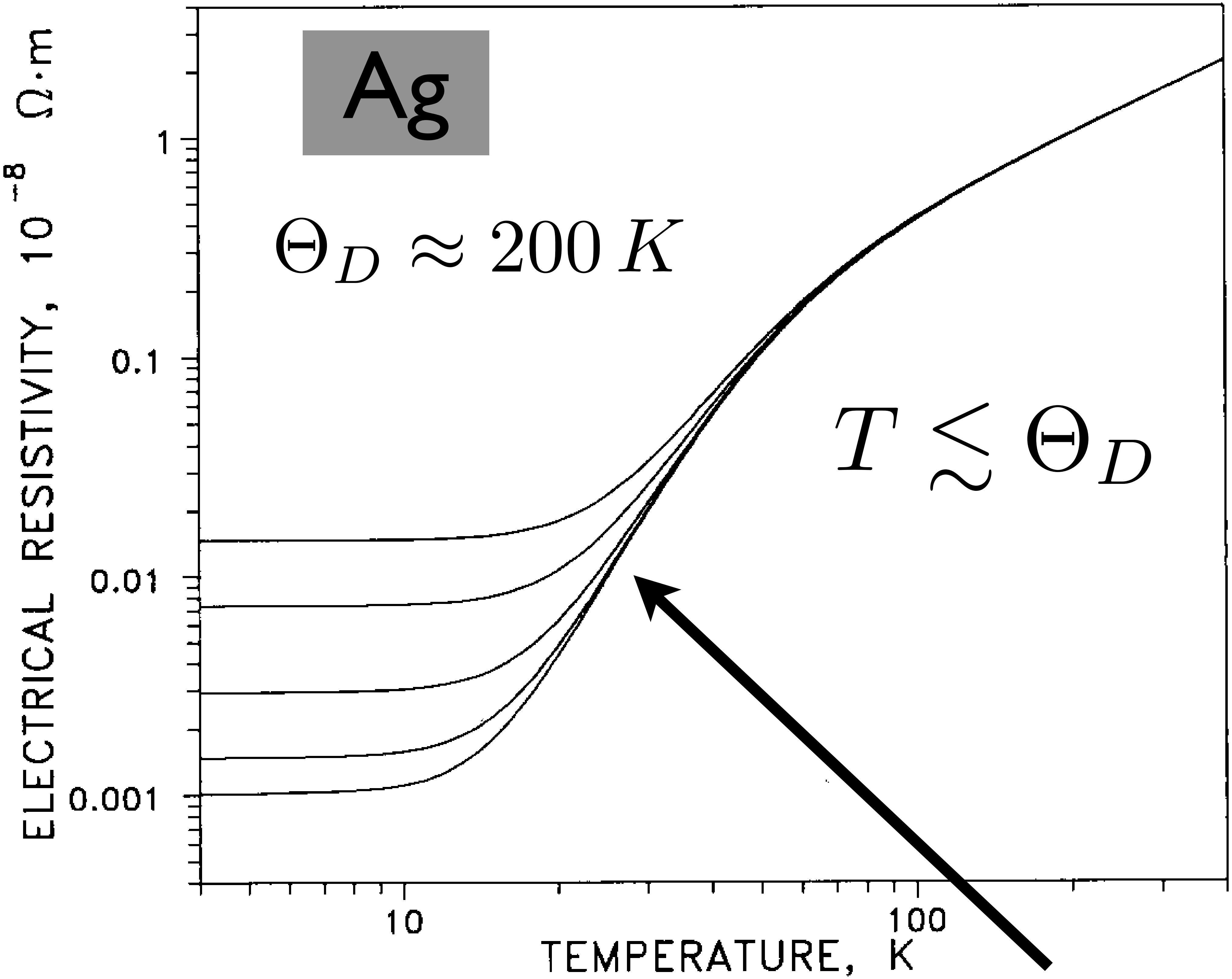
Maximal Frequency

$$\Theta_D$$

lowest temperature at which maximal-energy phonon excited

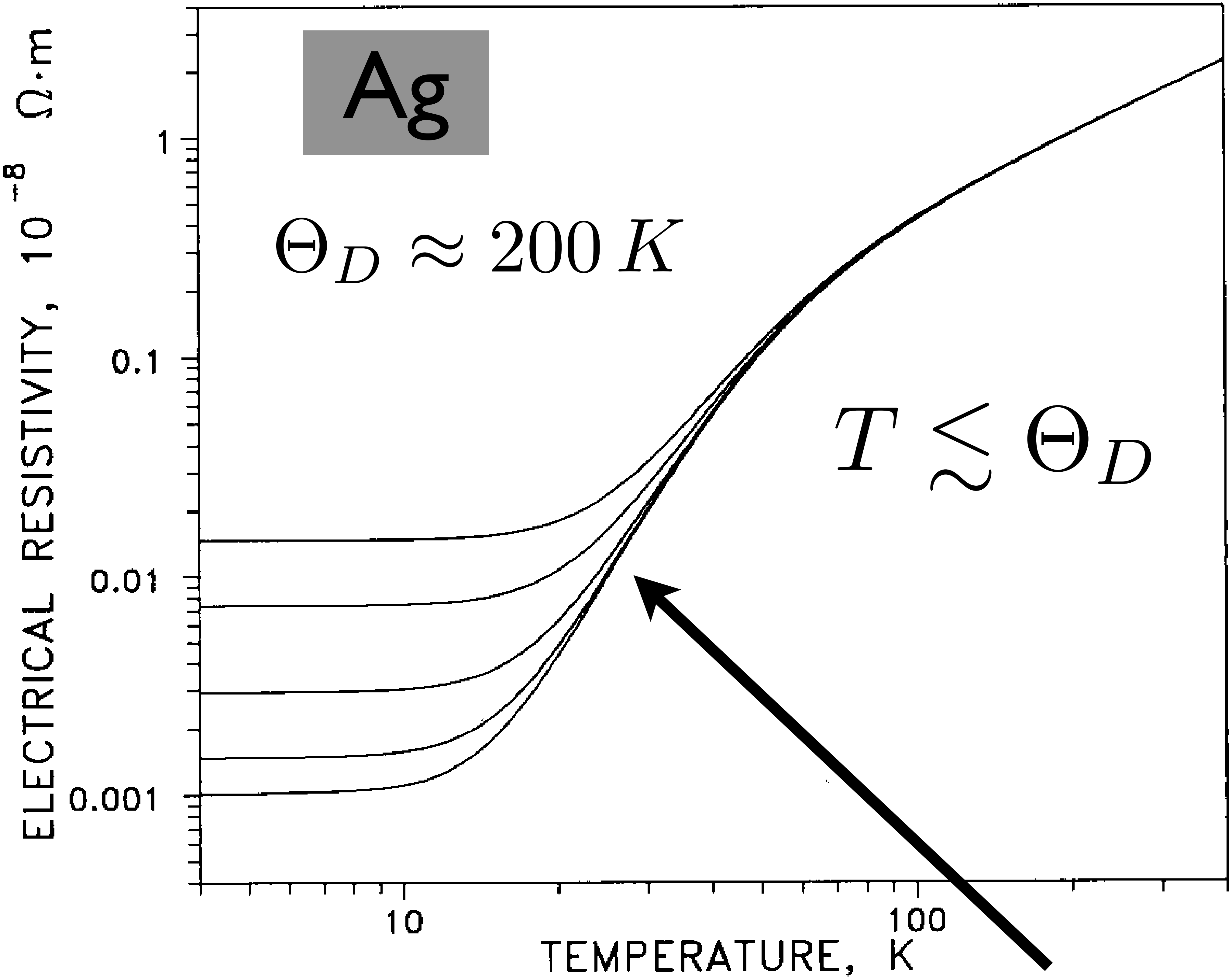


Ag
$\Theta_D \approx 200\,K$
$T \gtrsim \Theta_D$
ELECTRICAL RESISTIVITY, 10^{-8} Ω·m
1
0.1
0.01
0.001
10
100
TEMPERATURE, K
electron-phonon scattering
$\rho(T) \propto T$



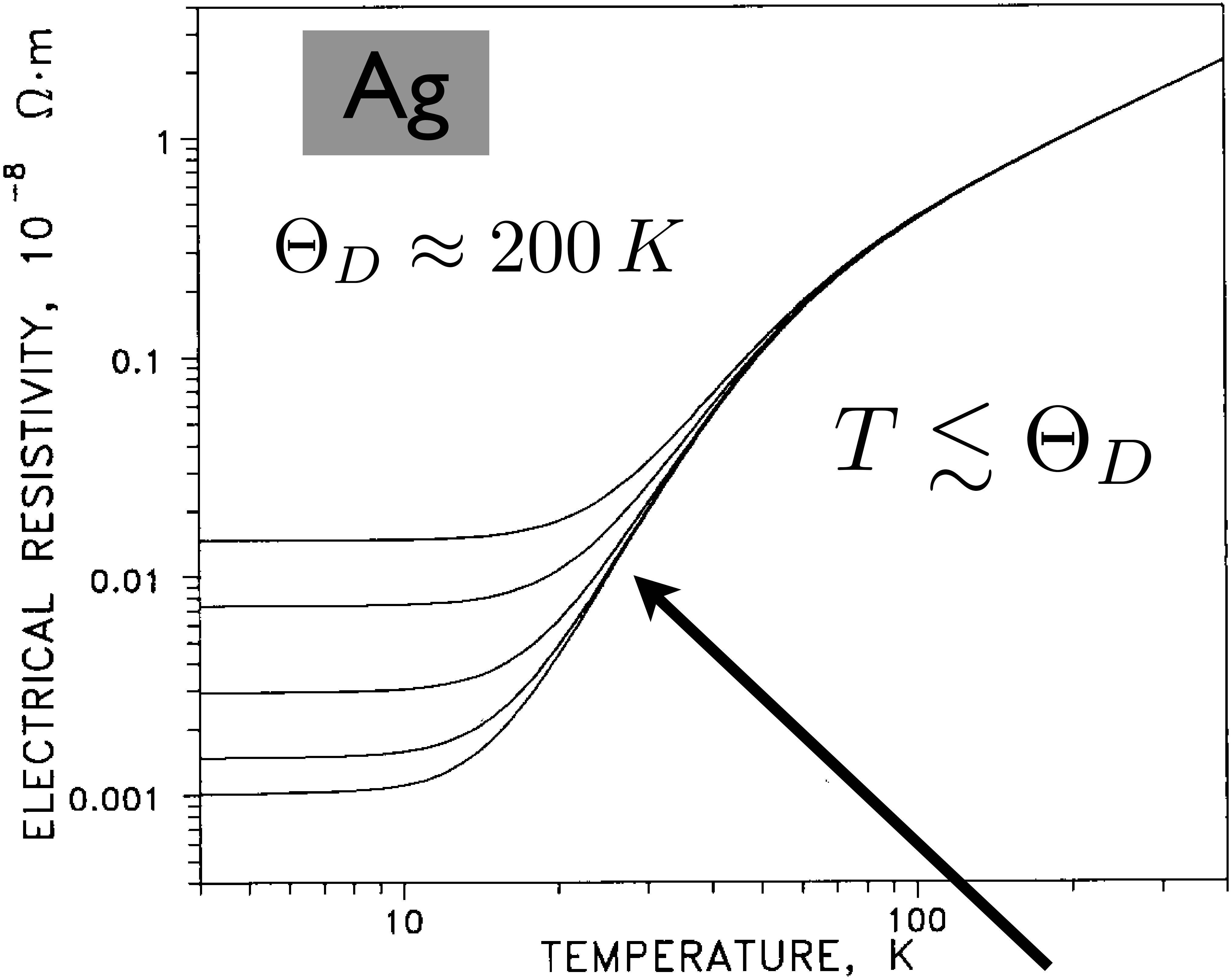
electron-phonon scattering

$$\rho(T) = \rho_0 + a\,T^2 + b\,T^5$$



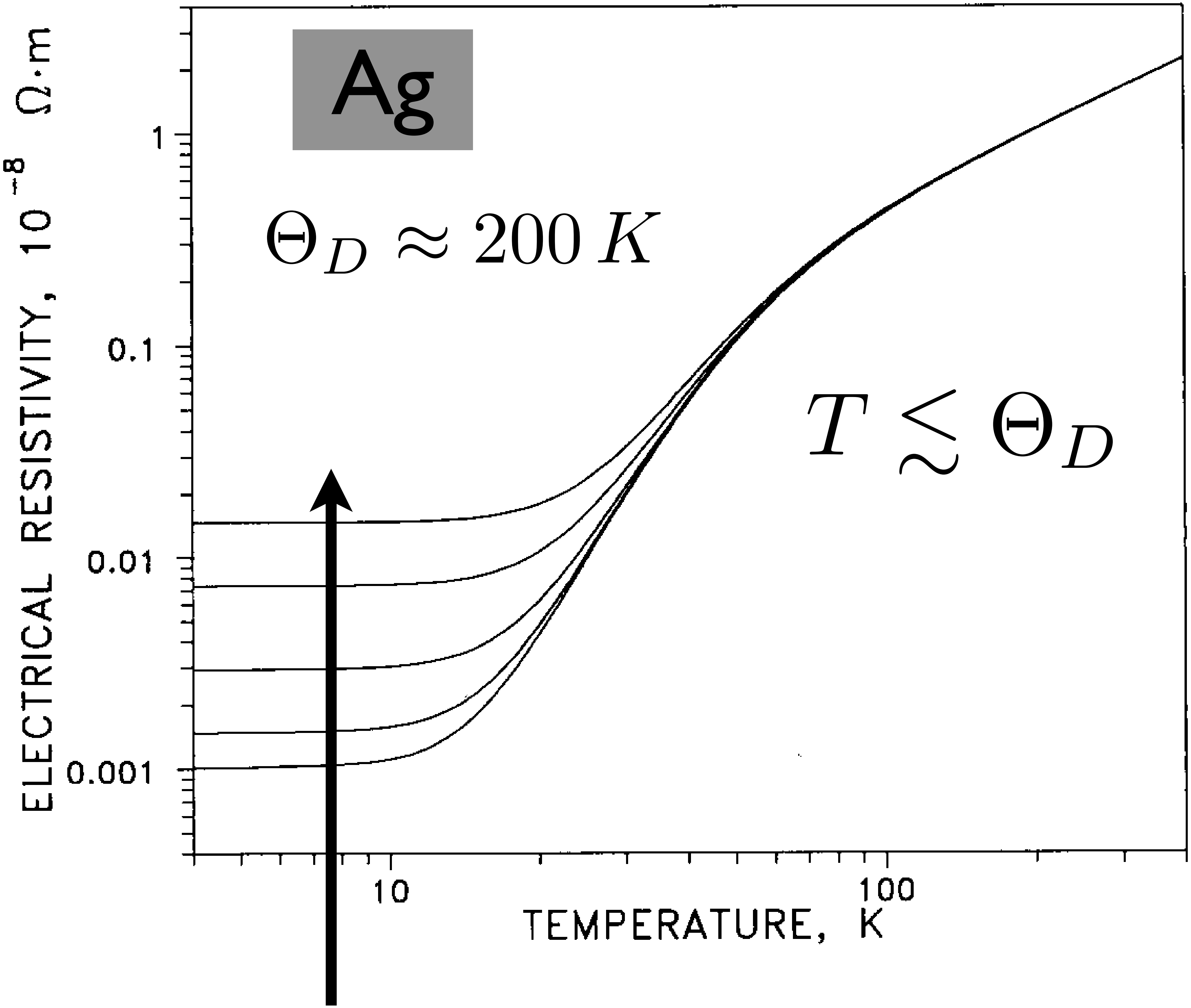
electron-electron scattering

$$\rho(T) = \rho_0 + a\,T^2 + b\,T^5$$



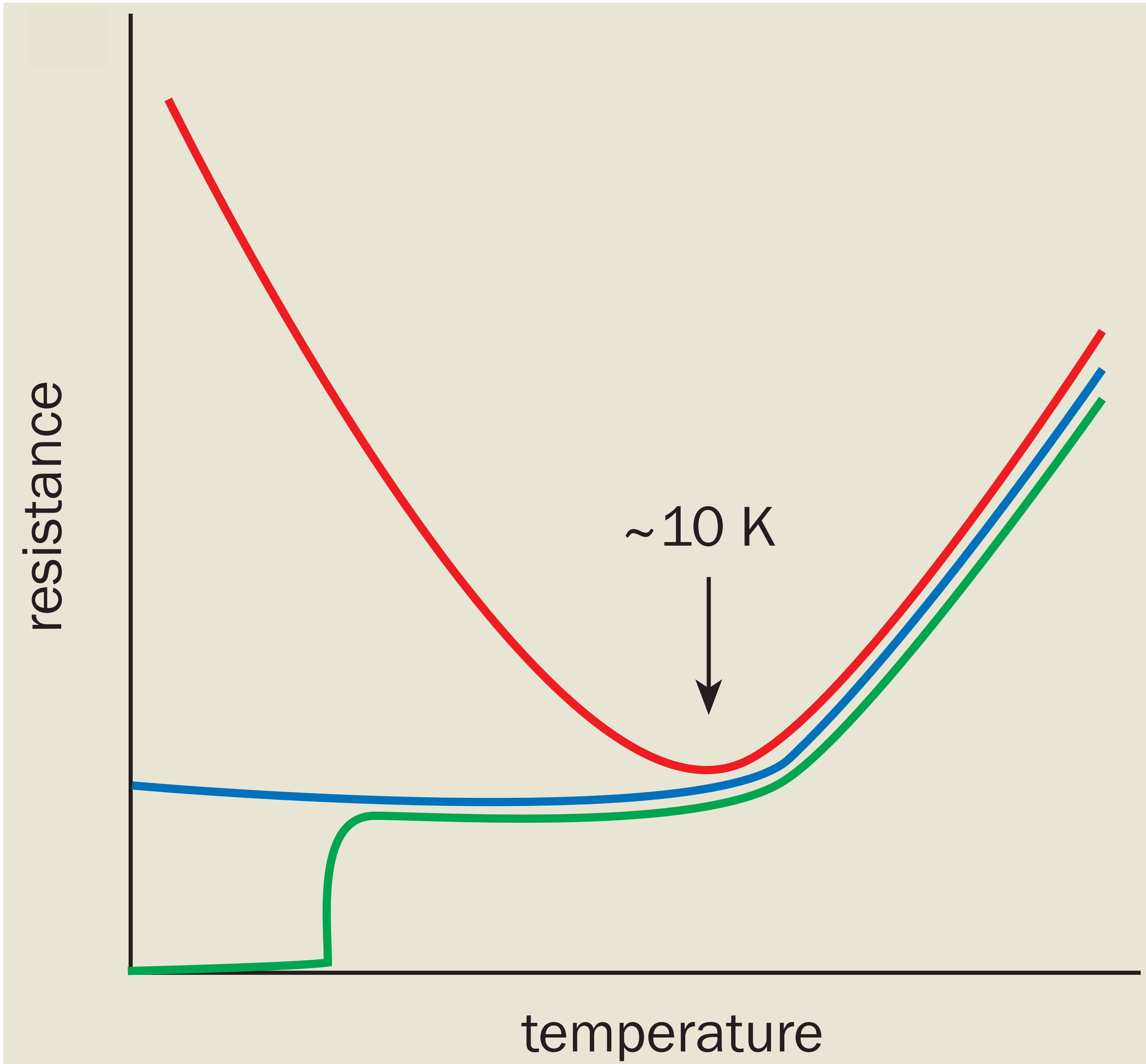
electron-impurity scattering

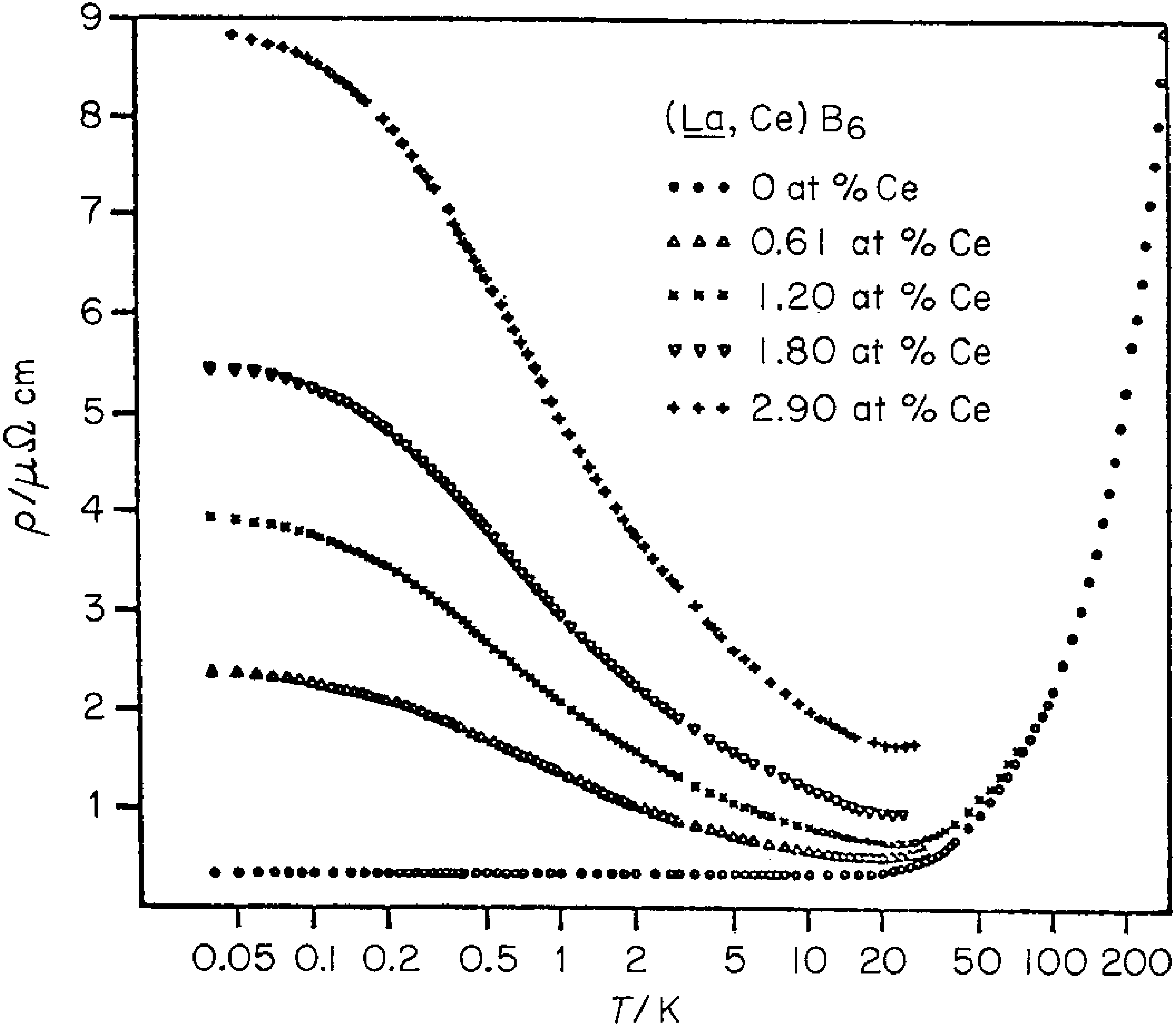
$$\rho(T) = \rho_0 + a\,T^2 + b\,T^5$$



increasing concentration of impurities

The Kondo Effect





Samwer and Winzer, Z. Phys B, 25, 269, 1976

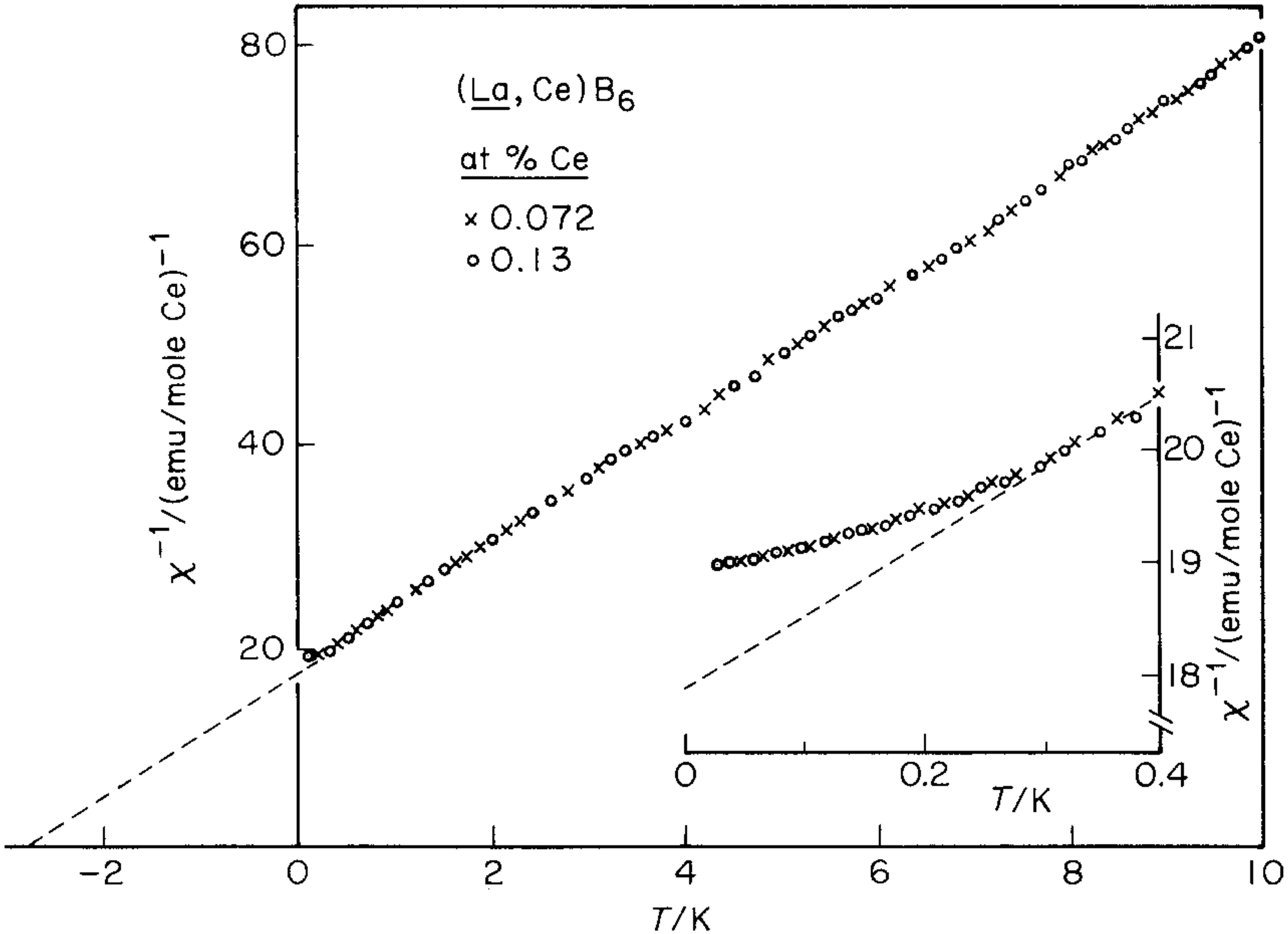
MAGNETIC Impurities

Fermi liquid

Pauli: $\chi \propto T^0$

Free magnetic moment

Curie: $\chi \propto T^{-1}$



Felsch, Z. Phys B, 29, 211, 1978

Progress of Theoretical Physics, Vol. 32, No. 1, July 1964

Resistance Minimum in Dilute Magnetic Alloys

Jun KONDO

The Kondo Hamiltonian

$$H_K = \sum_{k,\sigma} \varepsilon(k)\, c^\dagger_{k\sigma} c_{k\sigma} + g_K \vec{S} \cdot \sum_{k\sigma k'\sigma'} c^\dagger_{k\sigma} \frac{1}{2} \vec{\tau}_{\sigma\sigma'} c_{k'\sigma'}$$

$$c^\dagger_{k\sigma}\,,\, c_{k\sigma}$$

Conduction electrons

$$\sigma = \uparrow, \downarrow$$

Spin $SU(2)$

$$\varepsilon(k) = \frac{k^2}{2m} - \varepsilon_F$$

Dispersion relation

The Kondo Hamiltonian

$$H_K = \sum_{k,\sigma} \varepsilon(k)\, c^\dagger_{k\sigma} c_{k\sigma} + g_K \vec{S} \cdot \sum_{k\sigma k'\sigma'} c^\dagger_{k\sigma} \frac{1}{2} \vec{\tau}_{\sigma\sigma'} c_{k'\sigma'}$$

$\vec{S}$	Spin of magnetic impurity
$\vec{\tau}$	Pauli matrices
g_K	Kondo coupling
$g_K < 0$	Ferromagnetic
$g_K > 0$	Anti-Ferromagnetic

$$\rho(T) = \rho_0 + a\,T^2 + b\,T^5 + c\,g_{_K}^2 - \tilde{c}\,g_{_K}^3 \ln\left(T/\varepsilon_F\right)$$

$c,\ \tilde{c} \quad \propto$ concentration of impurities

$\varepsilon_F \quad =$ UV cutoff

$g_{_K} < 0$ Ferromagnetic $\Rightarrow$ as T decreases $\rho(T)$ DECREASES

$$\rho(T) = \rho_0 + a\,T^2 + b\,T^5 + c\,g_{_K}^2 - \tilde{c}\,g_{_K}^3 \ln\left(T/\varepsilon_F\right)$$

$c,\ \tilde{c} \quad \propto$ concentration of impurities

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~~$g_{_K} < 0$ Ferromagnetic $\Longrightarrow$ as T decreases $\rho(T)$ DECREASES~~

$$\rho(T) = \rho_0 + a\,T^2 + b\,T^5 + c\,g_{_K}^2 - \tilde{c}\,g_{_K}^3\,\ln\left(T/\varepsilon_F\right)$$

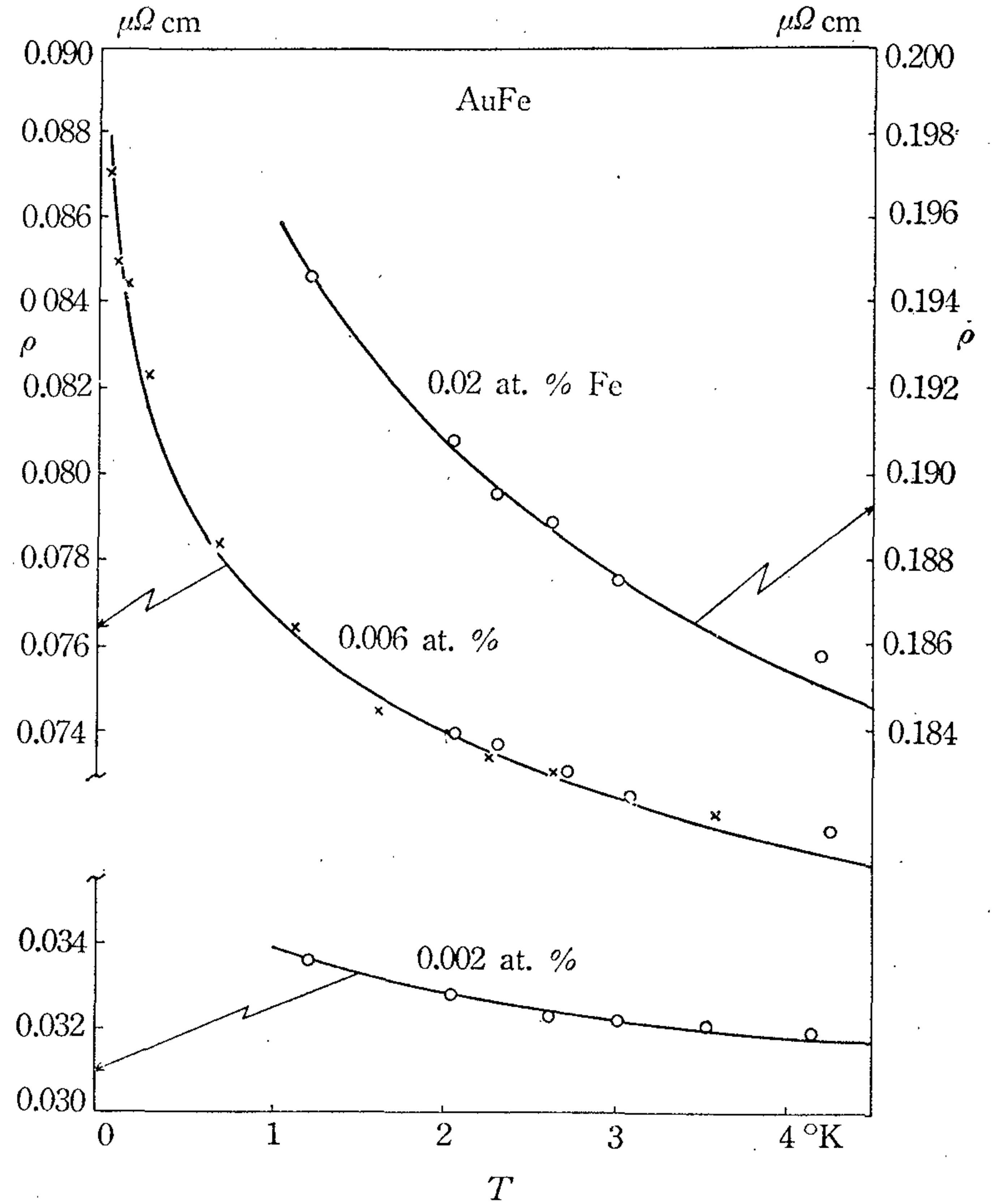
$c,\ \tilde{c}$ $\propto$ concentration of impurities

ε_F $=$ UV cutoff

$g_{_K} > 0$ $\Rightarrow$ as T decreases $\rho(T)$ INCREASES

Anti-Ferromagnetic

$$\rho(T) = \rho_0 + a\,T^2 + b\,T^5 + c\,g_K^2 - \tilde{c}\,g_K^3\,\ln(T/\varepsilon_F)$$



Breakdown of Perturbation Theory

$$\rho(T) = \rho_0 + a\,T^2 + b\,T^5 + c\,g_{_K}^2 - \tilde{c}\,g_{_K}^3 \ln\left(T/\varepsilon_F\right)$$

$\mathcal{O}(g_K^3)$ term is same order as $\mathcal{O}(g_K^2)$ term when

$$T_K \approx \varepsilon_F\, e^{-\frac{c}{\tilde{c}}\frac{1}{g_K}}$$

"Kondo temperature"

The Kondo Problem

Cross section for electron scattering off a **MAGNETIC** impurity **INCREASES** as energy **DECREASES**

The coupling GROWS at low energies

$$\beta_{g_K} \propto -g_K^2 + \mathcal{O}(g_K^3)$$

Asymptotic freedom!

$$T_K \sim \Lambda_{\mathrm{QCD}}$$

The Kondo Problem

The coupling diverges at low energy!

What is the ground state?

We know the answer!

Solutions of the Kondo Problem

Numerical RG (Wilson 1975)

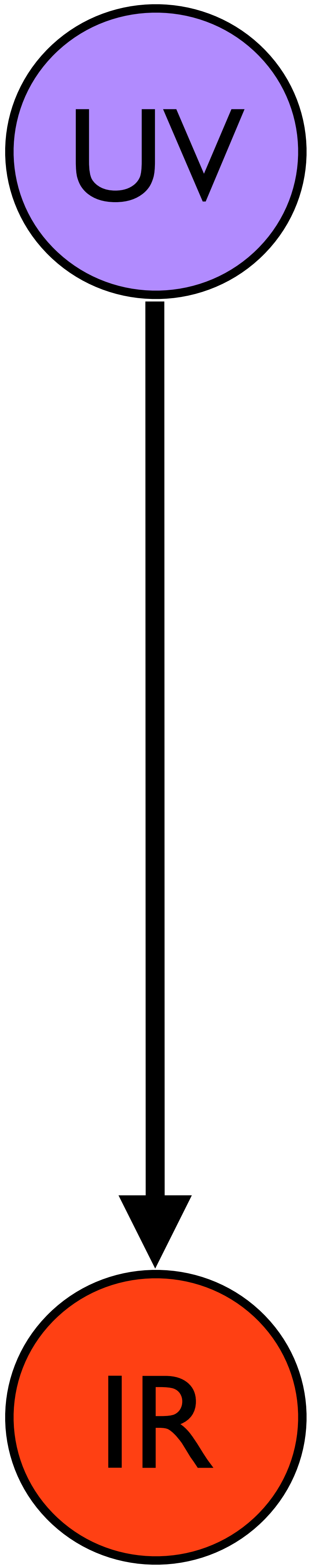
Fermi liquid description (Nozières 1975)

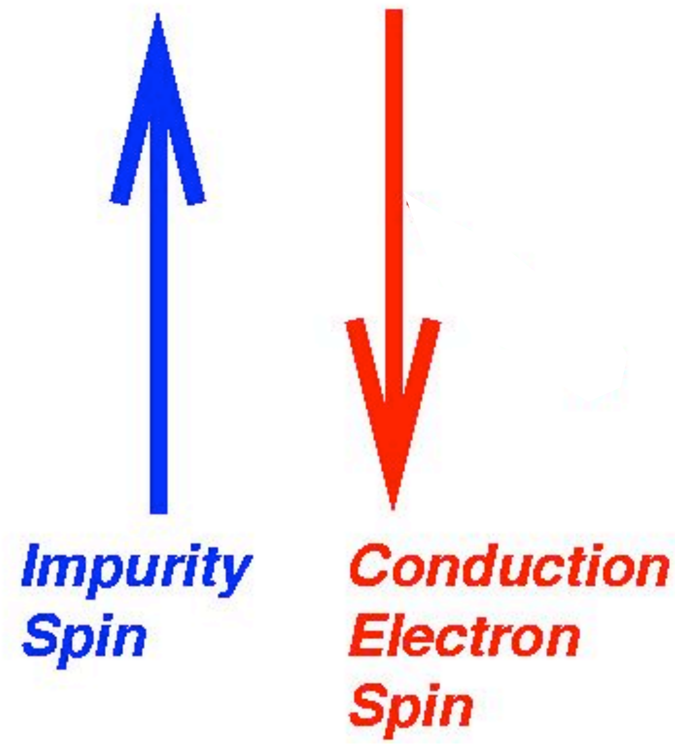
Bethe Ansatz/Integrability
(Andrei, Wiegmann, Tsvelick, Destri, ... 1980s)

Large-N expansion
(Anderson, Read, Newns, Doniach, Coleman, ...1970-80s)

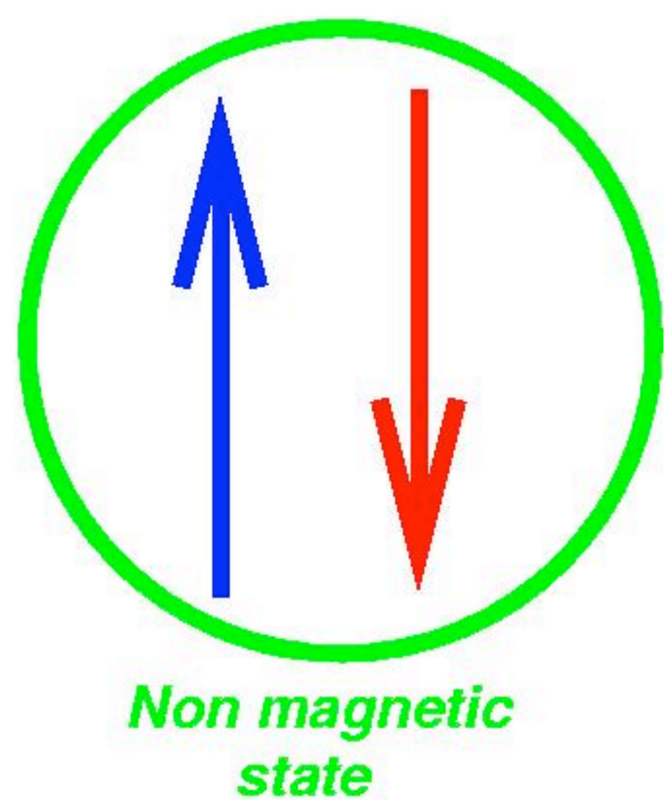
Quantum Monte Carlo
(Hirsch, Fye, Gubernatis, Scalapino,... 1980s)

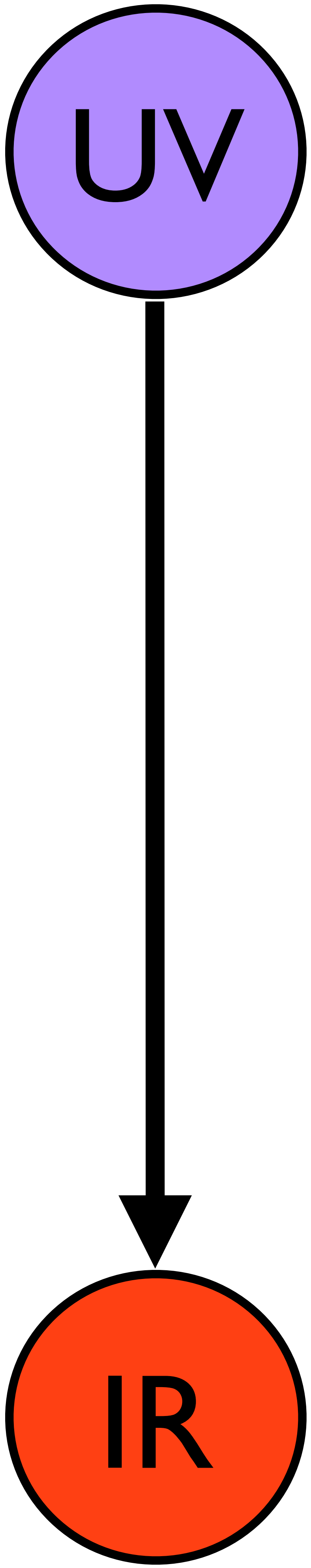
Conformal Field Theory (CFT)
(Affleck and Ludwig 1990s)

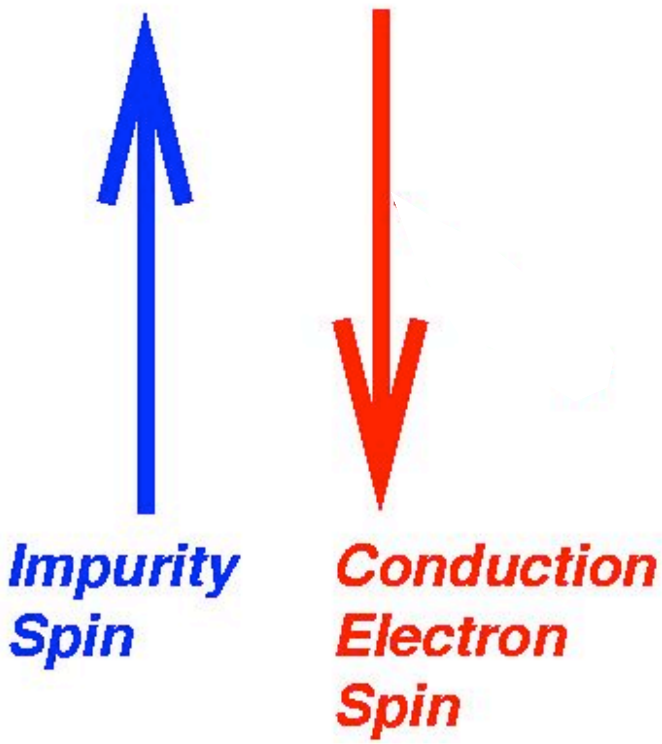




One electron binds with impurity
ground state is “Kondo singlet”



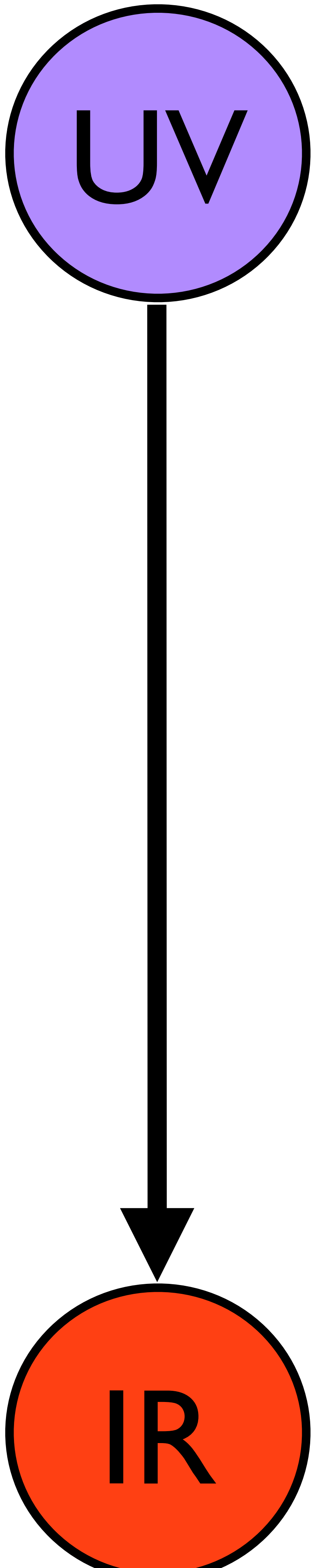




One electron binds with impurity ground state is “Kondo singlet”

$$\frac{1}{\sqrt{2}}\left(|\uparrow_i \downarrow_e\rangle - |\downarrow_i \uparrow_e\rangle\right)$$

Anti-symmetric singlet of $SU(2)$

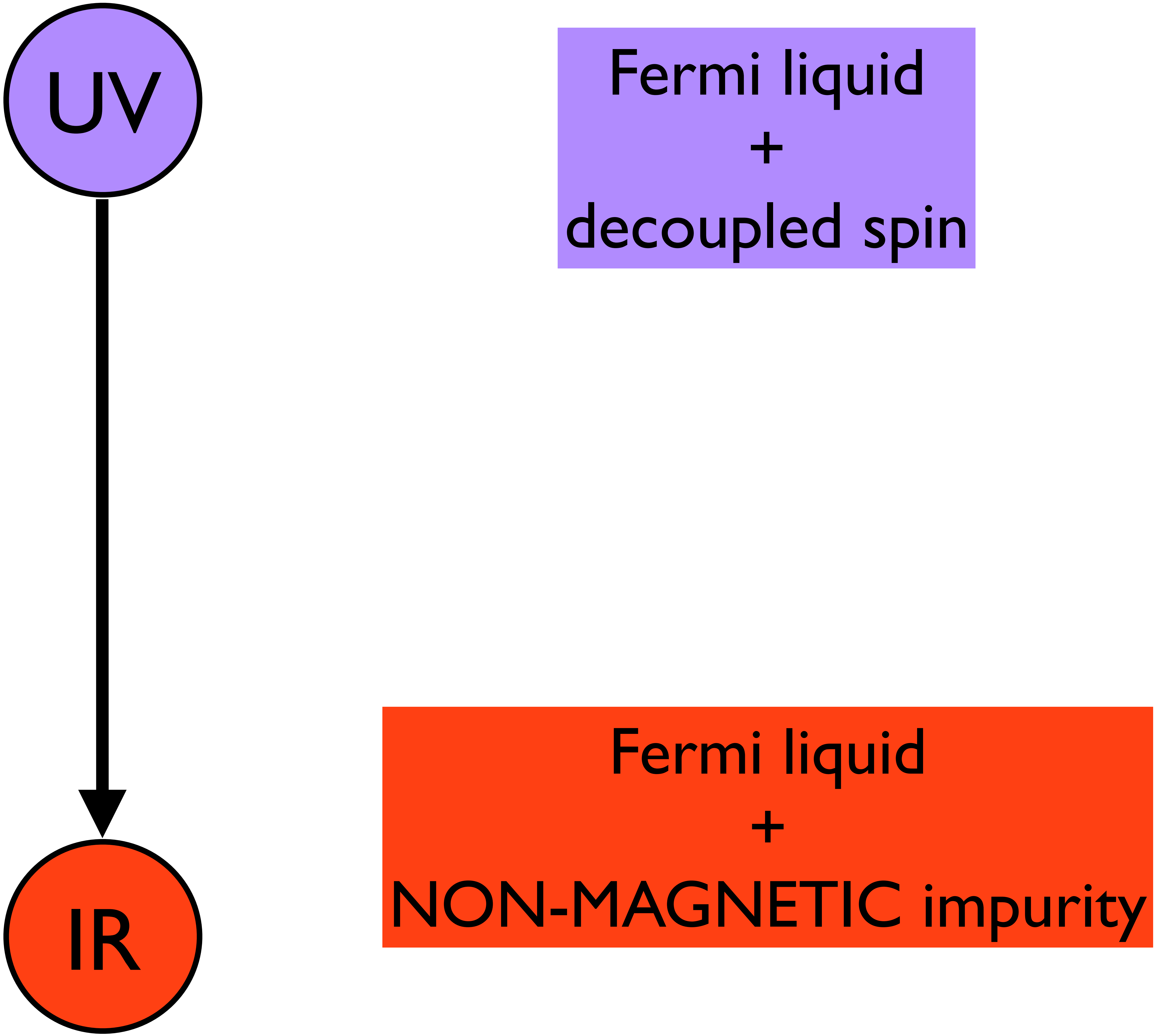


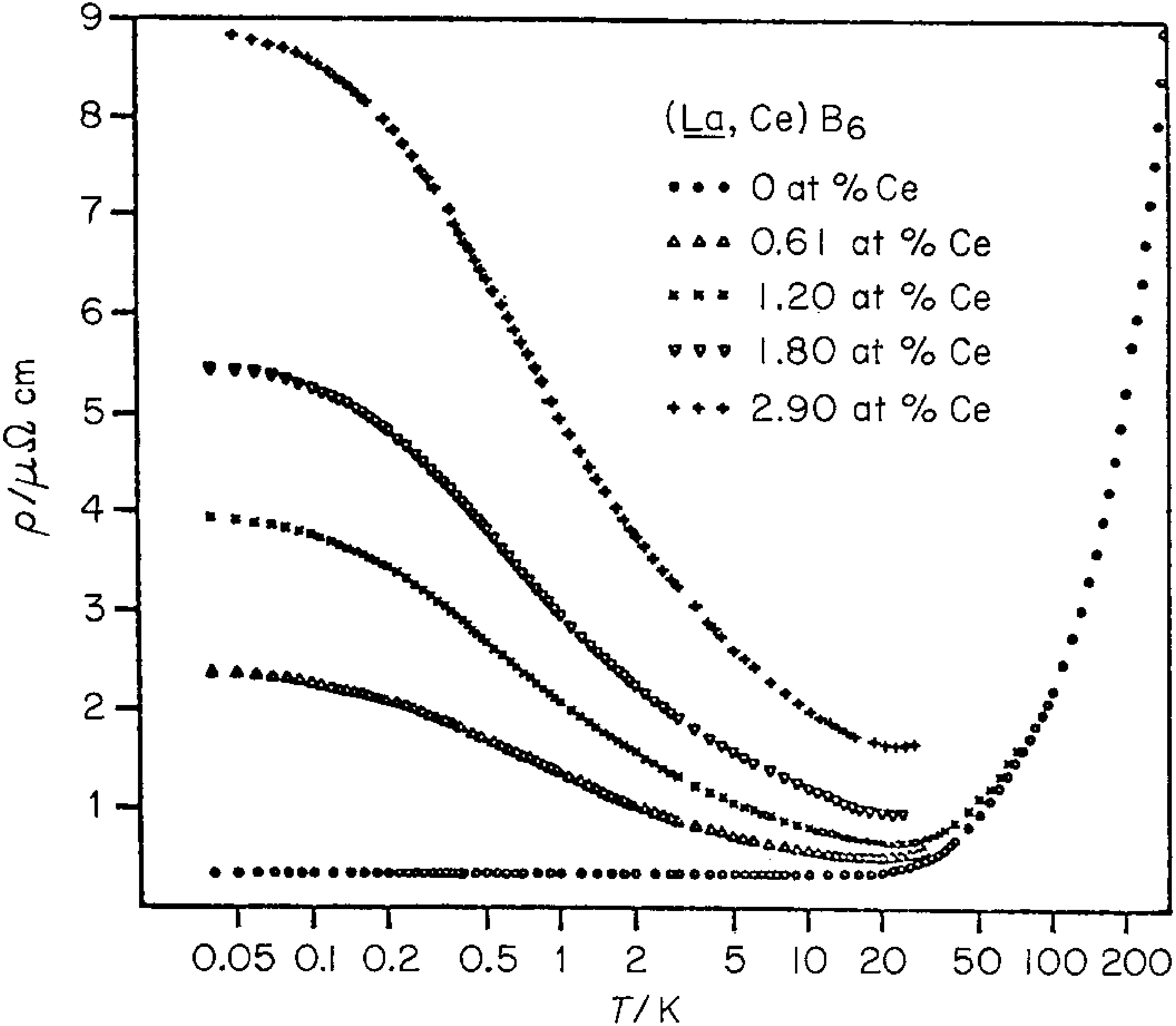
Fermi liquid
+
decoupled spin

Fermi liquid

+ NO spin

+ electrons EXCLUDED
from impurity location


UV
IR
Fermi liquid
+
decoupled spin
Fermi liquid
+
NON-MAGNETIC impurity



Samwer and Winzer, Z. Phys B, 25, 269, 1976

Kondo Effect in Many Systems

alloys of Cu, Ag, Au, Mg, Zn, ...

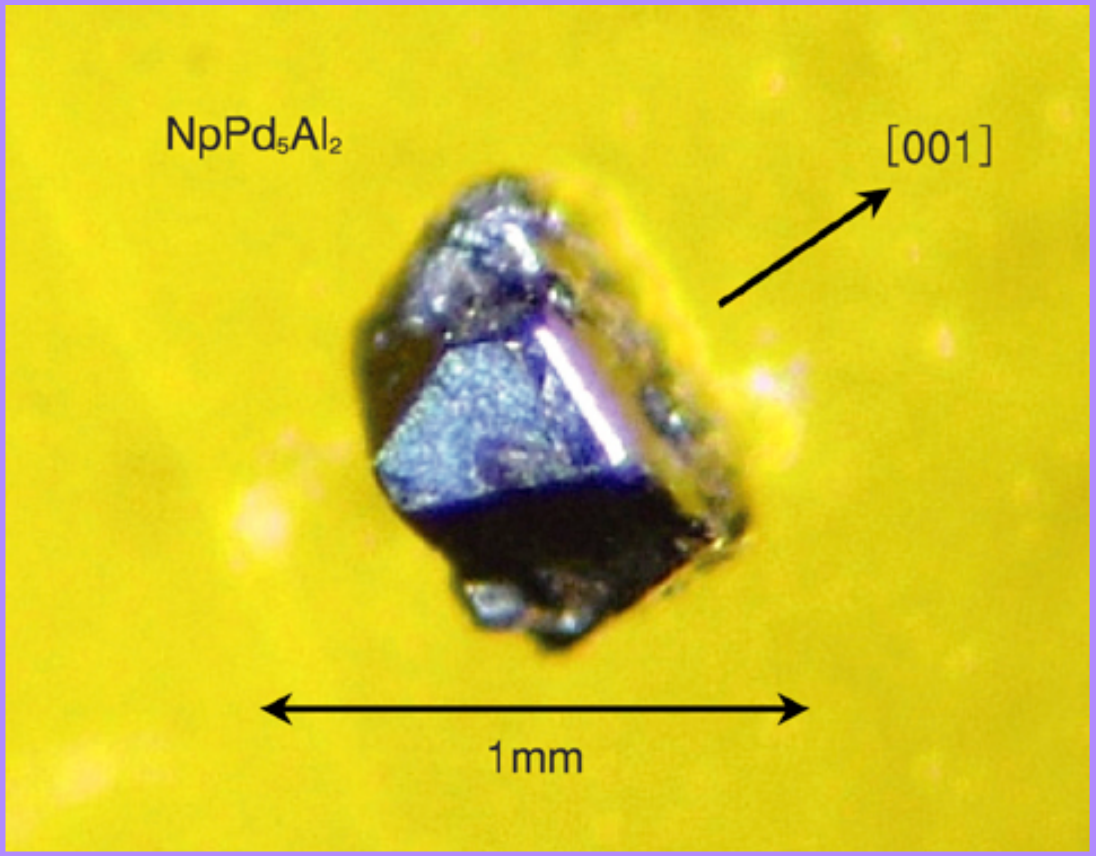
...with Cr, Fe, Mo, Mn, Re, Os, ... impurities

Heavy fermion compounds

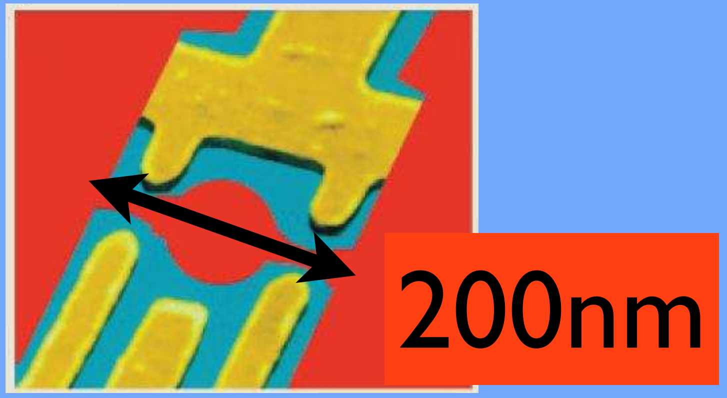
$CeCu_6$ $CePd_2Si_2$

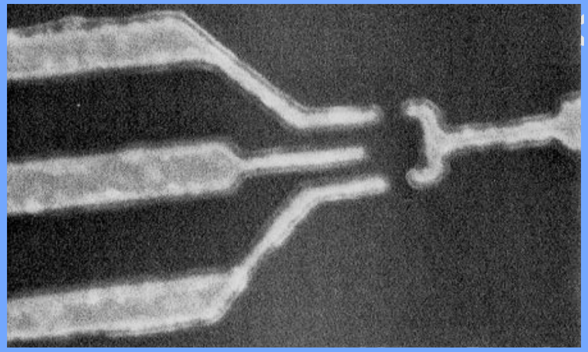
$YbAl_3$ $YbRh_2Si_2$

UBe_{13} UPt_3



Quantum dots





Generalizations

Enhance the spin group

$$SU(2) \rightarrow SU(N)$$

arXiv:1306.6326v1 [cond-mat.mes-hall] 26 Jun 2013

Observation of the SU(4) Kondo state in a double quantum dot

A. J. Keller[1], S. Amasha[1,†], I. Weymann[2], C. P. Moca[3,4], I. G. Rau[1,‡], J. A. Katine[5], Hadas Shtrikman[6], G. Zaránd[3], and D. Goldhaber-Gordon[1,*]

[1]Geballe Laboratory for Advanced Materials, Stanford University, Stanford, CA 94305, USA
[2]Faculty of Physics, Adam Mickiewicz University, Poznań, Poland
[3]BME-MTA Exotic Quantum Phases "Lendület" Group, Institute of Physics, Budapest University of Technology and Economics, H-1521 Budapest, Hungary
[4]Department of Physics, University of Oradea, 410087, Romania
[5]HGST, San Jose, CA 95135, USA
[6]Department of Condensed Matter Physics, Weizmann Institute of Science, Rehovot 96100, Israel
[†]Present address: MIT Lincoln Laboratory, Lexington, MA 02420, USA
[‡]Present address: IBM Research – Almaden, San Jose, CA 95120, USA
[*]Corresponding author; goldhaber-gordon@stanford.edu

Generalizations

Enhance the spin group

$$SU(2) \rightarrow SU(N)$$

Representation of impurity spin

$$s_{\text{imp}} = 1/2 \longrightarrow R_{\text{imp}}$$

Multiple "channels" or "flavors"

$$c \rightarrow c^{\alpha} \qquad \alpha = 1, \ldots, k$$

$$U(1) \times SU(k)$$

Generalizations

Kondo model specified by

$$N,\ R_{\mathrm{imp}},\ k$$

Apply the techniques mentioned above...

IR fixed point:

NOT always a fermi liquid

"Non-Fermi liquids"

Multiple Impurities

$$H = H_K + \sum_{ij} g_{ij}^{RKKY} \vec{S}_i \cdot \vec{S}_j$$

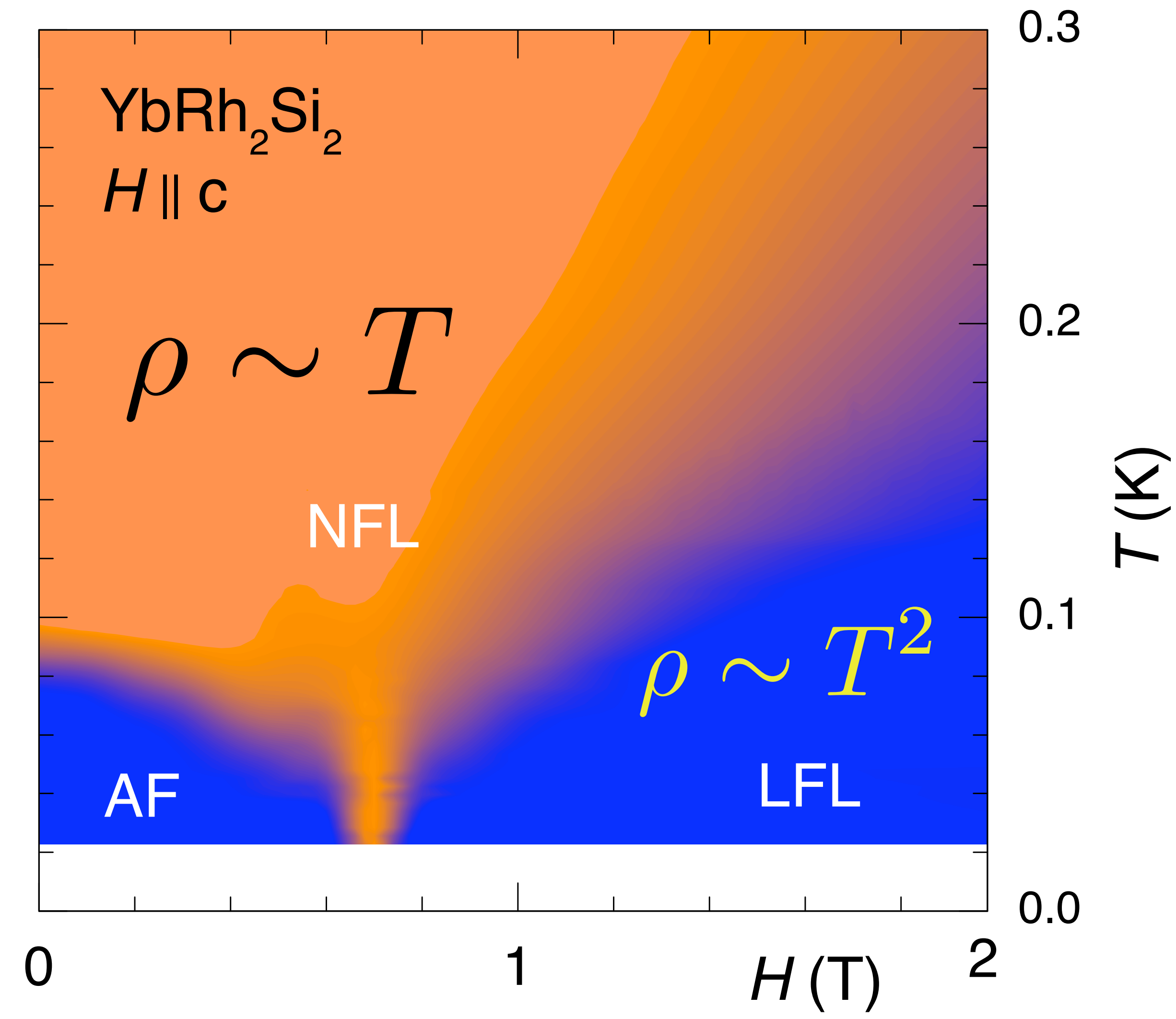
Ruderman-Kittel-Kasuya-Yosida (RKKY) coupling

Heavy fermion compounds

$$\mathrm{YbRh_2Si_2}$$

Kondo lattice

J. Custers et al., Nature 424, 524 (2003)



Solutions of the Kondo Problem

Numerical RG (Wilson 1975)

Fermi liquid description (Nozières 1975)

Bethe Ansatz/Integrability
(Andrei, Wiegmann, Tsvelick, Destri, ... 1980s)

Large-N expansion
(Anderson, Read, Newns, Doniach, Coleman, ...1970-80s)

Quantum Monte Carlo
(Hirsch, Fye, Gubernatis, Scalapino,... 1980s)

Conformal Field Theory (CFT)
(Affleck and Ludwig 1990s)

The Kondo Lattice...

Alexei Tsvelik

"... remains one of the biggest unsolved problems in condensed matter physics."

Alexei Tsvelik
QFT in Condensed Matter Physics
(Cambridge Univ. Press, 2003)

The Kondo Lattice...

Alexei Tsvelik

“... remains one of the

ms

ics.”

Let’s try AdS/CFT!

Alexei Tsvelik

QFT in Condensed Matter Physics

(Cambridge Univ. Press, 2003)

GOAL

Find a holographic description
of the
Kondo Effect

Solutions of the Kondo Problem

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CFT Approach to the Kondo Effect

Affleck and Ludwig 1990s

Reduction to one dimension

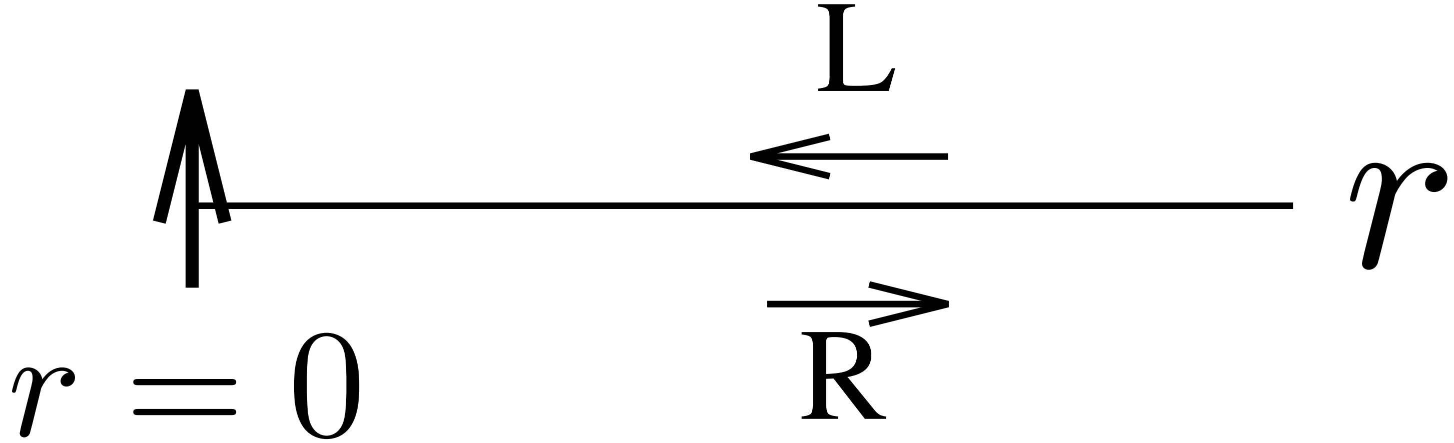
Kondo interaction preserves spherical symmetry

$$g_K \, \delta^3(\vec{x}) \, \vec{S} \cdot c^\dagger(\vec{x}) \, \frac{1}{2} \vec{\tau} \, c(\vec{x})$$

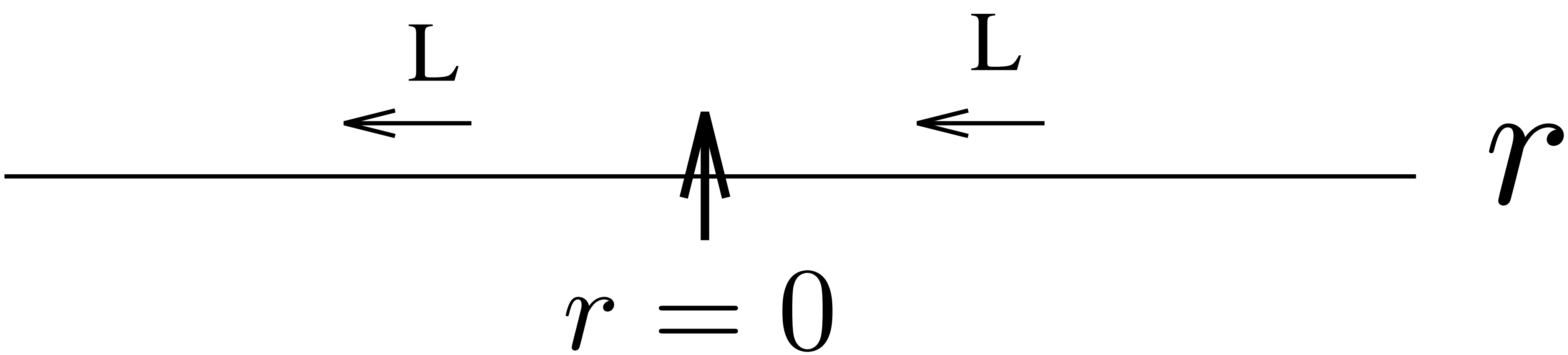
restrict to s-wave

restrict to momenta near k_F

$$c(\vec{x}) \approx \frac{1}{r} \left[e^{-ik_F r} \psi_L(r) - e^{+ik_F r} \psi_R(r) \right]$$



$$\psi_L(-r) \equiv \psi_R(+r)$$



CFT Approach to the Kondo Effect

$$H_K = \frac{v_F}{2\pi}\int_{-\infty}^{+\infty} dr\, \psi^{\alpha\dagger}_{L} i\partial_r \psi^{\alpha}_{L} + v_F \tilde{g}_K \vec{S}\cdot \psi^{\alpha}_{L}(0)^\dagger \frac{1}{2}\vec{\tau}\,\psi^{\alpha}_{L}(0)$$

$$\tilde{g}_K \equiv \frac{k_F^2}{2\pi^2 v_F} \times g_K$$

RELATIVISTIC chiral fermions

v_F = "speed of light"

CFT!

Spin $SU(N)$

R_{imp}

$k \geq 1$

$$J = \psi_L^{\alpha\dagger} \psi_L^{\alpha}$$

$U(1)$

$$\vec{J} = \psi_L^{\alpha\dagger} \frac{\vec{\tau}}{2} \psi_L^{\alpha}$$

$SU(N)$

$$J^A = \psi_L^{\alpha\dagger} t^A_{\alpha\alpha'} \psi_L^{\alpha'}$$

$SU(k)$

$$z \equiv \tau + ir$$

$$J^A(z) = \sum_{n \in \mathbb{Z}} z^{-n-1} J_n^A$$

$$[J_n^A, J_m^B] = i f^{ABC} J_{n+m}^C + N \frac{n}{2} \delta^{AB} \delta_{n,-m}$$

$SU(k)_N$ Kac-Moody Current Algebra

N counts net number of chiral fermions

CFT Approach to the Kondo Effect

$$H_K = \frac{v_F}{2\pi}\int_{-\infty}^{+\infty} dr\, \psi^{\alpha\dagger}_{L} i\partial_r \psi^{\alpha}_{L} + v_F \tilde{g}_K \vec{S}\cdot \psi^{\alpha}_{L}(0)^\dagger \frac{1}{2}\vec{\tau}\,\psi^{\alpha}_{L}(0)$$

Full symmetry:

$(1+1)d$ conformal symmetry

$$SU(N)_k \times SU(k)_N \times U(1)_{kN}$$

Sugawara Hamiltonian

Spin $SU(N)$

$R_{\rm imp}$

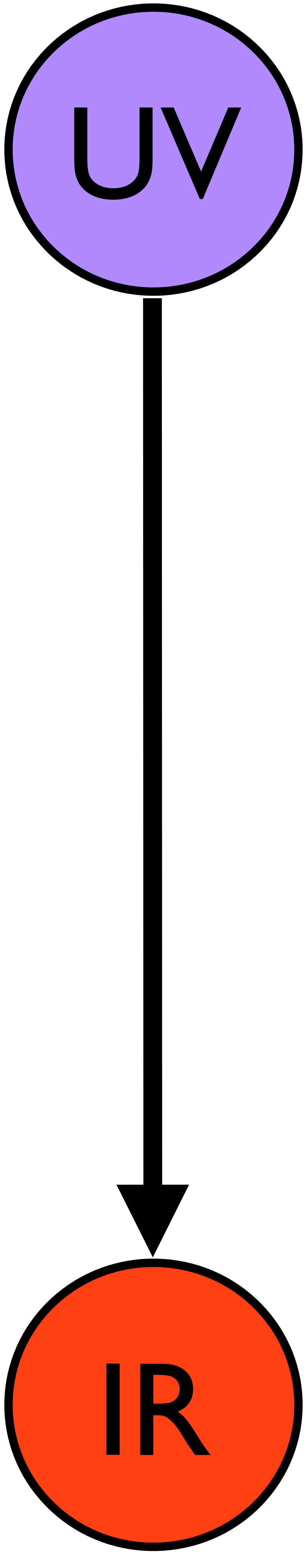
$k \geq 1$

$$H_K = \int dr \left[\frac{1}{4\pi N k} J^2 + \frac{1}{2\pi(k+N)} \vec{J}^2 + \frac{1}{2\pi(k+N)} J^A J^A \right] + \tilde{g}_K \vec{S} \cdot \vec{J}(0)$$

$$J = \psi^{\alpha\dagger}_L \psi^{\alpha}_L \qquad U(1)$$

$$\vec{J} = \psi^{\alpha\dagger}_L \frac{\vec{\tau}}{2} \psi^{\alpha}_L \qquad SU(N)$$

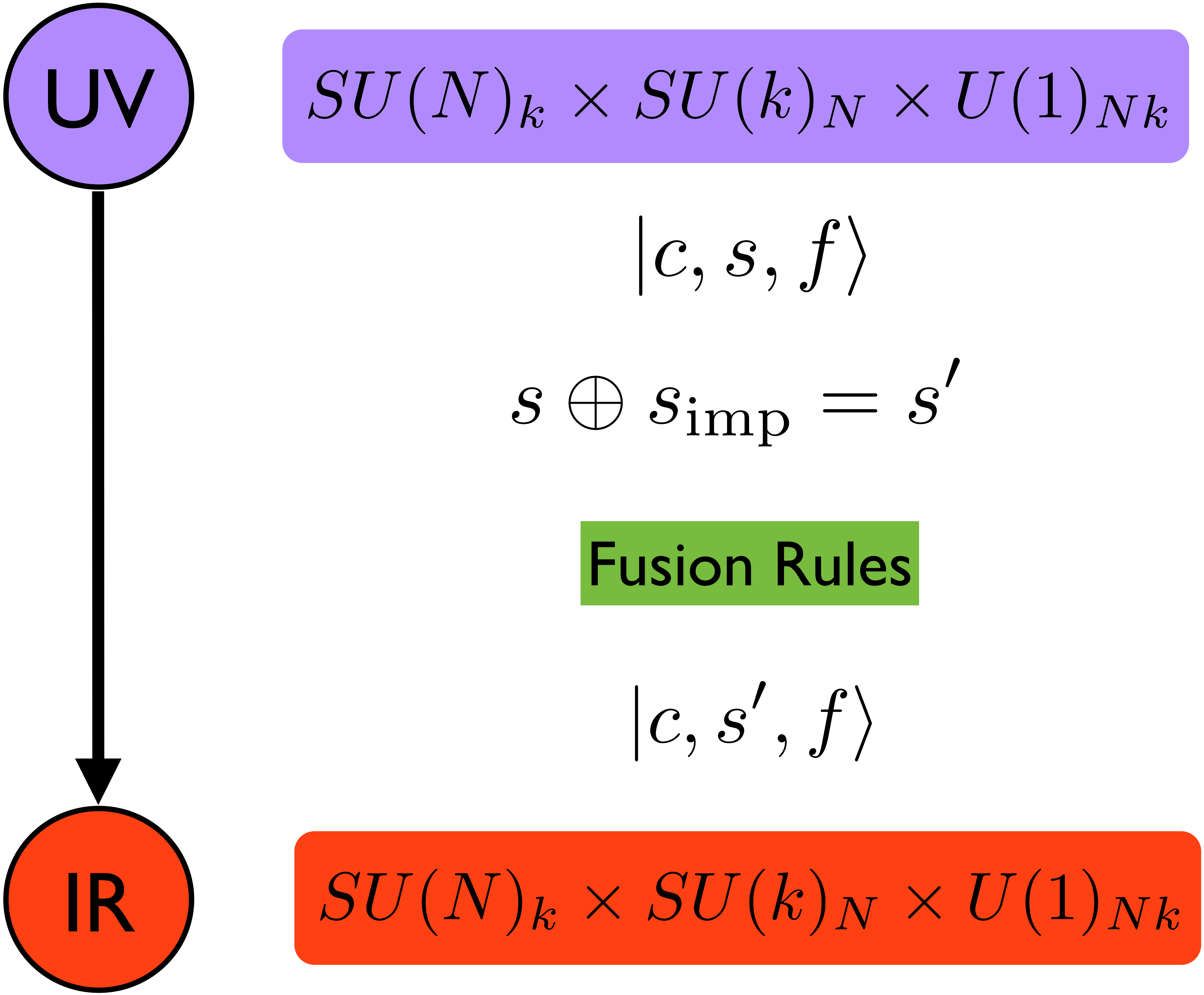
$$J^A = \psi^{\alpha\dagger}_L t^A_{\alpha\alpha'} \psi^{\alpha'}_L \qquad SU(k)$$

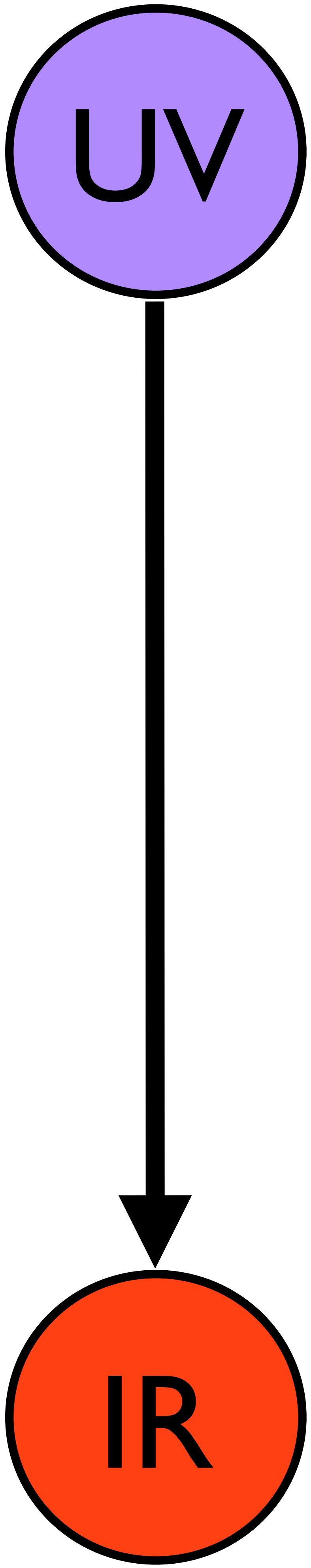


$$SU(N)_k \times SU(k)_N \times U(1)_{Nk}$$

Eigenstates are representations of the Kac-Moody algebra

$$SU(N)_k \times SU(k)_N \times U(1)_{Nk}$$


UV
$SU(N)_k \times SU(k)_N \times U(1)_{Nk}$
$|c, s, f\rangle$
$s \oplus s_{\text{imp}} = s'$
Fusion Rules
$|c, s', f\rangle$
IR
$SU(N)_k \times SU(k)_N \times U(1)_{Nk}$



$$SU(N)_k \times SU(k)_N \times U(1)_{Nk}$$

Fusion Rules

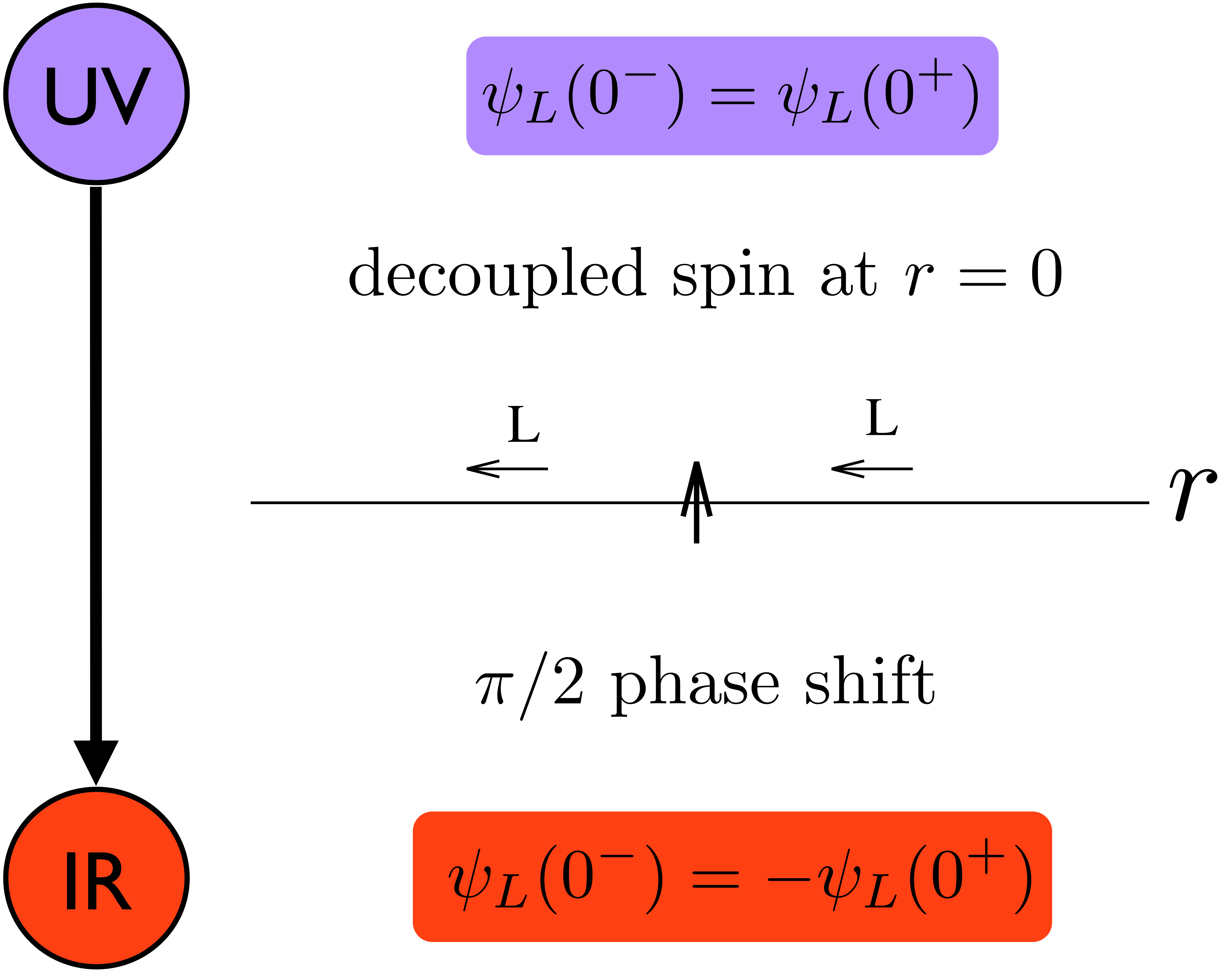
Example: $SU(2)_k$

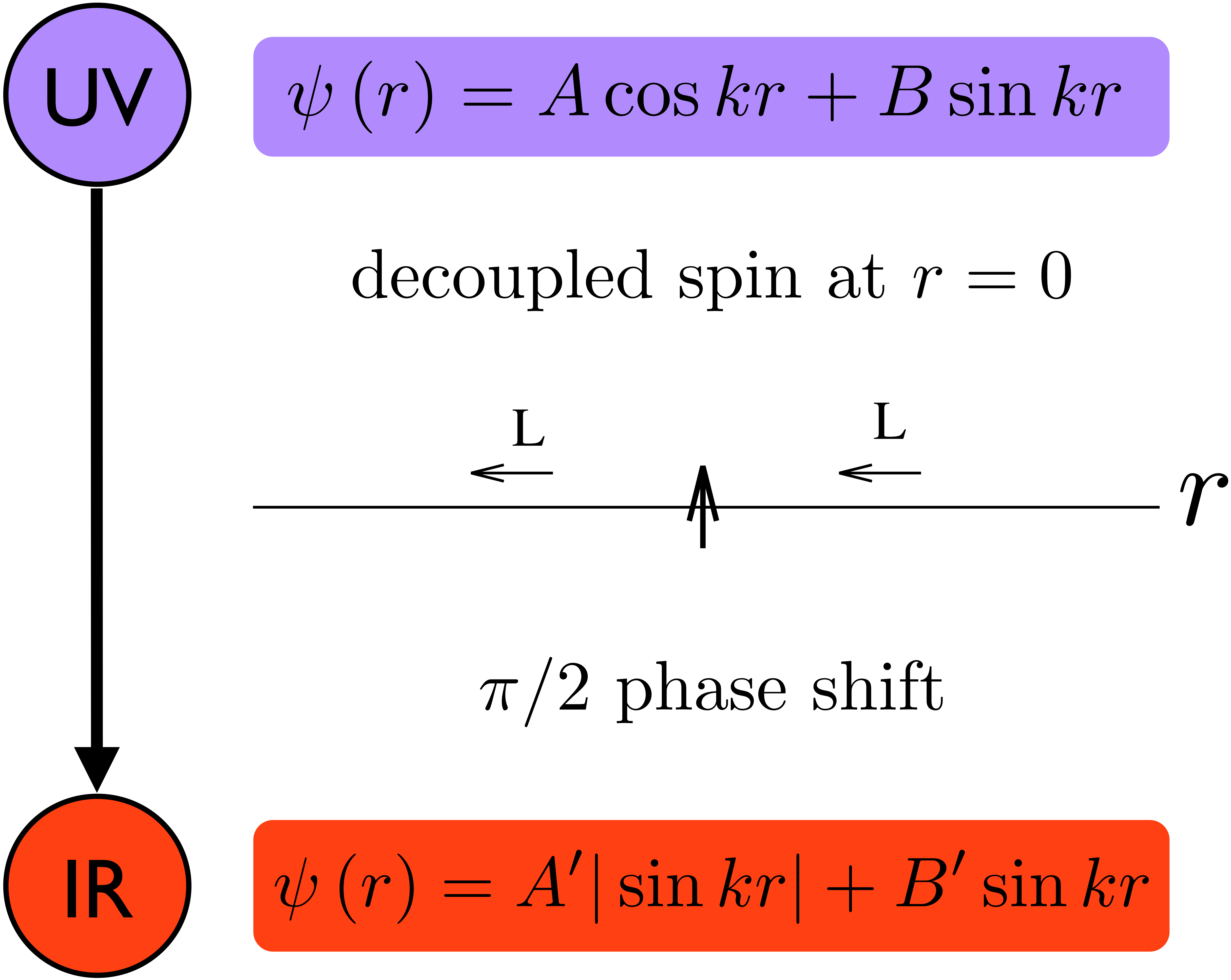
$$s \oplus s_{\text{imp}} = s'$$

$$|s - s_{\text{imp}}| \leq s' \leq \min\{s + s_{\text{imp}}, k - (s + s_{\text{imp}})\}$$

$$(\text{for } k - (s + s_{\text{imp}}) > 0)$$

$$SU(N)_k \times SU(k)_N \times U(1)_{Nk}$$


UV
$\psi_L(0^-) = \psi_L(0^+)$
decoupled spin at $r = 0$
L
L
r
$\pi/2$ phase shift
IR
$\psi_L(0^-) = -\psi_L(0^+)$


UV
$\psi(r) = A\cos kr + B\sin kr$
decoupled spin at $r = 0$
L
L
r
$\pi/2$ phase shift
IR
$\psi(r) = A'|\sin kr| + B'\sin kr$

CFT Approach to the Kondo Effect

Take-Away Messages

Central role of the Kac-Moody Algebra

Kondo coupling: $\vec{S} \cdot \vec{J}$

PHASE SHIFT

Outline:

- The Kondo Effect
- The CFT Approach
- A Top-Down Holographic Model
- A Bottom-Up Holographic Model
- Summary and Outlook

GOAL

Find a holographic description
of the
Kondo Effect

What classical action do we write
on the gravity side of the correspondence?

How do we describe holographically...

① The chiral fermions?

② The impurity?

③ The Kondo coupling?

Holography

Top-down:

AdS solution to a string or supergravity theory

Bottom-up:

AdS solution of some *ad hoc* Lagrangian

Top-Down Model

	0	1	2	3	4	5	6	7	8	9
N_c D3	X	X	X	X						
N_7 D7	X	X			X	X	X	X	X	X
N_5 D5	X				X	X	X	X	X	

3-3 and 5-5 and 7-7

3-7 and 7-3

3-5 and 5-3

7-5 and 5-7

Open strings

Top-Down Model

	0	1	2	3	4	5	6	7	8	9
N_c D3	X	X	X	X						
N_7 D7	X	X			X	X	X	X	X	X
N_5 D5	X				X	X	X	X	X	

3-3 and 5-5 and 7-7

3-7 and 7-3

3-5 and 5-3

7-5 and 5-7

CFT with holographic dual

Top-Down Model

	0	1	2	3	4	5	6	7	8	9
N_c D3	X	X	X	X						
N_7 D7	X	X			X	X	X	X	X	X
N_5 D5	X				X	X	X	X	X	

3-3 and 5-5 and 7-7

3-7 and 7-3

3-5 and 5-3

7-5 and 5-7

Decouple

Top-Down Model

	0	1	2	3	4	5	6	7	8	9
N_c D3	X	X	X	X						
N_7 D7	X	X			X	X	X	X	X	X
N_5 D5	X				X	X	X	X	X	

3-3 and 5-5 and 7-7

3-7 and 7-3

3-5 and 5-3

7-5 and 5-7

(1+1)-dimensional chiral fermions

Top-Down Model

	0	1	2	3	4	5	6	7	8	9
N_c D3	X	X	X	X						
N_7 D7	X	X			X	X	X	X	X	X
N_5 D5	X				X	X	X	X	X	

3-3 and 5-5 and 7-7

3-7 and 7-3

3-5 and 5-3

7-5 and 5-7

the impurity

Top-Down Model

	0	1	2	3	4	5	6	7	8	9
N_c D3	X	X	X	X						
N_7 D7	X	X			X	X	X	X	X	X
N_5 D5	X				X	X	X	X	X	

3-3 and 5-5 and 7-7

3-7 and 7-3

3-5 and 5-3

7-5 and 5-7

Kondo interaction

Previous work

Kachru, Karch, Yaida 0909.2639, 1009.3268

Mück 1012.1973

Faraggi and Pando-Zayas 1101.5145

Jensen, Kachru, Karch, Polchinski, Silverstein 1105.1772

Karaiskos, Sfetsos, Tsatis 1106.1200

Harrison, Kachru, Torroba 1110.5325

Benincasa and Ramallo 1112.4669, 1204.6290

Faraggi, Mück, Pando-Zayas 1112.5028

Itsios, Sfetsos, Zoakos 1209.6617

Top-Down Model

	0	1	2	3	4	5	6	7	8	9
N_c D3	X	X	X	X						
N_7 D7	X	X			X	X	X	X	X	X
N_5 D5	X				X	X	X	X	X	

3-3 and 5-5 and 7-7

3-7 and 7-3

3-5 and 5-3

7-5 and 5-7

Absent in previous constructions

The D3-branes

	0	1	2	3	4	5	6	7	8	9
N_c D3	X	X	X	X						

3-3 strings

$(3+1)$- dimensional $\mathcal{N}=4$ SUSY $SU(N_c)$ YM

$$\lambda \equiv g^2_{YM} N_c$$

$$\beta_\lambda = 0$$

CFT!

The D3-branes

	0	1	2	3	4	5	6	7	8	9
N_c D3	X	X	X	X						

3-3 strings

$(3+1)$- dimensional $\mathcal{N}=4$ SUSY $SU(N_c)$ YM

$$\lambda \equiv g_{YM}^2 N_c$$

$$N_c \to \infty \quad g_{YM}^2 \to 0$$

λ fixed

The D3-branes

	0	1	2	3	4	5	6	7	8	9
N_c D3	X	X	X	X						

3-3 strings

$(3+1)$- dimensional $\mathcal{N}=4$ SUSY $SU(N_c)$ YM

$$\lambda \equiv g_{YM}^2 N_c$$

$$N_c \longrightarrow \infty \quad g_{YM}^2 \longrightarrow 0$$

$$\lambda \longrightarrow \infty$$

The D3-branes

	0	1	2	3	4	5	6	7	8	9
N_c D3	X	X	X	X						

$\mathcal{N} = 4$ SYM

$N_c \to \infty$

$\lambda \to \infty$

=

Type IIB Supergravity

$AdS_5 \times S^5$

$$g_{YM}^2 \propto g_s$$

$$g_{YM}^2 N_c \propto L_{\mathrm{AdS}}^4 / \alpha'^2$$

$$L_{\mathrm{AdS}} \equiv 1$$

The D3-branes

	0	1	2	3	4	5	6	7	8	9
N_c D3	X	X	X	X						

$\mathcal{N} = 4$ SYM

$N_c \to \infty$

$\lambda \to \infty$

$=$

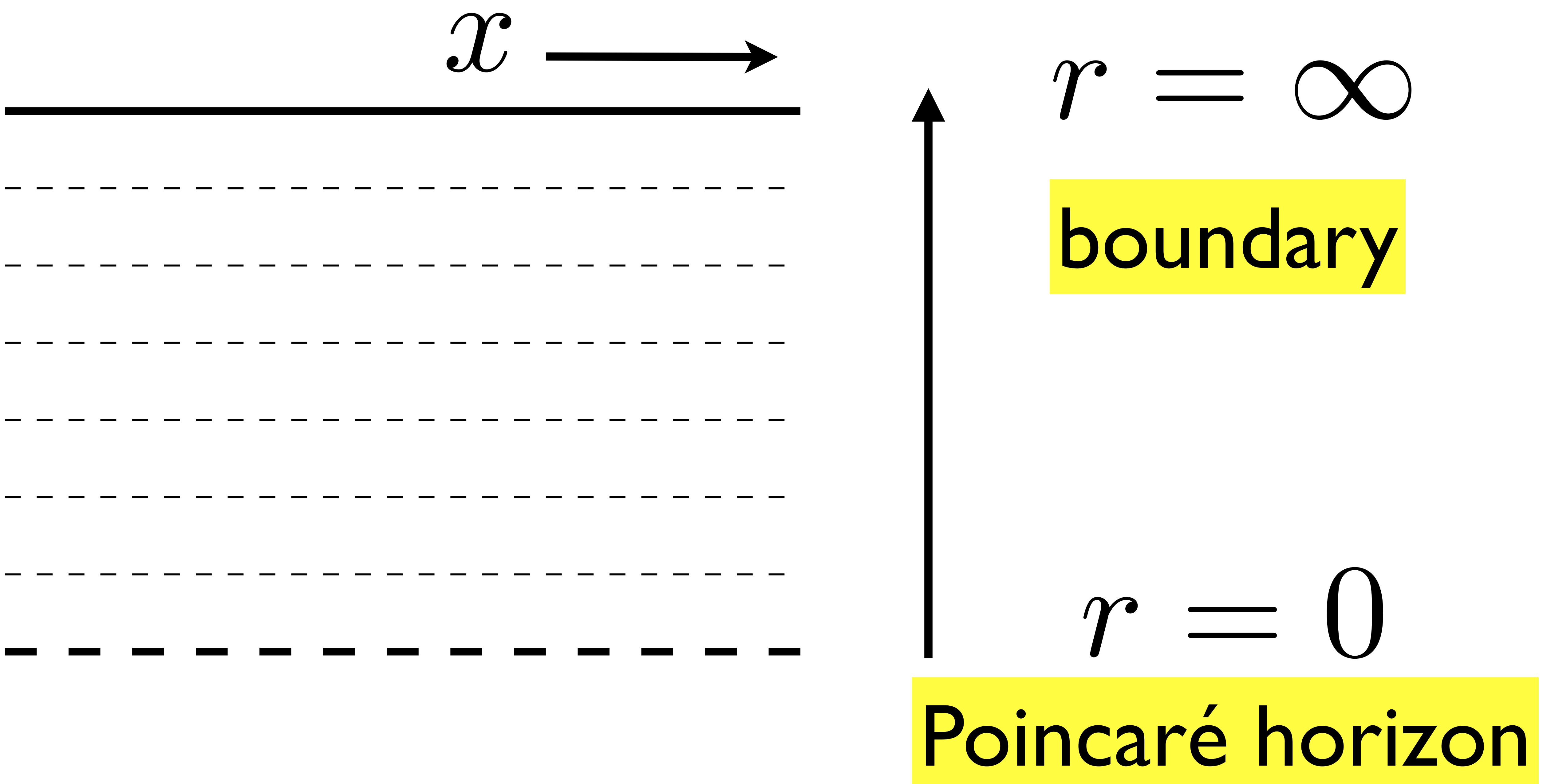
Type IIB Supergravity

$AdS_5 \times S^5$

$$\int_{S^5} F_5 \propto N_c \qquad F_5 = dC_4$$

Anti-de Sitter Space

$$ds^2 = \frac{dr^2}{r^2} + r^2\left(-dt^2 + dx^2 + dy^2 + dz^2\right)$$



Top-Down Model

	0	1	2	3	4	5	6	7	8	9
N_c D3	X	X	X	X						
N_7 D7	X	X			X	X	X	X	X	X
N_5 D5	X				X	X	X	X	X	

3-3 and 5-5 and 7-7

3-7 and 7-3

3-5 and 5-3

7-5 and 5-7

Decouple

	0	1	2	3	4	5	6	7	8	9
N_c D3	X	X	X	X						
N_7 D7	X	X			X	X	X	X	X	X
N_5 D5	X				X	X	X	X	X	

7-7

5-5

$(7+1)$-dim. $U(N_7)$ **SYM**

$(5+1)$-dim. $U(N_5)$ **SYM**

$$g_{Dp}^2 \propto g_s \, \alpha'^{\frac{p-3}{2}}$$

$$g_{YM}^2 \propto g_s$$

$$g_{YM}^2 N_c \propto 1/\alpha'^2$$

	0	1	2	3	4	5	6	7	8	9
N_c D3	X	X	X	X						
N_7 D7	X	X			X	X	X	X	X	X
N_5 D5	X				X	X	X	X	X	

7-7

5-5

$(7+1)$-dim. $U(N_7)$ **SYM**

$(5+1)$-dim. $U(N_5)$ **SYM**

$$g^2_{Dp} \propto g_s\, \alpha'^{\frac{p-3}{2}}$$

$$g^2_{D7} N_7 \propto \frac{N_7}{N_c}$$

$$g^2_{D5} N_5 \propto g_{\rm YM} \frac{N_5}{\sqrt{N_c}}$$

Probe Limit

$$N_c \to \infty \qquad g_{YM}^2 \to 0$$
$$N_7\,,\, N_5 \quad \text{fixed}$$

$$N_7/N_c \to 0 \;\; \text{and} \;\; N_5/N_c \to 0$$

$$g_{D7}^2 N_7 \propto \frac{N_7}{N_c} \to 0$$

$$g_{D5}^2 N_5 \propto g_{YM} \frac{N_5}{\sqrt{N_c}} \to 0$$

Probe Limit

SYM theories on D7- and D5-branes decouple

$U(N_7) \times U(N_5)$ becomes a global symmetry

Total symmetry:

$$\underbrace{SU(N_c)}_{\text{gauged}} \times \underbrace{U(N_7) \times U(N_5)}_{\text{global}}$$

(plus R-symmetry)

Top-Down Model

	0	1	2	3	4	5	6	7	8	9
N_c D3	X	X	X	X						
N_7 D7	X	X			X	X	X	X	X	X
N_5 D5	X				X	X	X	X	X	

3-3 and 5-5 and 7-7

3-7 and 7-3

3-5 and 5-3

7-5 and 5-7

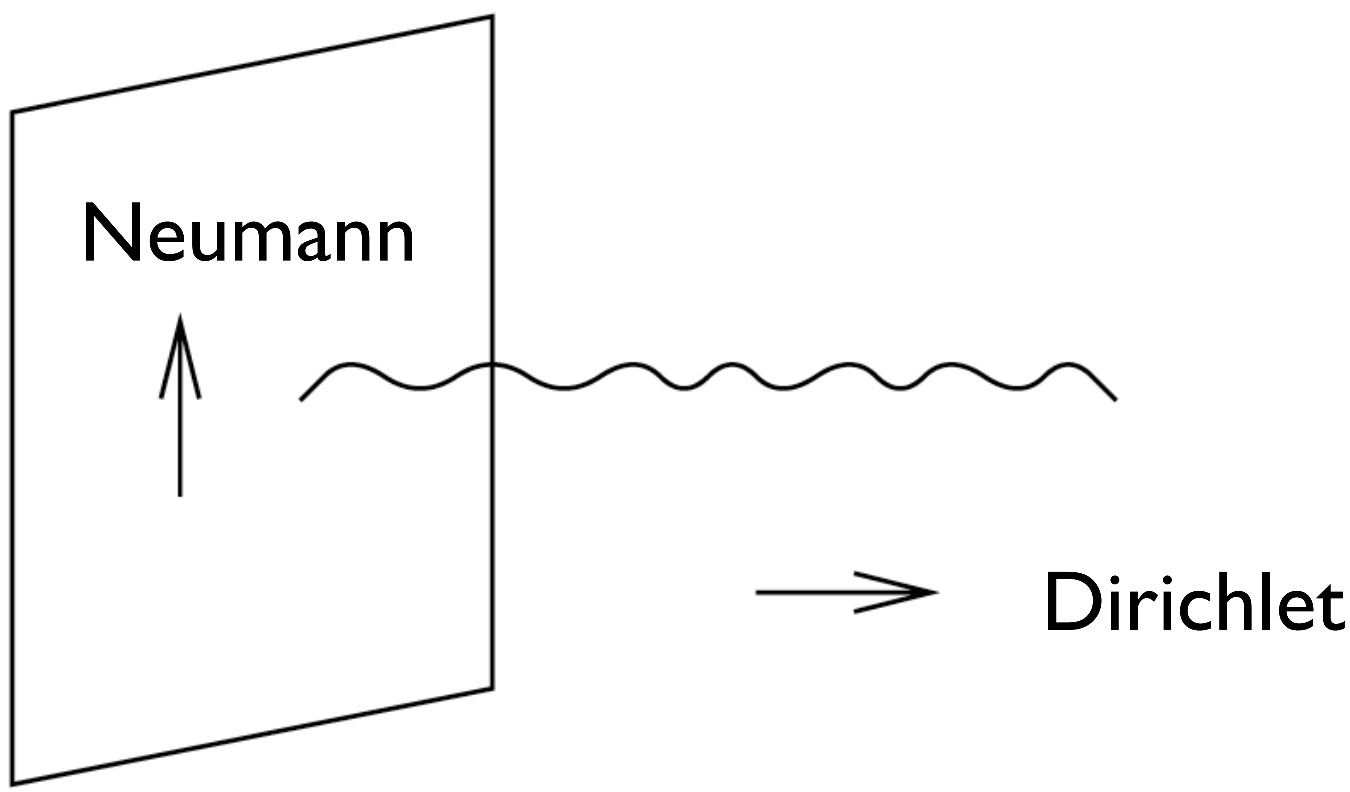
(1+1)-dimensional chiral fermions

The D7-branes

	0	1	2	3	4	5	6	7	8	9
N_c D3	X	X	X	X						
N_7 D7	X	X			X	X	X	X	X	X

Harvey and Royston 0709.1482, 0804.2854
Buchbinder, Gomis, Passerini 0710.5170

8 Neumann-Dirichlet (ND) intersection



The D7-branes

	0	1	2	3	4	5	6	7	8	9
N_c D3	X	X	X	X						
N_7 D7	X	X			X	X	X	X	X	X

Harvey and Royston 0709.1482, 0804.2854
Buchbinder, Gomis, Passerini 0710.5170

8 Neumann-Dirichlet (ND) intersection

1/4 SUSY

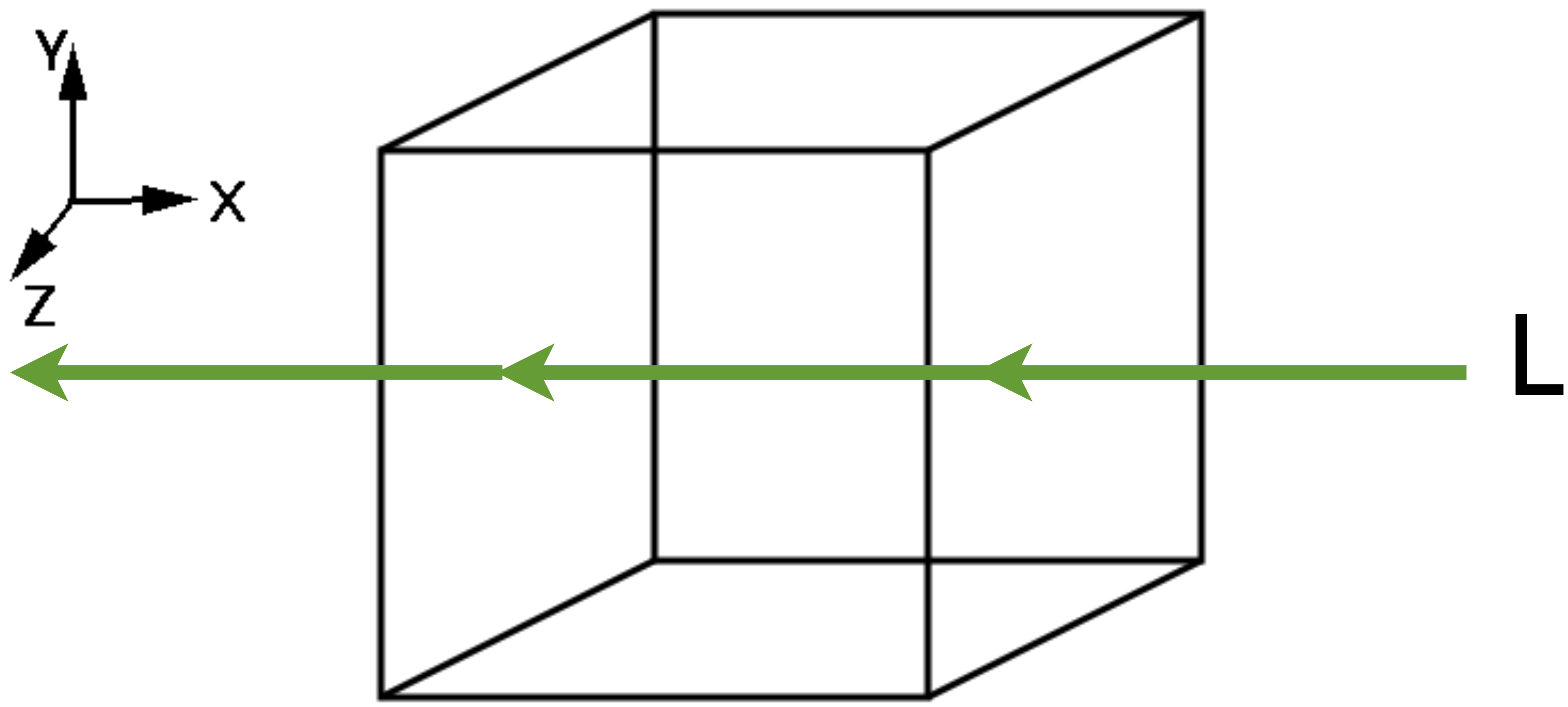
N_7 (1+1)-dimensional chiral fermions ψ_L

ψ_L NEUTRAL under SUSY: $\mathcal{N} = (0,8)$

The D7-branes

	0	1	2	3	4	5	6	7	8	9
N_c D3	X	X	X	X						
N_7 D7	X	X			X	X	X	X	X	X

N_7 (1+1)-dimensional chiral fermions ψ_L



The D7-branes

	0	1	2	3	4	5	6	7	8	9
N_c D3	X	X	X	X						
N_7 D7	X	X			X	X	X	X	X	X

N_7 (1+1)-dimensional chiral fermions ψ_L

$$S_{3\text{-}7} = \int dx^+ dx^- \psi_L^\dagger \left(i\partial_- - A_- \right) \psi_L$$

$$SU(N_c) \times U(N_7) \times U(N_5)$$

N_c	$\overline{N}_7$	singlet

The D7-branes

	0	1	2	3	4	5	6	7	8	9
N_c D3	X	X	X	X						
N_7 D7	X	X			X	X	X	X	X	X

N_7 (1+1)-dimensional chiral fermions ψ_L

$$S_{3\text{-}7} = \int dx^+ dx^- \psi_L^\dagger \left(i\partial_- - A_-\right) \psi_L$$

Kac-Moody algebra

$$SU(N_c)_{N_7} \times SU(N_7)_{N_c} \times U(1)_{N_c N_7}$$

The D7-branes

	0	1	2	3	4	5	6	7	8	9
N_c D3	X	X	X	X						
N_7 D7	X	X			X	X	X	X	X	X

N_7 $(1{+}1)$-dimensional chiral fermions ψ_L

Differences from Kondo

Do not come from reduction from $(3{+}1)$ dimensions

Genuinely relativistic

The D7-branes

	0	1	2	3	4	5	6	7	8	9
N_c D3	X	X	X	X						
N_7 D7	X	X			X	X	X	X	X	X

N_7 (1+1)-dimensional chiral fermions ψ_L

Differences from Kondo

$SU(N_c)$ is gauged!

$$\vec{J} = \psi_L^\dagger \vec{T} \psi_L$$

The D7-branes

	0	1	2	3	4	5	6	7	8	9
N_c D3	X	X	X	X						
N_7 D7	X	X			X	X	X	X	X	X

$SU(N_c)$ is gauged!

Gauge Anomaly!

Harvey and Royston 0709.1482, 0804.2854

Buchbinder, Gomis, Passerini 0710.5170

The D7-branes

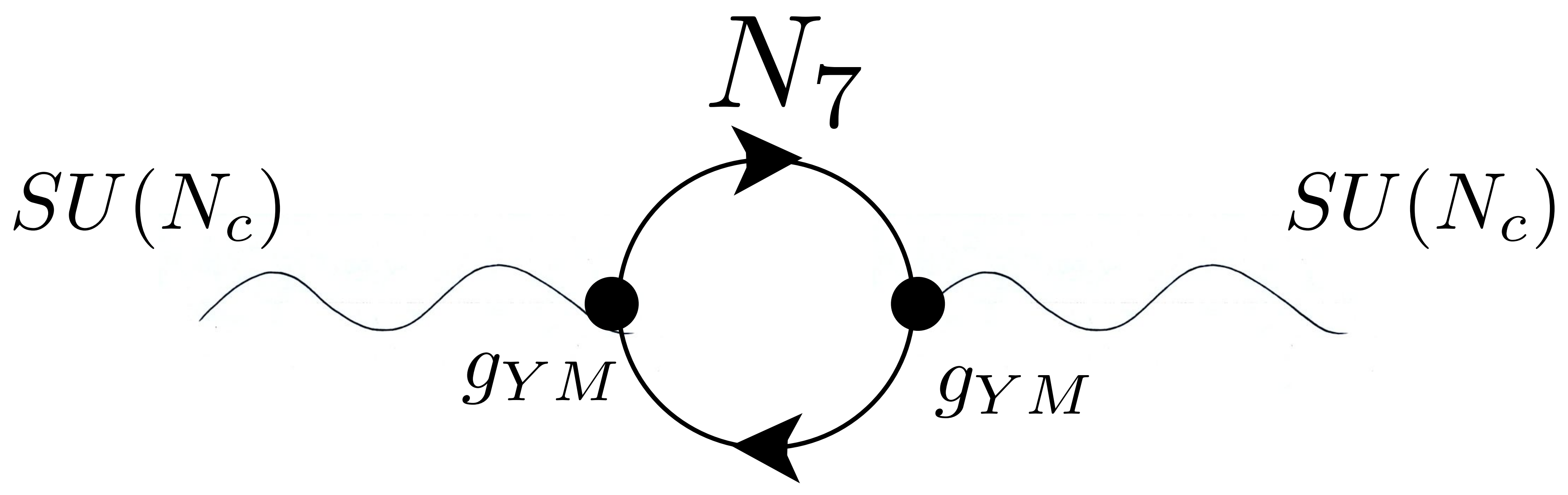
	0	1	2	3	4	5	6	7	8	9
N_c D3	X	X	X	X						
N_7 D7	X	X			X	X	X	X	X	X

$SU(N_c)$ is gauged!

Gauge Anomaly!

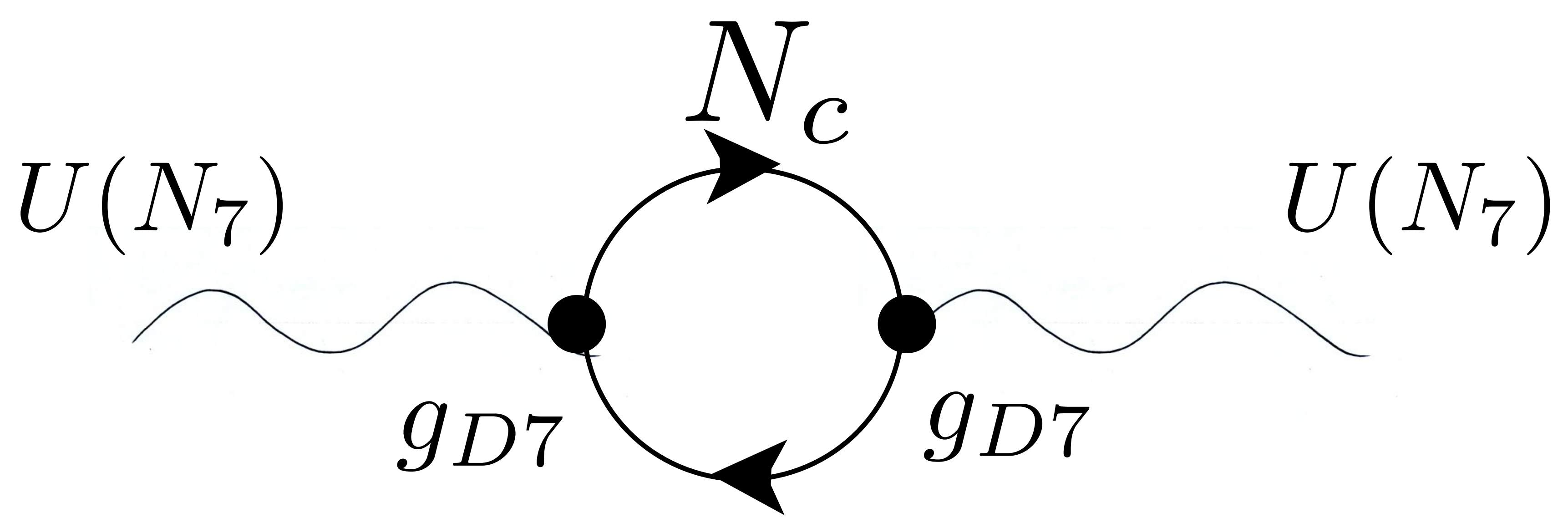
Probe Limit!

In the probe limit, the gauge anomaly is suppressed...



$\propto g_{YM}^2 N_7$

... but the global anomalies are not.



$\propto g_{D7}^2 N_c$

$$g_{D7}^2 \propto 1/N_c$$

In the probe limit, the gauge anomaly is suppressed...

$$SU(N_c)_{N_7} \longrightarrow SU(N_c)$$

... but the global anomalies are not.

$$SU(N_7)_{N_c} \times U(1)_{N_c N_7} \longrightarrow SU(N_7)_{N_c} \times U(1)_{N_c N_7}$$

$\mathcal{N} = 4$ SYM

$N_c \to \infty$

$\lambda \to \infty$

$=$

Type IIB Supergravity

$AdS_5 \times S^5$

Probe ψ_L

$=$

Probe D7-branes

$AdS_3 \times S^5$

$\mathcal{N} = 4$ SYM

$N_c \to \infty$

$\lambda \to \infty$

$=$

Type IIB Supergravity

$AdS_5 \times S^5$

Probe ψ_L

$=$

Probe D7-branes

$AdS_3 \times S^5$

$$ds^2 = \frac{dr^2}{r^2} + r^2\left(-dt^2 + dx^2 + dy^2 + dz^2\right) + ds^2_{S^5}$$

Current J	=	Gauge field A
Kac-Moody Algebra	=	Chern-Simons Gauge Field
rank and level of algebra	=	rank and level of gauge field

Gukov, Martinec, Moore, Strominger
hep-th/0403225

Kraus and Larsen
hep-th/0607138

Current J $=$ Gauge field A

$U(N_7)_{N_c}$

Gauge field on D7-brane

Decouples on field theory side...

...but not on the gravity side!

Probe D7-branes along $AdS_3 \times S^5$

$$S_{D7} = +\frac{1}{2} T_{D7} (2\pi\alpha')^2 \int P[C_4] \wedge \mathrm{tr}\, F \wedge F + \ldots$$

$$= -\frac{1}{2} T_{D7} (2\pi\alpha')^2 \int P[F_5] \wedge \mathrm{tr} \left(A \wedge dA + \frac{2}{3} A \wedge A \wedge A \right) + \ldots$$

$$= -\frac{N_c}{4\pi} \int_{AdS_3} \mathrm{tr} \left(A \wedge dA + \frac{2}{3} A \wedge A \wedge A \right) + \ldots$$

$U(N_7)_{N_c}$ Chern-Simons gauge field

Answer #1

The chiral fermions:

Chern-Simons Gauge Field in AdS_3

Top-Down Model

	0	1	2	3	4	5	6	7	8	9
N_c D3	X	X	X	X						
N_7 D7	X	X			X	X	X	X	X	X
N_5 D5	X				X	X	X	X	X	

3-3 and 5-5 and 7-7

3-7 and 7-3

3-5 and 5-3

7-5 and 5-7

the impurity

The D5-branes

	0	1	2	3	4	5	6	7	8	9
N_c D3	X	X	X	X						
N_5 D5	X				X	X	X	X	X	

Gomis and Passerini hep-th/0604007

8 ND intersection

N_5 $(0{+}1)$-dimensional fermions χ

$1/4$ SUSY

χ NEUTRAL under SUSY

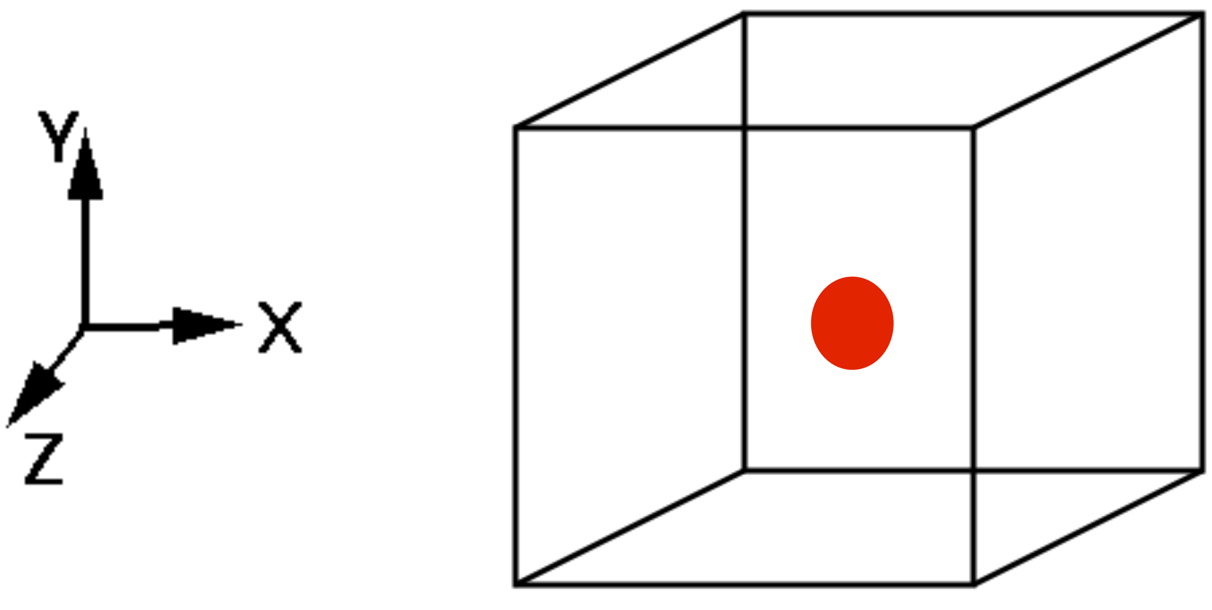
The D5-branes

	0	1	2	3	4	5	6	7	8	9
N_c D3	X	X	X	X						
N_5 D5	X				X	X	X	X	X	

Gomis and Passerini hep-th/0604007

8 ND intersection

N_5 $(0{+}1)$-dimensional fermions χ



The D5-branes

	0	1	2	3	4	5	6	7	8	9
N_c D3	X	X	X	X						
N_5 D5	X				X	X	X	X	X	

$$S_{3\text{-}5} = \int dt\, \chi^\dagger (i\partial_t - A_t - \Phi_9)\chi$$

$$SU(N_c) \times U(N_7) \times U(N_5)$$

$$N_c \qquad \text{singlet} \qquad \overline{N}_5$$

The D5-branes

	0	1	2	3	4	5	6	7	8	9
N_c D3	X	X	X	X						
N_5 D5	X				X	X	X	X	X	

$SU(N_c)$ is "spin"

$$\vec{S} = \chi^\dagger \vec{T} \chi$$

"slave fermions"

"Abrikosov pseudo-fermions"

Abrikosov, **Physics** 2, p.5 (1965)

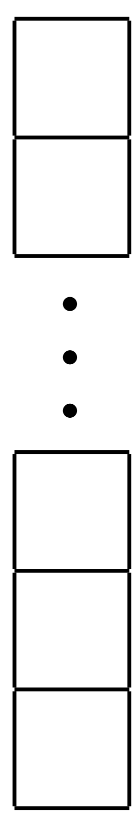
Gomis and Passerini hep-th/0604007

$$N_5 = 1$$

Integrate out χ

$$W_R = \mathrm{Tr}_R P \exp\left[i \int dt (A_t + \Phi_9) \right]$$

$R =$



$$\Bigg\} \quad Q = \sum_{\sigma=1}^{N_c} \chi_\sigma^\dagger \chi_\sigma$$

$U(N_5)$ charge "density"

$\mathcal{N} = 4$ SYM

$N_c \rightarrow \infty$

$\lambda \rightarrow \infty$

$=$

Type IIB Supergravity

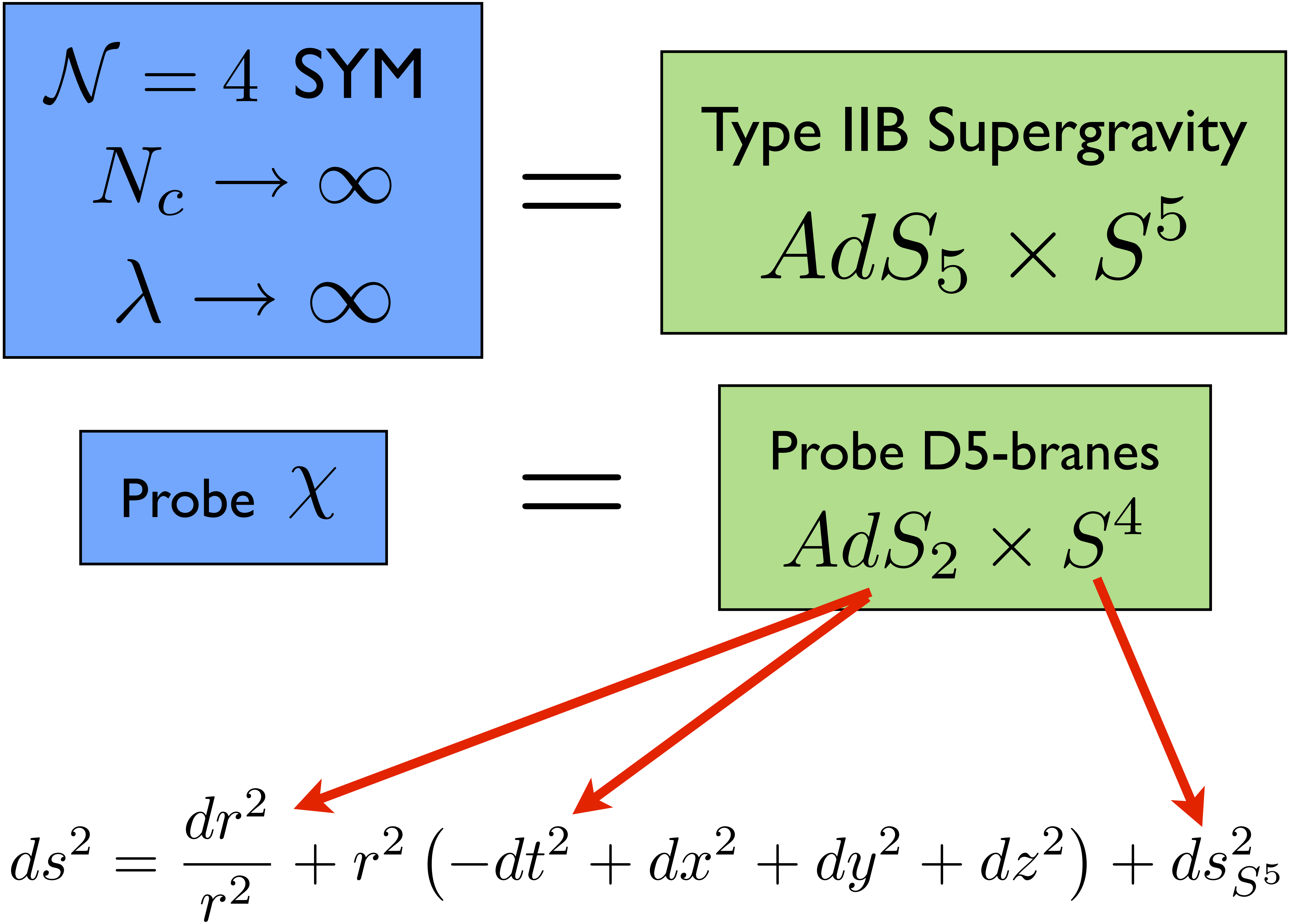
$AdS_5 \times S^5$

Probe χ

$=$

Probe D5-branes

$AdS_2 \times S^4$



$\mathcal{N} = 4$ SYM
$N_c \to \infty$
$\lambda \to \infty$
$=$
Type IIB Supergravity
$AdS_5 \times S^5$
Probe χ
$=$
Probe D5-branes
$AdS_2 \times S^4$
$ds^2 = \frac{dr^2}{r^2} + r^2 \left(-dt^2 + dx^2 + dy^2 + dz^2\right) + ds^2_{S^5}$

$\mathcal{N}=4$ SYM $N_c \to \infty$ $\lambda \to \infty$	$=$	Type IIB Supergravity $AdS_5 \times S^5$
Probe χ	$=$	Probe D5-branes $AdS_2 \times S^4$
$U(N_5)$ Current J	$=$	$U(N_5)$ Gauge field a
Q	$=$	Electric flux

Probe D5-brane along $AdS_2 \times S^4$

Camino, Paredes, Ramallo hep-th/0104082

$$S_{D5} = -T_{D5}\,(2\pi\alpha')^2\,\frac{1}{2}\int \mathrm{tr} f \wedge * f$$
$$+T_{D5}\,(2\pi\alpha')\int P[C_4] \wedge \mathrm{tr} f + \ldots$$

AdS_2 electric field f_{rt}

$$\sqrt{-g}\, f^{tr}\Big|_{\partial AdS_2} = Q = \sum_{\sigma=1}^{N_c} \chi_\sigma^\dagger \chi_\sigma$$

Answer #2

The impurity:

Yang-Mills Gauge Field in AdS_2

$R_{\rm imp}$ $=$ electric flux

Top-Down Model

	0	1	2	3	4	5	6	7	8	9
N_c D3	X	X	X	X						
N_7 D7	X	X			X	X	X	X	X	X
N_5 D5	X				X	X	X	X	X	

3-3 and 5-5 and 7-7

3-7 and 7-3

3-5 and 5-3

7-5 and 5-7

Kondo interaction

The Kondo Interaction

	0	1	2	3	4	5	6	7	8	9
N_5 D5	X				X	X	X	X	X	
N_7 D7	X	X			X	X	X	X	X	X

2 ND intersection

Complex scalar!

$$SU(N_c) \times U(N_7) \times U(N_5)$$

singlet $\qquad \overline{N}_7 \qquad N_5$

$$\mathcal{O} \equiv \psi_L^\dagger \chi$$

The Kondo Interaction

	0	1	2	3	4	5	6	7	8	9
N_5 D5	X				X	X	X	X	X	
N_7 D7	X	X			X	X	X	X	X	X

SUSY completely broken

TACHYON

$$m^2_{\text{tachyon}} = -\frac{1}{4\alpha'}$$

D5 becomes magnetic flux in the D7

The Kondo Interaction

$SU(N_c)$ is "spin"

$$\vec{J} = \psi_L^\dagger \vec{T} \psi_L \qquad \vec{S} = \chi^\dagger \vec{T} \chi$$

$$\vec{S} \cdot \vec{J} = \chi^\dagger \vec{T} \chi \cdot \psi_L^\dagger \vec{T} \psi_L$$

$$\vec{T}_{ij} \cdot \vec{T}_{kl} = \delta_{il}\delta_{jk} - \frac{1}{N_c}\delta_{ij}\delta_{kl}$$

$$\vec{S} \cdot \vec{J} = |\psi_L^\dagger \chi|^2 + \mathcal{O}(1/N_c)$$

"double trace"

$\mathcal{N} = 4$ SYM

$N_c \to \infty$

$\lambda \to \infty$

$=$

Type IIB Supergravity

$AdS_5 \times S^5$

Probe ψ_L $=$ Probe D7-branes $AdS_3 \times S^5$

Probe χ $=$ Probe D5-branes $AdS_2 \times S^4$

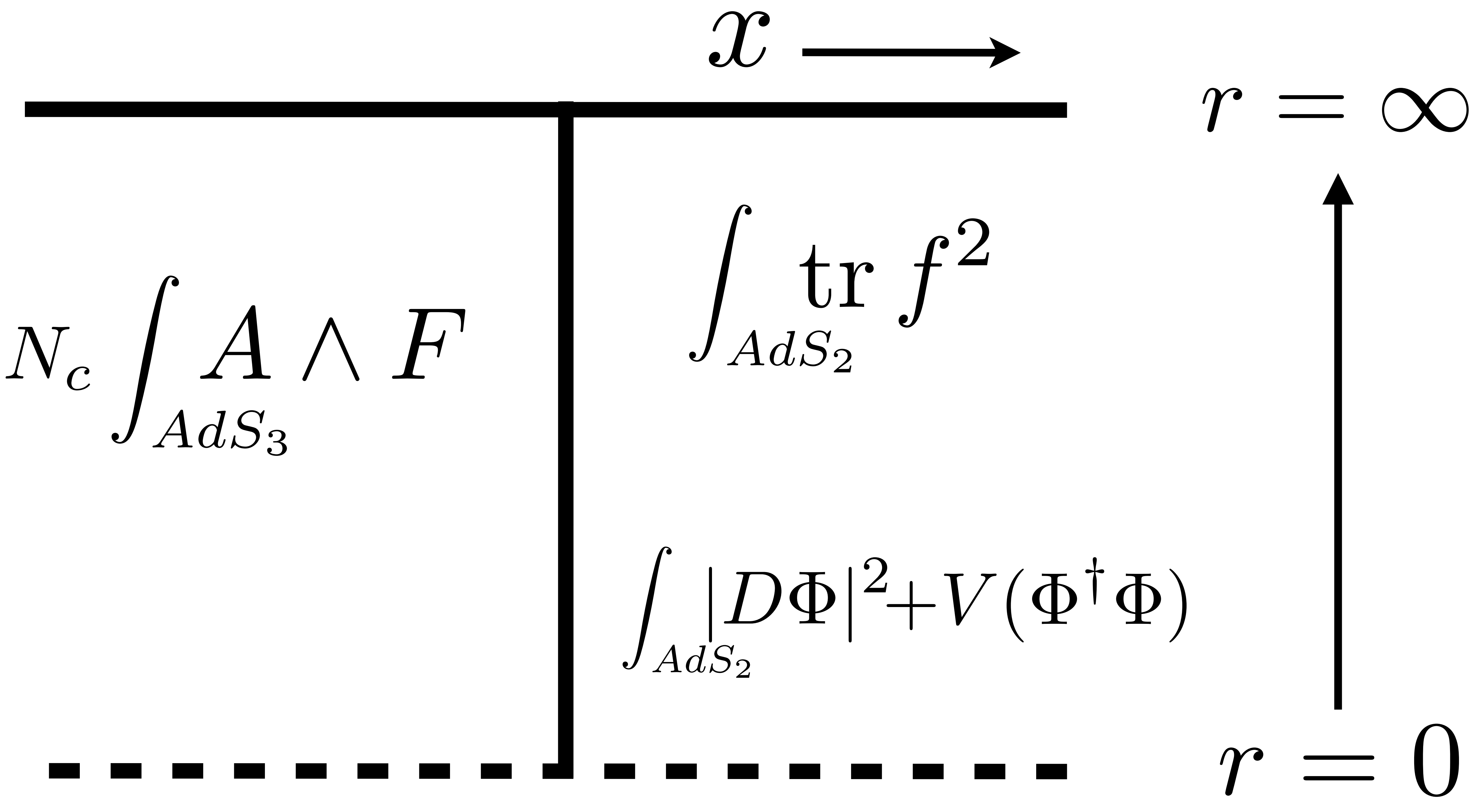
$\psi_L^\dagger \chi$ $=$ Bi-fundamental scalar $AdS_2 \times S^4$

Answer #3

The Kondo interaction:

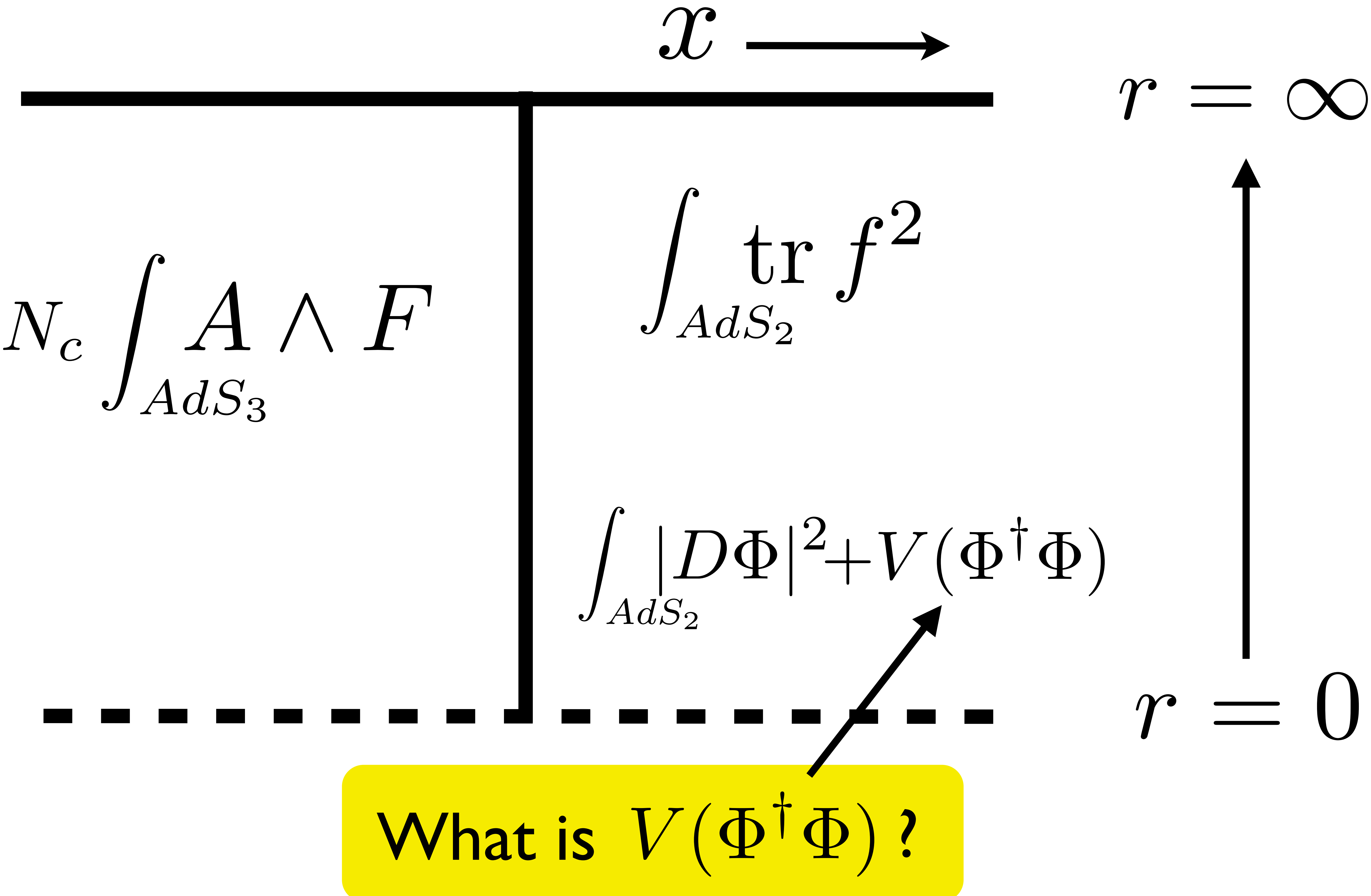
Bi-fundamental scalar in AdS_2

Top-Down Model



$$D\Phi = \partial\Phi + iA\Phi - ia\Phi$$

Top-Down Model



Top-Down Model

What is $V(\Phi^\dagger \Phi)$?

Calculation in $\mathbb{R}^{9,1}$

Gava, Narain, Samadi hep-th/9704006

Aganagic, Gopakumar, Minwalla, Strominger hep-th/0009142

Difficult to calculate in $AdS_5 \times S^5$

Top-Down Model

What is $V(\Phi^\dagger\Phi)$?

Calculation in $\mathbb{R}^{9,1}$

Gava, Narain, Samadi hep-th/9704006

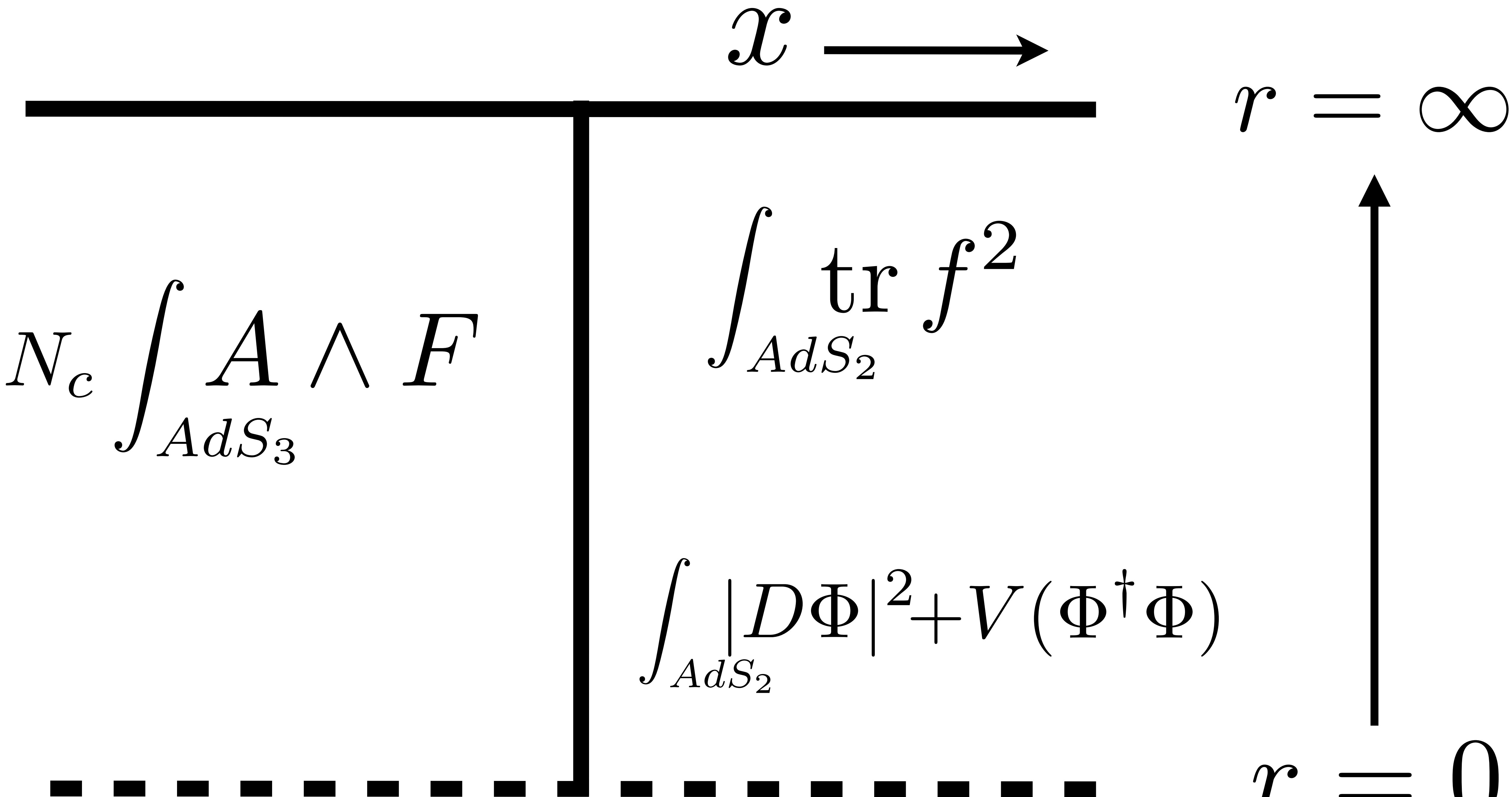
Aganagic, Gopakumar, Minwalla, Strominger hep-th/0009142

Switch to bottom-up model!

Outline:

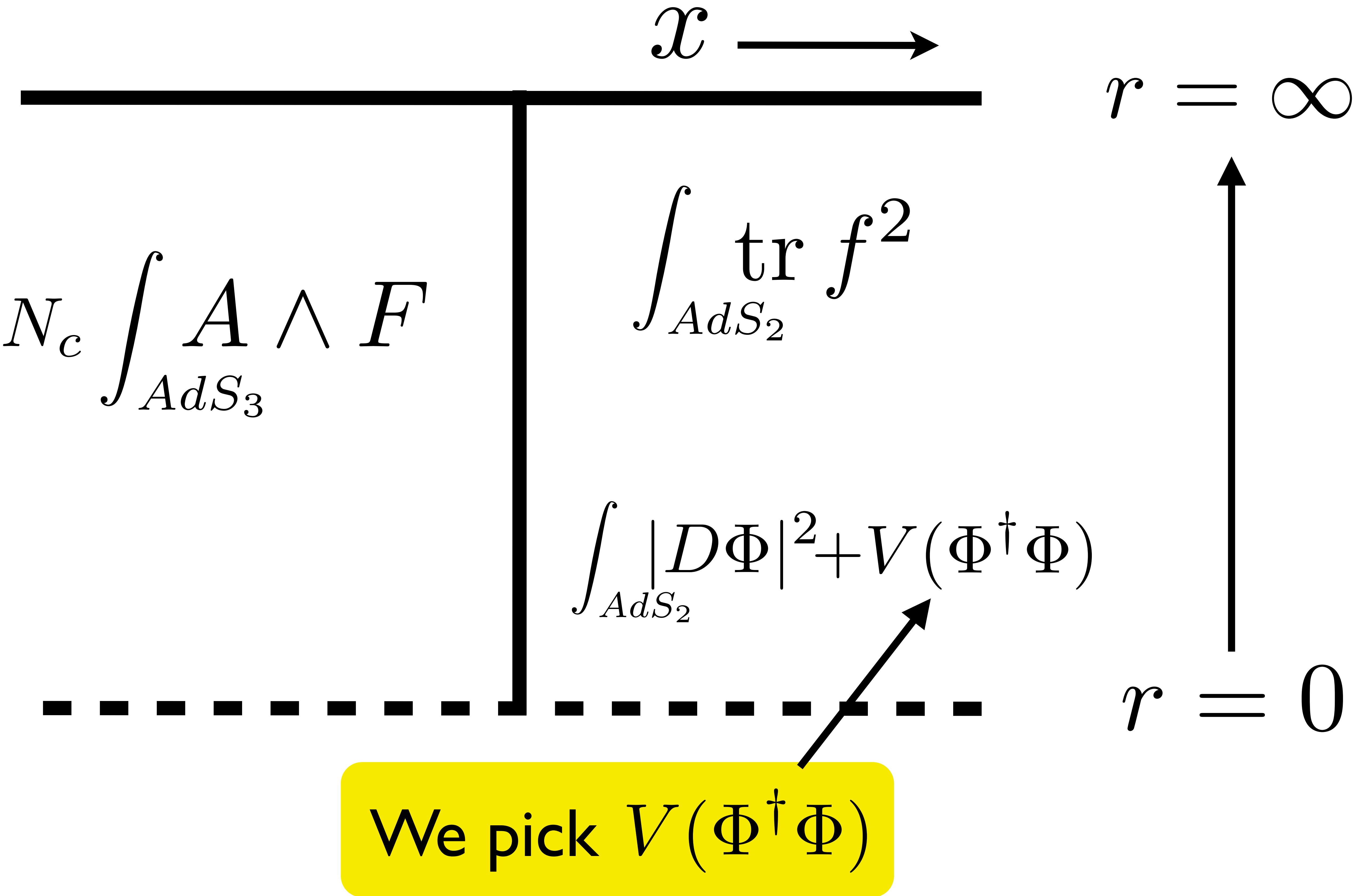
- The Kondo Effect
- The CFT Approach
- A Top-Down Holographic Model
- A Bottom-Up Holographic Model
- Summary and Outlook

Bottom-Up Model

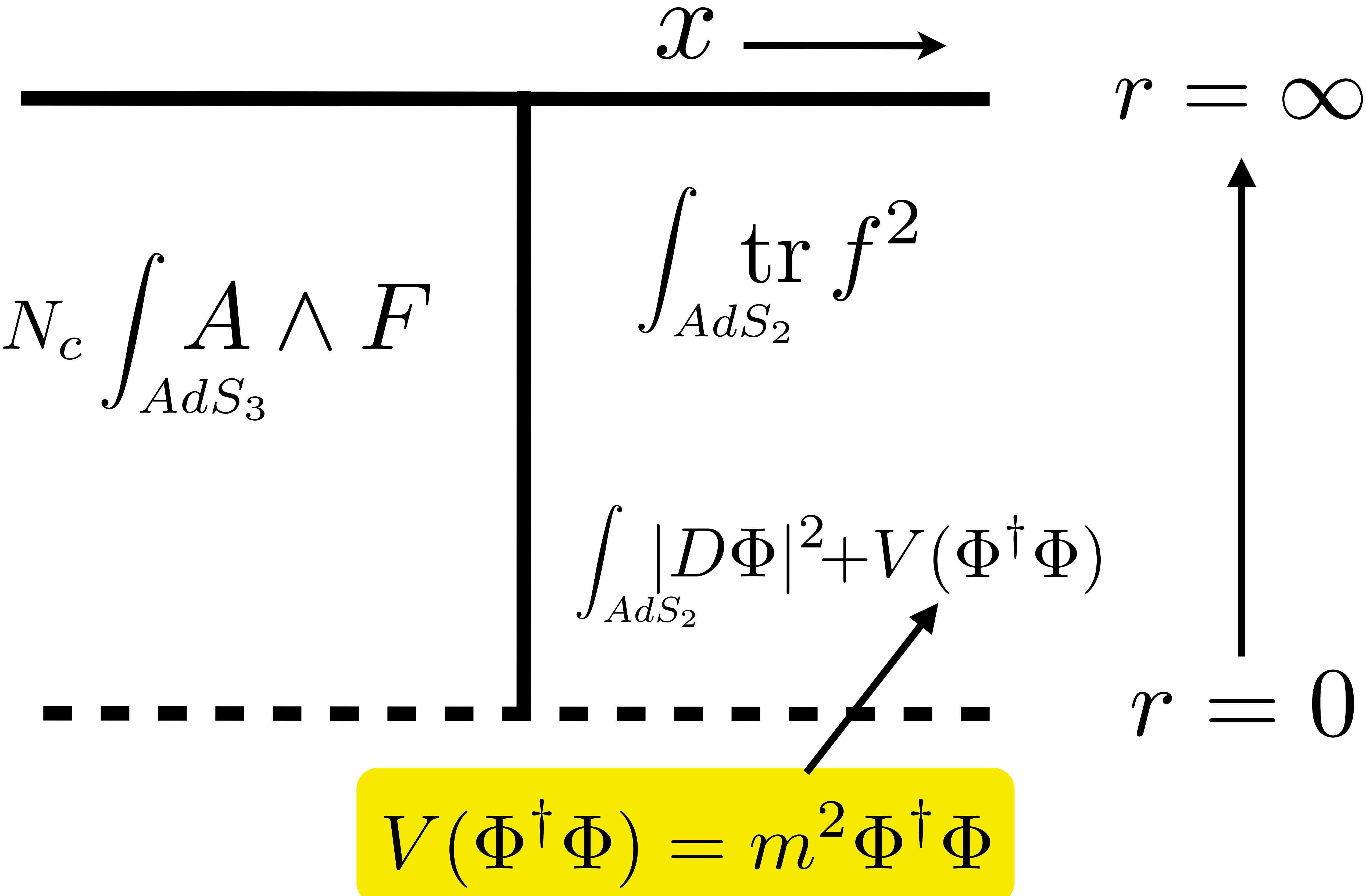


$$D\Phi = \partial\Phi + iA\Phi - ia\Phi$$

Bottom-Up Model



Bottom-Up Model



Bottom-Up Model

$$S = S_{CS} + S_{AdS_2}$$

$$S_{CS} = -\frac{N}{4\pi}\int \mathrm{tr}\left(A \wedge dA + \frac{2}{3} A \wedge A \wedge A\right)$$

$$S_{AdS_2} = -\int d^3x\, \delta(x)\sqrt{-g}\left[\frac{1}{4}\mathrm{tr} f^2 + |D\Phi|^2 + V(\Phi^\dagger \Phi)\right]$$

$$D\Phi = \partial\Phi + iA\Phi - ia\Phi$$

$$V(\Phi^\dagger\Phi) = m^2 \Phi^\dagger \Phi$$

Bottom-Up Model

$$S = S_{CS} + S_{AdS_2}$$

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Kondo model specified by

$$N,\ R_{\mathrm{imp}},\ k$$

Bottom-Up Model

$$U(k)_N$$

$$S_{CS} = -\frac{N}{4\pi}\int \mathrm{tr}\left(A\wedge dA + \frac{2}{3}A\wedge A\wedge A\right)$$

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Kondo model specified by

$$N,\ R_{\mathrm{imp}},\ k$$

Probe limit

$U(1)$ gauge fields

Chern-Simons

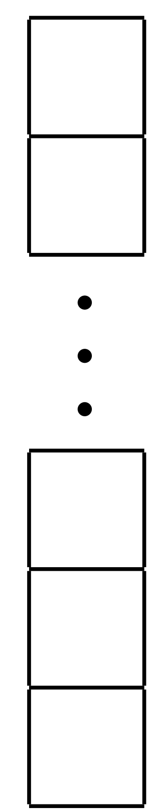
$$F = dA$$

AdS_2

$$f = da$$

Single channel

$$U(1)_{N_c}$$

$R_{\text{imp}} =$ 

Equations of Motion

$$\Phi = e^{i\psi}\phi$$

$$\mu, \nu = r, t, x \qquad\qquad m, n = r, t$$

$$\varepsilon^{m\mu\nu} F_{\mu\nu} = -\frac{4\pi}{N}\delta(x) J^m$$

$$\partial_n \left(\sqrt{-g}\, g^{nq} g^{mp} f_{qp}\right) = -J^m$$

$$\partial_m J^m = 0$$

$$\partial_m \left(\sqrt{-g}\, g^{mn} \partial_n \phi\right) = \sqrt{-g}\, g^{mn} (A_m - a_m + \partial_m \psi)(A_n - a_n + \partial_n \psi)\phi + \frac{1}{2}\sqrt{-g}\,\frac{\partial V}{\partial \phi}$$

$$J^m \equiv 2\sqrt{-g}\, g^{mn} \left(A_n - a_n + \partial_n \psi\right) \phi^2$$

Equations of Motion

Ansatz:

Static solution

After gauge fixing, only non-zero fields:

$$\phi(r) \qquad a_t(r) \qquad A_x(r)$$

$$f_{rt} = a_t'(r) \qquad F_{rx} = A_x'(r)$$

$$J^t(r) = -2\sqrt{-g}\, g^{tt} a_t \phi^2$$

Equations of Motion

$$J^t(r) = -2\sqrt{-g}\, g^{tt} a_t \phi^2$$

$$\varepsilon^{trx} F_{rx} = -\frac{4\pi}{N}\delta(x) J^t(r)$$

$$\partial_r \left(\sqrt{-g}\, g^{rr} g^{tt} f_{rt}\right) = -J^t(r)$$

$$\partial_r \left(\sqrt{-g}\, g^{rr}\, \partial_r \phi\right) - \sqrt{-g}\, g^{tt}\, a_t^2\, \phi - \sqrt{-g}\, m^2\, \phi = 0$$

Boundary Conditions

$$\sqrt{-g}\,f^{rt}\Big|_{\partial AdS_2} = Q$$

We choose $m^2 =$ Breitenlohner-Freedman bound

$$\phi(r) = c\, r^{-1/2} \log r + \tilde{c}\, r^{-1/2} + \ldots$$

Our double-trace (Kondo) coupling:

$$c = \tilde{g}_K\, \tilde{c}$$

Witten hep-th/0112258

AdS-Schwarzschild black hole

Hawking temperature $=$ T

$T > T_c$ $\quad \sqrt{-g} f^{tr}\big|_{\partial AdS_2} \neq 0 \qquad \phi(r) = 0$

$\langle \psi_L^\dagger \chi \rangle = 0$

$T < T_c$ $\quad \sqrt{-g} f^{tr}\big|_{\partial AdS_2} \neq 0 \qquad \phi(r) \neq 0$

$\langle \psi_L^\dagger \chi \rangle \neq 0$

A holographic superconductor in AdS_2

AdS-Schwarzschild black hole

Hawking temperature $=$ T

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$\langle \psi_L^\dagger \chi \rangle \neq 0$

Superconductivity???

AdS-Schwarzschild black hole

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$T < T_c$ $\sqrt{-g} f^{tr}\big|_{\partial AdS_2} \neq 0 \quad \phi(r) \neq 0$

$\langle \psi_L^\dagger \chi \rangle \neq 0$

The large-N Kondo effect!

Solutions of the Kondo Problem

Numerical RG (Wilson 1975)

Fermi liquid description (Nozières 1975)

Bethe Ansatz/Integrability
(Andrei, Wiegmann, Tsvelick, Destri, ... 1980s)

Large-N expansion
(Anderson, Read, Newns, Doniach, Coleman, ...1970-80s)

Quantum Monte Carlo
(Hirsch, Fye, Gubernatis, Scalapino,... 1980s)

Conformal Field Theory (CFT)
(Affleck and Ludwig 1990s)

Large-N Approach to the Kondo Effect

Spin $SU(N)$

$R_{\text{imp}} = \text{anti-symm.}$

$k = 1$

$N \longrightarrow \infty$ with $N g_K$ fixed

$$\vec{S} = \chi^\dagger \vec{T} \chi$$

$$\mathcal{O}(\tau) \equiv c^\dagger(0,\tau)\chi(\tau)$$

$$\underbrace{SU(N)}_{\text{singlet}} \times \underbrace{U(1) \times U(1)}_{\text{bi-fundamental}}$$

Large-N Approach to the Kondo Effect

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Coleman PRB 35, 5072 (1987)

Senthil, Sachdev, Vojta PRL 90, 216403 (2003)

$T > T_c$ $\quad \langle \mathcal{O} \rangle = 0$

$T < T_c$ $\quad \langle \mathcal{O} \rangle \neq 0$

$$T_c \simeq T_K$$

Large-N Approach to the Kondo Effect

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$T < T_c$ $\langle \mathcal{O} \rangle \neq 0$

$$U(1) \times U(1) \rightarrow U(1)$$

"(0+1)-DIMENSIONAL SUPERCONDUCTIVITY"

Large-N Approach to the Kondo Effect

Spin $SU(N)$

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Coleman PRB 35, 5072 (1987)

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$T > T_c$ $\langle \mathcal{O} \rangle = 0$

$T < T_c$ $\langle \mathcal{O} \rangle \neq 0$

The phase transition is an ARTIFACT of the large-N limit!

The actual Kondo effect is a crossover

AdS-Schwarzschild black hole

Hawking temperature $=$ T

$T > T_c$ $\quad \sqrt{-g} f^{tr}\big|_{\partial AdS_2} \neq 0 \quad \phi(r) = 0$

$\langle \psi_L^\dagger \chi \rangle = 0$

$T < T_c$ $\quad \sqrt{-g} f^{tr}\big|_{\partial AdS_2} \neq 0 \quad \phi(r) \neq 0$

$\langle \psi_L^\dagger \chi \rangle \neq 0$

The large-N Kondo effect!

The Phase Shift

$$J^t(r) = -2\sqrt{-g}\, g^{tt} a_t \phi^2$$

$$\varepsilon^{trx} F_{rx} = -\frac{4\pi}{N}\delta(x) J^t(r)$$

$$\partial_r \left(\sqrt{-g}\, g^{rr} g^{tt} f_{rt}\right) = -J^t(r)$$

$$\partial_r \left(\sqrt{-g}\, g^{rr}\, \partial_r \phi\right) - \sqrt{-g}\, g^{tt}\, a_t^2\, \phi - \sqrt{-g}\, m^2\, \phi = 0$$

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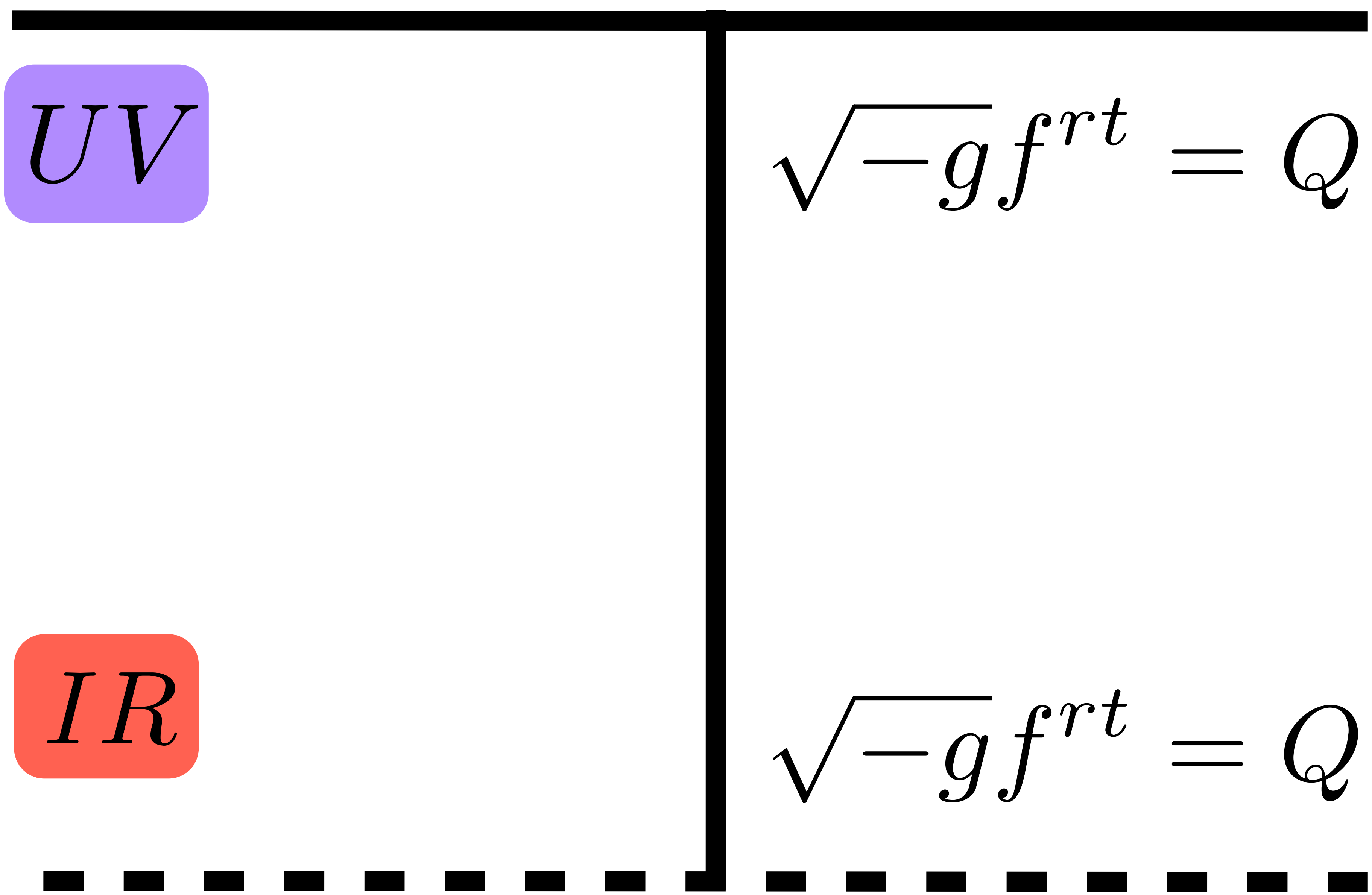
$$T > T_c$$

$$\phi(r) = 0$$

$$J^t(r) = 0$$

The Phase Shift

$T > T_c$ $\phi(r) = 0$ $J^t(r) = 0$



The Phase Shift

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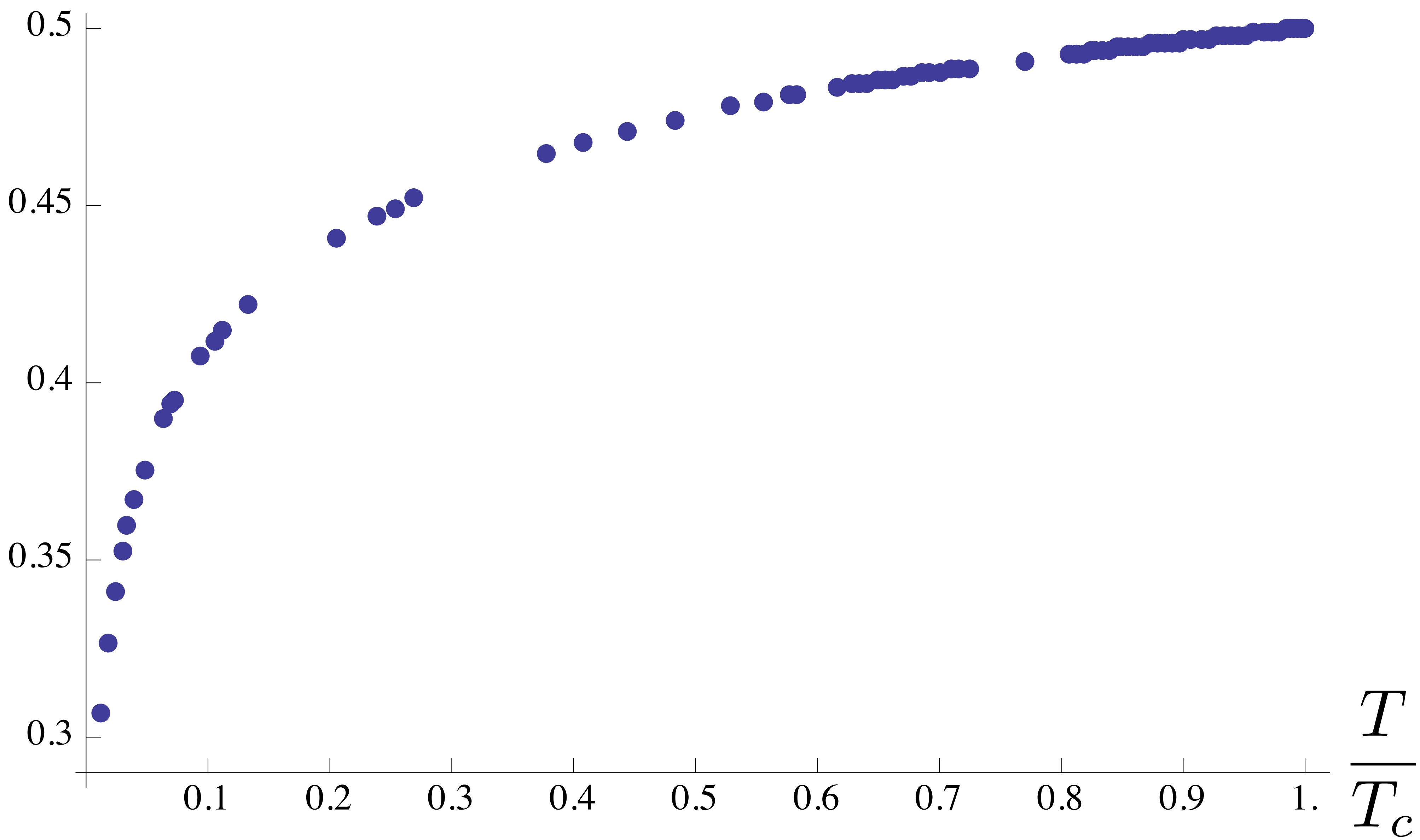
$T < T_c$ $\phi(r) \neq 0$ $J^t(r) \neq 0$

Screening of the Impurity

$$\sqrt{-g}f^{rt}\Big|_{\text{horizon}}$$

$$Q = 1/2$$



The Phase Shift

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$T < T_c$ $\phi(r) \neq 0$ $J^t(r) \neq 0$

The Phase Shift

$$J^t(r) = -2\sqrt{-g}\, g^{tt} a_t \phi^2$$

$$\varepsilon^{trx} F_{rx} = -\frac{4\pi}{N}\delta(x) J^t(r)$$

magnetic flux

electric charge density

$T < T_c$

$\phi(r) \neq 0$

$J^t(r) \neq 0$

The Phase Shift

$$\varepsilon^{trx} F_{rx} = 2\, \partial_r A_x(r) = -\frac{4\pi}{N} \delta(x) J^t(r)$$

Integrate up to some r

$$A_x|_{r\neq 0} - A_x|_{r=0} = -\frac{2\pi}{N} \delta(x) \int dr\, J^t(r)$$

Compactify x , integrate over x

$$\oint dx\; A_x|_{r\neq 0} - \oint dx\; A_x|_{r=0} = -\frac{2\pi}{N} \int dr\, J^t(r)$$

The Phase Shift

$T < T_c$ | $\phi(r) \neq 0$ | $J^t(r) \neq 0$

$$\int dx A_x = 0$$

UV

$$\downarrow$$

$$\int dx A_x \neq 0$$

IR

$$e^{i \int dx A_x}$$

Kraus and Larsen hep-th/0607138

The Phase Shift

$T < T_c$

$\phi(r) \neq 0$

$J^t(r) \neq 0$

UV

$$\sqrt{-g} f^{rt} = Q$$

IR

$$e^{i \int dx A_x}$$

$$\sqrt{-g} f^{rt} < Q$$

- Entropy?
- Heat capacity?
- Susceptibility?
- Resistivity?

Outline:

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Summary

What is the holographic dual of the Kondo effect?

Holographic superconductor in AdS_2

with a special boundary condition on the scalar

coupled as a defect

to a Chern-Simons gauge field in AdS_3

Outlook

- Multi-channel?
- Other impurity representations?
- Spin as global symmetry?
- Entanglement entropy?
- Quantum Quenches?
- Multiple impurities, RKKY?
- Suggestions welcome!

Thank You.