Fermi surfaces and gauge-gravity duality

Aspen Center for Physics, Feb 1-5, 2011

Lecture notes
arXiv:1010.0682
arXiv: 1012.0299

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PHYSICS
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Compressible quantum matter

- Consider a continuum quantum system with a globally conserved U(1) charge $\mathcal{Q}$ (the "electron density") in spatial dimension $d > 1$.

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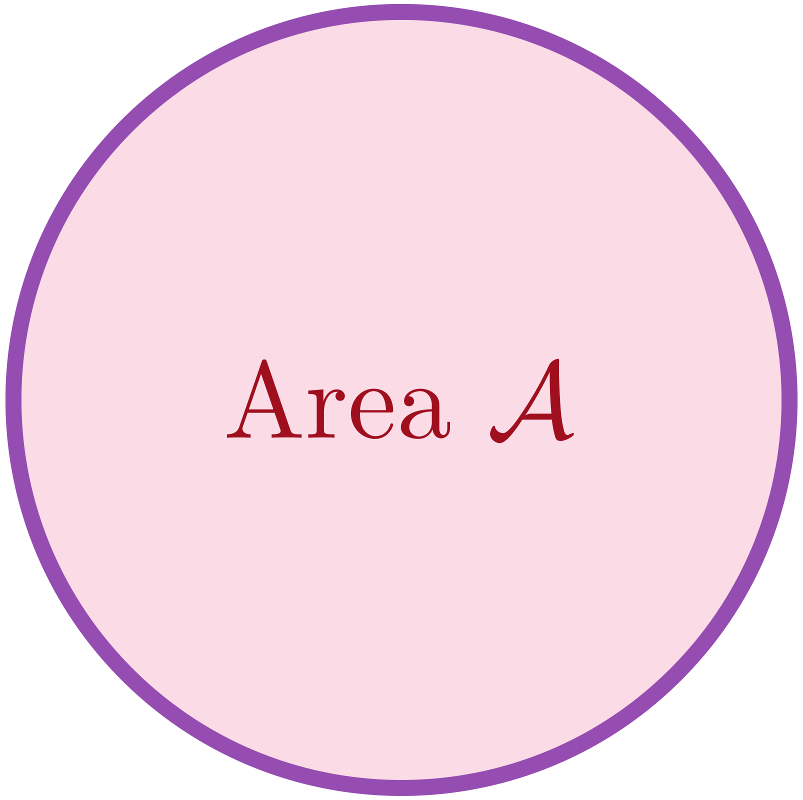
There are only a few established examples of such phases in condensed matter physics.
However, they appear naturally as duals of gravitational theories, and we want to interpret them in the gauge theory.

The Fermi surface

All known examples of such phases have a *Fermi surface*: the locus of zero energy singularities in momentum space in the two-point correlator of fermions carrying charge $\mathcal{Q}$.

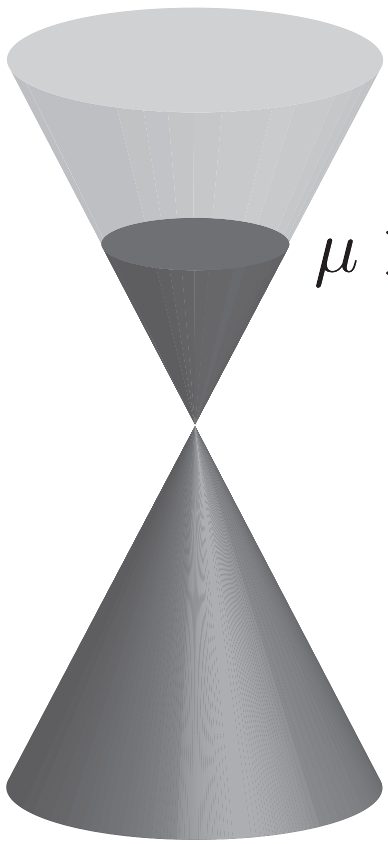
$$G^{-1}_{\text{fermion}}(k = k_F, \omega = 0) = 0.$$

Luttinger relations: The "volume (area)" $\mathcal{A}$ enclosed by the Fermi surface has a simple linear relation to $\langle \mathcal{Q} \rangle$.



The Fermi Liquid (FL)

Most common example: electrons with short-range interactions (or screened long-range interactions), which are adiabatically connected to the non-interacting limit. The electron Green's function G_c has a pole which crosses zero energy at $k = k_F$, and the Fermi surface has the same area as the non-interacting case.



$$\mathcal{L} = \bar{c}\,(\partial_a - \mu\delta_{at})\,\gamma^a c + 4 \text{ Fermi terms}$$

$$\mathcal{A} = \langle \bar{c}\gamma^t c \rangle = \langle \mathcal{Q} \rangle$$

$$G_c = \frac{1}{\omega - v_F(k - k_F) + i\omega^2}$$

Outline

1. Fermion-boson mixtures
   Luttinger relations with bosons

2. Gauge theories
   The fractionalized Fermi liquid (FL) phase*

3. Connections to semi-holographic theories
   Low energy theory of FL and FL phases*

4. Solvable models with infinite-range hopping
   Mapping to gravity duals on $AdS_2 \times R^d$

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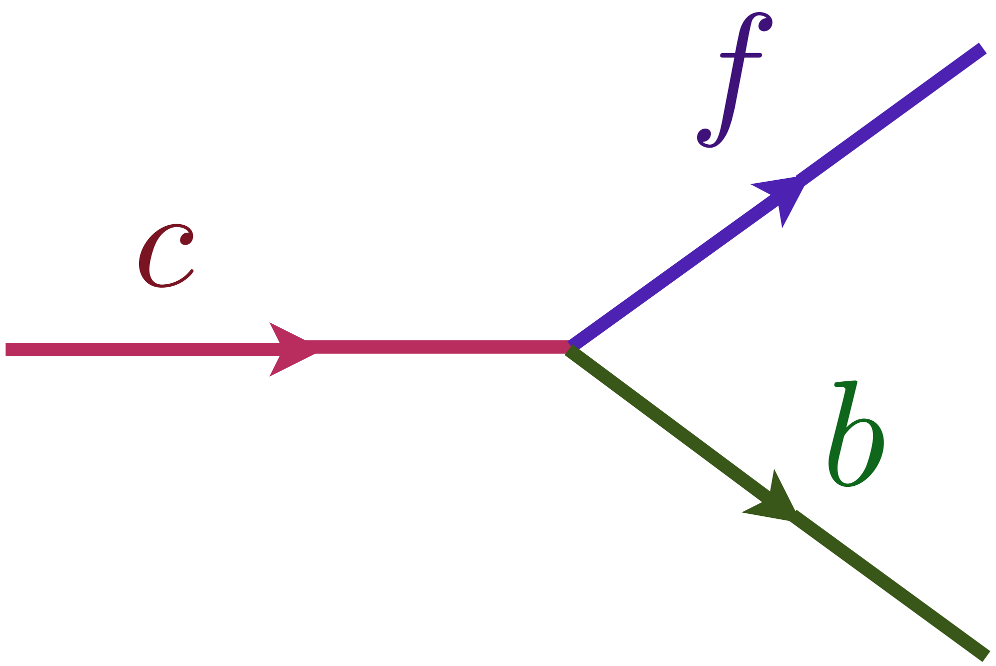
Introduce a second "flavor" of electrons, f, and allow c to decay into f and a boson b



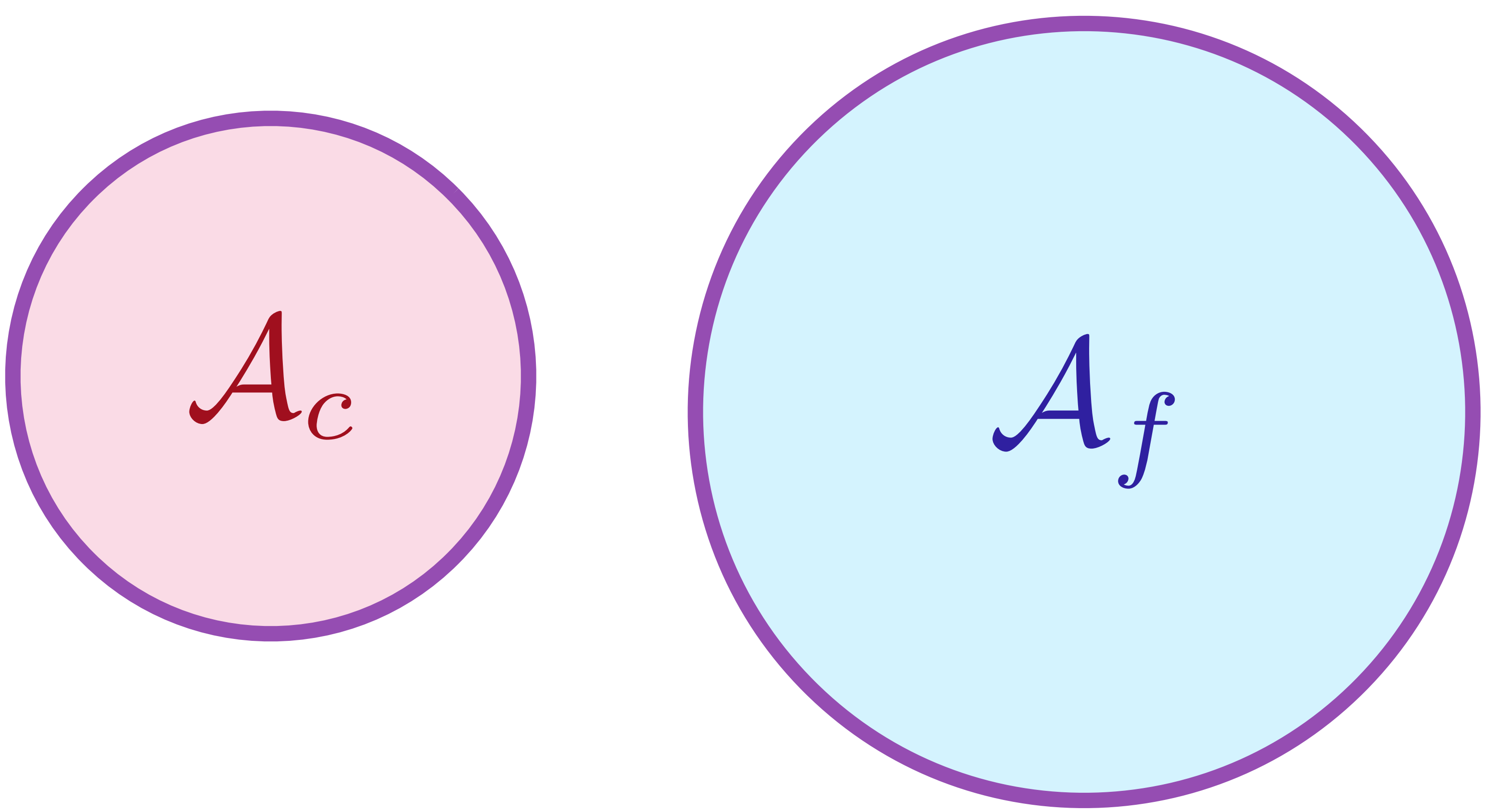
$$\mathcal{Q} = \bar{c}\,\gamma^t c + \overline{f}\gamma^t f$$
$$\mathcal{Q}_g = \overline{f}\gamma^t f - \bar{b}\,\overleftrightarrow{\partial_t}\, b$$

Two conserved charges:
$\mathrm{U}(1)\times\mathrm{U}_g(1)$

$$\mathcal{L} = \bar{c}\,(\partial_a - \mu\delta_{at})\,\gamma^a c + \overline{f}\,(\partial_a - (\mu + \mu_g)\delta_{at})\,\gamma^a f$$
$$+ \left|(\partial_a + \mu_g\delta_{at})b\right|^2 + s|b|^2 + \lambda(\bar{c} f b + \mathrm{c.c.}) + \ldots$$

There is a Luttinger relation for each conserved U(1) charge. However, the boson, b cannot have a Fermi surface in its Green's function, and so there is no area associated with it, although the boson density is *included* in the Luttinger relation

$$
\begin{aligned}
\mathcal{A}_c + \mathcal{A}_f &= \langle \bar{c}\gamma^t c \rangle + \langle \bar{f}\gamma^t f \rangle = \langle \mathcal{Q} \rangle \\
\mathcal{A}_f &= \langle \bar{f}\gamma^t f \rangle - \langle \bar{b}\, \overleftrightarrow{\partial_t}\, b \rangle = \langle \mathcal{Q}_g \rangle
\end{aligned}
$$

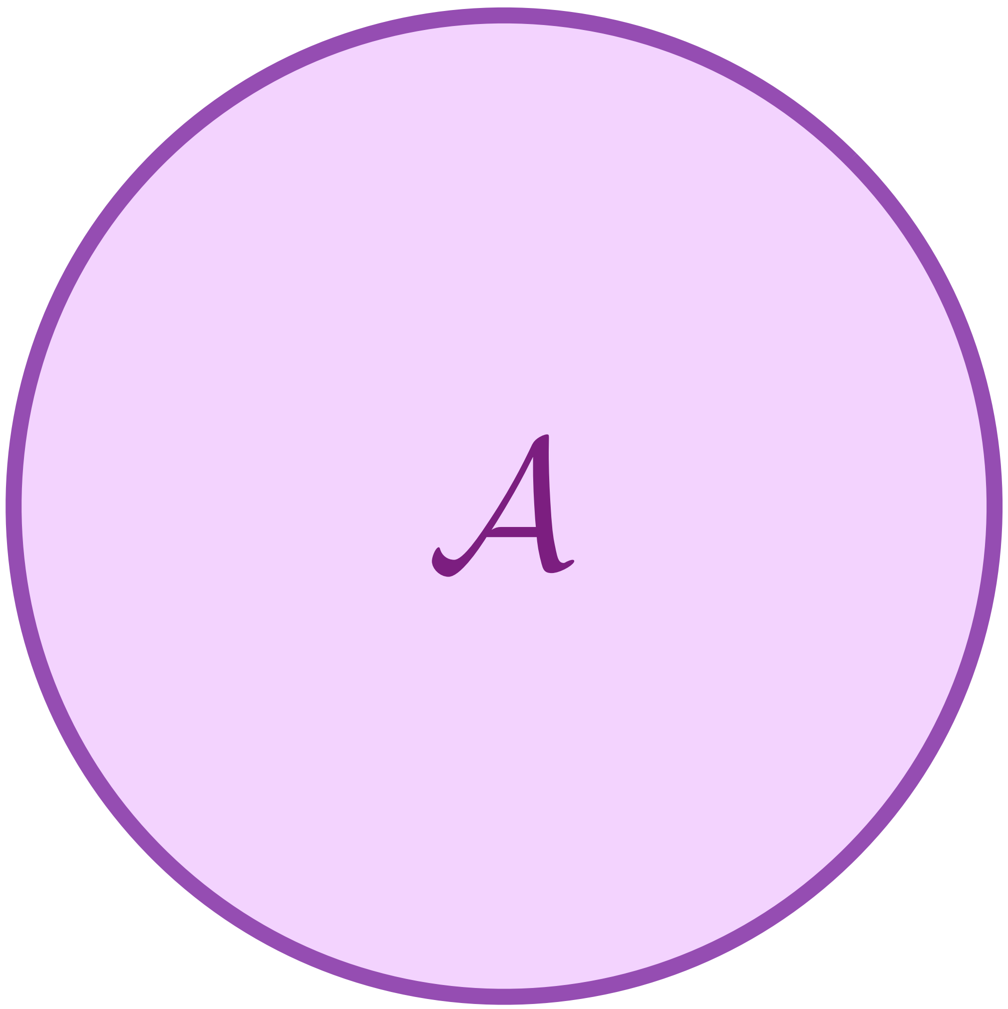


The b bosons have bound with f fermions to form c "molecules"

S. Powell, S. Sachdev, and H. P. Büchler, *Physical Review* B **72**, 024534 (2005)

If $\mathrm{U}_g(1)$ is spontaneously broken by condensation of b, only the Luttinger relation associated with U(1) applies. Also the c and f flavors can now mix ("hybridize"), and so form only a single Fermi surface when the mixing is large enough.

$$\mathcal{A} \quad = \quad \langle \overline{c}\,\gamma^t c \rangle + \left\langle \overline{f} \gamma^t f \right\rangle = \langle \mathcal{Q} \rangle$$



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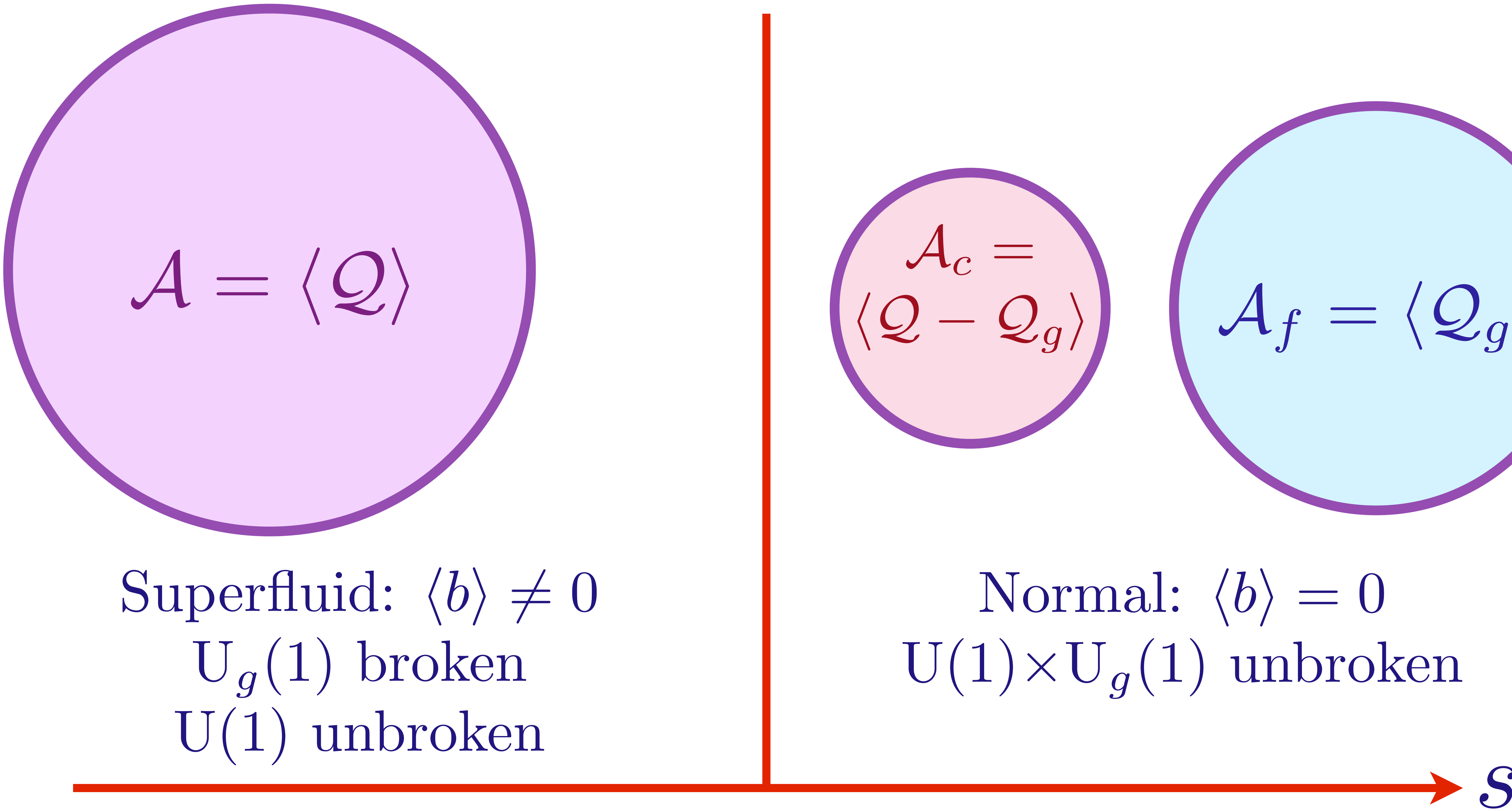
Phase diagram of boson-fermion mixture



$$\mathcal{L} = \bar{c}\left(\partial_a - \mu\delta_{at}\right)\gamma^a c + \bar{f}\left(\partial_a - (\mu + \mu_g)\delta_{at}\right)\gamma^a f$$
$$+ \left|(\partial_a + \mu_g\delta_{at})b\right|^2 + s|b|^2 + \lambda(\bar{c}fb + \text{c.c.}) + \ldots$$

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- Now gauge $\mathrm{U}_g(1)$ by a dynamical ("emergent") gauge field A_a.

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- Longitudinal gauge fluctuations are screened by the f fermions. But transverse gauge fluctuations remain unscreened, and are Landau-damped by excitations near the f Fermi surface. The theory of a Fermi surface coupled to transverse gauge fluctuations is *strongly coupled in two spatial dimensions.*

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- The overdamped transverse gauge modes lead to "non-Fermi liquid" broadening of the fermion pole near the f Fermi surface.

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- The overdamped transverse gauge modes lead to "non-Fermi liquid" broadening of the fermion pole near the f Fermi surface.
- The gauge-neutral c fermion also acquires a weaker non-Fermi liquid broadening.

$$\mathcal{L} = \bar{c}\,(\partial_a - \mu\delta_{at})\,\gamma^a c + \overline{f}\,(\partial_a - iA_a + (\mu + \mu_g)\delta_{at})\,\gamma^a f \\ + |(\partial_a + iA_a + \mu_g\delta_{at})b|^2 + s|b|^2 + \lambda(\bar{c}fb + \text{c.c.}) + \ldots$$

- However, *the locations of the Fermi surfaces are well defined, and the Luttinger relations apply as before.*

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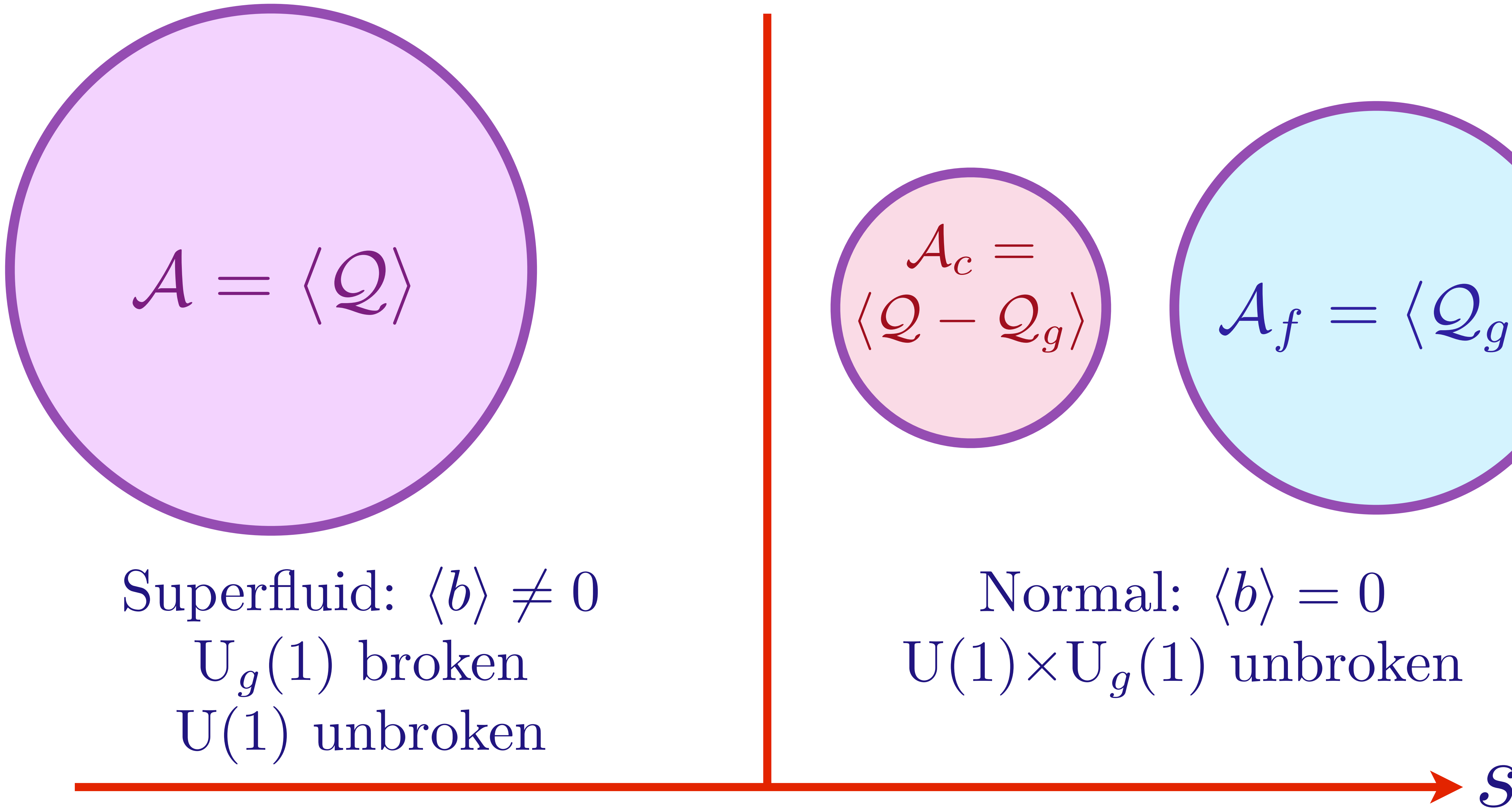
Phase diagram of boson-fermion mixture



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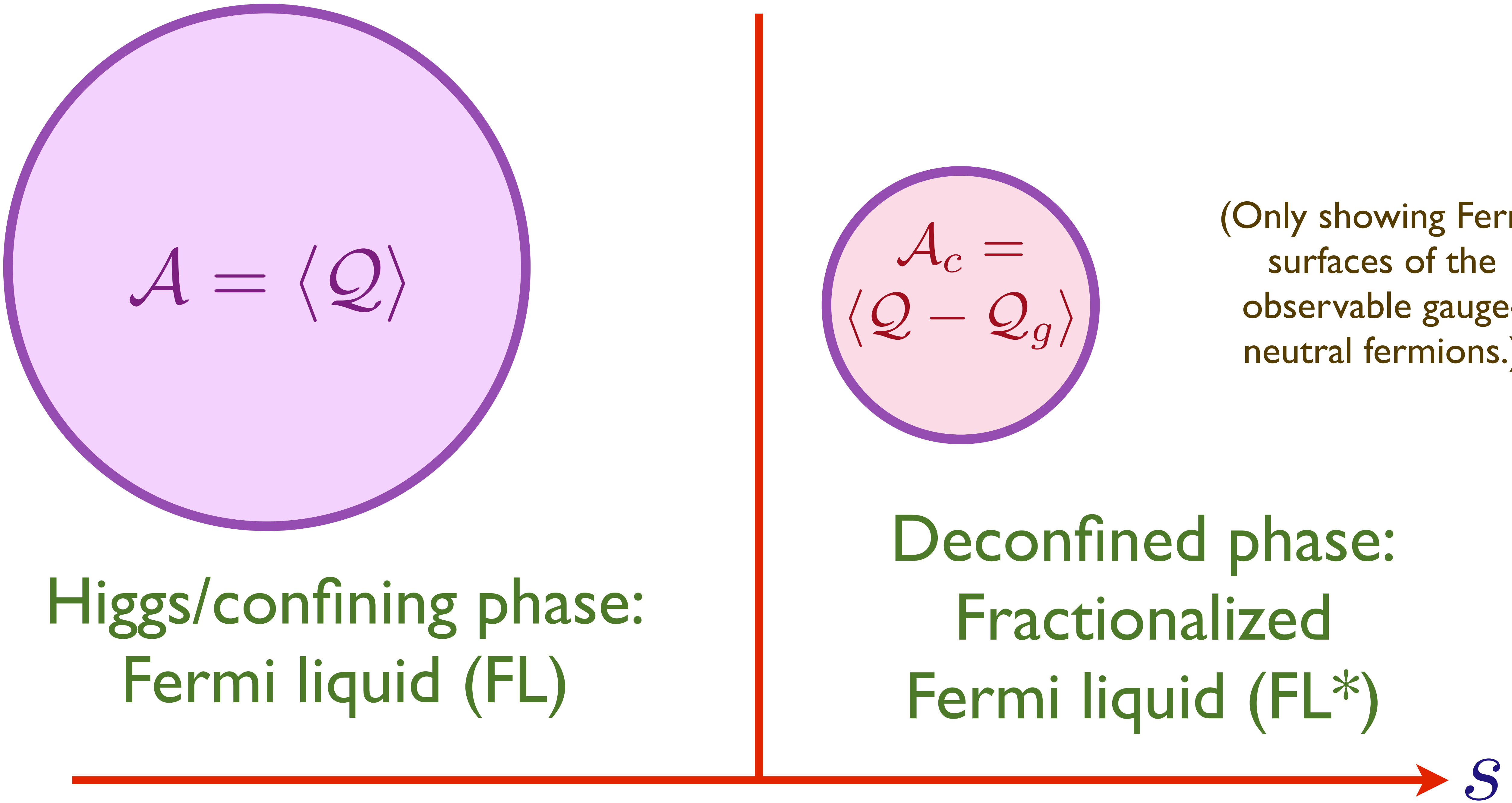
Phase diagram of $U_g(1)$ gauge theory



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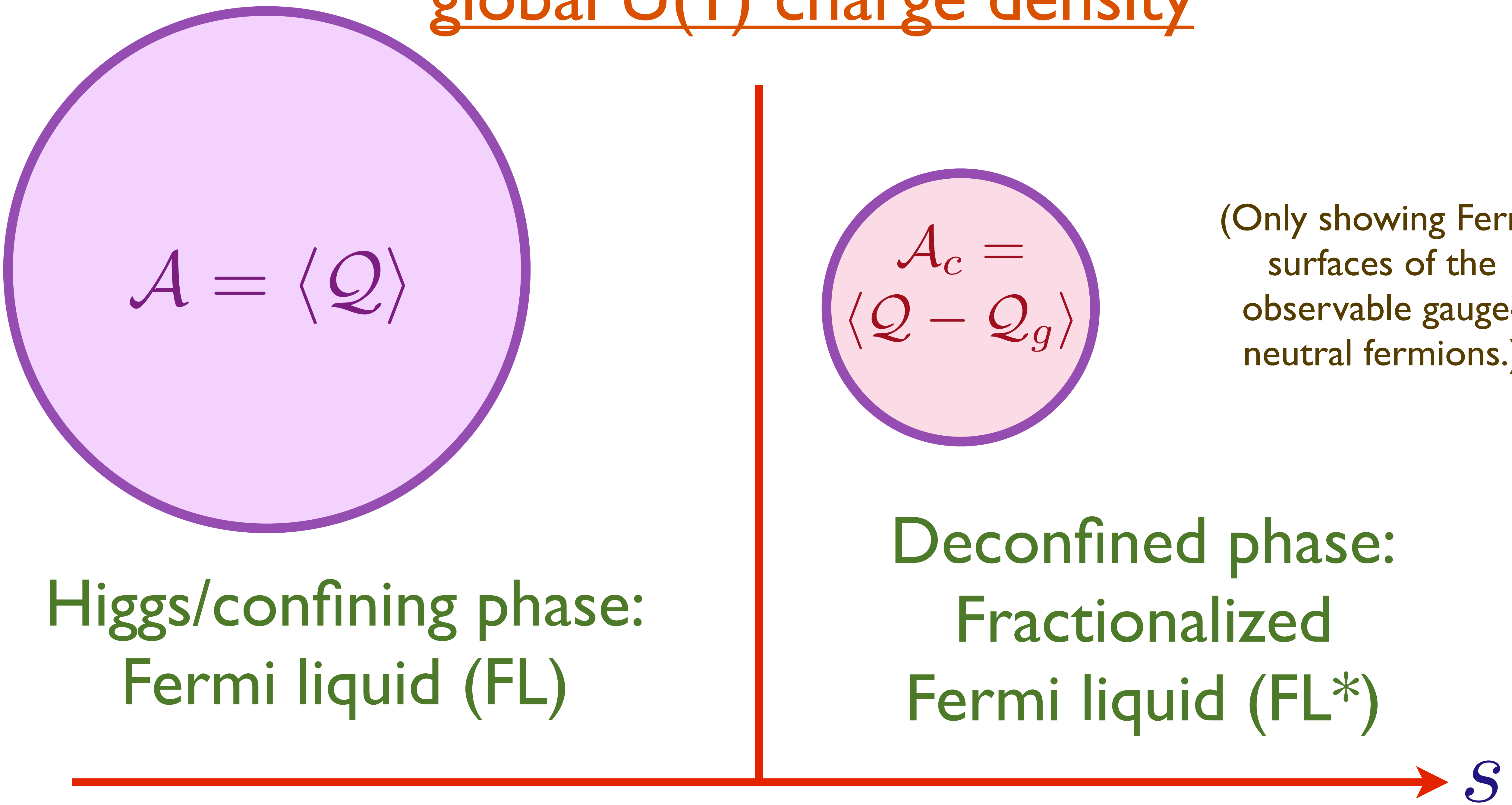
T. Senthil, M. Vojta, and S. Sachdev, *Physical Review* B **69**, 035111 (2004)

Phase diagram of gauge theories with global U(1) charge density



The same phase diagram applies when $U_g(1)$ is generalized to non-Abelian or discrete gauge groups. It also applies when the f Fermi surface is gapped by the lattice potential, or by pairing of the f fermions.

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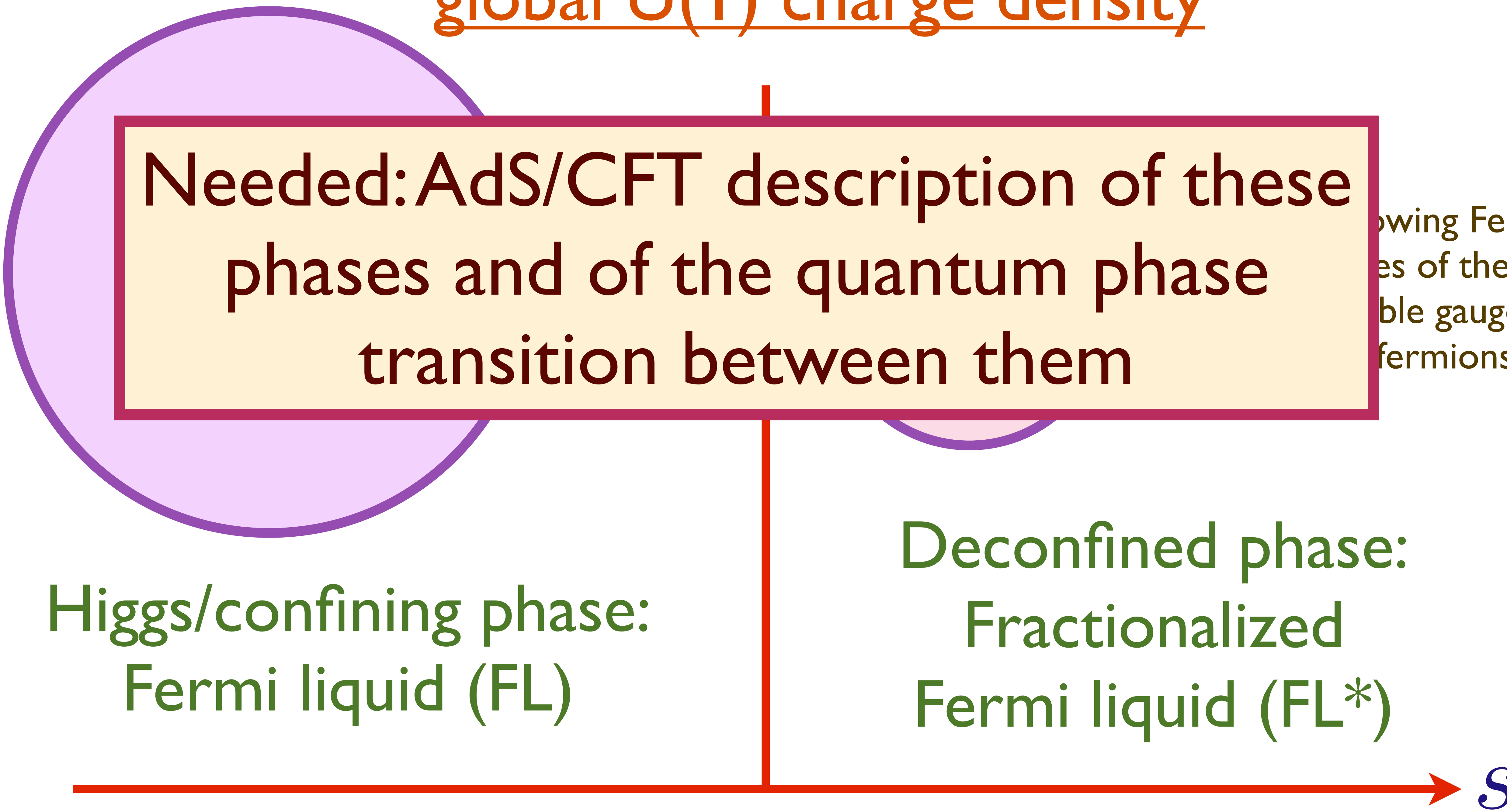

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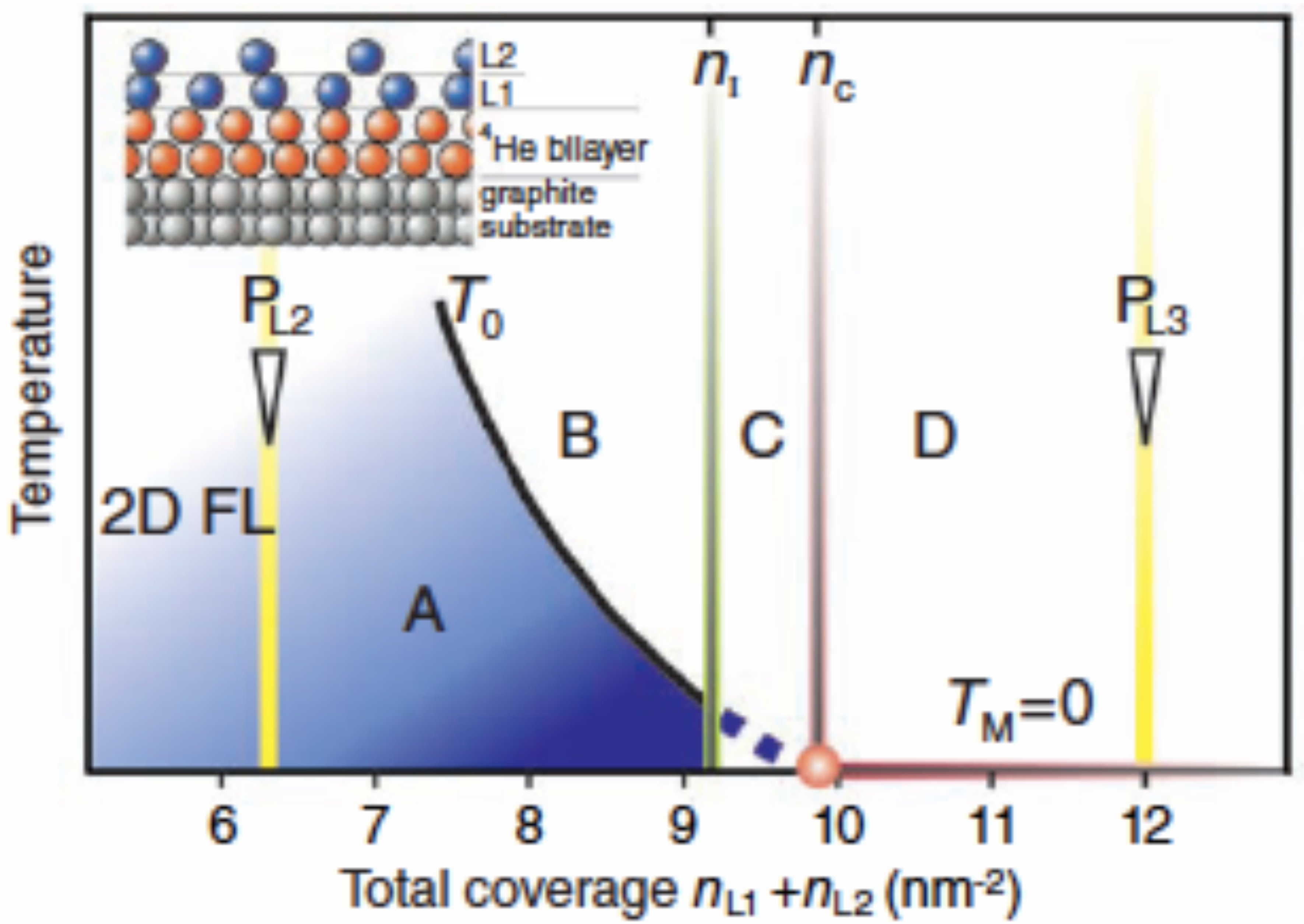
Bilayer ^{3}He: A Simple Two-Dimensional Heavy-Fermion System with Quantum Criticality

Science **317**, 1356 (2007)

Michael Neumann, Ján Nyéki, Brian Cowan, John Saunders*



A bilayer Hubbard model or a ``Kondo lattice”

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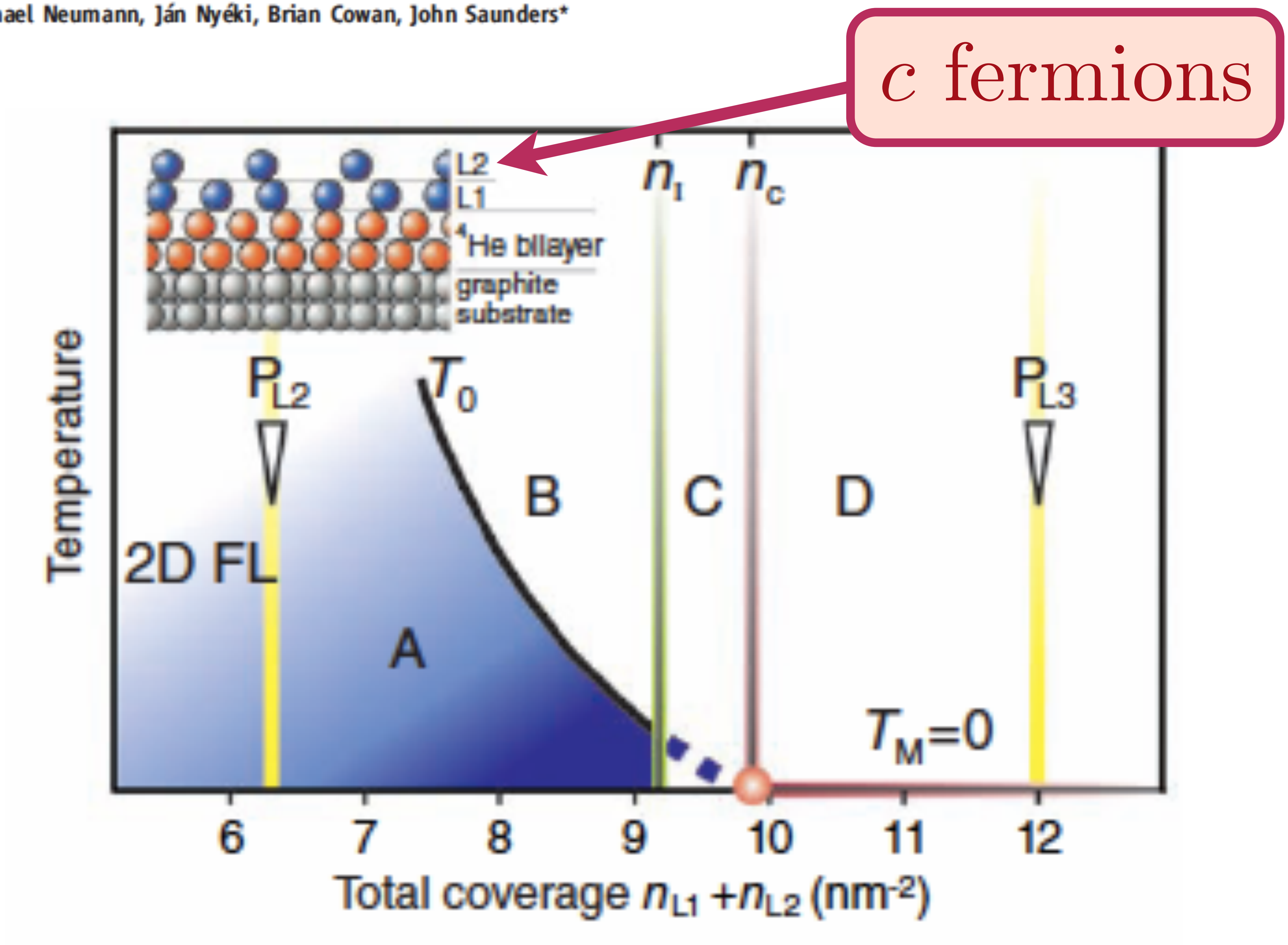

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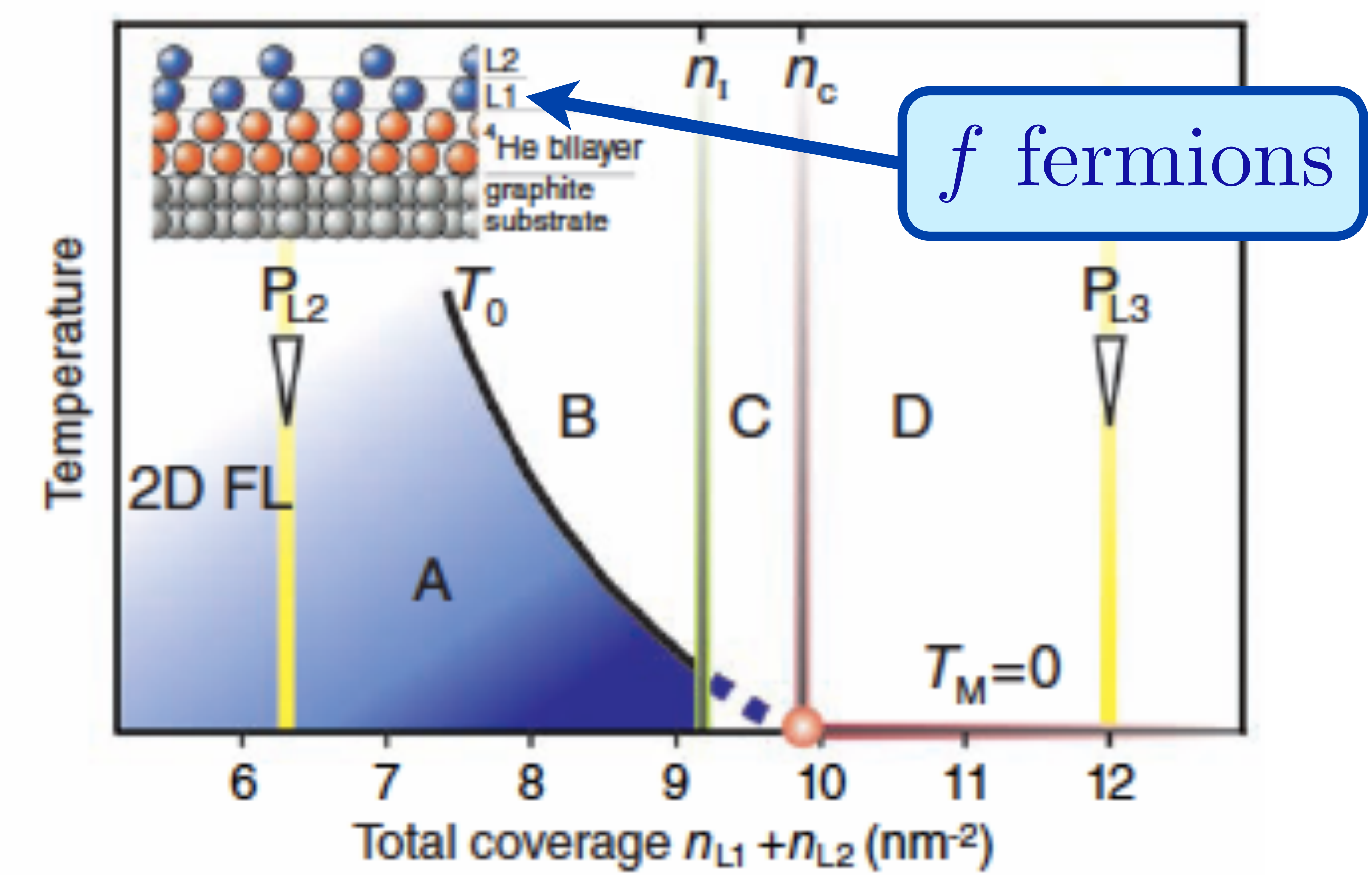

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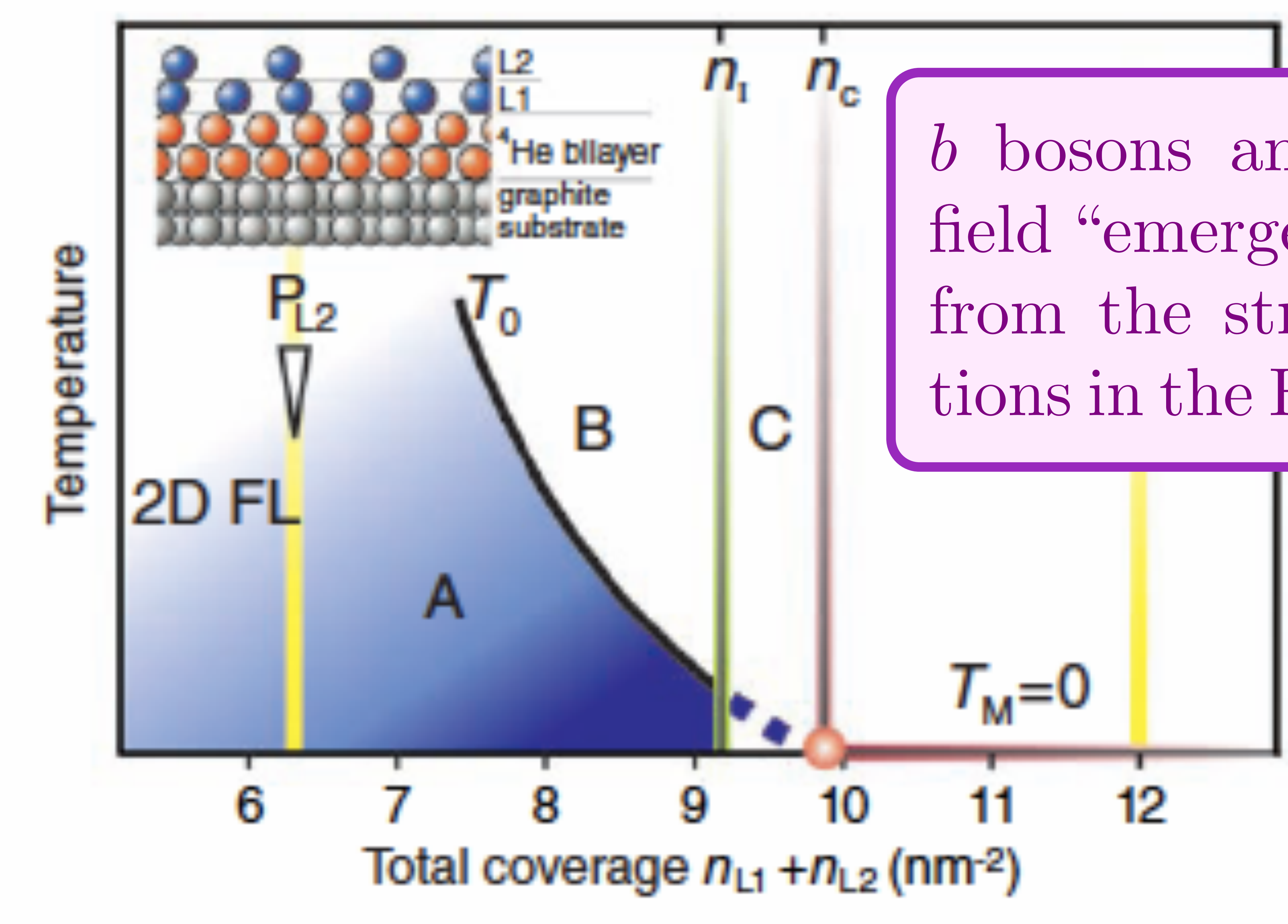

b bosons and A_a gauge field "emerge" dynamically from the strong interactions in the Hubbard model.

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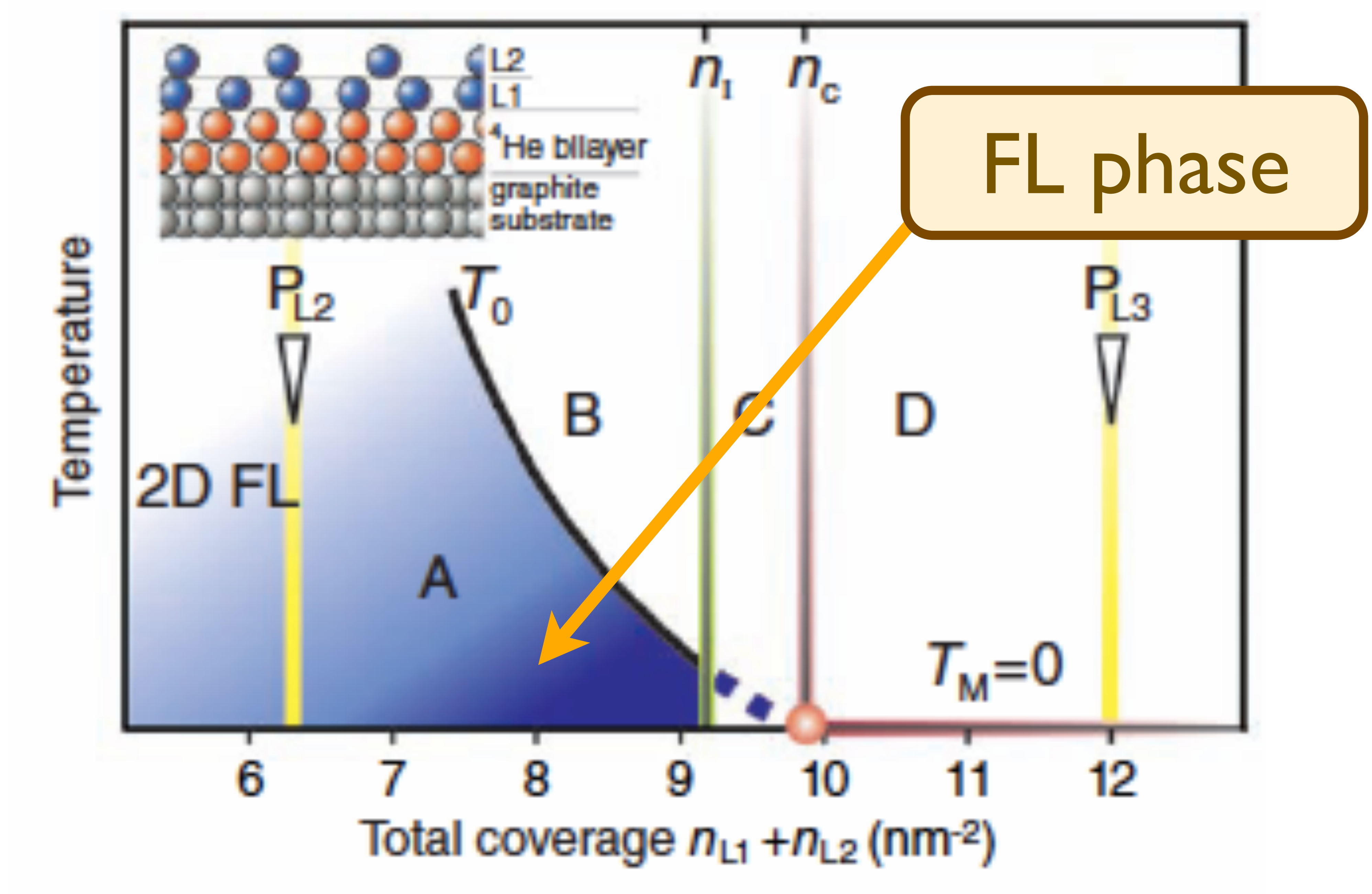

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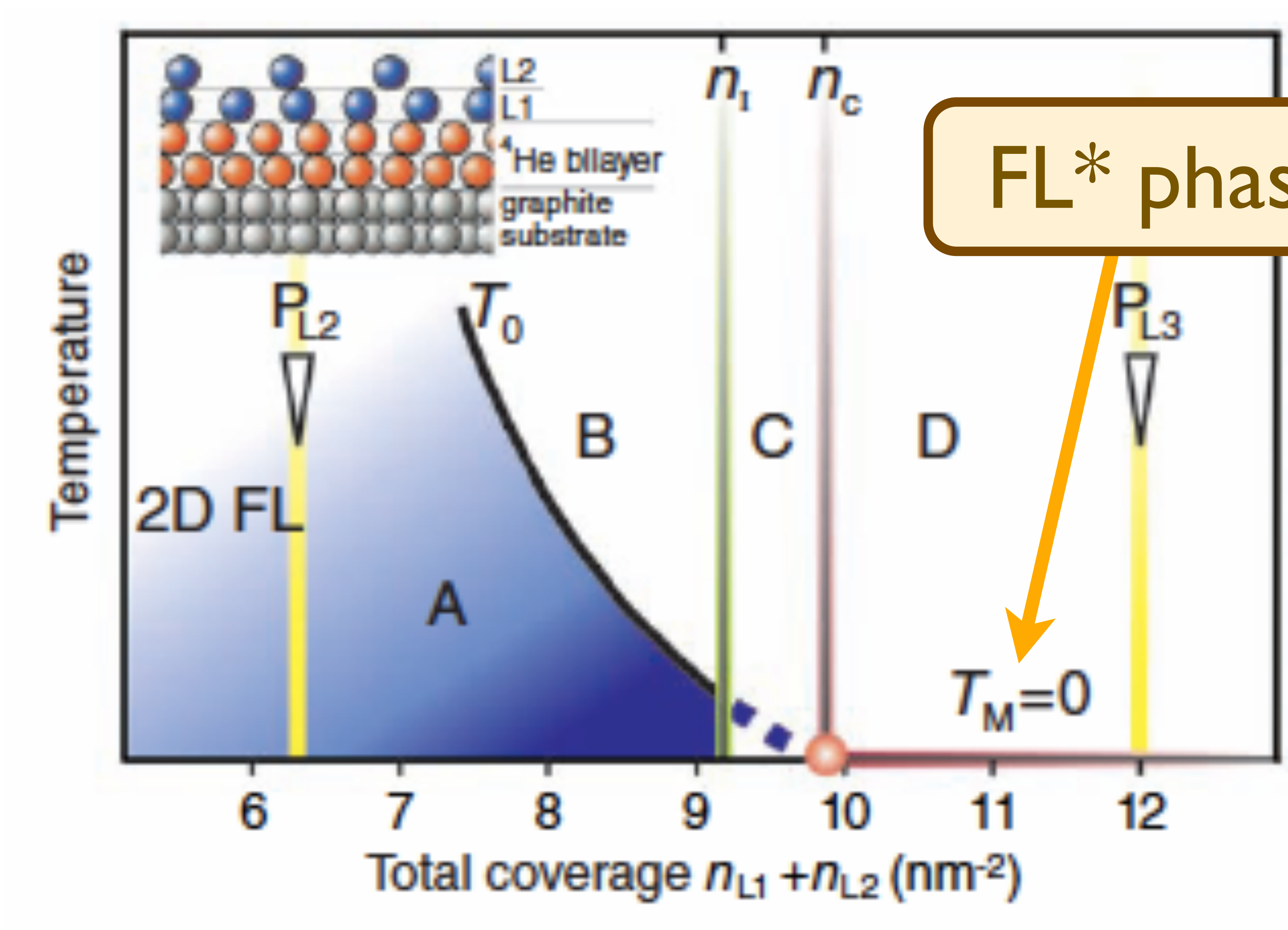

A bilayer Hubbard model or a ``Kondo lattice”

Outline

1. Fermion-boson mixtures
   Luttinger relations with bosons

2. Gauge theories
   The fractionalized Fermi liquid (FL) phase*

3. Connections to semi-holographic theories
   Low energy theory of FL and FL phases*

4. Solvable models with infinite-range hopping
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Low energy theory of FL* phase

Integrate out gapped b bosons, and write theory of c electrons as

$$\mathcal{L}_c = \bar{c}(\partial_a - \mu\delta_{at})c + \lambda(\bar{c}F + \overline{F}c)$$

- The c are the observable gauge-invariant fermions ("probe UV fermions").
- The F are composite gauge-invariant operators ("IR fermions"), carrying global U(1) charge, which probe the strongly-coupled physics of the f Fermi surface coupled to a fluctuating gauge field

  $$F \sim (\bar{f} f)c$$

  Note this also involves a contribution from the "probe sector" (the factor of c), so the UV and IR are not completely decoupled.

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If we ignore UV-IR mixing, this structure is formally the same as that in the semi-holographic theories of metals (T. Faulkner, H. Liu, J. McGreevy and D. Vegh, arXiv:0907.2694; T. Faulkner and J. Polchinski, arXiv:1001.5049.)

Low energy theory of FL phase

Now b is condensed; so write $b = e^{-i\vartheta}$ and integrate out the f fermions. Then the c electrons ("UV fermions") obey

$$\mathcal{L}_c = \bar{c}(\partial_a - \mu\delta_{at} - \Sigma_f - iA_a^{\text{ext}})c + \Pi_f(\widetilde{A}_a) + (\partial_a\vartheta - \widetilde{A}_a + A_a^{\text{ext}})^2$$

Here A_a^{ext} is an external source coupling to the global U(1) charge, $\widetilde{A}_a = A_a + A_a^{\text{ext}}$, and Σ_f and Π_f are the self-energy and effective action generated by integrating out the f.

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This structure is similar to the semi-holographic theory of Nickel and Son (arXiv:1009.3094).

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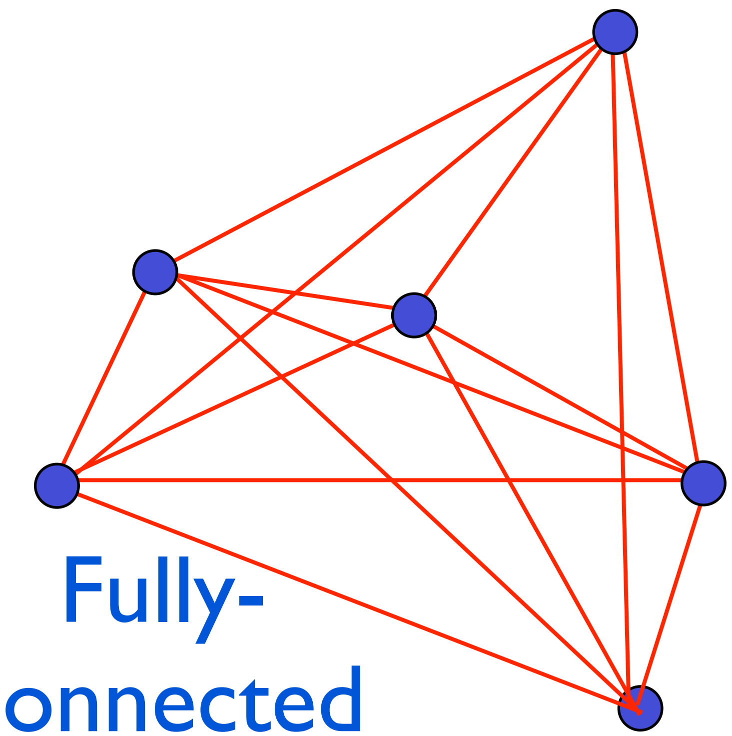
Solution of lattice models

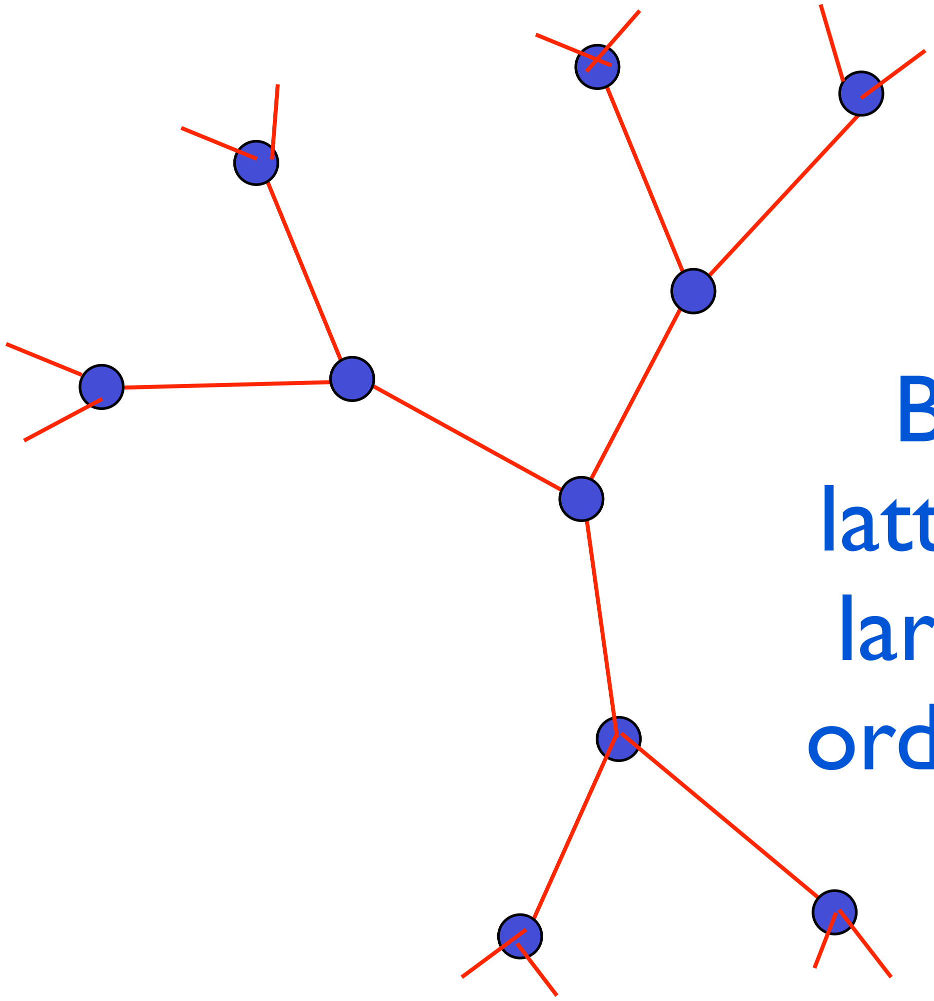
Place theory on lattice, integrate out b and A_a, to obtain Kondo lattice Hamiltonian

$$H = -\sum_{i<j} t_{ij} c_{i\alpha}^{\dagger} c_{j\alpha} + \sum_{i<j} J_H(i,j) \vec{S}_i \cdot \vec{S}_j + J_K \sum_i \vec{S}_i \cdot c_{i\alpha}^{\dagger} \vec{\sigma}_{\alpha\beta} c_{i\beta}$$

where $\vec{S}_i = f_{i\alpha}^{\dagger} \vec{\sigma}_{\alpha\beta} f_{\beta}$



Fully-connected cluster



Bethe lattice for large co-ordination

S. Sachdev and J. Ye, Phys. Rev. Lett. **70**, 3339 (1993).

A. Georges, O. Parcollet, and S. Sachdev, Phys. Rev. B **63**, 134406 (2001).

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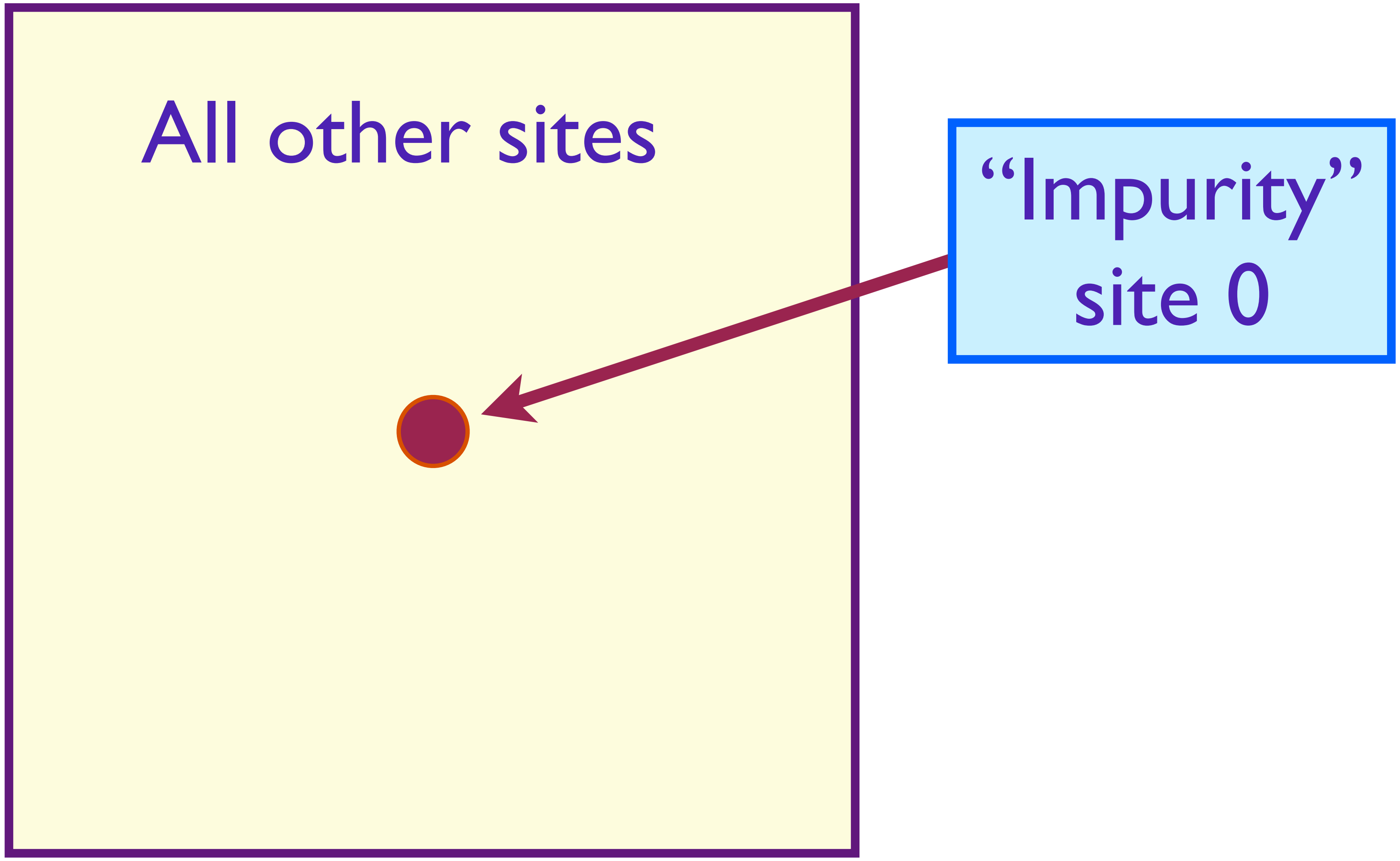

$$\mathcal{L} = \mathcal{L}_{\rm imp}[c_0, f_0] + c_0^\dagger F_{\rm bulk} + F_{\rm bulk}^\dagger c_0 + \mathcal{L}_{\rm bulk}$$

Has to be combined with a *self-consistency condition* between correlators on the impurity and the bulk.

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properties of the FL* phase:

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Obtain both FL and FL* phases;

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- The ground state has a non-zero entropy density
- The correlations of F_{bulk} are local ($z = \infty$)
- The correlations F_{bulk} in time have a conformal structure with scaling dimension Δ (as in the boundary of AdS_2)

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Obtain both FL and FL* phases;

properties of the FL* phase:

- The ground state has a non-zero entropy density
- The correlations of F_{bulk} are local ($z = \infty$)
- The correlations F_{bulk} in time have a conformal structure with scaling dimension Δ (as in the boundary of AdS_2)
- Imposition of the self-consistency condition between impurity and boundary yields the scaling dimension $\Delta = 1$, the 'marginal Fermi liquid' value.

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These features, and the resulting fermion correlator and transport properties, co-incide with those obtained (for general Δ) using the holographic $AdS_2 \times R^d$ theory defined on the extremal horizon of the Reissner-Nordstrom black hole (T. Faulkner, H. Liu, J. McGreevy and D. Vegh, arXiv:0907.2694)

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Conclusions

- Compressible quantum matter is characterized by Fermi surfaces.

- Fermi surfaces can be removed from the Luttinger count if the fermions acquire gauge charges

- Phases of a strongly-coupled gauge theory contains Fermi liquid (FL) and fractionalized Fermi liquid (FL*) phases: attractive candidate for a dual gravity theory

Conclusions

- Mean field Kondo lattice models capture the physics of holographic metals with a $AdS_2 \times R^d$ geometry

- Needed: Holographic theory without a factorized geometry, in which the probe fermions and the strongly-coupled IR refer to the same degrees of freedom.