# States of quantum matter with long-range entanglement in *d* spatial dimensions

## Gapped quantum matter

*Spin liquids, quantum Hall states*

## Conformal quantum matter

*Graphene, ultracold atoms, antiferromagnets*

## Compressible quantum matter

*Graphene, strange metals in high temperature superconductors, spin liquids*

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Liza Huijse

Max Metlitski

Brian Swingle

# Compressible quantum matter

*A. Fermi liquids:graphene*

*B. Holography: Reissner - Nördstrom solution*

*C. Non-Fermi liquids: nematic critical point (and U(1) spin liquids)*

*D. Holography: scaling arguments for entropy and entanglement entropy*

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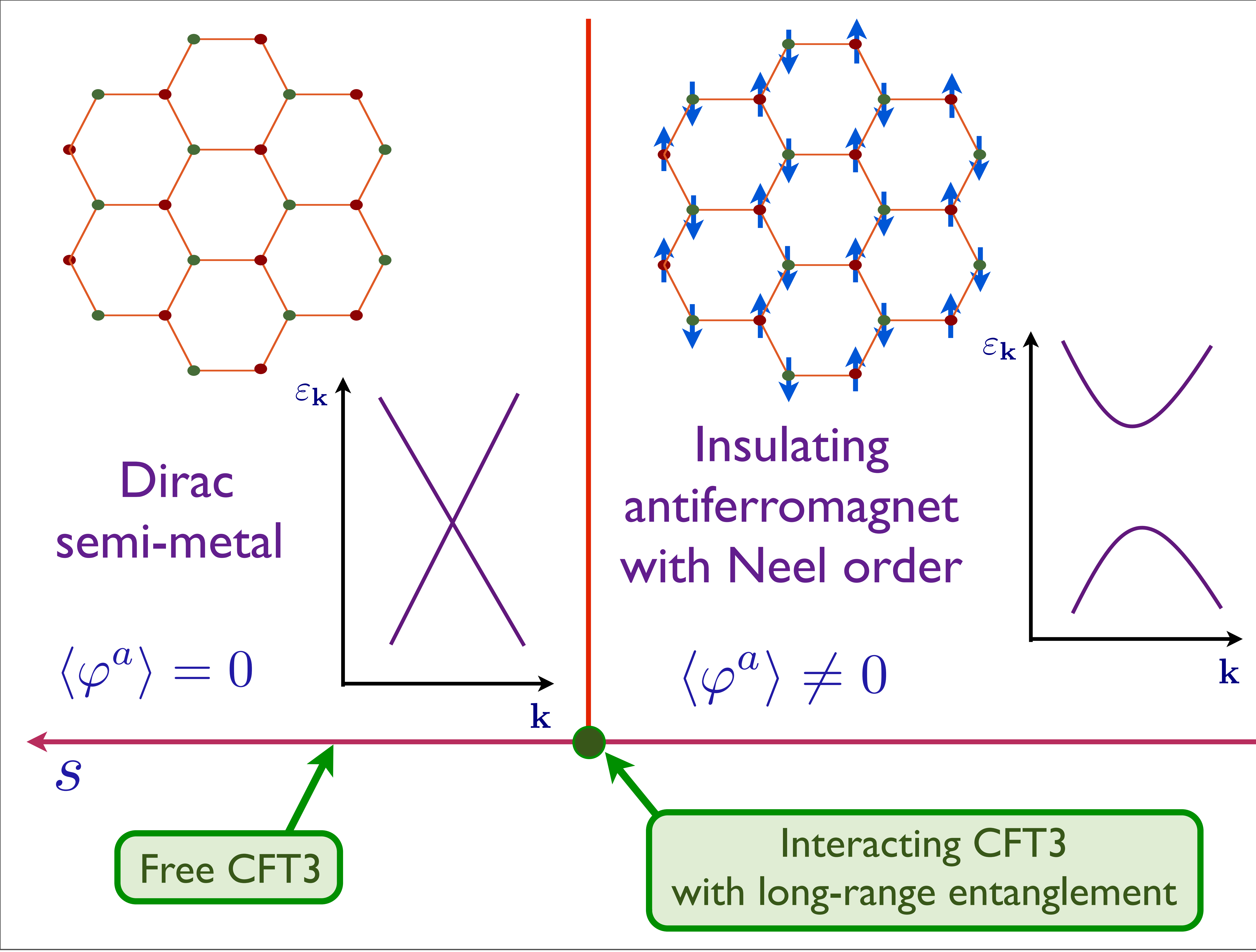
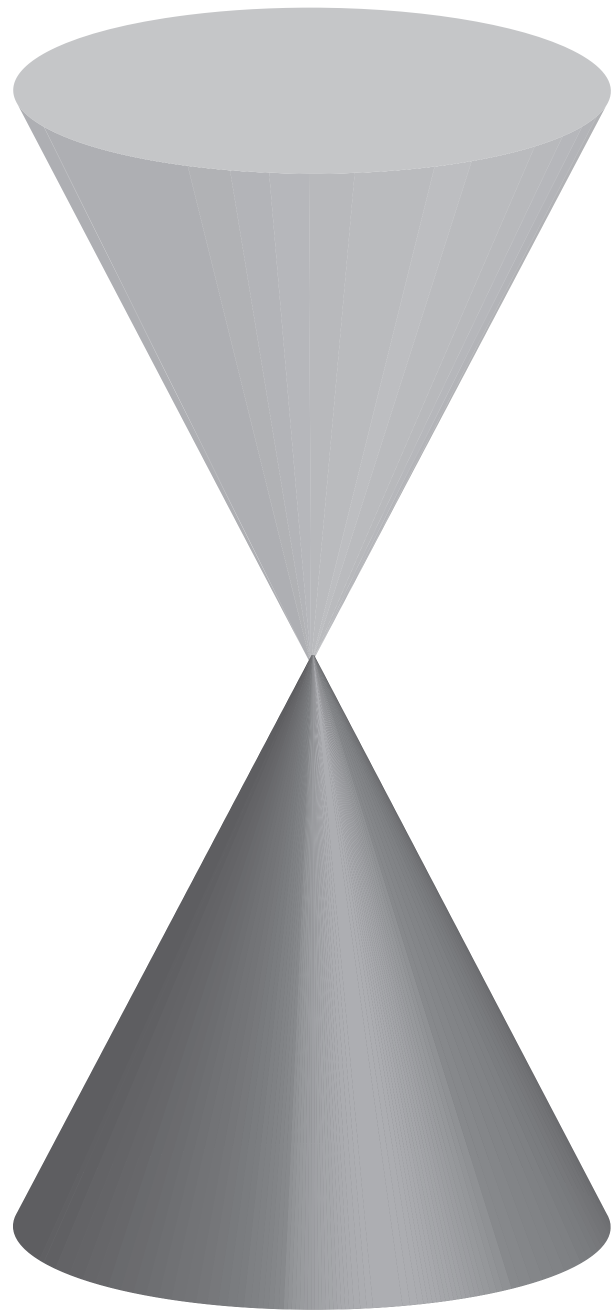


$\varepsilon_{\mathbf{k}}$
$\mathbf{k}$
Dirac semi-metal
$\langle \varphi^a \rangle = 0$
$\varepsilon_{\mathbf{k}}$
$\mathbf{k}$
Insulating antiferromagnet with Neel order
$\langle \varphi^a \rangle \neq 0$
$s$
Free CFT3
Interacting CFT3 with long-range entanglement

# Quantum phase transition in graphene tuned by a chemical potential (gate voltage)



Dirac
semi-metal

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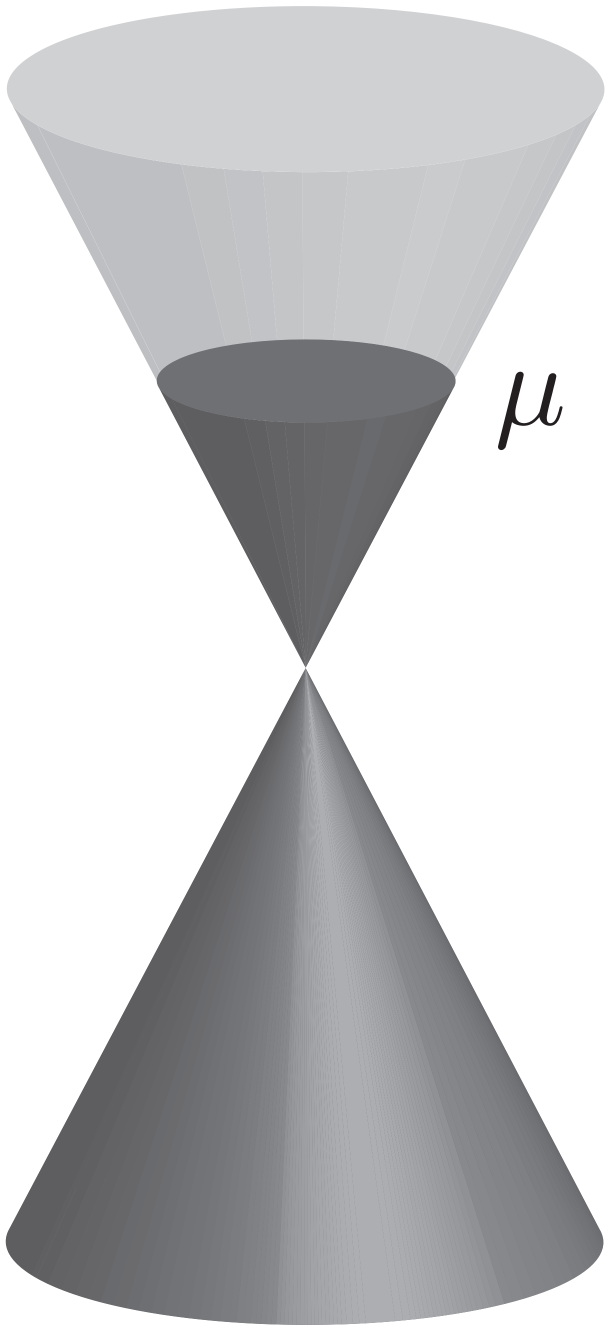
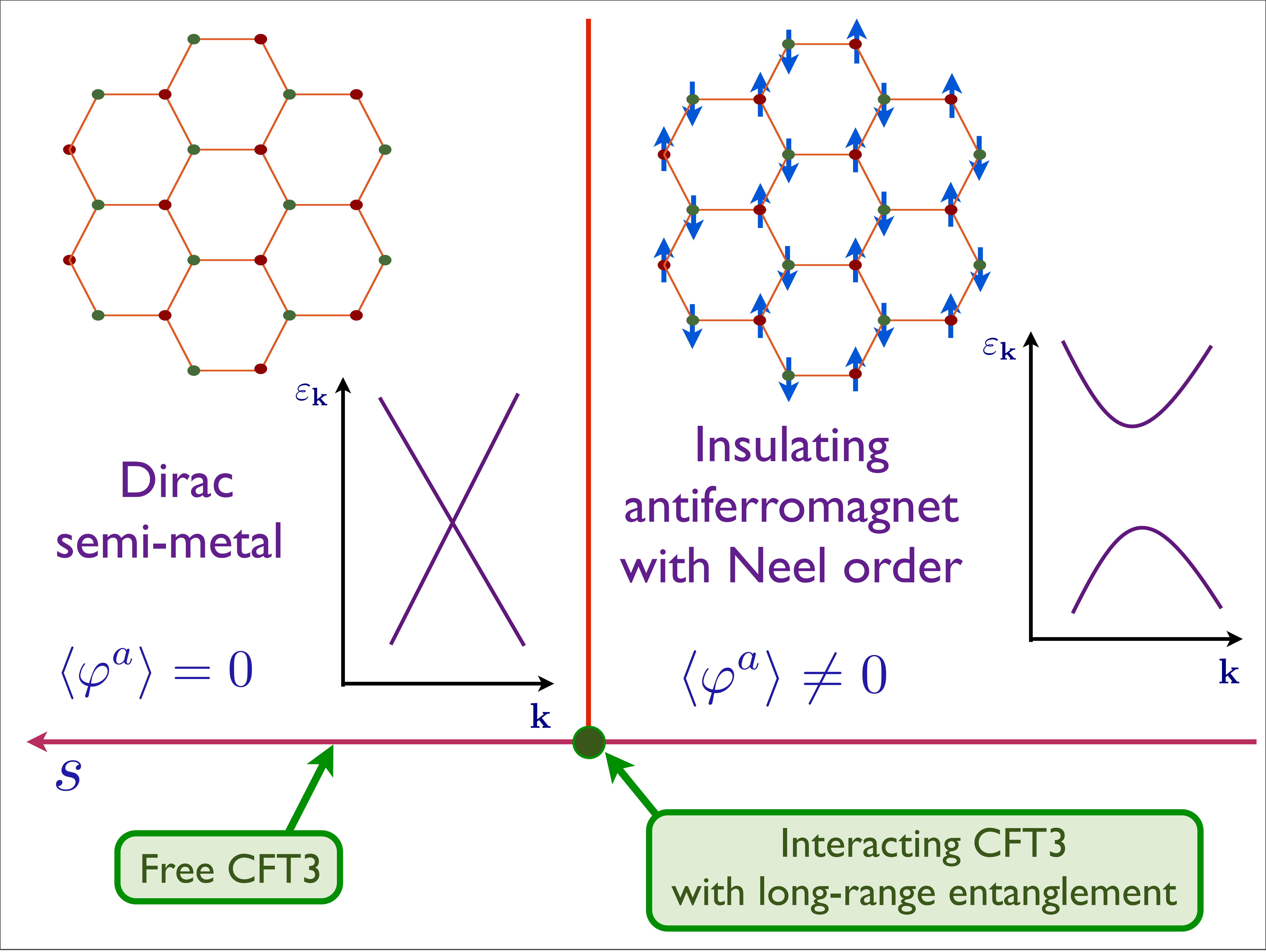



Electron
Fermi surface

# Quantum phase transition in graphene tuned by a chemical potential (gate voltage)


Hole
Fermi surface

Electron
Fermi surface


Dirac
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Free CFT3
Interacting CFT3
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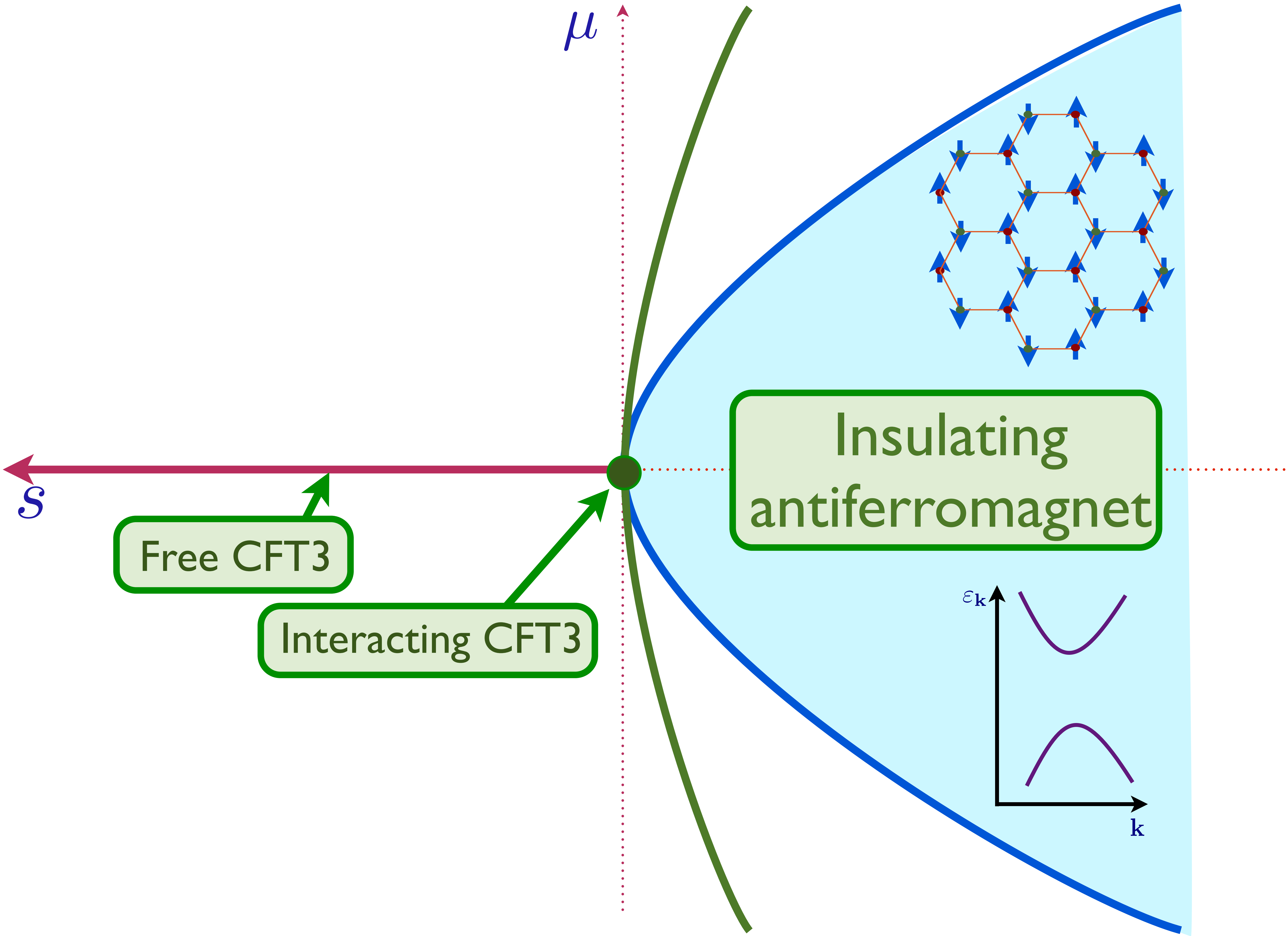
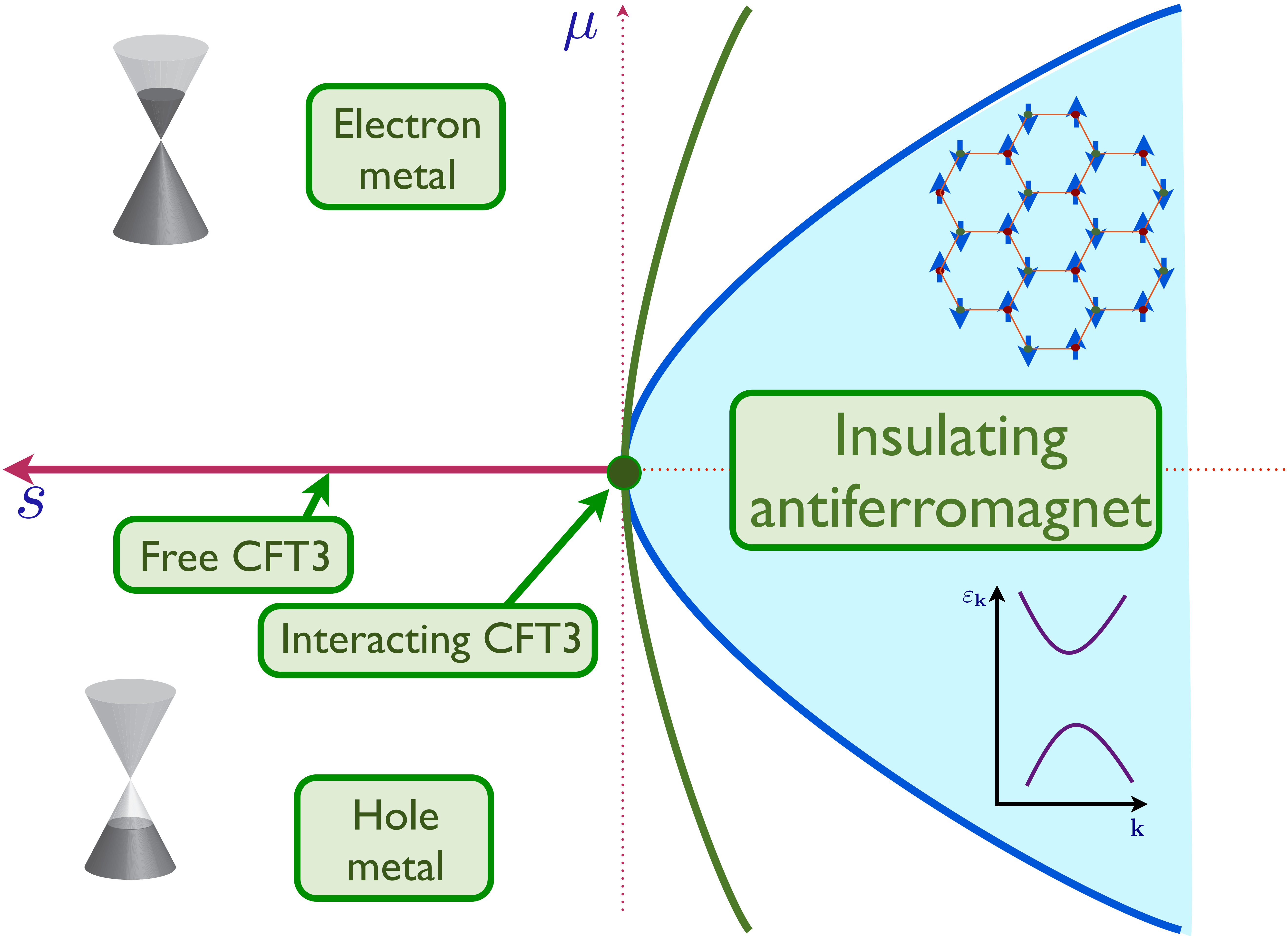
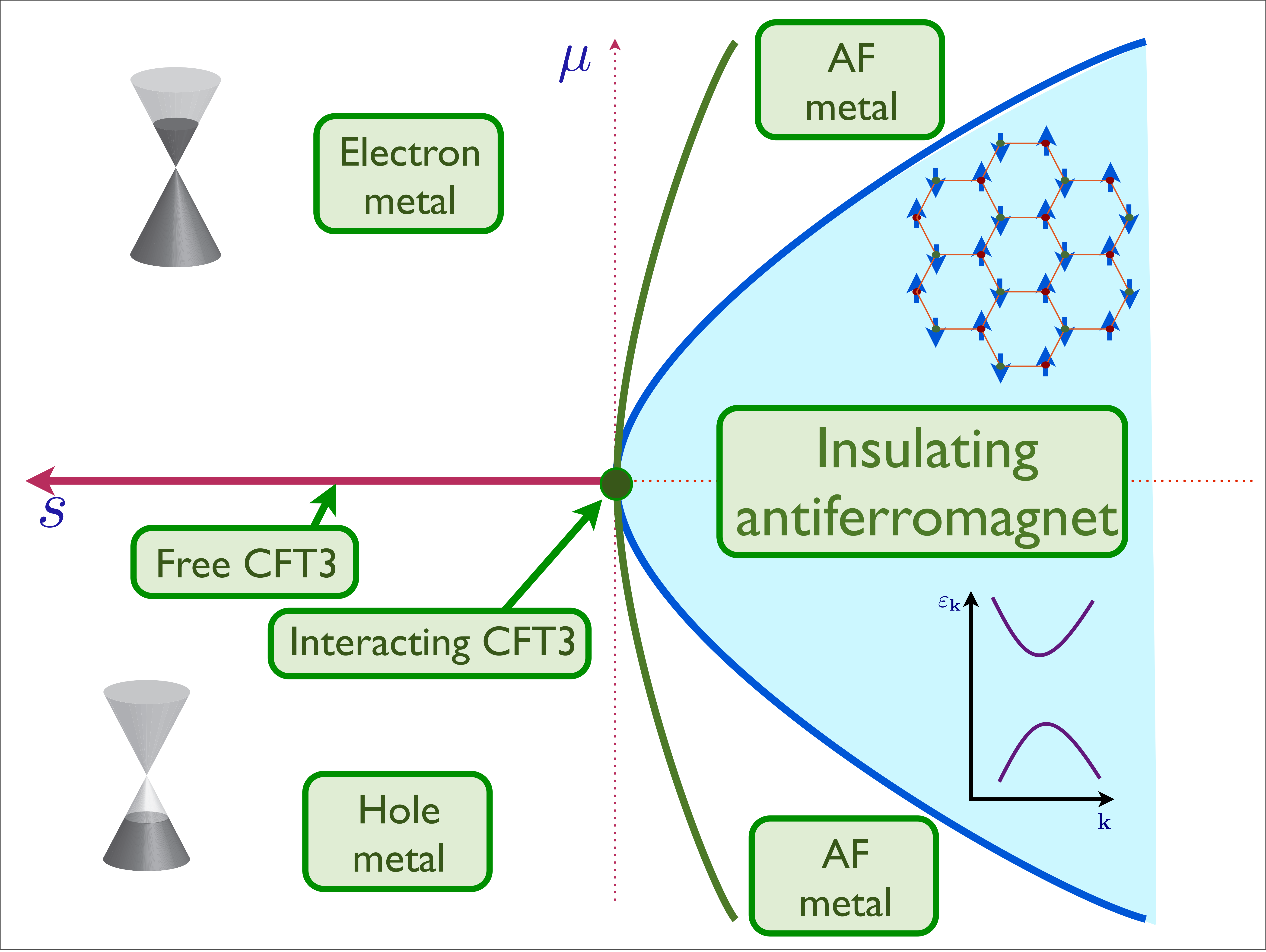


$\mu$
$s$
Free CFT3
Interacting CFT3
Insulating antiferromagnet
$\varepsilon_{\mathbf{k}}$
$\mathbf{k}$



$\mu$
Electron metal
Insulating antiferromagnet
$s$
Free CFT3
Interacting CFT3
$\varepsilon_{\mathbf{k}}$
$\mathbf{k}$
Hole metal



$\mu$
AF metal
Electron metal
Insulating antiferromagnet
$S$
Free CFT3
Interacting CFT3
$\varepsilon_{\mathbf{k}}$
$\mathbf{k}$
Hole metal
AF metal

# Transport in graphene at non-zero $\mu$

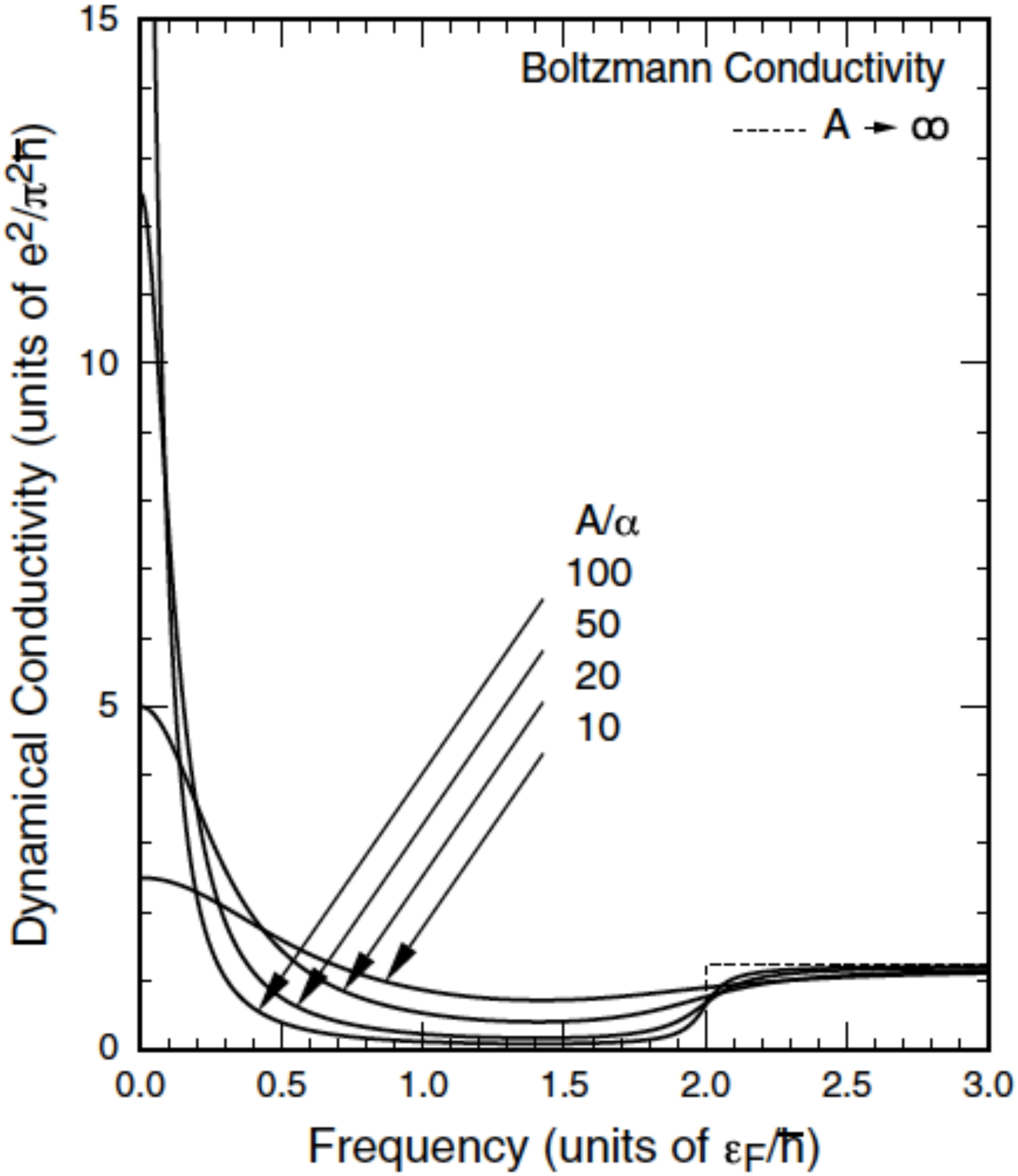
From the Kubo formula

$$\sigma(\omega) = 2\,(ev_F)^2\,\frac{\hbar}{i}\sum_{ss'}\int\frac{d^2k}{4\pi^2}\,\frac{f(\varepsilon_s(\mathbf{k})) - f(\varepsilon_{s'}(\mathbf{k}))}{(\varepsilon_s(\mathbf{k}) - \varepsilon_{s'}(\mathbf{k}))(\varepsilon_s(\mathbf{k}) - \varepsilon_{s'}(\mathbf{k}) + \hbar\omega + i\eta)}$$

where $\varepsilon_s(\mathbf{k}) = s\hbar v_F|\mathbf{k}|$ and $s, s' = \pm 1$ for the valence and conduction bands.

T. Ando, Y. Zheng and H. Suzuura, J. Phys. Soc. Jpn. **71** (2002) pp. 1318-1324

# Transport in graphene at non-zero $\mu$




$A$ is inversely proportional to disorder. In the clean limit $A \to \infty$, at $T = 0$

$$\text{Re}[\sigma(\omega)] = \frac{e^2}{\hbar}\left[\frac{\varepsilon_F}{\hbar}\delta(\omega) + \frac{1}{4}\theta(|\omega| - 2\varepsilon_F)\right]$$

Notice delta function is present even at $T = 0$ at non-zero density: this is a generic consequence of the conservation of momentum in any clean interacting Fermi liquid. Only "umklapp" scattering can broaden this delta function.

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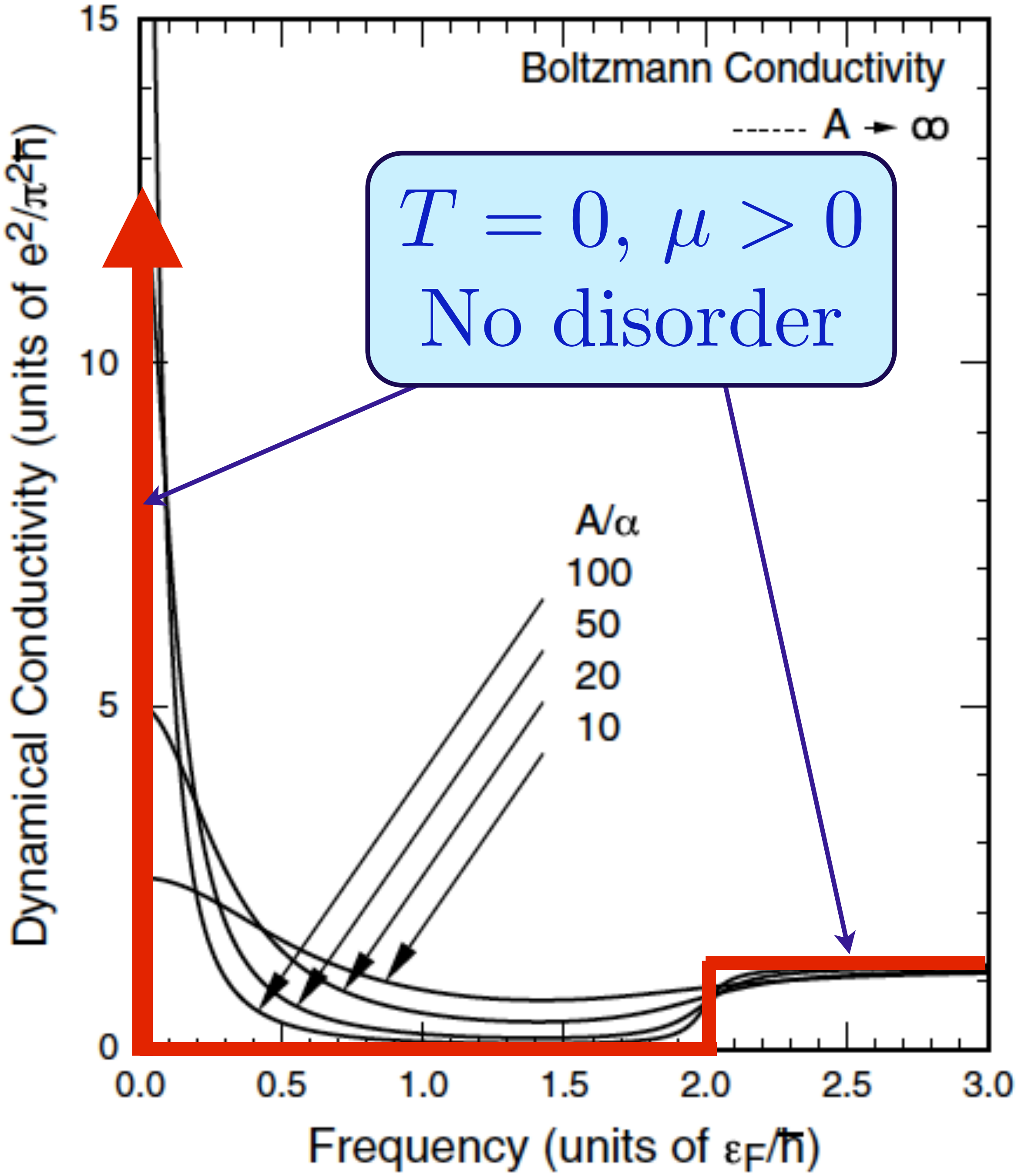


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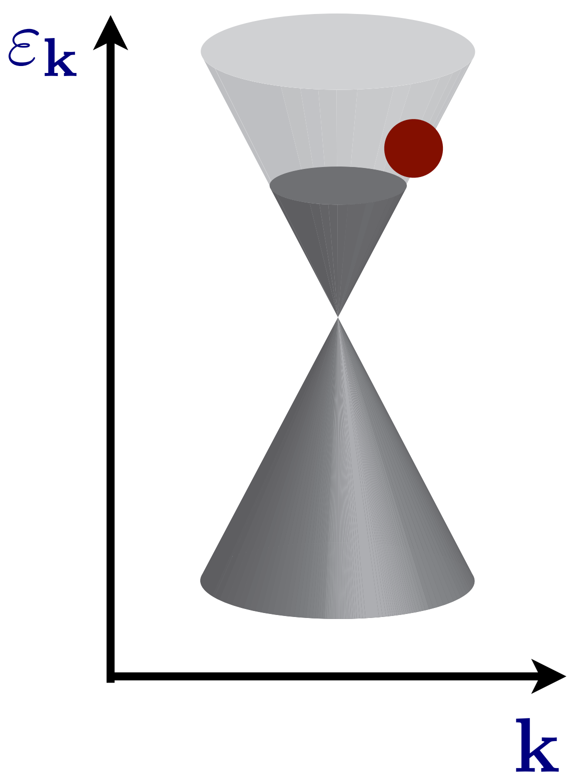
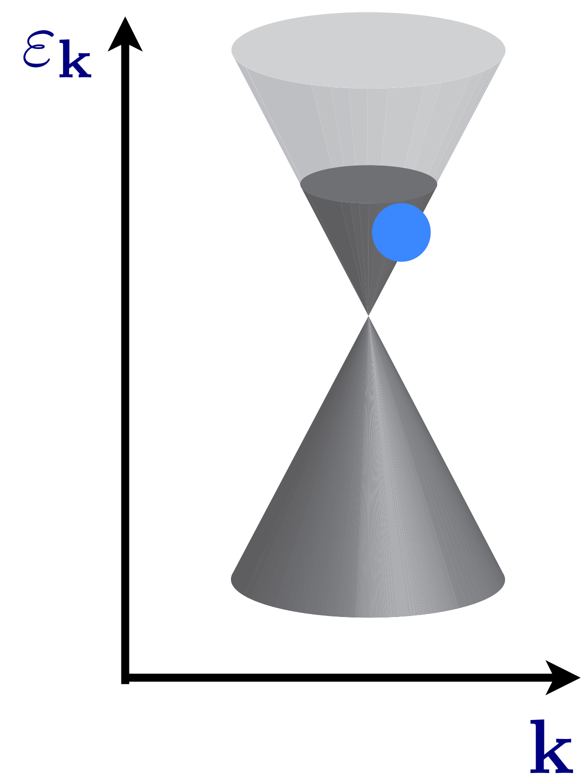
| Particles | Holes |
| --- | --- |
| Momentum | Momentum |
| Current | Current |

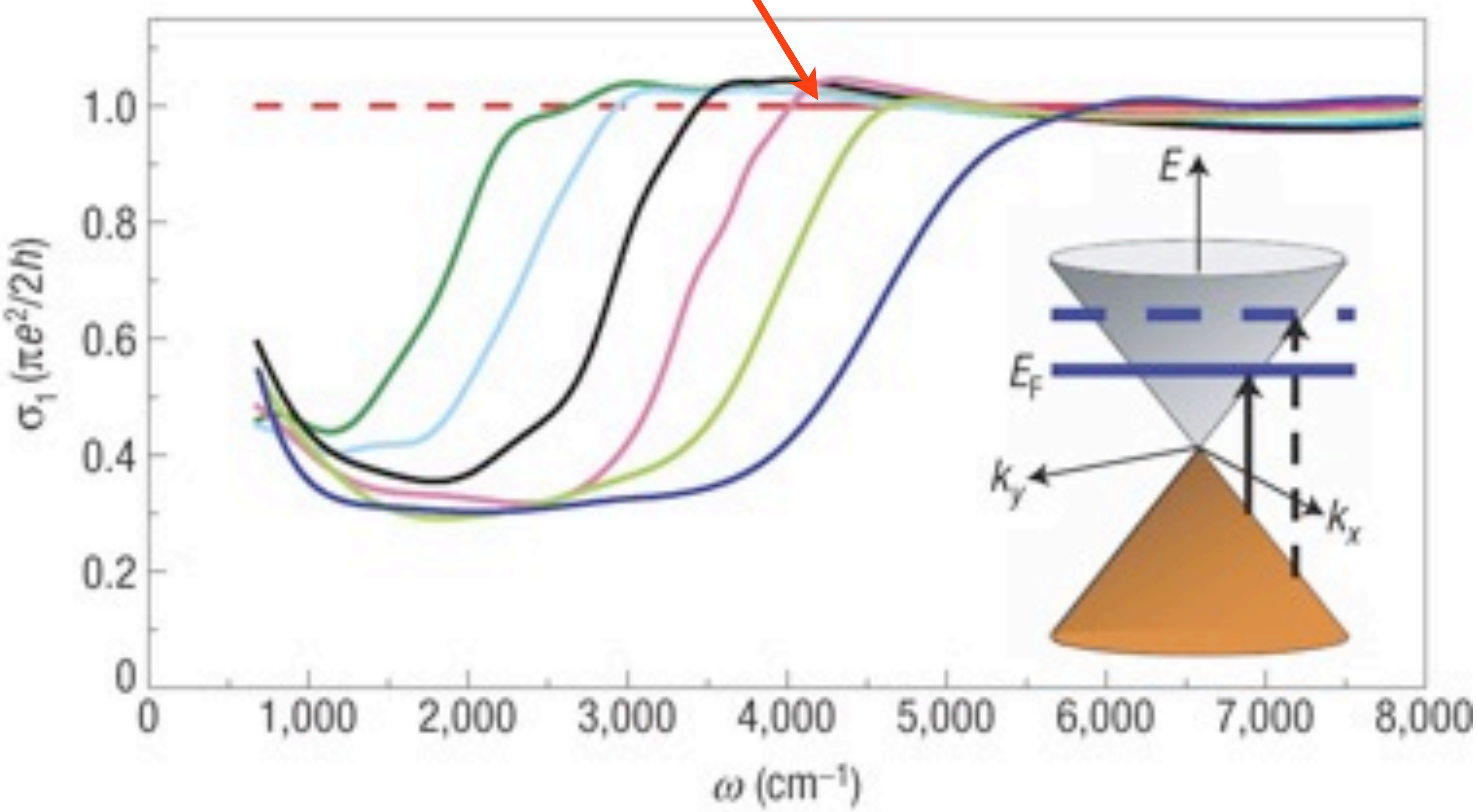



Current carrying state has non-zero momentum, and collisions cannot relax current to zero

# Optical conductivity of graphene

Undoped graphene




Z. Q. Li, E. A. Henriksen, Z. Jiang, Z. Hao, M. C. Martin, P. Kim, H. L. Stormer, and D. N. Basov, *Nature Physics* **4**, 532 (2008).

# Compressible quantum matter

*A. Fermi liquids:graphene*

*B. Holography: Reissner - Nördstrom solution*

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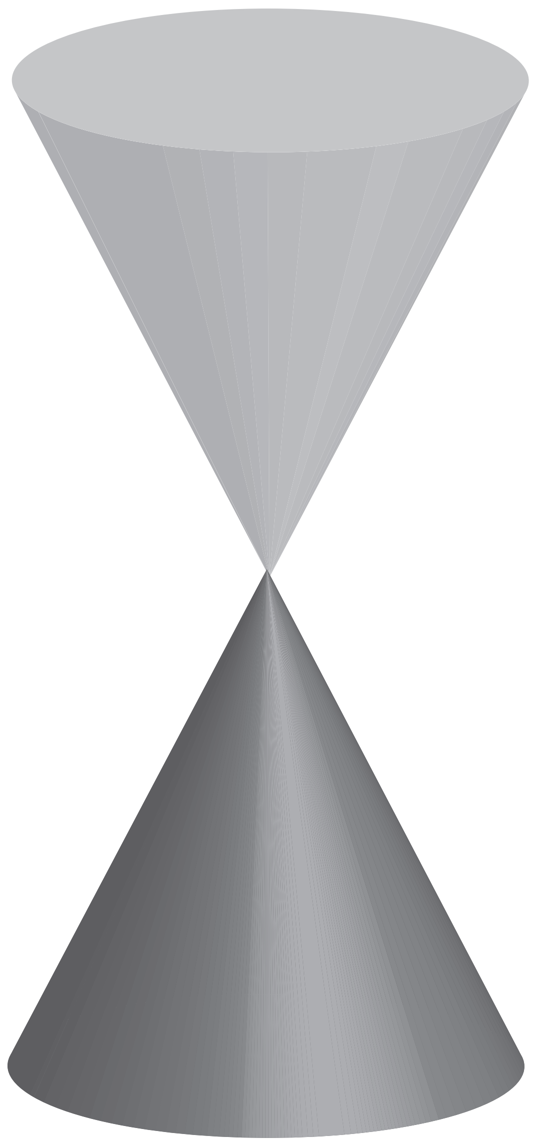
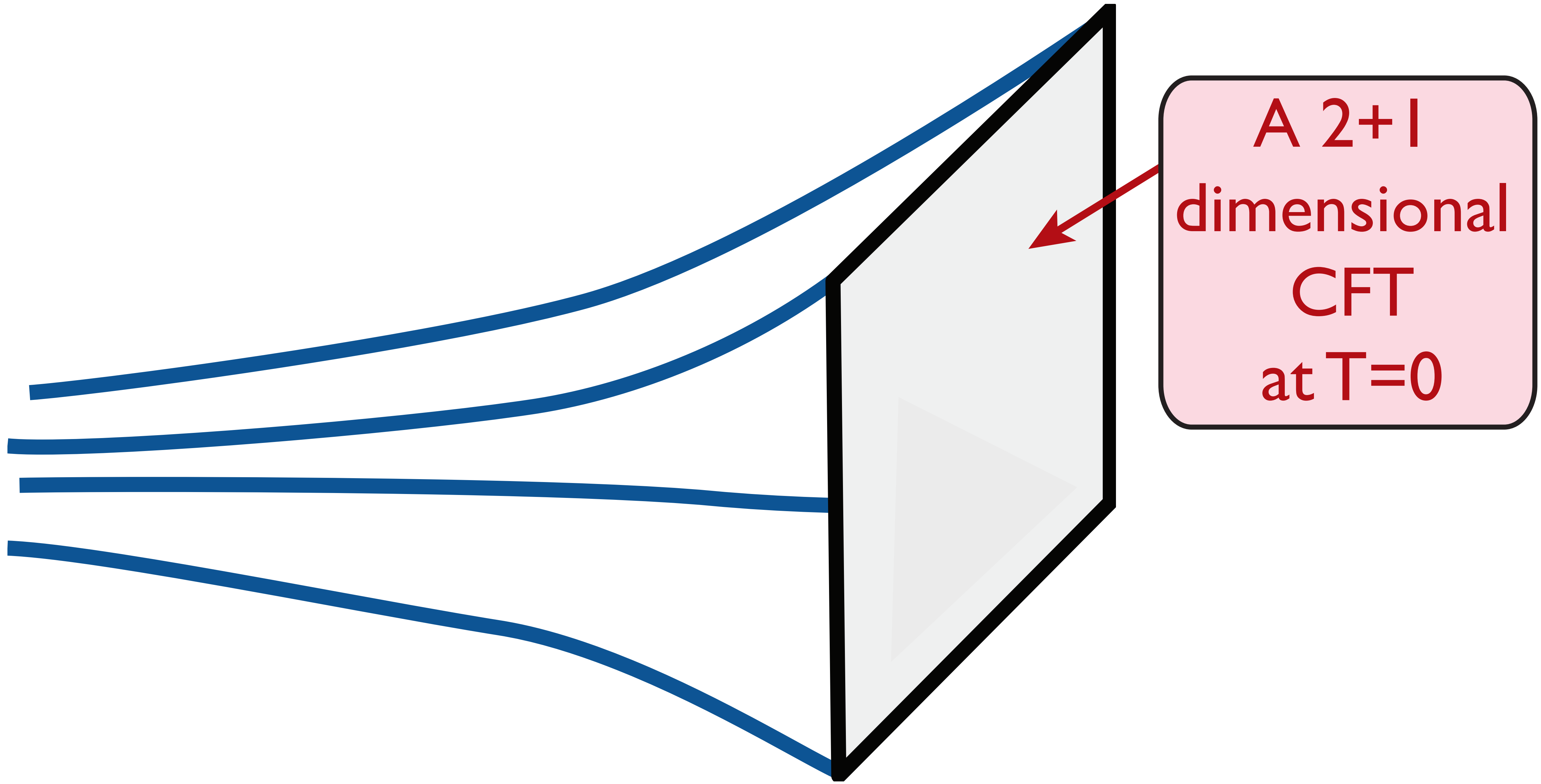
# Begin with a CFT

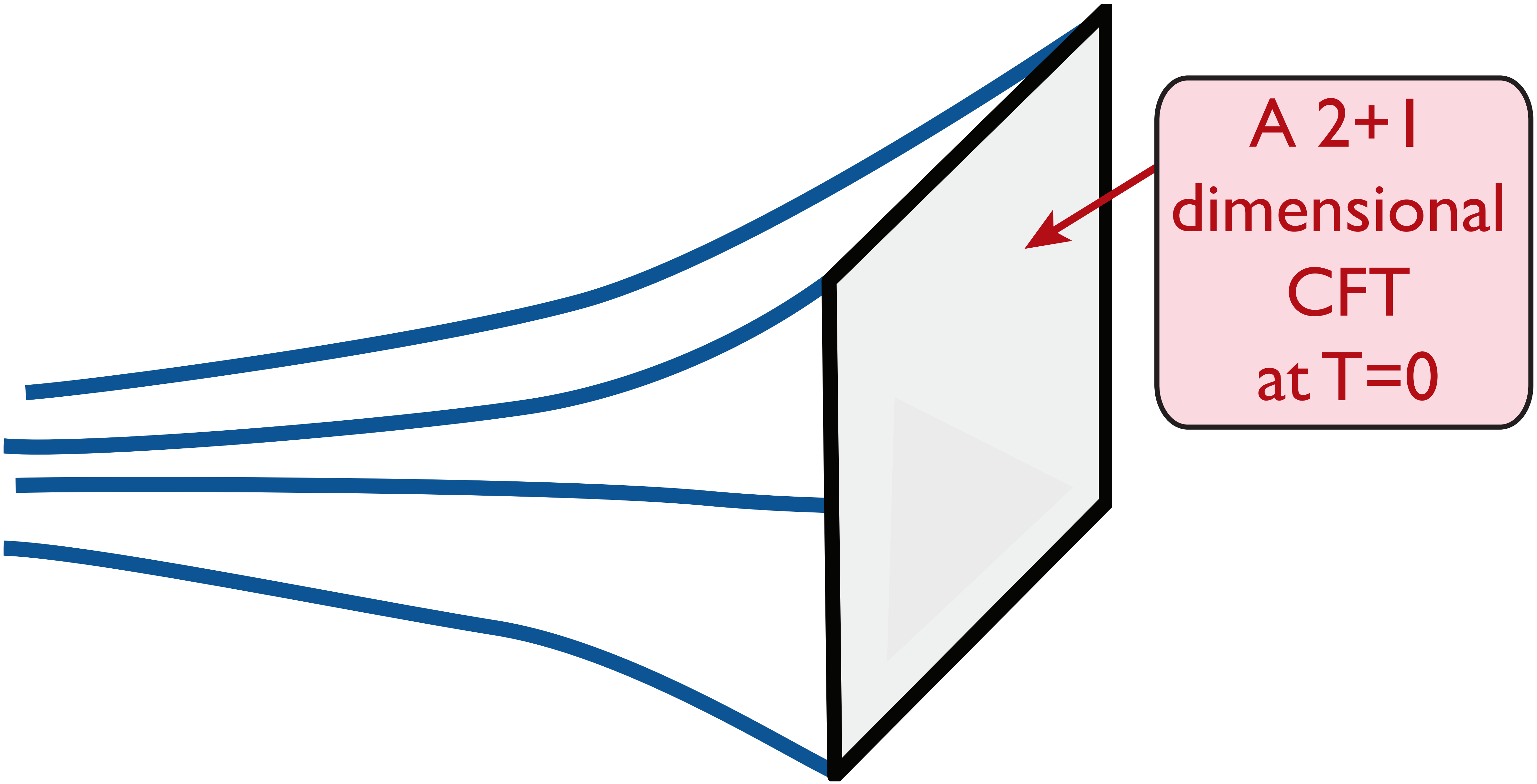


# Holographic representation: AdS$_4$




$$\mathcal{S} = \int d^4x \sqrt{-g} \left[ \frac{1}{2\kappa^2} \left( R + \frac{6}{L^2} \right) \right]$$

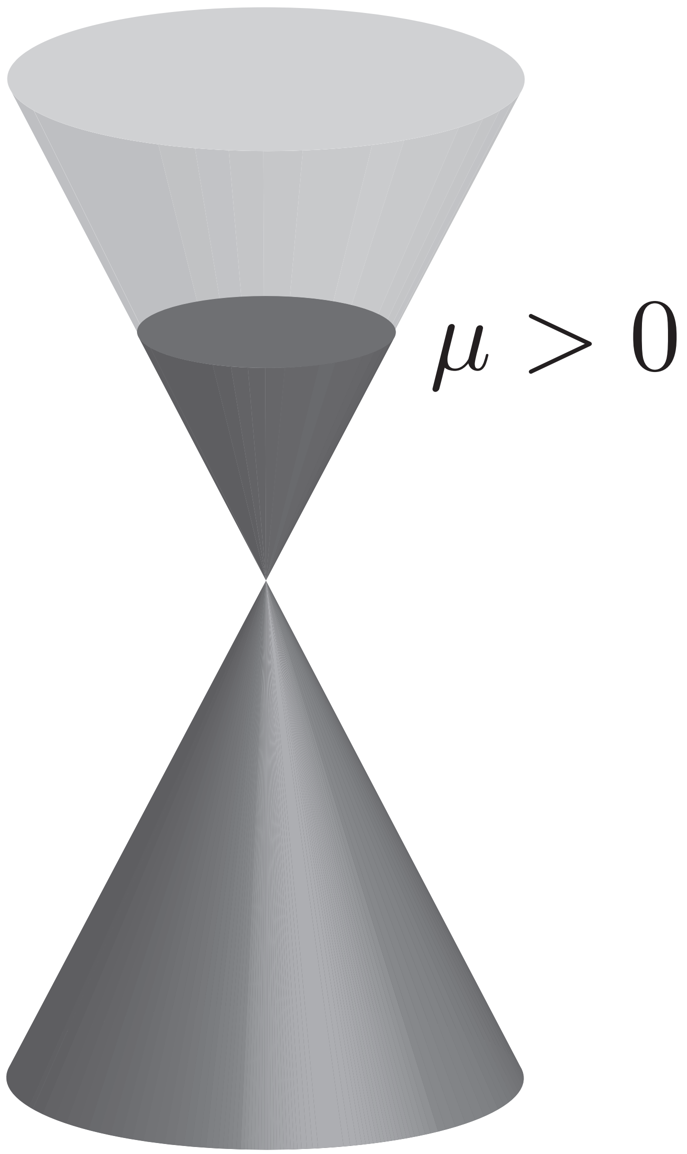
# Holographic representation: $AdS_4$




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

with $f(r) = 1$

# Apply a chemical potential



# AdS$_4$ theory of "nearly perfect fluids"

To leading order in a gradient expansion, charge transport in an infinite set of strongly-interacting CFT3s can be described by Einstein-Maxwell gravity/electrodynamics on AdS$_4$-Schwarzschild

$$\mathcal{S}_{EM} = \int d^4x \sqrt{-g} \left[ -\frac{1}{4g_4^2} F_{ab}F^{ab} \right] .$$

This is to be solved subject to the constraint

$$A_\mu(r \to 0, x, y, t) = \mathcal{A}_\mu(x, y, t)$$

where $\mathcal{A}_\mu$ is a source coupling to a conserved U(1) current $J_\mu$ of the CFT3

$$\mathcal{S} = \mathcal{S}_{CFT} + i \int dxdydt \mathcal{A}_\mu J_\mu$$

# $AdS_4$ theory of "nearly perfect fluids"

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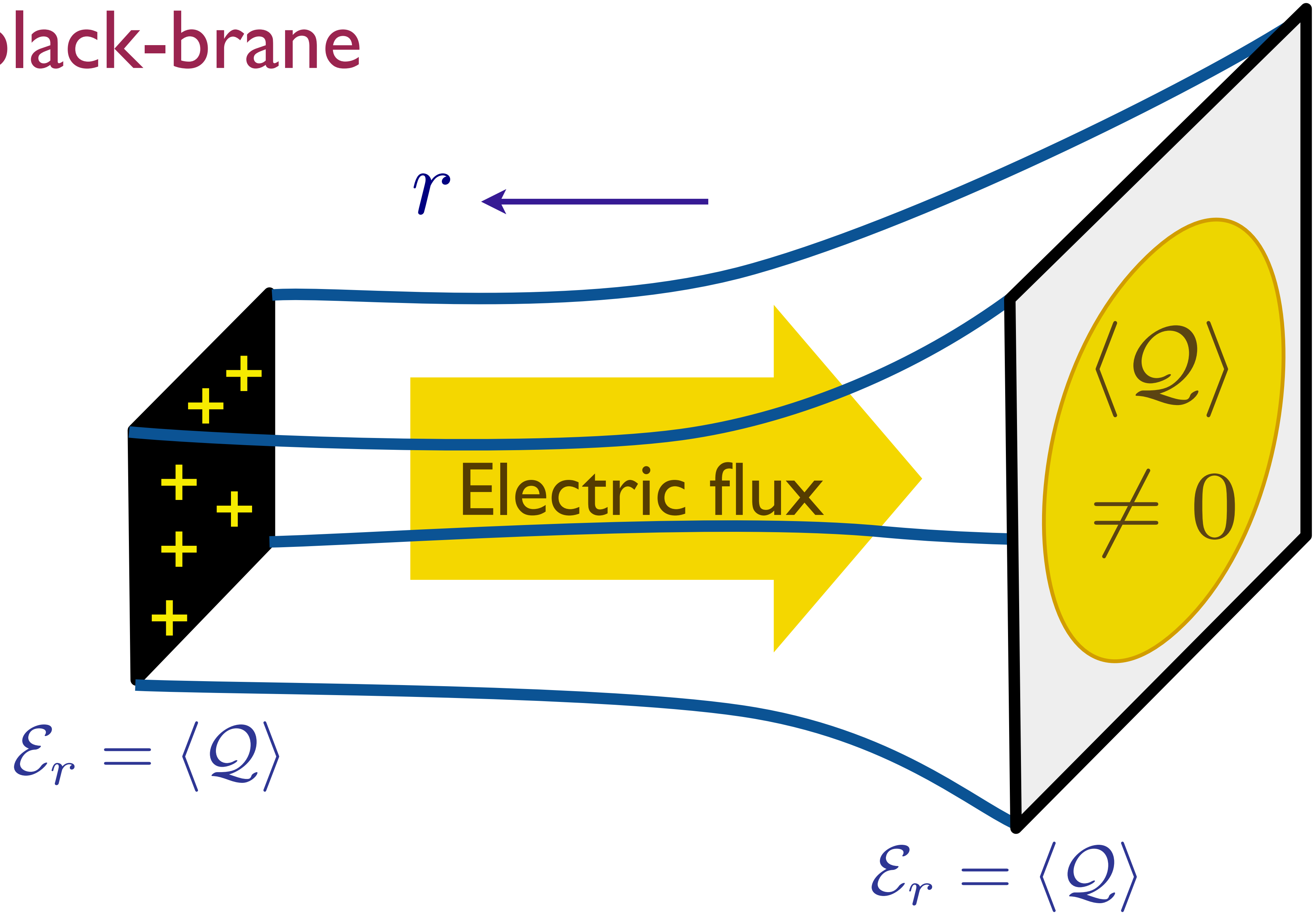
At non-zero chemical potential we simply require $\mathcal{A}_\tau = \mu$.

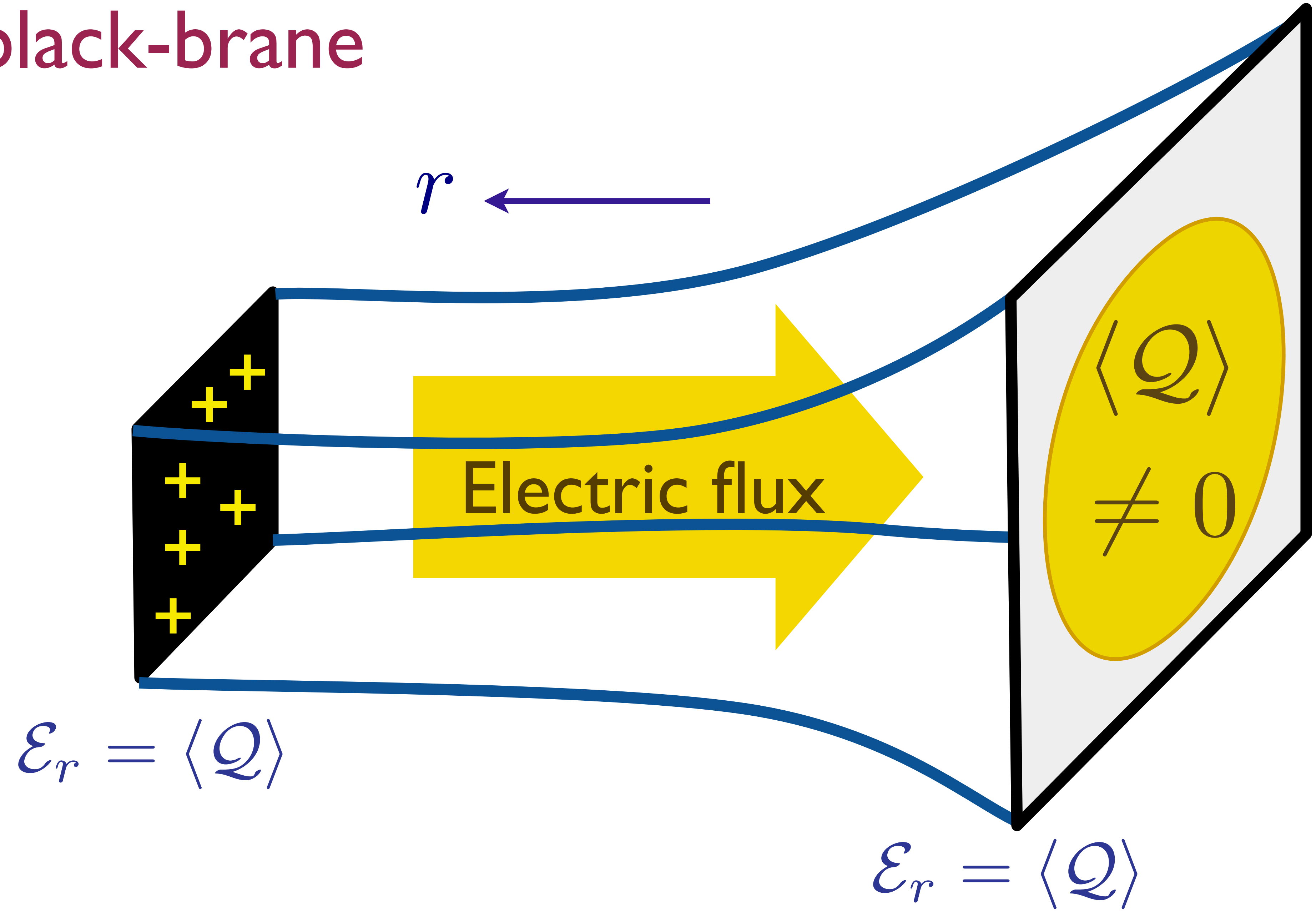
# The Maxwell-Einstein theory of the applied chemical potential yields a $AdS_4$-Reissner-Nordtröm black-brane




$$\mathcal{S} = \int d^4x \sqrt{-g} \left[ \frac{1}{2\kappa^2} \left( R + \frac{6}{L^2} \right) - \frac{1}{4g_4^2} F_{ab} F^{ab} \right]$$

S. A. Hartnoll, P. K. Kovtun, M. Müller, and S. Sachdev, Physical Review B **76**, 144502 (2007)

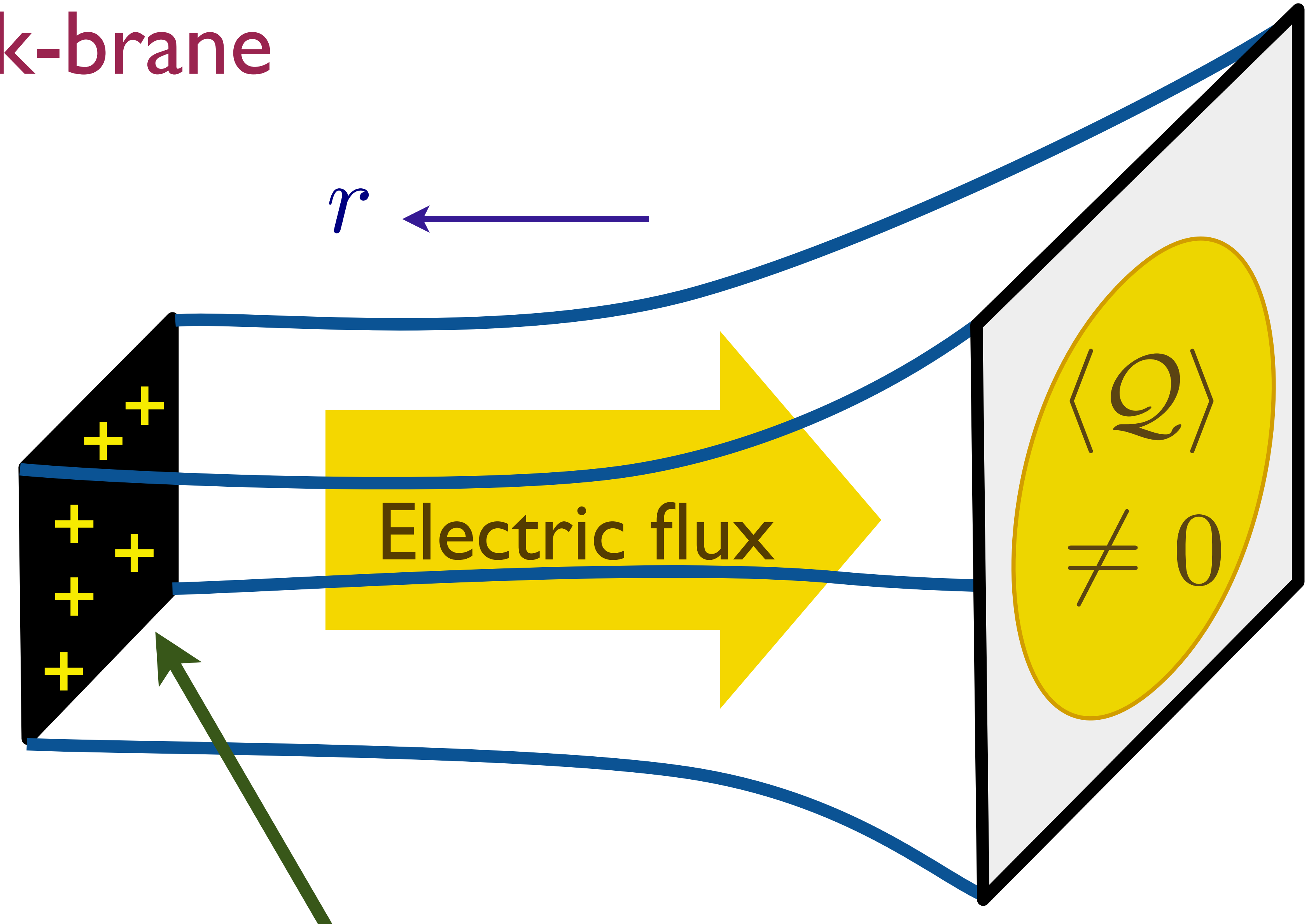
# The Maxwell-Einstein theory of the applied chemical potential yields a $AdS_4$-Reissner-Nordtröm black-brane




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

with $f(r) = \left(1 - \frac{r}{R}\right)^2 \left(1 + \frac{2r}{R} + \frac{3r^2}{R^2}\right)$ and $R = \frac{\sqrt{6}Lg_4}{\kappa\mu}$, and $A_\tau = \mu\left(1 - \frac{r}{R}\right)$

# The Maxwell-Einstein theory of the applied chemical potential yields a $AdS_4$-Reissner-Nordtröm black-brane

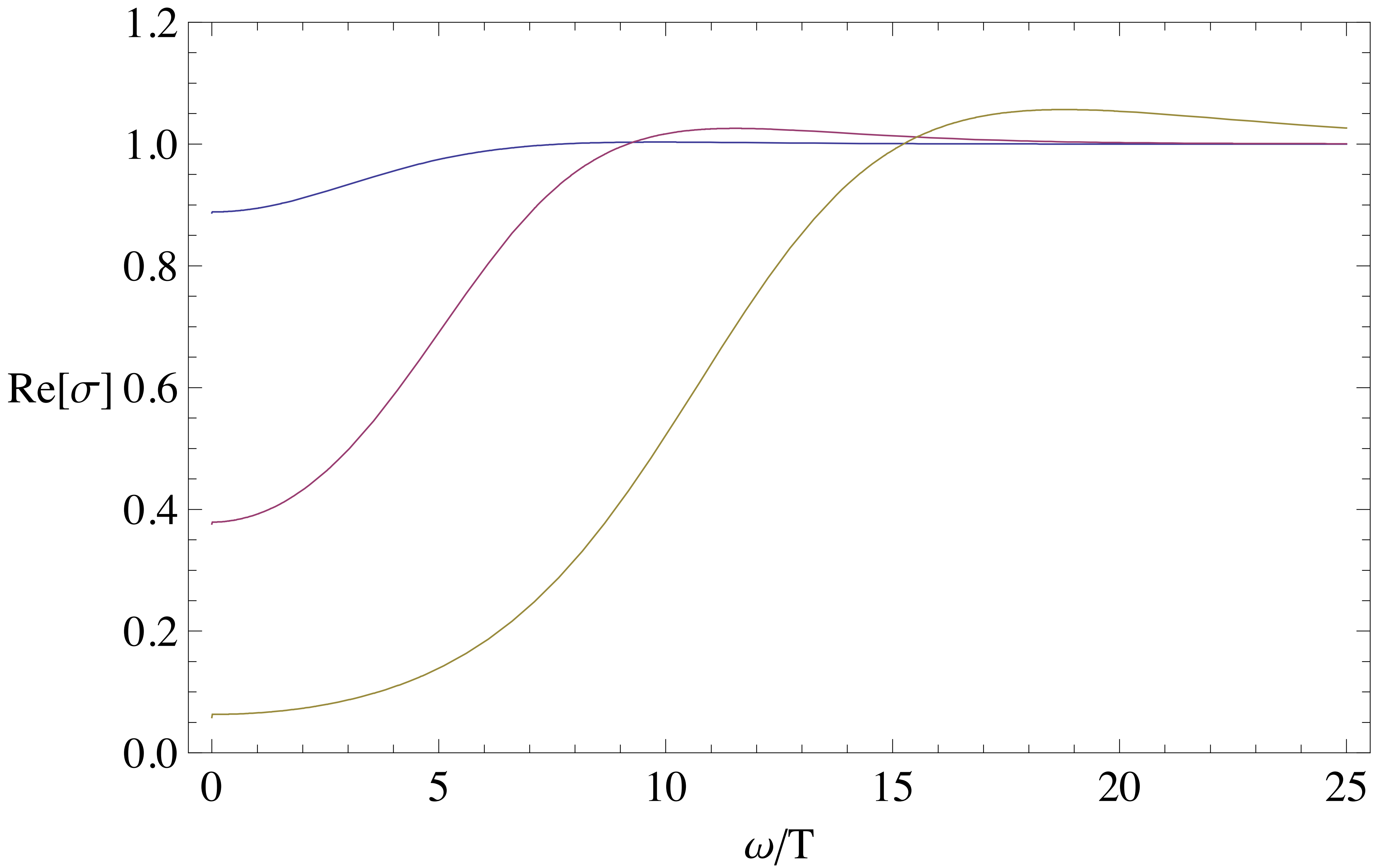



At $T = 0$, we obtain an extremal black-brane, with a near-horizon (IR) metric of $AdS_2 \times R^2$

$$ds^2 = \frac{L^2}{6}\left(\frac{-dt^2 + dr^2}{r^2}\right) + dx^2 + dy^2$$

T. Faulkner, H. Liu, J. McGreevy, and D. Vegh, arXiv:0907.2694

## Compute conductivity using response to a time-dependent vector potential as a function of $\omega/T$ and $\mu/T$




S.A. Hartnoll, arXiv:0903.3246

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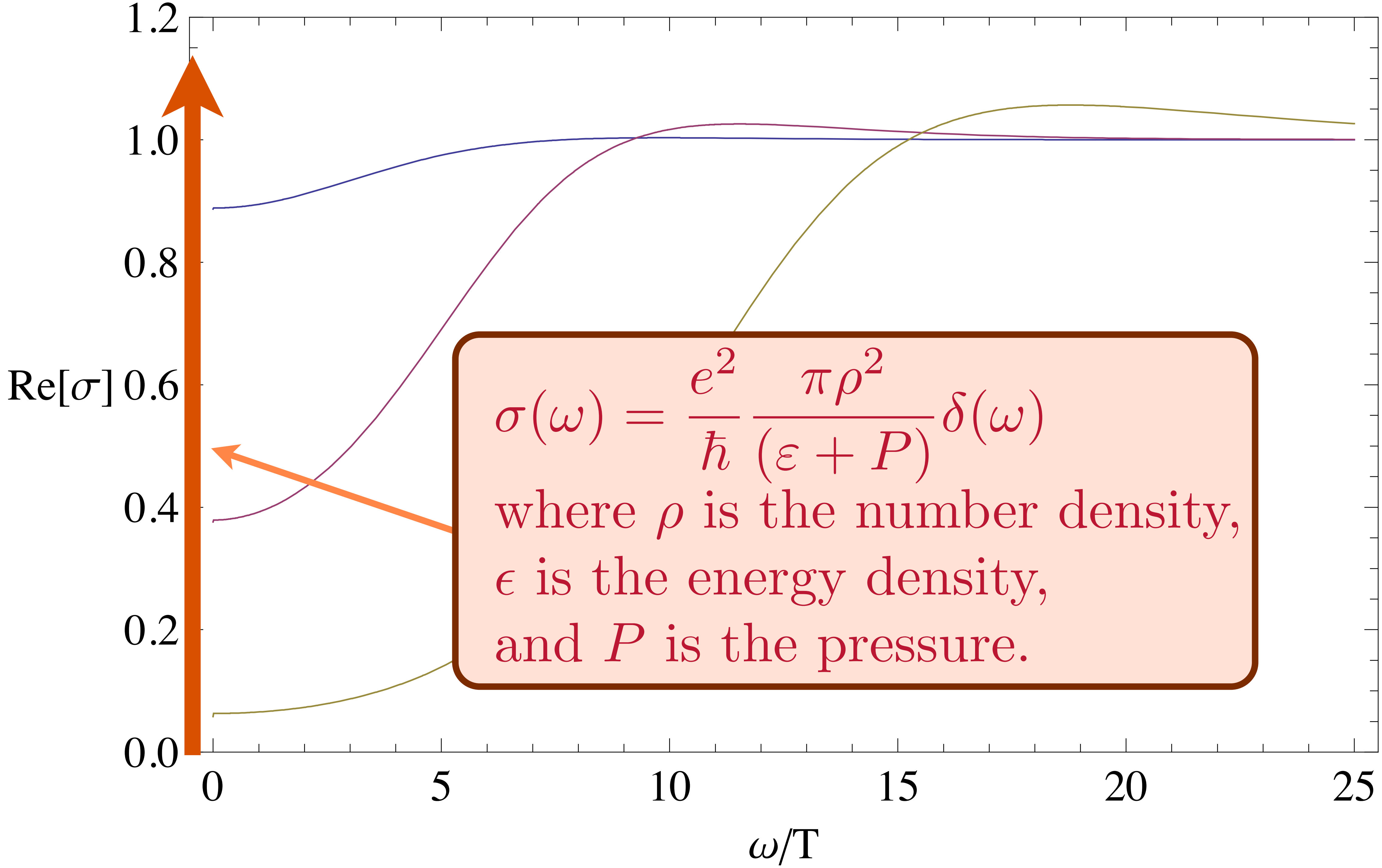


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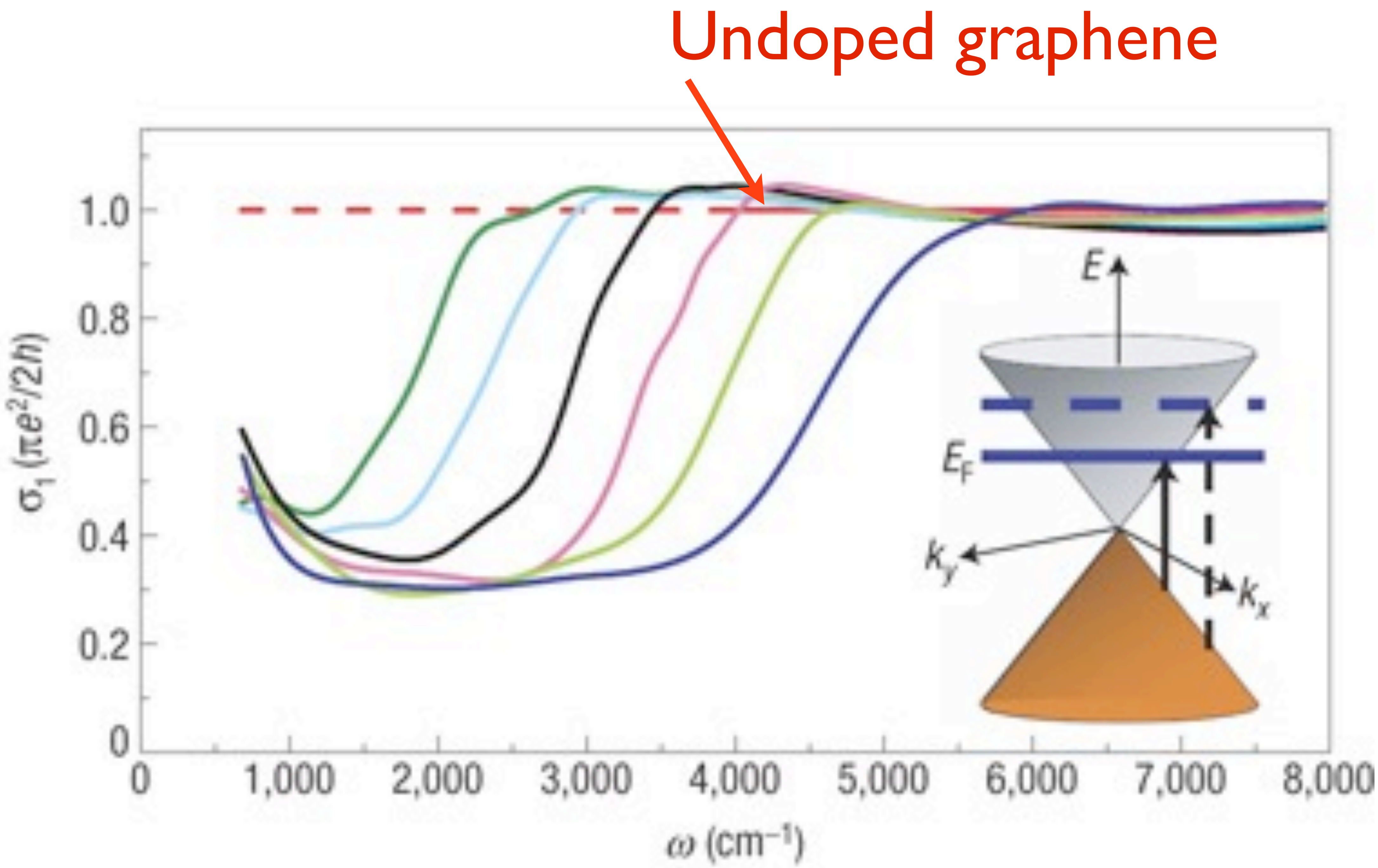
# Optical conductivity of graphene




Z. Q. Li, E. A. Henriksen, Z. Jiang, Z. Hao, M. C. Martin, P. Kim, H. L. Stormer, and D. N. Basov, *Nature Physics* **4**, 532 (2008).

# Features of $AdS_2 \times R^2$

- Has non-zero entropy density at $T = 0$, and "volume" law for entanglement entropy.

- Green's function of a probe fermion (a *mesino*) can have a Fermi surface, but self energies are momentum independent, and the singular behavior is the same on and off the Fermi surface

- Deficit of order $\sim N^2$ in the volume enclosed by the mesino Fermi surfaces: presumably associated with "hidden Fermi surfaces" of gauge-charged particles (the *quarks*).


S.-S. Lee, *Phys. Rev. D* **79**, 086006 (2009);
M. Cubrovic, J. Zaanen, and K. Schalm, *Science* **325**, 439 (2009);
T. Faulkner, H. Liu, J. McGreevy, and D. Vegh, arXiv:0907.2694
S. Sachdev, *Phys. Rev. Lett.* **105**, 151602 (2010).

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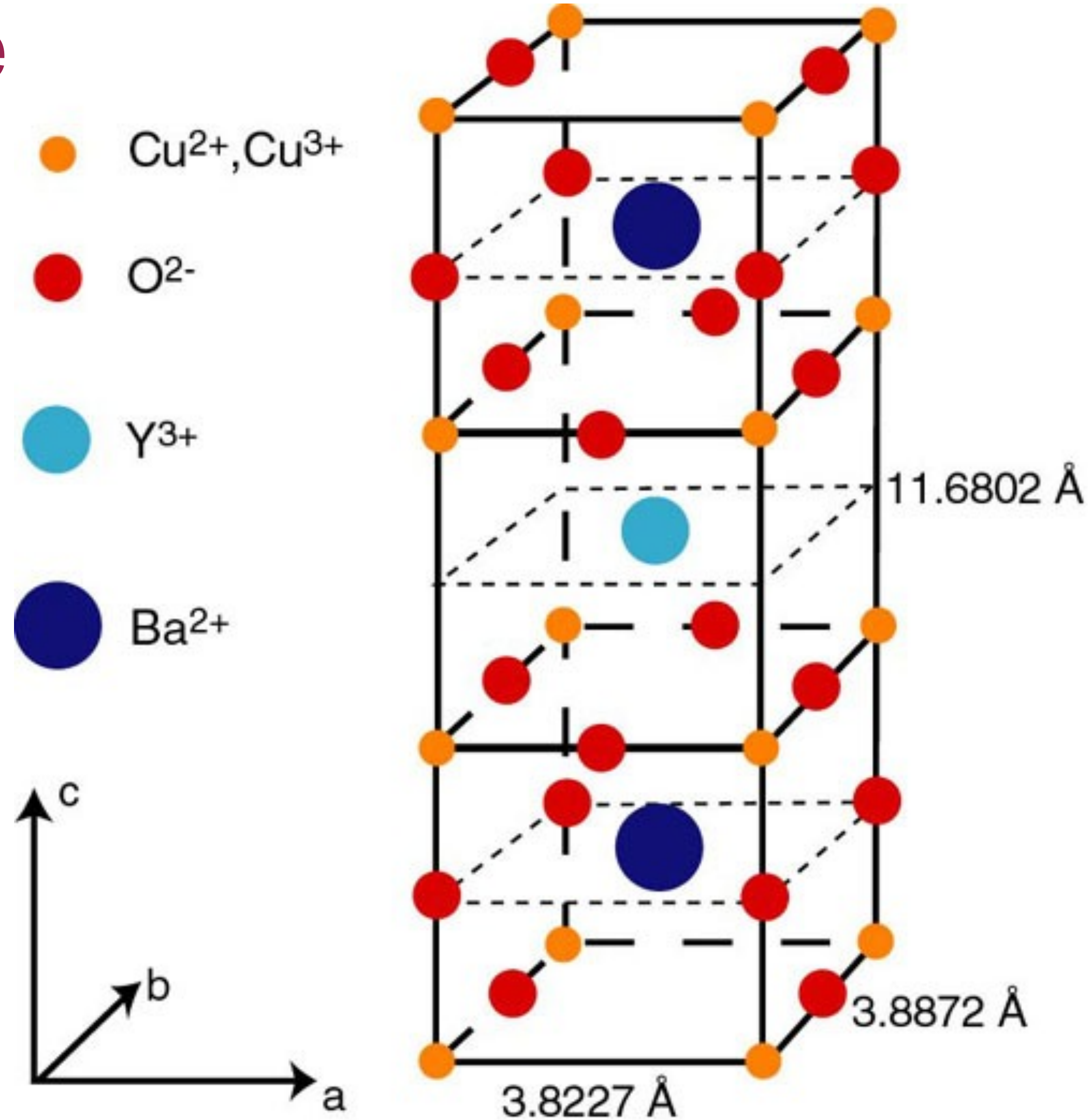
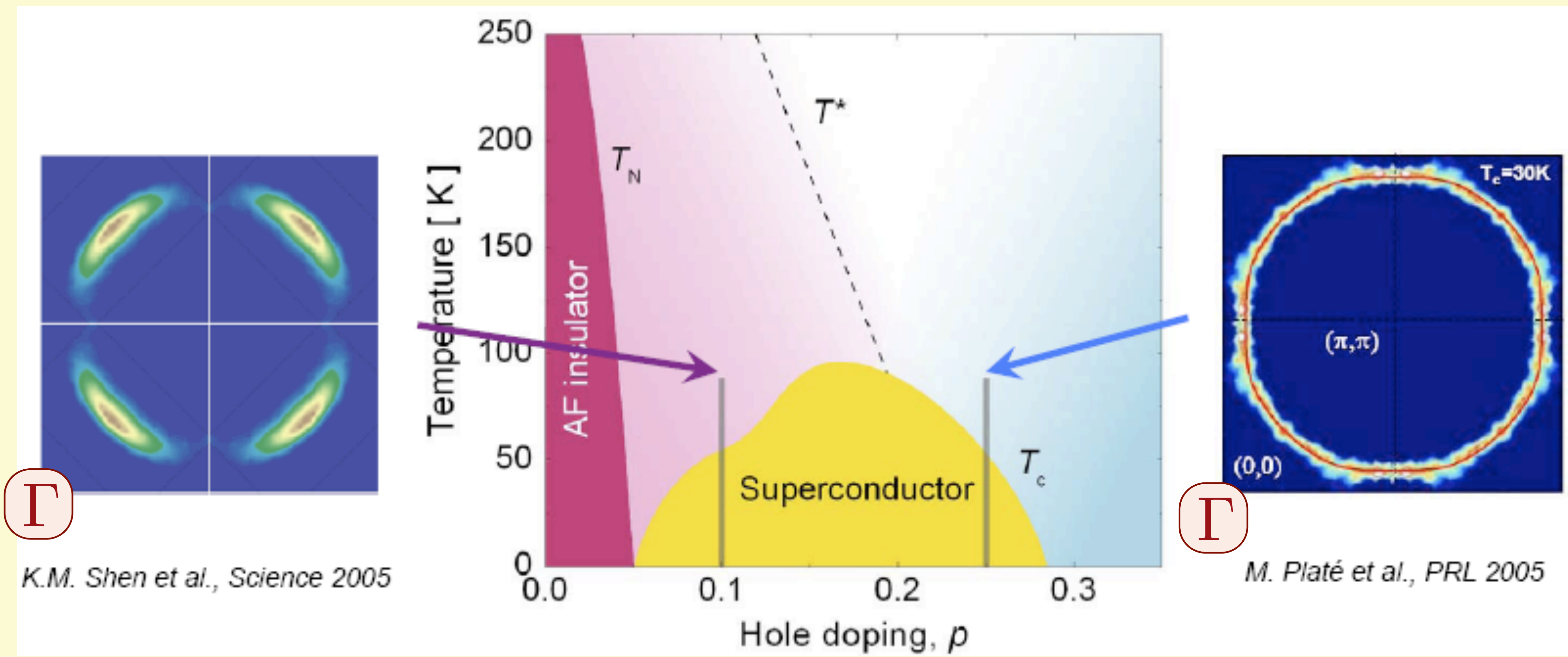
# High temperature superconductors




$$YBa_2Cu_3O_{6+x}$$

# Evolution of the (ARPES) Fermi surface on the cuprate phase diagram




Smaller hole Fermi-pockets

Large hole Fermi surface

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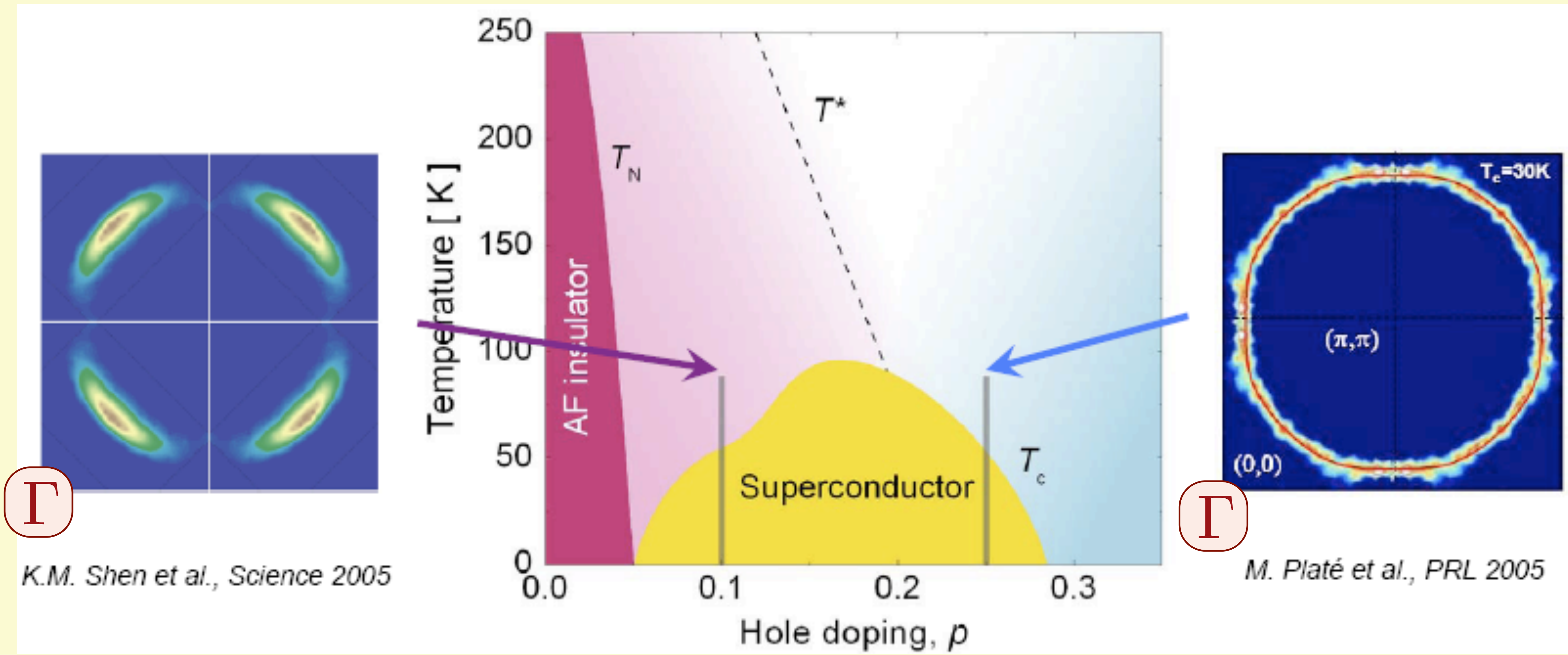


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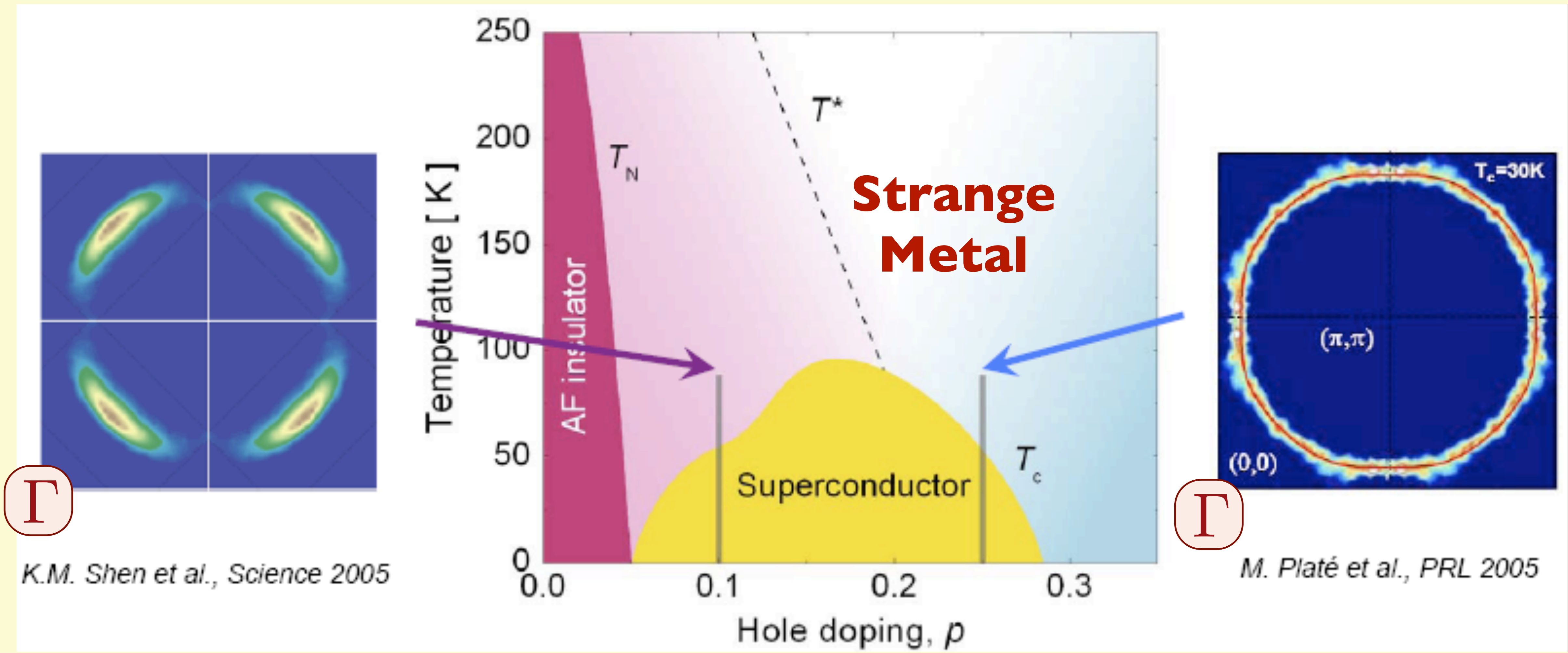
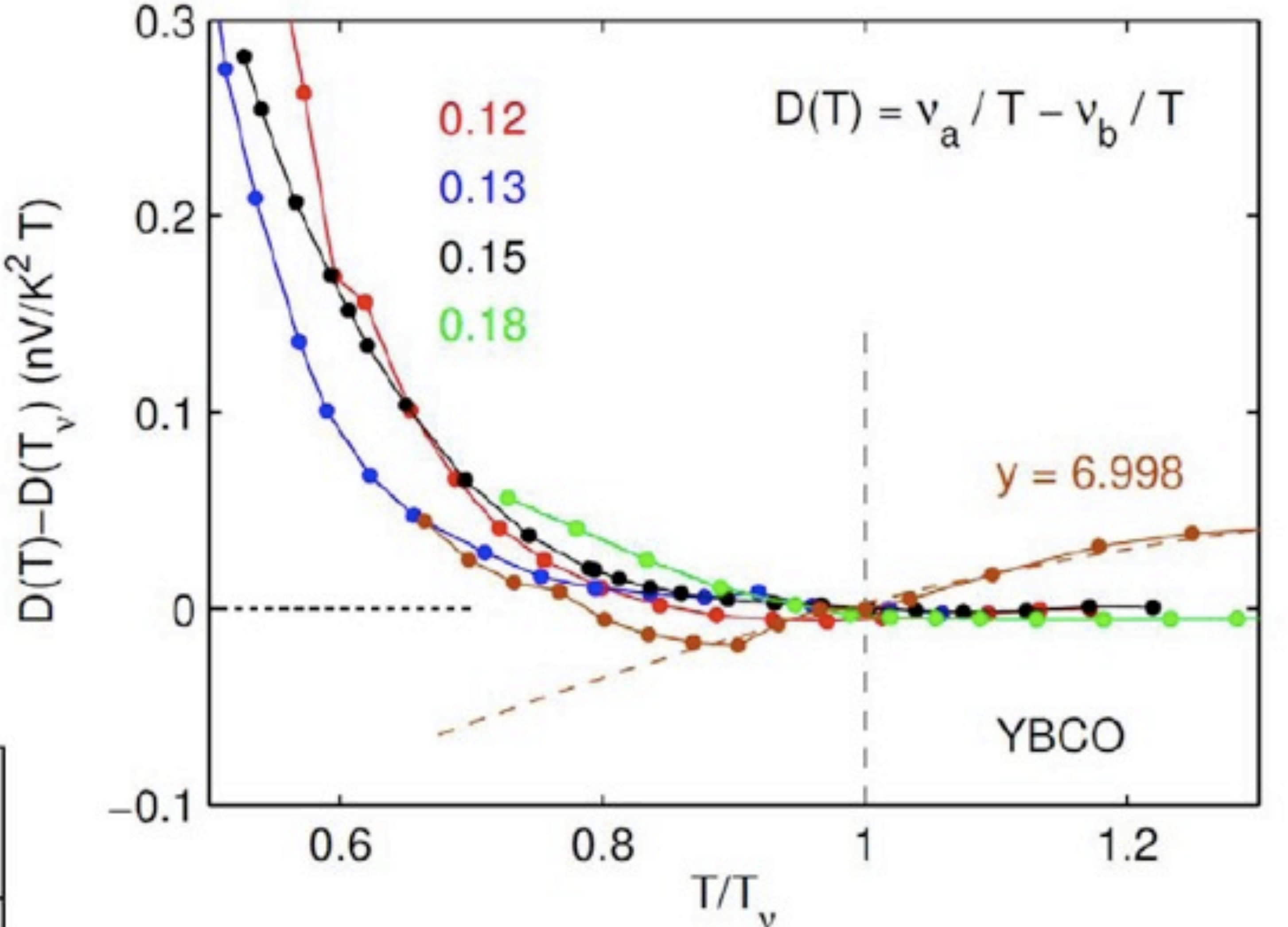


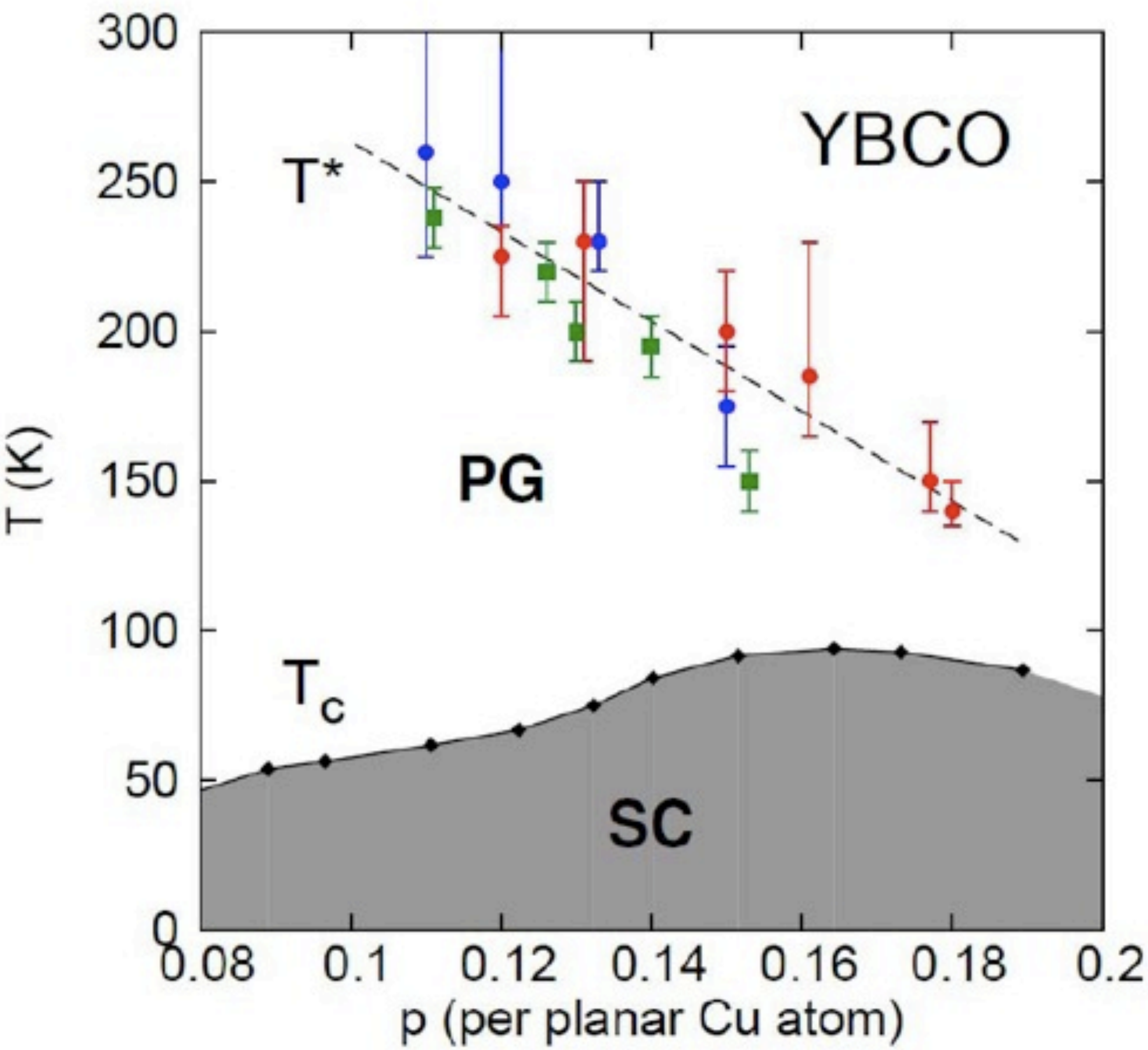

Smaller hole Fermi-pockets

Large hole Fermi surface

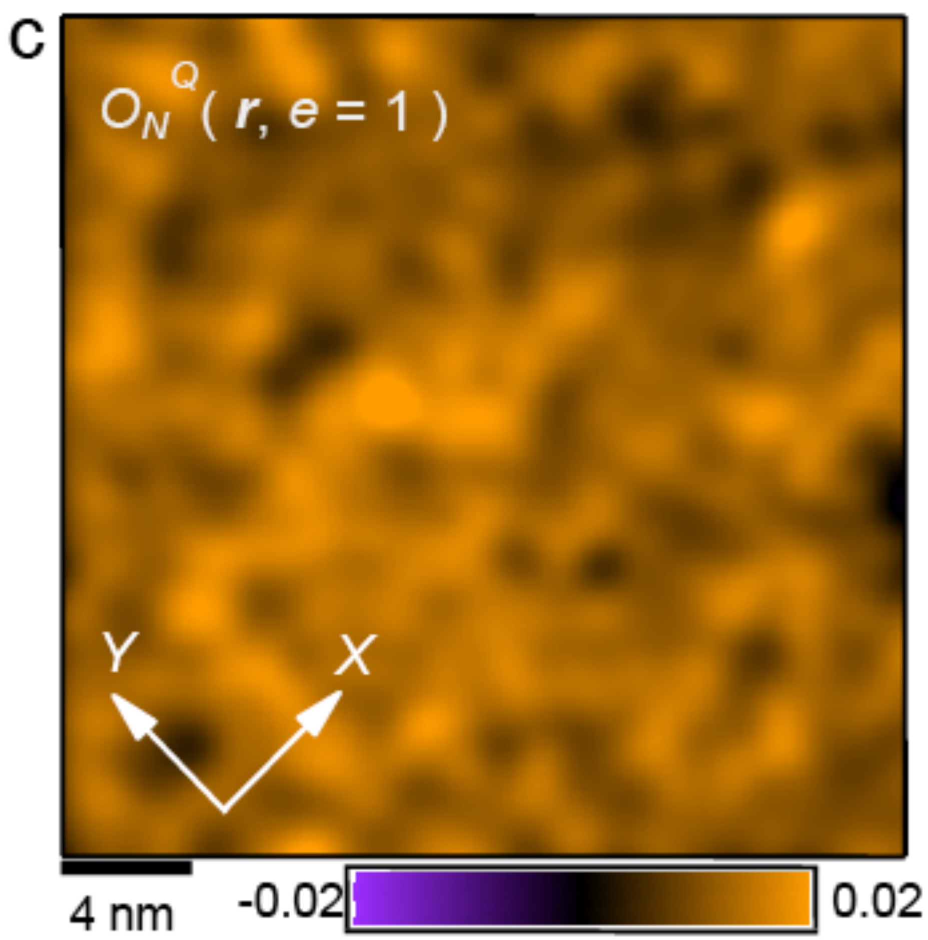
# Broken rotational symmetry in the pseudogap phase of a high-Tc superconductor

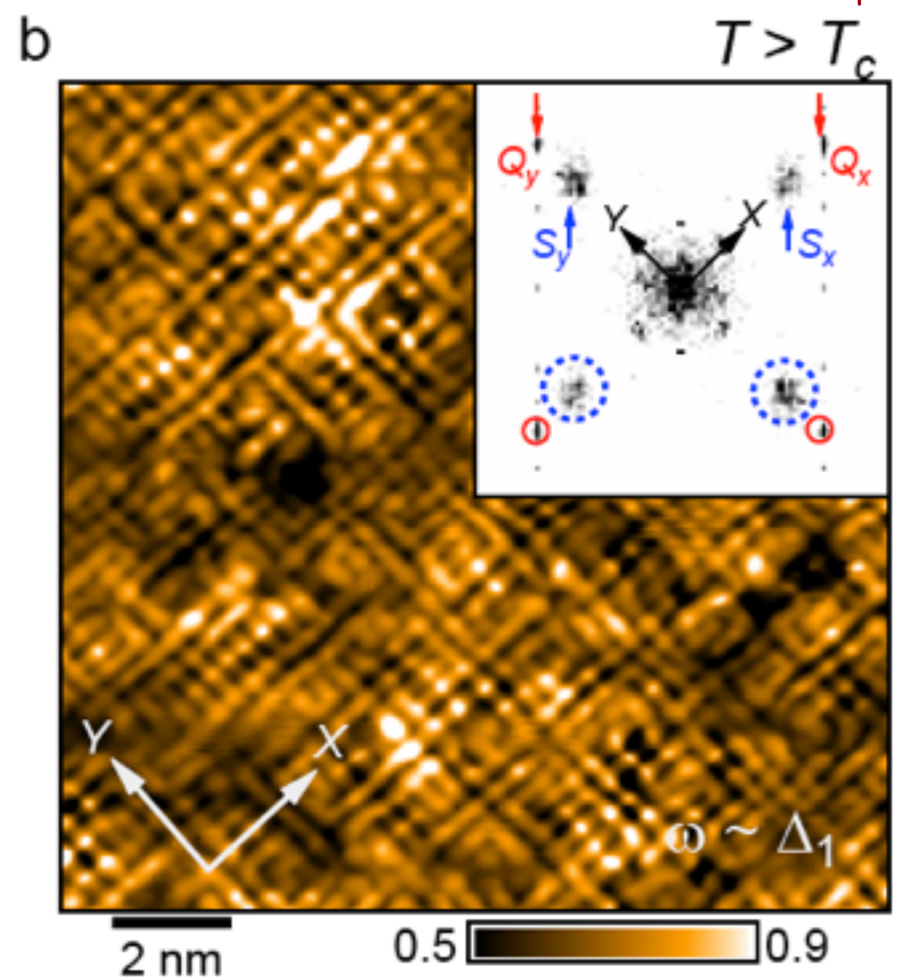
R. Daou, J. Chang, David LeBoeuf, Olivier Cyr-Choiniere, Francis Laliberte, Nicolas Doiron-Leyraud, B. J. Ramshaw, Ruixing Liang, D.A. Bonn, W. N. Hardy, and Louis Taillefer
*Nature*, **463**, 519 (2010).



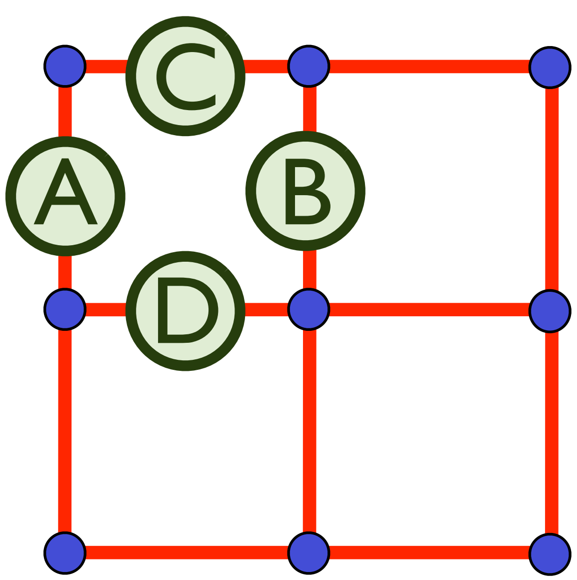



# STM measurements of $Z(r)$, the energy asymmetry in density of states in $Bi_2Sr_2CaCu_2O_{8+\delta}$.



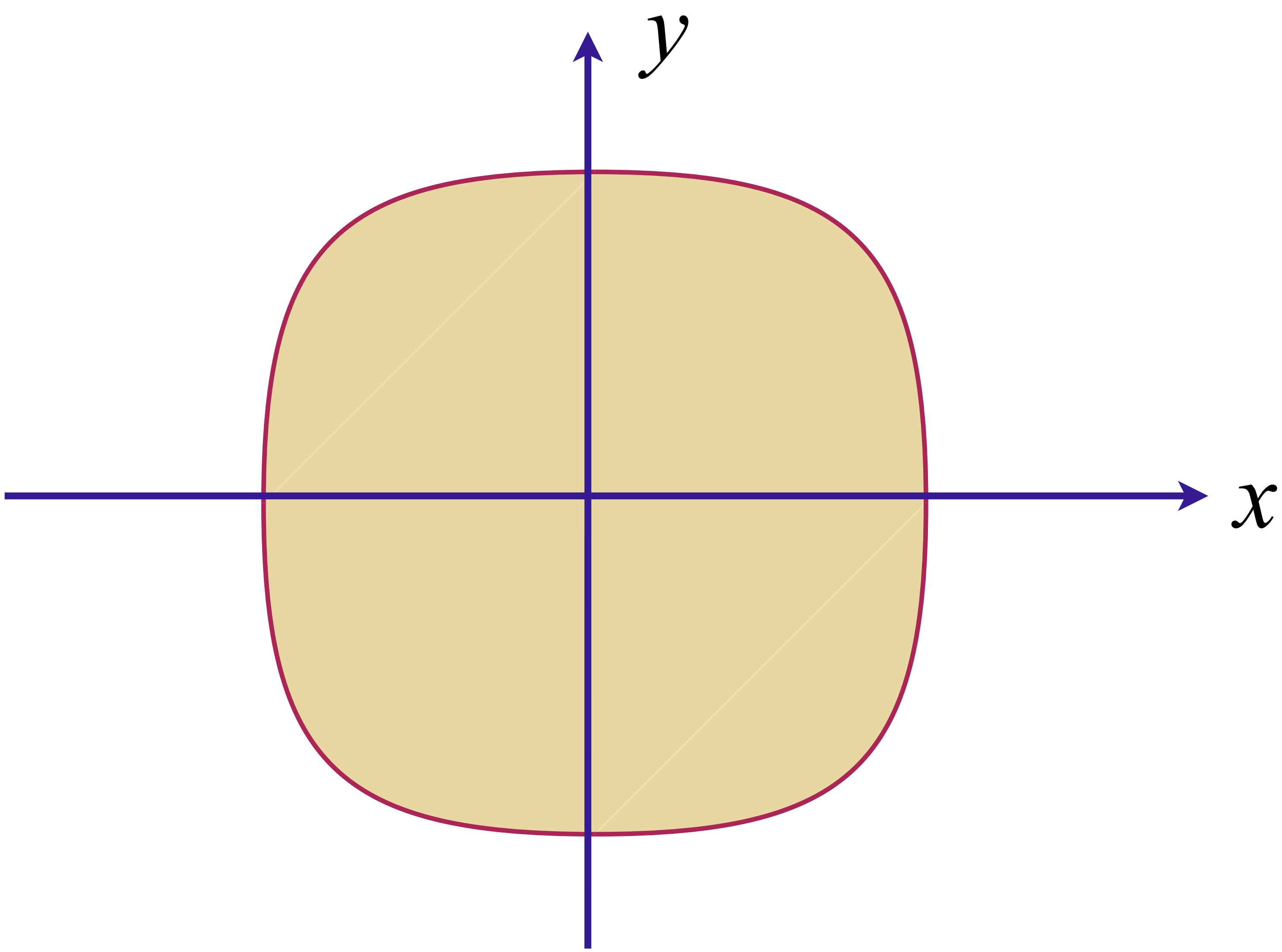

M. J. Lawler, K. Fujita, Jhinhwan Lee, A. R. Schmidt, Y. Kohsaka, Chung Koo Kim, H. Eisaki, S. Uchida, J. C. Davis, J. P. Sethna, and Eun-Ah Kim, Nature **466**, 347 (2010)




$$O_N = Z_A + Z_B - Z_C - Z_D$$

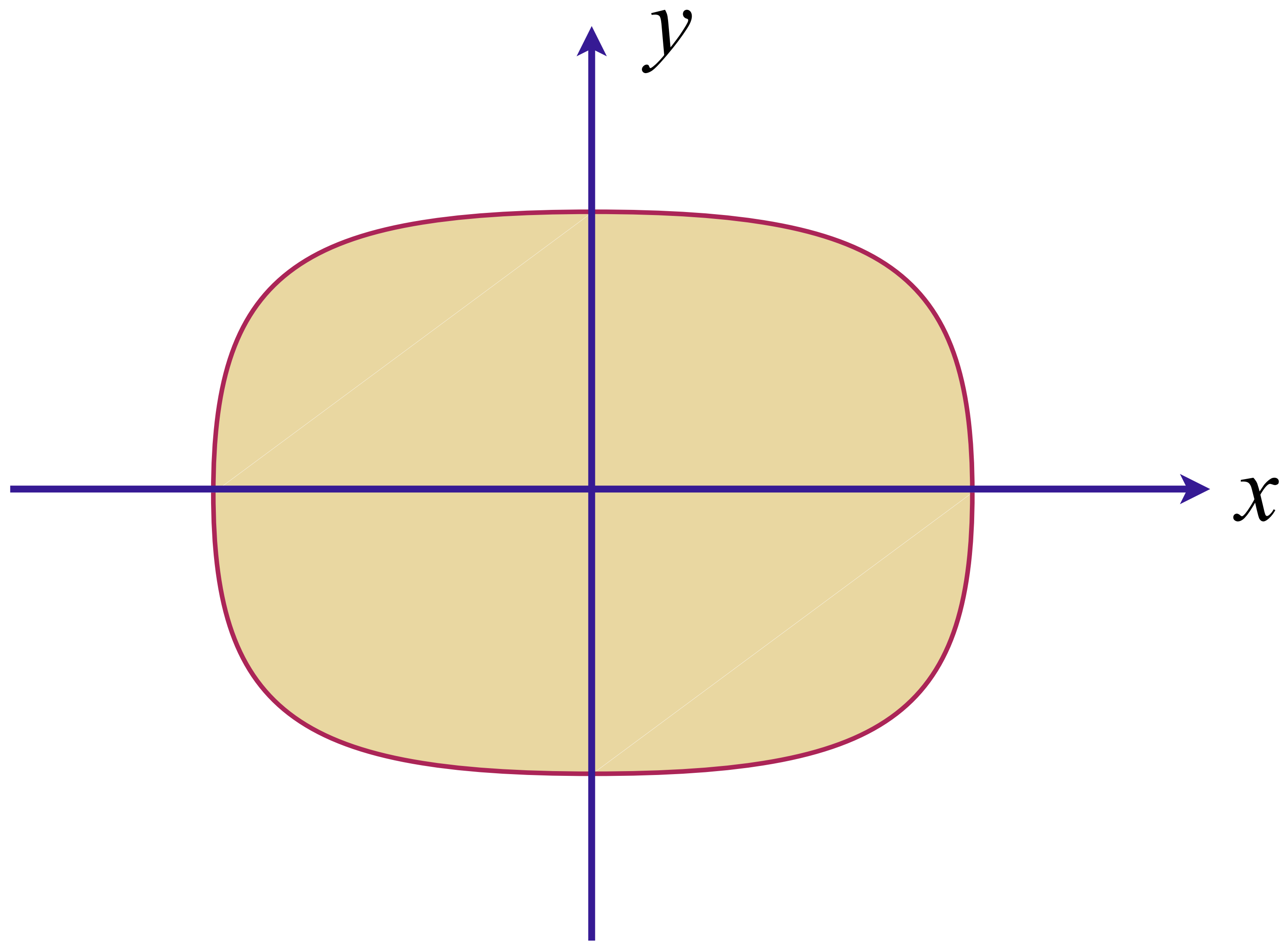
Strong anisotropy of electronic states between *x* and *y* directions: Electronic "Ising-nematic" order

# Quantum criticality of Ising-nematic ordering



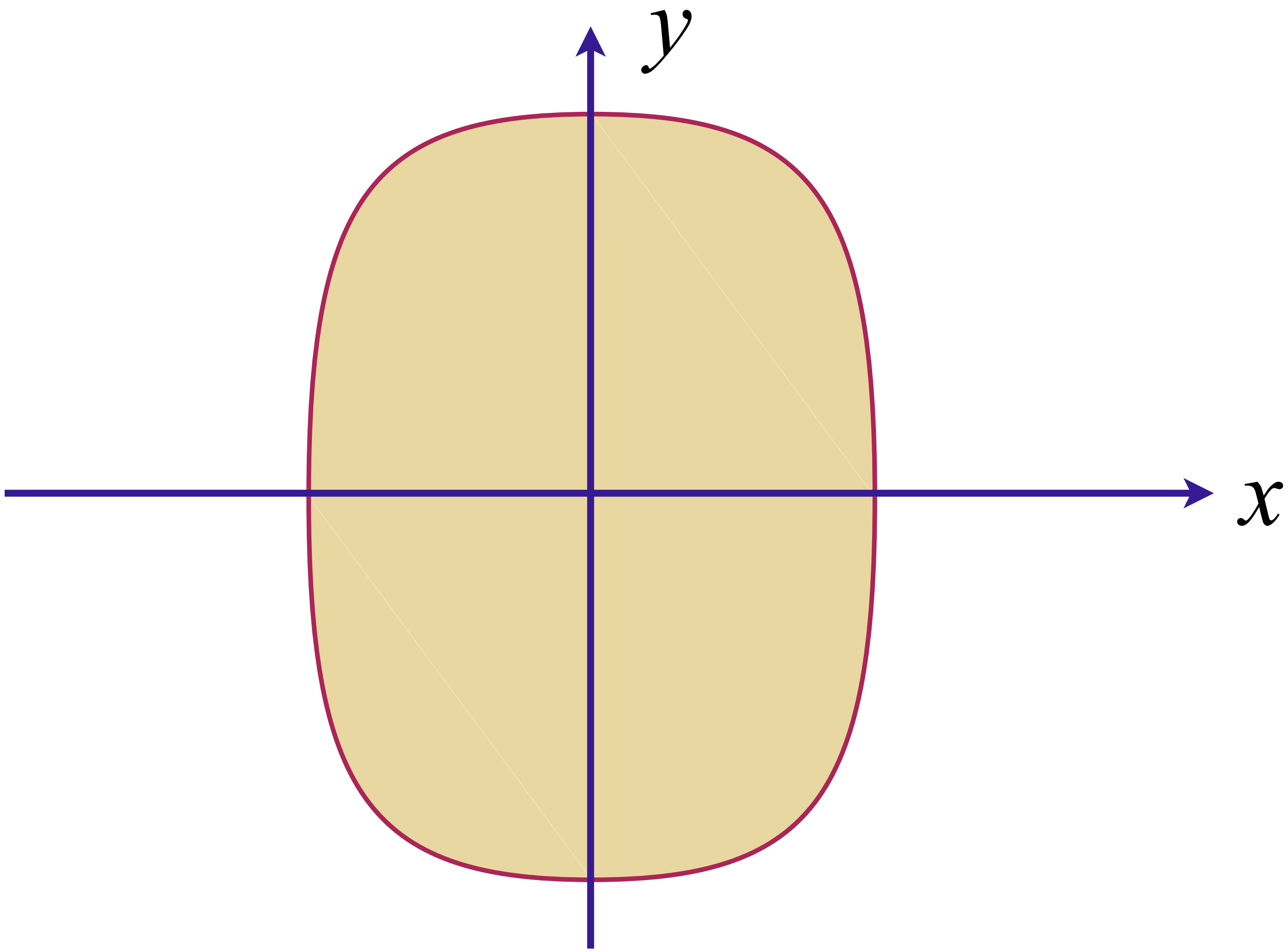

Fermi surface with full square lattice symmetry

# Quantum criticality of Ising-nematic ordering




Spontaneous elongation along $x$ direction:

# Quantum criticality of Ising-nematic ordering



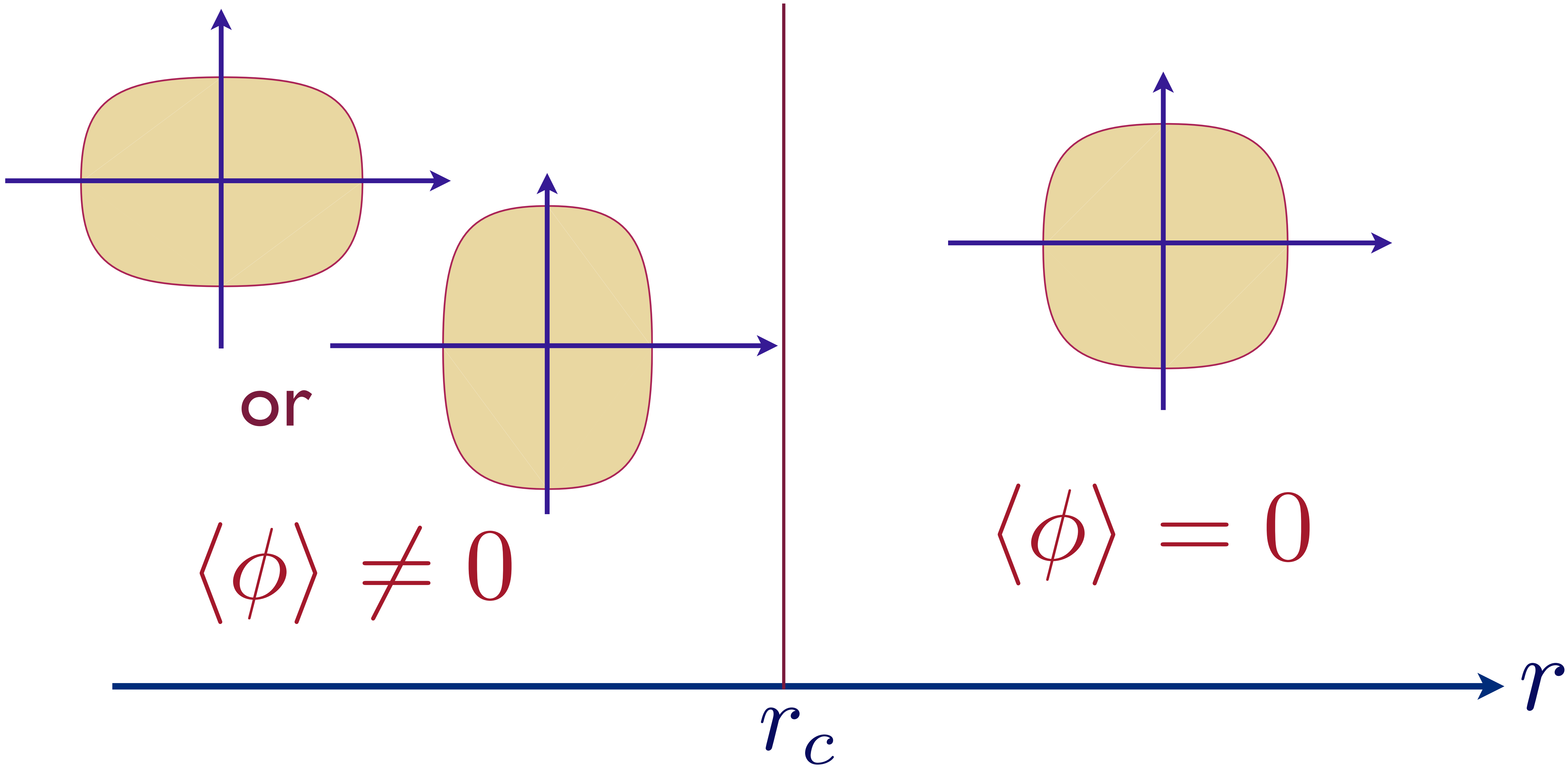

Spontaneous elongation along $y$ direction:

## Ising-nematic order parameter

$$\phi \sim \int d^2k \, (\cos k_x - \cos k_y) \, c^\dagger_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma}$$

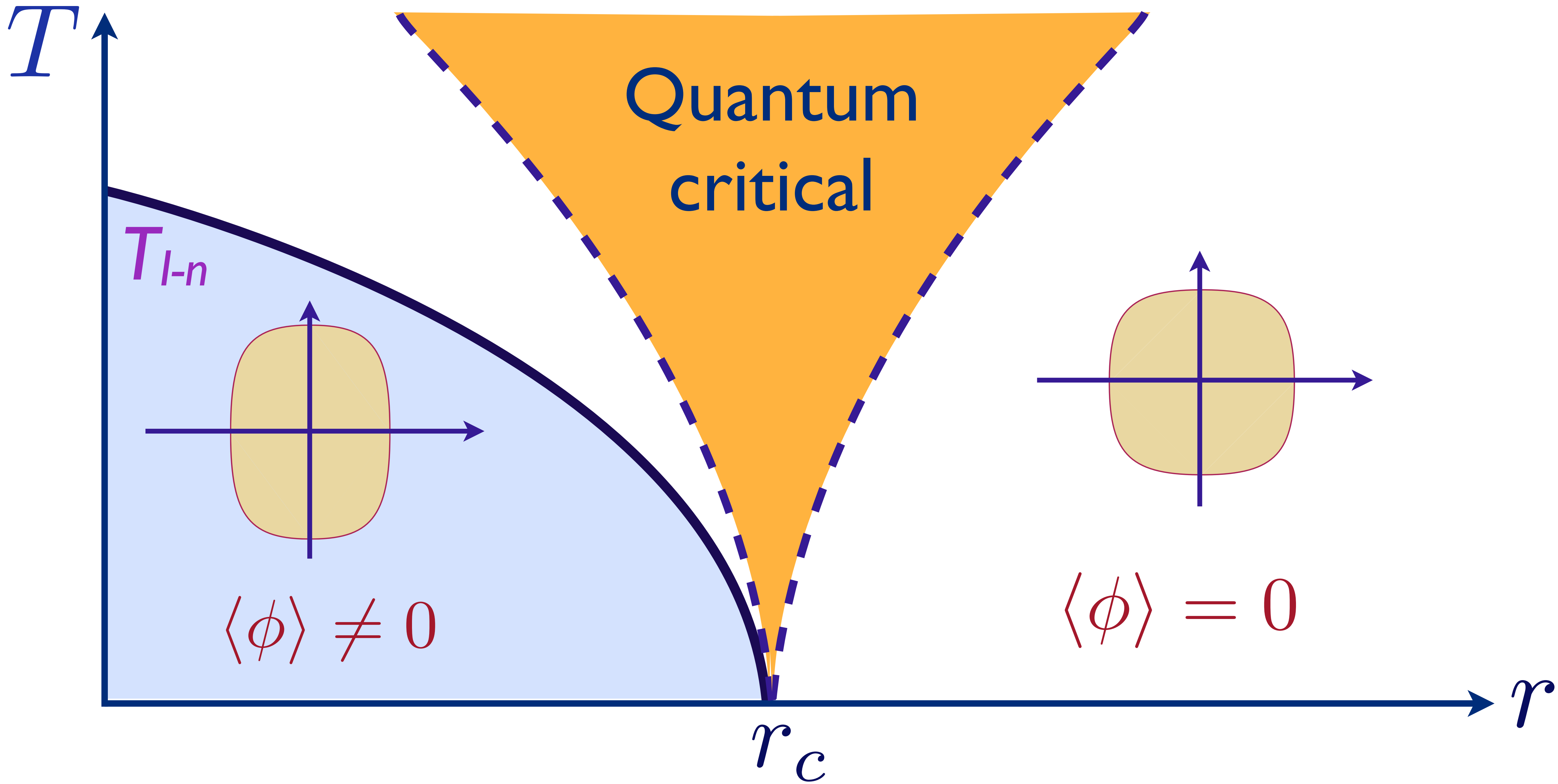
Measures spontaneous breaking of square lattice point-group symmetry of underlying Hamiltonian

# Quantum criticality of Ising-nematic ordering




Pomeranchuk instability as a function of coupling $r$

# Quantum criticality of Ising-nematic ordering




Phase diagram as a function of $T$ and $r$

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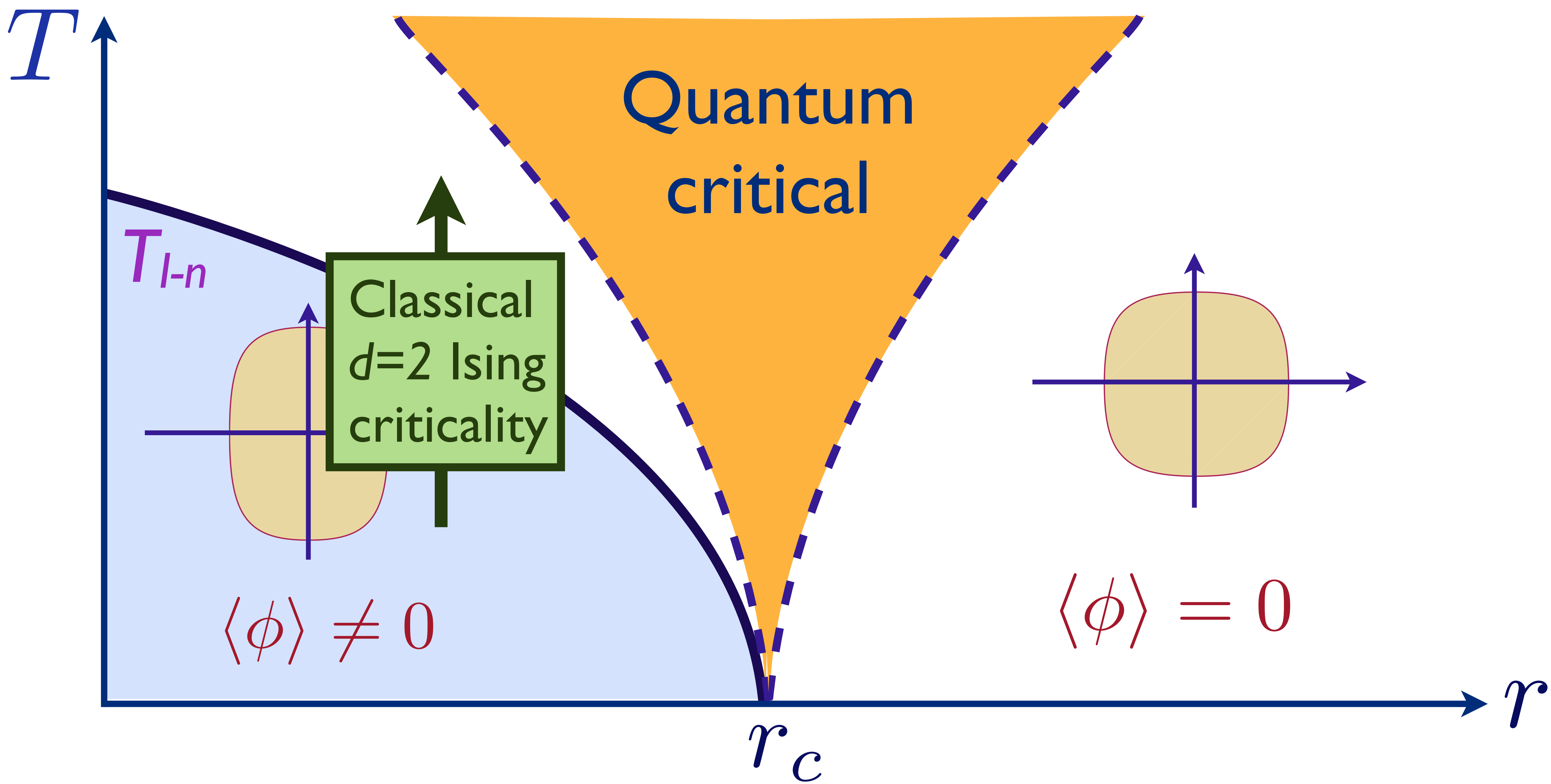


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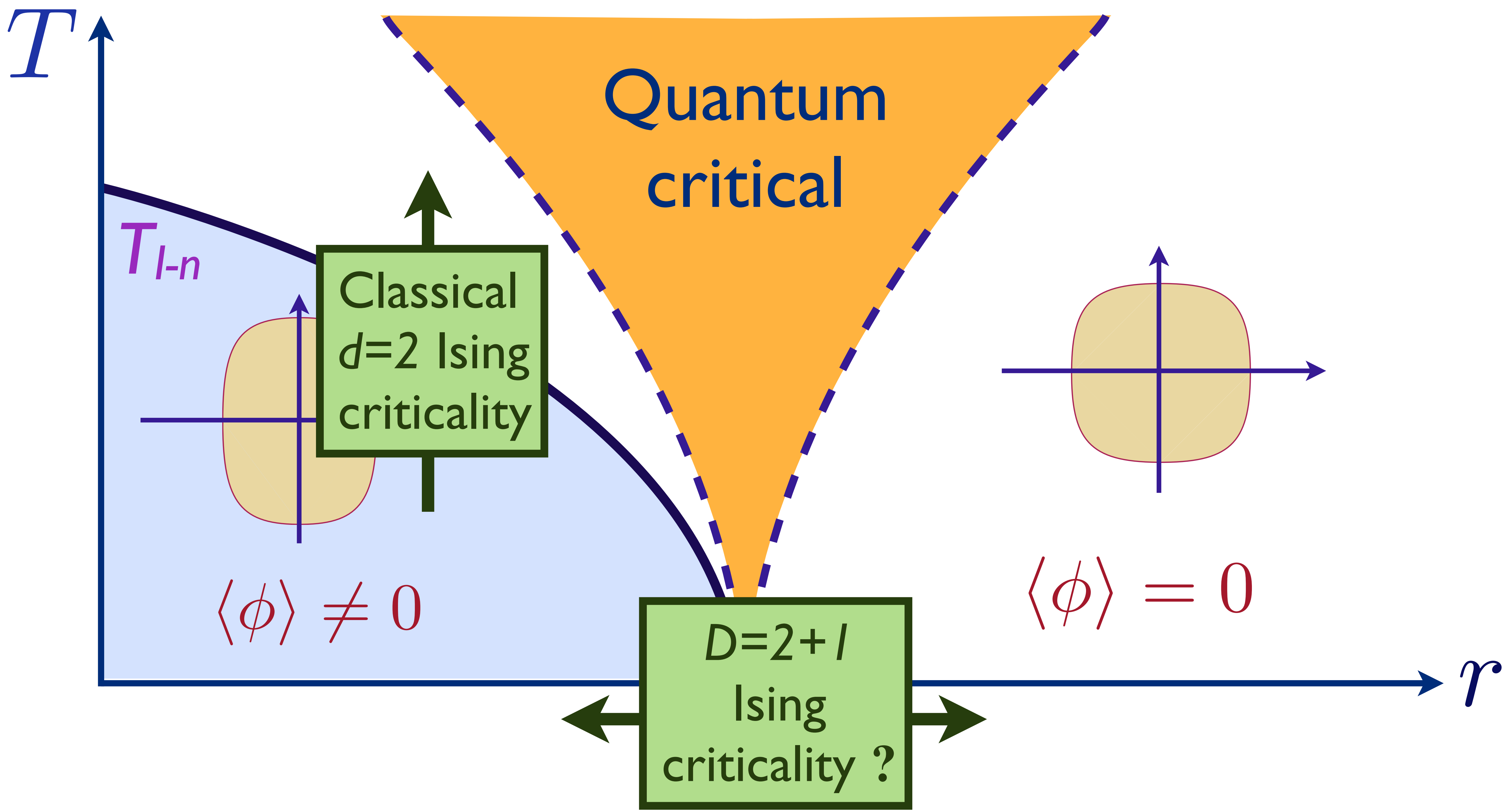


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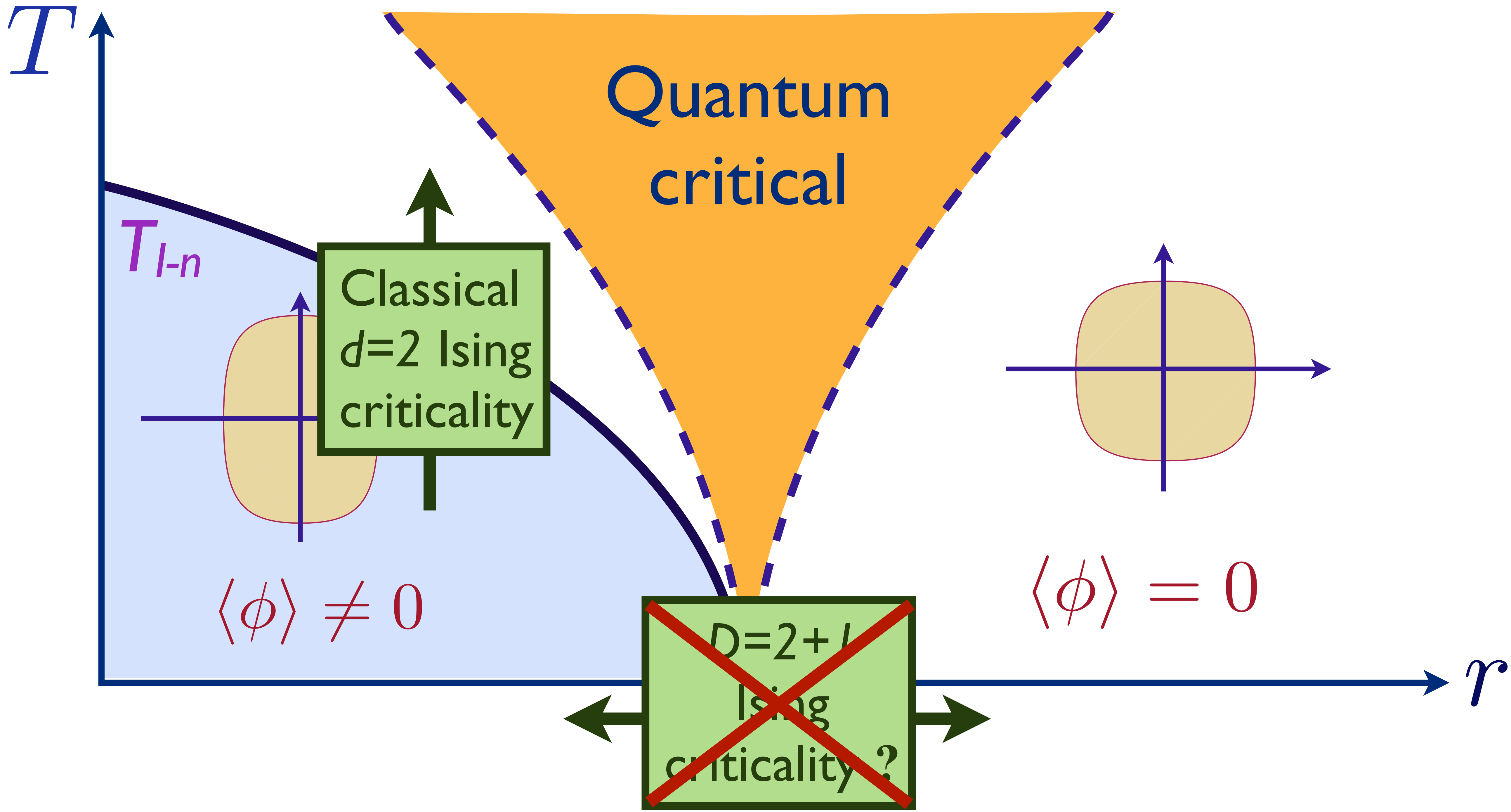
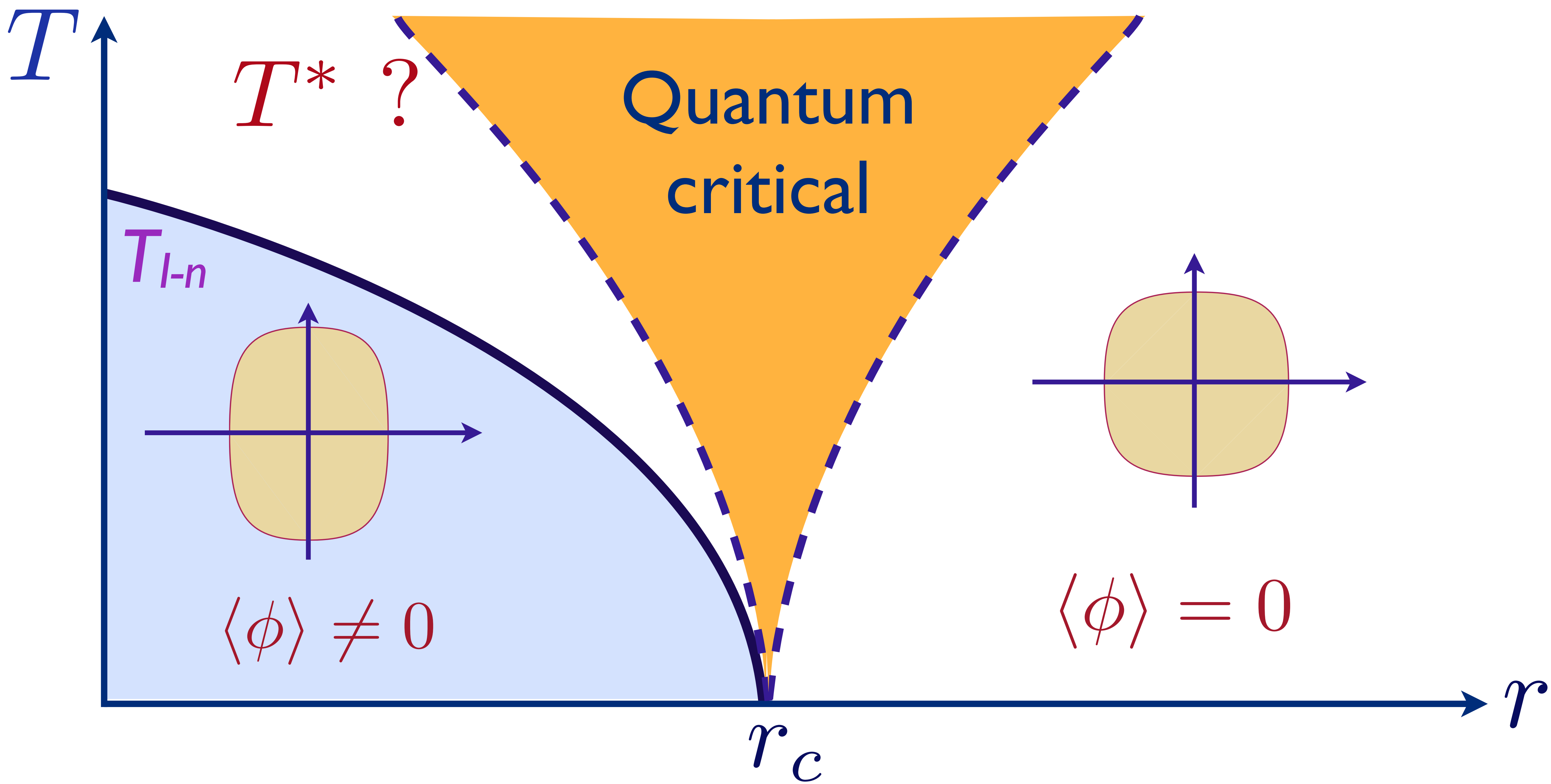



Phase diagram as a function of $T$ and $r$

# Quantum criticality of Ising-nematic ordering




Phase diagram as a function of $T$ and $r$

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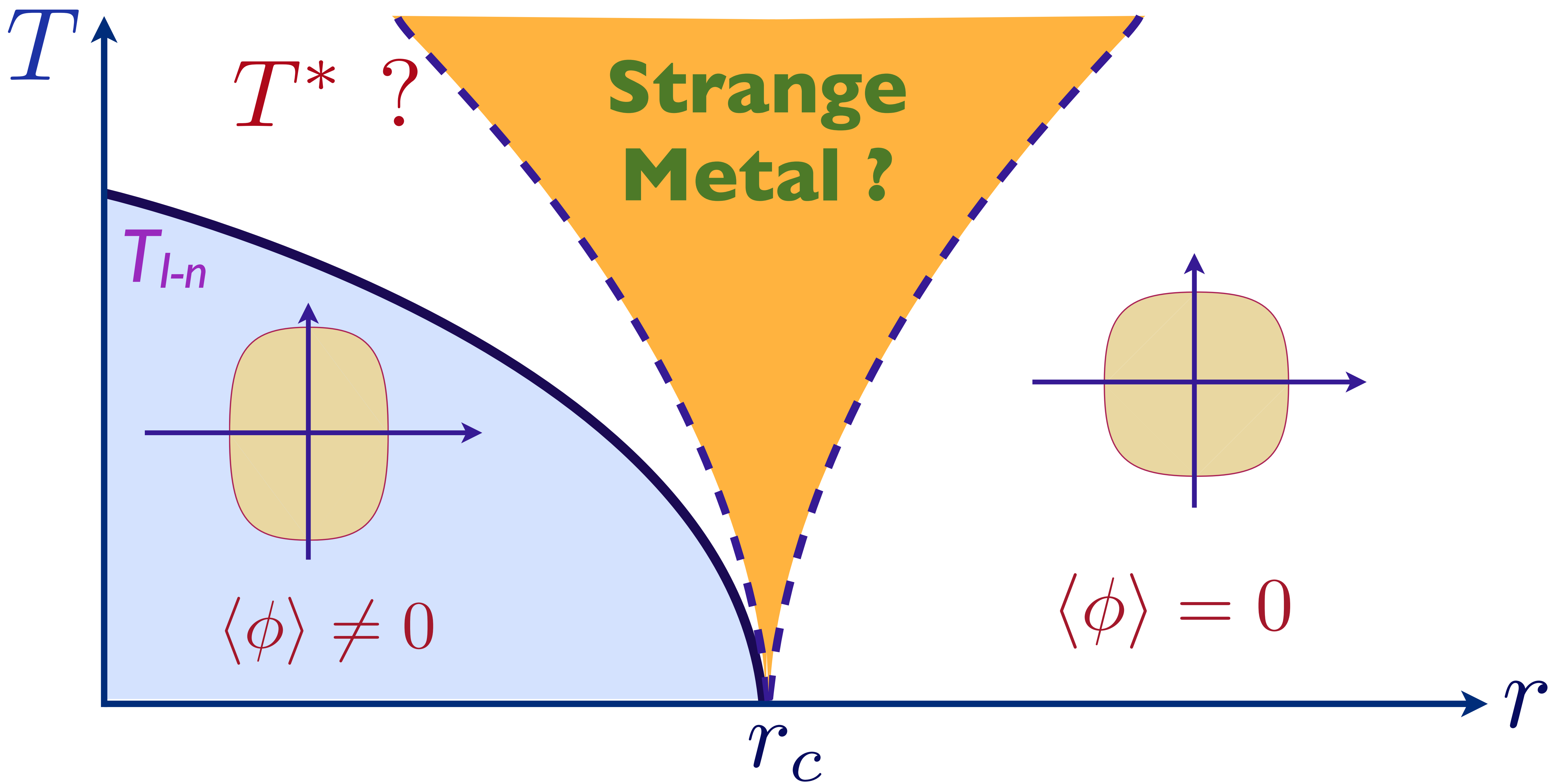


Phase diagram as a function of $T$ and $r$

# Quantum criticality of Ising-nematic ordering

Effective action for Ising order parameter

$$\mathcal{S}_\phi = \int d^2 r d\tau \left[ (\partial_\tau \phi)^2 + c^2 (\nabla \phi)^2 + (\lambda - \lambda_c) \phi^2 + u \phi^4 \right]$$

# Quantum criticality of Ising-nematic ordering

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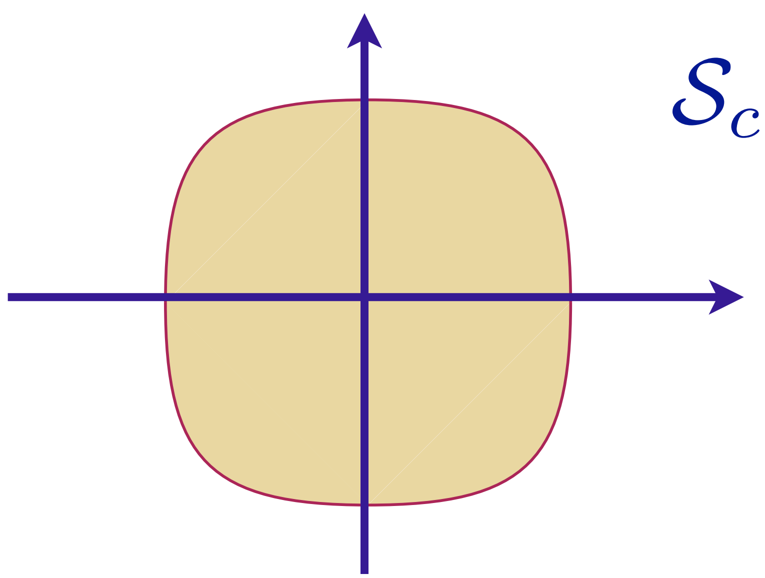
Effective action for electrons:



$$\mathcal{S}_c = \int d\tau \sum_{\alpha=1}^{N_f} \left[ \sum_i c_{i\alpha}^\dagger \partial_\tau c_{i\alpha} - \sum_{i<j} t_{ij} c_{i\alpha}^\dagger c_{i\alpha} \right]$$

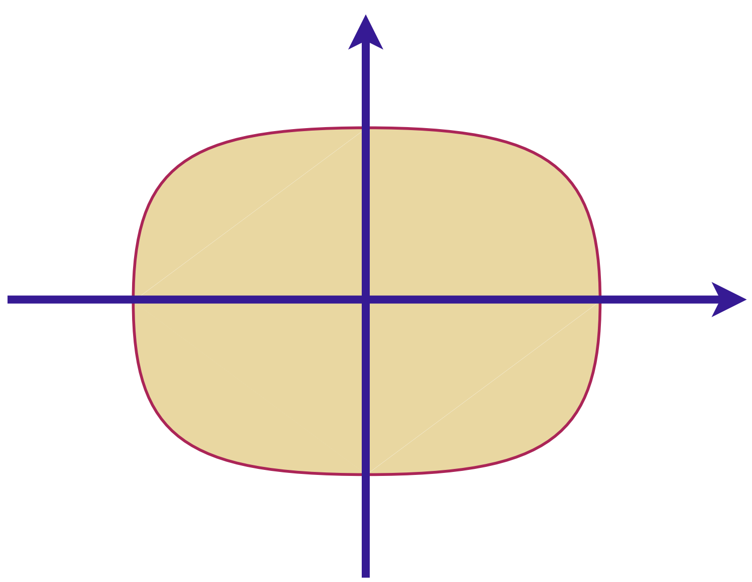
$$\equiv \sum_{\alpha=1}^{N_f} \sum_{\mathbf{k}} \int d\tau c_{\mathbf{k}\alpha}^\dagger \left( \partial_\tau + \varepsilon_{\mathbf{k}} \right) c_{\mathbf{k}\alpha}$$

# Quantum criticality of Ising-nematic ordering

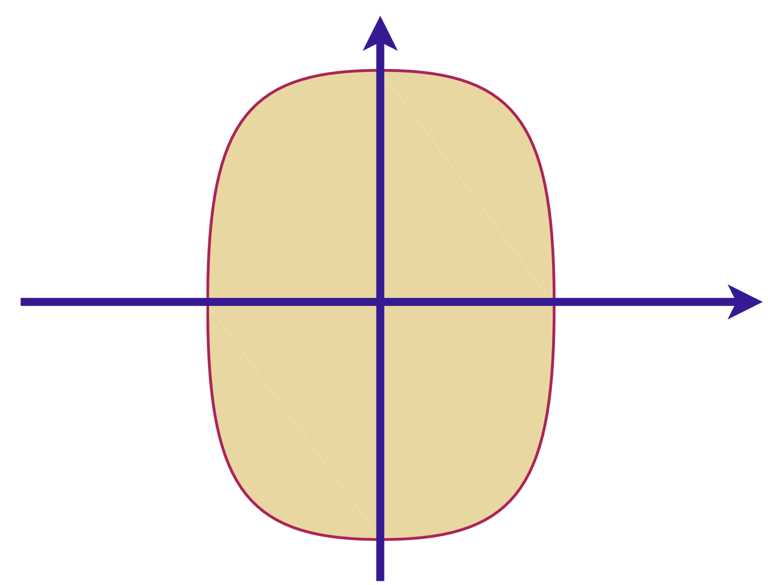
Coupling between Ising order and electrons

$$\mathcal{S}_{\phi c} = -\gamma \int d\tau \sum_{\alpha=1}^{N_f} \sum_{\mathbf{k},\mathbf{q}} \phi_{\mathbf{q}} \left(\cos k_x - \cos k_y\right) c^{\dagger}_{\mathbf{k}+\mathbf{q}/2,\alpha} c_{\mathbf{k}-\mathbf{q}/2,\alpha}$$

for spatially dependent $\phi$



$$\langle \phi \rangle > 0$$



$$\langle \phi \rangle < 0$$

# Quantum criticality of Ising-nematic ordering

$$\mathcal{S}_\phi = \int d^2r d\tau \left[ (\partial_\tau \phi)^2 + c^2 (\nabla \phi)^2 + (\lambda - \lambda_c)\phi^2 + u\phi^4 \right]$$

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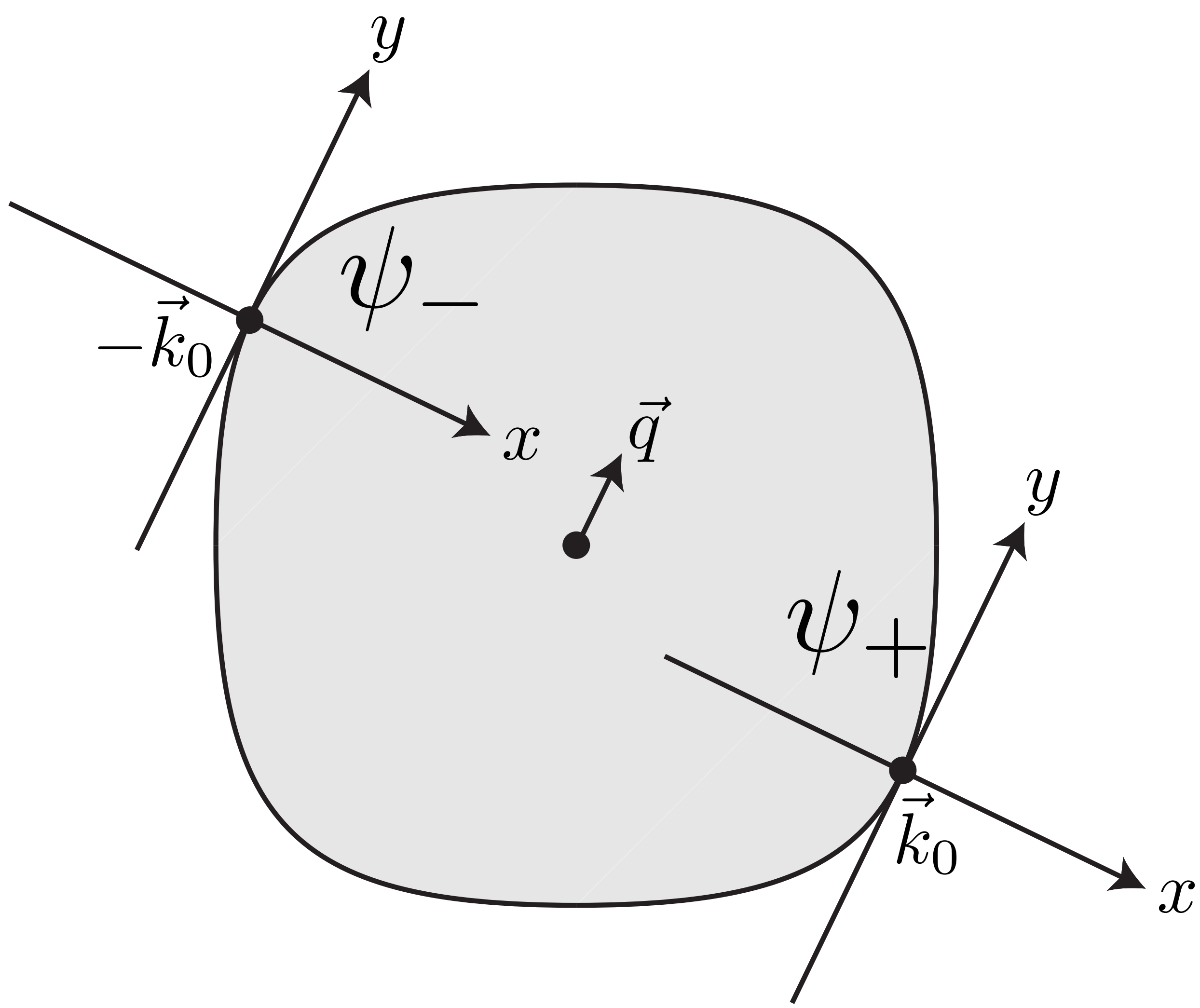
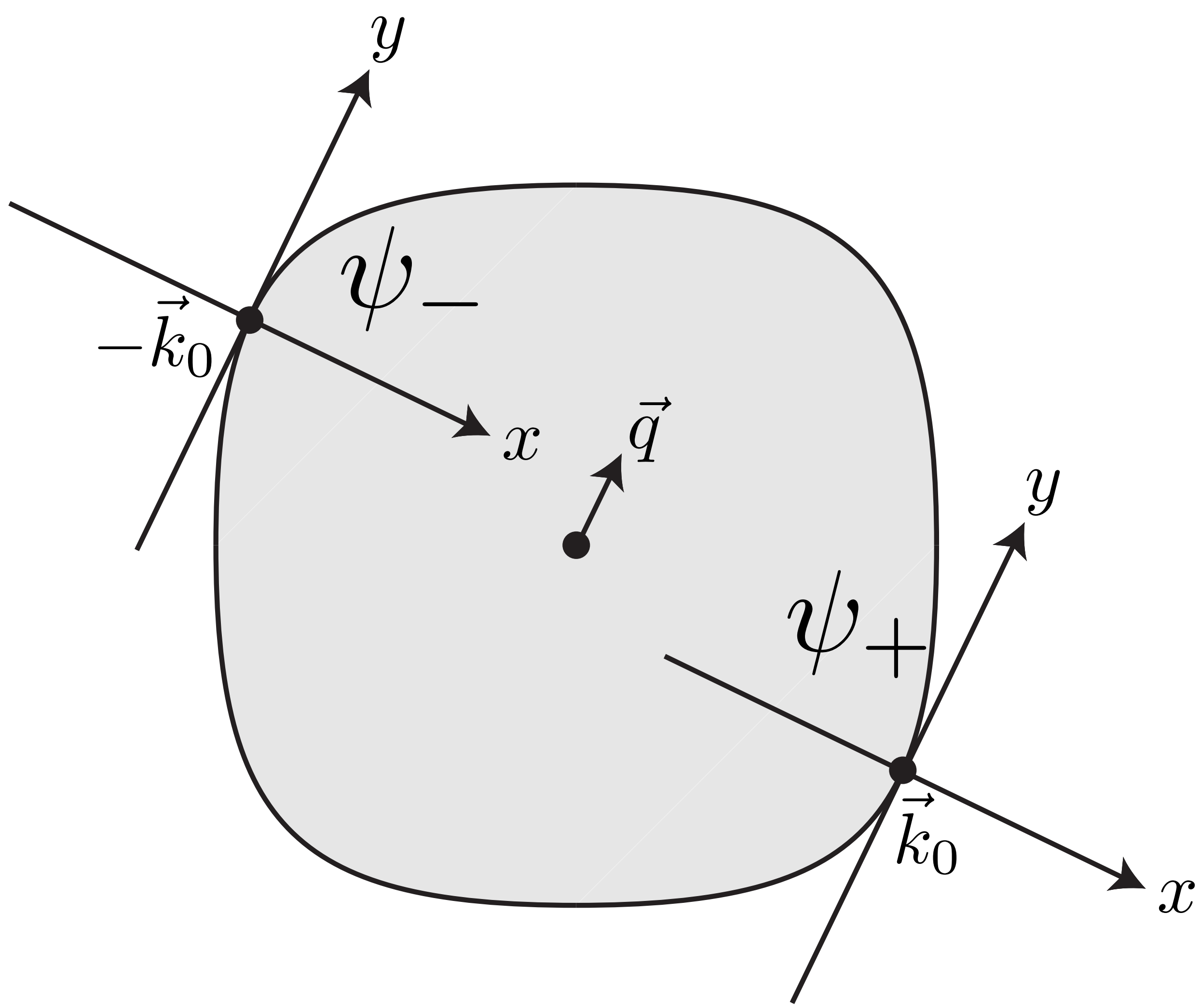
# Quantum criticality of Ising-nematic ordering



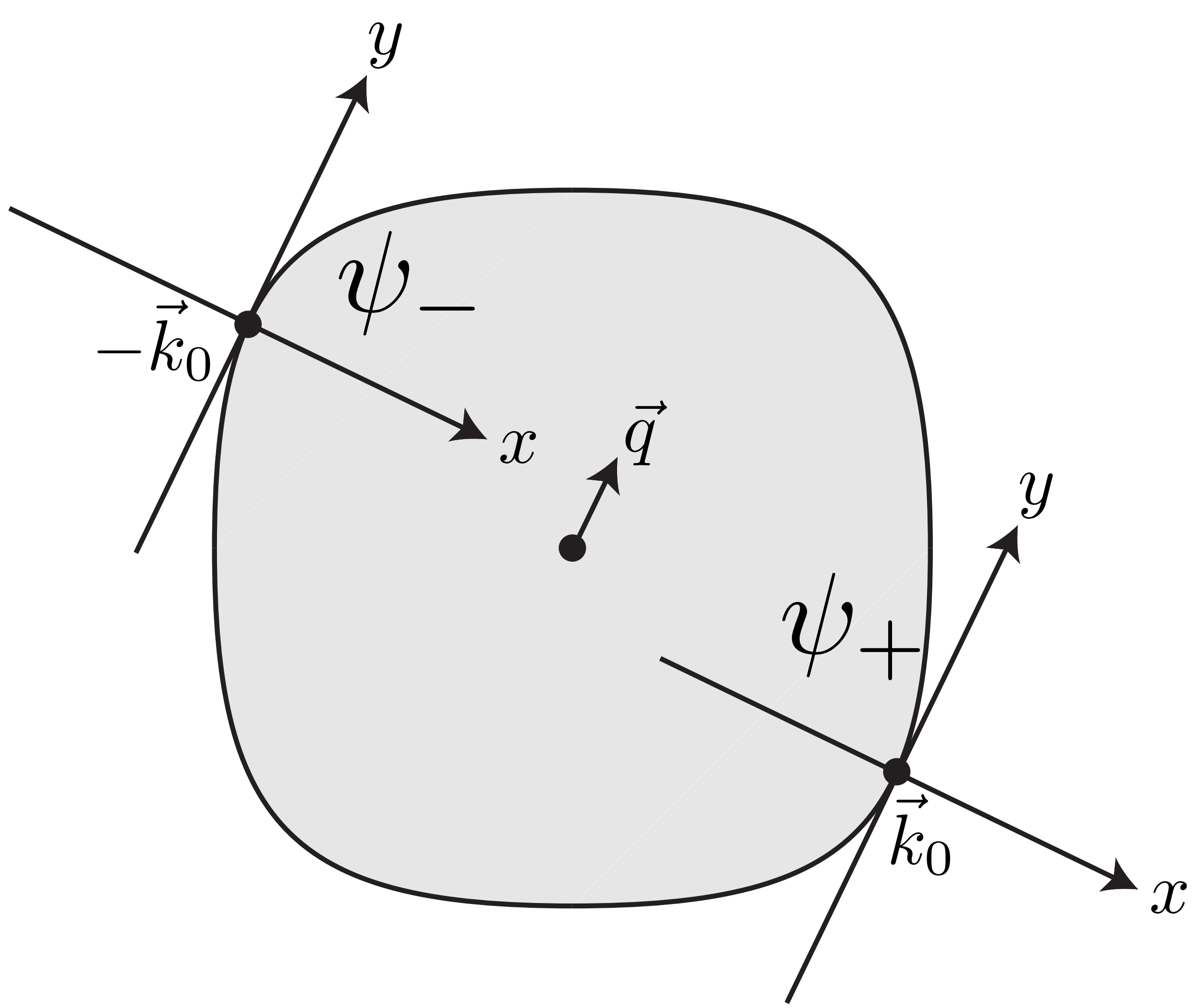

- $\phi$ fluctuation at wavevector $\vec{q}$ couples most efficiently to fermions near $\pm\vec{k}_0$.

# Quantum criticality of Ising-nematic ordering




- $\phi$ fluctuation at wavevector $\vec{q}$ couples most efficiently to fermions near $\pm\vec{k}_0$.
- Expand fermion kinetic energy at wavevectors about $\pm\vec{k}_0$ and boson ($\phi$) kinetic energy about $\vec{q} = 0$.

# Quantum criticality of Ising-nematic ordering



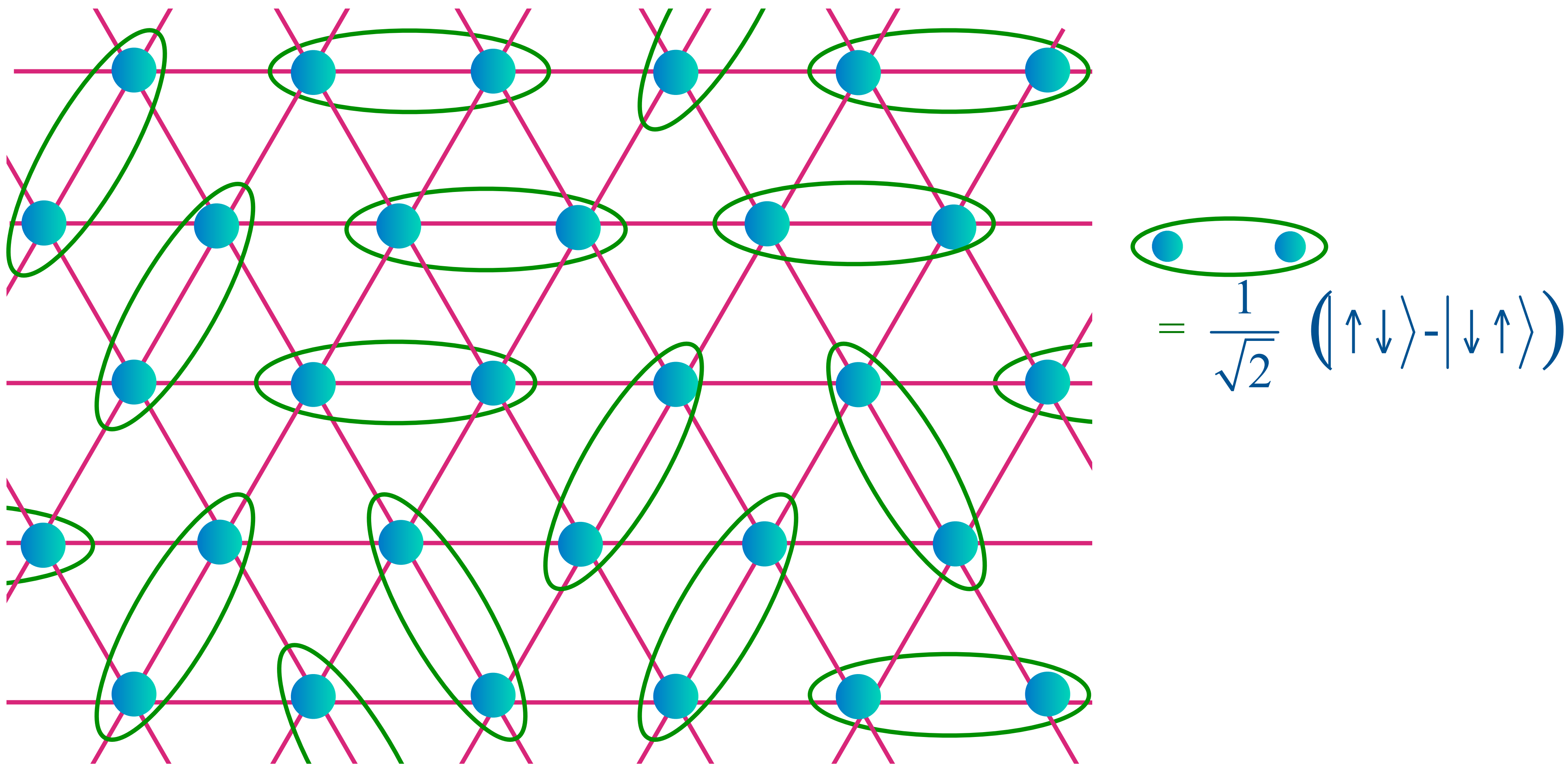

$$\mathcal{L}[\psi_\pm, \phi] =$$

$$\psi_+^\dagger \left(\partial_\tau - i\partial_x - \partial_y^2\right) \psi_+ + \psi_-^\dagger \left(\partial_\tau + i\partial_x - \partial_y^2\right) \psi_-$$

$$-\phi \left(\psi_+^\dagger \psi_+ + \psi_-^\dagger \psi_-\right) + \frac{1}{2g^2} \left(\partial_y \phi\right)^2$$

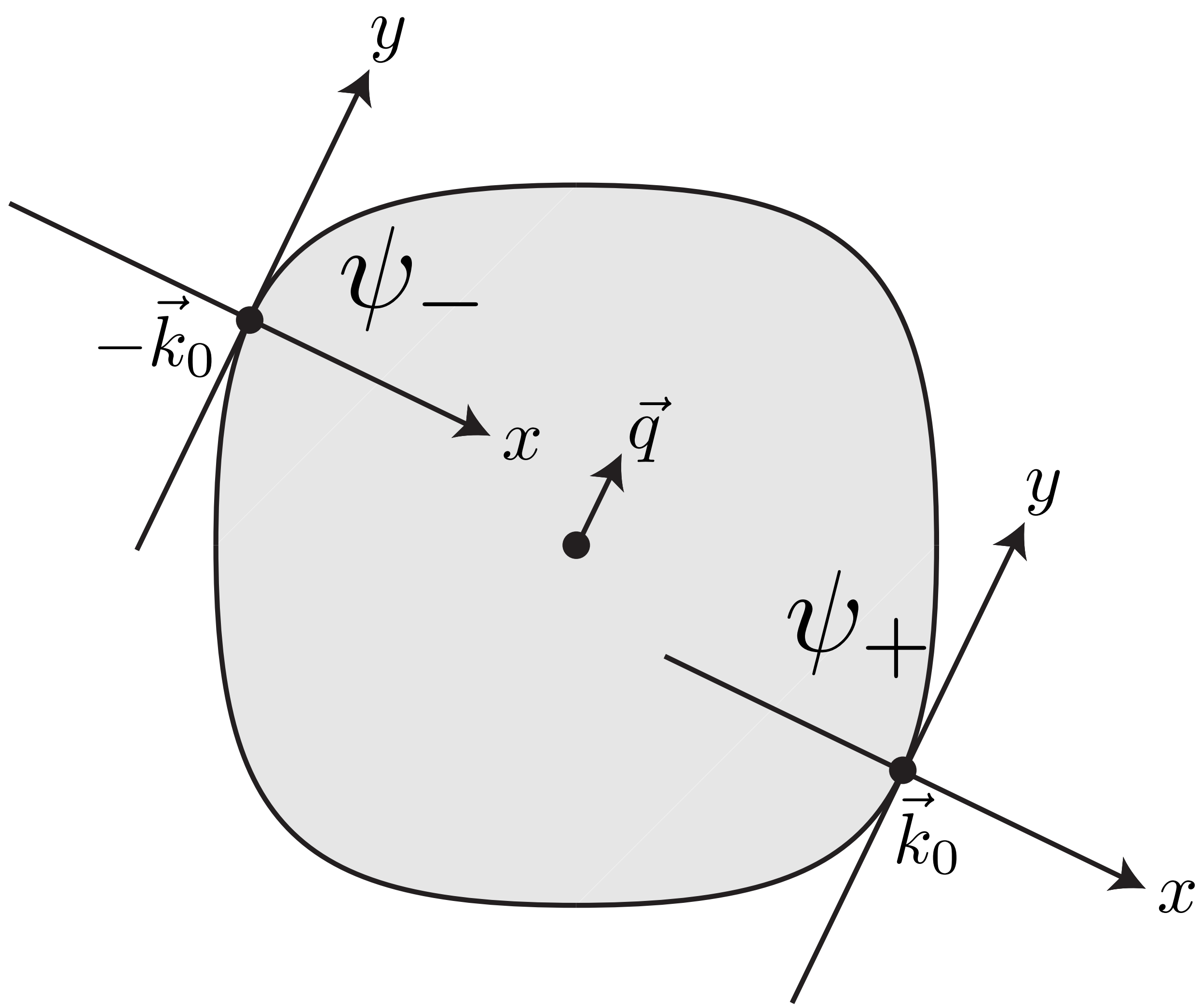
M. A. Metlitski and S. Sachdev, Phys. Rev. B **82**, 075127 (2010)

- Model of a spin liquid ("Bose metal"): couple fermions to a dynamical gauge field $A_\mu$.




$$\mathcal{L} = f_\sigma^\dagger \left( \partial_\tau - iA_\tau - \frac{(\nabla - i\mathbf{A})^2}{2m} - \mu \right) f_\sigma$$

# Quantum criticality of Ising-nematic ordering

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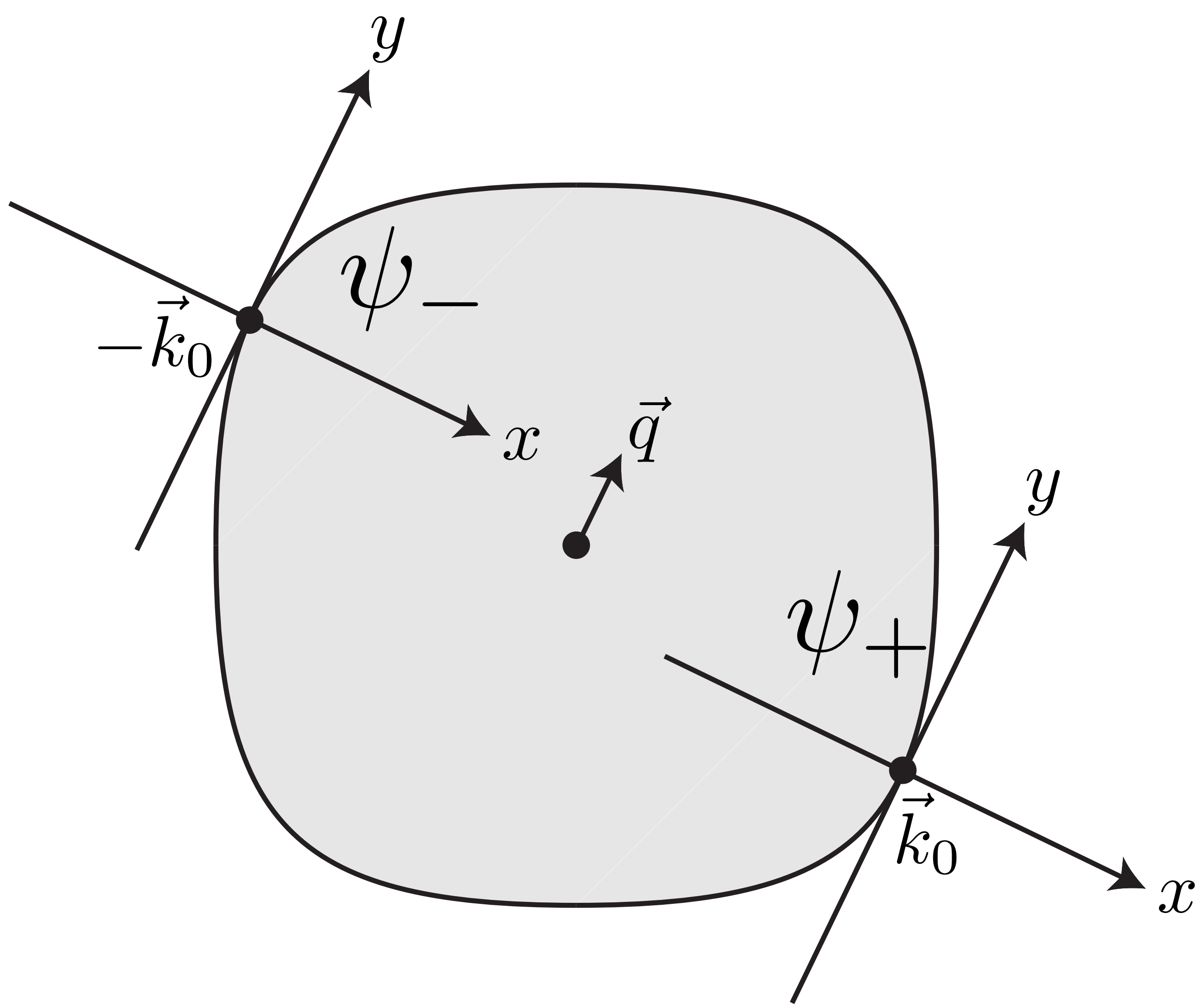
M. A. Metlitski and S. Sachdev, Phys. Rev. B **82**, 075127 (2010)

# Field theory of U(1) spin liquid




$$\mathcal{L}[\psi_\pm, a] =$$

$$\psi_+^\dagger \left(\partial_\tau - i\partial_x - \partial_y^2\right)\psi_+ + \psi_-^\dagger \left(\partial_\tau + i\partial_x - \partial_y^2\right)\psi_-$$

$$-a\left(\psi_+^\dagger\psi_+ - \psi_-^\dagger\psi_-\right) + \frac{1}{2g^2}\left(\partial_y a\right)^2$$

M. A. Metlitski and S. Sachdev, Phys. Rev. B **82**, 075127 (2010)

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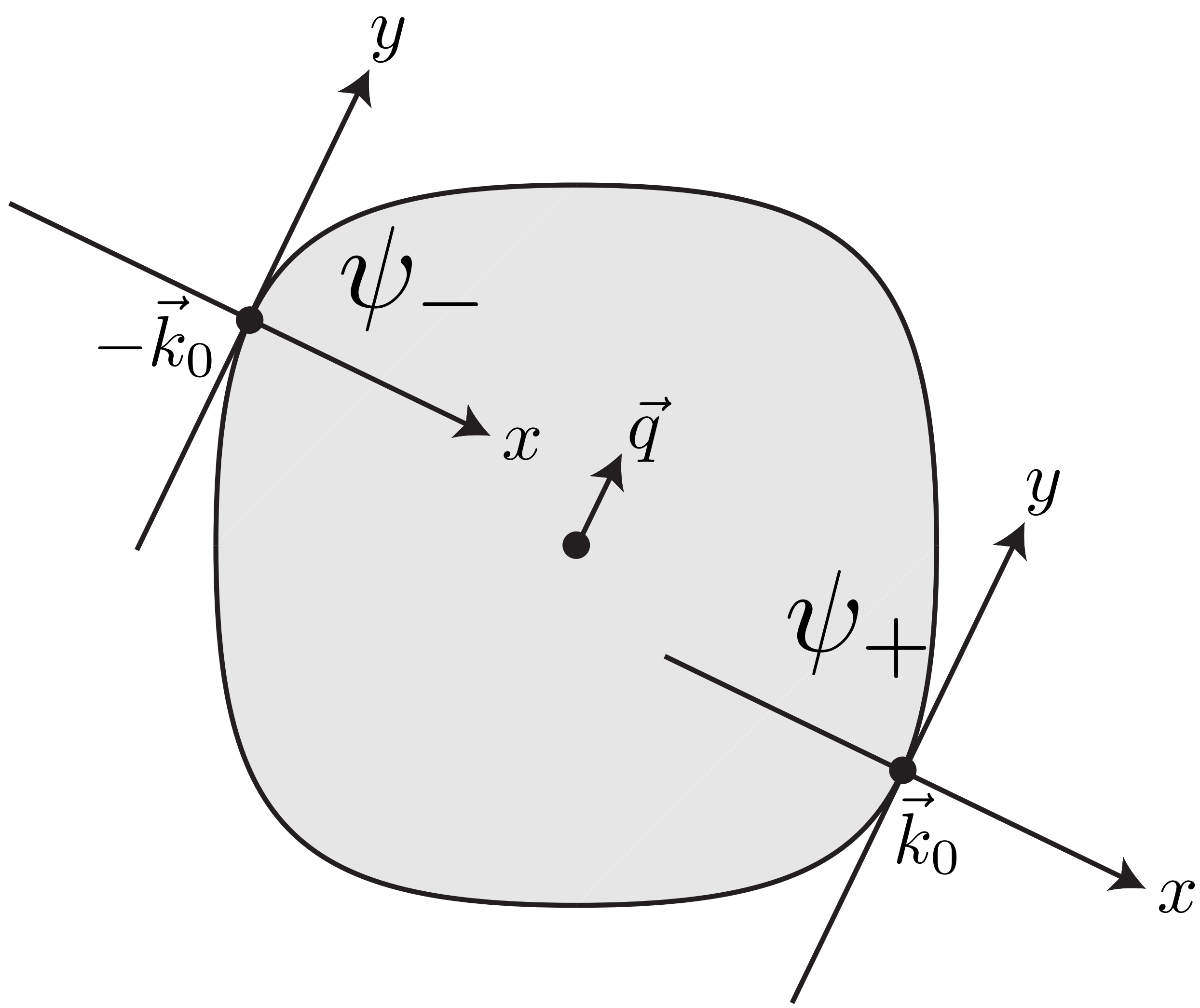


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M. A. Metlitski and S. Sachdev, Phys. Rev. B **82**, 075127 (2010)

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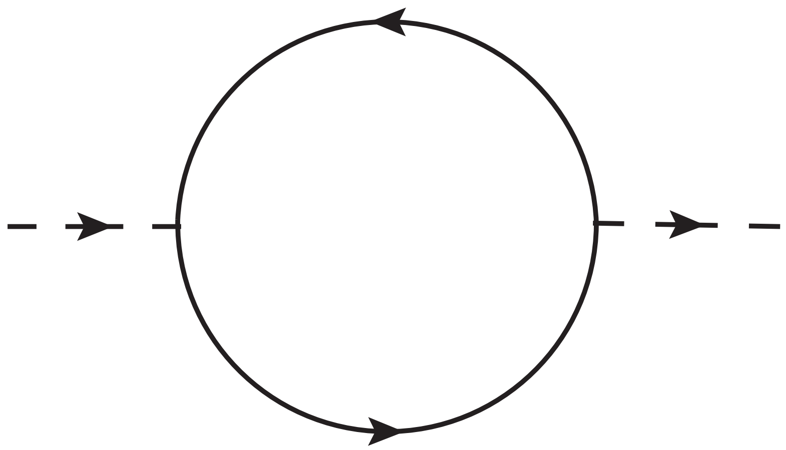
$$\mathcal{L} = \psi_+^\dagger \left(\partial_\tau - i\partial_x - \partial_y^2\right)\psi_+ + \psi_-^\dagger \left(\partial_\tau + i\partial_x - \partial_y^2\right)\psi_- - \phi\left(\psi_+^\dagger\psi_+ + \psi_-^\dagger\psi_-\right) + \frac{1}{2g^2}\left(\partial_y\phi\right)^2$$



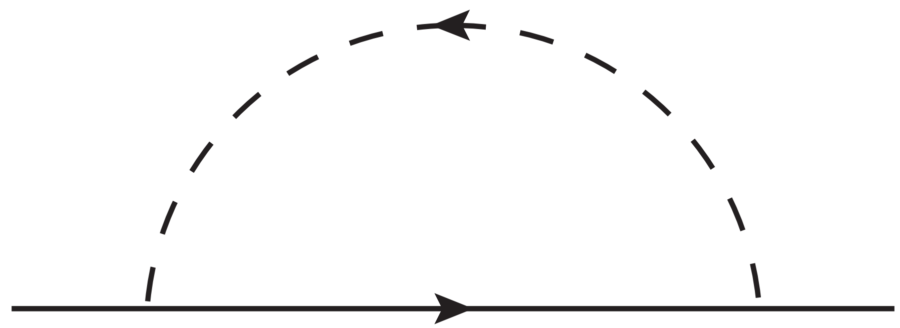
One loop $\phi$ self-energy with $N_f$ fermion flavors:

$$D(\vec{q},\omega) = N_f \int \frac{d^2k}{4\pi^2}\frac{d\Omega}{2\pi}\frac{1}{\left[-i(\Omega+\omega)+k_x+q_x+(k_y+q_y)^2\right]\left[-i\Omega-k_x+k_y^2\right]} = \frac{N_f}{4\pi}\frac{|\omega|}{|q_y|}$$

Landau-damping

# Quantum criticality of Ising-nematic ordering

$$\begin{aligned}\mathcal{L} &= \psi_+^\dagger \left(\partial_\tau - i\partial_x - \partial_y^2\right) \psi_+ + \psi_-^\dagger \left(\partial_\tau + i\partial_x - \partial_y^2\right) \psi_- \\ &\quad - \phi \left(\psi_+^\dagger \psi_+ + \psi_-^\dagger \psi_-\right) + \frac{1}{2g^2} \left(\partial_y \phi\right)^2\end{aligned}$$



Electron self-energy at order $1/N_f$:

$$\begin{aligned}\Sigma(\vec{k}, \Omega) &= -\frac{1}{N_f} \int \frac{d^2 q}{4\pi^2} \frac{d\omega}{2\pi} \frac{1}{\left[-i(\omega+\Omega) + k_x + q_x + (k_y + q_y)^2\right] \left[\frac{q_y^2}{g^2} + \frac{|\omega|}{|q_y|}\right]} \\ &= -i \frac{2}{\sqrt{3} N_f} \left(\frac{g^2}{4\pi}\right)^{2/3} \mathrm{sgn}(\Omega) |\Omega|^{2/3}\end{aligned}$$

# Quantum criticality of Ising-nematic ordering

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Schematic form of $\phi$ and fermion Green's functions

$$D(\vec{q},\omega) = \frac{1/N_f}{q_y^2 + \dfrac{|\omega|}{|q_y|}} \quad , \quad G_f(\vec{q},\omega) = \frac{1}{q_x + q_y^2 - i\,\mathrm{sgn}(\omega)|\omega|^{2/3}/N_f}$$

In *both* cases $q_x \sim q_y^2 \sim \omega^{1/z}$, with $z = 3/2$. Note that the bare term $\sim \omega$ in $G_f^{-1}$ is irrelevant.

Strongly-coupled theory without quasiparticles.

# Quantum criticality of Ising-nematic ordering

$$\mathcal{L} = \psi_+^\dagger \left(\partial_\tau - i\partial_x - \partial_y^2\right) \psi_+ + \psi_-^\dagger \left(\partial_\tau + i\partial_x - \partial_y^2\right) \psi_- - \phi \left(\psi_+^\dagger \psi_+ + \psi_-^\dagger \psi_-\right) + \frac{1}{2g^2} \left(\partial_y \phi\right)^2$$

Simple scaling argument for $z = 3/2$.

# Quantum criticality of Ising-nematic ordering

$$
\begin{aligned}
\mathcal{L}_{\rm scaling} &= \psi_+^\dagger \left(-i\partial_x - \partial_y^2\right) \psi_+ + \psi_-^\dagger \left(+i\partial_x - \partial_y^2\right) \psi_- \\
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Simple scaling argument for $z = 3/2$.

Under the rescaling $x \to x/s$, $y \to y/s^{1/2}$, and $\tau \to \tau/s^z$, we find invariance provided

$$\begin{aligned}\phi &\to \phi\, s^{(2z+1)/4} \\ \psi &\to \psi\, s^{(2z+1)/4} \\ g &\to g\, s^{(3-2z)/4}\end{aligned}$$

So the action is invariant provided $z = 3/2$.

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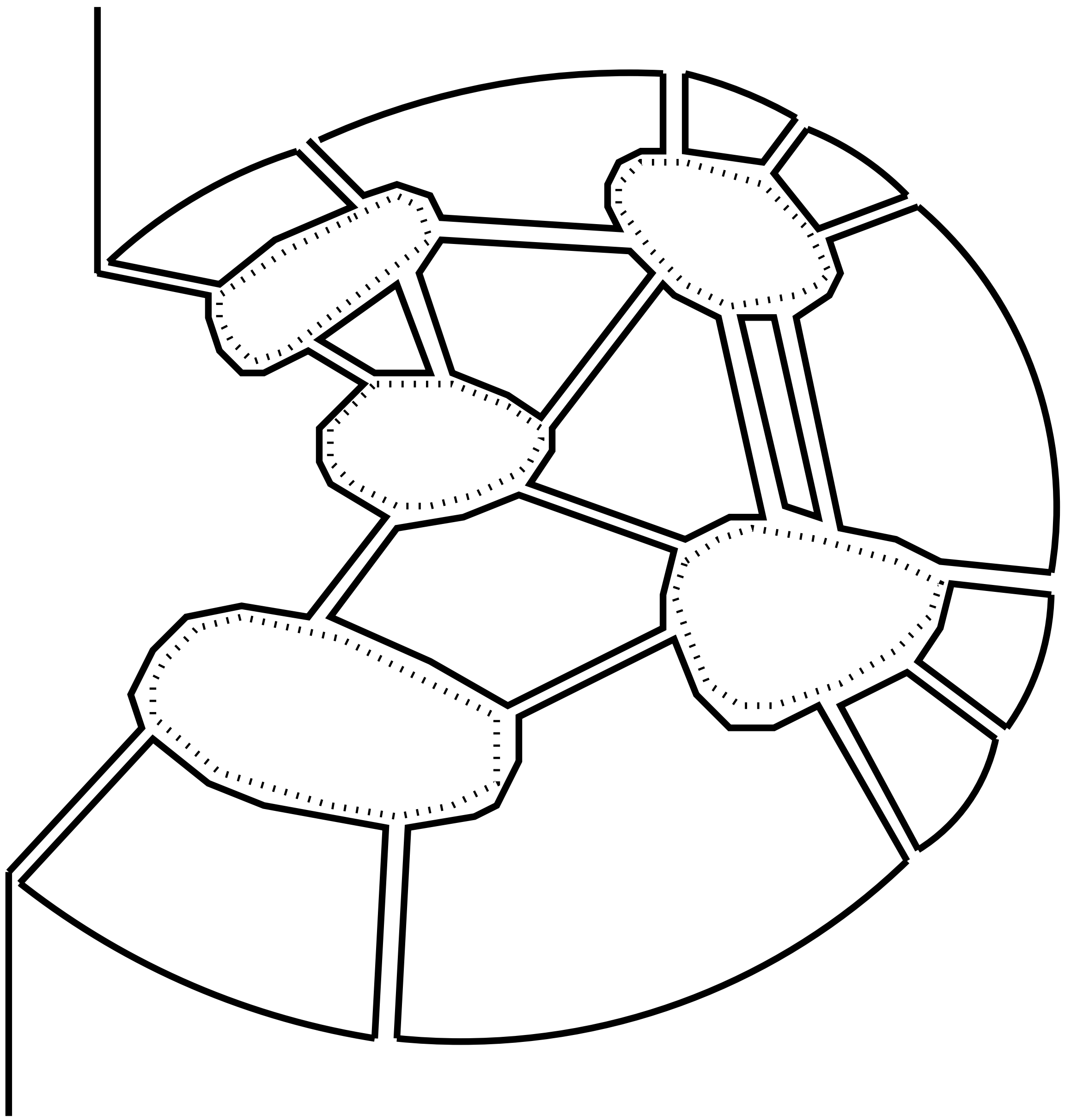
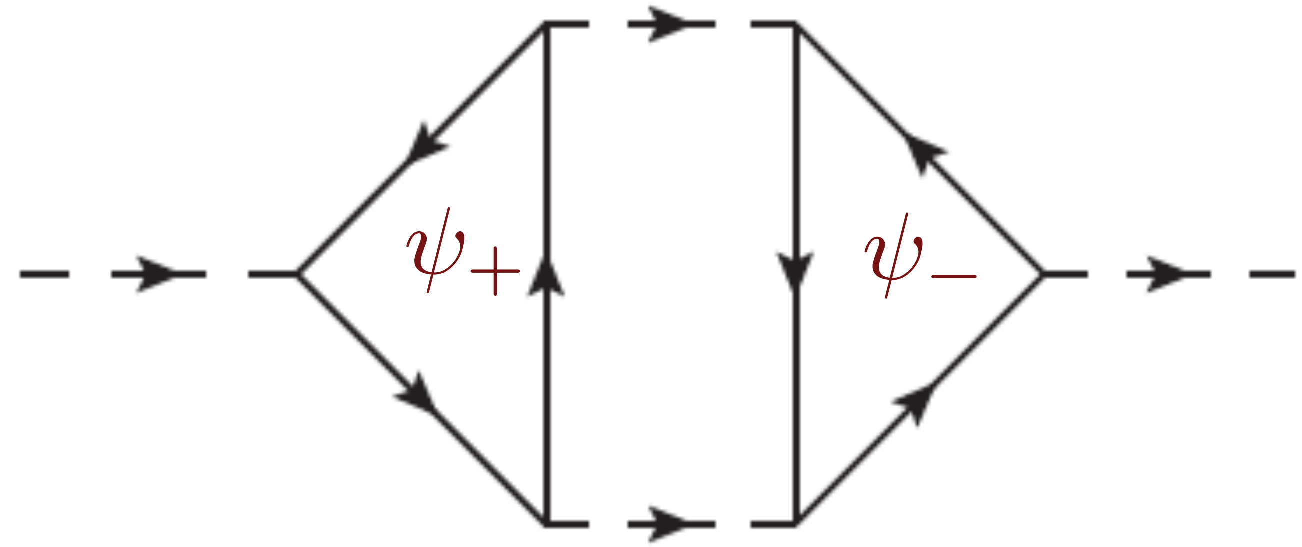
The $1/N_f$ expansion is *not* determined by counting fermion loops, because of infrared singularities created by the Fermi surface. The $|\omega|^{2/3}/N_f$ fermion self-energy leads to additional powers of $N_f$, and a breakdown in the loop expansion.

# Computations in the $1/N$ expansion





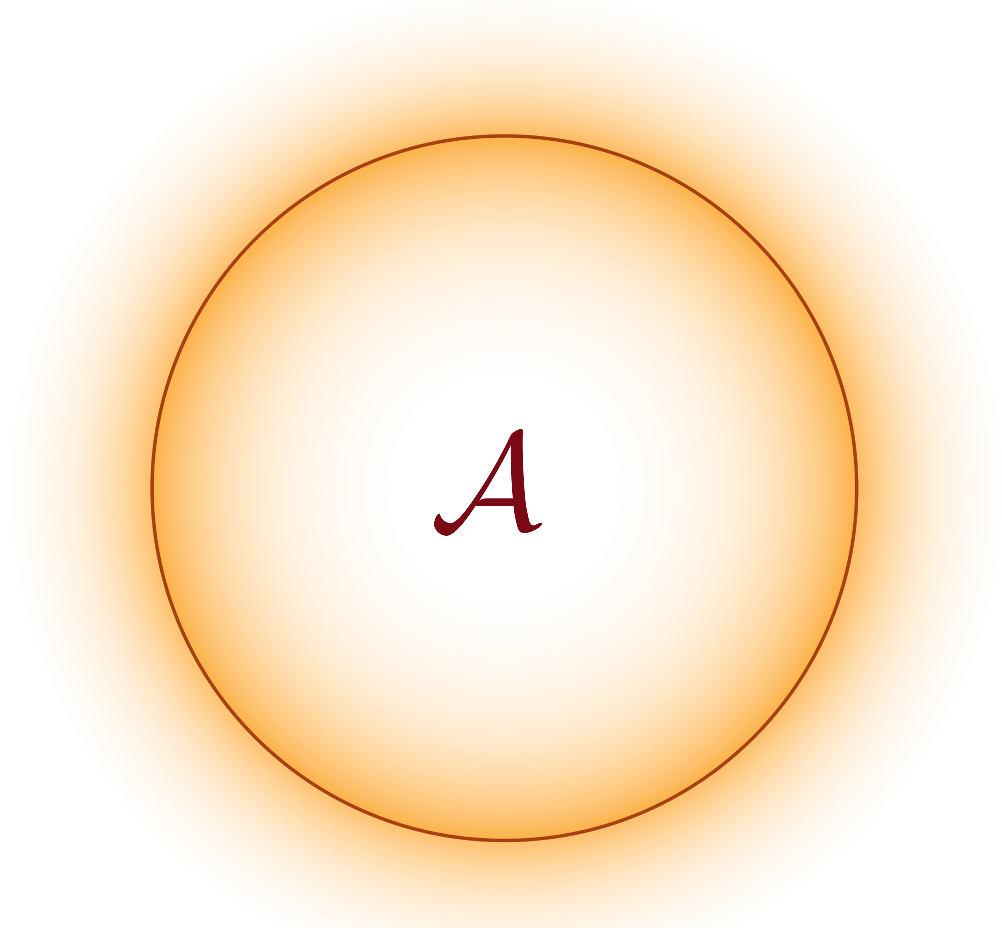

Graph mixing $\psi_+$ and $\psi_-$ is $\mathcal{O}\left(N^{3/2}\right)$ (instead of $\mathcal{O}\left(N\right)$), violating genus expansion

All planar graphs of $\psi_+$ alone are as important as the leading term

M. A. Metlitski and S. Sachdev, Phys. Rev. B **82**, 075127 (2010)

Sung-Sik Lee, *Physical Review* B **80**, 165102 (2009)

# Properties of the strange metal at the Ising-nematic critical point




- There is a sharp Fermi surface defined by the fermion Green's function: $G_f^{-1}(|\mathbf{k}| = k_F, \omega = 0) = 0$.

S.-S. Lee, Phys. Rev. B **80**, 165102 (2009)
M. A. Metlitski and S. Sachdev, Phys. Rev. B **82**, 075127 (2010)
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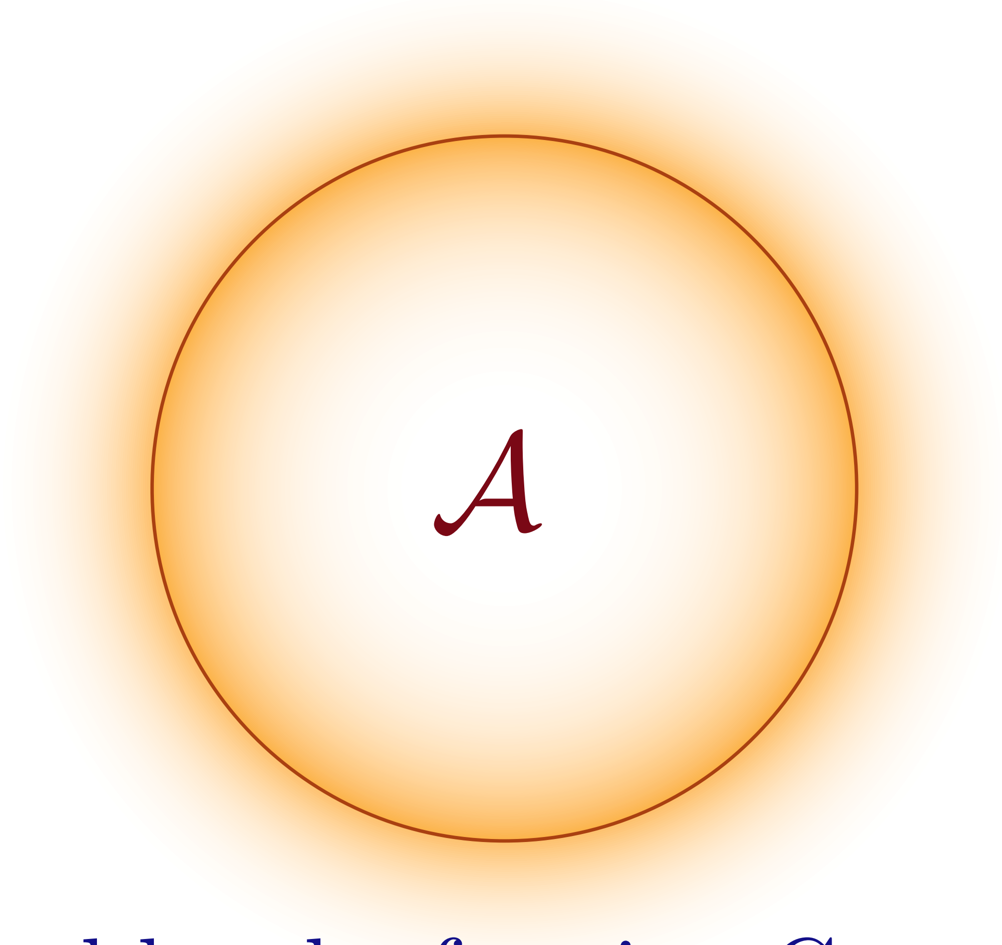


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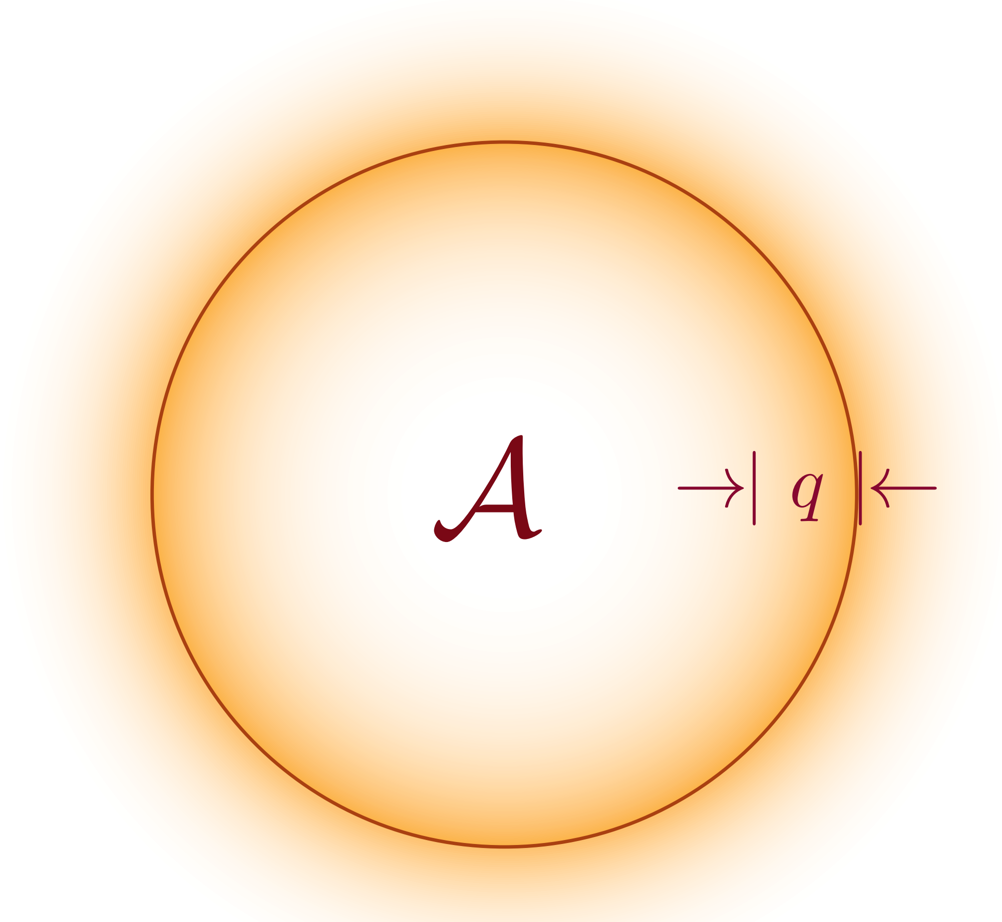


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- Area enclosed by the Fermi surface $\mathcal{A} = \mathcal{Q}$, the fermion density
- Critical continuum of excitations near the Fermi surface with energy $\omega \sim |q|^z$, where $q = |\mathbf{k}| - k_F$ is the distance from the Fermi surface and $z$ is the dynamic critical exponent.


S.-S. Lee, Phys. Rev. B **80**, 165102 (2009)
M. A. Metlitski and S. Sachdev, Phys. Rev. B **82**, 075127 (2010)
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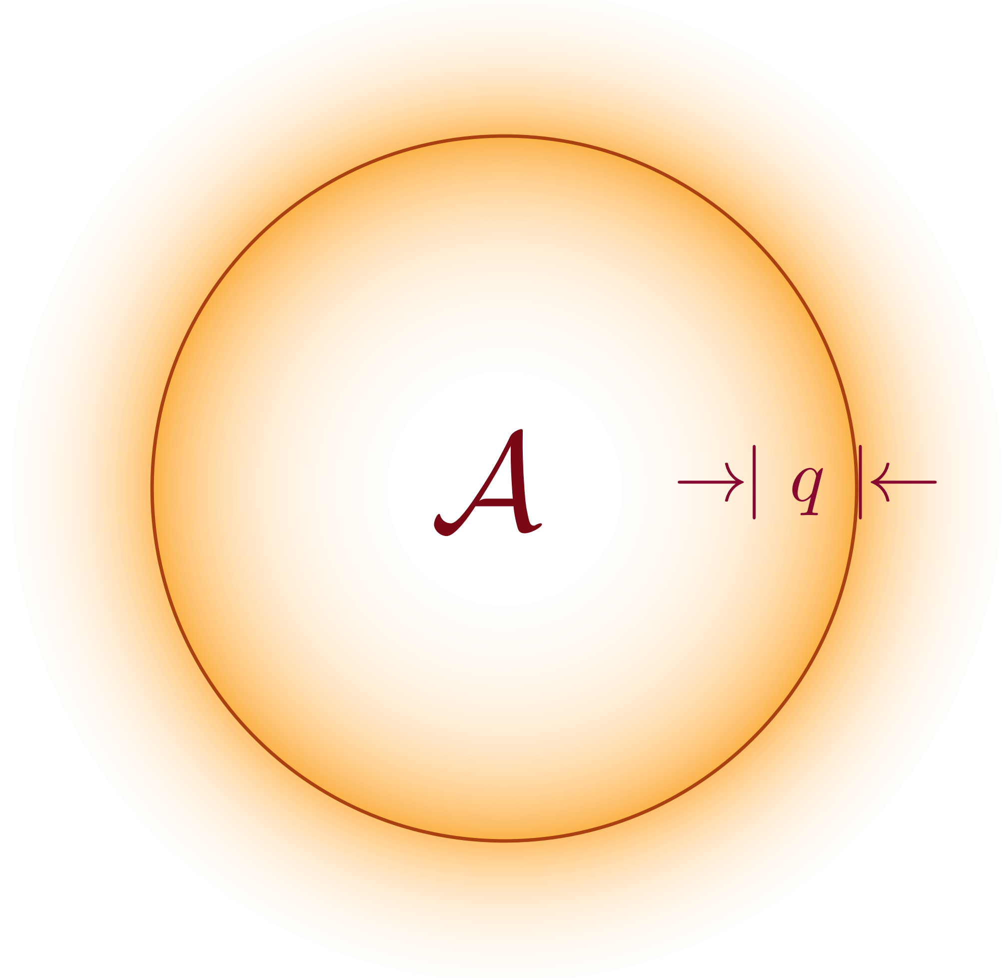


- Fermion Green's function $G_f^{-1} = q^{1-\eta} F(\omega/q^z)$. Three-loop computation shows $\eta \neq 0$ and $z = 3/2$.


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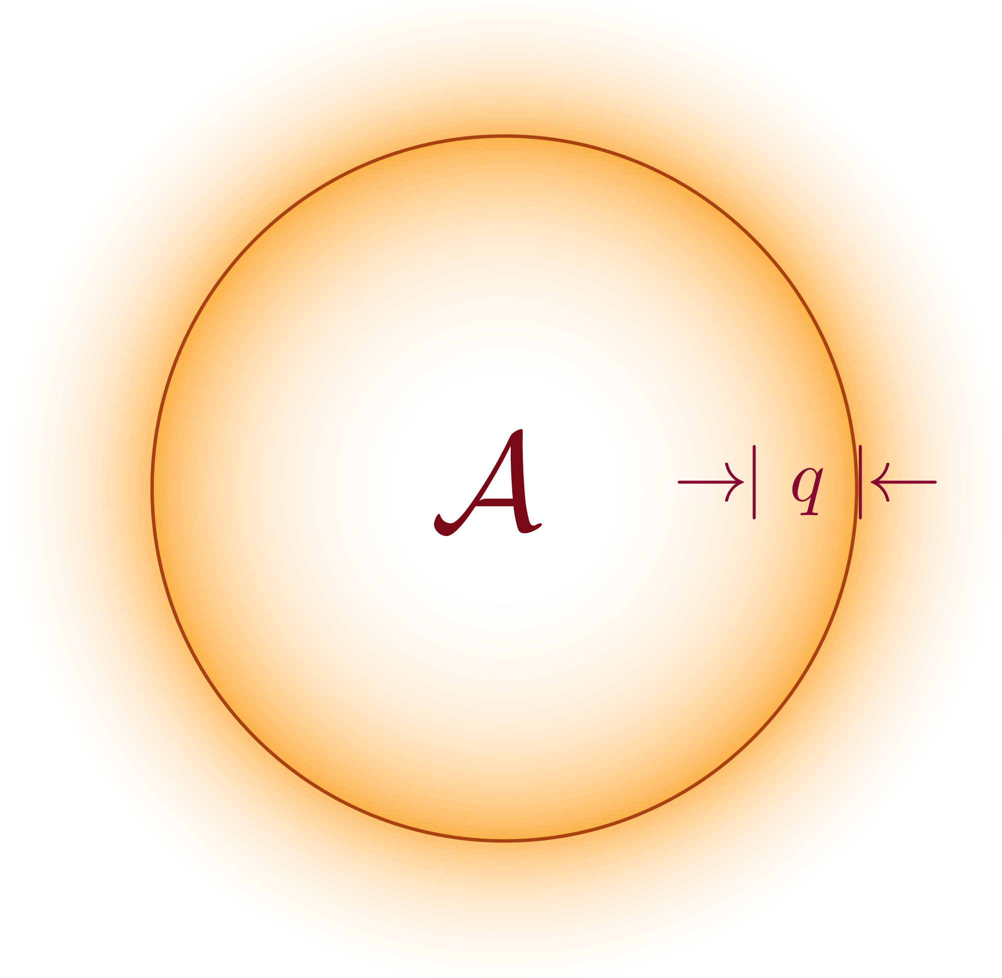
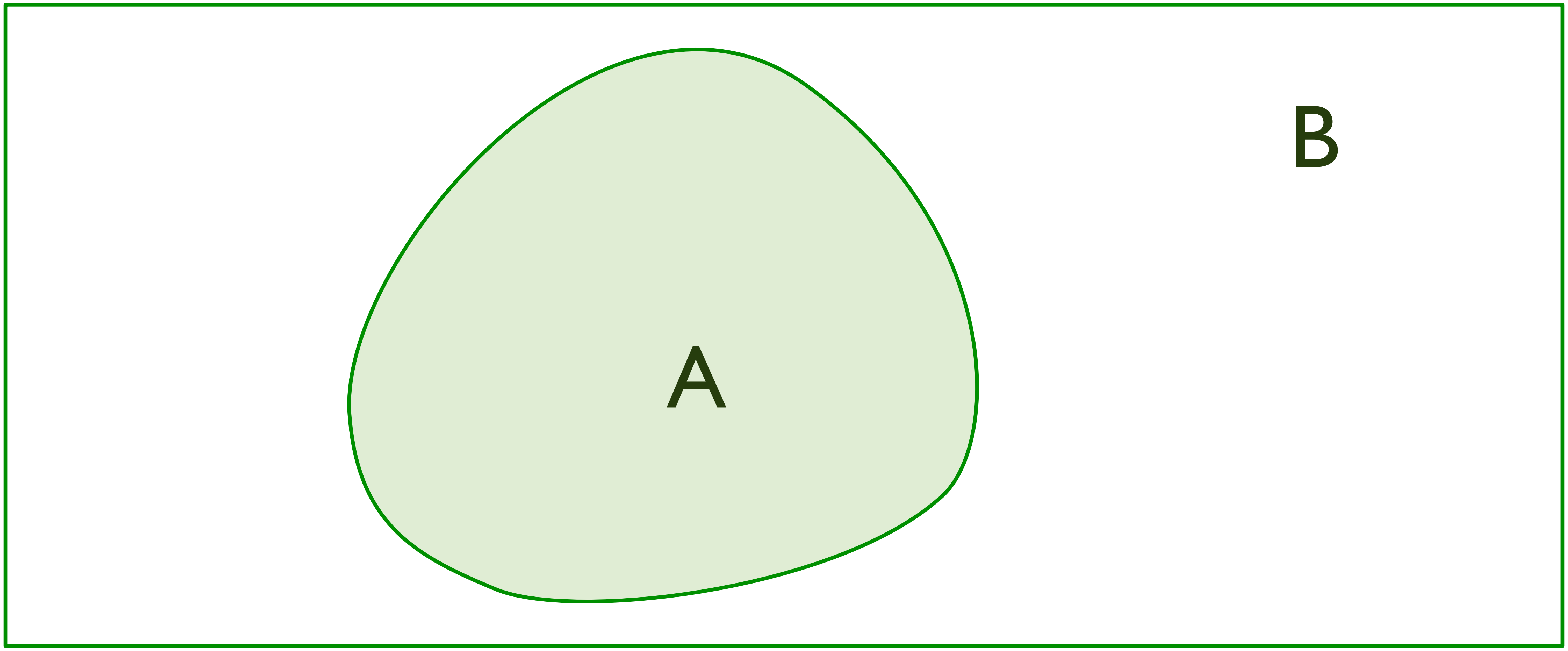



- Fermion Green's function $G_f^{-1} = q^{1-\eta} F(\omega/q^z)$. Three-loop computation shows $\eta \neq 0$ and $z = 3/2$.
- The phase space density of fermions is effectively one-dimensional, so the entropy density $S \sim T^{d_{\text{eff}}/z}$ with $d_{\text{eff}} = 1$.

S.-S. Lee, Phys. Rev. B **80**, 165102 (2009)
M. A. Metlitski and S. Sachdev, Phys. Rev. B **82**, 075127 (2010)
D. F. Mross, J. McGreevy, H. Liu, and T. Senthil, Phys. Rev. B **82**, 045121 (2010)

# Entanglement entropy

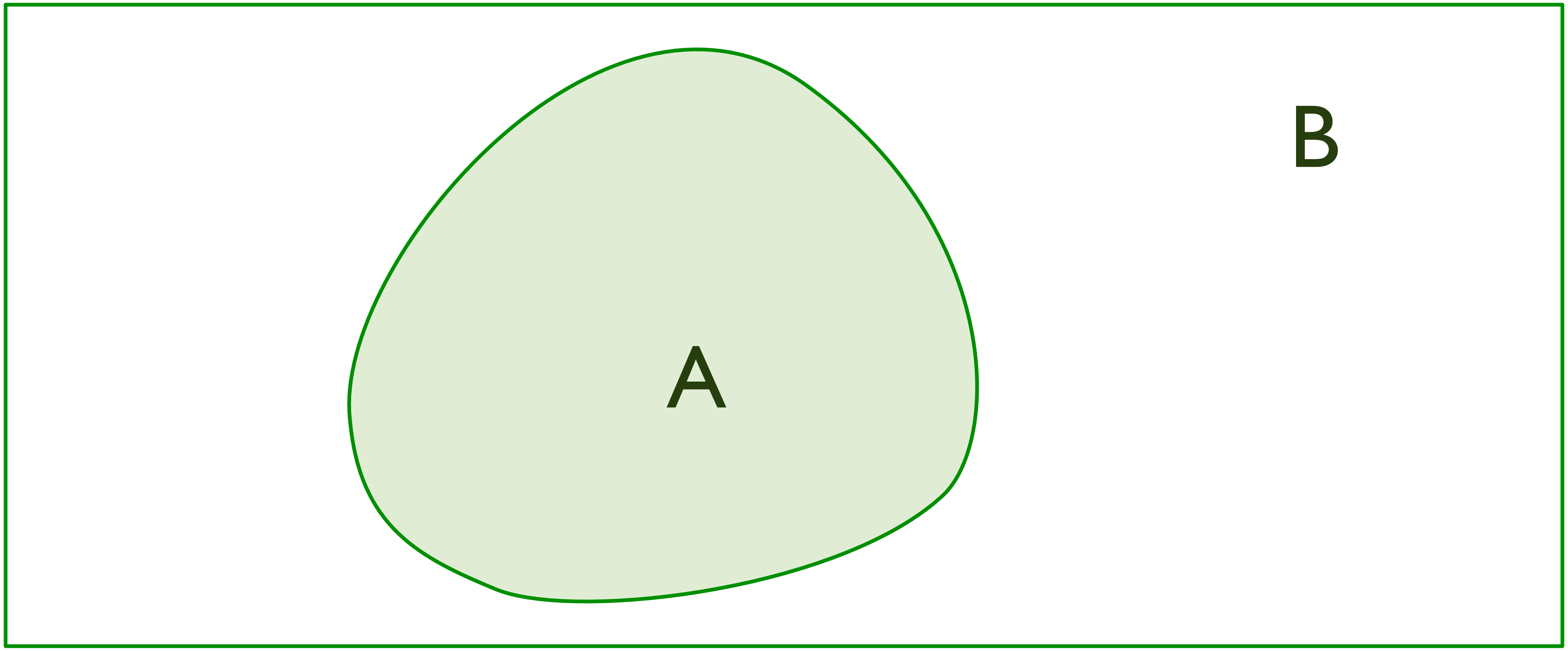



**Measure strength of quantum entanglement of region A with region B.**

$$\rho_A = \mathrm{Tr}_B \rho = \text{density matrix of region } A$$

**Entanglement entropy** $S_{EE} = -\mathrm{Tr} \left( \rho_A \ln \rho_A \right)$

# Entanglement entropy of Fermi surfaces

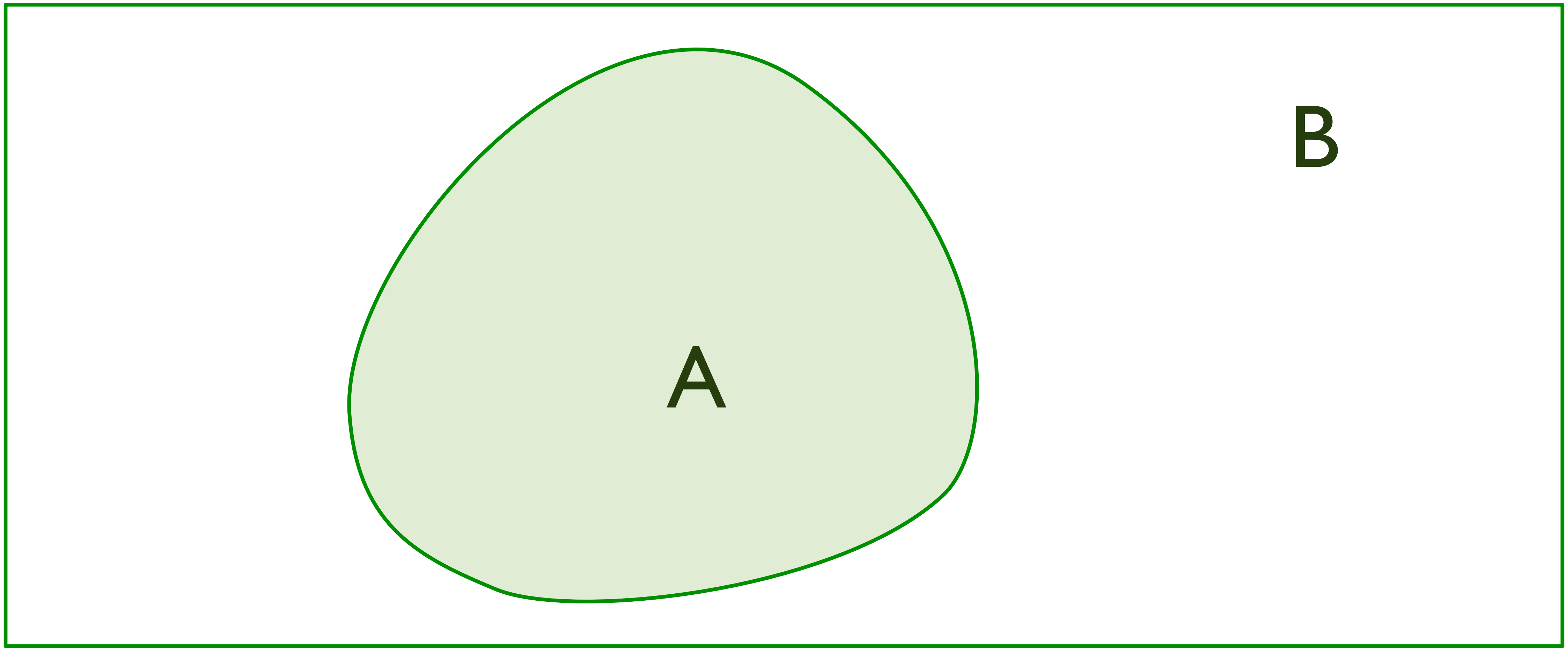



Logarithmic violation of "area law": $S_{EE} = \frac{1}{12}(k_F P)\ln(k_F P)$

for a circular Fermi surface with Fermi momentum $k_F$,
where $P$ is the perimeter of region A with an arbitrary smooth shape.

D. Gioev and I. Klich, *Physical Review Letters* **96**, 100503 (2006)
B. Swingle, *Physical Review Letters* **105**, 050502 (2010)

# Entanglement entropy of Fermi surfaces

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for a circular Fermi surface with Fermi momentum $k_F$,
where $P$ is the perimeter of region A with an arbitrary smooth shape.

Non-Fermi liquids have, at most, the "1/12" prefactor modified.

Y. Zhang, T. Grover, and A. Vishwanath, *Physical Review Letters* **107**, 067202 (2011)

# Compressible quantum matter

*A. Fermi liquids:graphene*

*B. Holography: Reissner - Nördstrom solution*

*C. Non-Fermi liquids: nematic critical point (and U(1) spin liquids)*

*D. Holography: scaling arguments for entropy and entanglement entropy*

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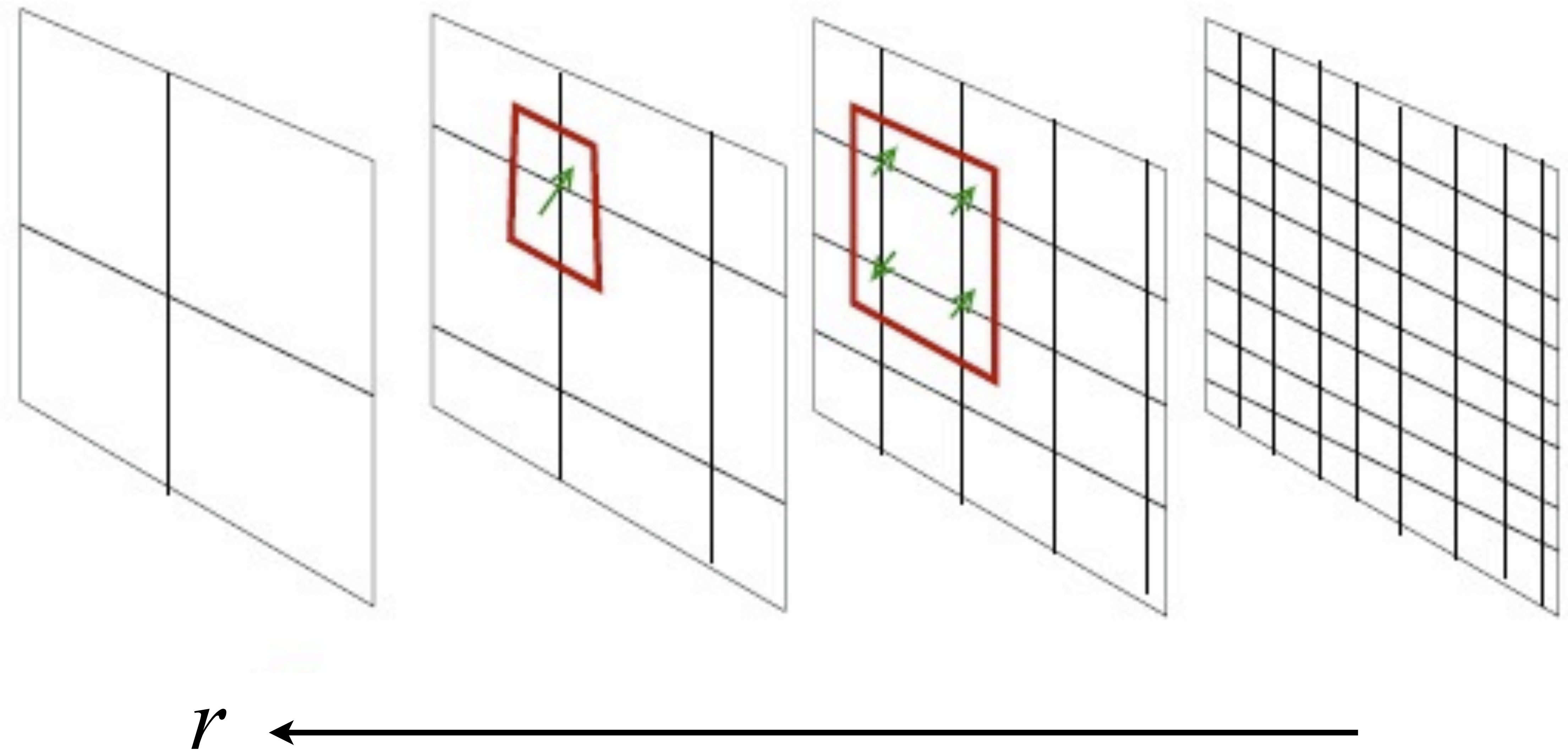
$r$

Consider the metric which transforms under rescaling as

$$\begin{aligned} x_i &\to \zeta\, x_i \\ t &\to \zeta^z\, t \\ ds &\to \zeta^{\theta/d}\, ds. \end{aligned}$$

This identifies $z$ as the dynamic critical exponent ($z = 1$ for "relativistic" quantum critical points).

$\theta$ is the violation of hyperscaling exponent.

L. Huijse, S. Sachdev, B. Swingle, Physical Review B **85**, 035121 (2012)

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This identifies $z$ as the dynamic critical exponent ($z = 1$ for "relativistic" quantum critical points).

$\theta$ is the violation of hyperscaling exponent.
The most general choice of such a metric is

$$ds^2 = \frac{1}{r^2}\left(-\frac{dt^2}{r^{2d(z-1)/(d-\theta)}} + r^{2\theta/(d-\theta)}dr^2 + dx_i^2\right)$$

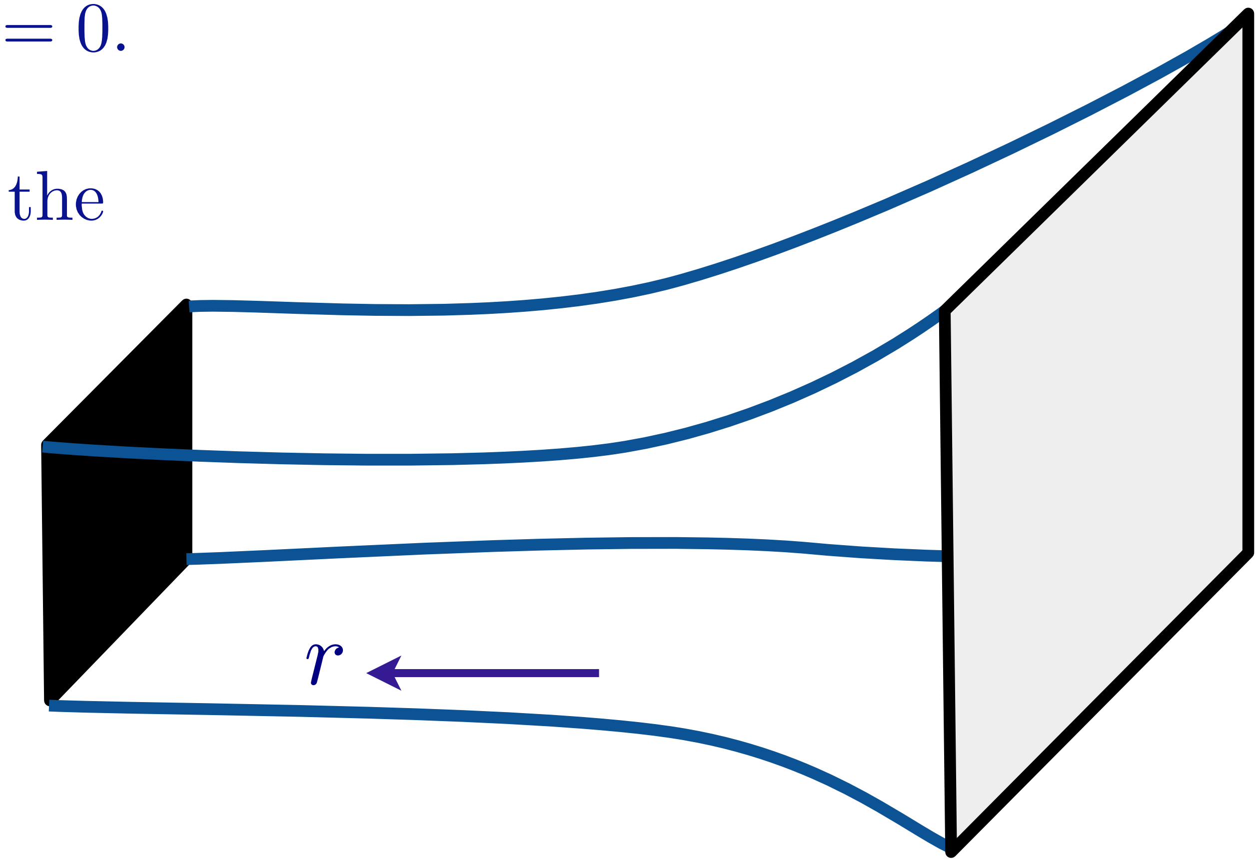
We have used reparametrization invariance in $r$ to choose so that it scales as $r \to \zeta^{(d-\theta)/d} r$.

L. Huijse, S. Sachdev, B. Swingle, Physical Review B **85**, 035121 (2012)

At $T > 0$, there is a "black-brane" at $r = r_h$.

The Beckenstein-Hawking entropy of the black-brane is the thermal entropy of the quantum system $r = 0$.

The entropy density, $S$, is proportional to the "area" of the horizon, and so $S \sim r_h^{-d}$



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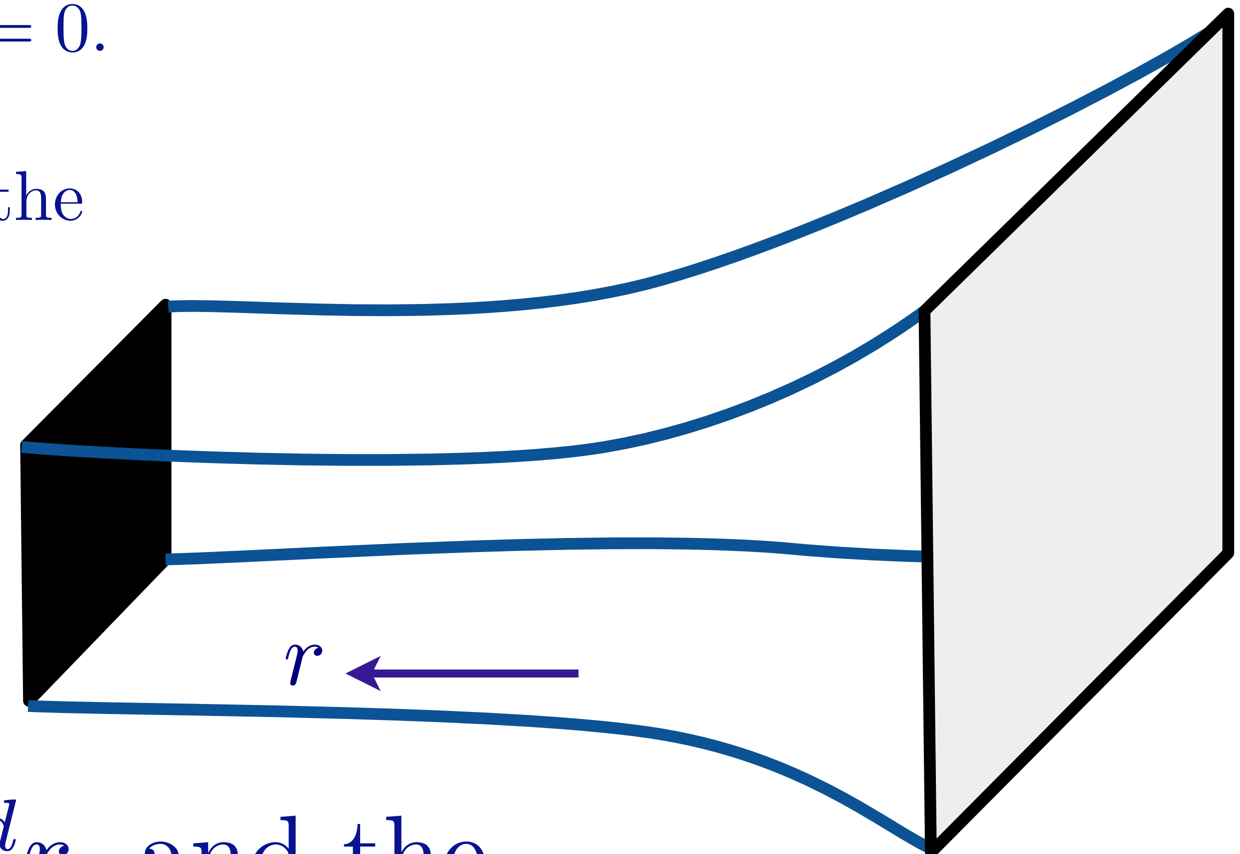



Under rescaling $r \to \zeta^{(d-\theta)/d} r$, and the temperature $T \sim t^{-1}$, and so

$$S \sim T^{(d-\theta)/z} = T^{d_{\text{eff}}/z}$$

where $\theta = d - d_{\text{eff}}$ measures "dimension deficit" in the phase space of low energy degrees of a freedom.

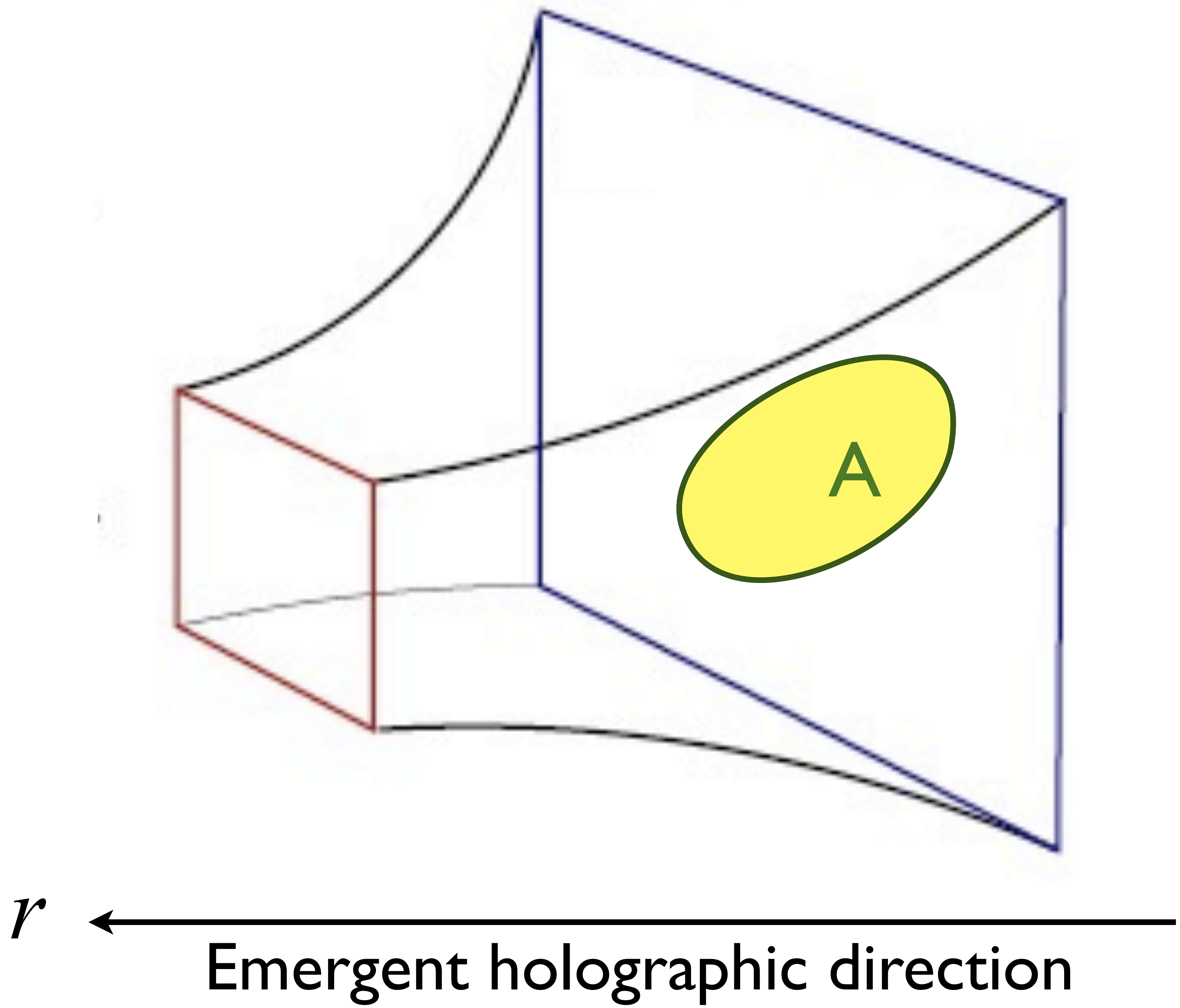
$$ds^2 = \frac{1}{r^2}\left(-\frac{dt^2}{r^{2d(z-1)/(d-\theta)}} + r^{2\theta/(d-\theta)}dr^2 + dx_i^2\right)$$

- The thermal entropy density scales as

$$S \sim T^{(d-\theta)/z}.$$

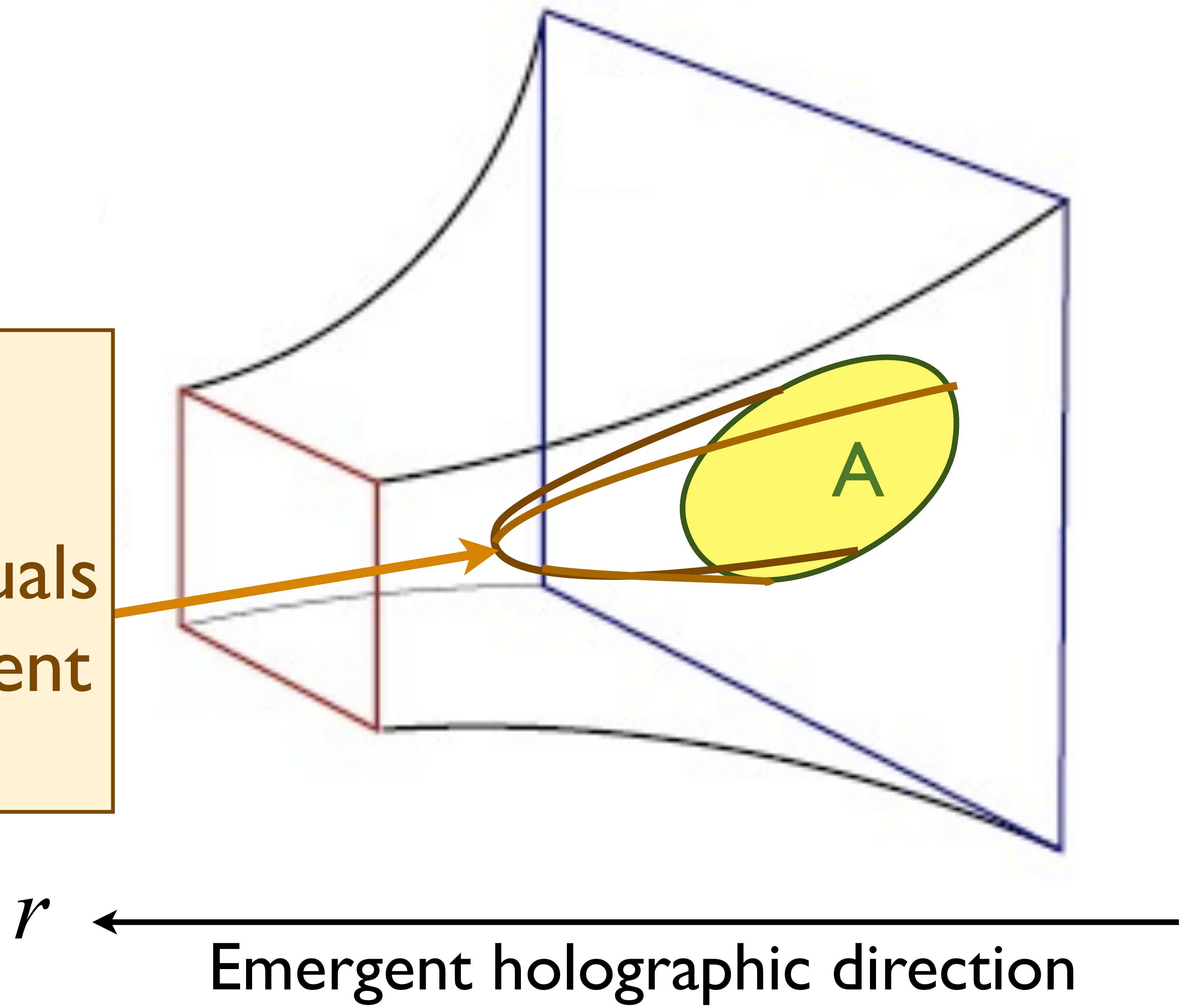
The third law of thermodynamics requires $\theta < d$.

# Holographic entanglement entropy



## Holographic entanglement entropy

**Area of minimal surface equals entanglement entropy**




S. Ryu and T. Takayanagi, Phys. Rev. Lett. 96, 18160 (2006).

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- The entanglement entropy, $S_E$, of an entangling region with boundary surface 'area' $P$ scales as

$$S_E \sim \begin{cases} P & , \quad \text{for } \theta < d-1 \\ P \ln P & , \quad \text{for } \theta = d-1 \\ P^{\theta/(d-1)} & , \quad \text{for } \theta > d-1 \end{cases}$$

  All local quantum field theories obey the "area law" (upto log violations) and so $\theta \leq d-1$.

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# Holography of non-Fermi liquids

$$ds^2 = \frac{1}{r^2}\left(-\frac{dt^2}{r^{2d(z-1)/(d-\theta)}} + r^{2\theta/(d-\theta)}dr^2 + dx_i^2\right)$$

$$\theta = d - 1$$

- The value of $\theta$ is fixed by requiring that the thermal entropy density $S \sim T^{1/z}$ for general $d$.
  Conjecture: this metric then describes a compressible state with a *hidden* Fermi surface of *quarks* coupled to gauge fields

L. Huijse, S. Sachdev, B. Swingle, Physical Review B **85**, 035121 (2012)

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- The null energy condition yields the inequality $z \geq 1 + \theta/d$. For $d = 2$ and $\theta = 1$ this yields $z \geq 3/2$. The field theory analysis gave $z = 3/2$ to three loops !

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N. Ogawa, T. Takayanagi, and T. Ugajin, arXiv:1111.1023
L. Huijse, S. Sachdev, B. Swingle, Physical Review B **85**, 035121 (2012)

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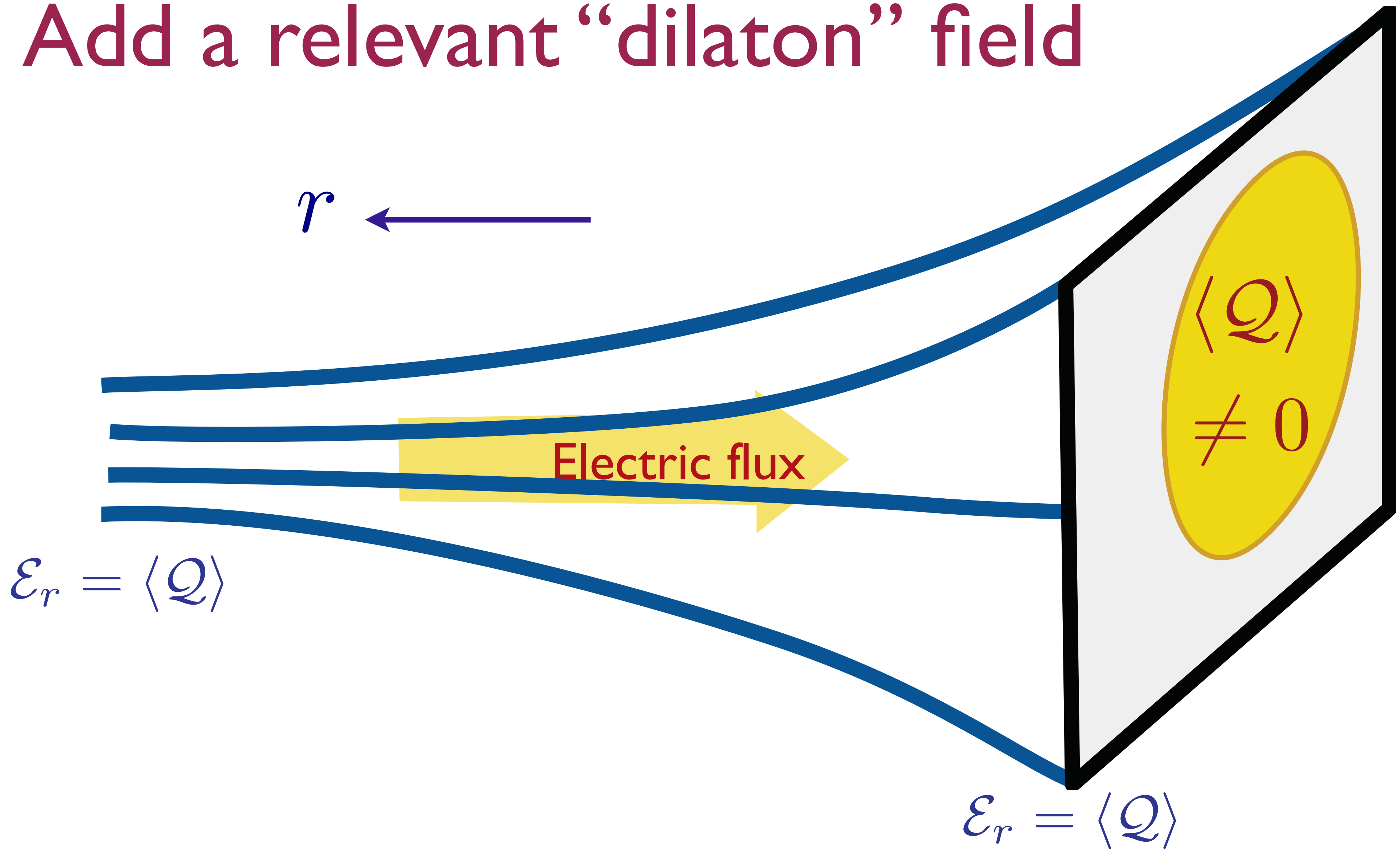
- The logarithmic violation is of the form $P \ln P$, where $P$ is the perimeter of the entangling region. This form is *independent* of the shape of the entangling region, just as is expected for a (hidden) Fermi surface !!!

L. Huijse, S. Sachdev, B. Swingle, Physical Review B **85**, 035121 (2012)

## Holographic theory of a non-Fermi liquid (NFL)

# Add a relevant "dilaton" field




$$\mathcal{S} = \int d^{d+2}x \sqrt{-g} \left[ \frac{1}{2\kappa^2} \left( R - 2(\nabla\Phi)^2 - \frac{V(\Phi)}{L^2} \right) - \frac{Z(\Phi)}{4e^2} F_{ab} F^{ab} \right]$$

with $Z(\Phi) = Z_0 e^{\alpha\Phi}$, $V(\Phi) = -V_0 e^{-\beta\Phi}$, as $\Phi \to \infty$.


C. Charmousis, B. Gouteraux, B. S. Kim, E. Kiritsis and R. Meyer, JHEP **1011**, 151 (2010).
S. S. Gubser and F. D. Rocha, Phys. Rev. D **81**, 046001 (2010).
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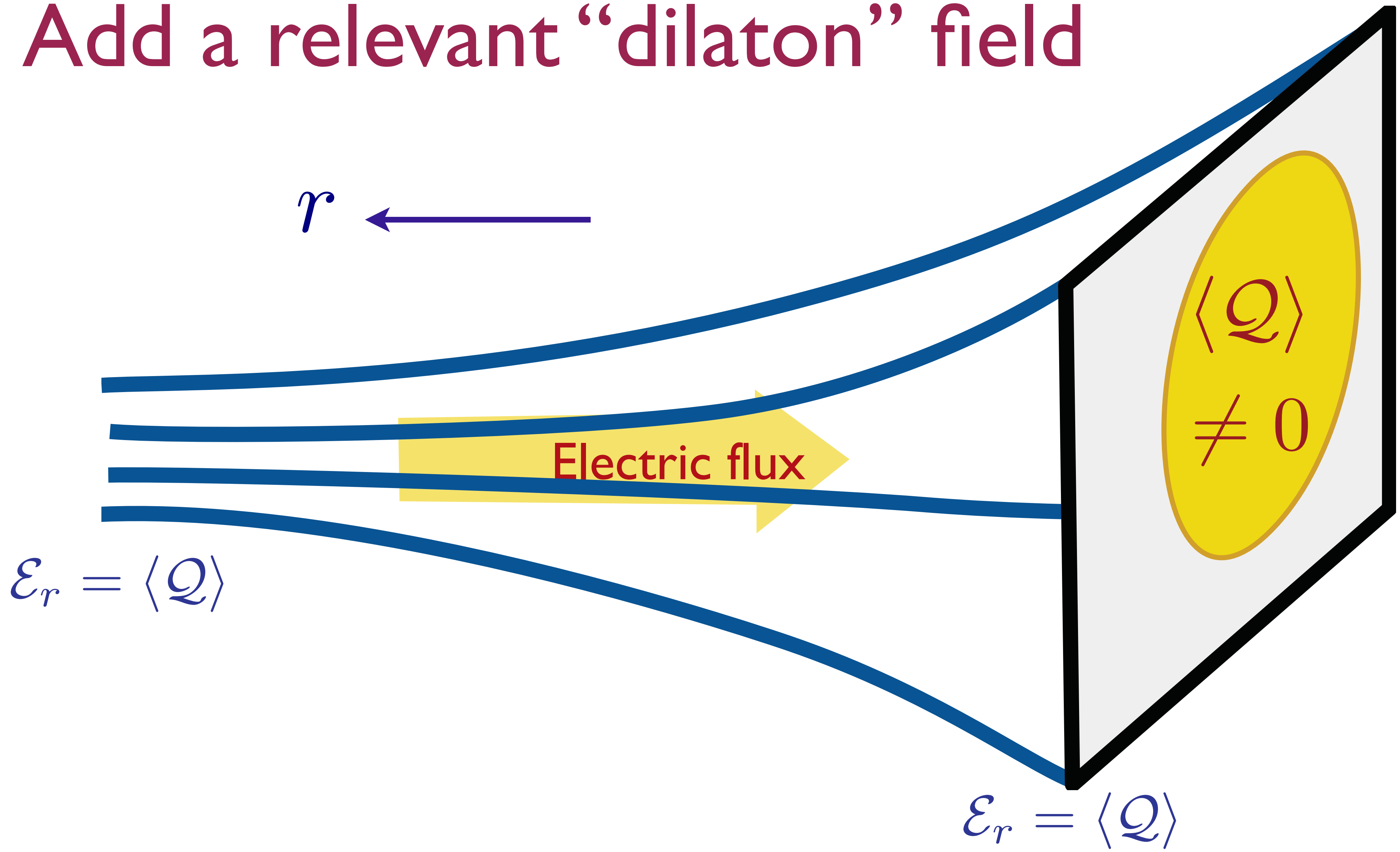


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**This is a "bosonization" of the Fermi surface**

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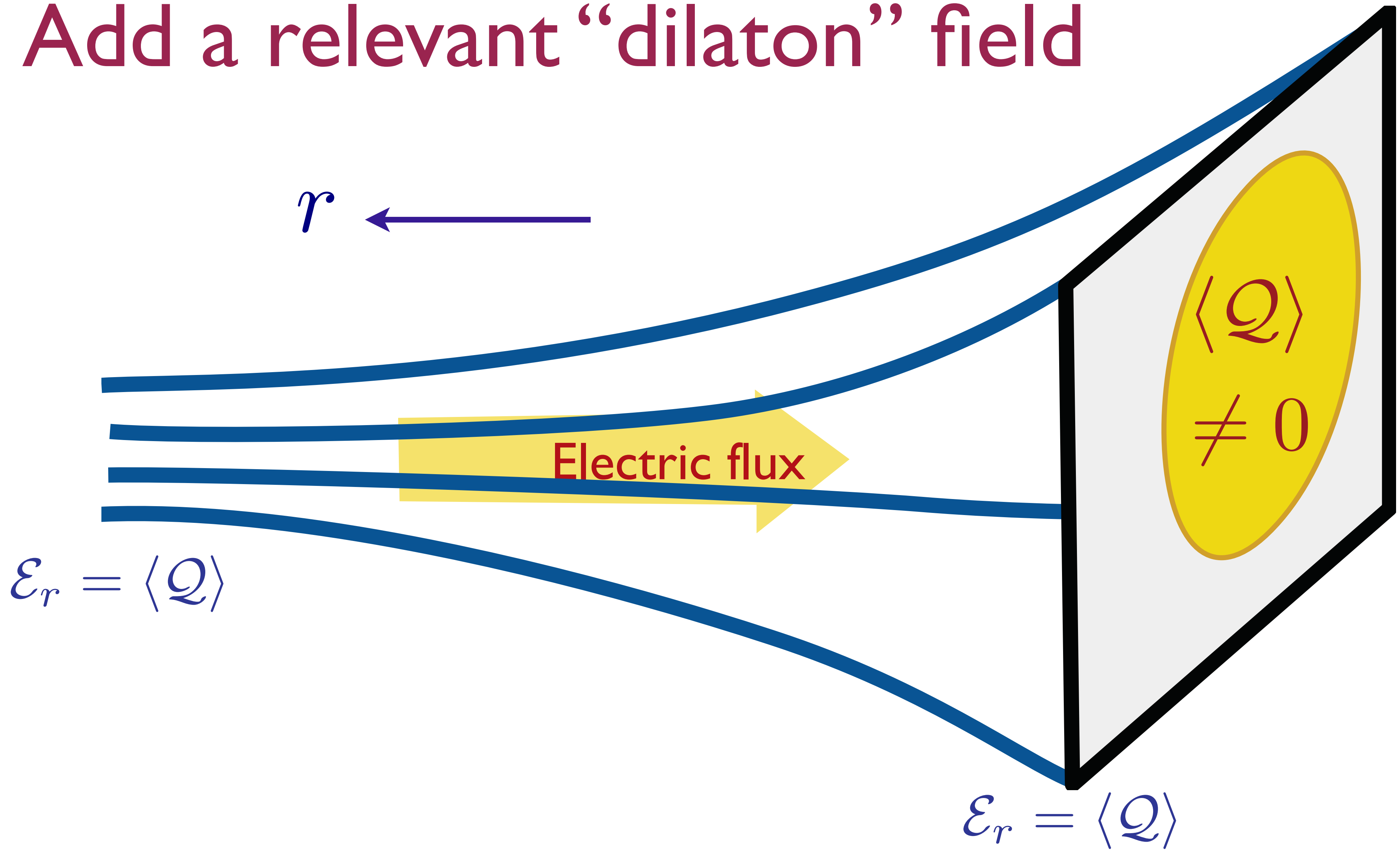


Leads to metric $ds^2 = L^2 \left( -f(r)dt^2 + g(r)dr^2 + \frac{dx^2 + dy^2}{r^2} \right)$

with $f(r) \sim r^{-\gamma}$ , $g(r) \sim r^{\delta}$, $\Phi(r) \sim \ln(r)$ as $r \to \infty$.

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- The entanglement entropy has log-violation of the area law

$$S_E = \Xi\, \mathcal{Q}^{(d-1)/d} P \ln P.$$

where $P$ is surface area of the entangling region, and $\Xi$ is a dimensionless constant which is independent of all UV details, of $\mathcal{Q}$, and of any property of the entangling region. Note $\mathcal{Q}^{(d-1)/d} \sim k_F^{d-1}$ via the Luttinger relation, and then $S_E$ is just as expected for a Fermi surface !!!!

L. Huijse, S. Sachdev, B. Swingle, Physical Review B **85**, 035121 (2012)

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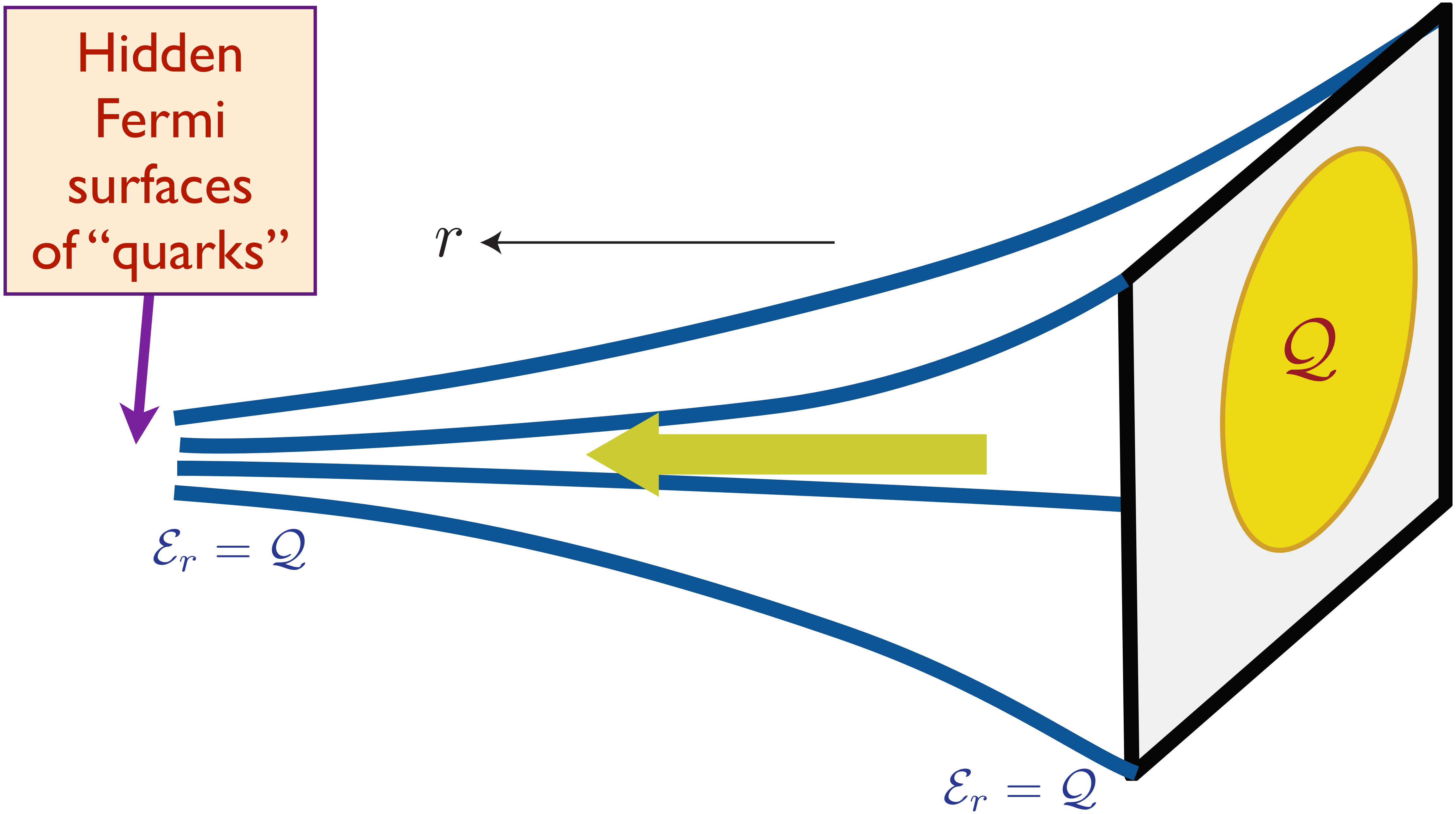
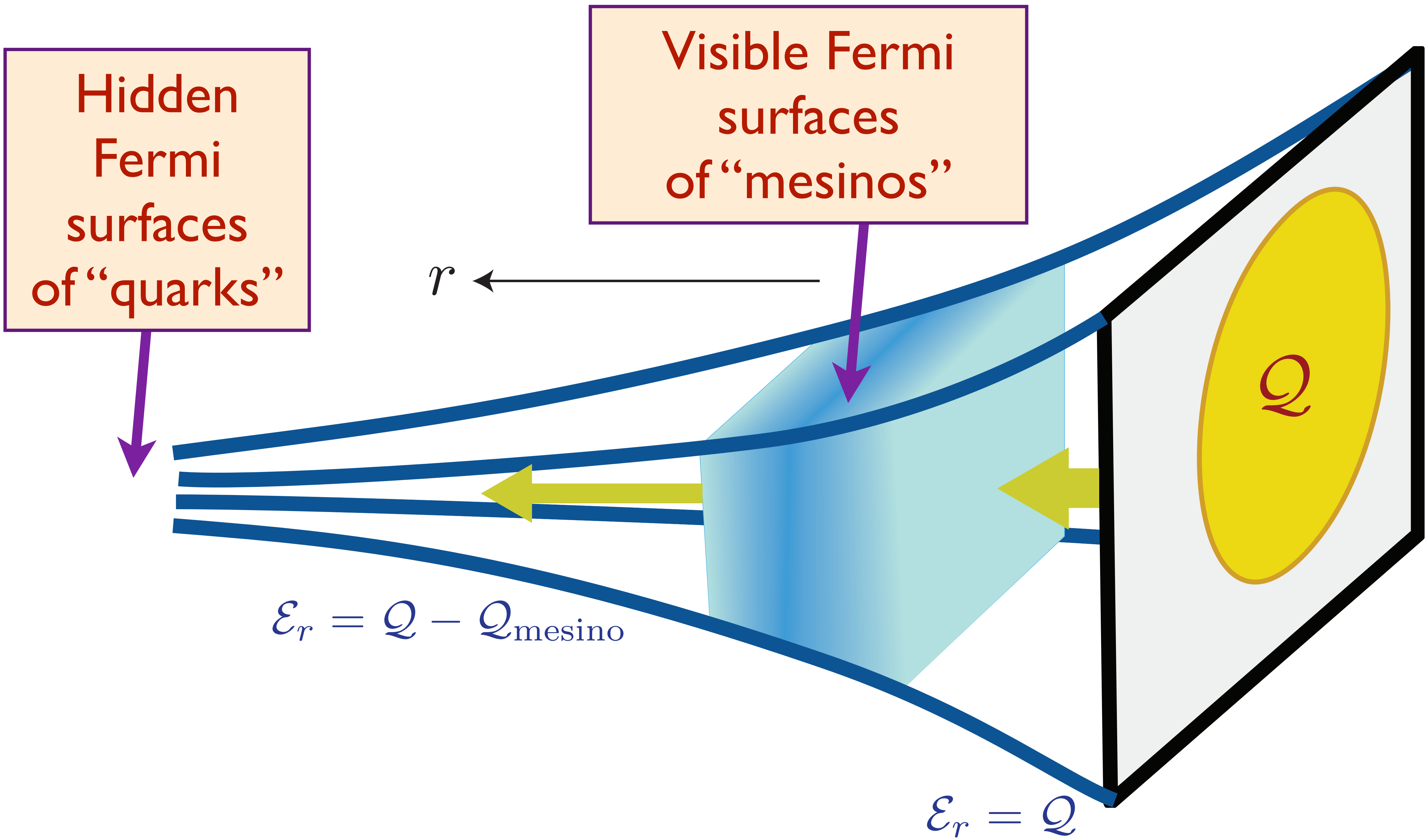



Gauss Law and the "attractor" mechanism
$\Leftrightarrow$ Luttinger theorem on the boundary

# Holographic theory of a fractionalized-Fermi liquid (FL*)




A state with *partial* confinement

S. Sachdev, *Physical Review Letters* **105**, 151602 (2010)
S. Sachdev, *Physical Review D* **84**, 066009 (2011)

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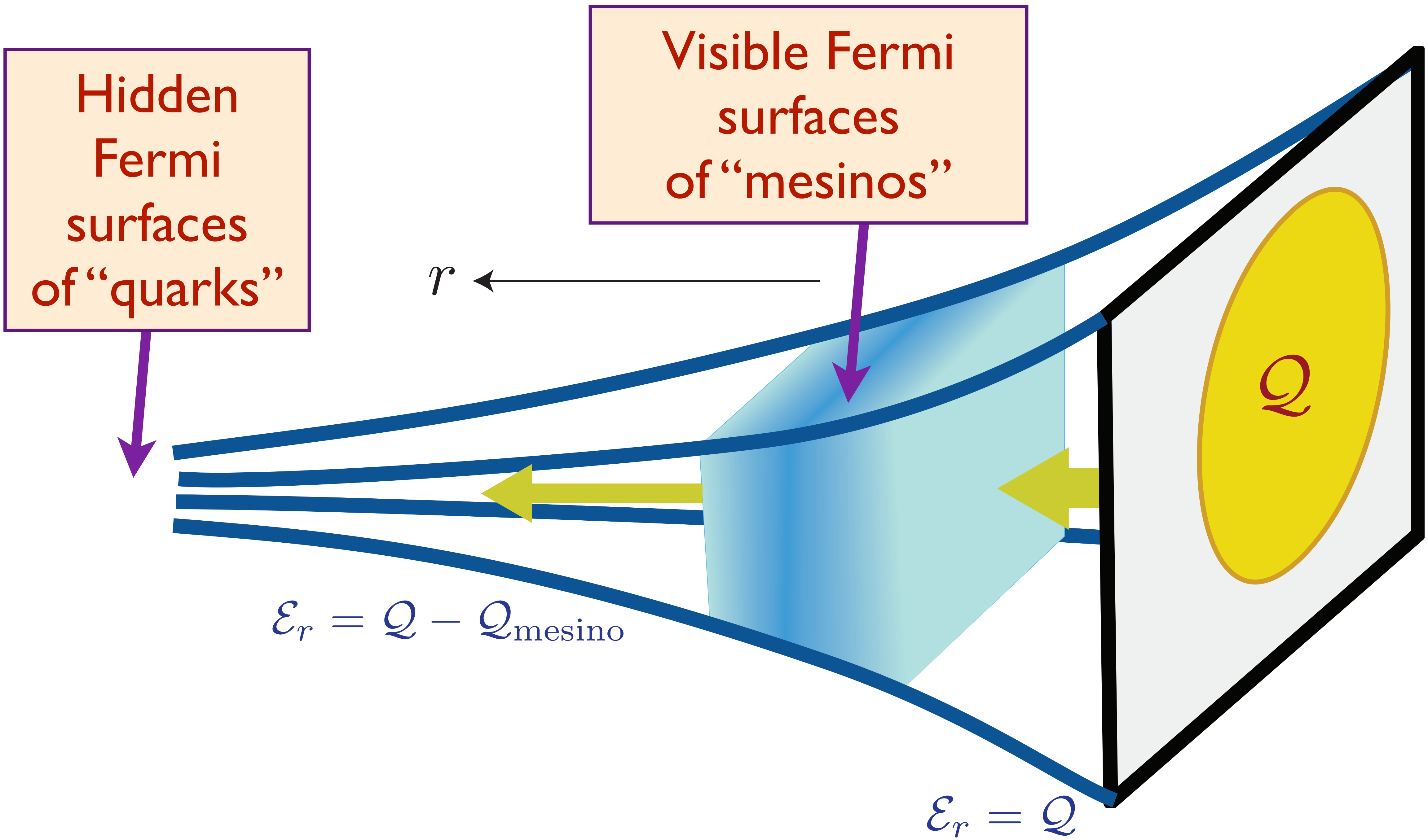
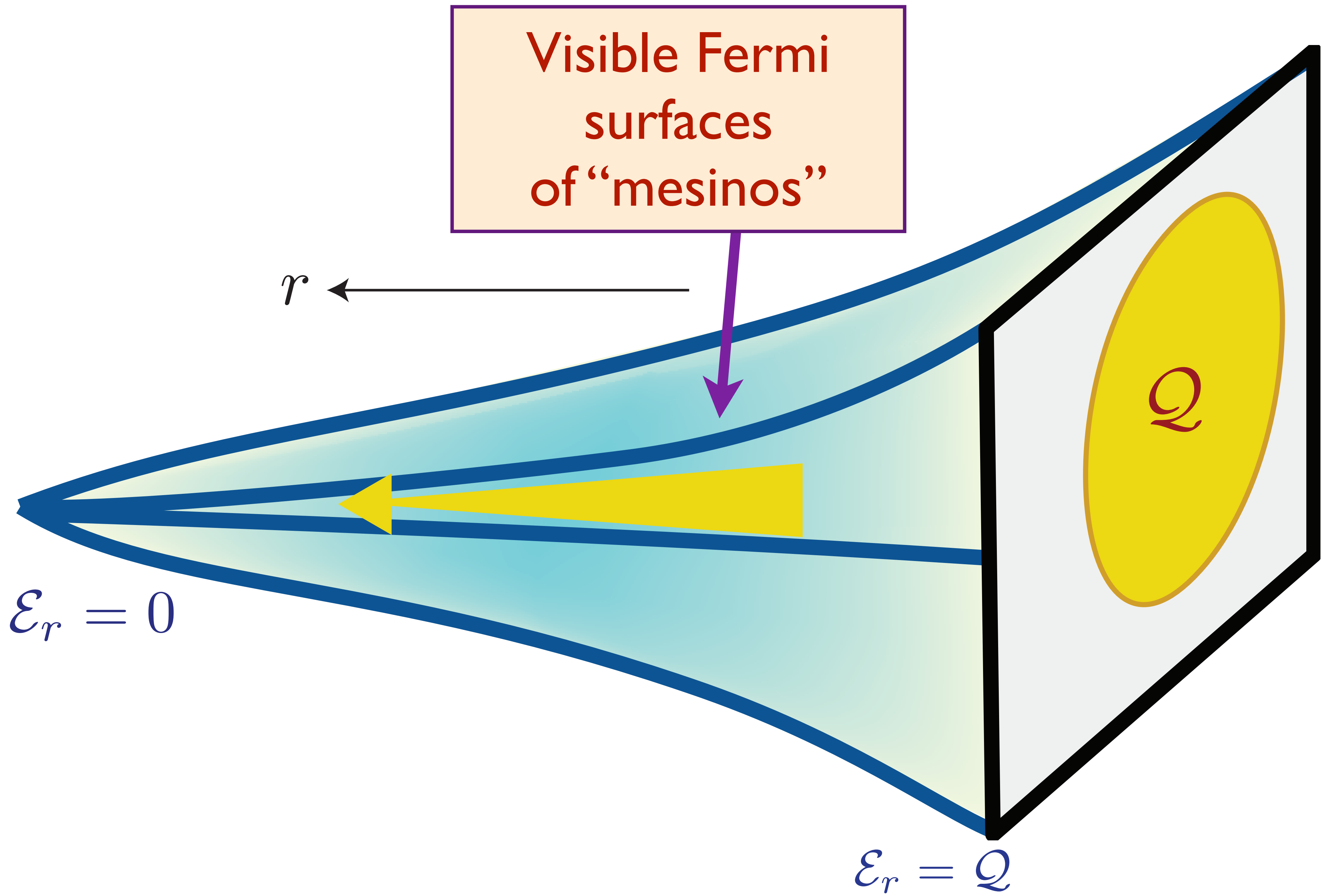



The "mesinos" corresponds to the Fermi surfaces obtained in the early probe fermion computation (S.-S. Lee, Phys. Rev. D **79**, 086006 (2009); H. Liu, J. McGreevy, and D. Vegh, arXiv:0903.2477; M. Čubrović, J. Zaanen, and K. Schalm, Science **325**, 439 (2009)).

These are spectators, and are expected to have well-defined quasiparticle excitations.

# Holographic theory of a Fermi liquid (FL)




- Confining geometry leads to a state which has all the properties of a Landau Fermi liquid.

S. Sachdev, Physical Review D **84**, 066009 (2011)

## Conclusions

# Compressible quantum matter

- Evidence for *hidden Fermi surfaces* in compressible states obtained for a class of holographic Einstein-Maxwell-dilaton theories. These theories describe a *non-Fermi liquid* (NFL) state of gauge theories at non-zero density.

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- Hidden Fermi surfaces can co-exist with Fermi surfaces of mesinos, leading to a state with *partial confinement*: the fractionalized Fermi liquid (FL*)