Entanglement, holography, and strange metals

Quantum Criticality and Novel Phases,
Dresden
August 27, 2012

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Liza Huijse

Max Metlitski

Brian Swingle

Breakup of Heavy Fermions on the Brink of “Phase *A*” in $CeCu_2Si_2$

P. Gegenwart, C. Langhammer, C. Geibel, R. Helfrich, M. Lang, G. Sparn, F. Steglich, R. Horn, L. Donnevert, A. Link, and W. Assmus

Phys. Rev. Lett. **81**, 1501 – Published 17 August 1998

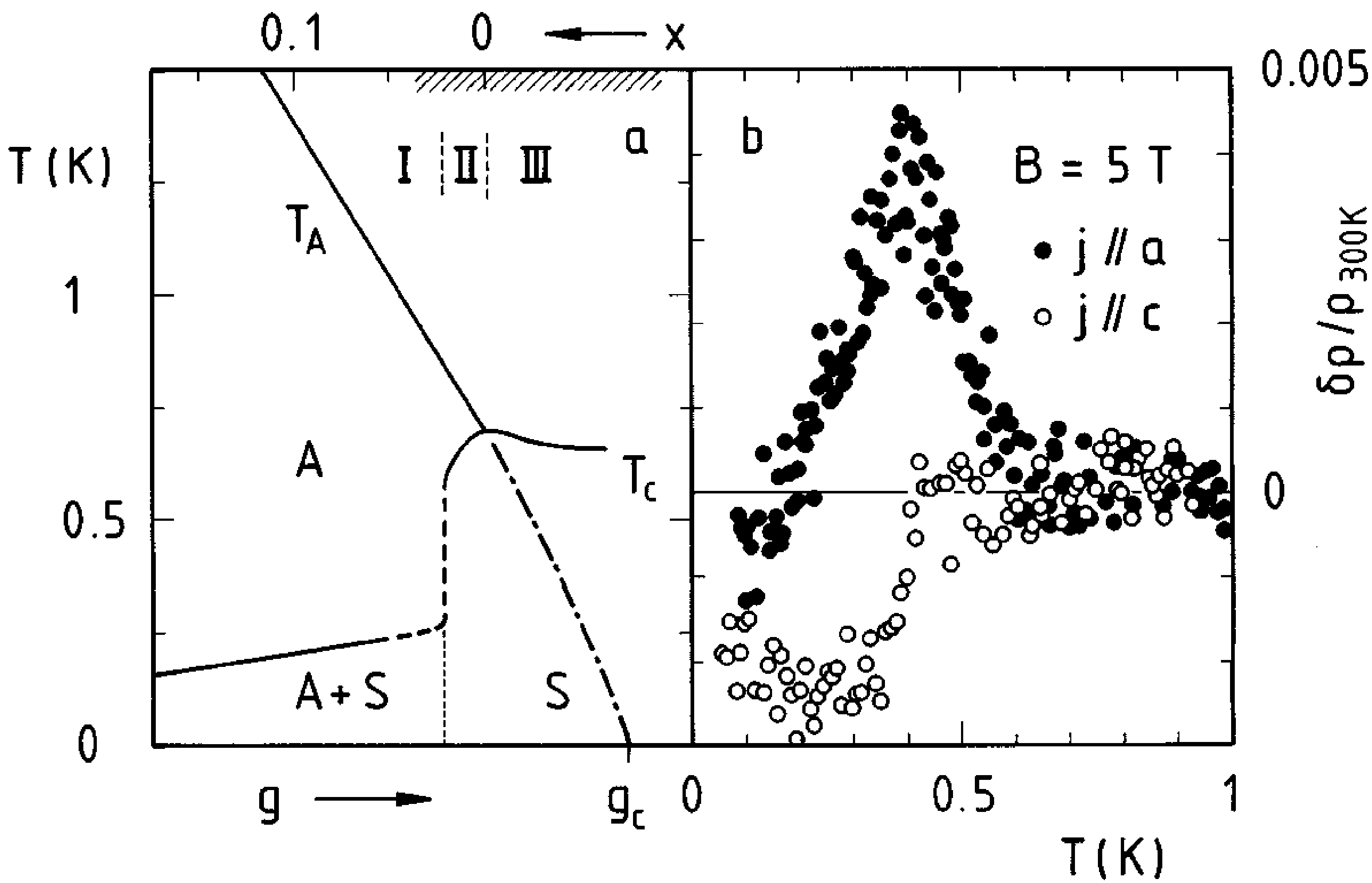
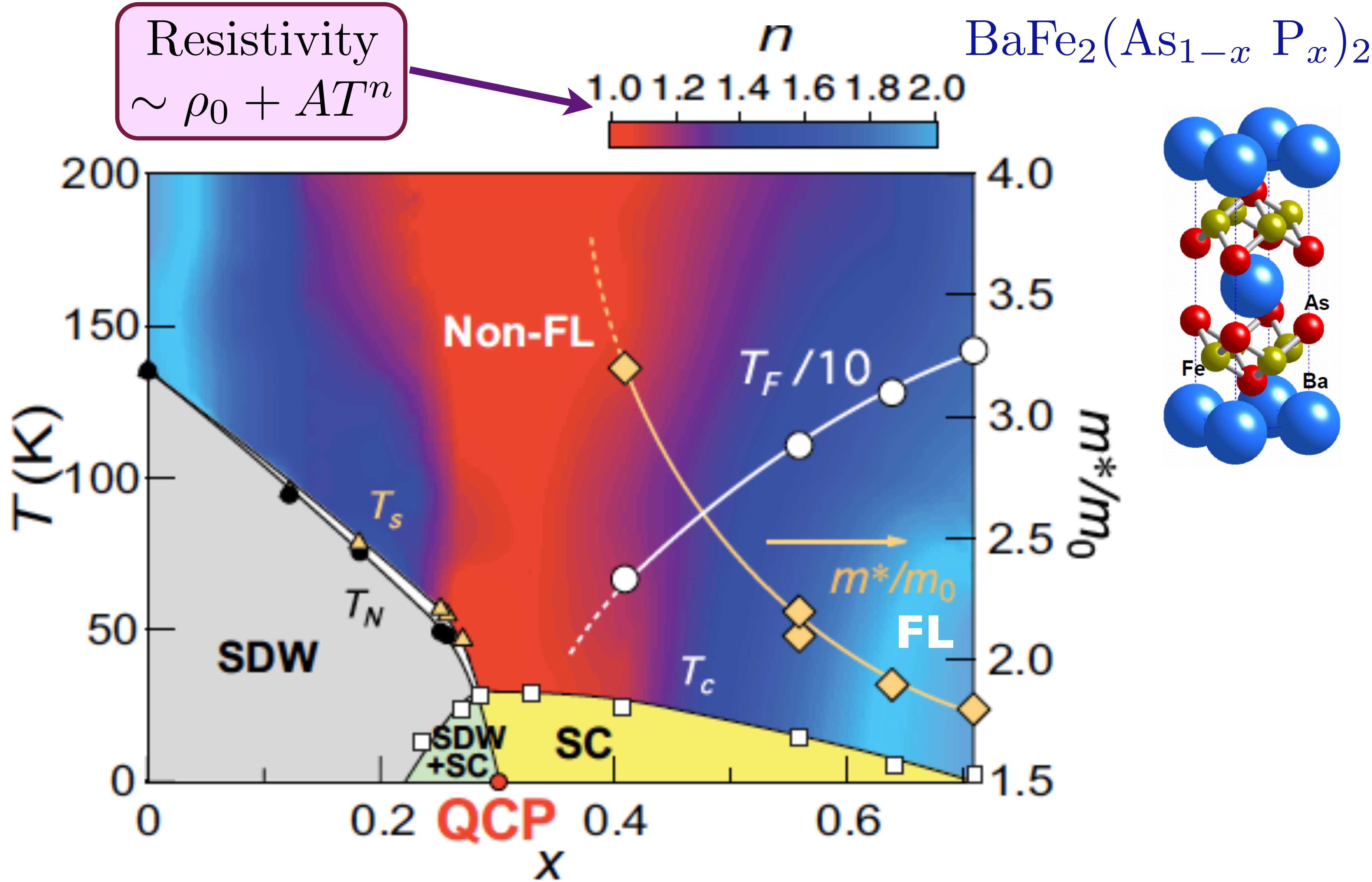


FIG. 1. (a) Schematic phase diagram for $CeCu_2Si_2$ at zero field, indicating existence ranges for phase *A*, superconductivity (*S*), and coexistence range (*A* + *S*). For samples labeled



K. Hashimoto, K. Cho, T. Shibauchi, S. Kasahara, Y. Mizukami, R. Katsumata, Y. Tsuruhara, T. Terashima, H. Ikeda, M. A. Tanatar, H. Kitano, N. Salovich, R. W. Giannetta, P. Walmsley, A. Carrington, R. Prozorov, and Y. Matsuda, *Science* **336**, 1554 (2012).

“Complex entangled” states of quantum matter, *not* adiabatically connected to independent particle states

Gapped quantum matter

Spin liquids, quantum Hall states

Conformal quantum matter

Quantum critical points in antiferromagnets, superconductors, and ultracold atoms; graphene

Compressible quantum matter

Non-Fermi liquids, strange metals, Bose metals

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?

Compressible quantum matter

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

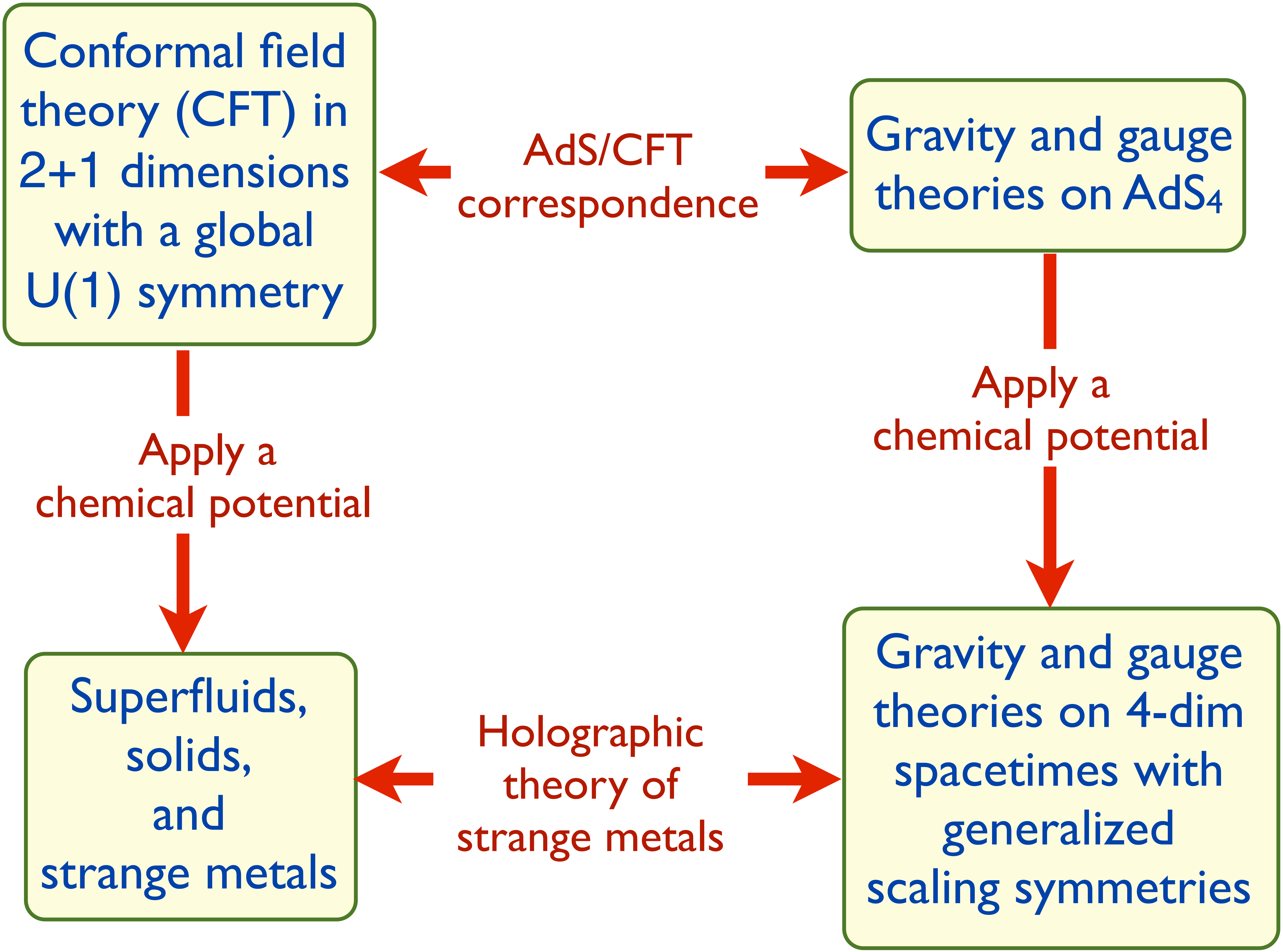
- Describe *zero temperature* phases where $d\langle\mathcal{Q}\rangle/d\mu \neq 0$, where μ (the "chemical potential") which changes the Hamiltonian, H, to $H - \mu\mathcal{Q}$.

The only compressible phase of traditional condensed matter physics which does not break the translational or $\mathrm{U}(1)$ symmetries is the Landau Fermi liquid

Our strategy here will be to start from conformal field theories, with a Hamiltonian $\mathcal{H}_{\text{CFT}}$ and a globally conserved U(1) charge $\mathcal{Q}$, which are (reasonably) well understood examples of quantum states without quasiparticle excitations.

Then we will "dope" them by applying a chemical potential, μ and classify compressible states of $\mathcal{H}_{\text{CFT}} - \mu\mathcal{Q}$.

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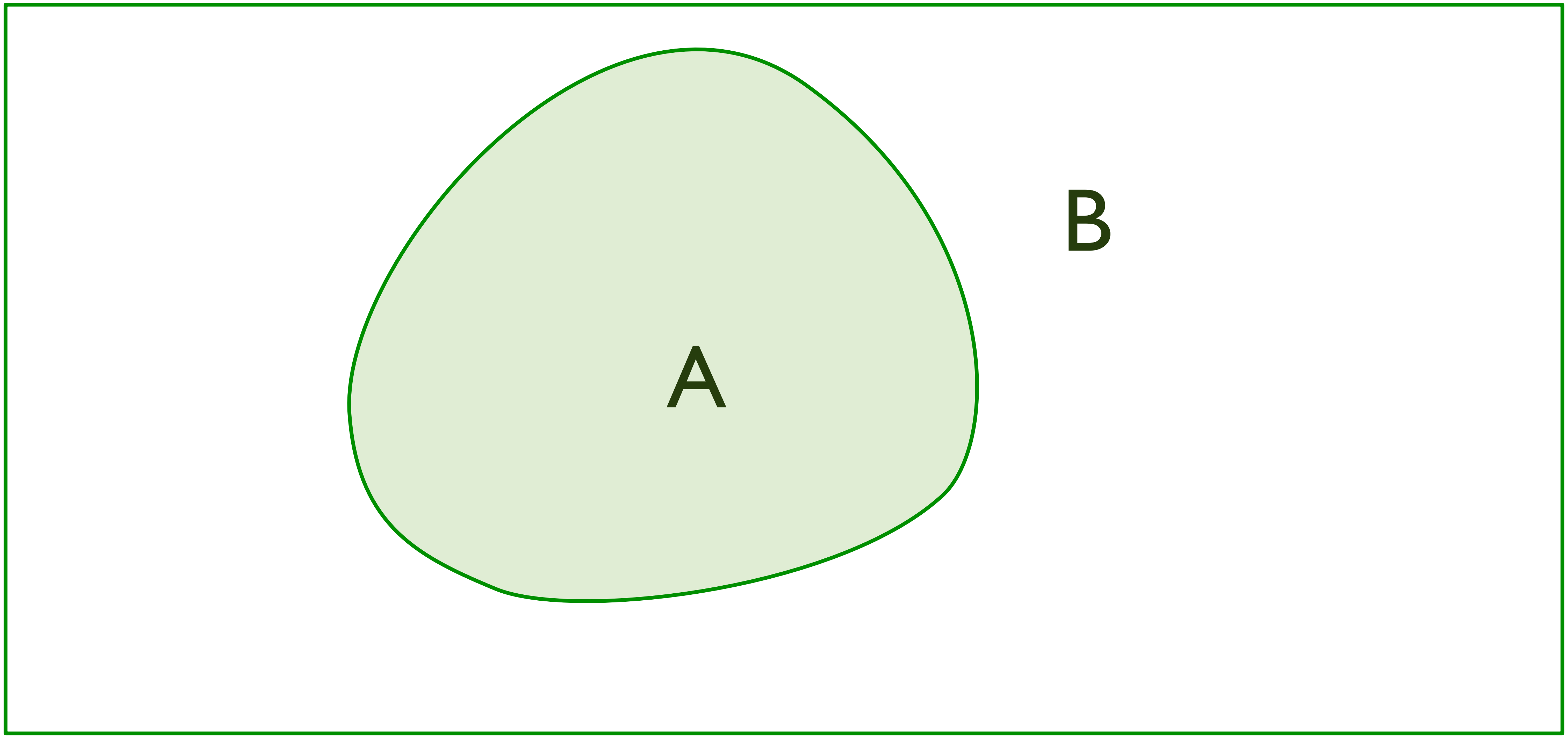
Entanglement entropy



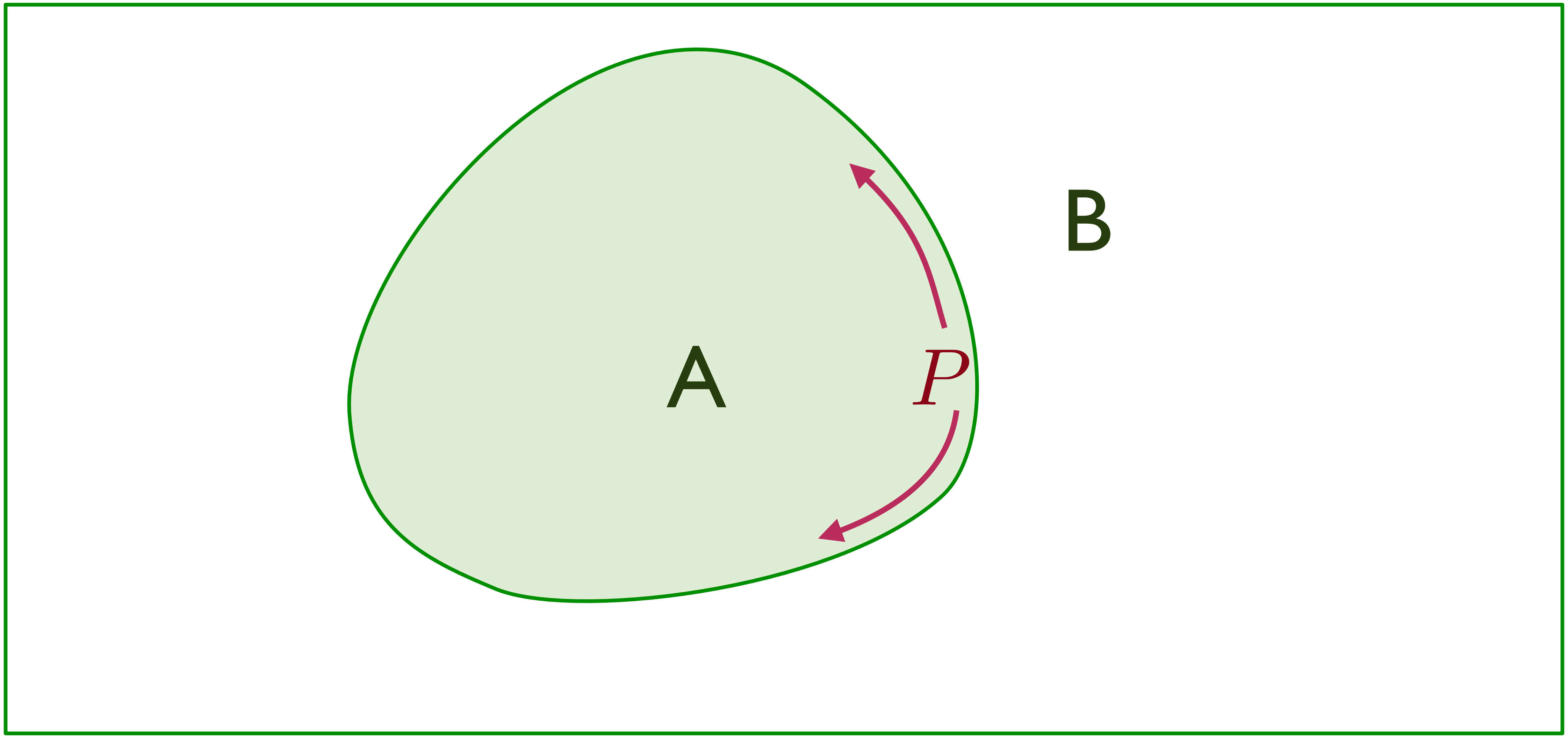
$$|\Psi\rangle \quad \Rightarrow \quad \text{Ground state of entire system,}$$
$$\rho = |\Psi\rangle\langle\Psi|$$

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

$$\textbf{Entanglement entropy } S_E = -\mathrm{Tr}\left(\rho_A \ln \rho_A\right)$$

M. Srednicki, Phys. Rev. Lett. **71**, 666 (1993)

Entanglement entropy of a band insulator

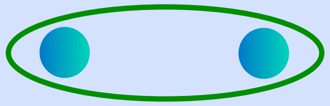


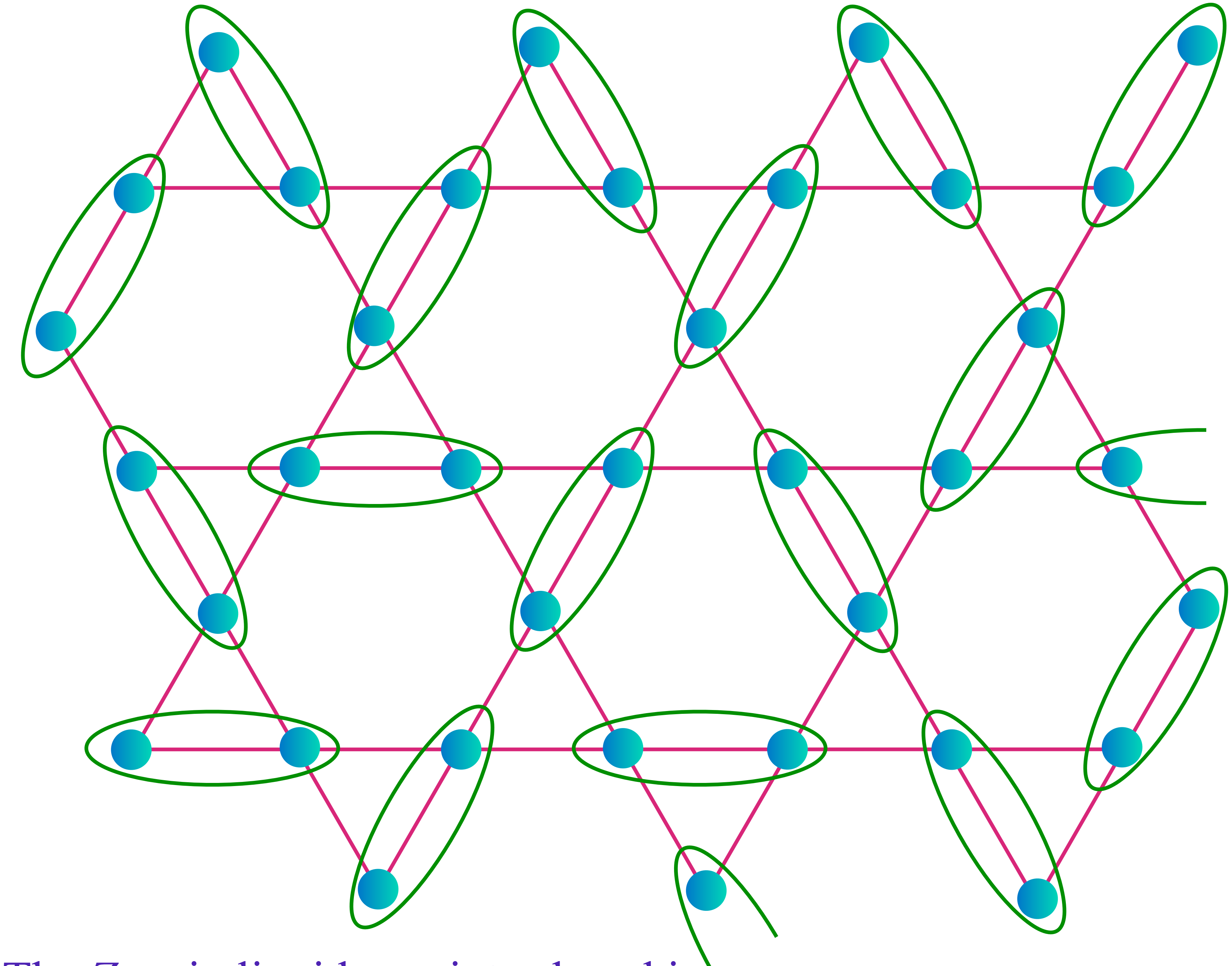
$$S_E = aP - b\exp(-cP)$$

where P is the surface area (perimeter) of the boundary between A and B.

Mott insulator: the Z_2 spin liquid

$$H = J \sum_{\langle ij \rangle} \vec{S}_i \cdot \vec{S}_j$$

 $= \frac{1}{\sqrt{2}} \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \right)$

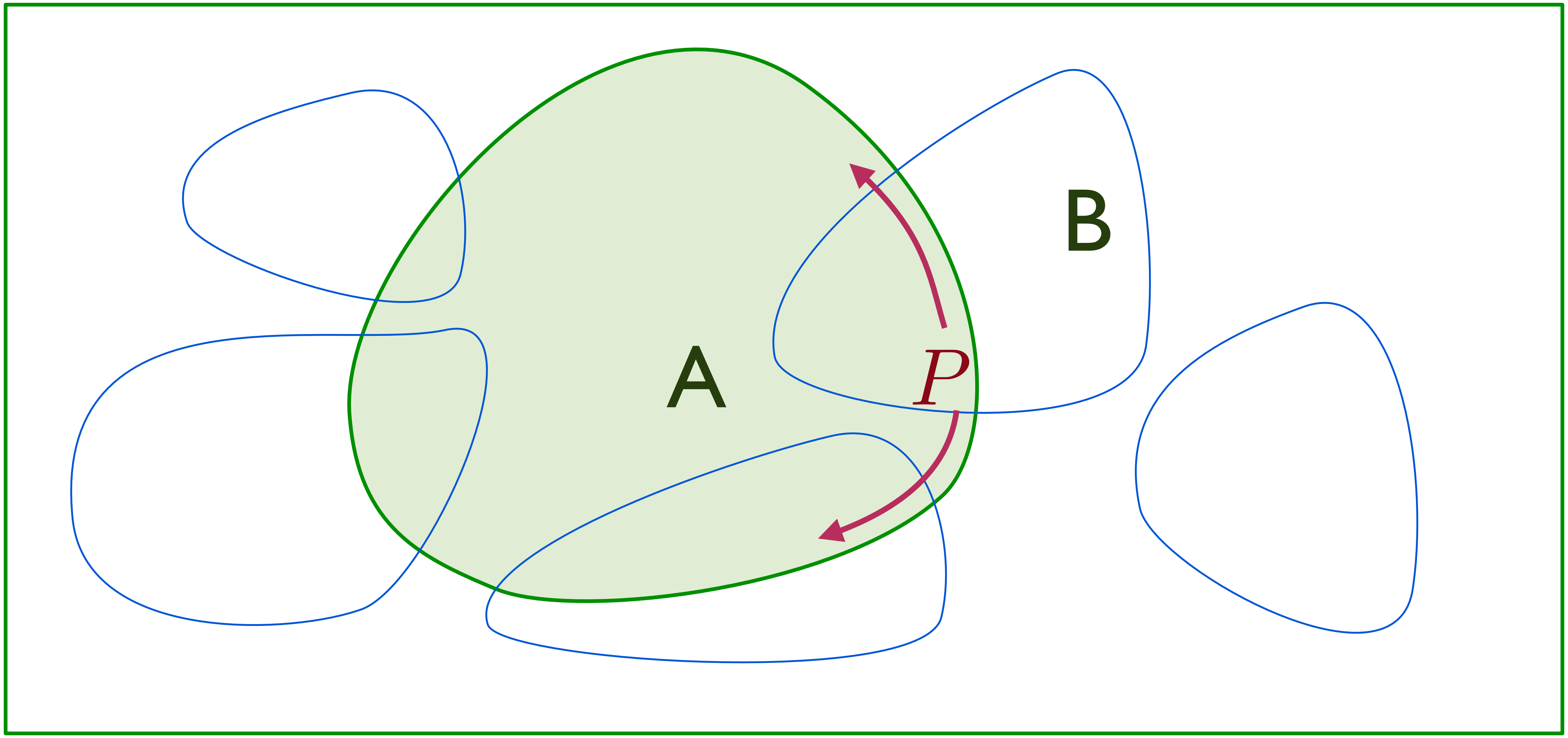


P. Fazekas and P. W. Anderson, *Philos. Mag.* **30**, 23 (1974).

S. Sachdev, *Phys. Rev. B* **45**, 12377 (1992)

The Z_2 spin liquid was introduced in
N. Read and S. Sachdev, *Phys. Rev. Lett*. **66**, 1773 (1991),
X.-G. Wen, *Phys. Rev. B* **44**, 2664 (1991)

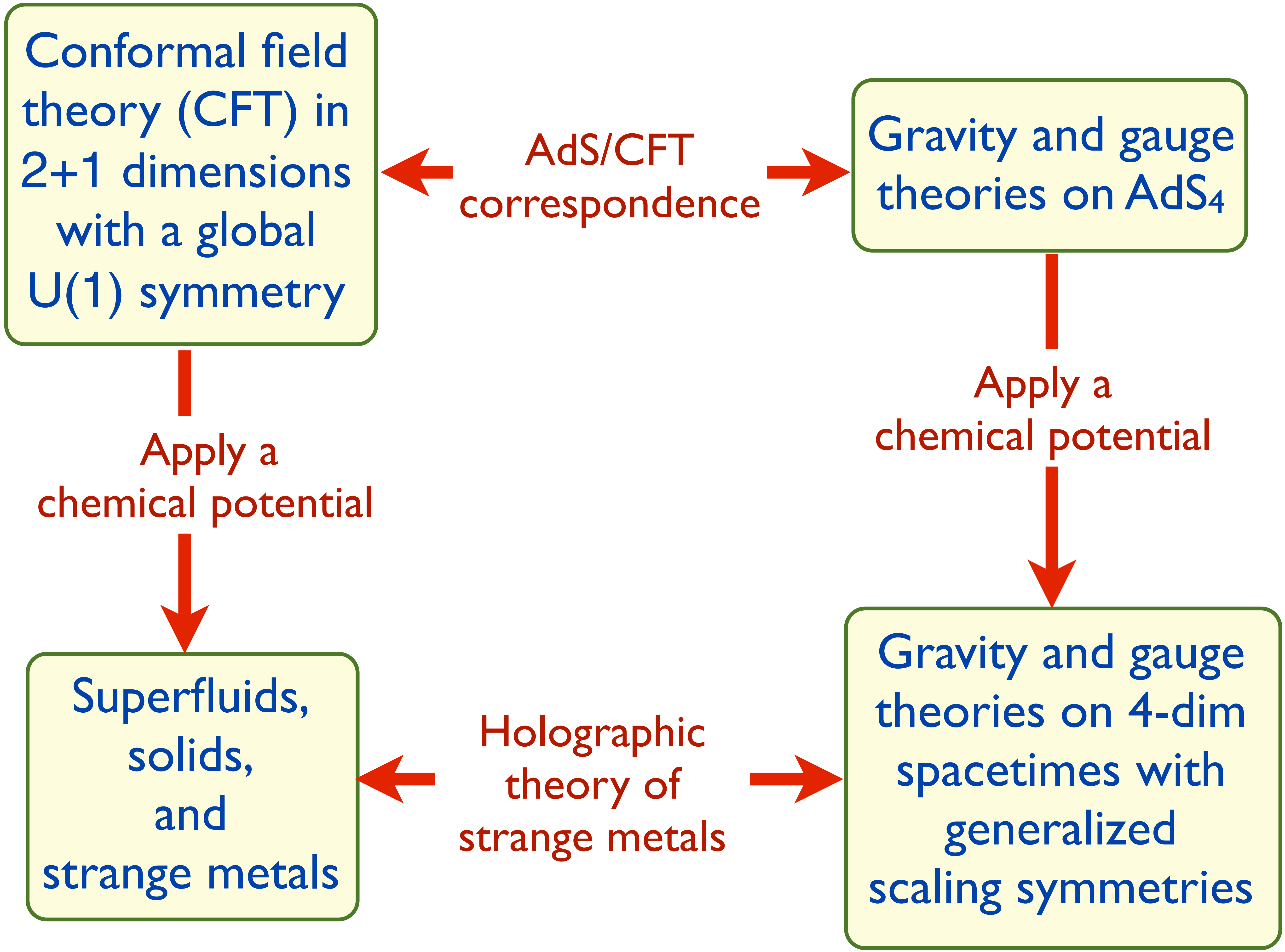
Entanglement in the Z_2 spin liquid



$$S_E = aP - \ln(2)$$

where P is the surface area (perimeter) of the boundary between A and B.

A. Hamma, R. Ionicioiu, and P. Zanardi, Phys. Rev. A **71**, 022315 (2005)
M. Levin and X.-G. Wen, Phys. Rev. Lett. **96**, 110405 (2006); A. Kitaev and J. Preskill, Phys. Rev. Lett. **96**, 110404 (2006)
Y. Zhang, T. Grover, and A. Vishwanath, Phys. Rev. B **84**, 075128 (2011)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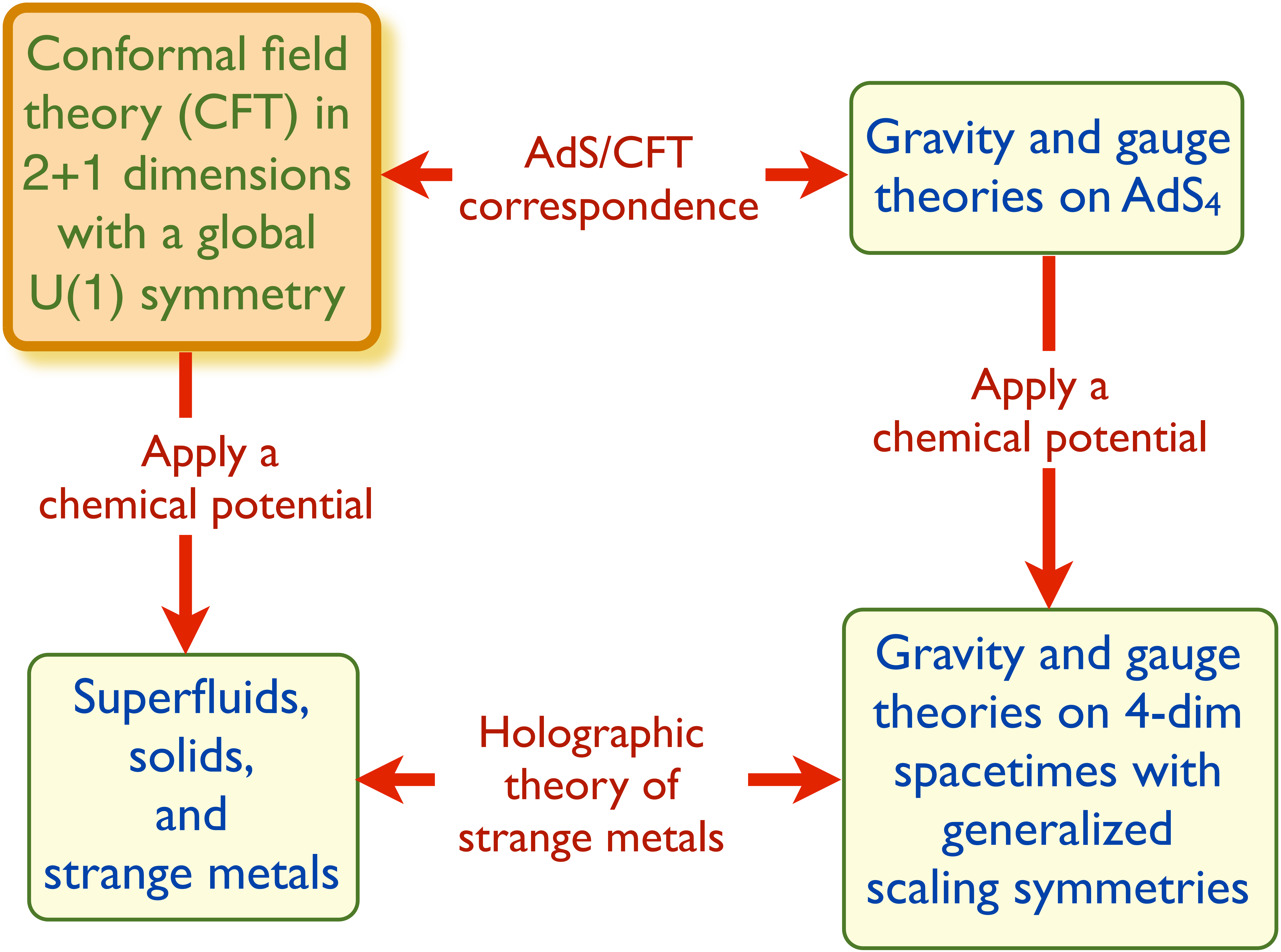
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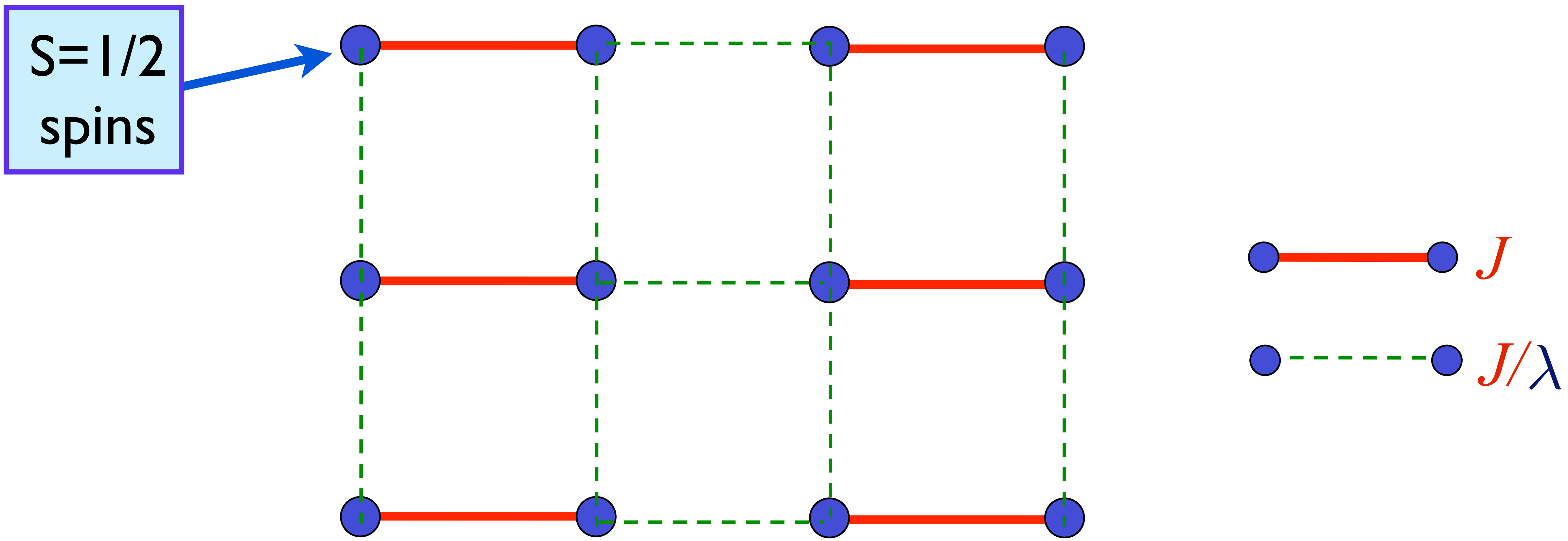
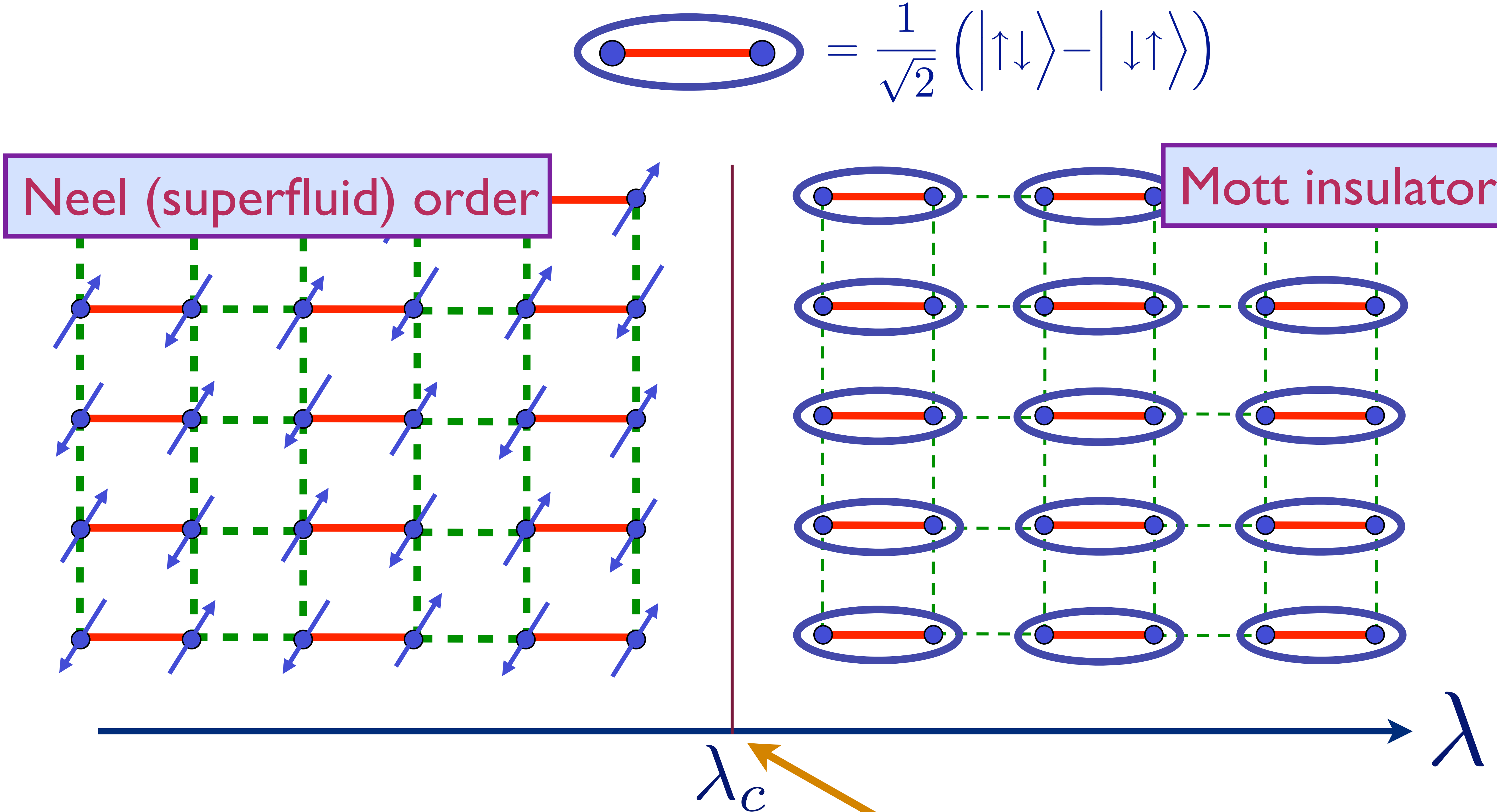
Coupled dimer XY antiferromagnet (hard core Bose gas)

$$\mathcal{H} = \sum_{\langle ij \rangle} J_{ij} (S_{xi} S_{xj} + S_{yi} S_{yj}) = \sum_{\langle ij \rangle} J_{ij} (b_i^\dagger b_j + \text{H.c.})$$

$$\text{U(1) conserved charge} \quad : \qquad \mathcal{Q} = \sum_i b_i^\dagger b_i$$



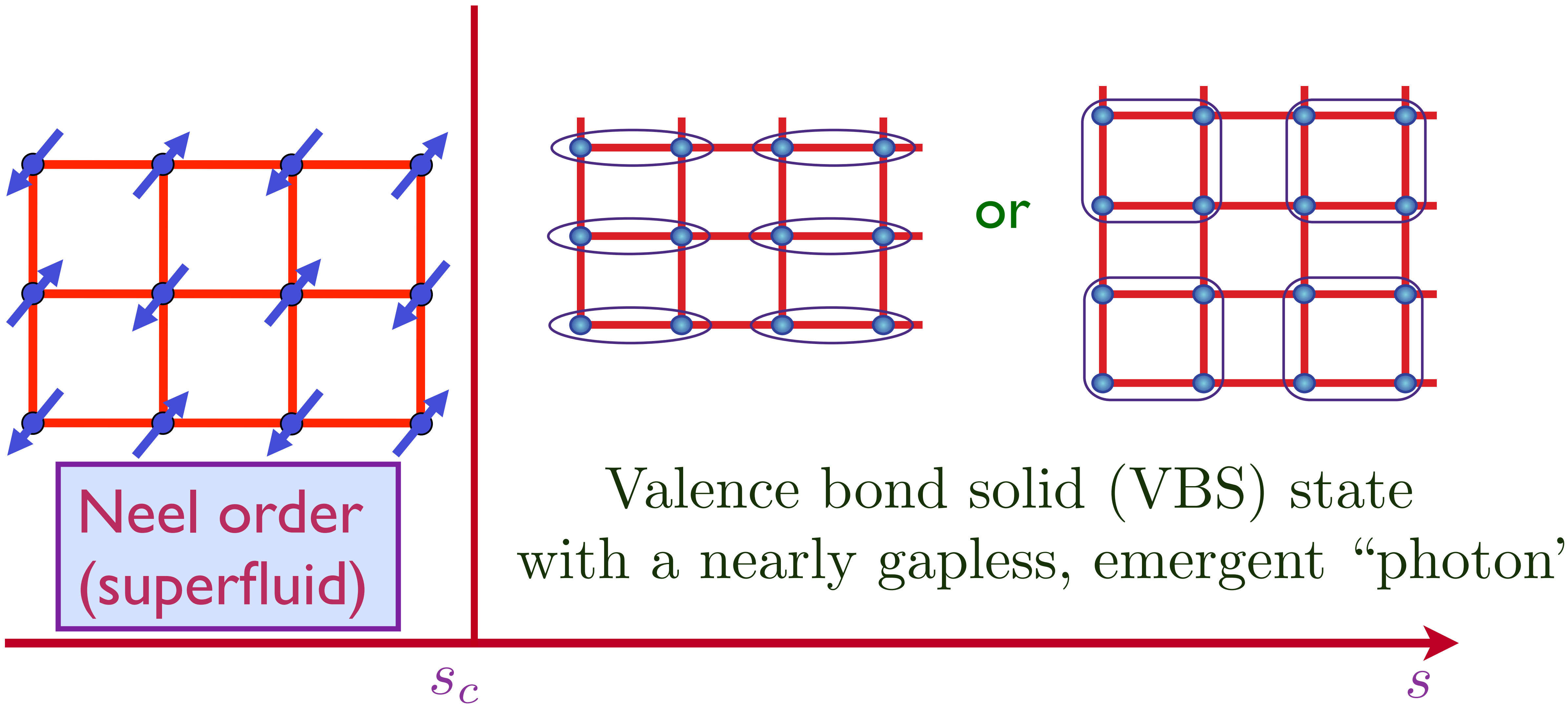
Examine ground state as a function of λ



Quantum critical point described by a CFT3 (O(2) Wilson-Fisher)

S. Chakravarty, B.I. Halperin, and D.R. Nelson, Phys. Rev. Lett. **60**, 1057 (1988).
N. Read and S. Sachdev, Phys. Rev. Lett. **62**, 1694 (1989).
A. W. Sandvik and D. J. Scalapino, Phys. Rev. Lett. **72**, 2777 (1994).

Quantum critical point in a frustrated square lattice XY antiferromagnet



$$\mathcal{H} = \sum_{\langle ij \rangle} J(S_{xi}S_{xj} + S_{yi}S_{yj}) + \ldots \quad = \quad \sum_{\langle ij \rangle} J(b_i^\dagger b_j + \text{H.c.})$$

$$+ \text{ ring exchange terms.}$$

$$\text{U(1) conserved charge} \quad : \quad \mathcal{Q} = \sum_i b_i^\dagger b_i$$

O.I. Motrunich and A. Vishwanath, *Phys. Rev. B* **70**, 075104 (2004).
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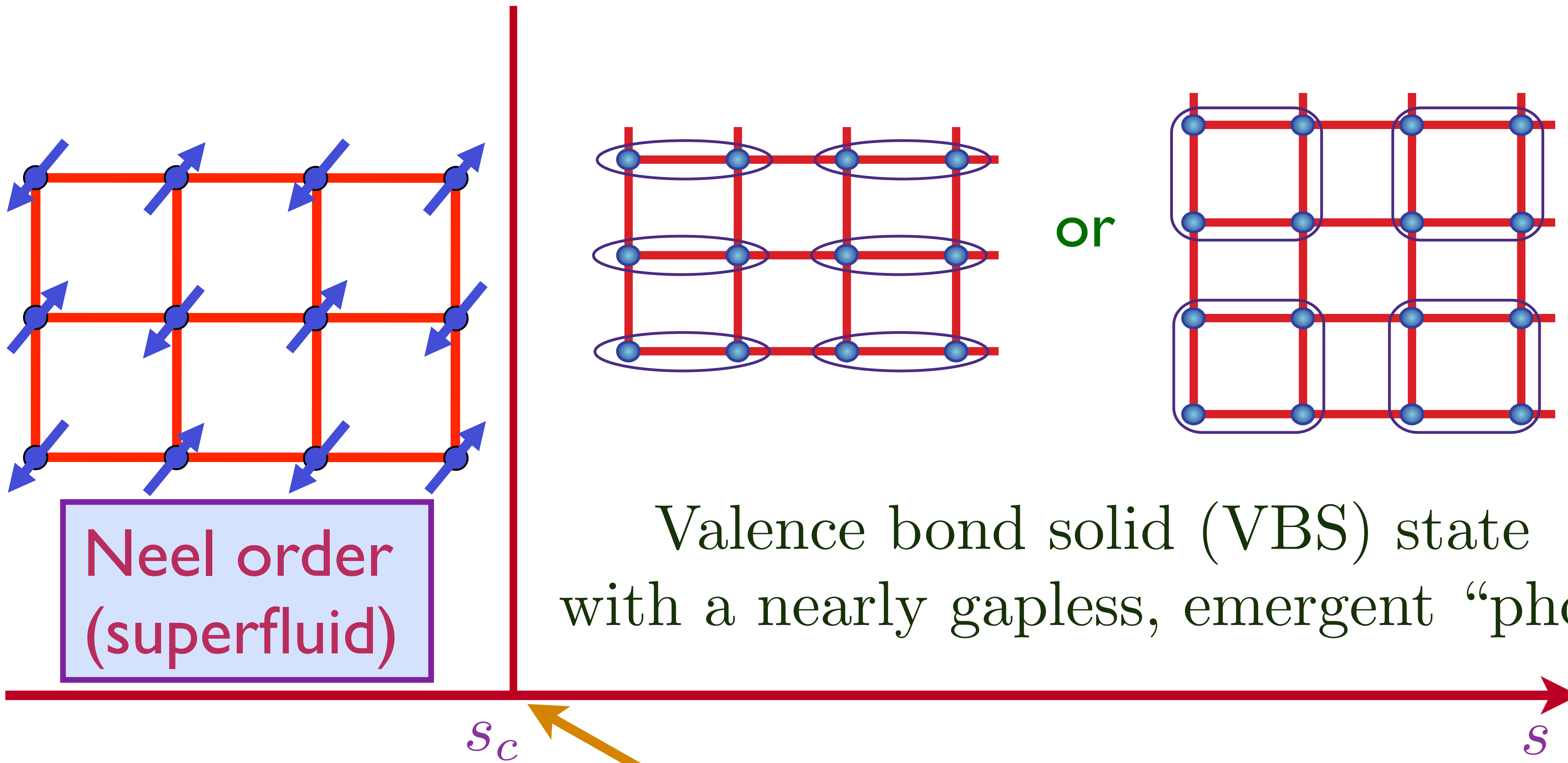


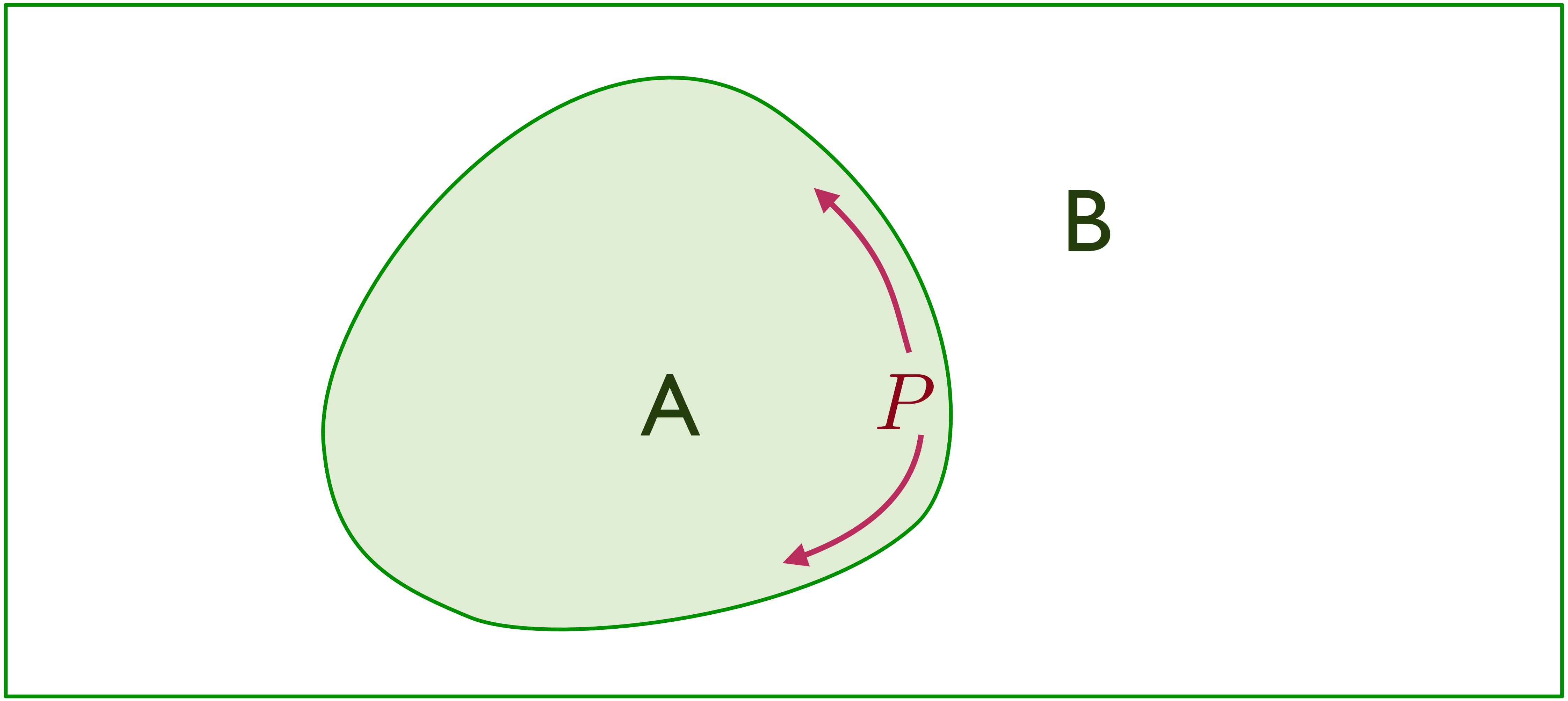
CFT3 of spinons $(z_\uparrow, z_\downarrow)$, with $b_i = (-1)^i z^*_{i\uparrow} z_{j\downarrow}$,
coupled to an emergent photon (A_μ)

$$\mathcal{S}_z = \int d^2 r d\tau \left[|(\partial_\mu - i A_\mu) z_\alpha|^2 + s|z_\alpha|^2 + u(|z_\alpha|^2)^2 + \frac{1}{2e_0^2}(\epsilon_{\mu\nu\lambda}\partial_\nu A_\lambda)^2 \right]$$

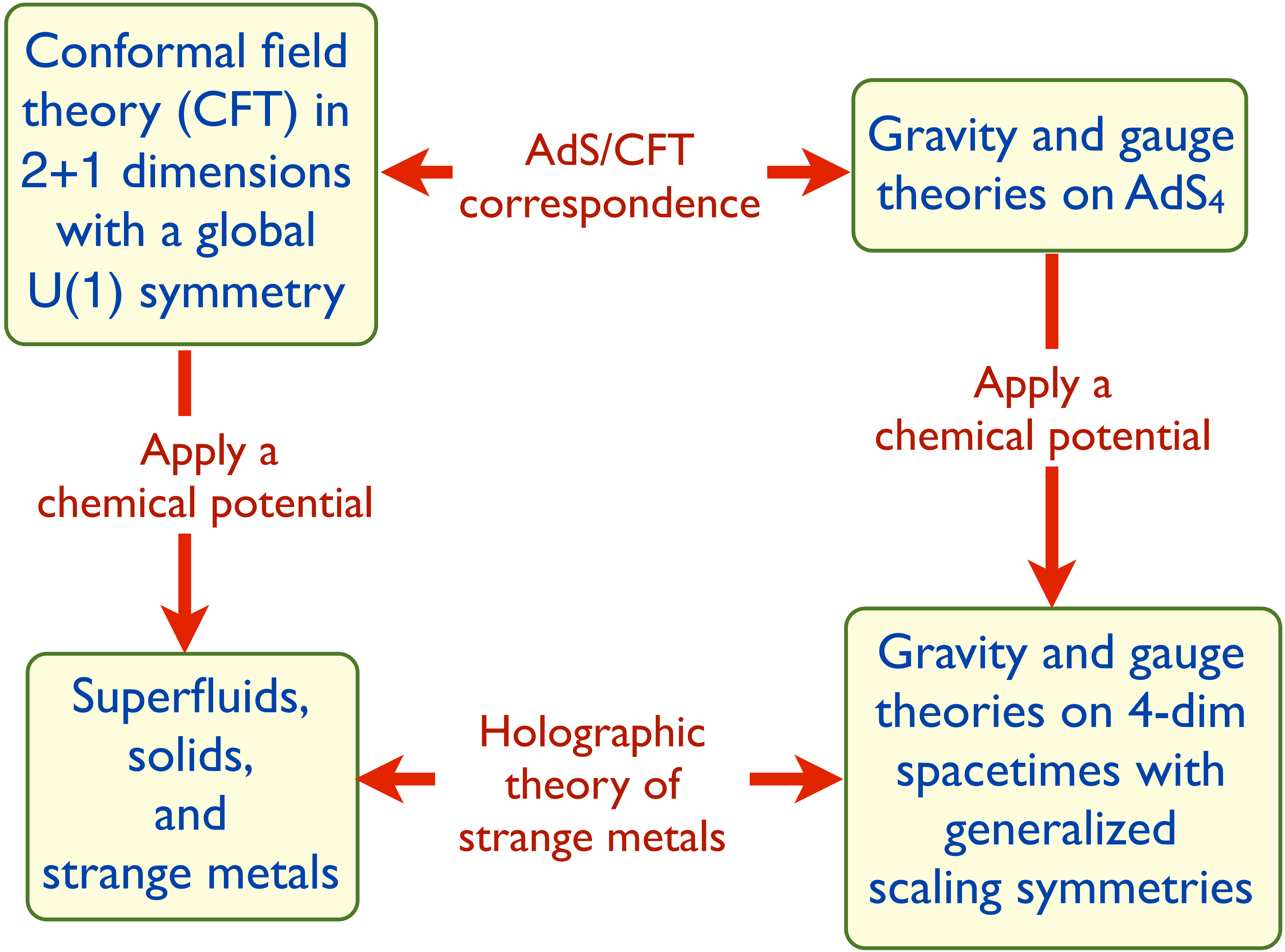
O.I. Motrunich and A. Vishwanath, *Phys. Rev. B* **70**, 075104 (2004).
T. Senthil, A. Vishwanath, L. Balents, S. Sachdev and M.P.A. Fisher, *Science* **303**, 1490 (2004).

Entanglement at the quantum critical point

- Entanglement entropy obeys $S_E = aP - \gamma$, where γ is a shape-dependent universal number associated with the CFT3.



M.A. Metlitski, C.A. Fuertes, and S. Sachdev, Phys. Rev. B 80, 115122 (2009)
B. Hsu, M. Mulligan, E. Fradkin, and Eun-Ah Kim, Phys. Rev. B 79, 115421 (2009)
H. Casini, M. Huerta, and R. Myers, JHEP 1105:036, (2011)
I. Klebanov, S. Pufu, and B. Safdi, arXiv:1105.4598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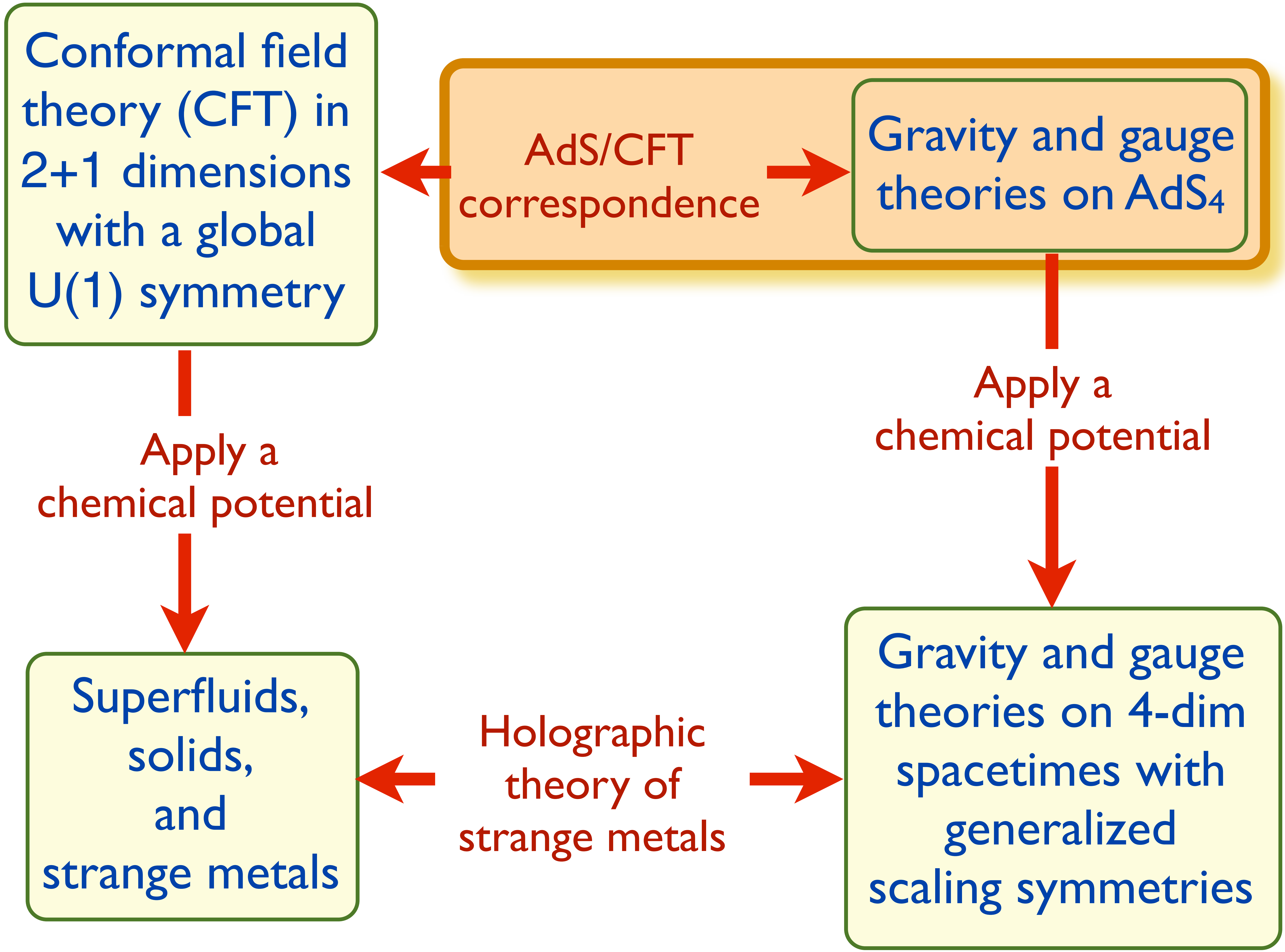
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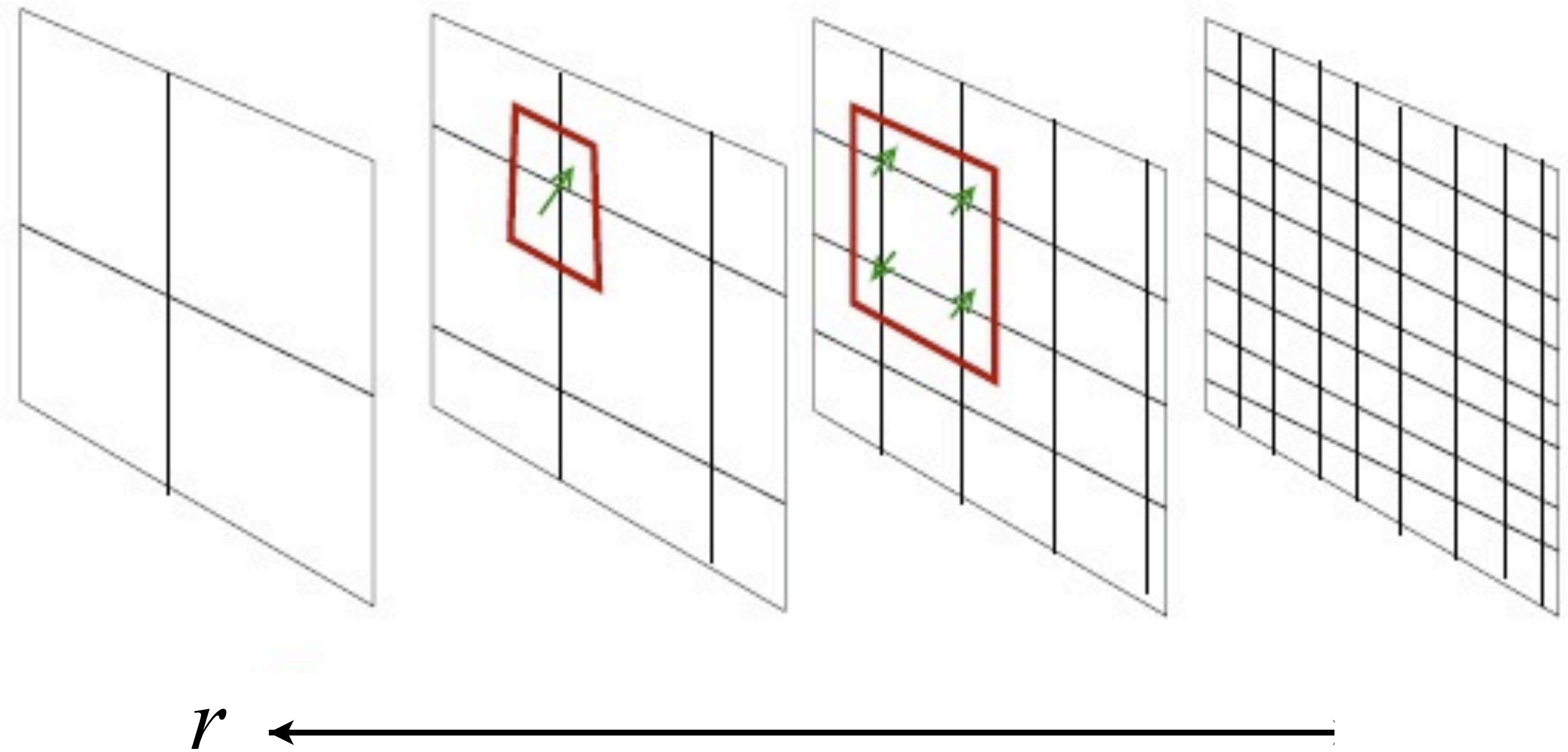
Holography



Key idea: $\Rightarrow$ Implement r as an extra dimension, and map to a local theory in $d+2$ spacetime dimensions.

For a relativistic CFT in d spatial dimensions, the metric in the holographic space is uniquely fixed by demanding the following scale transformaion $(i = 1 \ldots d)$

$$x_i \rightarrow \zeta x_i \quad , \quad t \rightarrow \zeta t \quad , \quad ds \rightarrow ds$$

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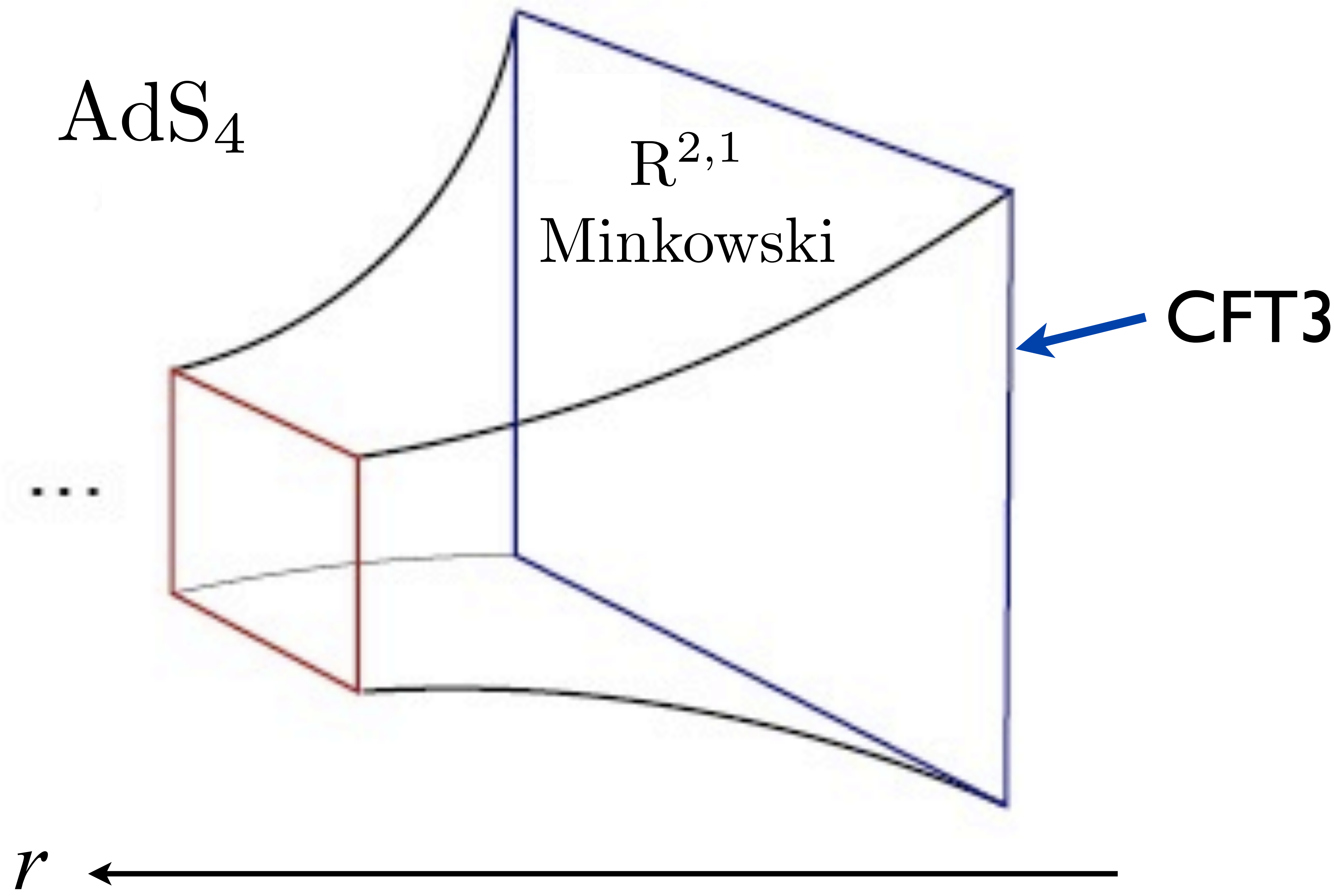
$$x_i \to \zeta x_i \quad , \quad t \to \zeta t \quad , \quad ds \to ds$$

This gives the unique metric

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

Reparametrization invariance in r has been used to the prefactor of dx_i^2 equal to $1/r^2$. This fixes $r \to \zeta r$ under the scale transformation. This is the metric of the space AdS_{d+2}.

AdS/CFT correspondence



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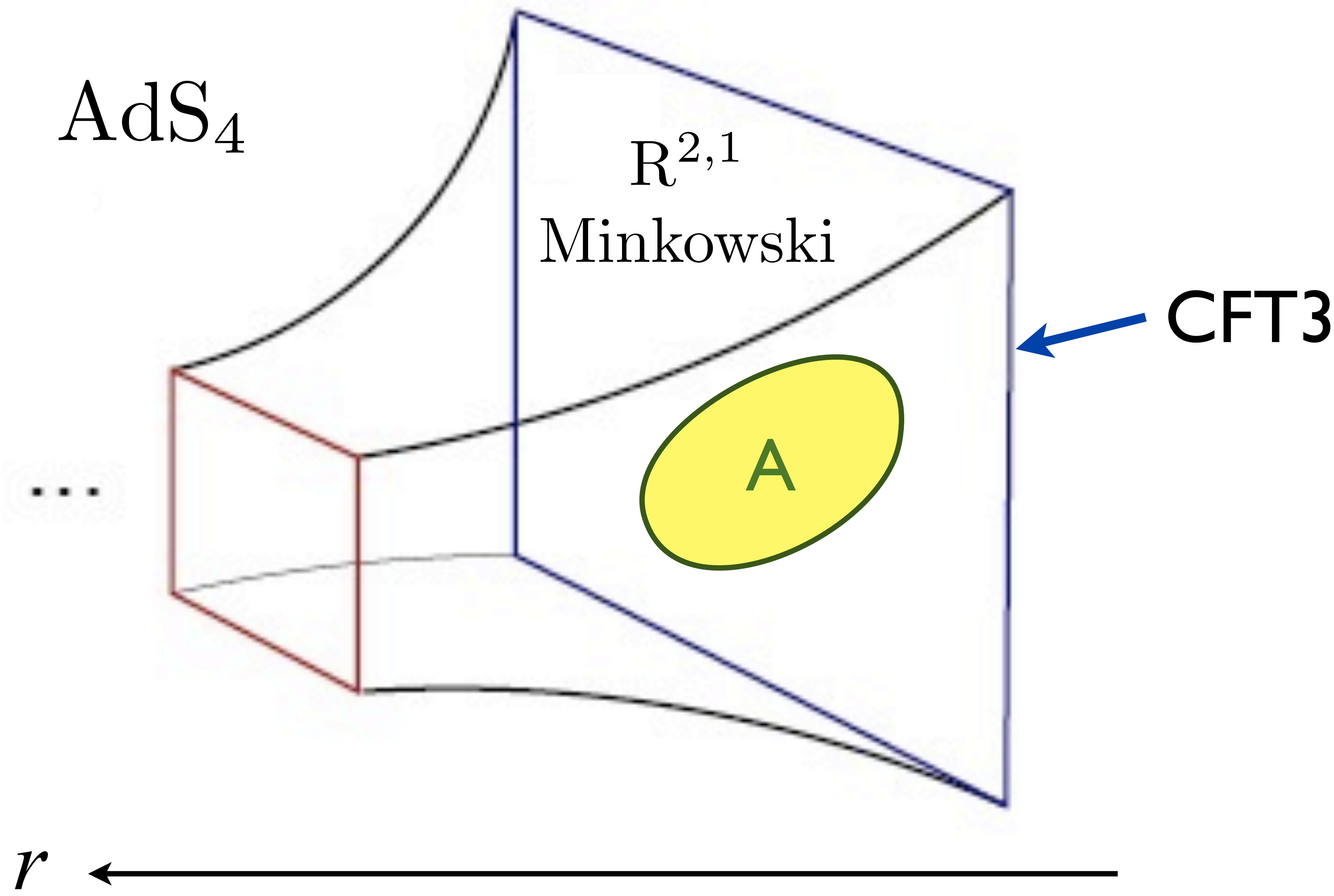

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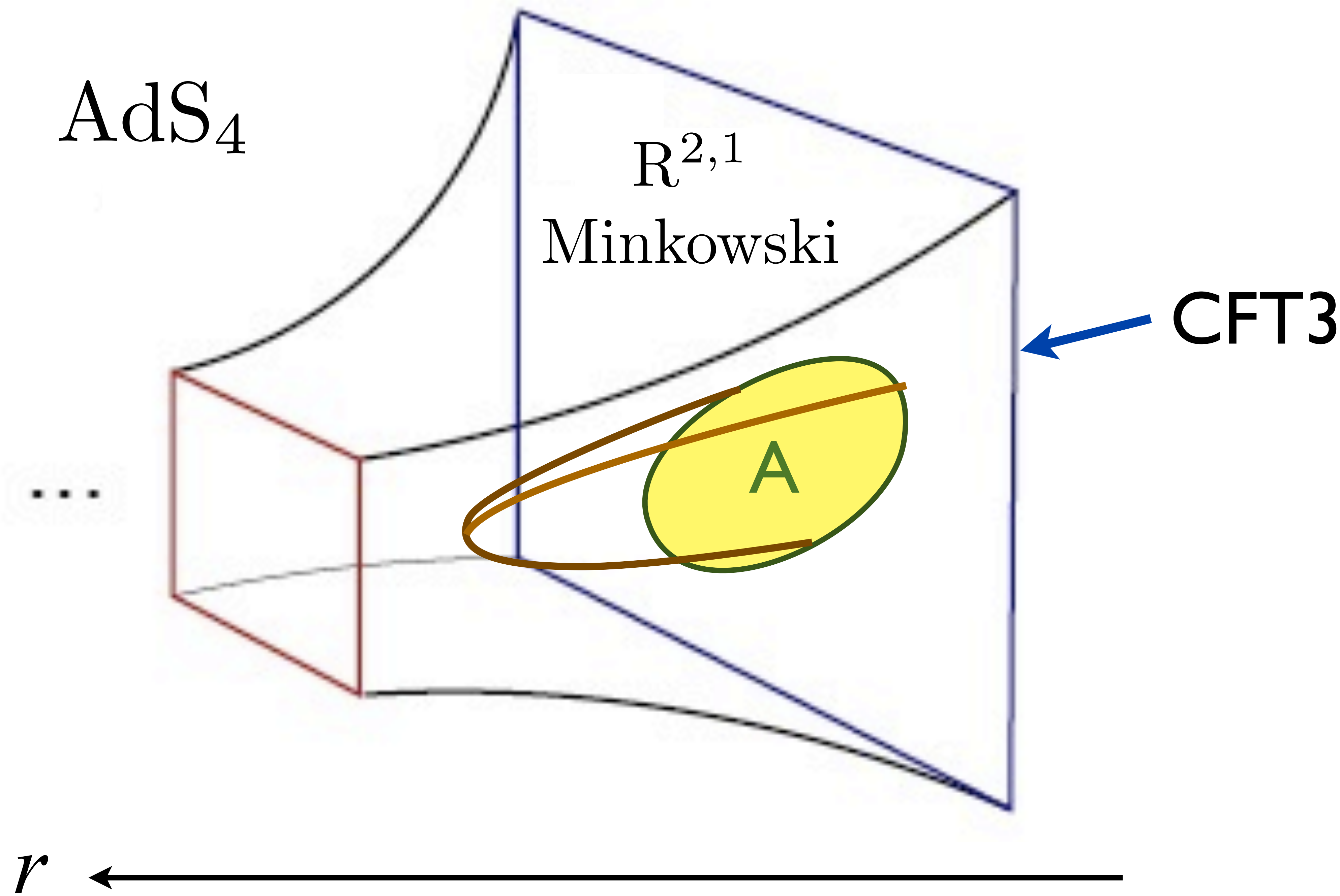
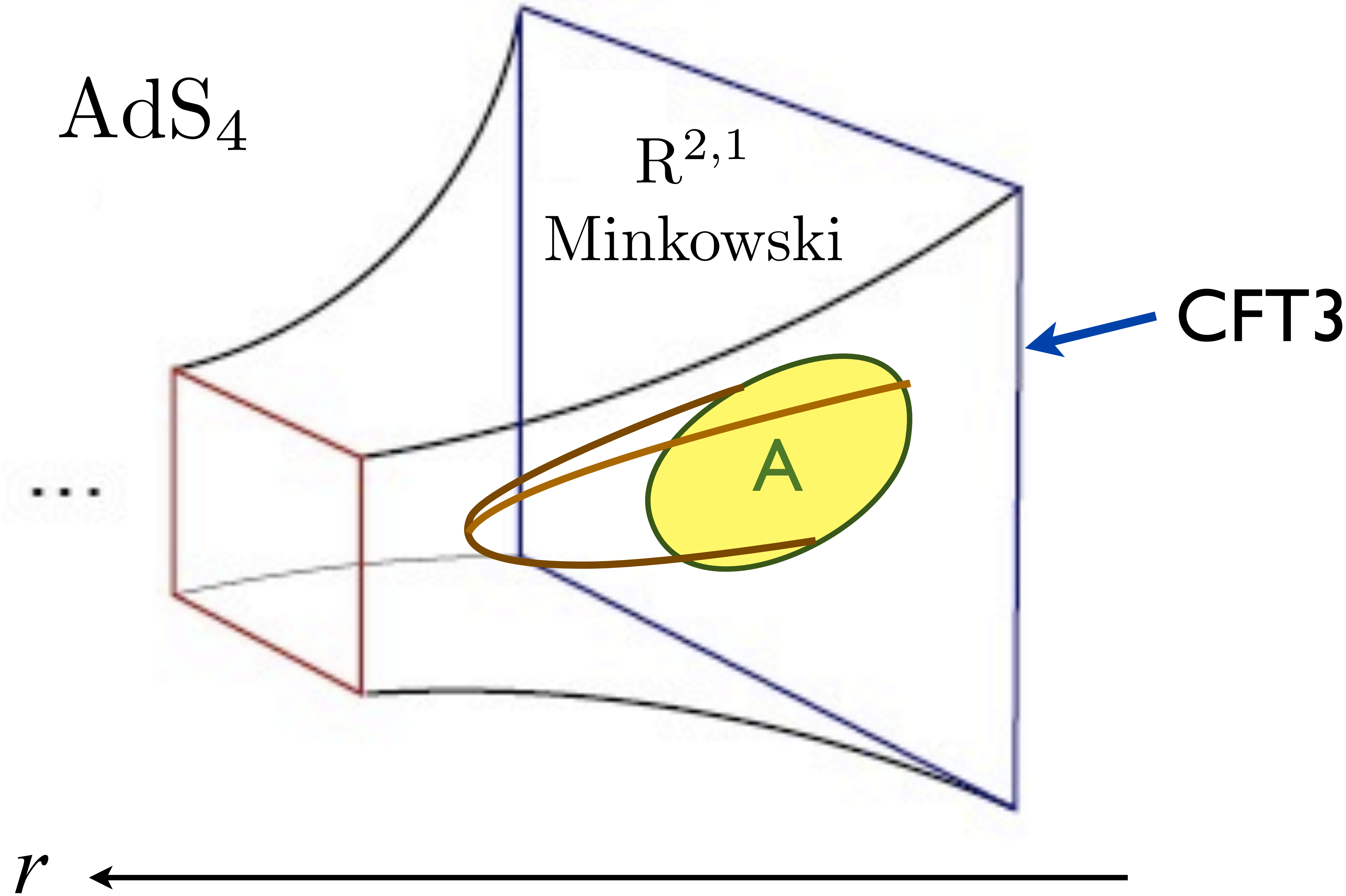


Associate entanglement entropy with an observer in the enclosed spacetime region, who cannot observe "outside" : *i.e.* the region is surrounded by an imaginary horizon.

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

AdS/CFT correspondence



The entropy of this region is bounded by its surface area
(Bekenstein-Hawking-'t Hooft-Susskind)

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

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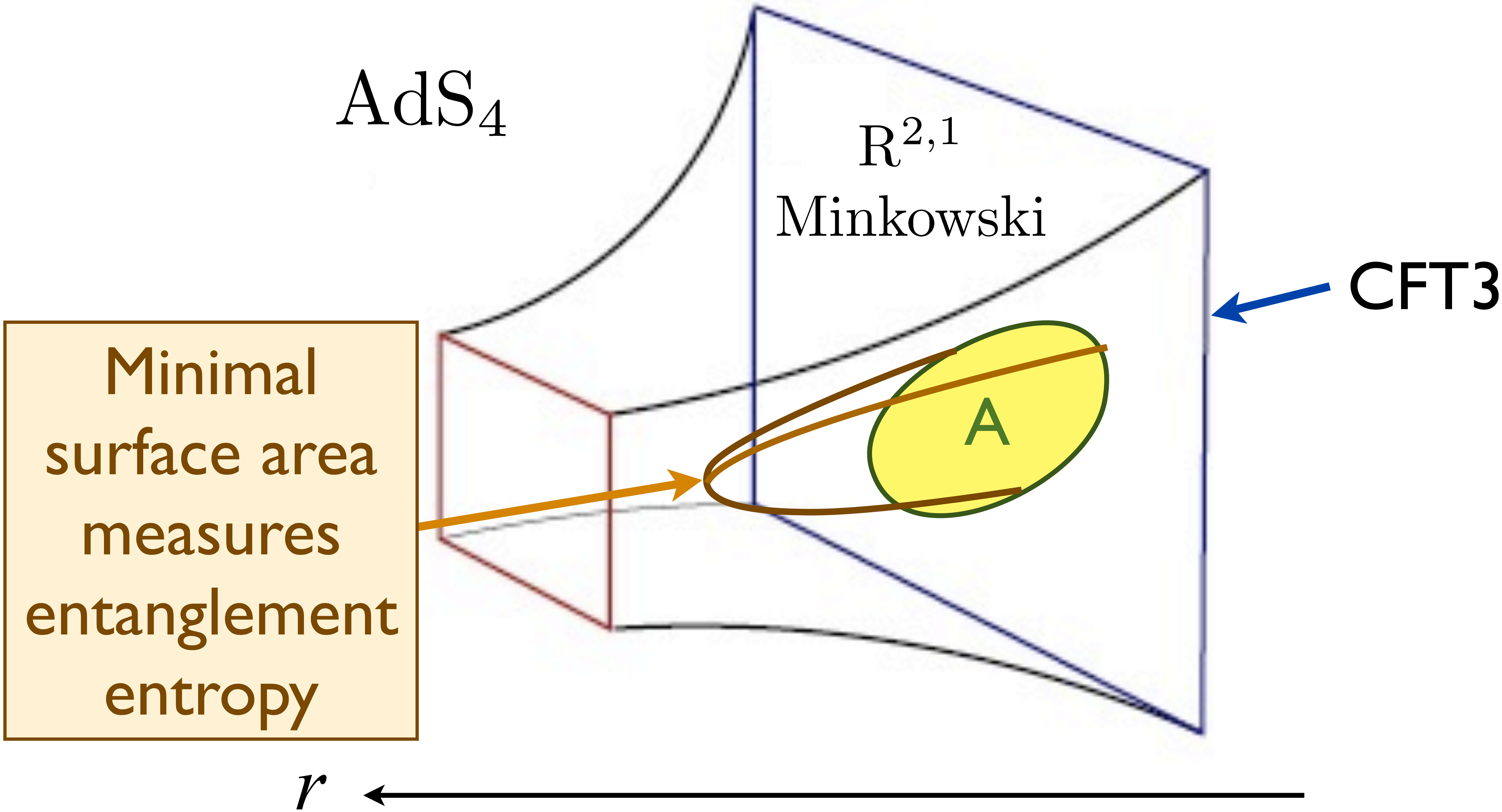

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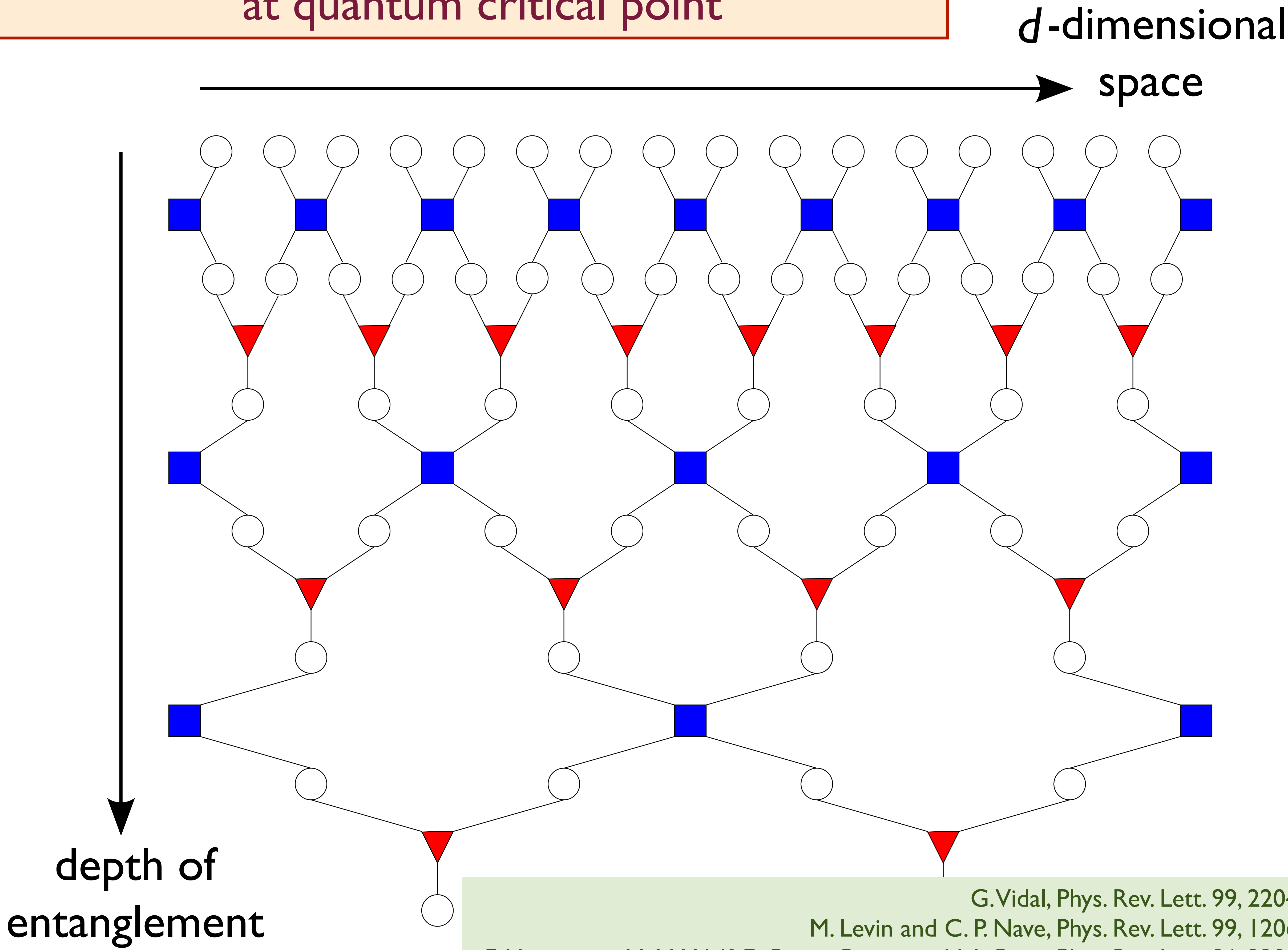
Tensor network representation of entanglement at quantum critical point



G. Vidal, Phys. Rev. Lett. 99, 220405 (2007)
M. Levin and C. P. Nave, Phys. Rev. Lett. 99, 120601 (2007)
F. Verstraete, M. M. Wolf, D. Perez-Garcia, and J. I. Cirac, Phys. Rev. Lett. 96, 220601 (2006)

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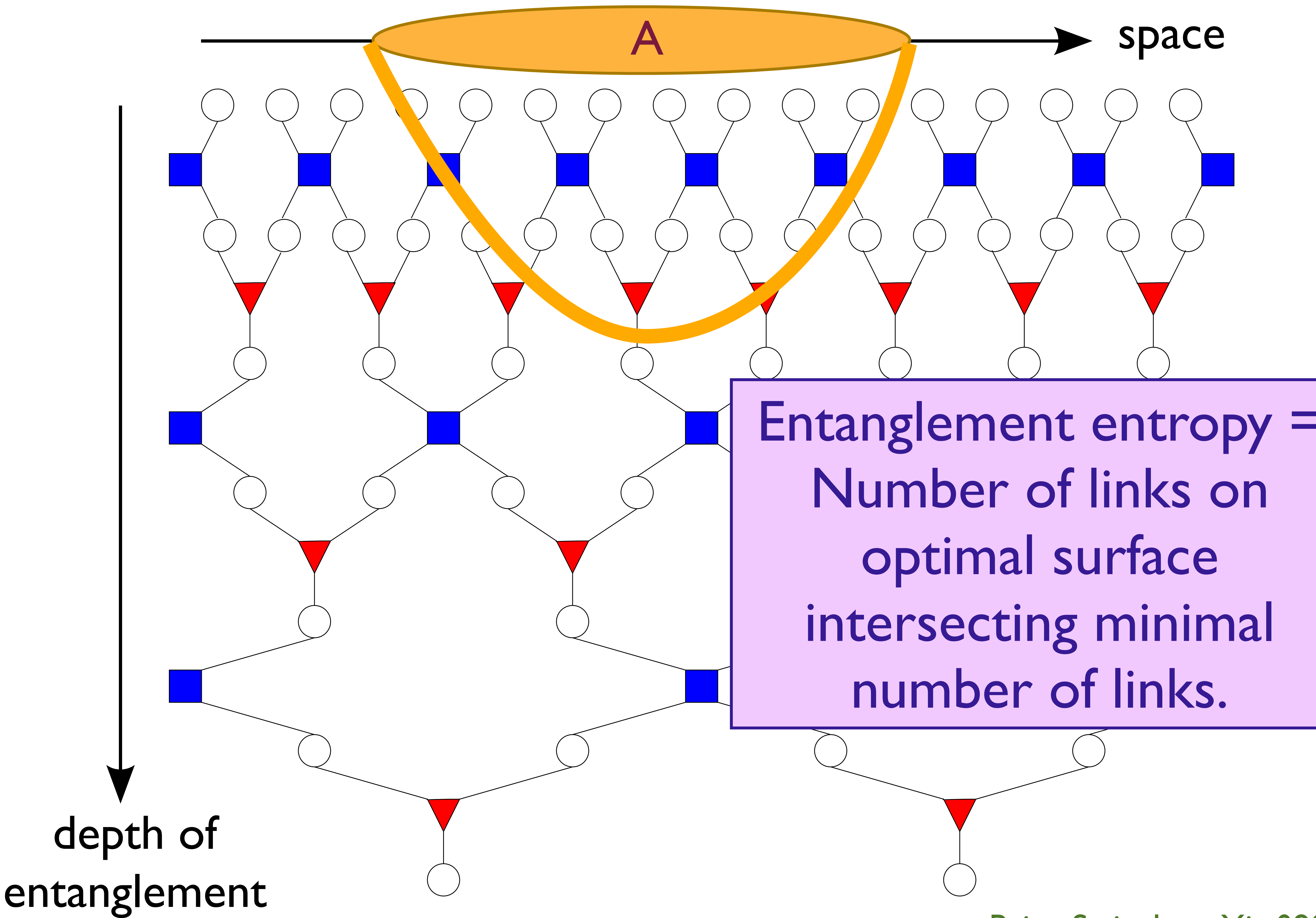

Entanglement entropy = Number of links on optimal surface intersecting minimal number of links.

Brian Swingle, arXiv:0905.1317

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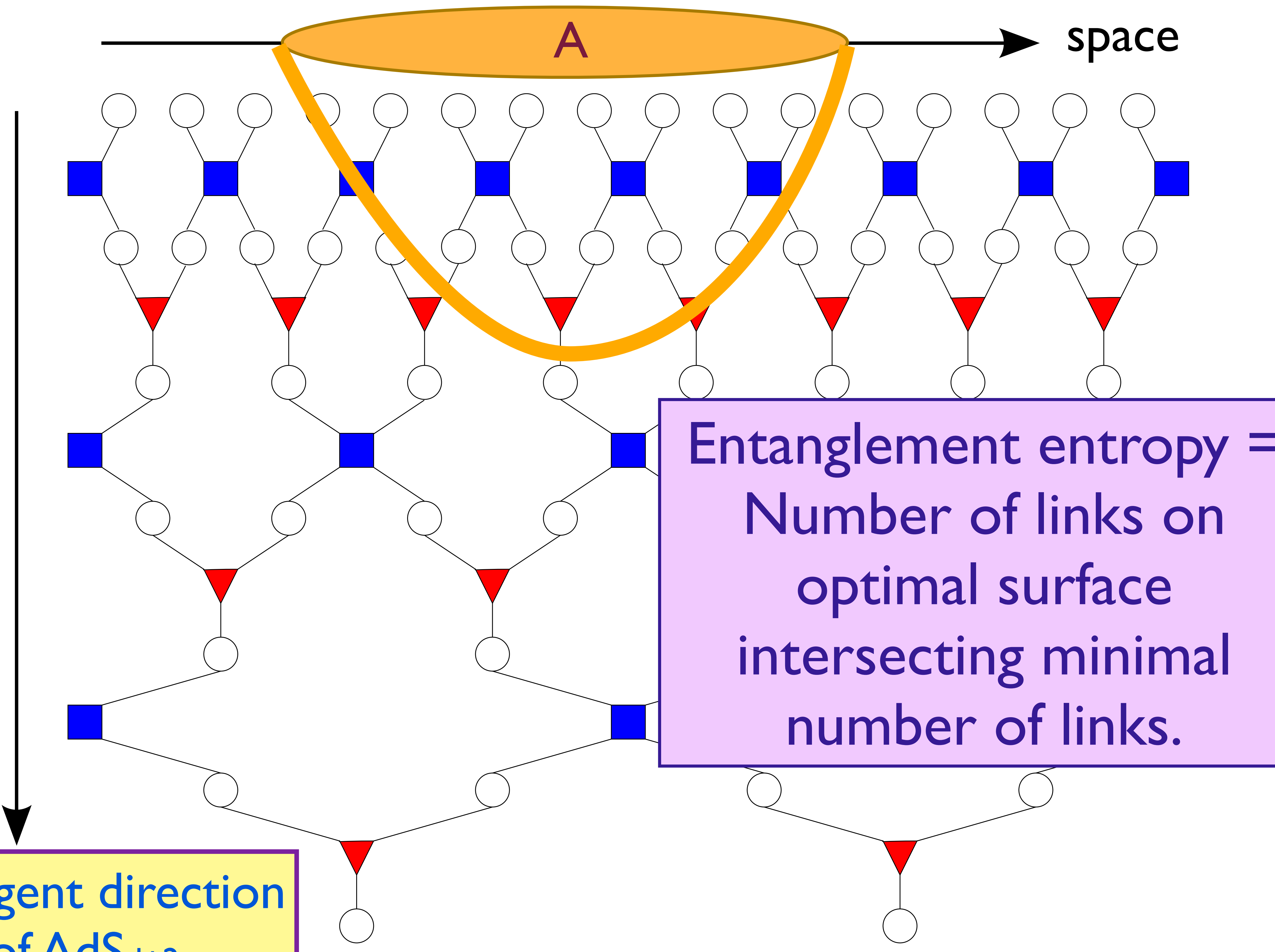

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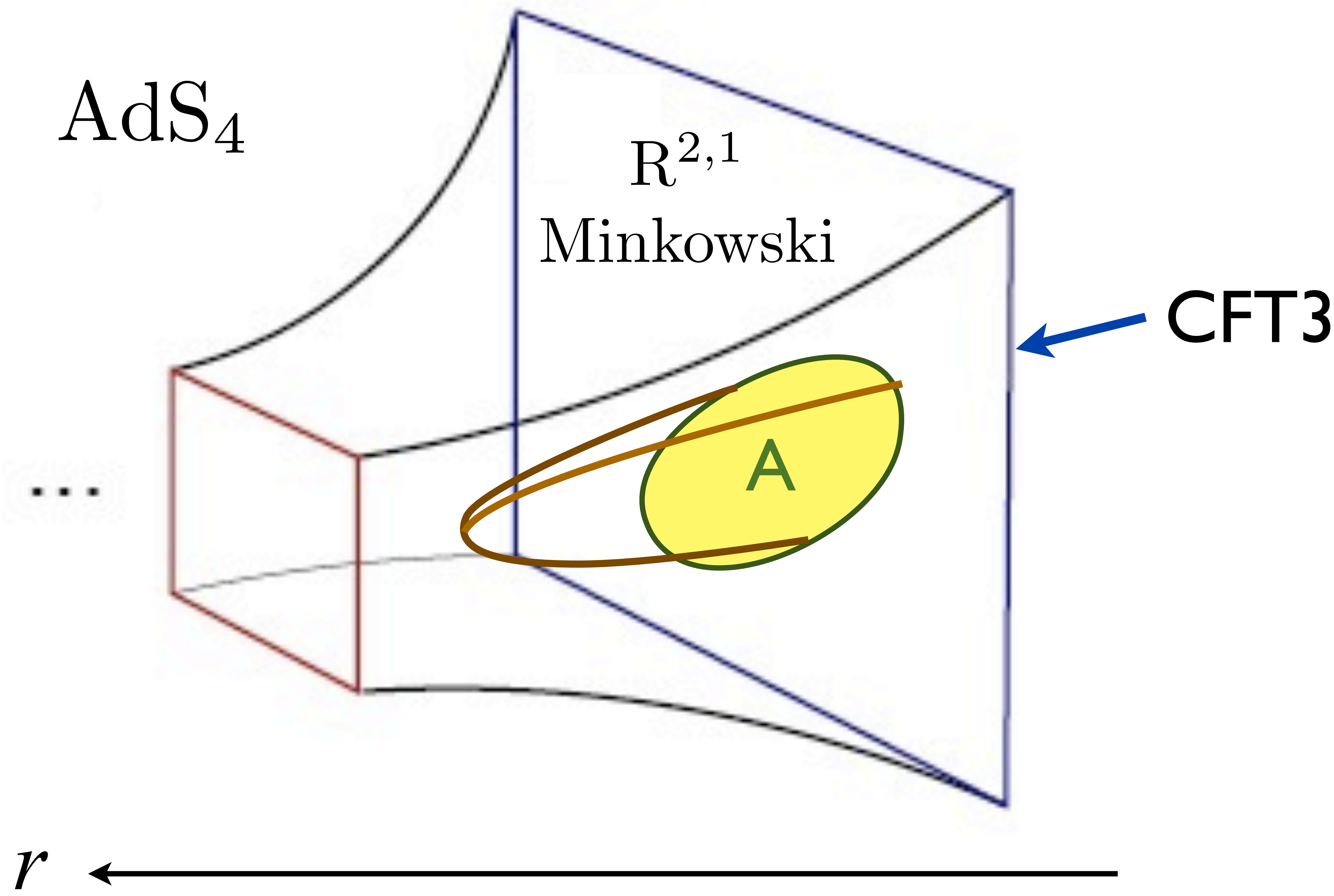
Emergent direction of AdS_{d+2}

Brian Swingle, arXiv:0905.1317

AdS/CFT correspondence



- Computation of minimal surface area yields
$$S_E = aP - \gamma,$$
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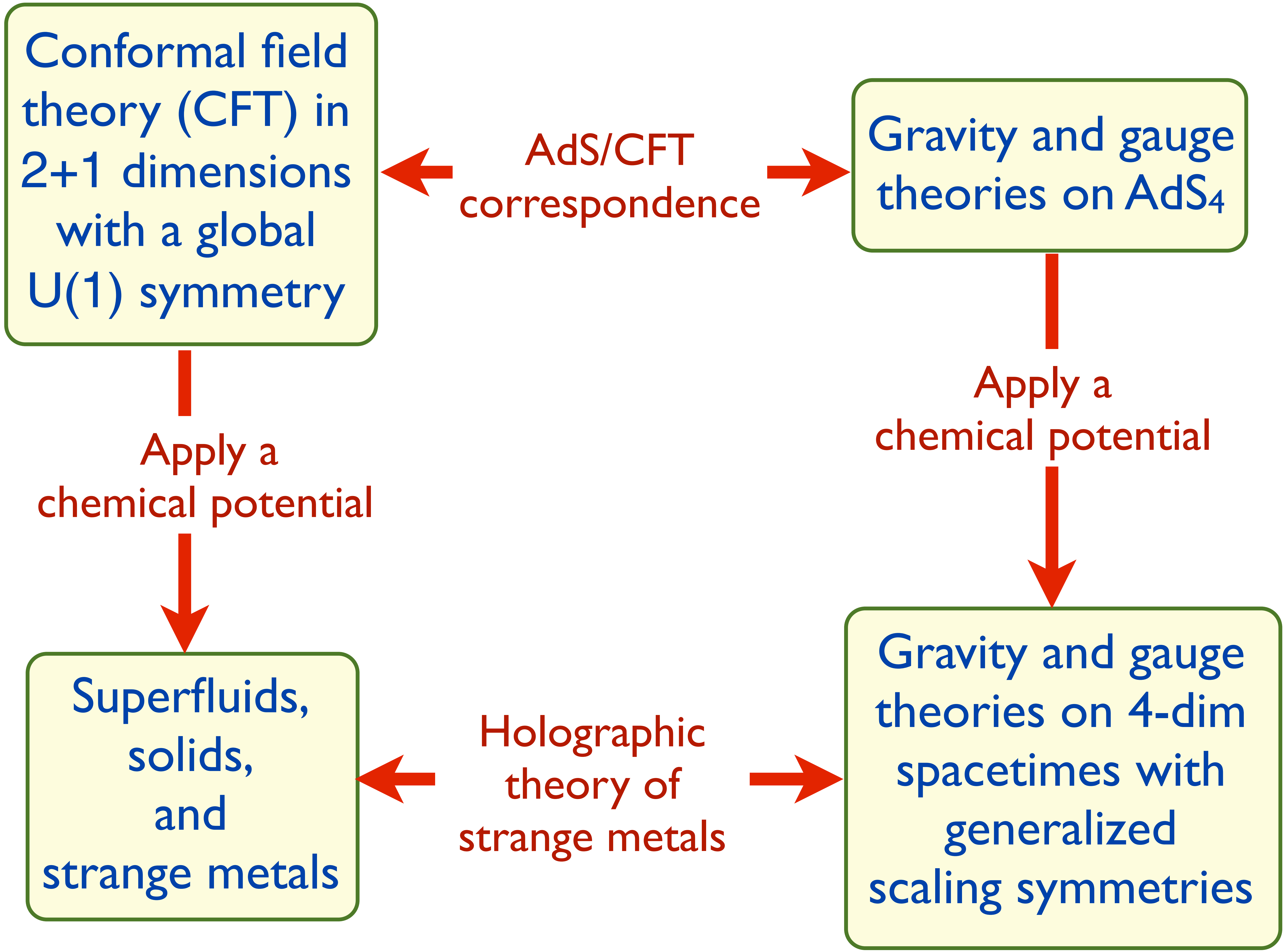
S. Ryu and T. Takayanagi, Phys. Rev. Lett. 96, 18160 (2006).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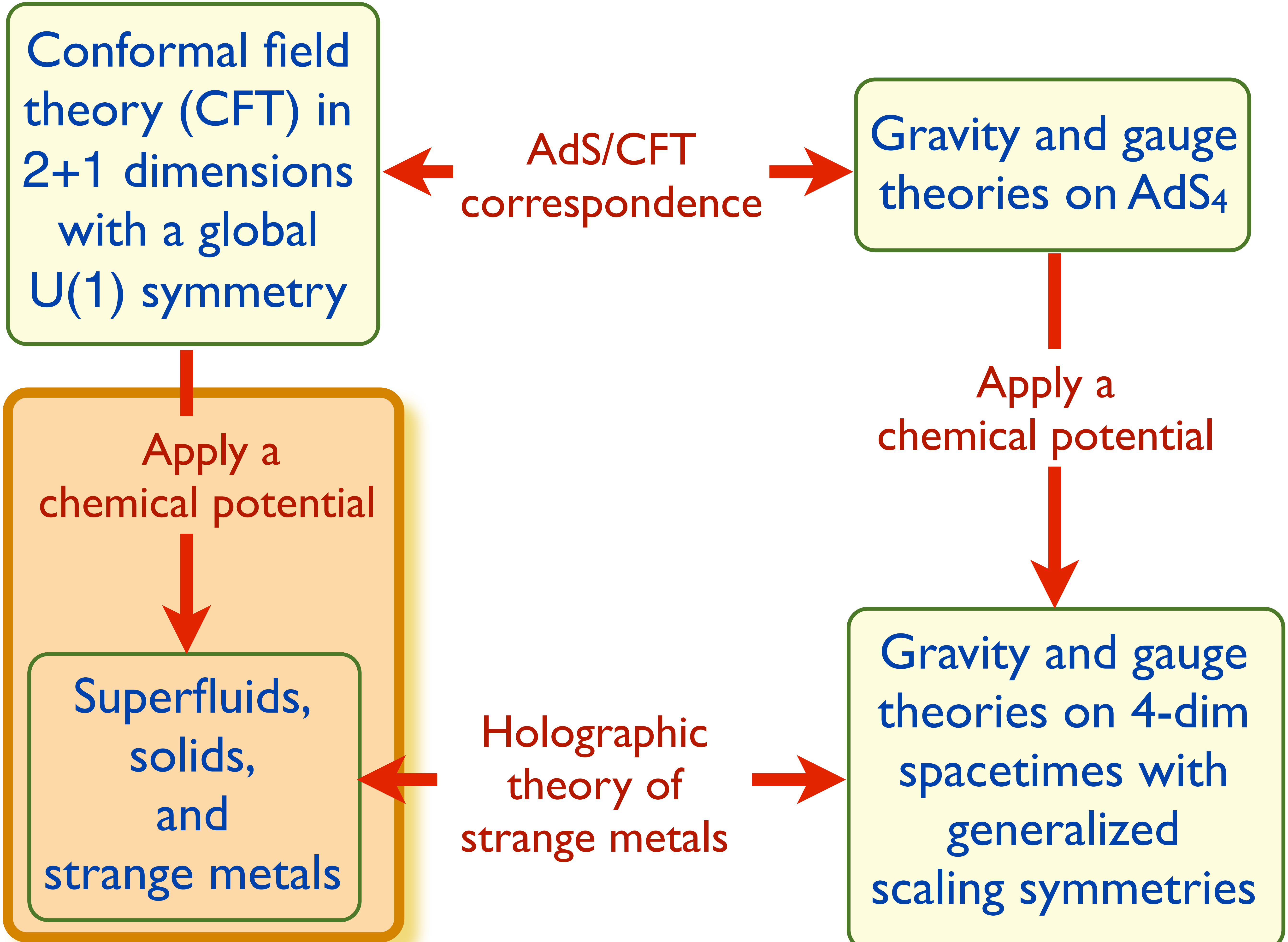
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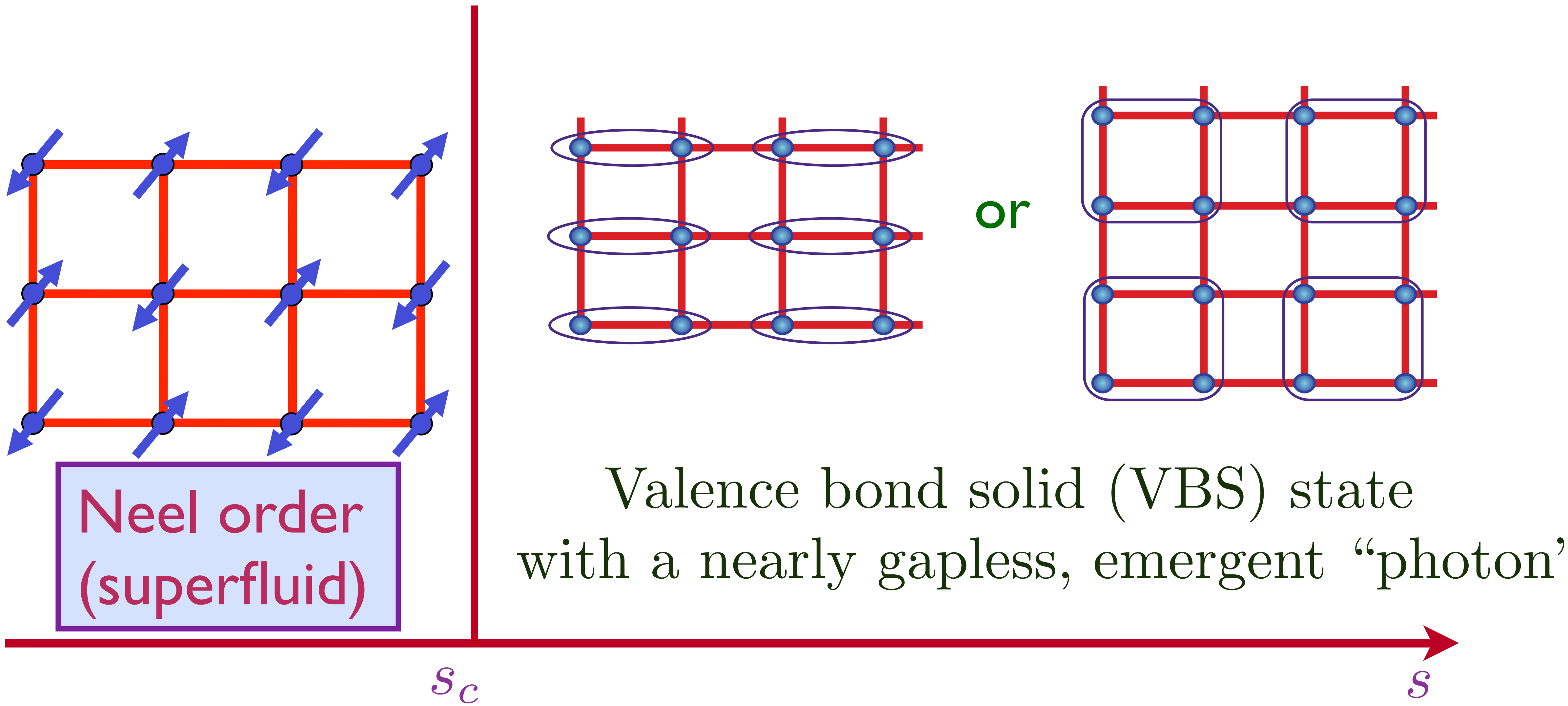
Quantum critical point in a frustrated square lattice XY antiferromagnet



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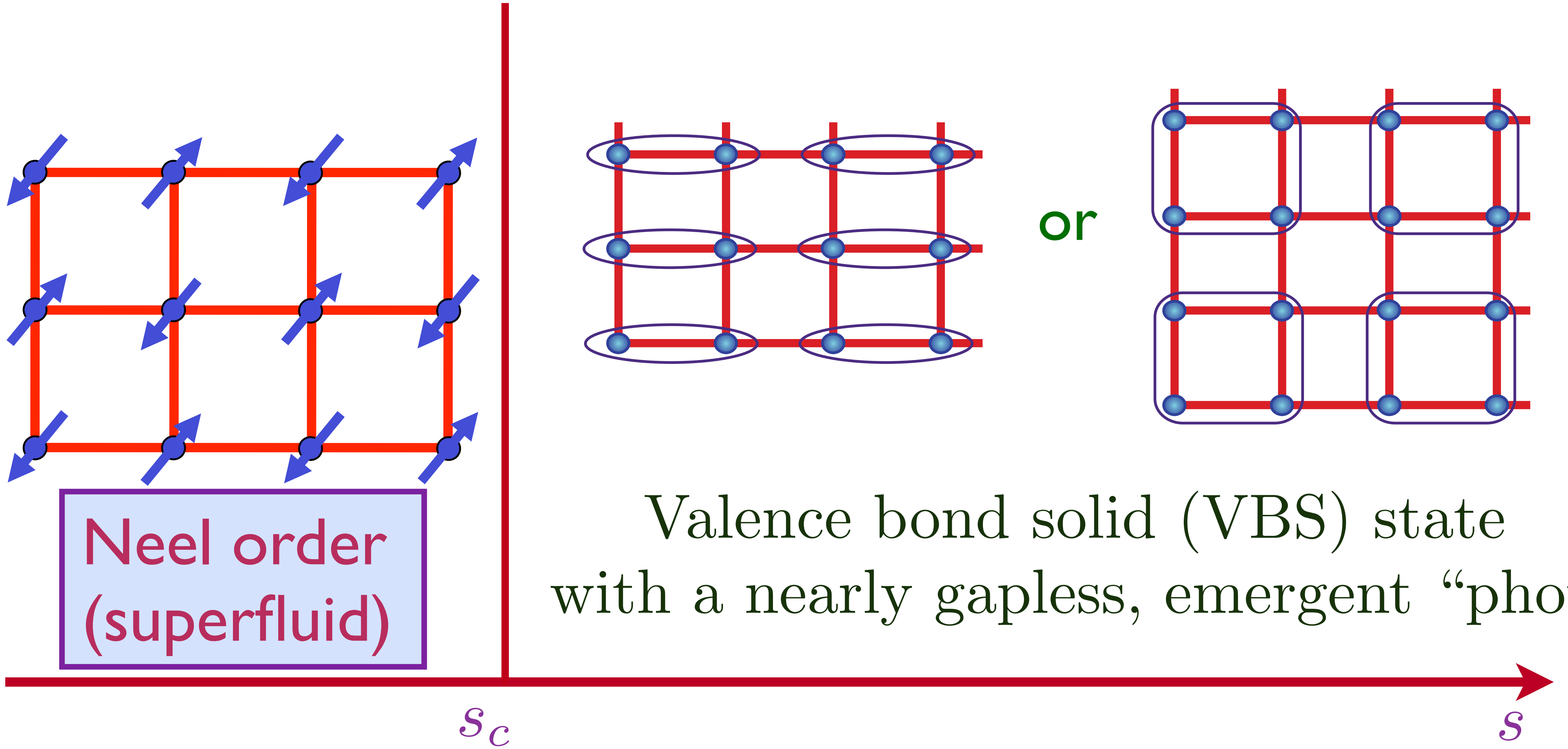

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$$+ \quad \text{ring exchange terms.} - \mu \mathcal{Q}$$

$$\text{U(1) conserved charge} \quad : \quad \mathcal{Q} = \sum_i b_i^\dagger b_i$$

Compressible quantum phases of a doped CFT3

- Superfluid (Néel order): breaks U(1) symmetry
- Solid (Wigner crystal): breaks translational symmetry
- Strange metal: a *Bose metal*, a compressible phase which breaks no symmetries.

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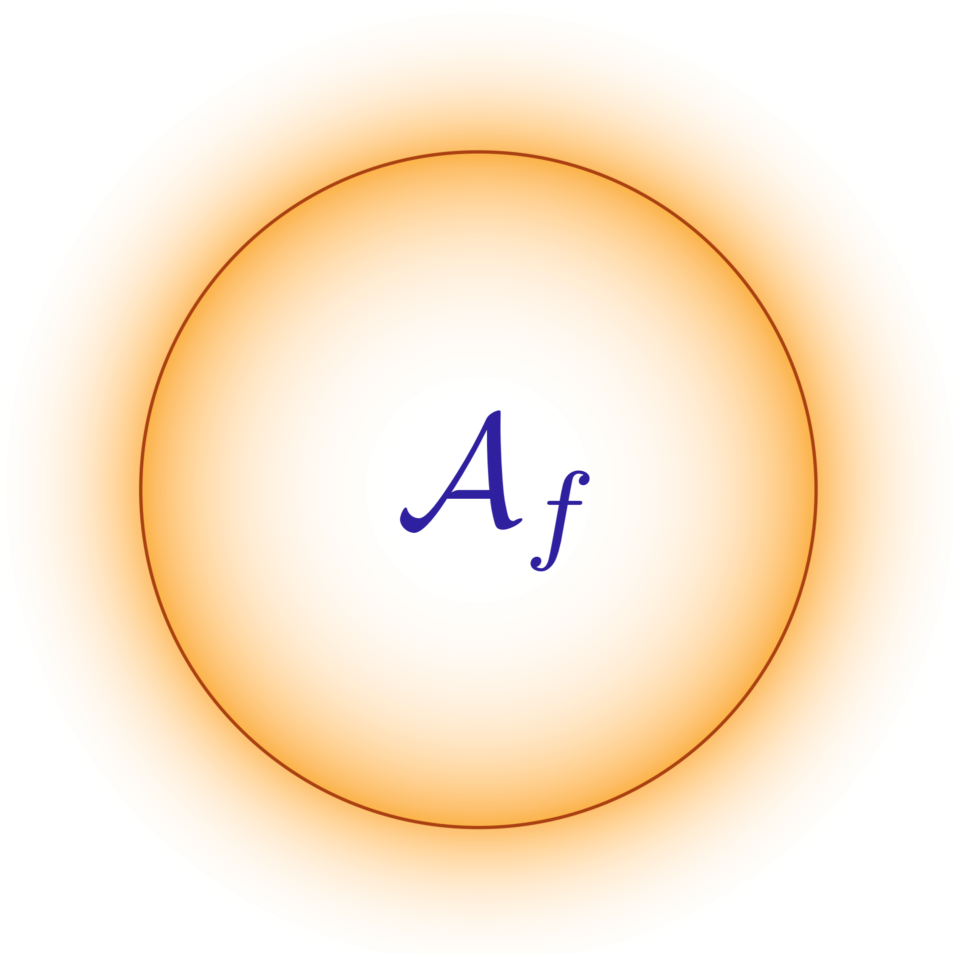
- **NFL**, the non-Fermi liquid *Bose metal*. The boson, b, fractionalizes into (say) 2 fermions, f_1 and f_2 ("*quarks*"), each of which forms a Fermi surface. Both fermions necessarily couple to an emergent gauge field, and so the Fermi surfaces are "*hidden*".



$$\mathcal{Q} = b^\dagger b$$

$$\mathcal{A}_f = \langle \mathcal{Q} \rangle$$

O. I. Motrunich and M. P. A. Fisher, *Physical Review* B **75**, 235116 (2007)
L. Huijse and S. Sachdev, *Physical Review* D **84**, 026001 (2011)
S. Sachdev, to appear

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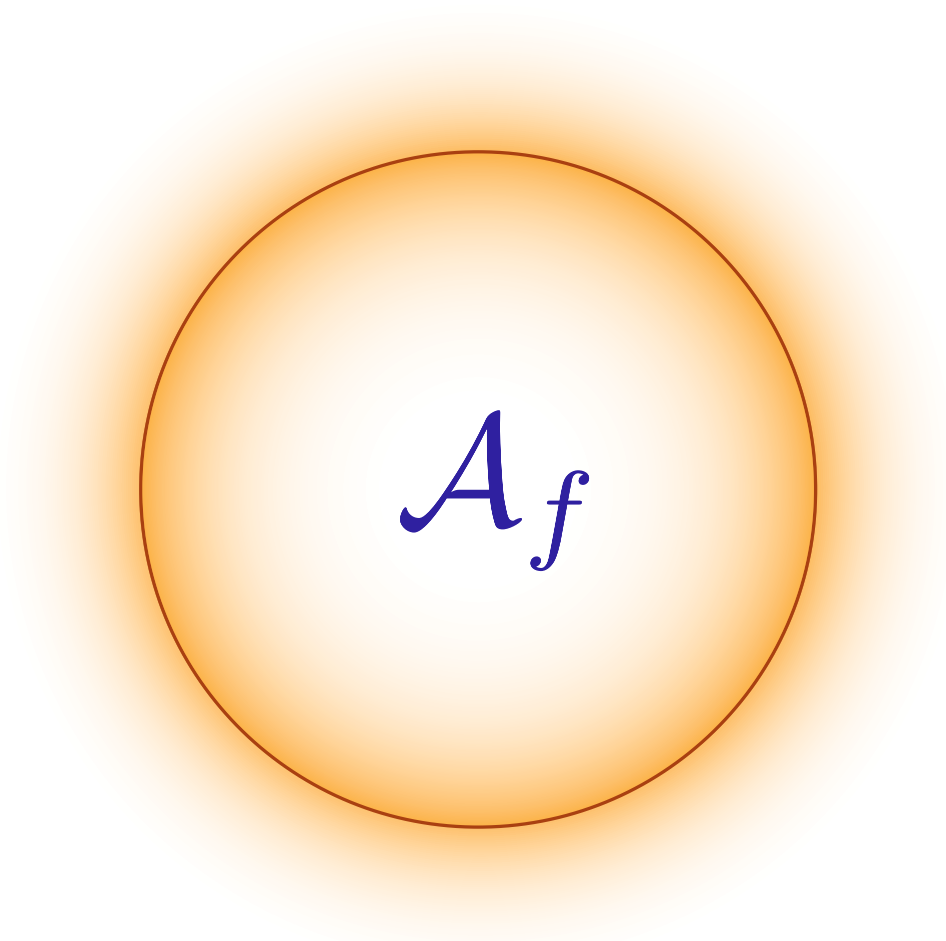

$$b \to f_1 f_2$$

Gauge invariance:

$$f_1(x) \to f_1(x) e^{i\theta(x)},$$
$$f_2(x) \to f_2(x) e^{-i\theta(x)}$$

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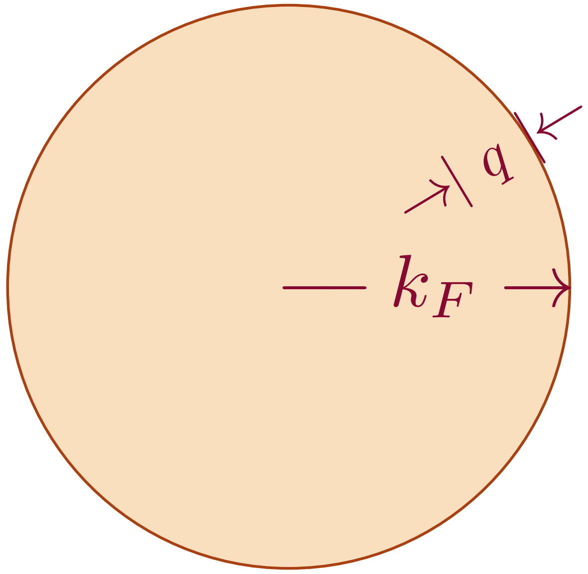
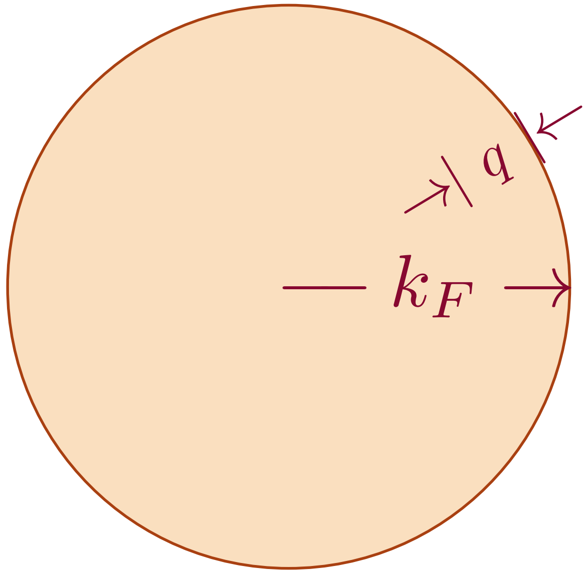
FL
Fermi liquid



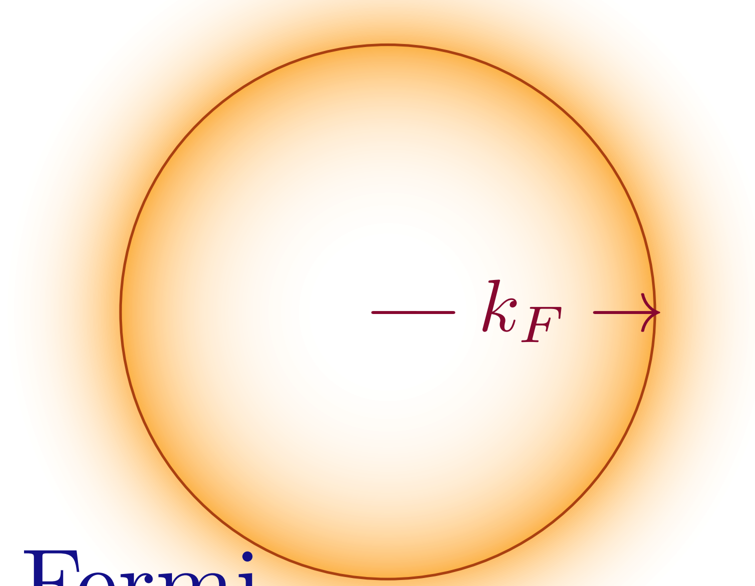
- $k_F^d \sim \mathcal{Q}$, the fermion density

FL Fermi liquid



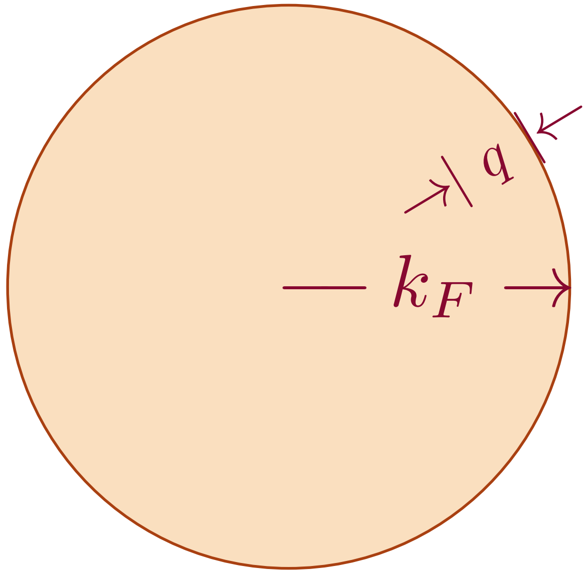
- $k_F^d \sim \mathcal{Q}$, the fermion density

NFL Bose metal



- Hidden Fermi surface with $k_F^d \sim \mathcal{Q}$.

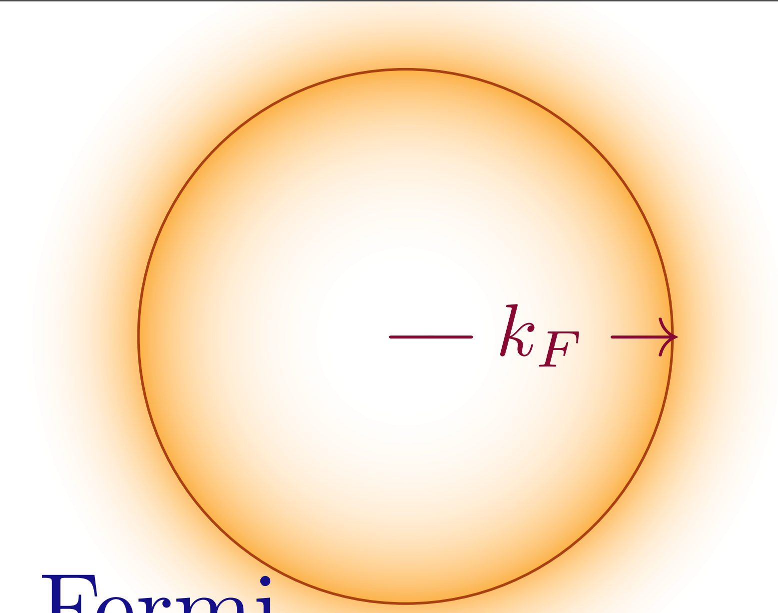
FL
Fermi liquid



- $k_F^d \sim \mathcal{Q}$, the fermion density

- Sharp fermionic excitations near Fermi surface with $\omega \sim |q|^z$, and $z = 1$.

NFL
Bose metal



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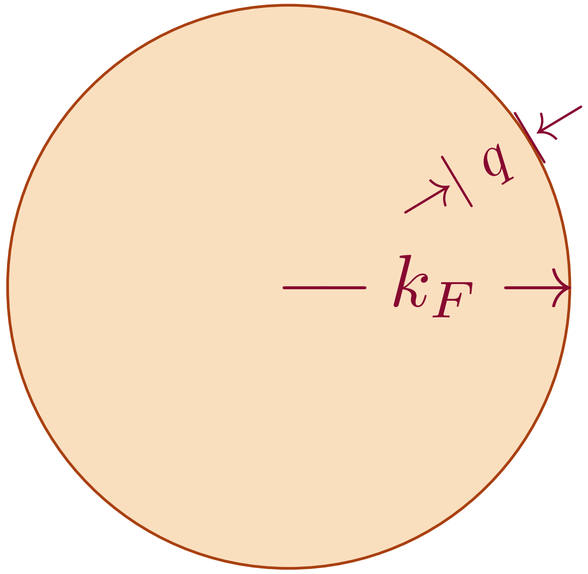
FL
Fermi liquid



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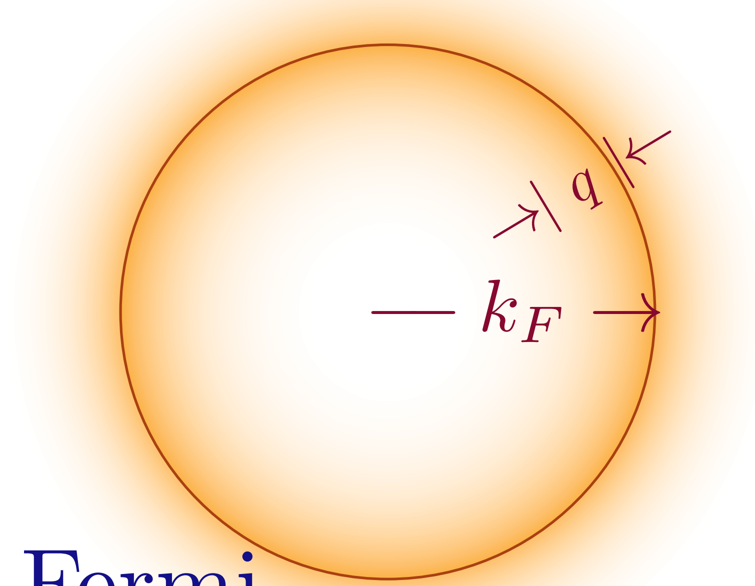
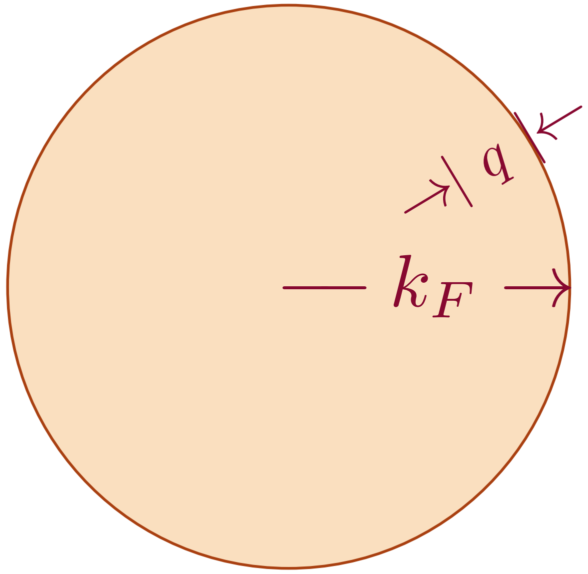


- Hidden Fermi surface with $k_F^d \sim \mathcal{Q}$.

- Diffuse fermionic excitations with $z = 3/2$ to three loops.

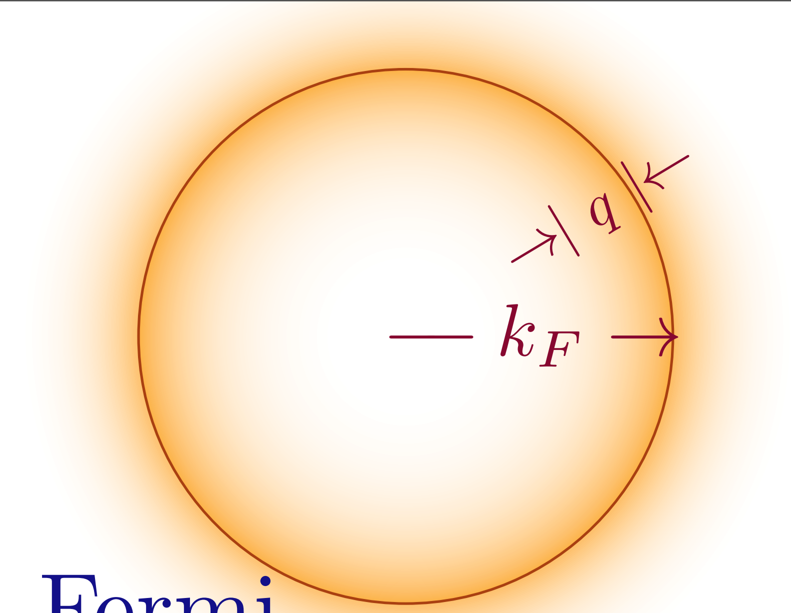
M. A. Metlitski and S. Sachdev, Phys. Rev. B **82**, 075127 (2010)

FL Fermi liquid

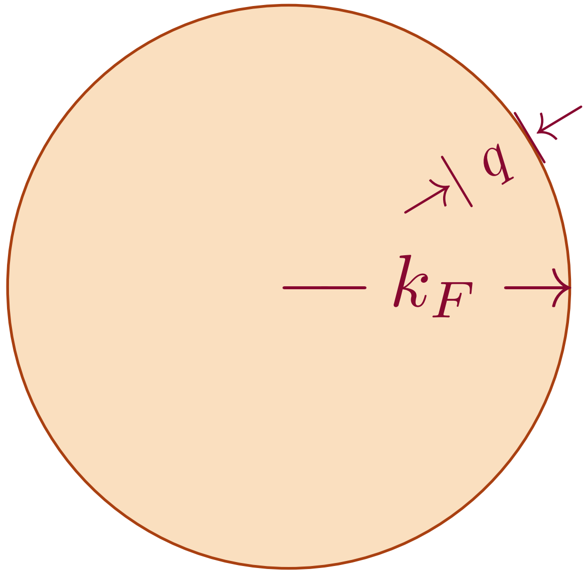
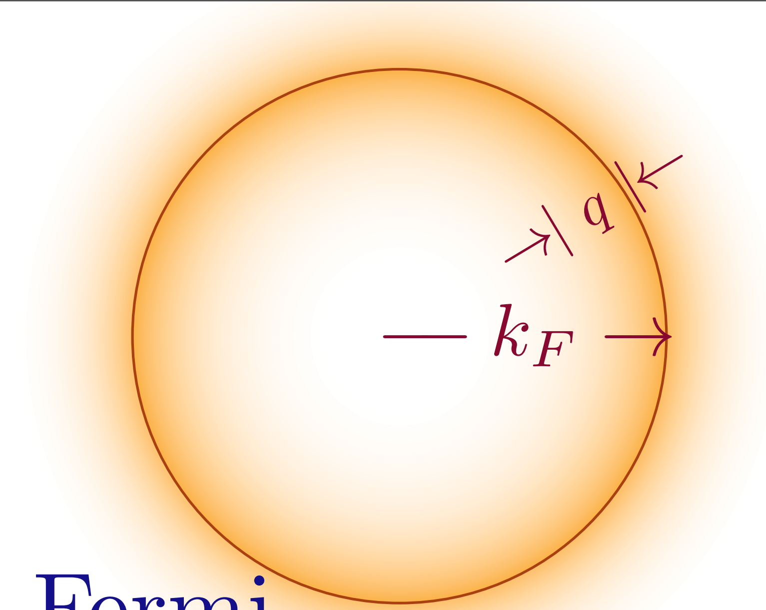


- $k_F^d \sim \mathcal{Q}$, the fermion density
- Sharp fermionic excitations near Fermi surface with $\omega \sim |q|^z$, and $z = 1$.
- Entropy density $S \sim T^{(d-\theta)/z}$ with violation of hyperscaling exponent $\theta = d - 1$.

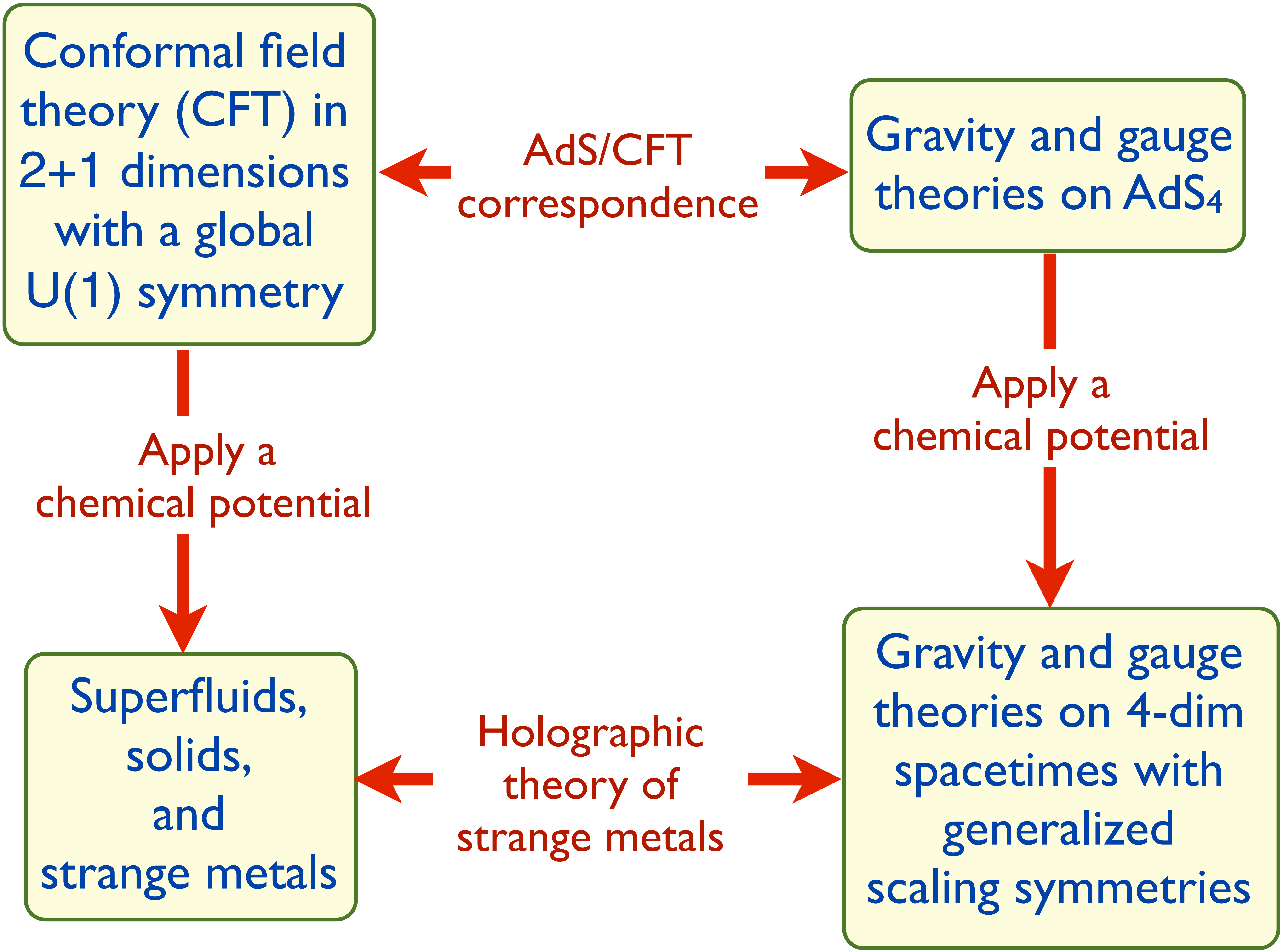
NFL Bose metal

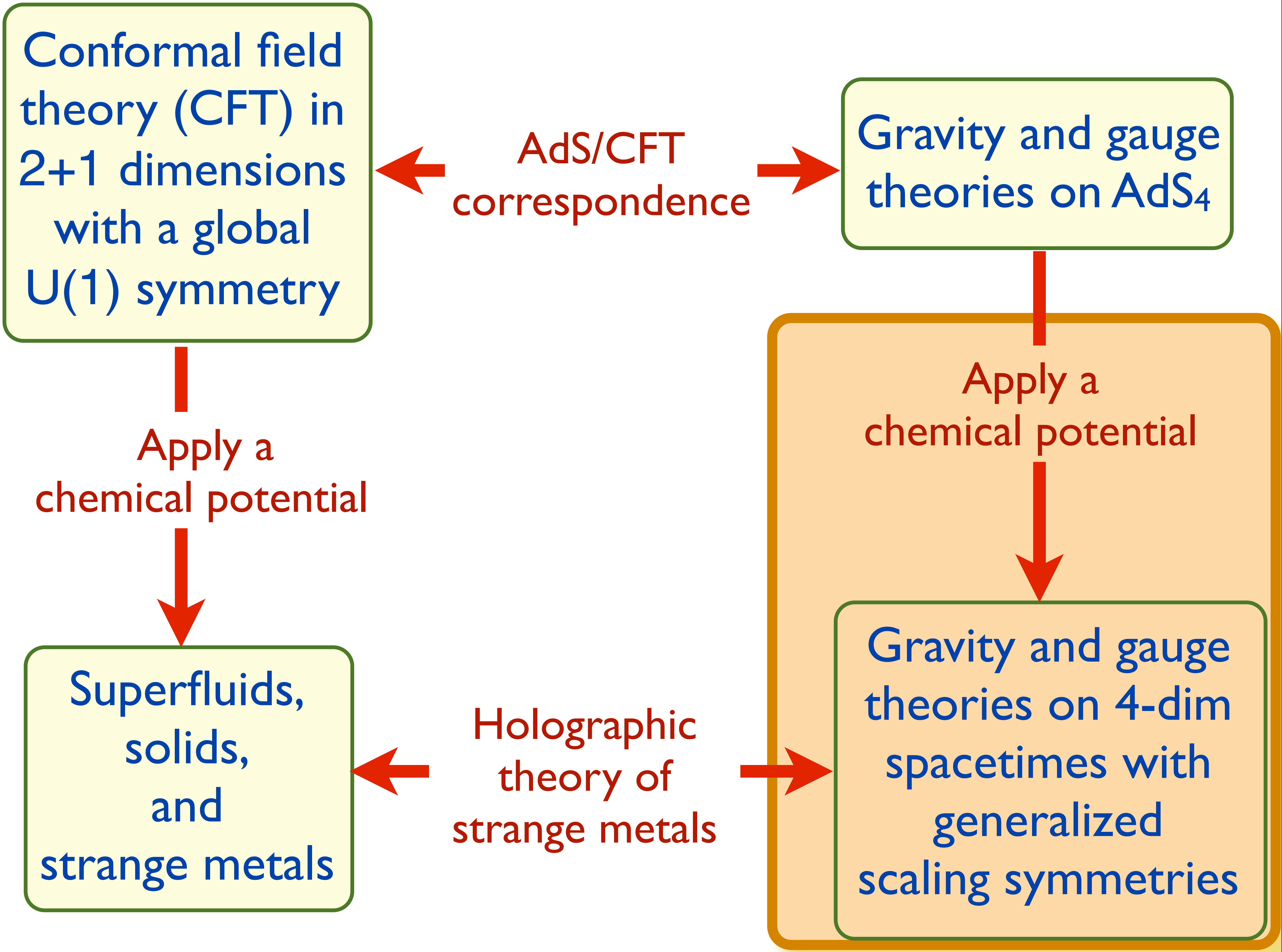


- Hidden Fermi surface with $k_F^d \sim \mathcal{Q}$.
- Diffuse fermionic excitations with $z = 3/2$ to three loops.
- $S \sim T^{(d-\theta)/z}$ with $\theta = d - 1$.

FL Fermi liquid	NFL Bose metal
 	
• $k_F^d \sim \mathcal{Q}$, the fermion density	• Hidden Fermi surface with $k_F^d \sim \mathcal{Q}$.
• Sharp fermionic excitations near Fermi surface with $\omega \sim \lvert q \rvert^z$, and $z = 1$.	• Diffuse fermionic excitations with $z = 3/2$ to three loops.
• Entropy density $S \sim T^{(d-\theta)/z}$ with violation of hyperscaling exponent $\theta = d - 1$.	• $S \sim T^{(d-\theta)/z}$ with $\theta = d - 1$.
• Entanglement entropy $S_E \sim k_F^{d-1} P \ln P$.	• $S_E \sim k_F^{d-1} P \ln P$.

Y. Zhang, T. Grover, and A. Vishwanath, *Phys. Rev. Lett.* **107**, 067202 (2011)


Conformal field theory (CFT) in 2+1 dimensions with a global U(1) symmetry
AdS/CFT correspondence
Gravity and gauge theories on AdS4
Apply a chemical potential
Apply a chemical potential
Superfluids, solids, and strange metals
Holographic theory of strange metals
Gravity and gauge theories on 4-dim spacetimes with generalized scaling symmetries


Conformal field theory (CFT) in 2+1 dimensions with a global U(1) symmetry
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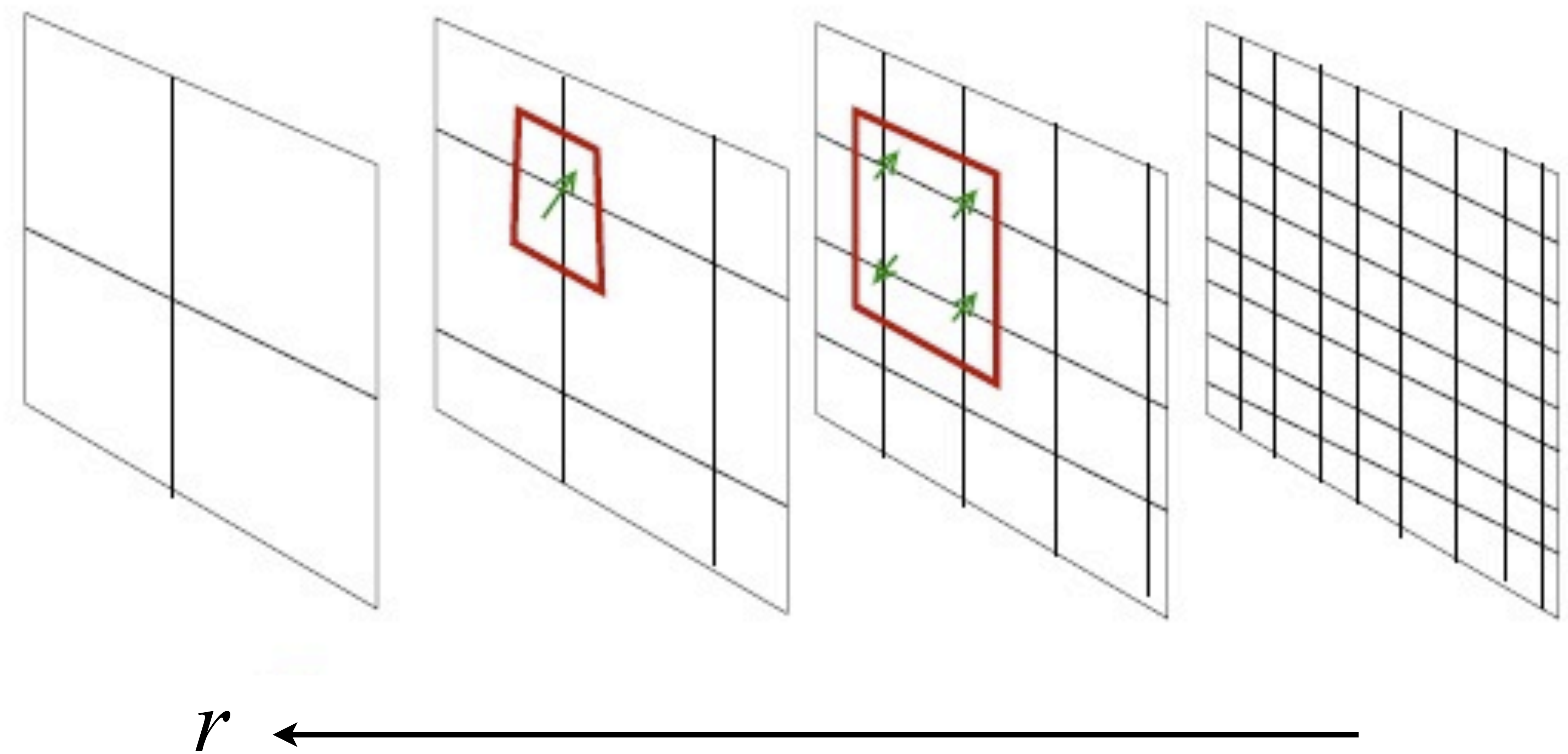
Holography



Consider the metric which transforms under rescaling as

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

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

θ 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).

θ 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 $r \rightarrow \zeta^{(d-\theta)/d} r$.

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

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

At $T > 0$, there is a *horizon*, and computation of its Bekenstein-Hawking entropy shows

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

So θ is indeed the violation of hyperscaling exponent as claimed. For a compressible quantum state we should therefore *choose* $\theta = d - 1$.
No additional choices will be made, and all subsequent results are consequences of the assumption of the existence of a holographic dual.

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

Holography of strange metals

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

$$\theta = d - 1$$

The null energy condition (stability condition for gravity) yields a new inequality

$$z \geq 1 + \frac{\theta}{d}$$

In $d = 2$, this implies $z \geq 3/2$. So the lower bound is precisely the value obtained from the field theory.

N. Ogawa, T. Takayanagi, and T. Ugajin, JHEP **1201**, 125 (2012).
L. Huijse, S. Sachdev, B. Swingle, Physical Review B **85**, 035121 (2012)

Holography of strange metals

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

$$\theta = d - 1$$

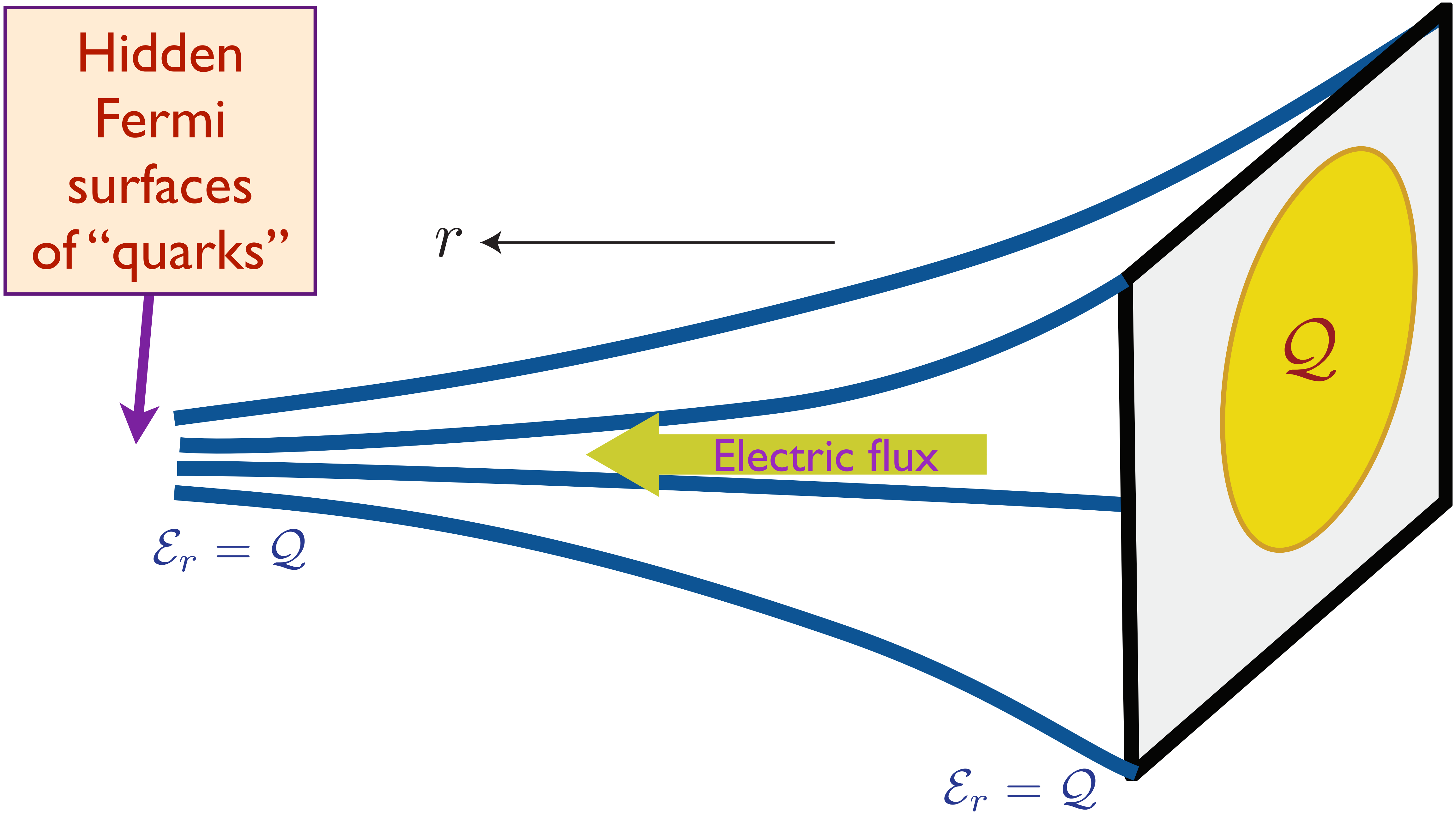
Application of the Ryu-Takayanagi minimal area formula to a dual Einstein-Maxwell-dilaton theory yields

$$S_E \sim \mathcal{Q}^{(d-1)/d} P \ln P$$

with a co-efficient *independent* of UV details and of the shape of the entangling region. These properties are just as expected for a circular Fermi surface with $\mathcal{Q} \sim k_F^d$.

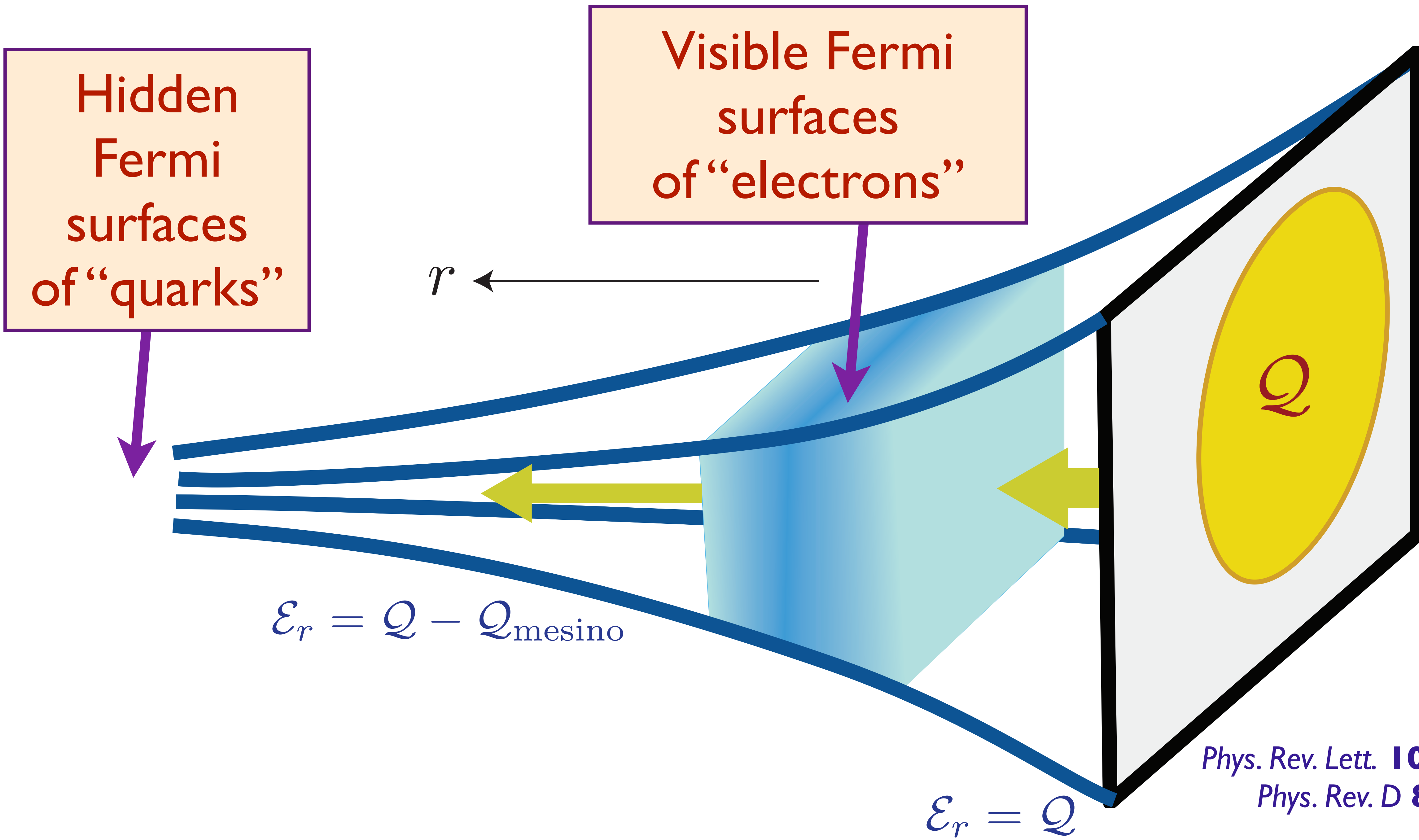
N. Ogawa, T. Takayanagi, and T. Ugajin, JHEP **1201**, 125 (2012).
L. Huijse, S. Sachdev, B. Swingle, Physical Review B **85**, 035121 (2012)

Holographic theory of a non-Fermi liquid (NFL)



Fully fractionalized state has all the electric flux exiting to the horizon at $r = \infty$

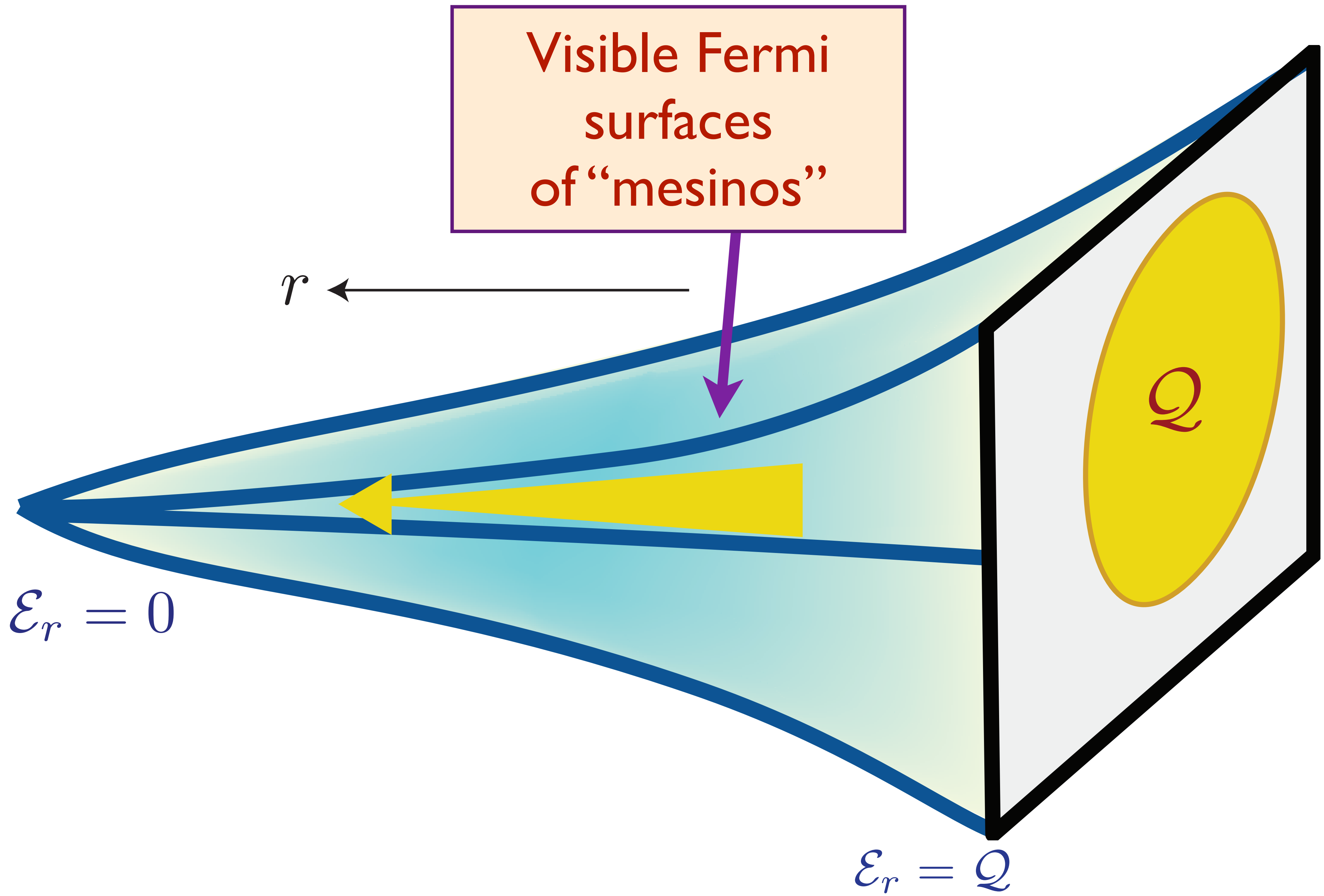
Holographic theory of a fractionalized-Fermi liquid (FL*)



S. Sachdev, *Phys. Rev. Lett.* **105**, 151602 (2010); *Phys. Rev. D* **84**, 066009 (2011)

A state with partial fractionalization, and partial electric flux exiting horizon: has a *small* Fermi surface of electrons

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)

Holography, fractionalization, and hidden Fermi surfaces

- Electric flux exiting the horizon corresponds to fractionalized component of the conserved density $\mathcal{Q}$, which is proposed to be associated with "hidden" Fermi surfaces of gauge-charged particles.

- Gauss Law and the "attractor" mechanism in the bulk
$\Leftrightarrow$ Luttinger theorem on the boundary theory.

“Complex entangled” states of quantum matter, *not* adiabatically connected to independent particle states

Gapped quantum matter

Spin liquids, quantum Hall states

Conformal quantum matter

Quantum critical points in antiferromagnets, superconductors, and ultracold atoms; graphene

Compressible quantum matter

Non-Fermi liquids, strange metals, Bose metals

Conclusions

Conformal quantum matter

- Holographic method offers new approaches to quantum critical transport, and non-equilibrium dynamics. Related to dynamics of black hole horizons.

Conclusions

Compressible quantum matter

- Obtained holographic representation as a doped conformal field theory. Yields models of non-Fermi liquids (NFL), fractionalized Fermi liquids (FL*), and Fermi liquids (FL) , in close correspondence with the phases expected from field theory