Fermion signs, entanglement and the strange metals

Jan Zaanen

plan

1. Reminder: the big picture of equilibrium AdS/CMT.

2. Holographic strange metals and infinite party entanglement.

3. Quantum critical phases, fractal nodes and entanglement entropy .

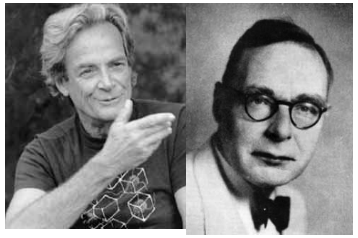
Quantum field theory = Statistical physics.

$$Z = \sum_{configs.} e^{-\frac{E_{config}}{k_B T}}$$

Path integral mapping

"Thermal QFT", Wick rotate:

$$t \to i\tau$$



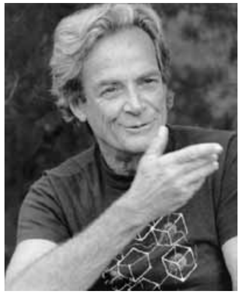
$$Z_\hbar = \sum_{worldhistories} e^{-\frac{S_{history}}{\hbar}}$$

But generically: the quantum partition function is not probabilistic: "sign problem", no mathematical control!

$$Z_\hbar = \sum_{worldhistories} (-1)^{history} e^{-\frac{S_{history}}{\hbar}}$$

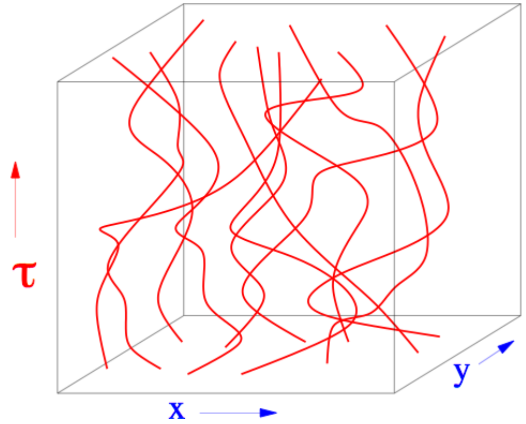
Fermions at a finite density: the sign problem.

Imaginary time first quantized path-integral formulation



$$\mathcal{Z} = \mathrm{Tr}\exp(-\beta\hat{\mathcal{H}}) = \int \mathrm{d}\mathbf{R}\rho(\mathbf{R},\mathbf{R};\beta)$$

$$\mathbf{R} = (\mathbf{r}_1,\ldots,\mathbf{r}_N) \in \mathbb{R}^{Nd}$$



$$\rho_{B/F}(\mathbf{R},\mathbf{R};\beta) = \frac{1}{N!}\sum_{\mathcal{P}}(\pm 1)^{\mathcal{P}}\rho_D(\mathbf{R},\mathcal{P}\mathbf{R};\beta) = \frac{1}{N!}\sum_{\mathcal{P}}(\pm 1)^{\mathcal{P}}\int_{\mathbf{R}\to\mathcal{P}\mathbf{R}}\mathcal{D}\mathbf{R}(\tau)\exp\left\{-\frac{1}{\hbar}\int_0^{\hbar/T}\mathrm{d}\tau\left(\frac{m}{2}\dot{\mathbf{R}}^2(\tau)+V(\mathbf{R}(\tau))\right)\right\}$$

Boltzmannons or Bosons:

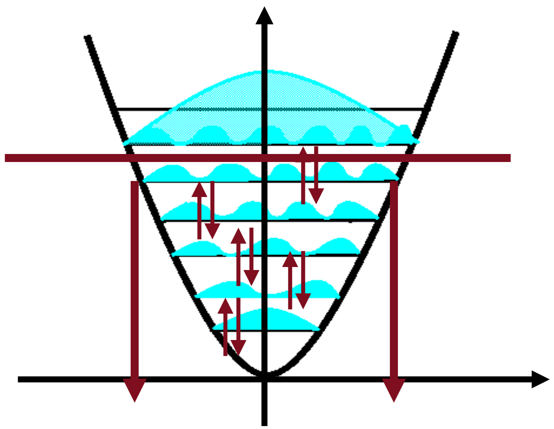
- integrand non-negative
- probability of equivalent classical system: (crosslinked) ringpolymers

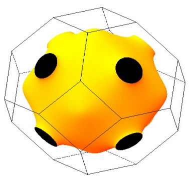
Fermions:

- negative Boltzmann weights
- non probablistic: NP-hard problem (Troyer, Wiese)!!!

Fermions: the tiny repertoire …

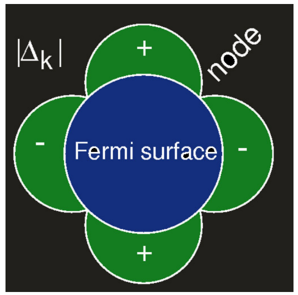
Fermiology

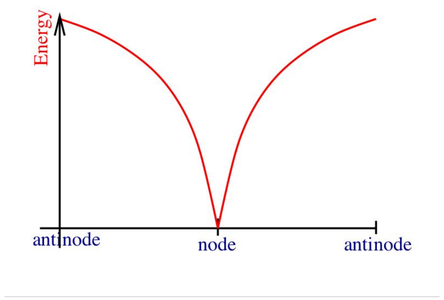




BCS superconductivity

$$\Psi_{BCS} = \Pi_k \left(u_k + v_k c^+_{k\uparrow} c^+_{-k\downarrow}\right) \left|vac.\right\rangle$$





29 years later: the "consensus document".

REVIEW

doi:10.1038/nature14165

From quantum matter to high-temperature superconductivity in copper oxides

B. Keimer[1], S. A. Kivelson[2], M. R. Norman[3], S. Uchida[4] & J. Zaanen[5]

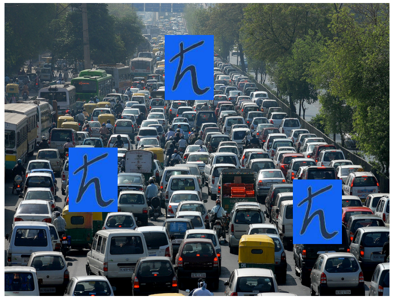
The discovery of high-temperature superconductivity in the copper oxides in 1986 triggered a huge amount of innovative scientific inquiry. In the almost three decades since, much has been learned about the novel forms of quantum matter that are exhibited in these strongly correlated electron systems. A qualitative understanding of the nature of the superconducting state itself has been achieved. However, unresolved issues include the astonishing complexity of the phase diagram, the unprecedented prominence of various forms of collective fluctuations, and the simplicity and insensitivity to material details of the 'normal' state at elevated temperatures.

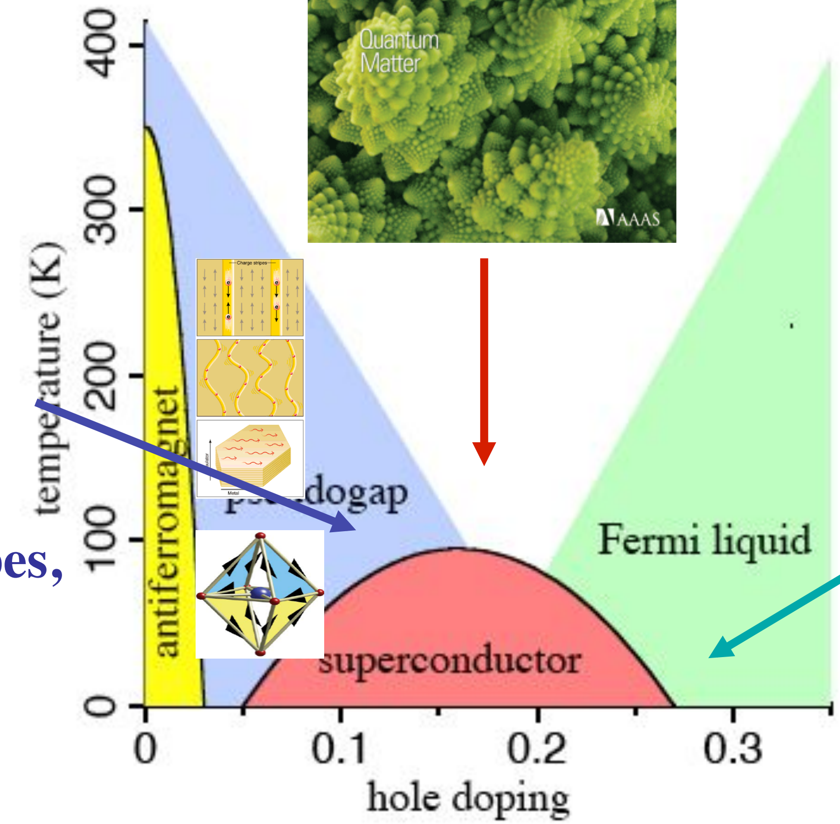
The high Tc enigma.

The clash: the quantum critical metal

… which is good for superconductivity!

The quantized traffic jam



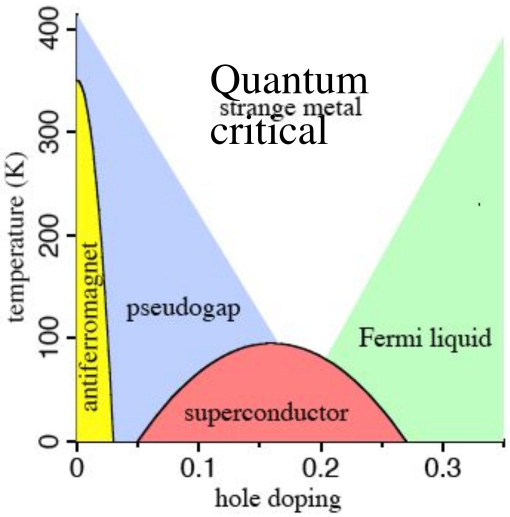


Exotic orders: stripes, orbital currents, nematics …

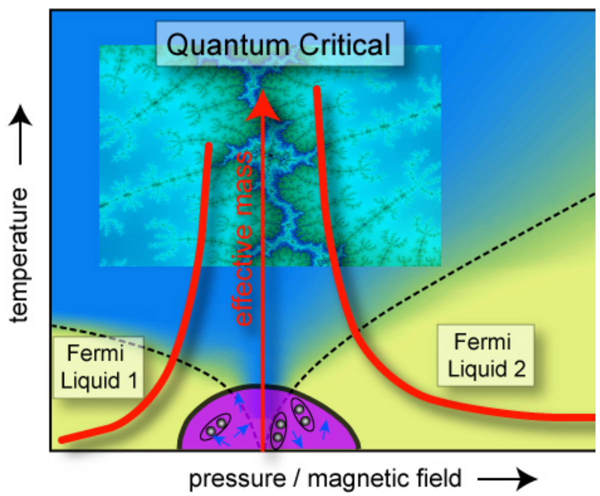
The quantum fog (Fermi gas) returns

A universal (?) phase diagram

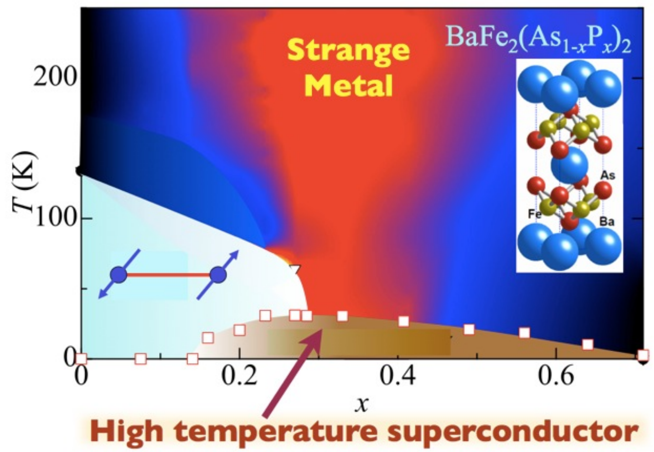
High Tc superconductors



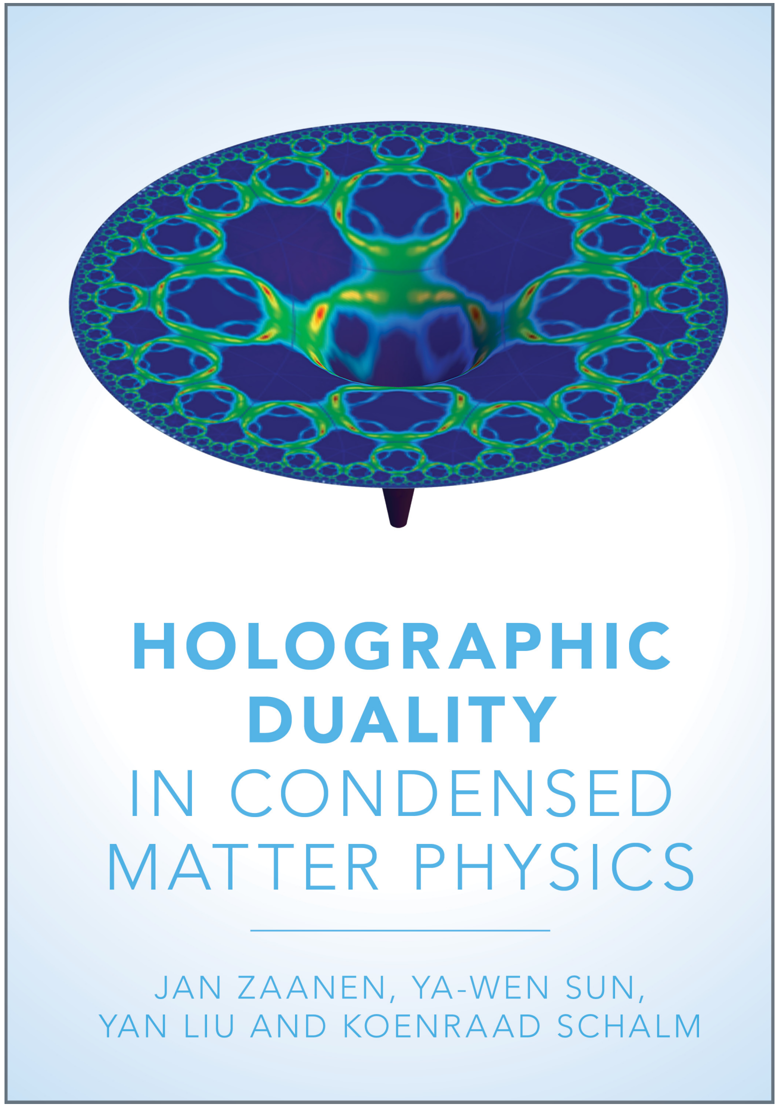
Heavy fermions



Iron superconductors (?)



Book sales …

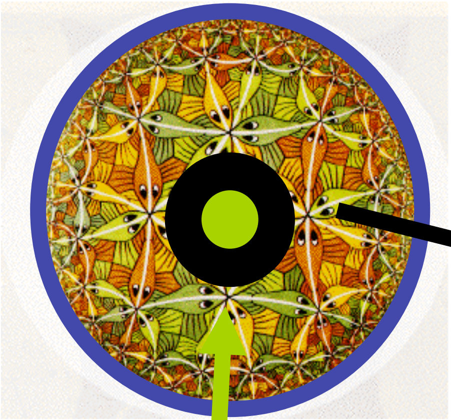


Cambridge University Press

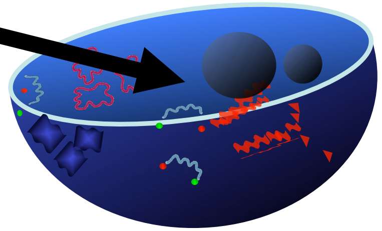
It is 600 pages and only € 70,99!

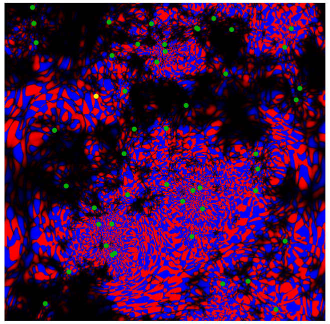
The charged back hole encoding for finite density (2008 - ????)

Anti de Sitter universe.



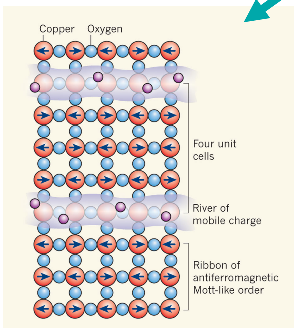
Finite density quantum matter:



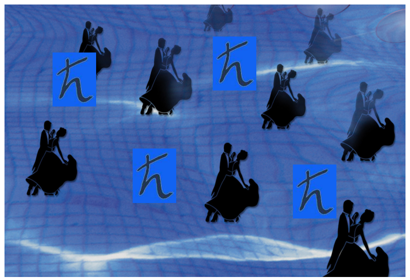


Holographic strange metals

Charged black hole in the middle



Stripy pseudogap orders

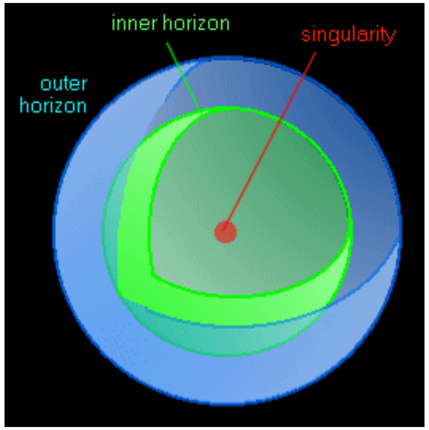


High Tc superconductors

Emergent Fermi liquids

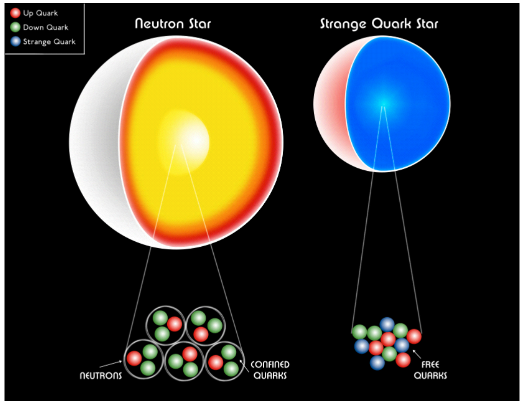
The holographic stable states: uncollapsing in an AdS "star".

(Reissner-Nordstrom)
"Black hole like object"



"fractionalized", "unstable": strange metal

"star like object"



"uncollapse"

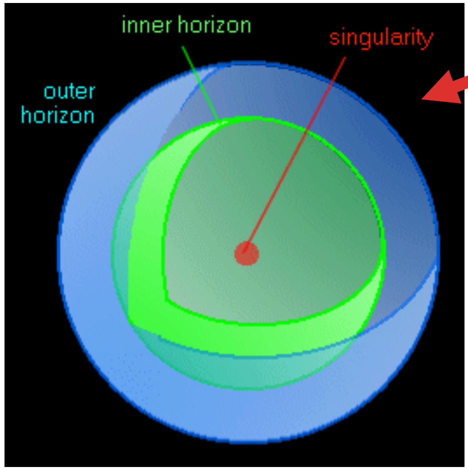
Phase transition

"Cohesive state":

Symmetry breaking: superconductor, crystal ("scalar hair")

Fermi-liquid ("electron star")

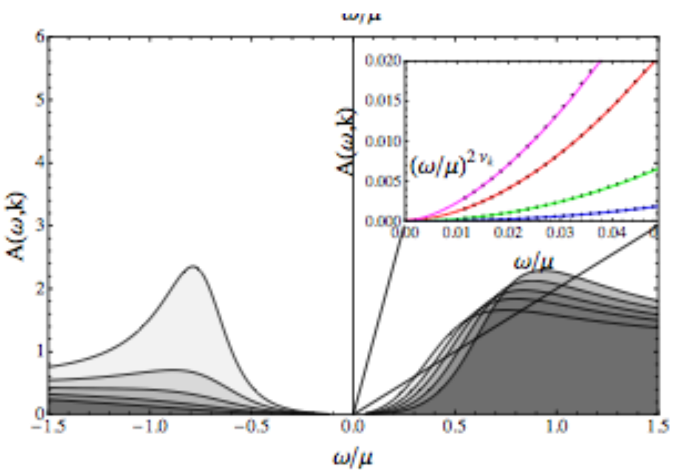
Finite density: the Reissner-Nordstrom strange metals (Liu et al.).



Near-horizon geometry of the extremal RN black hole:

- Space directions: flat, codes for simple Galilean invariance in the boundary.

- Time-radial(=scaling) direction: emergent AdS_2, codes for emergent temporal scale invariance!



Fermion spectral functions:

$$A(k,\omega) \propto G''_{AdS_2}(k,\omega) \propto \omega^{2\nu_k}$$

$$\nu_k = \frac{1}{\sqrt{6}}\sqrt{k^2 + \frac{1}{\xi^2}}$$

"Un-particle physics!"

"Scaling atlas" of holographic quantum critical phases.

Kiritsis

Deep interior geometry sets the scaling behavior in the emergent deep infrared of the field theory. Uniqueness of GR solutions:

1. "Cap-off geometry" = confinement: conventional superconductors, Fermi liquids ….

2. Geometry survives: "hyperscaling violating geometries" (Einstein – Maxwell – Dilaton – Scalar fields – Fermions).

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

$$x_i \to \zeta x_i, \quad t \to \zeta^z t, \quad ds \to \zeta^{\theta/d} ds$$

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

Quantum critical phases with unusual values of:

$z =$ **Dynamical critical exponent**

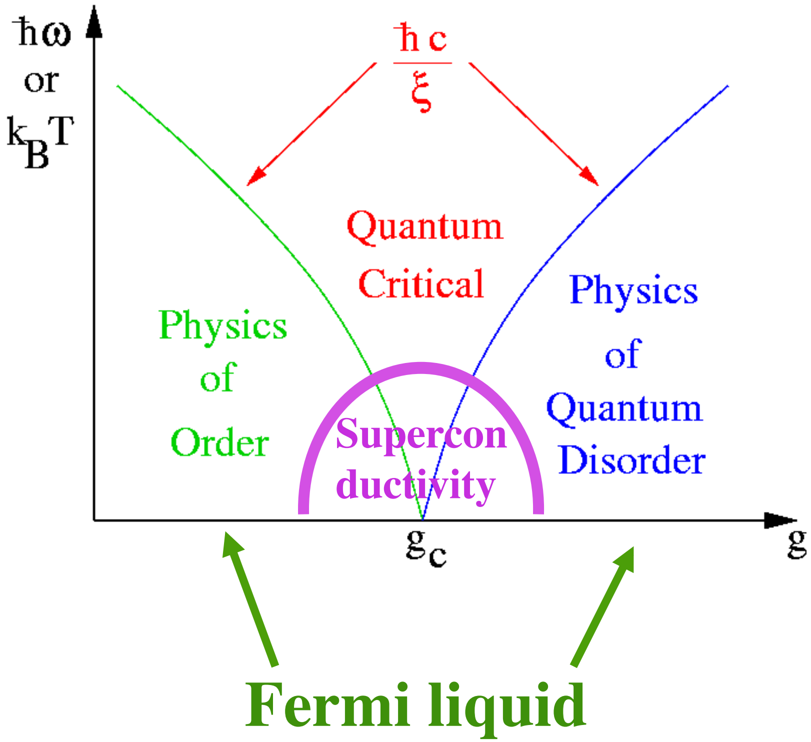
$\theta =$ **Hyperscaling violation exponent**

$\zeta =$ **Charge exponent**

Hertz-Millis metallic “Quantum Critical Point”

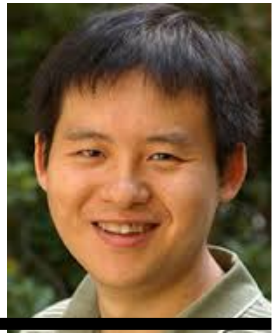
Assertion: in the “UV” a *Fermi-liquid* is formed co-existing with an electronic *order parameter* (e.g. magnet) interacting via a Yukawa coupling.

The *order parameter* is subjected to *a bosonic quantum phase transition*: always isolated unstable fixed point (stat phys rule book).



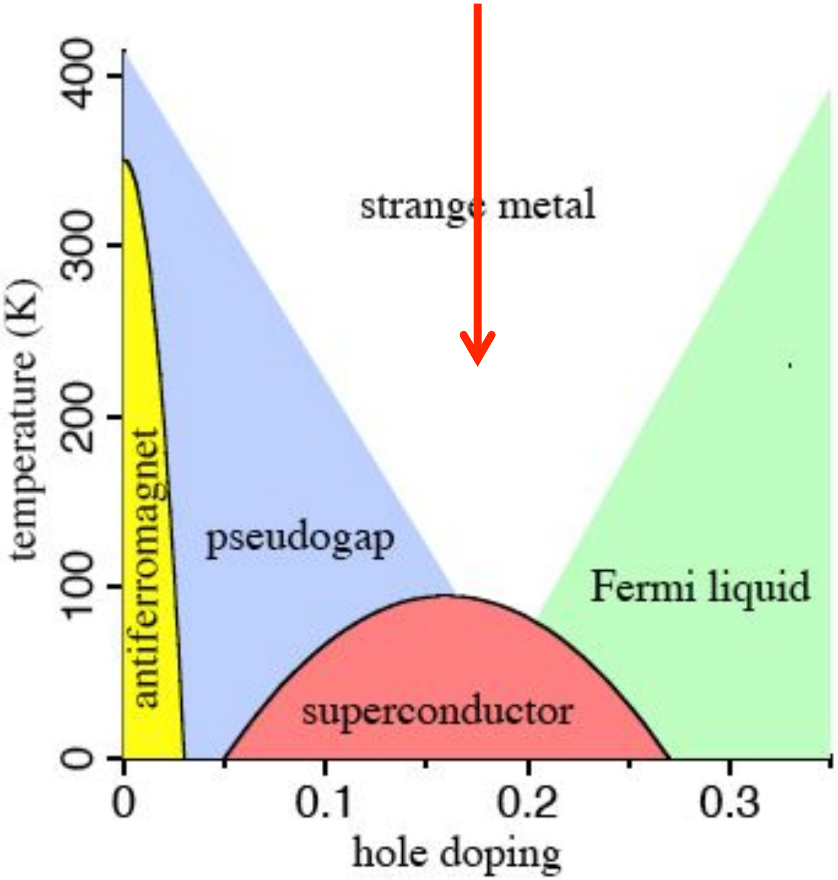
Electrons: *Fermi-gas* = heat bath *damping bosonic critical fluctuations*.

The unstable conformal metal of finite density holography.



Hong Liu

Conformal metal: quantum *critical* fermionic *phase not requiring fine tuning!*



Characterised by *non-bosonic scaling properties*: large (infinite) z, hyperscaling violation, charge …

Intrinsically *very unstable*: "mother" of Fermi-liquids, superconductors, stripes, CDW's, loop currents, electronic nematics, …

The finite temperature state: governed by *Planckian dissipation*.

plan

1. **Reminder: the big picture of equilibrium AdS/CMT.**

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3. **Quantum critical phases, fractal nodes and entanglement entropy .**

"The classical condensates: from crystals to Fermi-liquids."

States of matter that we understand are product!

$$\left|\Psi_0\{\Omega_i\}\right\rangle = \Pi_i \hat{X}_i^+(\Omega_i)\left|vac\right\rangle$$

- Crystals: put atoms in real space wave packets $X_i^+(R_i^0) \propto e^{(R_i^0-r)^\wedge 2/\sigma^2}\psi^+(r)$

- Magnets: put spins in generalized coherent state

$$X_i^+(\vec{n}_i) \propto e^{i\varphi_i/2}\cos(\theta_i/2)c_{i\uparrow}^+ + e^{-i\varphi_i/2}\sin(\theta_i/2)c_{i\downarrow}^+$$

- Superconductors/superfluids: put bosons/Cooper pairs in coherent superposition

$$X_{k/i}^{\ \ +} \propto u_k + v_k c_{k\uparrow}^+ c_{-k\downarrow}^+, \quad u_i + v_i e^{i\varphi_i} b_i^+$$

- Fermi gas/liquid special , but only "Fermi-Dirac entanglement"

$$\left|\Psi_{FL}\right\rangle = \Pi_k^{k_F} c_k^+ \left|vac\right\rangle$$

Quantum matter.

“Macroscopic stuff that can quantum compute all by itself”

$$|\Psi\rangle = \sum_{configs} A_{configs} |configs\rangle$$

- Topological incompressible systems, no low energy excitations but the whole carries quantum information: fractional quantum Hall, top. Superconductors/insulators (Majorana’s, theta vacuum, ..)

- Compressible systems: strongly interacting bosonic quantum critical states (CFT’s) have dense long range entanglements (this meeting)

- Compressible systems: are the strange metals of this kind??

Strongly interacting fermions at finite density: the fermion signs as entanglement resource!

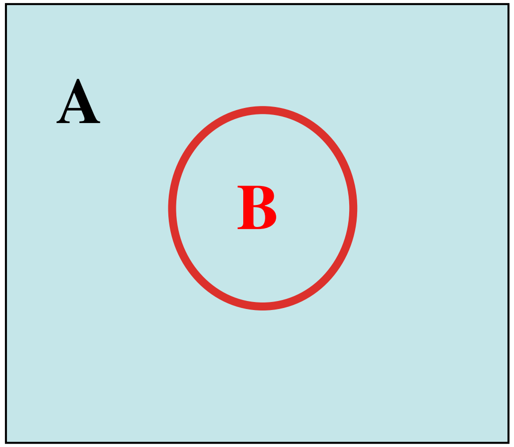
Bipartite entanglement entropy and quantum field theory.

Wilczek

$$\rho_A = Tr_B[\,\rho\,]$$

$$S_{vN} = Tr[\rho_A \ln \rho_A]$$

Measure of entanglement of degrees of freedom in spatial volume B with those in A.

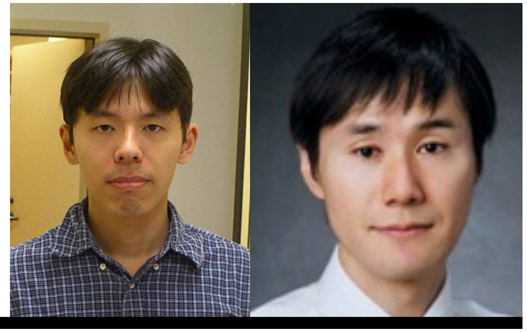


Generic energy eigenstates: S_{vN} scales with volume L^d of B.

Ground states of bosonic systems: S_{vN} scales with the area L^{d-1} of B.

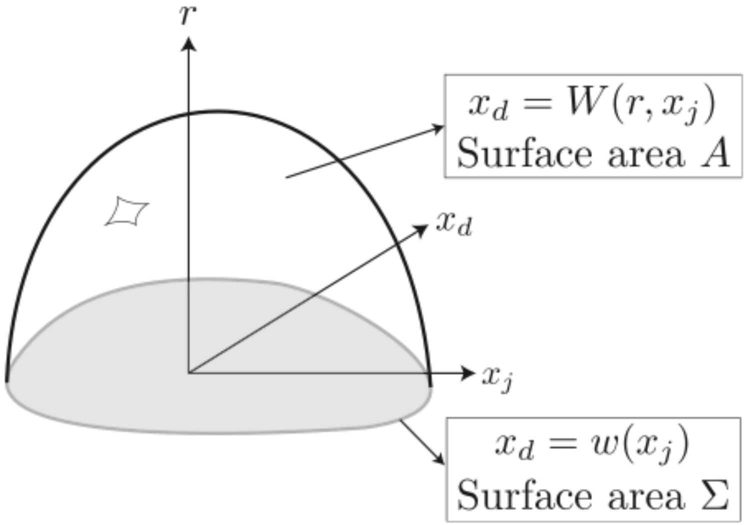
Fermi gas: longer ranged "signful" entangled $S_{vN} \sim L^{d-1} \ln(L^{d-1})$

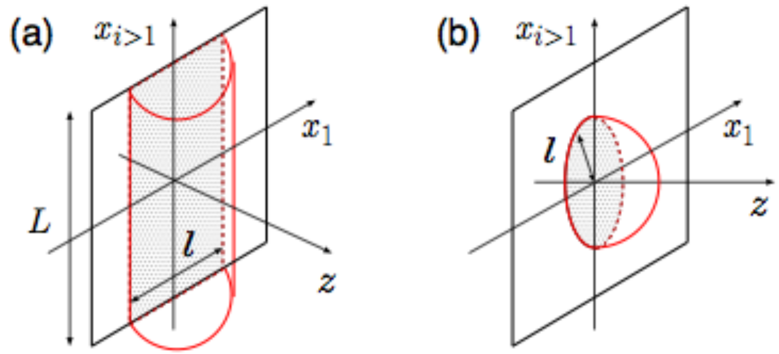
Entanglement entropy versus AdS/CFT.



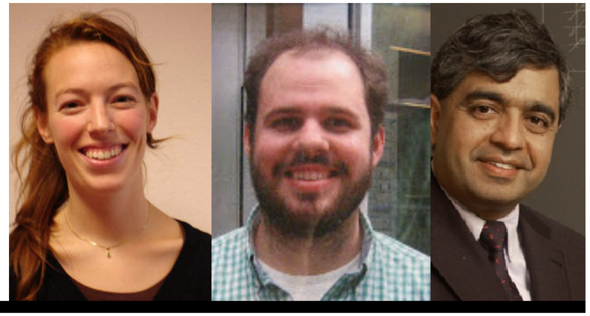
$$\rho_A = Tr_B[\rho] \qquad S_{vN} = Tr[\rho_A \ln \rho_A]$$

The spatial bipartite entanglement entropy in the boundary is dual to the area of the minimal surface in the bulk, bounded by the cut in the space of the boundary





Holographic strange metal entanglement entropy.



Huijse Swingle Sachdev

Einstein-Maxwell-Dilaton bulk => “hyperscaling violating geometry” (Kiritsis et al.): arXiv:1112.3314

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

Boundary: interpolating between “normal” and RN strange metals.

$$x_i \to \zeta x_i, \quad t \to \zeta^z t, \quad ds \to \zeta^{\theta/d} ds \qquad\qquad S \propto T^{(d-\theta)/z}$$

Entanglement entropy:

$S_{vN} \propto L^{d-1} \quad ,\theta < d-1$	**Bosonic fields**
$S_{vN} \propto L^{d-1}\ln L^{d-1}, \theta = d-1$	**Fermi liquid-like**
$S_{vN} \propto L^{\theta} \quad , d-1 < \theta < d$	**But this is longer ranged !**

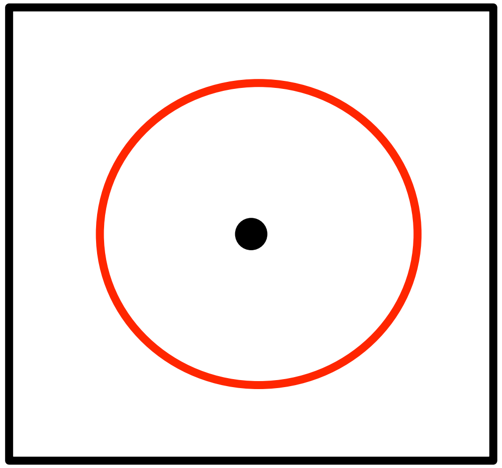
Hyperscaling violation.

Bosonic field theories: single point of masslessness in momentum space.

$$\theta = 0$$

Fermi gas: surface of masslessness with dimension d-1 in momentum space (Fermi-surface).

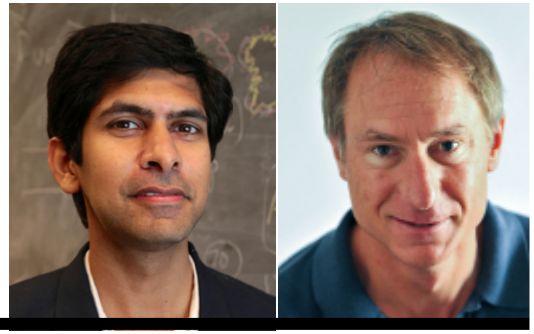
$$\theta = d - 1$$



Very exotic in Ginzburg-Landau-Wilson classical/bosonic physics. For Fermi gas rooted in "poor man's" antisymmetrization entanglement!

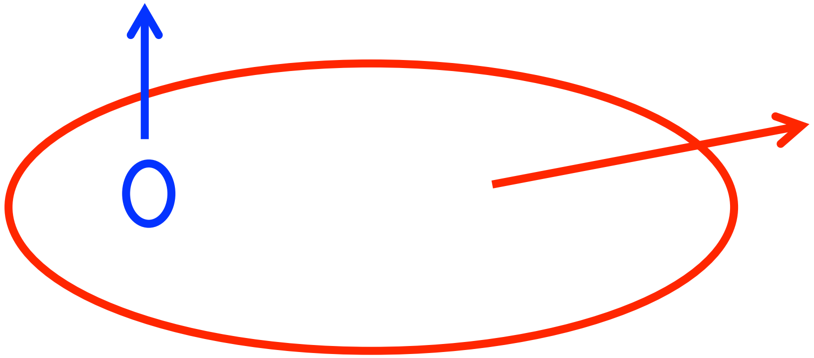
$$|k_1 k_2 \cdots k_n\rangle = \frac{1}{\sqrt{N}} \sum_P \eta_P |k_1(\mathcal{P}1)\rangle |k_2(\mathcal{P}2)\rangle \cdots |k_N(\mathcal{P}N)\rangle$$

Fermion signs and dense entanglement …



Grover Fisher
arXiv:1412.3534

S_{vN} area law: ground states of "sign-free" systems (bosons, tensor network states ..)



Energy eigenstates:

$$|\Psi_i\rangle = \sum_{conf} (-1)^{i,conf} |A^i_{conf}| |conf\rangle$$

$$(-1)^{i,conf} =$$

- Antisymmetrization => area log area S_{vN} (Fermi gas)

- Random => Volume S_{vN} (typical excited states)

The *quantum critical metallic phases* of holography are characterized by dense "sign driven" entanglement as characterized by the hyperscaling violation exponent!

plan

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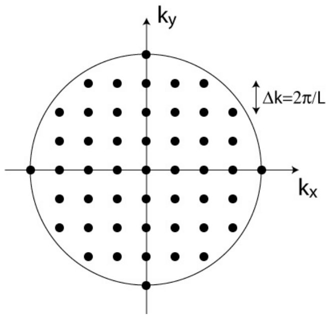
The nodal hypersurface

Antisymmetry of the wave function

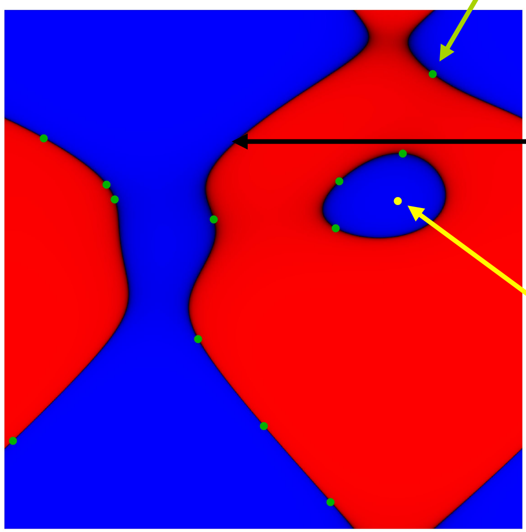
$$\Psi(\mathbf{r}_1, \ldots, \mathbf{r}_i, \ldots, \mathbf{r}_j, \ldots, \mathbf{r}_N) = -\Psi(\mathbf{r}_1, \ldots, \mathbf{r}_j, \ldots, \mathbf{r}_i, \ldots, \mathbf{r}_N)$$

Free Fermions

$$\Psi_0(\mathbf{R}) \sim \mathrm{Det}\left(e^{i\mathbf{k}_i\mathbf{r}_j}\right)_{ij}$$



d=2



Pauli hypersurface

$$P = \bigcup_{i \neq j} P_{ij}$$

$$P_{ij} = \{\mathbf{R} \in \mathbb{R}^{Nd} | \mathbf{r}_i = \mathbf{r}_j\}$$

$$\mathrm{dim}P = Nd - d$$

Nodal hypersurface

$$\Omega = \{\mathbf{R} \in \mathbb{R}^{Nd} | \Psi(\mathbf{R}) = 0\}$$

$$\mathrm{dim}\Omega = Nd - 1$$

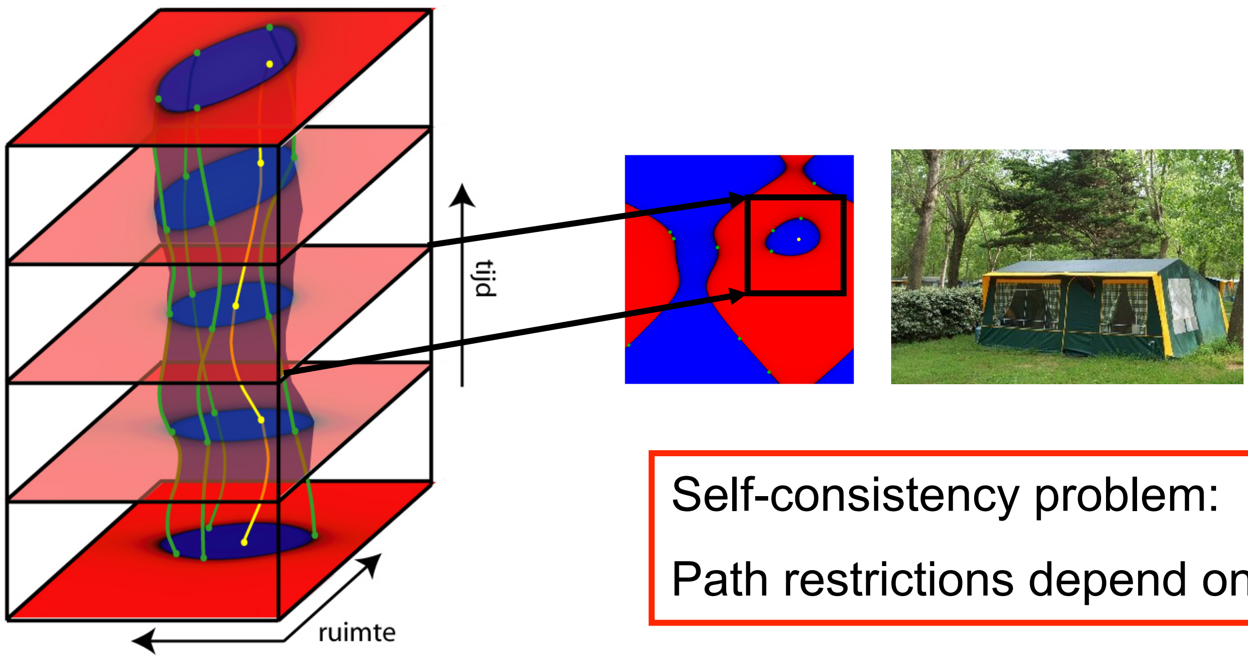
Test particle

Constrained path integrals

Formally we can solve the sign problem!!

$$\rho_F(\mathbf{R},\mathbf{R};\beta) = \frac{1}{N!}\sum_{\mathcal{P},\text{even}} \int_{\gamma:\mathbf{R}\to\mathcal{P}\mathbf{R}}^{\gamma\in\Gamma(\mathbf{R},\mathcal{P}\mathbf{R})} \mathcal{D}\mathbf{R}(\tau)\exp\left\{-\frac{1}{\hbar}\int_0^{\hbar/T} \mathrm{d}\tau\left(\frac{m}{2}\dot{\mathbf{R}}^2(\tau)+V(\mathbf{R}(\tau))\right)\right\}$$

$$\Gamma(\mathbf{R},\mathbf{R}') = \{\gamma:\mathbf{R}\to\mathbf{R}' | \rho_F(\mathbf{R},\mathbf{R}(\tau);\tau)\neq 0\}$$



Ceperley, J. Stat. Phys. (1991)

Self-consistency problem:

Path restrictions depend on ρ_F !

Reading the worldline picture

Fermi-energy: confinement energy imposed by local geometry

$$l^2(\tau) = \langle (\mathbf{r}_i(\tau) - \mathbf{r}_i(0))^2 \rangle = 2d\mathcal{D}\tau = 2d\frac{\hbar}{2m}\tau$$

$$l^2(\tau_c) \simeq r_s^2 \rightarrow \tau_c \simeq \frac{1}{2d}\frac{2m}{\hbar}n^{-2/d}$$

$$\hbar\omega_c = \frac{\hbar}{\tau_c} \simeq d\frac{\hbar^2}{2m}n^{2/d} \simeq E_F$$

Average node to node spacing

$$\sim r_s = \left(\frac{V}{N}\right)^{1/d} = n^{-1/d}$$

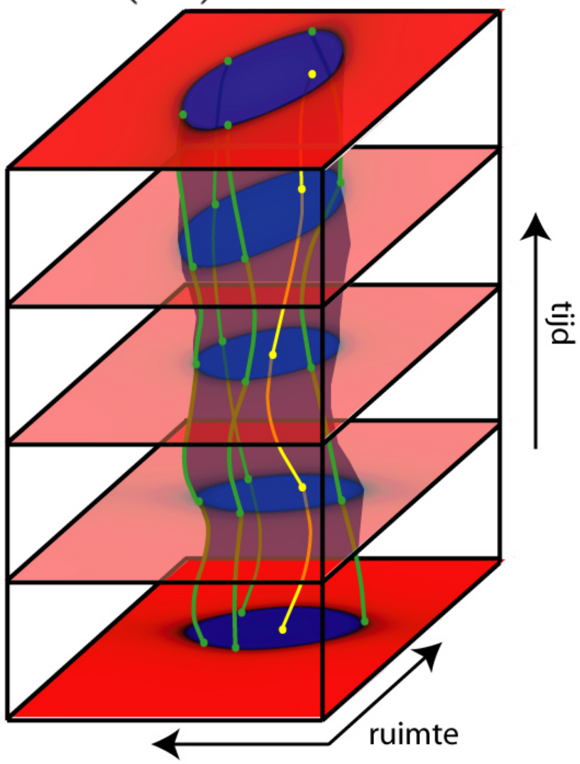
Fermi surface encoded globally: $\rho_F = Det\left(e^{ik_i r_j}\right) = 0$

Change in coordinate of one particle changes the nodes everywhere

Finite T: $\rho_F = (4\pi\lambda\beta)^{-dN/2} Det\left[\exp\left(-\frac{(r_i - r_{j0})^2}{4\lambda\tau}\right)\right]$

$$\lambda = \hbar^2/(2M)$$

Non-locality length: $\lambda_{nl} = v_F \tau_{inel} = v_F \left(\frac{E_F}{k_B T}\right)\left(\frac{\hbar}{k_B T}\right)$



Key to fermionic quantum criticality

Kruger JZ

Phys. Rev. B **78**, 035104 (2008)

At the QCP scale invariance, no E_F → **Nodal surface has to become fractal !!!**

Turning on the backflow

Nodal surface has to become fractal !!!

↓

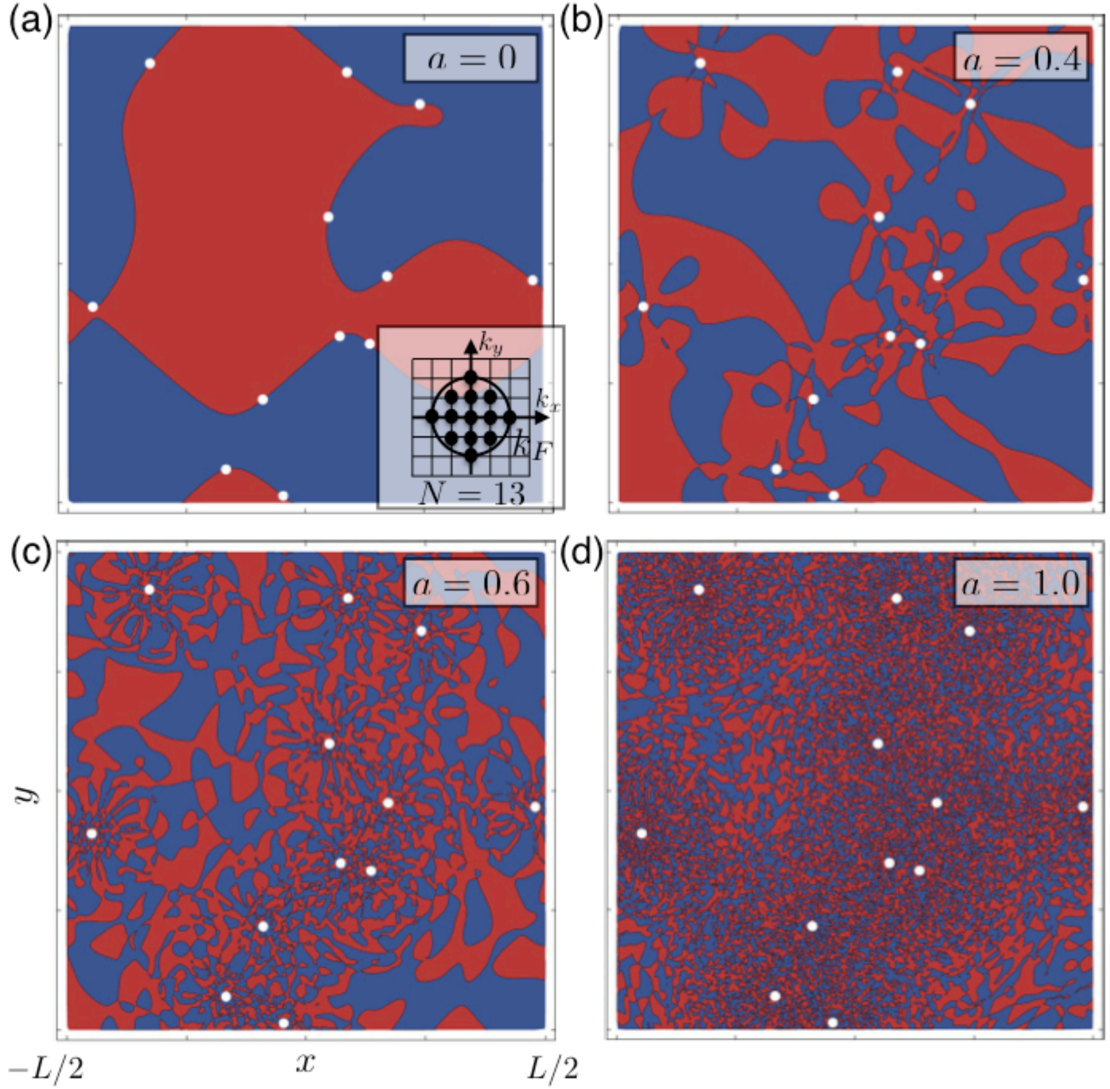
Try backflow wave functions

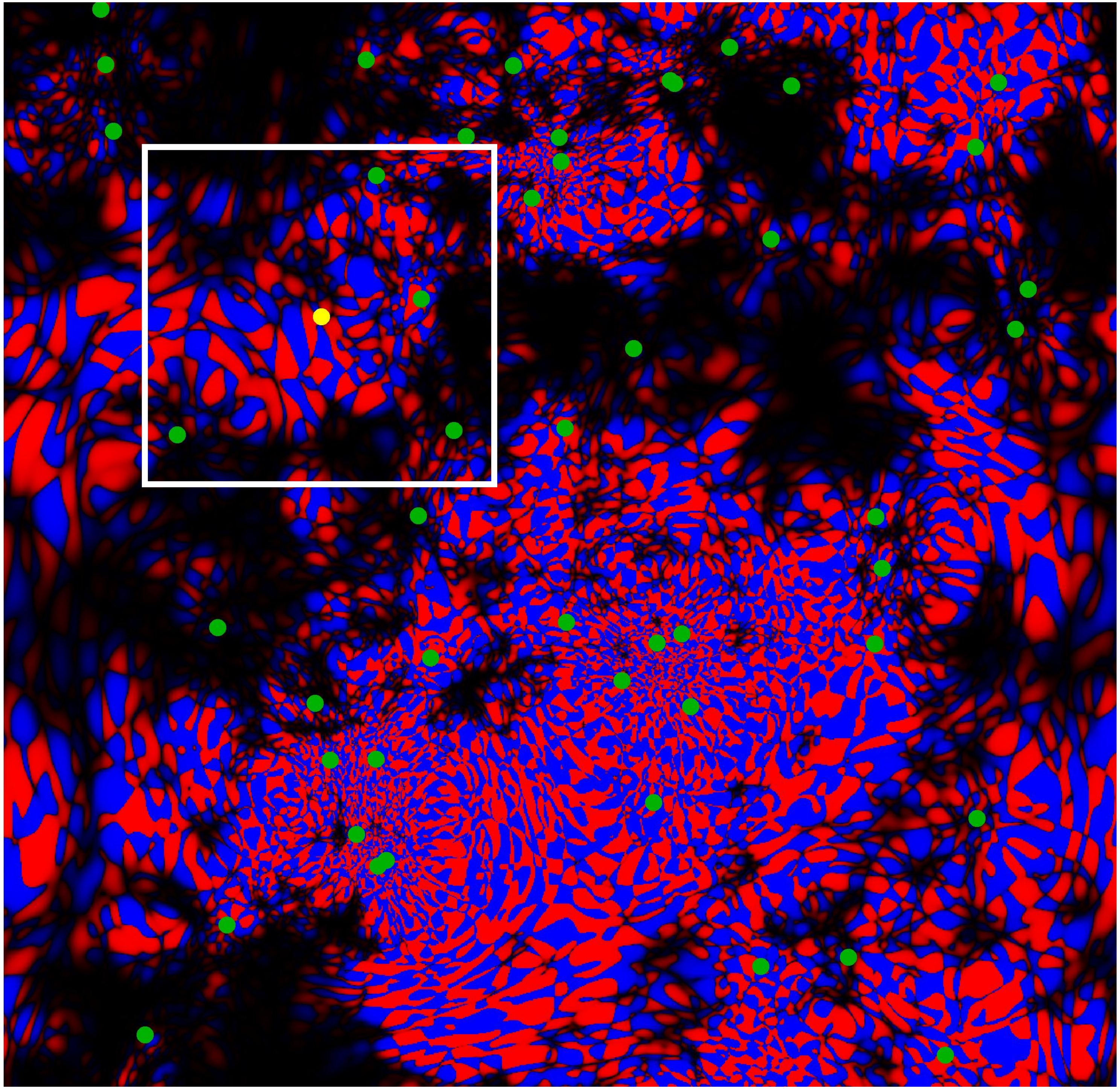
$$
\begin{aligned}
\psi_{bf}(\mathbf{R}) \quad &\sim \quad \mathrm{Det}\left(e^{i\mathbf{k}_i \tilde{\mathbf{r}}_j}\right)_{ij} \\
\tilde{\mathbf{r}}_j \quad &= \quad \mathbf{r}_j + \sum_{l(\neq j)} \eta(r_{jl})(\mathbf{r}_j - \mathbf{r}_l)
\end{aligned}
$$

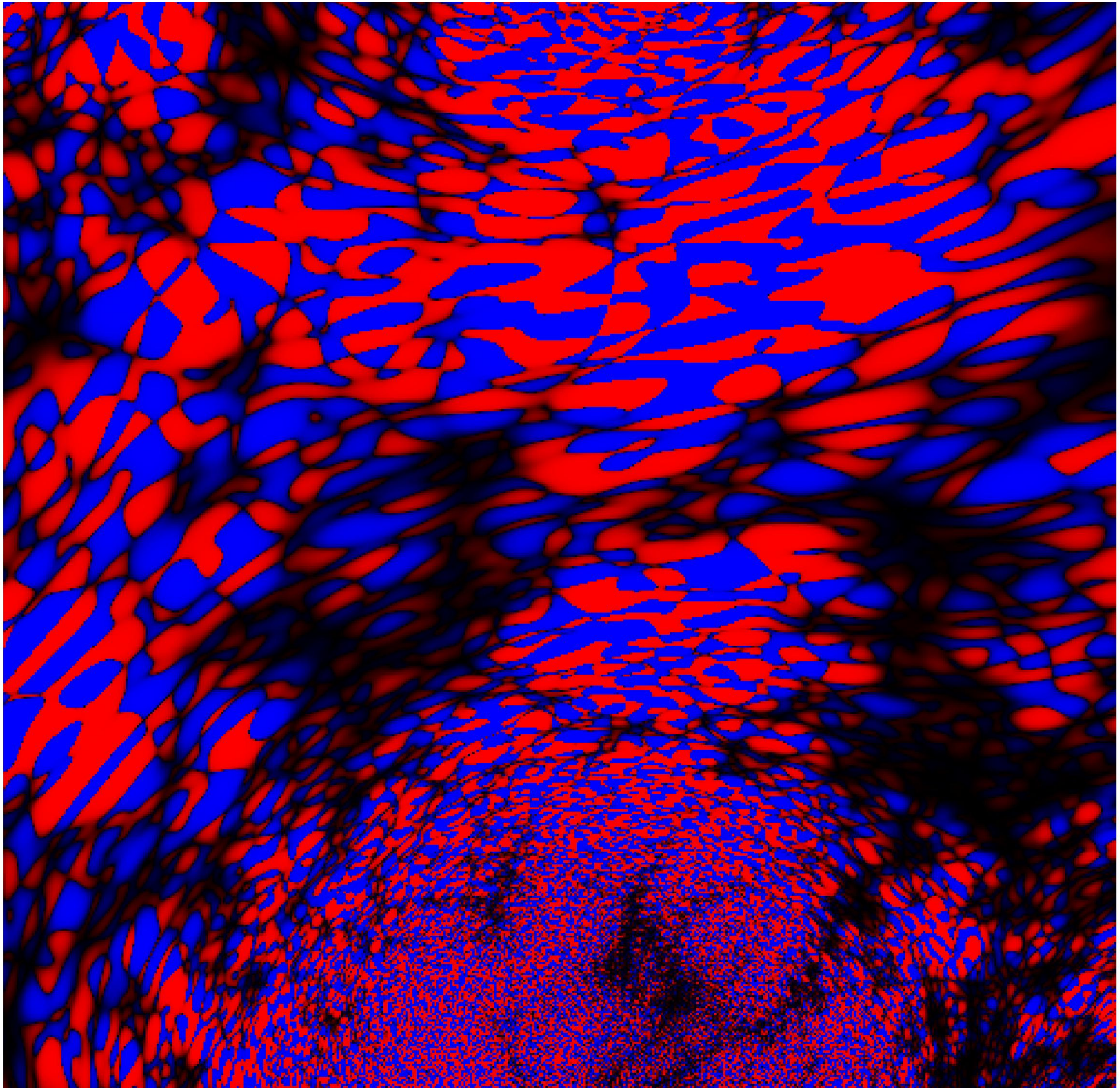
$$
\eta(r) = \frac{a^3}{r^3 + r_0^3}
$$

Collective (hydrodynamic) regime:

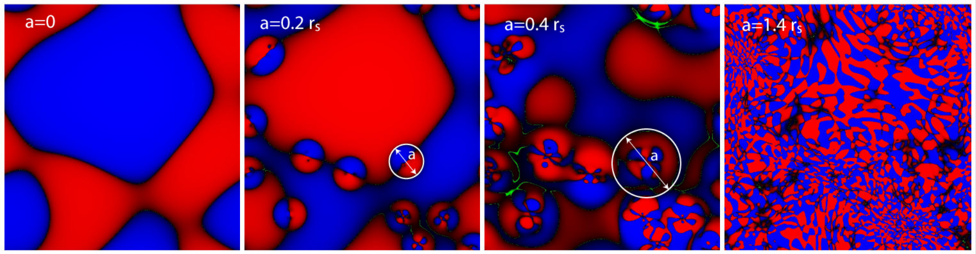
$$
a \gg r_s
$$



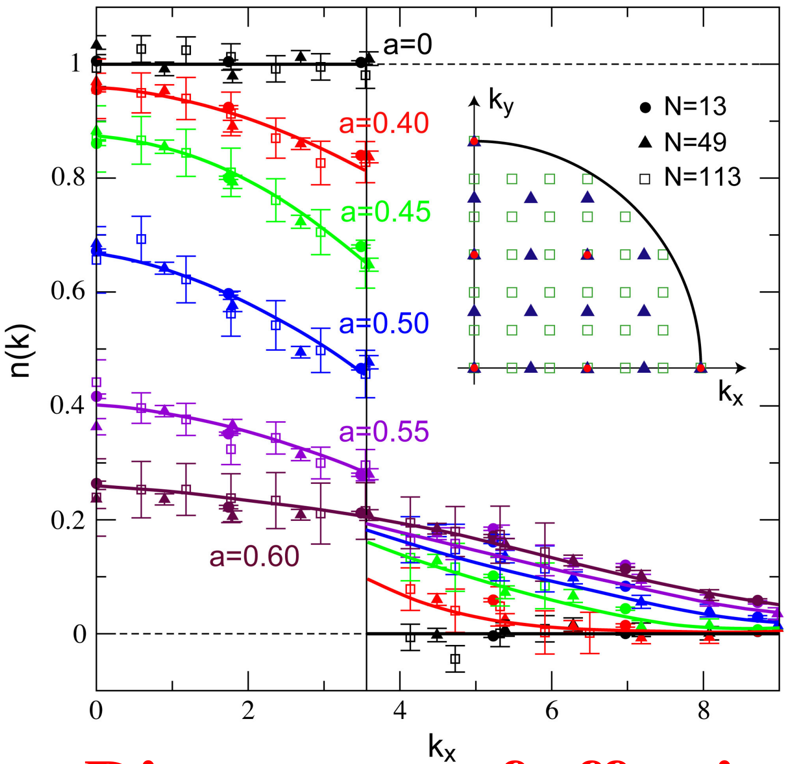


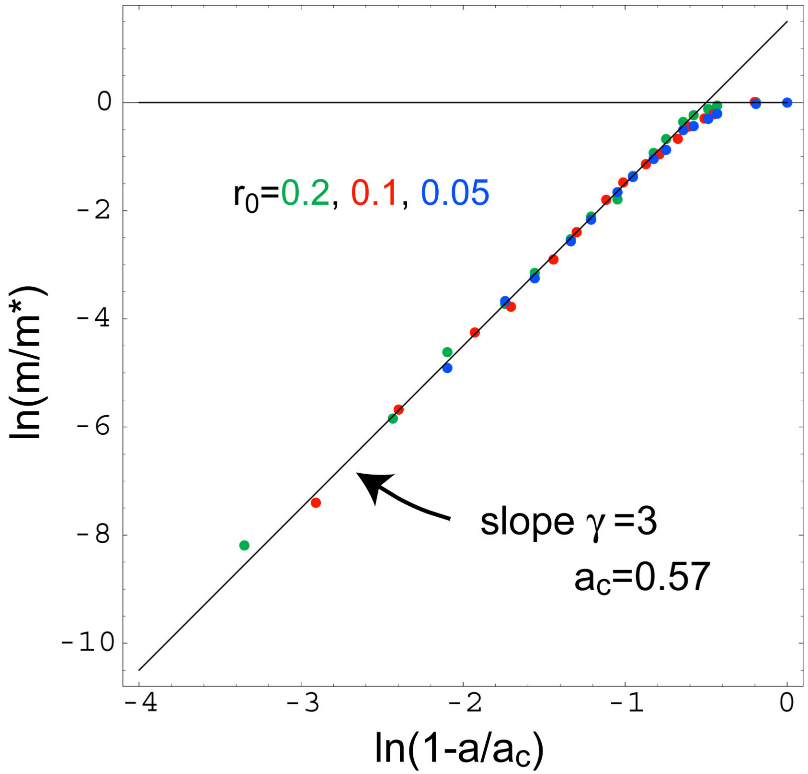


MC calculation of n(k)



$$\frac{m}{m^*} \propto \left(1 - \frac{a}{a_c}\right)^3$$





Divergence of effective mass as $a \rightarrow a_c$

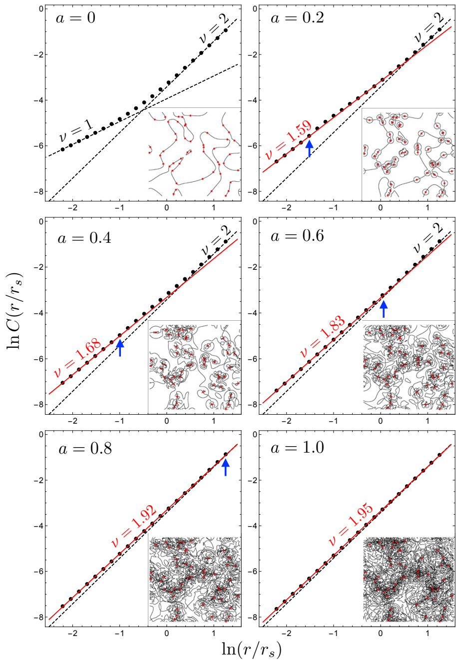
Haussdorff dimension nodal surface (arXiv:1605.02477).

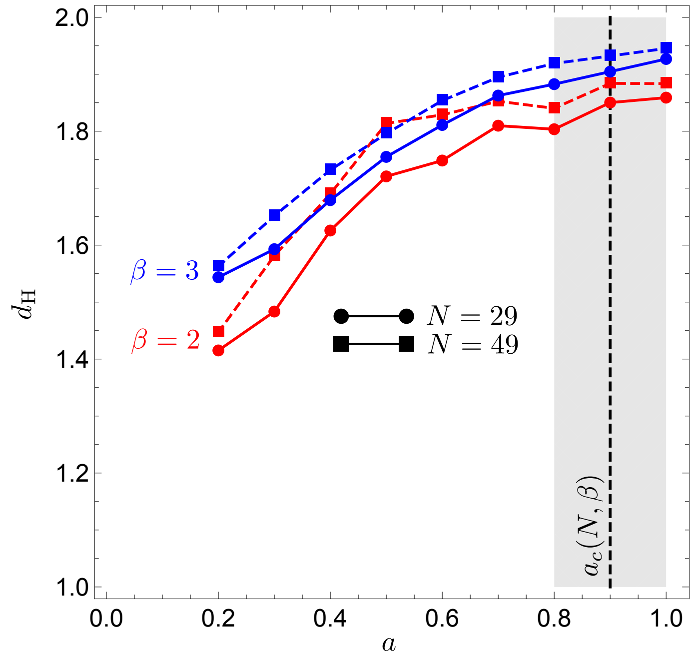
Kaplis

Kruger

$$\Psi(\boldsymbol{r}_1, \ldots, \boldsymbol{r}_N) = \mathcal{N} \det \left(e^{\imath \boldsymbol{k}_i \cdot \tilde{\boldsymbol{r}}_j} \right)$$

$$\tilde{\boldsymbol{r}}_i = \boldsymbol{r}_i + \sum_{j(\neq i)} \eta(|\boldsymbol{r}_i - \boldsymbol{r}_j|)(\boldsymbol{r}_i - \boldsymbol{r}_j) \quad \eta(r) = a^\beta / \left(r^\beta + r_0^\beta \right)$$

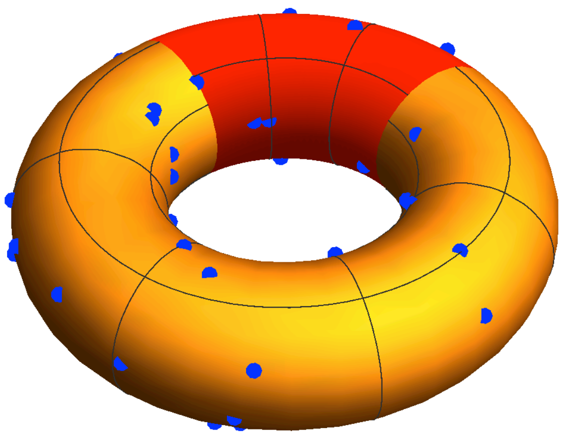




Computing the second Renyi entropy.

Kaplis Kruger

Second Renyi entropy: leading contribution scales like vN entropy.



$$S^q(z) = \frac{\ln(Tr\rho_A^q)}{1-q}, \quad q = 2$$

$$\rho(\mathbf{R}, \mathbf{R}') = \psi^*(\mathbf{R})\psi(\mathbf{R}')$$

$$\psi_{bf}(\mathbf{R}) \sim \text{Det}\left(e^{i\mathbf{k}_i\tilde{\mathbf{r}}_j}\right)_{ij}$$

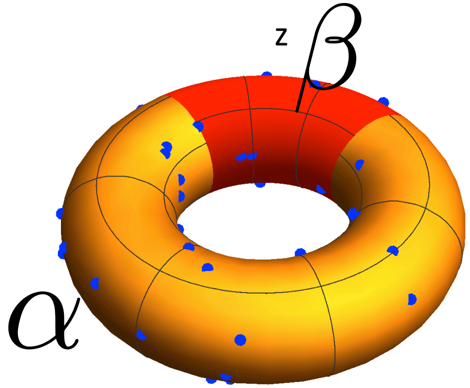
$$\tilde{\mathbf{r}}_j = \mathbf{r}_j + \sum_{l(\neq j)} \eta(r_{jl})(\mathbf{r}_j - \mathbf{r}_l)$$

Backflow range exponent “eta” (=3 for hydro backflow) : $\eta(r) = \frac{a^\eta}{r^\eta + r_0^\eta}$

Computing the second Renyi entropy.

Kaplis

Kruger



Hastings et al., PRL **104**, 157201 (2010):

$$\rho_A(\alpha,\alpha') = \sum_\beta \Psi^*(\alpha,\beta)\Psi(\alpha',\beta),$$

$$\hat{\mathrm{Swap}}_B|\alpha,\beta\rangle|\alpha',\beta'\rangle = |\alpha,\beta'\rangle|\alpha',\beta\rangle$$

$$e^{-S_2} = \sum_{\alpha\alpha'\beta\beta'} \Psi^*(\alpha,\beta)\Psi(\alpha',\beta)\Psi^*(\alpha',\beta')\Psi(\alpha,\beta') = \langle \hat{\mathrm{Swap}}_B\rangle$$

High dimensional integral, average $F(\alpha,\beta;\alpha',\beta') = \dfrac{\Psi(\alpha',\beta)\Psi(\alpha,\beta')}{\Psi(\alpha,\beta)\Psi(\alpha',\beta')}$

over Markov chains with probability distribution:

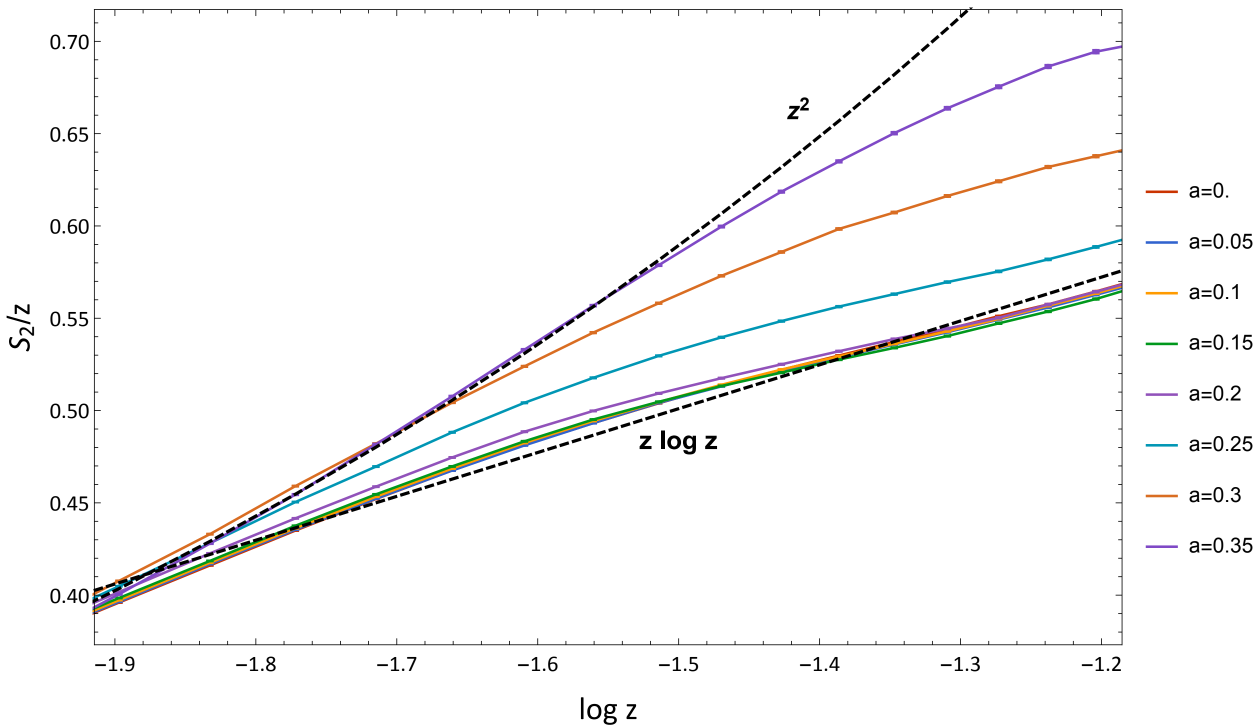
$$P(\alpha,\beta;\alpha',\beta') = |\Psi(\alpha,\beta)|^2\cdot|\Psi(\alpha',\beta')|^2 = |\Psi(\boldsymbol{r}_1,\ldots\boldsymbol{r}_N)|^2\cdot|\Psi(\boldsymbol{r}'_1,\ldots,\boldsymbol{r}'_N)|^2.$$

Fractal nodes and entanglement entropy.


Kaplis Kruger

Second Renyi entropy: $S^q(z) = \frac{\ln(Tr\rho_A^q)}{1-q}, \quad q = 2$

Hydrodynamical backflow, for increasing backflow length a (a_c =0.5):



Finite size scaling Reny Entropy (arXiv:1605.02477).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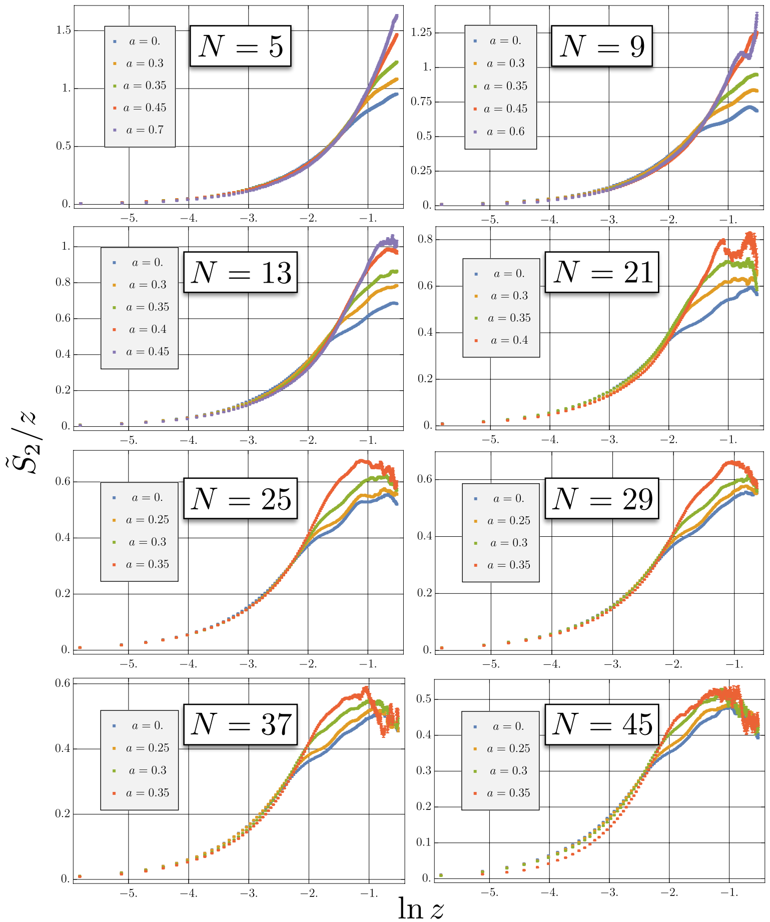
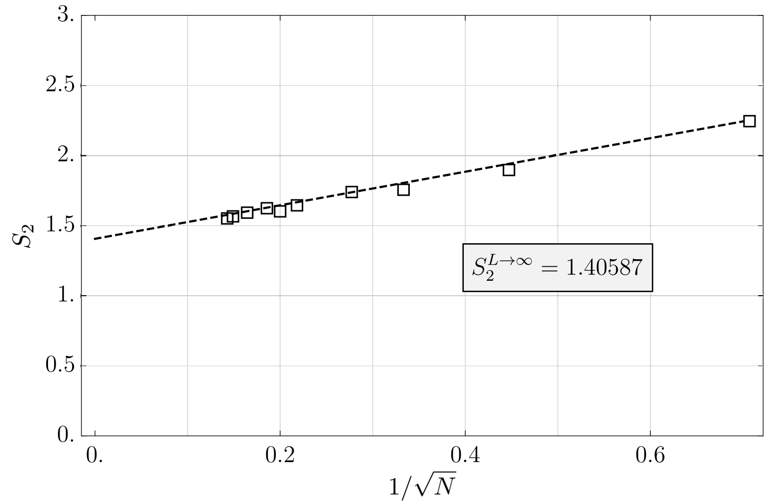
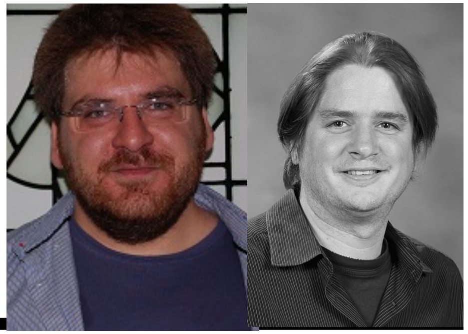


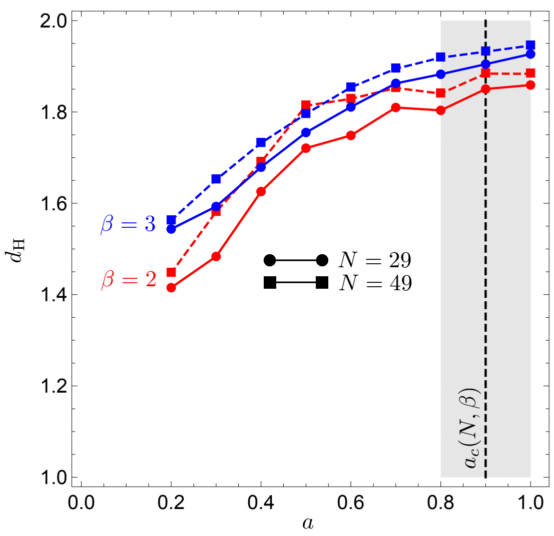


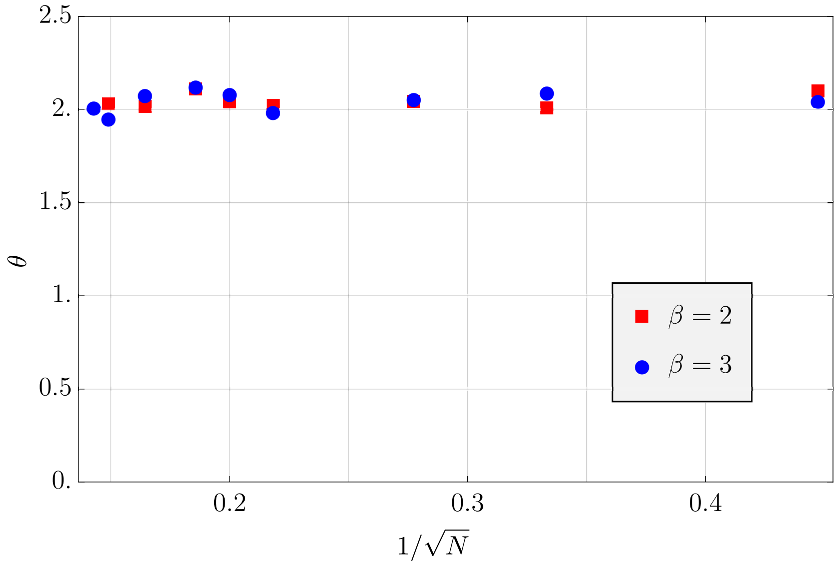
Alarmingly fast convergence with particle number!

Fractal nodes and the Reny Entropy (arXiv:1605.02477).



Kaplis Kruger





It is always volume regardless the Haussdorff dimension of the fractal nodal surface!

Conclusions.

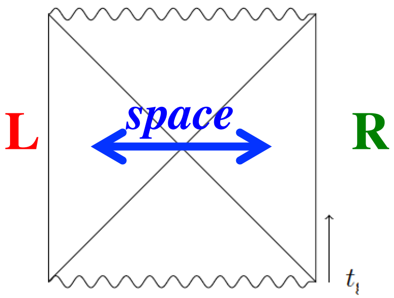
- Non-Fermi-liquids as densely entangled states of quantum matter: "signs" are a blessing!

- Holographic principle: non-FL quantum liquids at finite density are quantum critical phases characterized by non-Wilsonian scaling properties (space vs. time, "hyperscaling violation", …).

- Insensitivity of entanglement entropy to sign structure: fractal nodes yield always volume scaling. Anomalous dimensions of the entanglement entropy of holographic strange metals??

- A new known unknown of quantum gravity: "charged geometry" is dual to extreme IR quantum entanglement ...

ER=EPR and the extremal black holes.



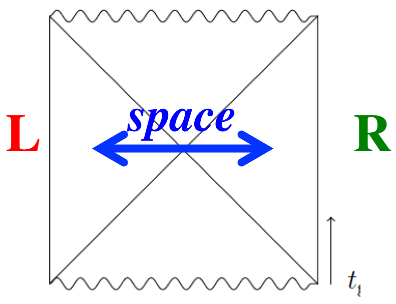
Global geometry: "maximally entangled" thermofield double state.

$$|\Psi_0\rangle = \sum_i e^{-E_i/(k_B T_H)} |E_i\rangle_L |E_i\rangle_R$$

Poincare patch/causal boundary observer:

$$\rho_C = \sum_i e^{-E_i/(k_B T_H)} |E_i\rangle_C \langle E_i|_C$$

ER=EPR and the extremal black holes.



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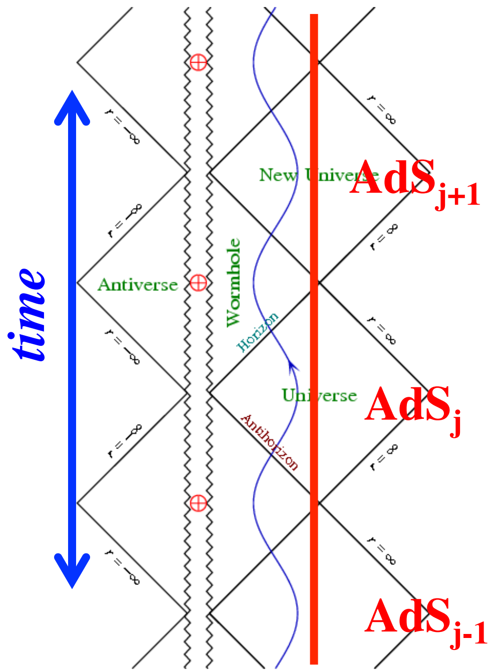


Global geometry: ***infinite*** number of patches, "***time like*** oriented", "maximally" entangled ?

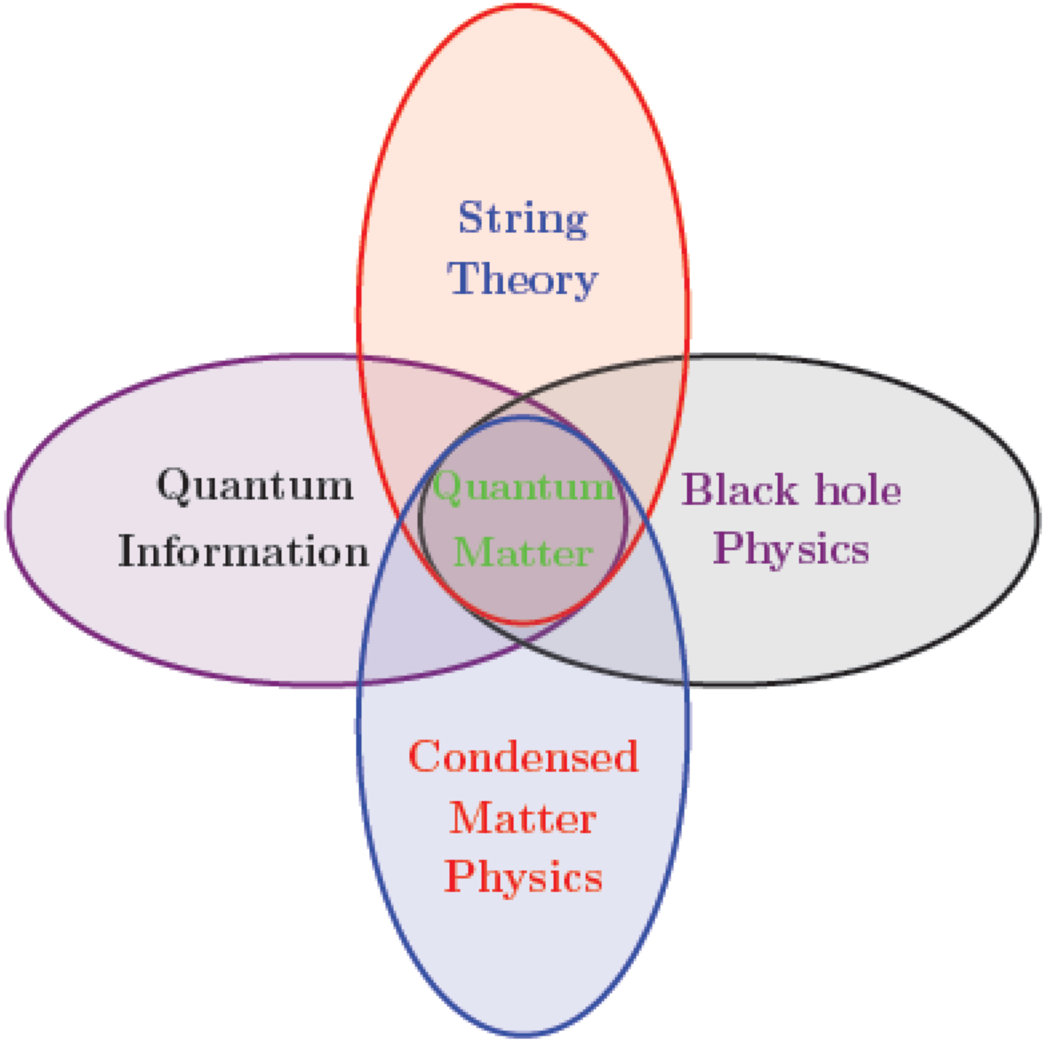
$$|\Psi_0\rangle = \sum_i C^0_{j_1,\cdots,j_i\cdots j_\infty} |\vec{P}_i\rangle_{j_1} \cdots |\vec{P}_i\rangle_{j_i} \cdots |\vec{P}_i\rangle_{j_\infty}$$

Poincare patch/causal boundary observer:

$$\rho_C = \sum_i f(P_i,\mu) |\vec{P}_i\rangle_C \langle \vec{P}_i|_C$$

***Mixed* state (OK), "*local*" attitude, but the function f has to be real and positive ??**

Koenraad's cloverleaf ….



Magnitude of momentum relaxation.

According to the cuprate optical conductivity the momentum relaxation rate is:

$$\frac{1}{\tau_{\exp}} \approx \frac{k_B T}{\hbar}$$

According to "massive gravity", the RN strange metal has a momentum relaxation rate:

$$\frac{1}{\tau_{\exp}} = A \frac{\hbar}{l^2 m_e} \frac{S}{k_B} = A \frac{\hbar^2}{\mu l^2 m_e} \frac{k_B T}{\hbar} \qquad \textbf{assuming} \qquad \frac{S}{k_B} = \frac{k_B T}{\mu}$$

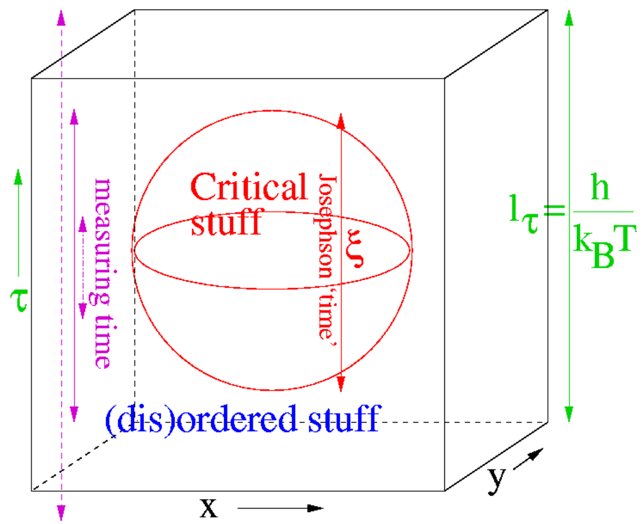
It follows for the microscopic mean free path:

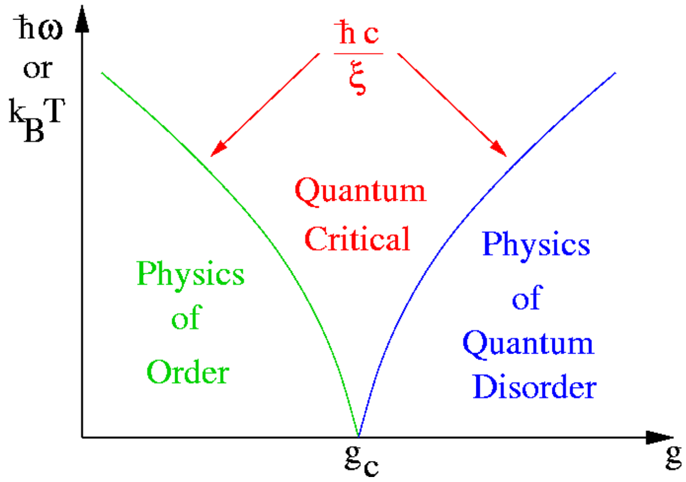
$$l = \hbar \sqrt{\frac{A}{\mu m_e}} \approx 10^{-9} m$$

Quantum criticality.

Sachdev's book "quantum phase transitions"

Scale invariance of the quantum dynamics (in space and time) is dynamically generated, as emergent phenomenon.

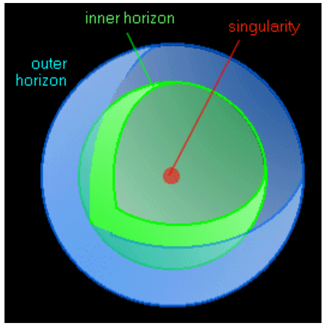




In the higher dimensional (bosonic) quantum field theories which are understood this only happens at isolated points in coupling constant space.

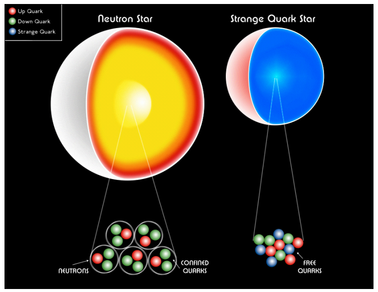
The holographic Fermi-liquid: uncollapsing in the "electron star".

Reissner-Nordstrom BH



uncollapse

"charged neutron star"



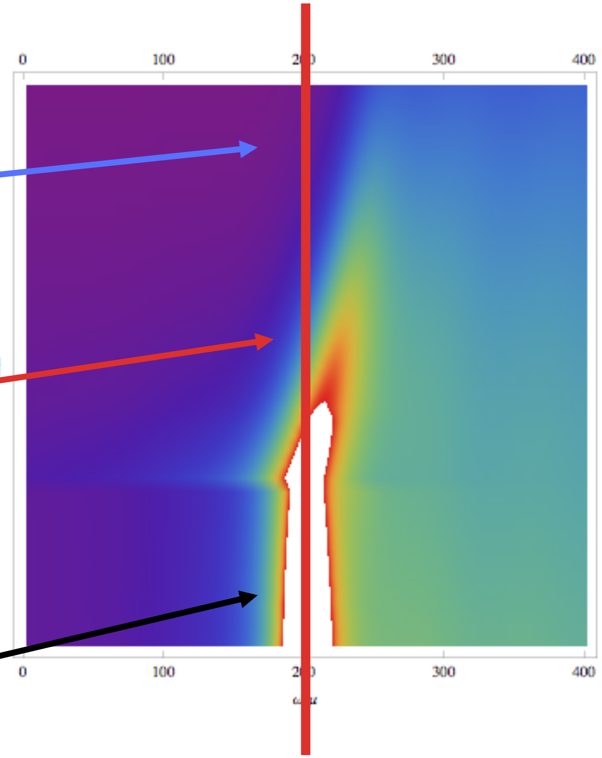
Hartnoll et al., Schalm et al.

"Photoemission" in the boundary

Strange metal

Relaxational Fermi surface

Fermi-surface (Fermi liquid)



Empty.

Empty.

Empty.