The Gauge/Gravity duality and its applications

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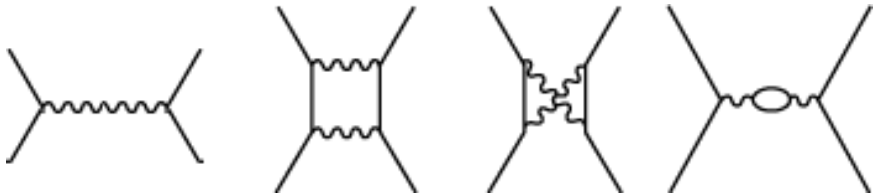
Perturbative Quantum Field Theory and its limitations

- **Perturbative QFT**

$$\mathcal{L} = \partial_\mu \phi \partial^\mu \phi + m^2 \phi^2 \; + \; \mathbf{g}\phi^{\mathbf{4}} + ...$$

for $\mathbf{g} \ll 1$



- **Phenomena beyond perturbation theory**

-QCD/Nuclear (confinement, quark gluon plasma...)

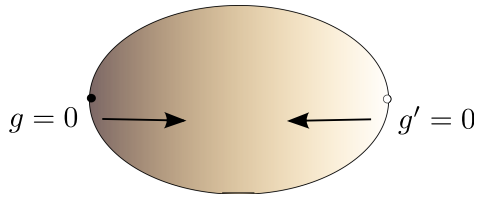
-Beyond the Standard Model (new physics, technicolor...)

-Condensed Matter (superconductivity, critical points...)

-Gravity (black holes, early cosmology...)

Duality

- A physical system may have more than one equivalent descriptions.

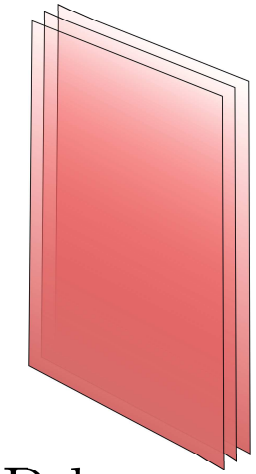


- Coupling constants inversely related!

$$g' \sim \frac{1}{g}$$

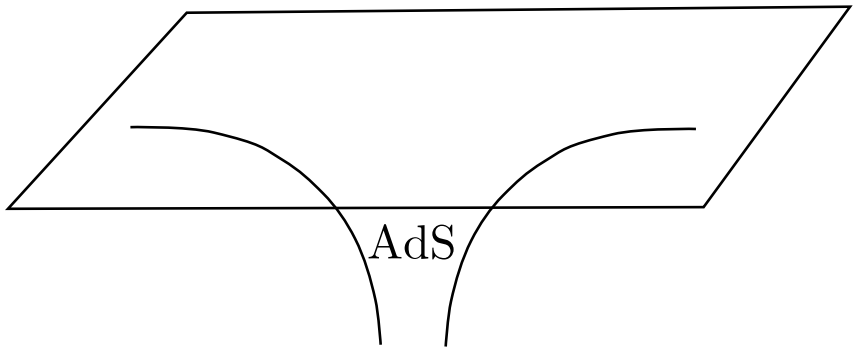
- Strong coupling problem $\Leftrightarrow$ weakly coupled in "dual theory".
- Known dualities: string theories, SUSY gauge theories,...

Holographic Duality (AdS/CFT correspondence)



D-branes

$\Leftrightarrow$



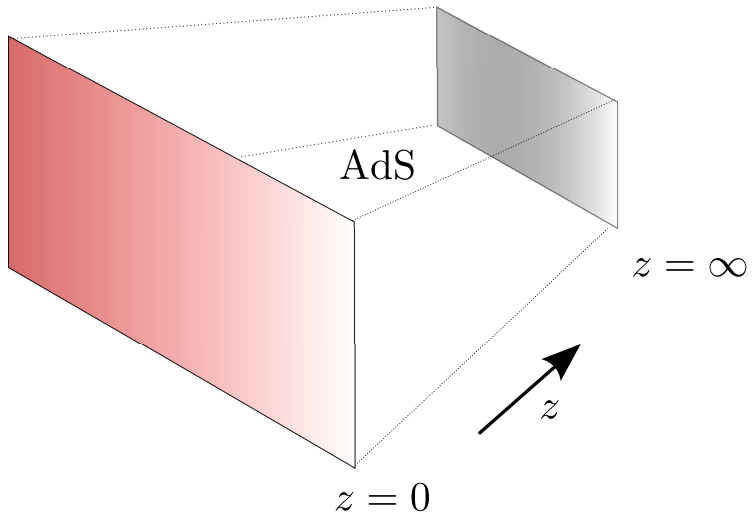
Quantum Field Theory $\Leftrightarrow$ **Gravity**

d dimensions $\qquad$ $d+1$ dimensions

Holographic Duality (AdS/CFT correspondence)

- Anti de Sitter space (AdS)

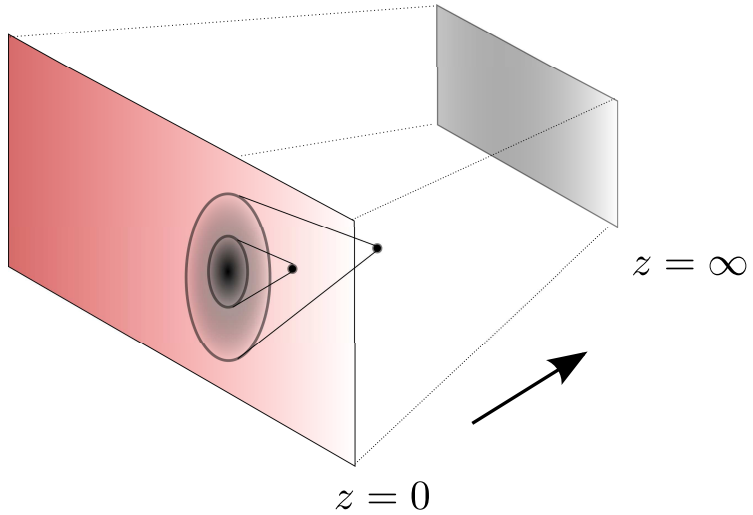
$$ds^2 = \frac{-dt^2 + d\vec{x}^2 + dz^2}{z^2}$$



- Quantum filed theory lives on the the "boundary" of AdS ($z = 0$).

Holographic Duality (AdS/CFT correspondence)

- Extra dimension $\Rightarrow$ "scale" in quantum field theory



- Radial evolution $\Rightarrow$ RG-flow

- Scale invariant theories $\Rightarrow$

  AdS geometry $ds^2 = \frac{-dt^2+d\vec{x}^2+dz^2}{z^2}$

  invariant under $(t, \vec{x}, z) \to (\lambda t, \lambda \vec{x}, \lambda z)$.

Holographic Duality (AdS/CFT correspondence)

- Fields in gravity $\Leftrightarrow$ local operators in dual QFT

$$\phi(x,z) \Leftrightarrow \mathcal{O}(x)$$

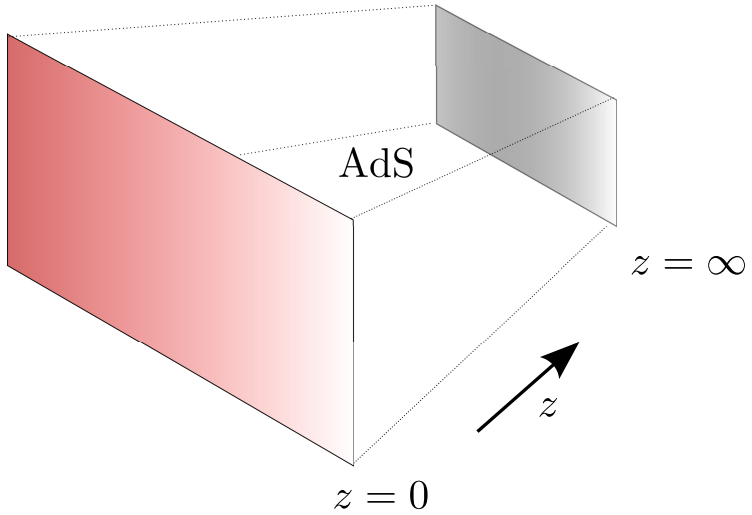
$$A_\mu(x,z) \Leftrightarrow J_\mu(x)$$

$$g_{\mu\nu}(x,z) \Leftrightarrow T_{\mu\nu}(x)$$

- Boundary values $\widetilde{\phi}(x) = lim_{z\to 0}\phi(x,z) \Leftrightarrow$ "sources" for operators in QFT

$$\langle e^{\int dx \widetilde{\phi}(x)\mathcal{O}(x)} \rangle_{QFT} = \mathcal{Z}_{gravity}(\phi \to \widetilde{\phi})$$

Holographic Duality (AdS/CFT correspondence)



QFT correlators are given by

$$\langle \mathcal{O}(x_1)....\mathcal{O}(x_n)\rangle_{QFT} = \frac{\delta^n}{\delta\widetilde{\phi}(x_1)...\delta\widetilde{\phi}(x_n)} e^{-S_{gravity}(\widetilde{\phi})}$$

- **QUANTUM correlators in strongly coupled QFT from** (semi-) **CLASSICAL gravitational computations !**

Holographic Duality (AdS/CFT correspondence)

- Hilbert spaces of two systems are equivalent.

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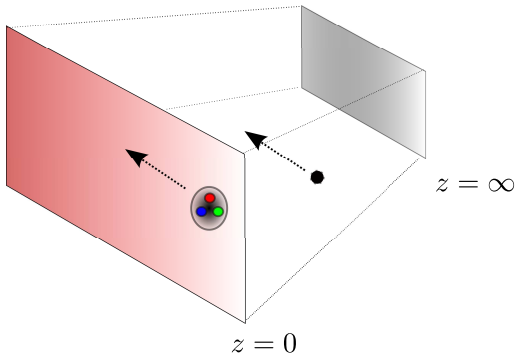
- Particle in AdS $\Leftrightarrow$ "hadrons, glueballs" in gauge theory



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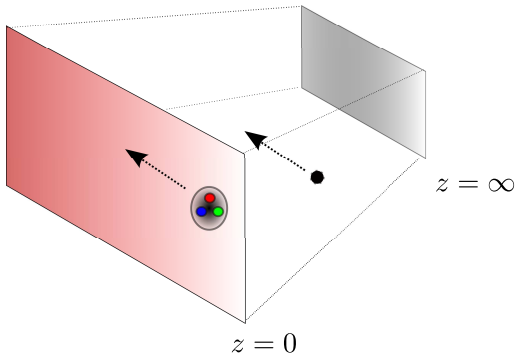
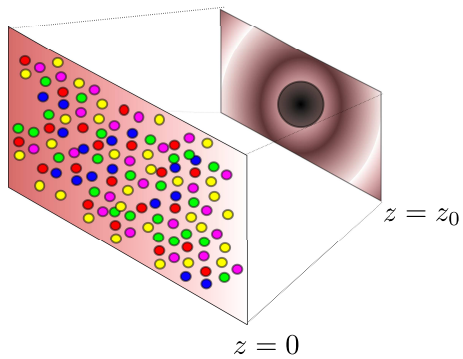


- Black Hole in AdS $\Leftrightarrow$ quark gluon plasma in gauge theory



Importance of holography

- Quantum field theory $\Leftrightarrow$ Gravity

- $(\Rightarrow)$ **Fundamental questions in gravity**

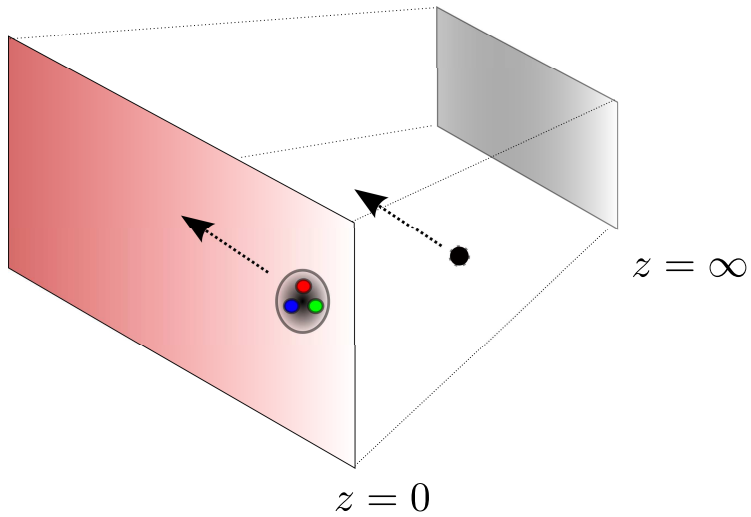
  emergence of spacetime, black holes, singularities, cosmology,...

- $(\Leftarrow)$ **Applications**

  strongly coupled systems in terms of weakly coupled gravity

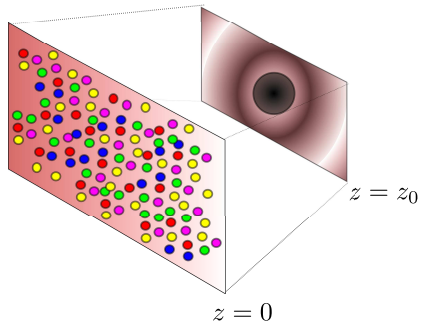
Confinement in QCD

- Hadron/meson masses = ?



- Hadron masses $\Leftrightarrow$ eigenvalues of a **classical** ordinary differential equation! (easy)
- Results (qualitatively) close to QCD.

Black Holes and Quark Gluon Plasma



$$ds^2 = -\frac{f(z)}{z^2}dt^2 + \frac{1}{f(z)z^2}dz^2 + \frac{1}{z^2}d\vec{x}^2 \quad , \quad f(z) = 1 - \frac{z^4}{z_0^4}$$

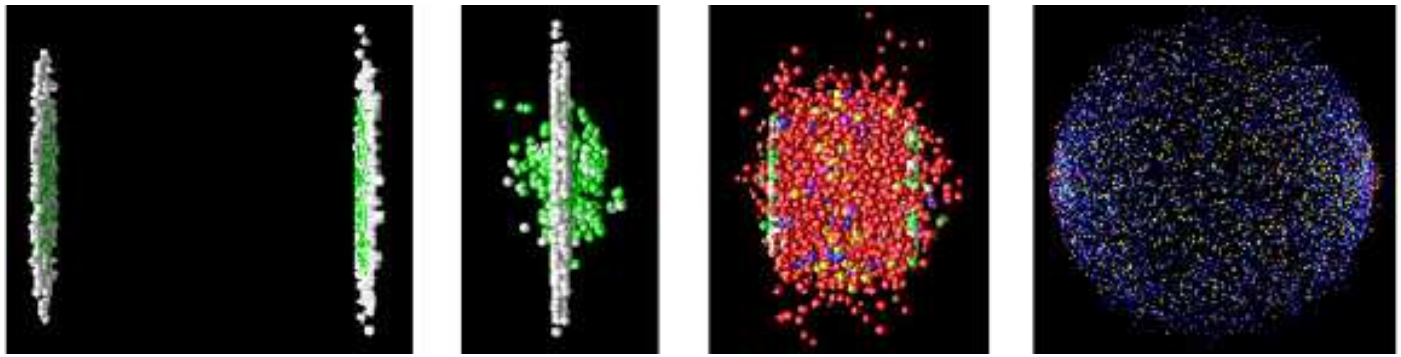
- Energy $\Leftrightarrow$ Mass , Entropy $\Leftrightarrow$ Horizon Area
- $\Rightarrow$ Equation of State for quark-gluon plasma at strong coupling!
- Verified by numerical simulations.

Dynamical processes in QCD

- So far $\Rightarrow$ "static" questions. Can also be addressed by lattice
- For dynamical processes (time-dependent) lattice/numerical computations are very difficult
- AdS/CFT can sometimes be used to study such questions

For example

Experiments at RHIC and LHC



Heavy ion collision $\Rightarrow$

Fireball of quark gluon plasma $\Rightarrow$

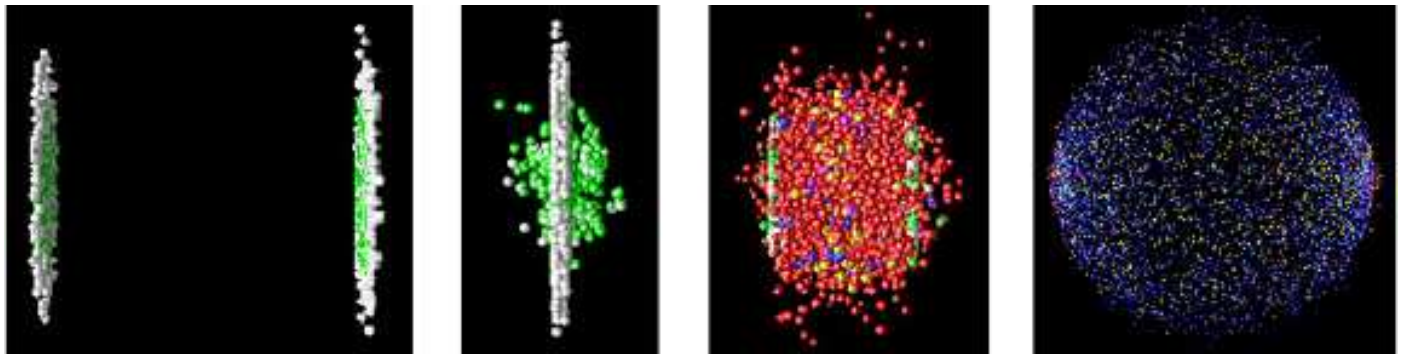
Decay via hadronization

Extremely complicated, numerics difficult

mel

Interpretation in gravity

QGP Fireball $\Leftrightarrow$ Black Hole

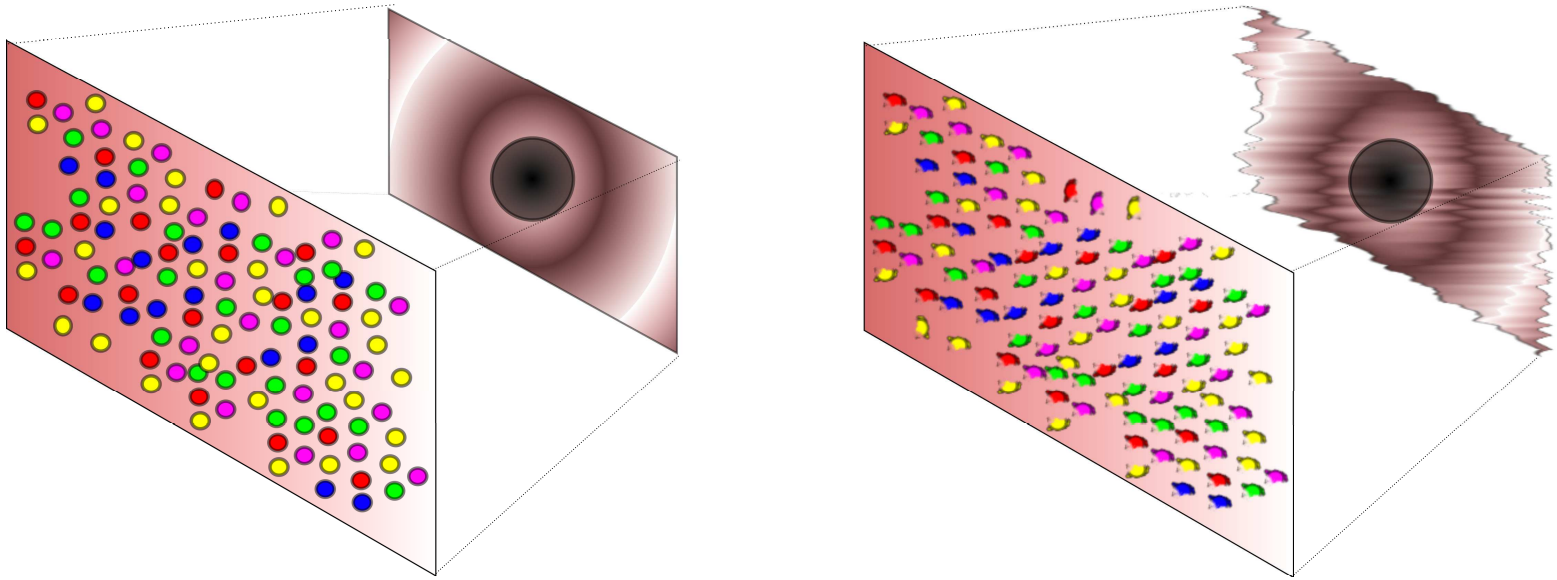


Collision of particles$\Rightarrow$

Black Hole formation$\Rightarrow$

Hawking evaporation into particles

Black Holes and Hydrodynamics



- Black hole horizon behaves like a “membrane”.
- Fluctuations of black hole horizon correspond to fluctuations of density/temperature of quark gluon plasma.

EINSTEIN EQUATIONS

$\Leftrightarrow$

NAVIER-STOKES EQUATIONS

Viscosity of Quark-Gluon Plasma

- Navier Stokes equations

$$\nabla \vec{v} = 0$$

$$\frac{\partial \vec{v}}{\partial t} + (\vec{v} \cdot \nabla)\vec{v} - \eta \nabla^2 \vec{v} = -\nabla P$$

where η is the "viscosity coefficient"

- Measured by thermal 2-point function

$$\langle T_{\mu\nu}(x)\, T_{\rho\sigma}(0) \rangle$$

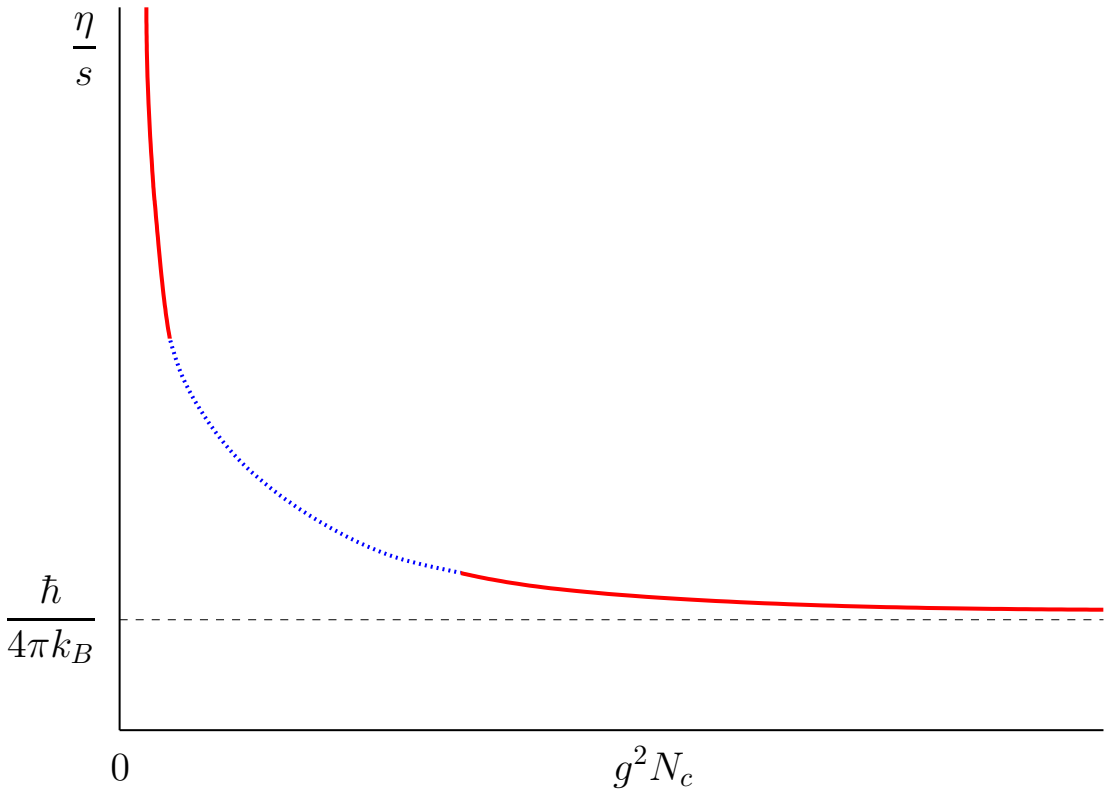
- in AdS/CFT: $T_{\mu\nu} \quad \Leftrightarrow \quad g_{\mu\nu}$ (graviton)

- Gravity gives

$$\frac{\eta}{s} = \frac{1}{4\pi}$$

(close to observed value for QGP)

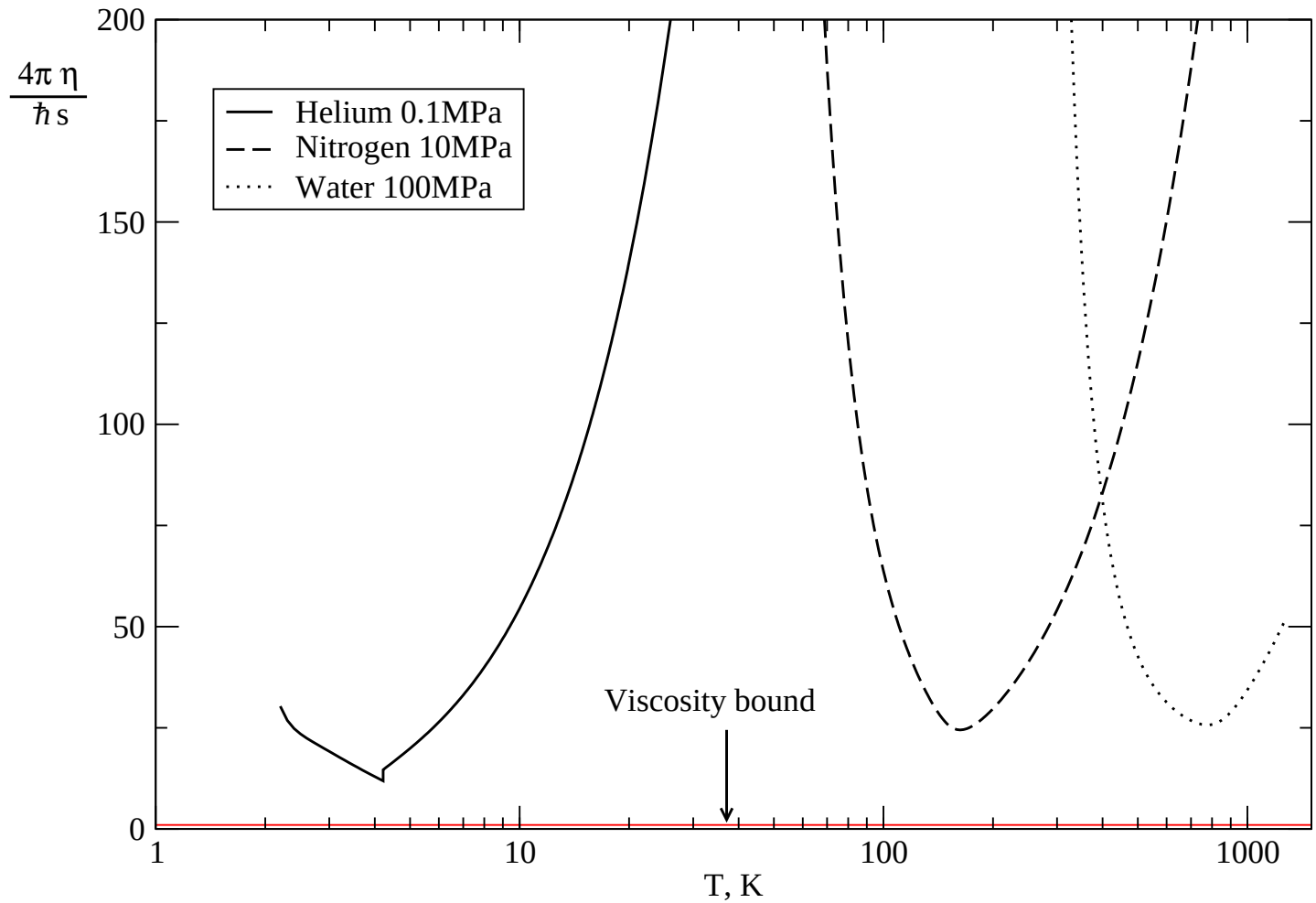
Viscosity Bound



For all values of the coupling we find that

$$\frac{\eta}{s} \geq \frac{1}{4\pi}$$

Viscosity Bound

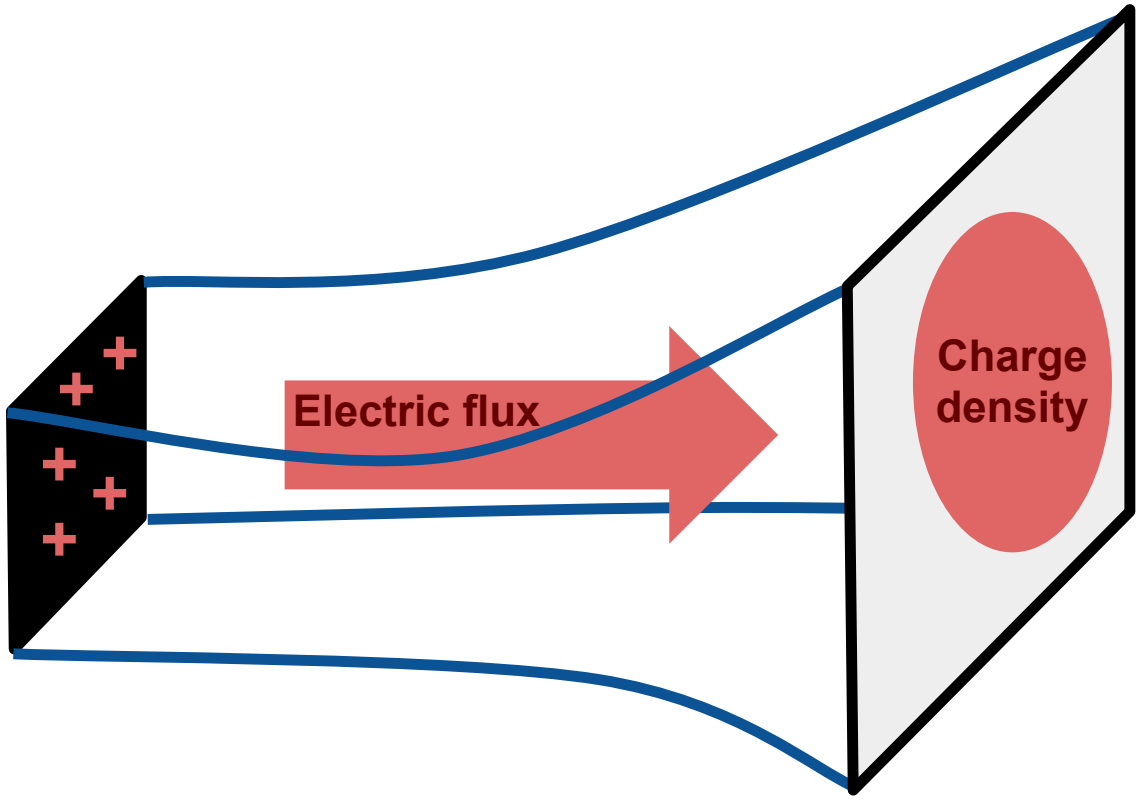


All known materials obey the bound

Condensed Matter Physics

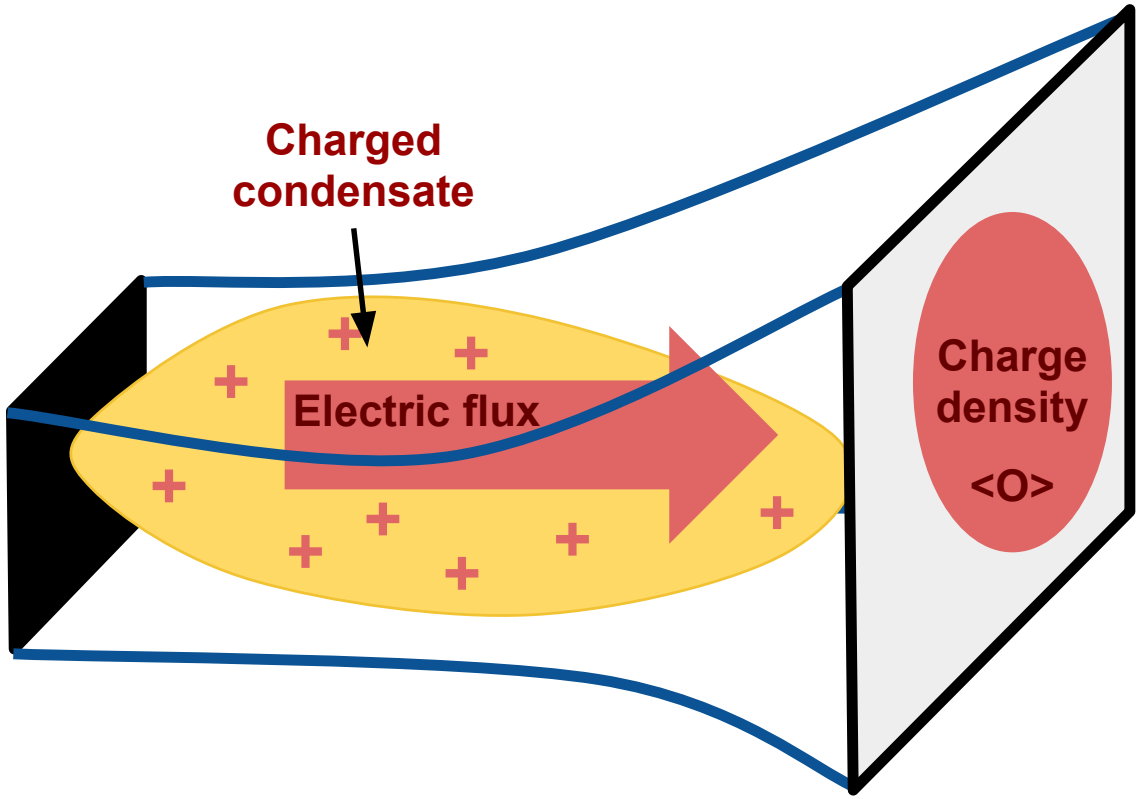
- More general (strongly interacting) quantum field theories
- Superconductivity $\Leftrightarrow$ superradiant instability of charged black holes
- Strongly coupled fermions and black holes

Holographic superconductors



- Charged Black Hole
- Superradiant instability

Holographic superconductors

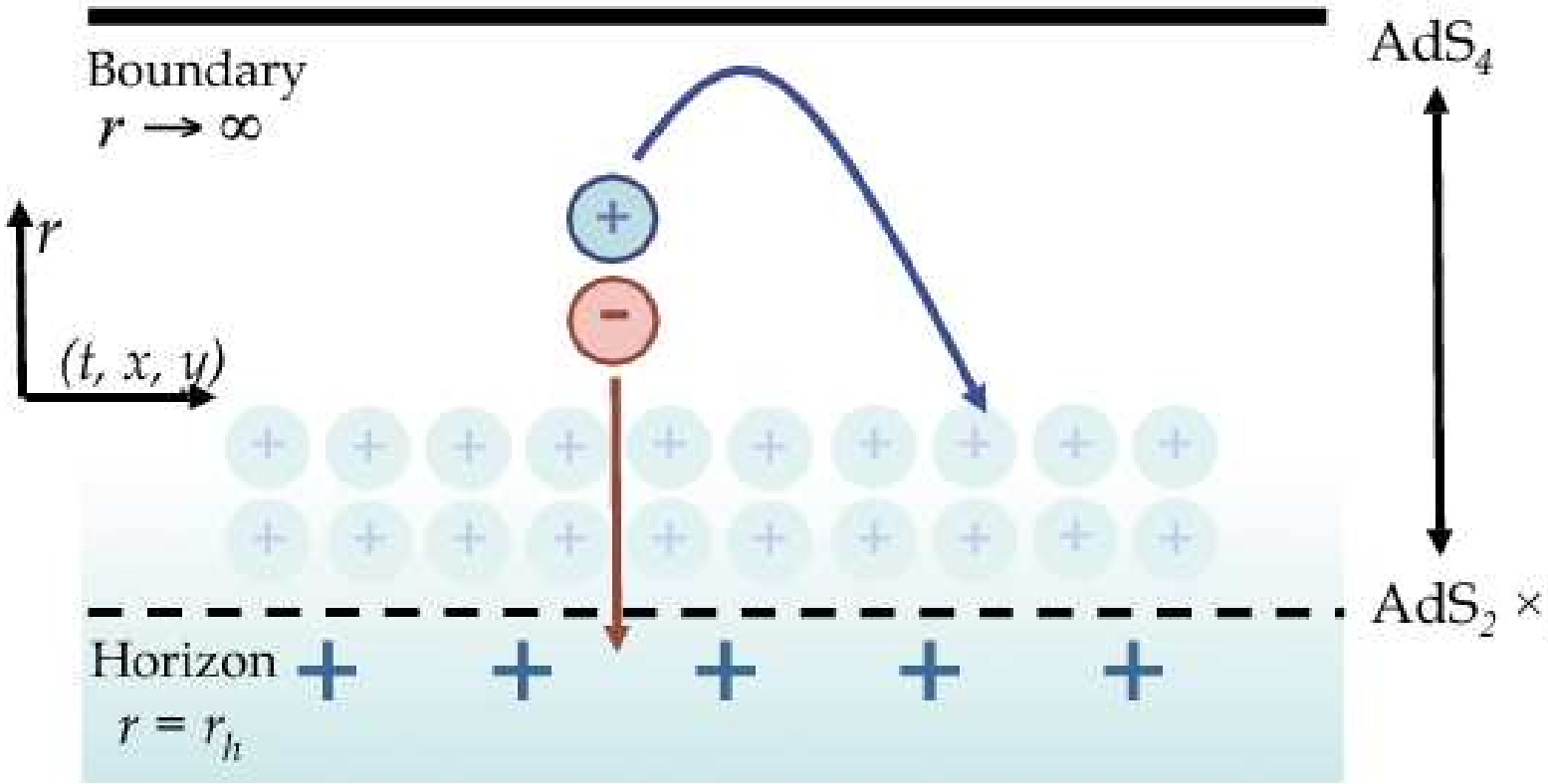


- $\langle \mathcal{O} \rangle \neq 0 \qquad \Rightarrow \qquad U(1)$ broken
- Black Hole with scalar hair $\Leftrightarrow$ "Holographic superconductor"

Hairy black holes

- New exact solutions of BH + scalar hair
- New **phases** of strongly coupled gauge theories
- Used to compute equation of state, transport coefficients etc.

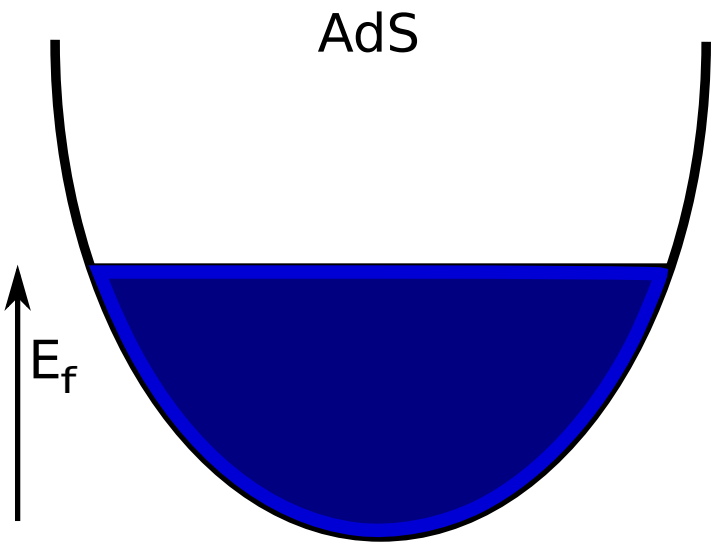
Stongly coupled fermions

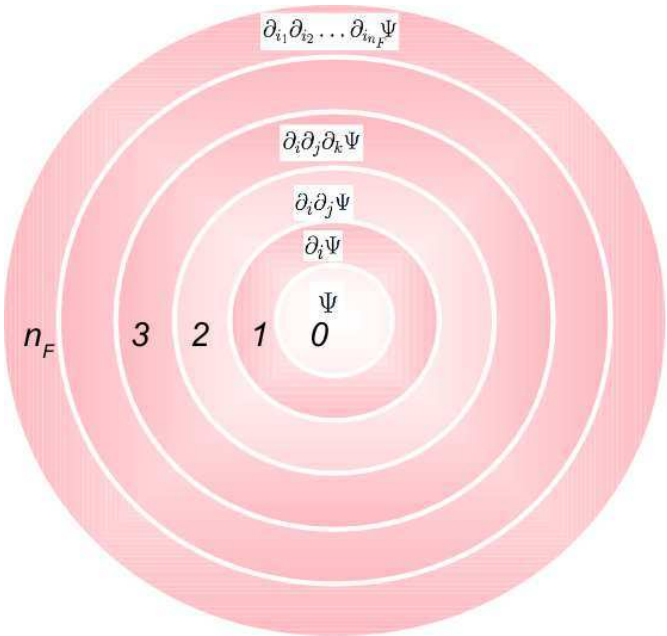


- (Non)-Fermi liquids

Holographic stars

Fill AdS with degenerate fermions

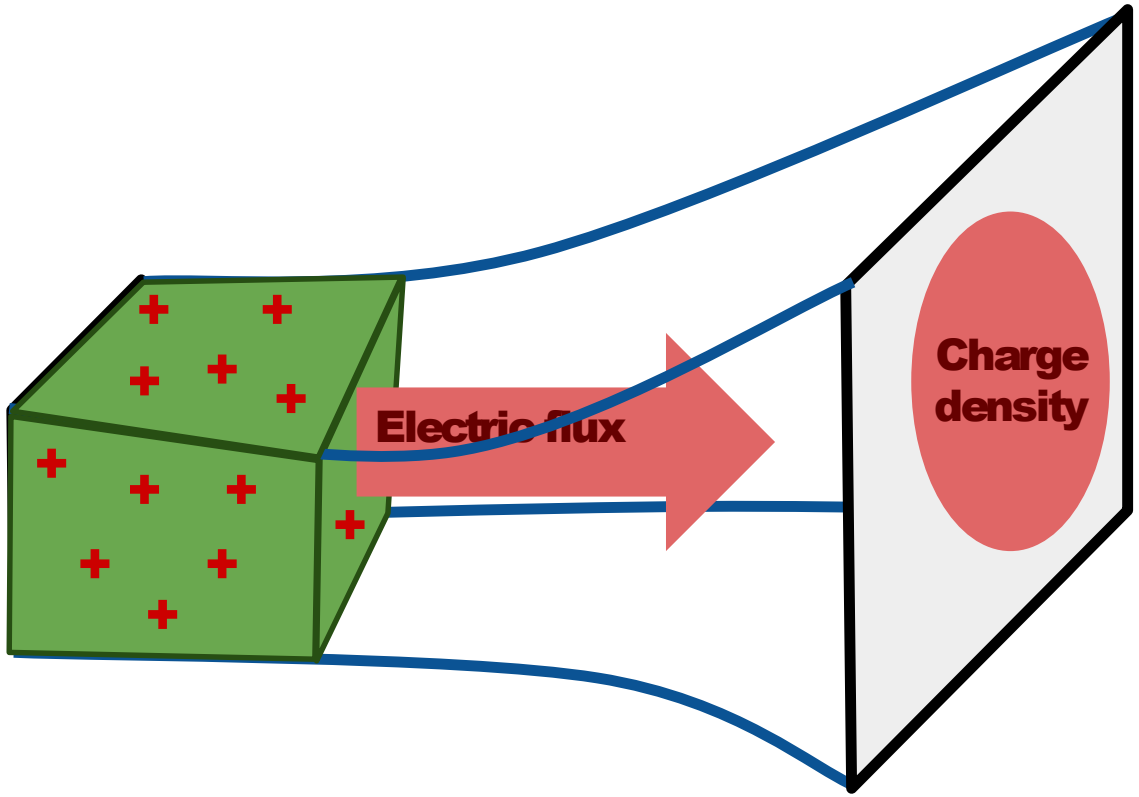




Fermion star = fermionic "multi-trace operator"

$$|\Phi\rangle = \Psi \prod_i \partial_i\Psi \prod_{i,j} \partial_i\partial_j\Psi \dots \prod_{i_1,\dots,i_{n_F}} \partial_{i_1}\dots\partial_{i_{n_F}}\Psi$$

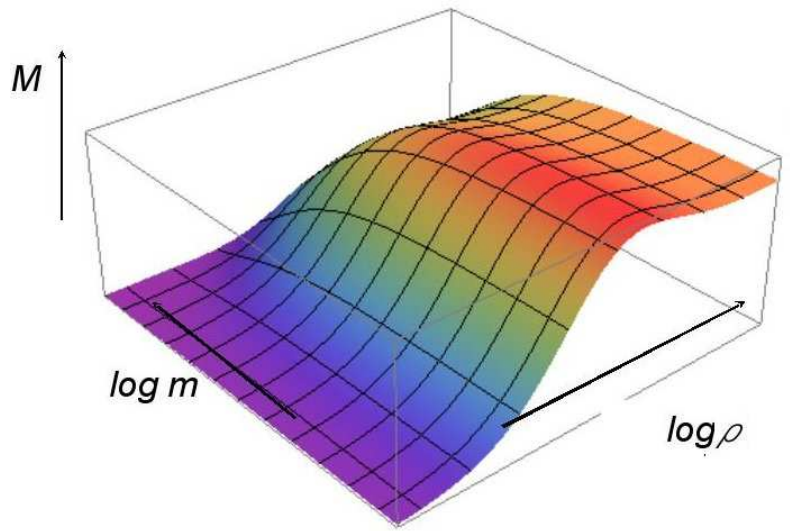
Holographic stars



"Degenerate Star" in AdS $\Leftrightarrow$ High density "nuclear matter" in gauge theory

Holographic stars

- Solve Tolman-Oppenheimer-Volkov equations (GR + fermionic fluid) to find solution for star



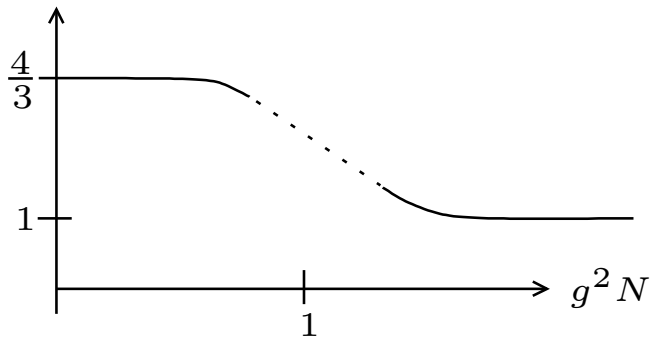
- For $\rho > \rho_c$ gravitational collapse to black hole
- Gravitational collapse $\Leftrightarrow$ (1st order) finite-density deconfinement transision in gauge theory
- "Chandrasekhar bound" $\Leftrightarrow$ Bound on density of nuclear matter

Quantum Gravity and Cosmology

Quantum aspects of Black Holes

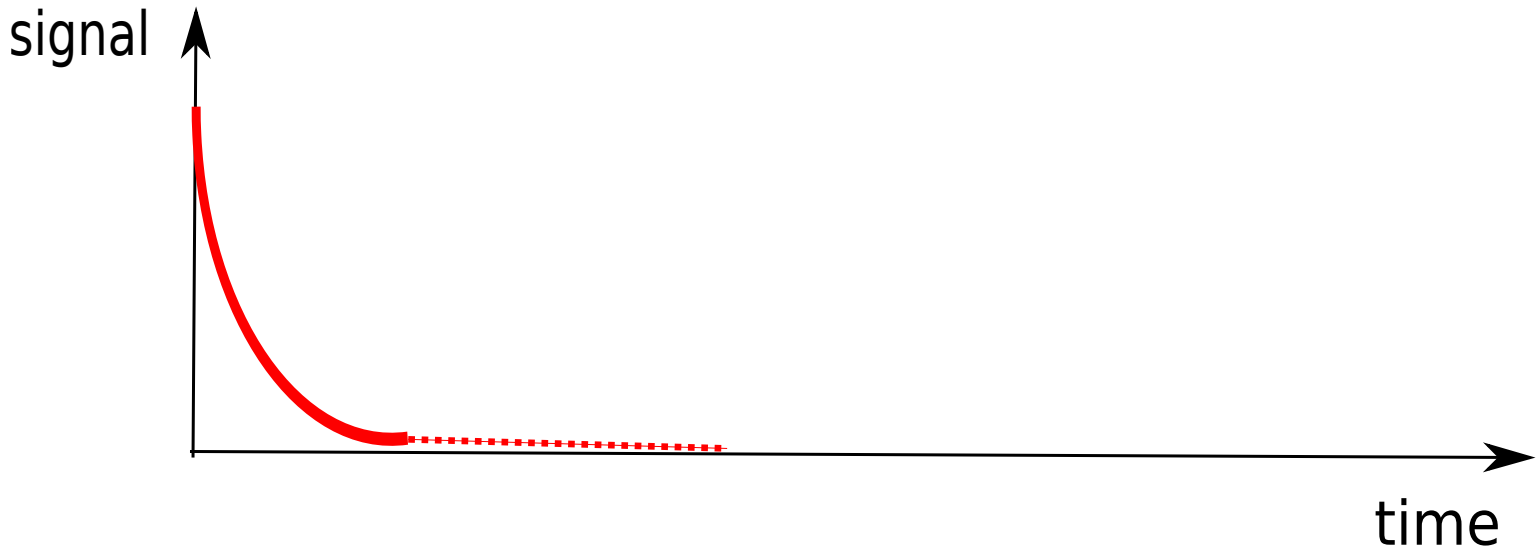
- Black hole in AdS $\Leftrightarrow$ QGP at finite temperature
- Estimate black hole entropy from weakly coupled gauge theory

$$\frac{\mathrm{S}}{\frac{\pi^2}{2}N^2T^3V}$$



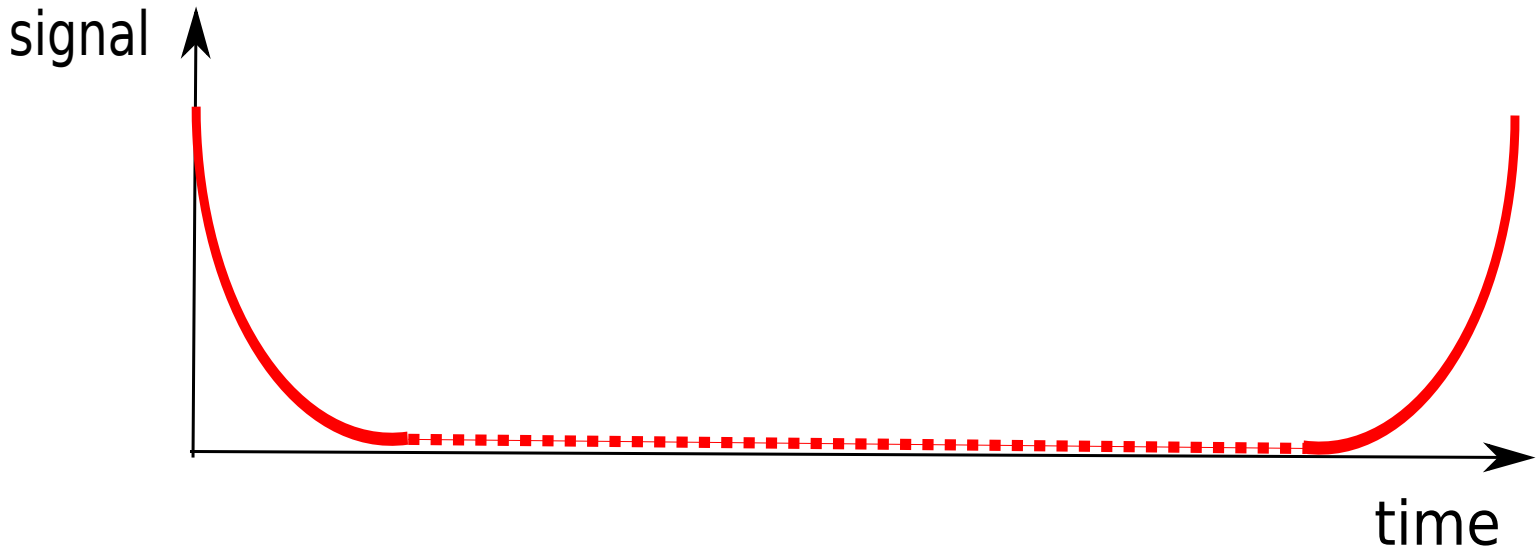
- Correct entropy up to a factor of 3/4 !
- Numerical simulation of gauge theory $\Rightarrow$ exact agreement

Information Paradox



- Infalling matter destroyed. Where is info?
- (Apparent) conflict with Unitarity
- Dual gauge theory is manifestly unitary $\Rightarrow$ No information loss

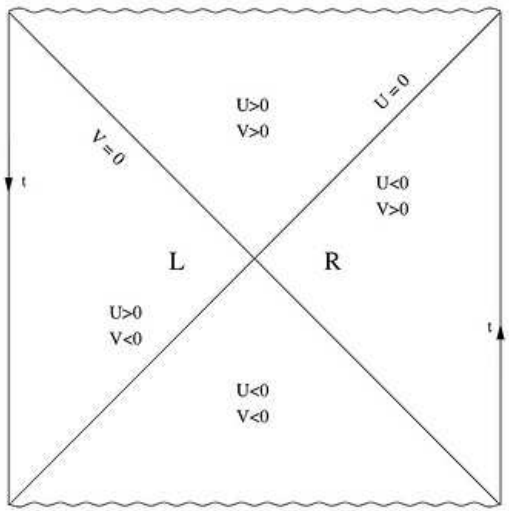
Information Paradox



Using gauge theory:

INFORMATION COMES OUT OF THE BLACK HOLE!!!

Seeing behind the black hole horizon



- Local bulk observables $\Rightarrow$ Infalling observer
- Singularity resolution?
- Big-Bang singularity?

Challenges in Phenomenology and Cosmology

- AdS/CFT provides us with many examples of strongly coupled QFTs
- What if BSM physics is strongly coupled (for example technicolor etc.)?
- Models with warped extra dimensions
- Inflation, power spectrum
- Holography for de-Sitter $(\Lambda > 0)$

THANK YOU