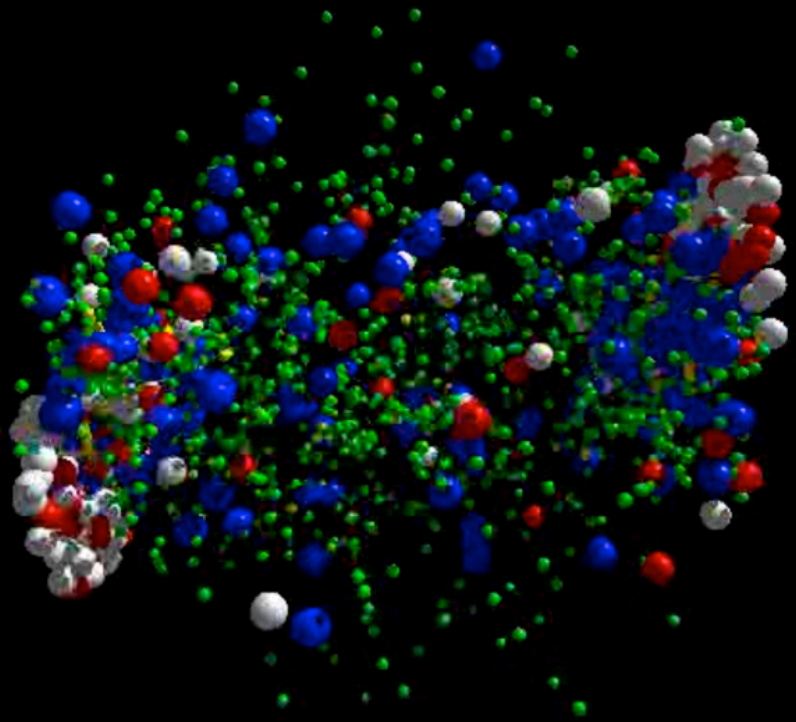
Strong Coupling Isotropization Simplified





David Mateos
ICREA & University of Barcelona

Work with M.Heller, W. van der Schee, M. Spalinski & D. Trancanelli

Plan

- Gauge/gravity & QCD: Limitations and insights.
- Isotropization of a strongly coupled QGP.

The QCD challenge

- QCD remains a challenge after many years.

The QCD challenge

- QCD remains a challenge after many years.

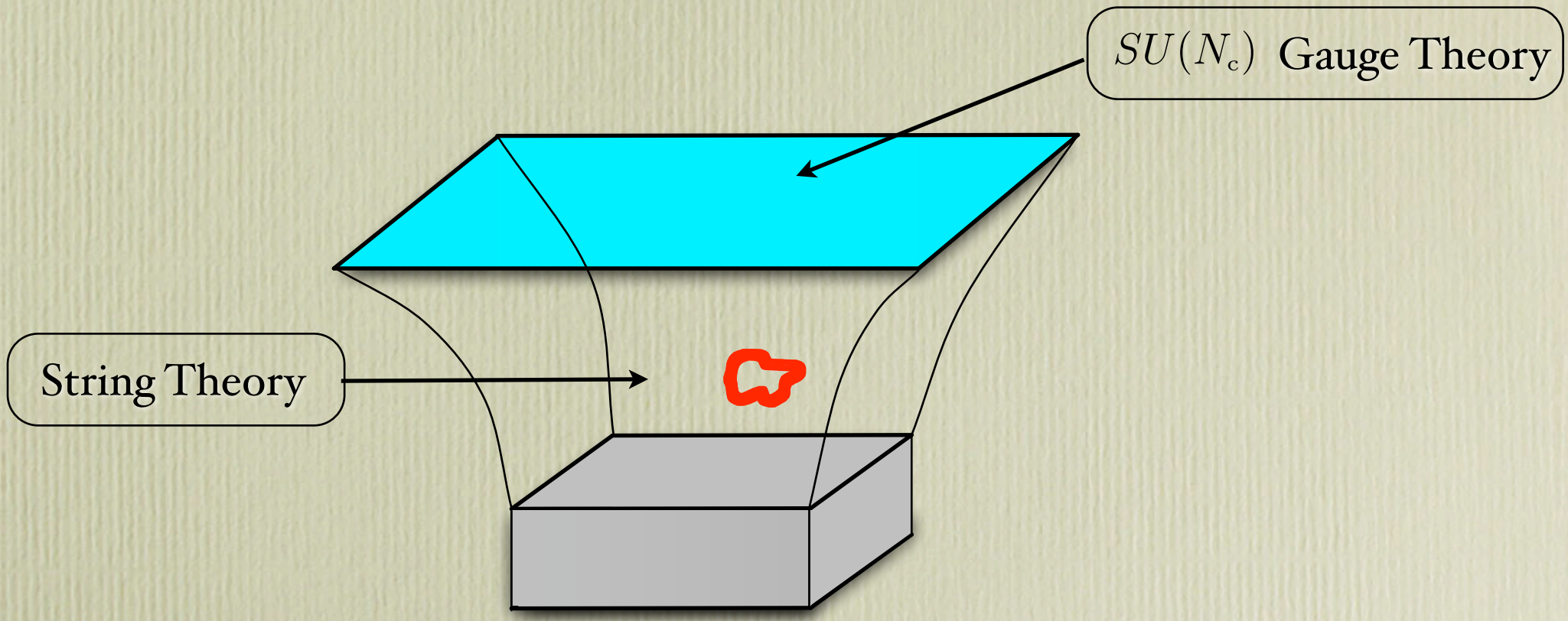
- We have some good tools but they all have limitations. For example:

  - Perturbation theory: Weak coupling.
  - Lattice: Difficult to apply to real-time phenomena.
  - Etc.

The gauge/string duality

(= AdS/CFT correspondence = Holography)

Maldacena '97

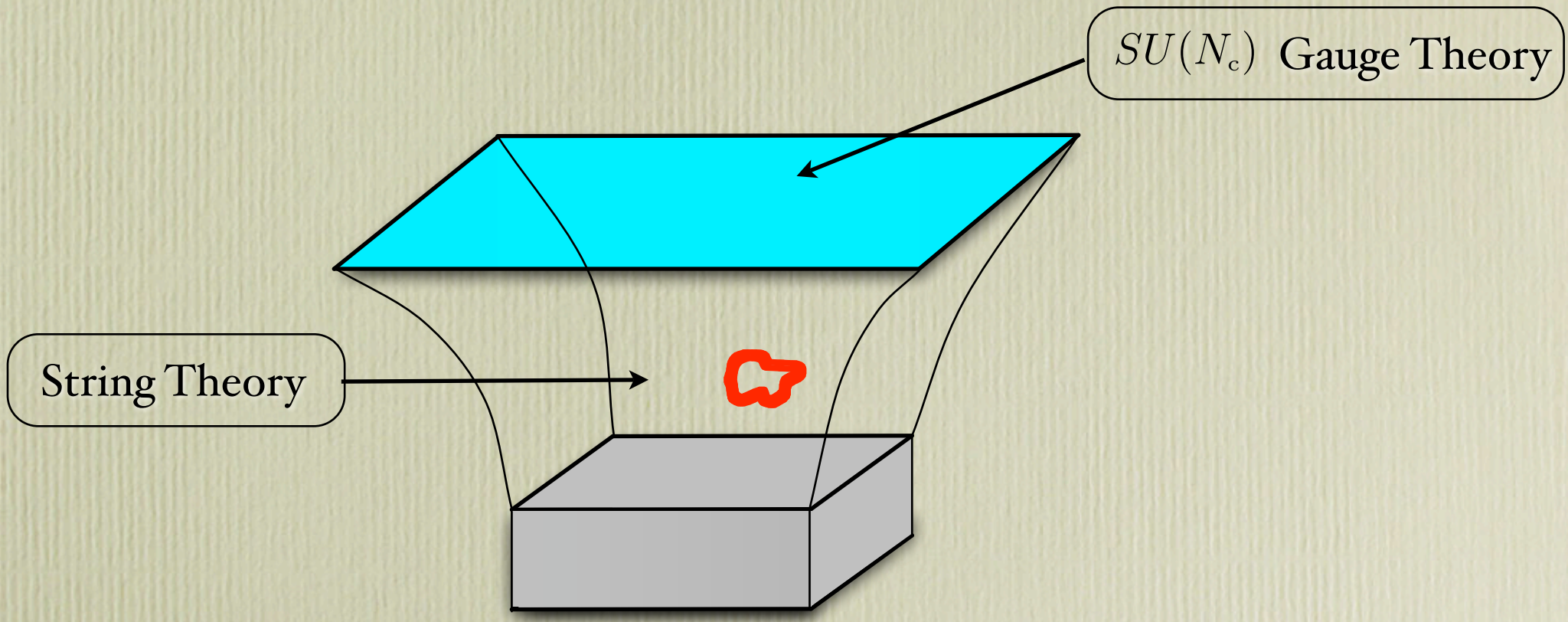


- Exact equivalence at *all* energies, N_c and $\lambda = g^2_{\rm YM} N_c$!

The gauge/string duality

(= AdS/CFT correspondence = Holography)

Maldacena '97



- Exact equivalence at *all* energies, N_c and $\lambda = g^2_{\rm YM} N_c$!
- *Disclaimer:* Not proven but much evidence.

From viewpoint of a *theorist*

- Duality is a remarkable development:

Quantum gravity = Ordinary QFT

In terms of *applications* to QCD

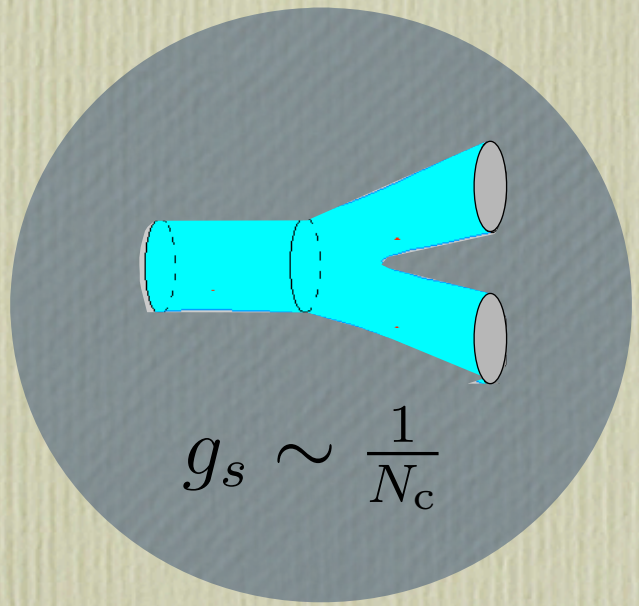
At present the duality has its own limitations



Complementary tool

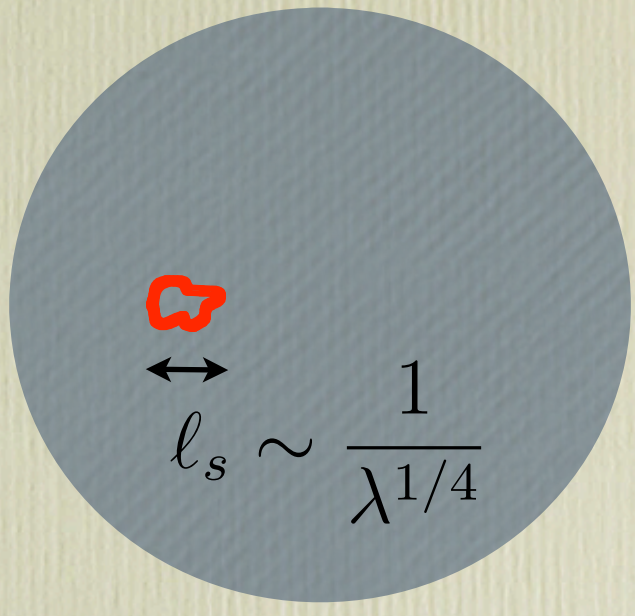
Limitations

$N_c \to \infty$



Suppresses quantum corrections.

$\lambda = g_{\rm YM}^2 N_c \to \infty$

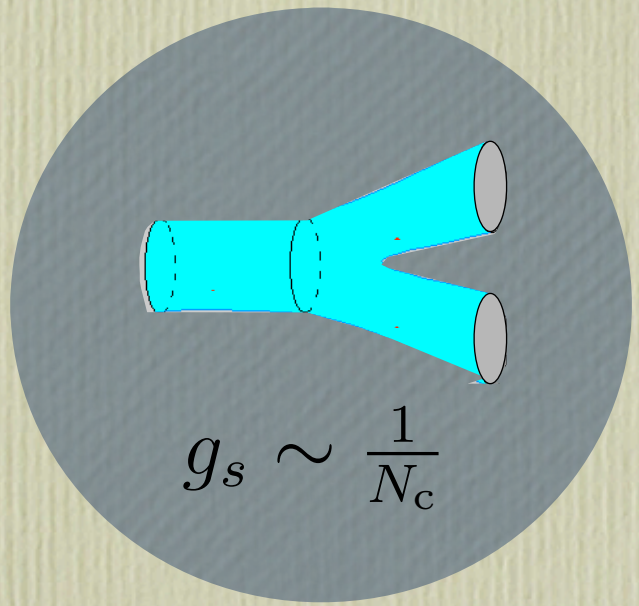


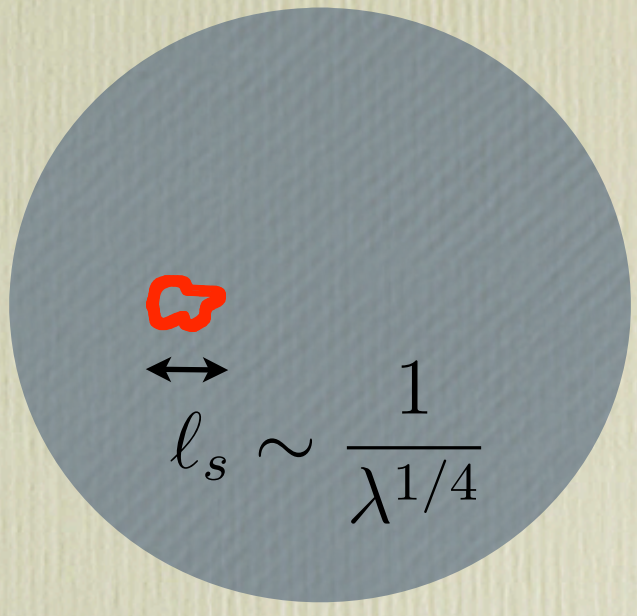
Makes the string tiny.

Limitations

$N_c \to \infty$

$\lambda = g_{\rm YM}^2 N_c \to \infty$





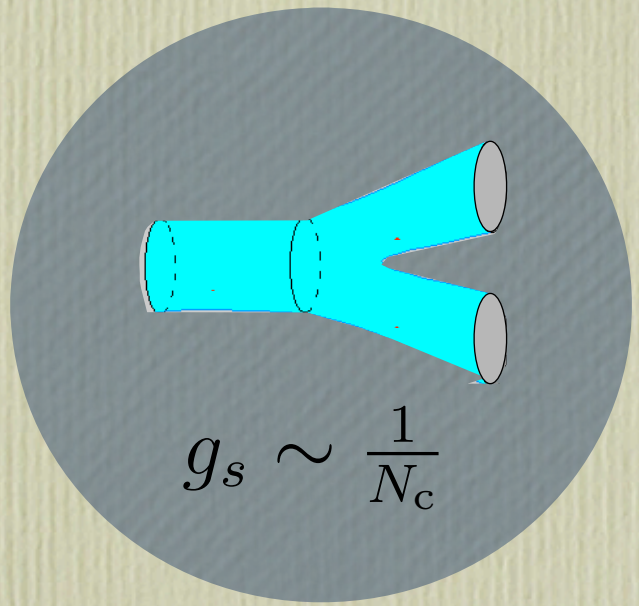
Suppresses quantum corrections.

Makes the string tiny.

→ Classical Gravity!

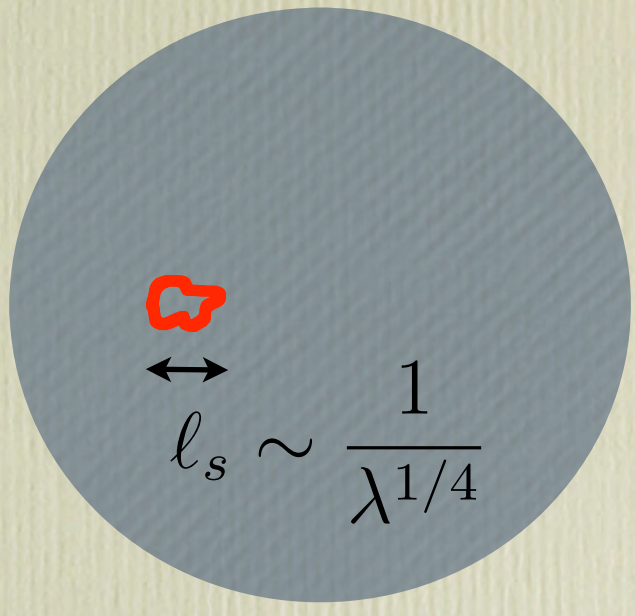
Limitations

$N_c \to \infty$



Suppresses quantum corrections.

$\lambda = g_{\rm YM}^2 N_c \to \infty$



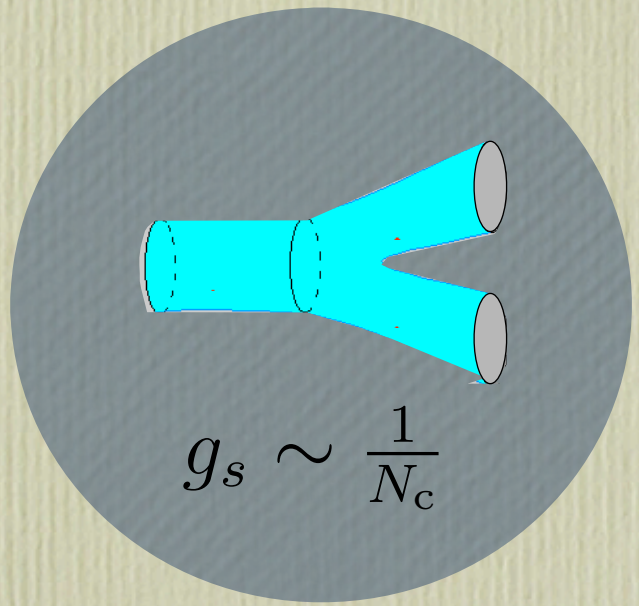
Makes the string tiny.

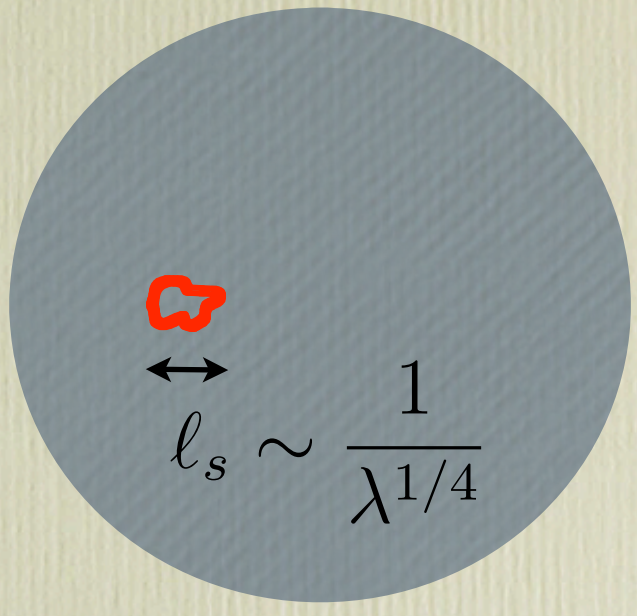
Technical difficulties, *not* fundamental limitations.

Limitations

$N_c \to \infty$

$\lambda = g_{\rm YM}^2 N_c \to \infty$





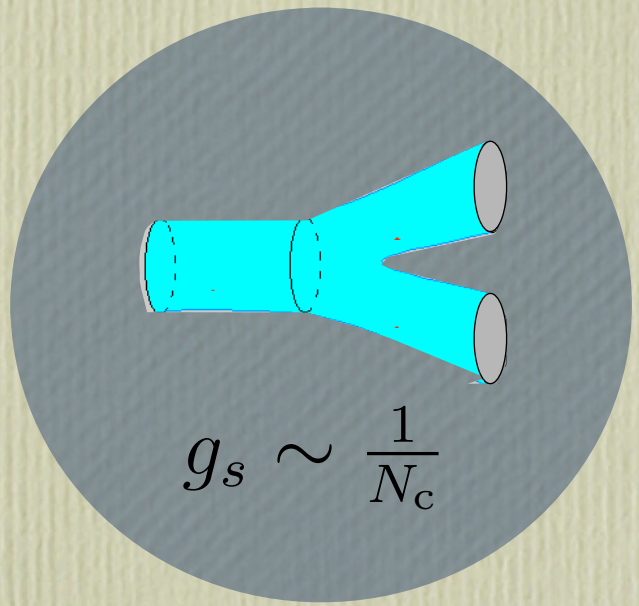
Suppresses quantum corrections.

Makes the string tiny.

Solving large-N_c would be great progress!

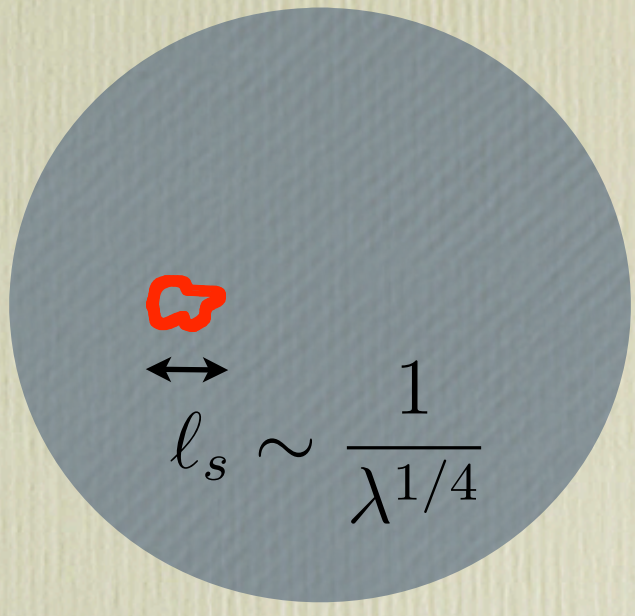
Limitations

$N_c \to \infty$



Suppresses quantum corrections.

$\lambda = g_{\rm YM}^2 N_c \to \infty$

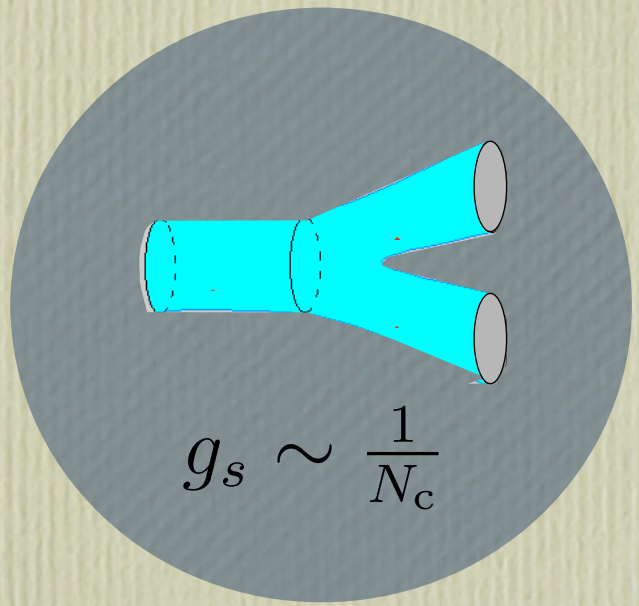


Makes the string tiny.

- Asymptotically free.
- Dynamically generated scale.
- Confinement.
- Deconfinement phase transition.
- ...

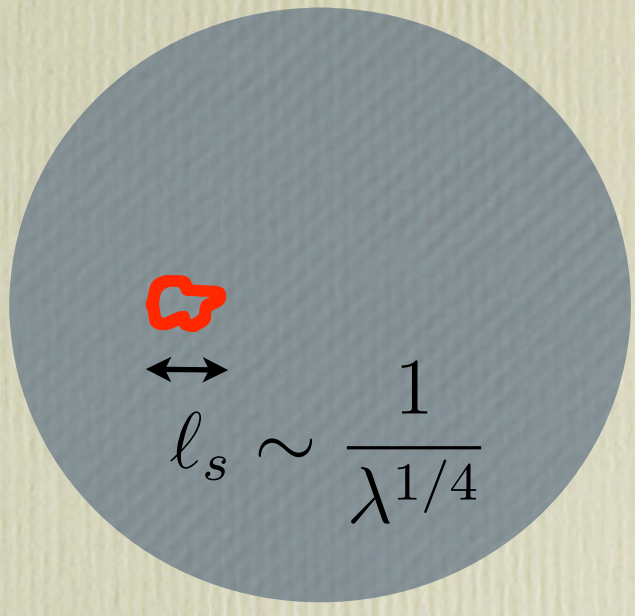
Limitations

$N_c \to \infty$



Suppresses quantum corrections.

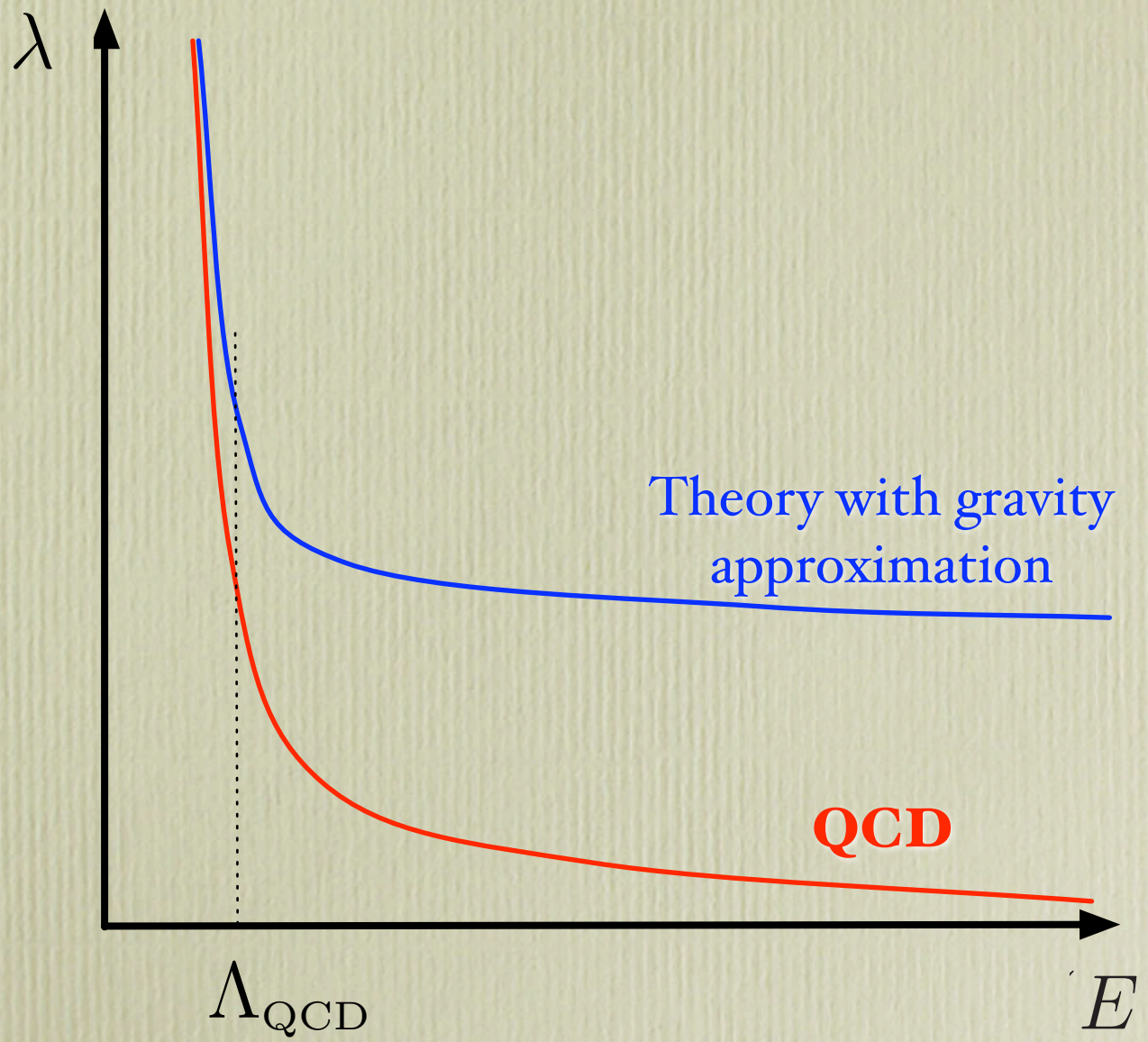
$\lambda = g_{\rm YM}^2 N_c \to \infty$



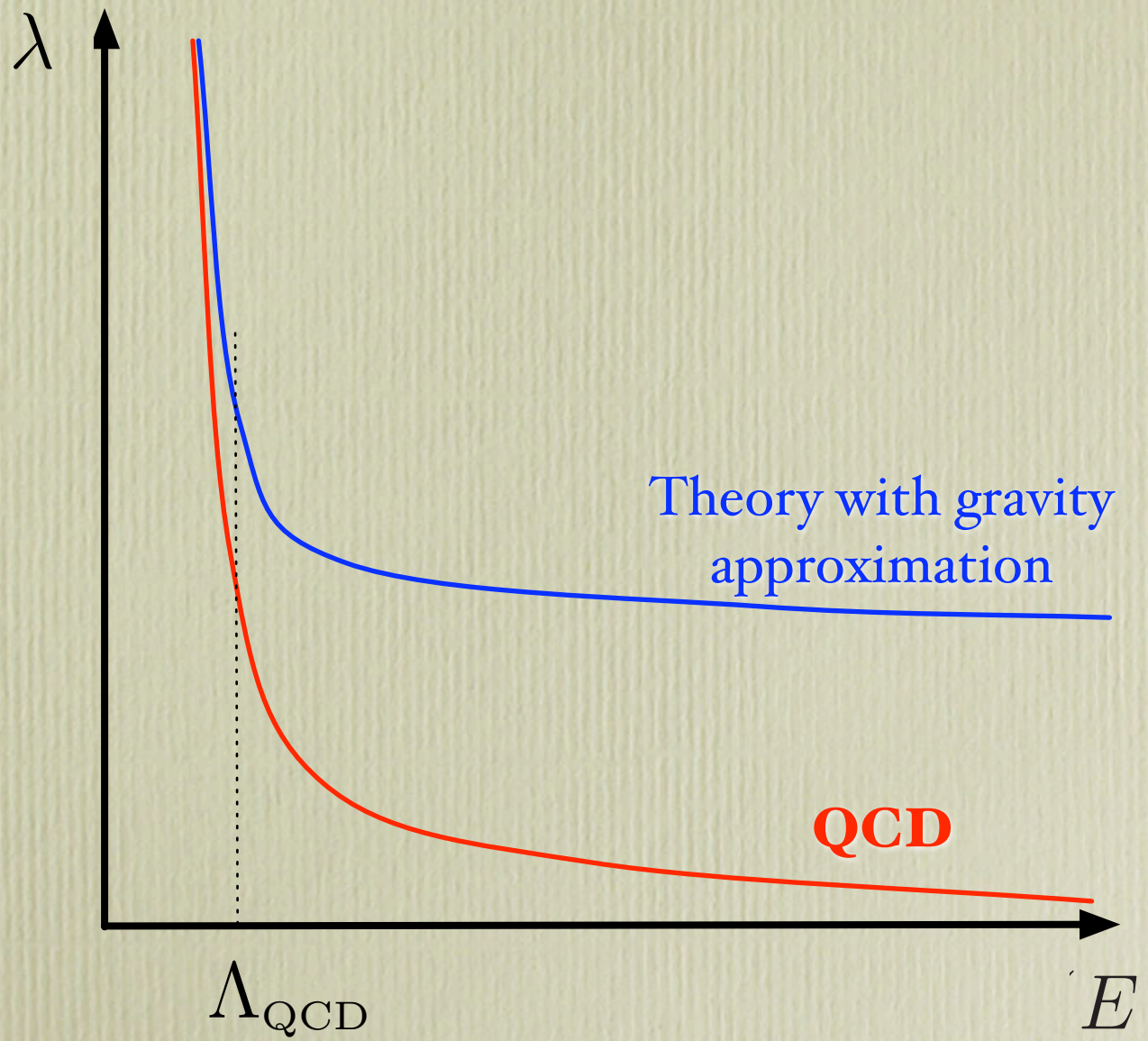
Makes the string tiny.

Strong coupling means *no* asymptotic freedom!

Limitations



Limitations



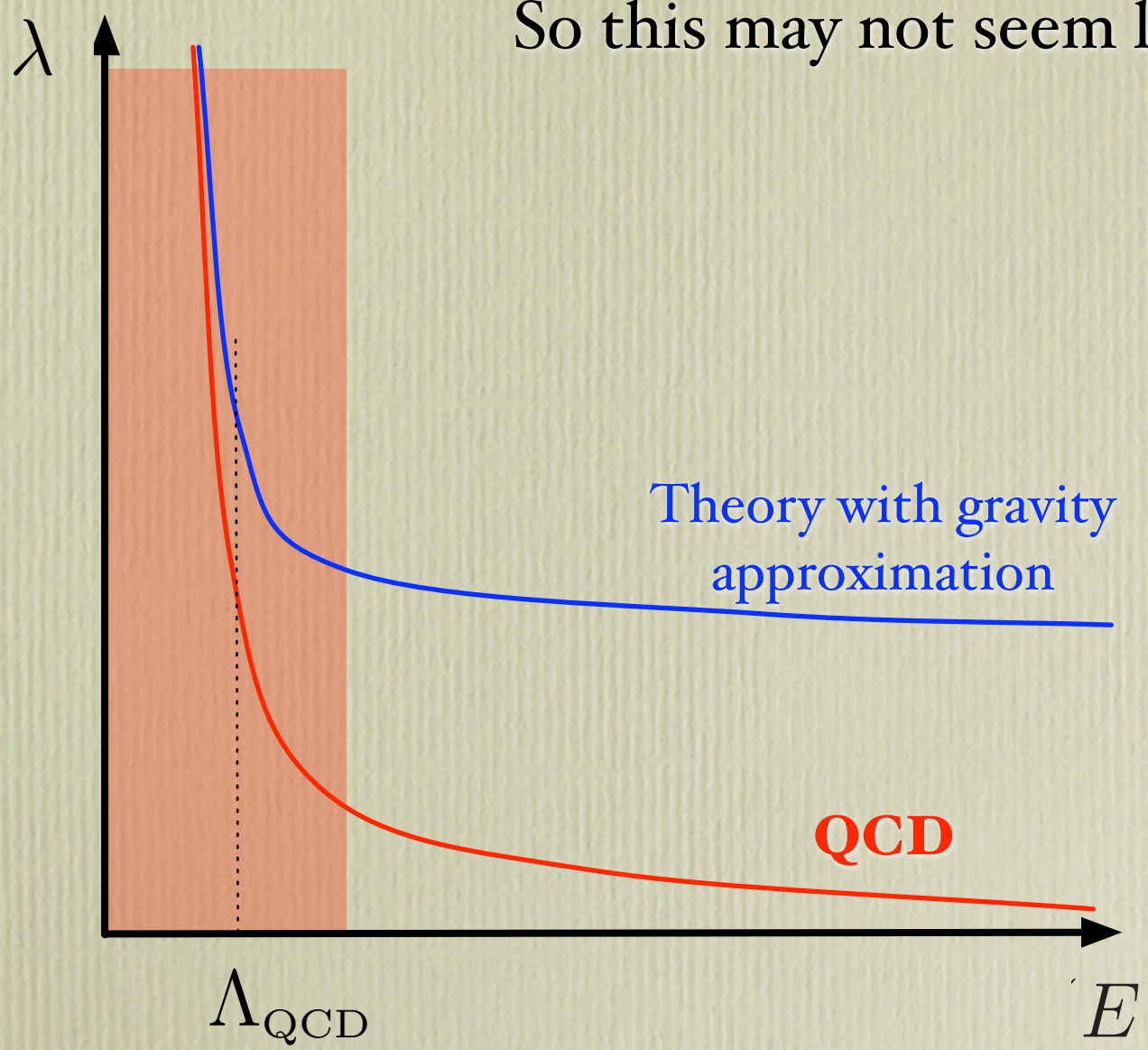
Need not be CFT!

(AdS/CFT is a misnomer)

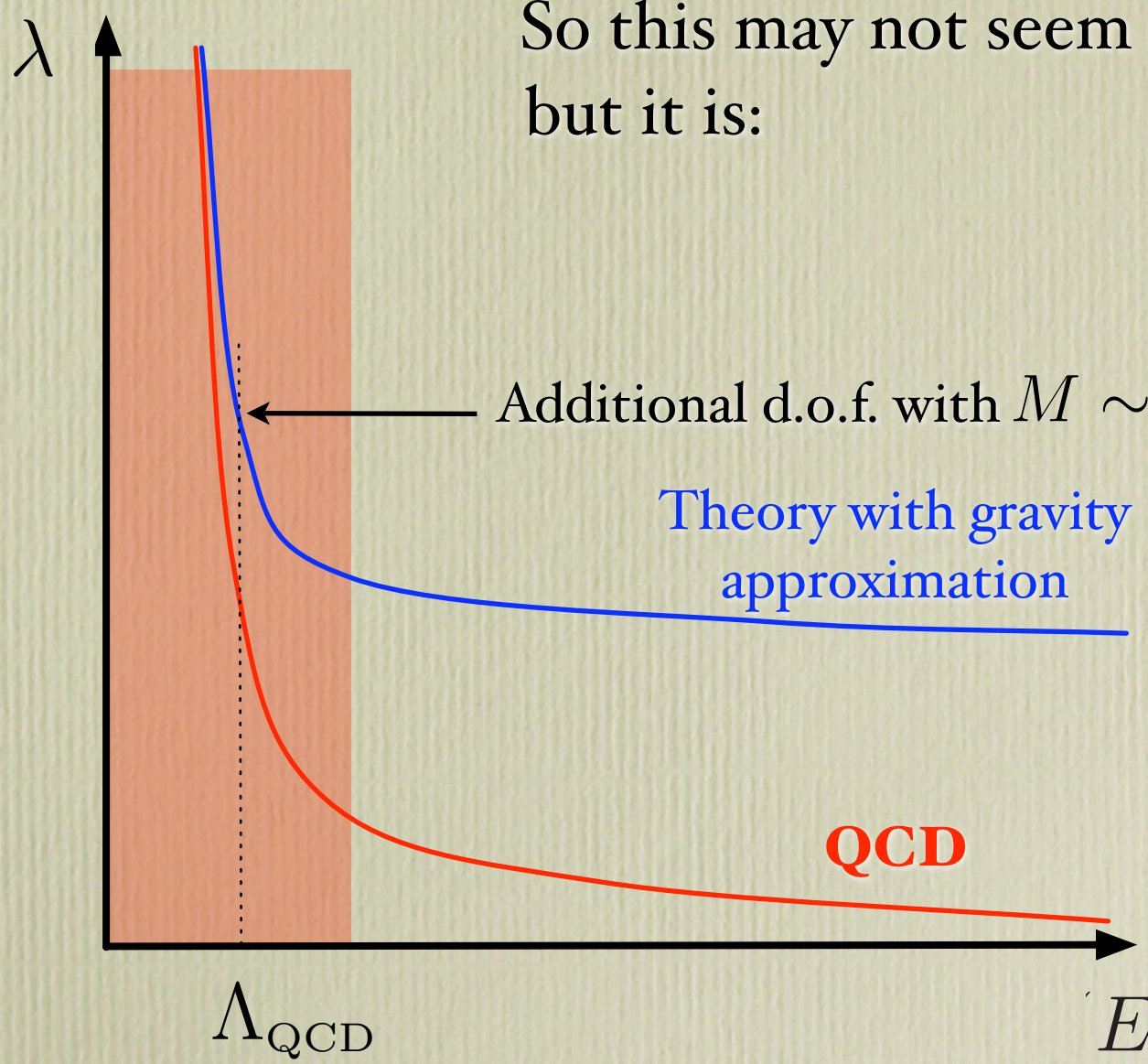
- Confinement.
- SχSB.
- Thermal phase transitions.
- Etc.

Limitations

So this may not seem like a big deal...



Limitations



Therefore

- At present gauge/string duality is not a tool for *precision* QCD physics.

Therefore

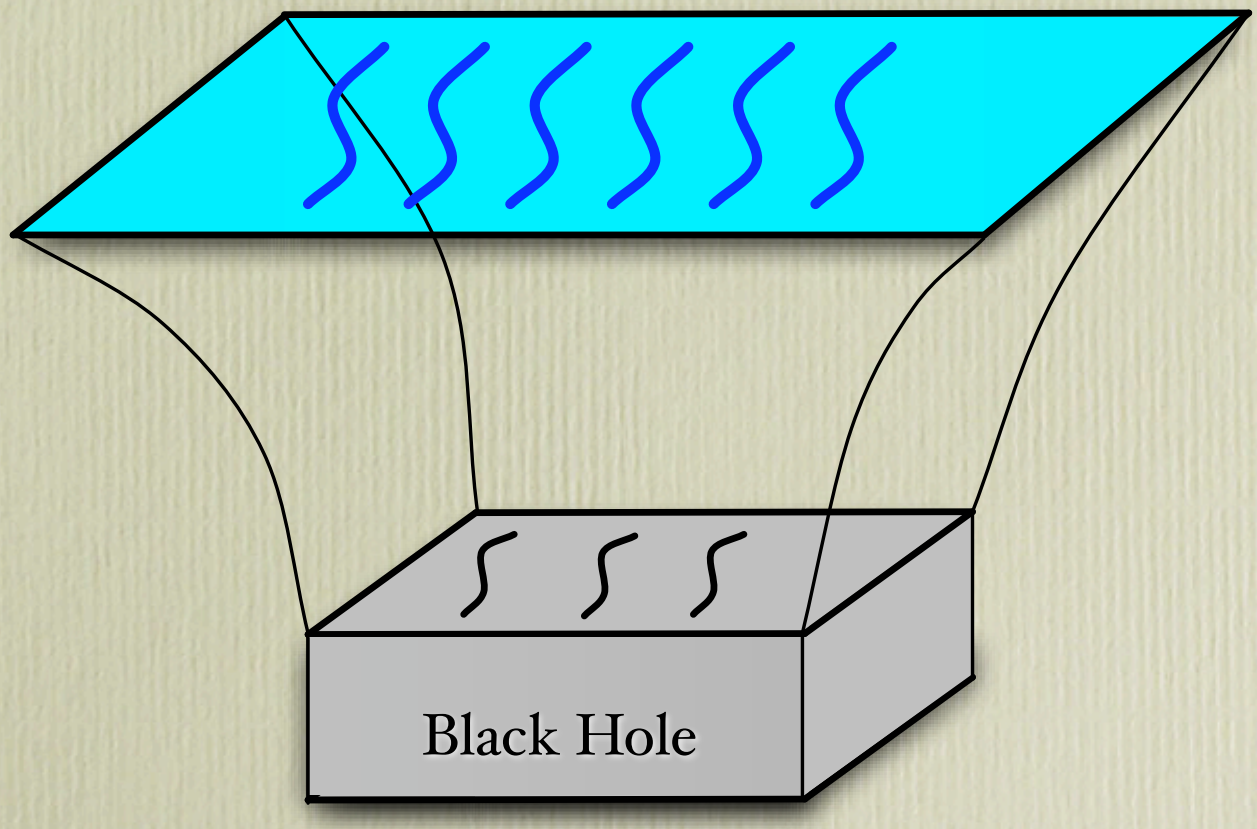
- At present gauge/string duality is not a tool for *precision* QCD physics.
- However, *certain* results may be universal enough to apply to QCD in *certain* regimes:
  - Quantitative ballpark estimates.
  - Qualitative insights.

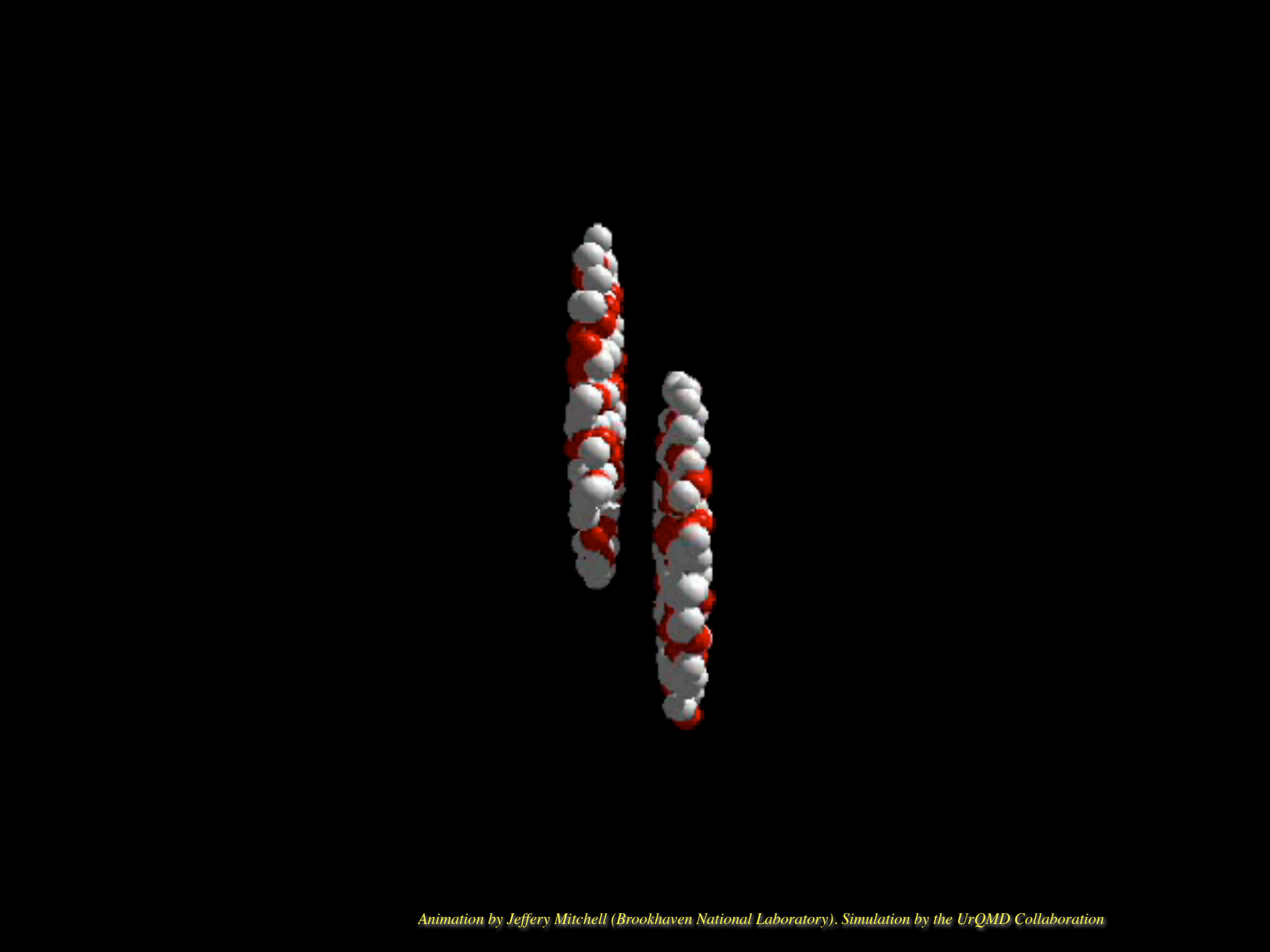
Therefore

- At present gauge/string duality is not a tool for *precision* QCD physics.
- However, *certain* results may be universal enough to apply to QCD in *certain* regimes:
  - Quantitative ballpark estimates.
  - Qualitative insights.
- This can be very useful!

Last decade: Near equilibrium QGP

Deconfinement = Black Hole





Animation by Jeffery Mitchell (Brookhaven National Laboratory). Simulation by the UrQMD Collaboration

Out of equilibrium

Out-of-equilibrium QFT

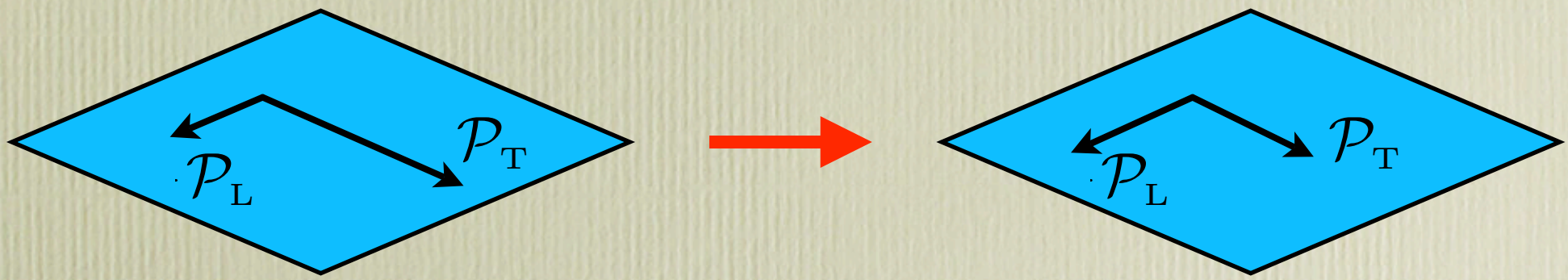


Classical Dynamical General Relativity in AdS

In the context of HIC

- Fast isotropization of the QGP (~ 1 fm/c) remains a challenge.

- Consider simplest possible set-up in AdS/CFT:
  Isotropization of homogeneous 4D CFT plasma
  (e.g. N=4 SYM plasma).

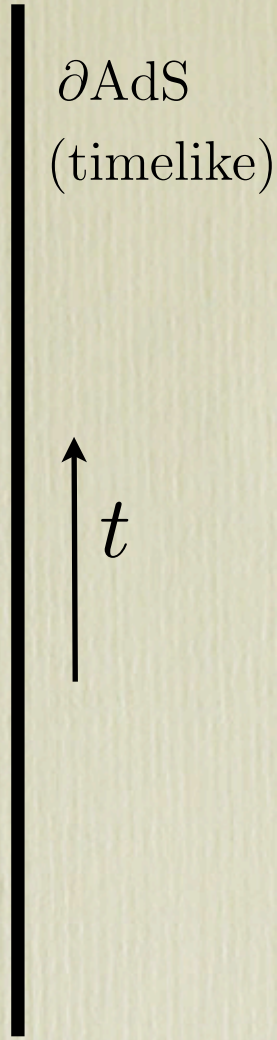


$t = 0$ $\qquad$ t_{iso}

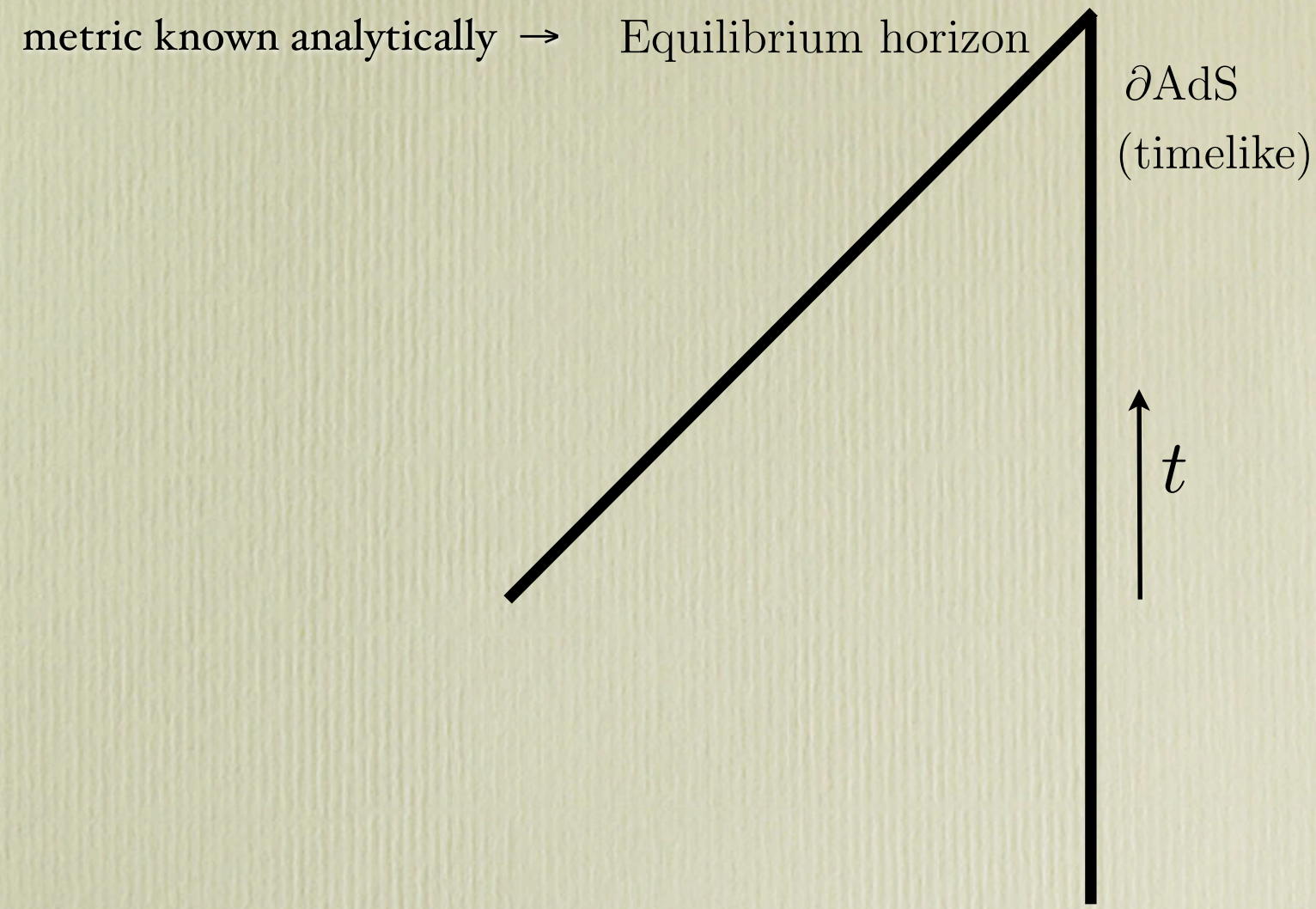
In the context of HIC

- Fast isotropization of the QGP (~ 1 fm/c) remains a challenge.
- Consider simplest possible set-up in AdS/CFT:
  Isotropization of homogeneous 4D CFT plasma
  (e.g. N=4 SYM plasma).
- Homogeneity: $\partial_\mu T^{\mu\nu} = 0 \;\rightarrow\; \partial_t T^{00} = 0 \;\rightarrow\; \mathcal{E}_i = \mathcal{E}_f$
- No hydrodynamics: $\omega \;\rightarrow\; 0 \;\text{ as }\; q \;\rightarrow\; 0$
- Only “quasi-normal modes” (QNM).

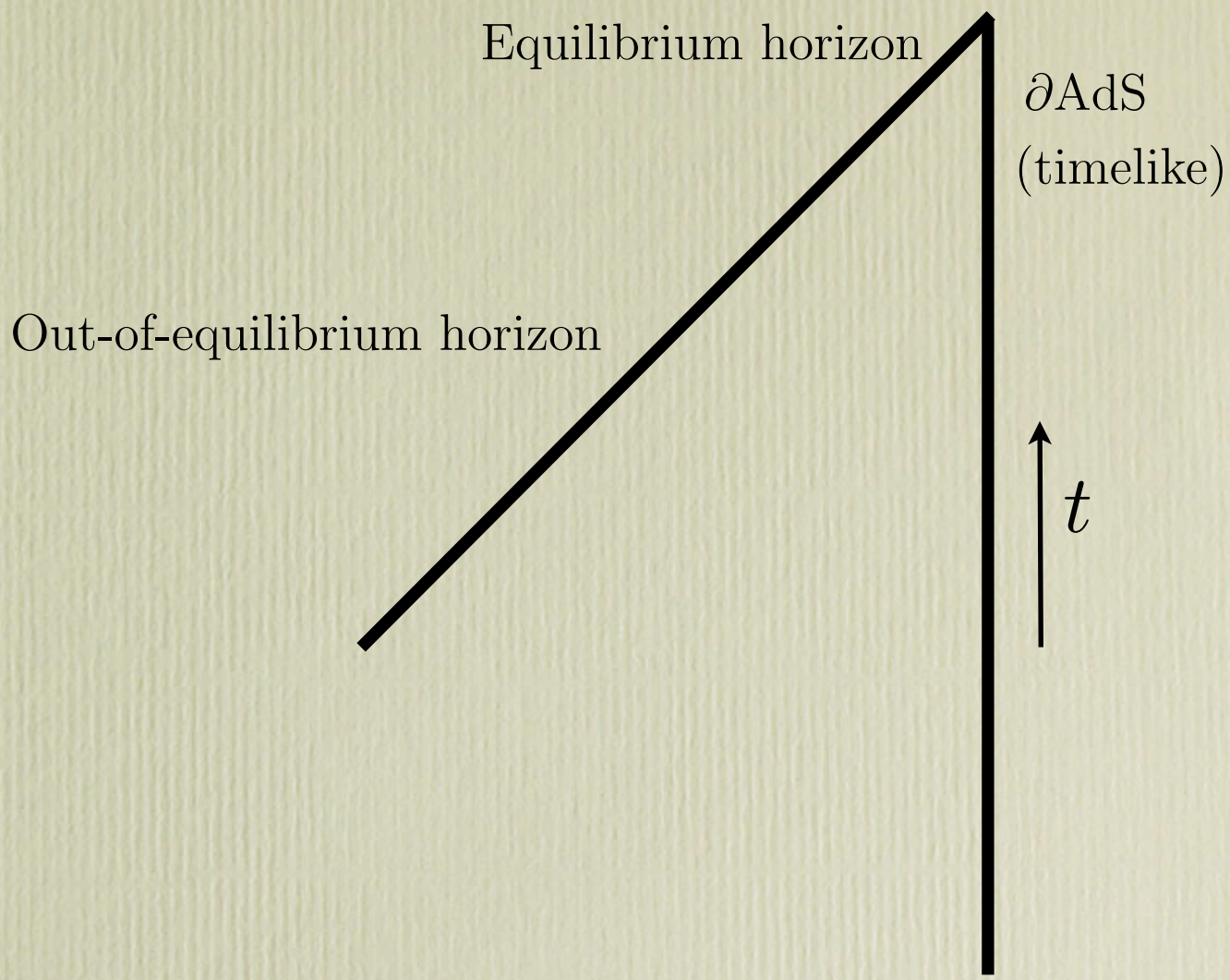
Posing the problem: Causal Structure



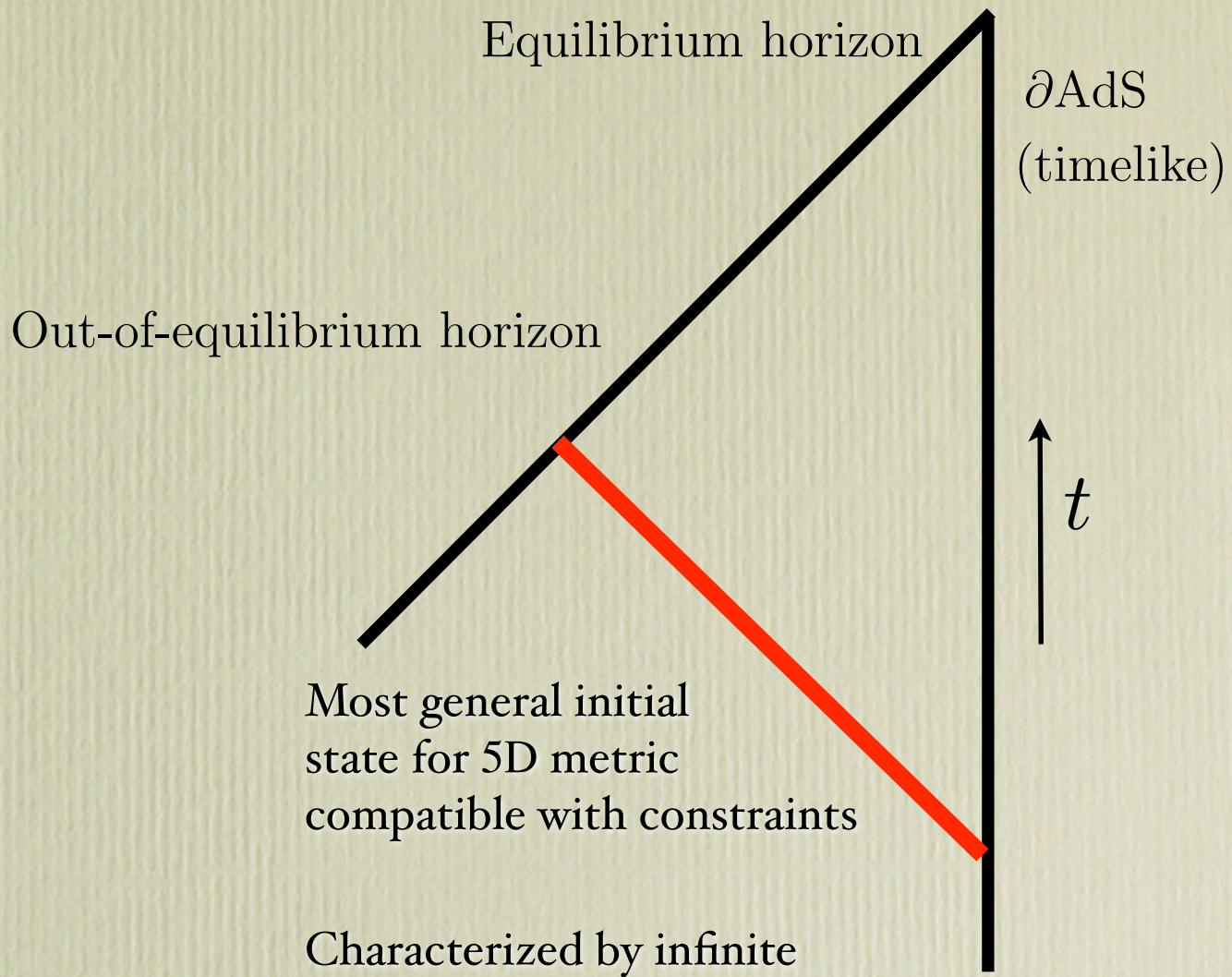
Posing the problem: Causal Structure



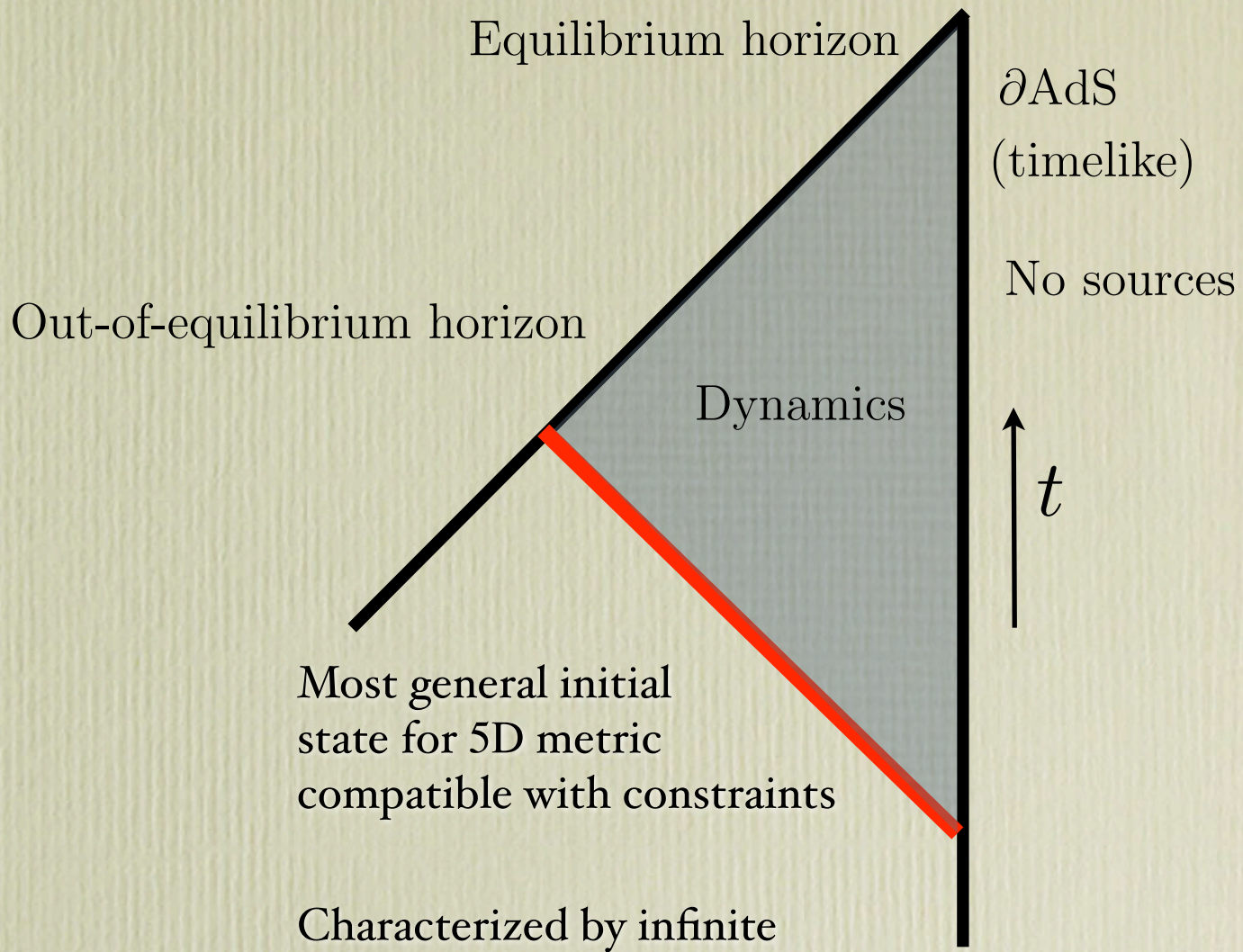
Posing the problem: Causal Structure



Posing the problem: Causal Structure



Posing the problem: Causal Structure



Most general initial state for 5D metric compatible with constraints

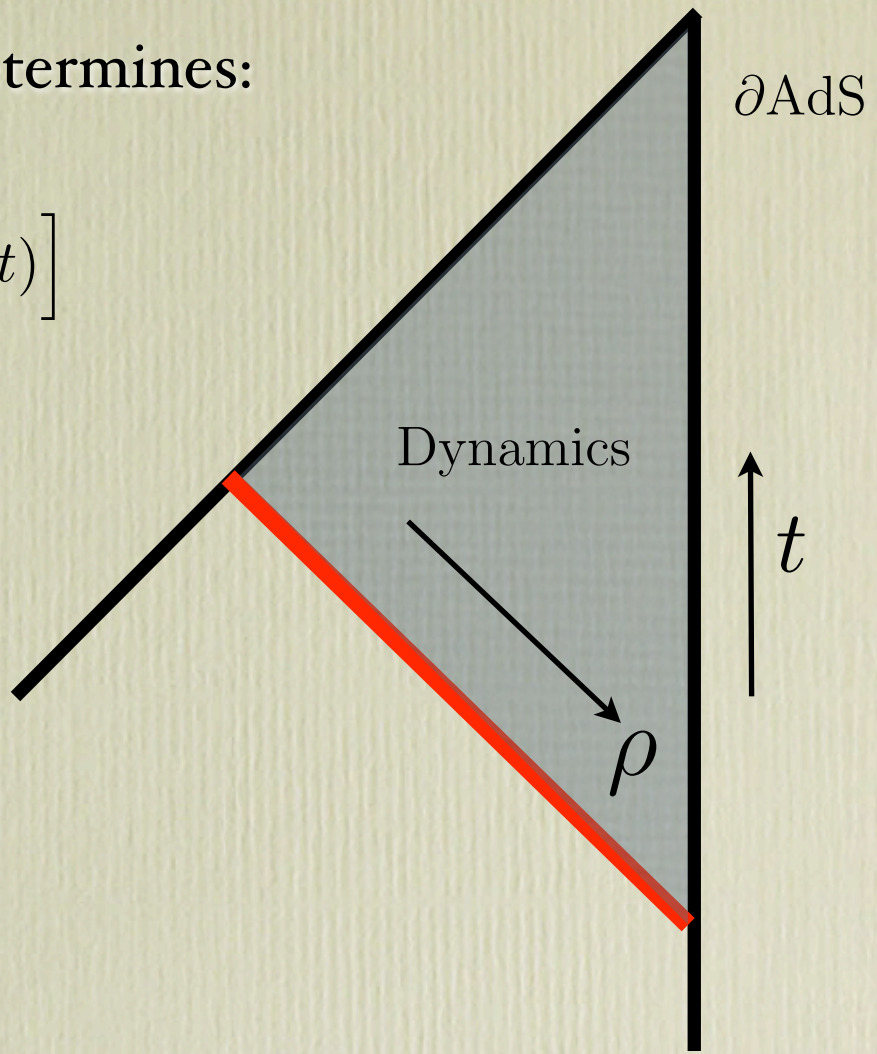
Characterized by infinite number of scales.

Posing the problem

- Near-boundary fall-off of metric determines:

$$\langle T_{\mu\nu} \rangle = \frac{N_c^2}{2\pi^2} \mathrm{diag}\Big[\mathcal{E},\, \mathcal{P}_{\mathrm{L}}(t),\, \mathcal{P}_{\mathrm{T}}(t),\, \mathcal{P}_{\mathrm{T}}(t)\Big]$$

- Interested in: $\Delta\mathcal{P} = \mathcal{P}_{\mathrm{T}} - \mathcal{P}_{\mathrm{L}}$



- Evolve initial state according to:
  - Full, non-linear EEQs.
  - EEQs linearized around final equilibrium state.

Motivation: Close-limit Approximation

Price & Pullin '94

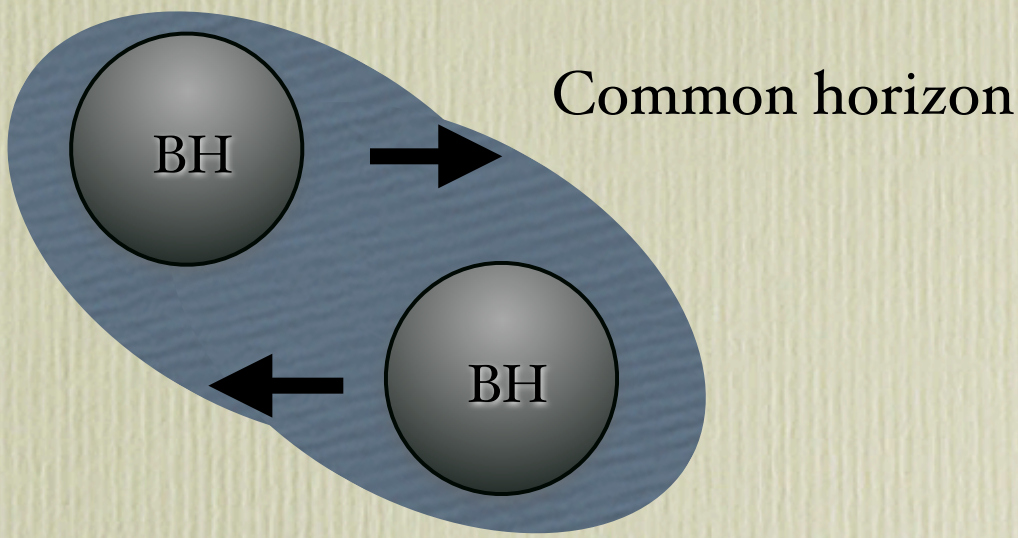
- BH collision in asymptotically flat 4D general relativity:



Motivation: Close-limit Approximation

Price & Pullin '94

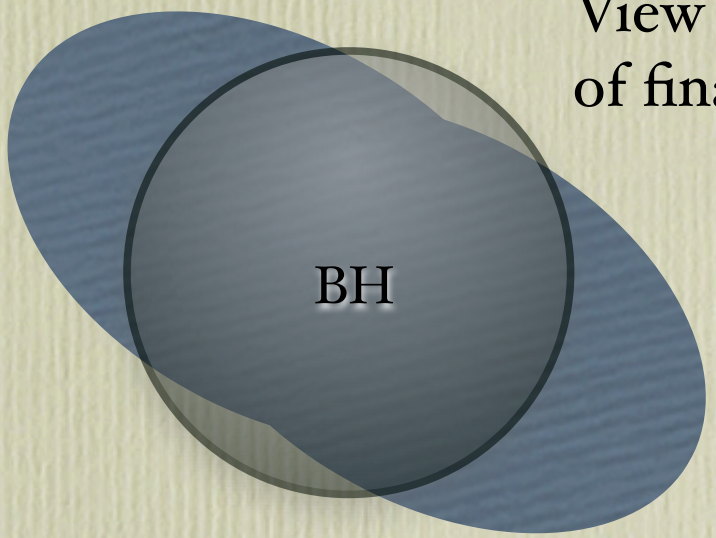
- BH collision in asymptotically flat 4D general relativity:



Motivation: Close-limit Approximation

Price & Pullin '94

- BH collision in asymptotically flat 4D general relativity:

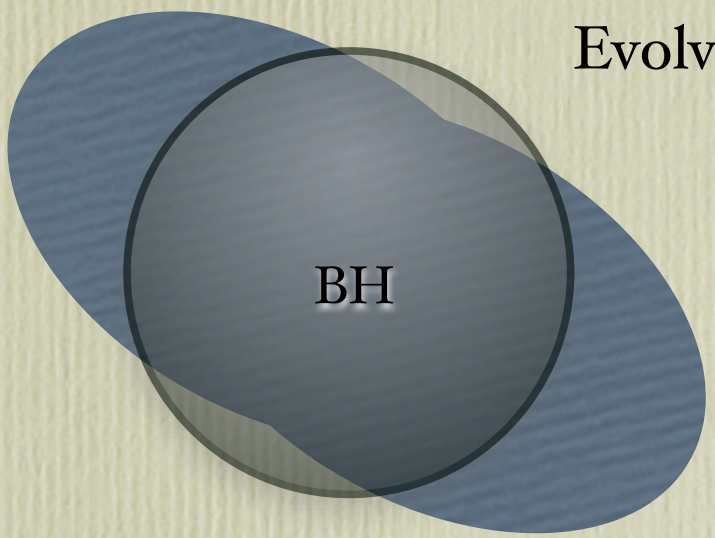


View as perturbation of final BH

Motivation: Close-limit Approximation

Price & Pullin '94

- BH collision in asymptotically flat 4D general relativity:

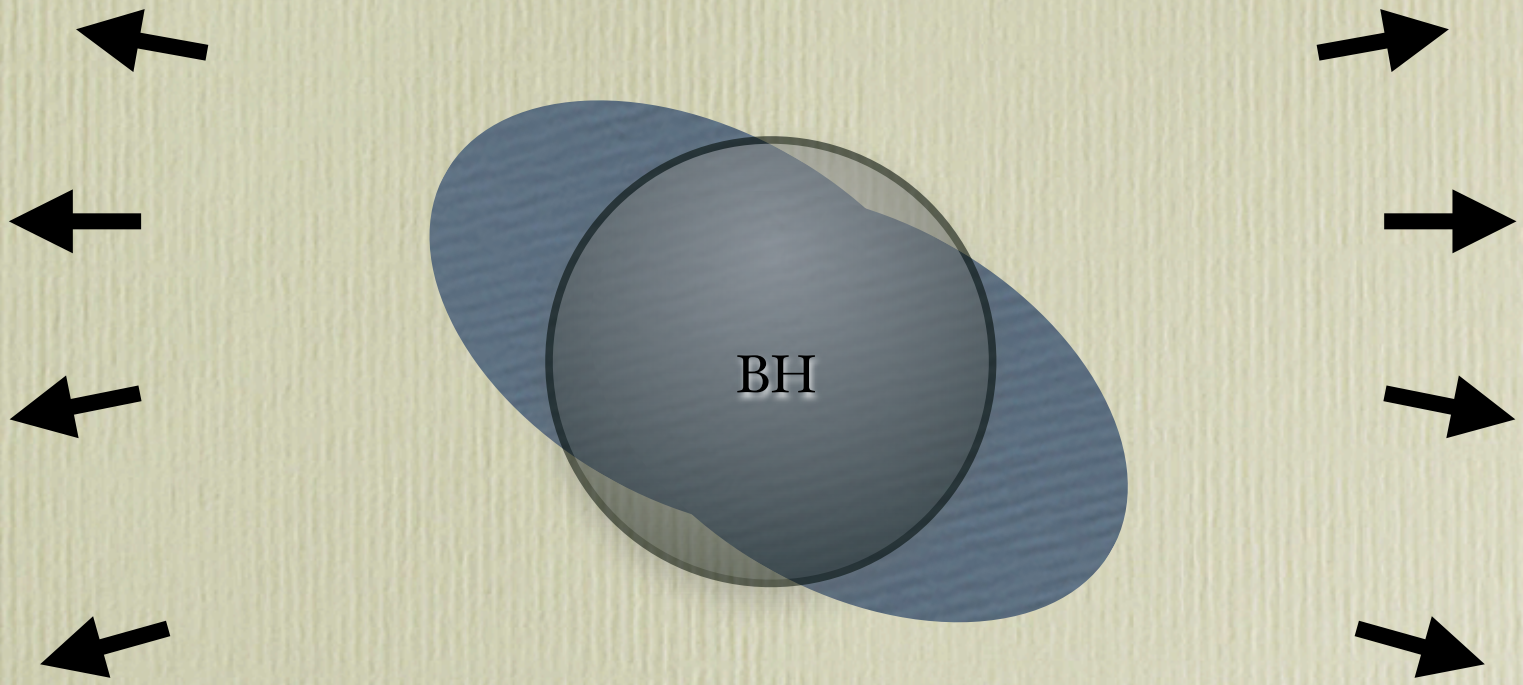


Evolve linearized EEQs

Motivation: Close-limit Approximation

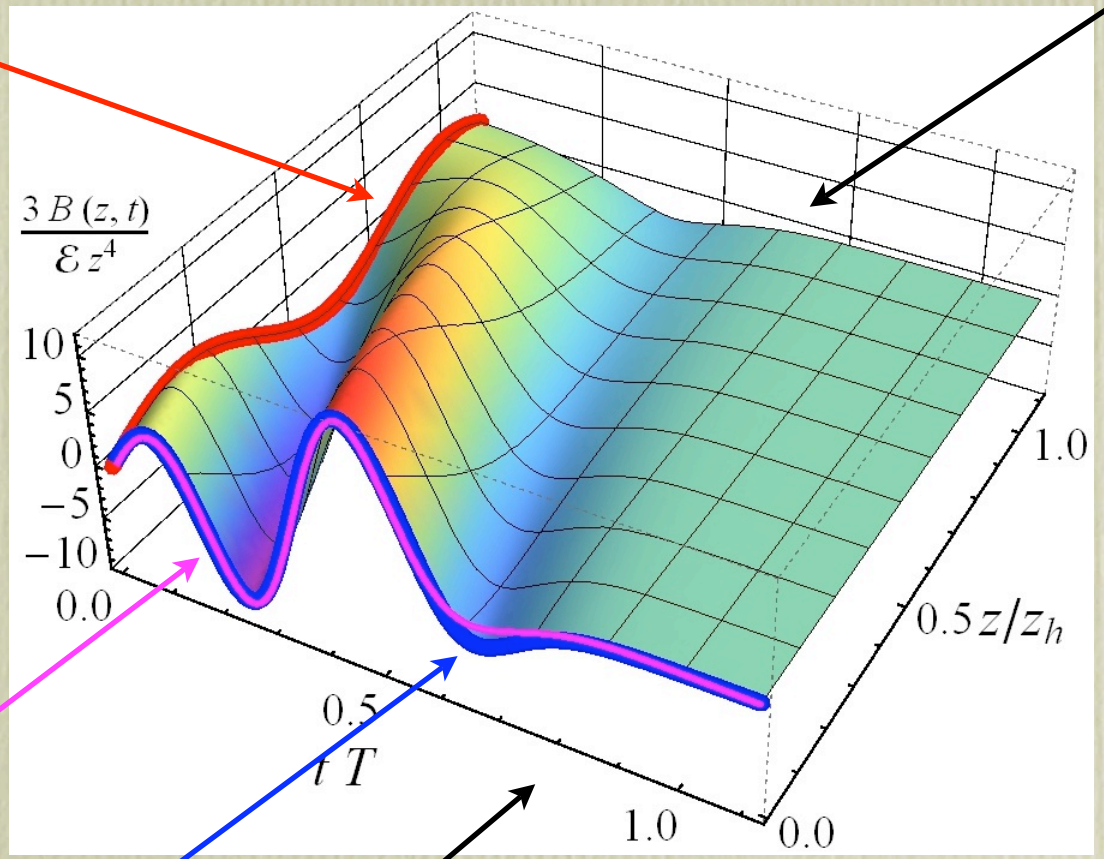
Price & Pullin '94

- BH collision in asymptotically flat 4D general relativity:

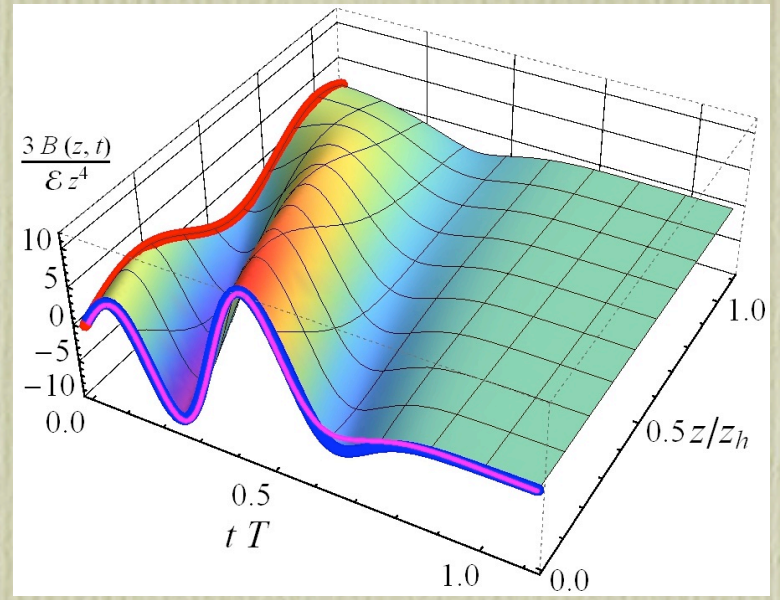


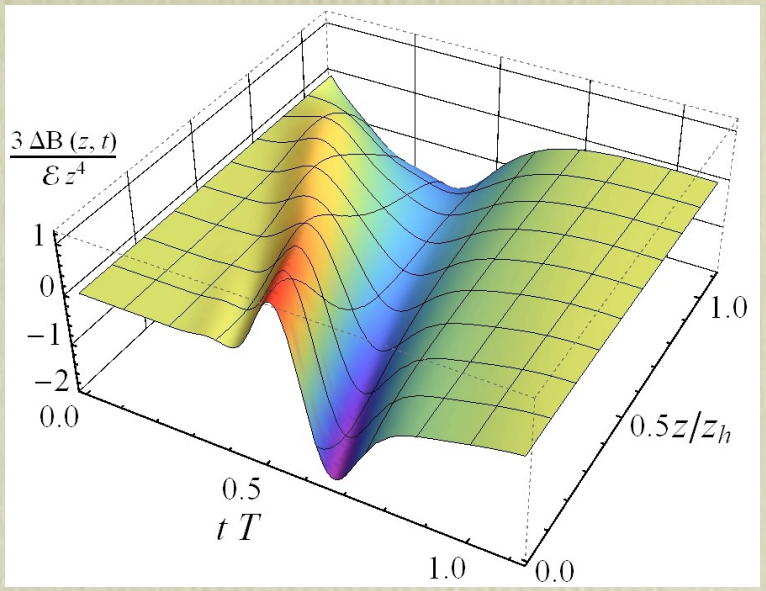
- Wave-form at infinity accurately reproduced
  (but perhaps non-asymptotic properties would not be).
- Analog in AdS: Boundary stress-tensor.

Results


Horizon
Initial state
$\frac{3\,B\,(z,t)}{\mathcal{E}\,z^4}$
10
5
0
−5
−10
0.0
0.5
$t\,T$
1.0
0.0
0.5 z/z_h
1.0
$z = 1/\rho$
Linear $\Delta\mathcal{P}(t)/\mathcal{E}$
Full $\Delta\mathcal{P}(t)/\mathcal{E}$
∂AdS

Results

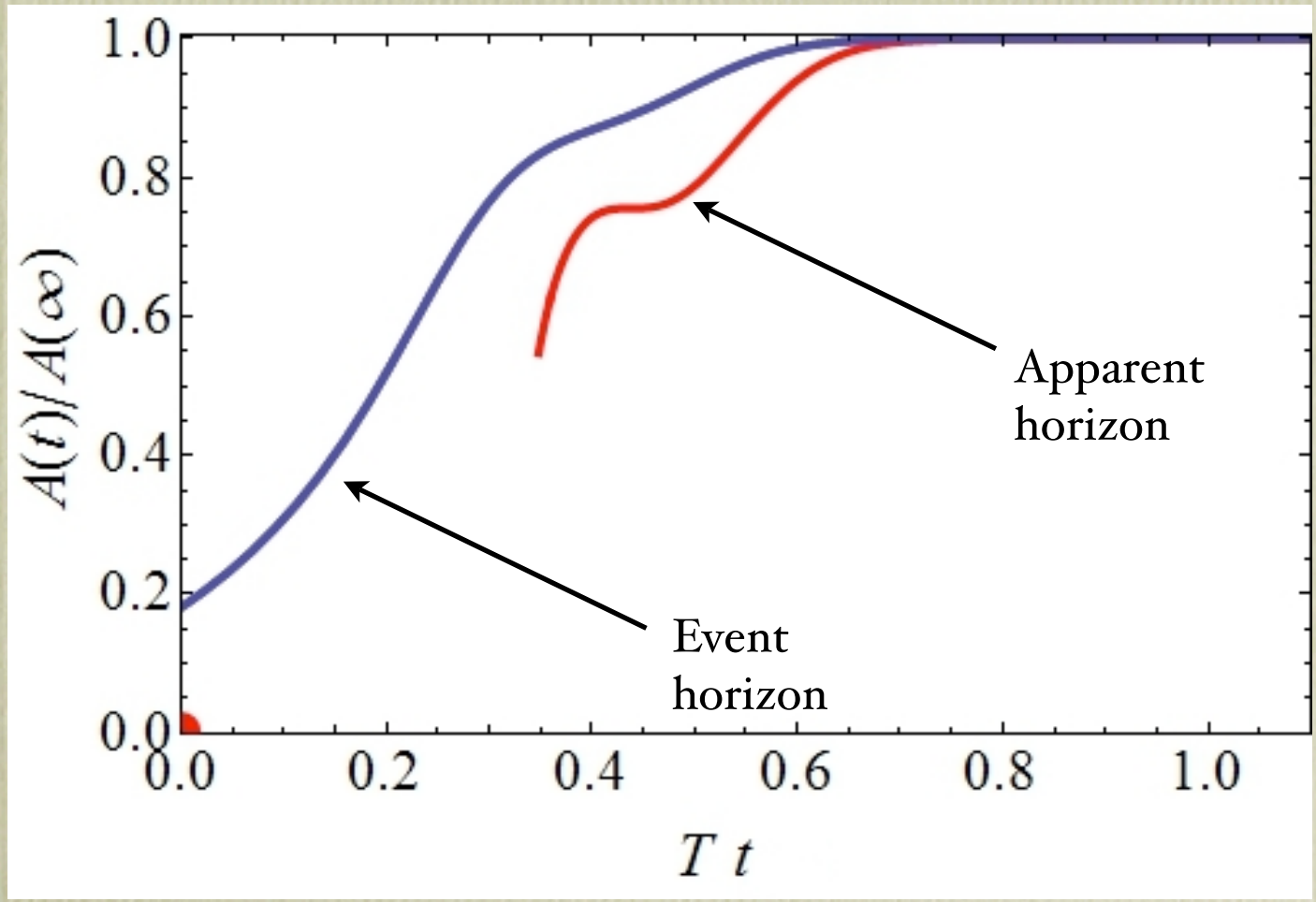




- Over 2000 initial profiles.
- Ratio of scales gives accuracy: 2/10 ~ 20%
- $\Delta\mathcal{P}(t)/\mathcal{E} \sim 10$ implies far from equilibrium.

Results

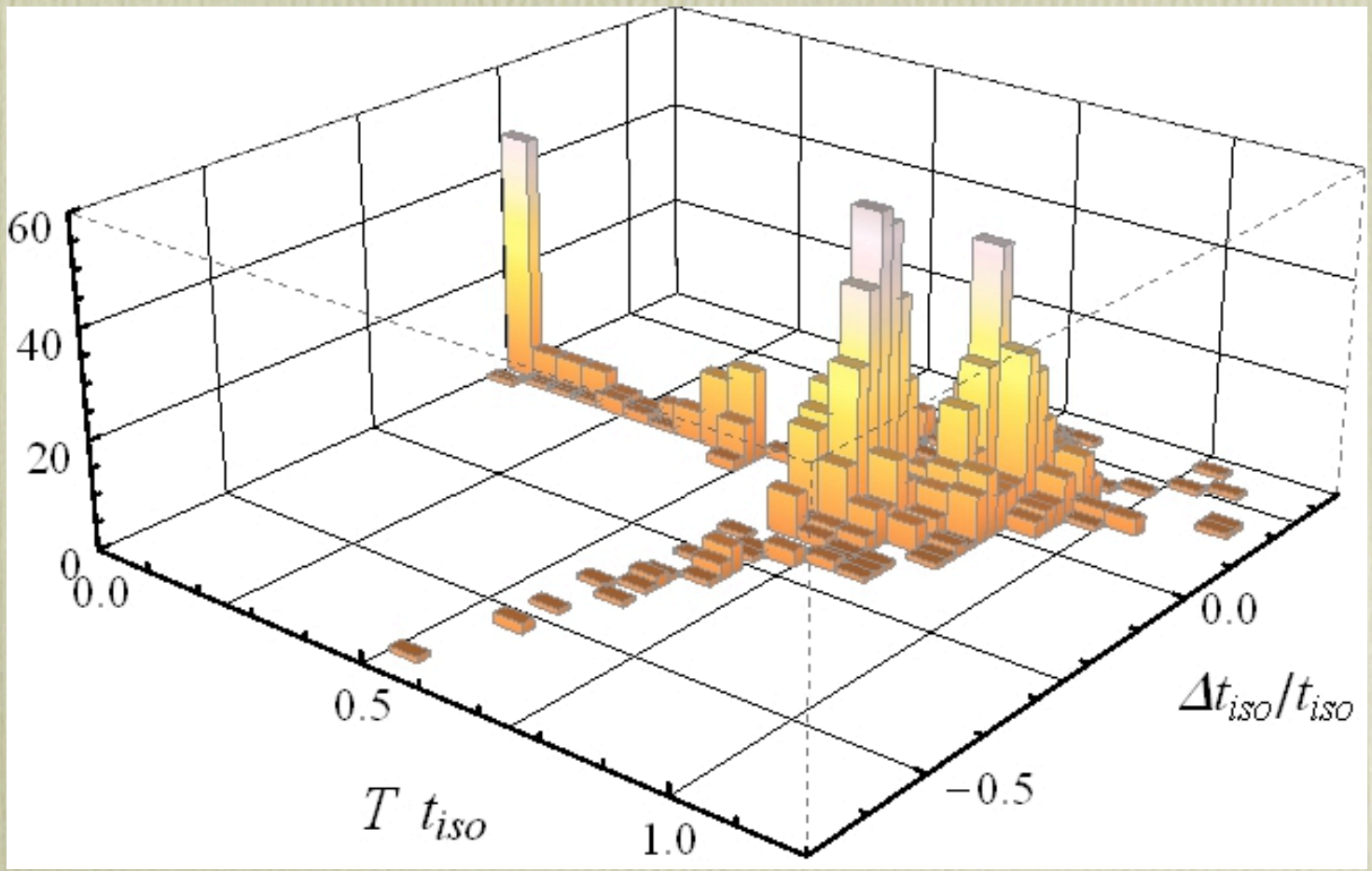
- "Entropy" increases during isotropization.



Results

- Isotropization time of order 1/T predicted by LA within 20%.

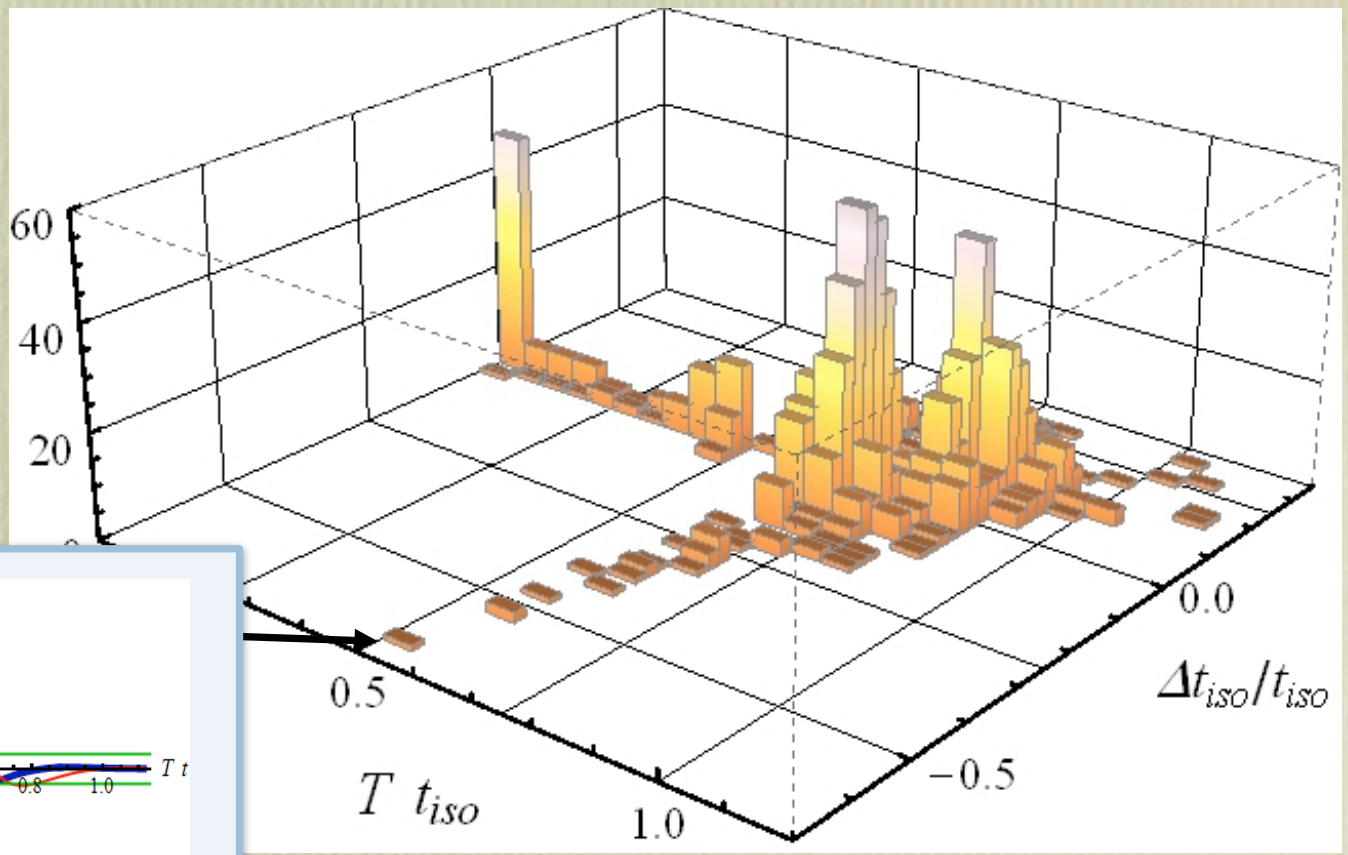
  $\Delta\mathcal{P}(t)/\mathcal{E} \leq 0.1$

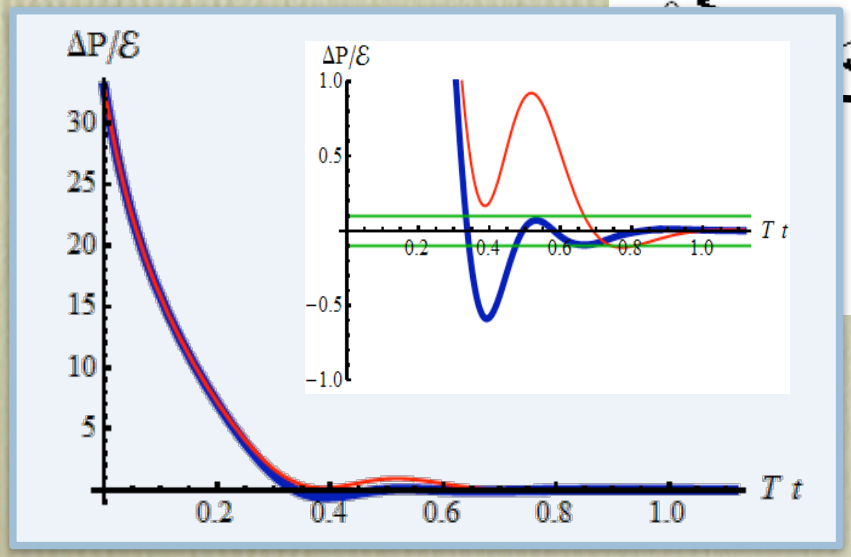


Results

- Isotropization time of order 1/T predicted by LA within 20%.

$$\Delta\mathcal{P}(t)/\mathcal{E} \leq 0.1$$

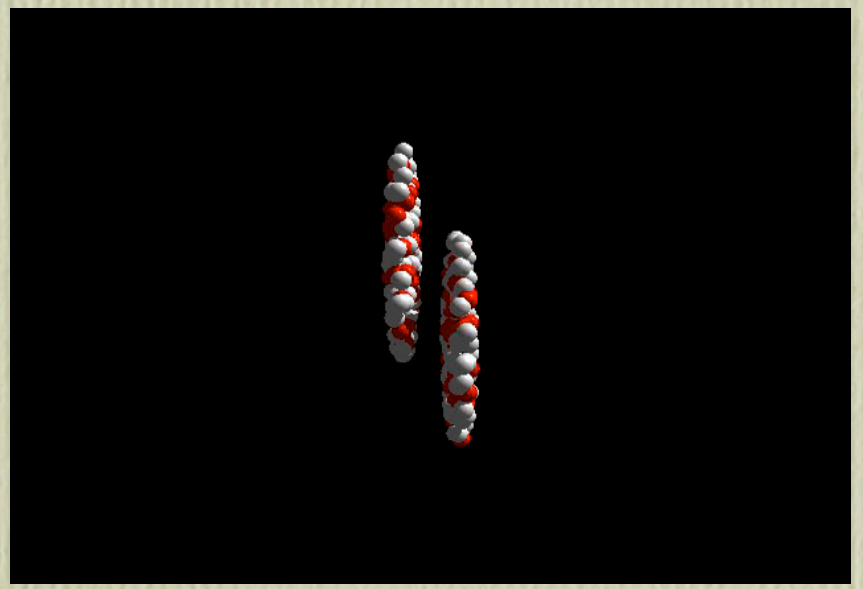




In progress

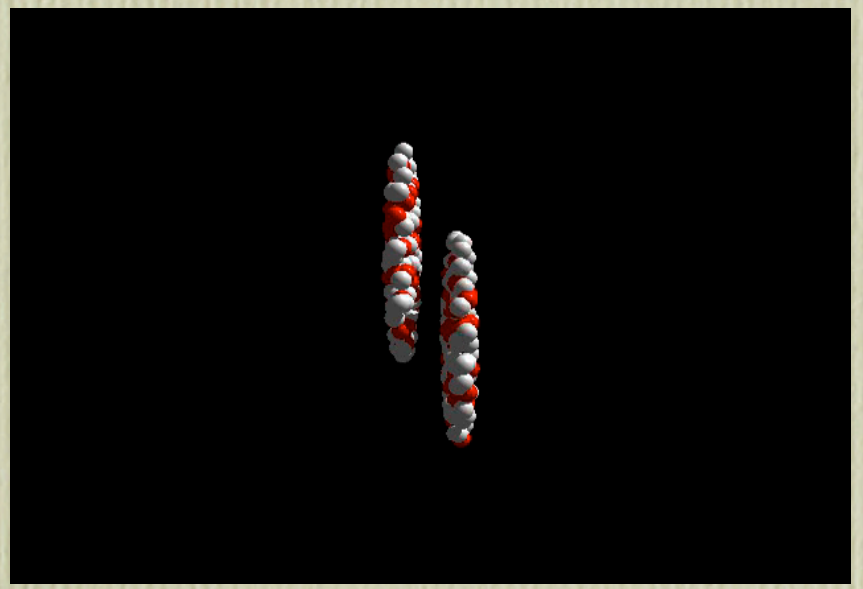
- Next step: Include hydrodynamics (boost-invariant case).
- Preliminary results indicate it works.

Potential implication

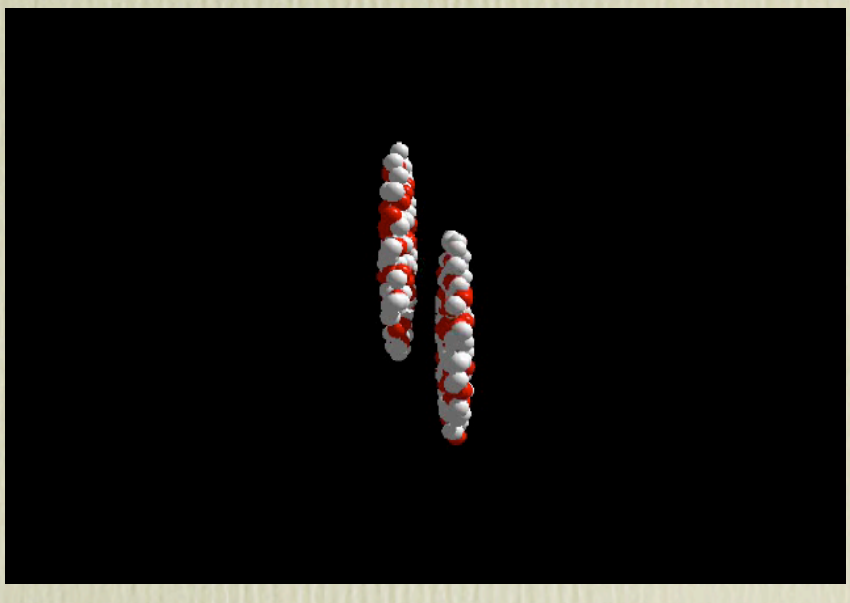


Initial state

Potential implication



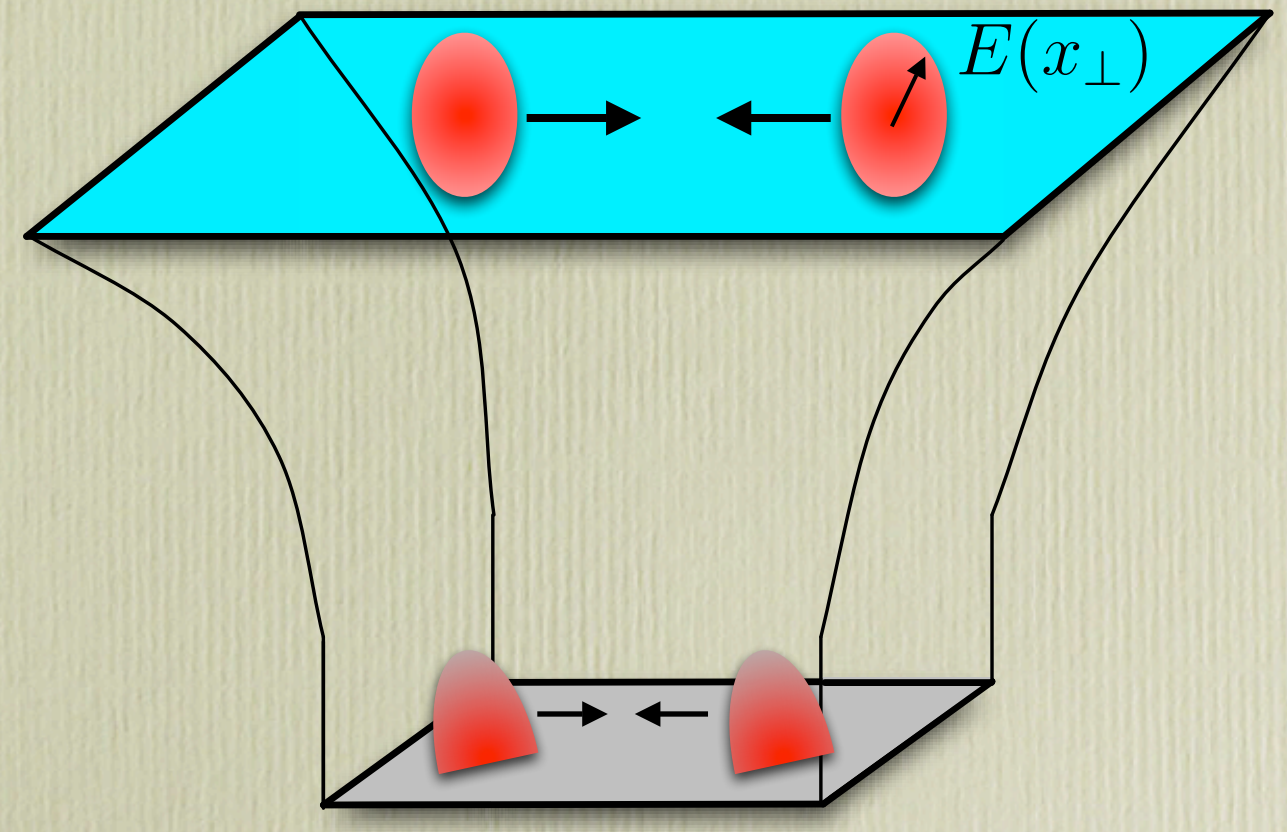
Map?



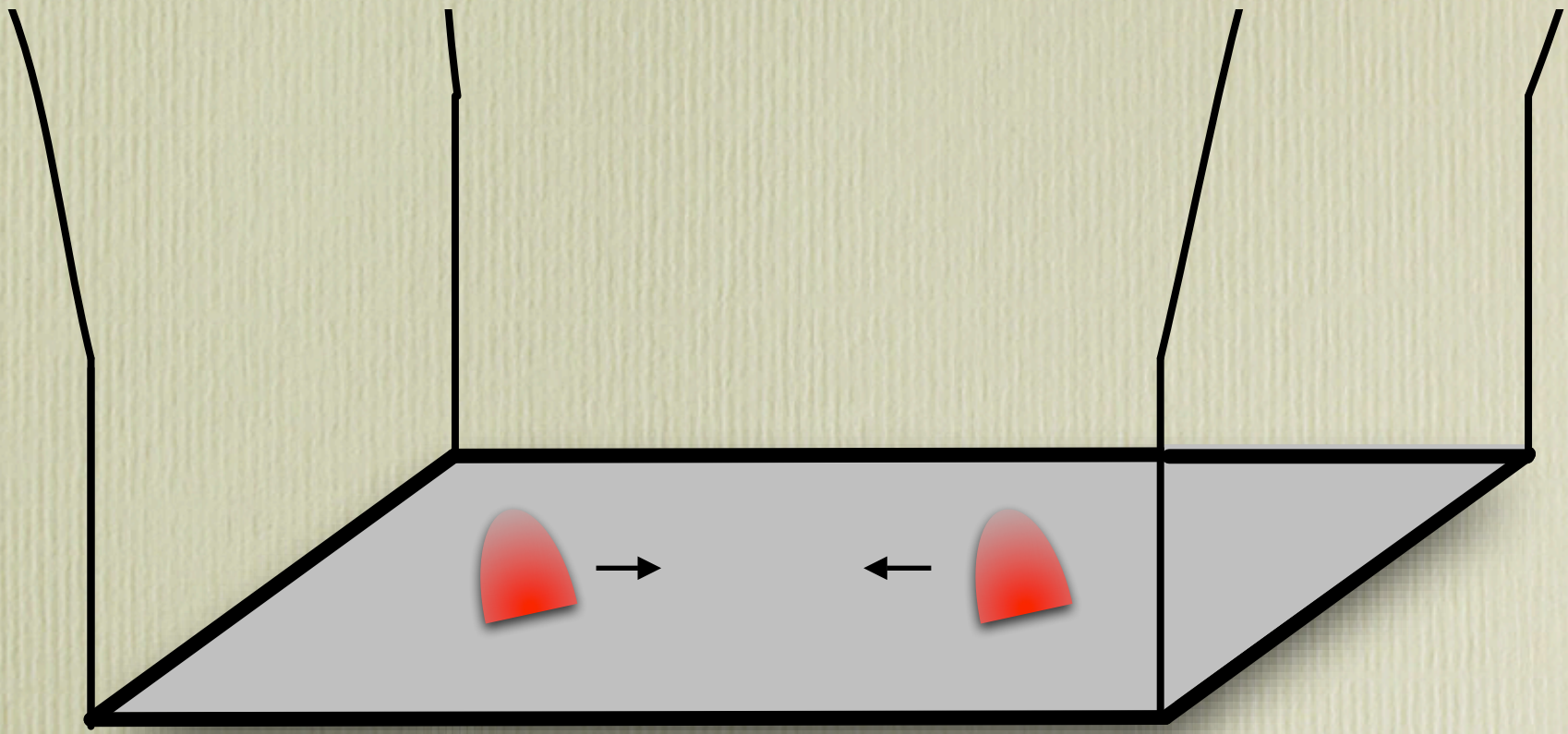
Initial state

Hydro becomes applicable

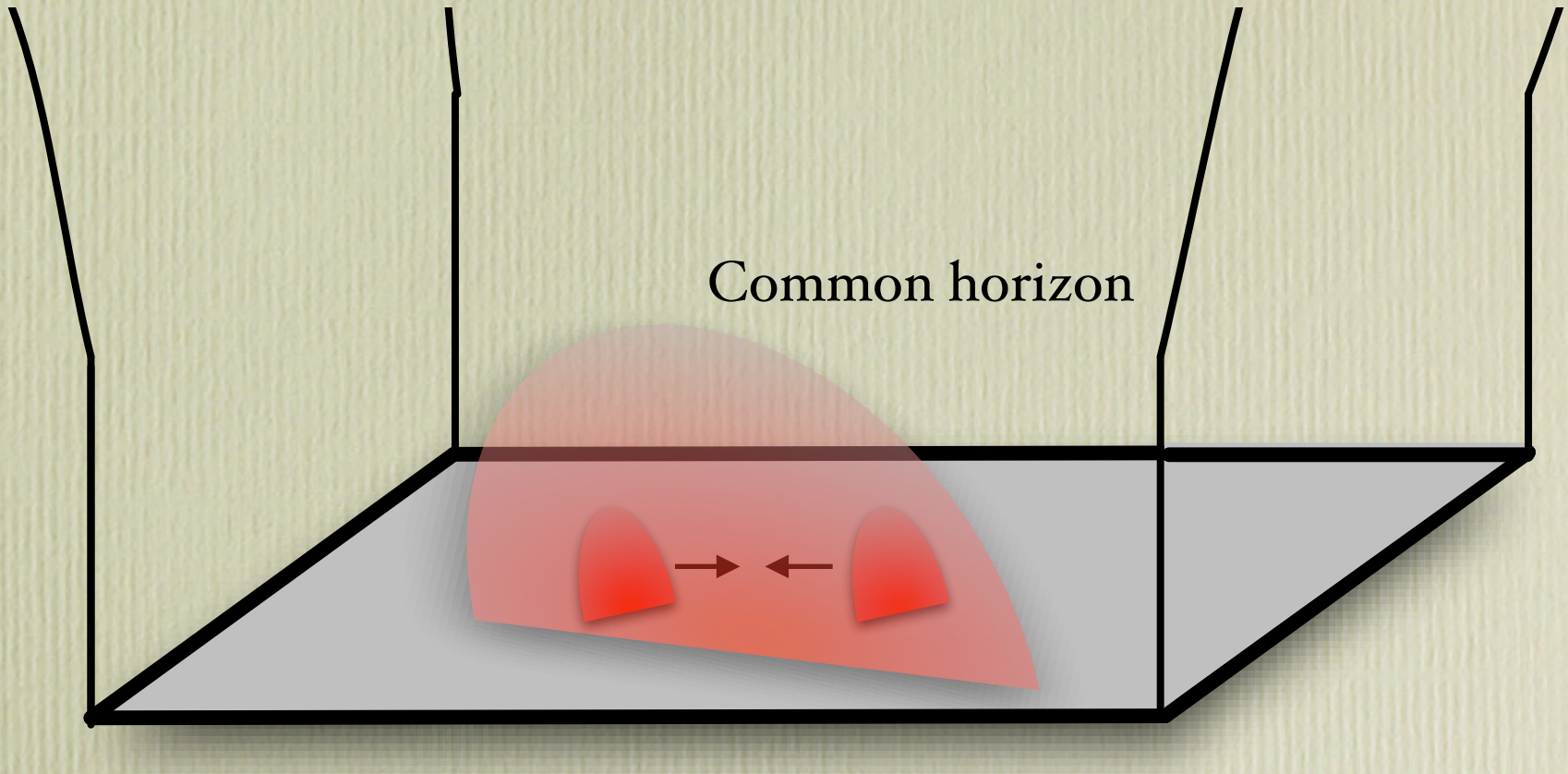
Potential implication



Potential implication



Potential implication



Full non-linearity of gravity encoded in the initial horizon.

Thank you.