# Exploring Cosmic Censorship in a Holographic Collider

*Javier Subils,*
July 18

**International Conference Center, 国际会议中心**
Yanqi lake campus of University of Chinese Academy of Sciences (UCAS),
Huairou, Beijing, China

Based on 2411.17806, in collaboration with *M. Aragonés Fontboté, D. Mateos, G. Pérez Martín and W. van der Schee.*

Utrecht University

# Motivation

General relativity is an effective theory of gravity,

$$S = \frac{M_{\rm P}^2}{16\pi} \int \sqrt{-g}\ R$$

# Motivation

General relativity is an effective theory of gravity,

$$S = \frac{M_{\mathrm{P}}^2}{16\pi} \int \sqrt{-g}\; R$$

as such, it is expected to work as long as curvature invariants are small.

# Motivation

General relativity is an effective theory of gravity,

$$S = \frac{M_{\mathrm{P}}^2}{16\pi} \int \sqrt{-g}\ R$$

as such, it is expected to work as long as curvature invariants are small.

Conversely, corrections to the theory become relevant in highly curved regions of spacetime, as it happens near **singularities**.

But these are hidden behind horizons (**Cosmic censorship**).

# Motivation

General relativity is an effective theory of gravity,

$$S = \frac{M_{\mathrm{P}}^2}{16\pi} \int \sqrt{-g}\; R$$

as such, it is expected to work as long as curvature invariants are small.

Conversely, corrections to the theory become relevant in highly curved regions of spacetime, as it happens near **singularities**.

But these are hidden behind horizons (**Cosmic censorship**).

*Is there any system where corrections to general relativity are relevant?*

# Motivation

General relativity is an effective theory of gravity,

$$S = \frac{M_{\mathrm{P}}^2}{16\pi} \int \sqrt{-g}\ R$$

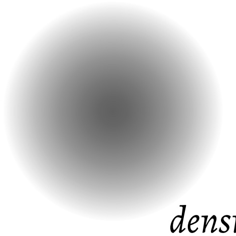
as such, it is expected to work as long as curvature invariants are small.

Conversely, corrections to the theory become relevant in highly curved regions of spacetime, as it happens near **singularities**.

But these are hidden behind horizons (**Cosmic censorship**).

*Is there any system where corrections to general relativity are relevant?*
*Can we probe quantum gravity at all?*

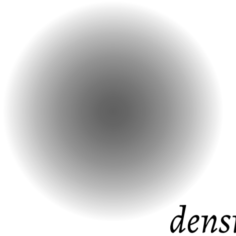
# Violations of Cosmic Censorship



*density profile*

In 4D, **critical collapse**, [*Choptuik; **Phys.Rev.Lett. 70, 9***]

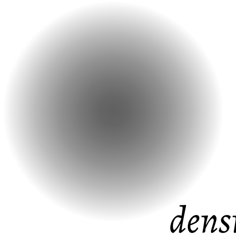
# Violations of Cosmic Censorship



*density profile*

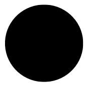
In 4D, **critical collapse**, [*Choptuik;* ***Phys.Rev.Lett. 70, 9***]

# Violations of Cosmic Censorship



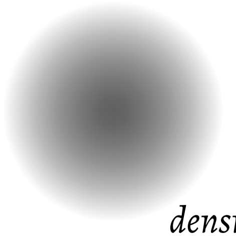
*density profile*

In 4D, **critical collapse**, [*Choptuik; **Phys.Rev.Lett. 70, 9***]

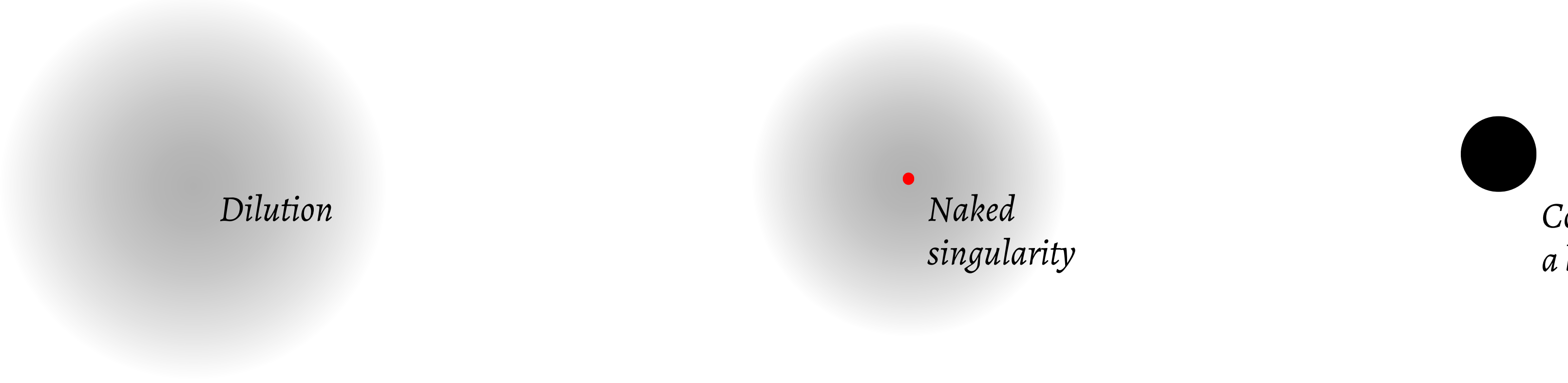



*Collapse into*
*a black hole*

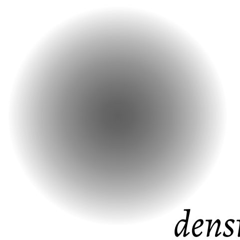
# Violations of Cosmic Censorship




In 4D, **critical collapse**, [*Choptuik; **Phys.Rev.Lett. 70, 9***]

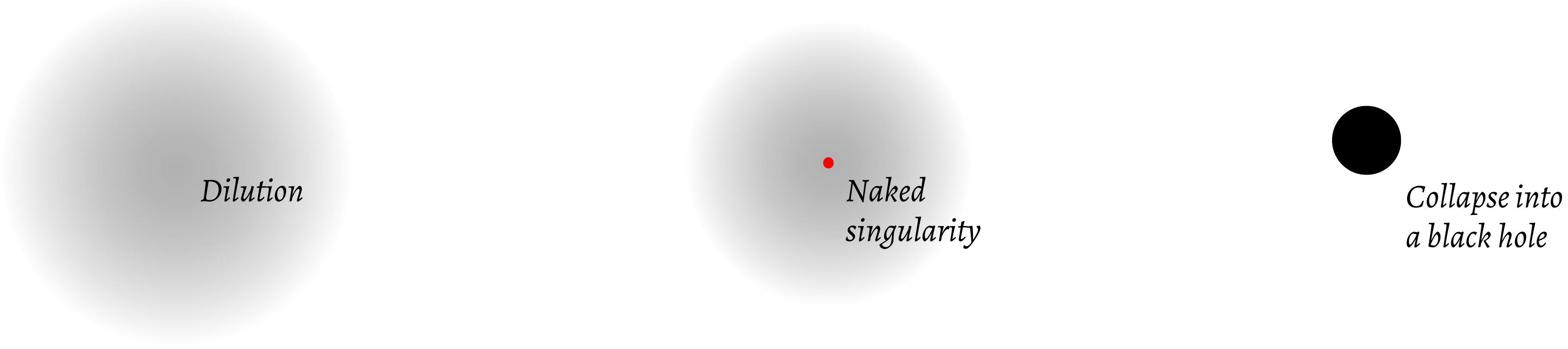


# Violations of Cosmic Censorship



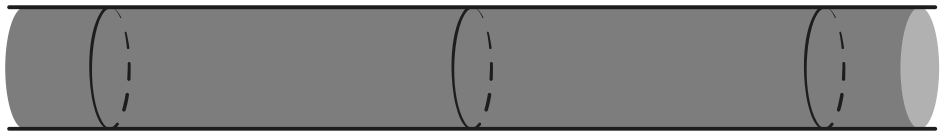
*density profile*

In 4D, **critical collapse**, [*Choptuik;* ***Phys.Rev.Lett. 70, 9***]

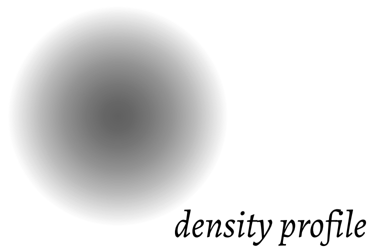



In higher dimensions, Gregory-Laflamme instability

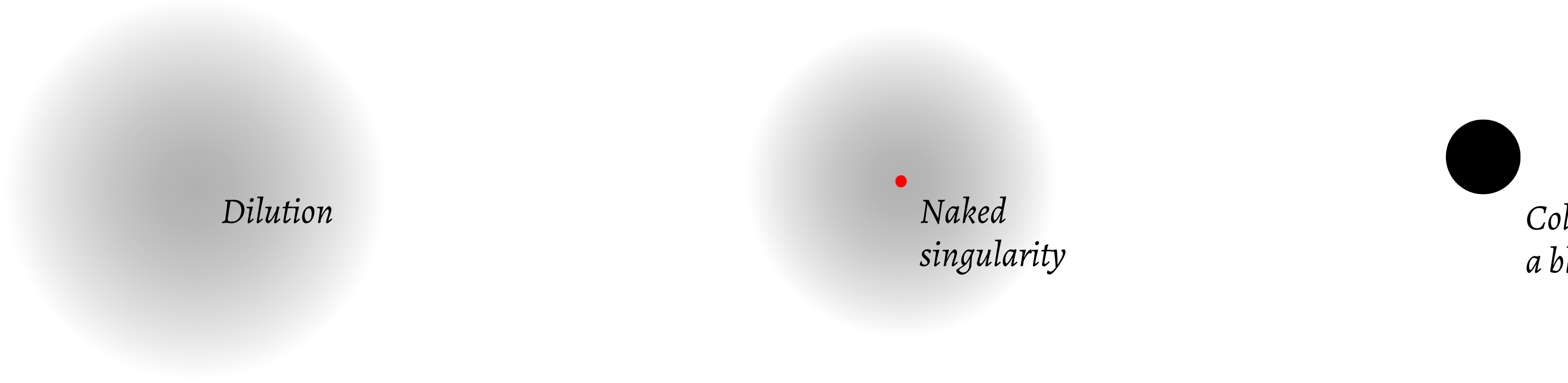
[*Gregory, Laflamme;* ***hep-th/9301052***], [*Lehner, Pretorius;* ***1006.5960***], [*Figueras, França, Gu;* ***2210.13501***]



# Violations of Cosmic Censorship

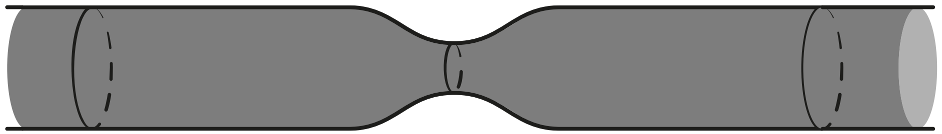



In 4D, **critical collapse**, [*Choptuik;* ***Phys.Rev.Lett. 70, 9***]

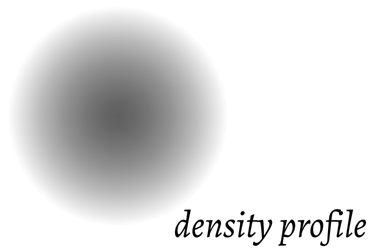



In higher dimensions, Gregory-Laflamme instability

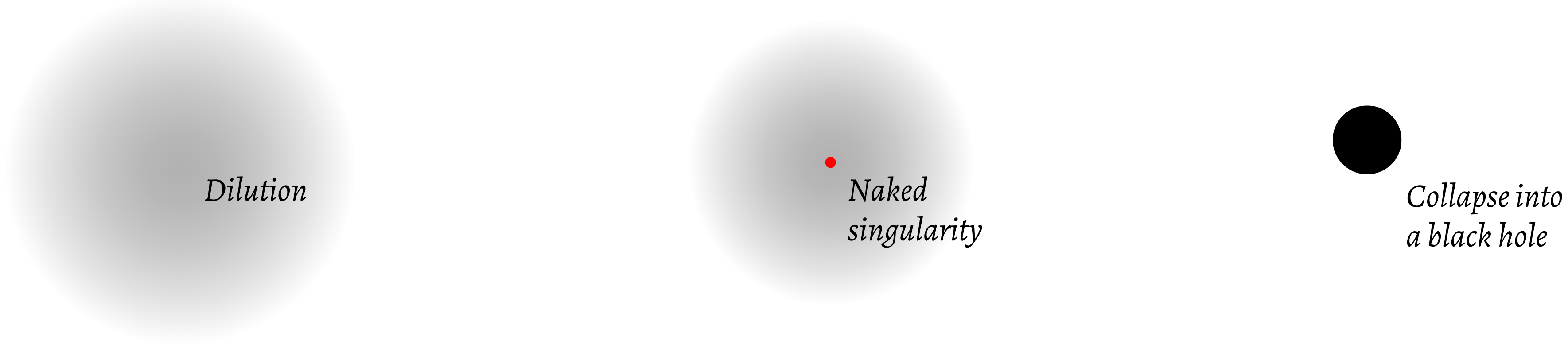
[*Gregory, Laflamme;* ***hep-th/9301052***], [*Lehner, Pretorius;* ***1006.5960***], [*Figueras, França, Gu;* ***2210.13501***]



# Violations of Cosmic Censorship

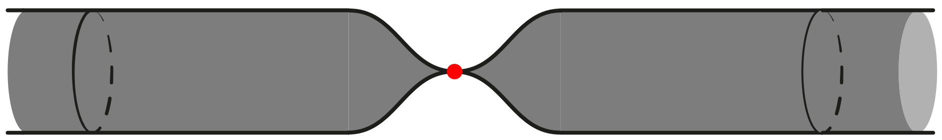



In 4D, **critical collapse**, [*Choptuik;* ***Phys.Rev.Lett. 70, 9***]

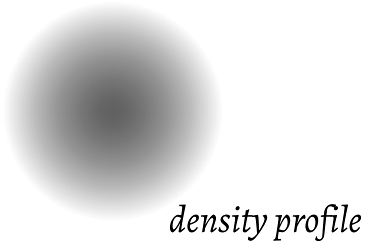



In higher dimensions, Gregory-Laflamme instability

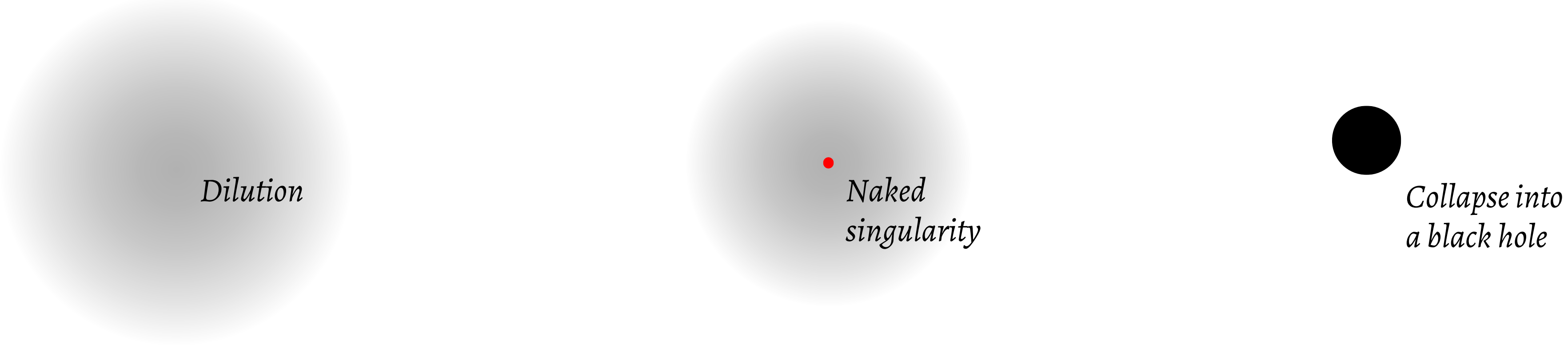
[*Gregory, Laflamme;* ***hep-th/9301052***], [*Lehner, Pretorius;* ***1006.5960***], [*Figueras, França, Gu;* ***2210.13501***]



# Violations of Cosmic Censorship

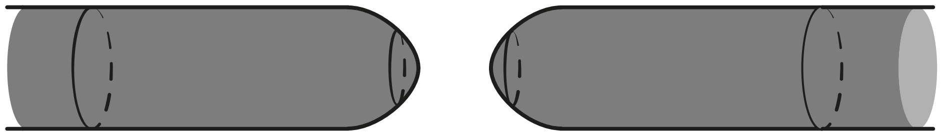



In 4D, **critical collapse**, [*Choptuik; **Phys.Rev.Lett. 70, 9***]




In higher dimensions, Gregory-Laflamme instability

[*Gregory, Laflamme; **hep-th/9301052***], [*Lehner, Pretorius; **1006.5960***], [*Figueras, França, Gu; **2210.13501***]



See also [*Emparan, Sanchez-Garitaonandia, Tomašević; **2411.14998***]

# Question:

Is there any situation where curvature invariants grow over
an **extended region of spacetime**, without fine-tined initial conditions?

*Yes, simple and robust.*

# Question:

Is there any situation where curvature invariants grow over
an **extended region of spacetime**, without fine-tined initial conditions?

*Yes, simple and robust.*

# Contents

- The model and setup (*standard*),
- Growth of curvature invariants at the horizon.

See also [*Crisford, Horowitz, Santos;* ***1709.07880***], [*Horowitz, Santos, Way;* ***1604.06465***]

# The model

Consider

$$S = \frac{2}{\ell_p^3} \int \mathrm{d}^5 x \sqrt{-G} \left( \frac{R}{4} - \frac{1}{2} \partial_M \phi \partial^M \phi - V(\phi) \right)$$

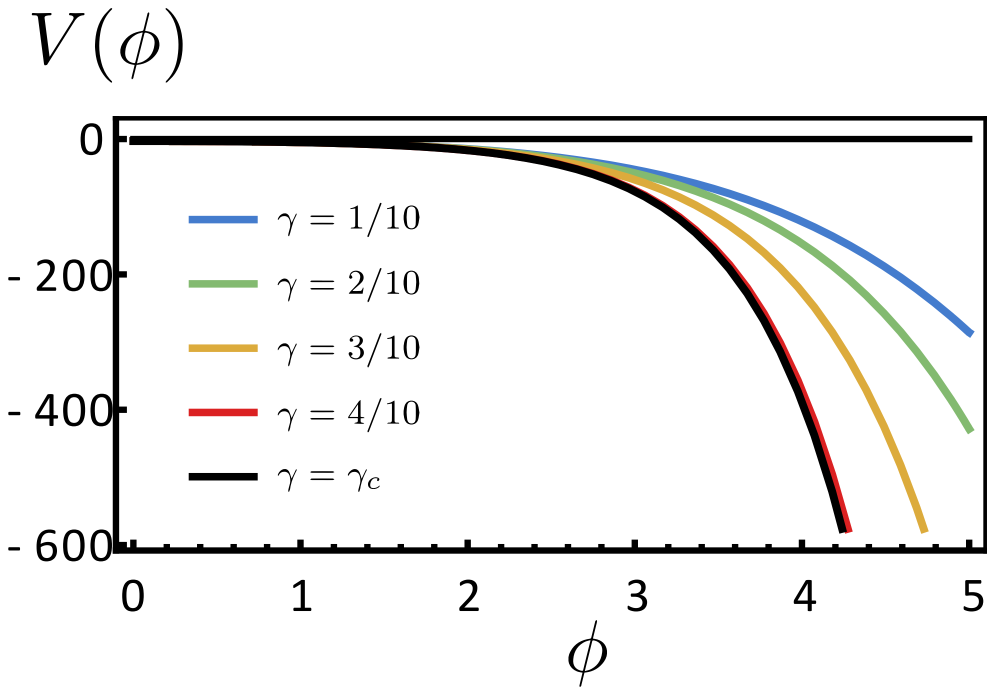
# The model

Consider

$$S = \frac{2}{\ell_p^3} \int \mathrm{d}^5x \sqrt{-G} \left( \frac{R}{4} - \frac{1}{2}\partial_M \phi \partial^M \phi - V(\phi) \right)$$

We choose a potential such that

- There is a maximum at $\phi = 0$, asymptotically AdS solution.



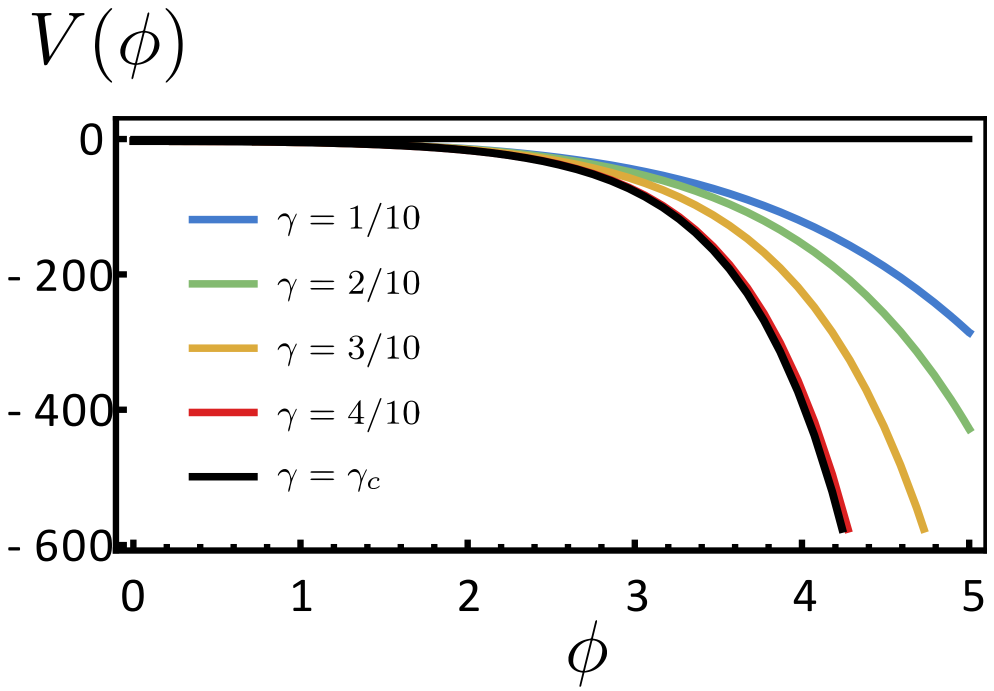
# The model

Consider

$$S = \frac{2}{\ell_p^3}\int \mathrm{d}^5x\sqrt{-G}\left(\frac{R}{4} - \frac{1}{2}\partial_M\phi\partial^M\phi - V(\phi)\right)$$

We choose a potential such that

- There is a maximum at $\phi = 0$, asymptotically AdS solution.
- About $\phi = 0$, $\phi$ has mass such that $\Delta = 3$.
- This introduces a source that explicitly breaks conformal $\Lambda$ symmetry.



# The model

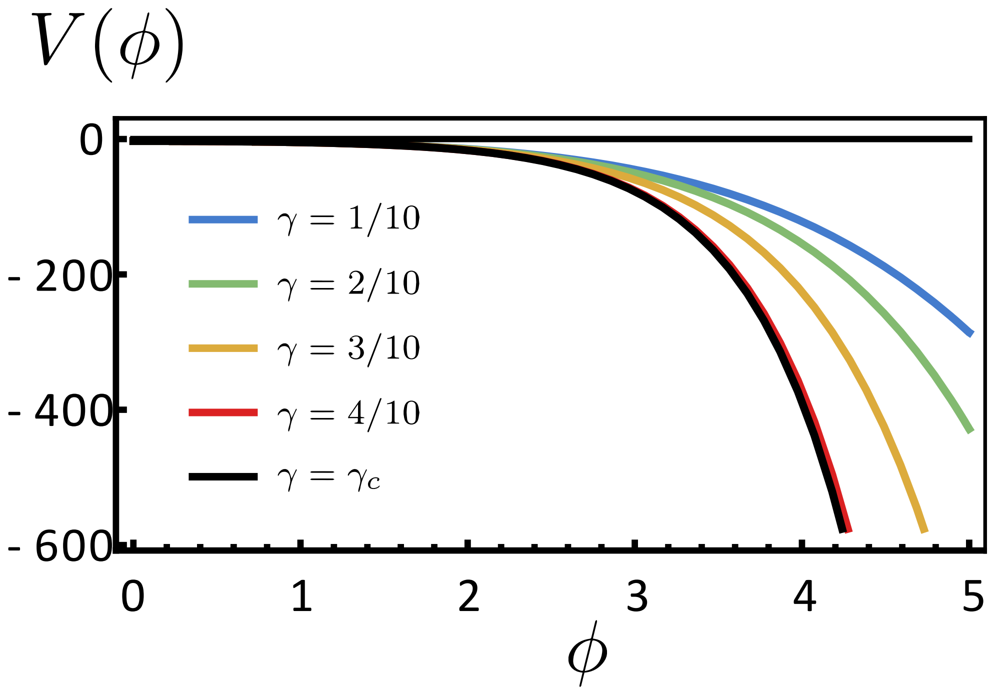
Consider

$$S = \frac{2}{\ell_p^3}\int d^5x\sqrt{-G}\left(\frac{R}{4} - \frac{1}{2}\partial_M\phi\partial^M\phi - V(\phi)\right)$$

We choose a potential such that

- There is a maximum at $\phi = 0$, asymptotically AdS solution.
- About $\phi = 0$, $\phi$ has mass such that $\Delta = 3$.
- This introduces a source that explicitly breaks conformal $\Lambda$ symmetry.
- There is a run-away direction:

$$V(\phi) \propto -e^{4\gamma\phi}$$



# Is $V(\phi) \propto -e^{4\gamma\phi}$ sensible?

*If you are worried about positivity of the energy:*

# Is $V(\phi) \propto -e^{4\gamma\phi}$ sensible?

*If you are worried about positivity of the energy:*

Potentials that are unbounded from below are not necessarily problematic in AdS

[*Breitenlohner, Freedman,* ***Annals Phys. 144 (1982) 249***].

Stability theorems exist in AdS

[*Towsend,* ***Phys. Lett. B 148, 44 (1984)***], [*Amsel, Hertog, Hollands, Marolf,* ***hep-th/0701038***].

# Is $V(\phi) \propto -e^{4\gamma\phi}$ sensible?

*If you are worried about positivity of the energy:*

Potentials that are unbounded from below are not necessarily problematic in AdS

[*Breitenlohner, Freedman,* ***Annals Phys. 144 (1982) 249***].

Stability theorems exist in AdS

[*Towsend,* ***Phys. Lett. B 148, 44 (1984)***], [*Amsel, Hertog, Hollands, Marolf,* ***hep-th/0701038***].

*But AdS is not an (exact) solution in our case since we are introducing a source...*

# Is $V(\phi) \propto -e^{4\gamma\phi}$ sensible?

*But AdS is not an (exact) solution in our case:*

True, in this case the lowest energy state is expected to be given by “BPS solutions”.

[*Towsend, Skenderis*, ***hep-th/9909070***].

# Is $V(\phi) \propto -e^{4\gamma\phi}$ sensible?

*But AdS is not an (exact) solution in our case:*

True, in this case the lowest energy state is expected to be given by "BPS solutions". [*Towsend, Skenderis*, ***hep-th/9909070***].

Our potential is given in terms of a "**superpotential**":

$$V(\phi) = -\frac{4}{3}W(\phi)^2 + \frac{1}{2}\left(\frac{\partial W(\phi)}{\partial\phi}\right)^2$$

And we have "BPS-like" solutions, solving first-order equations

$$\partial_\rho(\text{metric}) \propto W \qquad \partial_\rho(\phi) \propto \partial_\phi W$$

# Is $V(\phi) \propto -e^{4\gamma\phi}$ sensible?

*But AdS is not an (exact) solution in our case:*

True, in this case the lowest energy state is expected to be given by "BPS solutions". [*Towsend, Skenderis*, ***hep-th/9909070***].

Our potential is given in terms of a "**superpotential**":

$$V(\phi) = -\frac{4}{3}W(\phi)^2 + \frac{1}{2}\left(\frac{\partial W(\phi)}{\partial\phi}\right)^2$$

And we have "BPS-like" solutions, solving first-order equations

$$\partial_\rho(\text{metric}) \propto W \qquad \partial_\rho(\phi) \propto \partial_\phi W$$

$$W(\phi) = \frac{1}{4\gamma^2 L}\left[1 - 6\gamma^2 - \cosh(2\gamma\phi)\right]$$

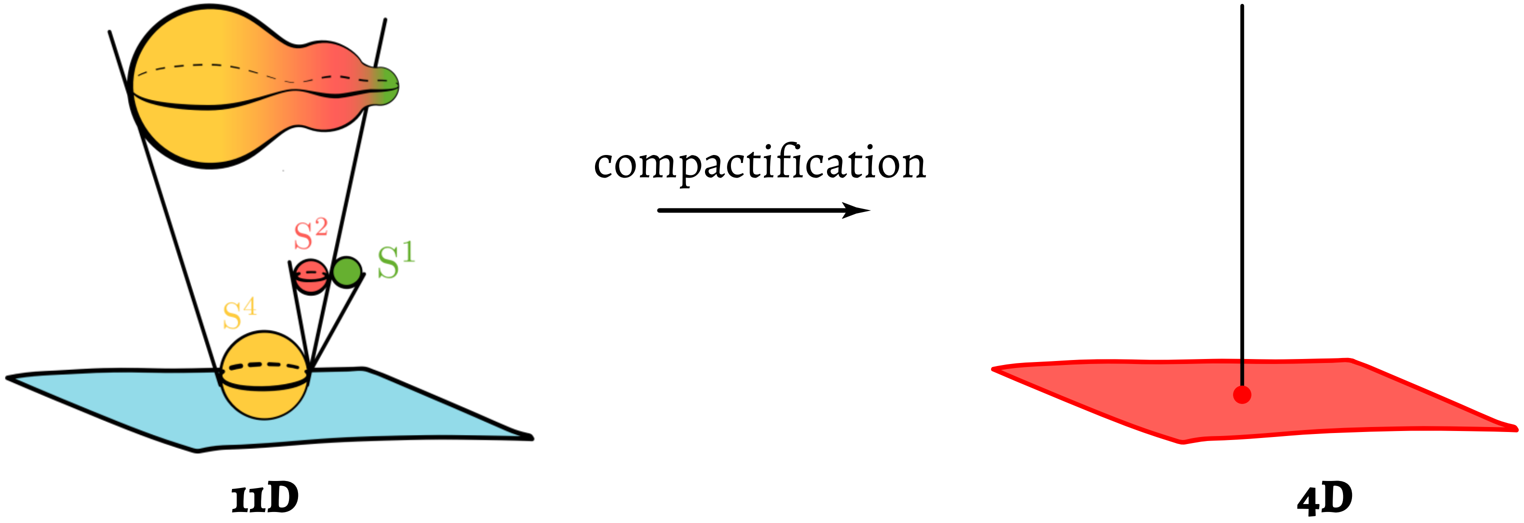
# Is $V(\phi) \propto -e^{4\gamma\phi}$ sensible?

*If you wonder about how motivated this is:*

# Is $V(\phi) \propto -e^{4\gamma\phi}$ sensible?

*If you wonder about how motivated this is:*

This kind of run-away behaviour is generic in String Theory compactifications. In top-down constructions, there are cases with similarly diverging potentials and regular ground states.




[*Faedo, Pravos, **JS**, Mateos; **1702.05988***], [*Elander, Faedo, **JS**, Mateos; **2002.08279***].

# Is $V(\phi) \propto -e^{4\gamma\phi}$ sensible?

*If you wonder about how motivated this is:*

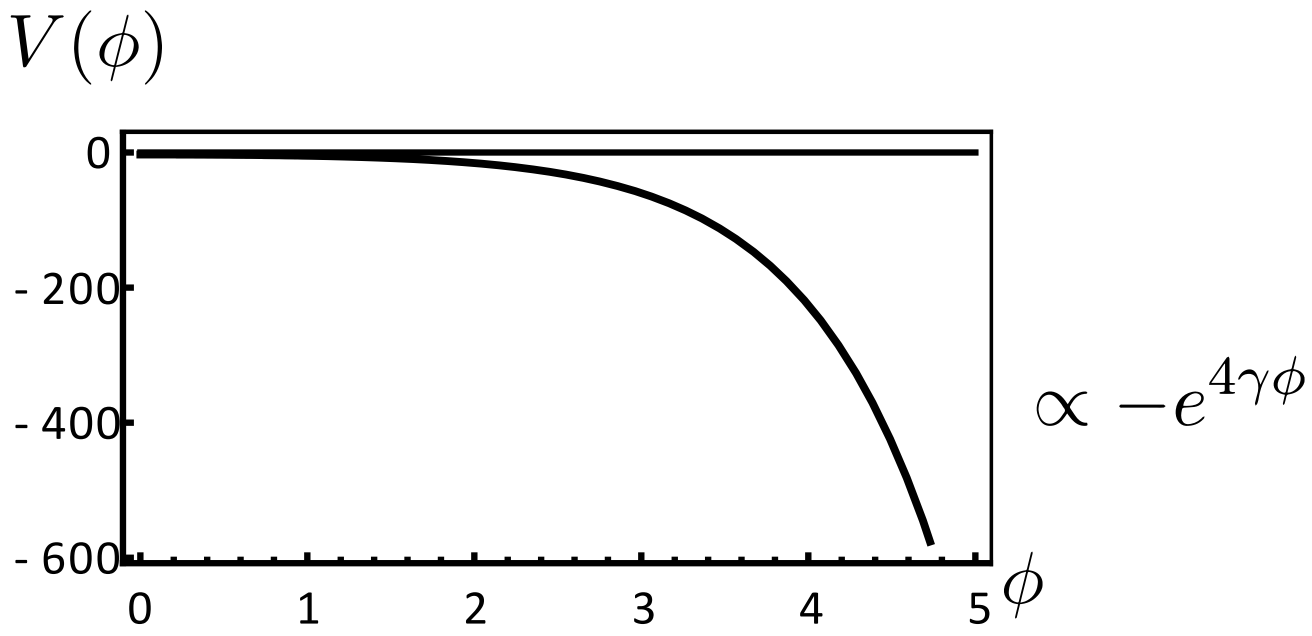
This kind of run-away behaviour is generic in String Theory compactifications. In top-down constructions, there are cases with similarly diverging potentials and regular ground states.

And other examples:

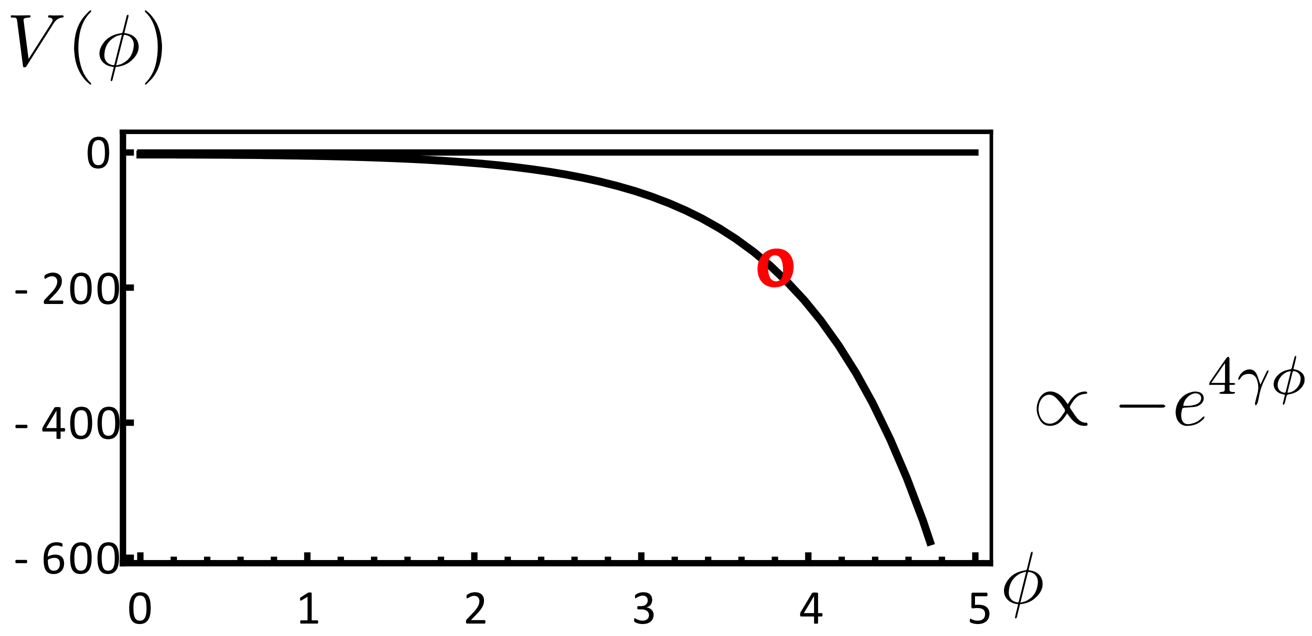
- CGLP solution (Stenzel Space) [*Cvetic, Gibbons, Lu, Pope;* ***hep-th/0012011***], [*Dias, Hartnett, Niehoff, Santos;* ***1704.02323***].
- GPPZ solution [*Girardello, Petrini, Poratti, Zaffaroni;* ***hep-th/9909047***], [*Bena, Dias, Hartnett, Niehoff, Santos;* ***1805.06463***].
- Klebanov – Strassler [*Klebanov, Strassler;* ***hep-th/0007191***], [*Buchel;* ***1809.08484***].

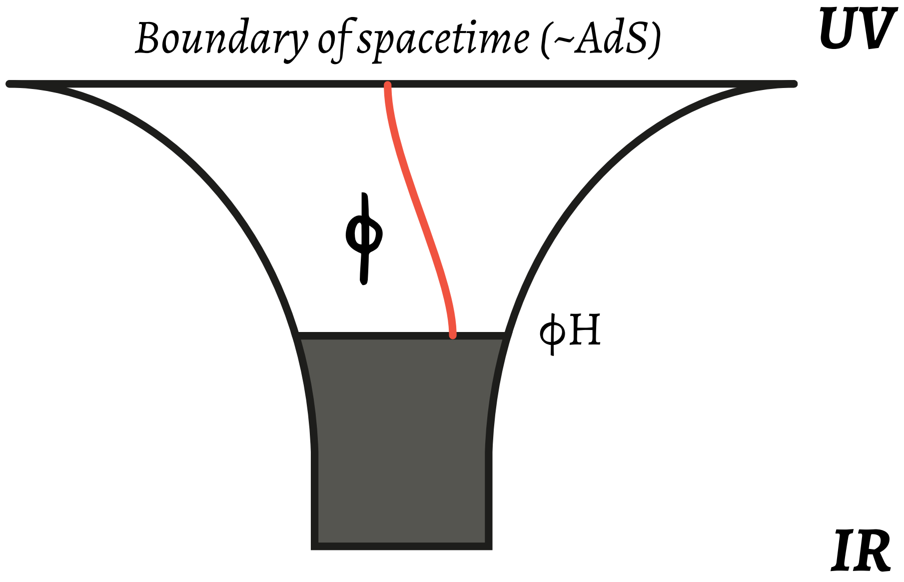
*and more...*

# Thermodynamics



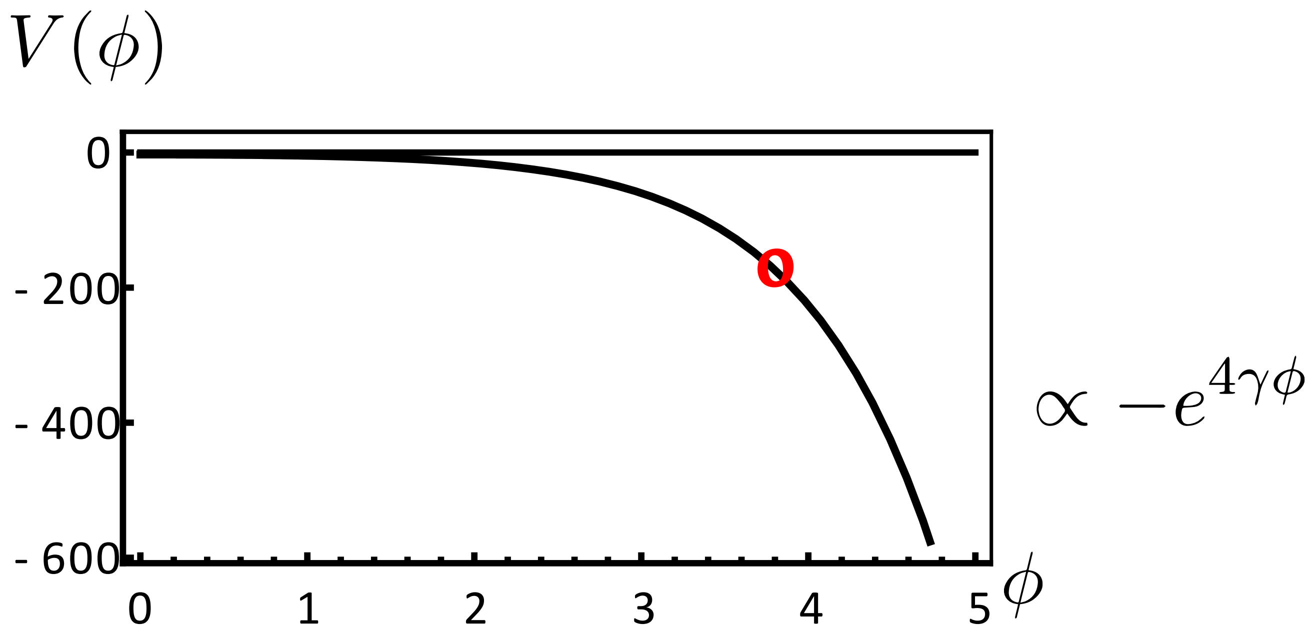
# Thermodynamics

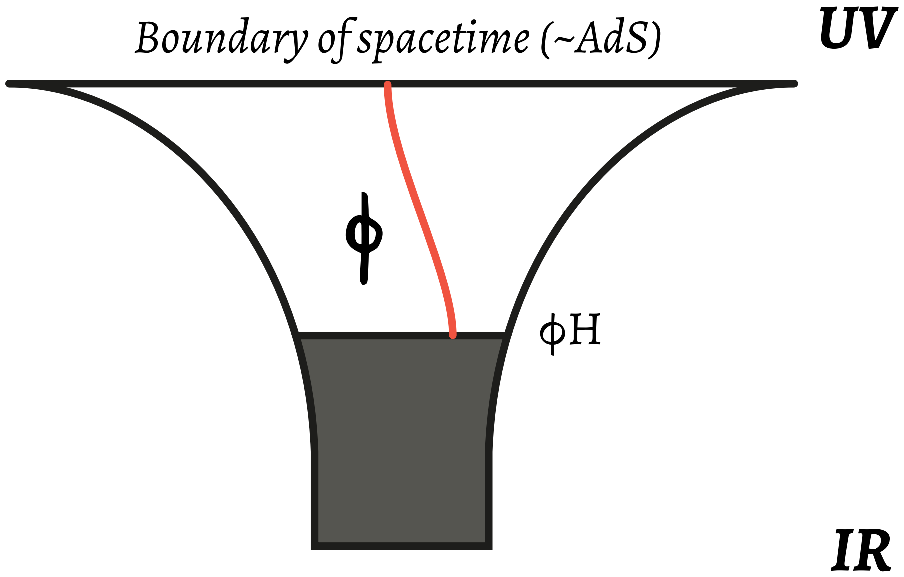



Properties of **black branes** relate to properties of the **dual plasma**

# Thermodynamics

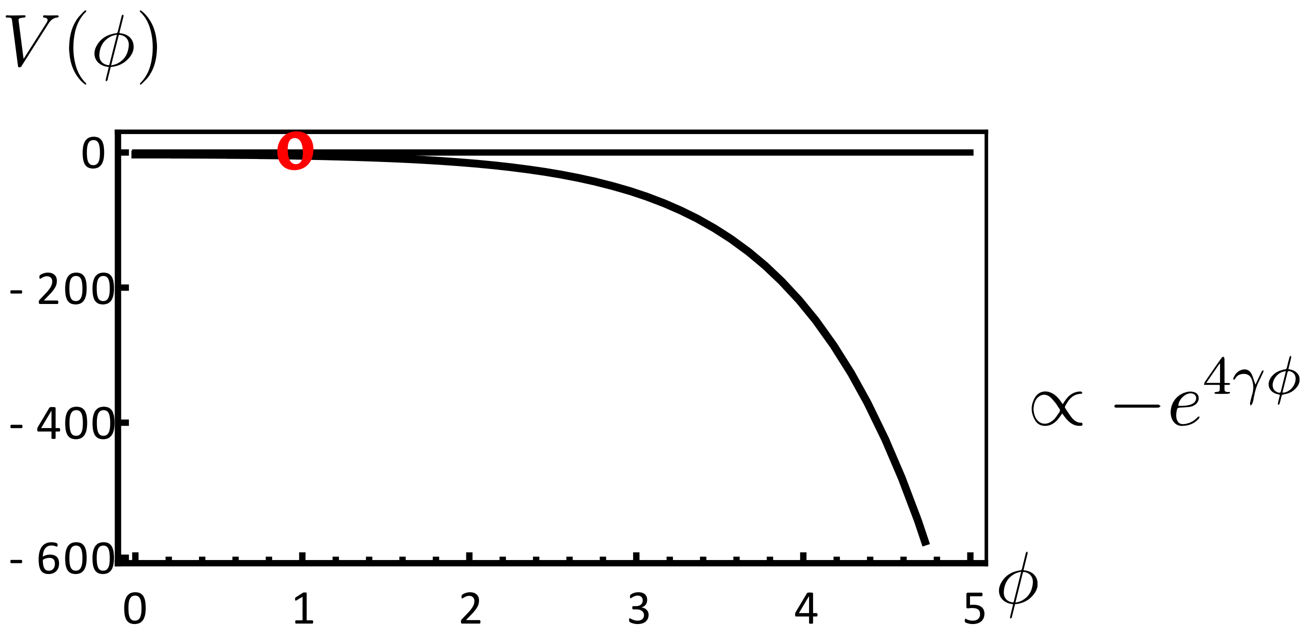


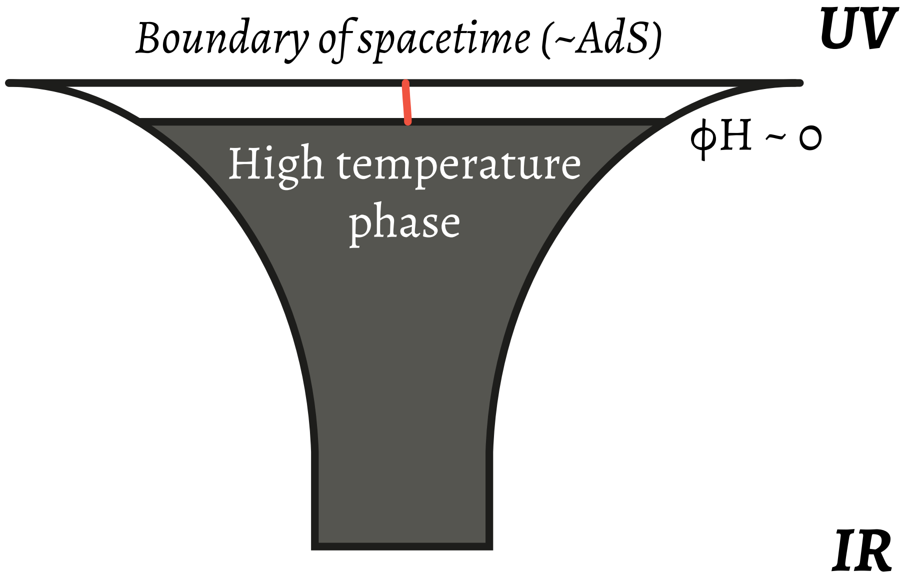




Properties of **black branes** relate to properties of the **dual plasma**

- horizon area ~ entropy (***s***) ,
- surface gravity ~ temperature (***T***) ,
- mass ~ energy (***ε***) ,
- on-shell action ~ free energy (***f***), pressure (***p***) .

# Thermodynamics

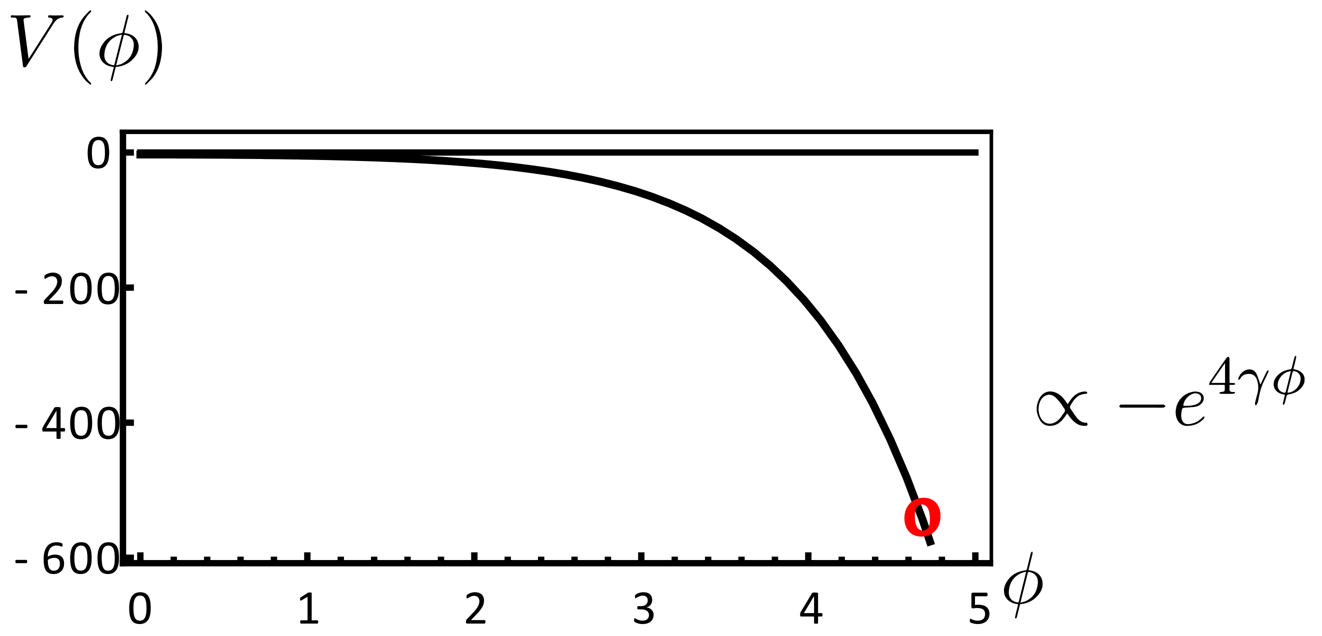


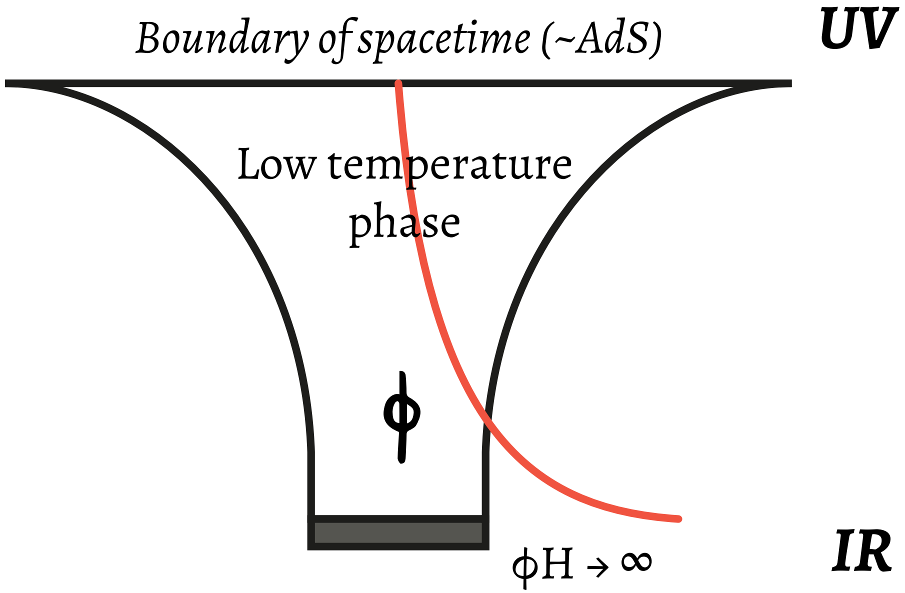




Properties of **black branes** relate to properties of the **dual plasma**

- horizon area ~ entropy (***s***) ,
- surface gravity ~ temperature (***T***) ,
- mass ~ energy (***ε***) ,
- on-shell action ~ free energy (***f***), pressure (***p***) .

# Thermodynamics

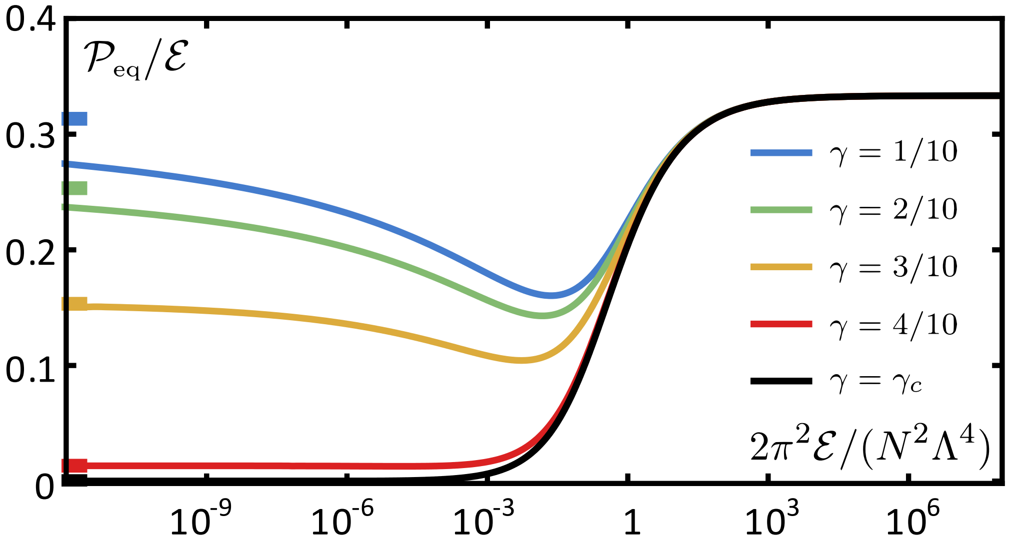


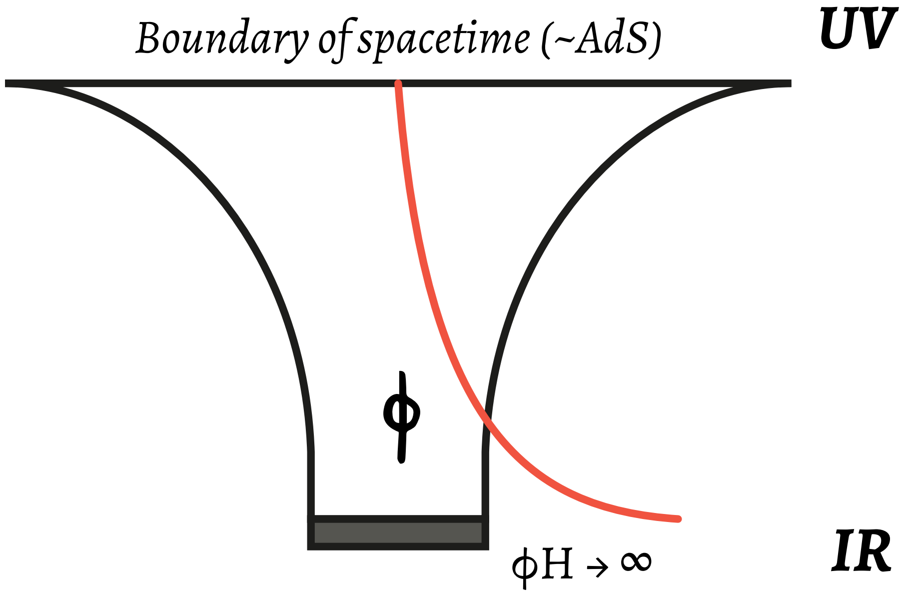




Properties of **black branes** relate to properties of the **dual plasma**

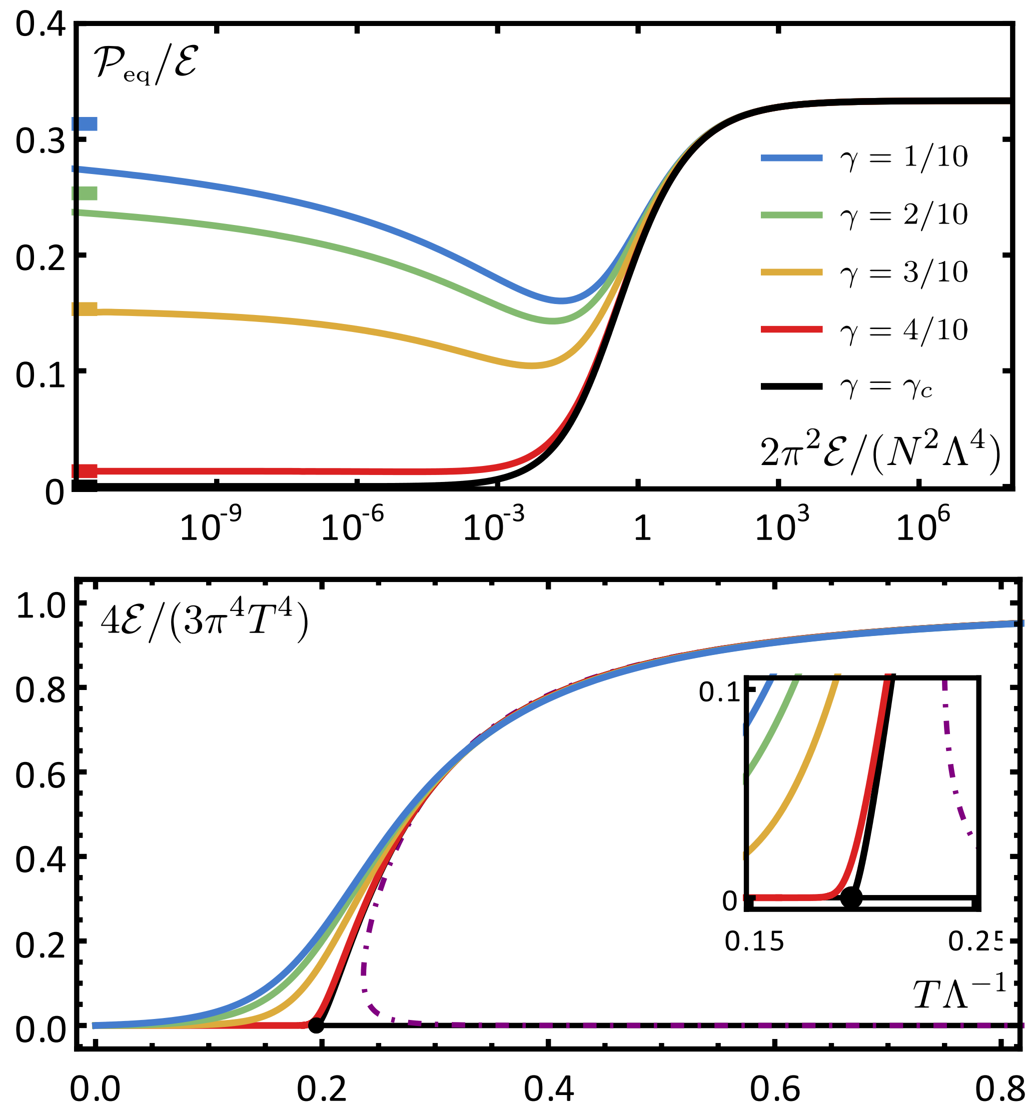
- horizon area ~ entropy (***s***) ,
- surface gravity ~ temperature (***T***) ,
- mass ~ energy (***ε***) ,
- on-shell action ~ free energy (***f***), pressure (***p***) .

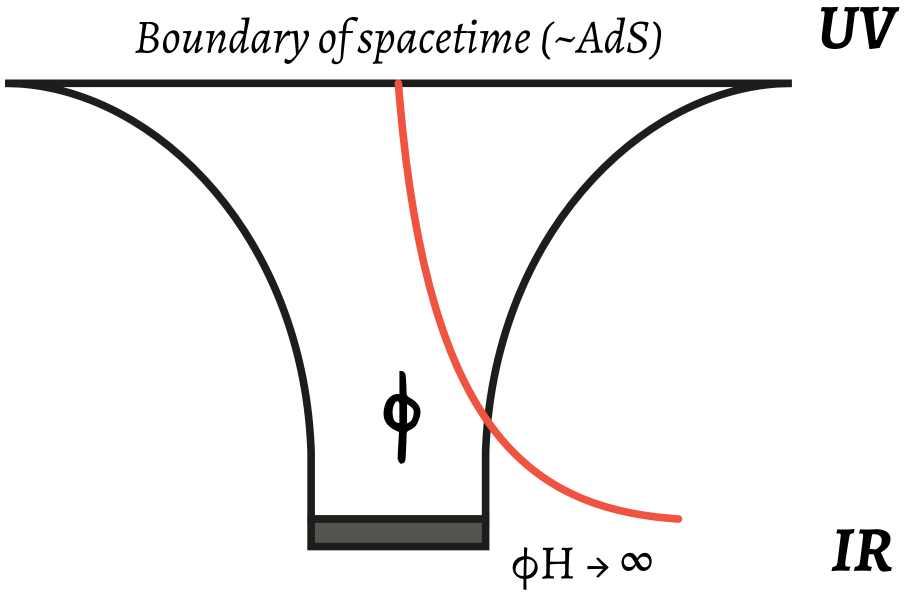
# Thermodynamics



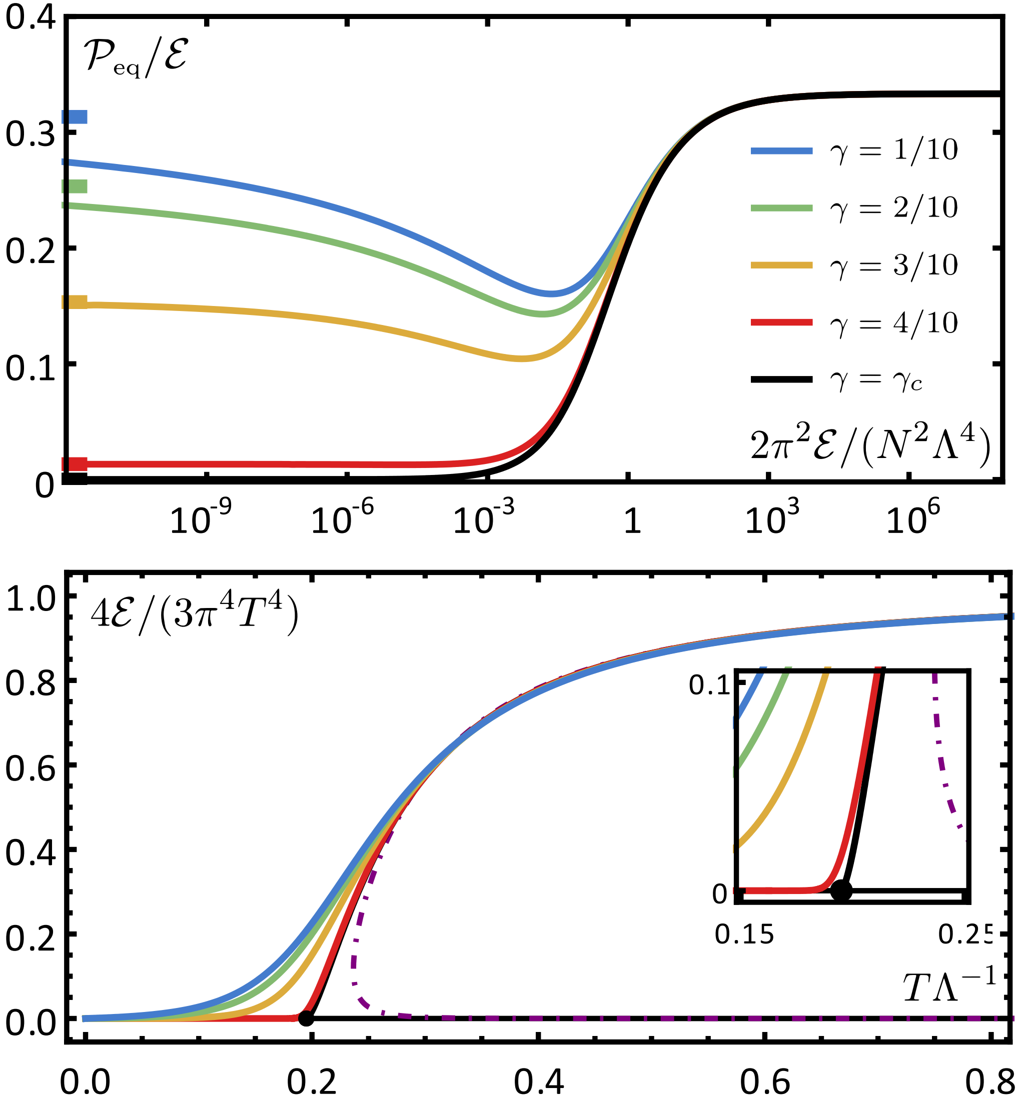



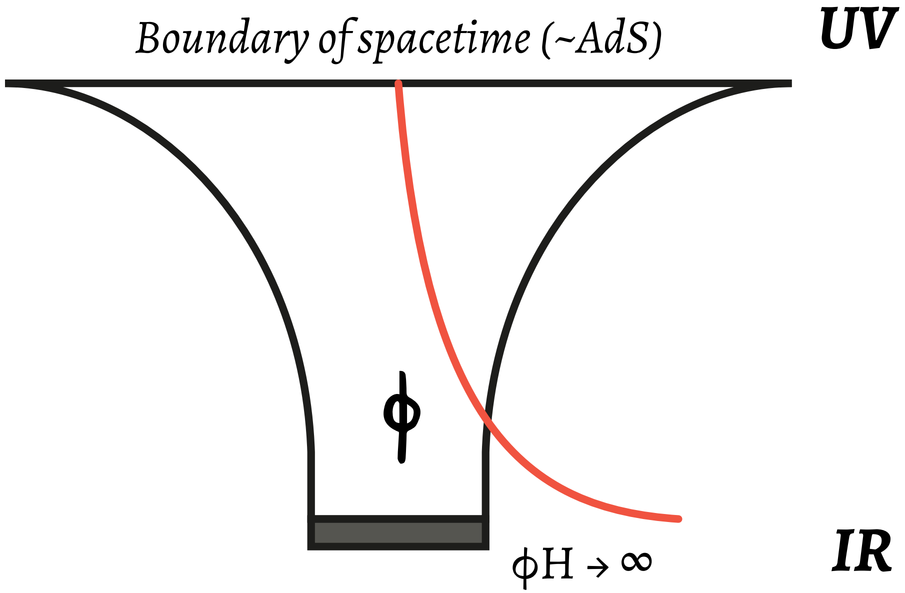
# Thermodynamics



# Thermodynamics

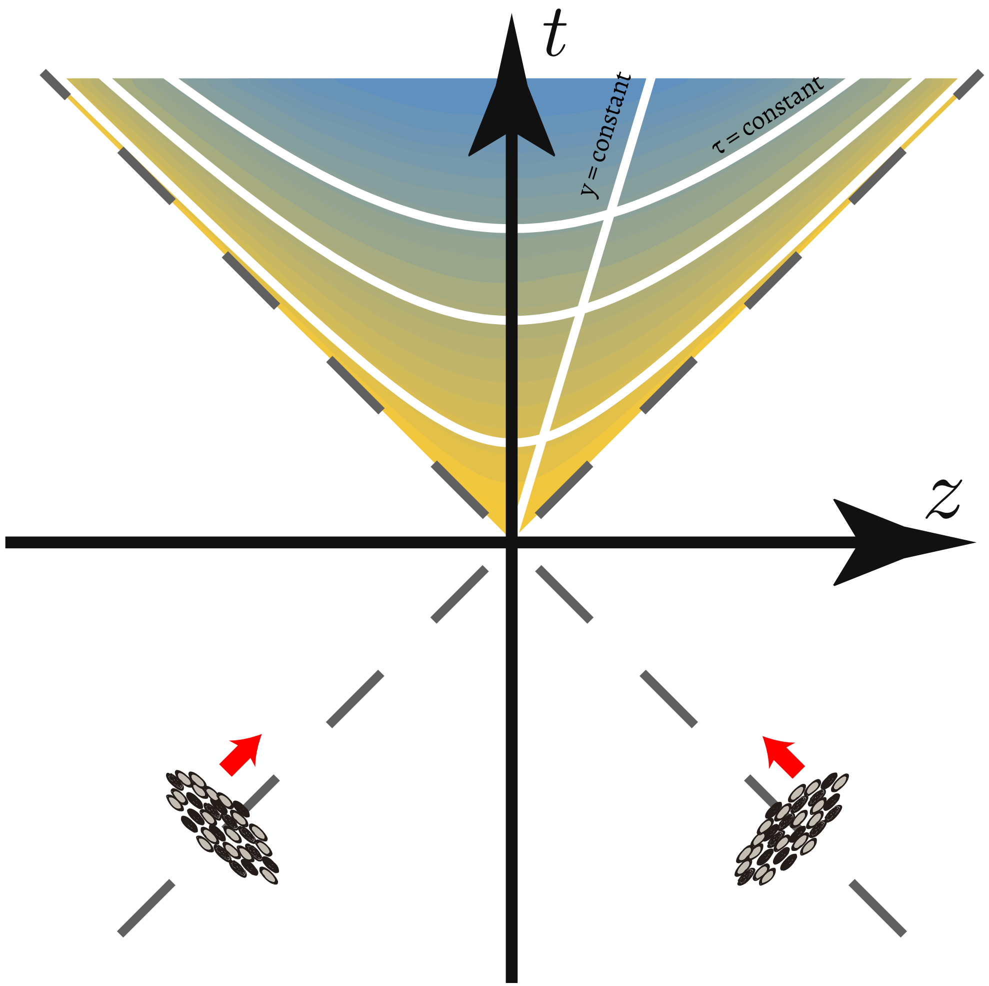



Is there a way to reach this highly curved **macroscopic region** dynamically, from smooth (weakly curved) initial data?

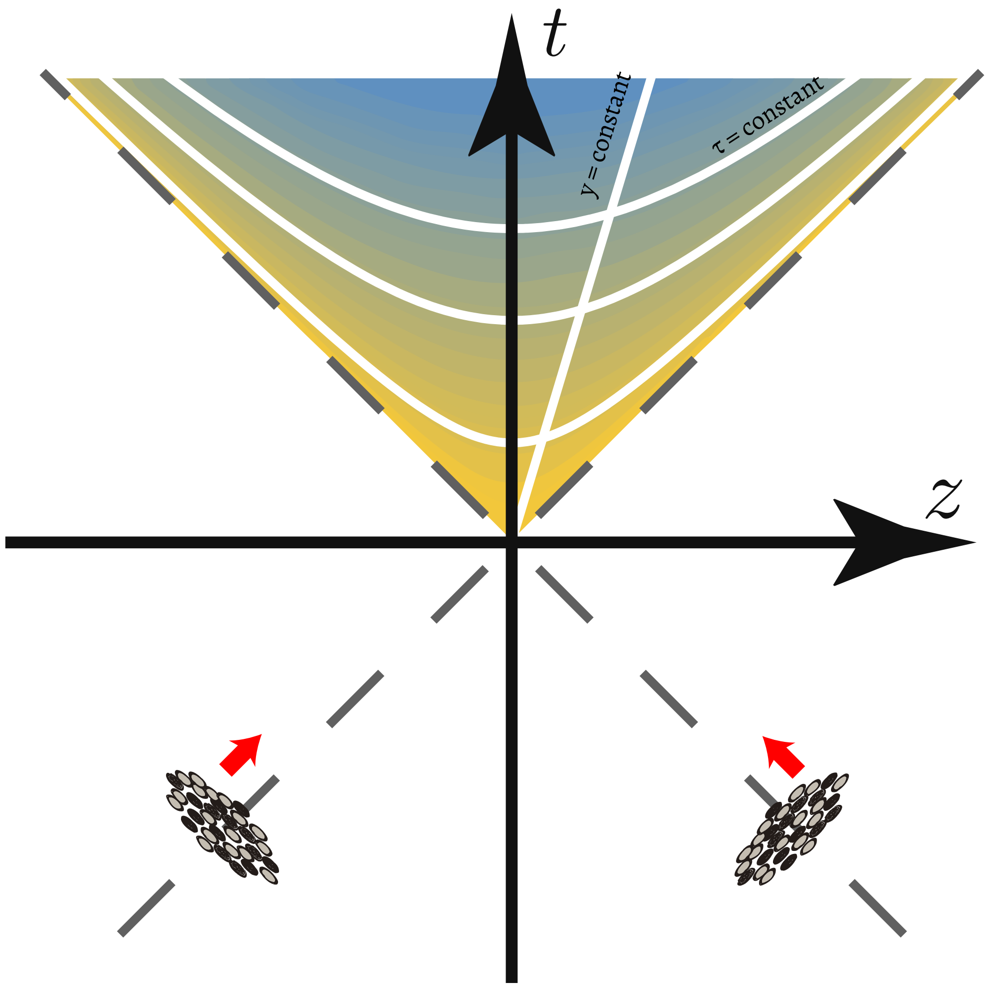
Credit: Maximilien Brice (CERN)

# Heavy-ion collision




[*Bjorken*; ***Phys.Rev.D* 27 (1983)**].

# Heavy-ion collision




After an initial, **out-of-equilibrium** regime, the evolution is well described by **hydrodynamics**:

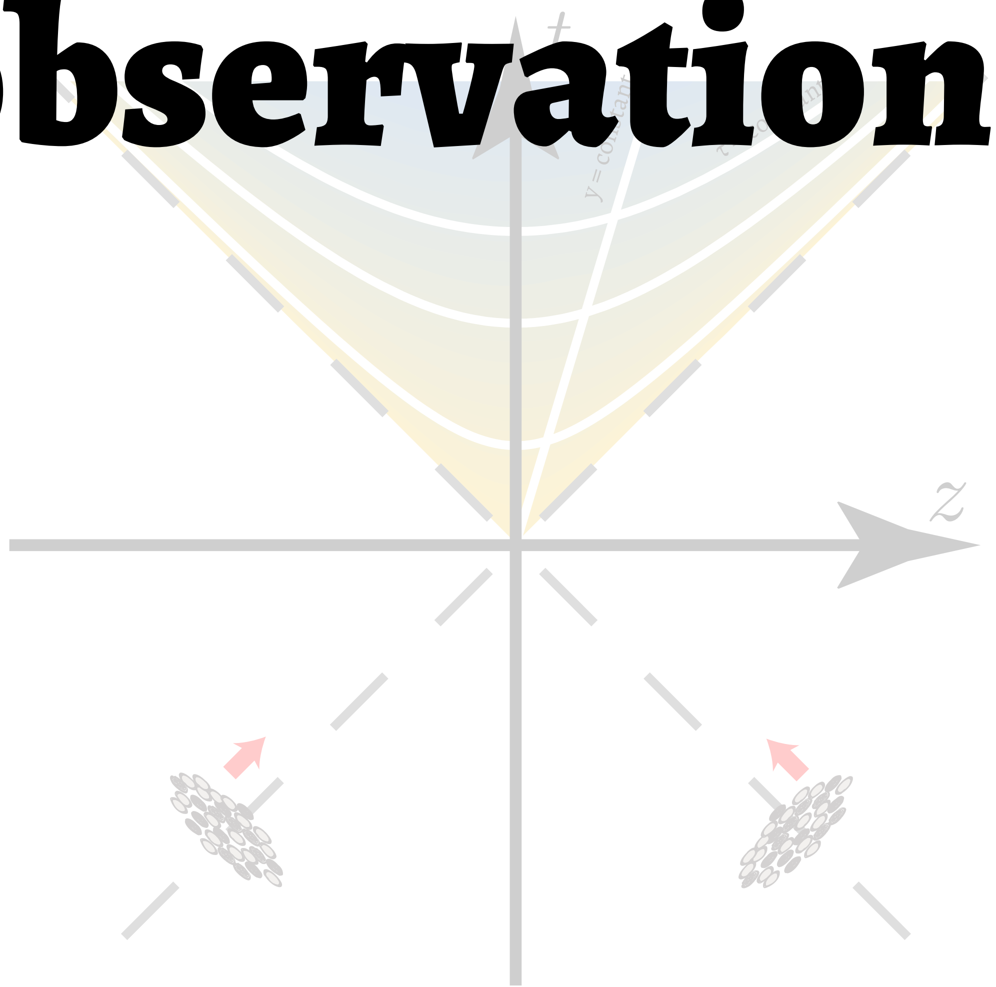
$$\nabla_\mu T^{\mu\nu} = 0$$

$T^{\mu\nu}$ is the energy-momentum tensor of the fluid,

$T^{\mu\nu}$ = ideal terms +
viscosities $(\partial)$ +
2nd order viscous terms $(\partial^2)$ +
...

[*Bjorken*; ***Phys.Rev.D* 27 (1983)**].

# Key observation:




If we consider our holographic model in a **boost-invariant setup**, for *rather generic* initial conditions, after a brief out-of-equilibrium regime the system will be well described by hydrodynamics.

If so, the fluid will cool down, the scalar roll down the unbounded potential and curvature invariants grow at the horizon.

We solve

$$S = \frac{2}{\ell_p^3} \int \mathrm{d}^5 x \sqrt{-G} \left( \frac{R}{4} - \frac{1}{2} \partial_M \phi \partial^M \phi - V(\phi) \right)$$

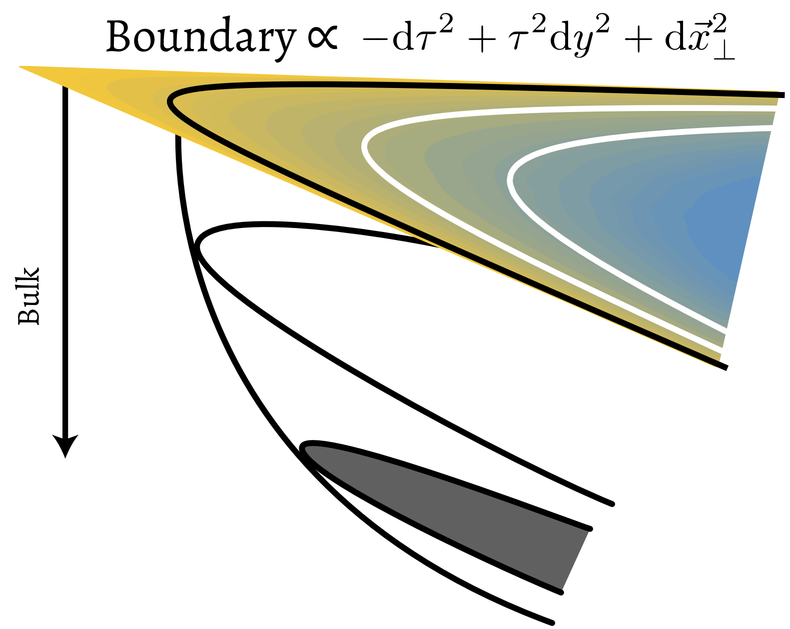
If we consider our holographic model in a **boost-invariant setup**, for *rather generic* initial conditions, after a brief out-of-equilibrium regime the system will be well described by hydrodynamics.

If so, the fluid will cool down, the scalar roll down the unbounded potential and curvature invariants grow at the horizon.

We solve

$$S = \frac{2}{\ell_p^3} \int d^5x \sqrt{-G} \left( \frac{R}{4} - \frac{1}{2} \partial_M \phi \partial^M \phi - V(\phi) \right)$$

demanding:




[*Bellantuomo, Janik, Jankowski, Soltanpanahi;* ***2002.08279***].

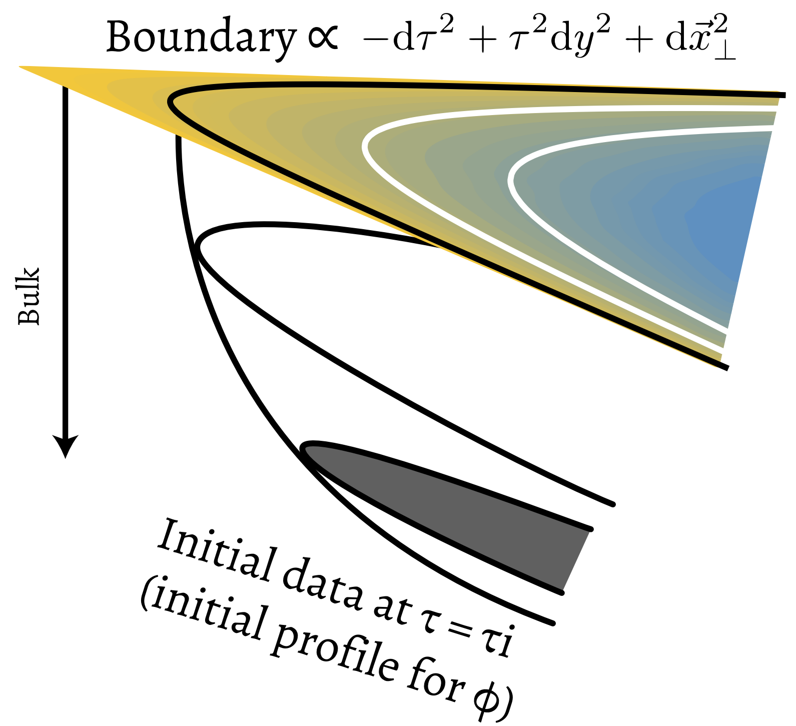
If we consider our holographic model **in a boost-invariant setup**, for *rather generic* initial conditions, after a brief out-of-equilibrium regime the system will be well described by hydrodynamics.

If so, the fluid will cool down, the scalar roll down the unbounded potential and curvature invariants grow at the horizon.

We solve

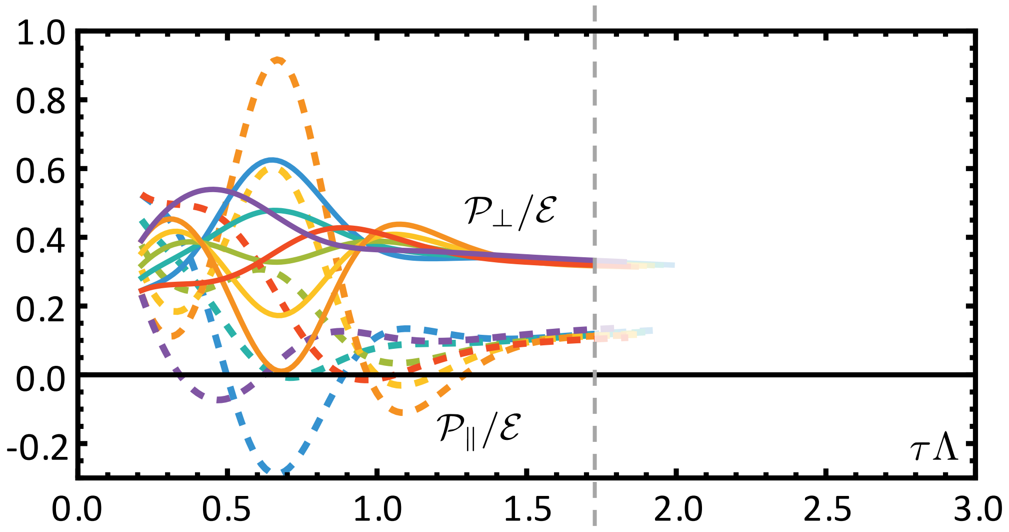
$$S = \frac{2}{\ell_p^3}\int \mathrm{d}^5x\sqrt{-G}\left(\frac{R}{4} - \frac{1}{2}\partial_M\phi\partial^M\phi - V(\phi)\right)$$

demanding:



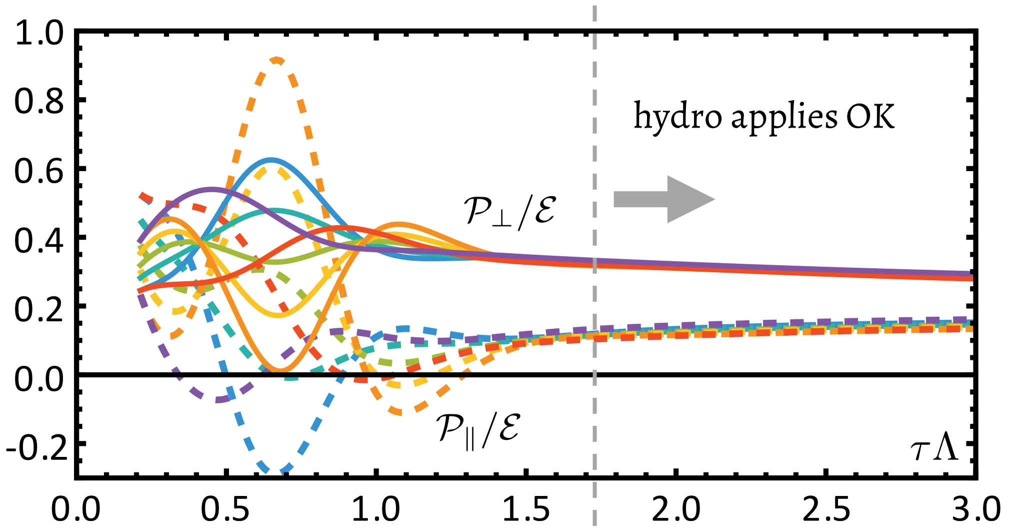

If we consider our holographic model **in a boost-invariant setup**, for *rather generic* initial conditions, after a brief out-of-equilibrium regime the system will be well described by hydrodynamics.

If so, the fluid will cool down, the scalar roll down the unbounded potential and curvature invariants grow at the horizon.



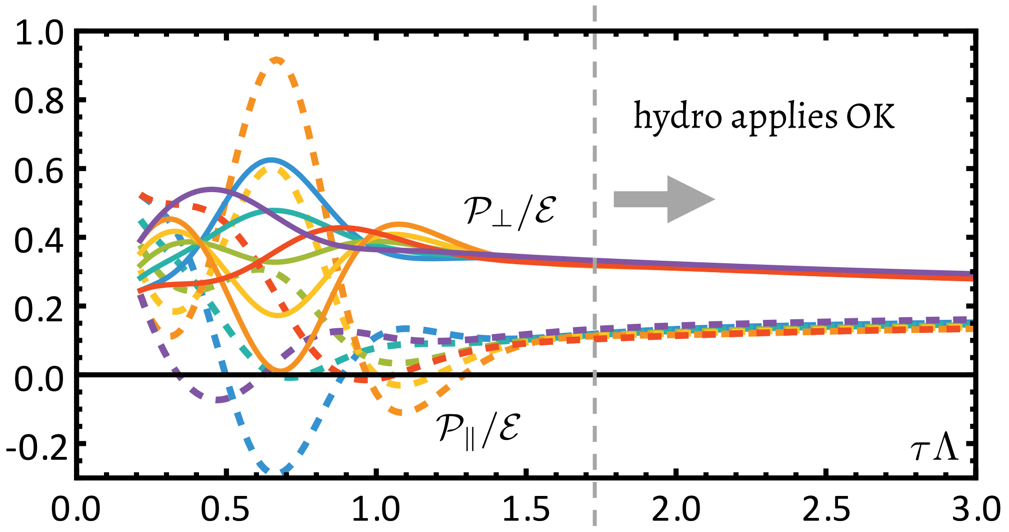

If we consider our holographic model in a **boost-invariant setup**, for *rather generic* initial conditions, after a brief out-of-equilibrium regime the system will be well described by hydrodynamics.

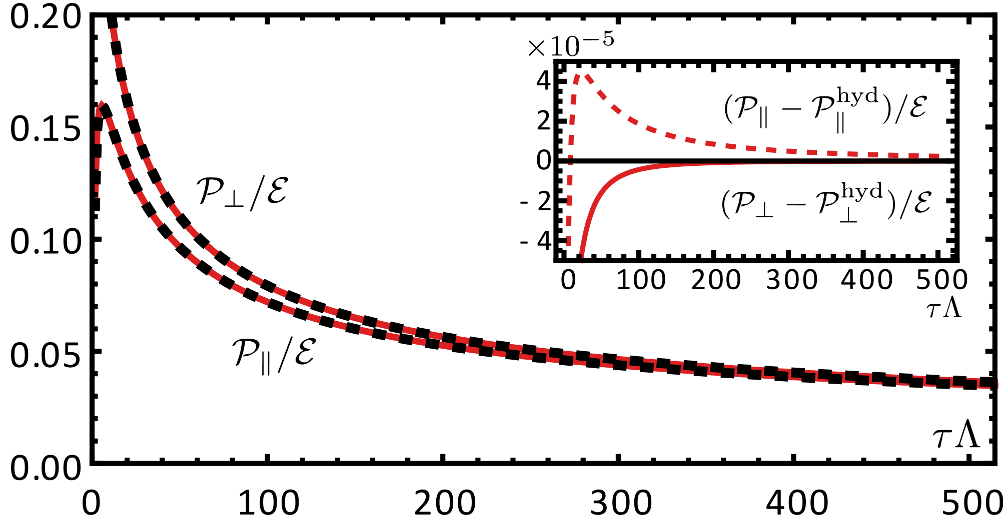
If so, the fluid will cool down, the scalar roll down the unbounded potential and curvature invariants grow at the horizon.




If we consider our holographic model in a **boost-invariant setup**, for *rather generic* initial conditions, after a brief out-of-equilibrium regime the system will be well described by hydrodynamics.

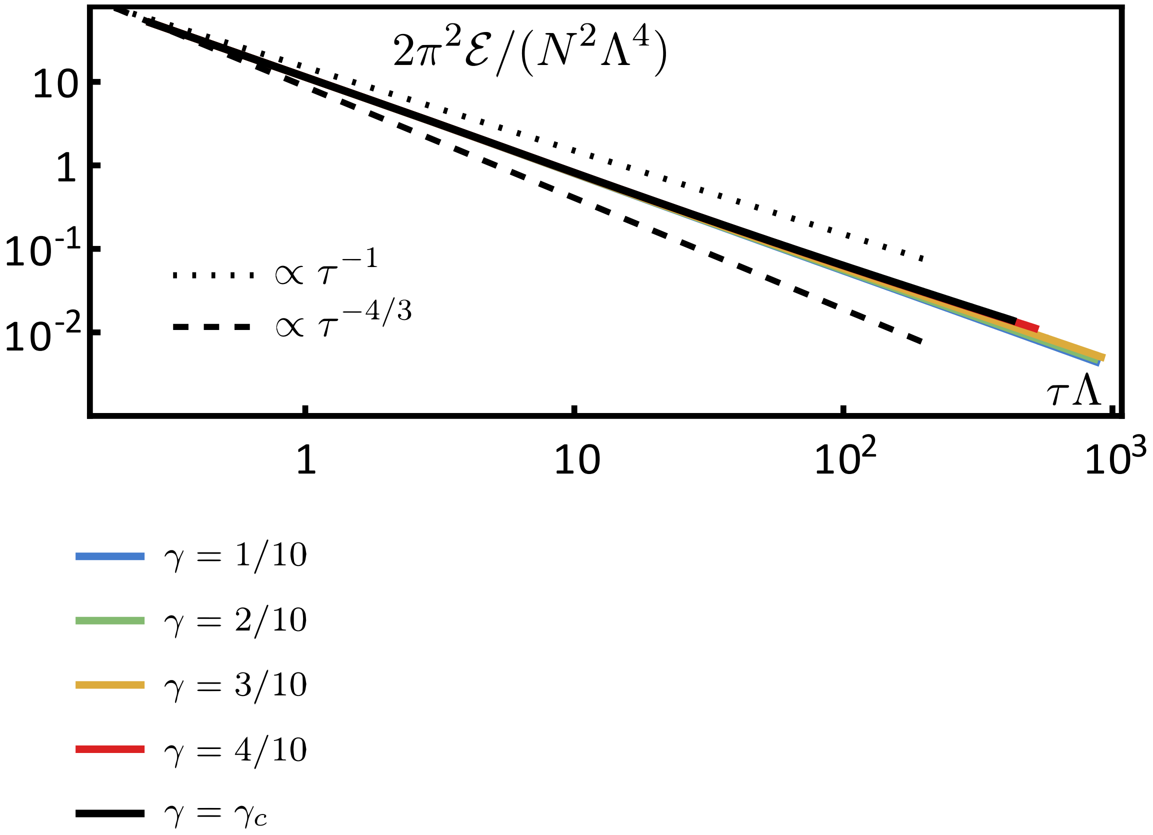
If so, the fluid will cool down, the scalar roll down the unbounded potential and curvature invariants grow at the horizon.




If we consider our holographic model in a **boost-invariant setup**, for *rather generic* initial conditions, after a brief out-of-equilibrium regime the system will be well described by hydrodynamics.

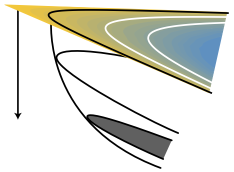
If so, the fluid will cool down, the scalar roll down the unbounded potential and curvature invariants grow at the horizon.




If we consider our holographic model in a **boost-invariant setup**, for *rather generic* initial conditions, after a brief out-of-equilibrium regime the system will be well described by hydrodynamics.

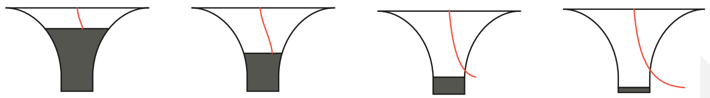
If so, the fluid will cool down, the scalar roll down the unbounded potential and curvature invariants grow at the horizon.

Full numerical evolution:



*keep solving Einstein equations (costly)*

Fluid/gravity:



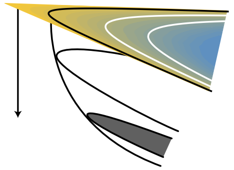
*solve hydro equation*
$\nabla_\mu T^{\mu\nu} = 0$

*approximate the bulk metric by the corresponding black brane solution*

If we consider our holographic model in a **boost-invariant setup**, for *rather generic* initial conditions, after a brief out-of-equilibrium regime the system will be well described by hydrodynamics.

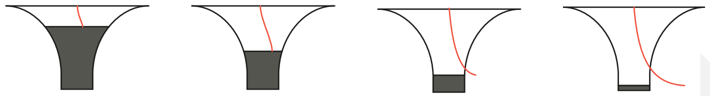
If so, the fluid will cool down, the scalar roll down the unbounded potential and curvature invariants grow at the horizon.

Full numerical evolution:



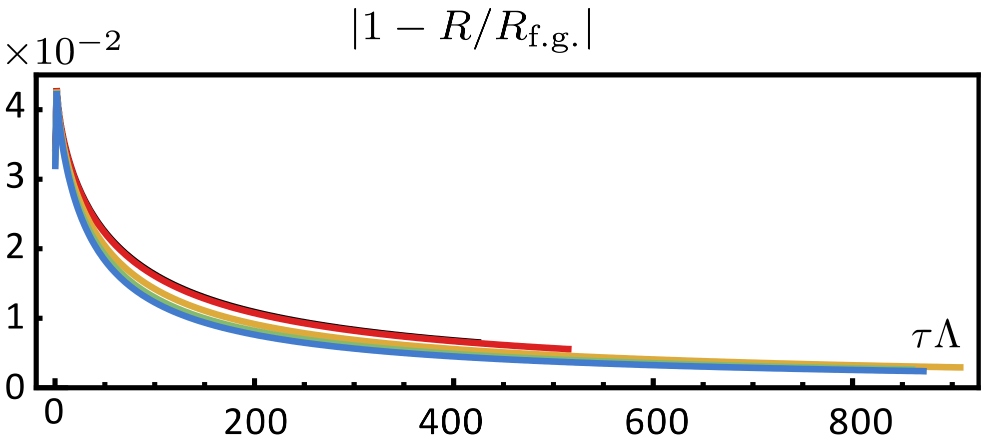
*keep solving Einstein equations (costly)*

Fluid/gravity:



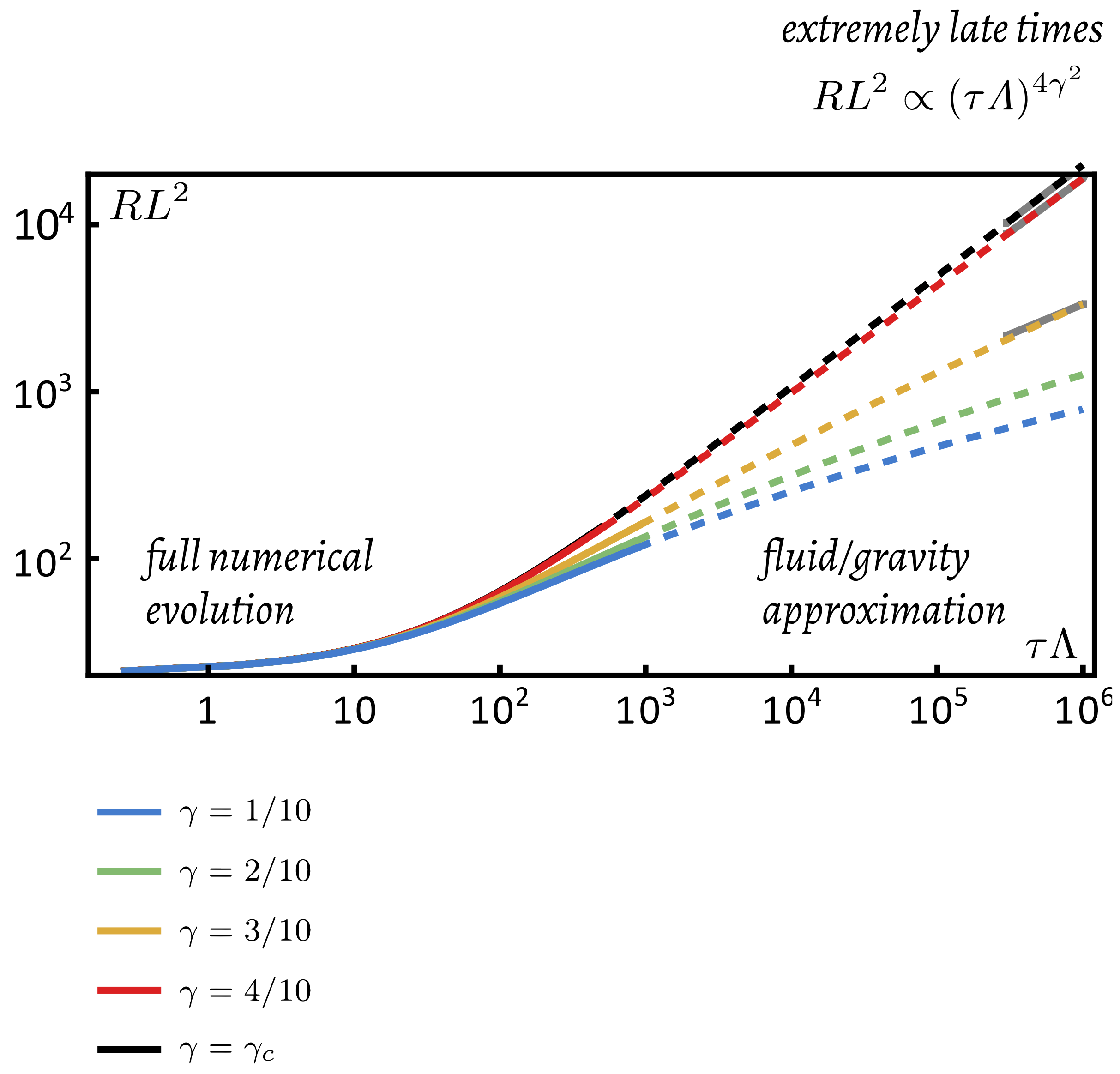
*solve hydro equation*
$\nabla_\mu T^{\mu\nu} = 0$

*approximate the bulk metric by the corresponding black brane solution*




If we consider our holographic model in a **boost-invariant setup**, for *rather generic* initial conditions, after a brief out-of-equilibrium regime the system will be well described by hydrodynamics.

If so, the fluid will cool down, the scalar roll down the unbounded potential and curvature invariants grow at the horizon.



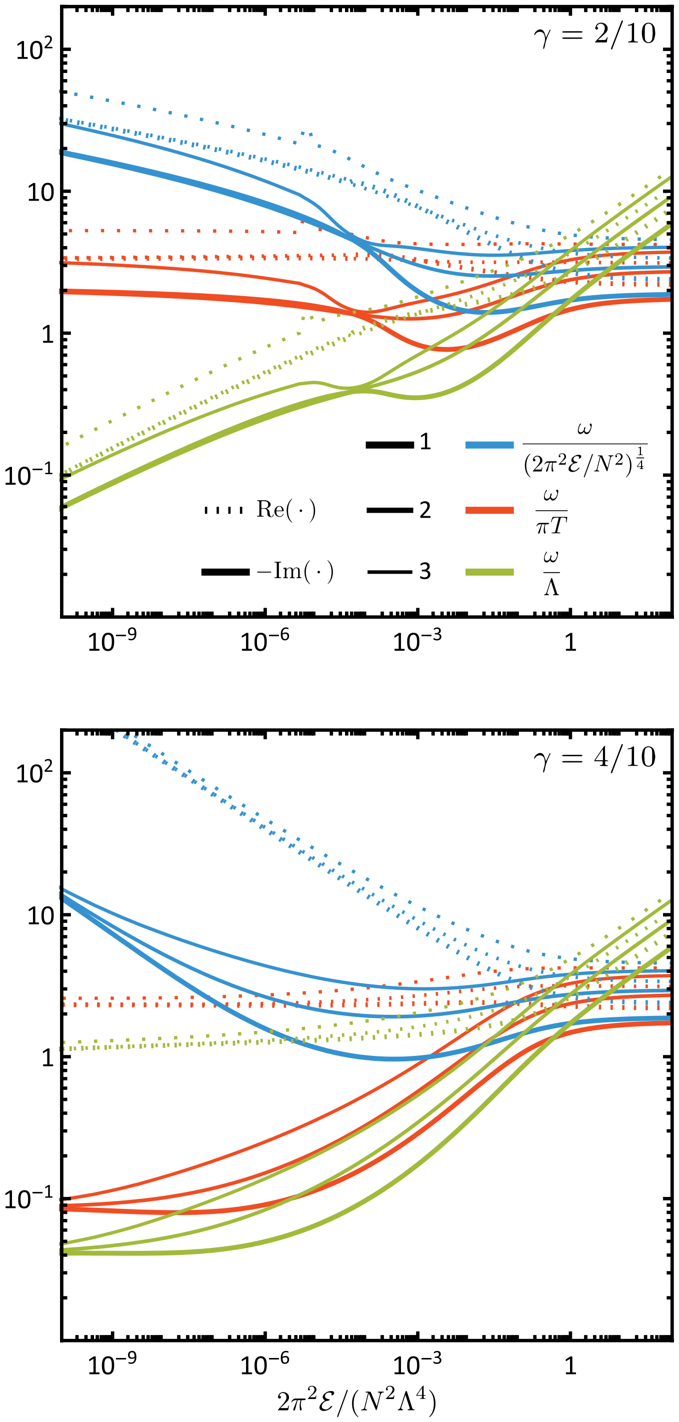

[*Gursoy, Jarvinen, Policastro;* ***1507.08628***].

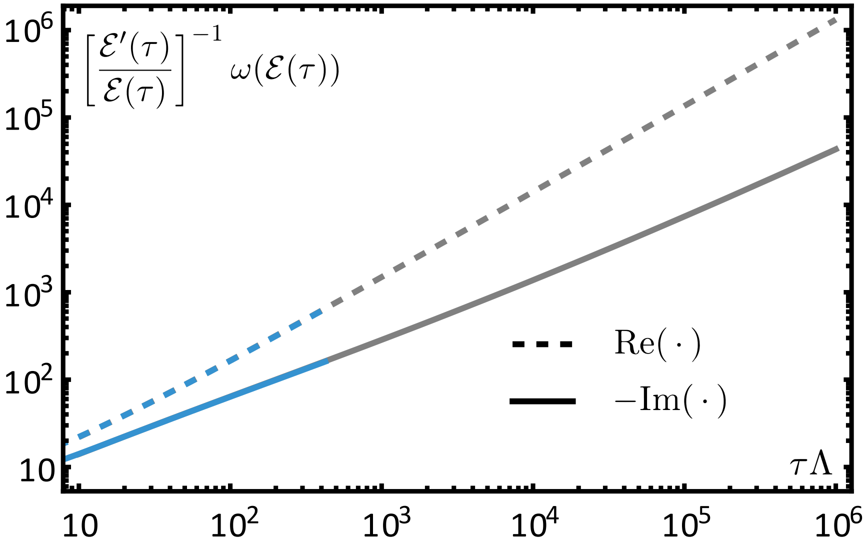
If we consider our holographic model in a **boost-invariant setup**, for *rather generic* initial conditions, after a brief out-of-equilibrium regime the system will be well described by hydrodynamics.

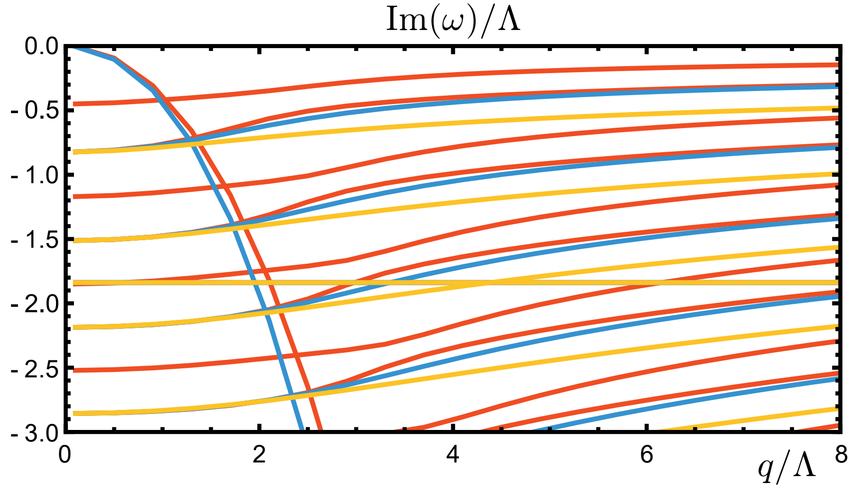
If so, the fluid will cool down, the scalar roll down the unbounded potential and curvature invariants grow at the horizon.

# Stability

(comment dS)



# Conclusion

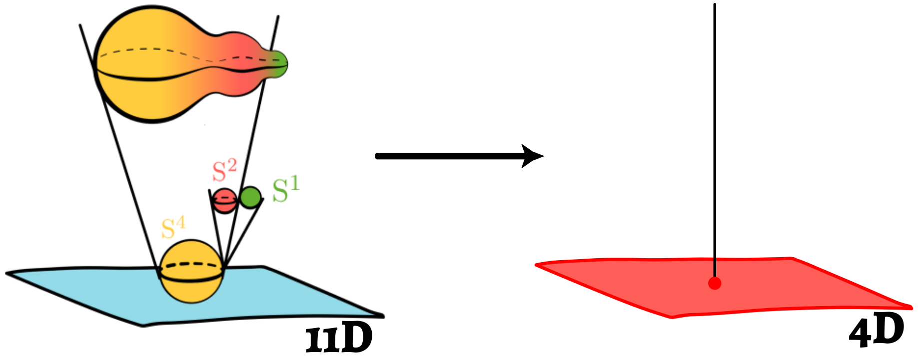
*(Please hold on: unconventionally this is not the last slide :)*

- I presented a way to generate **dynamically** large curvatures in the bulk in a **macroscopic region**. Information about deviations from the classical theory are accessible via the dual gauge theory.

- Strictly speaking, it is not a violation of Cosmic Censorship (because it takes infinite time). *But violates it in spirit*.

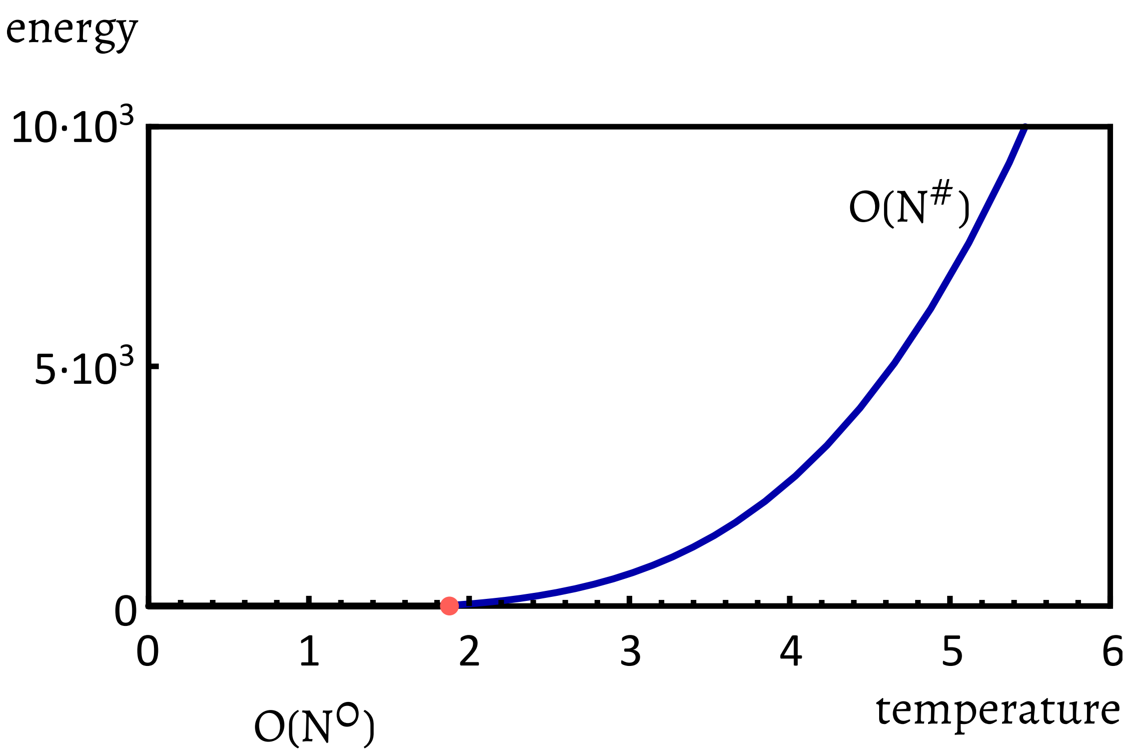
- The setup is generic: found in several string theory models,
  It is robust, simple and intuitive: relies on cooling down the system.

# How is the singularity resolved in String Theory?



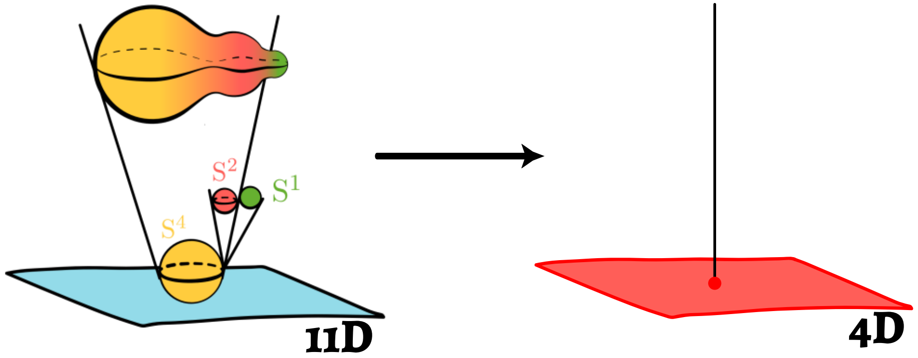

- The **family of black branes** behave as the critical case.

- There is a **regular ground state** in 11D.

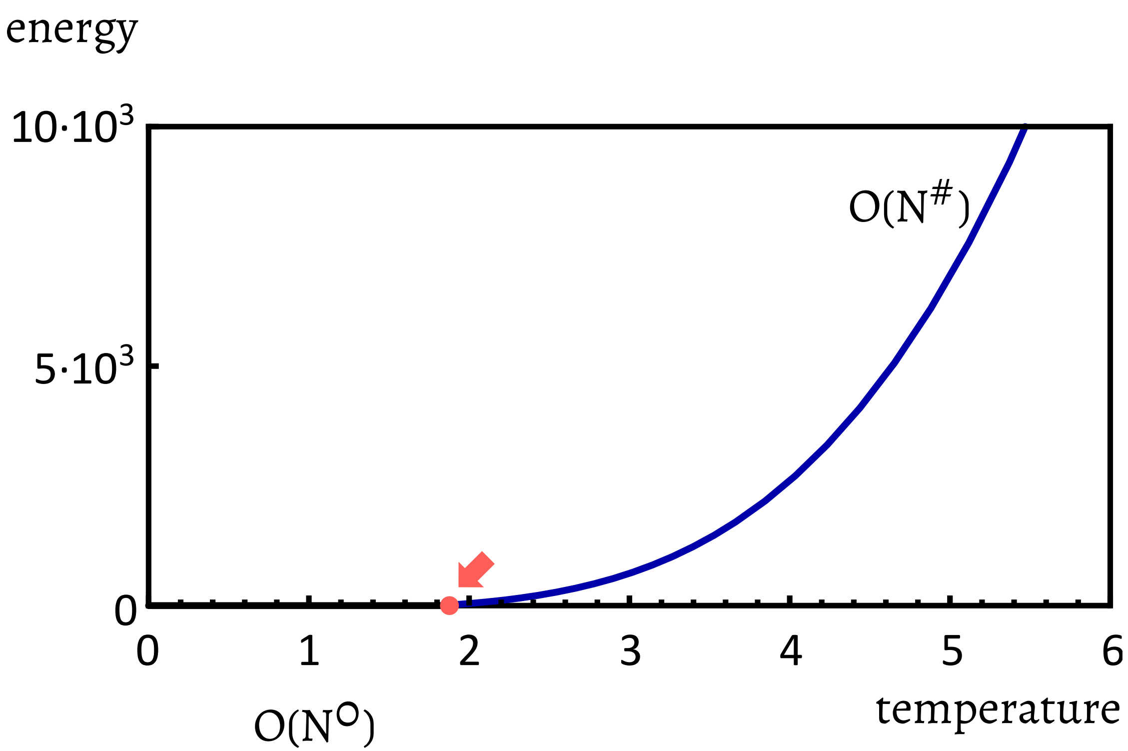



[*Faedo, Pravos, **JS**, Mateos; **1702.05988***], [*Elander, Faedo, **JS**, Mateos; **2002.08279***].

# How is the singularity resolved in String Theory?

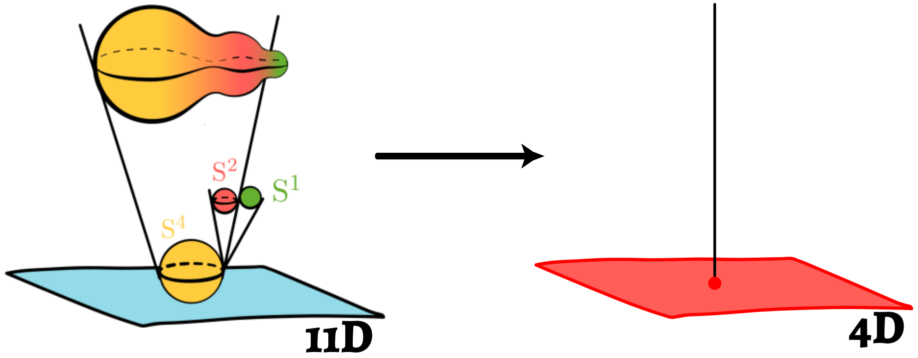



- The **family of black branes** behave as the critical case.
- There is a **regular ground state** in 11D.
- But in the "**extremal limit**" we do not recover it.




[*Faedo, Pravos, **JS**, Mateos; **1702.05988***], [*Elander, Faedo, **JS**, Mateos; **2002.08279***].

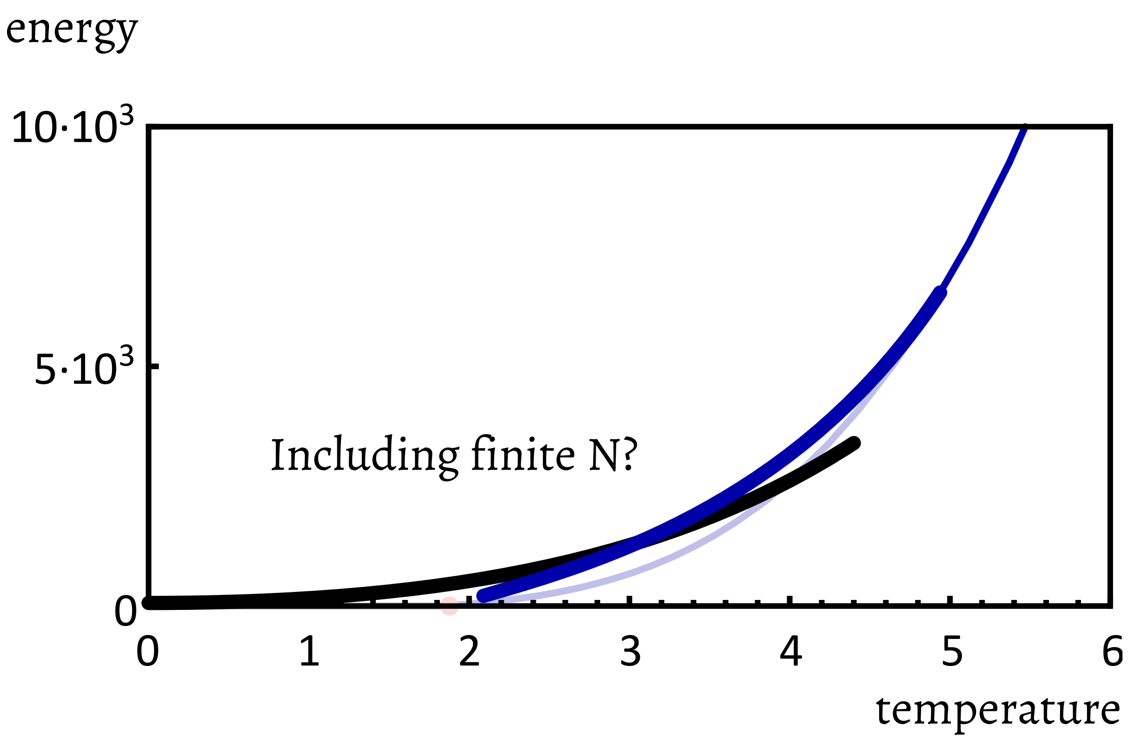
# How is the singularity resolved in String Theory?




- The **family of black branes** behave as the critical case.

- There is a **regular ground state** in 11D.

- But in the "**extremal limit**" we do not recover it.




[*Faedo, Pravos,* ***JS****, Mateos;* ***1702.05988***], [*Elander, Faedo,* ***JS****, Mateos;* ***2002.08279***].

# Can we do better?

- Strictly speaking, it is not a violation of Cosmic Censorship (because it takes infinite time). *But violates it in spirit*.

# Can we do better?

- Can we generate large curvatures in a **macroscopic region** in finite time and in a string theory model?

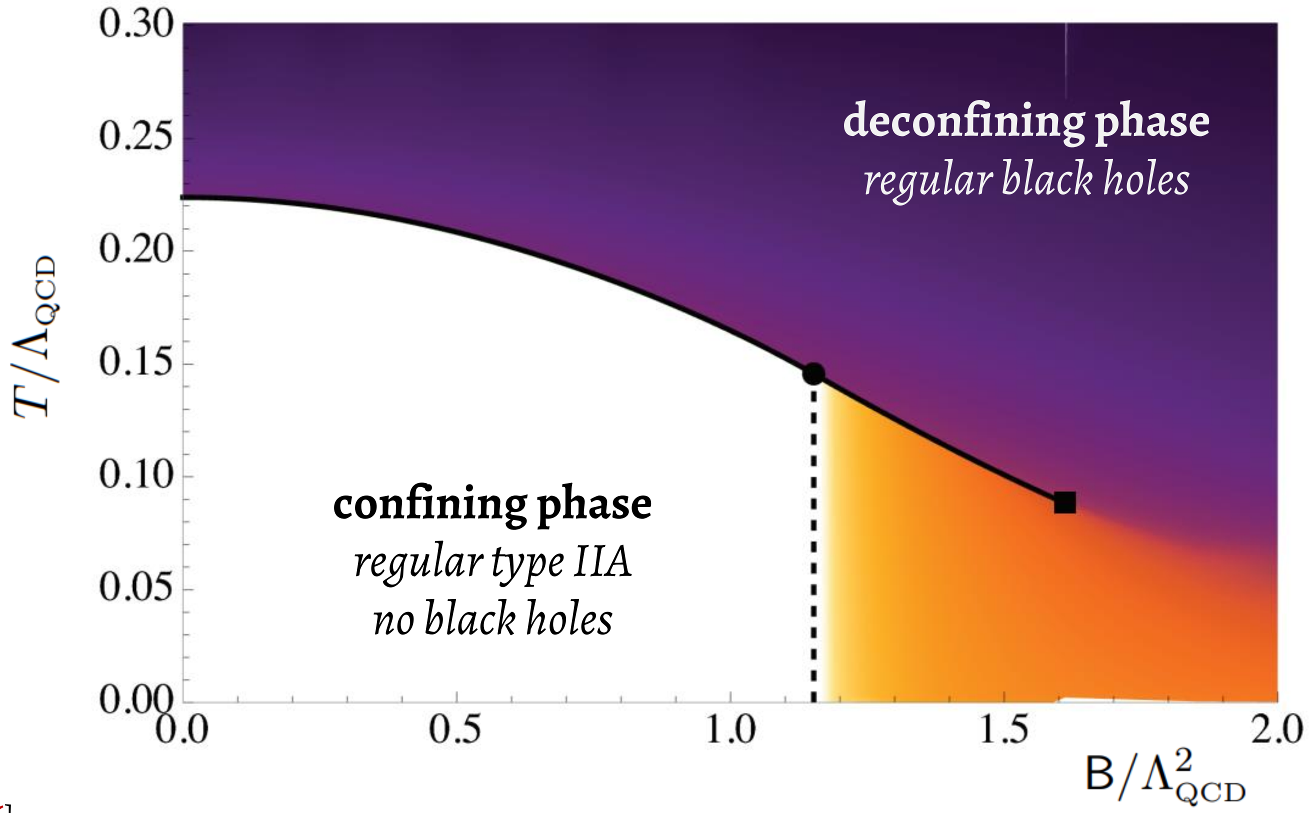
  - *Obstruction*: get rid of so much energy / entropy. We need an open system.

- Strictly speaking, it is not a violation of Cosmic Censorship (because it takes infinite time). *But violates it in spirit*.

# Can we do better?

- Can we generate large curvatures in a **macroscopic region** in finite time and in a string theory model?

    - *Obstruction*: get rid of so much energy / entropy. We need an <u>open system</u>.

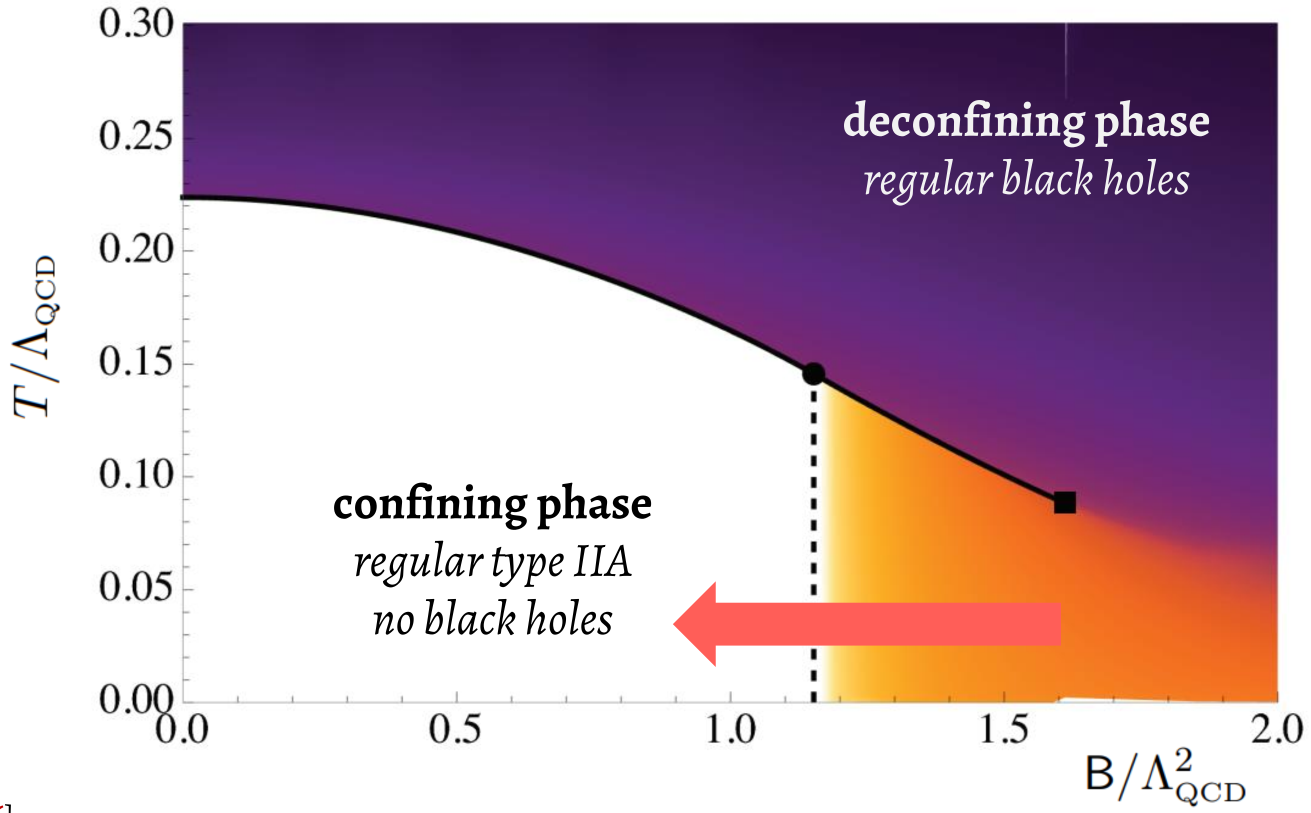



[*Faedo, Hoyos, **JS**; 2212.04996*]

- Strictly speaking, it is not a violation of Cosmic Censorship (because it takes infinite time). *But violates it in spirit.*

# Can we do better?

- Can we generate large curvatures in a **macroscopic region** in finite time and in a string theory model?
  - *Obstruction*: get rid of so much energy / entropy. We need an open system.




[*Faedo, Hoyos, **JS**; 2212.04996*]

# Thanks.