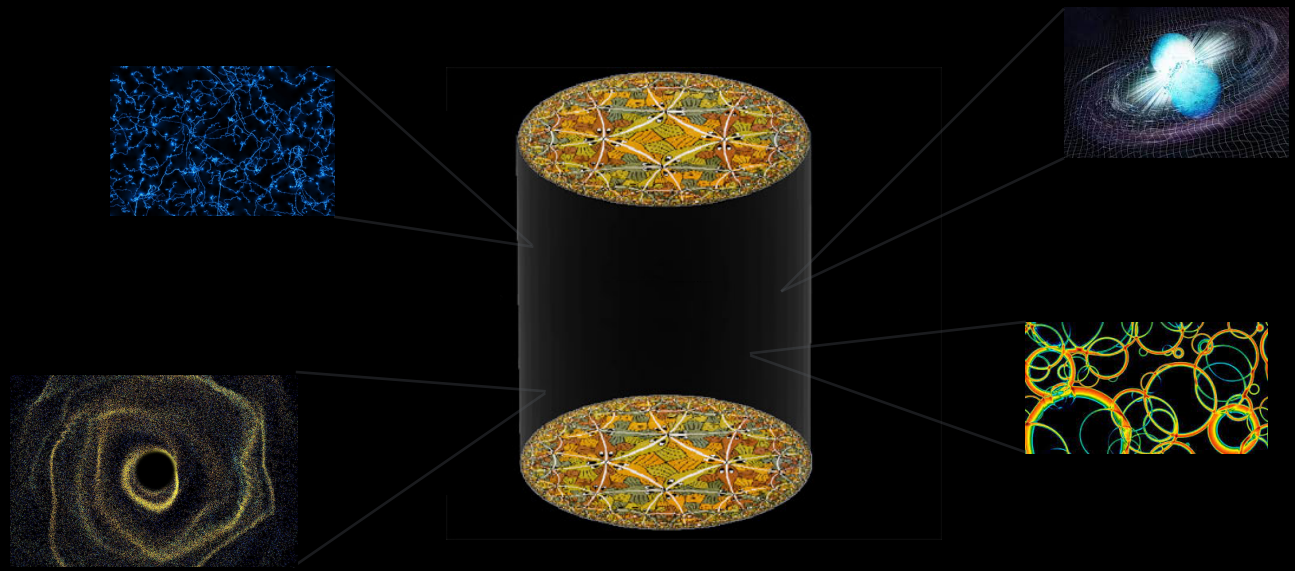
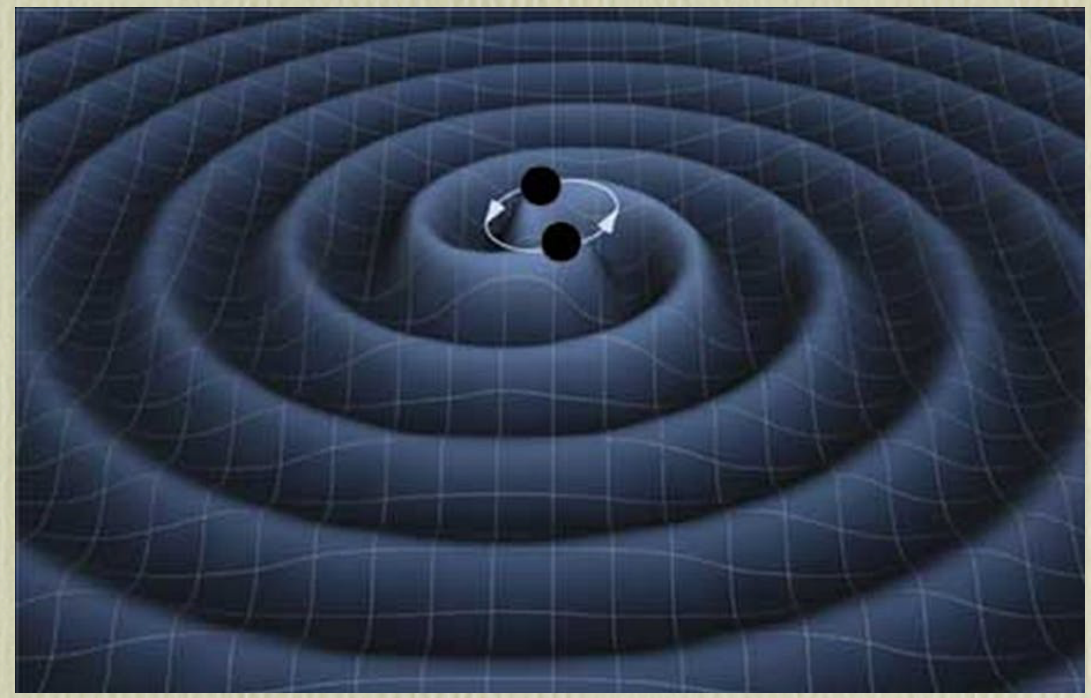
Holography in the Gravitational Wave Era



David Mateos
ICREA & University of Barcelona

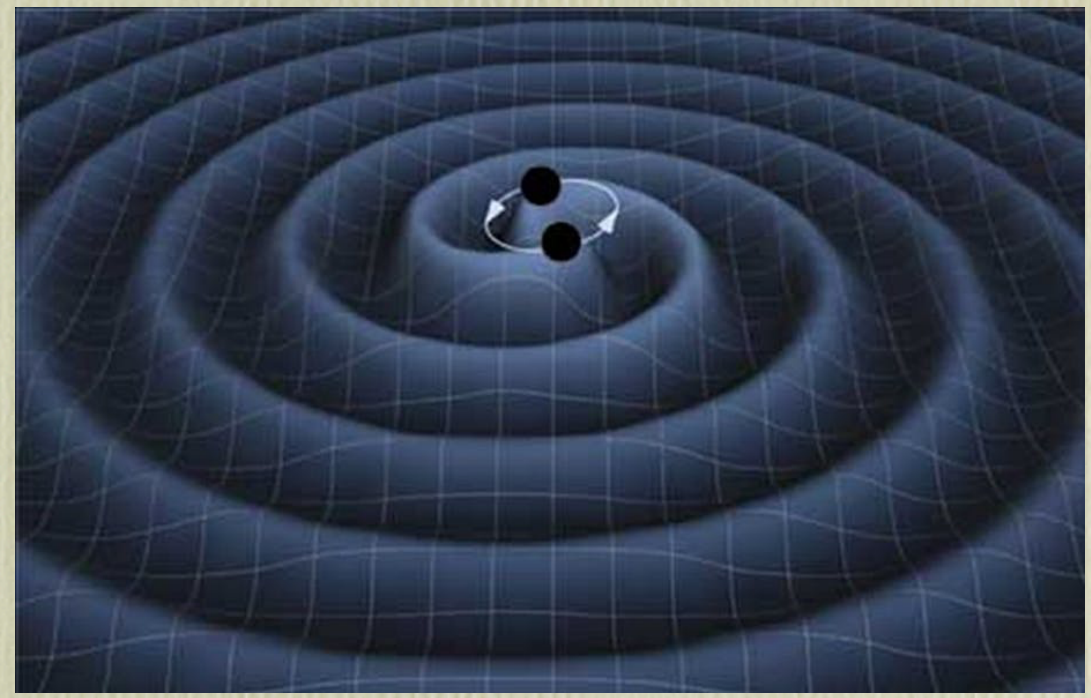
Yago Bea, Jorge Casalderrey-Solana, Christian Ecker, Thanasis Giannakopoulos, Aron Jansen, Sven Krippendorf, Mikel Sanchez-Garitaonandia, Wilke van der Schee, Alexandre Serantes, Miguel Zilhão

One discovery



- Gravitational Waves (GWs)

Two new experimental windows

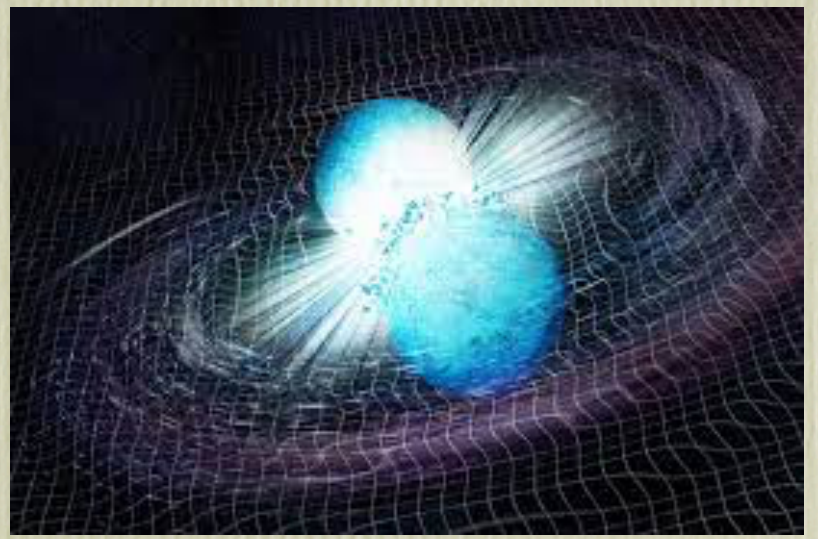


- Into the strong-field regime of General Relativity.
- Into the properties of quantum matter.

Often intertwined

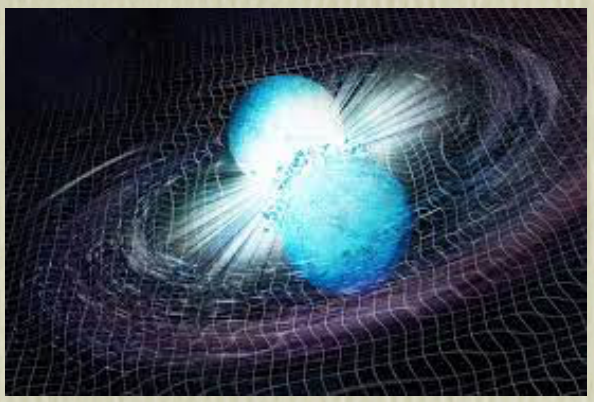
For example in Neutron Star (NS) mergers:

quarks + gluons + gravity.



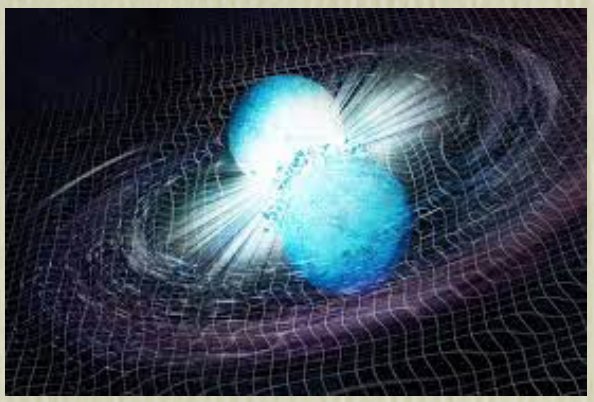
Both SM and BSM matter

- In some cases the matter is SM matter.
  - E.g. neutron star mergers:

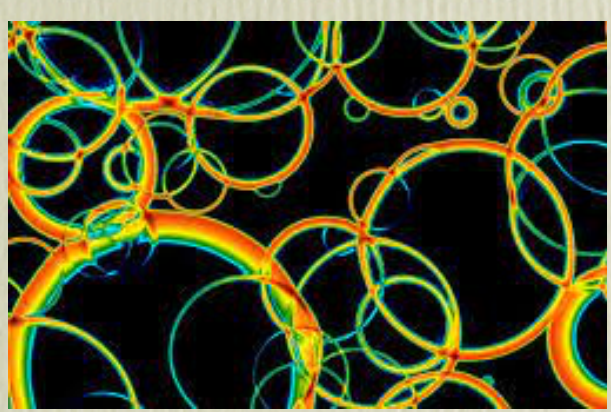


Both SM and BSM matter

- In some cases the matter is SM matter.
  - E.g. neutron star mergers:



- In other cases the putative matter is BSM matter.
  - E.g. cosmological phase transitions:



Golden opportunity for Holography

- This matter is often strongly coupled and/or out of equilibrium.
- Holography is usually the only first-principle tool.
- This morning we will give you an overview.
- I will focus on phase transitions.

Plan

- Holography
- Cosmological phase transitions

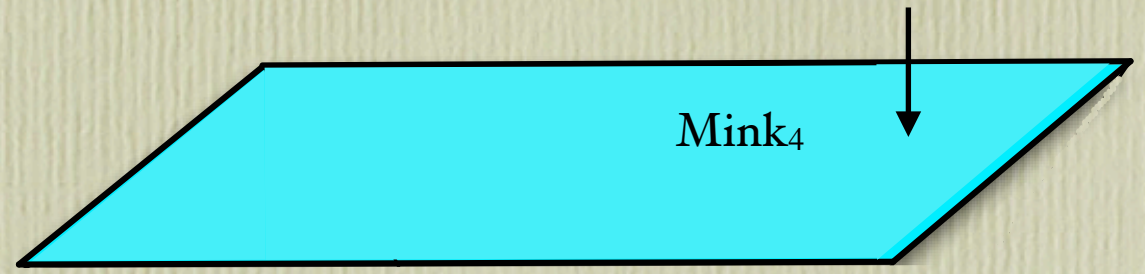
No dynamical gravity

- New holographic framework to include dynamical gravity

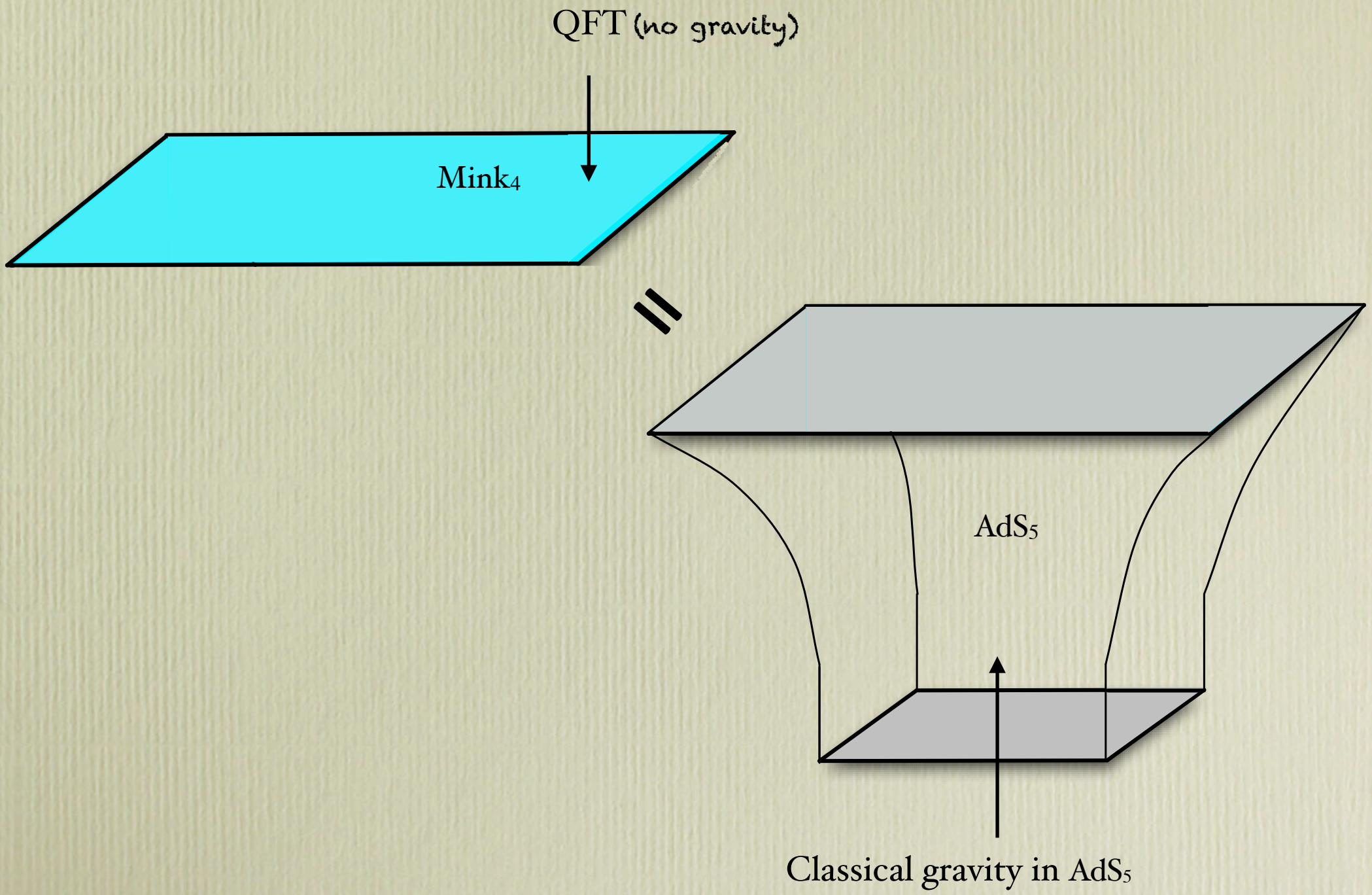
Holography

Holography

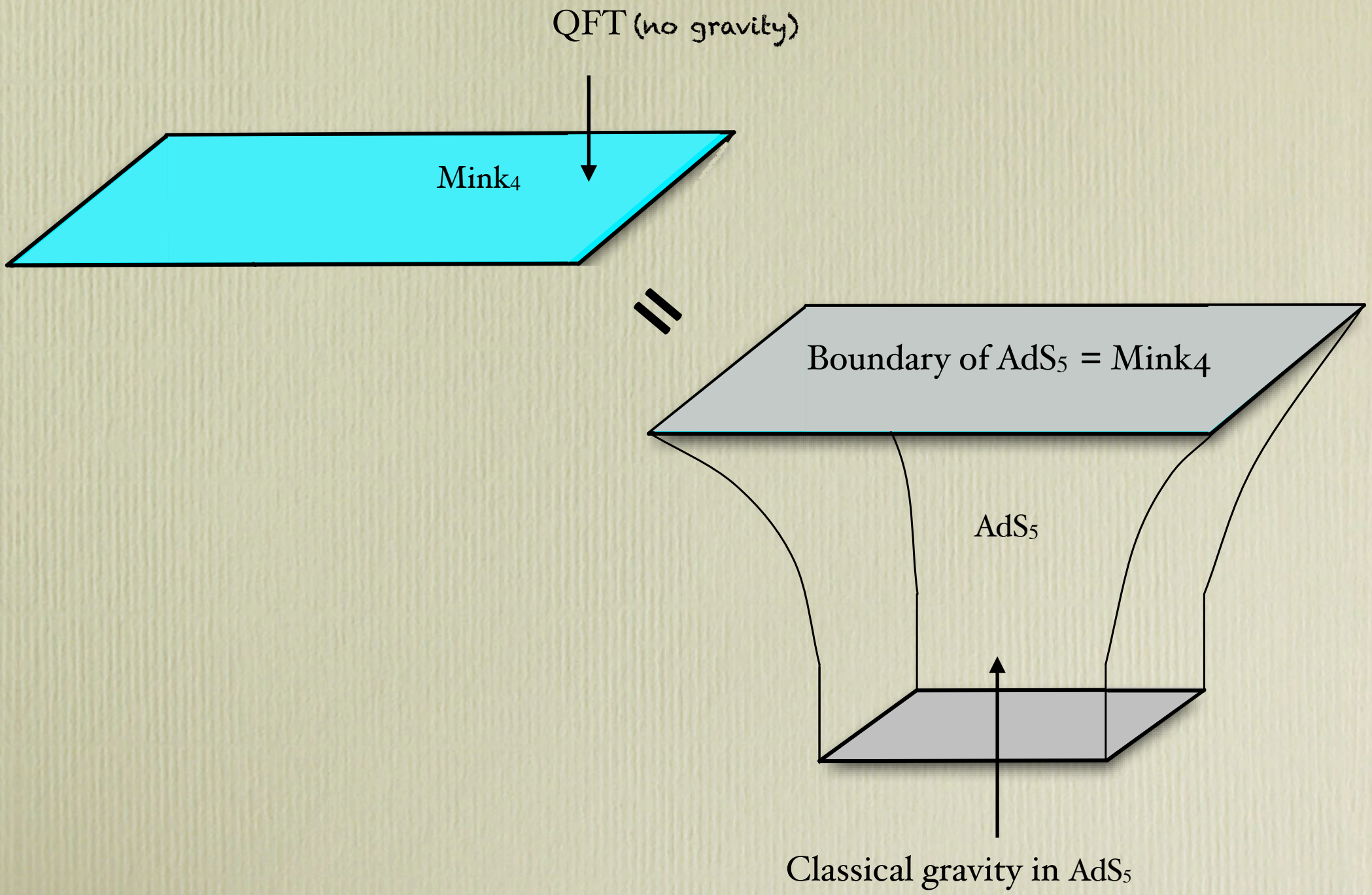
QFT (no gravity)



Holography

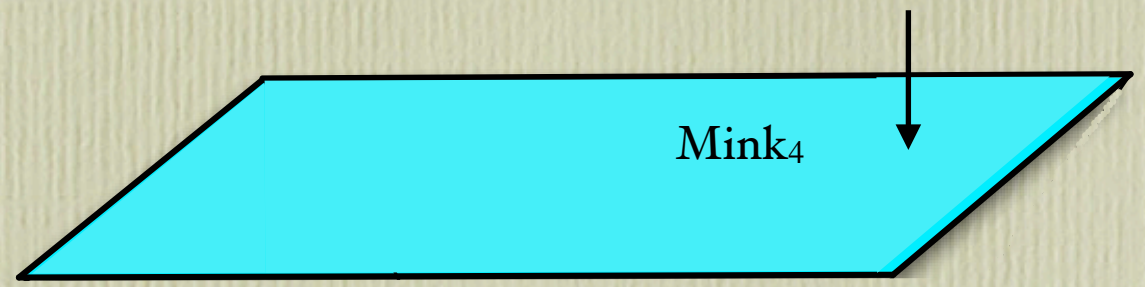


Holography

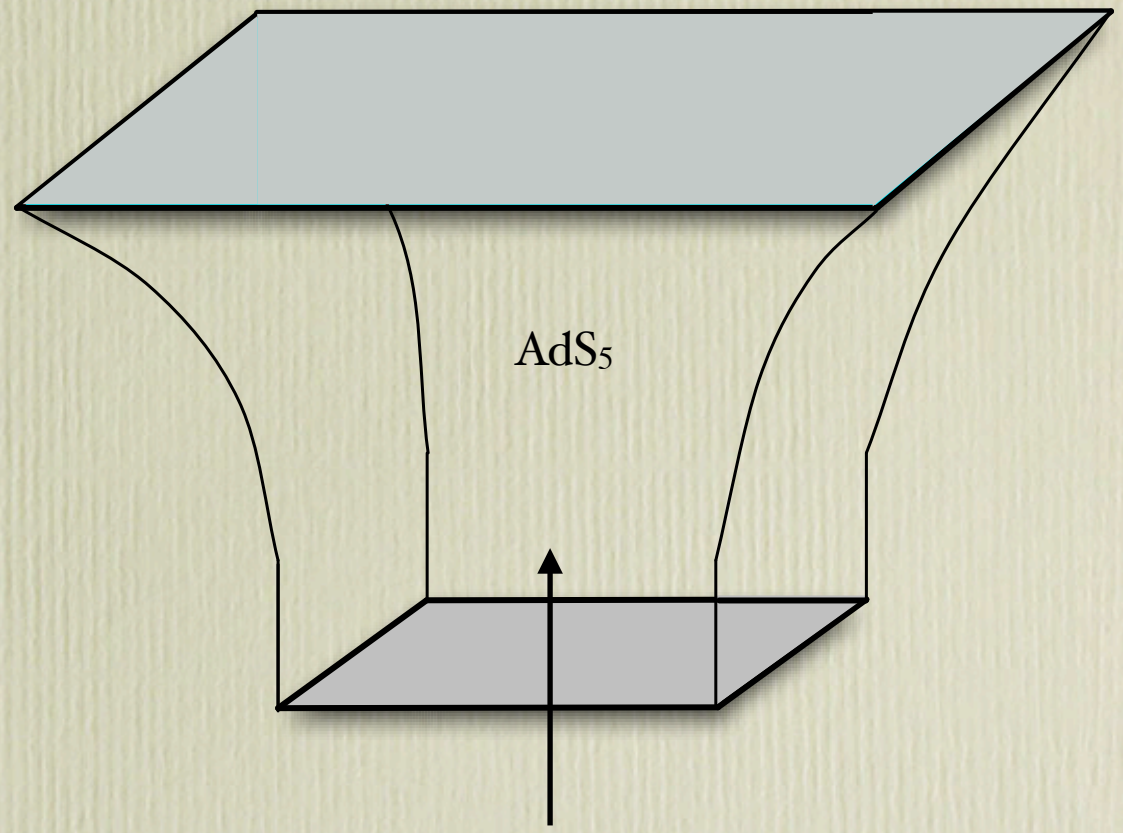

QFT (no gravity)
Mink4
=
Boundary of AdS5 = Mink4
AdS5
Classical gravity in AdS5

Holography

QFT (no gravity)

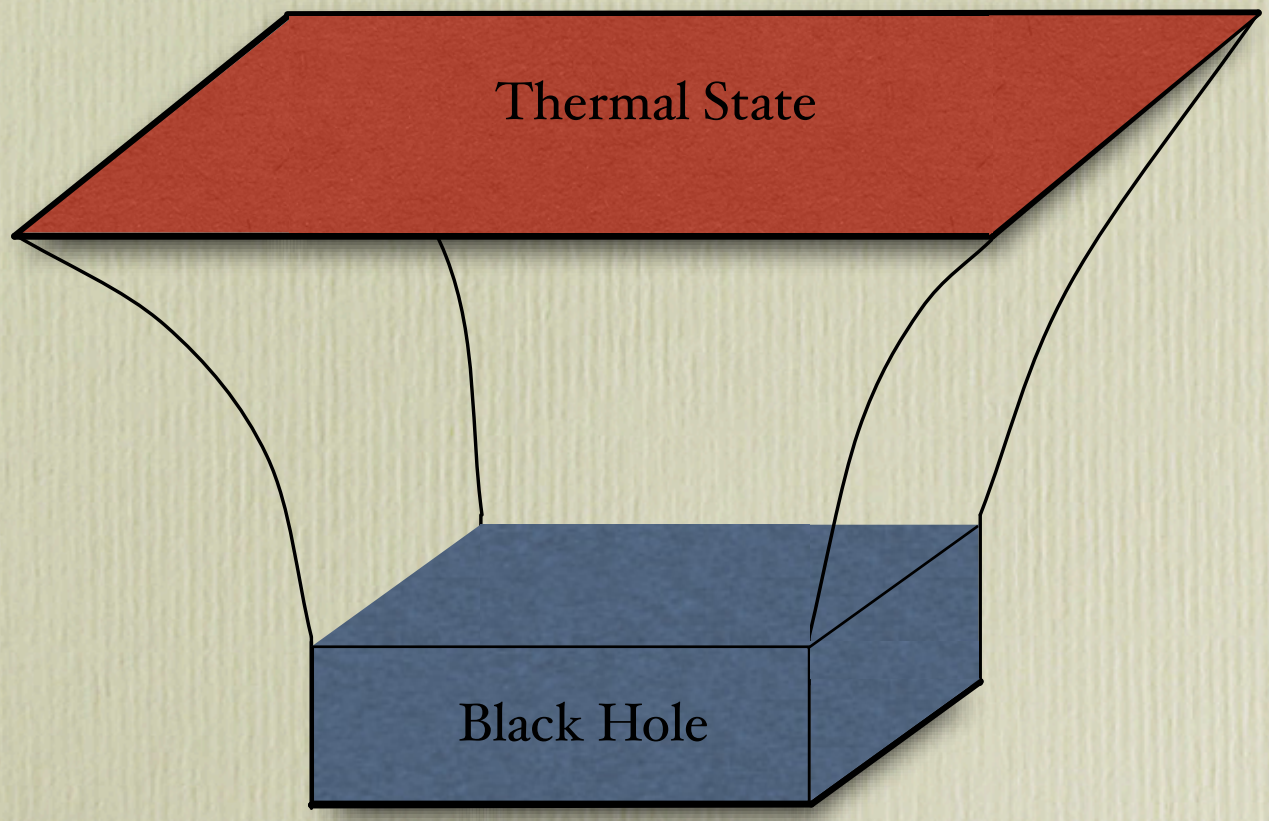


at the boundary of AdS_5

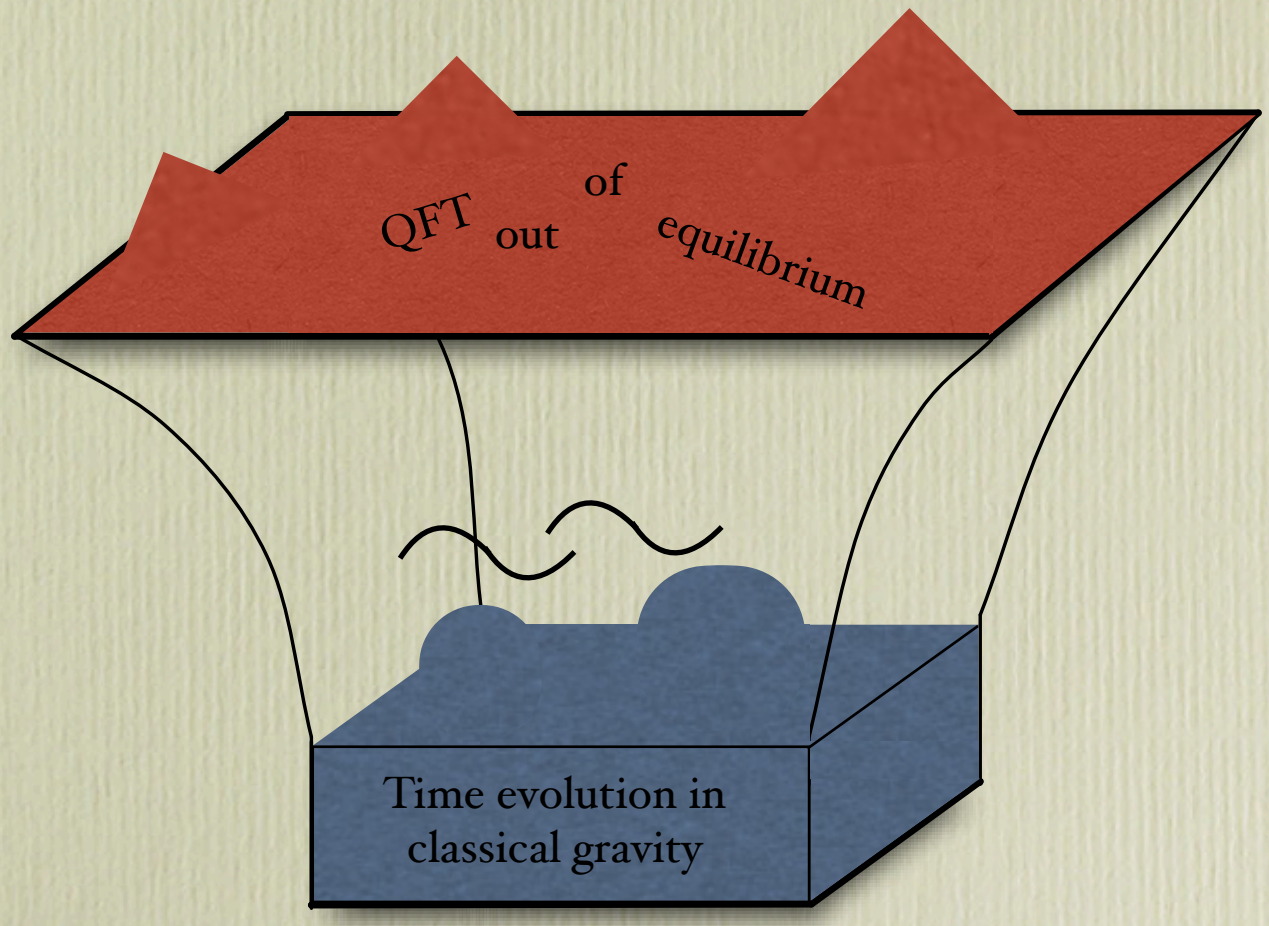


Classical gravity in AdS_5

Thermal physics = Black hole physics



The power of holography



For this talk you can think of AdS_5 as a computational device

Disclaimer

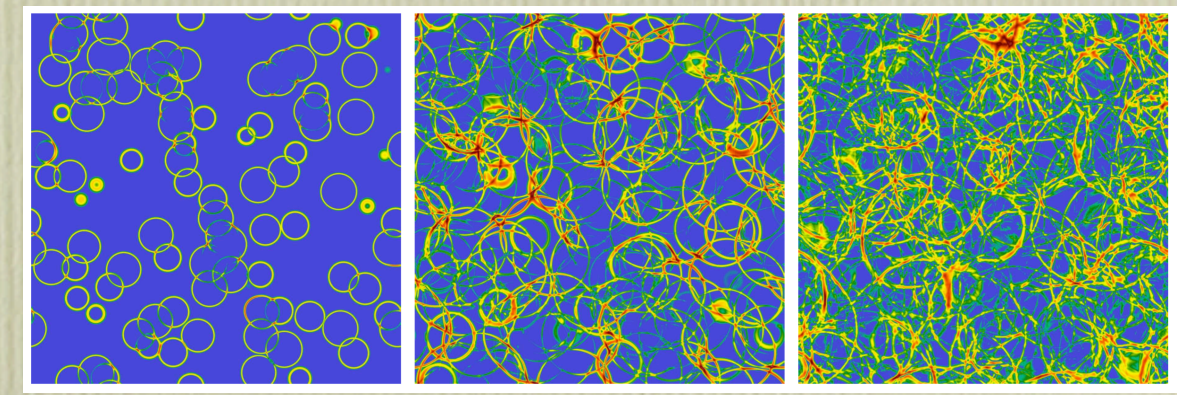
- We do not know a gravity dual for each QFT.
- All statements in this talk are for QFTs with a gravity dual.
- Since this is a large class the hope is to learn about generic properties.

Cosmological Phase Transitions

Cosmological phase transitions

- They can proceed via the nucleation of bubbles (e.g. boiling water).

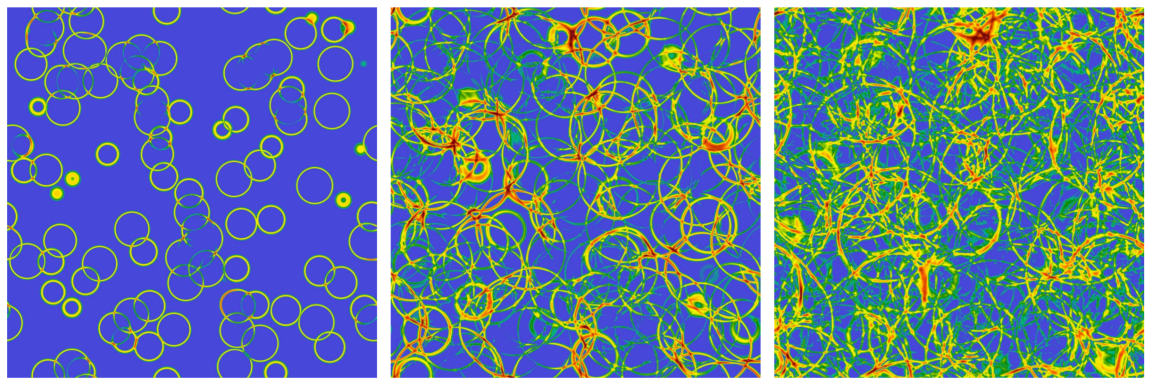
Picture from Hindmarsh, Huber, Rummukainen & Weir '15

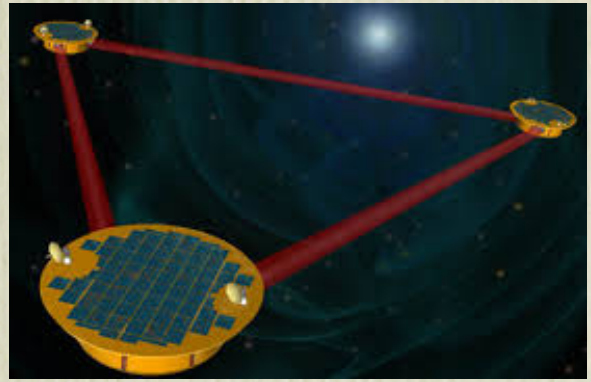


Cosmological phase transitions

- They can proceed via the nucleation of bubbles (e.g. boiling water).
- These bubbles could have produced GWs detectable by e.g. LISA.

Picture from Hindmarsh, Huber, Rummukainen & Weir '15





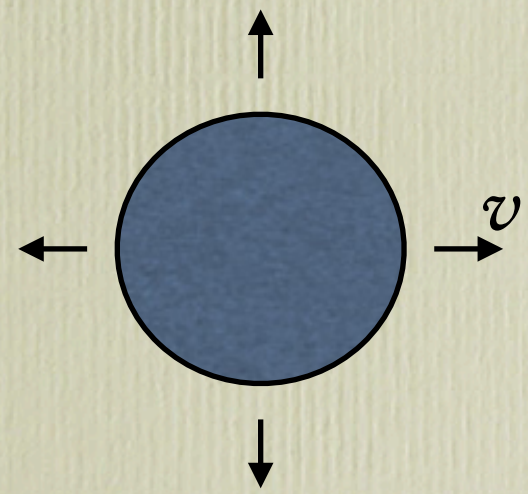
Cosmological phase transitions

- GW spectrum is most sensitive to the bubble wall velocity.

- This parameter is also the most challenging to compute because the wall is out of equilibrium.

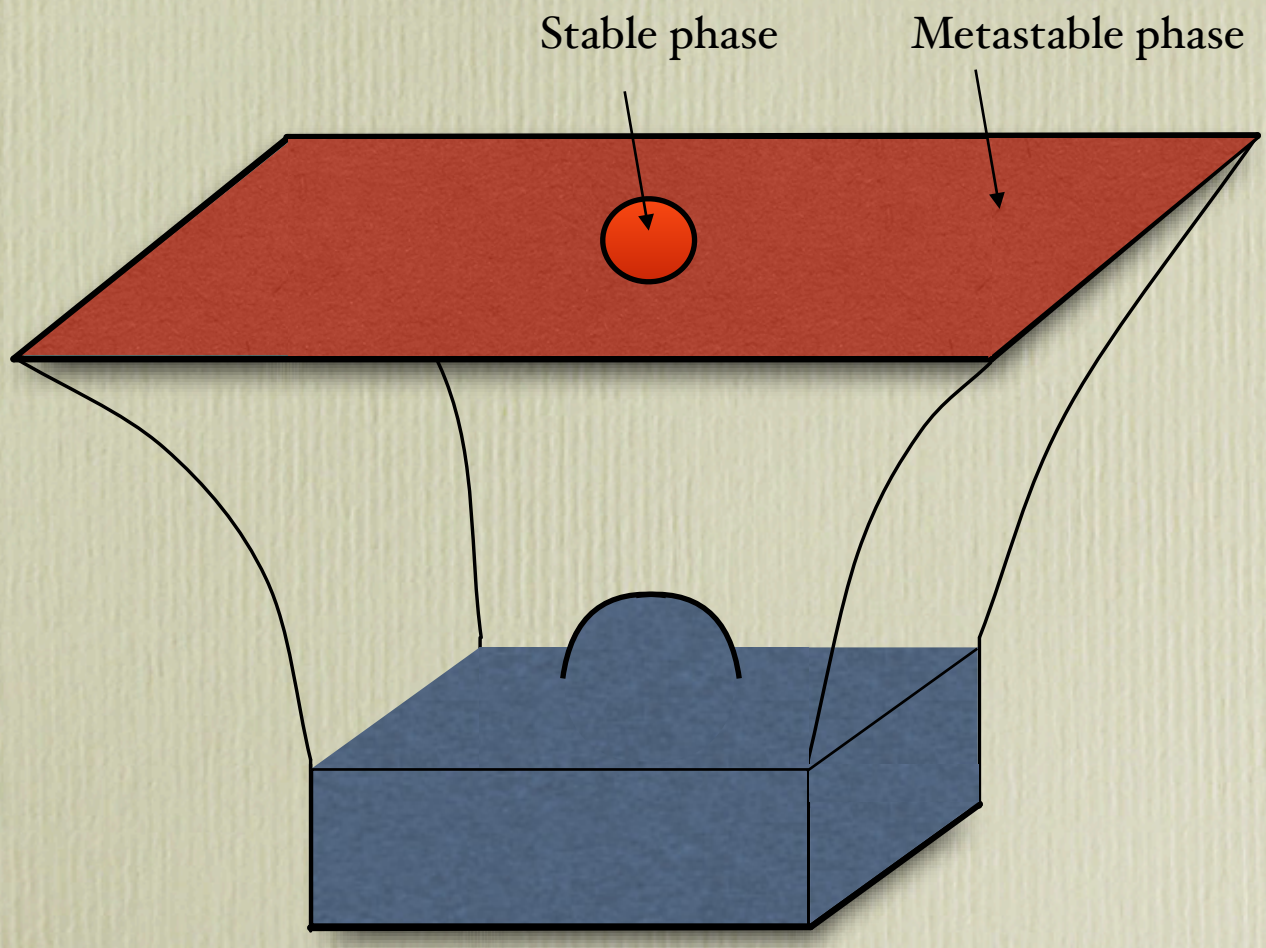
Moore & Prokopec ’95
Bodeker & Moore ’17
Höche, Kozaczuk, Long, Turner & Y. Wang ‘20

- But it can be computed in holographic models.



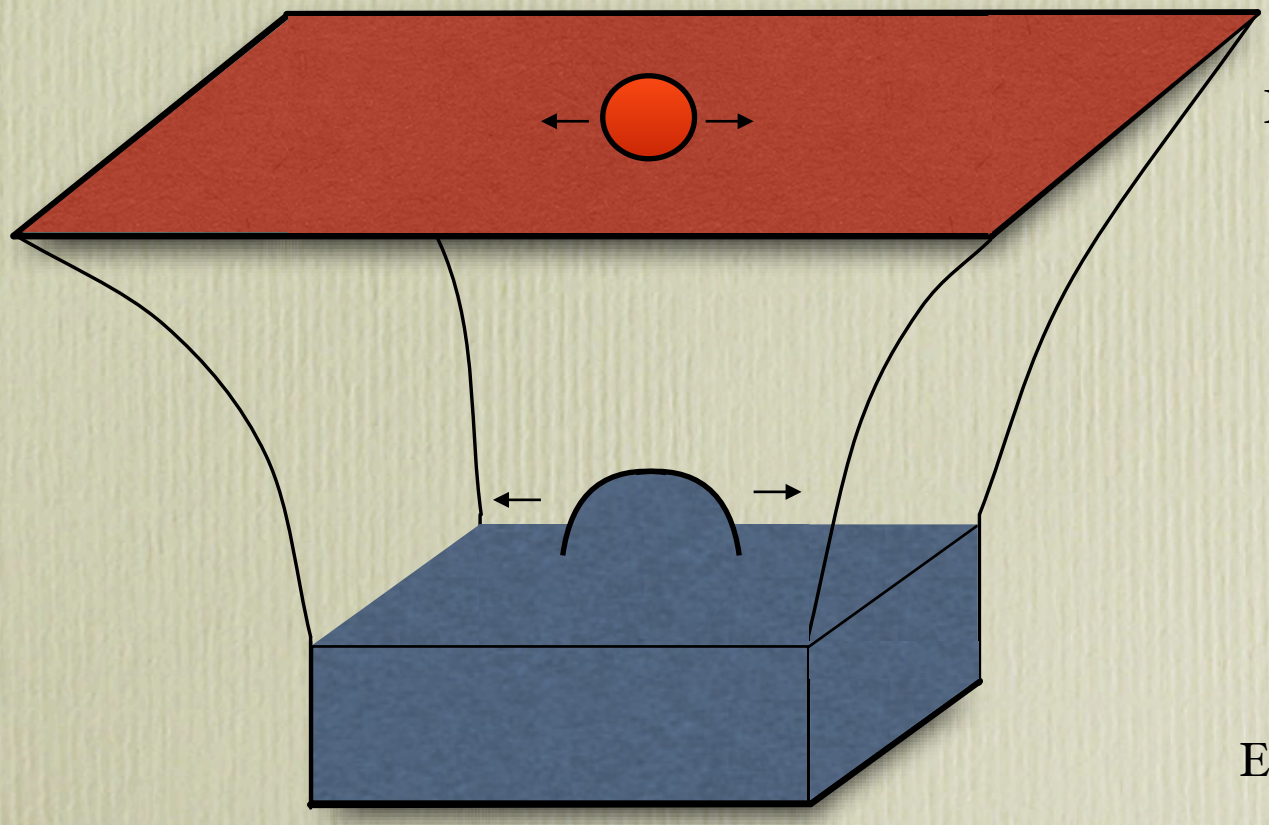
Strategy

- Set up initial conditions...



Strategy

- Set up initial conditions… and let it go.

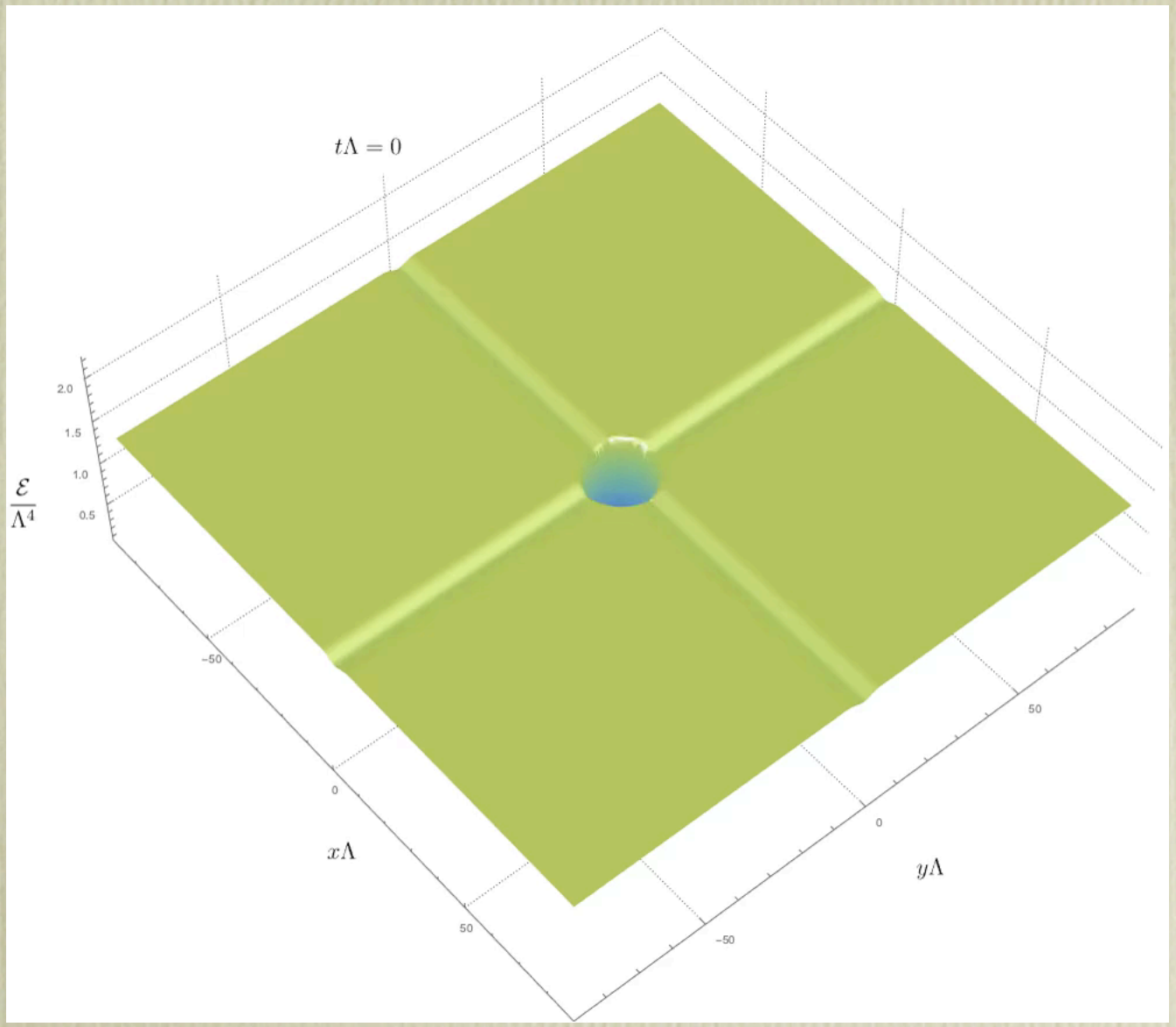


Read off boundary
stress tensor

Solve classical
Einstein equations

Bubble expansion

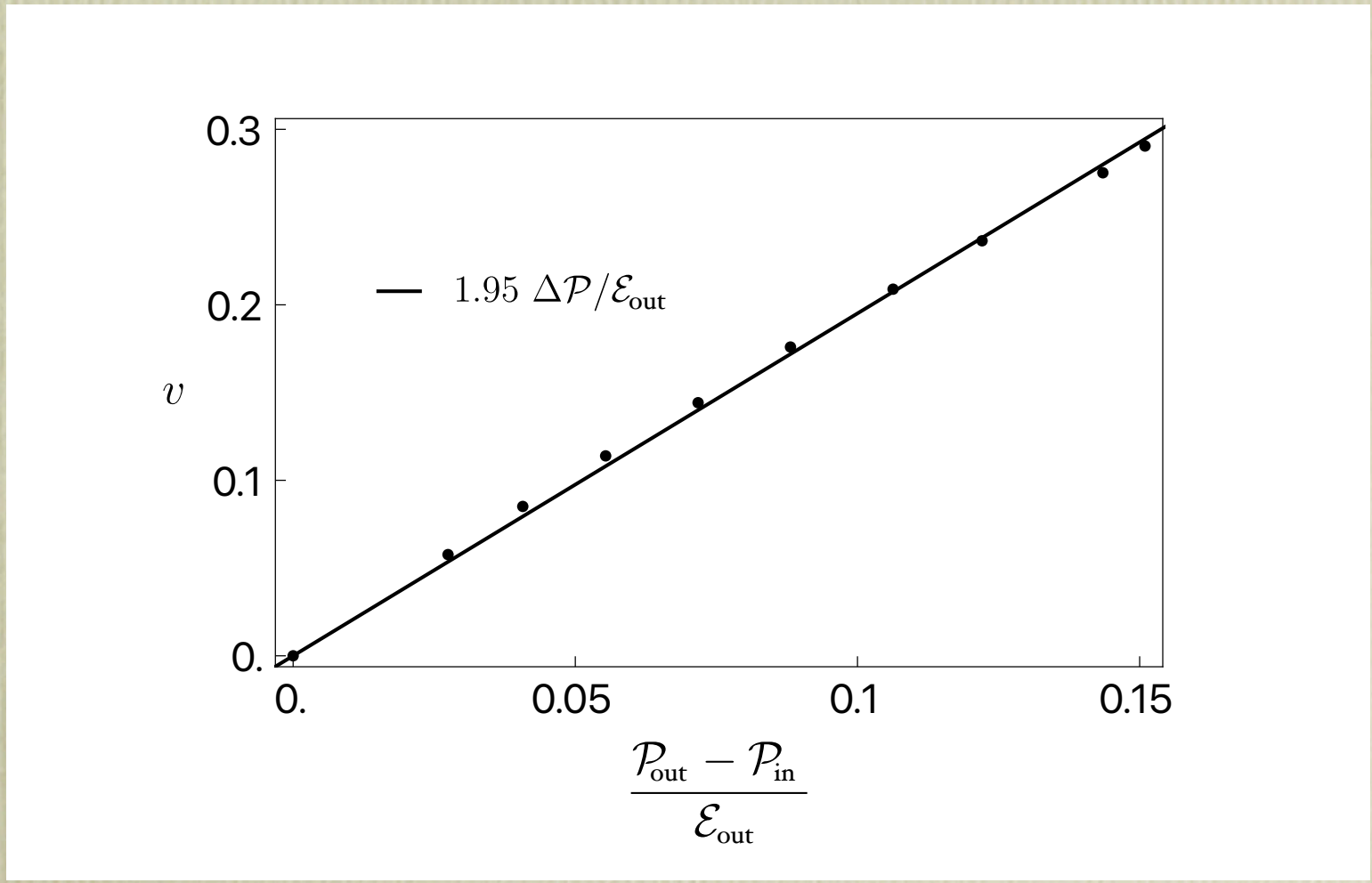
Bea, Casalderrey, Giannakopoulos, DM, Sanchez-Garitaonandia & Zilhao '21
Bigazzi, Caddeo, Canneti & Cotrone '21
Bea, Casalderrey, Giannakopoulos, Jansen, DM, Sanchez-Garitaonandia & Zilhao '22



Bubble wall velocity

Bea, Casalderrey, Giannakopoulos, DM, Sanchez-Garitaonandia & Zilhao '21

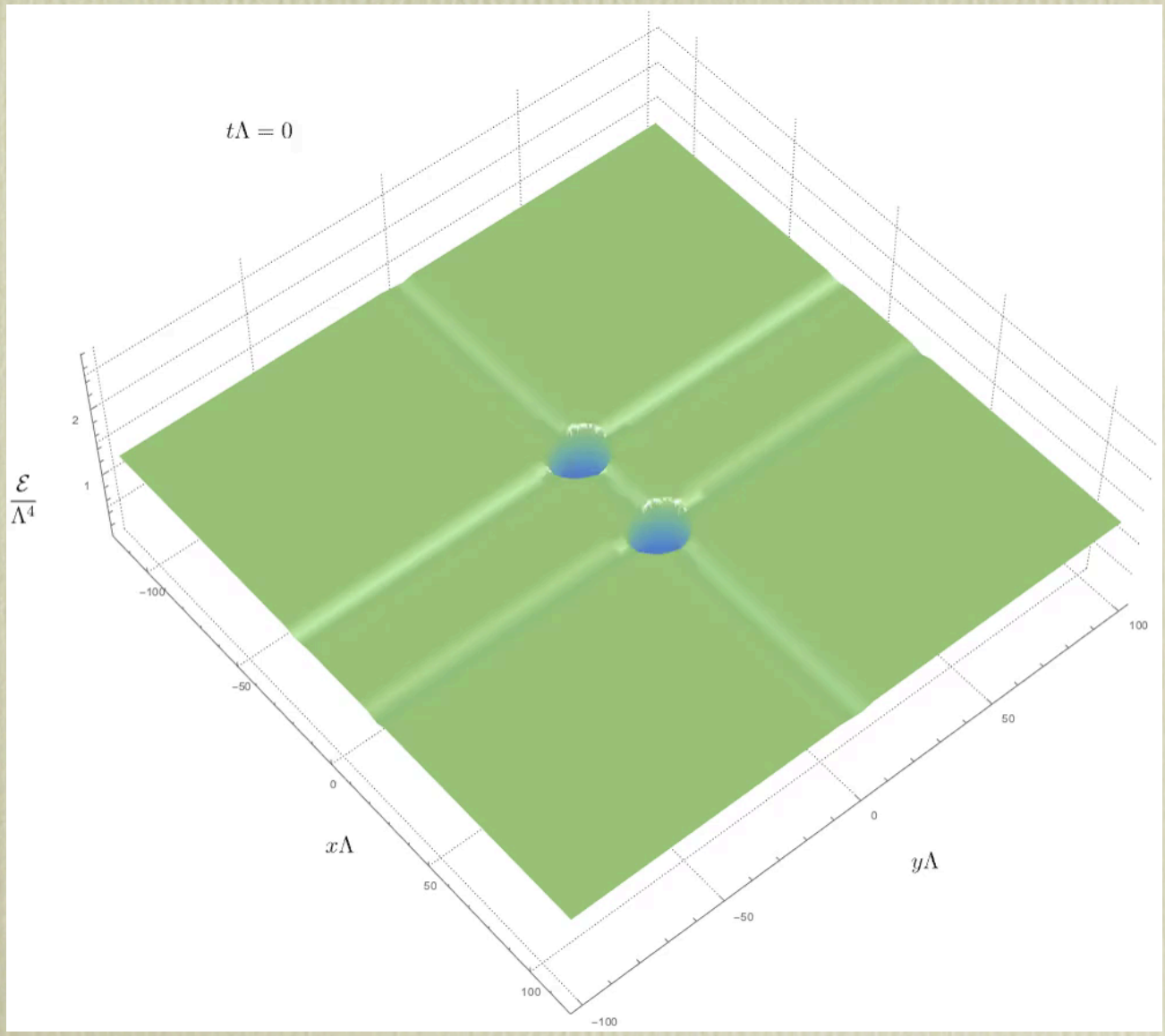
- First calculation of bubble wall at strong coupling (*preliminary*):



Bubble collisions and GW spectrum

Bea, Casalderrey, Giannakopoulos, Jansen, DM, Sanchez-Garitaonandia & Zilhao (in progress)

- Computing the GW spectrum requires considering collisions of bubbles.



Bubble collisions and GW spectrum

Bea, Casalderrey, Giannakopoulos, Jansen, DM, Sanchez-Garitaonandia & Zilhao (in progress)

- Computing the GW spectrum requires considering collisions of bubbles.

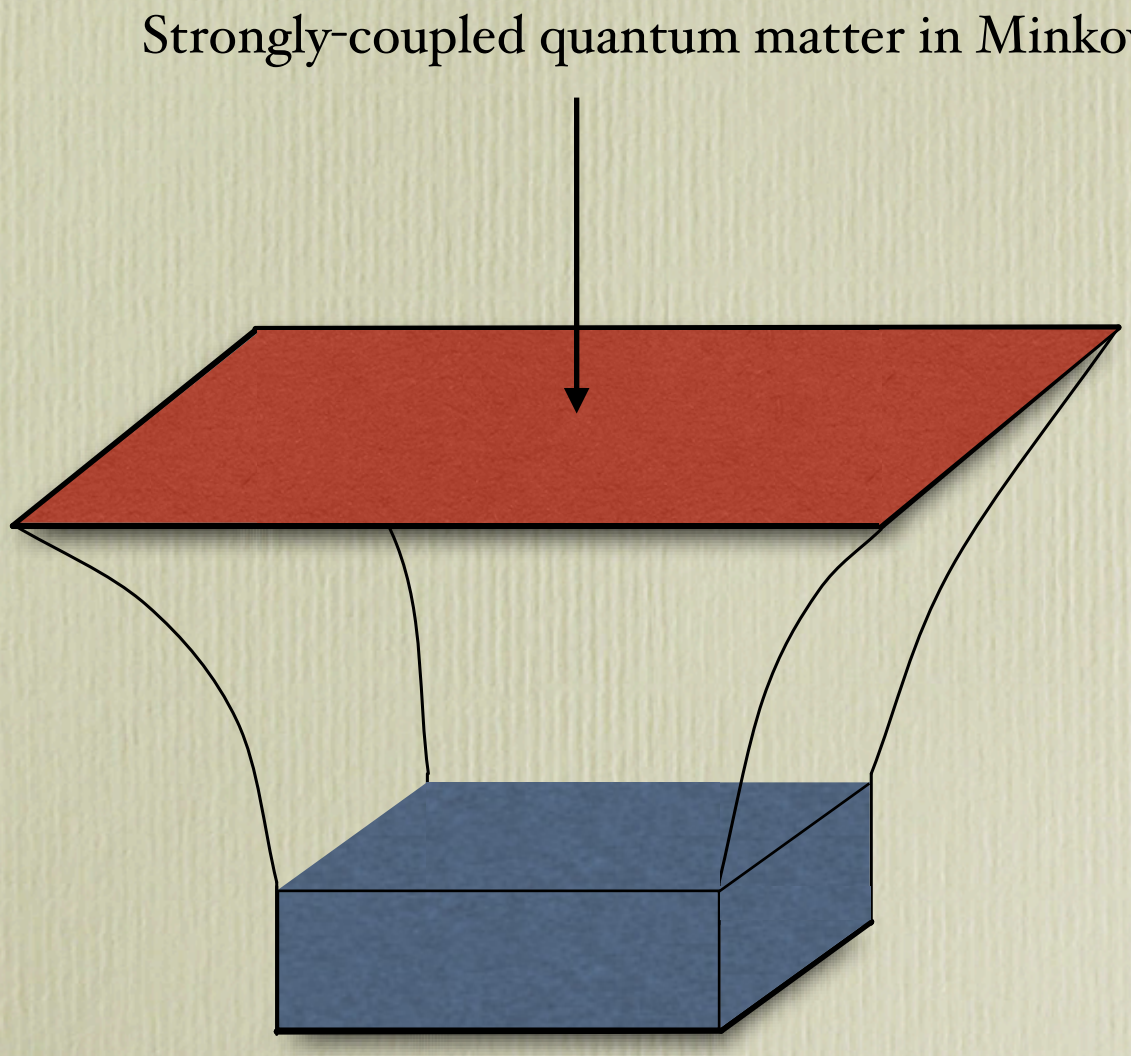
- In this description all the post-nucleation dynamics is included:

  - Bubble expansion.
  - Bubble collisions.
  - Sound modes.
  - Turbulence.
  - Etc.

Holography with Dynamical Boundary Gravity

Dynamical gravity at the boundary

- So far we have studied:



Dynamical gravity at the boundary

- But many problems require:

Strongly-coupled quantum matter + Classical dynamical gravity

$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} + \Lambda\, g_{\mu\nu} = 8\pi G \langle T_{\mu\nu} \rangle$$

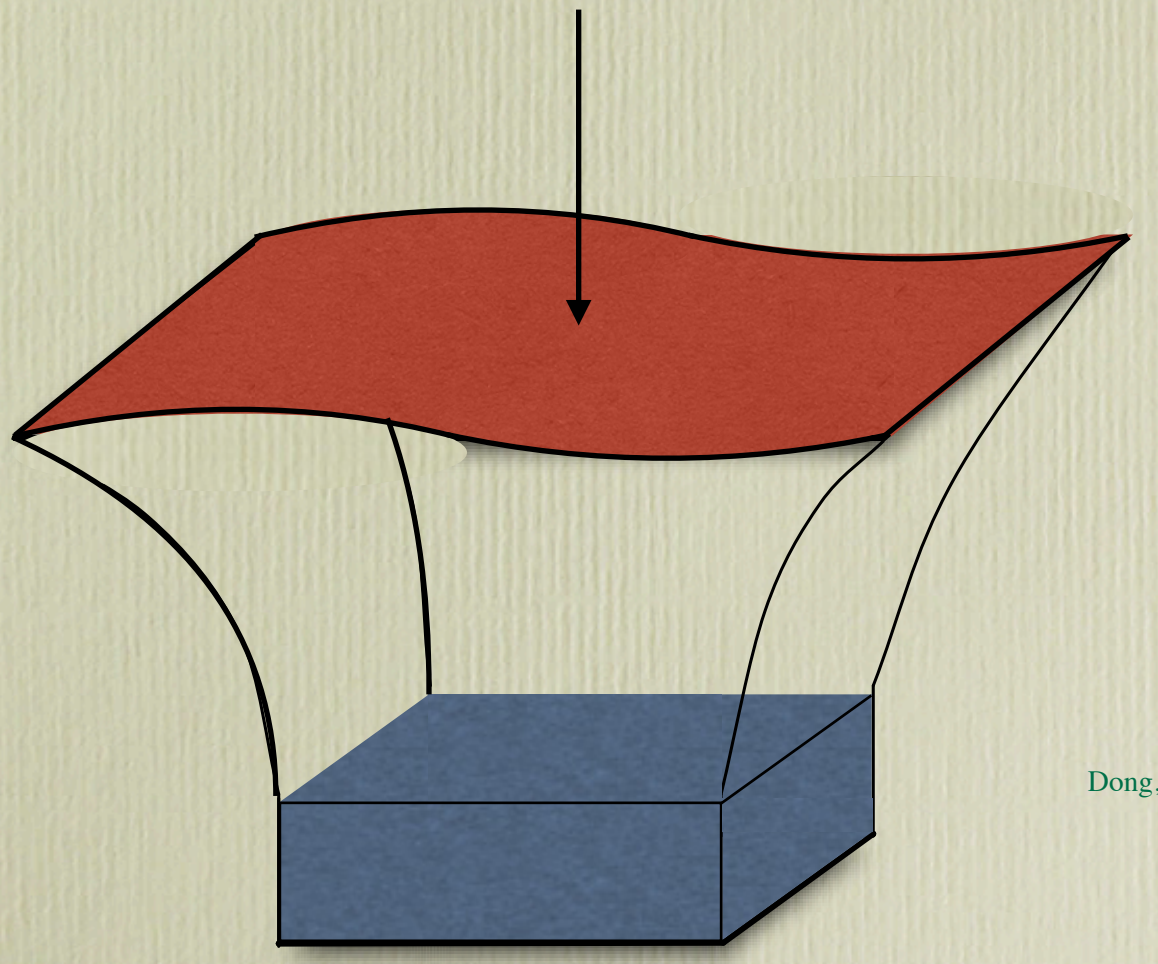
- Cosmological phase transitions
- Cosmological defects (cosmic strings, etc)
- Neutron star mergers
- (P)reheating
- Primordial black holes
- Etc

Dynamical gravity at the boundary

Casalderrey, Ecker, DM & van der Schee '21

- So we need a new holographic framework:

Strongly-coupled quantum matter + Classical dynamical gravity



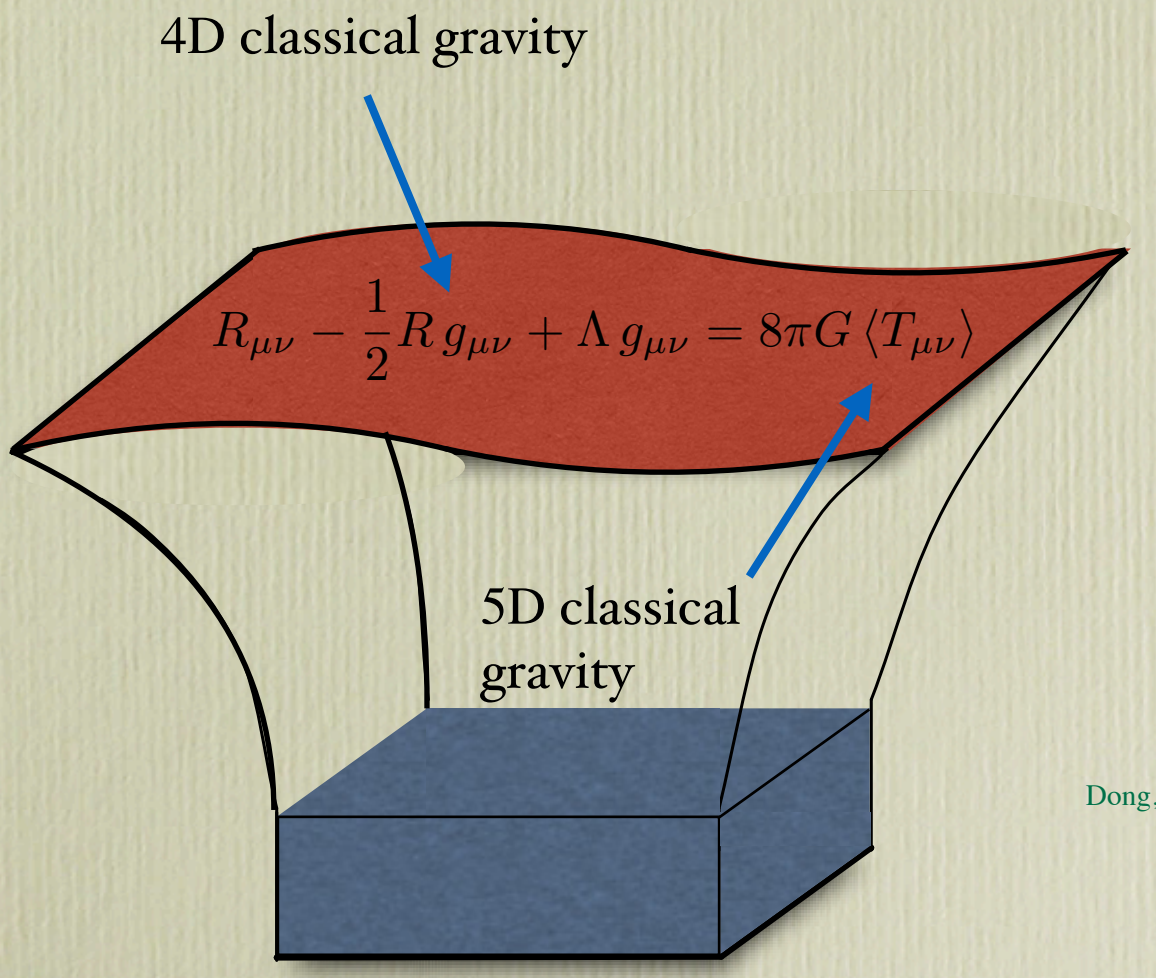
Related previous work

Gubser '99
Csaki, Graesser, Kolda & Terning '99
Kehagias & Kiritsis '99
Cline, Grojean & Servant '99
Csaki, Graesser, Randall & Terning '99
Dvali, Gabadadze, & Porrati '00
Karch & Randall '00
Kiritsis '05
Compere & Marolf '08
Apostolopoulos, Siopsis & Tetradis '08
Erdmenger, Ghoroku & Meyer '11
Dong, Horn, Matsuura, Silverstein & Torroba '12
Banerjee, Bhowmick, Sahay & Siopsis '12
Fischetti, Kastor & Traschen '14
Buchel '16
Buchel '17
Emparan, Frassino & Way '20
Ghosh, Kiritsis, Nitti & Witkowski '20

Dynamical gravity at the boundary

Casalderrey, Ecker, DM & van der Schee '21

- So we need a new holographic framework:

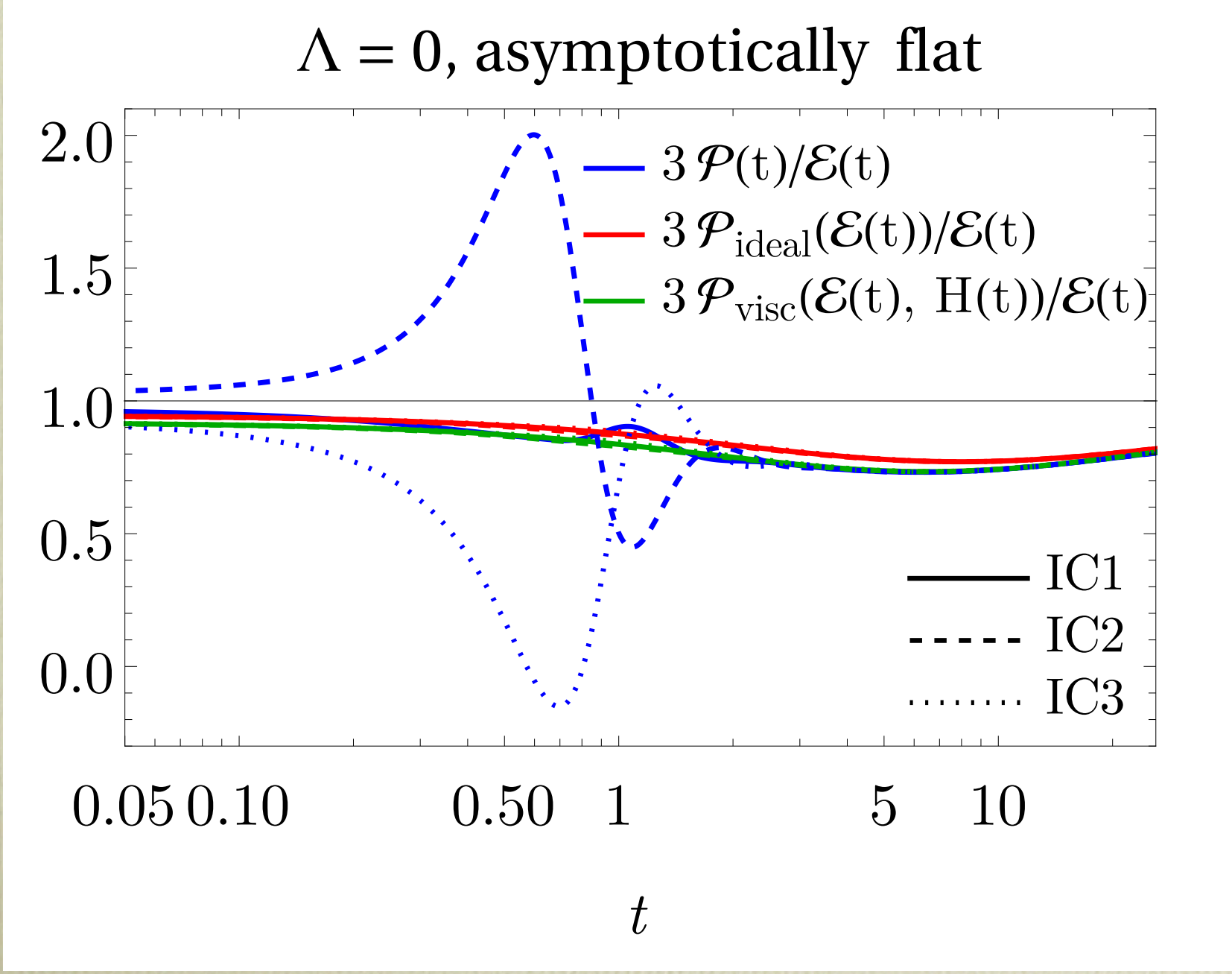


Related previous work

Gubser '99
Csaki, Graesser, Kolda & Terning '99
Kehagias & Kiritsis '99
Cline, Grojean & Servant '99
Csaki, Graesser, Randall & Terning '99
Dvali, Gabadadze, & Porrati '00
Karch & Randall '00
Kiritsis '05
Compere & Marolf '08
Apostolopoulos, Siopsis & Tetradis '08
Erdmenger, Ghoroku & Meyer '11
Dong, Horn, Matsuura, Silverstein & Torroba '12
Banerjee, Bhowmick, Sahay & Siopsis '12
Fischetti, Kastor & Traschen '14
Buchel '16
Buchel '17
Emparan, Frassino & Way '20
Ghosh, Kiritsis, Nitti & Witkowski '20

Example: Far-from-equilibrium FLRW Cosmology

Casalderrey, Ecker, DM & van der Schee '21



Thank you!