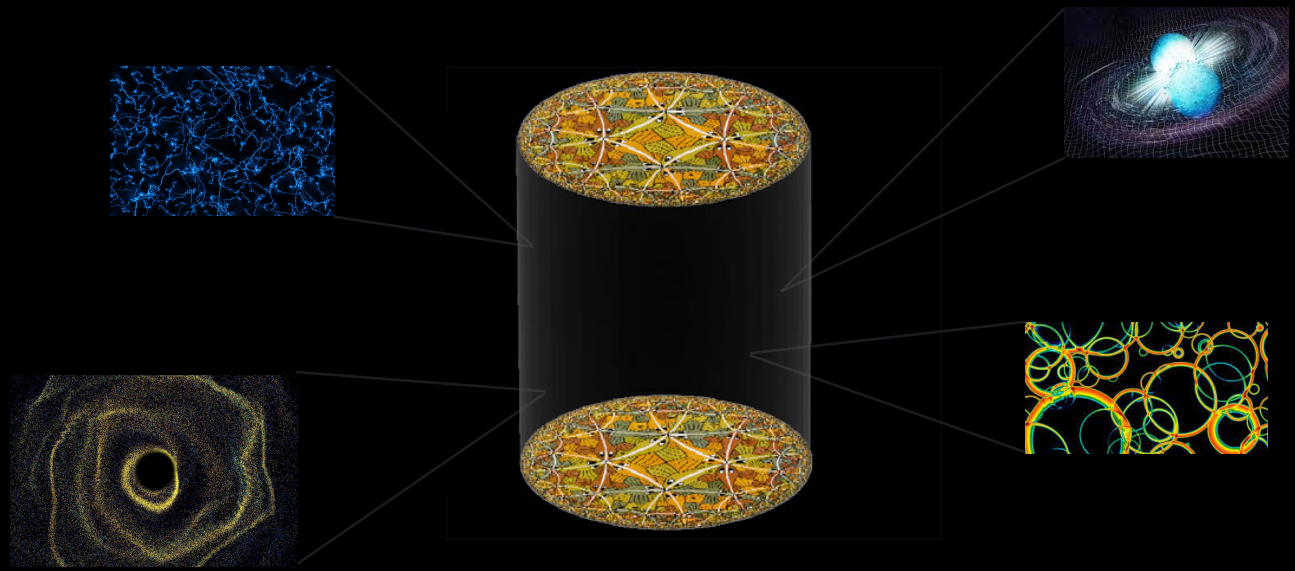
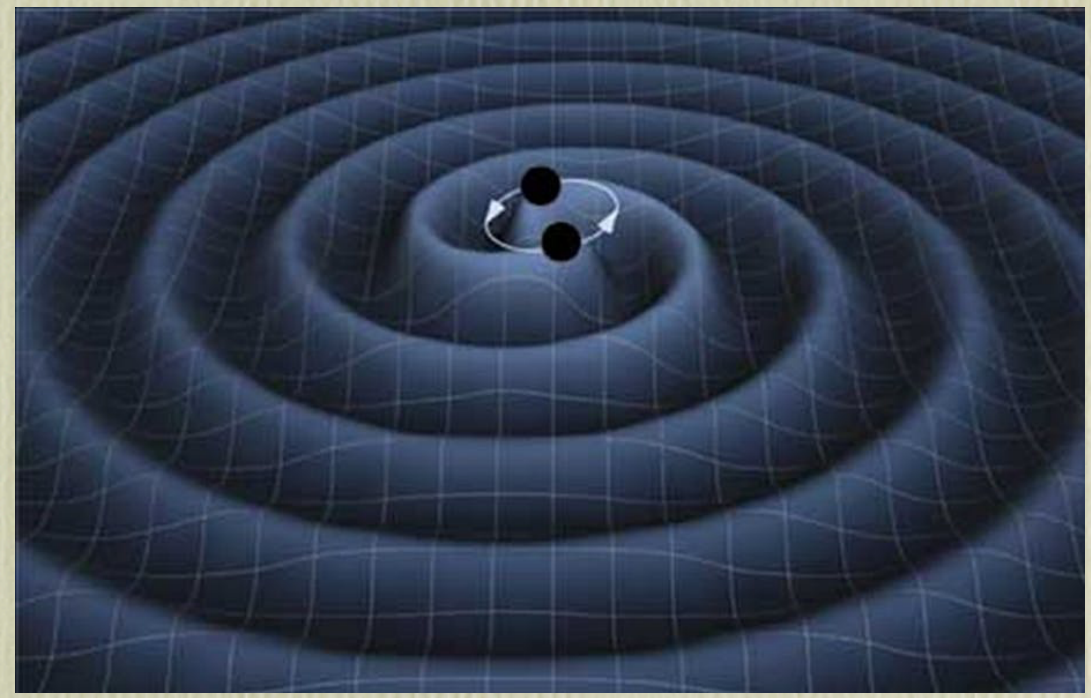
Holography in the Gravitational Wave Era



David Mateos
ICREA & University of Barcelona

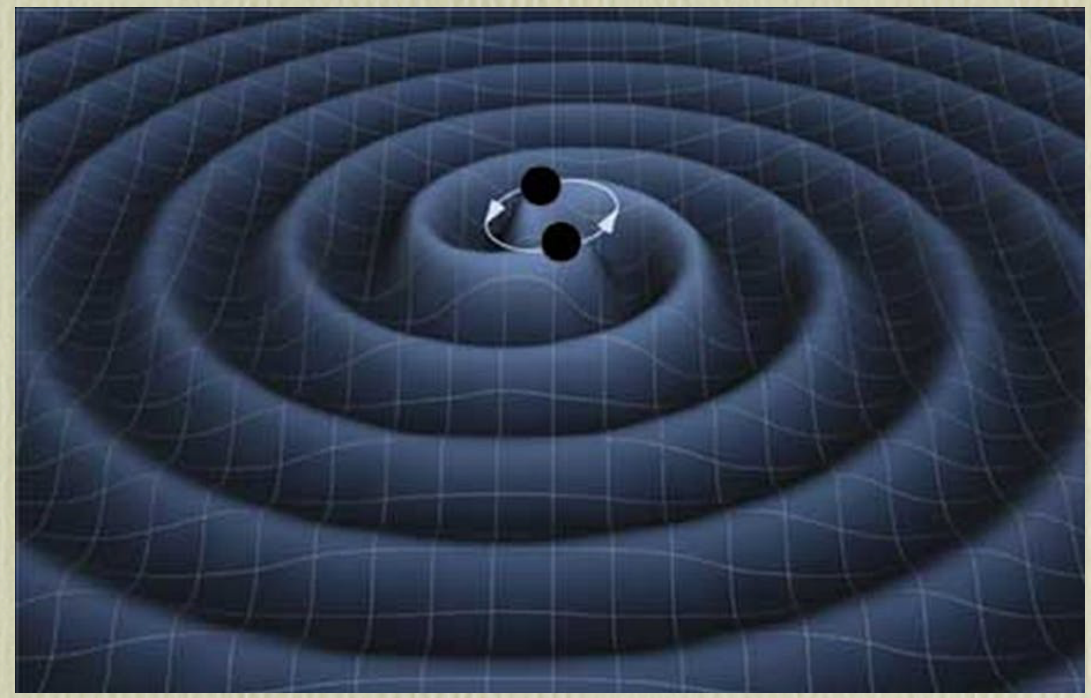
STRONG 2020

One discovery



- Gravitational Waves (GWs)

Two new experimental windows

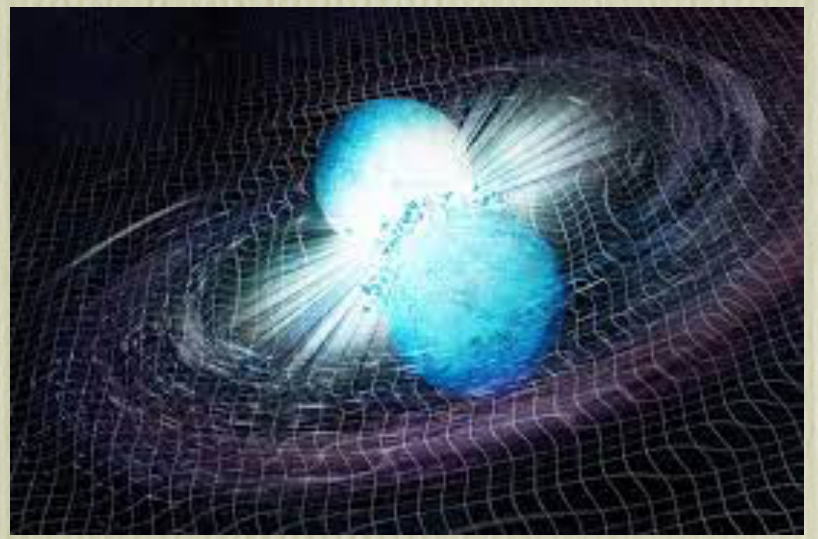


- Into the strong-field regime of General Relativity.
- Into the properties of quantum matter.

Often intertwined

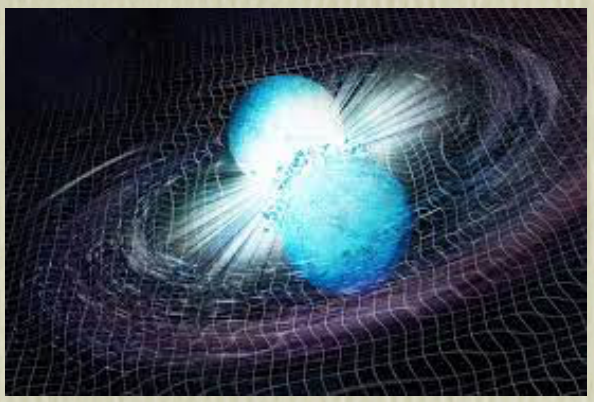
For example in Neutron Star mergers:

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

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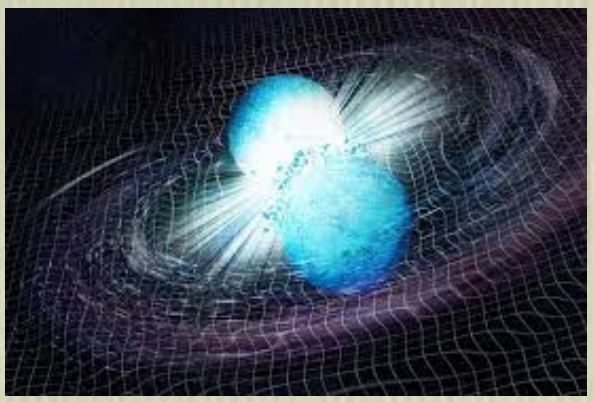
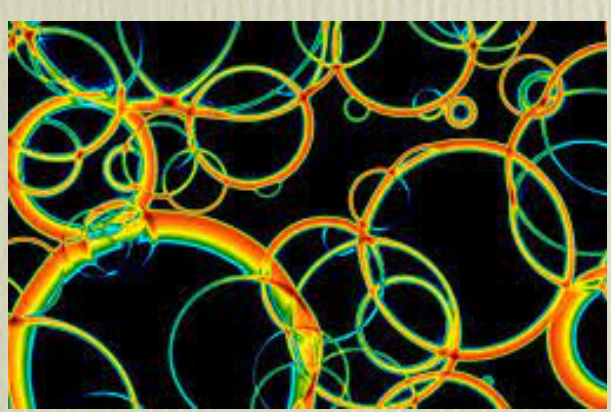


- In other cases the putative matter is BSM matter.
  - E.g. cosmological phase transitions:



Golden opportunity

- Maximizing the discovery potential requires a theoretical understanding of quantum matter coupled to dynamical gravity.
- This matter is often strongly coupled and/or out of equilibrium.
- Holography is usually the only first-principle tool.
- Today I will give an overview.

Plan

- Holography
- Cosmological phase transitions
  - Via bubble nucleation
  - Spinodal instability

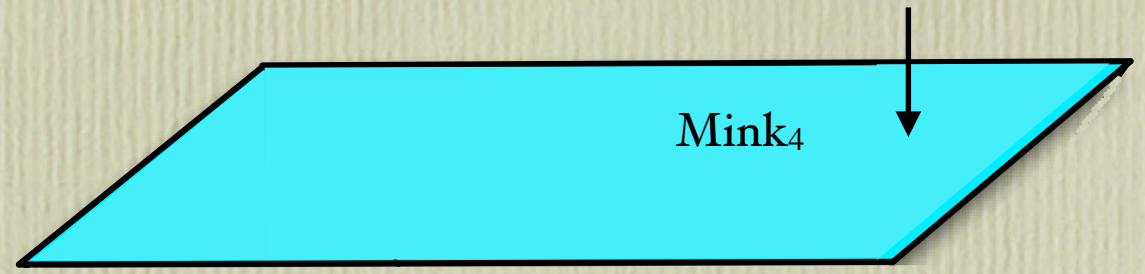
Ignore the expansion of the Universe
(no dynamical gravity)

- New holographic framework to include dynamical gravity
- Outlook (if time permits)
  - Baryogenesis
  - Primordial black holes
  - (P)Reheating
  - Thermal inflation

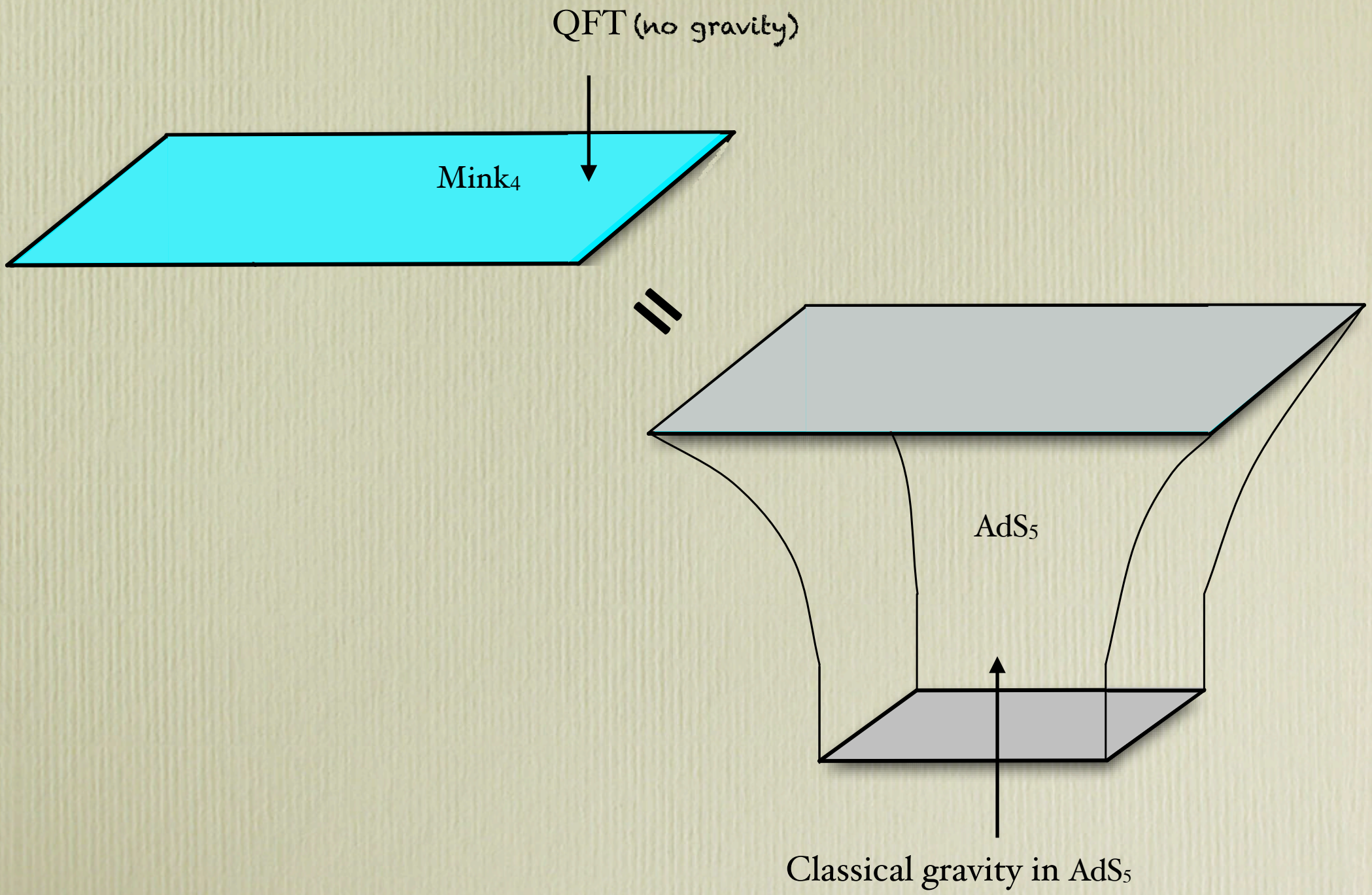
Holography

Holography

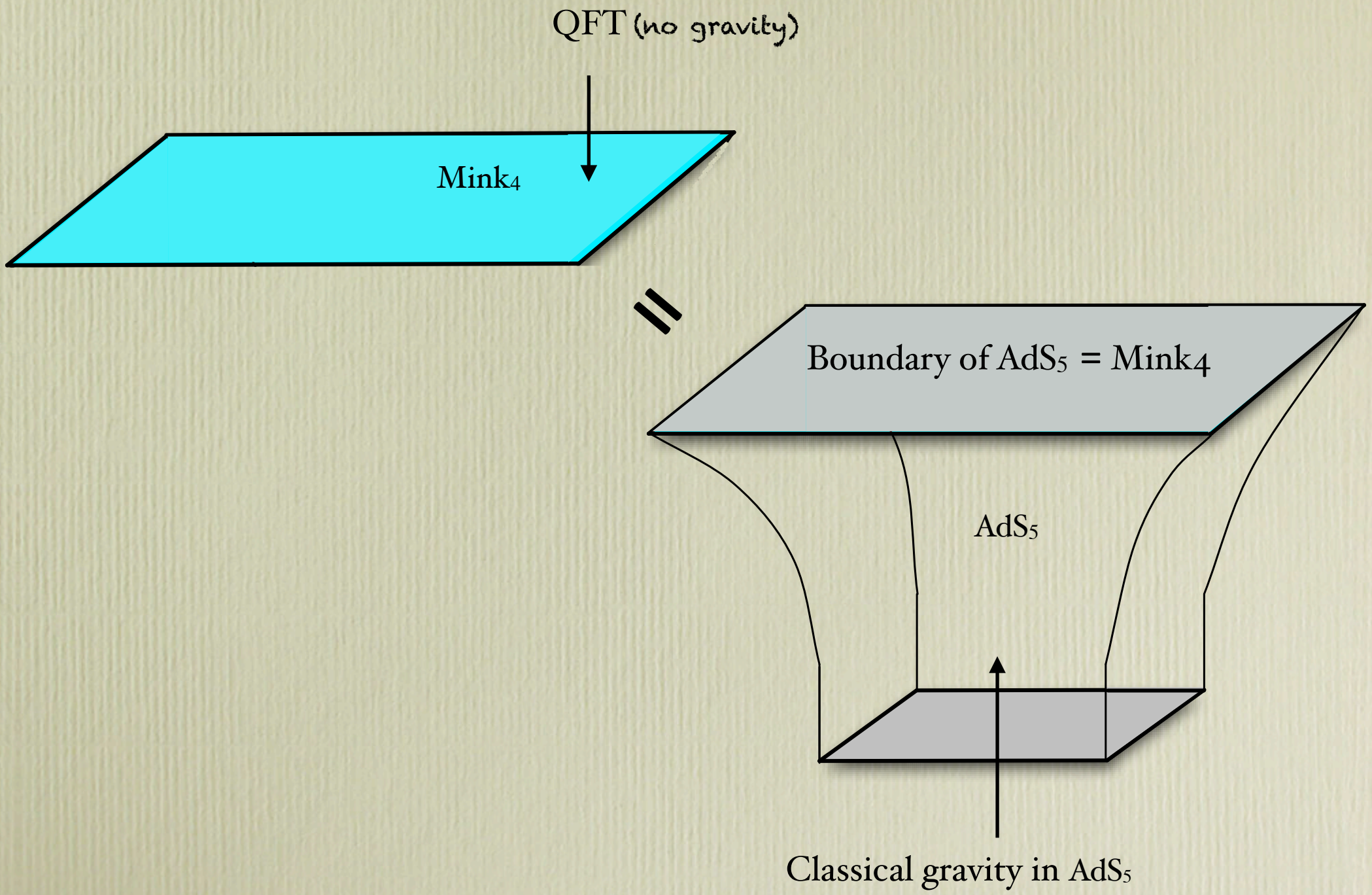
QFT (no gravity)



Holography

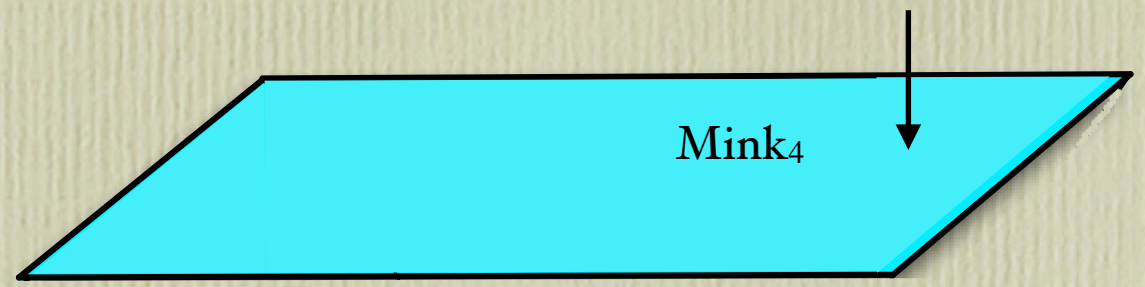


Holography

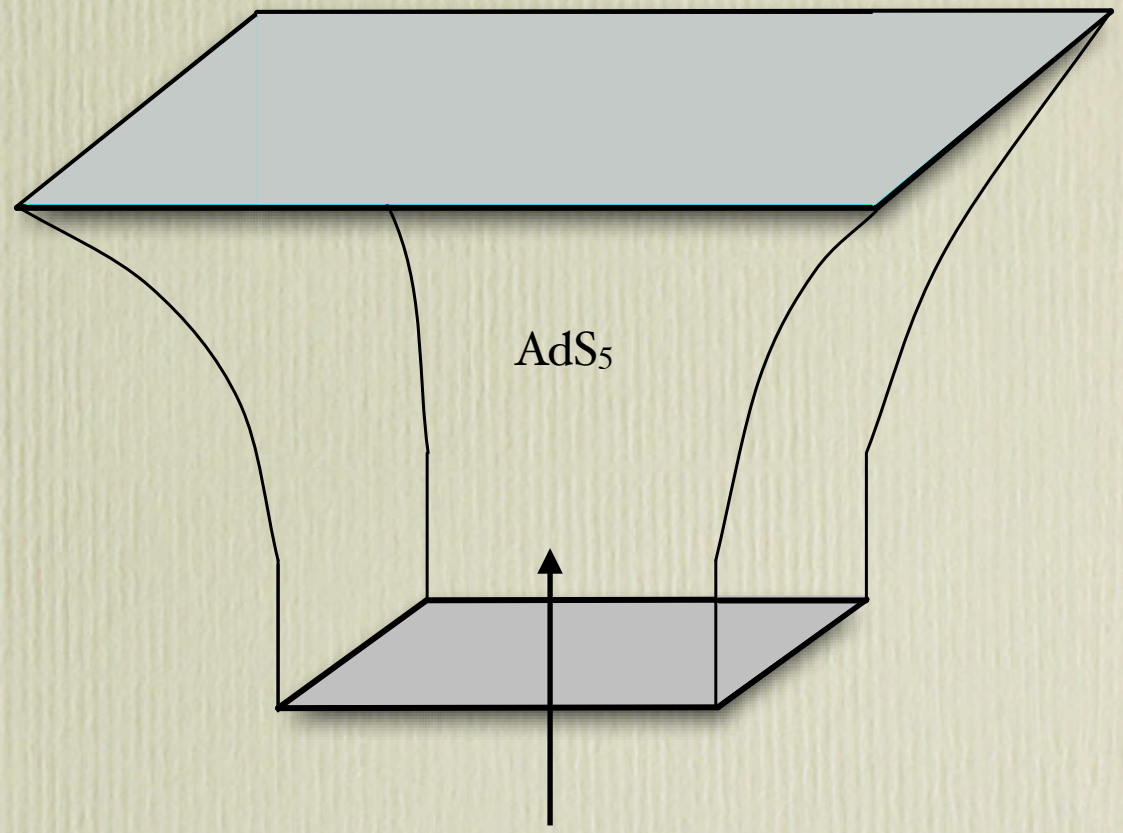

QFT (no gravity)
Mink4
=
Boundary of AdS5 = Mink4
AdS5
Classical gravity in AdS5

Holography

QFT (no gravity)

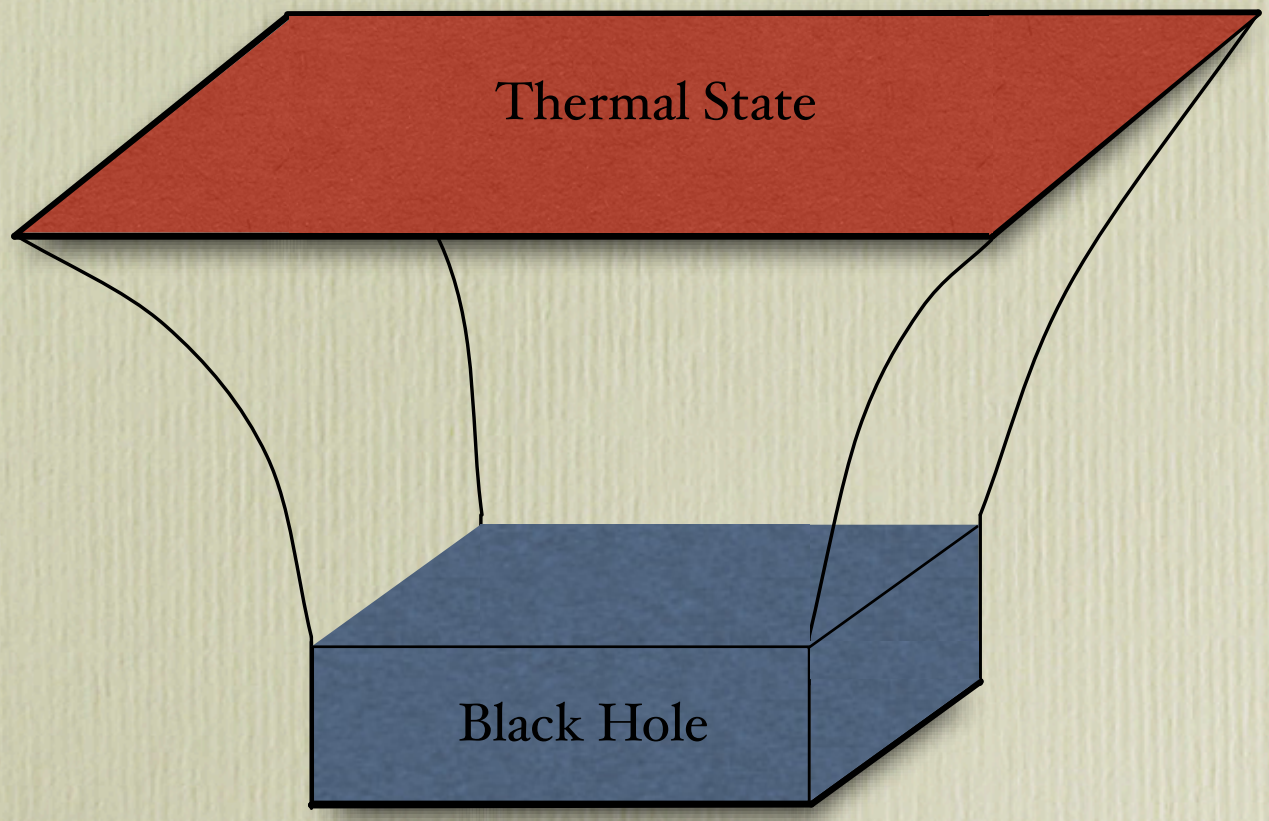


at the boundary of AdS_5

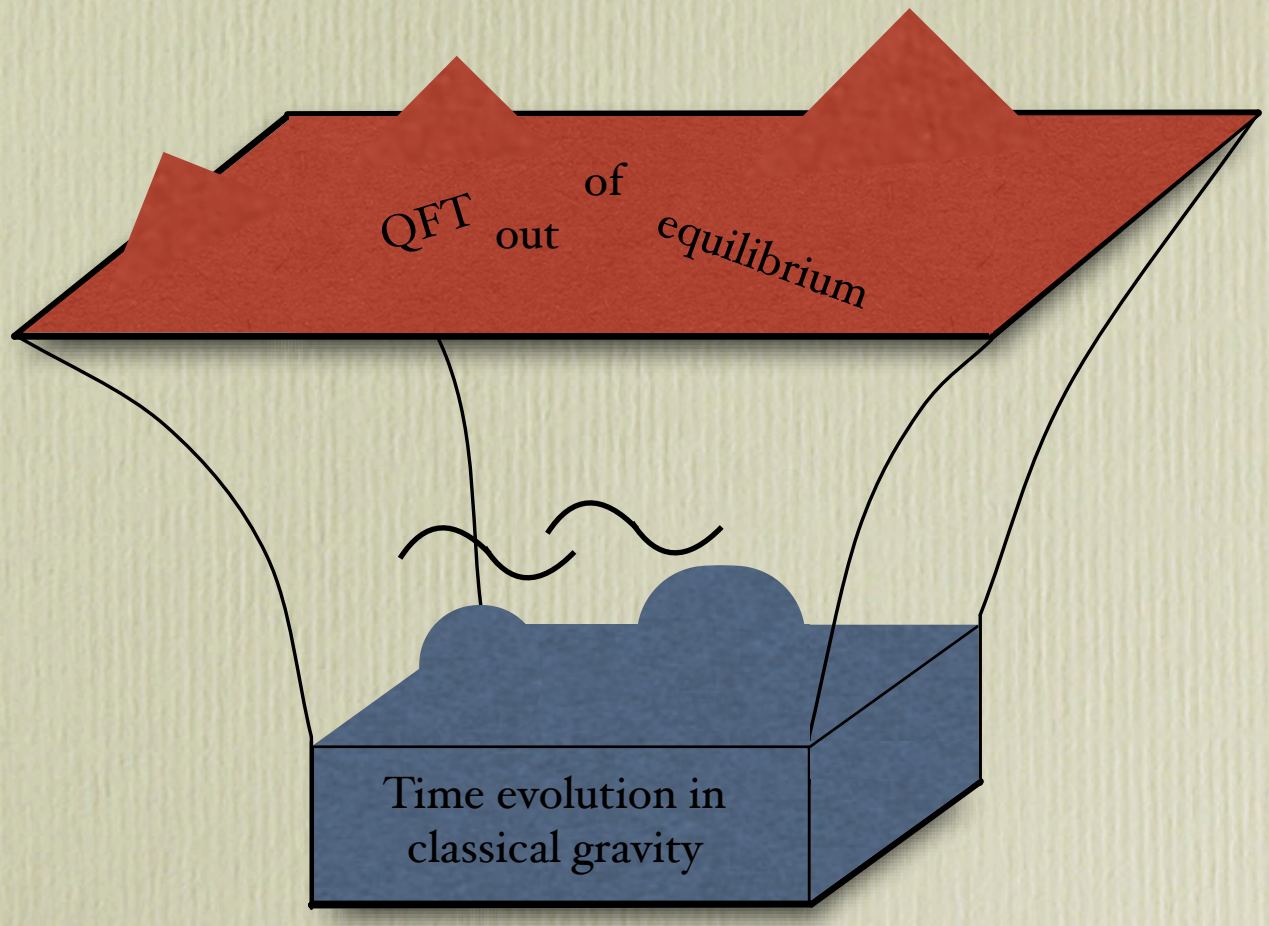


Classical gravity in AdS_5

Thermal physics = Black hole physics



The power of holography



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

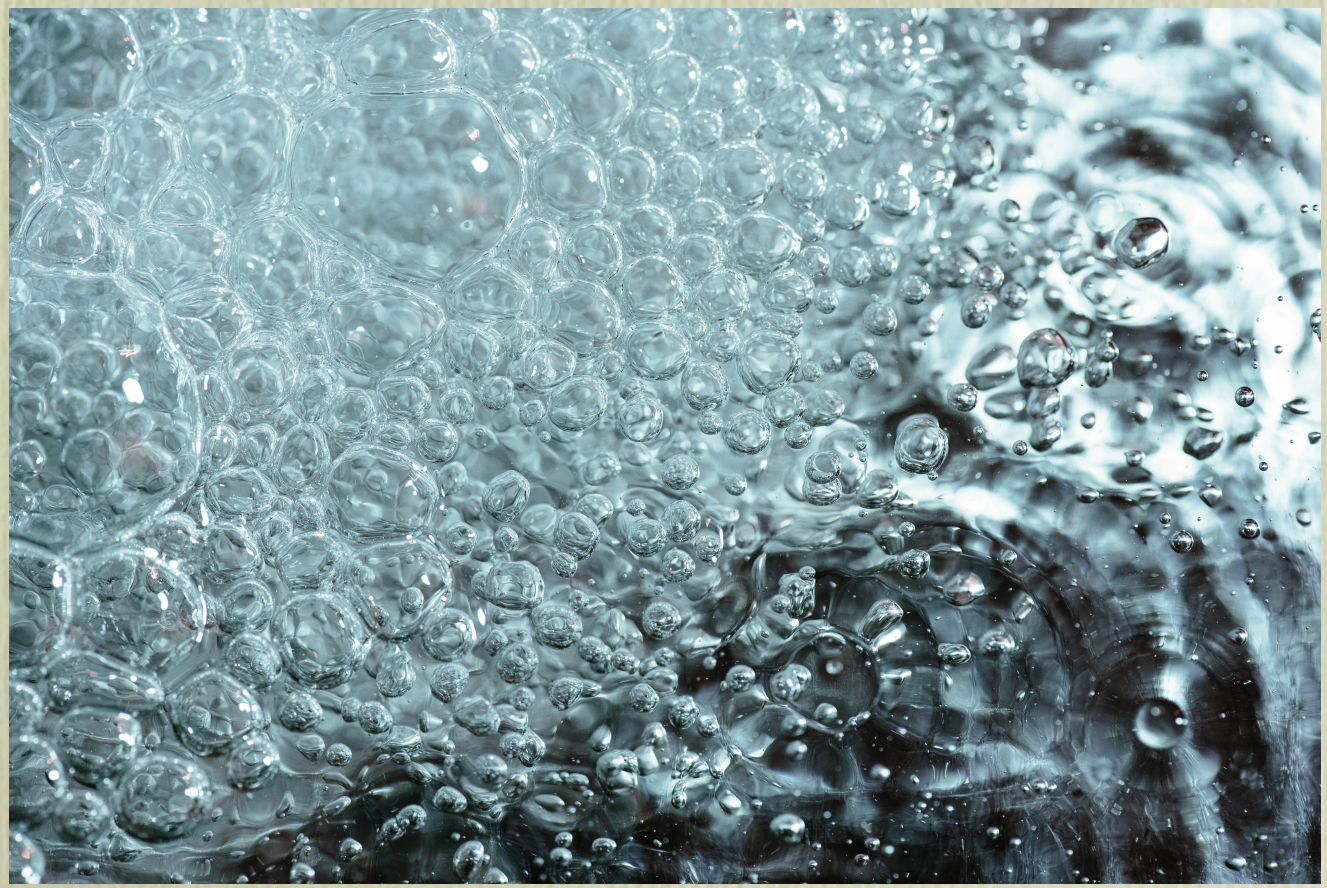
Disclaimer

- 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: Bubble Nucleation

Cosmological phase transitions

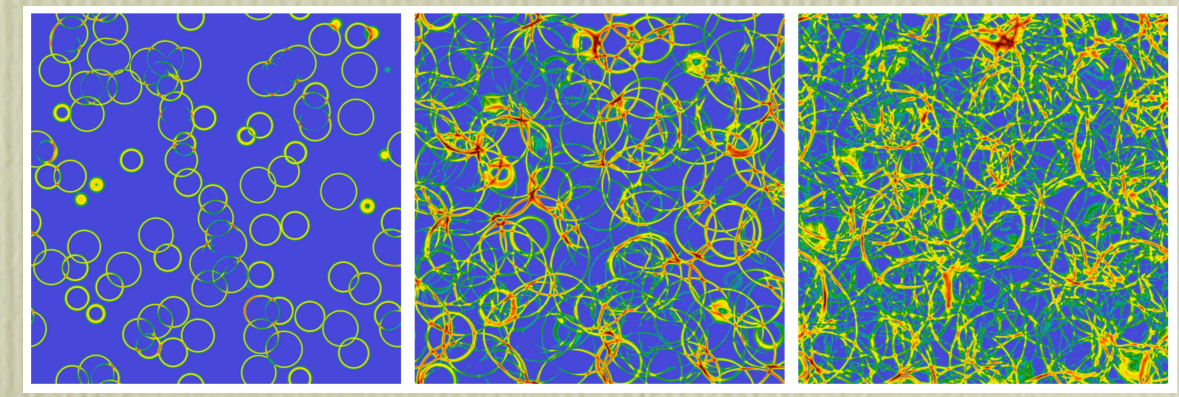
- First-order phase transitions are ubiquitous in Nature.
- They can proceed via the nucleation of bubbles (e.g. boiling water).

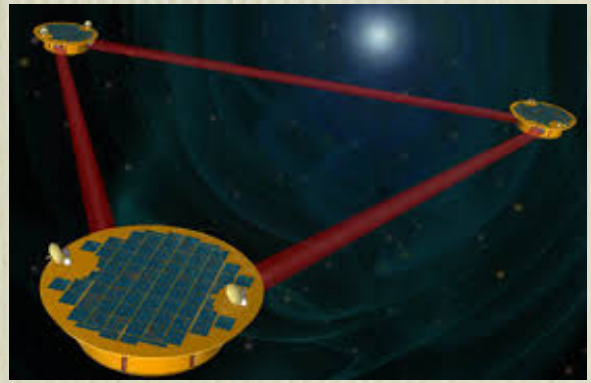


Cosmological phase transitions

- Do they occur in particle physics?
- Exciting: The Universe would have undergone it!
- Resulting bubbles could have produced GWs detectable by e.g. LISA.

Picture from Hindmarsh, Huber, Rummukainen & Weir '15





Cosmological phase transitions

- They do not happen within the Standard Model:
  - QCD transition is a crossover. Aoki, Endrodi, Fodor, Katz & Szabo ‘06
  - EW transition is a crossover. Kajantie, Laine, Rummukainen & Shaposhnikov ’96; Laine & Rummukainen ‘98; Rummukainen, Tsypin, Kajantie, Laine & Shaposhnikov ‘ 98

➡ The discovery of GWs from a cosmological phase transition would be the discovery of physics BSM.

Cosmological phase transitions

- In fact, the EW transition is 1-st order even in minimal extensions of the SM.

Carena, Quiros & Wagner ‘96
Delepine, Gerard, Felipe & Weyers’96
Laine & Rummukainen ‘98
Huber & Schmidt, ‘01
Grojean, Servant & Wells, ’04
Huber, Konstandin, Prokopec & Schmidt ’06
Profumo, Ramsey-Musolf & Shaughnessy ‘07
Barger, Langacker, McCaskey, Ramsey-Musolf & Shaughnessy ’07
Laine, Nardini & Rummukainen ’12
Dorsch, Huber & No ‘13
Damgaard, Haarr, O’Connell & Tranberg ‘15

- And the signal could be seen at LISA.

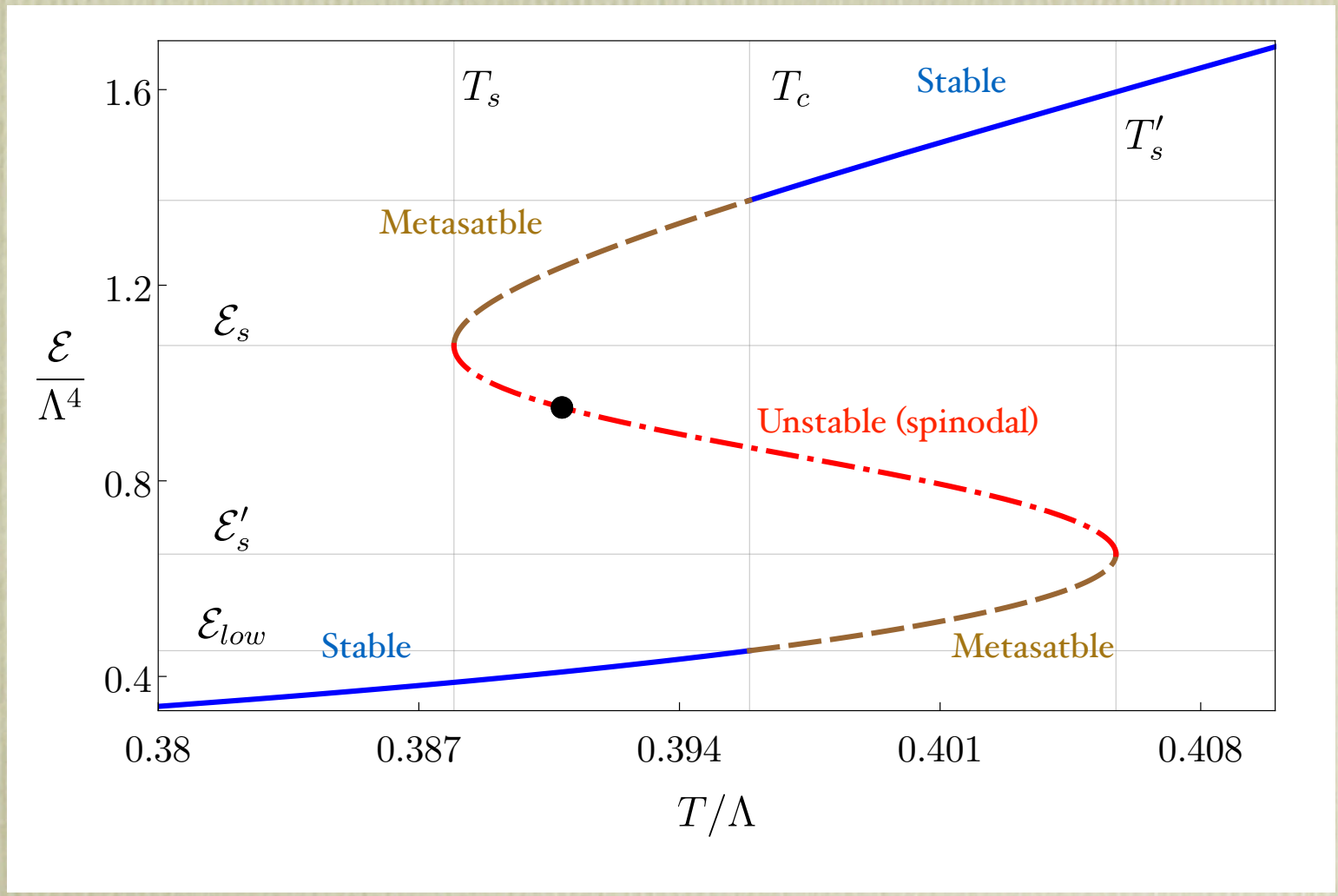
- For this reason a lot of work has been devoted to this case.

Cosmological phase transitions

- Today I would like to broaden the focus and keep in mind that:

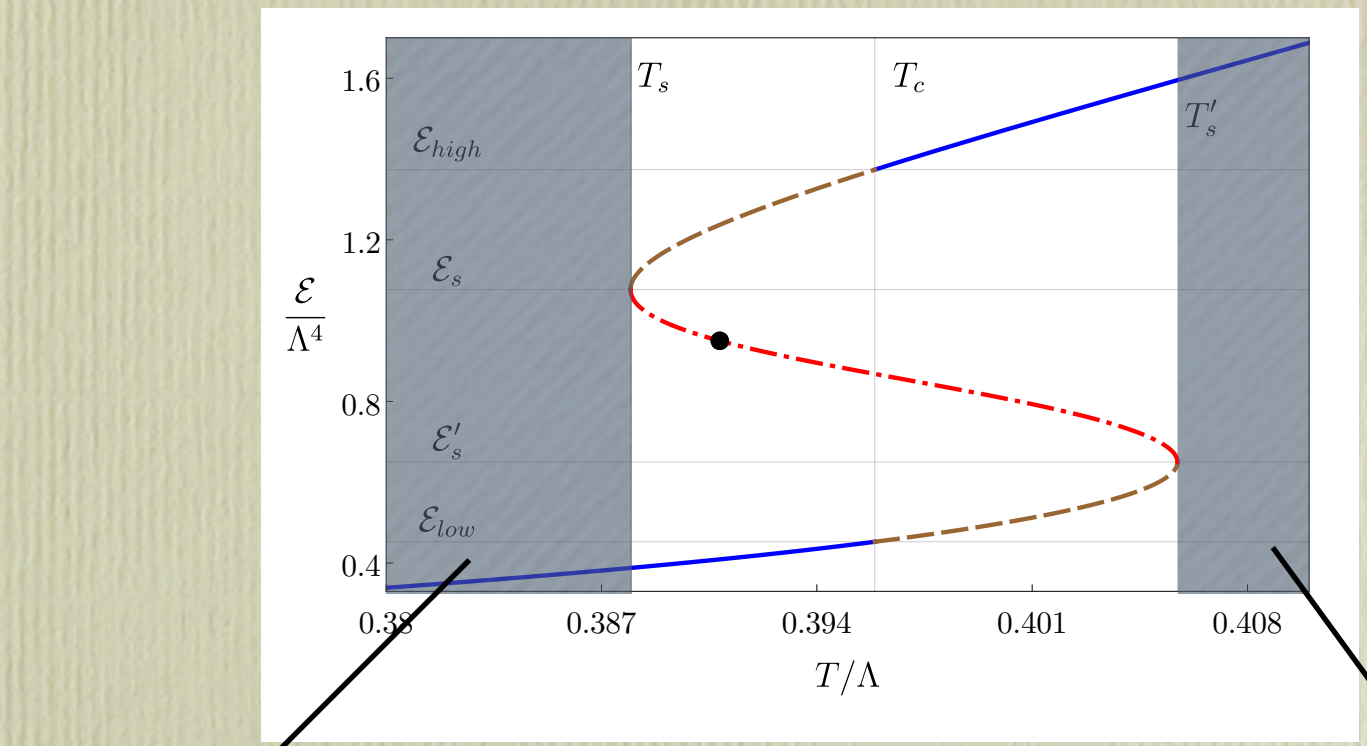
  - Phase transition could take place at $T \neq T_{EW}$
  - Phase transition could take place in a dark sector with $T \neq T_{SM}$

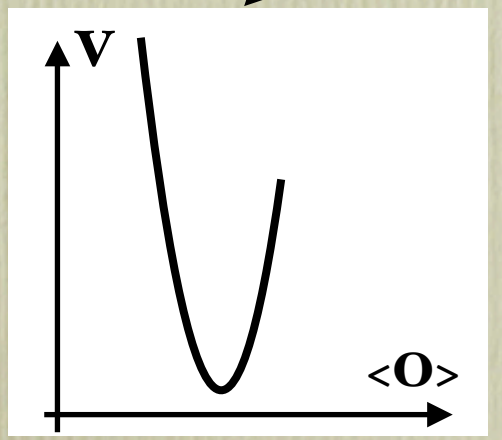
First-order phase transition

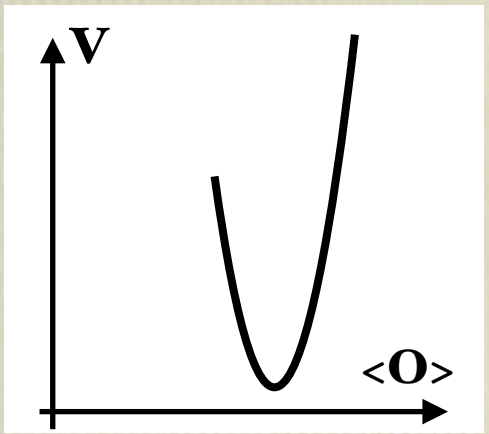


First-order phase transition

- In terms of an effective potential:

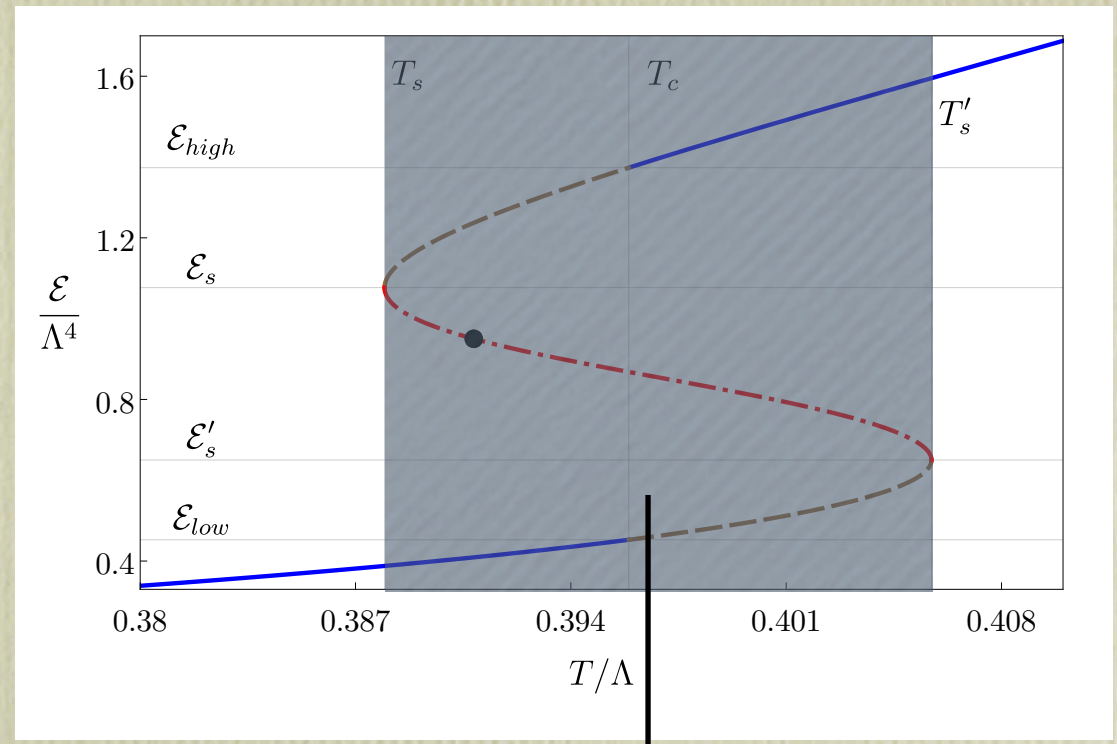


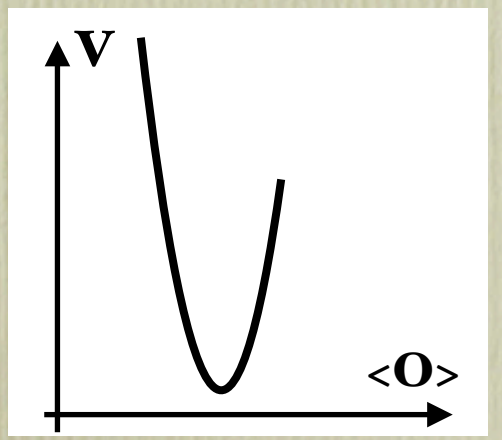


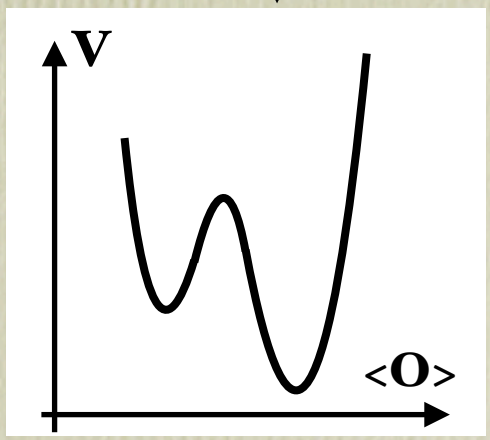


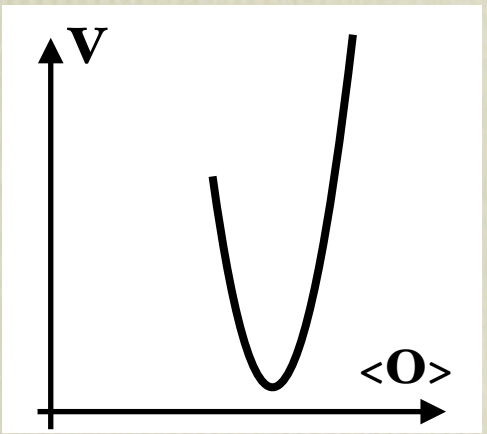
First-order phase transition

- In terms of an effective potential:

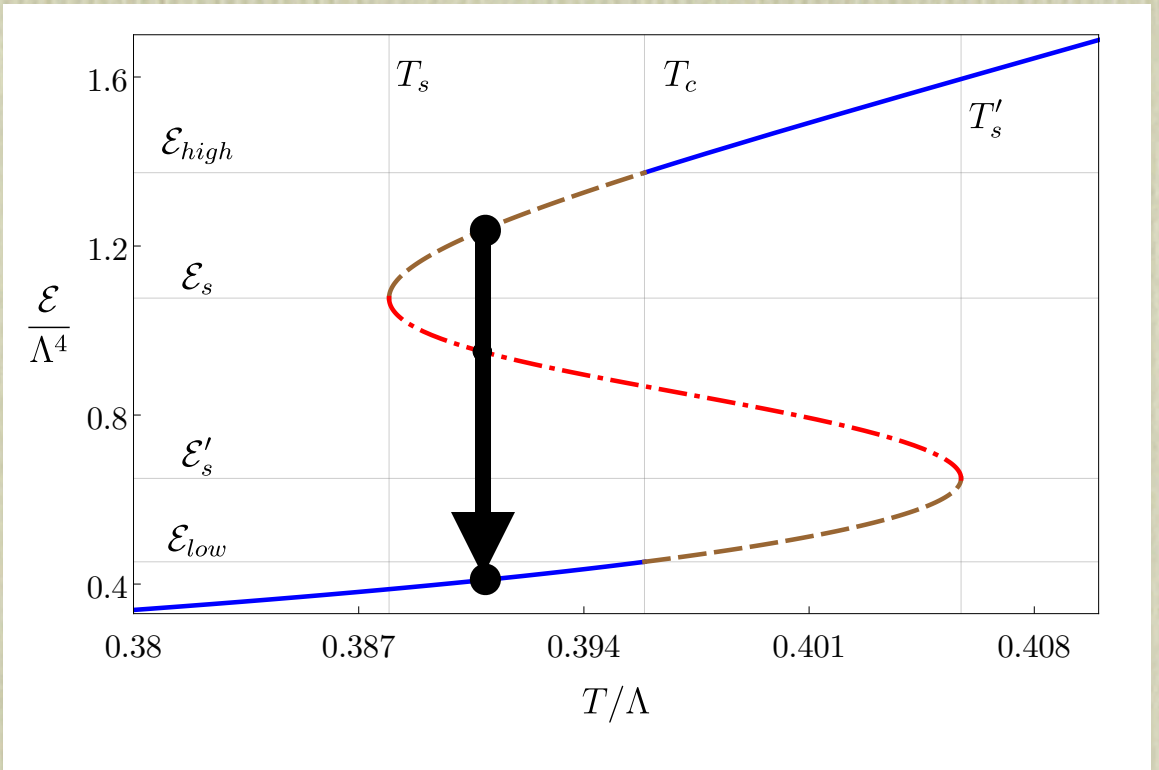


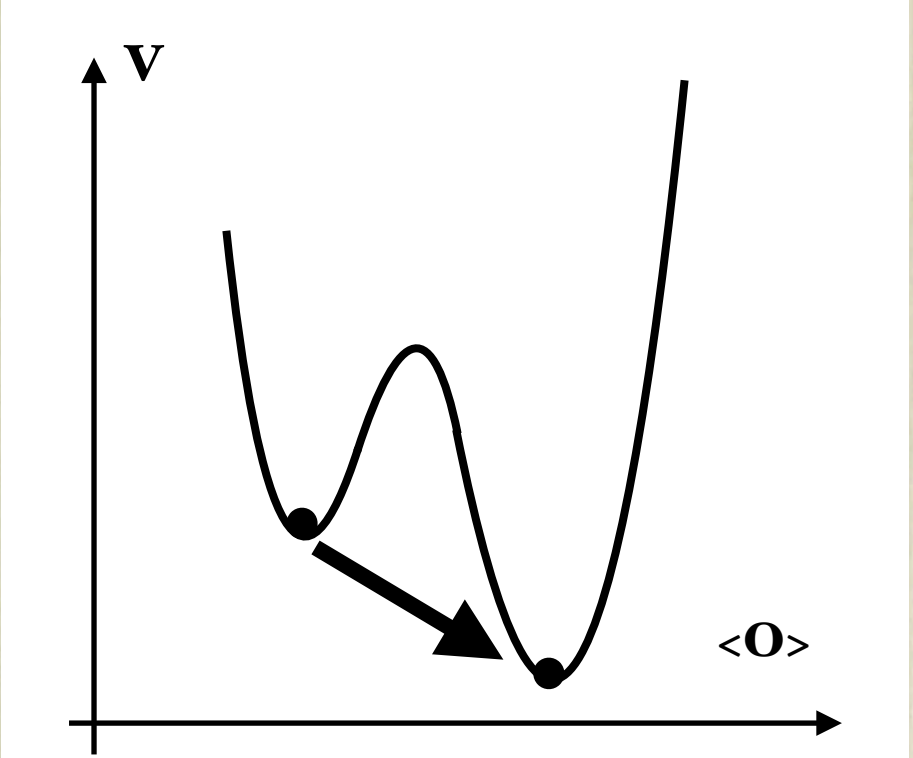






Transition via bubble nucleation



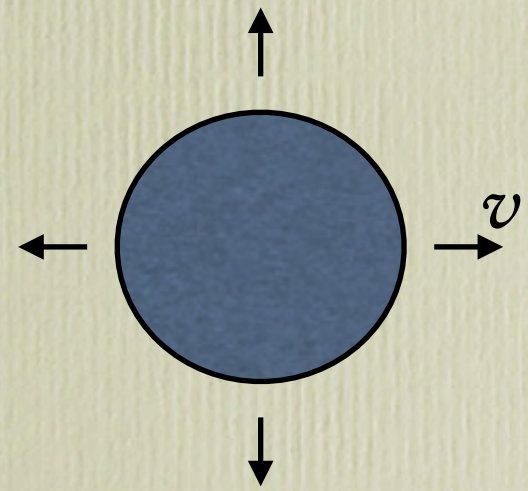


Cosmological phase transitions

- Once bubbles are nucleated, subsequent dynamics produces GWs.
- 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.

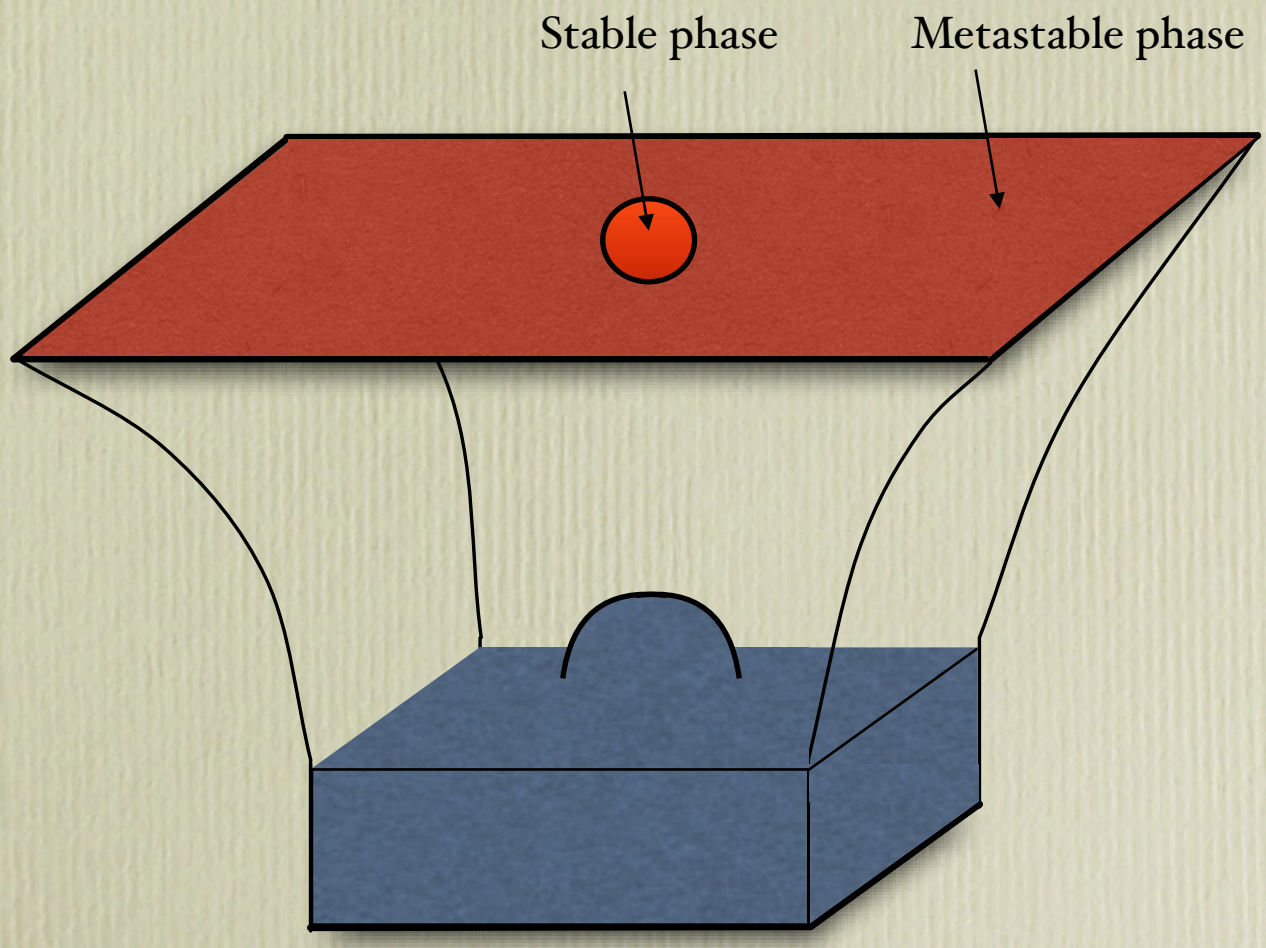
Moore & Prokopec '95
Bodeker & Moore '17
Höche, Kozaczuk, Long, Turner & Y. Wang '20

- But it can be computed in holographic models.



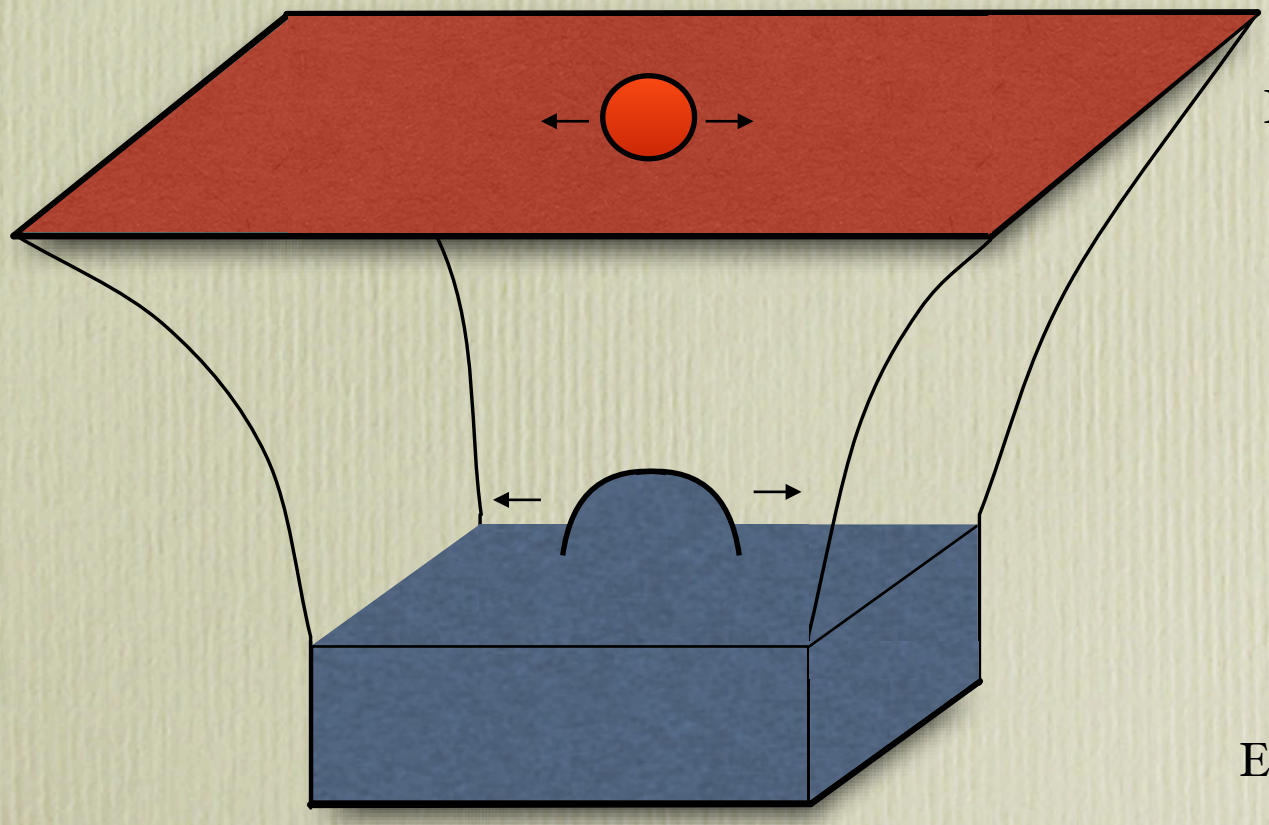
Strategy

- Set up initial conditions...



Strategy

- Set up initial conditions… and let it go.

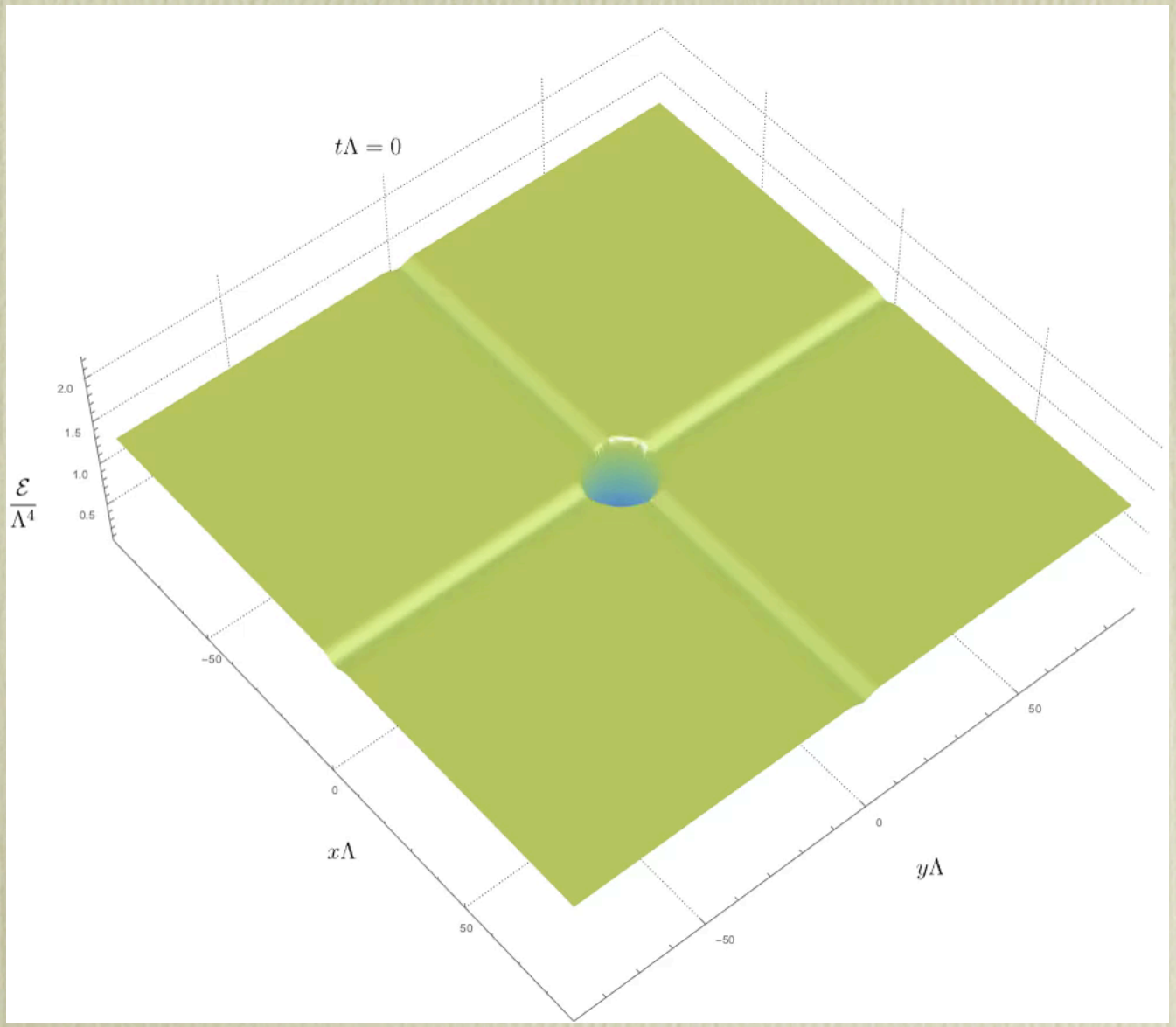


Read off boundary
stress tensor

Solve classical
Einstein equations

Bubble expansion

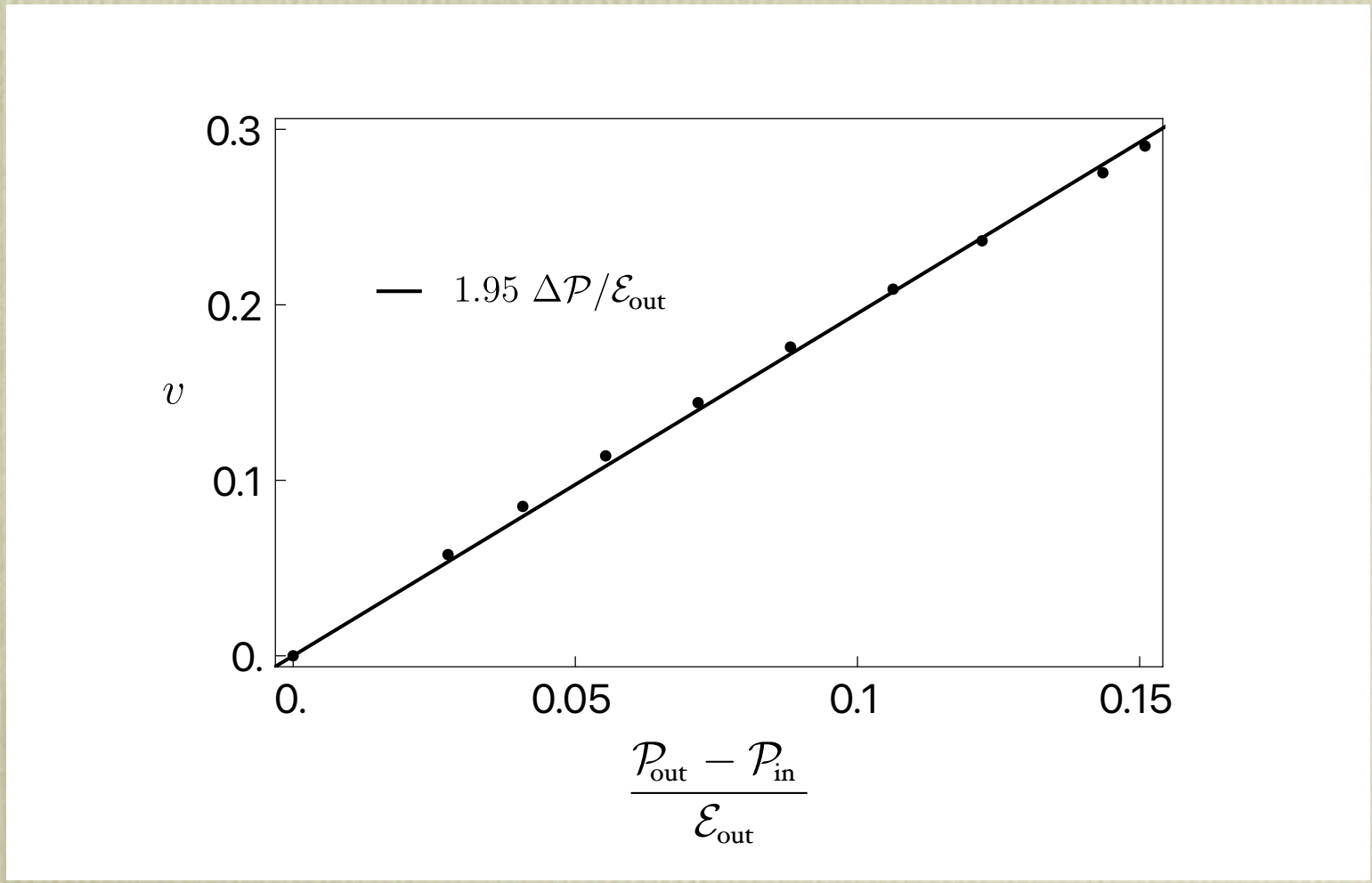
Bea, Casalderrey, Giannakopoulos, DM, Sanchez-Garitaonandia & Zilhao '21
Bigazzi, Caddeo, Canneti & Cotrone '21
Bea, Casalderrey, Giannakopoulos, Jansen, DM, Sanchez-Garitaonandia & Zilhao '22



Bubble wall velocity

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

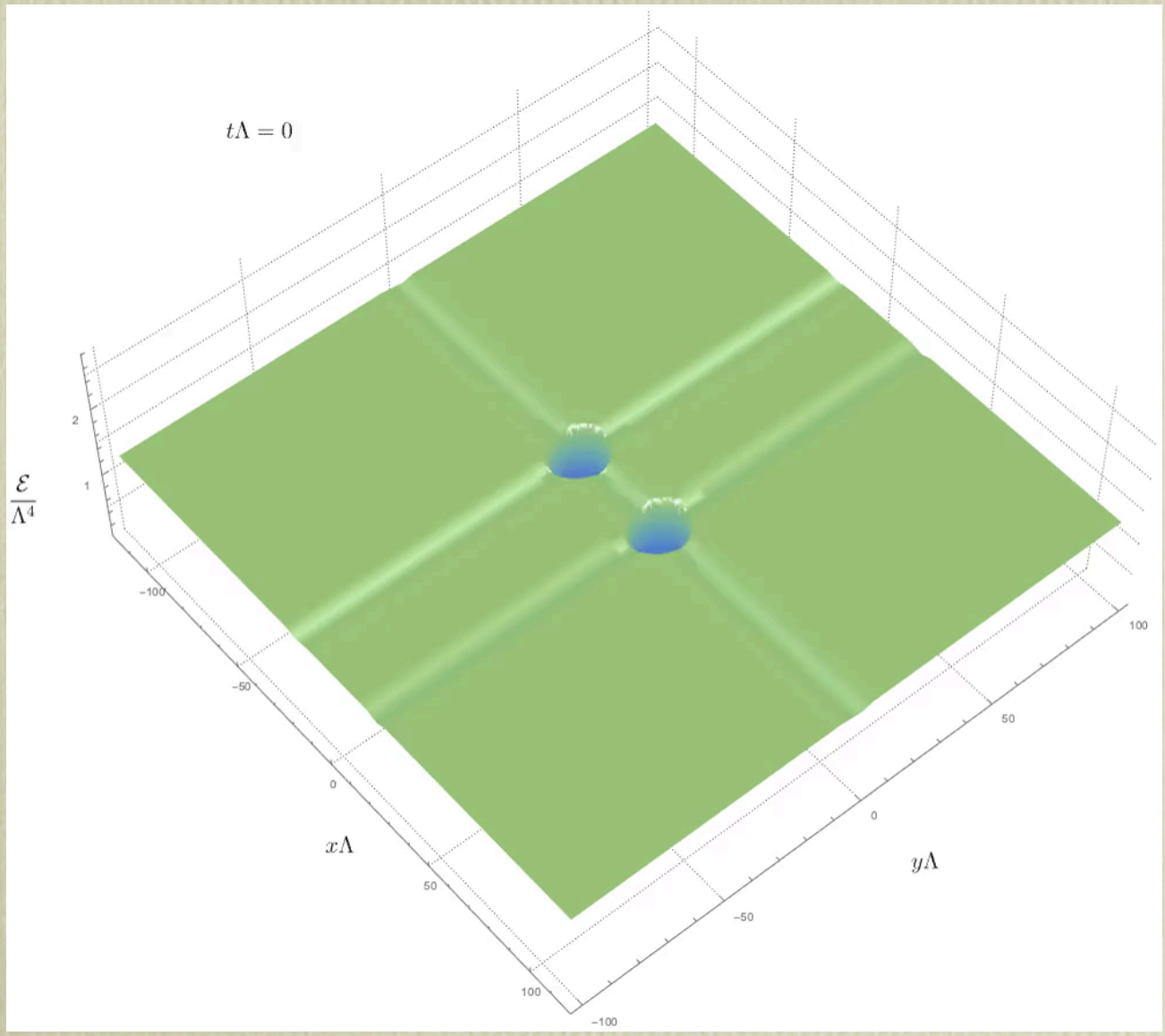
- First calculation of bubble wall at strong coupling (*preliminary*):



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)

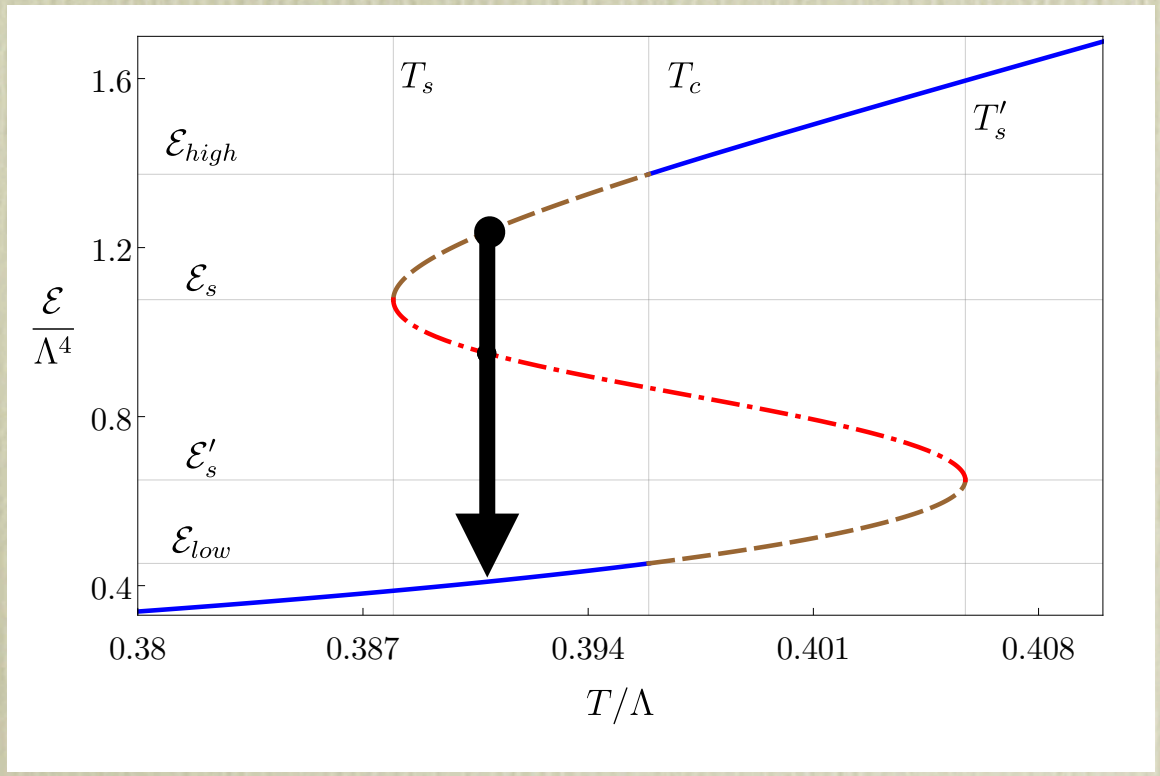
- Computing the GW spectrum requires considering collisions of bubbles.
- In this description all the post-nucleation dynamics is included:
  - Bubble expansion.
  - Bubble collisions.
  - Sound modes.
  - Turbulence.
  - Etc.
- Conventional treatment includes some assumptions + approximations.
- Holography allows for a complete reformulation of the problem.
- Discovery of new effects + verification of assumptions/approximations.

Cosmological Phase Transitions: Spinodal Instability

Spinodal gravitational waves

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

- If #d.o.f. is large then nucleation is suppressed.

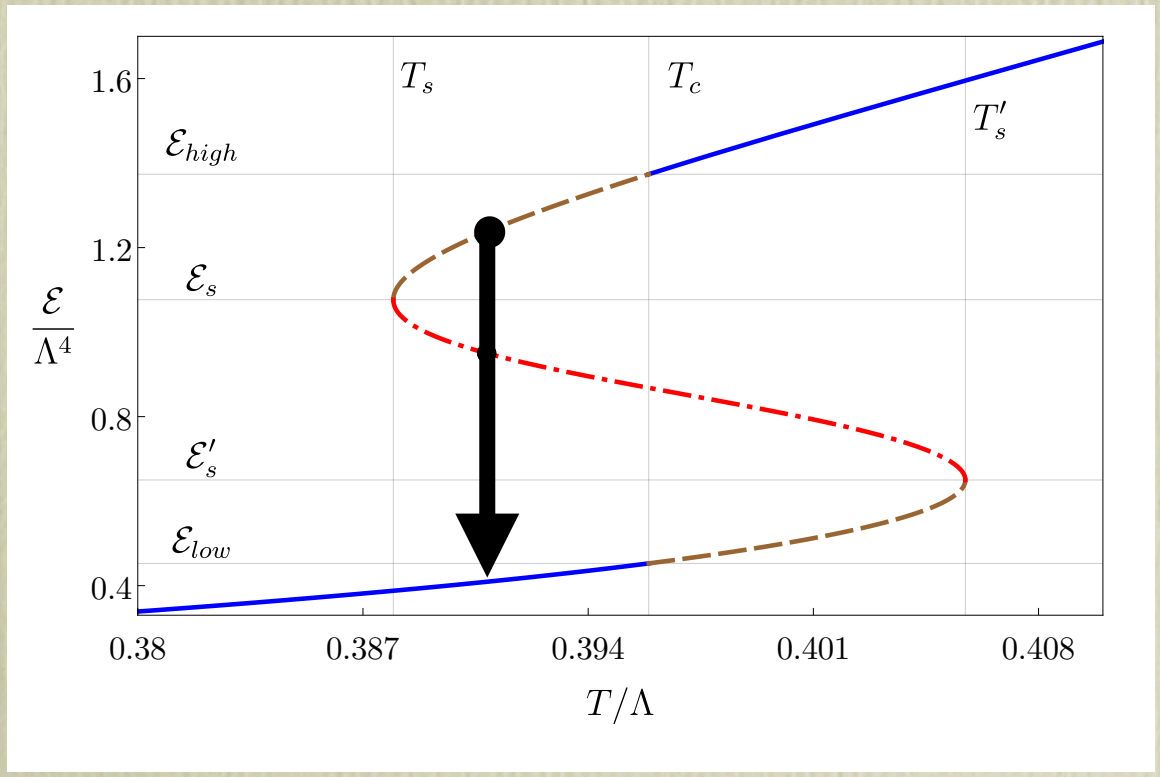


Spinodal gravitational waves

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

- If #d.o.f. is large then nucleation is suppressed.
- For example, in large-N gauge theory:

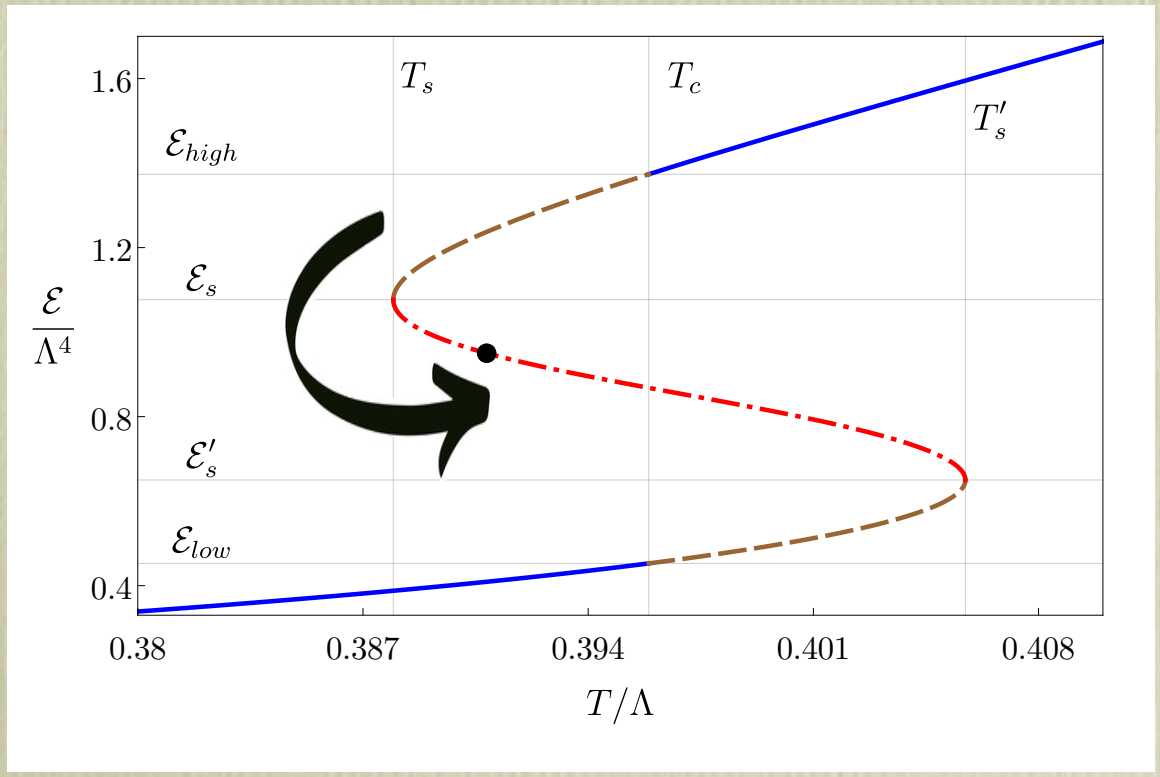
$$P \sim e^{-S_{critical\ bubble}} \sim e^{-N^2}$$



Spinodal gravitational waves

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

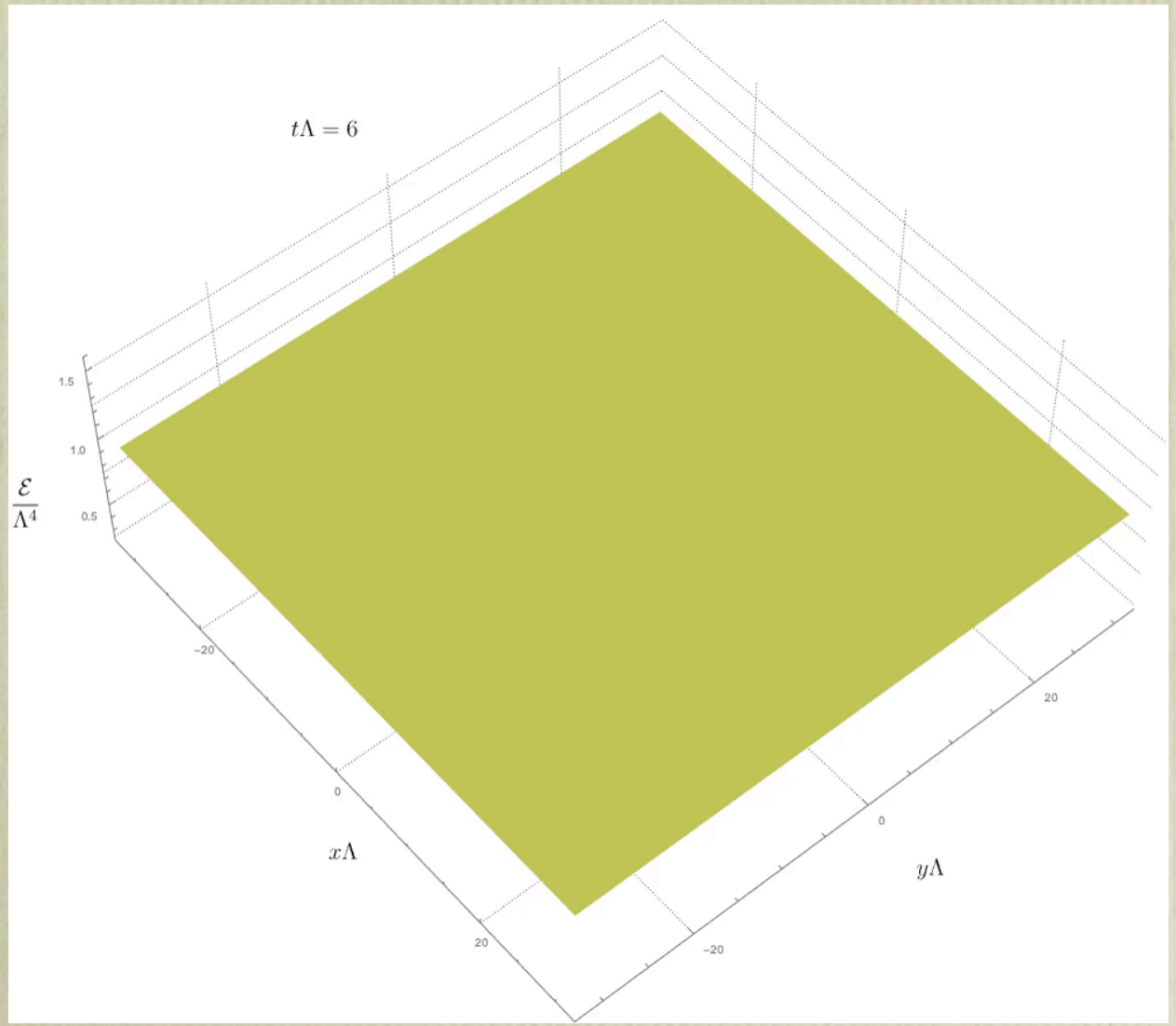
- Under these circumstances the Universe enters the spinodal region.
- In this phase small fluctuations grow exponentially.



Spinodal gravitational waves

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

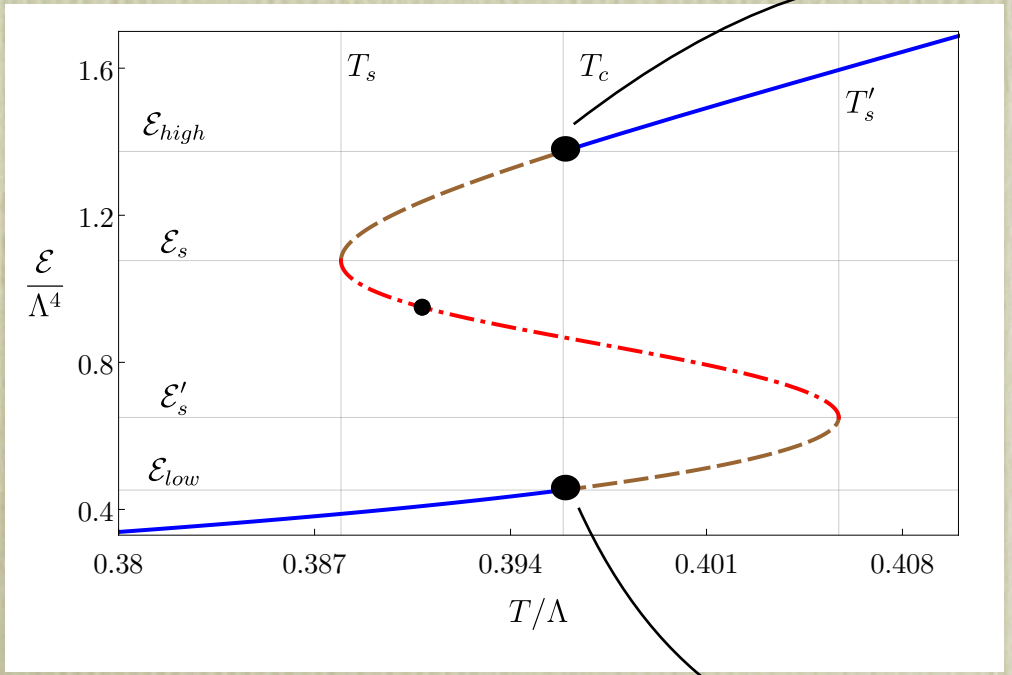
- Holography can compute the evolution if we *ignore the expansion of the Universe*:

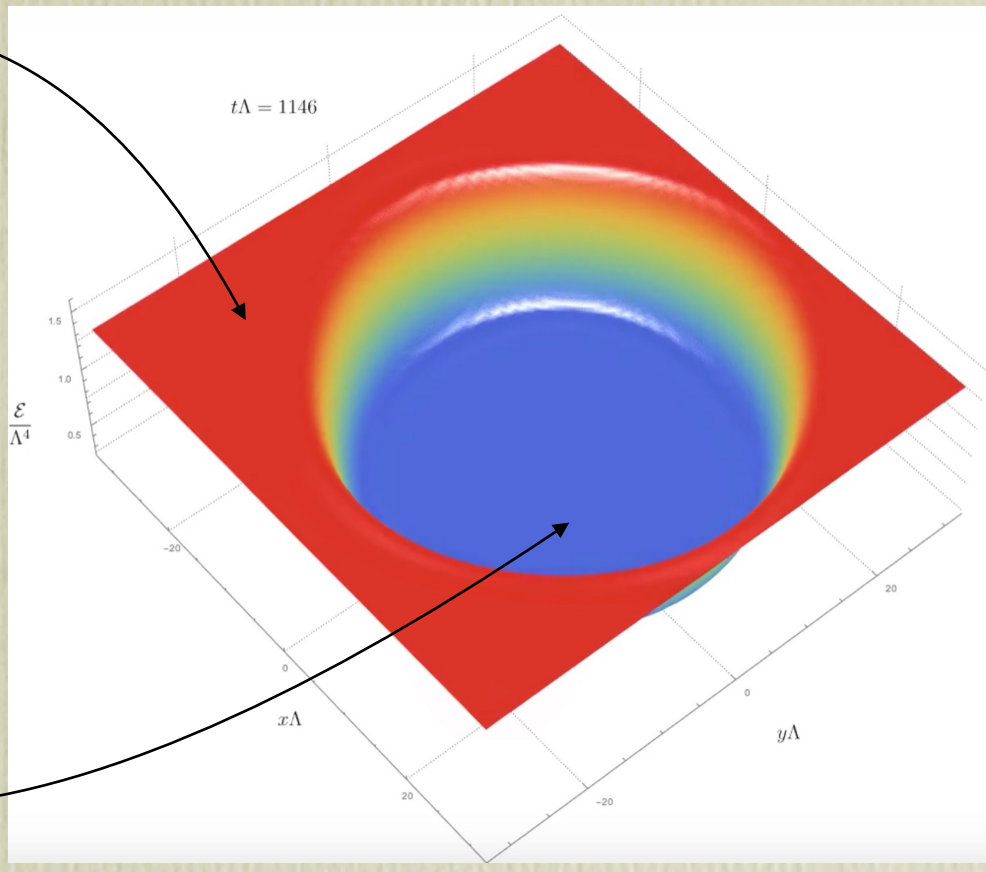


Spinodal gravitational waves

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

- Final state in fixed box with constant total energy is phase separated state at constant $T=T_c$:

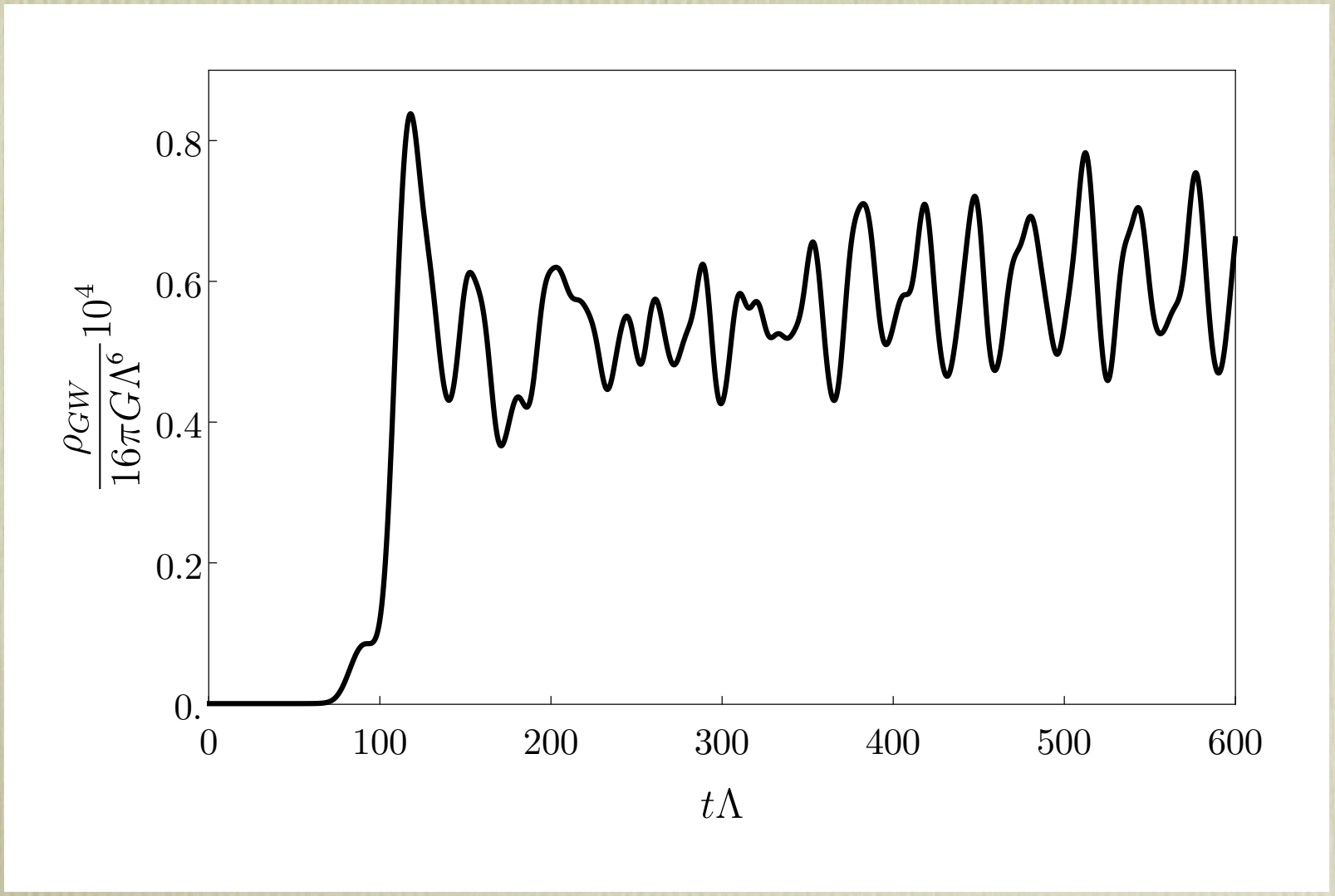




Spinodal gravitational waves

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

- Fast redistribution of energy produces GWs.



Spinodal gravitational waves

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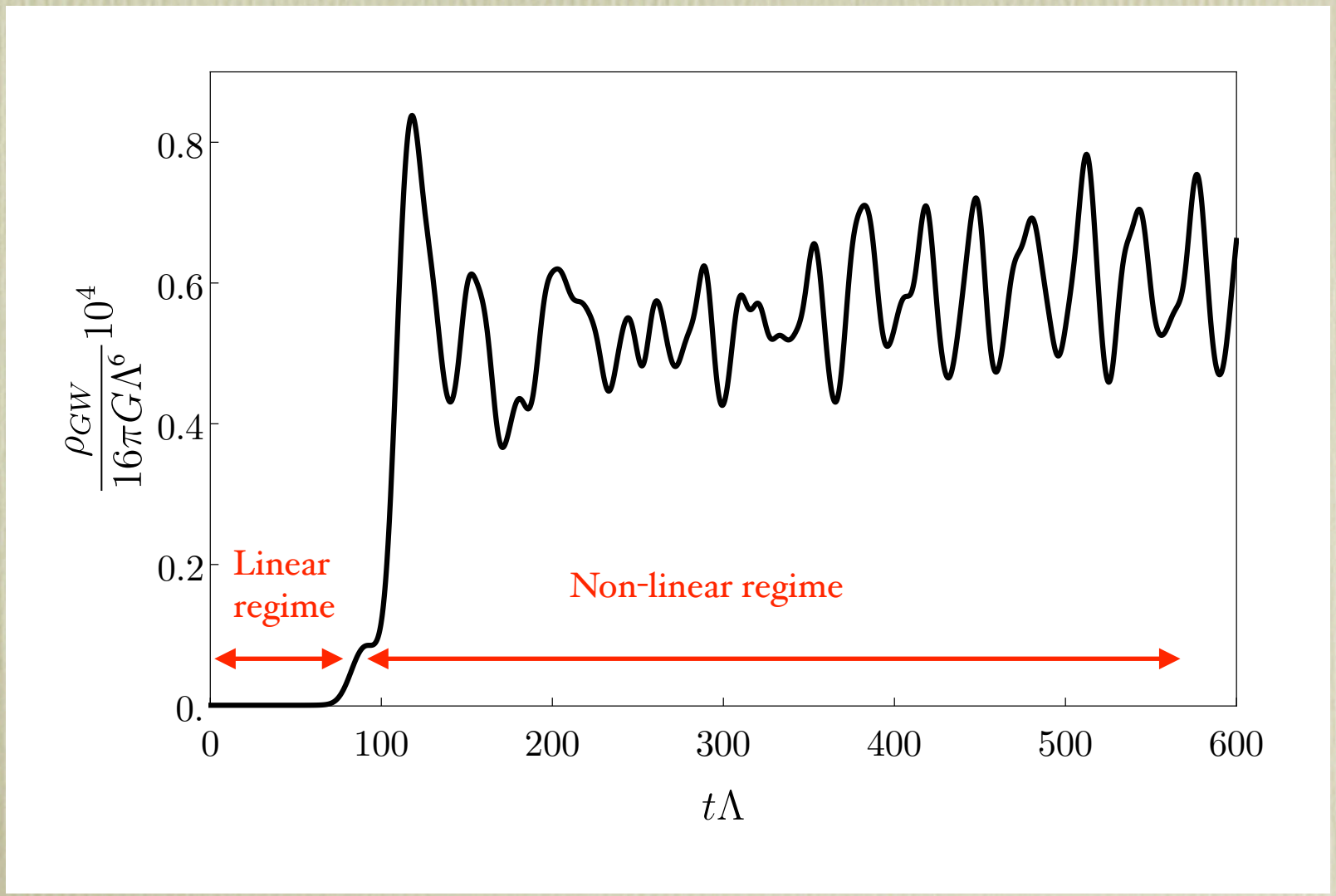


Spinodal gravitational waves

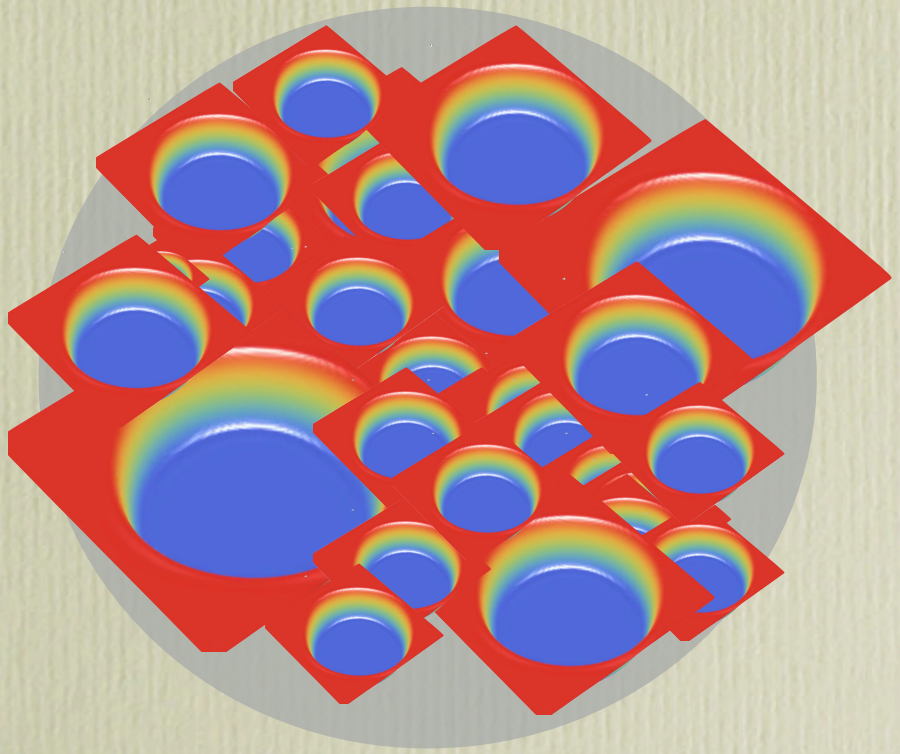
Bea, Casalderrey, Giannakopoulos, Jansen, DM, Sanchez-Garitaonandia & Zilhao (in progress)

- Time and length scales are parametrically shorter than 1/H.

Spinodal gravitational waves

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

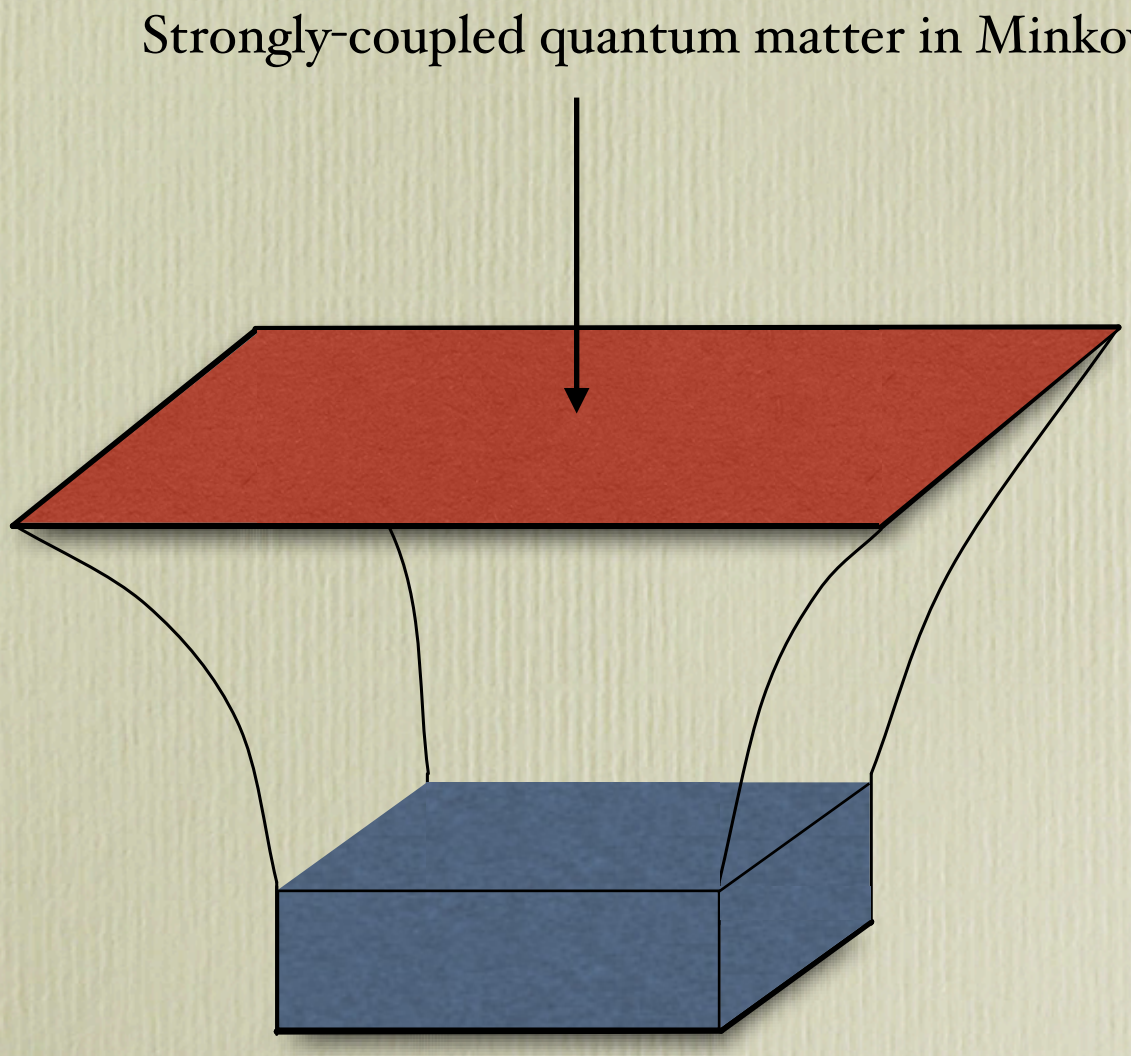
- Time and length scales are parametrically shorter than 1/H.
- The result is a very inhomogeneous state within a Hubble patch.
- Subsequent dynamics is very long and very non-linear.



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

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

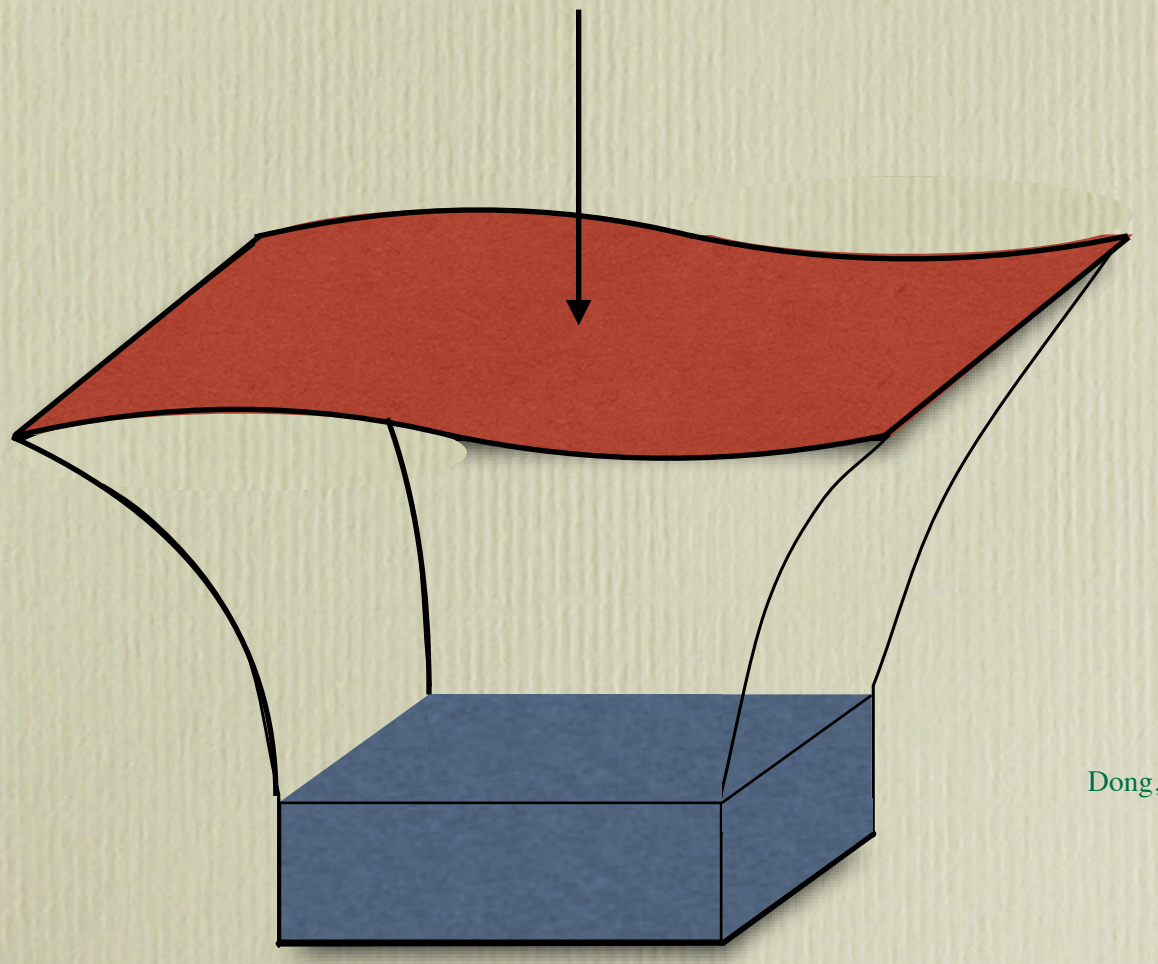
- Cosmological phase transitions
- Cosmological defects (cosmic strings, etc)
- Neutron star mergers
- (P)reheating
- Primordial black holes
- Etc

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
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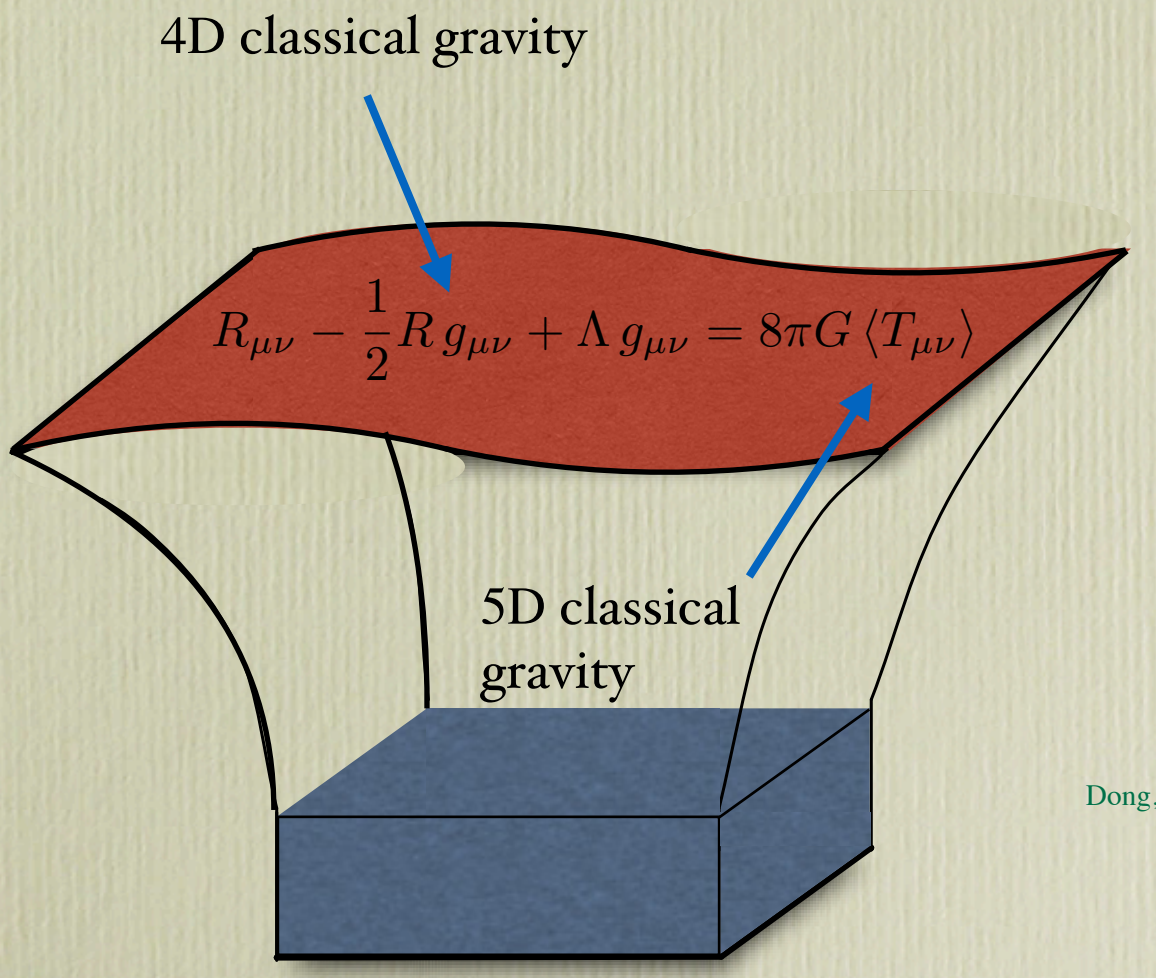
Buchel '16
Buchel '17
Emparan, Frassino & Way '20
Ghosh, Kiritsis, Nitti & Witkowski '20

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
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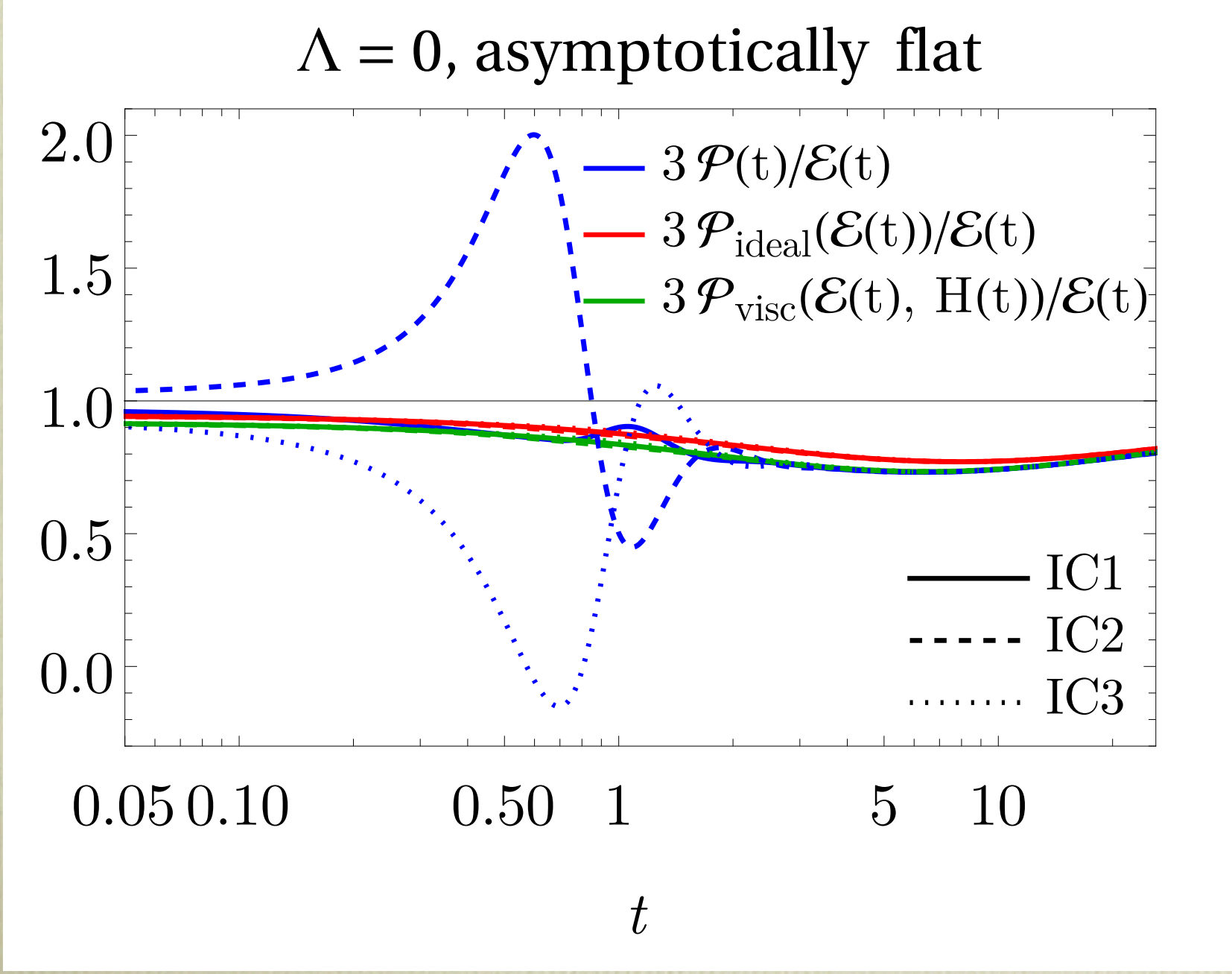
Example: Far-from-equilibrium FLRW Cosmology

Casalderrey, Ecker, DM & van der Schee '21



Outlook

Baryogenesis

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

- Generating matter-antimatter asymmetry requires Sakharov's conditions, which include departure from thermal equilibrium.

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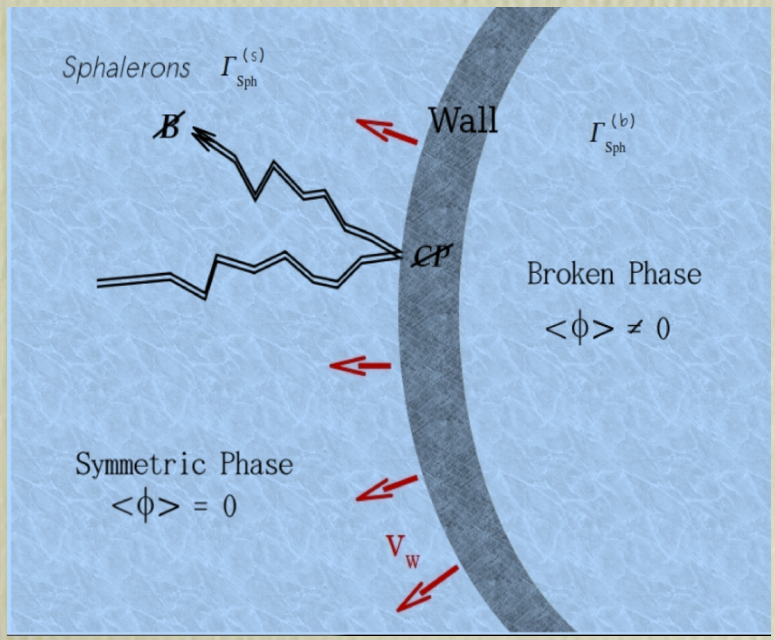
- Bubble wall provides one mechanism.
- Holography allows us to study this non-perturbatively.



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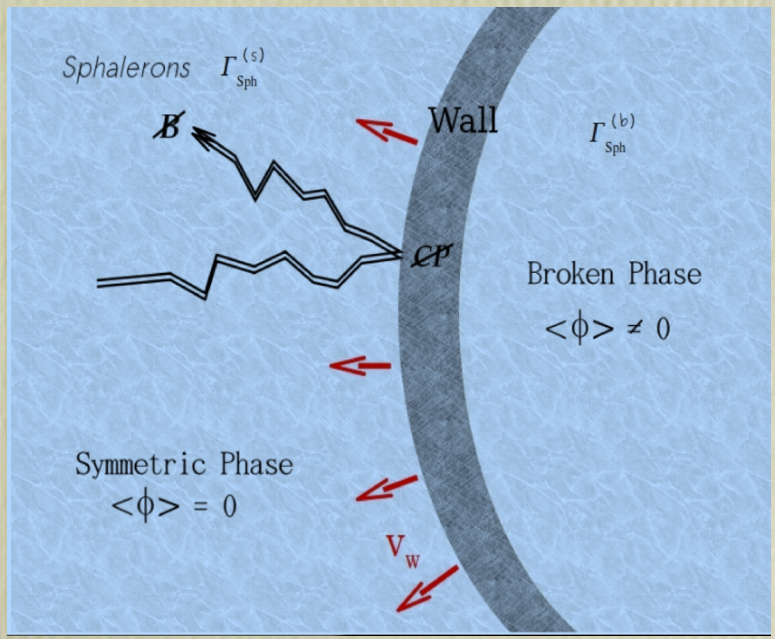
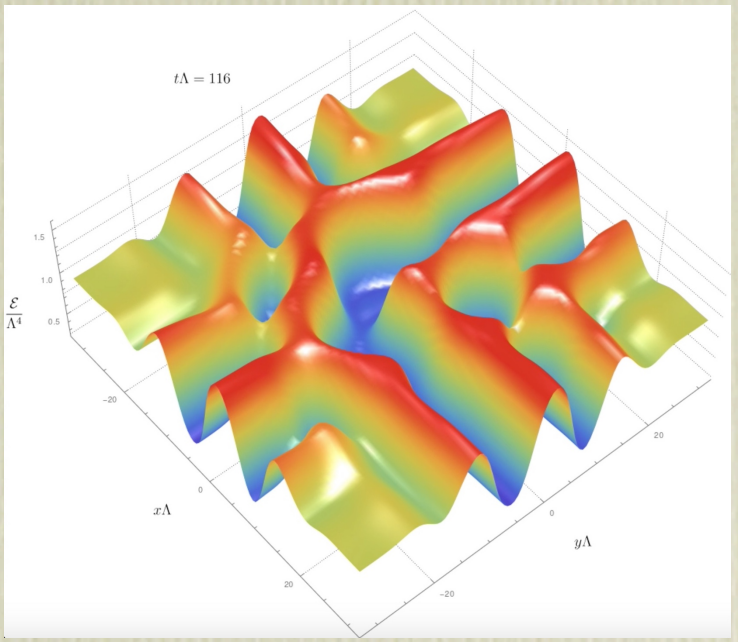
Bea, Casalderrey, Giannakopoulos, Jansen, DM, Sanchez-Garitaonandia & Zilhao (in progress)

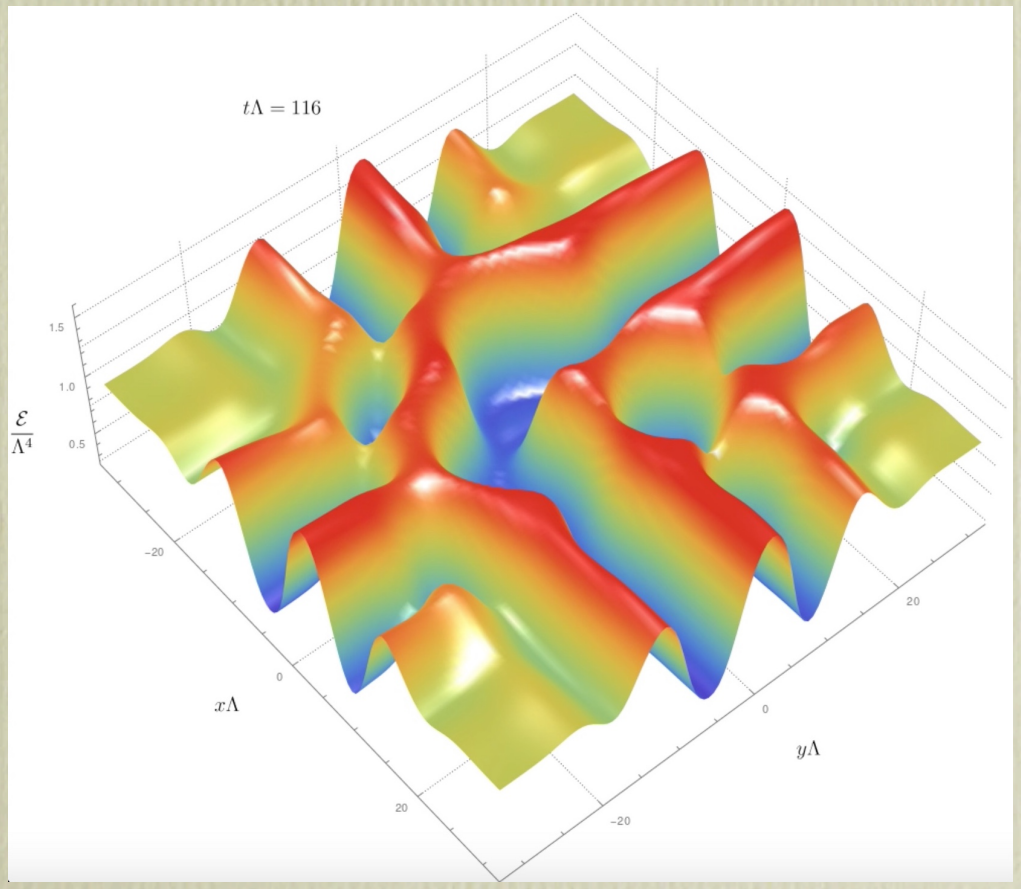
- Generating matter-antimatter asymmetry requires Sakharov's conditions, which include departure from thermal equilibrium.
- Bubble wall provides one mechanism.
- Holography allows us to study this non-perturbatively.
- The spinodal instability provides a new mechanism.





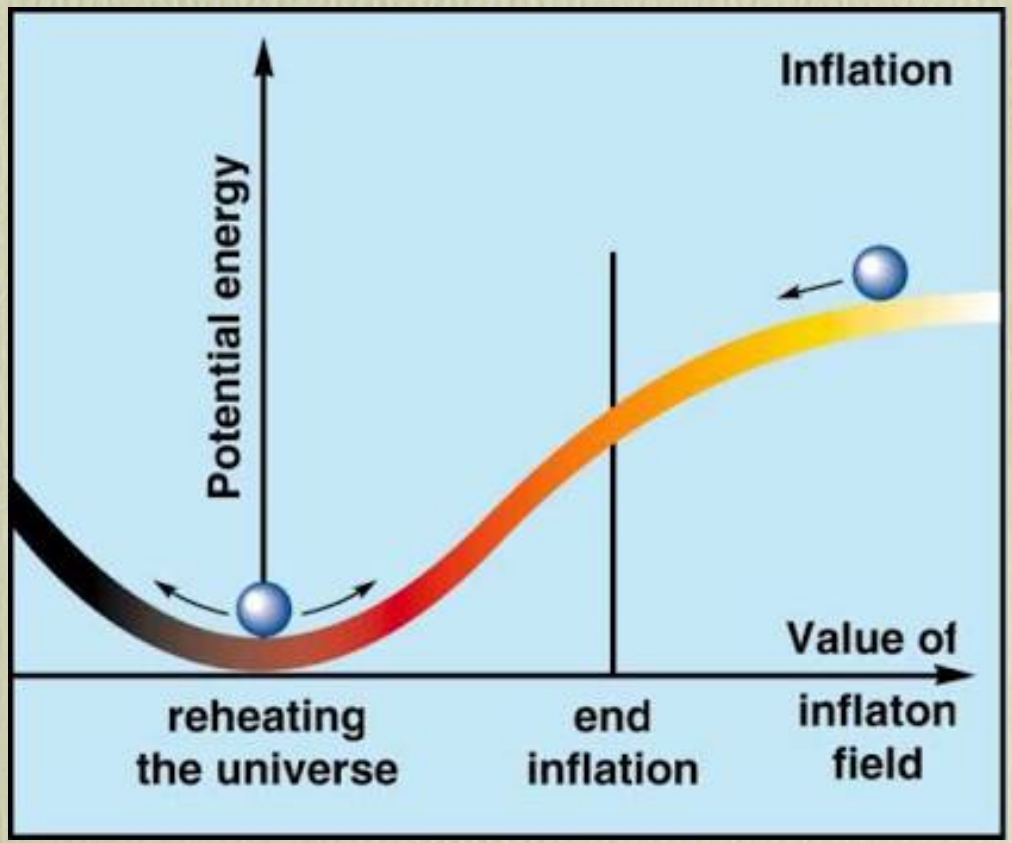
Primordial black holes

- PBHs are natural dark matter candidates.
- Formation requires large density fluctuation.
- This is a hallmark of the spinodal dynamics:



(P)Reheating

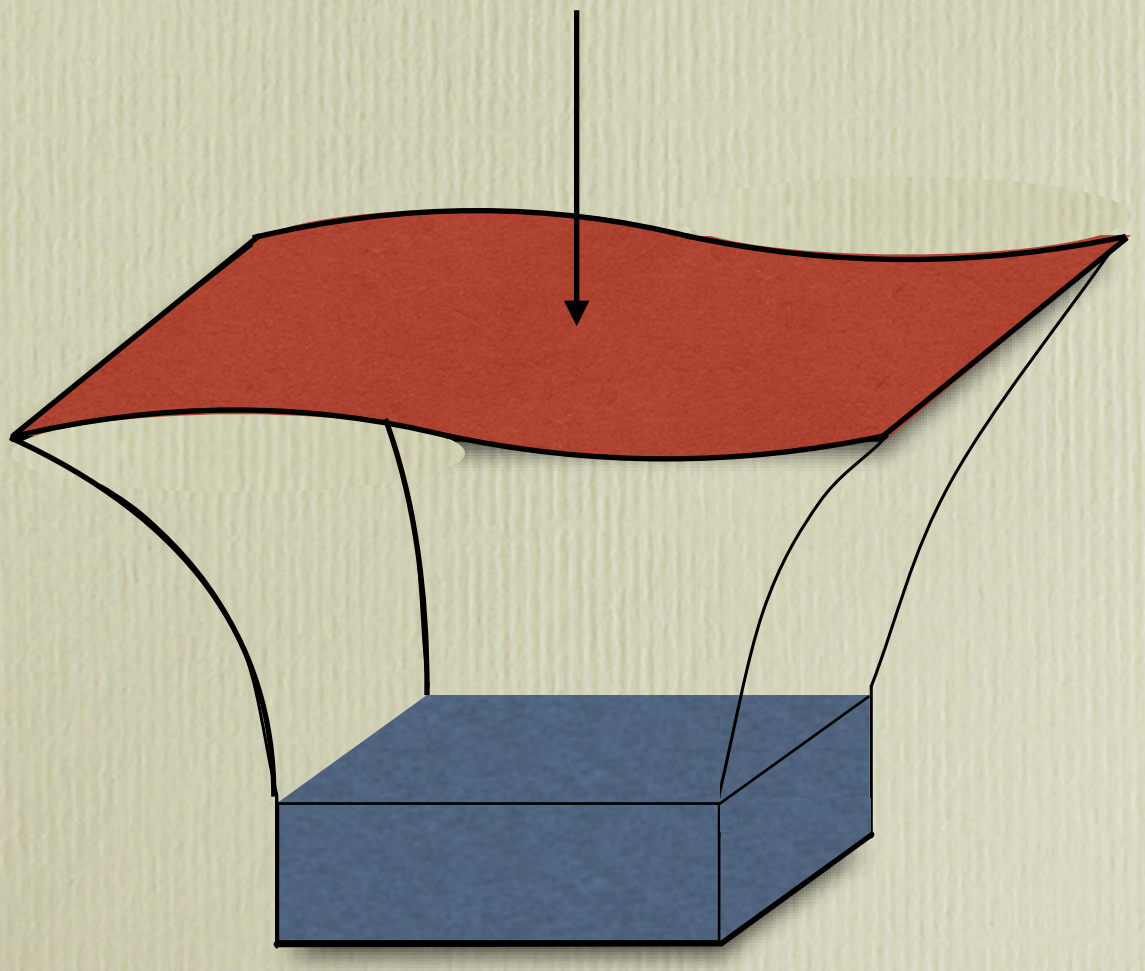
- Involves out-of-equilibrium physics.



(P)Reheating

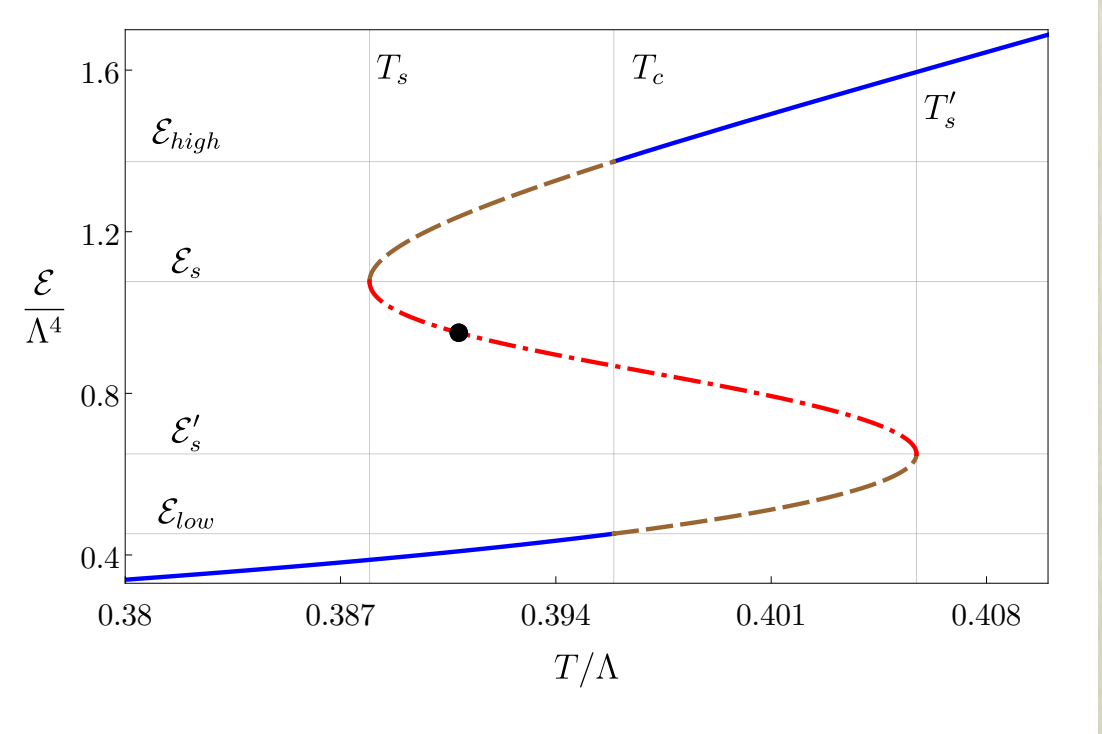
- Involves out-of-equilibrium physics.
- Can be modelled as:

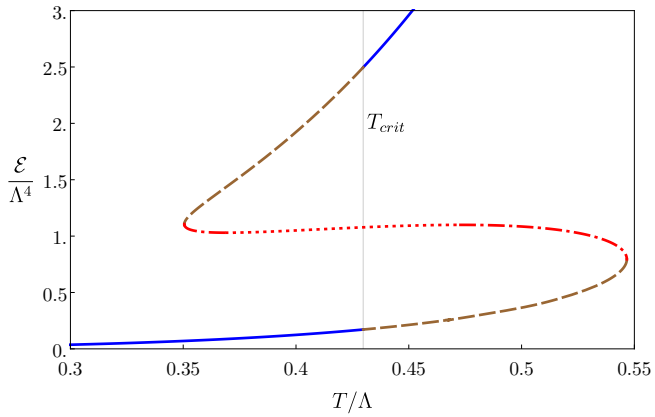
Strongly-coupled quantum matter + dynamical gravity + dynamical inflaton

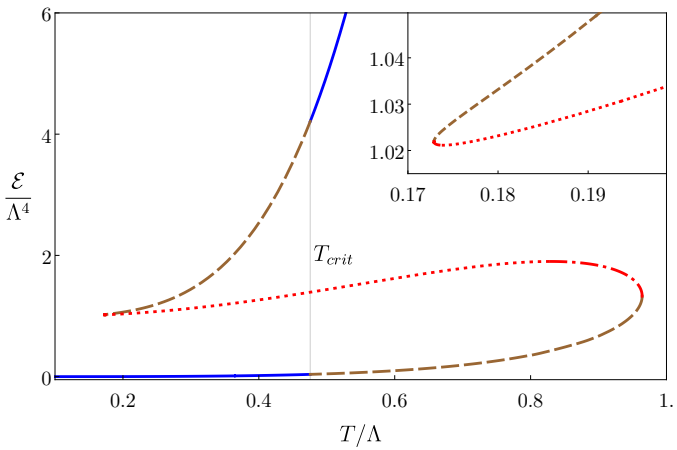


Thermal inflation

- As the Universe rolls down the metastable branch, E+3P can become negative → accelerated expansion.
- If in addition P/E reaches -1 → expansion is exponential.
- In our model this does or does not happen depending on the parameters.




$\frac{\mathcal{E}}{\Lambda^4}$
T_{crit}
T/Λ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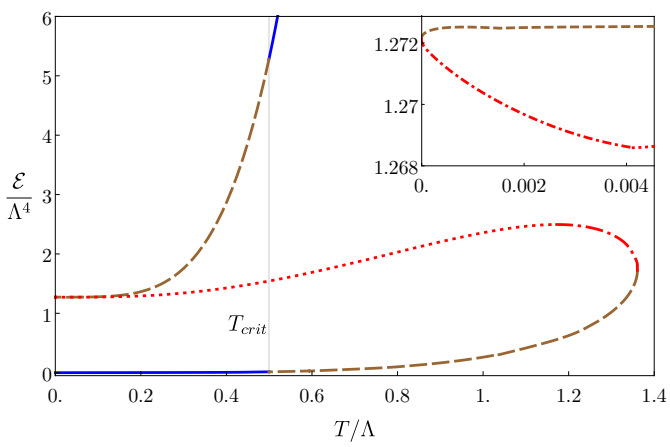
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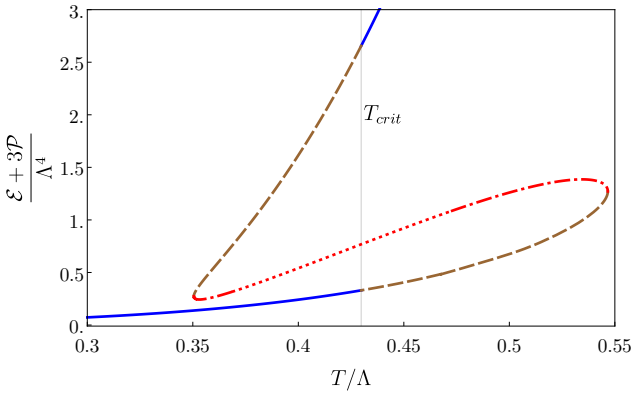
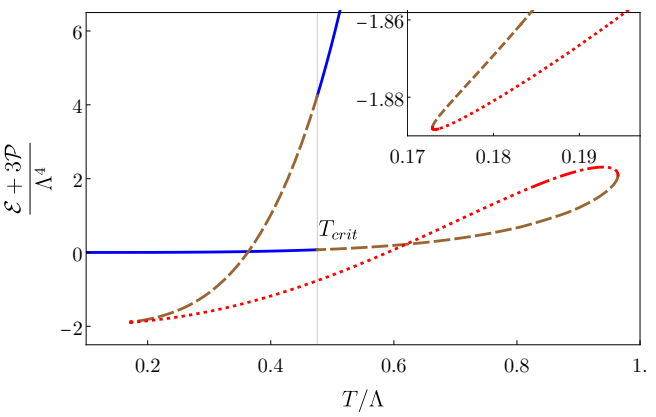

$\frac{\mathcal{E}+3\mathcal{P}}{\Lambda^4}$
T_{crit}
T/Λ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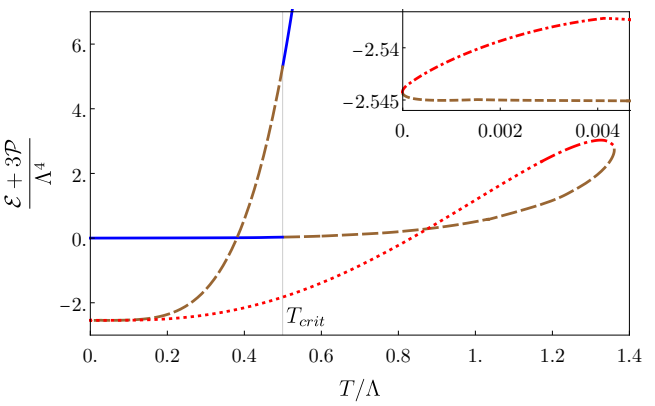
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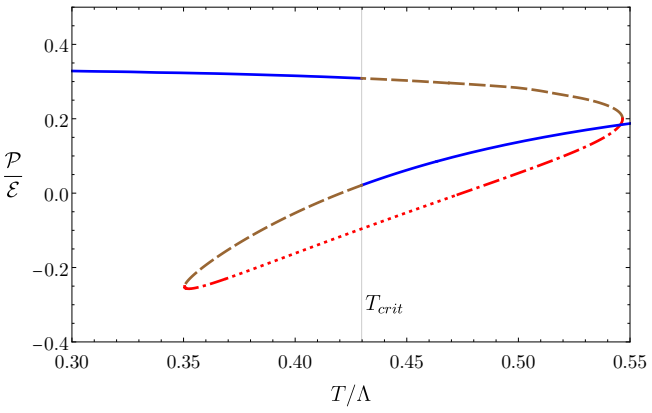
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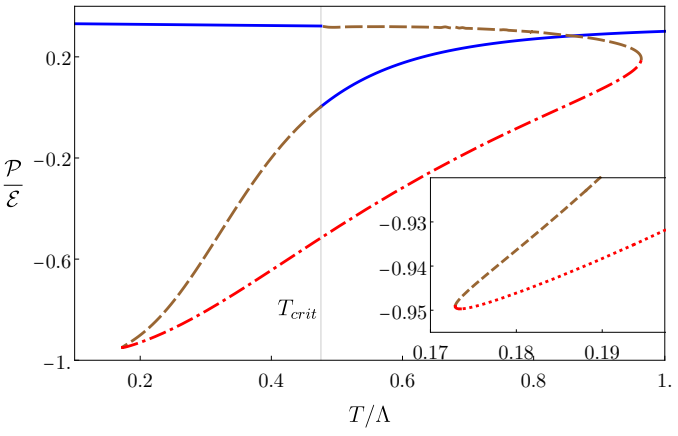
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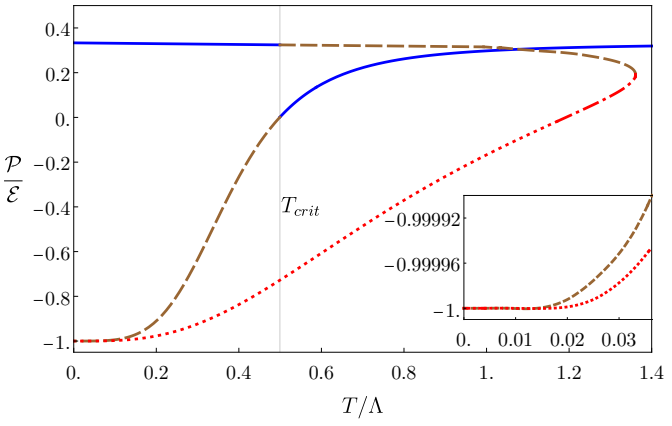
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Thank you!