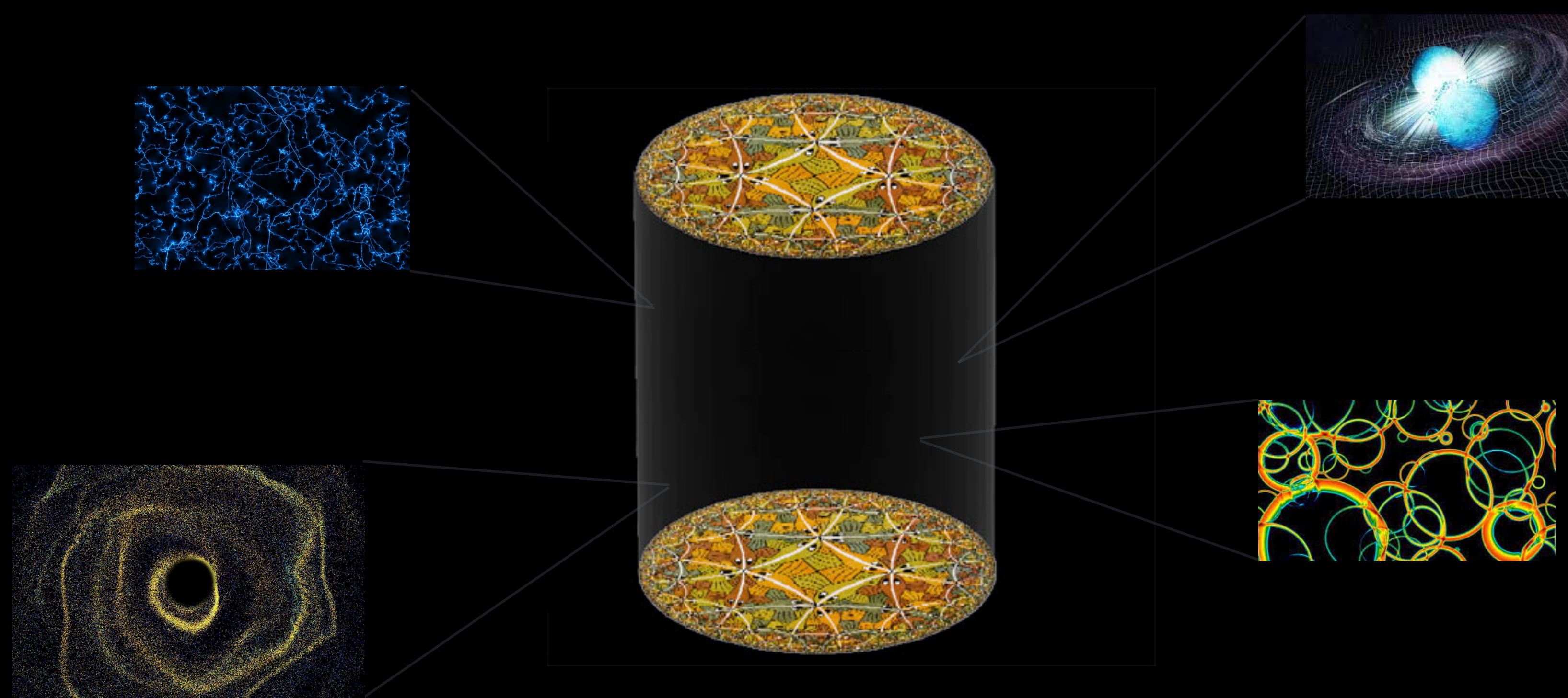
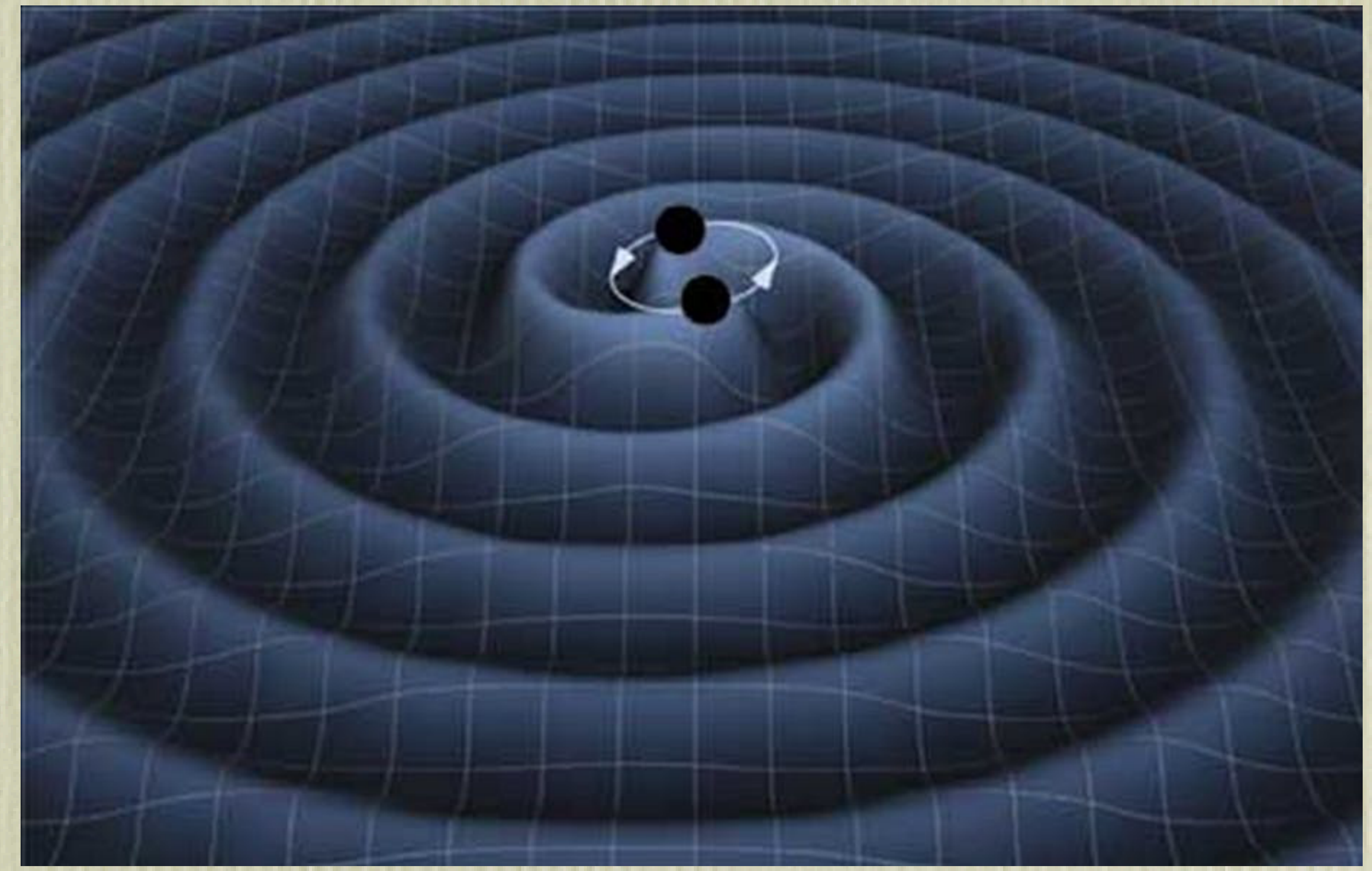
AdS/CAP



David Mateos
ICREA & University of Barcelona

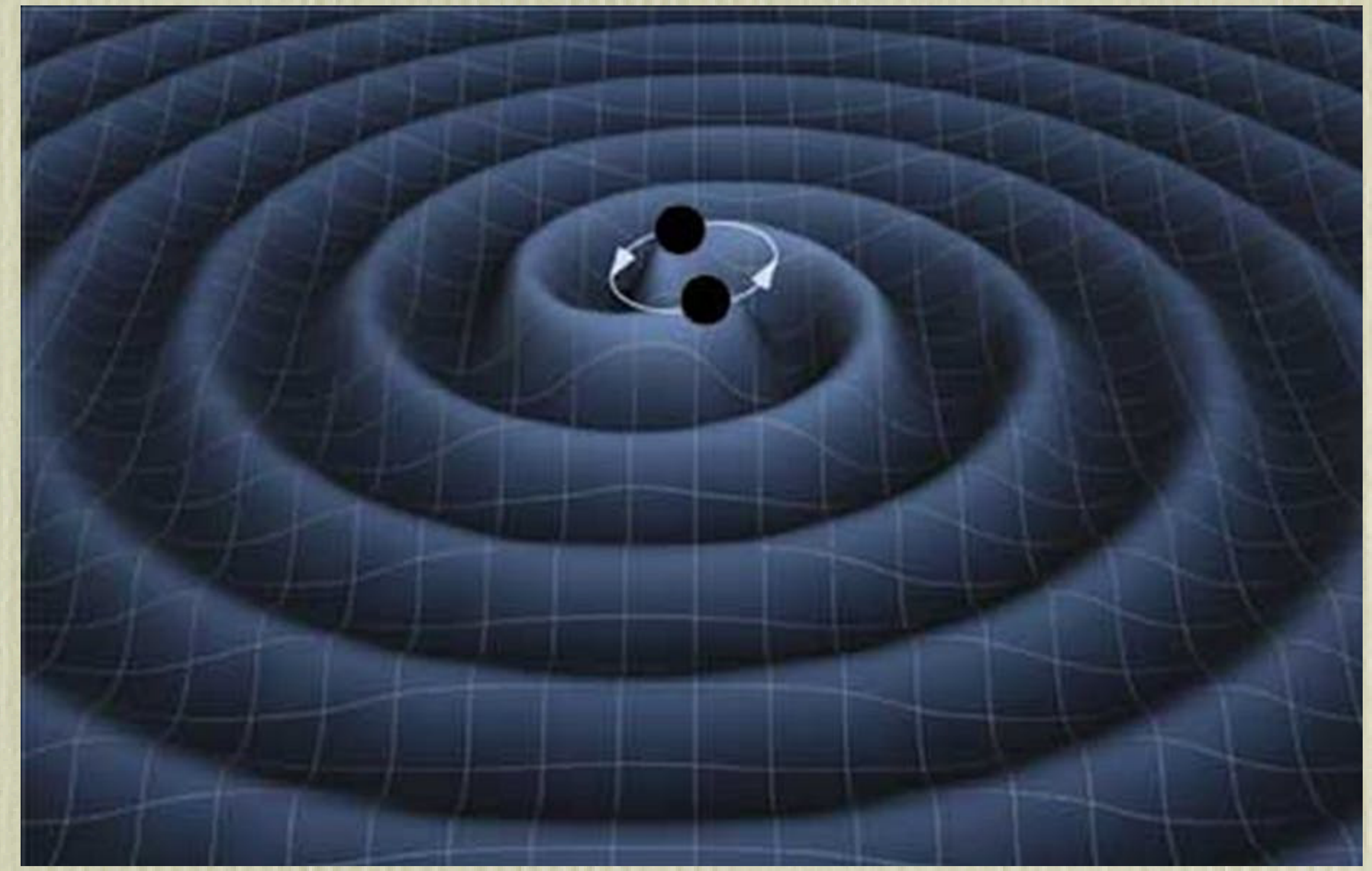
Yago Bea, Jorge Casalderrey-Solana, Christian Ecker, Thanasis Giannakopoulos, Aron Jansen, Sven Krippendorf,
Mikel Sanchez-Garitaonandia, Wilke van der Schee, Alexandre Serantes, Miguel Zilhão

One discovery



- Gravitational Waves (GWs)

Two new experimental windows

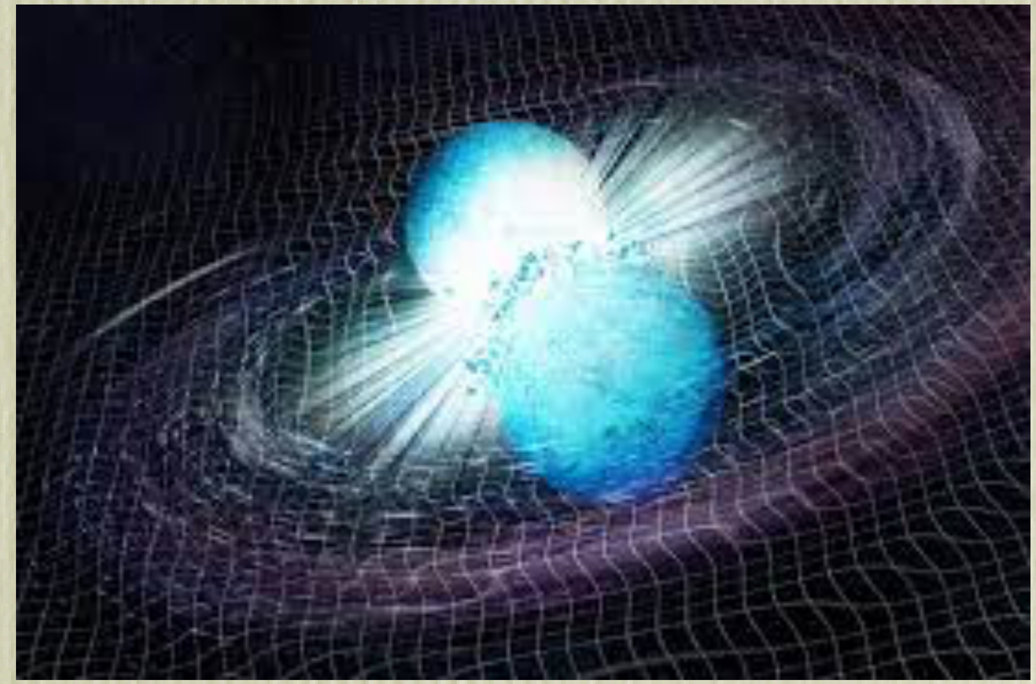


- Into the strong-field regime of General Relativity.
- Into the properties of quantum matter.

Often intertwined

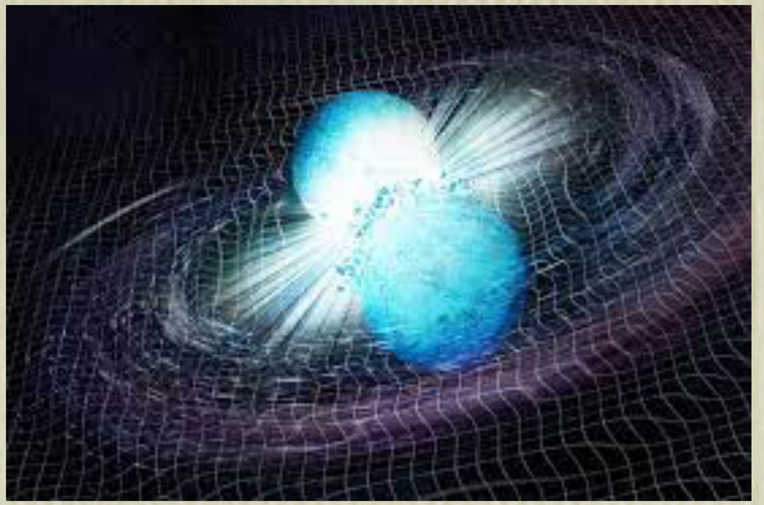
For example in Neutron Star (NS) mergers:

quarks + gluons + gravity.



Both SM and BSM matter

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



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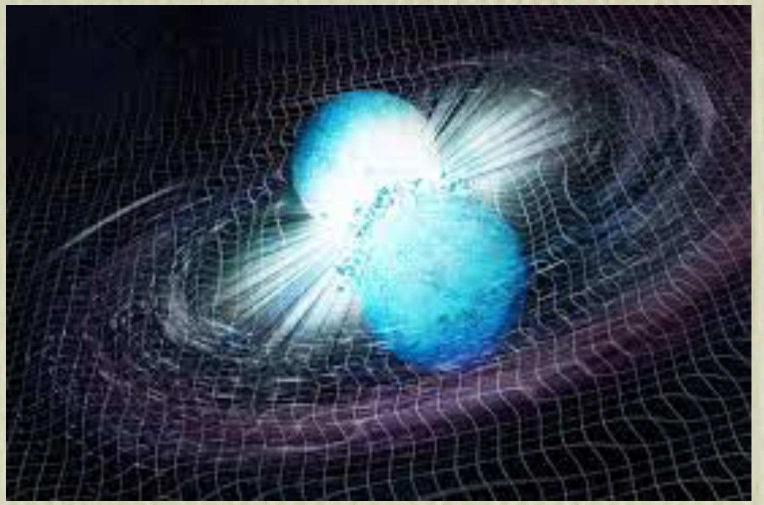
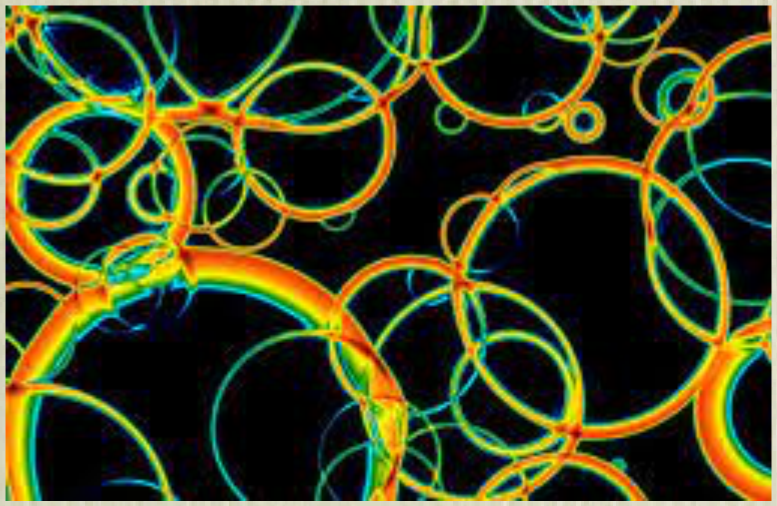


- In other cases the putative matter is BSM matter.
  - E.g. cosmological phase transitions:



Golden opportunity for Holography

- Maximizing the discovery potential requires understanding quantum matter coupled to dynamical gravity.

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- Maximizing the discovery potential requires understanding quantum matter coupled to dynamical gravity.

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- Holography is usually the only first-principle tool.

- Today I will give you an overview with a focus on phase transitions.

Plan

- Holography a.k.a. AdS/CFT

Plan

- Holography a.k.a. AdS/CFT
- Cosmological phase transitions
  - Via bubble nucleation
  - Spinodal instability

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No dynamical gravity
(ignore expansion of the Universe)

- Phase transitions in neutron star mergers

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  See talk by Mikel Sanchez for details

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No dynamical gravity
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- New holographic framework to include dynamical gravity

- Outlook (if time permits)

- Thermal inflation
- Spacetime singularities
- Primordial Black Holes
- (P)Reheating

The team

Yago Bea
(UB)

Jorge Casalderrey
(UB)

Christian
Ecker
(U Frankfurt)

Thanasis
Giannakopoulos
(IST Lisbon)

Aron Jansen
(eScience)

Sven
Krippendorf
(LMU Munich)

Mikel
Sanchez
(UB)

Wilke
Van der Schee
(CERN)

Alexandre
Serantes
(UB)

Miguel Zilhao
(Aveiro U)

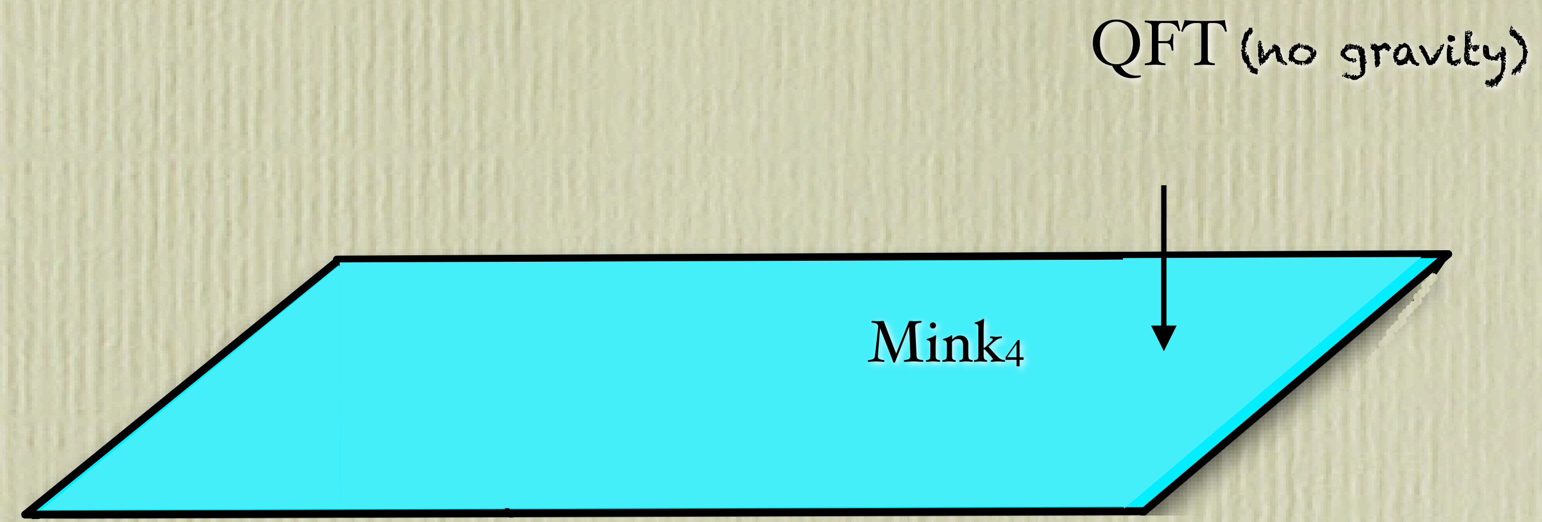
The team

Two PhD opportunities in Barcelona will open soon.

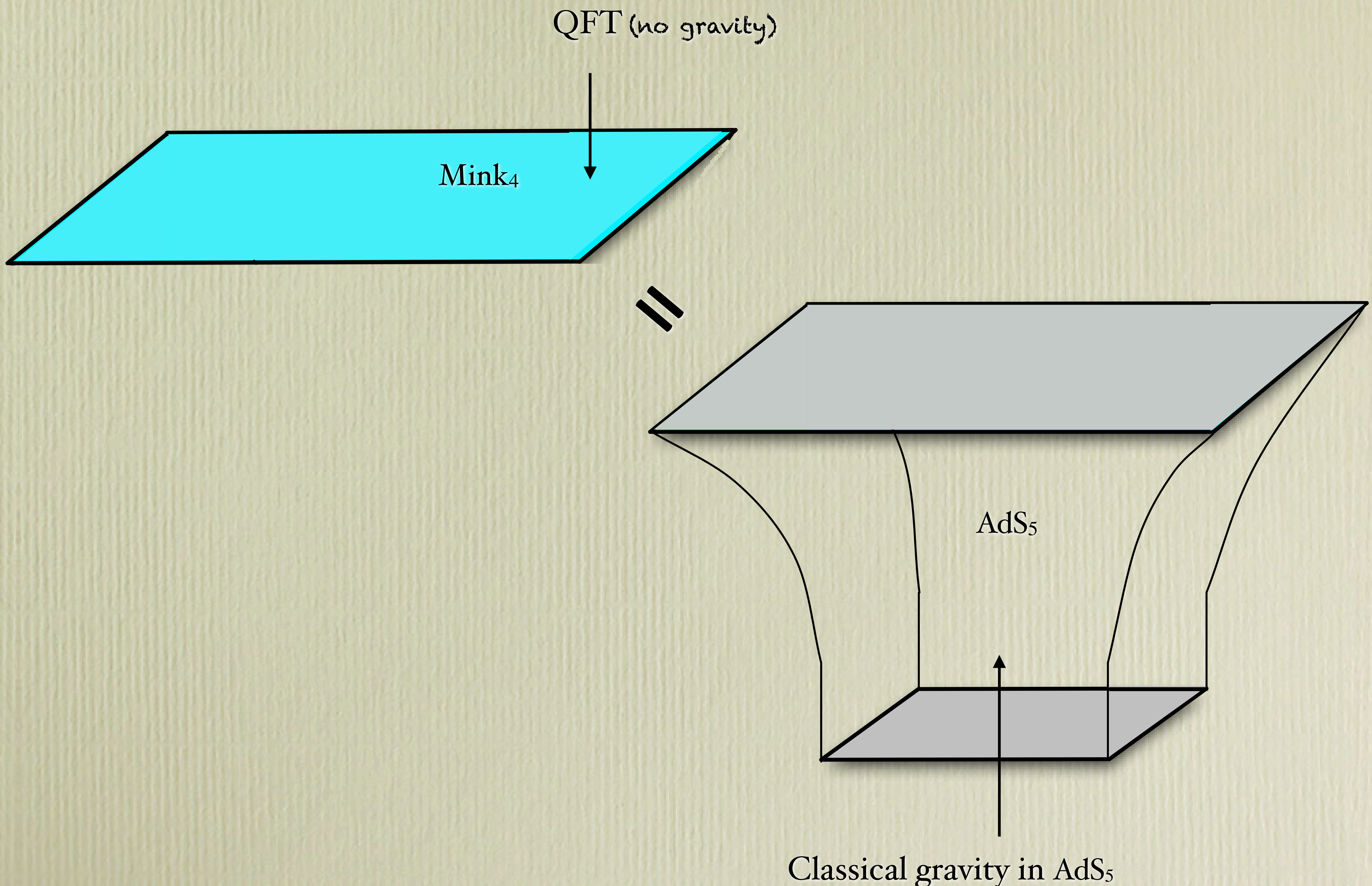
Please tell interested candidates to contact me *as soon as possible* (dmateos@fqa.ub.edu)

Holography

Holography



Holography



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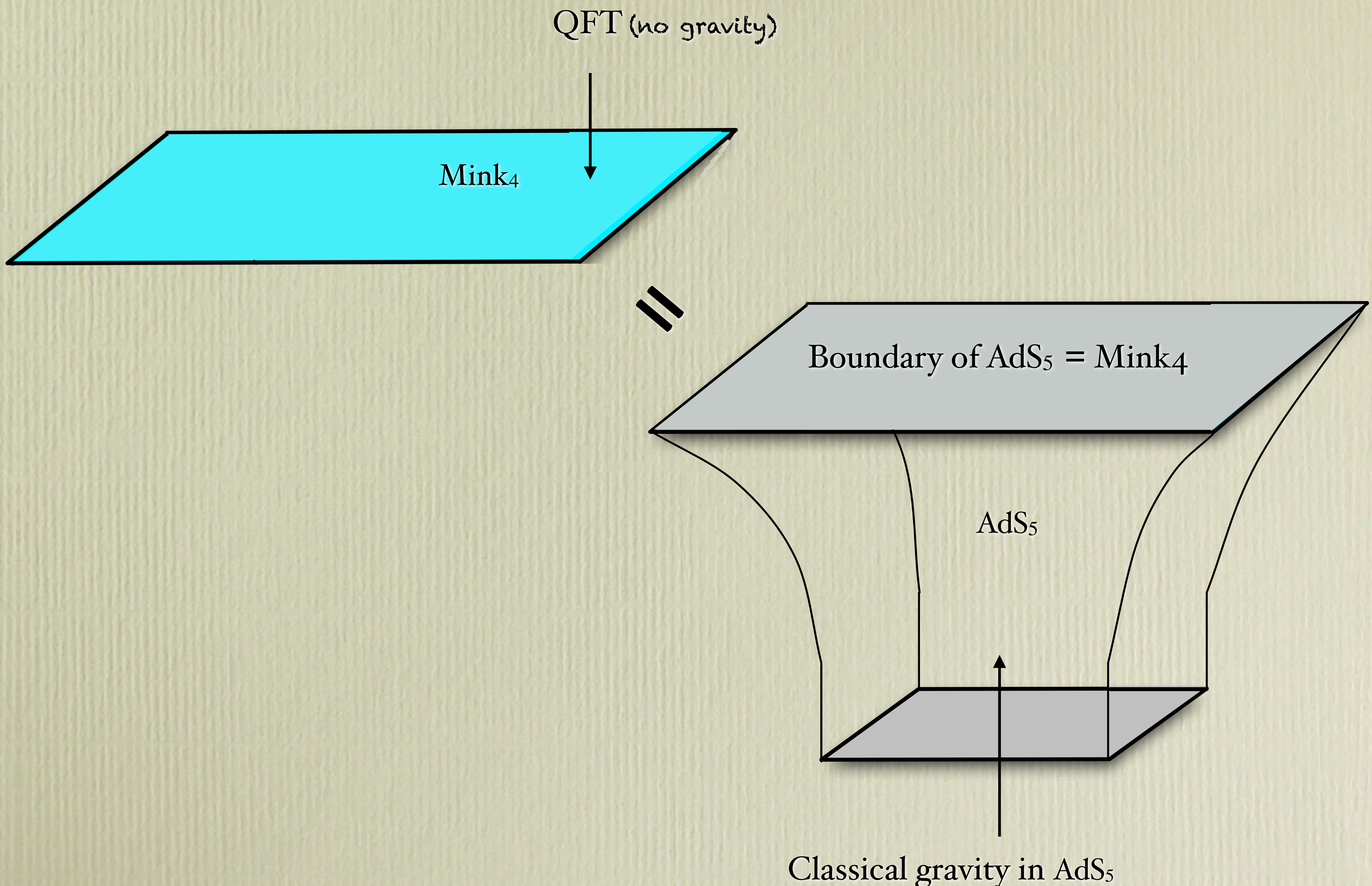
QFT (no gravity)
Mink$_4$
=
Boundary of AdS$_5$ = Mink$_4$
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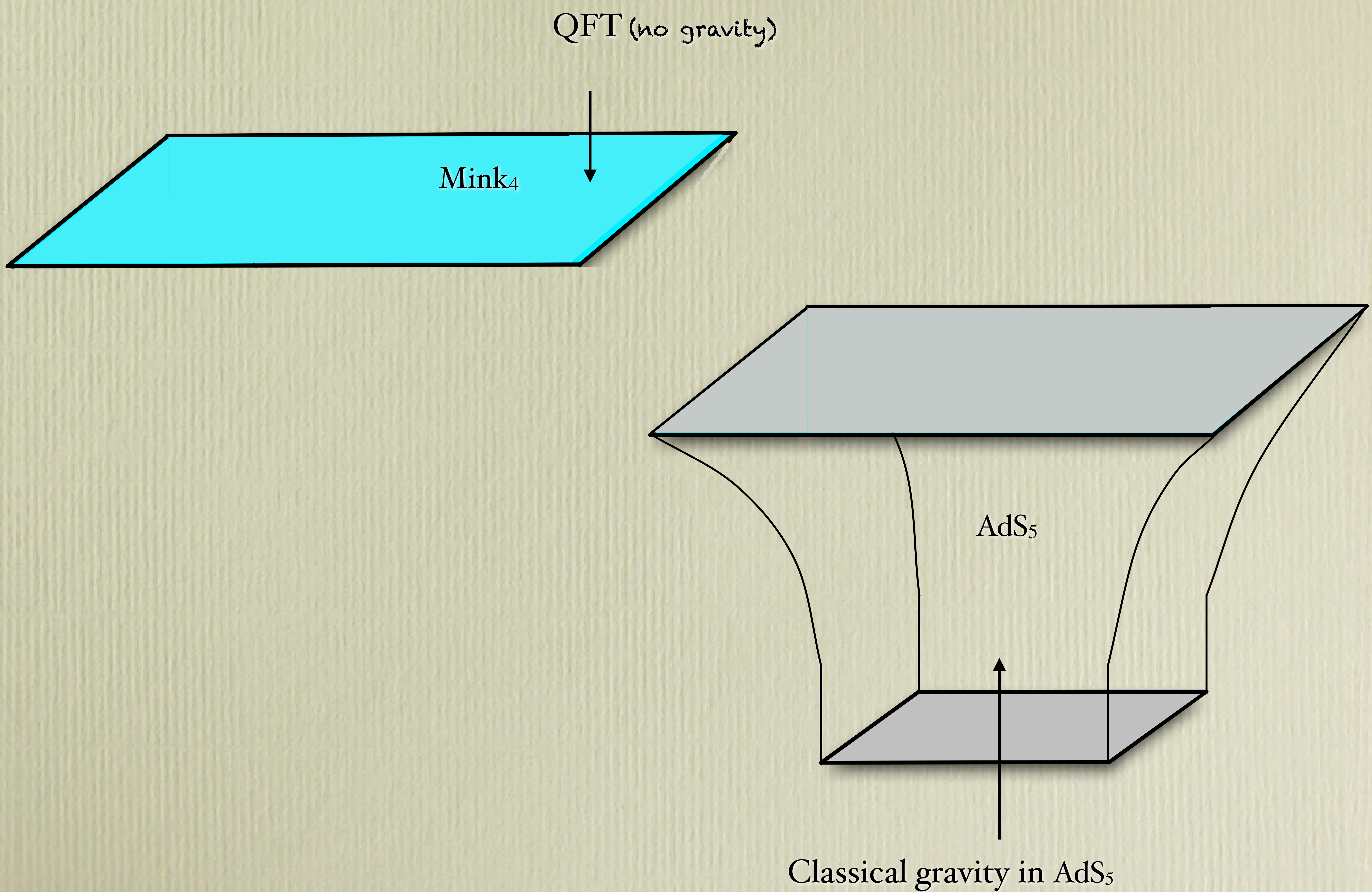
Holography



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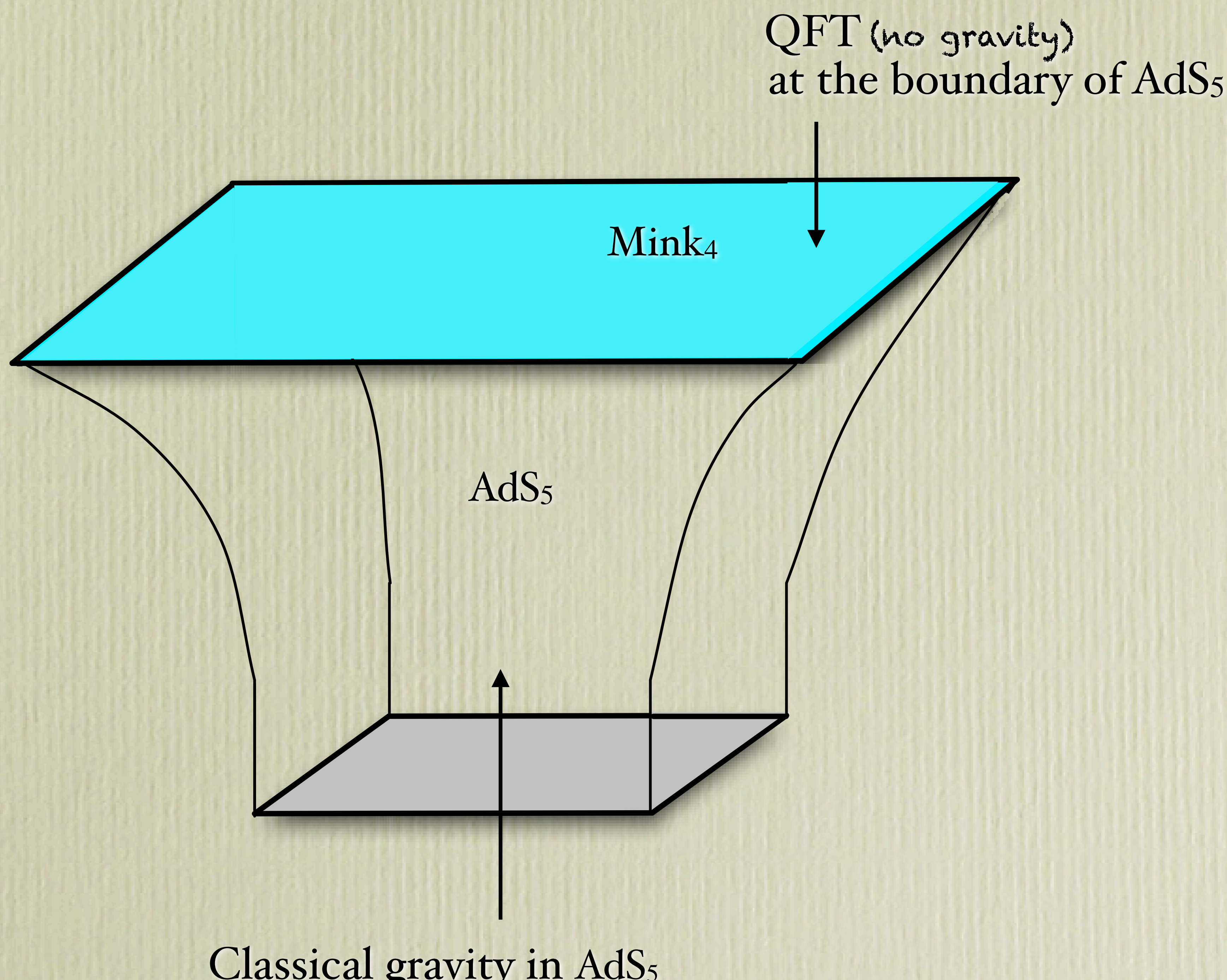
QFT (no gravity)
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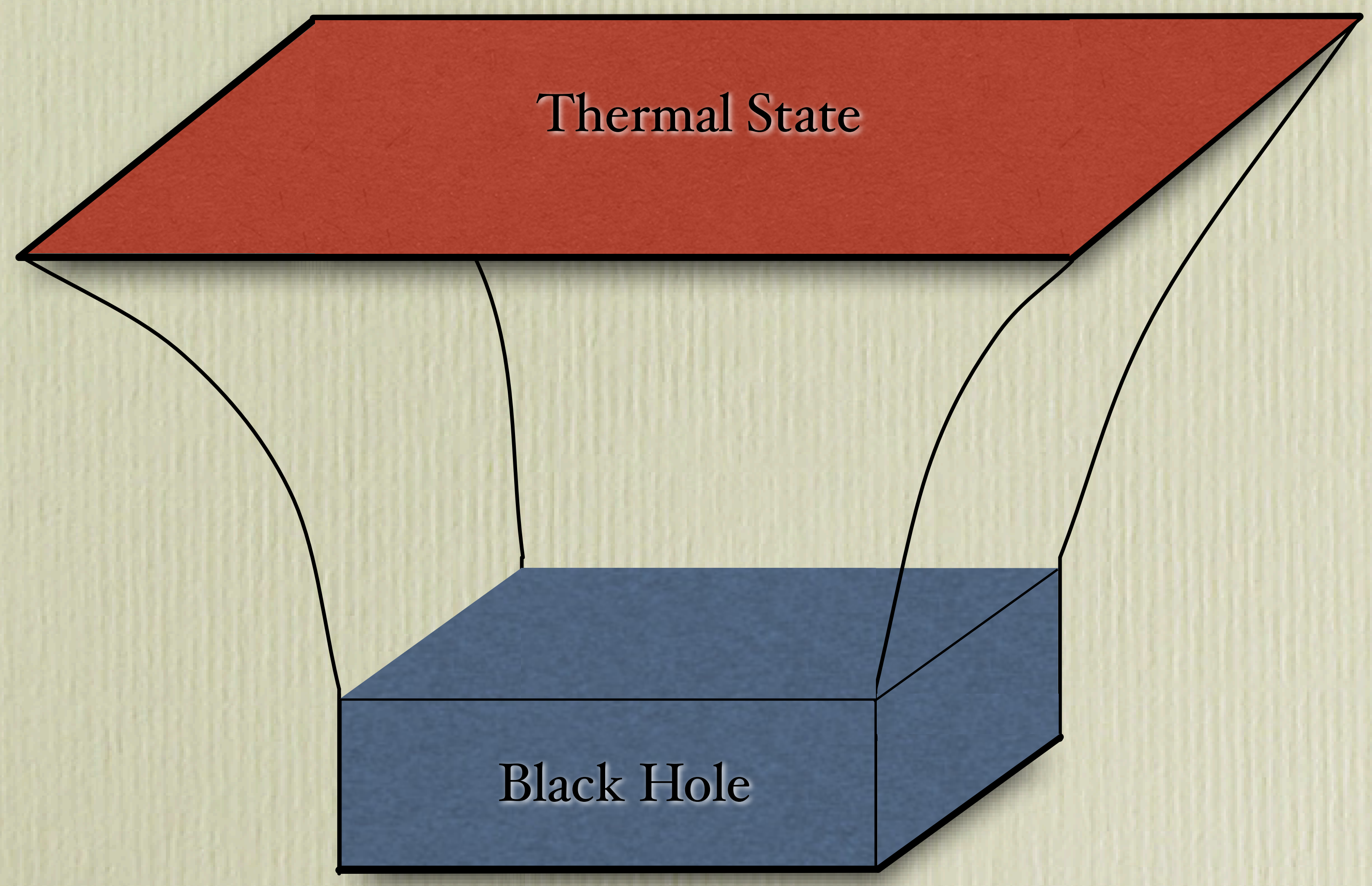
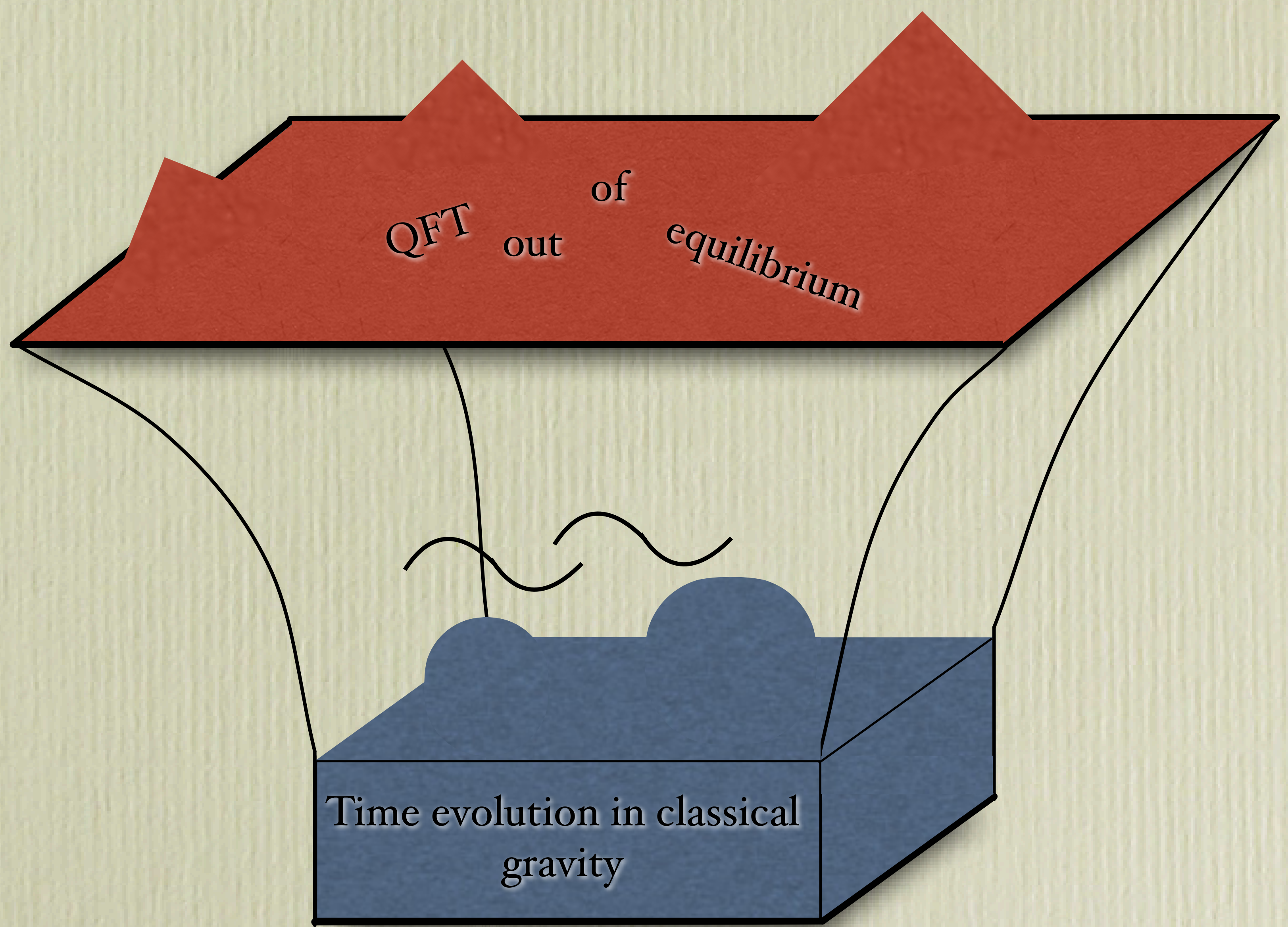
Thermal physics = Black hole physics



The power of holography



The power of holography

Non-String Theorists: You can think of AdS_5 as a computational device

The power of holography

Non-String Theorists: You can think of AdS_5 as a computational device

String Theorists: Think of a new application of AdS/CFT

AdS/CAP

↑

Cosmology and **A**stro**P**hysics

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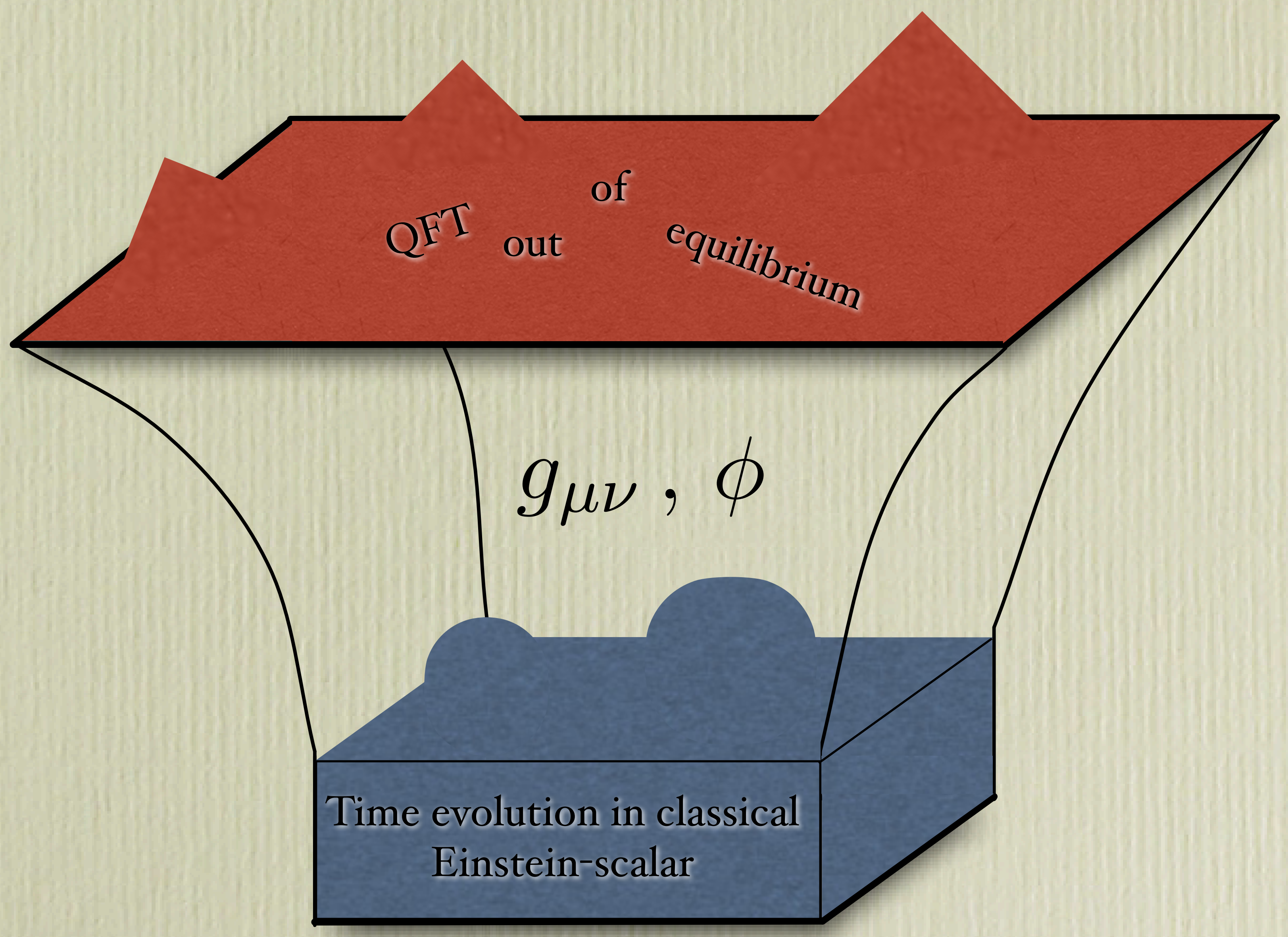
- Since this is a large class the hope is to learn about generic properties.

The holographic model



Cosmological Phase Transitions:
Bubble Nucleation

Cosmological phase transitions

- First-order phase transitions are ubiquitous in Nature.

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?

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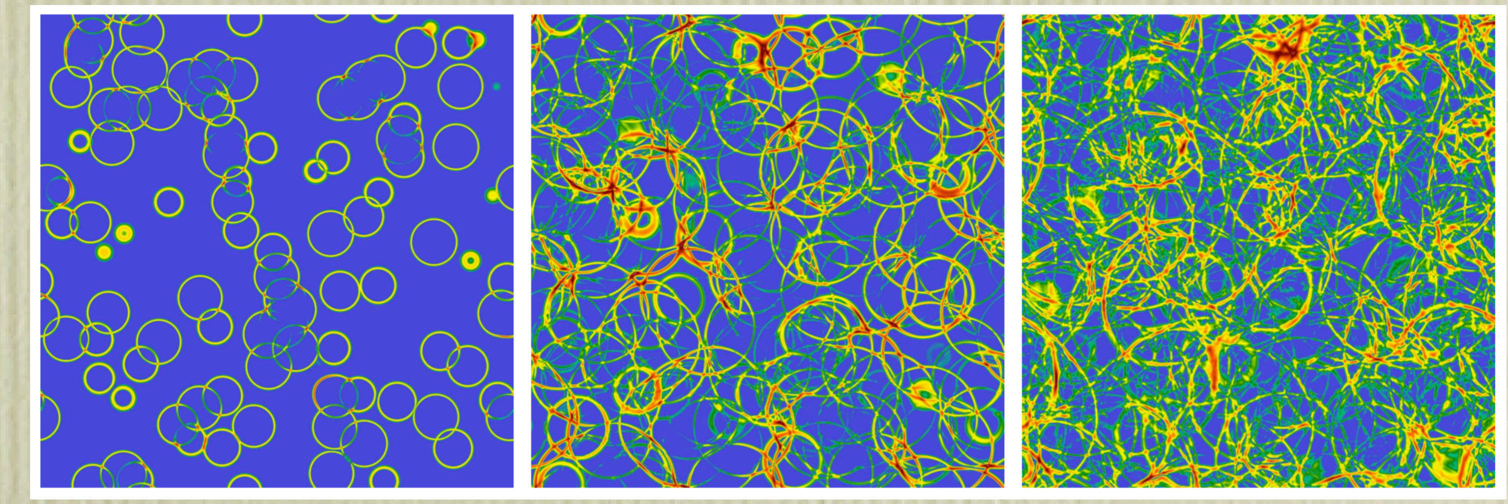
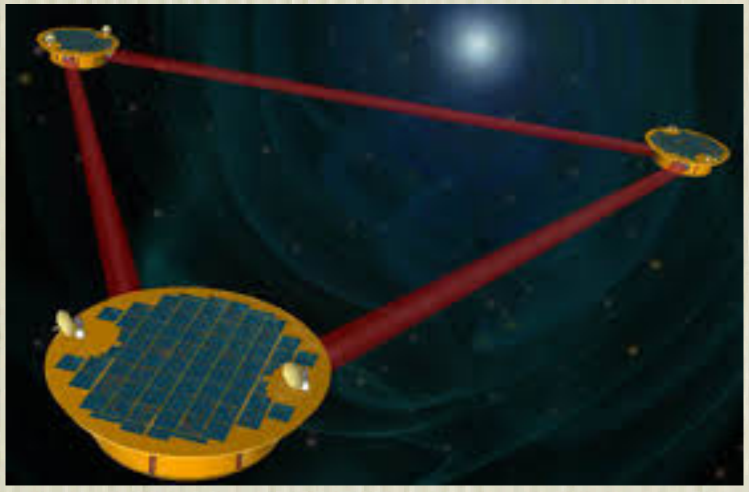
- Exciting: The Universe would have undergone it!

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

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

➡ And it may be our only window into that physics

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

Cosmological phase transitions

- And the signal might be seen at LISA.

Caprini et al, arXiv:1910.13125 [astro-ph.CO]

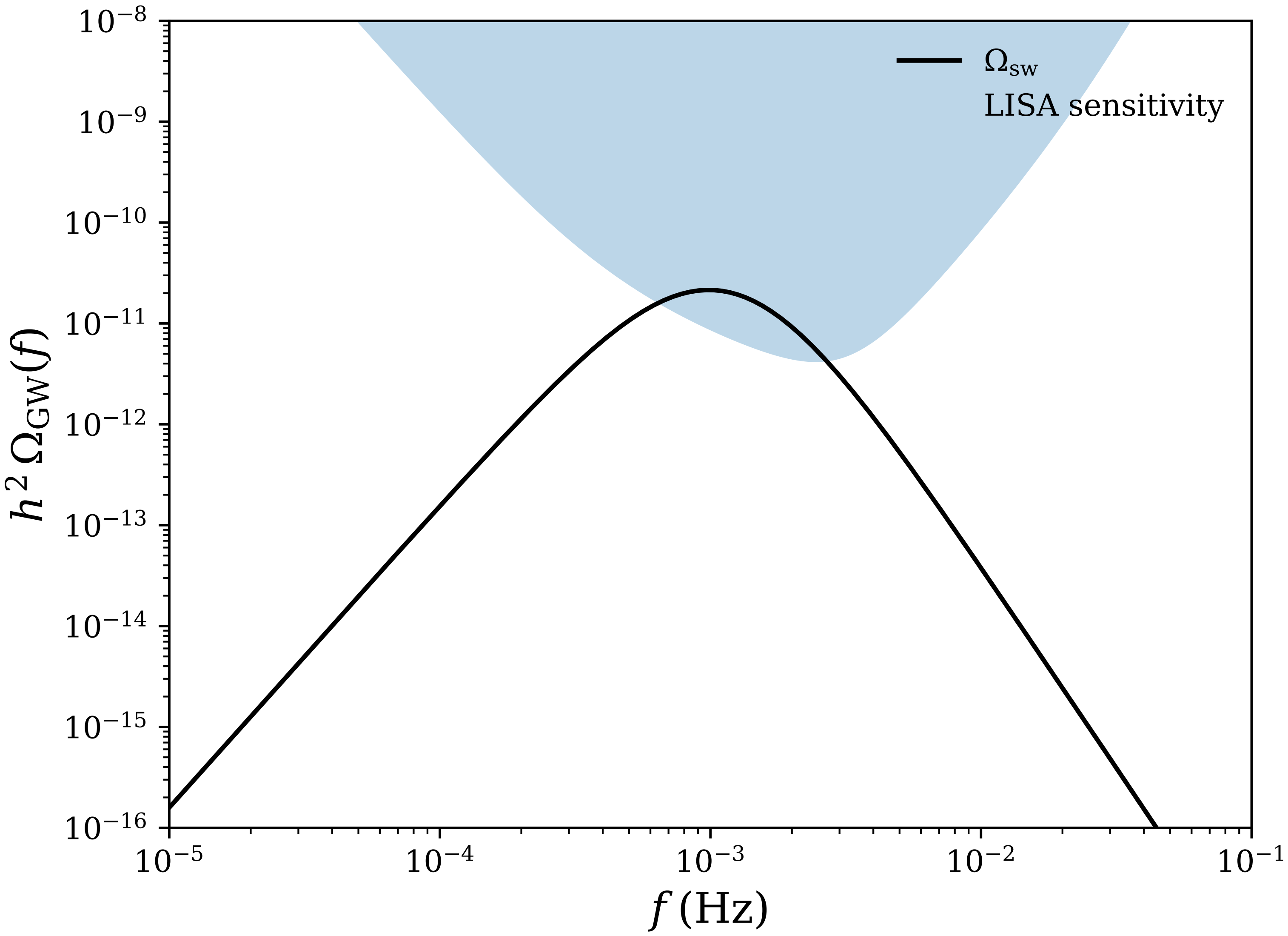
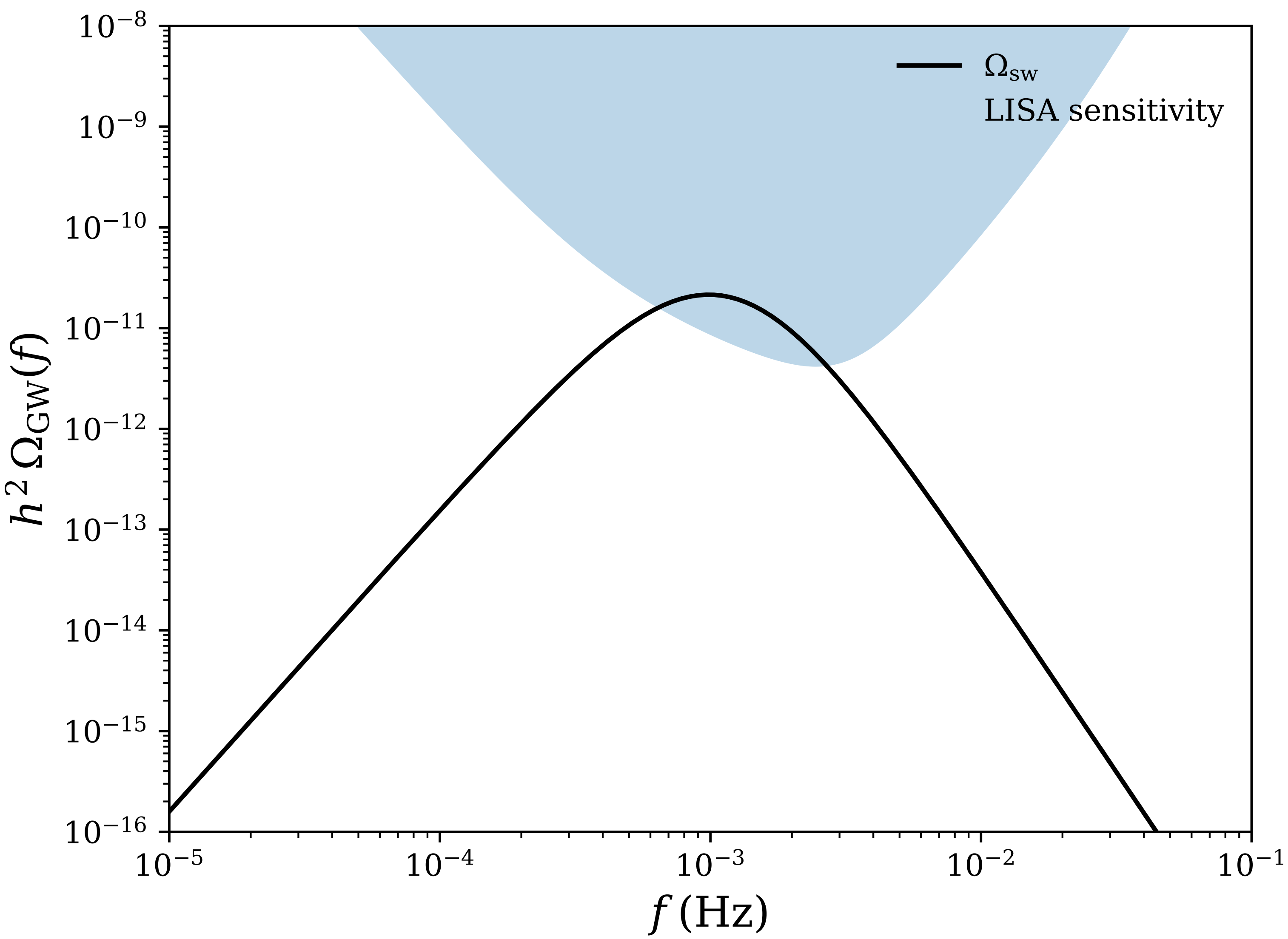


Figure 3: Example output of the PTPlot tool. The plot shows an example of the GW power spectrum from a first-order PT, along with the LISA sensitivity curve ($h^2\Omega_{\mathrm{Sens}}(f)$ taken from the LISA Science Requirements Document [65]). The parameters of the example model are $v_{\mathrm{w}} = 0.9$, $\alpha = 0.1$, $\beta/H_* = 50$, $T_* = 200$ GeV, $g_* = 100$.

Cosmological phase transitions

- And the signal might be seen at LISA.
- For this reason a lot of work has been devoted to this case.

Caprini et al, arXiv:1910.13125 [astro-ph.CO]



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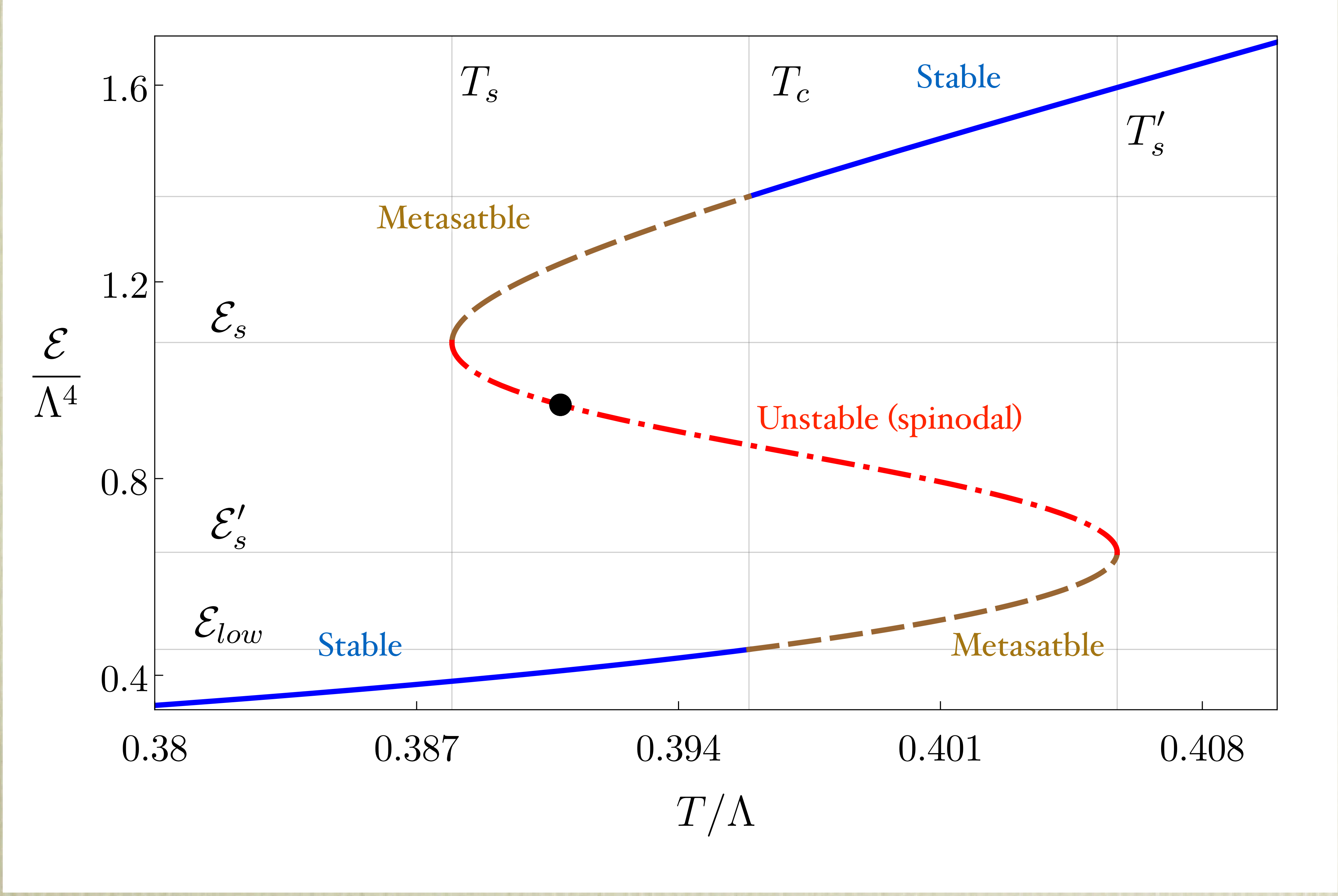
Cosmological phase transitions

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

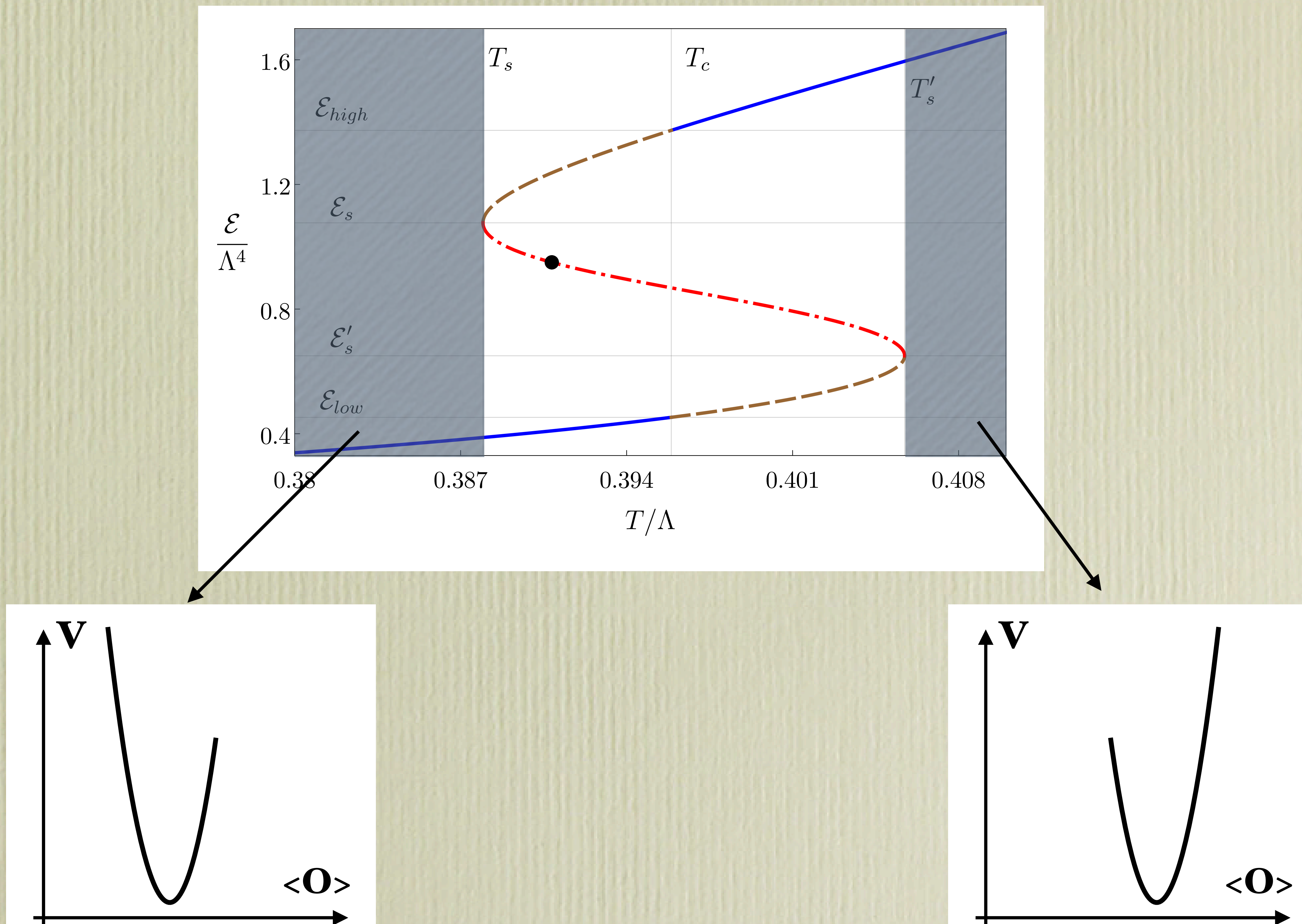
  - Phase transition could take place at $T \neq T_{EW}$
  - Phase transition could take place in a dark sector with $T \neq T_{SM}$

First-order phase transition



First-order phase transition

- In terms of an effective potential:



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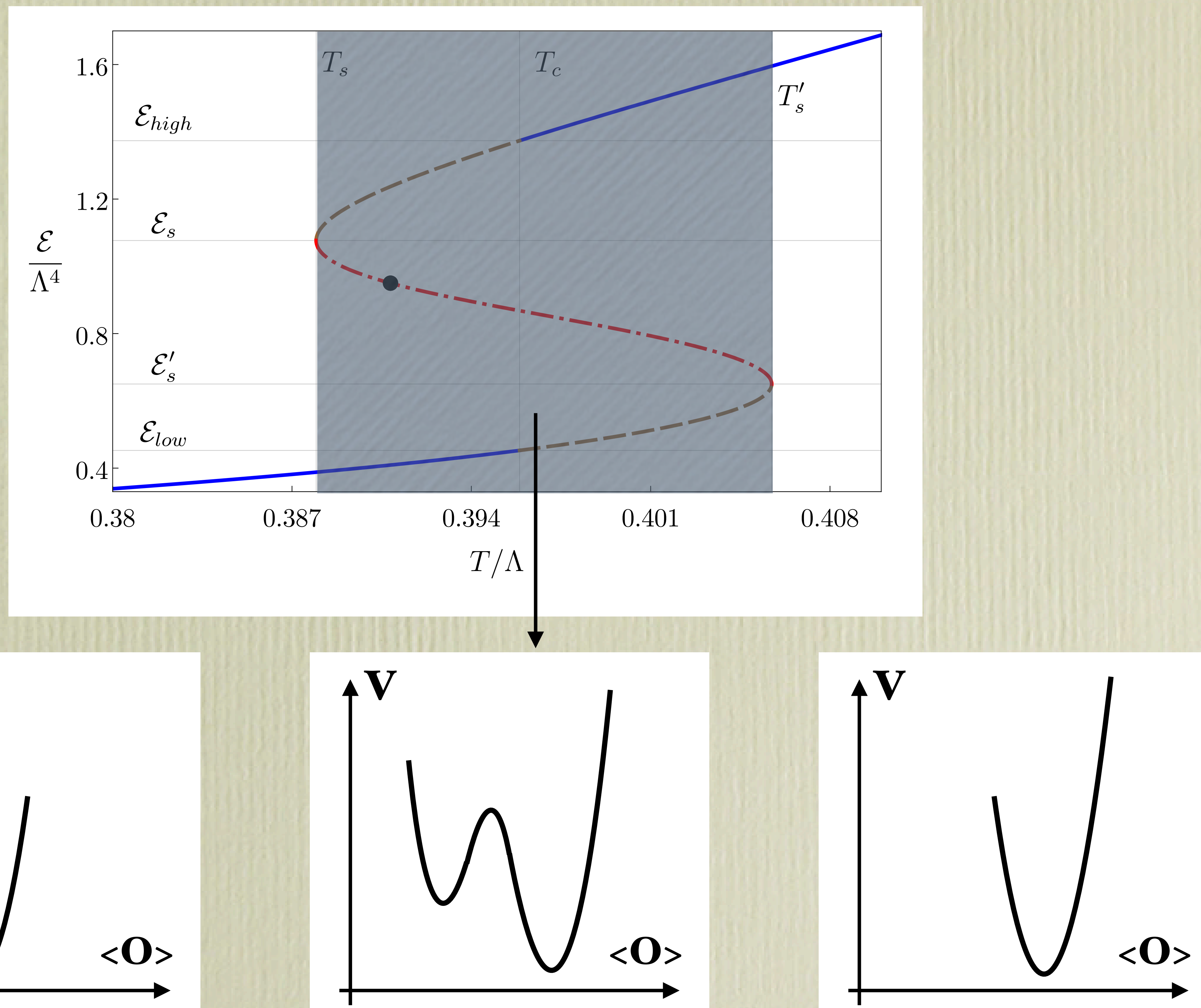
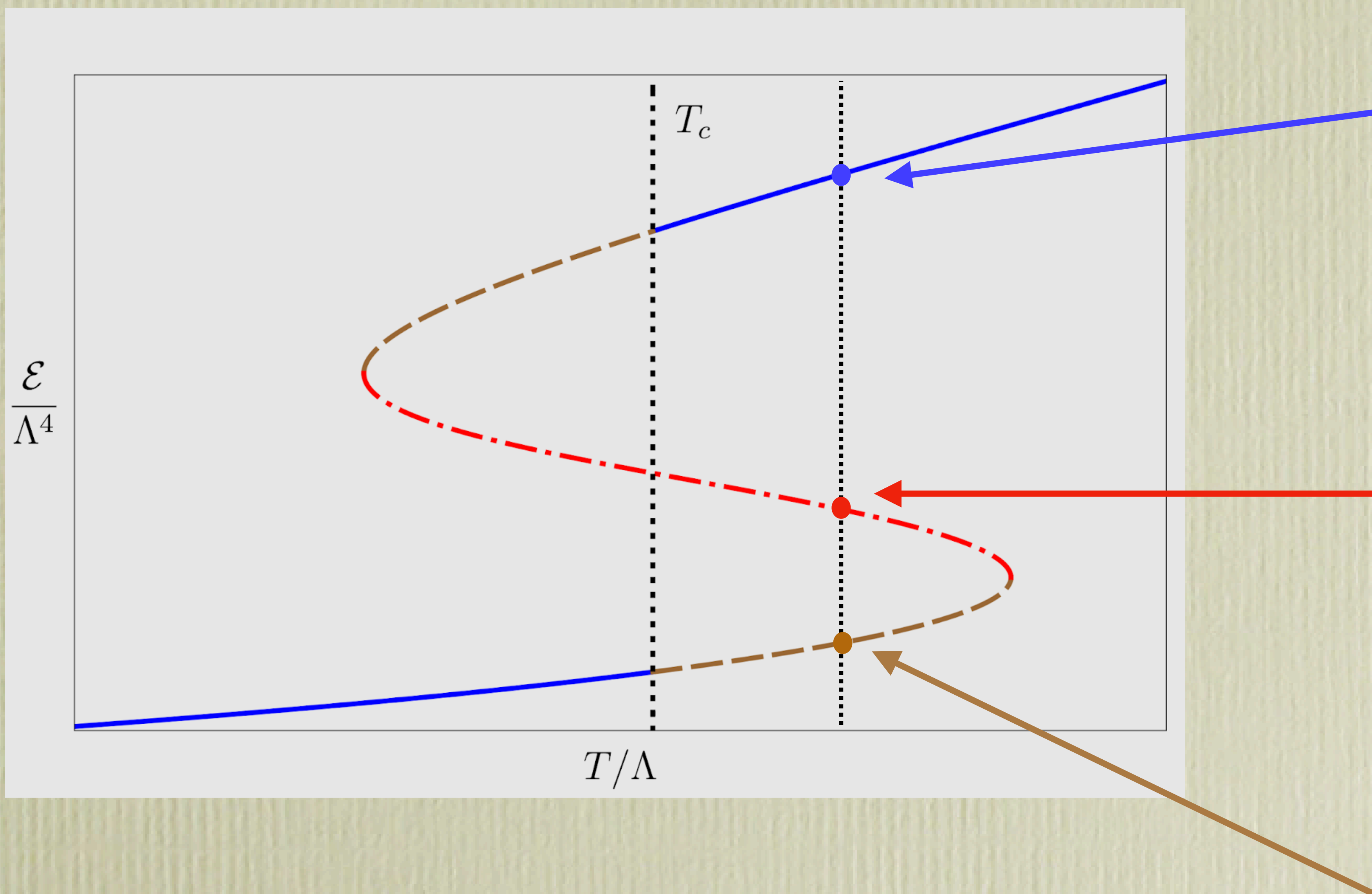
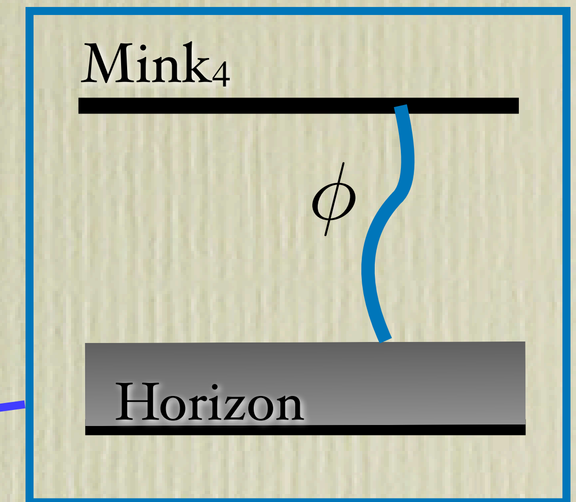
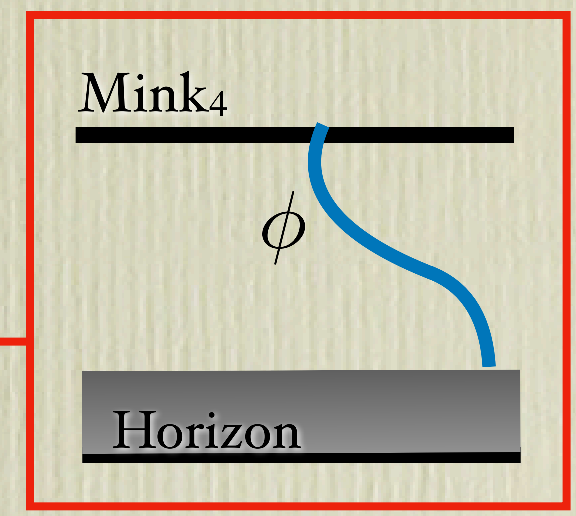


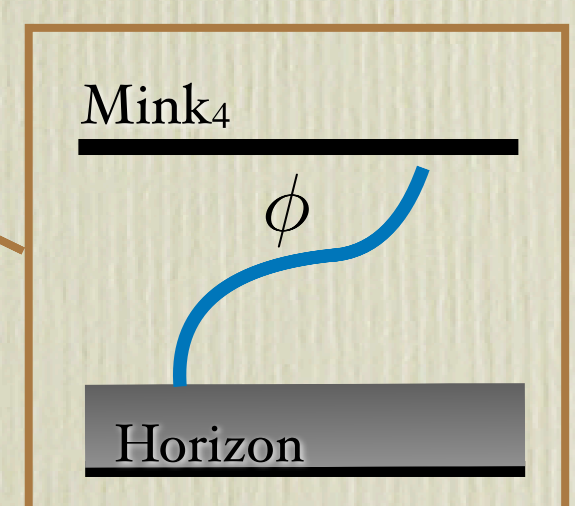
First-order phase transition

- On the gravity side the solutions are distinguished by the scalar hair (and the metric)

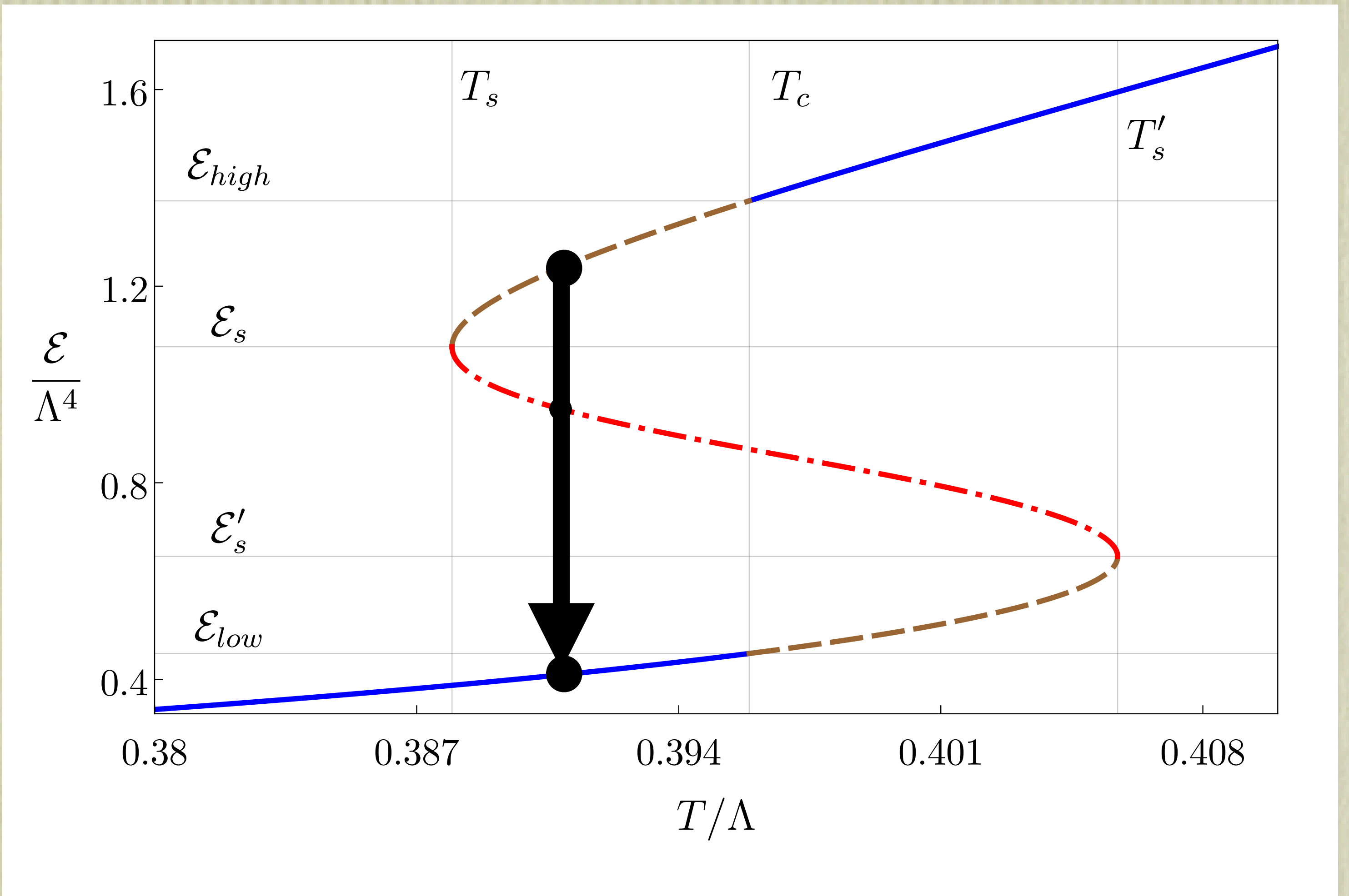


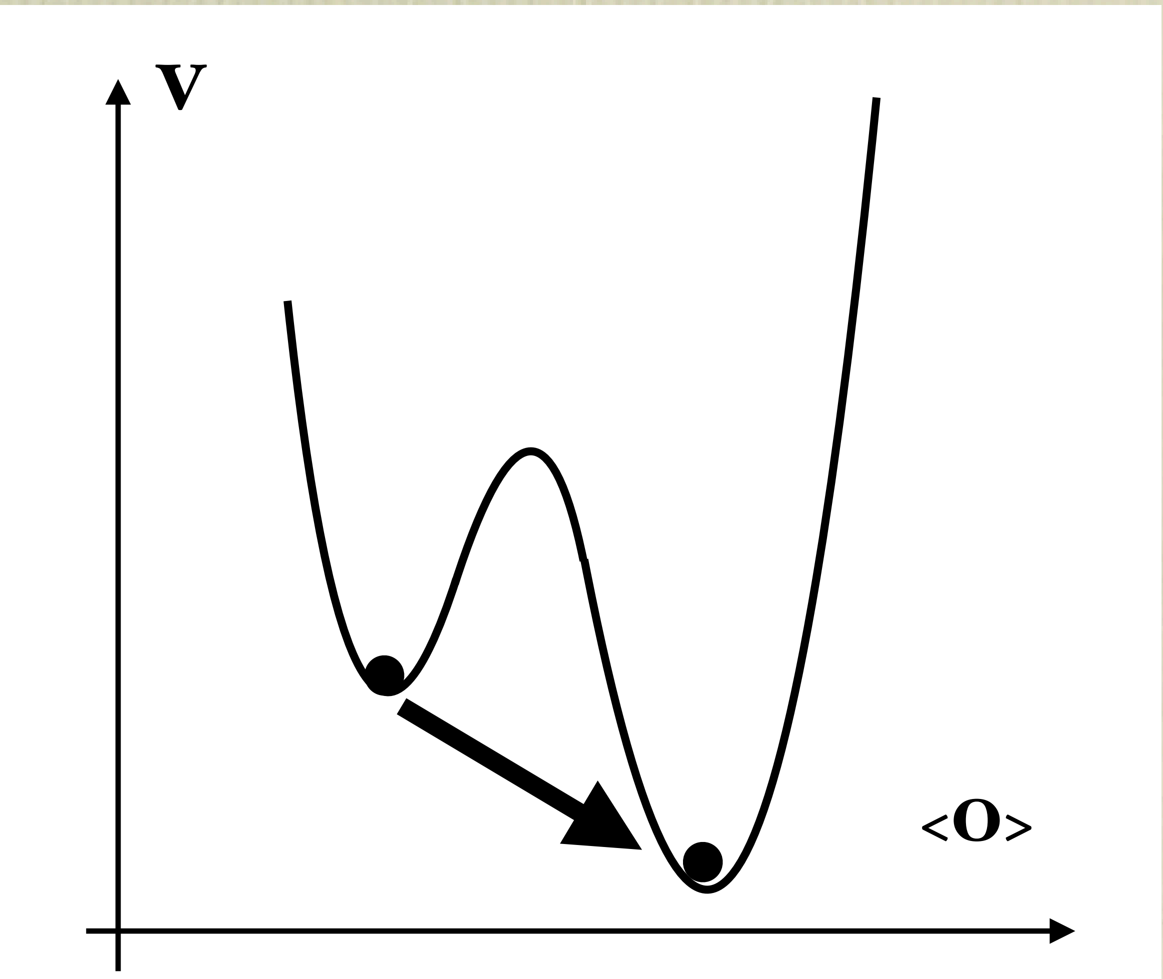






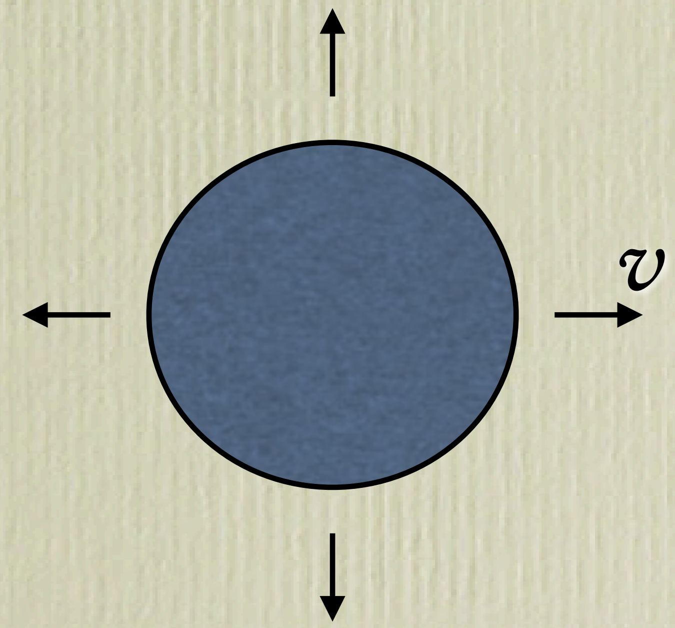
Transition via bubble nucleation





Cosmological phase transitions

- Once bubbles are nucleated, subsequent dynamics produces GWs.



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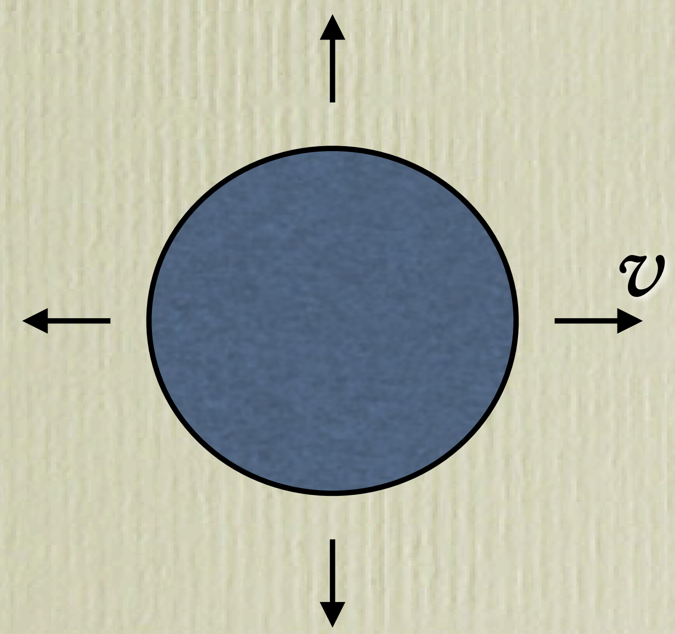
- GW spectrum is most sensitive to the bubble wall velocity.



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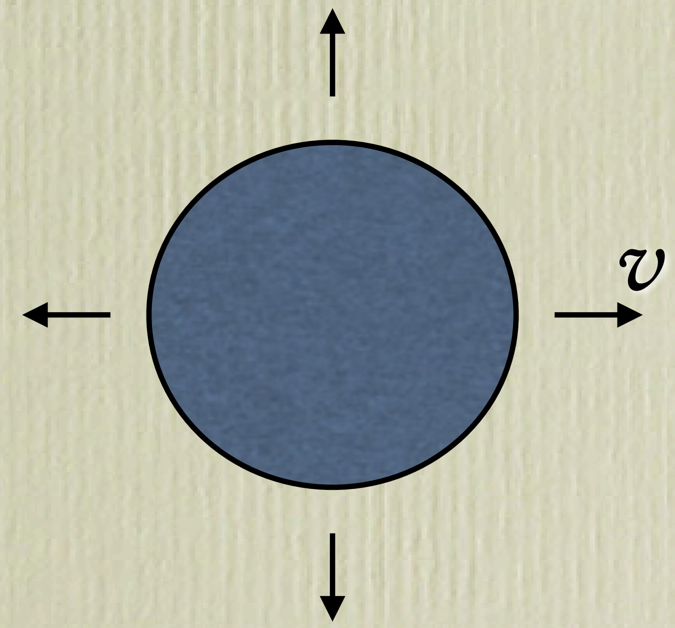
Moore & Prokopec ’95
Bodeker & Moore ’17
Höche, Kozaczuk, Long, Turner & Y. Wang ‘20



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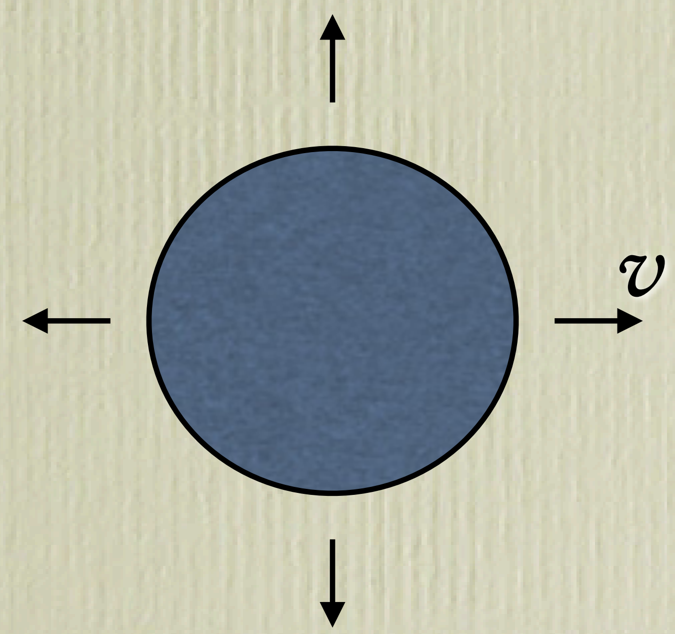
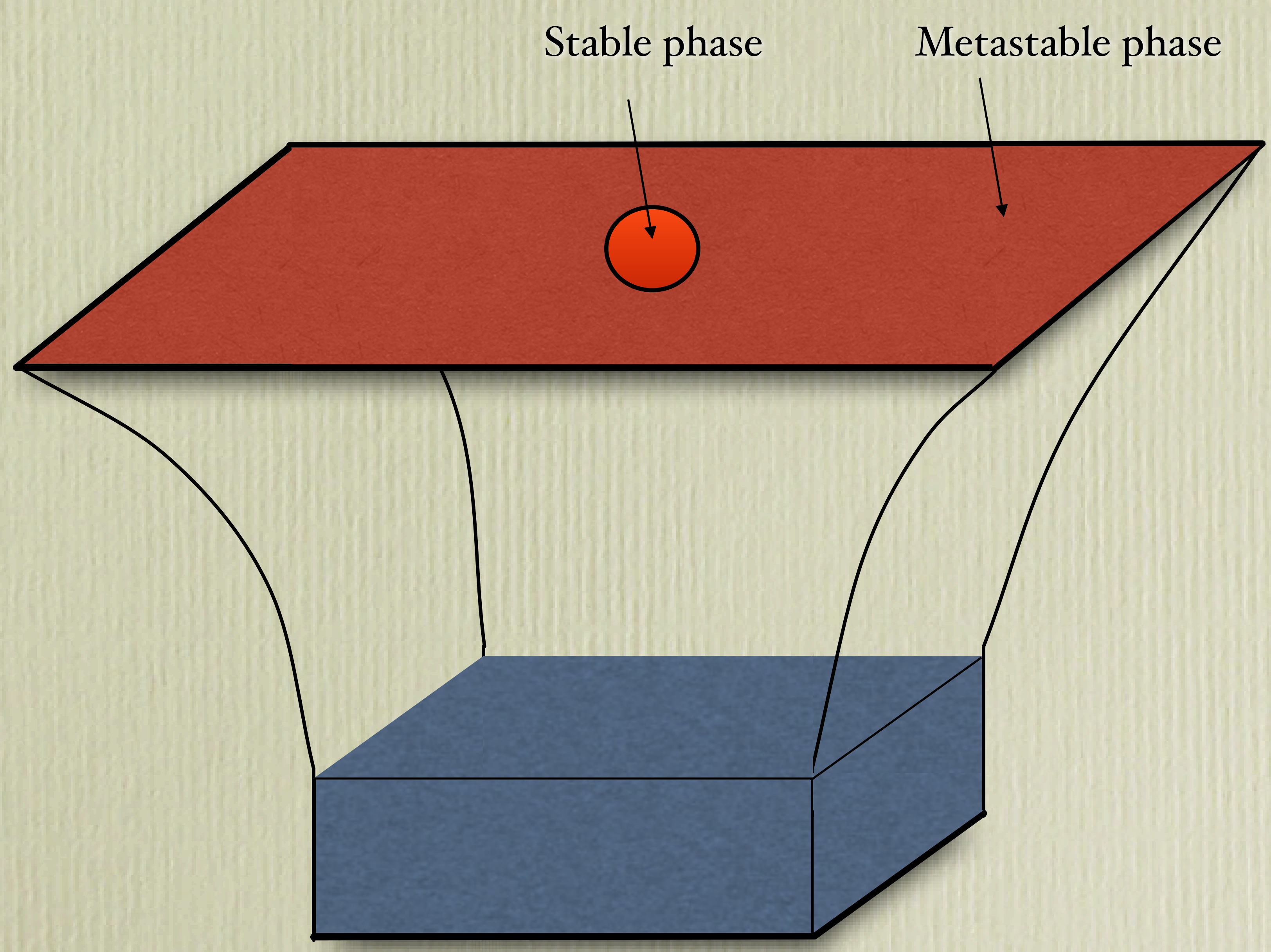
- But it can be computed in holographic models.



Strategy

- Set up initial conditions...



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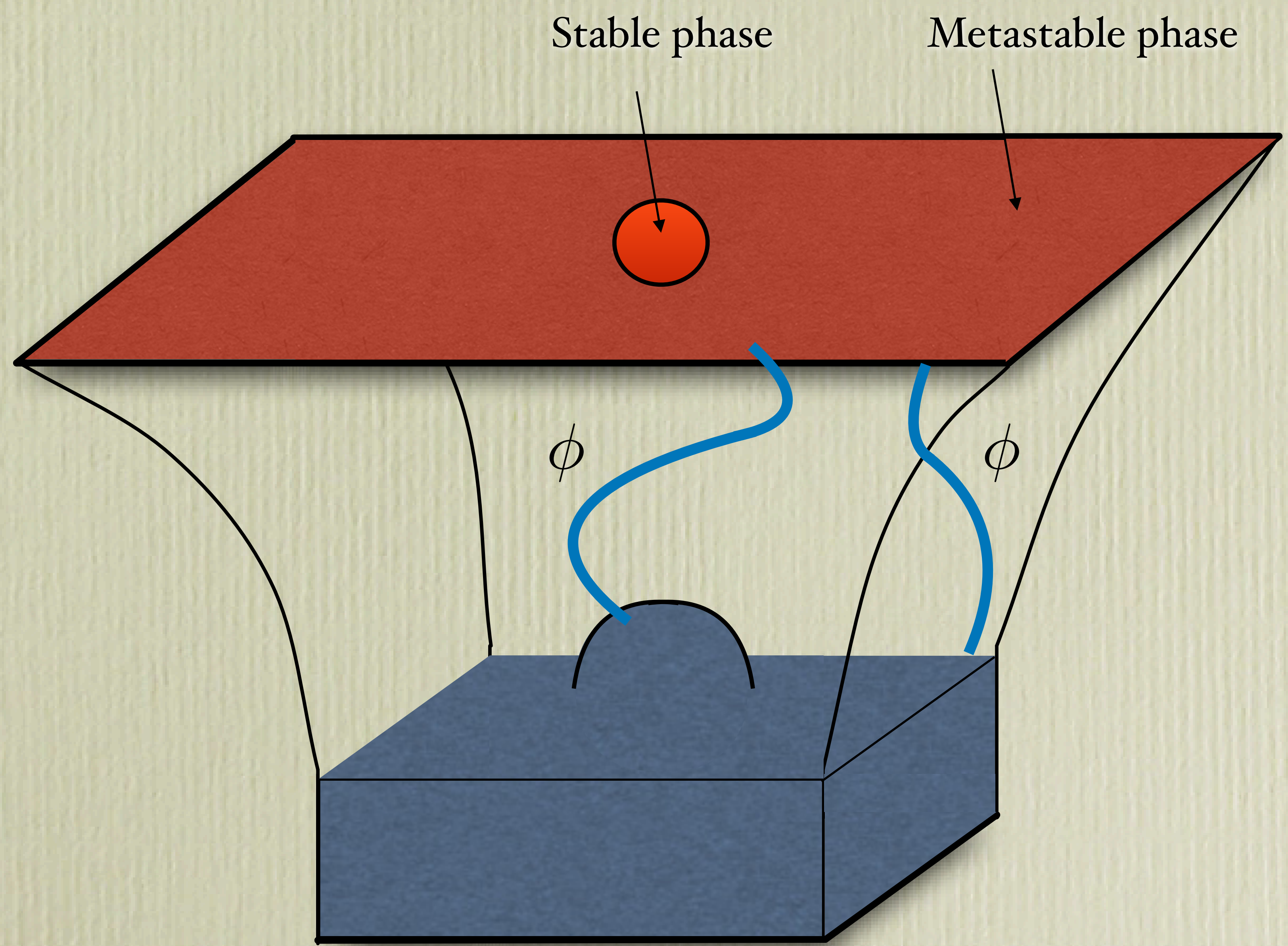
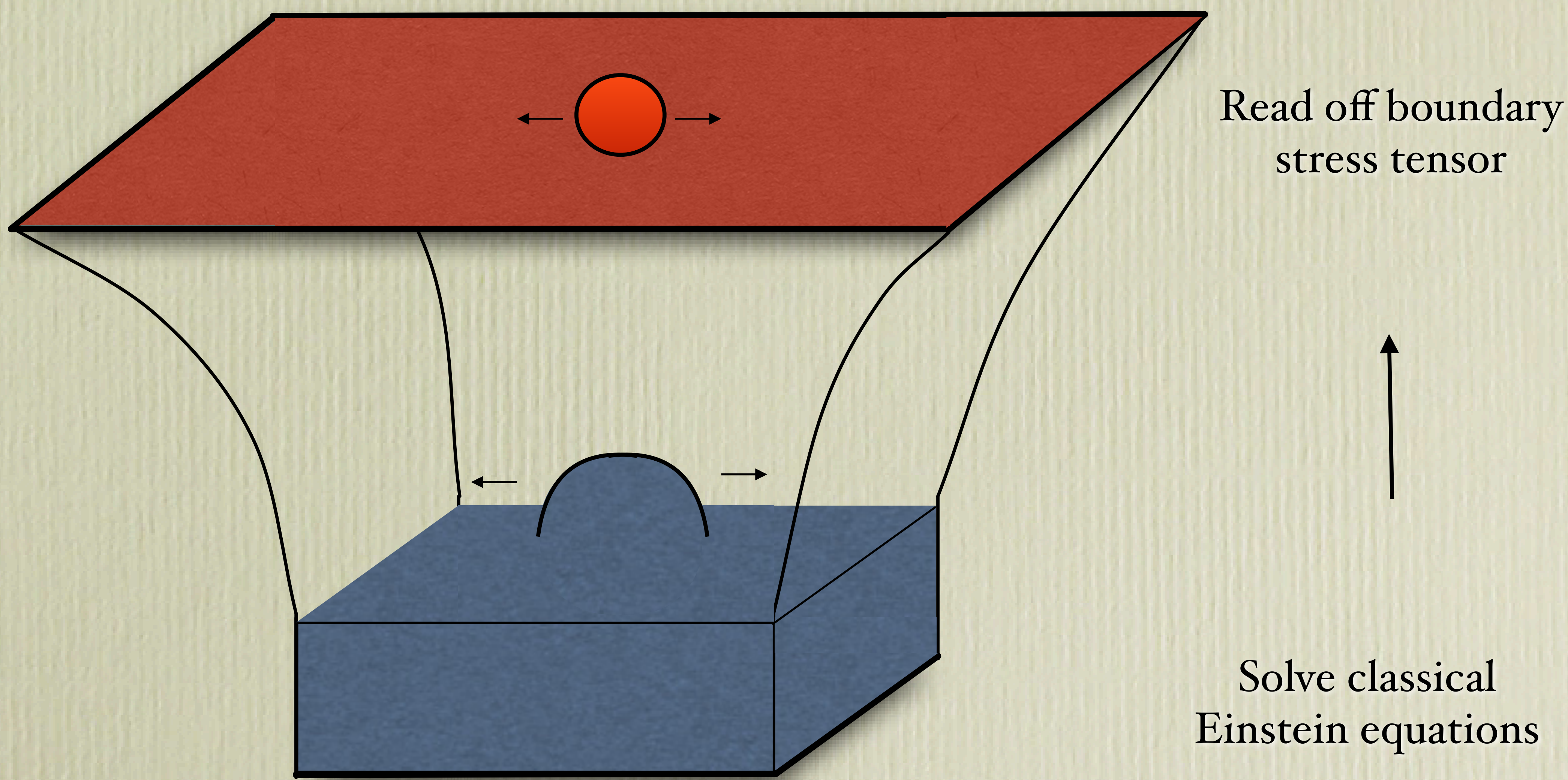


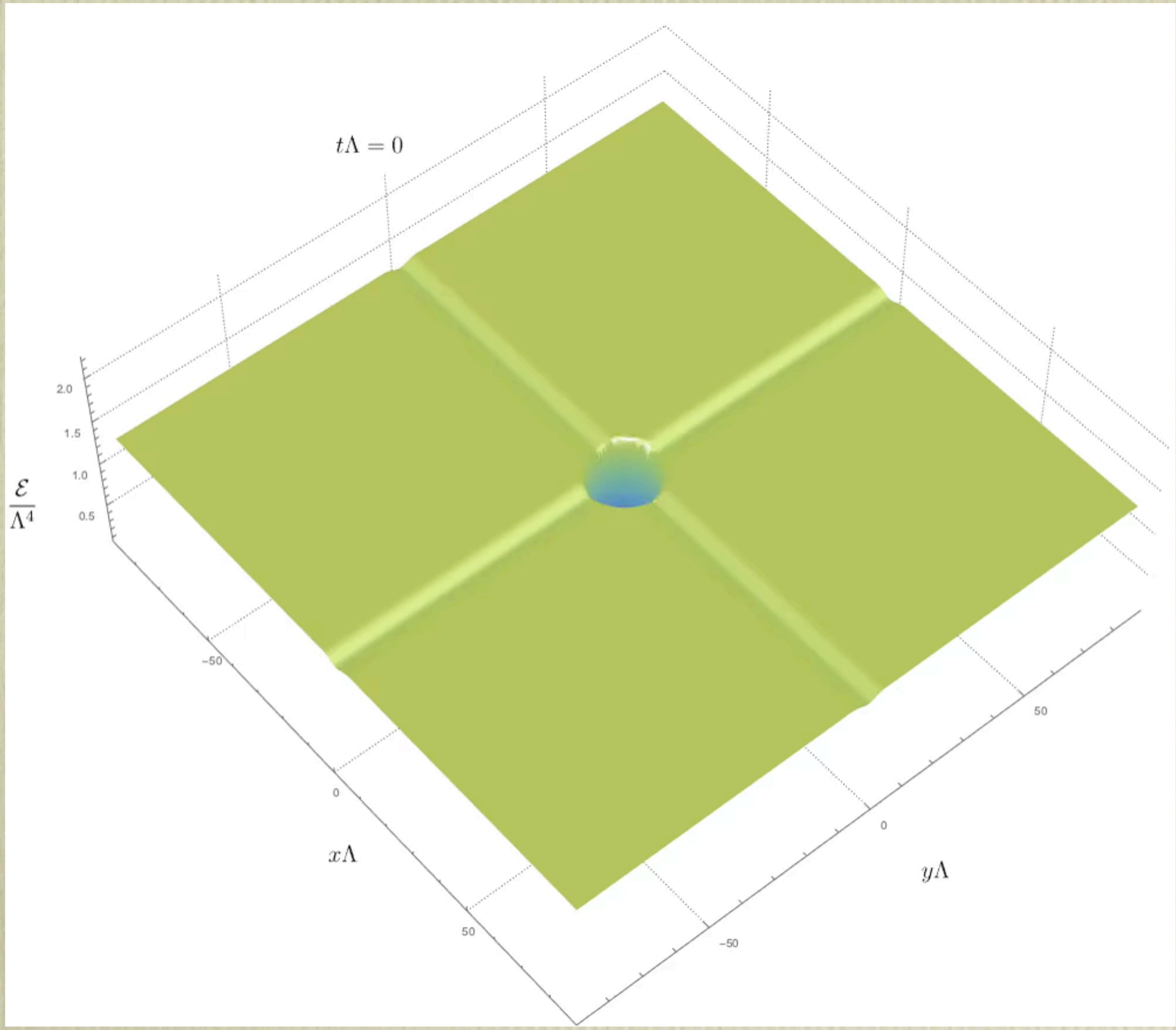
Strategy

- Set up initial conditions... and let it go.



Bubble expansion

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



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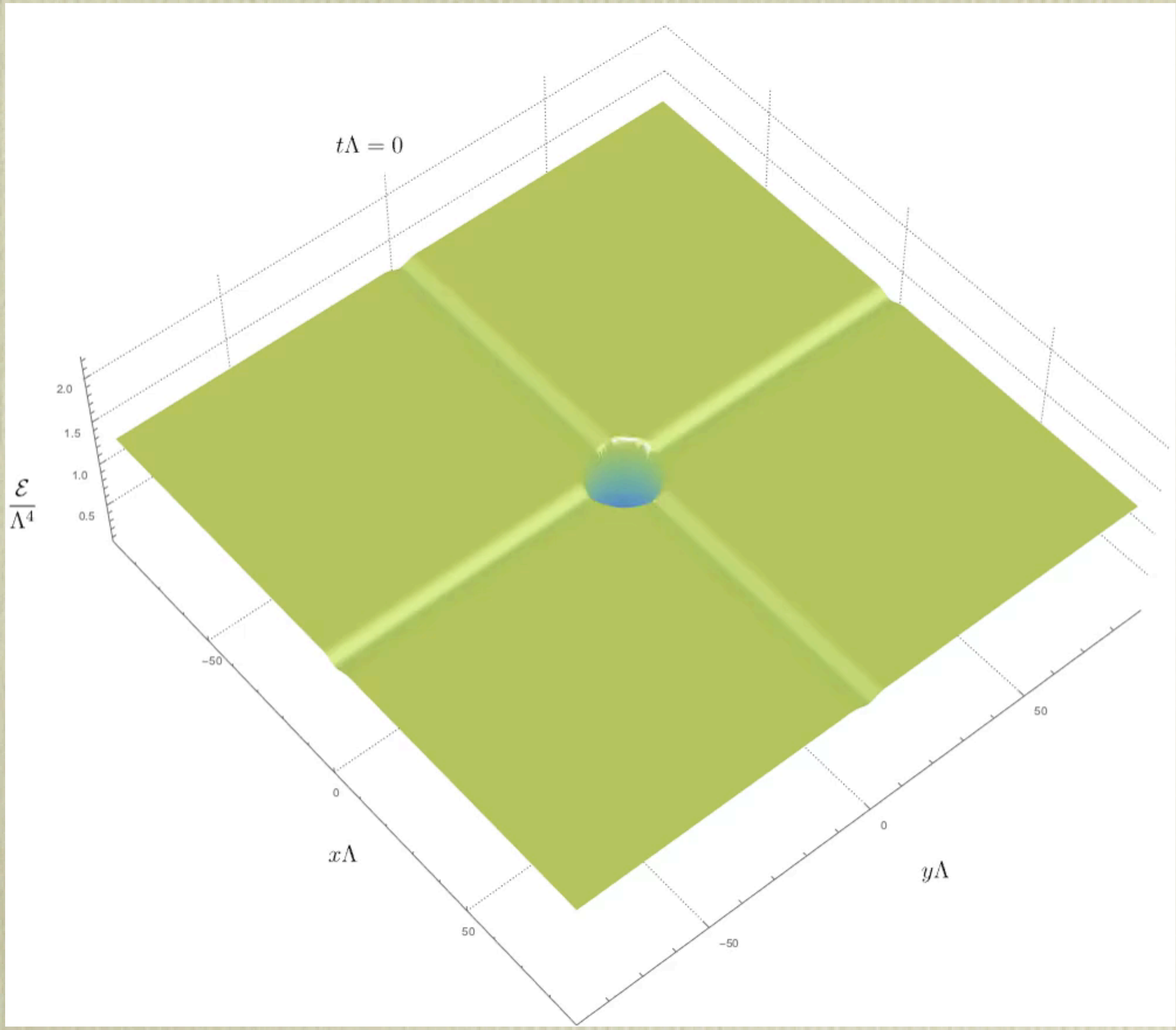
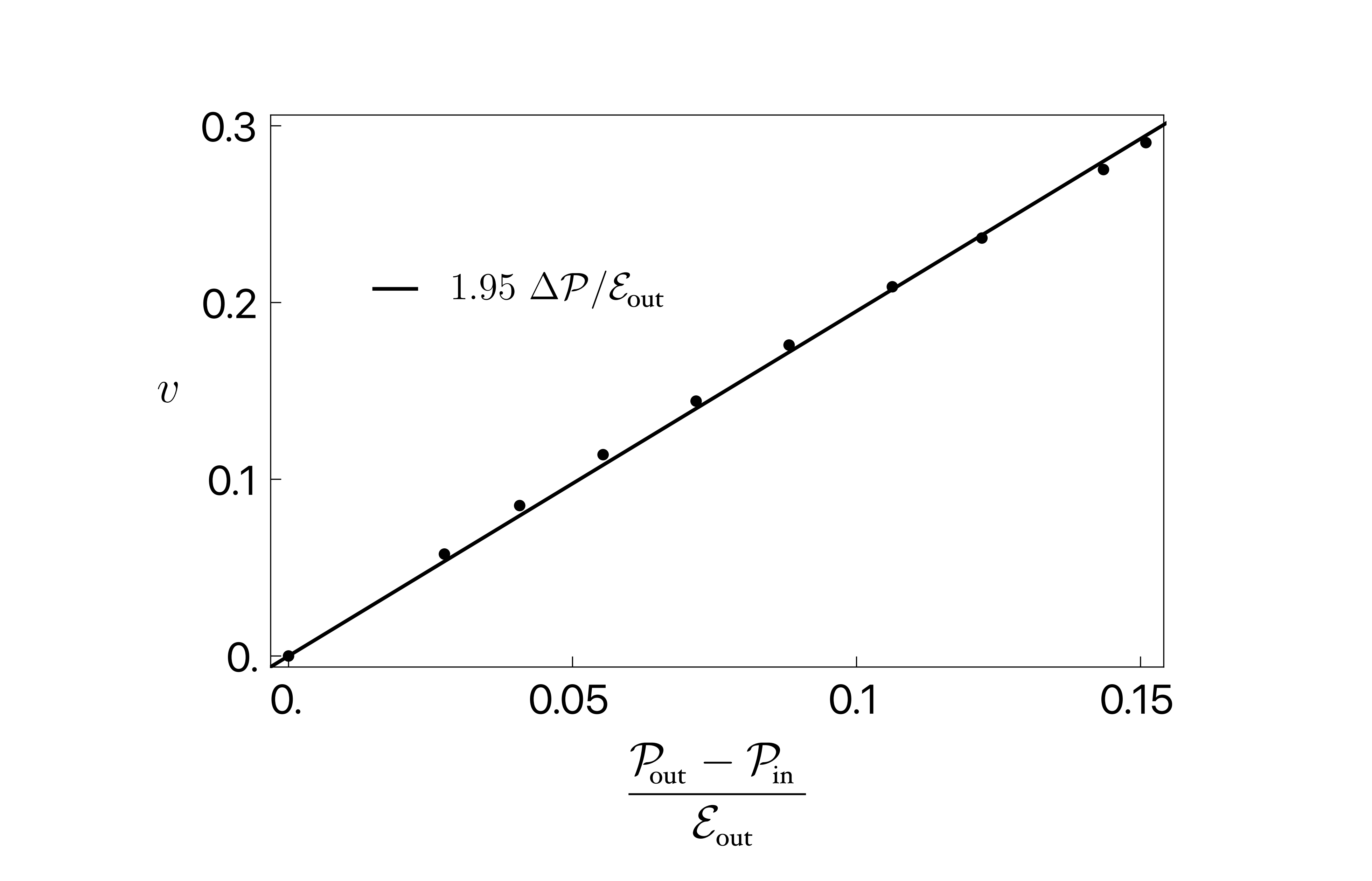


Bubble wall velocity

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

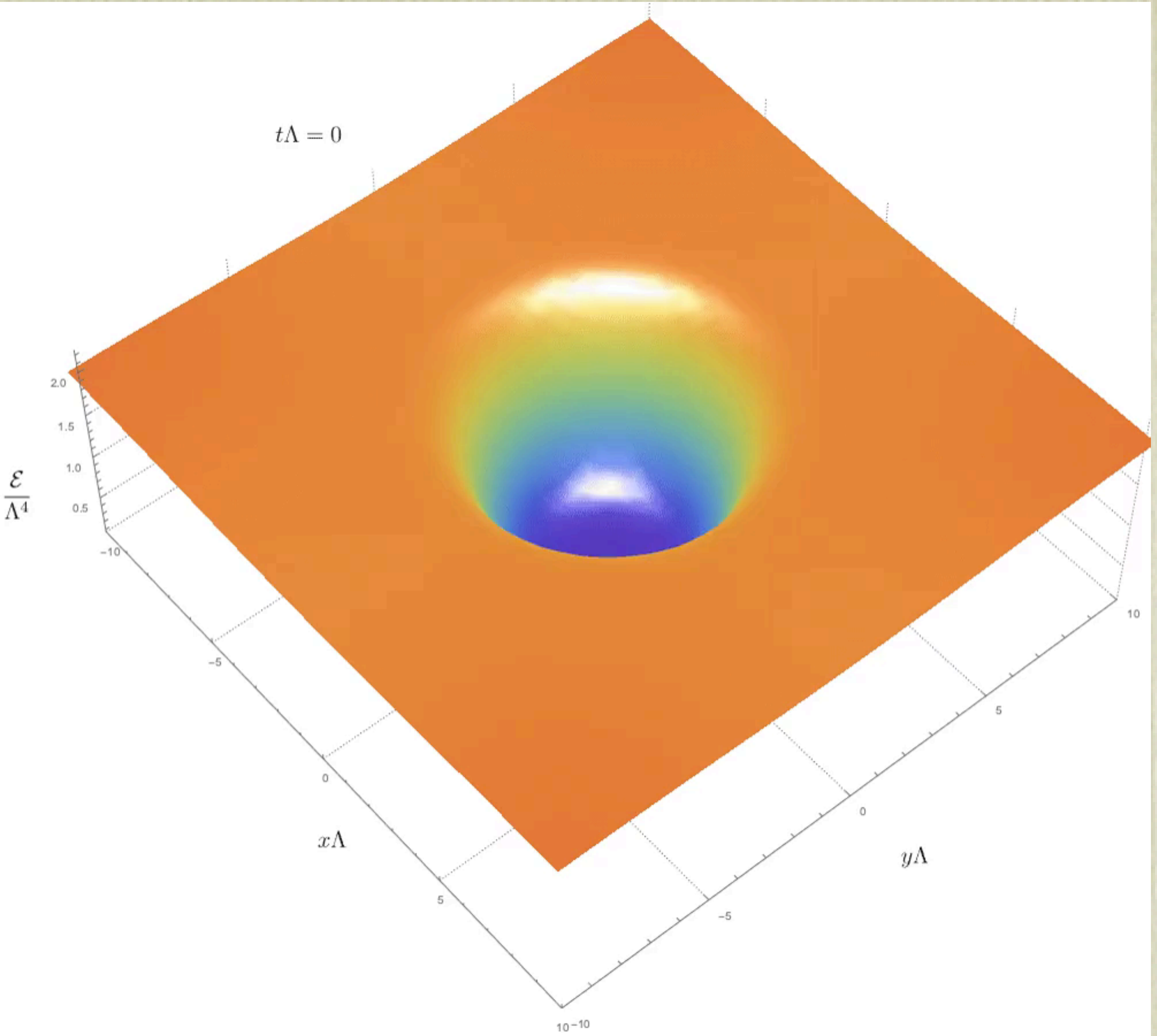
- First calculation of bubble wall at strong coupling (*preliminary*):



Critical bubbles

Bea, Casalderrey, Giannakopoulos, Jansen, DM, Sanchez-Garitaonandia & Zilhao '22

- If initial bubble is too small it collapses instead of expanding:



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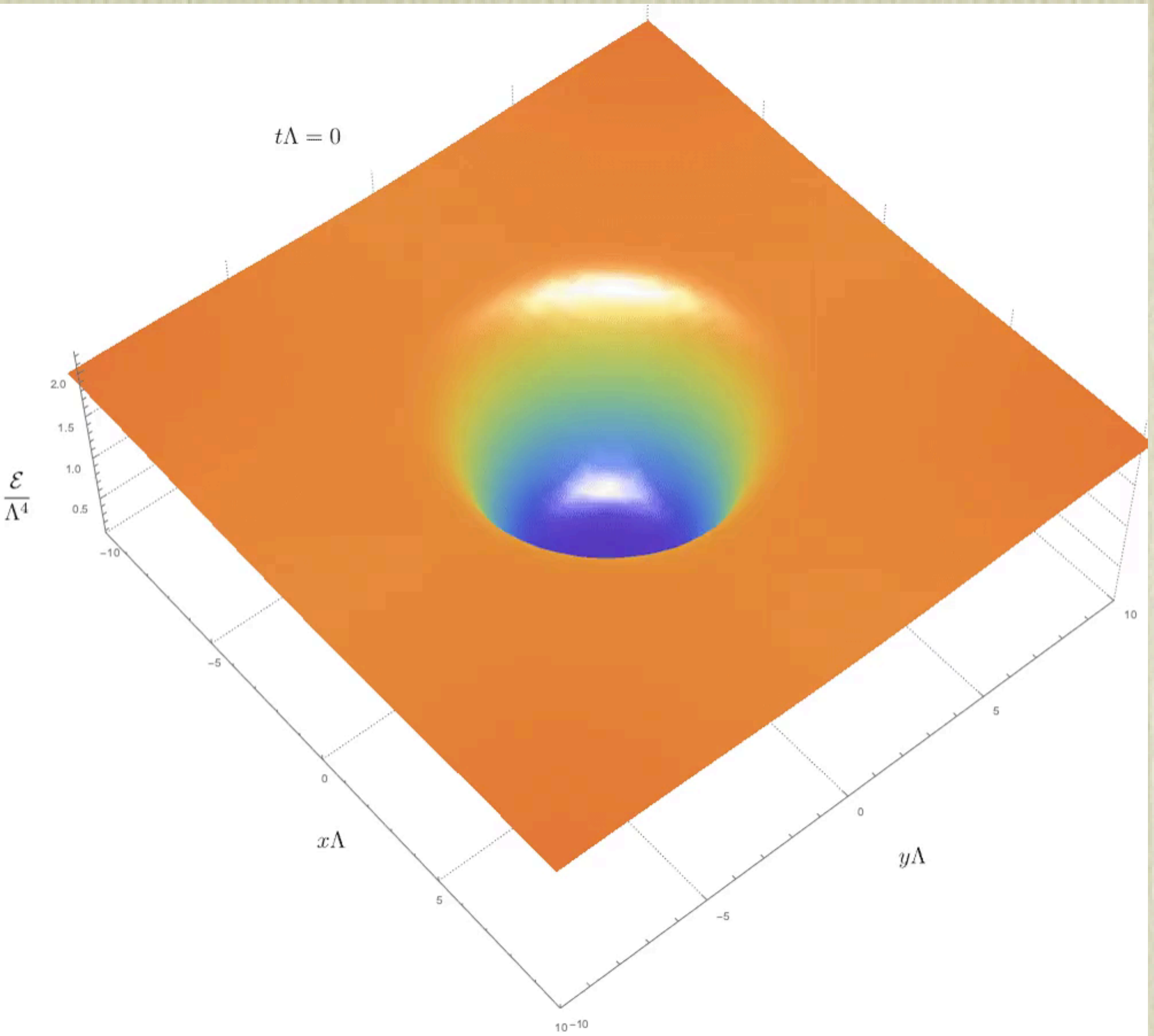
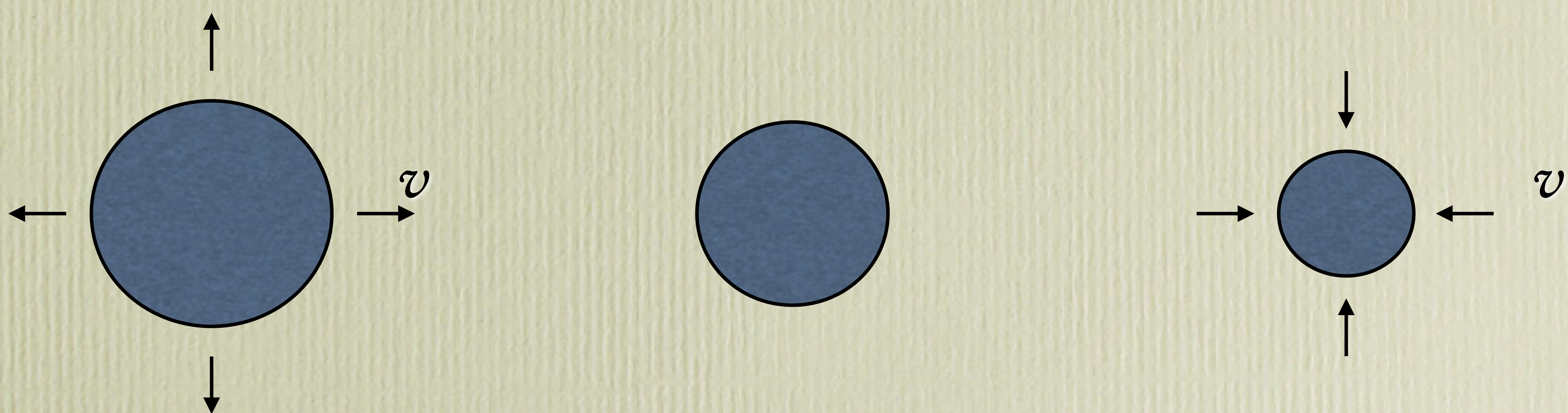


Critical bubbles

Bea, Casalderrey, Giannakopoulos, Jansen, DM, Sanchez-Garitaonandia & Zilhao ‘22

- By tuning initial conditions, this allows us to find the critical bubble:



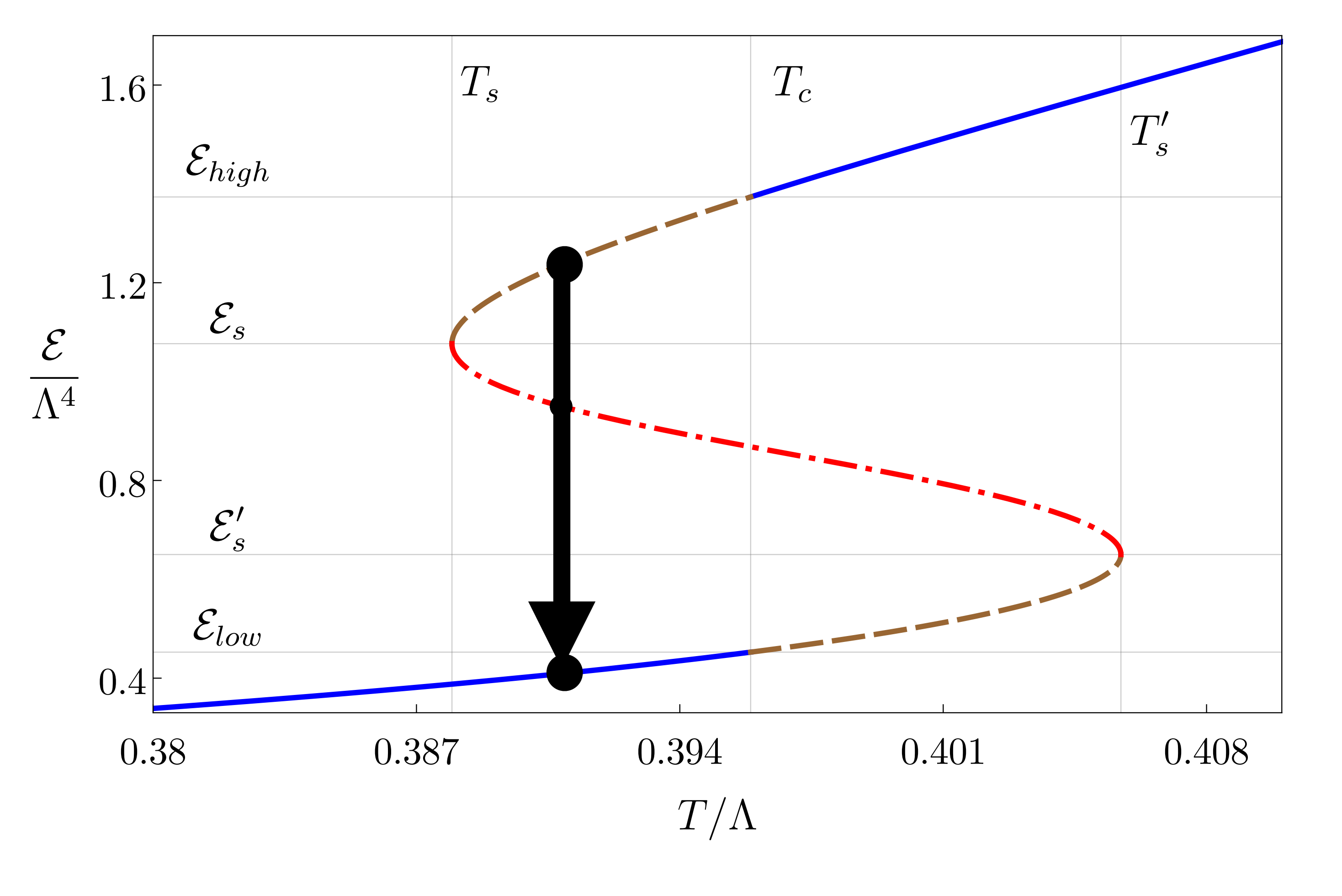
Expanding

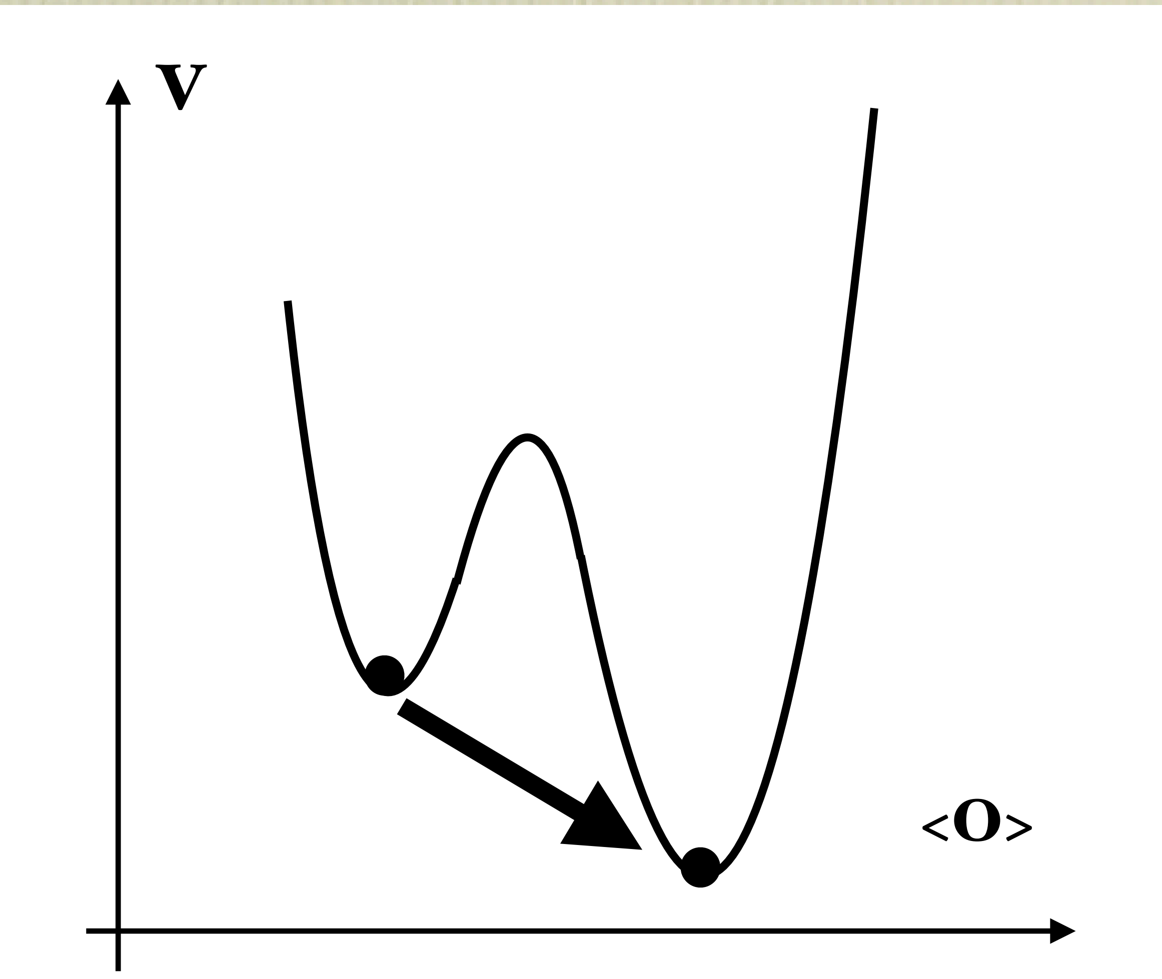
Critical

Collapsing

Critical bubbles

- Critical bubble is important because it determines nucleation probability:



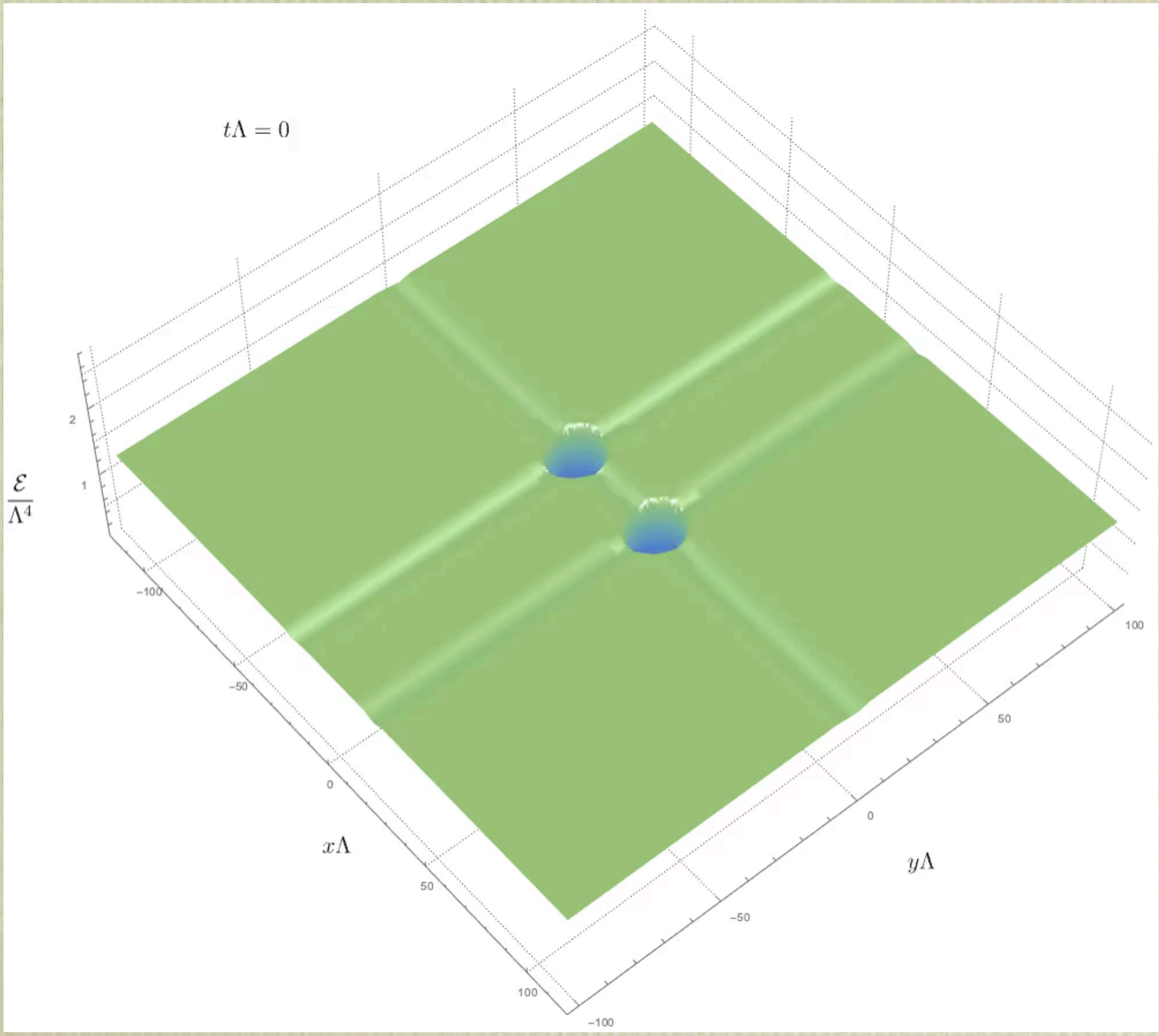


$$P \sim e^{-S_{critical\ bubble}}$$

Bubble collisions and GW spectrum

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

- Computing the GW spectrum requires considering collisions of bubbles.



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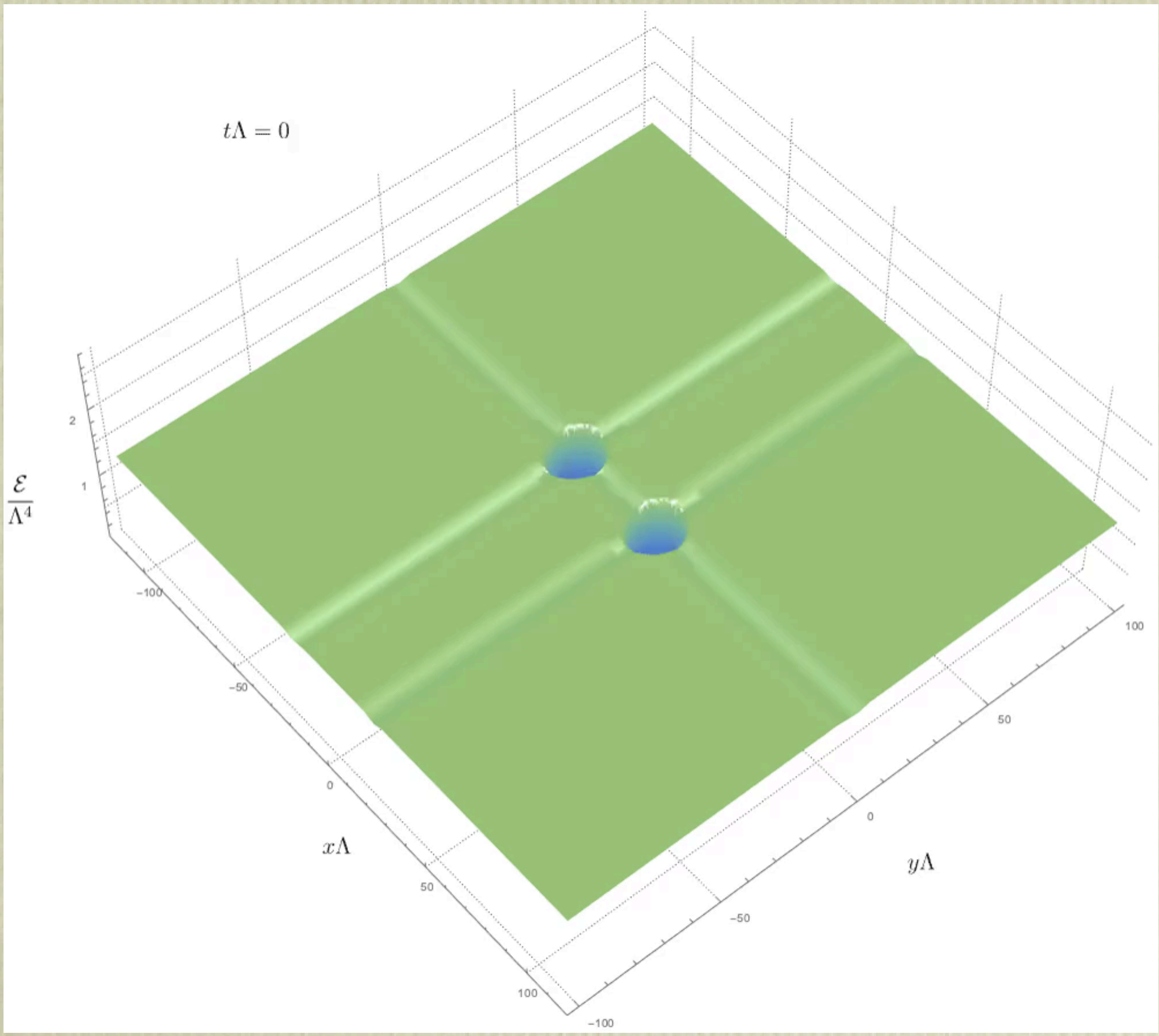


Bubble collisions and GW spectrum

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:

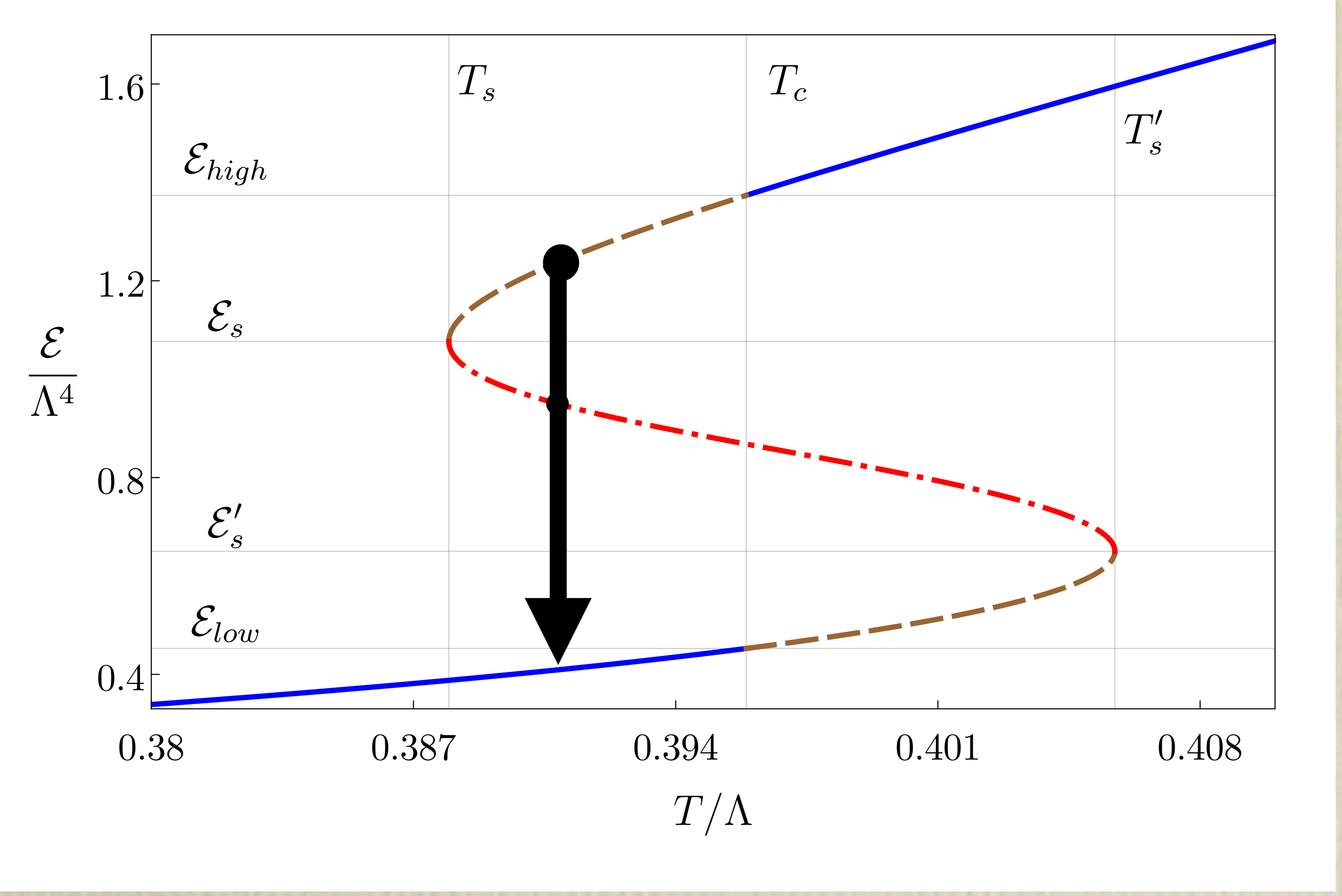
    - Bubble expansion.
    - Bubble collisions.
    - Sound modes.
    - Turbulence.
    - Etc.

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.

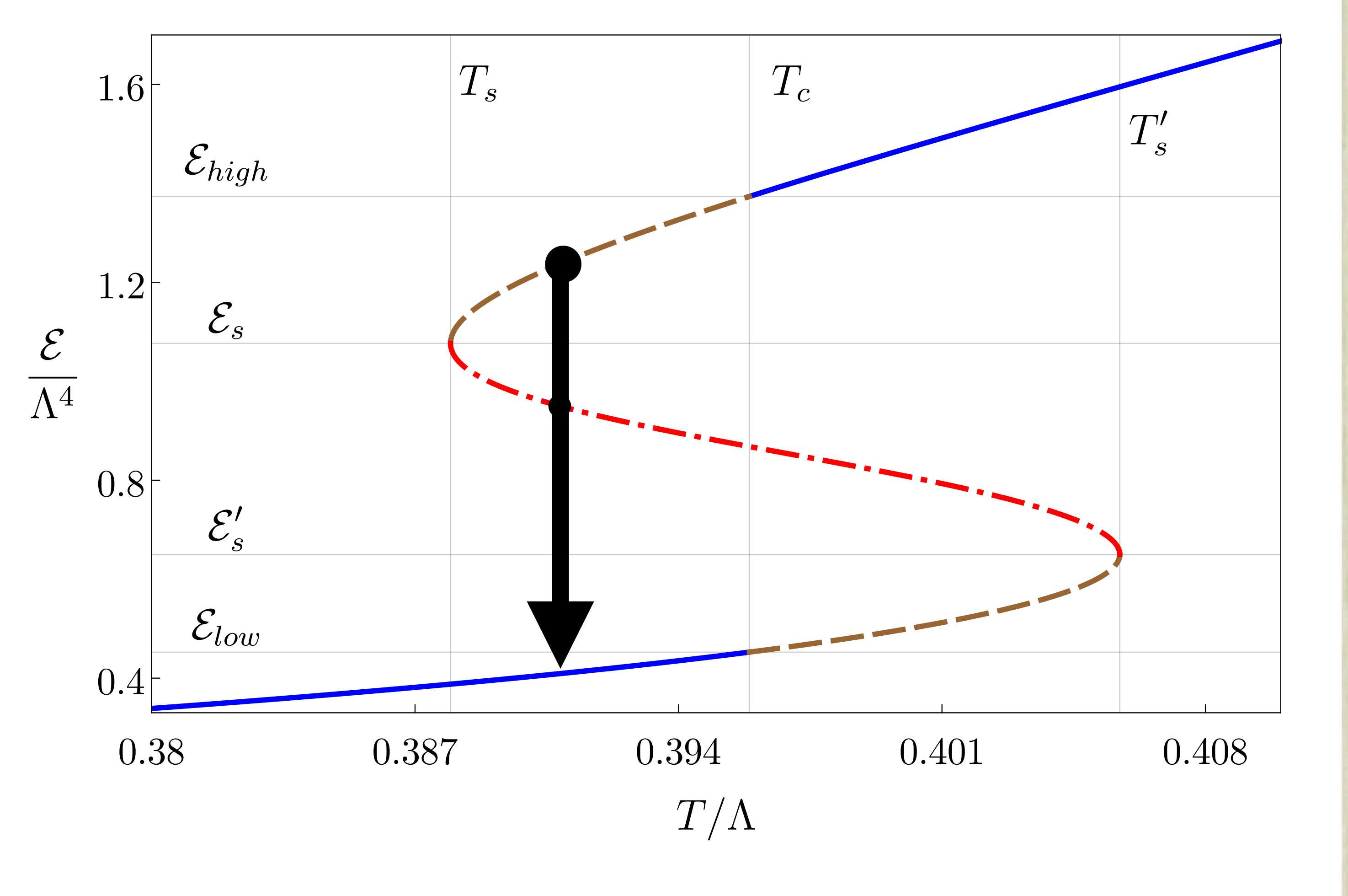


Spinodal gravitational waves

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:

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



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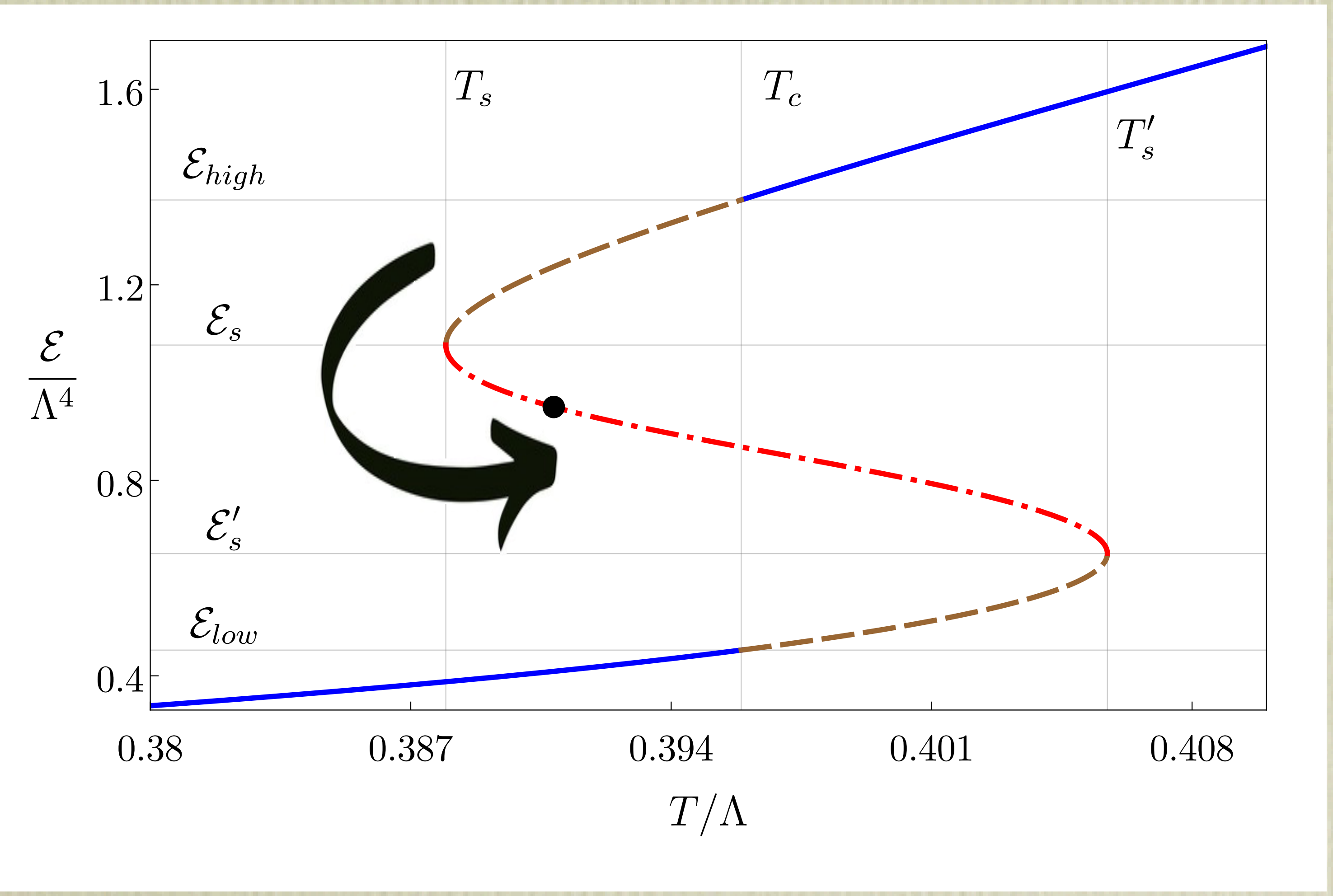
Bea, Casalderrey, Giannakopoulos, Jansen, Krippendorf, DM, Sanchez-Garitaonandia & Zilhao ‘21

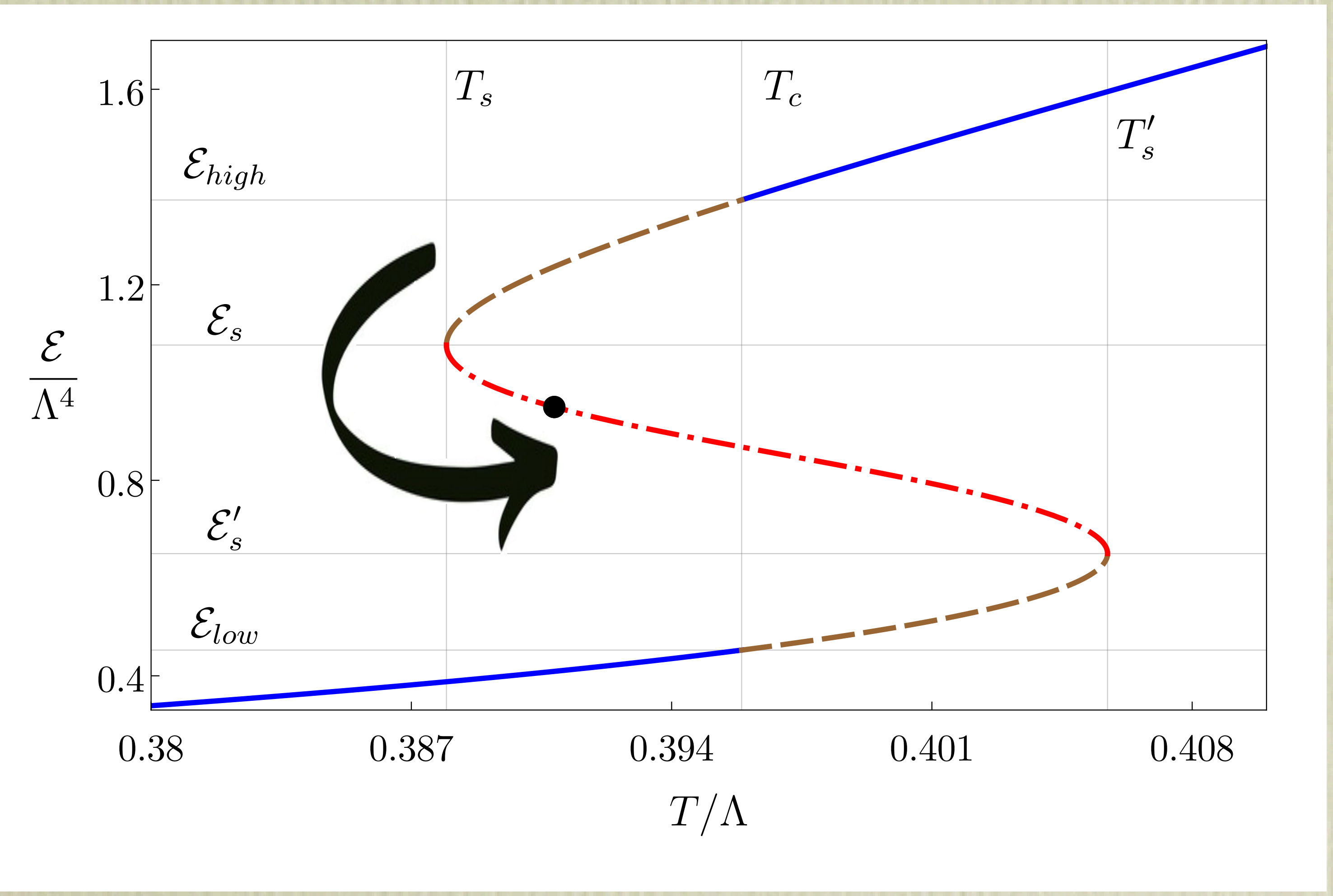
- Under these circumstances the Universe enters the spinodal region.



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.



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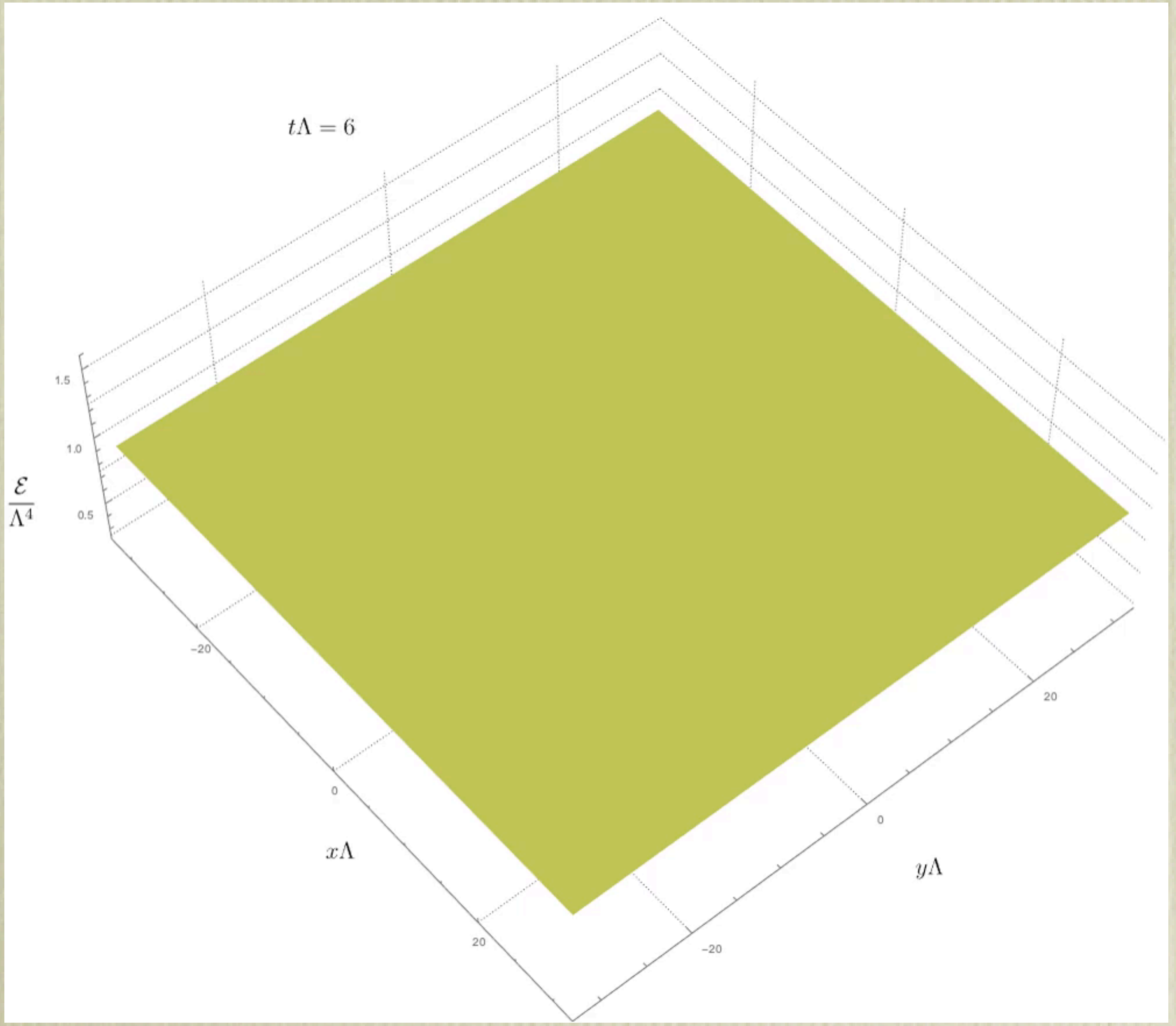
- Holography can compute the evolution if we *ignore the expansion of the Universe*:



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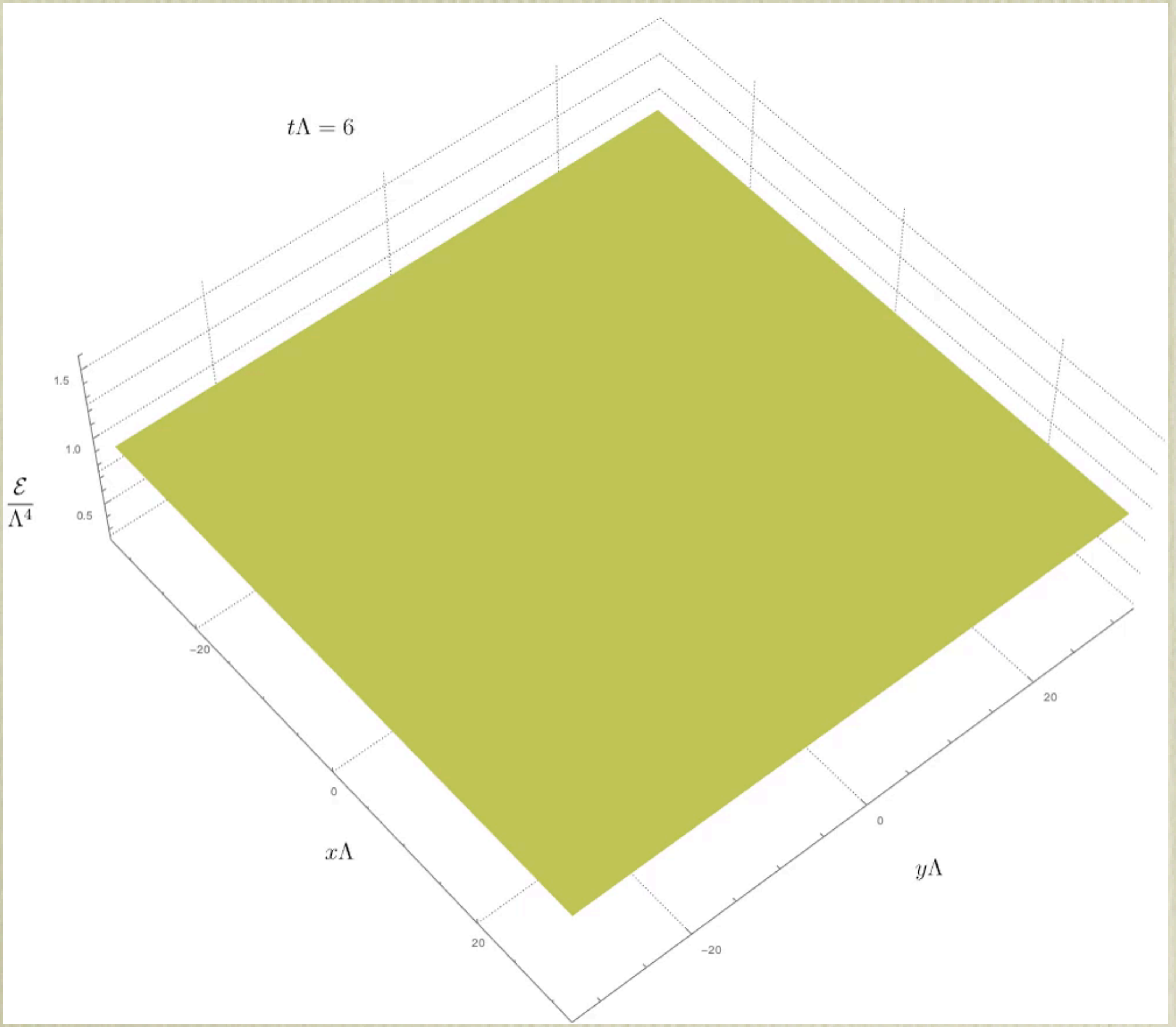
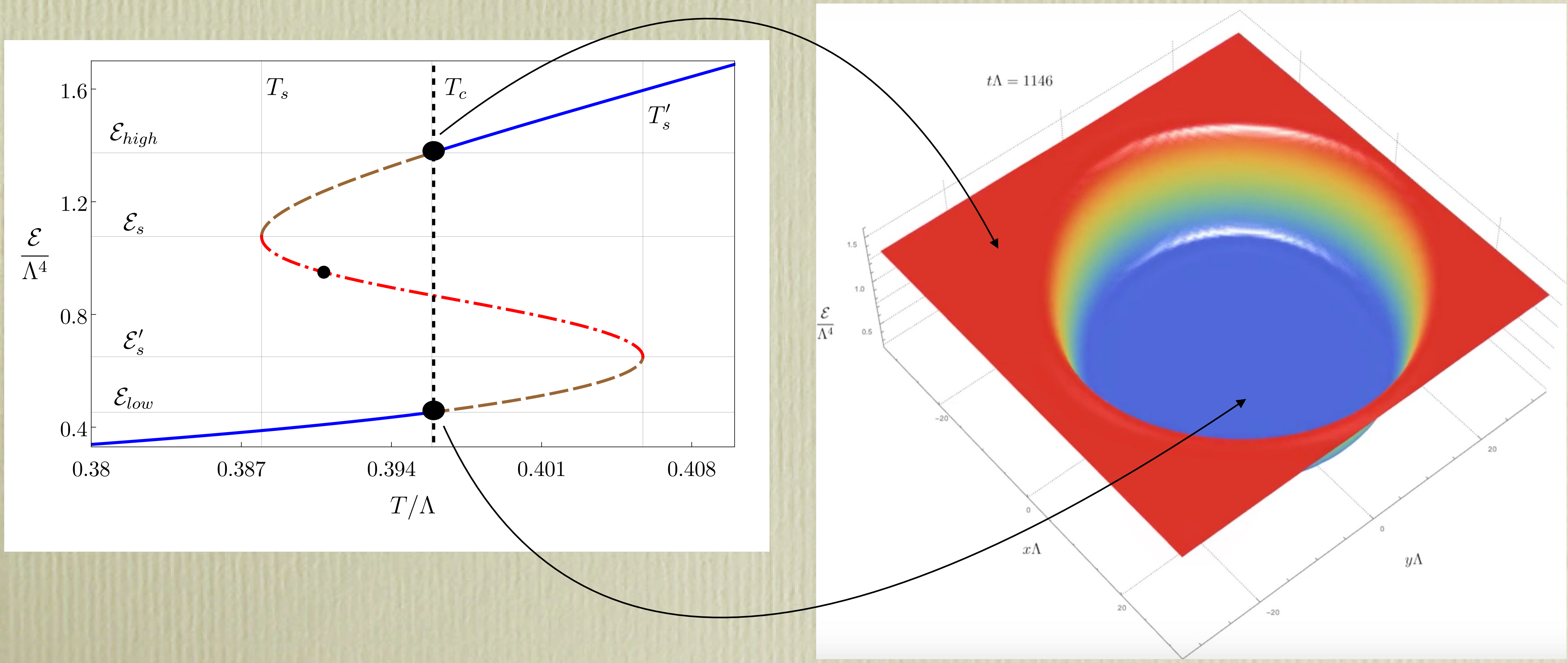


Spinodal gravitational waves

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

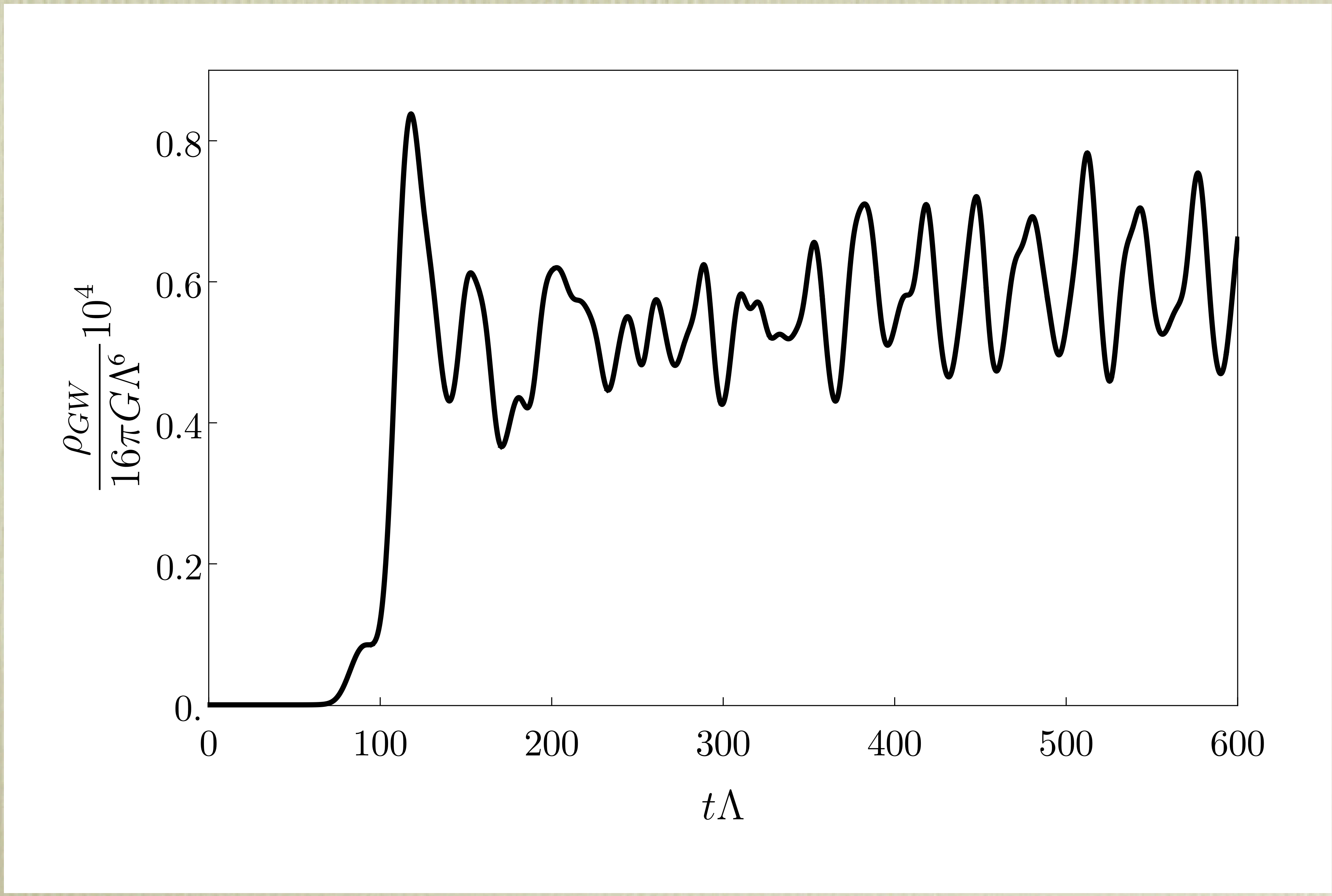
- Final state in fixed box with constant total energy is phase separated state at constant T=T_c :



Spinodal gravitational waves

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

- Fast redistribution of energy produces GWs.



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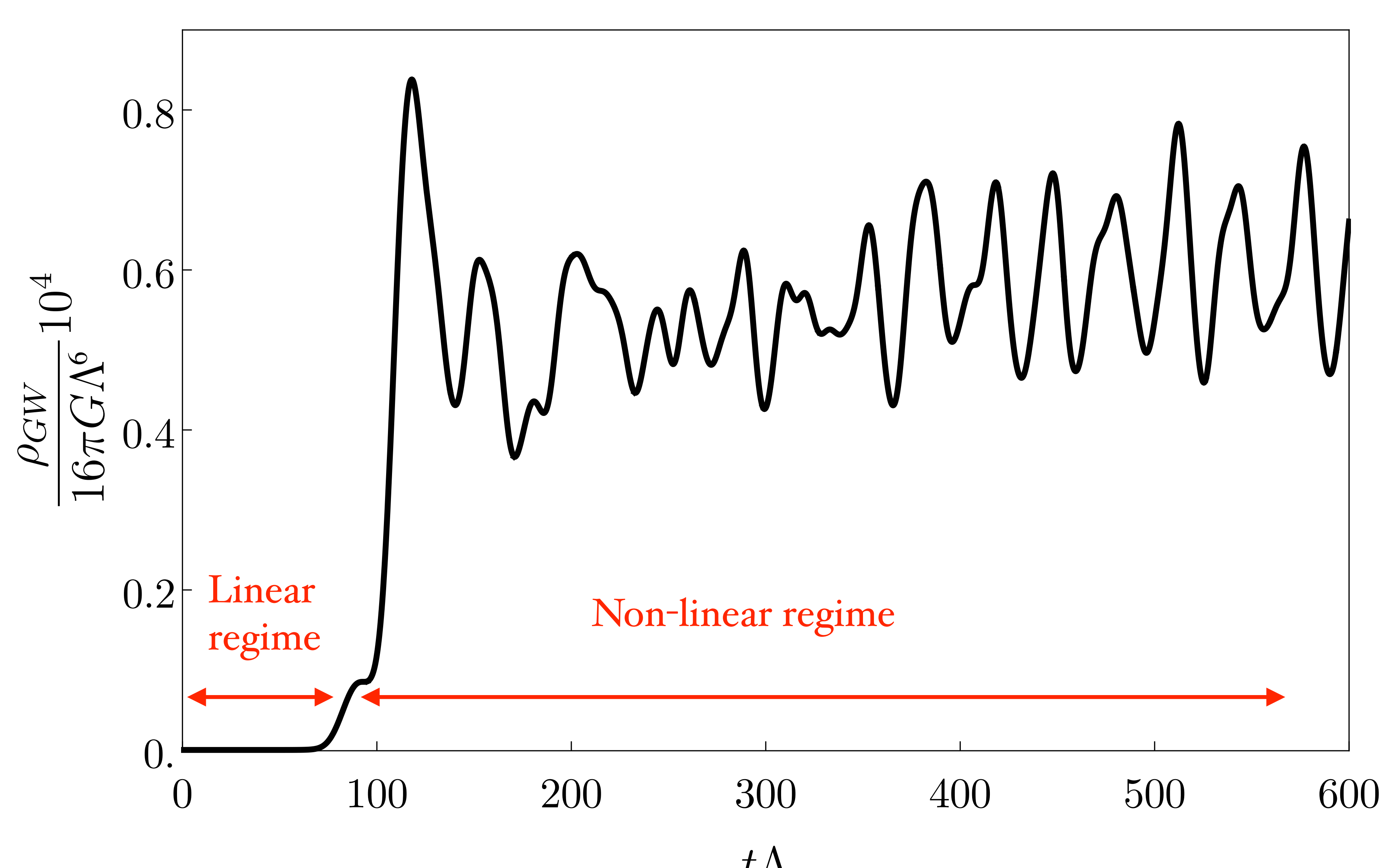

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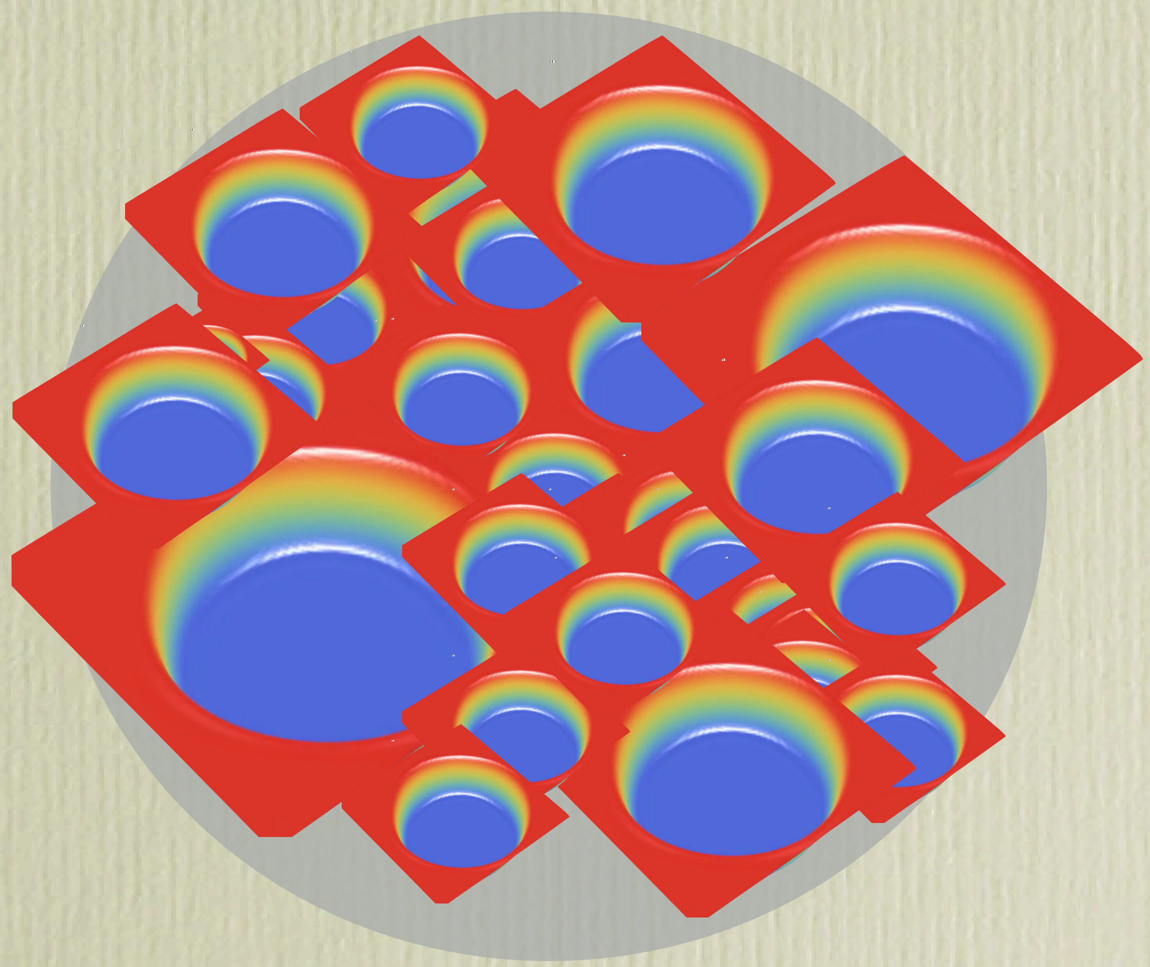

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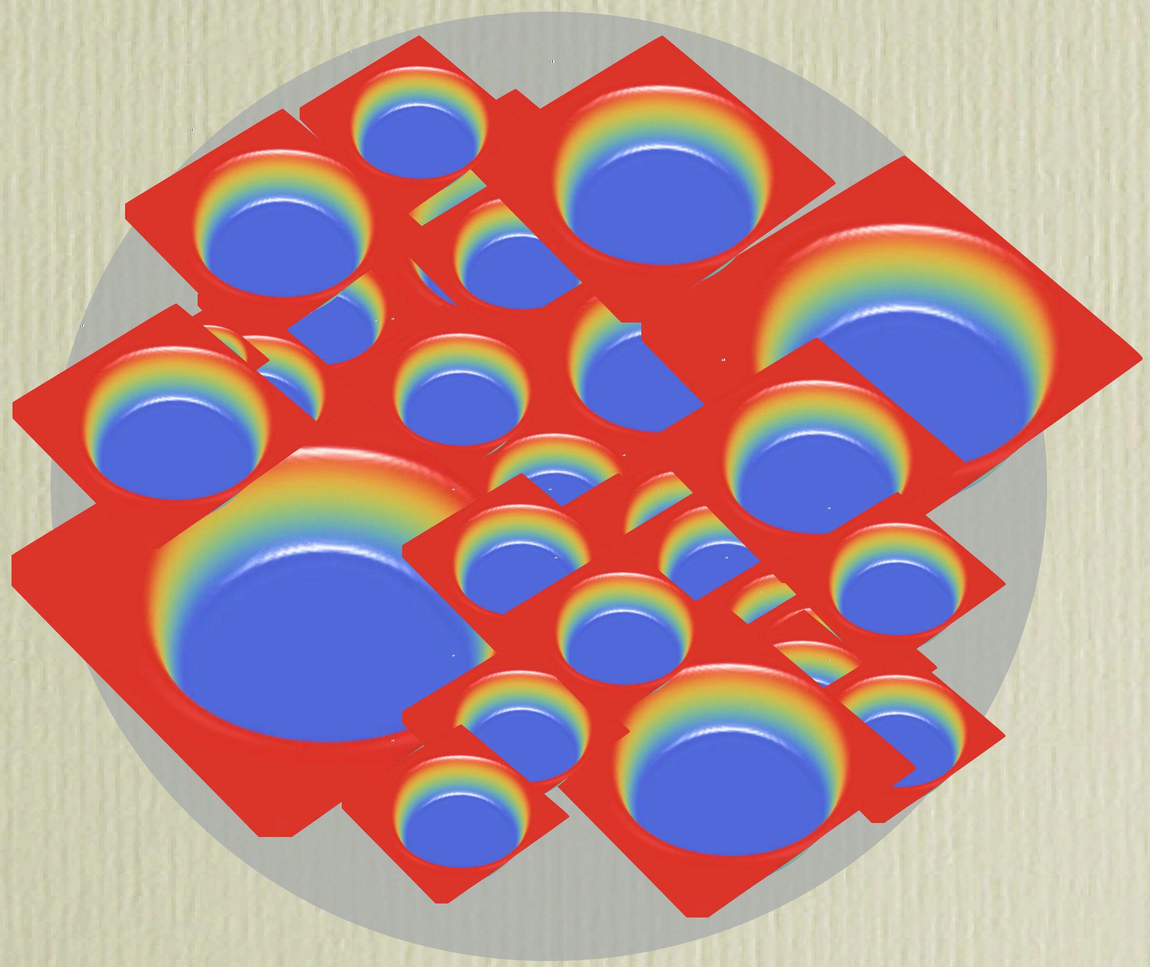
- Time and length scales are parametrically shorter than H^{-1}.
- The result is a very inhomogeneous state within a Hubble patch.
- Subsequent dynamics is very long and very non-linear.



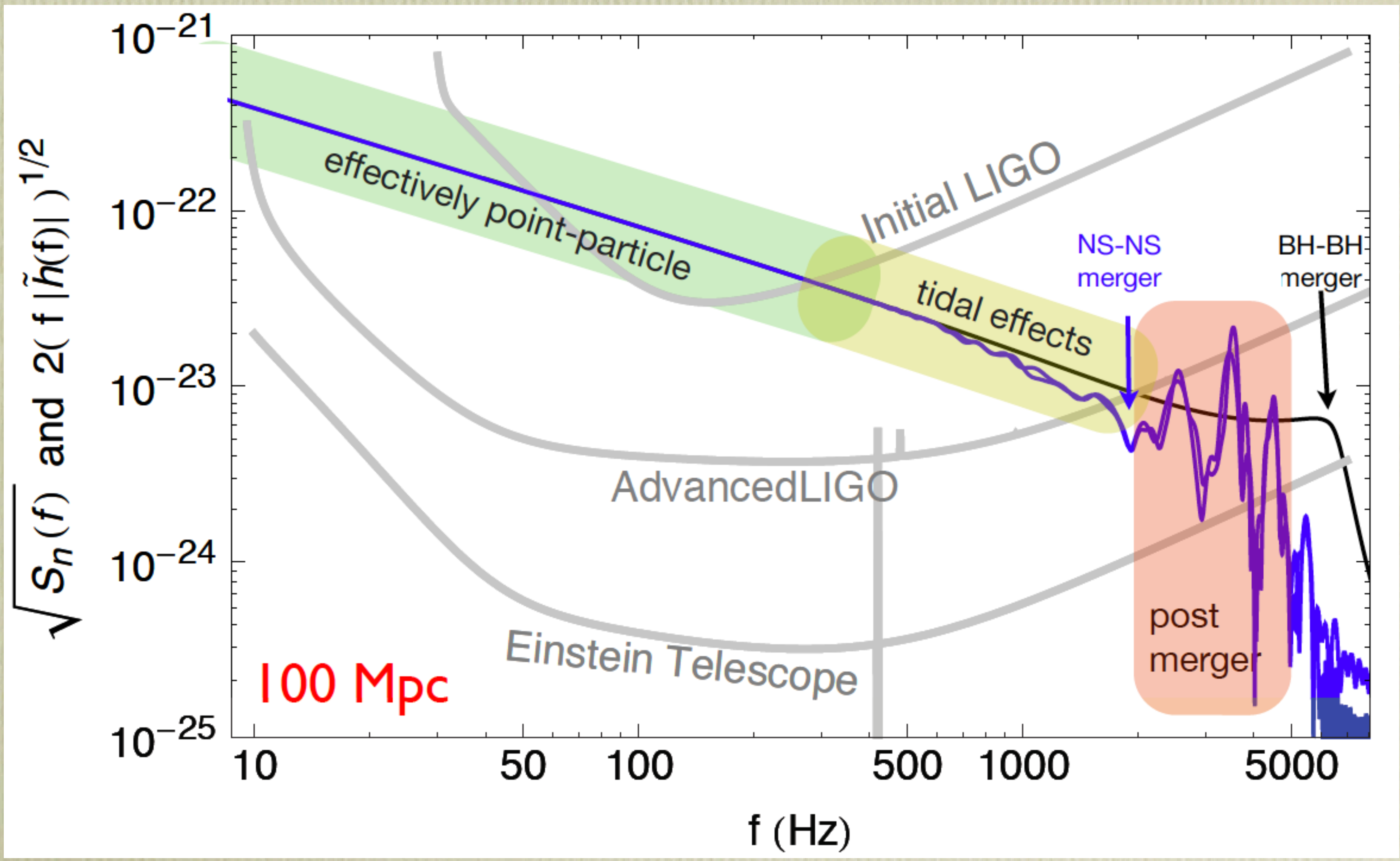
Spinodal gravitational waves

See talk by Mikel Sanchez for more details

Phase Transitions in Neutron Star Mergers

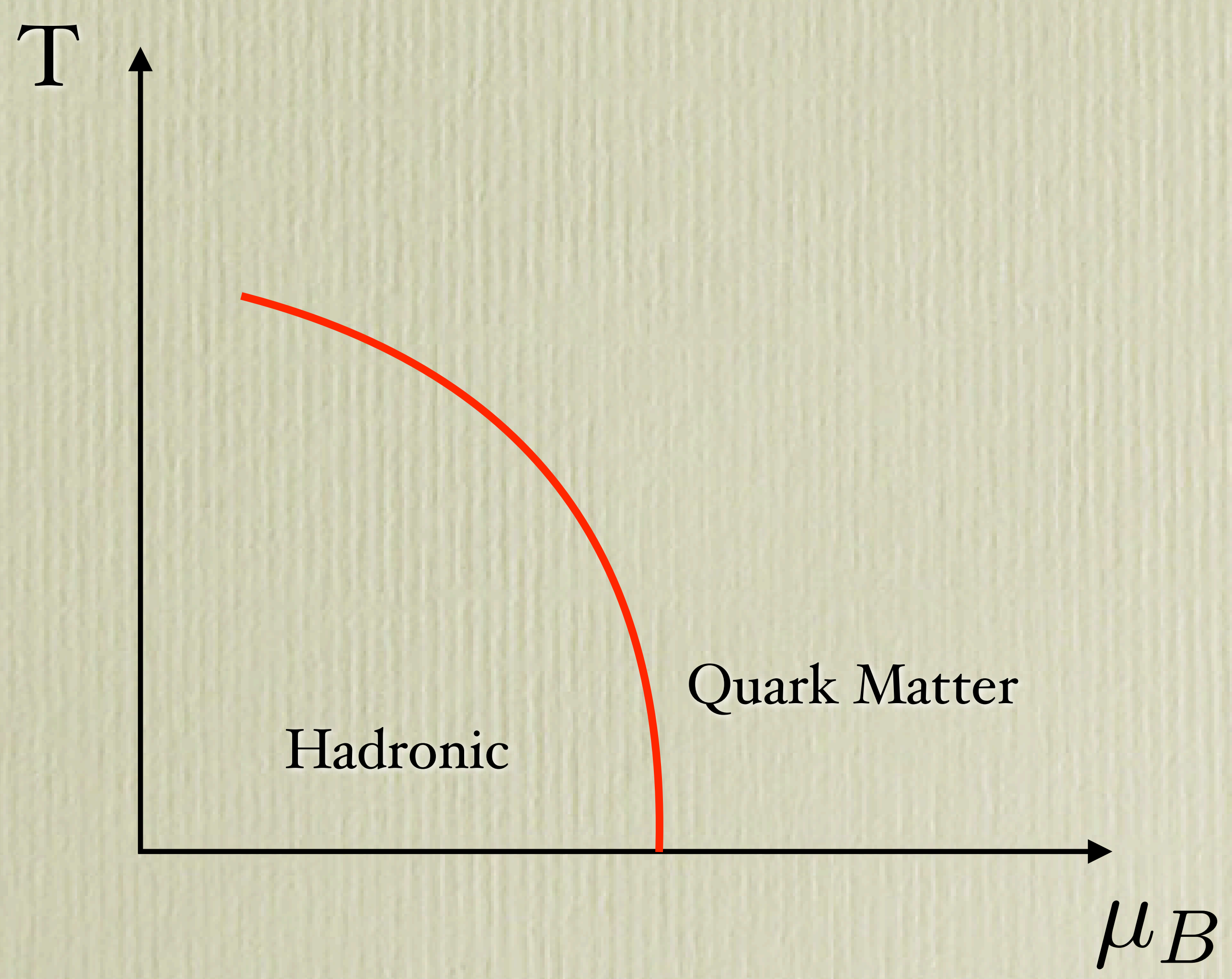
Neutron star mergers

- Known to produce signal in kHz range.



Neutron star mergers

- Known to produce signal in kHz range.
- However, suppose that QCD has a first-order phase transition, e.g.:

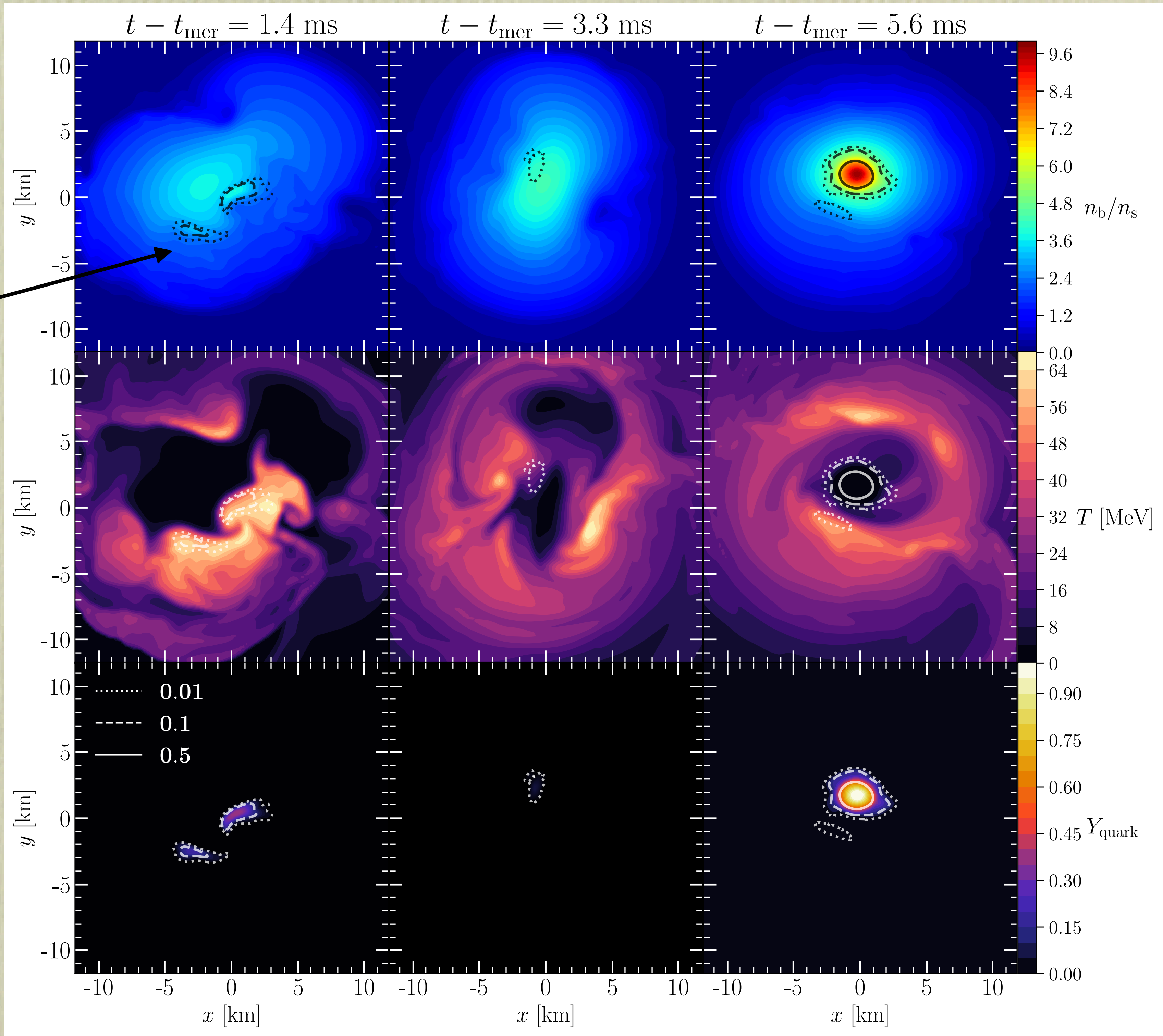


Neutron star mergers

- Then simulations show the formation of quark matter.

Tootle, Ecker, Topolski, Demircik, Jarvinen, & Rezzolla '22

Hot or Compressed Spots (HoCS)



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Casalderrey-Solana, DM & Sanchez-Garitaonandia '22

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- But they have not discussed the *mechanism* for its formation:
  Nucleation of superheated/supercompressed bubbles.

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Casalderrey-Solana, DM & Sanchez-Garitaonandia '22

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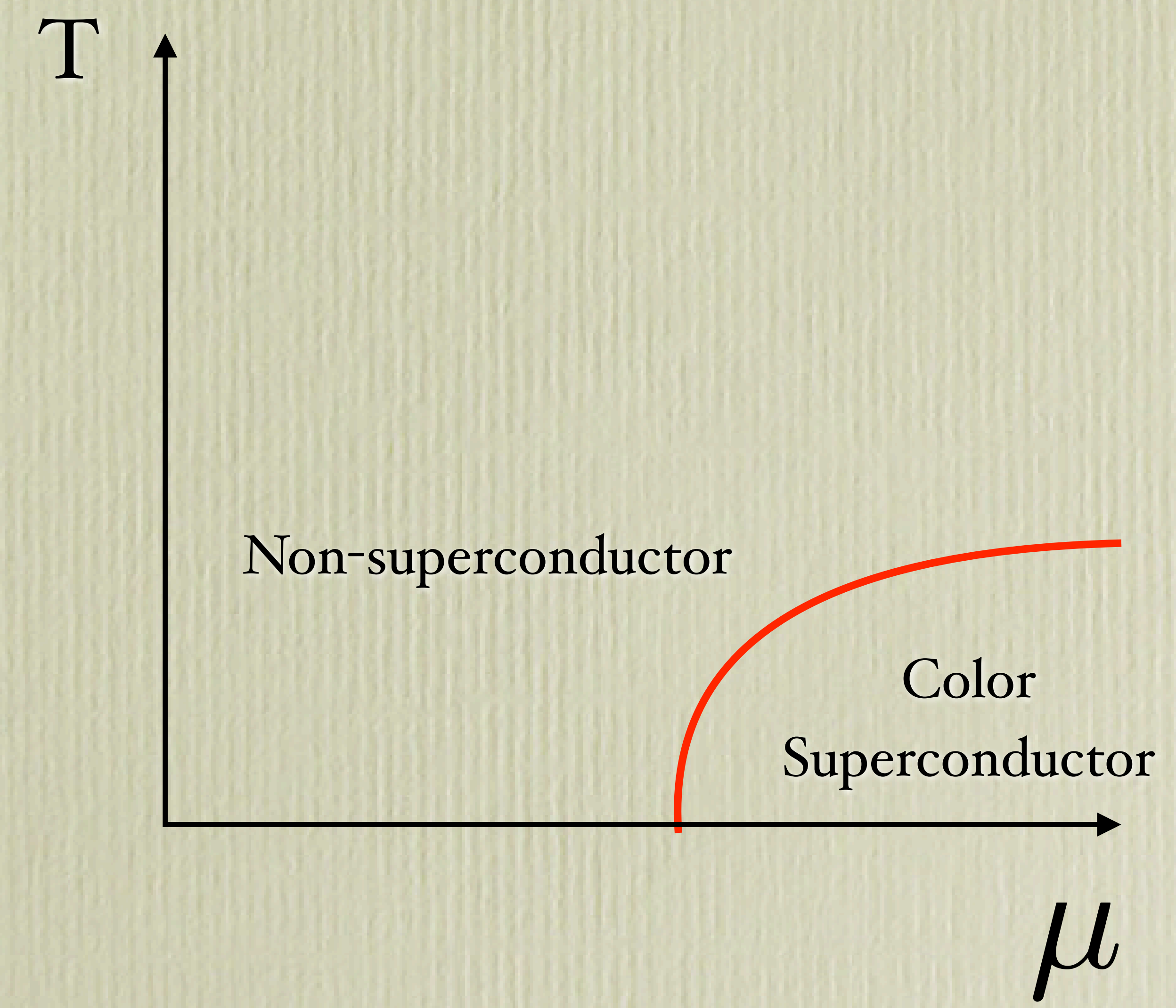
- But they have not discussed the *mechanism* for its formation: Nucleation of superheated/supercompressed bubbles.
- As in Cosmology, this leads to the production of GWs.
- The frequency is in the MHz range.
- The amplitude is large enough that it might be detectable in future experiments at distances of tens of Mpc.

Neutron star mergers

- Density in NS merger can reach 10 x saturation density, so....



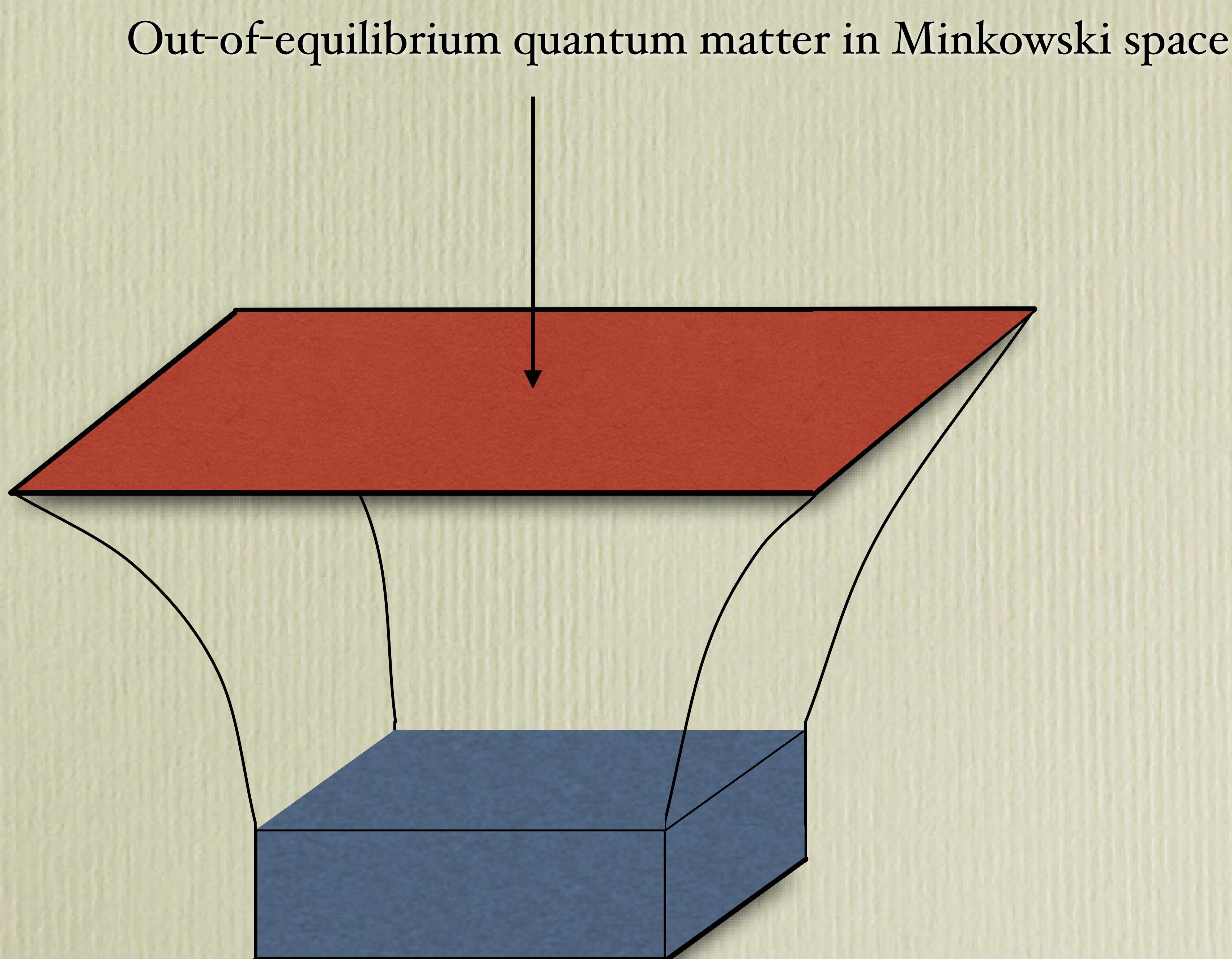
Neutron star mergers

See talk by Mikel Sanchez for more details

Holography with Dynamical Boundary Gravity

Dynamical gravity at the boundary

- So far we have studied:



Dynamical gravity at the boundary

- But many problems require:

Out-of-equilibrium quantum matter + Classical dynamical gravity

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

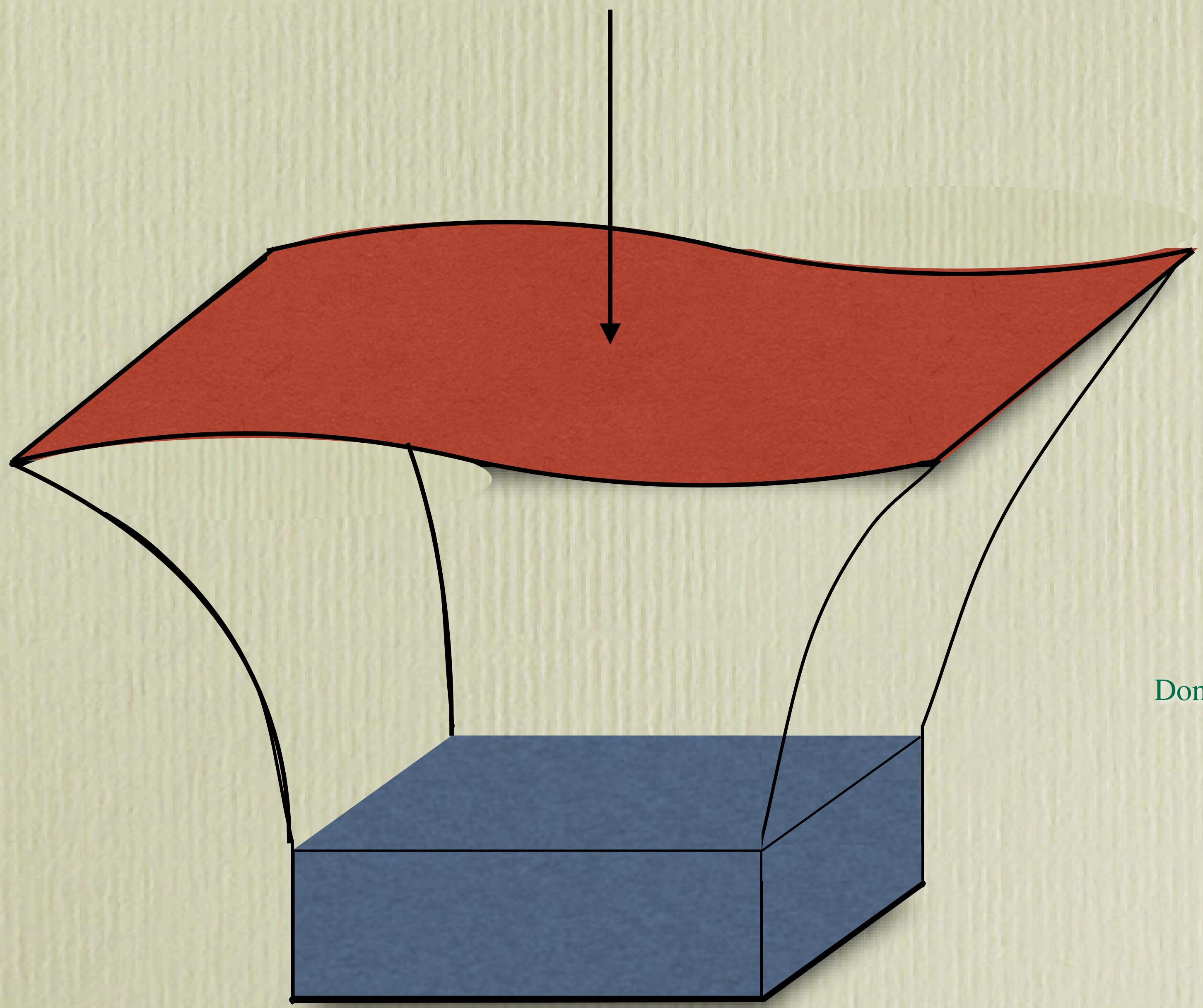
- Cosmological phase transitions
- Cosmological defects (cosmic strings, etc)
- Neutron star mergers
- (P)reheating
- Primordial black holes
- Etc

Dynamical gravity at the boundary

Casalderrey, Ecker, DM & van der Schee '21

- So we need a new holographic framework:

Out-of-equilibrium quantum matter + Classical dynamical gravity



Some related work
Gubser '99
Csaki, Graesser, Kolda & Terning '99
Kehagias & Kiritsis '99
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Karch & Randall '00
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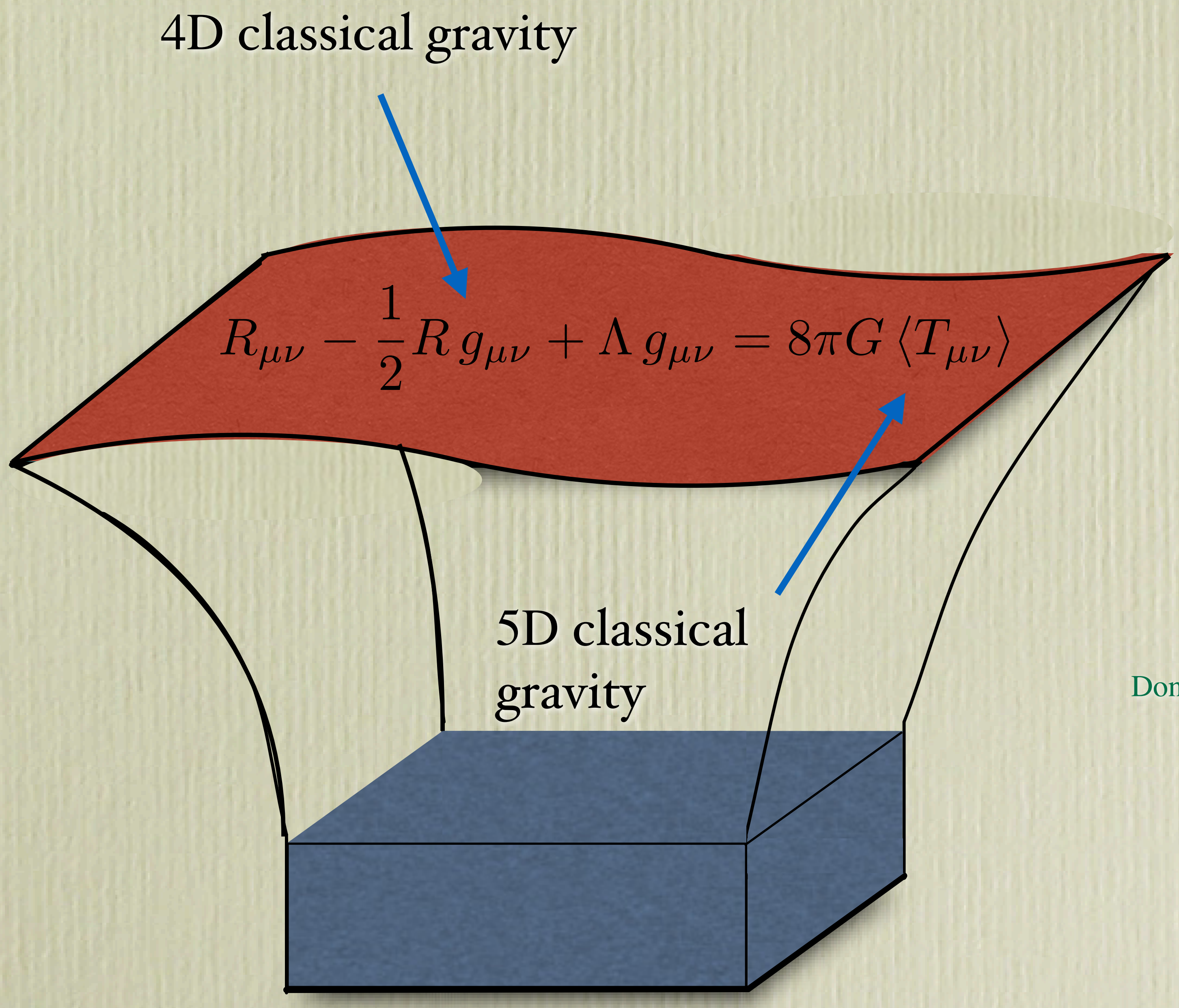

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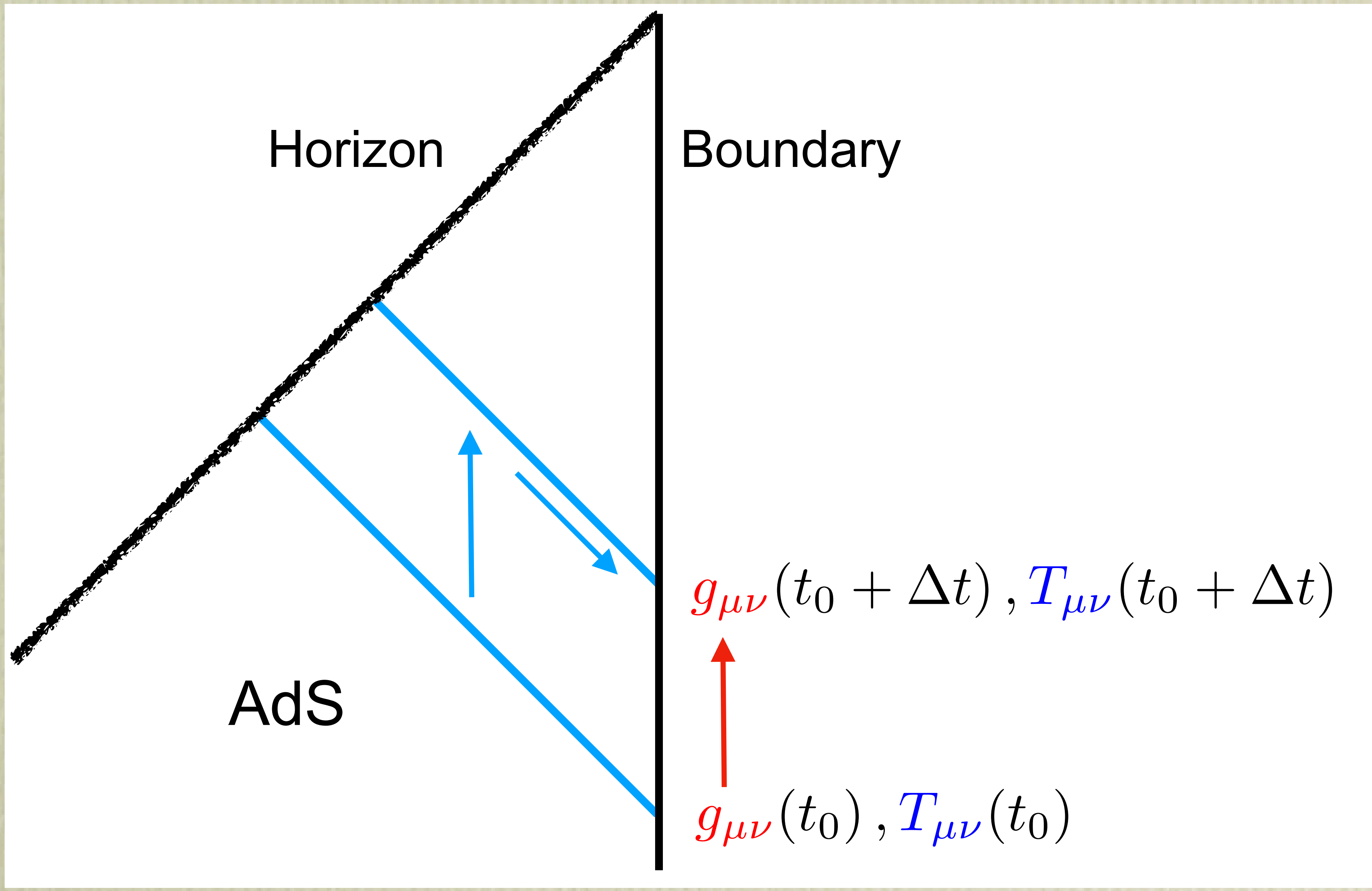
Dynamical gravity at the boundary

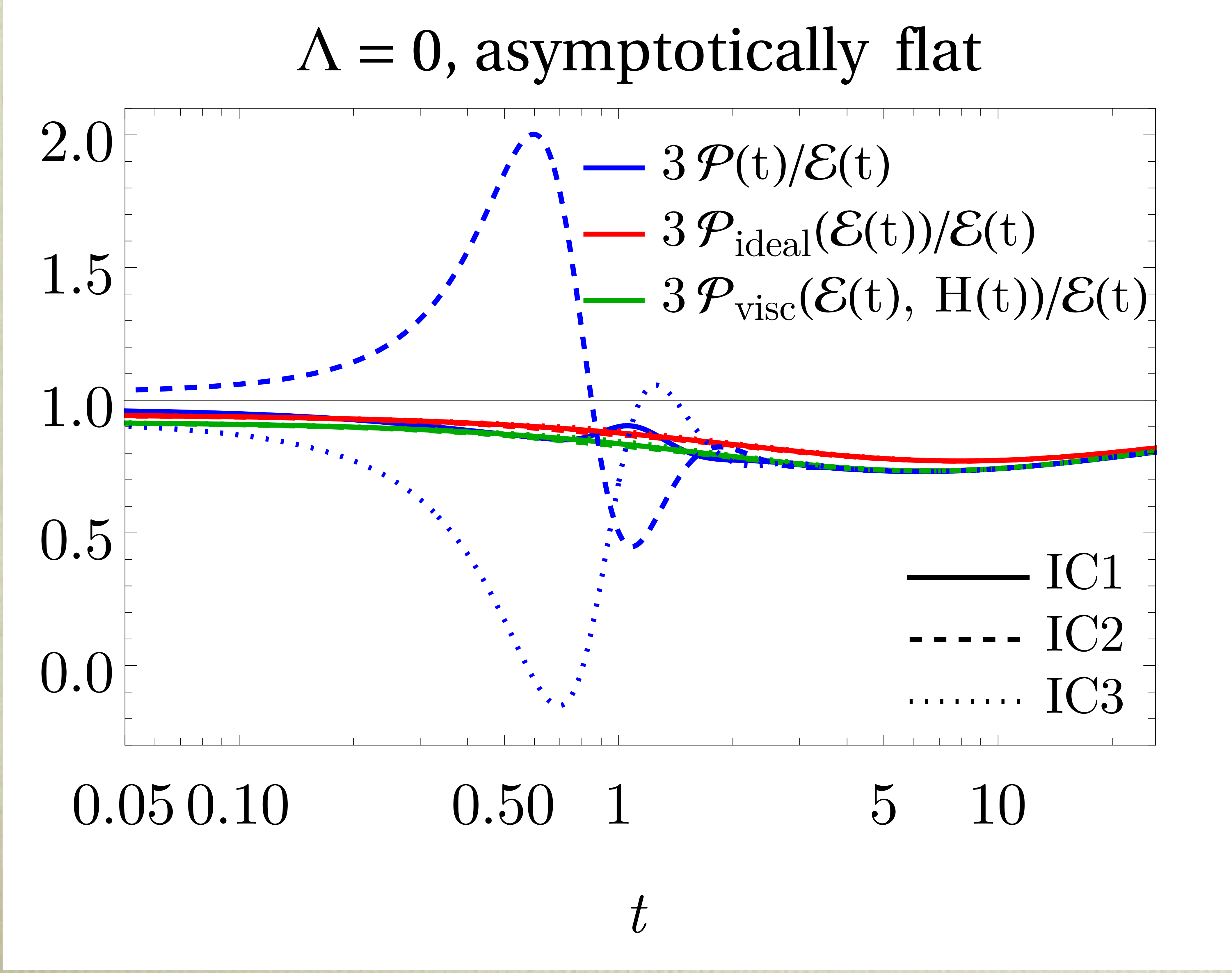
Casalderrey, Ecker, DM & van der Schee '21

- More precisely:



Example: Far-from-equilibrium FLRW Cosmology

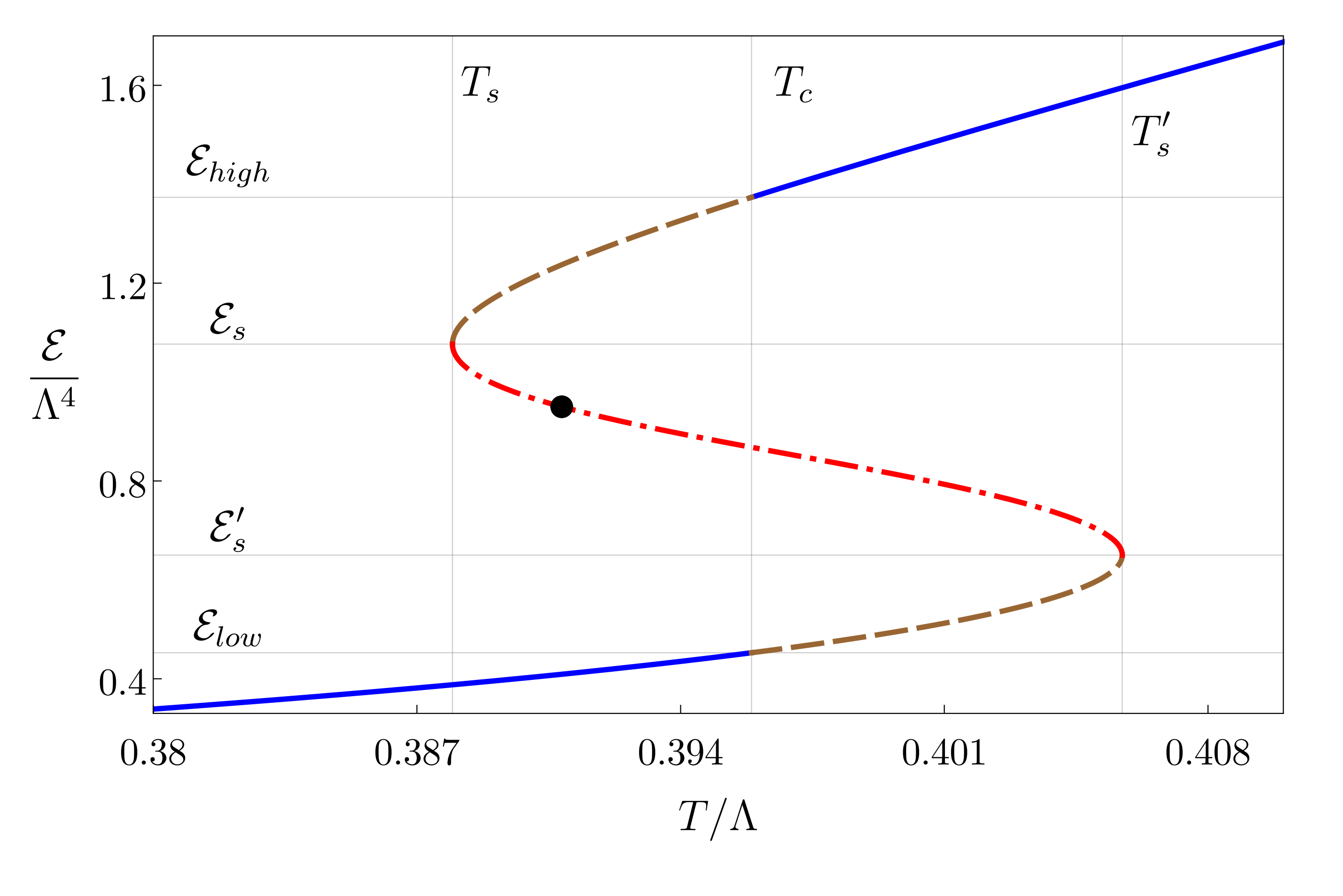
Casalderrey, Ecker, DM & van der Schee '21



Outlook

Thermal inflation

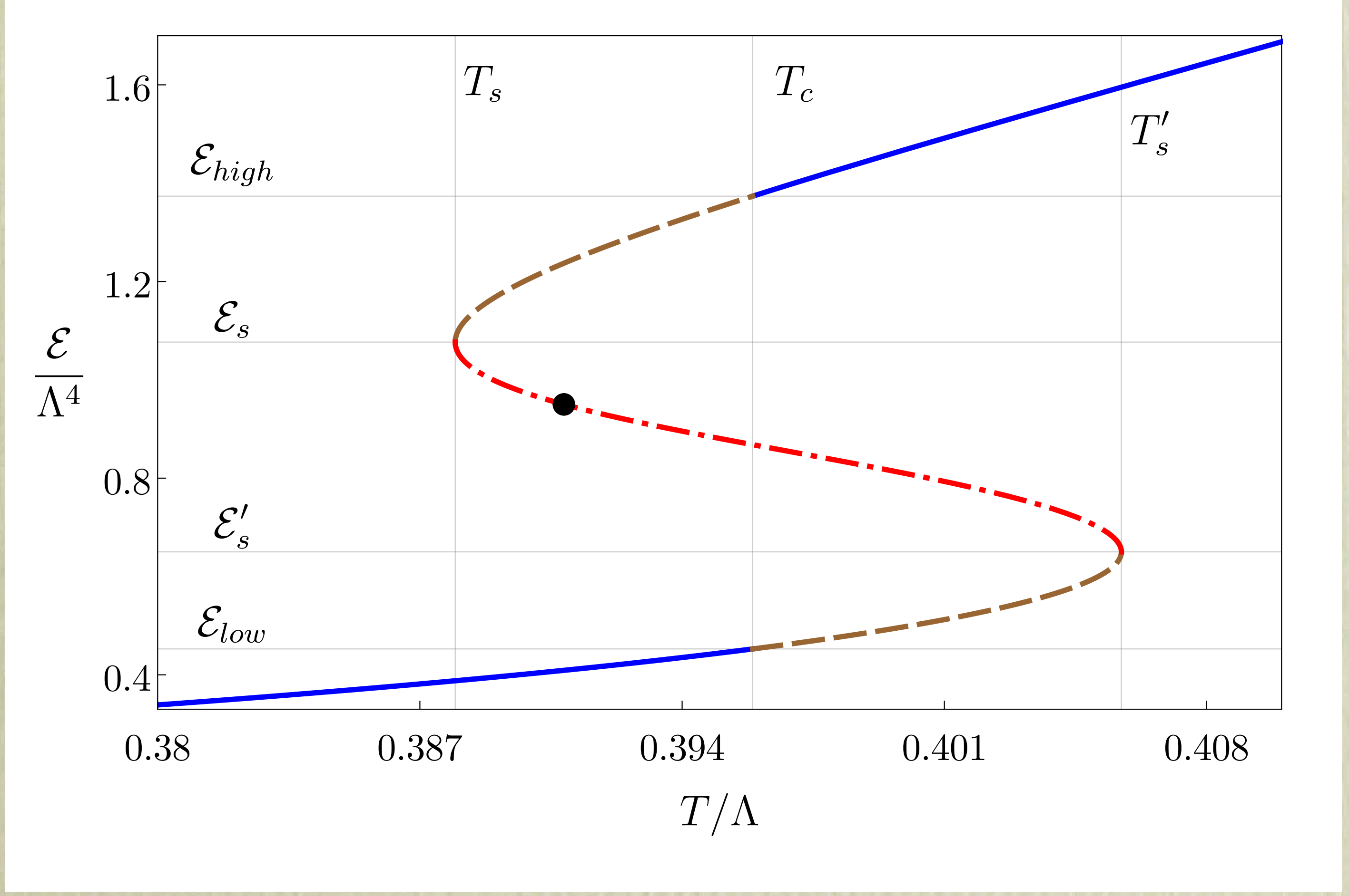
- As the Universe rolls down the metastable branch, E+3P can become negative
  → accelerated expansion.



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.



Thermal inflation

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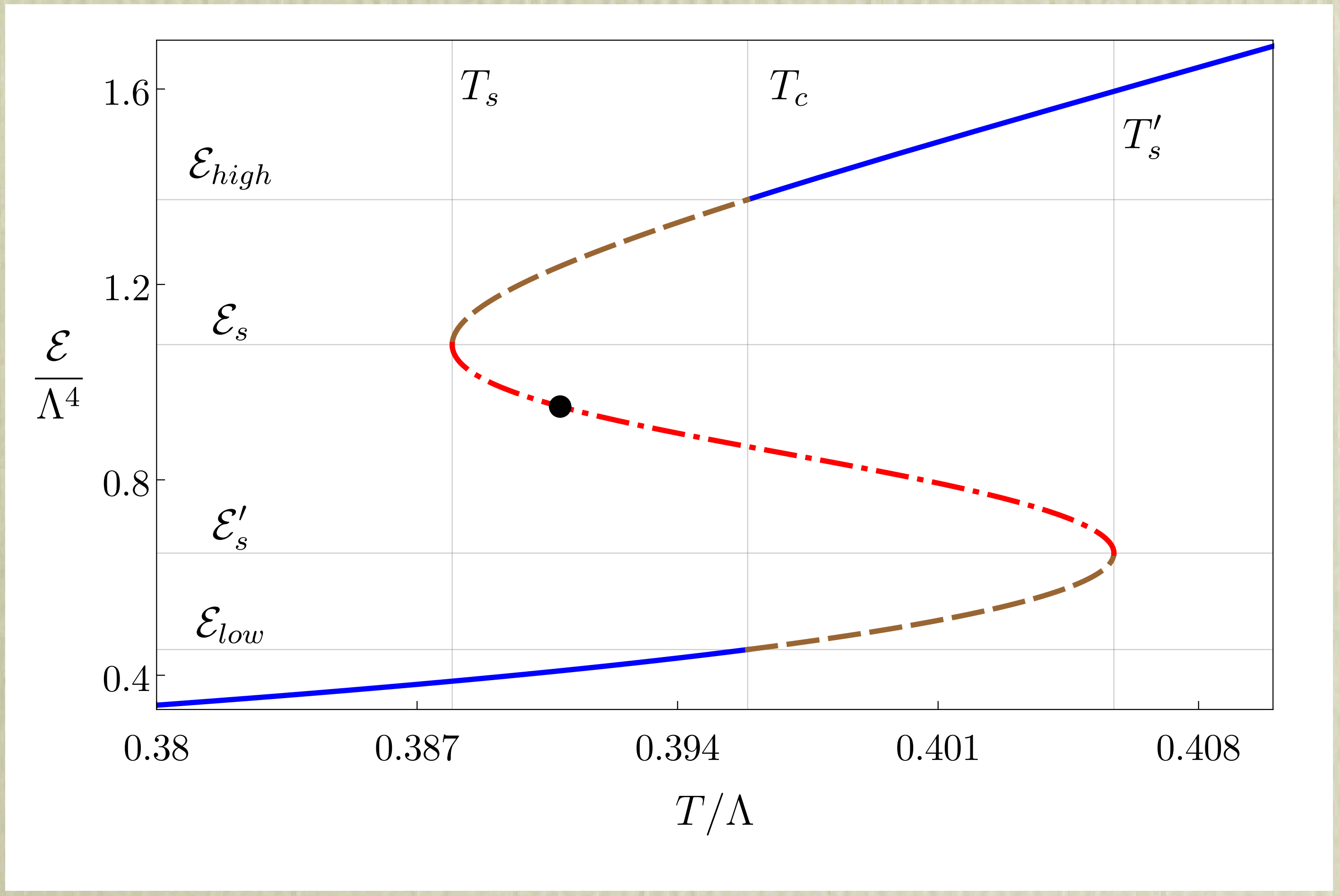
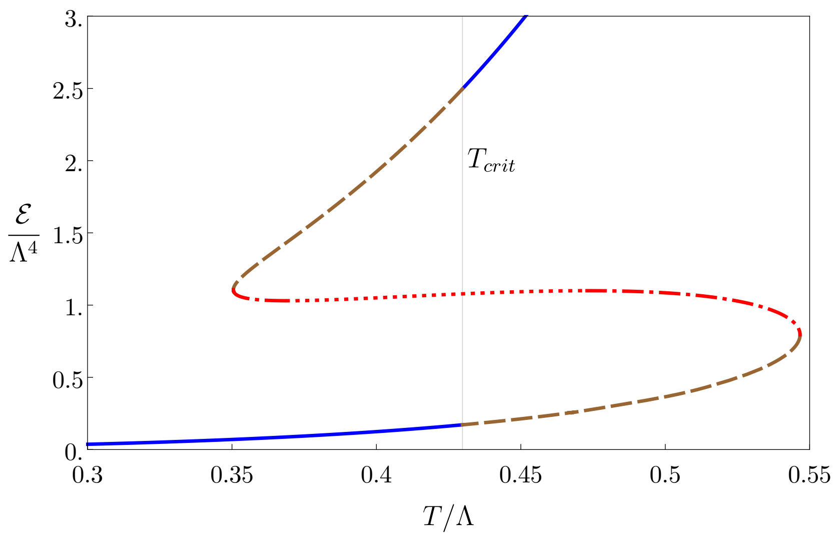
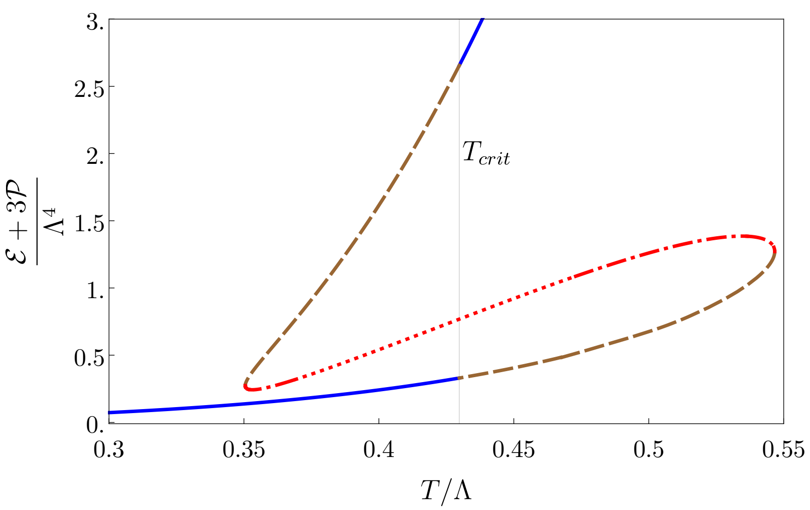
- In our model this does or does not happen depending on the parameters.

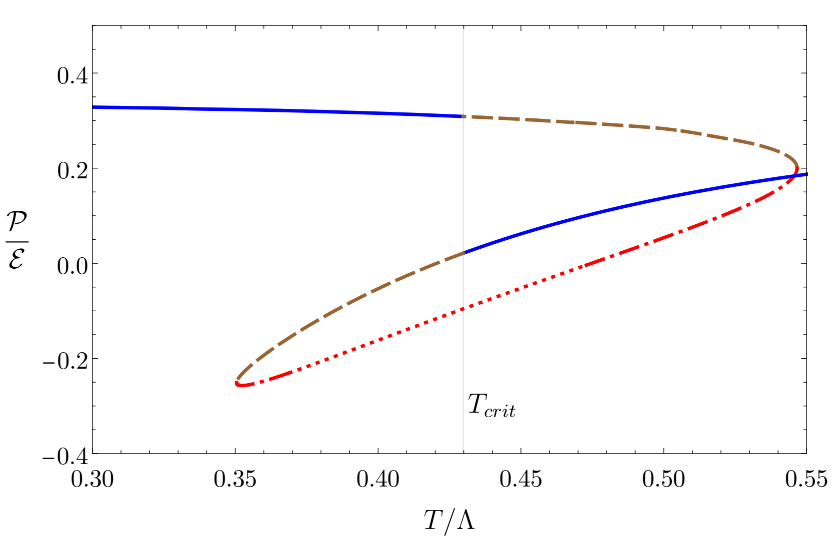




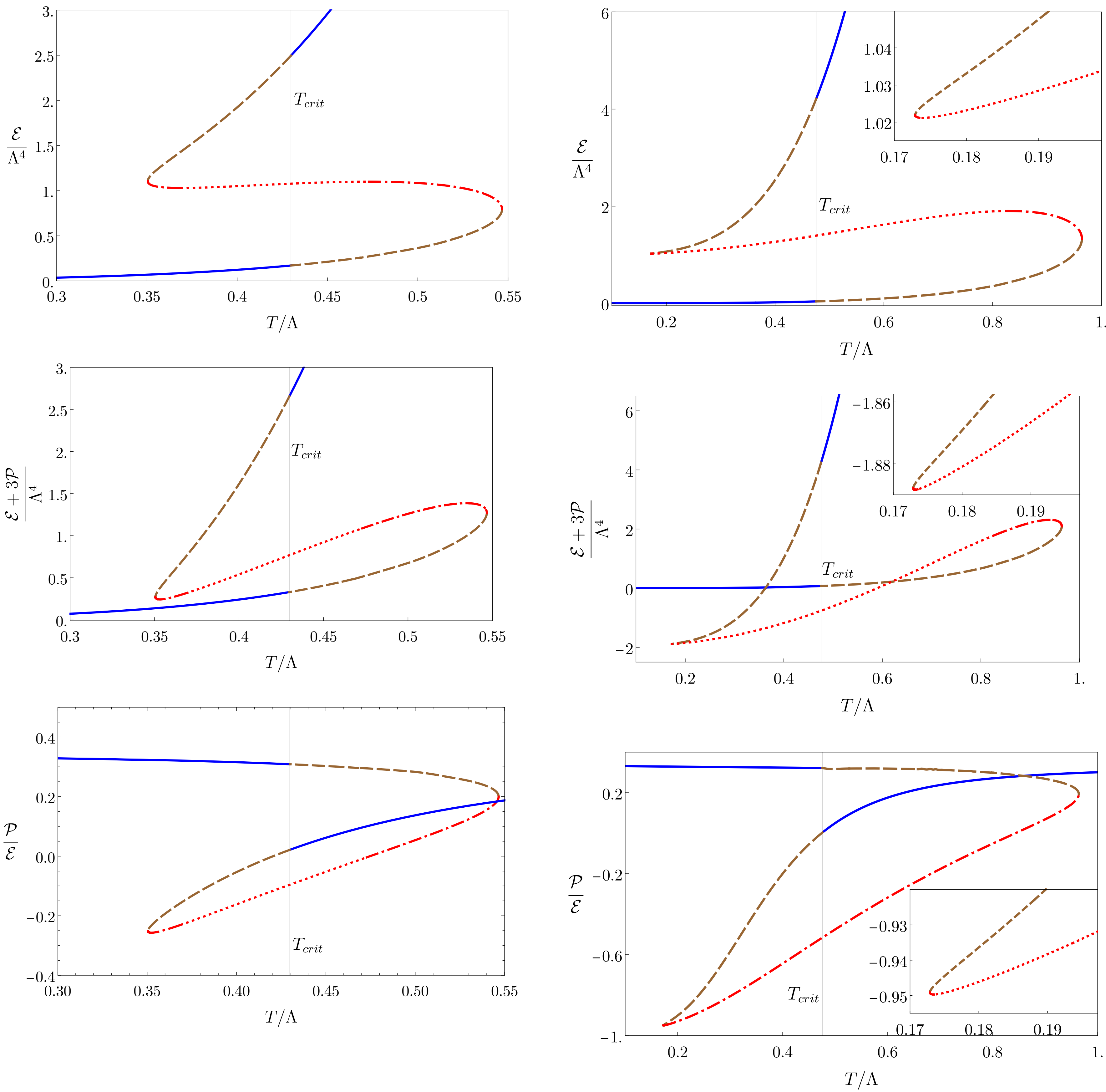
$\frac{\mathcal{E}}{\Lambda^4}$
T_{crit}
T/Λ
0.3
0.35
0.4
0.45
0.5
0.55
0.
0.5
1.
1.5
2.
2.5
3.



$\frac{\mathcal{E}+3\mathcal{P}}{\Lambda^4}$
T_{crit}
T/Λ
0.3
0.35
0.4
0.45
0.5
0.55
0.
0.5
1.
1.5
2.
2.5
3.



$\frac{\mathcal{P}}{\mathcal{E}}$
T_{crit}
T/Λ
0.30
0.35
0.40
0.45
0.50
0.55
−0.4
−0.2
0.0
0.2
0.4



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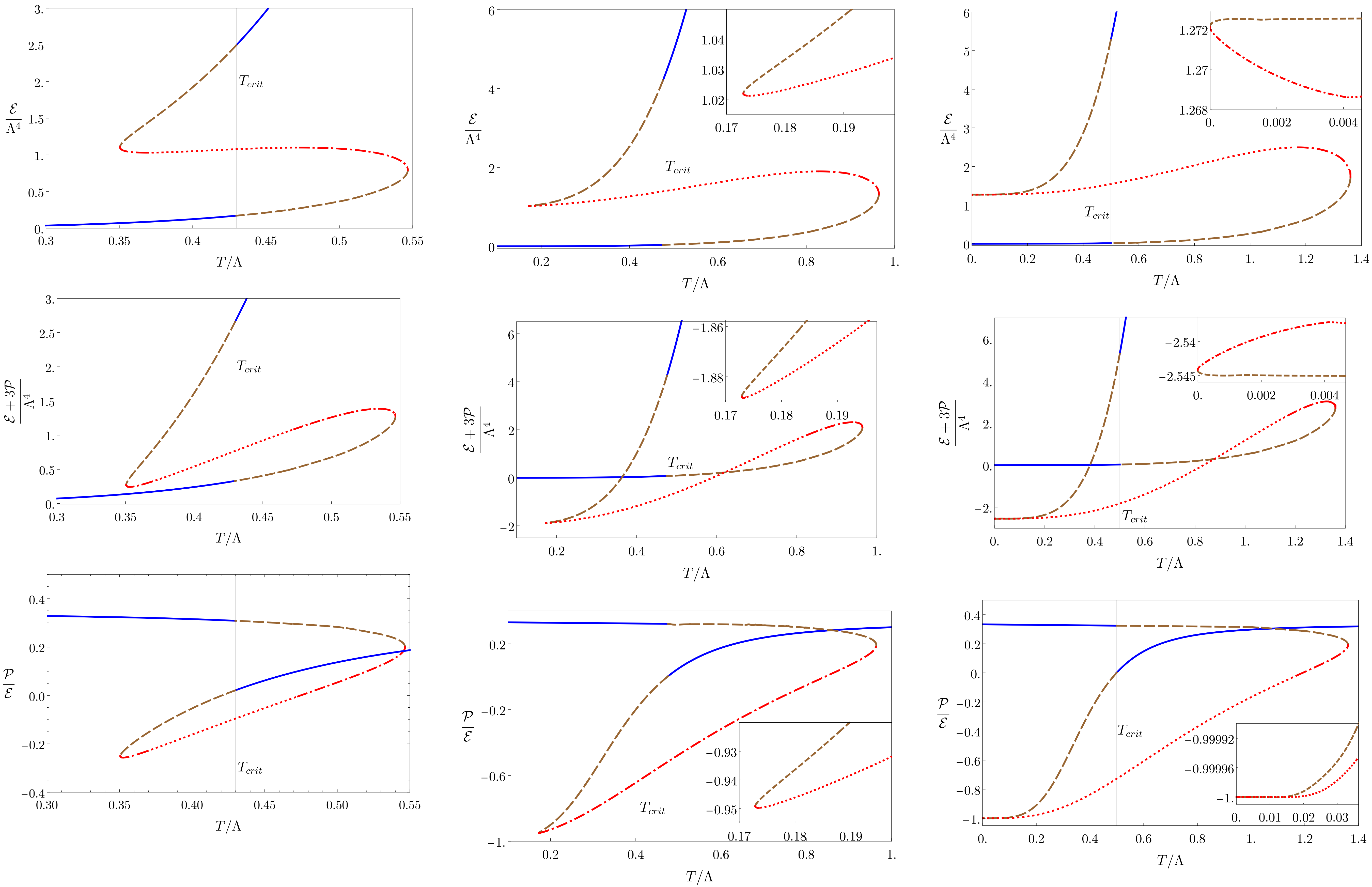
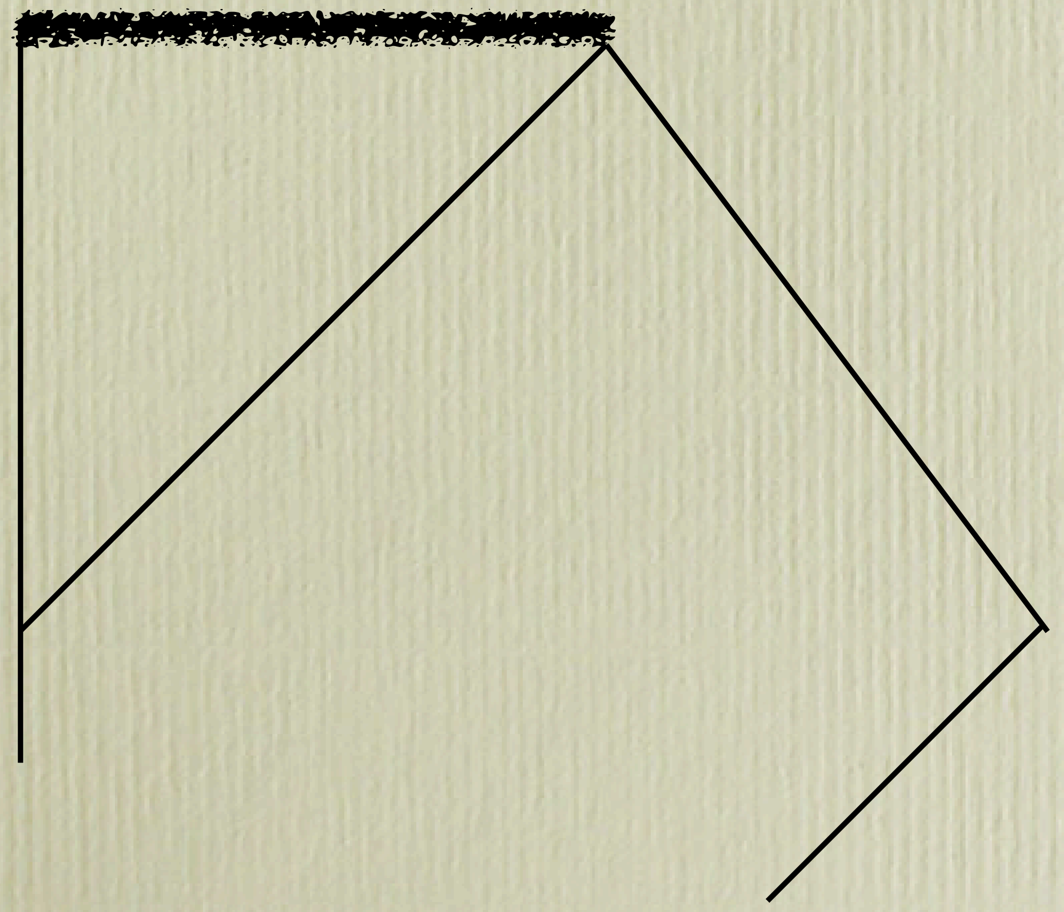


$\frac{\mathcal{E}}{\Lambda^4}$
T_{crit}
T/Λ
$\frac{\mathcal{E}+3\mathcal{P}}{\Lambda^4}$
$\frac{\mathcal{P}}{\mathcal{E}}$

Spacetime singularities

- Classical GR predicts spacetime singularities.

- Most mysterious ones are spacelike singularities.



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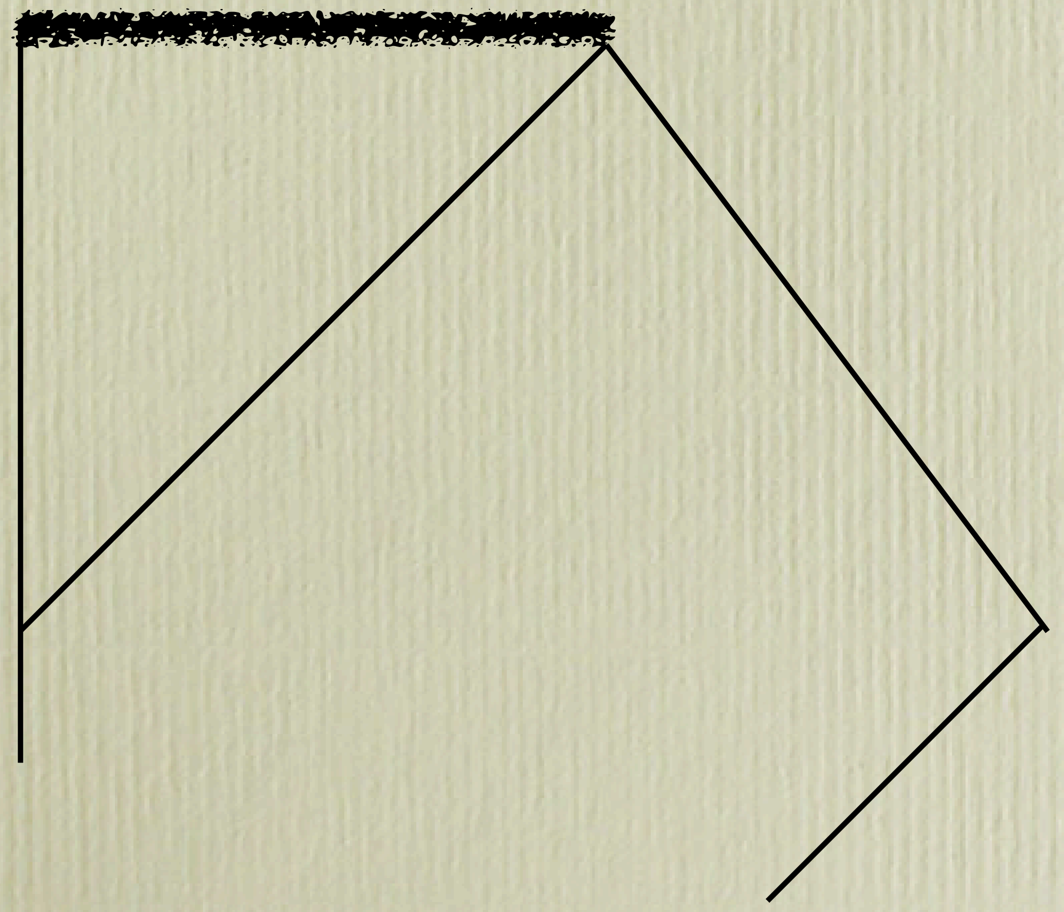

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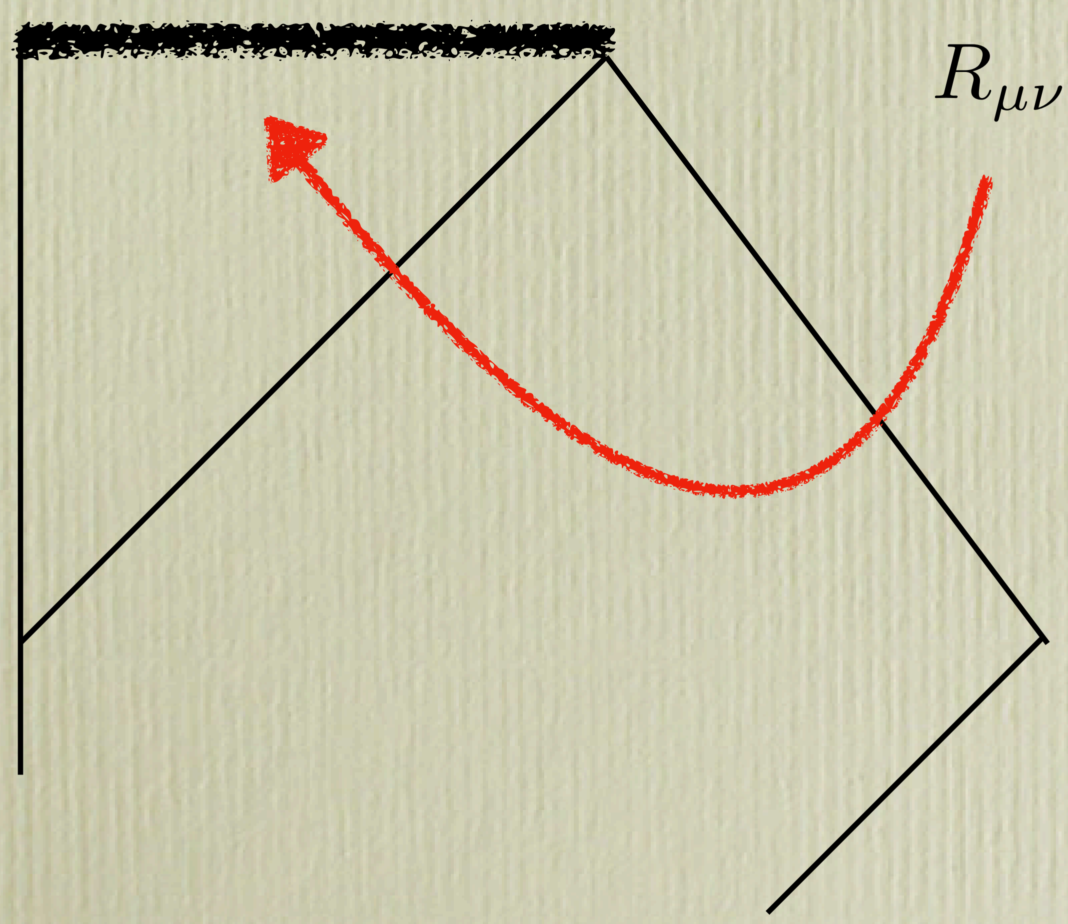
- But may the back reaction of quantum fields change/resolve the singularity?



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

Primordial black holes

- PBHs are natural dark matter candidates.
- Formation requires large density fluctuation.

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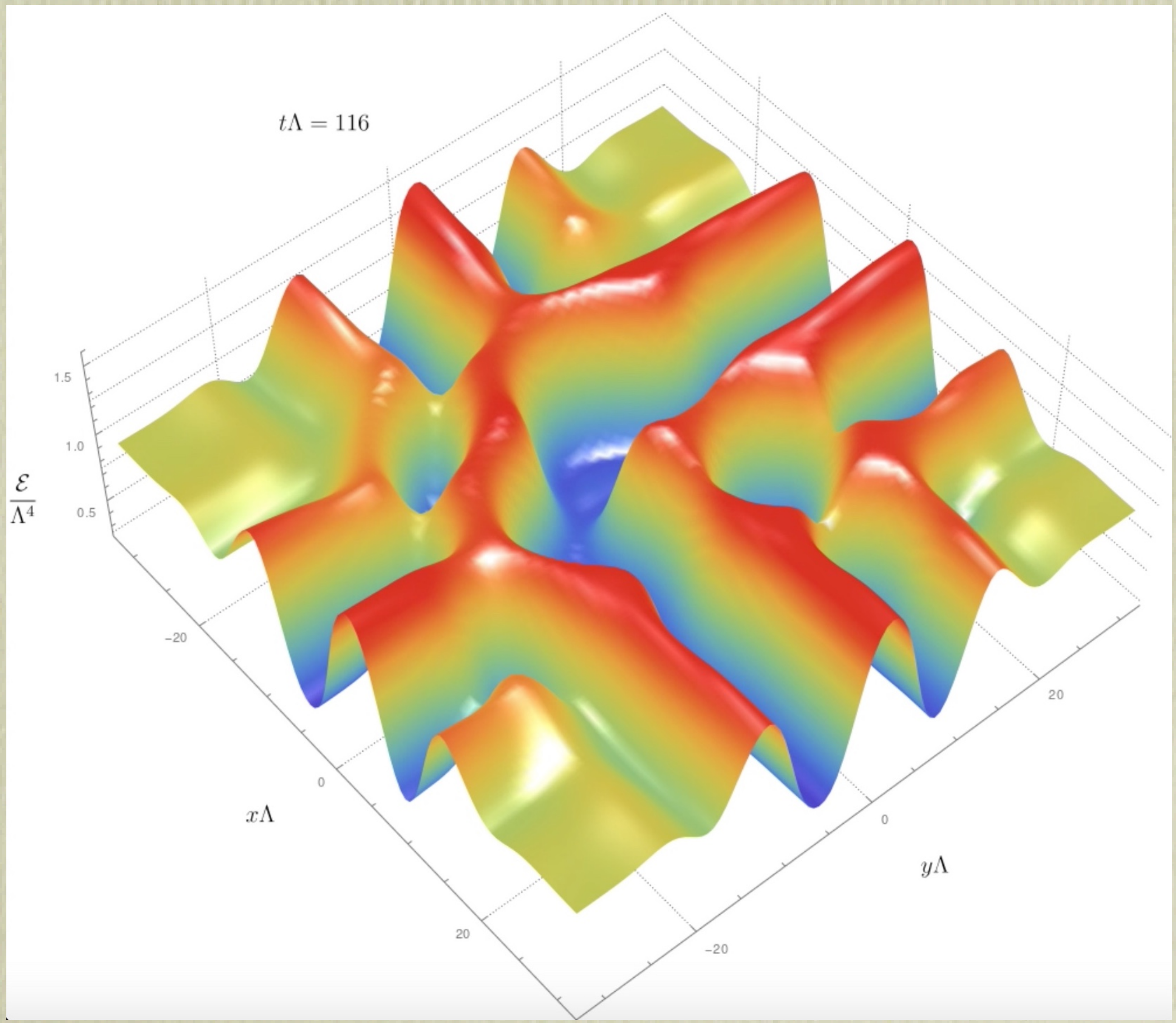
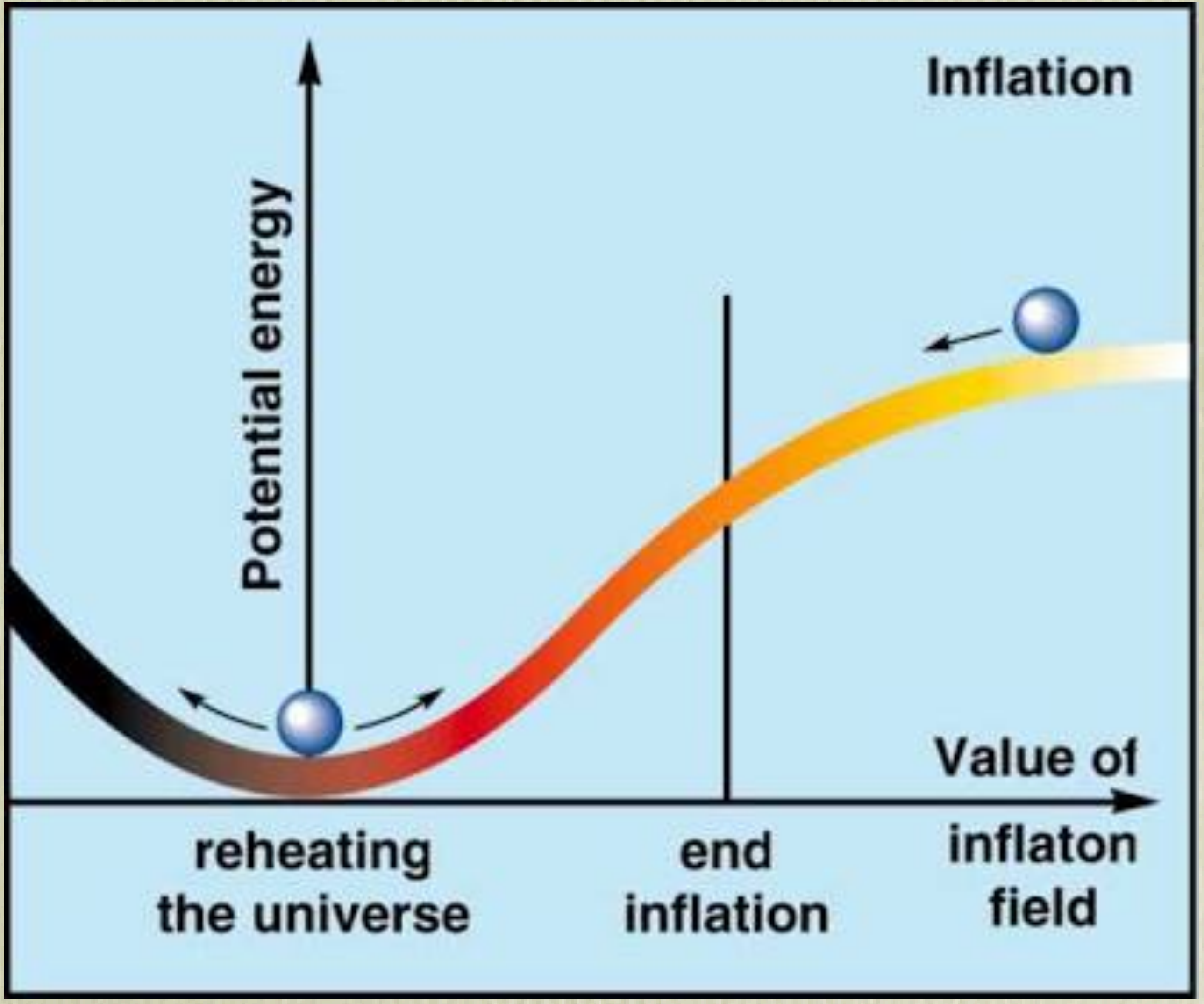
- Formation requires large density fluctuation.
- This is a hallmark of the spinodal dynamics:



(P)Reheating

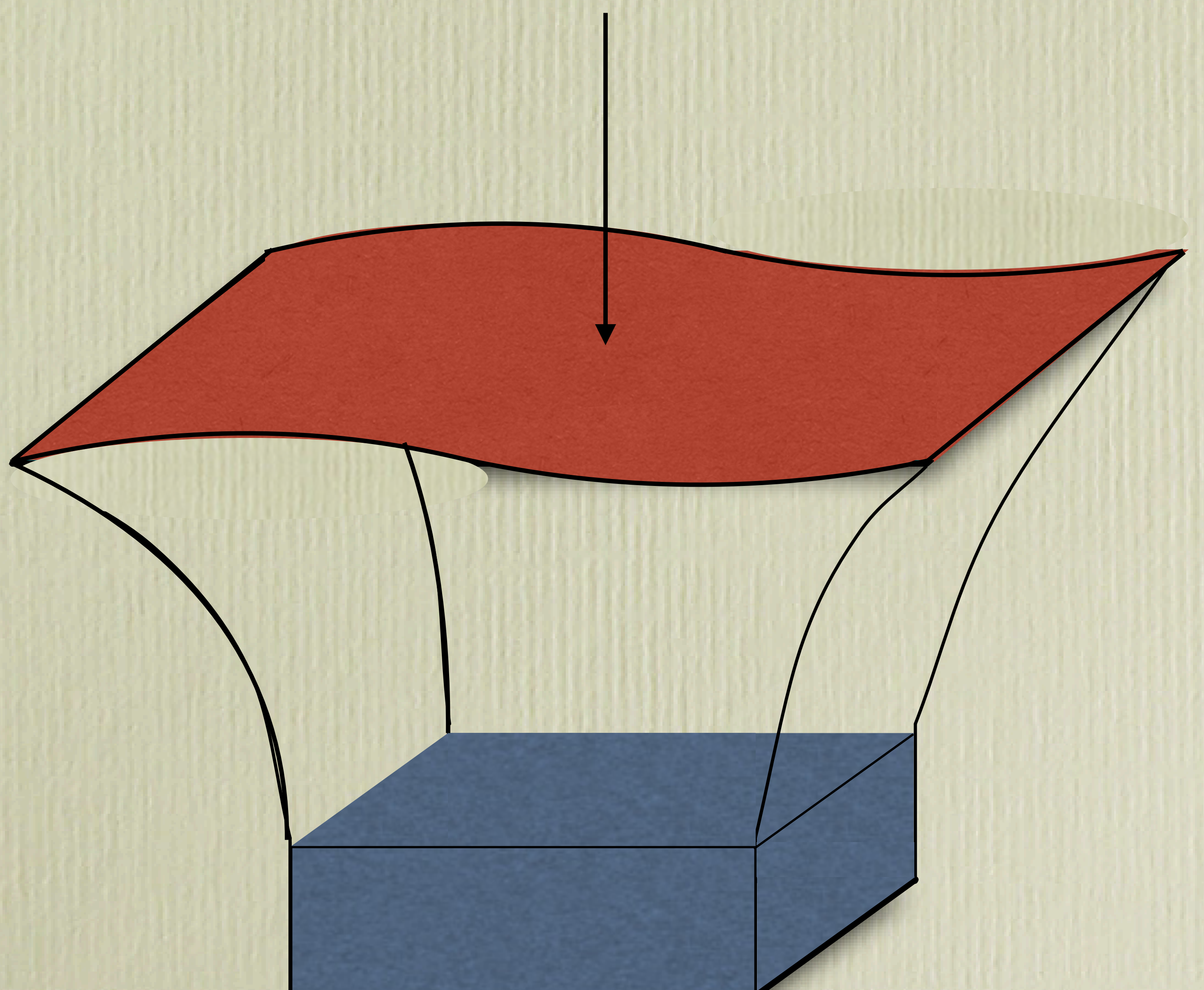
- Involves out-of-equilibrium physics.



(P)Reheating

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

Out-of-equilibrium quantum matter + dynamical gravity + dynamical inflaton



The team

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Thank you!