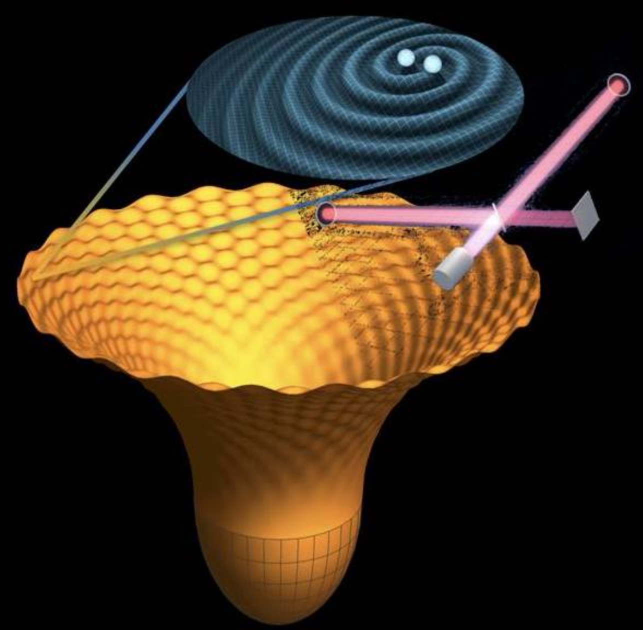
Strong-coupling dynamics and entanglement in de Sitter space



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References

- Based on 2011.08194 [hep-th] with J. Casalderrey-Solana, C. Ecker and W. Van der Schee
- Will not cite any other references but want to mention inspiring work by Alex Buchel.

Introduction

- Holography has provided insights into dynamics of strongly-coupled in flat space, specially out of equilibrium.

- Example: Quark-gluon plasma created in heavy ion collisions.

- Today I would like to extend this to curved spacetime.

Introduction

- Theoretical motivation: Curvature may lead to new interesting effects.

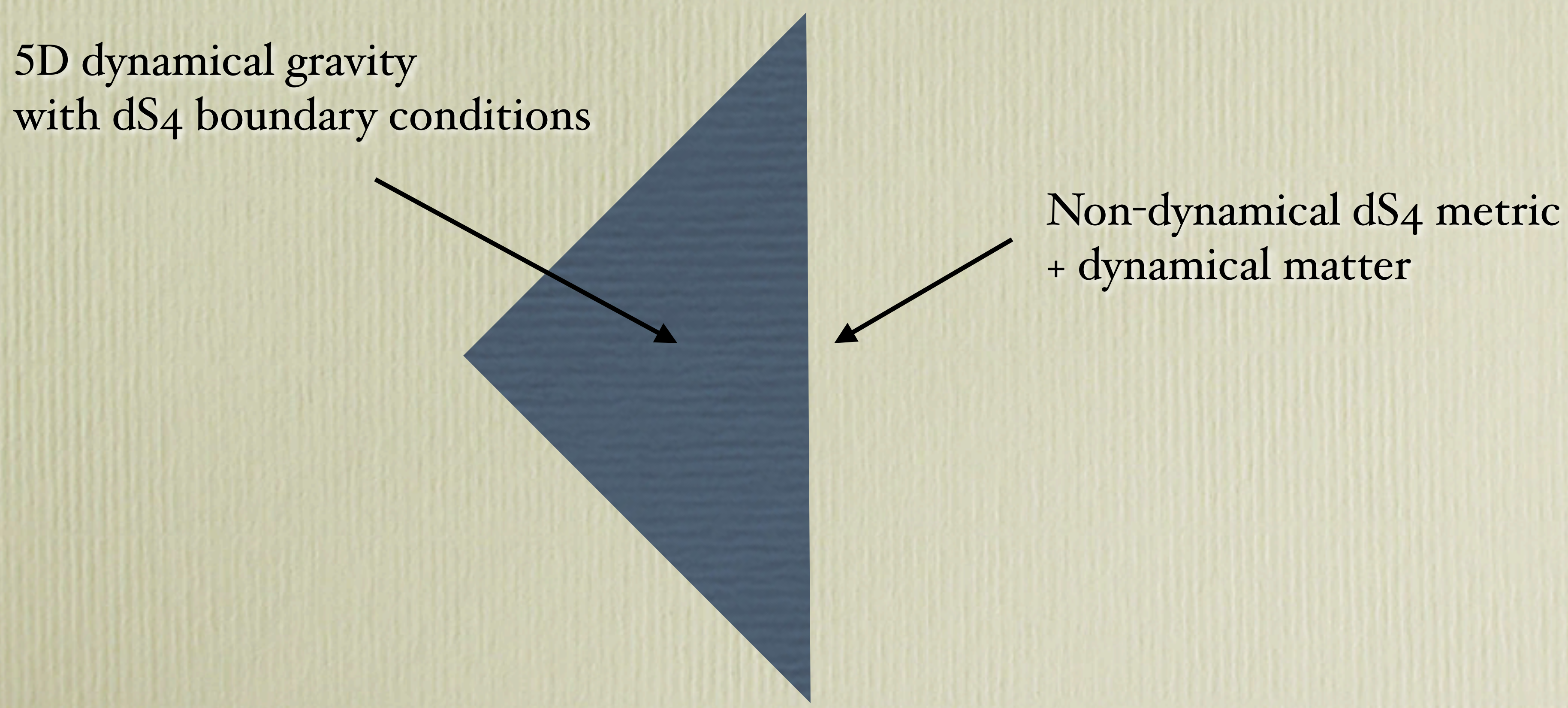
- Some phenomenological motivations come from Cosmology:
  - QCD phase transition.
  - GUT theories.
  - Dark Matter could be strongly self-interacting.

- For simplicity I will take the cosmological background to be dS_4.

Introduction

- Disclaimer: Holography will only describe the strongly coupled matter in dS, not dS itself.

In other words I am not doing dS/CFT.



Introduction

- Simplifications:
  - Simplest expanding metric: dS with Hubble rate H.

$$ds_{\mathrm{b}}^2 = g_{(0)ij}\mathrm{d}x^i\mathrm{d}x^j = -\mathrm{d}t^2 + e^{2Ht}\mathrm{d}\vec{x}^2$$

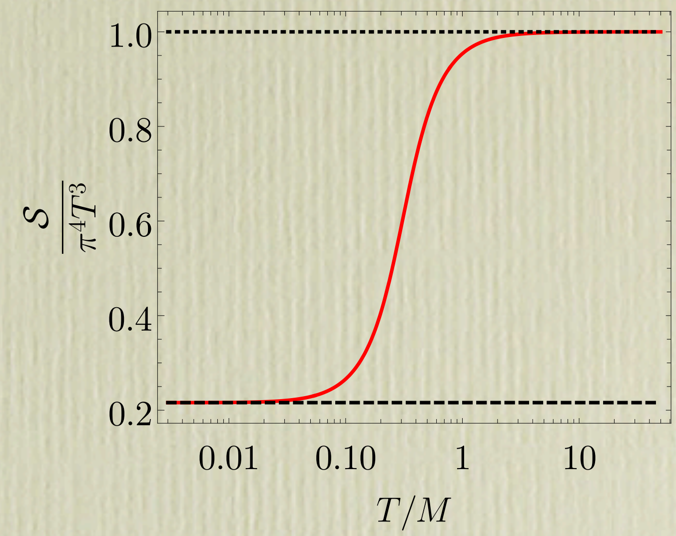
  - Ignore back reaction of matter on dS metric.
  - Spatially homogeneous states.
  - Simple non-conformal 4D gauge theory.

- Non-conformality is crucial because dS is conformal to Minkowski.

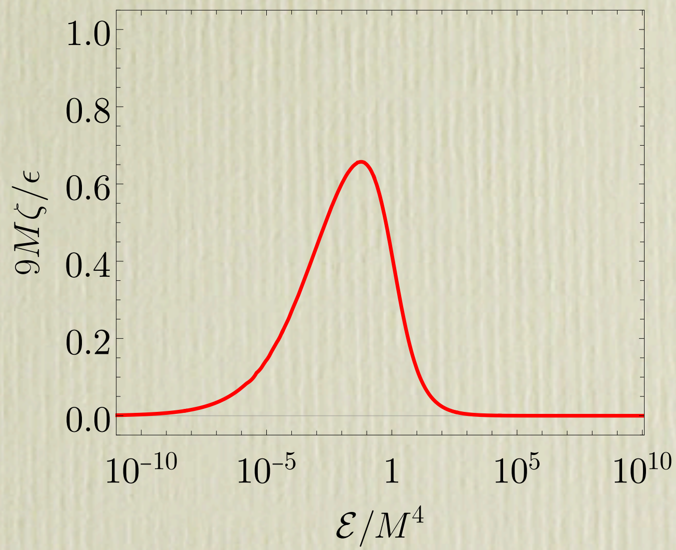
The model

- In 5D: Gravity + scalar field with potential with two AdS extrema.

- Gauge theory RG-flows from UV to IR fixed points at scale M=1.



- Crucially, the bulk viscosity is non-zero.



The model

- Important: Energy density and pressure are scheme-dependent.

- Therefore, I will often subtract their late-time value, since this difference is scheme-independent.

- Equivalently, I could choose a renormalization scheme such that their values at asymptotically late times vanish.

Initial states

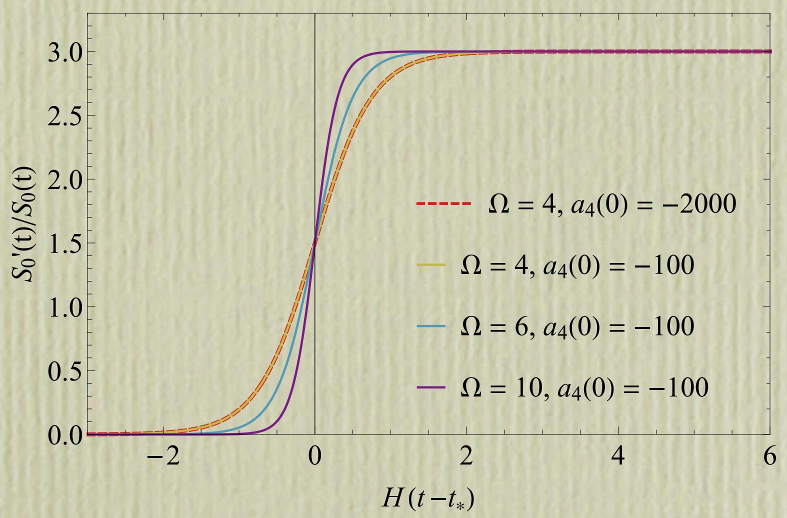
- Start with equilibrium thermal state in Minkowski and turn on H smoothly.

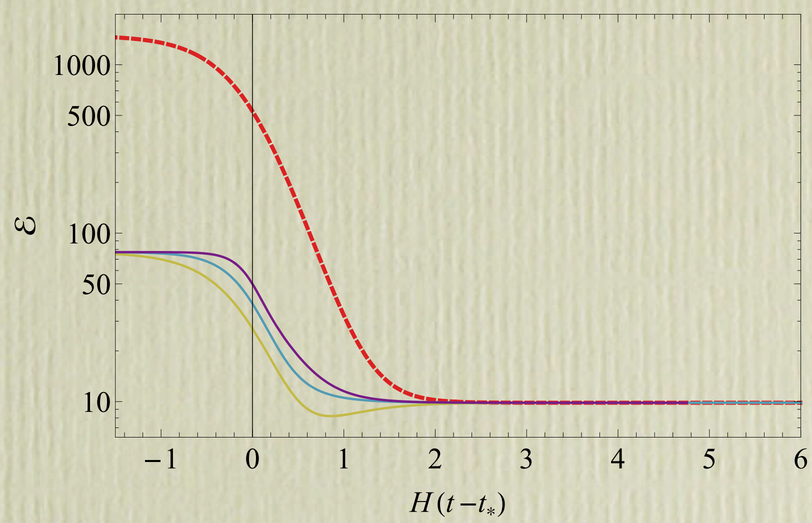
- This leads to a transient period with non-constant H in which the boundary metric interpolates between Mink4 and dS4.

- After this we are left with what we want to study: An excited gauge theory state in dS4.

Dynamics

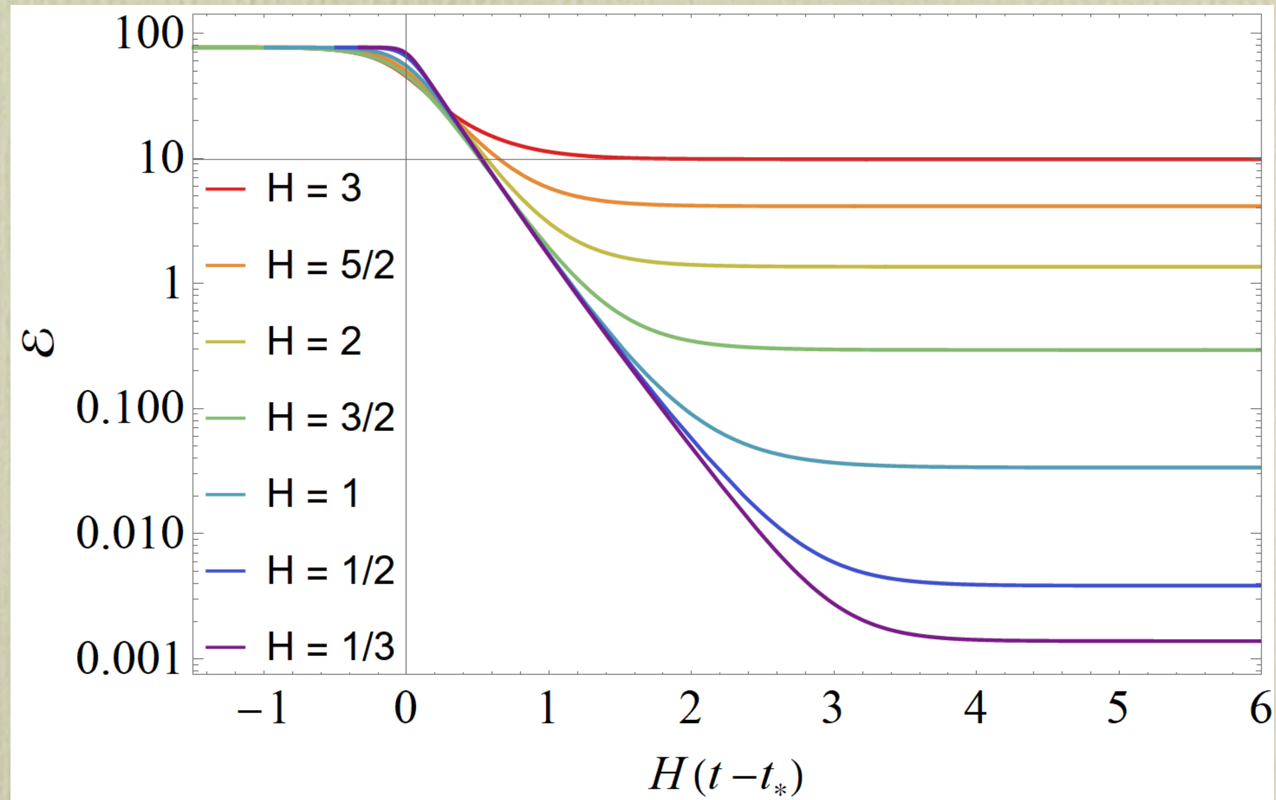
- Late-time state is independent of the turn-on procedure:





Dynamics

- Energy density and pressure dilute exponentially due to expansion (recall late-time values are scheme-dependent):



Dynamics

- Interesting physics is in how they dilute.

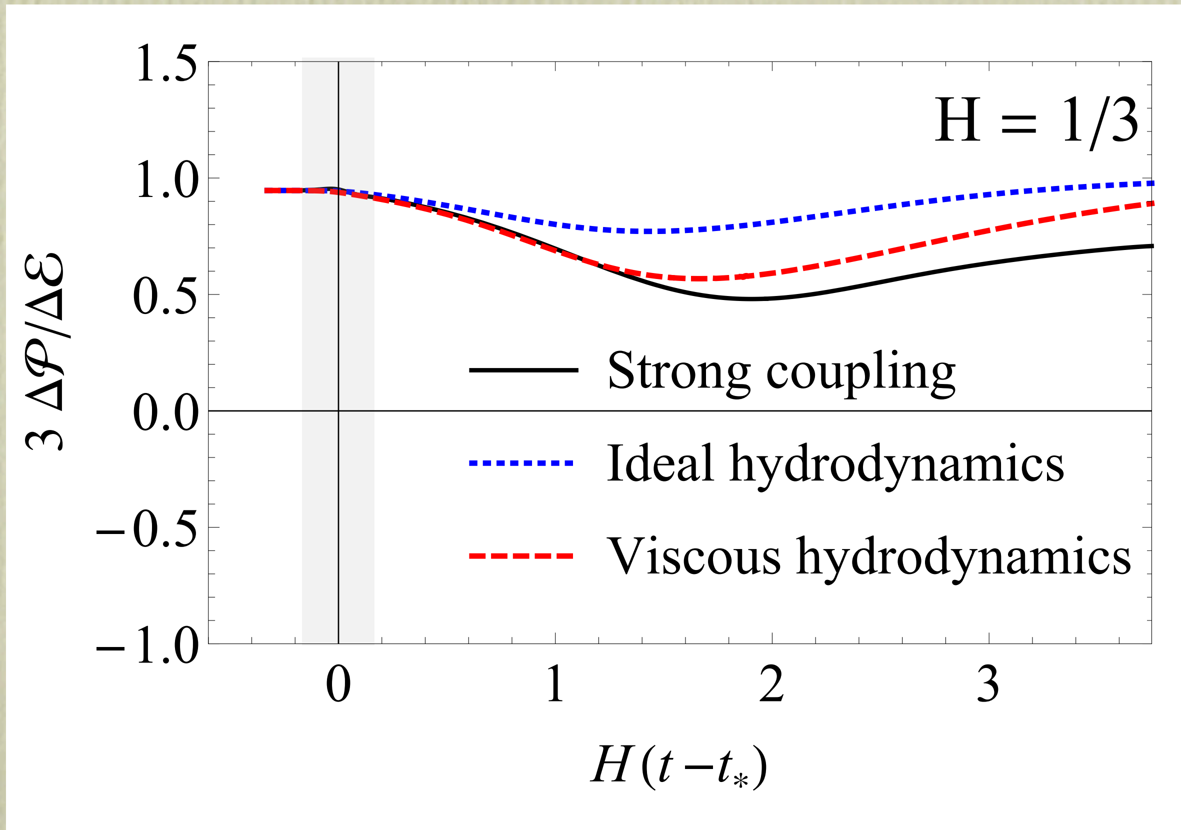
- For scheme-independence we will look at $\Delta\mathcal{P}/\Delta\mathcal{E}$

- For example, is this close to equilibrium EoS in flat space?

- Or is it well predicted by hydrodynamics during the evolution?

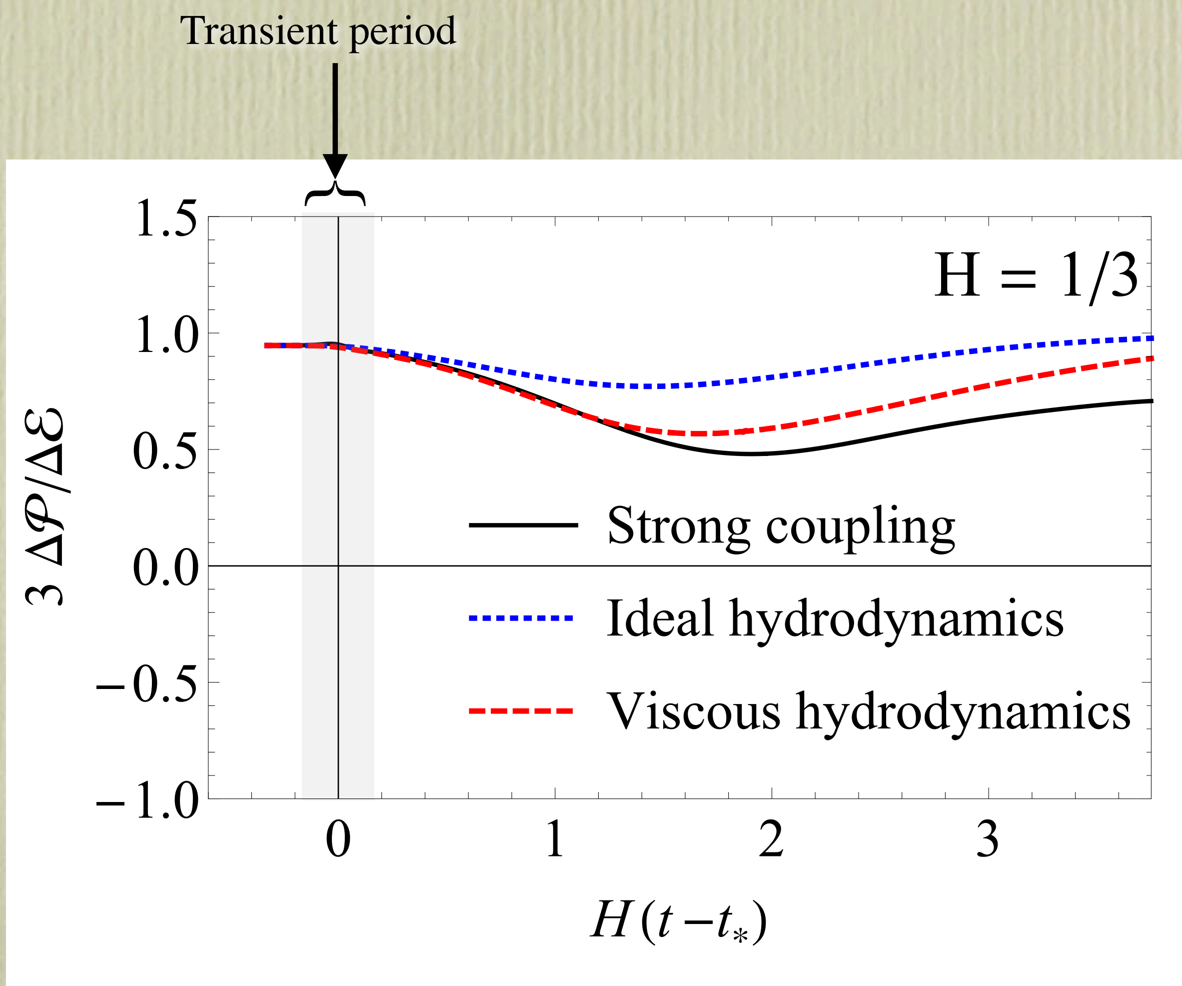
- Let us start with small H compared to M:

Dynamics



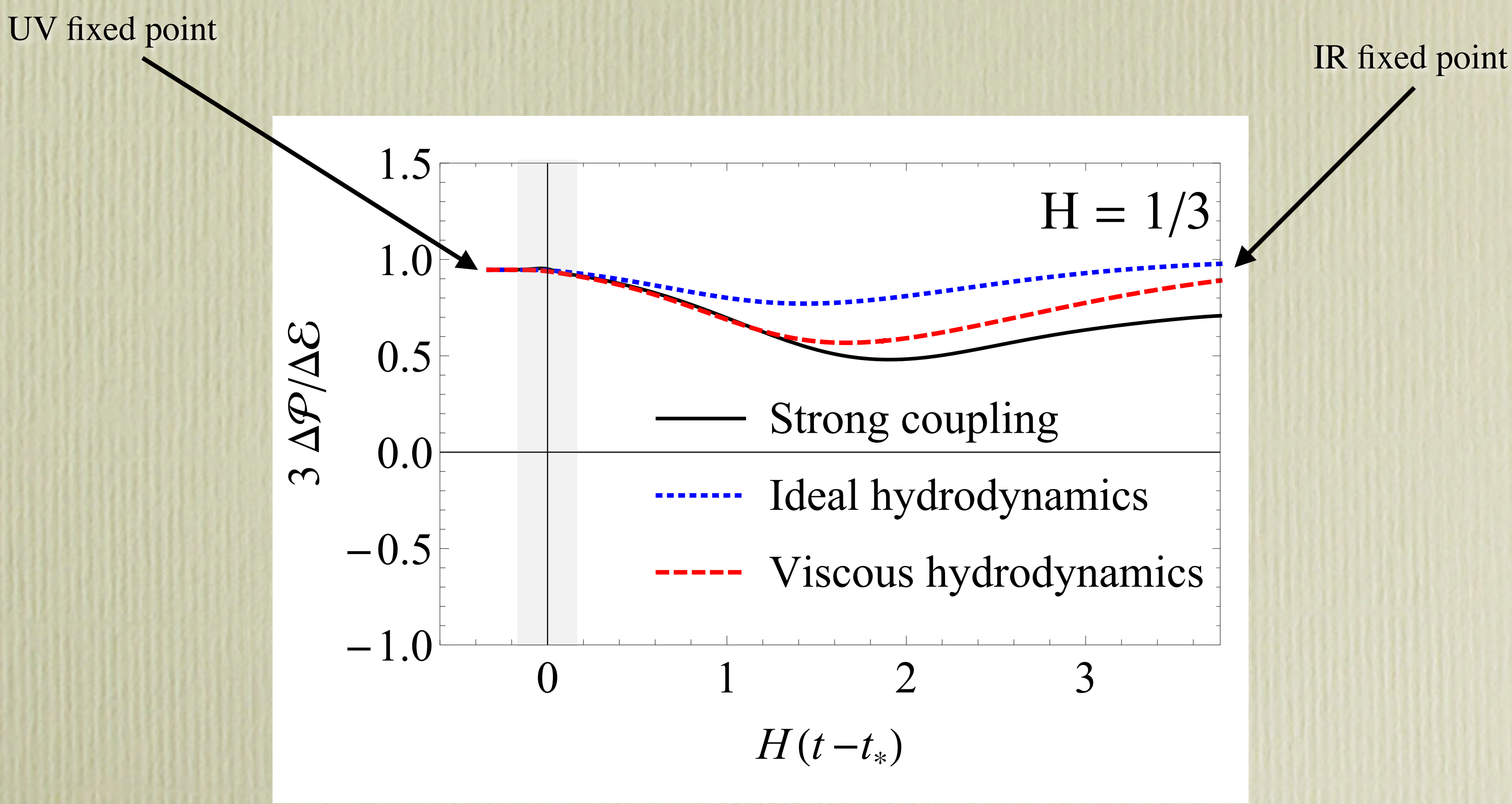
H = 1/3
Strong coupling
Ideal hydrodynamics
Viscous hydrodynamics
3 ΔP/ΔE
H(t − t*)
1.5
1.0
0.5
0.0
−0.5
−1.0
0
1
2
3

Dynamics



Transient period
H = 1/3
1.5
1.0
0.5
0.0
−0.5
−1.0
$3\,\Delta\mathcal{P}/\Delta\mathcal{E}$
0
1
2
3
$H(t-t_*)$
Strong coupling
Ideal hydrodynamics
Viscous hydrodynamics

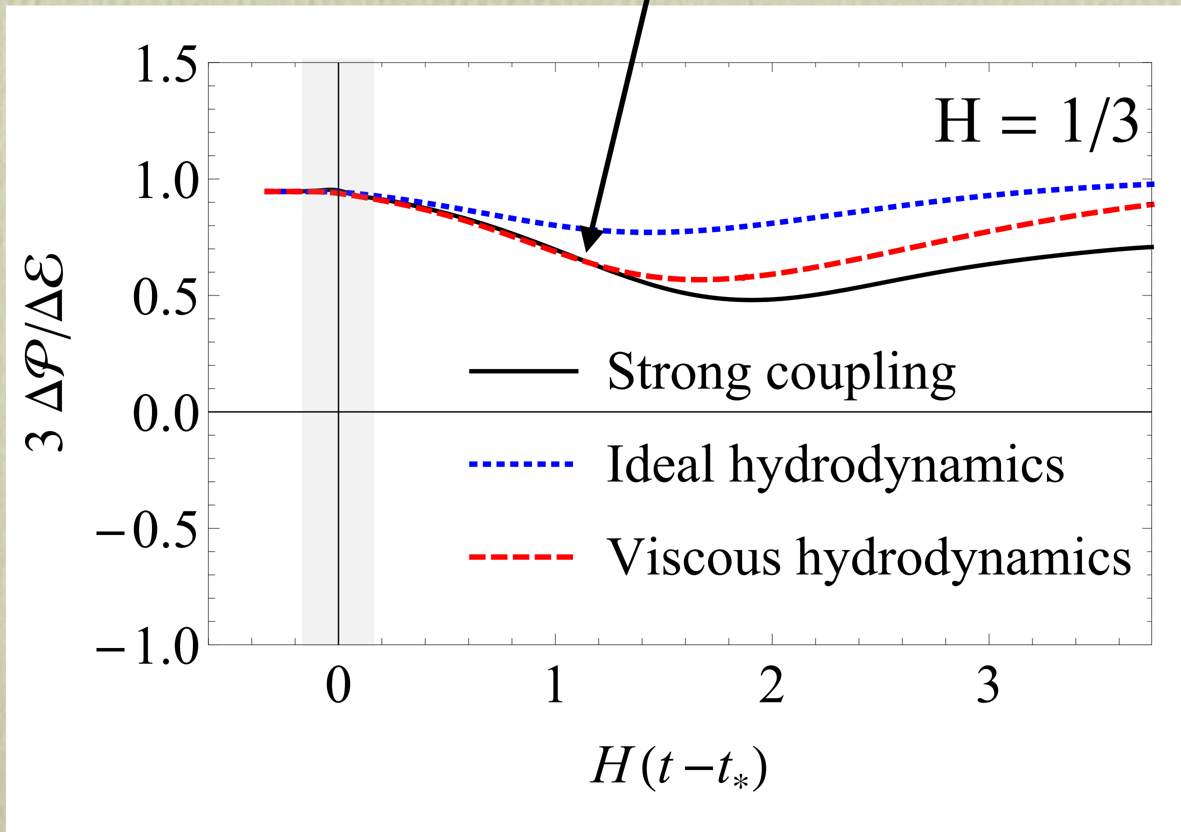
Dynamics



UV fixed point
IR fixed point
H = 1/3
3 ΔP/ΔE
1.5
1.0
0.5
0.0
−0.5
−1.0
0
1
2
3
H(t − t*)
Strong coupling
Ideal hydrodynamics
Viscous hydrodynamics

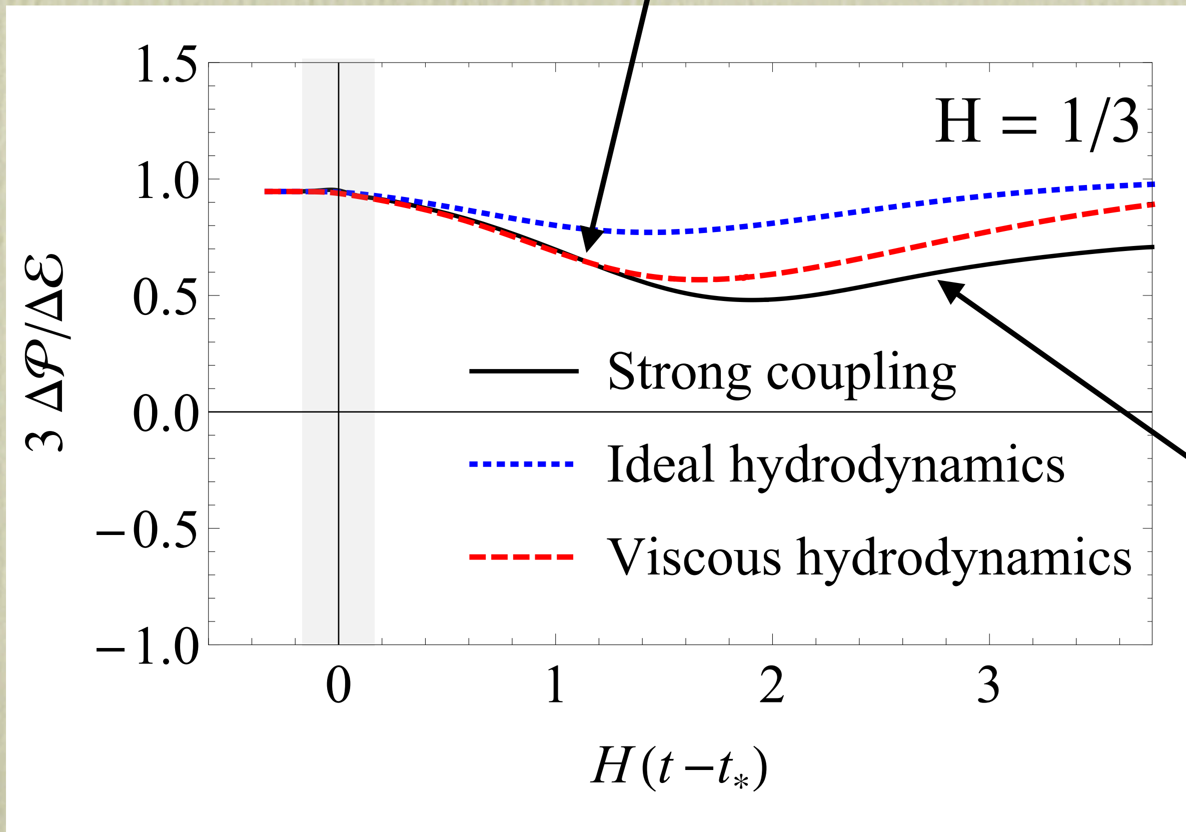
Dynamics

System described by hydro with important viscous effects



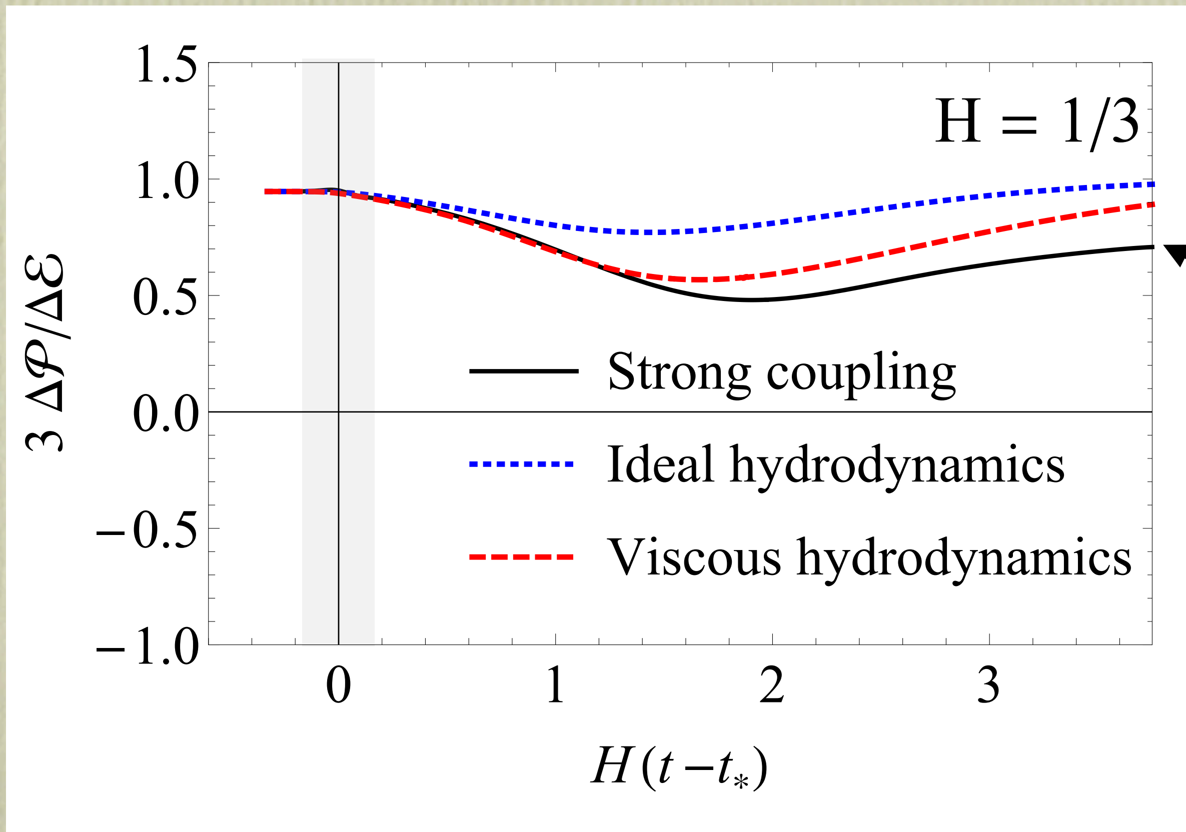
Dynamics

System described by hydro with important viscous effects



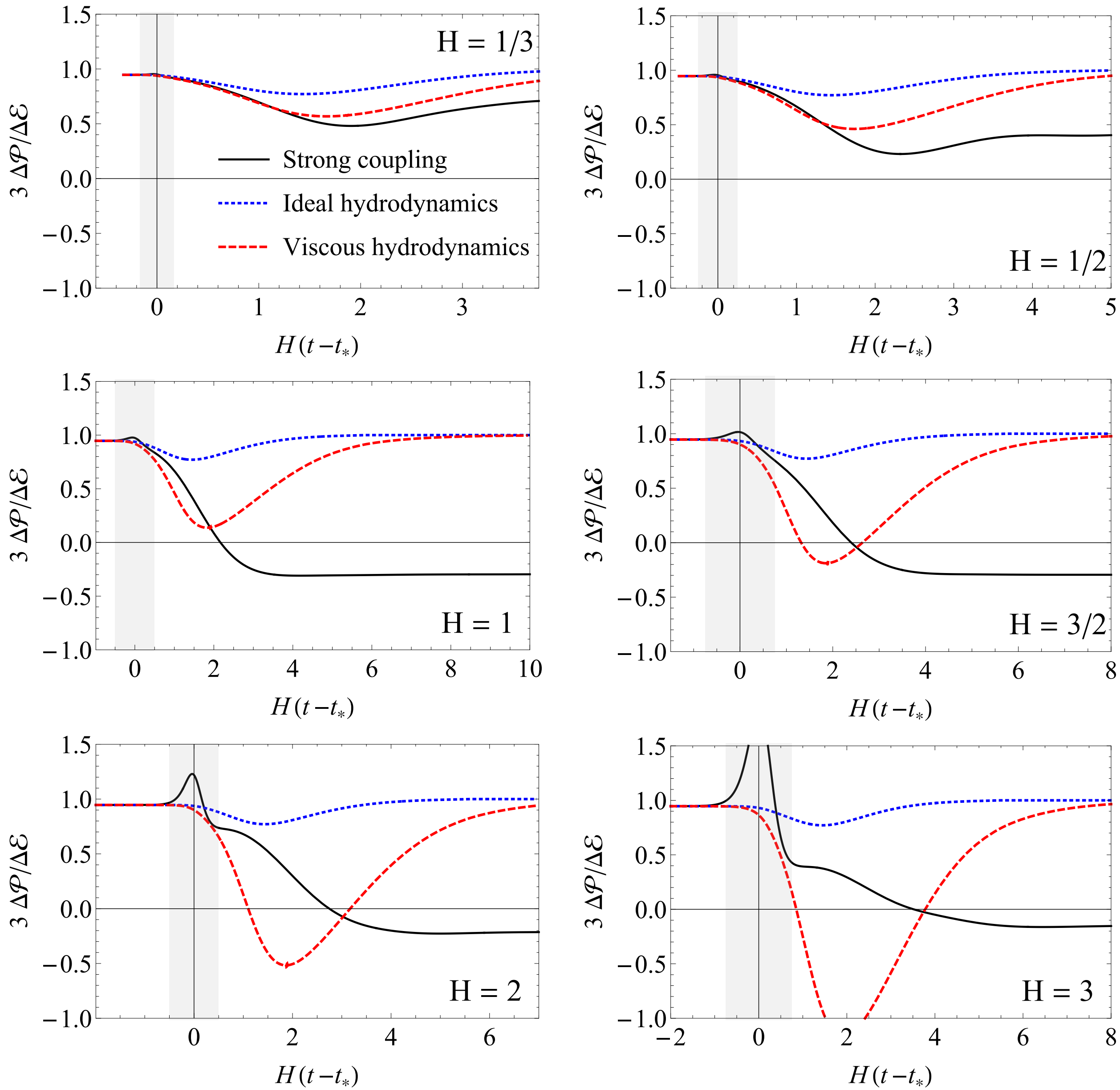
At sufficiently late times always far from equilibrium

Dynamics



Effective EoS at asymptotically late times

- As H increases, system no longer described by hydro:



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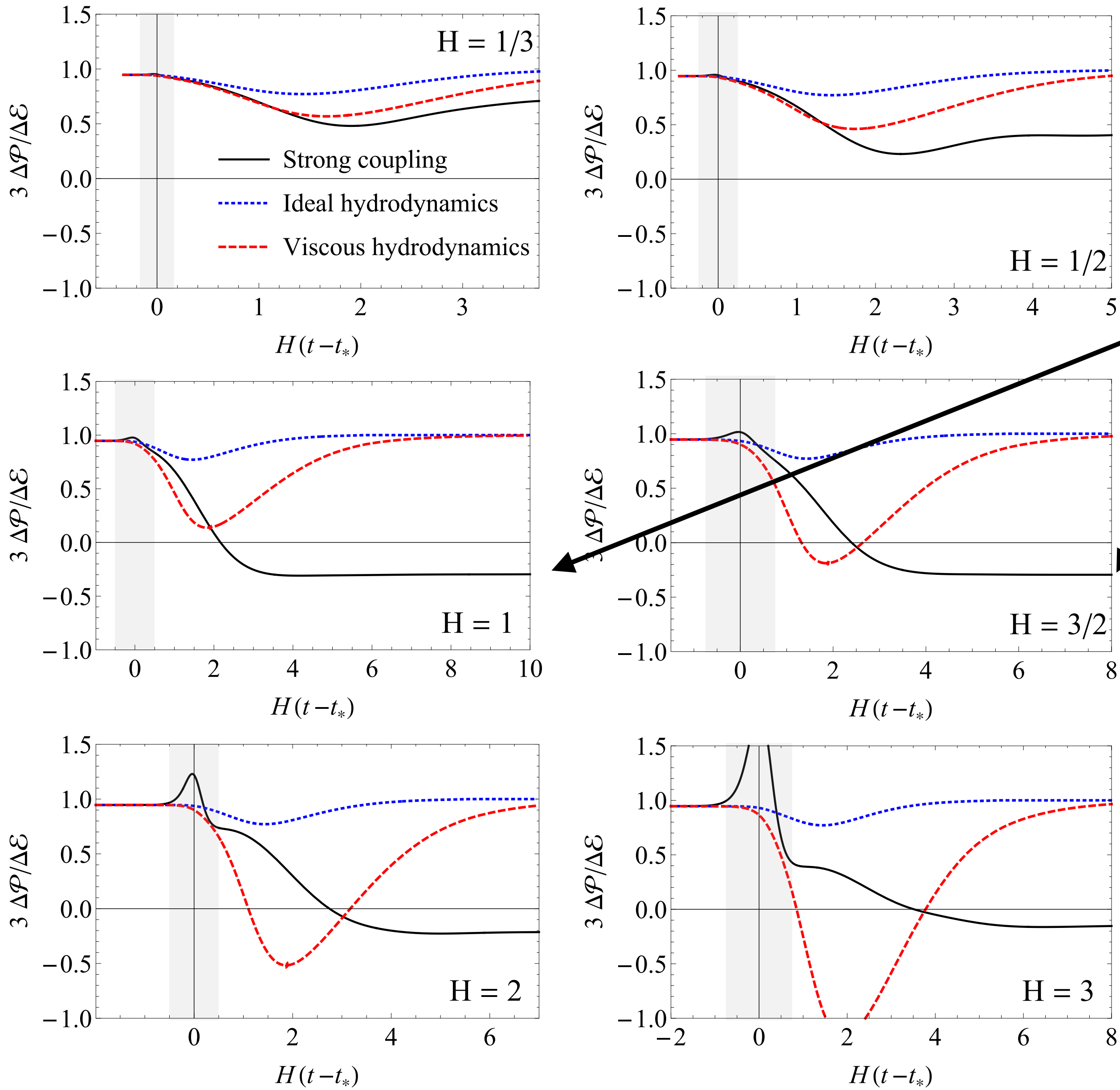
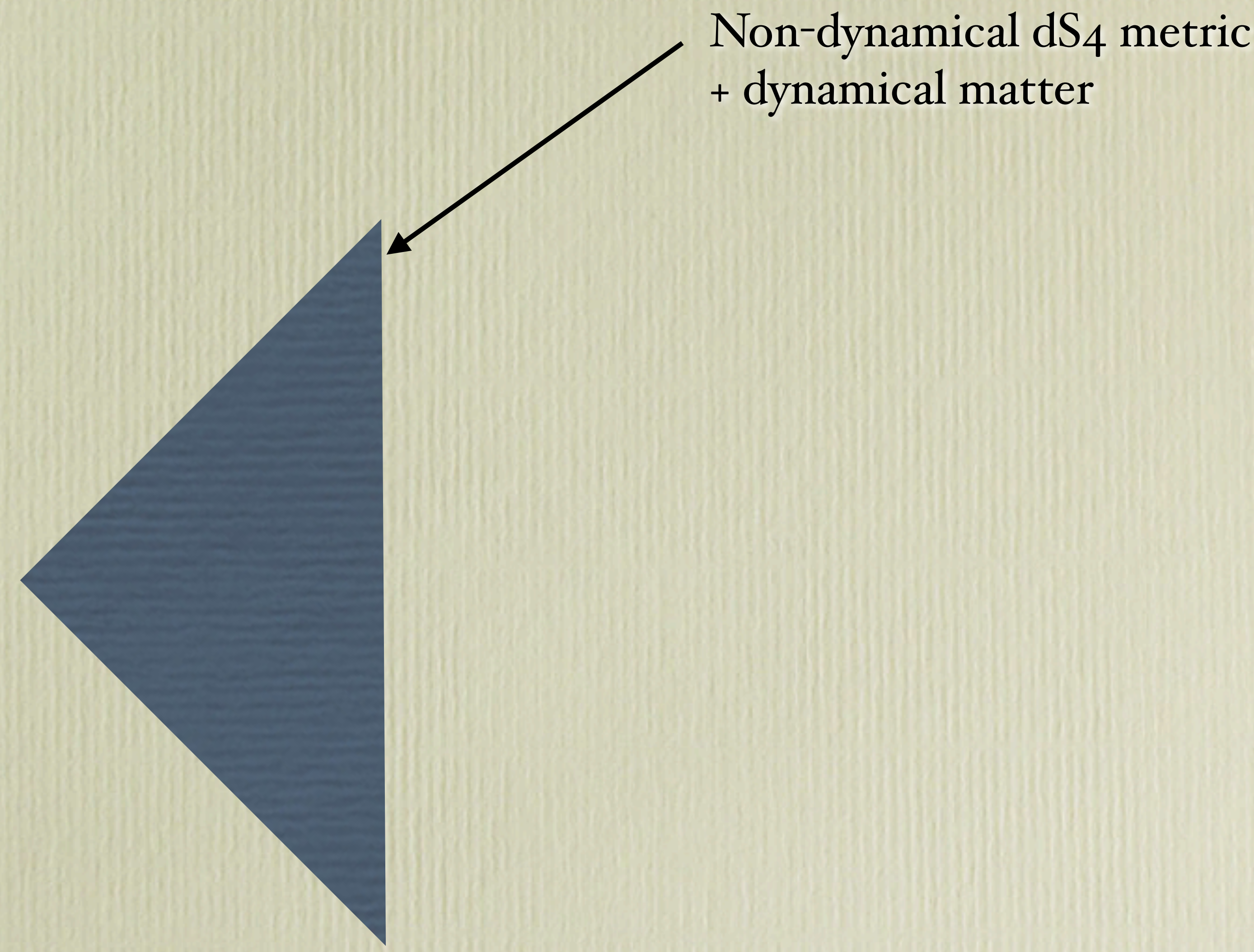
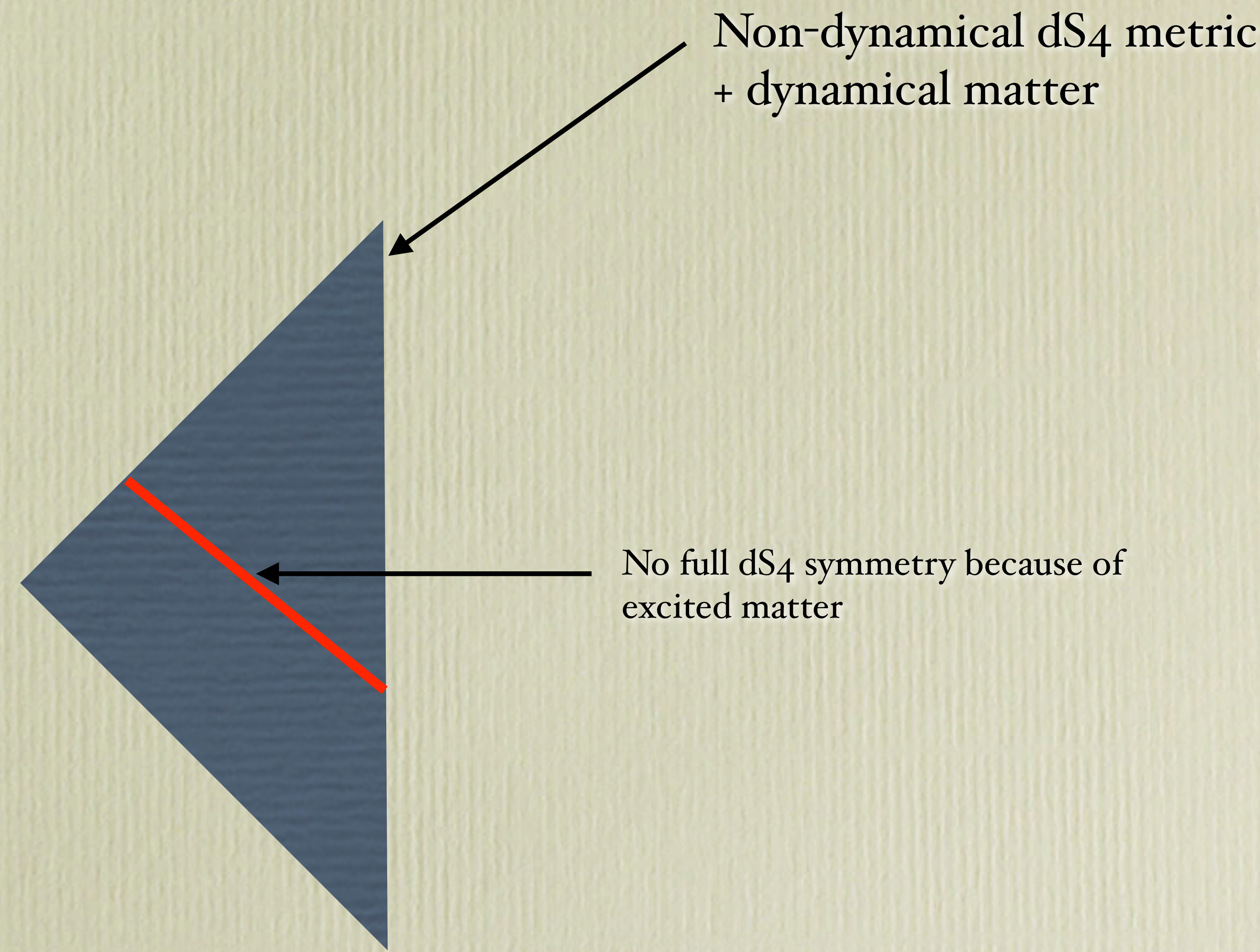


Pressure in effective EoS can become negative for H ~M

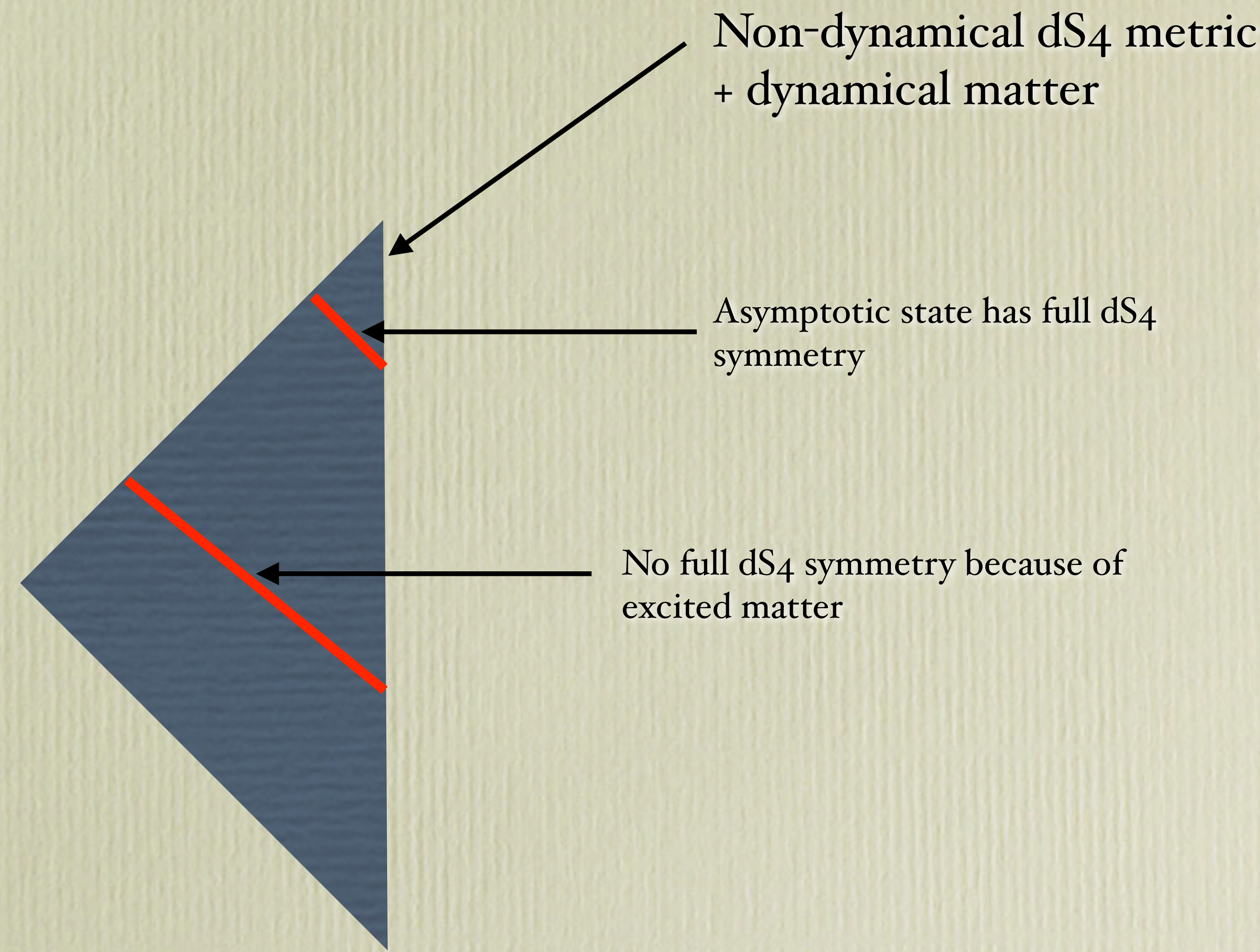
Late-time state



Late-time state

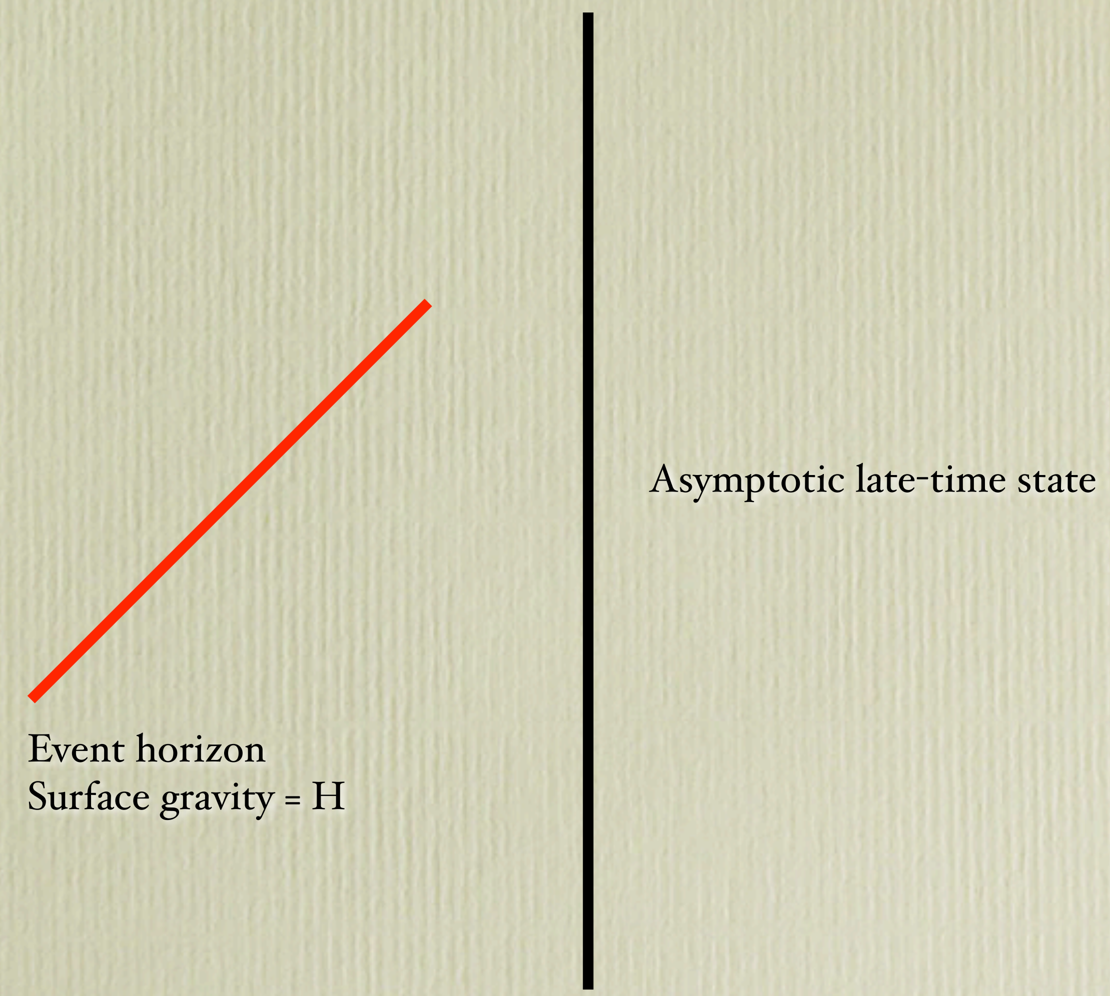


Late-time state

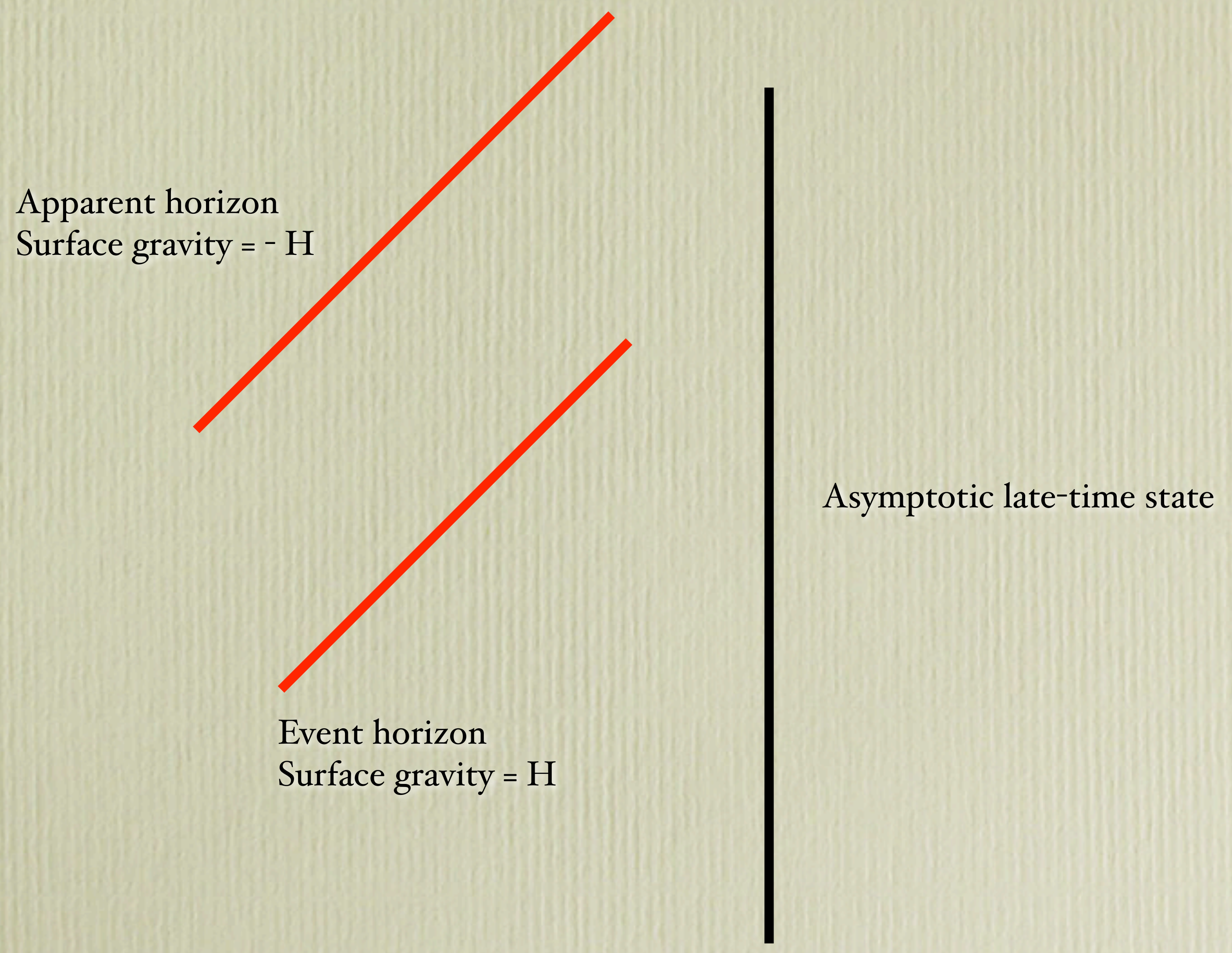


- This means that emergent, effective EoS can be determined from QNM-like perturbations of late-time state.

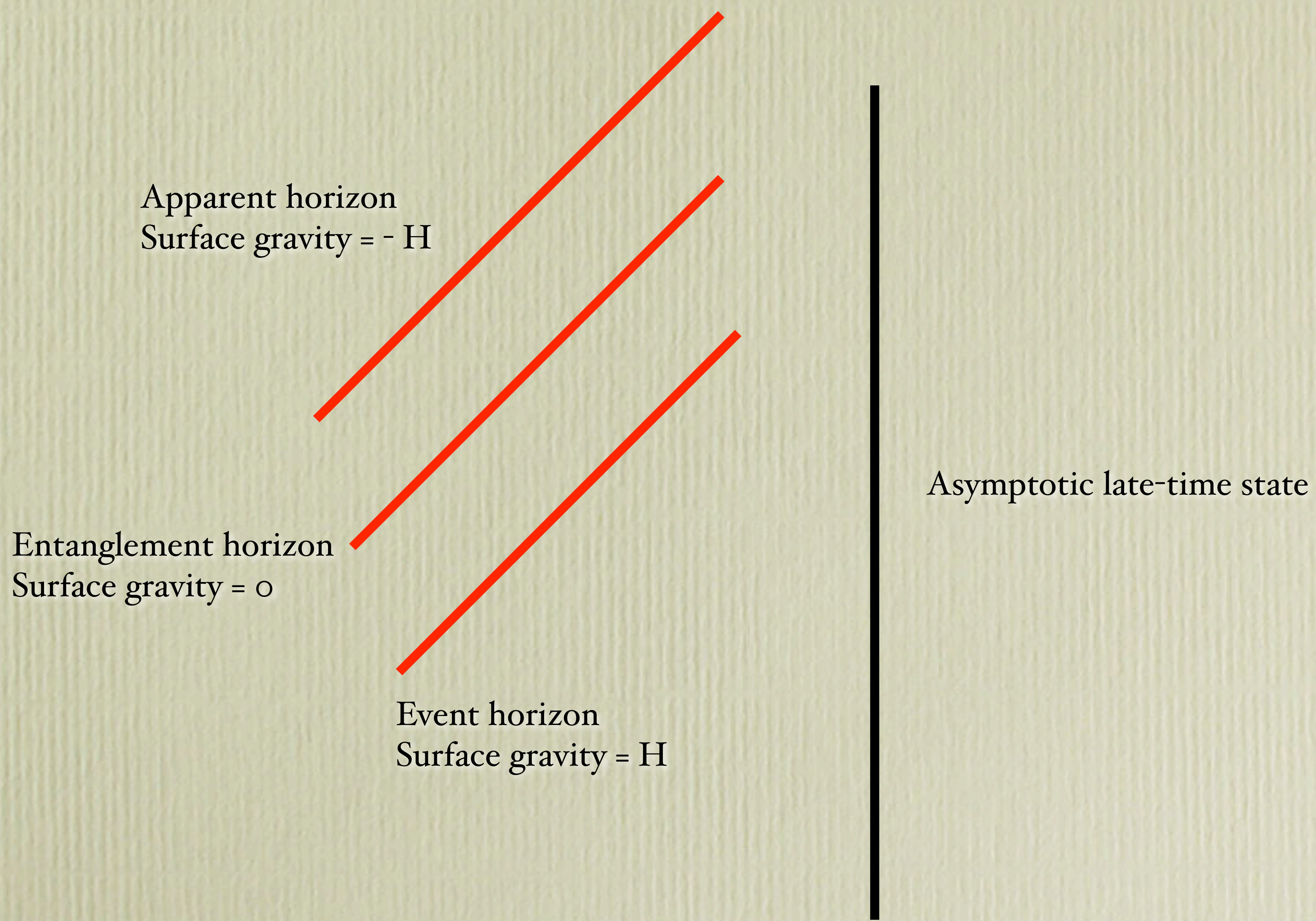
Three horizons in the late-time state



Three horizons in the late-time state



Three horizons in the late-time state

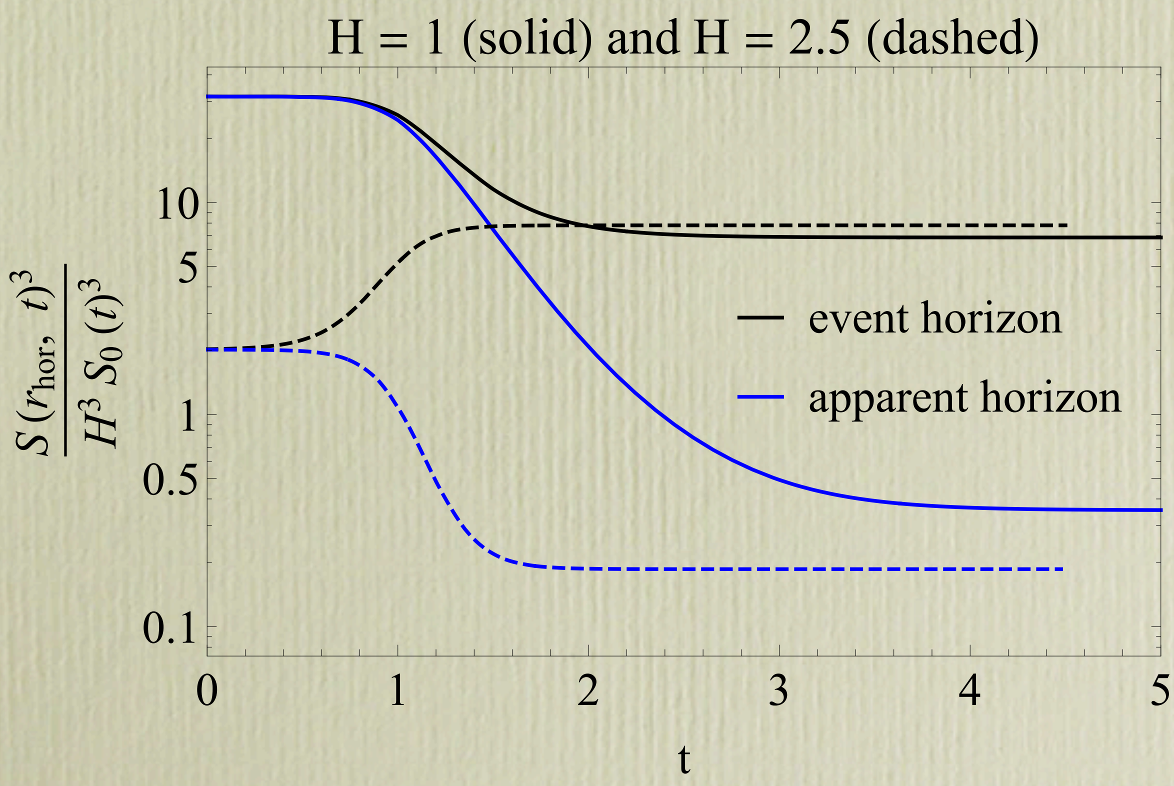


Three horizons in the late-time state

- Difference between EH and AH due to dynamical nature of the state.
- Both areas grow as $\exp(3Ht)$.

Three horizons in the late-time state

- Difference between EH and AH due to dynamical nature of the state.
- Both areas grow as exp(3Ht).
- Dividing by this factor:

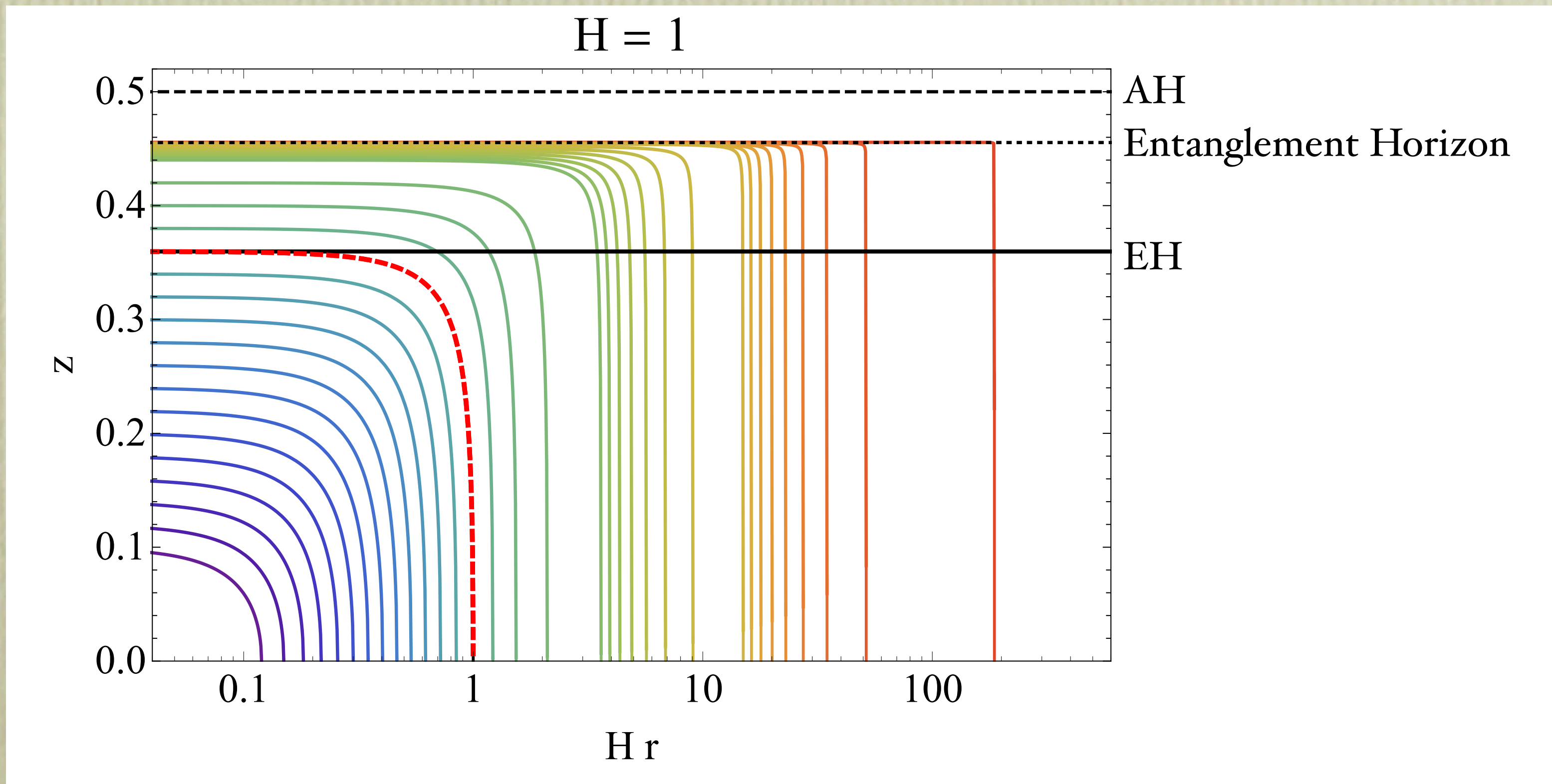


Entanglement entropy

- Consider entanglement entropy of ball of radius r at the boundary.

Entanglement entropy

- Consider entanglement entropy of ball of radius r at the boundary.
- If r is smaller than dS cosmological horizon then extremal surface does not penetrate the EH.
- If r is larger than dS cosmological horizon then extremal surface penetrates the EH but only top to Entanglement Horizon.



Outlook

- More general cosmologies.
- Non-homogeneous states.
- Theories with phase transitions.
- Backreaction on the 4D metric.

Thank you