Price for NEC-Violation

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This talk is mostly based on

- e-Print: arXiv:**1209.2961** [astro-ph.CO]
  with *Ignacy Sawicki*
- e-Print: arXiv: **1304.3903** [hep-th]
  with *Damien Easson, Ignacy Sawicki*

Plan

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- What is NEC, and why it is weird but interesting to violate it?

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- An interesting example of a different beginning of the universe: “Galilean Genesis” and “Subluminal Galilean Genesis”
- Sub- and superluminality in phase space and UV completion
- Conclusions

What is the NEC?

NULL ENERGY CONDITION:

$$\boxed{T_{\mu\nu} n^\mu n^\nu \geq 0}$$

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Energy-Momentum Tensor

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NULL ENERGY CONDITION:

Energy-Momentum Tensor

$$T_{\mu\nu} n^\mu n^\nu \geq 0$$

for all null vectors n^μ, i.e. vectors for which:

$$g_{\mu\nu} n^\mu n^\nu = 0$$

the *weakest* of all *local* classical energy conditions

NEC for perfect fluids and in cosmology

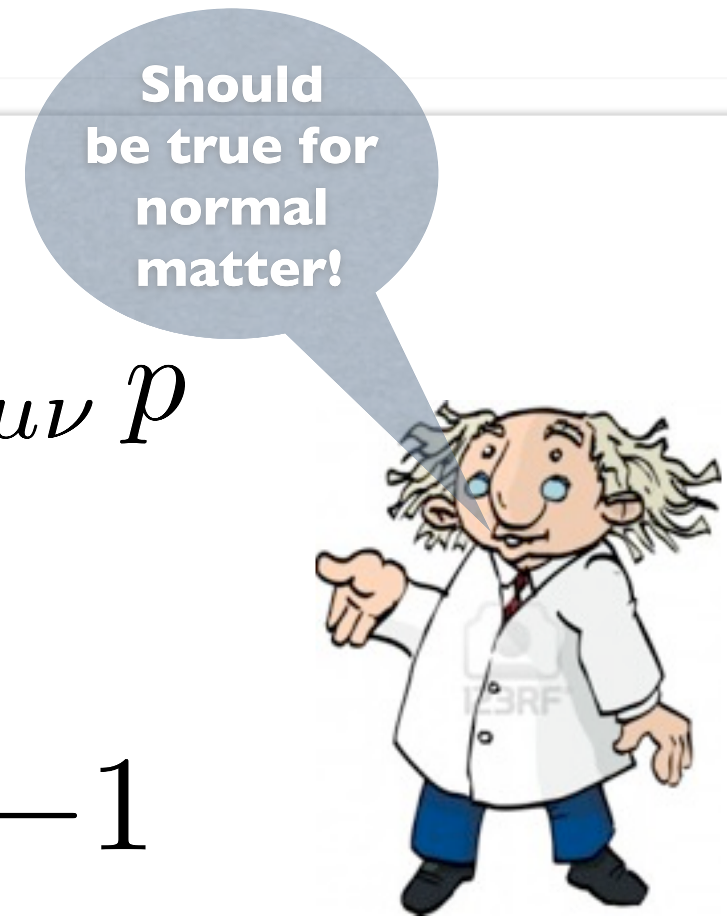
for a perfect fluid:

$$T_{\mu\nu} = (\varepsilon + p)\, u_\mu u_\nu - g_{\mu\nu}\, p$$

NEC $\Longleftrightarrow$ $p + \varepsilon \geq 0$

for a positive ε: equation of state $w \equiv p/\varepsilon \geq -1$

NEC for perfect fluids and in cosmology



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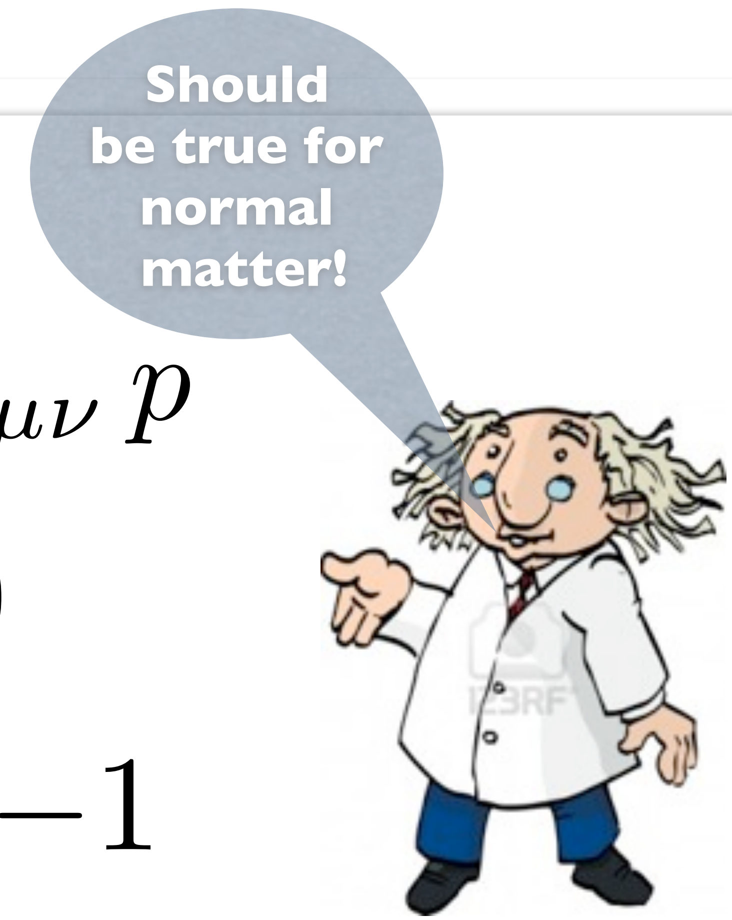

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in cosmology:

$$\dot{H} = -4\pi\,(\varepsilon + p) + \frac{k}{a^2}$$

the **NEC** implies that the Hubble parameter *can never grow* in open and flat Friedmann universes

Why is it interesting to look at "Phantom" NEC-violating models with

$$w < -1 \quad ?$$

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- Dark Energy observations

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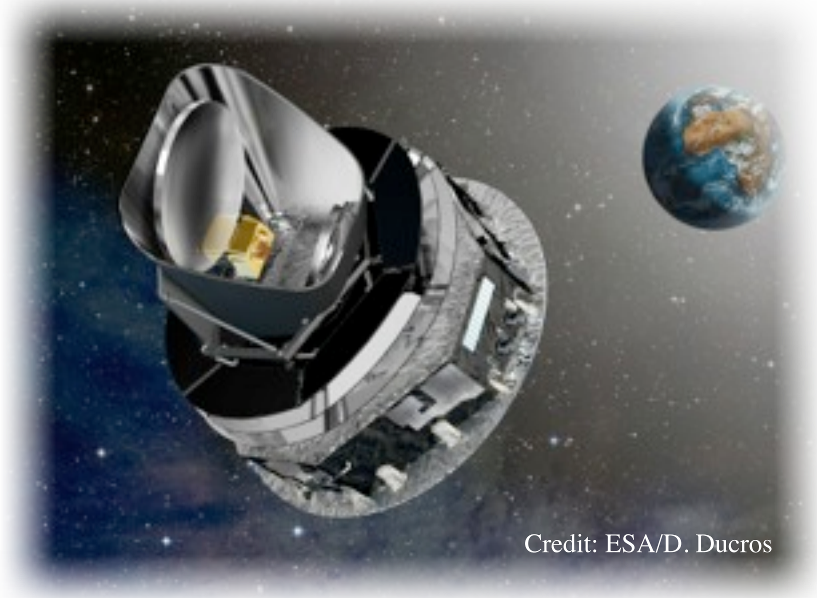
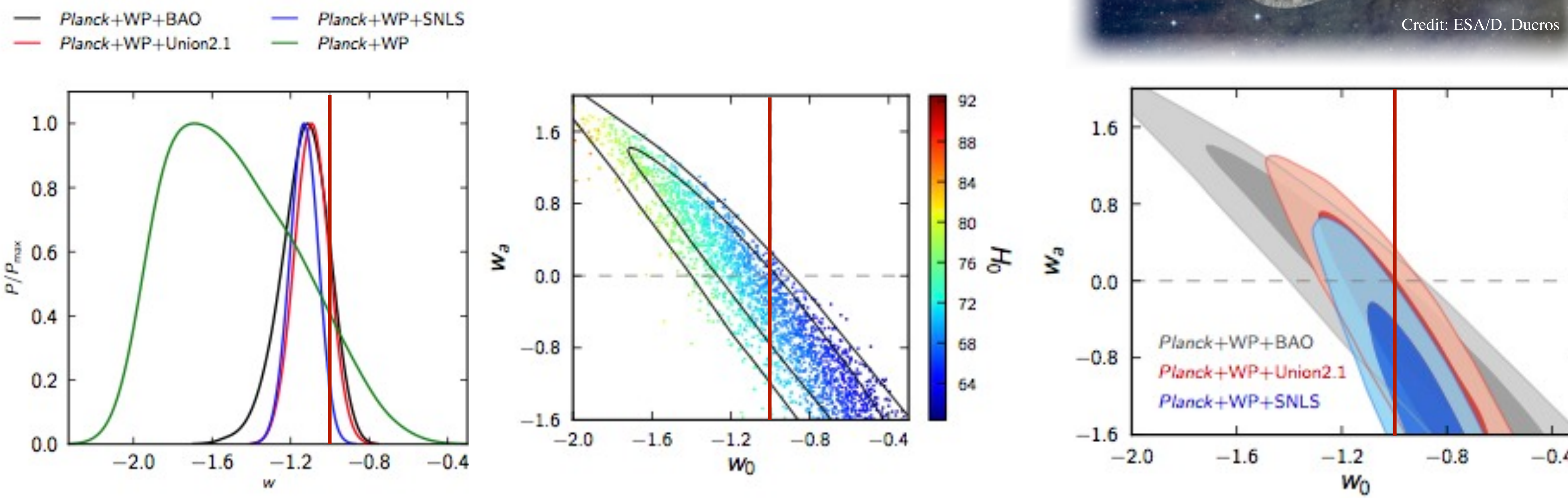
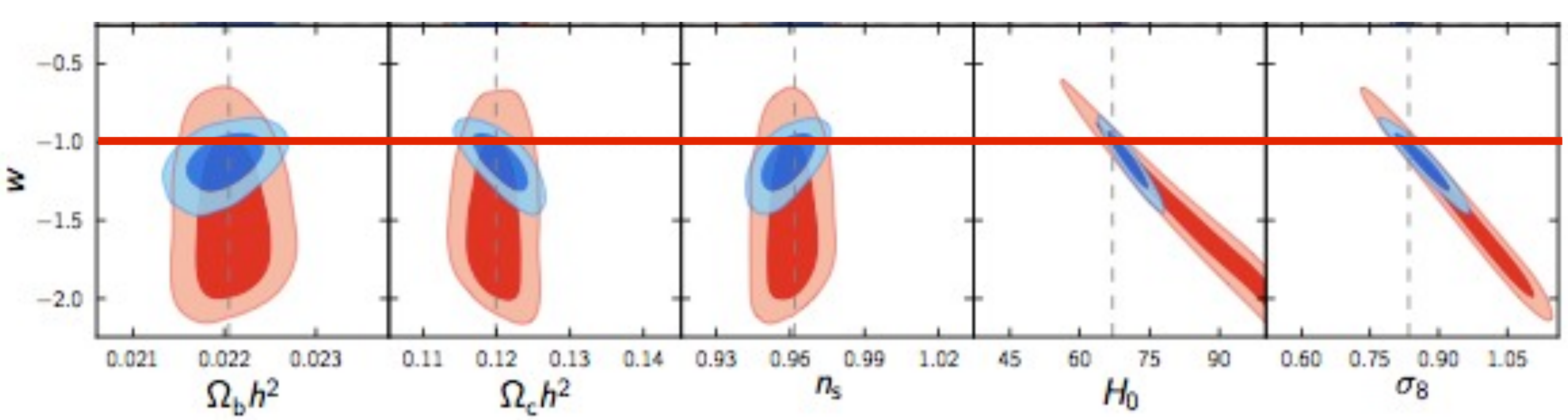
- Dark Energy observations
- Early Universe exotics: bouncing cosmology, possible avoidance of initial singularity (i.e. strong nonperturbative quantum gravity), inflationary models with blue tilted gravity waves etc...

Dark Energy equation of state after Planck 2013:







Dark Energy equation of state
Conclusion of Planck 2013:

"The addition of BAO data to the CMB data gives a tight constraint of $w = -1.13 \pm 0.12$. However, adding the SNLS SNe data gives $w = -1.135 \pm 0.069$ and adding the H measurement gives $w = -1.244 \pm 0.095$. Adding either of the two data sets which show tension with the CMB measurements for the base ΛCDM model, draws the solutions into the phantom domain ($w < -1$) at about the 2 σ level. In contrast, if we use the BAO data in addition to the CMB, we find no evidence for dynamical dark energy; these data are compatible with a cosmological constant, as assumed in the base ΛCDM model."

$w < -1$ **is definitely allowed, if not preferred!**

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arbitrary EMT

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- observer **B** boosted with 4-velocity $V^{\mu} = \dfrac{u^{\mu} + v\left(n^{\mu} - u^{\mu}\right)}{\sqrt{1 - v^2}}$

measures energy density $\varepsilon_V = T_{\mu\nu} V^{\mu} V^{\nu}$

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measures energy density $\varepsilon_V = T_{\mu\nu} V^\mu V^\nu$

for velocities close to the speed of light : $\varepsilon_V \simeq \dfrac{T_{\mu\nu} n^\mu n^\nu}{1 - v^2}$

arbitrary negative!

Broken NEC on just one configuration where the energy density can be positive

Lorentz invariance:
A can *create* the same field configurations *observed* by **B**

There are exist configurations with infinitely negative energy density - the Hamiltonian is unbounded from below

Flying through a NEC-violating "perfect fluid" / cosmological configuration

- Spatial part of the fluid momentum density $p_\mu = T_{\mu\nu} V^\nu$ always points in the same direction as the velocity of the observer - it *helps* to boost further!
- For speeds $v > v_{\mathrm{sp}} \equiv 1/\left|w\right|$ momentum density of the fluid becomes *spacelike*
- For speeds $v > v_{\mathrm{neg}} \equiv 1/\sqrt{-w}$ energy density of the fluid becomes *negative*, thus by busting further the observer measures even more negative energy density in the fluid

- If the speed of the sound waves in this NEC-violating fluid is higher than $v_{\rm neg}$, they feel negative energy around them. The sound waves definitely interact with the fluid!

- This looks like well known run-away instability despite of the point that the sound waves can be ghost free, have positive energy, and real sound speed

- Similarly to the well known situation with ghosts the time scale of instability depends on details of the interaction - there are examples when the instability related to ghosts is slow - *Emparan, Garriga (2005); Garriga, Vilenkin (2012)*

Can NEC be broken by a renormalizable scalar field?

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wrong sign- "ghost"

$$\mathscr{L} = -\frac{1}{2}g^{\mu\nu}\,\partial_\mu\phi\partial_\nu\phi - V\left(\phi\right)$$

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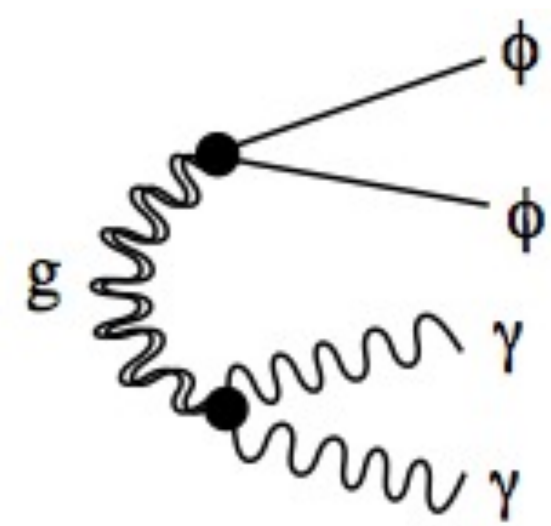
Catastrophic quantum instability!



+ Lorentz symmetry → ***infinite* rate of production**

No Lorentz symmetry → $\Gamma_{0\to 2\gamma 2\phi} \sim \dfrac{\Lambda^8}{M_{\rm Pl}^4}$

Cline, Jeon, Moore, (2003)

But do we have any reasonable theory where this Phantom is possible i.e. not immediately inconsistent?

Galilean Genesis, Idea

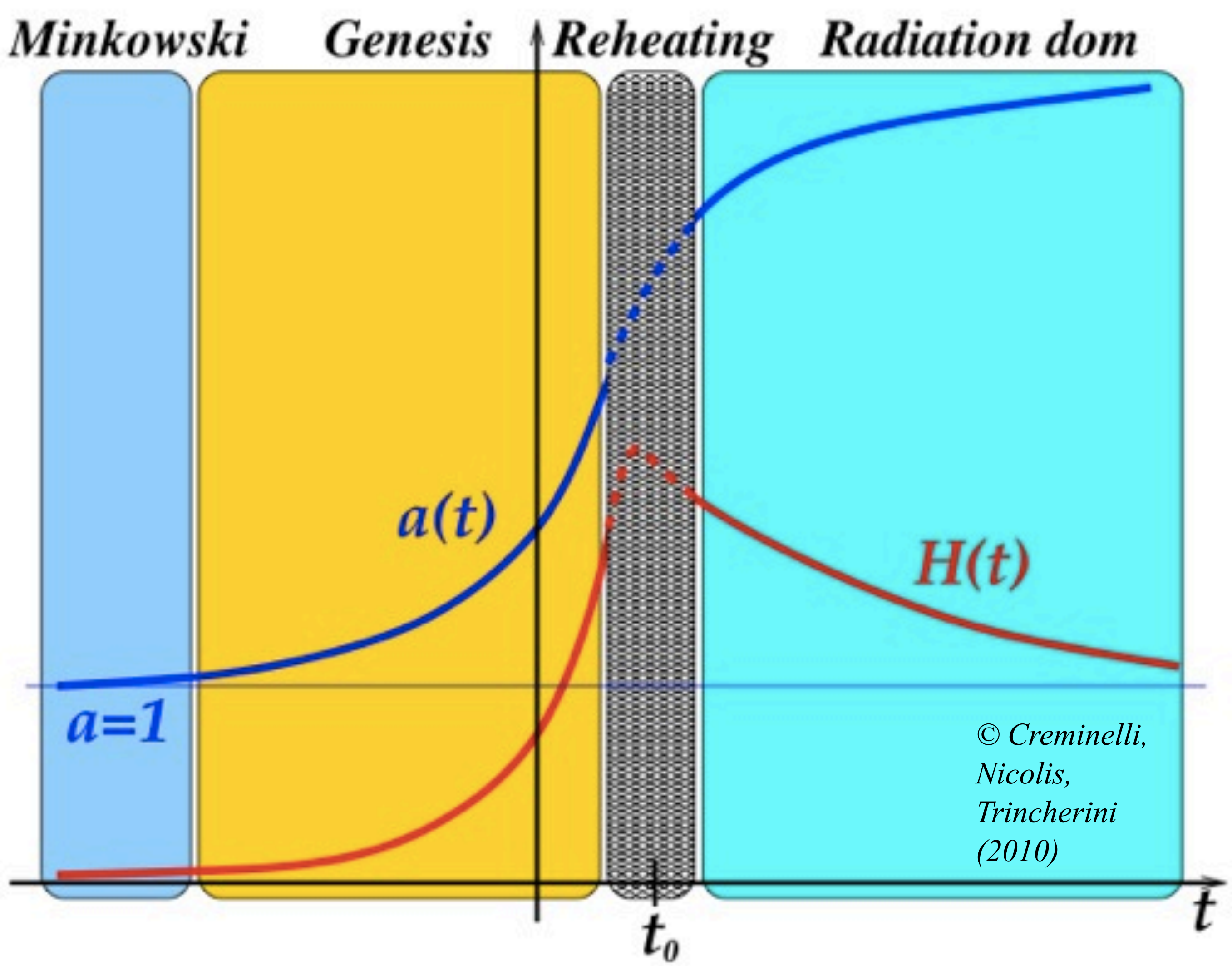
Paolo Creminelli, Alberto Nicolis, Enrico Trincherini (2010)

- Beginning of the universe from the Minkowski spacetime
- The Galileon scalar field π drastically violates the Null-Energy-Condition - $\dot{H} \gg H^2$
  - superinflation without ghosts and gradient instabilities
- cosmological solution $\pi = -\log\left(-H_0 t\right)$ is an attractor
- cosmological perturbations can be generated à la curvaton mechanism through a non-minimal coupling

$$g_{\mu\nu}^{\sigma\mathrm{matter}} = e^{2\pi} g_{\mu\nu}$$

  to an additional “curvaton” σ scalar field
- on the attractor solution $g_{\mu\nu}^{\sigma\mathrm{matter}}$ mimics dS so that perturbations can be approximately scale-invariant

Galilean Genesis ?



- Classical superinflation leads to a Big-Rip singularity in the future
  - to an "*end of time*"

- similar to the ekpyrotic models where the perturbations are generated in a *contracting* stage *before* the singularity

- It is not clear how to exit from the superinflationary stage and enter standard hot big-bang cosmology *cf. Laurence Perreault Levasseur, R. Brandenberger, Anne-Christine Davis (2011)*

Galilean Genesis, Theory

$$S_\pi = \int \mathrm{d}^4x\sqrt{-g}\left[-f^2e^{2\pi}\left(\partial\pi\right)^2 + \frac{\gamma}{2}\left(\partial\pi\right)^4 + \gamma\left(\partial\pi\right)^2\Box\pi\right]$$

$$\gamma = \left(\frac{f}{\Lambda}\right)^3 \gg 1$$

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No standard Wilsonian UV-completion

Adams, Arkani-Hamed, Dubovsky, Nicolis, Rattazzi (2006)

In the Galilean Genesis, in the past, for $t \to -\infty$

$$c_{\mathrm{s}} \simeq 1 - \left(\frac{4f}{3H_0 t} \right)^2$$

Potentially dangerous because the neighboring solutions can have $c_{\mathrm{s}} > 1$

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Subluminal Galilean Genesis

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Creminelli, Hinterbichler, Khoury, Nicolis, Trincherini (2012)

$$S_\pi = \int \mathrm{d}^4x \sqrt{-g} \left[-f^2 e^{2\pi} \left(\partial\pi\right)^2 + \gamma \frac{\beta}{2} \left(\partial\pi\right)^4 + \gamma \left(\partial\pi\right)^2 \Box\pi \right]$$

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↓

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NEW

$$\beta = 1 + \alpha$$

$$\gamma = \left(\frac{f}{\Lambda}\right)^3 \gg 1$$

known to lead to superluminal propagation around some backgrounds

↓

No standard Wilsonian UV-completion

the dynamics and the genesis solution
are practically the same but

$$c_s^2\Big|_{\text{genesis}} = \frac{3-\alpha}{3\,(1+\alpha)} < 1$$

for

$$0 < \alpha < 3$$

subluminality for solutions close to the Genesis solution

Is *Subluminal Genesis* subluminal?

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Is there a standard Wilsonian UV-Completion?

A different face of the Galileon

field redefinition

$$\pi = \log(\phi/f)$$

$$S_\phi = \int \mathrm{d}^4x\sqrt{-g}\left[-(\partial\phi)^2 + \gamma\left(\frac{\beta-2}{2}\right)\frac{(\partial\phi)^4}{\phi^4} + \gamma\,\frac{(\partial\phi)^2}{\phi^2}\,\frac{\Box\phi}{\phi}\right]$$

f only enters into the non-minimal coupling with σ-matter

$$g_{\mu\nu}^{\mathrm{matter}} = e^{2\pi} g_{\mu\nu} = \left(\frac{\phi}{f}\right)^2 g_{\mu\nu}$$

this coupling cannot be universal, because otherwise the "*Genesis*" is just *Inflation*

Unusual Scaling

rescaling coordinates $x^\mu \to \gamma^{1/2}\, y^\mu$

$$S_\phi \to \gamma\, S_\phi \quad \text{and} \quad S_{\rm EH} \to \gamma\, S_{\rm EH}$$

for minimally coupled matter $\rho \to \rho/\gamma$

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Neither f nor Λ really affect the dynamics of the system without σ-matter

These parameters disappear from all equations!

The only parameter is $\beta = 1 + \alpha$

$$0 < \alpha < 3$$

Cosmological dynamics

rescaled coordinates $m = \dot{\pi}\,\gamma^{1/2}$ and $h = H\,\gamma^{1/2}$

$$\pi' = m$$
$$m' = f_1\,(m, \pi, h)$$
$$h' = f_2\,(m, \pi, h)$$

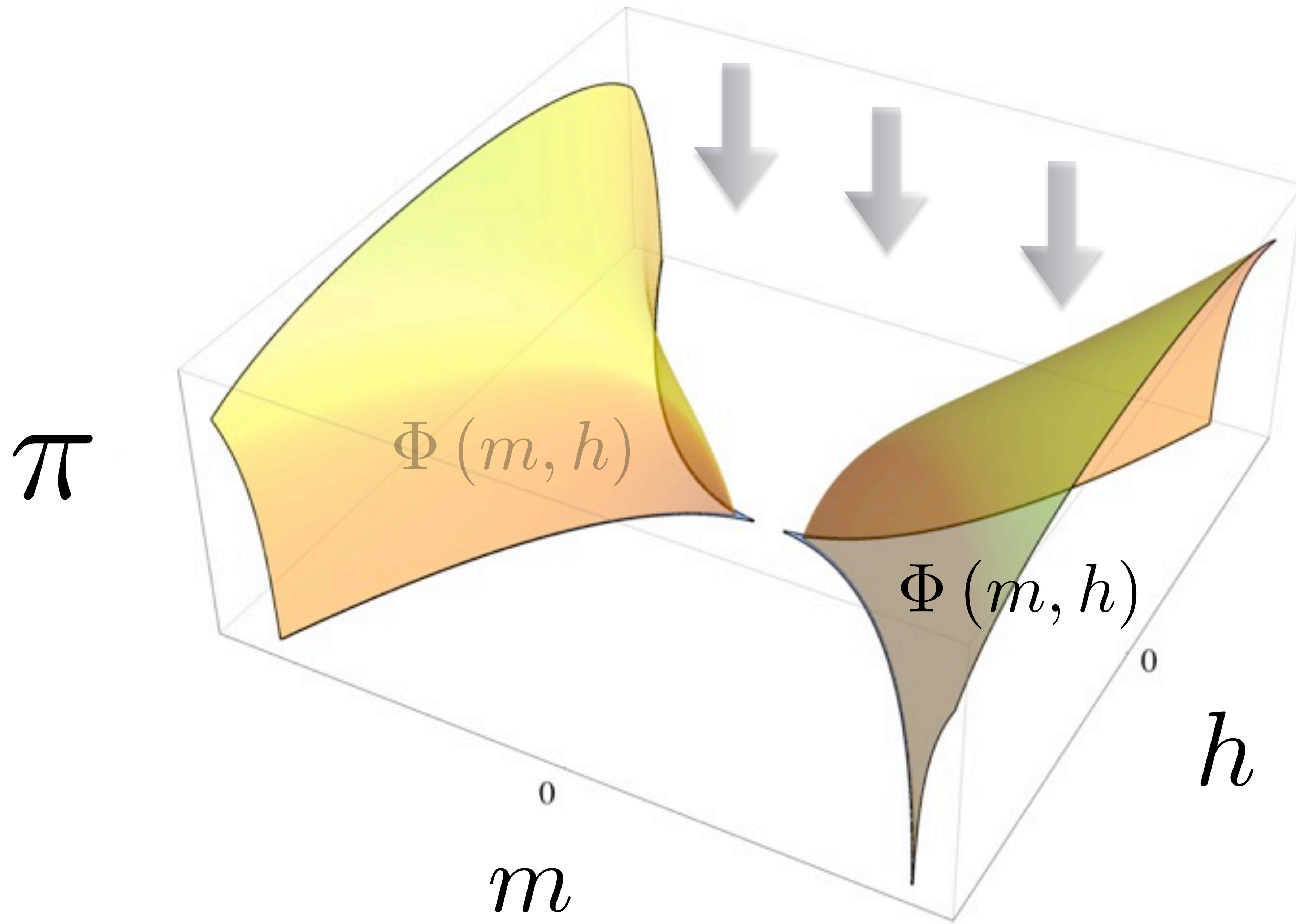
+

Constraint
Friedmann Equation

$$h^2 = \varepsilon\,(h, m, \pi)$$

2 independent variables

Good (m, h) coordinates for the cosmological Phase Space



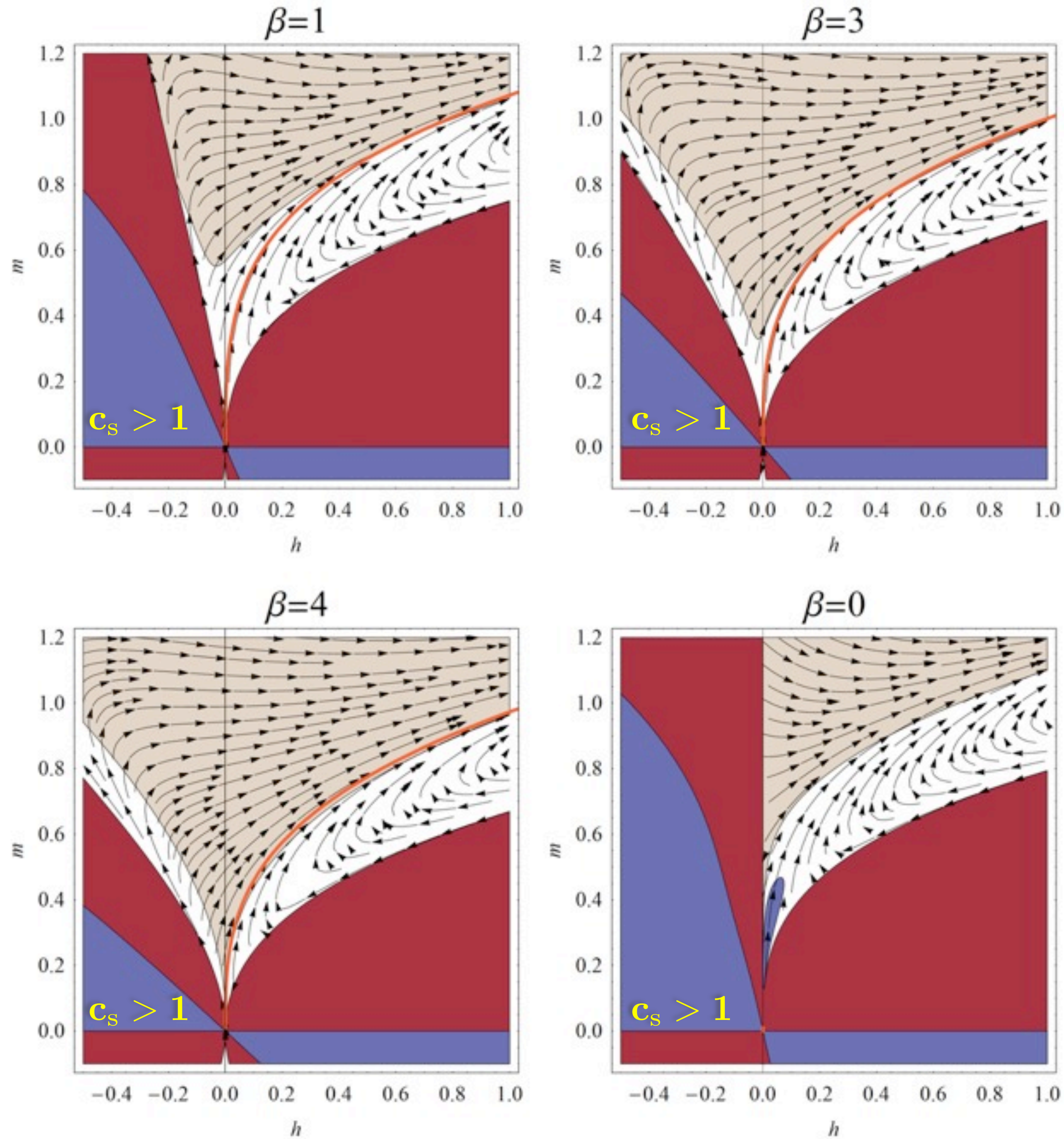
Action for Cosmological Perturbations

$$S_\zeta = \frac{1}{2}\int \mathrm{d}t\,\mathrm{d}^3x\,a^3\mathcal{A}\left[\dot{\zeta}^2 - \frac{c_\mathrm{s}^2}{a^2}\left(\partial_i\zeta\right)^2\right]$$

- the normalization $\mathcal{A} = \dfrac{m^2 D}{\left(h - m^3\right)^2}$
- no ghosts $\Rightarrow$ $\dfrac{m^2}{3}D = 2h^2 + m^4\left(2m^2+\beta\right) > 0$
- sound speed $c_\mathrm{s}^2 = 1 - \dfrac{12}{\left(Dm\right)^2}\, m\mathscr{P}\left(m,h\right)$

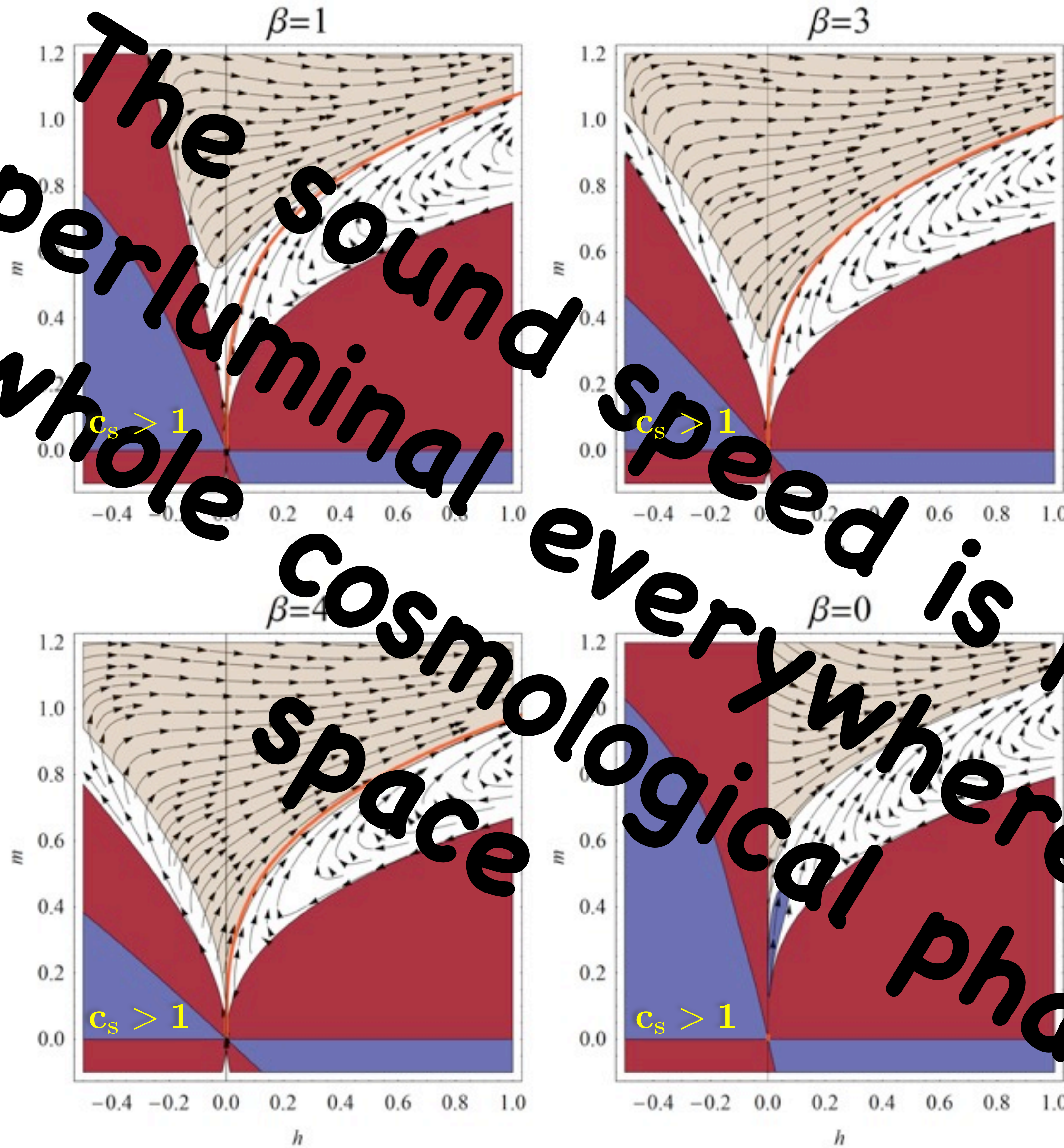
$$\mathscr{P}\left(m,h\right) = 8h^3 + 2h^2 m\left(1-4m^2+\beta\right) + 4hm^4\left(2m^2-1\right) + m^5\left(4m^4+5m^2\beta+(\beta-1)\beta\right)$$

what is the sign of $m\mathscr{P}\left(m,h\right)$ in $\Phi\left(m,h\right)$?



β=1
β=3
β=4
β=0
$c_s > 1$
$c_s > 1$
$c_s > 1$
$c_s > 1$
m
h

The sound speed is not superluminal everywhere in the whole cosmological phase space



However,...

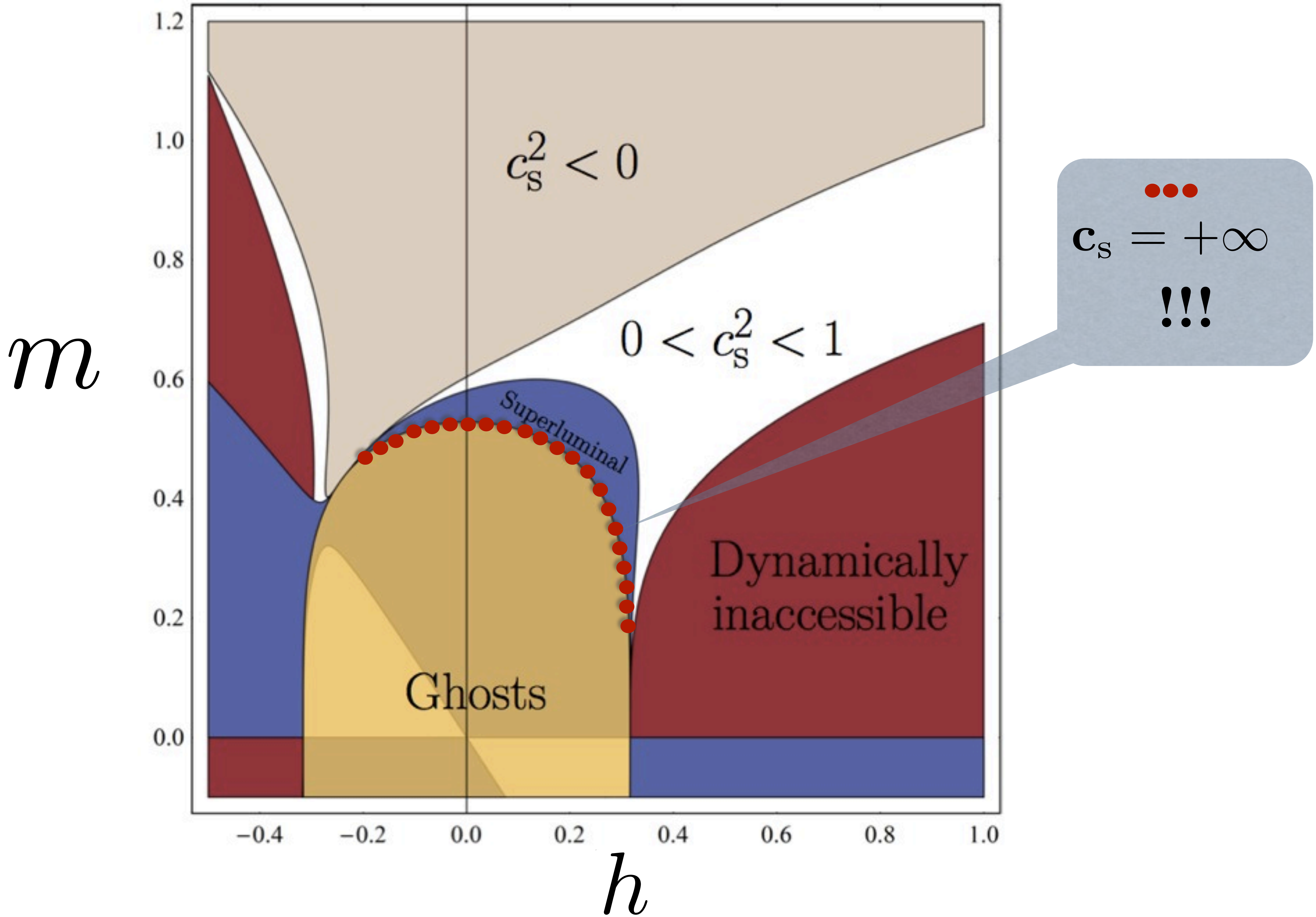
- There is no reason to exclude configurations with a substantial presence of other minimally coupled matter e.g. radiation
- Indeed a substantial portion of radiation is needed to reheat.
- But UV completion should depend on properties (e.g. subluminality) of *all connected* configurations available.
- Can these configurations be subluminal?

Can matter, which is coupled to the Galileon only in the standard way - indirectly through gravity, be relevant for the UV completion?

External matter has two effects

- now the phase space is 3d (m, π, ρ) and there are *more* (m, π) configurations available = solutions are different
- because the Galileon is *not a perfect fluid* the sound speed not only depends on local Galileon initial data (m, π) but also on the Ricci tensor and in particular on the external energy density

external radiation



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- As the only systems known so far to violate the NEC without ghosts and gradient instabilities are *Generalized Galileons / Horndeski theories* , it seems that any nonstandard beginning of the universe or / and Phantom DE require superluminality and consequently a nonstandard UV-completion.

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Thanks a lot for attention!