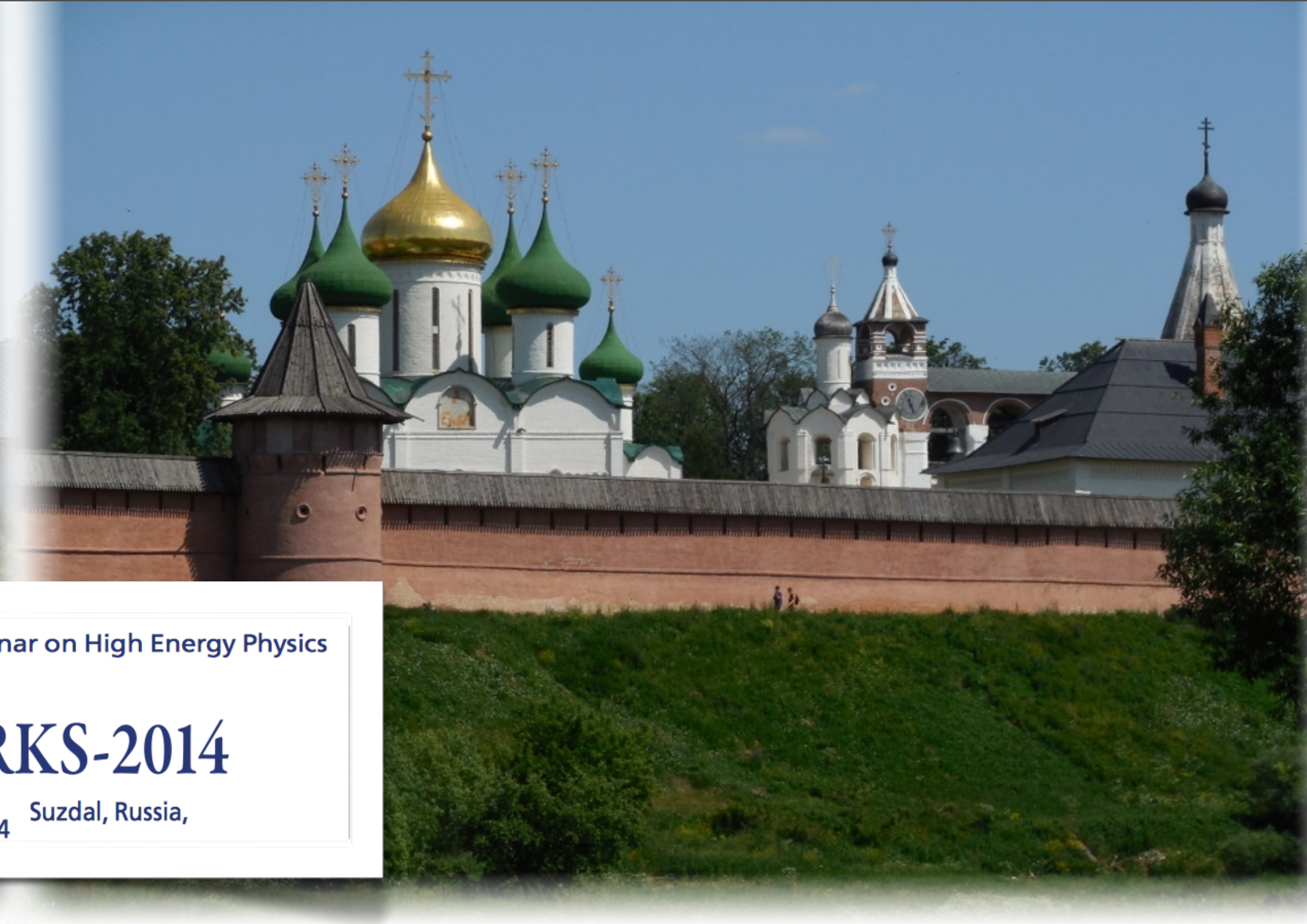

18th International Seminar on High Energy Physics
QUARKS-2014
2-8 June, 2014 Suzdal, Russia,

NEC-Breaking,

Instabilities and UV-Completion

Alexander Vikman

LMU
LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN

05.06.14

This talk is mostly based on

- ***Hidden Negative Energies in Strongly Accelerated Universes***
  e-Print: arXiv:**1209.2961** [astro-ph.CO]
  with *Ignacy Sawicki*

- ***When Matter Matters***
  e-Print: arXiv: **1304.3903** [hep-th]
  with *Damien Easson, Ignacy Sawicki*

What is the NEC?

NULL ENERGY CONDITION:

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

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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 ⟺ inertial mass density $p + \varepsilon \geq 0$

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

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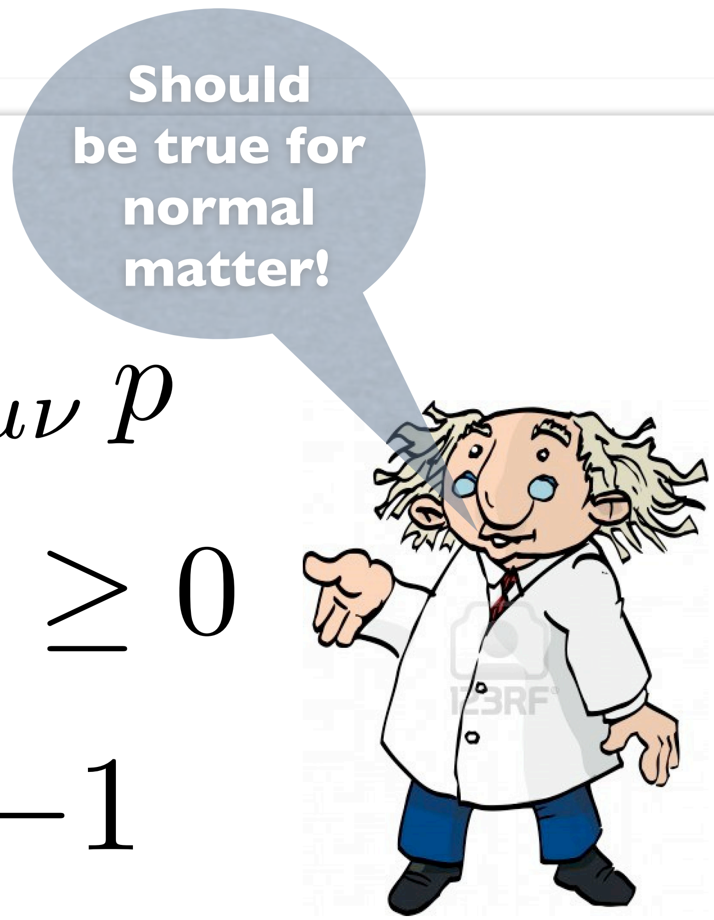

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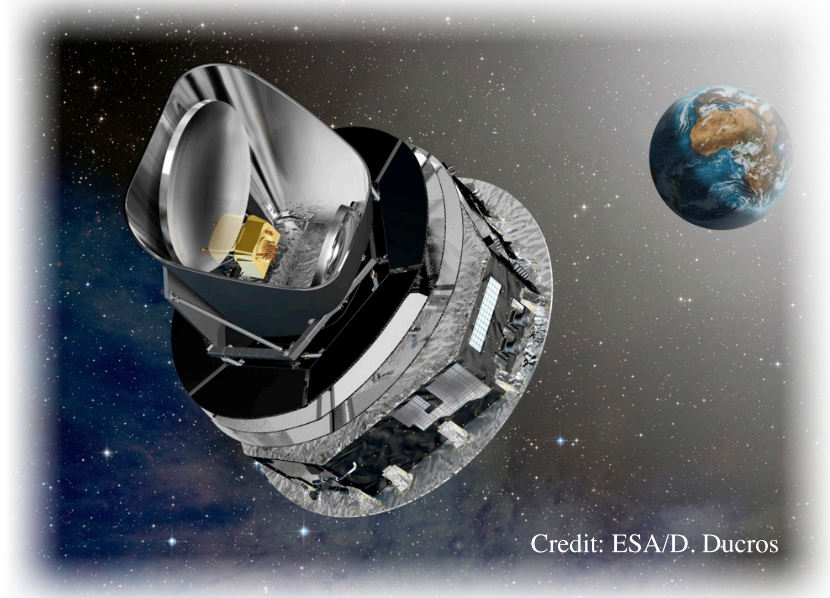
---

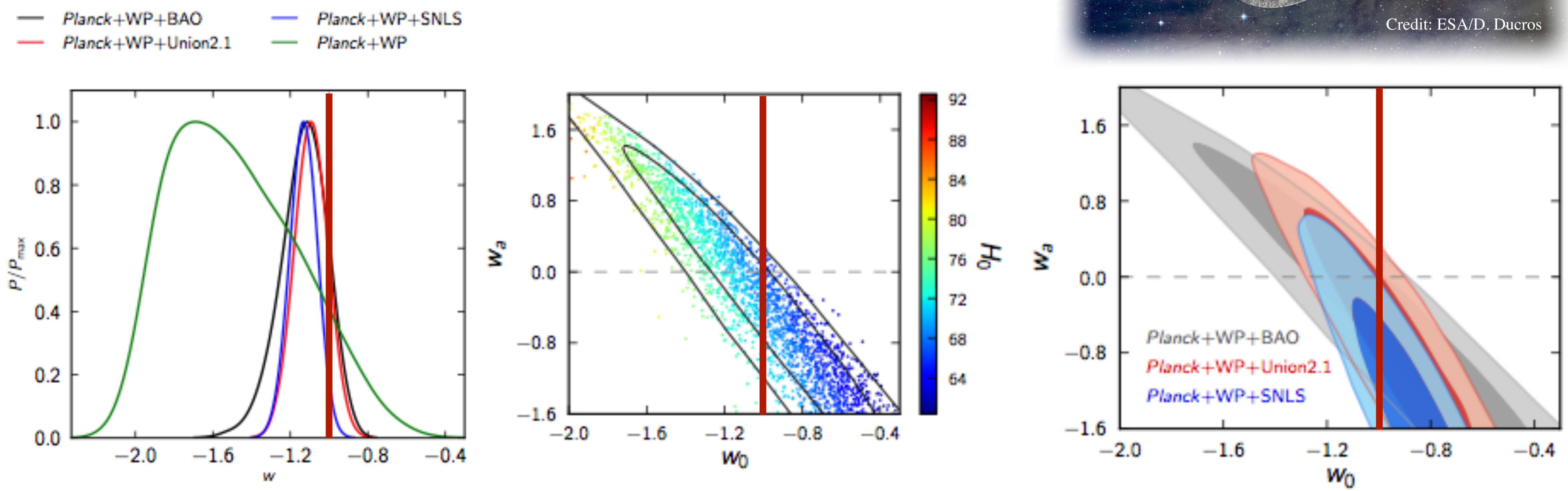
in cosmology:

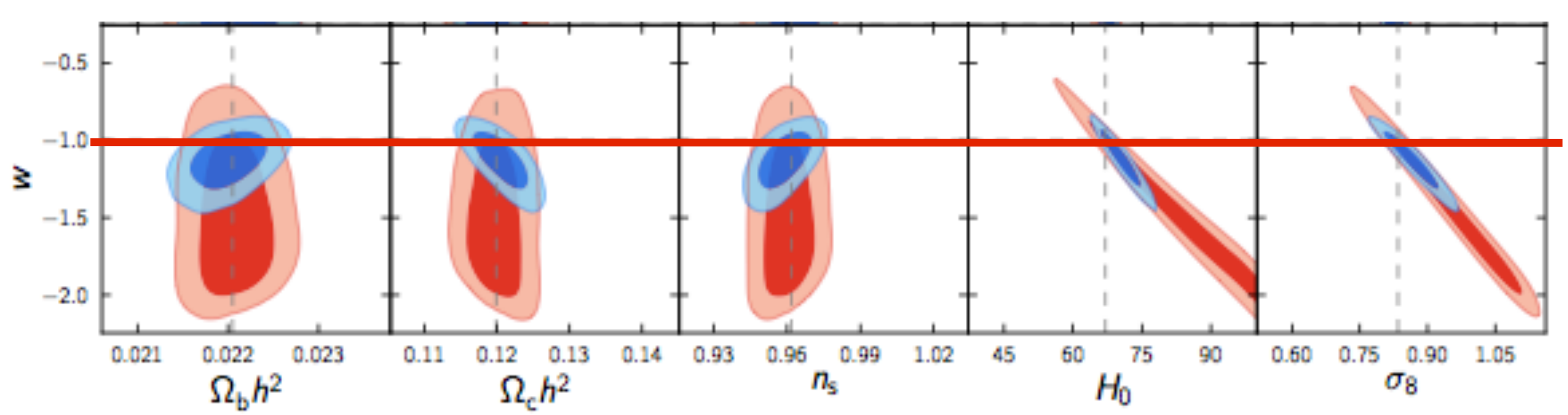
$$\dot{H} = -4\pi\,(\varepsilon + p) + \frac{k}{a^2}$$

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

Dark Energy equation of state after Planck 2013:







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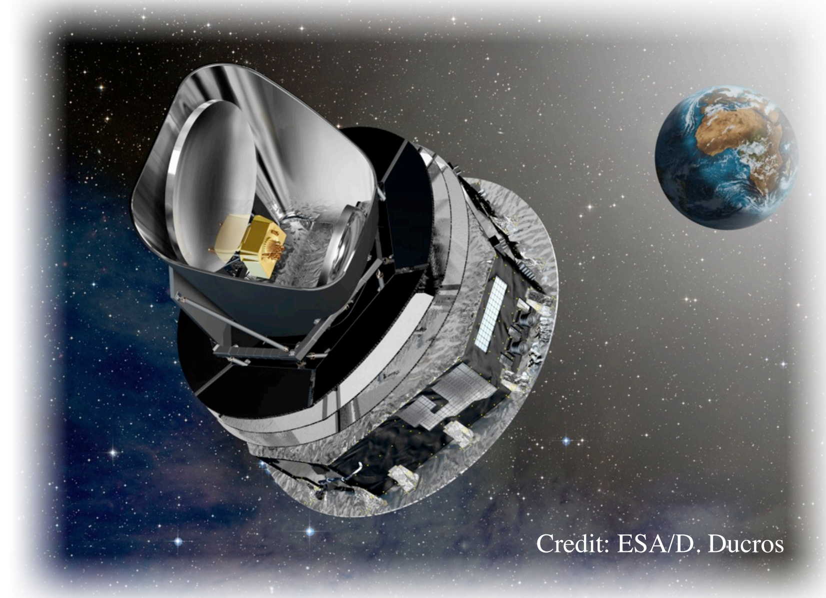

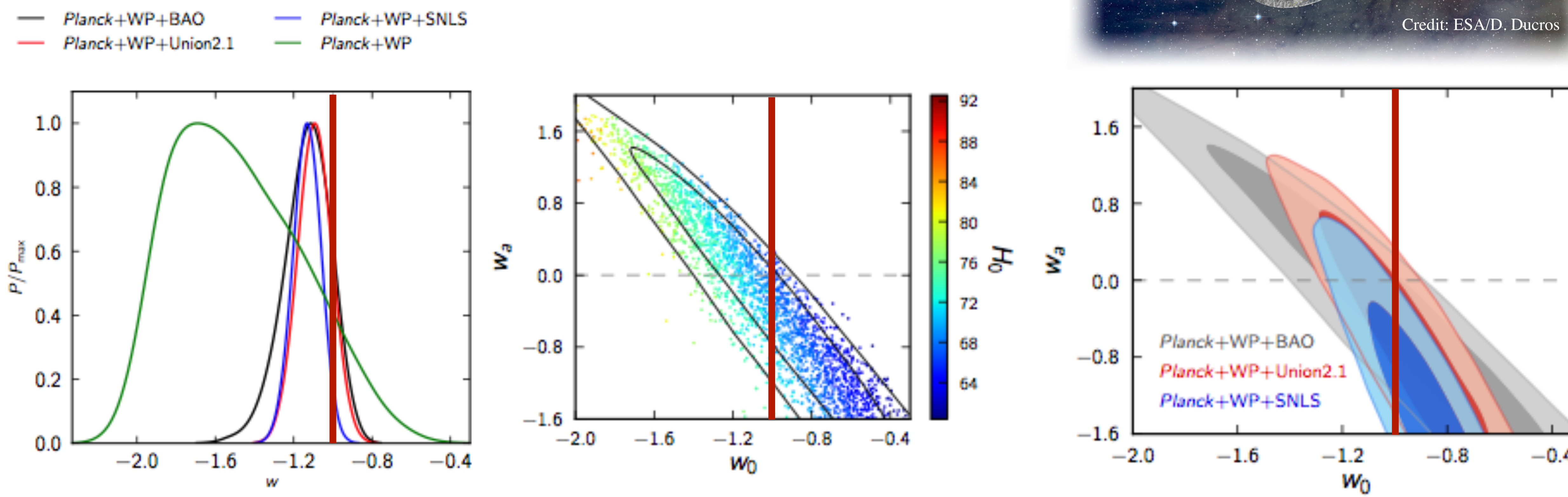

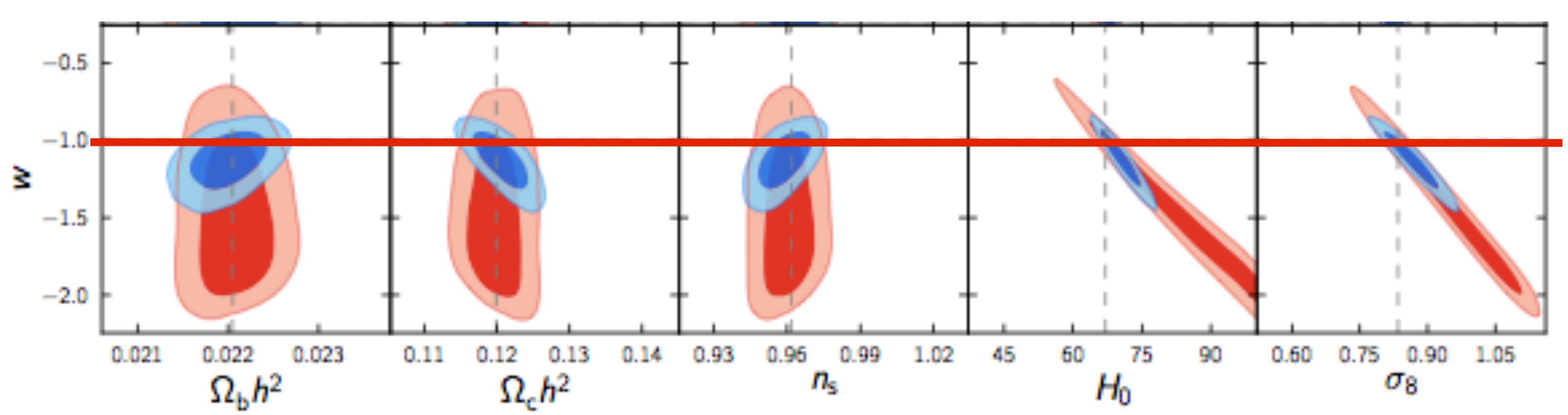

$w < -1$ **is definitely allowed *by data*, if not preferred!**

Can NEC be broken by a renormalizable scalar field?

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wrong sign- "ghost"

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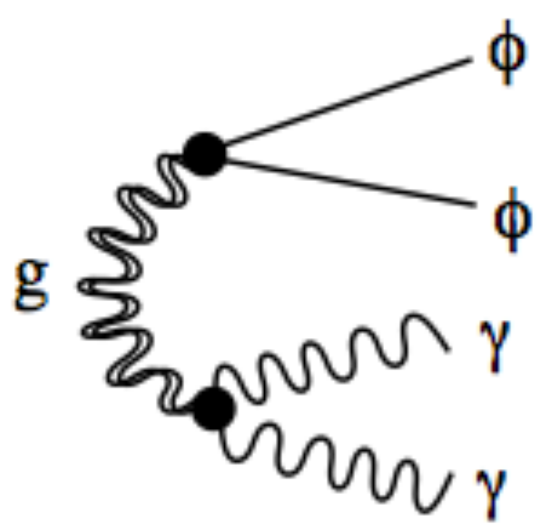
Catastrophic quantum instability!



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

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

Cline, Jeon, Moore, (2003)

Let us try non-renormalizable theories: k-essence / simple perfect fluid without vorticity

$$\mathscr{L} = P\left(X\right) \qquad \text{where} \qquad X = \frac{1}{2}g^{\mu\nu}\,\partial_\mu\phi\partial_\nu\phi$$

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

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⇓

either the theory is ghosty

$\mathcal{A} < 0$

or it suffers from gradient instabilities

$c_\mathrm{s}^2 < 0$

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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 (density) 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!

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Run-Away Instability?

- If the speed of the sound waves in this NEC-violating fluid is higher than v_{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 / phonons can carry positive energy, and propagate with a real sound speed

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- ? Superluminal propagation of perturbations & standard local Wilsonian UV- Completion

Example:

(Subluminal) Galilean Genesis

Creminelli, Nicolis, Trincherini (2010)

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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no normal
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troubles for reheating

$$\beta = 1+\alpha$$

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

known to lead to superluminal propagation around static backgrounds

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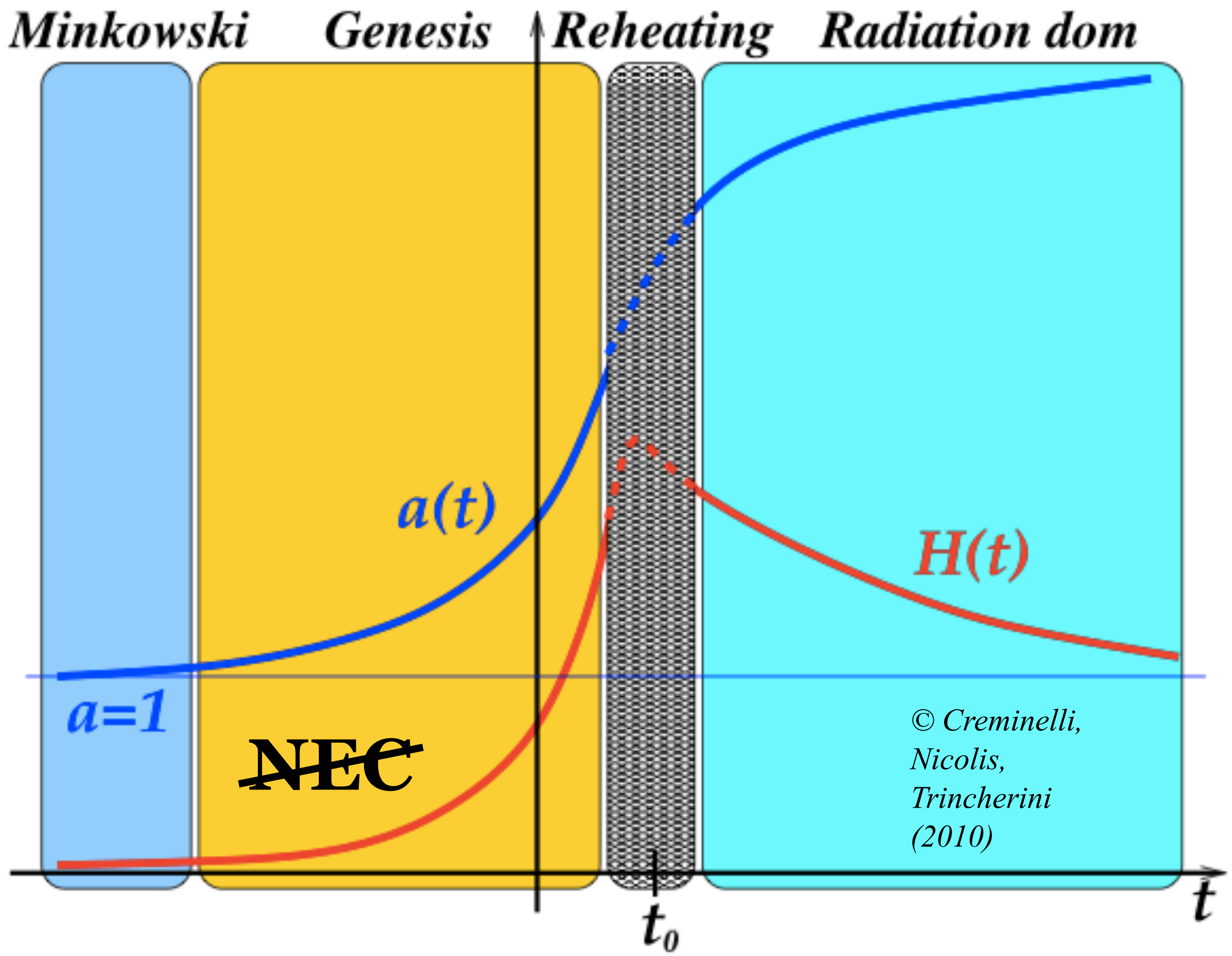
Adams, Arkani-Hamed, Dubovsky, Nicolis, Rattazzi (2006)

Galilean Genesis



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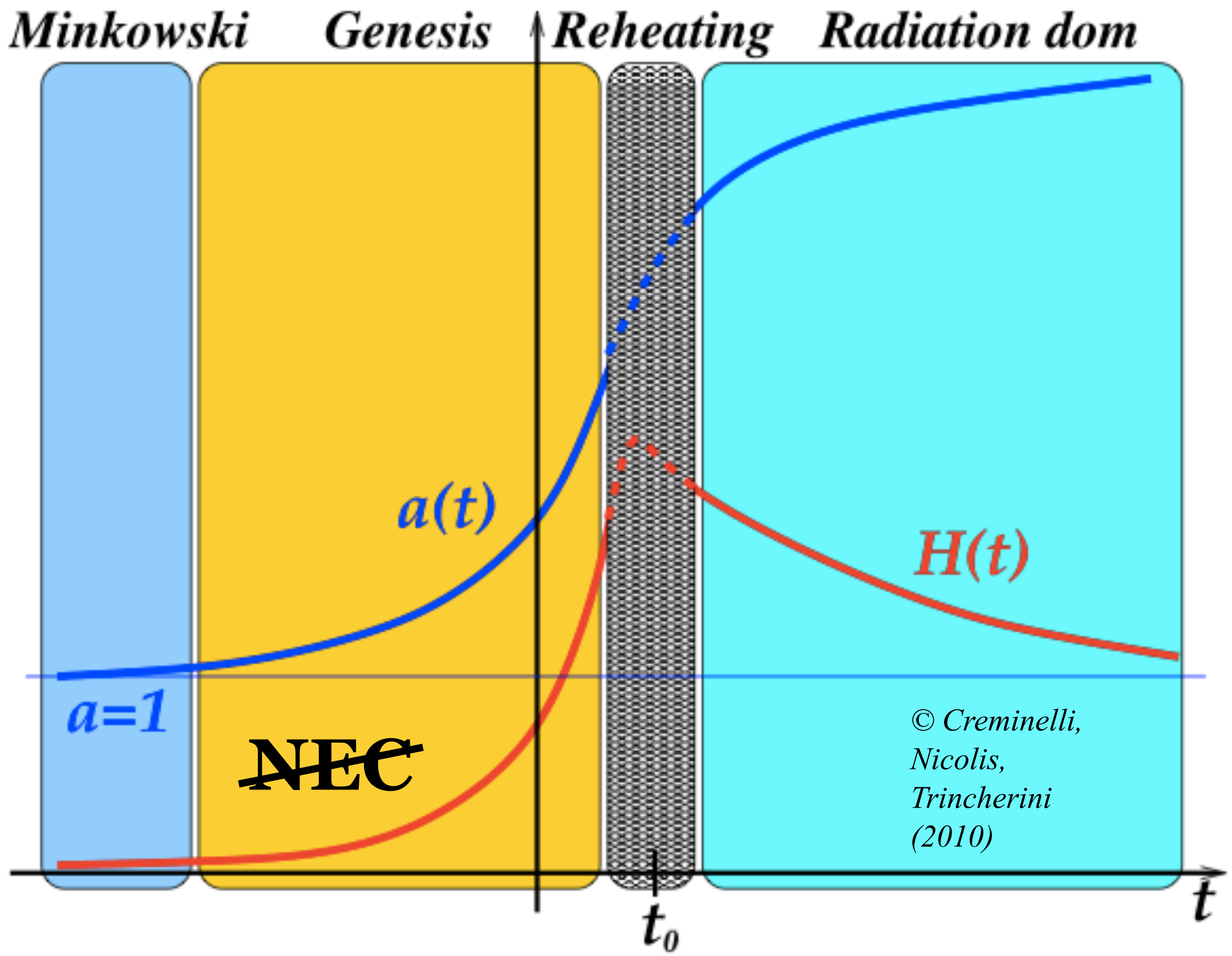

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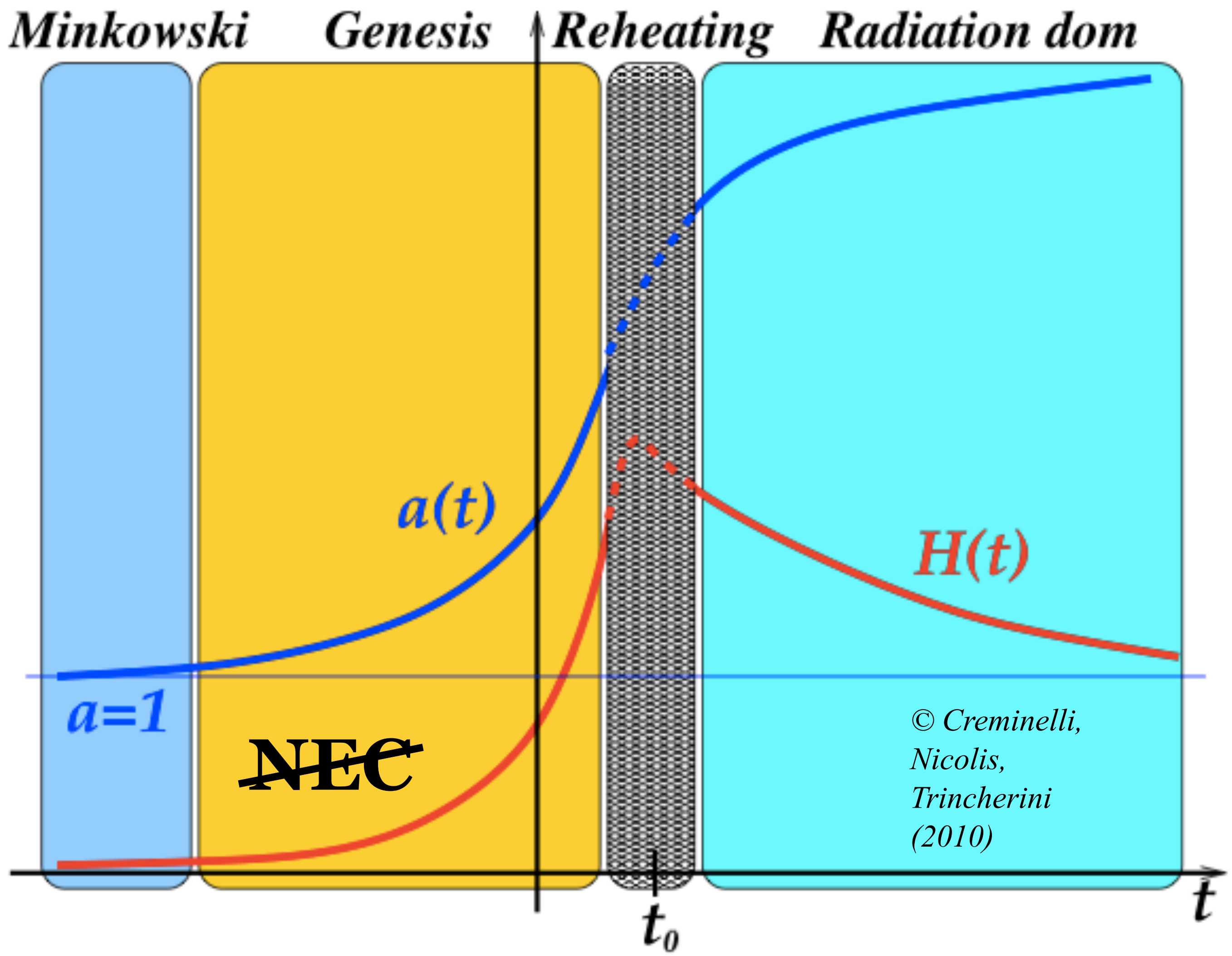

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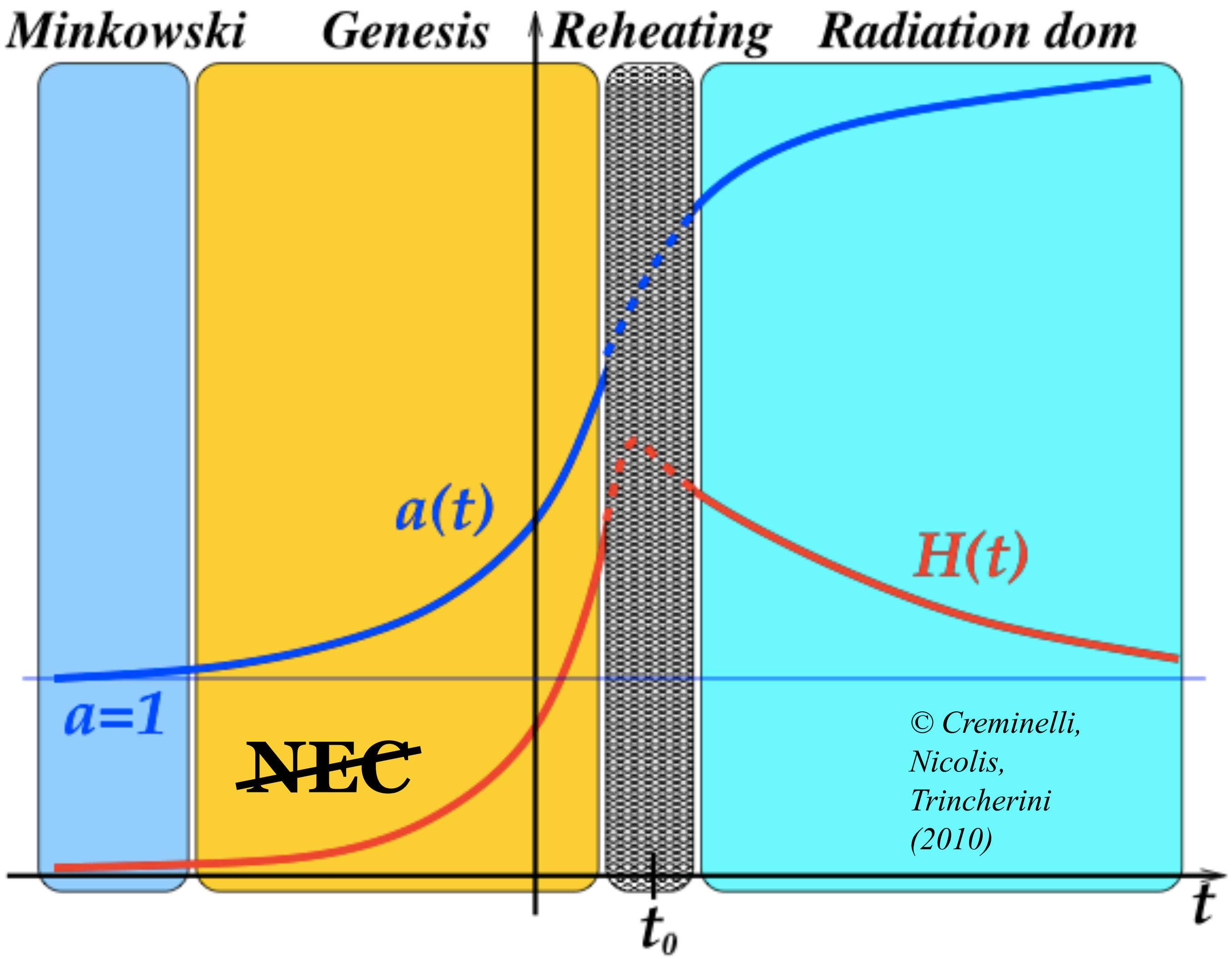

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- Similarly to the ekpyrotic models the perturbations are generated *before* the singularity but here it is due to a novel type of the curvaton mechanism

Is (*Subluminal) Genesis* subluminal?

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Is there a standard Wilsonian UV-Completion?

Cosmological dynamics

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

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

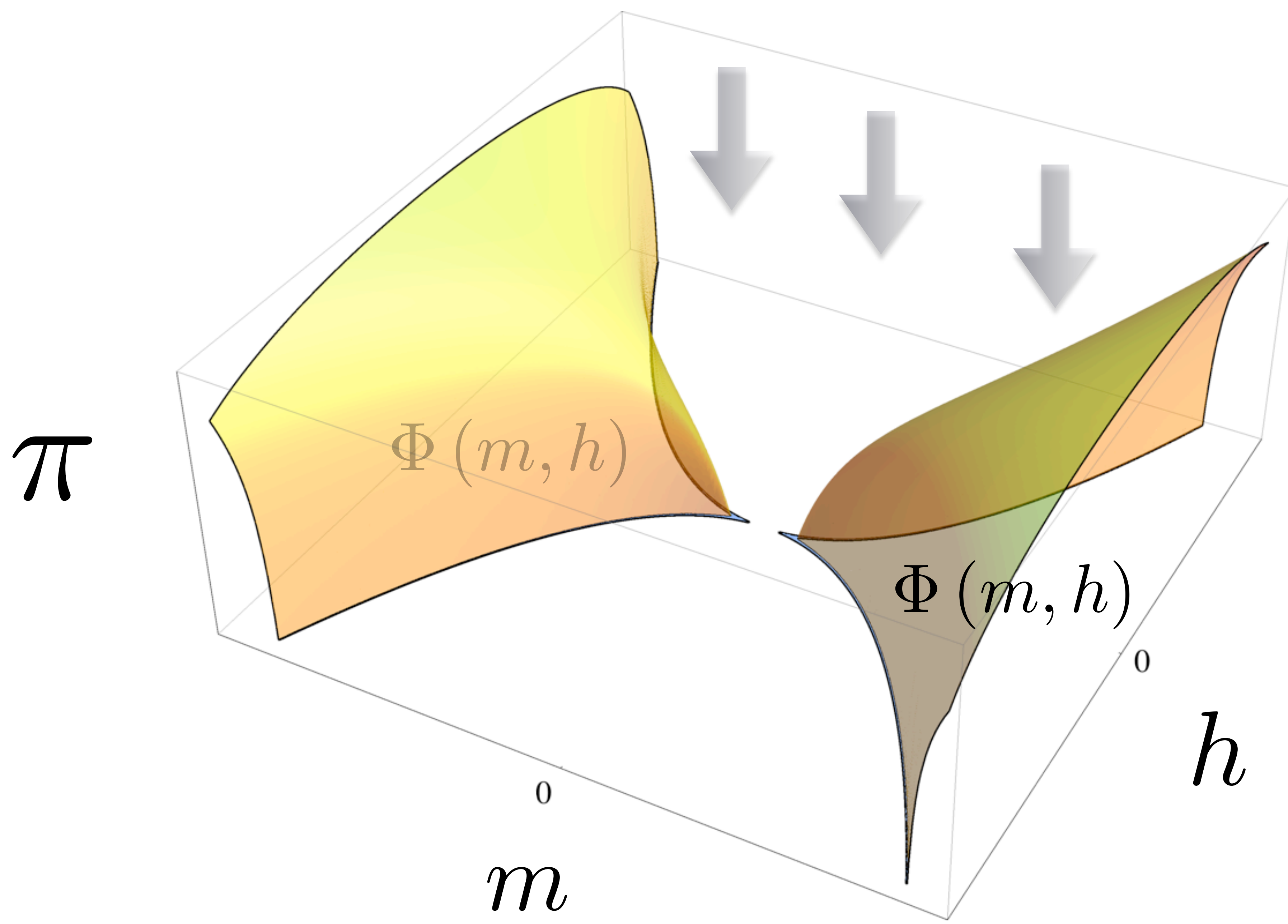
+

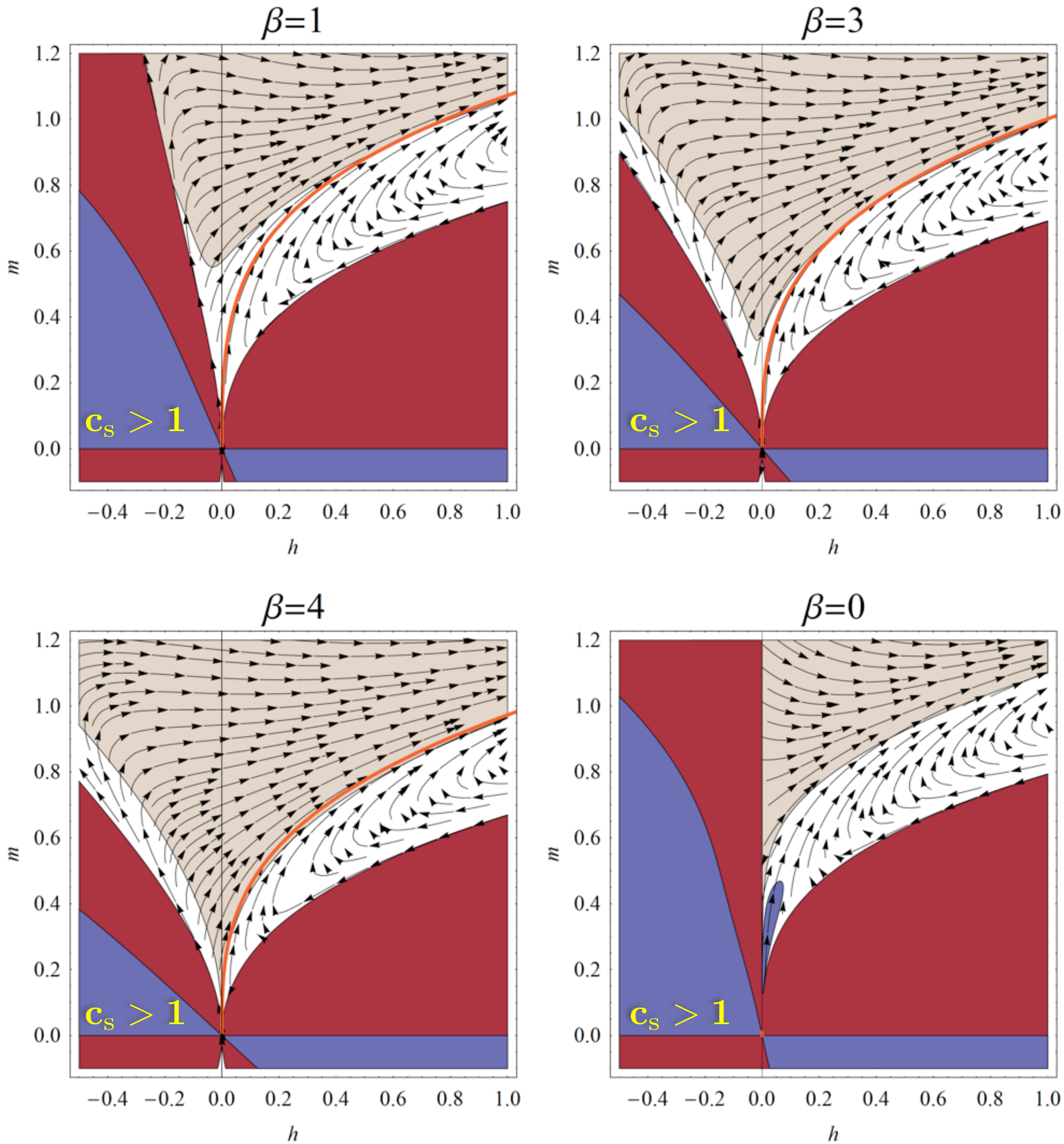
Constraint
Friedmann Equation

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

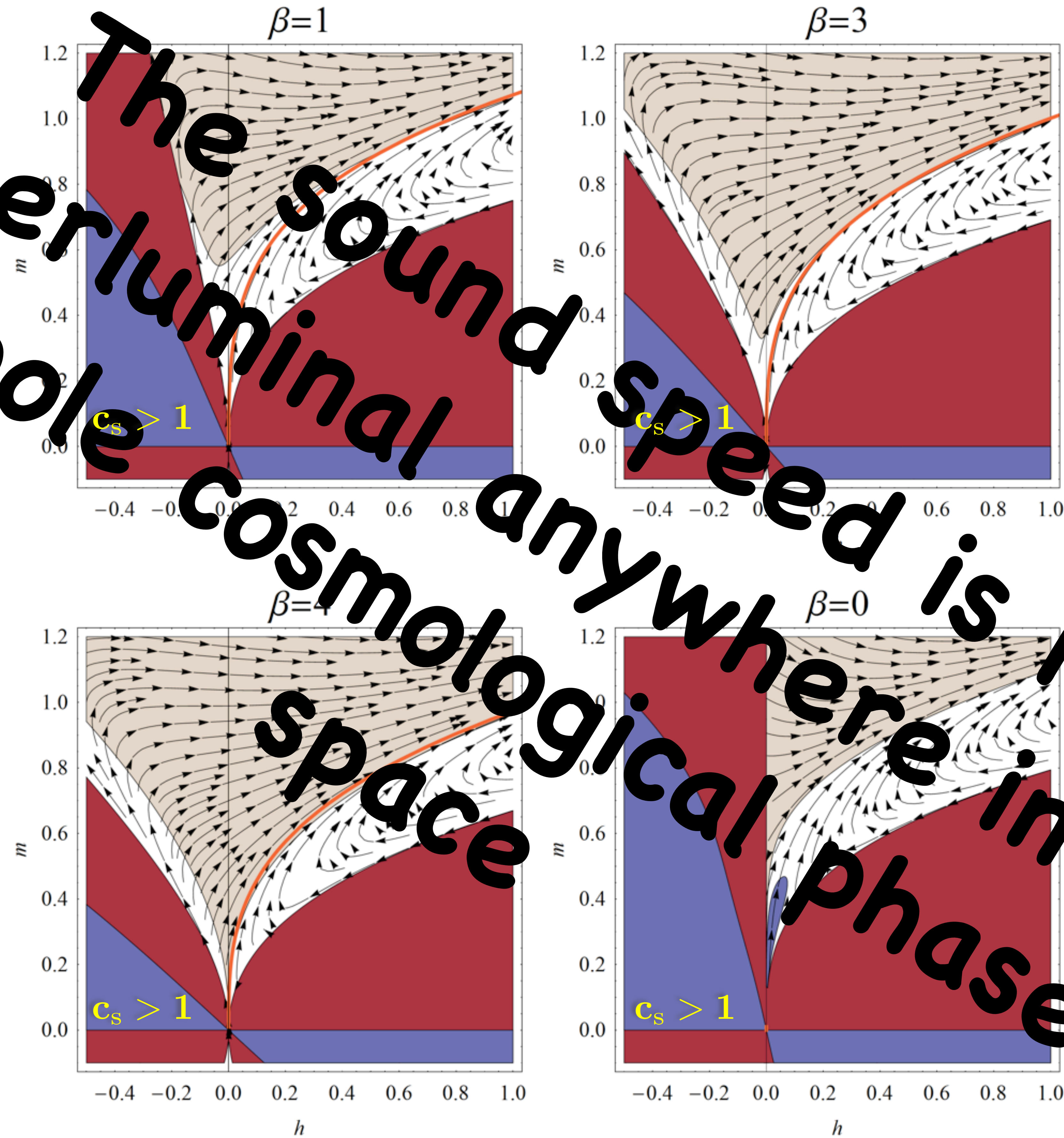
2 independent variables

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

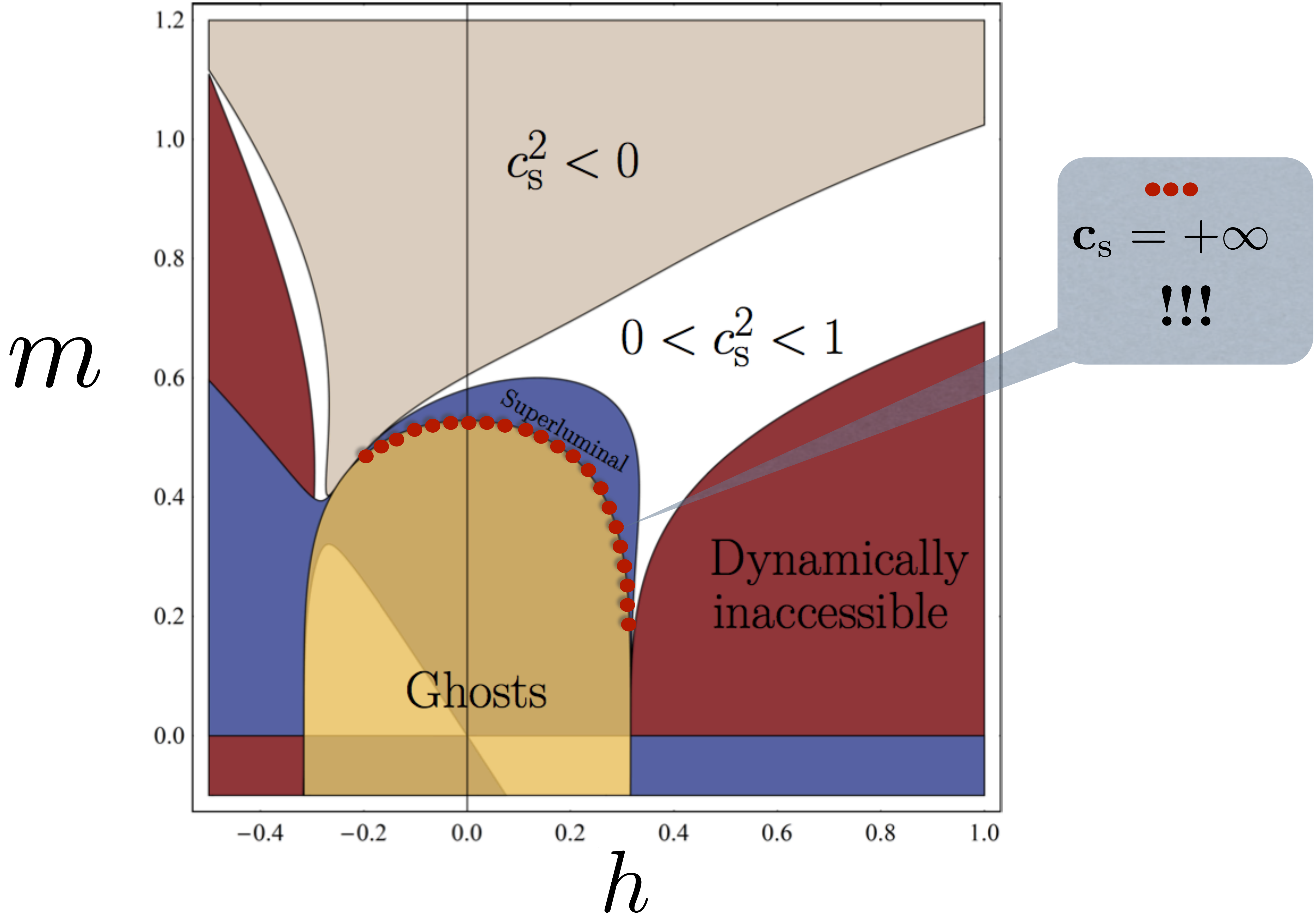



β=1
β=3
β=4
β=0
m
h
1.2
1.0
0.8
0.6
0.4
0.2
0.0
−0.4
−0.2
0.0
0.2
0.4
0.6
0.8
1.0
$c_s > 1$

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



External Radiation



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Thanks a lot for attention!