New Frontiers in Early-Universe Cosmology

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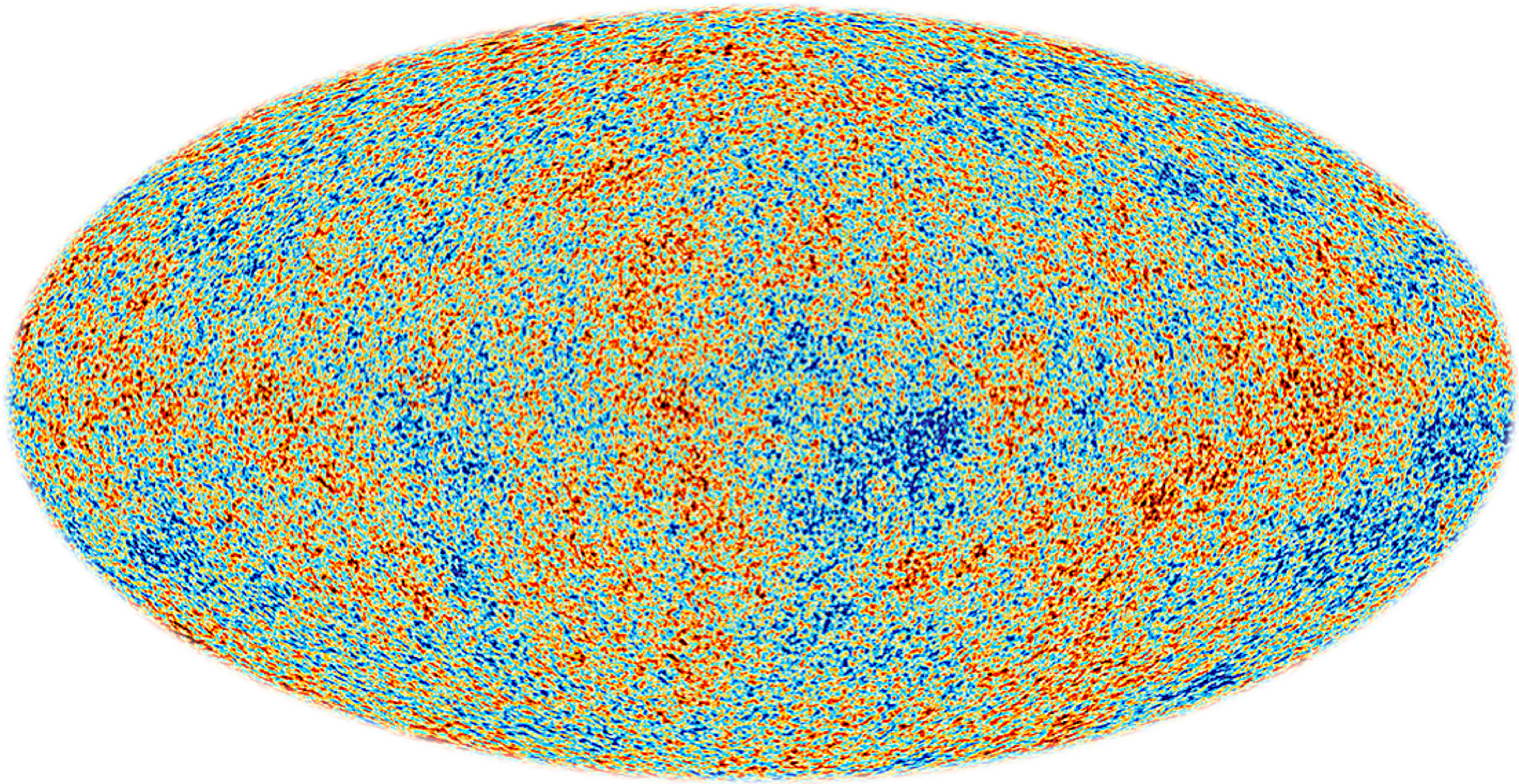
characteristic features of the very early universe



As we make progress in our understanding,
our view of which problems are `hard' changes.

`hard’ problems:

- singularity resolution & its cosmological implications
  Brandenberger; Graham, Kaplan, Rajendran; Ijjas & Steinhardt; Vafa, …
- models based on modified gravity
  Ijjas, Steinhardt, Pretorius; Lehner, Kovacs & Reall, …
- non-linear & non-perturbative cosmological dynamics within Einstein gravity
  Clough, Flauger; East, Senatore; Ijjas, Steinhardt, Pretorius

Cosmology & General Relativity

$$R_{\alpha\beta} = T_{\alpha\beta} - \tfrac{1}{2} g_{\alpha\beta} T_{\lambda}{}^{\lambda}$$
$$\nabla^{\beta} T_{\alpha\beta} = 0$$

$$\xrightarrow{?}$$

$$H^{-1} = \left({}^{a}/_{a_0}\right)^{\varepsilon}$$
$$\varepsilon = -\,{}^{\dot{H}}/_{H^2}$$

conventional picture of smoothing & flattening:

Step #1: a Hubble patch becomes smooth following a `natural succession' of events

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{1}{3}\left(\frac{\rho_m^0}{a^3} + \frac{\rho_r^0}{a^4}\right) - \frac{k}{a^2} + \frac{\sigma^2}{a^6} + \frac{1}{3}\left(\frac{\rho_\phi^0}{a^{2\epsilon}}\right)$$

"survival of the largest"

Step #2: space-time becomes flat and smooth on super-Hubble scales while the Hubble radius $|H|^{-1}$ evolves at a different rate than the scale factor **a**:

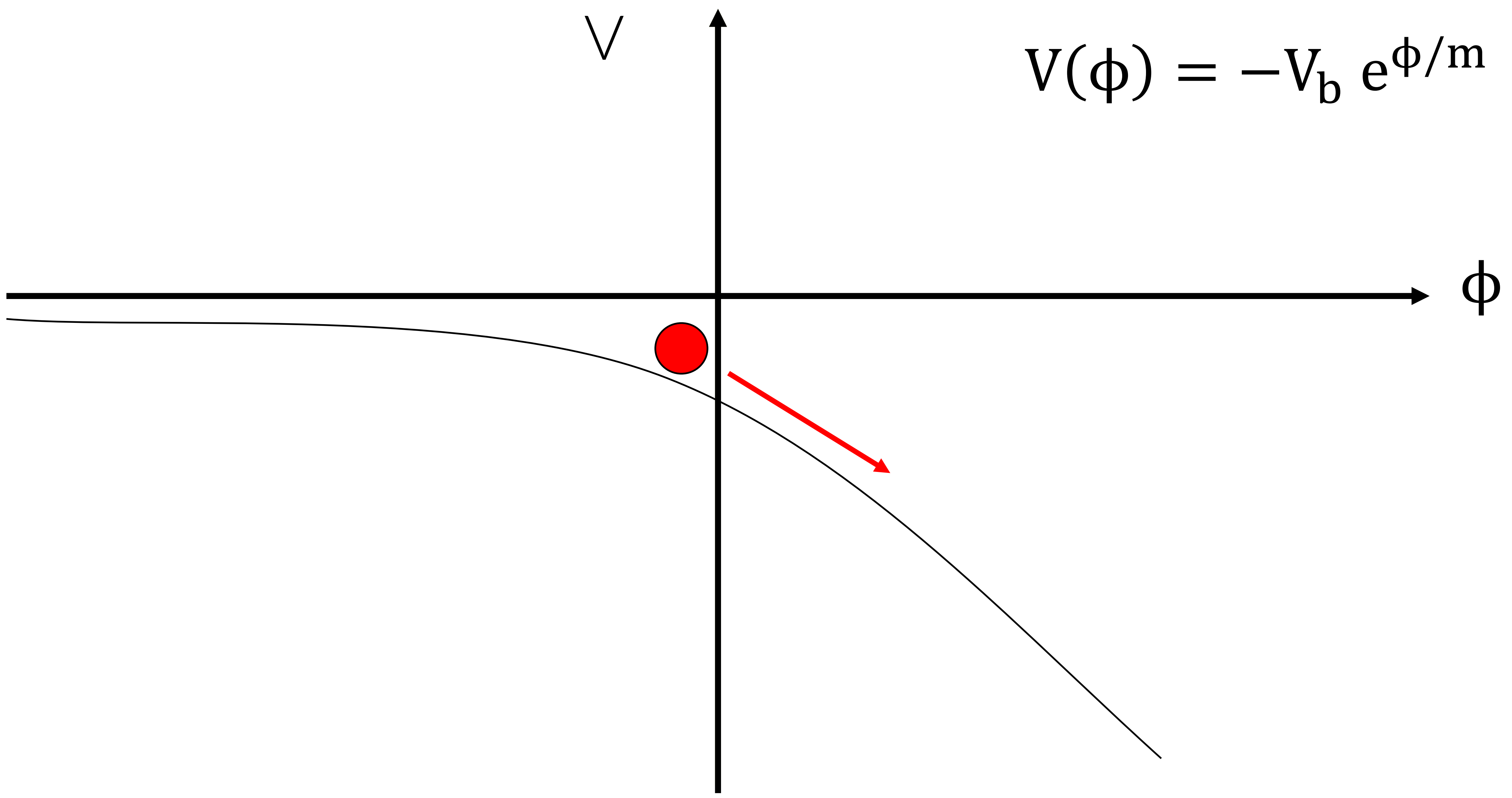
$$|H|^{-1} \sim a^{\varepsilon}$$

`rate' is determined by the stress-energy content characterized by the equation-of-state $\epsilon \equiv \frac{3}{2}\left(1 + \frac{p}{\varrho}\right)$

What can cause slow contraction ($\varepsilon \gg 3$)?

$$\varepsilon = \frac{3\left(\frac{1}{2}\dot{\phi}^2\right)}{\frac{1}{2}\dot{\phi}^2 + V(\phi)}$$

$$\boxed{V < 0 \Longrightarrow \varepsilon > 3}$$



$$V(\phi) = -V_b\, e^{\phi/m}$$

$$\varepsilon = 1/2m^2$$

$\mathrm{m} = 0.1$ or 0.01 in Planck units

$$\Rightarrow \varepsilon = 50 \text{ or } 5000$$

$$a(t) = (t/t_0)^{1/\varepsilon}$$

$$|H|^{-1} \sim a^{\varepsilon}$$

slow contraction is different!

w/W.G. Cook, E. Y. Davies, D. Garfinkle, I. Glushchenko, F. Pretorius, P.J. Steinhardt, and A.P. Sullivan

arXiv: 2109.09768 ; 2104.12293; 2103.00584; 2006.04999; 2006.01172

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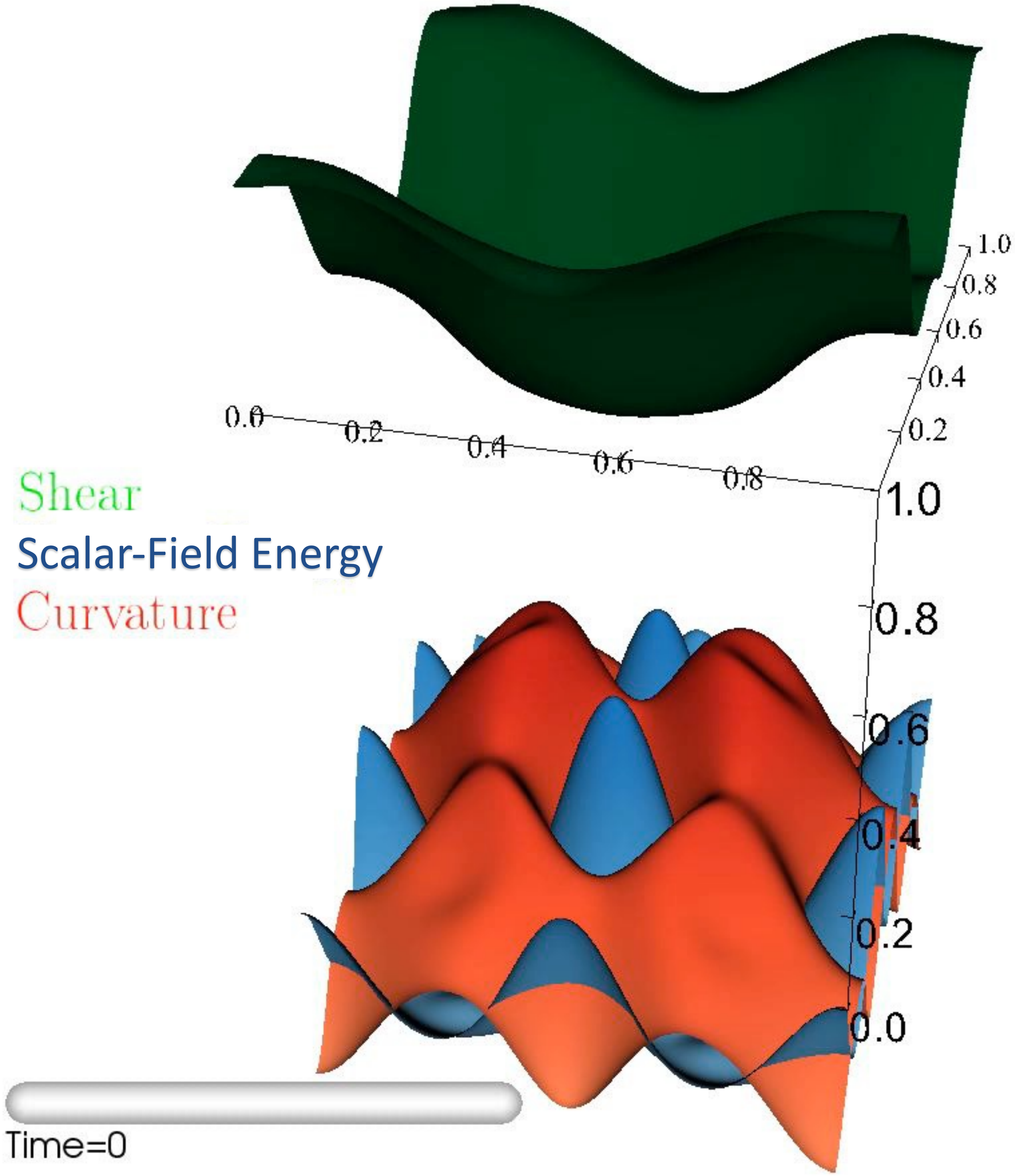
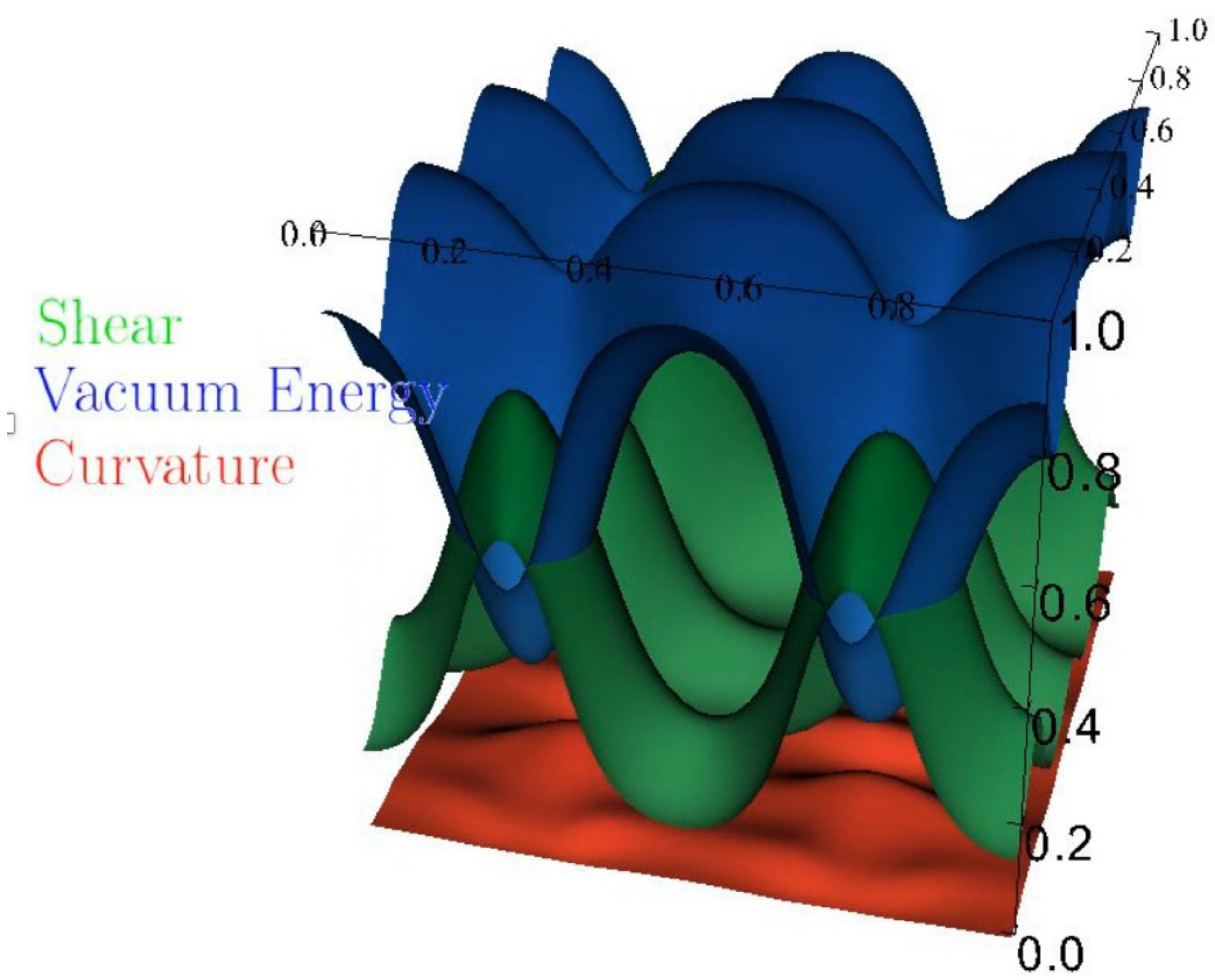


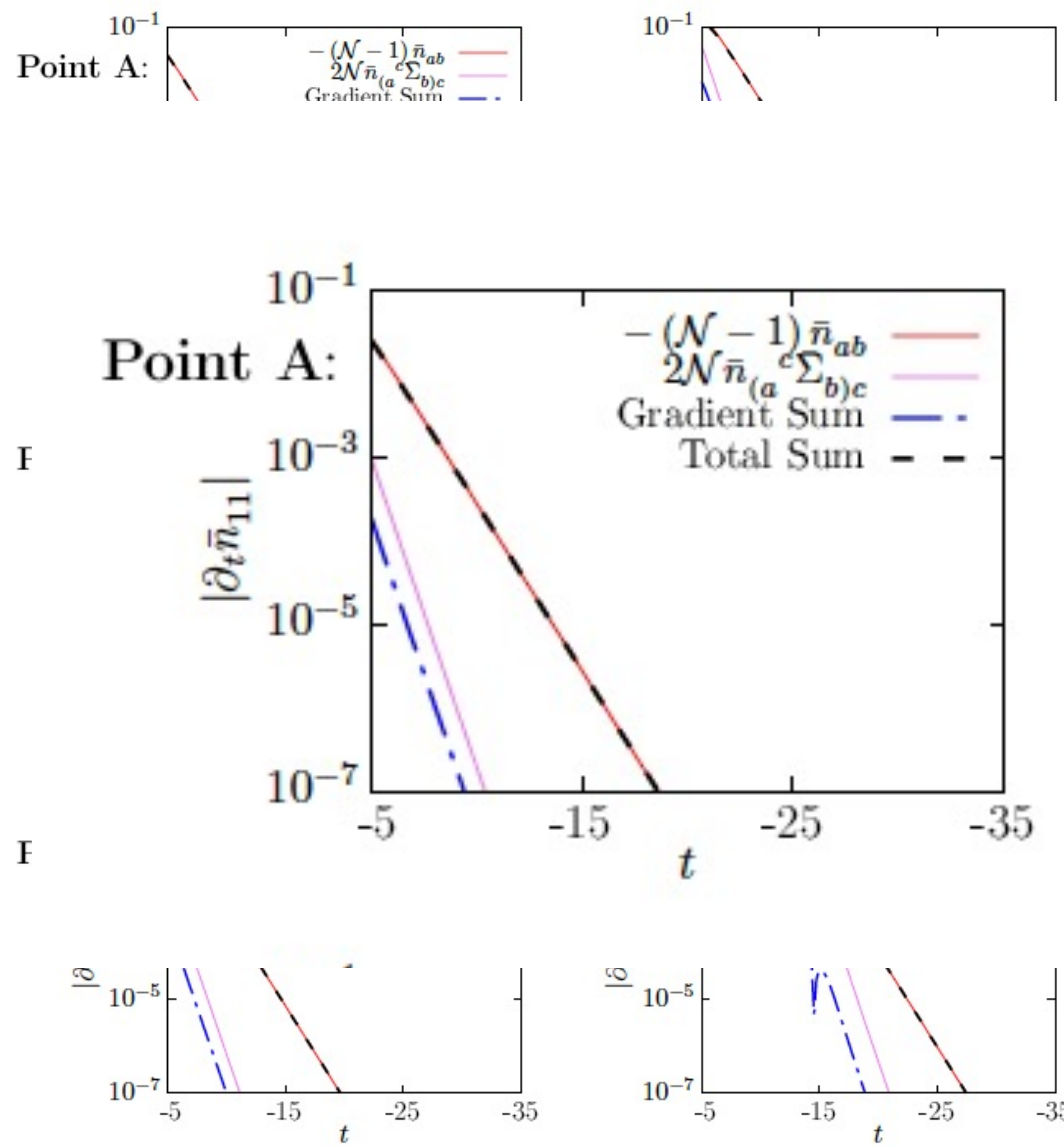
Shear
Scalar-Field Energy
Curvature
0.0
0.2
0.4
0.6
0.8
1.0
0.2
0.4
0.6
0.8
1.0
0.0
0.2
0.4
0.6
0.8
1.0
Time=0

Smoothing through Ultralocality

arXiv: 2104.12293; 2103.00584; 2006.04999; 2006.01172

$$\partial_t \bar{n}_{ab} = -\Big(\mathcal{N}-1\Big)\bar{n}_{ab} + \mathcal{N}\Big(2\bar{n}_{(a}{}^{c}\bar{\Sigma}_{b)c} - \epsilon^{cd}{}_{(a}\bar{E}_c{}^i\partial_i\bar{\Sigma}_{b)d}\Big) - \epsilon^{cd}{}_{(a}\bar{\Sigma}_{b)d}\bar{E}_c{}^i\partial_i\mathcal{N}$$





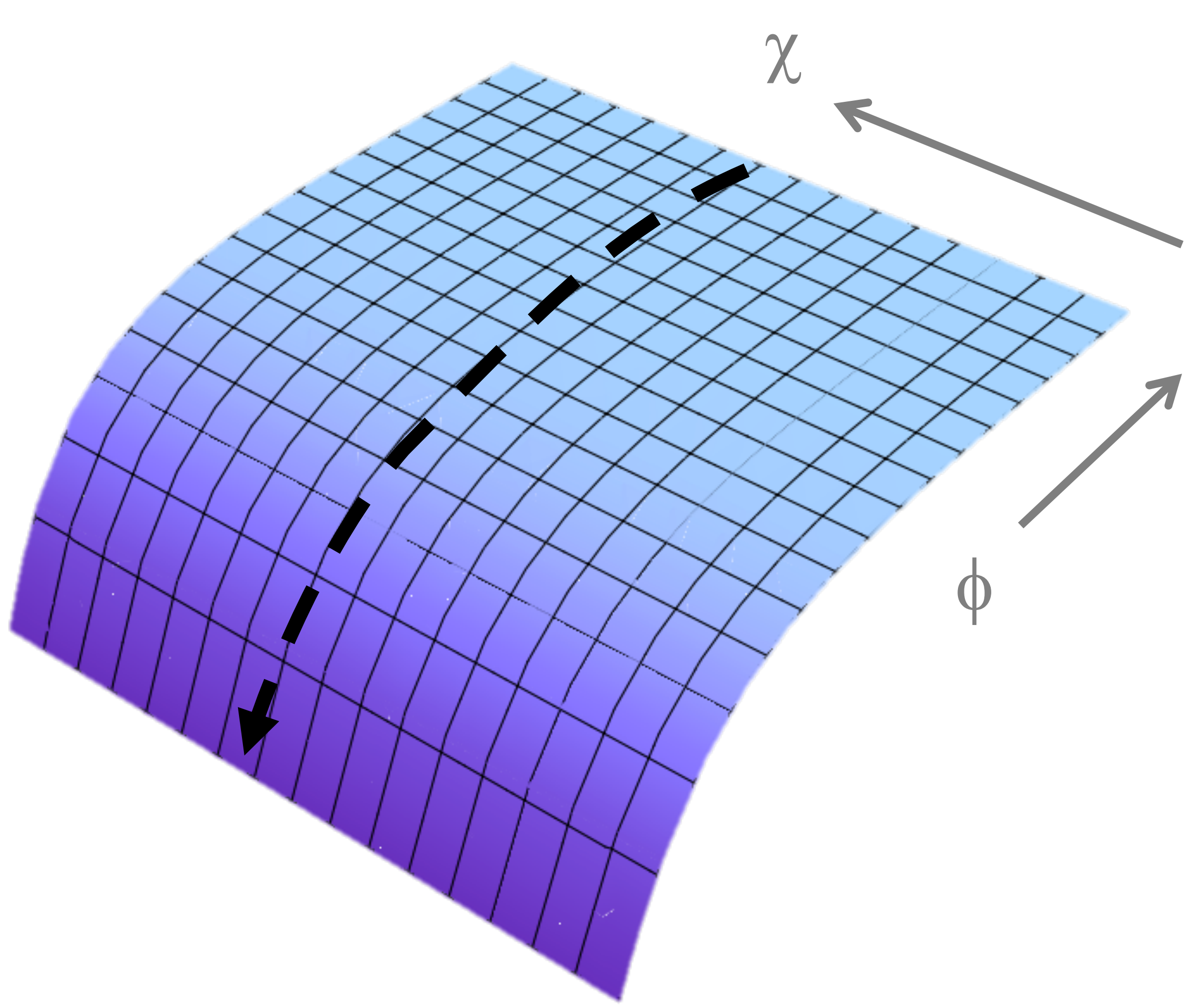
Generation of primordial perturbations

e.g., Ijjas et al.: PRD 89 (2014)123520

$$\mathcal{S} = \int d^4x\sqrt{-g}\left(\frac{1}{2}R - \frac{1}{2}(\partial_\mu\phi)^2 + V_0\exp(-\sqrt{2\epsilon}\phi) - \frac{1}{2}\Omega^2(\phi)(\partial_\mu\chi)^2\right)$$

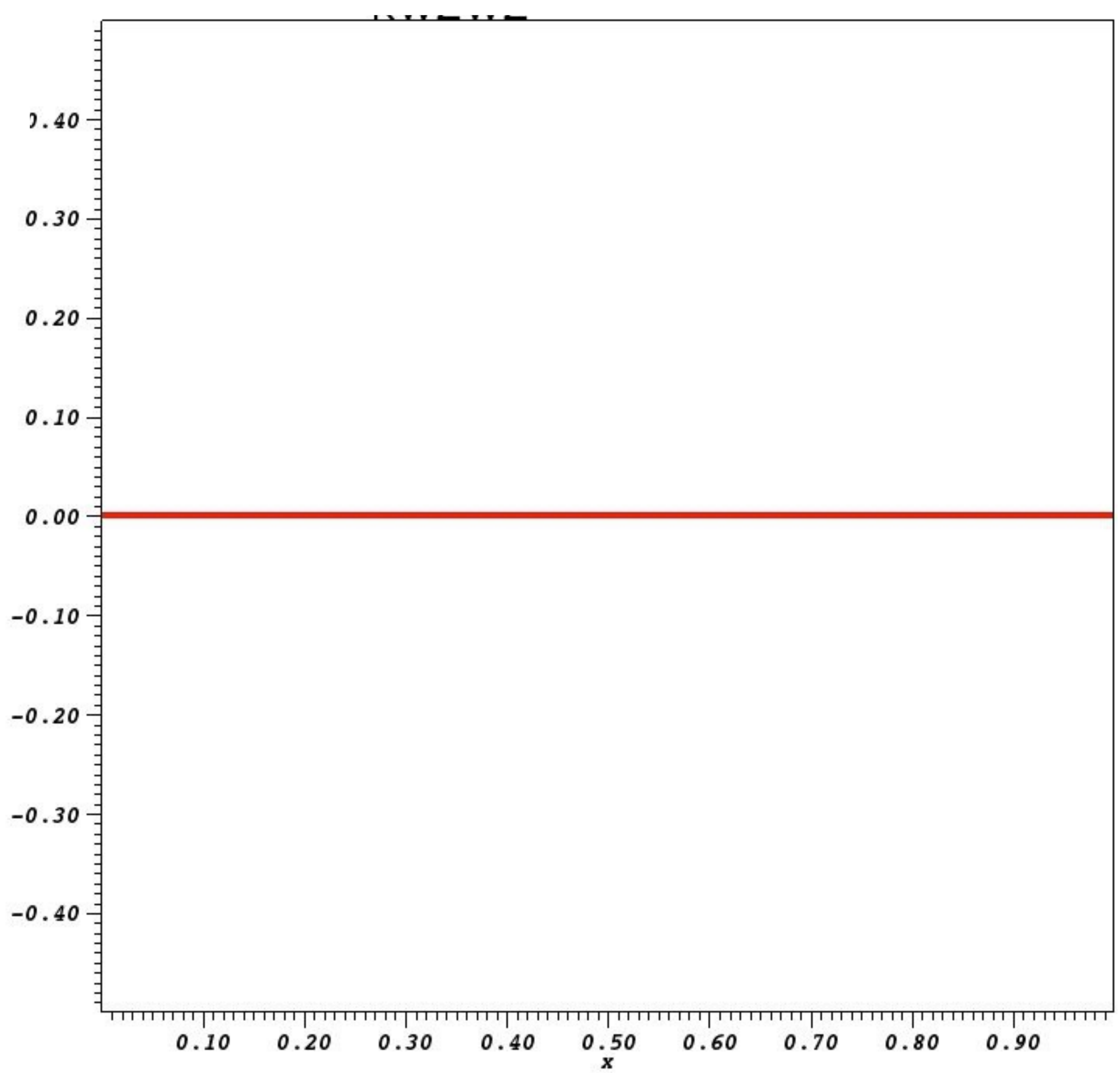
FRW BACKGROUND:

$$H^2 = \frac{1}{3}\left(\frac{1}{2}\dot{\phi}^2 + \frac{1}{2}\Omega^2(\phi)\dot{\chi}^2 + V(\phi)\right),$$
$$\ddot{\phi} + 3H\dot{\phi} - \Omega\Omega_{,\phi}\dot{\chi}^2 + V_{,\phi} = 0,$$
$$\ddot{\chi} + \left(3H + 2\frac{\dot{\Omega}}{\Omega}\right)\dot{\chi} = 0,$$



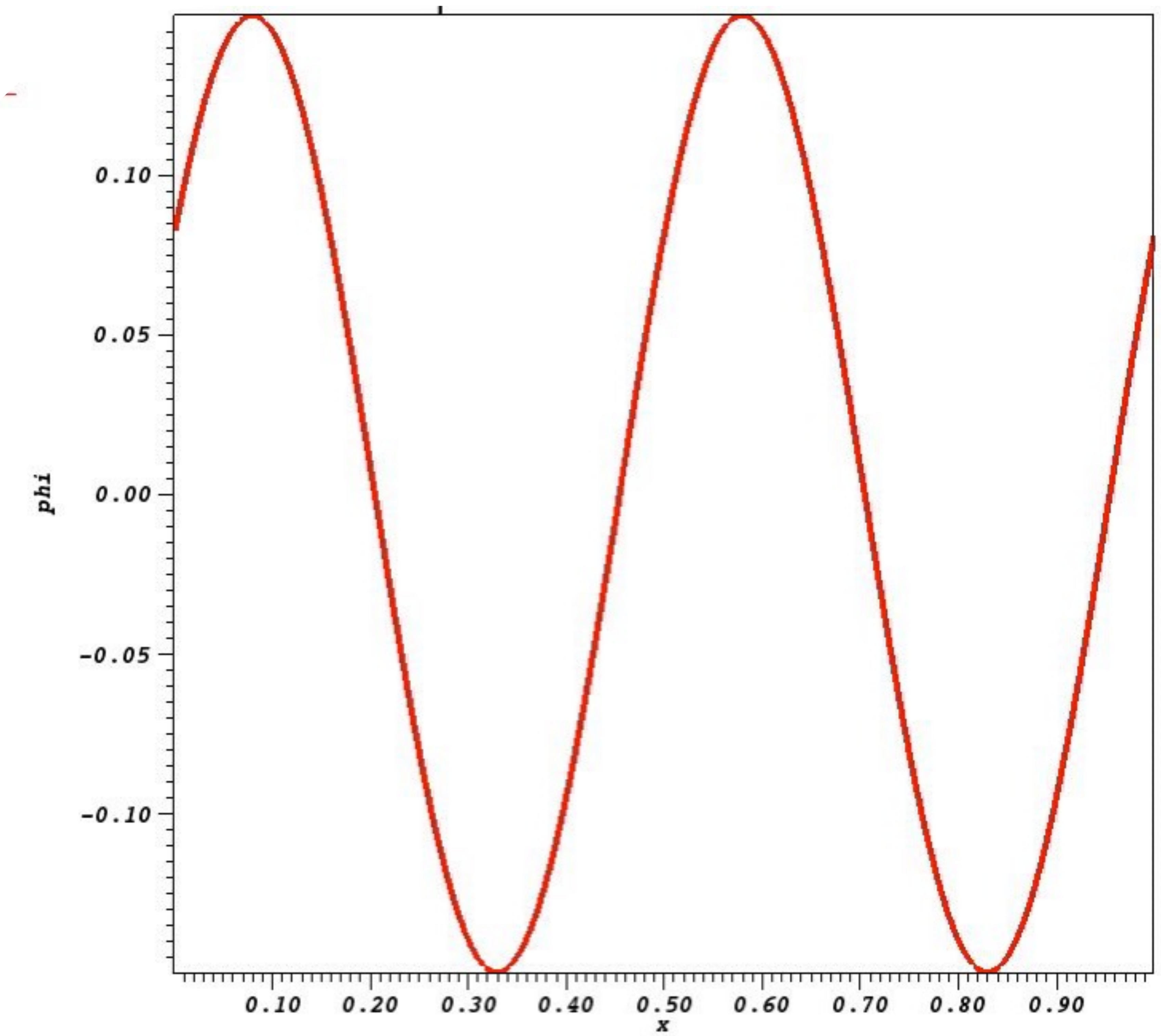
Non-perturbative analysis

arXiv: 2109.09768



Time=0

time evolution of the entropic field's kinetic energy density



Time=0

time evolution of the background field

Non-perturbative analysis

arXiv: 2109.09768

shear – blue

curvature – red

matter – green