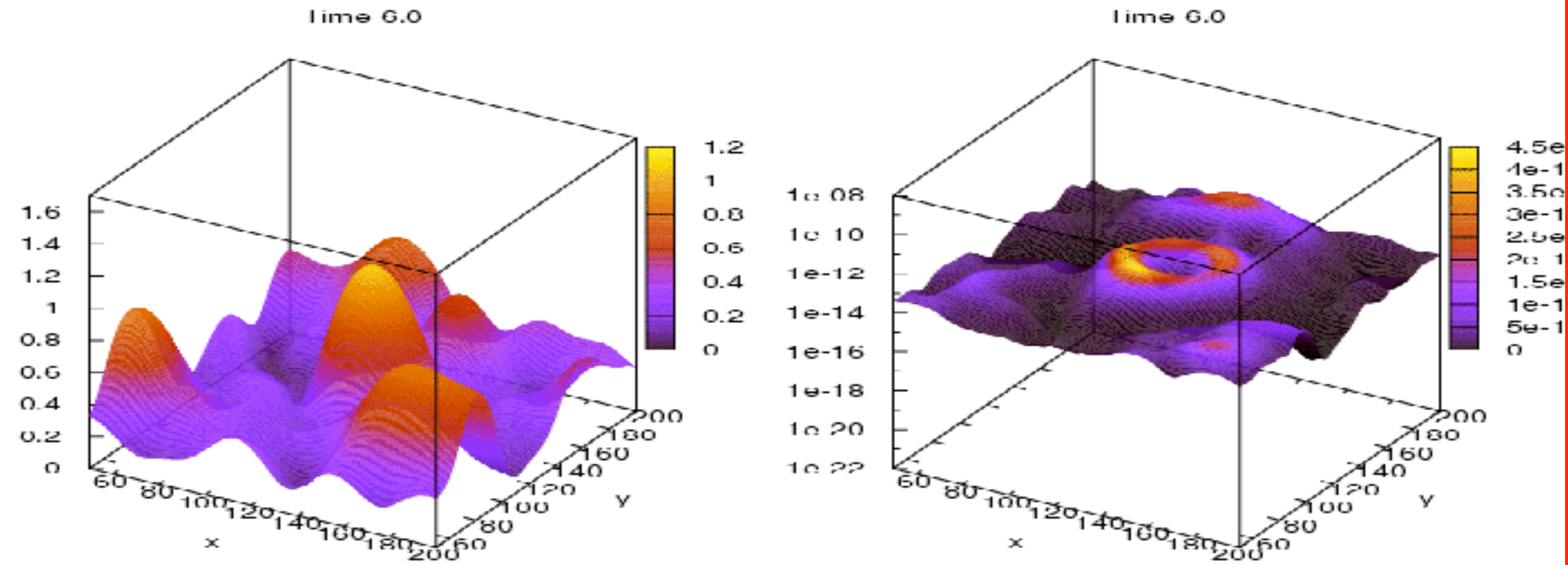
GRAVITATIONAL WAVES from (p)REHEATING

DANIEL G. FIGUEROA

CERN TH-Div / IFT-Madrid



PLANCK 2010, CERN, Genève, Switzerland

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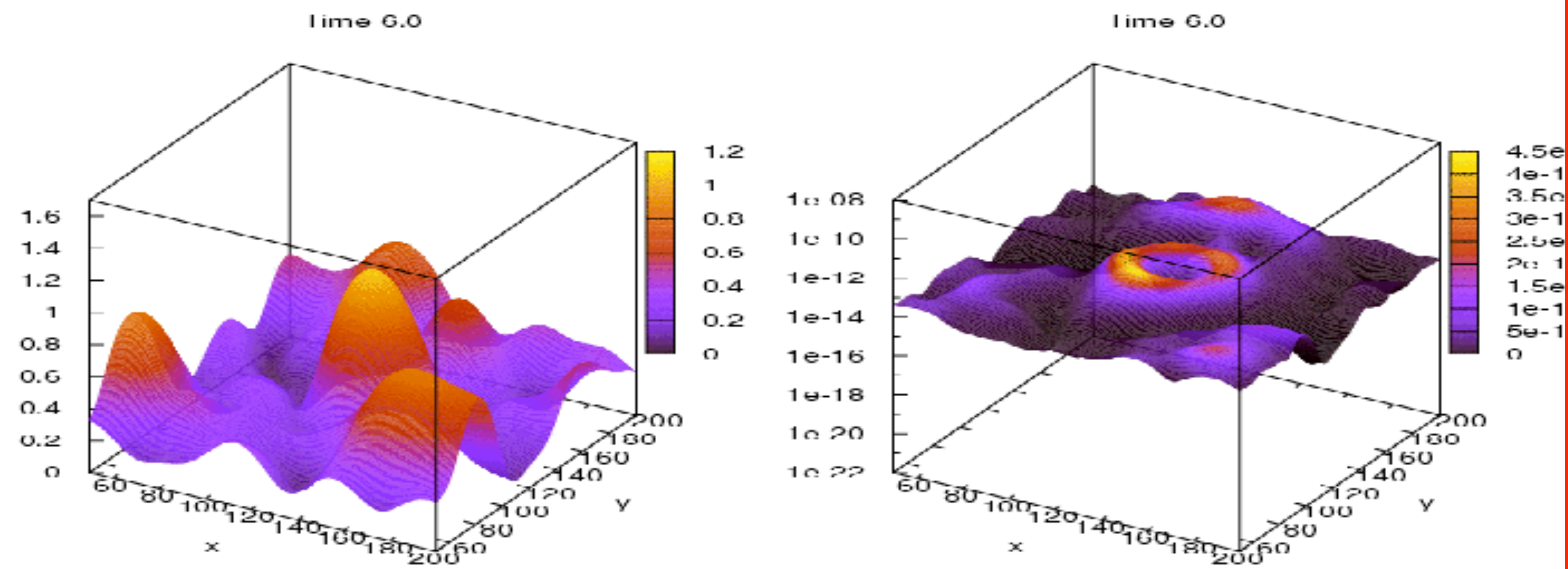


PLANCK 2010, CERN, Genève, Switzerland

HYBRID PREHEATING: GLOBAL PHASE TRANSITIONS

$$-g^2\Phi^{\rm T}\Phi\chi^2 - V(\chi)$$

$$-\partial_\mu\Phi^{\rm T}\partial^\mu\Phi - \lambda\left(\Phi^{\rm T}\Phi - \frac{v^2}{2}\right)^2$$

$\chi < \chi_c$

$m_\phi^2 < 0$

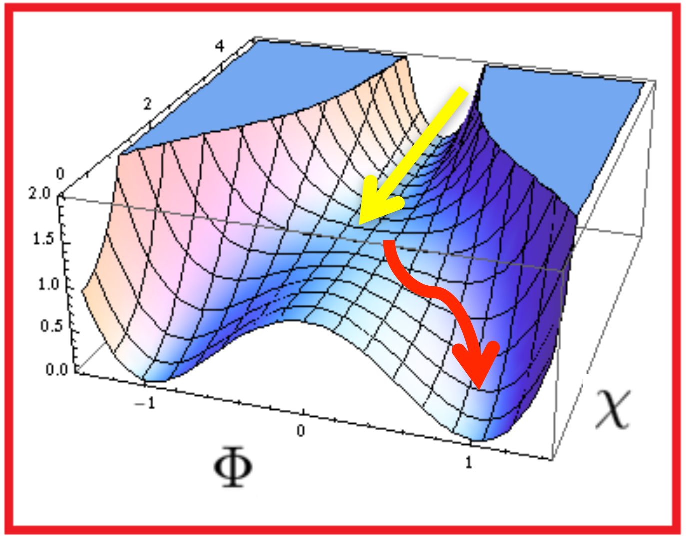
Tachyonic Instability

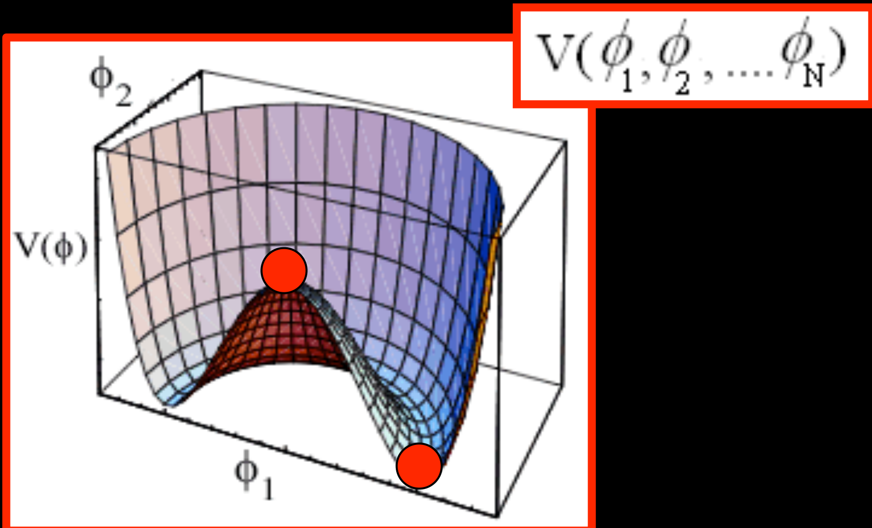
$$\Phi^{\rm T} = (\phi_1, \phi_2, ..., \phi_N)$$

(SSB)

$$\Phi^{\rm T}\Phi = \sum_a \phi_a^2 = v^2$$

(V.E.V.)





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(SSB)

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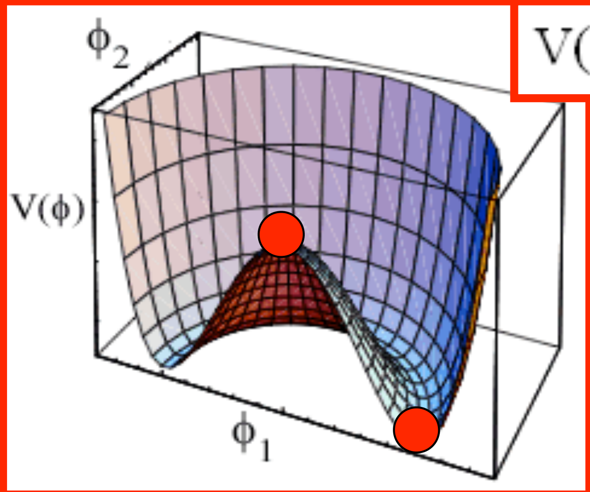
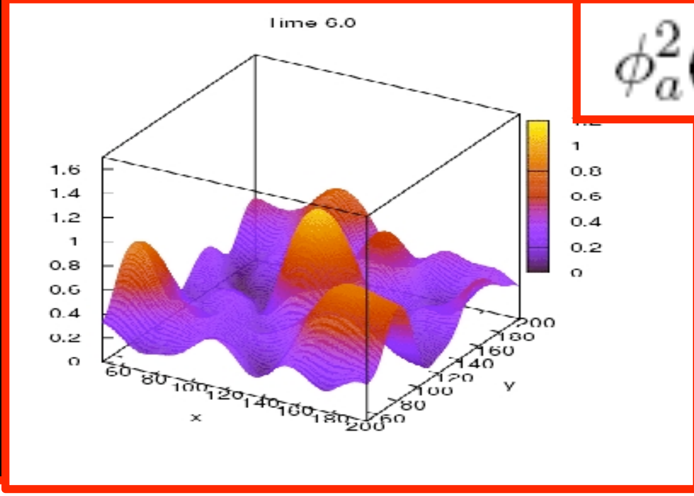
$V(\phi_1, \phi_2, \ldots \phi_N)$



$\phi_a^2(\mathbf{x})$



SYMMETRY BREAKING

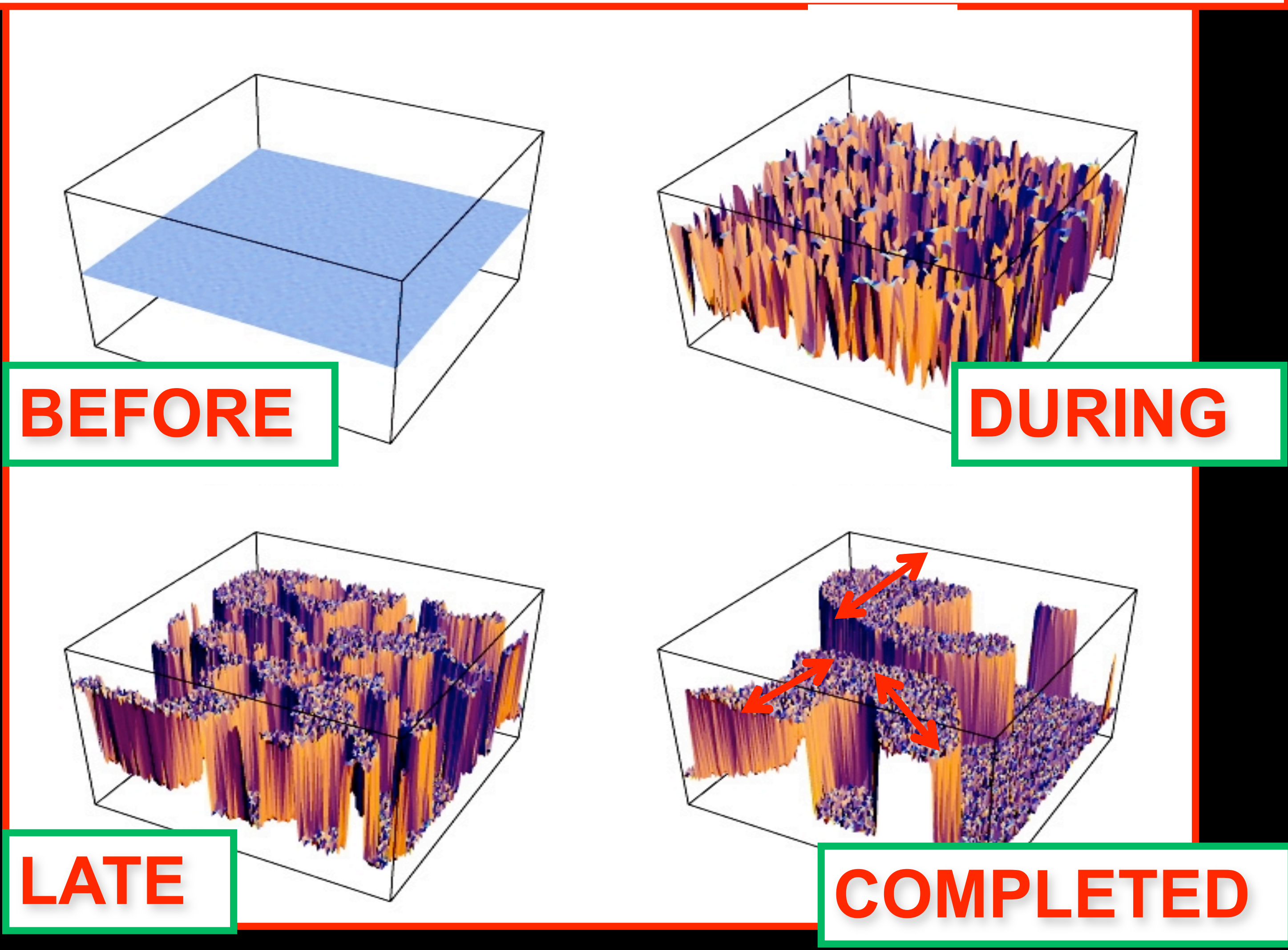
INHOMOGENEITIES

(RELATIVISTIC WAVES of MATTER)

EVOLUTION of an EARLY UNIVERSE PHASE TRANSITION

O(N)

O(N-1)



Pictorial Purposes

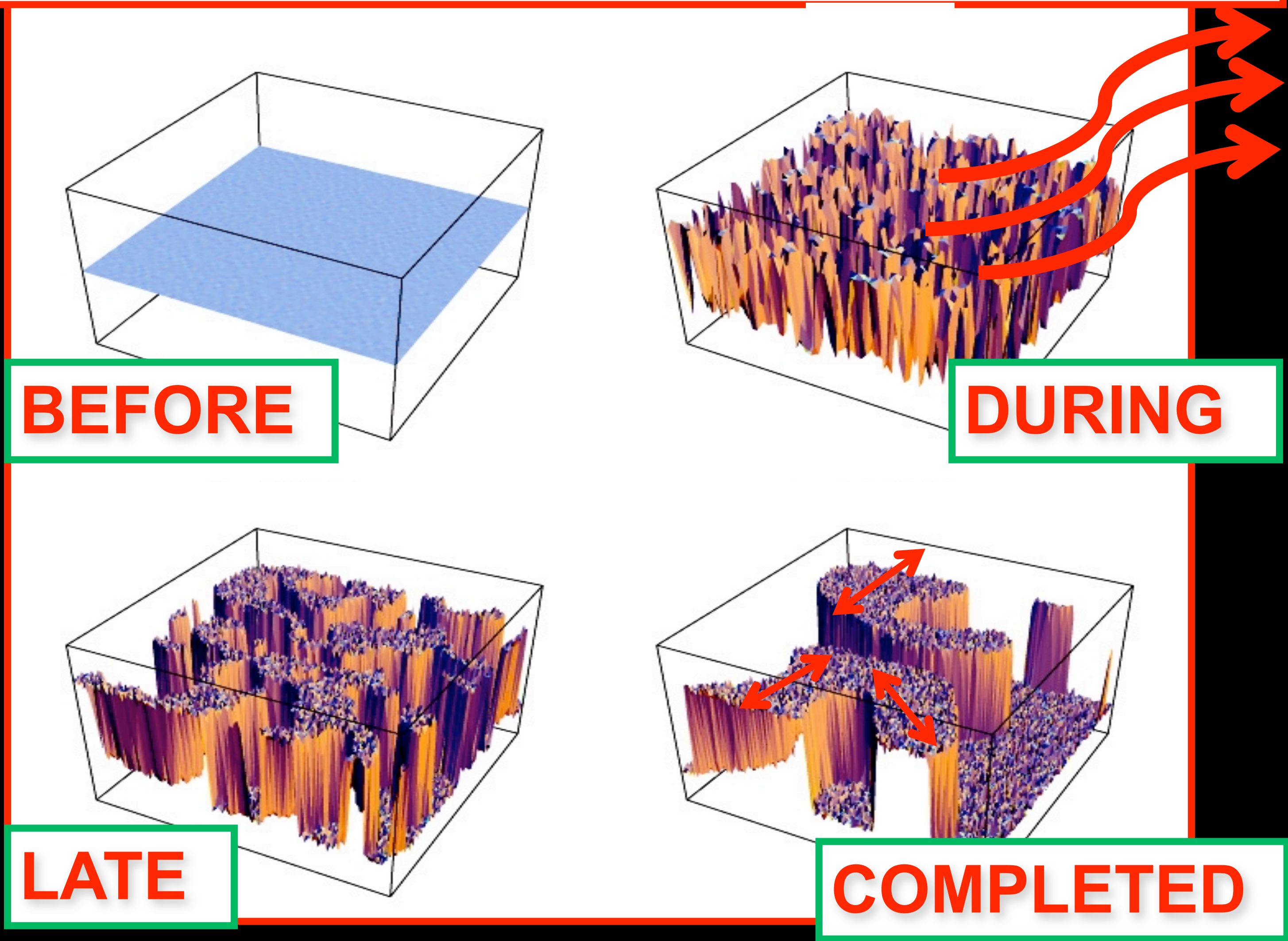
Z_2

$\phi \longrightarrow +V, \ -V$

EVOLUTION of an EARLY UNIVERSE PHASE TRANSITION

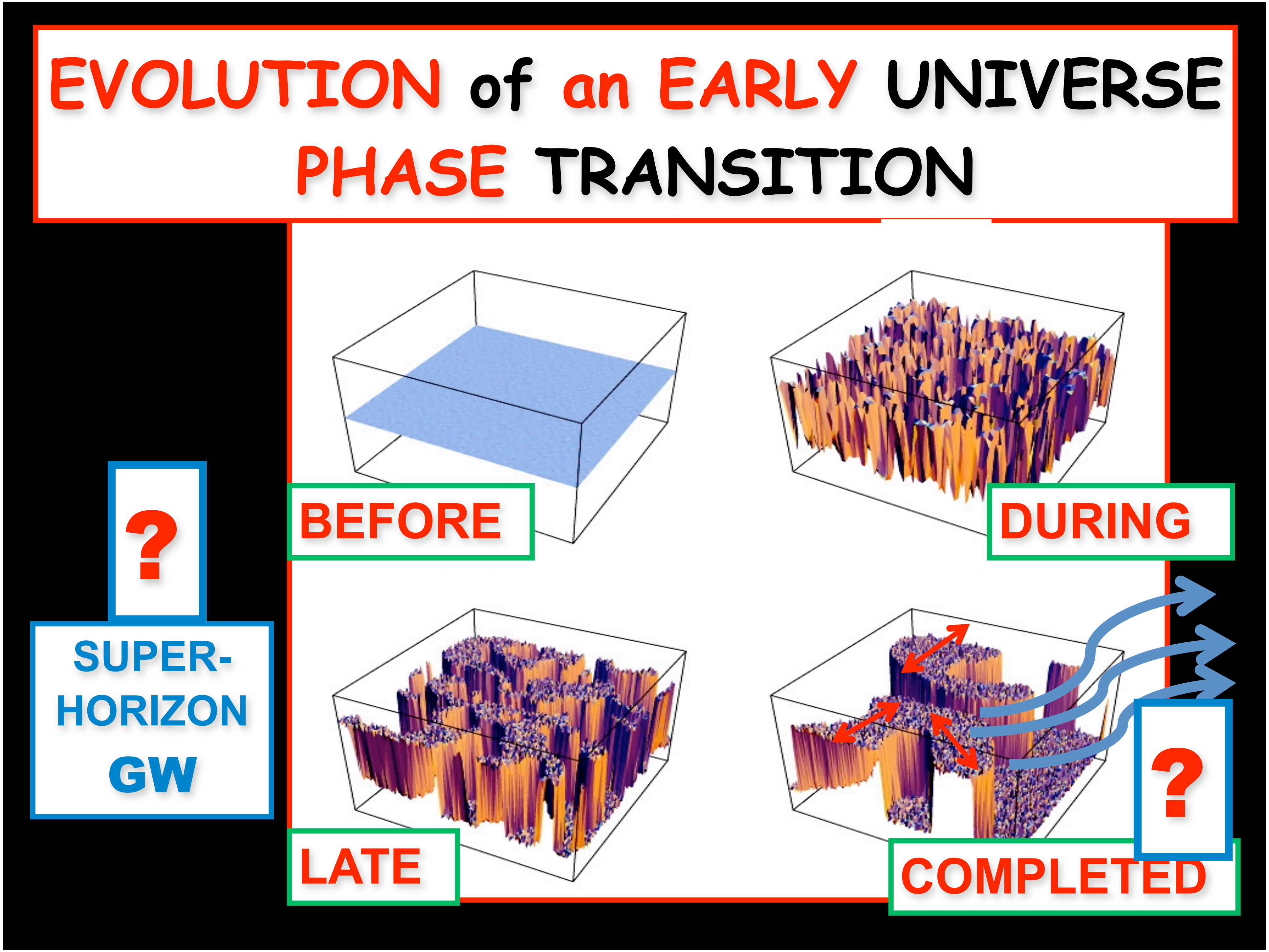
SUB-HORIZON

GW

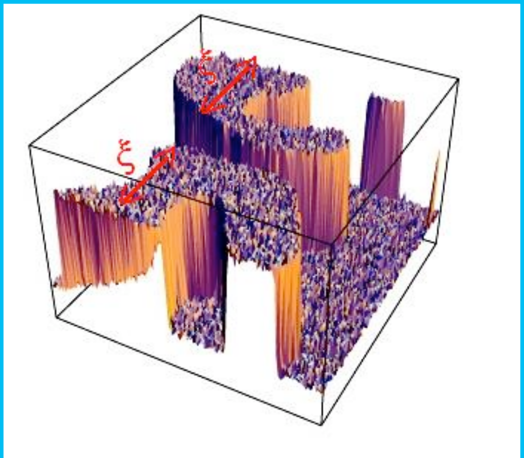


GARCIA-BELLIDO et al 2007/8

DUFAUX et al 2008/9


EVOLUTION of an EARLY UNIVERSE
PHASE TRANSITION
?
SUPER-
HORIZON
GW
BEFORE
DURING
LATE
COMPLETED
?

After the PHASE TRANSITION (NON-Linear SIGMA MODEL)



UNIVERSE EXPANDING
(CAUSAL HORIZON)

FIELD SELF-ORDERS

$(\xi \uparrow\uparrow , \xi < 1/H)$

$$\mathbf{O(N)} \rightarrow \mathbf{O(N\text{-}1)}: \begin{cases} \sum_a \phi_a^2 = v^2 & \text{(CONSTRAINT)} \\ \Box \phi_a + V'(\phi_a) = 0 & \text{(EOM)} \end{cases} \Rightarrow \boxed{\Box \phi_a + (\partial_\mu \phi_a \cdot \partial^\mu \phi_a)\, \phi_a = 0}$$

LARGE-N LIMIT:
$(N \geq 4)$

$$\boxed{\phi_a(\mathbf{k},\eta) = (k\eta)^{\frac{1}{2}-\gamma}\, C_1(\mathbf{k})\, J_\nu(k\eta)} \quad (a = \eta^\gamma)$$

$(k\eta_* < 1$, Super-Horizon Scales$)$

GRAVITATIONAL WAVE BACKGROUND

$\phi_a(\mathbf{k},\eta) \rightarrow T_{\mu\nu}(\phi_a) \rightarrow \Pi^{TT}_{\mu\nu}(\phi_a) \rightarrow \Box h_{\mu\nu} = 16\pi G\, \Pi^{TT}_{\mu\nu}$

FIELD FLUCTUATIONS

STRESS tensor

ANISOTROPIC (TT) STRESS tensor

GW EQUATIONS (TT metric perturb.)

$$\rho_{GW} = \frac{<\dot{h}_{\mu\nu}\dot{h}^{\mu\nu}>}{16\pi G} = \int \frac{d\rho_{GW}(k,\eta)}{d\log k} d\log k \rightarrow \Omega_{GW}(k,\eta) \equiv \frac{1}{\rho_c}\frac{d\rho_{GW}(k,\eta)}{d\log k}$$

TECHNICALLY

$$\left\langle \phi_a(\mathbf{k},\eta)\, \phi_a(\mathbf{k},\eta) \right\rangle \rightarrow \left\langle \Pi^{TT}_{\mu\nu}(\phi_a)\Pi^{TT}_{\mu\nu}(\phi_a) \right\rangle \rightarrow \left\langle \dot{h}_{\mu\nu}\, \dot{h}_{\mu\nu} \right\rangle$$

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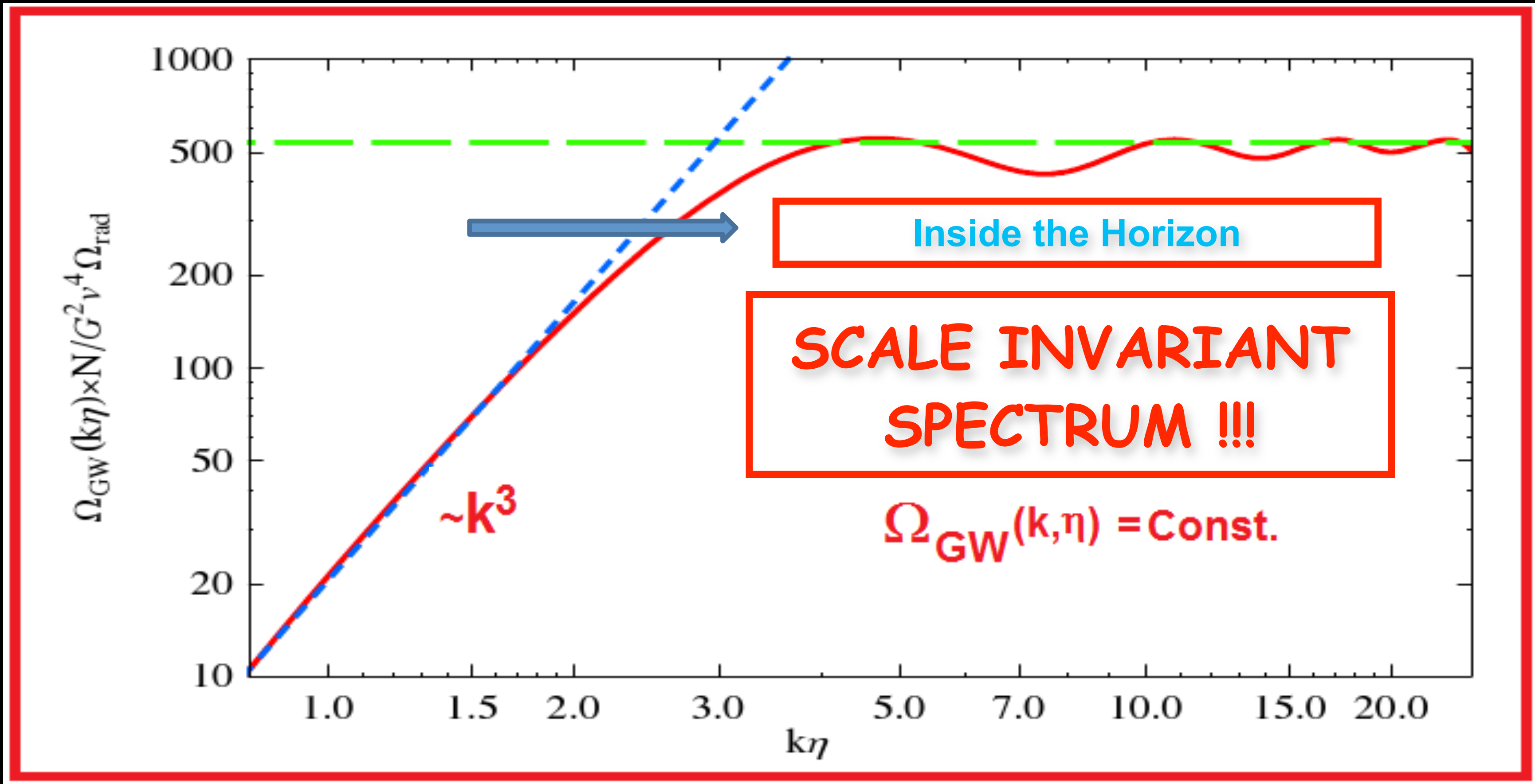

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$\phi_a(\mathbf{k},\eta)$ → $T_{\mu\nu}(\phi_a)$ → $\Pi^{TT}_{\mu\nu}(\phi_a)$ → $\Box h_{\mu\nu} = 16\pi G\, \Pi^{TT}_{\mu\nu}$

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GW EQUATIONS (TT metric perturb.)

SCALE INVARIANT SPECTRUM !!!

(FREQ. INDEPENDENT)

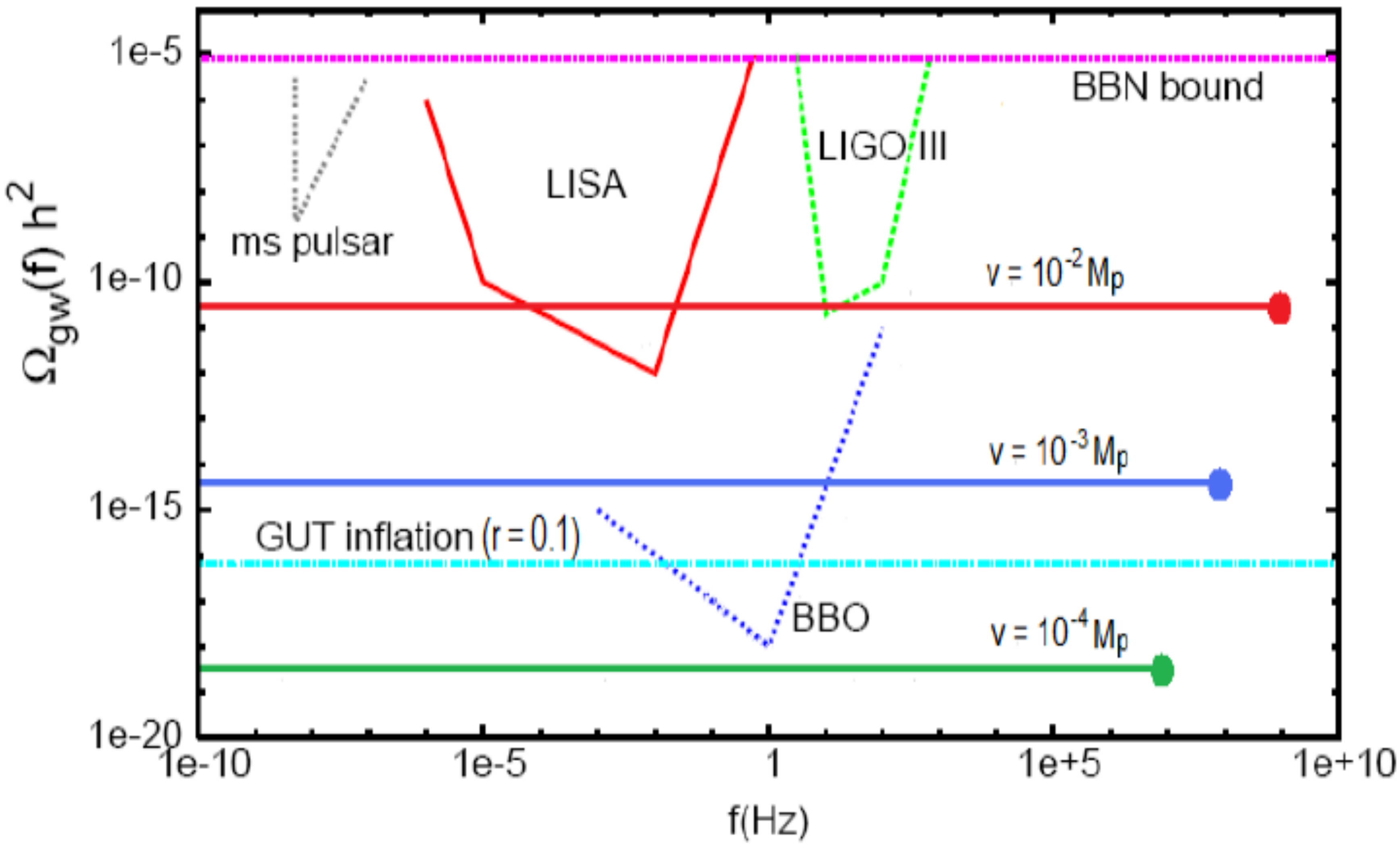
$$\Omega_{\rm GW}(k,\eta_0) \simeq \frac{511}{N}\Omega_{\rm rad}\left(\frac{v}{M_{\rm Pl}}\right)^4$$

$$\mathcal{R} \equiv \frac{\Omega_{\rm GW}(k,\eta_0)}{\Omega^{\rm (inf)}_{\rm GW}(k,\eta_0)} \simeq \frac{256}{N}$$

Jones-Smith et al, 2008

Fenu, DGF, Durrer, Garcia-Bellido 2009

GRAVITATIONAL WAVE BACKGROUND



SUMMARY

- Any (Global) Phase Transition (after Hybrid Reheating) produces a GW Background which today is freq. Indepedendent.

- If the Energy Scale assciated to the Symmetry Breaking process is around the GUT scale, this GWB can be observed (LIGO,BBO,…)

- Inflation also produces a (almost) scale invariant GW spectrum, however, for the same energy scale M:

$$\mathcal{R} \equiv \frac{\Omega_{\rm GW}(k,\eta_0)}{\Omega_{\rm GW}^{\rm (inf)}(k,\eta_0)} \simeq \frac{256}{N}$$

Fenu, Figueroa, Durrer, Garcia-Bellido
JCAP 0910:005,2009 (ArXiv: 0908.0425)

BEYOND

- It's extremely important to learn how to distinguish both GW backgrounds, since if B-modes are detected in the CMB (Planck, CMBpol,…), we might be incorrectly infering the energy scale of Inflation

Garcia-Bellido, Durrer, Fenu, DGF, Kunz
JCAP 0910:005,2009 (ArXiv: 0908.0425)

- Another consequence of the Self-Ordering Dynamics of the fields after the Symmetry Breaking, is that they also generate a huge NON-GAUSSIANITY in the matter perturbations, see

DGF, Caldwell, Kamionkowski
PRD 2010, In Press (ArXiv: 1003.0672)

- If the Phase Transition (after Hybrid Reheating) is not Global, but rather there are Gauge Fields present:

Dufaux, DGF, Garcia-Bellido (ArXiv: 1006.XXYY)