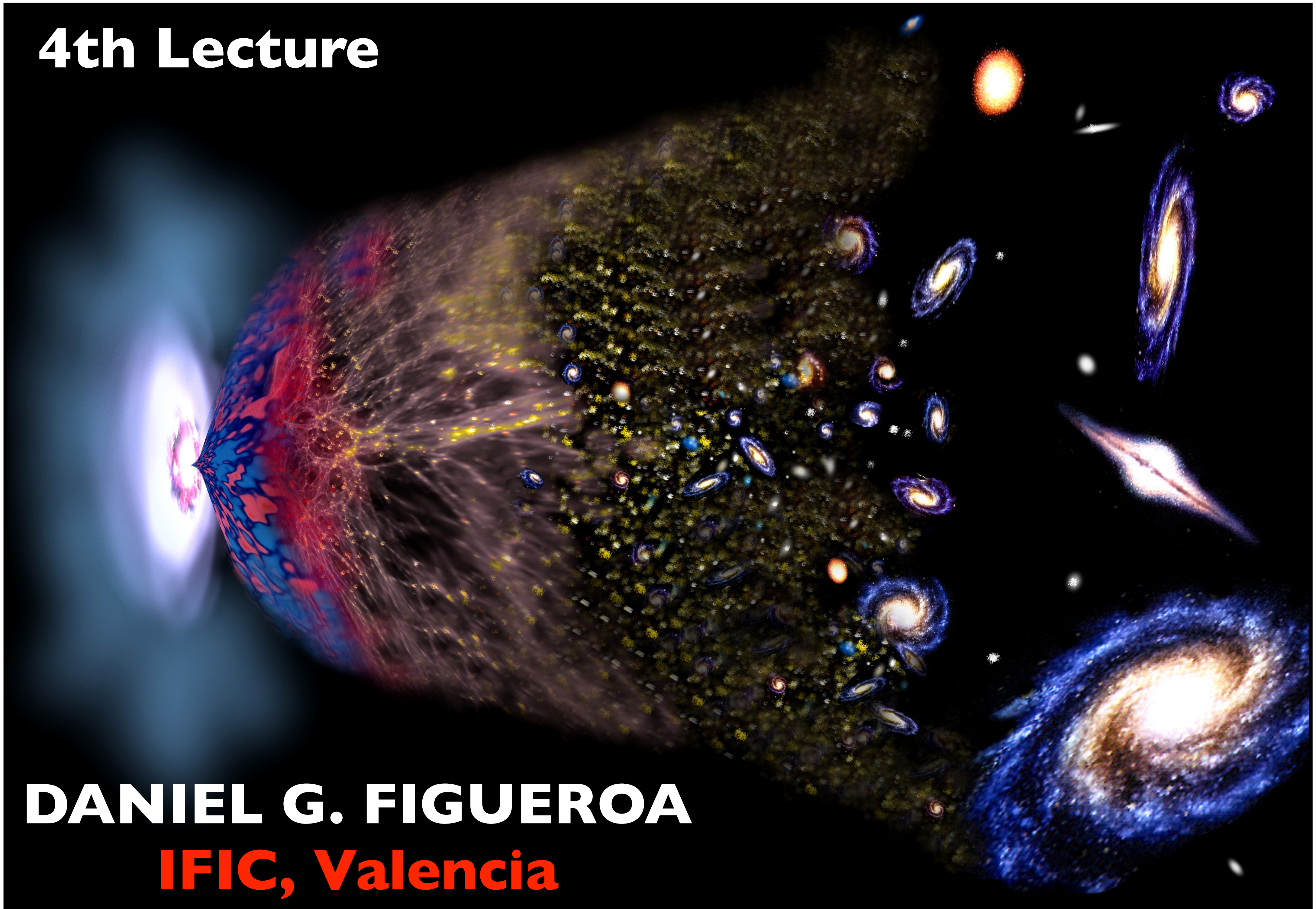
GRAVITATIONAL WAVE
— BACKGROUNDS —



GGI LECTURES ON THE THEORY OF FUNDAMENTAL INTERACTIONS — 2022 Program (3rd week)

OUTLINE

1st Bloc

1) Cosmology/GR + GW def. ✓

2nd Bloc

2) GWs from Inflation ✓

3) GWs from Preheating

4) GWs from Phase Transitions

5) GWs from Cosmic Defects

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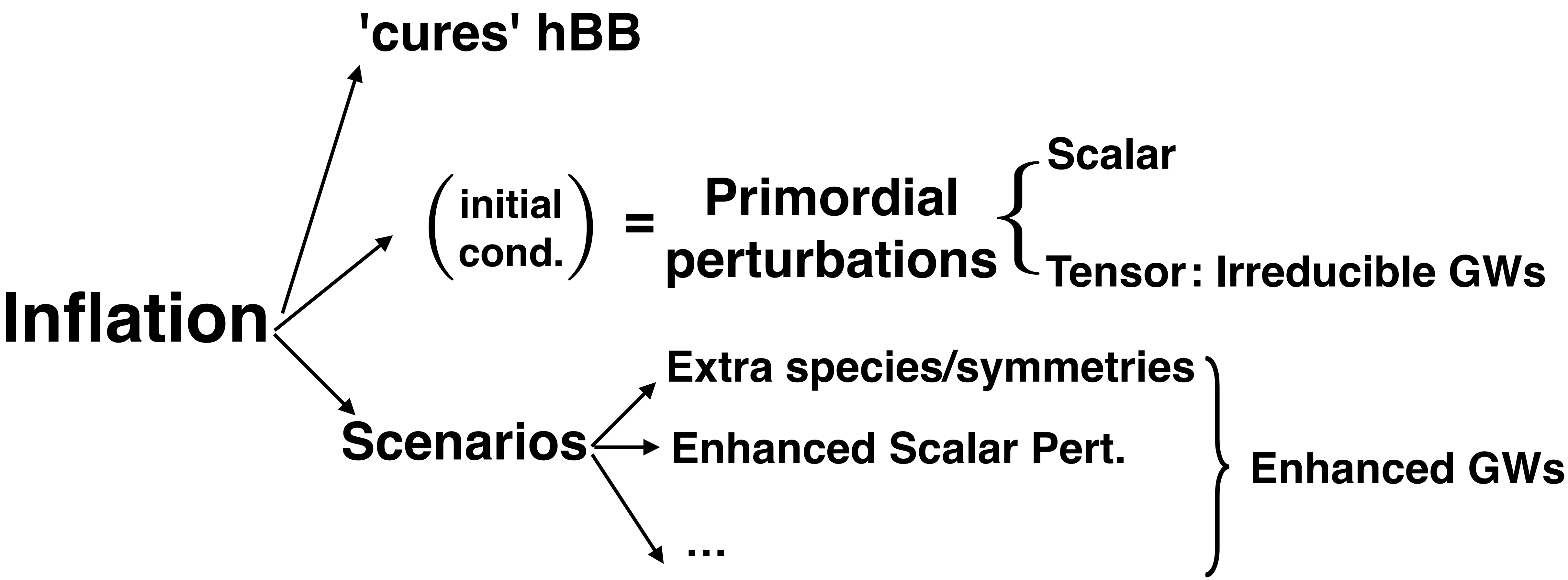
INFLATIONARY COSMOLOGY



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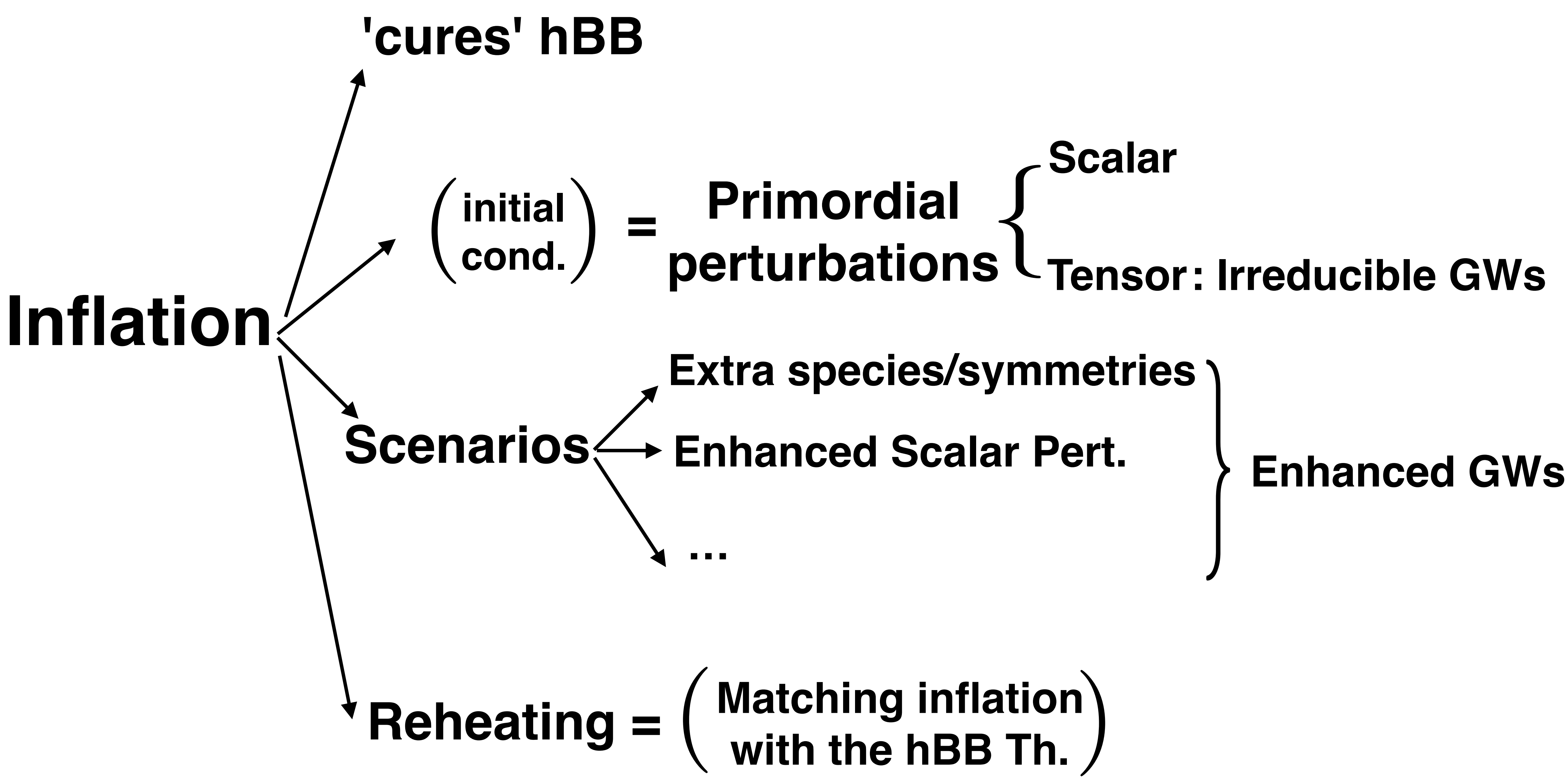

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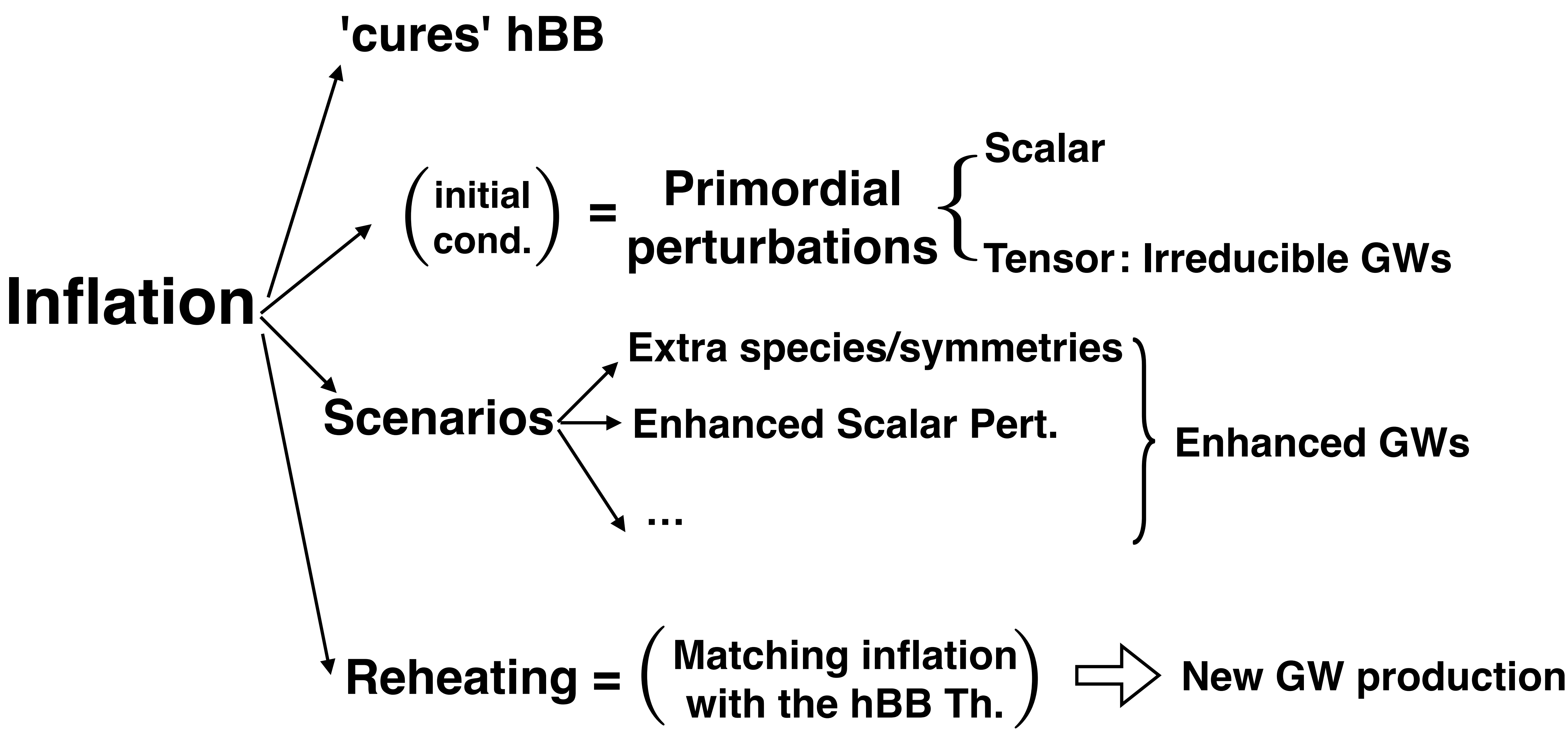


INFLATIONARY COSMOLOGY

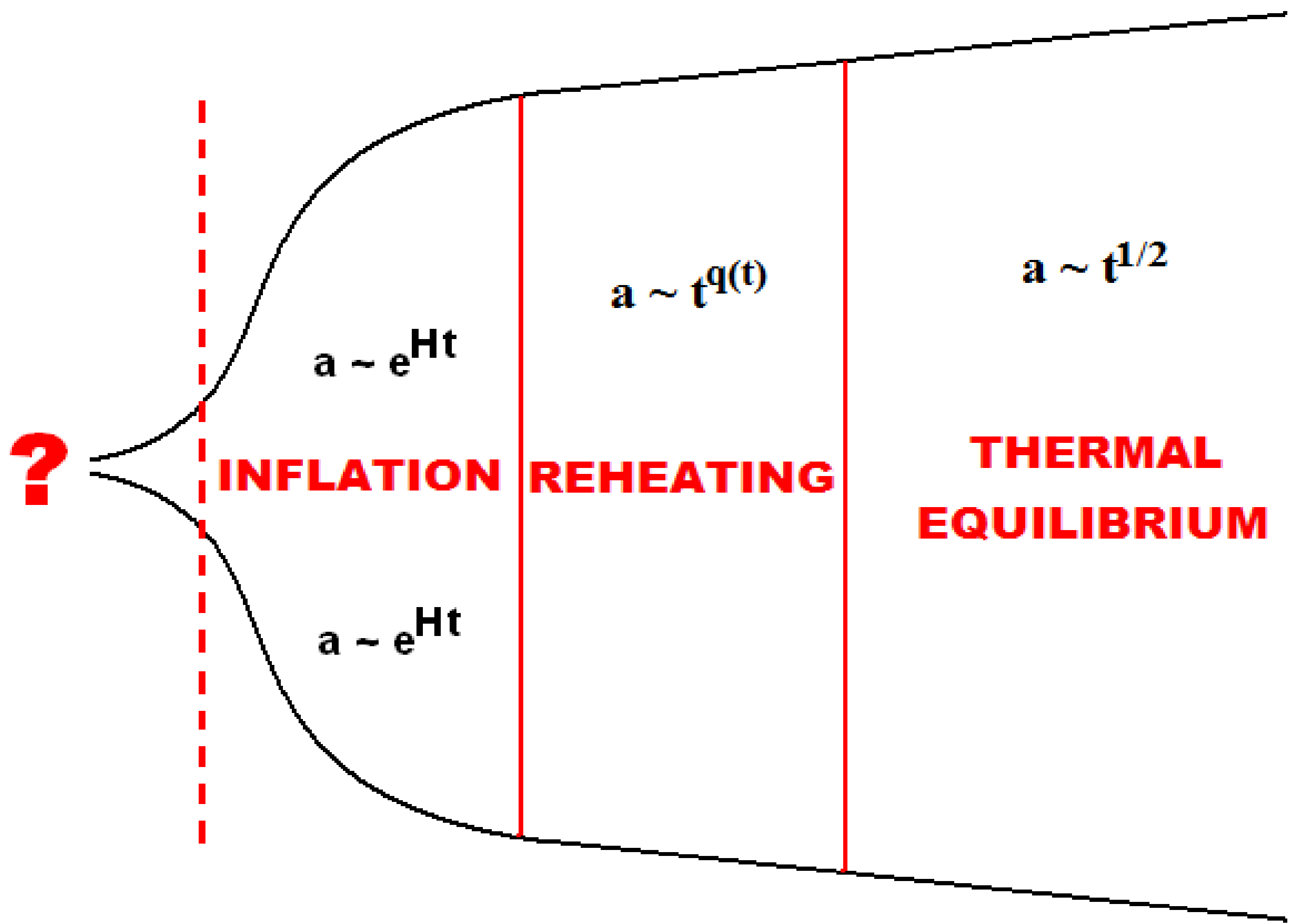
Inflation

- 'cures' hBB
- (initial cond.) = Primordial perturbations
  - Scalar
  - Tensor : Irreducible GWs
- Scenarios
  - Extra species/symmetries
  - Enhanced Scalar Pert.
  - ...

  Enhanced GWs
- Reheating = (Matching inflation with the hBB Th.) ⇨ New GW production

INFLATIONARY REHEATING

INFLATION $\longrightarrow$ REHEATING $\longrightarrow$ BIG BANG THEORY



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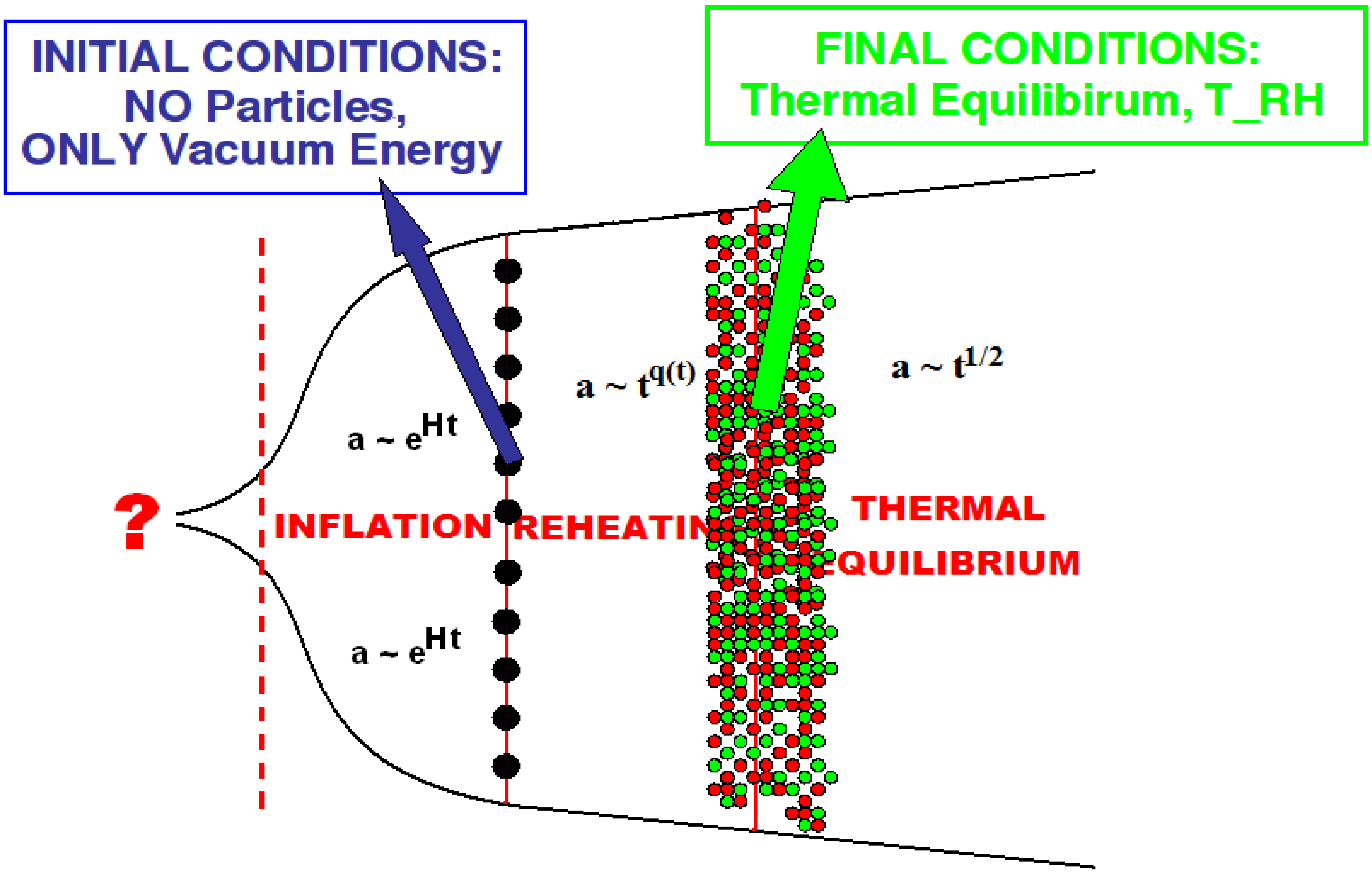

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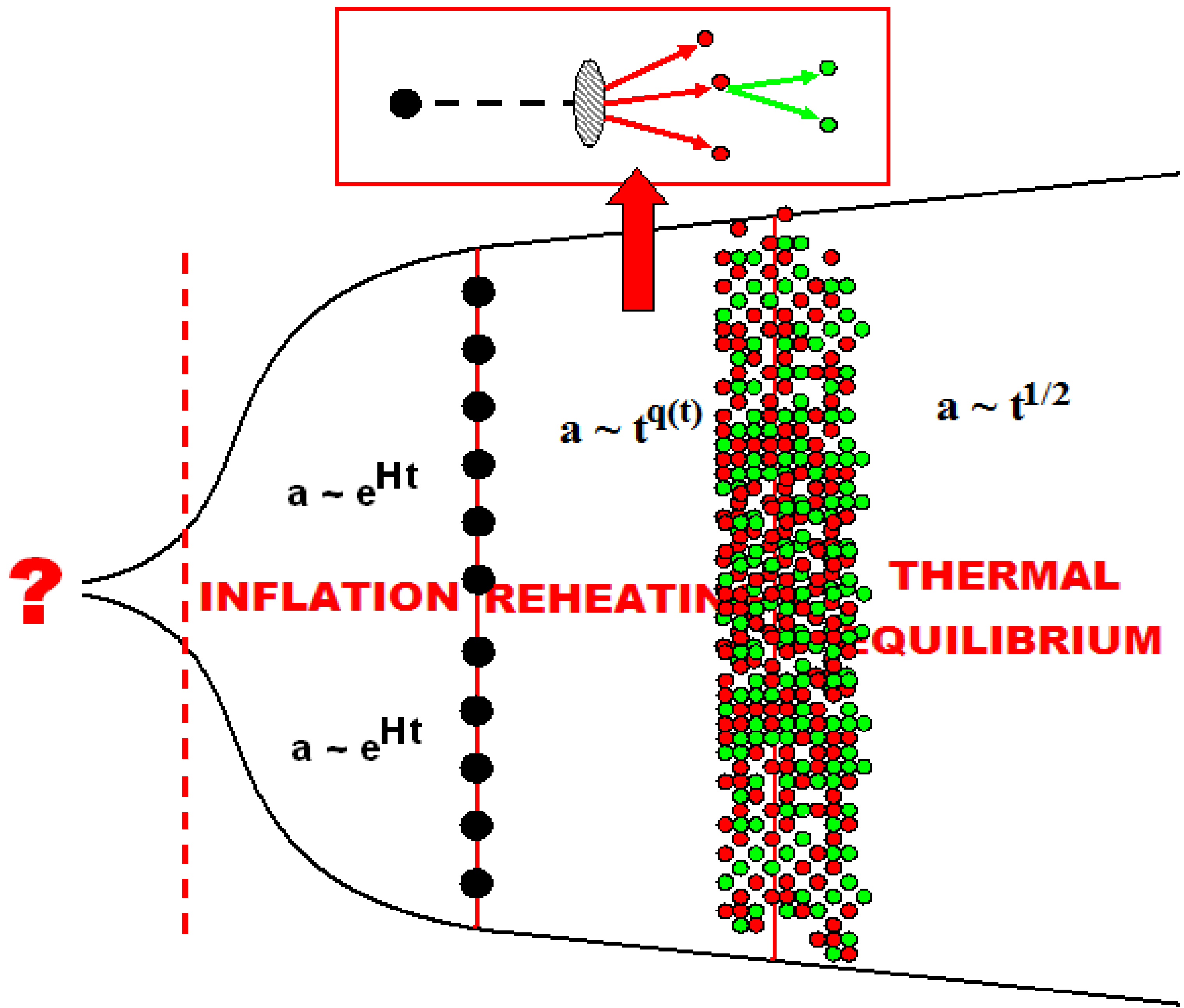

INFLATIONARY REHEATING

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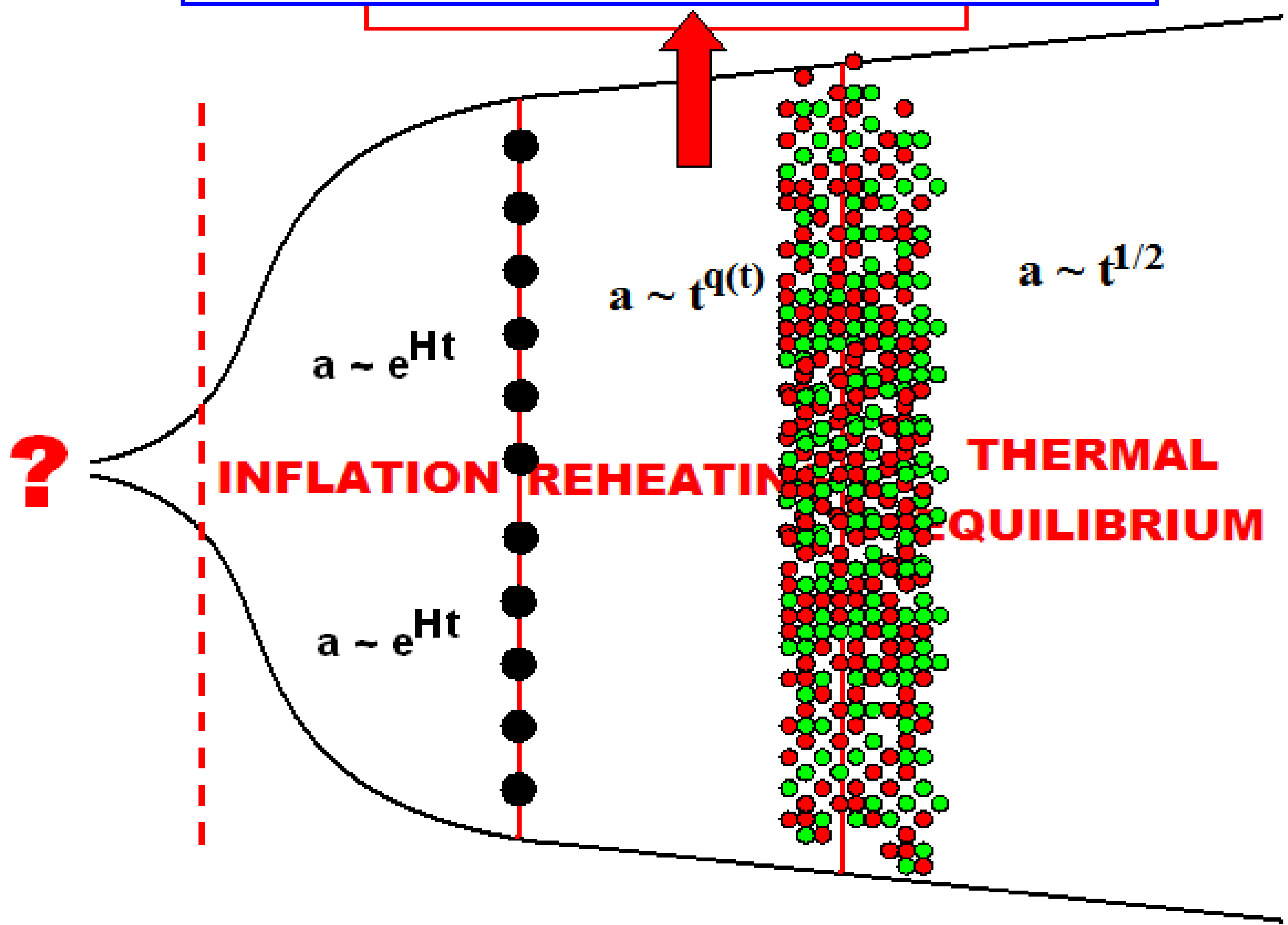
$$\mathcal{L} = \mathcal{L}(\phi, \varphi_i, \psi_j, A_\mu, h_{\mu\nu}, \ldots)$$



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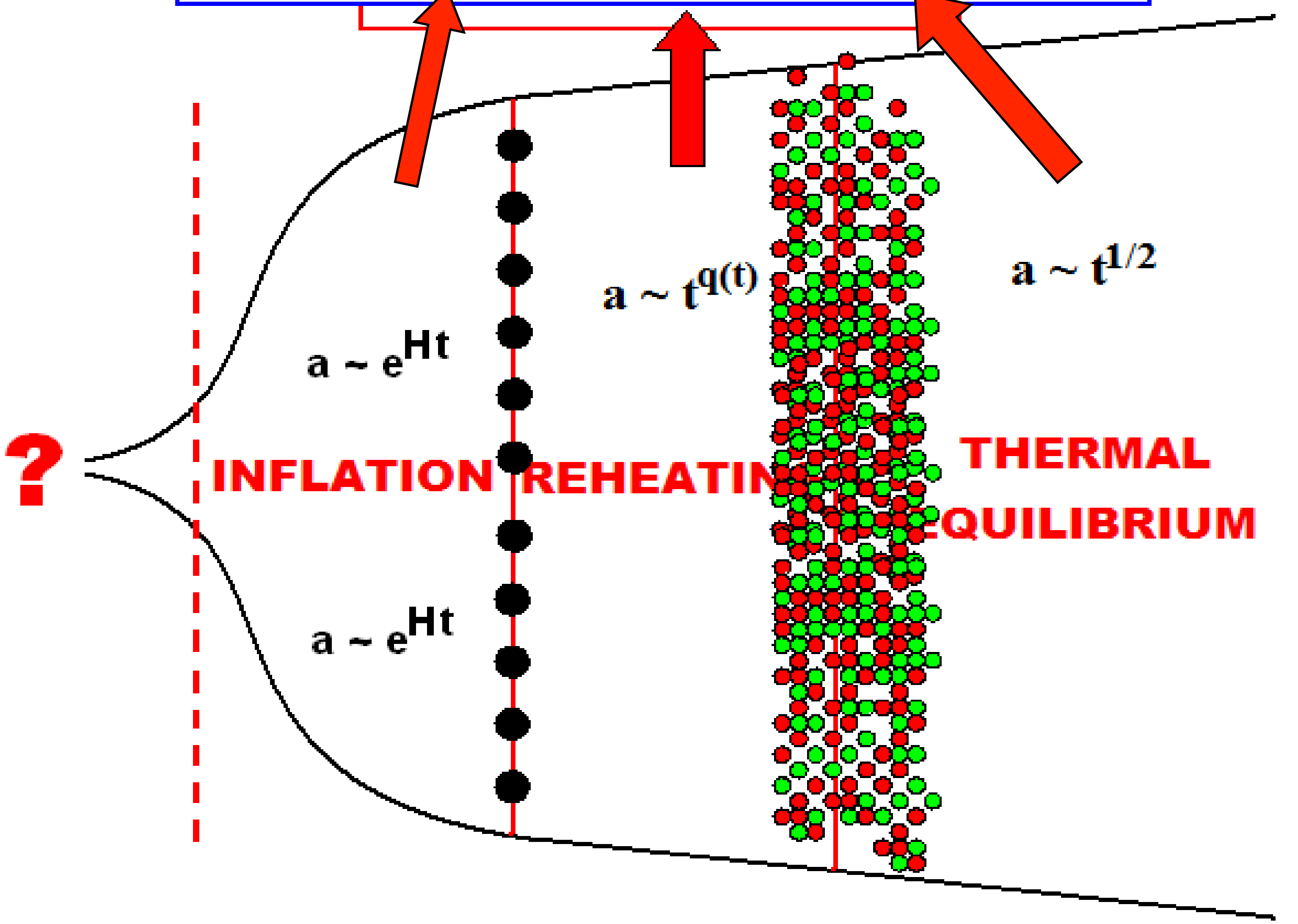

SCALAR REHEATING

1) $V(\phi,\chi) = \quad \frac{1}{4}\lambda\phi^4 \quad + \quad \frac{1}{2}m_\chi^2\chi^2 \quad + \quad \frac{1}{2}g^2\phi^2\chi^2$ (Chaotic)

2) $V(\phi,\chi) = \quad \frac{1}{2}\mu^2\phi^2 \quad + \quad \frac{\lambda}{4}(\chi^2 - v^2)^2 \quad + \quad \frac{1}{2}g^2\phi^2\chi^2$ (Hybrid)

INFLATON **MATTER** **COUPLING**

SCALAR REHEATING

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INFLATON **MATTER** **COUPLING**

(**Ruled out for inflation,**
Not for reheating !)

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INFLATON **MATTER** **COUPLING**

$$\begin{cases} \ddot{\phi}(t) + 3H\dot{\phi} + V'(\phi) = 0 & (\textbf{Inflaton Zero-Mode} \; : \text{Damped Oscillator}) \\ \Box\phi_k + F(\int dq \phi_q \chi_{|k-q|})\phi_k + ... = 0 & (\textbf{Inflaton Fluctuations}) \\ \Box\chi_k + F(\int dq \chi_q, \phi_{|k-q|})\chi_k + ... = 0 & (\textbf{Matter Fluctuations}) \end{cases}$$

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DYNAMICS:

Non-Linear, Non-Perturbative & Far-From-Equilibrium

$$\mathbf{k}_i \pm \Delta\mathbf{k}_i \rightarrow \varphi_k(t), n_k(t) \sim exp\{\mu_k\, t\}$$

SCALAR (P)REHEATING

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SCALAR (P)REHEATING

1) $$V(\phi,\chi) = \frac{\lambda}{n}\phi^n + \frac{1}{2}m_\chi^2\chi^2 + \frac{1}{2}g^2\phi^2\chi^2$$ **(monomial)**

SCALAR (P)REHEATING

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SCALAR (P)REHEATING

1) Chaotic Scenarios: PARAMETRIC RESONANCE

SCALAR (P)REHEATING

1) Chaotic Scenarios: PARAMETRIC RESONANCE

MATTER FIELD FLUCTUATIONS

$$\underset{(n\,=\,4)}{\text{Massless}} : X_k'' + (\kappa^2 + \; q\, cn^2(z))X_k = 0 \quad \text{(Lamé Eq.)} \qquad q \equiv \frac{g^2}{\lambda}; \;\; \kappa \equiv \frac{k}{\omega_*} \;\; ; \;\; z \equiv \omega_* t$$

$$[X = a^{3/2}\chi]$$

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$$z \equiv \omega_* t\ ;\ \ \omega_* \equiv m_\phi$$

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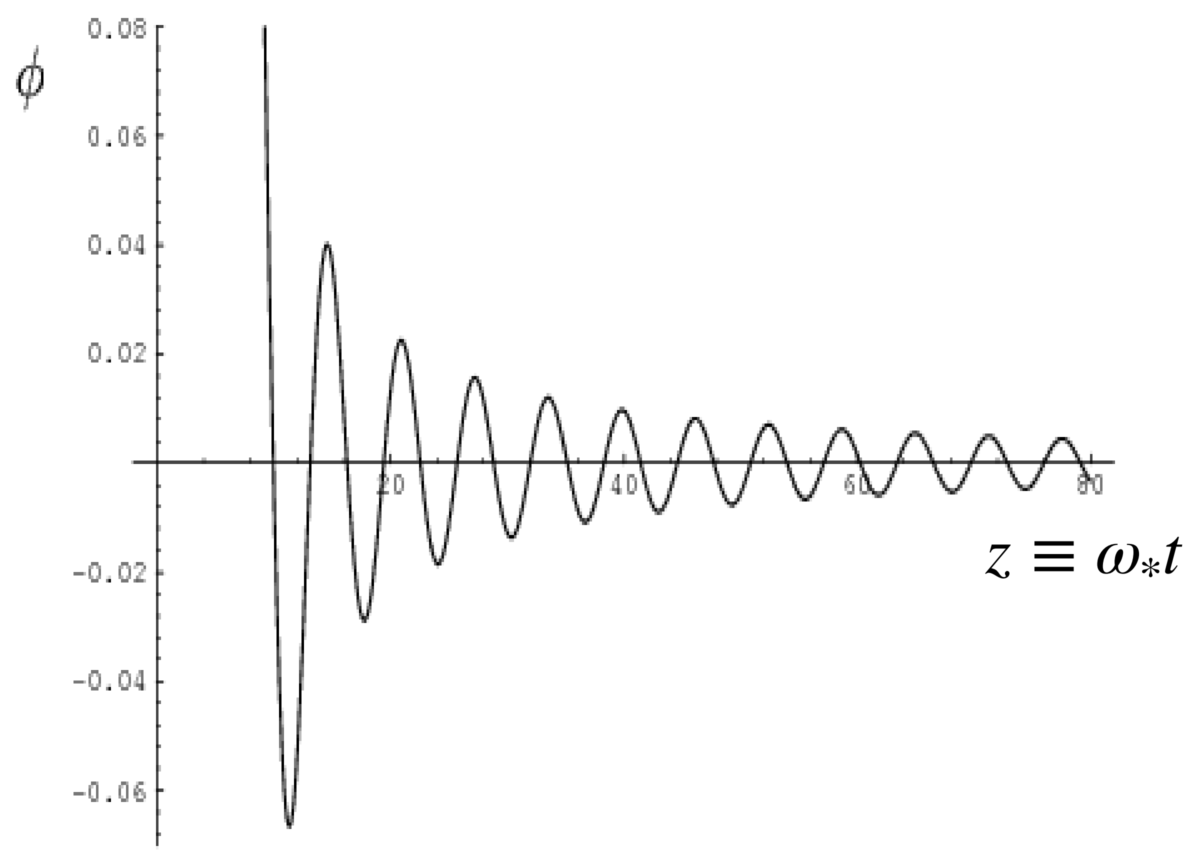

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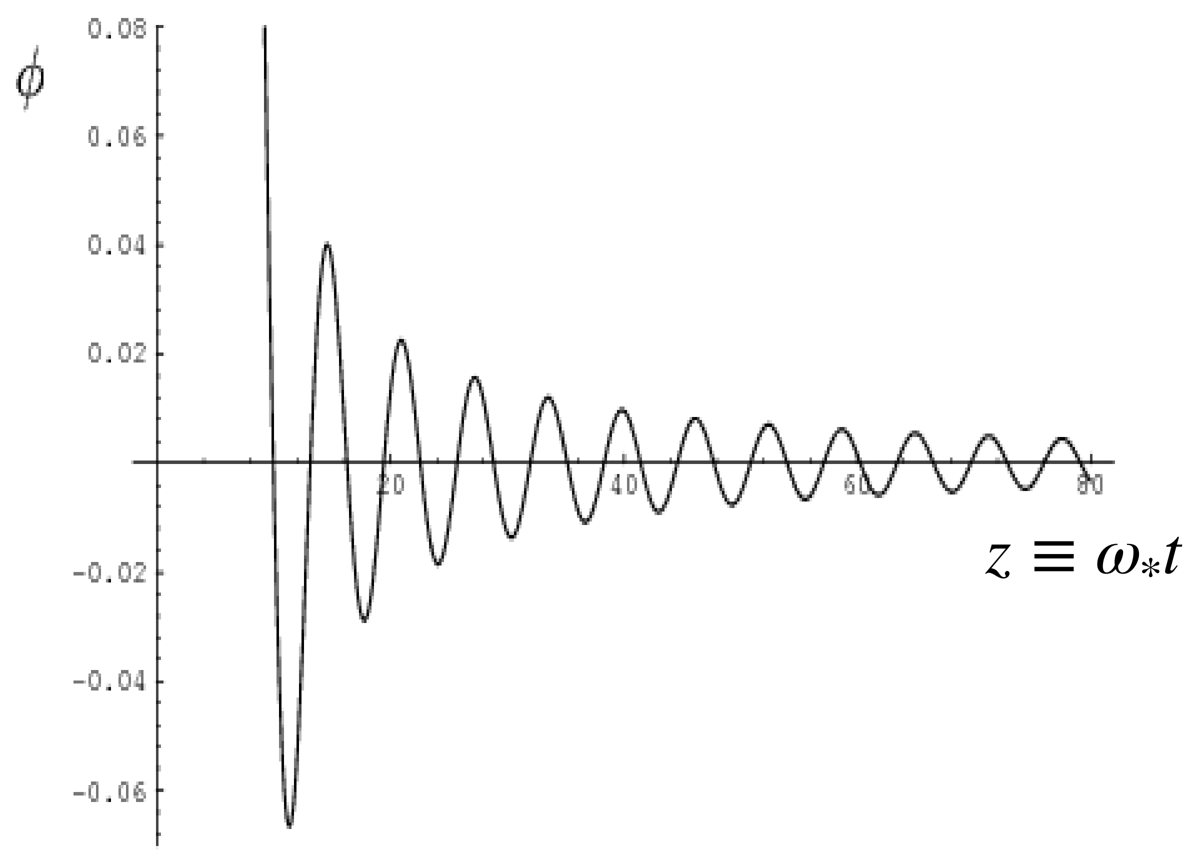
$$\left.\begin{matrix} \\ \\ \end{matrix}\right\} \quad \begin{matrix} X_k \sim e^{\mu_k t} \\ n_k \sim e^{\mu_k t} \end{matrix}$$



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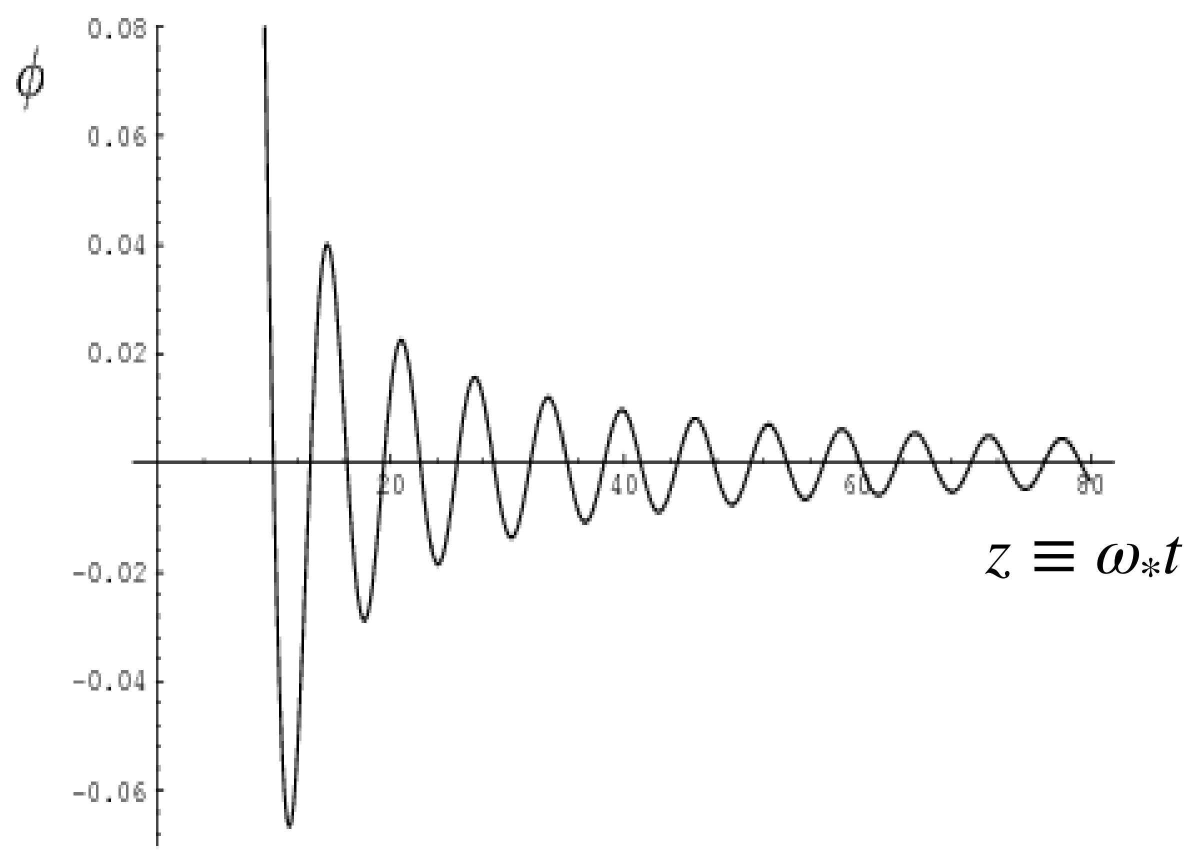

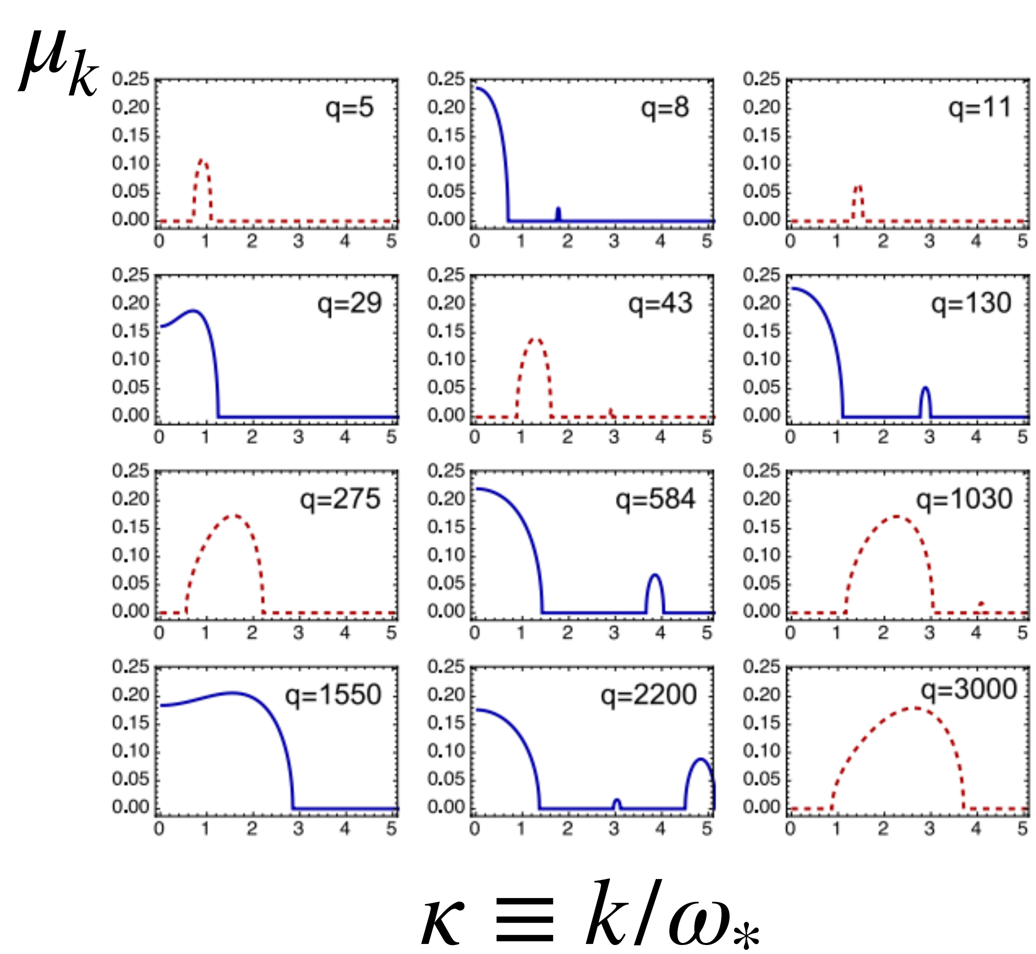

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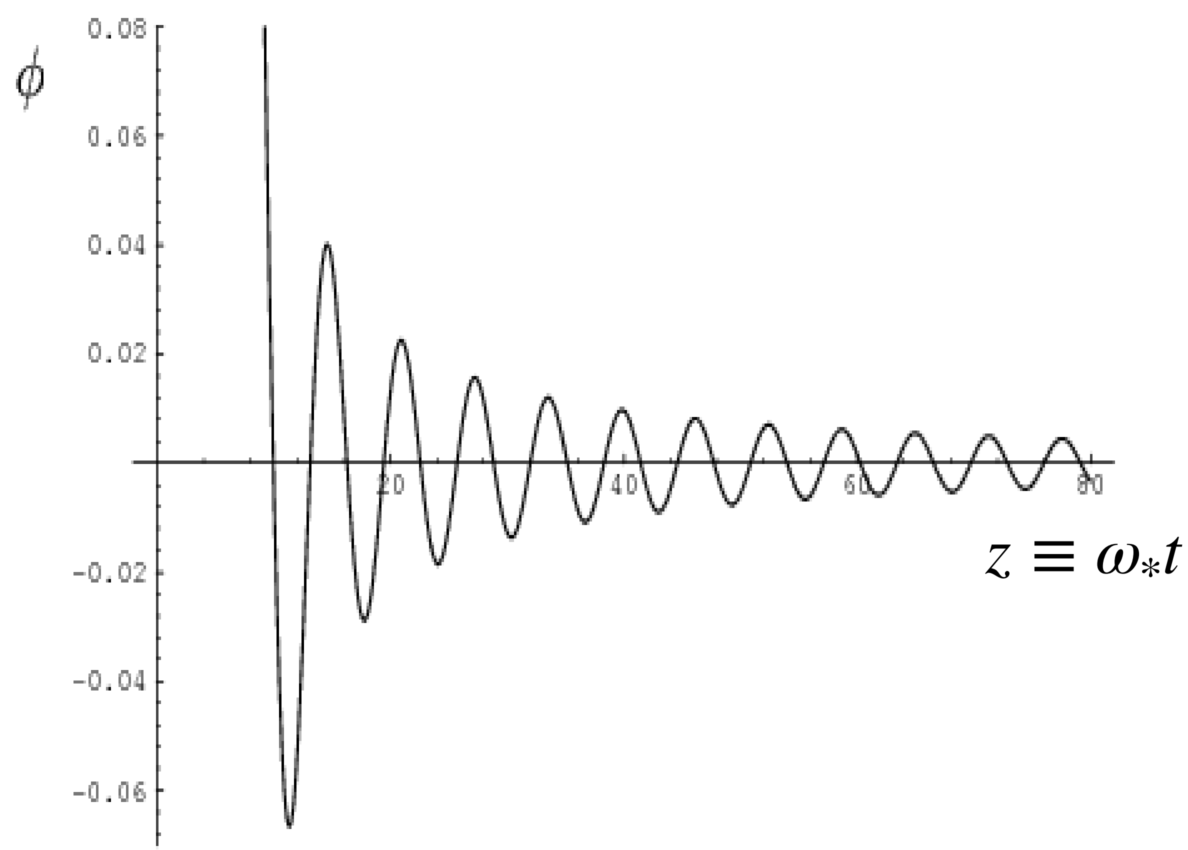

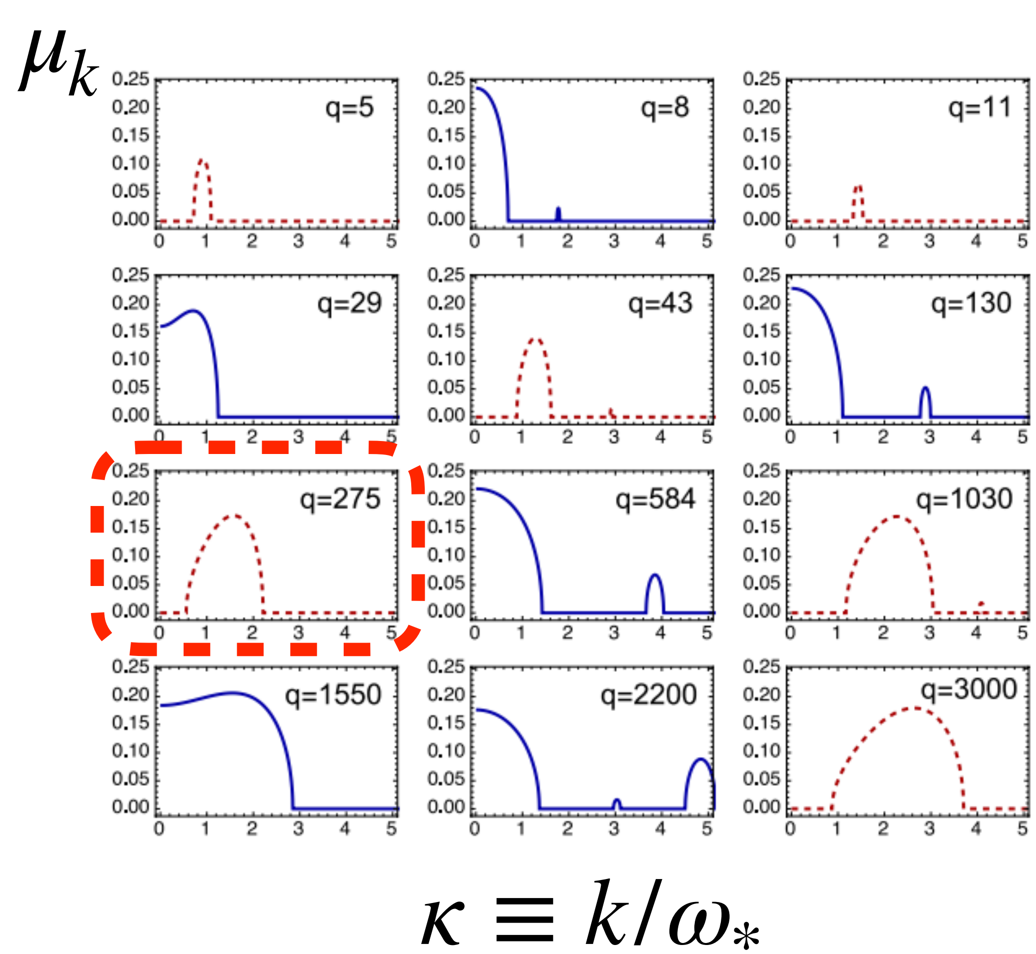

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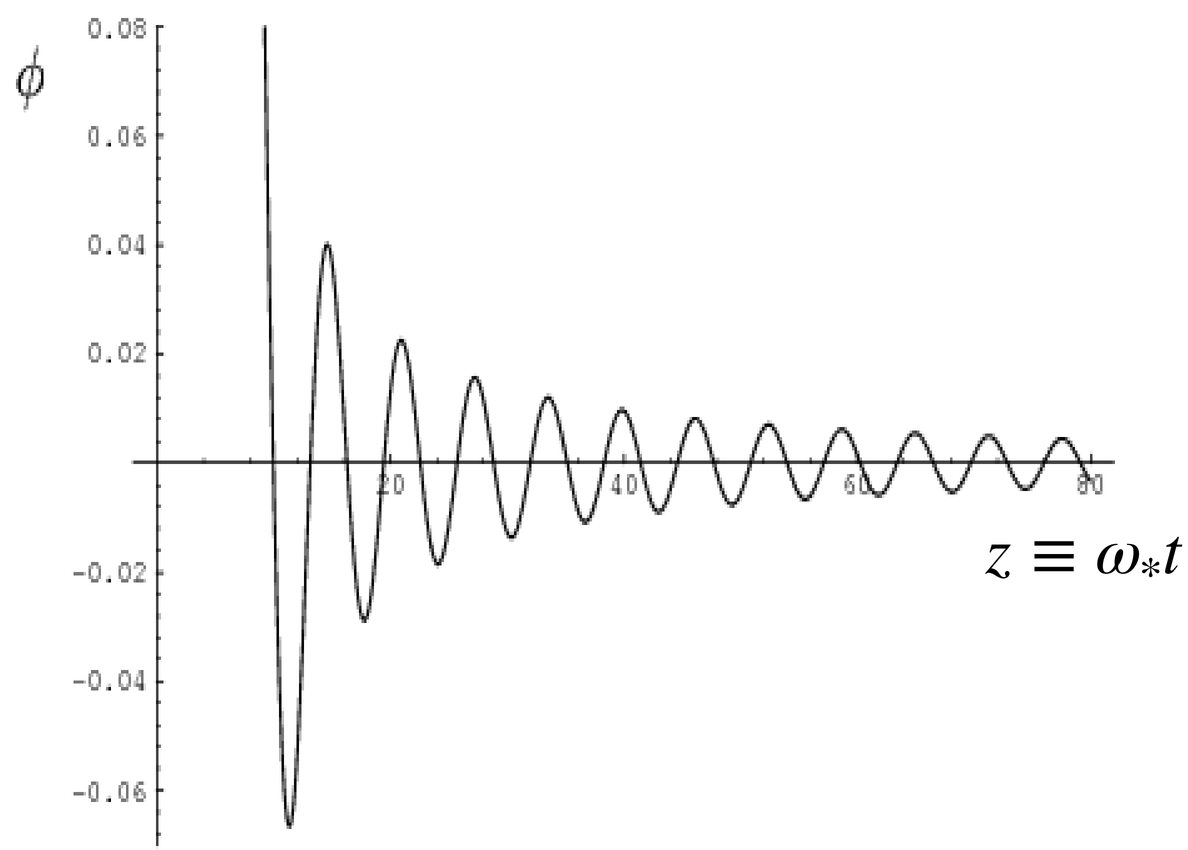

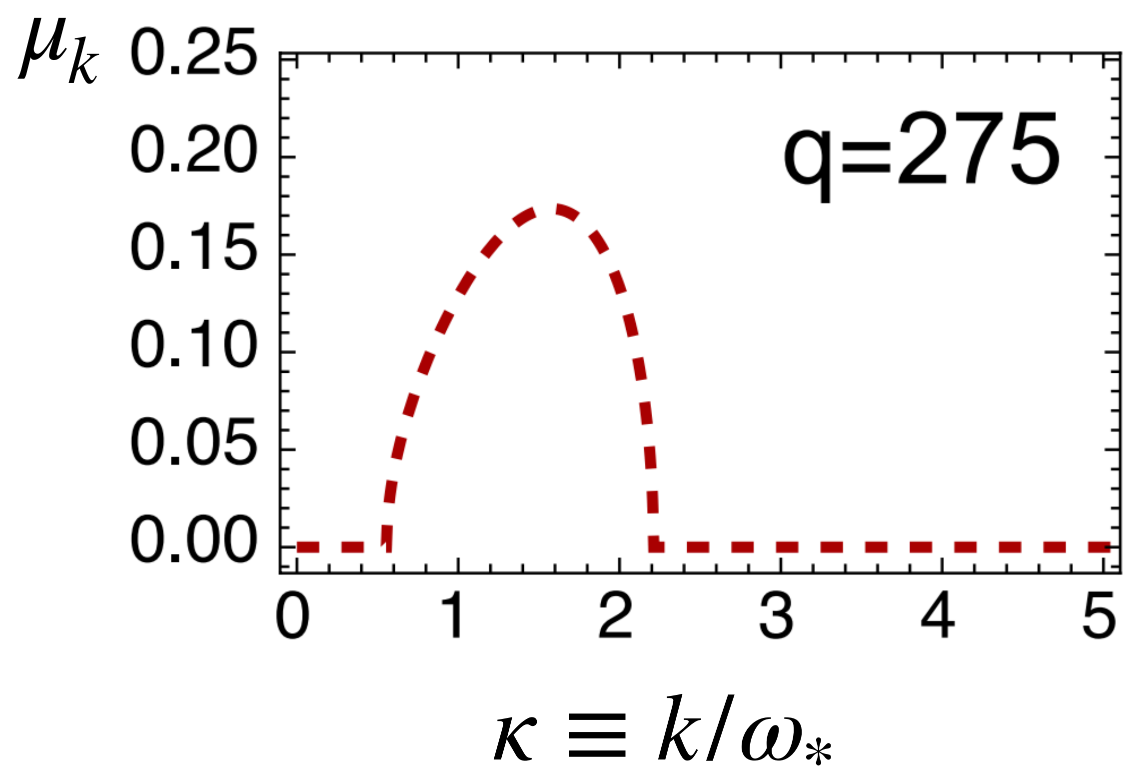

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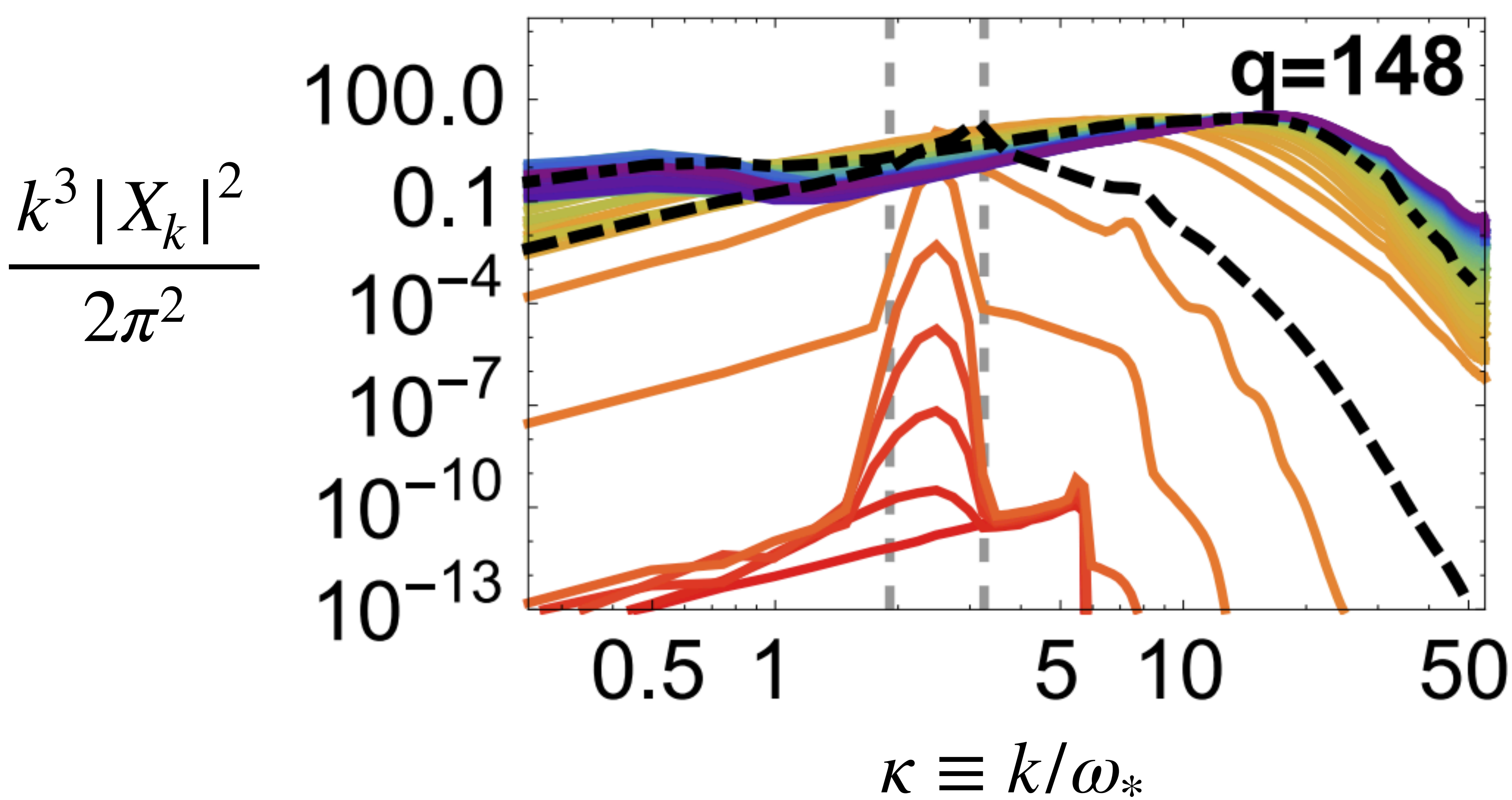

SCALAR (P)REHEATING

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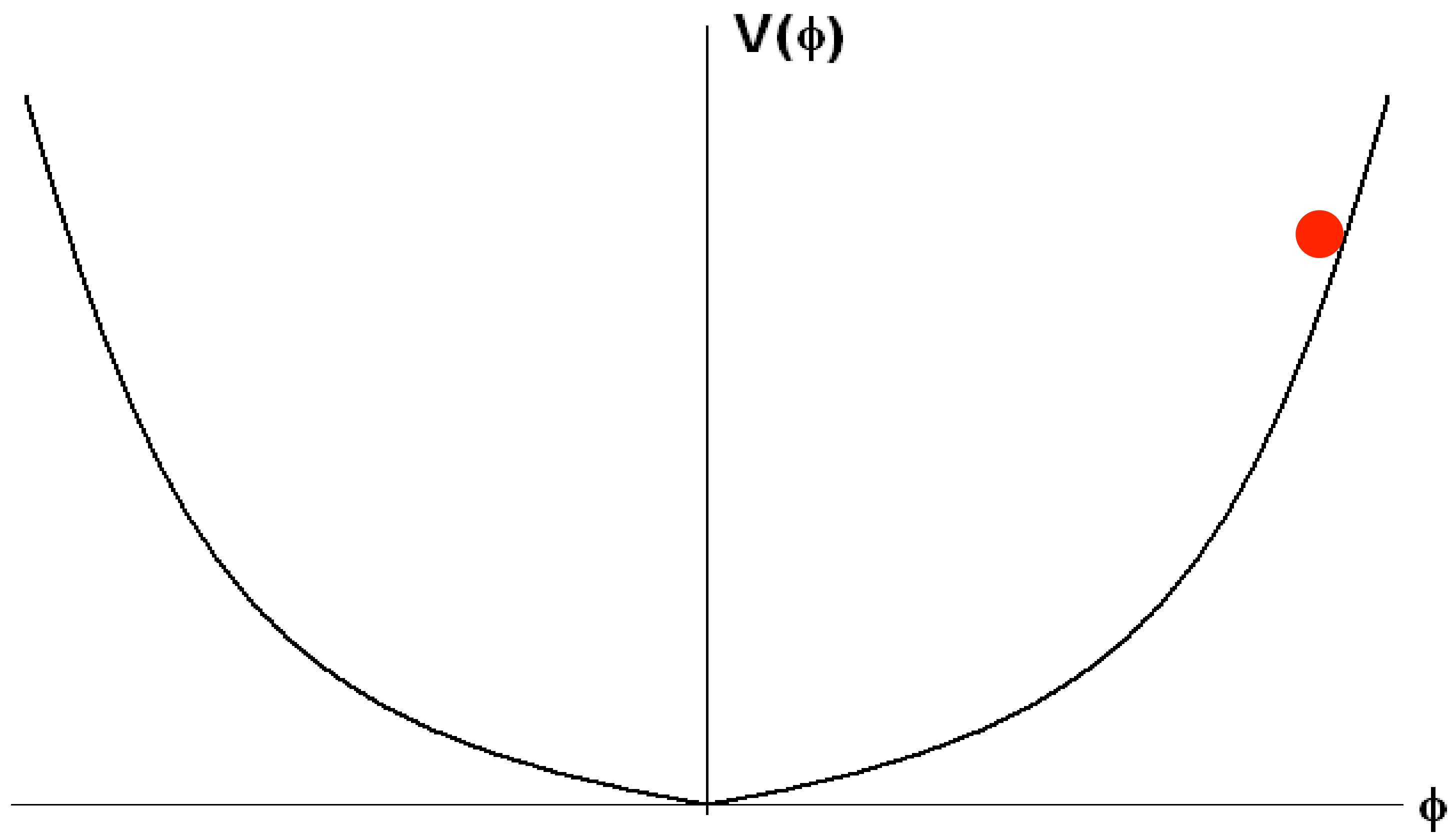
$$V(\phi,\chi) = \quad V(\phi) \quad + \quad \tfrac{1}{2}m_\chi^2\chi^2 \quad + \quad \tfrac{1}{2}g^2\phi^2\chi^2 \quad \text{(Chaotic Models)}$$

$$X_k'' + [\kappa^2 + m^2(\phi)]X_k = 0 \quad \text{(Fluctuations of Matter)}$$



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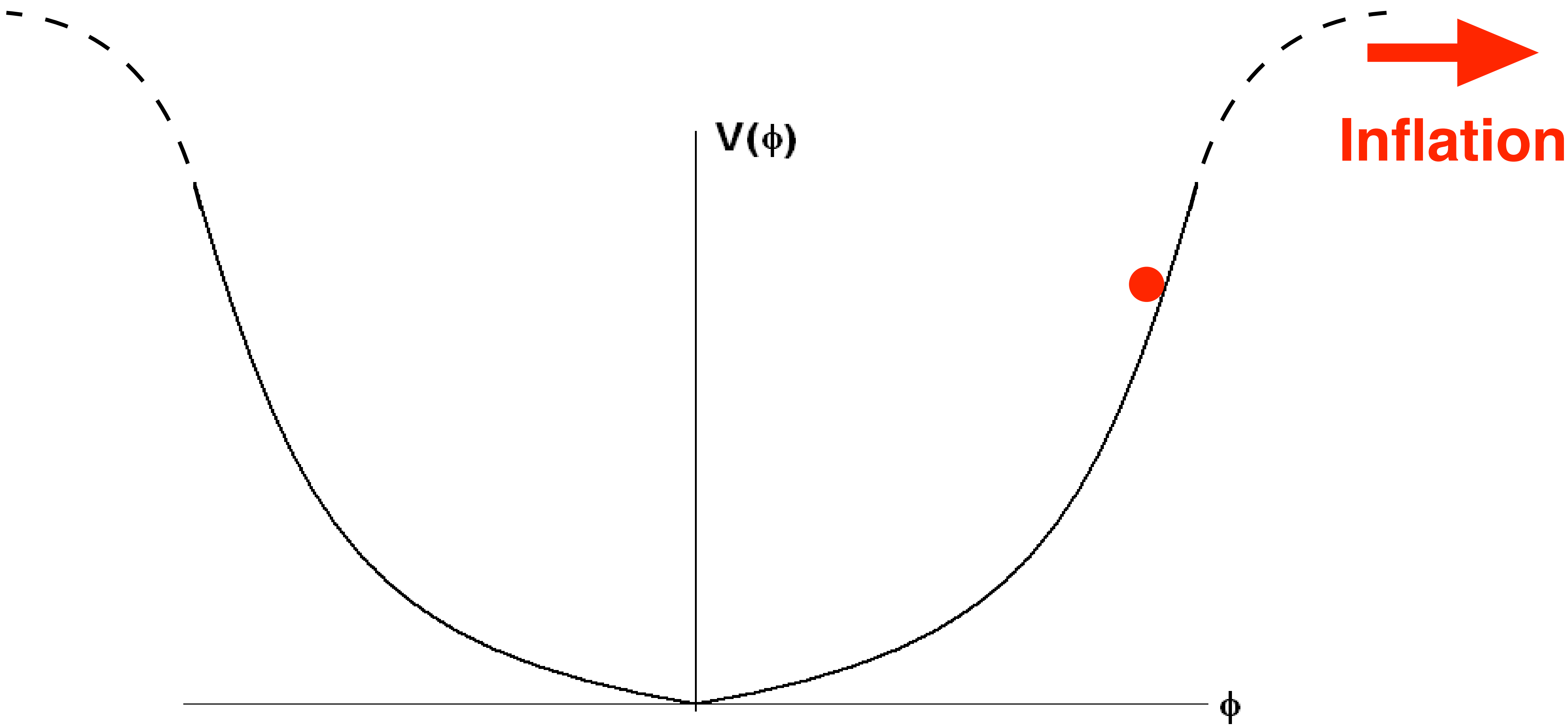

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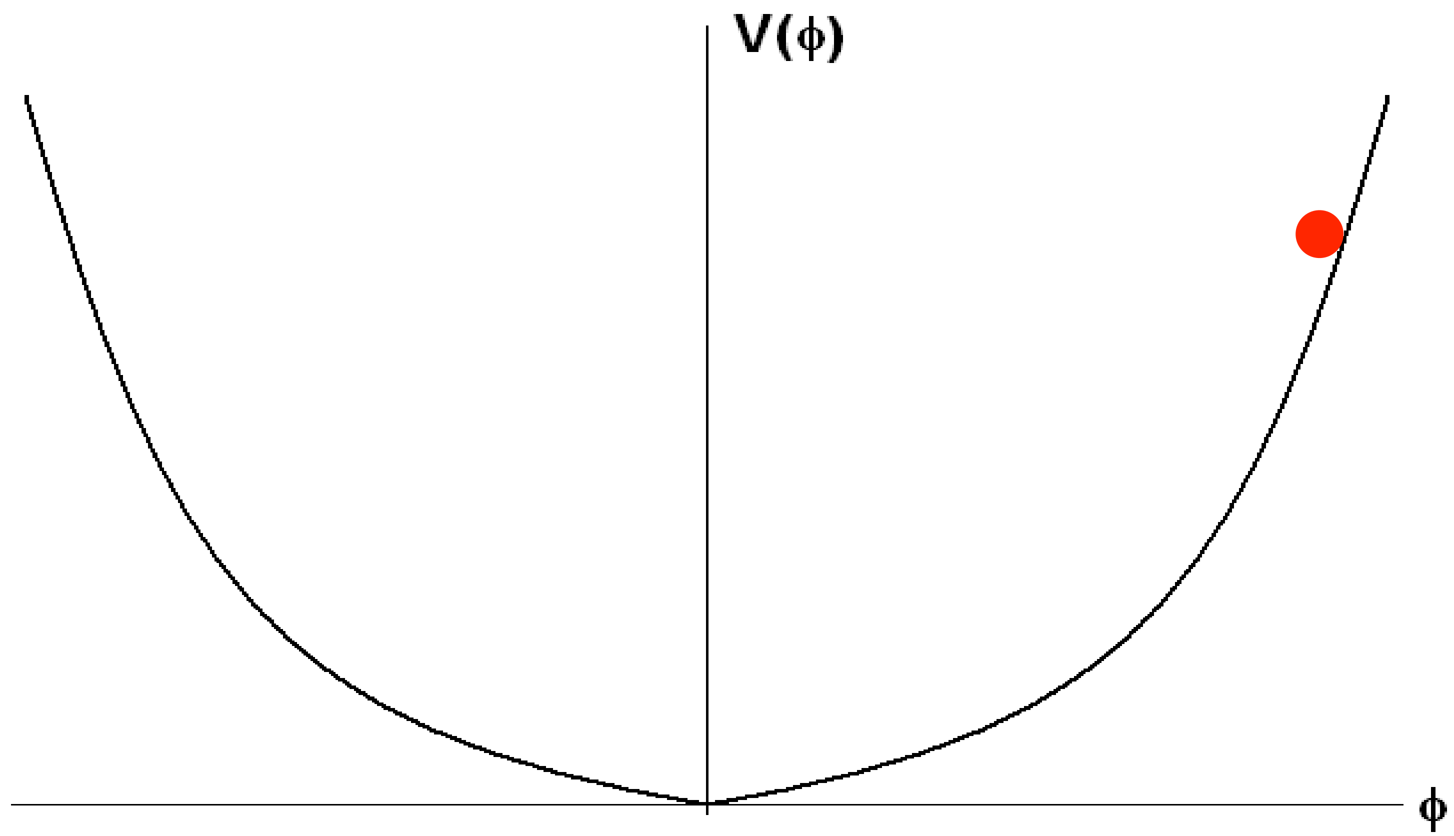

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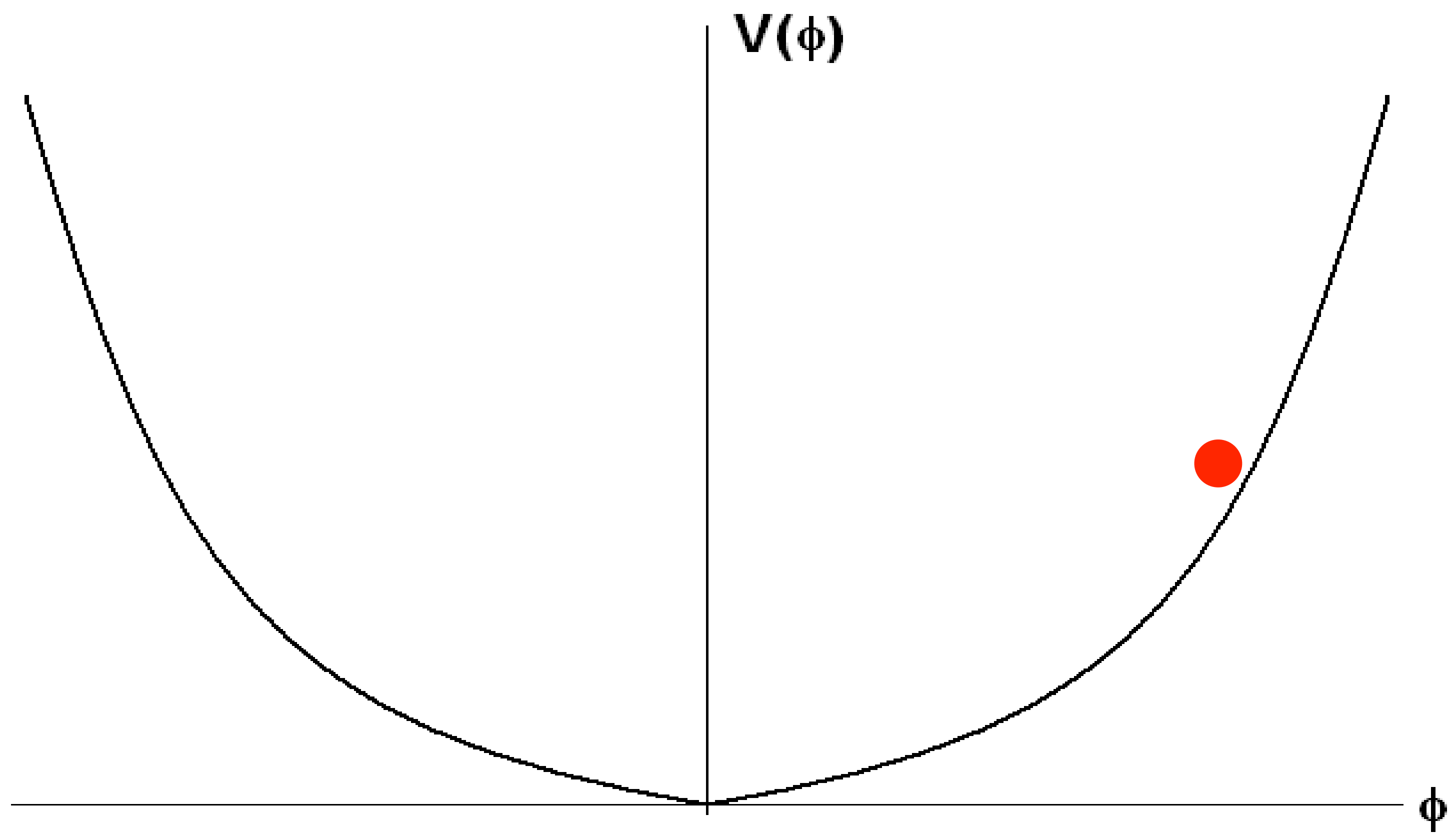

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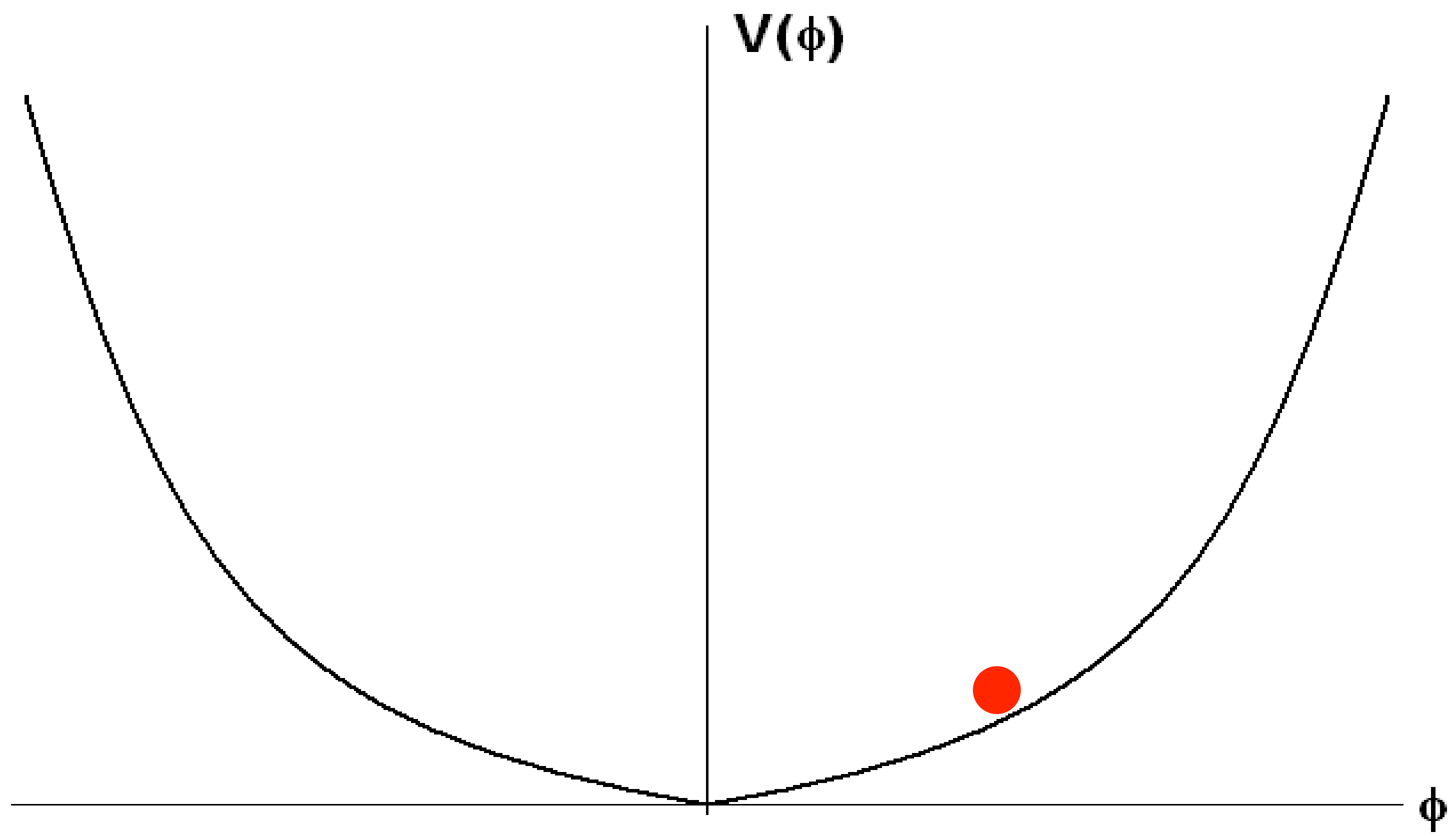

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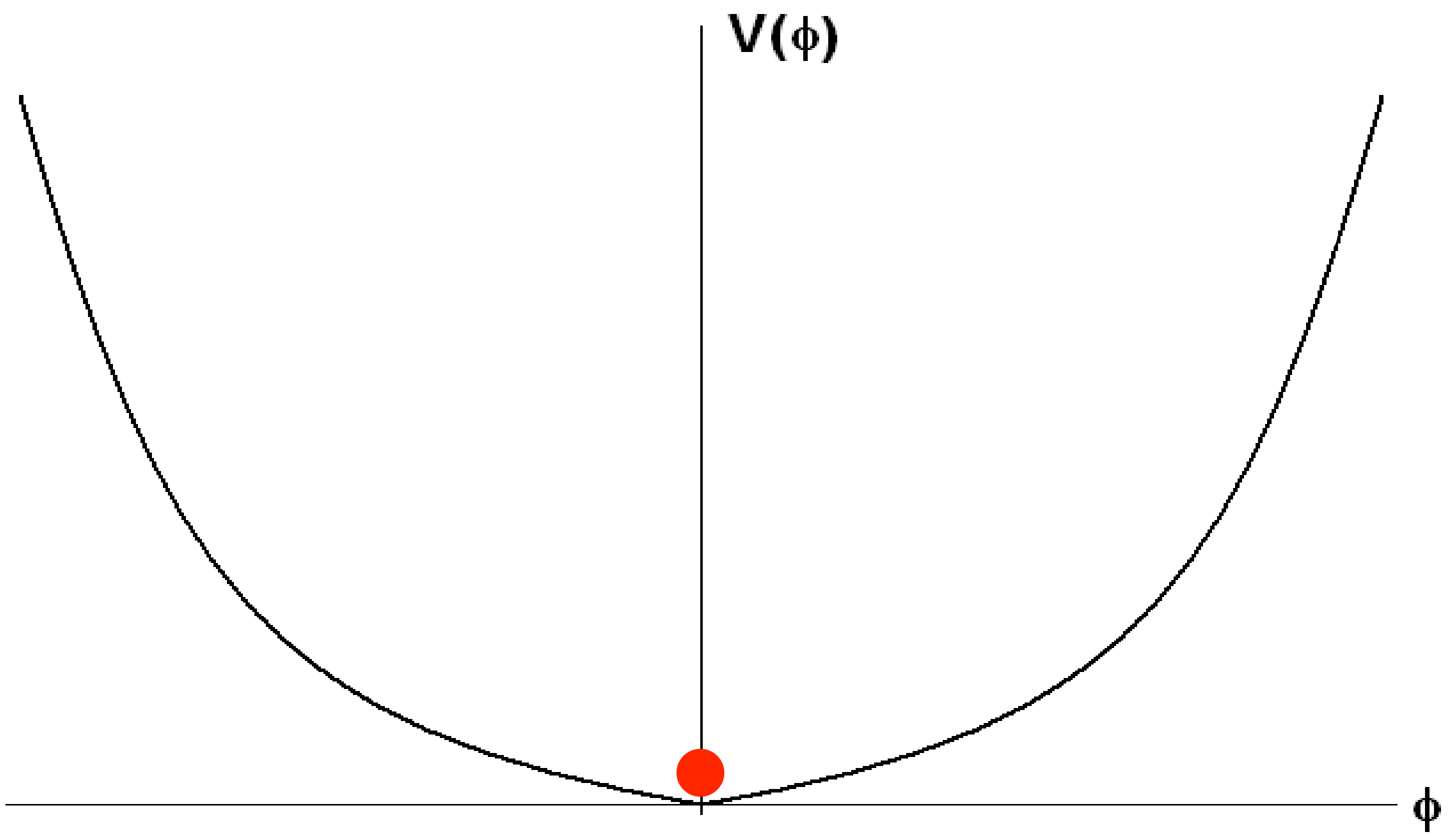

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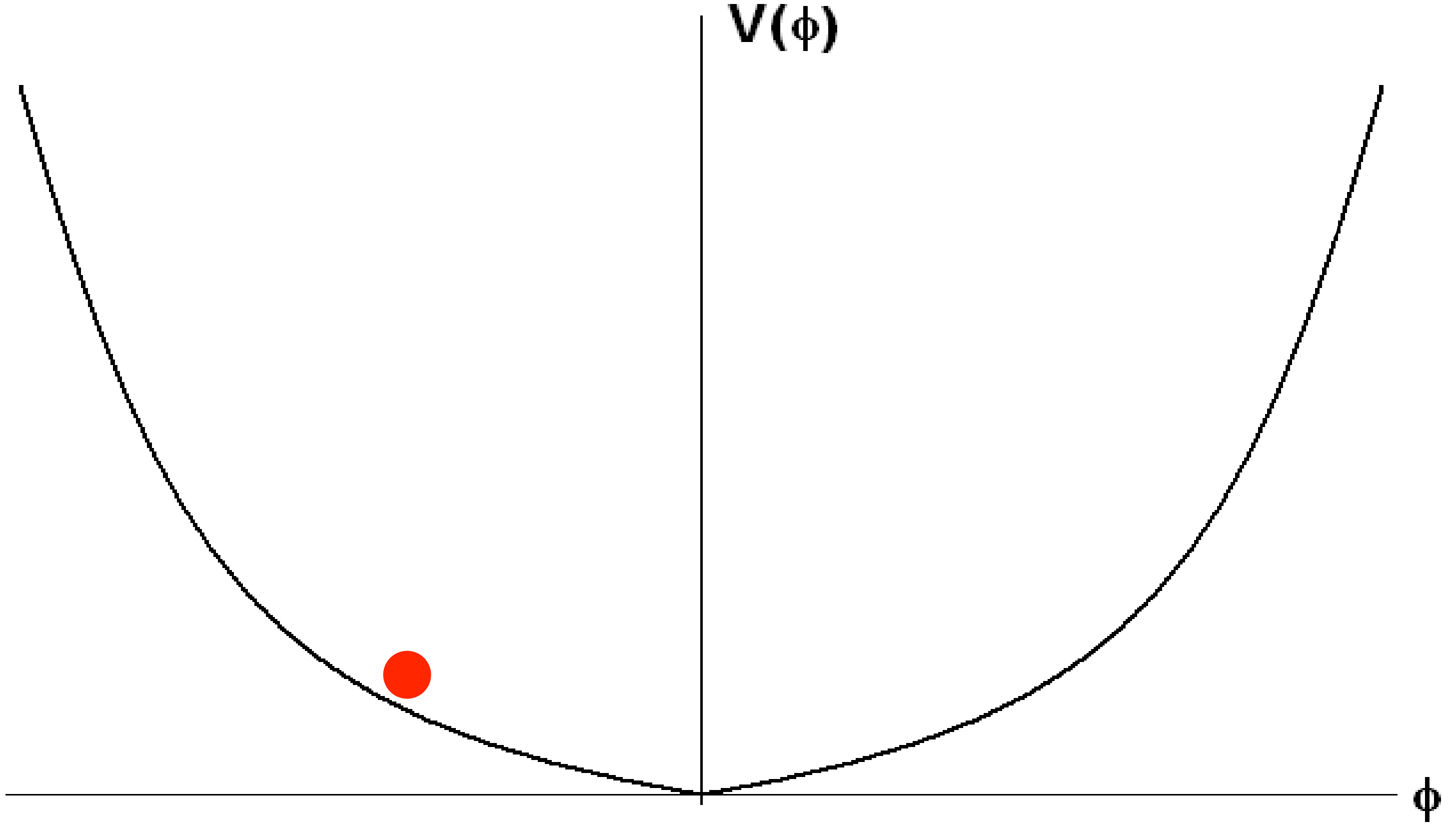

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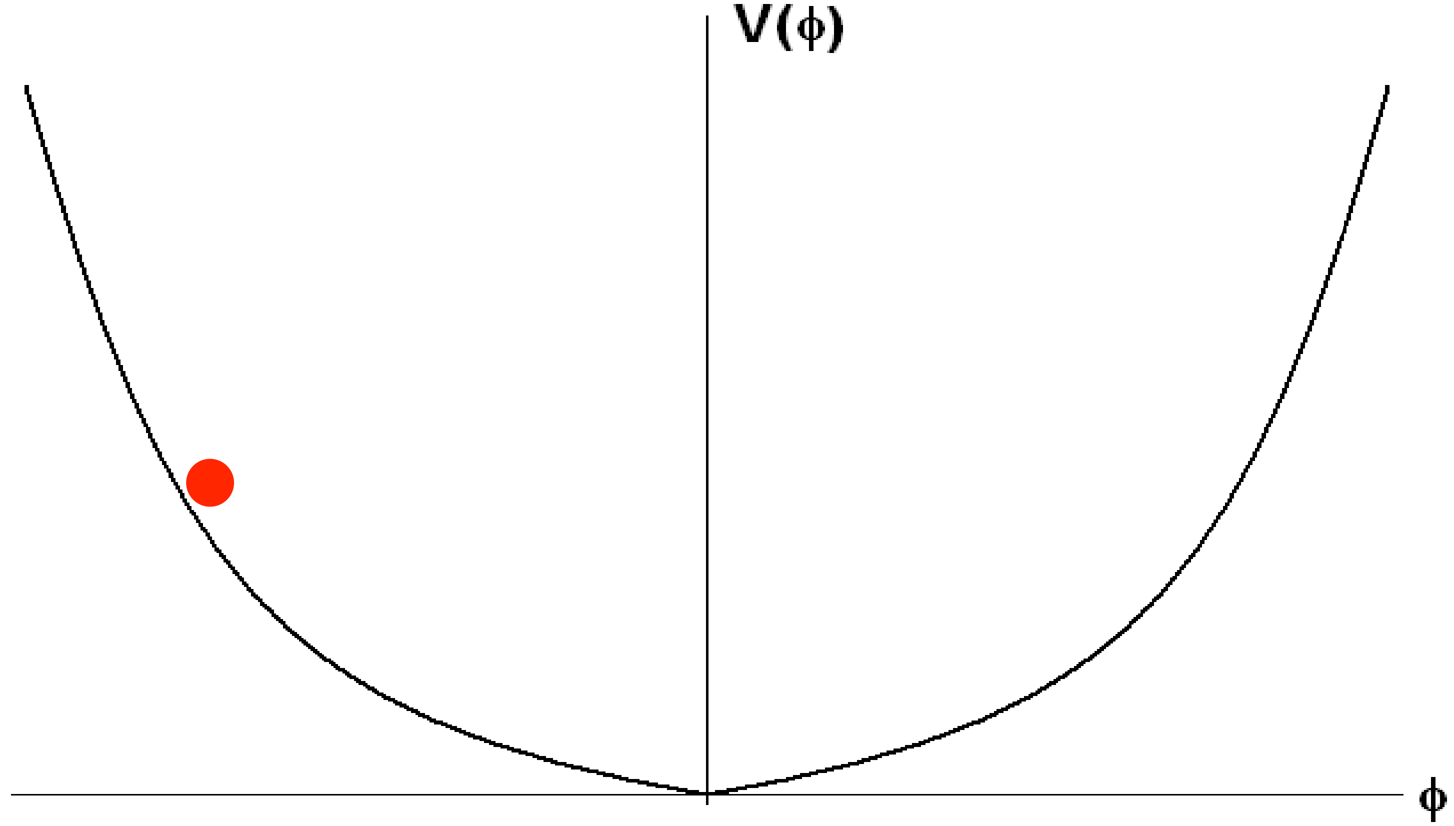

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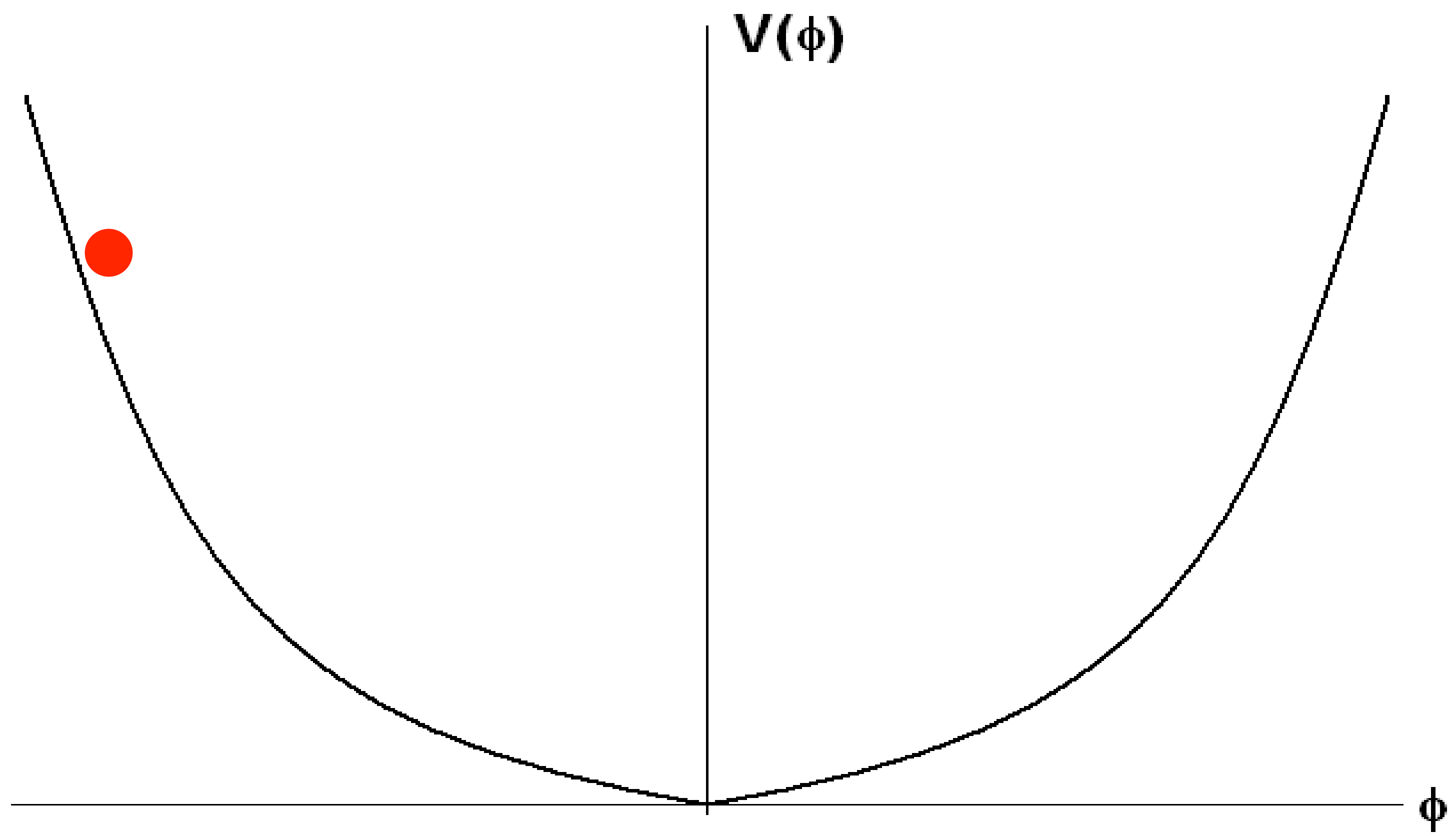

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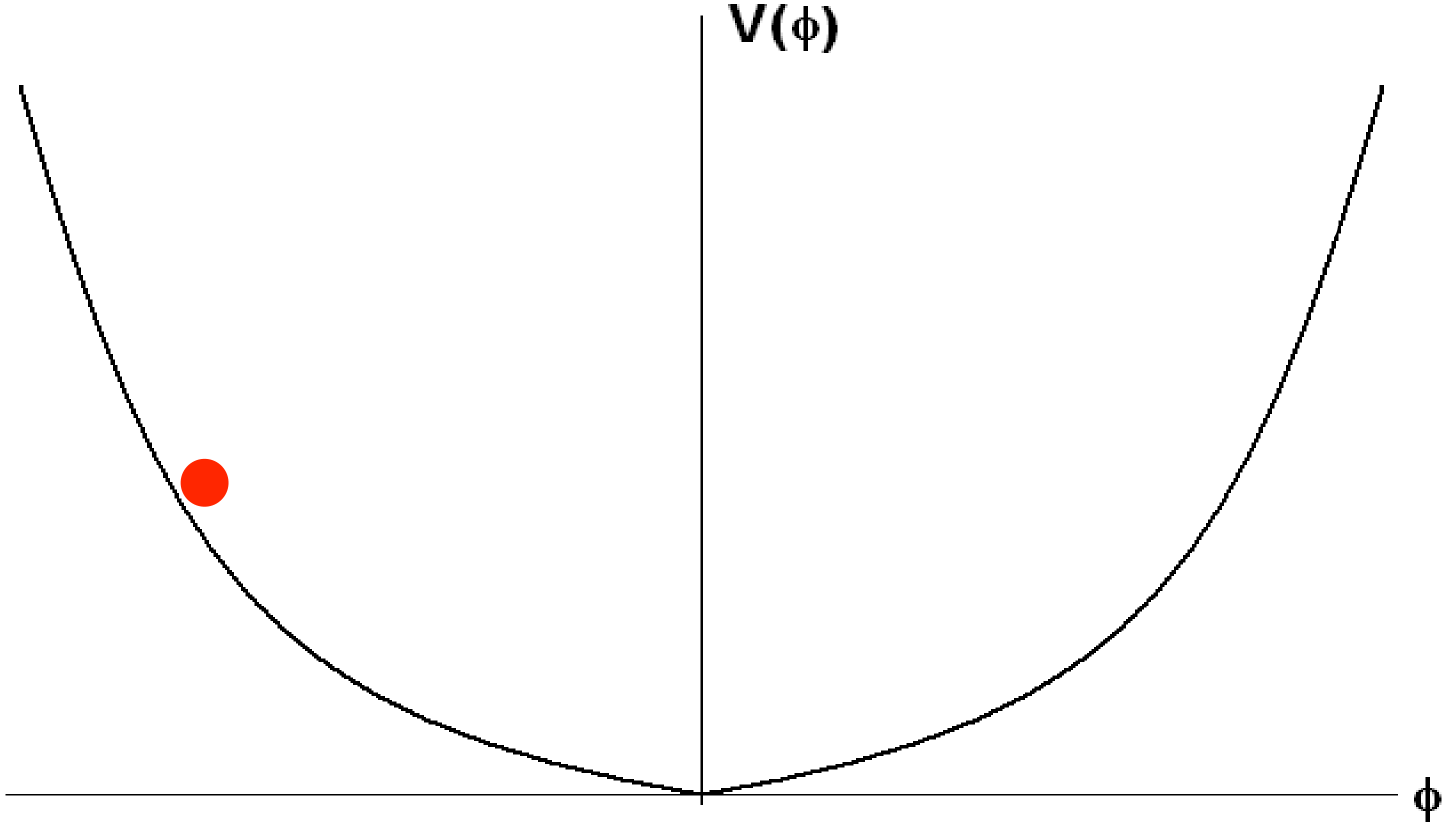

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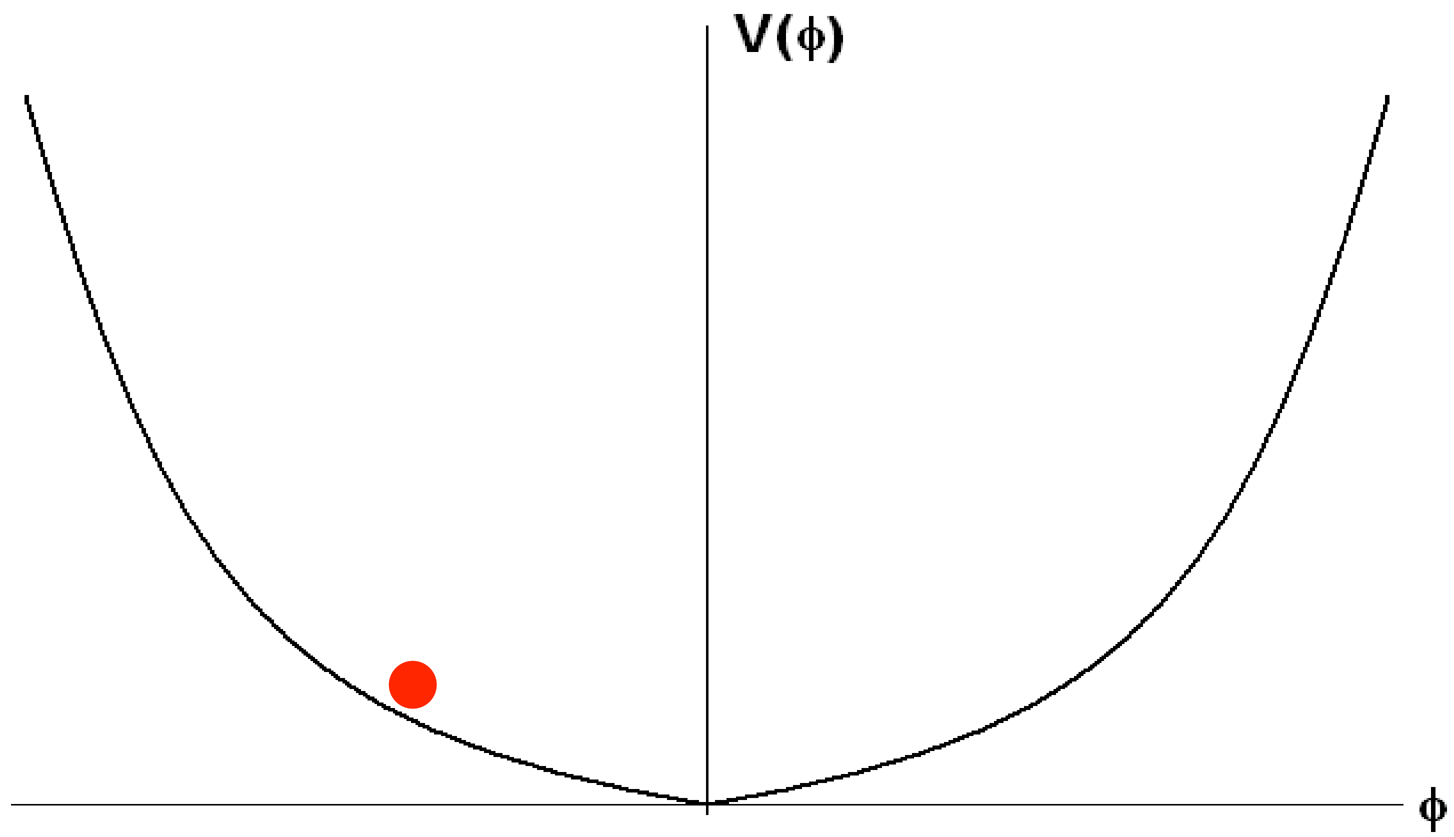

SCALAR (P)REHEATING

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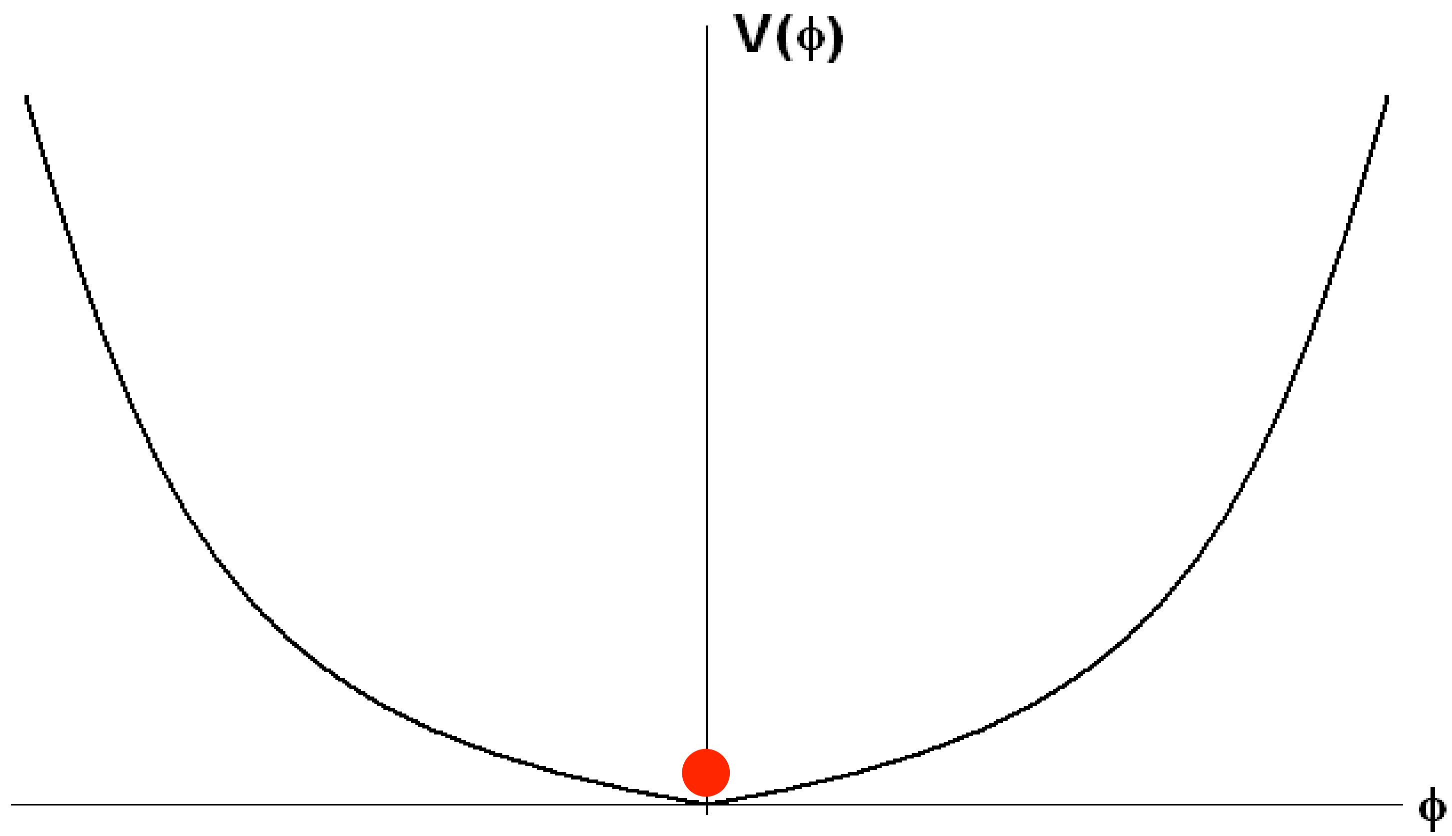

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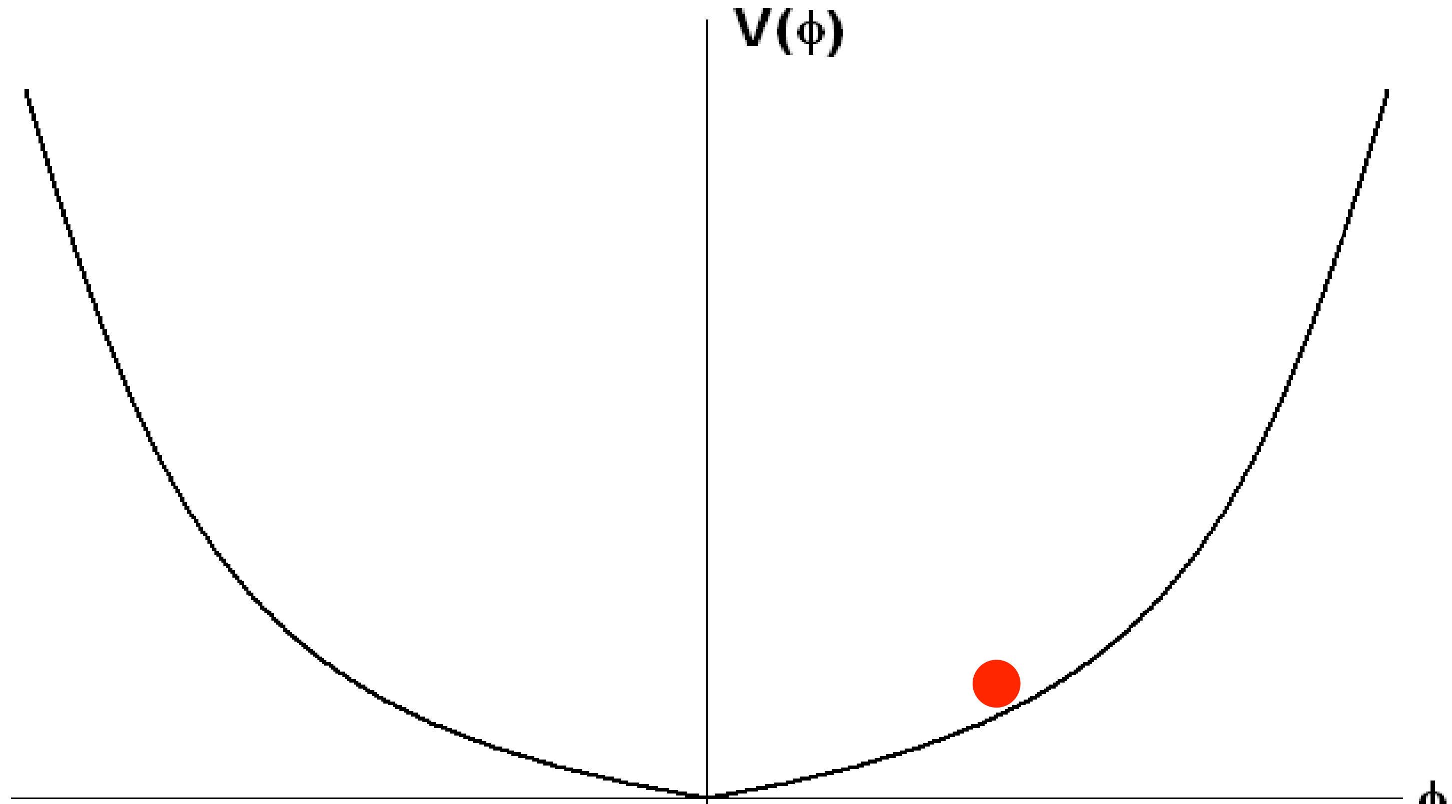

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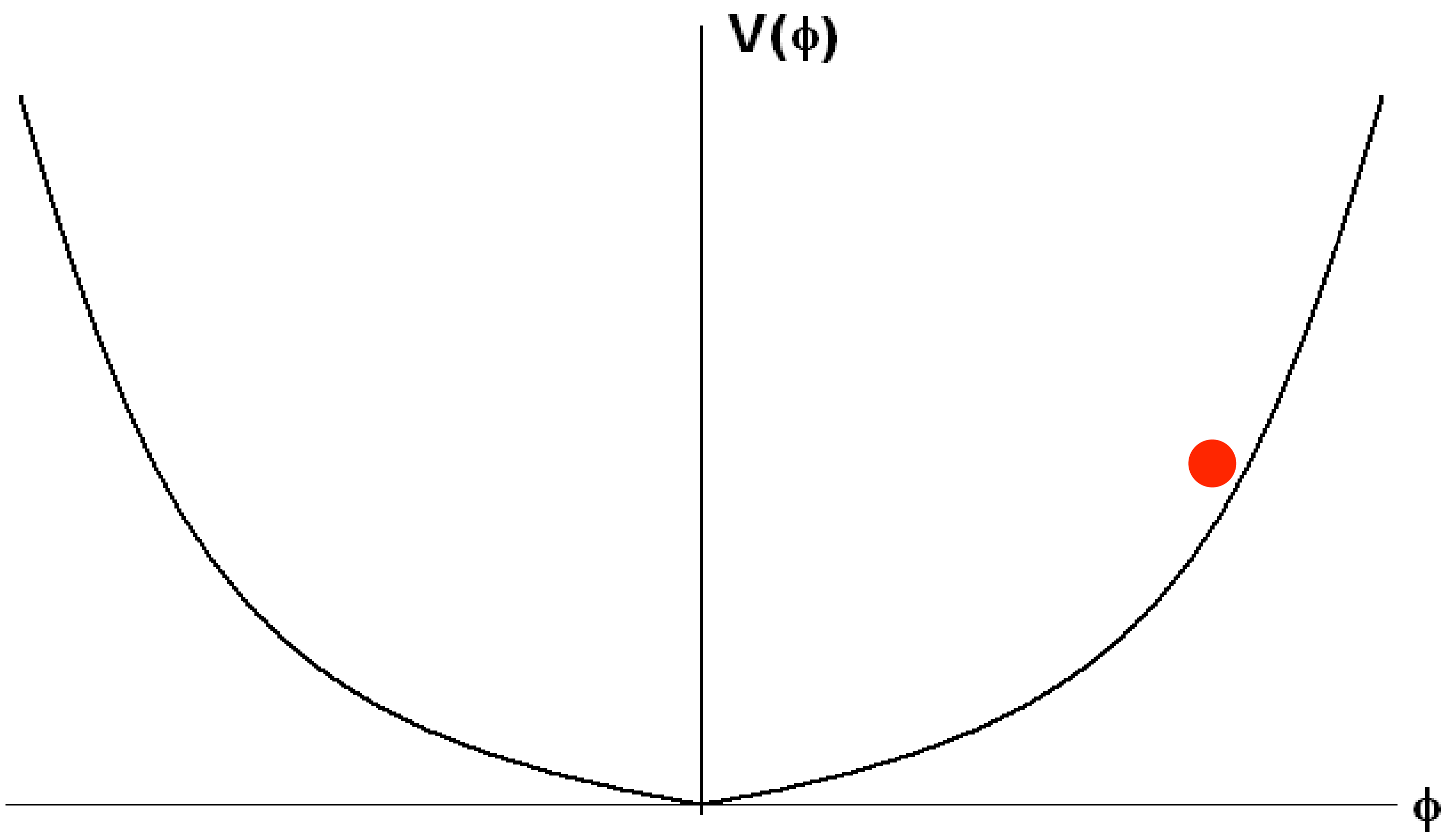

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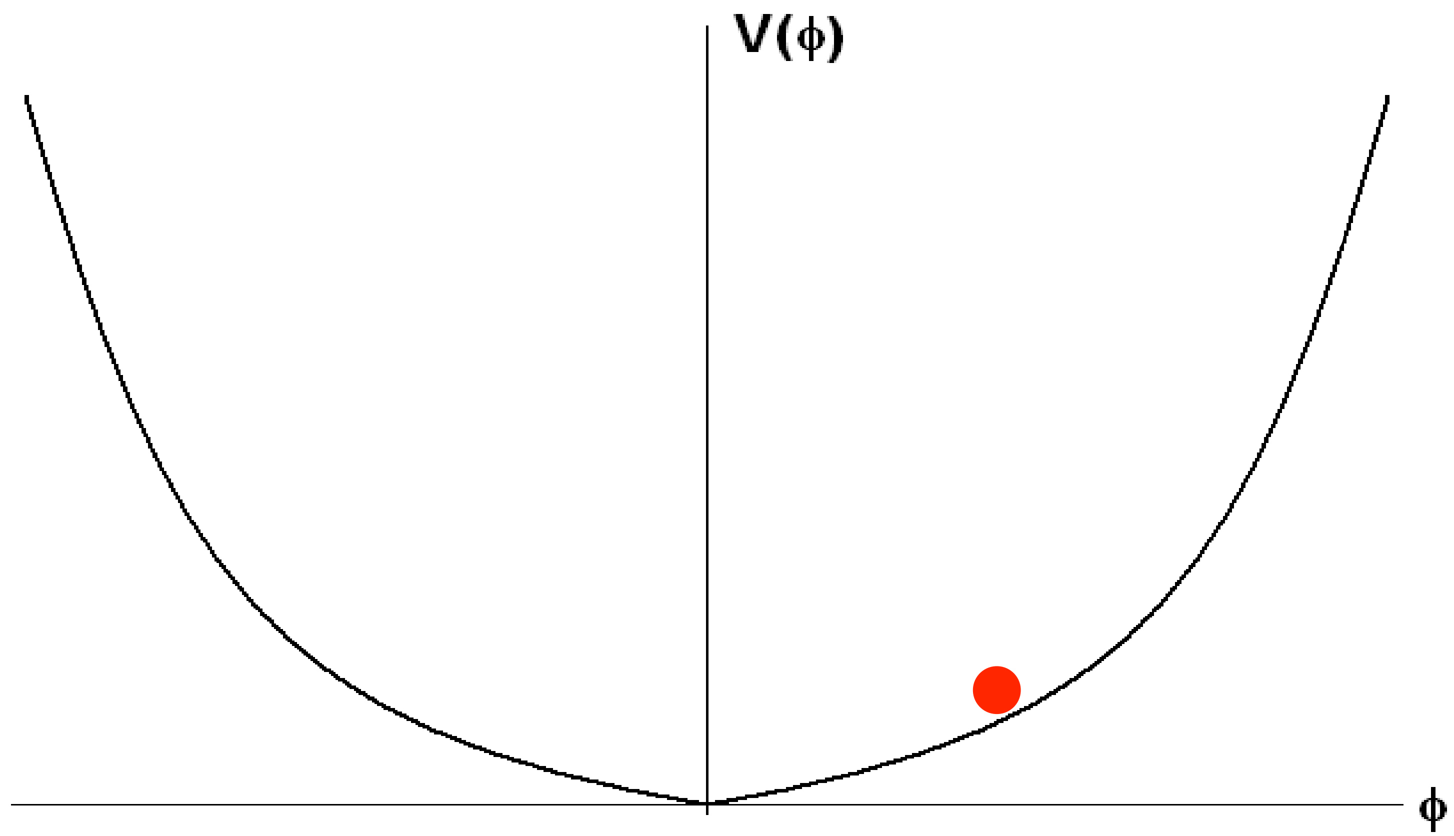

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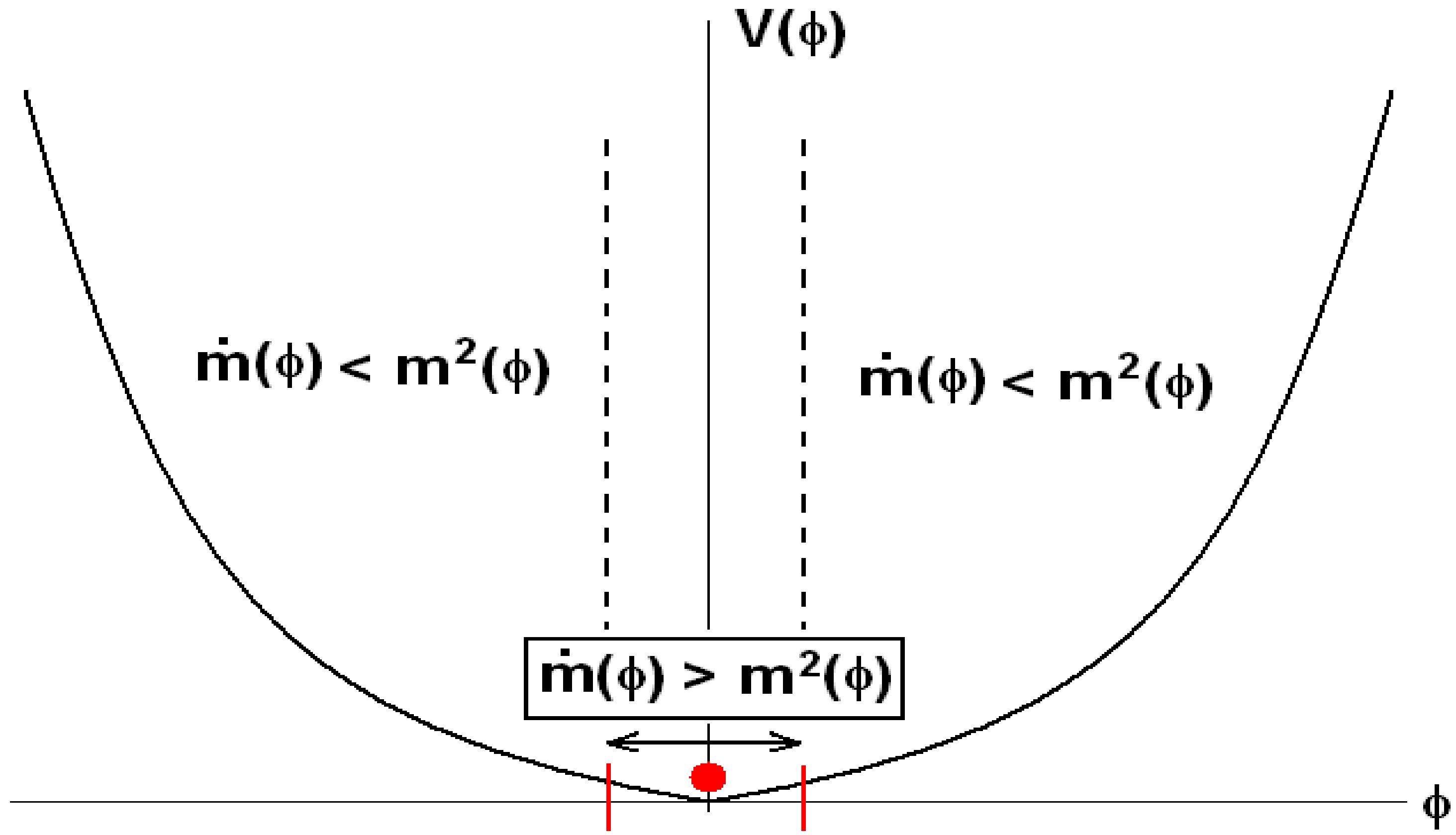

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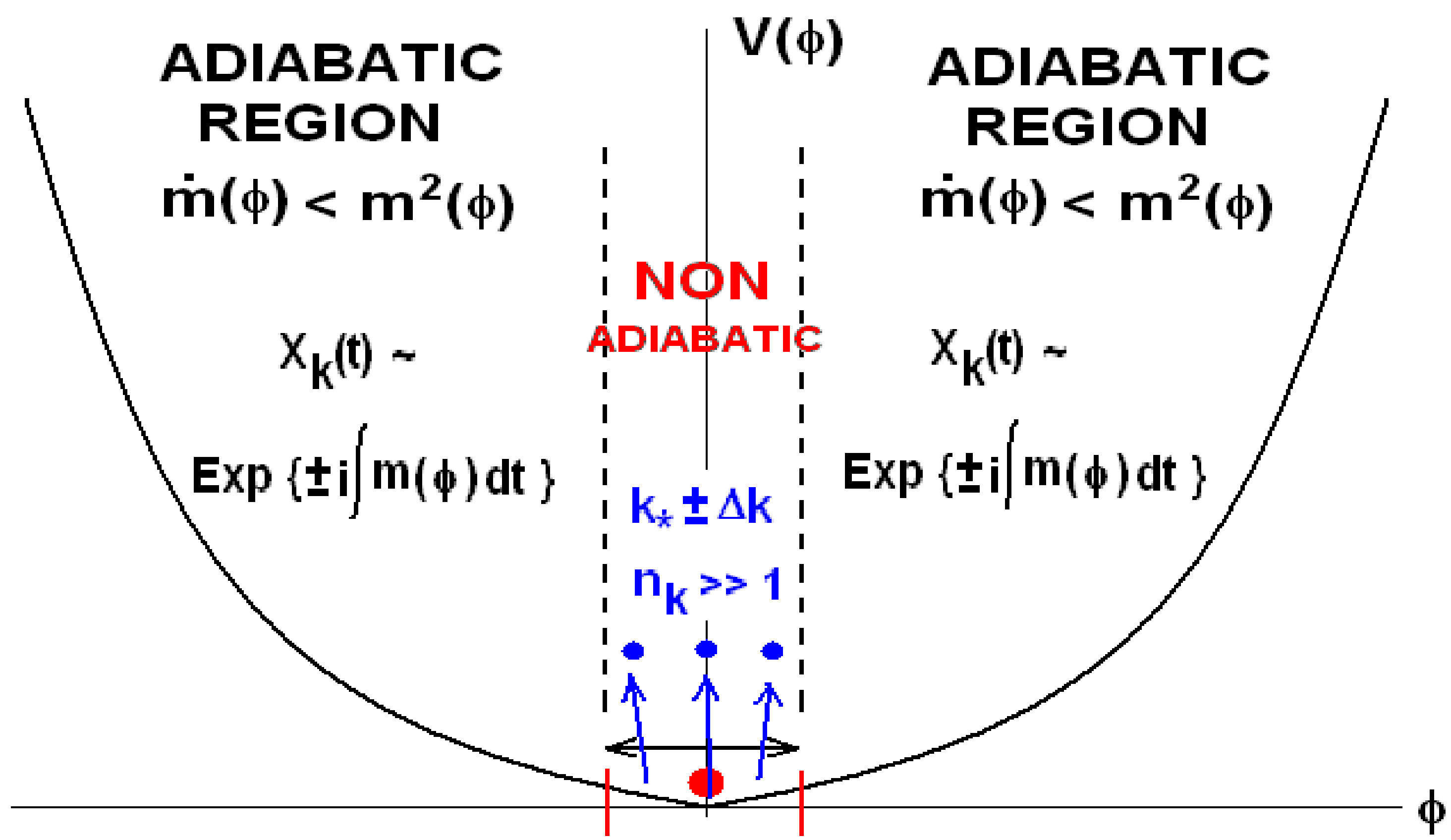

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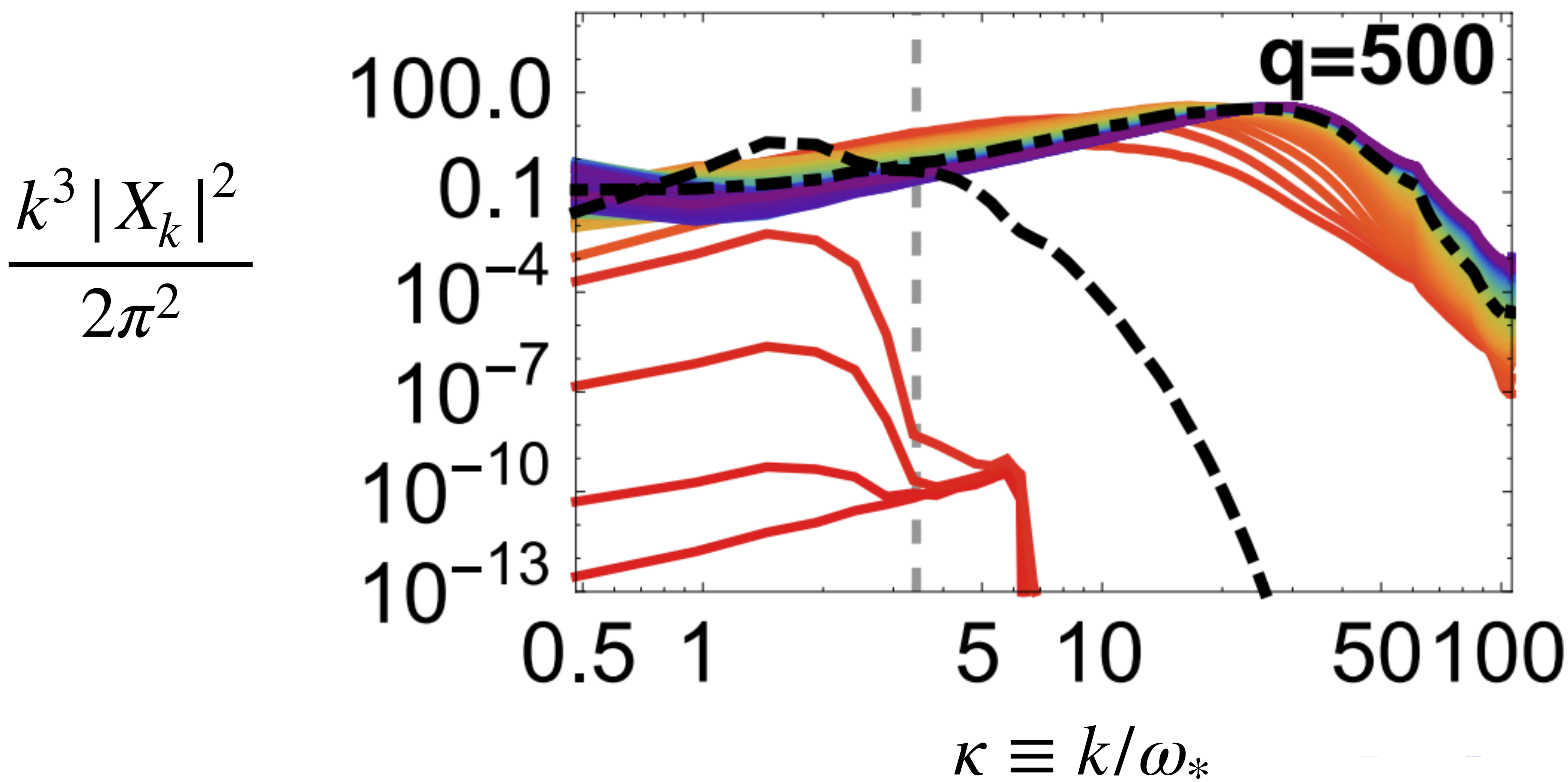
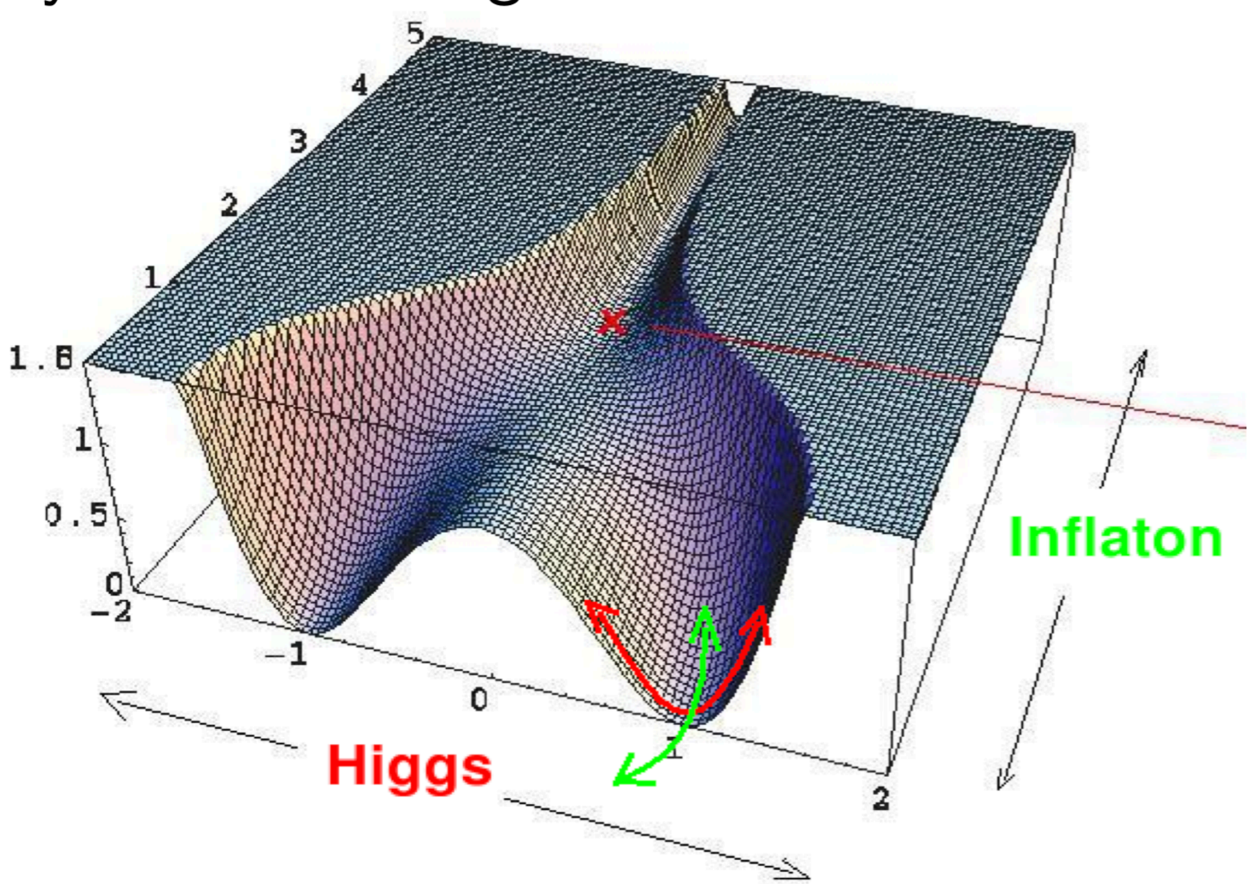


SCALAR (P)REHEATING

2) Hybrid Scenarios : SPINODAL INSTABILITY

$$\left.\begin{aligned}&\ddot{\phi}(t) + (\mu^2 + g^2|\chi|^2)\phi(t) = 0 \\ &\ddot{\chi}_k + \left(k^2 + m^2\left(\frac{\phi^2}{\phi_c^2} - 1\right) + \lambda|\chi|^2\right)\chi_k = 0\end{aligned}\right\}$$

Hybrid Preheating



SCALAR (P)REHEATING

2) Hybrid Scenarios : SPINODAL INSTABILITY

inflaton mass coupling

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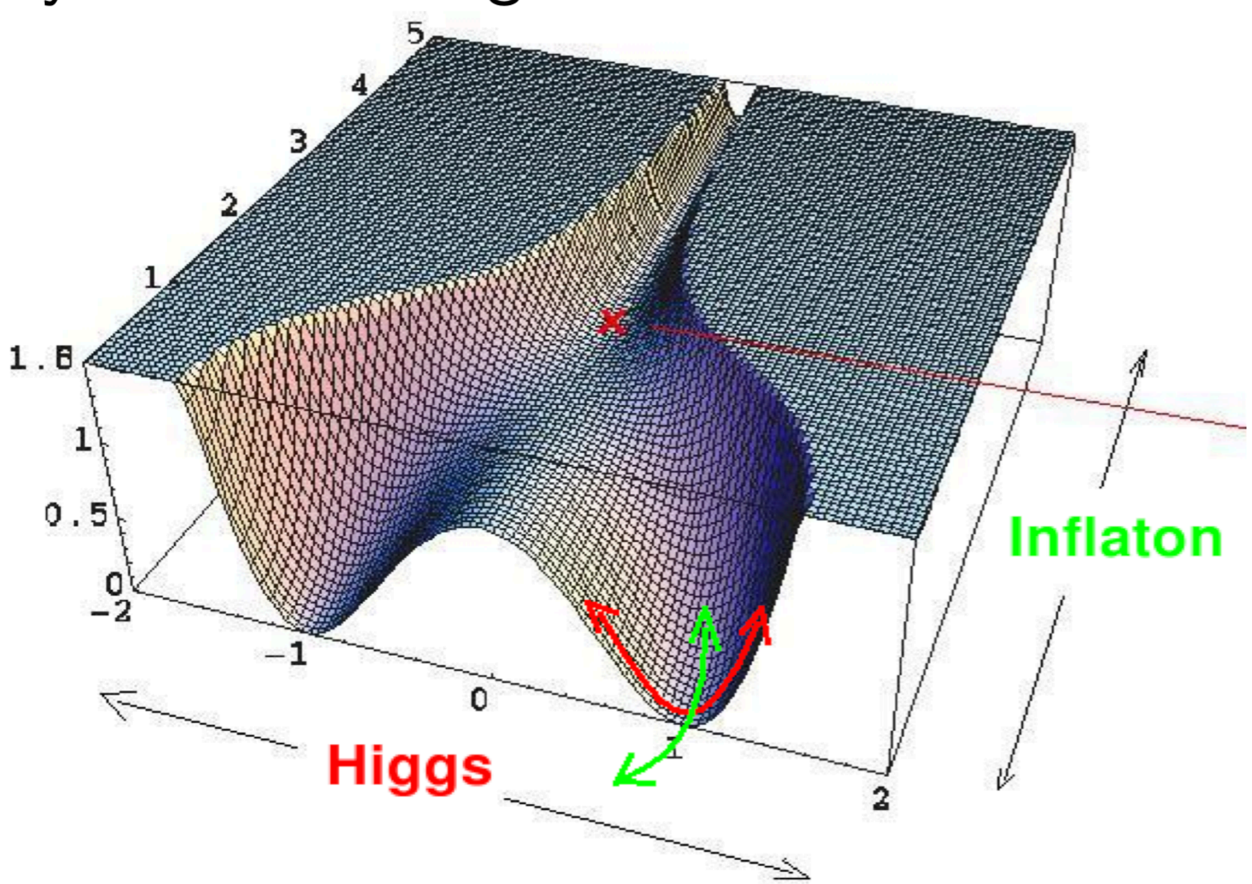
Self-coupling V.E.V.

$$m = \sqrt{\lambda} v$$

$$\phi_c \equiv m/g$$ Critical value

Hybrid Preheating



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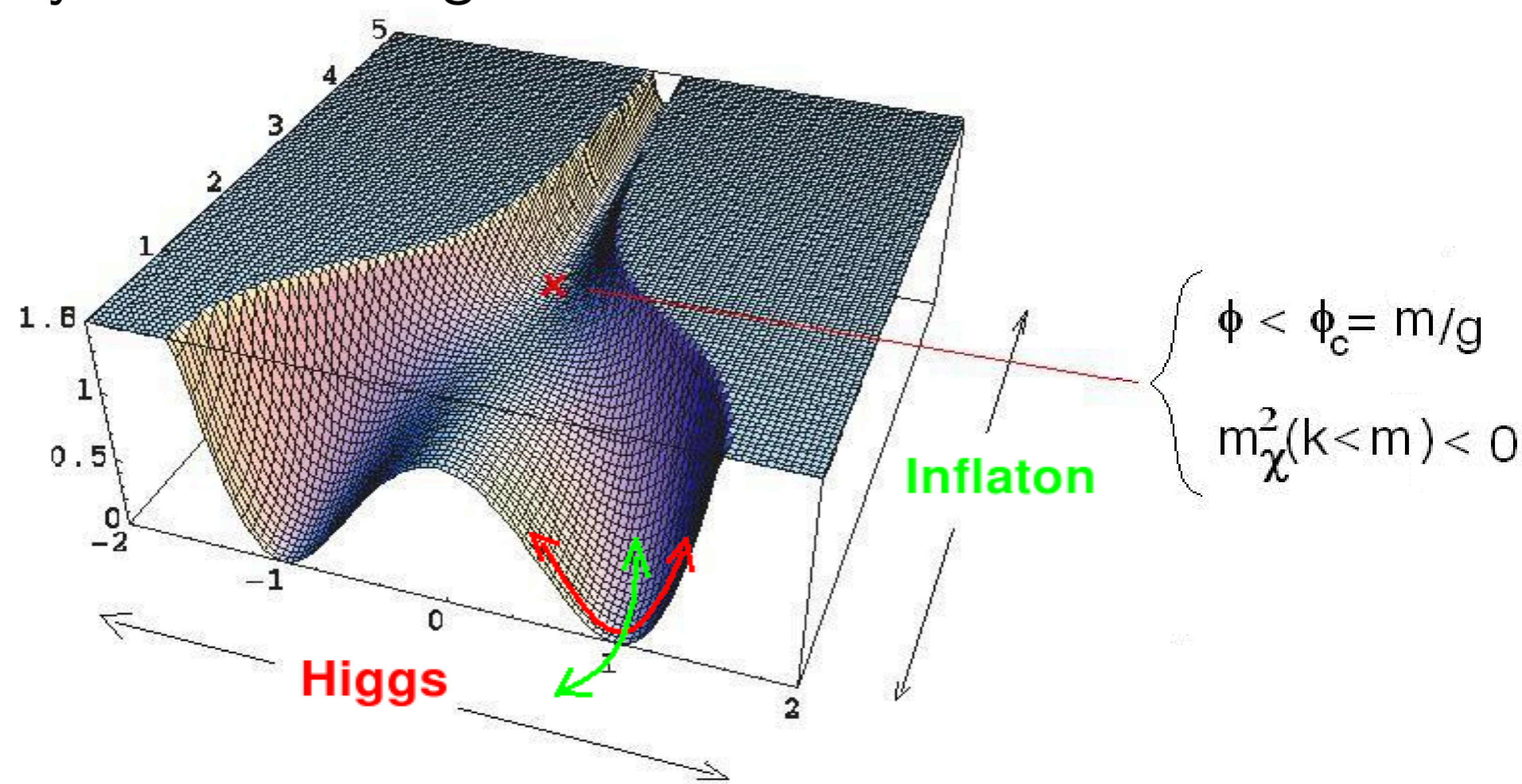

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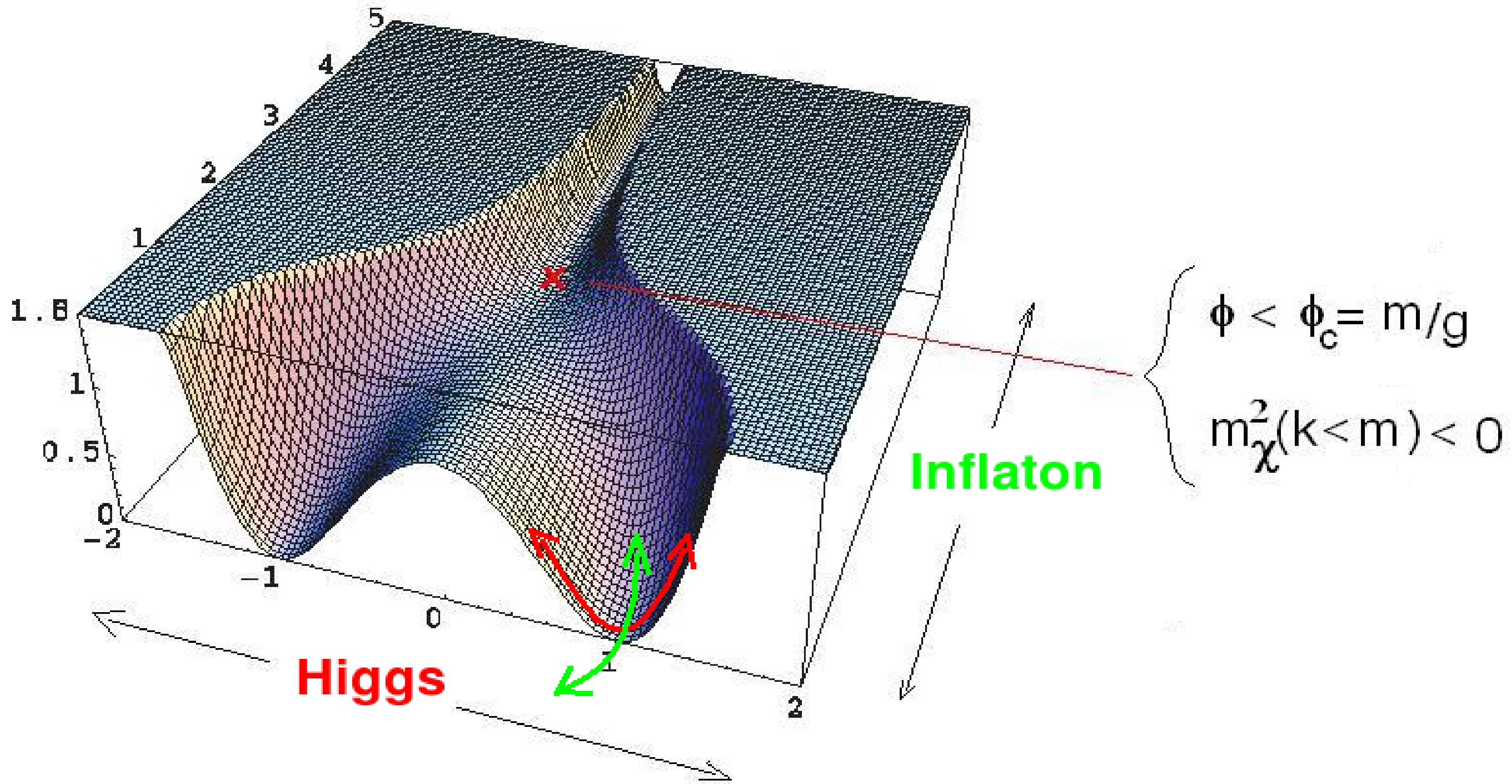

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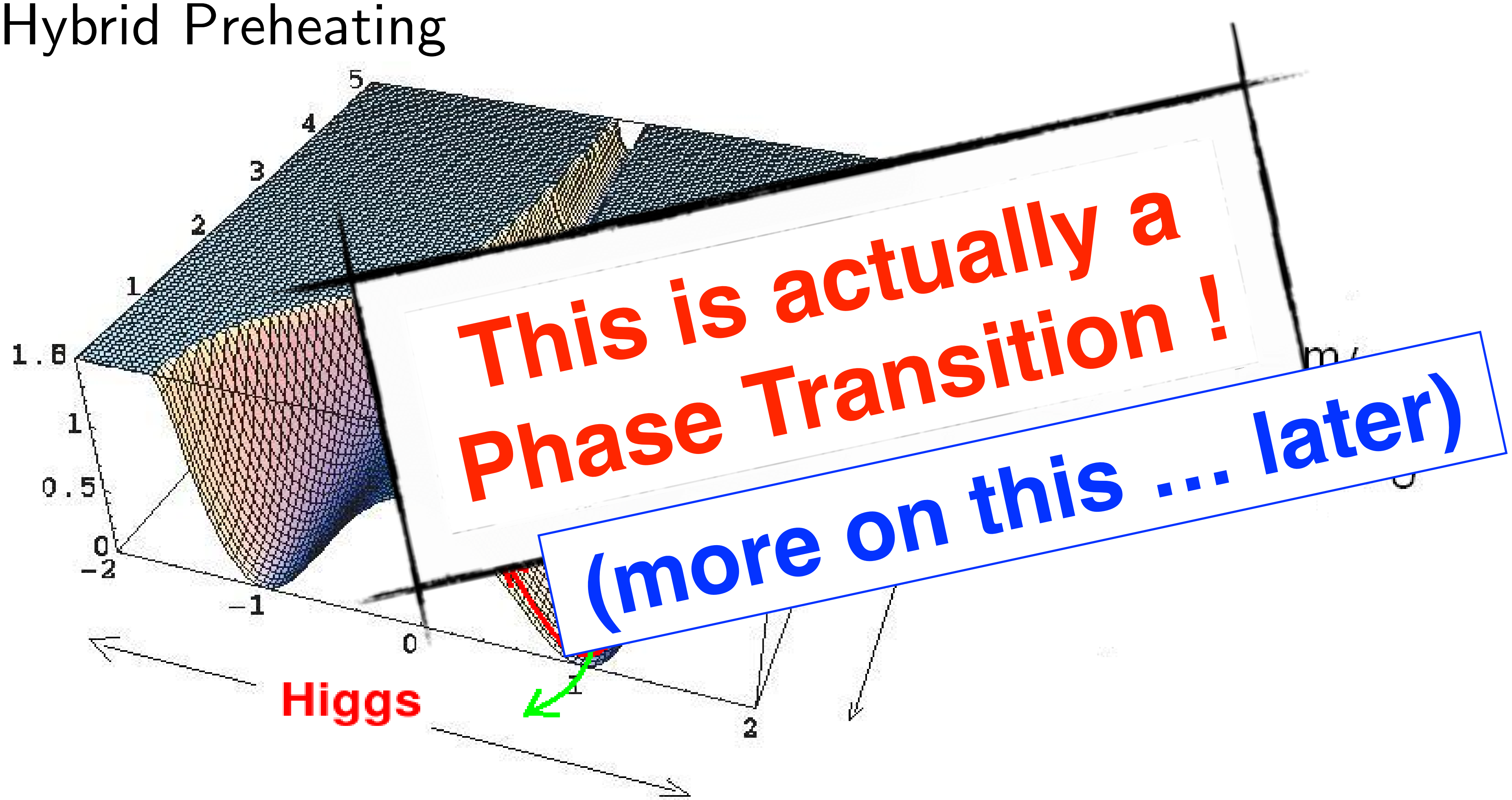

INFLATIONARY PREHEATING

Physics of (p)REHEATING: $\ddot{\varphi}_k + \omega^2(k,t)\varphi_k = 0$

$$\begin{cases} \textbf{Hybrid Preheating}: & \omega^2 = k^2 + m^2(1 - V\,t) < 0 \quad (\text{Tachyonic}) \\ \textbf{Chaotic Preheating}: & \omega^2 = k^2 + \Phi^2(t)\sin^2\mu t \quad (\text{Periodic}) \end{cases}$$

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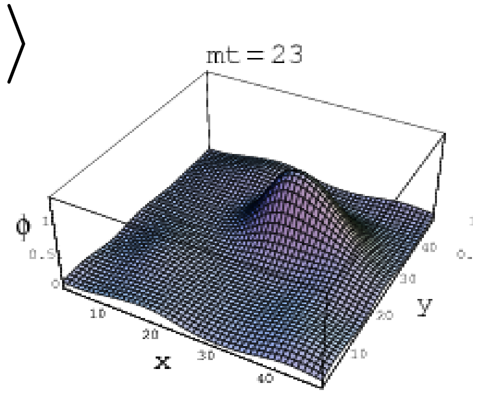

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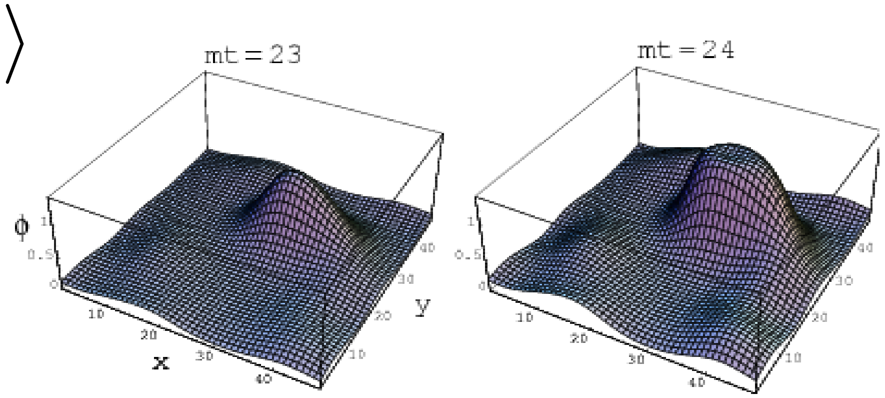

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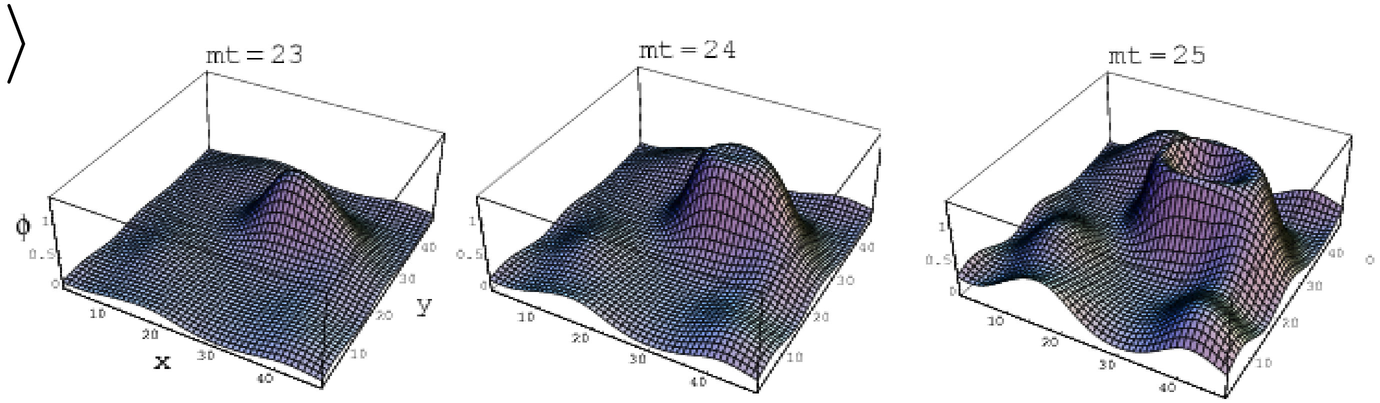

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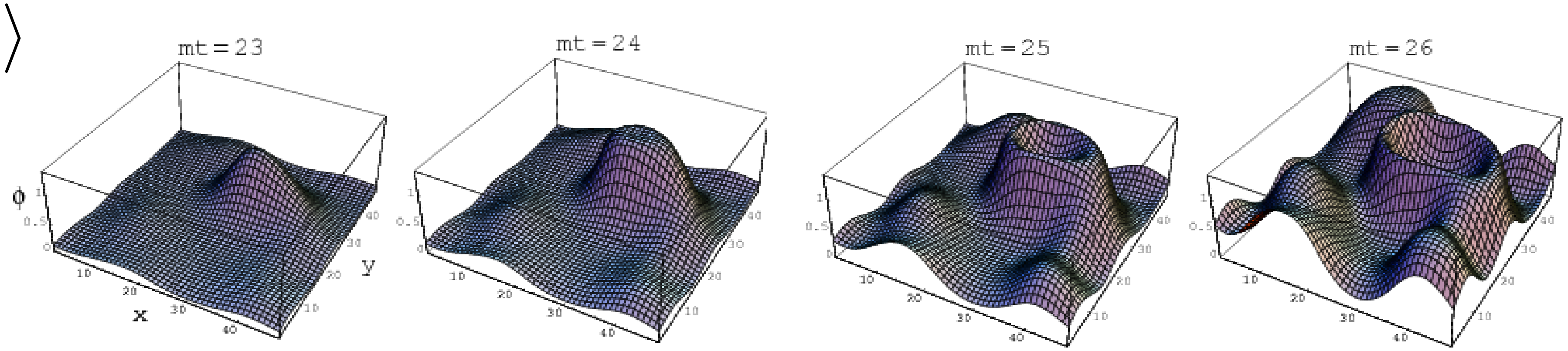

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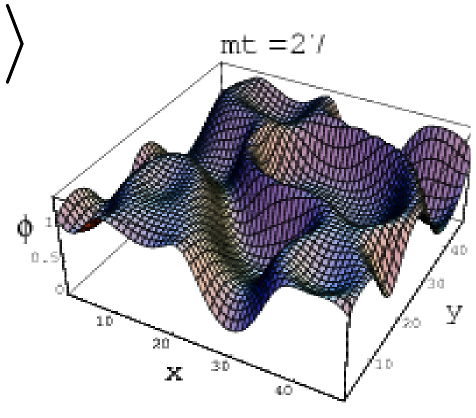

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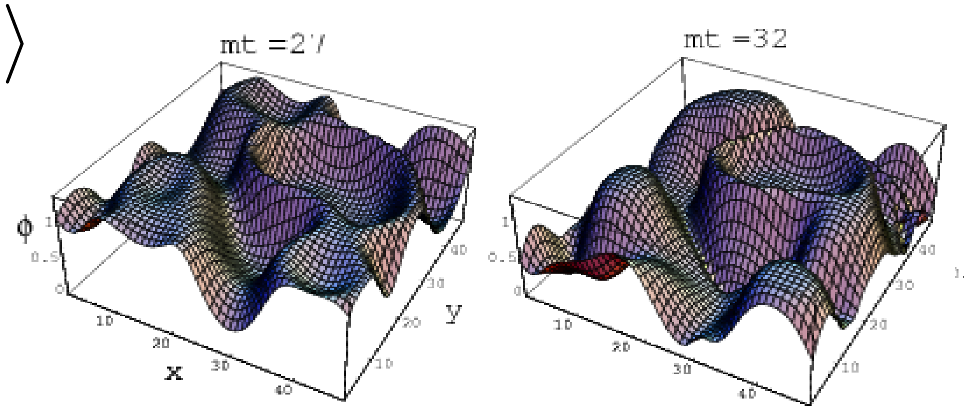

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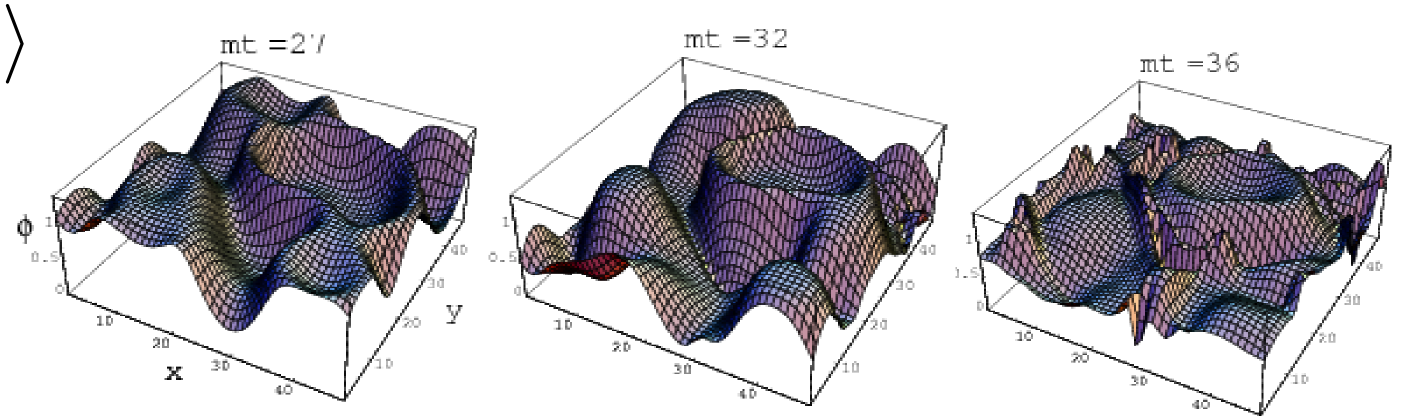

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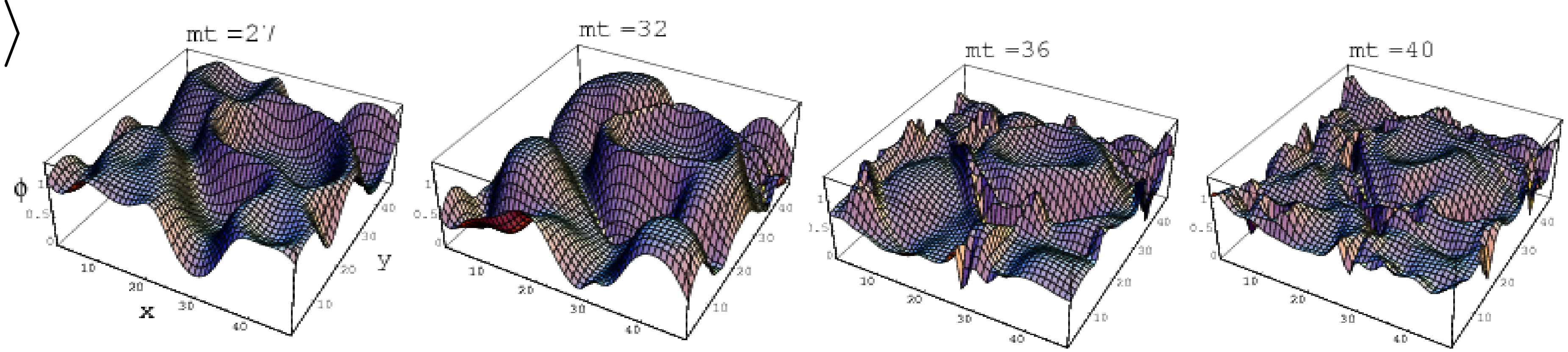

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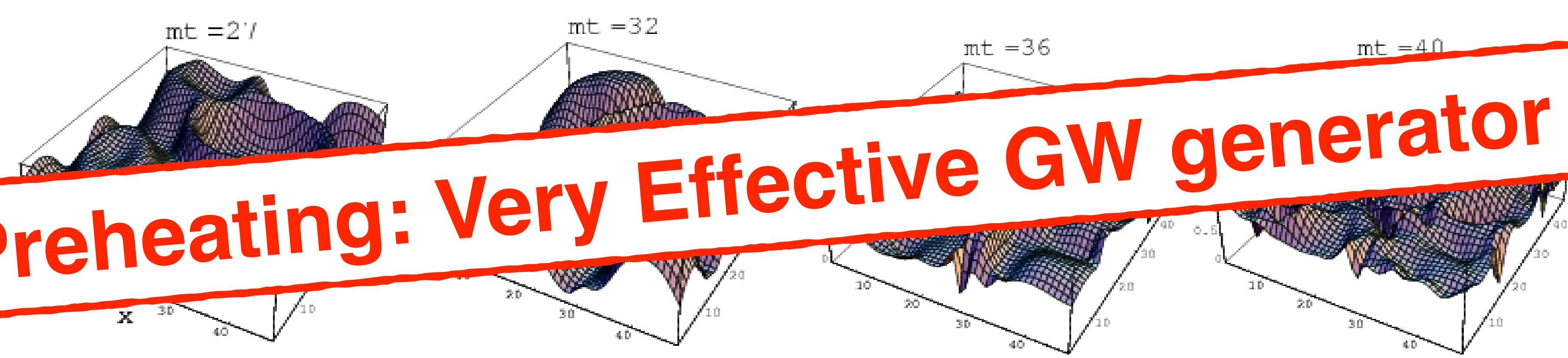

Preheating: Very Effective GW generator !

INFLATIONARY PREHEATING

Lattice Simulations: Dynamics

non-linear

out-Eq

INFLATIONARY PREHEATING

Lattice Simulations: Dynamics → **non-linear** → **out-Eq**

- Scalars $(n_k \gg 1)$: $\qquad \Box\phi + V_{,\phi} = 0,\ \Box\chi_a + V_{,\chi_a} = 0$

Semi-classical regime $\pi_k \approx \kappa\phi_k + ...$ **(Squeezed States)**

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- FLRW: $H^2 = \frac{8\pi G}{3}\rho, \quad \frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p)$, $\left\{ \begin{array}{l} \rho = \langle \rho_\phi + \rho_\chi + ... \rangle \\ p = \langle p_\phi + p_\chi + ... \rangle \end{array} \right.$

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• GW: $h''_{ij} + 2\mathcal{H}h'_{ij} - \nabla^2 h_{ij} = 16\pi G \Pi_{ij}^{\mathrm{TT}}, \qquad \Pi_{ij}^{TT} = \{\partial_i\chi^a\partial_j\chi^a\}^{TT}$

$ds^2 = a^2(-d\tau^2 + (\delta_{ij} + h_{ij})dx^i dx^j), \qquad \mathrm{TT}: \begin{cases} h_{ii} = 0 \\ h_{ij,j} = 0 \end{cases}$

INFLATIONARY PREHEATING

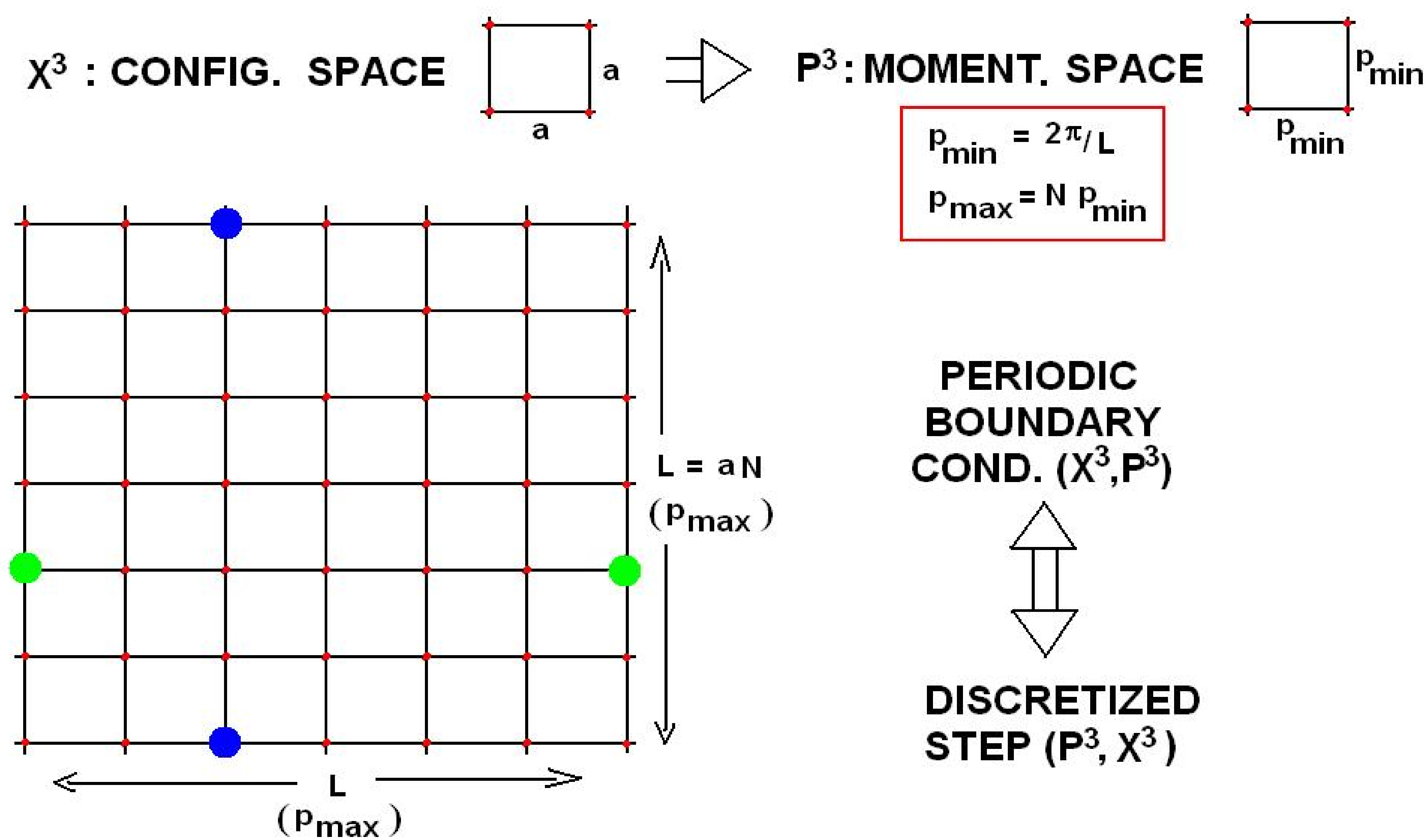
Lattice Simulations: Dynamics

non-linear

out-Eq

$$\partial_\mu O(x) \to (O(x+\mu) - O(x-\mu))/2a_\mu$$

$$\partial_\mu \partial_\mu O(x) \to (O(x+2\mu) + O(x-2\mu) - 2O(x))/4a_\mu^2$$



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$$\Pi_{ij}(\mathbf{k}, t) \equiv \int d^3\mathbf{x} e^{+i\mathbf{k}\mathbf{x}} (\hat{k}) \Pi_{ij}(\mathbf{x}, t) \quad \text{(Fourier Transform)}$$

$$\Pi^{(\rm TT)}_{ij}(\mathbf{k}, t) \equiv \Lambda_{ij,lm}(\hat{k}) \Pi_{ij}(\mathbf{k}, t) \quad \text{(TT-Projection)}$$

$$\Pi^{(\rm TT)}_{ij}(\mathbf{x}, t) \equiv \int \frac{d^3\mathbf{k}}{(2\pi)^3} e^{-i\mathbf{k}\mathbf{x}} \Lambda_{ij,lm}(\hat{k}) \Pi_{lm}(\mathbf{k}, t) \quad \text{(Fourier back)}$$

INFLATIONARY PREHEATING

Lattice Simulations: Dynamics $\rightarrow$ **non-linear**, **out-Eq**

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TT: Non-local operation !

$$\Pi_{ij}(\mathbf{k}, t) \equiv \int d^3\mathbf{x} e^{+i\mathbf{kx}} \ldots$$ (Fourier Transform)

Numerically Prohibited !

(TT-Projection)

$$\Pi^{(T\ldots}_{ij}(\mathbf{x}, t) \equiv \int \frac{d^3\mathbf{k}}{(2\pi)^3} e^{-i\mathbf{kx}} \Lambda_{ij,lm}(\hat{k})\Pi_{lm}(\mathbf{k}, t)$$ (Fourier back)

INFLATIONARY PREHEATING

Lattice Simulations: Dynamics → **non-linear** → **out-Eq**

Building the Solution:

$$\begin{cases} h_{ij}(\mathbf{k},t) = \Lambda_{ij,lm}(\hat{\mathbf{k}})u_{lm}(\mathbf{k},t) \\ \\ u_{lm}(\mathbf{k},t) = \int_{t_0}^{t} dt' G(t-t')\Pi^{\text{eff}}_{lm}(\mathbf{k},t') \end{cases}$$

INFLATIONARY PREHEATING

Lattice Simulations: Dynamics → **non-linear** → **out-Eq**

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1) Non-Physical eq.:

$$\ddot{u}_{ij}(\mathbf{x},t) + 3H\dot{u}_{ij}(\mathbf{x},t) - \tfrac{\nabla^2}{a^2}u_{ij}(\mathbf{x},t) = \frac{2}{m_p^2}\left\{\phi^a{}_{,i}\,\phi^a{}_{,j}\right\}(\mathbf{x},t)$$

INFLATIONARY PREHEATING

Lattice Simulations: Dynamics → non-linear → out-Eq

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INFLATIONARY PREHEATING

Lattice Simulations: Dynamics $\to$ **non-linear**, $\to$ **out-Eq**

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INFLATIONARY PREHEATING

Lattice Simulations: Dynamics

$\rightarrow$ **non-linear**

$\rightarrow$ **out-Eq**

Building the Solution:
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$\boxed{\text{Only when needed !}}$

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INFLATIONARY PREHEATING

Lattice Simulations: Dynamics $\rightarrow$ **non-linear** $\rightarrow$ **out-Eq**

Outputs: $\rho_{GW} = \frac{1}{32\pi G}\frac{1}{L^3}\int d^3\mathbf{x}\,\dot{h}_{ij}\dot{h}_{ij} = \frac{1}{32\pi G}\frac{1}{L^3}\int d^3\mathbf{k}|\dot{h}_{ij}(t,\mathbf{k})|^2$

INFLATIONARY PREHEATING

Lattice Simulations: Dynamics → non-linear, out-Eq

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INFLATIONARY PREHEATING

Lattice Simulations: Dynamics → non-linear, out-Eq

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DGF 2007

INFLATIONARY PREHEATING

Lattice Simulations: Dynamics → non-linear, out-Eq

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3) Snapshots: $h_{ij}(t,\mathbf{x}) = (2\pi)^{-3/2}\int d^3k e^{-i\mathbf{k}\mathbf{x}}\Lambda_{ij,lm}(\hat{\mathbf{k}})u_{lm}(t,\mathbf{k})$

DGF 2007

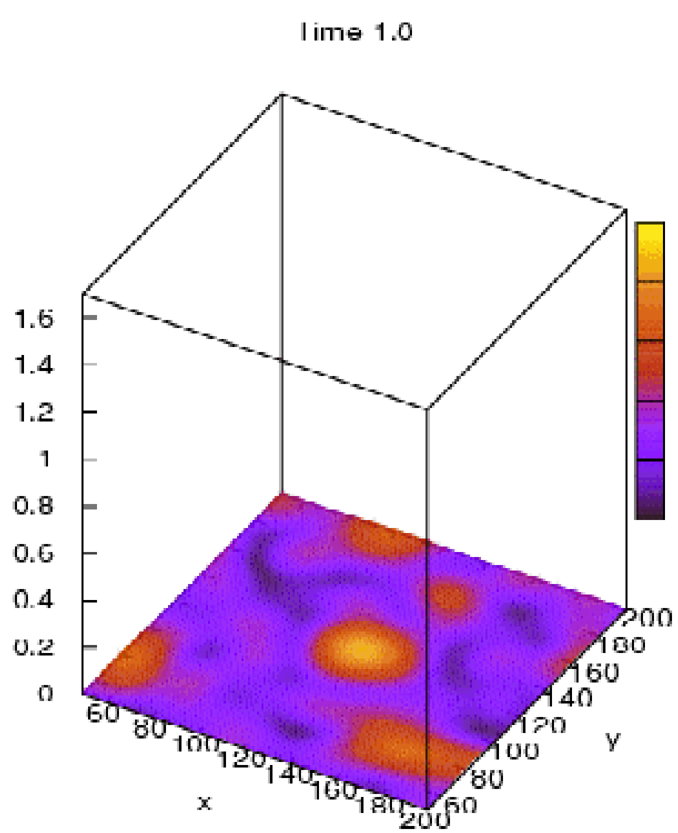
INFLATIONARY PREHEATING

Lattice Simulations: Dynamics → **non-linear**, **out-Eq**

Hybrid Preheating

$$V(\phi,\chi) = \frac{\lambda}{4}(|\chi|^2 - v^2)^2 + \frac{1}{2}|\chi|^2\phi^2 + V(\phi)$$

Animation by
Alfonso Sastre



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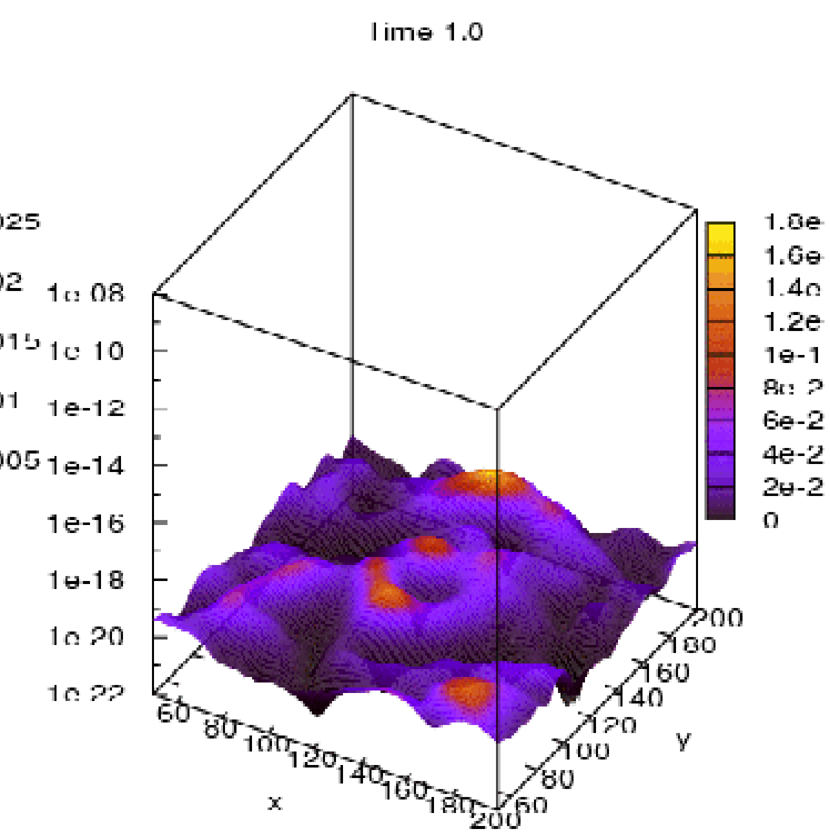

GW **(Energy density)**

INFLATIONARY PREHEATING

Lattice Simulations: Dynamics → **non-linear**, **out-Eq**

Hybrid Preheating

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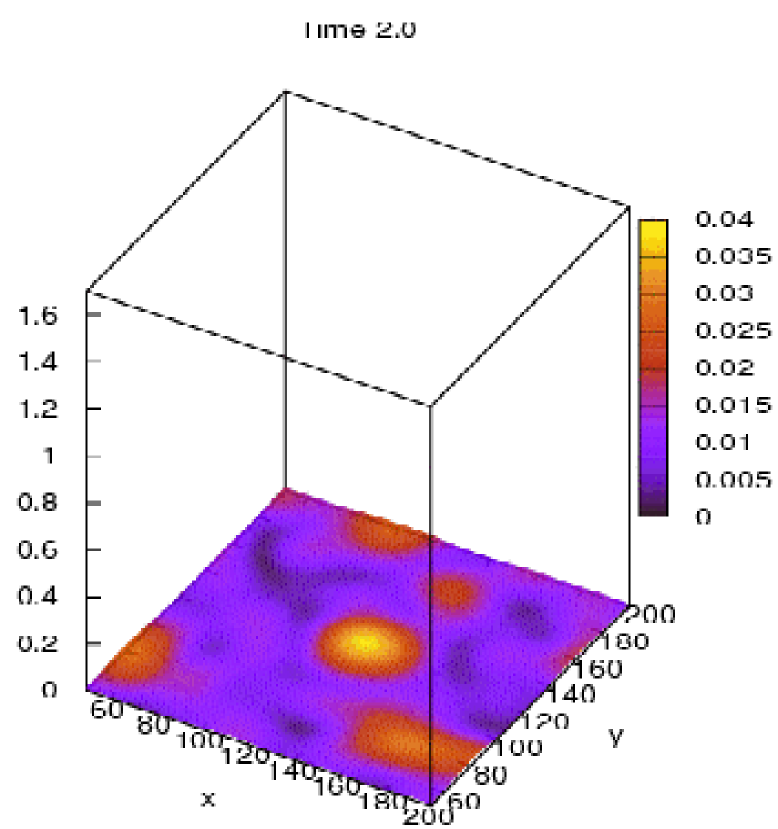

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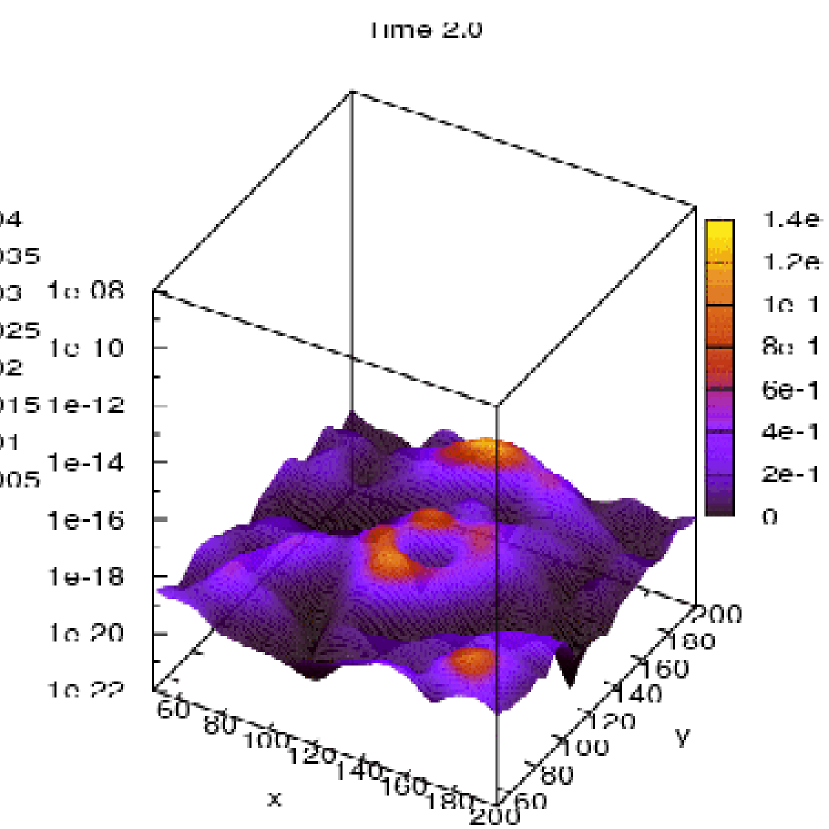

GW **(Energy density)**

INFLATIONARY PREHEATING

Lattice Simulations: Dynamics → **non-linear**, **out-Eq**

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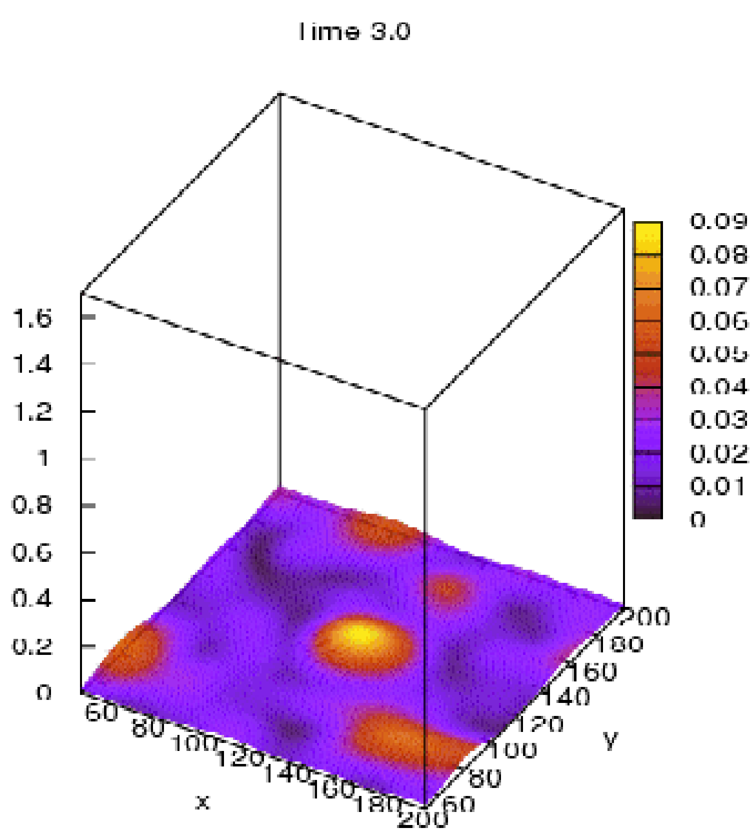

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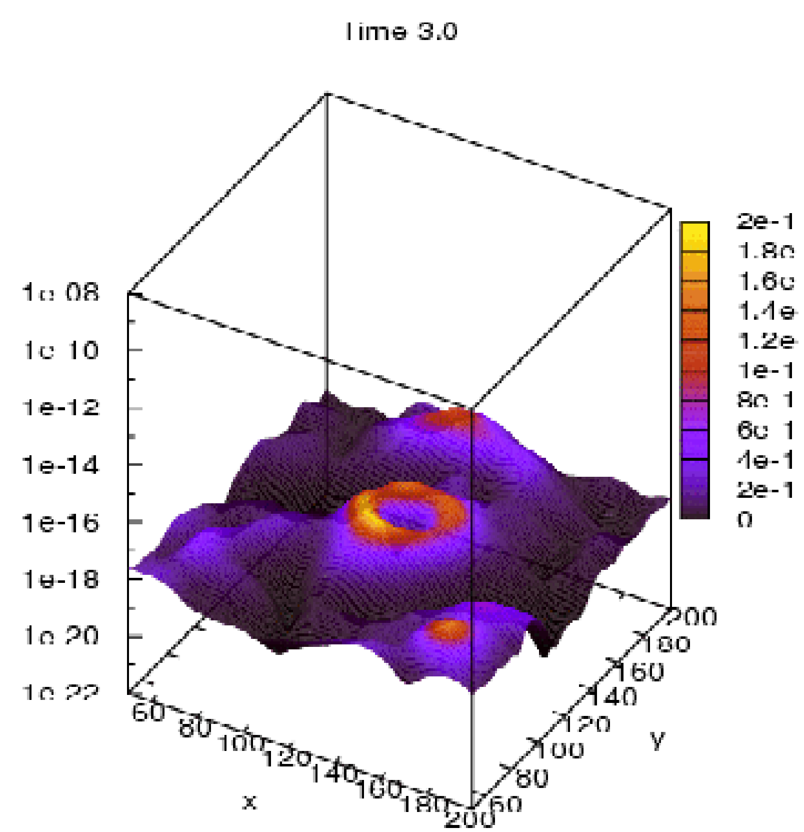

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INFLATIONARY PREHEATING

Lattice Simulations: Dynamics → **non-linear**, **out-Eq**

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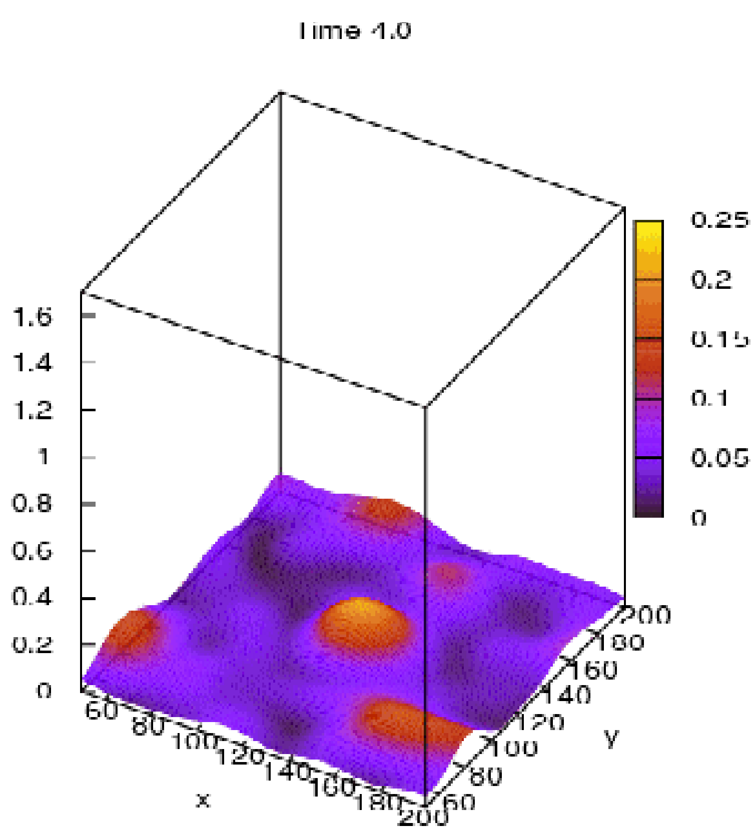

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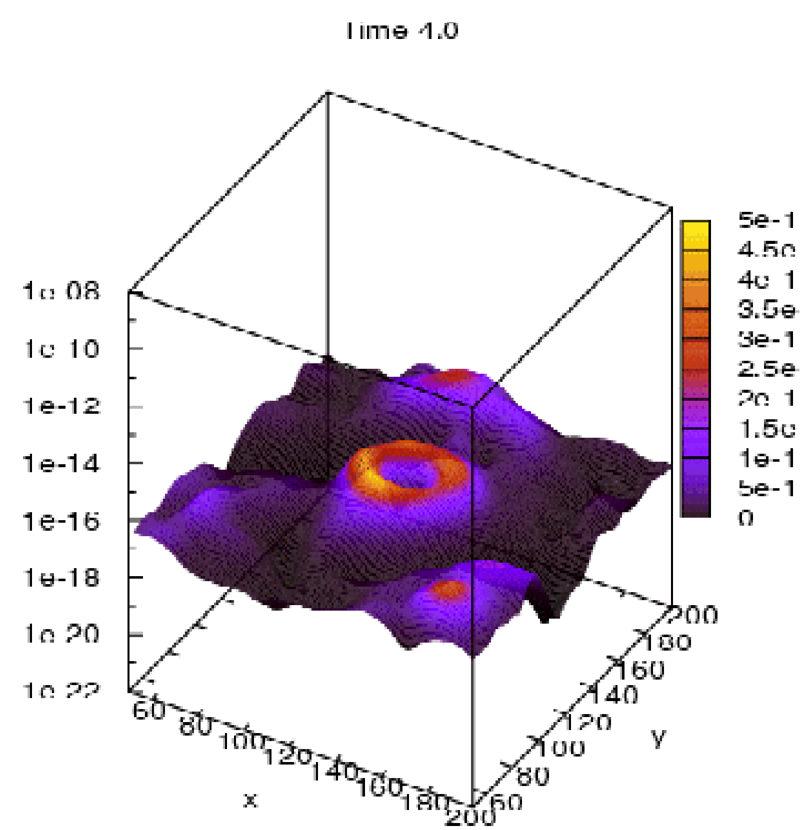

GW **(Energy density)**

INFLATIONARY PREHEATING

Lattice Simulations: Dynamics → **non-linear** / **out-Eq**

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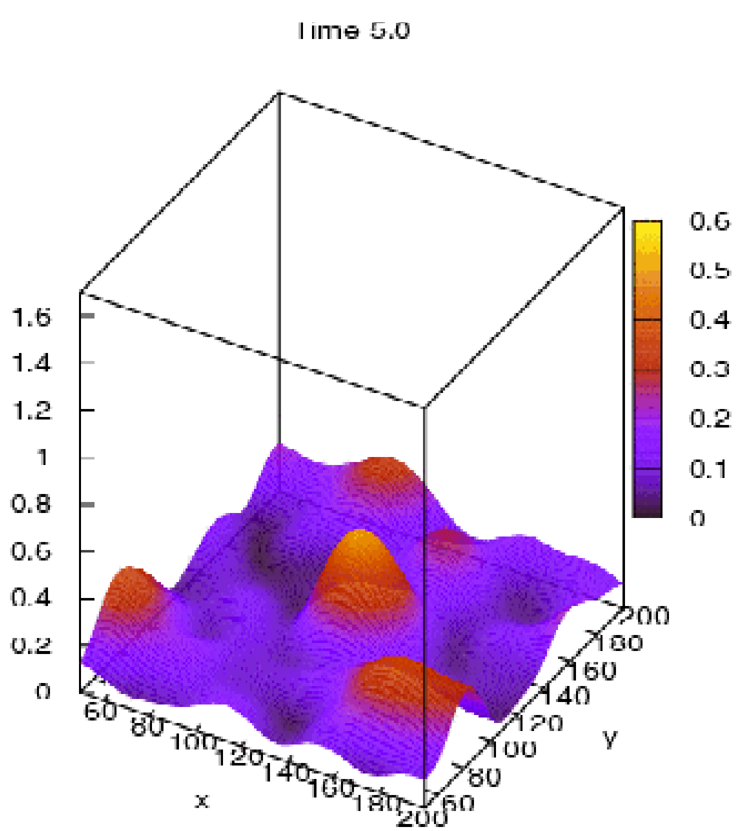

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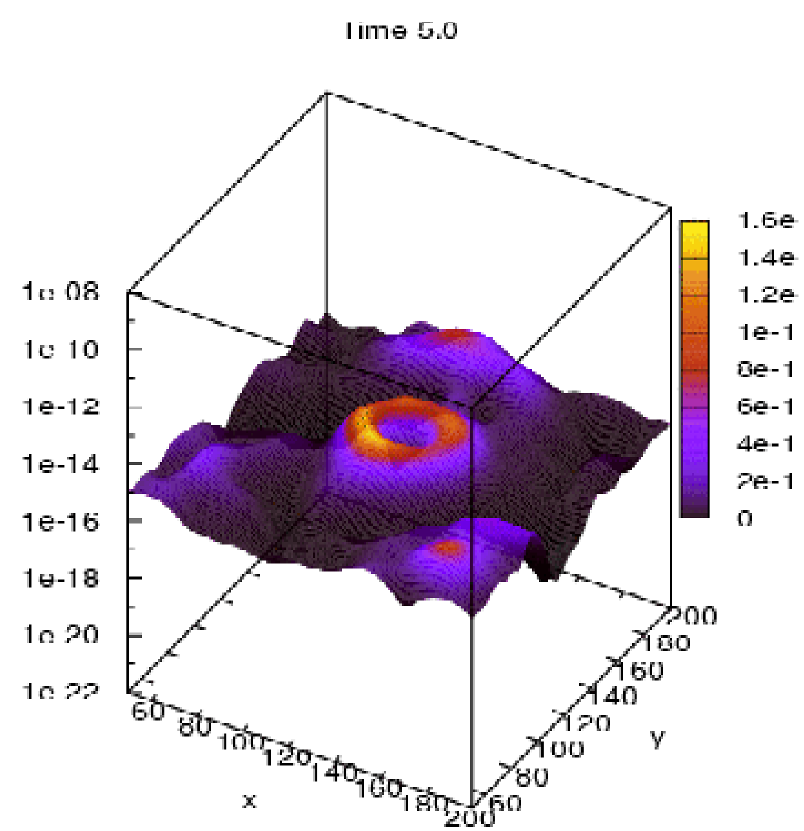

GW **(Energy density)**

INFLATIONARY PREHEATING

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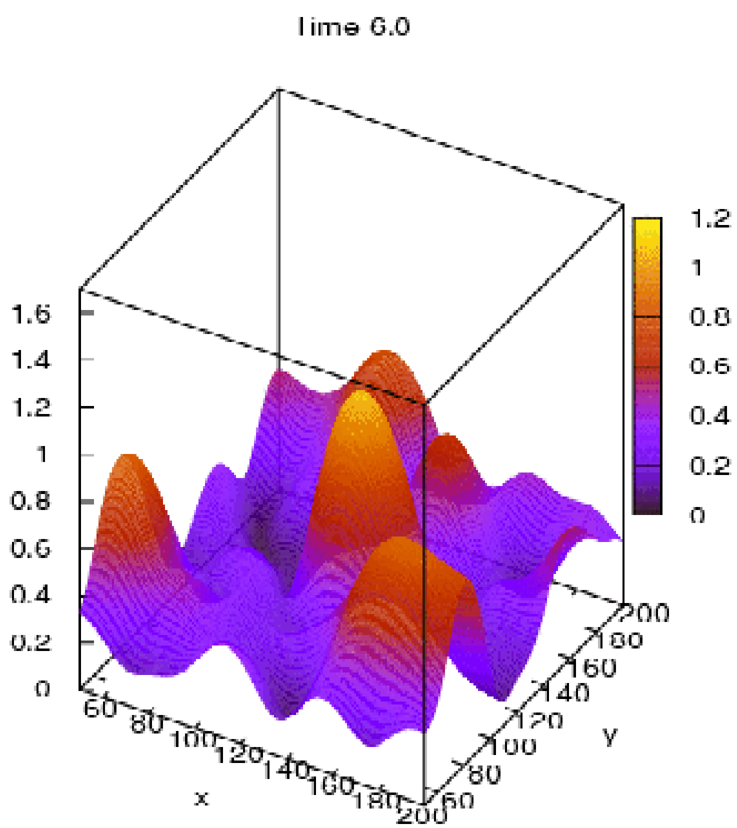

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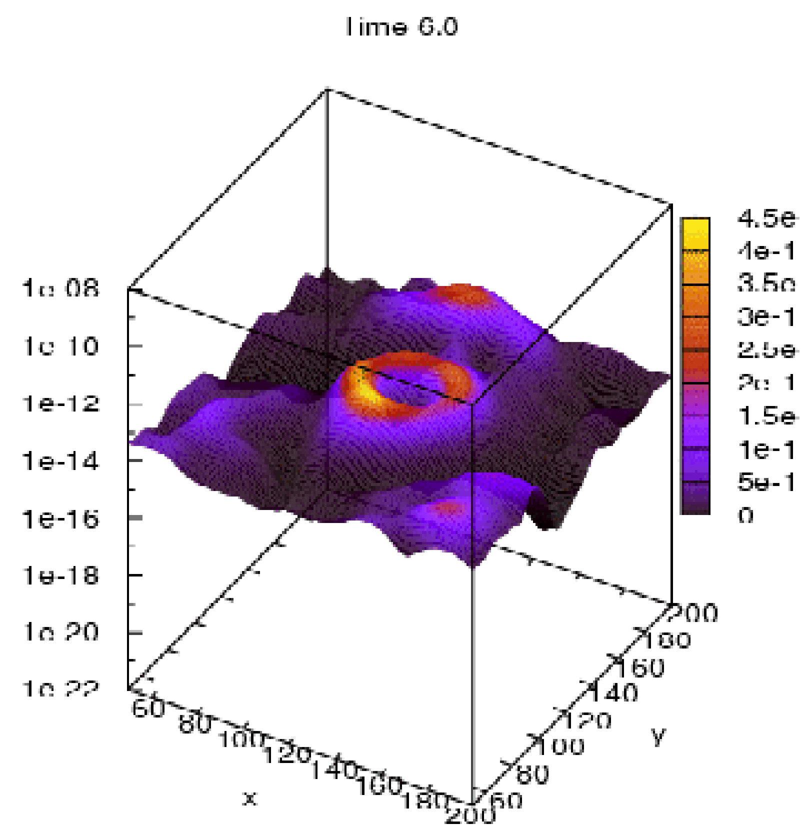

GW (Energy density)

INFLATIONARY PREHEATING

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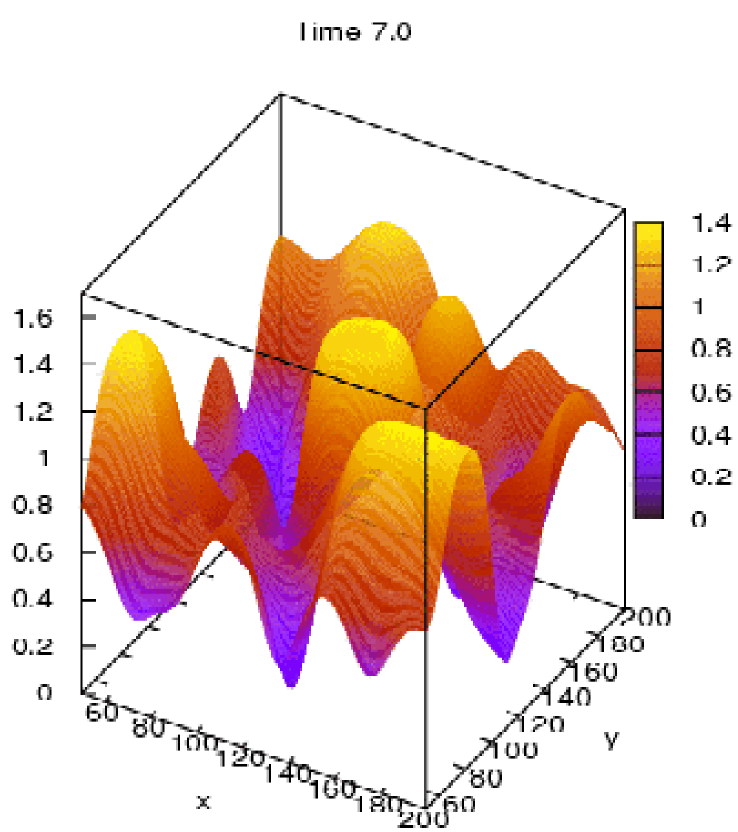

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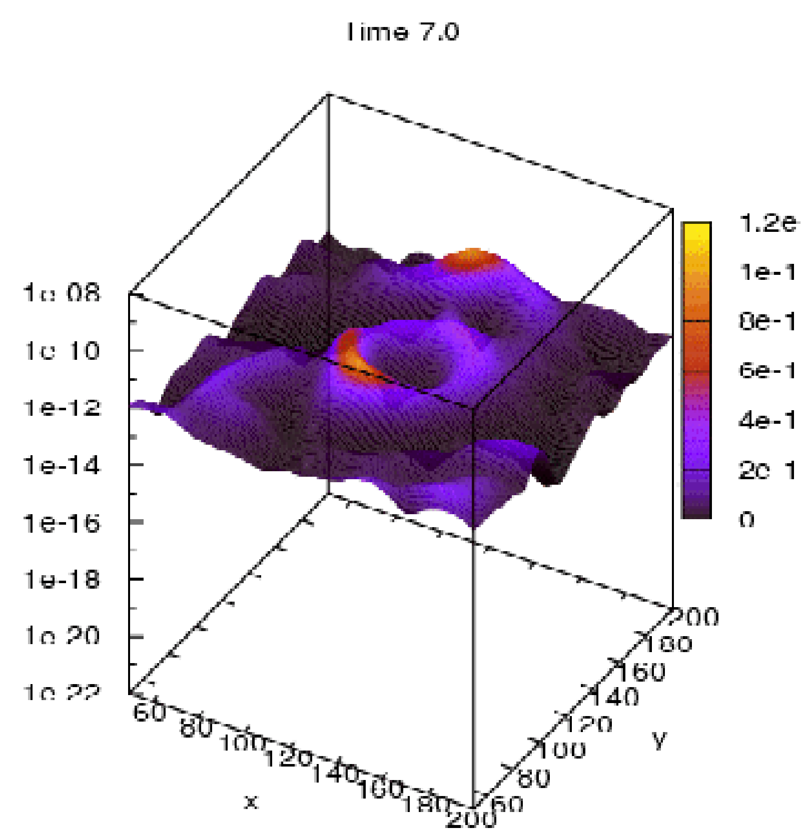

GW (Energy density)

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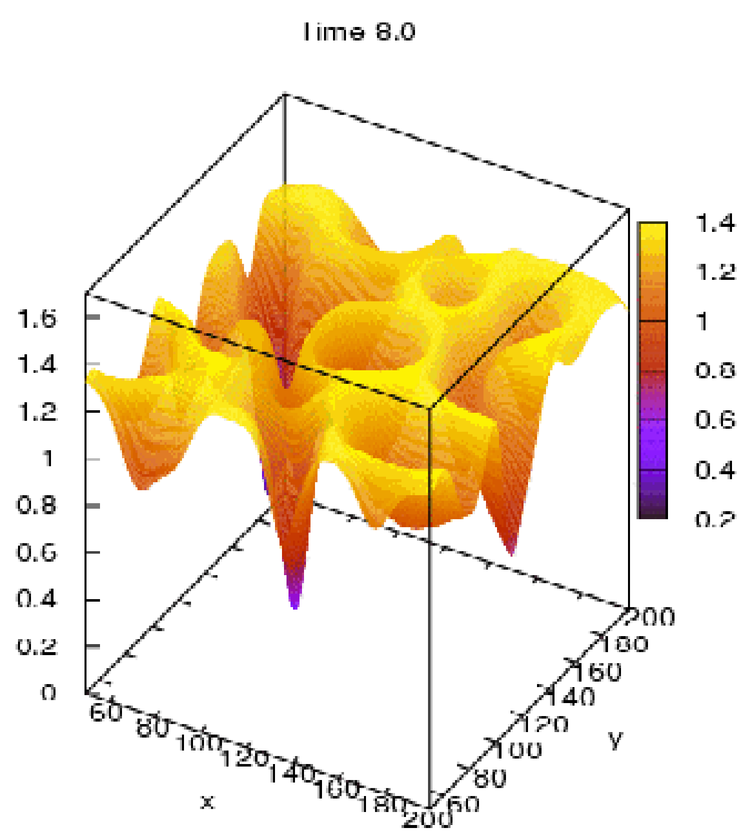

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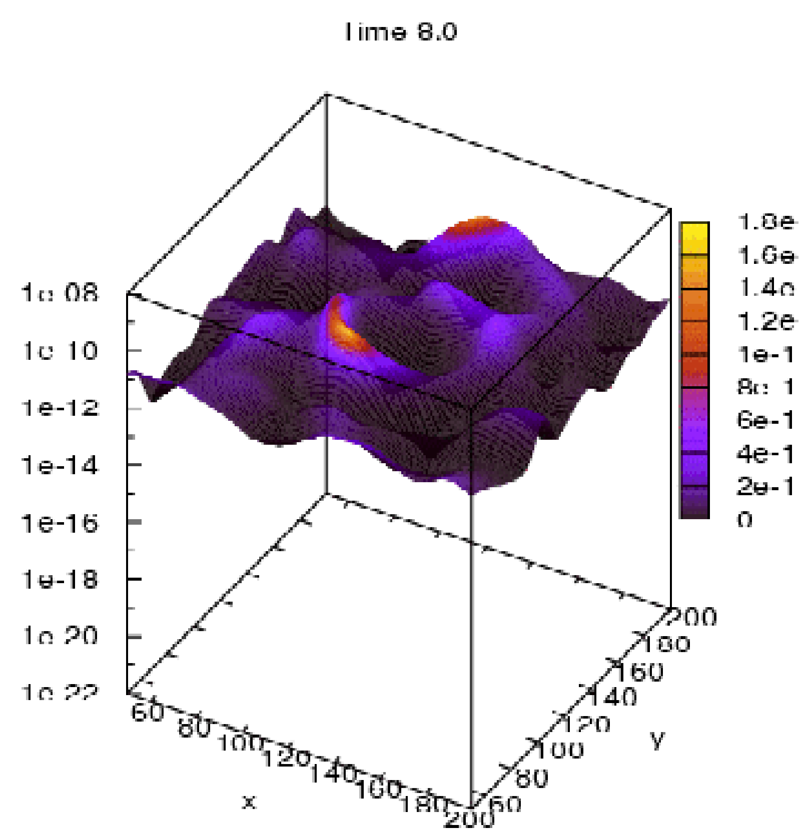

GW (Energy density)

INFLATIONARY PREHEATING

Lattice Simulations: Dynamics → **non-linear** → **out-Eq**

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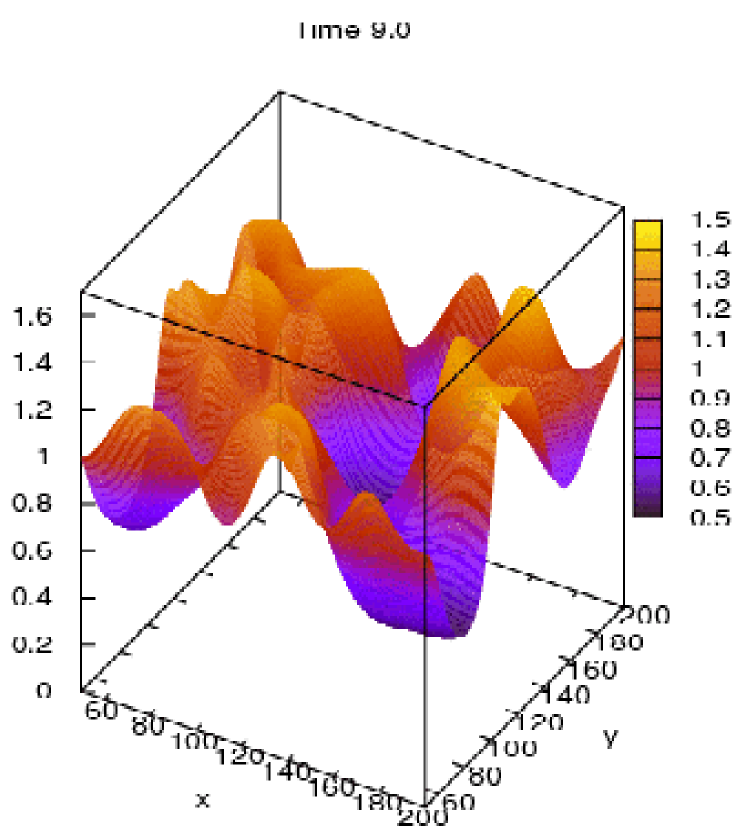

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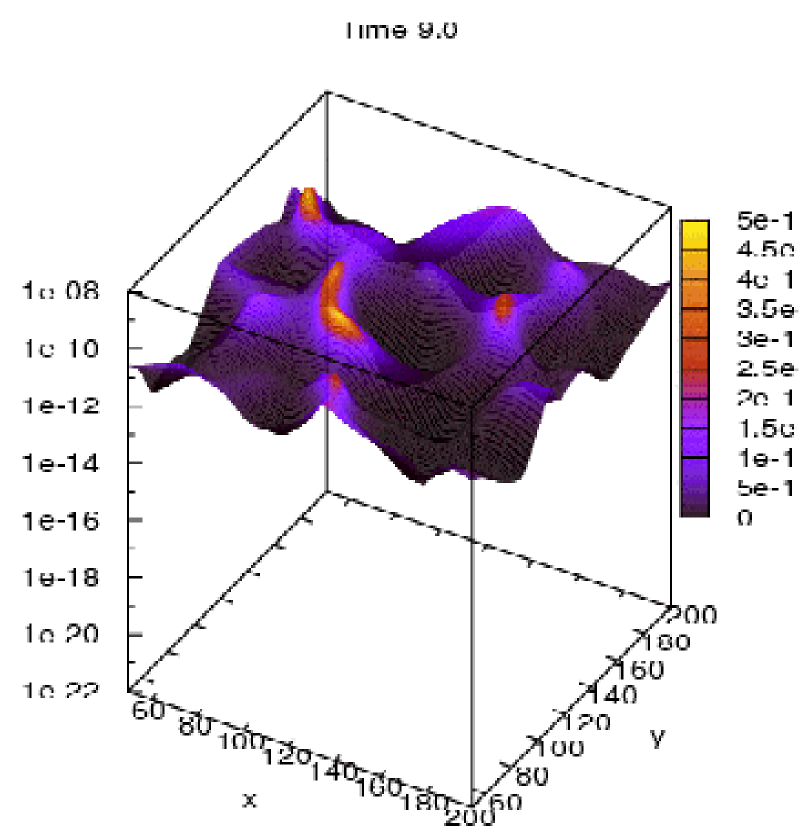

GW (Energy density)

INFLATIONARY PREHEATING

Lattice Simulations: Dynamics

non-linear

out-Eq

Hybrid Preheating

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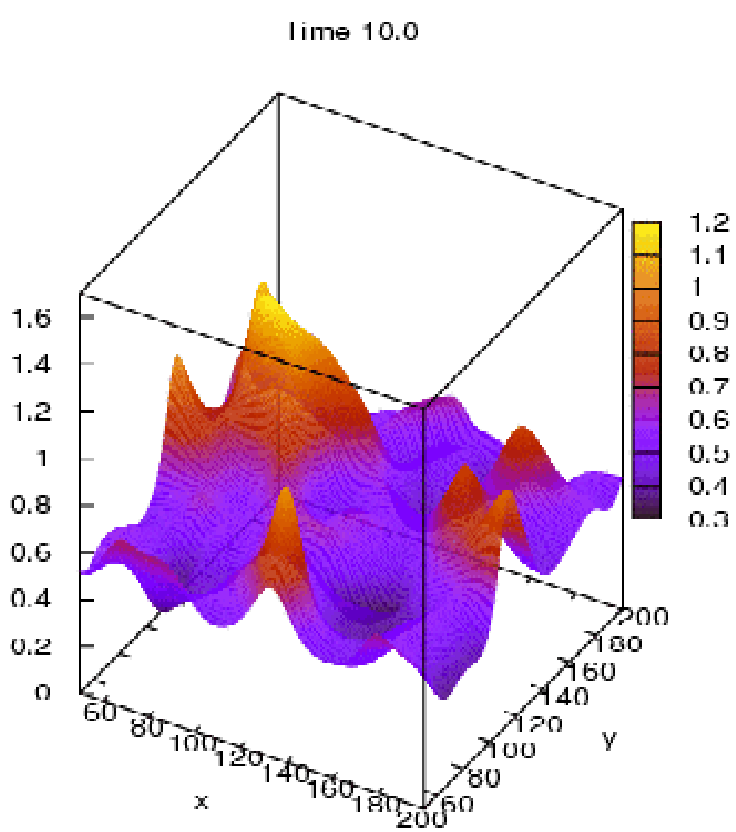

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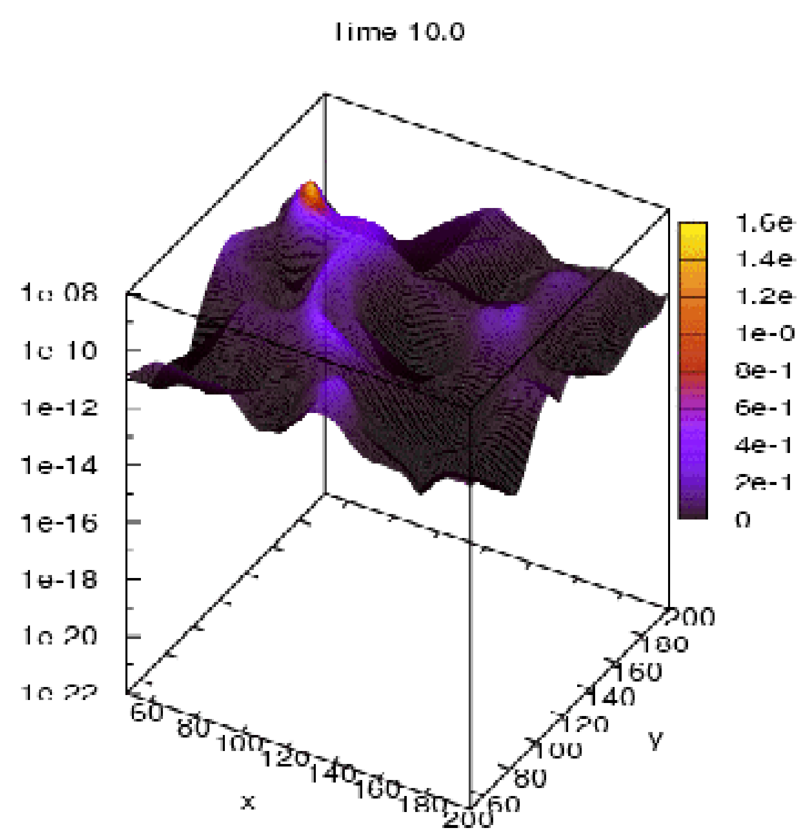

GW (Energy density)

INFLATIONARY PREHEATING

Lattice Simulations: Dynamics → **non-linear**, **out-Eq**

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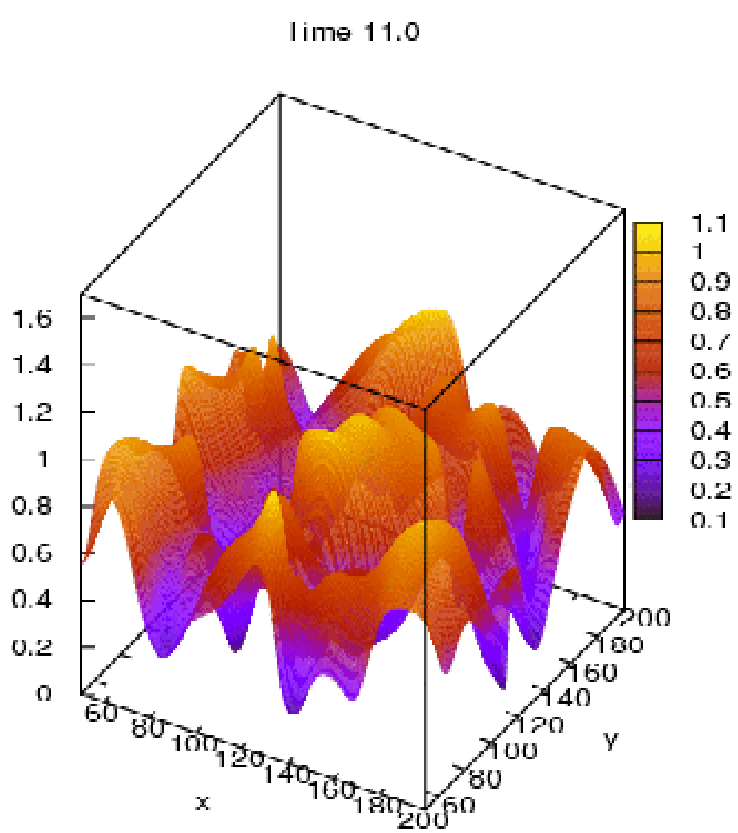

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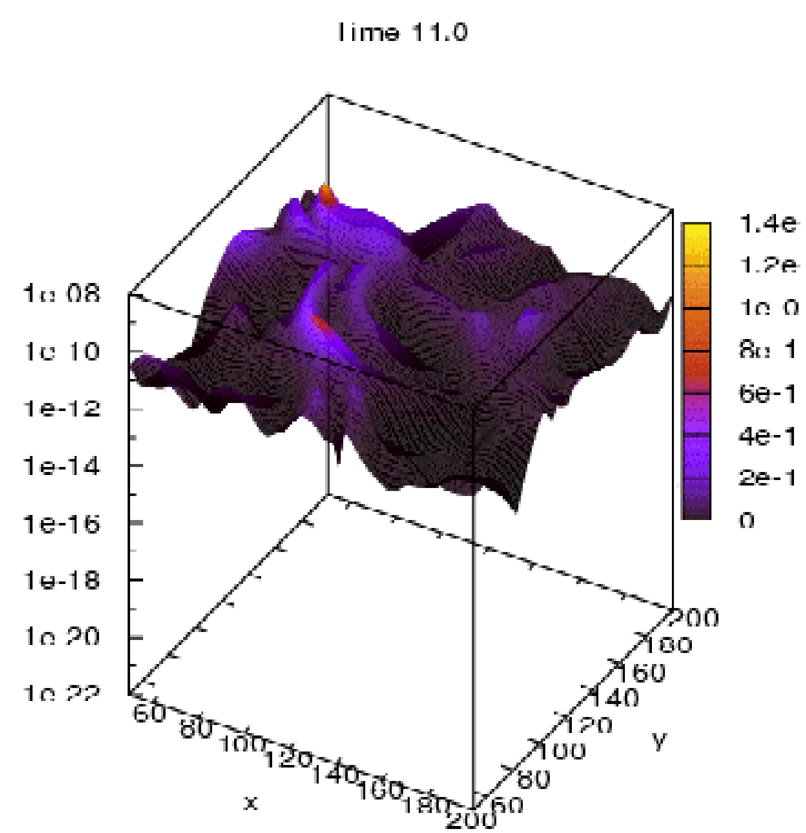

GW (Energy density)

INFLATIONARY PREHEATING

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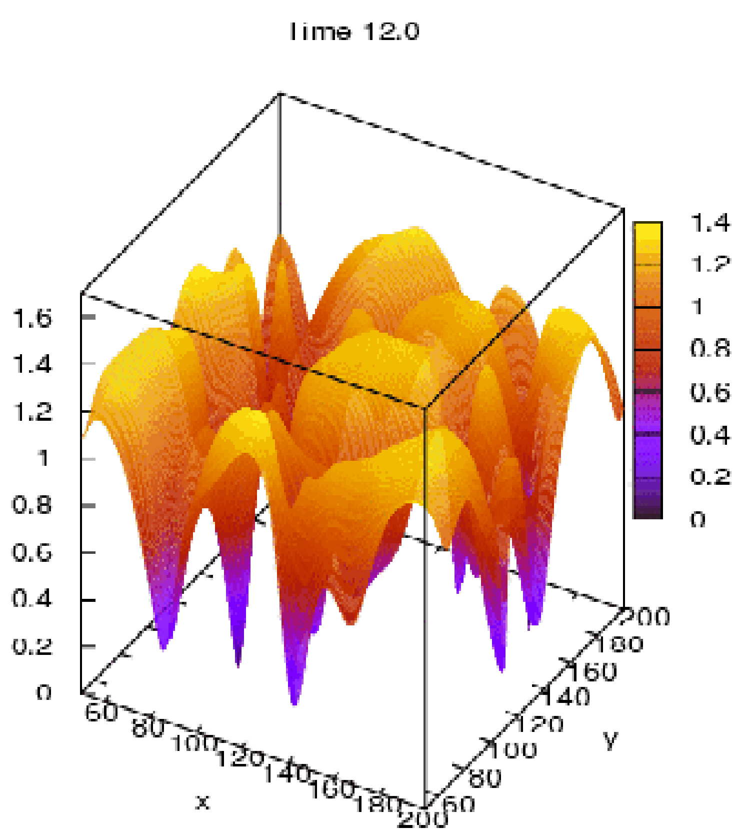

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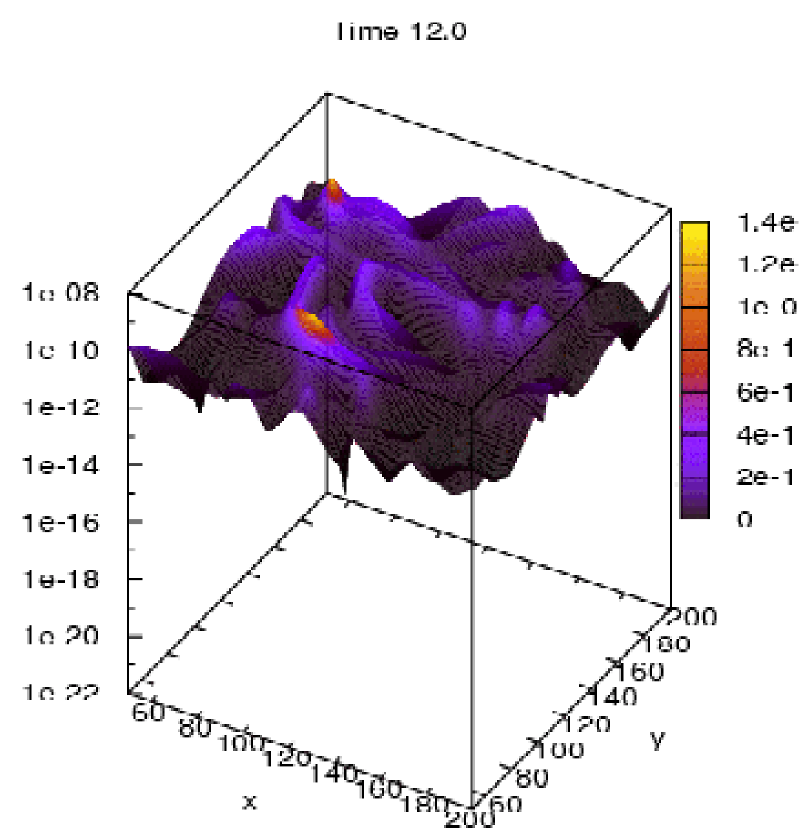

GW **(Energy density)**

INFLATIONARY PREHEATING

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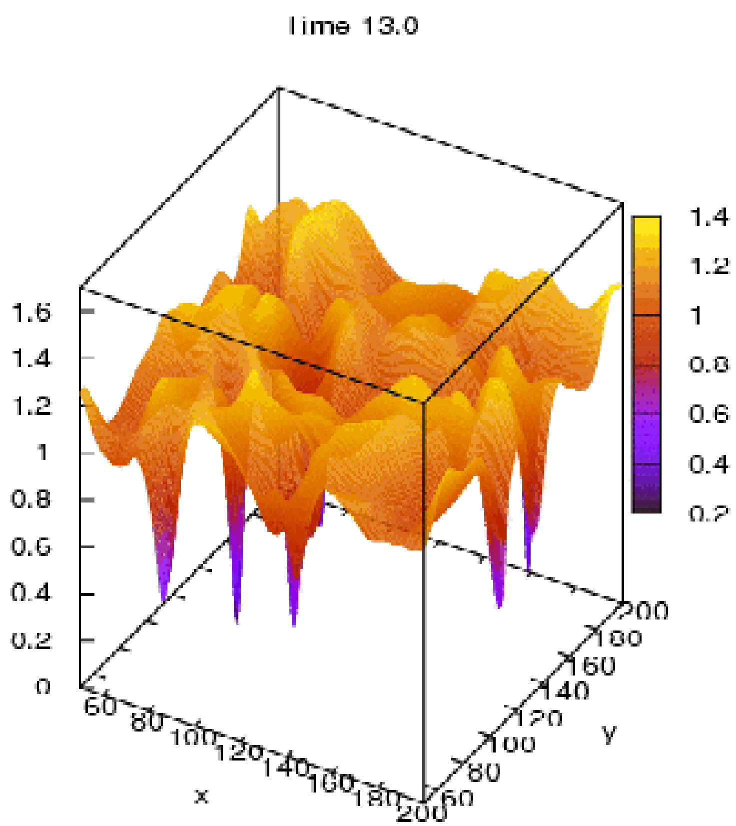

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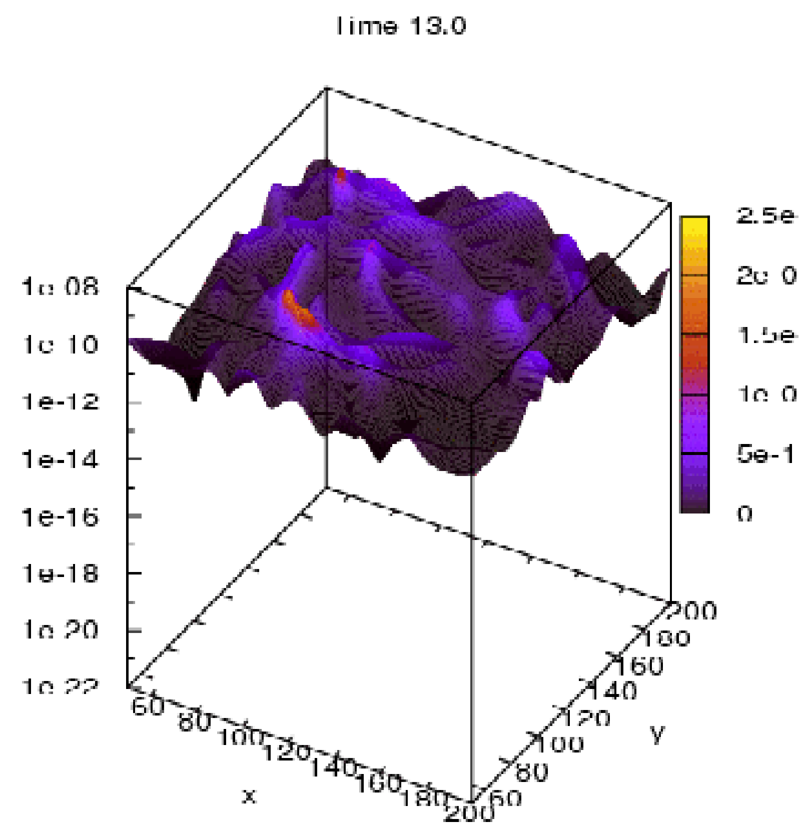

GW **(Energy density)**

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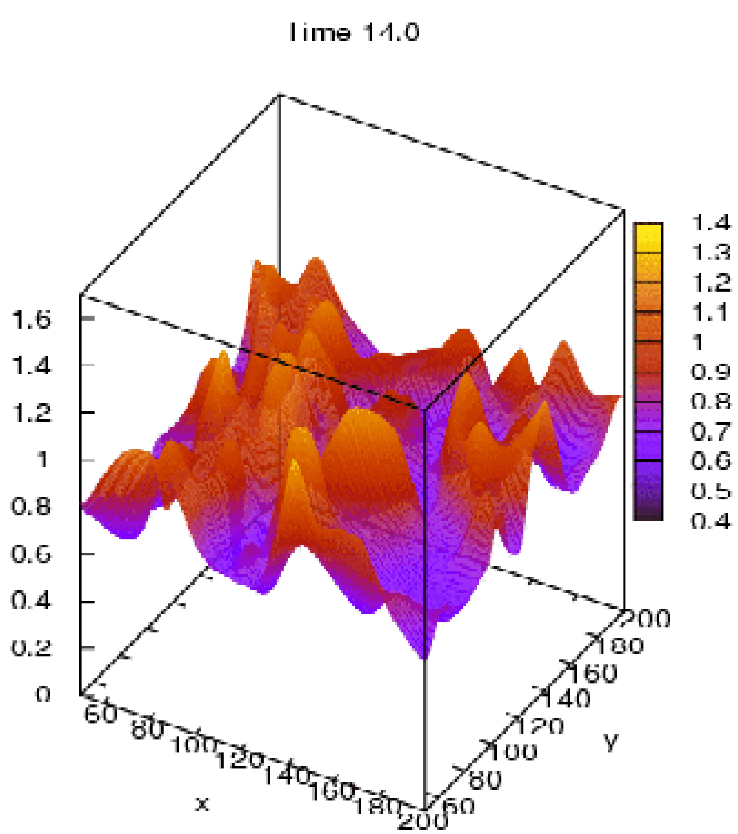

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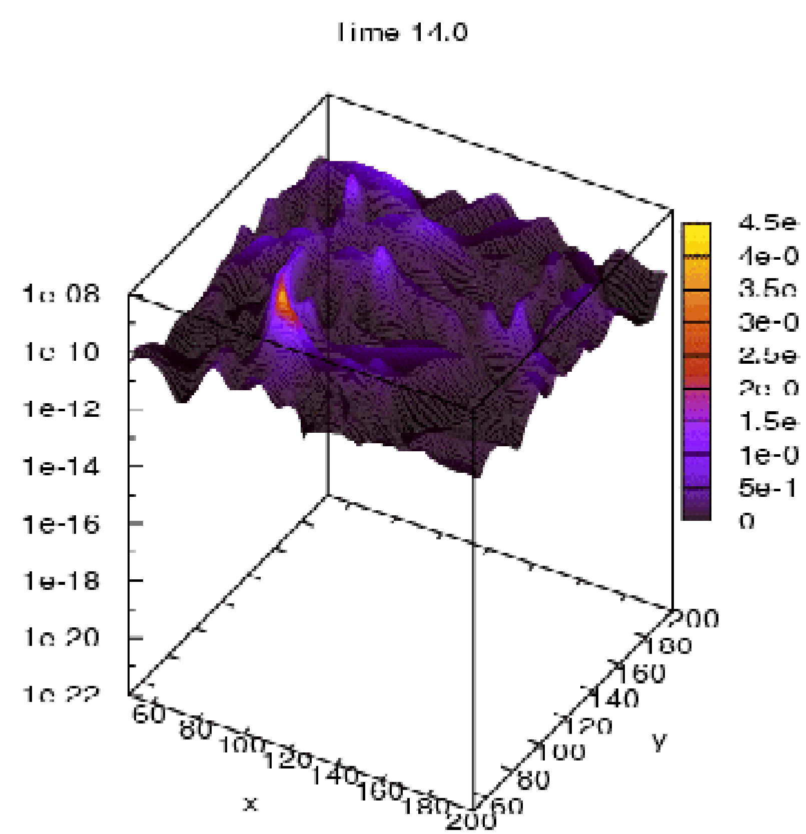

GW **(Energy density)**

INFLATIONARY PREHEATING

Lattice Simulations: Dynamics → non-linear, out-Eq

Hybrid Preheating

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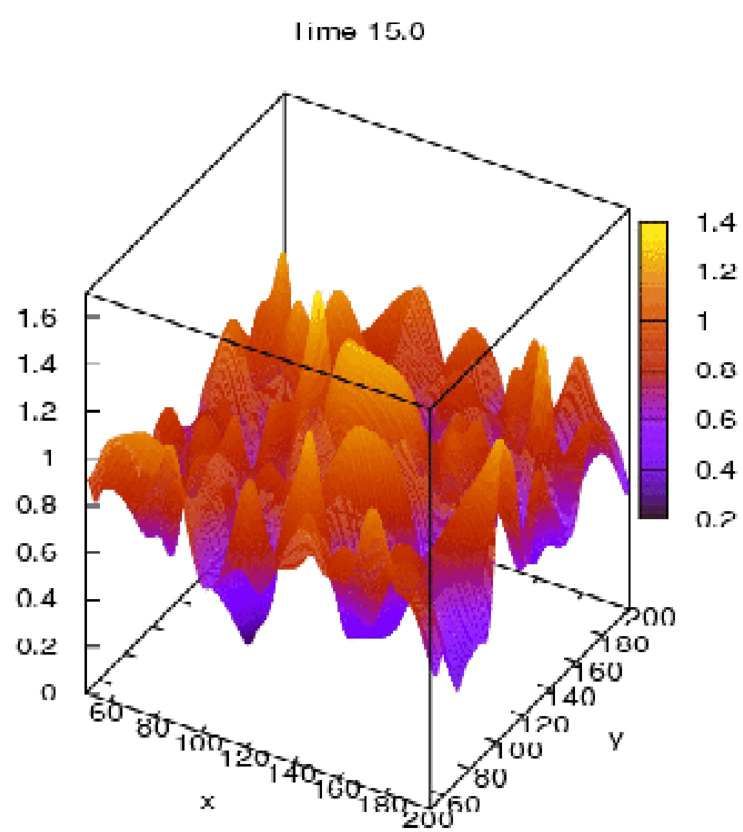

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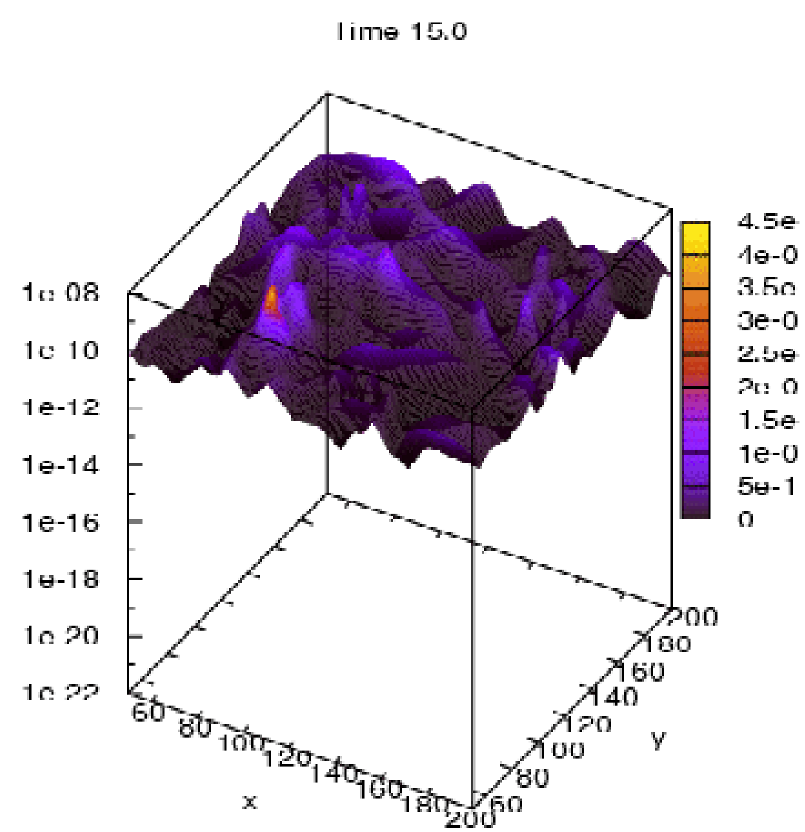

GW (Energy density)

INFLATIONARY PREHEATING

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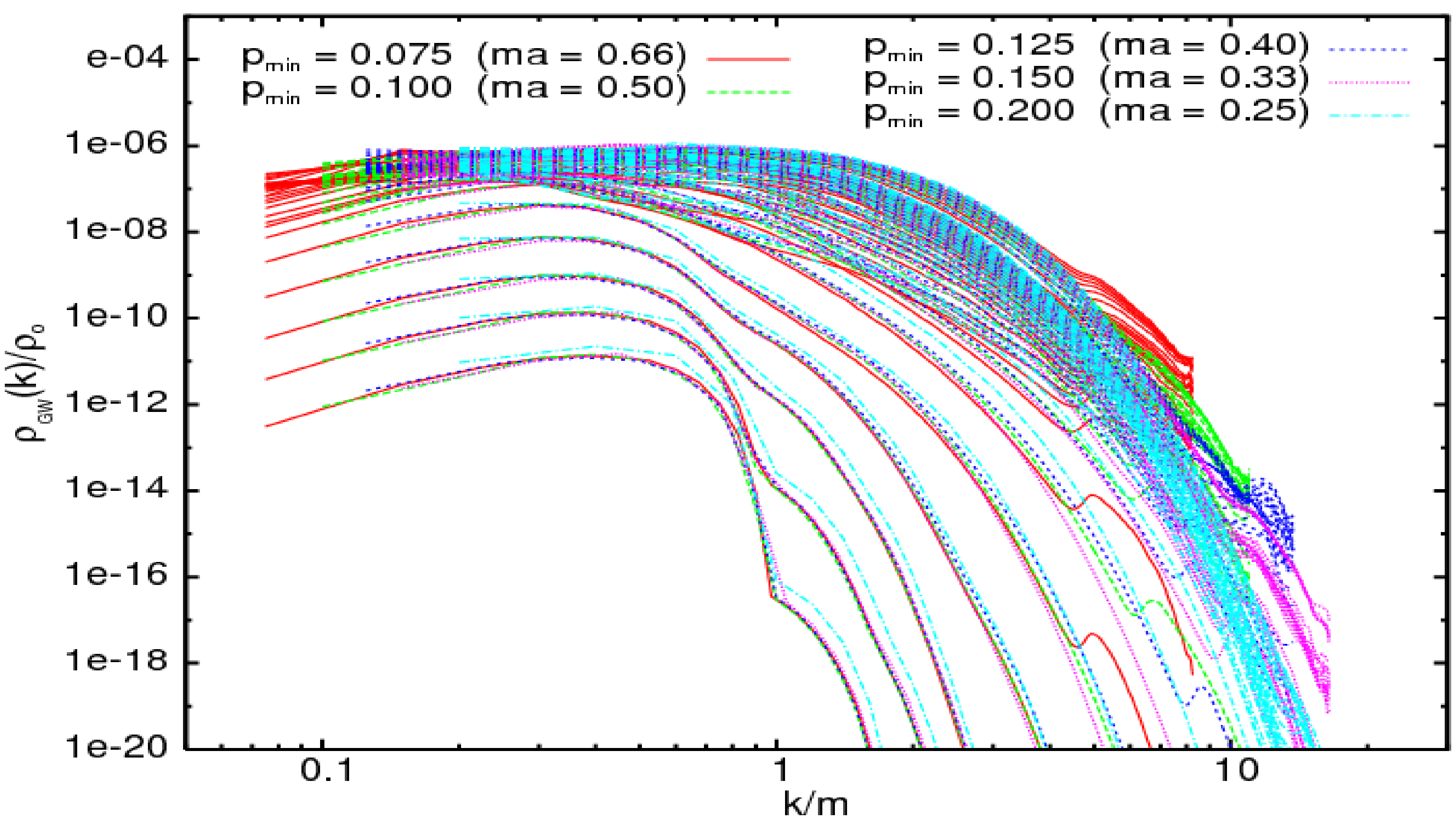
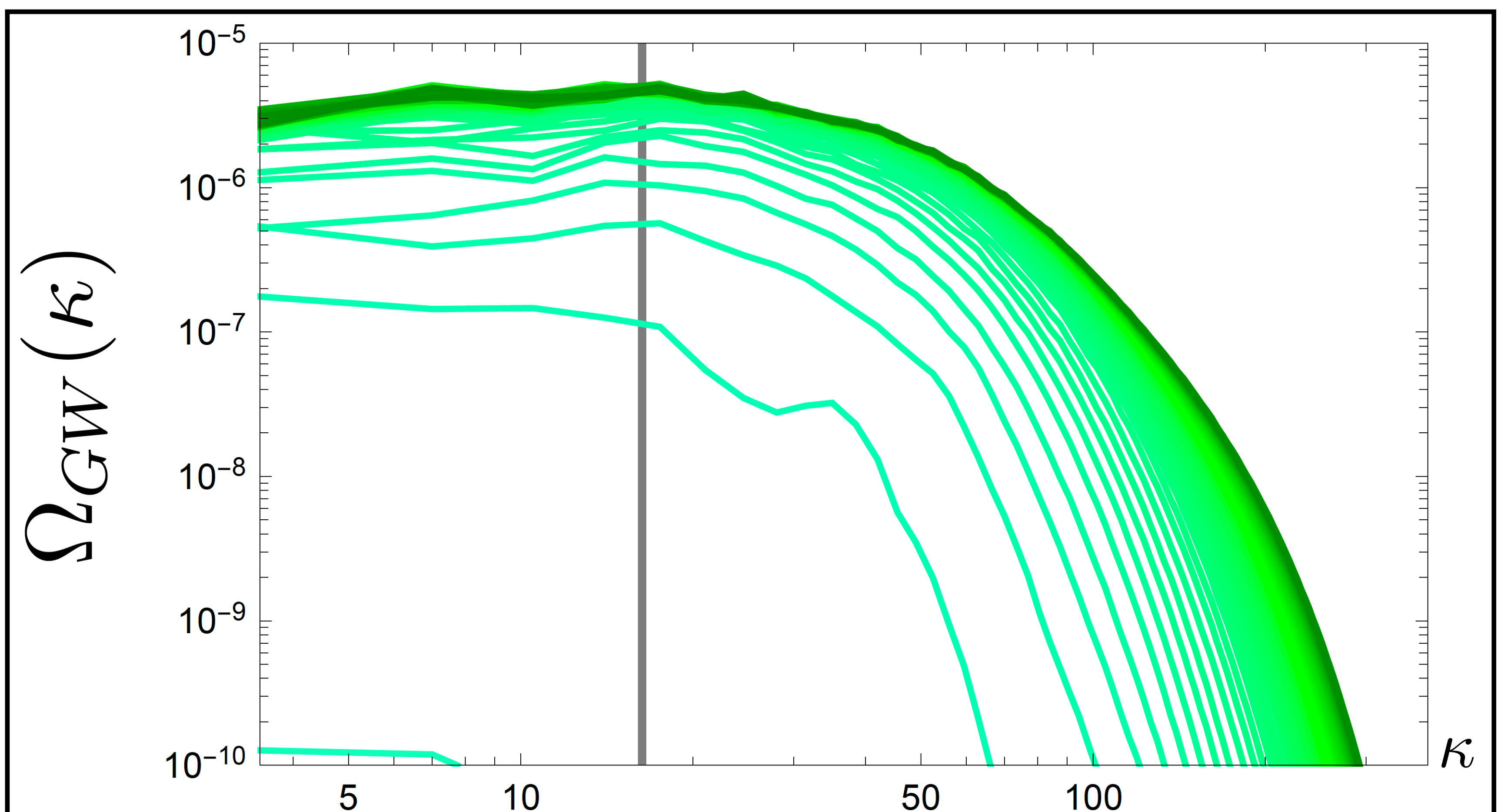
3 stages: **Exp. Instabilities** → **Non-linearities** → **Relaxation**

$$\frac{1}{\rho_{\rm tot}}\,\frac{d\rho_{\rm GW}}{d\log k}$$



GW Spectrum

Parameter Dependence (Peak amplitude**)**



(DGF, Torrentí JCAP 2017)

GW Spectrum

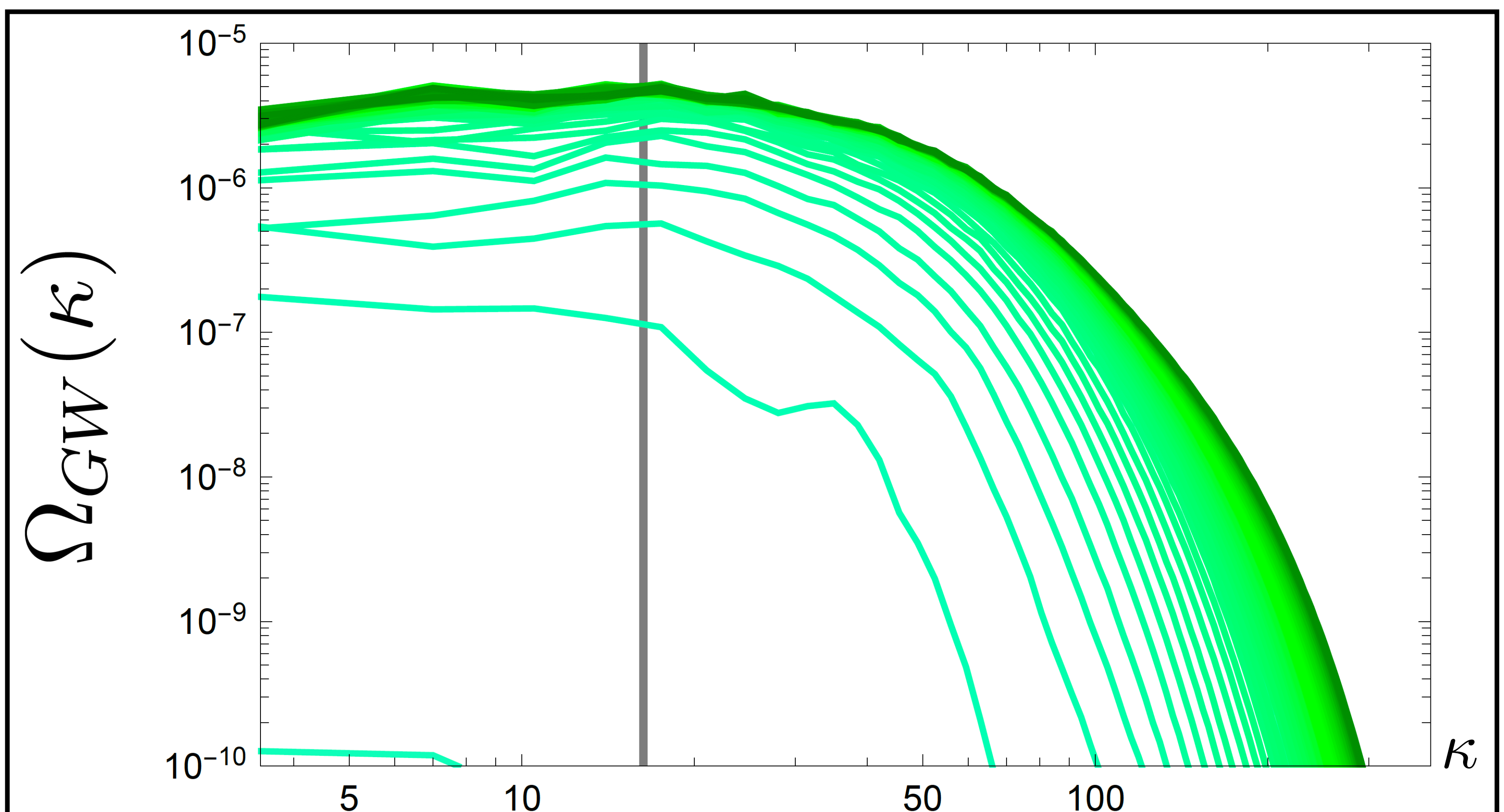
Parameter Dependence (Peak amplitude)

$$\boxed{\omega^2 \equiv V''(\Phi_I)}$$

Monomial Models: $$\Omega^{(o)}_{\rm GW} \sim A^2 \frac{\omega^6}{\rho m_p^2}\, q^{-1/2}$$

$$\boxed{q \equiv \frac{g^2 \Phi_{\rm i}^2}{\omega^2}}$$

Resonance Param.



$$\boxed{k_p \propto q^{2/3}}$$

Peak Position

(DGF, Torrentí JCAP 2017)

GW Spectrum

Parameter Dependence (Peak amplitude)

Monomial Models: $\Omega_{\rm GW}^{(o)} \sim 10^{-9}\,,$

Large amplitude !

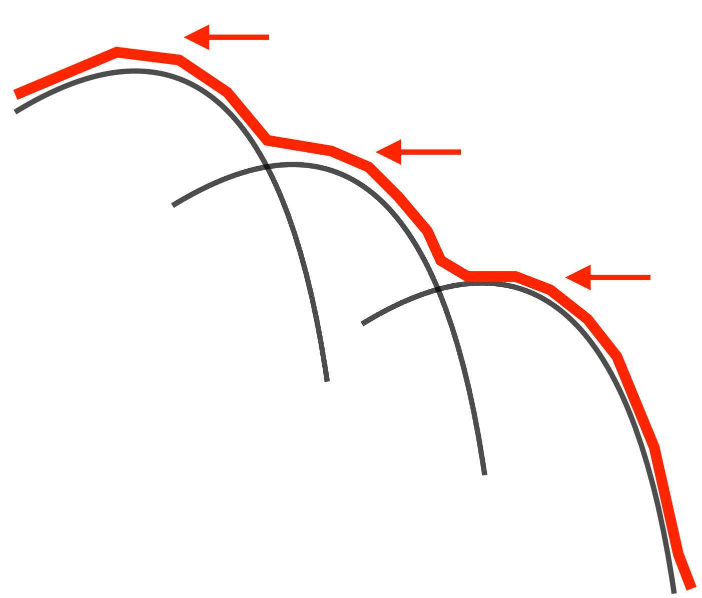
GW Spectrum

Parameter Dependence (Peak amplitude)

Monomial Models: $\Omega_{\rm GW}^{(o)} \sim 10^{-9}\,,$

Large amplitude!

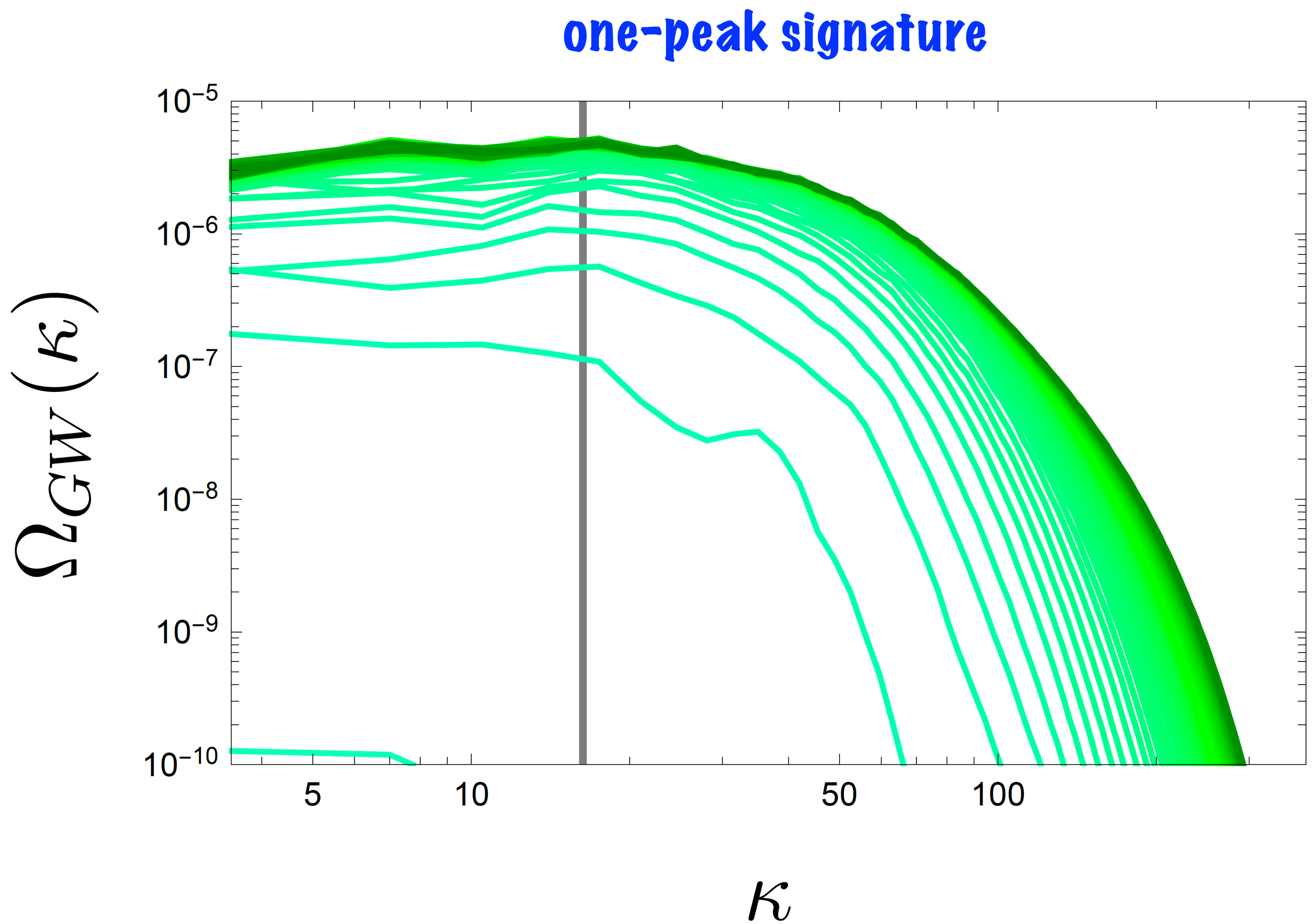
$\Omega_{\rm GW} \propto q^{-1/2}$ ⟶ **Spectroscopy of particle couplings?**



different couplings
... different peaks?

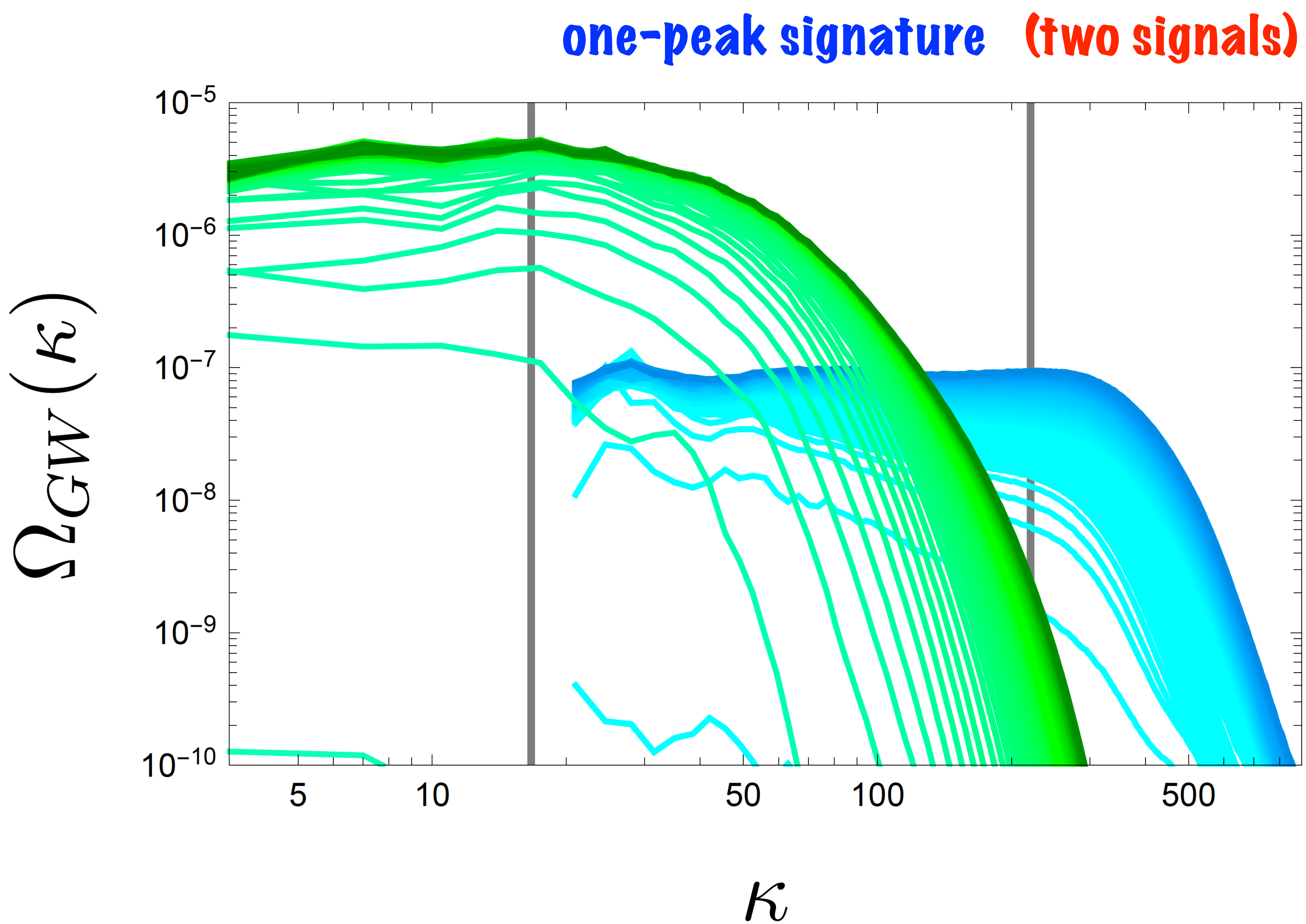
GW Spectroscopy

Parameter Dependence (Peak amplitude**)**



GW Spectroscopy

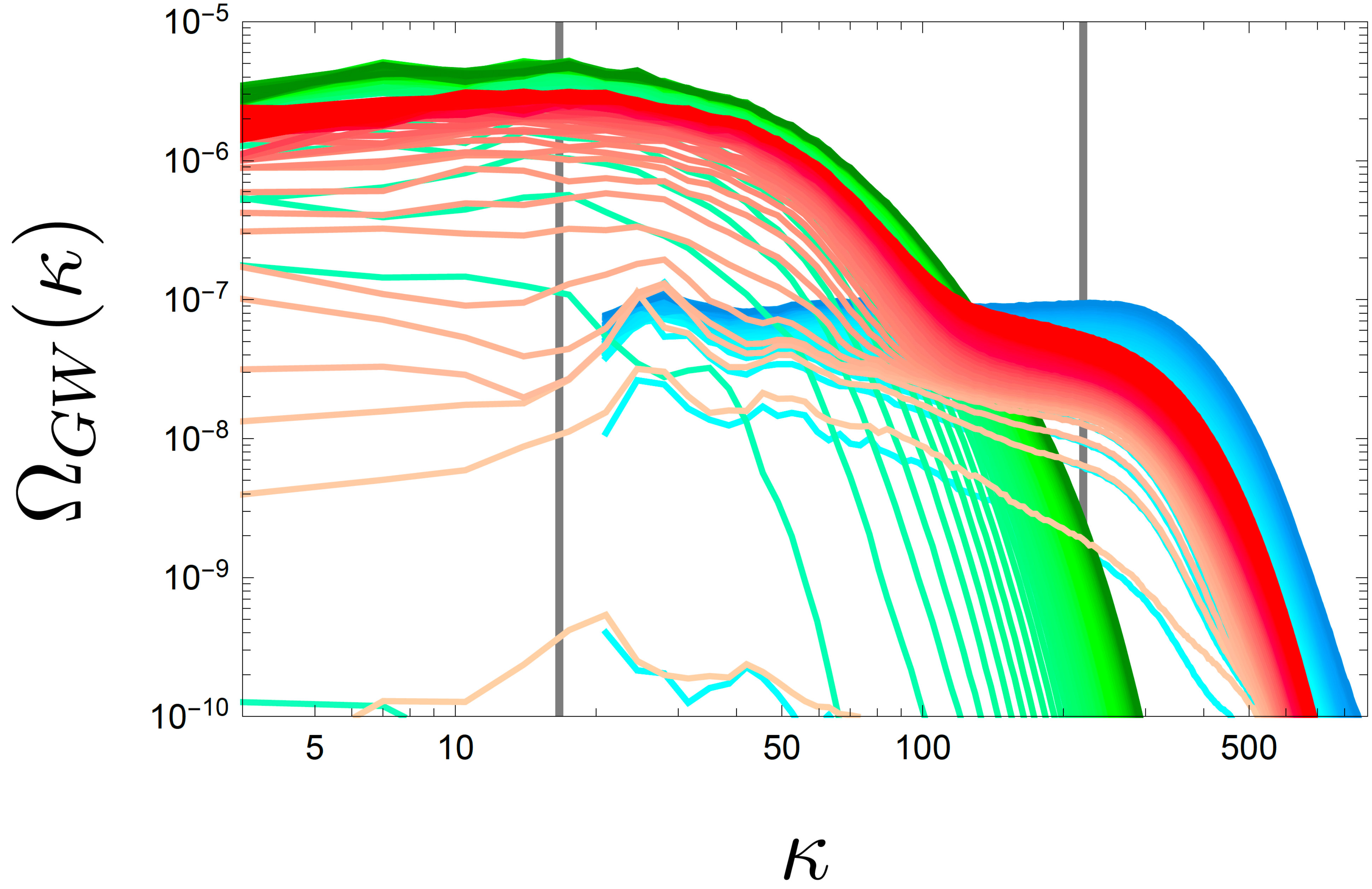
Parameter Dependence (Peak amplitude**)**



GW Spectroscopy

Parameter Dependence (Peak amplitude**)**

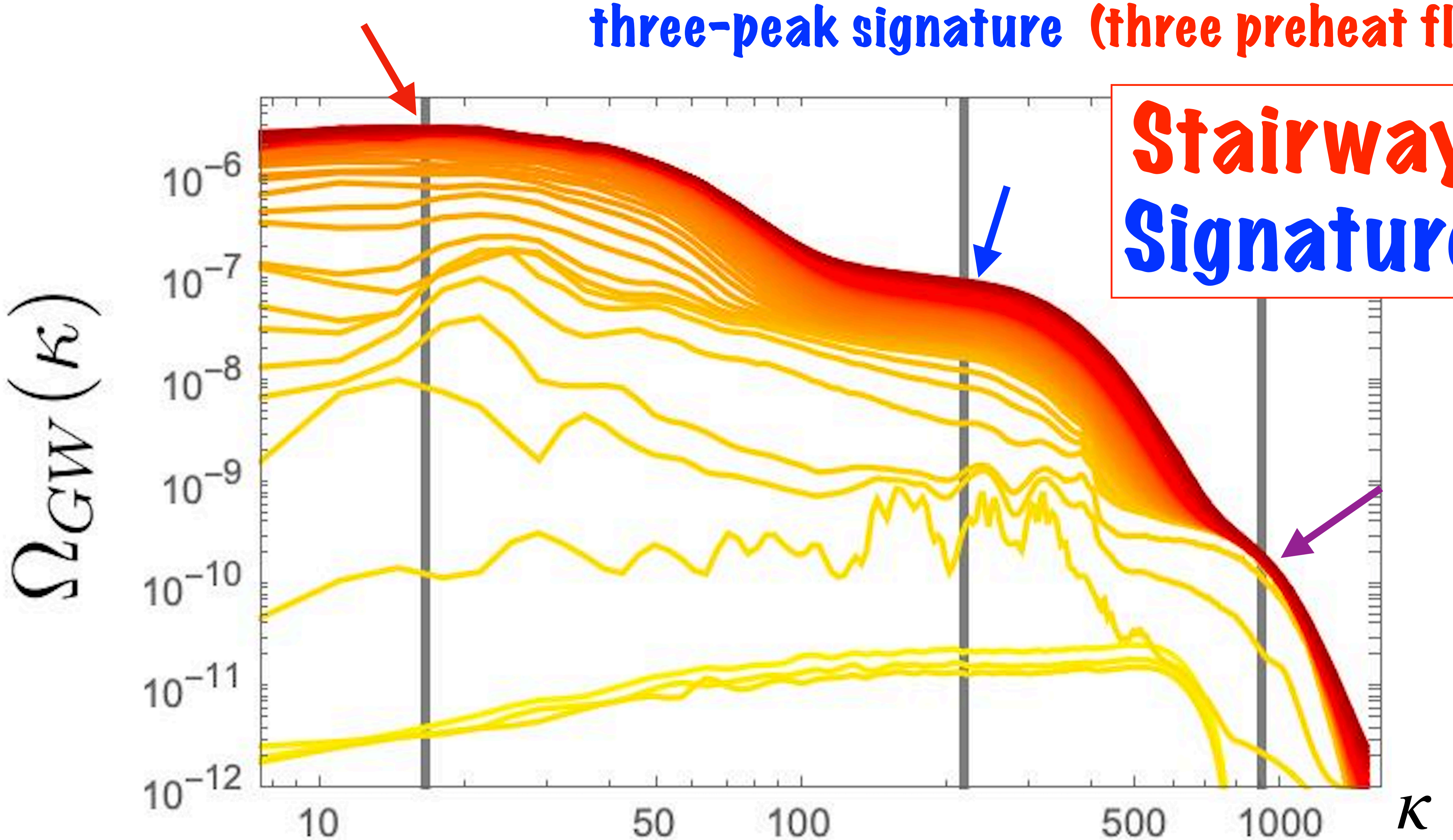
two-peak signature (two preheat flds)



GW Spectroscopy

Parameter Dependence (Peak amplitude**)**

three-peak signature (three preheat flds)

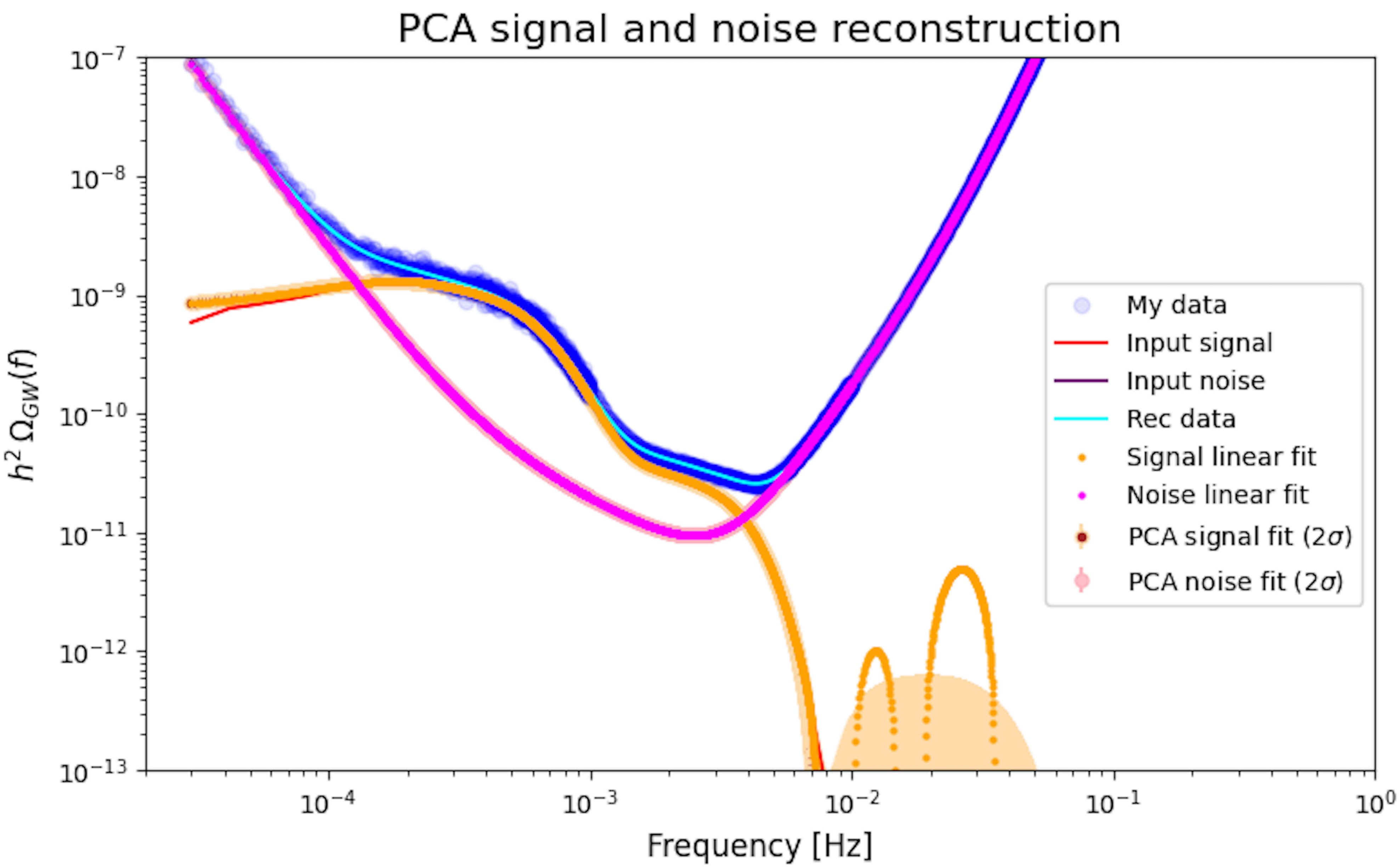


DGF, Florio, Loayza, Pieroni (work in progress)

GW Spectroscopy

Reconstruction (2-peak signal)

@ LISA

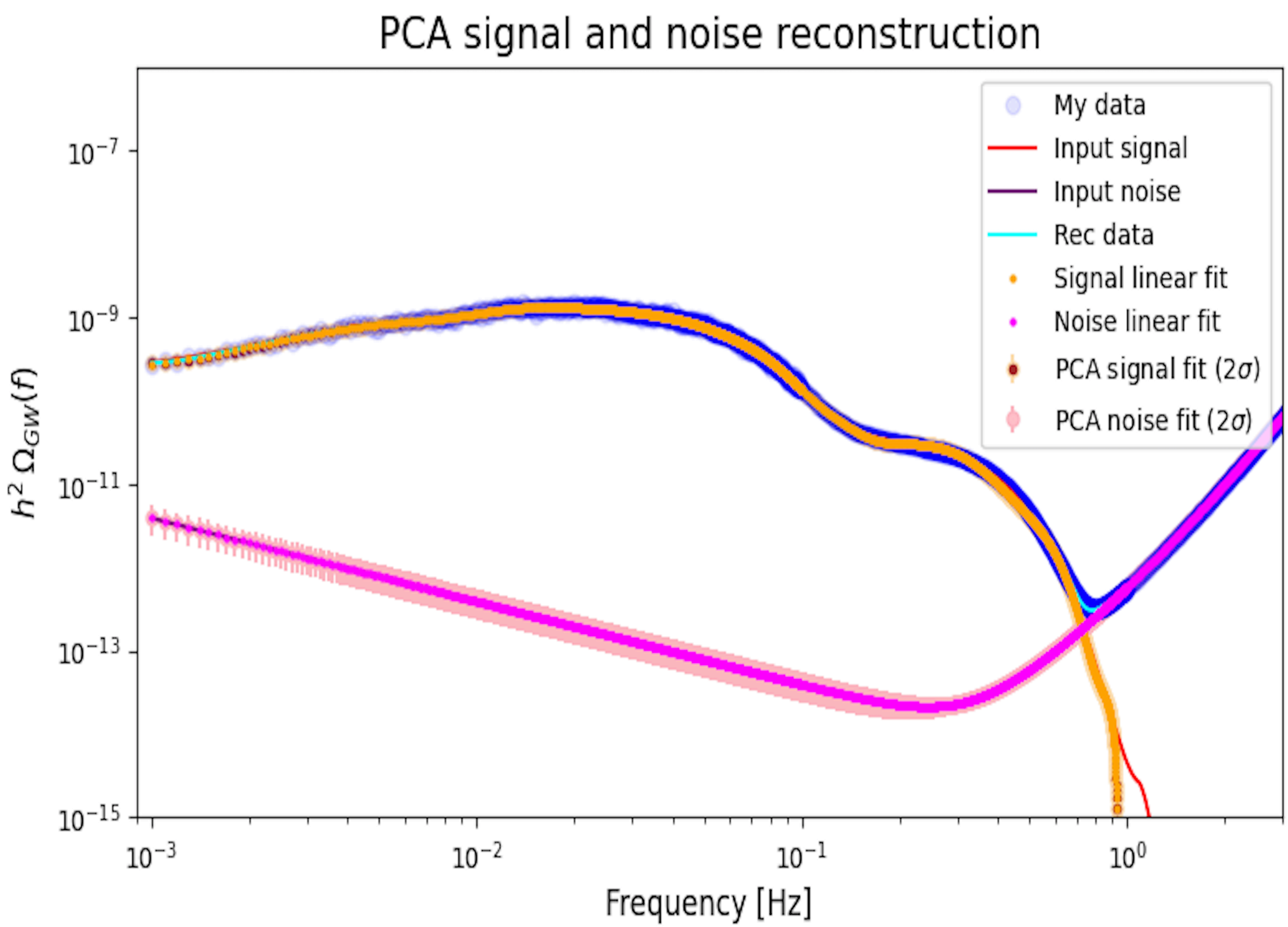


Note: Put by hand at LISA frequencies

GW Spectroscopy

Reconstruction (2-peak signal)

@ BBO

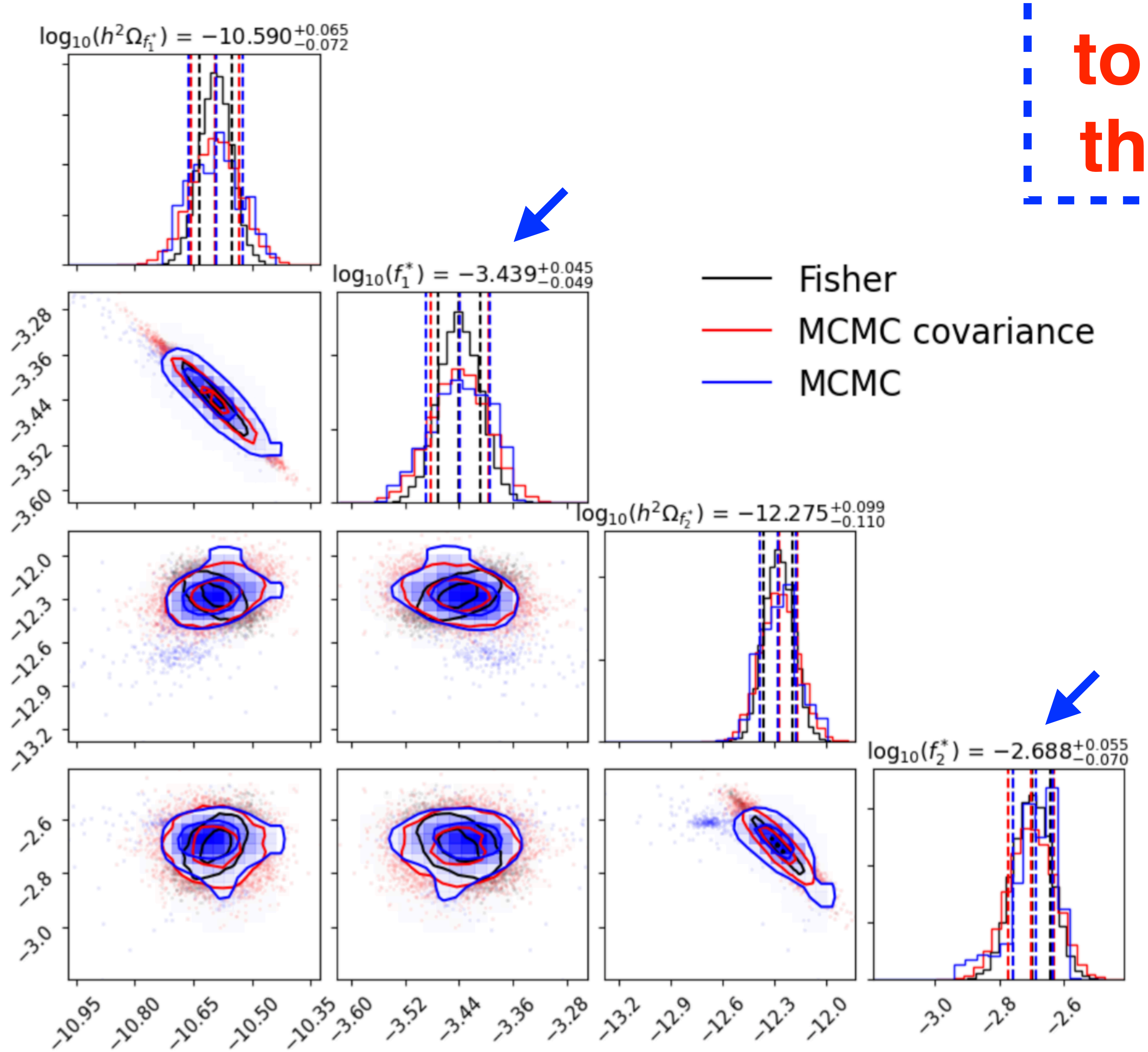


Note: Put by hand at BBO frequencies

GW Spectroscopy

LISA Reconstruction (2-peak signal)

Couplings to better than 1%



GW Spectroscopy

Reconstruction (2-peak signal)

Monomial Models: $\Omega_{\rm GW}^{(o)} \sim 10^{-9}\,,$ $f_o \sim 10^8 - 10^9 \text{ Hz}$

Large amplitude ! ... at high Frequency !

Very unfortunate... no detectors there !

GW Spectroscopy

Reconstruction (2-peak signal)

Monomial Models: $\Omega_{\rm GW}^{(o)} \sim 10^{-9}\,,$ $f_o \sim 10^{8} - 10^{9}\ \rm Hz$

Large amplitude ! **... at high Frequency !**

Our example serves as proof of principle !

Very unfortunate... no detectors there !

INFLATIONARY (p)REHEATING (pRH)

Parameter Dependence (Peak amplitude**)**

Hybrid Models: $\Omega_{\rm GW}^{(o)} \propto \left(\frac{v}{m_p}\right)^2 \times f(\lambda, g^2) \quad , \qquad f_o \sim \lambda^{1/4} \times 10^9 \ {\rm Hz}$

INFLATIONARY (p)REHEATING (pRH)

Parameter Dependence (Peak amplitude**)**

Hybrid Models: $\Omega_{\rm GW}^{(o)} \sim 10^{-11}$

Large amplitude !

$(\text{for } v \simeq 10^{16}~\text{GeV})$

INFLATIONARY (p)REHEATING (pRH)

Parameter Dependence (Peak amplitude**)**

Hybrid Models: $\Omega_{\rm GW}^{(o)} \sim 10^{-11}\,, \quad @ \left\{ \begin{array}{l} f_o \sim 10^8 - 10^9 \text{ Hz} \\ \\ \end{array} \right.$

$\boxed{\lambda \sim 0.1}$ (natural)

Large amplitude !

(for $v \simeq 10^{16}$ GeV)

INFLATIONARY (p)REHEATING (pRH)

Parameter Dependence (Peak amplitude**)**

Hybrid Models:

$$\Omega_{\rm GW}^{(o)} \sim 10^{-11}\,, \quad @ \begin{cases} f_o \sim 10^8 - 10^9 \ \text{Hz} \\ \\ f_o \sim 10^2 \ \text{Hz} \end{cases}$$

$\boxed{\lambda \sim 0.1}$ (natural)

$\boxed{\lambda \sim 10^{-28}}$ (fine-tuning)

Large amplitude !

(for $v \simeq 10^{16}$ GeV)

INFLATIONARY (p)REHEATING (pRH)

Parameter Dependence (Peak amplitude**)**

Hybrid Models:

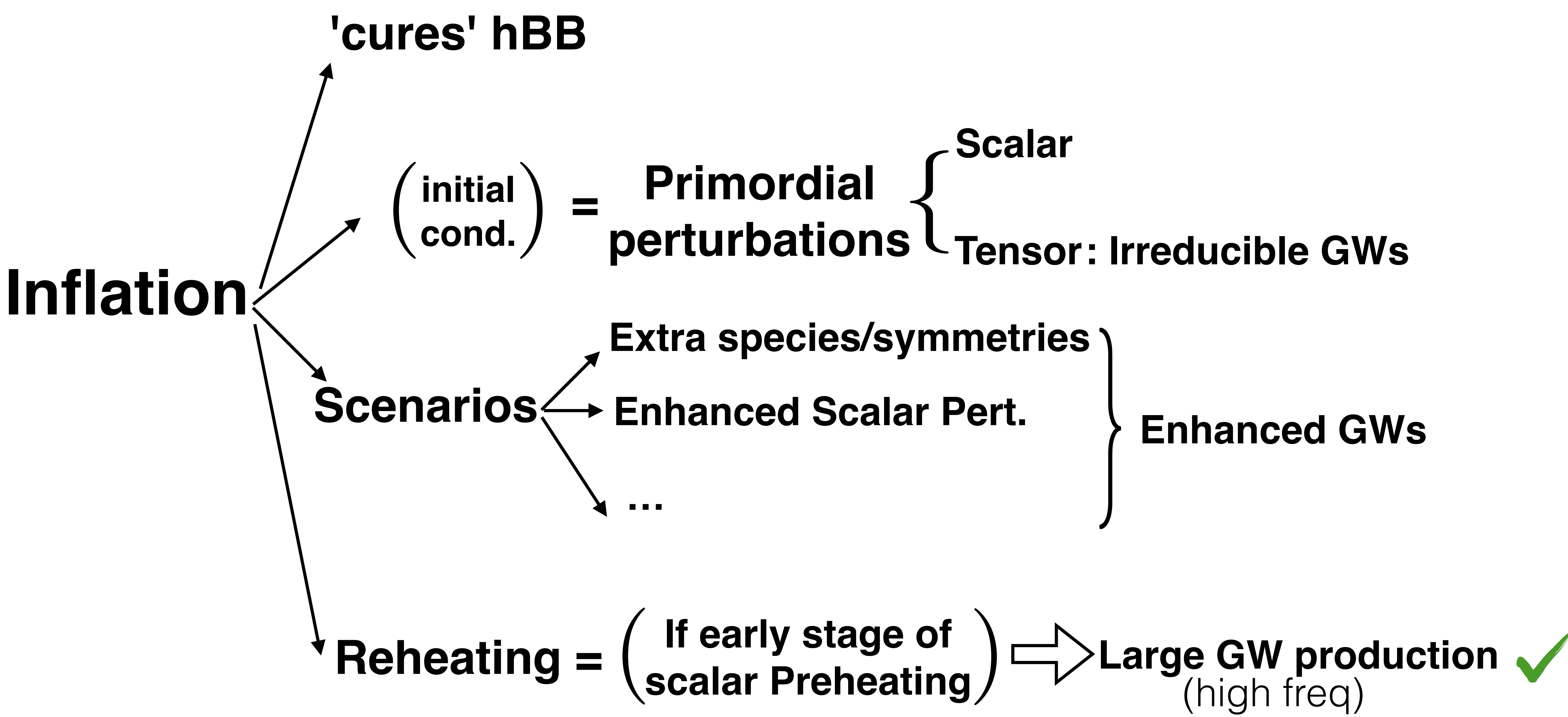
$$\Omega^{(o)}_{\rm GW} \sim 10^{-11}\,, \quad @ \begin{cases} f_o \sim 10^8 - 10^9~\text{Hz} & \boxed{\lambda \sim 0.1}~\text{(natural)} \\ f_o \sim 10^2~\text{Hz} & \boxed{\lambda \sim 10^{-28}}~\text{(fine-tuning)} \end{cases}$$

Large amplitude !

(for $v \simeq 10^{16}$ GeV)

realistically speaking ...

INFLATIONARY COSMOLOGY



OUTLINE

1st Bloc

1) Cosmology/GR + GW def. ✓

2nd Bloc

2) GWs from Inflation ✓

3) GWs from Preheating ✓

4) GWs from Phase Transitions

5) GWs from Cosmic Defects

OUTLINE

1st Bloc

1) Cosmology/GR + GW def. ✓

2nd Bloc

2) GWs from Inflation ✓

3) GWs from Preheating ✓

4) GWs from Phase Transitions

5) GWs from Cosmic Defects

EARLY UNIVERSE

'cures' hBB

$\left(\begin{array}{c}\text{initial}\\ \text{cond.}\end{array}\right)$ = Primordial perturbations

Scalar: CMB ΔT anisotropies (eventually Galaxies)

Tensor: Irreducible GWs (CMB B-mode Pol.)

Inflation

Scenarios

Extra species/symmetries

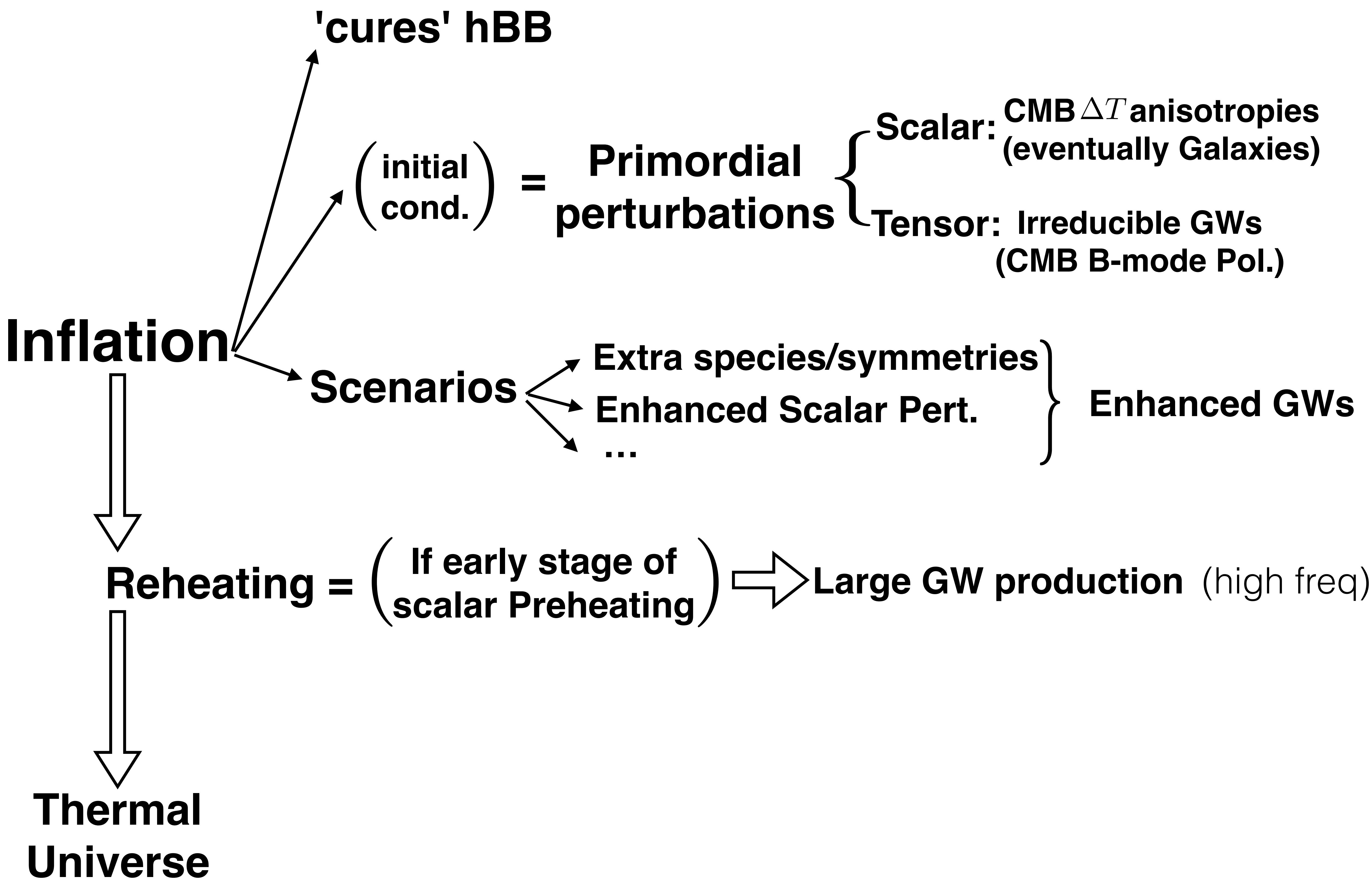
Enhanced Scalar Pert.

...

Enhanced GWs

Reheating = $\left(\begin{array}{c}\text{If early stage of}\\ \text{scalar Preheating}\end{array}\right)$ $\Rightarrow$ Large GW production (high freq)

EARLY UNIVERSE



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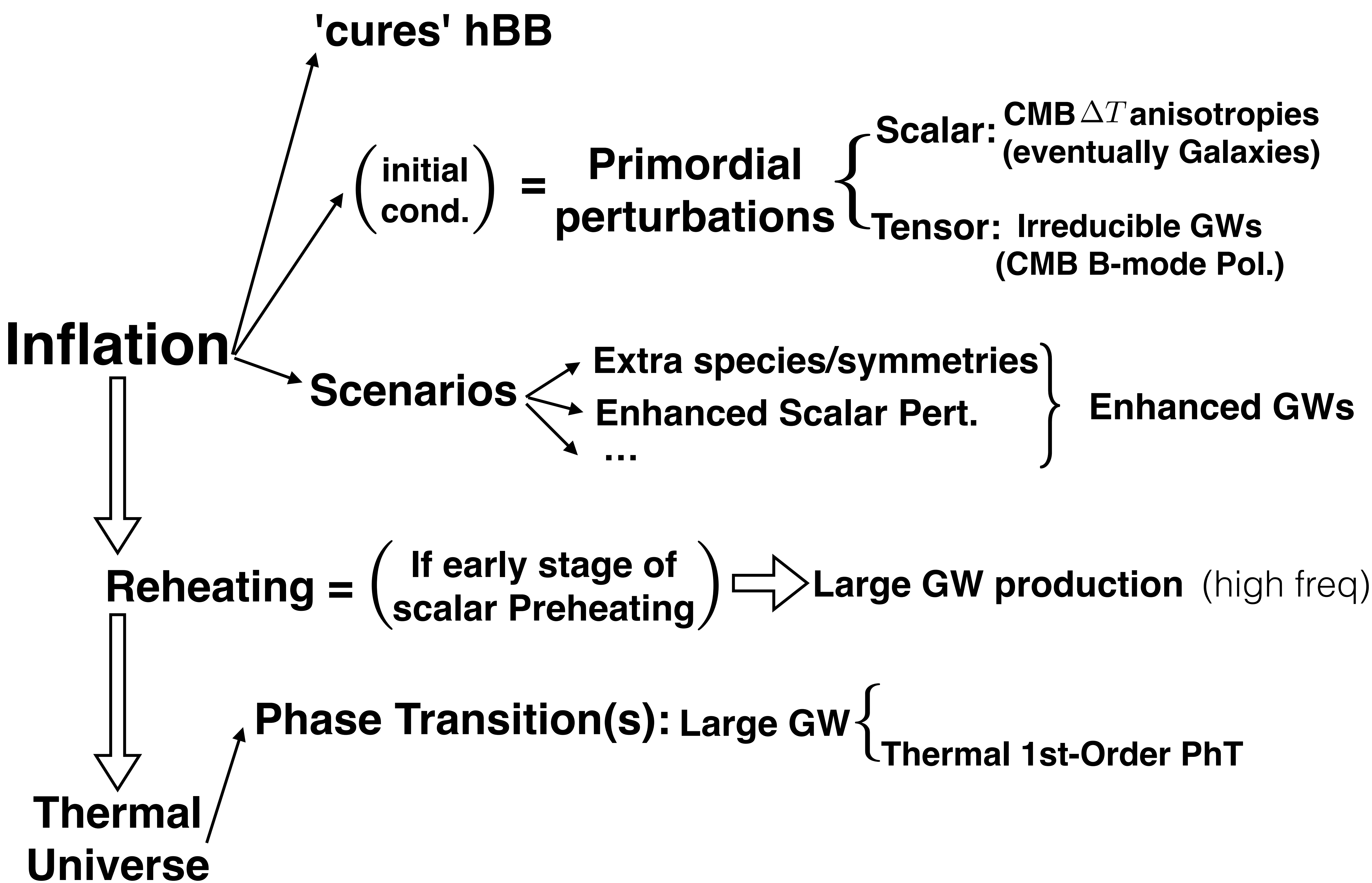
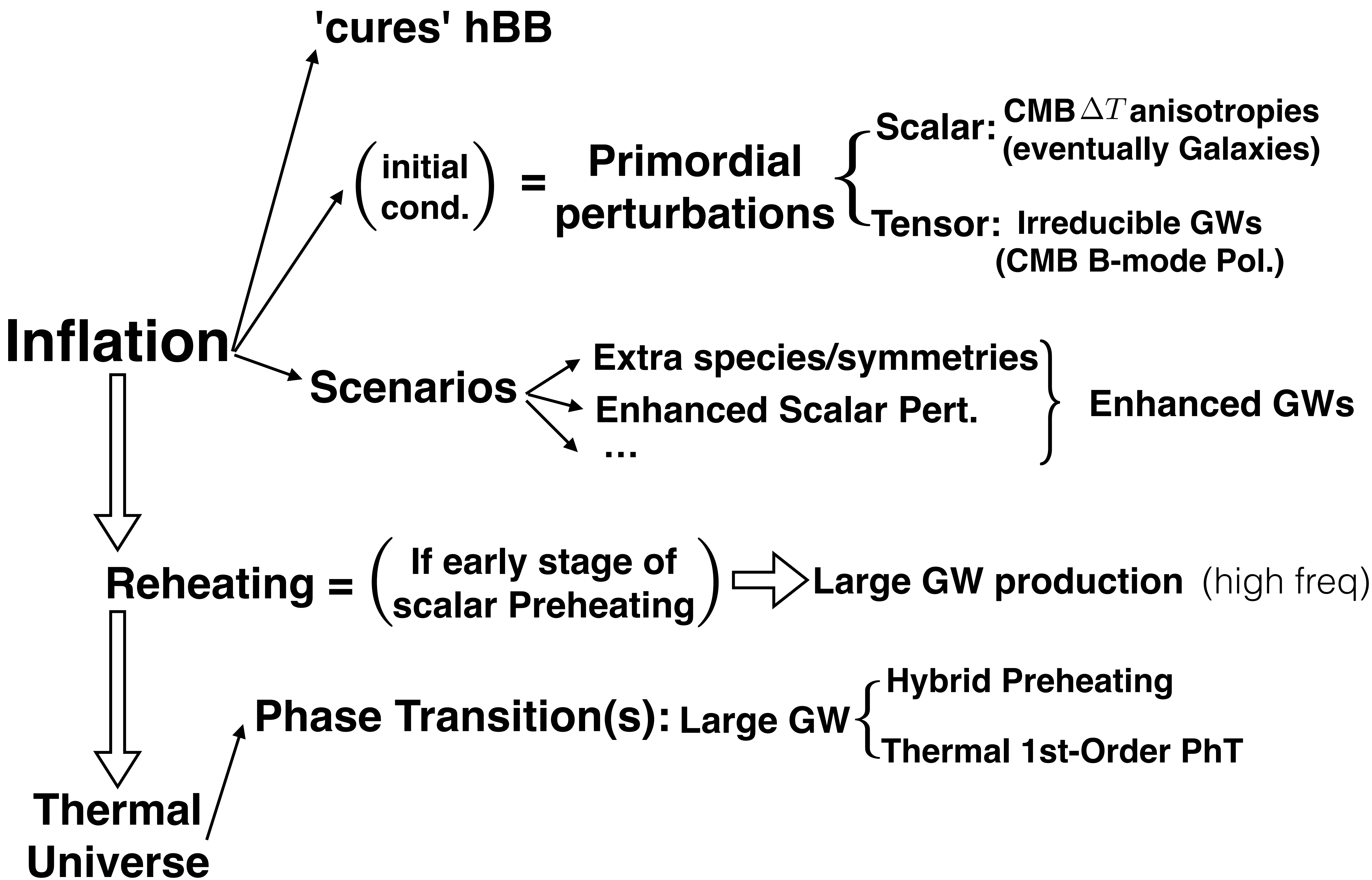


EARLY UNIVERSE



EARLY UNIVERSE

Inflation

- 'cures' hBB
- (initial cond.) = Primordial perturbations
  - Scalar: CMB ΔT anisotropies (eventually Galaxies)
  - Tensor: Irreducible GWs (CMB B-mode Pol.)
- Scenarios
  - Extra species/symmetries
  - Enhanced Scalar Pert.
  - ...
  - Enhanced GWs

Reheating = (If early stage of scalar Preheating) ⇒ Large GW production (high freq)

Thermal Universe

Phase Transition(s): Large GW
- Hybrid Preheating
- Thermal 1st-Order PhT

EARLY UNIVERSE

Inflation

→ 'cures' hBB

→ (initial cond.) = Primordial perturbations
- Scalar: CMB ΔT anisotropies (eventually Galaxies)
- Tensor: Irreducible GWs (CMB B-mode Pol.)

→ Scenarios
- → Extra species/symmetries
- → Enhanced Scalar Pert.
- → ...

} Enhanced GWs

⇓

Reheating = (If early stage of scalar Preheating) ⇒ Large GW production (high freq)

⇓

Thermal Universe

Phase Transition(s): Large GW
- Hybrid Preheating
- Thermal 1st-Order PhT

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Inflation

Scenarios

- Extra species/symmetries
- Enhanced Scalar Pert.
- ...

Enhanced GWs

Reheating = $\begin{pmatrix}\text{If early stage of}\\ \text{scalar Preheating}\end{pmatrix}$ $\Rightarrow$ Large GW production (high freq)

Phase Transition(s): Large GW

- Hybrid Preheating
- Thermal 1st-Order PhT

Thermal Universe

So before going thermal, let's continue (p)reheating !

OUTLINE

1st Bloc

1) Cosmology/GR + GW def. ✓

2nd Bloc

2) GWs from Inflation ✓

3) GWs from Preheating

3rd Bloc

4) GWs from Phase Transitions

5) GWs from Cosmic Defects

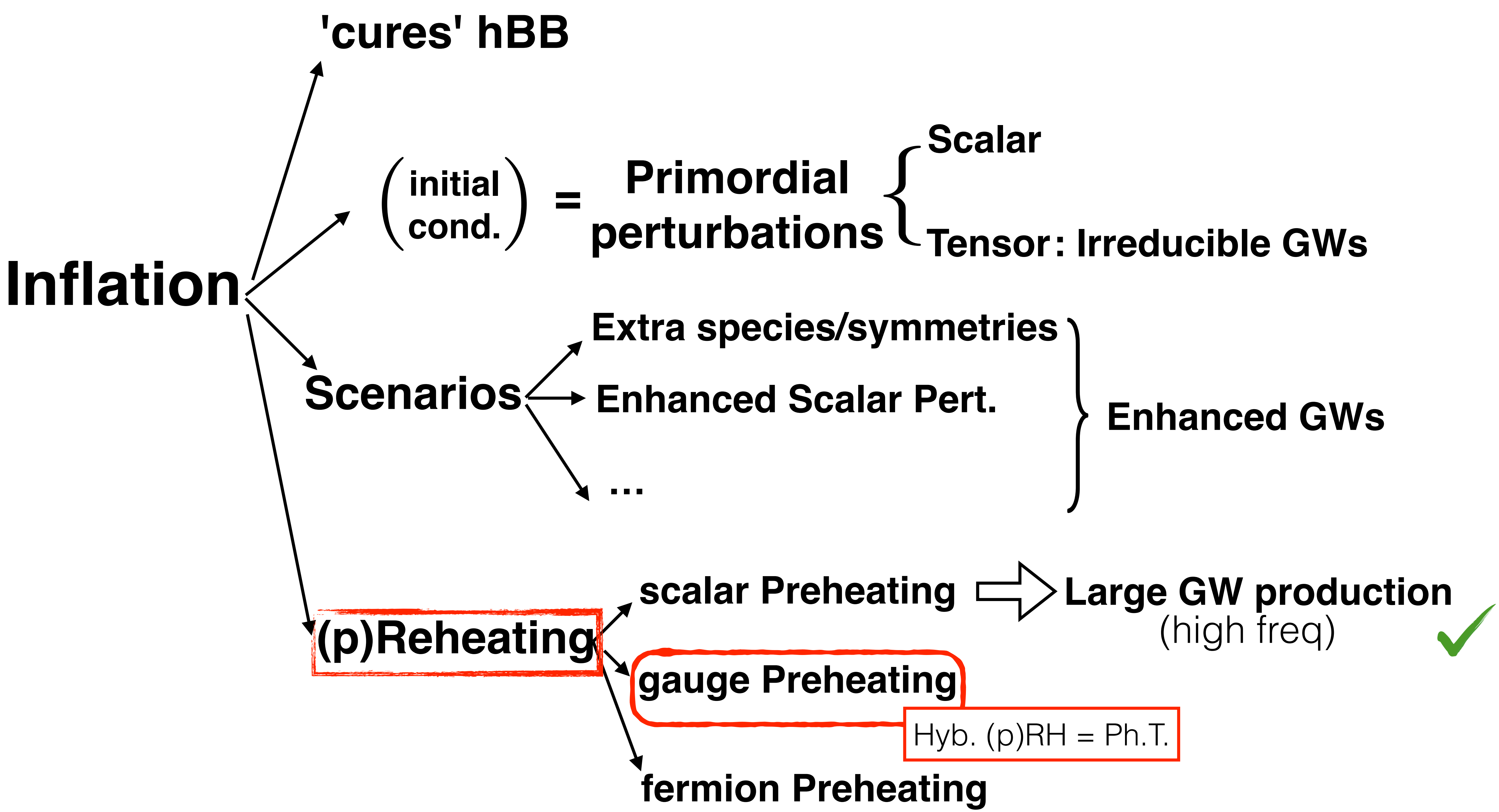
INFLATIONARY COSMOLOGY

Inflation

- 'cures' hBB
- $\begin{pmatrix}\text{initial}\\ \text{cond.}\end{pmatrix}$ = Primordial perturbations
  - Scalar
  - Tensor: Irreducible GWs
- Scenarios
  - Extra species/symmetries
  - Enhanced Scalar Pert.
  - ...

  Enhanced GWs
- (p)Reheating
  - scalar Preheating $\Rightarrow$ Large GW production (high freq)
  - gauge Preheating
  - fermion Preheating

INFLATIONARY COSMOLOGY



GAUGE (P)REHEATING

Hybrid Preheating = Higgs+Inflaton model

inflaton mass

coupling

Self-coupling

V.E.V.

Inflaton: $\ddot{\phi}(t) + (\mu^2 + g^2|\chi|^2)\phi(t) = 0$

Higgs: $\ddot{\chi}_k + \left(k^2 + m^2\left(\frac{\phi^2}{\phi_c^2} - 1\right) + \lambda|\chi|^2\right)\chi_k = 0$

$m = \sqrt{\lambda}v$

$\phi_c \equiv m/g$ Critical value

GAUGE (P)REHEATING

Hybrid Preheating = Higgs+Inflaton model

$$\left.\begin{array}{ll} \textbf{Inflaton:} & \ddot{\phi}(t) + (\mu^2 + g^2|\chi|^2)\phi(t) = 0 \\[2ex] \textbf{Higgs:} & \ddot{\chi}_k + \left(k^2 + m^2\left(\frac{\phi^2}{\phi_c^2} - 1\right) + \lambda|\chi|^2\right)\chi_k = 0 \end{array}\right\}$$

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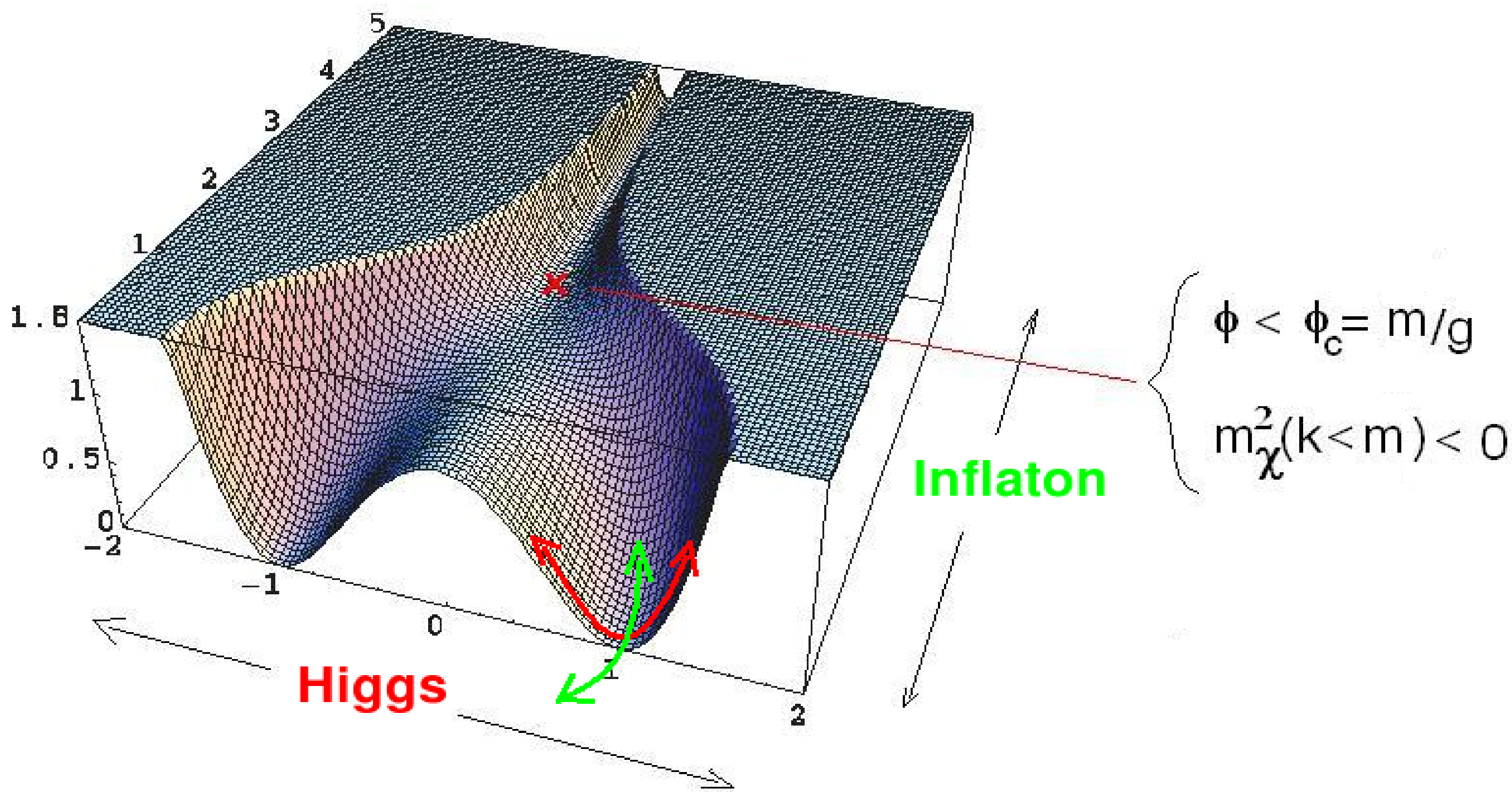
$m = \sqrt{\lambda} v$

$\phi_c \equiv m/g$

Hybrid Preheating = Phase Transition



GAUGE (P)REHEATING

Hybrid Preheating = Higgs+Inflaton model

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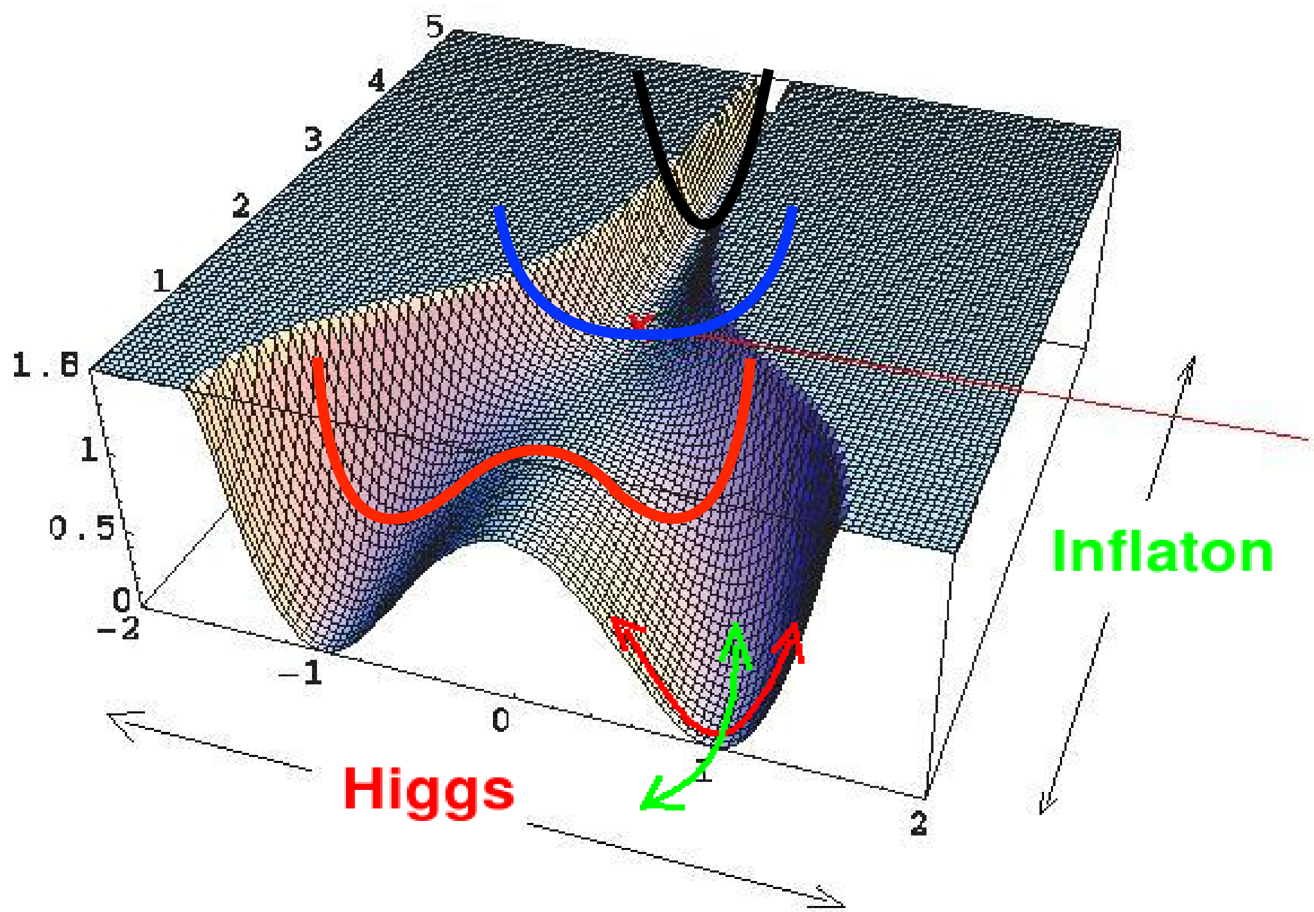
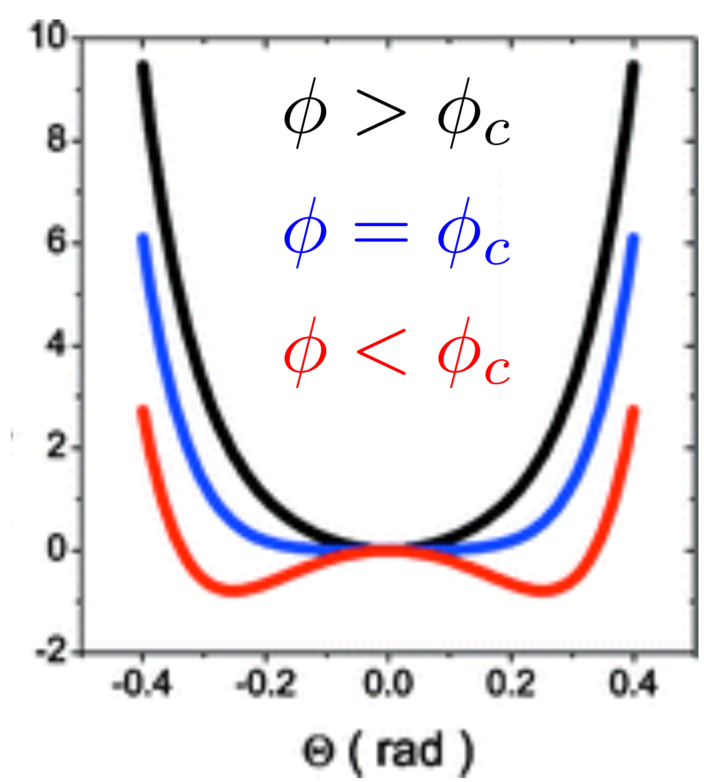
Hybrid Preheating = Phase Transition





GAUGE (P)REHEATING

Hybrid Preheating = Higgs+Inflaton model

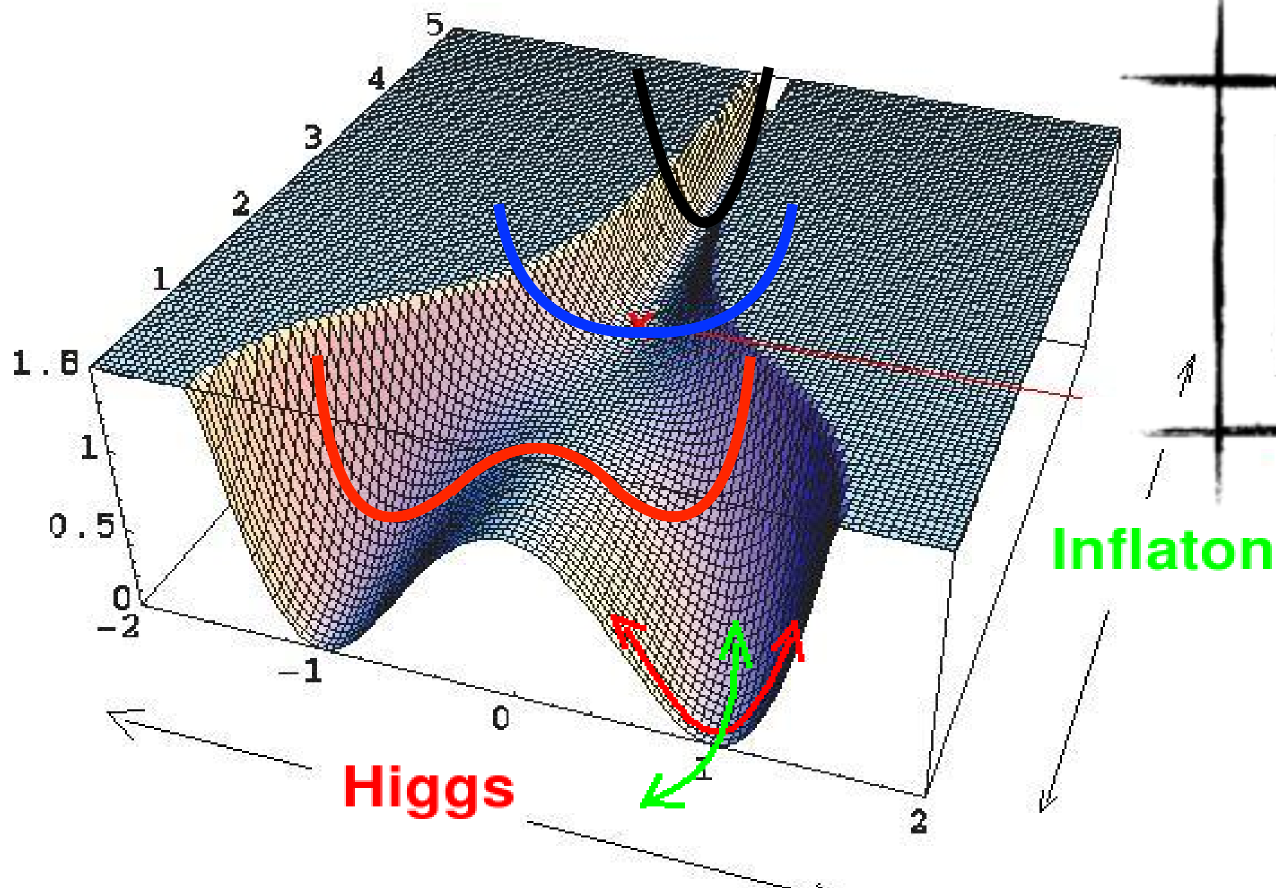
Inflaton: $\ddot{\phi}(t) + (\mu^2 + g^2|\chi|^2)\phi(t) = 0$

Higgs: $\ddot{\chi}_k + \left(k^2 + m^2\left(\frac{\phi^2}{\phi_c^2} - 1\right) + \lambda|\chi|^2\right)\chi_k = 0$

$(k < m = \sqrt{\lambda} v)$

$\chi_k, n_k \sim e^{\sqrt{m^2 - k^2}\, t}$

Hybrid Preheating = Phase Transition



It is a Phase transition !
by Tachyonic Instability

$\langle\chi\rangle = 0 \quad \to \langle\chi\rangle = v$

GAUGE (P)REHEATING

The Abelian-Higgs+Inflaton model

$$L = -\frac{1}{4}F^a_{\mu\nu}F_a^{\mu\nu} + Tr[(D_\mu\Phi)^+ D^\mu\Phi] + \frac{1}{2}(\partial_\mu\chi)^2 - V(\Phi,\chi)$$

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu \qquad D_\mu = \partial_\mu - ieA_\mu$$

$$V(\phi,\chi) = \frac{\lambda}{4}(\phi^2 - v^2)^2 + \frac{g^2}{2}\phi^2\chi^2 + \frac{1}{2}m^2\chi^2$$

Just to confuse you a little bit: now $\begin{cases} \chi : inflaton \\ \Phi = \dfrac{\phi}{\sqrt{2}} : Higgs \end{cases}$

GAUGE (P)REHEATING

The Abelian-Higgs+Inflaton model

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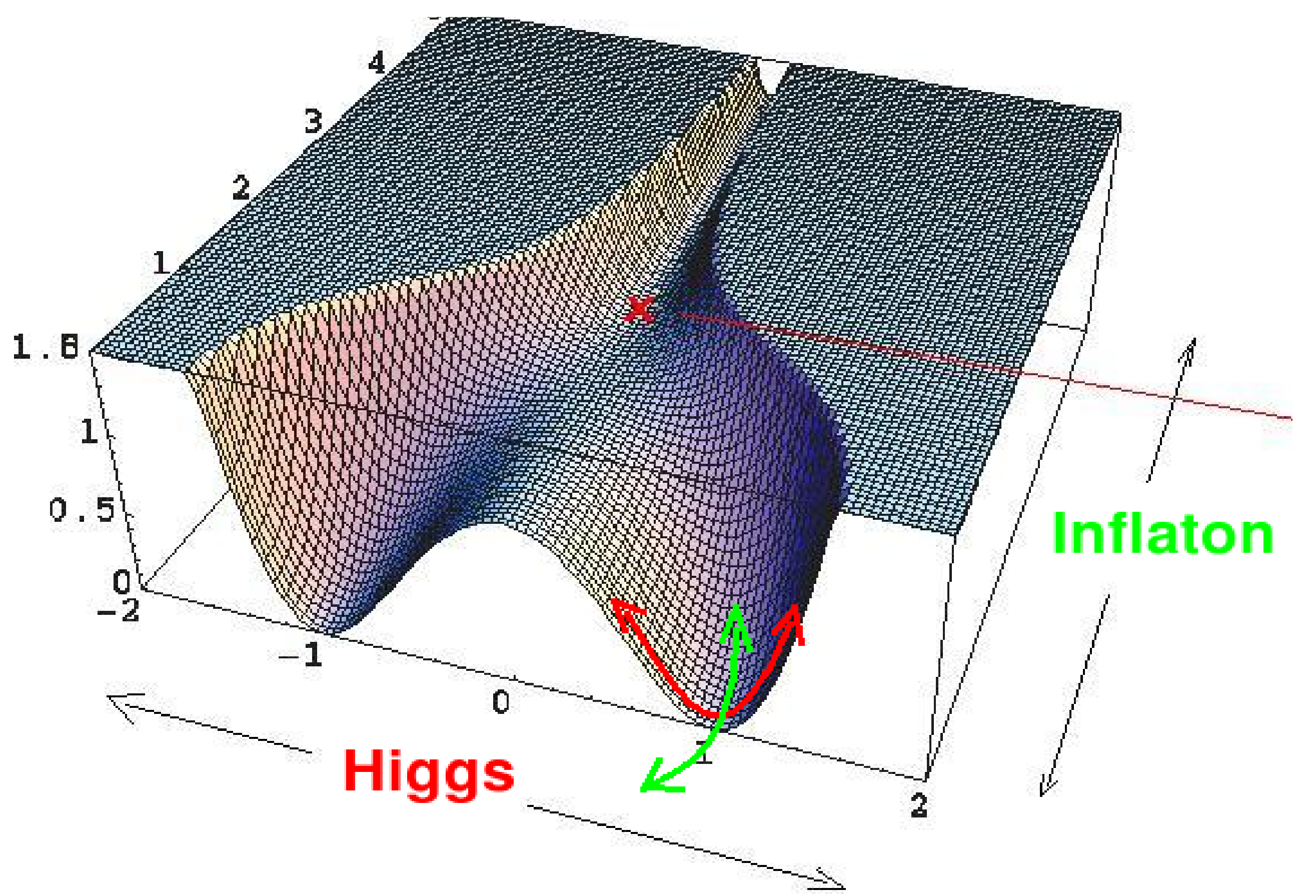

GAUGE (P)REHEATING

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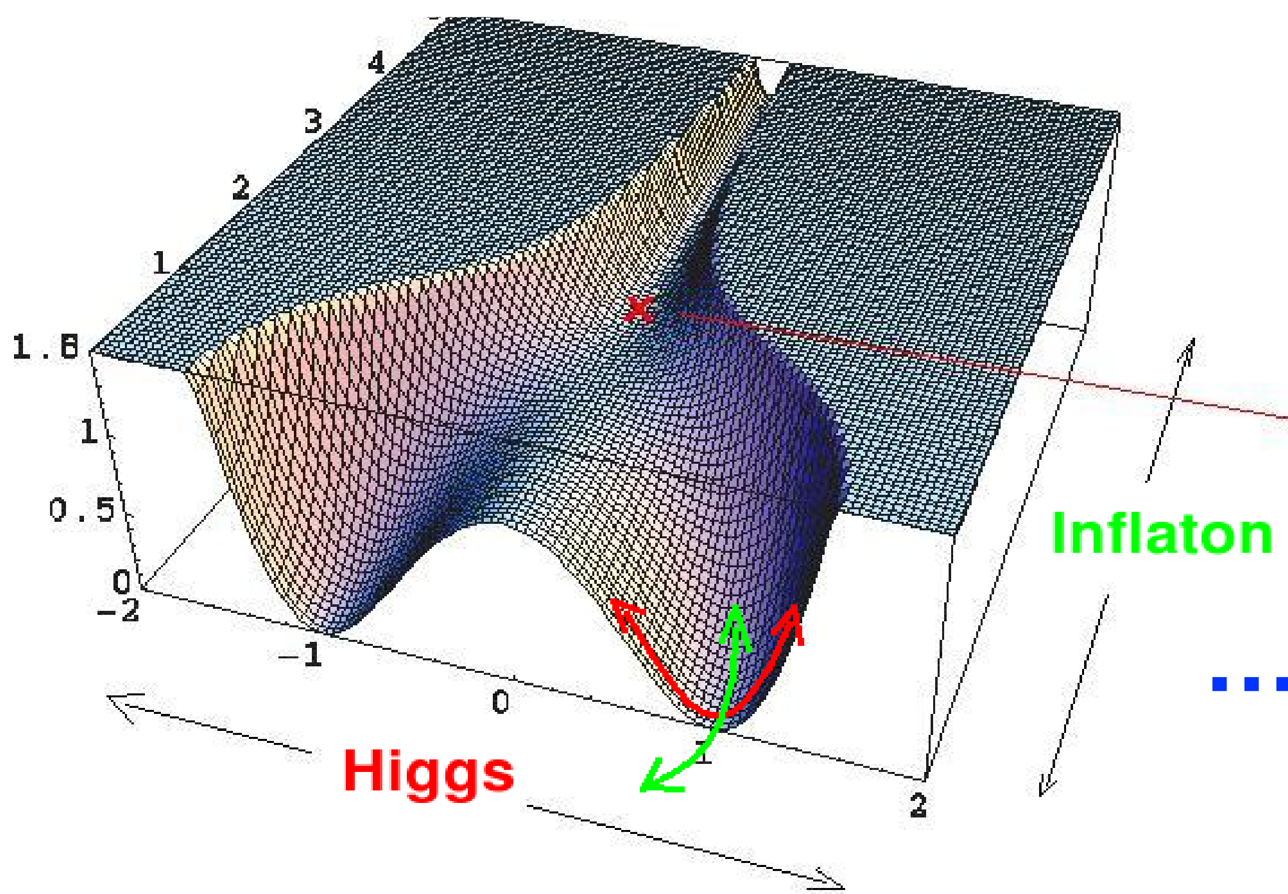

... now there are gauge field(s) !

... so you excite the Higgs, you excite Gauge flds !

GAUGE (P)REHEATING

The Abelian-Higgs+Inflaton model

$$L = -\frac{1}{4} F^{a}_{\mu\nu} F_{a}^{\mu\nu} + Tr[(D_\mu \Phi)^{+} D^{\mu} \Phi] + \frac{1}{2} (\partial_\mu \chi)^2 - V(\Phi, \chi)$$

GAUGE (P)REHEATING

The Abelian-Higgs+Inflaton model

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EOM: $\begin{cases} \text{Minkowski,} \\ \text{Temporal Gauge } (A_0 = 0) \end{cases}$

$$\begin{aligned} \ddot{\varphi} - D_i D_i \varphi + V_{,\varphi^*} &= 0 && \rightarrow \text{SCALARS eom} \\ \ddot{A}_i - \partial_j \partial_j A_i + \partial_i \partial_j A_j &= 2e^2 \, \mathrm{Im} \, [\varphi^* \, D_i \varphi] && \rightarrow \text{VECTORS eom} \\ \partial_i \dot{A}_i &= 2e^2 \, \mathrm{Im} \, [\varphi^* \, \dot{\varphi}] \ . && \rightarrow \text{GAUSS law} \end{aligned}$$

GAUGE (P)REHEATING

The Abelian-Higgs+Inflaton model

$$L = -\frac{1}{4} F^a_{\mu\nu} F_a^{\mu\nu} + Tr[(D_\mu \Phi)^+ D^\mu \Phi] + \frac{1}{2}(\partial_\mu \chi)^2 - V(\Phi, \chi)$$

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→ SCALARS eom

→ VECTORS eom

→ GAUSS law

GW EOM

$$\ddot{h}_{ij} - \partial_k \partial_k h_{ij} = 16\pi G\, \Pi^{TT}_{ij}$$

$$\Pi^{TT}_{ij} = \left[\partial_i \chi \partial_j \chi + 2\,\mathrm{Re}\left[D_i \varphi\,(D_j \varphi)^*\right] - B_i B_j - E_i E_j\right]^{TT}$$

GAUGE (P)REHEATING

The Abelian-Higgs+Inflaton model

$$L = -\frac{1}{4}F^a_{\mu\nu}F_a^{\mu\nu} + Tr[(D_\mu\Phi)^+ D^\mu\Phi] + \frac{1}{2}(\partial_\mu\chi)^2 - V(\Phi,\chi)$$

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→ SCALARS eom

→ VECTORS eom

→ GAUSS law

GW EOM

$$\ddot{h}_{ij} - \partial_k\partial_k h_{ij} = 16\pi G\,\Pi^{TT}_{ij}$$

$$\Pi^{TT}_{ij} = \left[\partial_i\chi\partial_j\chi + 2\,\mathrm{Re}\,[D_i\varphi\,(D_j\varphi)^*] - B_iB_j - E_iE_j\right]^{TT}$$

COVARIANT

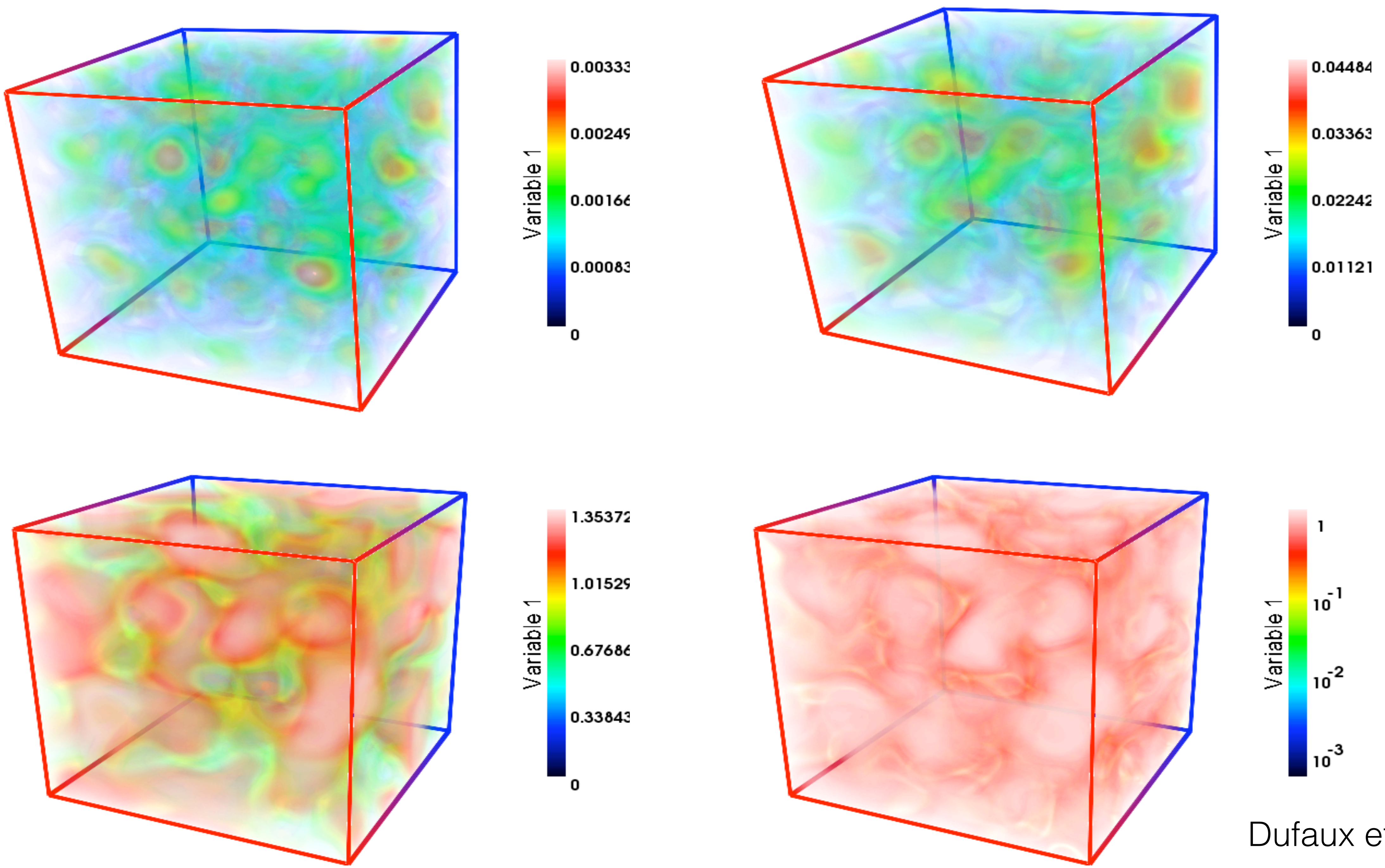
MAGNETIC

ELECTRIC

GAUGE (P)REHEATING

The Abelian-Higgs+Inflaton model

DYNAMICS OF THE HIGGS: $\mathrm{mt} = 5.5 \to \mathrm{mt} = 23$

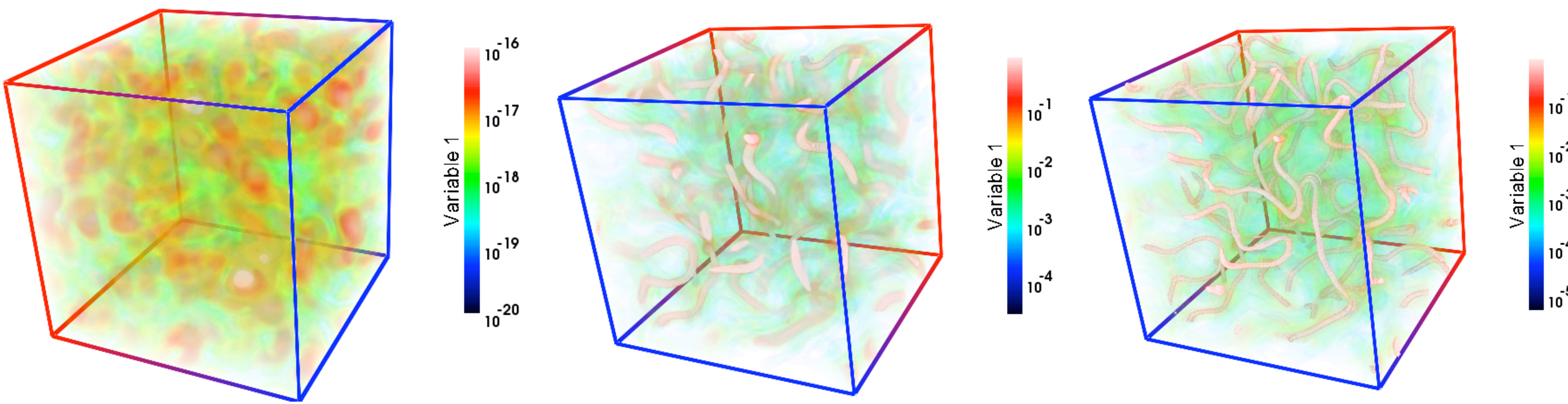


Dufaux et al 2010

GAUGE (P)REHEATING

The Abelian-Higgs+Inflaton model

DYNAMICS OF THE MAGNETIC FIELD: $mt = 5.5 \to mt = 17$



Dufaux et al 2010

GAUGE (P)REHEATING

The Abelian-Higgs+Inflaton model

$$L = -\frac{1}{4} F^{a}_{\mu\nu} F_{a}^{\mu\nu} + Tr[(D_{\mu}\Phi)^{+} D^{\mu}\Phi] + \frac{1}{2}(\partial_{\mu}\chi)^{2} - V(\Phi, \chi)$$

What's going on !?

Cosmic Strings are formed

GAUGE (P)REHEATING

The Abelian-Higgs+Inflaton model

$$L = -\frac{1}{4} F^{a}_{\mu\nu} F_{a}^{\mu\nu} + Tr[(D_\mu \Phi)^{+} D^{\mu} \Phi] + \frac{1}{2}(\partial_{\mu}\chi)^2 - V(\Phi, \chi)$$

What's going on !?

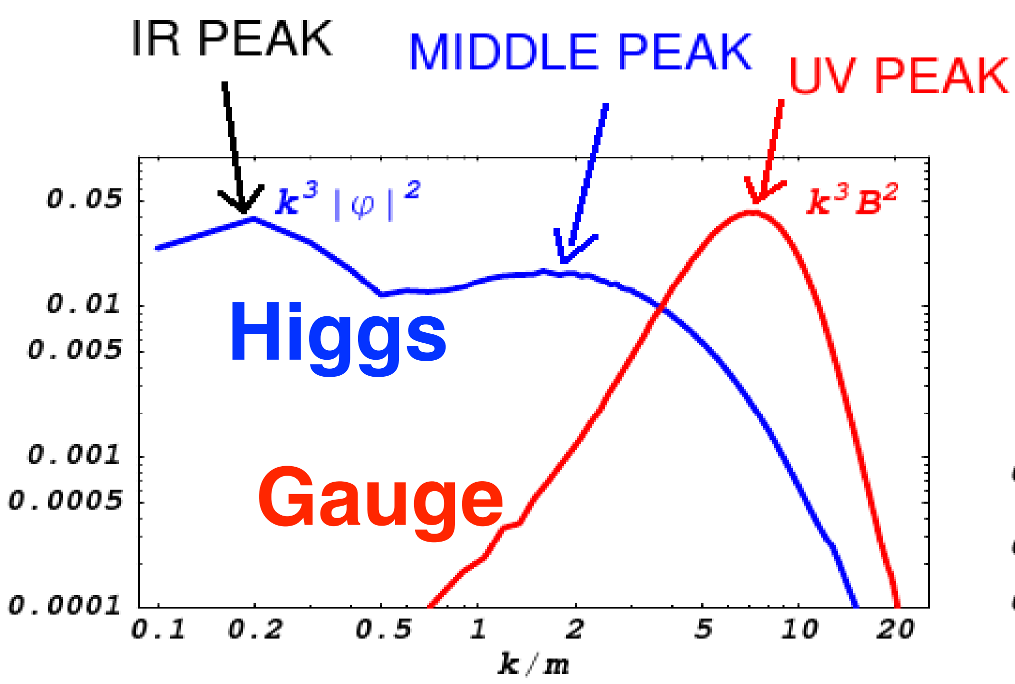
Cosmic Strings are formed

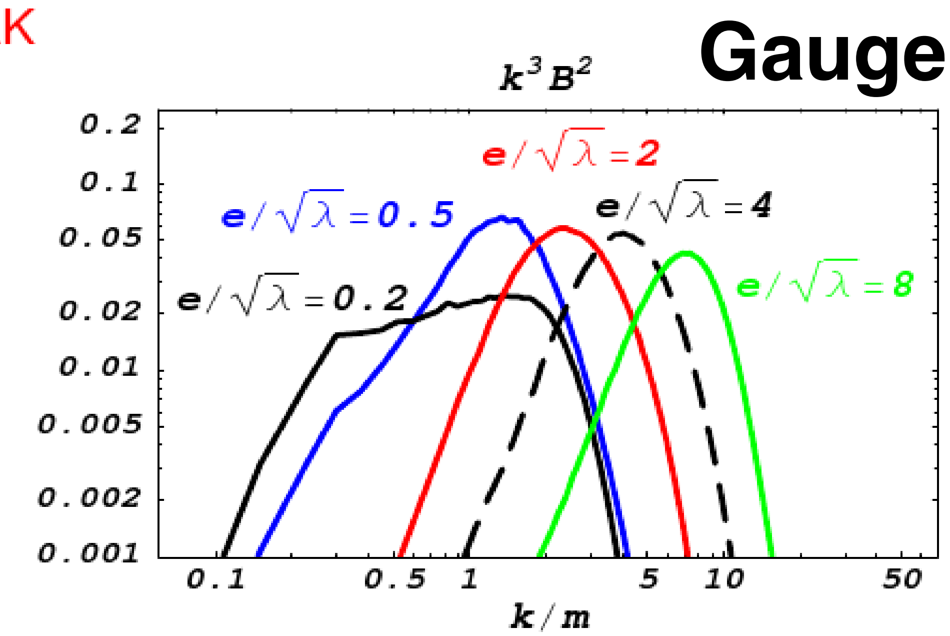
(Topological Defects $\longrightarrow$ 5th Lecture)

GAUGE (P)REHEATING

The Abelian-Higgs+Inflaton model

SCALARS AND VECTORS' SPECTRA:

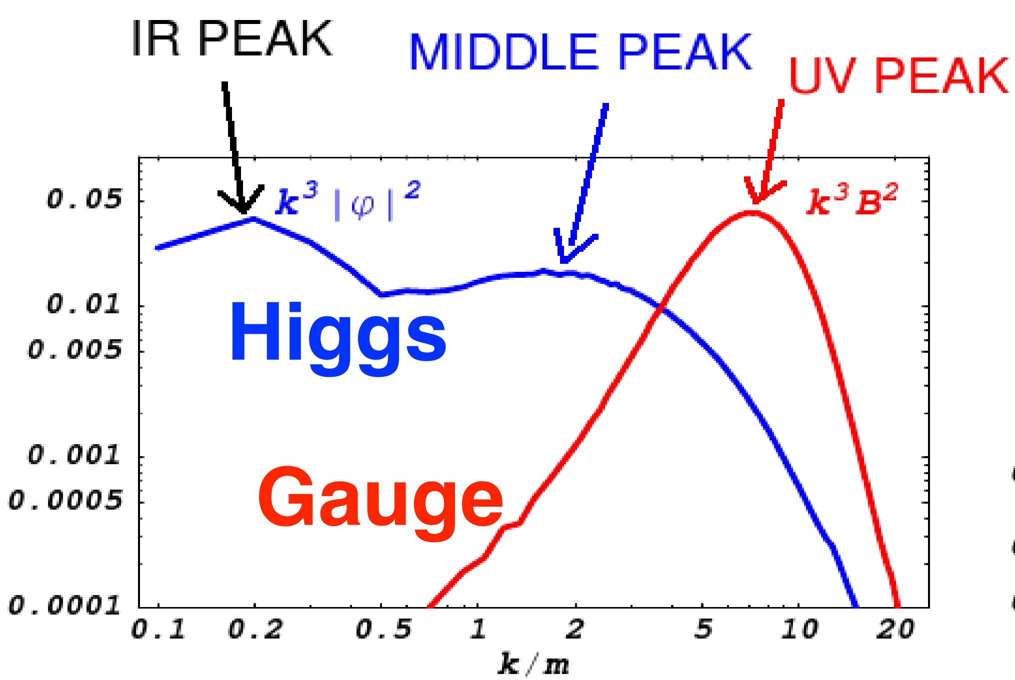


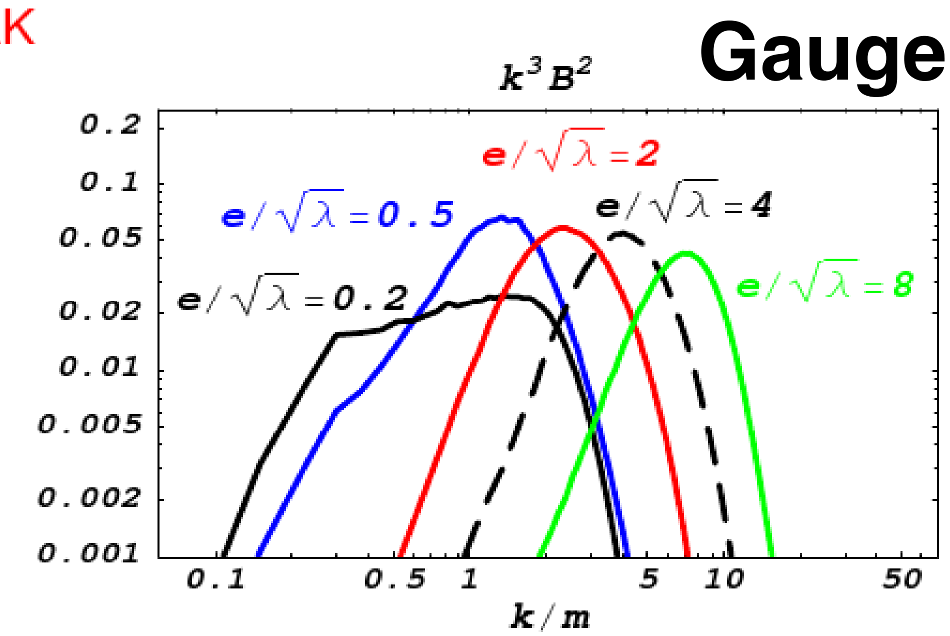


GAUGE (P)REHEATING

The Abelian-Higgs+Inflaton model

SCALARS AND VECTORS' SPECTRA:





PARAMETERS ABELIAN-HIGGS Model: $m \equiv \sqrt{\lambda} v,\ \lambda/g^2,\ e/\sqrt{\lambda},\ V_c$

MIDDLE PEAK: $\left\{ \begin{array}{l} \text{Higgs mass} \\ \text{(Inflaton Velocity)}^{1/3} \end{array} \right\}$ --> Tachyonic Scale, Bubbles' Size

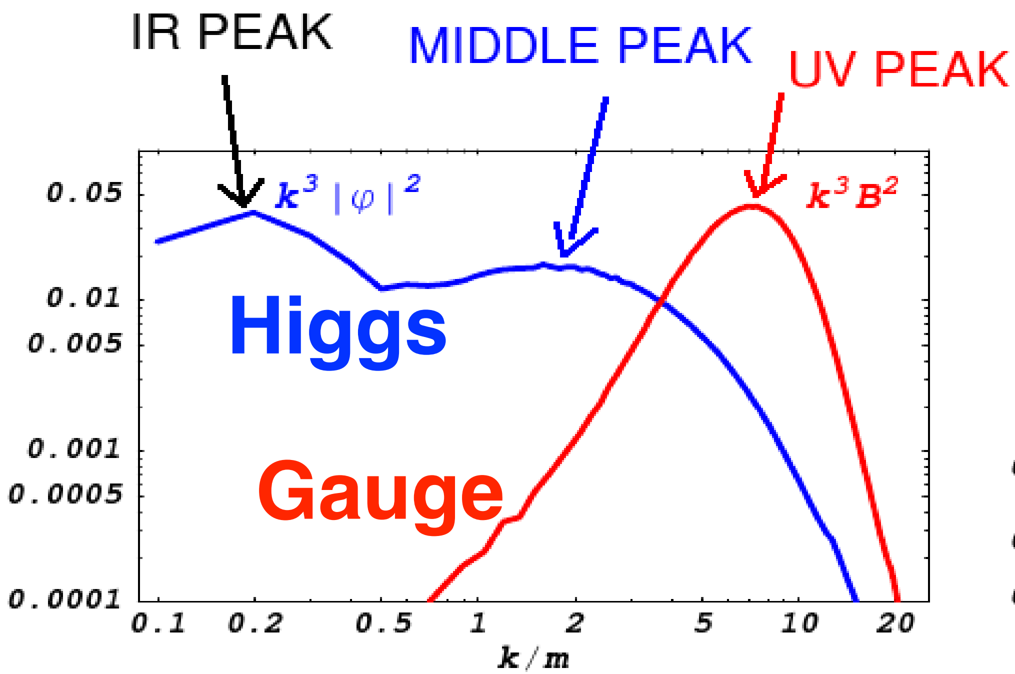
IR PEAK : Inflaton Velocity, Higgs+Inflaton Couplings (Dufaux et al 2009)

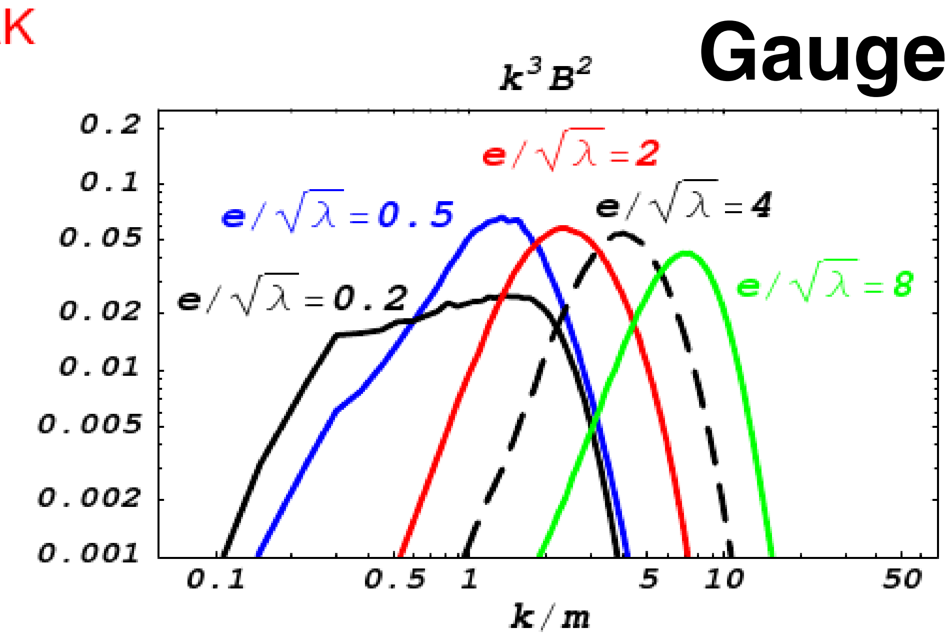
UV PEAK: Vector mass / Higgs Mass

GAUGE (P)REHEATING

The Abelian-Higgs+Inflaton model

SCALARS AND VECTORS' SPECTRA:





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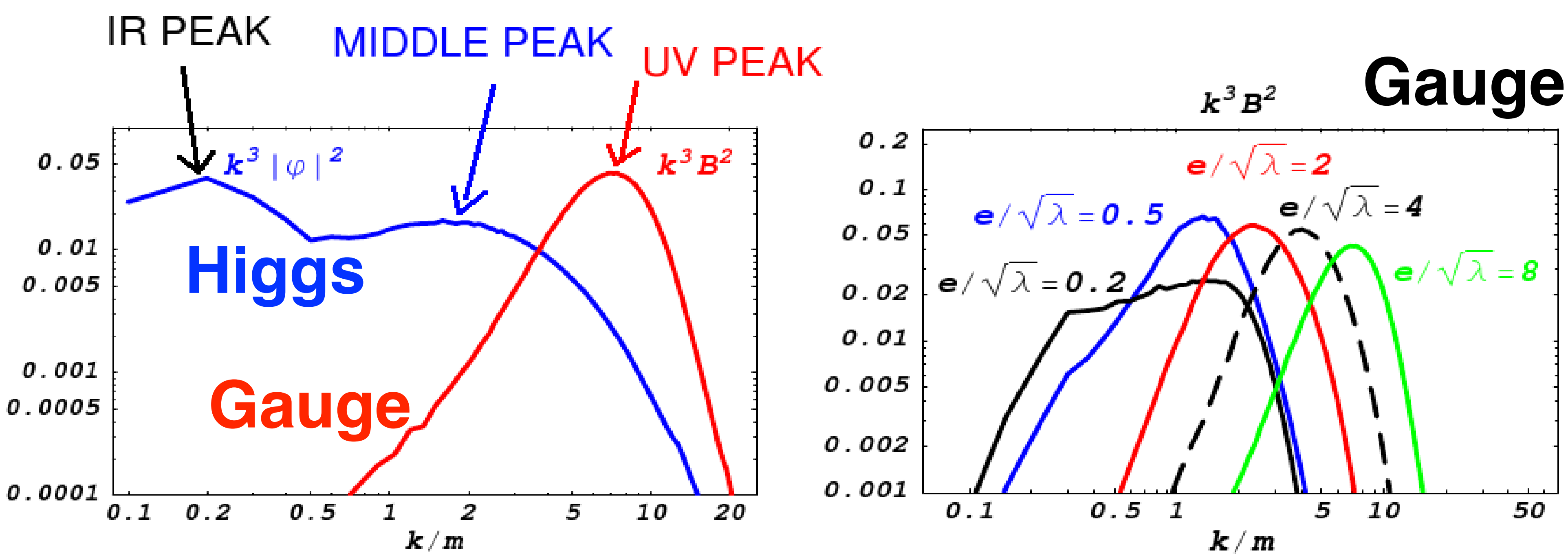
GAUGE (P)REHEATING

The Abelian-Higgs+Inflaton model

SCALARS AND VECTORS' SPECTRA:



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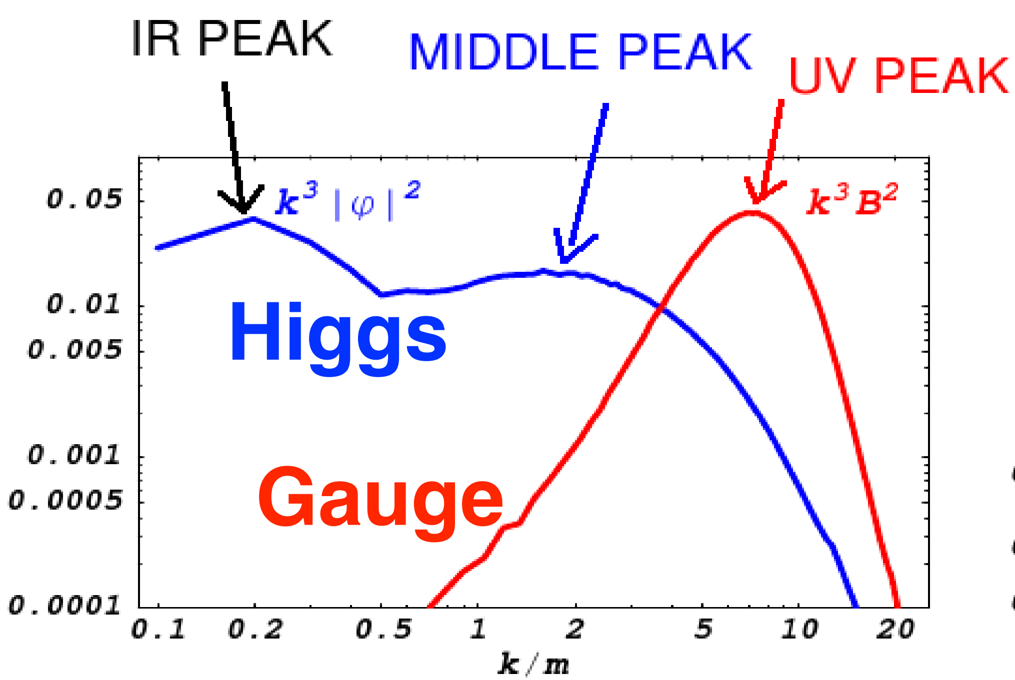
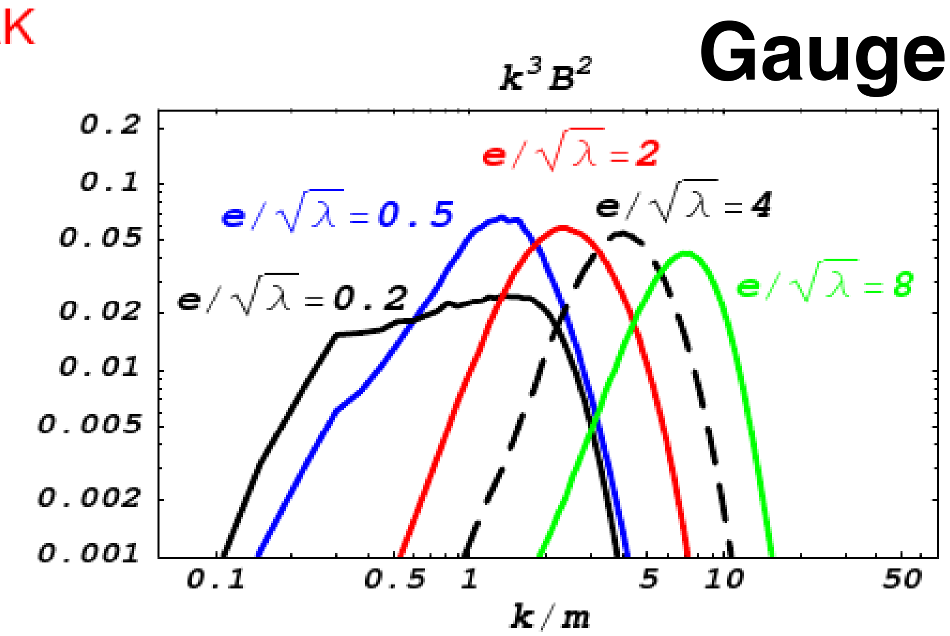
GAUGE (P)REHEATING

The Abelian-Higgs+Inflaton model

SCALARS AND VECTORS' SPECTRA:





PARAMETERS ABELIAN-HIGGS Model: $m \equiv \sqrt{\lambda} v$, λ/g^2, $e/\sqrt{\lambda}$, V_c

MIDDLE PEAK: $\left\{ \begin{array}{l} \text{Higgs mass} \\ \text{(Inflaton Velocity)}^{1/3} \end{array} \right\}$ --> Tachyonic Scale, Bubbles' Size

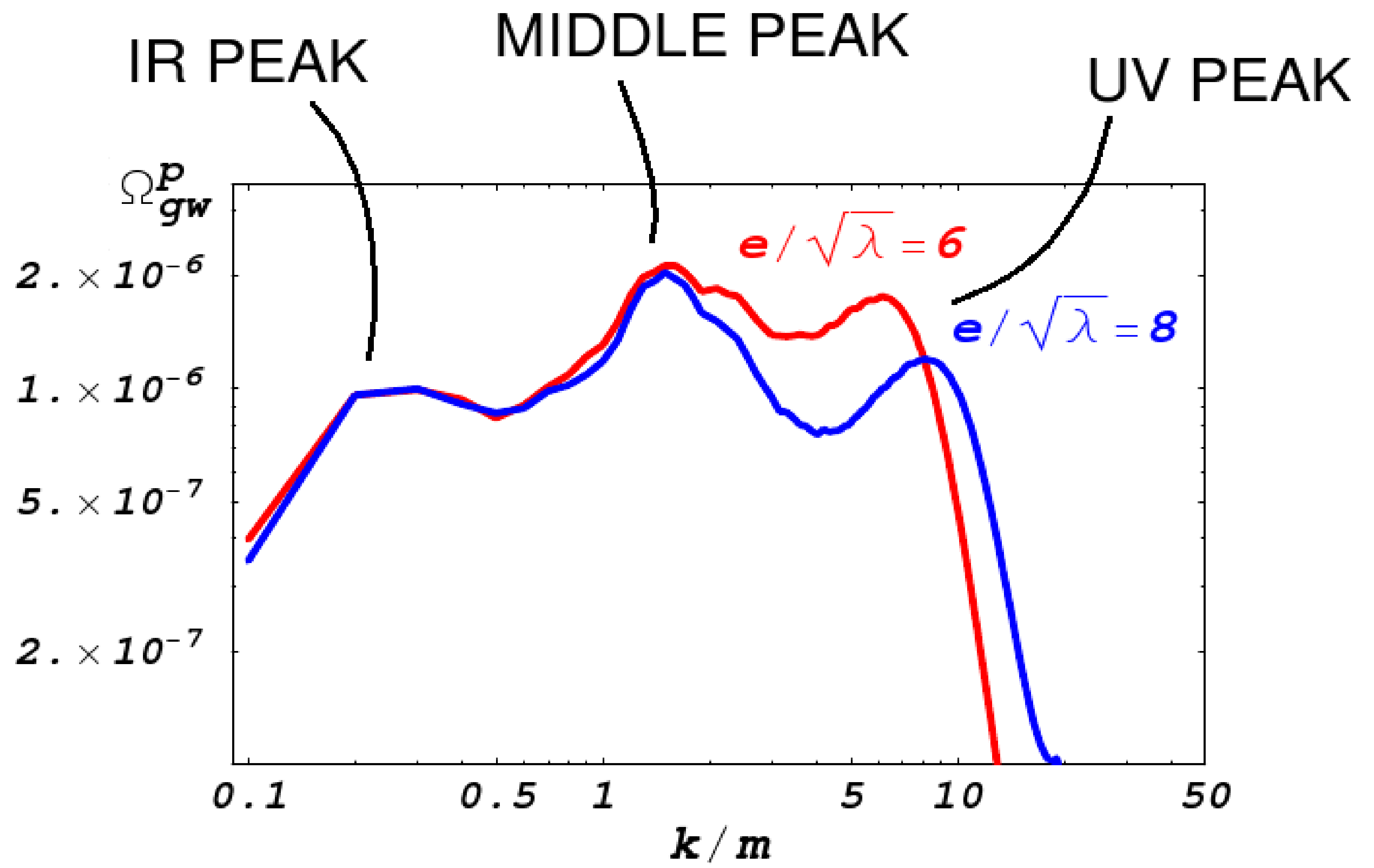
IR PEAK : Inflaton Velocity, Higgs+Inflaton Couplings

UV PEAK: Vector mass / Higgs Mass

GAUGE (P)REHEATING

The Abelian-Higgs+Inflaton model

GRAVITATIONAL WAVES SPECTRA:

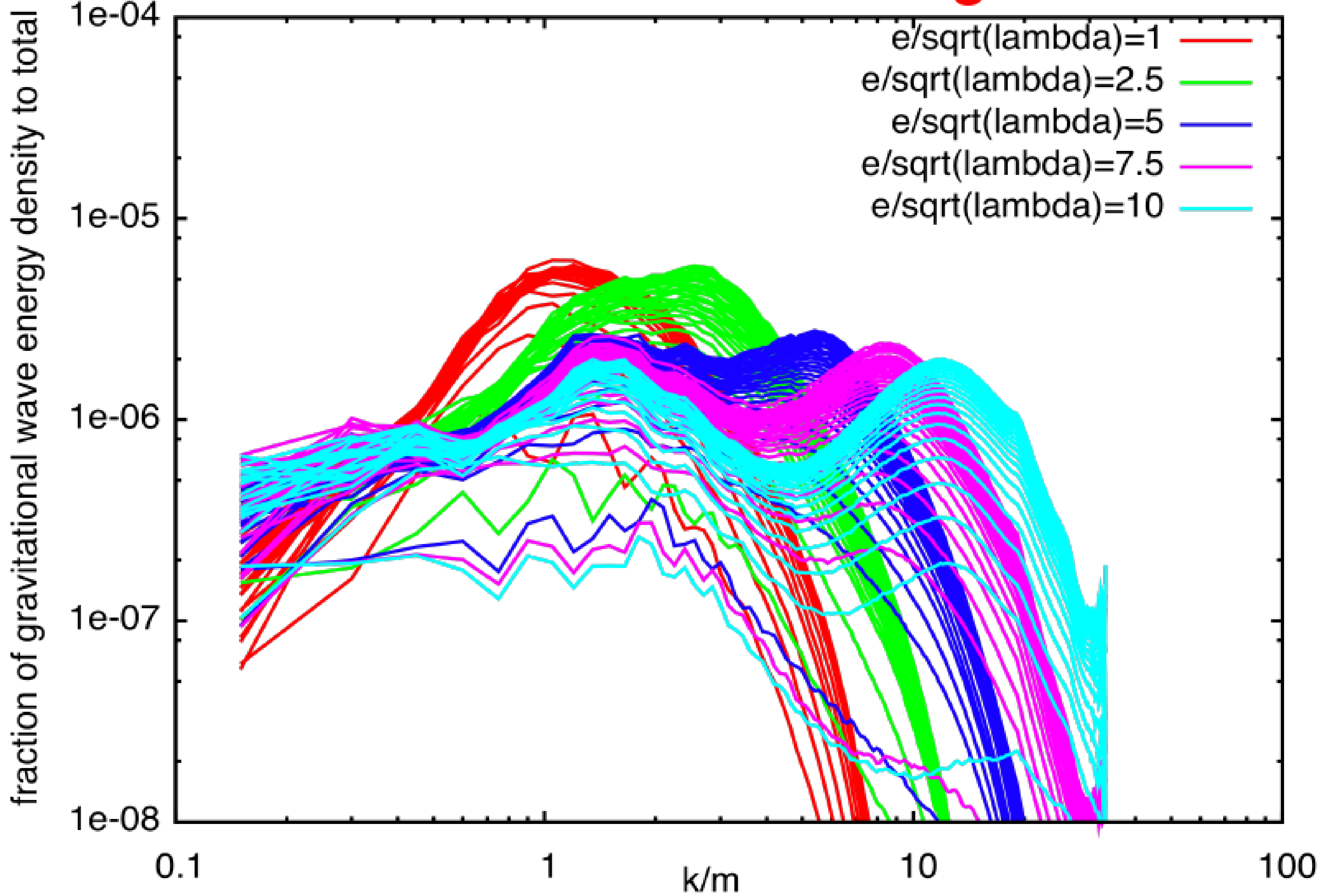


GAUGE (P)REHEATING

The Abelian-Higgs+Inflaton model

GRAVITATIONAL WAVES SPECTRA:

Evolution of GW background



GAUGE (P)REHEATING

The Abelian-Higgs+Inflaton model

GW SPECTRA: ANALYTICS:

IR and Middle Peaks' Amplitude: F(g, λ, V_c)

UV peak Amplitude: Lattice Simulations

$$f_1 \lesssim f\,(g, \lambda, V_c) \qquad \text{(IR peak)}$$

$$f_2 \approx \lambda^{1/4}\, 10^{11}\,\text{Hz} \qquad \text{(Middle peak)}$$

$$f_3 \approx \frac{e}{\sqrt{\lambda}}\, \lambda^{1/4}\, 10^{11}\,\text{Hz} \qquad \text{(UV peak)}$$

RED-SHIFTED

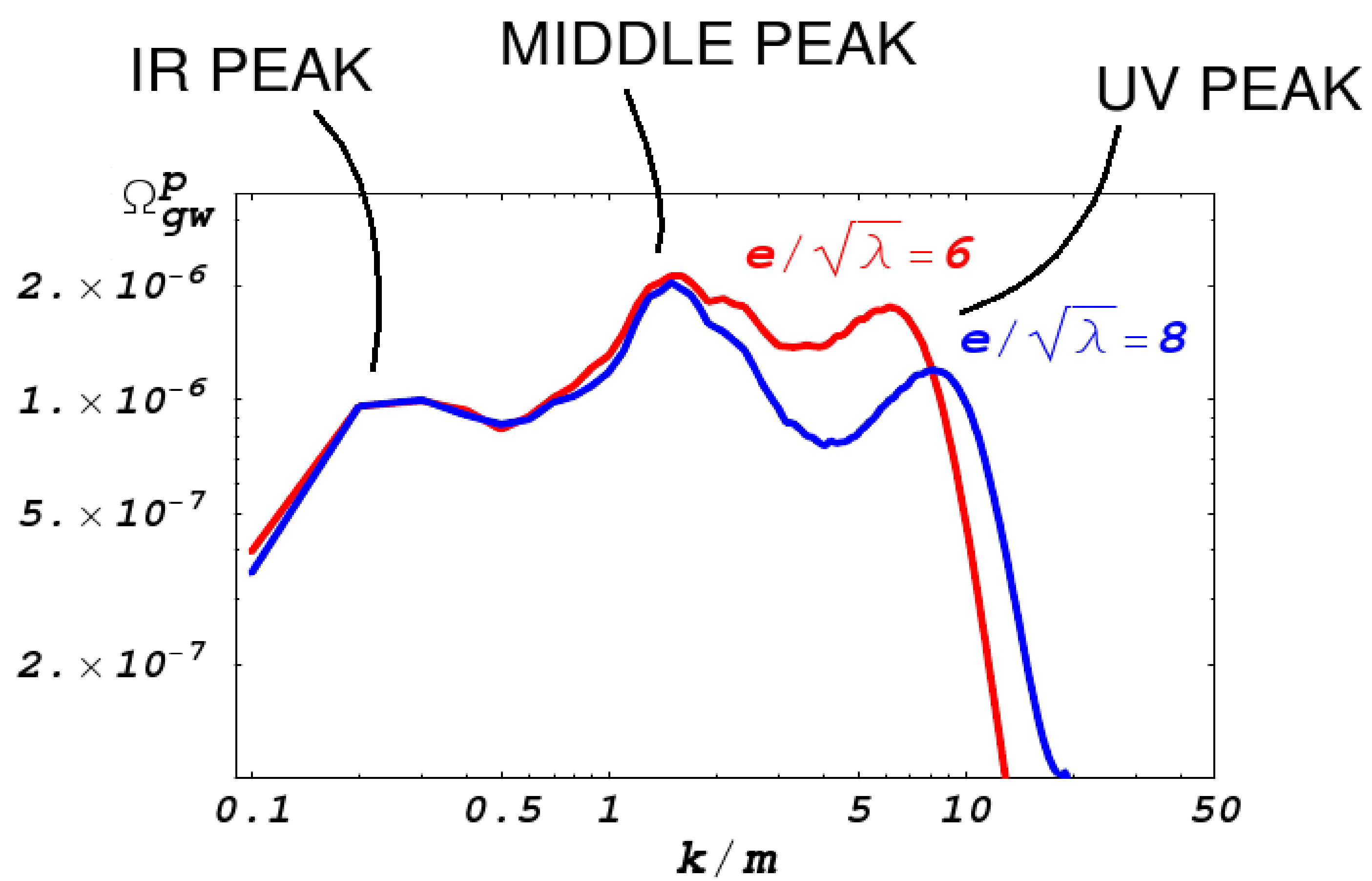
FREQUENCIES

$f\,(g, \lambda, V_c) \longrightarrow$ Dufaux et al '09

GAUGE (P)REHEATING

The Abelian-Higgs+Inflaton model

Several Peaks !
(particle physics spectroscopy)



GAUGE (P)REHEATING

The Abelian-Higgs+Inflaton model

Several Peaks !
(particle physics
spectroscopy)

$$\Omega_{\rm GW}^{(o)} \sim 10^{-11}\,,$$

Large amplitude(s) !

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$$\Omega_{\rm GW}^{(o)} \sim 10^{-11}\,, \quad @ \quad f_o \sim 10^8 - 10^9 \text{ Hz}$$

Large amplitude(s) !   ... but at high Frequency !

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Very unfortunate... no high frequency detectors !

  

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Large amplitude(s) ! ... but at high Frequency !

We Should look for this effect at low-freq models !

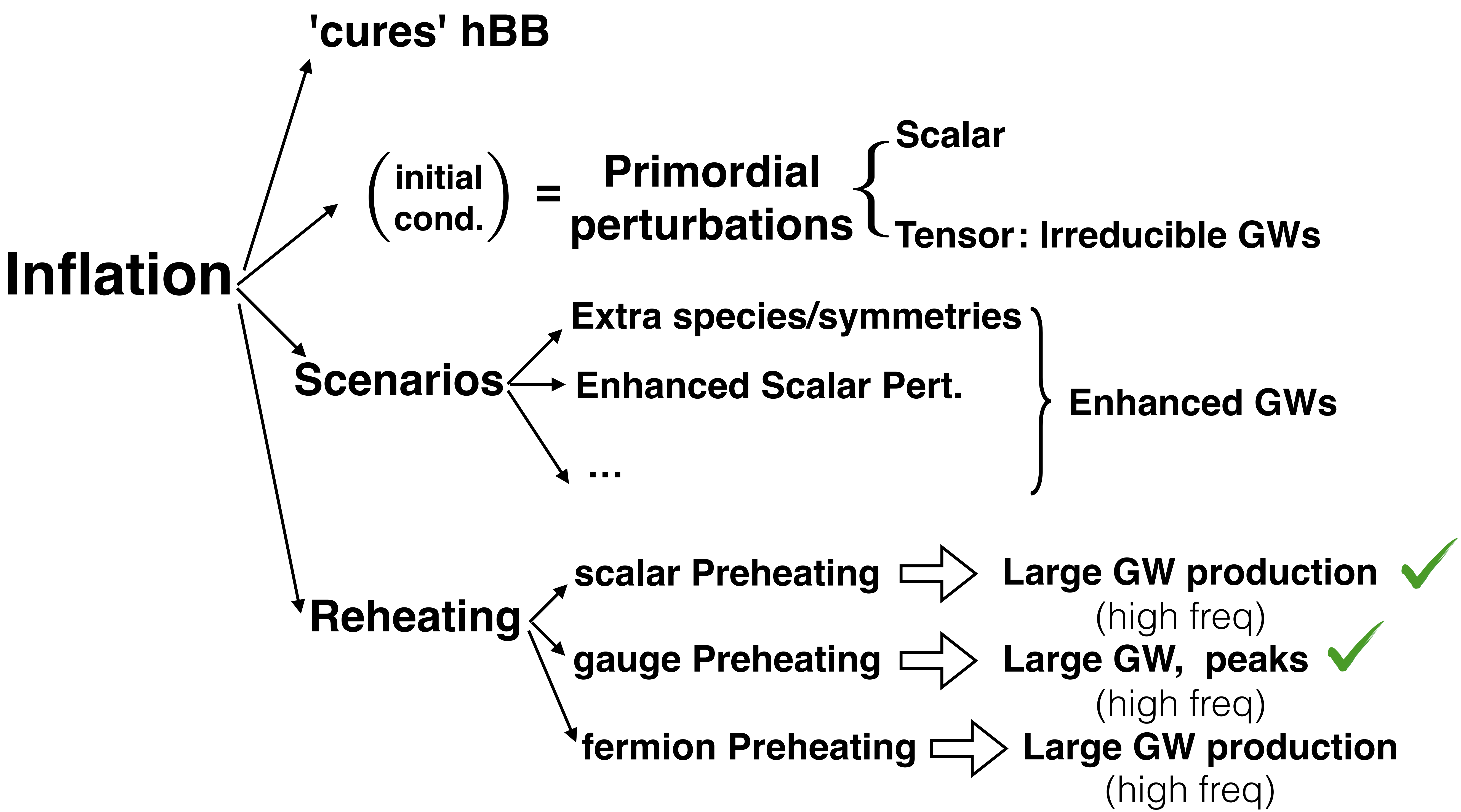
Very unfortunate... no high frequency detectors !

INFLATIONARY COSMOLOGY

Inflation

- 'cures' hBB
- (initial cond.) = Primordial perturbations
  - Scalar
  - Tensor: Irreducible GWs
- Scenarios → Enhanced GWs
  - Extra species/symmetries
  - Enhanced Scalar Pert.
  - ...
- Reheating
  - scalar Preheating ⇒ Large GW production ✓ (high freq)
  - gauge Preheating ⇒ Large GW, peaks ✓ (high freq)
  - fermion Preheating

INFLATIONARY COSMOLOGY



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1203.4943
1306.6911

INFLATIONARY COSMOLOGY

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  - ...
  - (all of the above) → Enhanced GWs
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  - scalar Pr
  - gau
  - fern

More things on RH:

$* \ \mathrm{SM}\ (\Phi, \Psi_a, A_\mu)$

$* \ \mathrm{GW\ \ anisotropies}$

INFLATIONARY COSMOLOGY

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More things on RH:

0812.3622 + 0812.4624

$* \ \mathrm{SM}$

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* SM

1304.2657 + 1309.1148

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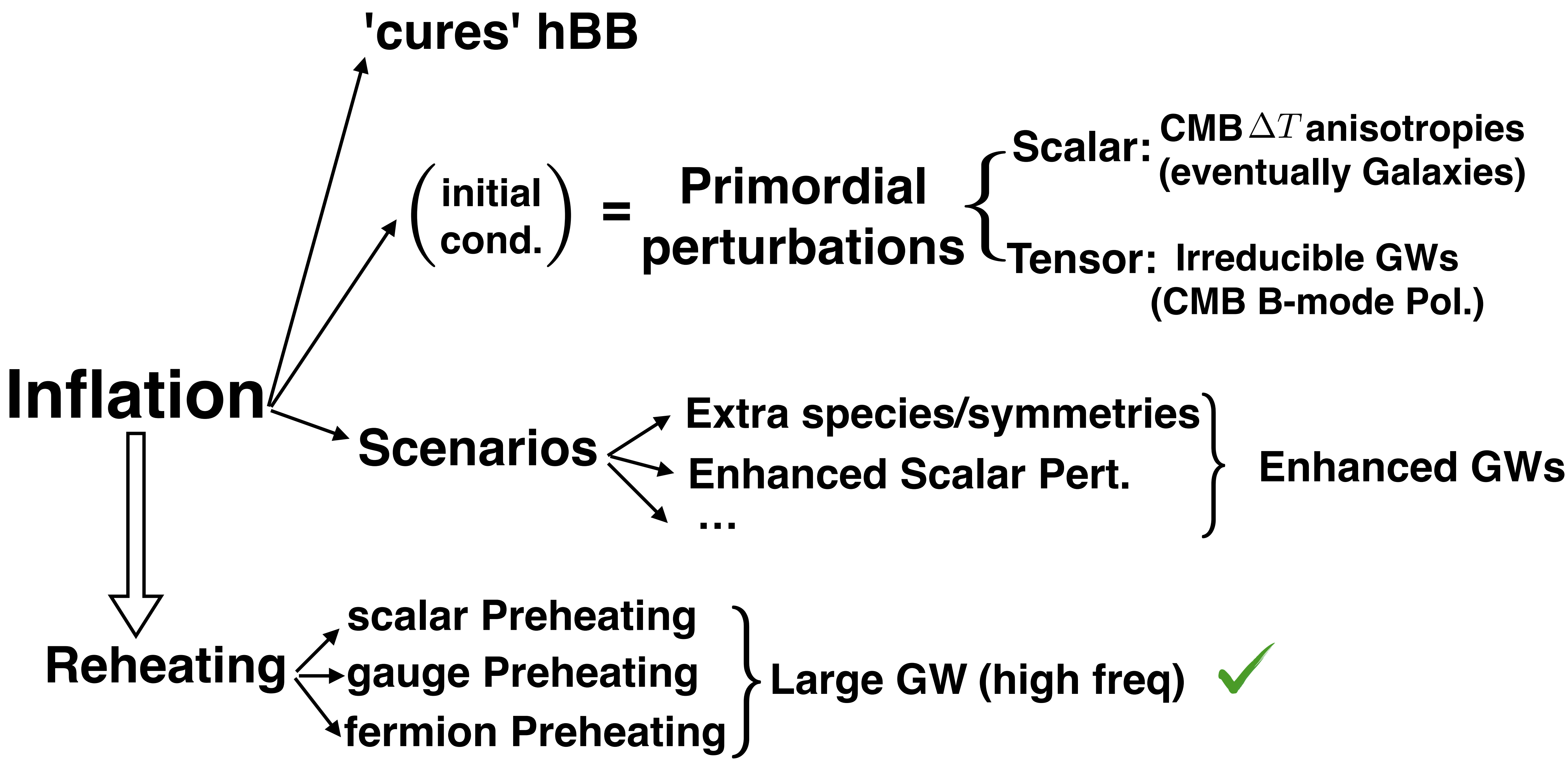
EARLY UNIVERSE



EARLY UNIVERSE

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- Scalar: CMB ΔT anisotropies (eventually Galaxies)
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Scenarios

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Enhanced GWs

Reheating

- scalar Preheating
- gauge Preheating
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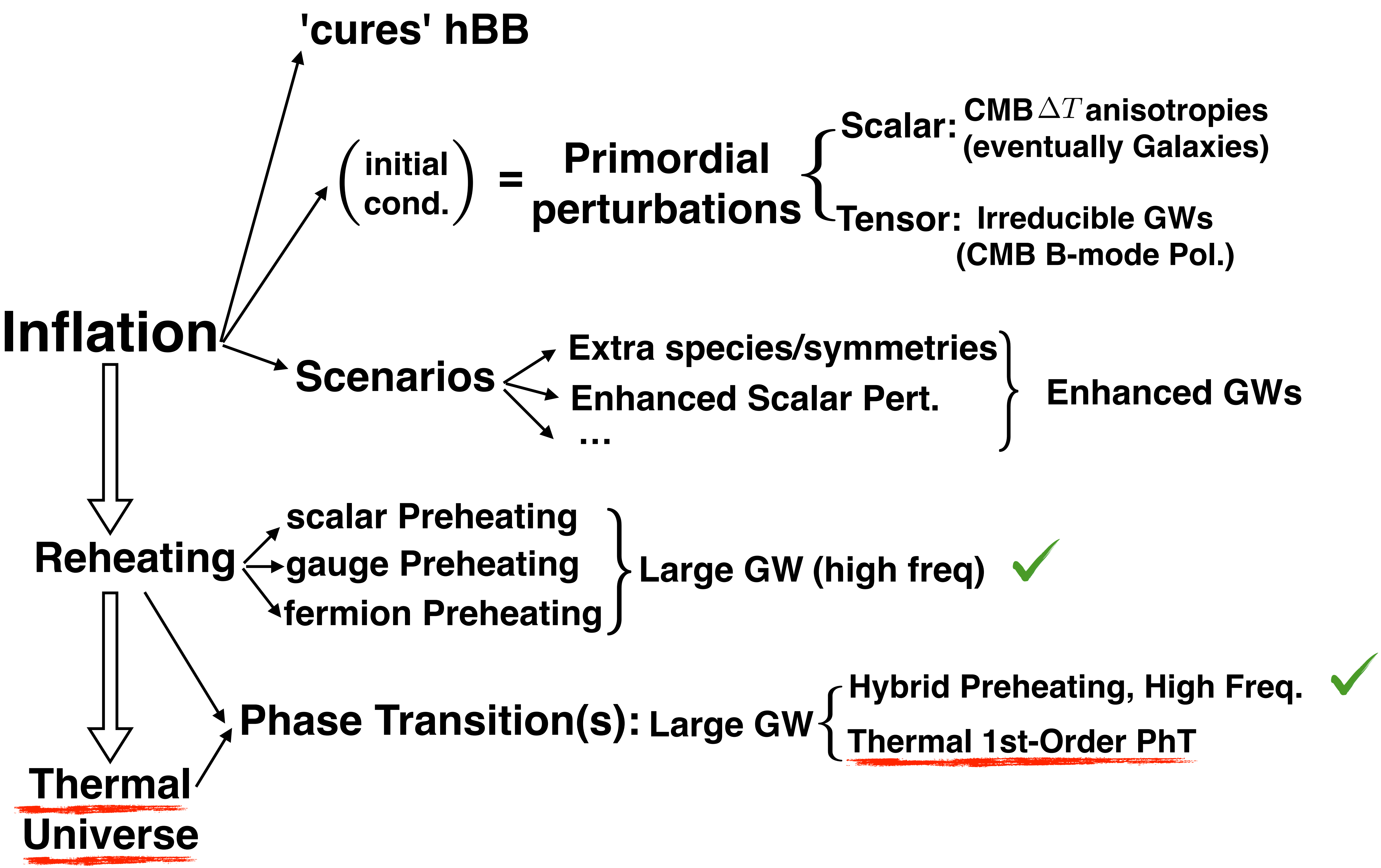
Large GW (high freq)

Phase Transition(s): Large GW

- Hybrid Preheating, High Freq.

EARLY UNIVERSE



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Phase Transition(s): Large GW

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Thermal 1st-Order PhT

Thermal Universe

GWs from first order phase transitions

* **GW causal source**: cannot 'operate' beyond the **horizon**

$$\boxed{f_* = \frac{H(T_*)}{\epsilon_*}}$$

$$\boxed{\epsilon_* \leq 1}$$

parameter characterising source

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Hubble rate $\updownarrow$ temperature

$$\underset{\text{@ Today}}{f_c} = \underset{\text{@ Emission time}}{f_*}\frac{a_*}{a_0} = \frac{2 \cdot 10^{-5}}{\epsilon_*}\frac{T_*}{1\,\mathrm{TeV}}\,\mathrm{Hz}$$

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for $\boxed{\epsilon_* \simeq 10^{-2}}$ $\boxed{T_* \simeq 1\,\mathrm{TeV}}$

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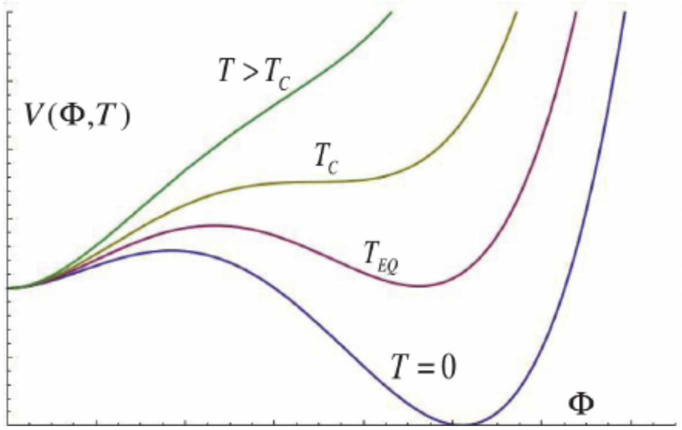
LISA Freq !

for $\boxed{\epsilon_* \simeq 10^{-2}}$ $\boxed{T_* \simeq 1\,\mathrm{TeV}}$ **~ EW scale !**

GWs from first order phase transitions

Universe expands, temperature decreases: phase transition triggered !

* Potential barrier separates
true and **false** vacua



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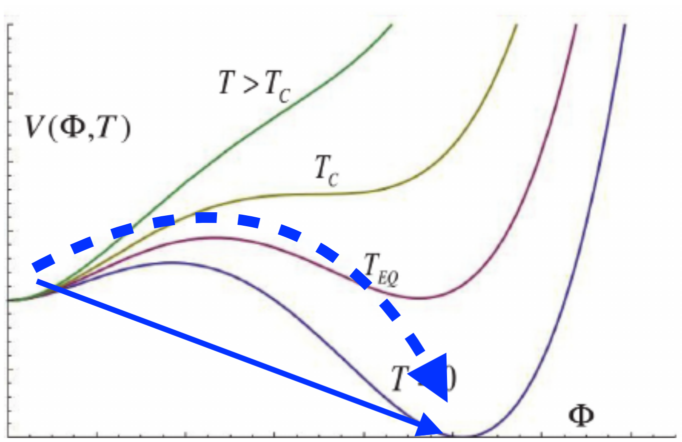

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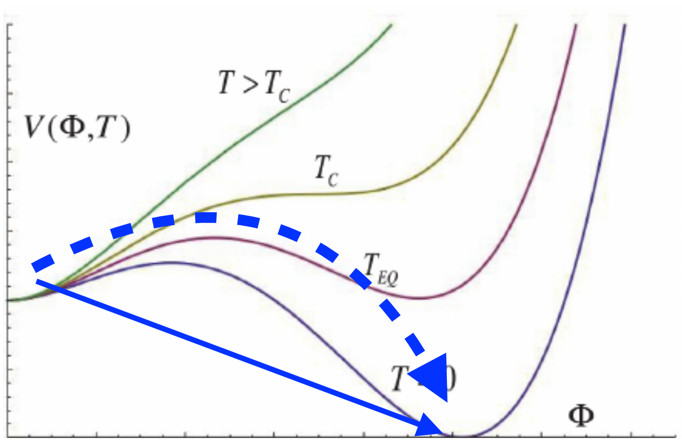
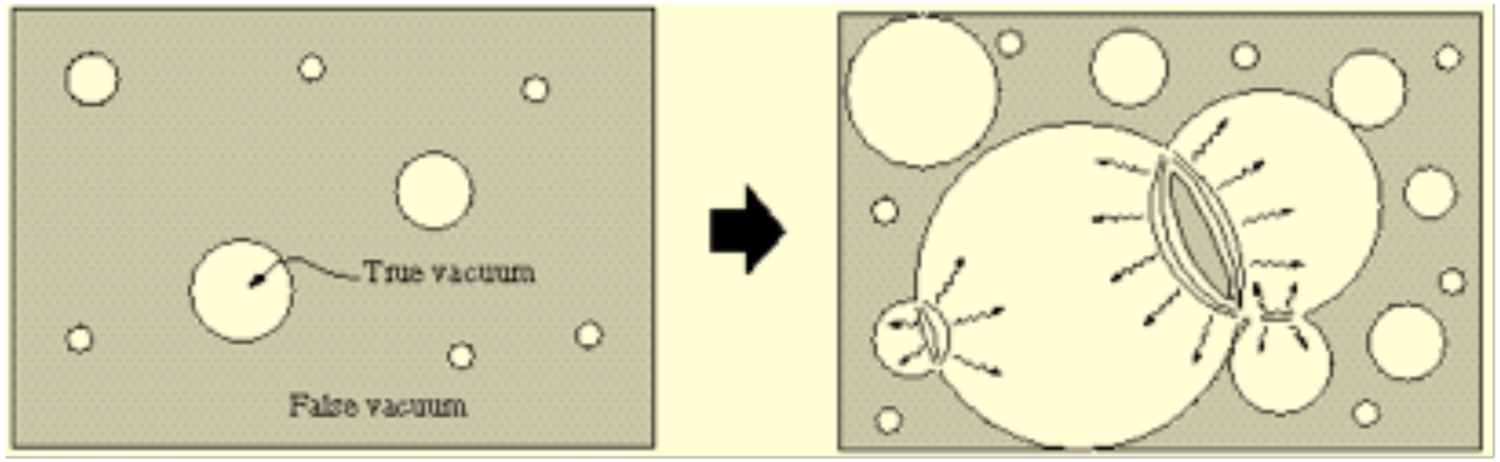


bubble nucleation



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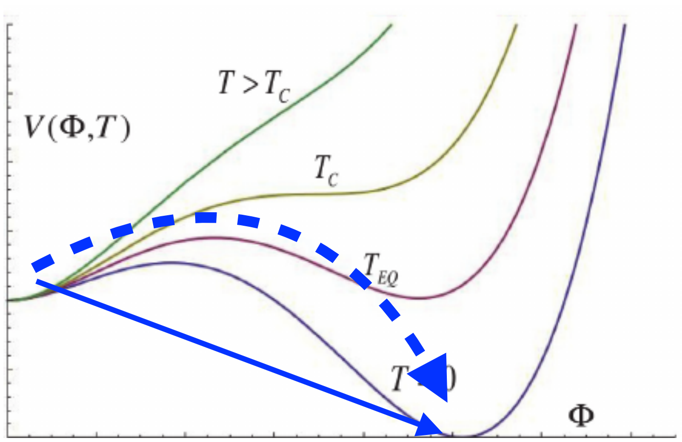

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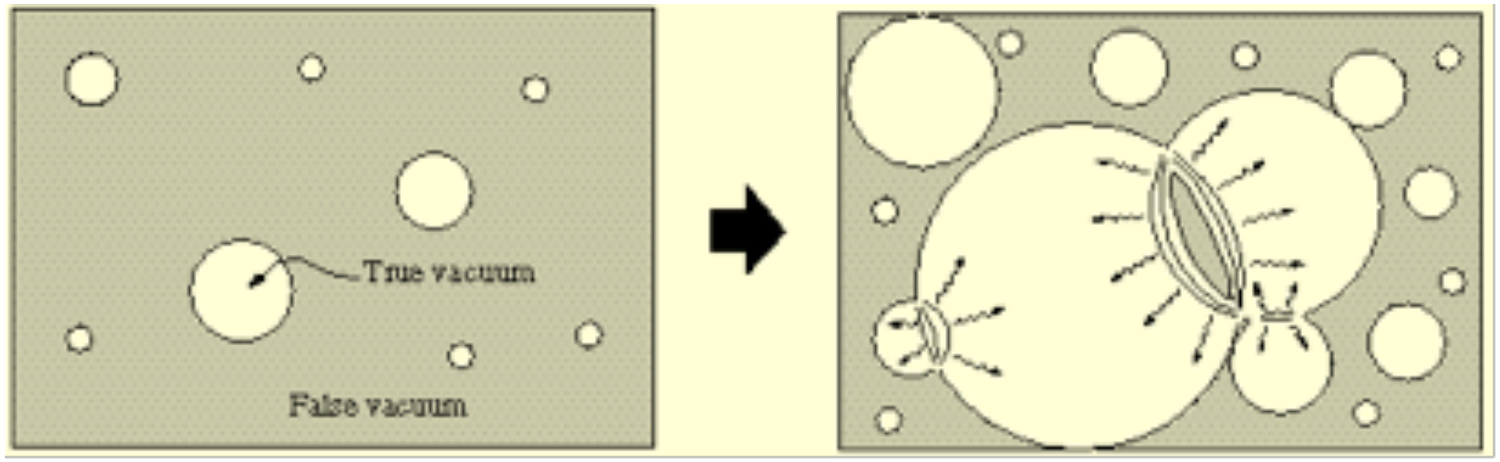

source: Π_{ij} tensor
anisotropic stress

- collisions of bubble walls

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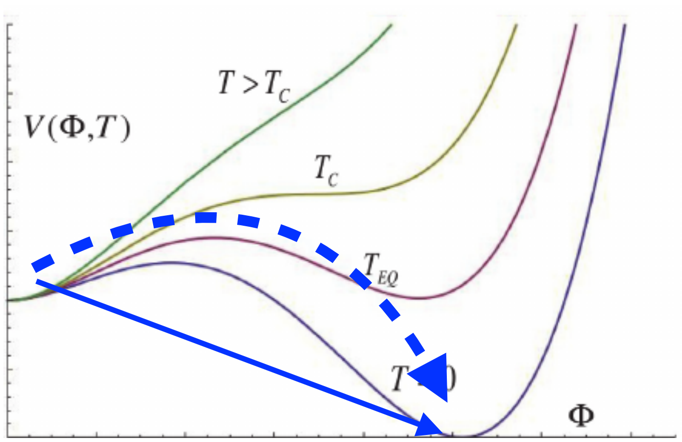

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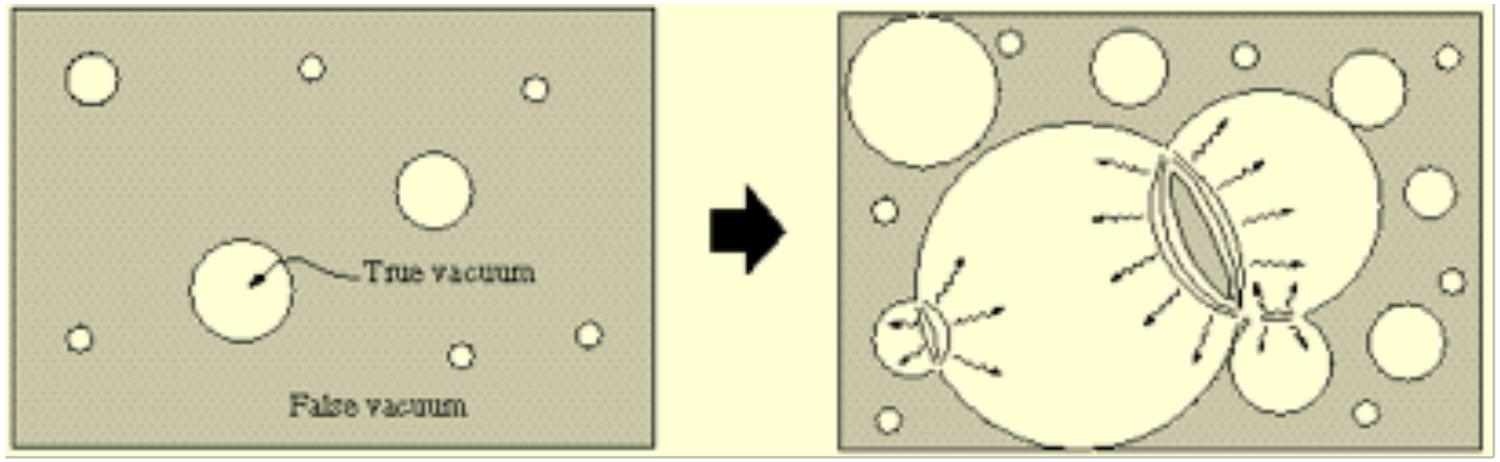

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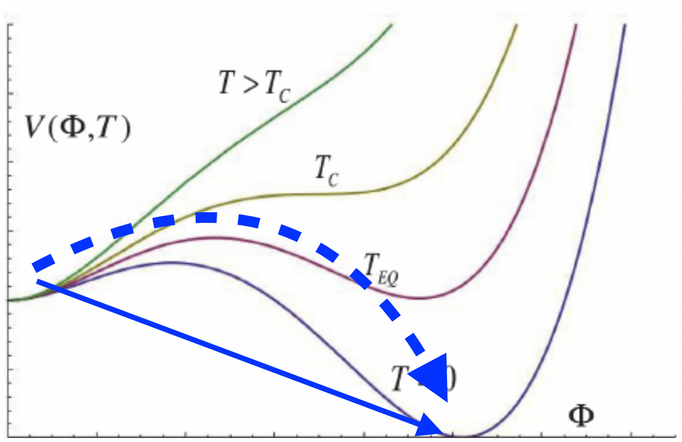

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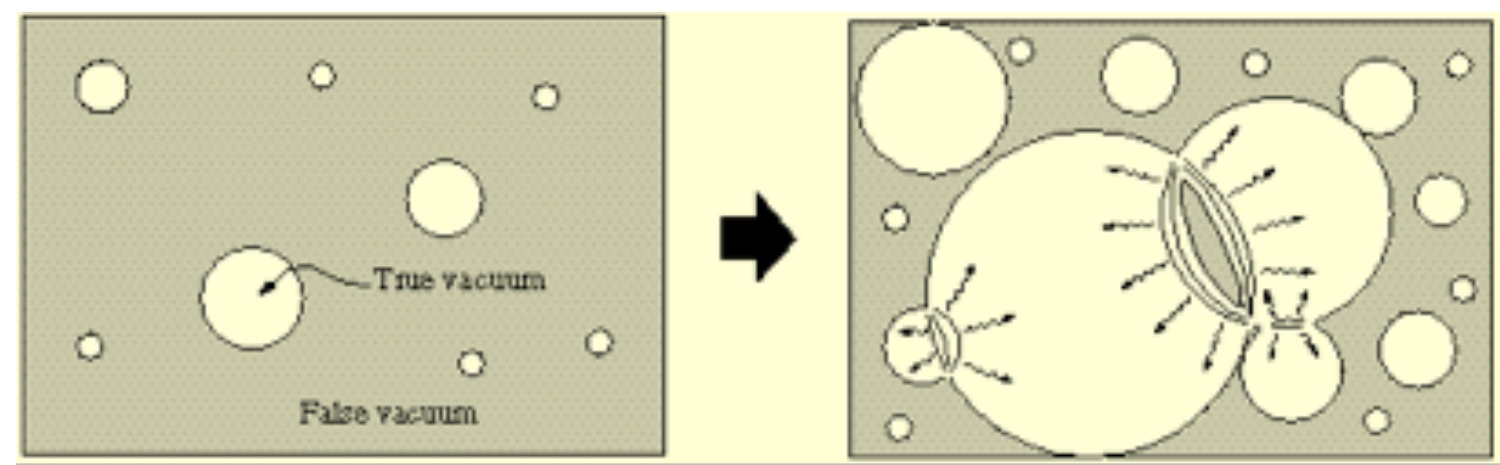

source: Π_{ij} tensor
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- collisions of bubble walls
- sound waves and turbulence in the fluid
- primordial magnetic fields (MHD turbulence)

GWs from first order phase transitions

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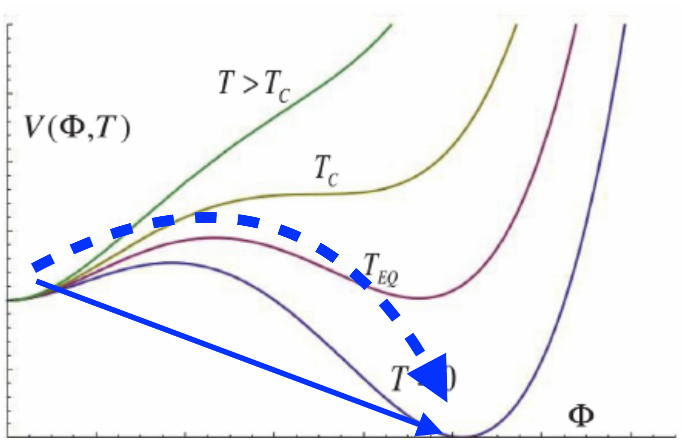

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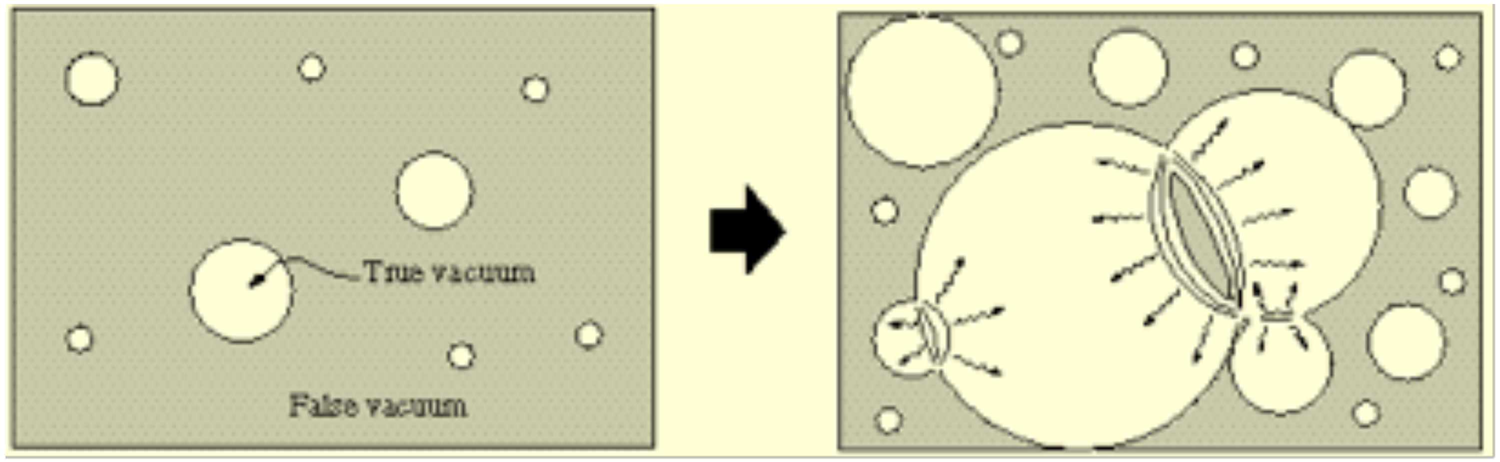

Technically

source: Π_{ij} tensor
anisotropic stress

$$\Pi_{ij} \sim \partial_i\phi\,\partial_j\phi$$

$$\Pi_{ij} \sim \gamma^2(\rho+p)\,v_i v_j$$

$$\Pi_{ij} \sim \frac{(E^2+B^2)}{3} - E^i E^j - B^i B^j$$

What is ϵ in 1st Order PhT's?

$$f_c = f_* \frac{a_*}{a_0} = \frac{2 \cdot 10^{-5}}{\epsilon_*} \frac{T_*}{1\,\mathrm{TeV}}\,\mathrm{Hz}$$

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β^{-1} : duration of PhT

$v_b \leq 1$: speed of bubble walls

$\longrightarrow R_* = v_b\, \beta^{-1}$ size of bubbles at collision

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size of bubbles at collision

$$\boxed{\epsilon \simeq \frac{H_*}{\beta}\,,\; H_*\, R_*}$$

BUBBLE COLLISION

SOUND WAVES AND MDH TURBULENCE

Parameters determining the GW spectrum

Freq. (today)

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Parameter List

(not independent)

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Amplitude (today)

$$\Omega_{\mathrm{GW}} \sim \Omega_{\mathrm{rad}}\,\epsilon_*^2 \left(\frac{\rho_{\mathrm{s}}^*}{\rho_{\mathrm{tot}}^*}\right)^2$$

$$\frac{\rho_{\mathrm{s}}^*}{\rho_{\mathrm{tot}}^*} = \frac{\kappa\,\alpha}{1+\alpha}$$

$$\alpha = \frac{\rho_{\mathrm{vac}}}{\rho_{\mathrm{rad}}^*}$$

$$\kappa = \frac{\rho_{\mathrm{kin}}}{\rho_{\mathrm{vac}}}$$

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Amplitude (today)

$\Omega_{\rm GW}$

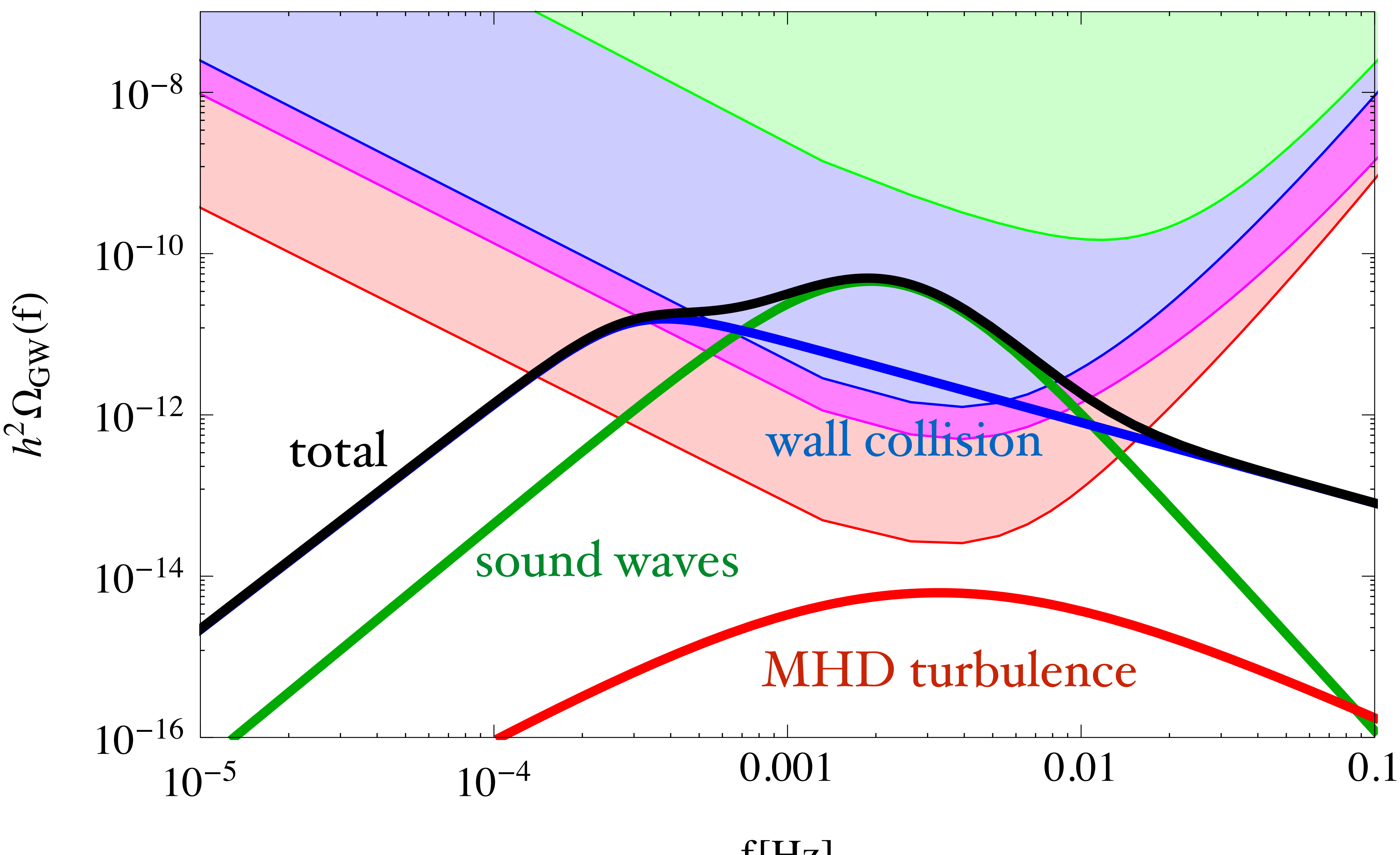
$$\alpha = \frac{\rho_{\rm vac}}{\rho^*_{\rm rad}}$$

$$\kappa = \frac{\rho_{\rm kin}}{\rho_{\rm vac}}$$

not most general !

Hydro-dynamical effects & turbulence separate treatment

Example of spectrum



Caprini et al, arXiv:1512.06239

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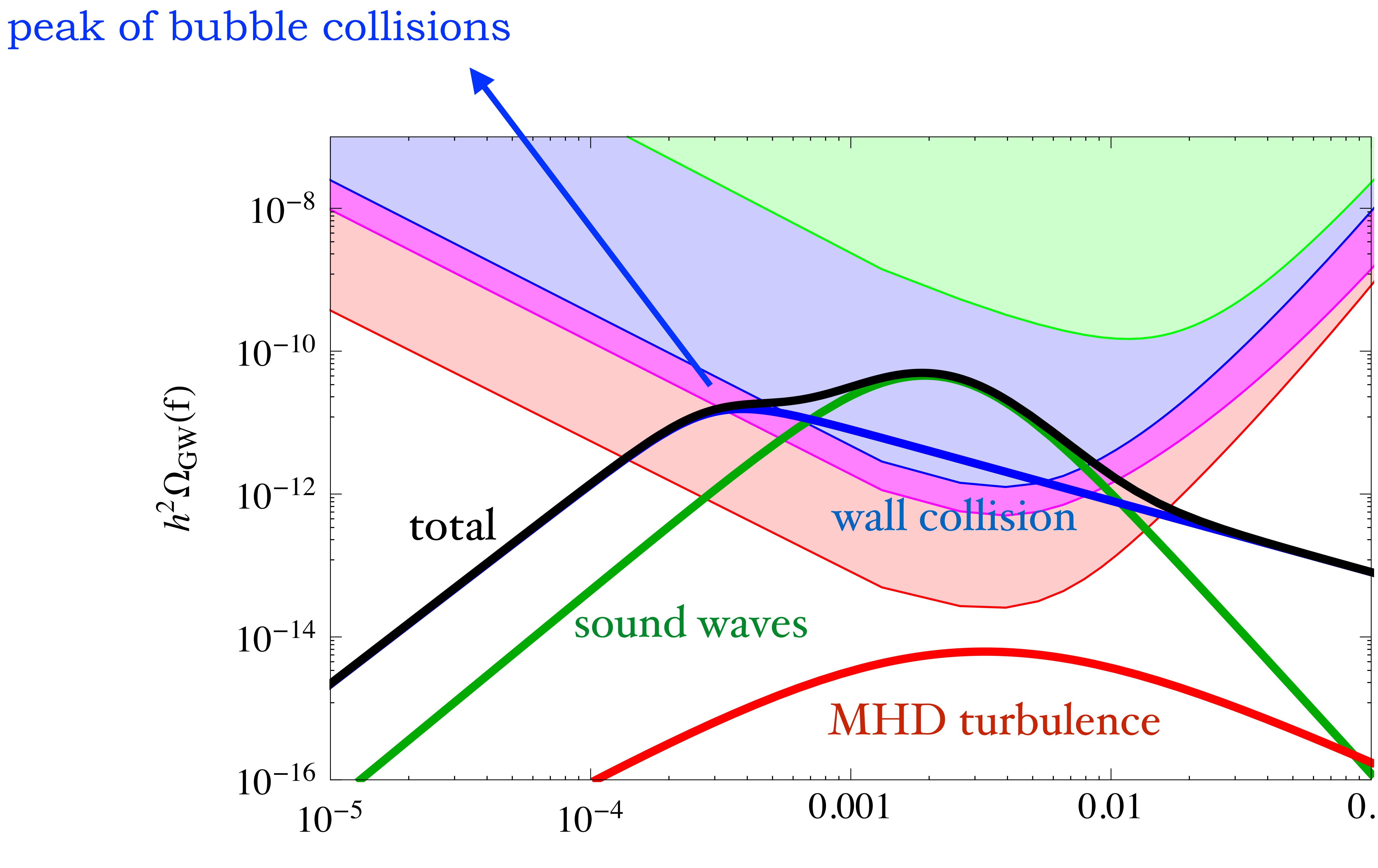

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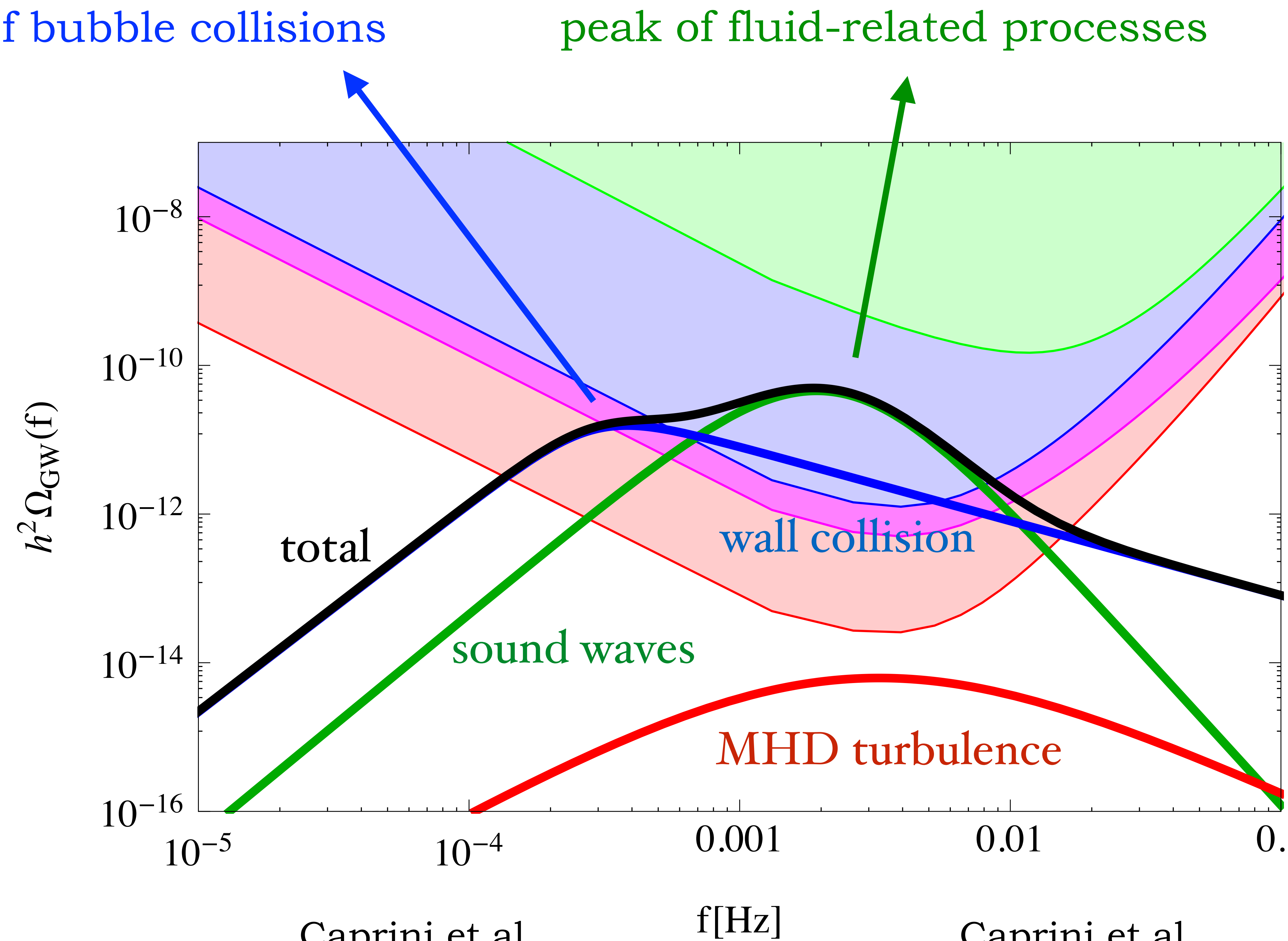

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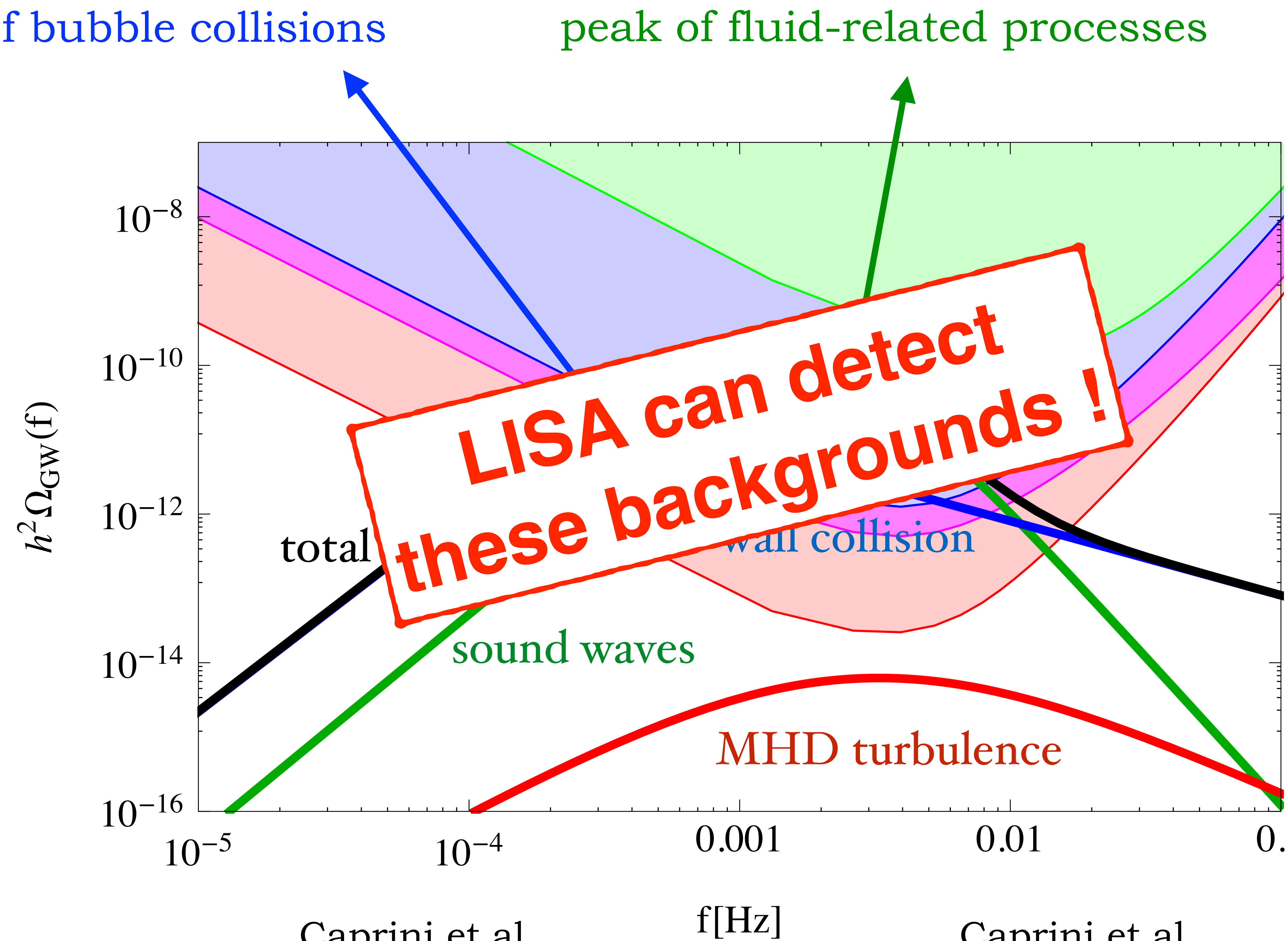

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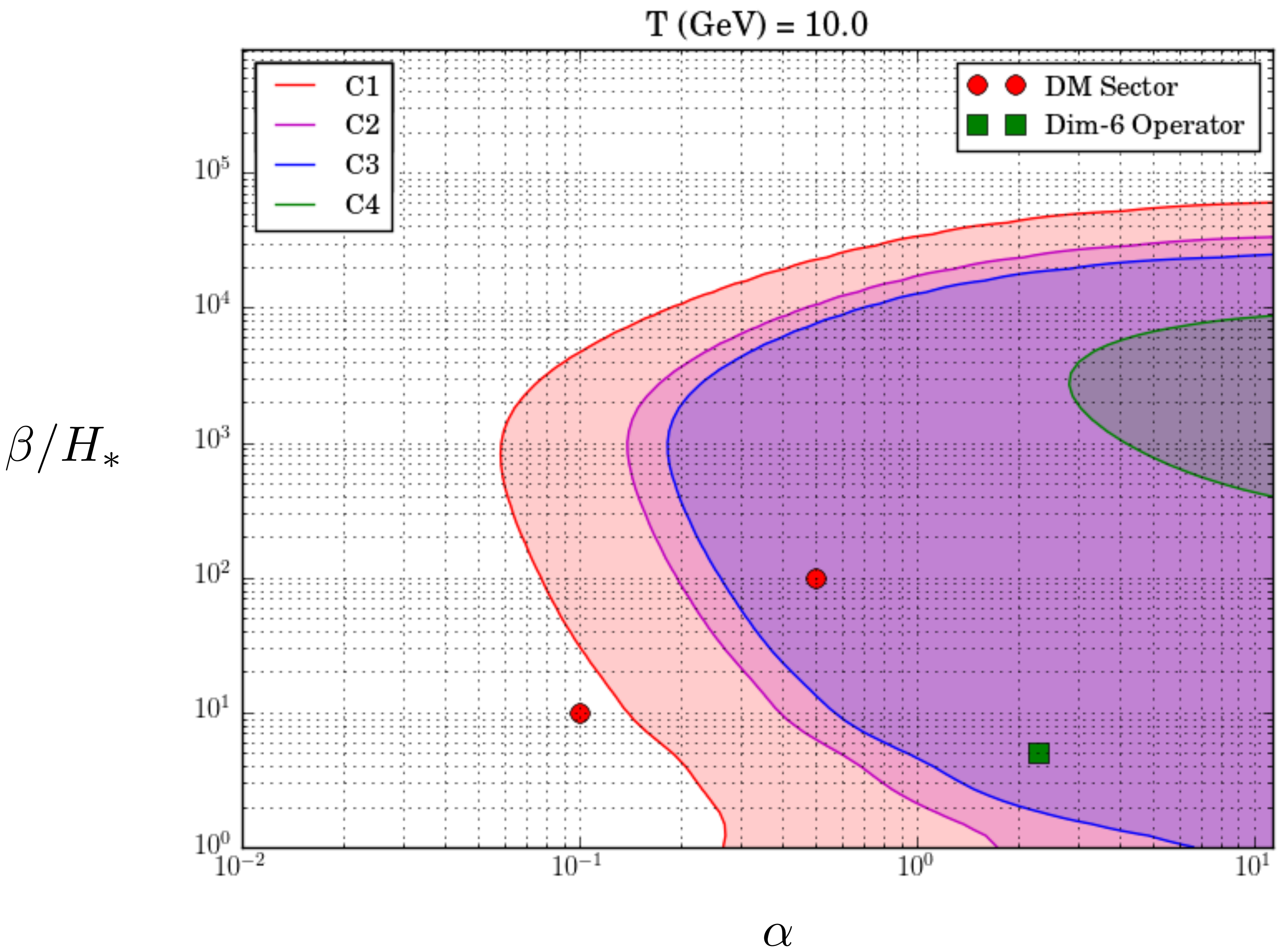
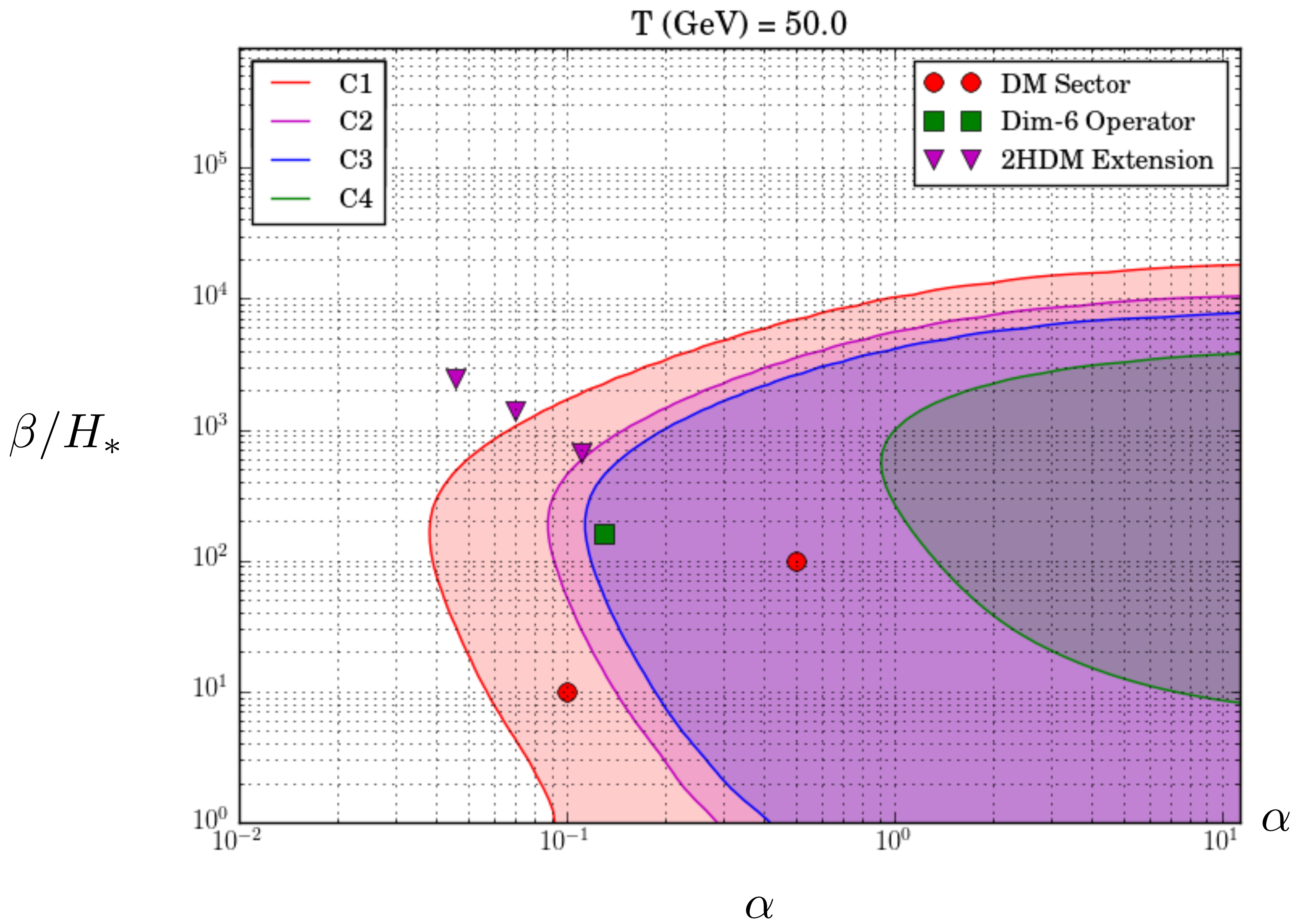
Detection prospects for LISA



Caprini et al, 2015/2016 (LISA 1PhT working group)

Detection prospects for LISA



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Evaluation of the signal

- **bubble collisions**: **analytical** and **numerical** simulations

  Huber, Konstandin '08   Cutting, Hindmarsh et al 2018, …

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- **MDH turbulence**: **analytical** evaluation

  Kosowsky et al '07, Caprini et al '09, Niksa et al '18

  numerical Pol et al 2019

Models for EWPT and beyond

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Cosmology and Particle Physics interplay!
Connections with baryon asymmetry & dark matter

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Conn

nterplay!
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  - Dark sector: provides DM ... PhT (Schwall
  - ... the dilaton/radion
  - ... like models (Randall and Servant 2015)

GW —> new probe of BSM physics!
(complementary to particle colliders)

Can we really detect a 1st-O Ph-T ?

* LISA/ET can, but LHC pressures typical BSM extensions to promote EW-PhT into First Order

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* LISA/ET can, but LHC pressures typical BSM extensions to promote EW-PhT into First Order

* Assuming LHC does not rule out models, LISA/ET can detect/constrain significant fraction of Param Space

* Predictions depend on many assumptions (particularly in sound waves), so is our modelling correct?

* Even if we detect it, then we infer α and β , but what BSM model is behind? not univocal !

EARLY UNIVERSE

'cures' hBB

(initial cond.) = Primordial perturbations

Scalar: CMB ΔT anisotropies (eventually Galaxies)

Tensor: Irreducible GWs (CMB B-mode Pol.)

Inflation

Scenarios

Extra species/symmetries

Enhanced Scalar Pert.

...

Enhanced GWs

Reheating

scalar Preheating

gauge Preheating

fermion Preheating

Large GW (high freq)

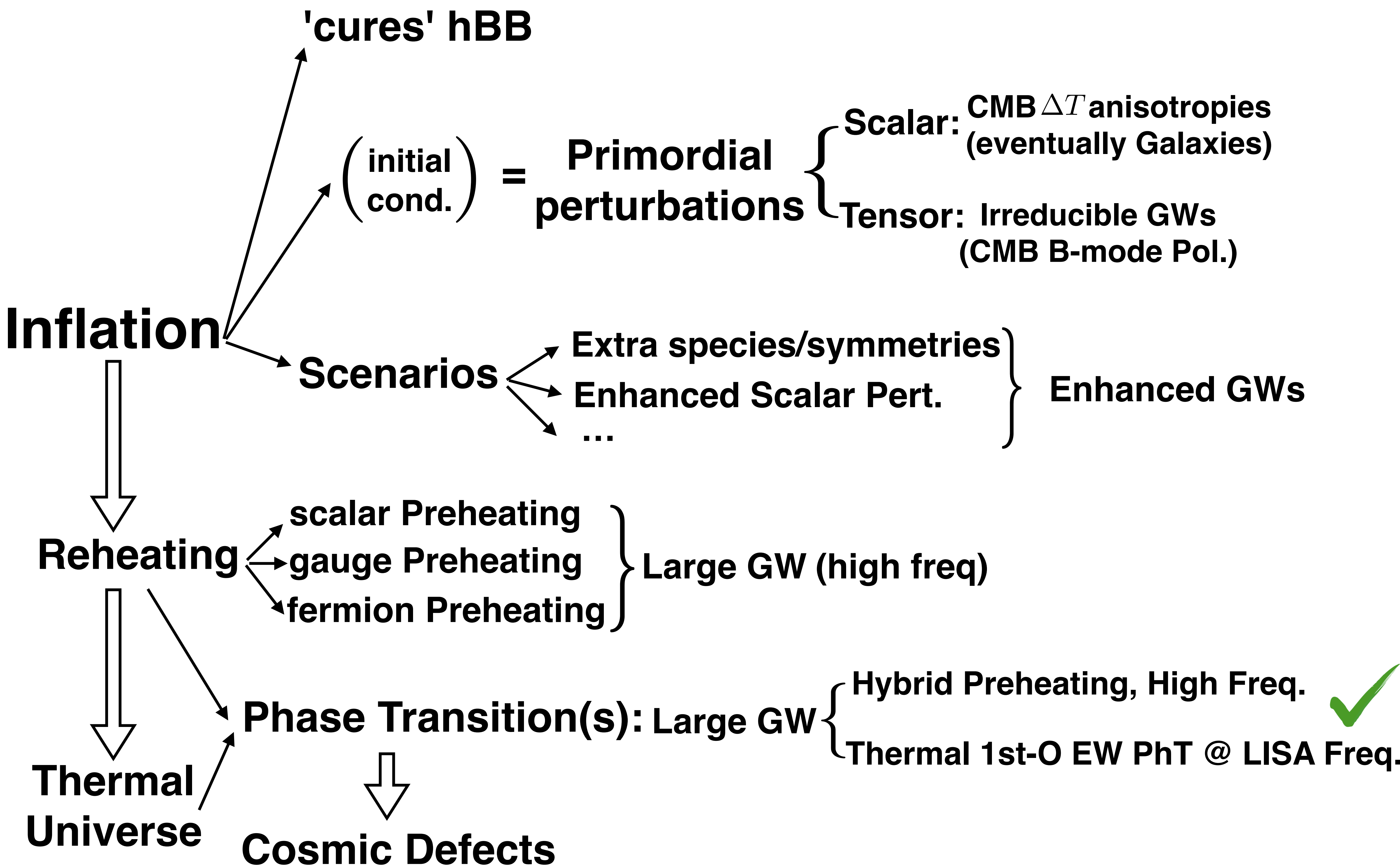
Thermal Universe

Phase Transition(s): Large GW

Hybrid Preheating, High Freq. ✓

Thermal 1st-O EW PhT @ LISA Freq.

EARLY UNIVERSE



EARLY UNIVERSE

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Enhanced GWs

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Large GW (high freq)

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Thermal Universe

...ects

To Be Continued ...