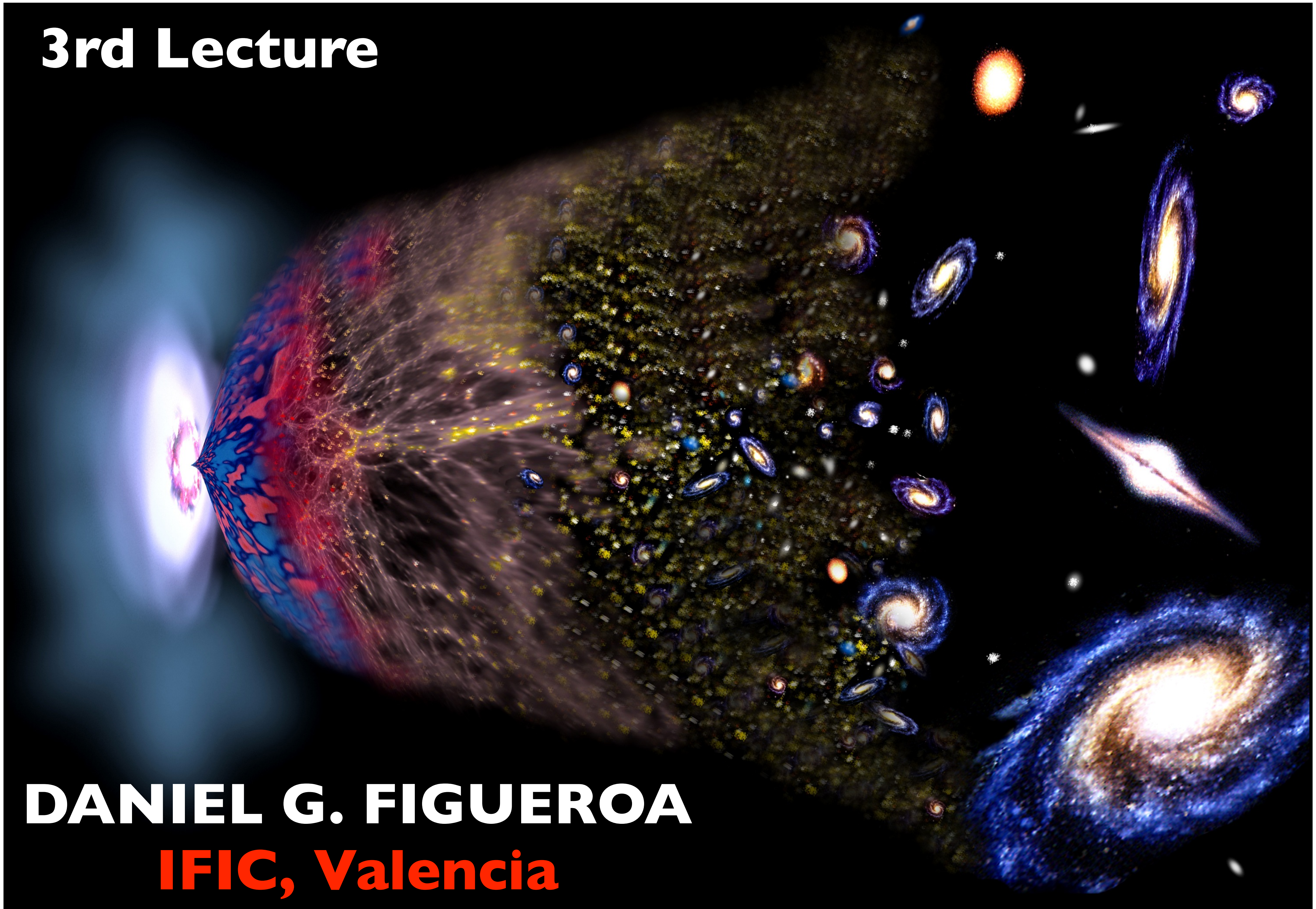
GRAVITATIONAL WAVE
— BACKGROUNDS —



3rd Lecture

DANIEL G. FIGUEROA
IFIC, Valencia

MITP Summer School - CrossLinks of Early Universe Cosmology, 15 July - August 2, 2024

Gravitational Wave Backgrounds

OUTLINE

1) Grav. Waves (GWs) ✓ — 1st Topic

Early Universe Sources:

2) GWs from Inflation ✓

3) GWs from Preheating

4) GWs from Phase Transitions

5) GWs from Cosmic Defects

Core Topics

6) Astrophysical Background(s)

7) Observational Constraints/Prospects

← (Briefly)

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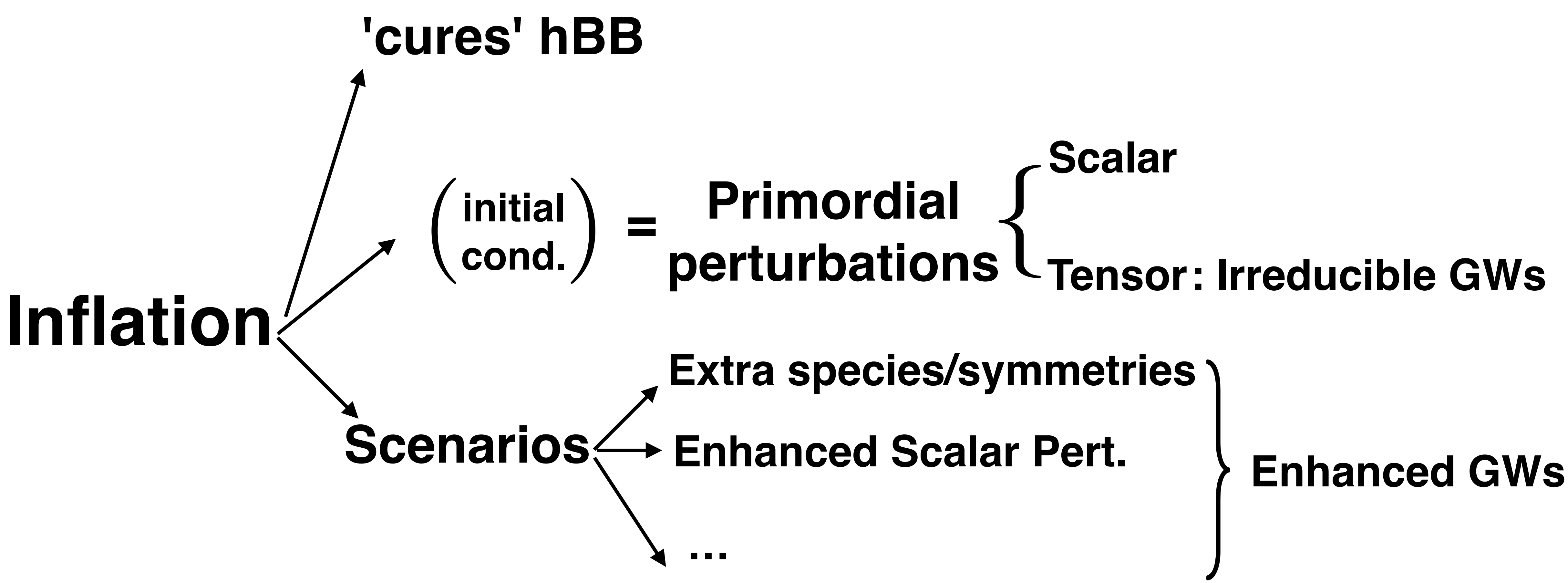
INFLATIONARY COSMOLOGY



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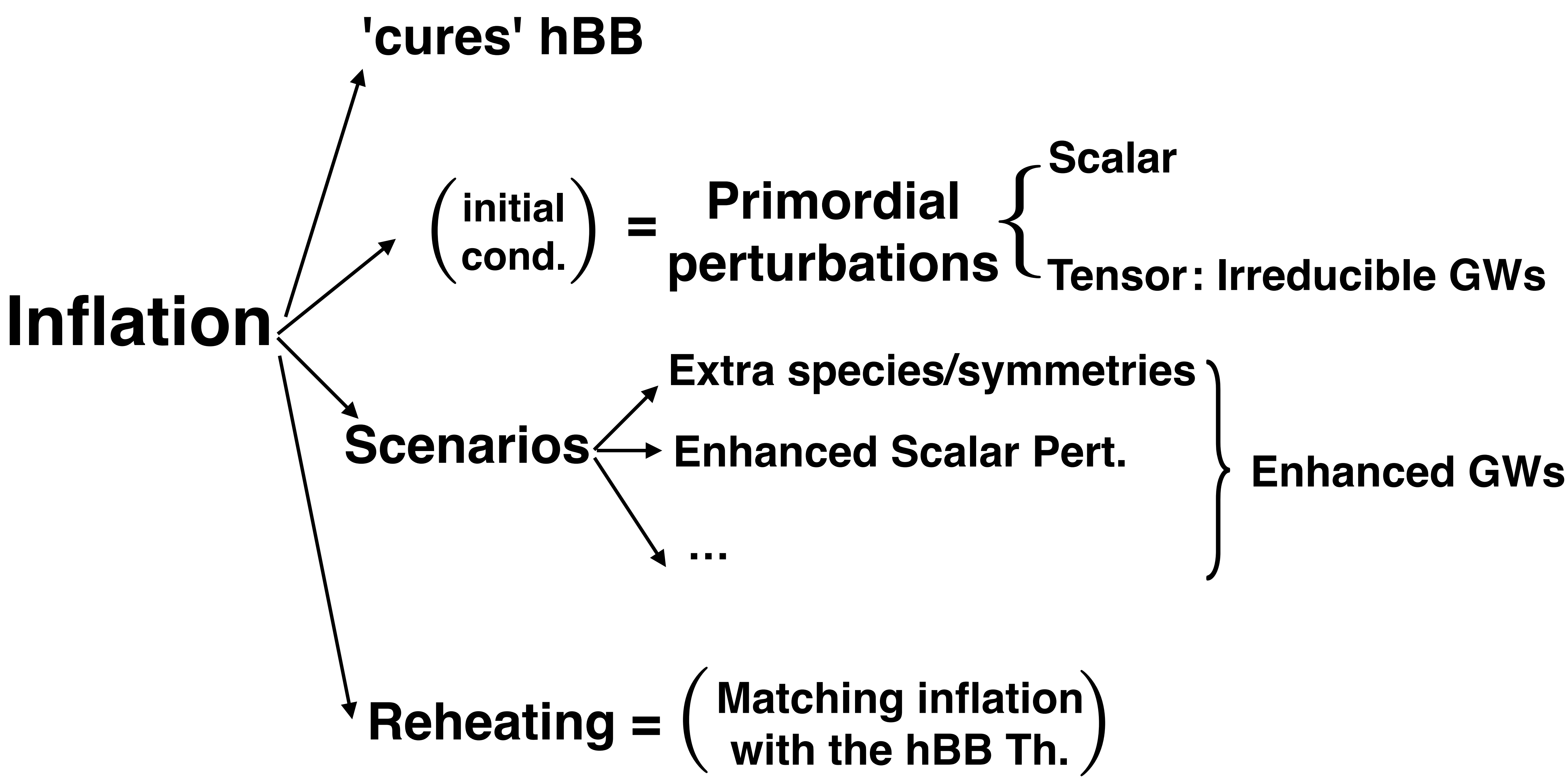

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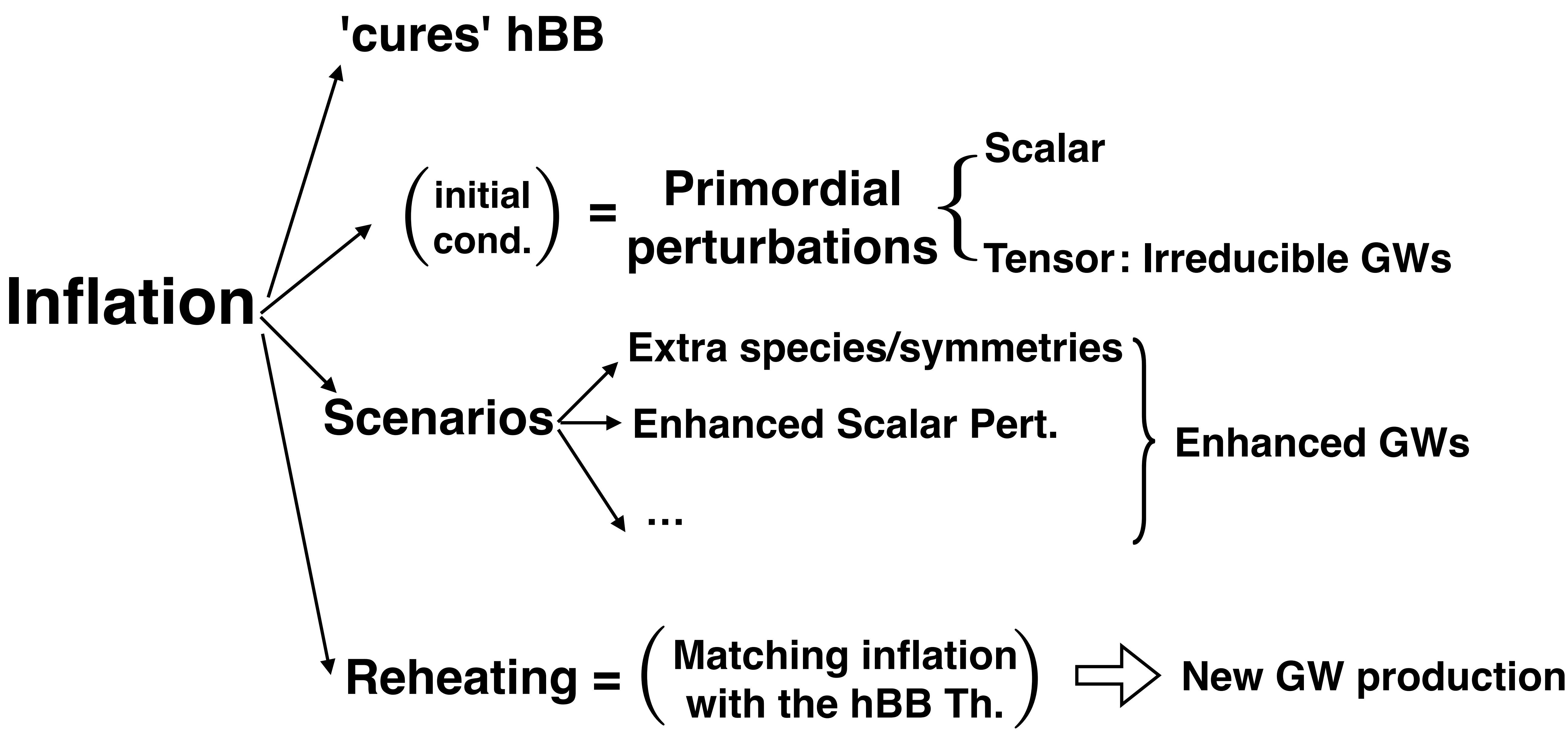

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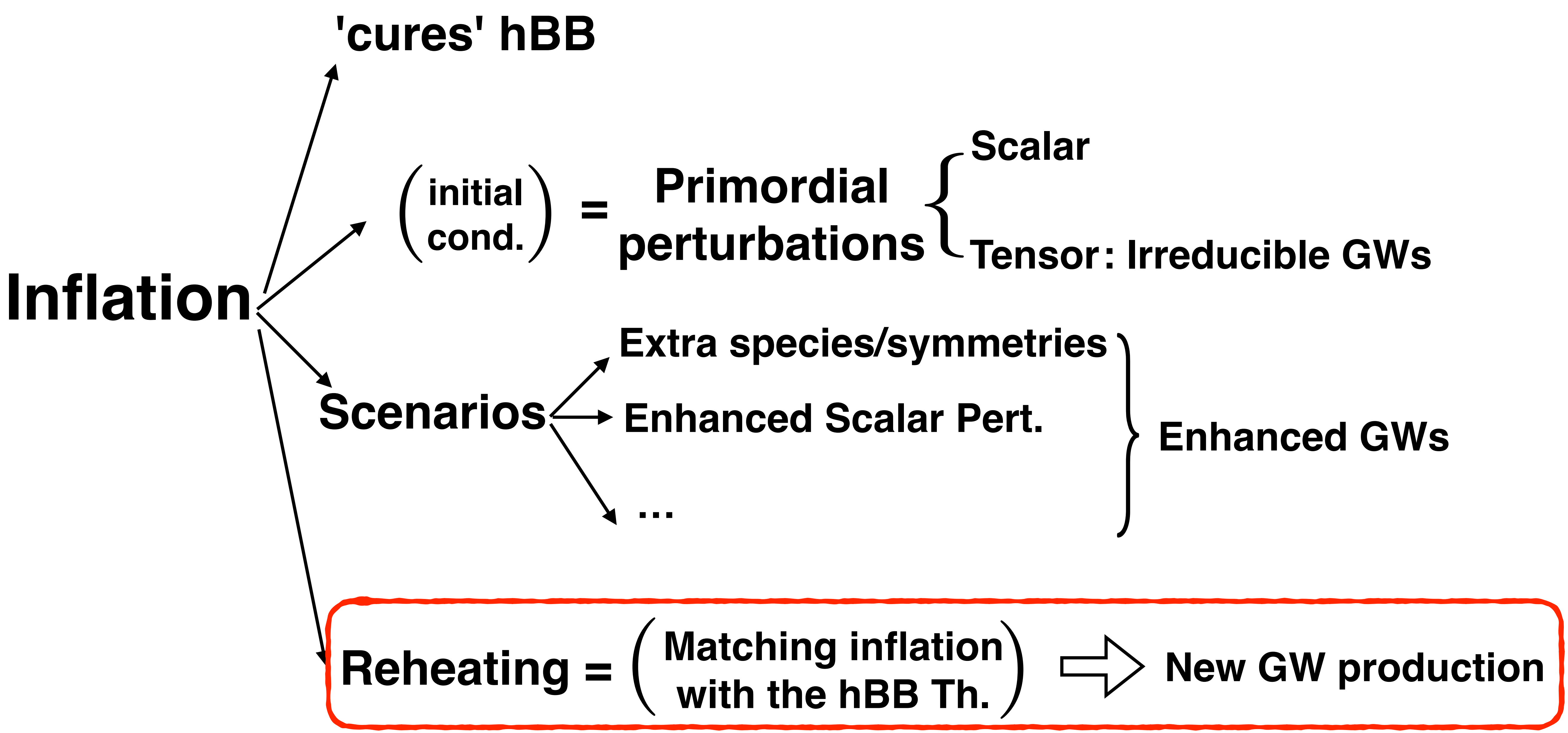
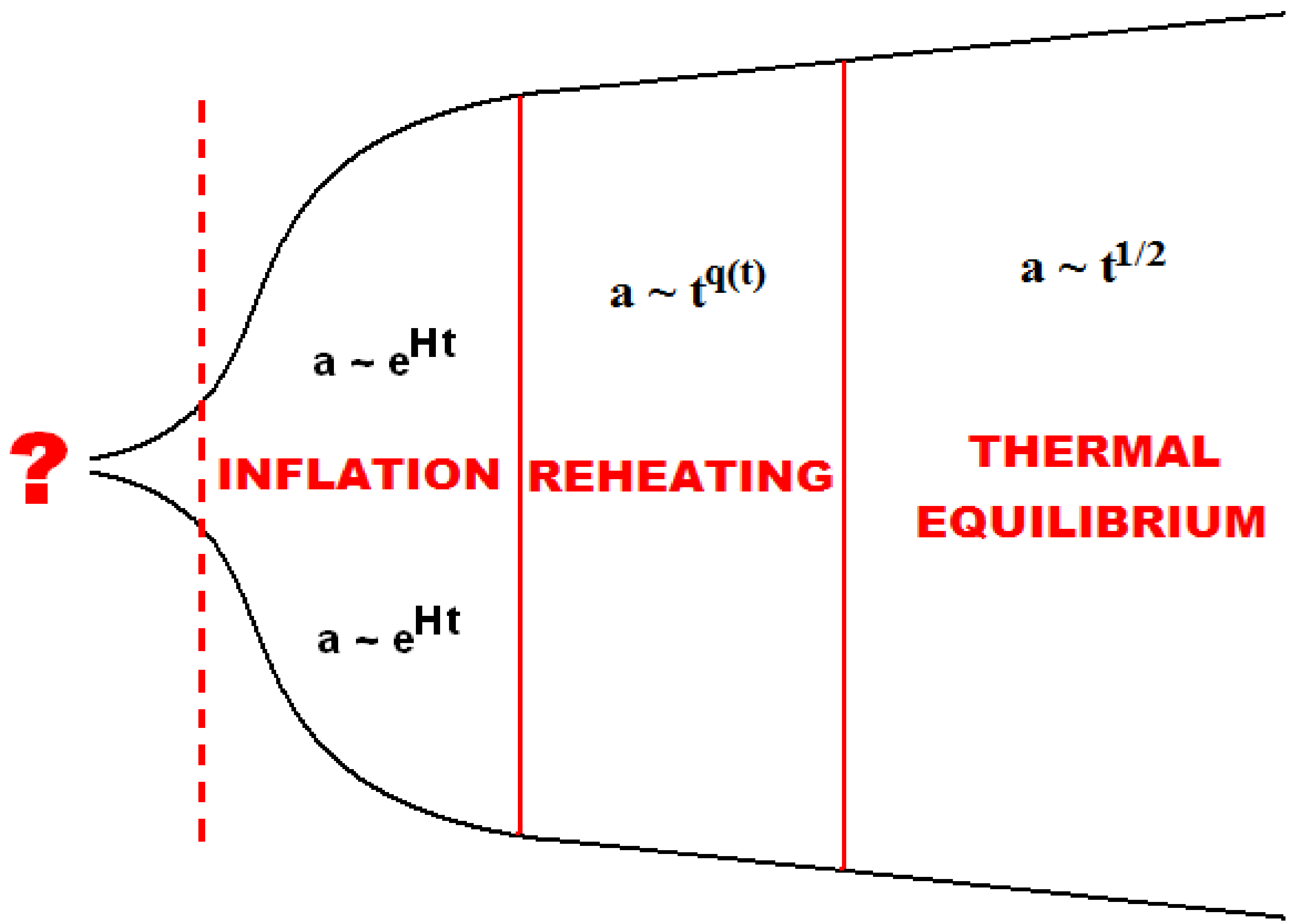


INFLATIONARY REHEATING

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



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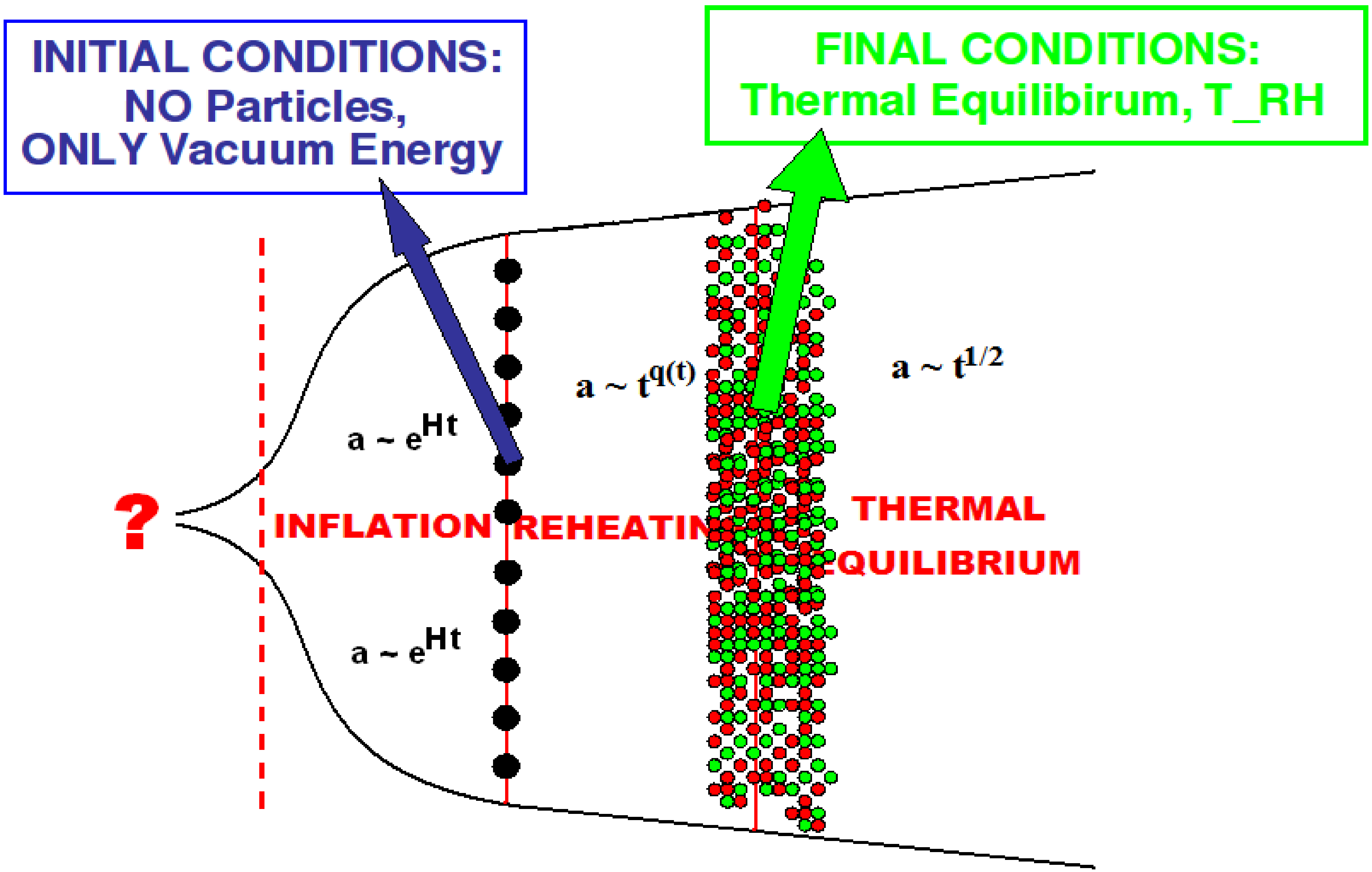

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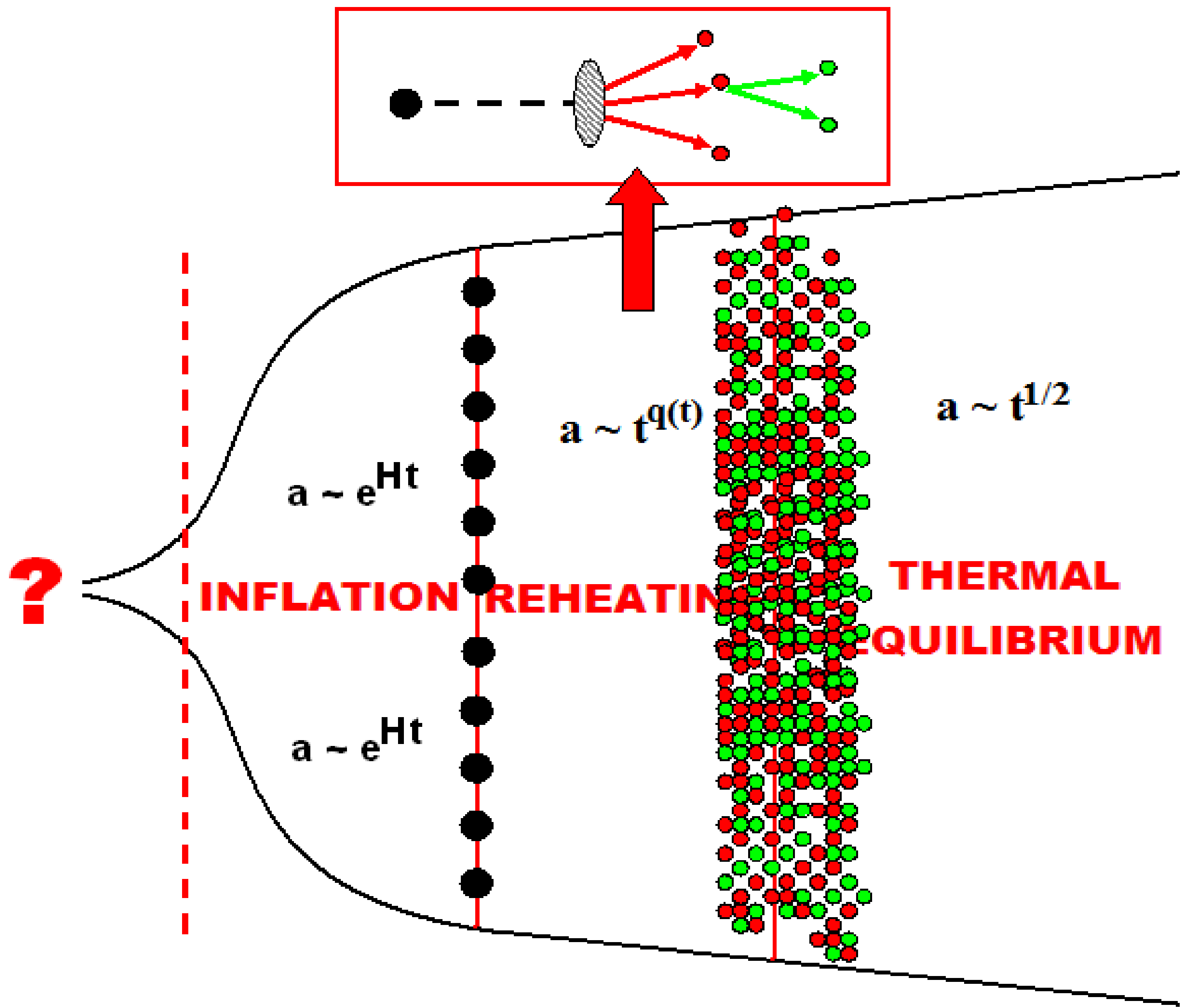
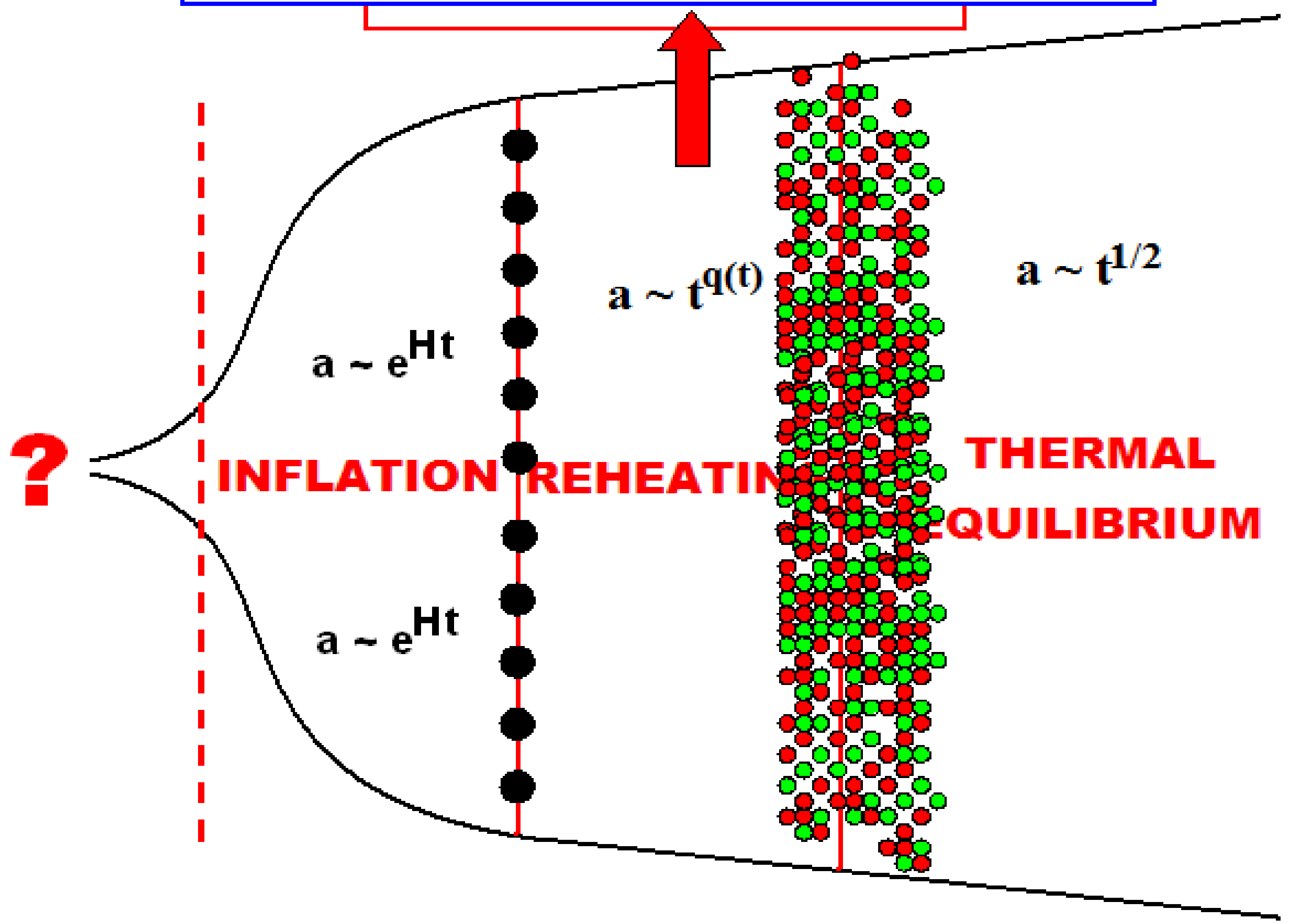


INFLATIONARY REHEATING

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

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



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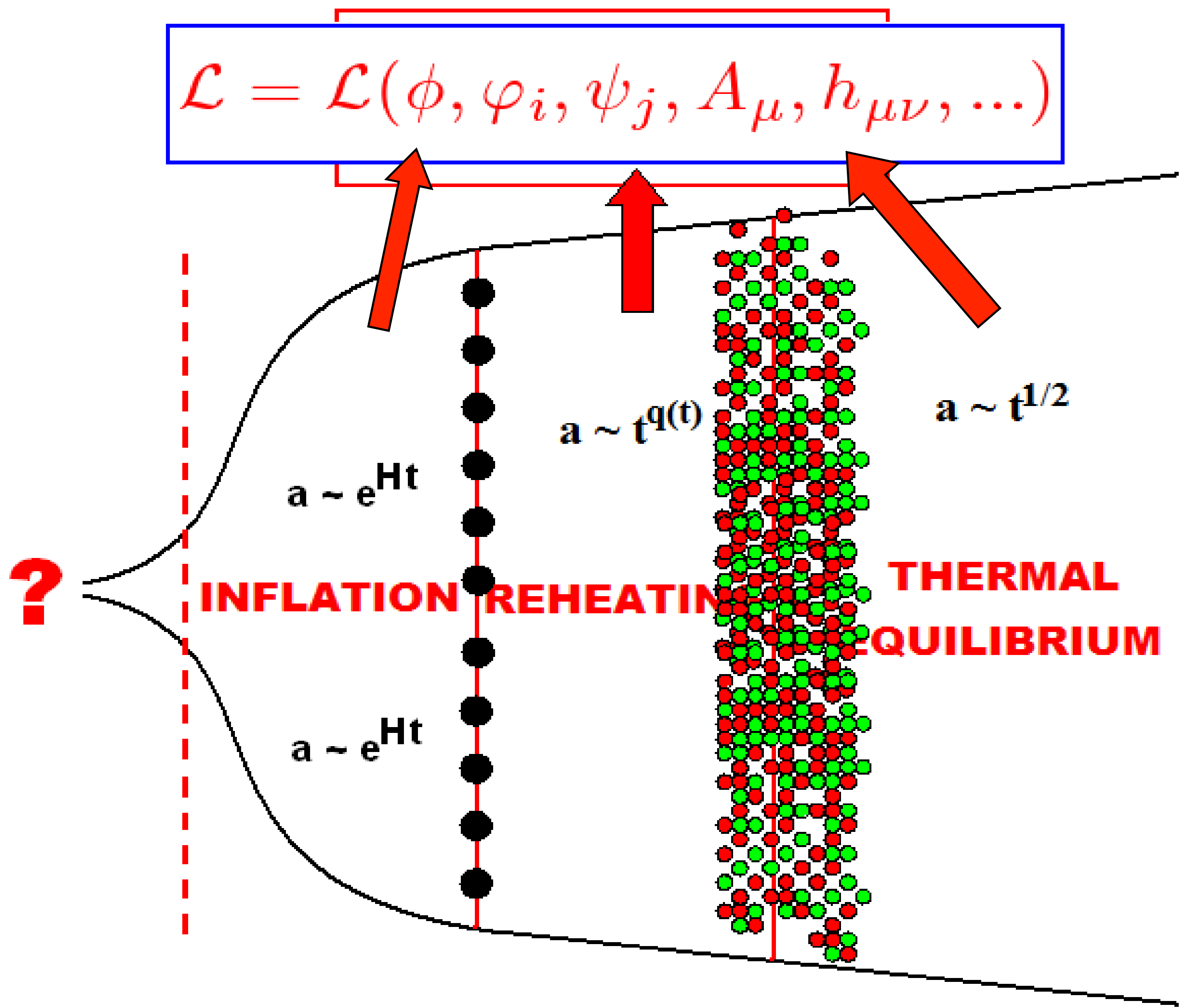

SCALAR REHEATING

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

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

INFLATON **DAUGHTER** **COUPLING**

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

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

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

SCALAR (P)REHEATING

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

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↑

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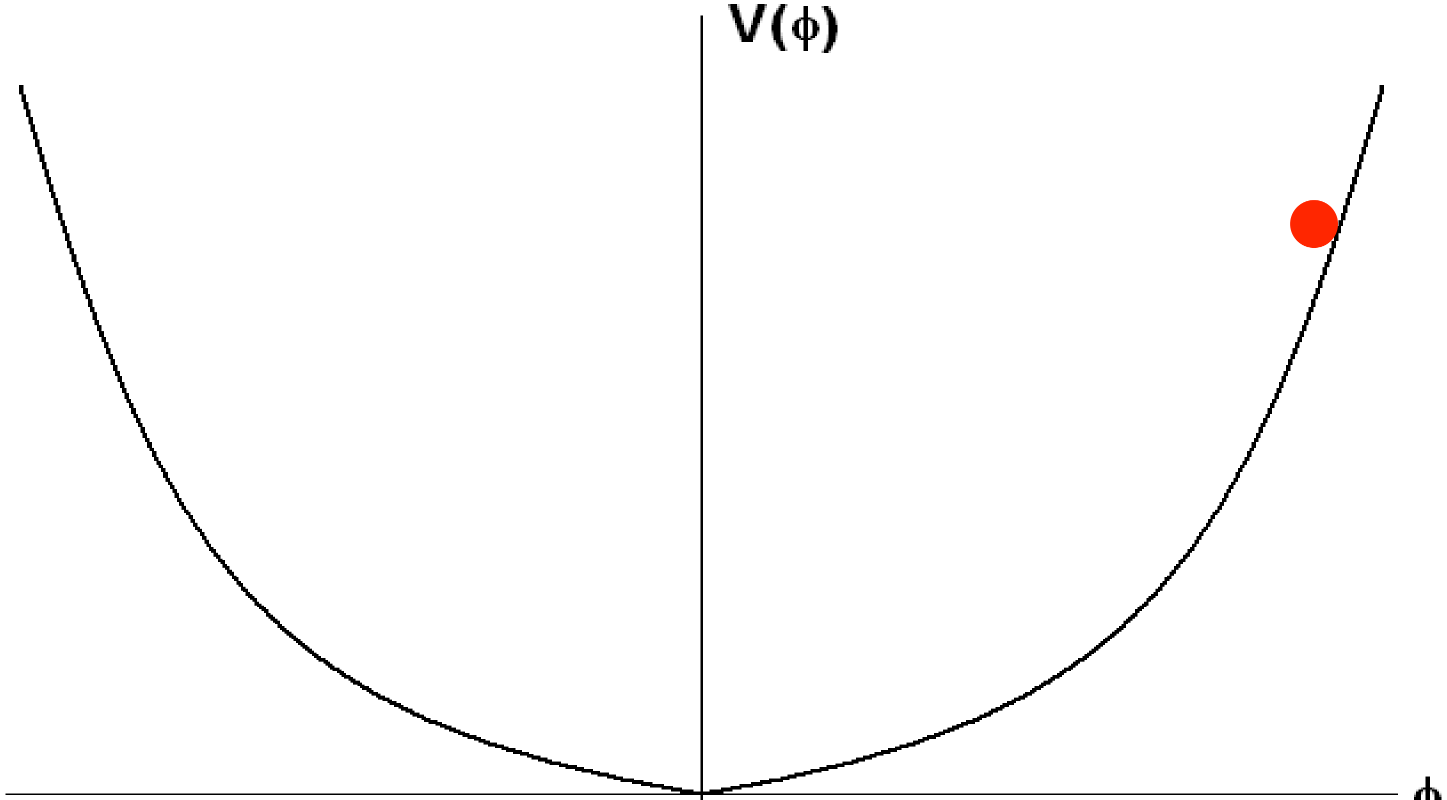

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e.g. Alpha Attractors

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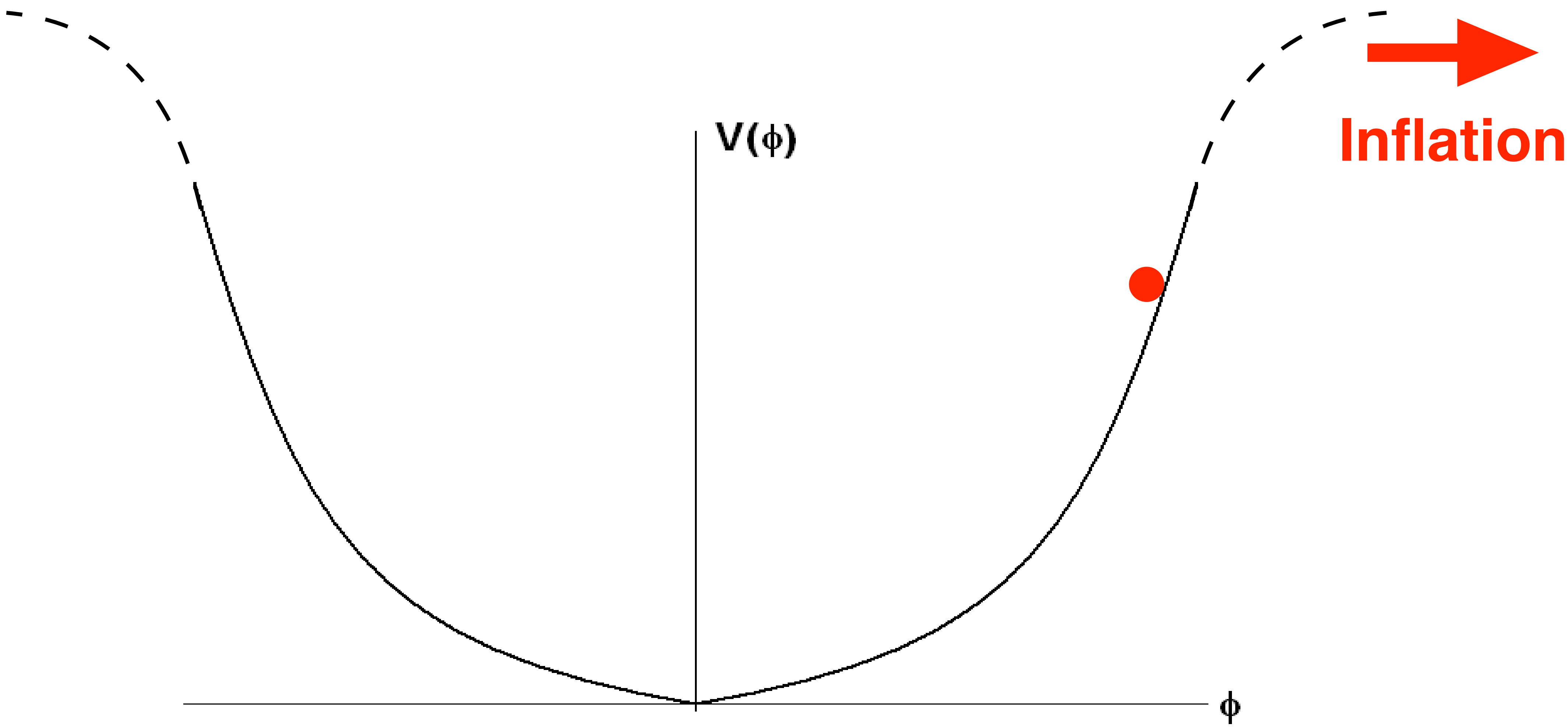

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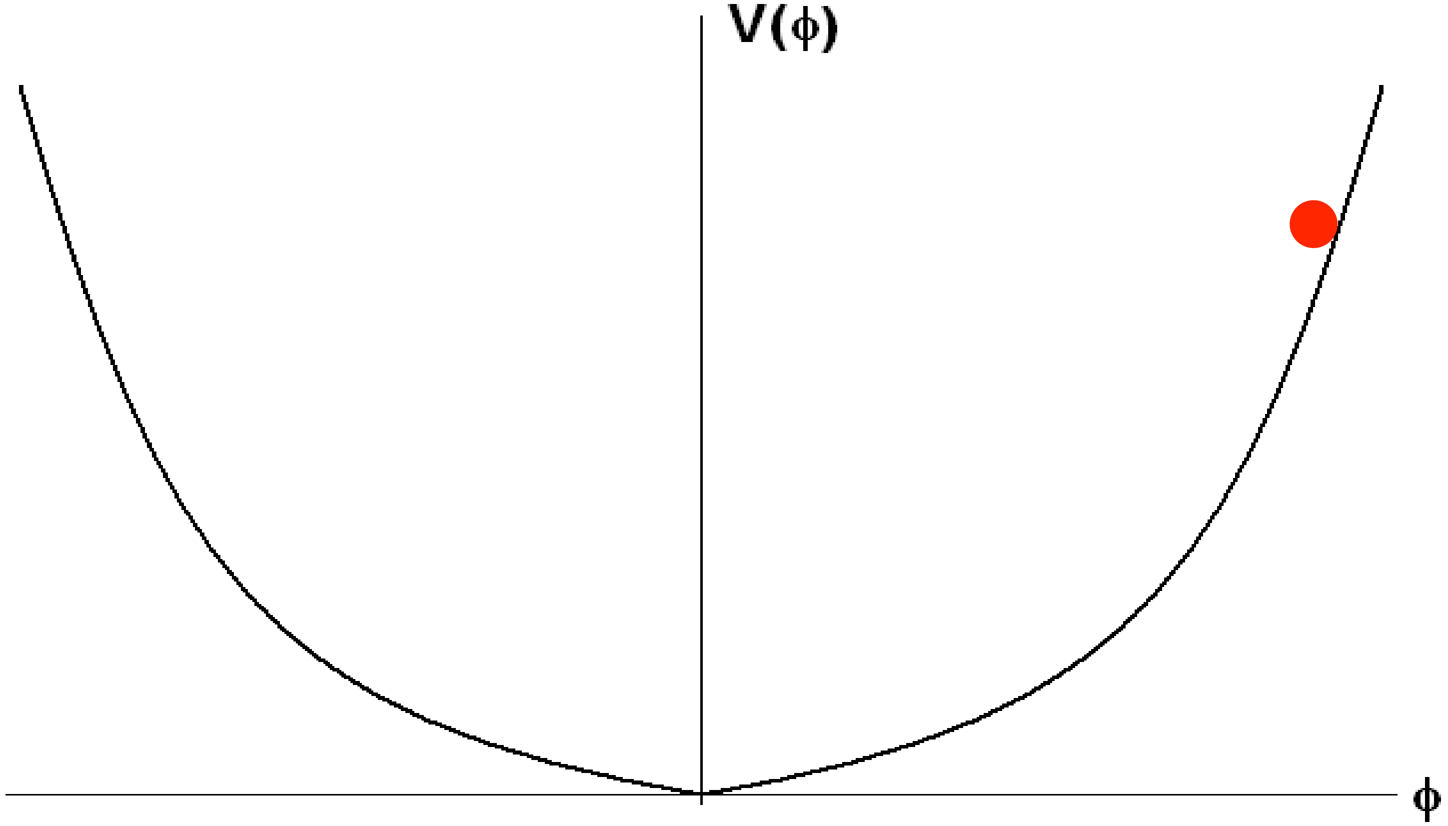

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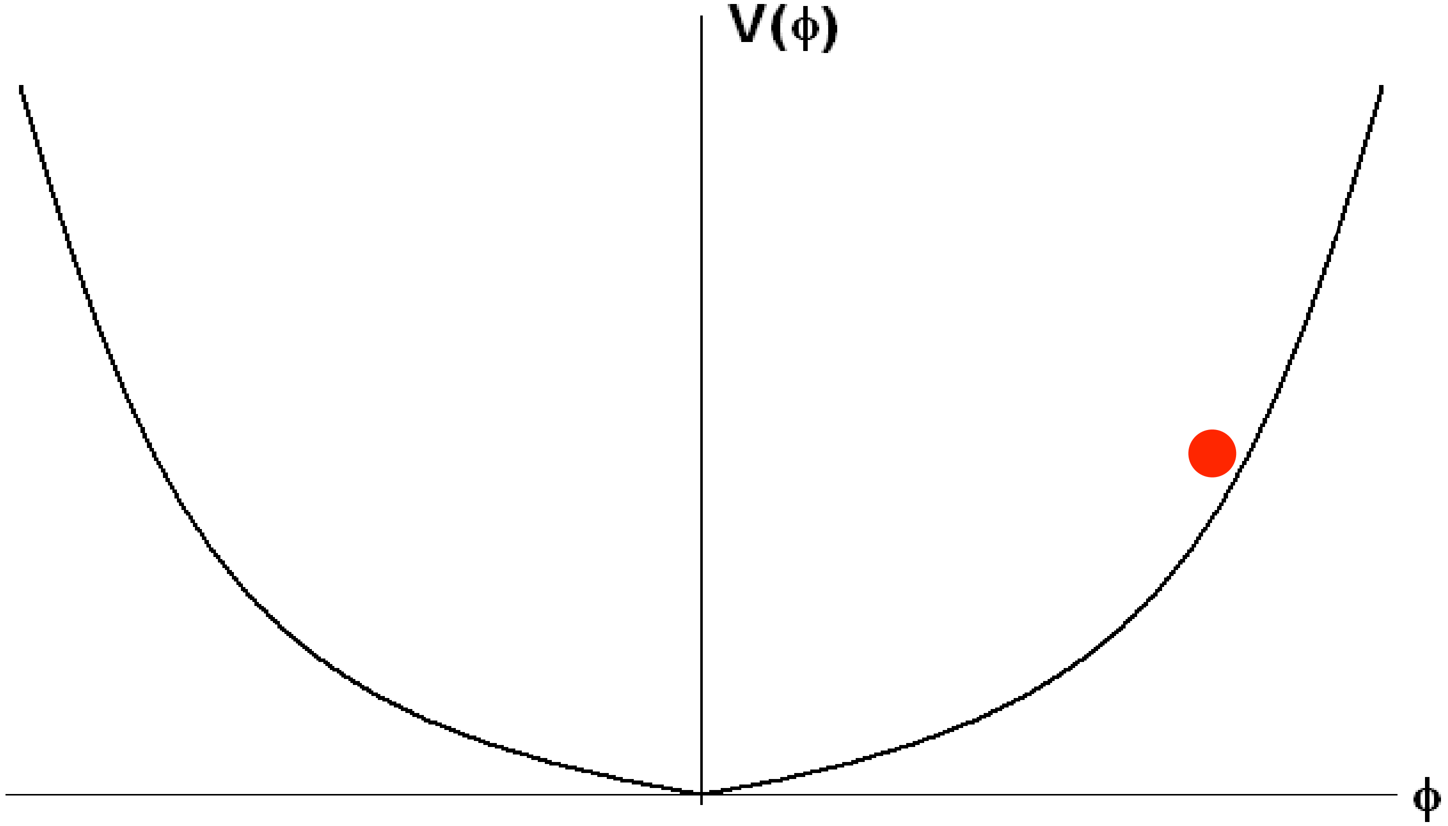

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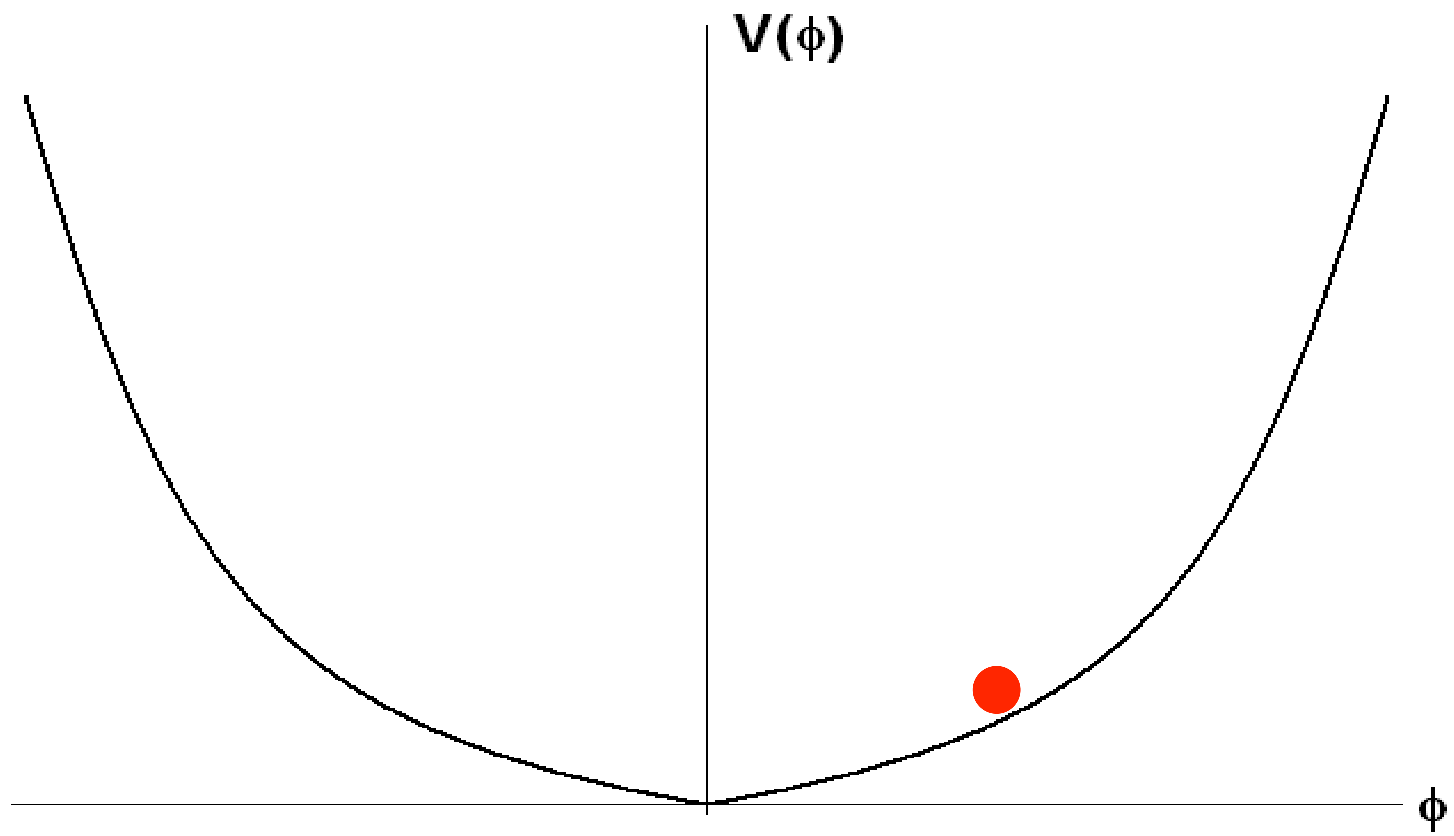

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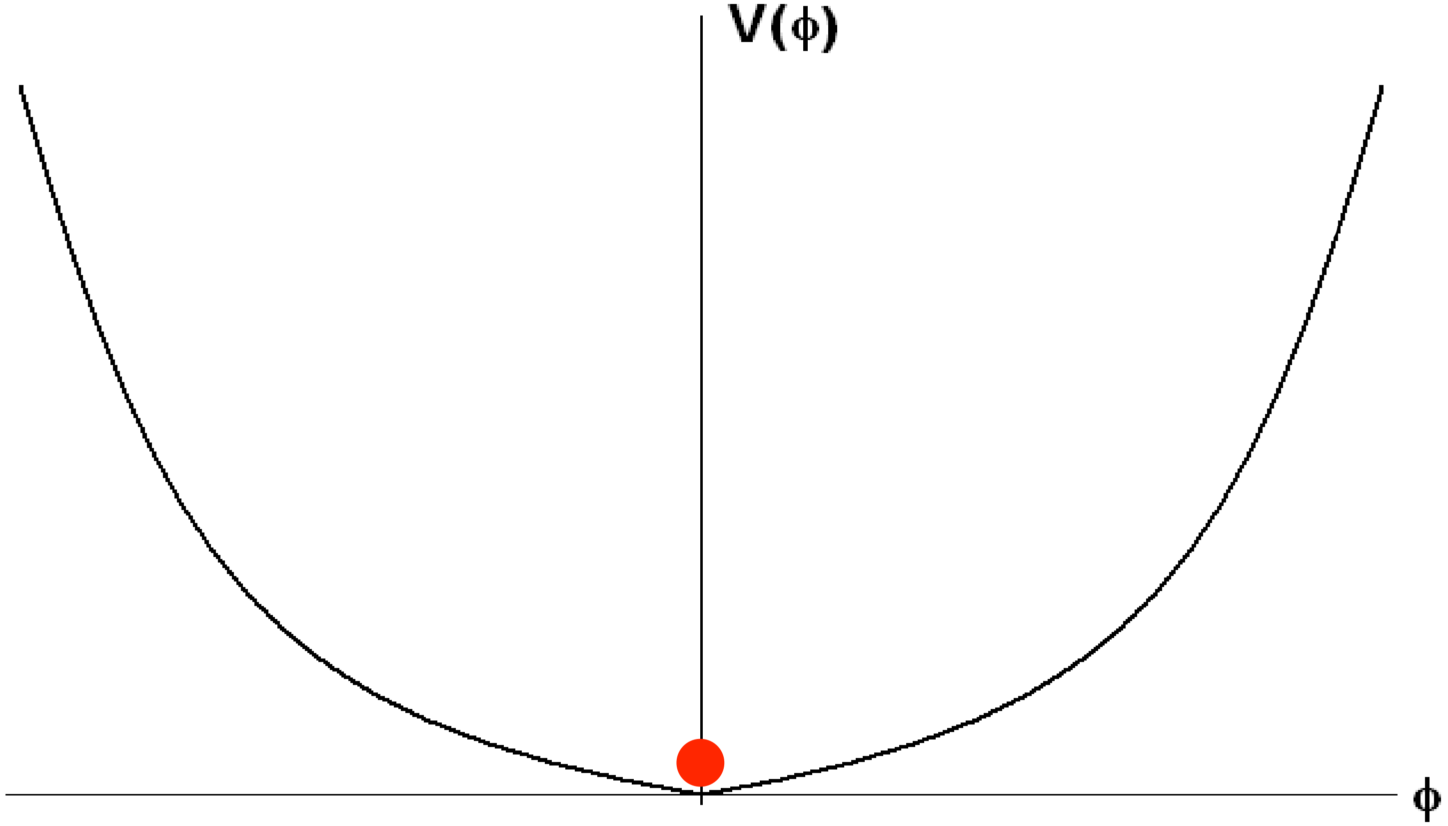

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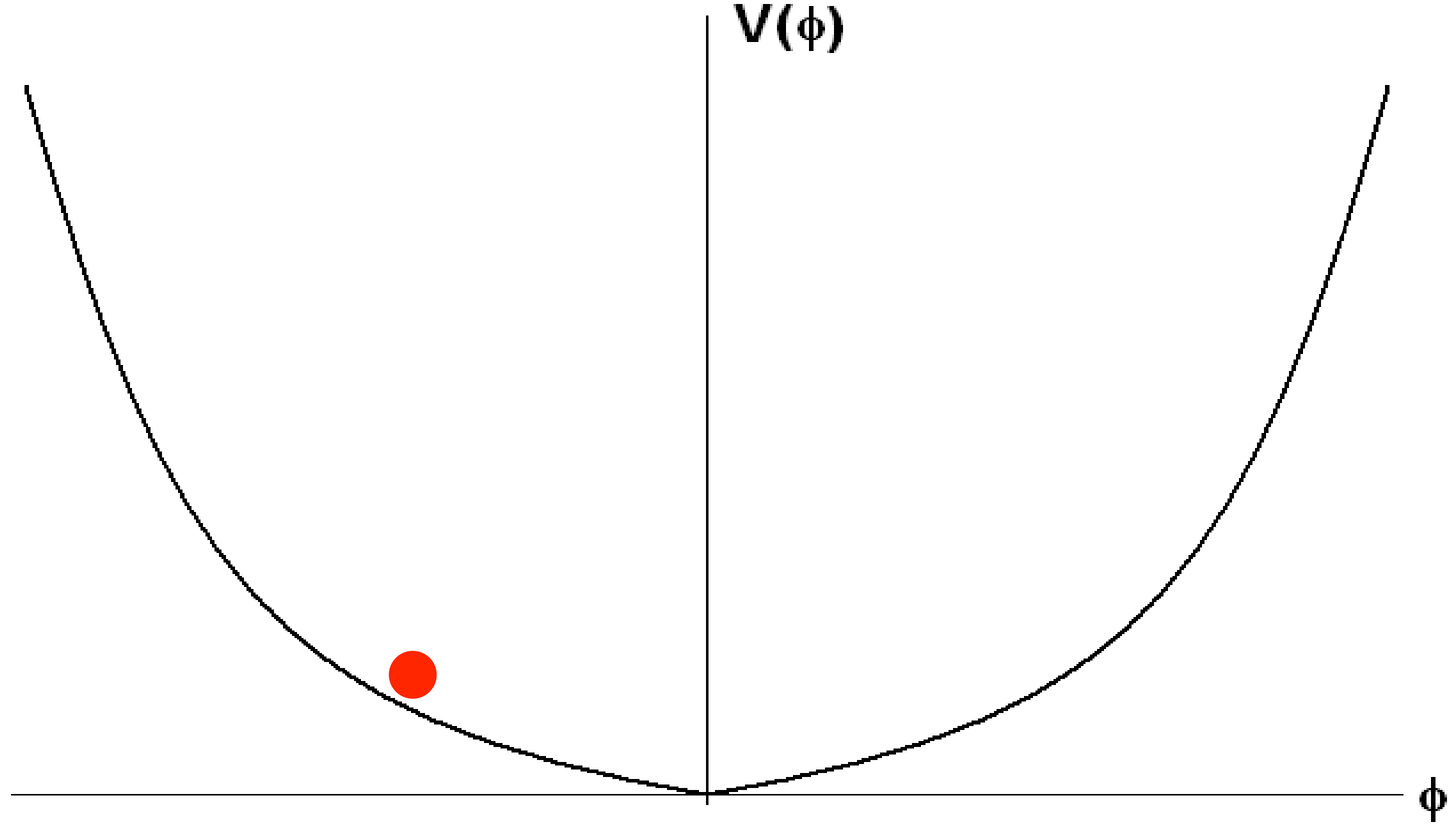

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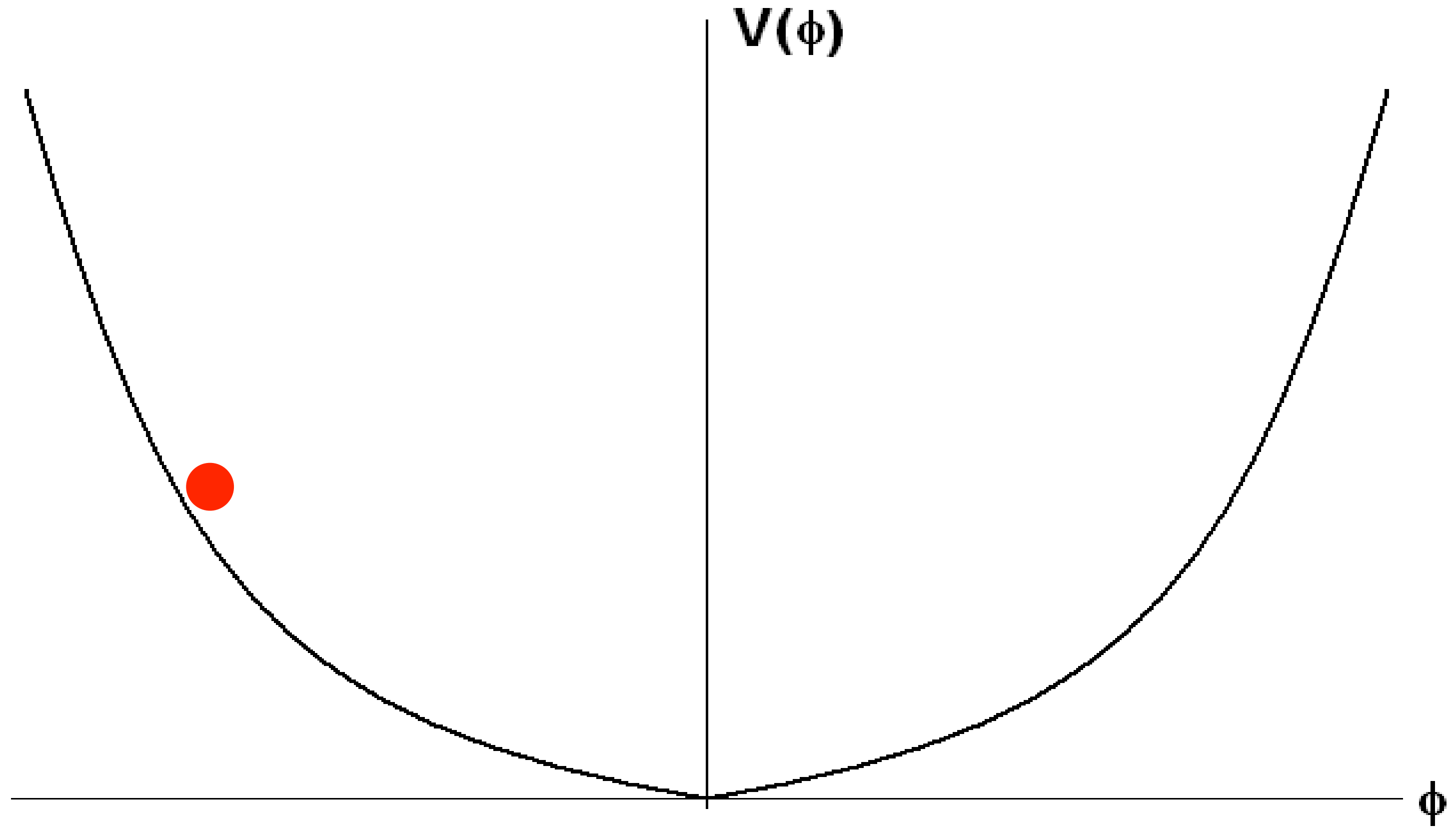

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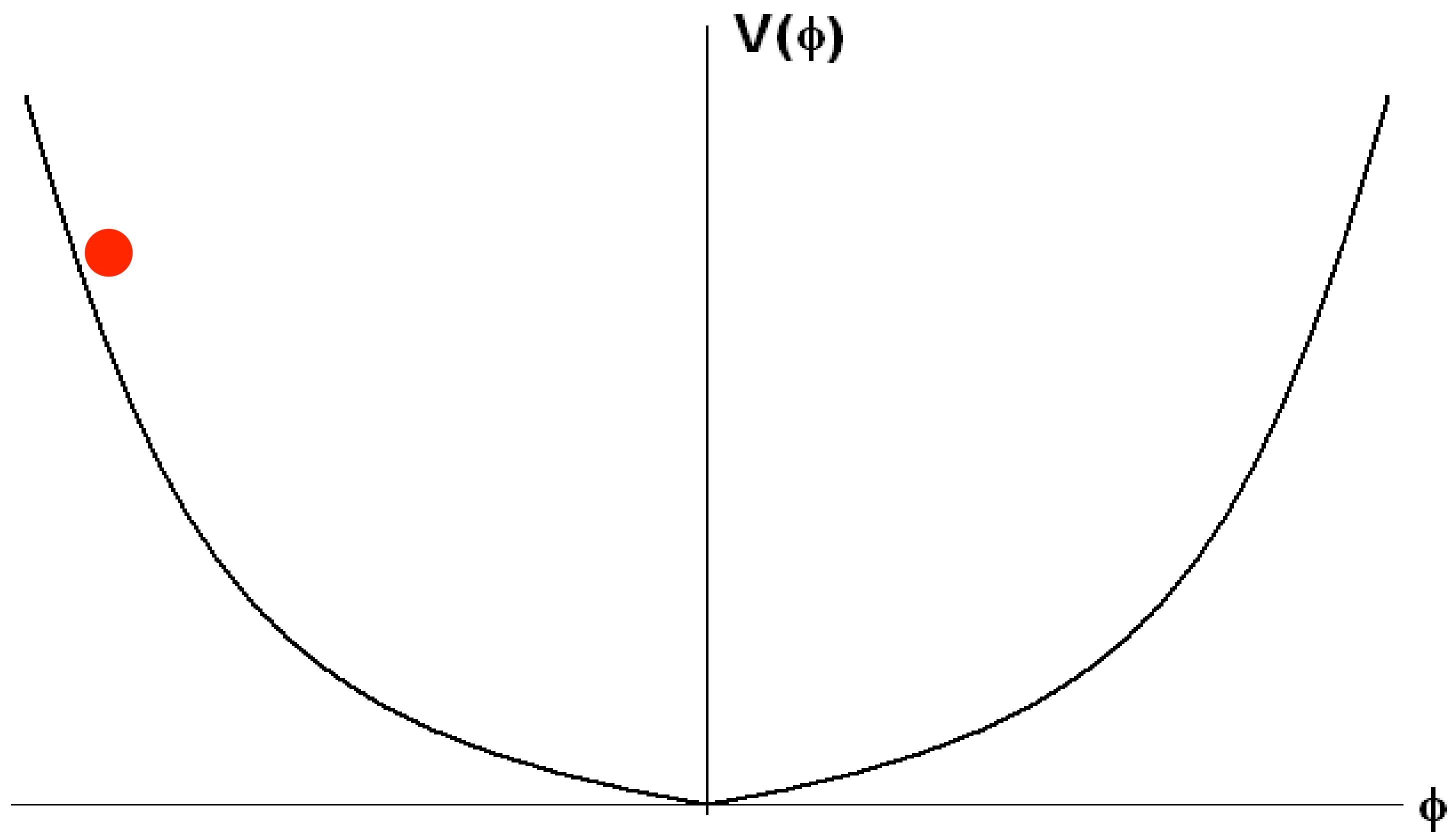

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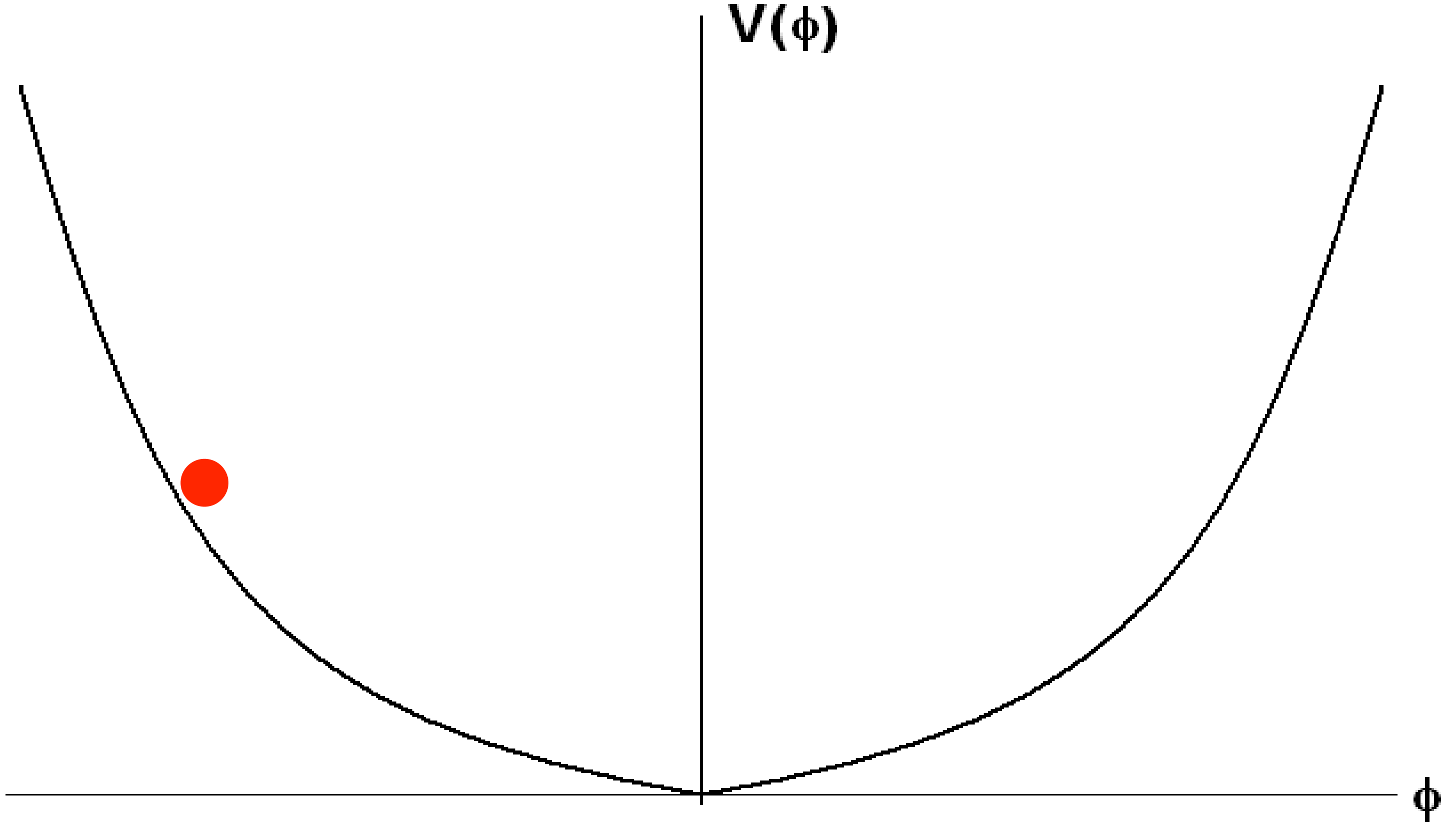

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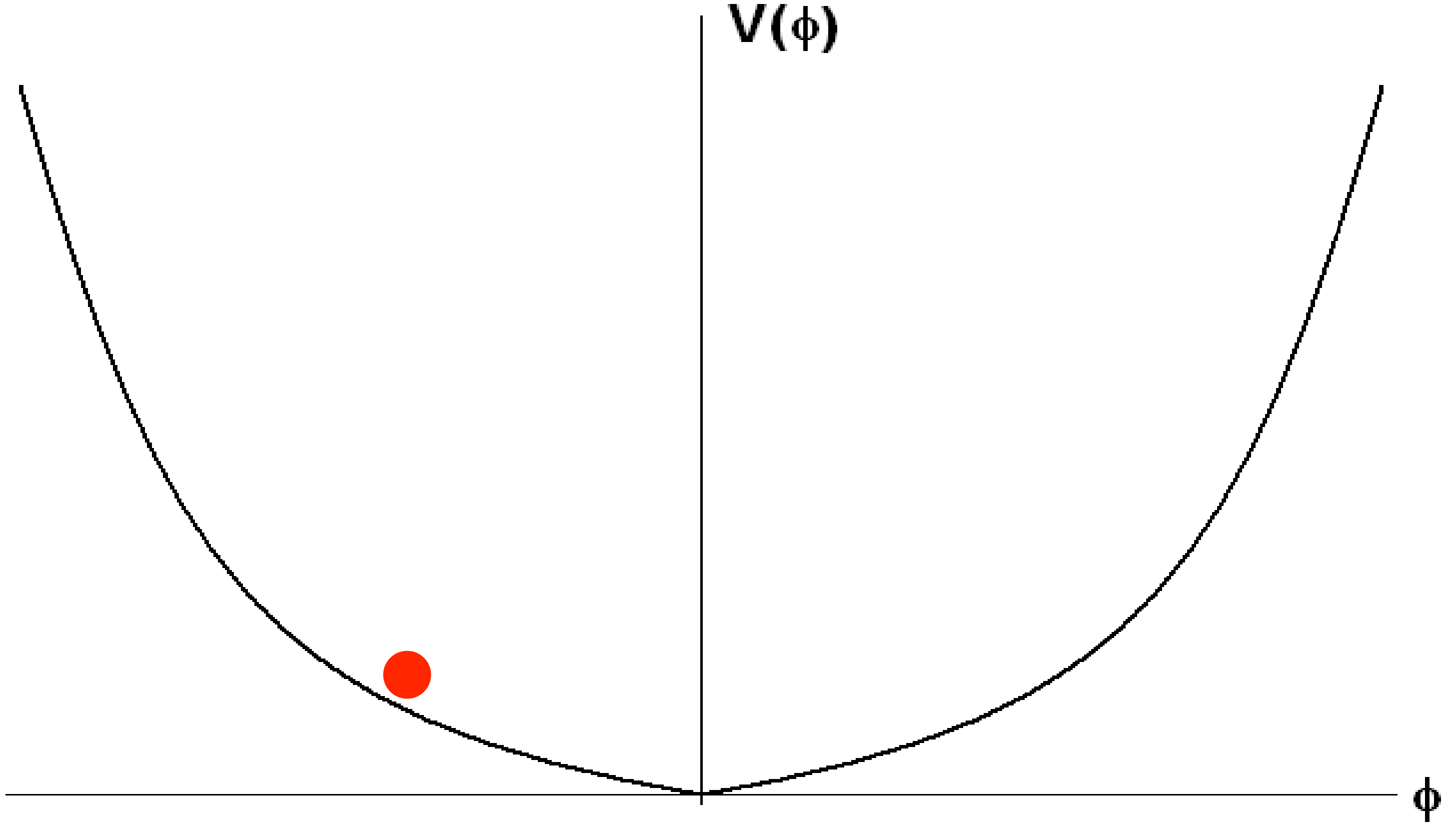

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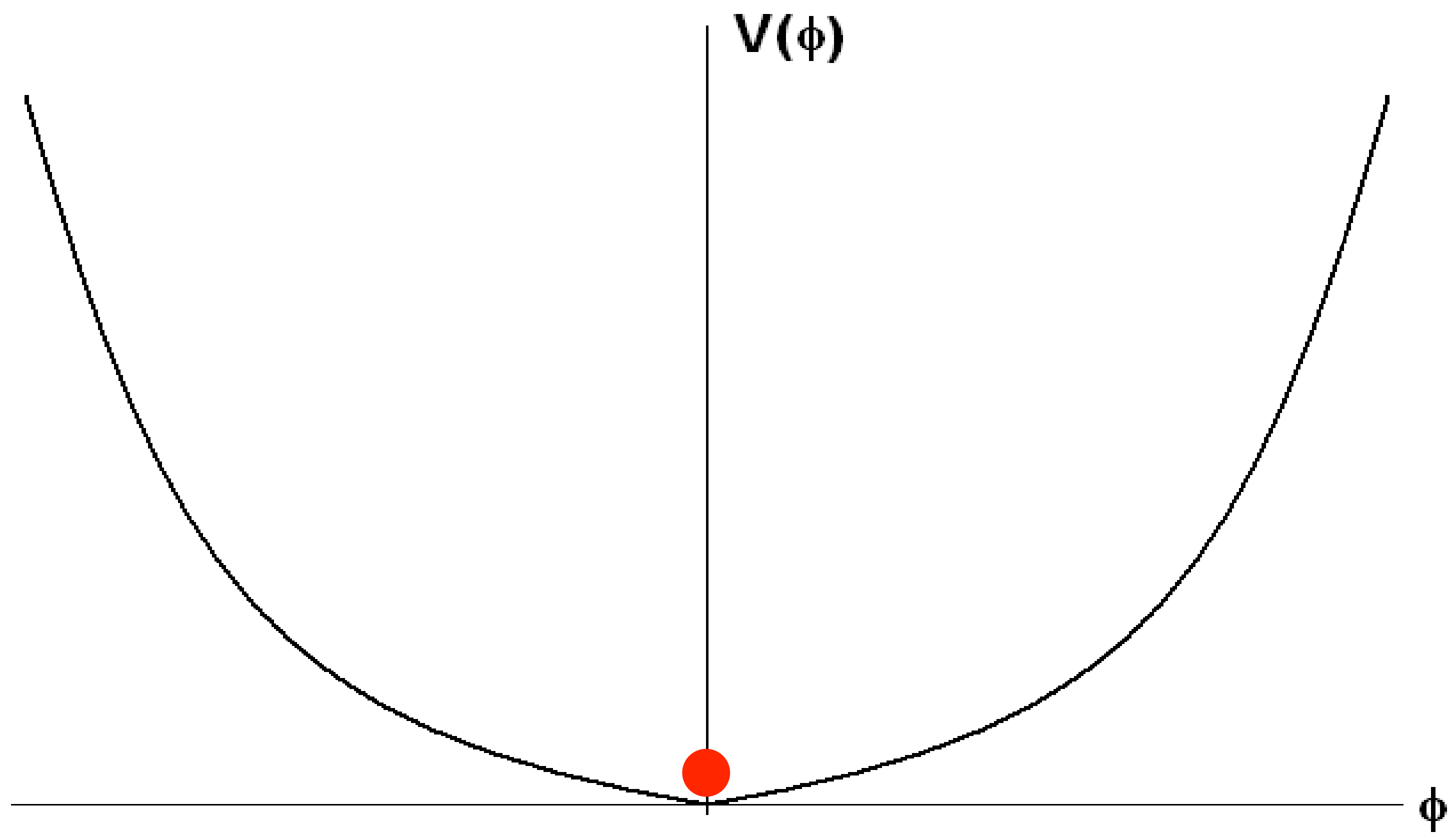

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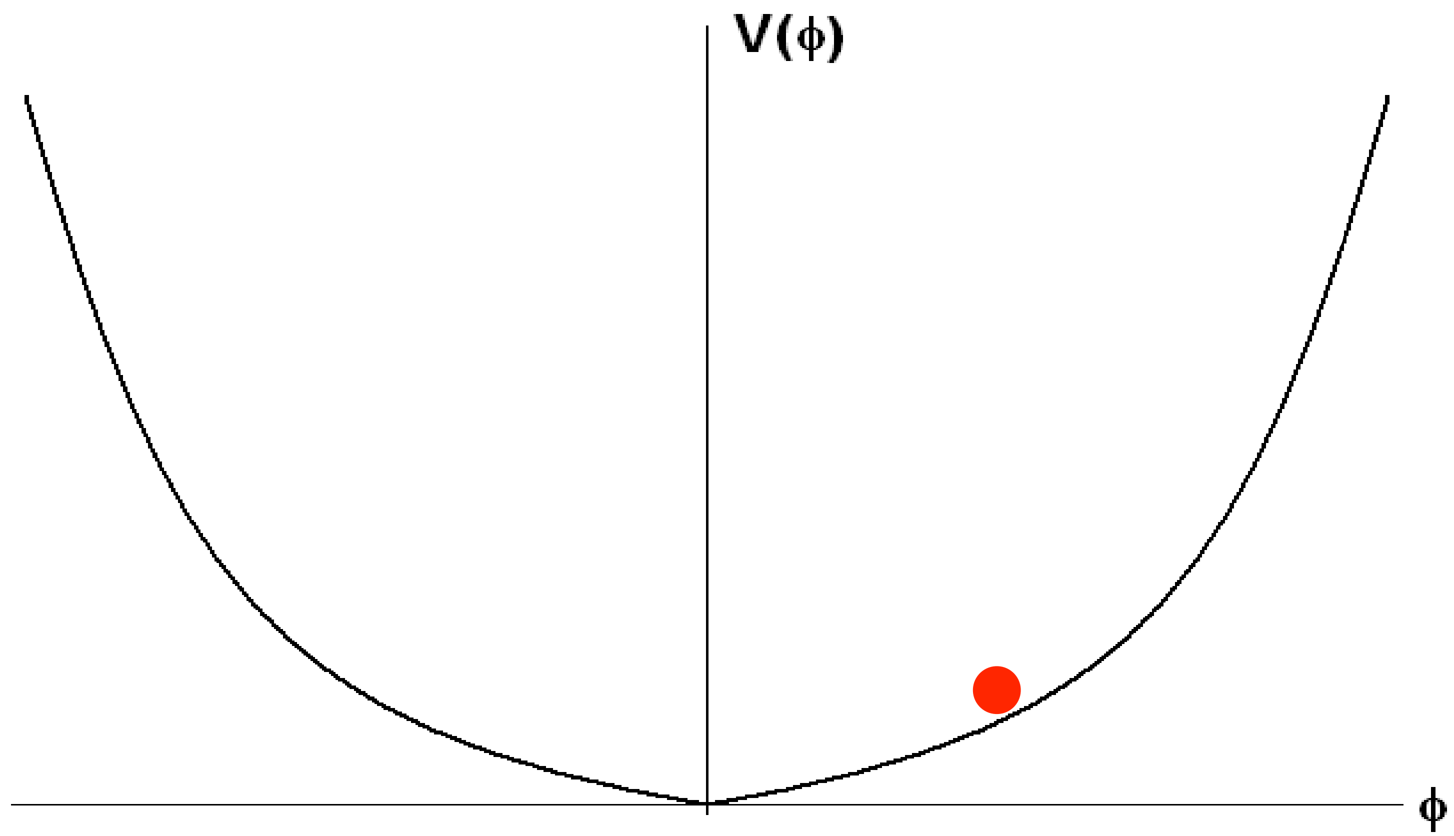

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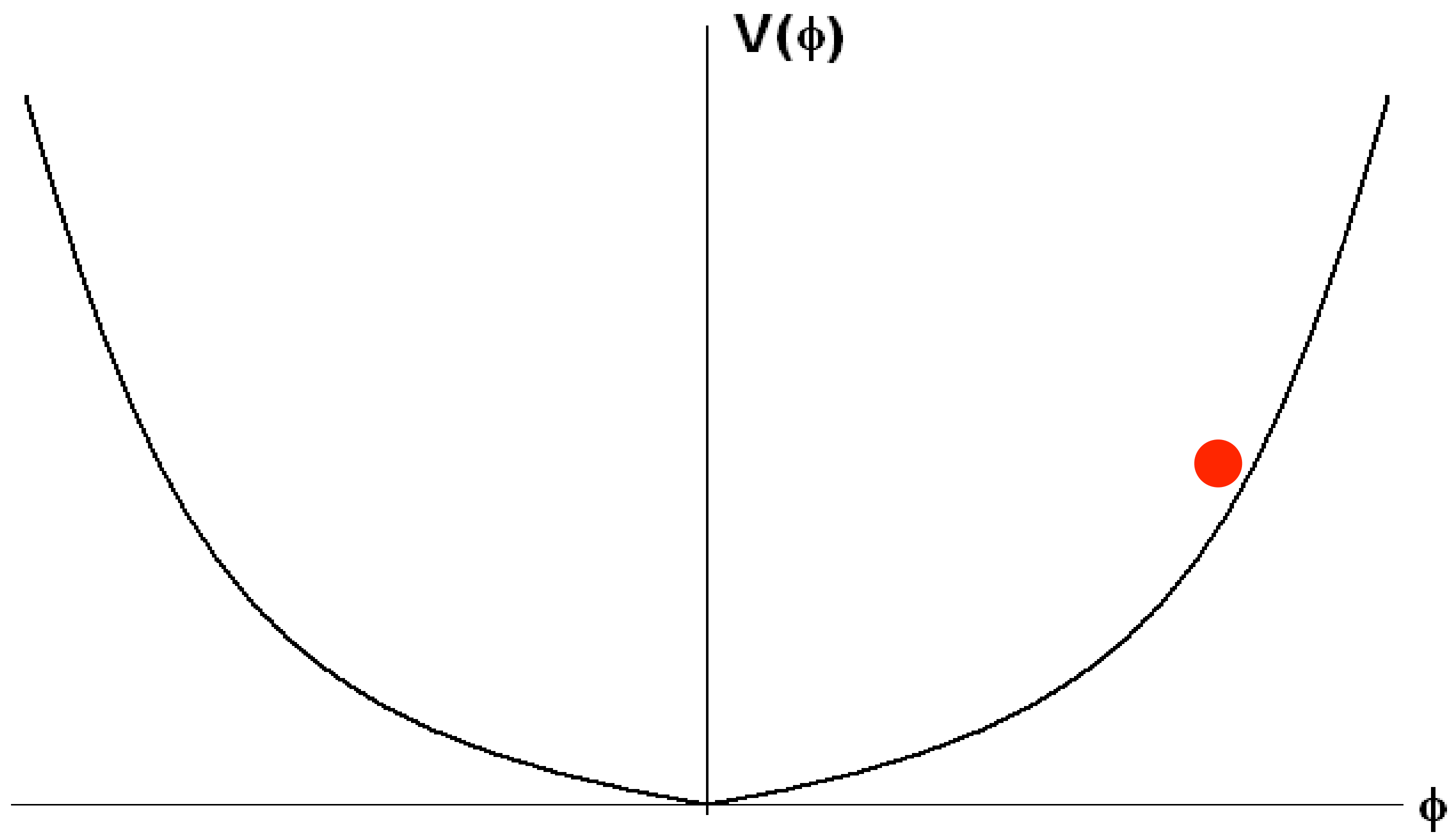

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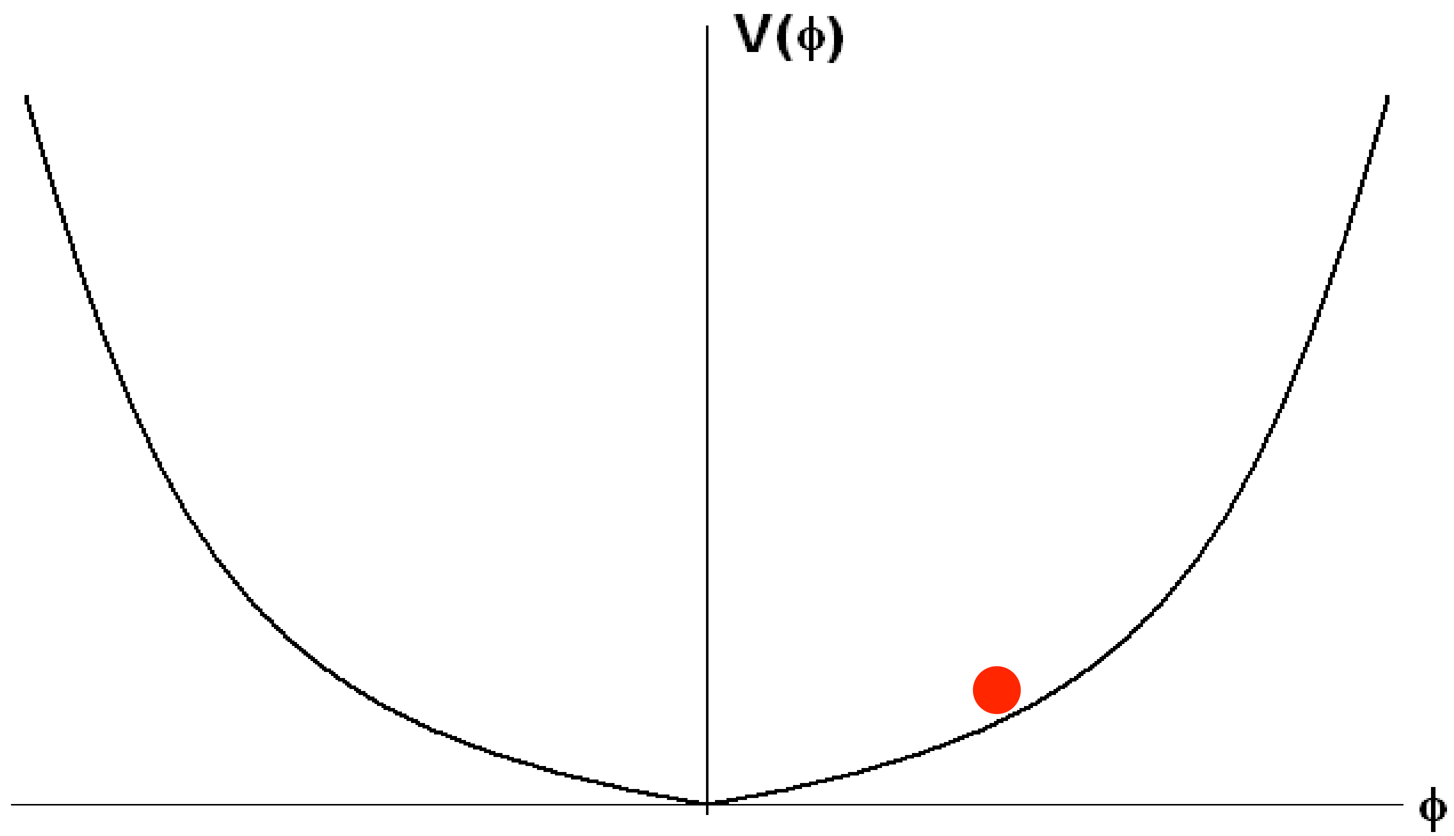

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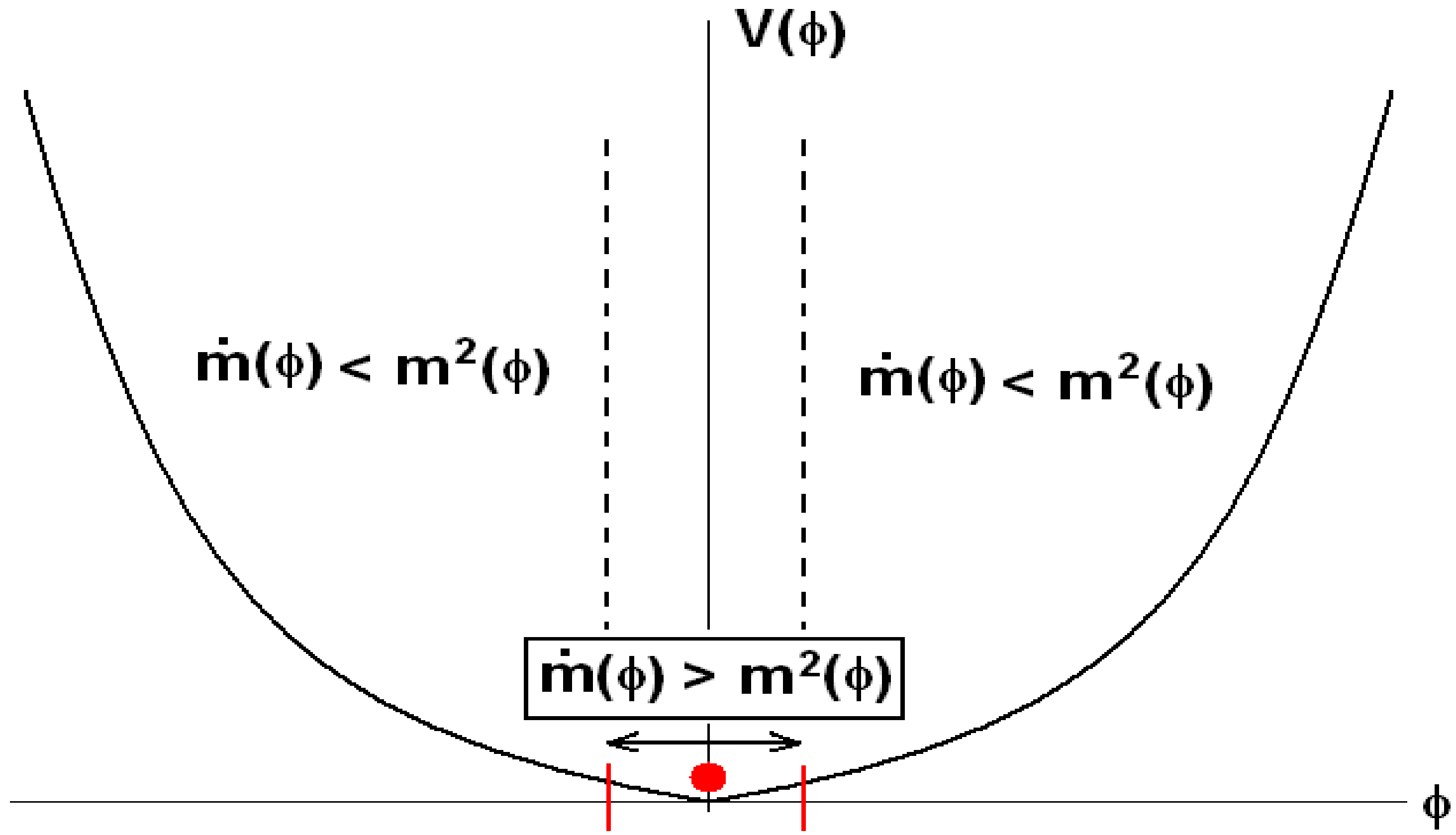

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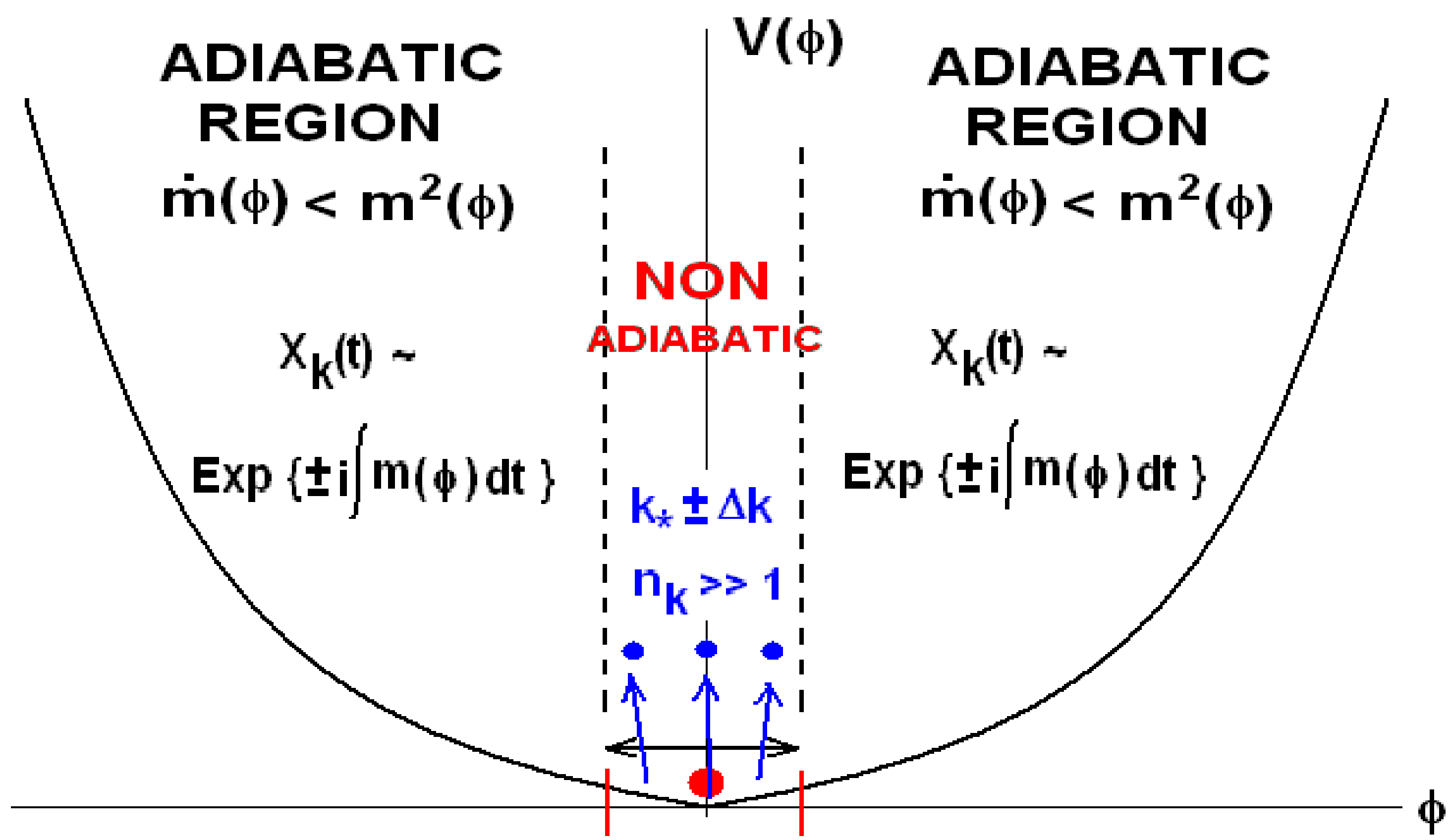

SCALAR (P)REHEATING

1) Chaotic Scenarios: PARAMETRIC RESONANCE

MATTER FIELD FLUCTUATIONS

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

(n = 4)

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

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$$\underset{(n=2)}{\text{Massive}} : X_k'' + (A_k - 2q\cos(2z))X_k = 0 \quad \text{(Mathieu Eq.)} \qquad q \equiv \frac{g^2\phi_*^2}{4\omega_*^2}\ ;\ \ \kappa \equiv \frac{k}{\omega_*}$$

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

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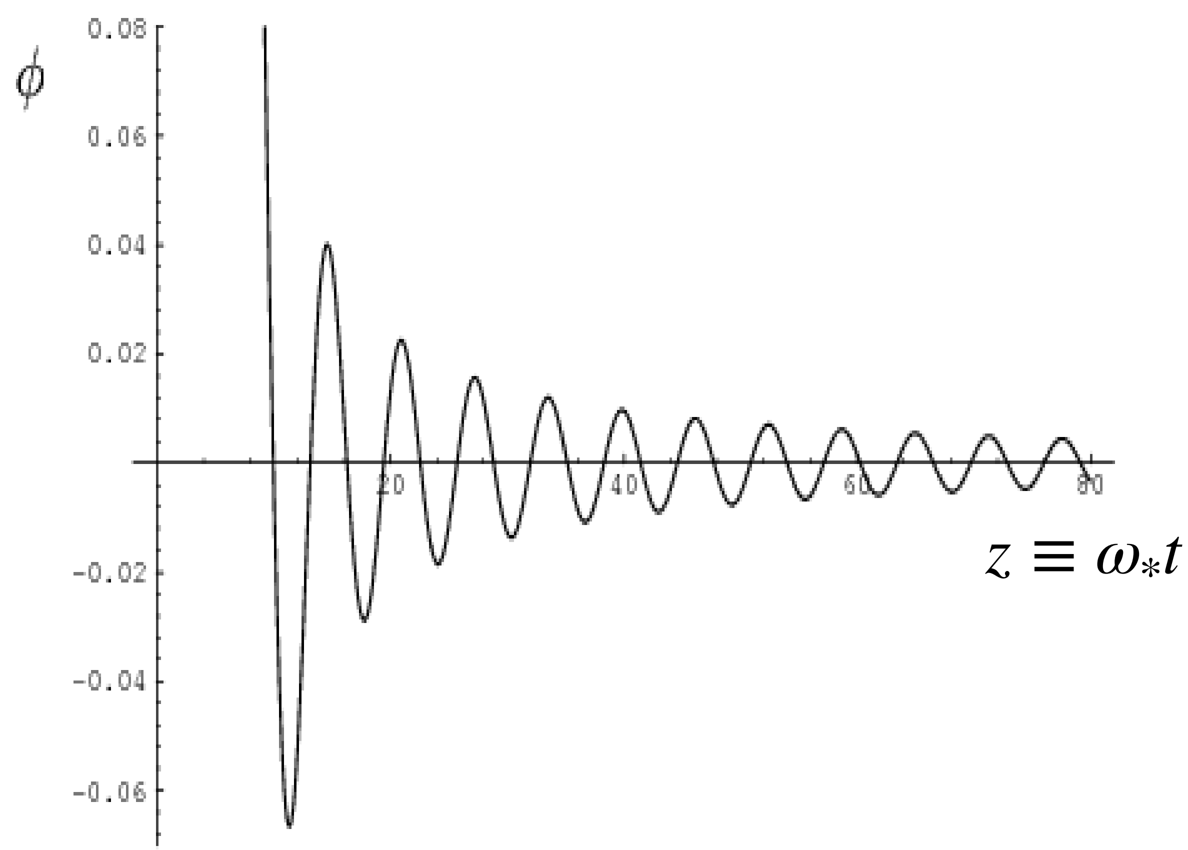

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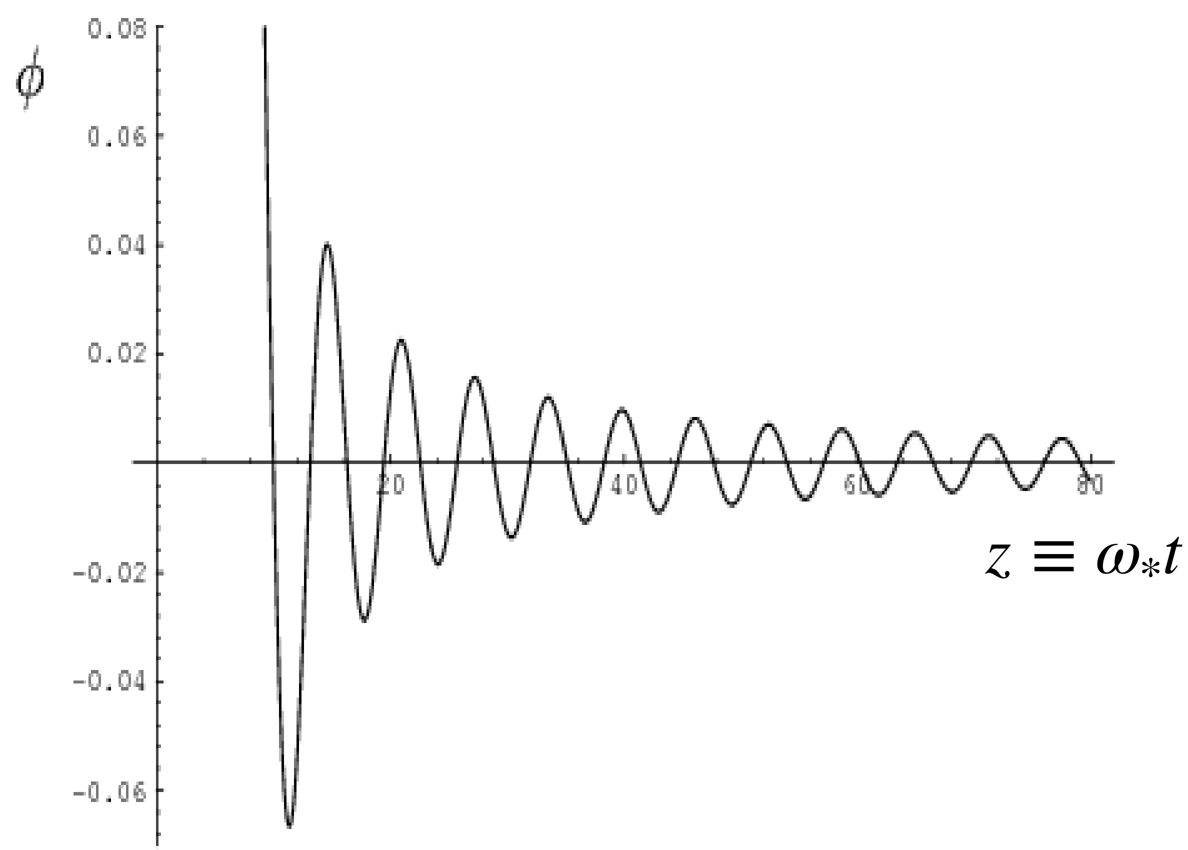

SCALAR (P)REHEATING

1) Chaotic Scenarios: PARAMETRIC RESONANCE

Broad (q > 1)

MATTER FIELD FLUCTUATIONS

$$\text{Massless}_{(n=4)} : X_k'' + (\kappa^2 + \; q\, cn^2(z))X_k = 0 \quad \text{(Lamé Eq.)}$$

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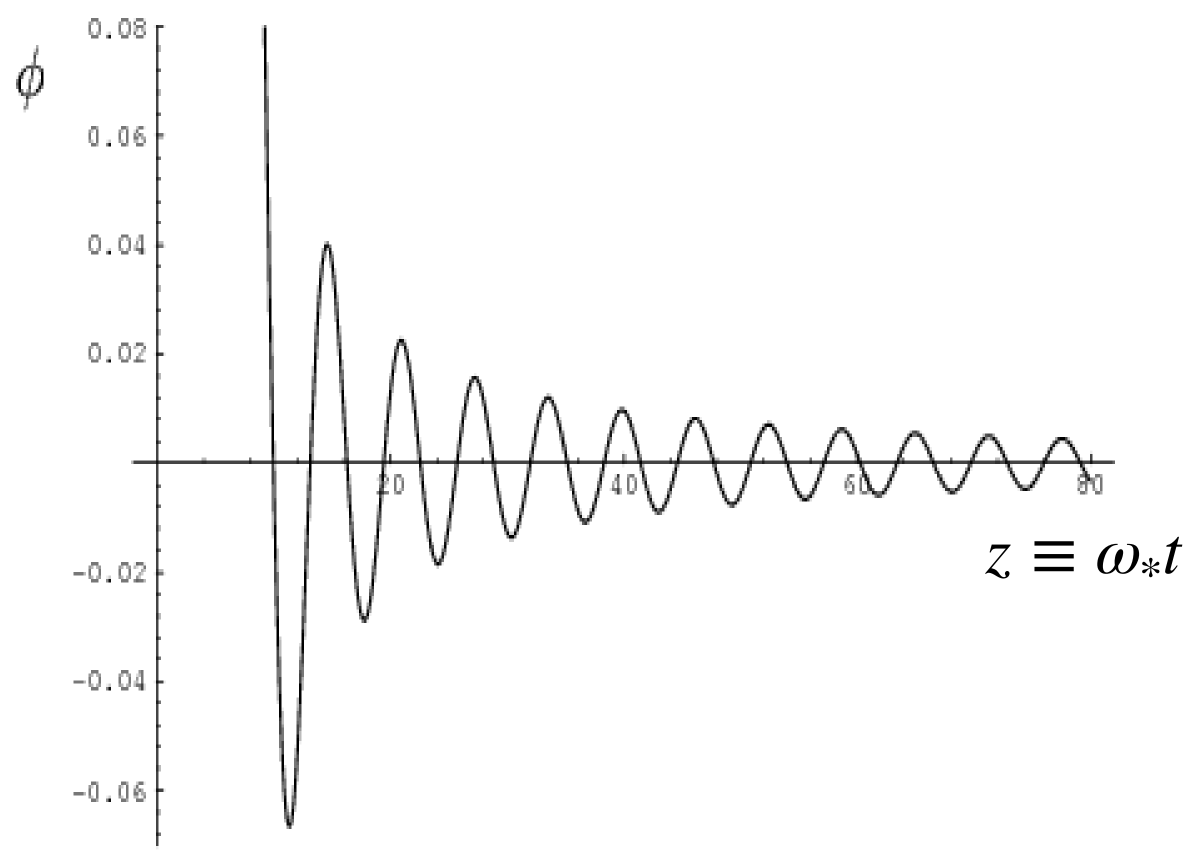
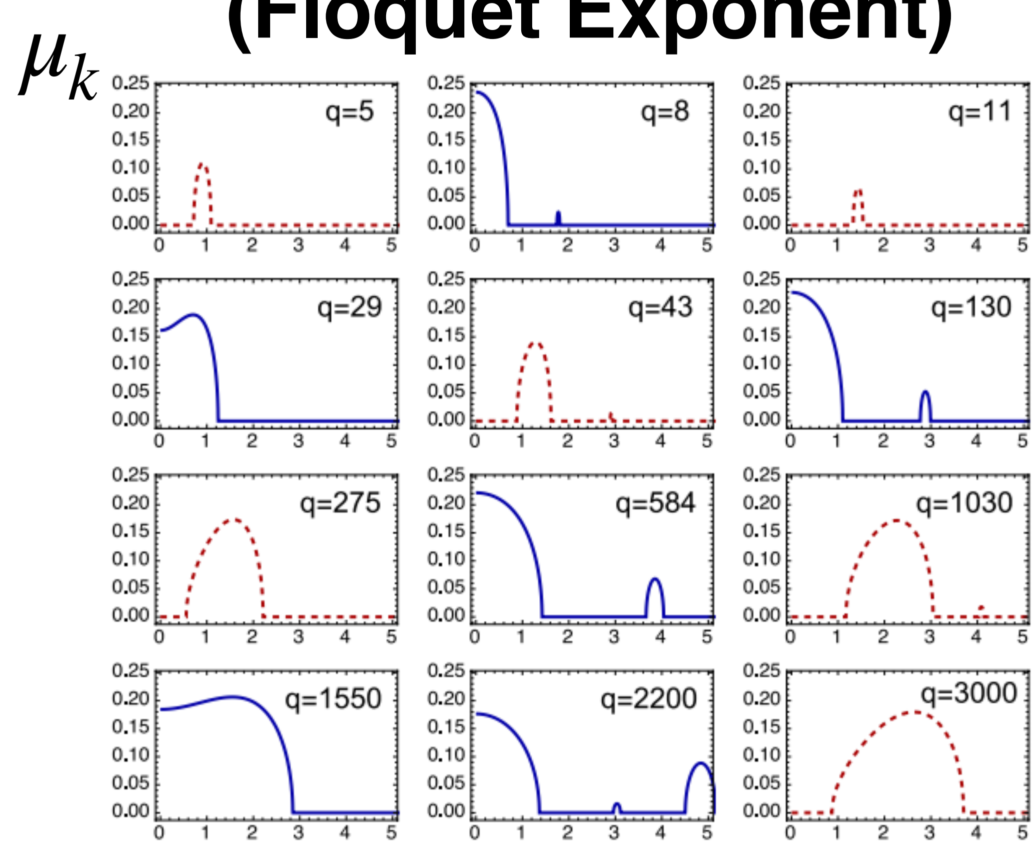


(Floquet Exponent)



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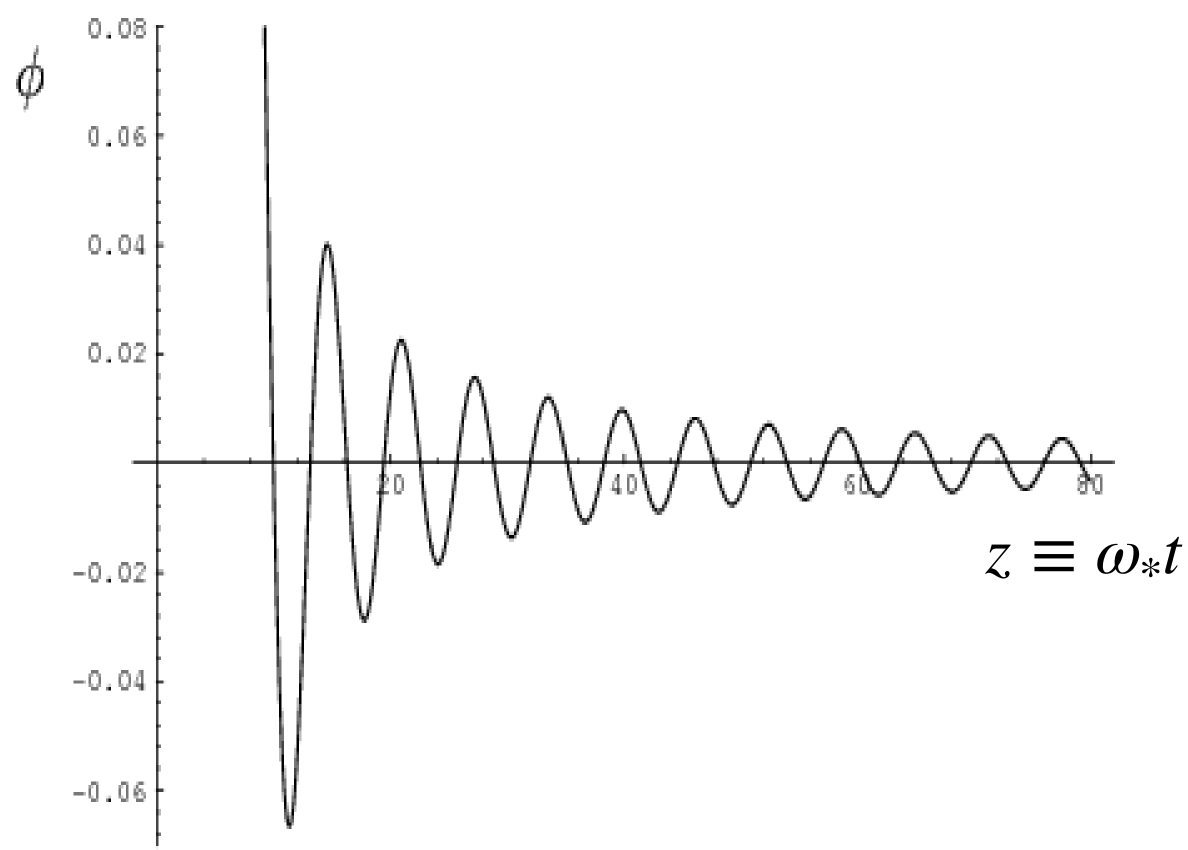

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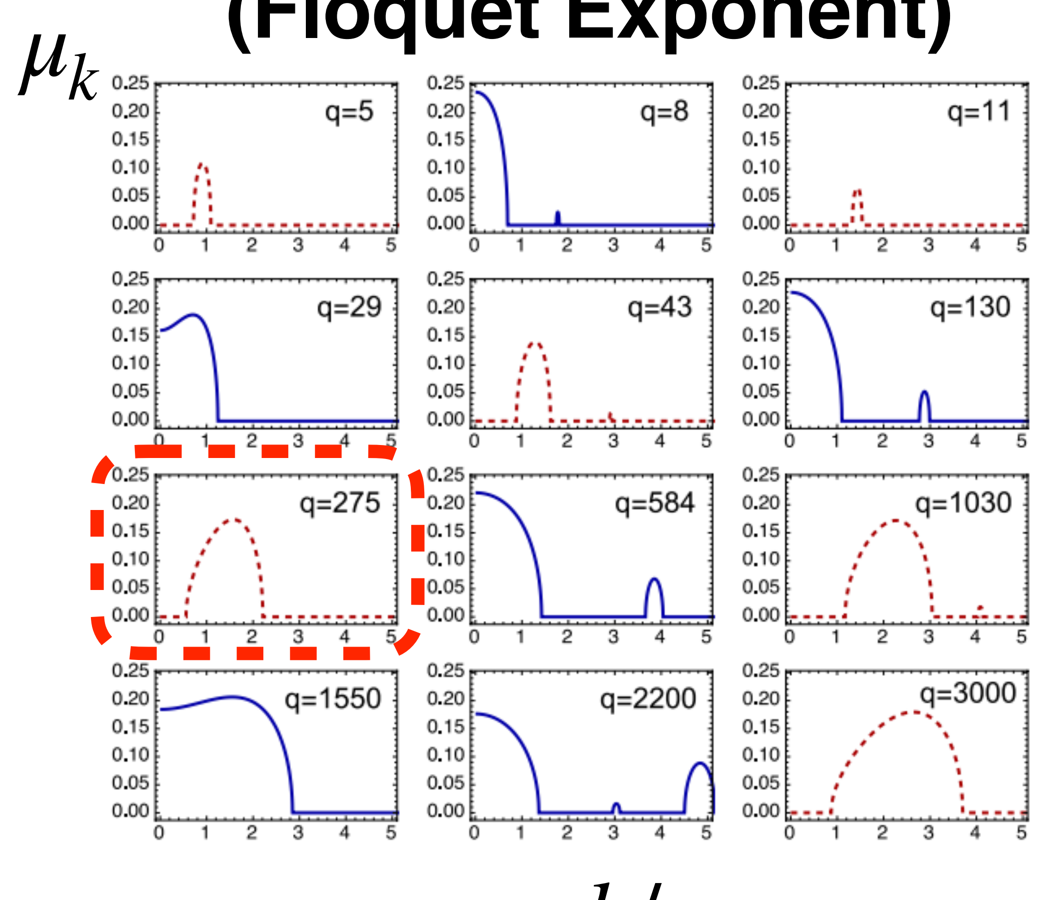

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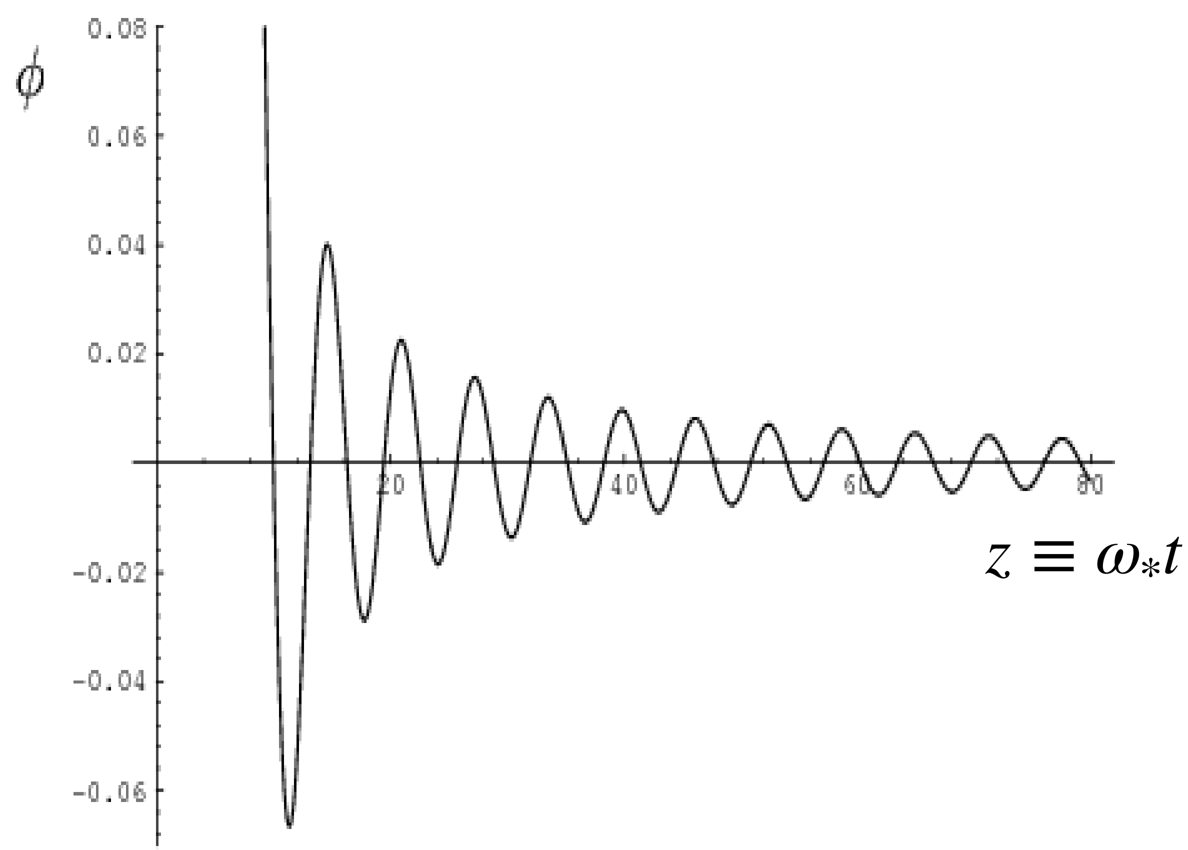

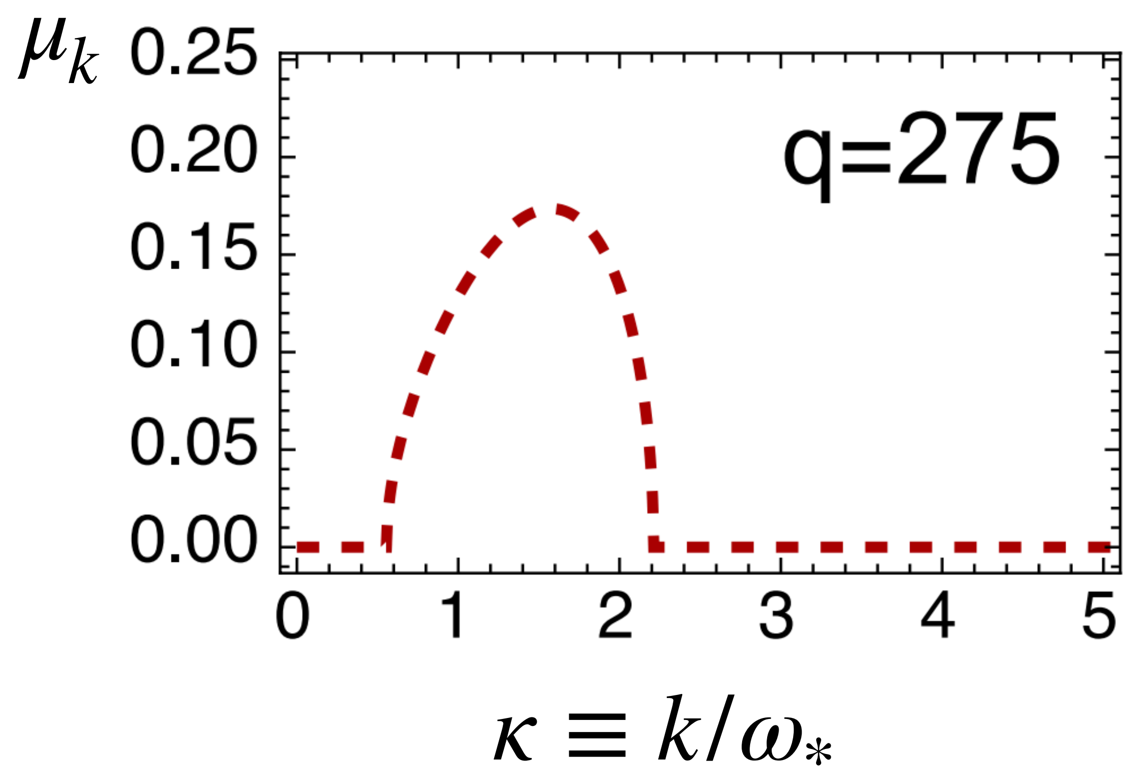

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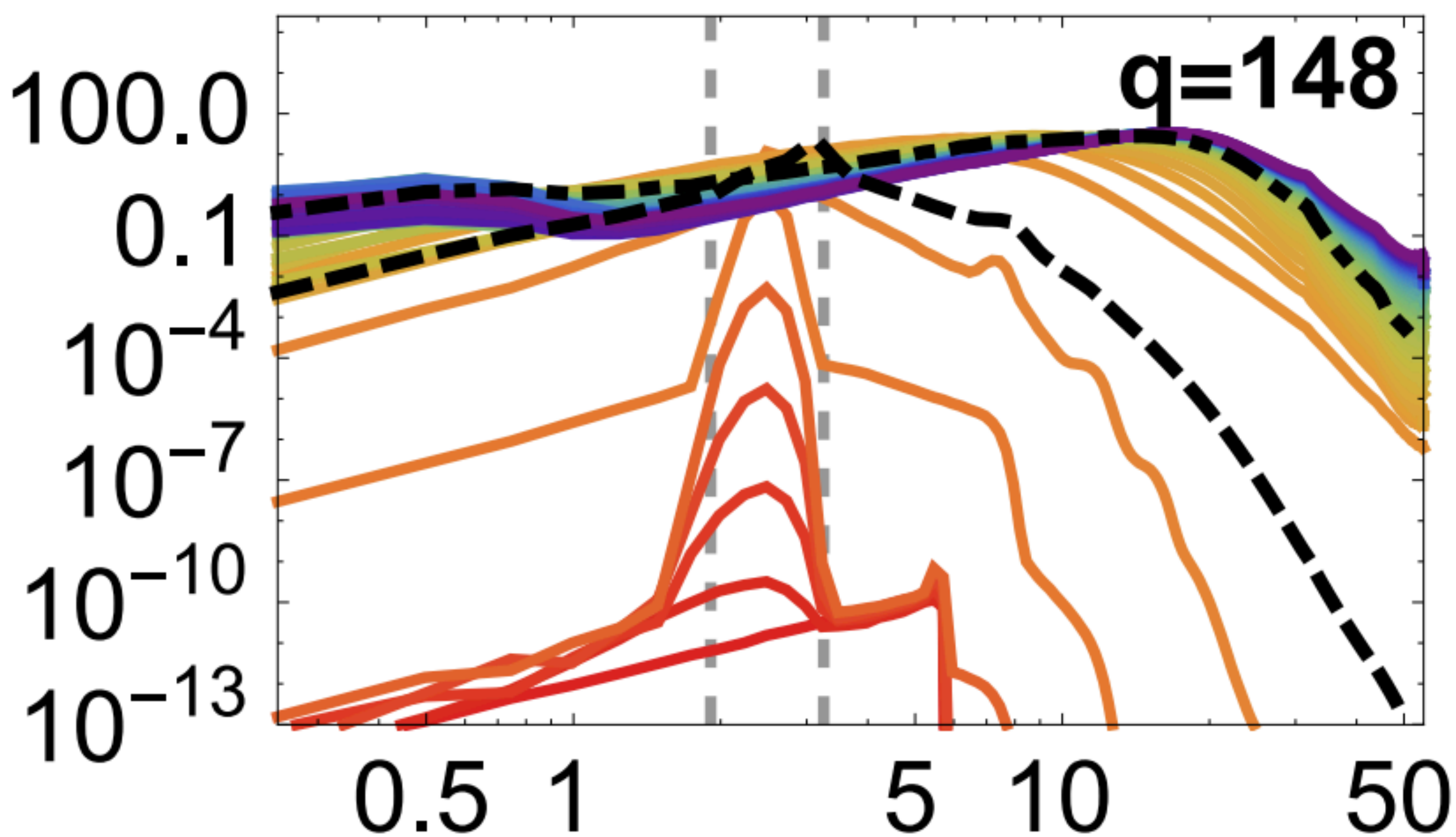
$$\frac{k^3 |X_k|^2}{2\pi^2}$$



$$\kappa \equiv k/\omega_*$$

SCALAR (P)REHEATING

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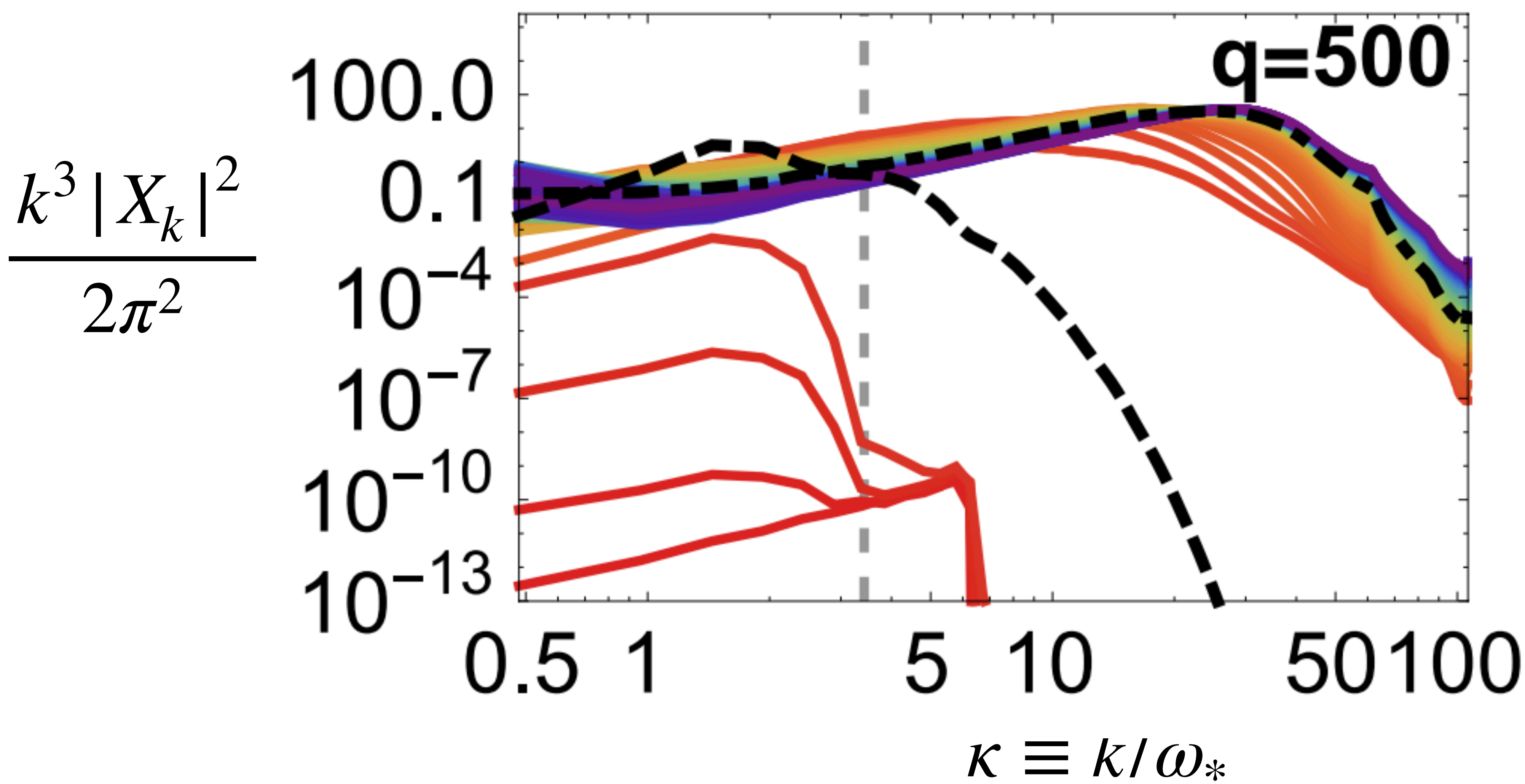
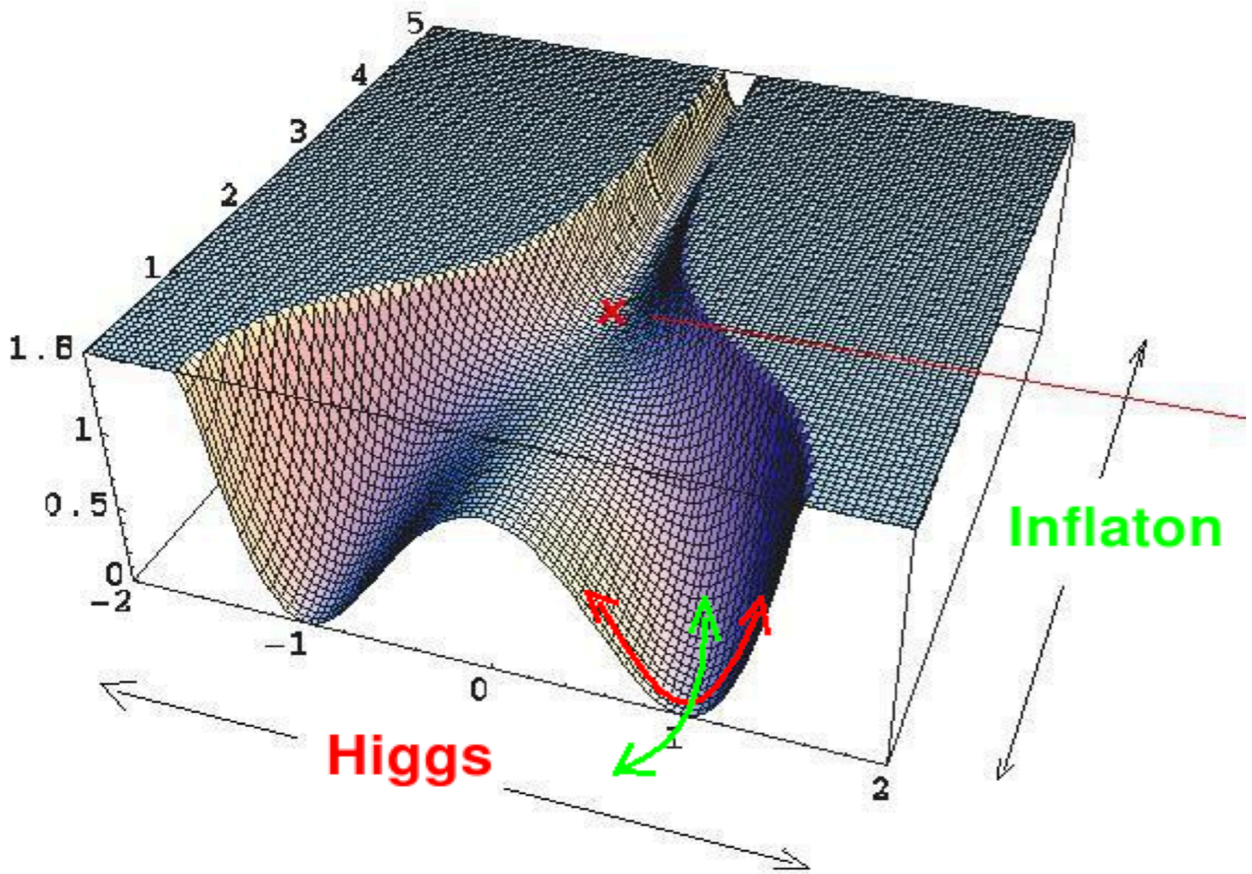


SCALAR (P)REHEATING

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

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

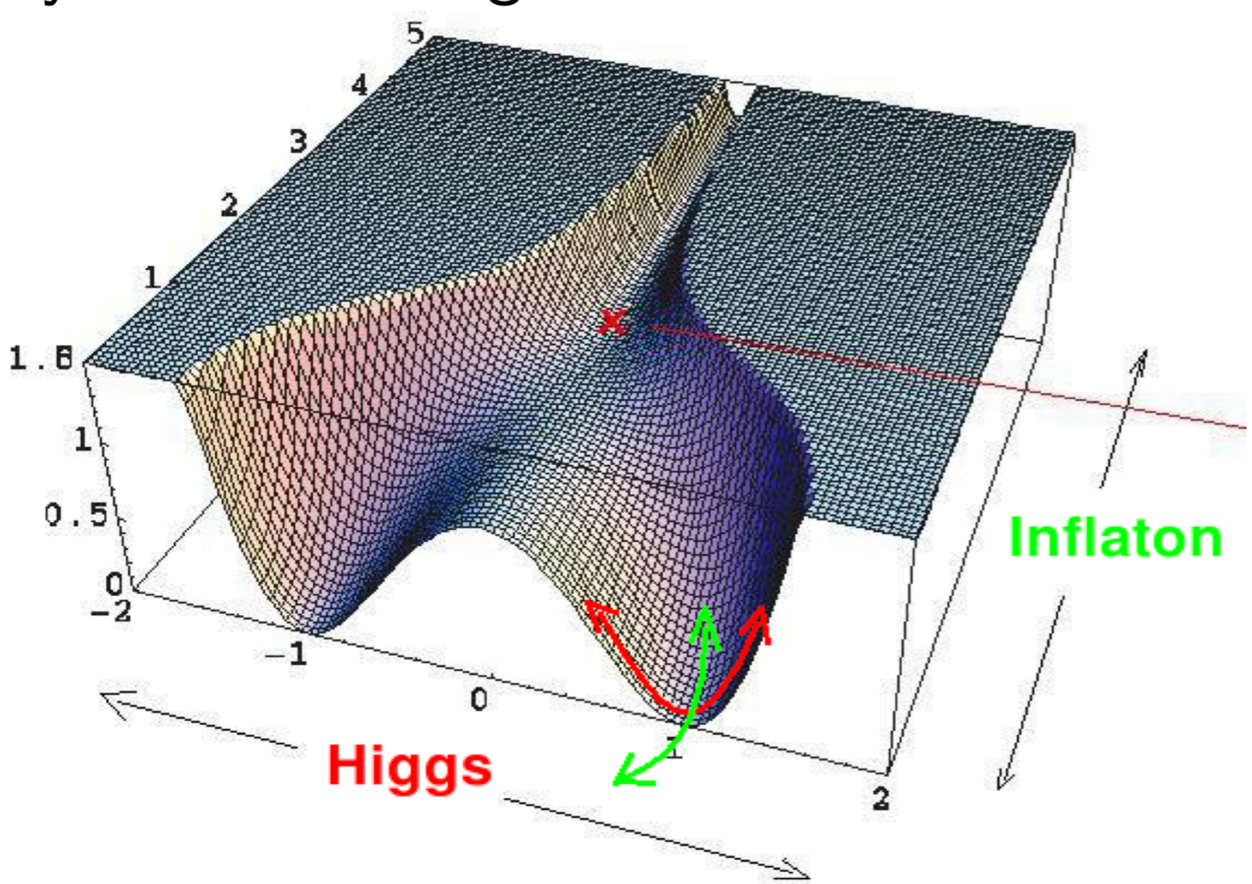
$$\ddot{\chi}_k + \Big(k^2 + \underbrace{m^2\left(\frac{\phi^2}{\phi_c^2} - 1\right)}_{(g^2\phi^2 - m^2)} + \lambda|\chi|^2\Big)\chi_k = 0$$

Self-coupling — V.E.V.

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

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

Hybrid Preheating



SCALAR (P)REHEATING

2) Hybrid Scenarios : SPINODAL INSTABILITY

inflaton mass → μ^2; coupling → g^2

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

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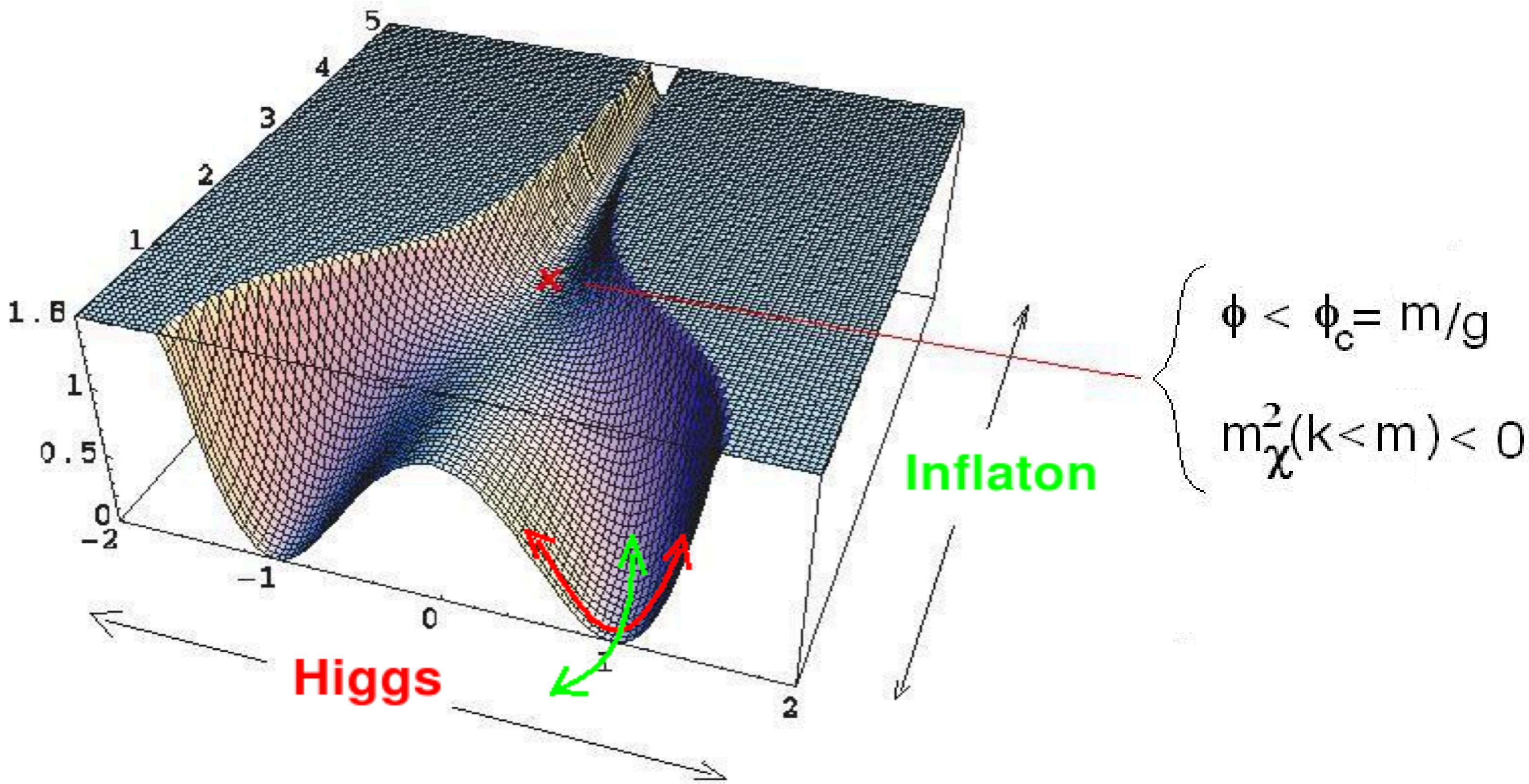

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$$\chi_k, n_k \sim e^{\sqrt{m^2 - k^2}\,t}$$

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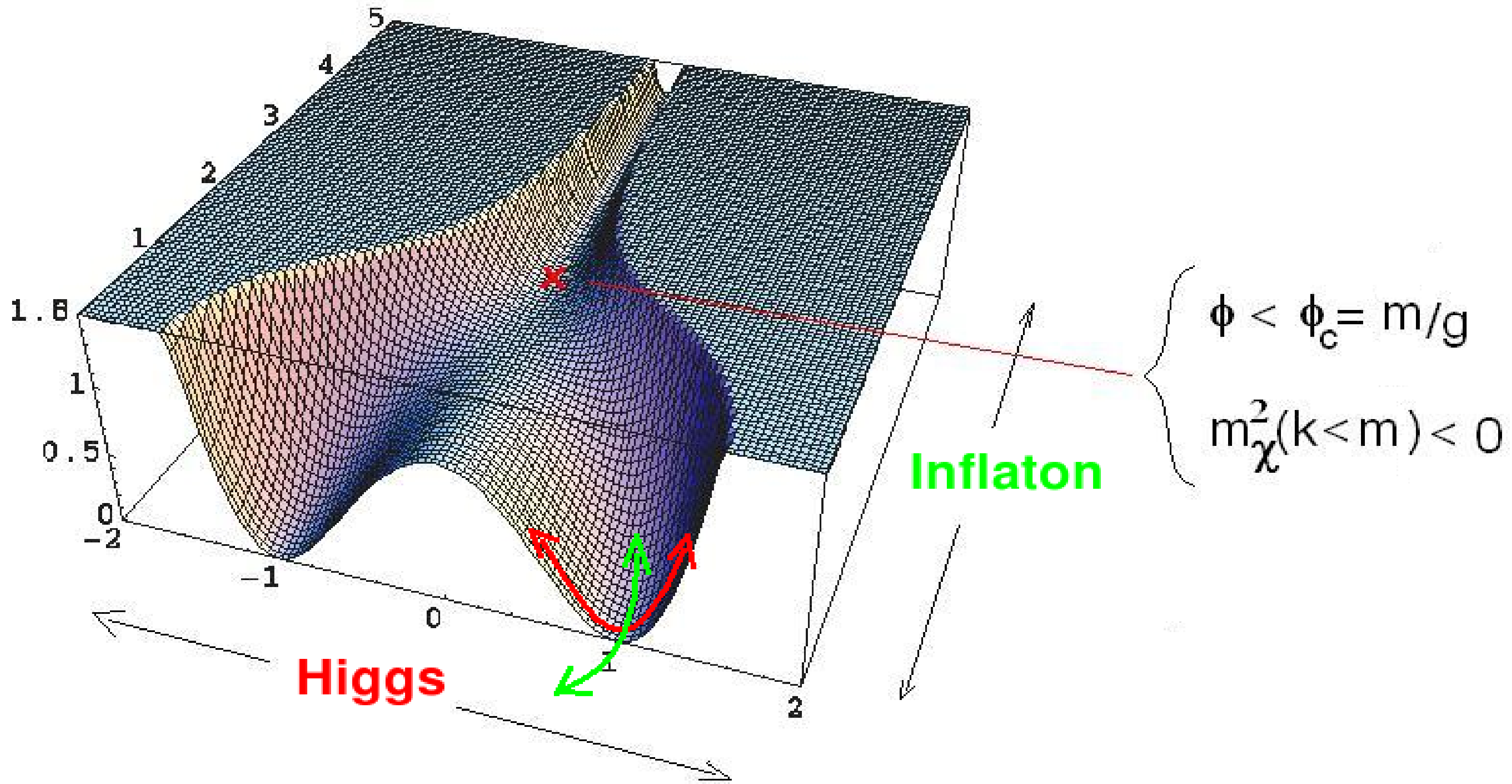

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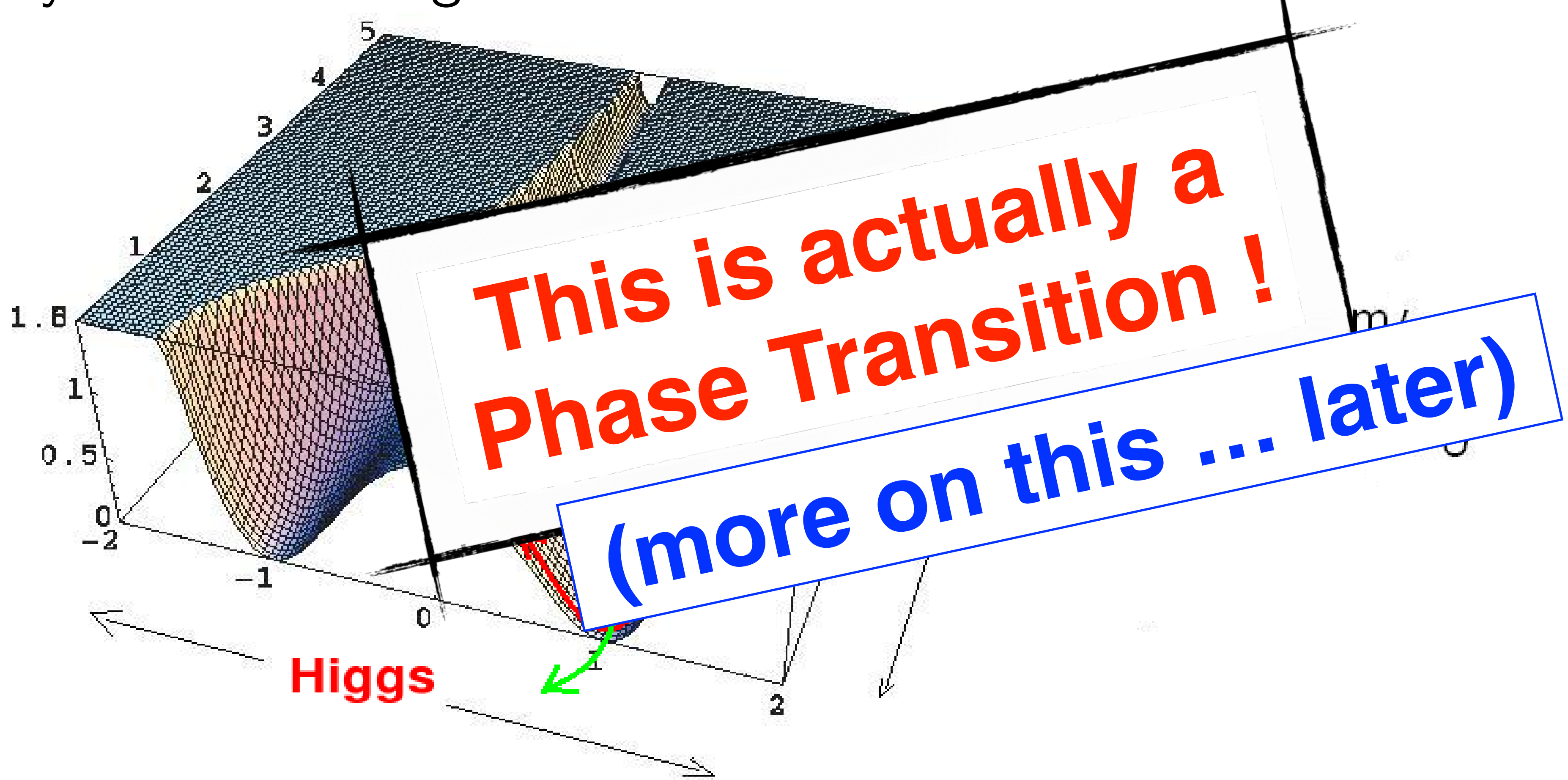

This is actually a Phase Transition !

(more on this ... later)

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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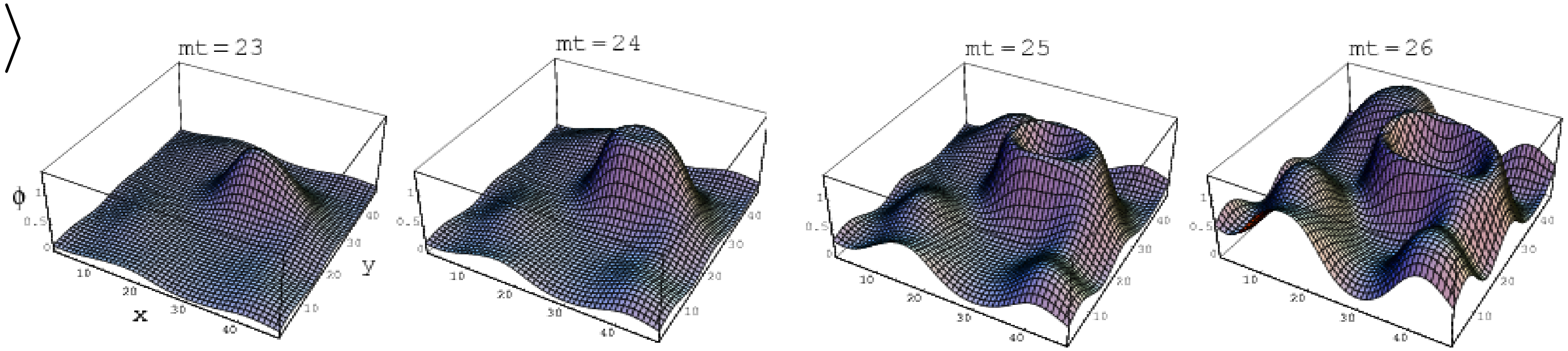
$\sqrt{\langle|\varphi|^2\rangle}$



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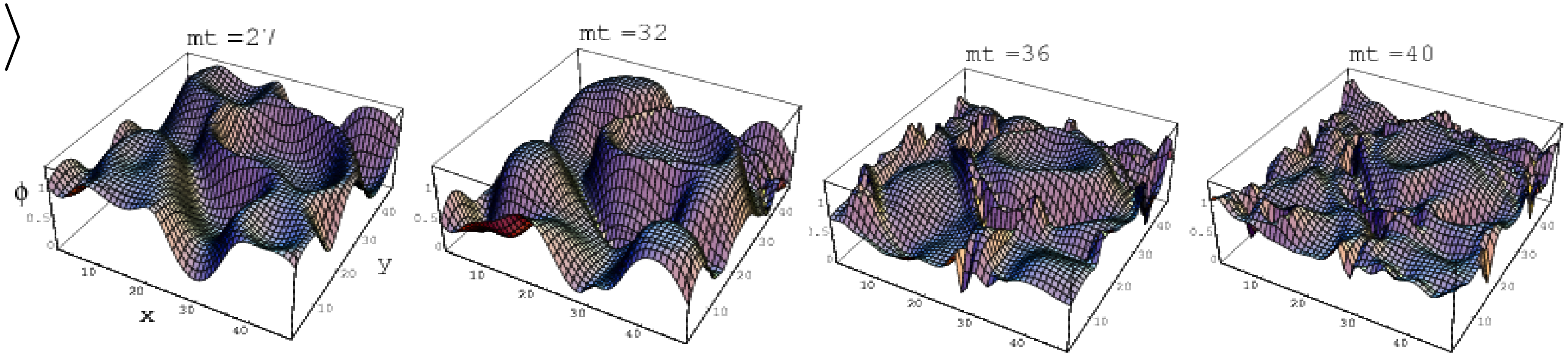

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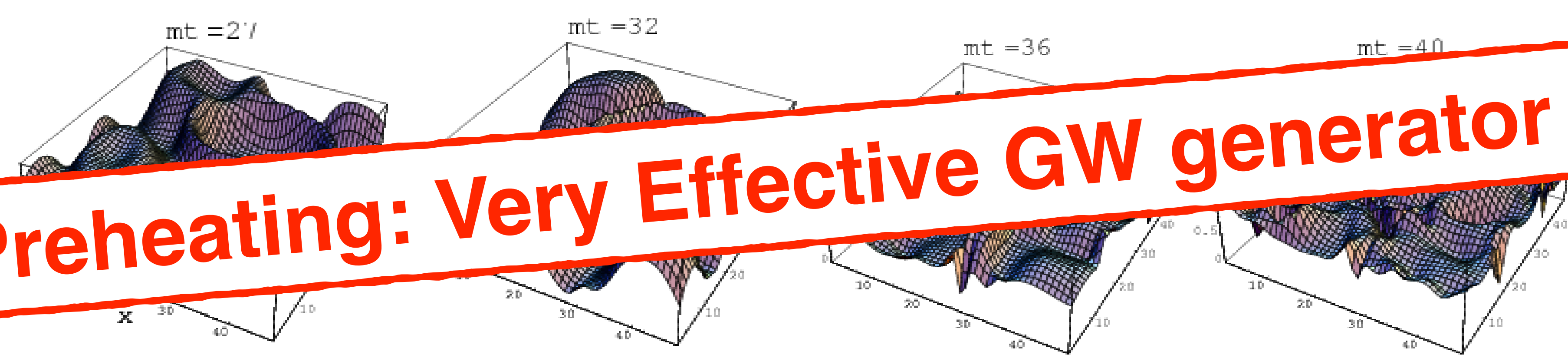

Preheating: Very Effective GW generator !

INFLATIONARY PREHEATING

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

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

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

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

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

$$ds^2 = a^2(-d\tau^2 + (\delta_{ij} + h_{ij})dx^i dx^j), \qquad {\rm TT} : \left\{ \begin{array}{l} h_{ii} = 0 \\ h_{ij,j} = 0 \end{array} \right.$$

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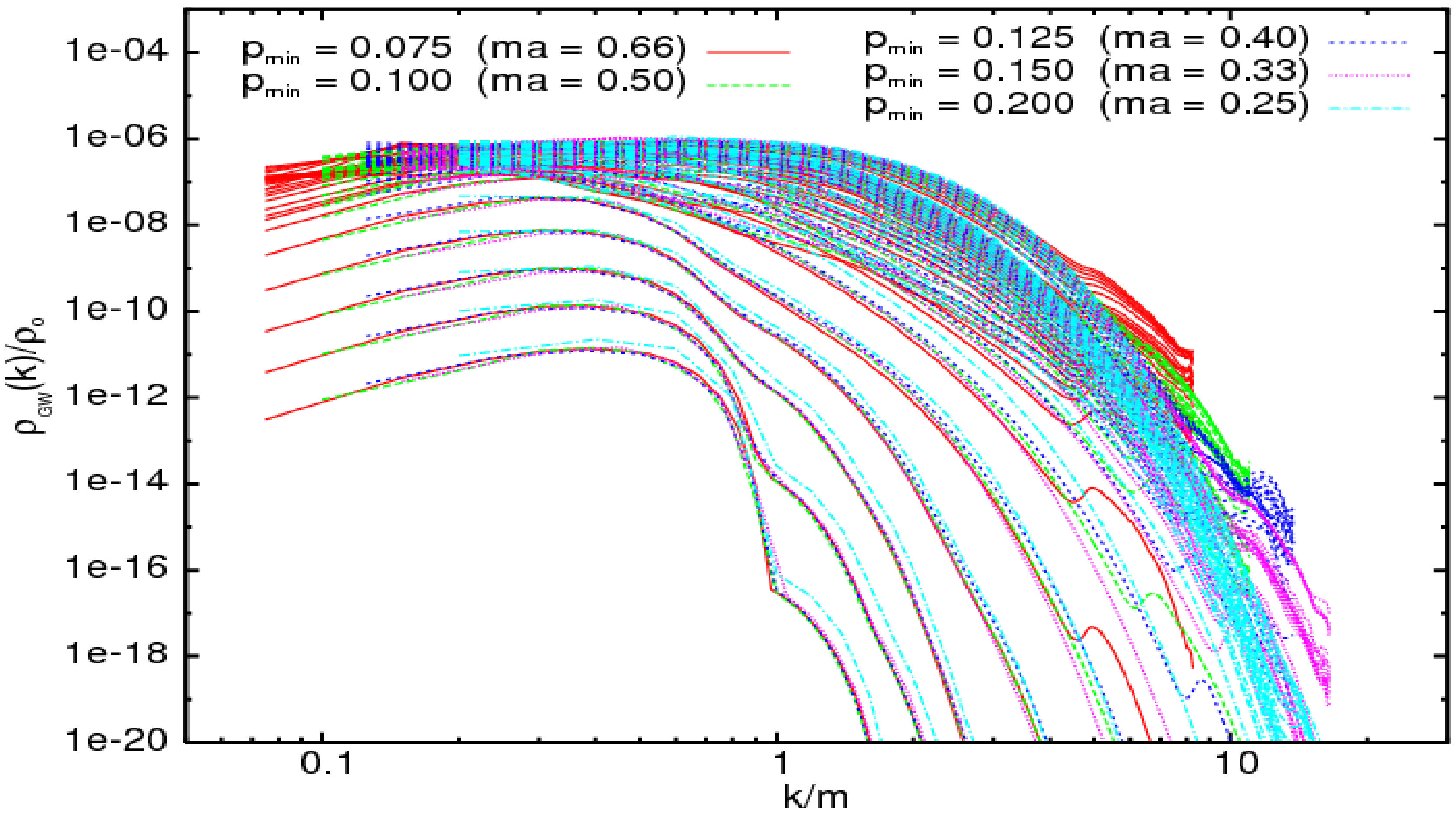
How do you obtain TT?

GW Spectrum

Parameter Dependence (Peak amplitude**)**

Hybrid Models:

$\Omega_{GW}(k,t)$

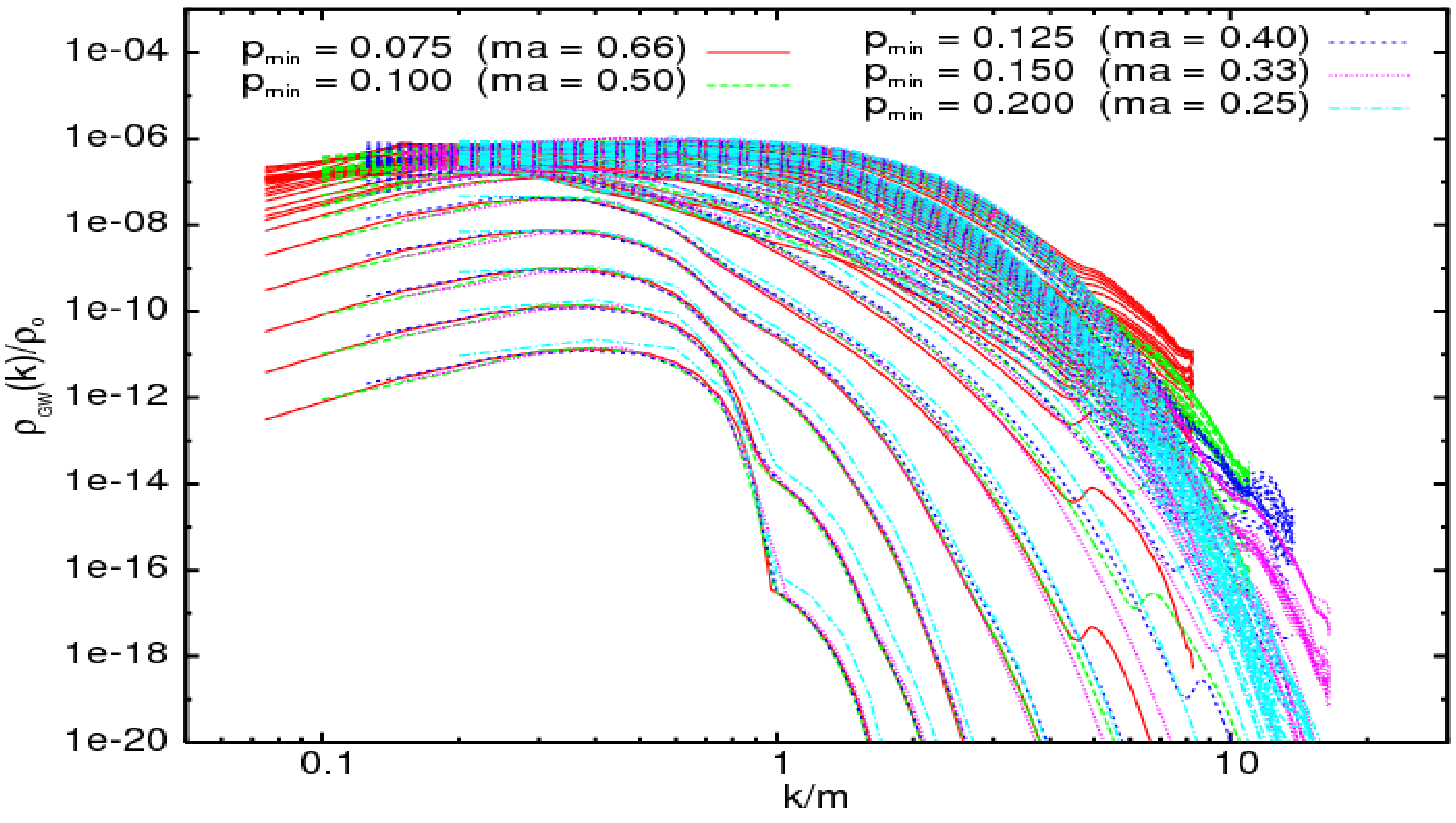


GW Spectrum

Parameter Dependence (Peak amplitude**)**

Hybrid Models: $$\Omega_{\rm GW}^{(o)} \propto \left(\frac{v}{m_p}\right)^2 \times f(\lambda, g^2)$$

$\Omega_{\rm GW}(k,t)$



GW Spectrum

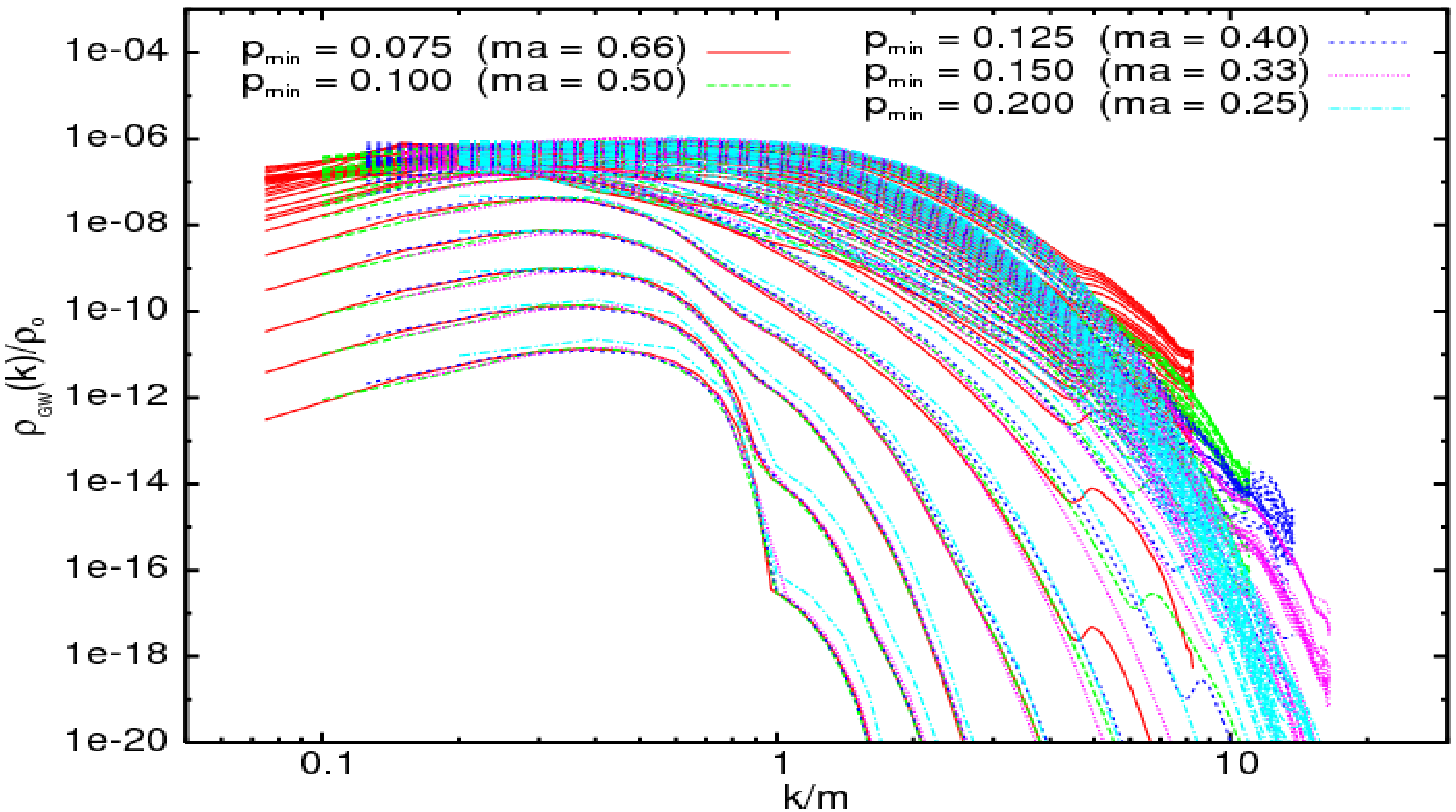
Parameter Dependence (Peak amplitude)

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

Large amplitude !

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

$\Omega_{\rm GW}(k,t)$



GW Spectrum

Parameter Dependence (Peak amplitude**)**

Hybrid Models: $\Omega_{\rm GW}^{(o)} \sim 10^{-11}\,, \quad @ \begin{cases} f_o \sim 10^8 - 10^9 \ \text{Hz} \end{cases}$ $\boxed{\lambda \sim 0.1}$ (natural)

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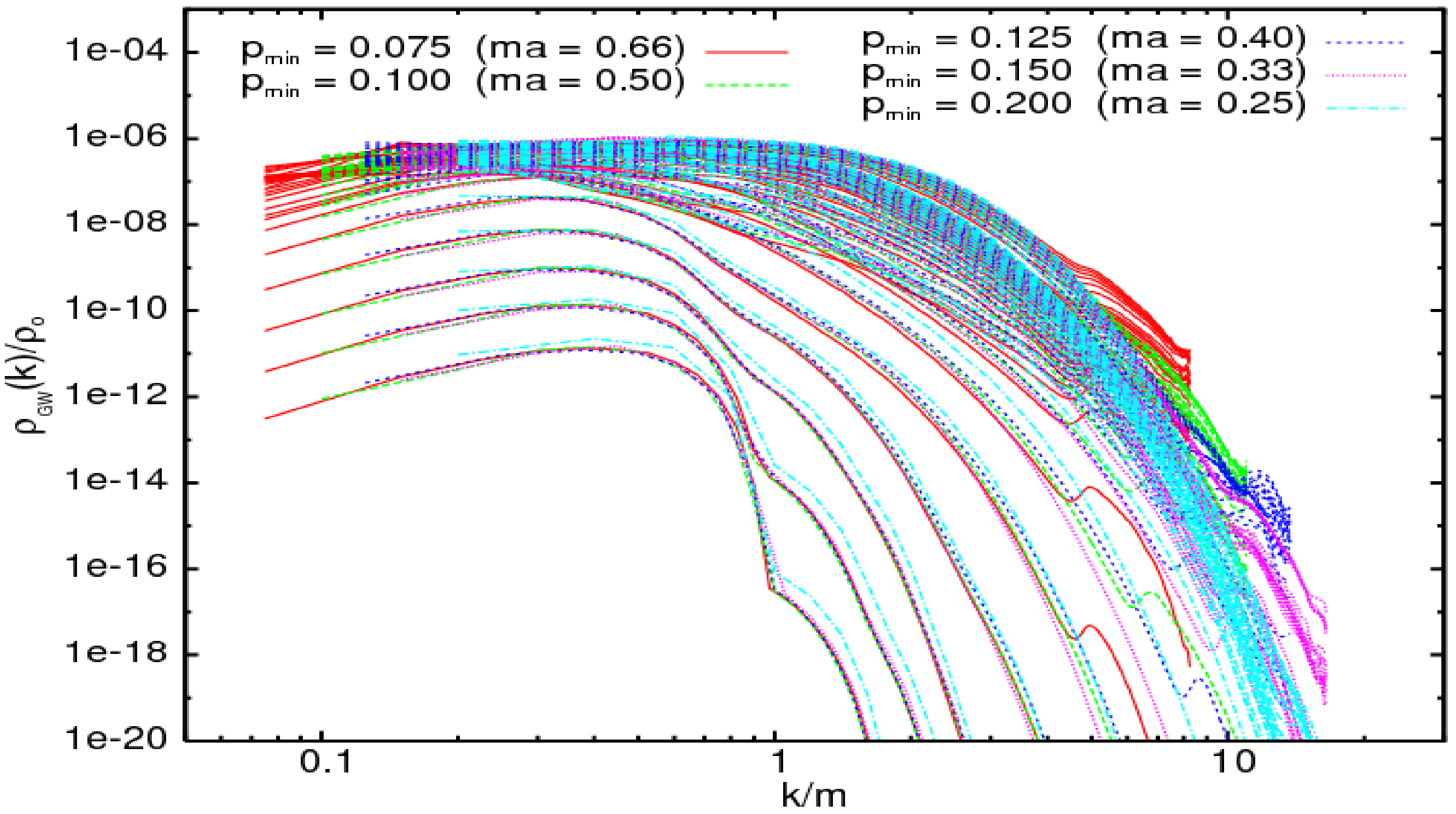

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$\lambda \sim 0.1$ (natural)

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

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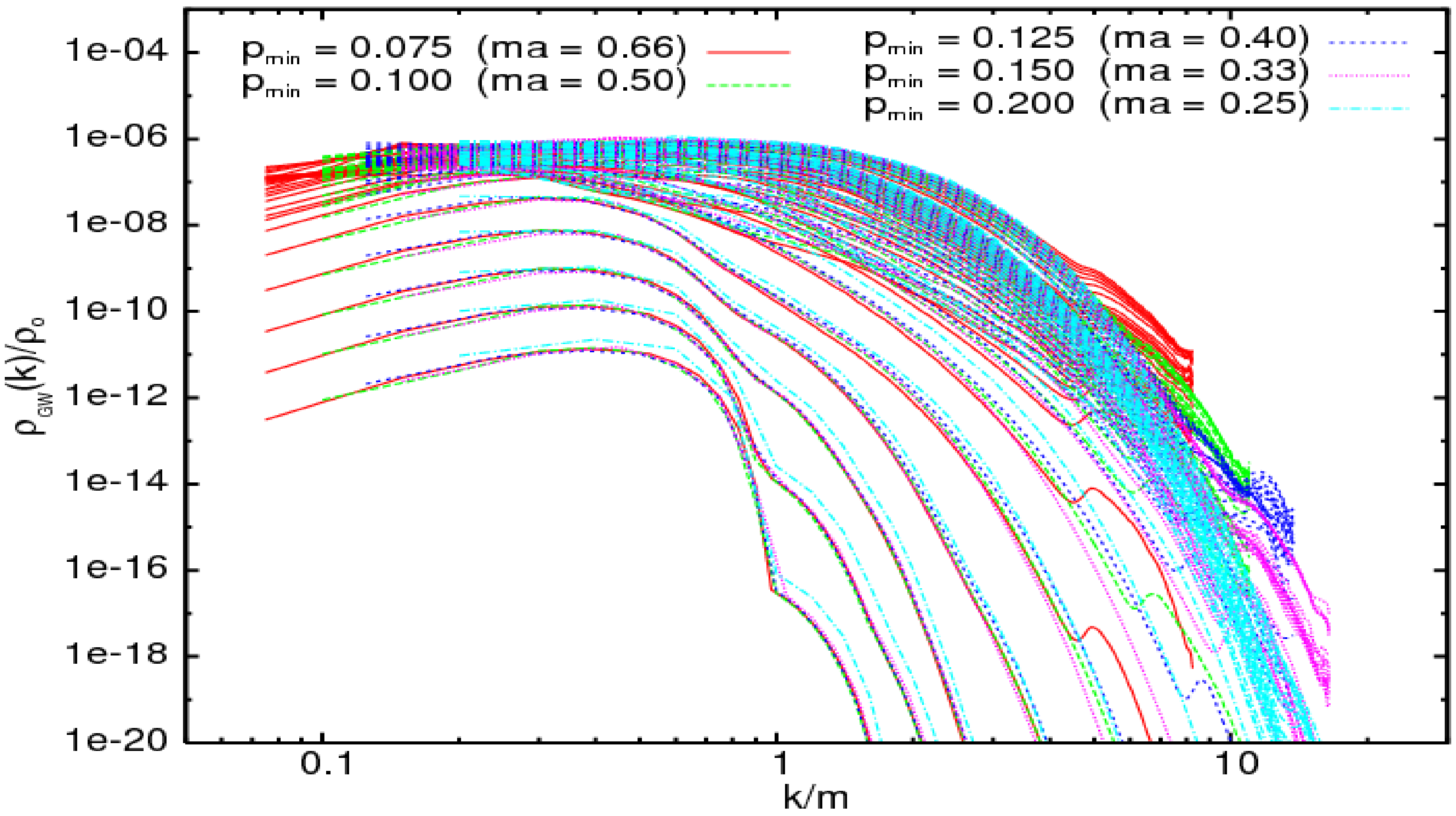
$\Omega_{GW}(k,t)$



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Large amplitude !

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

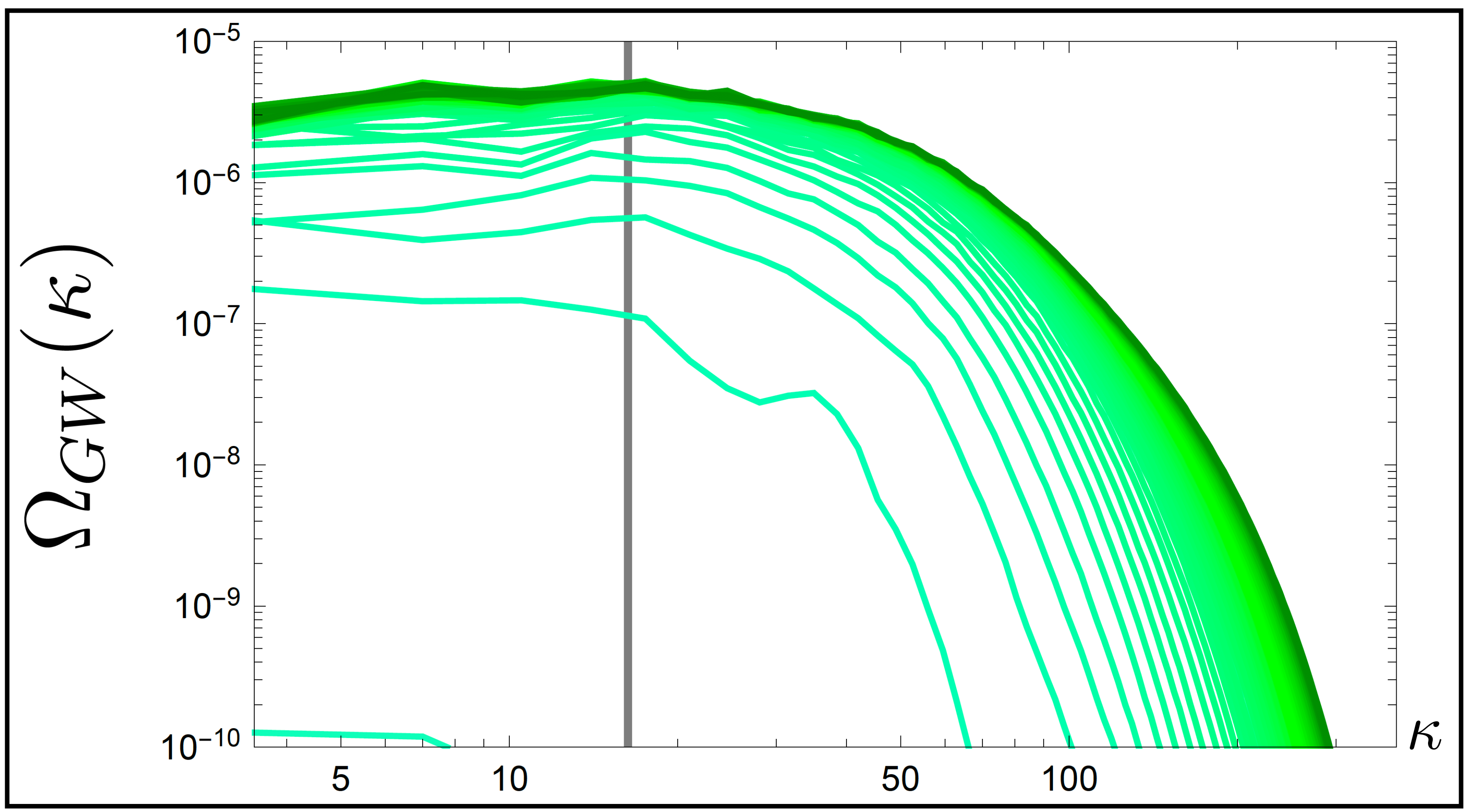
realistically speaking ... **Not observable !**

GW Spectrum

Parameter Dependence (Peak amplitude**)**

Monomial Models: **Single peak spectrum !**
(single daughter fld)

$$\Omega_{\rm GW} \equiv \frac{1}{\rho_c}\frac{d\rho_{\rm GW}}{d\log k}$$



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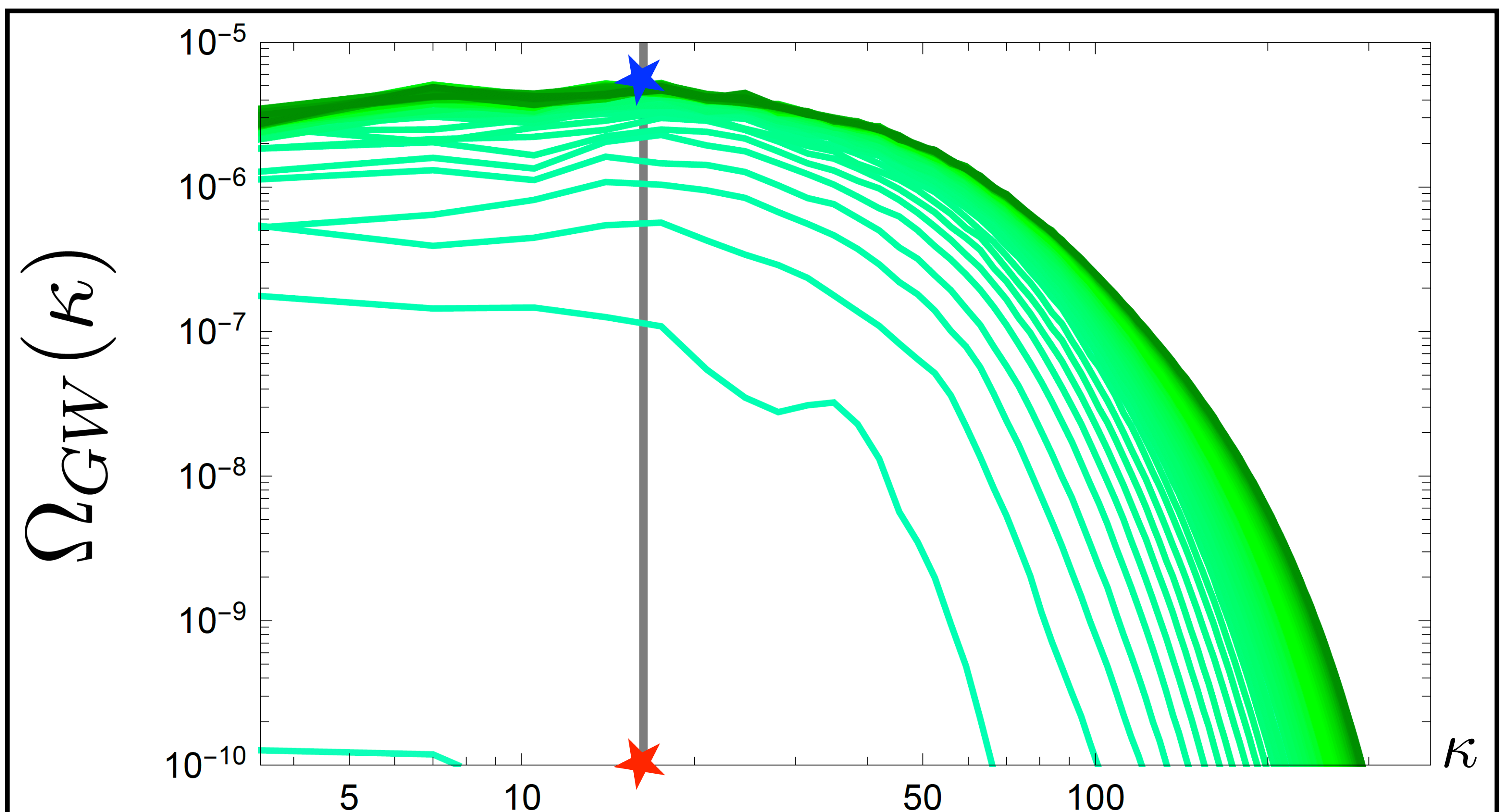

$$q \equiv \frac{g^2 \Phi_{\rm i}^2}{\omega^2}$$

Resonance Param.

GW Spectrum

Parameter Dependence (Peak amplitude**)**

$$\omega^2 \equiv V''(\Phi_I)$$

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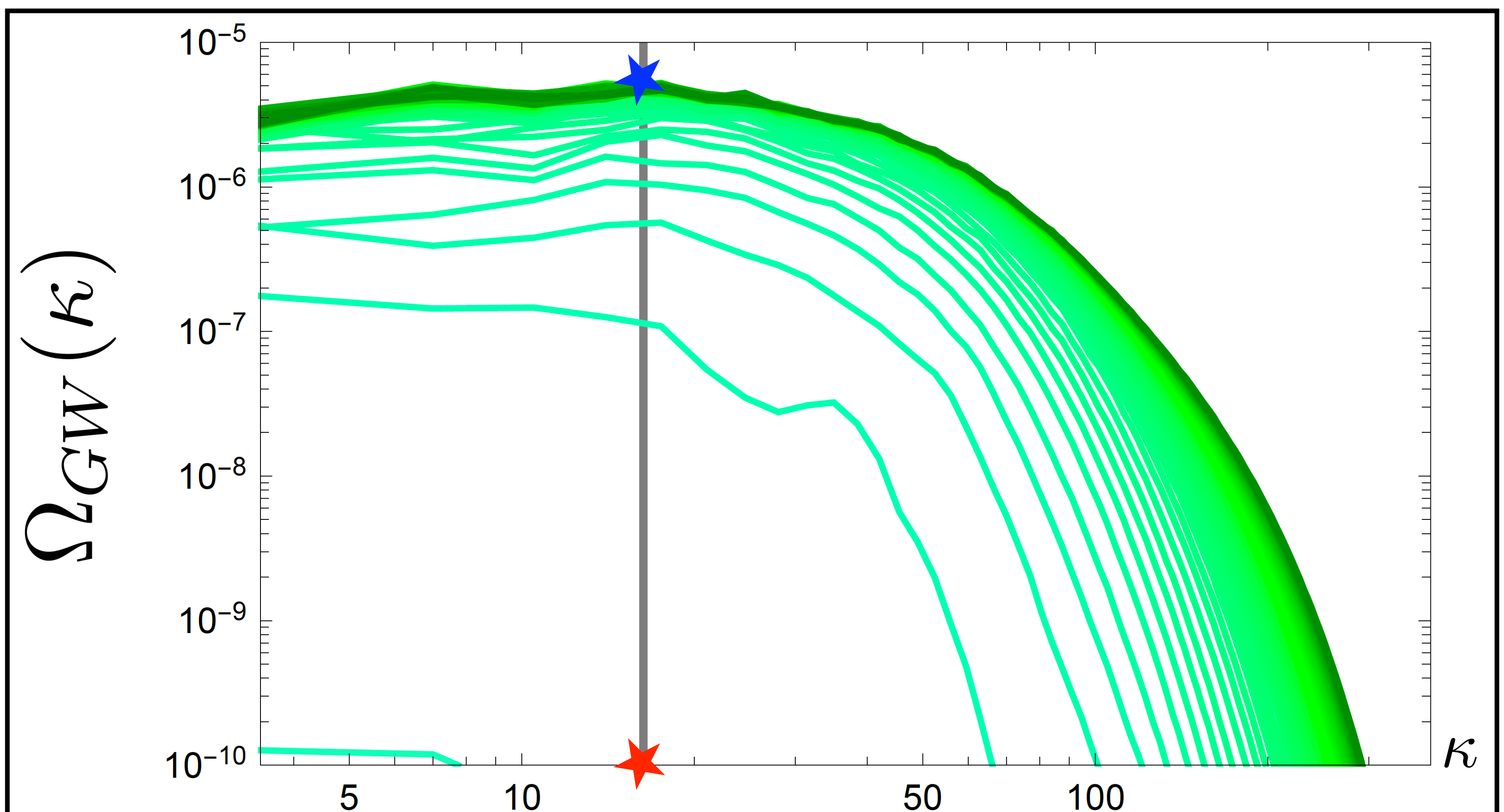


GW Spectrum

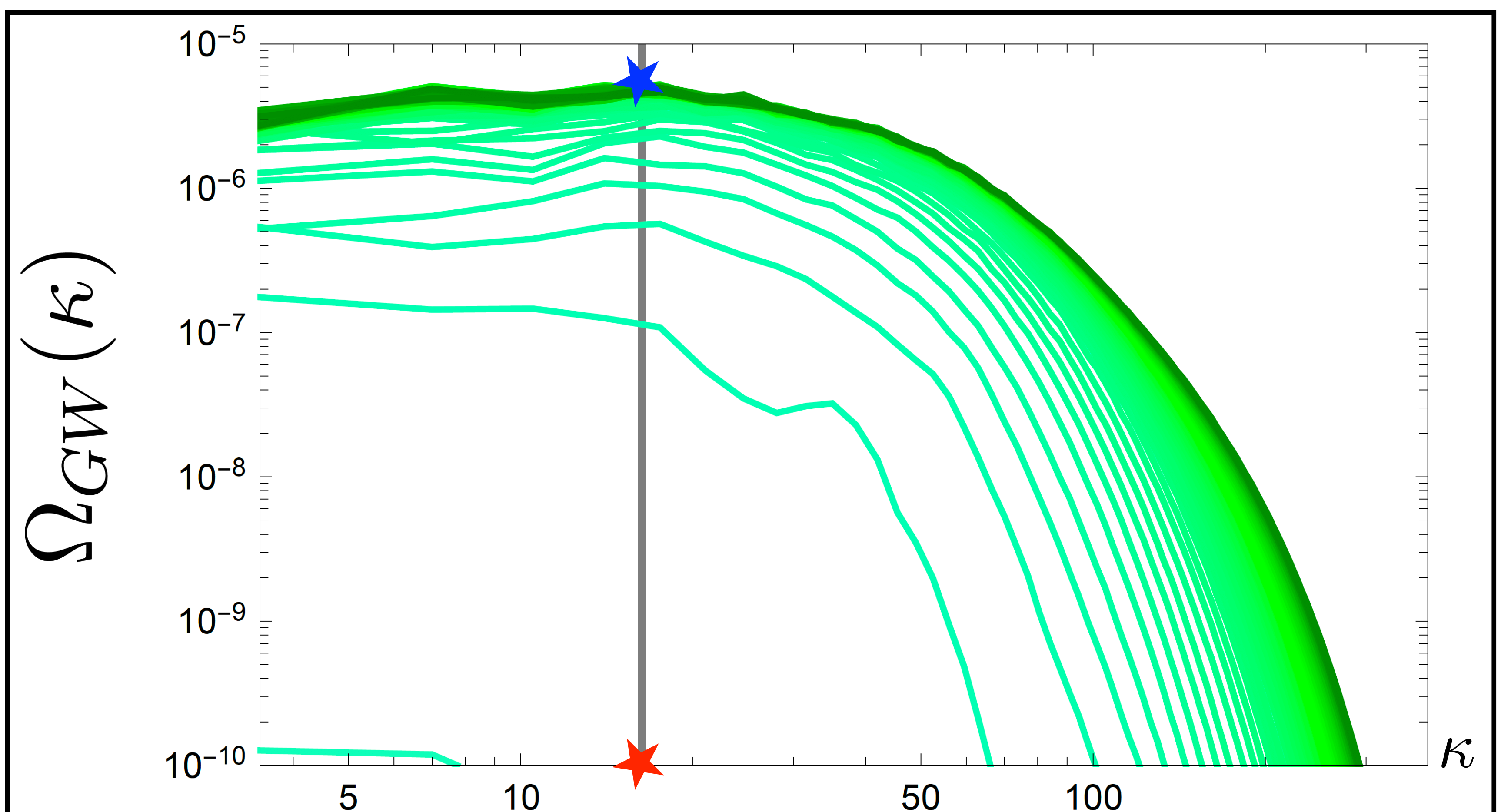
Parameter Dependence (Peak amplitude**)**

Monomial Models: $\Omega^{(o)}_{\rm GW} \propto \dfrac{\omega^6}{\rho m_p^2} q^{-1}$

$\omega^2 \equiv V''(\Phi_I)$

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

Resonance Param.



(DGF, Torrentí JCAP 2017)

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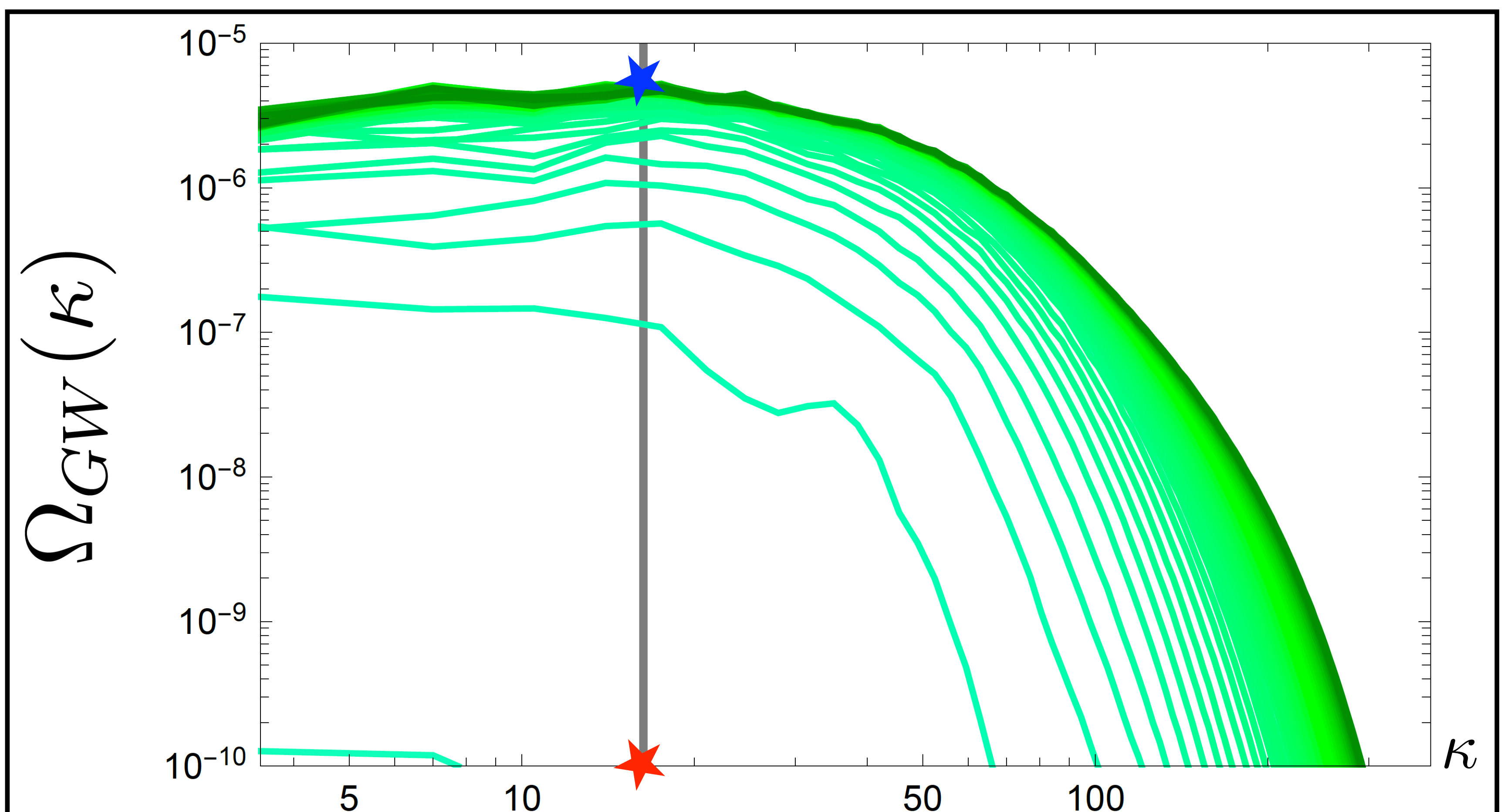

$k_p \propto q^{1/2}$

Peak Position

(DGF, Torrentí JCAP 2017)

GW Spectrum

Parameter Dependence (Peak amplitude)

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

Large amplitude !

Khlebnikov, Tkachev '97
Easther, Giblin, Lim '06-'08
DGF, G[a]-Bellido, et al '07-'10
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Many others afterwards ...

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Large amplitude !

… at high Frequency !

$f_o \sim 10^8 - 10^9~{\rm Hz}$

Very unfortunate !

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$$\Omega_{\rm GW} \propto q^{-1} \propto 1/g^2$$

$$(f_{\rm peak} \propto q^{1/2} \propto g)$$

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→ **What if multiple species with $g_i \neq g_j$?**

GW Spectrum

Parameter Dependence (Peak amplitude)

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

Large amplitude !

Khlebnikov, Tkachev '97
Easther, Giblin, Lim '06-'08
DGF, G[a]-Bellido, et al '07-'10
Kofman, Dufaux et al '07-'09
Many others afterwards …

$$\Omega_{\rm GW} \propto q^{-1} \propto 1/g^2$$

$$(f_{\rm peak} \propto q^{1/2} \propto g)$$

(DGF, Torrentí JCAP 2017)

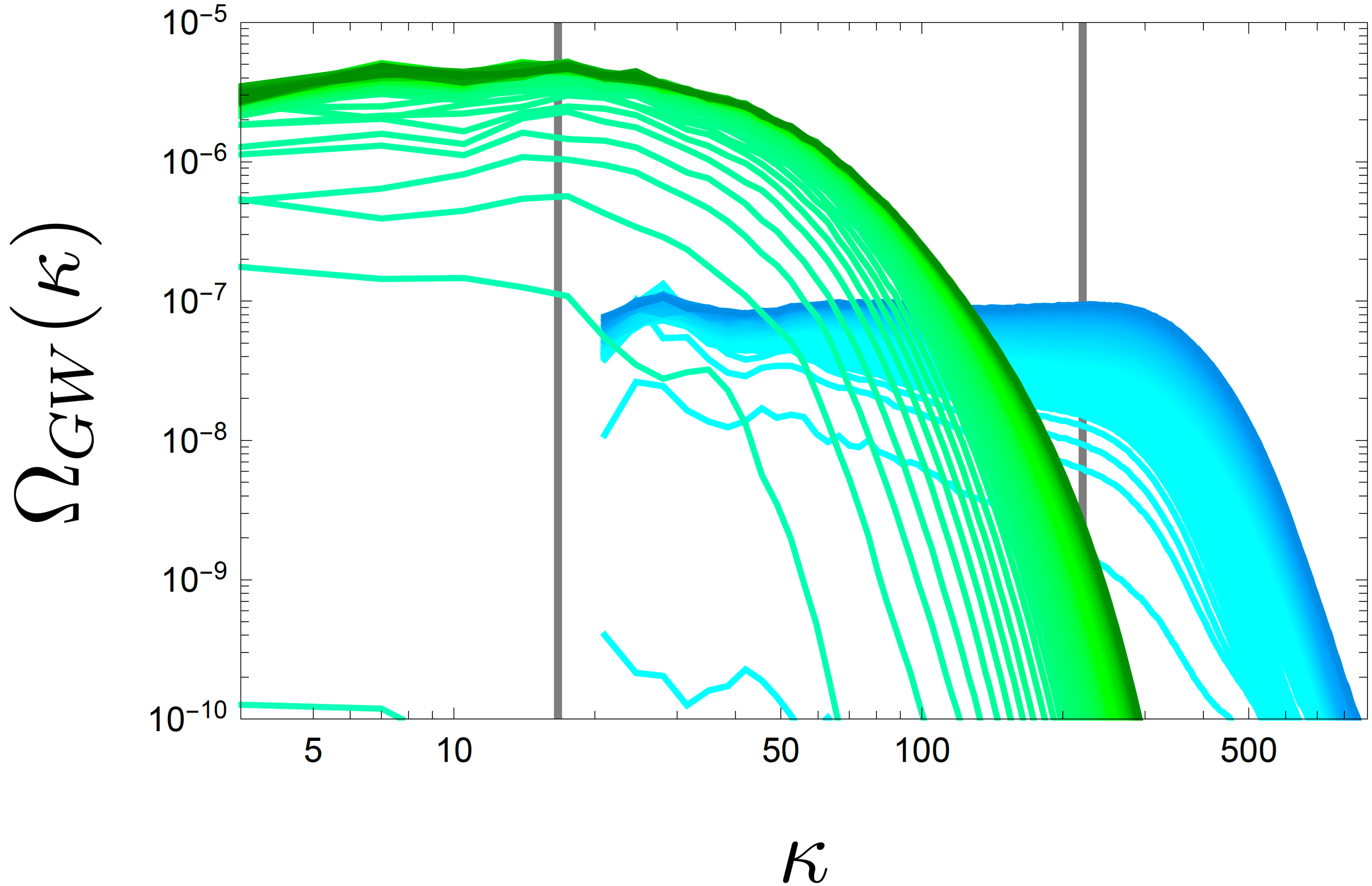
⟶ **What if multiple species with $g_i \neq g_j$?**

Spectroscopy of particle couplings ?

GW Spectroscopy

Parameter Dependence (Peak amplitude**)**

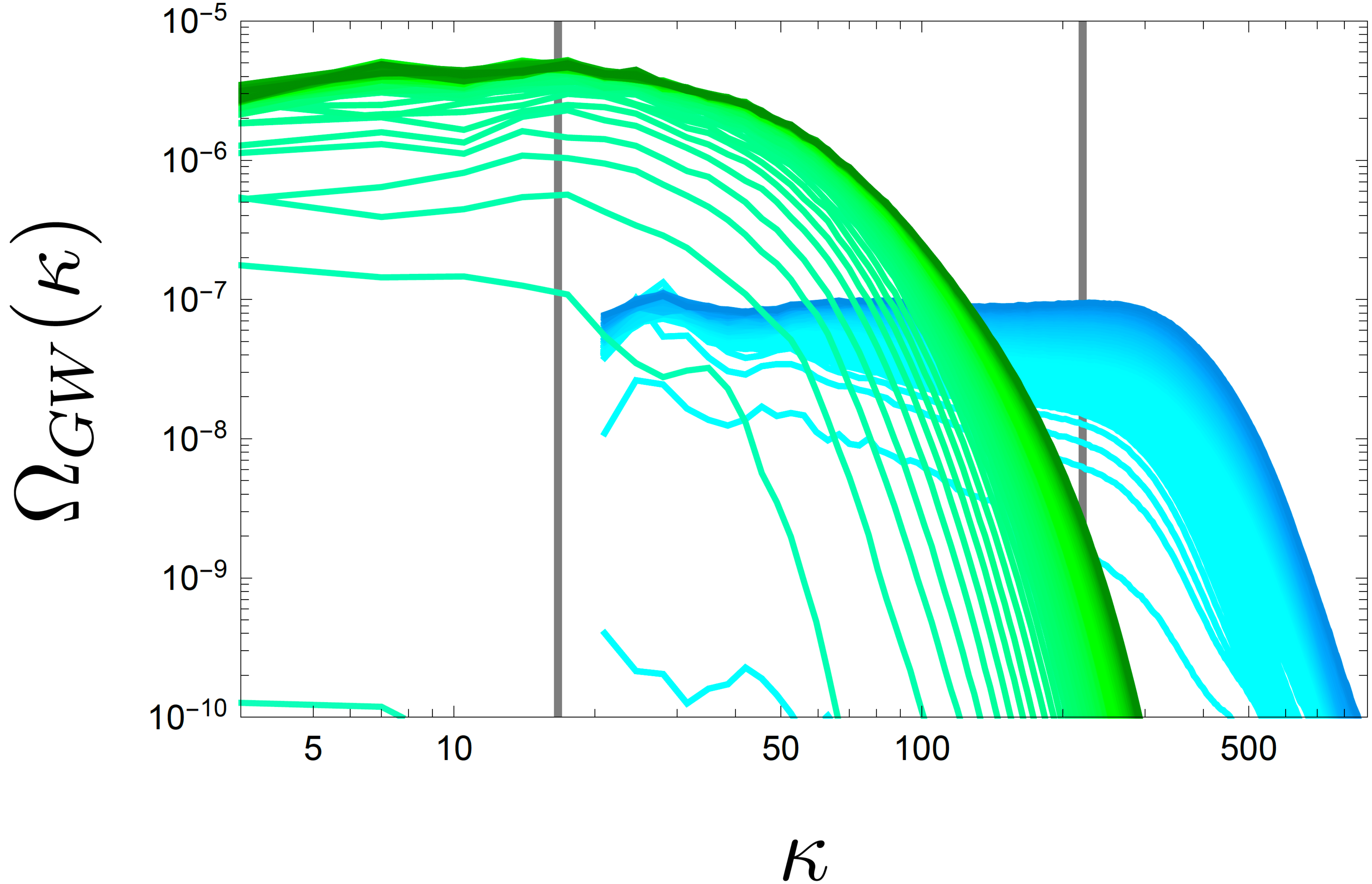
$$V(\phi) + \frac{1}{2}g_1^2\phi^2\chi_1^2 \quad ; \quad V(\phi) + \frac{1}{2}g_2^2\phi^2\chi_2^2$$



GW Spectroscopy

Parameter Dependence (Peak amplitude**)**

$$V(\phi) + \frac{1}{2}g_1^2\phi^2\chi_1^2 + \frac{1}{2}g_2^2\phi^2\chi_2^2 \quad ?$$



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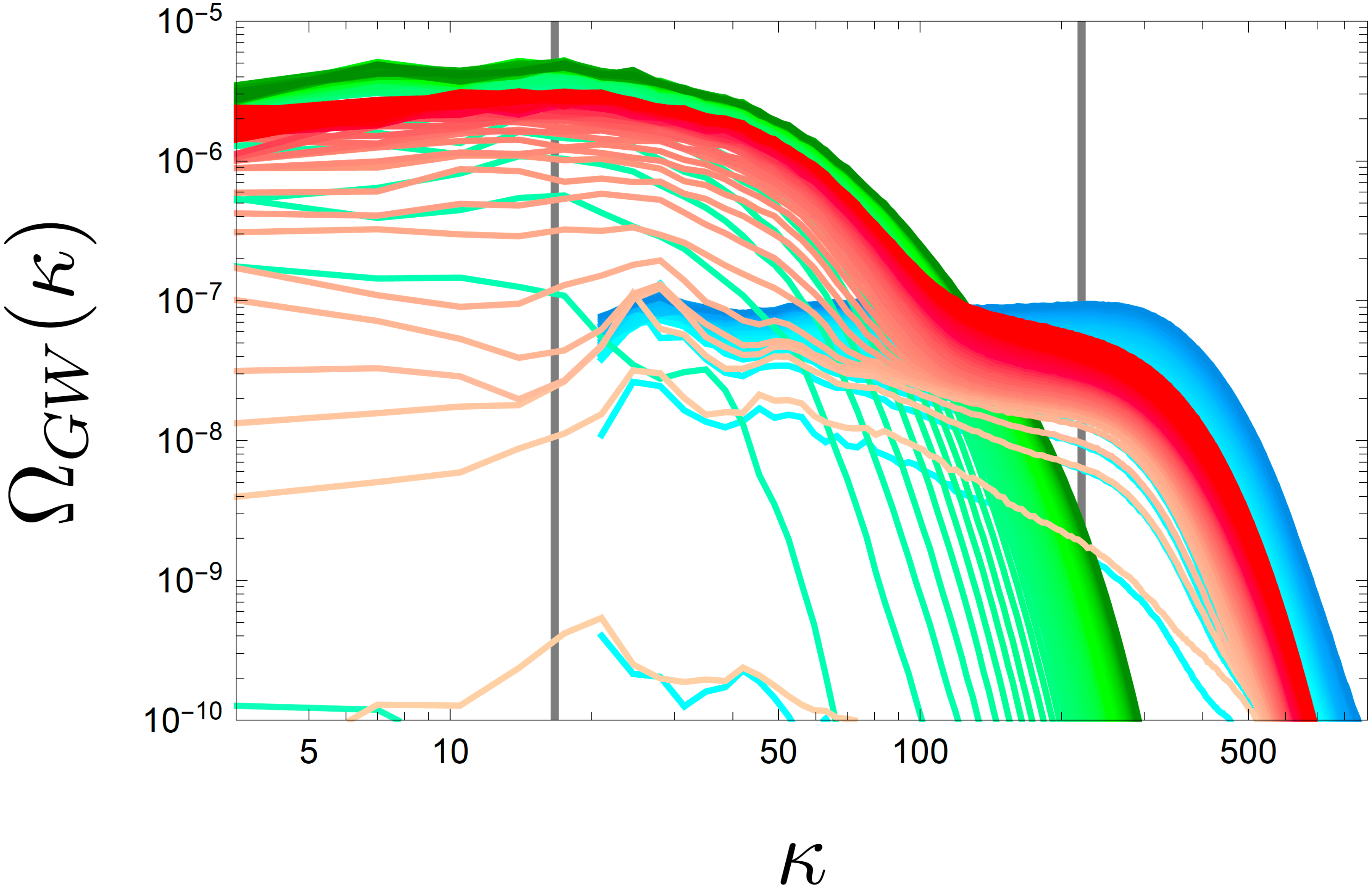

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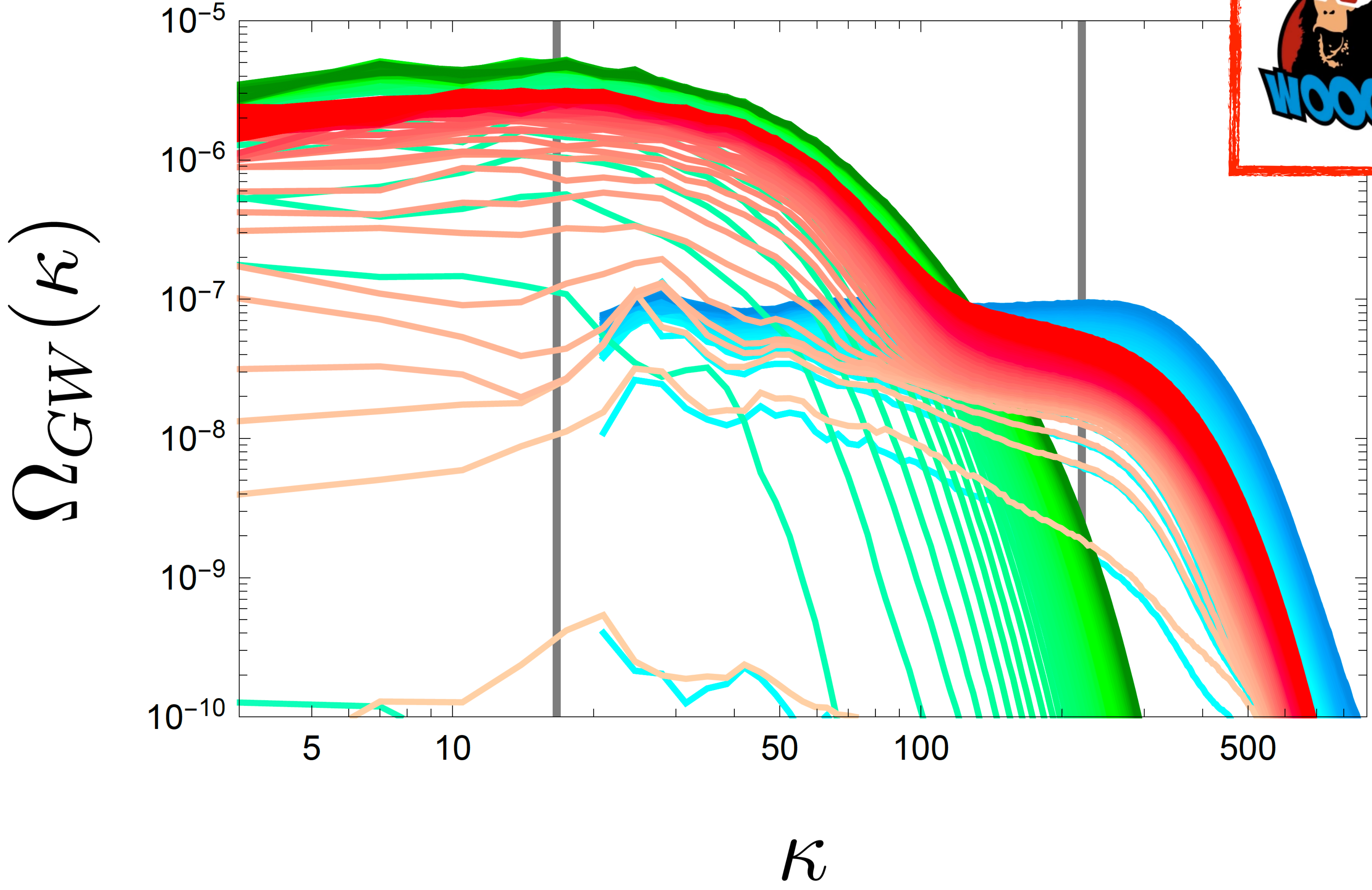

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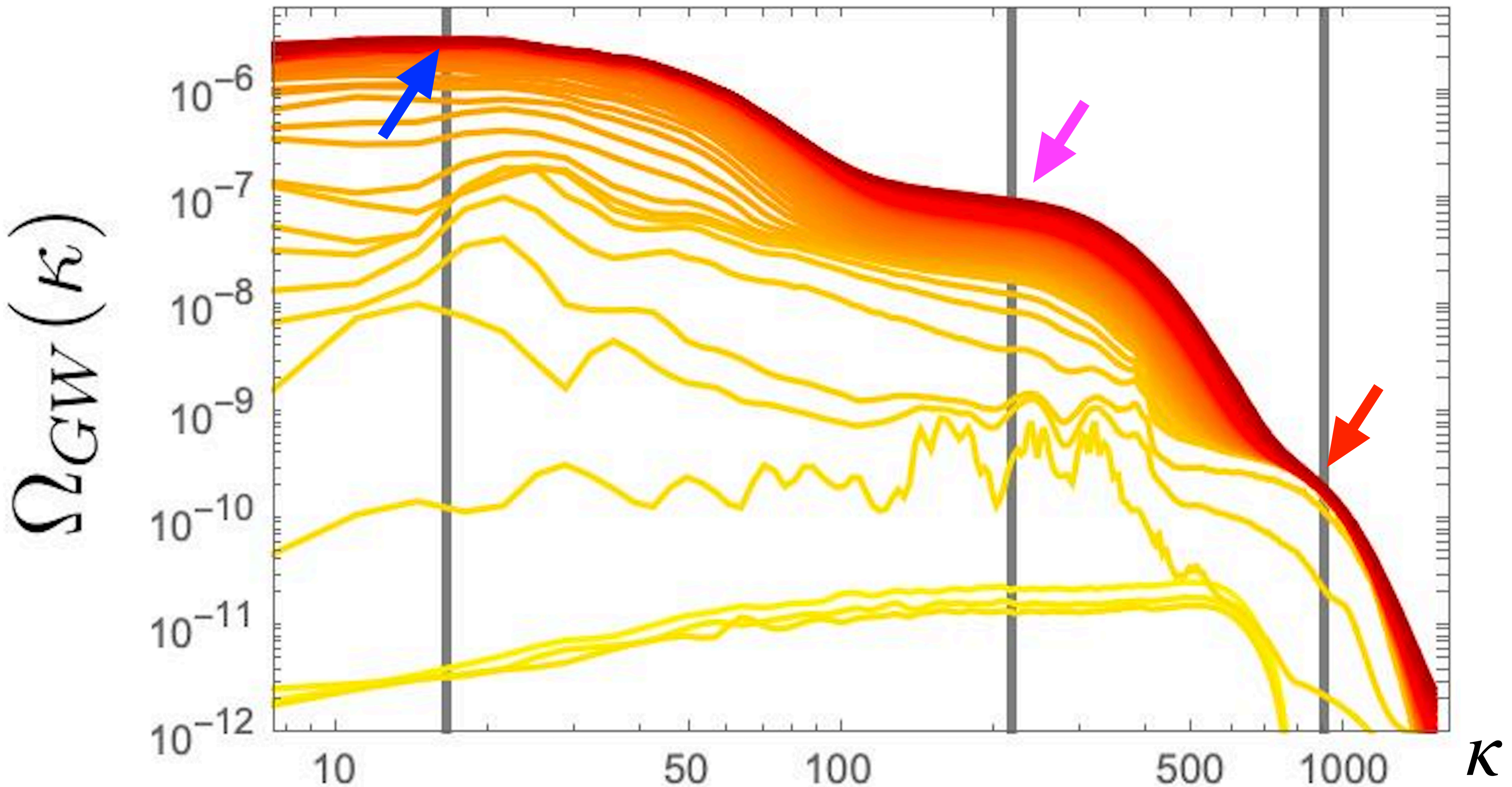

Phys. Rev. D 106 (2022) 6, 063522 **;** **2202.05805**

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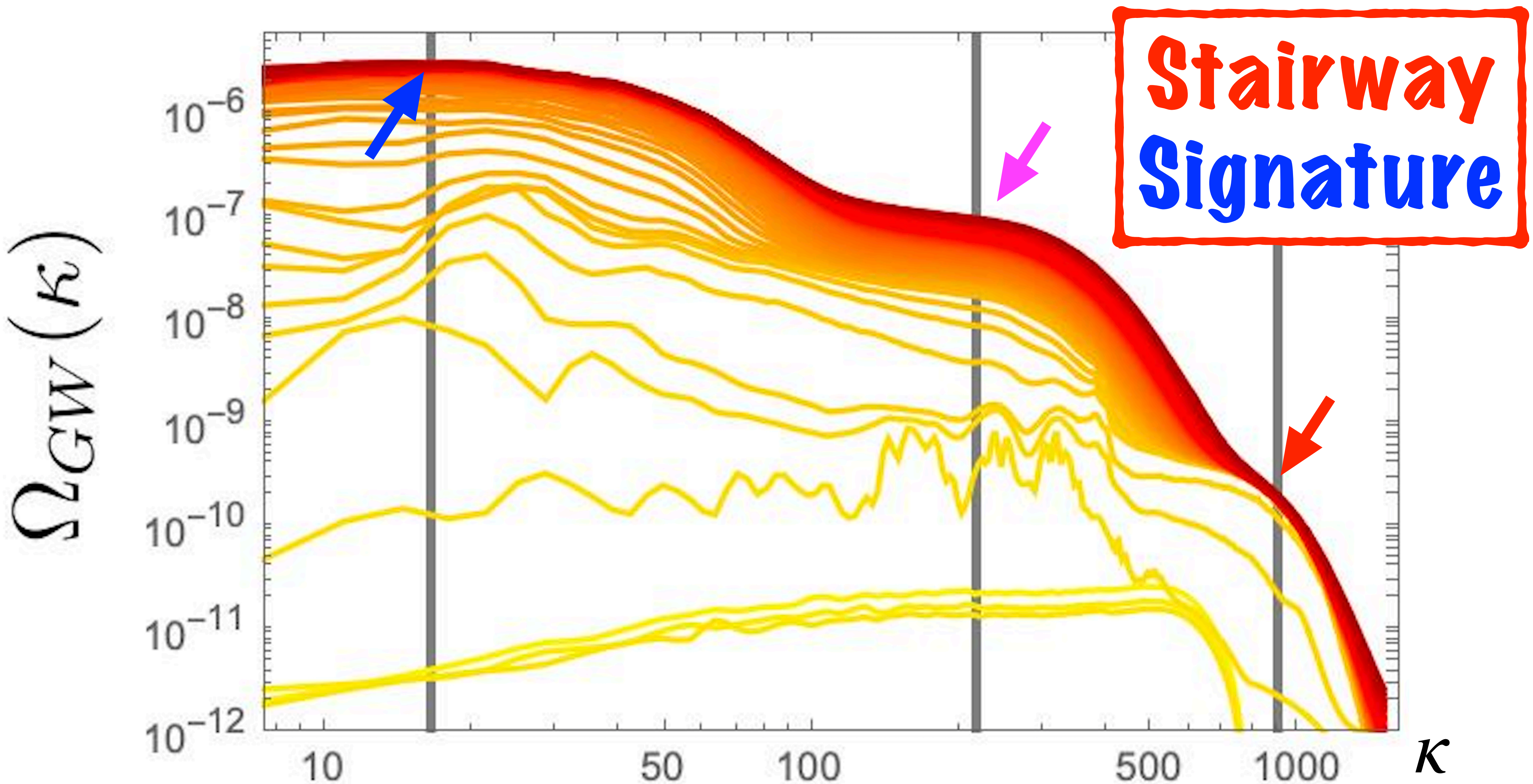

Phys. Rev. D 106 (2022) 6, 063522 ; 2202.05805

GW Spectroscopy

Reconstruction (2-peak signal)

@ LISA

Note: Shift by hand to LISA frequencies

GW Spectroscopy

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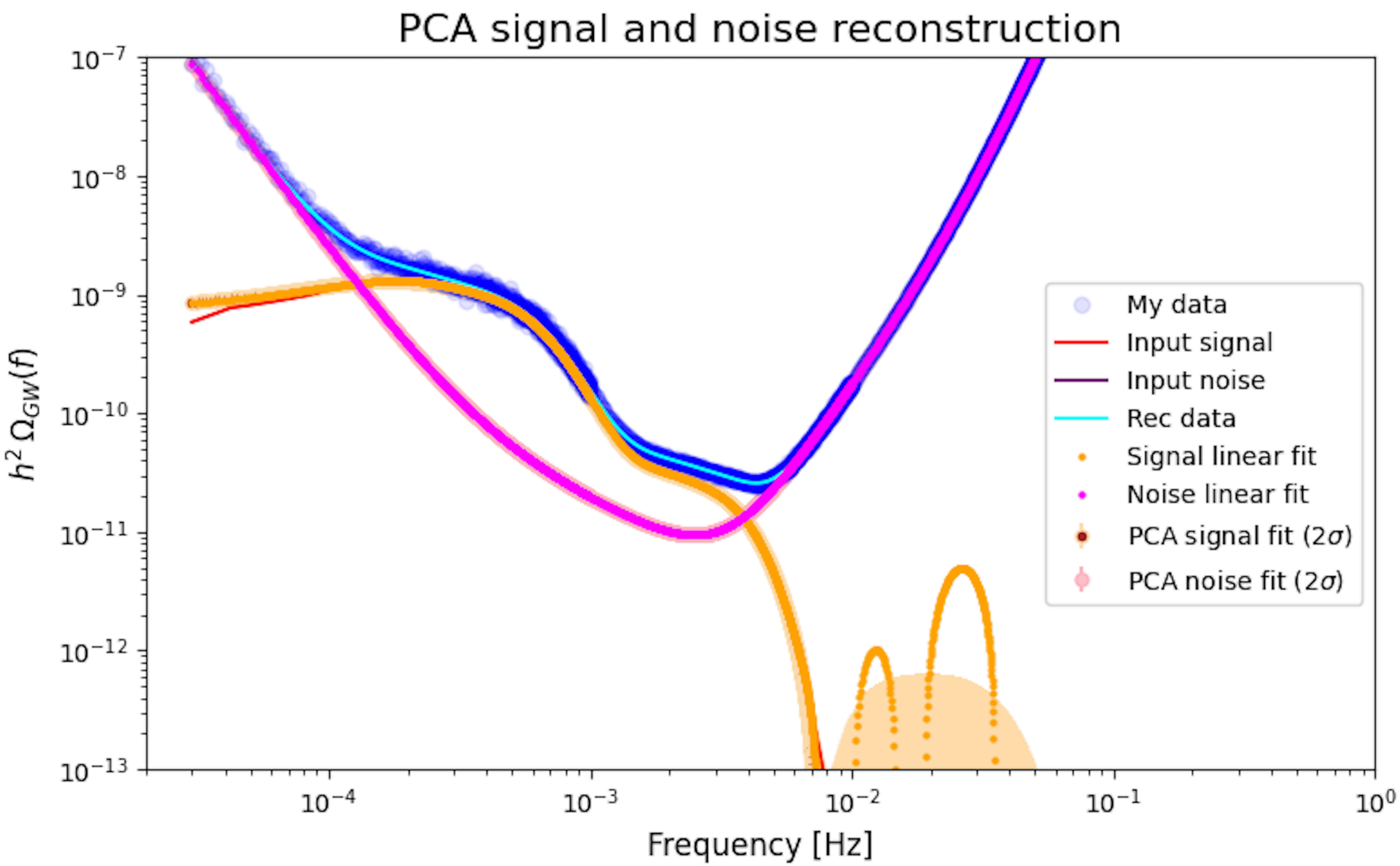

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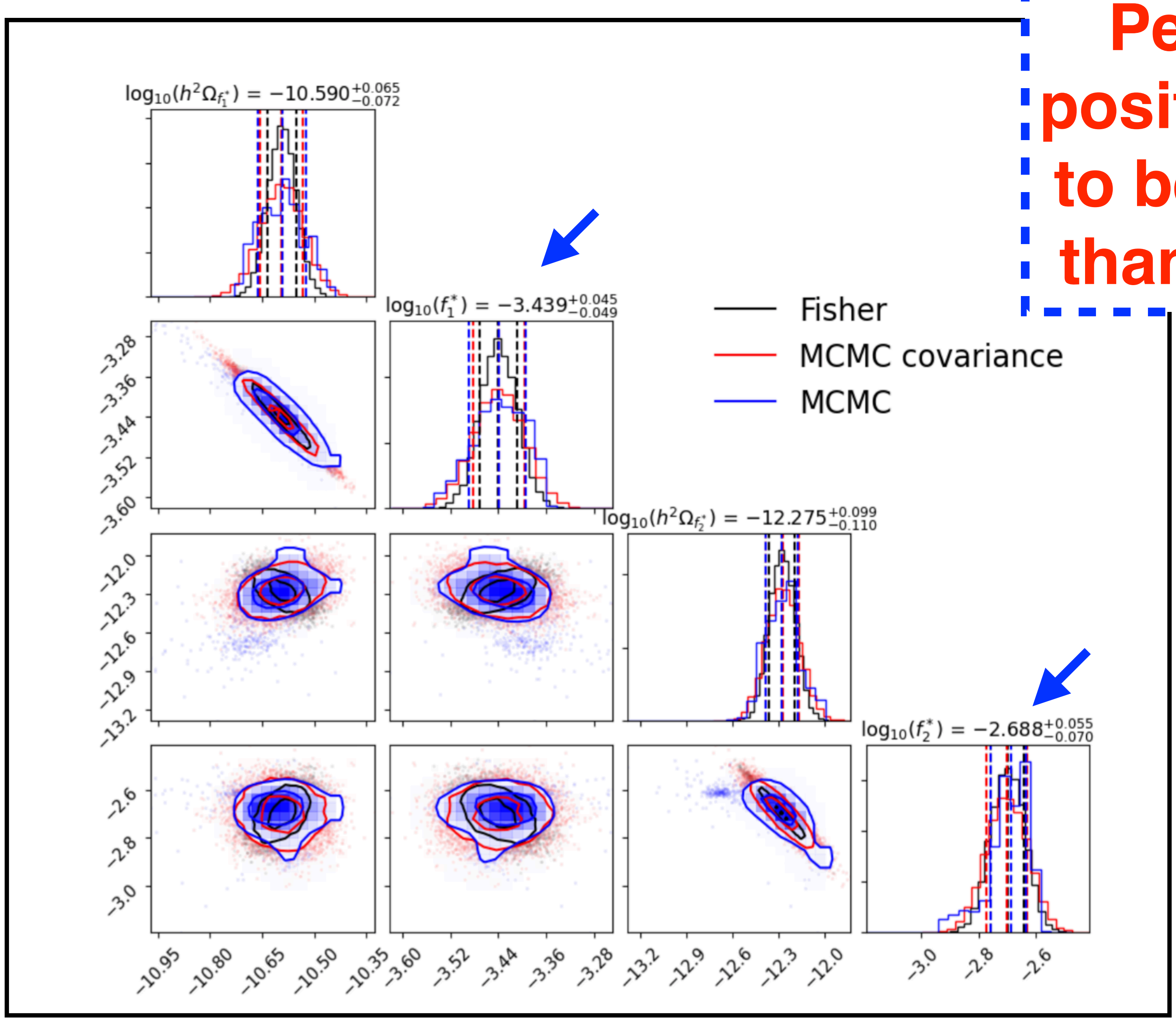


Peak positions to better than 1%

Phys.Rev.D 106 (2022) 6, 063522, [2202.05805]

GW Spectroscopy

Reconstruction (2-peak signal)

@ LISA

Coupling Reconstruction !

Theoretical	LISA	BBO
$g_1 = 1.16 \cdot 10^{-3}$	$1.66^{+4.01}_{-0.55} \cdot 10^{-3}$	$0.76^{+0.73}_{-0.18} \cdot 10^{-3}$
$g_2 = 8.2 \cdot 10^{-3}$	$4.39^{+14.3}_{-1.53} \cdot 10^{-3}$	$7.64^{+21.8}_{-2.61} \cdot 10^{-3}$

Phys.Rev.D 106 (2022) 6, 063522, **2202.05805**

GW Spectroscopy

Our example serves as proof of principle !

Possible new door to particle physics interactions with GW backgrounds !

GW Spectroscopy

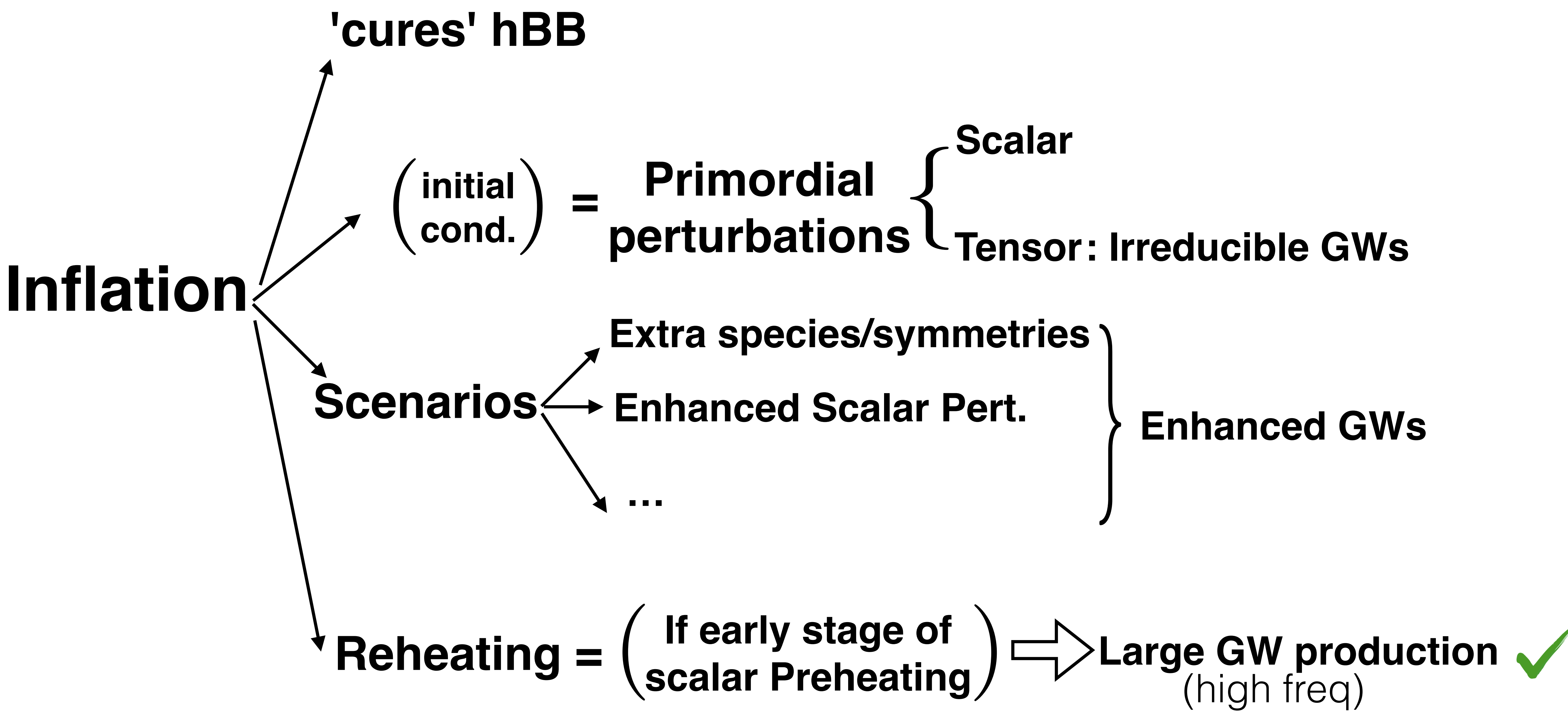
Our example serves as proof of principle !

Possible new door to particle physics
interactions with GW backgrounds !

Multi-peak Stairway
signatures expected at:
low scale (p)reheating
phase transitions
.....

High-Freq GW
Detection ?

INFLATIONARY COSMOLOGY



Gravitational Wave Backgrounds

OUTLINE

1) Grav. Waves (GWs) ✓ — 1st Topic

Early Universe Sources:

2) GWs from Inflation ✓

3) GWs from Preheating ✓

4) GWs from Phase Transitions

5) GWs from Cosmic Defects

Core Topics

6) Astrophysical Background(s)

7) Observational Constraints/Prospects

← (Briefly)

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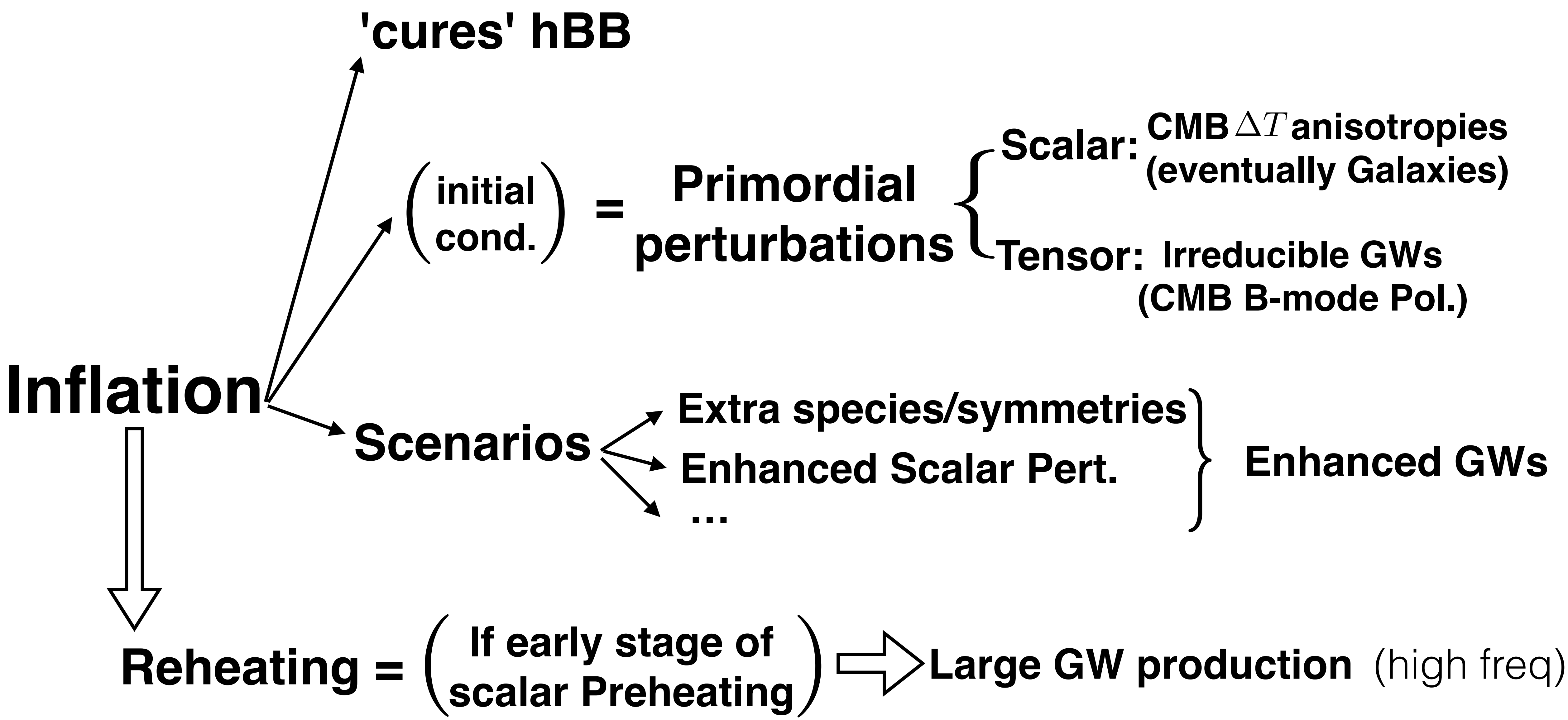

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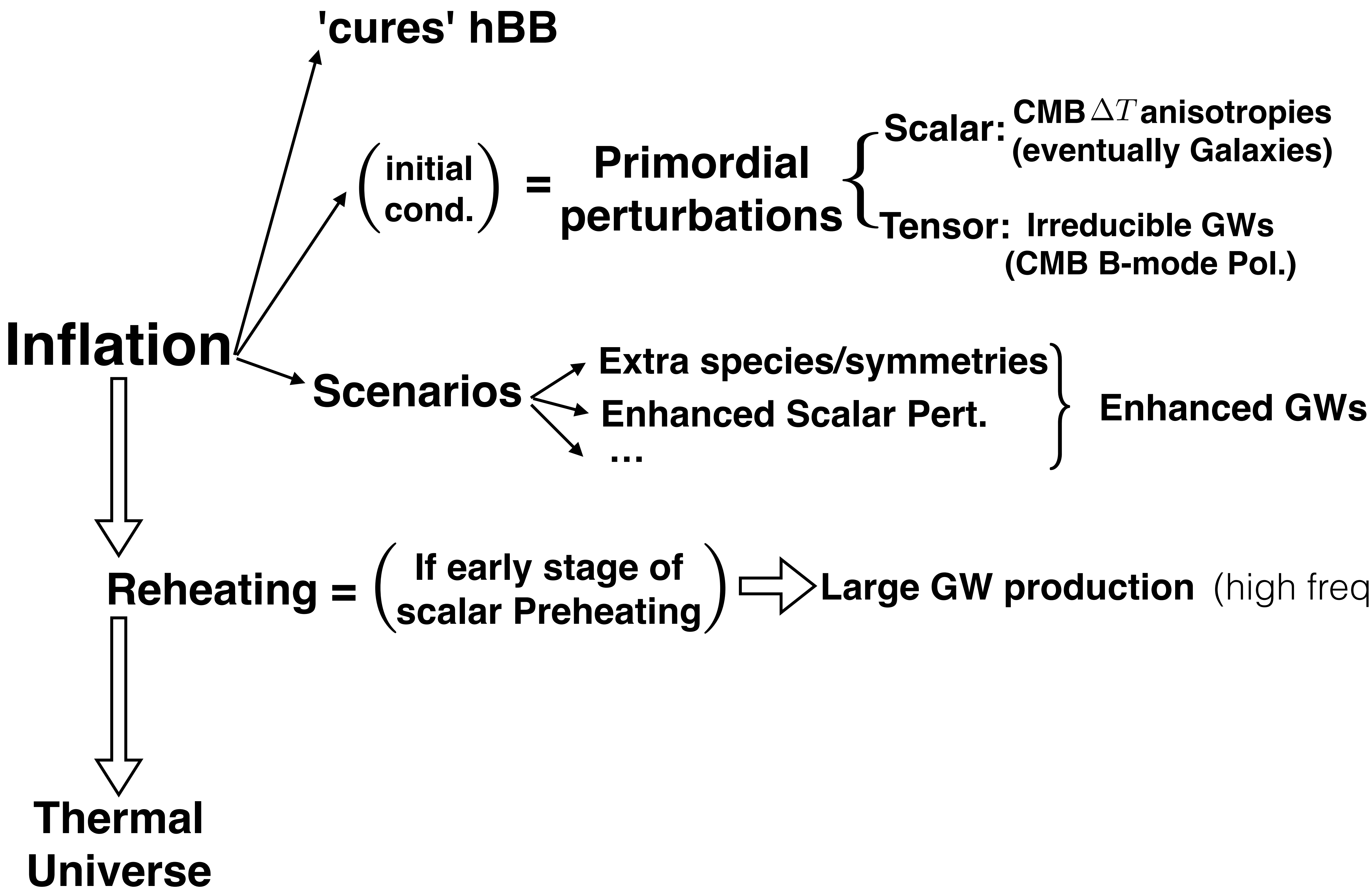

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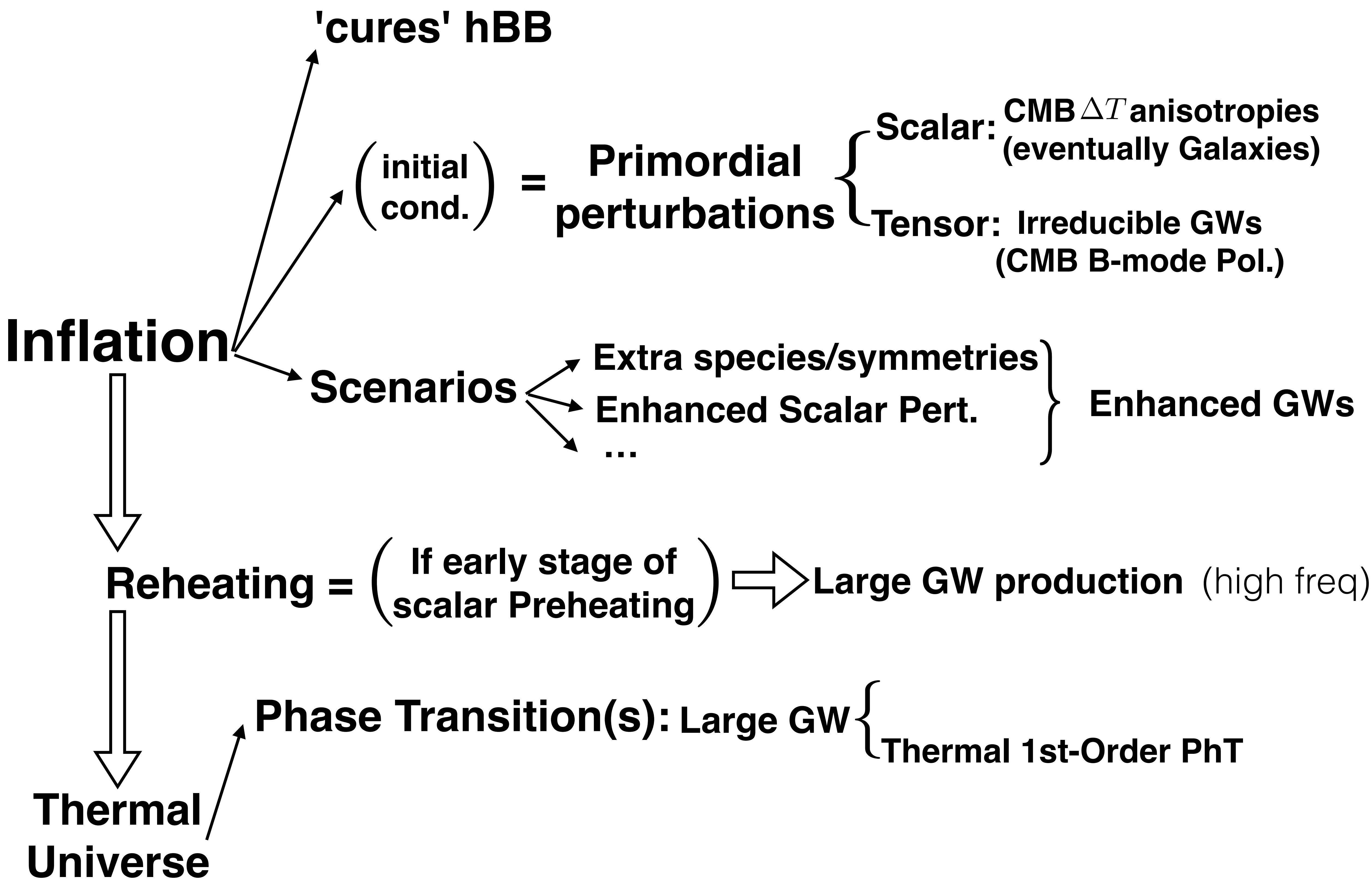

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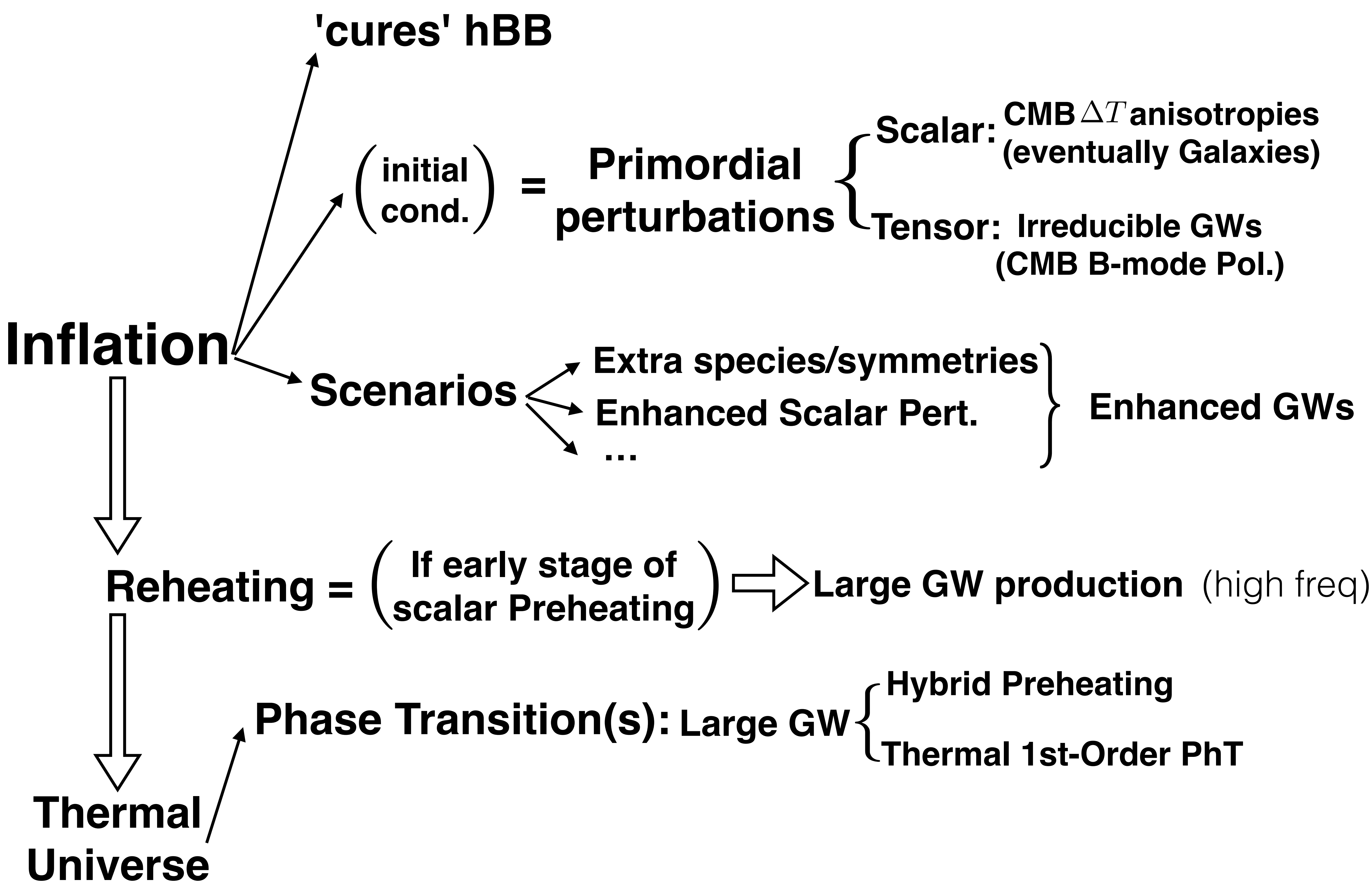

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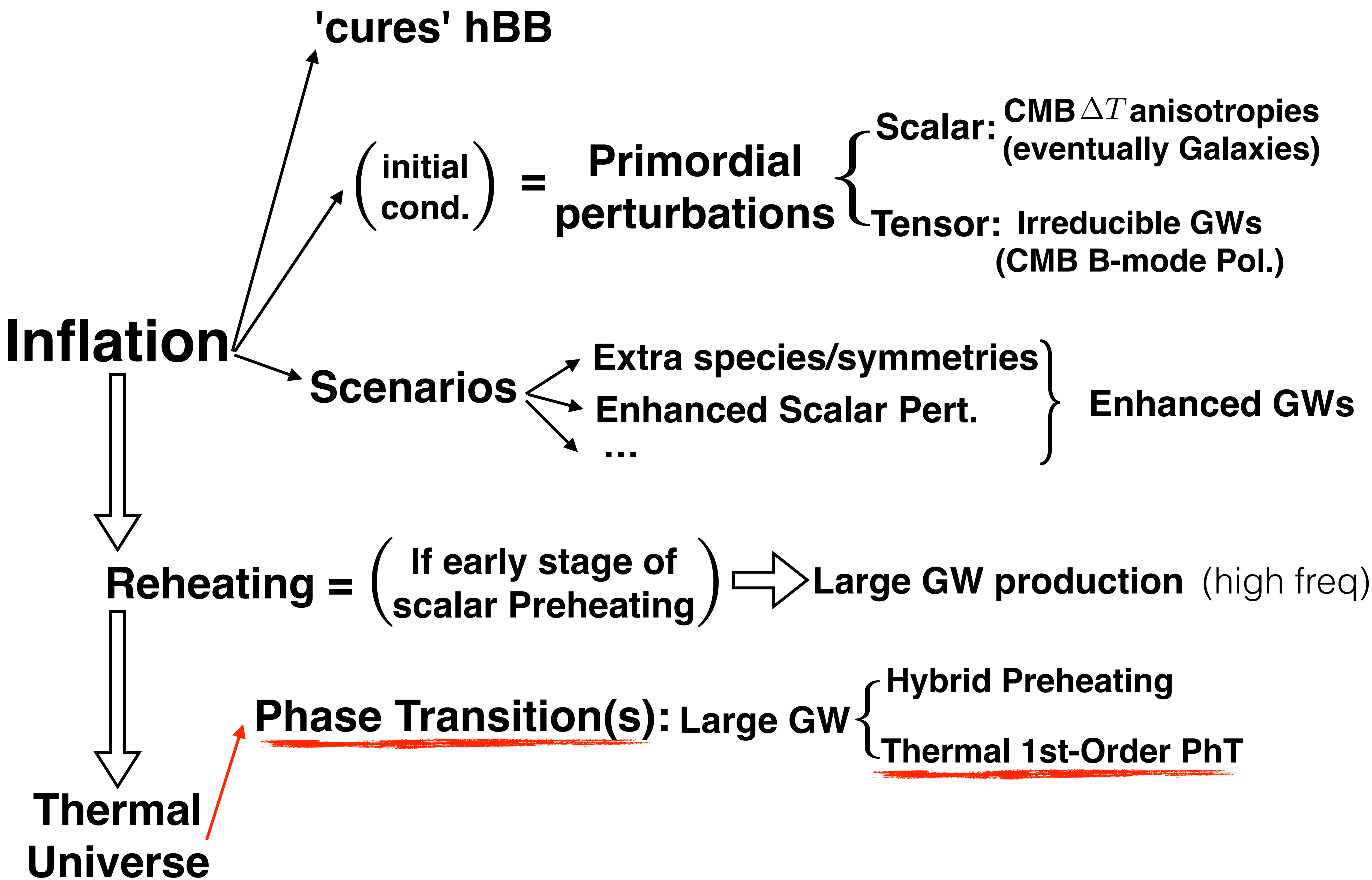

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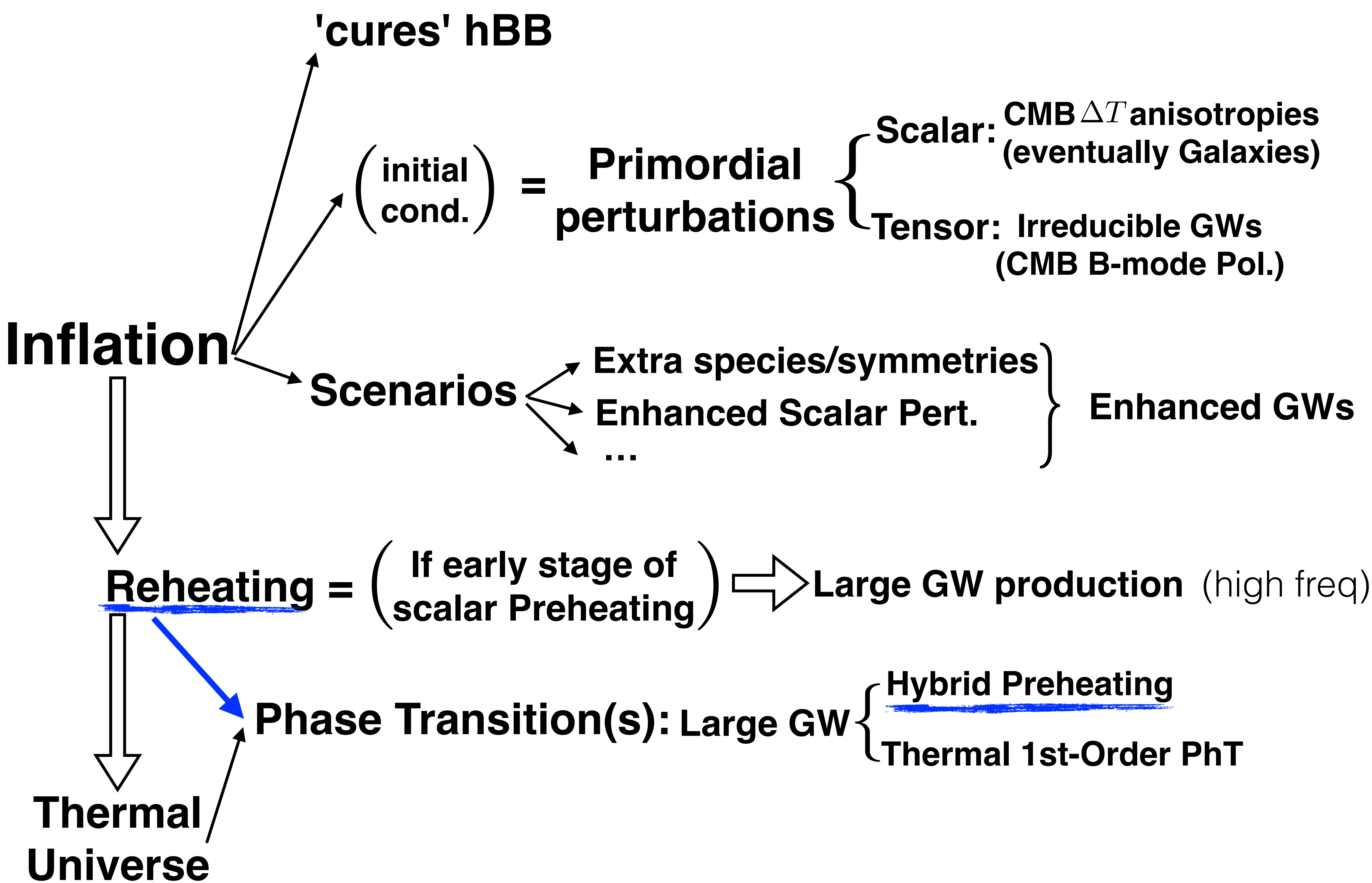

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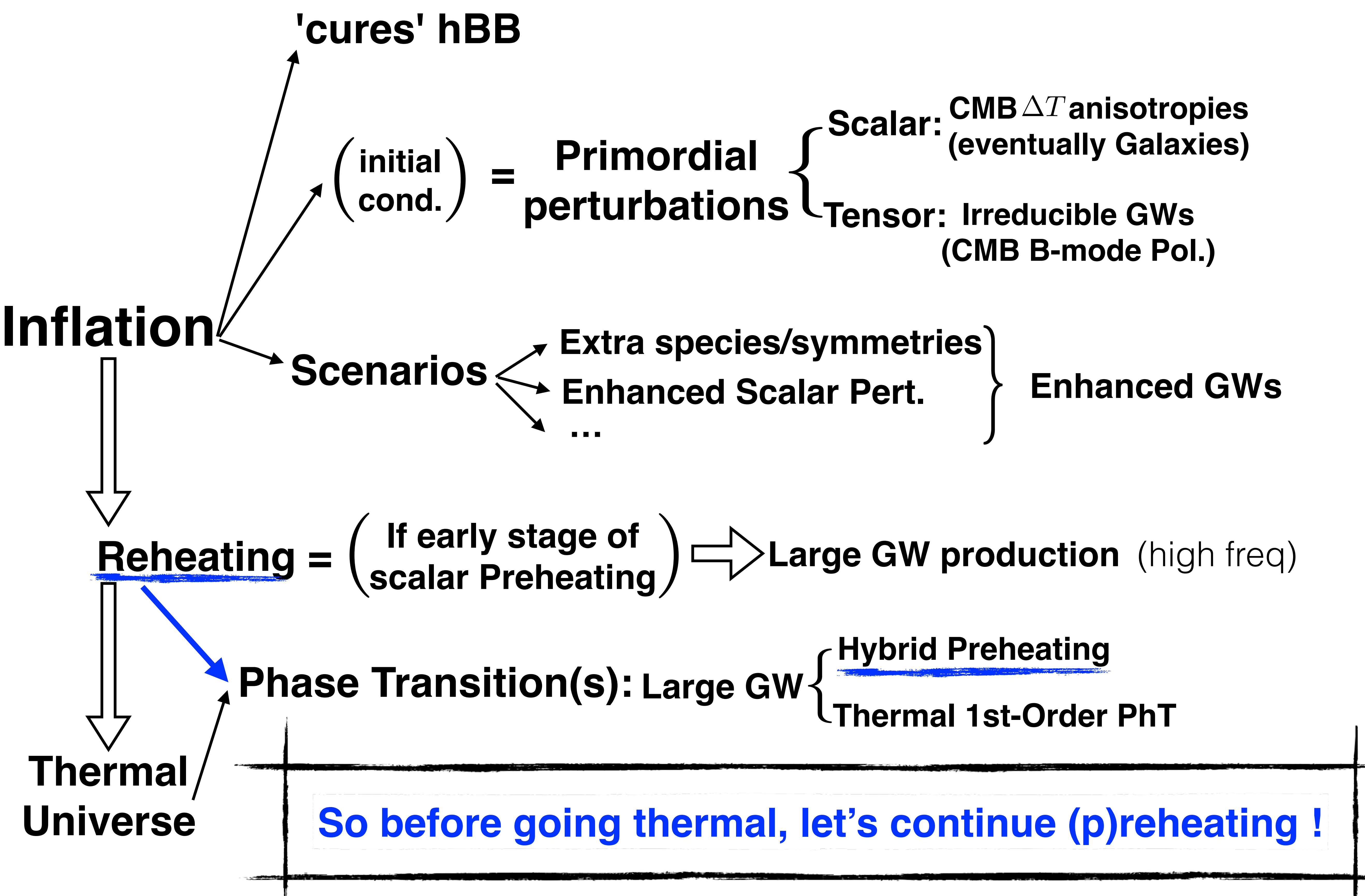

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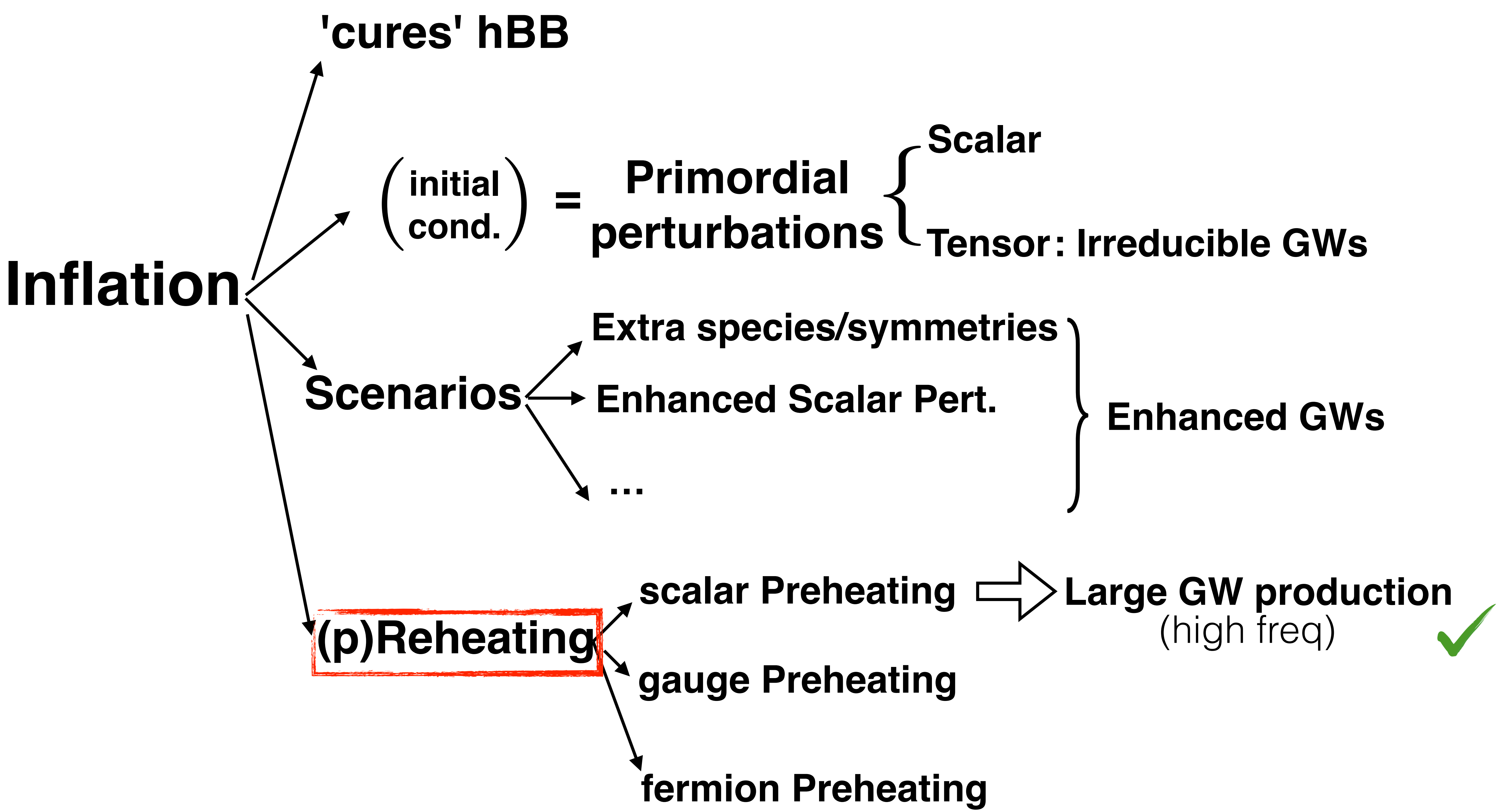

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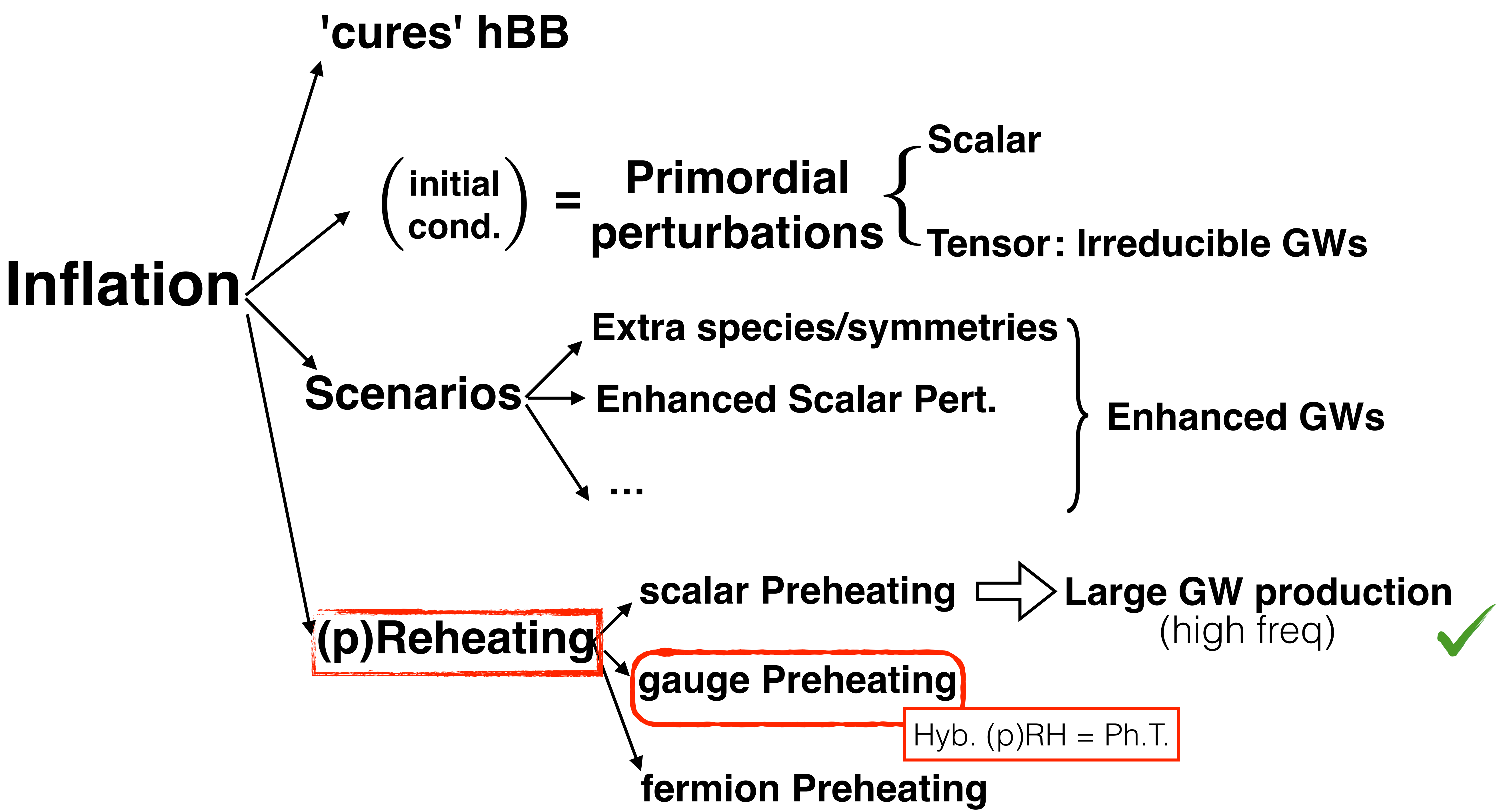

GAUGE (P)REHEATING

Hybrid Preheating = Higgs+Inflaton model

inflaton mass ↖ coupling ↗

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

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

Self-coupling ↖ V.E.V. ↙

$m = \sqrt{\lambda} v$

$\phi_c \equiv m/g$ Critical value

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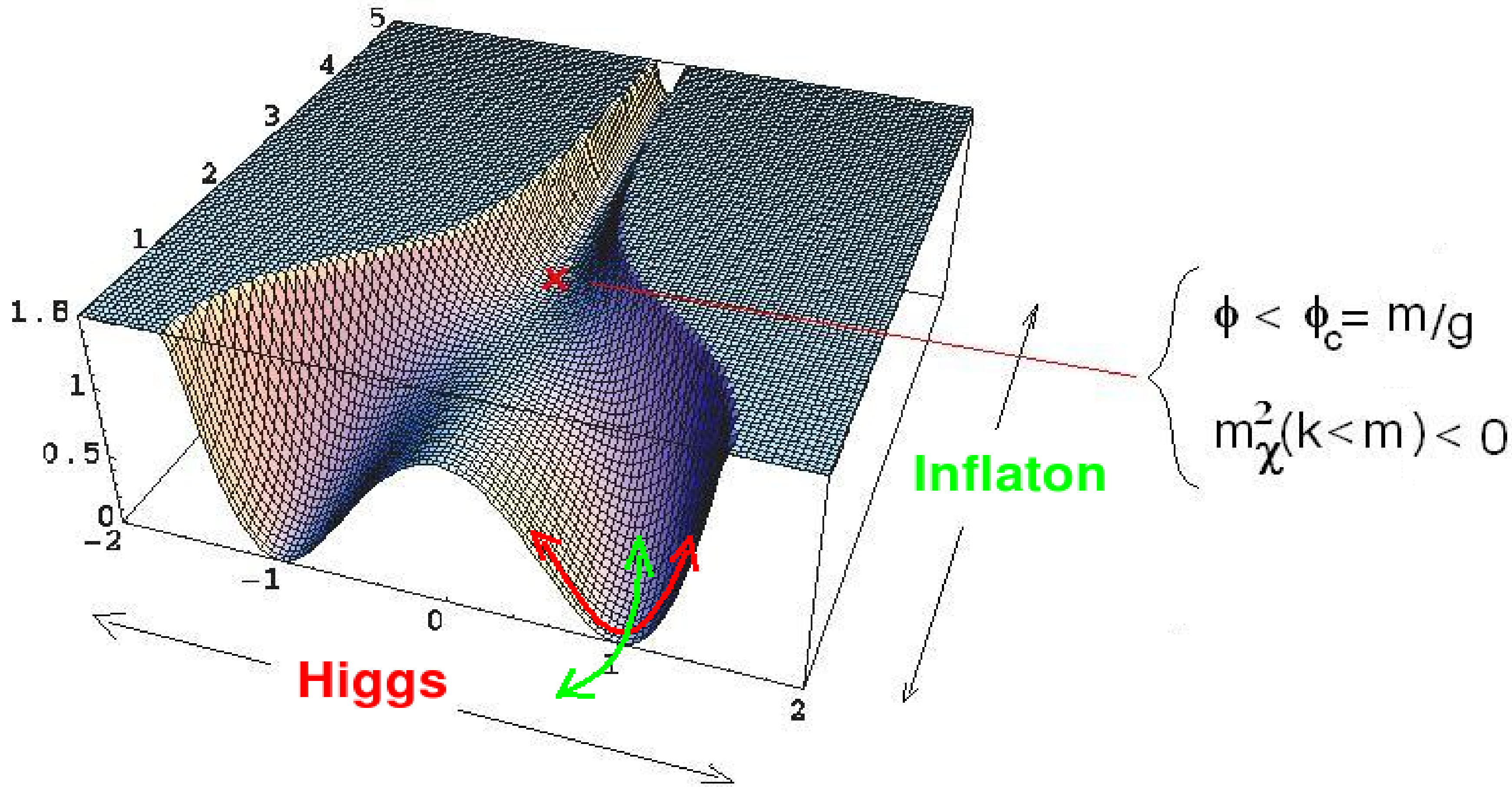
Hybrid Preheating = Phase Transition



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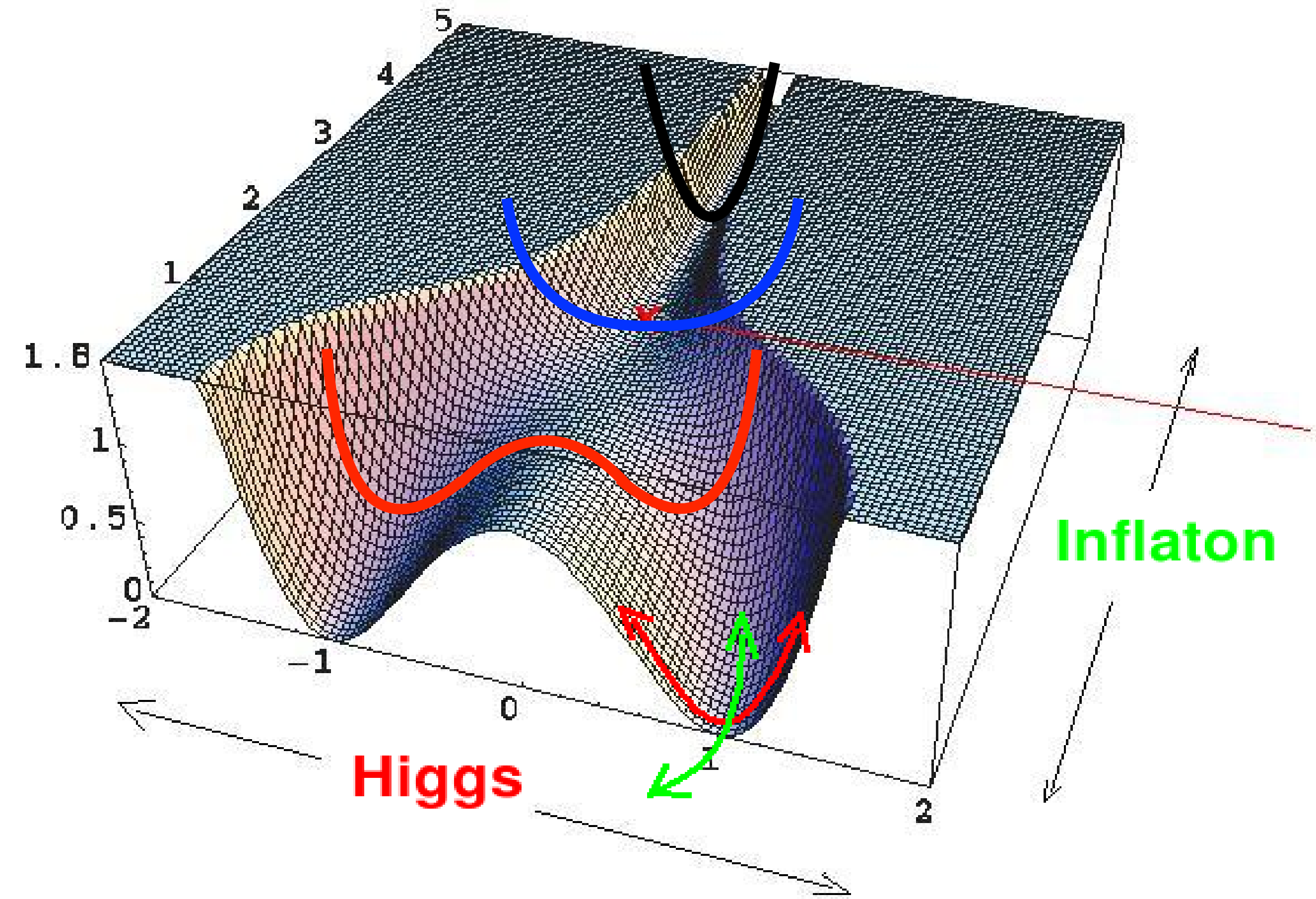

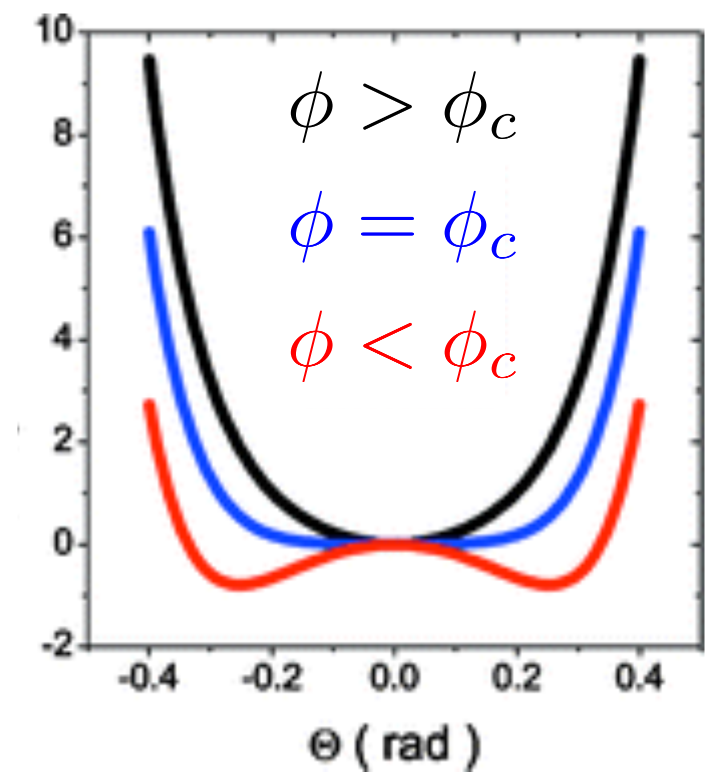

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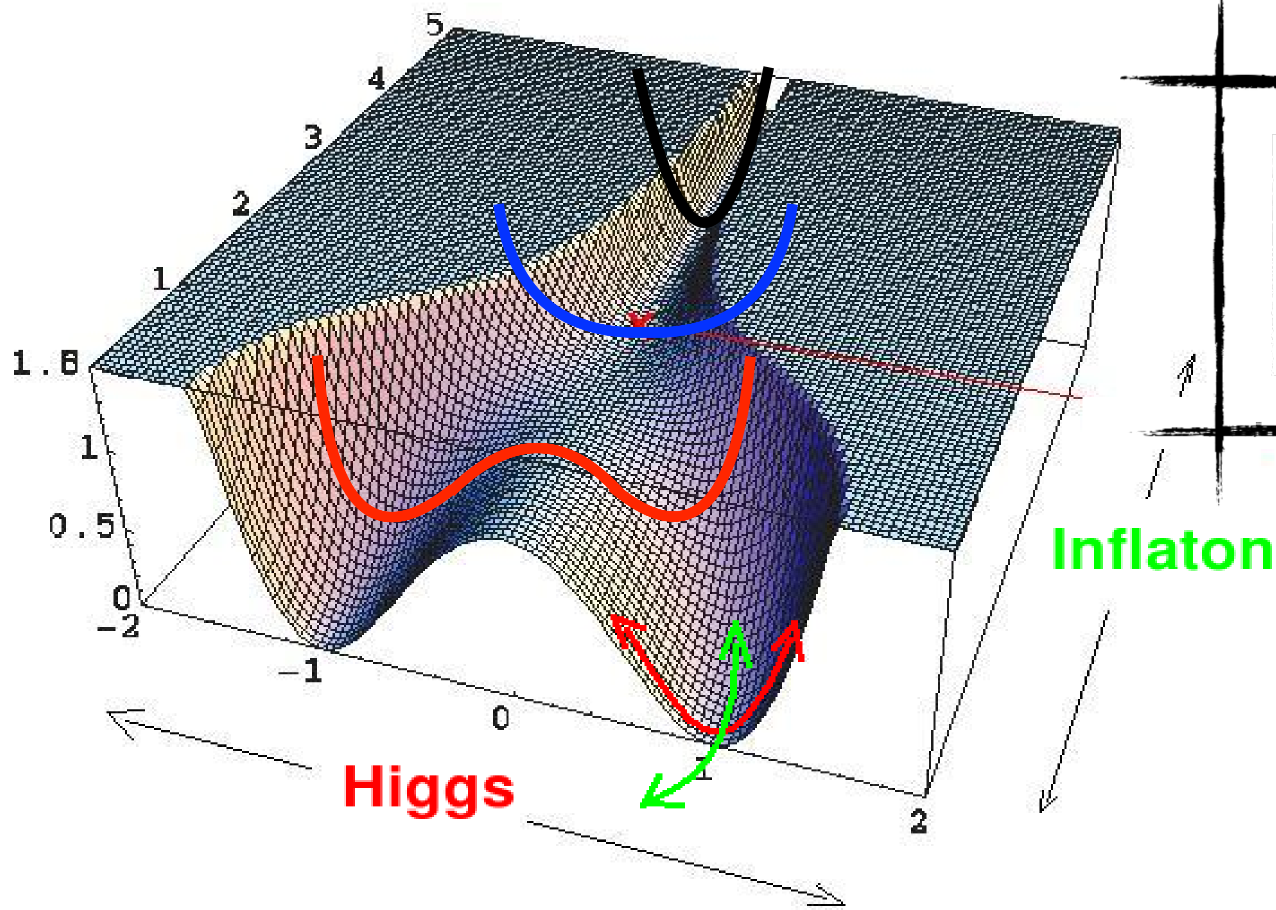
$(k < m = \sqrt{\lambda} v)$

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

Hybrid Preheating = Phase Transition



It is a Phase transition !
by Tachyonic Instability

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

GAUGE (P)REHEATING

The Abelian-Higgs+Inflaton model

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

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

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

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

GAUGE (P)REHEATING

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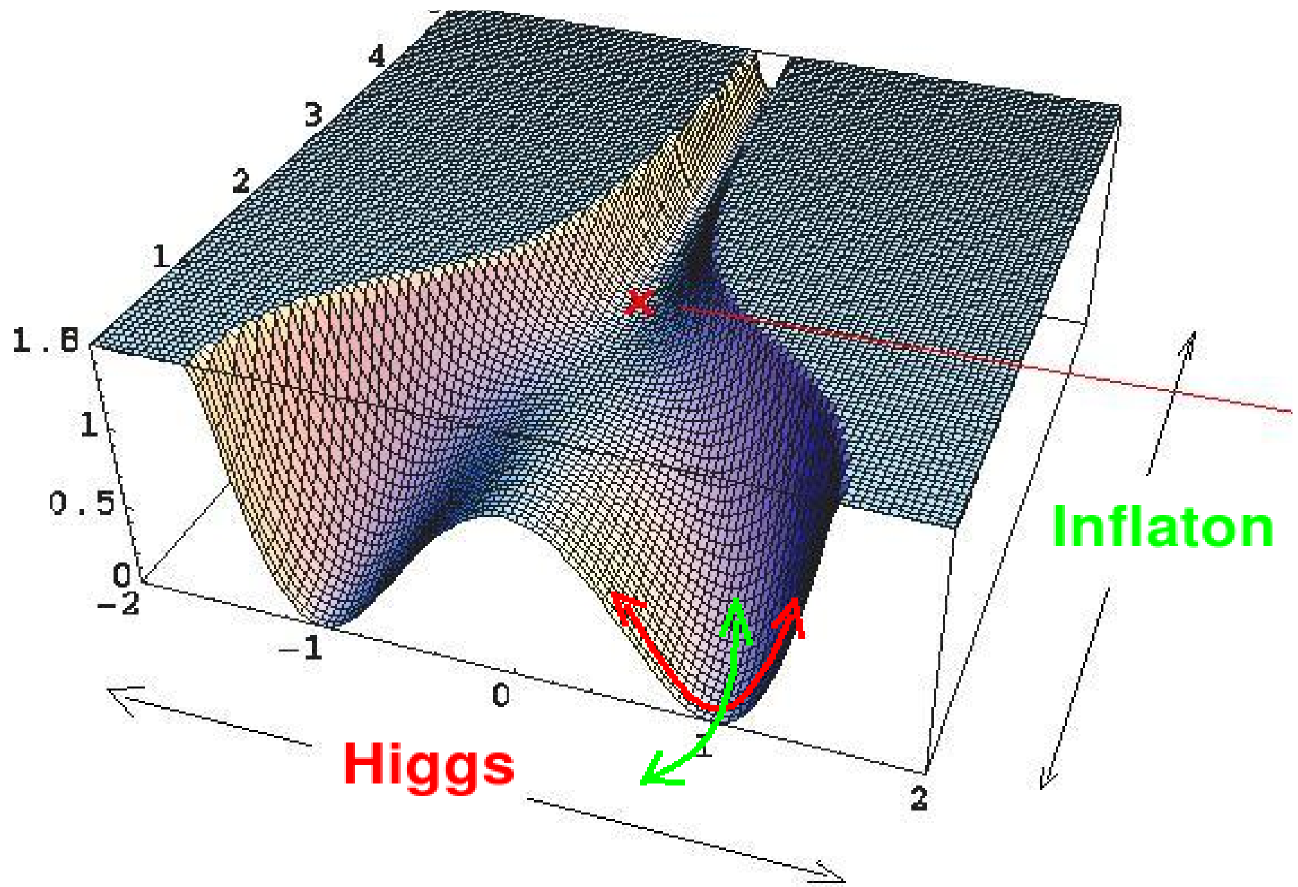

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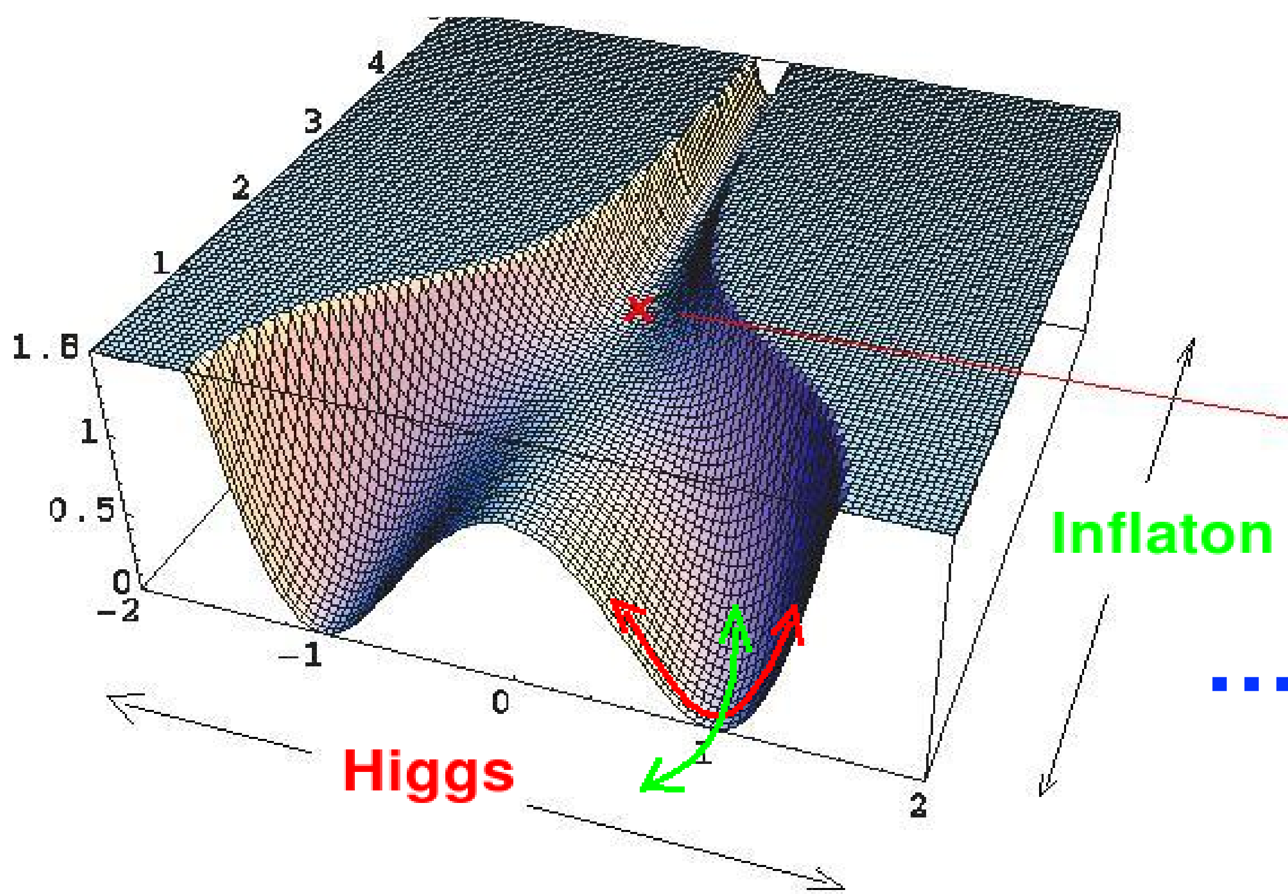

… now there are gauge field(s) !

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

GAUGE (P)REHEATING

The Abelian-Higgs+Inflaton model

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GAUGE (P)REHEATING

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EOM: { Minkowski, Temporal Gauge ($A_0 = 0$)

$$\ddot{\varphi} - D_i D_i \varphi + V_{,\varphi^*} = 0$$ → SCALARS eom

$$\ddot{A}_i - \partial_j \partial_j A_i + \partial_i \partial_j A_j = 2e^2 \,\mathrm{Im}\,[\varphi^* D_i \varphi]$$ → VECTORS eom

$$\partial_i \dot{A}_i = 2e^2 \,\mathrm{Im}\,[\varphi^* \dot{\varphi}] \;.$$ → GAUSS law

GAUGE (P)REHEATING

The Abelian-Higgs+Inflaton model

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

EOM: Minkowski, Temporal Gauge ($A_0 = 0$)

$$\begin{aligned} \ddot{\varphi} - D_i D_i \varphi + V_{,\varphi^*} &= 0 \\ \ddot{A}_i - \partial_j\partial_j A_i + \partial_i\partial_j A_j &= 2e^2\,\mathrm{Im}\left[\varphi^*\, D_i\varphi\right] \\ \partial_i \dot{A}_i &= 2e^2\,\mathrm{Im}\left[\varphi^*\,\dot{\varphi}\right] \ . \end{aligned}$$

→ SCALARS eom

→ VECTORS eom

→ GAUSS law

GW EOM

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

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

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

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

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

COVARIANT

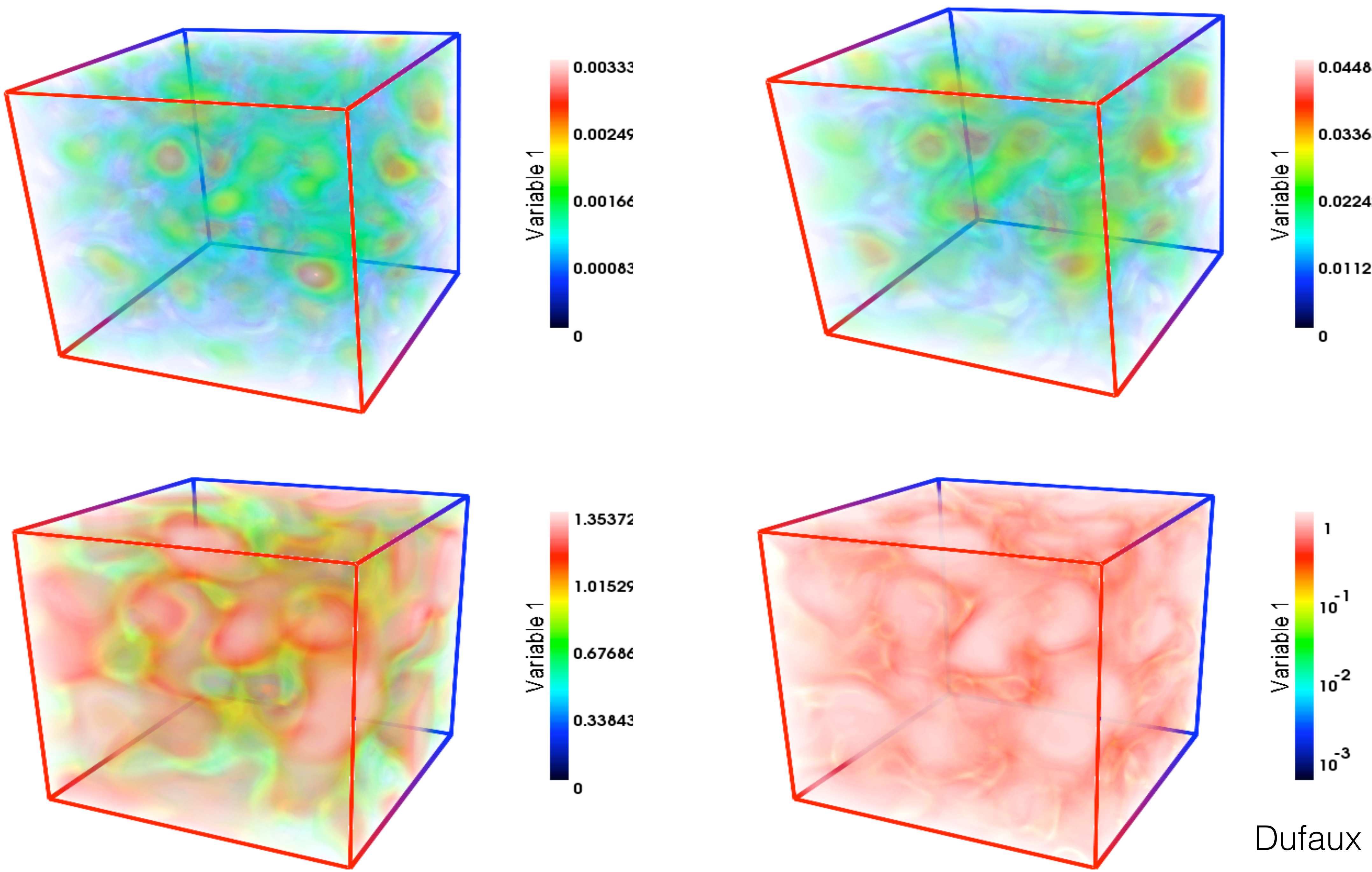
MAGNETIC

ELECTRIC

GAUGE (P)REHEATING

The Abelian-Higgs+Inflaton model

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

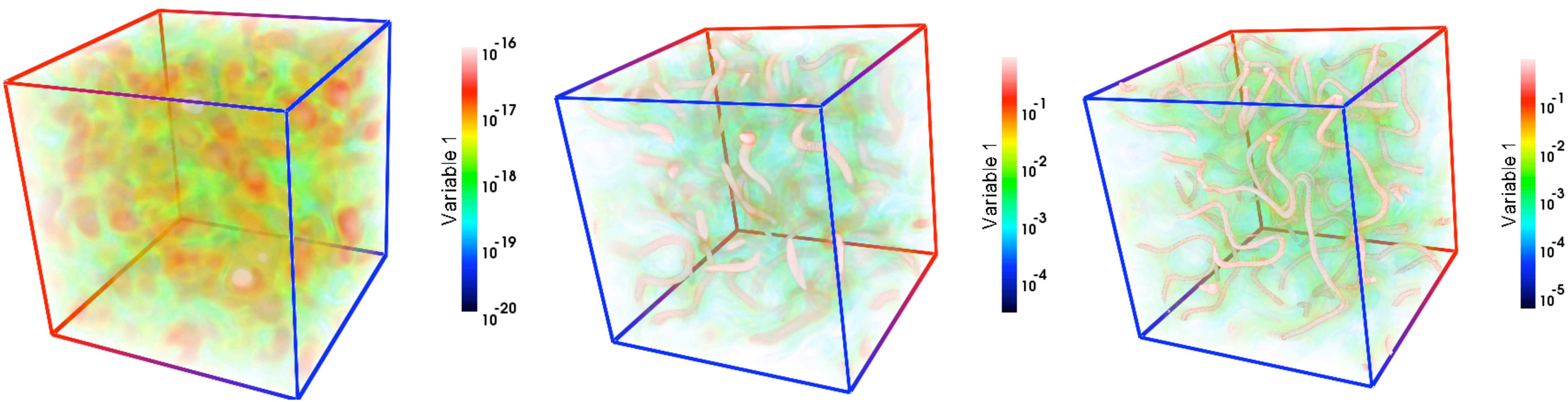


Dufaux et al 2010

GAUGE (P)REHEATING

The Abelian-Higgs+Inflaton model

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



Dufaux et al 2010

GAUGE (P)REHEATING

The Abelian-Higgs+Inflaton model

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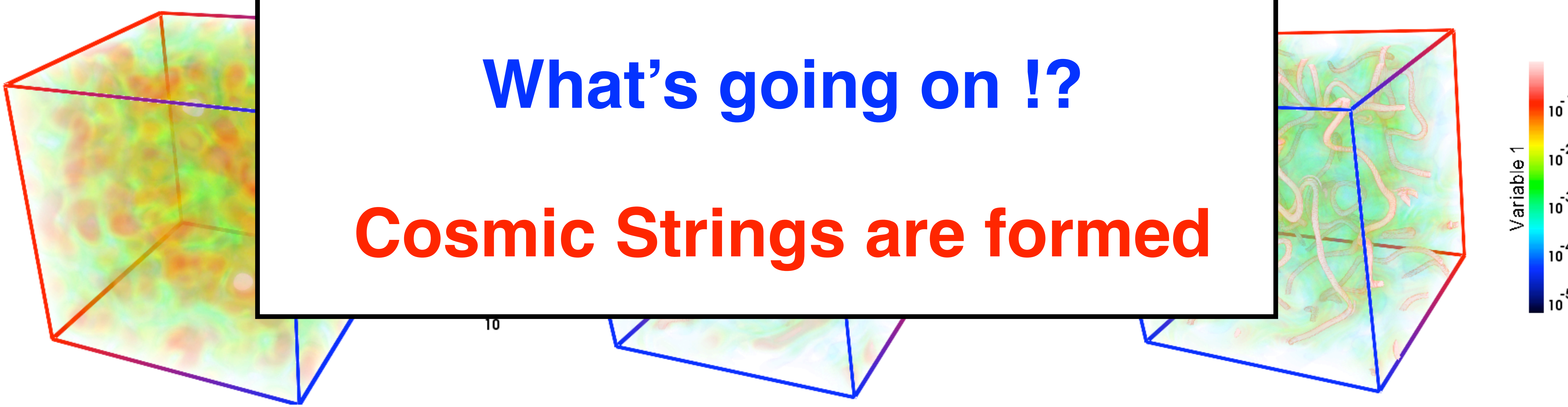


What's going on !?

Cosmic Strings are formed

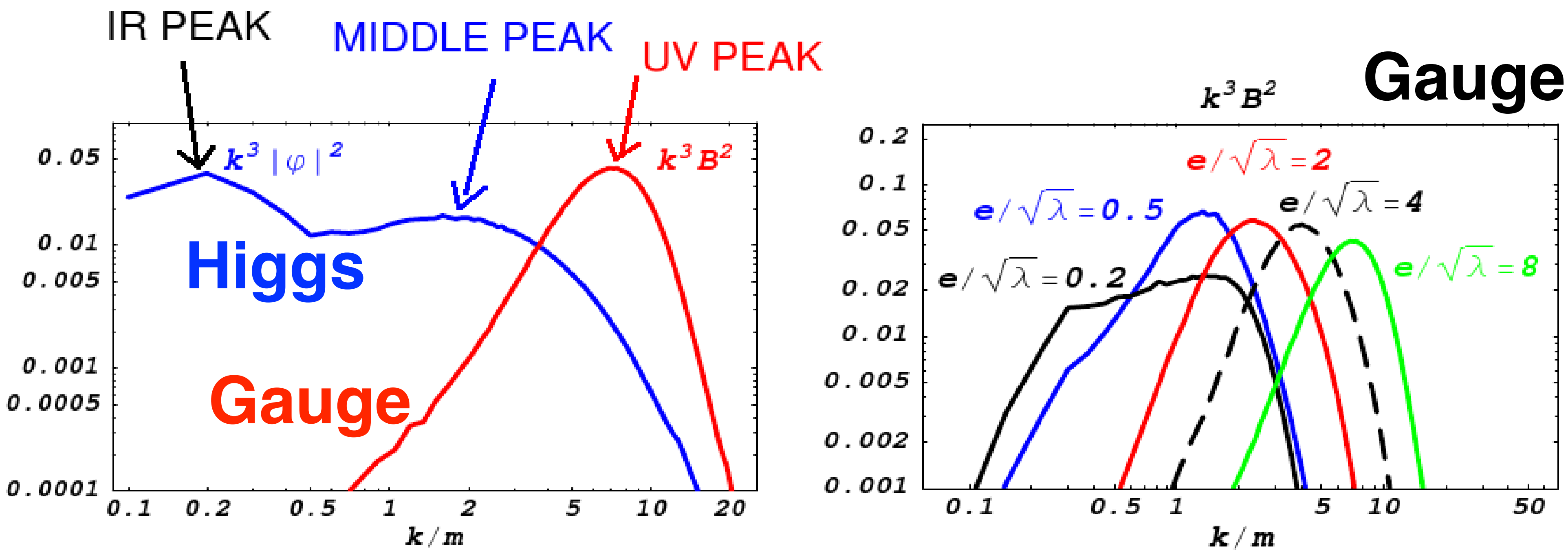
(Topological Defects ⟶ 4th Lecture)

Dufaux et al 2010

GAUGE (P)REHEATING

The Abelian-Higgs+Inflaton model

SCALARS AND VECTORS' SPECTRA:



Dufaux et al 2010

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The Abelian-Higgs+Inflaton model

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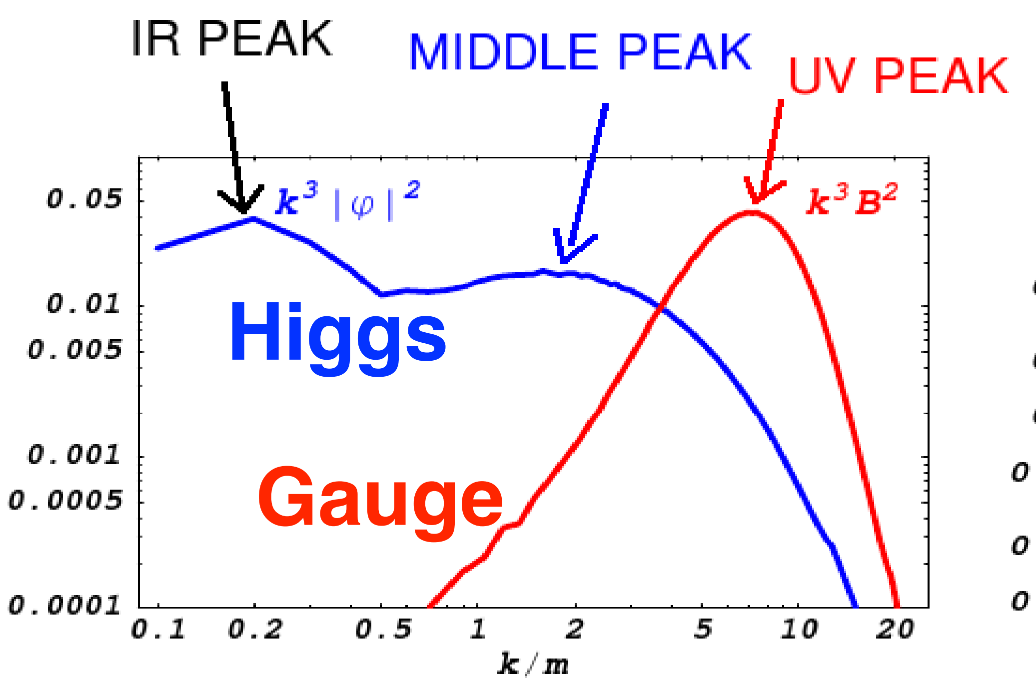
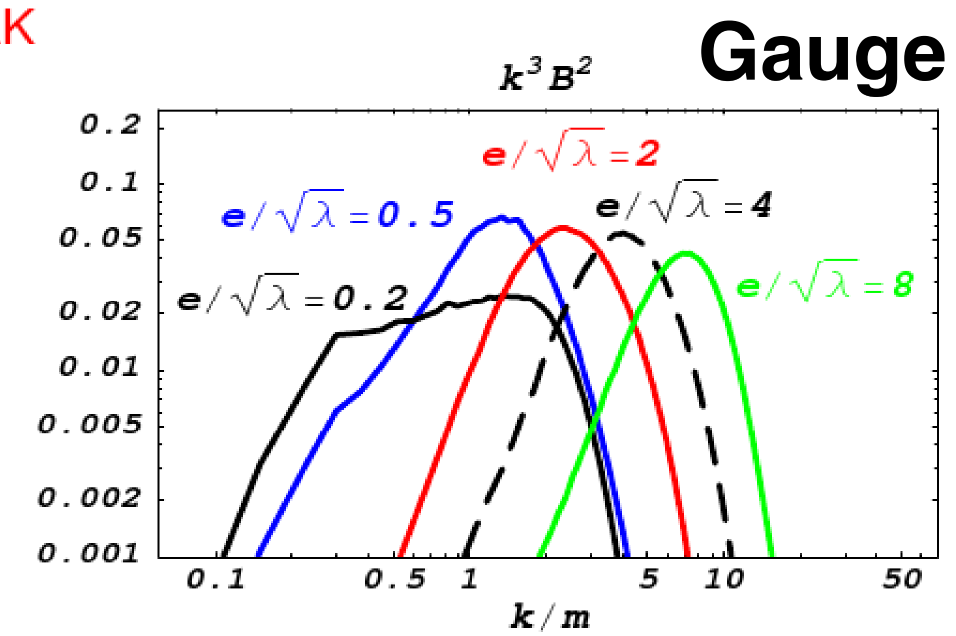




How do the GW spectrum look ?

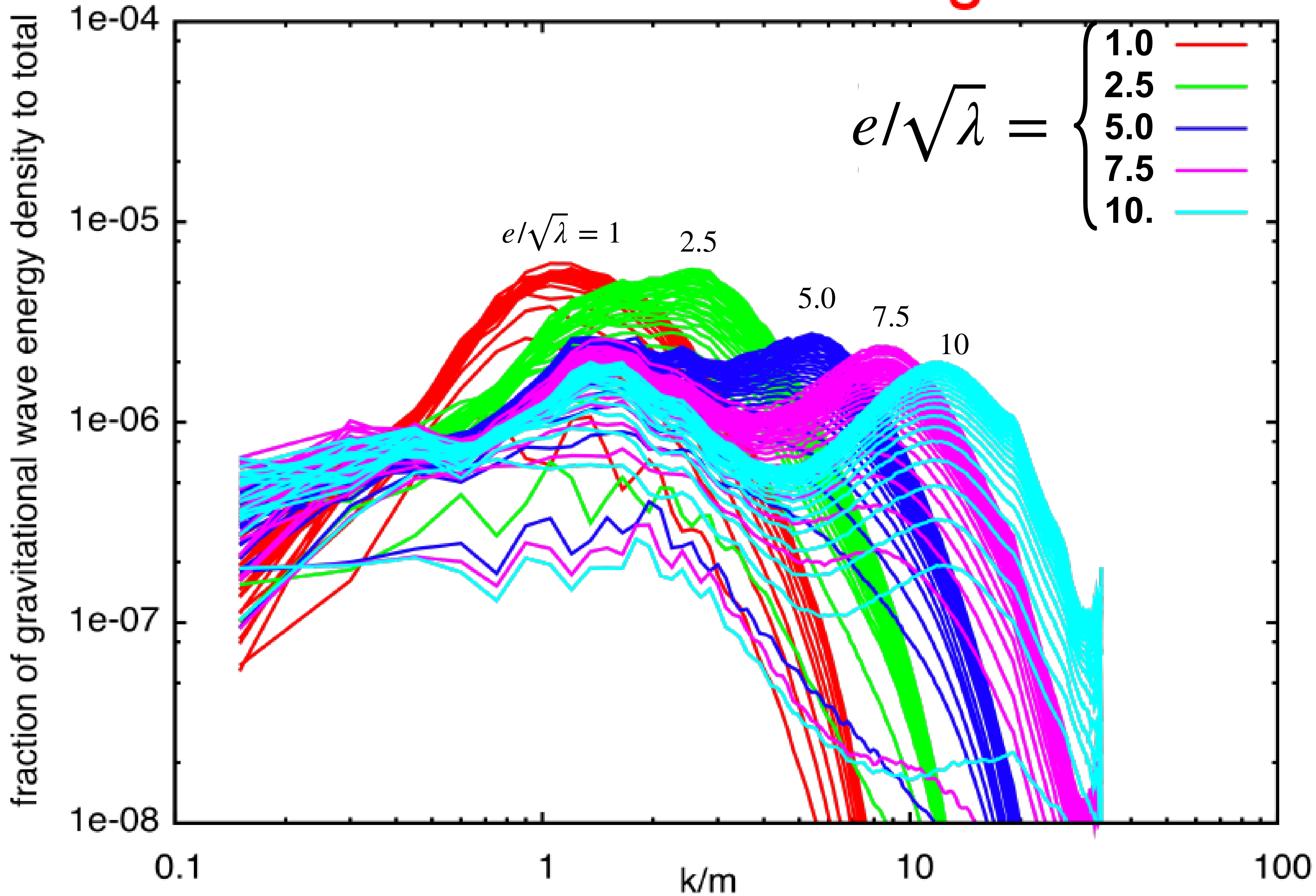
Dufaux et al 2010

GAUGE (P)REHEATING

The Abelian-Higgs+Inflaton model

GRAVITATIONAL WAVES SPECTRA:

Evolution of GW background



Dufaux et al 2010

GAUGE (P)REHEATING

The Abelian-Higgs+Inflaton model

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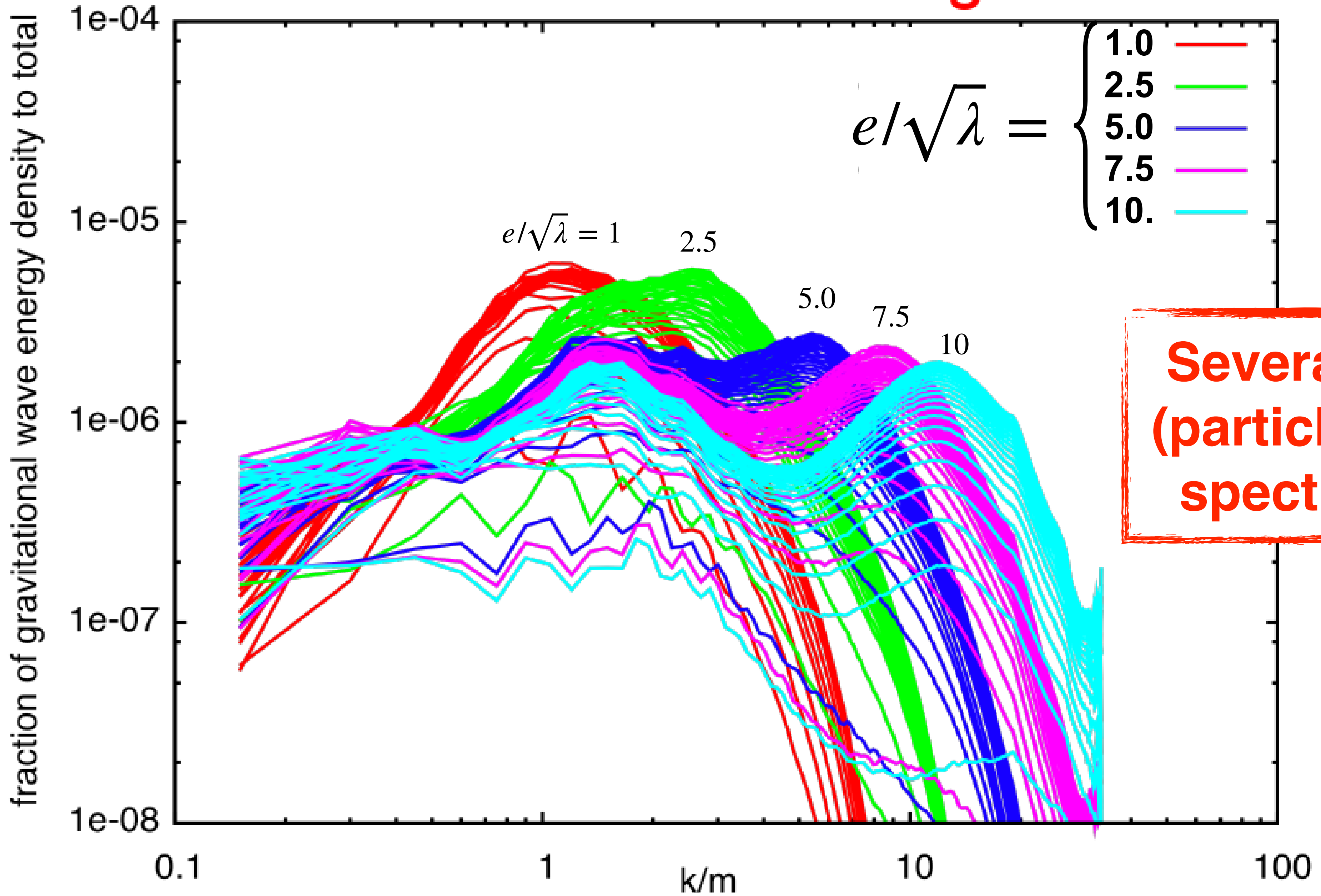

Several Peaks !
(particle physics spectroscopy)

Dufaux et al 2010

GAUGE (P)REHEATING

The Abelian-Higgs+Inflaton model

Several Peaks !
(particle physics spectroscopy)

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

Large amplitude(s) !

GAUGE (P)REHEATING

The Abelian-Higgs+Inflaton model

Several Peaks !
(particle physics spectroscopy)

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

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

Dufaux et al 2010

GAUGE (P)REHEATING

The Abelian-Higgs+Inflaton model

Several Peaks !
(particle physics spectroscopy)

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

Very unfortunate... no good high freq. detectors !

GAUGE (P)REHEATING

The Abelian-Higgs+Inflaton model

Several Peaks !
(particle physics spectroscopy)

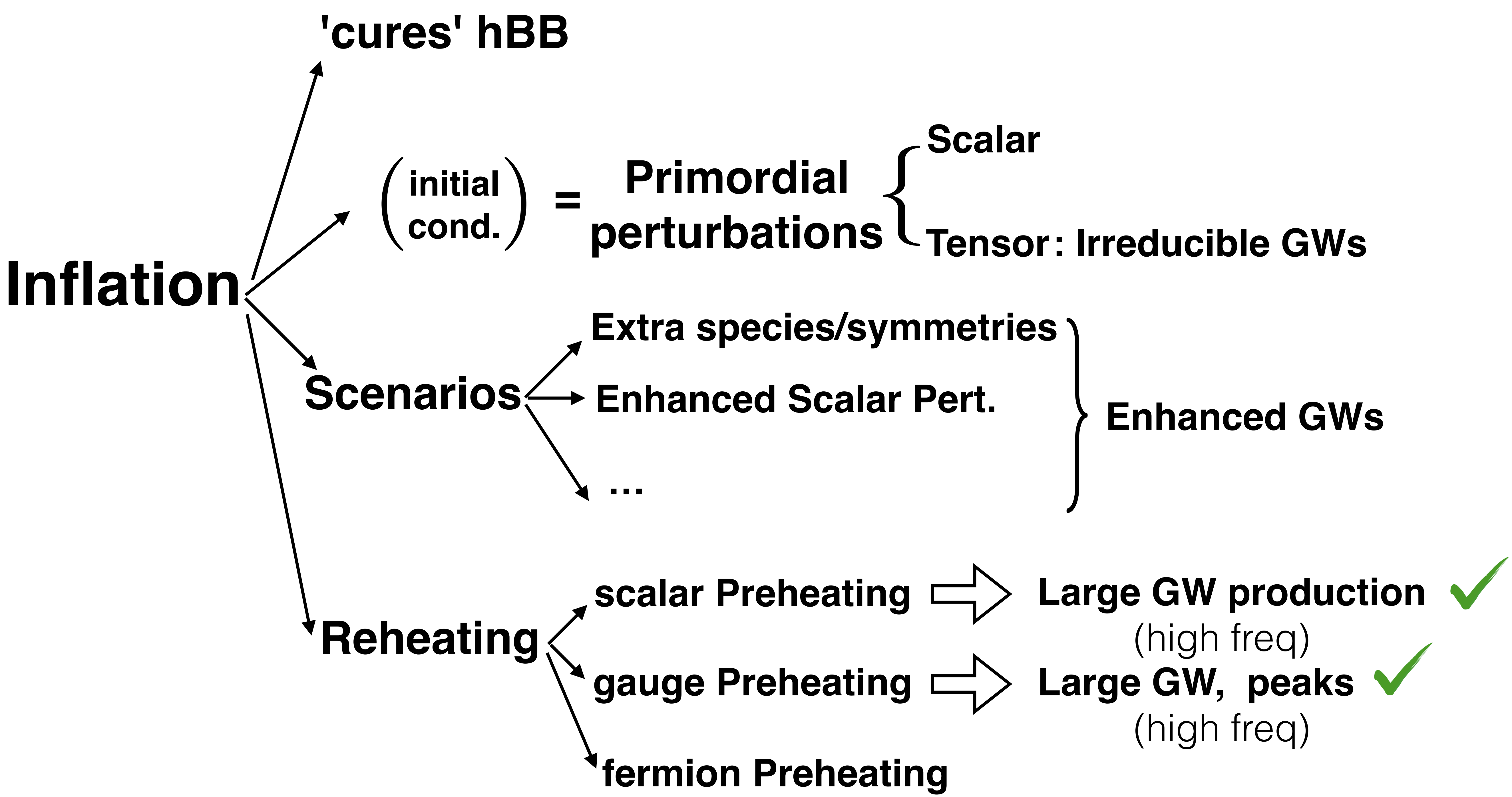
$$\Omega^{(o)}_{\rm GW} \sim 10^{-11}\,, \quad @ \quad f_o \sim 10^8 - 10^9 \text{ Hz}$$

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

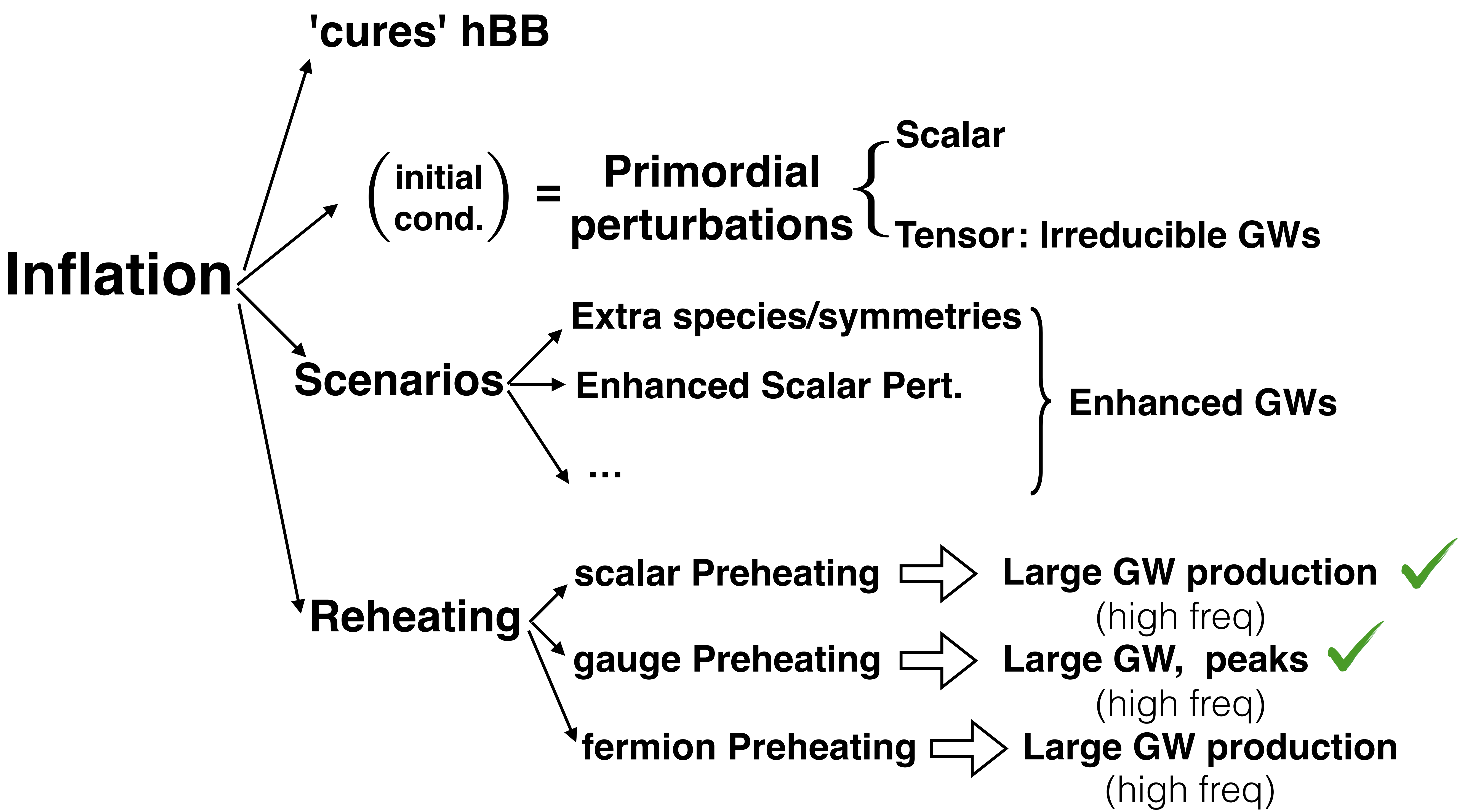
We Should look for this effect at low-freq models !

Very unfortunate... no good high freq. detectors !

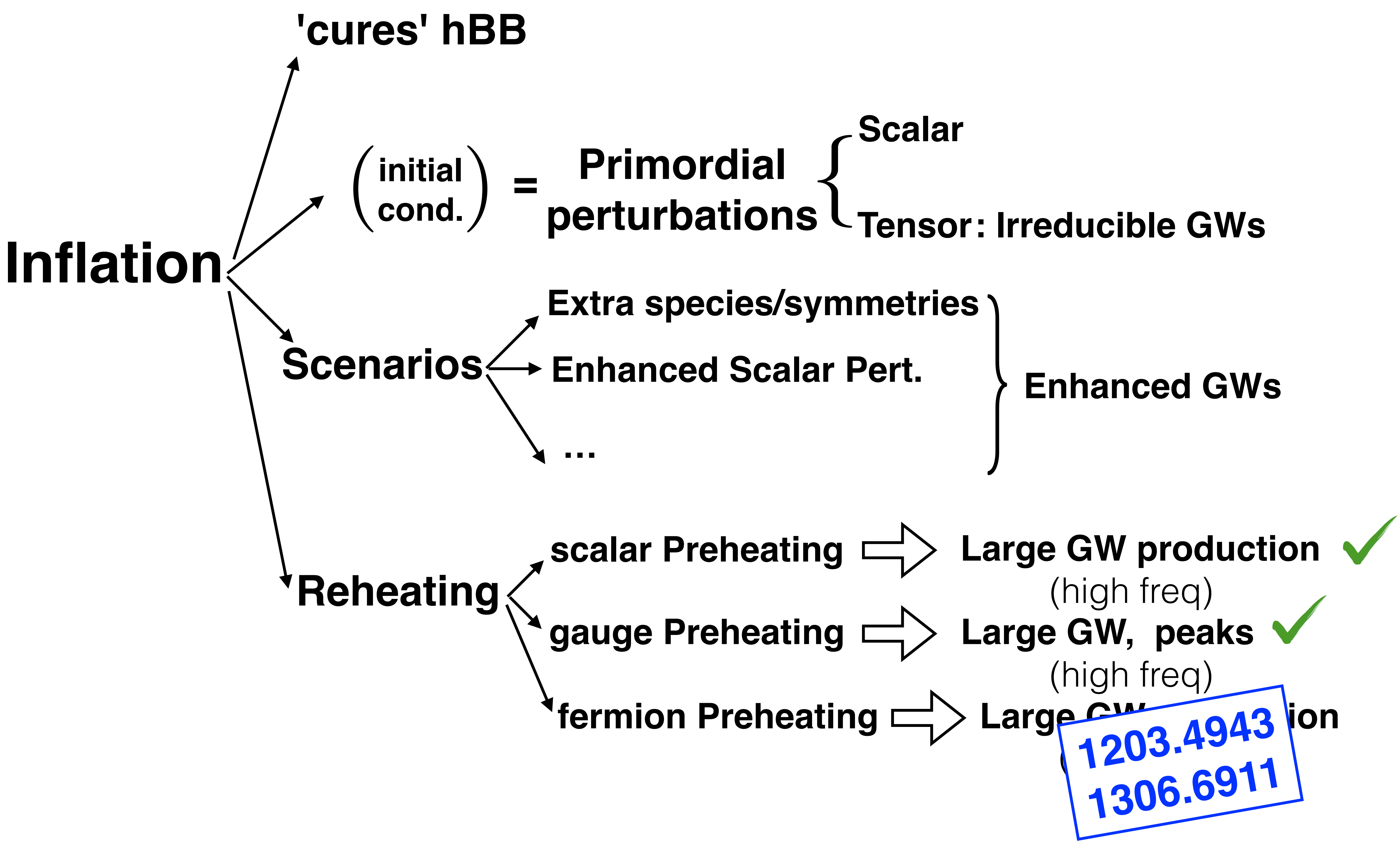
INFLATIONARY COSMOLOGY



INFLATIONARY COSMOLOGY



INFLATIONARY COSMOLOGY



INFLATIONARY COSMOLOGY

Inflation

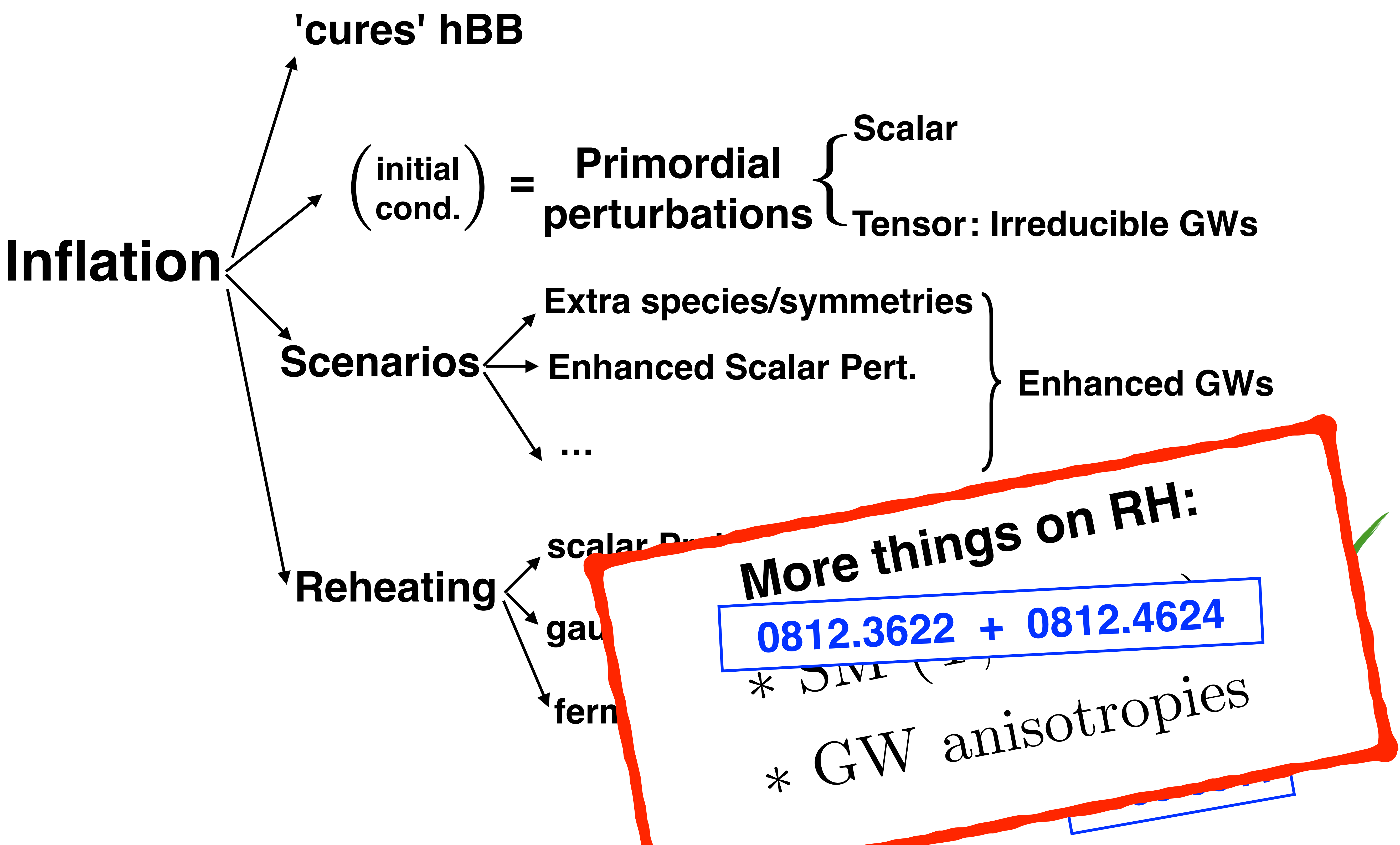
- 'cures' hBB
- (initial cond.) = Primordial perturbations
  - Scalar
  - Tensor : Irreducible GWs
- Scenarios
  - Extra species/symmetries
  - Enhanced Scalar Pert.
  - ...
  - } Enhanced GWs
- Reheating
  - scalar Pr
  - gau
  - ferm

More things on RH:

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

$* \ \mathrm{GW}$ anisotropies

INFLATIONARY COSMOLOGY



INFLATIONARY COSMOLOGY

Inflation

'cures' hBB

(initial cond.) = Primordial perturbations
- Scalar
- Tensor: Irreducible GWs

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

} Enhanced GWs

Reheating
- scalar Pr...
- gau...
- ferm...

More things on RH:

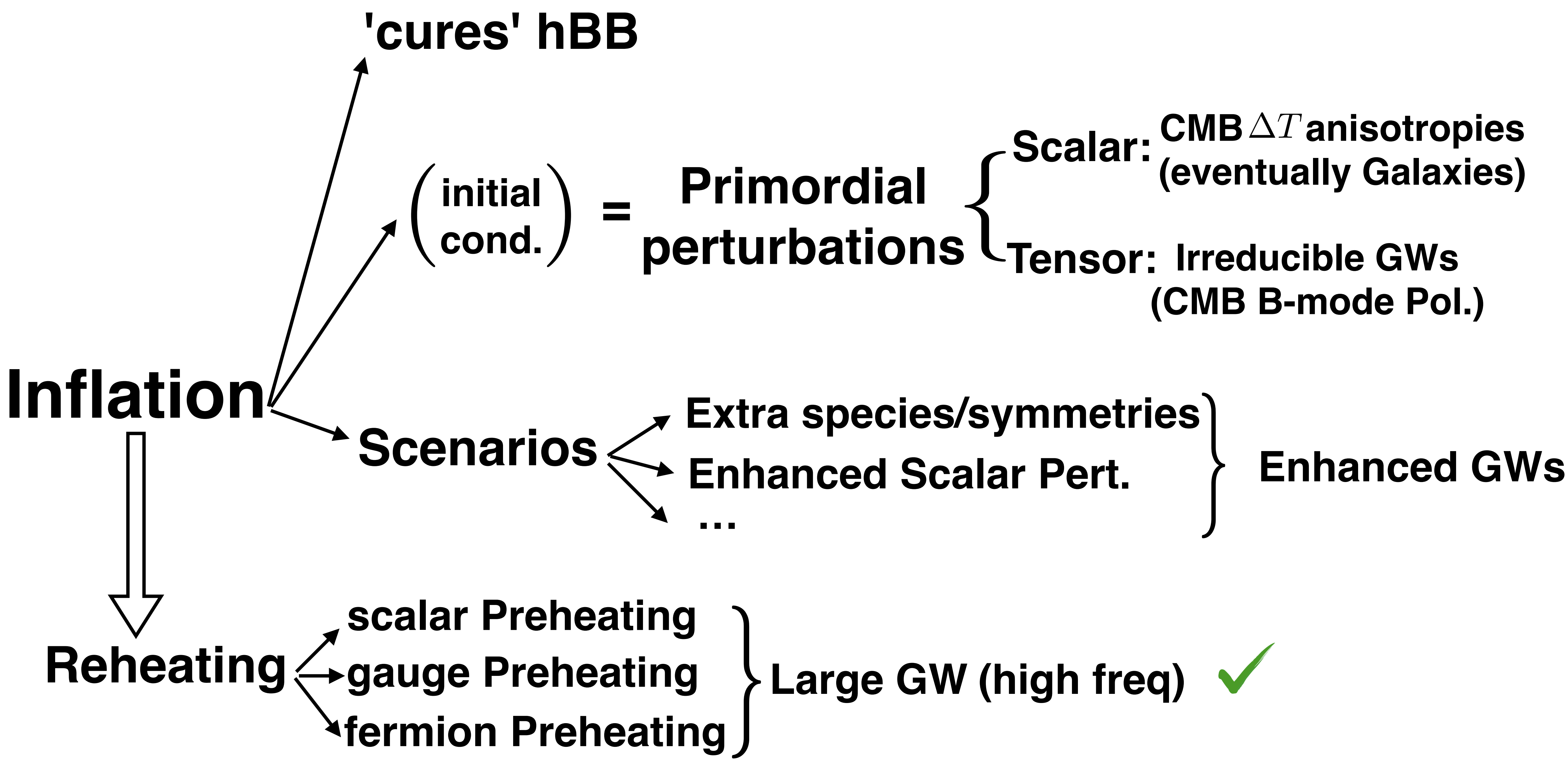
0812.3622 + 0812.4624

* SM (...)

1304.2657 + 1309.1148

* GW an...

EARLY UNIVERSE



EARLY UNIVERSE

Inflation

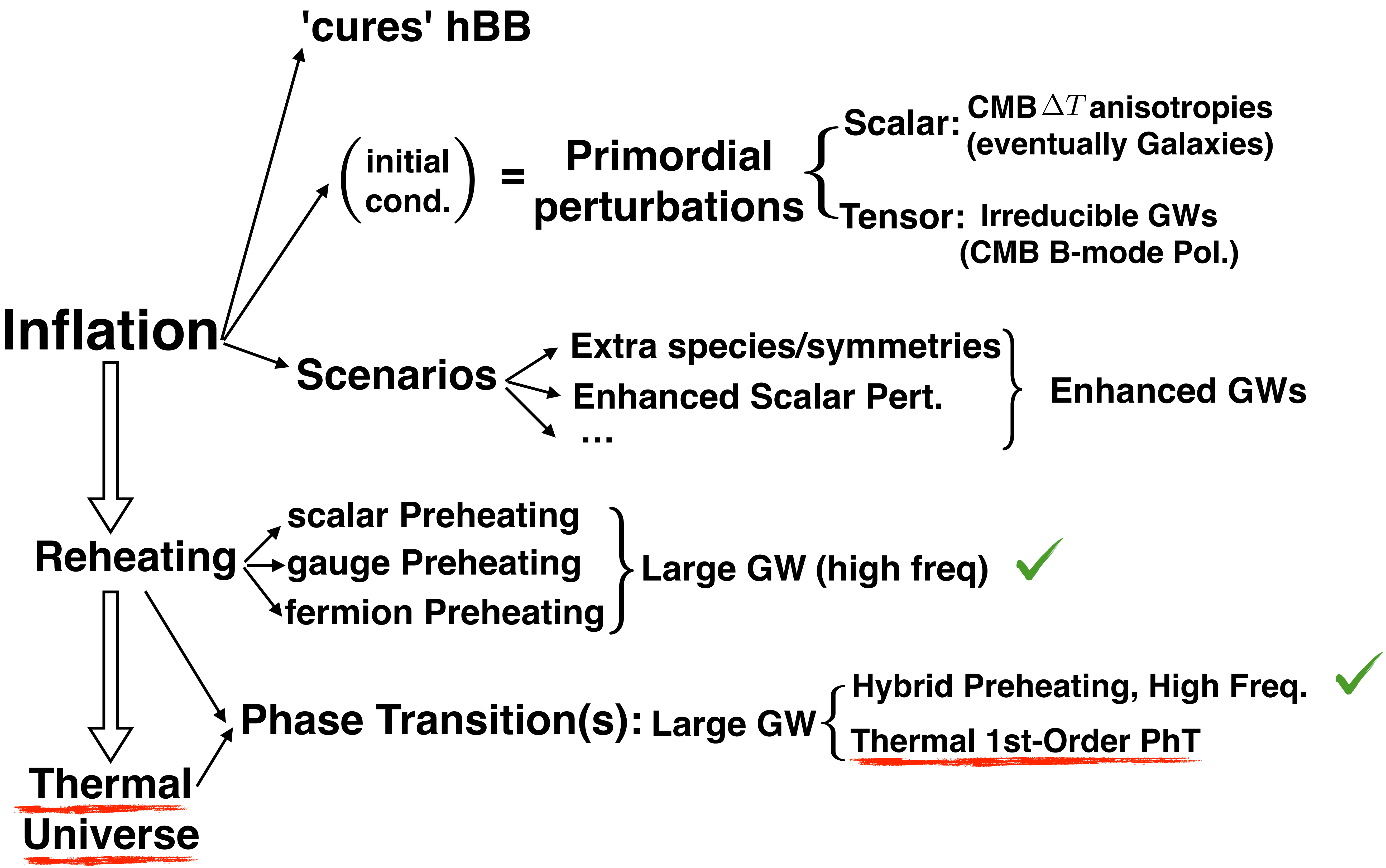
- 'cures' hBB
- (initial cond.) = Primordial perturbations
  - Scalar: CMB ΔT anisotropies (eventually Galaxies)
  - Tensor: Irreducible GWs (CMB B-mode Pol.)
- Scenarios
  - Extra species/symmetries
  - Enhanced Scalar Pert.
  - ...
  - } Enhanced GWs

Reheating

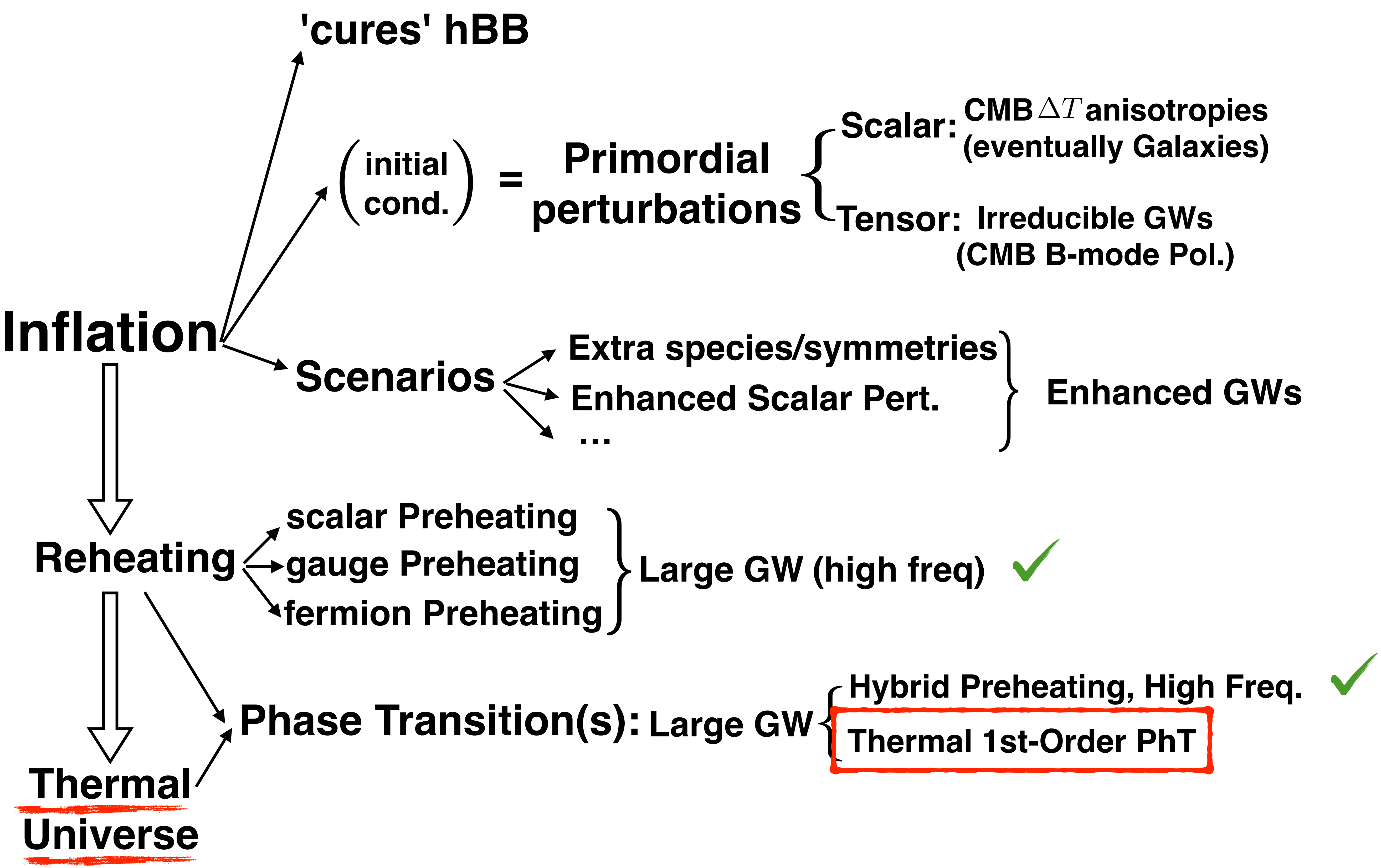
- scalar Preheating
- gauge Preheating
- fermion Preheating
- } Large GW (high freq) ✓

Phase Transition(s): Large GW { Hybrid Preheating, High Freq. ✓

EARLY UNIVERSE



EARLY UNIVERSE



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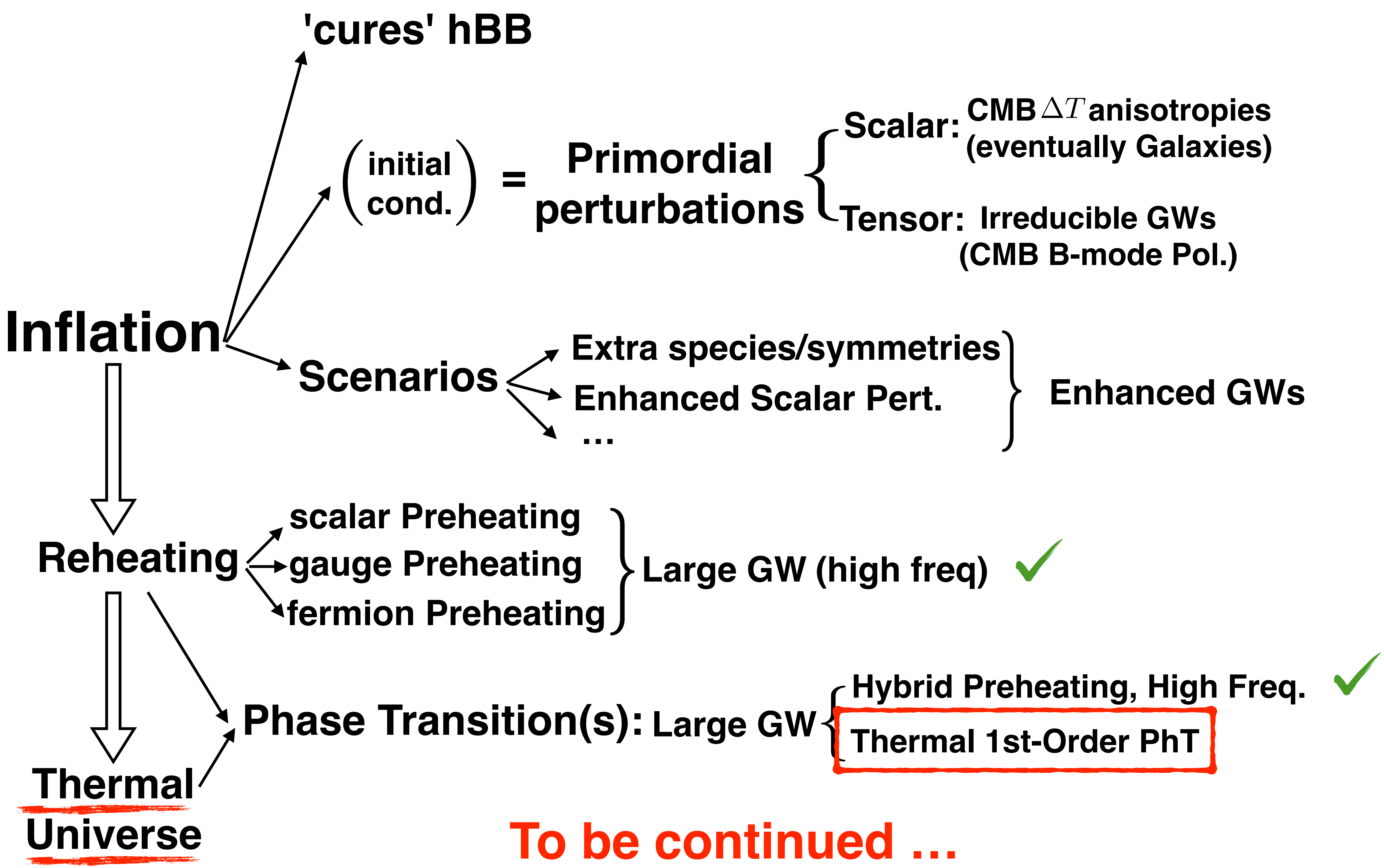


To be continued ...

Back-up Slides

INFLATIONARY PREHEATING

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

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

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

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

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

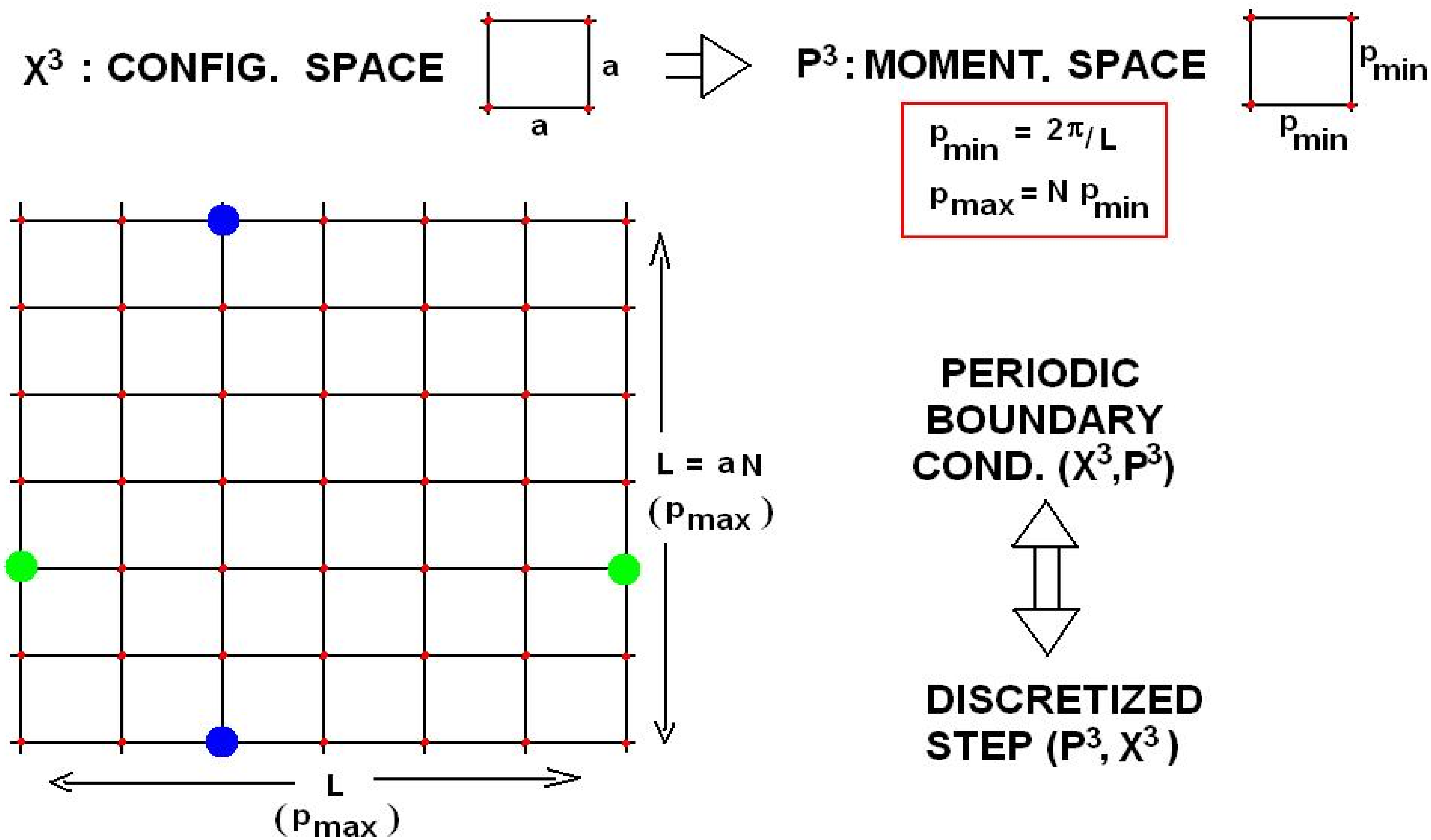
$$ds^2 = a^2(-d\tau^2 + (\delta_{ij} + h_{ij})dx^i dx^j), \quad {\rm TT}: \left\{ \begin{array}{l} h_{ii} = 0 \\ h_{ij,j} = 0 \end{array} \right.$$

INFLATIONARY PREHEATING

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

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

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



INFLATIONARY PREHEATING

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

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

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TT: **Non-local operation !**

INFLATIONARY PREHEATING

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

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TT: Non-local operation !

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

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

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

INFLATIONARY PREHEATING

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

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TT: Non-local operation !

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

(TT-Projection)

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

Numerically Prohibited !

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.:

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

INFLATIONARY PREHEATING

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

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2) Fourier transform: $u_{ij}(\mathbf{x},t) \rightarrow u_{ij}(\mathbf{k},t)$

INFLATIONARY PREHEATING

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

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INFLATIONARY PREHEATING

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

Building the Solution:

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Only when needed !

3) Proyection: $h_{ij}(\mathbf{k},t) = \Lambda_{ij,lm}(\hat{\mathbf{k}})u_{lm}(\mathbf{k},t)$

INFLATIONARY PREHEATING

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

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

DGF 2007

INFLATIONARY PREHEATING

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

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1) Total GW density:
$\rho_{GW} = \frac{1}{32\pi G L^3} \times \int k^2 dk \int d\Omega\,\Lambda_{ij,lm}(\hat{\mathbf{k}})\dot{u}_{ij}(t,\mathbf{k})\dot{u}^*_{lm}(t,\mathbf{k})$

INFLATIONARY PREHEATING

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

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2) Spectrum: $\frac{d\rho}{d\log k} = \frac{1}{8GL^3} k^3 \left\langle \Lambda_{ij,lm}(\hat{\mathbf{k}})\dot{u}_{ij}(t,\mathbf{k})\dot{u}^*_{lm}(t,\mathbf{k})\right\rangle_{4\pi}$

INFLATIONARY PREHEATING

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

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

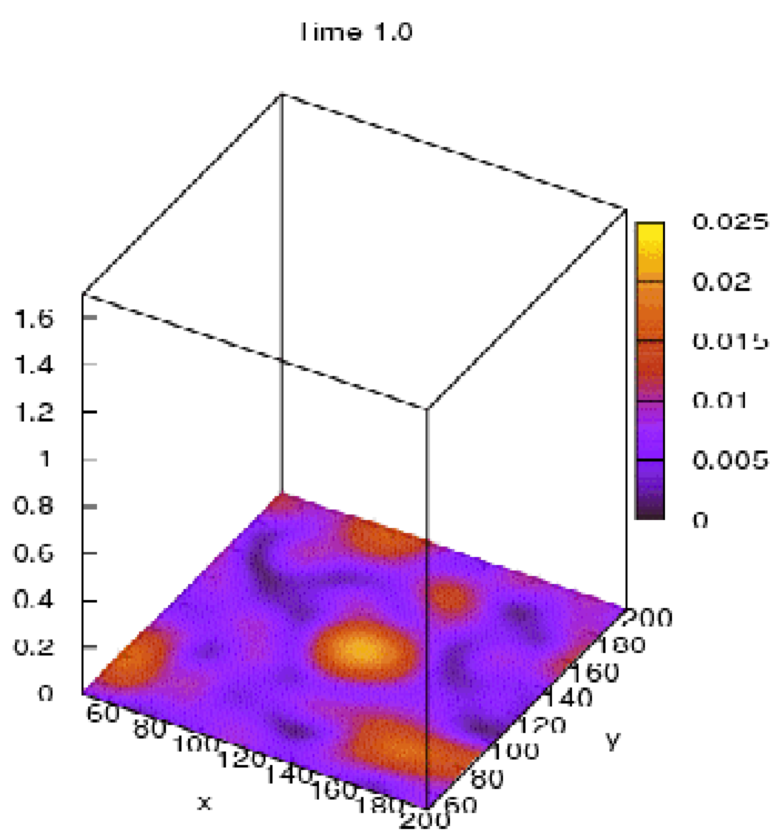
INFLATIONARY PREHEATING

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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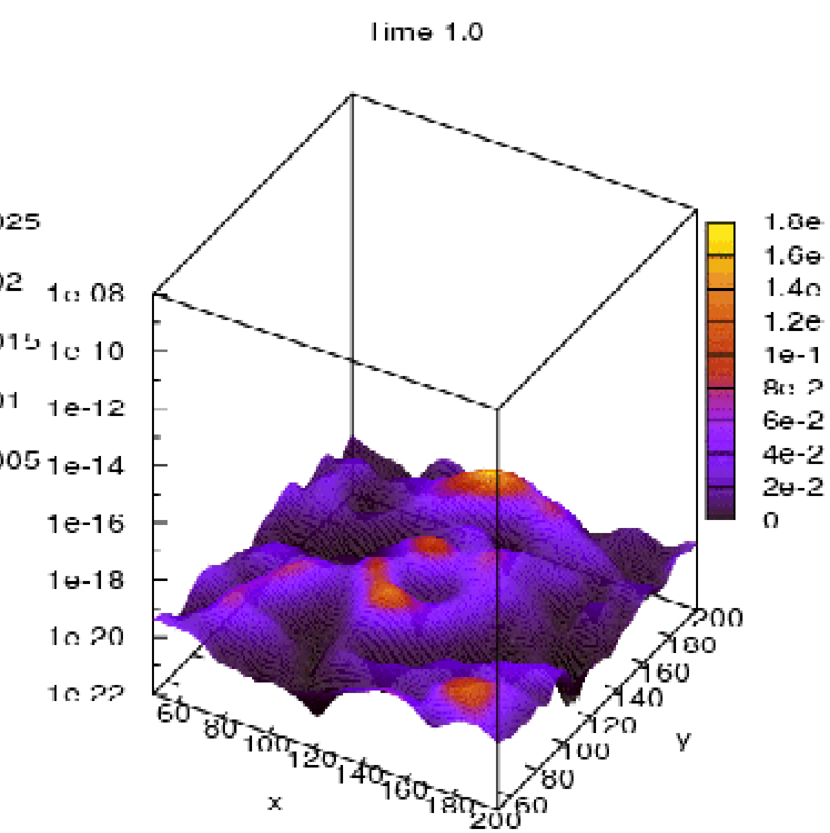

GW **(Energy density)**

INFLATIONARY PREHEATING

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

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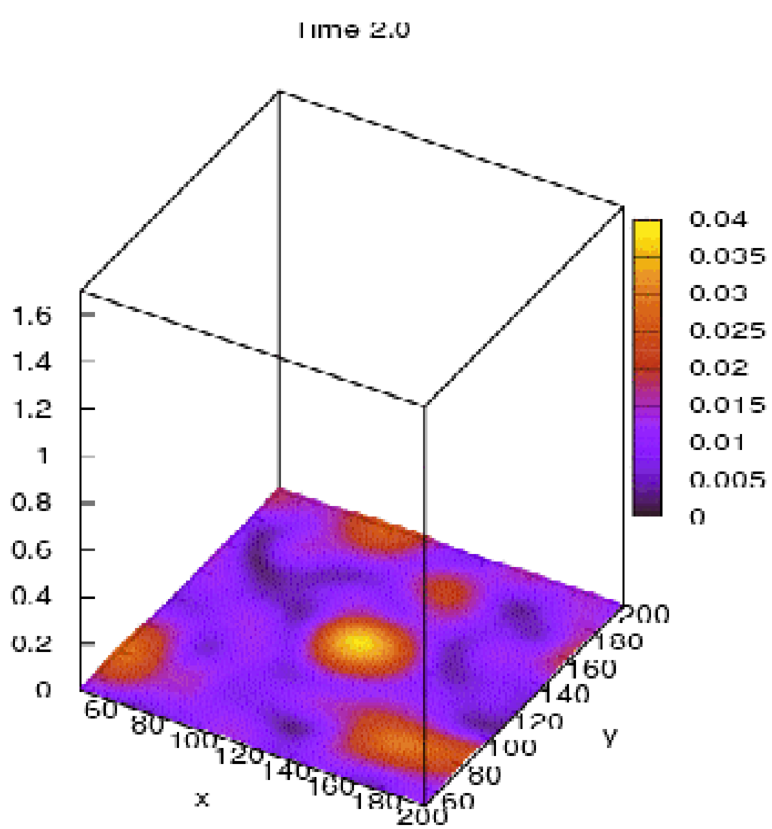

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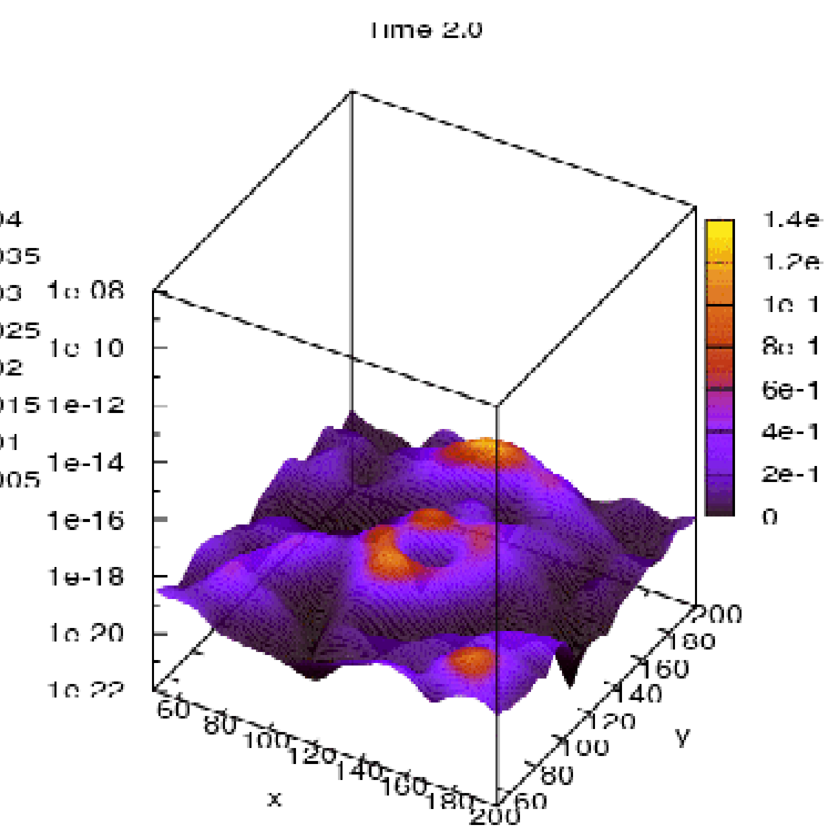

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INFLATIONARY PREHEATING

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

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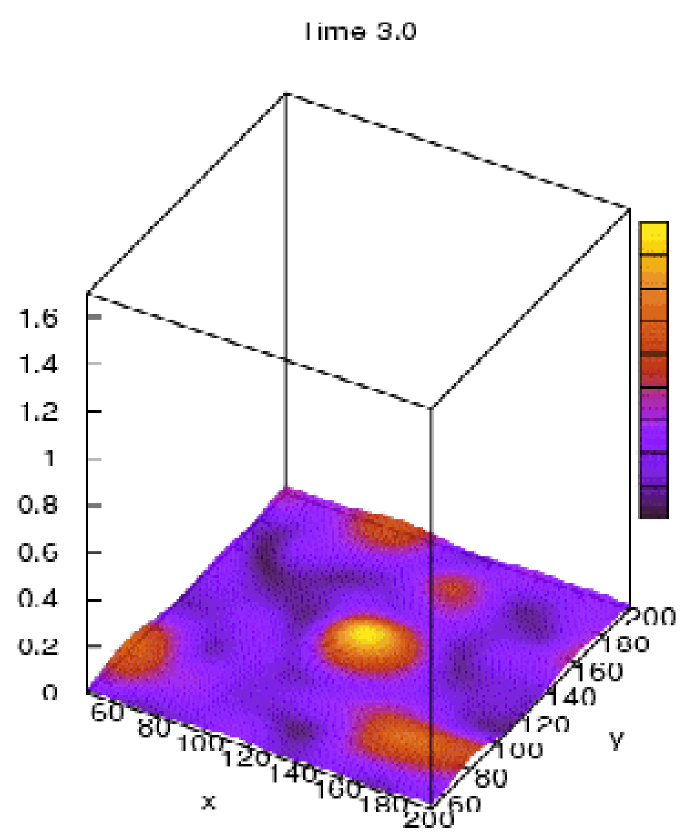

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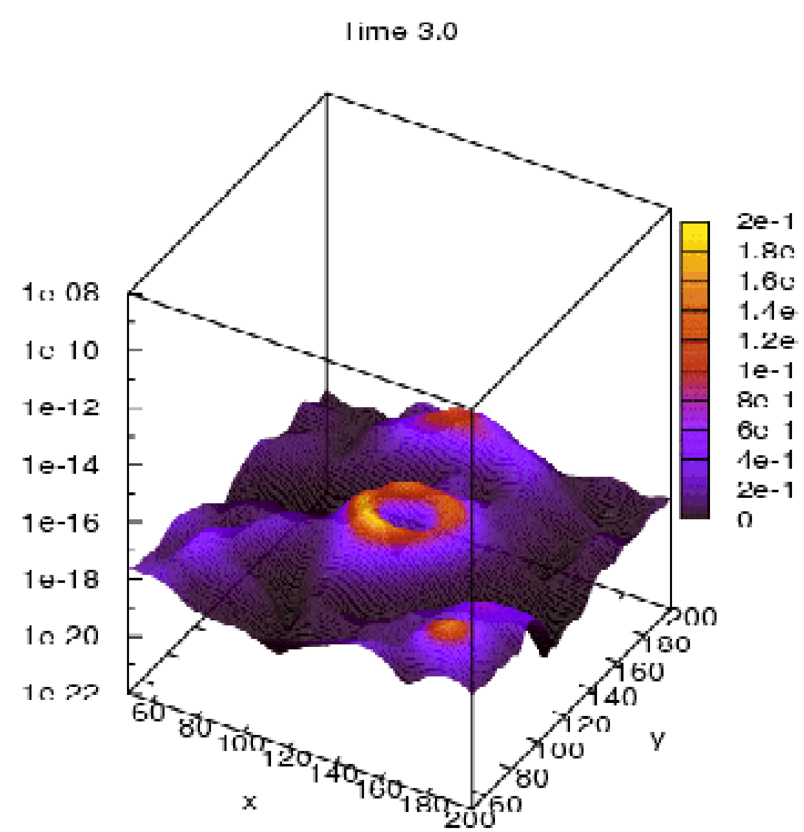

GW (Energy density)

INFLATIONARY PREHEATING

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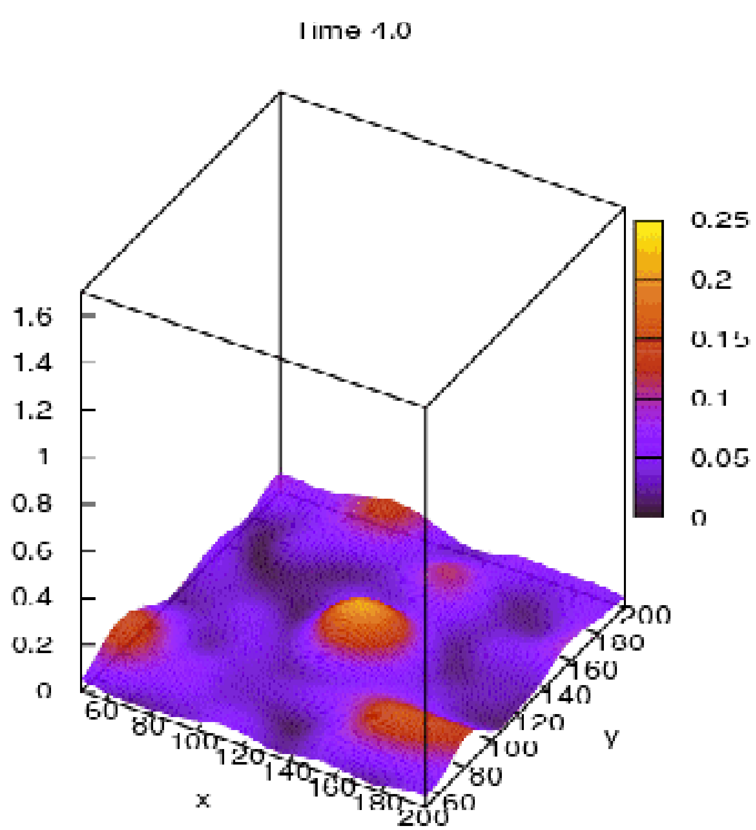

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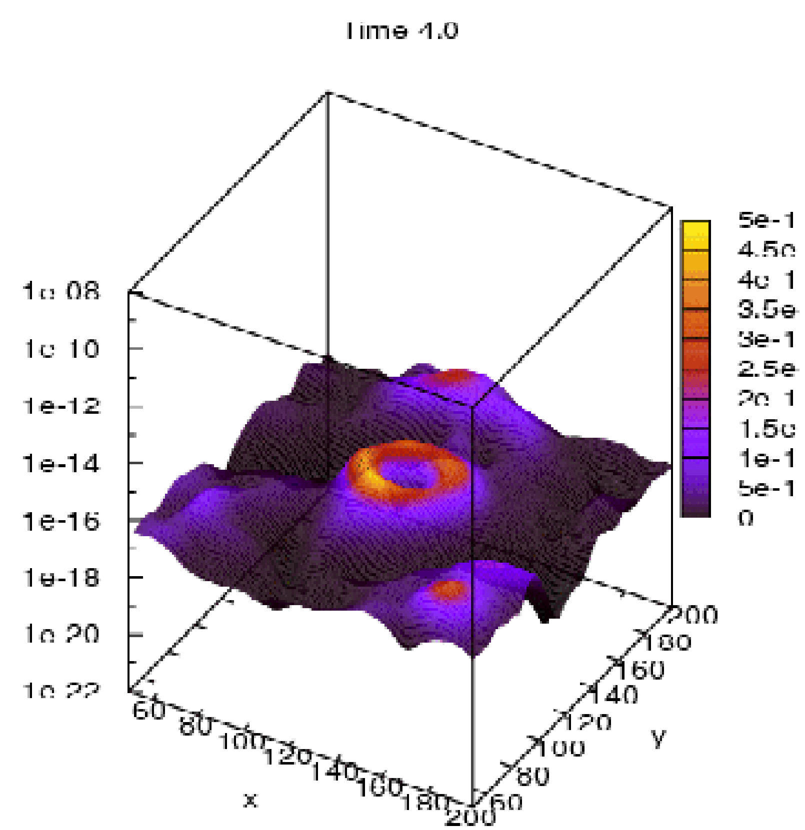

GW **(Energy density)**

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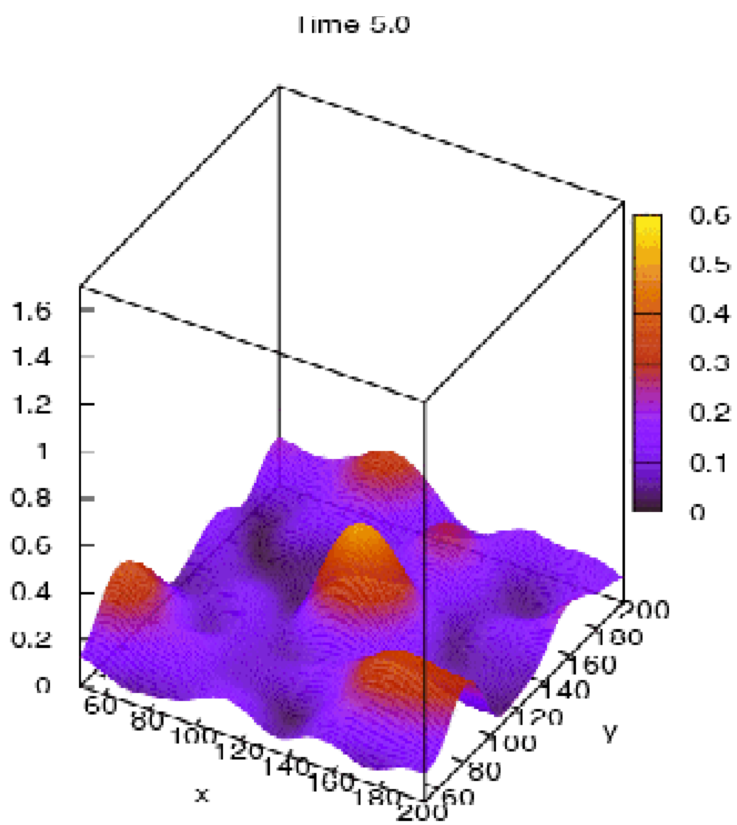

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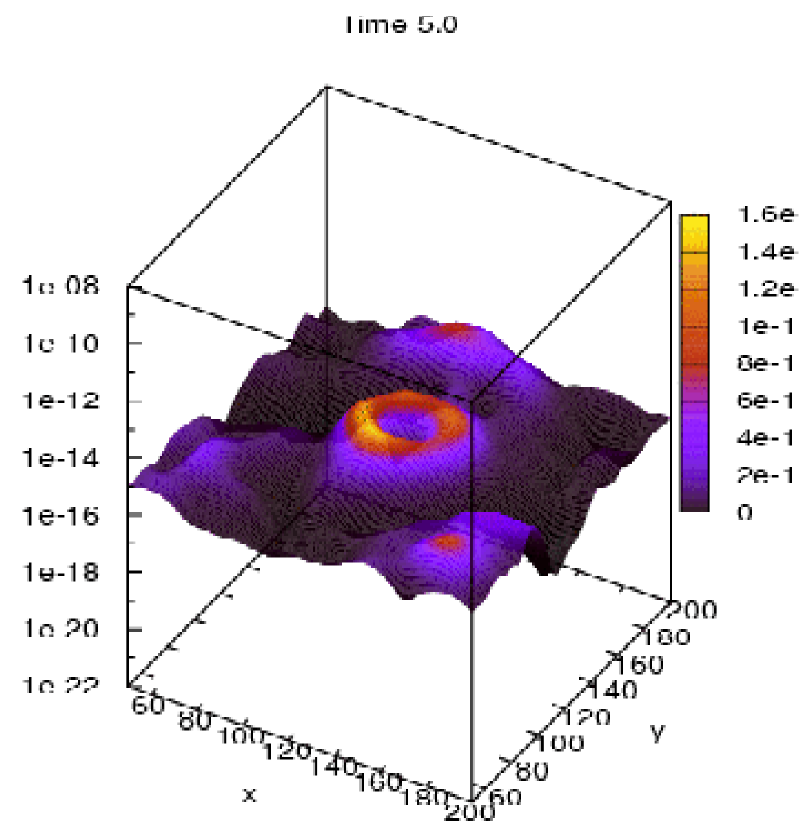

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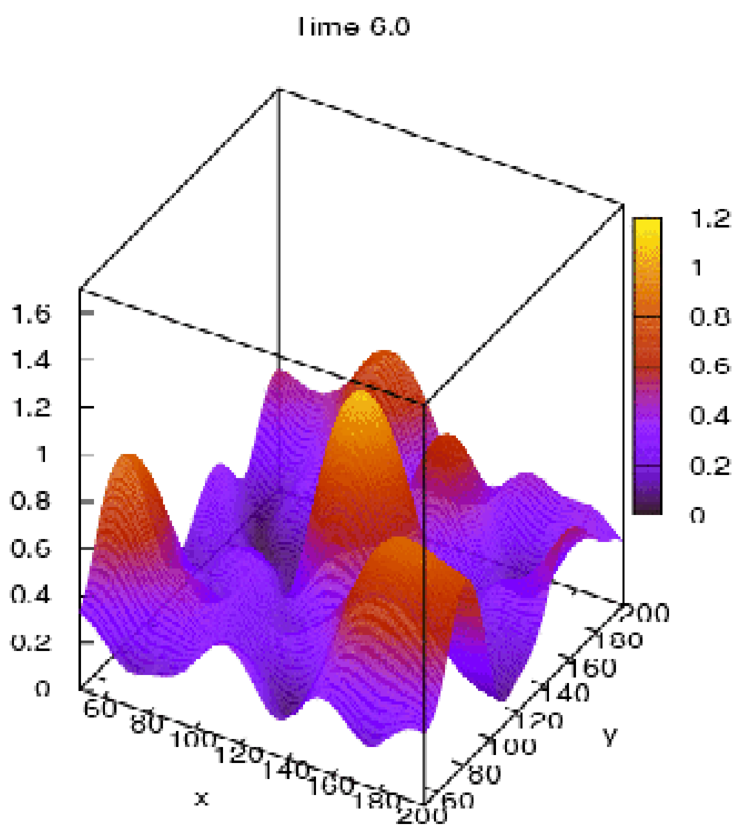

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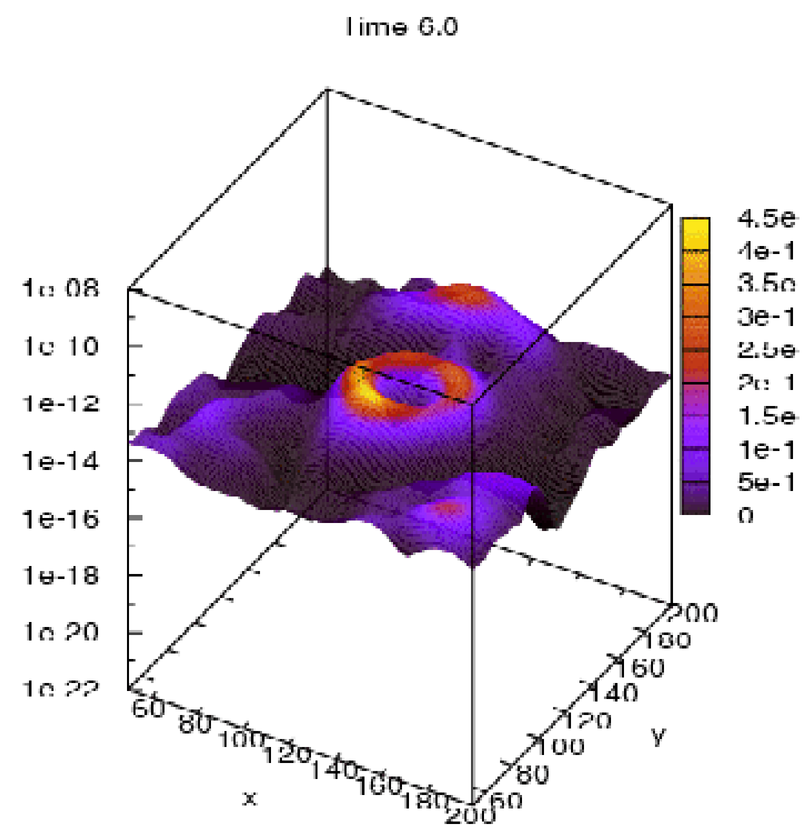

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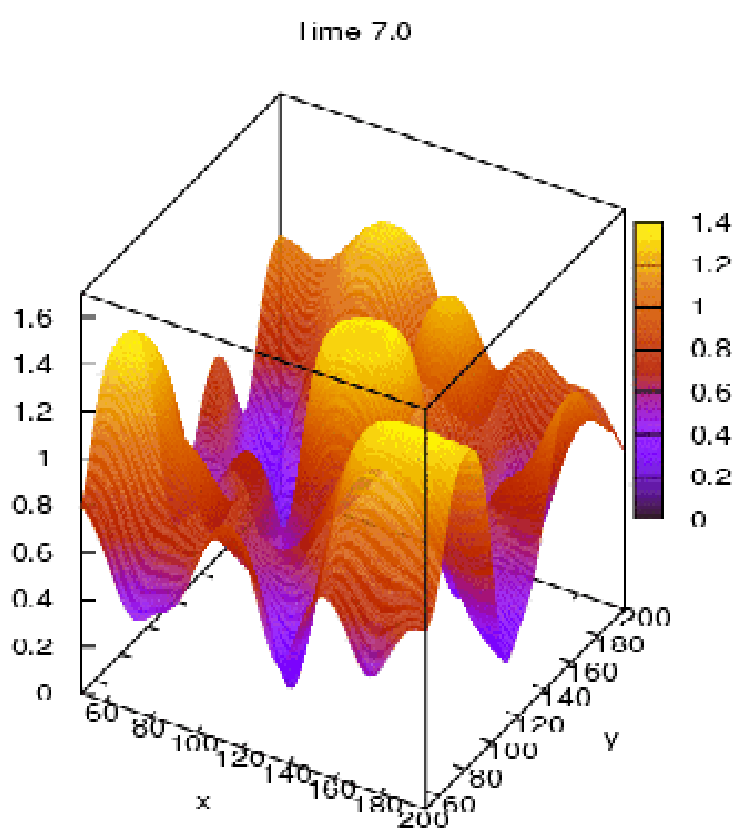

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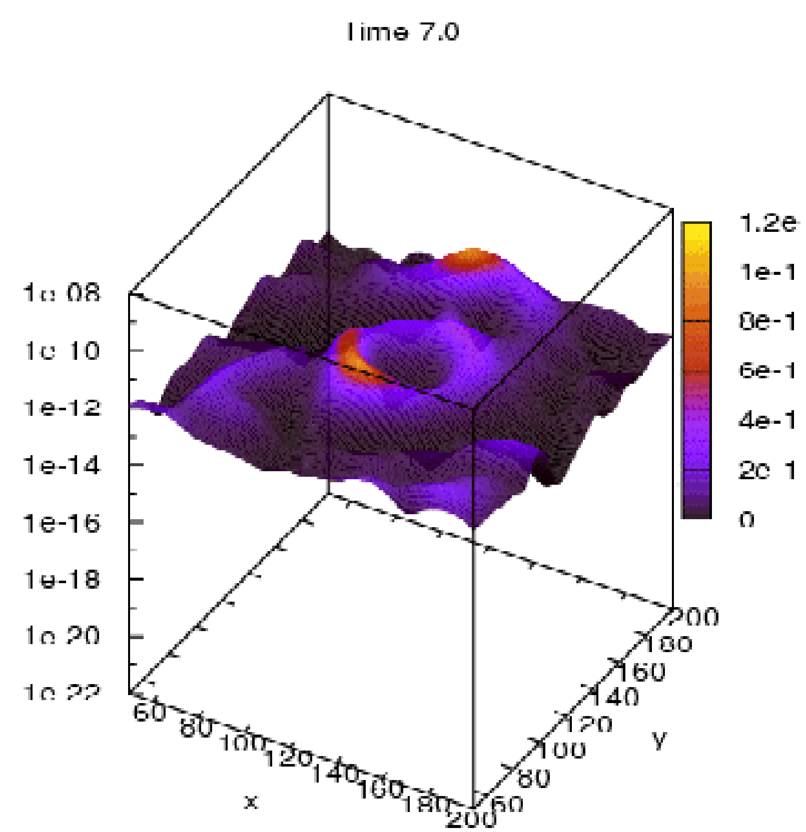

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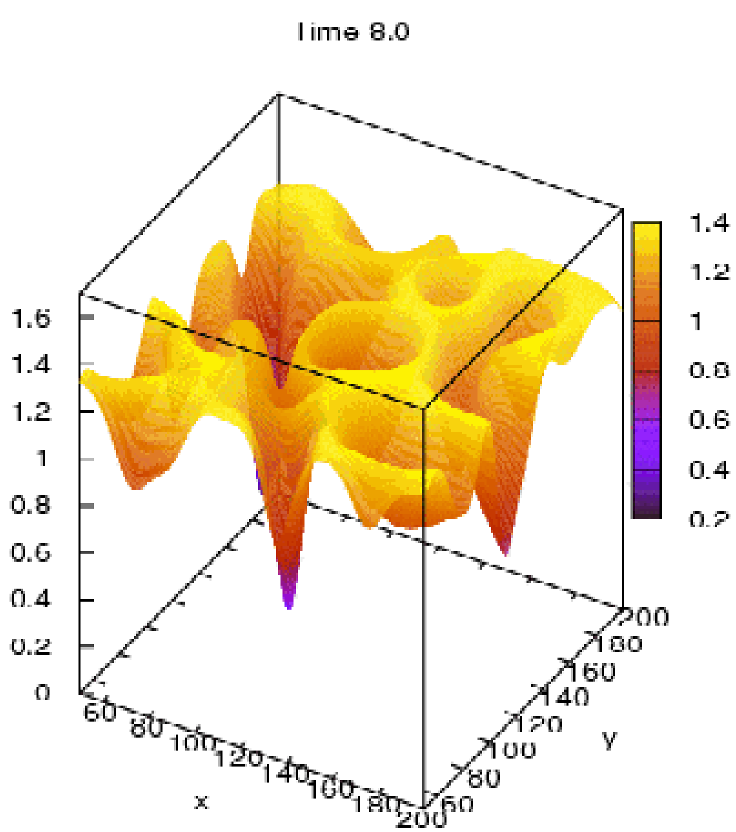

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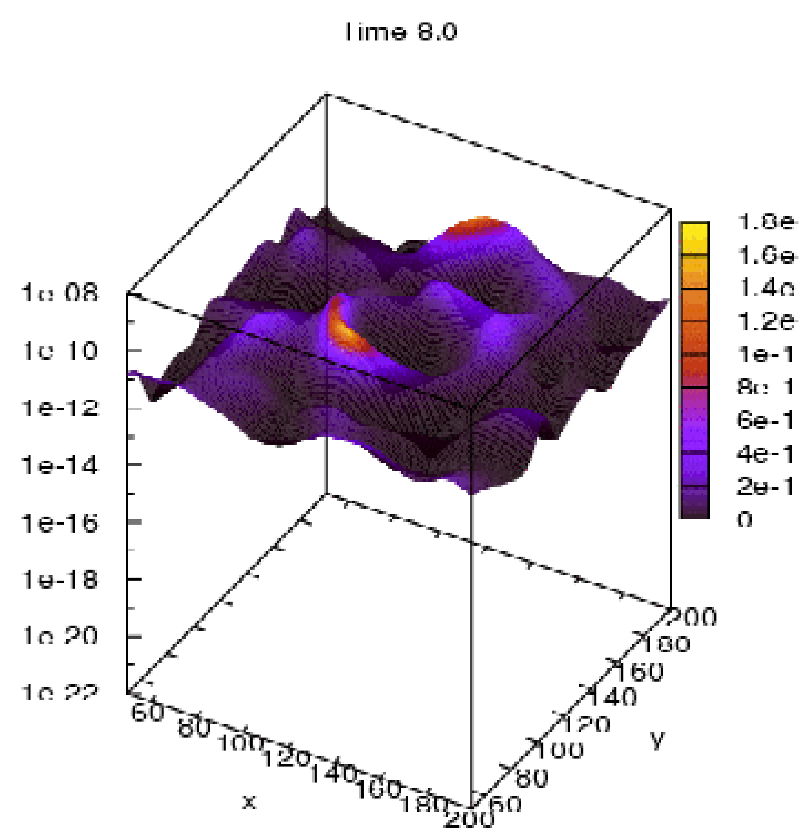

GW (Energy density)

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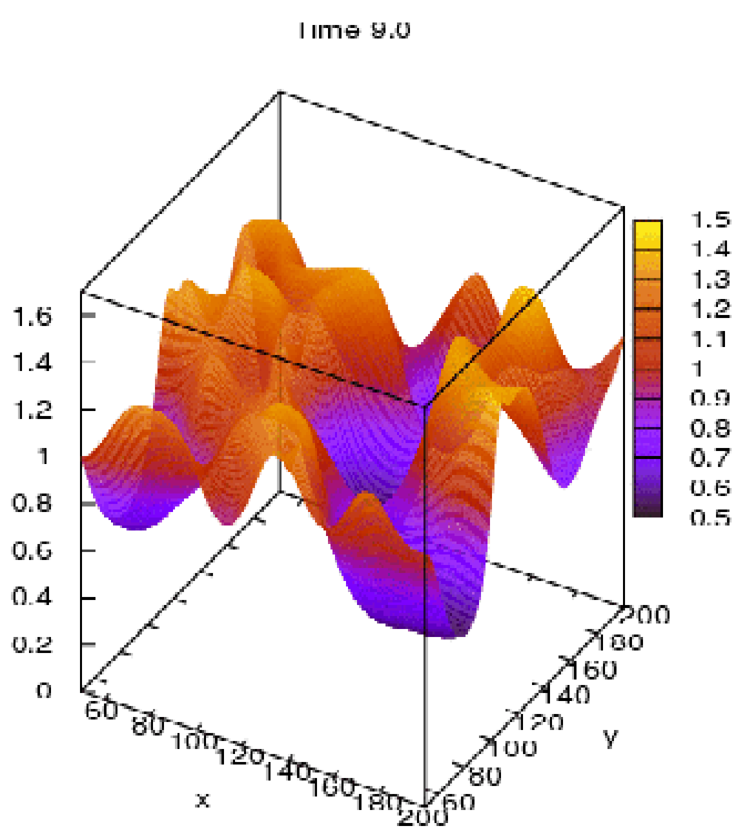

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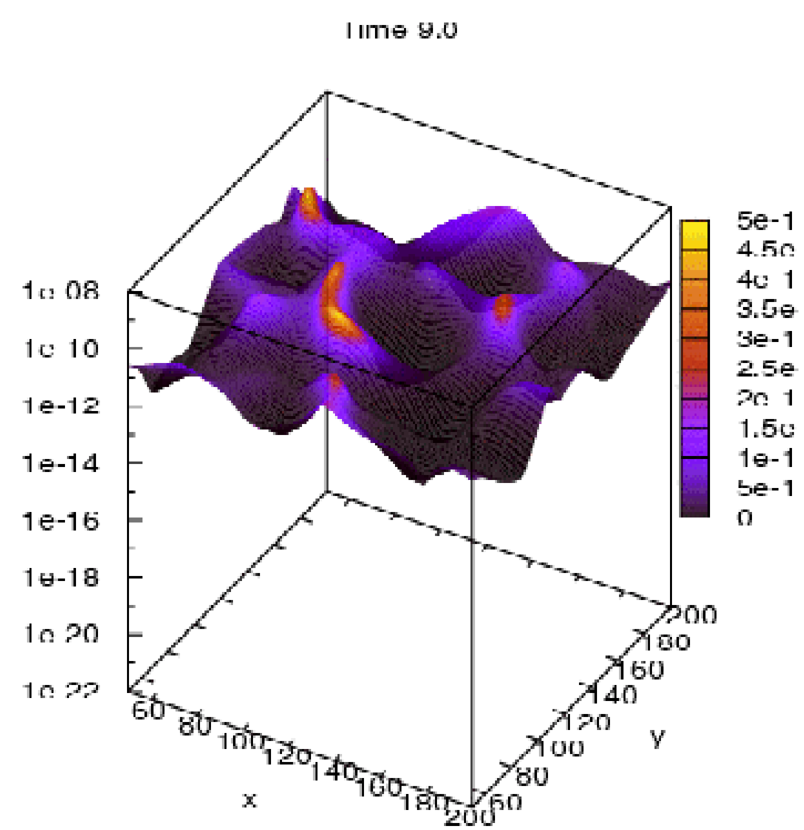

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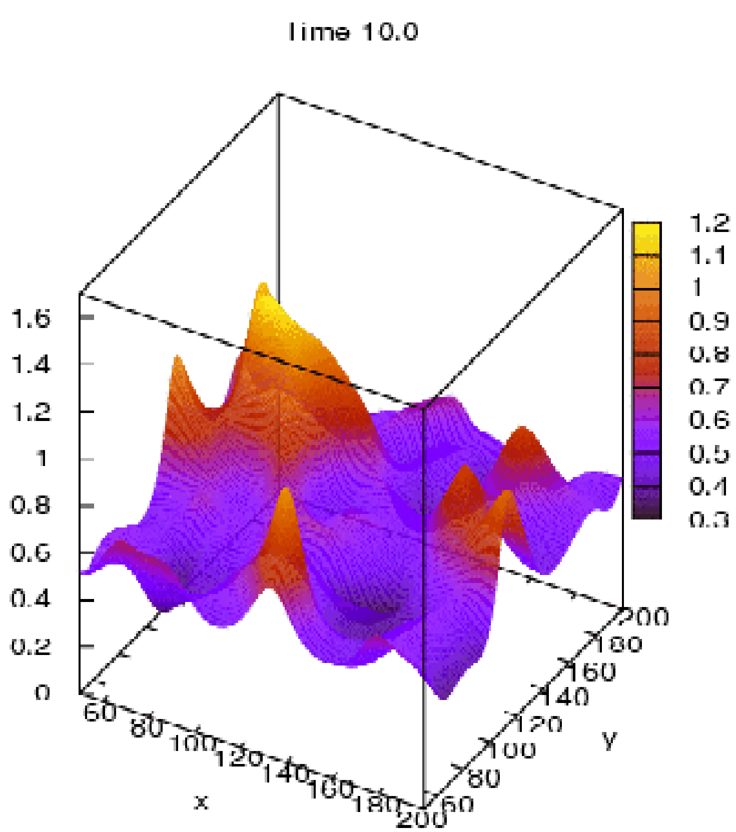

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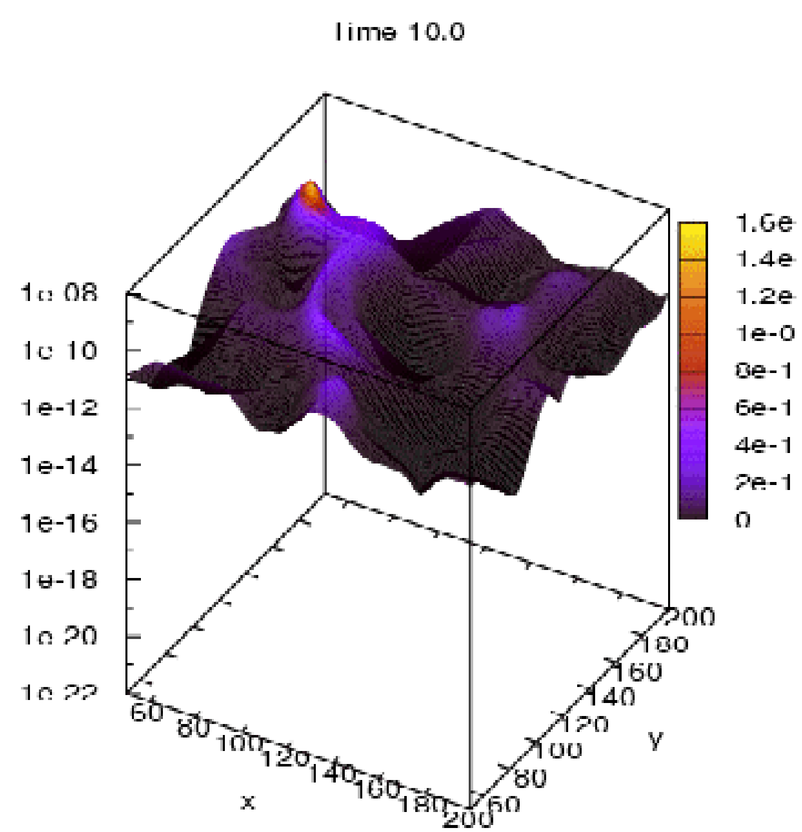

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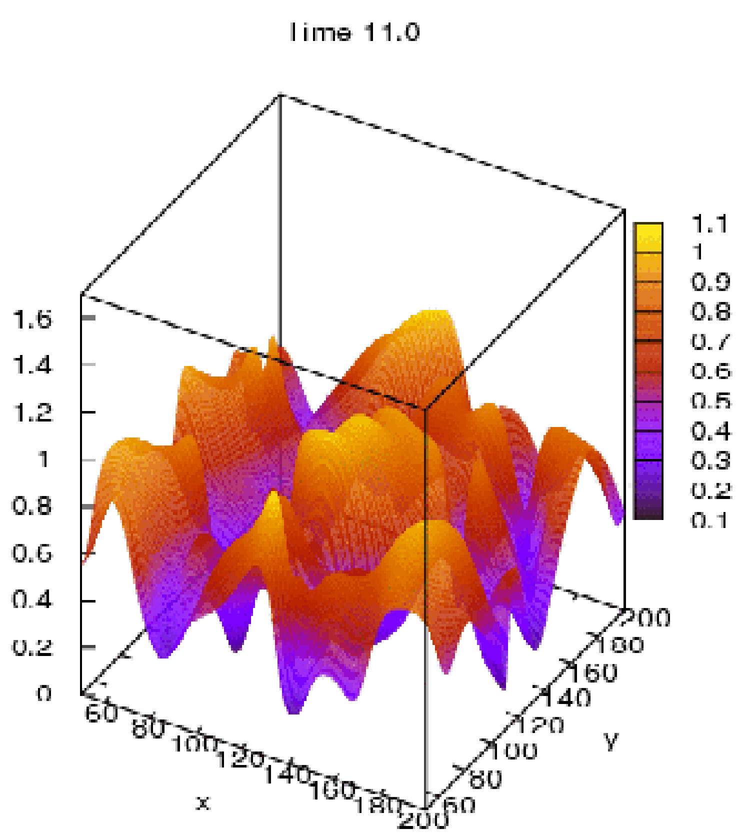
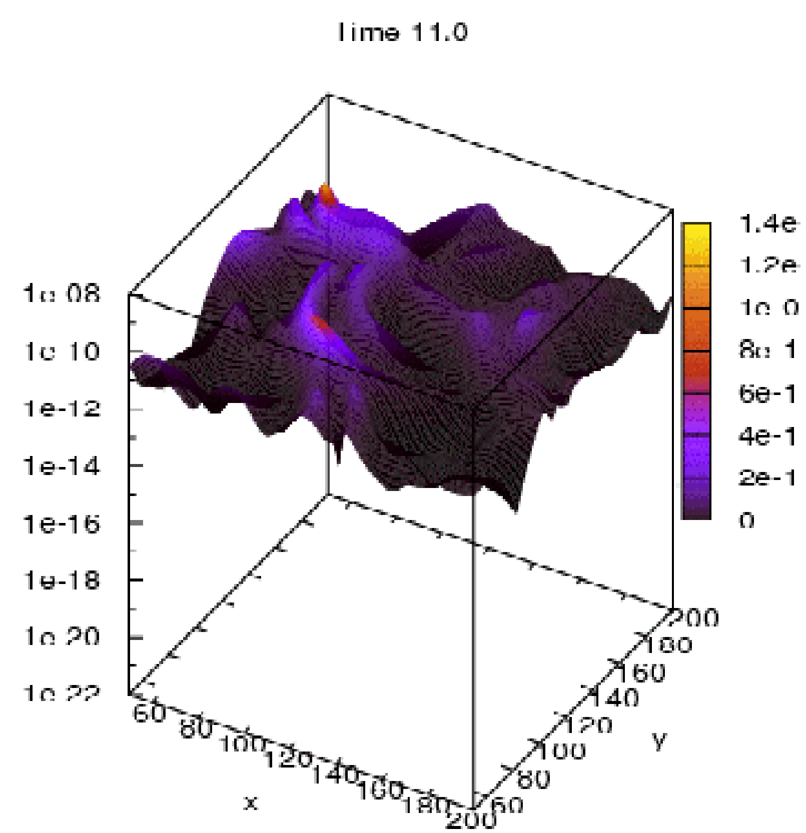
Animation by Alfonso Sastre



Higgs



GW (Energy density)

INFLATIONARY PREHEATING

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

Hybrid Preheating

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

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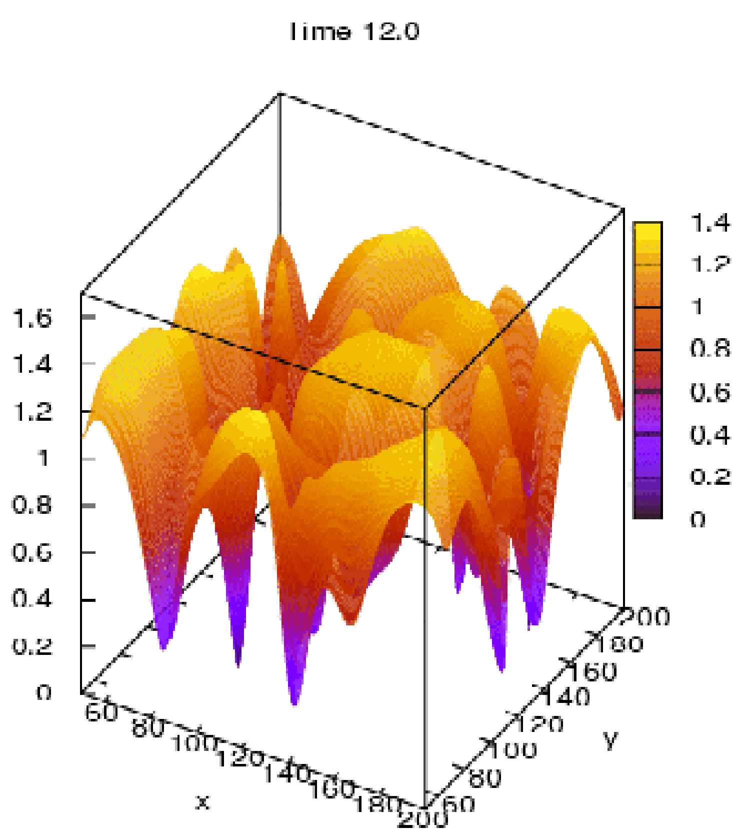
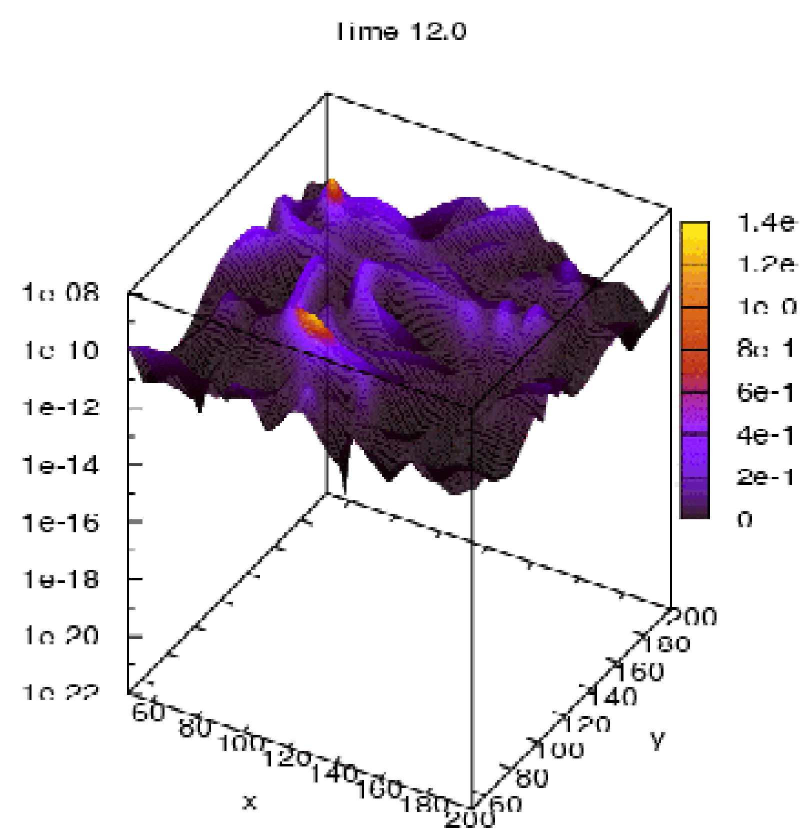


Higgs



GW (Energy density)

INFLATIONARY PREHEATING

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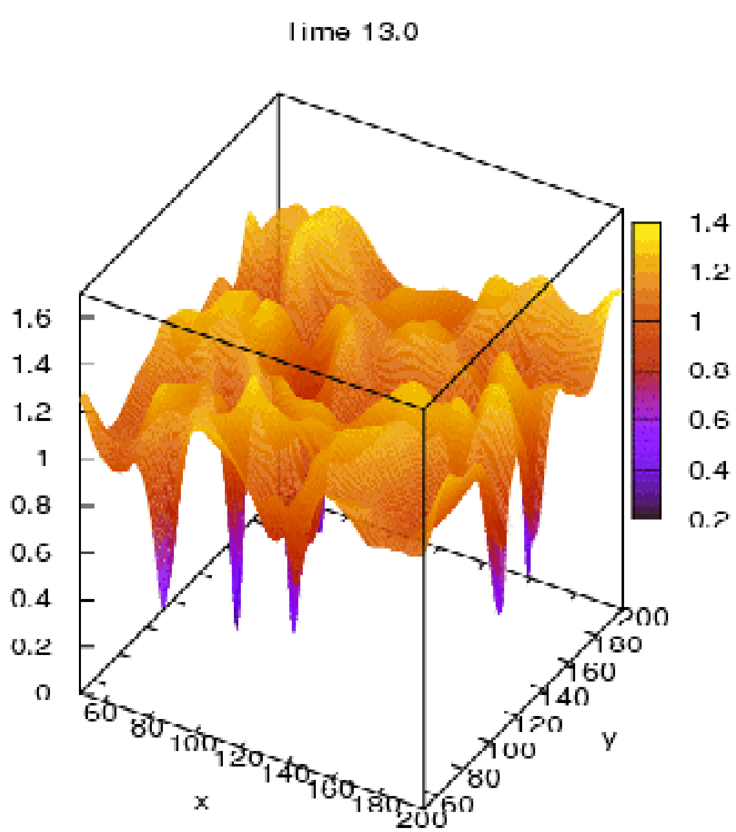
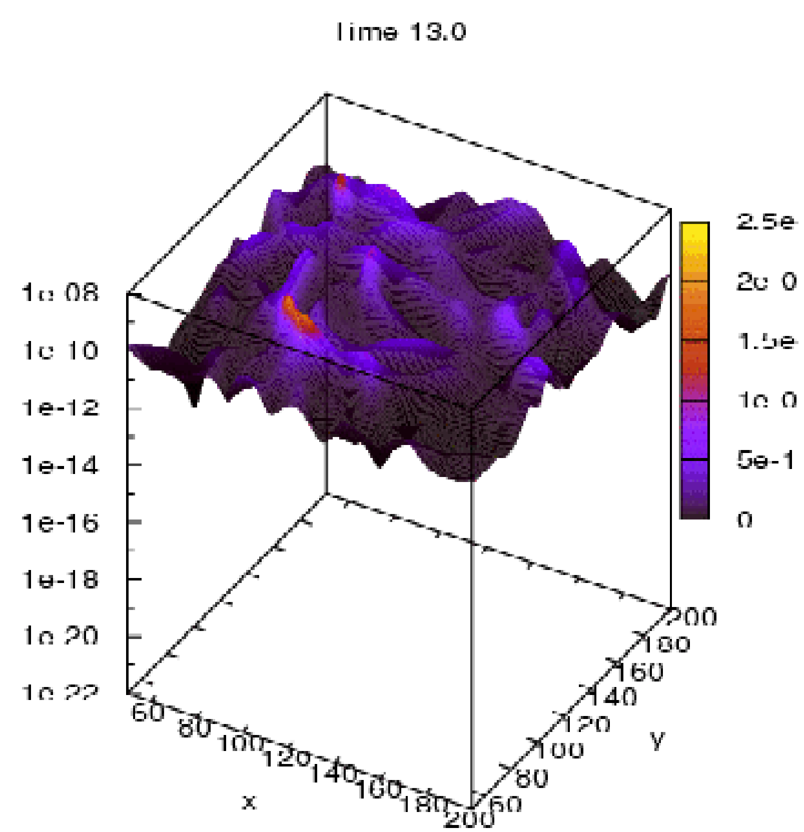
Animation by Alfonso Sastre



Higgs



GW **(Energy density)**

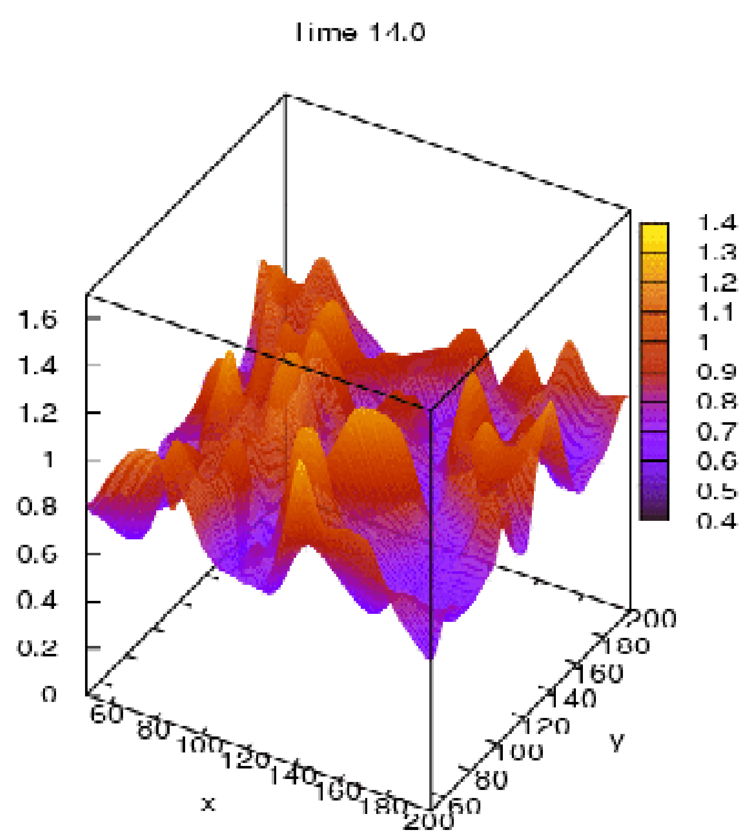
INFLATIONARY PREHEATING

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

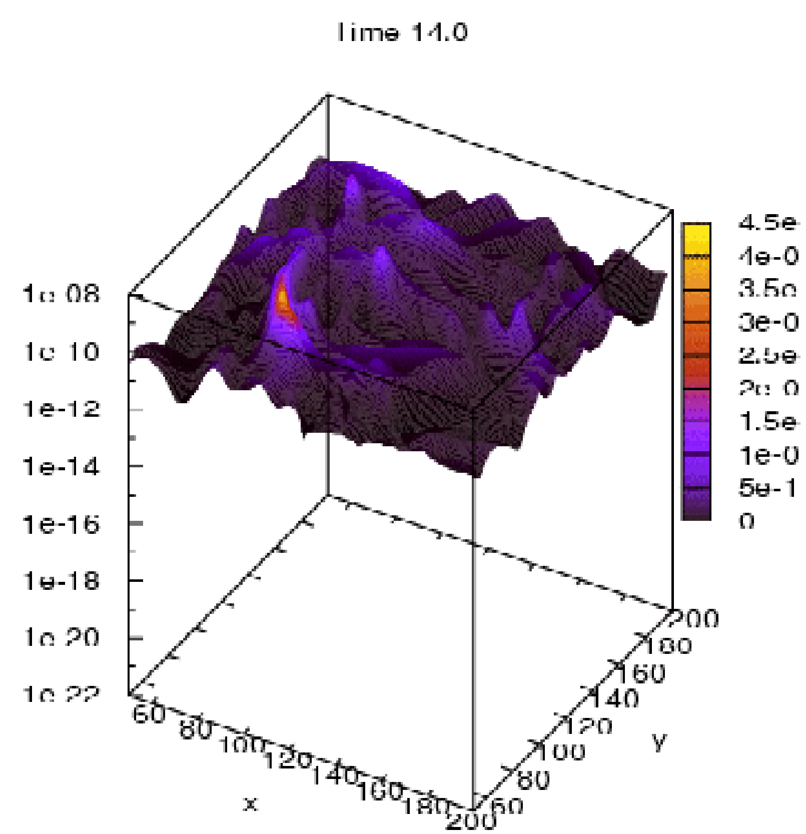
Hybrid Preheating

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

Animation by Alfonso Sastre



Higgs



GW **(Energy density)**

INFLATIONARY PREHEATING

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

Hybrid Preheating

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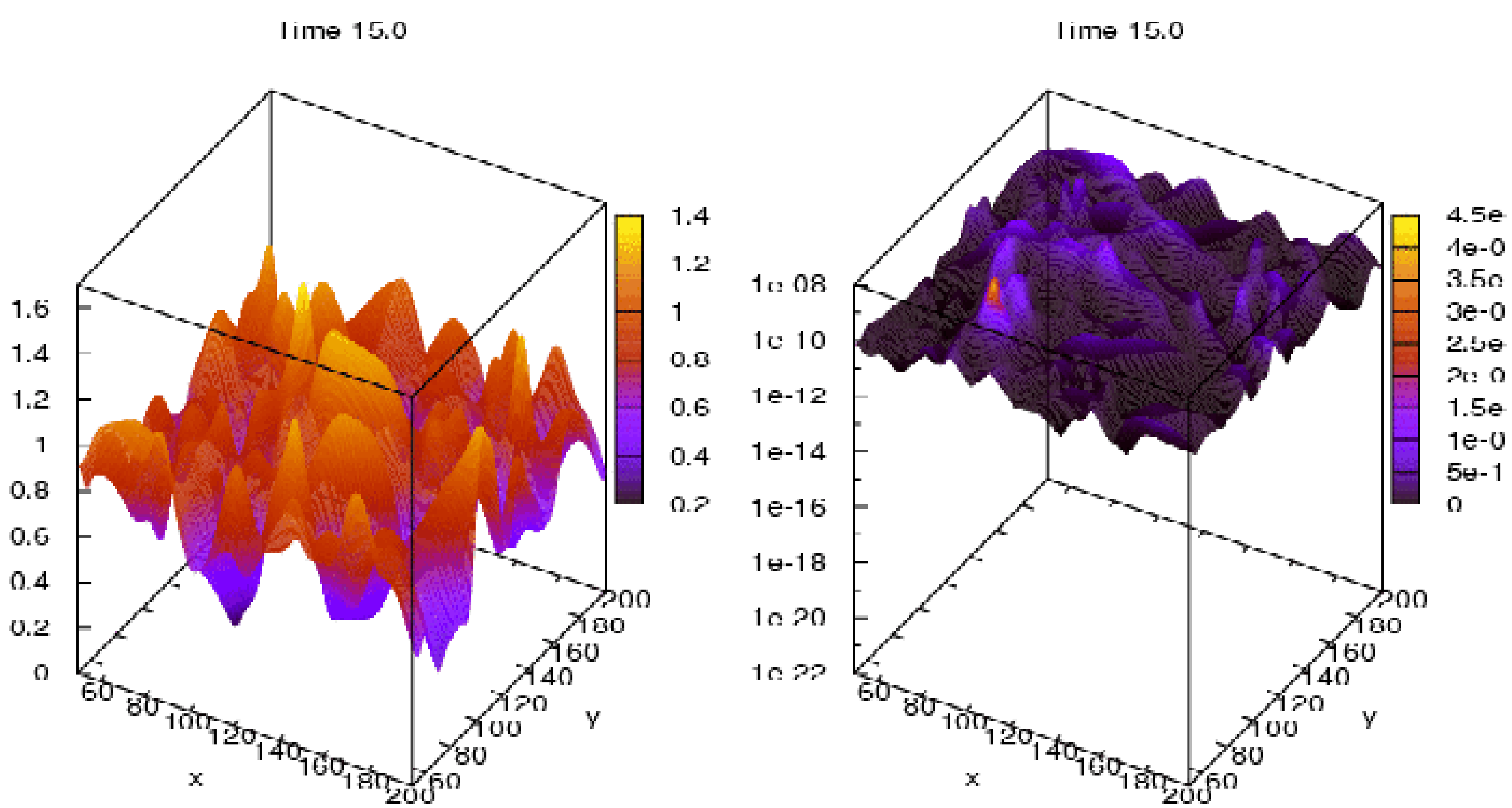
Animation by
Alfonso Sastre

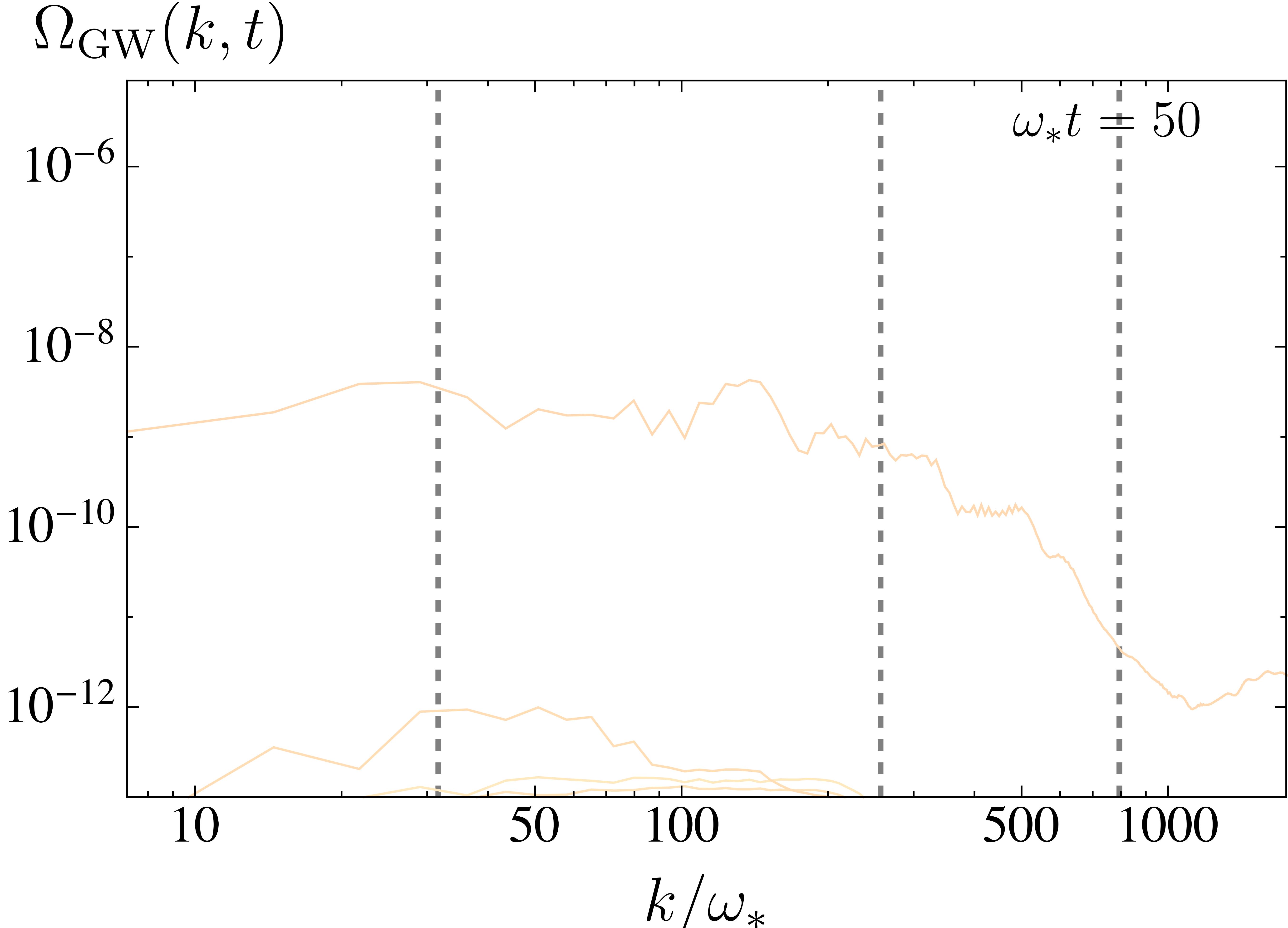


Higgs **GW** **(Energy density)**

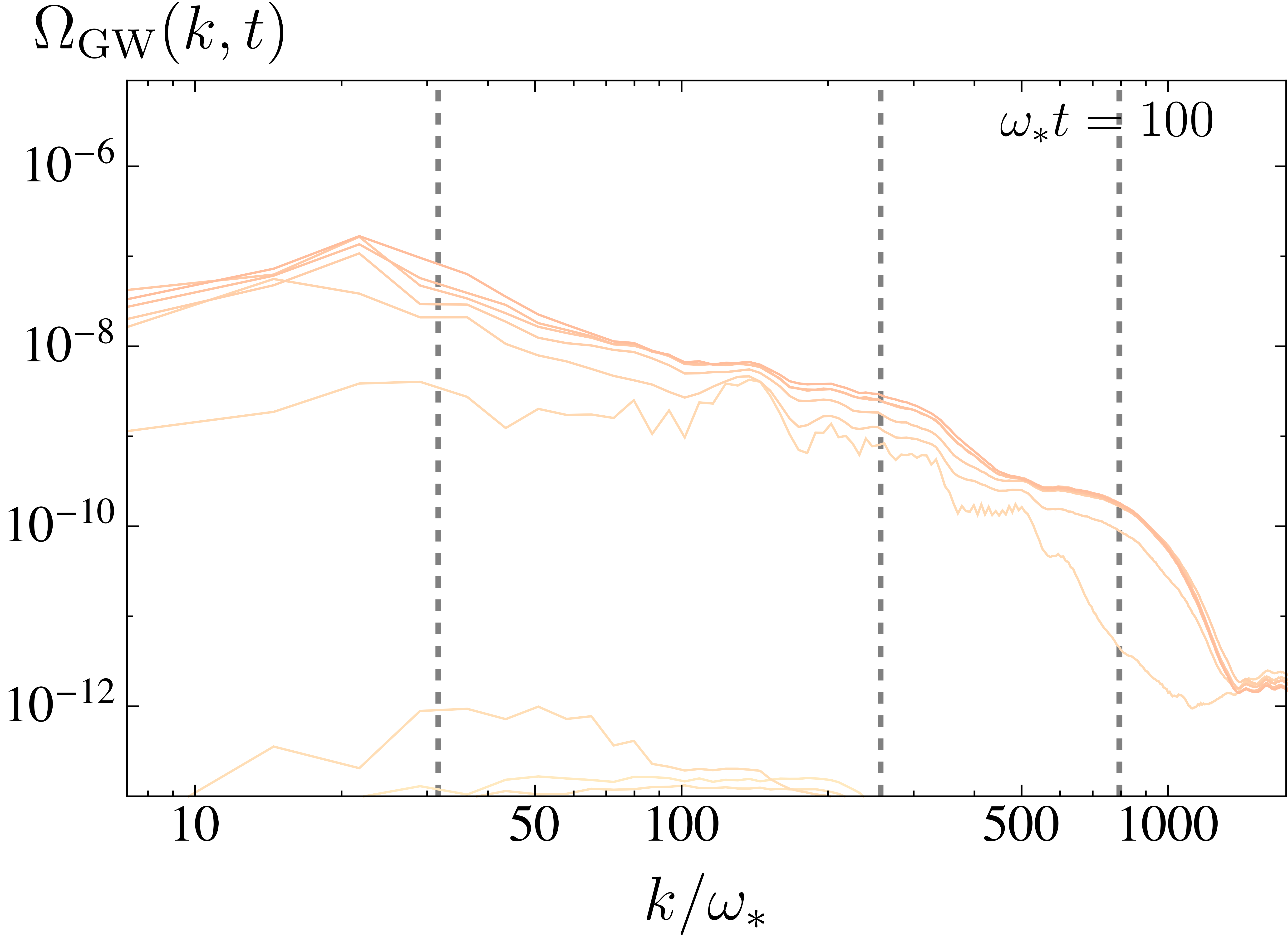
Three-peak signature
(three preheat flds)

$$V(\phi) \;+\; \frac{1}{2}g_1^2\phi^2\chi_1^2 \;+\; \frac{1}{2}g_2^2\phi^2\chi_2^2 \;+\; \frac{1}{2}g_3^2\phi^2\chi_3^2$$

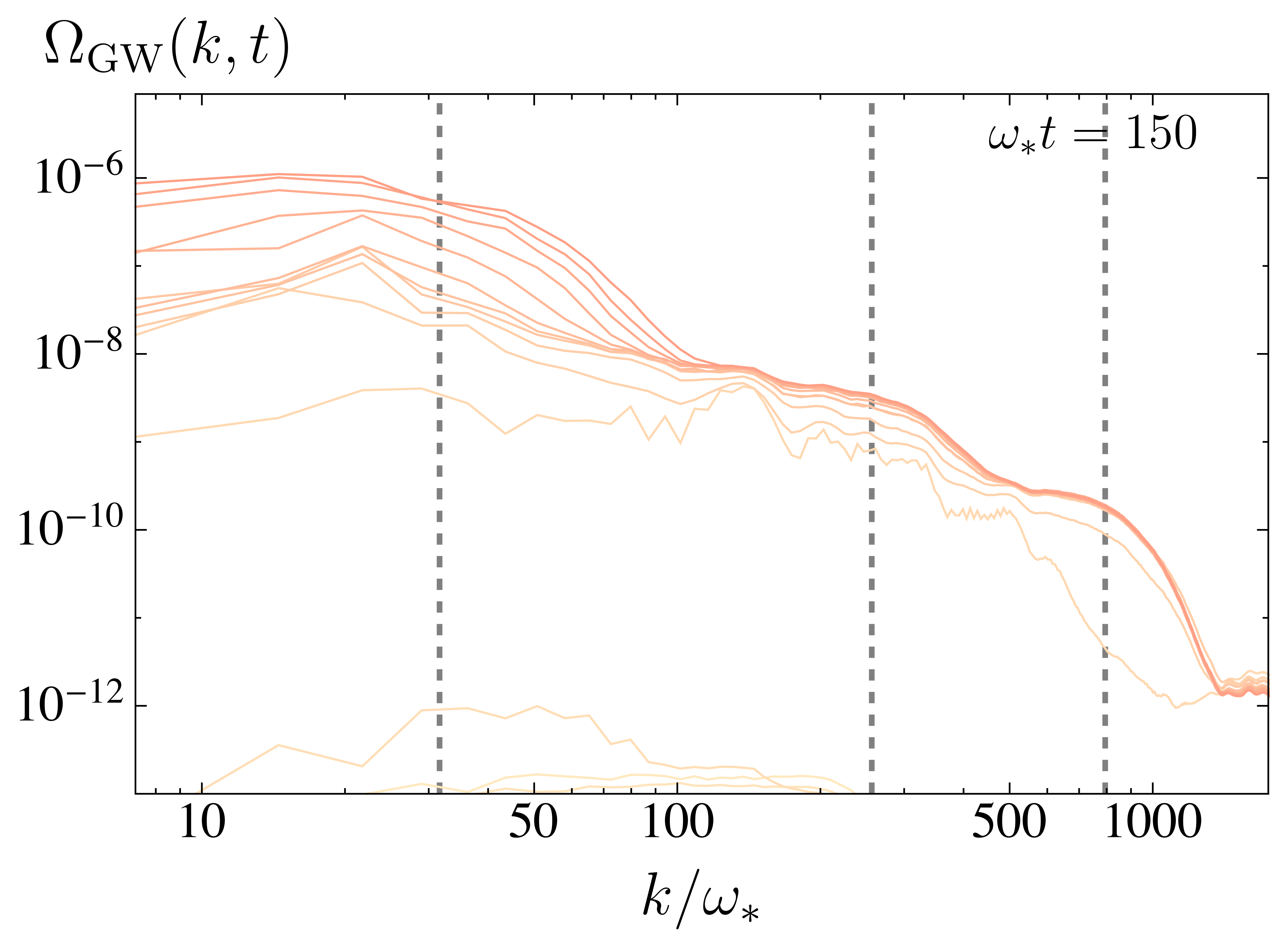
ANIMATION
(by Nico Loayza)

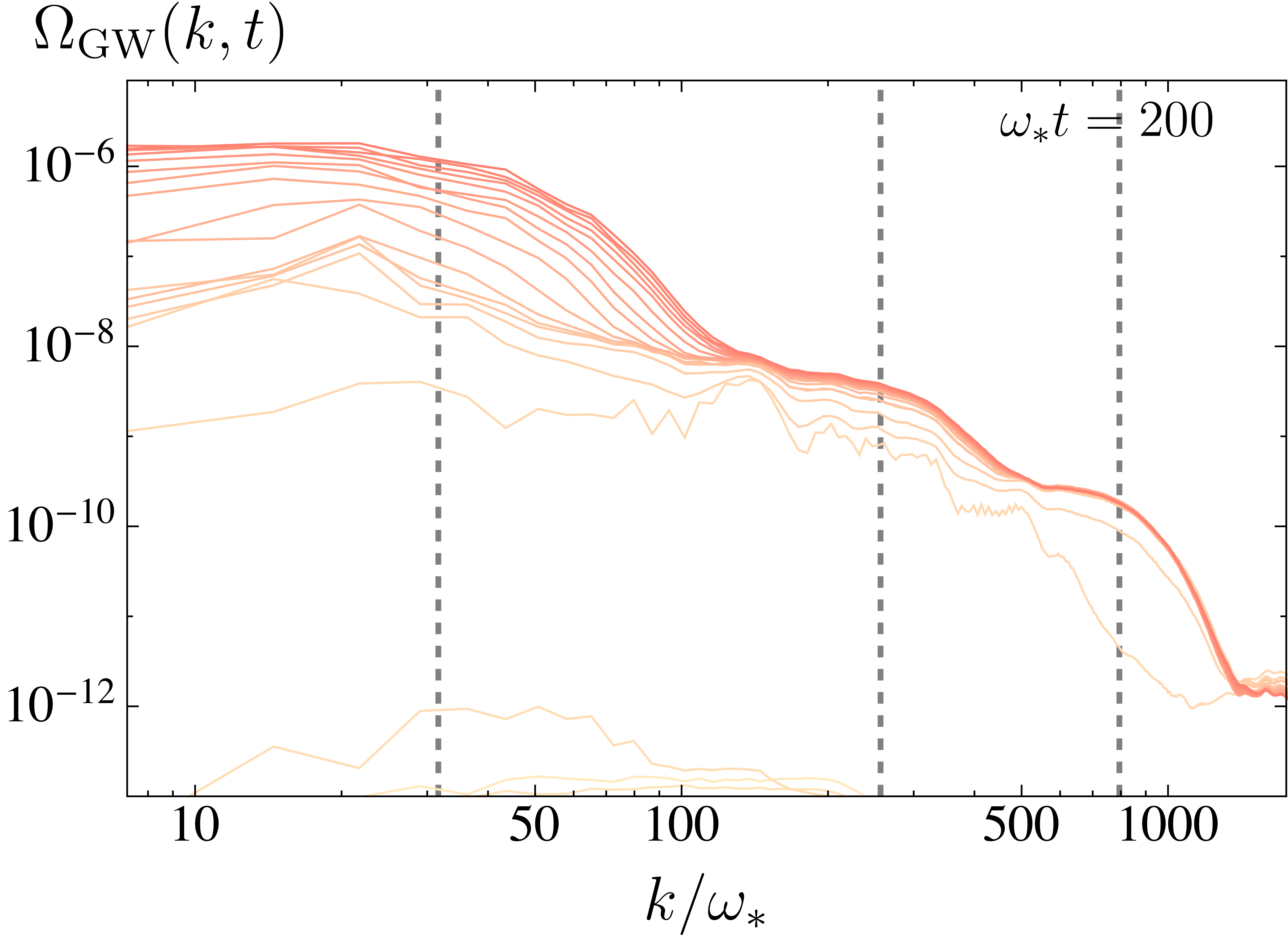


$\Omega_{\mathrm{GW}}(k,t)$
$\omega_* t = 50$
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10
50
100
500
1000
k/ω_*

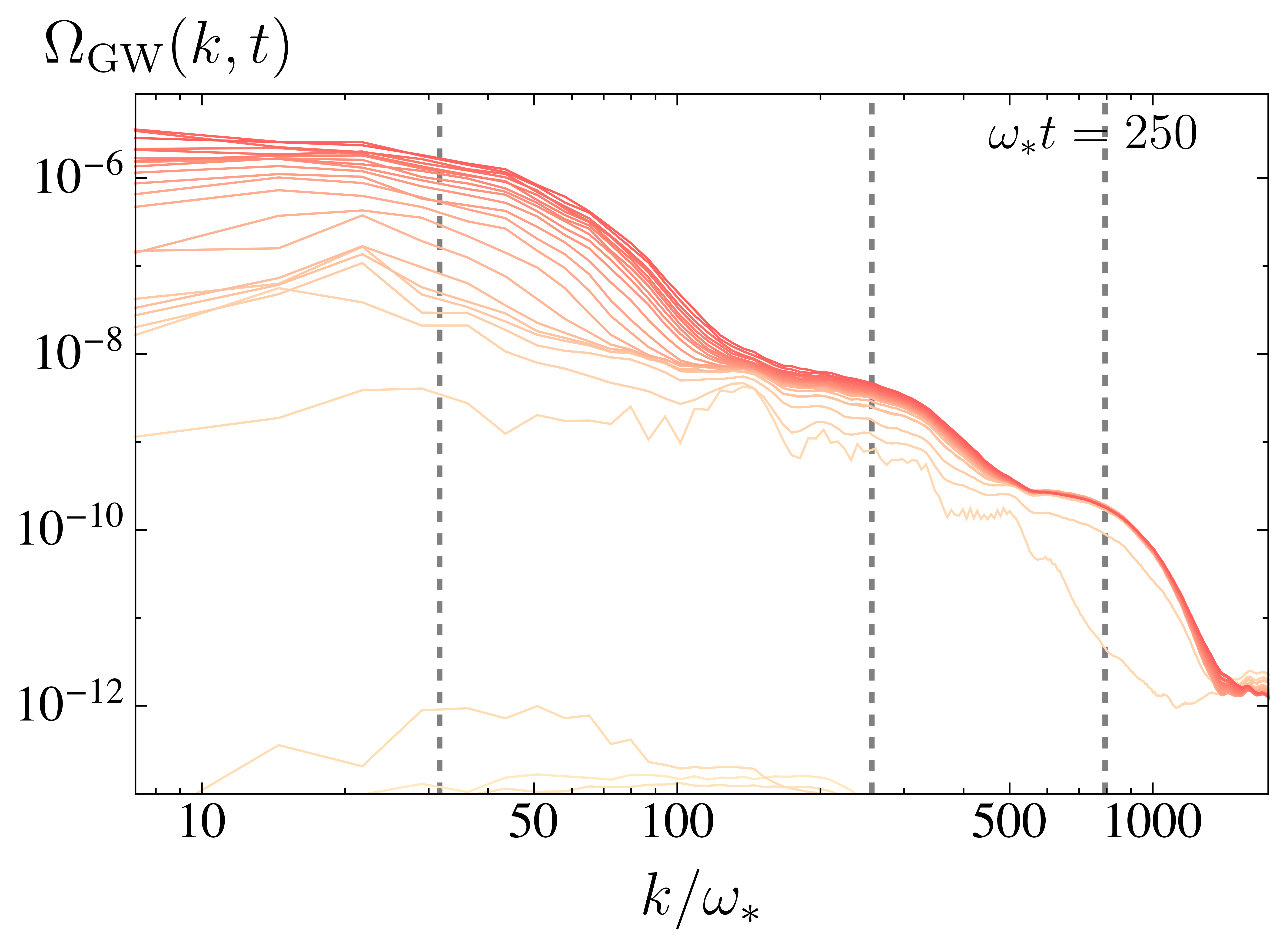


$\Omega_{\rm GW}(k,t)$
$\omega_* t = 100$
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10
50
100
500
1000
k/ω_*

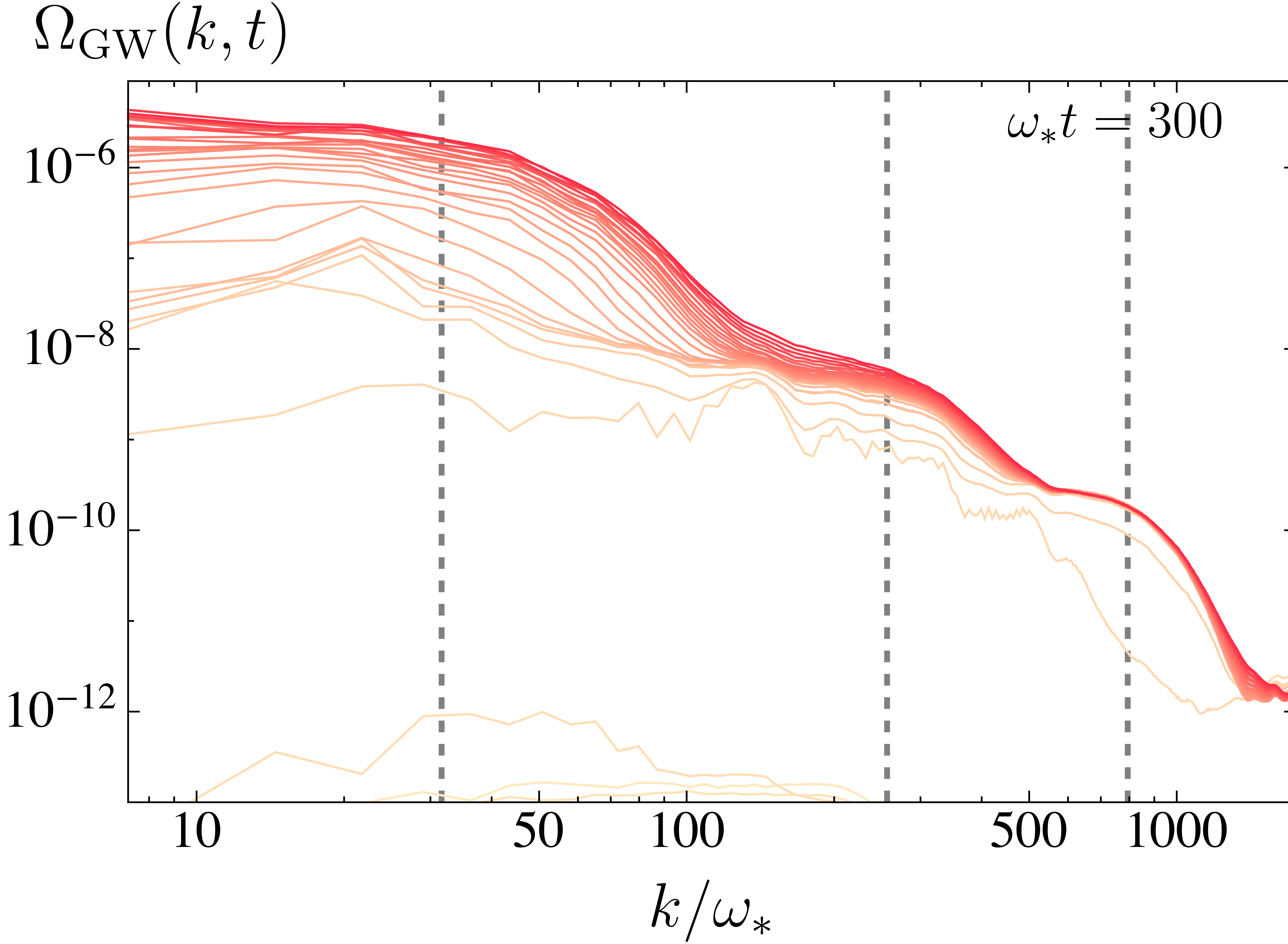

$\Omega_{\rm GW}(k,t)$
$\omega_* t = 150$
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10
50
100
500
1000
k/ω_*



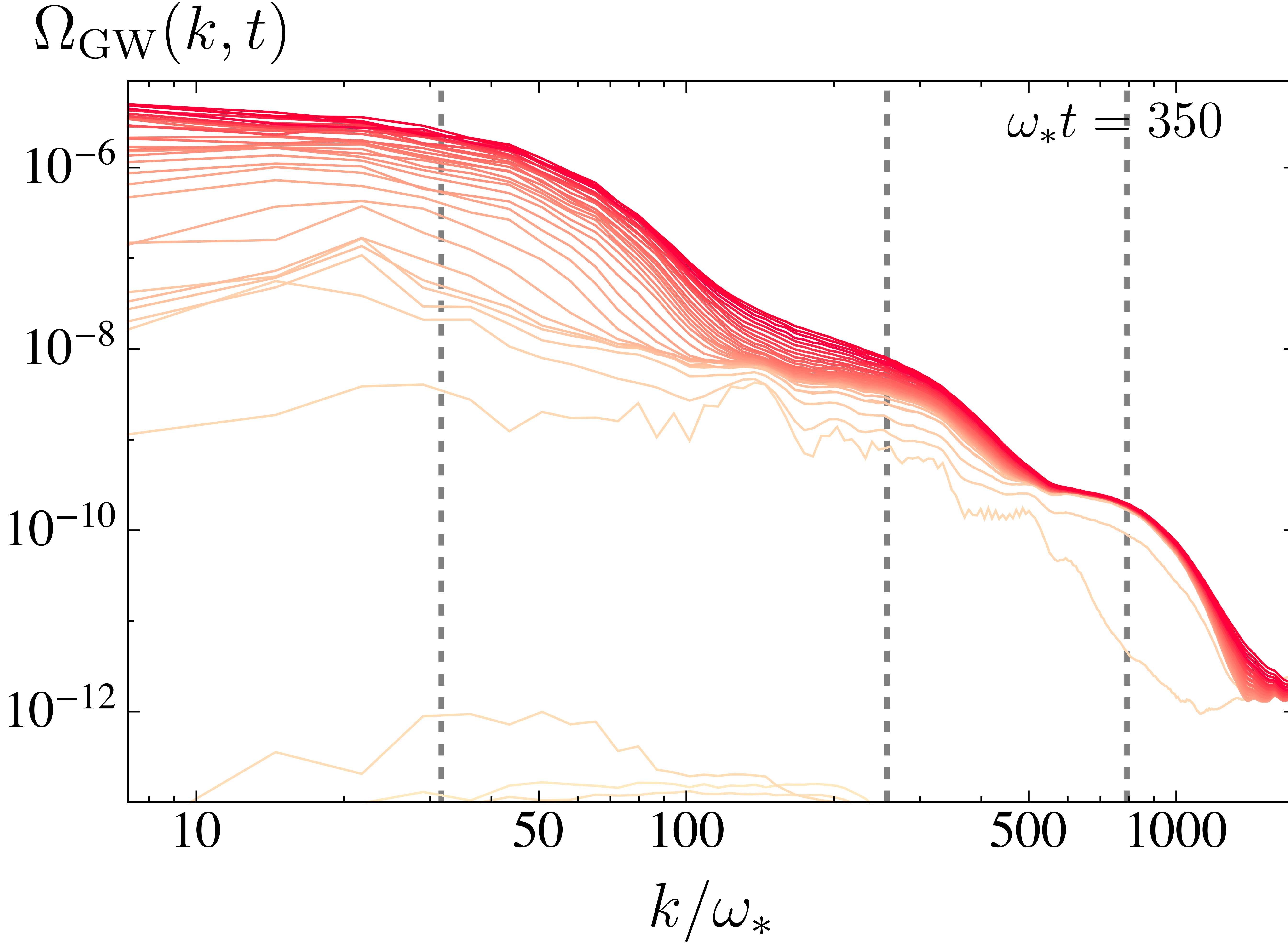
$\Omega_{\rm GW}(k,t)$
$\omega_* t = 200$
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10
50
100
500
1000
k/ω_*

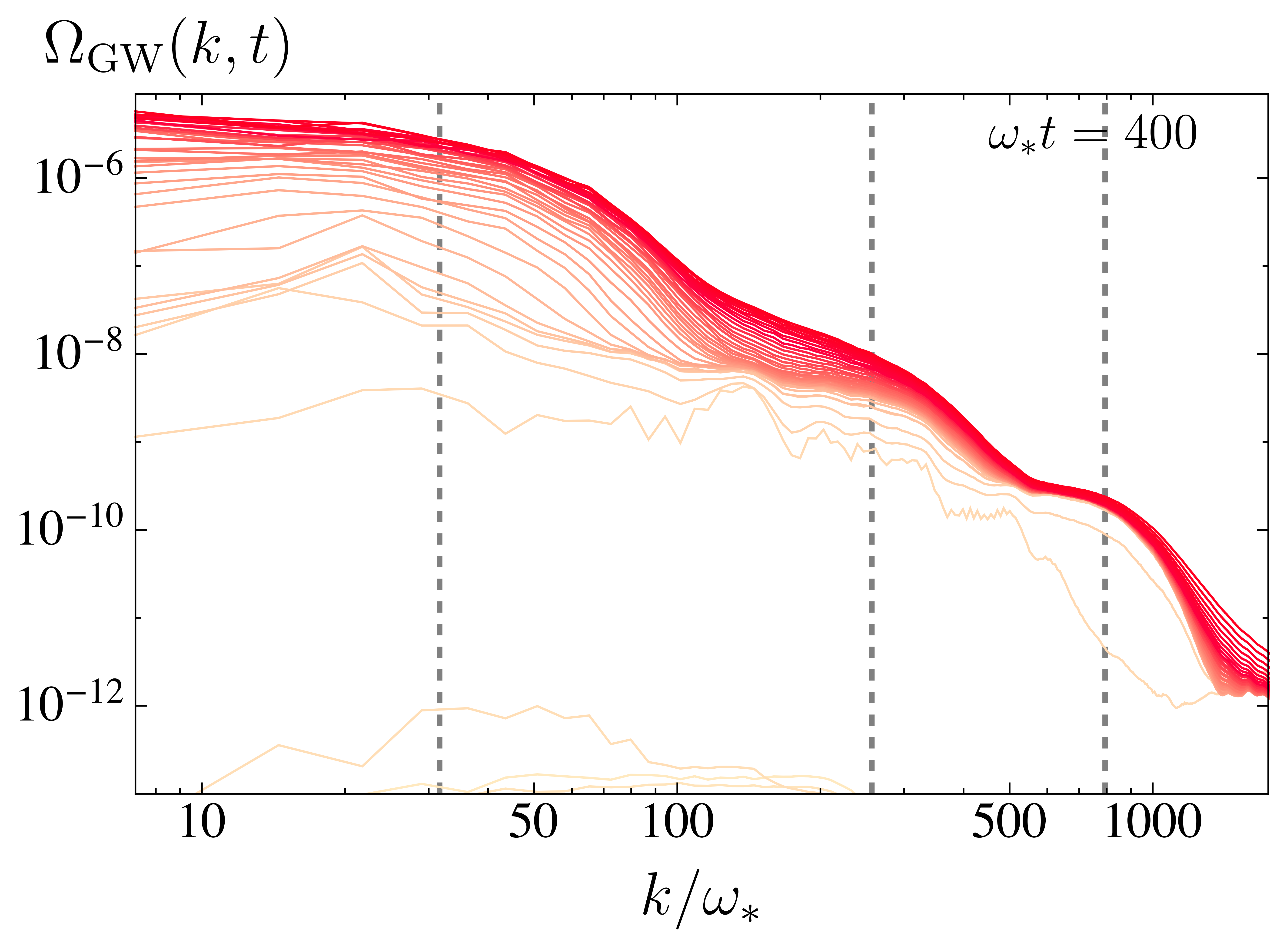


$\Omega_{\rm GW}(k,t)$
$\omega_* t = 250$
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10
50
100
500
1000
k/ω_*

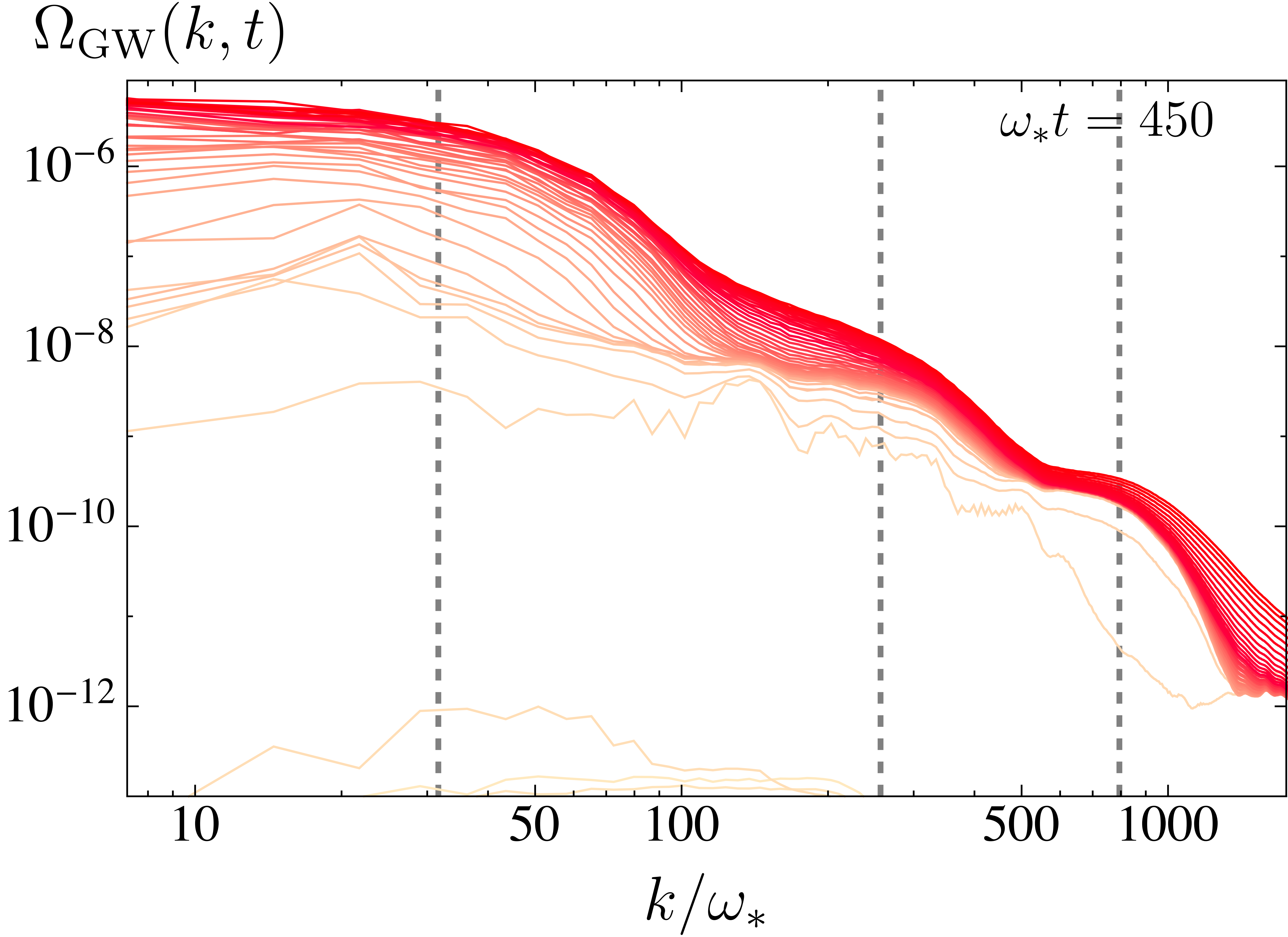


$\Omega_{\rm GW}(k,t)$
$\omega_* t = 300$
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10
50
100
500
1000
k/ω_*

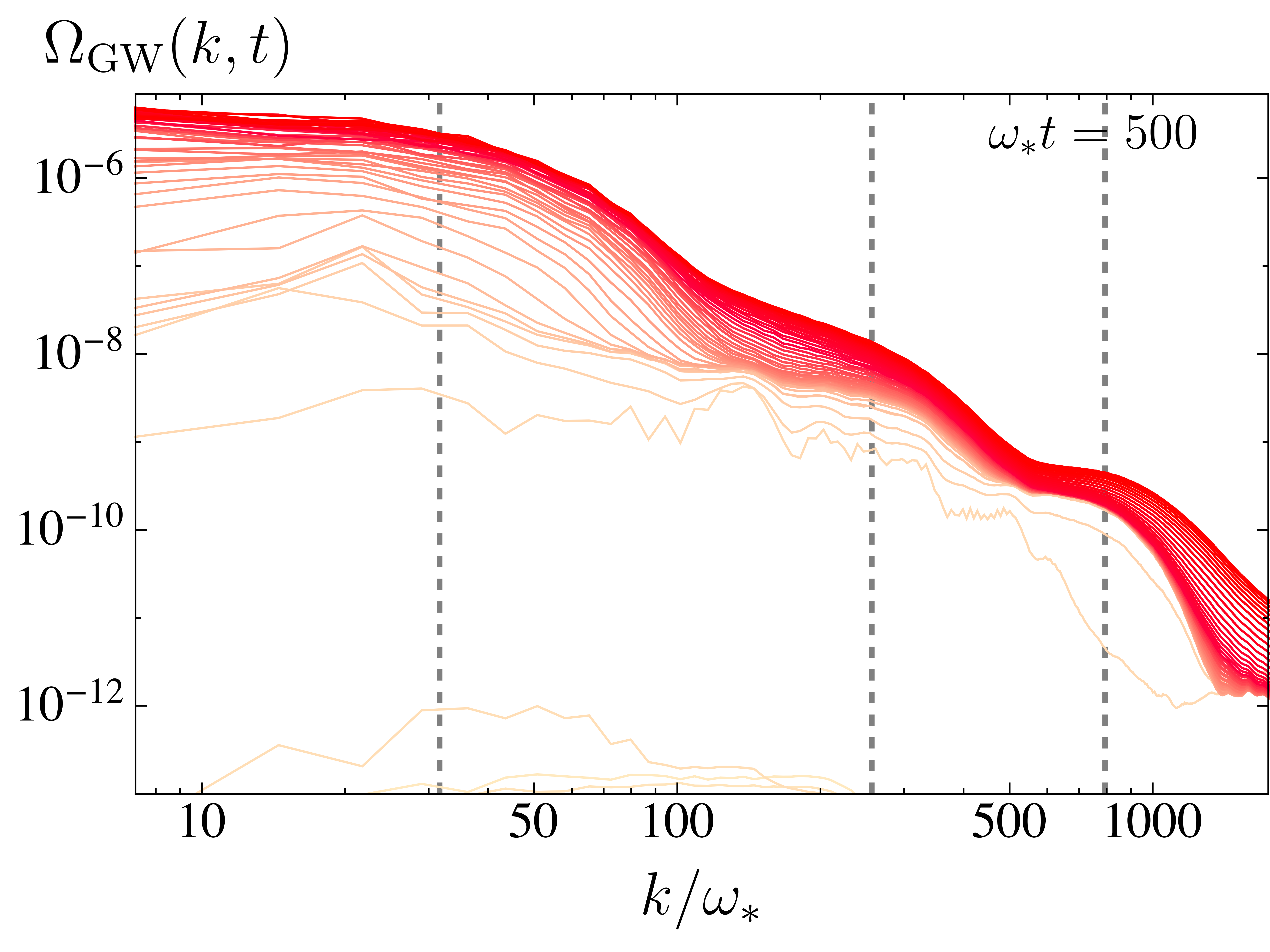

$\Omega_{\rm GW}(k,t)$
$\omega_* t = 350$
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10
50
100
500
1000
k/ω_*



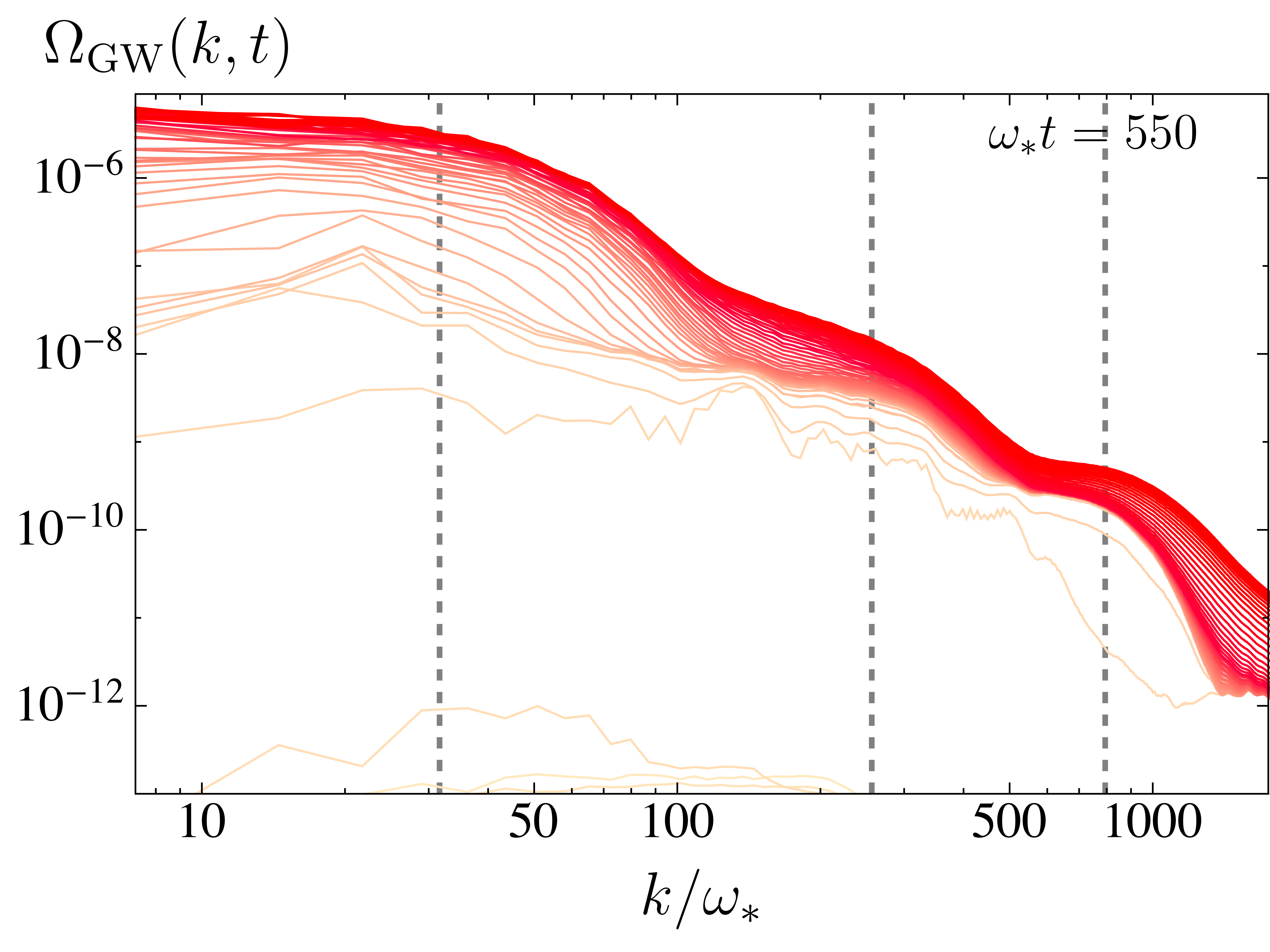
$\Omega_{\rm GW}(k,t)$
$\omega_* t = 400$
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10
50
100
500
1000
k/ω_*



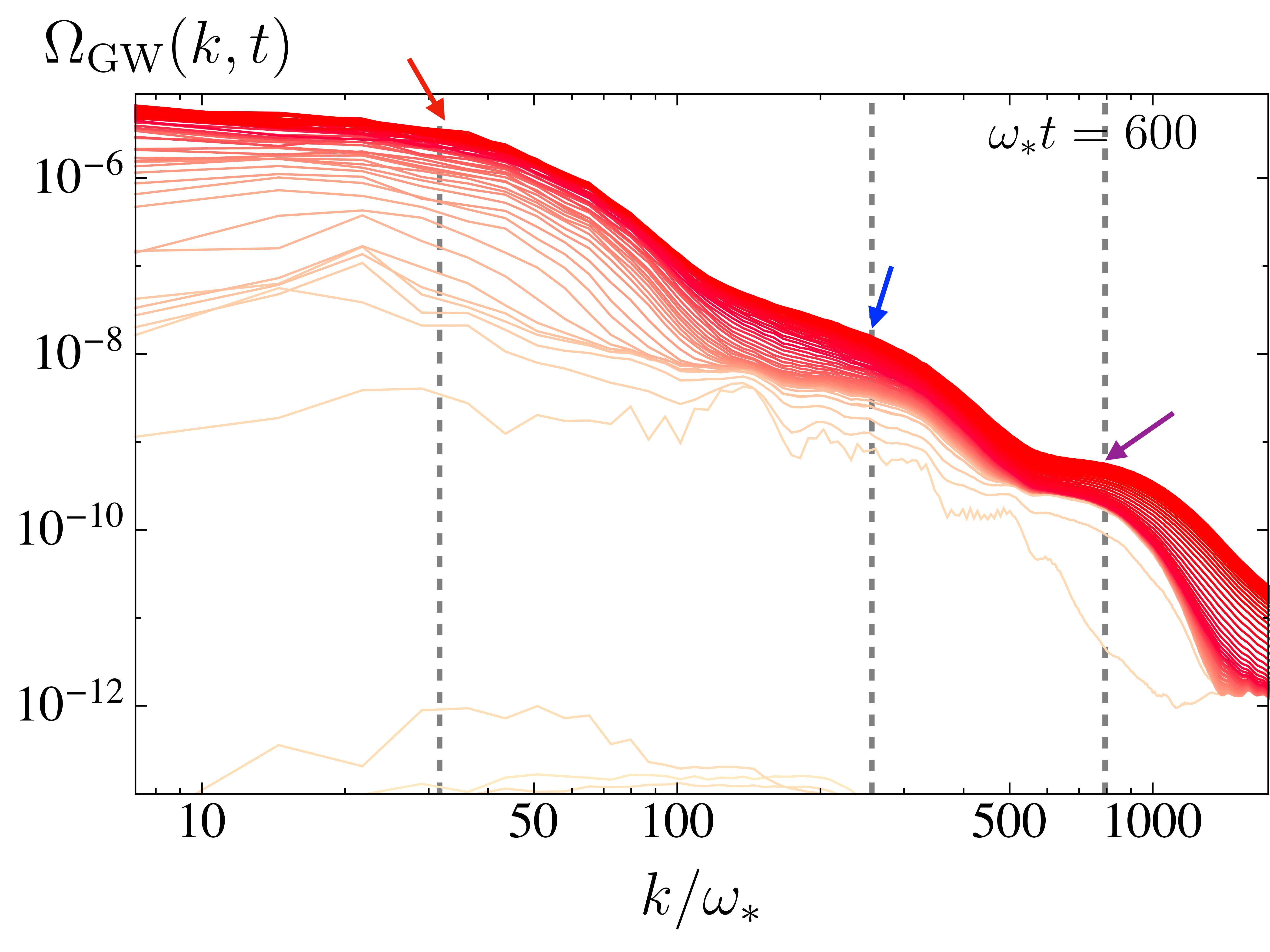
$\Omega_{\rm GW}(k,t)$
$\omega_* t = 450$
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10
50
100
500
1000
k/ω_*



$\Omega_{\rm GW}(k,t)$
$\omega_* t = 500$
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10
50
100
500
1000
k/ω_*



$\Omega_{\rm GW}(k,t)$
$\omega_* t = 550$
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10
50
100
500
1000
k/ω_*



$\Omega_{\rm GW}(k,t)$
$\omega_* t = 600$
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10
50
100
500
1000
k/ω_*