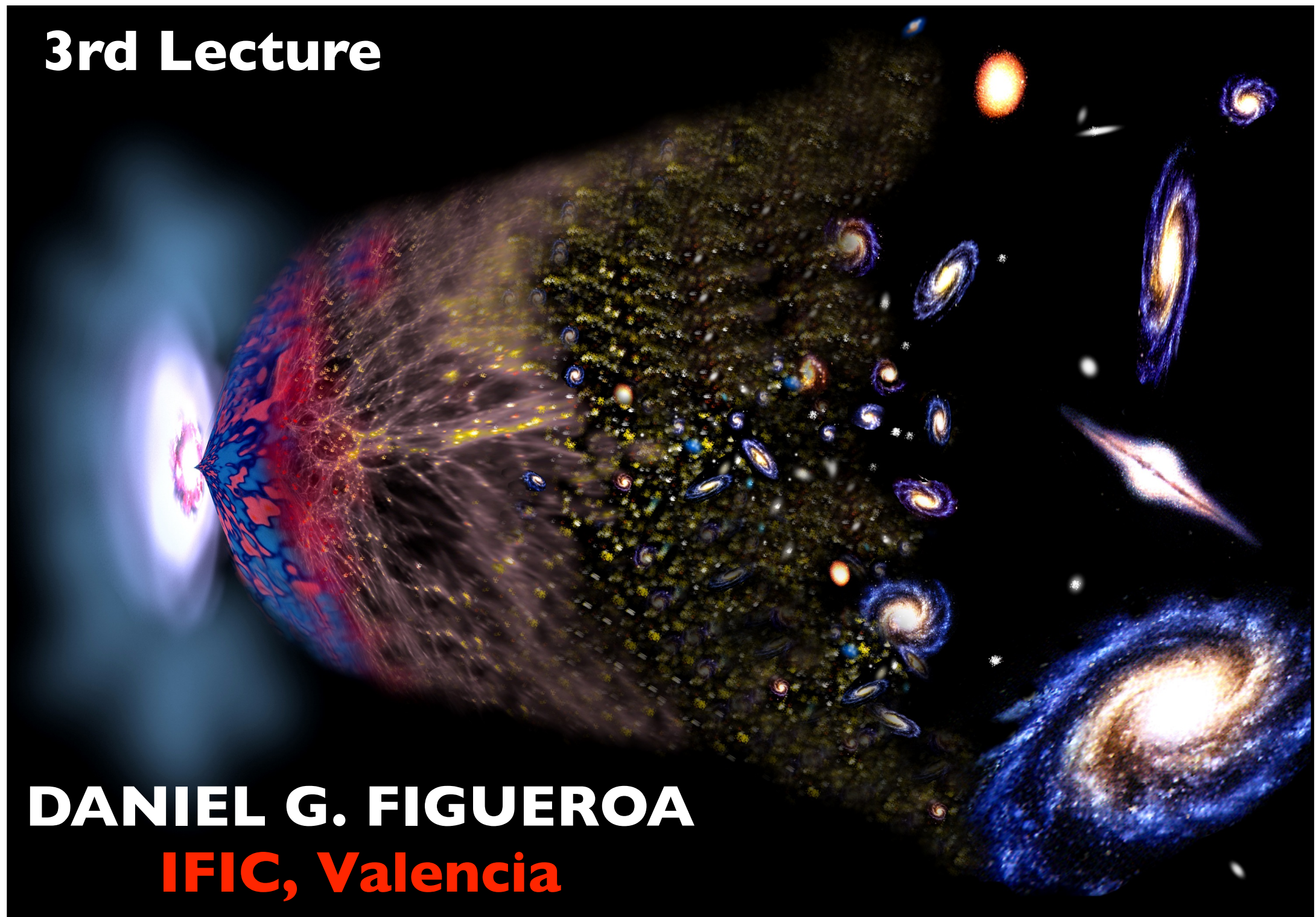


GRAVITATIONAL WAVE — BACKGROUNDS —

3rd Lecture



DANIEL G. FIGUEROA
IFIC, Valencia

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)

Gravitational Wave Backgrounds

OUTLINE



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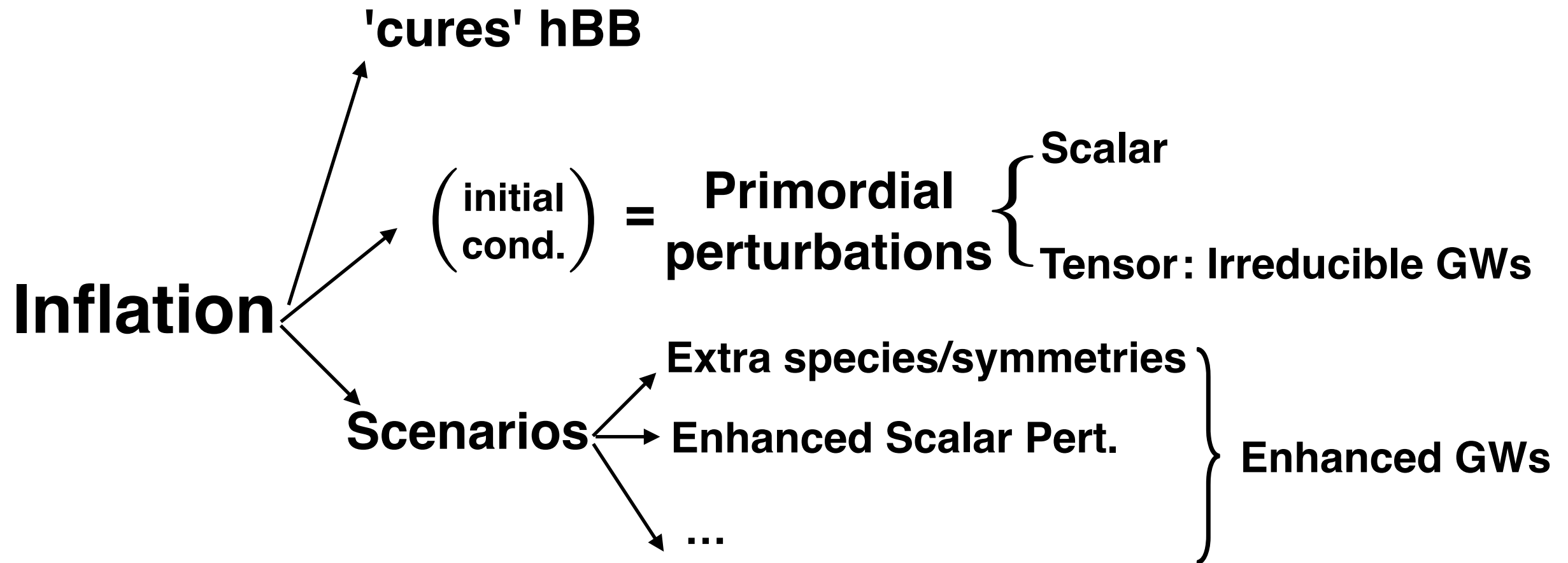
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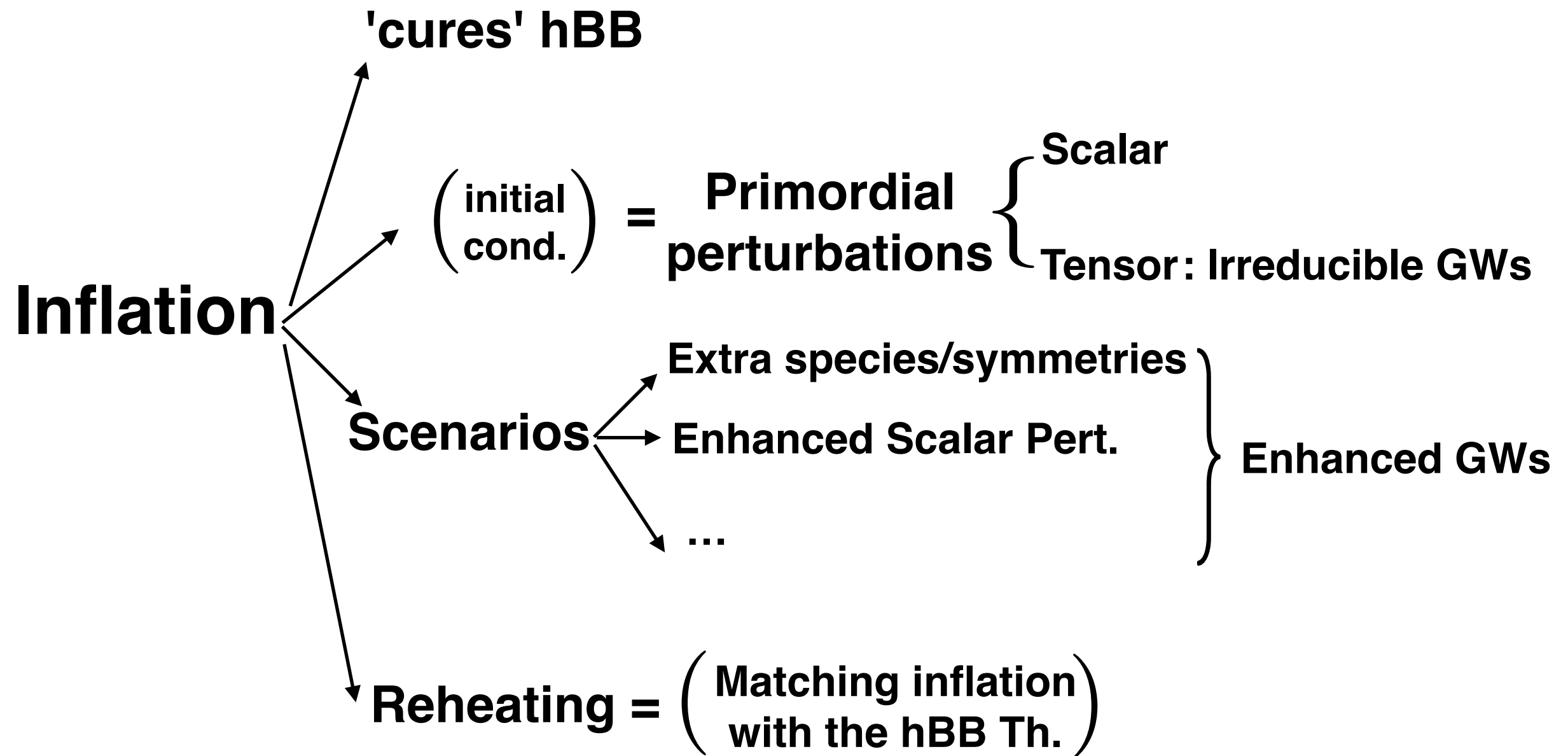
7) Observational Constraints/Prospects

← (Briefly)

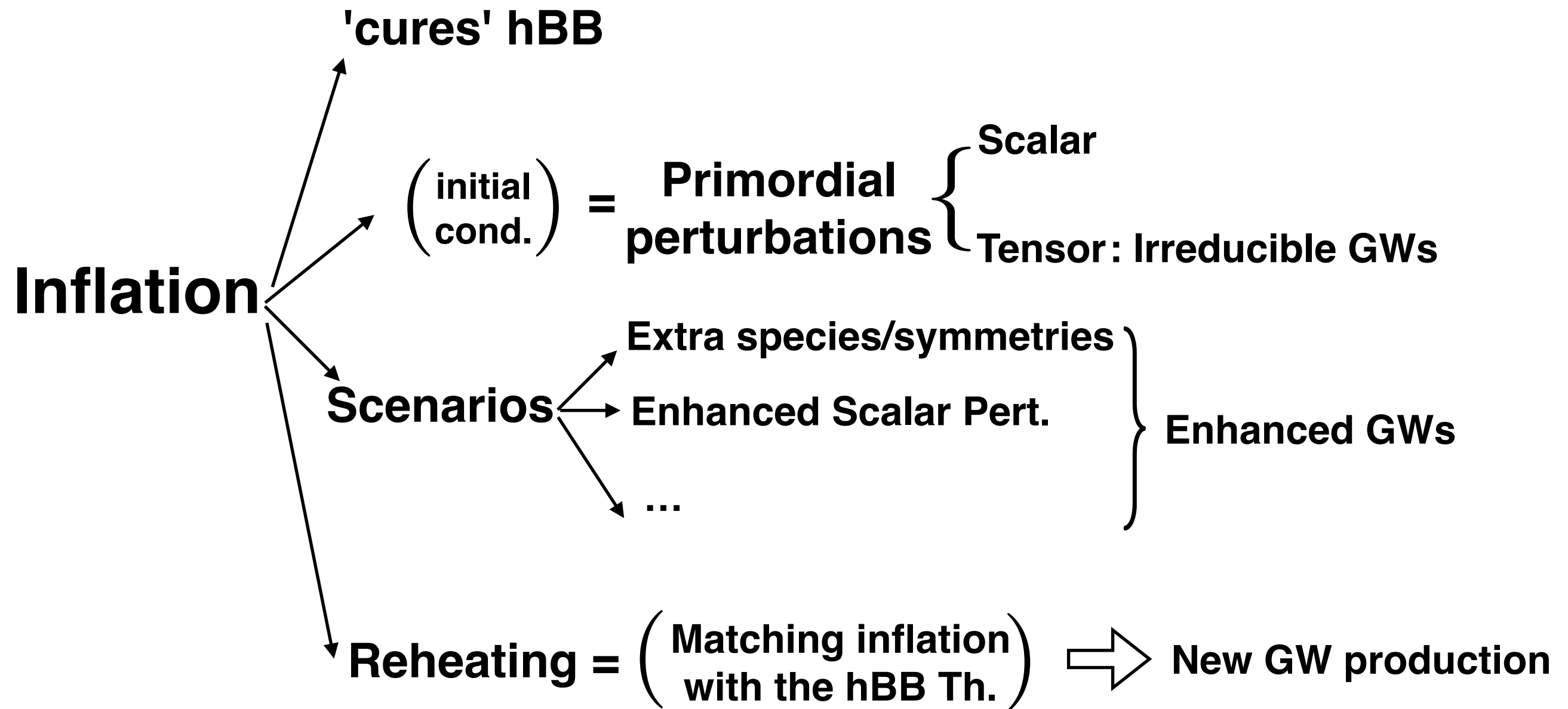
INFLATIONARY COSMOLOGY



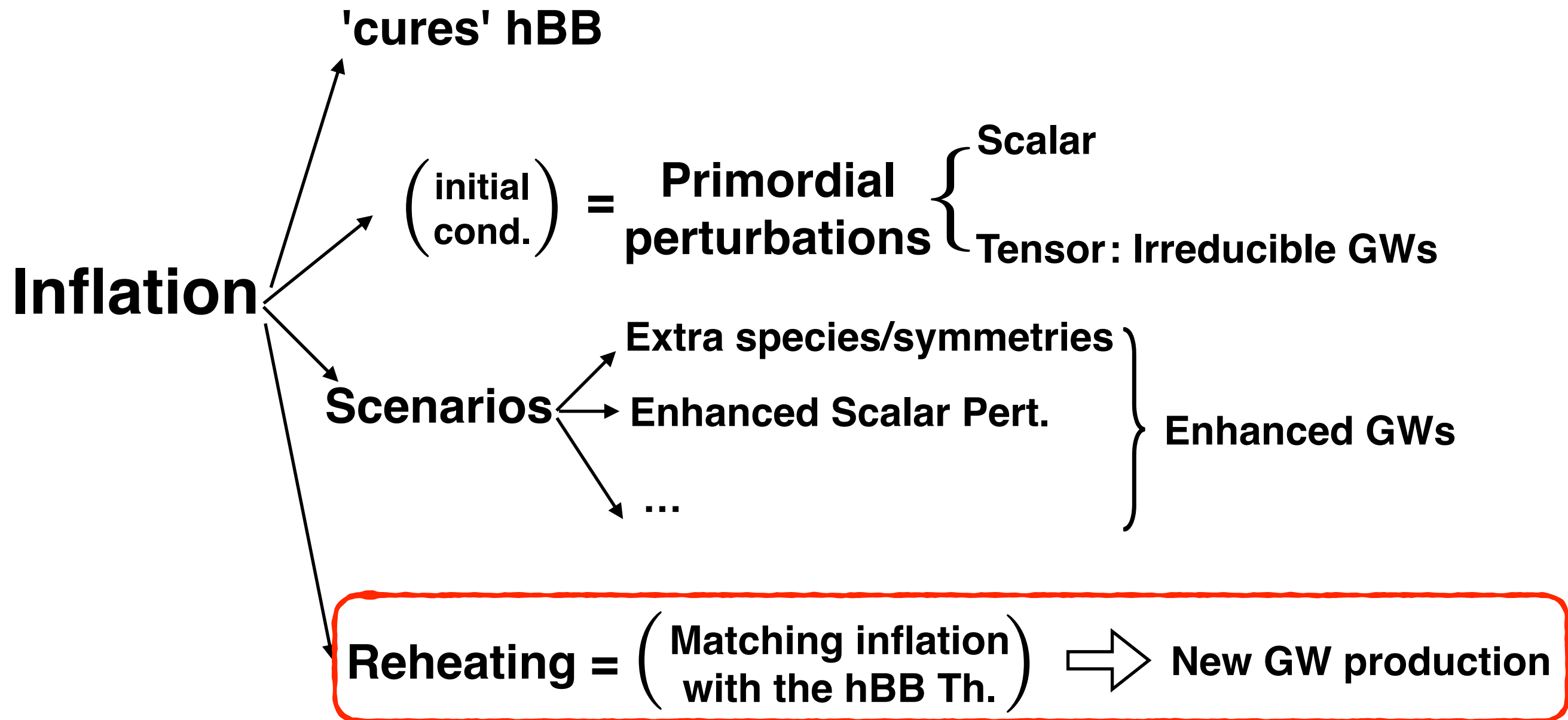
INFLATIONARY COSMOLOGY



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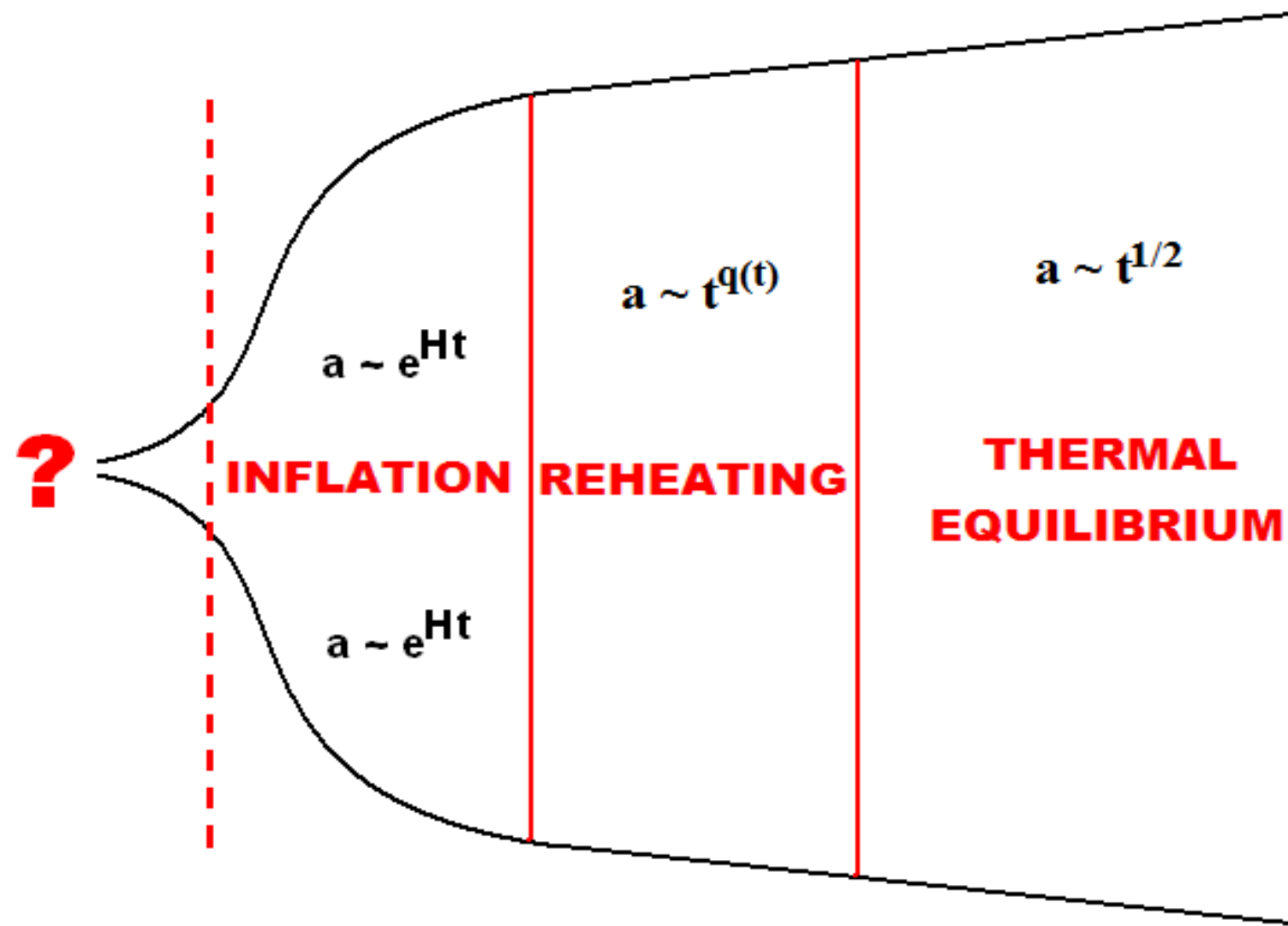


INFLATIONARY COSMOLOGY



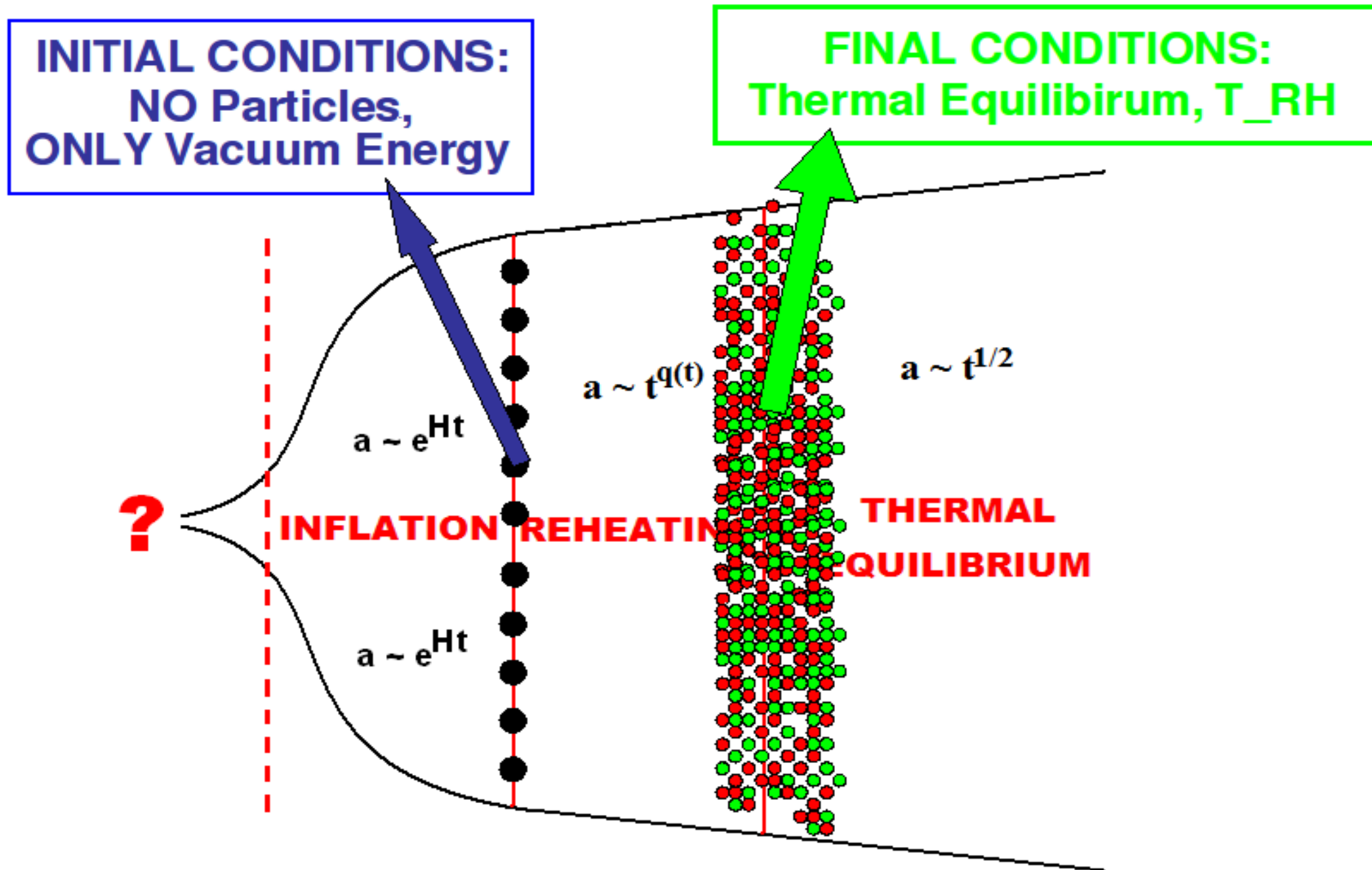
INFLATIONARY REHEATING

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



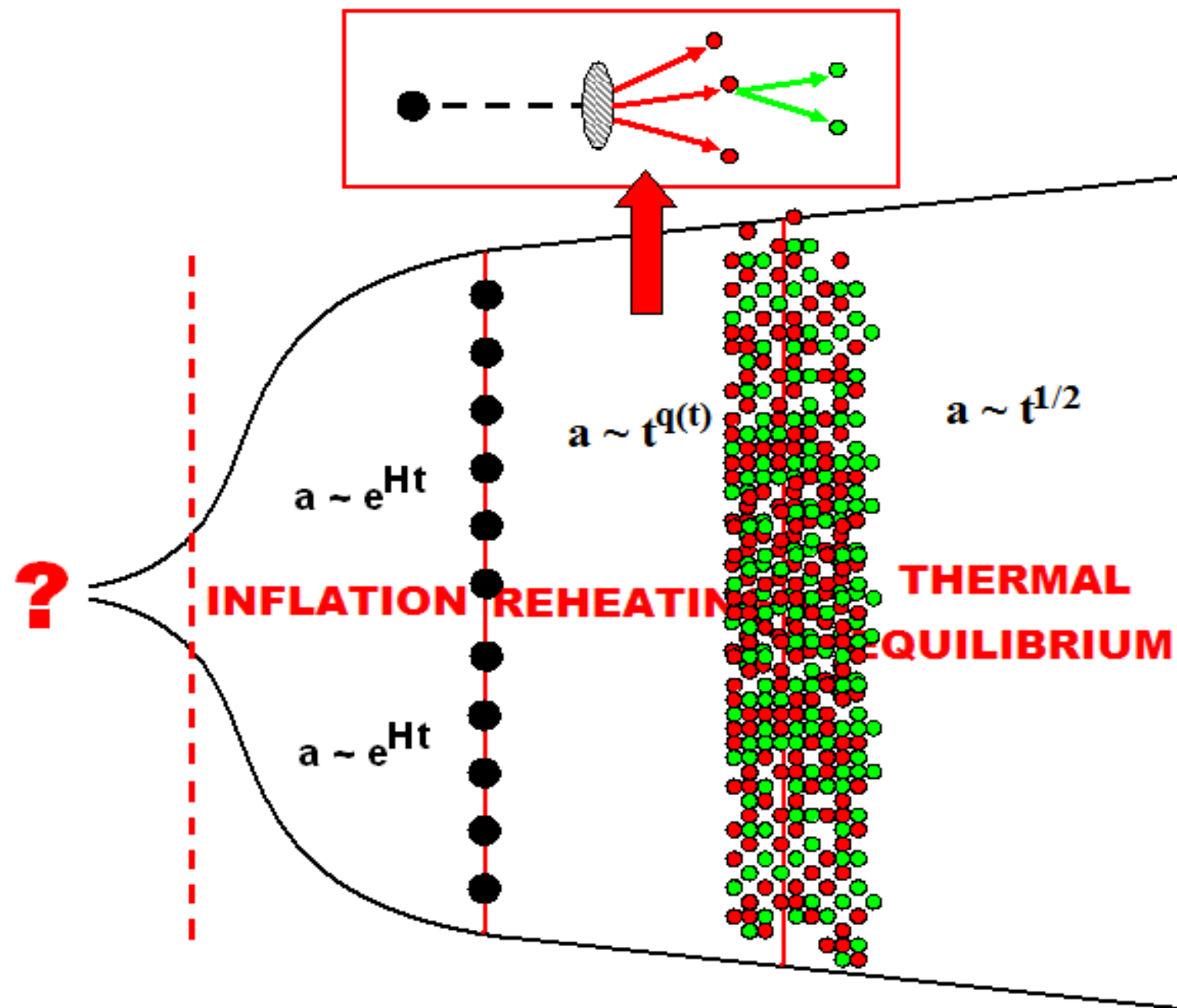
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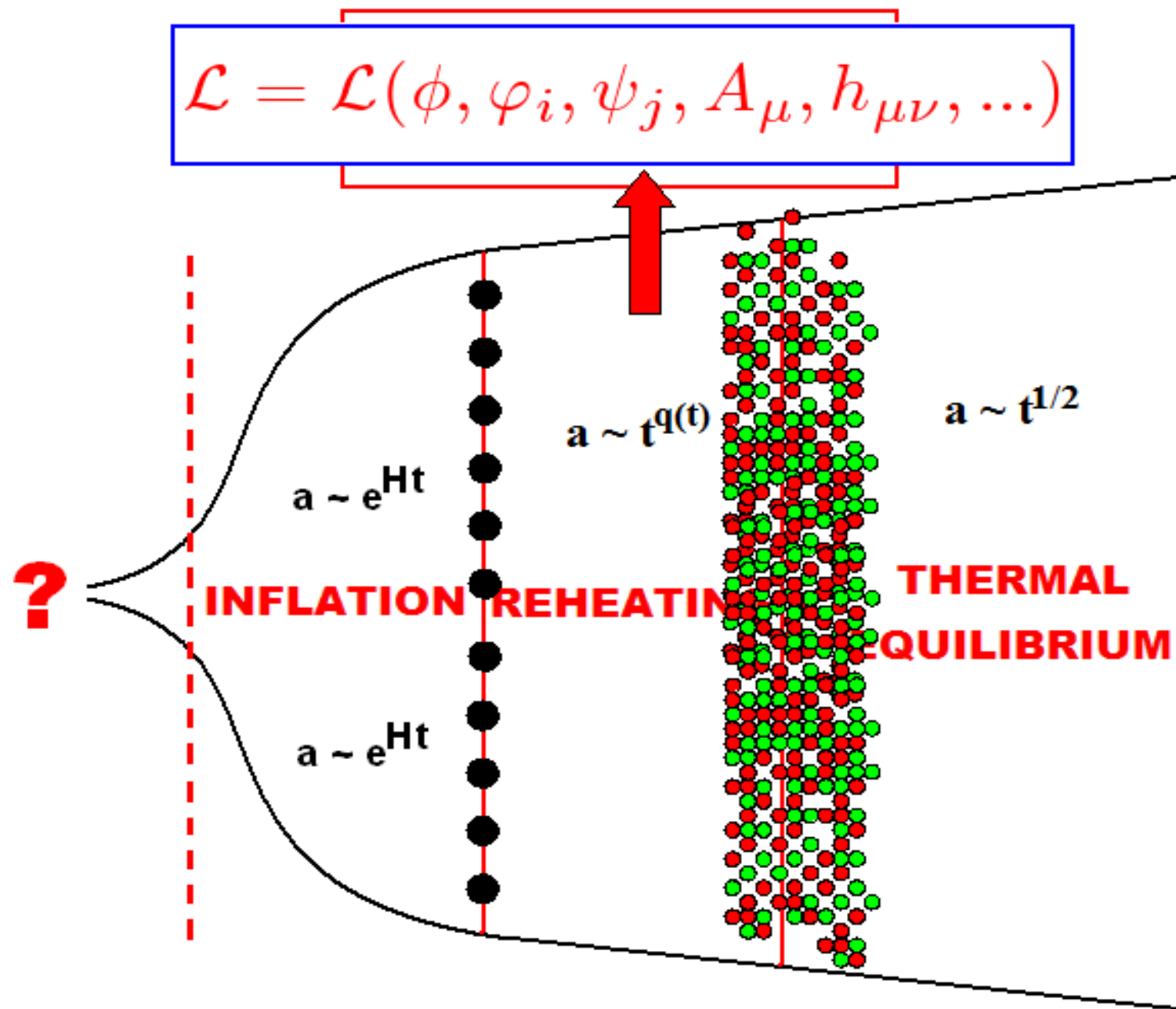
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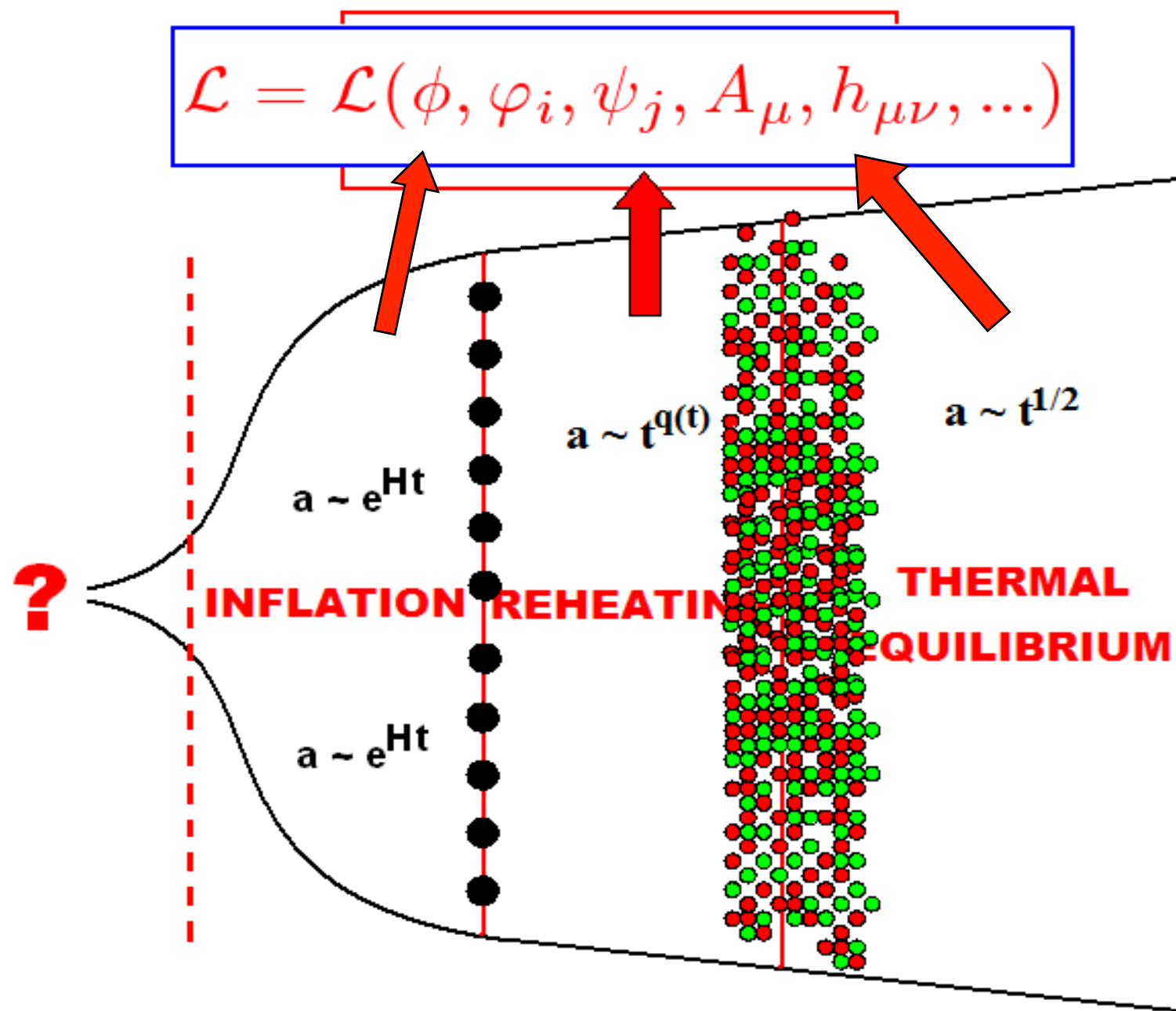
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INFLATIONARY REHEATING

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



SCALAR REHEATING

$$\begin{aligned} 1) \quad V(\phi, \chi) &= \frac{1}{4}\lambda\phi^4 + \frac{1}{2}m_\chi^2\chi^2 + \frac{1}{2}g^2\phi^2\chi^2 \quad (\text{Chaotic}) \\ 2) \quad V(\phi, \chi) &= \frac{1}{2}\mu^2\phi^2 + \frac{\lambda}{4}(\chi^2 - v^2)^2 + \frac{1}{2}g^2\phi^2\chi^2 \quad (\text{Hybrid}) \end{aligned}$$

INFLATON **MATTER** **COUPLING**

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

MATTER

COUPLING



(Ruled out for inflation,
Not for reheating !)

SCALAR REHEATING

$$\begin{aligned}
 1) \quad V(\phi, \chi) &= \underbrace{\frac{1}{4}\lambda\phi^4}_{\text{INFLATON}} + \underbrace{\frac{1}{2}m_\chi^2\chi^2}_{\text{MATTER}} + \frac{1}{2}g^2\phi^2\chi^2 \quad (\text{Chaotic}) \\
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 \end{aligned}$$

$$\left\{ \begin{aligned}
 &\ddot{\phi}(t) + 3H\dot{\phi} + V'(\phi) = 0 \quad (\text{Inflaton Zero-Mode : Damped Oscillator}) \\
 &\square\phi_k + F(\int dq\phi_q\chi_{|k-q|})\phi_k + \dots = 0 \quad (\text{Inflaton Fluctuations}) \\
 &\square\chi_k + F(\int dq\chi_q, \phi_{|k-q|})\chi_k + \dots = 0 \quad (\text{Matter Fluctuations})
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SCALAR REHEATING

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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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DYNAMICS:

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

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

SCALAR (P)REHEATING

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

SCALAR (P)REHEATING

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SCALAR (P)REHEATING

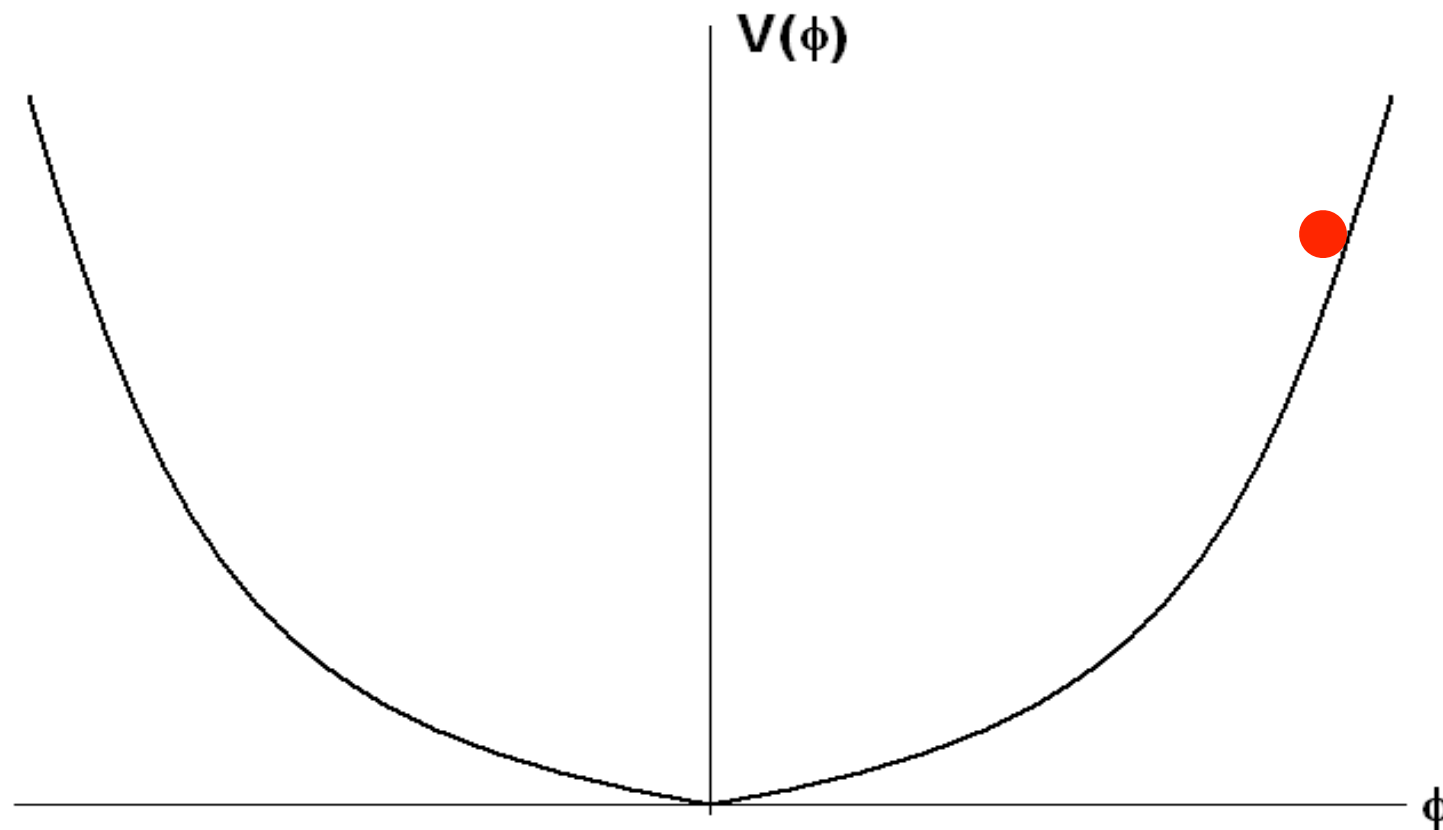
- 1) Chaotic Scenarios: PARAMETRIC RESONANCE

SCALAR (P)REHEATING

1) Chaotic Scenarios: PARAMETRIC RESONANCE

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

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

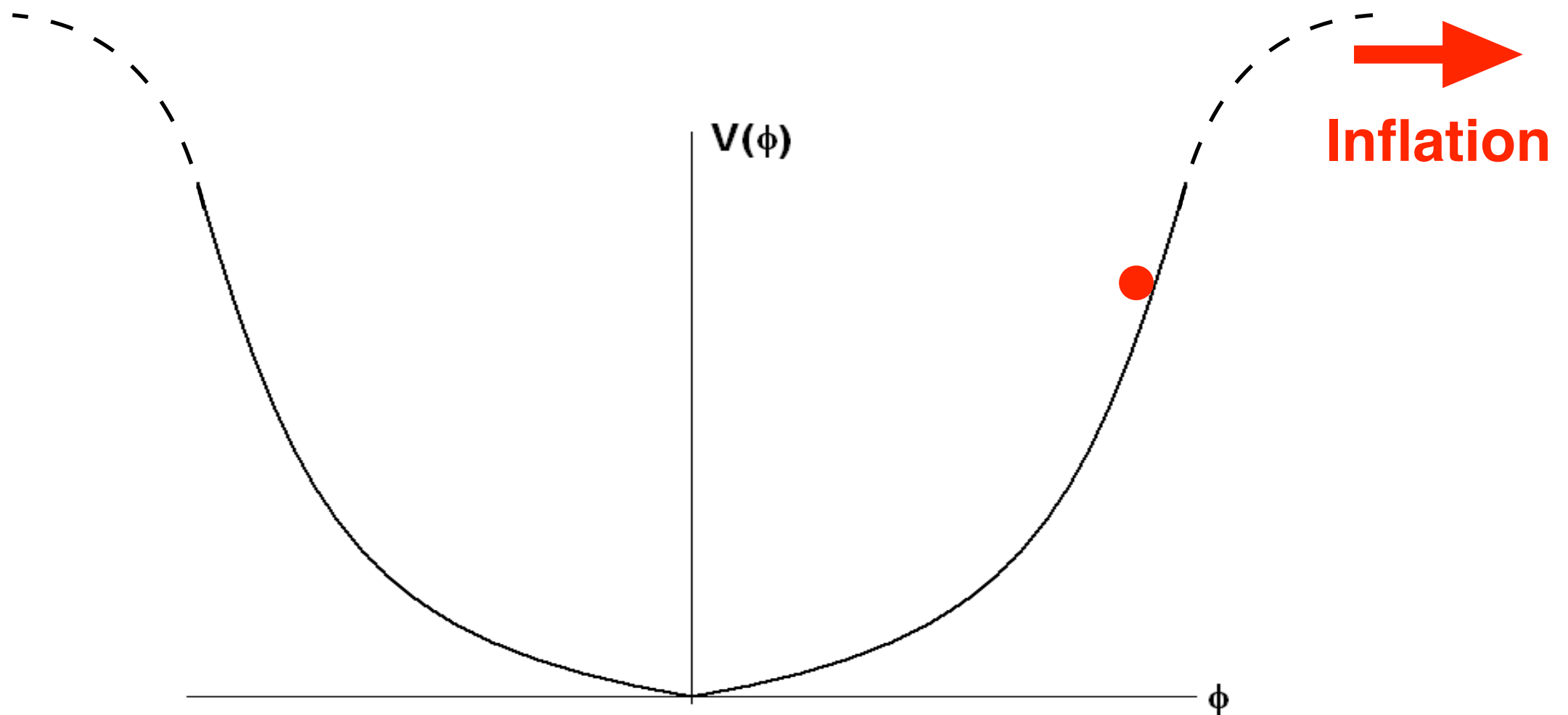


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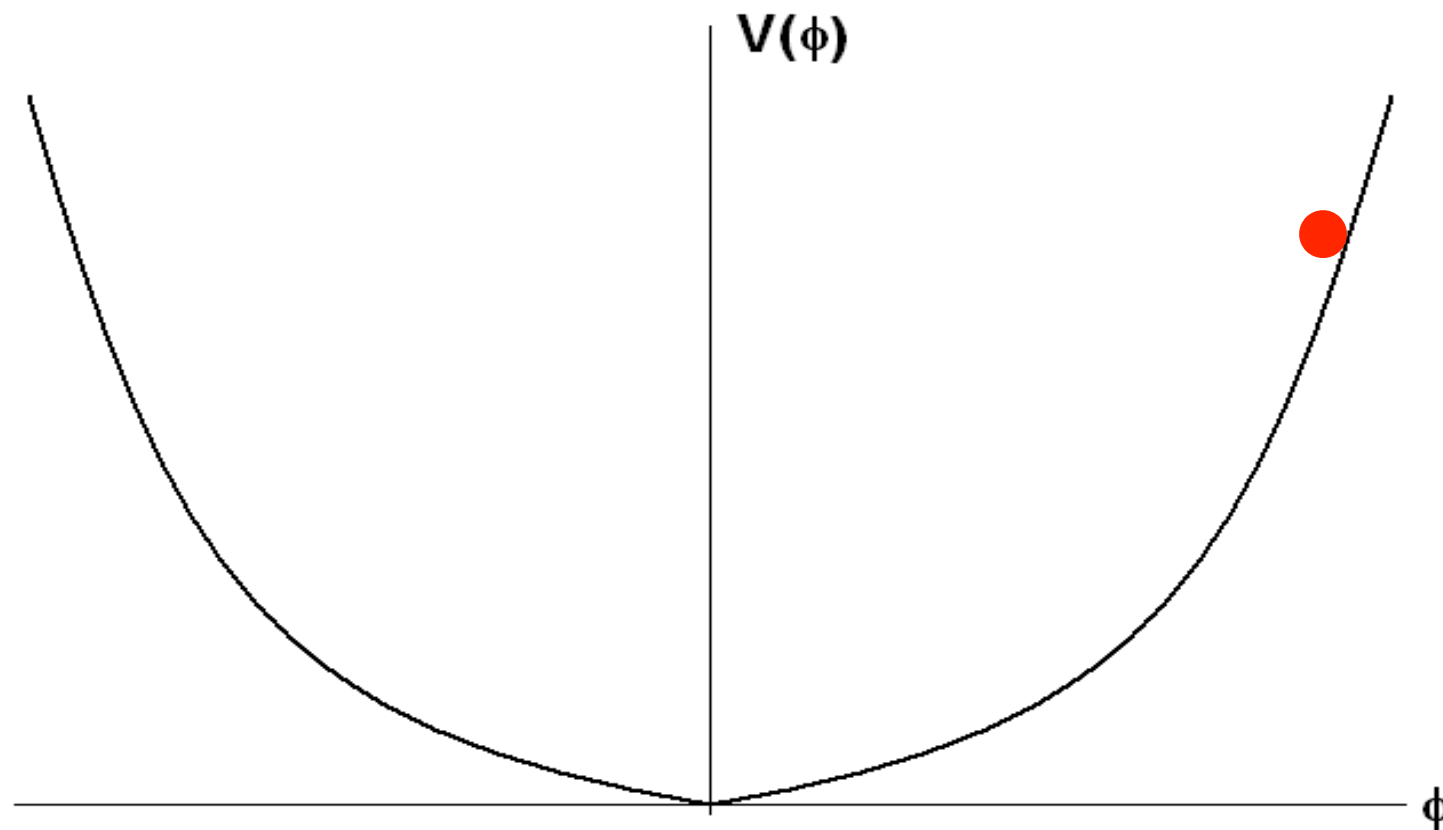


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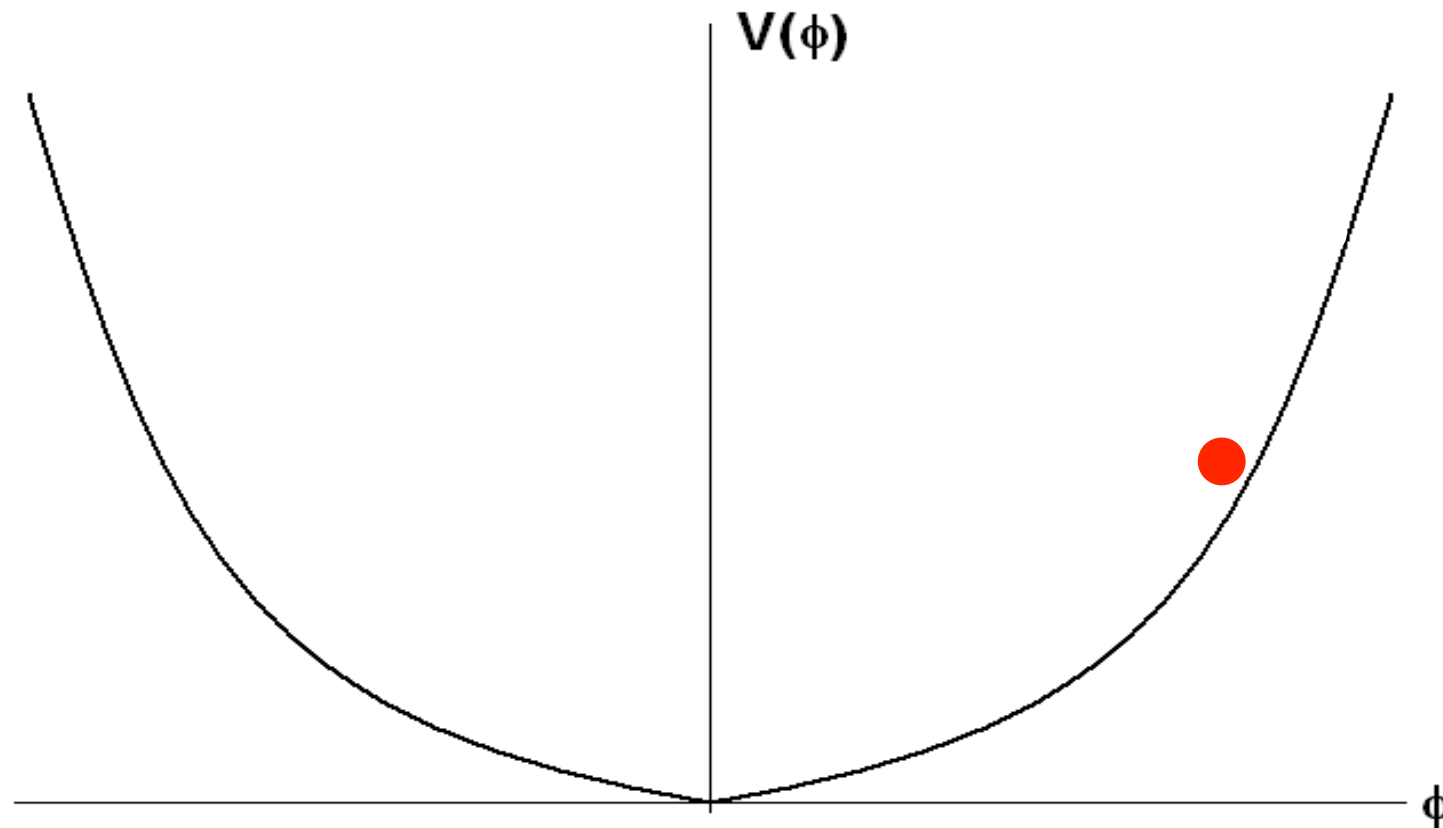


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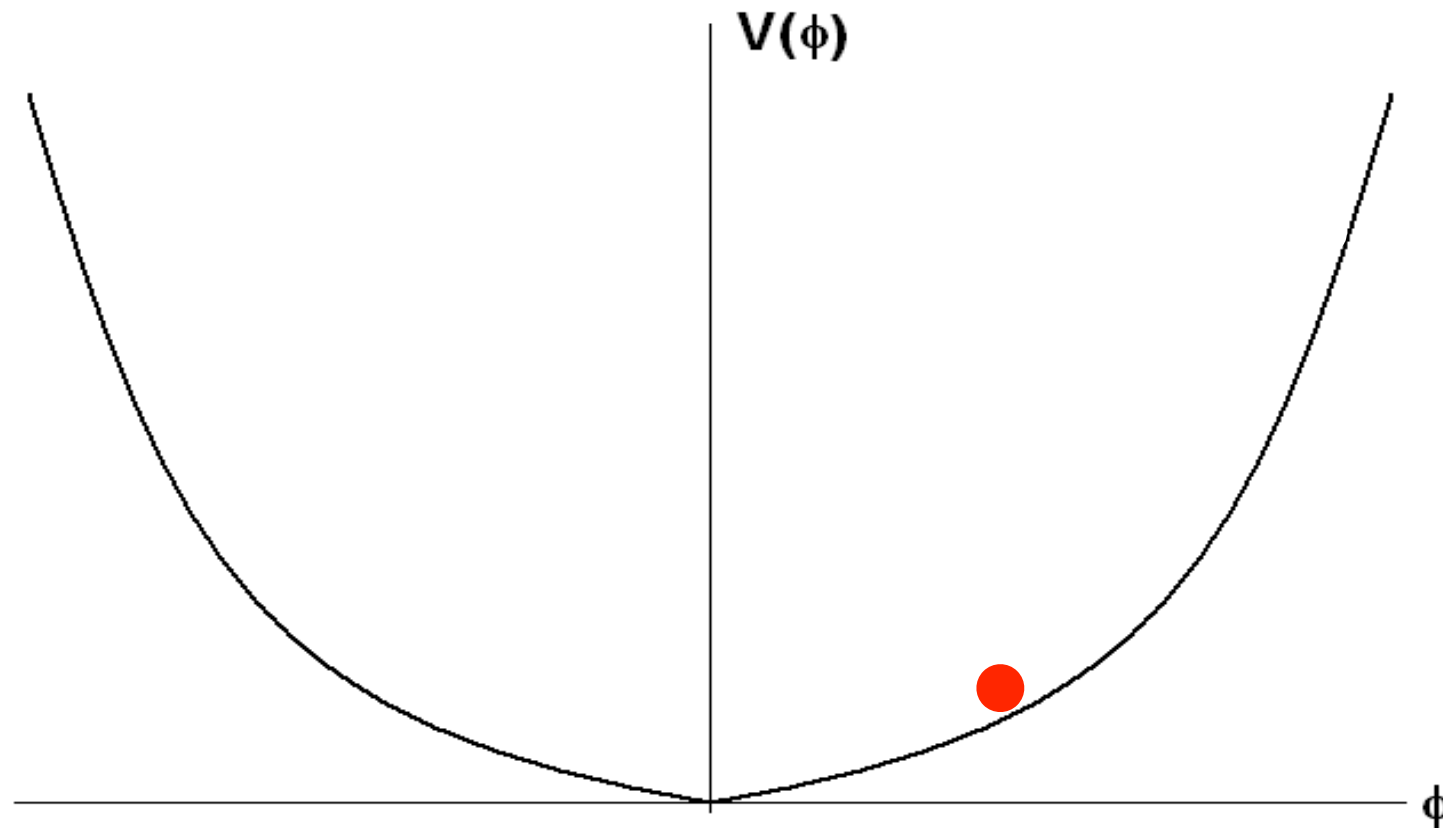


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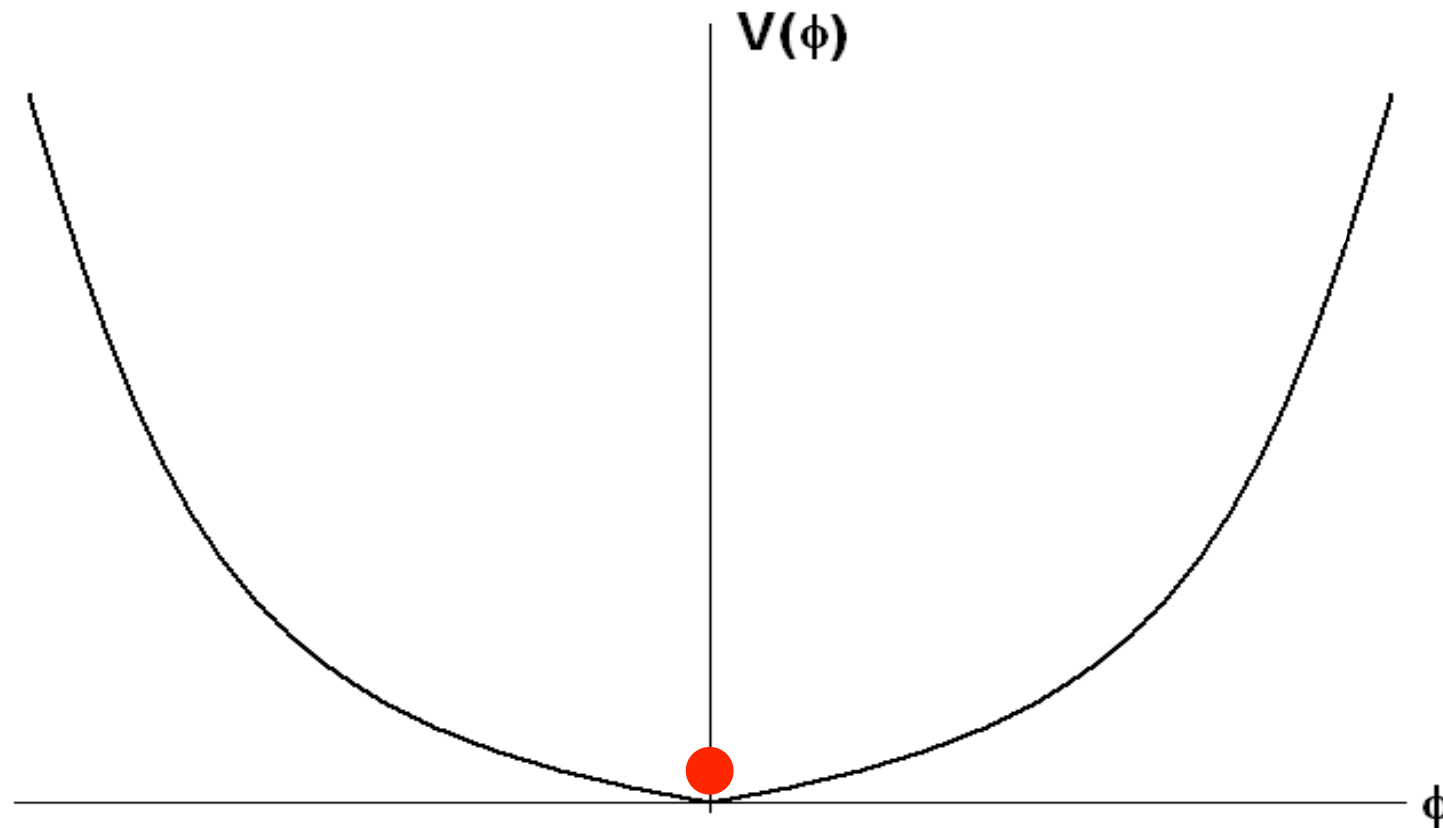


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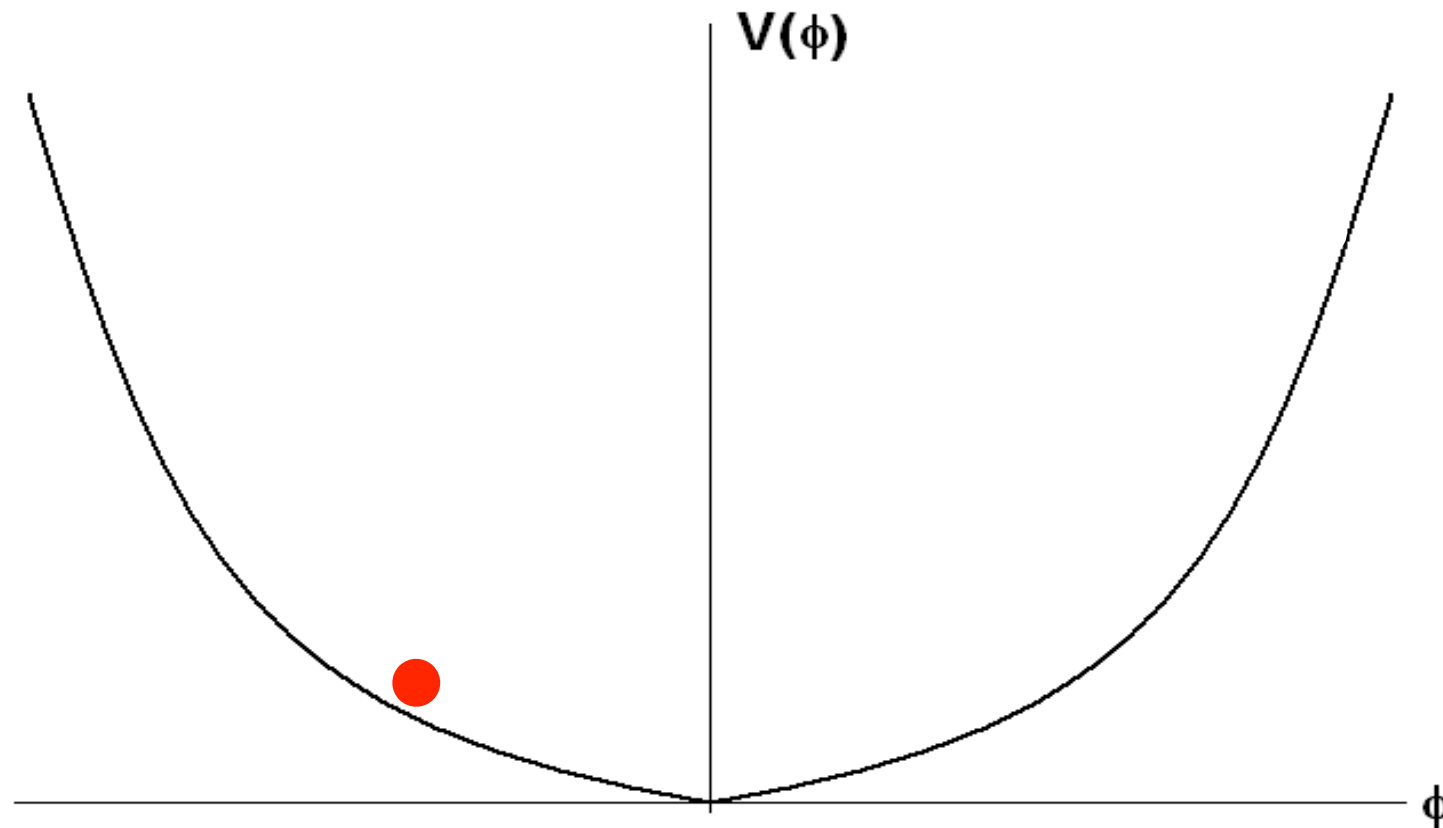


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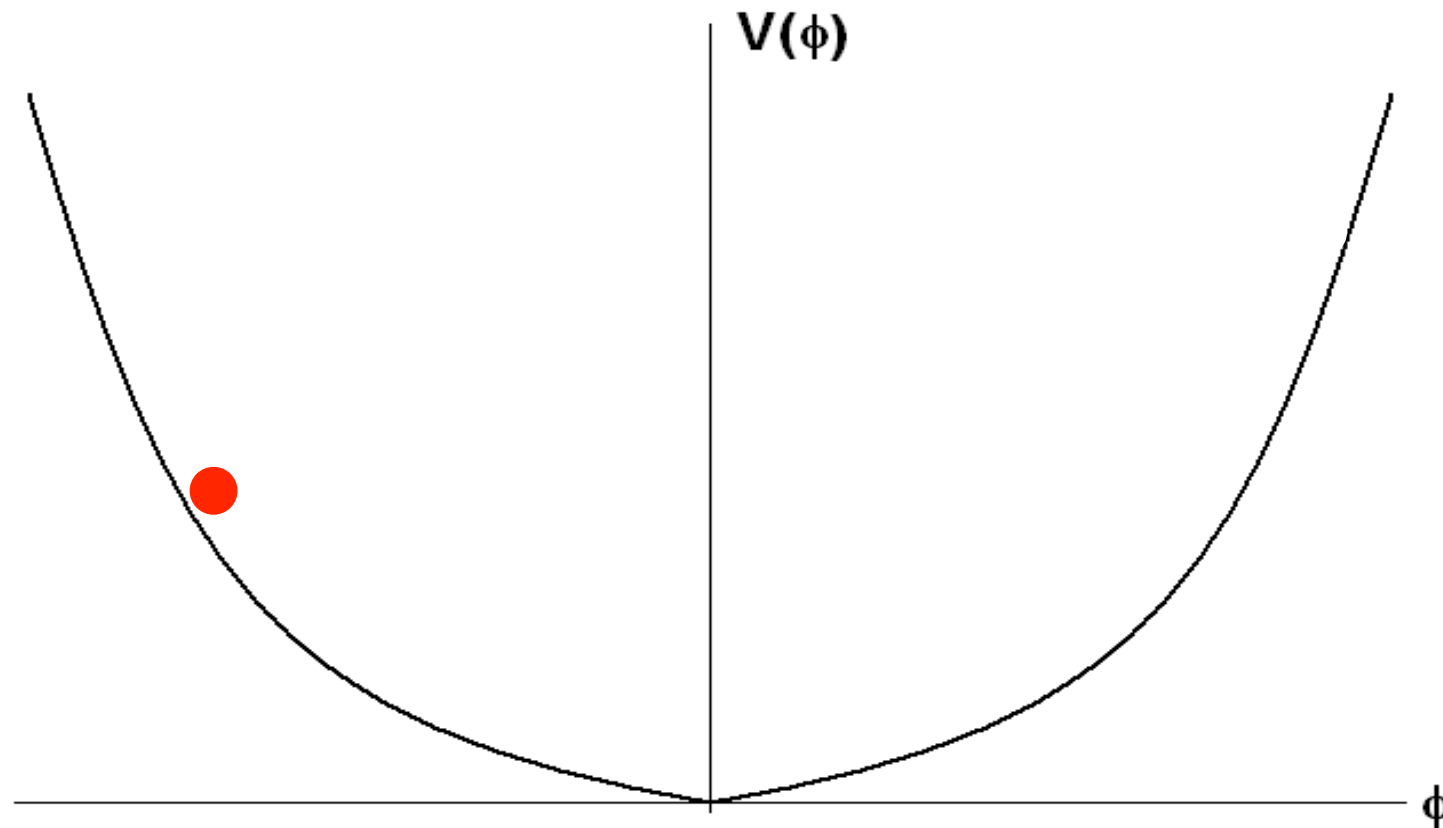


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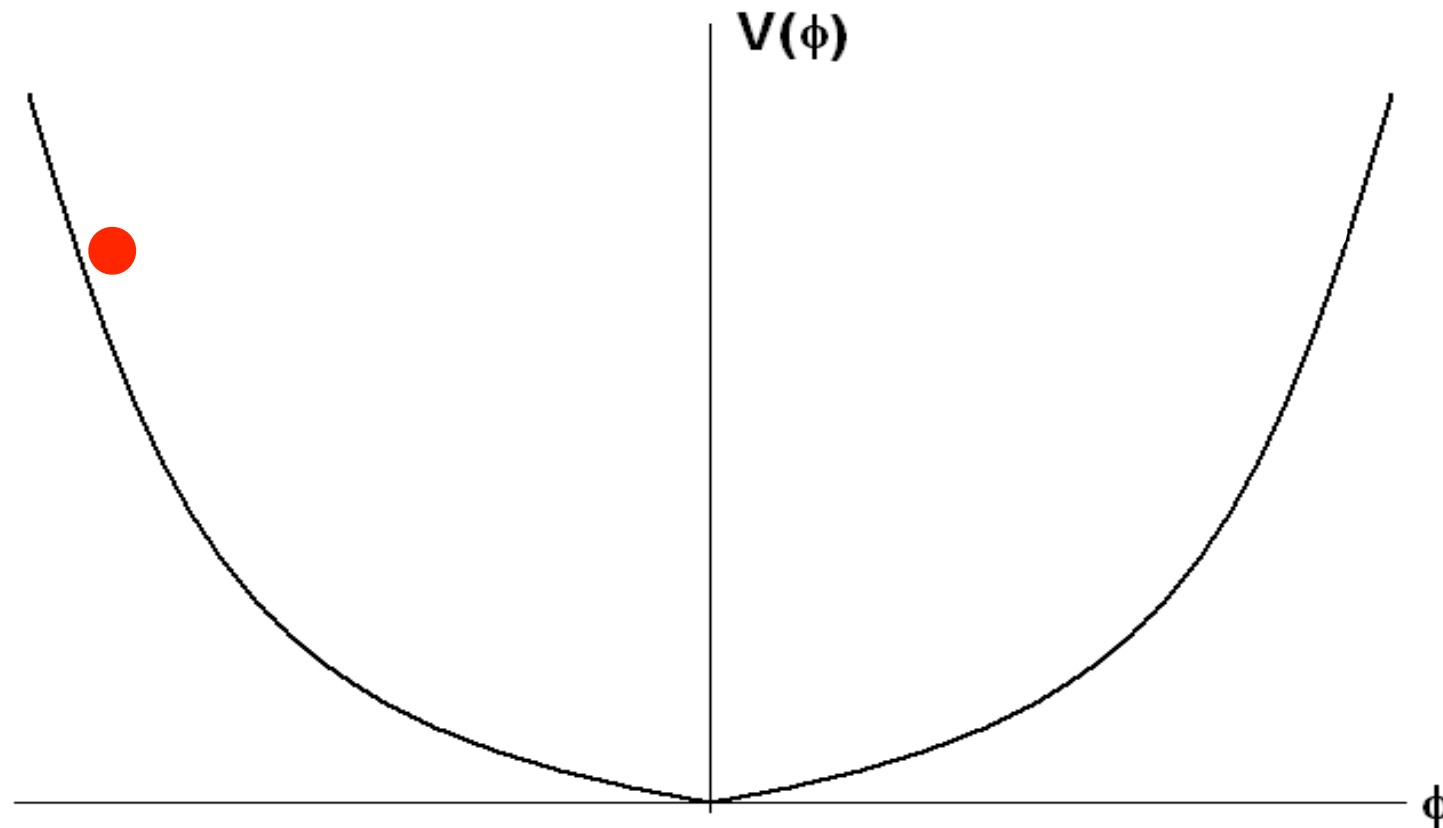


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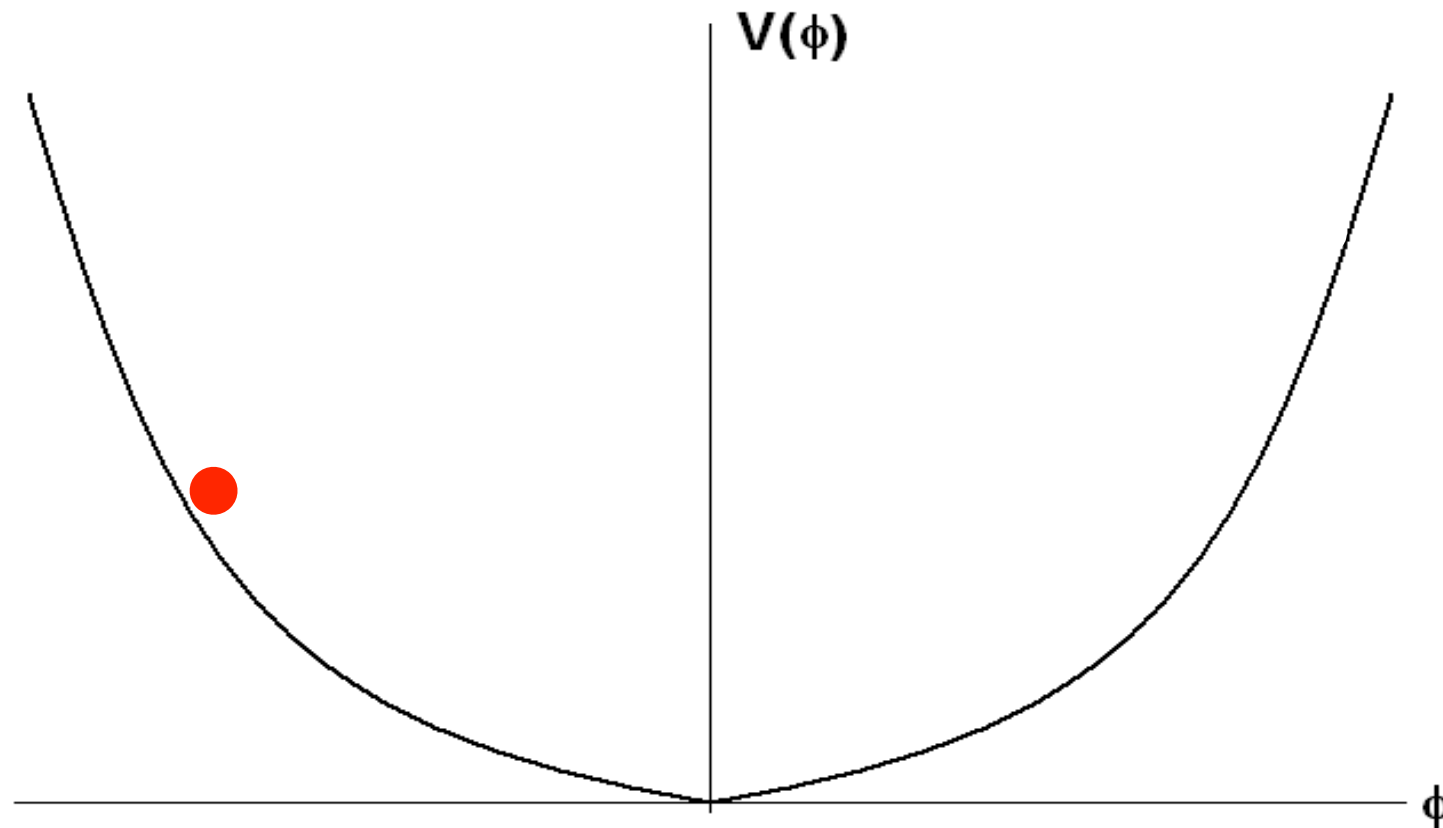


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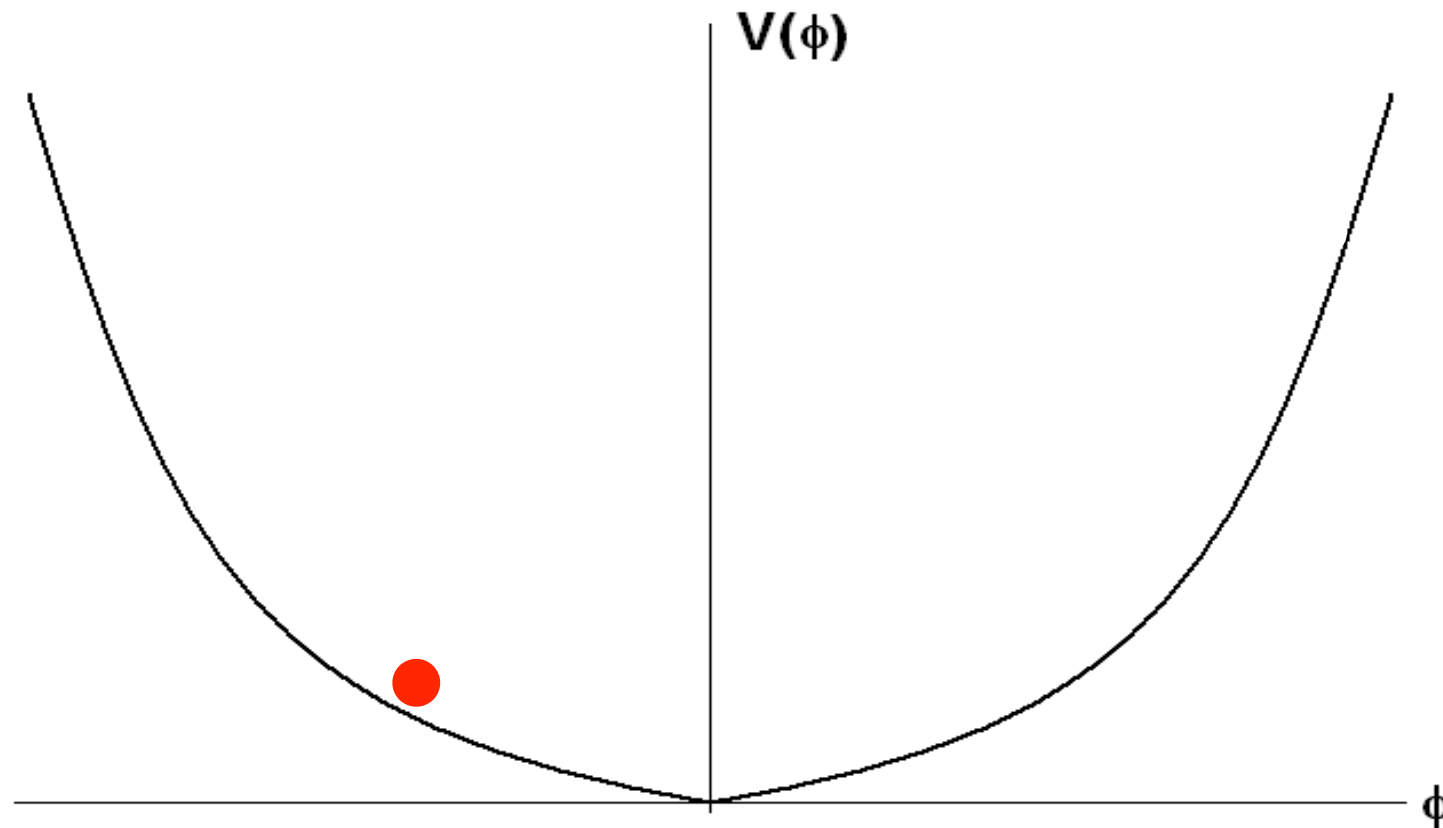


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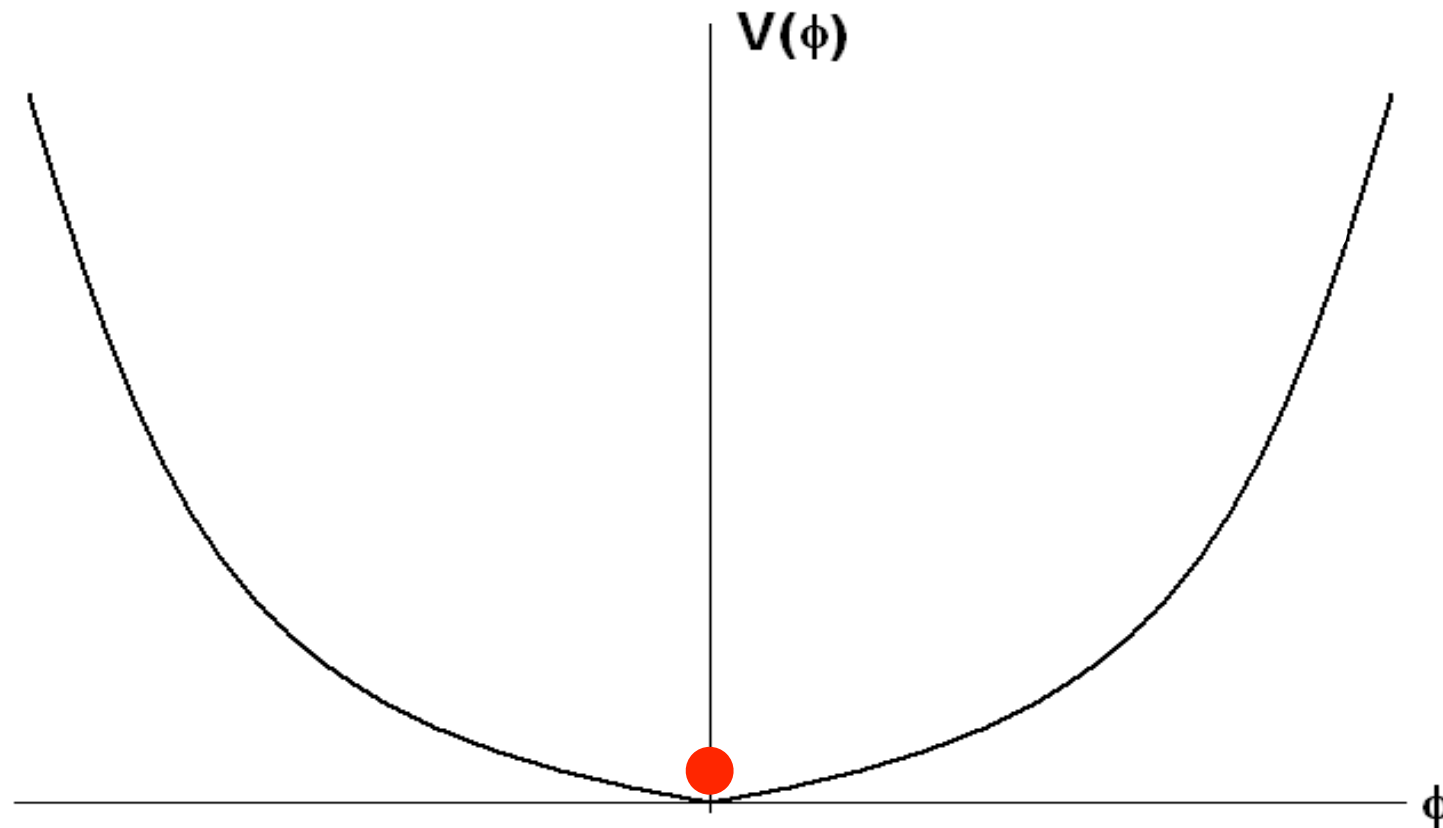


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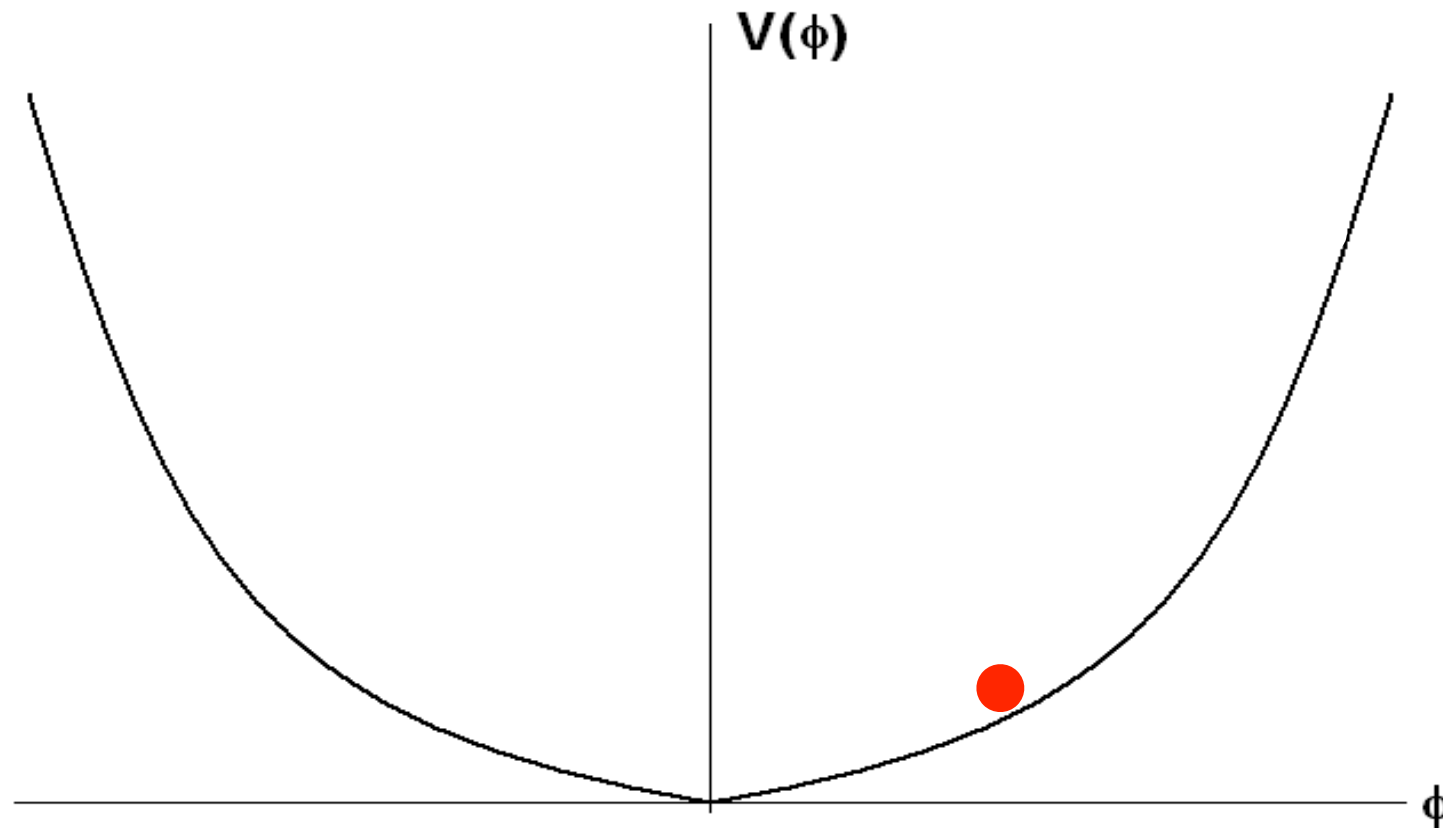


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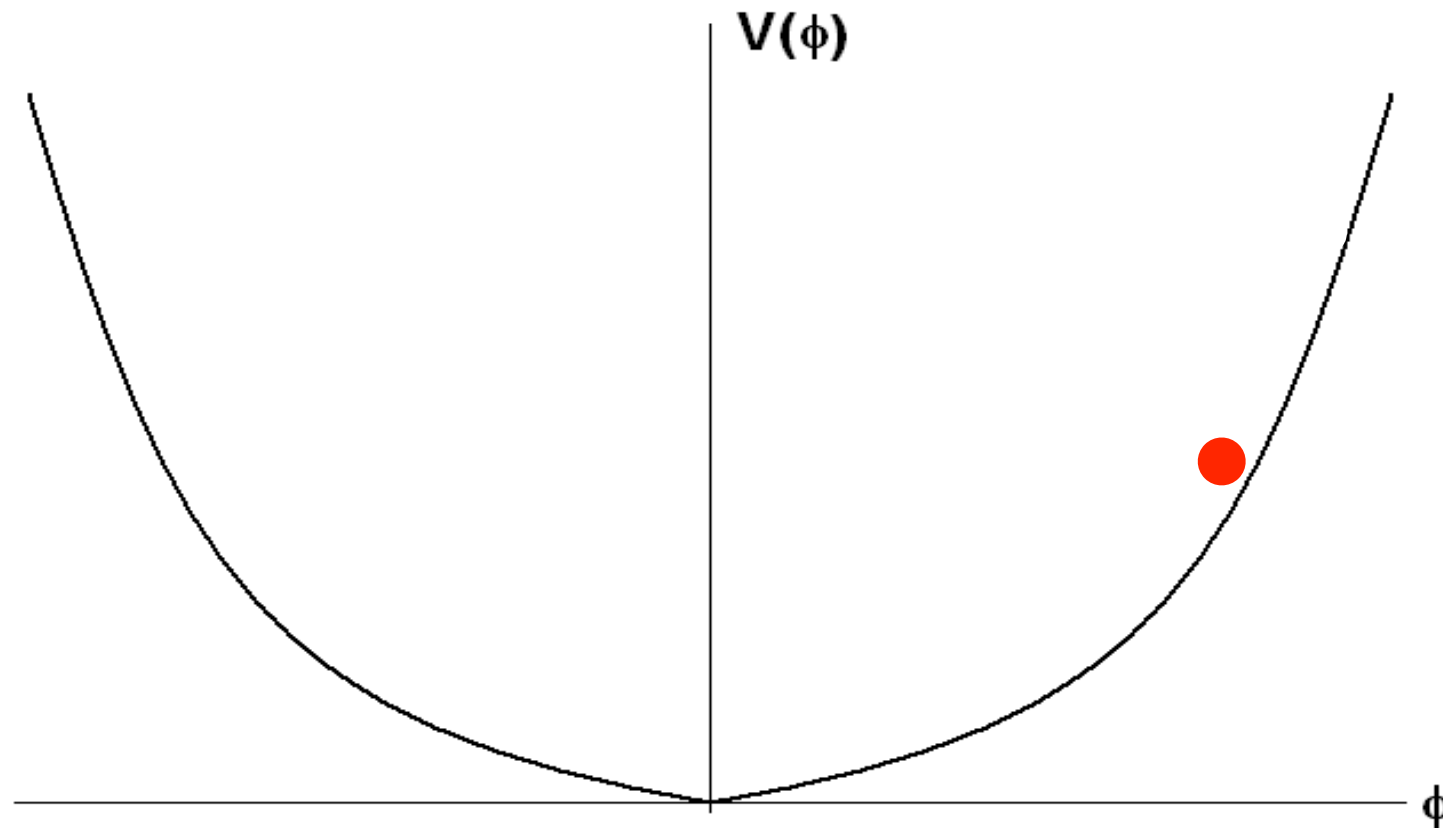


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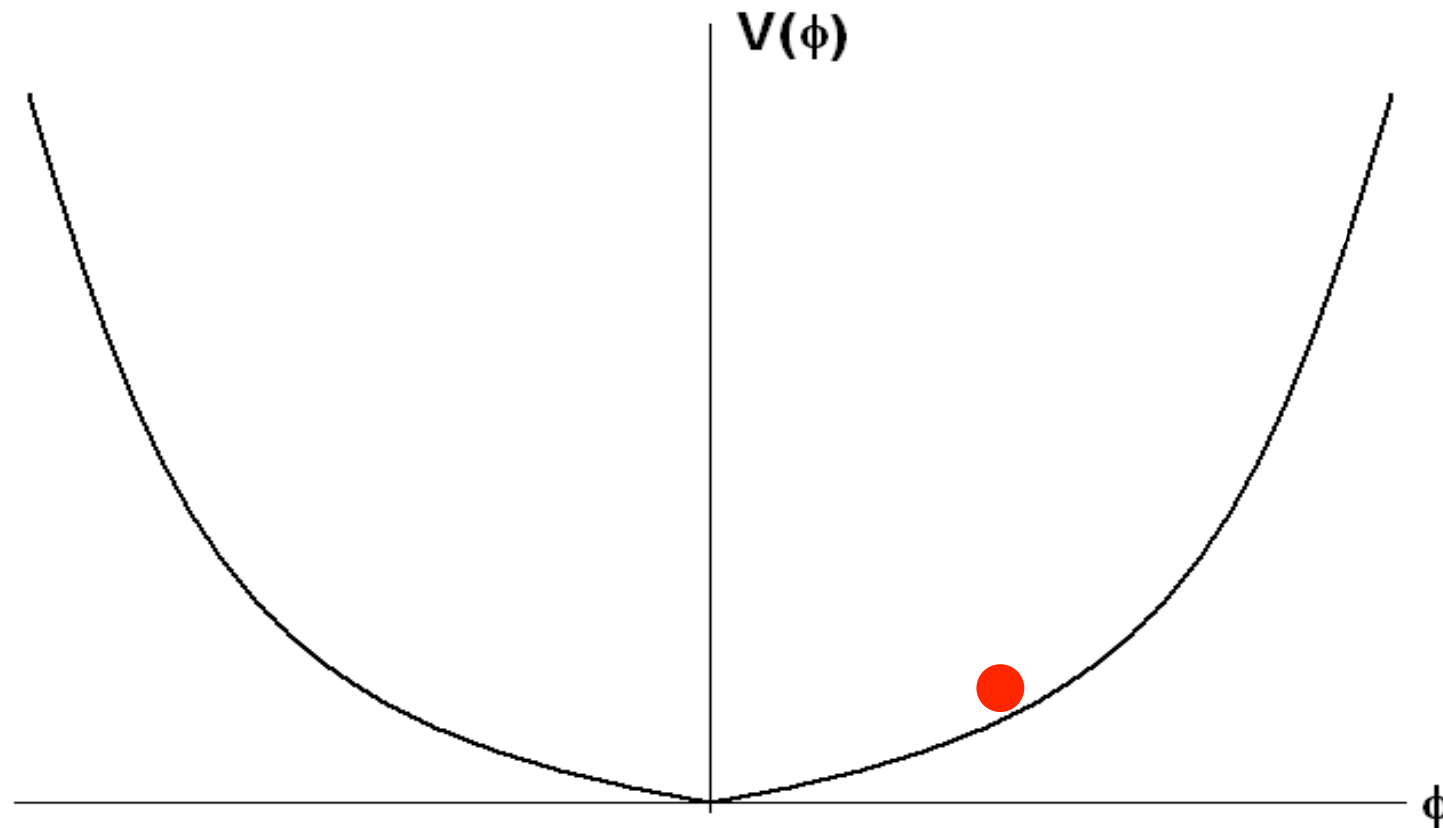


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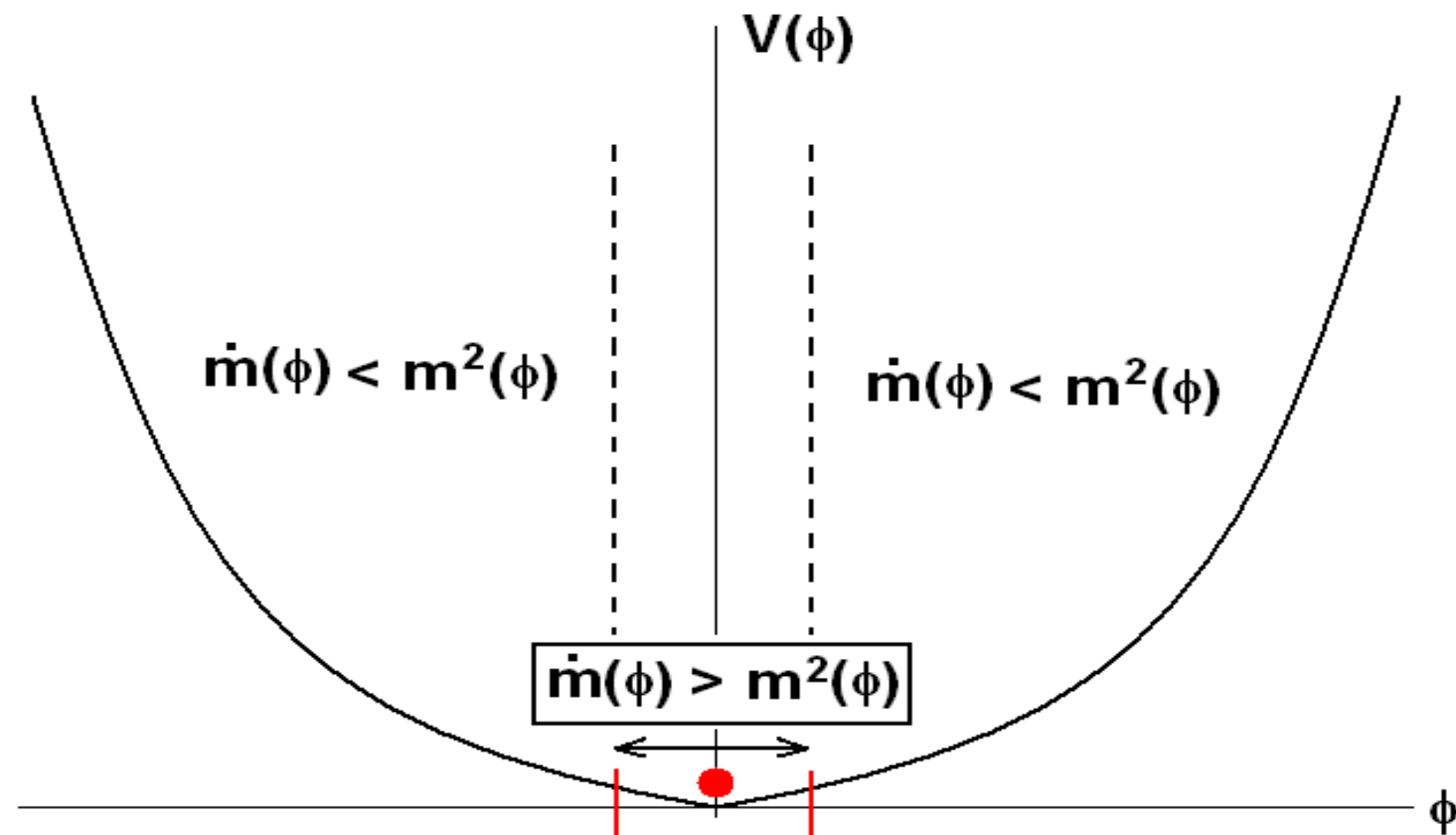


SCALAR (P)REHEATING

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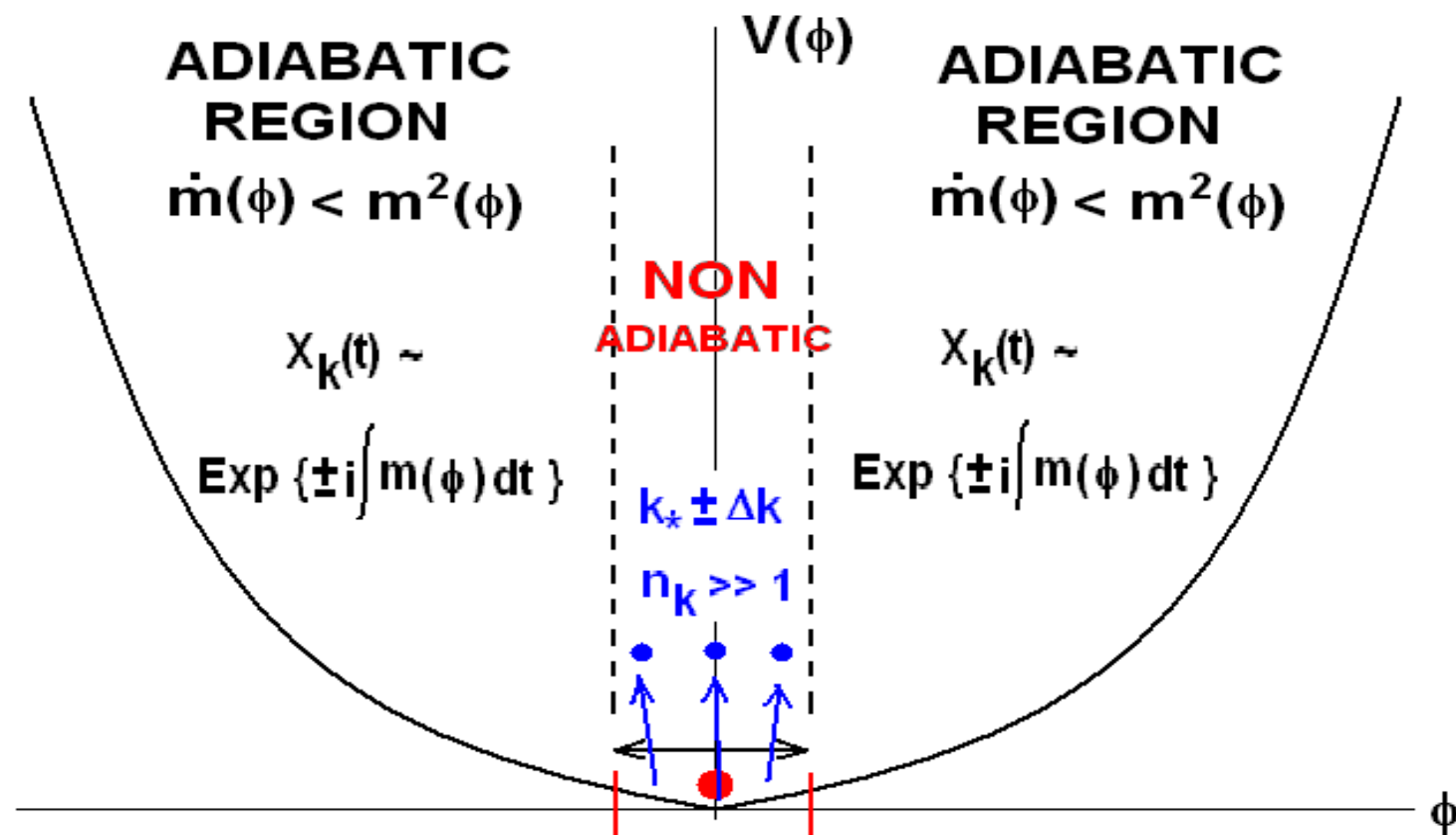


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SCALAR (P)REHEATING

1) Chaotic Scenarios: PARAMETRIC RESONANCE

MATTER FIELD FLUCTUATIONS

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

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

SCALAR (P)REHEATING

1) Chaotic Scenarios: PARAMETRIC RESONANCE

MATTER FIELD FLUCTUATIONS

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(n = 4)

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

(n = 2)

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

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

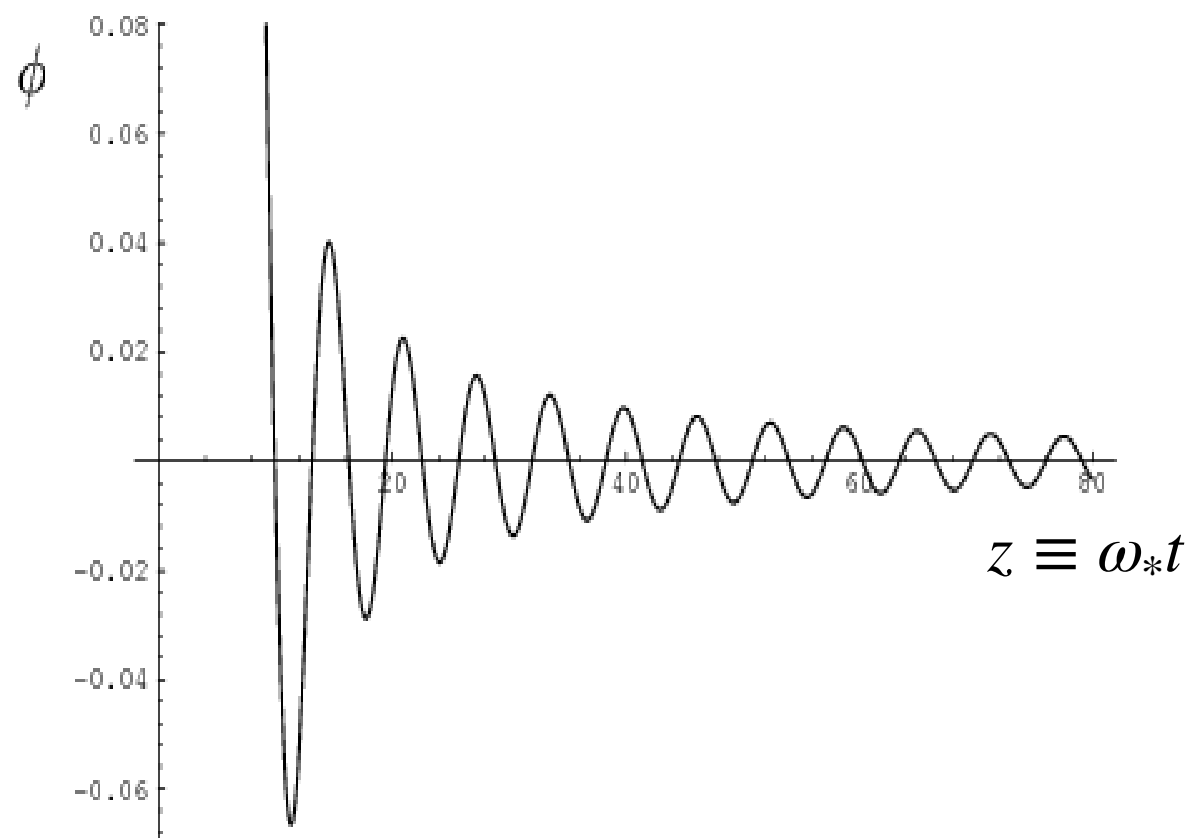
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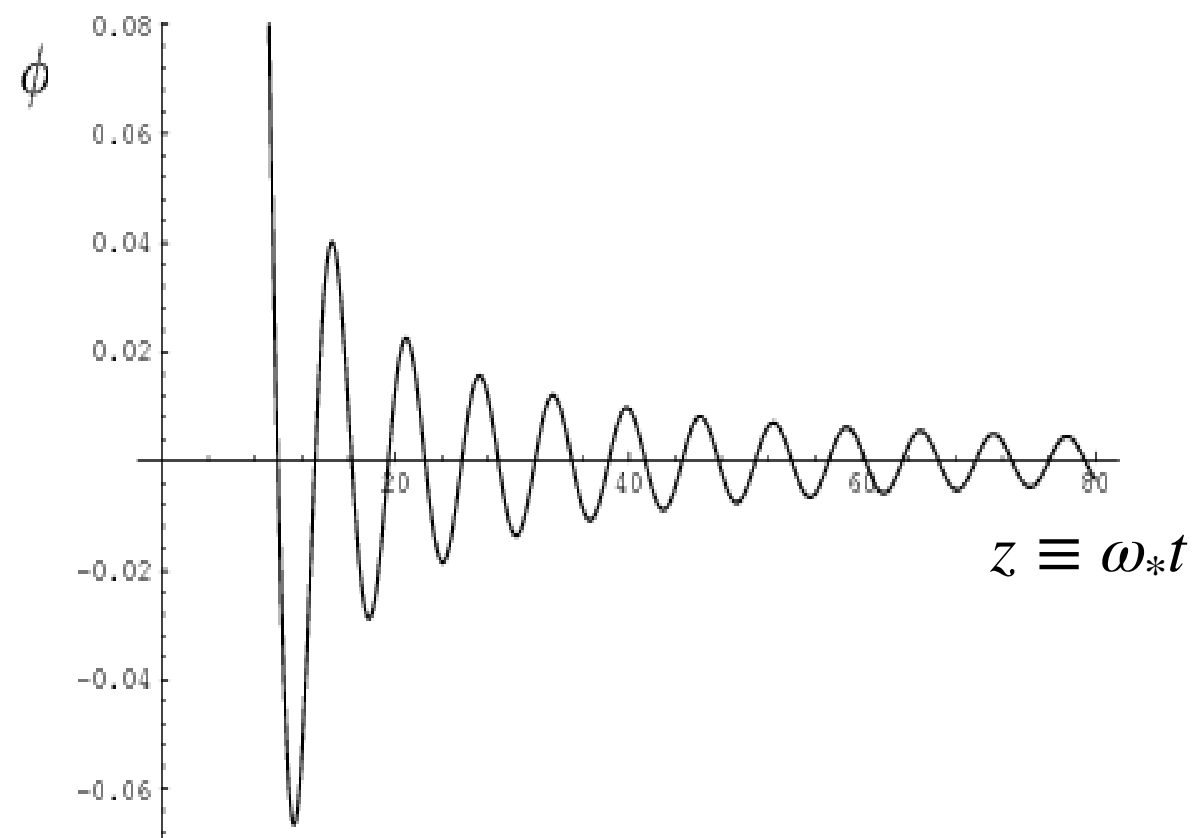


SCALAR (P)REHEATING

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SCALAR (P)REHEATING

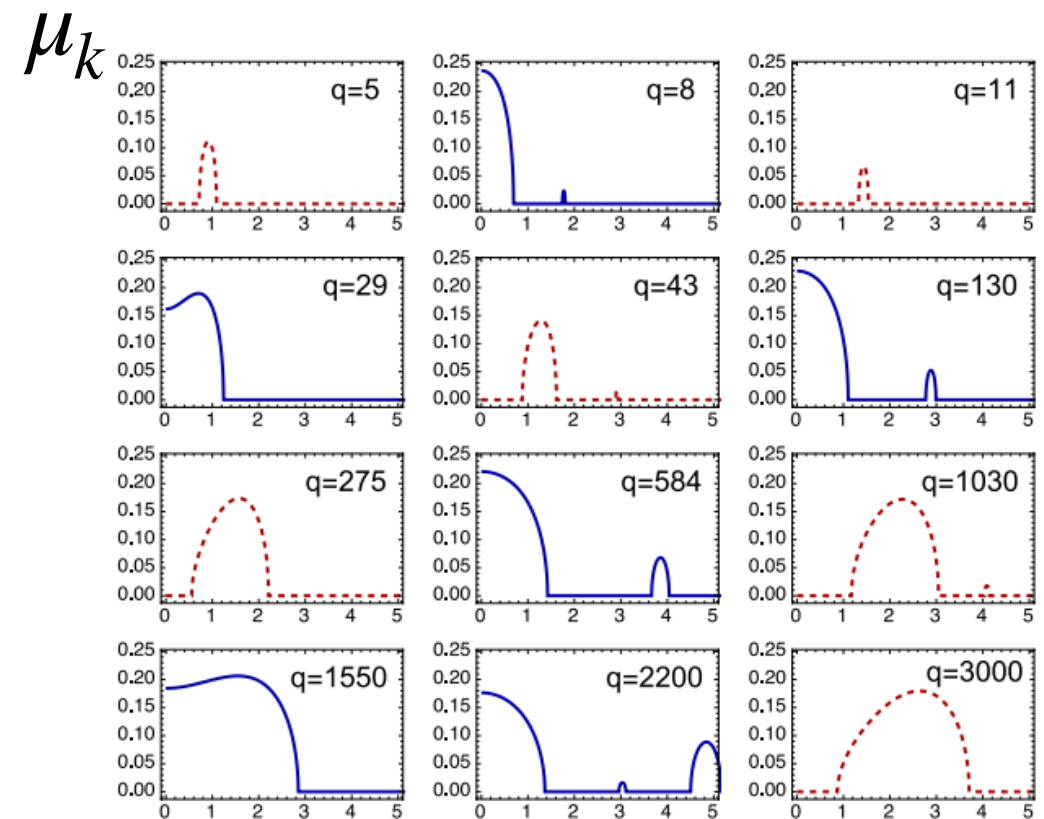
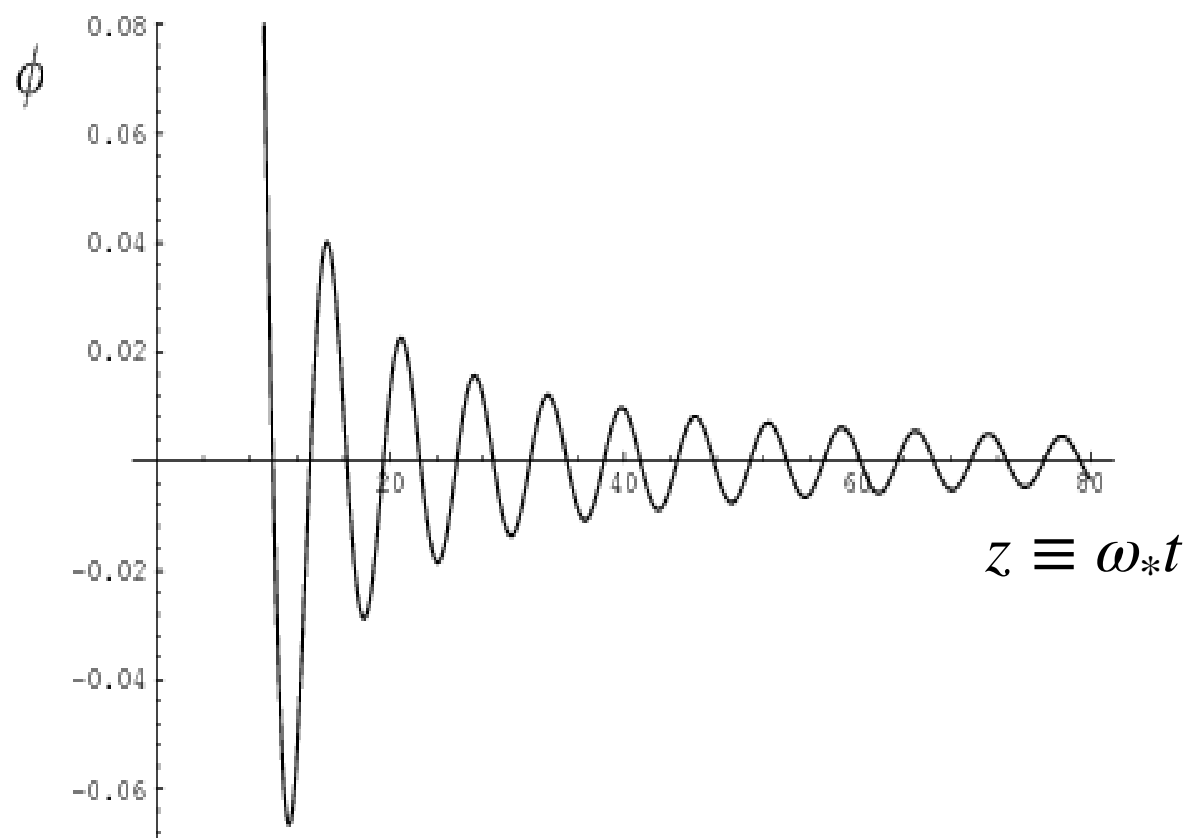
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$$\kappa \equiv k/\omega_*$$

SCALAR (P)REHEATING

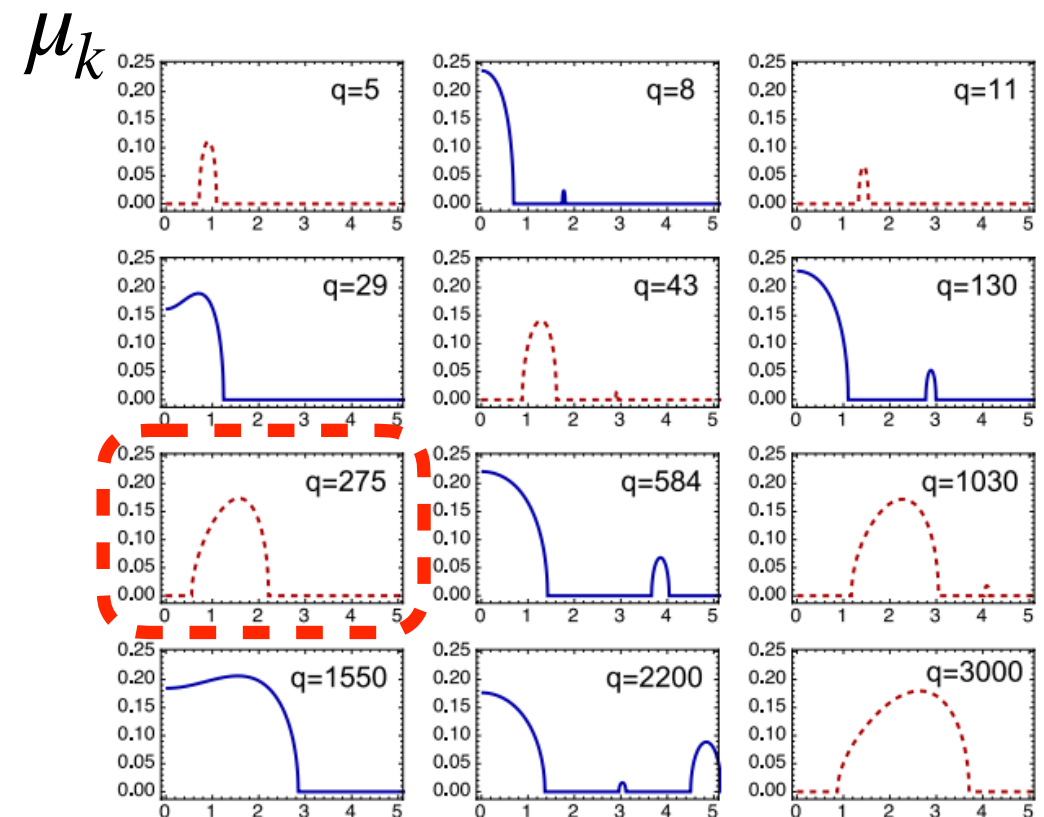
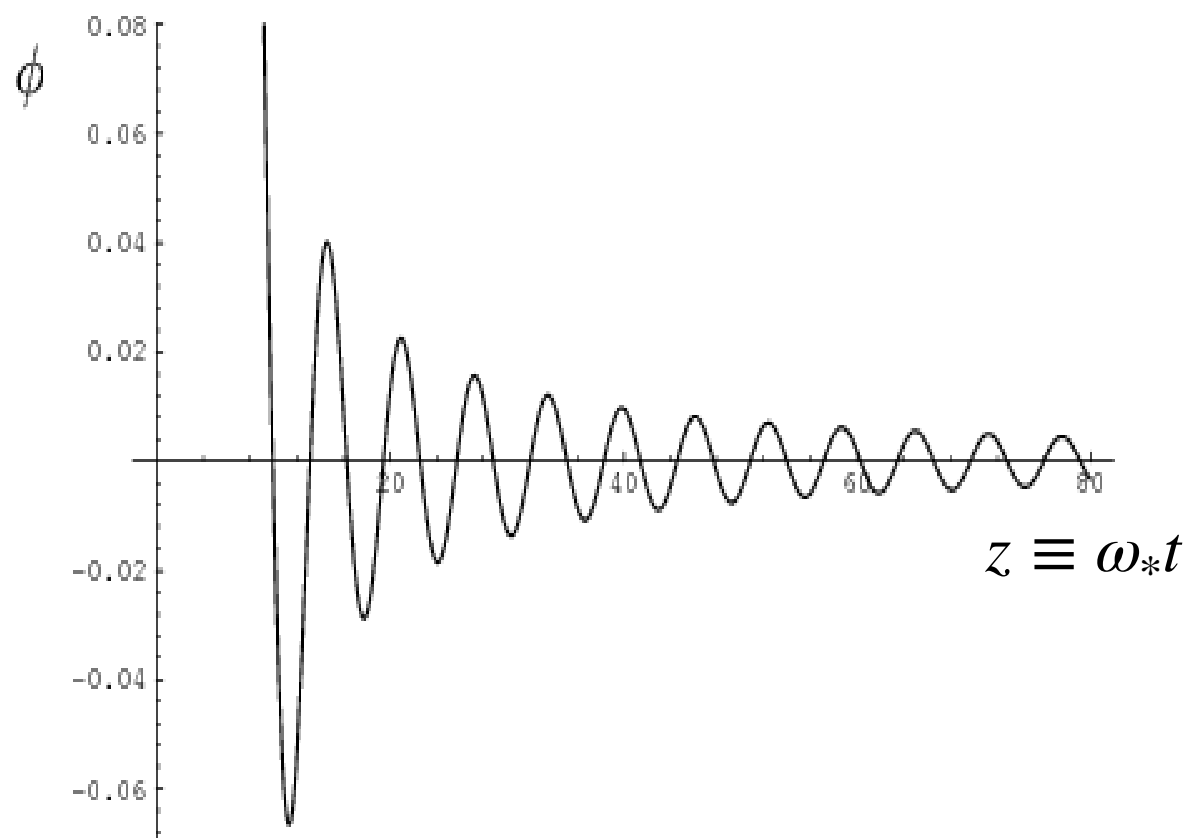
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$$\kappa \equiv k/\omega_*$$

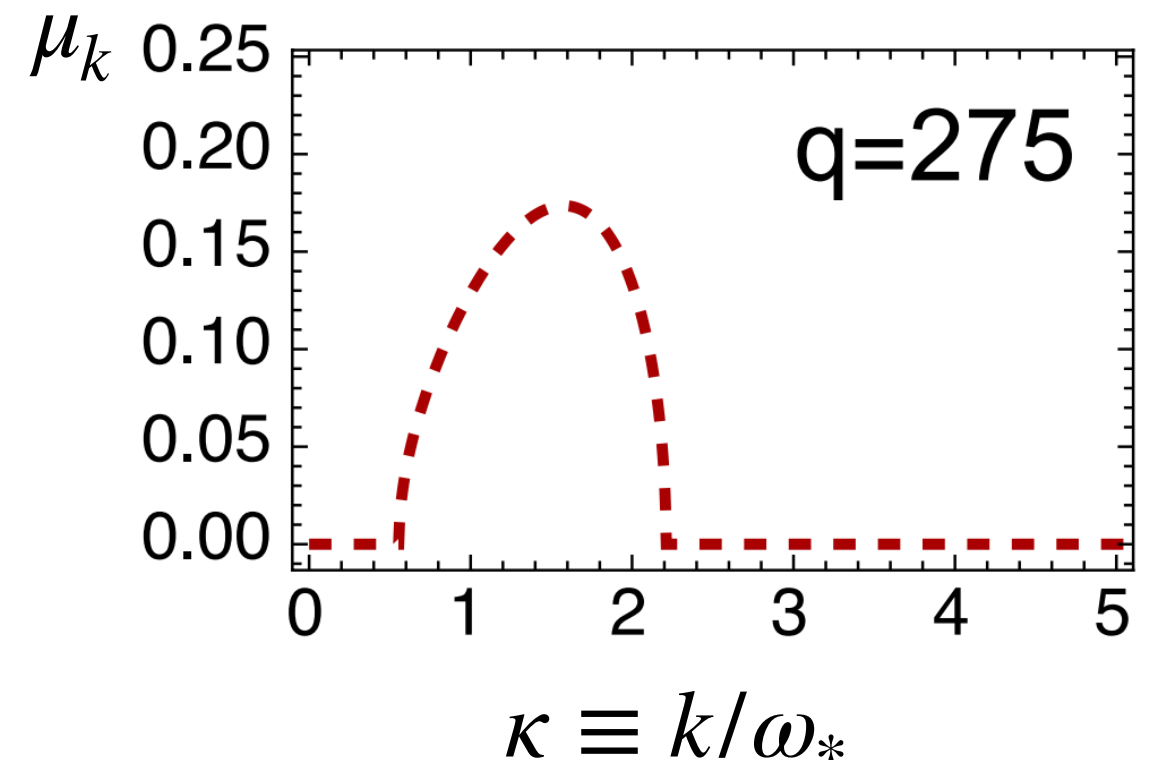
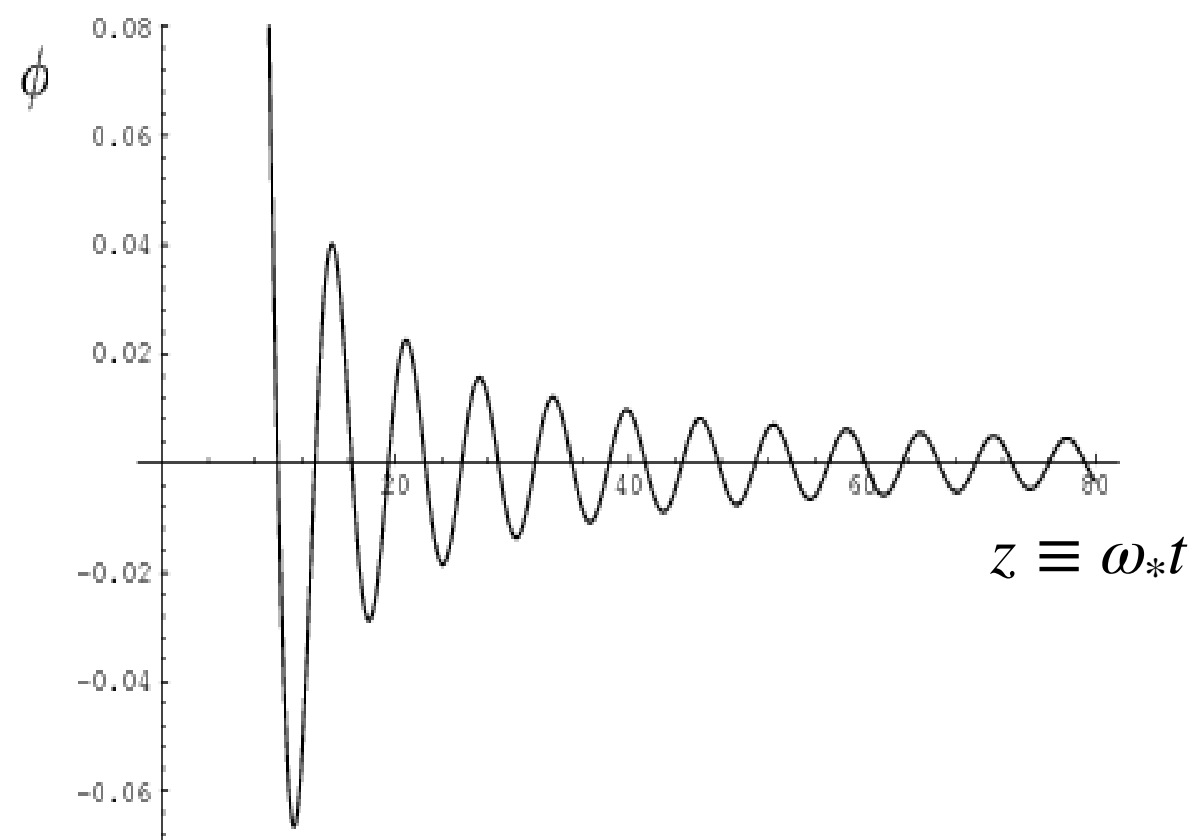
SCALAR (P)REHEATING

1) Chaotic Scenarios: PARAMETRIC RESONANCE

MATTER FIELD FLUCTUATIONS

$$\left. \begin{array}{l} \text{Massless : } X_k'' + (\kappa^2 + q \operatorname{cn}^2(z)) X_k = 0 \quad (\text{Lamé Eq.}) \\ \text{Massive : } X_k'' + (A_k - 2q \cos(2z)) X_k = 0 \quad (\text{Mathieu Eq.}) \end{array} \right\} \begin{array}{l} X_k \sim e^{\mu_k t} \\ n_k \sim e^{\mu_k t} \end{array}$$

(n = 4) (n = 2)



SCALAR (P)REHEATING

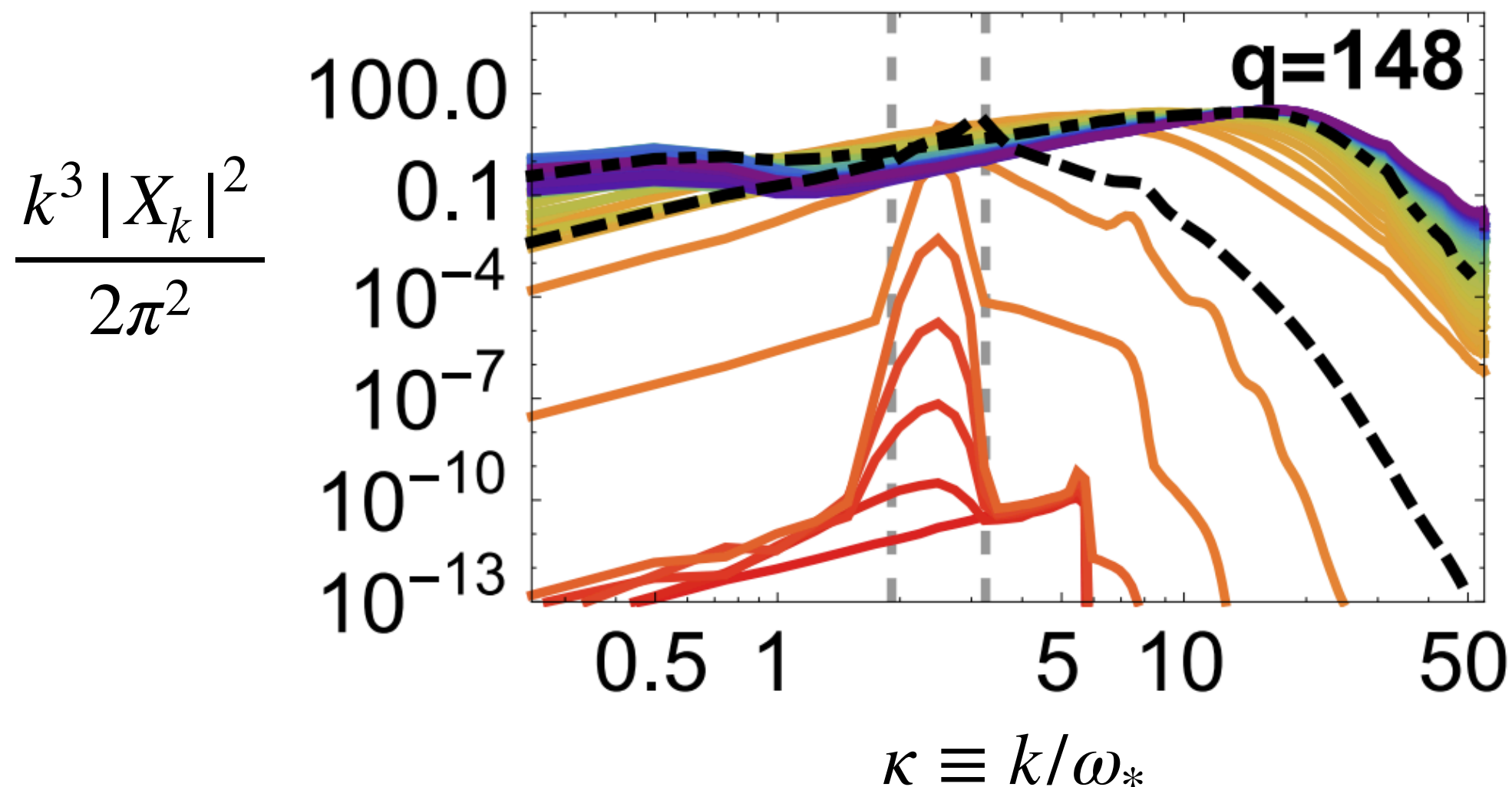
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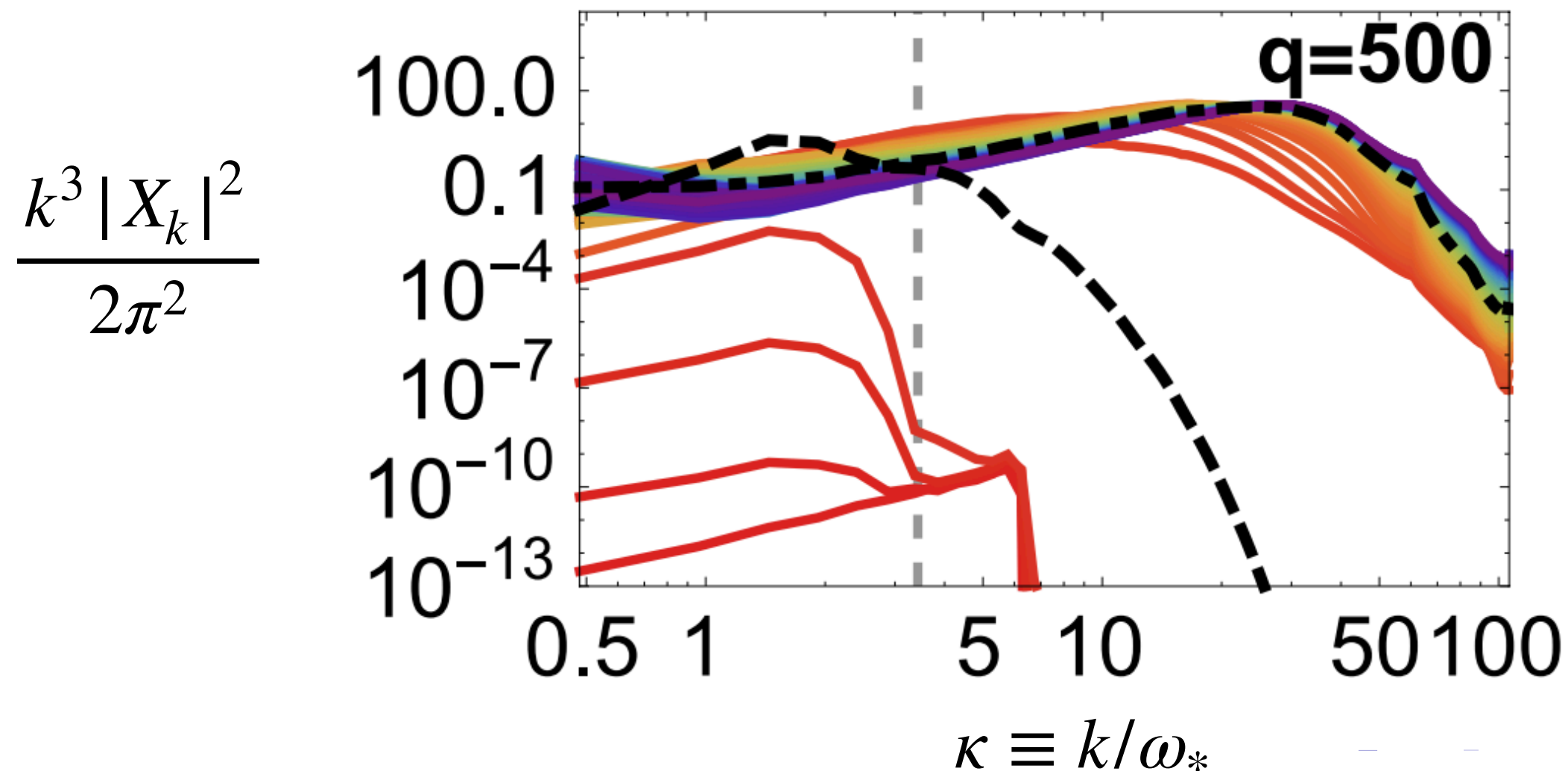


SCALAR (P)REHEATING

1) Chaotic Scenarios: PARAMETRIC RESONANCE

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

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

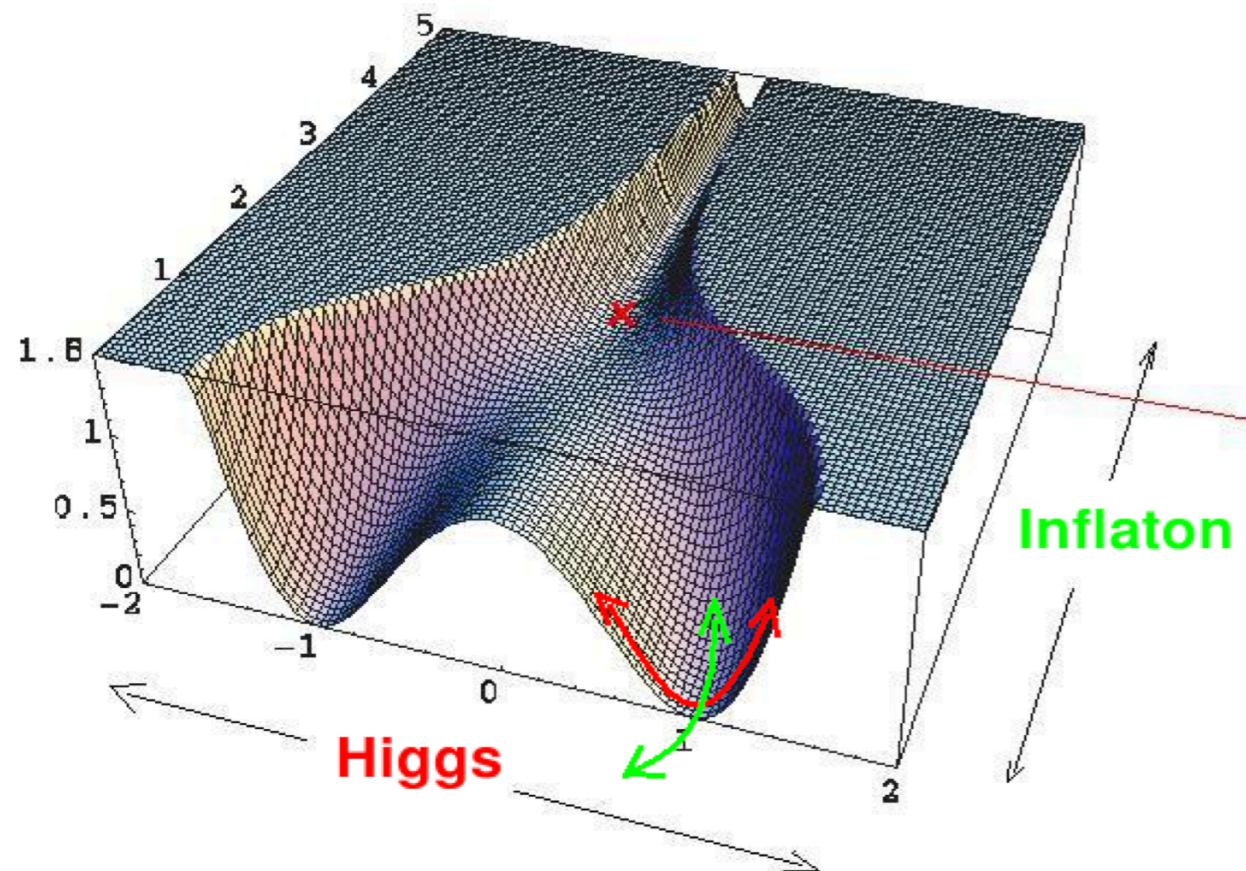


SCALAR (P)REHEATING

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

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

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

Self-coupling

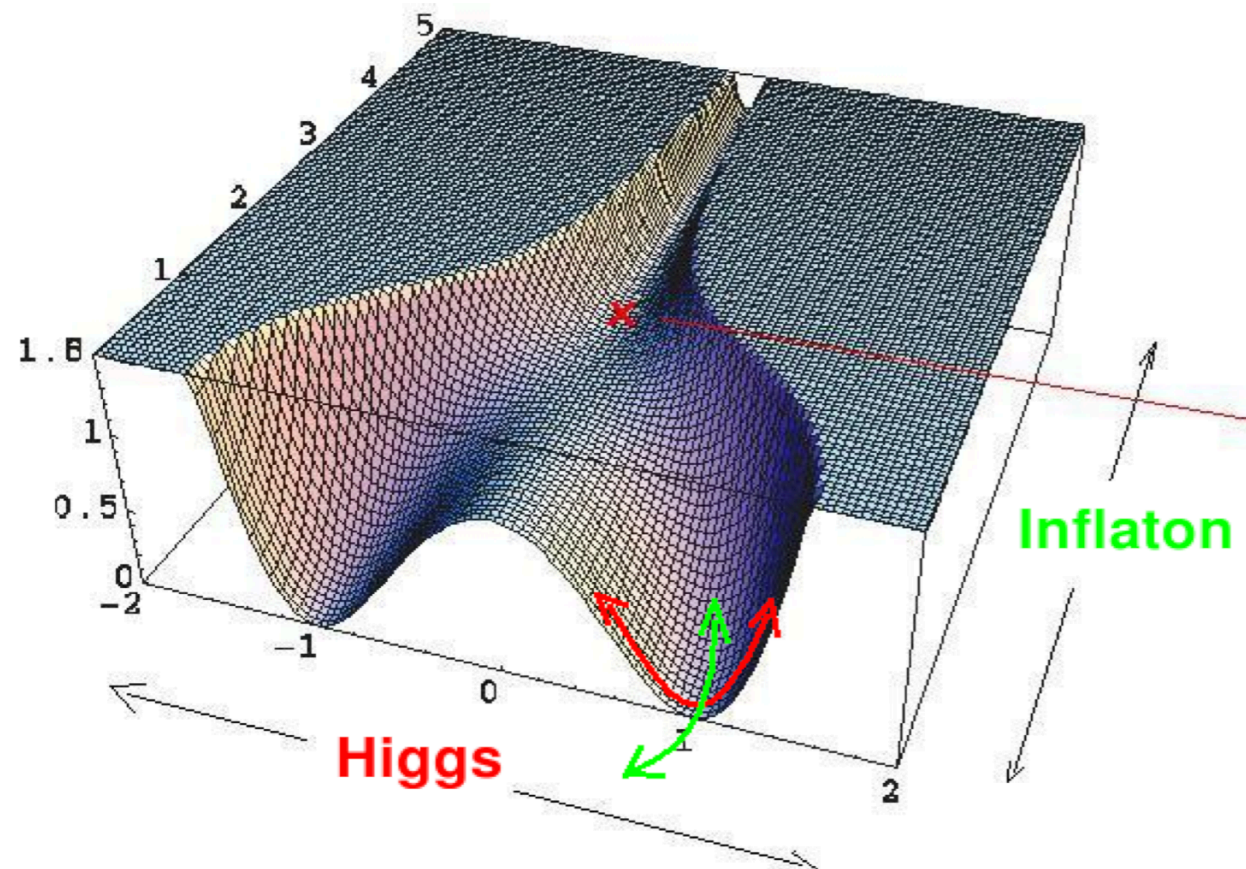
V.E.V.

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

$$\phi_c \equiv m/g$$

Critical
value

Hybrid Preheating



SCALAR (P)REHEATING

2) Hybrid Scenarios : SPINODAL INSTABILITY

inflaton mass $\nearrow$ coupling $\nearrow$

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

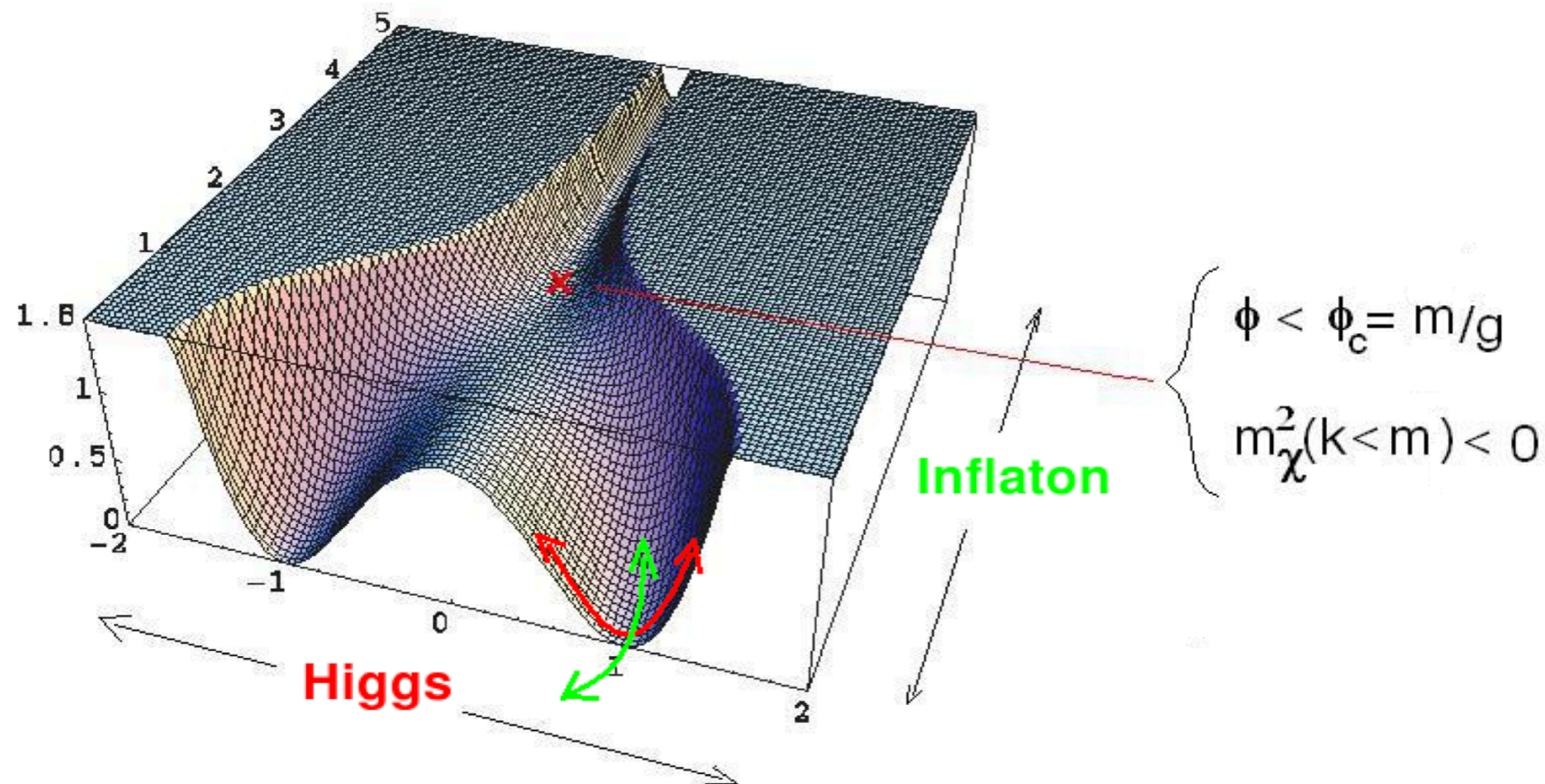
$$\ddot{\chi}_k + \left(k^2 + m^2 \left(\frac{\phi^2}{\phi_c^2} - 1\right) + \lambda|\chi|^2\right)\chi_k = 0$$

Self-coupling $\nwarrow$ V.E.V. $\nwarrow$

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SCALAR (P)REHEATING

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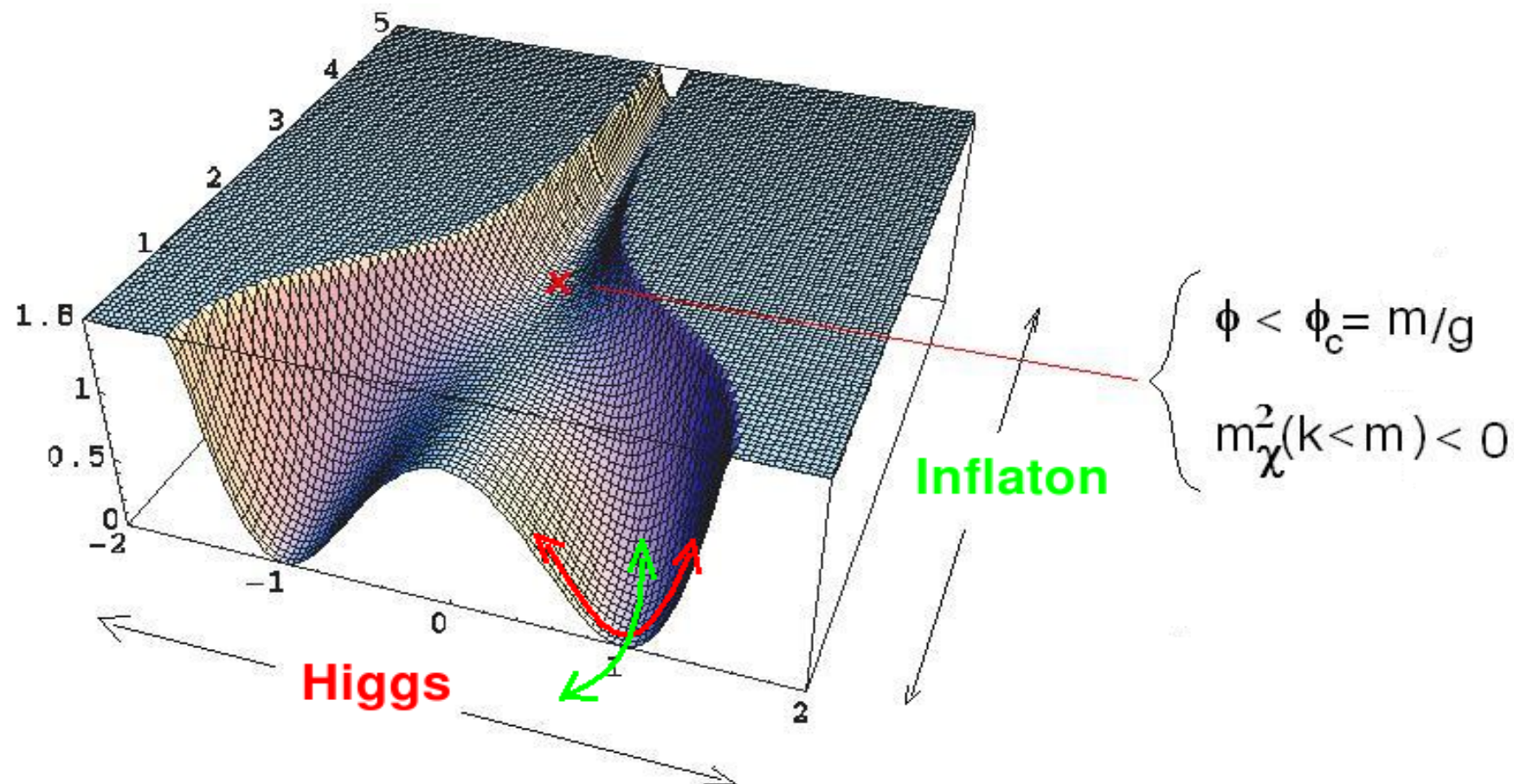
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$$(k < m = \sqrt{\lambda}v)$$

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

Hybrid Preheating



SCALAR (P)REHEATING

2) Hybrid Scenarios : SPINODAL INSTABILITY

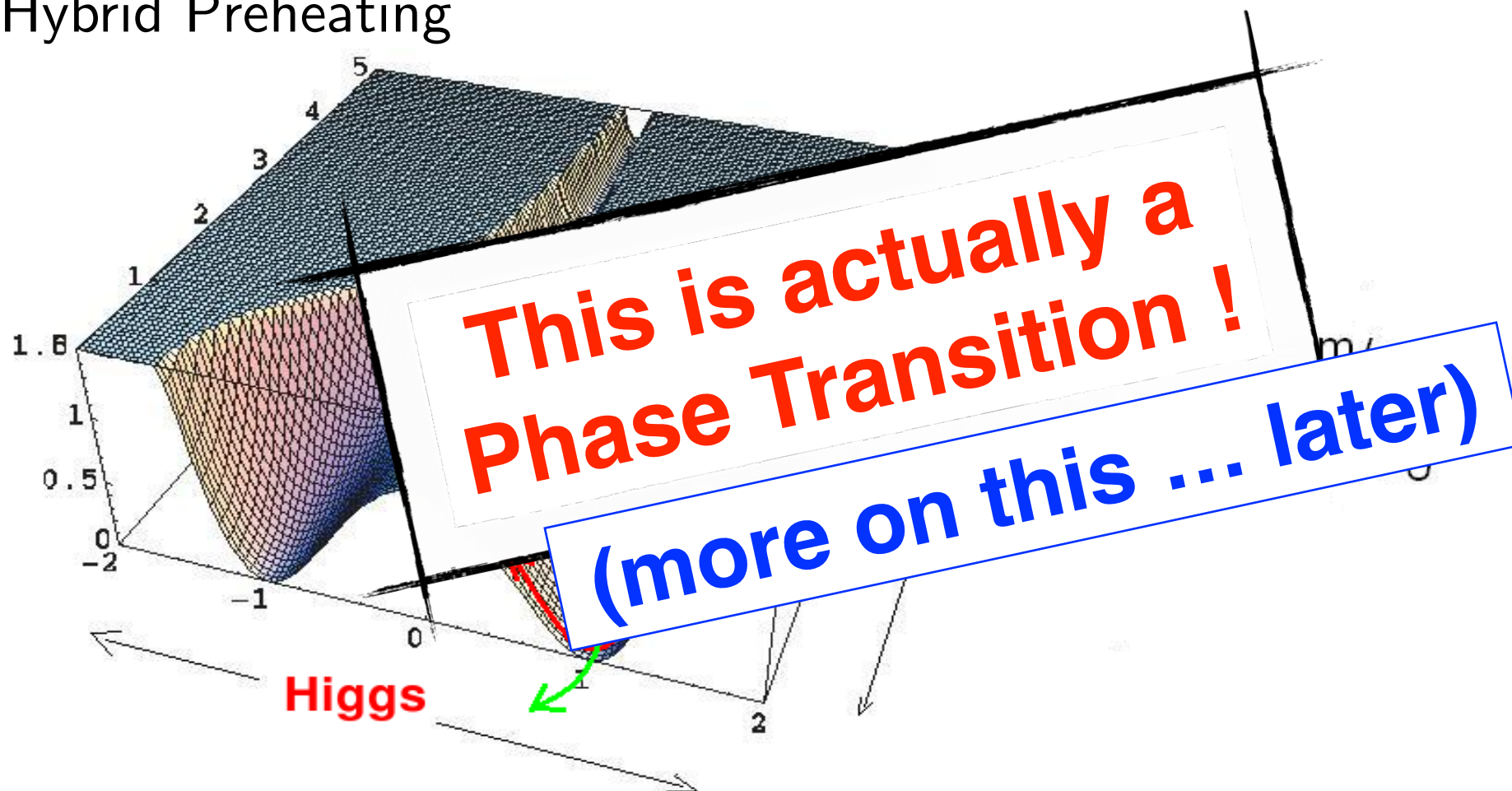
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Hybrid Preheating



INFLATIONARY PREHEATING

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

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

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- - -

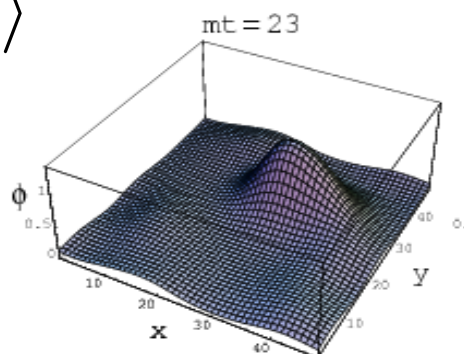
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$$\sqrt{\langle |\varphi|^2 \rangle}$$



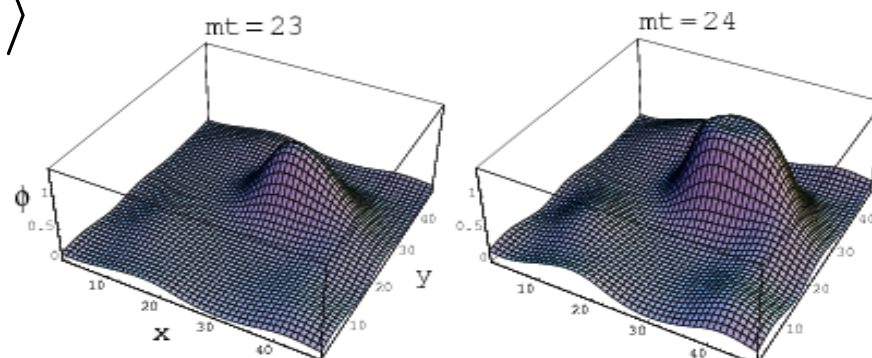
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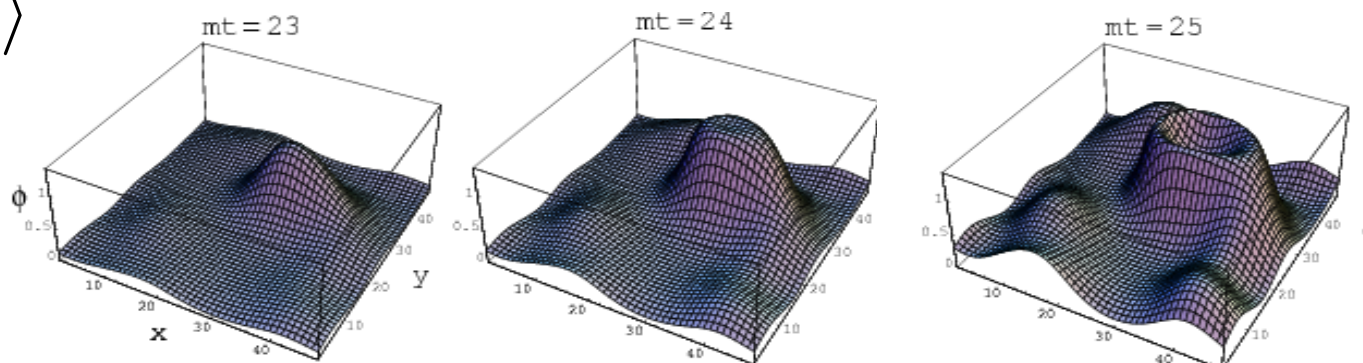
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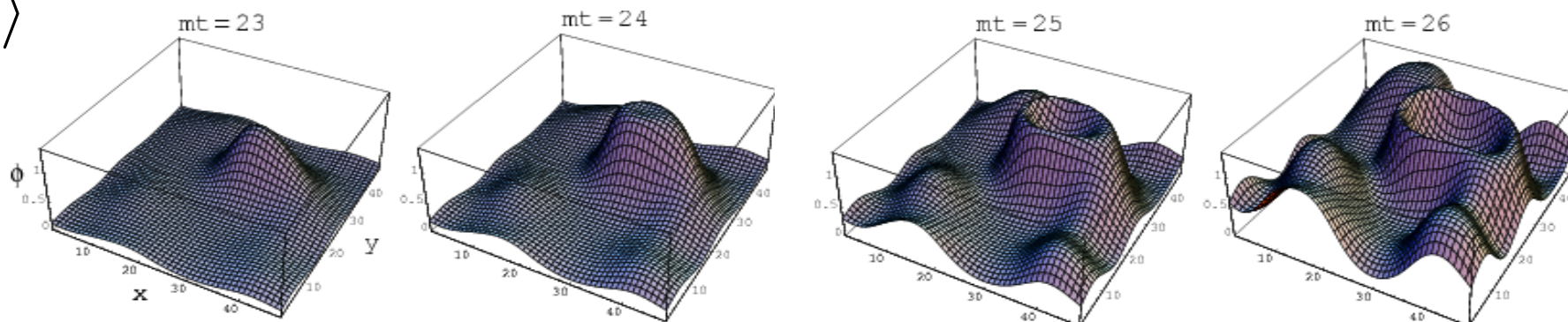
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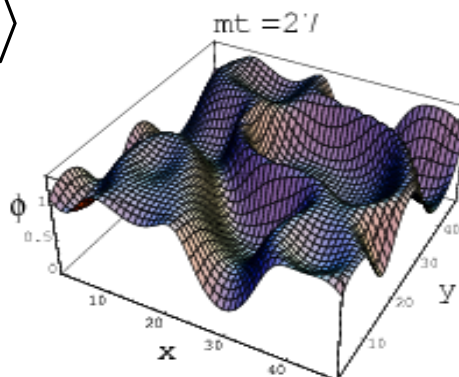
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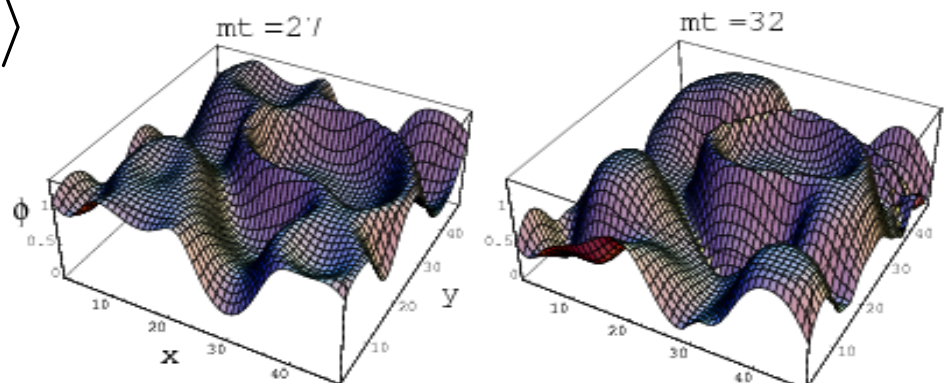
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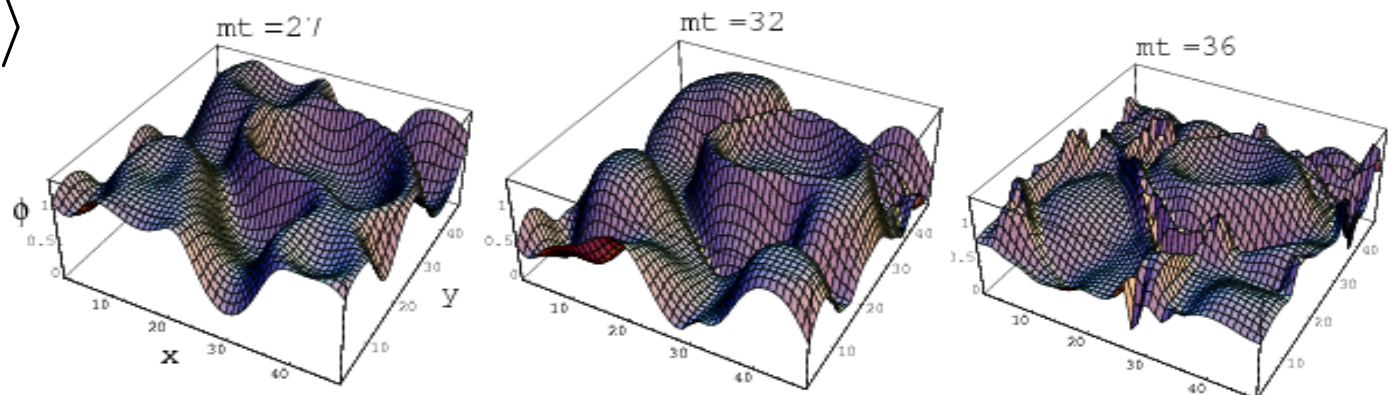
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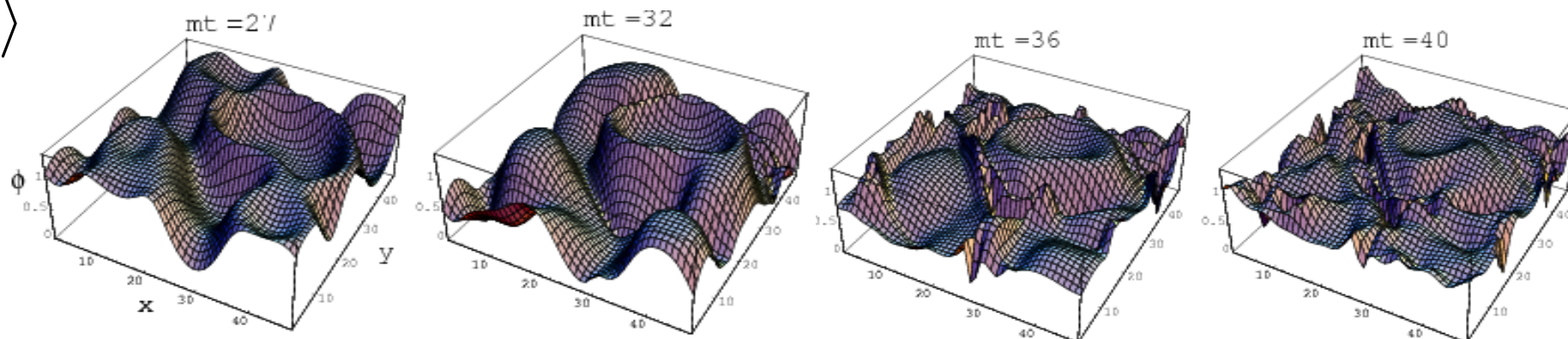
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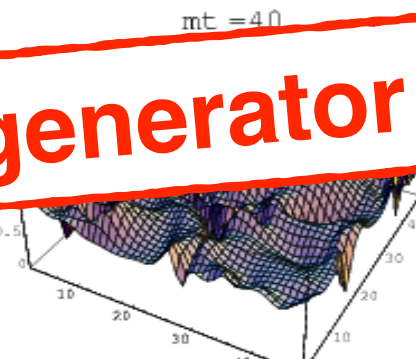
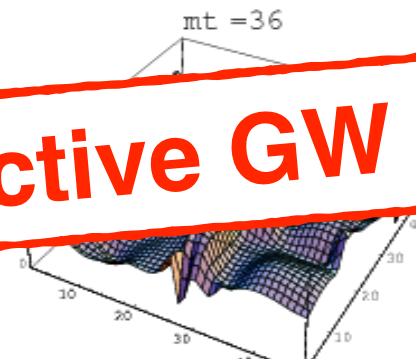
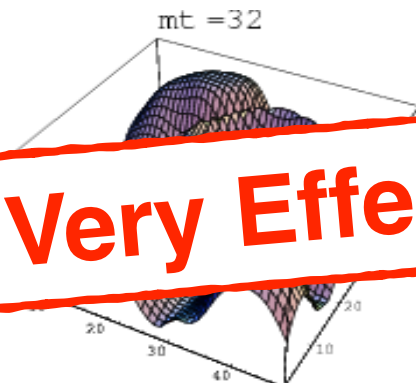
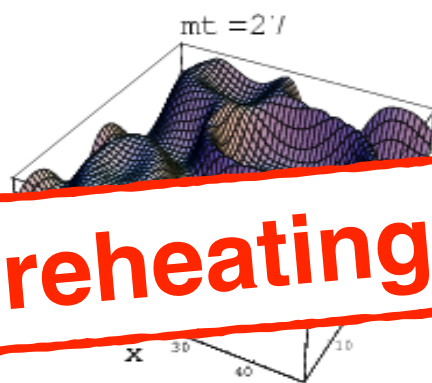
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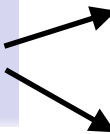
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$$\sqrt{\langle |\varphi|^2 \rangle}$$



Preheating: Very Effective GW generator !

INFLATIONARY PREHEATING

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

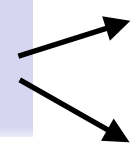
INFLATIONARY PREHEATING

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

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

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

INFLATIONARY PREHEATING

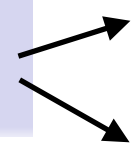
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- FLRW: $H^2 = \frac{8\pi G}{3}\rho$, $\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p)$, $\left\{ \begin{array}{l} \rho = \langle \rho_\phi + \rho_\chi + \dots \rangle \\ p = \langle p_\phi + p_\chi + \dots \rangle \end{array} \right.$

INFLATIONARY PREHEATING

Lattice Simulations: Dynamics  **non-linear**
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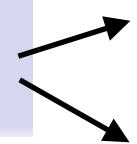
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- GW: $h''_{ij} + 2\mathcal{H}h'_{ij} - \nabla^2 h_{ij} = 16\pi G \Pi_{ij}^{\text{TT}}$, $\Pi_{ij}^{\text{TT}} = \{\partial_i \chi^a \partial_j \chi^a\}^{\text{TT}}$

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

INFLATIONARY PREHEATING

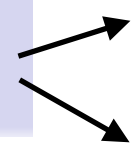
Lattice Simulations: Dynamics  **non-linear**
out-Eq

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TT: Non-local operation !

INFLATIONARY PREHEATING

Lattice Simulations: Dynamics  **non-linear**
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TT: Non-local operation !

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

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

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

INFLATIONARY PREHEATING

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

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

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TT: Non-local operation !

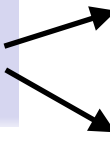
$\Pi_{ij}(\mathbf{k}, t) \equiv \int d^3\mathbf{x} e^{+i\mathbf{k}\mathbf{x}} \hat{\Pi}_{ij}(\mathbf{x}, t)$ (Fourier Transform)

Numerically Prohibited !

(TT-Projection)

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

INFLATIONARY PREHEATING

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

Building the Solution:
$$\left\{ \begin{array}{l} h_{ij}(\mathbf{k}, t) = \Lambda_{ij,lm}(\hat{\mathbf{k}}) u_{lm}(\mathbf{k}, t) \\ u_{lm}(\mathbf{k}, t) = \int_{t_0}^t dt' G(t - t') \Pi_{lm}^{\text{eff}}(\mathbf{k}, t') \end{array} \right.$$

INFLATIONARY PREHEATING

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

Building the Solution:
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1) Non-Physical eq.:

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

INFLATIONARY PREHEATING

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

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

1) Non-Physical eq.:

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

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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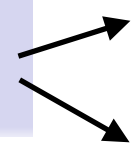
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INFLATIONARY PREHEATING

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

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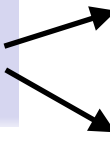
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2) Fourier transform: $u_{ij}(\mathbf{x}, t) \rightarrow u_{ij}(\mathbf{k}, t)$

Only when needed !

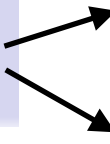
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INFLATIONARY PREHEATING

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

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

INFLATIONARY PREHEATING

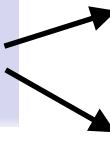
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$$\rho_{GW} = \frac{1}{32\pi G L^3} \times \int k^2 dk \int d\Omega \Lambda_{ij,lm}(\hat{\mathbf{k}}) \dot{u}_{ij}(t, \mathbf{k}) \dot{u}_{lm}^*(t, \mathbf{k})$$

INFLATIONARY PREHEATING

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

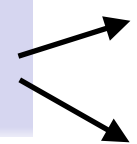
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INFLATIONARY PREHEATING

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

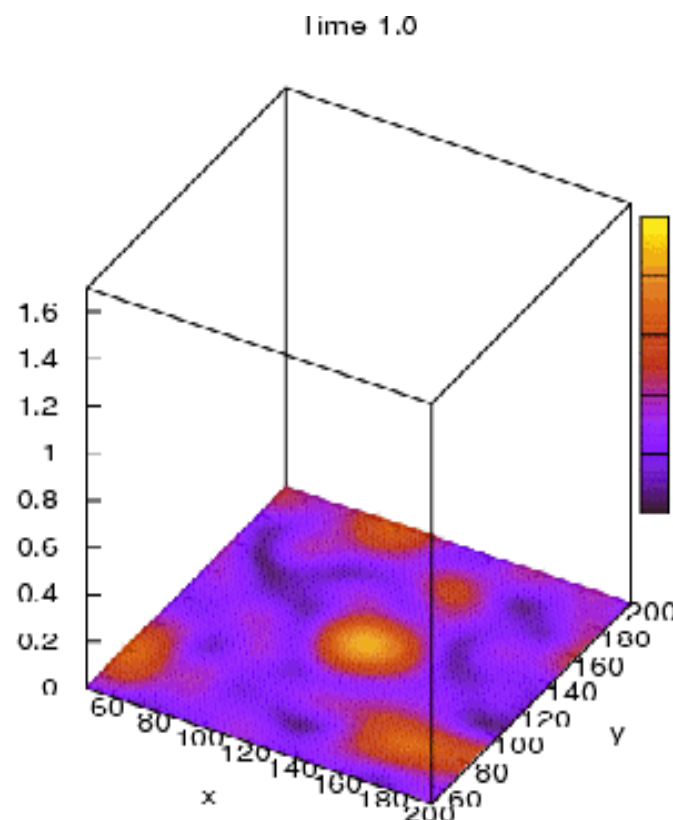
INFLATIONARY PREHEATING

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

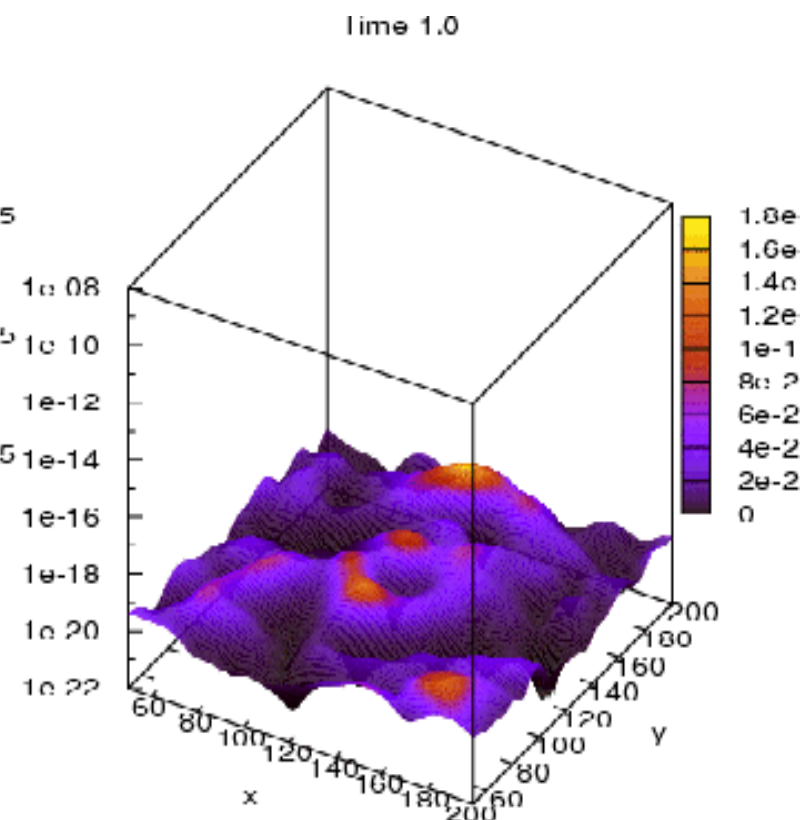
Hybrid Preheating

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

Animation by
Alfonso Sastre



Higgs



GW (Energy density)

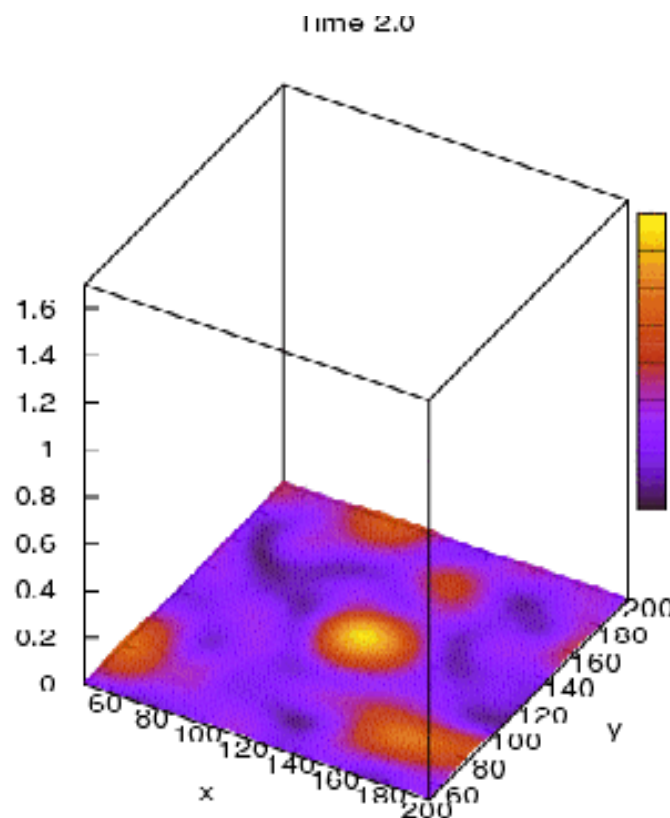
INFLATIONARY PREHEATING

Lattice Simulations: Dynamics $\rightarrow$ non-linear
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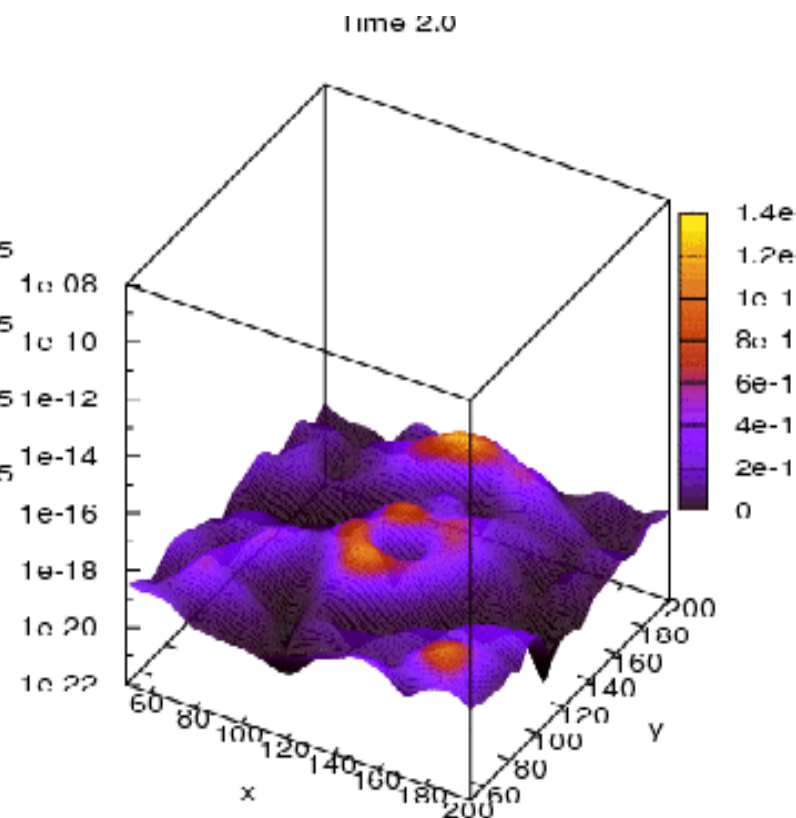
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Higgs



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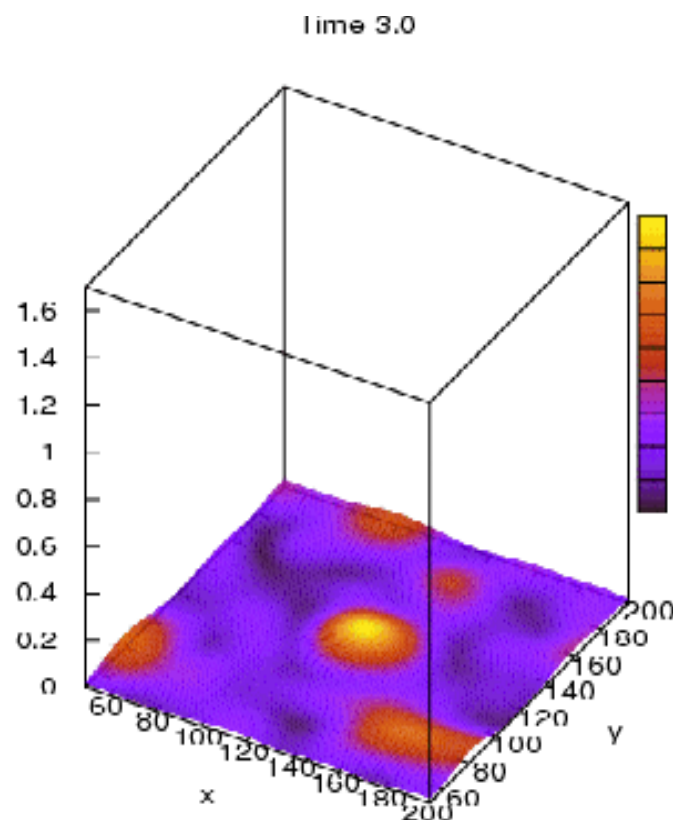
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Lattice Simulations: Dynamics $\rightarrow$ non-linear
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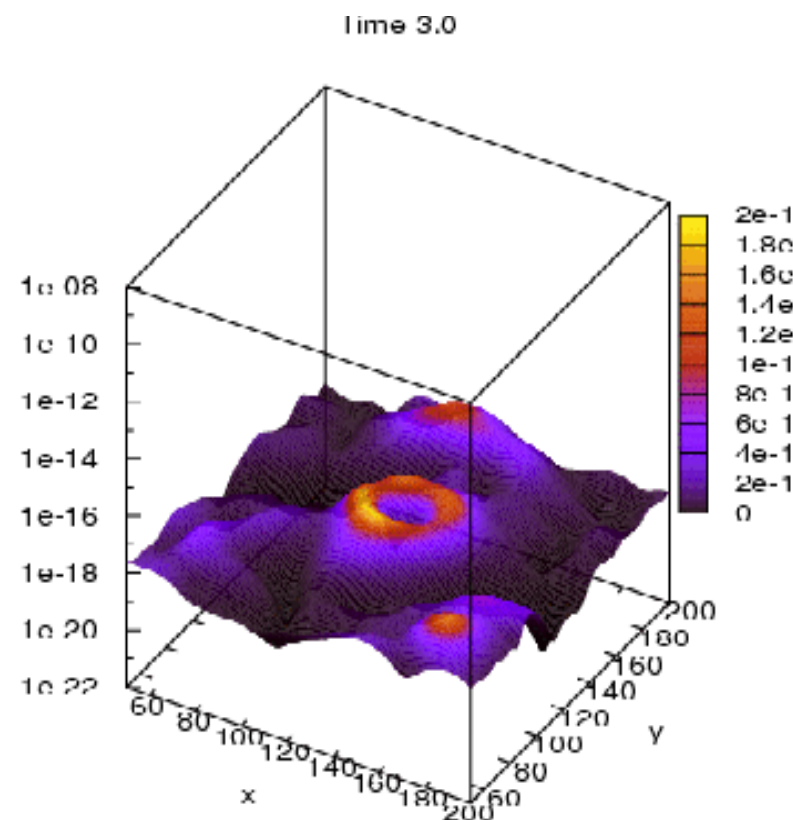
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GW (Energy density)

INFLATIONARY PREHEATING

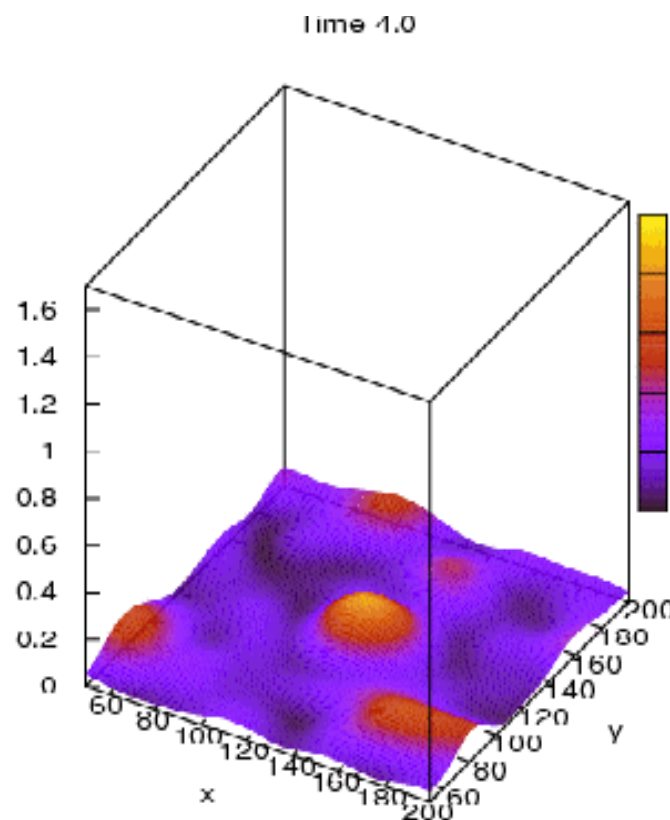
Lattice Simulations: Dynamics

non-linear
out-Eq

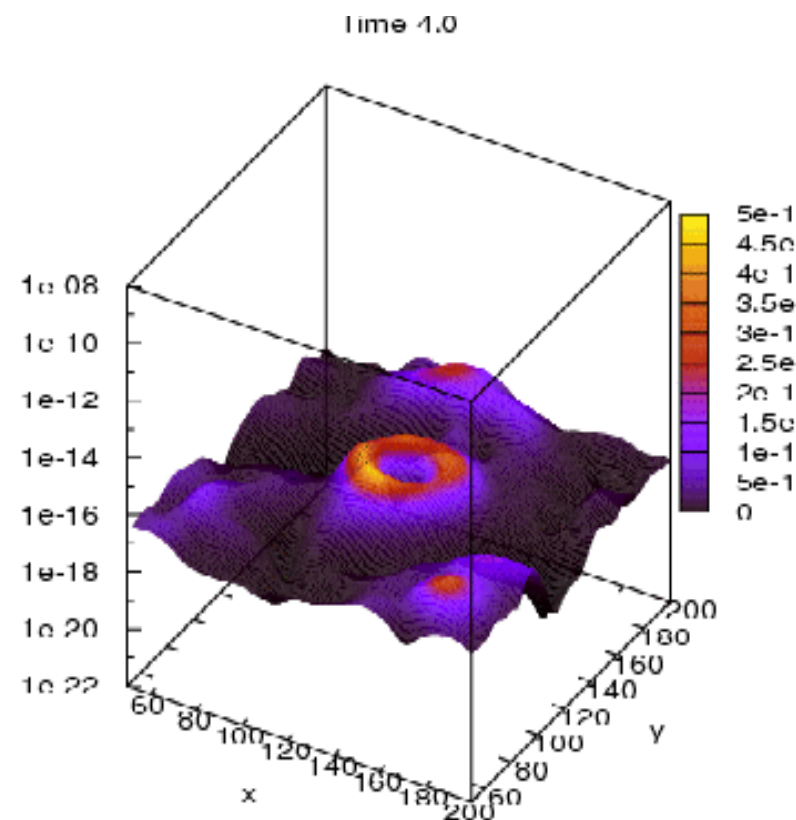
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Higgs



GW (Energy density)

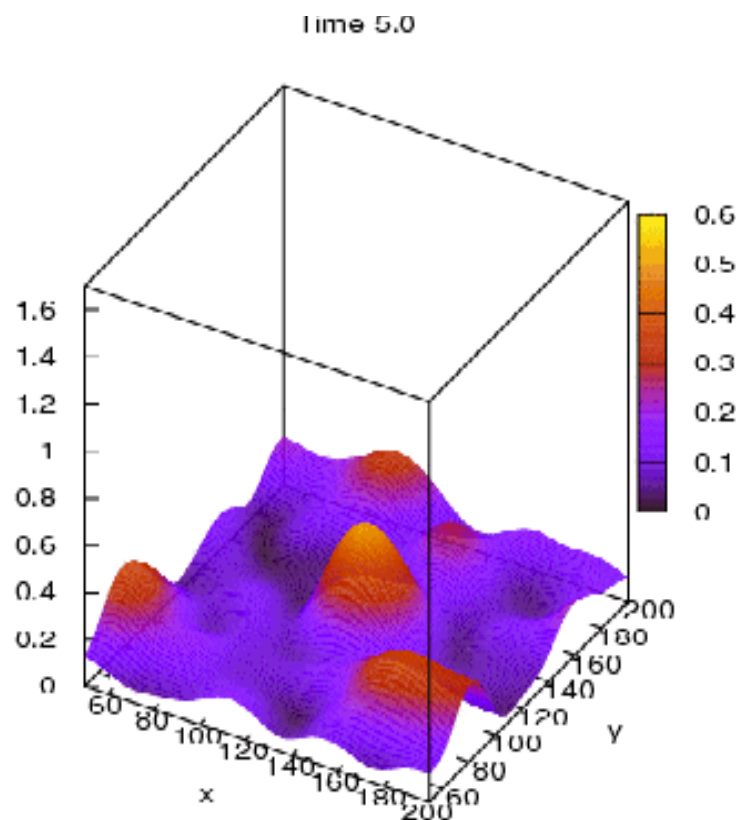
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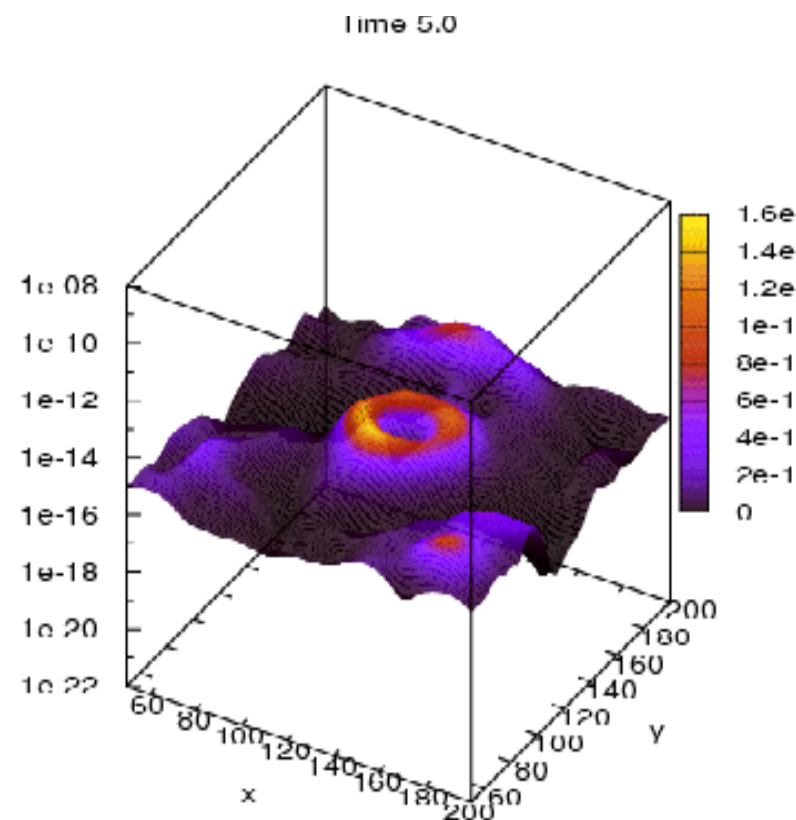
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Higgs



GW (Energy density)

INFLATIONARY PREHEATING

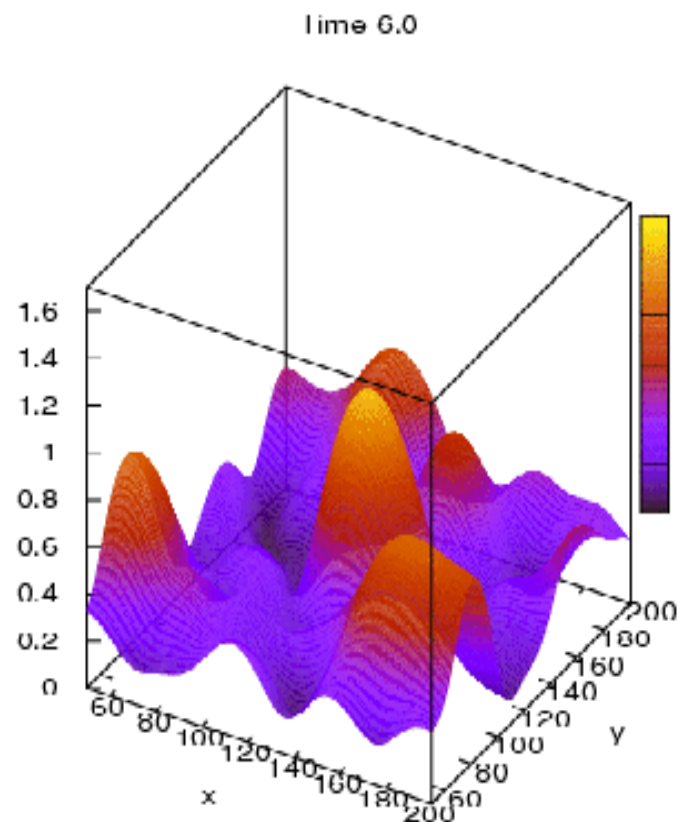
Lattice Simulations: Dynamics

non-linear
out-Eq

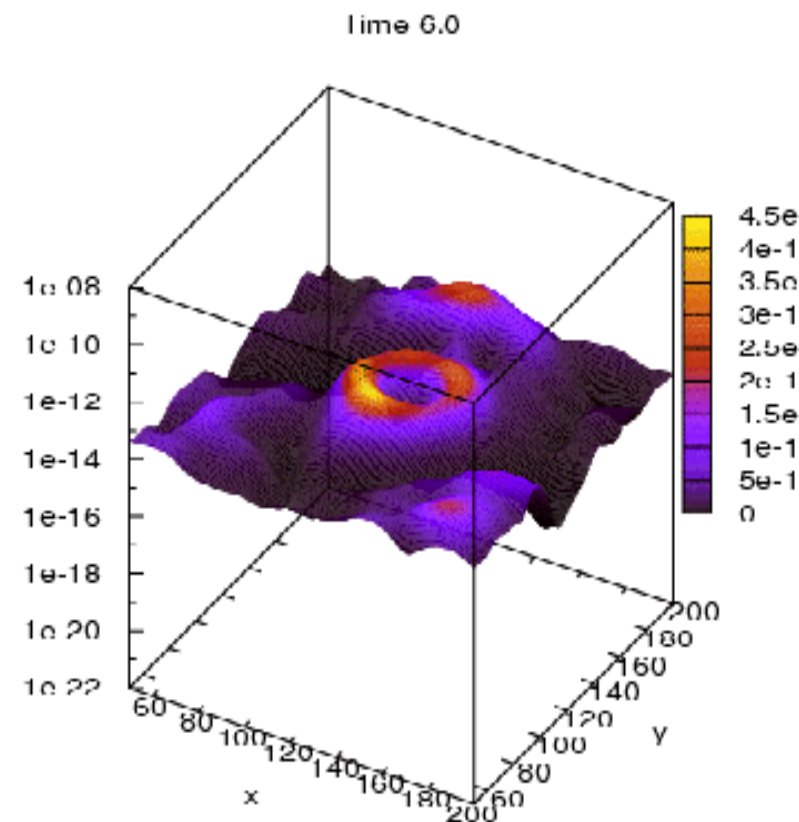
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Higgs



GW (Energy density)

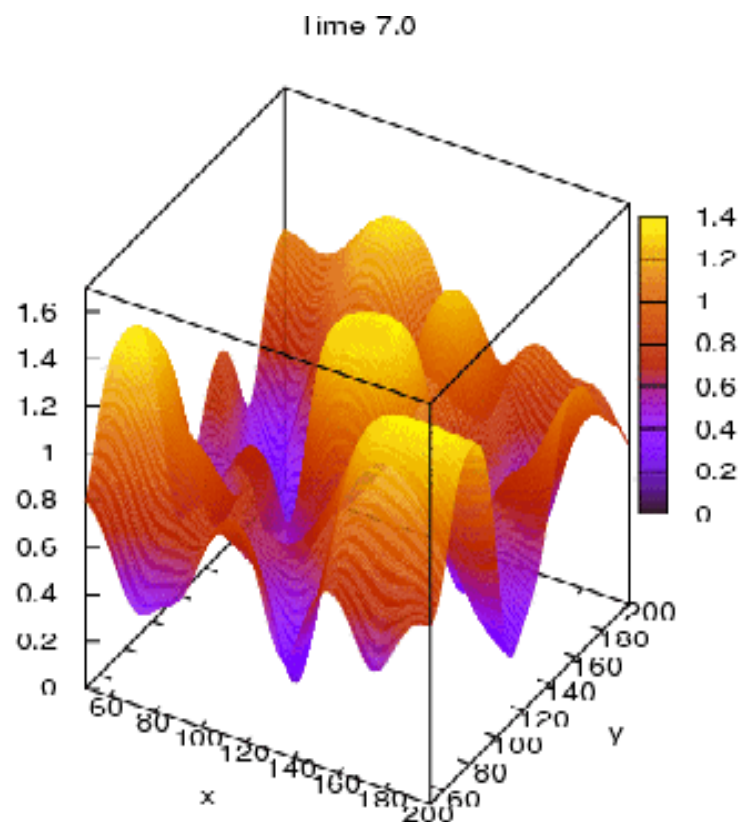
INFLATIONARY PREHEATING

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

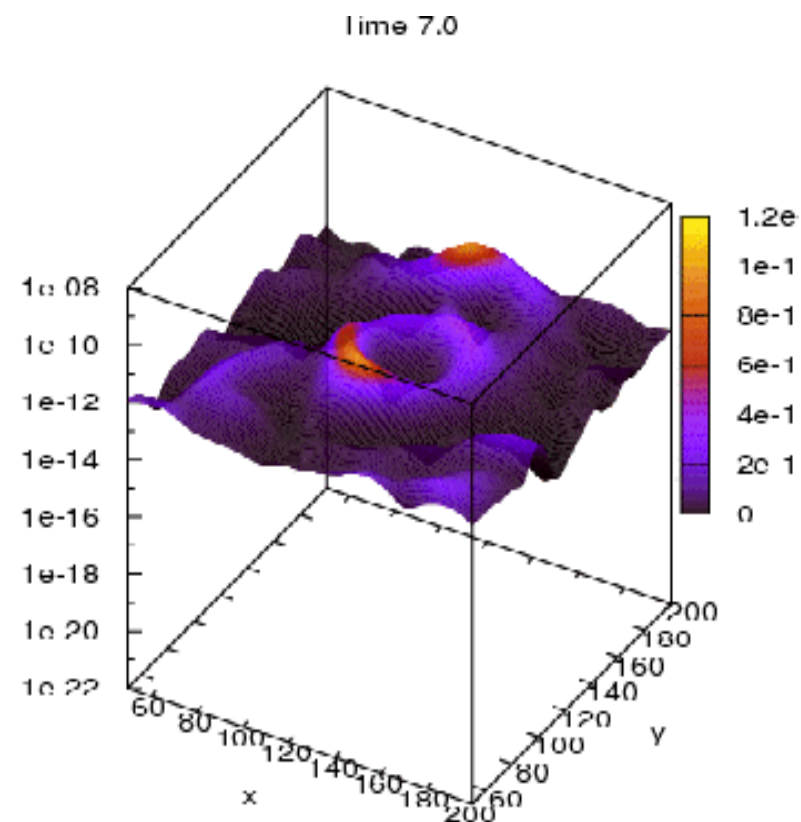
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Higgs



GW (Energy density)

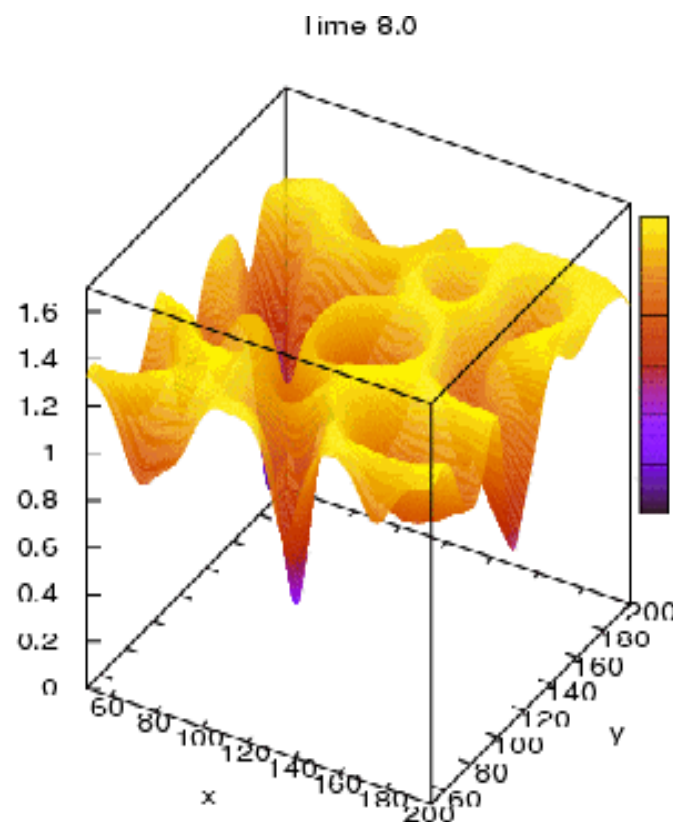
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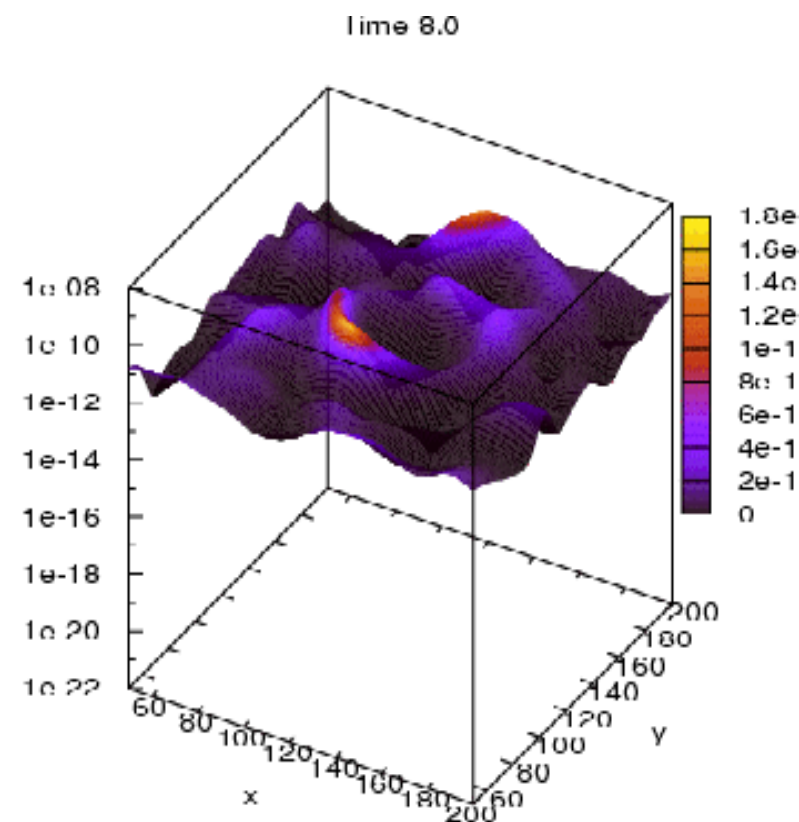
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Higgs



GW (Energy density)

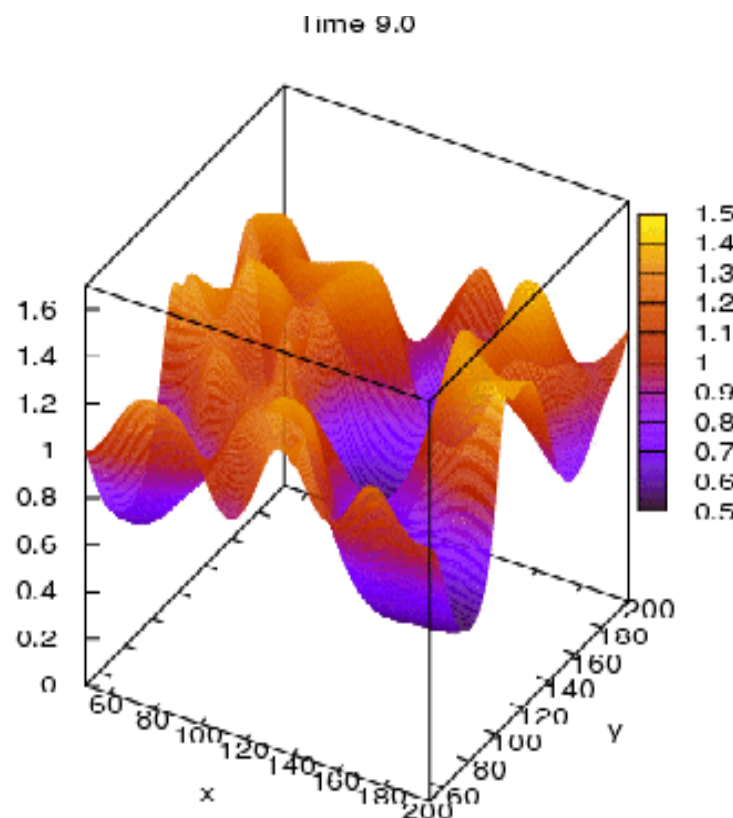
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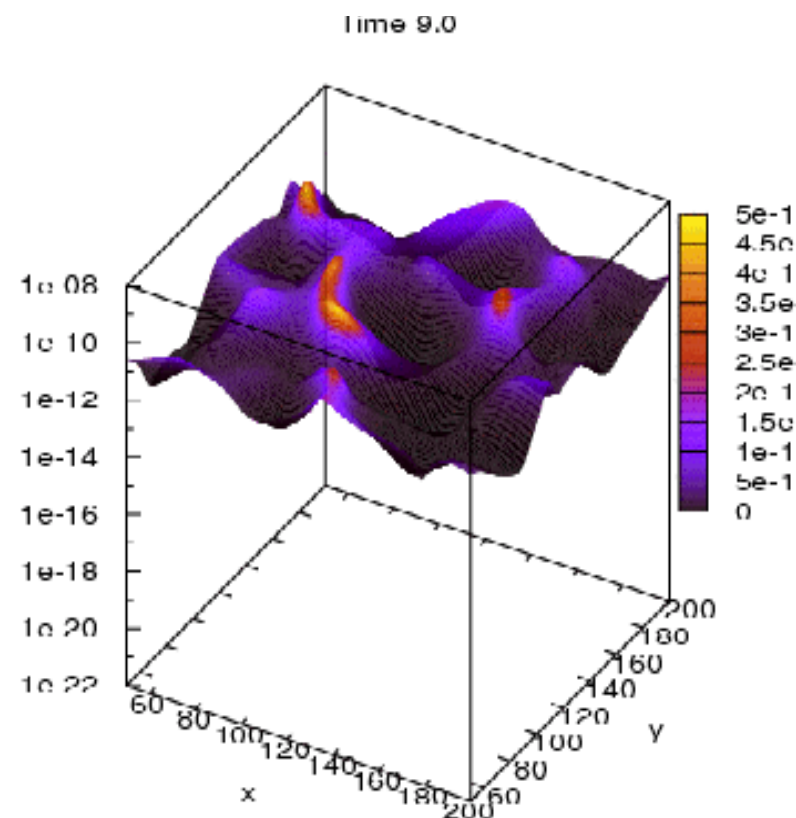
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GW (Energy density)

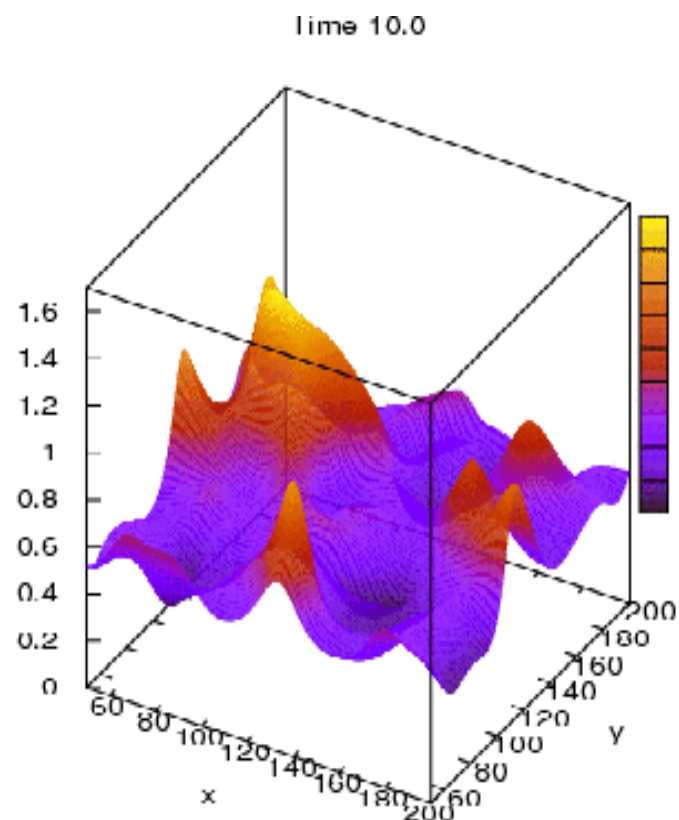
INFLATIONARY PREHEATING

Lattice Simulations: Dynamics $\rightarrow$ non-linear
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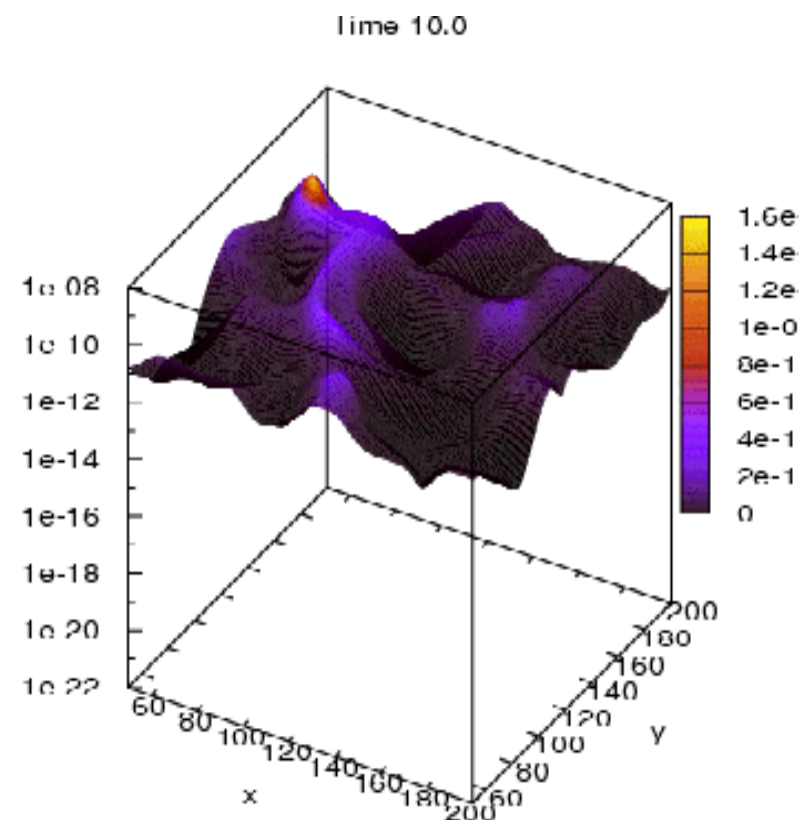
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GW (Energy density)

INFLATIONARY PREHEATING

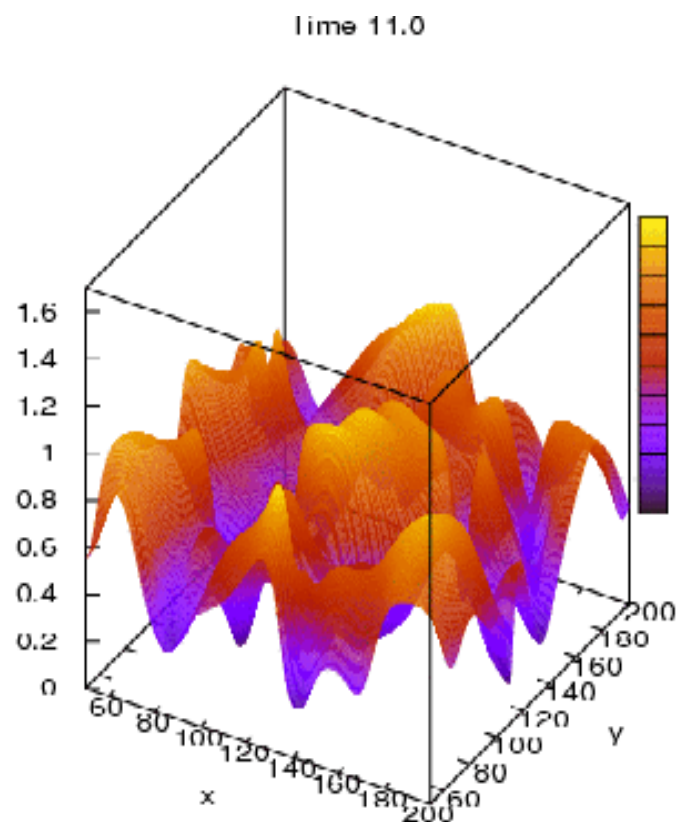
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non-linear
out-Eq

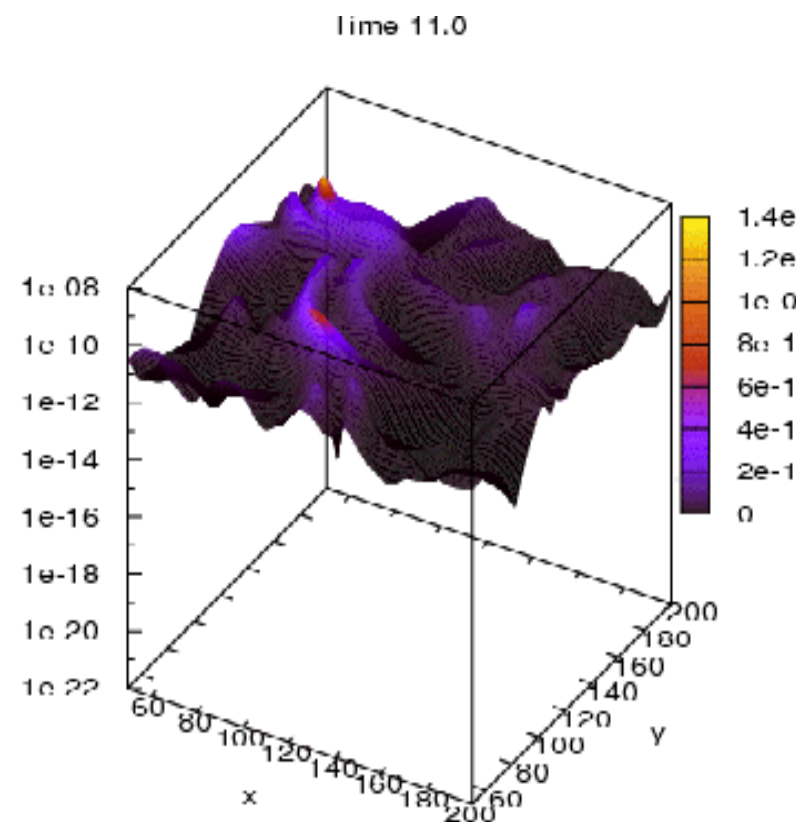
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GW (Energy density)

INFLATIONARY PREHEATING

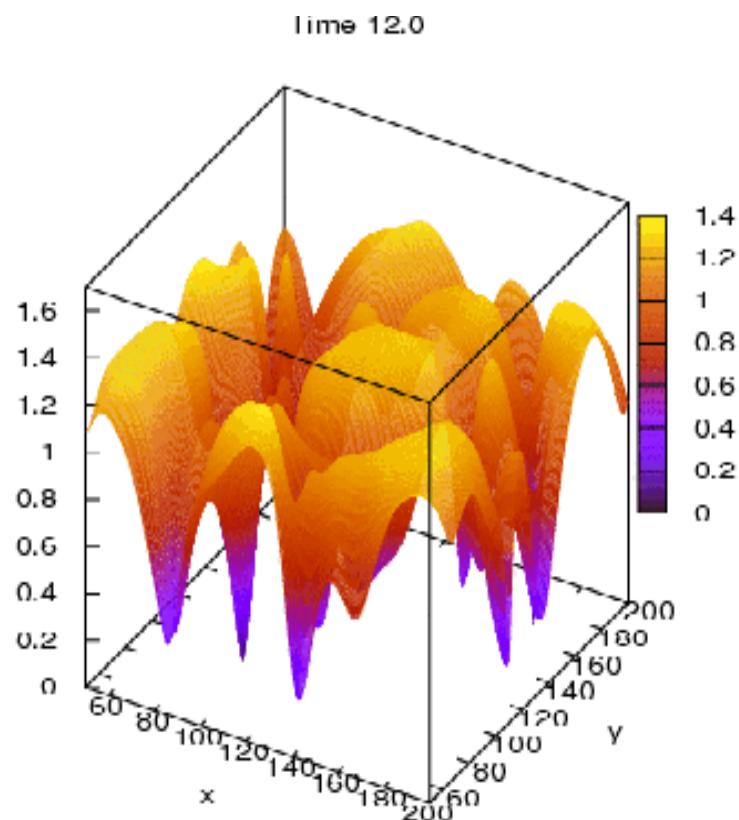
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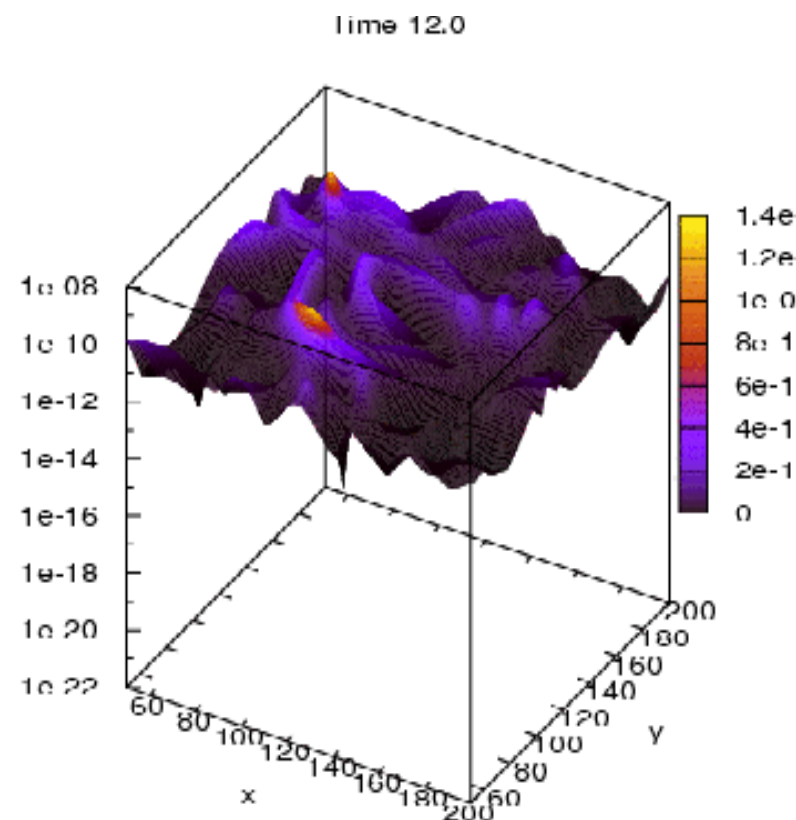
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Higgs



GW (Energy density)

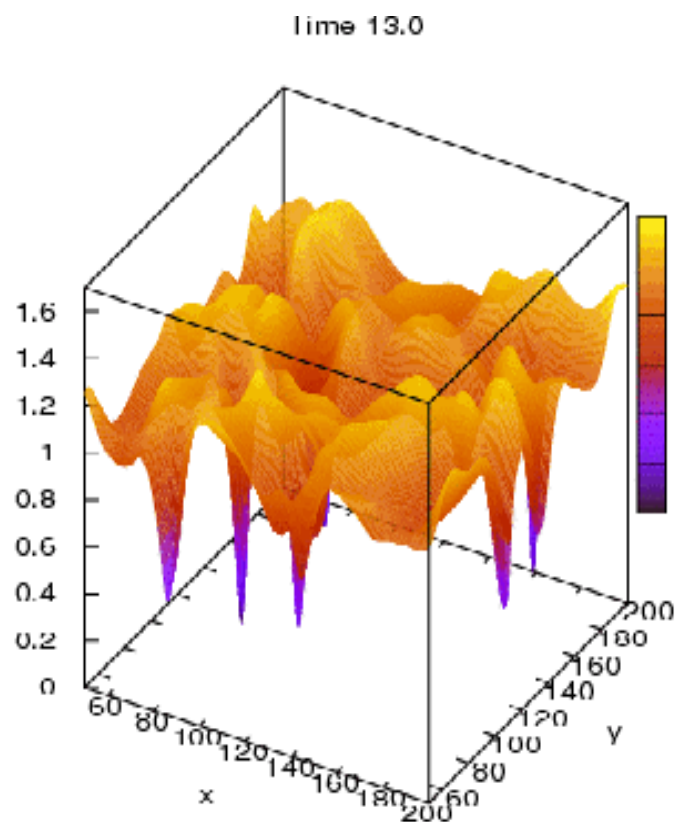
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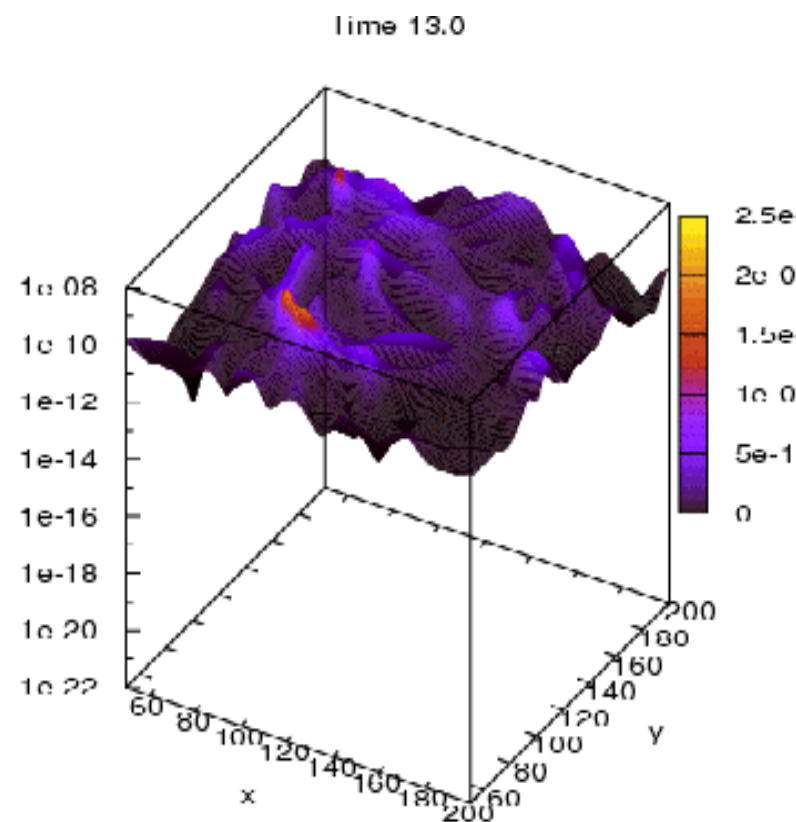
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Higgs



GW (Energy density)

INFLATIONARY PREHEATING

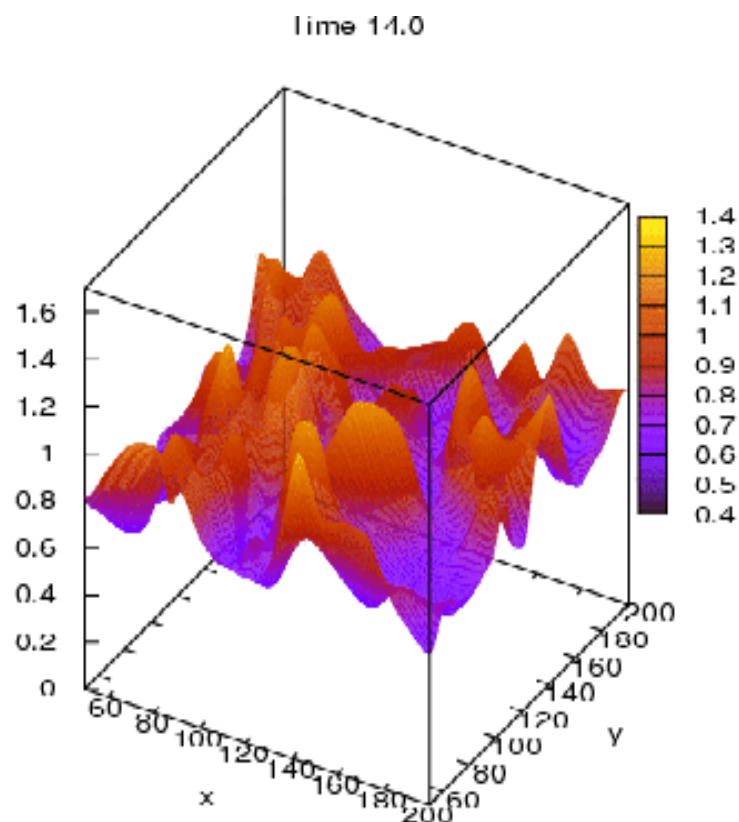
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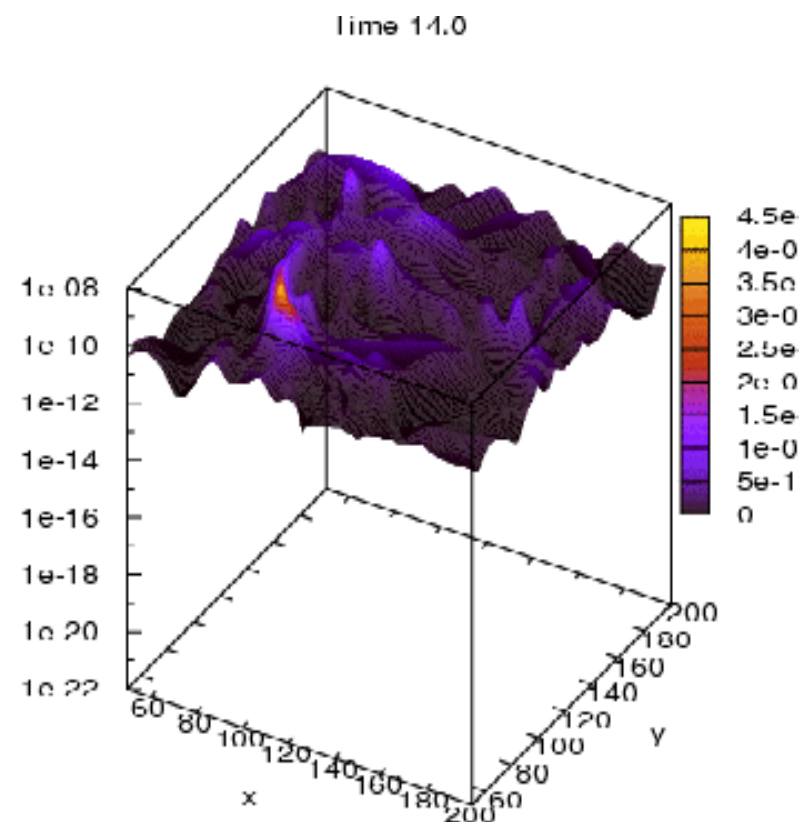
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Animation by
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Higgs



GW (Energy density)

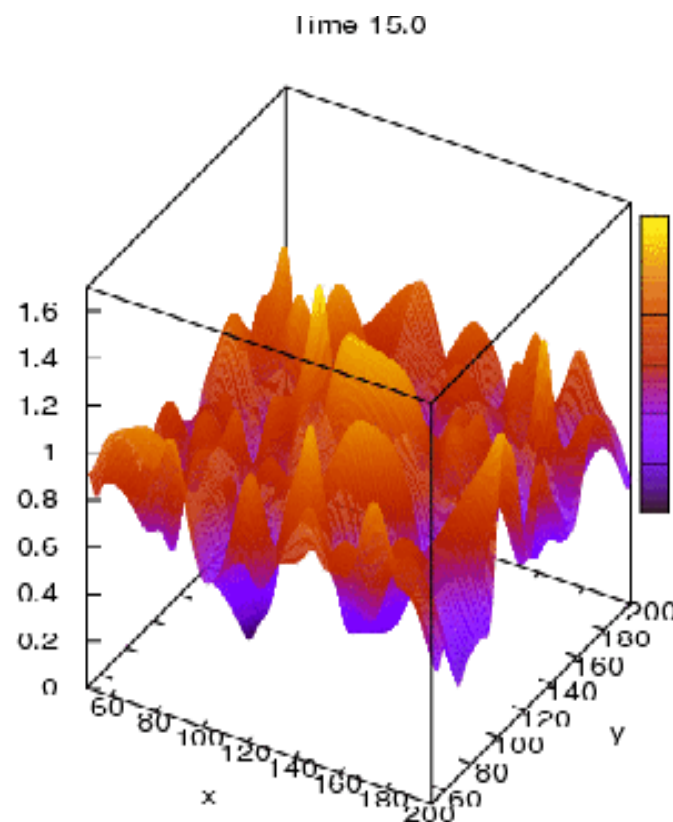
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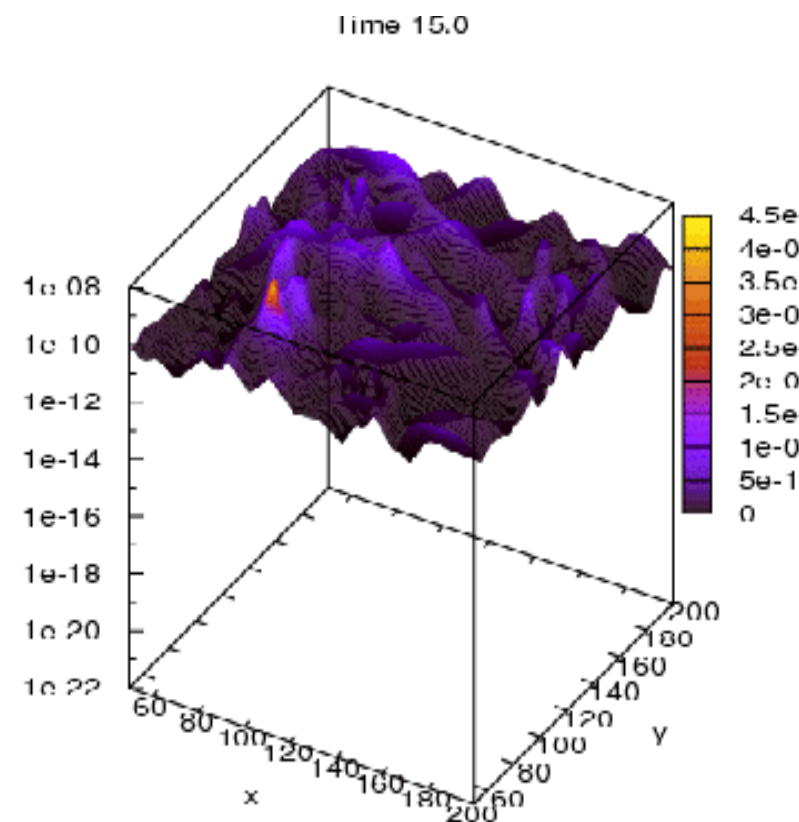
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Animation by
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Higgs



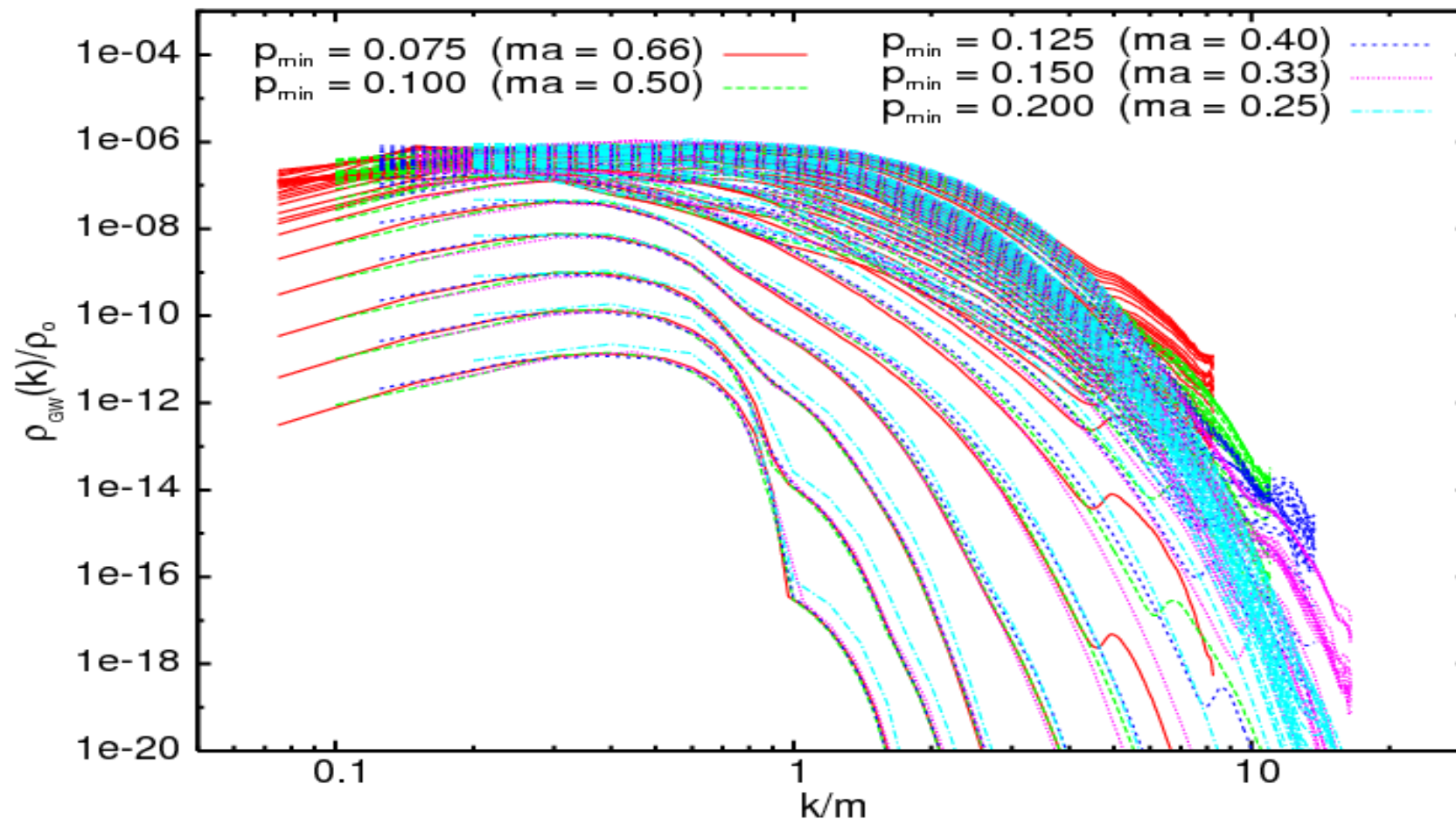
GW (Energy density)

GW Spectrum

Parameter Dependence (Peak amplitude)

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

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



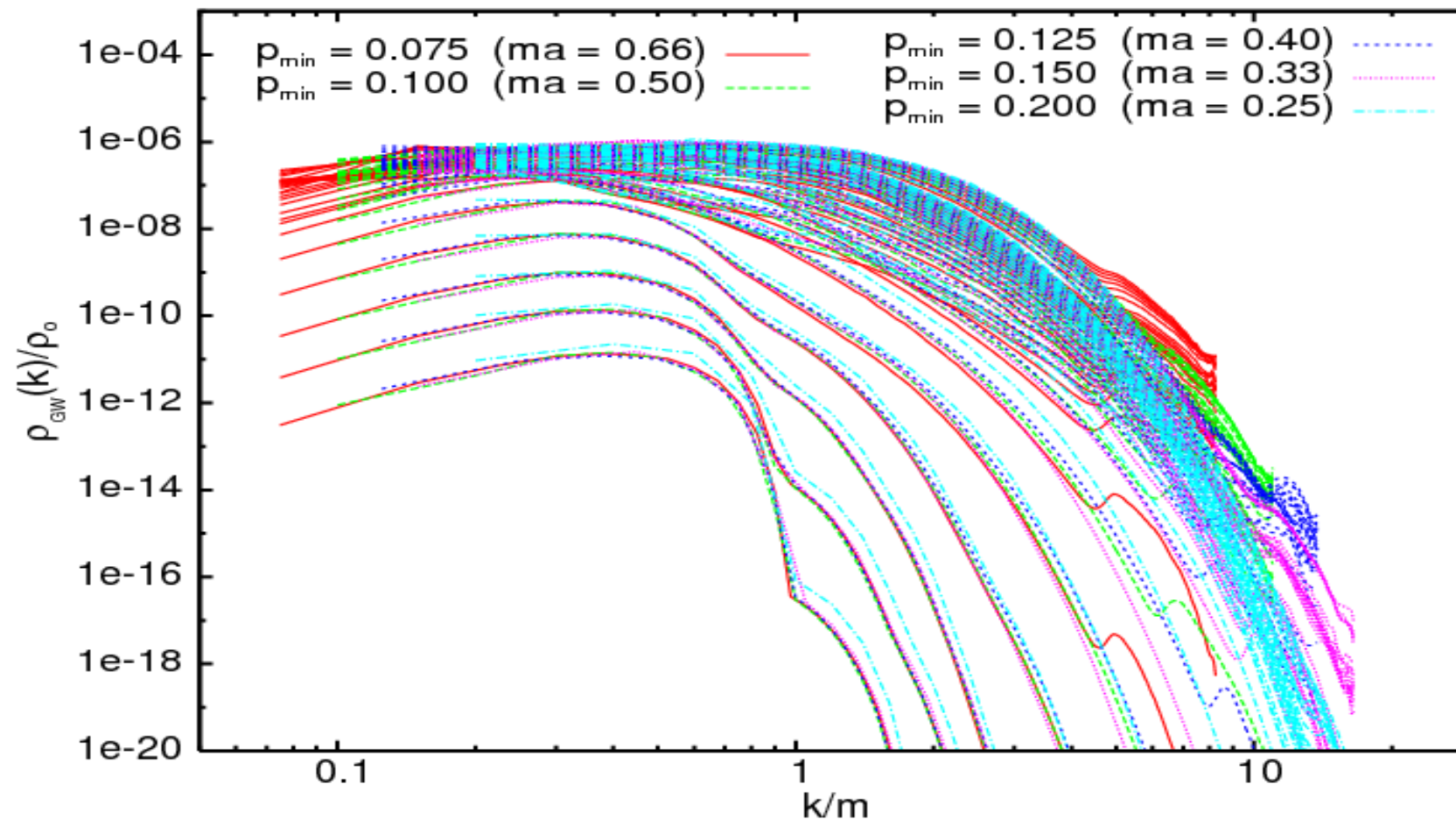
GW Spectrum

Parameter Dependence (Peak amplitude)

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

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

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



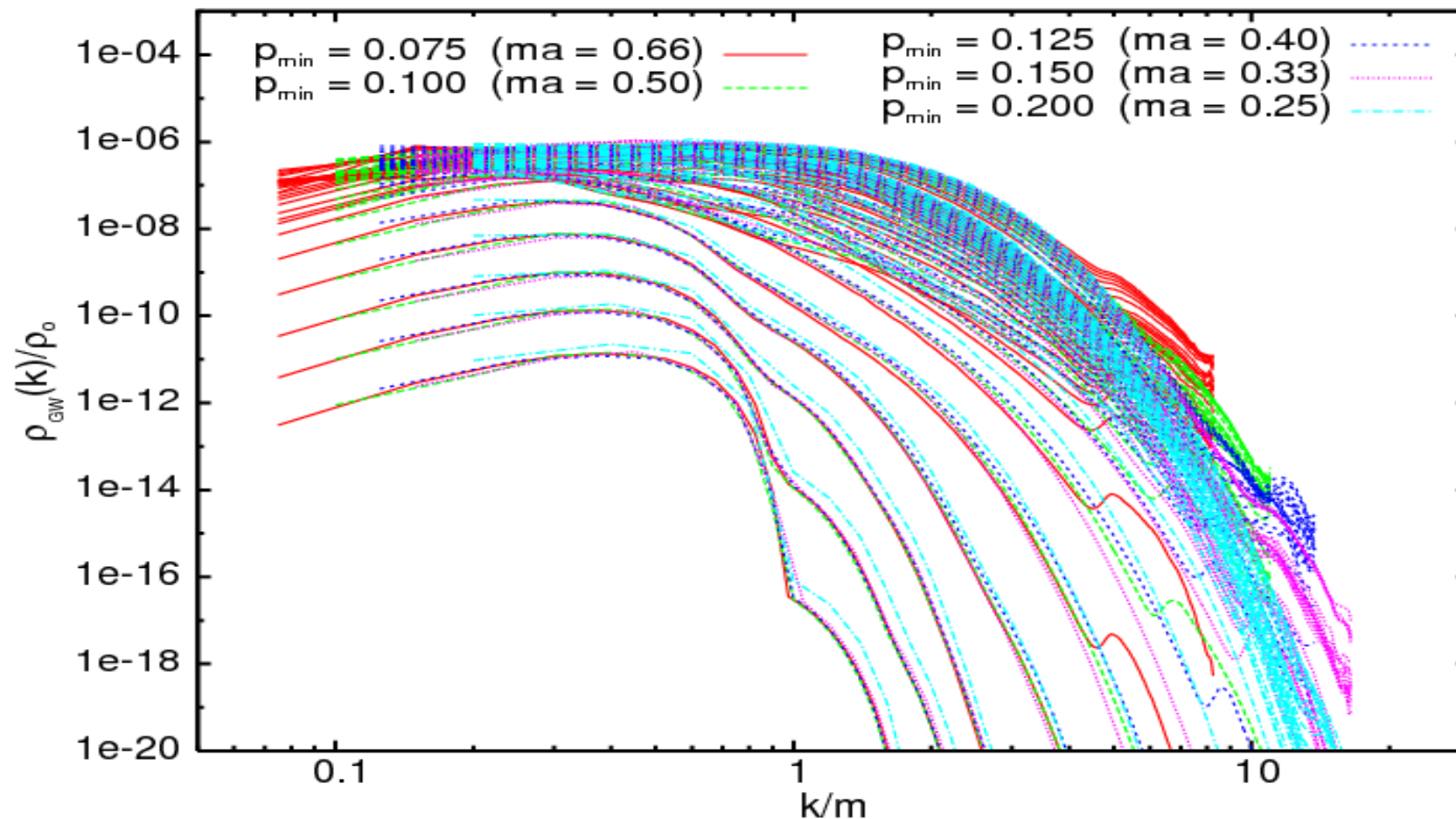
GW Spectrum

Parameter Dependence (Peak amplitude)

Hybrid Models: $\Omega_{\text{GW}}^{(o)} \sim 10^{-11}$, @ $\left\{ \begin{array}{l} f_o \sim 10^8 - 10^9 \text{ Hz} \\ \lambda \sim 0.1 \\ \text{(natural)} \end{array} \right.$

Large amplitude !
(for $v \simeq 10^{16} \text{ GeV}$)

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



GW Spectrum

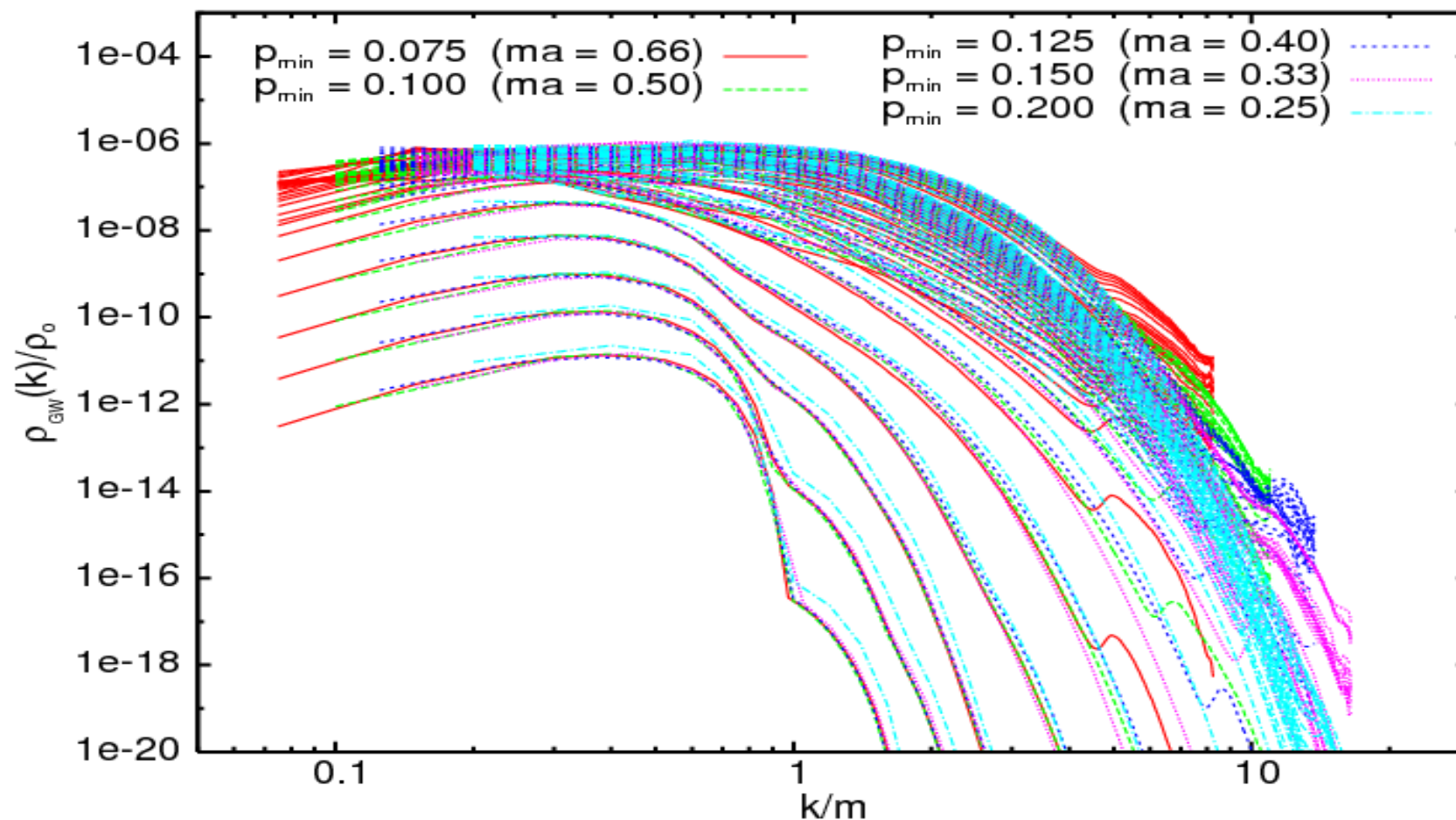
Parameter Dependence (Peak amplitude)

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

Large amplitude!
(for $v \simeq 10^{16} \text{ GeV}$)

$\lambda \sim 0.1$ (natural)
 $\lambda \sim 10^{-28}$ (fine-tuning)

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



GW Spectrum

Parameter Dependence (Peak amplitude)

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Large amplitude !
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realistically speaking ...

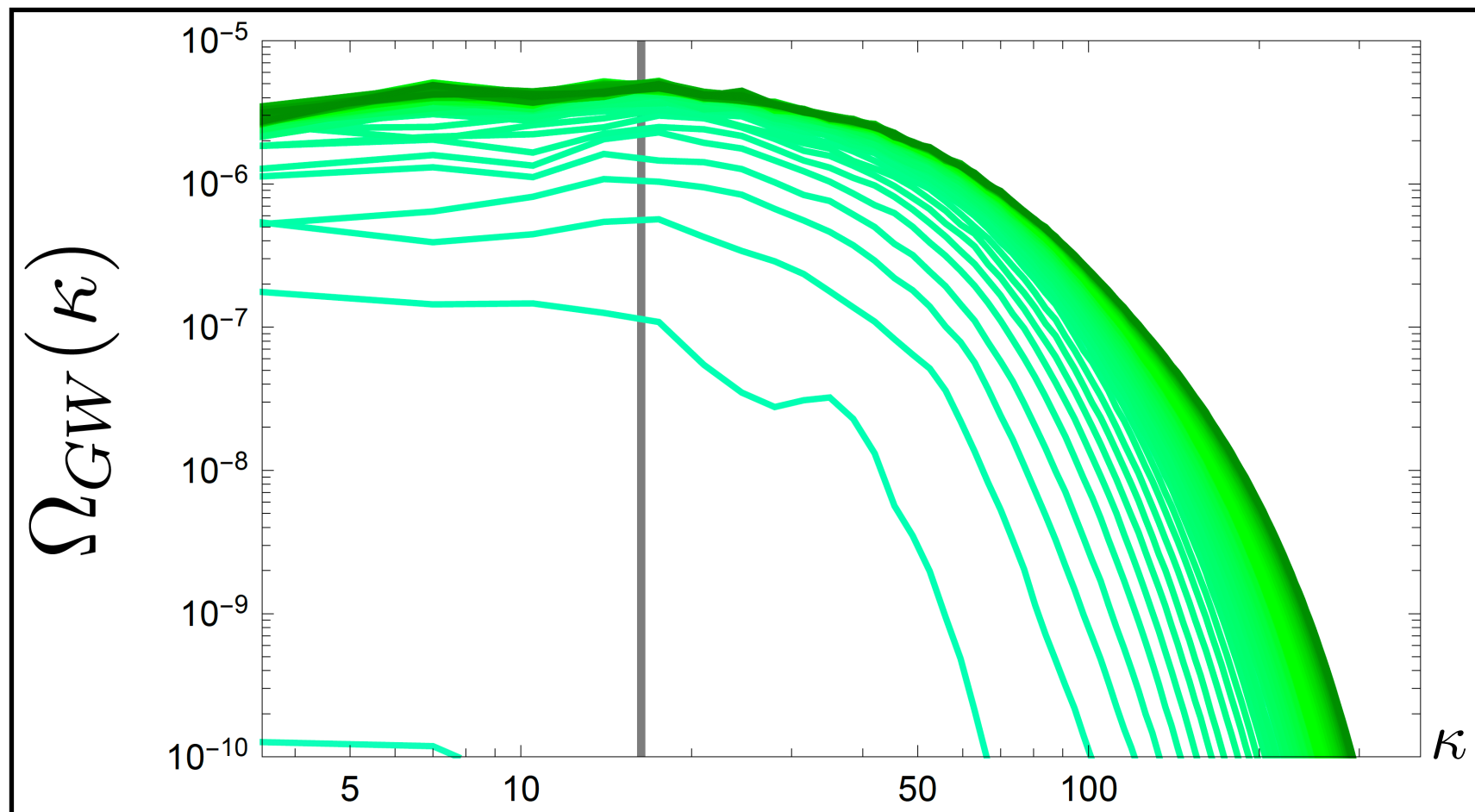


GW Spectrum

Parameter Dependence (Peak amplitude)

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

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



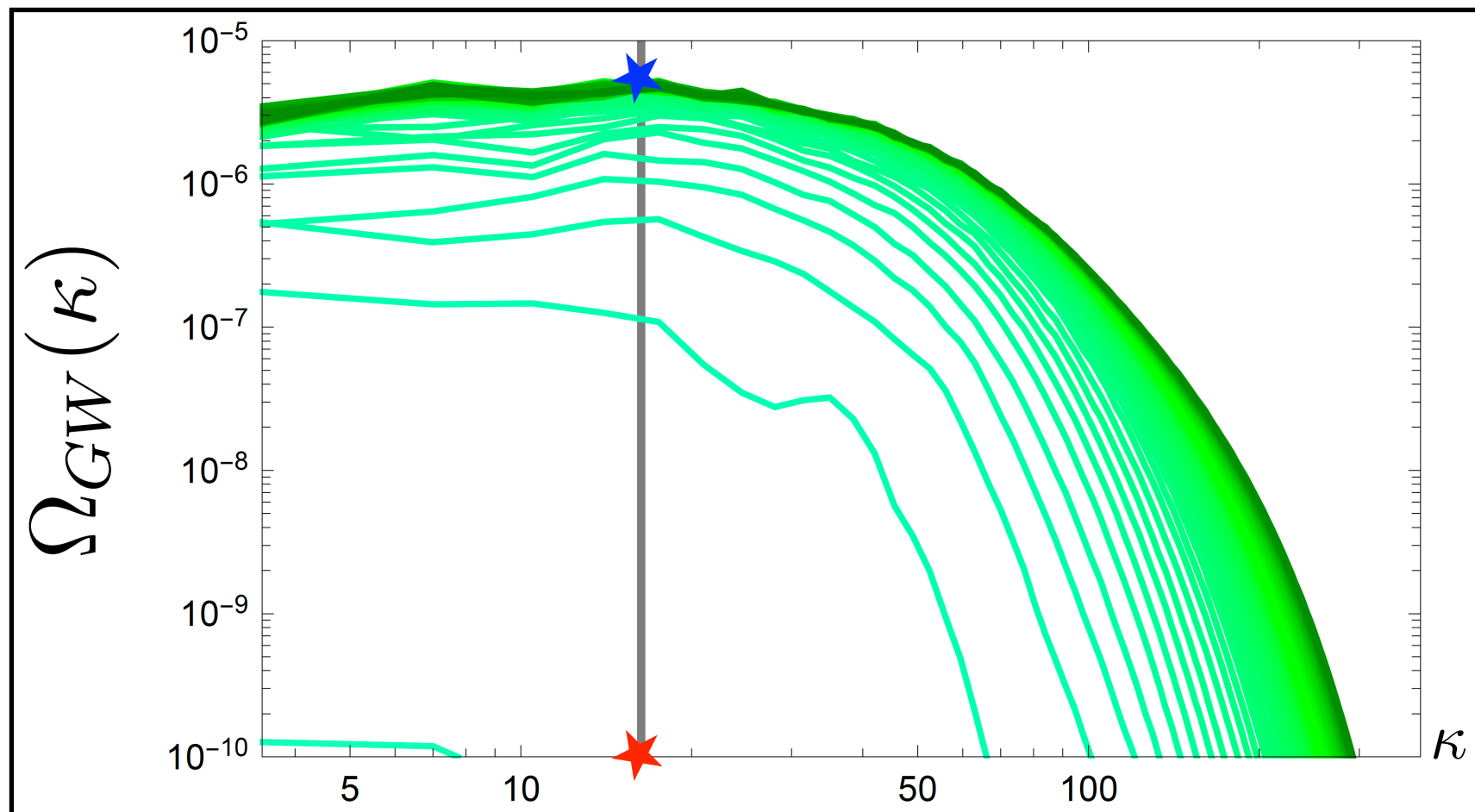
GW Spectrum

Parameter Dependence (Peak amplitude)

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

$$q \equiv \frac{g^2 \Phi_i^2}{\omega^2}$$

**Resonance
Param.**



GW Spectrum

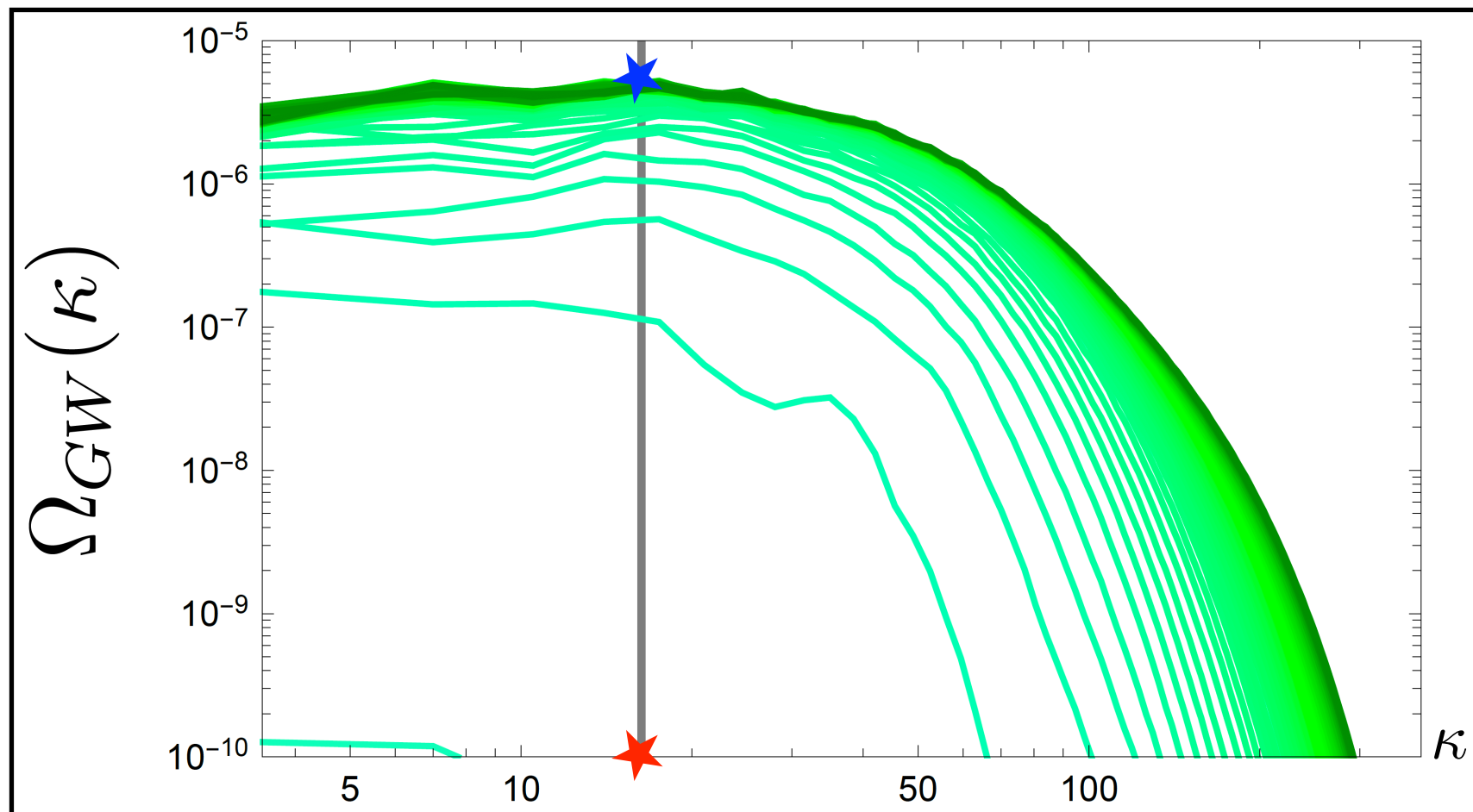
Parameter Dependence (Peak amplitude)

Monomial Models: **Single peak spectrum !**
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$$\omega^2 \equiv V''(\Phi_I)$$

$$q \equiv \frac{g^2 \Phi_i^2}{\omega^2}$$

**Resonance
Param.**



GW Spectrum

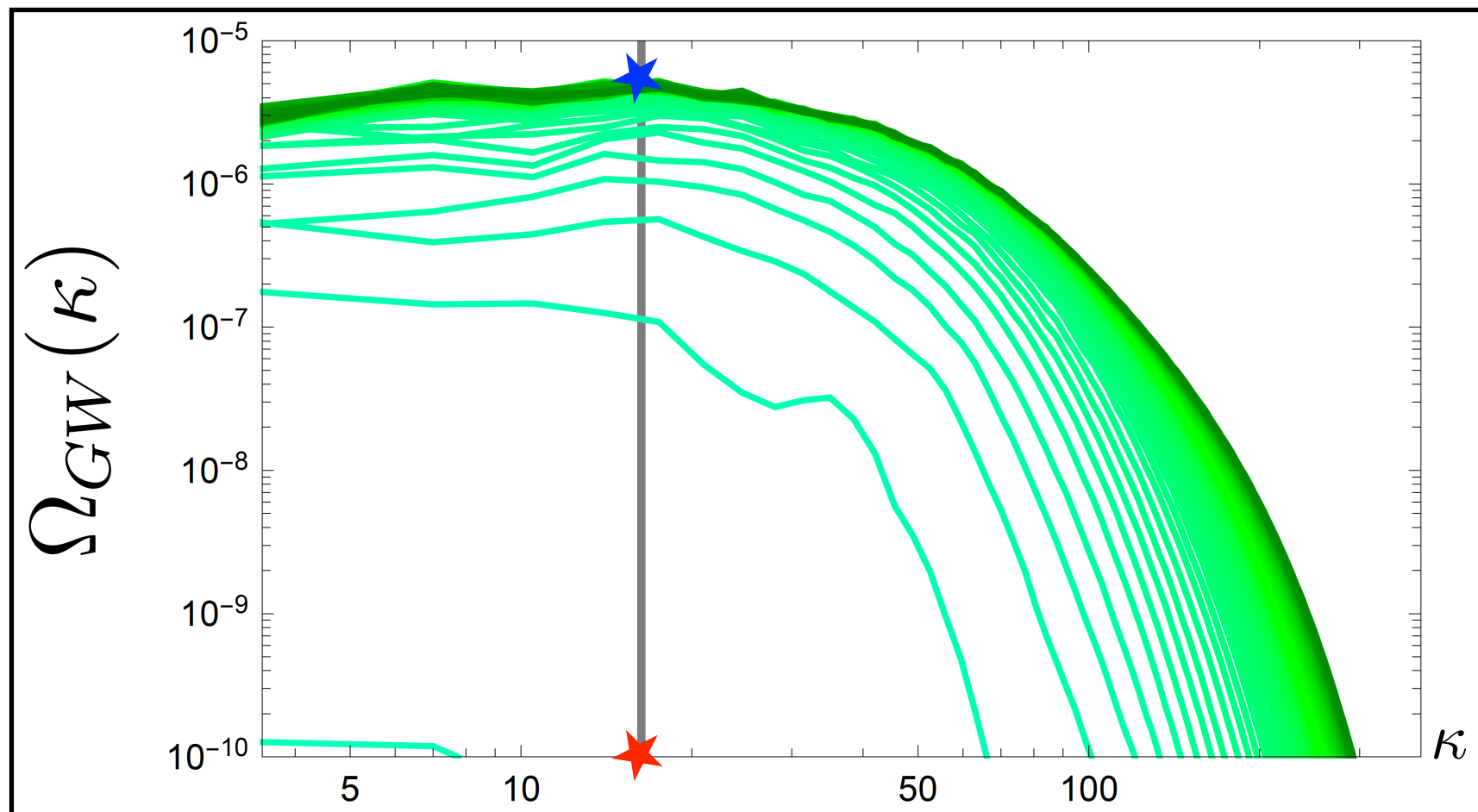
Parameter Dependence (Peak amplitude)

Monomial Models: $\Omega_{\text{GW}}^{(o)} \propto \frac{\omega^6}{\rho m_p^2} q^{-1}$

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

$q \equiv \frac{g^2 \Phi_i^2}{\omega^2}$

Resonance Param.



(DGF, Torrentí JCAP 2017)

GW Spectrum

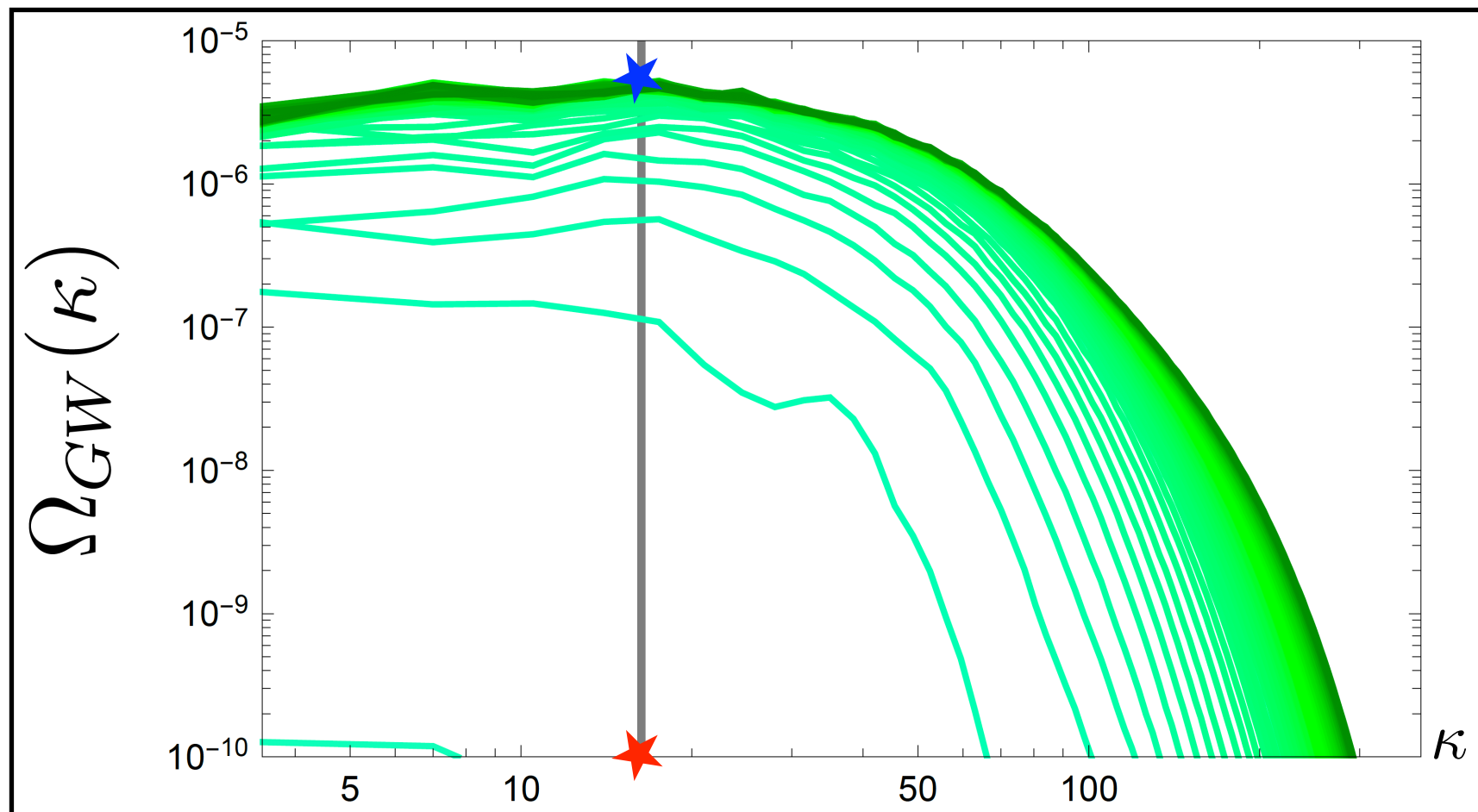
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Resonance Param.



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

**Peak
Position**

(DGF, Torrentí JCAP 2017)

GW Spectrum

Parameter Dependence (Peak amplitude)

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

GW Spectrum

Parameter Dependence (Peak amplitude)

Monomial Models: $\Omega_{\text{GW}}^{(o)} \sim 10^{-9},$
Large amplitude !

... at high Frequency !

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

Very unfortunate !

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 ...

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

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

(DGF, Torrentí JCAP 2017)

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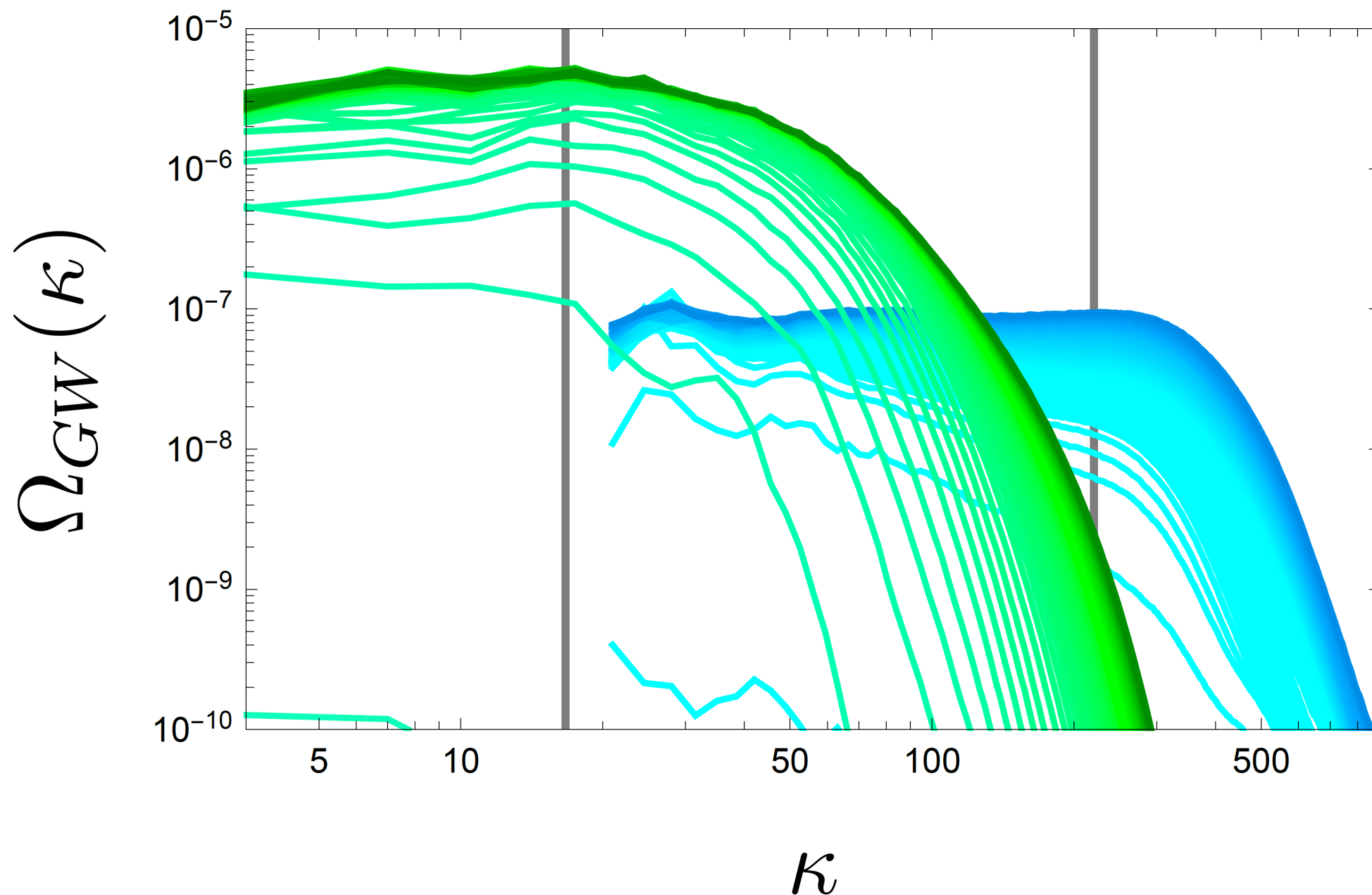
(DGF, Torrentí JCAP 2017)

→ **What if multiple species with $g_i \neq g_j$?**
Spectroscopy of particle couplings ?

GW Spectroscopy

Parameter Dependence (Peak amplitude)

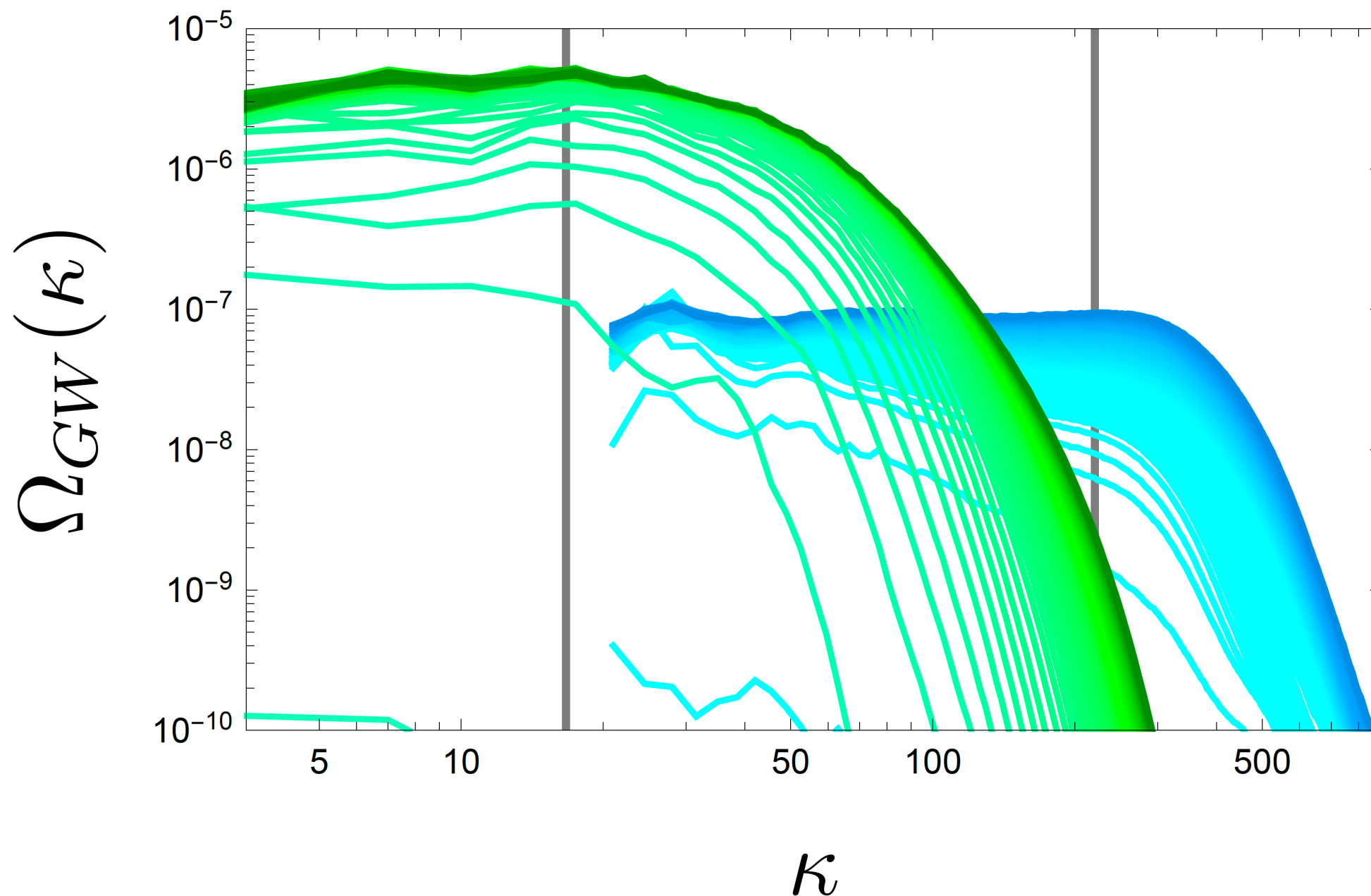
$$V(\phi) + \frac{1}{2}g_1^2\phi^2\chi_1^2 \quad ; \quad V(\phi) + \frac{1}{2}g_2^2\phi^2\chi_2^2$$



GW Spectroscopy

Parameter Dependence (Peak amplitude)

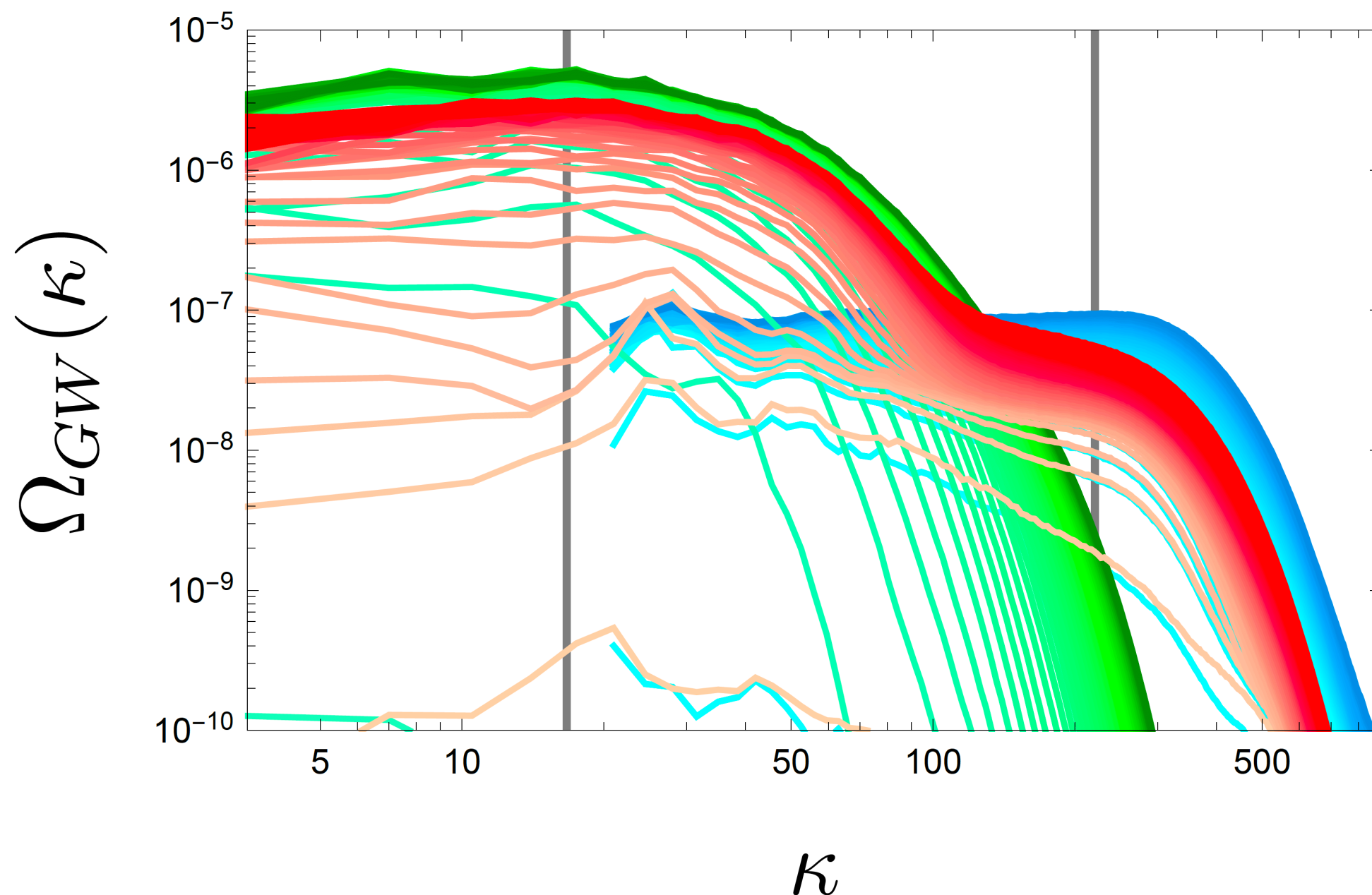
$$V(\phi) + \frac{1}{2}g_1^2\phi^2\chi_1^2 + \frac{1}{2}g_2^2\phi^2\chi_2^2 \quad ?$$



GW Spectroscopy

Parameter Dependence (Peak amplitude)

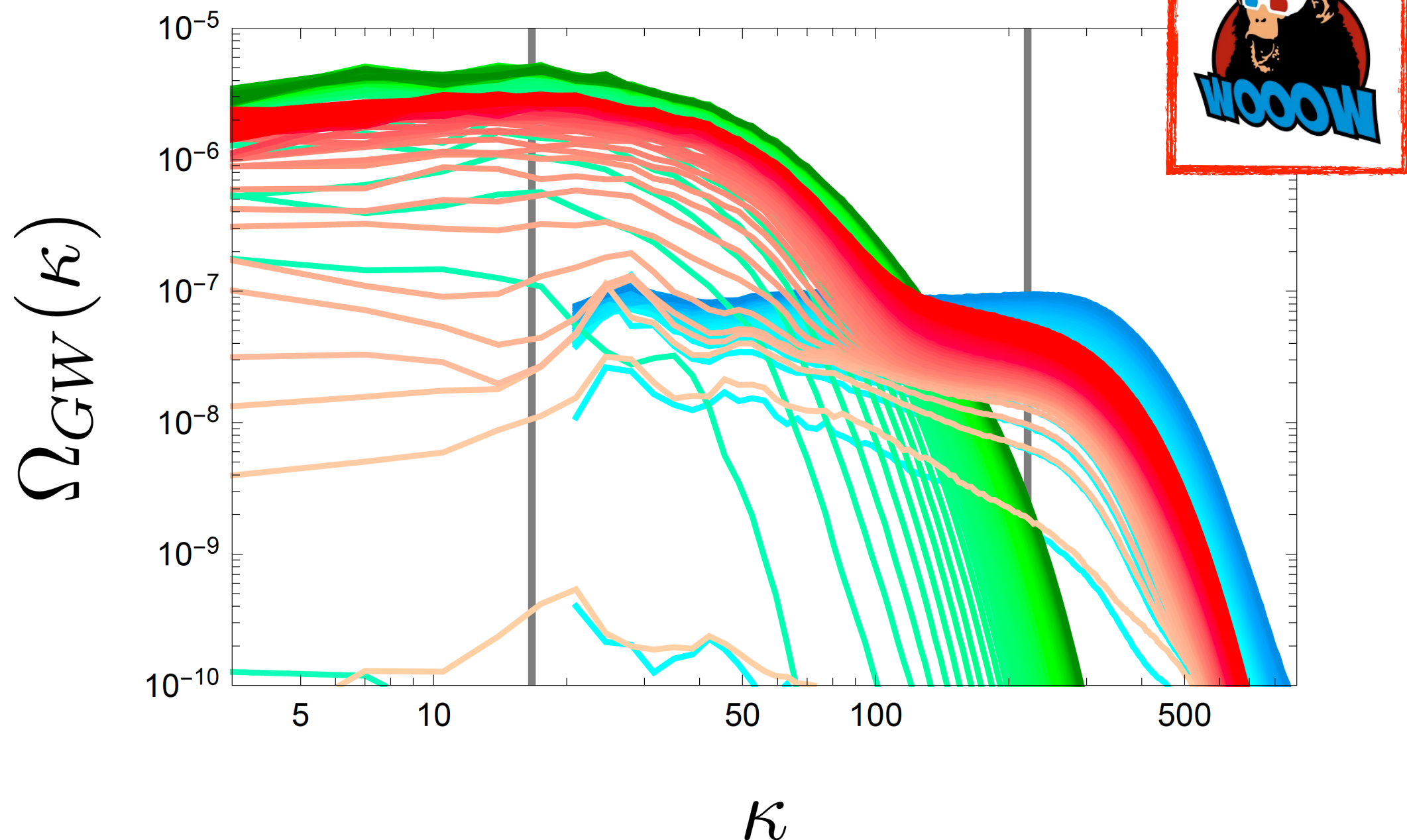
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GW Spectroscopy

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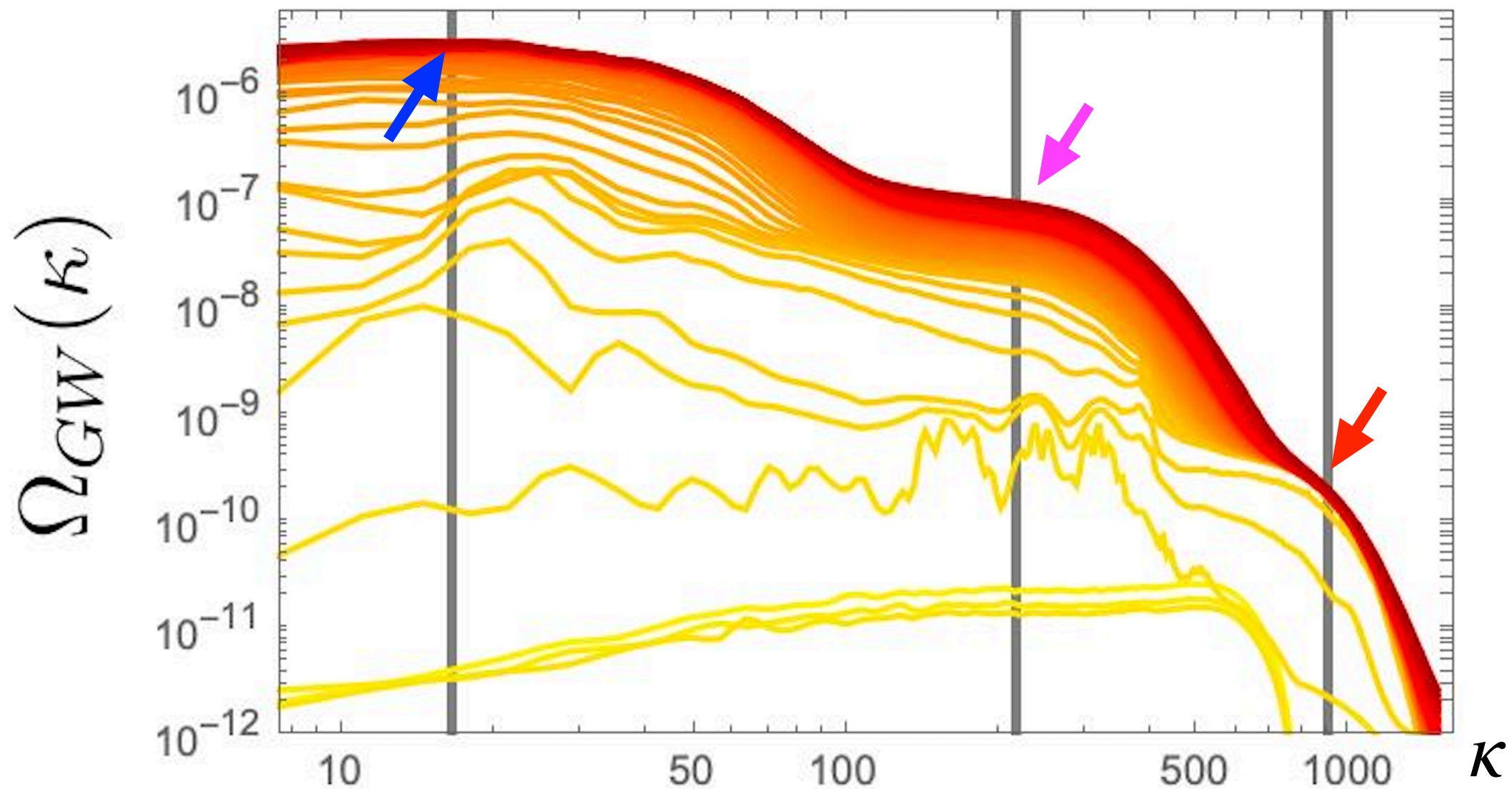
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GW Spectroscopy

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$$V(\phi) + \frac{1}{2} \mathbf{g}_1^2 \phi^2 \chi_1^2 + \frac{1}{2} \mathbf{g}_2^2 \phi^2 \chi_2^2 + \frac{1}{2} \mathbf{g}_3^2 \phi^2 \chi_3^2$$

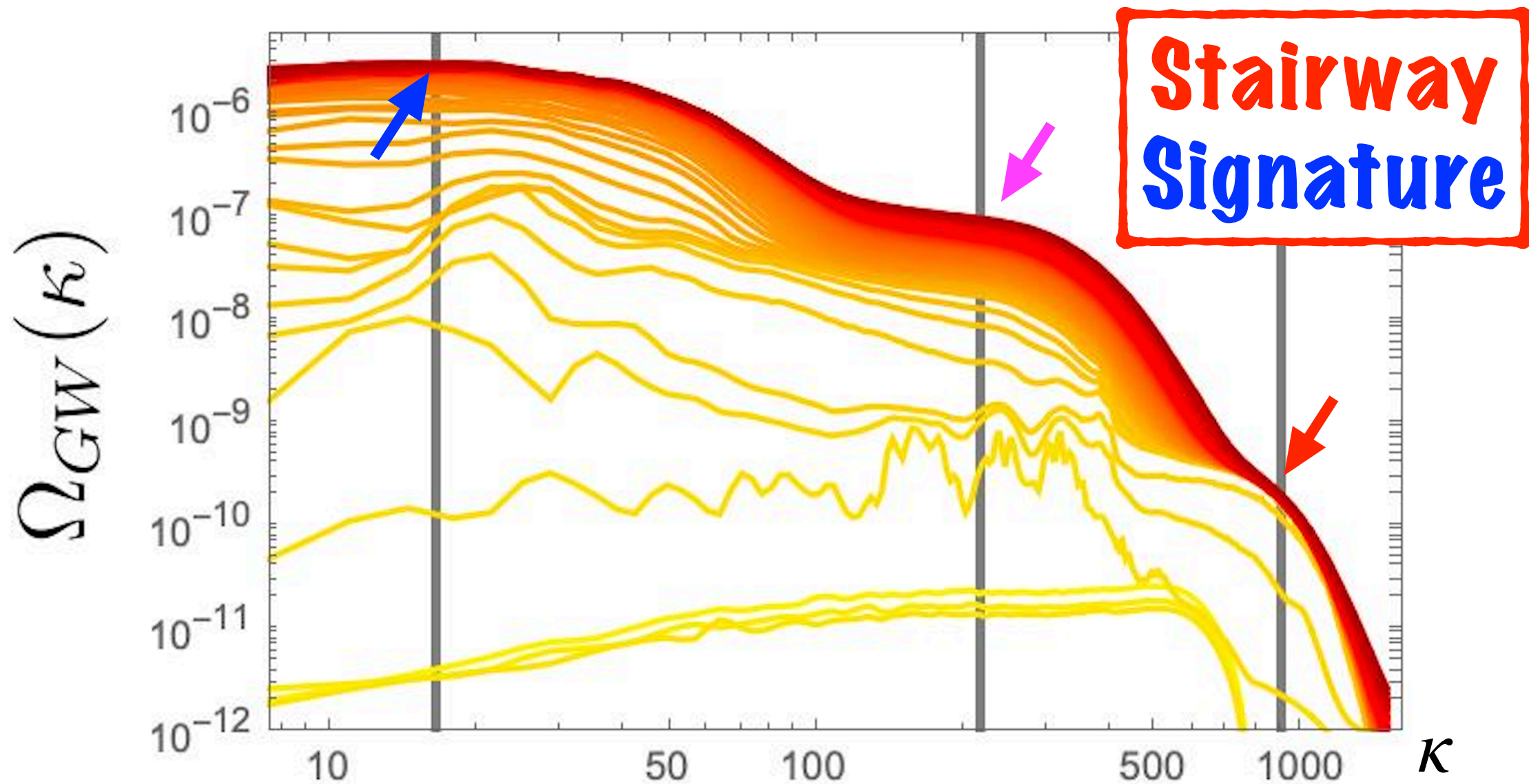


Phys. Rev. D 106 (2022) 6, 063522 ; [2202.05805](#)

GW Spectroscopy

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

GW Spectroscopy

Reconstruction (2-peak signal)

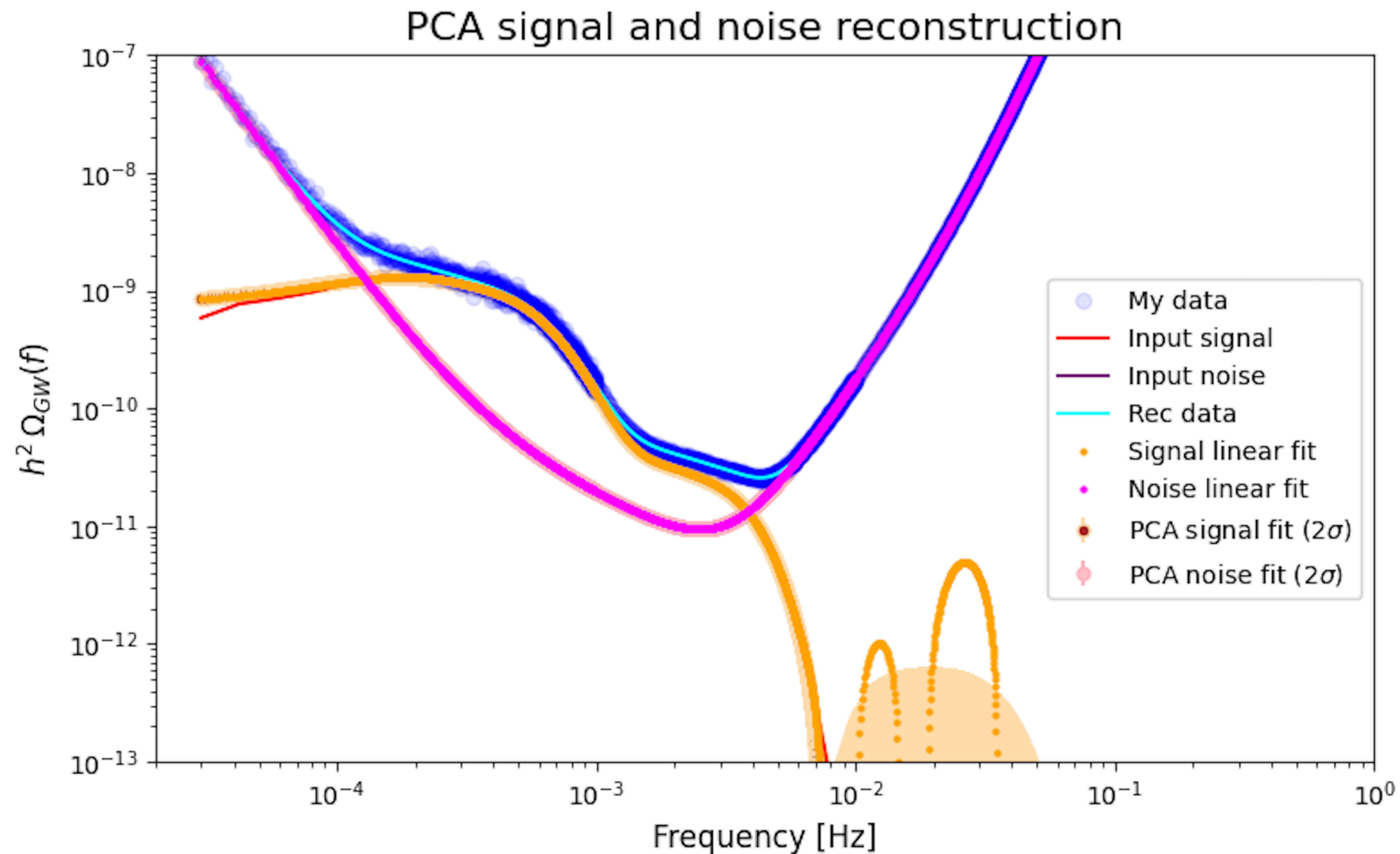
@ LISA

Note: Shift by hand to LISA frequencies

GW Spectroscopy

Reconstruction (2-peak signal)

@ LISA

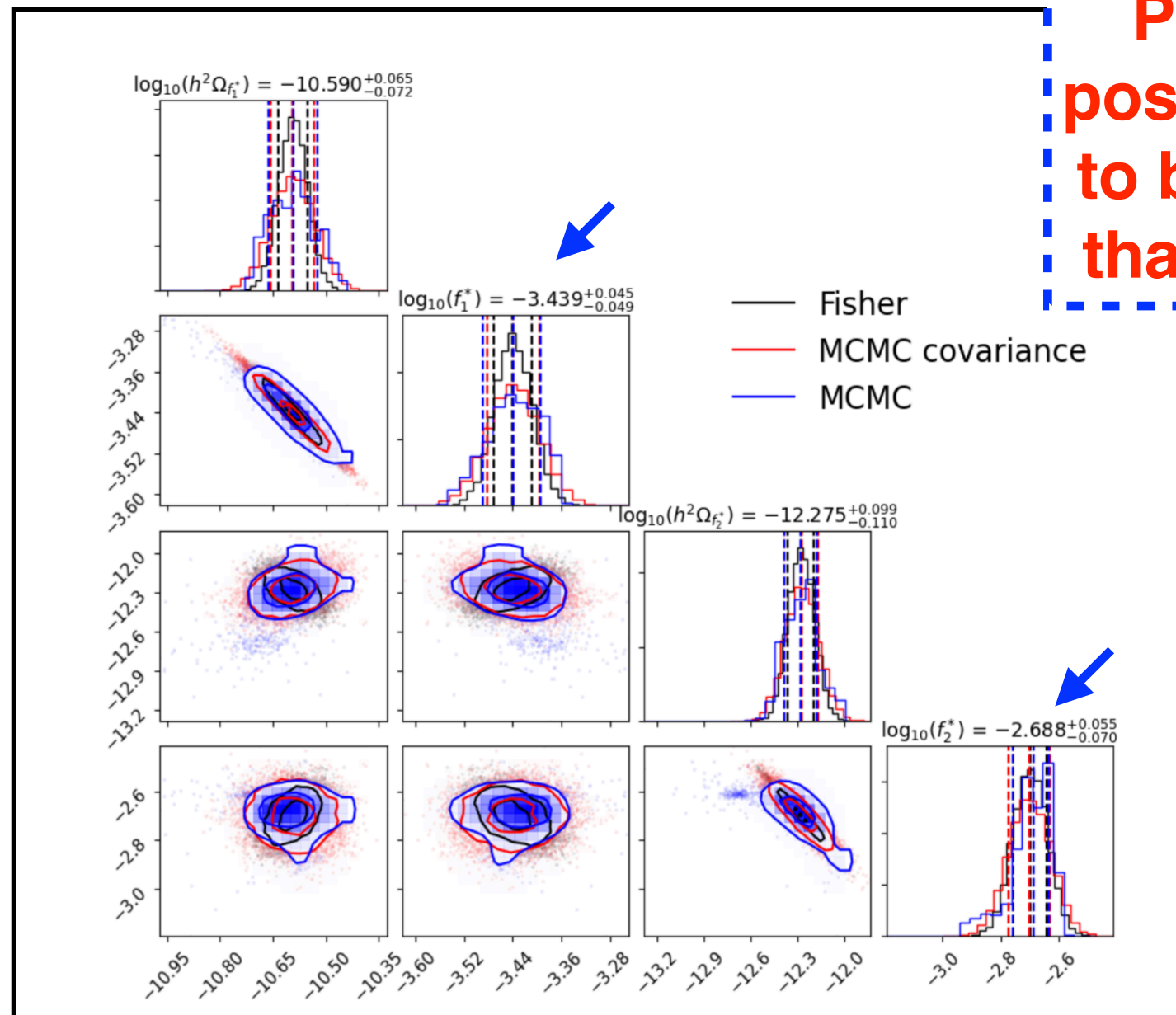


Note: Shift by hand to LISA frequencies

GW Spectroscopy

Reconstruction (2-peak signal)

@ LISA



GW Spectroscopy

Reconstruction (2-peak signal)

@ LISA

Coupling Reconstruction !

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

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 !

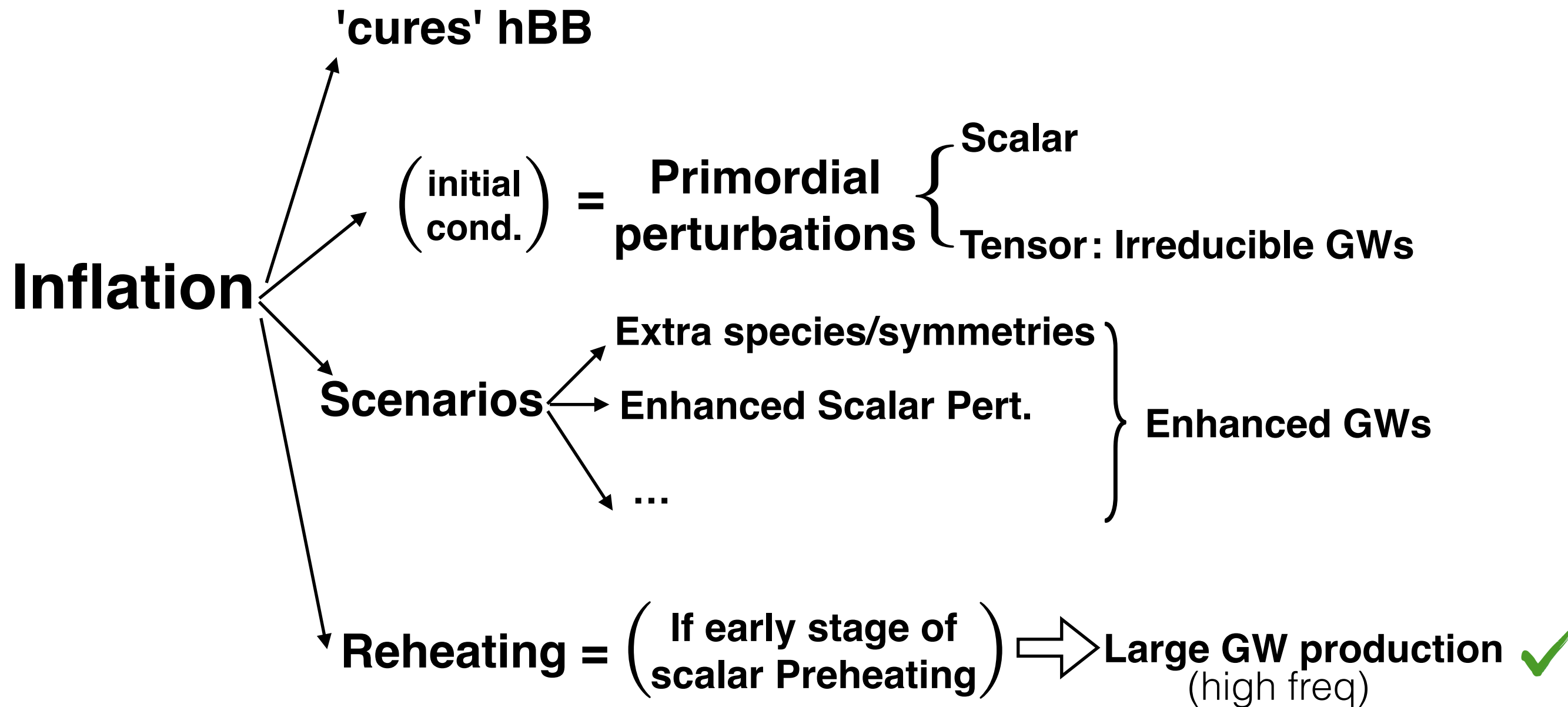
**Possible new door to particle physics
interactions with GW backgrounds !**

**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) 

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)

Gravitational Wave Backgrounds

OUTLINE

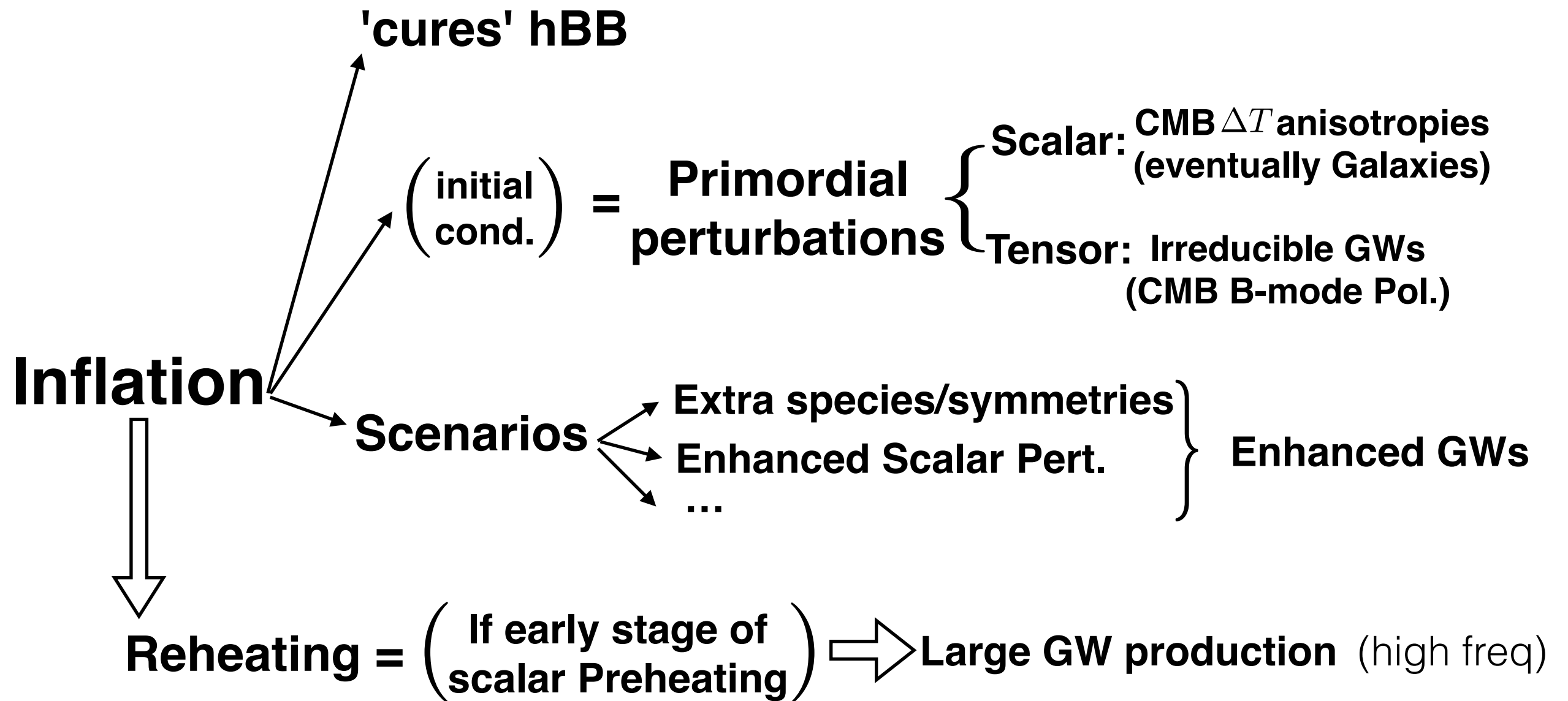
- ✓ 1) Grav. Waves (GWs) 1st Topic
- 2) GWs from Inflation ✓
- 3) GWs from Preheating ✓
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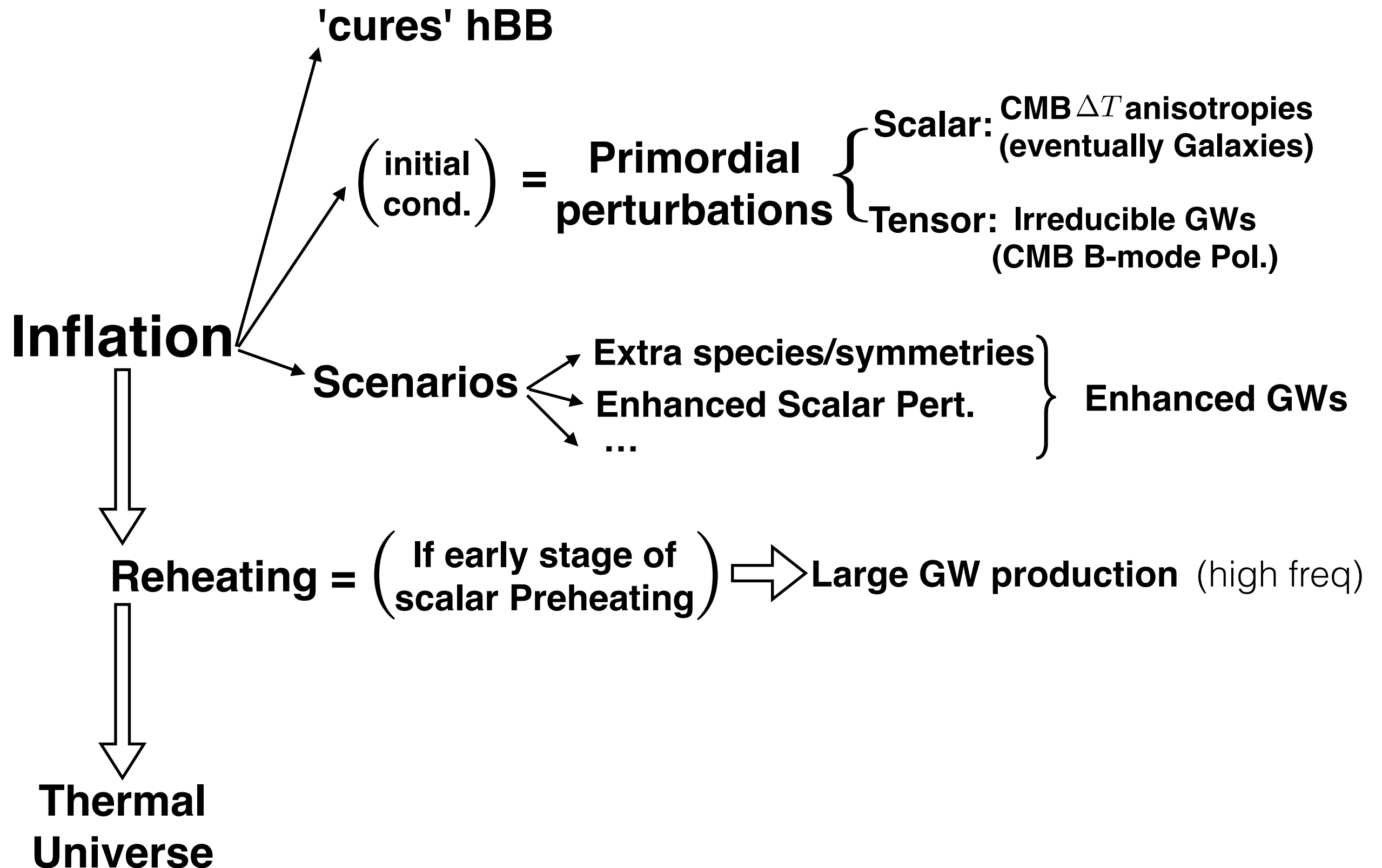
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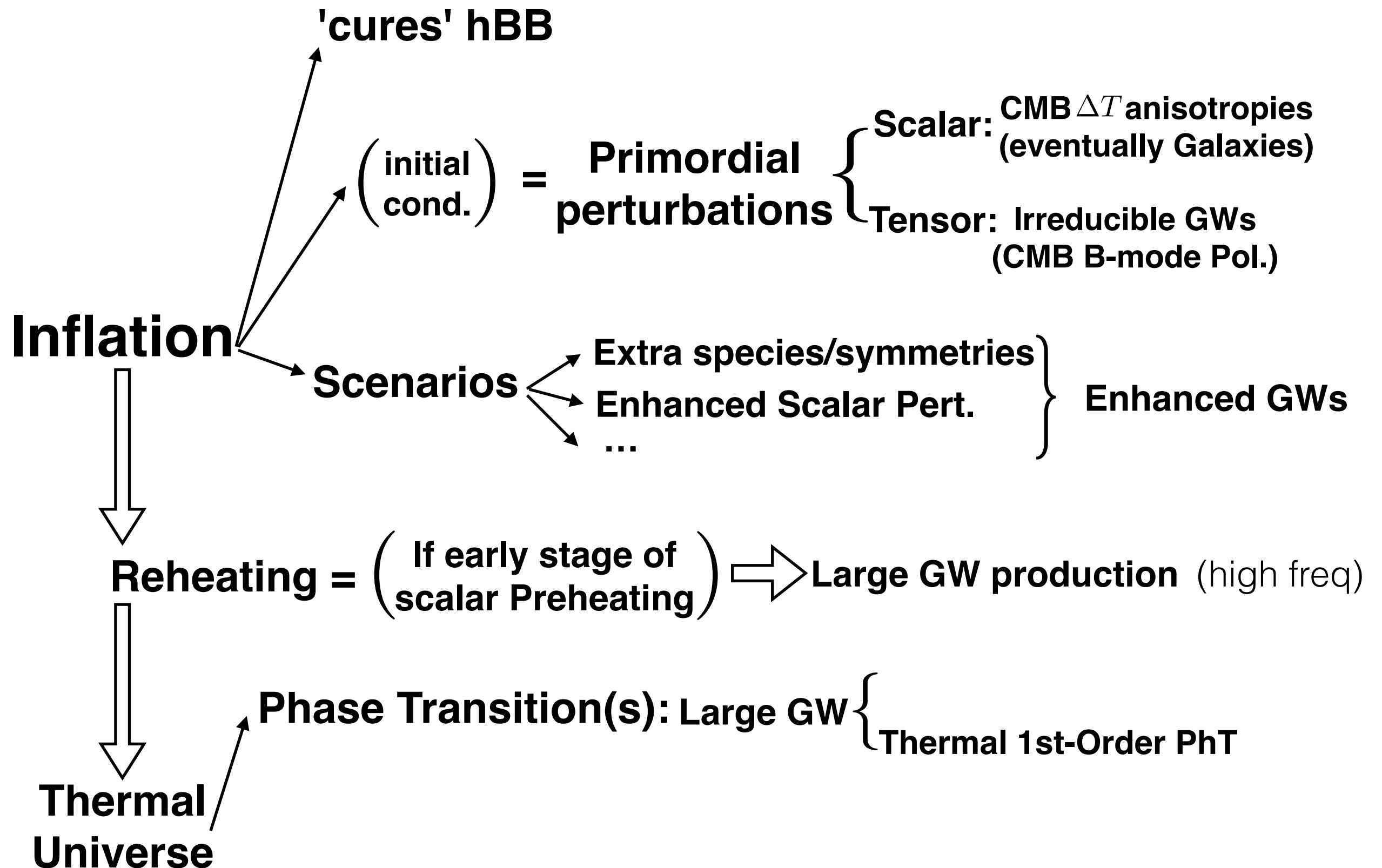
EARLY UNIVERSE



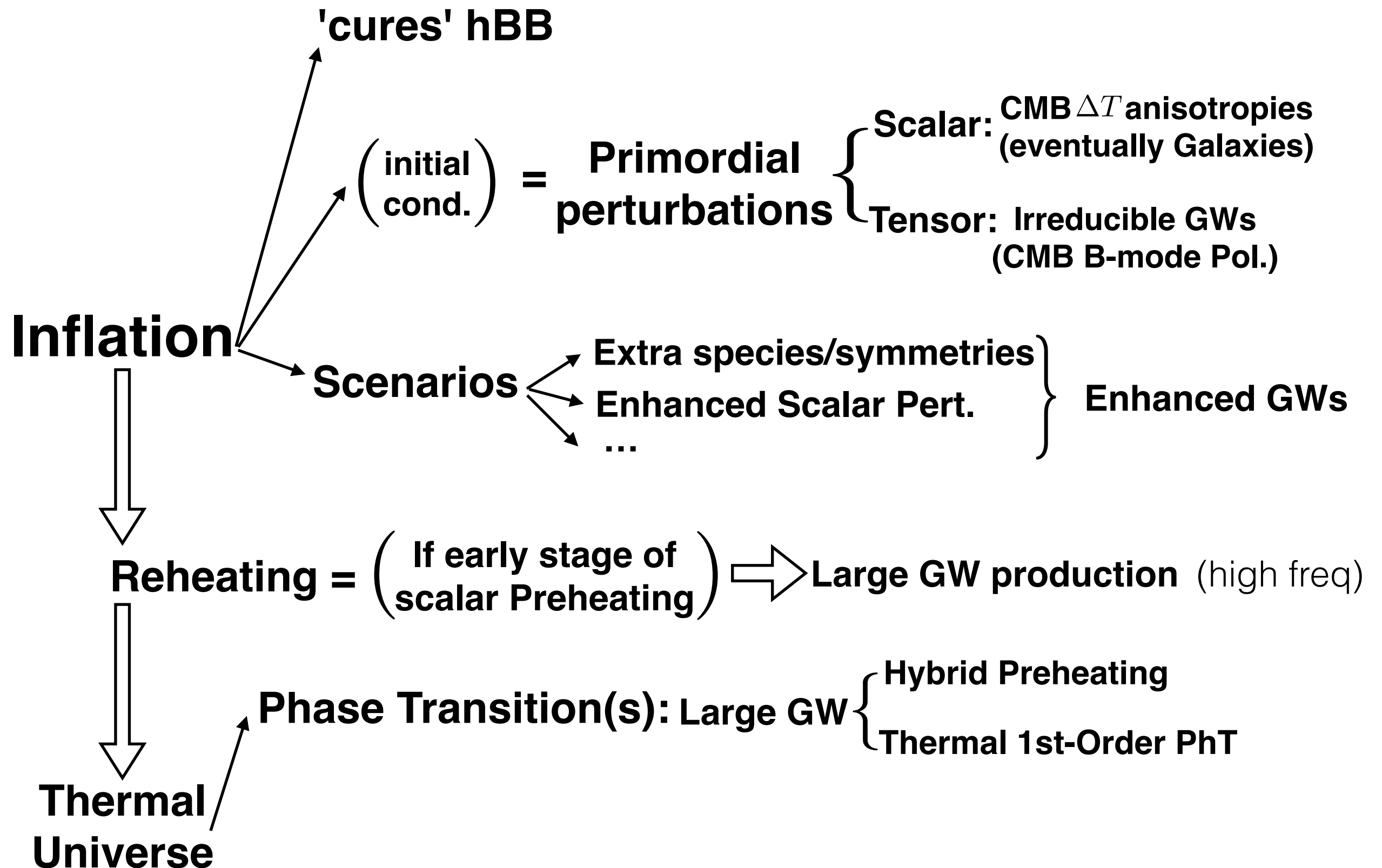
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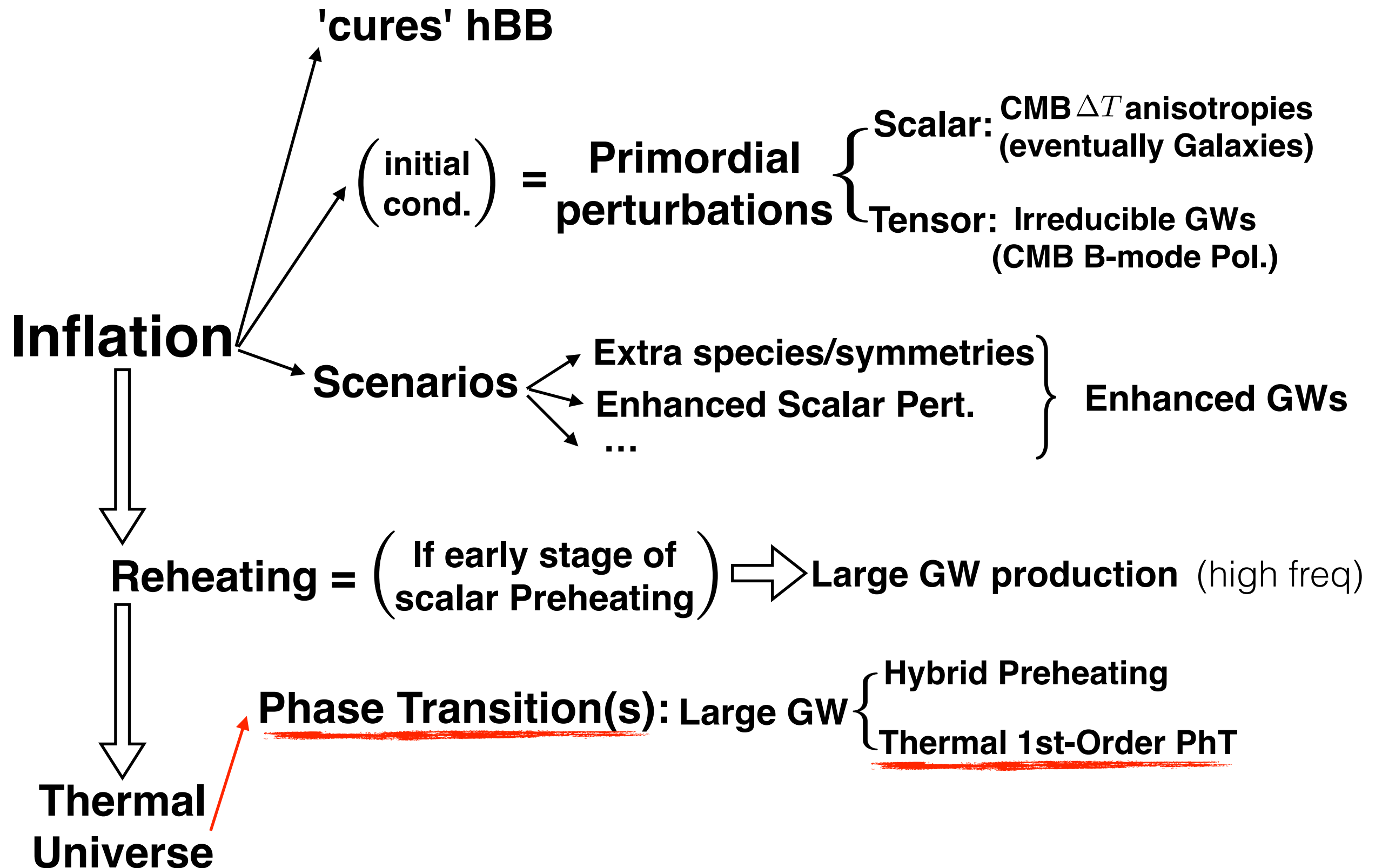
EARLY UNIVERSE



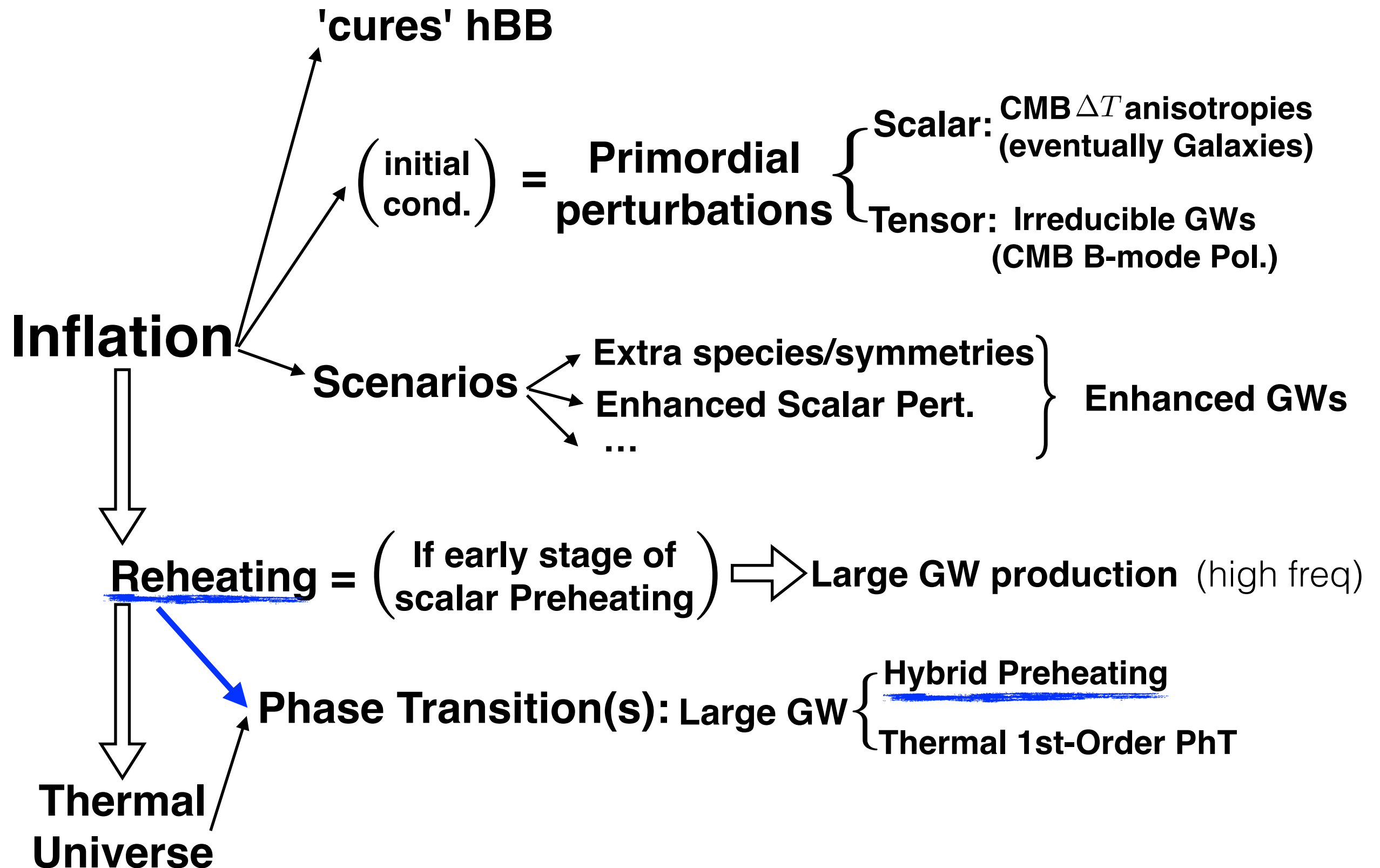
EARLY UNIVERSE



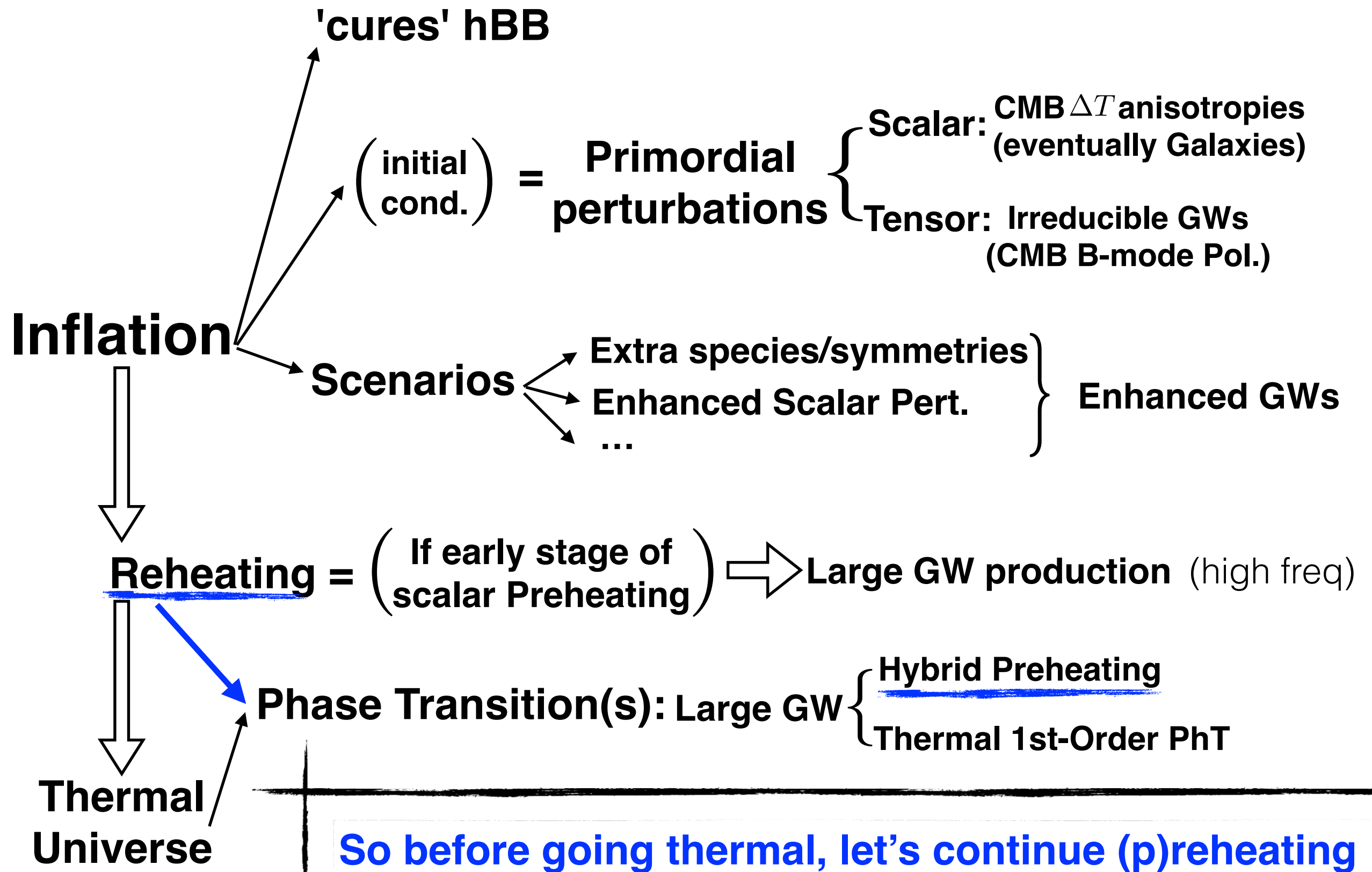
EARLY UNIVERSE



EARLY UNIVERSE



EARLY UNIVERSE



Gravitational Wave Backgrounds

OUTLINE



1) Grav. Waves (GWs)

1st Lecture

Early
Universe
Sources

2) GWs from Inflation

3) GWs from Preheating

4) GWs from Phase Transitions

5) GWs from Cosmic Defects

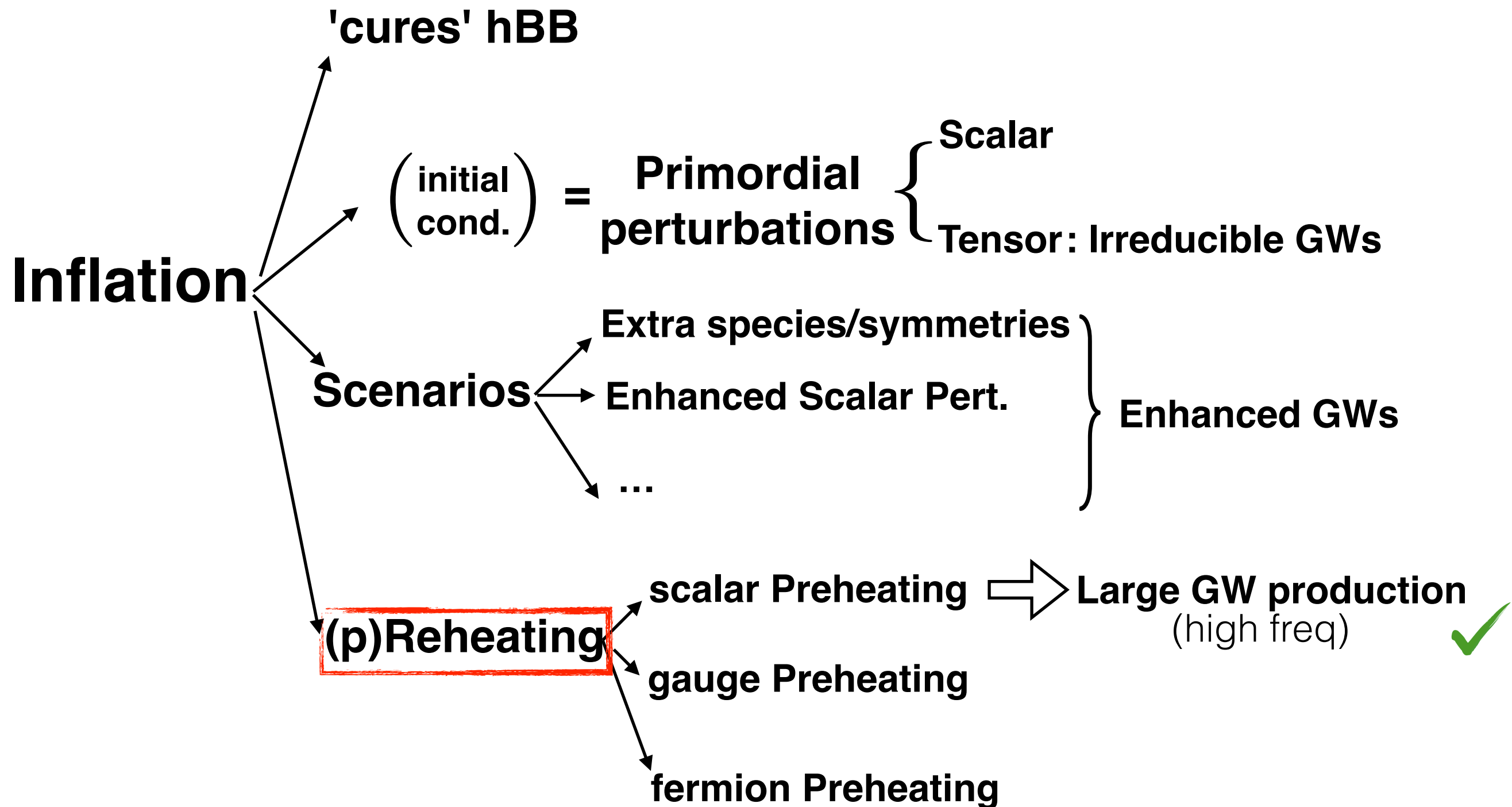
Core
Topics

6) Astrophysical Background(s)

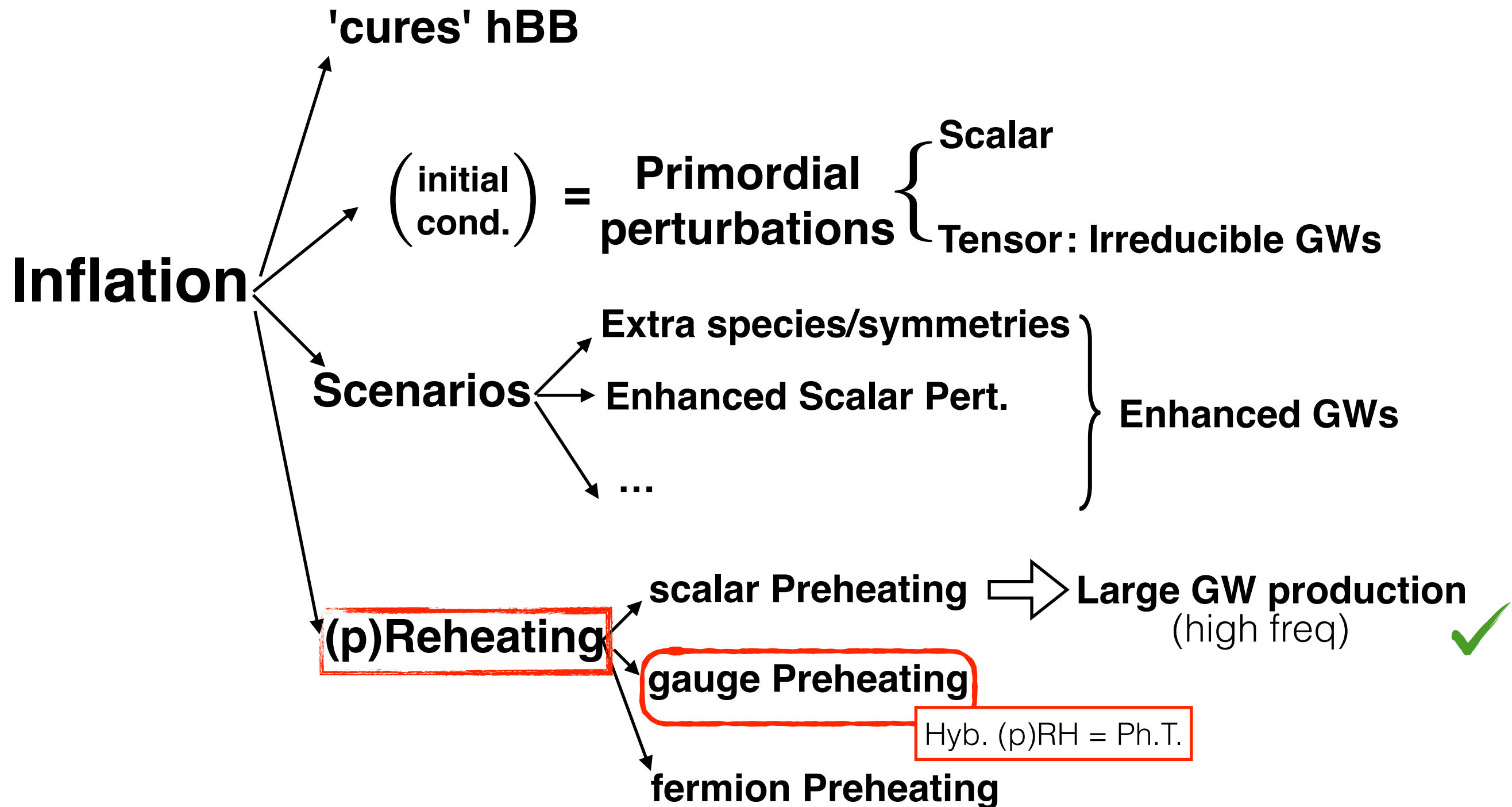
7) Observational Constraints/Prospects

(Briefly)

INFLATIONARY COSMOLOGY



INFLATIONARY COSMOLOGY



GAUGE (P)REHEATING

Hybrid Preheating = Higgs+Inflaton model

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

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

inflaton mass $\swarrow$ $\searrow$ coupling

Self-coupling $\nwarrow$ $\nearrow$ V.E.V.

$m = \sqrt{\lambda}v$

$\phi_c \equiv m/g$ Critical value

GAUGE (P)REHEATING

Hybrid Preheating = Higgs+Inflaton model

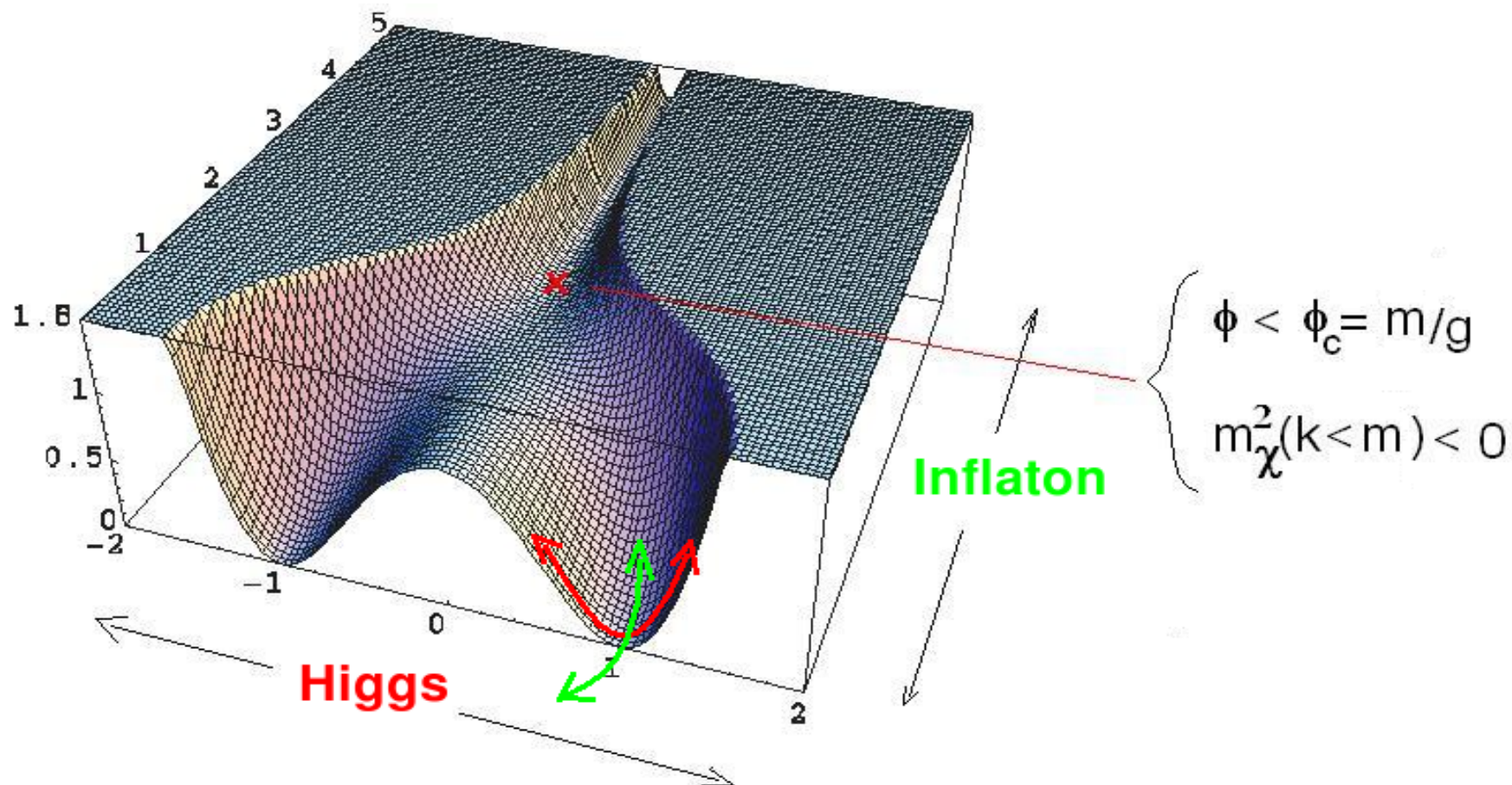
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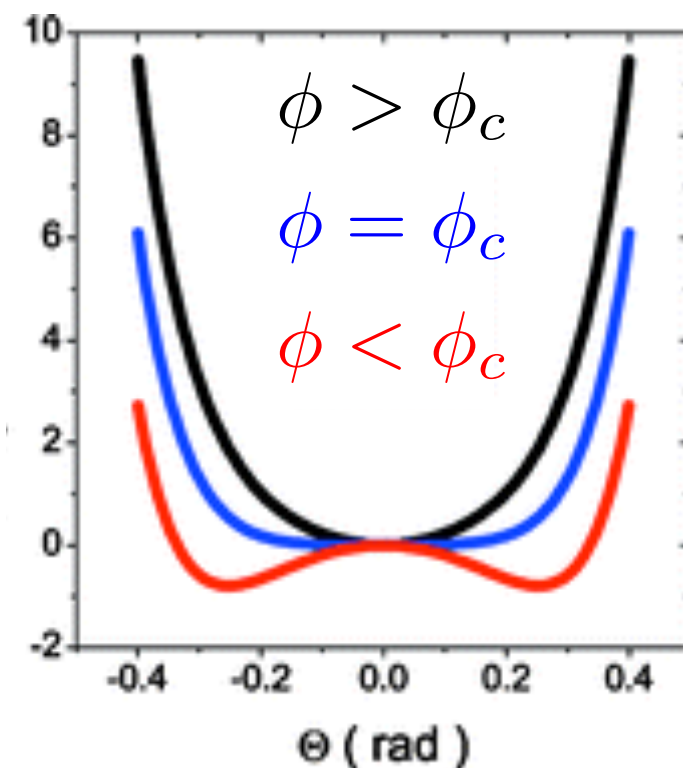
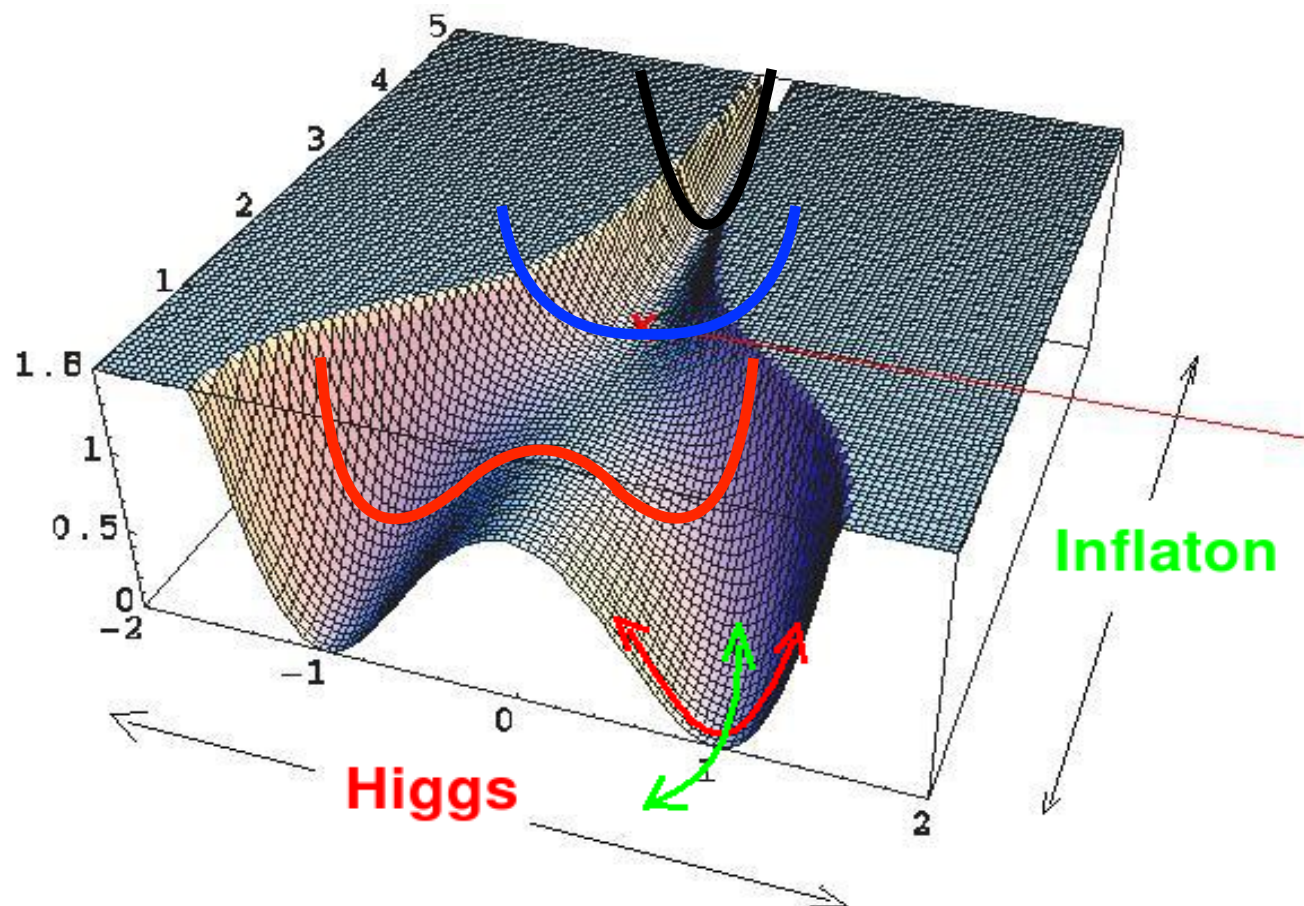


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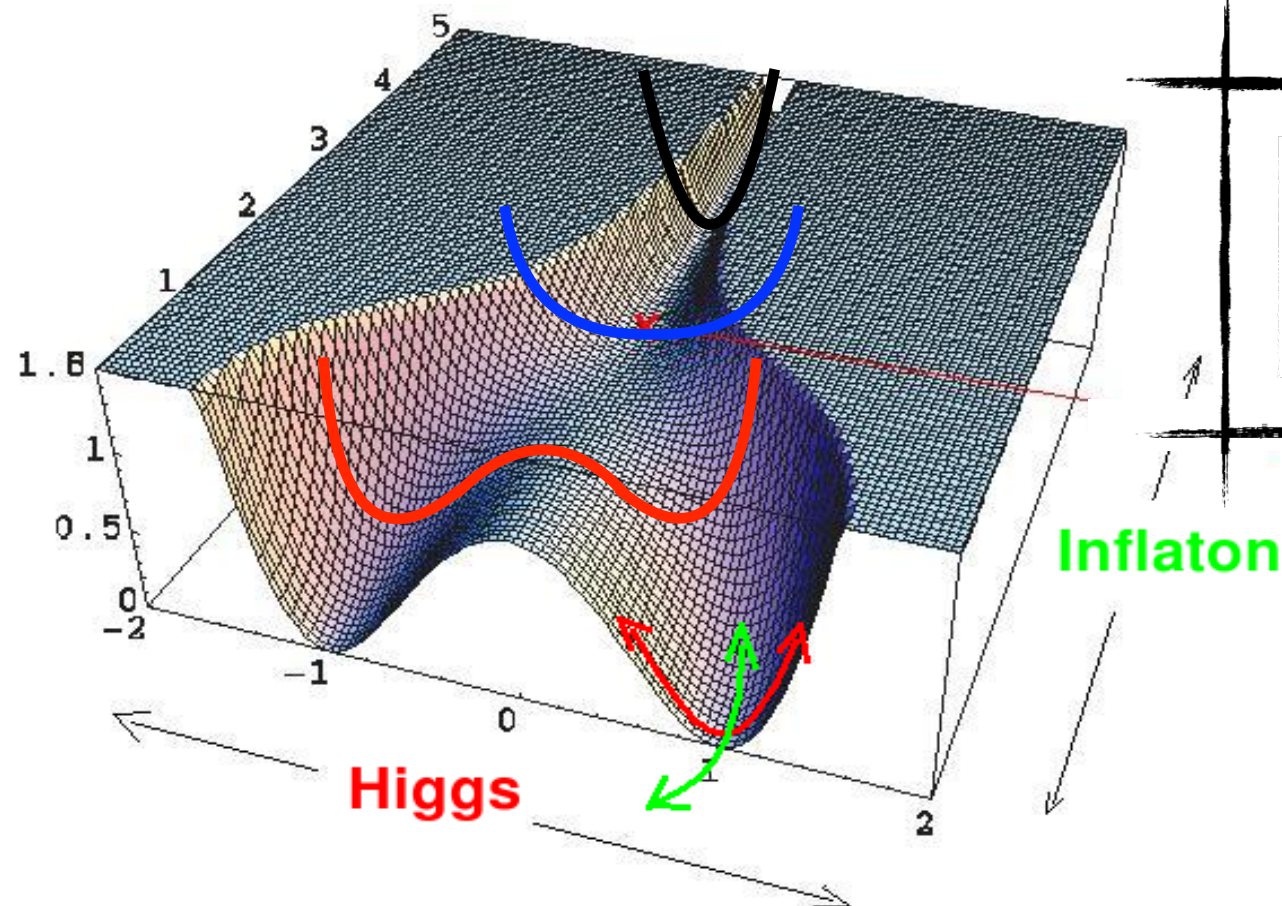


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Hybrid Preheating = Phase Transition



**It is a Phase transition !
by Tachyonic Instability**

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

GAUGE (P)REHEATING

The Abelian-Higgs+Inflaton model

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

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

$$D_\mu = \partial_\mu - ieA_\mu$$

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

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

GAUGE (P)REHEATING

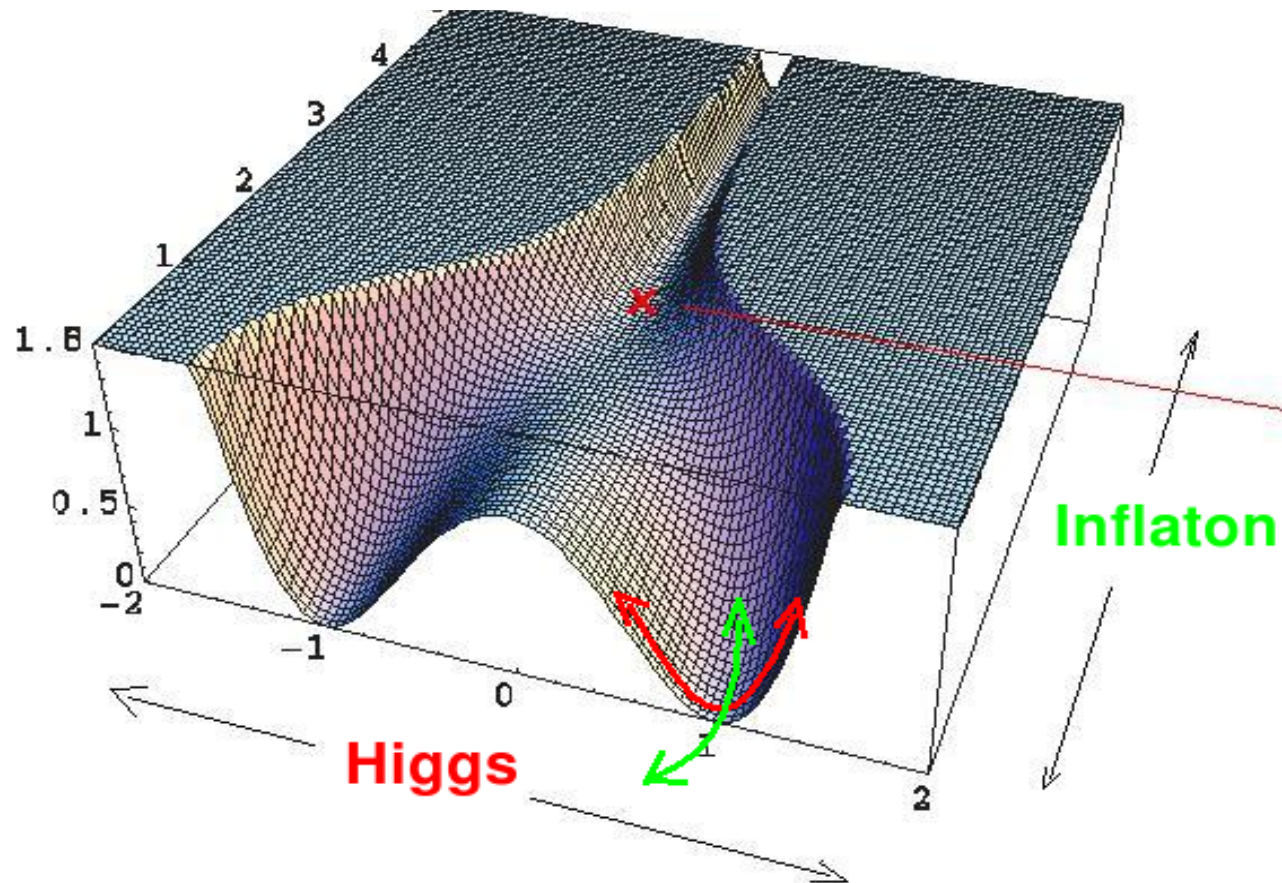
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GAUGE (P)REHEATING

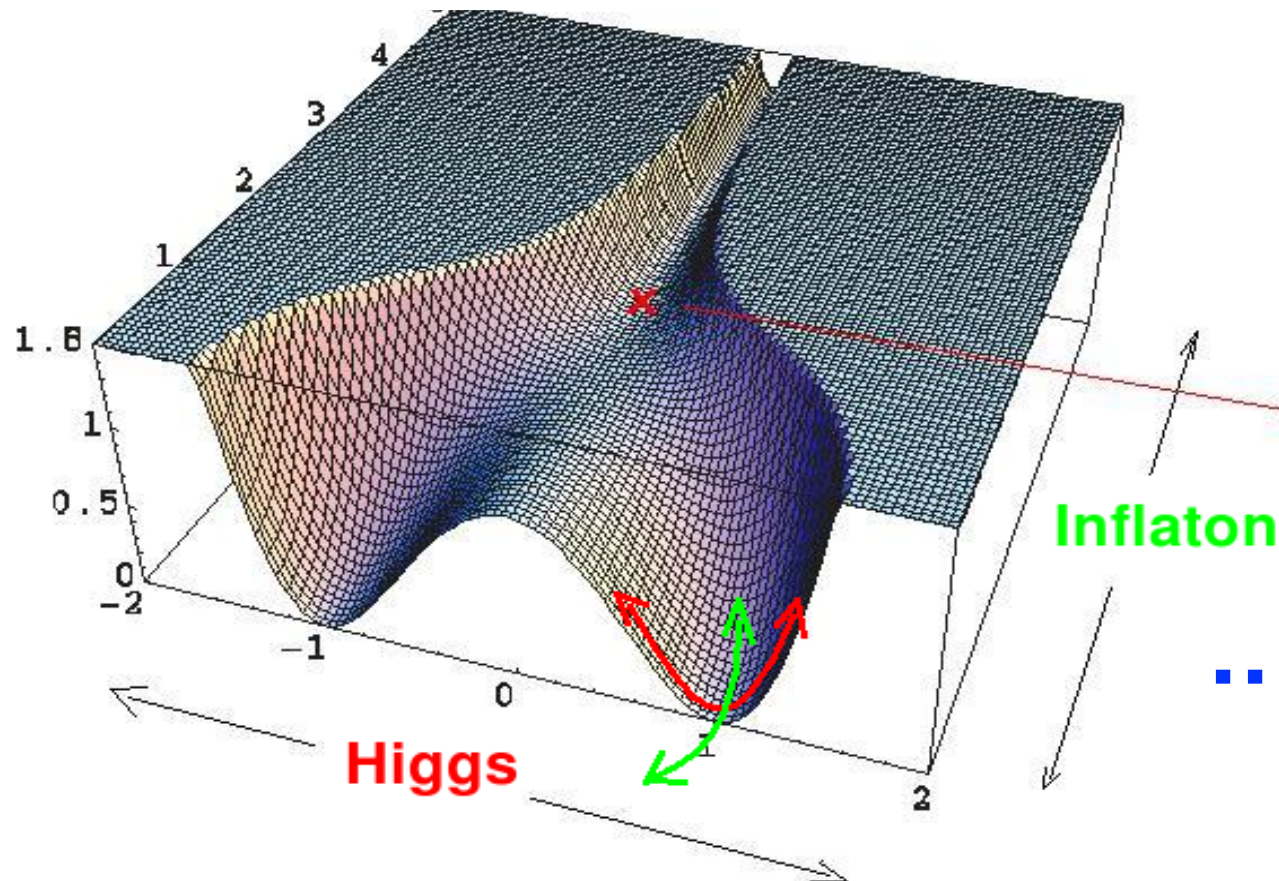
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... now there
are gauge field(s) !

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

GAUGE (P)REHEATING

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EOM: $\begin{cases} \text{Minkowski,} \\ \text{Temporal Gauge (A}_0=0) \end{cases}$

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

$$\ddot{A}_i - \partial_j \partial_j A_i + \partial_i \partial_j A_j = 2e^2 \text{Im} [\varphi^* D_i \varphi]$$

$$\partial_i \dot{A}_i = 2e^2 \text{Im} [\varphi^* \dot{\varphi}] .$$

→ SCALARS eom

→ VECTORS eom

→ GAUSS law

GAUGE (P)REHEATING

The Abelian-Higgs+Inflaton model

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SCALARS eom

VECTORS eom

GAUSS law

GW EOM

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

$$\Pi_{ij}^{\text{TT}} = [\partial_i \chi \partial_j \chi + 2 \text{Re} [D_i \varphi (D_j \varphi)^*] - B_i B_j - E_i E_j]^{\text{TT}}$$

GAUGE (P)REHEATING

The Abelian-Higgs+Inflaton model

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

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COVARIANT

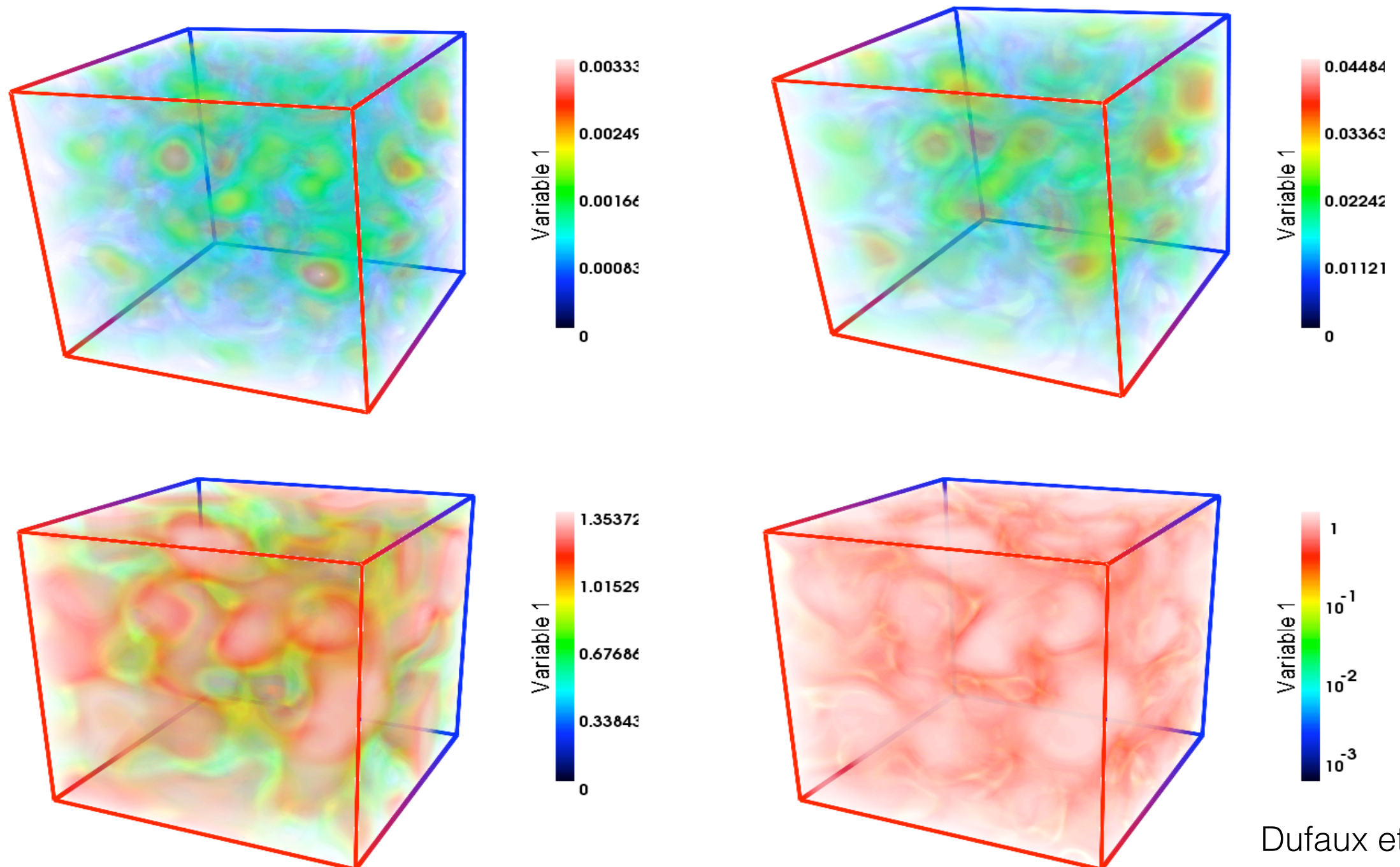
MAGNETIC

ELECTRIC

GAUGE (P)REHEATING

The Abelian-Higgs+Inflaton model

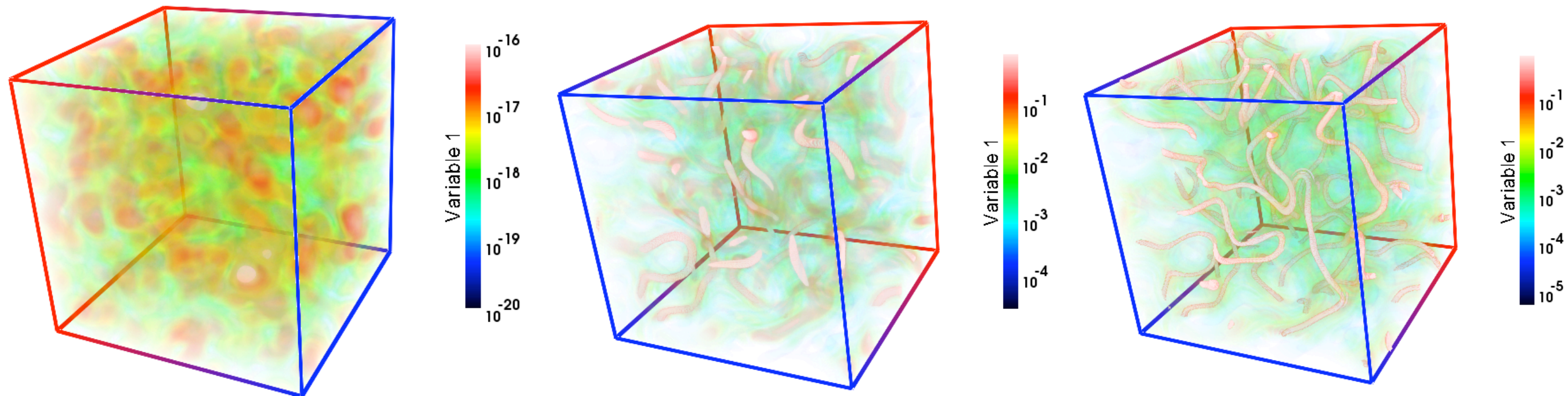
DYNAMICS OF THE **HIGGS**: $m_t = 5.5 \rightarrow m_t = 23$



GAUGE (P)REHEATING

The Abelian-Higgs+Inflaton model

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



GAUGE (P)REHEATING

The Abelian-Higgs+Inflaton model

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What's going on !?

Cosmic Strings are formed

GAUGE (P)REHEATING

The Abelian-Higgs+Inflaton model

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What's going on !?

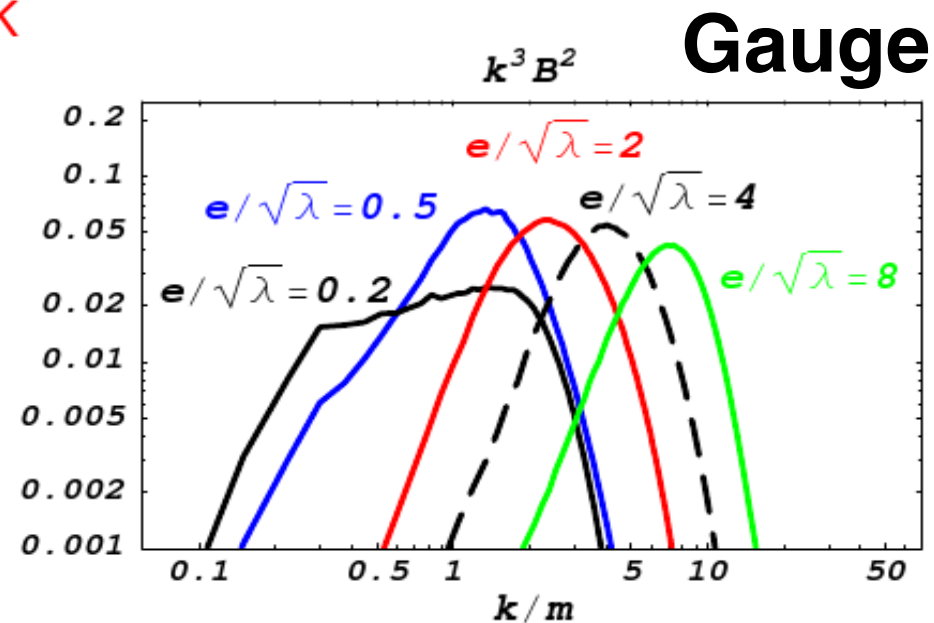
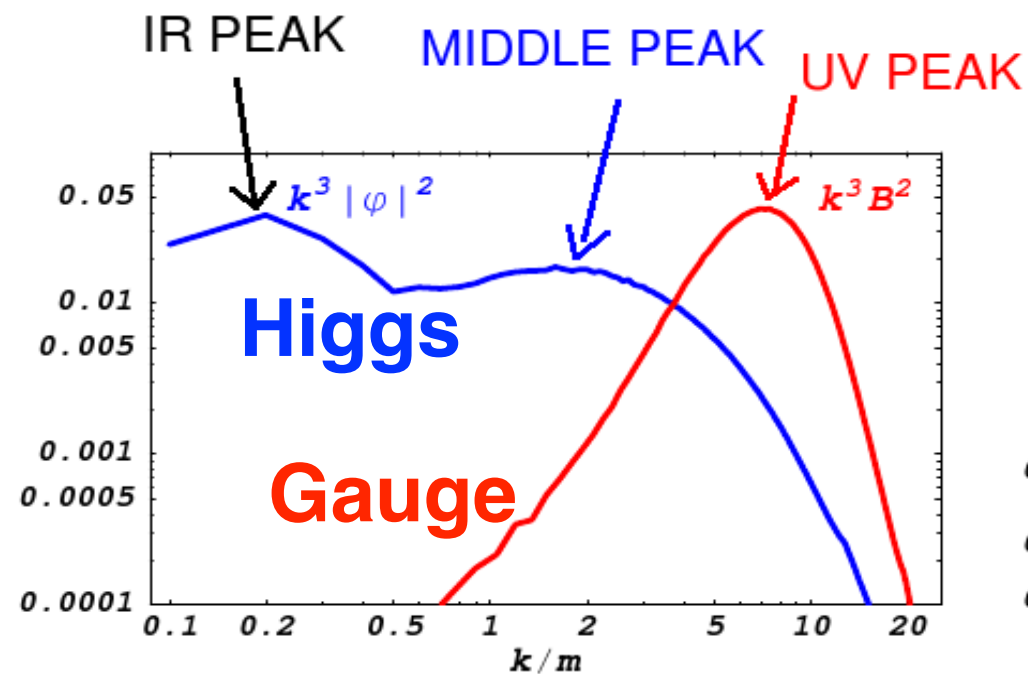
Cosmic Strings are formed

(Topological Defects $\longrightarrow$ 4th Lecture)

GAUGE (P)REHEATING

The Abelian-Higgs+Inflaton model

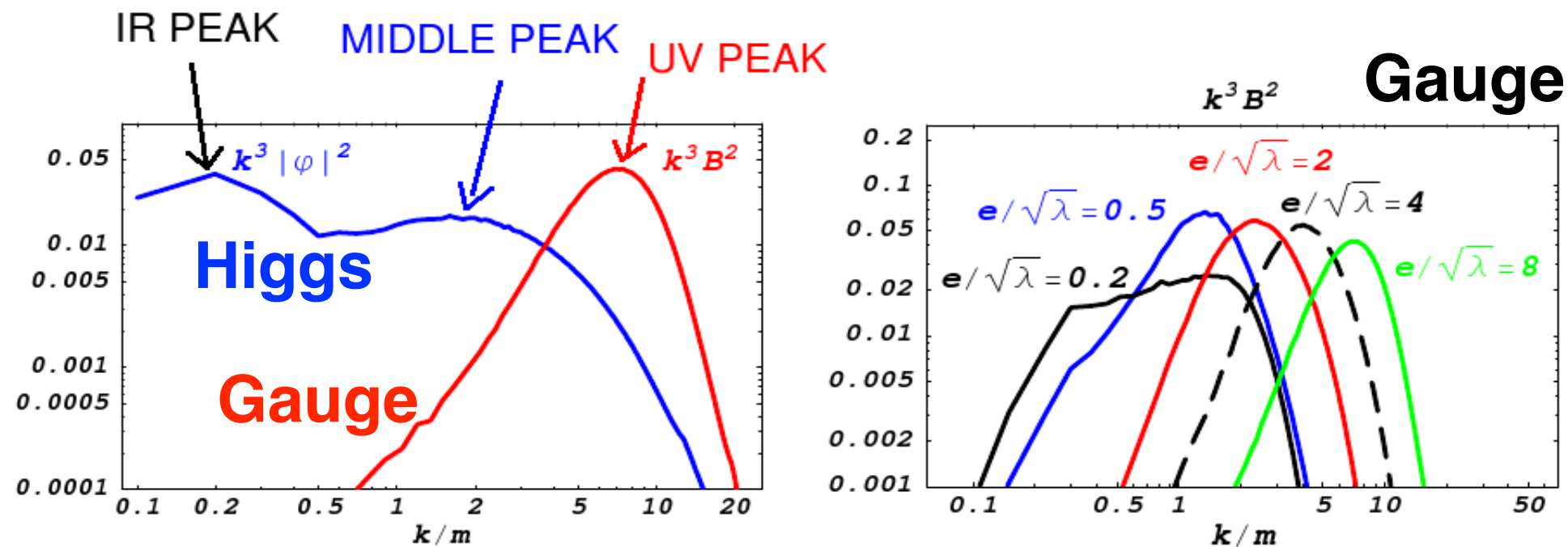
SCALARS AND VECTORS' SPECTRA:



GAUGE (P)REHEATING

The Abelian-Higgs+Inflaton model

SCALARS AND VECTORS' SPECTRA:



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

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

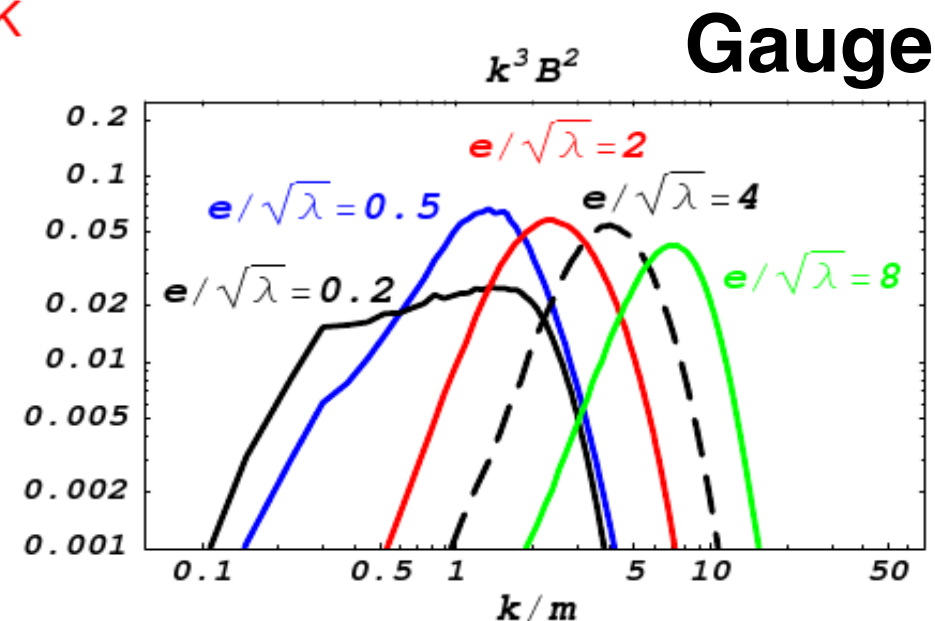
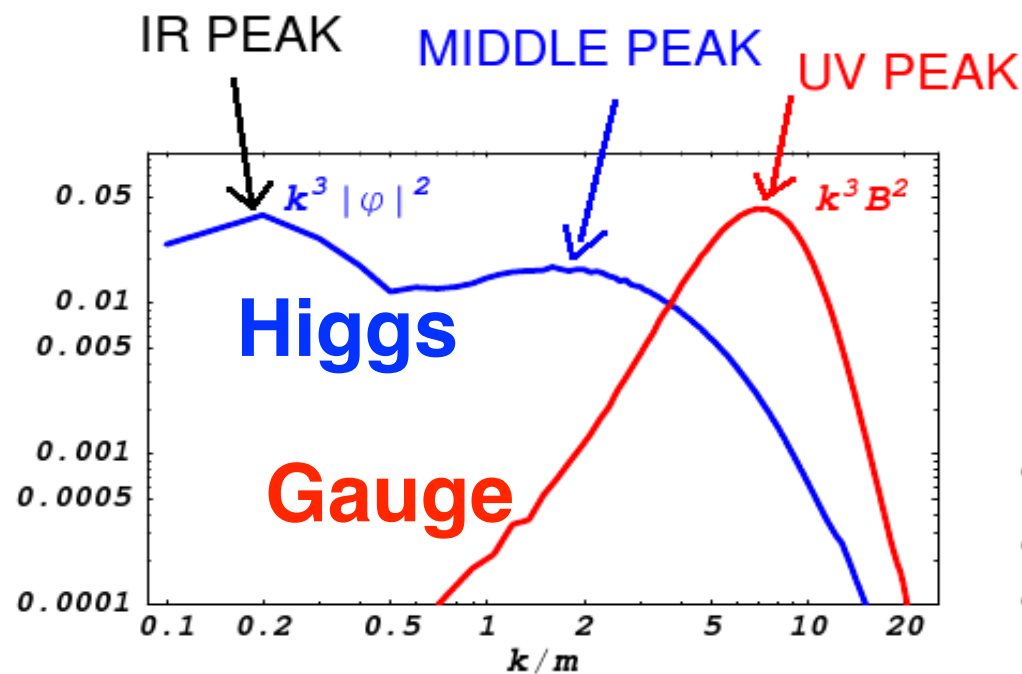
IR PEAK : Inflaton Velocity, Higgs+Inflaton Couplings (Dufaux et al 2009)

UV PEAK: Vector mass / Higgs Mass

GAUGE (P)REHEATING

The Abelian-Higgs+Inflaton model

SCALARS AND VECTORS' SPECTRA:



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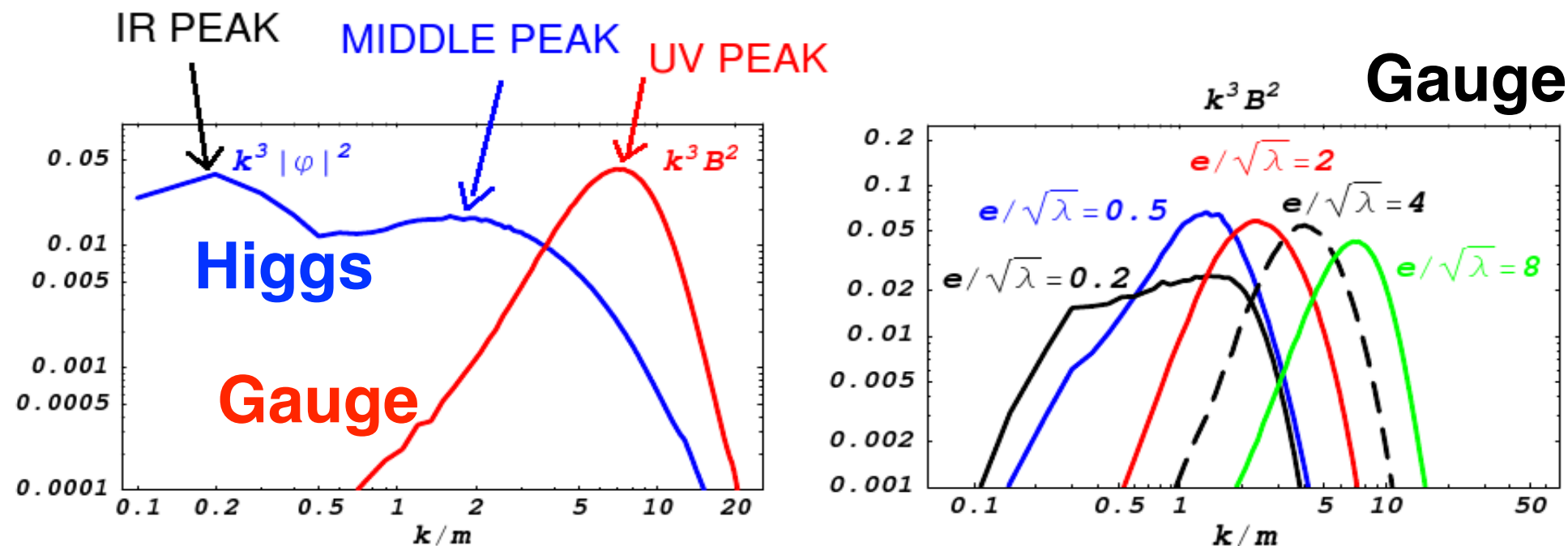
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GAUGE (P)REHEATING

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

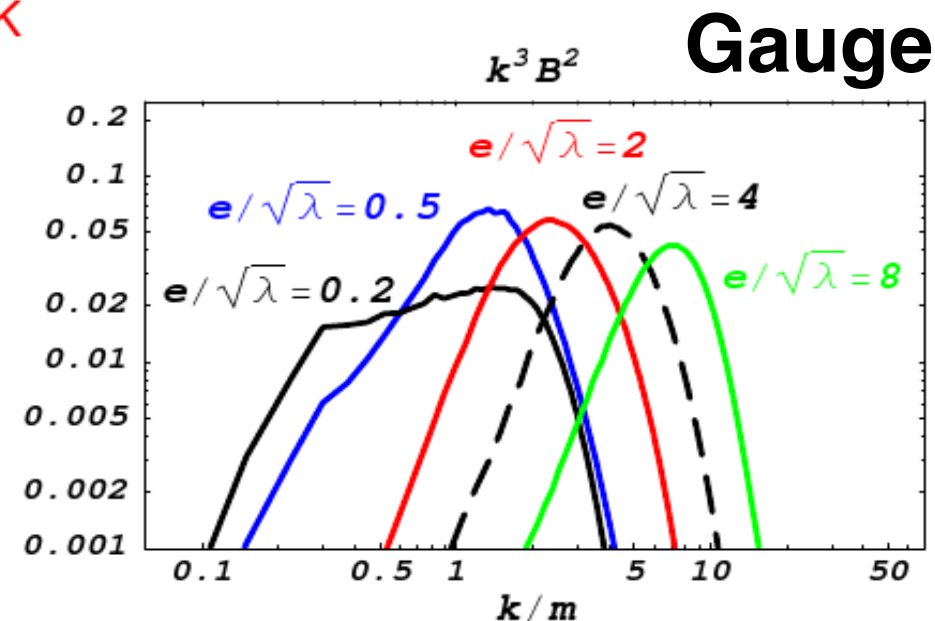
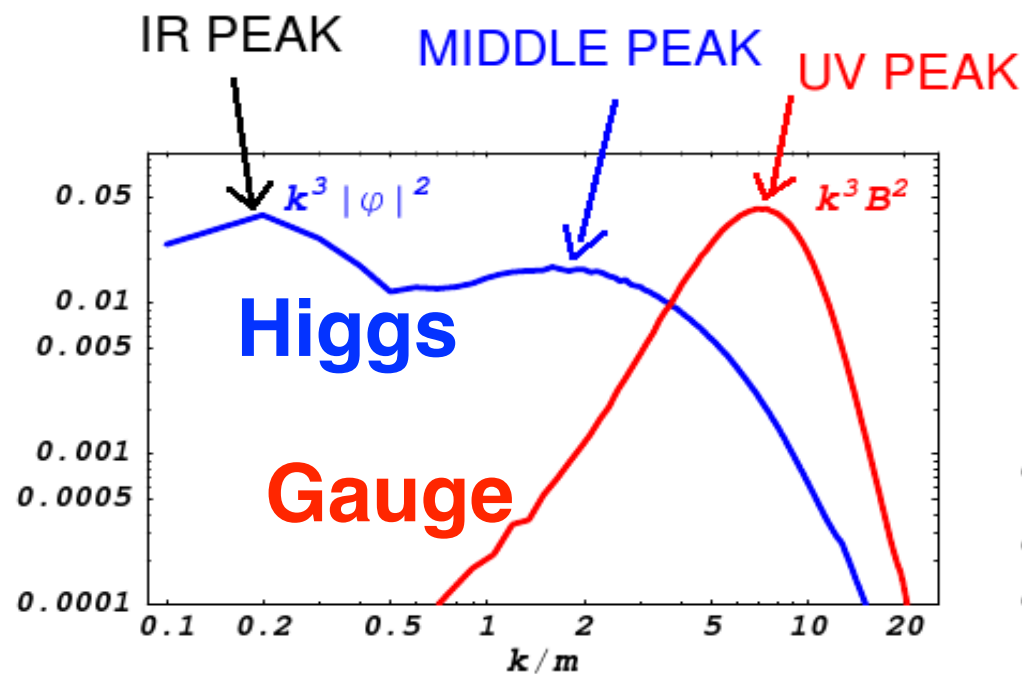
IR PEAK: Inflaton Velocity, Higgs+Inflaton Couplings

UV PEAK: Vector mass / Higgs Mass

GAUGE (P)REHEATING

The Abelian-Higgs+Inflaton model

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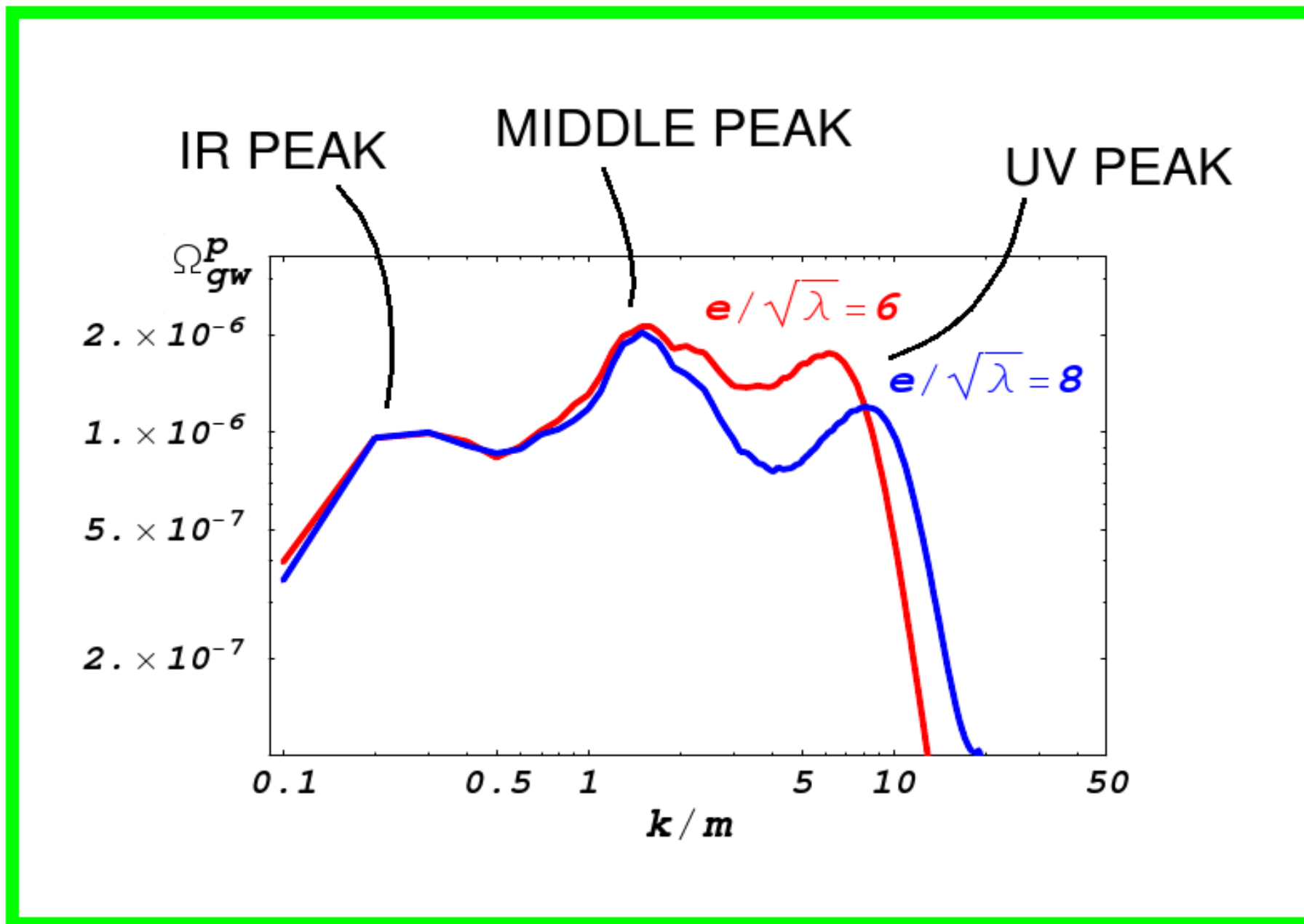
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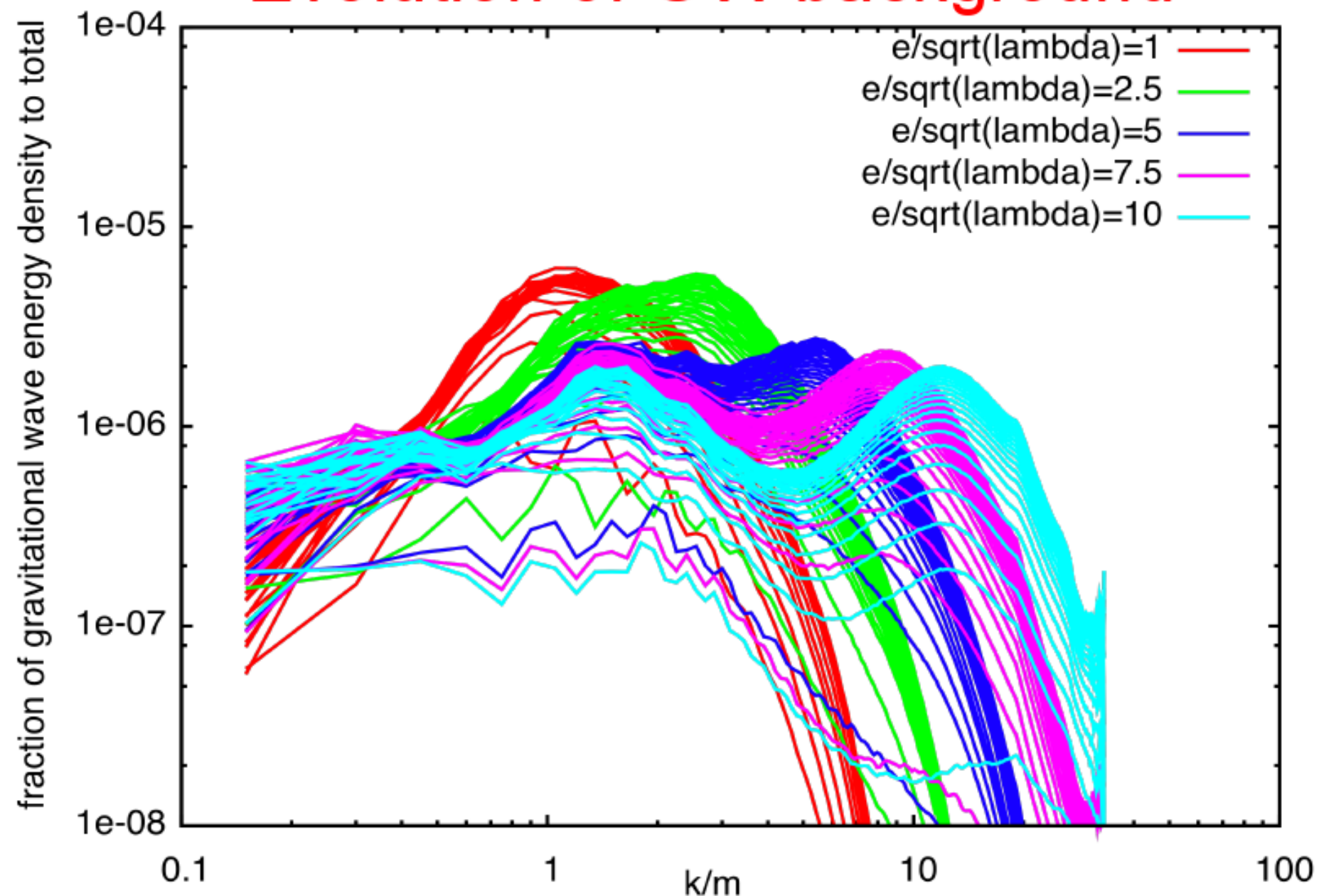


GAUGE (P)REHEATING

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: $F(g, \lambda, V_c)$

UV peak Amplitude: Lattice Simulations

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

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

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

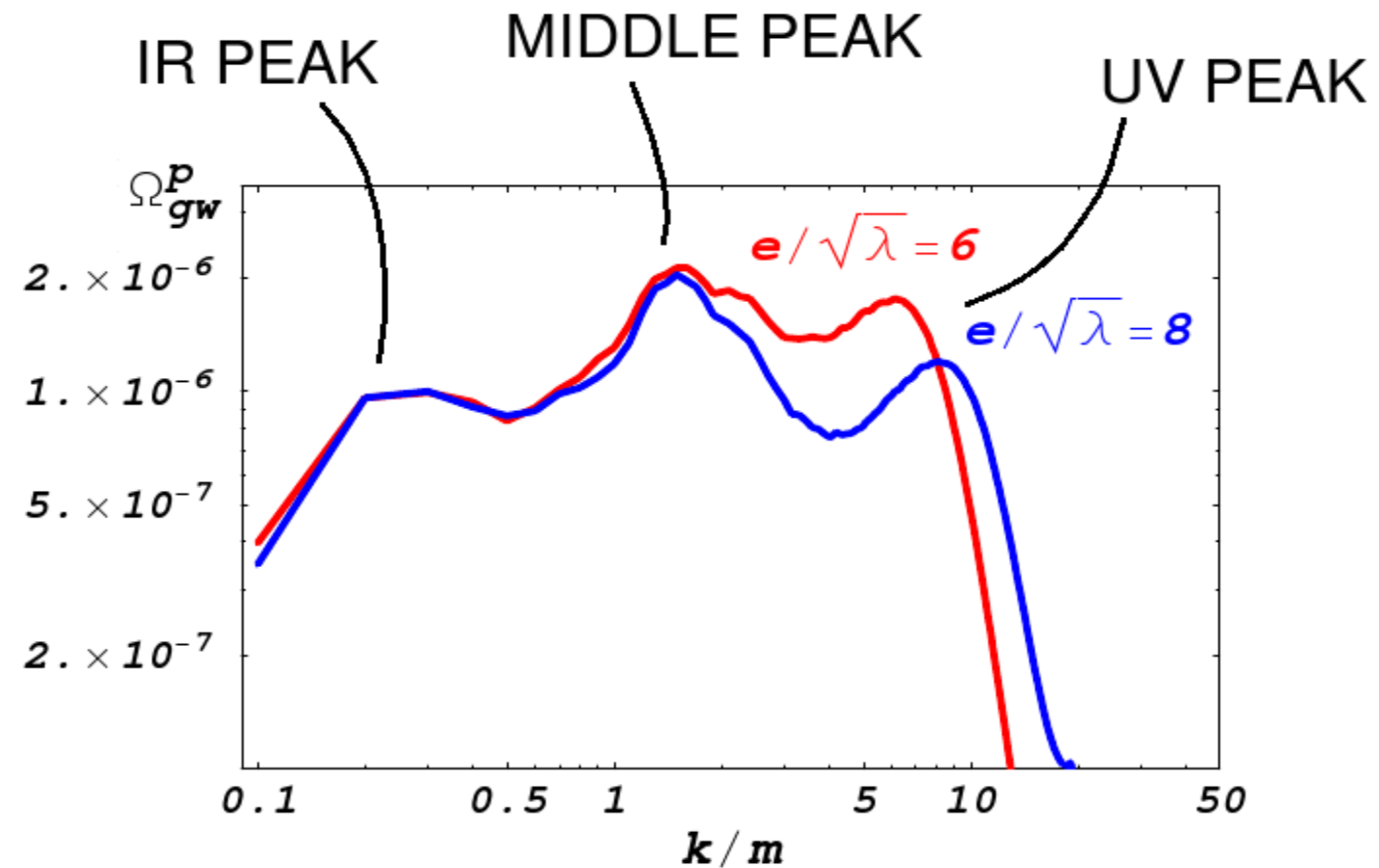
RED-SHIFTED
FREQUENCIES

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

GAUGE (P)REHEATING

The Abelian-Higgs+Inflaton model

Several Peaks !
(particle physics spectroscopy)



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Several Peaks !
(particle physics
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$$\Omega_{\text{GW}}^{(\text{o})} \sim 10^{-11},$$

Large amplitude(s) !

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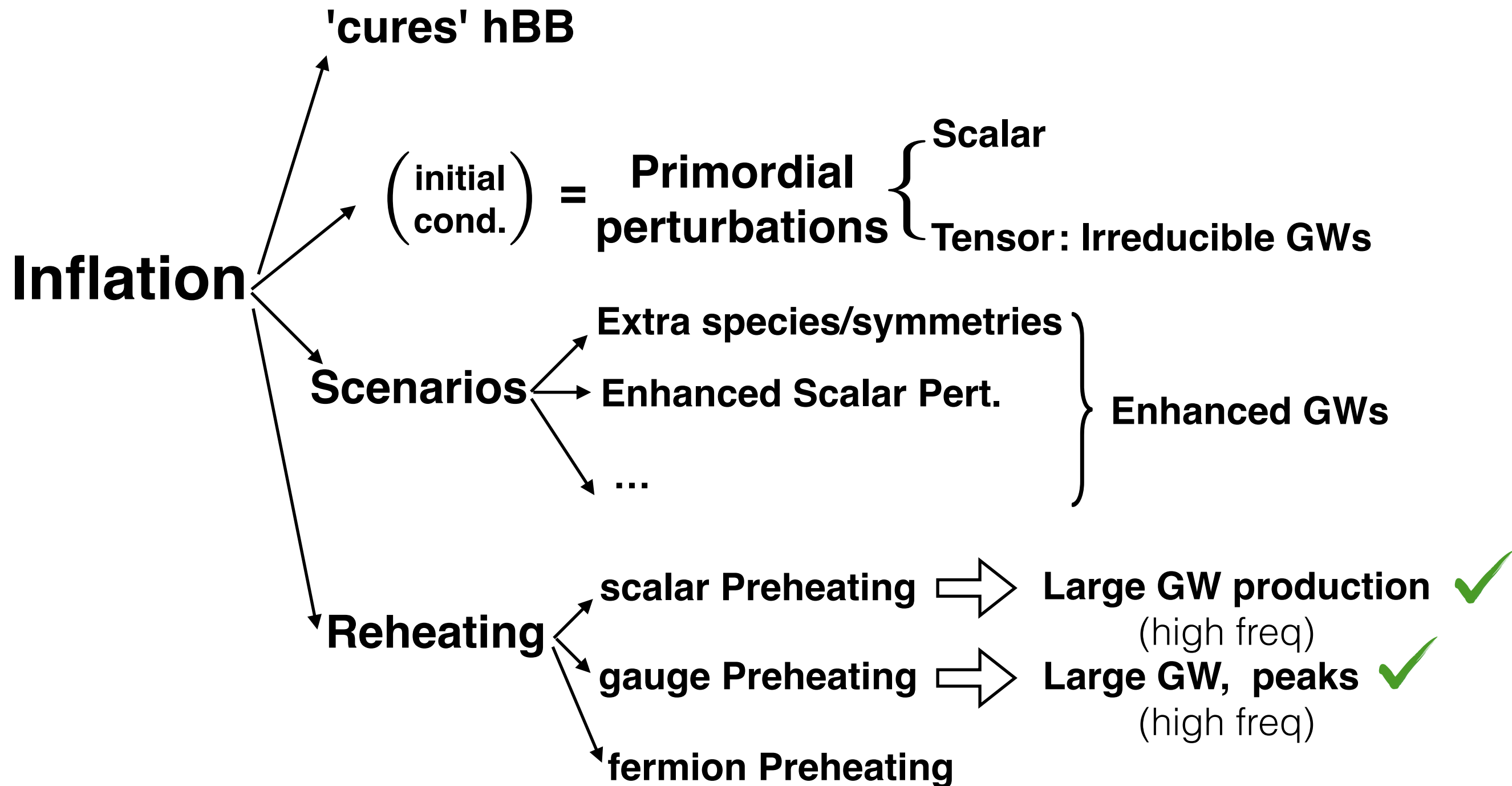
Large amplitude(s) ! ... but at high Frequency !

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

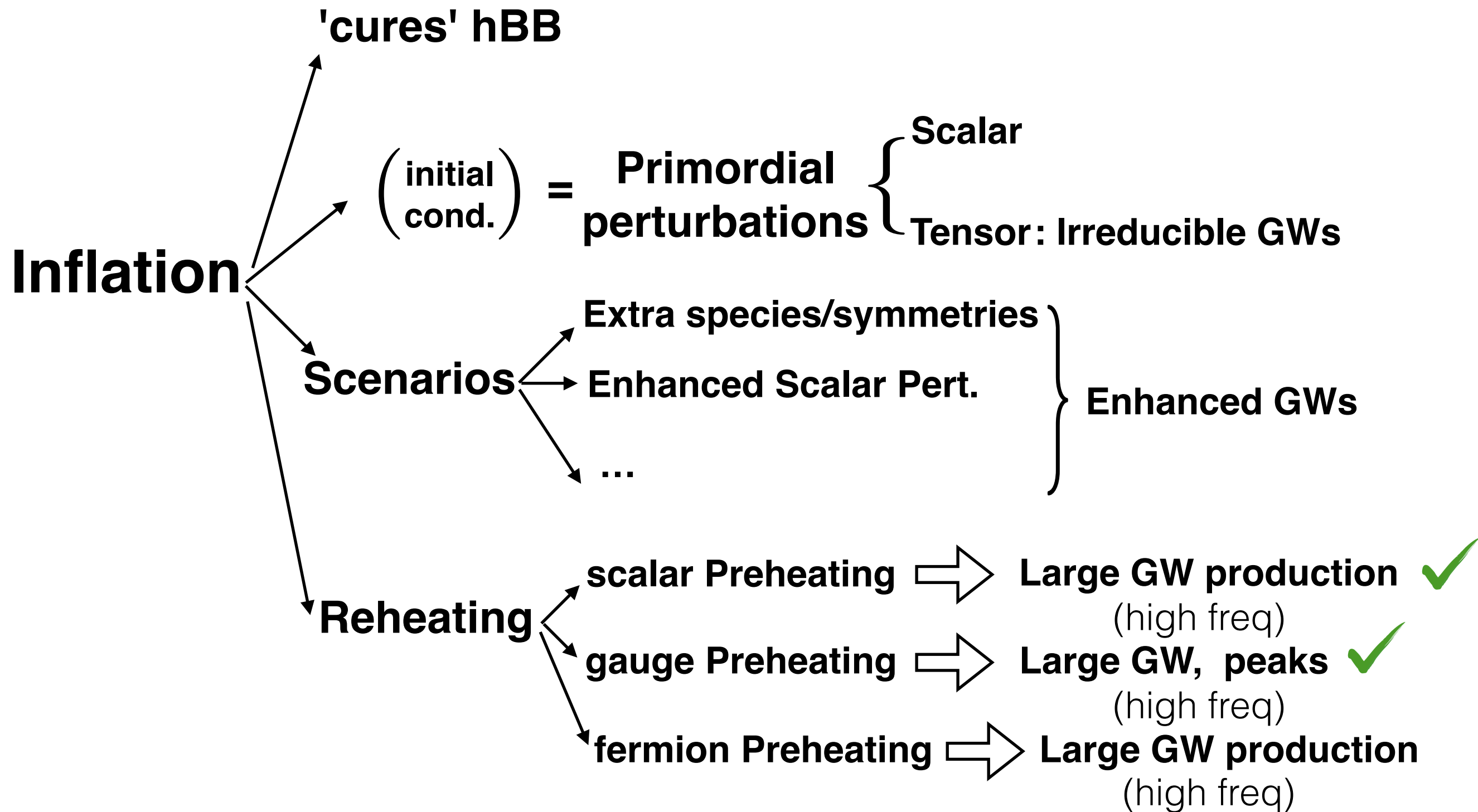
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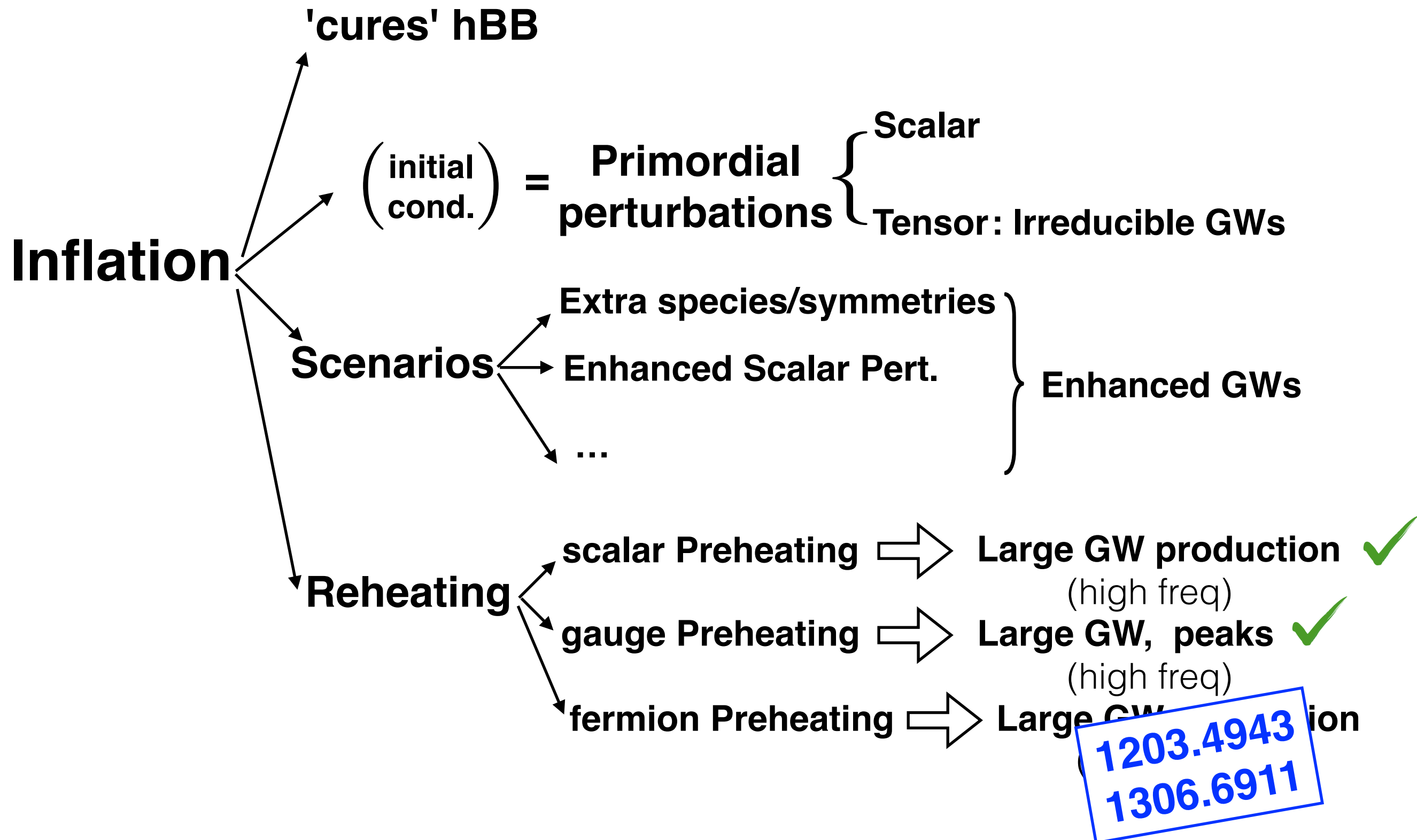
INFLATIONARY COSMOLOGY



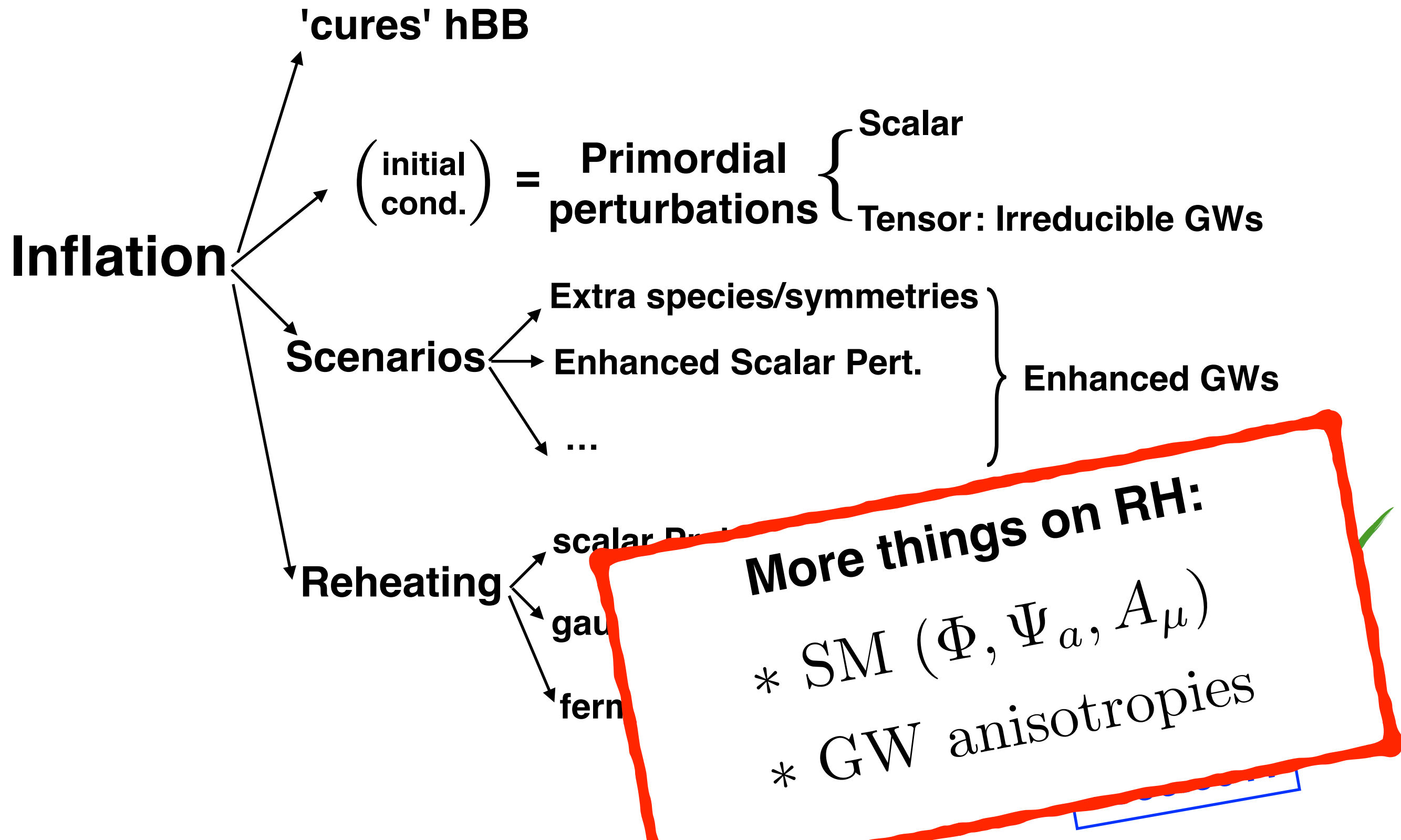
INFLATIONARY COSMOLOGY



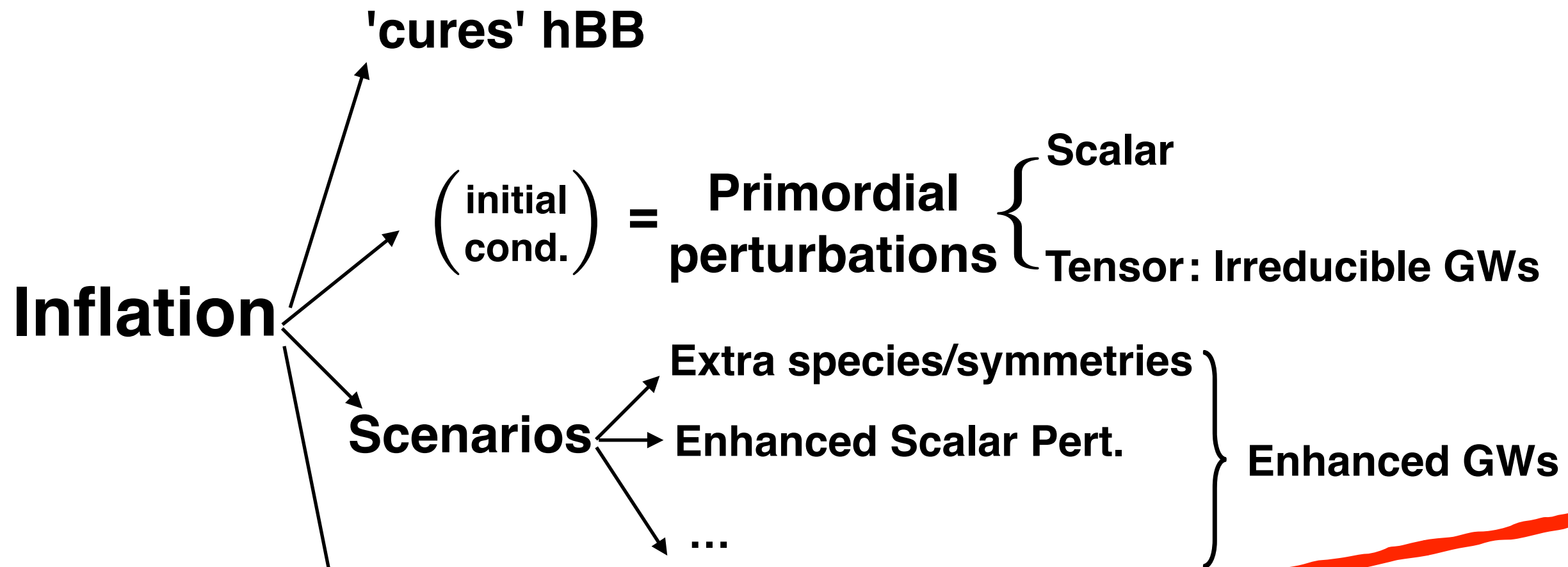
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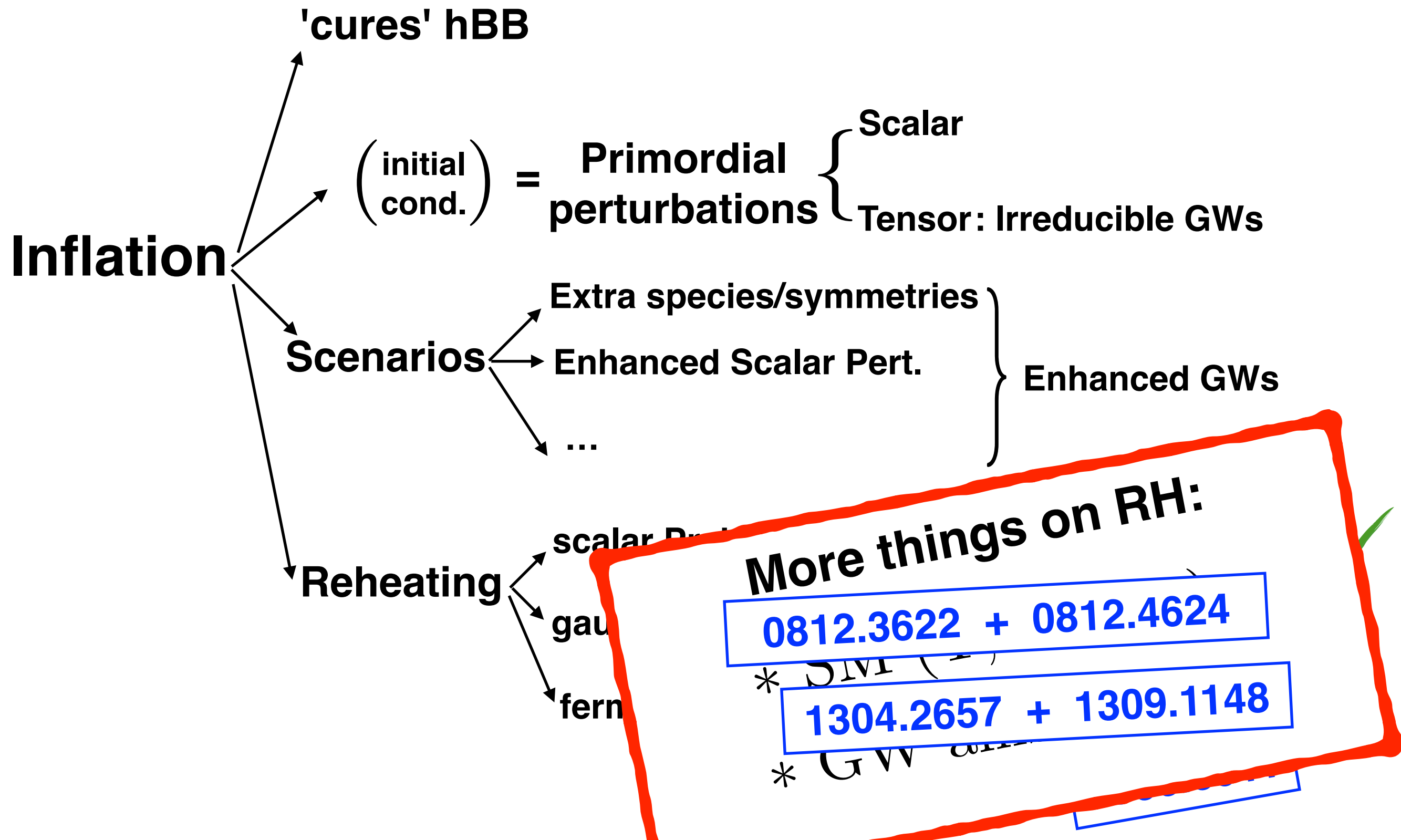
More things on RH:

0812.3622 + 0812.4624

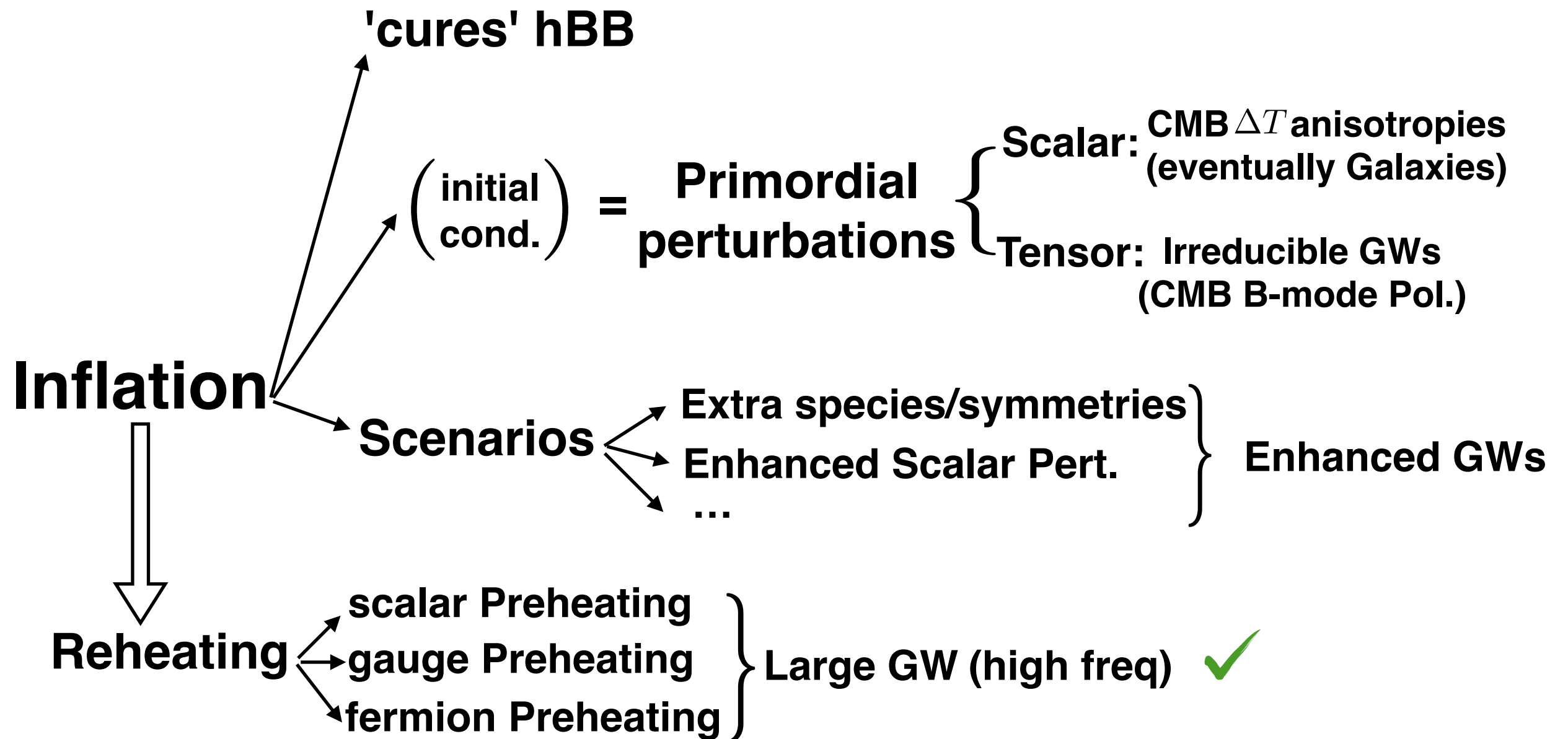
* $\Delta_{\text{SW}}(\tau)$

* GW anisotropies

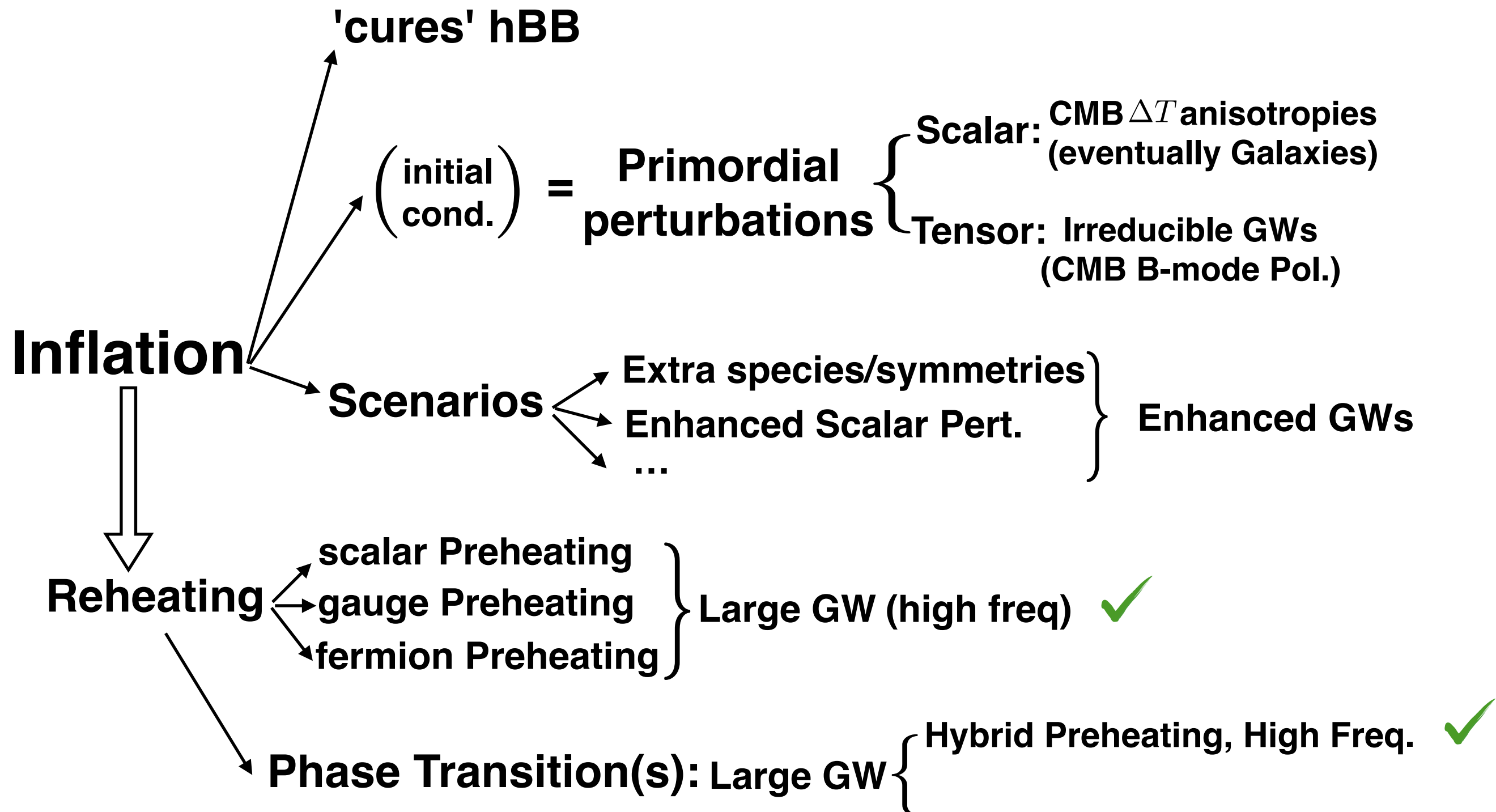
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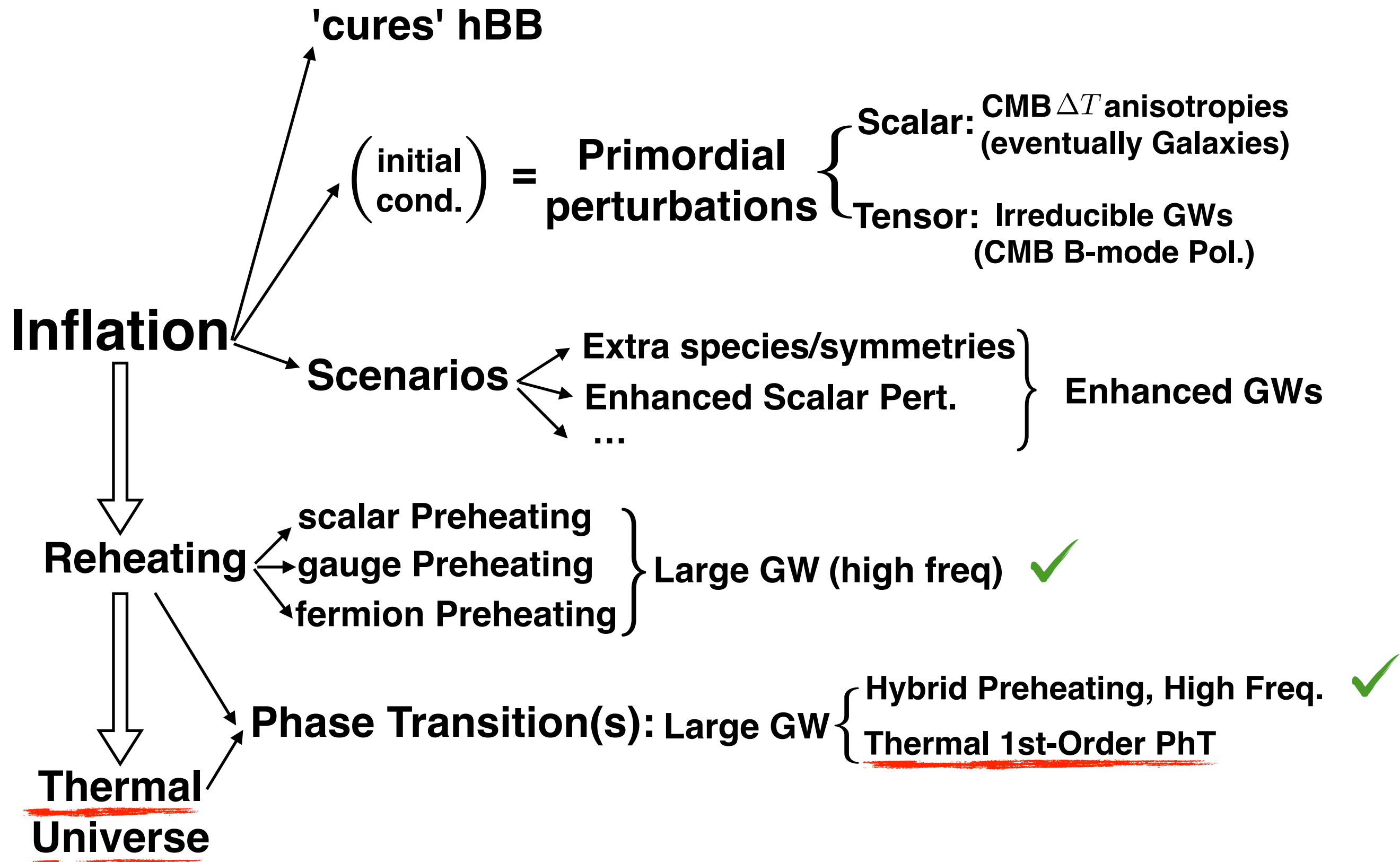
EARLY UNIVERSE



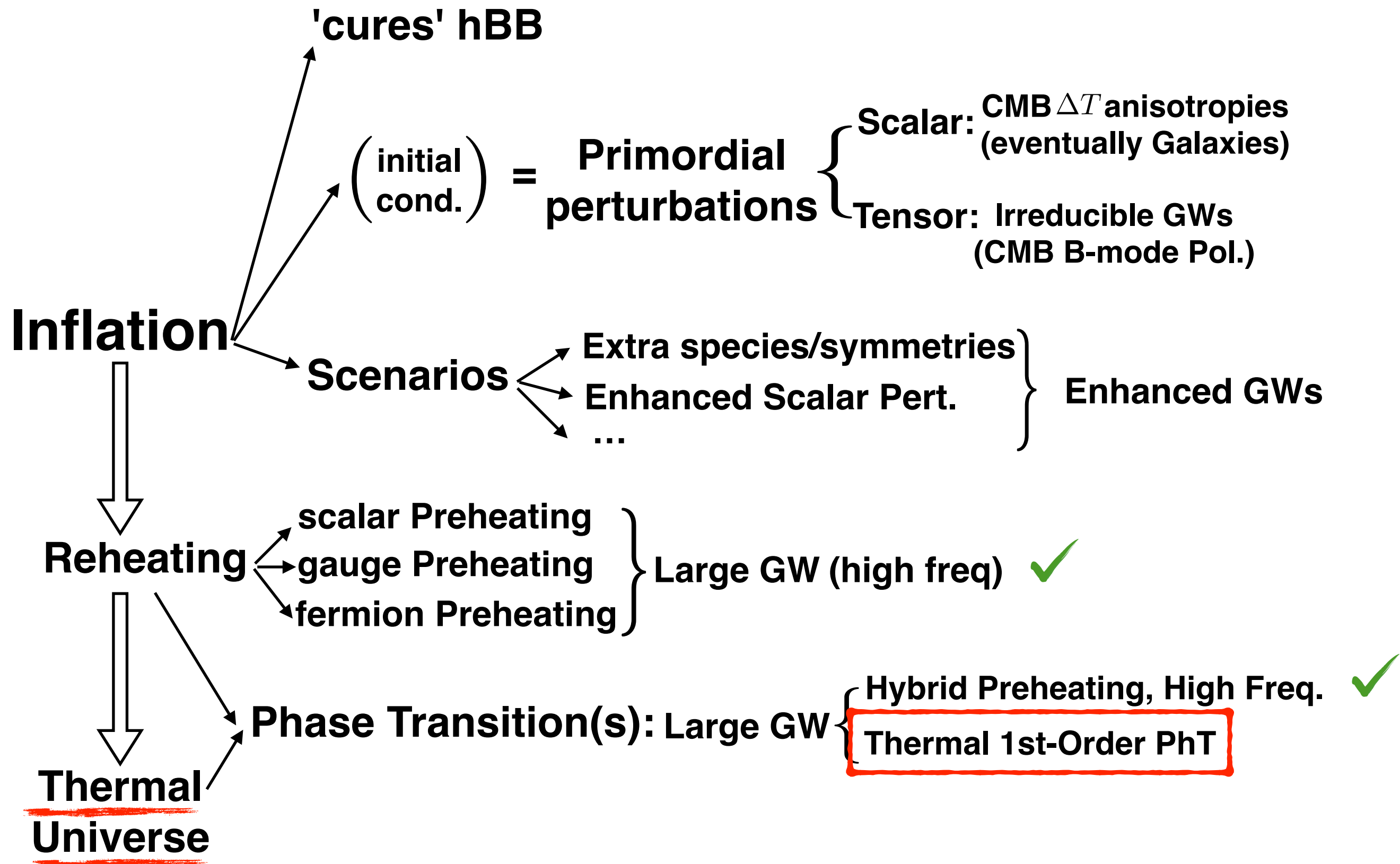
EARLY UNIVERSE



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GWs from first order phase transitions

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

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

$$\epsilon_* \leq 1$$

parameter characterising source

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Hubble rate }
↕
temperature

↑ @ Today
↑ @ Emission time

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

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

for

$$\epsilon_* \simeq 10^{-2}$$

$$T_* \simeq 1 \text{ TeV}$$

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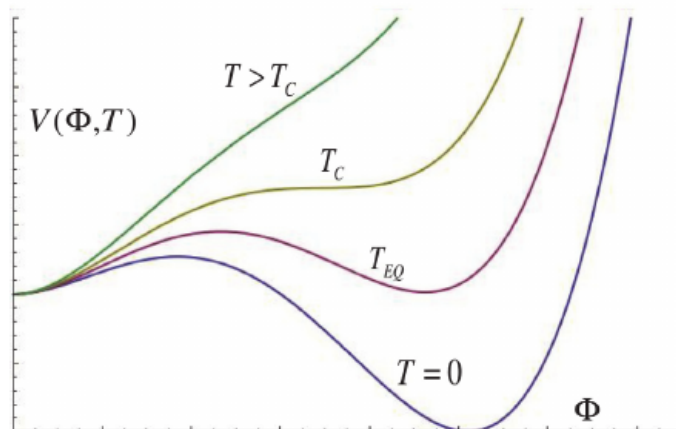
$\simeq \text{mHz}$ **LISA Freq !**

for $\epsilon_* \simeq 10^{-2}$ $T_* \simeq 1 \text{ TeV}$ **$\sim \text{EW scale !}$**

GWs from first order phase transitions

Universe expands, temperature decreases: phase transition triggered !

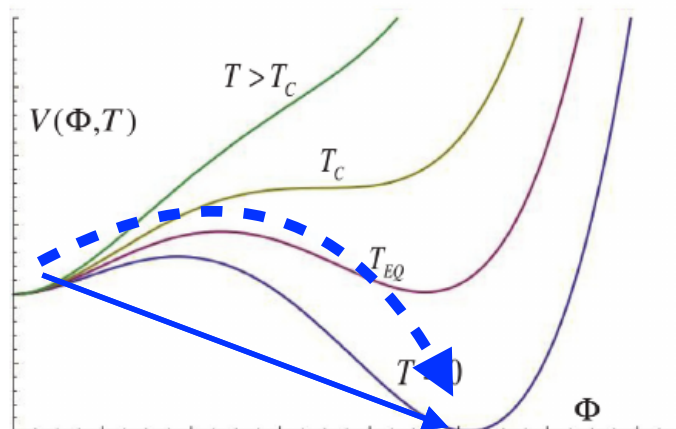
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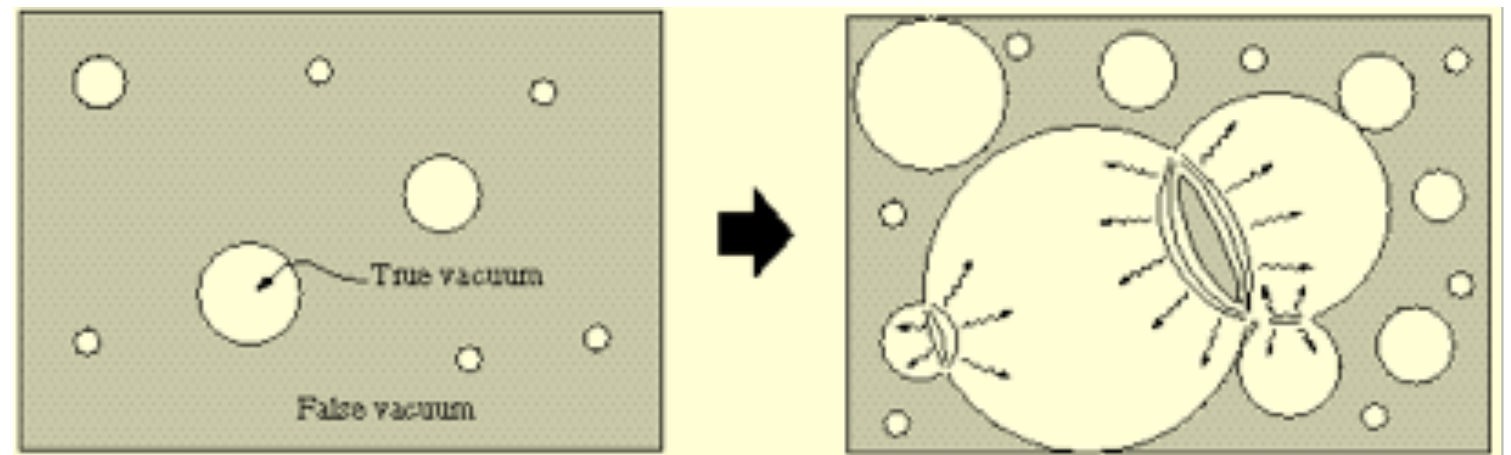
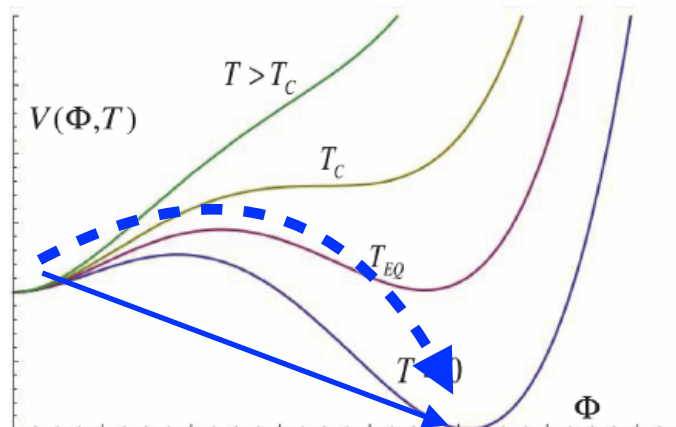


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"bubble" formation

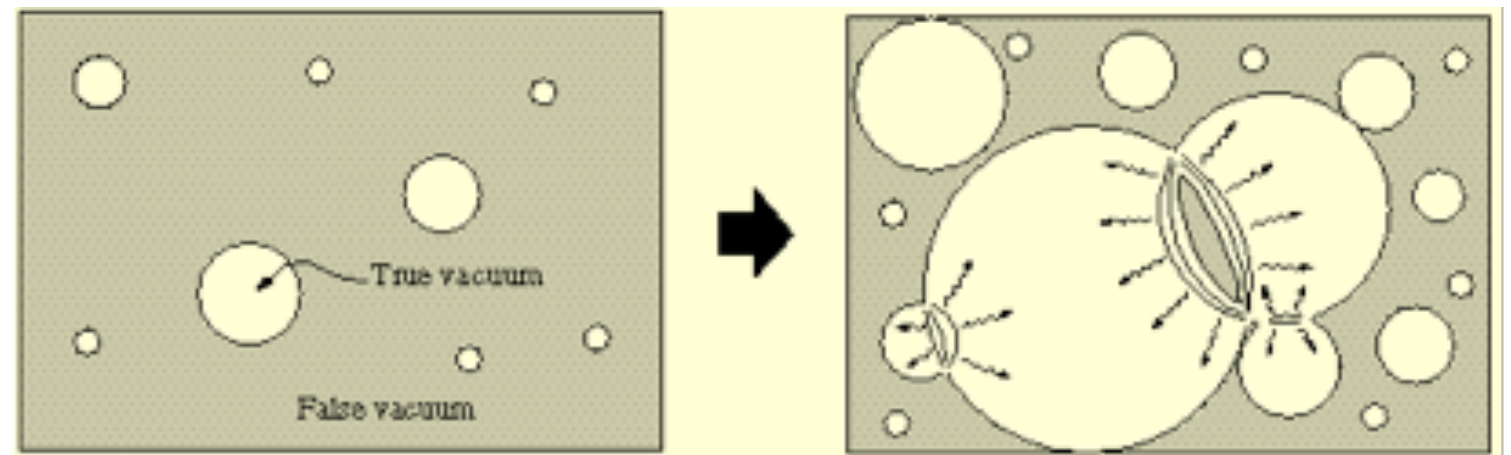
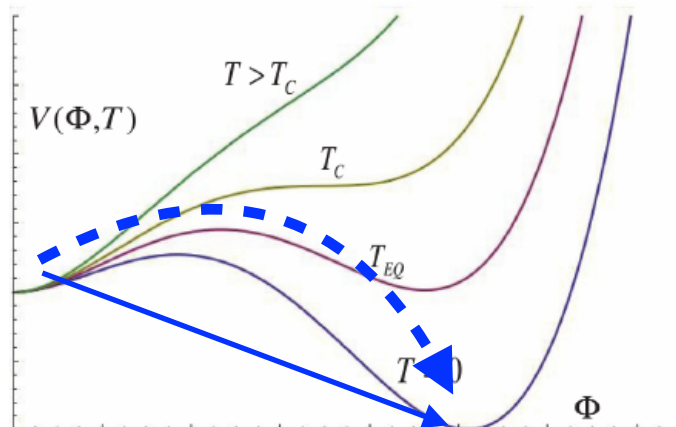


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source: Π_{ij} tensor
anisotropic stress

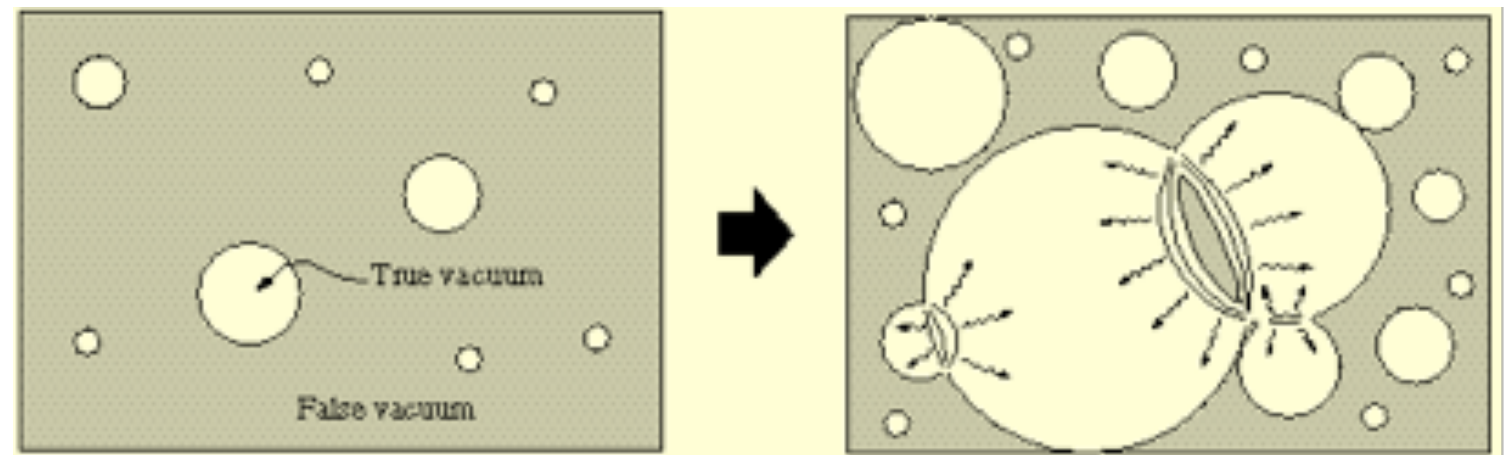
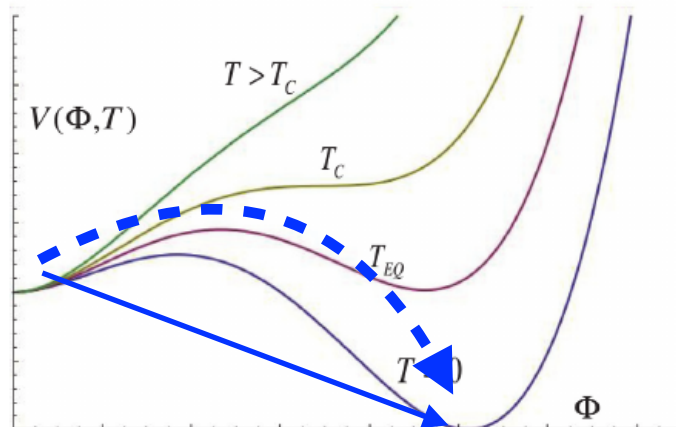
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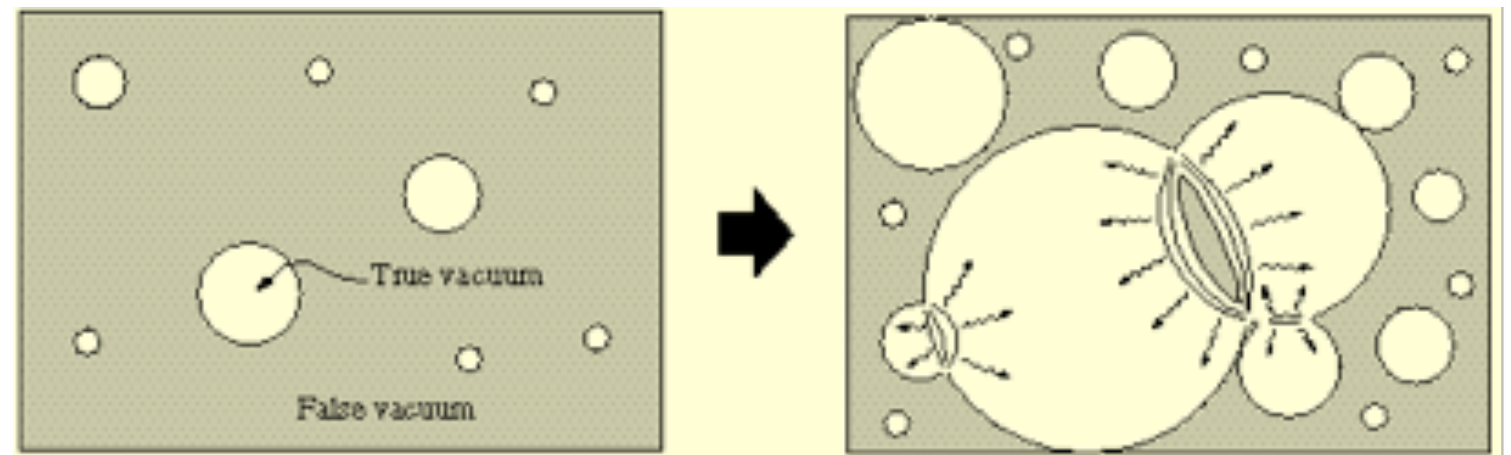
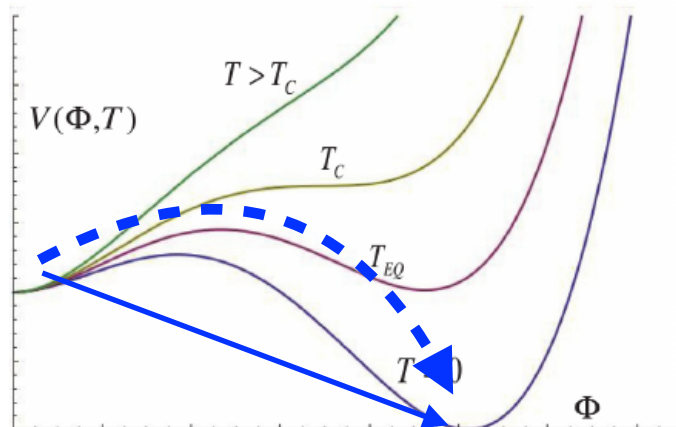
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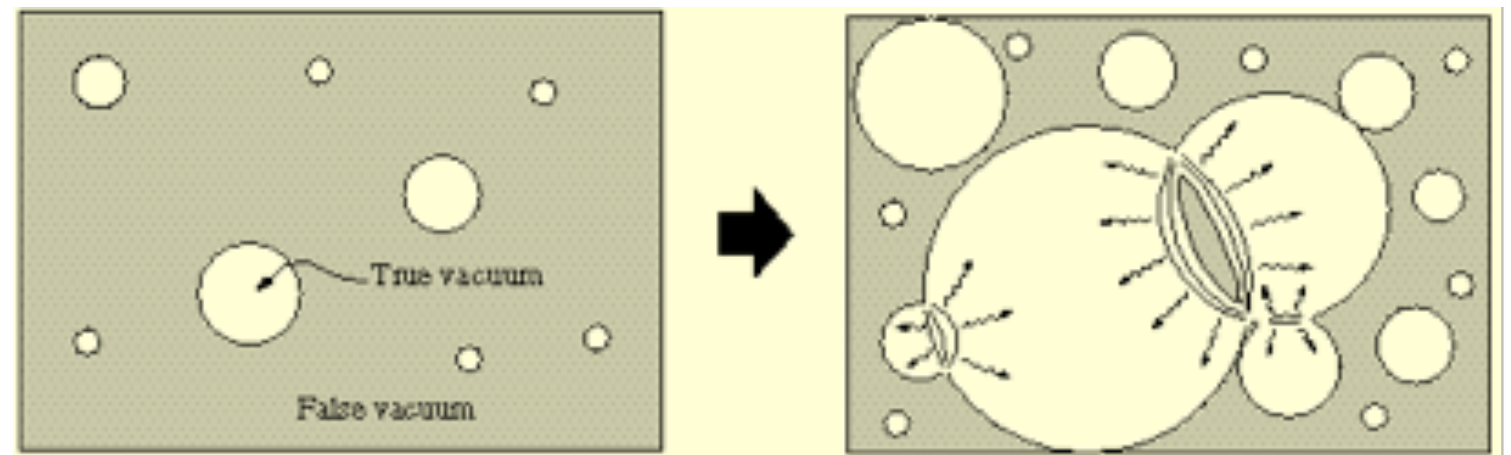
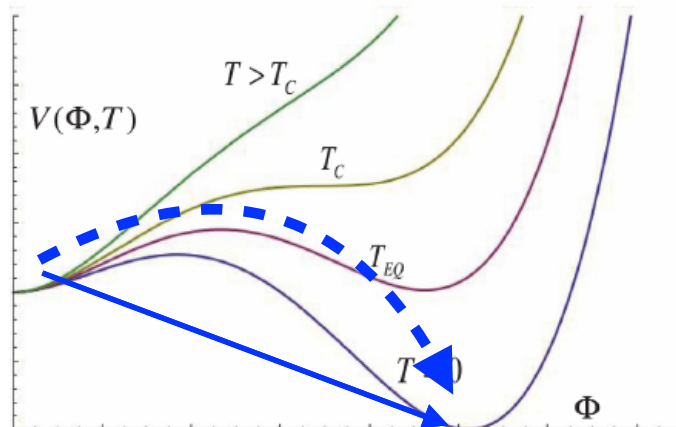
- collisions of bubble walls
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- primordial magnetic fields (MHD turbulence)

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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?

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

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BUBBLE COLLISION

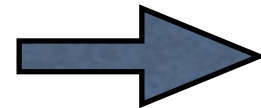
**SOUND WAVES AND
MDH TURBULENCE**

Parameters determining the GW spectrum

Freq.
(today)

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Parameter List
(not independent)

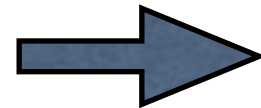
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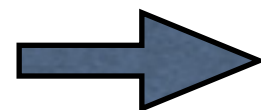


Parameter List
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$$\frac{\beta}{H_*}, \quad v_b, \quad T_*$$

Amplitude
(today)

$$\Omega_{\text{GW}} \sim \Omega_{\text{rad}} \epsilon_*^2 \left(\frac{\rho_s^*}{\rho_{\text{tot}}^*} \right)^2$$



$$\frac{\rho_s^*}{\rho_{\text{tot}}^*} = \frac{\kappa \alpha}{1 + \alpha}$$

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

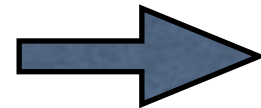
$$\kappa = \frac{\rho_{\text{kin}}}{\rho_{\text{vac}}}$$

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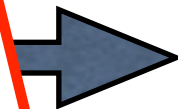
$$\frac{\beta}{H_*}, \quad v_b, \quad T_*$$

Amplitude
(today)

$$\Omega_{\text{GW}}$$

not most general !

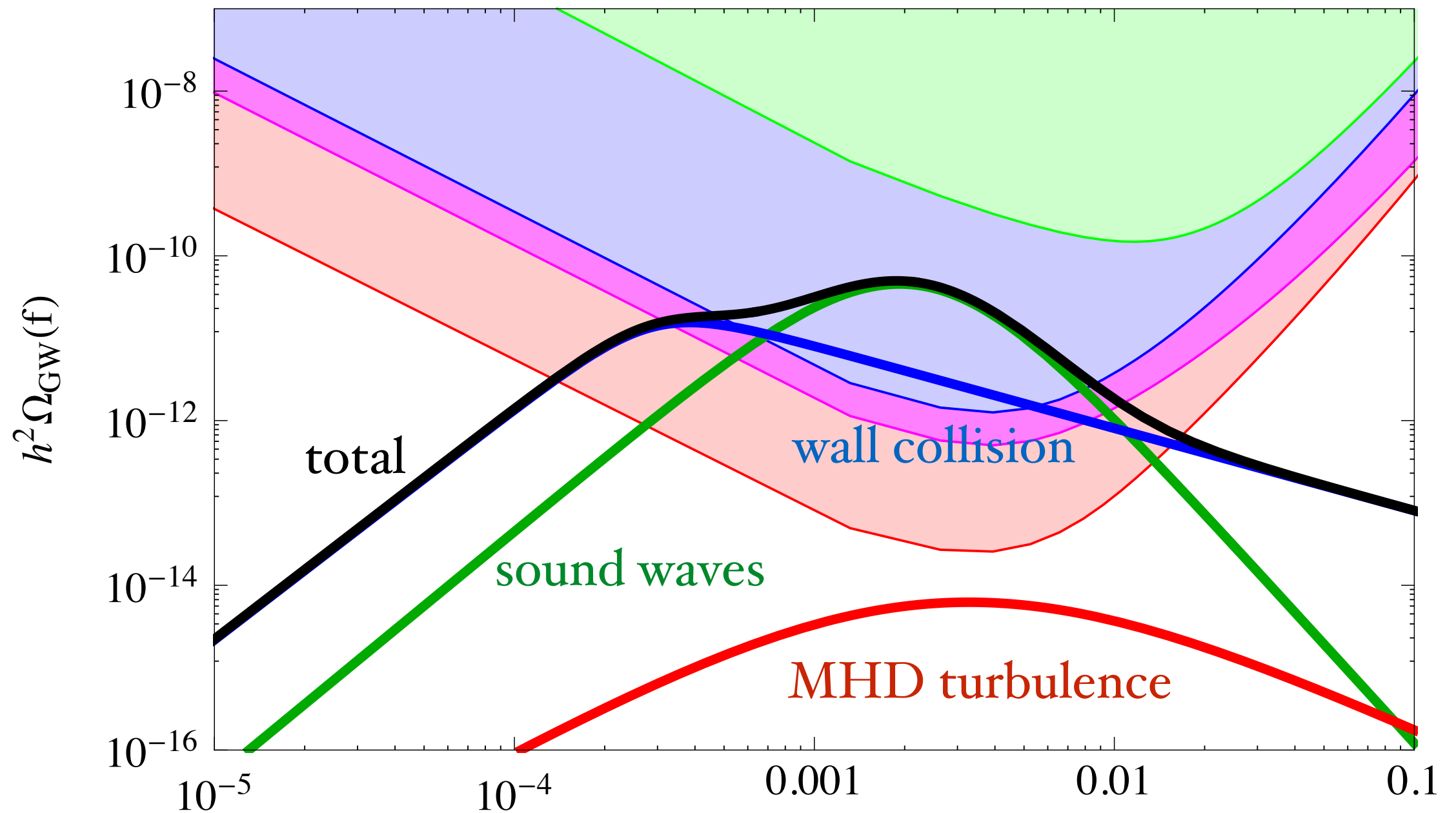
**Hydro-dynamical
effects & turbulence
separate treatment**



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

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Example of spectrum



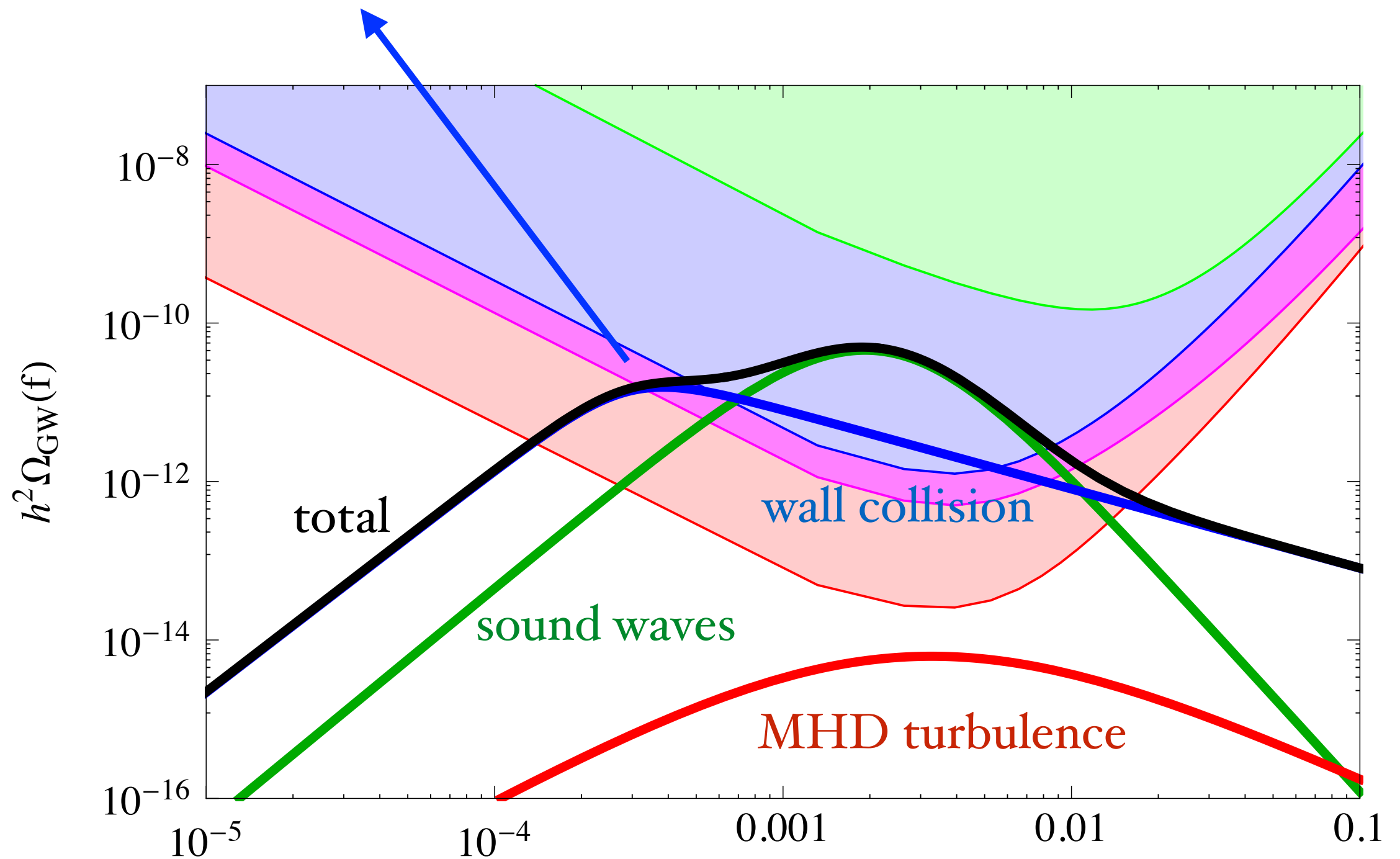
Caprini et al,
arXiv:1512.06239

f [Hz]

Caprini et al,
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Example of spectrum

peak of bubble collisions



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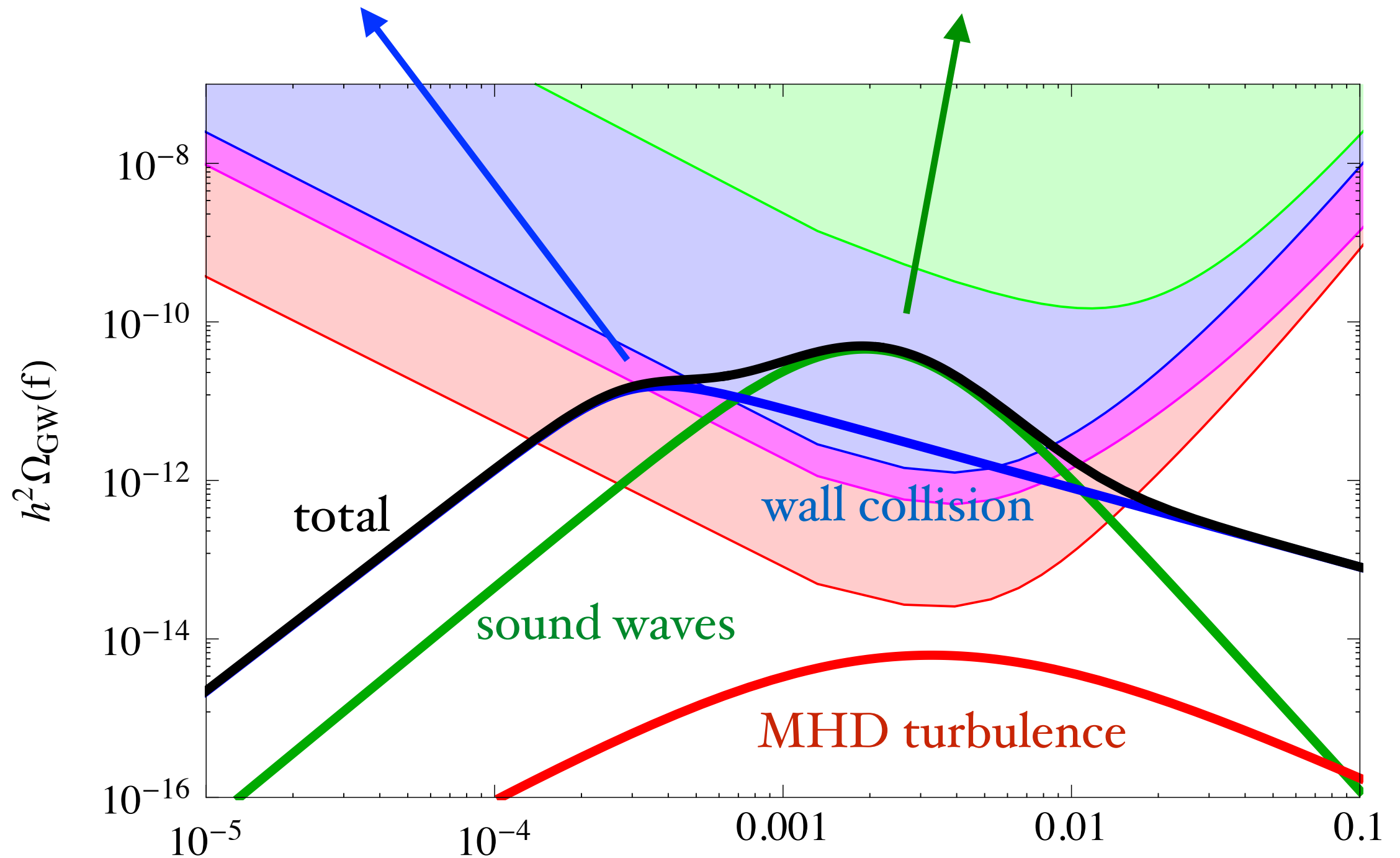
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peak of fluid-related processes



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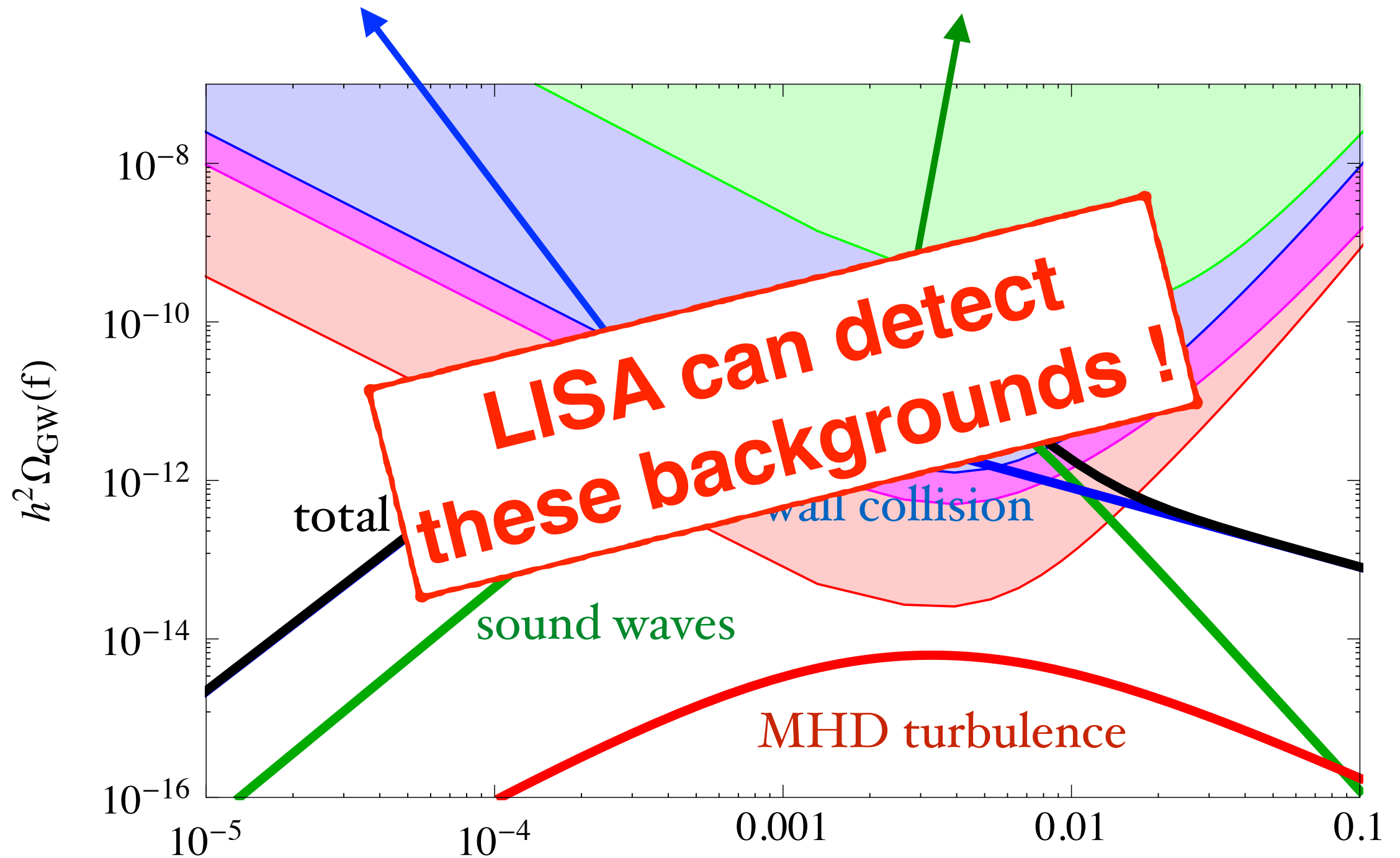
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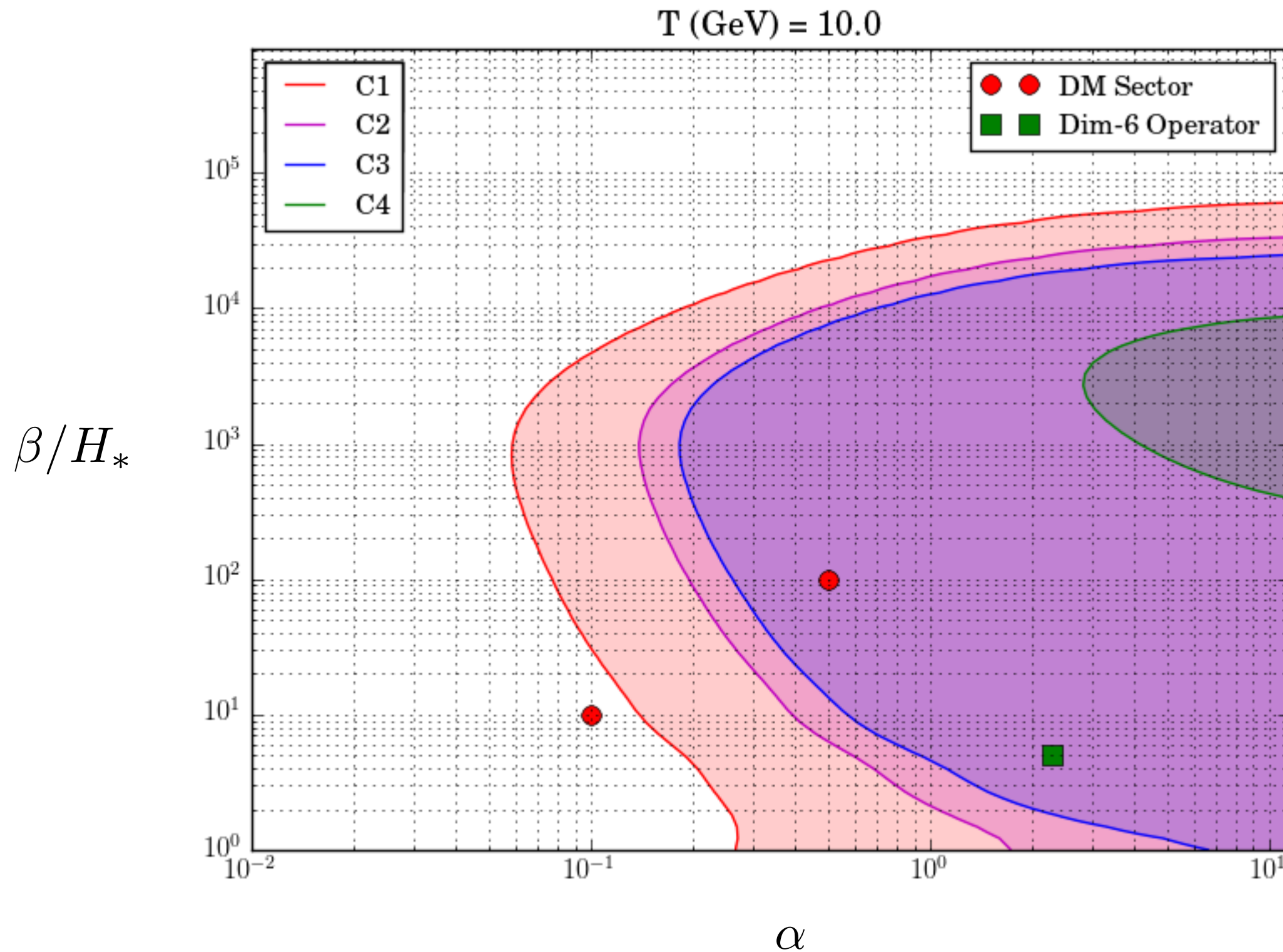
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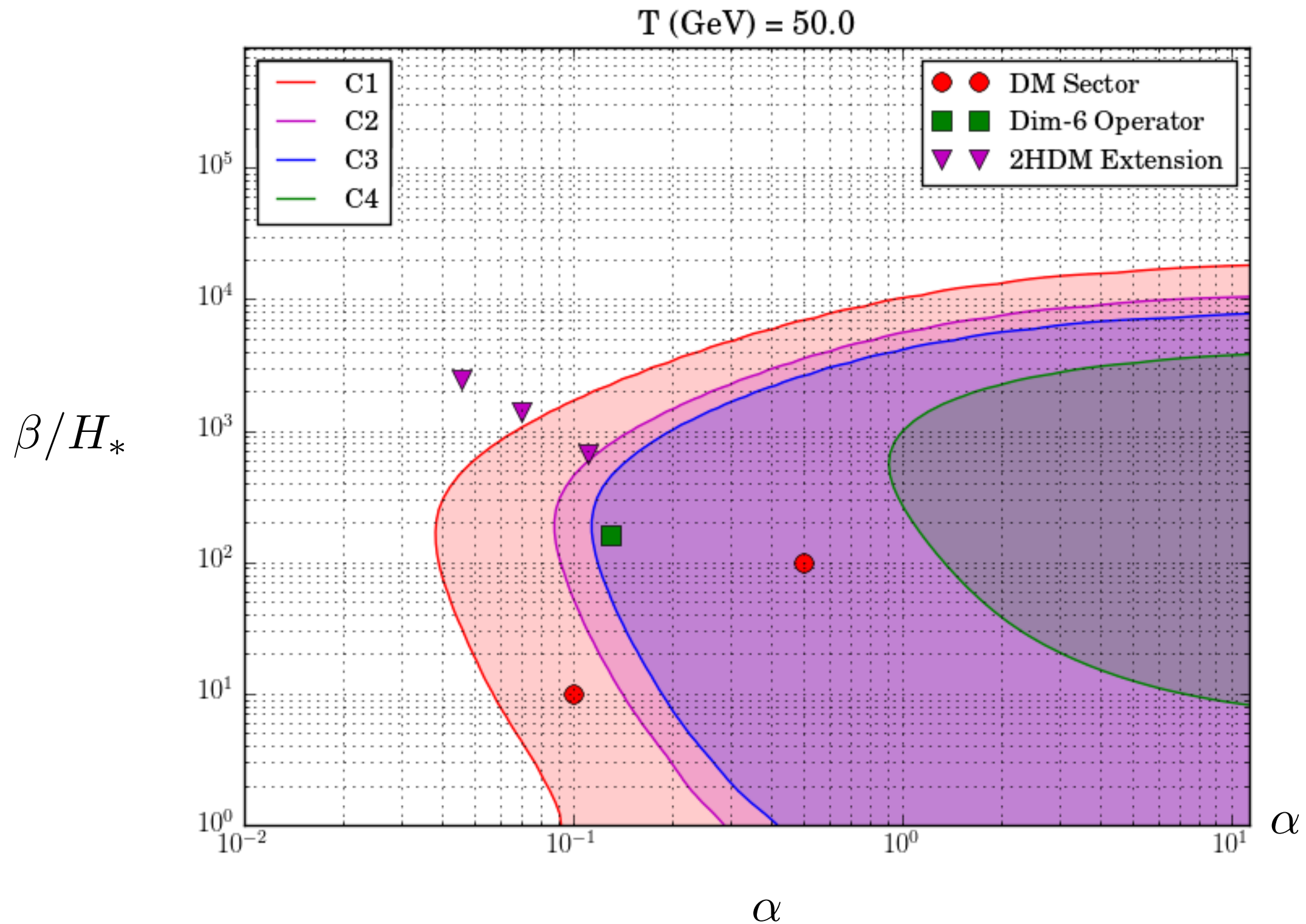
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Detection prospects for LISA



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

Detection prospects for LISA



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

- **LISA** sensitive to energy scale **10 GeV - 100 TeV !**
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Cosmology and Particle Physics interplay!
Connections with baryon asymmetry & dark matter

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- sin

Conn

Problem: LHC is putting great pressure over BSM scenarios

Interplay!
& dark matter

(Schwaller et al 2015)

(Kuznetsov et al 2013)

(Giddens et al 2004)

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Conn

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(ar 2015)

(ackuz et al 2013)

(t al 2004)

- ... and beyond the EWPT

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(Schwell)

**GW → new probe of BSM physics!
(complementary to particle colliders)**

PhT

the dilaton/radion
like models (Randall and Servant 2015)

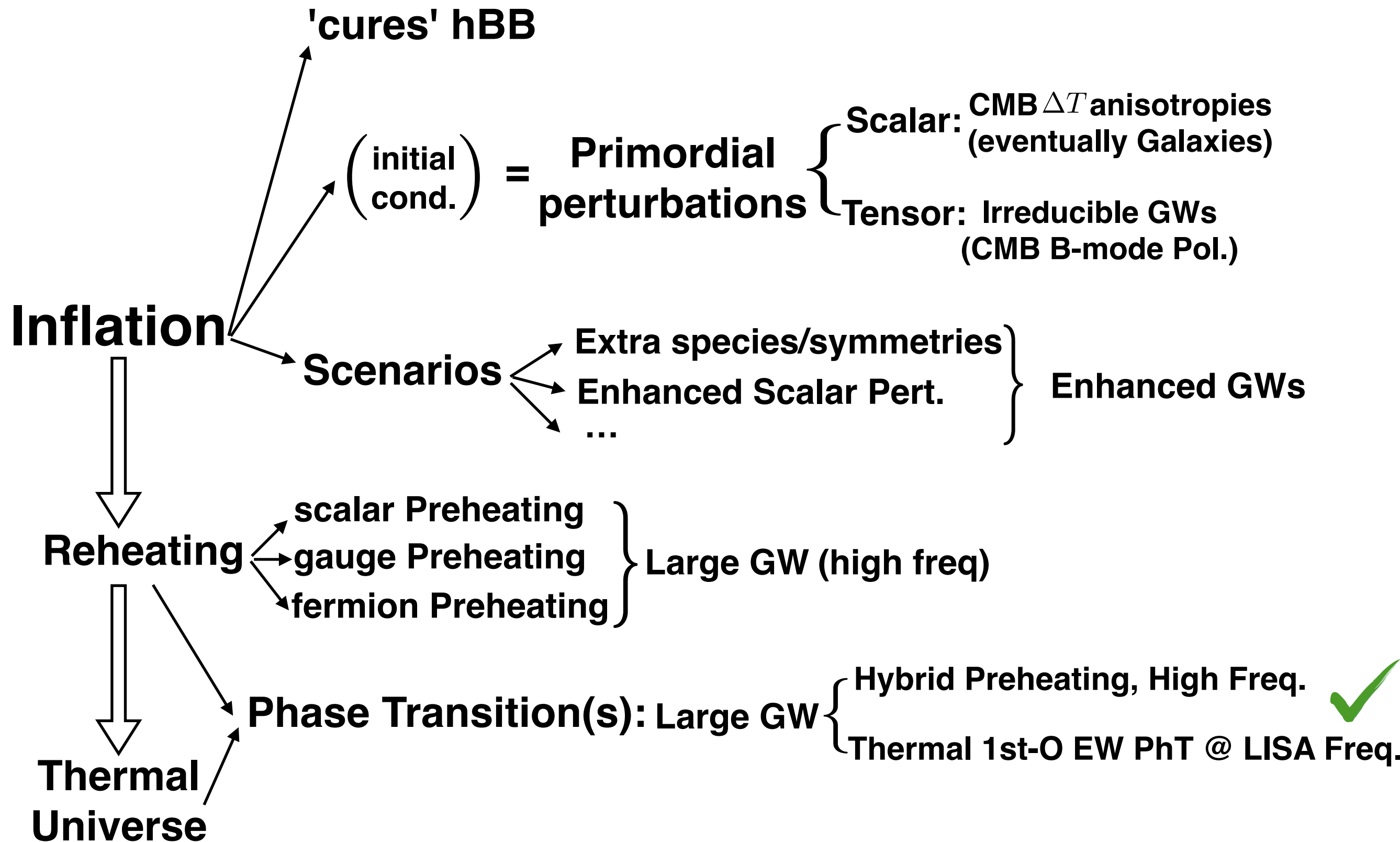
Can we really detect a 1st-O Ph-T ?

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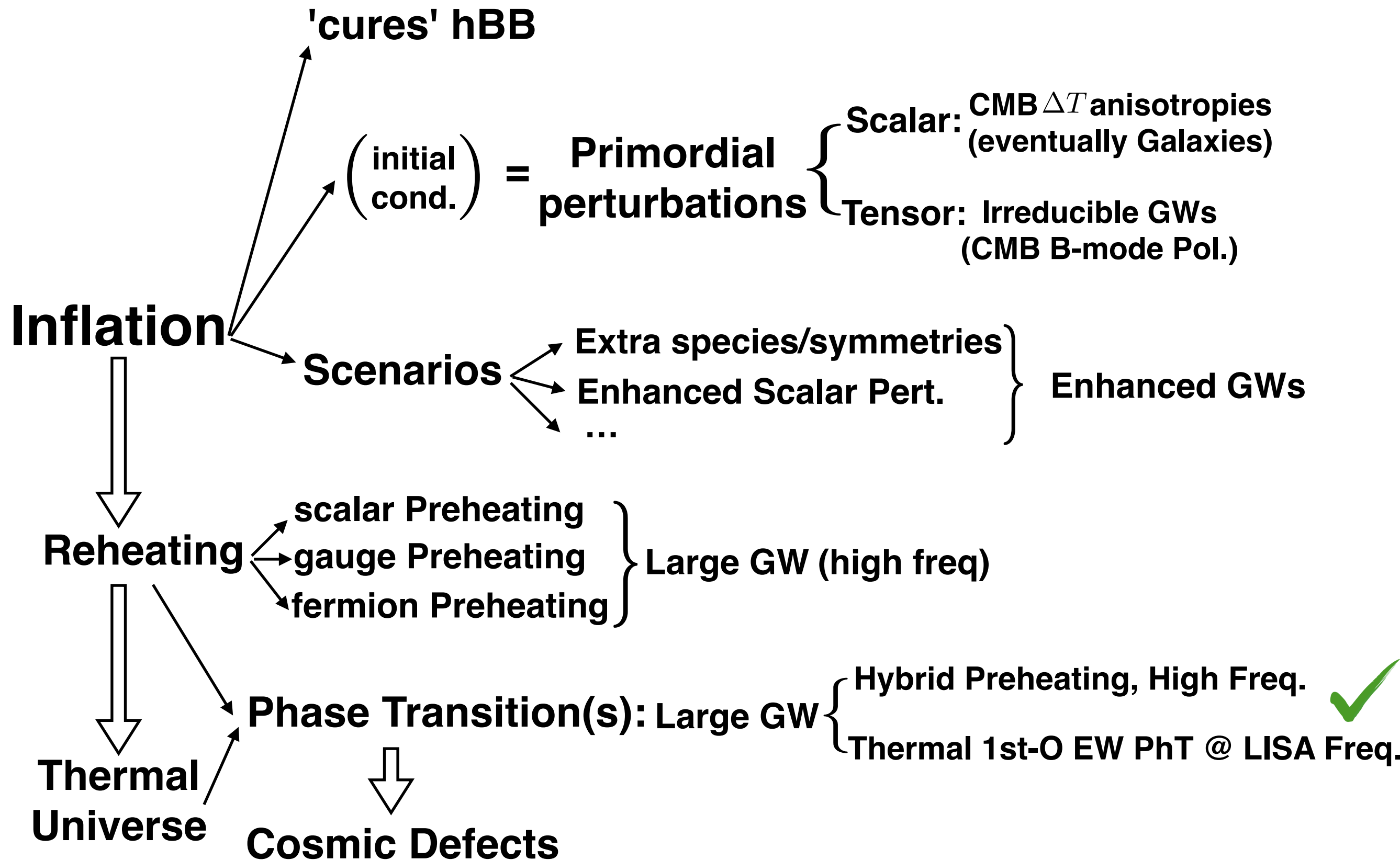
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- * Predictions depend on many assumptions (particularly in sound waves), so is our modelling correct?
- * Even if we detect it, then we infer α and β , but what BSM model is behind? **not univocal !**

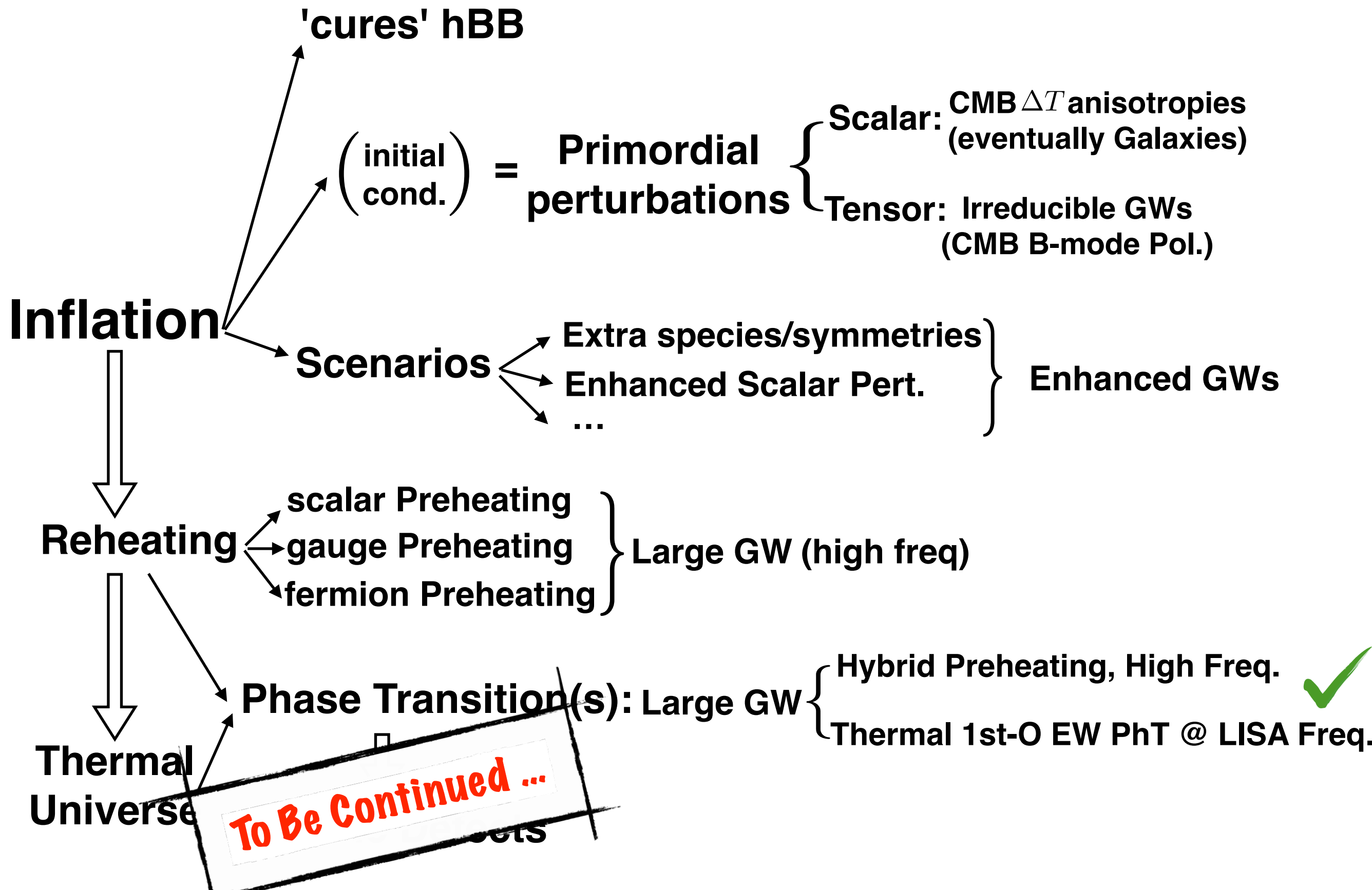
EARLY UNIVERSE



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EARLY UNIVERSE



Back-up Slides

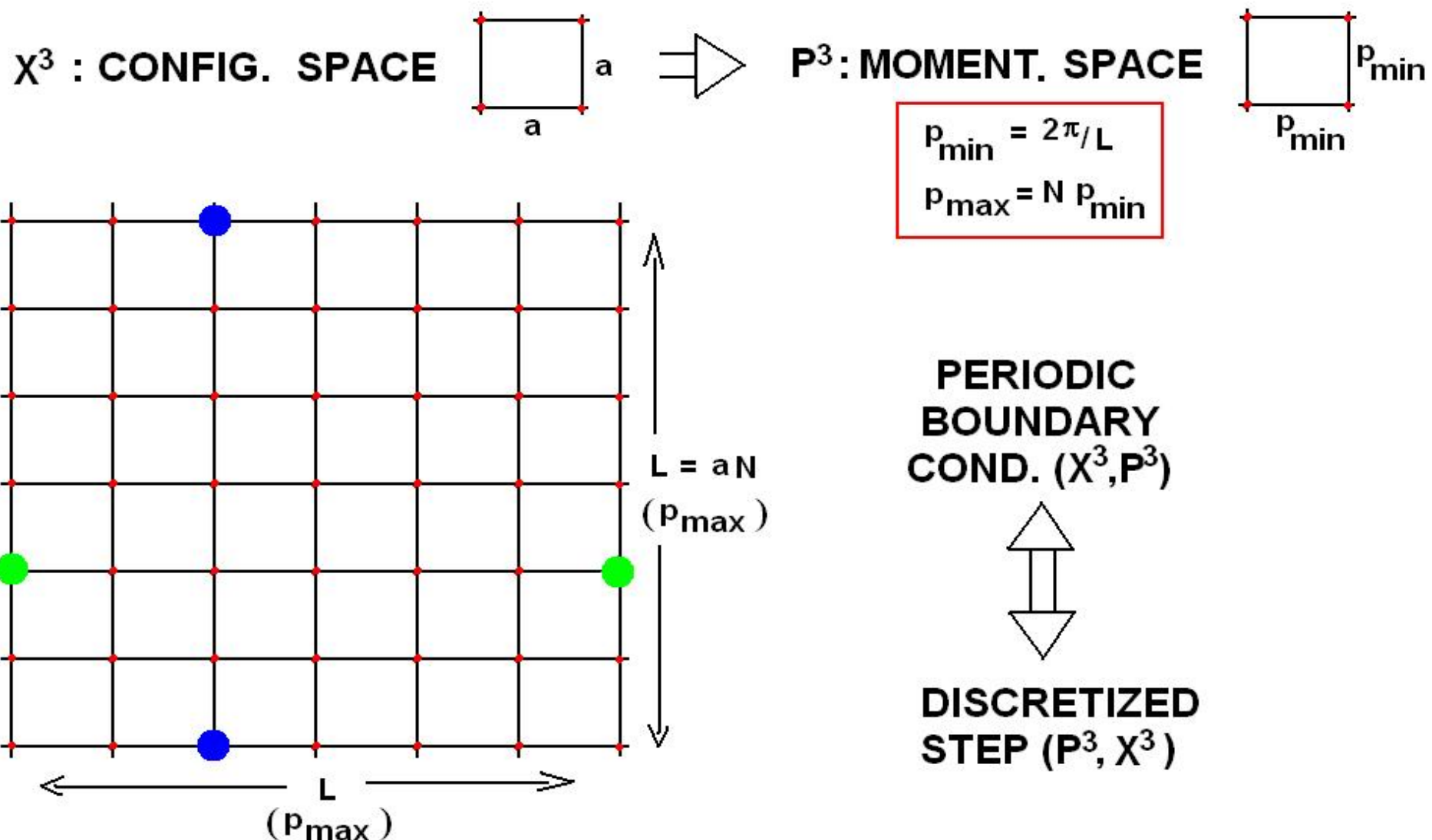
INFLATIONARY PREHEATING

Lattice Simulations: Dynamics

non-linear
out-Eq

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

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



INFLATIONARY PREHEATING

Lattice Simulations: Dynamics

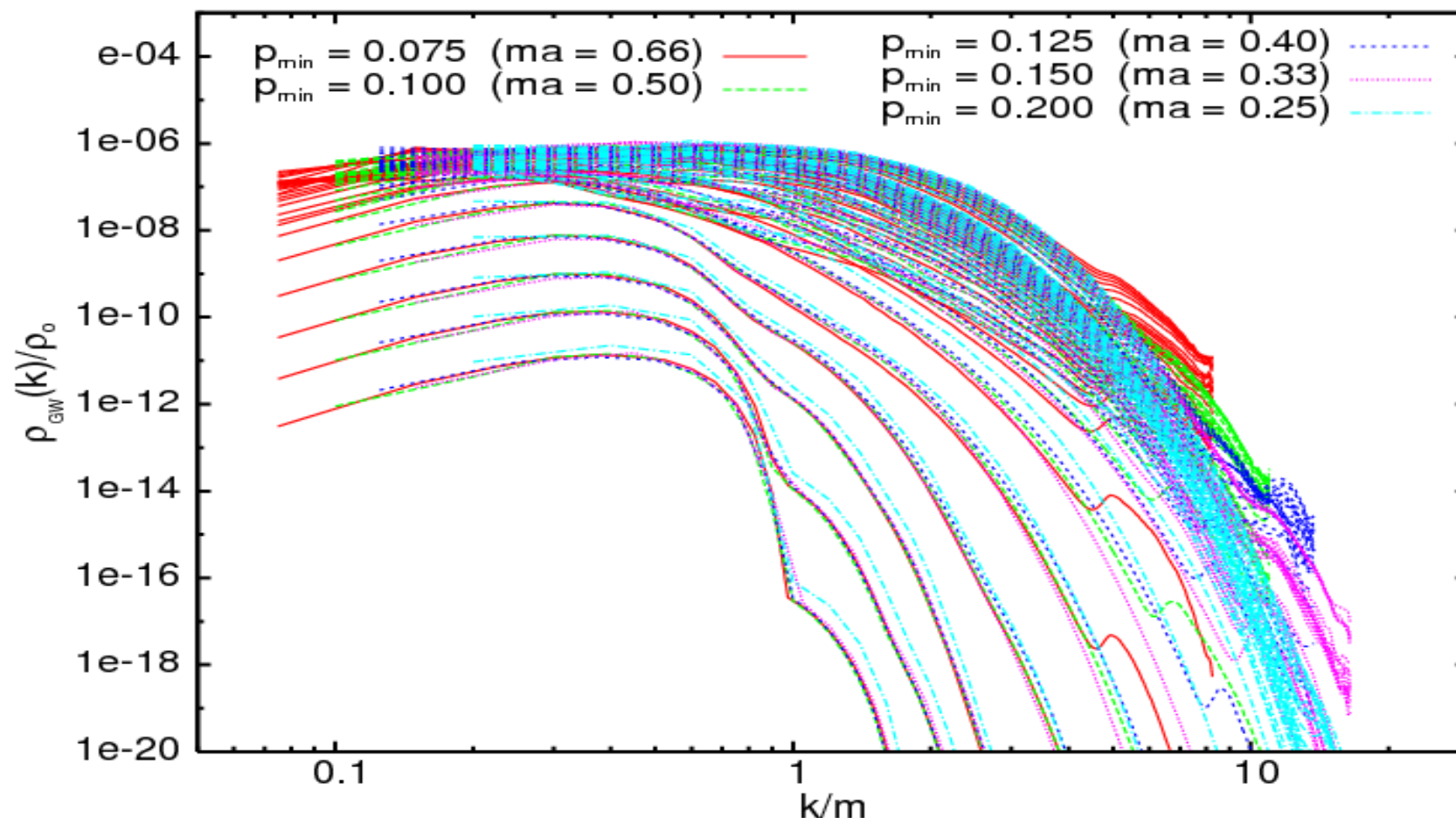
non-linear
out-Eq

Hybrid Preheating

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

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

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



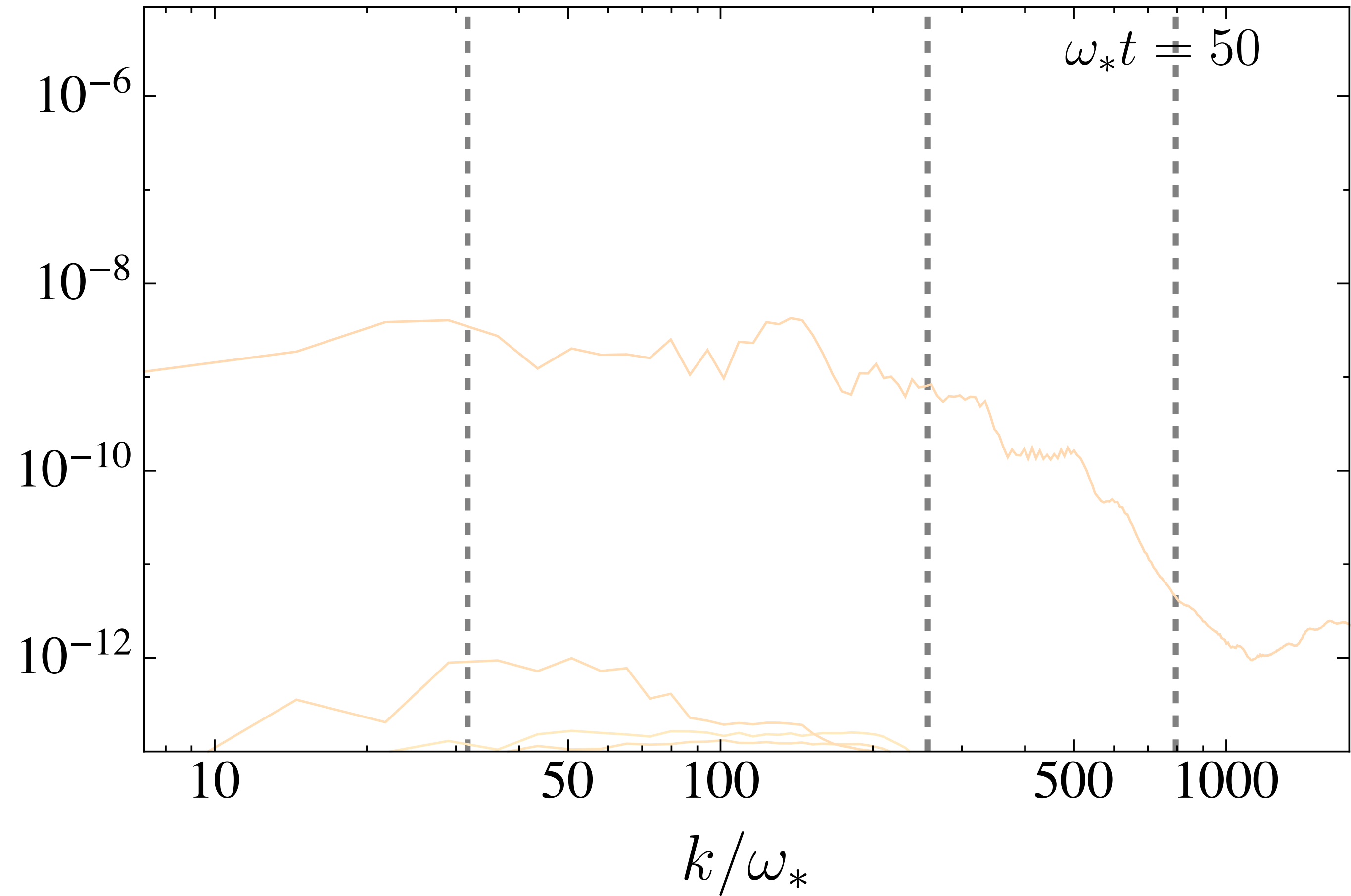
Three-peak signature
(three preheat flds)

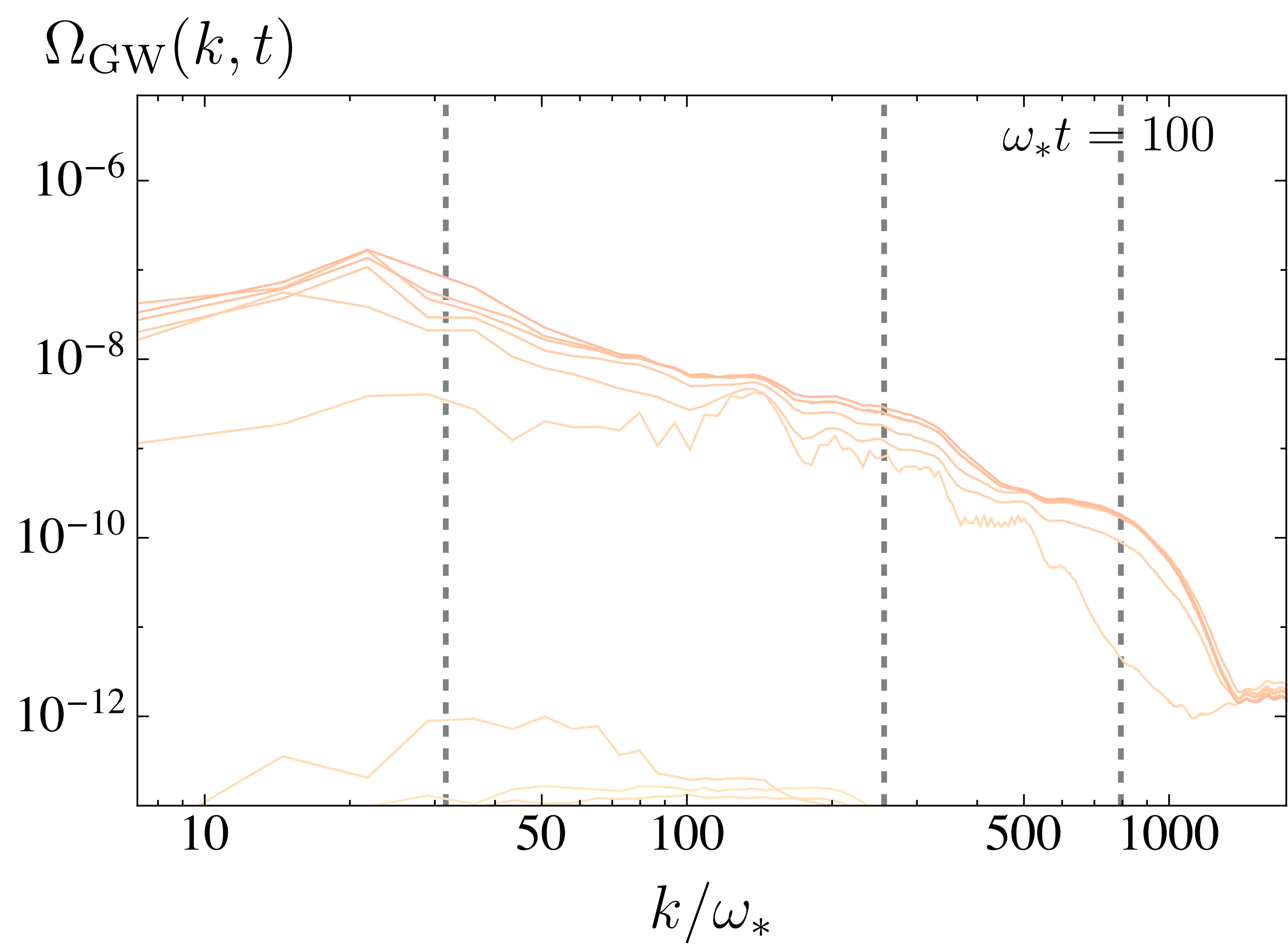
$$V(\phi) + \frac{1}{2}g_1^2\phi^2\chi_1^2 + \frac{1}{2}g_2^2\phi^2\chi_2^2 + \frac{1}{2}g_3^2\phi^2\chi_3^2$$

ANIMATION
(by Nico Loayza)

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

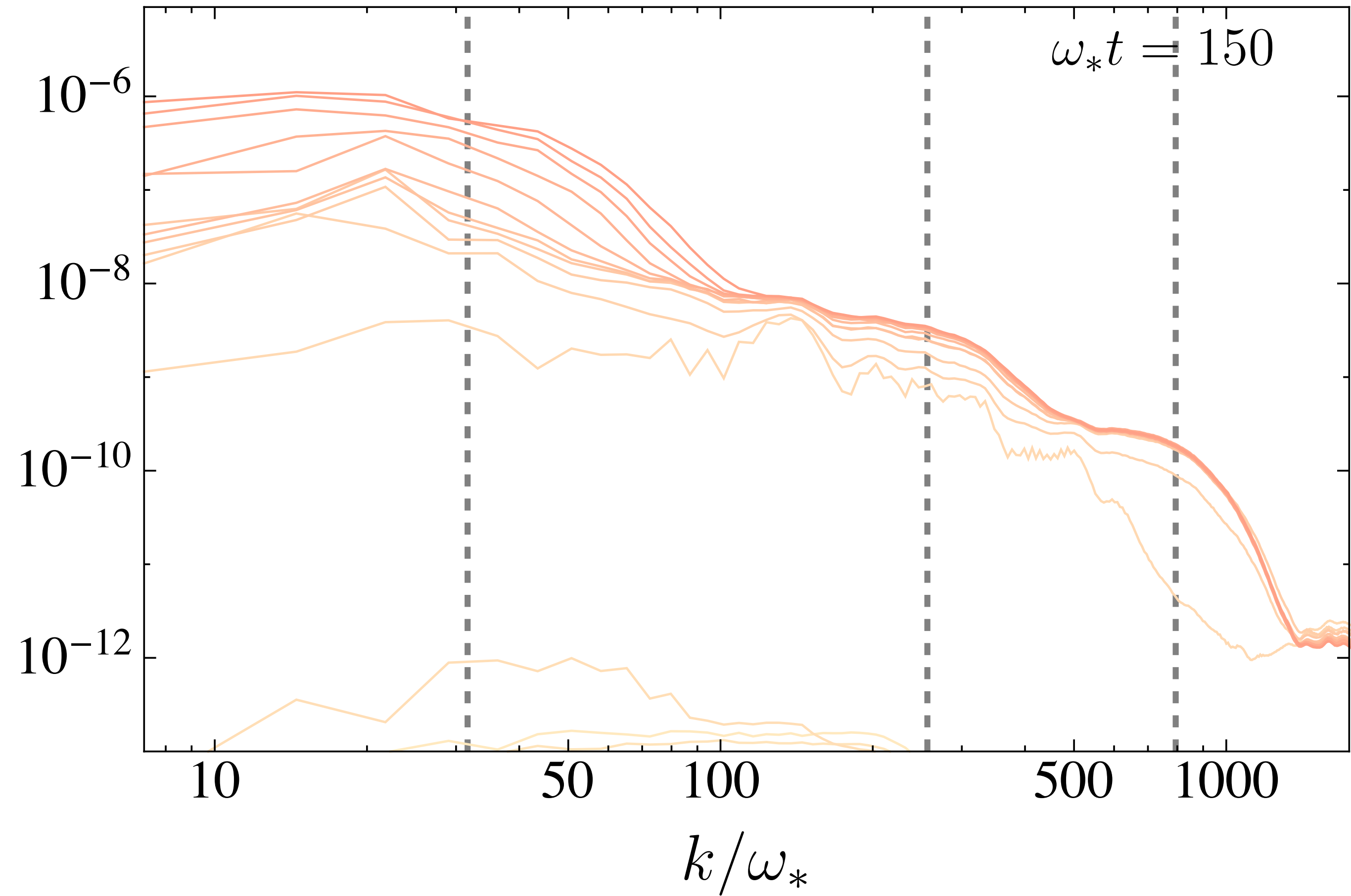
$$\omega_* t = 50$$





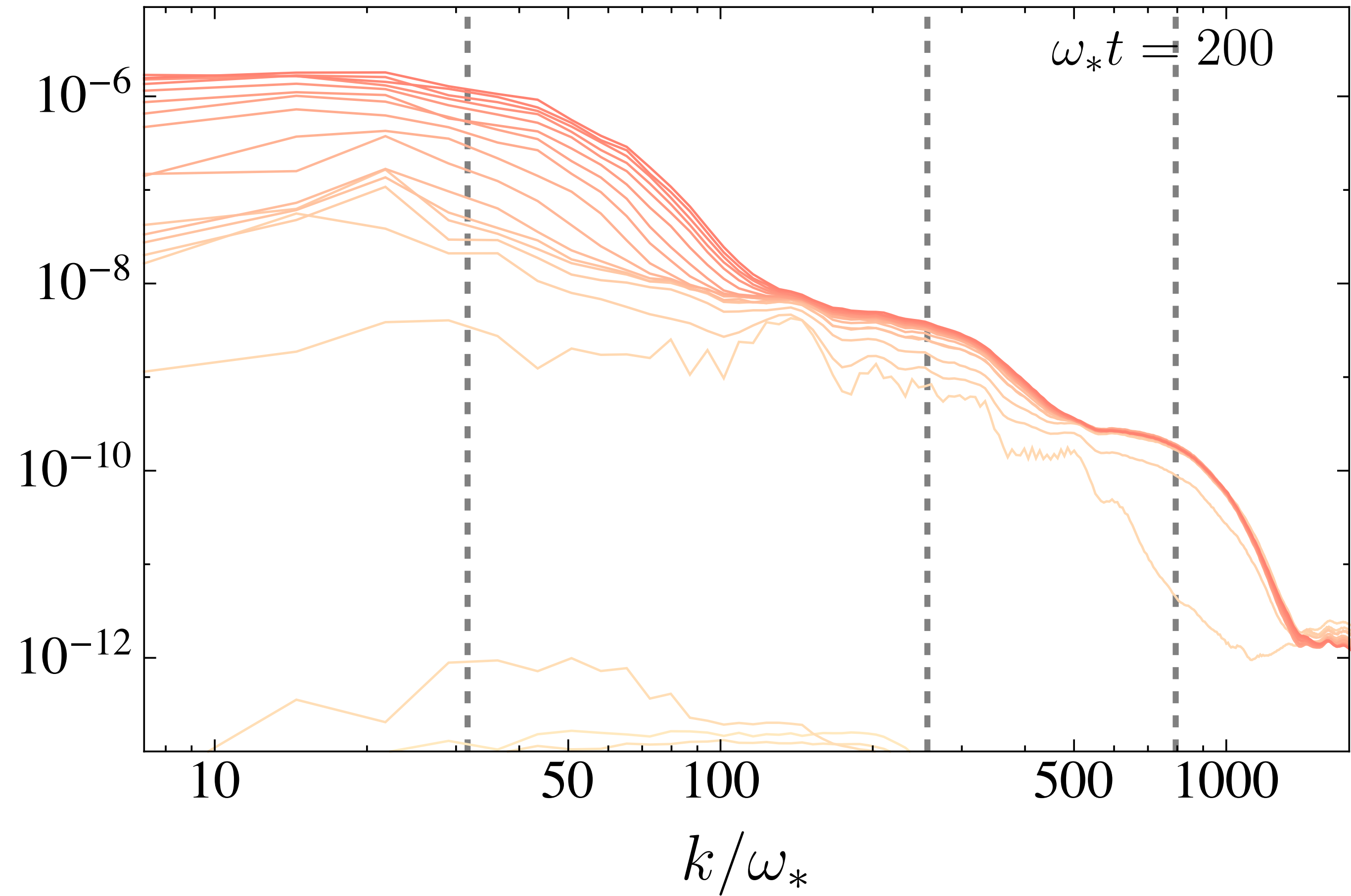
$$\Omega_{\text{GW}}(k, t)$$

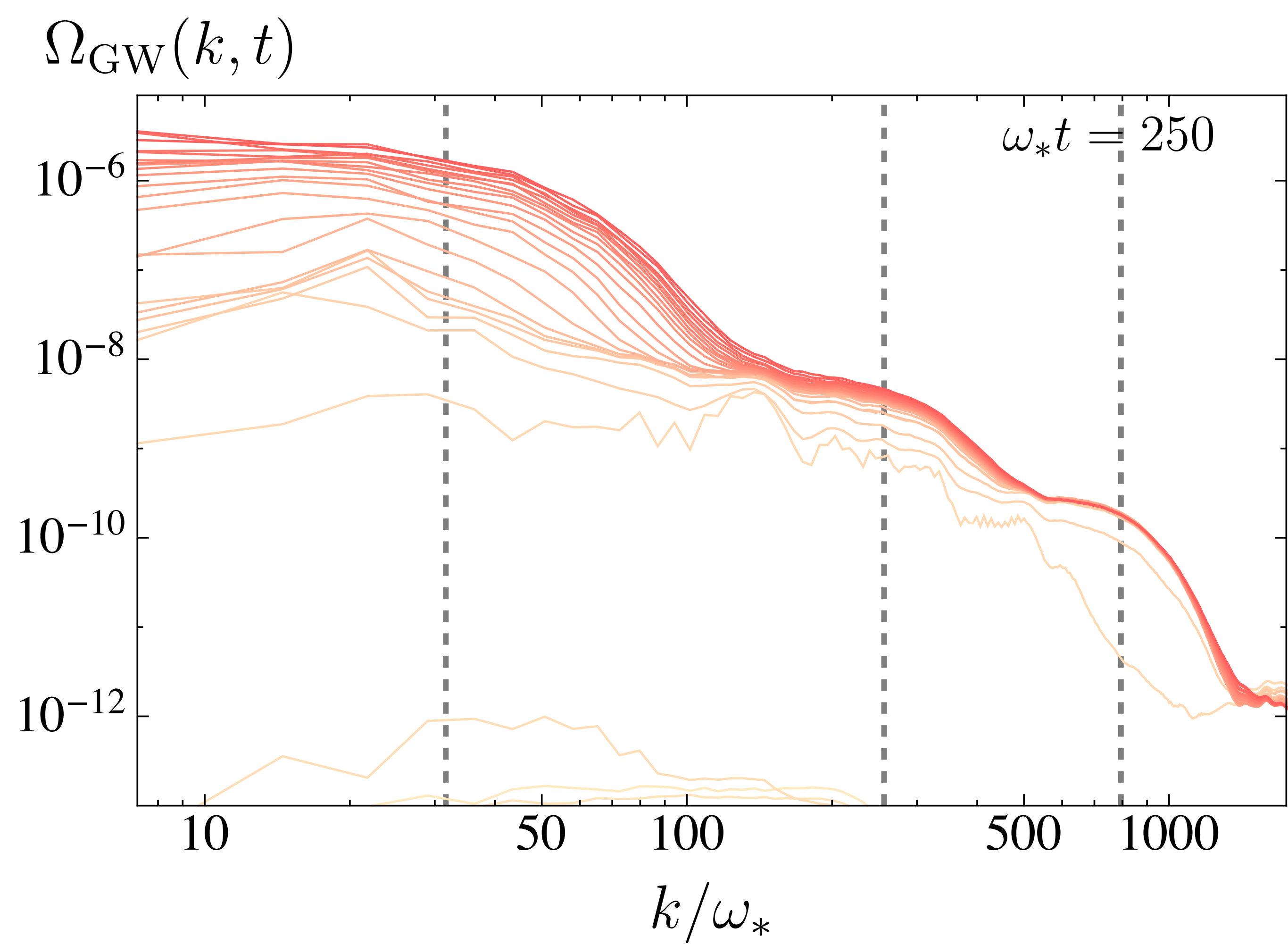
$$\omega_* t = 150$$

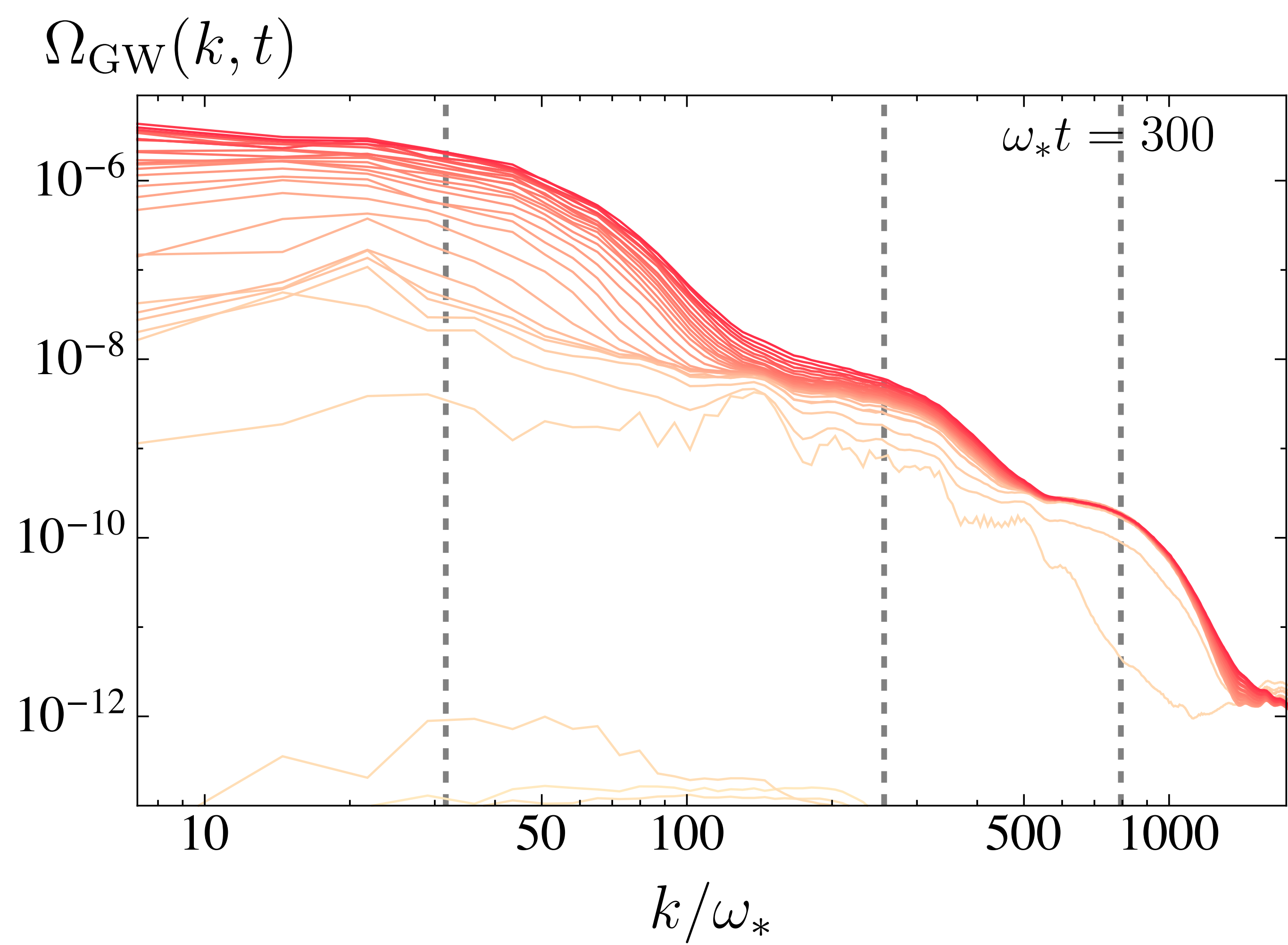


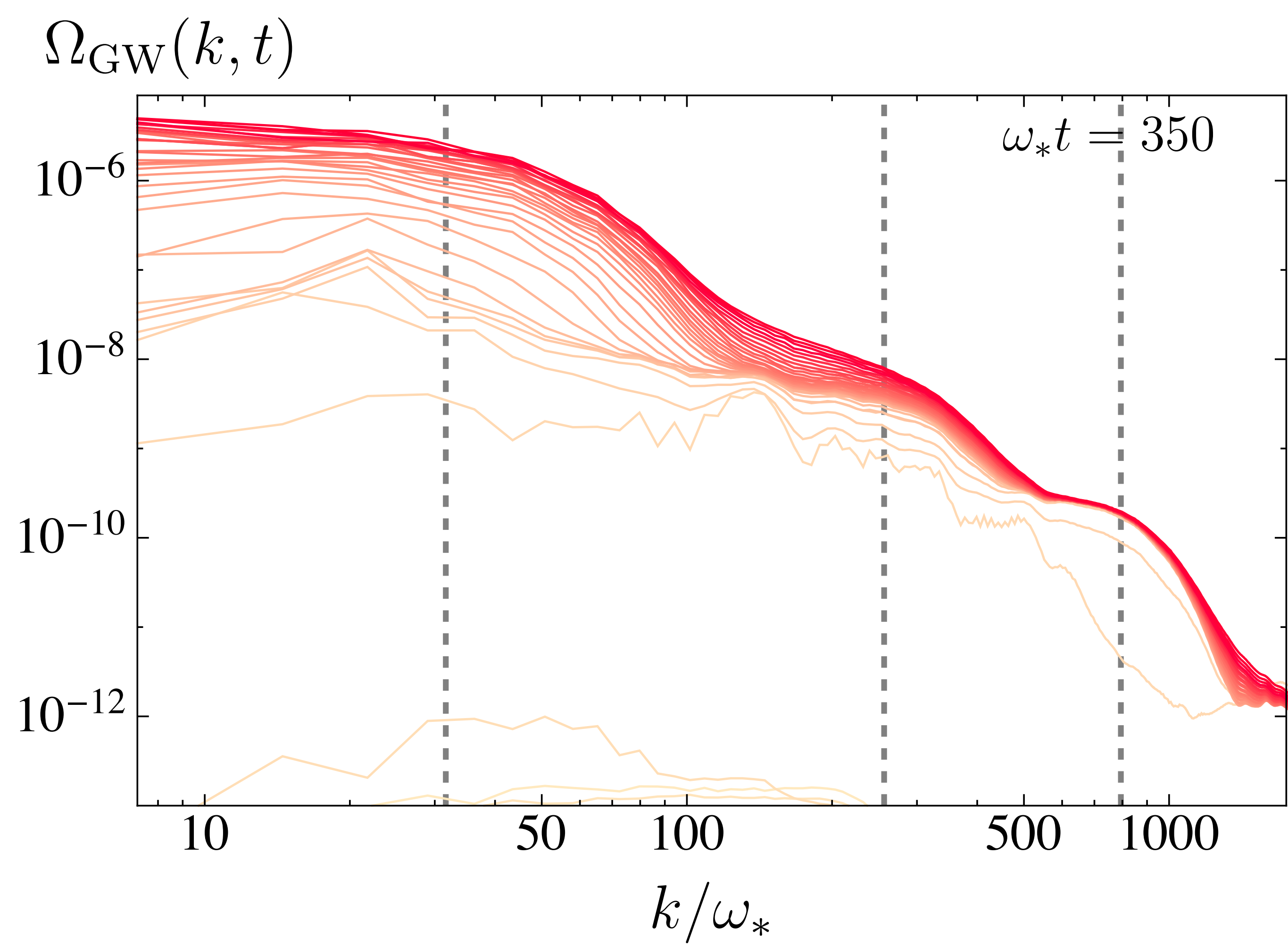
$$\Omega_{\text{GW}}(k, t)$$

$$\omega_* t = 200$$



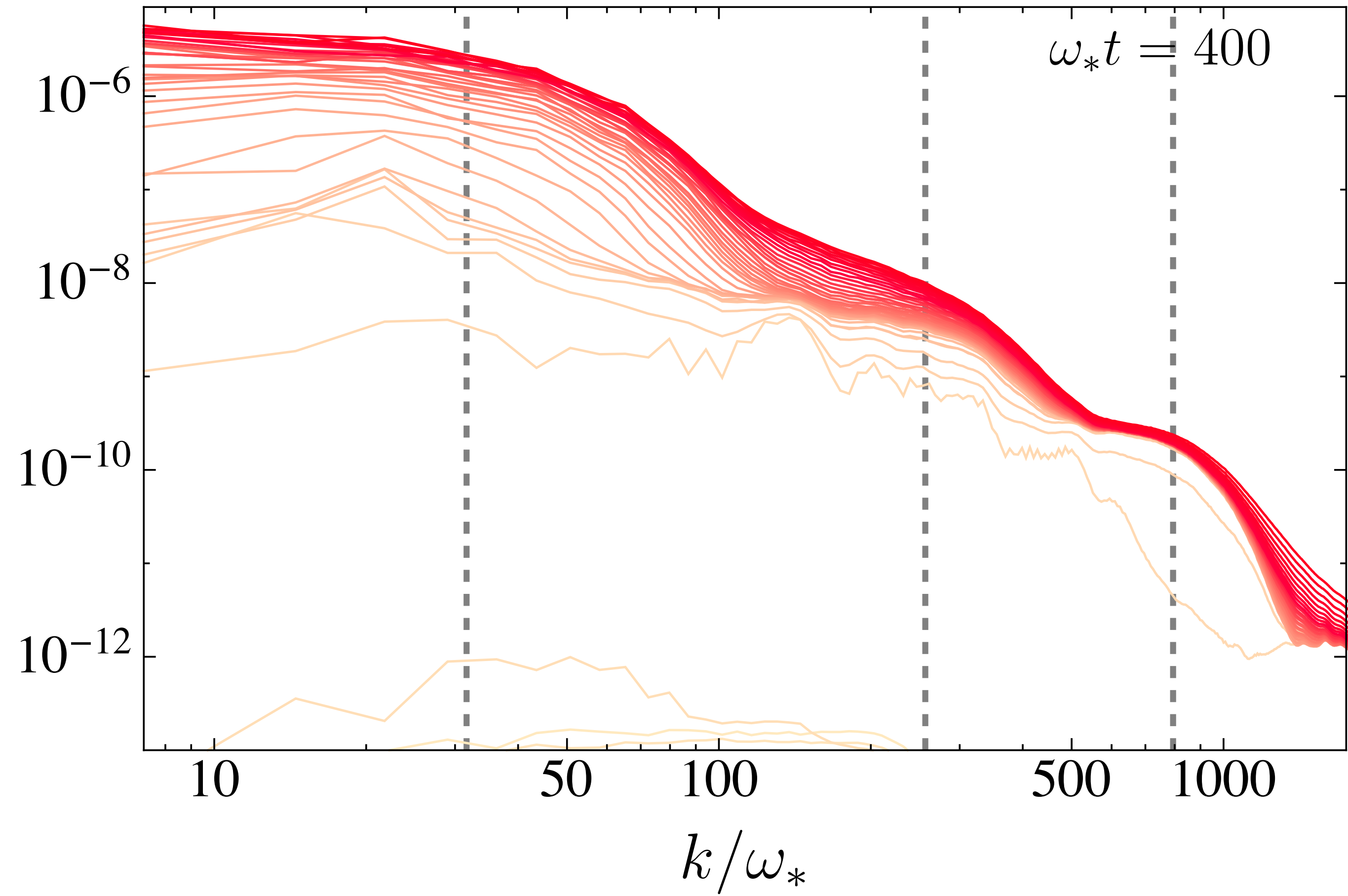






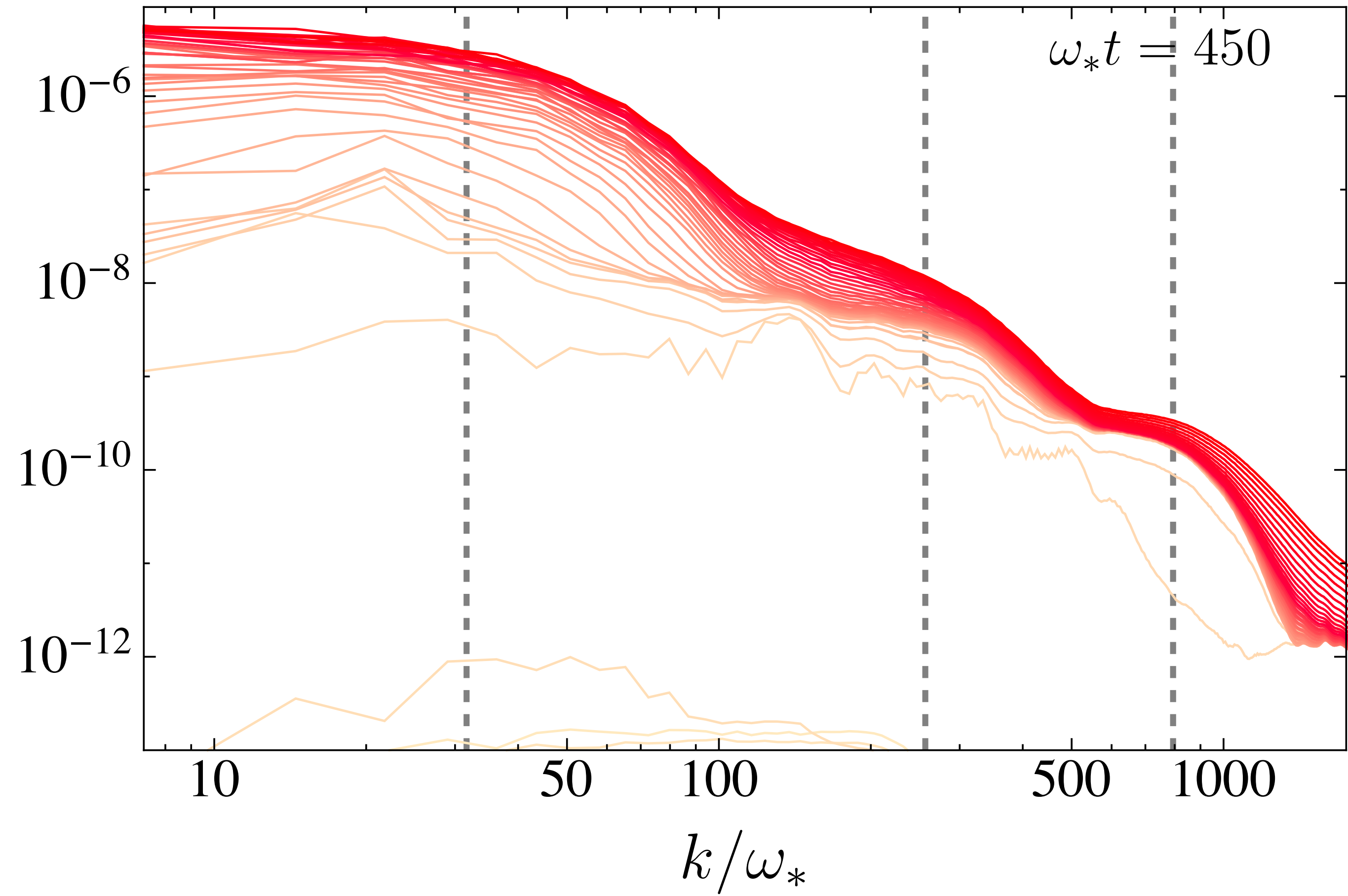
$$\Omega_{\text{GW}}(k, t)$$

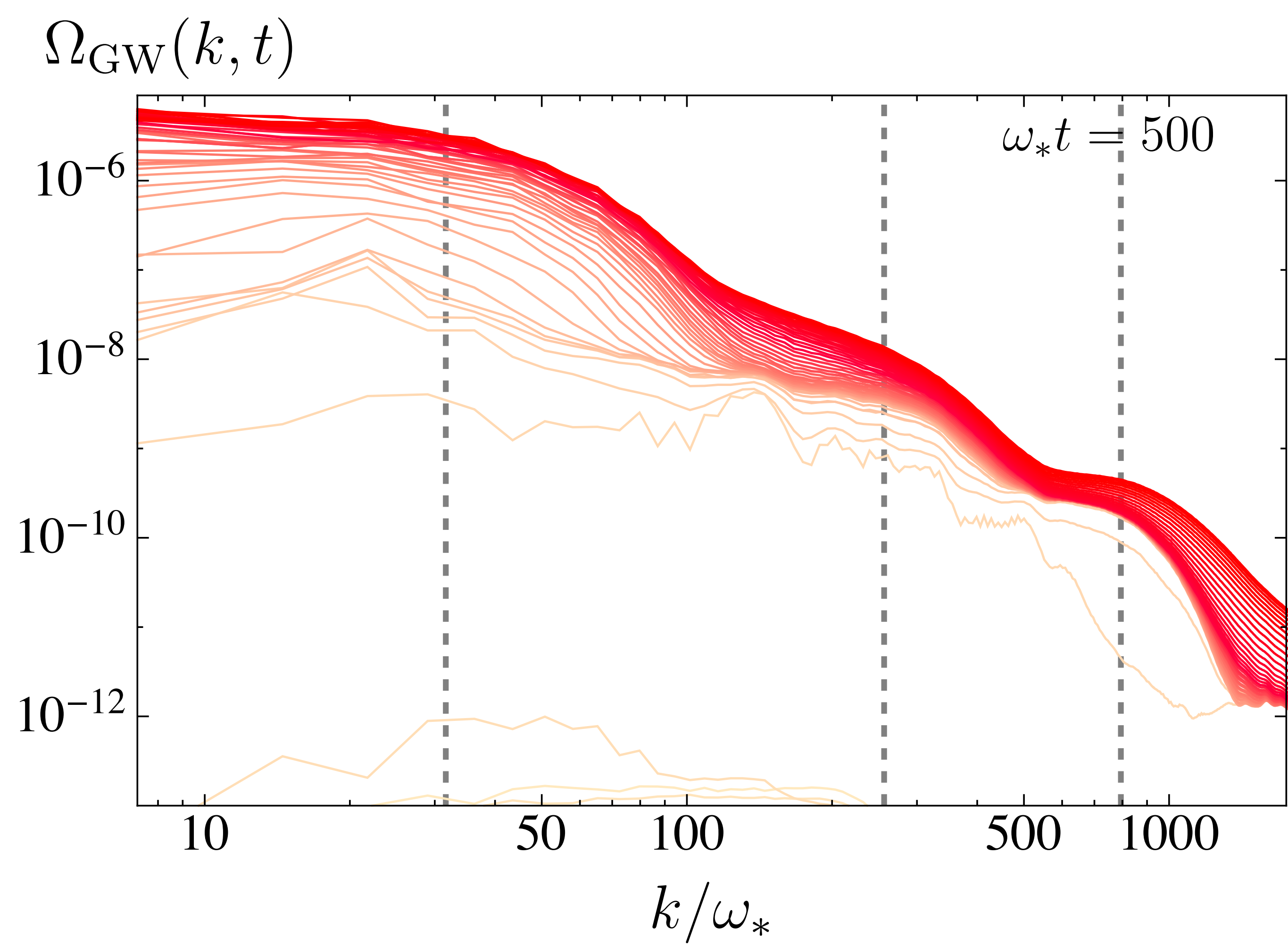
$$\omega_* t = 400$$



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

$$\omega_* t = 450$$





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

