A Stiff Post-Inflationary HIGGStory of the Universe

Daniel G. FiGUEROA
Theory Division, CERN, Switzerland

with: Torrenti & Garcia–Bellido
(+ Enqvist, Meriniemi, Rajantie)

2nd eLISA CosWG workshop, Sept. 2015, Stavanger, Norway

Despite the title, I shall be talking about ...

0. **Gravitational Waves (GW): Probe of the early Universe**

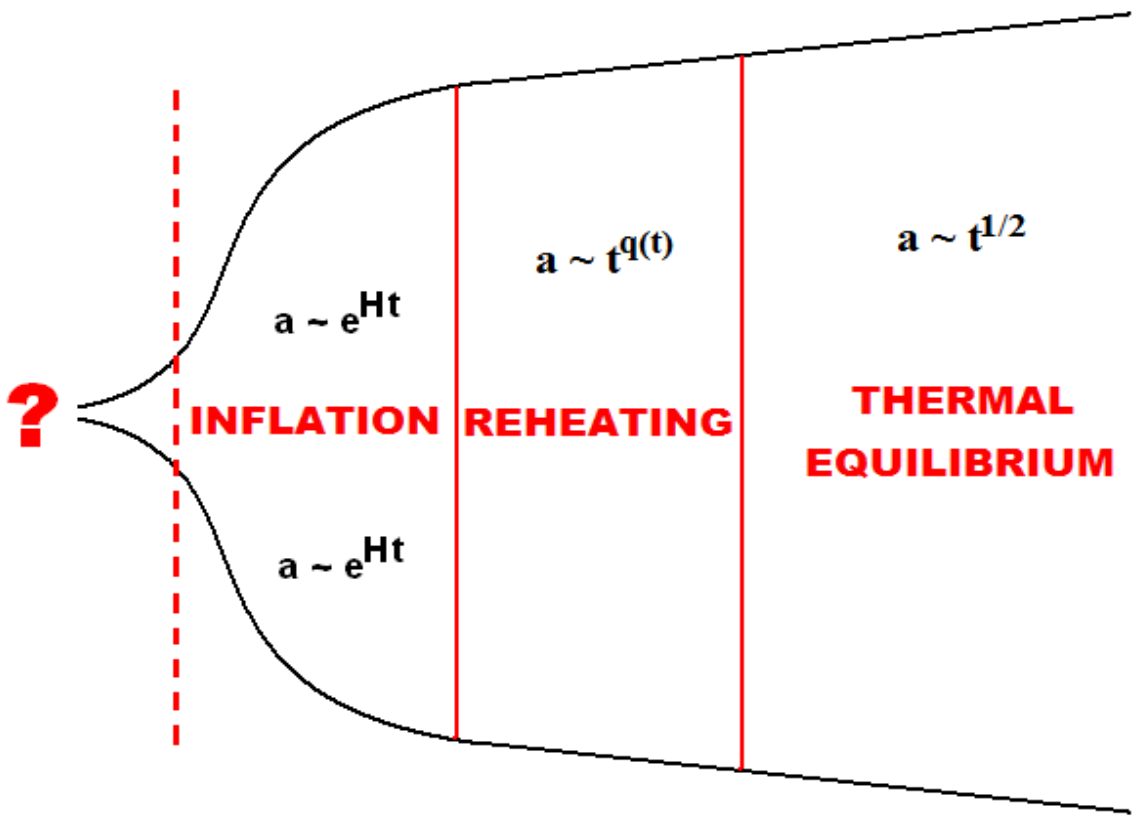
1. **Non-Perturbative Field Excitation (Out-of-Eq.) $\Rightarrow$ GW**

2. **Applications to the Standard Model (SM)**

0. Context: the early Universe ($t_{\rm Inf} < t < t_{\rm BBN}$)

INFLATION $\longrightarrow$ **REHEATING** $\longrightarrow$ **THERMAL ERA**

(Particle Production,
PhTs, Cosmic Defects, ...)



1. Gravitational Waves: Probe of the Early Universe

1. **WEAKNESS of GRAVITY**:

   DISADVANTAGE: DIFFICULT DETECTION
   ADVANTAGE: GW DECOUPLE upon Production

2. **ADVANTAGE**: GW $\rightarrow$ Probe for Early Universe

$$\rightarrow \begin{cases} \textbf{Decouple} \rightarrow \text{Spectral Form Retained} \\ \textbf{Specific HEP} \Leftrightarrow \text{Specific GW} \end{cases}$$

3. **Physical Processes**:

$$\left\{ \begin{array}{l} \text{Inflation} \\ \left.\begin{array}{l} \text{pReheating} \\ \text{Phase Transitions} \\ \text{Cosmic Defects} \\ \text{Turbulence?} \end{array}\right\} (\text{Post} - \text{Inflationary}) \end{array} \right.$$

1. Gravitational Waves: Probe of the Early Universe

1. **WEAKNESS of GRAVITY**:

   DISADVANTAGE: DIFFICULT DETECTION
   ADVANTAGE: GW DECOUPLE upon Production

2. **ADVANTAGE**: GW $\rightarrow$ Probe for Early Universe

$$\rightarrow \begin{cases} \textbf{Decouple} \rightarrow \text{Spectral Form Retained} \\ \textbf{Specific HEP} \Leftrightarrow \text{Specific GW} \end{cases}$$

3. **Physical Processes**:

$$\left\{ \begin{array}{l} \text{Inflation} \\ \left\{ \begin{array}{l} \text{pReheating} \\ \text{Phase Transitions} \\ \text{Cosmic Defects} \\ \text{Turbulence?} \end{array} \right\} (\text{Post} - \text{Inflationary}) \end{array} \right.$$

1. Gravitational Waves: Probe of the Early Universe

1. **WEAKNESS of GRAVITY**:

   DISADVANTAGE: DIFFICULT DETECTION
   ADVANTAGE: GW DECOUPLE upon Production

2. **ADVANTAGE**: GW $\rightarrow$ Probe for Early Universe

$$\rightarrow \begin{cases} \textbf{Decouple} \rightarrow \text{Spectral Form Retained} \\ \textbf{Specific HEP} \Leftrightarrow \text{Specific GW} \end{cases}$$

3. **Physical Processes**:

$$\left\{ \begin{array}{l} \text{Inflation} \\ \left\{ \begin{array}{l} \text{pReheating} \\ \text{Phase Transitions} \\ \text{Cosmic Defects} \\ \text{Turbulence?} \end{array} \right\} (\text{Post} - \text{Inflationary}) \end{array} \right.$$

1. Gravitational Waves (GWs)

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

Eom: $h''_{ij} + 2\mathcal{H}h'_{ij} - \nabla^2 h_{ij} = 16\pi G \Pi^{\mathrm{TT}}_{ij}$, $\quad \Pi_{ij} = T_{ij} - \langle T_{ij} \rangle_{\mathrm{FRW}}$

Transverse-Traceless (TT) dof carry energy out of the source!!!

- GW Source(s): (SCALARS , VECTOR , FERMIONS)

$$\Pi^{TT}_{ij} \quad \propto \quad \{\partial_i \chi^a \partial_j \chi^a\}^{TT}, \quad \{E_i E_j + B_i B_j\}^{TT}, \quad \{\bar{\psi}\gamma_i D_j \psi\}^{TT}$$

1. Gravitational Waves (GWs)

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

Eom: $h''_{ij} + 2\mathcal{H}h'_{ij} - \nabla^2 h_{ij} = 16\pi G \Pi^{\mathrm{TT}}_{ij}$, $\quad \Pi_{ij} = T_{ij} - \langle T_{ij} \rangle_{\mathrm{FRW}}$

Transverse-Traceless (TT) dof carry energy out of the source!!!

- GW Source(s): (SCALARS , VECTOR , FERMIONS)

$$\Pi^{TT}_{ij} \propto \{\partial_i \chi^a \partial_j \chi^a\}^{TT}, \ \{E_i E_j + B_i B_j\}^{TT}, \ \{\bar{\psi}\gamma_i D_j \psi\}^{TT}$$

1. Gravitational Waves (GWs)

- GW Source(s): (SCALARS , VECTOR , FERMIONS)

$$\Pi_{ij}^{TT} \propto \{\partial_i \chi^a \partial_j \chi^a\}^{TT}, \quad \{E_i E_j + B_i B_j\}^{TT}, \quad \{\bar{\psi}\gamma_i D_j \psi\}^{TT}$$

- GW Spectrum:

$$\frac{d\rho_{\rm GW}}{d\log k}(k,t) \propto \frac{Gk^3}{a^4(t)} \int_0^t \int_0^t dt_1 dt_2 \, \mathcal{G}(k, t_2 - t_1)\, \Pi^2(k, t_1, t_2)$$

UTC: $\left\langle \Pi_{ij}^{\rm TT}(\mathbf{k}, t_1)\, \Pi_{ij}^{\rm TT}(\mathbf{k}', t_2) \right\rangle \equiv (2\pi)^3\, \Pi^2(k, t_1, t_2)\, \delta^{(3)}(\mathbf{k} - \mathbf{k}')$

1. Gravitational Waves (GWs)

- GW Source(s): (SCALARS , VECTOR , FERMIONS)

$$\Pi_{ij}^{TT} \propto \{\partial_i \chi^a \partial_j \chi^a\}^{TT}, \quad \{E_i E_j + B_i B_j\}^{TT}, \quad \{\bar{\psi}\gamma_i D_j \psi\}^{TT}$$

- GW Spectrum:

$$\frac{d\rho_{\rm GW}}{d\log k}(k,t) \propto \frac{Gk^3}{a^4(t)} \int_0^t \int_0^t dt_1 dt_2 \, \mathcal{G}(k, t_2 - t_1) \, \Pi^2(k, t_1, t_2)$$

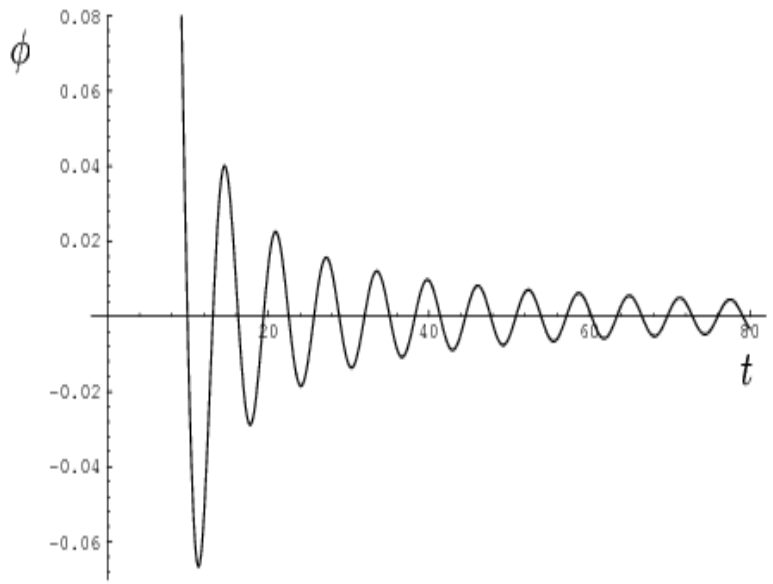
UTC: $\left\langle \Pi_{ij}^{\rm TT}(\mathbf{k}, t_1) \, \Pi_{ij}^{\rm TT}(\mathbf{k}', t_2) \right\rangle \equiv (2\pi)^3 \, \Pi^2(k, t_1, t_2) \, \delta^{(3)}(\mathbf{k} - \mathbf{k}')$

Contents ...

1. Non-Perturbative Excitation of fields

Scalar field after Inflation: $V(\phi)$ (inflaton, curvaton, ... Higgs ?)

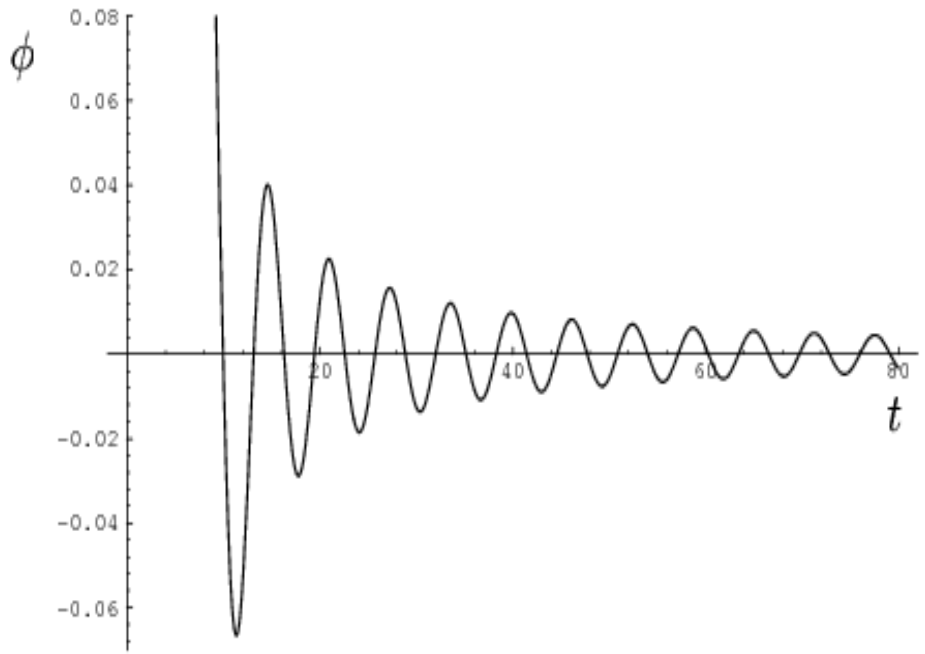
Coherent Oscillations: $\phi(t) \approx \Phi(t) f(t), \quad f(t+T) = f(t)$



1. Non-Perturbative Excitation of fields

Bosons: $g^2\phi^2\chi^2$: Oscillations $\rightarrow$ χ – Particle Creation
(Non-Pert., Out-of-Eq.)

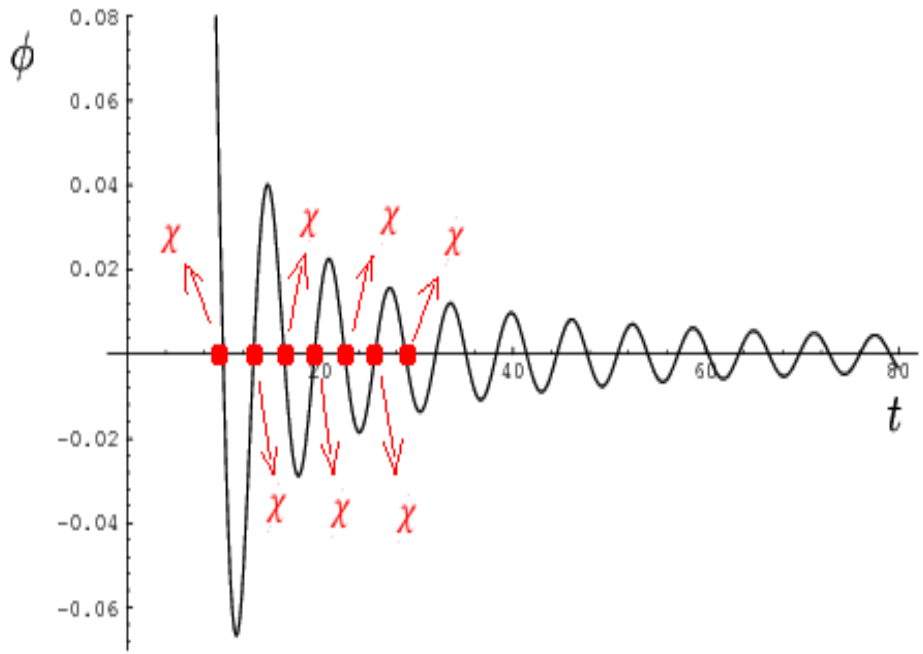
$$\frac{d^2}{dt^2}\chi_{\mathbf{k}} + \omega^2_{\mathbf{k}}(t)\chi_{\mathbf{k}}(t) = 0\,, \quad \omega^2_{\mathbf{k}}(t) = k^2 + a^2(t)g^2\phi^2(t)$$



1. Non-Perturbative Excitation of fields

Bosons: $g^2\phi^2\chi^2$: Oscillations $\rightarrow$ χ – Particle Creation
(Non-Pert., Out-of-Eq.)

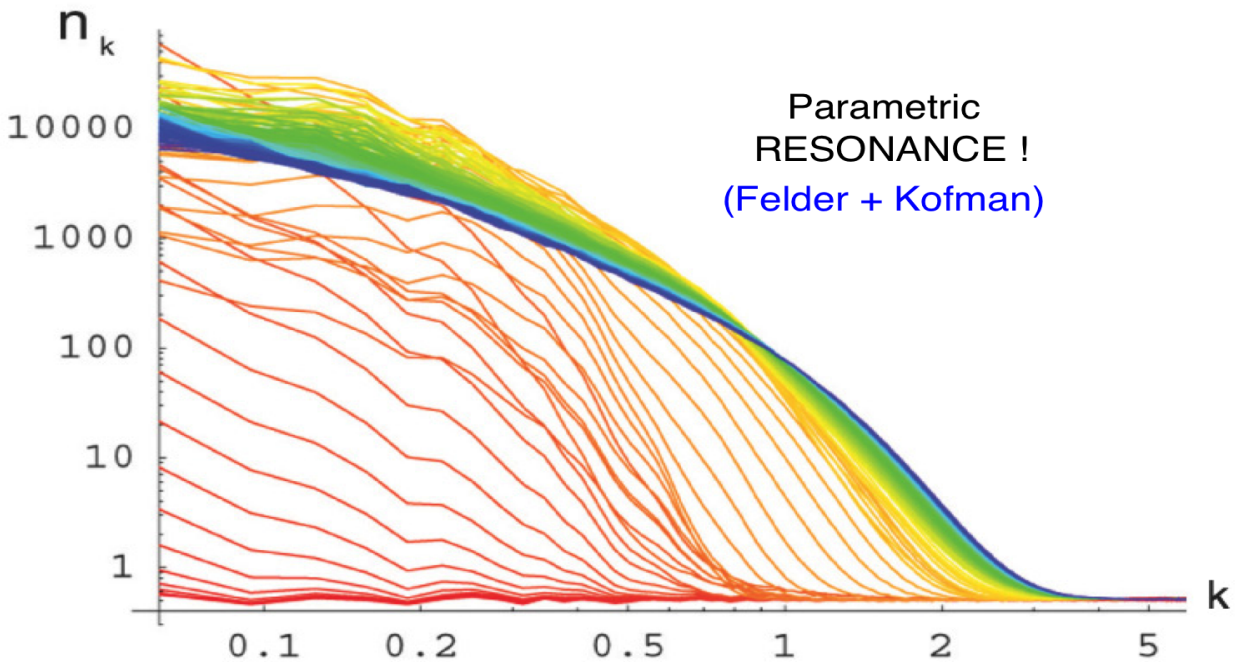
$\frac{d^2}{dt^2}\chi_{\mathbf{k}} + \omega^2_{\mathbf{k}}(t)\chi_{\mathbf{k}}(t) = 0\,, \quad \frac{d}{dt}\omega_{\mathbf{k}} \gg \omega^2_{\mathbf{k}}(t)$



1. Non-Perturbative Excitation of fields

Bosons: $g^2\phi^2\chi^2$: Oscillations $\rightarrow$ χ – Particle Creation
(Non-Pert., Out-of-Eq.)

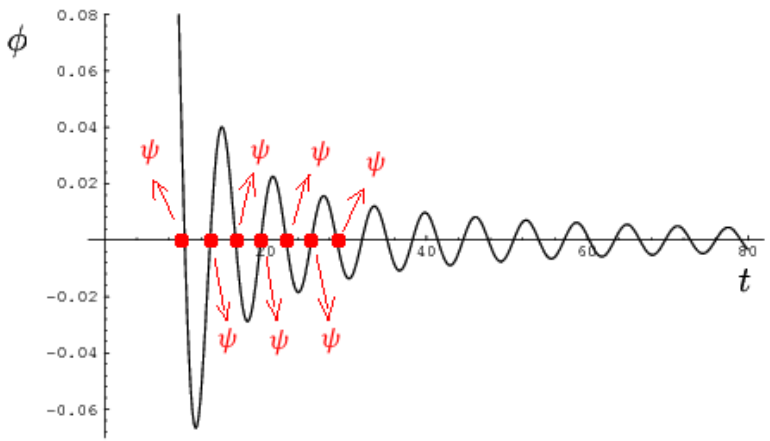
$$\frac{d^2}{dt^2}\chi_{\mathbf{k}} + \omega^2_{\mathbf{k}}(t)\chi_{\mathbf{k}}(t) = 0\,, \quad \frac{d}{dt}\omega_{\mathbf{k}} \gg \omega^2_{\mathbf{k}}(t)$$

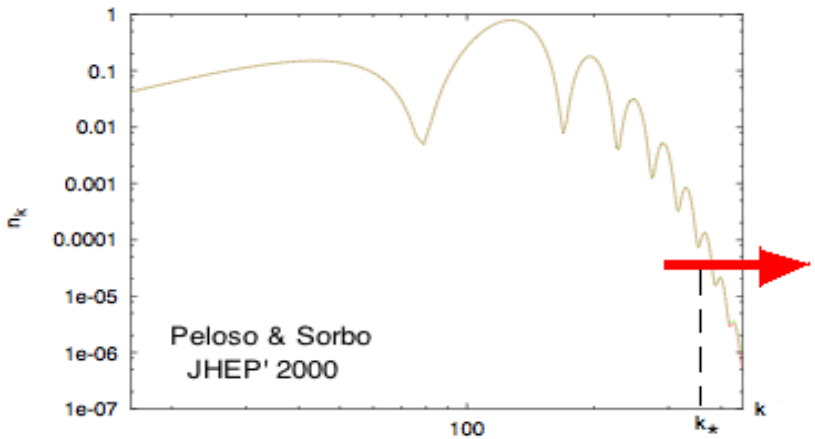


1. Non-Perturbative Excitation of fields

Fermions?: $y\phi\bar{\psi}\psi$: Oscillations $\rightarrow$ ψ – Particle Creation
(Non-Pert., Out-of-Eq.)

$$\frac{d^2}{dt^2}u_{\mathbf{k},\pm} + \left(\omega^2_{\mathbf{k}}(t) \pm i\frac{d(am_\psi)}{dt}\right)u_{\mathbf{k},\pm}(t) = 0\,, \qquad \frac{d}{dt}\omega_{\mathbf{k}} \gg \omega^2_{\mathbf{k}}(t)$$





[Greene & Kofman 99,00, Saffin & Tranberg 2011]

Fermions & Bosons Out-of-Eq $\rightarrow$ GWs !

$$\textbf{IR-Sphere}: \left\{ \begin{array}{c} n_k(k \lesssim k_*) \neq 1 \left\{ \begin{array}{l} \lesssim 1(F), \\ \gg 1(B) \end{array} \right. \\ \\ n_k(k \gg k_*) \rightarrow 0 \end{array} \right\} \Rightarrow \; T^{(j)}_{**}, \sim \bar{\psi}\gamma\partial\psi, \; \partial\phi\partial\phi$$

$$\left[\left(T^{(j)}_{\mu\nu} \right)^{\rm TT} \rightarrow \; \text{GW Source !} \right]$$

GWs: $\quad \frac{d\rho_{\rm GW}}{d\log k}(k,t) \propto \frac{Gk^3}{a^4(t)} \int_0^t \int_0^t \, dt_1 dt_2 \, \mathcal{G}(k, t_2 - t_1) \, \Pi^2(k, t_1, t_2)$

UTC: $\left\langle T^{\rm TT}_{ij}(\mathbf{k}, t_1) \, T^{\rm TT}_{ij}(\mathbf{k}', t_2) \right\rangle \equiv (2\pi)^3 \, \Pi^2(k, t_1, t_2) \, \delta^{(3)}(\mathbf{k} - \mathbf{k}')$

(B): Dufaux, Easther, Felder, Figueroa, G^a-Bellido, Giblin, Khlebnikov, Kofman, Lim, Tkachev, ... (F): Enqvist, Figueroa, Meriniemi

But... 'who' is ϕ?

"Traditionally": $\phi \rightarrow$ Inflaton $\Rightarrow$ (p)reheating!... but ...

.... only known scalar field $\rightarrow \phi$: SM higgs, so ...

... Option 1: SM higgs = inflaton? ($\Rightarrow$ Higgs-Inflation), or ...

... Option 2: SM higgs decoupled from Inflation? ($\Rightarrow$ Higgs-spectator)

Contents ...

ϕ = SM Higgs

Only fundamental scalar field known $\rightarrow \phi$: SM Higgs:

Option 1: SM Higgs = inflaton $\Rightarrow$ Higgs-Inflation,

Option 2: SM Higgs decoupled from Inflation $\Rightarrow$ Higgs-spectator
(or weakly coupled to)

2. SM Higgs during Inflation

SM HIGGS (SPECTATOR) during INFLATION

- **Inflation**: dS(H_*), $\quad (v \equiv 246 \text{ GeV} \ll H_* \lesssim 10^{14} \text{ GeV})$

- **SM Higgs**: $\Phi = \frac{\varphi}{\sqrt{2}} \rightarrow V(\varphi) = \frac{\lambda(\mu)}{4}\varphi^4, \quad \mu = \varphi \gg v$

- **Prob. Dist**: φ light $(|V''| < H_*^2) \Rightarrow \begin{cases} \text{Random Walk } (k < aH_*) \\ P_{\text{eq}}(\varphi) \propto \text{Exp}\{-c\lambda_*(\varphi/H_*)^4\} \end{cases}$

- **End of Inflation**: $\varphi_* = \alpha H_*/\lambda_*^{1/4} \qquad \alpha \in [0.001, 1]$ (99.9 %)

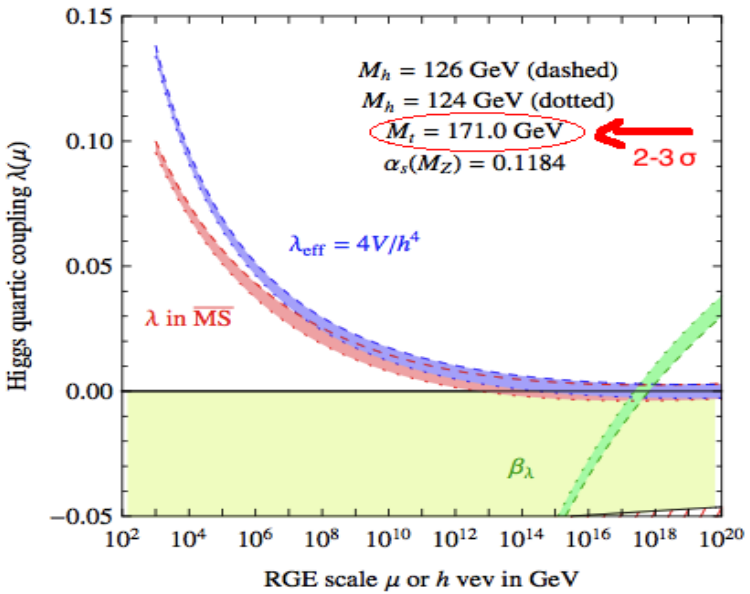
2. SM Higgs during Inflation

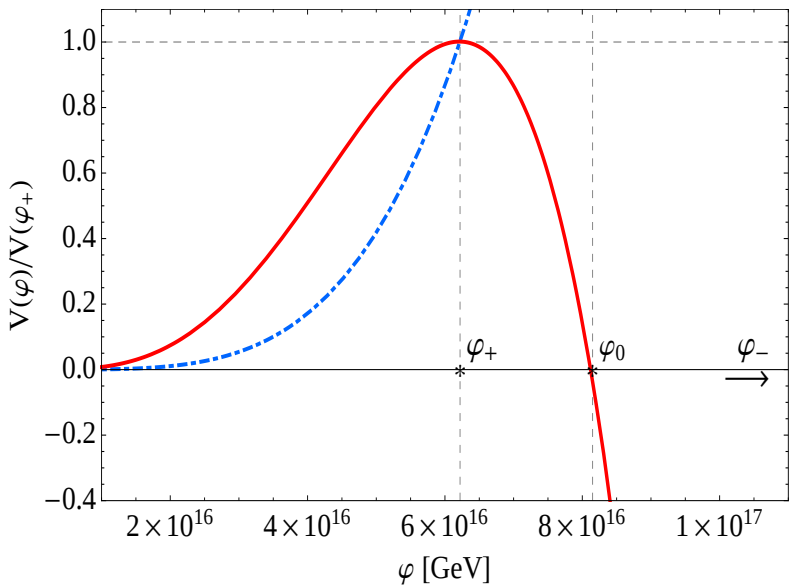
SM HIGGS (SPECTATOR) during INFLATION

- **Inflation**: dS(H_*), $\quad (v \equiv 246 \text{ GeV} \ll H_* \lesssim 10^{14} \text{ GeV})$
- **SM Higgs**: $\Phi = \frac{\varphi}{\sqrt{2}} \rightarrow V(\varphi) = \frac{\lambda(\mu)}{4}\varphi^4, \quad \mu = \varphi \gg v$
- **Prob. Dist**: φ light $(|V''| < H_*^2) \Rightarrow \begin{cases} \text{Random Walk } (k < aH_*) \\ P_{\text{eq}}(\varphi) \propto \text{Exp}\{-c\lambda_*(\varphi/H_*)^4\} \end{cases}$
- **End of Inflation**: $\varphi_* = \alpha H_*/\lambda_*^{1/4} \qquad \alpha \in [0.001, 1]$ (99.9 %)

Stability of the SM during Inflation ?

$$V(\varphi) = \frac{\lambda(\varphi)}{4}\varphi^4 \qquad \lambda \sim 10^{-5} - 10^{-2}$$





(Degrassi et al 2012, Bezrukov and Shaposhnikov 2012)

2. SM Higgs during Inflation

SM HIGGS (SPECTATOR) during INFLATION

- **Inflation**: dS(H_*), $\quad (v \equiv 246 \text{ GeV} \ll H_* \lesssim 10^{14} \text{ GeV})$
- **SM Higgs**: $\Phi = \frac{\varphi}{\sqrt{2}} \rightarrow V(\varphi) = \frac{\lambda(\mu)}{4}\varphi^4, \quad \mu = \varphi \gg v$
- **Prob. Dist**: φ light $(|V''| < H_*^2) \Rightarrow \begin{cases} \text{Random Walk } (k < aH_*) \\ P_{\text{eq}}(\varphi) \propto \text{Exp}\{-c\lambda_*(\varphi/H_*)^4\} \end{cases}$
- **End of Inflation**: $\varphi_* = \alpha H_*/\lambda_*^{1/4} \qquad \alpha \in [0.001, 1]$ (99.9 %)

2. SM Higgs during Inflation

SM HIGGS (SPECTATOR) during INFLATION

- **Inflation**: $\mathrm{dS}(H_*)$, $\quad (v \equiv 246\ \mathrm{GeV} \ll H_* \lesssim 10^{14}\ \mathrm{GeV})$
- **SM Higgs**: $\Phi = \frac{\varphi}{\sqrt{2}} \ \rightarrow \ V(\varphi) = \frac{\lambda(\mu)}{4}\varphi^4, \quad \mu = \varphi \gg v$
- **Prob. Dist**: φ light $(|V''| < H_*^2) \Rightarrow \begin{cases} \text{Random Walk } (k < aH_*) \\ P_{\mathrm{eq}}(\varphi) \propto \mathrm{Exp}\{-c\lambda_*(\varphi/H_*)^4\} \end{cases}$
- **End of Inflation**: $\varphi_* = \alpha H_*/\lambda_*^{1/4} \qquad \alpha \in [0.001, 1]$ (99.9 %)

2. SM Higgs during Inflation

SM HIGGS (SPECTATOR) during INFLATION

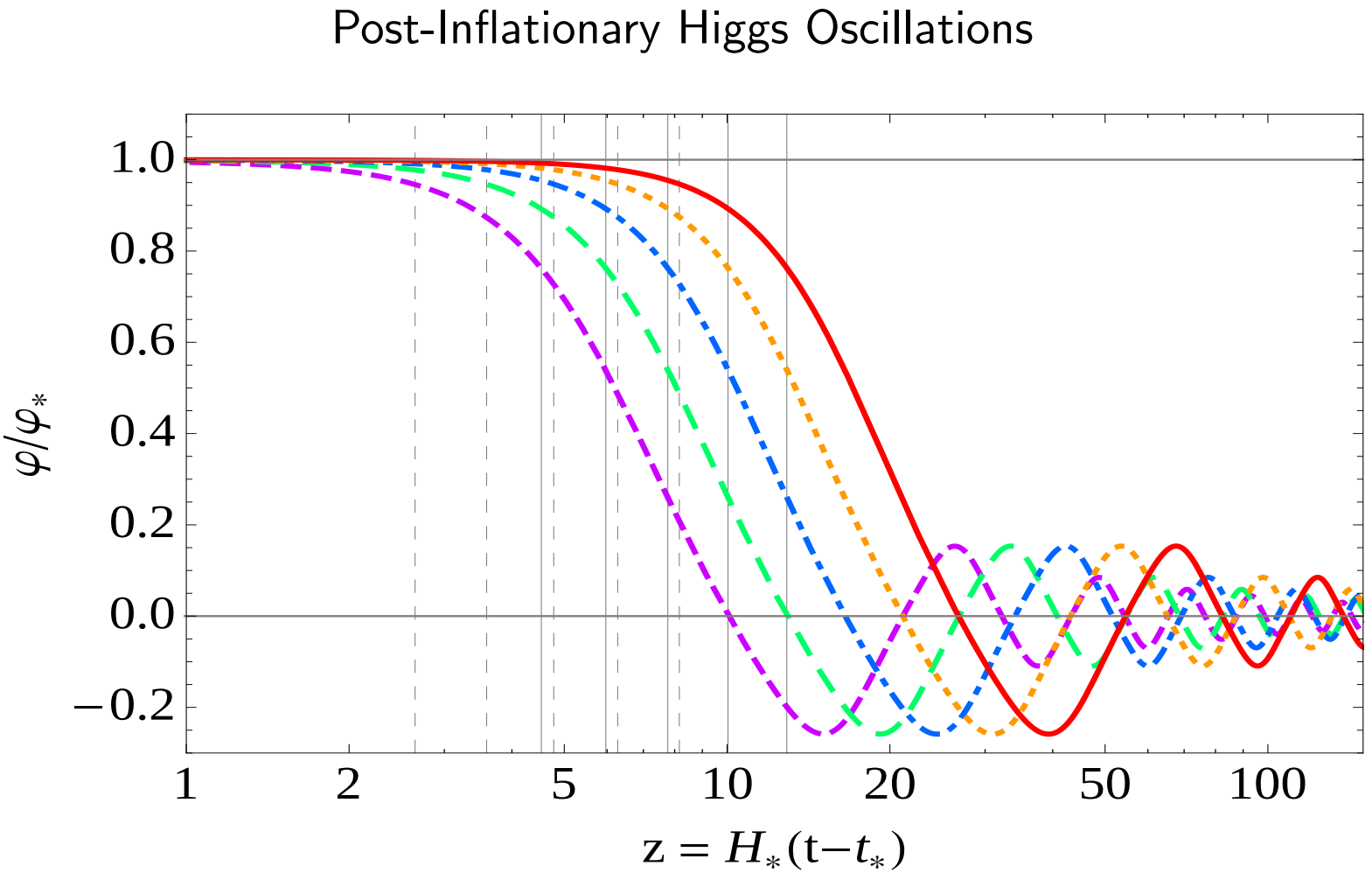
- **Inflation**: dS(H_*), $\quad (v \equiv 246 \text{ GeV} \ll H_* \lesssim 10^{14} \text{ GeV})$
- **SM Higgs**: $\Phi = \frac{\varphi}{\sqrt{2}} \rightarrow V(\varphi) = \frac{\lambda(\mu)}{4}\varphi^4, \quad \mu = \varphi \gg v$
- **Prob. Dist**: φ light $(|V''| < H_*^2) \Rightarrow \begin{cases} \text{Random Walk } (k < aH_*) \\ P_{\text{eq}}(\varphi) \propto \text{Exp}\{-c\lambda_*(\varphi/H_*)^4\} \end{cases}$
- **End of Inflation**: $\varphi_* = \alpha H_*/\lambda_*^{1/4} \qquad \alpha \in [0.001, 1]$ (99.9 %)

2. SM Higgs during Inflation

SM HIGGS (SPECTATOR) during INFLATION

- **Inflation**: dS(H_*), $\quad (v \equiv 246 \text{ GeV} \ll H_* \lesssim 10^{14} \text{ GeV})$
- **SM Higgs**: $\Phi = \frac{\varphi}{\sqrt{2}} \;\rightarrow\; V(\varphi) = \frac{\lambda(\mu)}{4}\varphi^4, \quad \mu = \varphi \gg v$
- **Prob. Dist**: φ light $(|V''| < H_*^2) \Rightarrow \begin{cases} \text{Random Walk } (k < aH_*) \\ P_{\text{eq}}(\varphi) \propto \text{Exp}\{-c\lambda_*(\varphi/H_*)^4\} \end{cases}$
- **End of Inflation**: $\varphi_* \neq 0 \;\; (V \propto \varphi^4) \;\; \Rightarrow \;\;$ Higgs Oscillations (!)

Higgs Osc. $\rightarrow$ SM $\Psi^{(j)}, A_\mu^{(j)}$ Param. Exc. !



Higgs Osc. $\rightarrow$ SM $\Psi^{(j)}, A_\mu^{(j)}$ Param. Exc. !

Fermions: $\quad j = \left\{ \begin{array}{c} \{t,b,c,s,u,d\} \\ \{e,\mu,\tau\} \end{array} \right\}$

$y_j \varphi \bar{\psi}_j \psi_j : \quad \frac{d^2}{d\tau^2} u^{(j)}_{k,\pm} + \left(\kappa^2 + q_j (a\varphi)^2 \pm i\sqrt{q_j}\frac{d}{d\tau}(a\varphi)\right) u^{(j)}_{k,\pm} = 0\,, \quad q_j \equiv \frac{y_j^2}{\lambda_{\rm I}}$

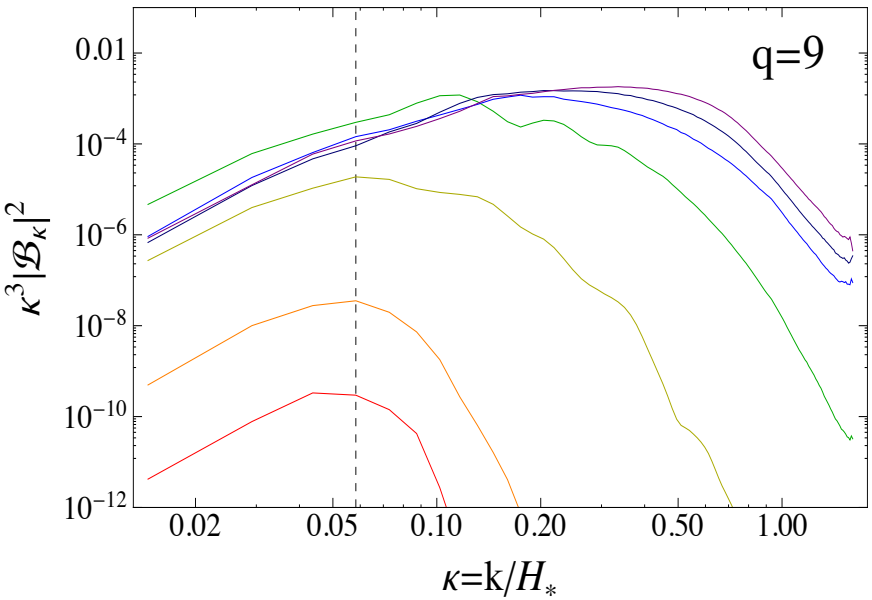
Bosons: $\quad j = \left\{ \begin{array}{c} \{W_\mu^{1,2,3}, B_\mu\} \\ (\{W_\mu^{\pm}, Z_\mu\}) \end{array} \right\}$

$g_j^2 \varphi^2 A_\mu A^\mu : \quad \frac{d^2}{d\tau^2} u^{(j)}_k + \left(\kappa^2 + q_j (a\varphi)^2\right) u^{(j)}_k = J_j(k) + N.L.\,, \quad q_j \equiv \frac{g_j^2}{\lambda_{\rm I}}$
$\in |(D_\mu \varphi)|^2$

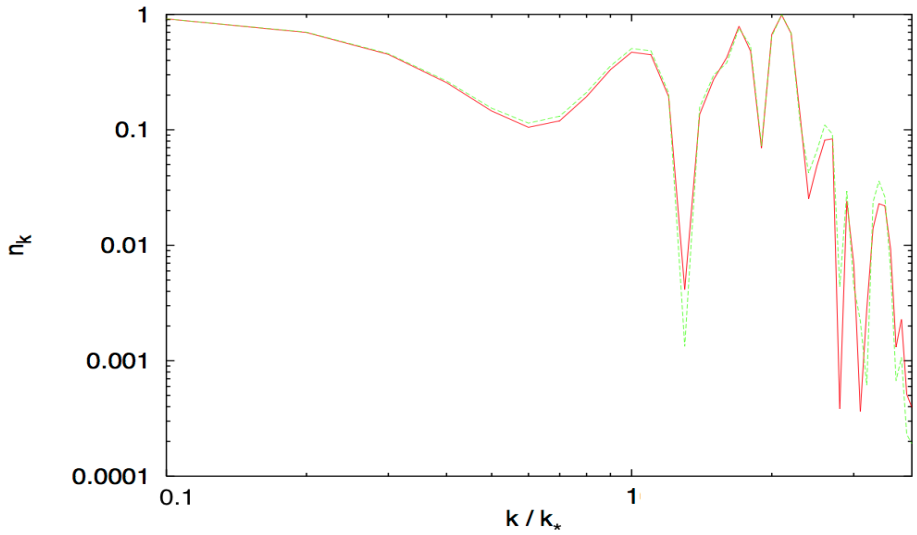
Higgs Osc. $\rightarrow$ SM $\Psi^{(j)}, A_\mu^{(j)}$ Param. Exc. !

Post-Inflationary production of SM species

Gauge Bosons



Fermions



$$\left(\begin{array}{l}\text{Enqvist, Nurmi, Meriniemi 2013}\\ \text{+ Rusak 2014,} \quad \text{+ Weir 2015}\\ \text{DGF, Torrenti, Garcia–Bellido 2015}\end{array}\right)$$

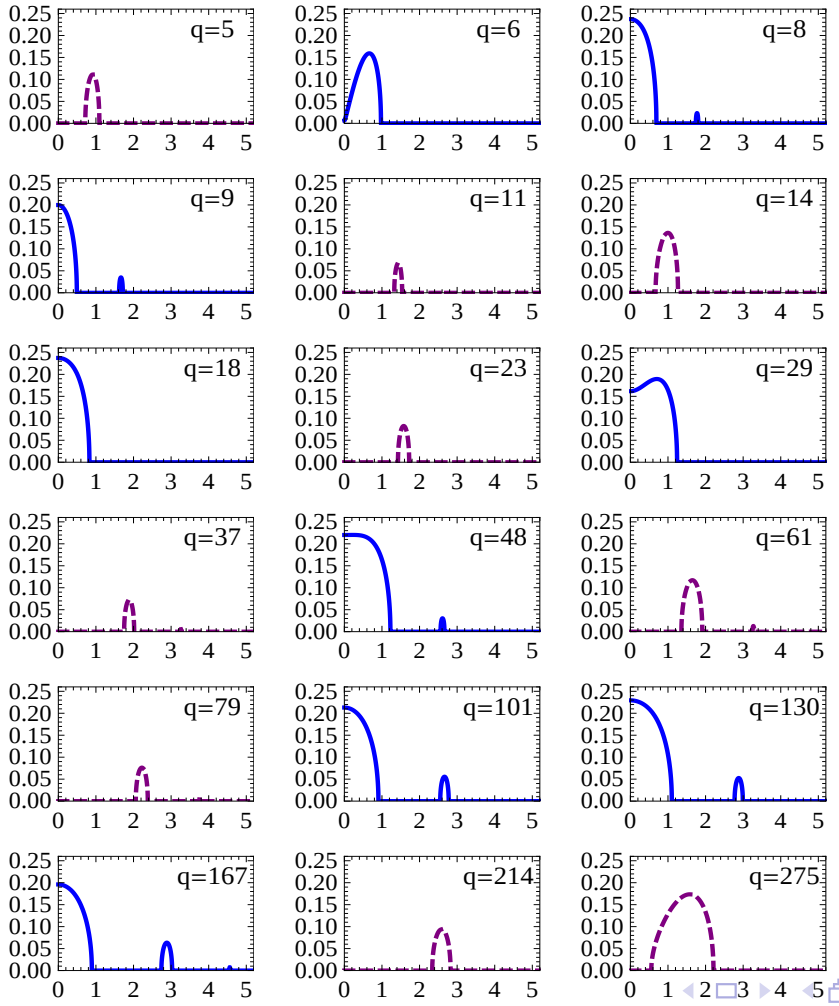
DGF 2014

Higgs Osc. $\rightarrow$ SM $\Psi^{(j)}, A_\mu^{(j)}$ Param. Exc. !

Post-Inflationary production of SM species: $n_k \propto \mathrm{Exp}(\mu_k\, t)$

Resonances

μ_k

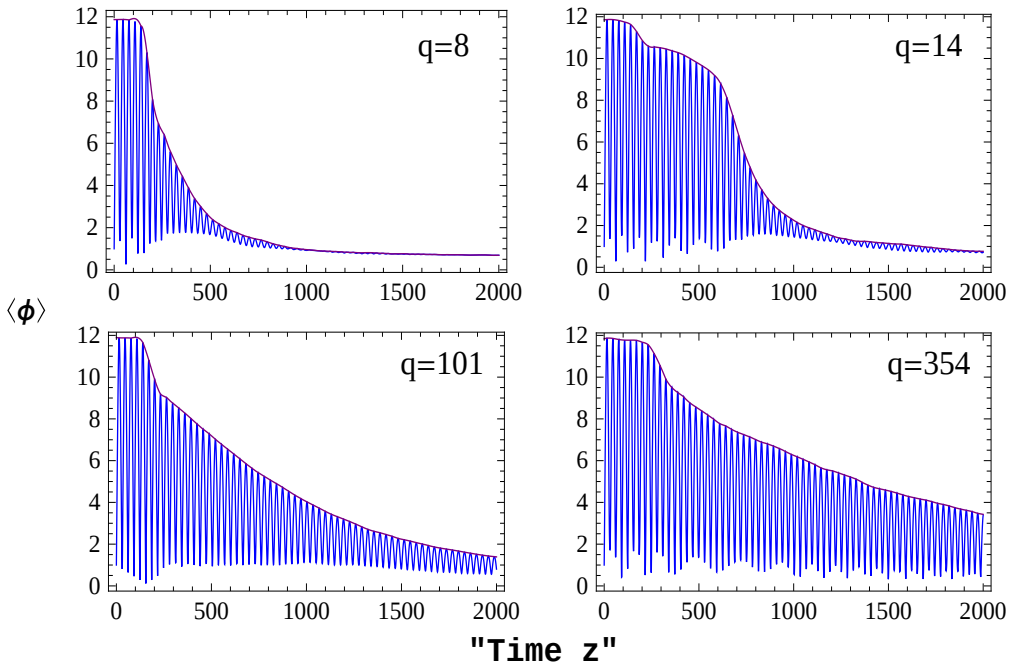


DGF
G^a-Bellido
Torrenti
2015

Higgs Osc. $\rightarrow$ SM $\Psi^{(j)}, A_\mu^{(j)}$ Param. Exc. !

[DGF, Garcia-Bellido, Torrenti 2015]

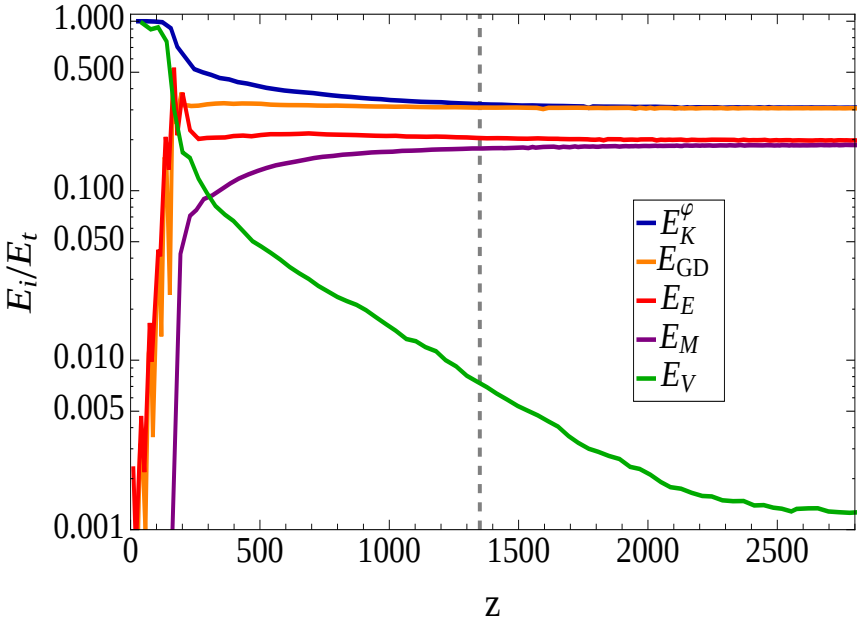
Higgs Decay



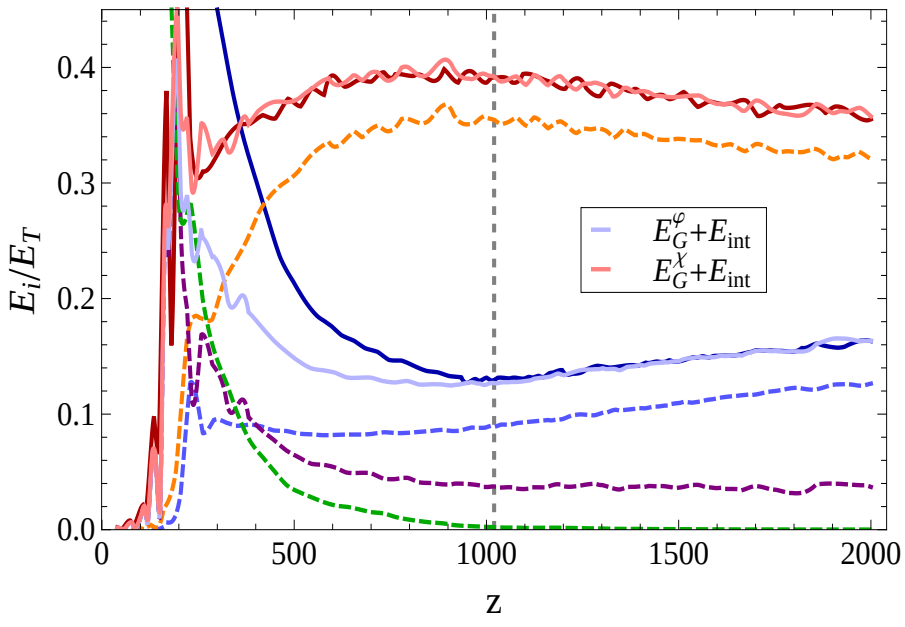
Higgs Osc. $\rightarrow$ SM $\Psi^{(j)}, A_\mu^{(j)}$ Param. Exc. !

[DGF, Garcia-Bellido, Torrenti 2015]

Energy Transfer



Relaxation/Equipartition



SM Ψ's, A_μ's (Param. Exc.) $\Rightarrow$ GWs

GRAVITATIONAL WAVE PRODUCTION

$$j = \left\{ \begin{array}{c} F : \{u, d\}, \{l^{\pm}\} \\ B : \{W^{\pm}, Z\} \end{array} \right\} \quad \Rightarrow \quad \Omega_{\rm GW}^{(j)}(k) \equiv \frac{1}{\rho_c} \frac{d\rho_{\rm GW}}{d \log k}(k; q_j) \,, \quad q_j \equiv \frac{y_j^2}{\lambda_{\rm I}}, \frac{g_j^2}{\lambda_{\rm I}}$$

$$n_k^{(j)}(k \lesssim k_*^{(j)}) \quad \Rightarrow \quad \Omega_{\rm GW}^{(j)}(k) \propto q_j^{\frac{3}{2}+\delta} \,, \qquad \left\{ \begin{array}{l} k_p \sim k_*^{(j)} \ (\text{Peak}) \\ \propto k^3, \ k \ll k_p (\text{IR}) \\ \propto e^{-k/k_*}, \ k \gg k_p (\text{UV}) \end{array} \right.$$

$$k_*^{(j)} \simeq q_j^{\frac{1}{4}} H_* \qquad (\delta \ll 1)$$

SM Ψ's, A_μ's (Param. Exc.) $\Rightarrow$ GWs

Universal Scaling :

$$\Omega_{\rm GW}(k; q_j) \propto q_j{}^{\frac{3}{2}+\delta}\, \mathcal{U}(k/k_p)\,, \qquad k_p \simeq q^{\frac{1}{4}} H_*$$

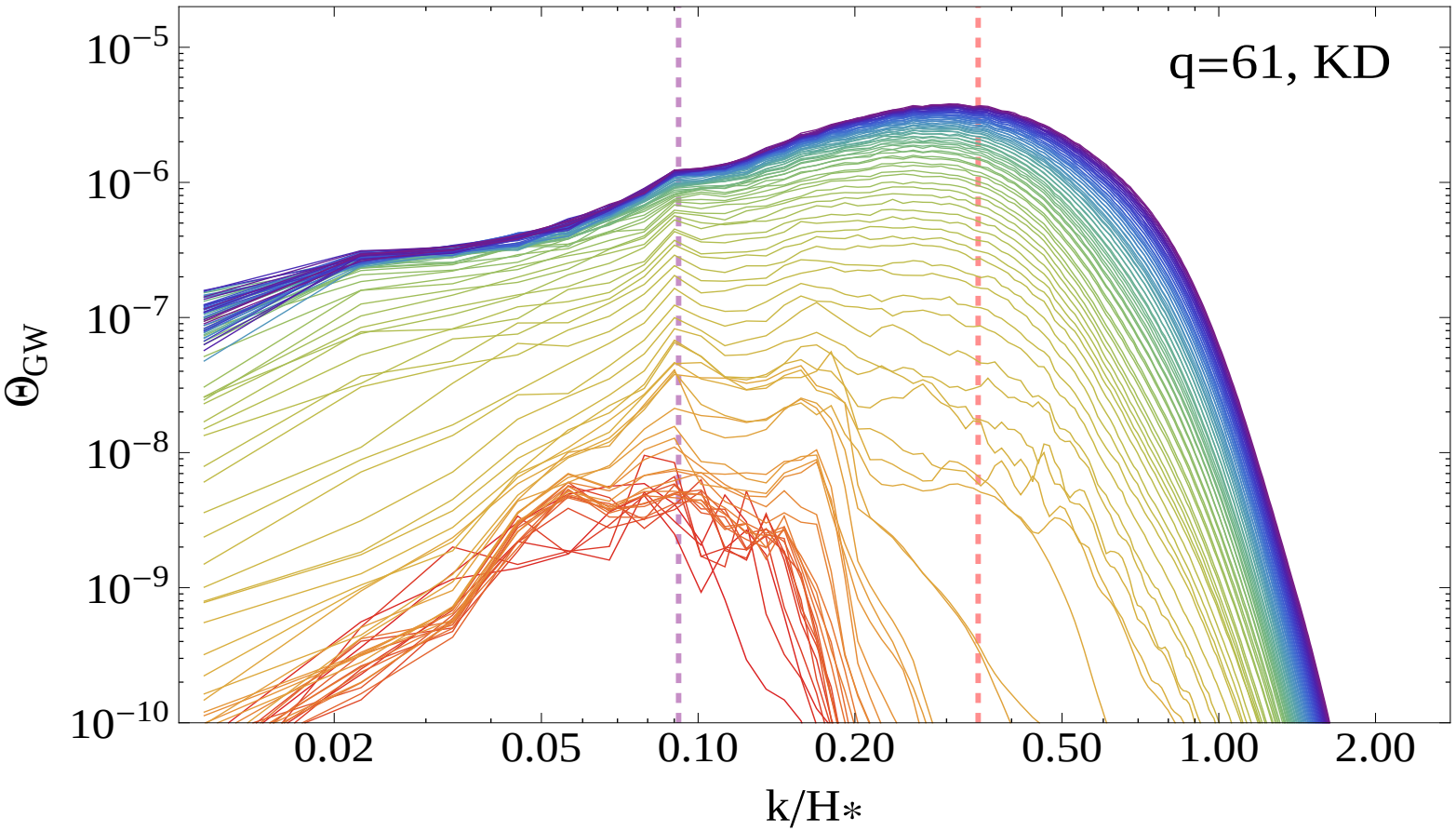
Total GWs :

$$\Omega_{\rm GW}(k) \propto \sum_F q_F{}^{\frac{3}{2}+\delta_F}\, \mathcal{U}_F(k; q_F) \;+\; \sum_B q_B{}^{\frac{3}{2}+\delta_B}\, \mathcal{U}_B(k; q_B)$$

SM Ψ's, A_μ's (Param. Exc.) $\Rightarrow$ GWs

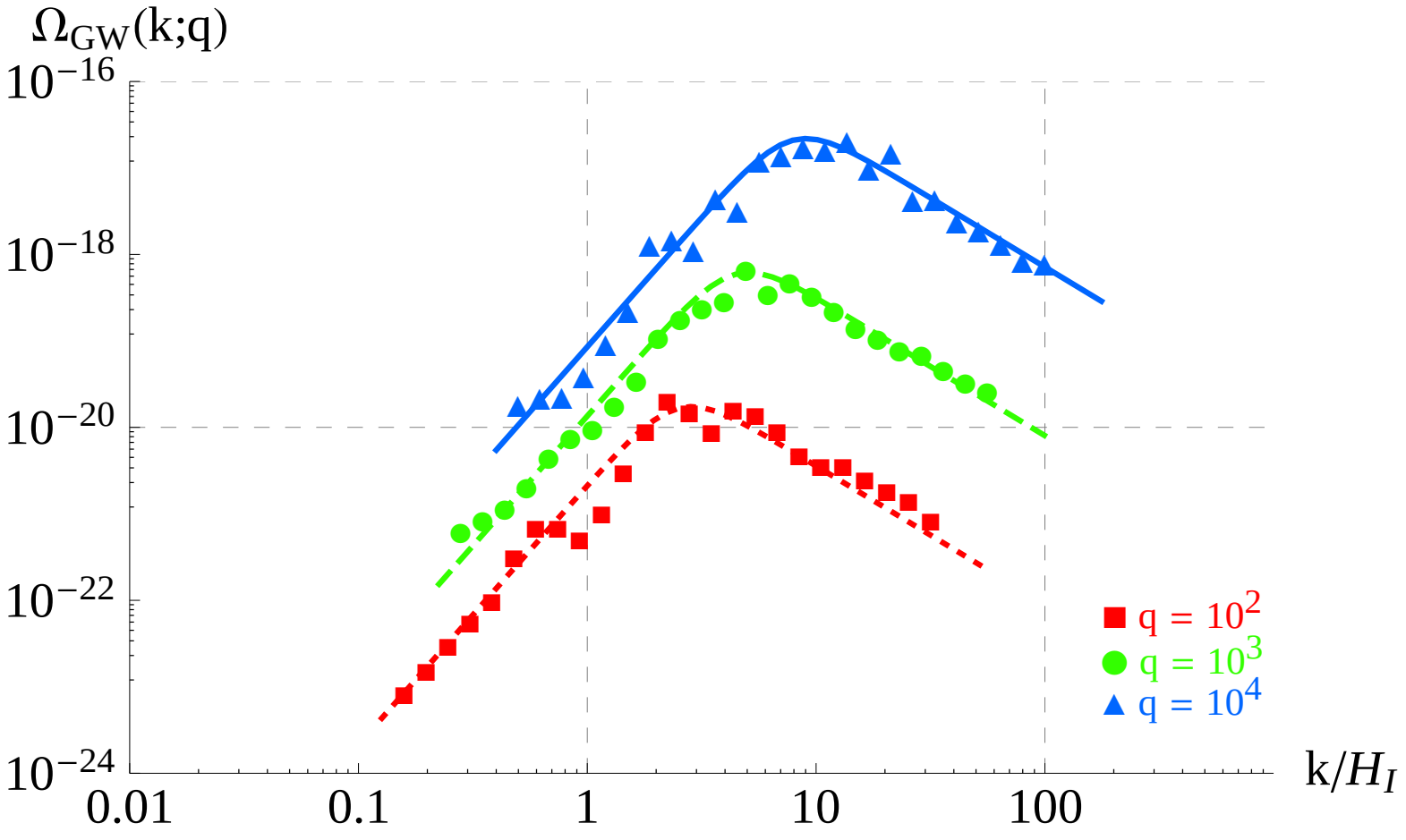
GAUGE BOSONS: $h^2\Omega^{(0)}_{\rm GW}(f) \propto q^{3/2} \propto g^3 \Rightarrow$ All Gauge Bosons contribute!

$\Omega_{\rm GW}(k,t) \equiv \left(\frac{H_*}{m_p}\right)^2 \Theta(k,t)$ [DGF, Garcia-Bellido, Torrenti 2015]



SM Ψ's, A_μ's (Param. Exc.) $\Rightarrow$ GWs

FERMIONS: $h^2\Omega^{(0)}_{\rm GW}(f) \propto q^{3/2} \propto y^3 \Rightarrow$ Top quark dominates!



SM Ψ's, A_μ's (Param. Exc.) $\Rightarrow$ GWs

$$\Omega_{\rm GW}(k) \propto \sum_F {q_F}^{1.5+\delta_F}\, \mathcal{U}_F(k;q_F) \;+\; \sum_B {q_B}^{1.5+\delta_B}\, \mathcal{U}_B(k;q_B)$$

$$\frac{\mathcal{U}_B(k;q)}{\mathcal{U}_F(k;q)} \gg 1 \;\Rightarrow\; \Omega^{\rm tot}_{\rm GW} \simeq \Omega^{(t)}_{\rm GW} + \Omega^{(W,Z)}_{\rm GW} \simeq \Omega^{(W,Z)}_{\rm GW} \left(\begin{array}{c} \text{Gauge Bosons} \\ \text{dominate !} \end{array} \right)$$

$$\text{GW Peak Today}: \begin{cases} f_p^{(t)} \sim 10^7 \left(\frac{H_*}{H_*^<}\right)^{\frac{1}{2}} \left(\frac{a_*}{a_{\rm RD}}\right)^{\frac{(1-3w)}{4}} \text{Hz}\,, \\ h^2\Omega^{(\rm p)}_{\rm GW}\big|_{\rm t} \sim 10^{-24} \left(\frac{0.01}{\lambda}\right)^{\frac{3}{2}} \left(\frac{H_*}{H_*^<}\right)^4 \left(\frac{a_*}{a_{\rm RD}}\right)^{1-3w} \end{cases}$$

$(g_Z^2 \approx 2g_W^2 \sim 0.6)$ $\qquad$ $(H_*^{(<)} \simeq 10^{14}\ \text{GeV}, \quad w = EOS)$

Post-Inflationary expansion history: EoS $w \equiv p/\rho$

What IF $w > +1/3$ (STIFF)? then $\rho_{BG} \propto \frac{1}{a^{4+\delta}}, \quad \delta > 0$

GW Today : $h^2 \Omega_{\rm GW}^{(\rm p)}\big|_{\rm t} \sim 10^{-24} \left(\frac{0.01}{\lambda}\right)^{\frac{3}{2}} \left(\frac{H_*}{H_*^<}\right)^4 \left(\frac{a_{\rm RD}}{a_*}\right)^{|3w-1|}$

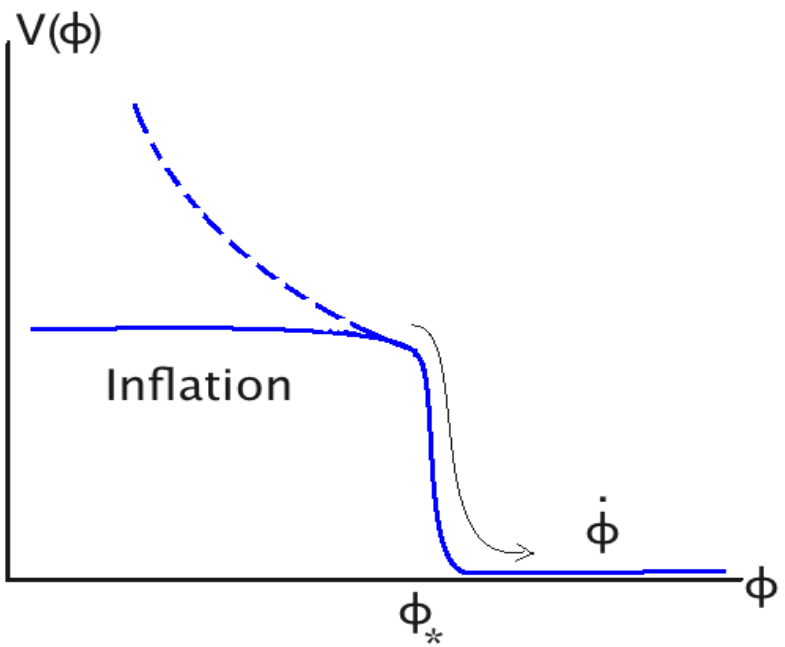
$$\text{GW Boost factor} \sim \left(\frac{a_{\rm RD}}{a_*}\right)^{|3w-1|} \gg 1$$

Post-Inflationary expansion history: EoS $w \equiv p/\rho$

How STIFF can 'we' be??

MAX. $w = +1$ (Kination-Domination): $\Rightarrow$ $\rho_{BG} \propto \frac{1}{a^6}$

GW Today : $h^2 \Omega_{\rm GW}^{(\rm p)}\big|_{\rm t} \sim 10^{-24} \left(\frac{0.01}{\lambda}\right)^{\frac{3}{2}} \left(\frac{H_*}{H_*^<}\right)^4 \left(\frac{a_{\rm RD}}{a_*}\right)^2$

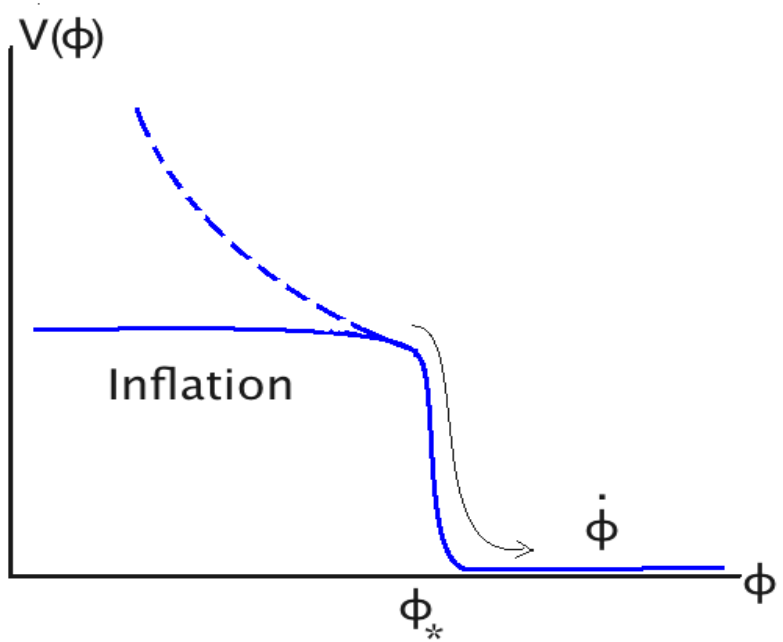


Post-Inflationary expansion history: EoS $w \equiv p/\rho$

How STIFF can 'we' be??

MAX. $w = +1$ (Kination-Domination): $\Rightarrow \ \rho_{BG} \propto \frac{1}{a^6}$

GW Today : $h^2 \Omega_{\rm GW}^{(\rm p)}\big|_{\rm t} \sim 10^{-24} \left(\frac{0.01}{\lambda}\right)^{\frac{3}{2}} \left(\frac{H_*}{H_*^<}\right)^4 \left(\frac{a_{\rm RD}}{a_*}\right)^2 \sim 10^{-11}$



- **GW boost !** (H_* independent)

- **Reheating the Universe into the SM fields !!**

Contents ...

Is this the end of the story?

All effects considered?? **No!**

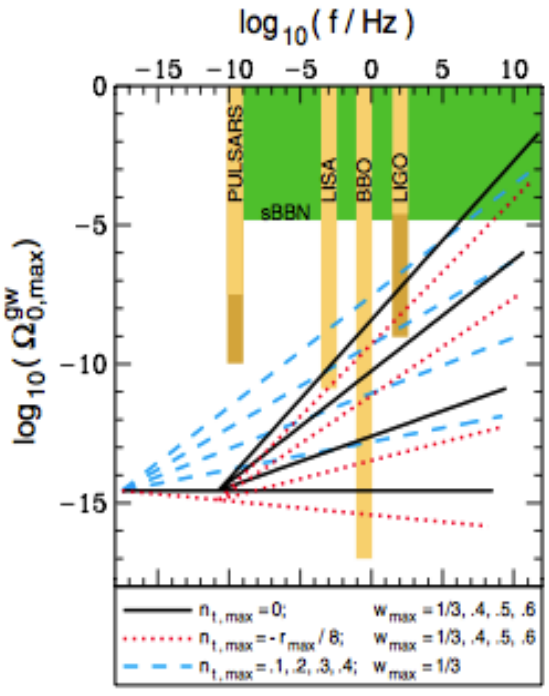
Decay widths, backreaction, rescattering, thermalization
MUST BE INCLUDED!

Need: Kurkela & Moore thermalization like-studies!!

After you re-scatter, backreact and thermalize... Is this the end of the story?

If KD $w = +1$ then Boost to Inflationary GW!

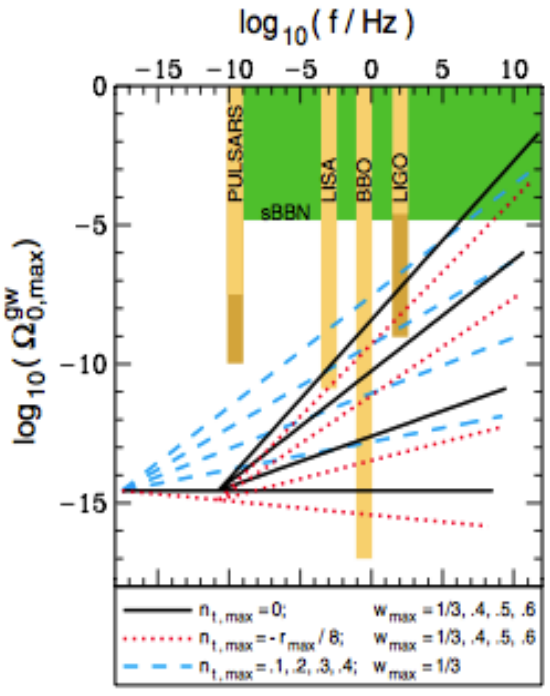
Boyle and Buonanno 2007



After you re-scatter, backreact and thermalize... Is this the end of the story?

If KD $w = +1$ then Boost to Inflationary GW!

Boyle and Buonanno 2007

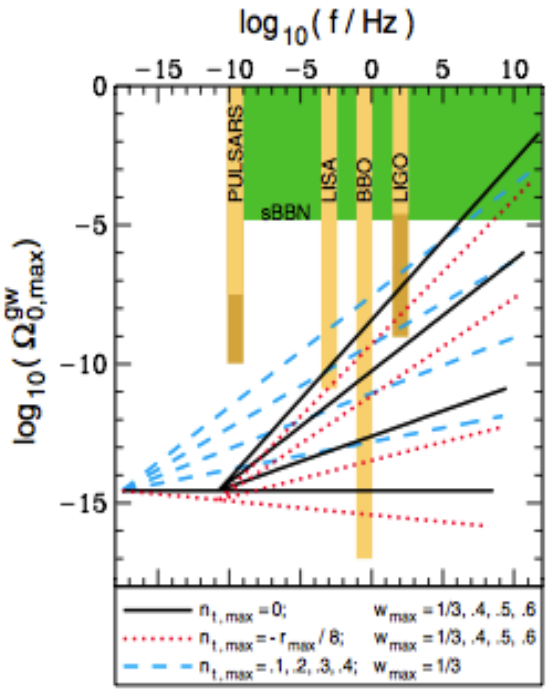


Upps, do we have a big Problem here?

After you re-scatter, backreact and thermalize... Is this the end of the story?

If KD $w = +1$ then Boost to Inflationary GW!

Boyle and Buonanno 2007



Upps, do we have a big Problem here?

Not really!

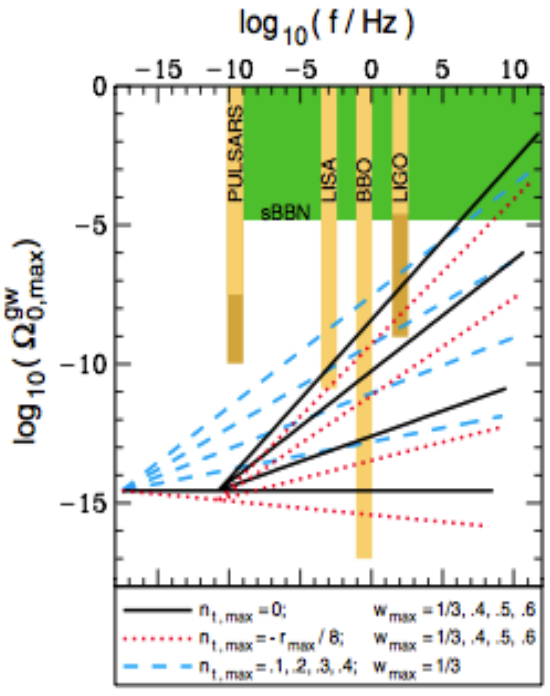
B&B: T_rad ~ T_{BBN} = 1 MeV → f_e ~ 10^{-11} Hz

RH: T_rh ~ 10^{7} GeV → f_e ~ 0.1 Hz

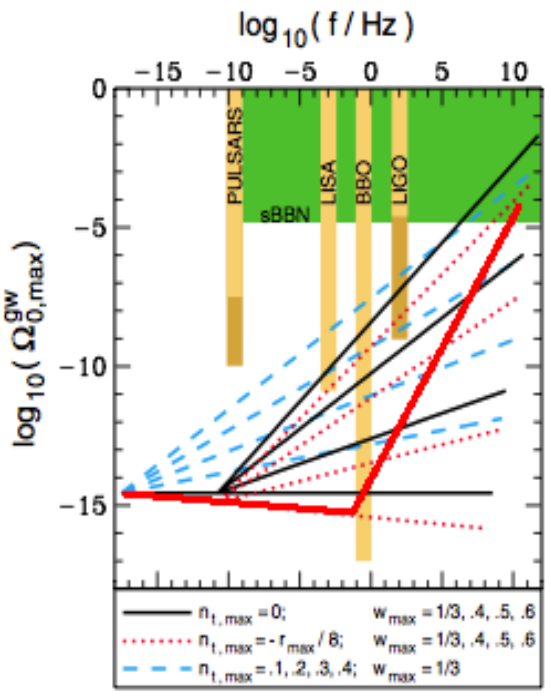
After you re-scatter, backreact and thermalize... Is this the end of the story?

If KD $w = +1$ then Boost to Inflationary GW!

Boyle and Buonanno 2007

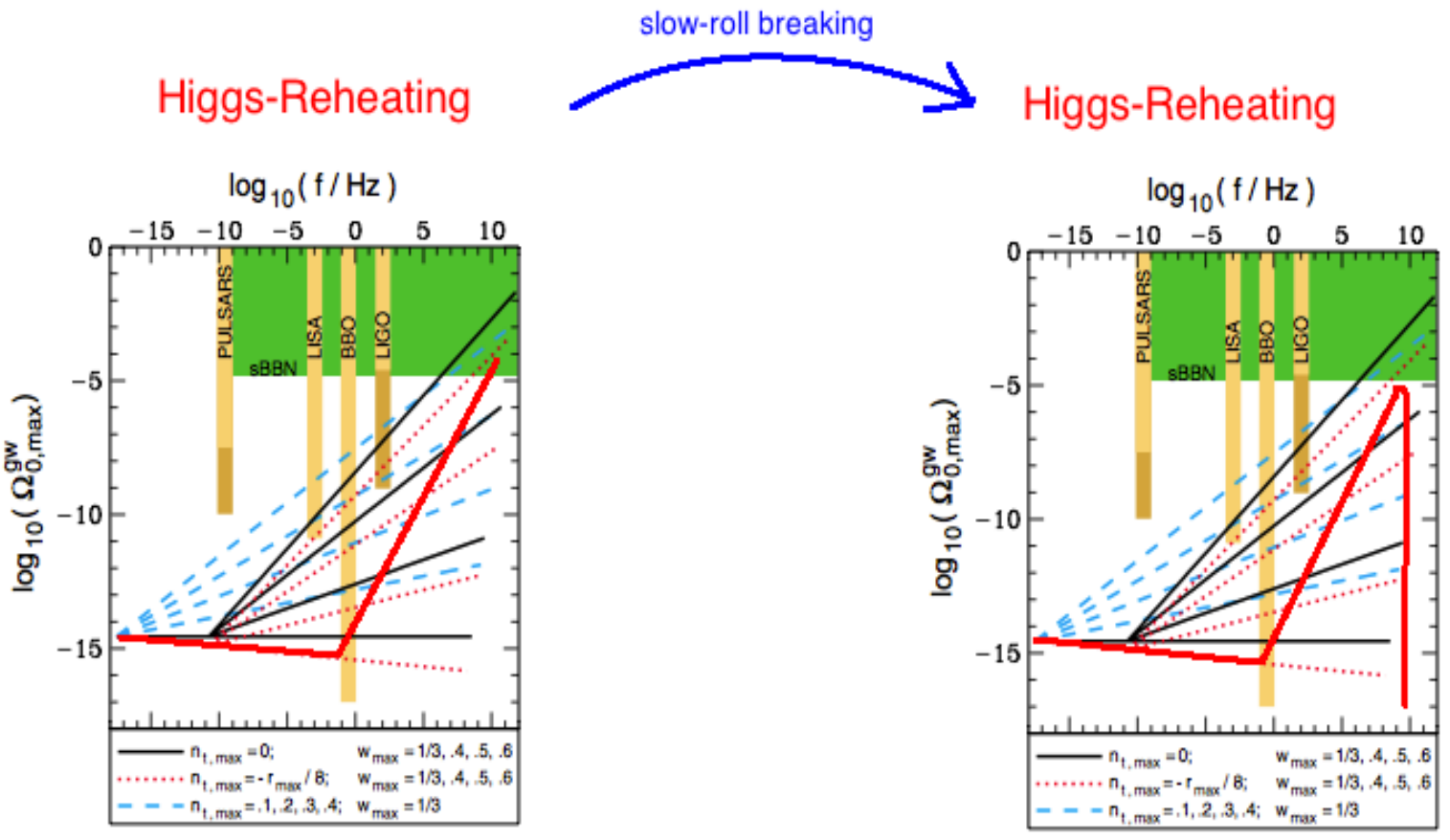


Higgs-Reheating



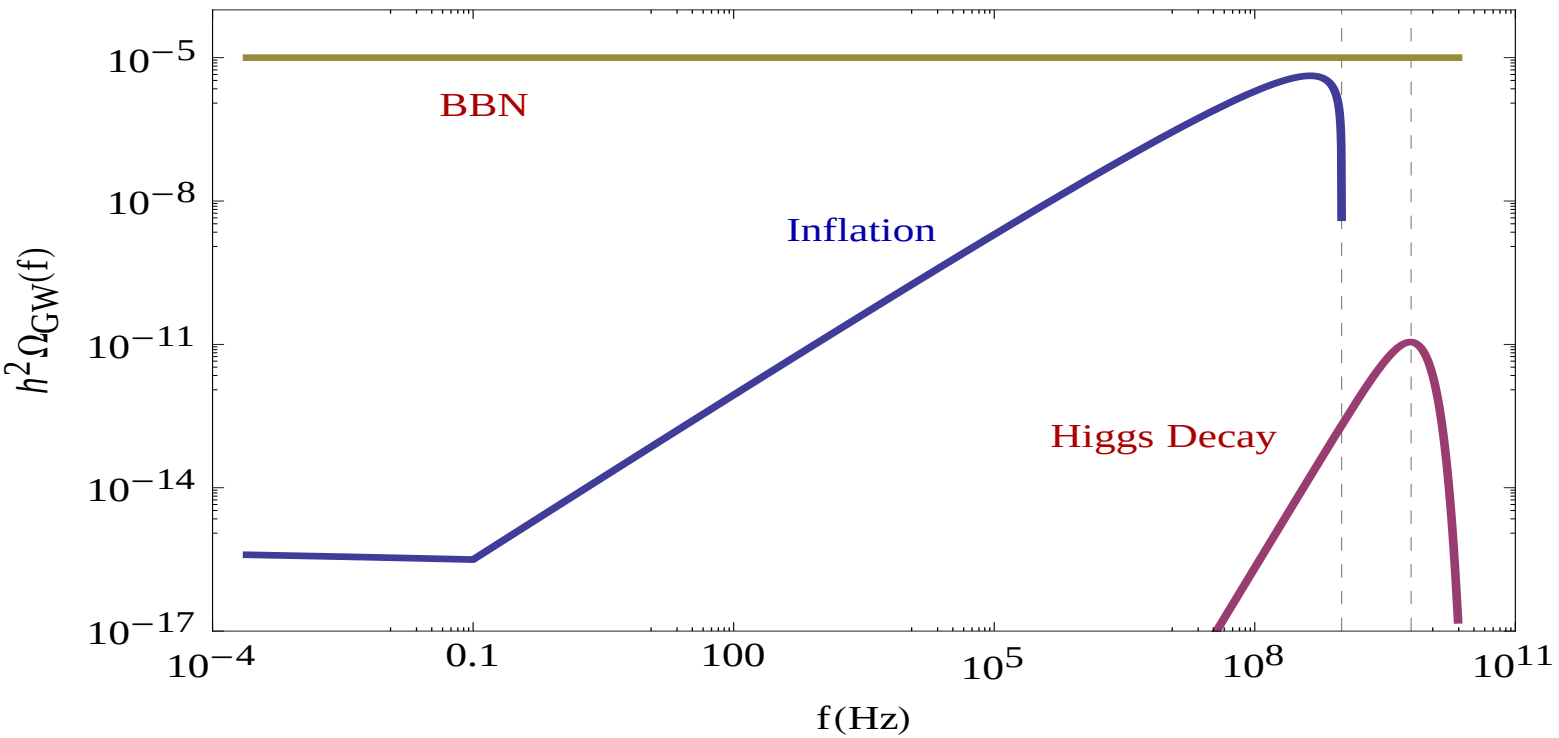
After you re-scatter, backreact and thermalize... Is this the end of the story?

If KD $w = +1$ then Boost to Inflationary GW!



After you re-scatter, backreact and thermalize... Is this the end of the story?

If KD $w = +1$ then Boost to Inflationary GW!



Summary I: SM Param. Excitations $\Rightarrow$ GWs

1. Inflation, $dS(H_*) \Rightarrow$ Higgs Osc.$\Rightarrow A'_\mu s, \Psi' s$ (Param. Excitation).
2. $\{\Psi_a\} \rightarrow h^2\Omega^{(0)}_{\rm GW}(f) \propto q_a^{3/2} \propto y_a^3 \Rightarrow$ Top Quark dominates
   $\{A^a_\mu\} \rightarrow \frac{\Omega^{(B)}_{\rm GW}}{\Omega^{(B)}_{\rm GW}} \gg 1 \Rightarrow$ Gauge Bosons dominate (!)
3. $$\left\{ \begin{array}{l} f_p \simeq \epsilon_*^{\frac{1}{4}} \delta^{\frac{1}{2}} \cdot 10^7\,{\rm Hz}\,, \\ h^2\Omega^{(0)}_{\rm GW} \simeq \epsilon_* \delta^4 \cdot 10^{-24} \left(\frac{0.01}{\lambda}\right)^{\frac{3}{2}} \end{array} \right\}, \qquad \left\{ \begin{array}{l} \delta \equiv \frac{H_*}{H_*^<} \\ \epsilon_* \equiv \left(\frac{a_*}{a_{\rm RD}}\right)^{(1-3w)} \end{array} \right.$$
4. but ... perturbative decays, re-scattering, thermalization, ... missing!
5. Universal Effect: Inflation + SM Higgs $\Rightarrow$ GW (SM)
6. If $w = +1$ (Kination-Domination) $\Rightarrow h^2\Omega^{(0)}_{\rm GW} \simeq 10^{-11}$ [double peak]
7. Higgs Inflation: $h^2\Omega_{\rm GW} \simeq 10^{-11}\,, \quad f_p \simeq 10^{10}$ Hz [Single Peak]

Summary I: SM Param. Excitations $\Rightarrow$ GWs

1. Inflation, $dS(H_*) \Rightarrow$ Higgs Osc.$\Rightarrow A'_\mu s, \Psi' s$ (Param. Excitation).
2. $\{\Psi_a\} \rightarrow h^2\Omega^{(0)}_{\rm GW}(f) \propto q_a^{3/2} \propto y_a^3 \Rightarrow$ Top Quark dominates
   $\{A^a_\mu\} \rightarrow \frac{\Omega^{(B)}_{\rm GW}}{\Omega^{(B)}_{\rm GW}} \gg 1 \Rightarrow$ Gauge Bosons dominate (!)
3. $$\left\{ \begin{array}{l} f_p \simeq \epsilon_*^{\frac{1}{4}} \delta^{\frac{1}{2}} \cdot 10^7\,{\rm Hz}\,, \\ h^2\Omega^{(0)}_{\rm GW} \simeq \epsilon_* \delta^4 \cdot 10^{-24} \left(\frac{0.01}{\lambda}\right)^{\frac{3}{2}} \end{array} \right\}, \qquad \left\{ \begin{array}{l} \delta \equiv \frac{H_*}{H_*^<} \\ \epsilon_* \equiv \left(\frac{a_*}{a_{\rm RD}}\right)^{(1-3w)} \end{array} \right.$$
4. but ... perturbative decays, re-scattering, thermalization, ... missing!
5. Universal Effect: Inflation + SM Higgs $\Rightarrow$ GW (SM)
6. If $w = +1$ (Kination-Domination) $\Rightarrow h^2\Omega^{(0)}_{\rm GW} \simeq 10^{-11}$ [double peak]
7. Higgs Inflation: $h^2\Omega_{\rm GW} \simeq 10^{-11}\,, \quad f_p \simeq 10^{10}$ Hz [Single Peak]

Summary I: SM Param. Excitations $\Rightarrow$ GWs

1. Inflation, $dS(H_*) \Rightarrow$ Higgs Osc.$\Rightarrow A'_\mu s, \Psi' s$ (Param. Excitation).
2. $\{\Psi_a\} \rightarrow h^2\Omega^{(0)}_{\rm GW}(f) \propto q_a^{3/2} \propto y_a^3 \Rightarrow$ Top Quark dominates
   $\{A^a_\mu\} \rightarrow \frac{\Omega^{(B)}_{\rm GW}}{\Omega^{(B)}_{\rm GW}} \gg 1 \Rightarrow$ Gauge Bosons dominate (!)
3. $$\left\{ \begin{array}{l} f_p \simeq \epsilon_*^{\frac{1}{4}} \delta^{\frac{1}{2}} \cdot 10^7\,{\rm Hz}\,, \\ h^2\Omega^{(0)}_{\rm GW} \simeq \epsilon_* \delta^4 \cdot 10^{-24} \left(\frac{0.01}{\lambda}\right)^{\frac{3}{2}} \end{array} \right\}, \quad \left\{ \begin{array}{l} \delta \equiv \frac{H_*}{H_*^<} \\ \epsilon_* \equiv \left(\frac{a_*}{a_{\rm RD}}\right)^{(1-3w)} \end{array} \right.$$
4. but ... perturbative decays, re-scattering, thermalization, ... missing!
5. Universal Effect: Inflation + SM Higgs $\Rightarrow$ GW (SM)
6. If $w = +1$ (Kination-Domination) $\Rightarrow h^2\Omega^{(0)}_{\rm GW} \simeq 10^{-11}$ [double peak]
7. Higgs Inflation: $h^2\Omega_{\rm GW} \simeq 10^{-11}\,, \quad f_p \simeq 10^{10}$ Hz [Single Peak]

Summary I: SM Param. Excitations $\Rightarrow$ GWs

1. Inflation, $dS(H_*) \Rightarrow$ Higgs Osc.$\Rightarrow A'_\mu s, \Psi' s$ (Param. Excitation).
2. $\{\Psi_a\} \rightarrow h^2\Omega^{(0)}_{\rm GW}(f) \propto q_a^{3/2} \propto y_a^3 \Rightarrow$ Top Quark dominates
   $\{A^a_\mu\} \rightarrow \frac{\Omega^{(B)}_{\rm GW}}{\Omega^{(B)}_{\rm GW}} \gg 1 \Rightarrow$ Gauge Bosons dominate (!)
3. $$\left\{ \begin{array}{l} f_p \simeq \epsilon_*^{\frac{1}{4}} \delta^{\frac{1}{2}} \cdot 10^7\,{\rm Hz}\,, \\ h^2\Omega^{(0)}_{\rm GW} \simeq \epsilon_* \delta^4 \cdot 10^{-24} \left(\frac{0.01}{\lambda}\right)^{\frac{3}{2}} \end{array} \right\}, \quad \left\{ \begin{array}{l} \delta \equiv \frac{H_*}{H_*^<} \\ \epsilon_* \equiv \left(\frac{a_*}{a_{\rm RD}}\right)^{(1-3w)} \end{array} \right.$$
4. but ... perturbative decays, re-scattering, thermalization, ... missing!
5. Universal Effect: Inflation + SM Higgs $\Rightarrow$ GW (SM)
6. If $w = +1$ (Kination-Domination) $\Rightarrow h^2\Omega^{(0)}_{\rm GW} \simeq 10^{-11}$ [double peak]
7. Higgs Inflation: $h^2\Omega_{\rm GW} \simeq 10^{-11}\,, \quad f_p \simeq 10^{10}$ Hz [Single Peak]

Summary I: SM Param. Excitations $\Rightarrow$ GWs

1. Inflation, $dS(H_*) \Rightarrow$ Higgs Osc.$\Rightarrow A'_\mu s, \Psi' s$ (Param. Excitation).
2. $\{\Psi_a\} \rightarrow h^2\Omega^{(0)}_{\rm GW}(f) \propto q_a^{3/2} \propto y_a^3 \Rightarrow$ Top Quark dominates
   $\{A^a_\mu\} \rightarrow \frac{\Omega^{(B)}_{\rm GW}}{\Omega^{(B)}_{\rm GW}} \gg 1 \Rightarrow$ Gauge Bosons dominate (!)
3. $$\left\{ \begin{array}{l} f_p \simeq \epsilon_*^{\frac{1}{4}} \delta^{\frac{1}{2}} \cdot 10^7\,{\rm Hz}\,, \\ h^2\Omega^{(0)}_{\rm GW} \simeq \epsilon_* \delta^4 \cdot 10^{-24} \left(\frac{0.01}{\lambda}\right)^{\frac{3}{2}} \end{array} \right\}, \quad \left\{ \begin{array}{l} \delta \equiv \frac{H_*}{H_*^<} \\ \epsilon_* \equiv \left(\frac{a_*}{a_{\rm RD}}\right)^{(1-3w)} \end{array} \right.$$
4. but ... perturbative decays, re-scattering, thermalization, ... missing!
5. Universal Effect: Inflation + SM Higgs $\Rightarrow$ GW (SM)
6. If $w = +1$ (Kination-Domination) $\Rightarrow h^2\Omega^{(0)}_{\rm GW} \simeq 10^{-11}$ [double peak]
7. Higgs Inflation: $h^2\Omega_{\rm GW} \simeq 10^{-11}\,, \quad f_p \simeq 10^{10}$ Hz [Single Peak]

Summary I: SM Param. Excitations $\Rightarrow$ GWs

1. Inflation, $dS(H_*) \Rightarrow$ Higgs Osc.$\Rightarrow A'_\mu s, \Psi' s$ (Param. Excitation).
2. $\{\Psi_a\} \rightarrow h^2\Omega^{(0)}_{\rm GW}(f) \propto q_a^{3/2} \propto y_a^3 \Rightarrow$ Top Quark dominates
   $\{A^a_\mu\} \rightarrow \frac{\Omega^{(B)}_{\rm GW}}{\Omega^{(B)}_{\rm GW}} \gg 1 \Rightarrow$ Gauge Bosons dominate (!)
3. $$\left\{ \begin{array}{l} f_p \simeq \epsilon_*^{\frac{1}{4}} \delta^{\frac{1}{2}} \cdot 10^7\,{\rm Hz}\,, \\ h^2\Omega^{(0)}_{\rm GW} \simeq \epsilon_* \delta^4 \cdot 10^{-24} \left(\frac{0.01}{\lambda}\right)^{\frac{3}{2}} \end{array} \right\}, \quad \left\{ \begin{array}{l} \delta \equiv \frac{H_*}{H_*^<} \\ \epsilon_* \equiv \left(\frac{a_*}{a_{\rm RD}}\right)^{(1-3w)} \end{array} \right.$$
4. but ... perturbative decays, re-scattering, thermalization, ... missing!
5. Universal Effect: Inflation + SM Higgs $\Rightarrow$ GW (SM)
6. If $w = +1$ (Kination-Domination) $\Rightarrow h^2\Omega^{(0)}_{\rm GW} \simeq 10^{-11}$ [double peak]
7. Higgs Inflation: $h^2\Omega_{\rm GW} \simeq 10^{-11}\,, \quad f_p \simeq 10^{10}$ Hz [Single Peak]

Summary I: SM Param. Excitations $\Rightarrow$ GWs

1. Inflation, $dS(H_*) \Rightarrow$ Higgs Osc.$\Rightarrow A'_\mu s, \Psi' s$ (Param. Excitation).
2. $\{\Psi_a\} \rightarrow h^2\Omega^{(0)}_{\rm GW}(f) \propto q_a^{3/2} \propto y_a^3 \Rightarrow$ Top Quark dominates
   $\{A^a_\mu\} \rightarrow \frac{\Omega^{(B)}_{\rm GW}}{\Omega^{(B)}_{\rm GW}} \gg 1 \Rightarrow$ Gauge Bosons dominate (!)
3. $$\left\{ \begin{array}{l} f_p \simeq \epsilon_*^{\frac{1}{4}} \delta^{\frac{1}{2}} \cdot 10^7\,{\rm Hz}\,, \\ h^2\Omega^{(0)}_{\rm GW} \simeq \epsilon_* \delta^4 \cdot 10^{-24} \left(\frac{0.01}{\lambda}\right)^{\frac{3}{2}} \end{array} \right\}, \quad \left\{ \begin{array}{l} \delta \equiv \frac{H_*}{H_*^<} \\ \epsilon_* \equiv \left(\frac{a_*}{a_{\rm RD}}\right)^{(1-3w)} \end{array} \right.$$
4. but ... perturbative decays, re-scattering, thermalization, ... missing!
5. Universal Effect: Inflation + SM Higgs $\Rightarrow$ GW (SM)
6. If $w = +1$ (Kination-Domination) $\Rightarrow h^2\Omega^{(0)}_{\rm GW} \simeq 10^{-11}$ [double peak]
7. Higgs Inflation: $h^2\Omega_{\rm GW} \simeq 10^{-11}\,, \quad f_p \simeq 10^{10}$ Hz [Single Peak]

"This is the end, my only friend, the end, ...", The Doors

THANKS YOU FOR YOUR ATTENTION!!!

SM Higgs post-inflaionary decay and GW production REFERENCES:

- GW from Fermions: Enqvist, DGF, Meriniemi 2013
- SM Higgs decay (analytical): Enqvist, Nurmi, Rusak 2013, 2014
- GW from Higgs decay into Fermions: DGF 2014
- SM Higgs decay (lattice, Abelian): DGF, G^a-Bellido, Torrenti 2015
- SM Higgs decay (lattice, non-Abelian): Enqvist, Nurmi, Rusak, Weir 2015
- GW from Higgs decay (lattice): DGF, G^a-Bellido, Torrenti [Coming!]