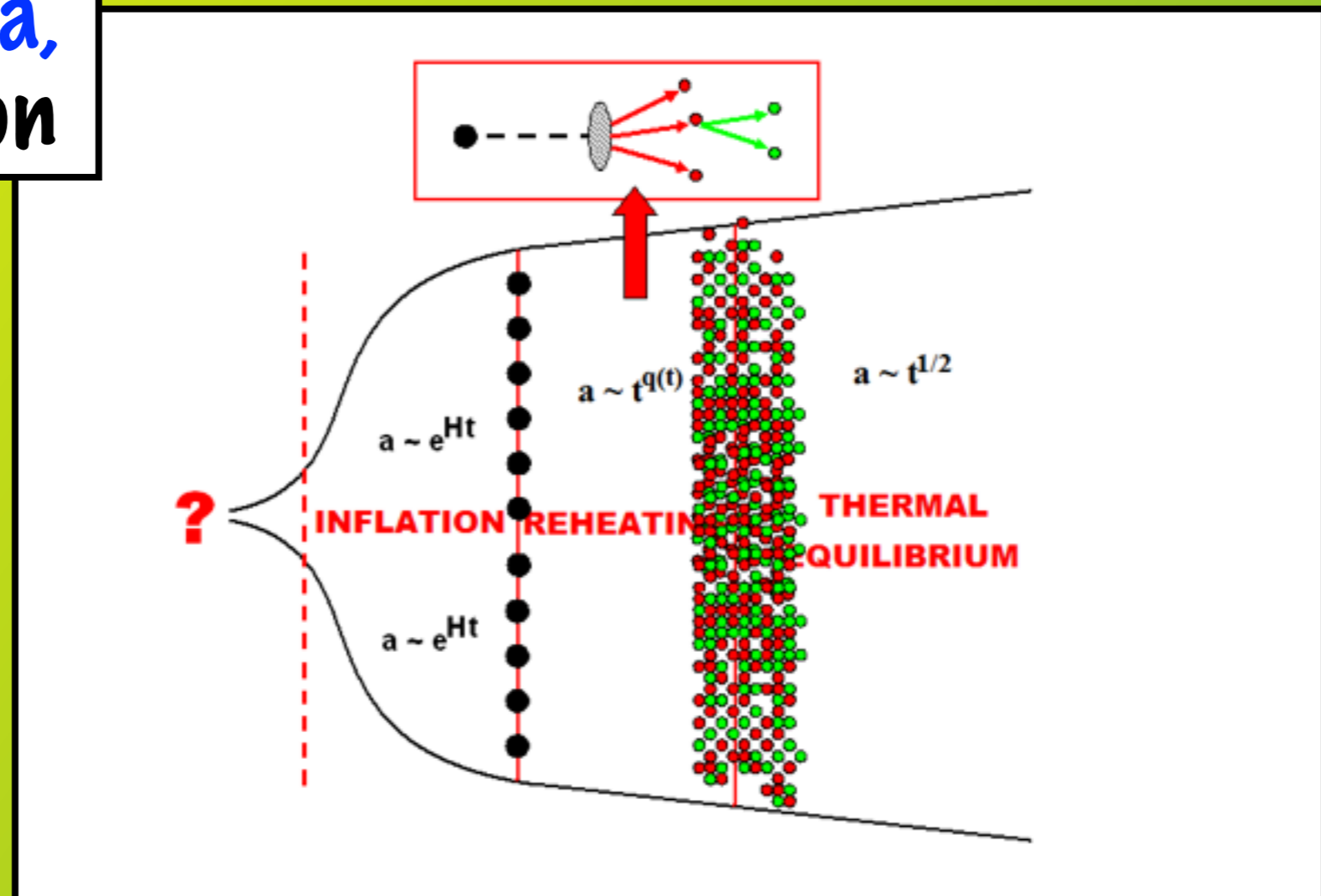


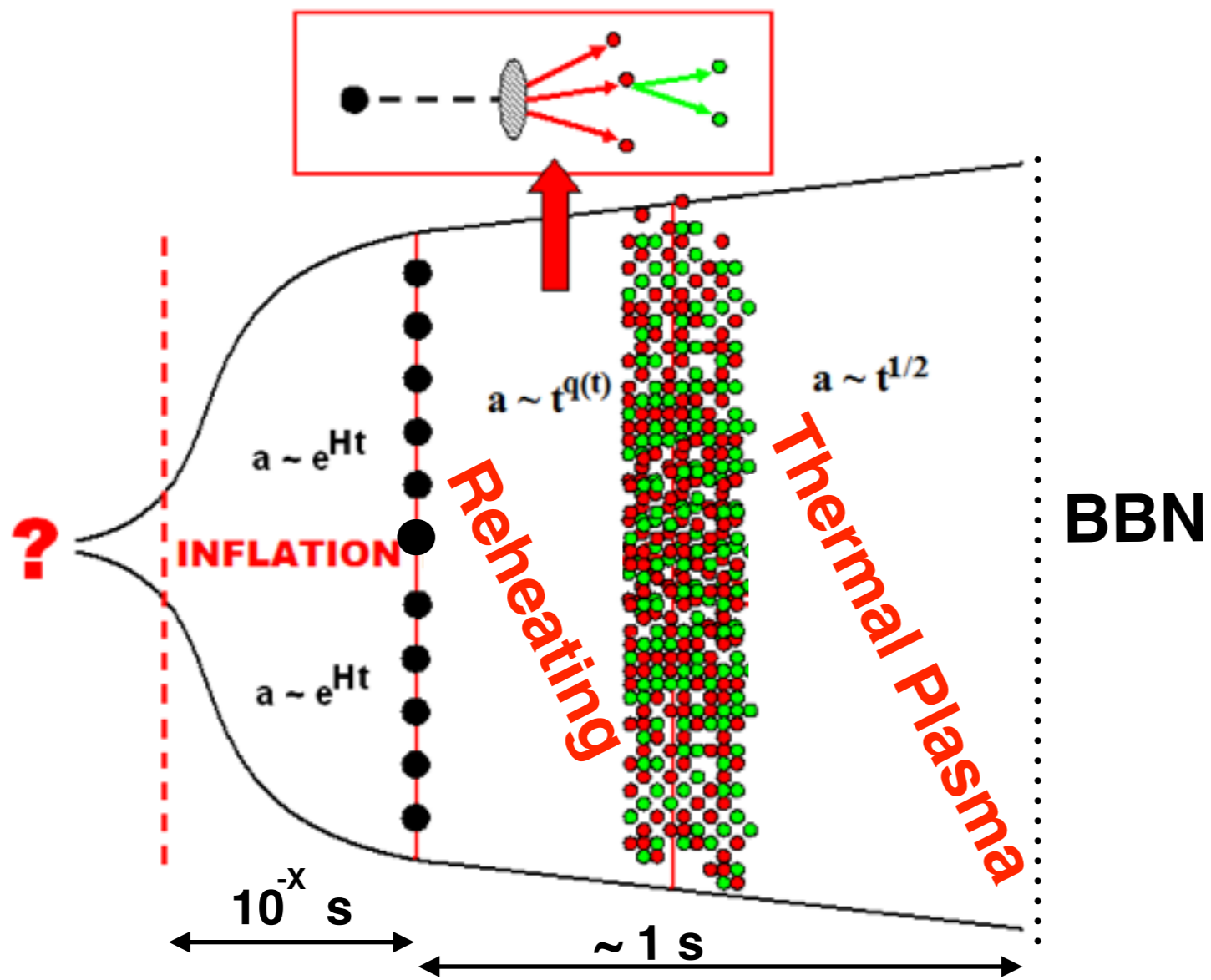
A Stiff HIGGStory of the Early Universe

Daniel G. Figueroa,
CERN, TH Division



The Problem:

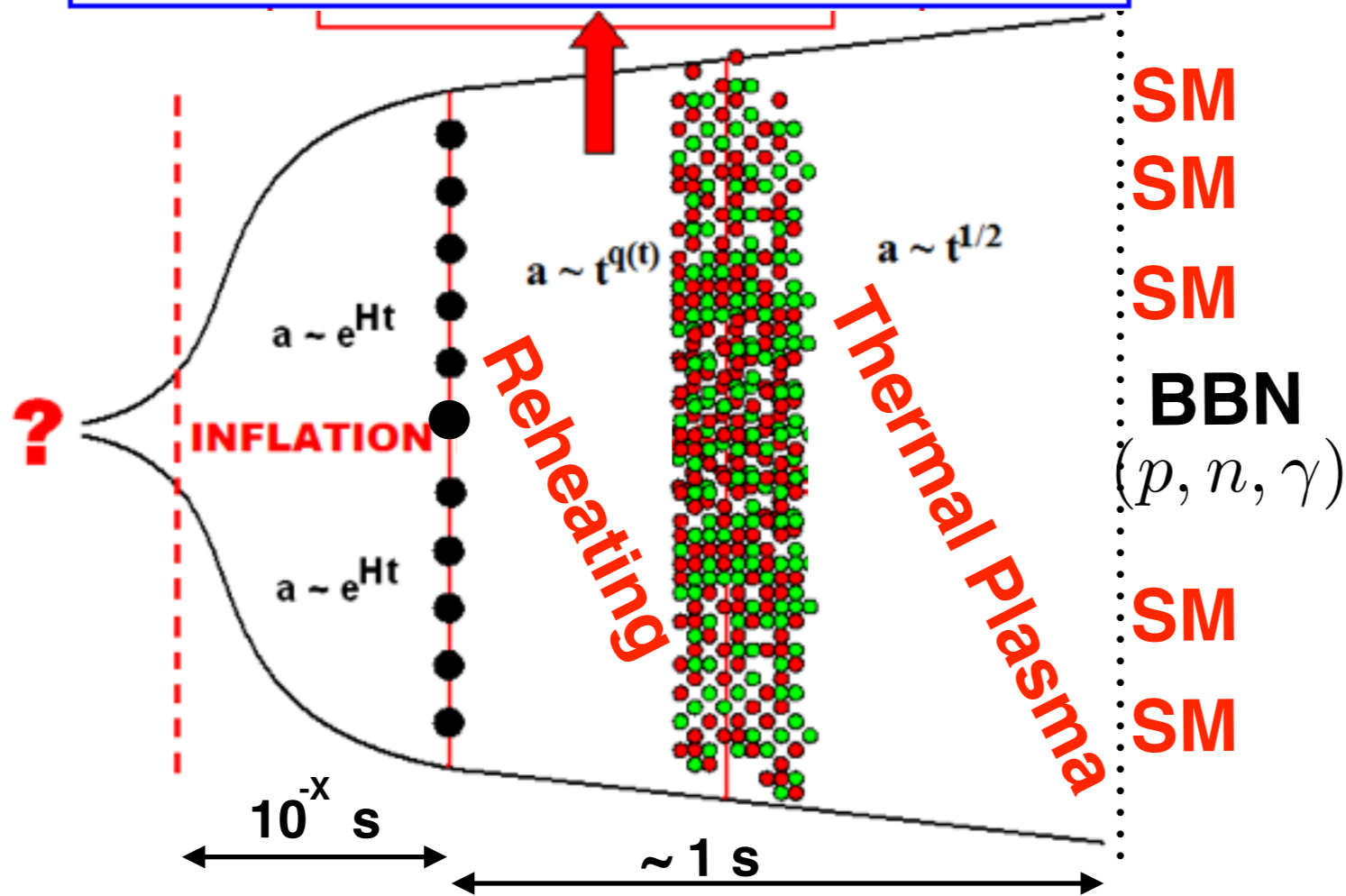
(p)Reheating the Universe



Successful Reheating:

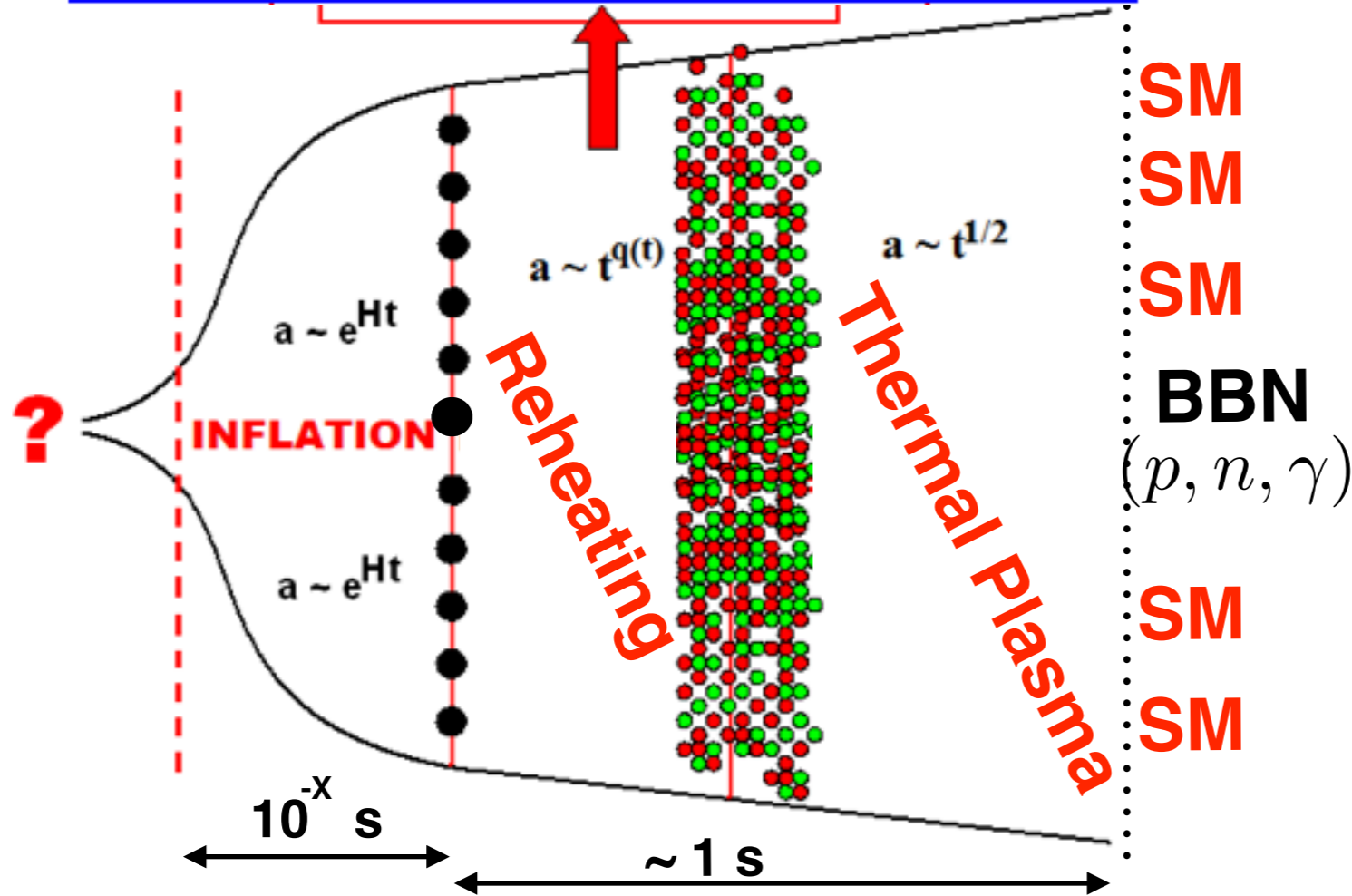
(p)Reheating into the Standard Model

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



(p)Reheating into the Standard Model

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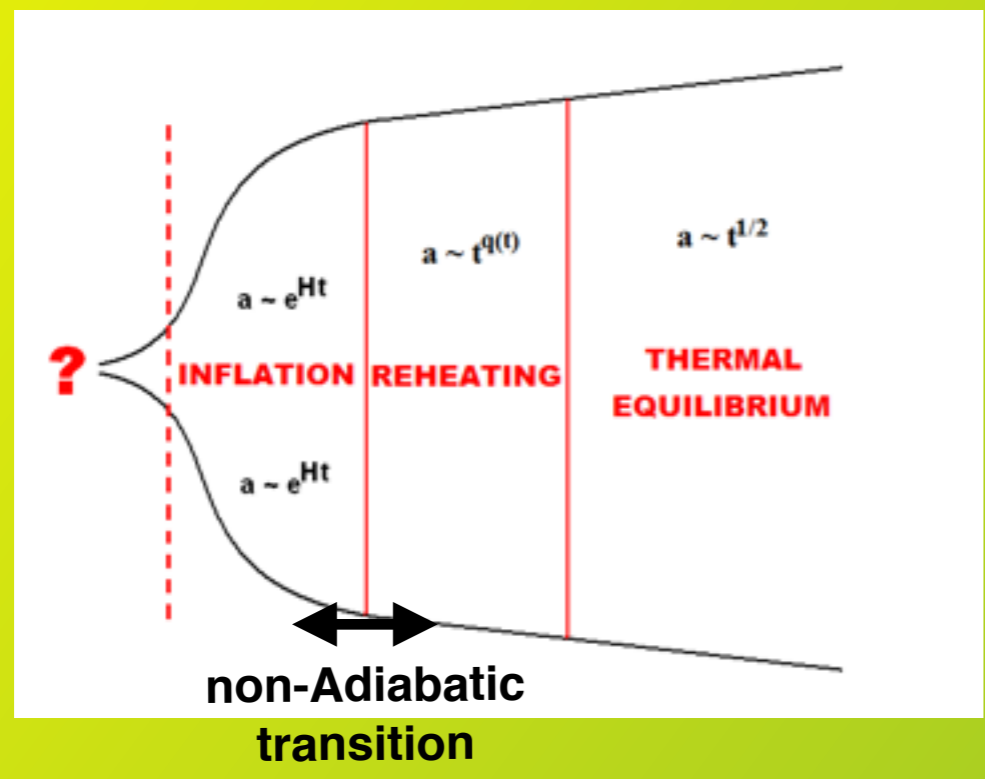


Connection between SM and Inflationary Sector ???

- * Higgs Portals ?
- * Mediator fields ?
- * No coupling ?

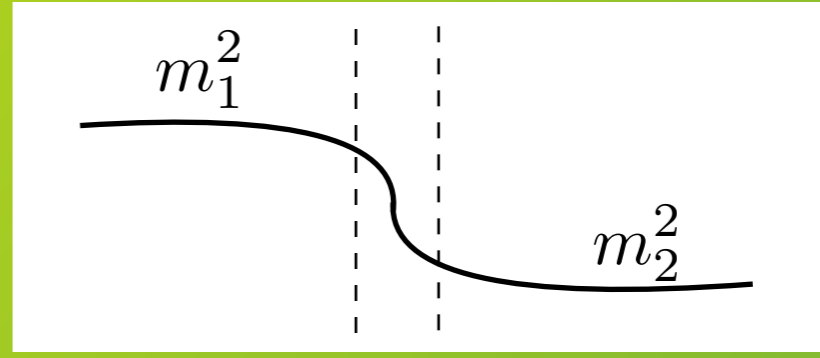
(p) Reheating into the Standard Model
No Coupling to Inflaton

$$\frac{\lambda}{4} (|\varphi|^2 - v^2)^2 + \frac{\xi}{2} R |\varphi|^2$$



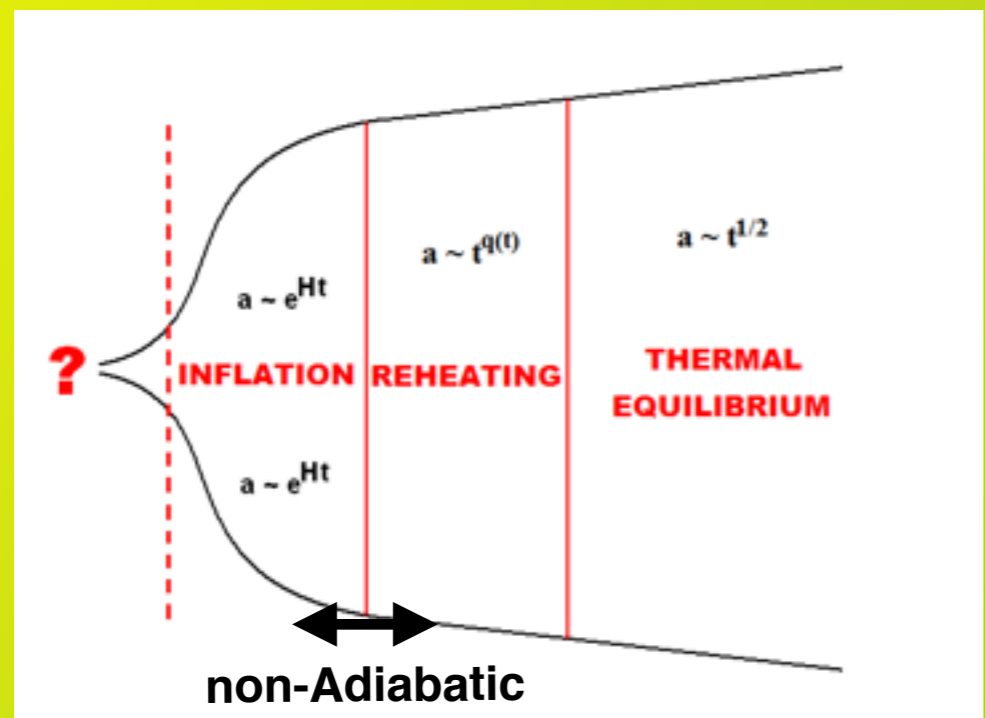
- * Inf: $m_\varphi^2 = \xi R = 12\xi H^2$
- * After: $m_\varphi^2 = \xi R = 3(1 - 3w)\xi H^2$

Equation of State



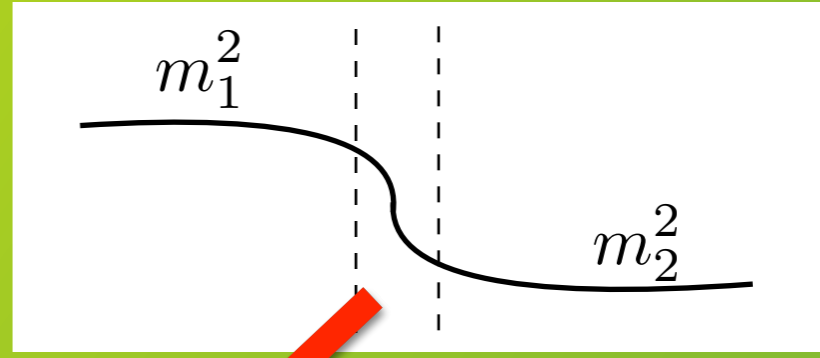
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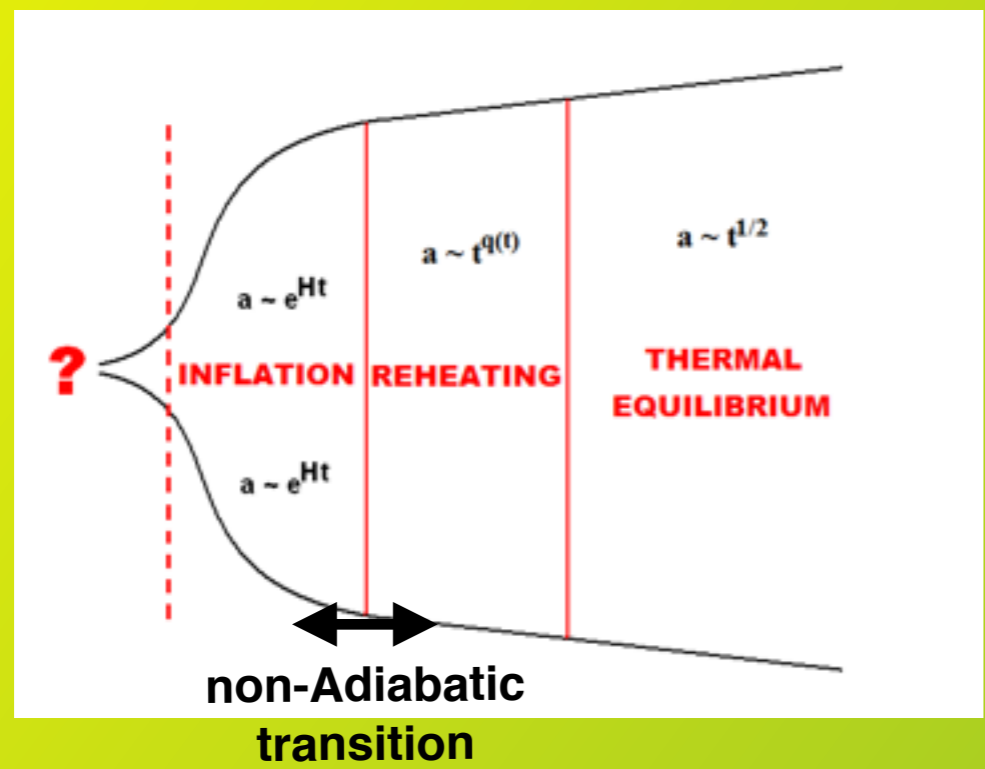
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Equation of State



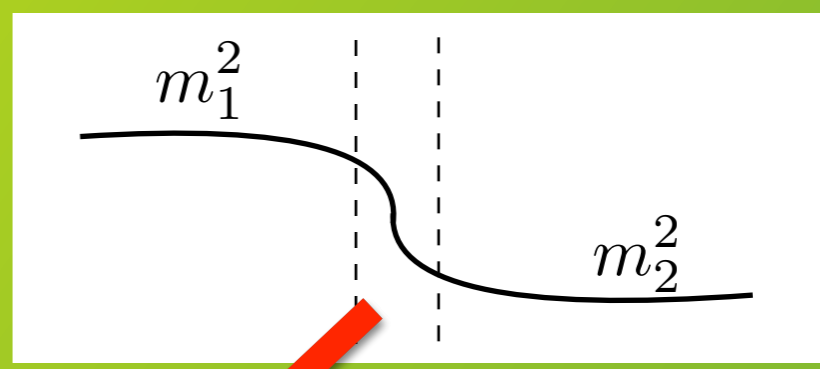
(p)Reheating into the Standard Model
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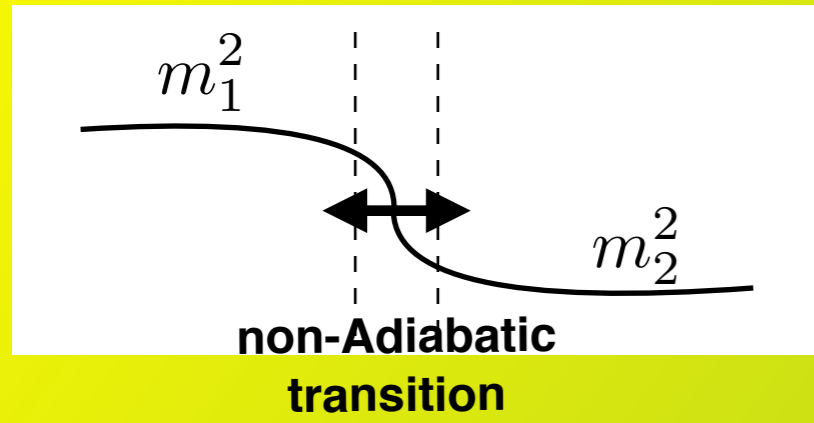
Equation of State



Higgs-Excited !!!

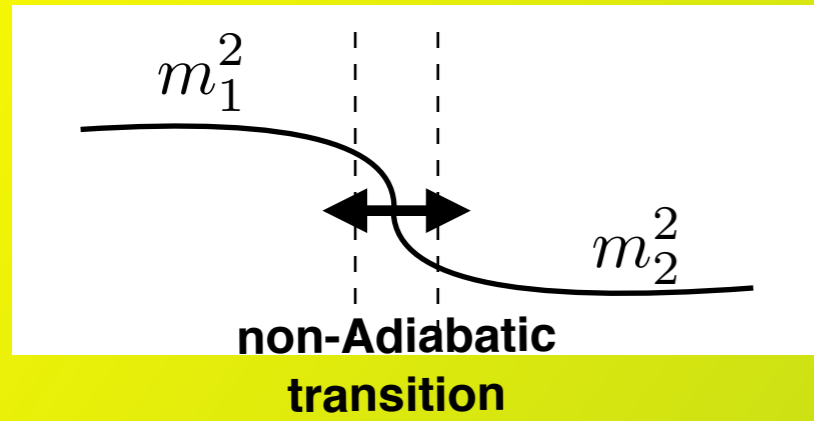


Higgs-Excited !!!



Higgs-Excitation !!!

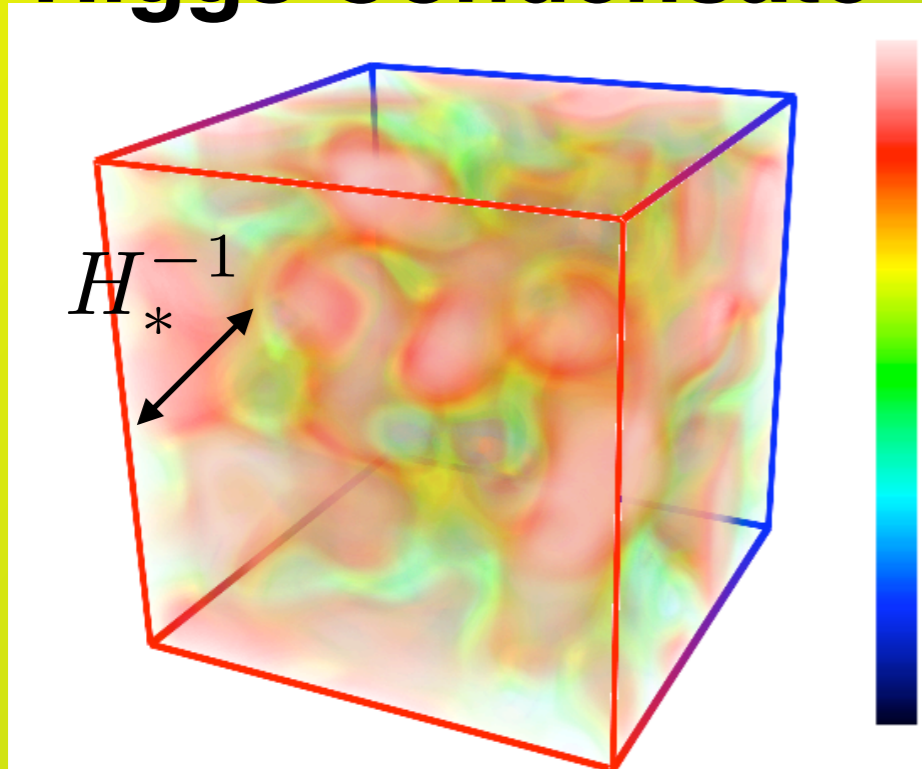
$$\langle \varphi^2 \rangle = \mathcal{O}(10^{-3}) \left(1 - \frac{m_1}{m_2} \right)^2 \frac{H_*^2}{\sqrt{\xi}}$$



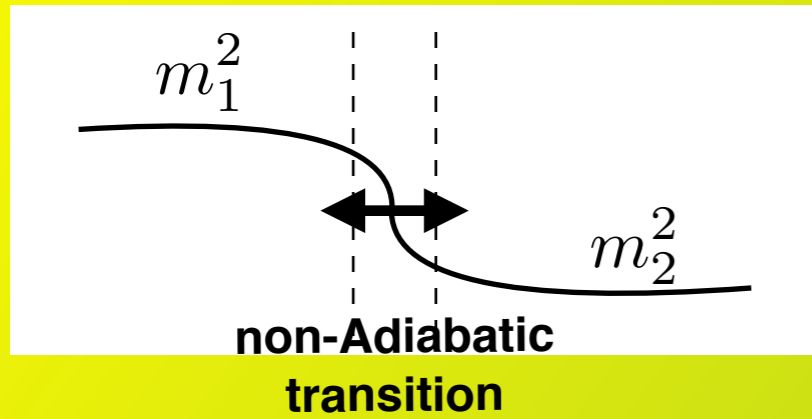
Higgs-Excitation !!!

$$\langle \varphi^2 \rangle = \mathcal{O}(10^{-3}) \left(1 - \frac{m_1}{m_2} \right)^2 \frac{H_*^2}{\sqrt{\xi}}$$

Higgs Condensate



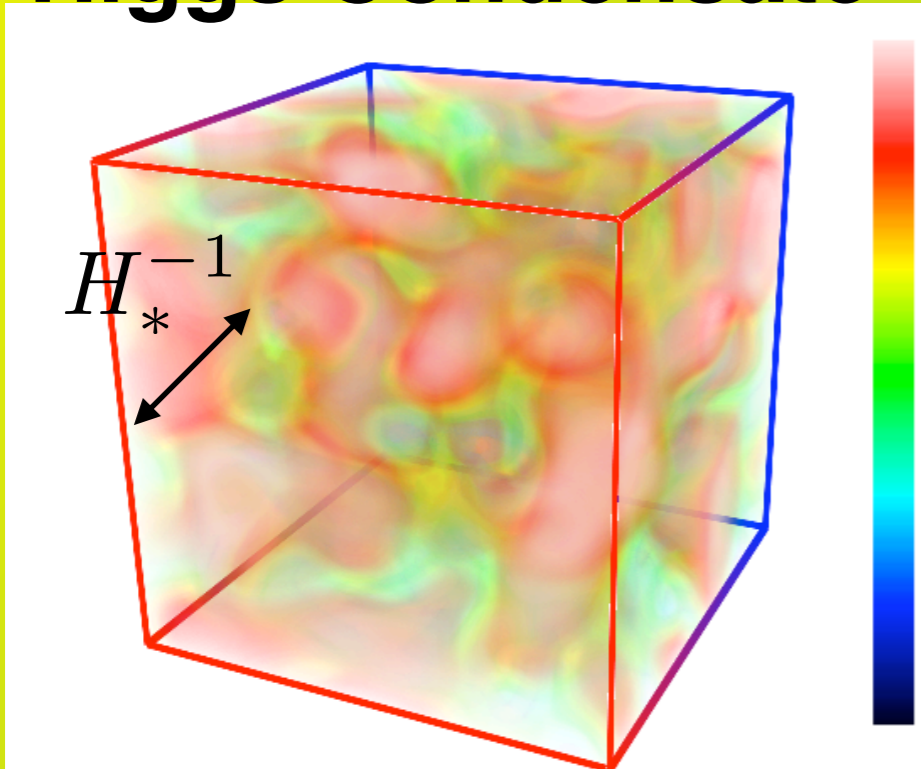
$$\frac{\lambda}{4} (|\varphi|^2 - v^2)^2 + \frac{\xi}{2} R |\varphi|^2$$



Higgs-Excitation !!!

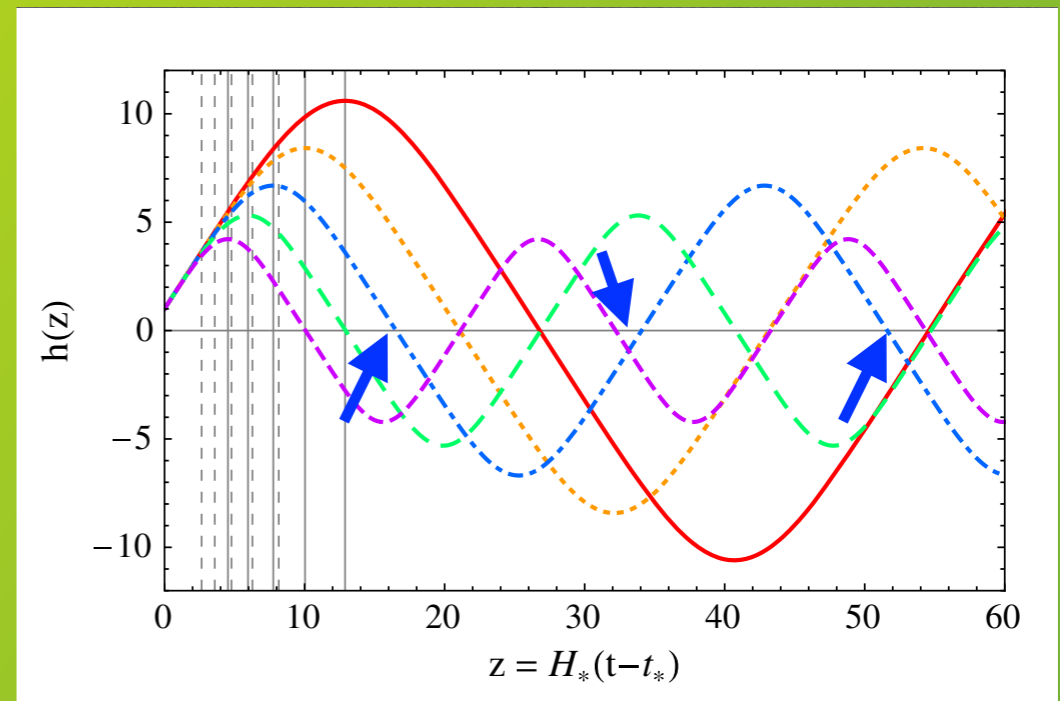
$$\langle \varphi^2 \rangle = \mathcal{O}(10^{-3}) \left(1 - \frac{m_1}{m_2} \right)^2 \frac{H_*^2}{\sqrt{\xi}}$$

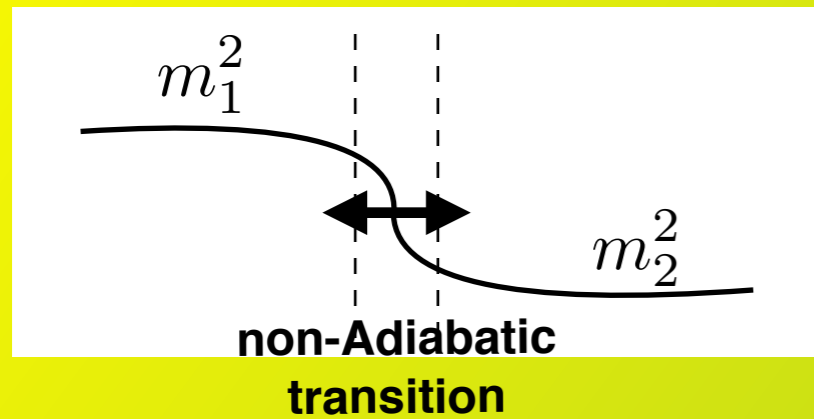
Higgs Condensate



$$\frac{\lambda}{4} (|\varphi|^2 - v^2)^2 + \frac{\xi}{2} R |\varphi|^2$$

Higgs Condensate Oscillates!

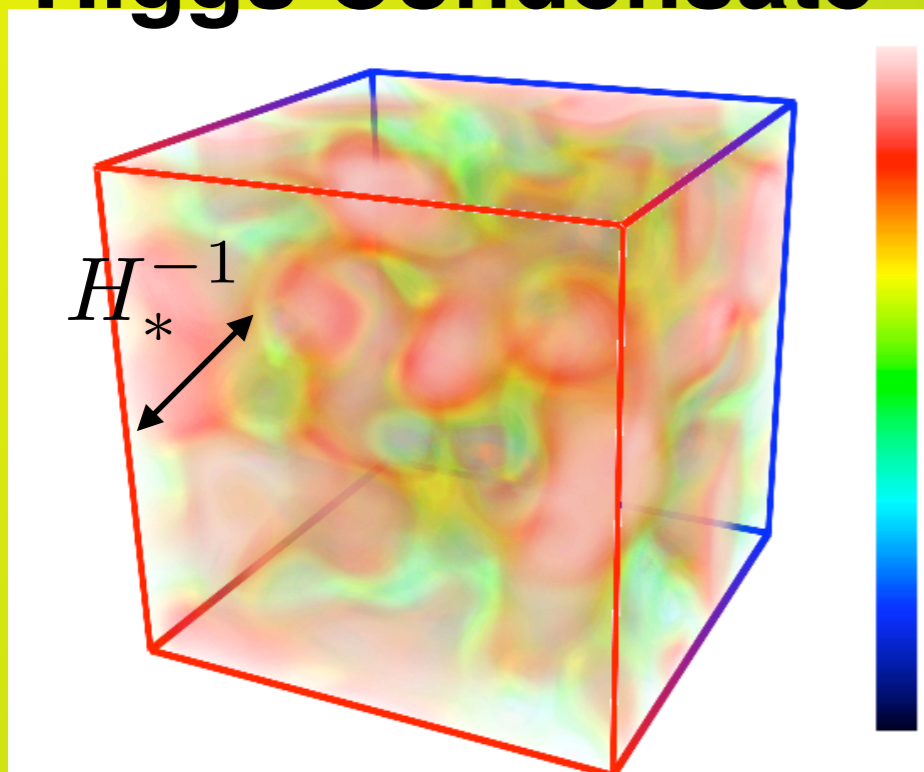




Higgs-Excitation !!!

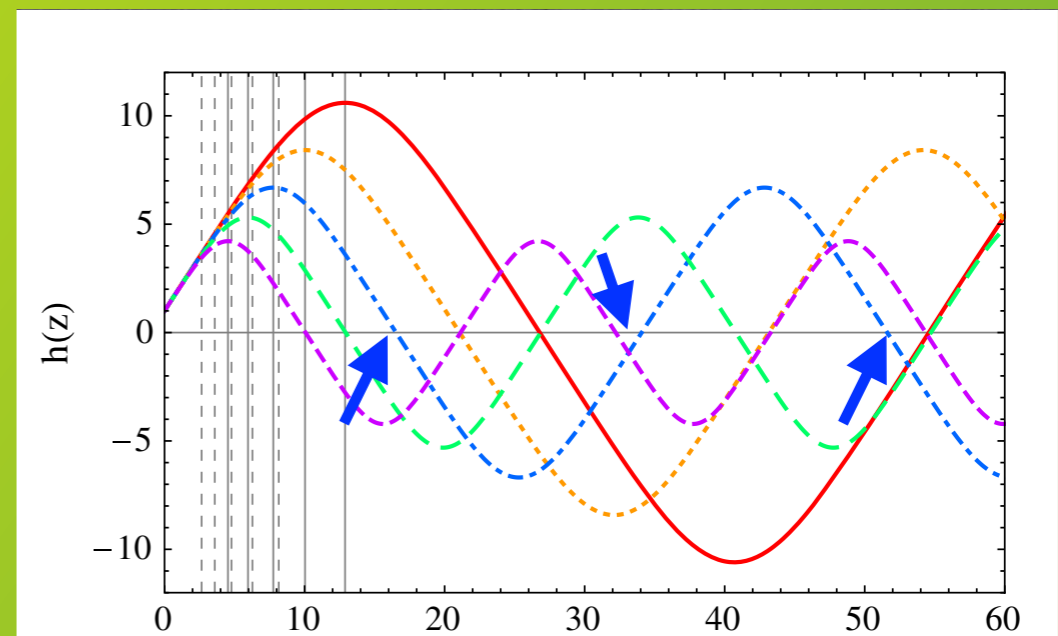
$$\langle \varphi^2 \rangle = \mathcal{O}(10^{-3}) \left(1 - \frac{m_1}{m_2} \right)^2 \frac{H_*^2}{\sqrt{\xi}}$$

Higgs Condensate



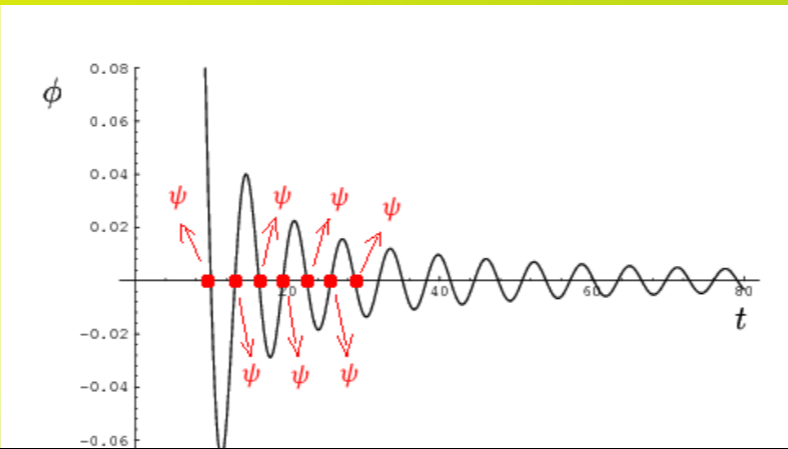
$$\frac{\lambda}{4} (|\varphi|^2 - v^2)^2 + \frac{\xi}{2} R |\varphi|^2$$

Higgs Condensate Oscillates!



SM species produced due to non-Perturbative Effects !!!

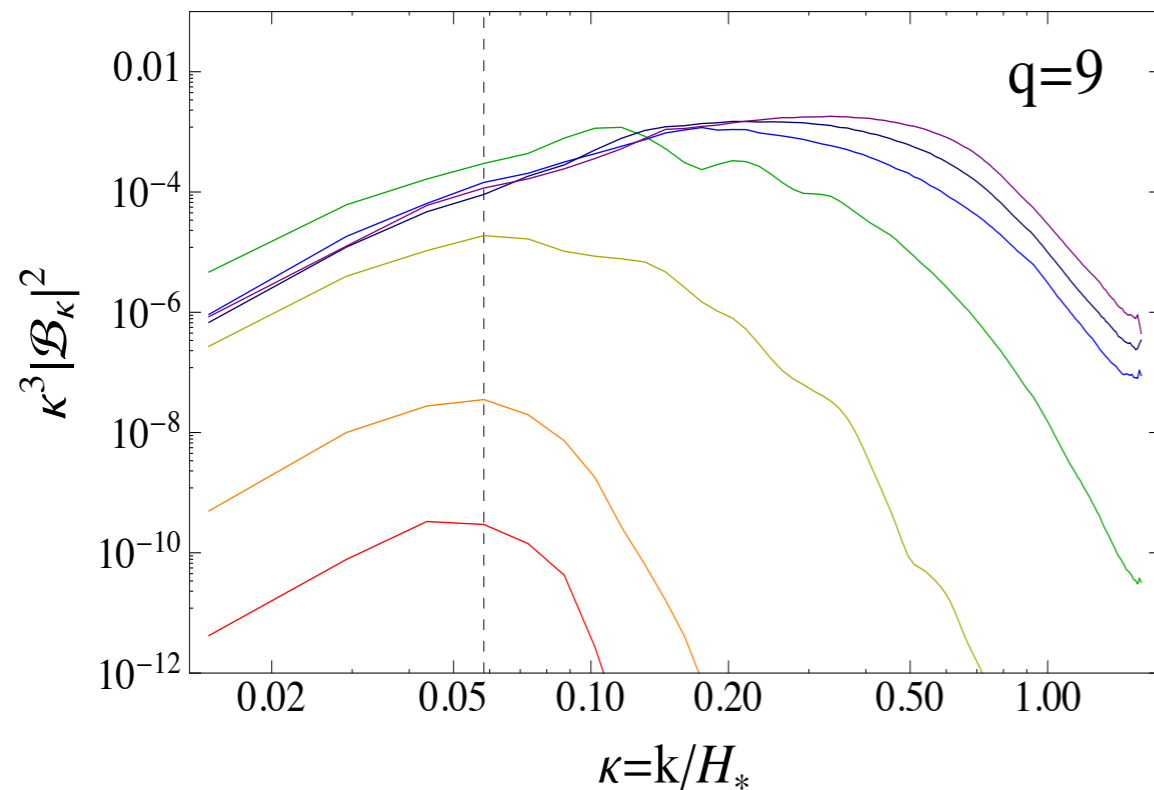
Higgs Condensate Oscillations:



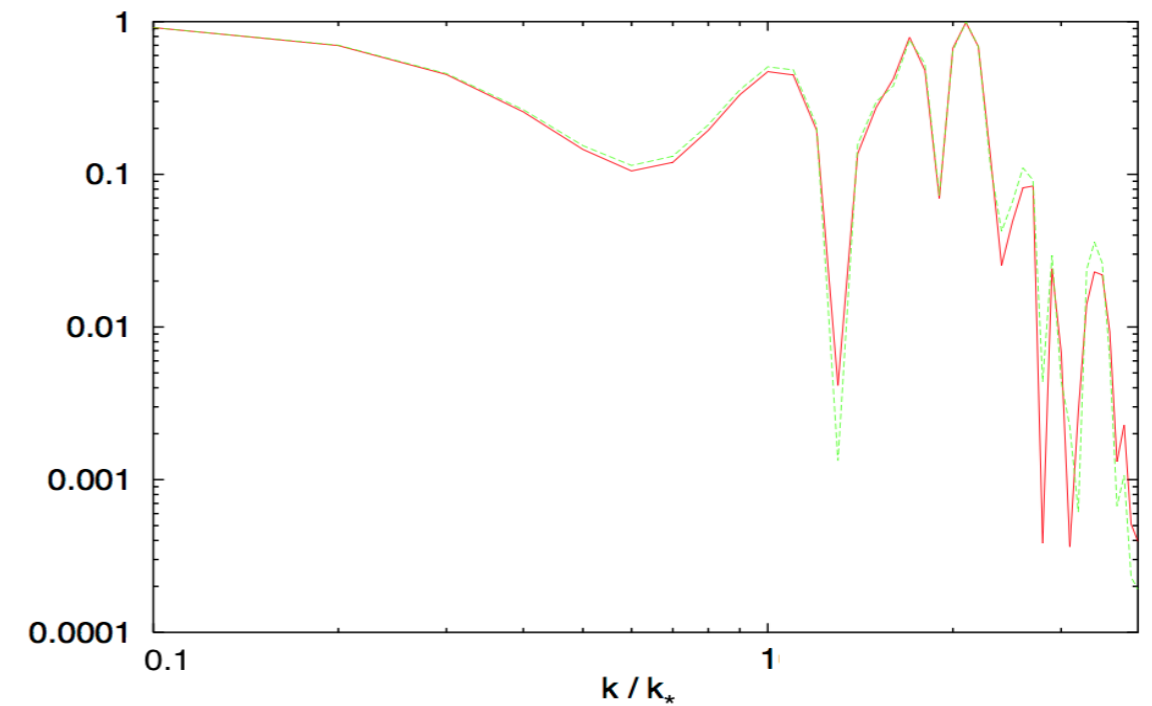
**All SM species
explosively
produced!!!**

Post-Inflationary production of SM species

Gauge Bosons



Fermions

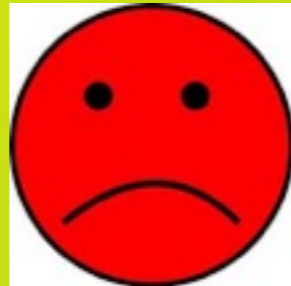


(Enqvist, Nurmi, Meriniemi 2013
+ Rusak 2014, + Weir 2015
DGF, Torrenti, Garcia-Bellido 2015)

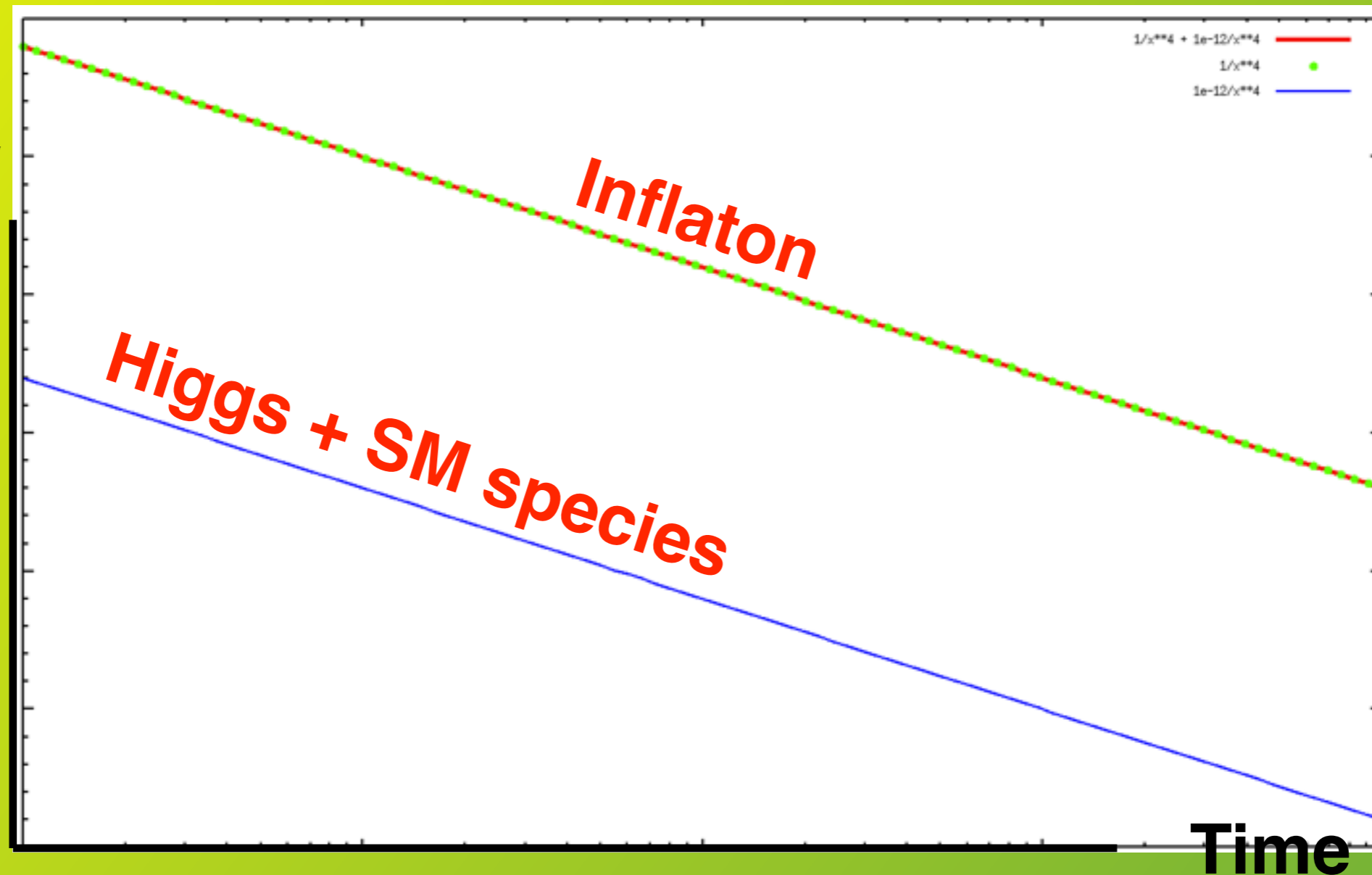
DGF 2014

$$\text{Initially : } \langle \lambda \varphi_*^4 \rangle \ll H_*^2 m_p^2$$

**SM produced!
but subdominant**



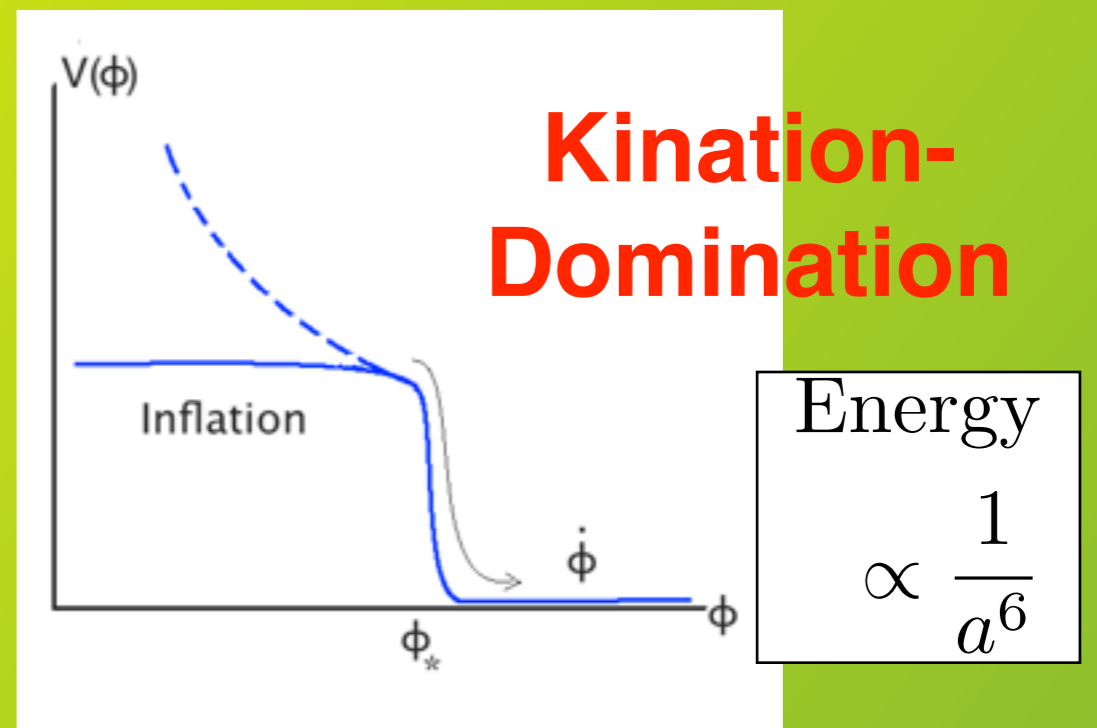
Energy



Time

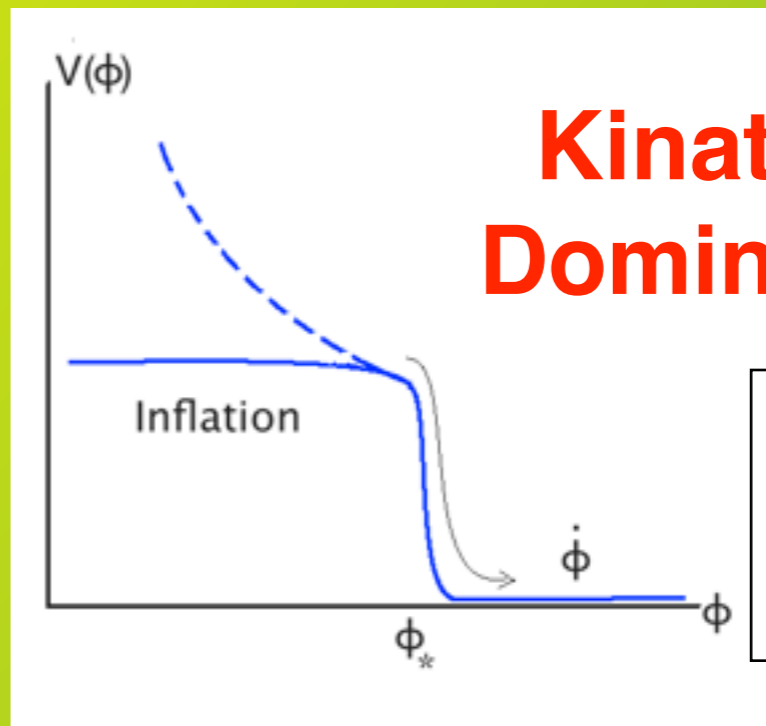
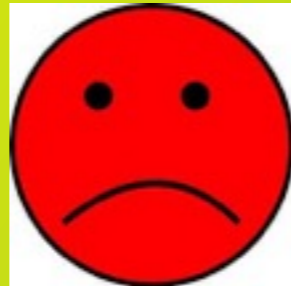
$$\text{Initially : } \langle \lambda \varphi_*^4 \rangle \ll H_*^2 m_p^2$$

**SM produced!
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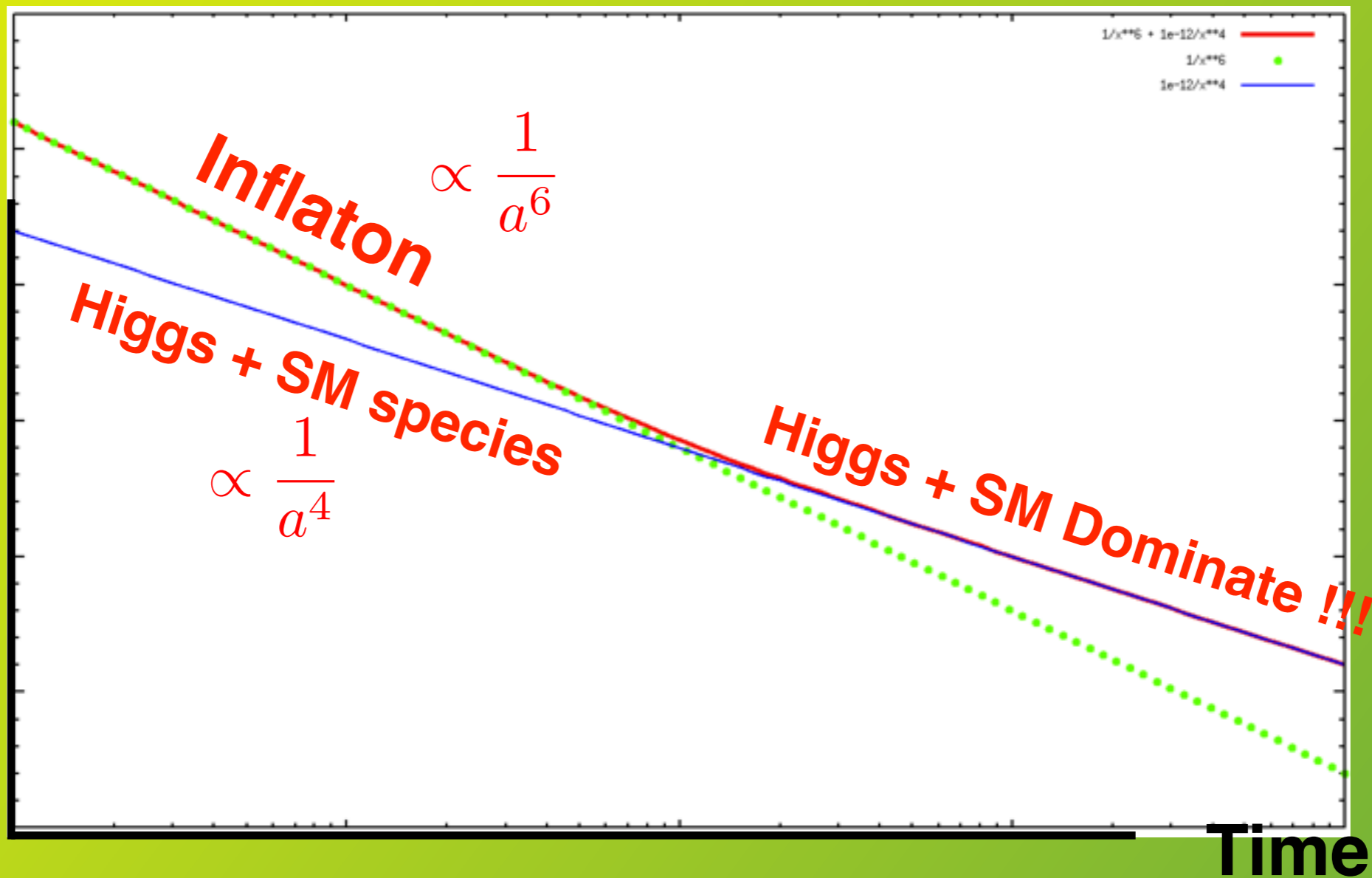


Initially : $\langle \lambda \phi_*^4 \rangle \ll H_*^2 m_p^2$

**SM produced!
but subdominant**



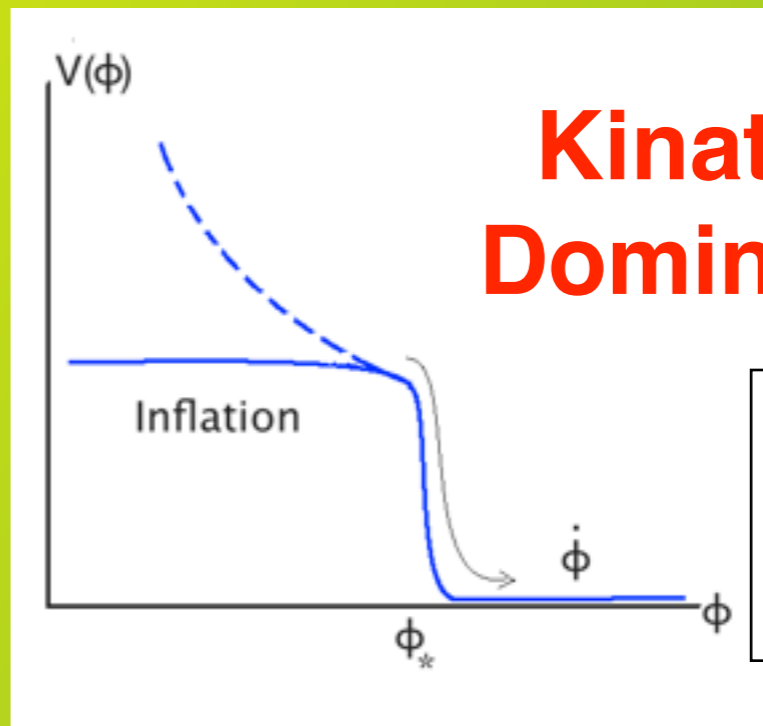
Energy



Time

Initially : $\langle \lambda \phi_*^4 \rangle \ll H_*^2 m_p^2$

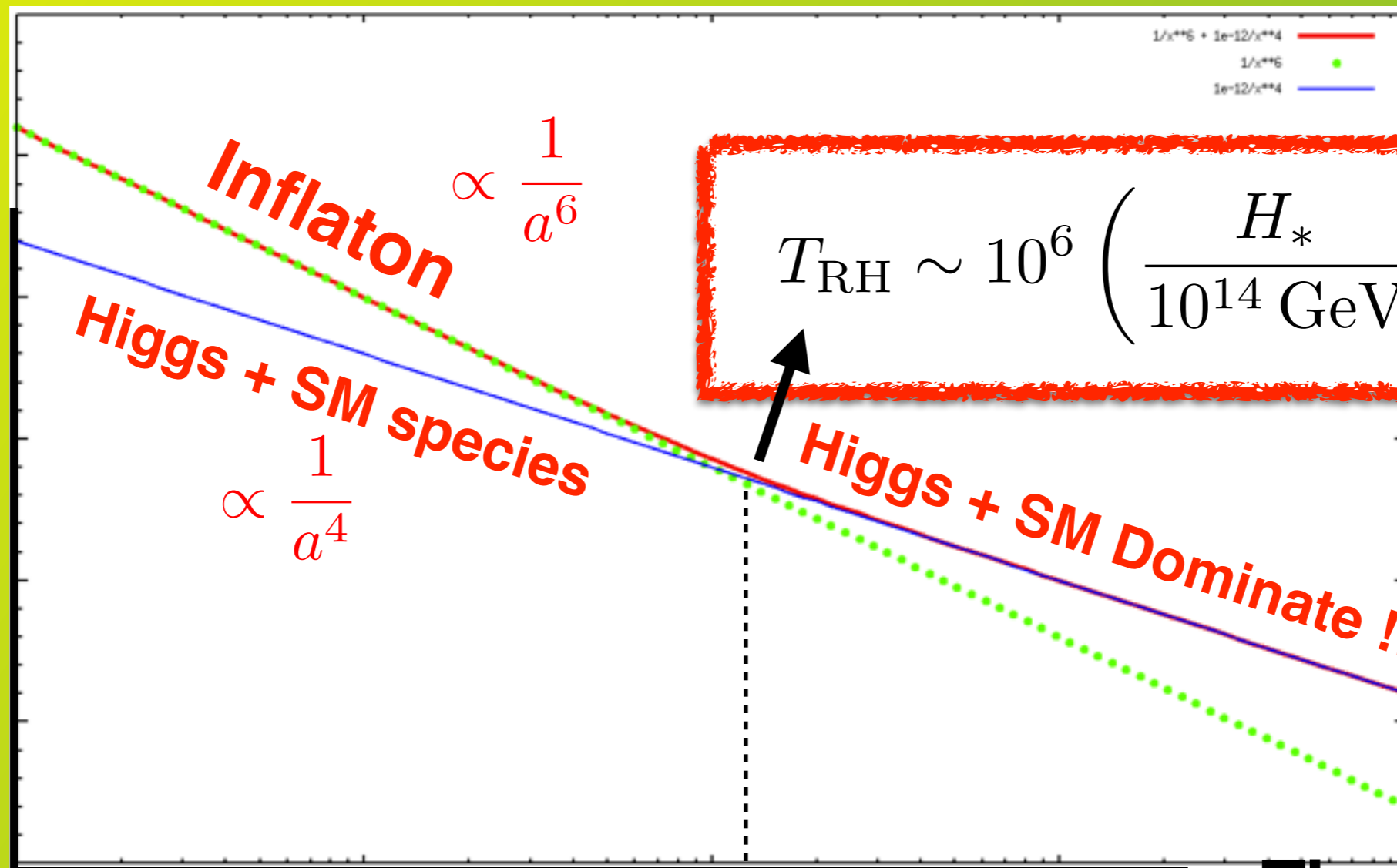
**SM produced!
and dominates**



**Kination-
Domination**

Energy
 $\propto \frac{1}{a^6}$

Energy



$T_{RH} \sim 10^6 \left(\frac{H_*}{10^{14} \text{ GeV}} \right)^2 \text{ GeV}$

Time

If there is Kination-Domination ...

Consequences:

1) Reheating the Universe



2) GW from Higgs decay products

3) Inflationary GW - blue tilted !

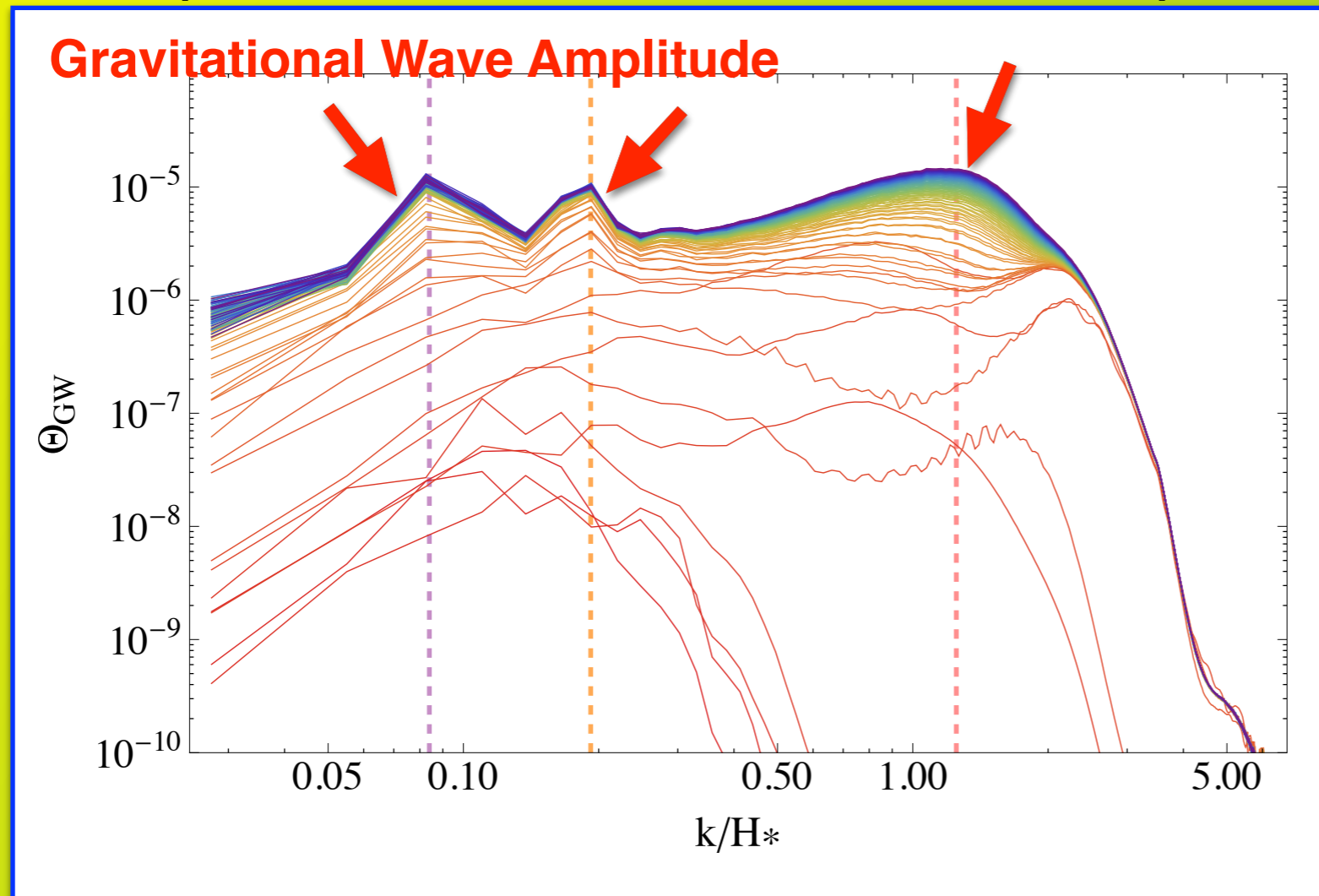
Gravitational Waves from Higgs decay Products

Explosive Particle Production !

(DGF, J. García-Bellido, Torrenti 2015)



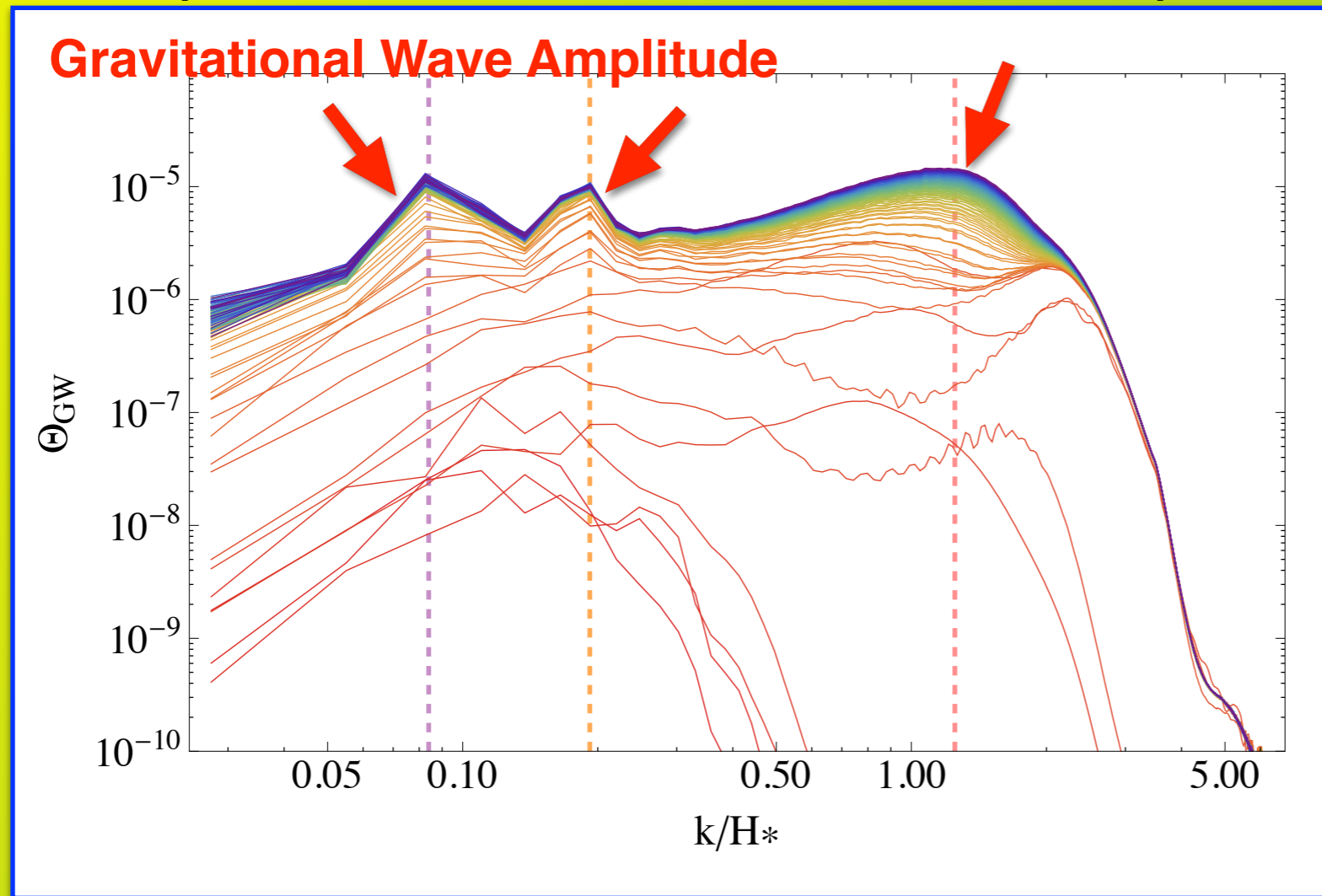
Gravitational Wave Generation



$$\text{GW Today : } h^2 \Omega_{\text{GW}}^{(p)}|_t \sim 10^{-32} \left(\frac{0.01}{\lambda}\right)^{\frac{3}{2}} \left(\frac{H_*}{H_*^<}\right)^4 \left(\frac{a_{\text{RD}}}{a_*}\right)^{|3w-1|} \sim ?$$

Gravitational Waves from Higgs decay Products

(DGF, J. García-Bellido, Torrenti 2015)



Explosive Particle Production !



Gravitational Wave Generation



**NO
OBSERVABLE !!**

$$\text{GW Today : } h^2 \Omega_{\text{GW}}^{(p)}|_t \sim 10^{-32} \underbrace{\left(\frac{0.01}{\lambda}\right)^{\frac{3}{2}}}_{\text{Running Self-Coupling}} \underbrace{\left(\frac{H_*}{H_*^<}}_{\text{Hubble Rate}}\right)^4 \underbrace{\left(\frac{a_{\text{RD}}}{a_*}\right)^{|3w-1|}}_{\text{Equation of State}} \sim 10^{-20}$$

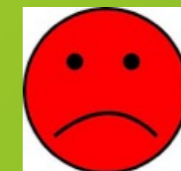
If there is Kination-Domination ...

Consequences:

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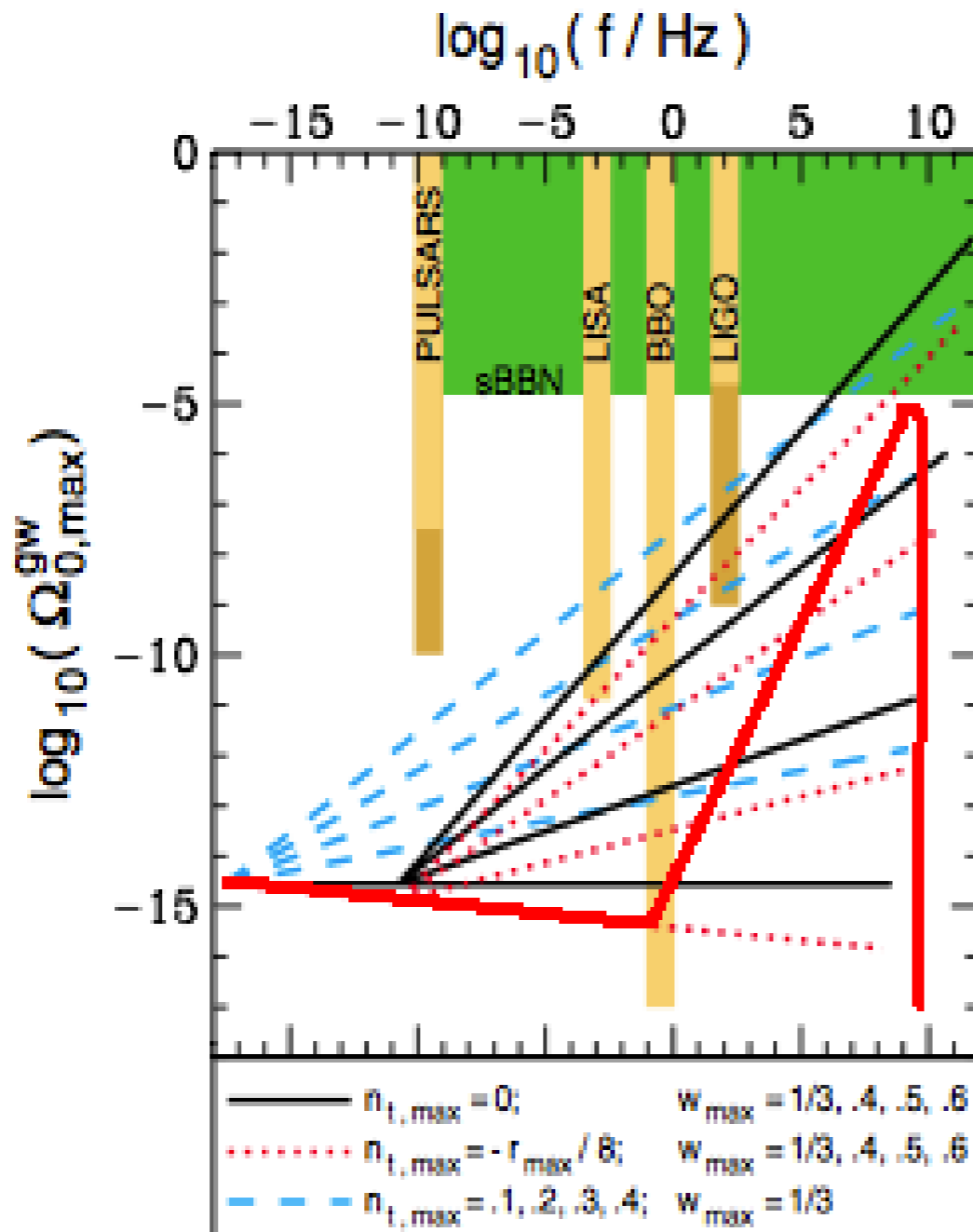


3) Inflationary GW - blue tilted !

Gravitational Waves from Inflation

Kination
Domination

(DGF, J. García-Bellido, Torrenti 2015)



Boyle and Buonanno 2007

High-Freq. Tail
Inflationary
Gravitational Wave
Background
Uplifted

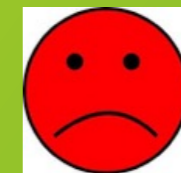
If there is Kination-Domination ...

Consequences:

1) Reheating the Universe



2) GW from Higgs decay products



3) Inflationary GW - blue tilted !



Summary:

*** Universal Mechanism to produce the SM !!!**

*** SM subdominant → irrelevant?
(baryogenesis, magnetogenesis, DM ???)**

*** If Kination-Domination: SM species dominate!
(eventually)**

Reheating the Universe into the SM!!!

+ Observable blue-shift Inflationary-GW