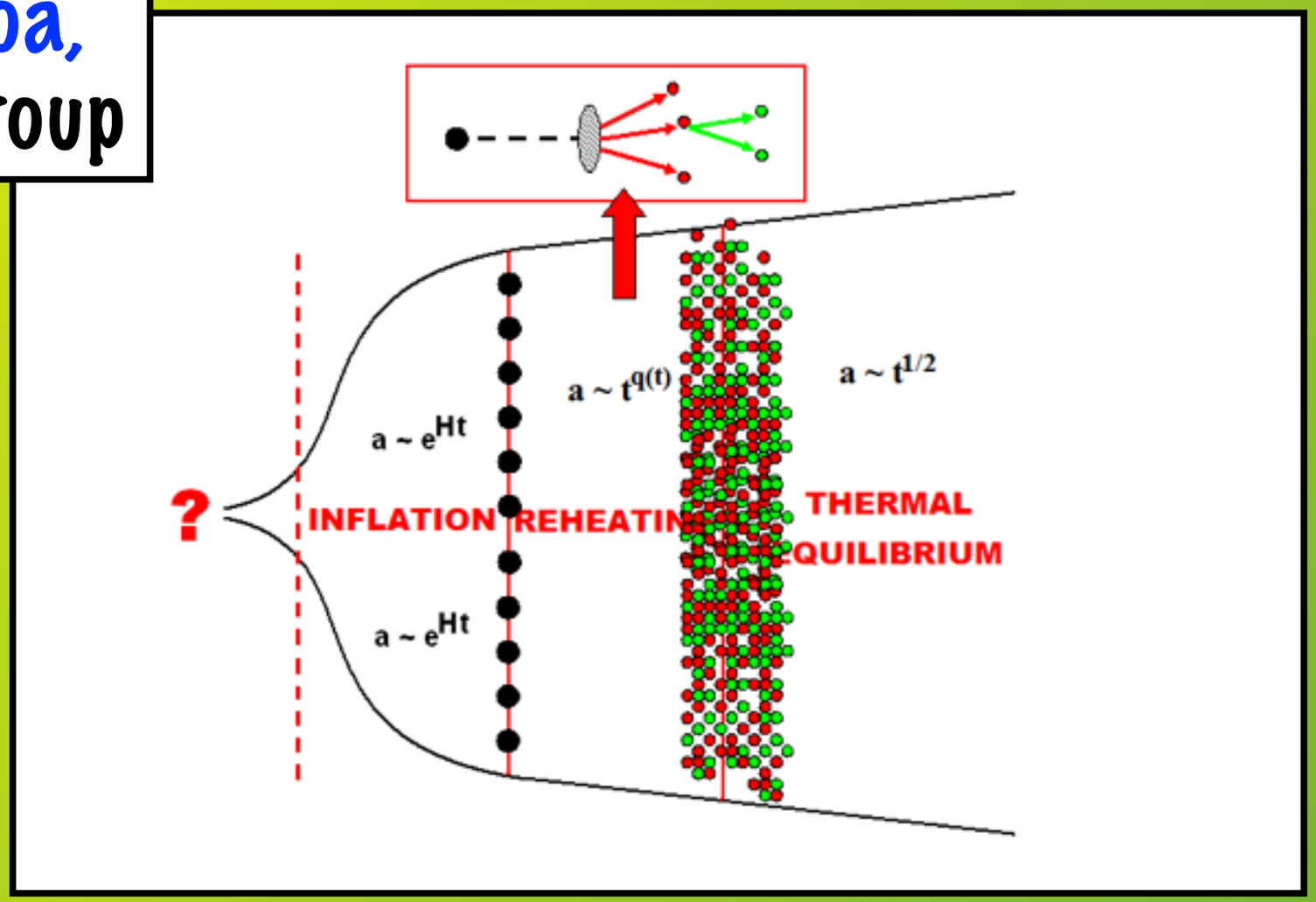
The SM HiGGS as the origin of the 'hot BiG BANG'

Daniel G. Figueroa,
CERN, Theory Group



The Big Bang and the little bangs 2016, CERN

CERN CINECLUB

Tonight 8:00pm,

@ Council Chamber
(Here!)

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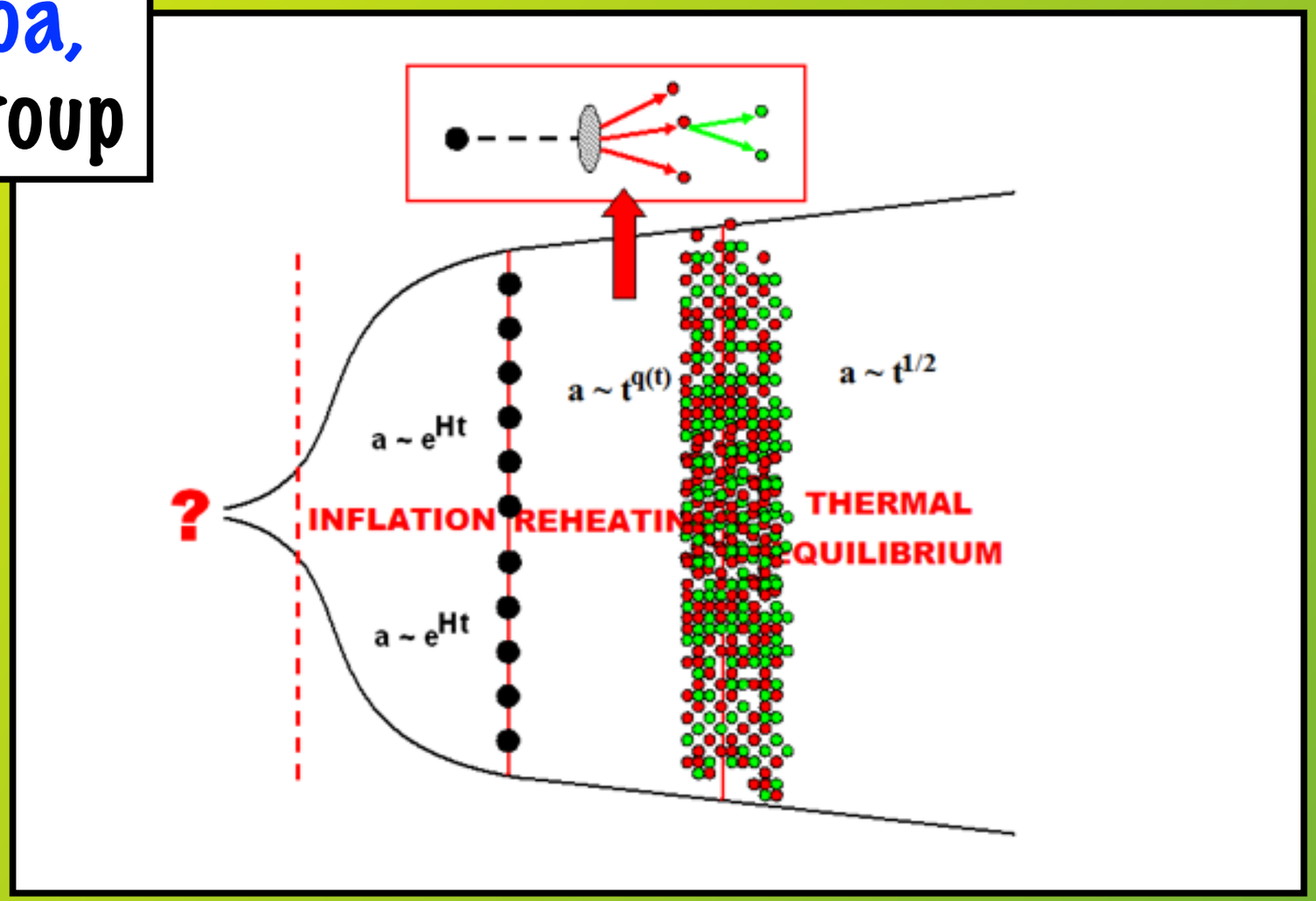
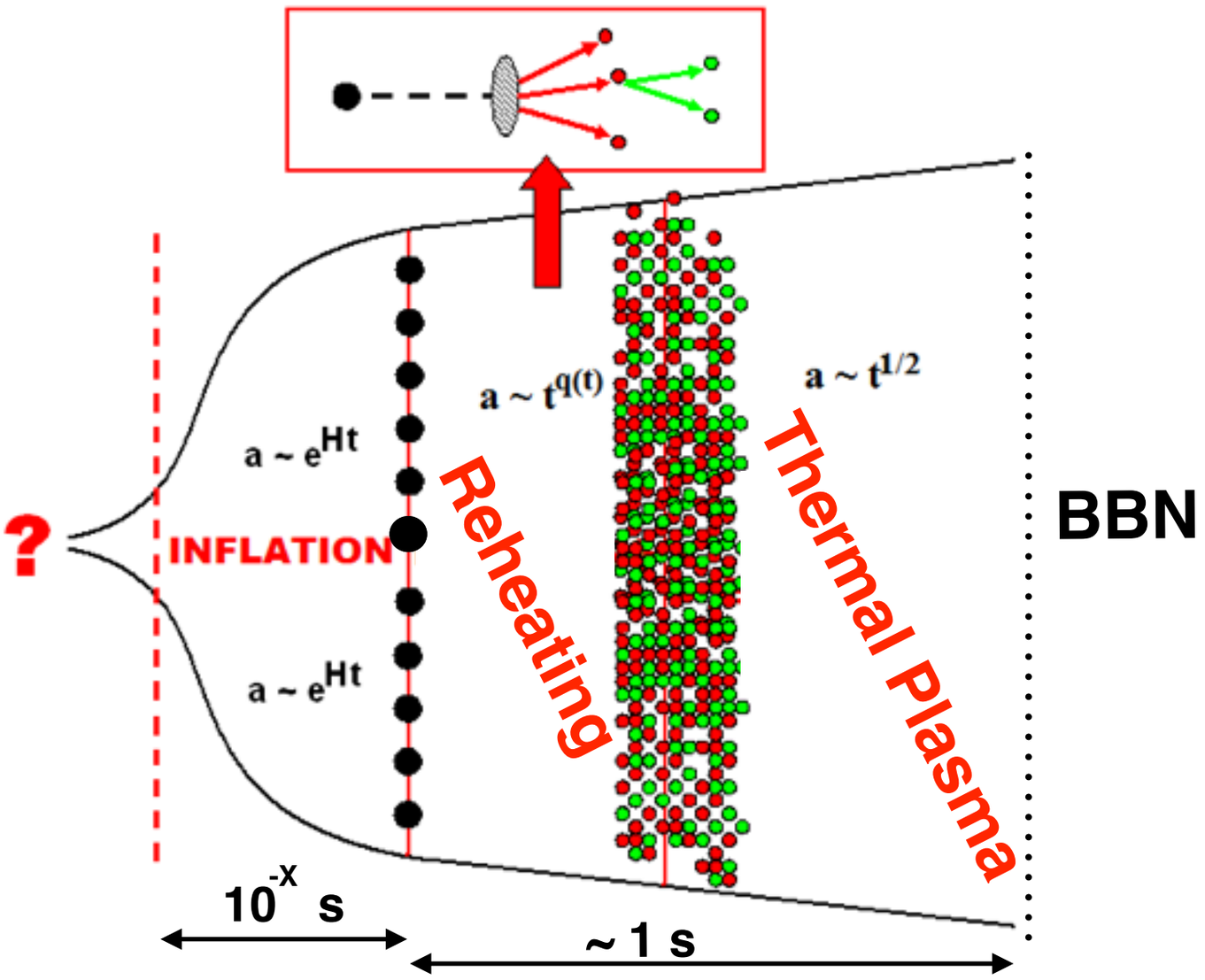


The Big Bang and the little bangs 2016, CERN

The Problem: **(p)Reheating into a Thermal Plasma** ≡ (Origin of the 'hot Big Bang')



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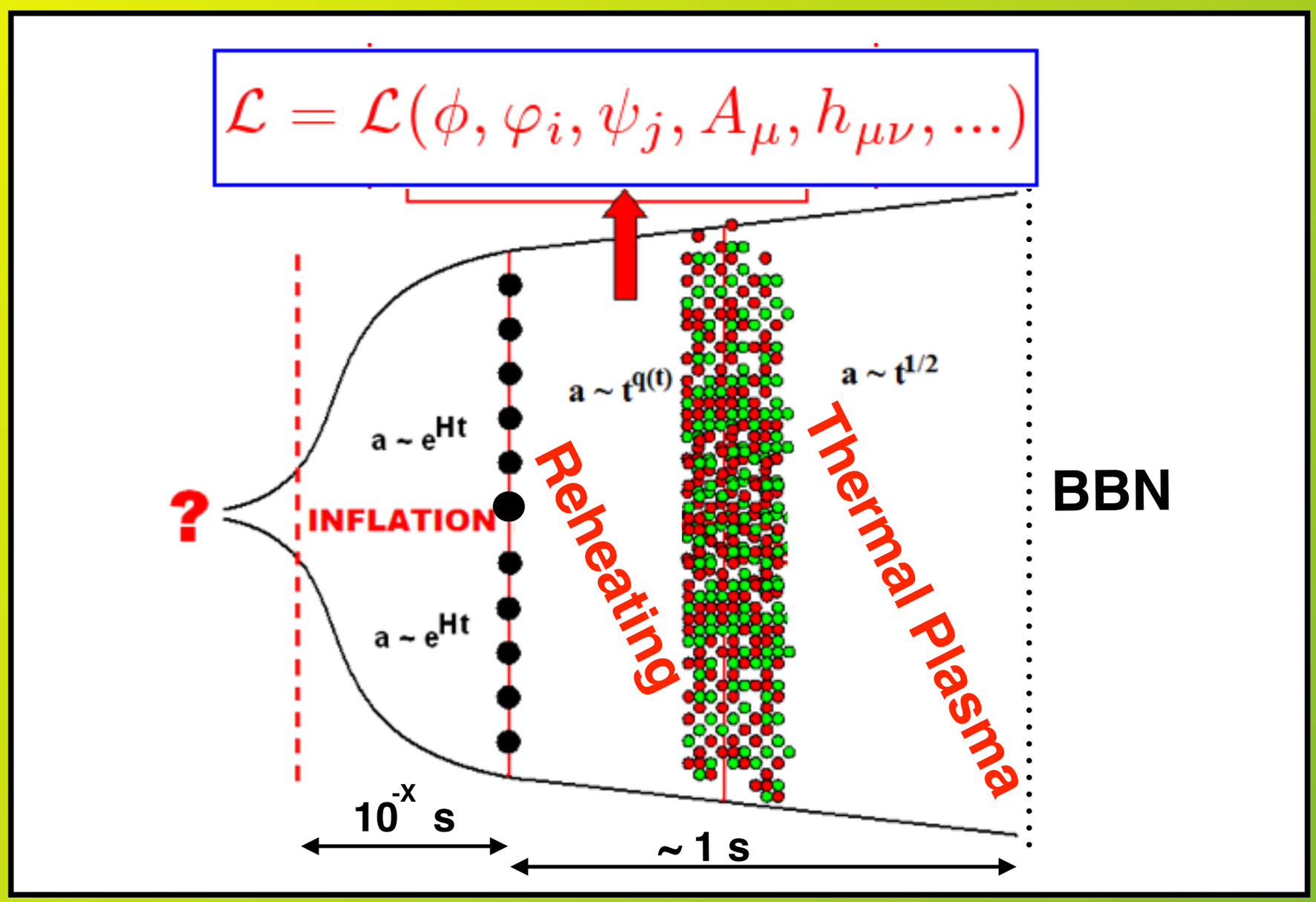
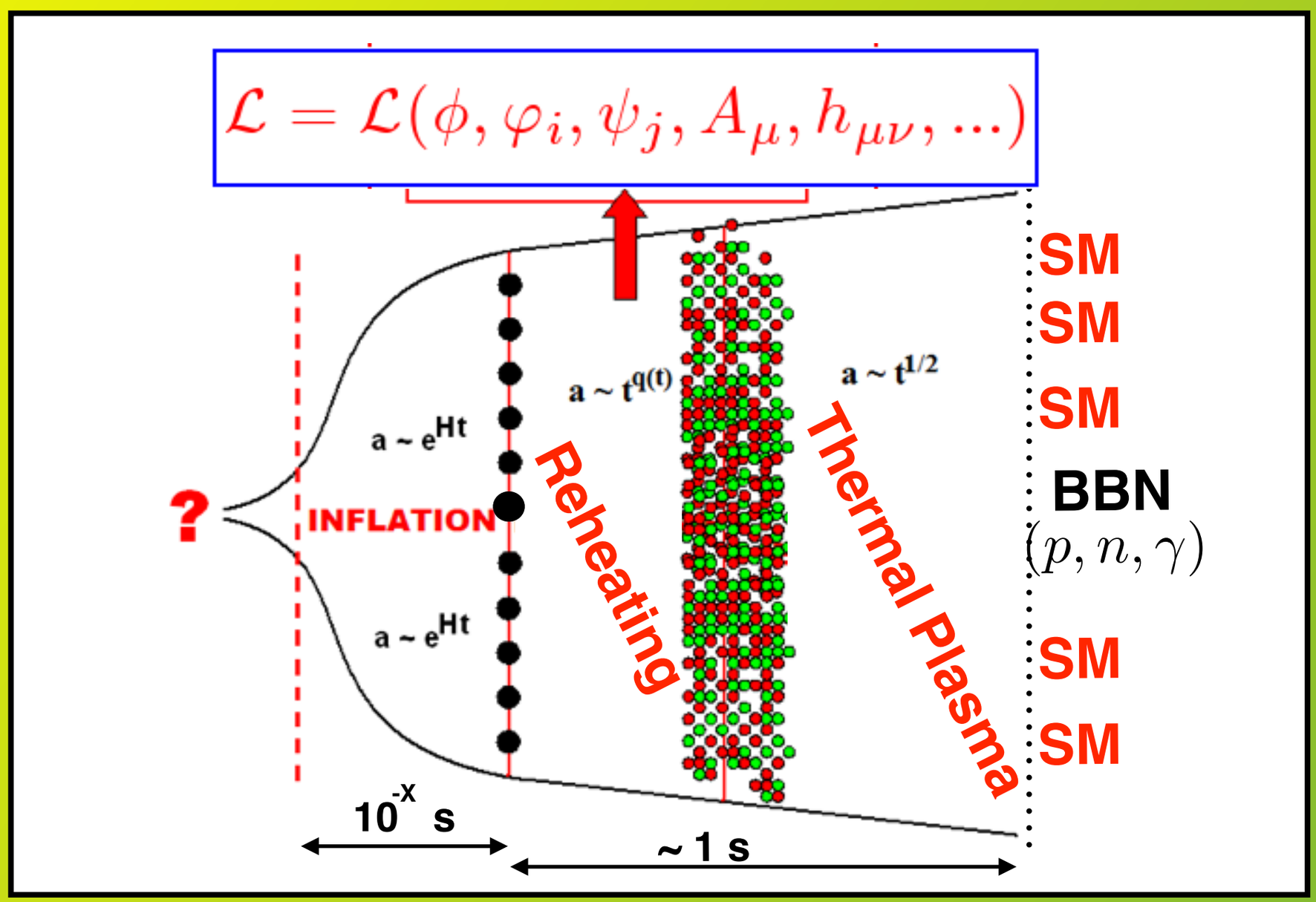


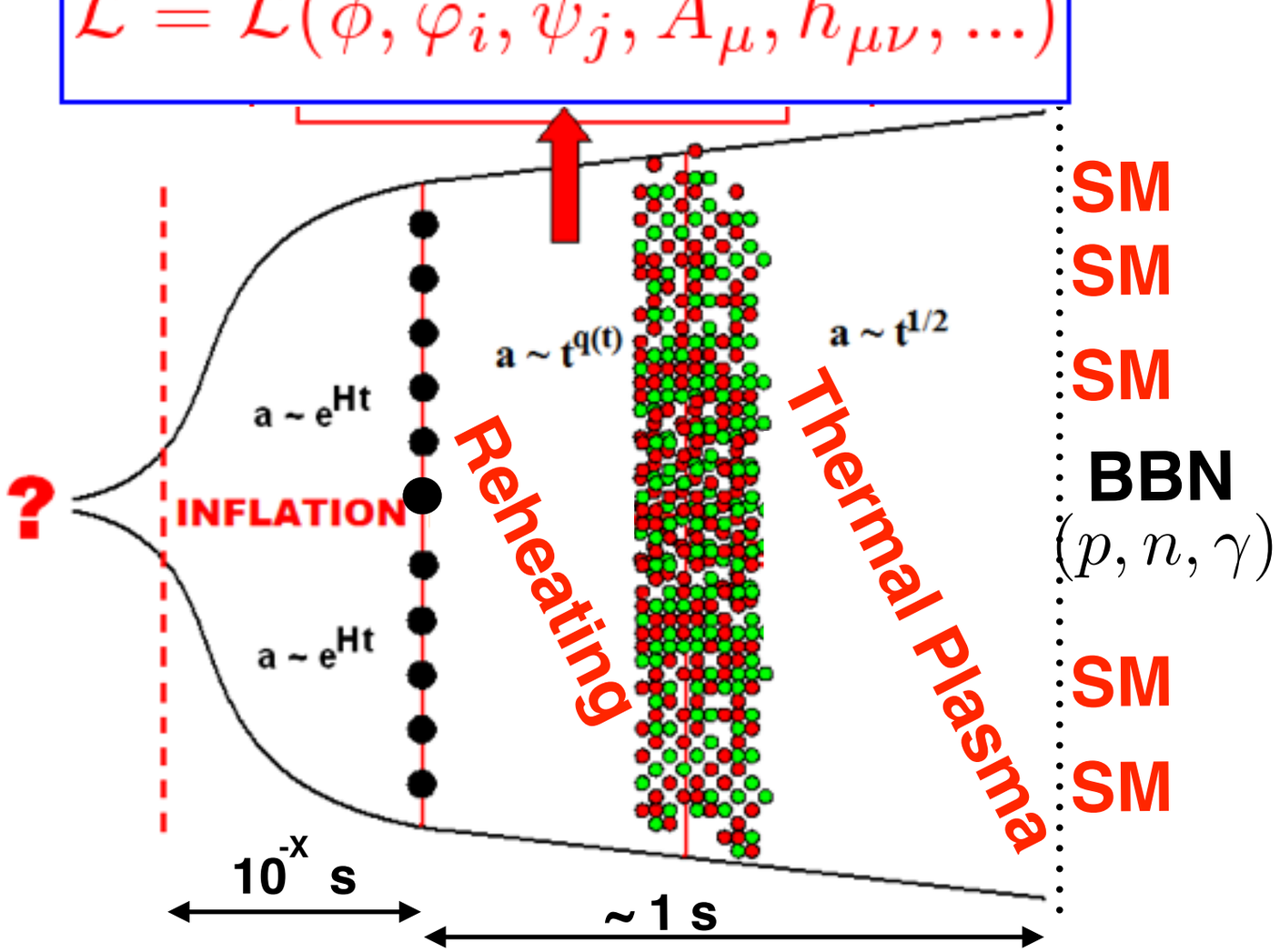
Successful Reheating: (p)Reheating into the Standard Model $\equiv$ (Origin of the 'hot Big Bang')



Successful Reheating:

(p)Reheating into the Standard Model

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



Connection between SM and Inflationary Sector ???

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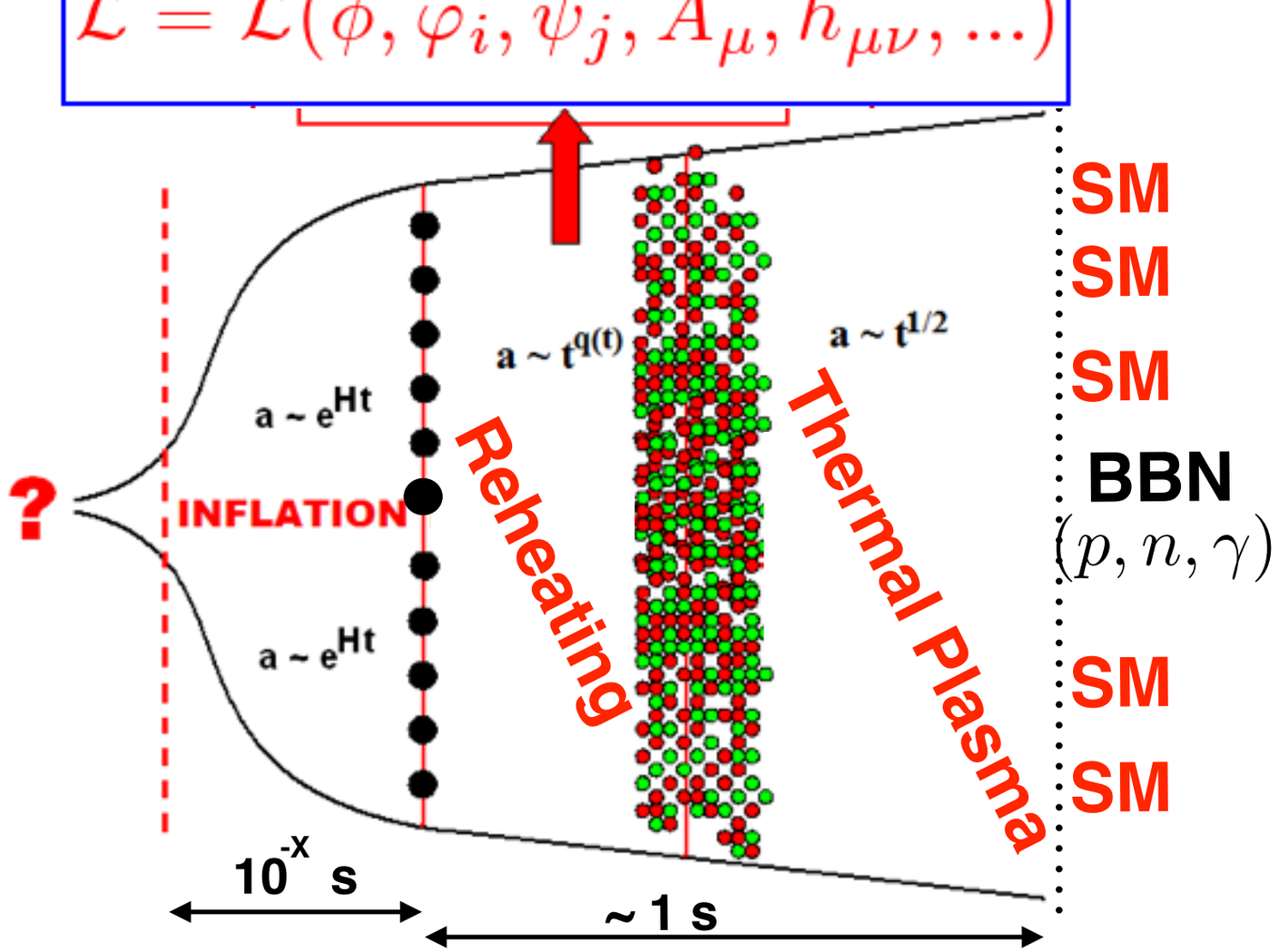

Connection between SM and Inflationary Sector ???

Mediator fields ?

$$g^2\phi^2\chi^2$$

$$+$$

$$h^2\chi^2\mathcal{H}^2$$

Successful Reheating:

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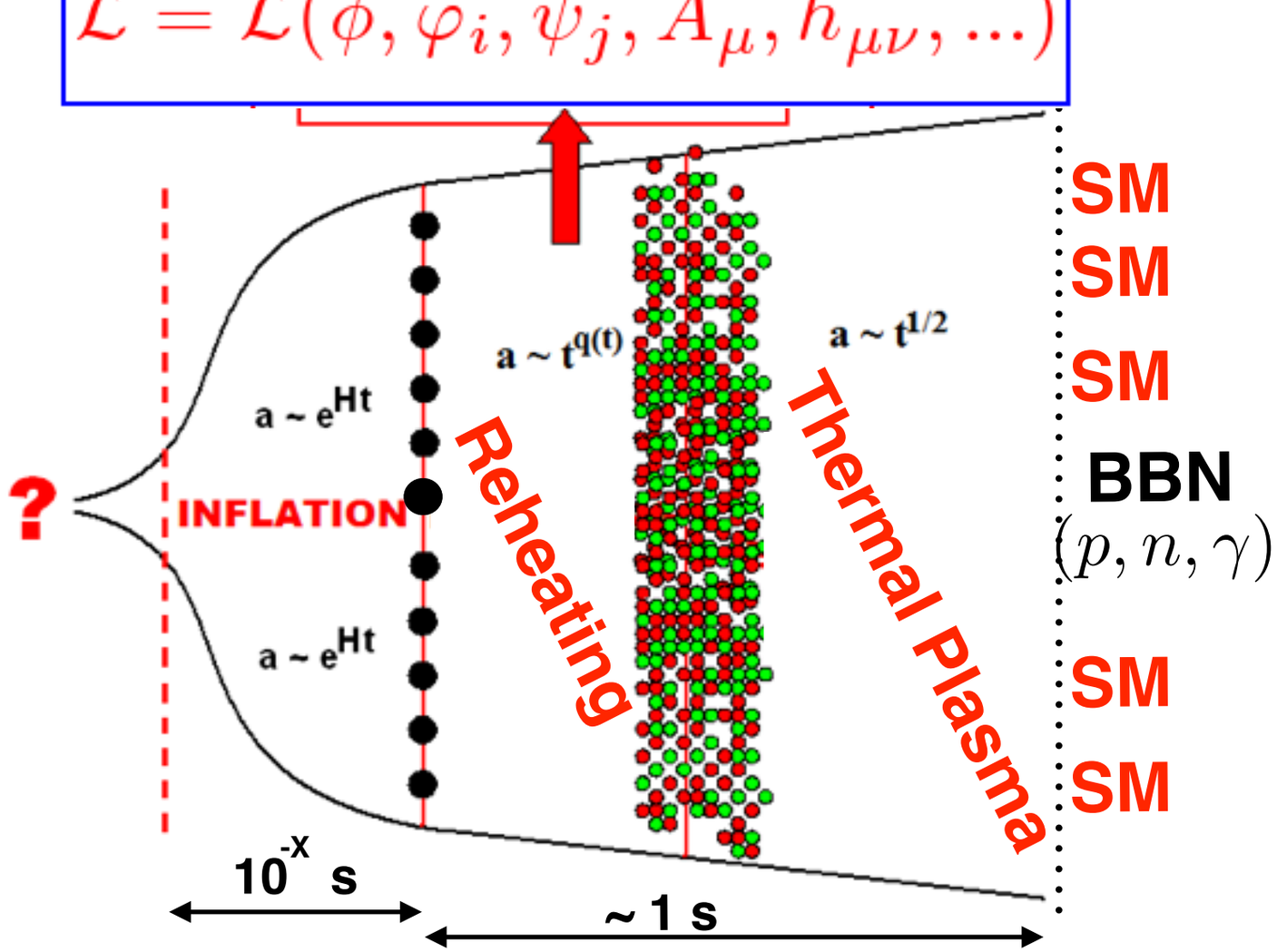

Connection between SM and Inflationary Sector ???

Higgs-Portal ?

$$g^2\phi^2|\mathcal{H}|^2$$

Successful Reheating:

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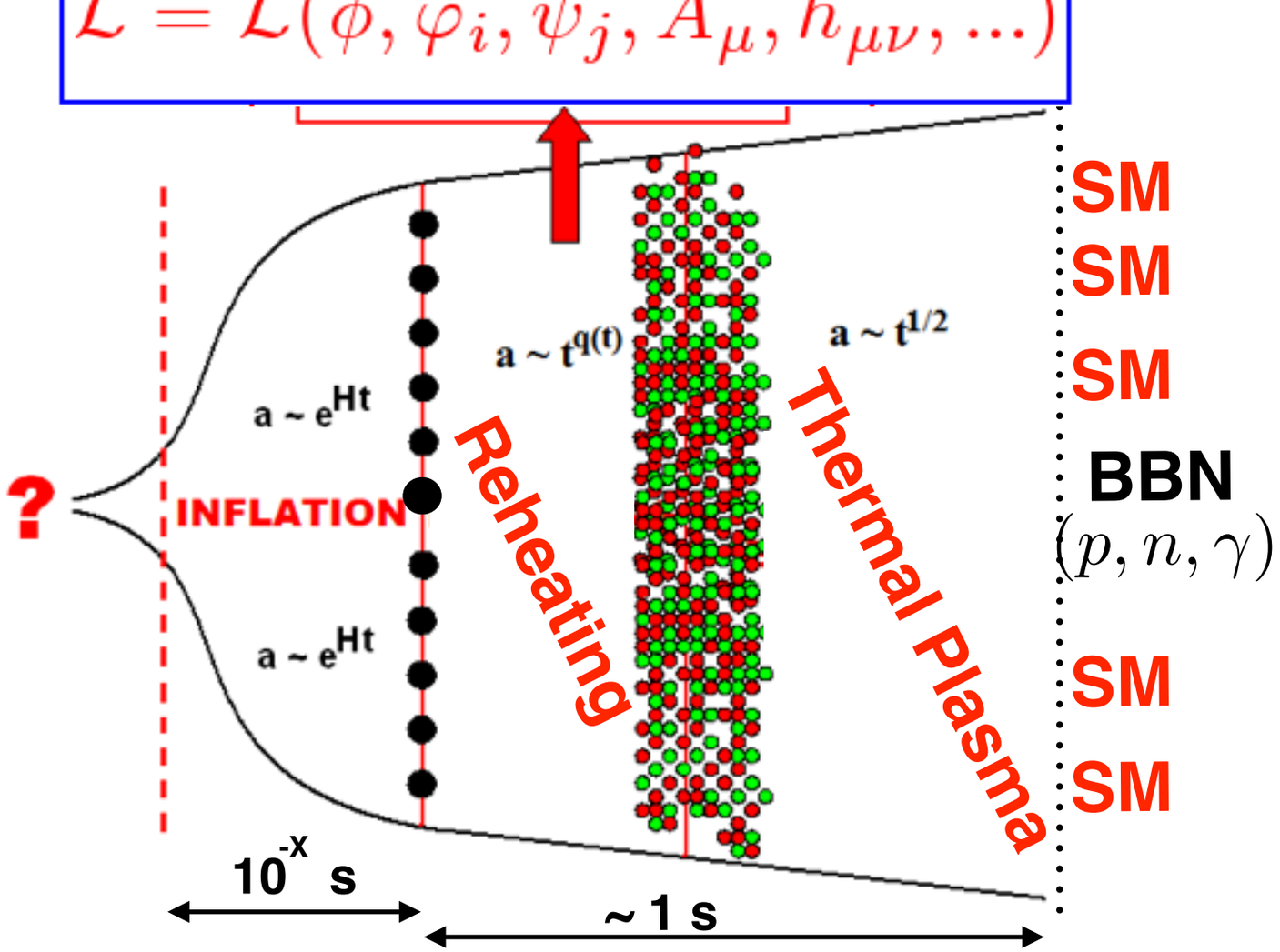

Connection between SM and Inflationary Sector ???

No coupling ?

$$\cancel{g^2 \phi^2 |\mathcal{H}|^2}$$

$$(g^2 \ll 1)$$

Successful Reheating:

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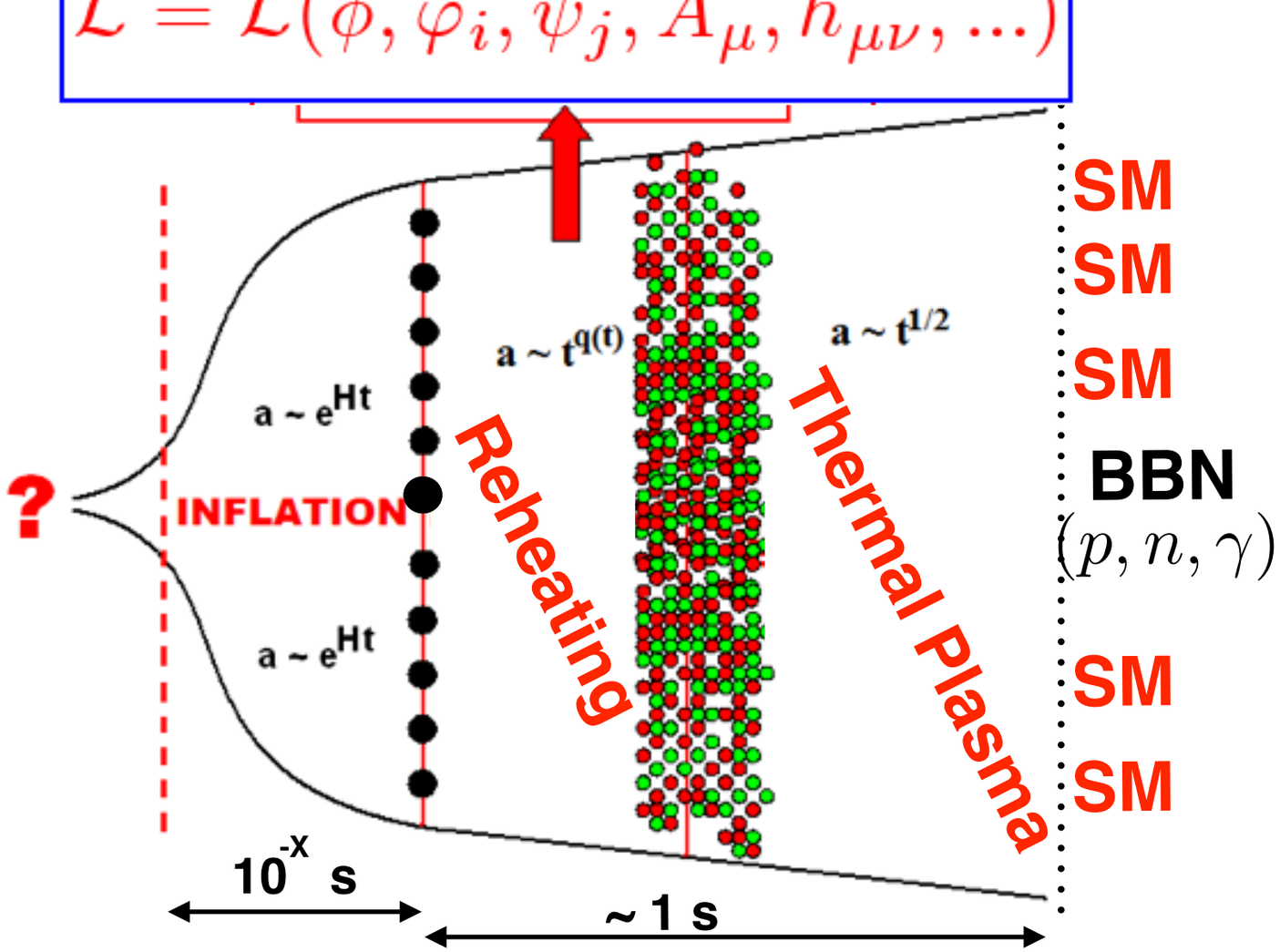

Connection between SM and Inflationary Sector ???

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

(p)Reheating into the Standard Model

During Inflation …

No Coupling to Inflaton

1) LIGHT

$$m_\varphi^2 < H_*^2$$

2) HEAVY

$$m_\varphi^2 > H_*^2$$

(p)Reheating into the Standard Model

(No Coupling to Inflaton)

1) LIGHT → **@ Inflation**

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(p)Reheating into the Standard Model

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

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

(p)Reheating into the Standard Model

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Starobinsky & Yokoyama '94

(p)Reheating into the Standard Model

(No Coupling to Inflaton)

2) HEAVY → **@ Inflation** $m_\varphi^2 > H_*^2$

(p)Reheating into the Standard Model

(No Coupling to Inflaton)

2) HEAVY → **@ Inflation** $\quad m_\varphi^2 > H_*^2$

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

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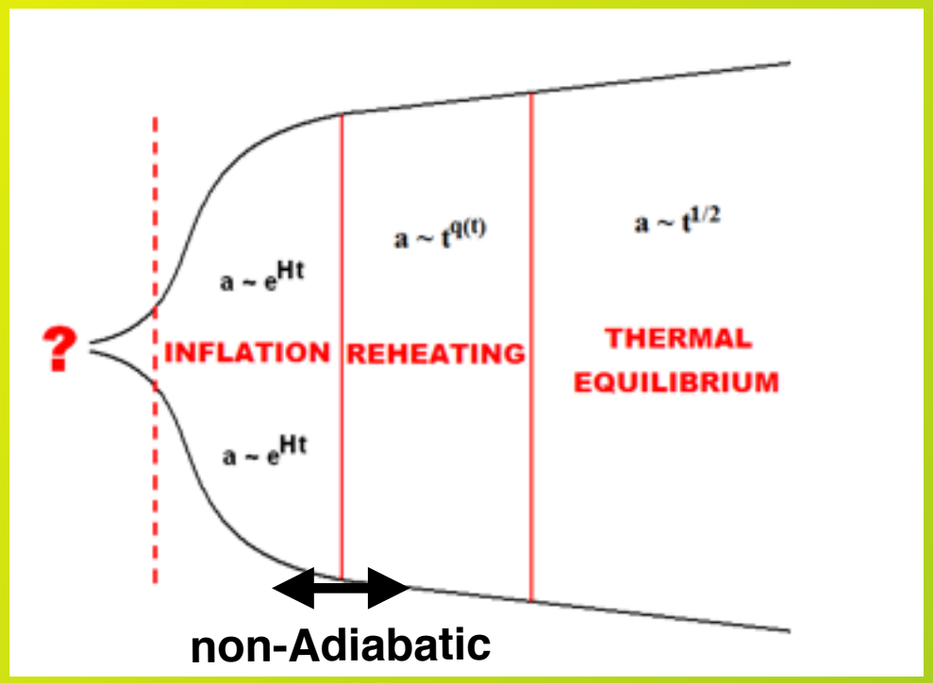
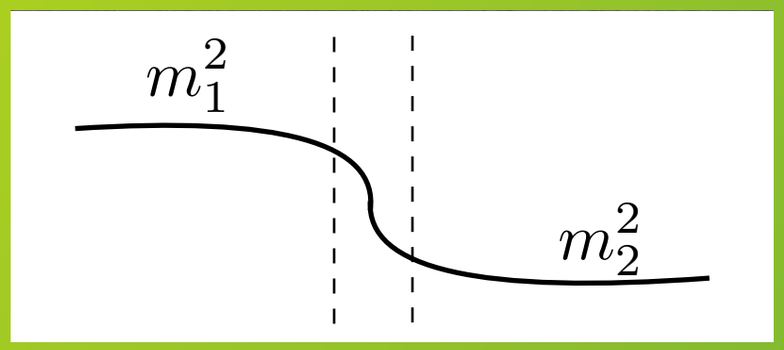


$$* \text{ Inf: } m_\varphi^2 = \xi R = 12\xi H^2$$

$$* \text{ After: } m_\varphi^2 = \xi R = 3(1-3w)\xi H^2$$

Equation of State



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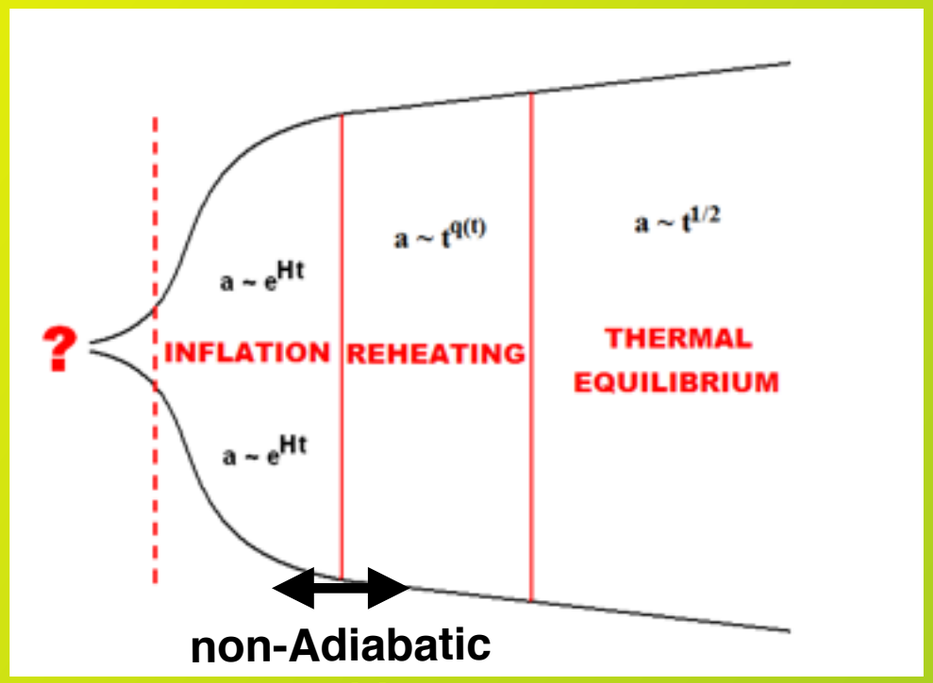

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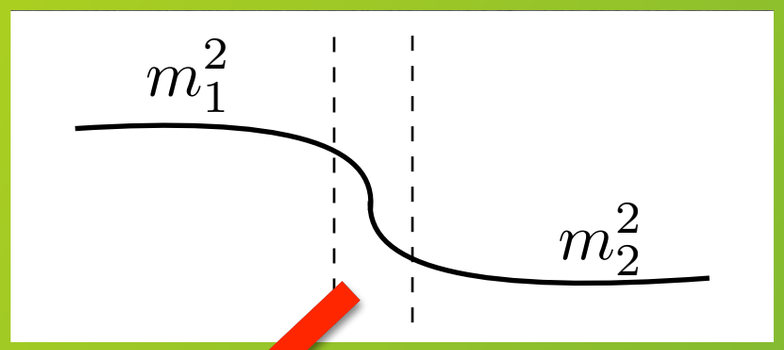

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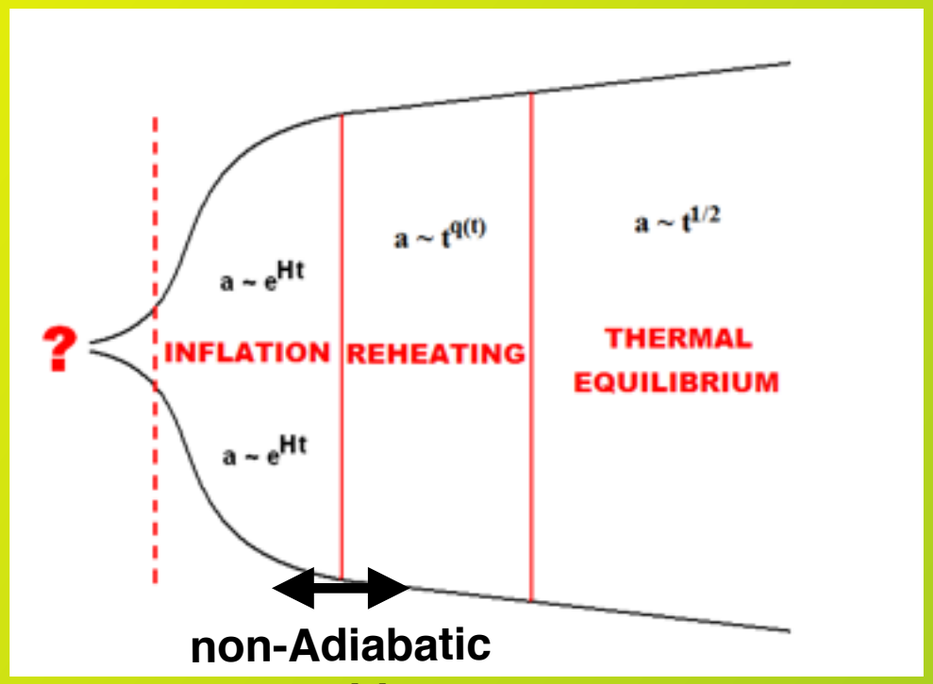

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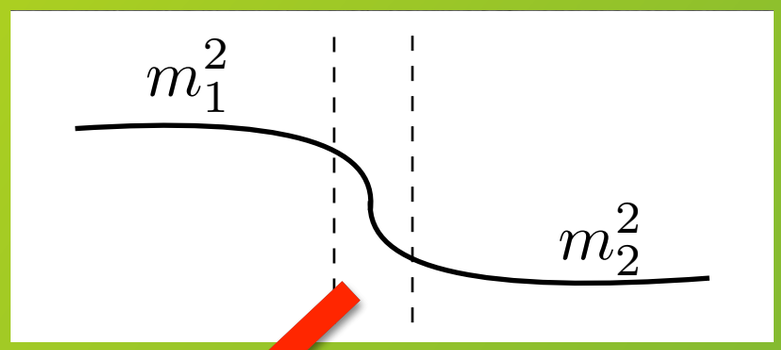

Higgs-Excited !

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[Rajantie et al 2014-2015]

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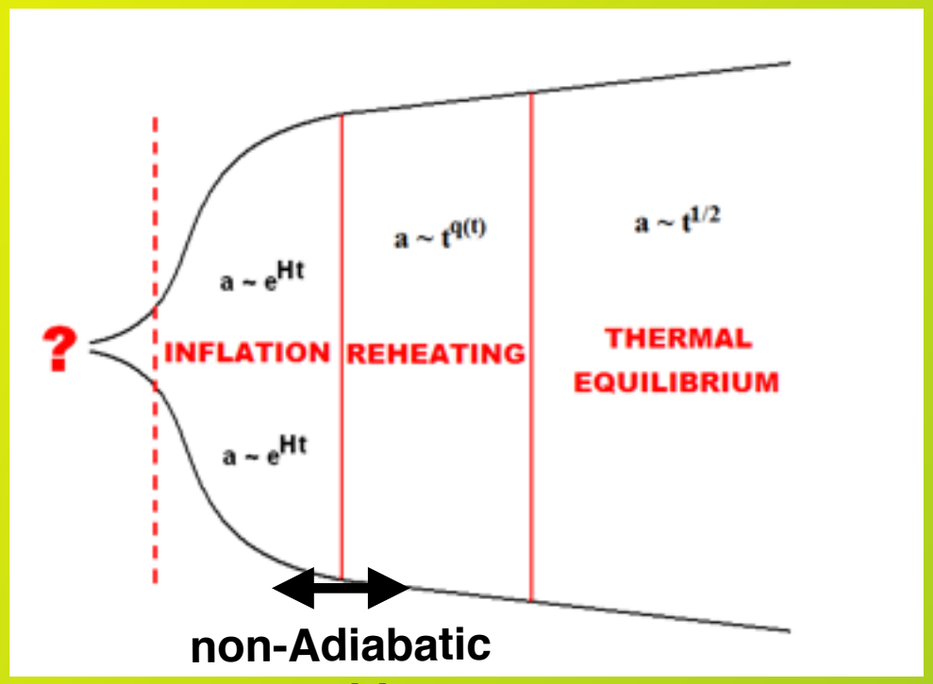

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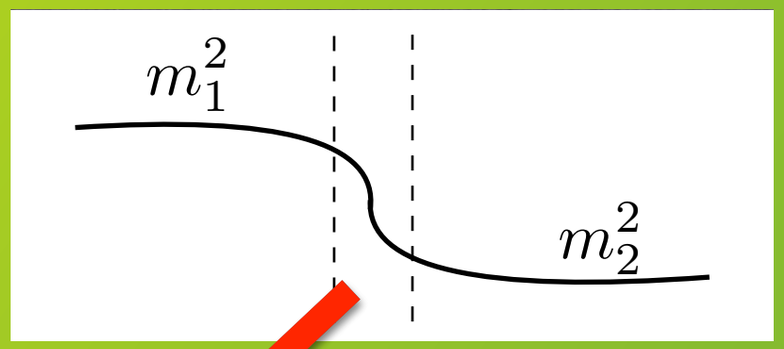

Higgs-Excitation !

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

[Rajantie et al 2014-2015]

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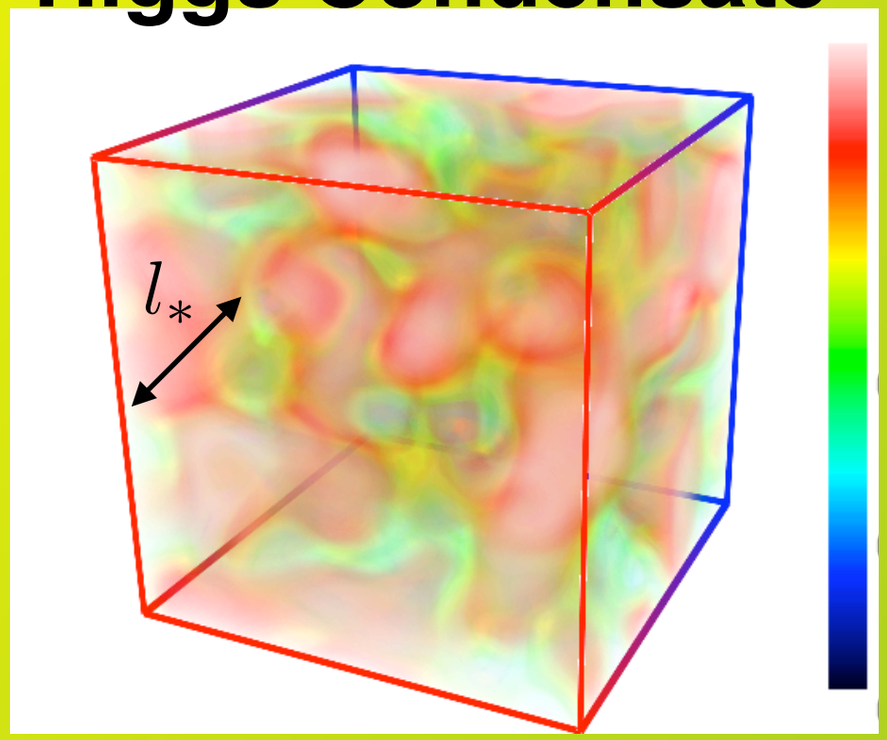

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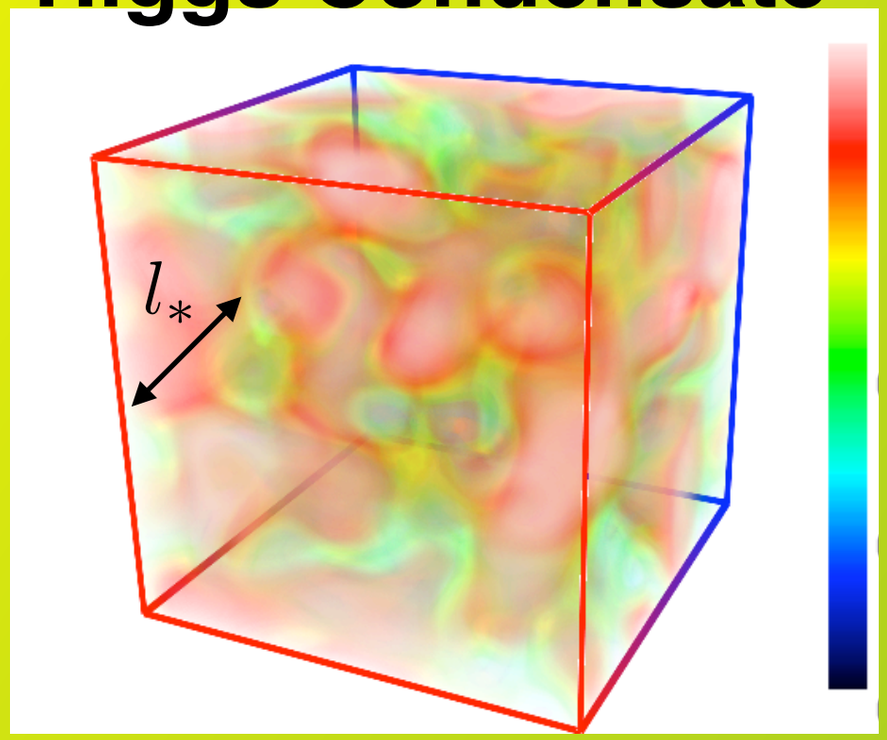

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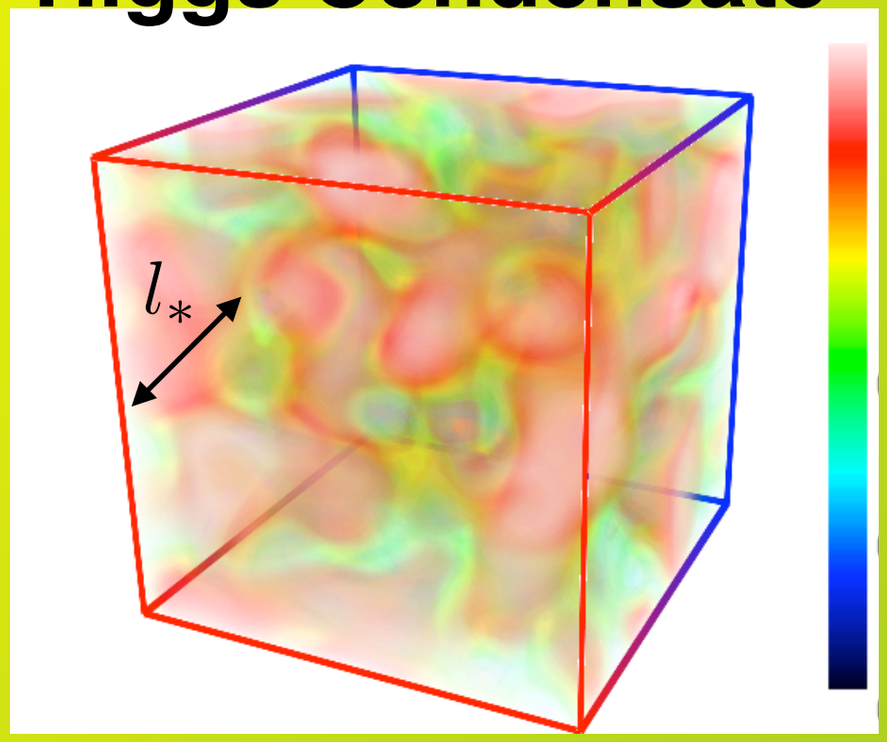

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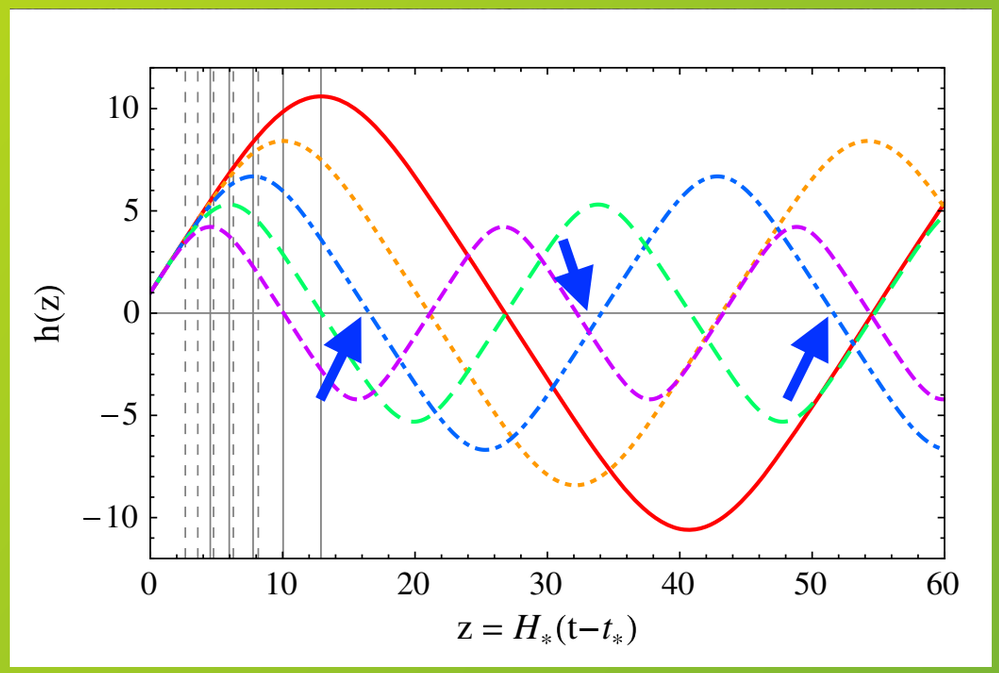
Higgs Condensate Oscillates!



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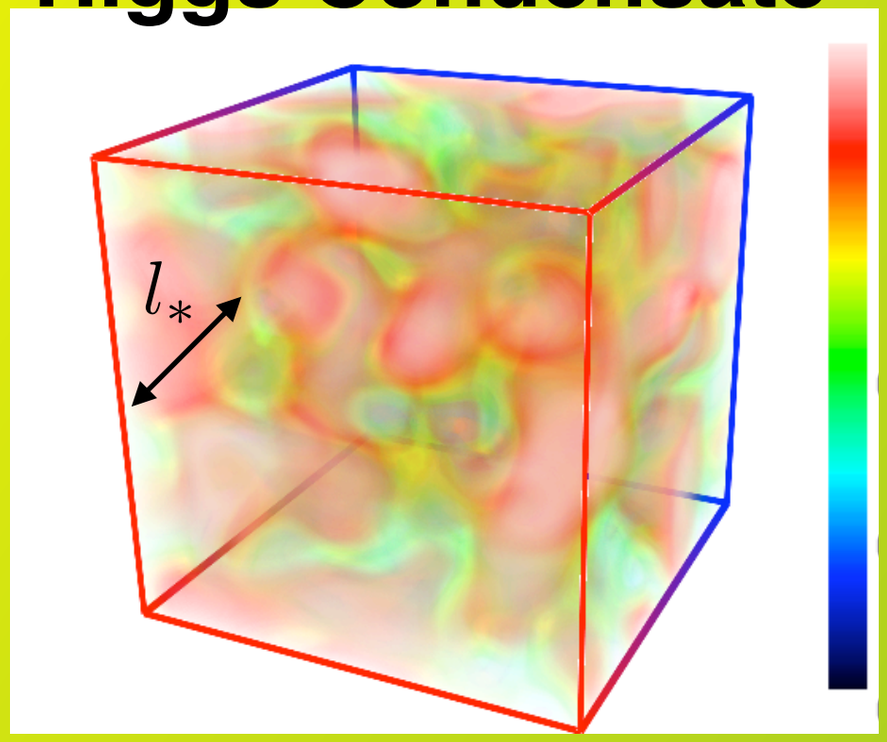

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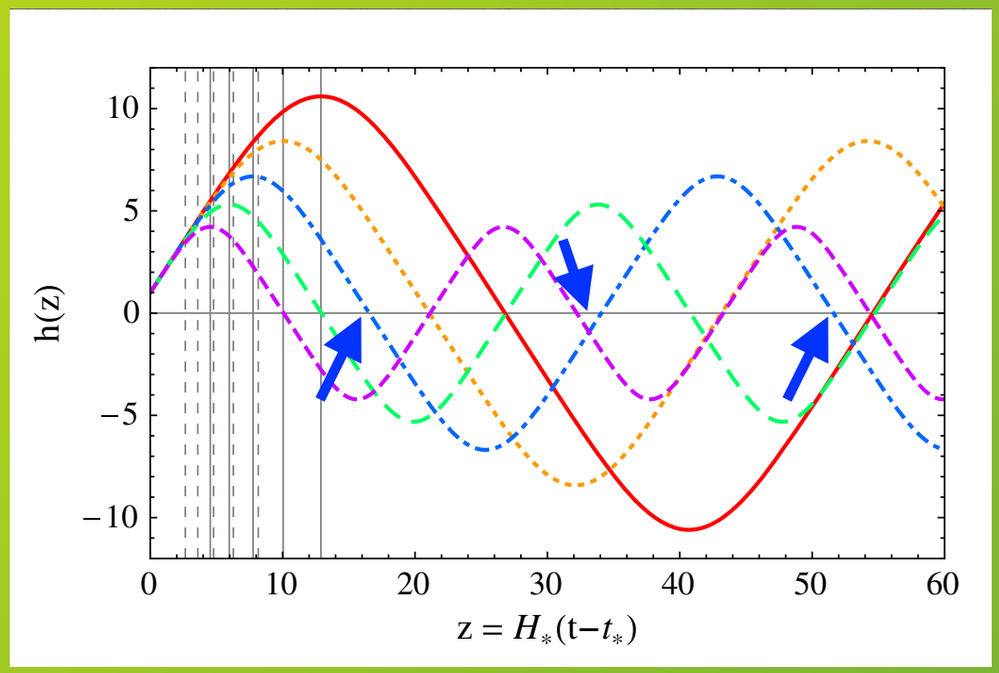
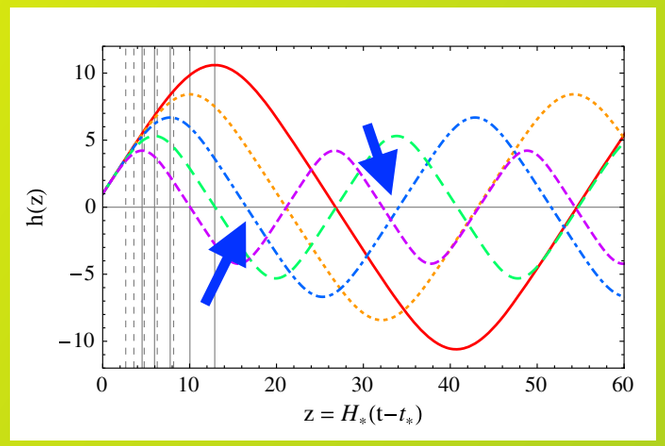


SM species produced due to non-Perturbative Effects !

[Greene et al 1997]

Higgs Condensate Oscillations:



All SM species explosively produced!

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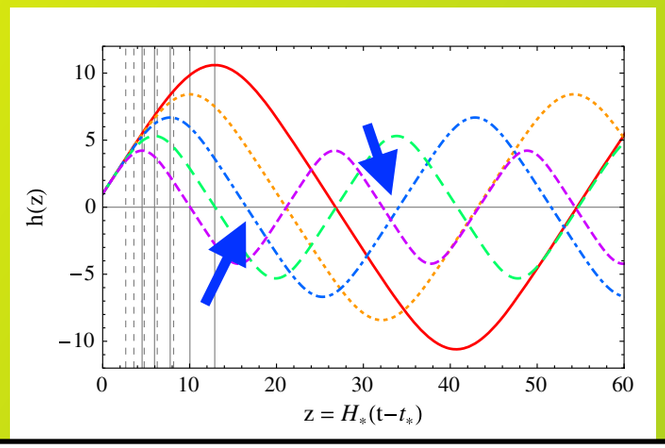

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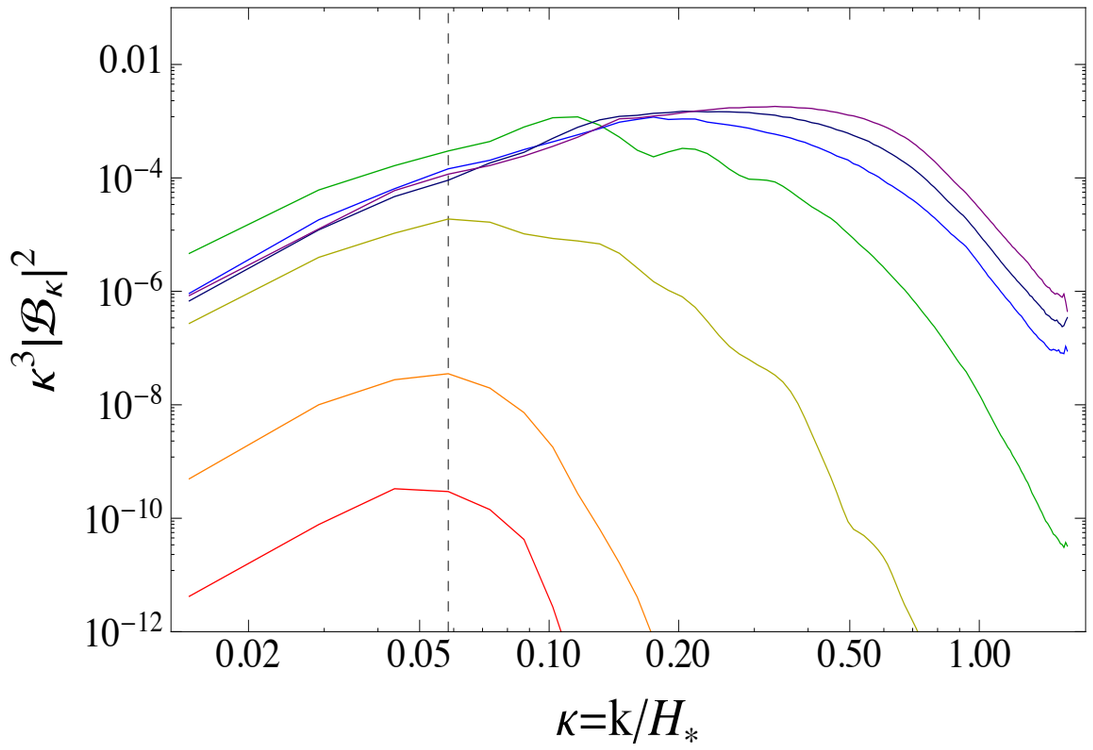
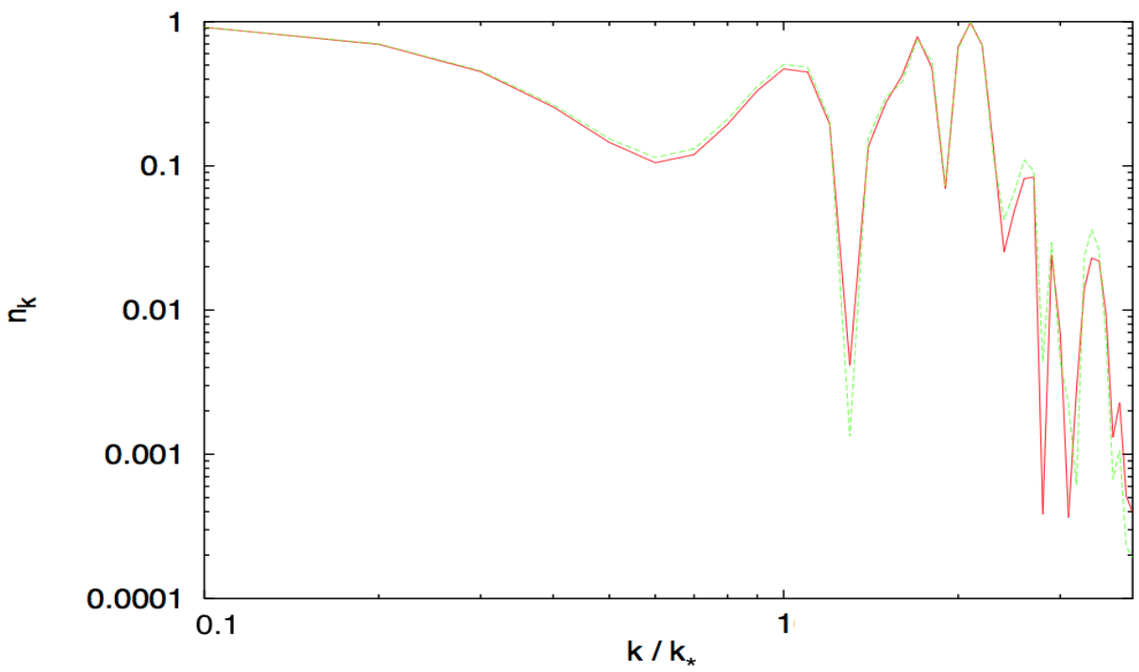
Post-Inflationary production of SM species

Gauge Bosons



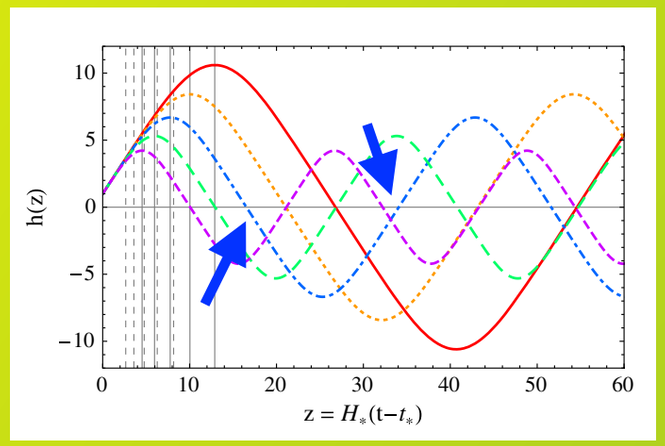
(Enqvist, Nurmi, Meriniemi 2013
+ Rusak 2014, + Weir 2015
DGF, Torrenti, Garcia–Bellido 2015)

Fermions



DGF 2014

Higgs Condensate Oscillations:



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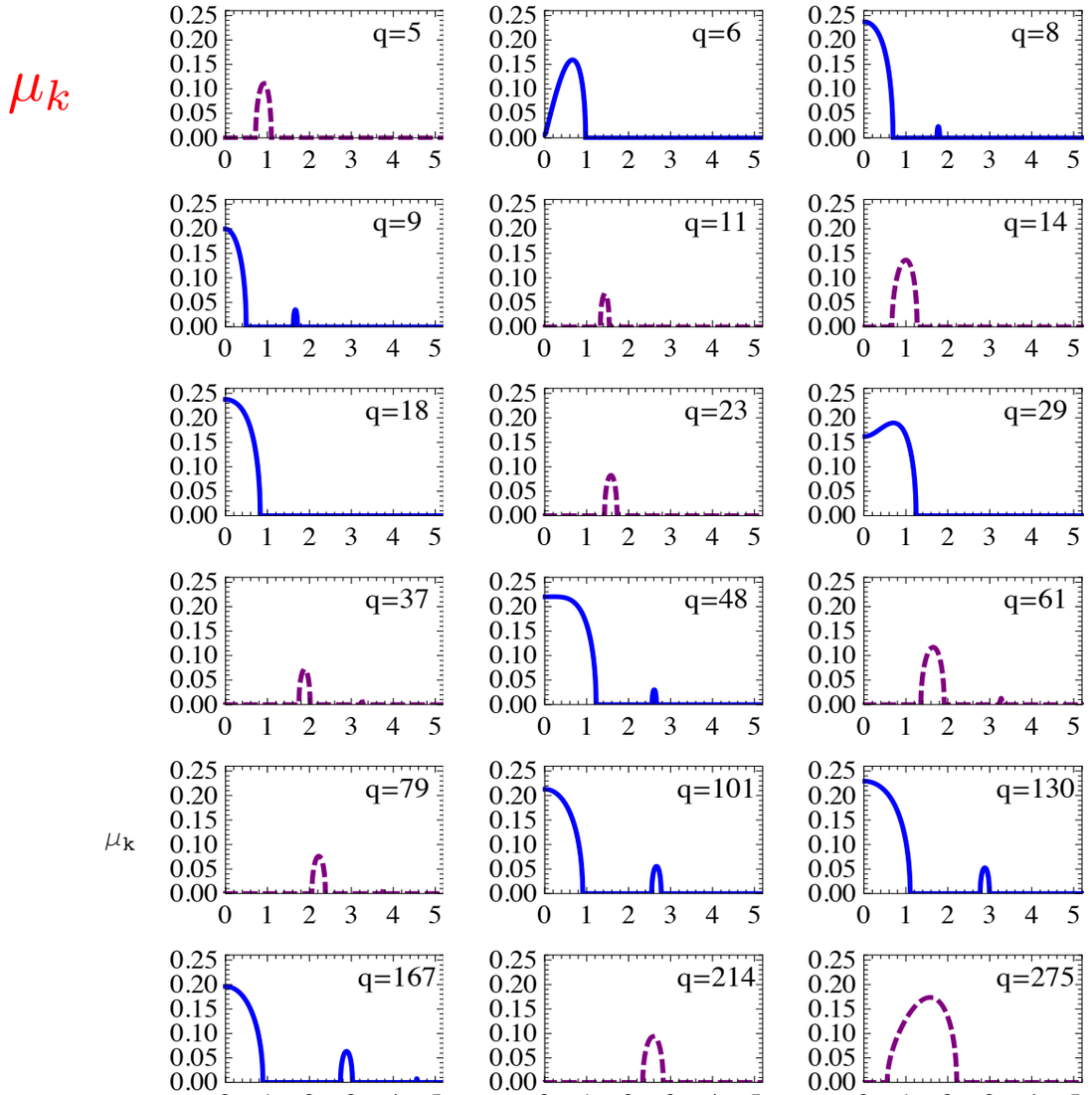
Post-Inflationary production of SM species: $n_k \propto \mathrm{Exp}(\mu_k\, t)$

Gauge Boson Resonances



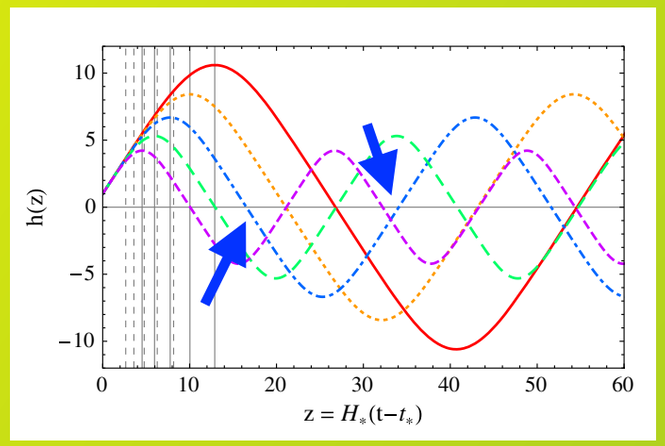
Non-Perturbative Particle Production (Greene et al 1997)

[DGF, Ga-Bellido, Torrenti 2015]

$$q \equiv \frac{g^2}{\lambda}$$

Resonance Parameter

Higgs Condensate Oscillations:



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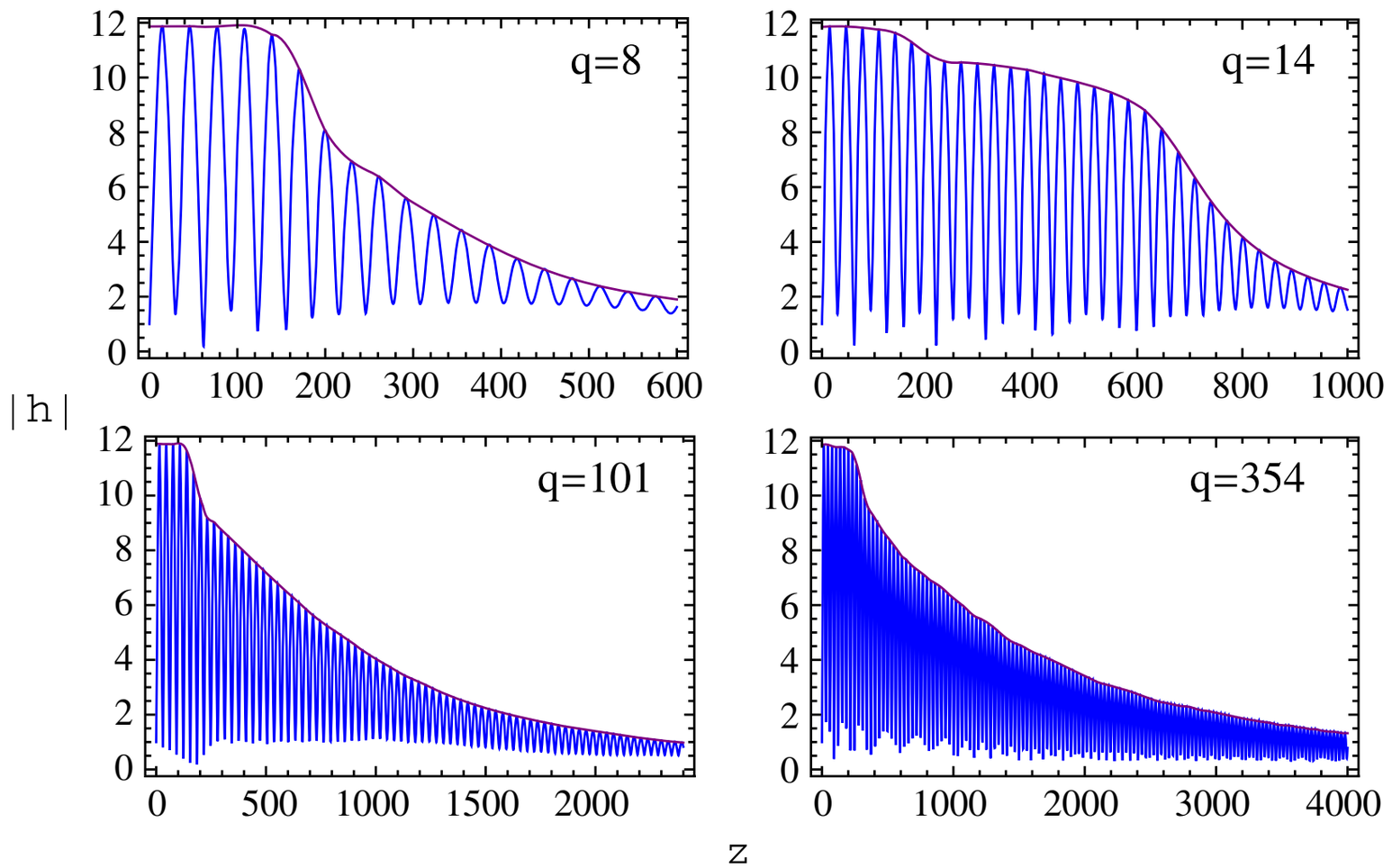
$$h = a(t)\varphi(t)$$



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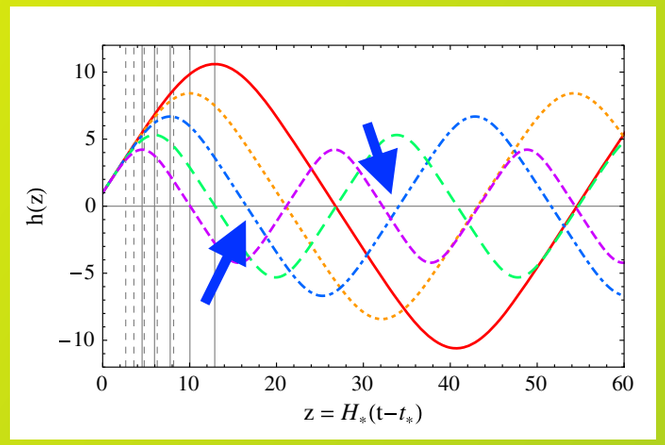

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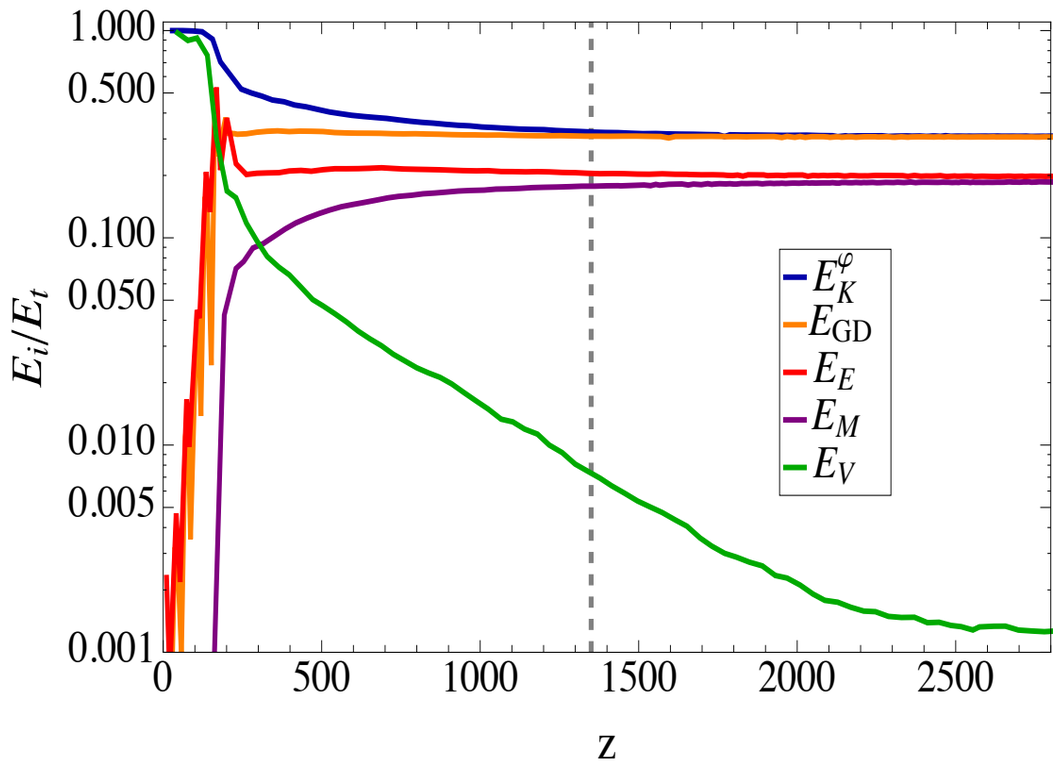
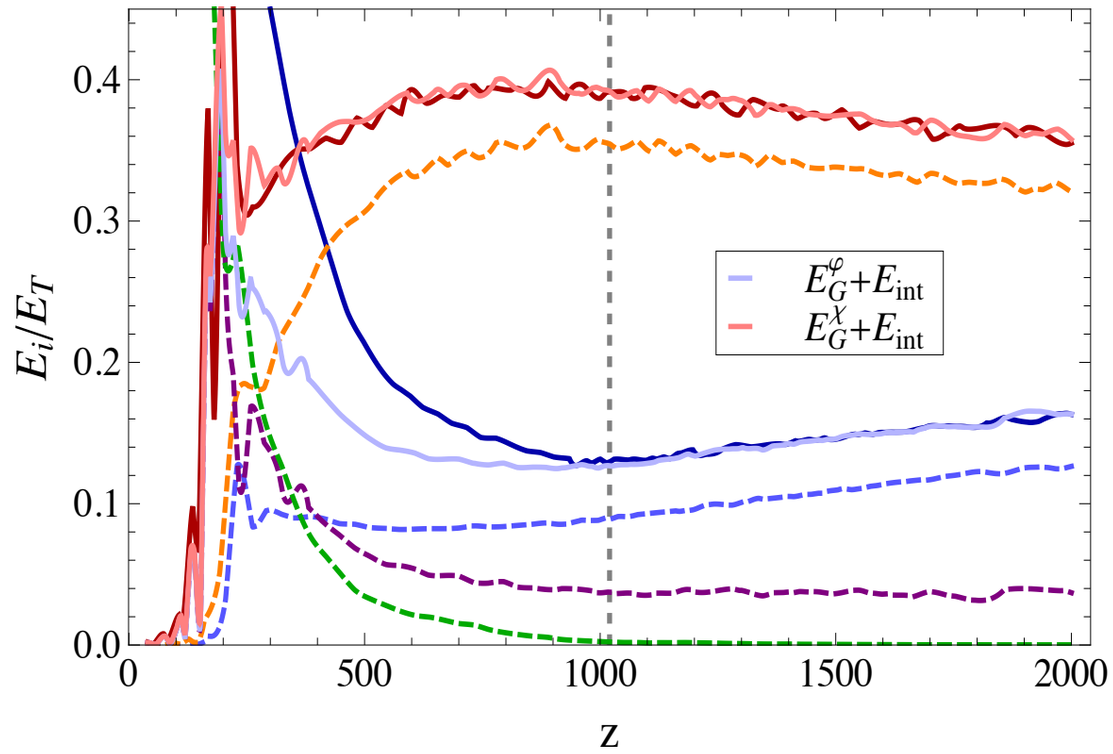
Energy Transfer



Relaxation/Equipartition



[DGF, Ga-Bellido, Torrenti 2015]

Summary

Higgs @ Inflation

No Coupling to Inflaton

1) LIGHT

2) HEAVY

After Inflation

$$\langle \varphi^2 \rangle \sim \mathcal{O}(0.1) H_*^2$$

1) $l_* \gg H_*^{-1}$

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Higgs Condensate Oscillates!

SM species always created due to Non-Perturb effects!

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UNiVERSAL SM Excitation !

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[Both: LIGHT & HEAVY]

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

SM produced! but subdominant

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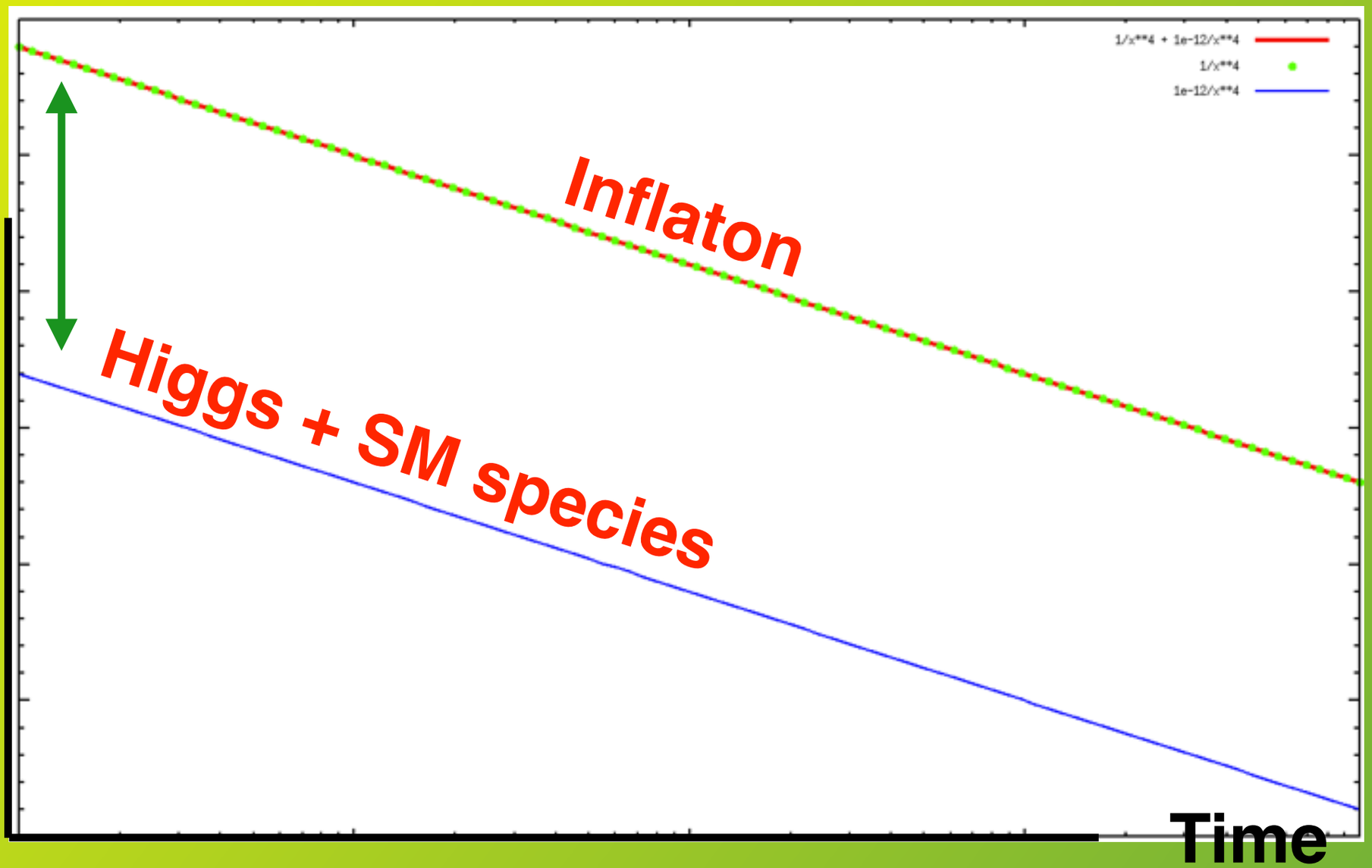

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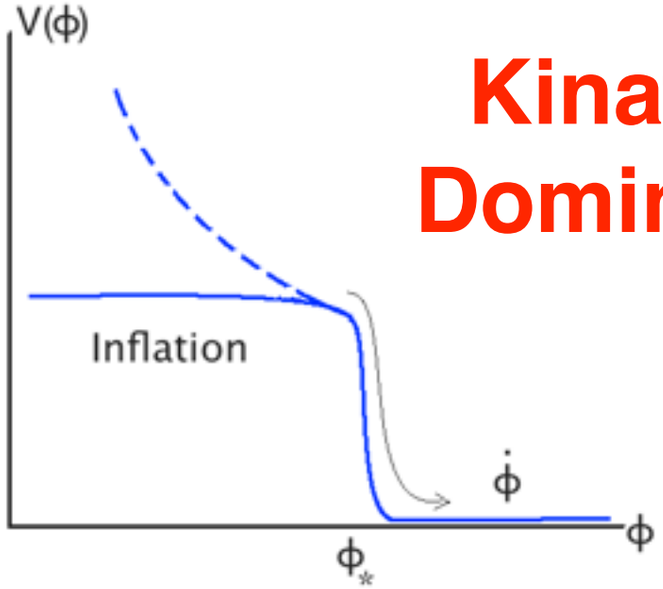
Kination-Domination



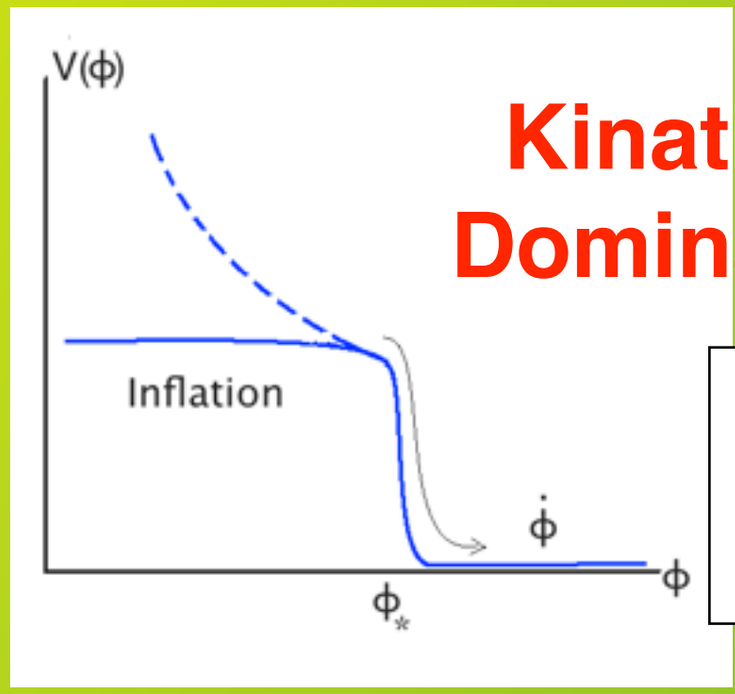
$$\text{Energy} \propto \frac{1}{a^6}$$

[Spokoiny '93
Joyce '97]

SM Excitation

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

SM produced! and dominates



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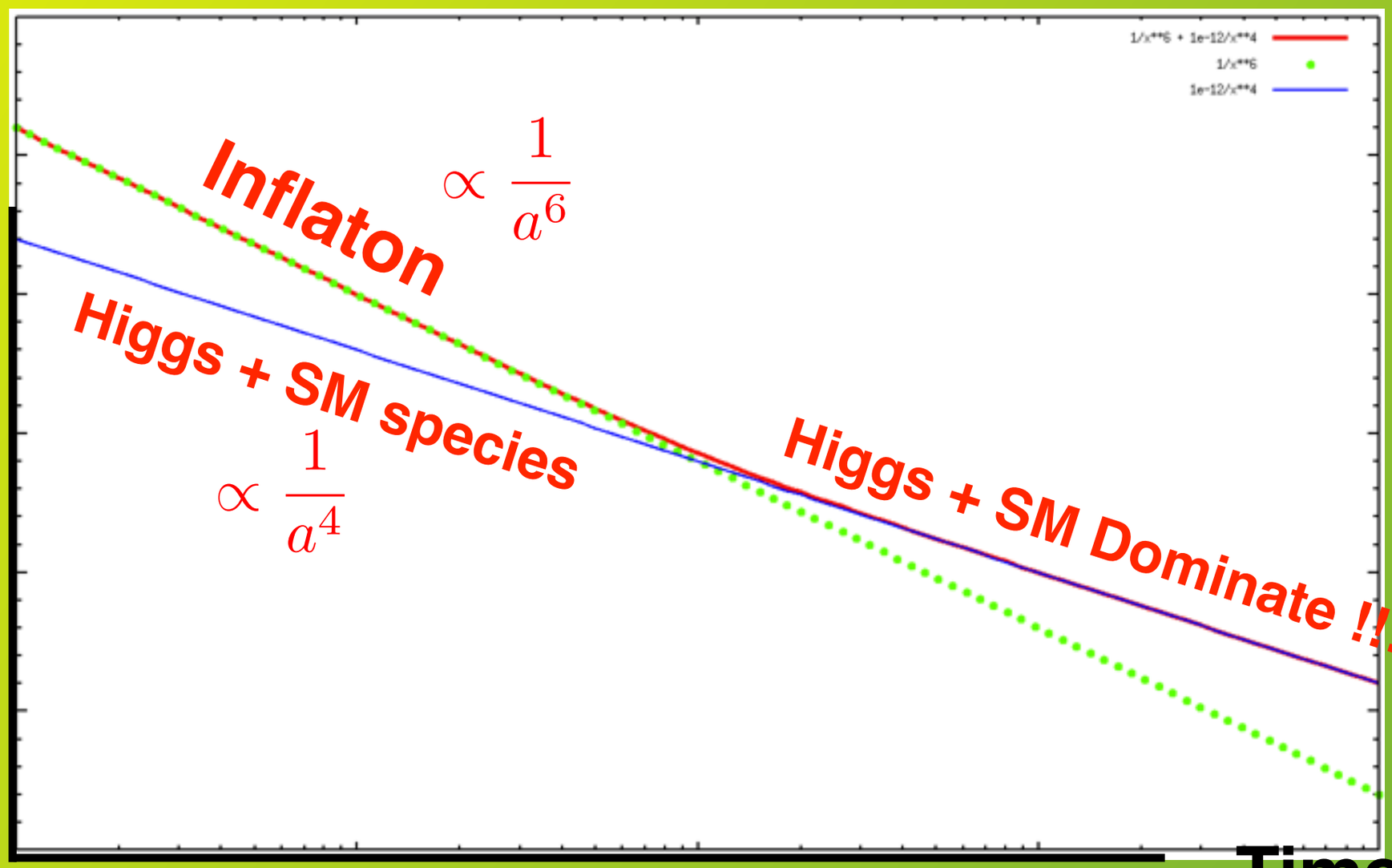

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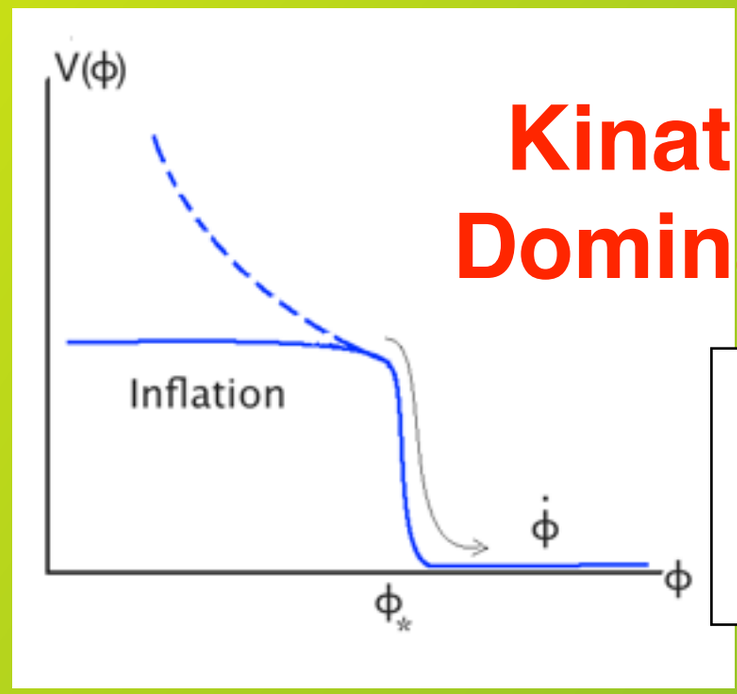

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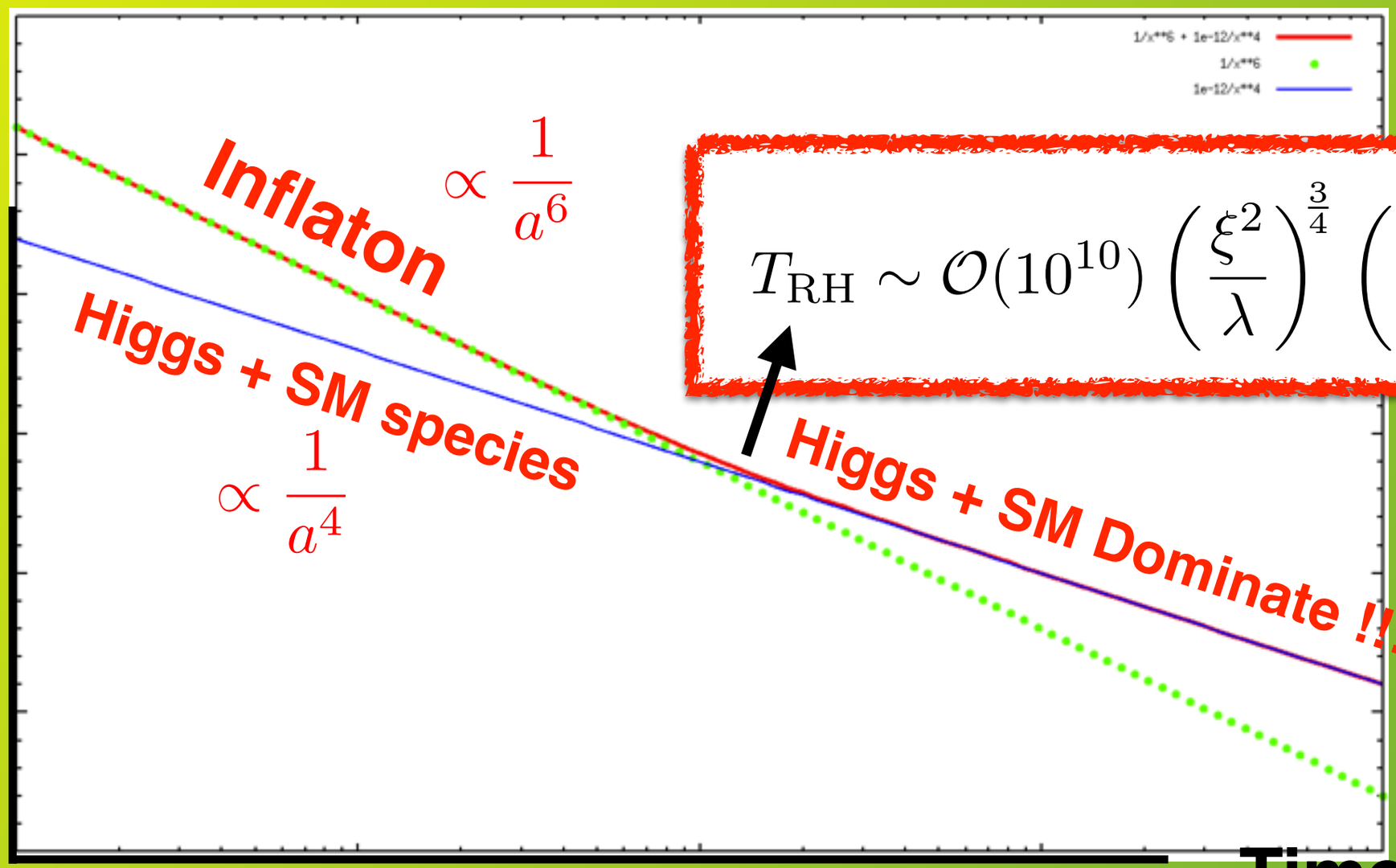

$$T_{\rm RH} \sim \mathcal{O}(10^{10}) \left(\frac{\xi^2}{\lambda}\right)^{\frac{3}{4}} \left(\frac{H_*}{H_*^{\rm max}}\right)^2$$

Case HEAVY

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Higgs @ Inflation

No Coupling to Inflaton

- **1) LIGHT**
- **2) HEAVY**

After Inflation

1) $P_\xi \sim 0.1\sqrt{\lambda} \gg 2 \cdot 10^{-9}$ @ CMB scales

2) $P_\zeta \sim 0.01/\sqrt{\xi}$ @ Very Small Scales

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✓

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

Universal Production !

Explosive Particle Production !

Gravitational Wave Generation

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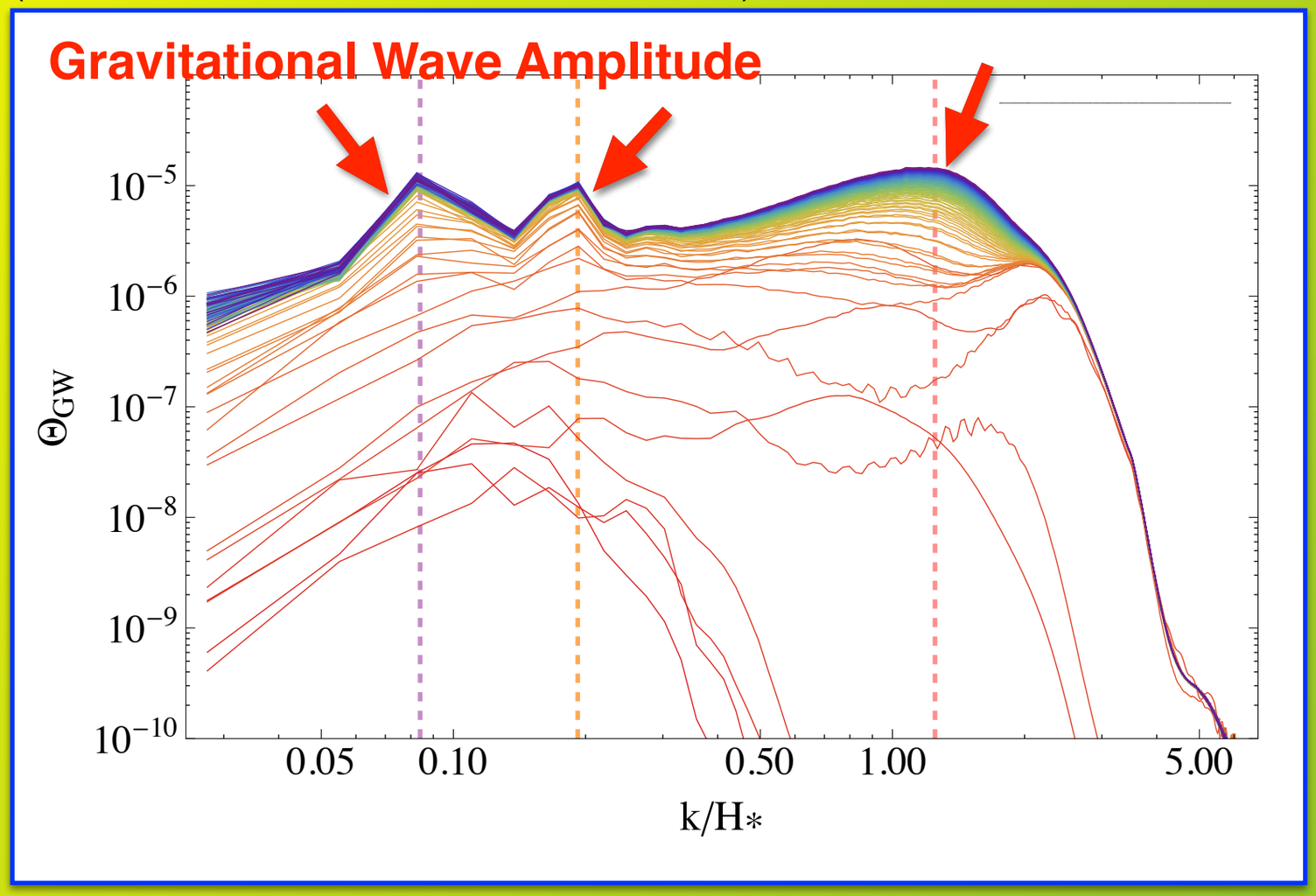
(DGF, J. García-Bellido, Torrenti 2016)



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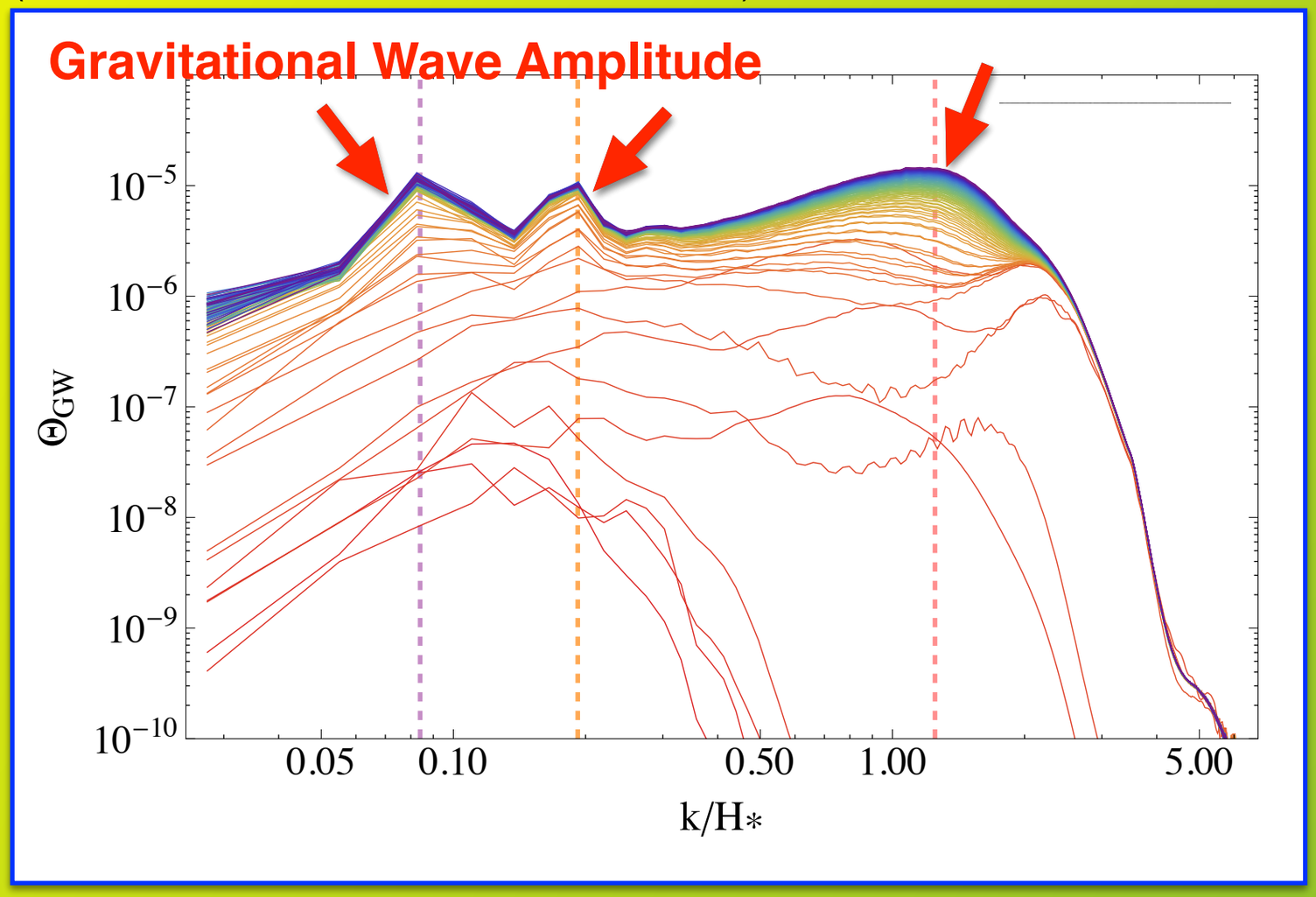

$$\text{GW Today}: h^2\Omega_{\rm GW}^{(\rm p)}\big|_{\rm t} \sim 10^{-29}\left(\frac{0.01}{\lambda}\right)^{\frac{3}{2}}\left(\frac{H_*}{H_*^<}\right)^4\left(\frac{a_{\rm RD}}{a_*}\right)^{|3w-1|} \sim \ ?$$

Running Self-Coupling · Hubble Rate · Equation of State

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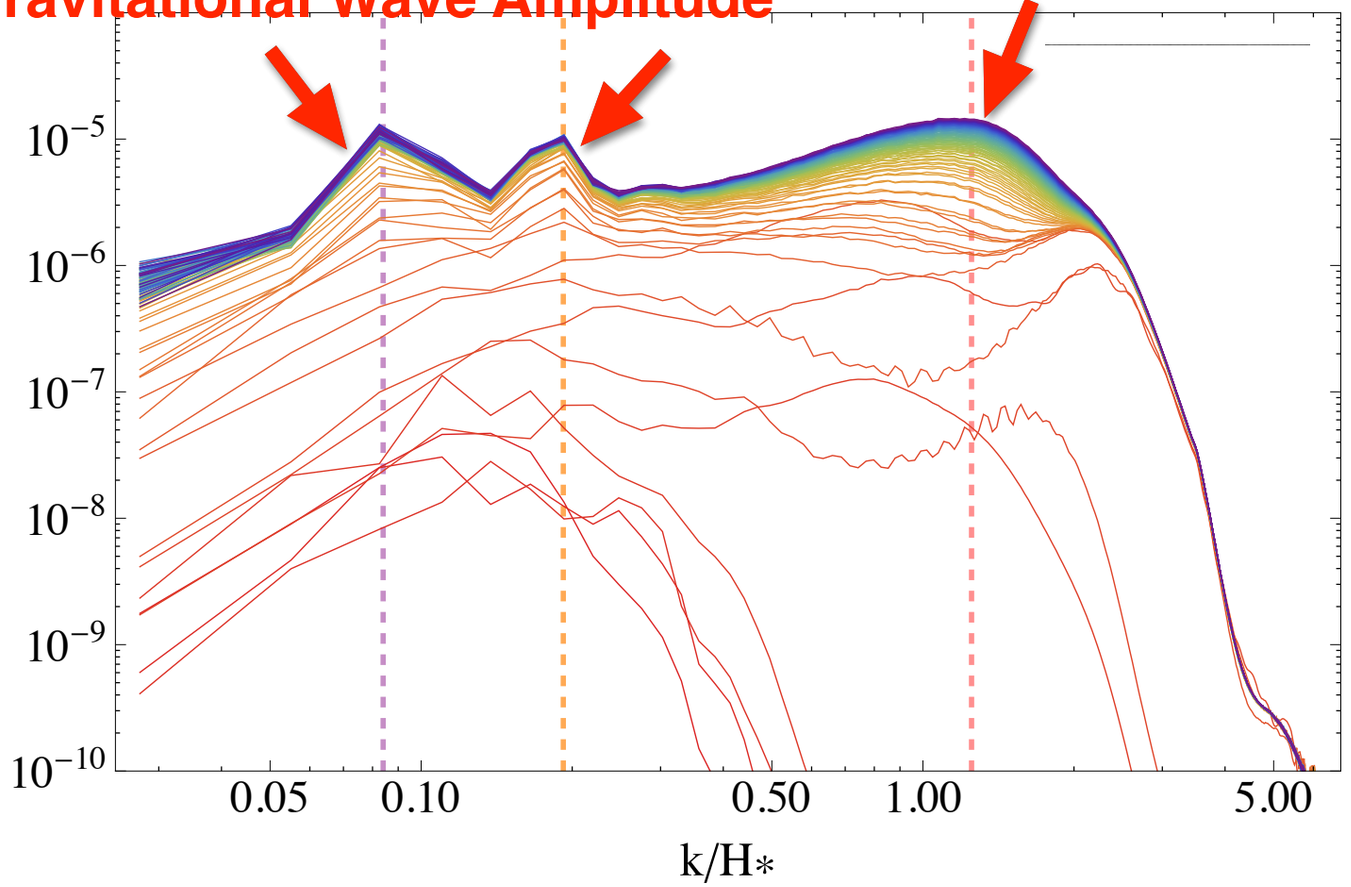
Gravitational Wave Amplitude



Explosive Particle Production !

Gravitational Wave Generation

NO OBSERVABLE !!

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Running Self-Coupling · Hubble Rate · Equation of State

@ $f_* \sim 10^{10}$Hz

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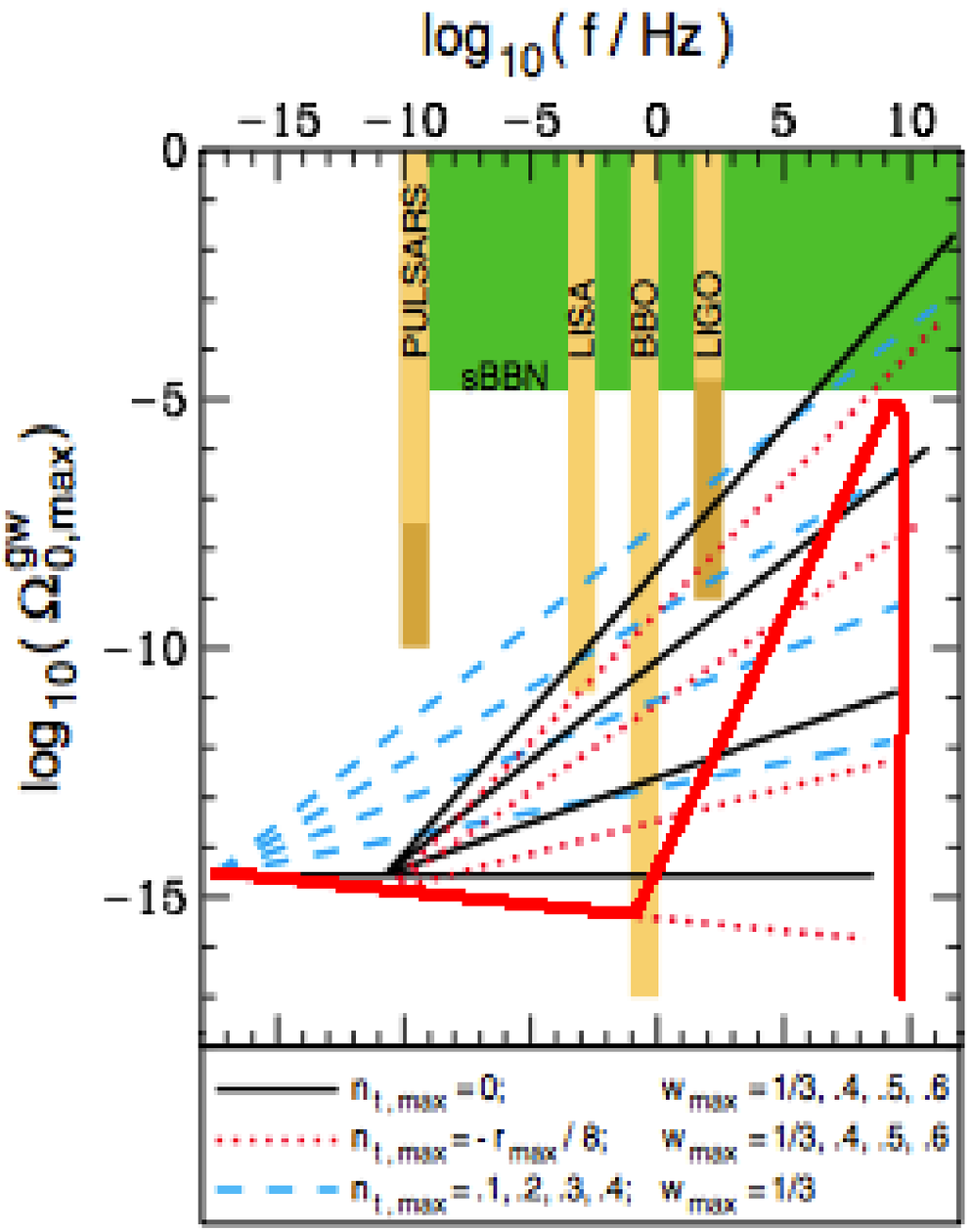
Gravitational Waves from Inflation

Kination Domination

(DGF, Torrenti 2016)



Boyle and Buonanno 2007

High-Freq. Tail
Inflationary Gravitational Wave Background
Uplifted

Observable ?

If there is Kination-Domination ...

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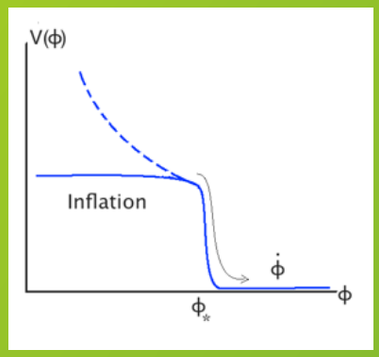
Work in Progress …

UNiVERSAL
SM Excitation !

[Both: LIGHT & HEAVY]

But….
KD assumed to enhance the SM energy density



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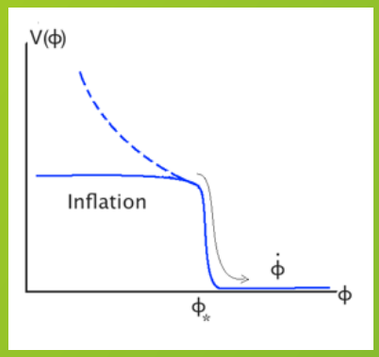
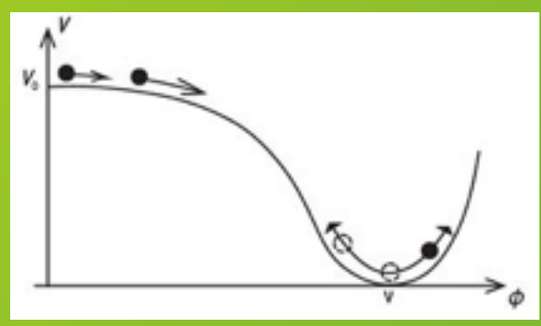


So….
What If the inflaton oscillates (potential with minimum)



UNiVERSAL SM Excitation

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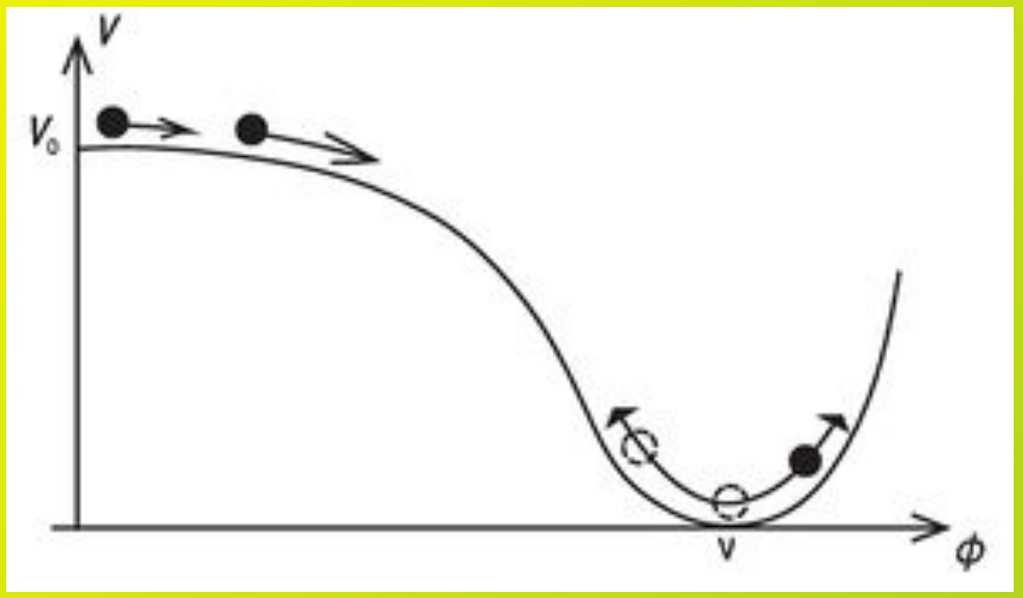

(SM weakly coupled to Inflaton)

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

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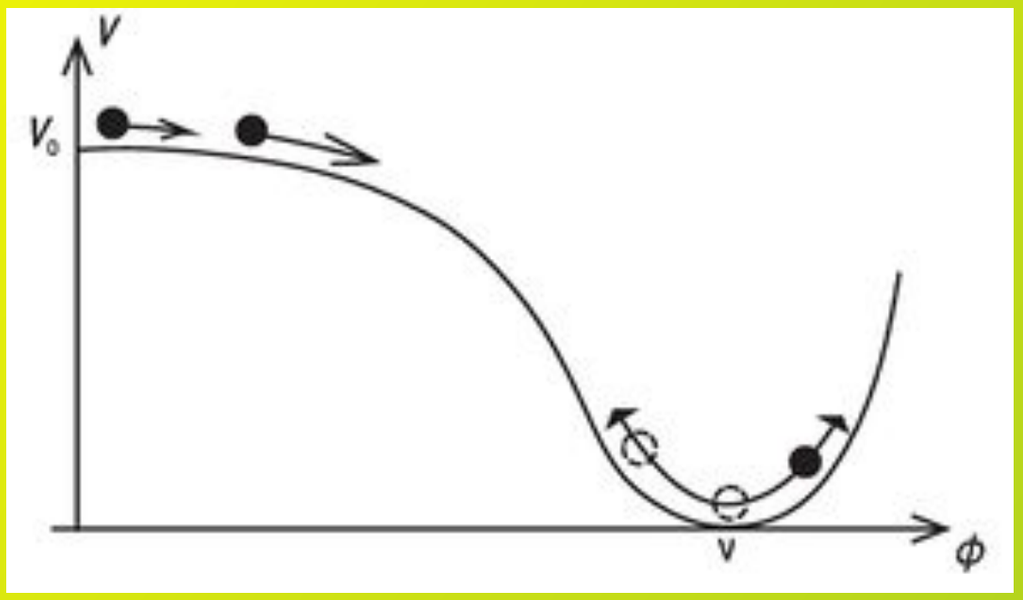

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@ End of INF

$$\langle\varphi^2\rangle \sim \mathcal{O}(0.1)H_*^2$$

$$\lambda\langle\varphi^4\rangle \ll m_p^2 H_*^2$$

After INF…

$$R = \frac{1}{m_p^2}\left[4V(\phi) - (\dot{\phi})^2\right]$$

Curvature Oscillates !

[Rajantie et al, 2015]

Inflaton oscillating —> Curvature Oscillating

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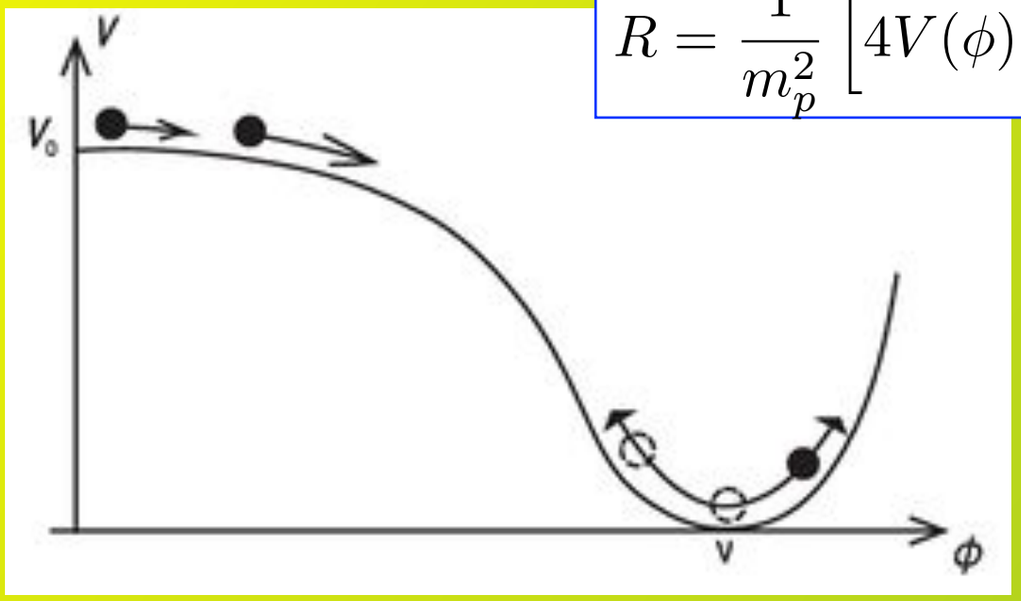

Curvature Oscillates

$\Downarrow$ If $\xi \gtrsim \mathcal{O}(1)$

Tachyonic Resonance !

$\Downarrow$

Energy transferred to Higgs + SM

(DGF, Torrenti, Rajantie, 2016 [Work in Progress])

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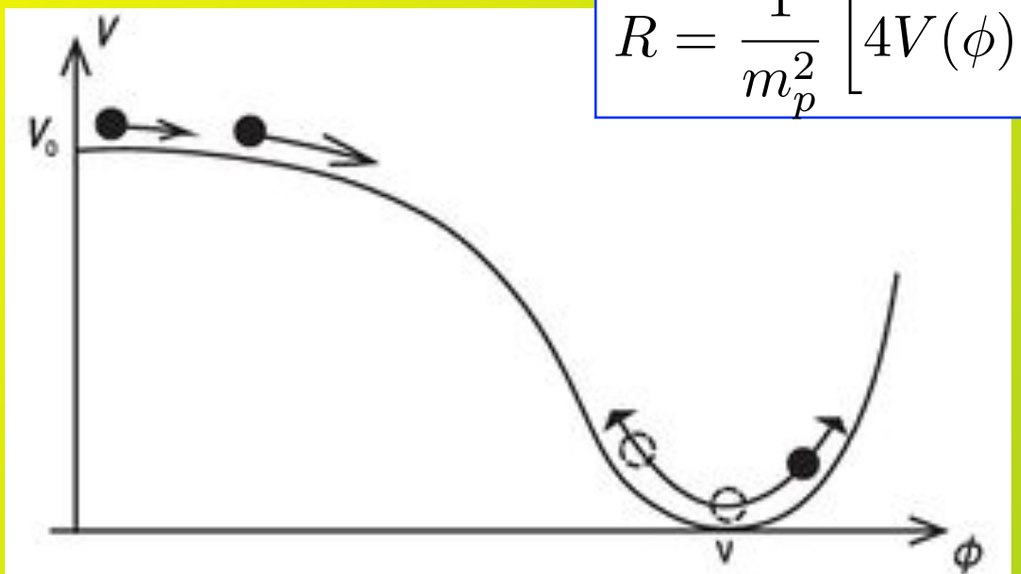

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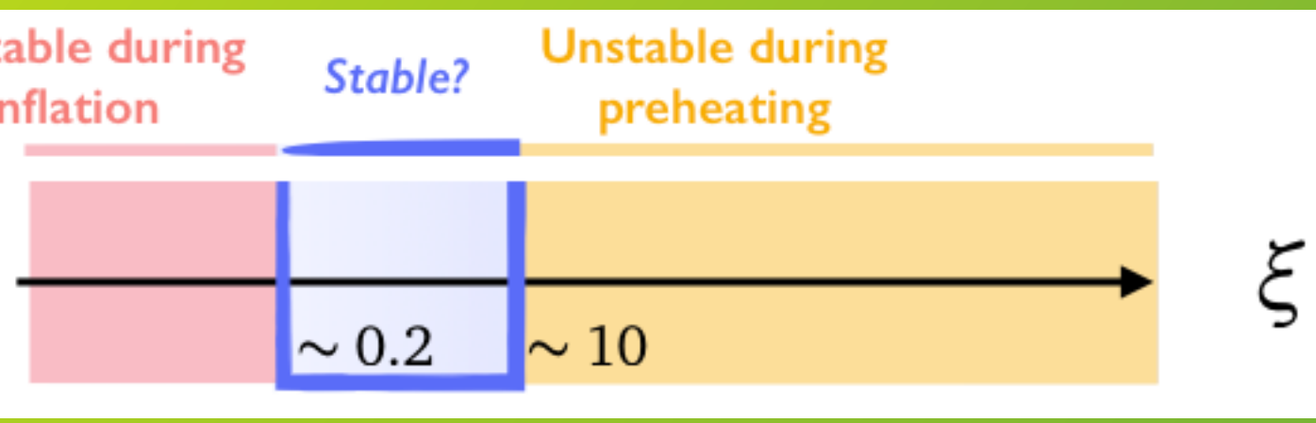
Rajantie et al 2015
Mukaida et al 2016

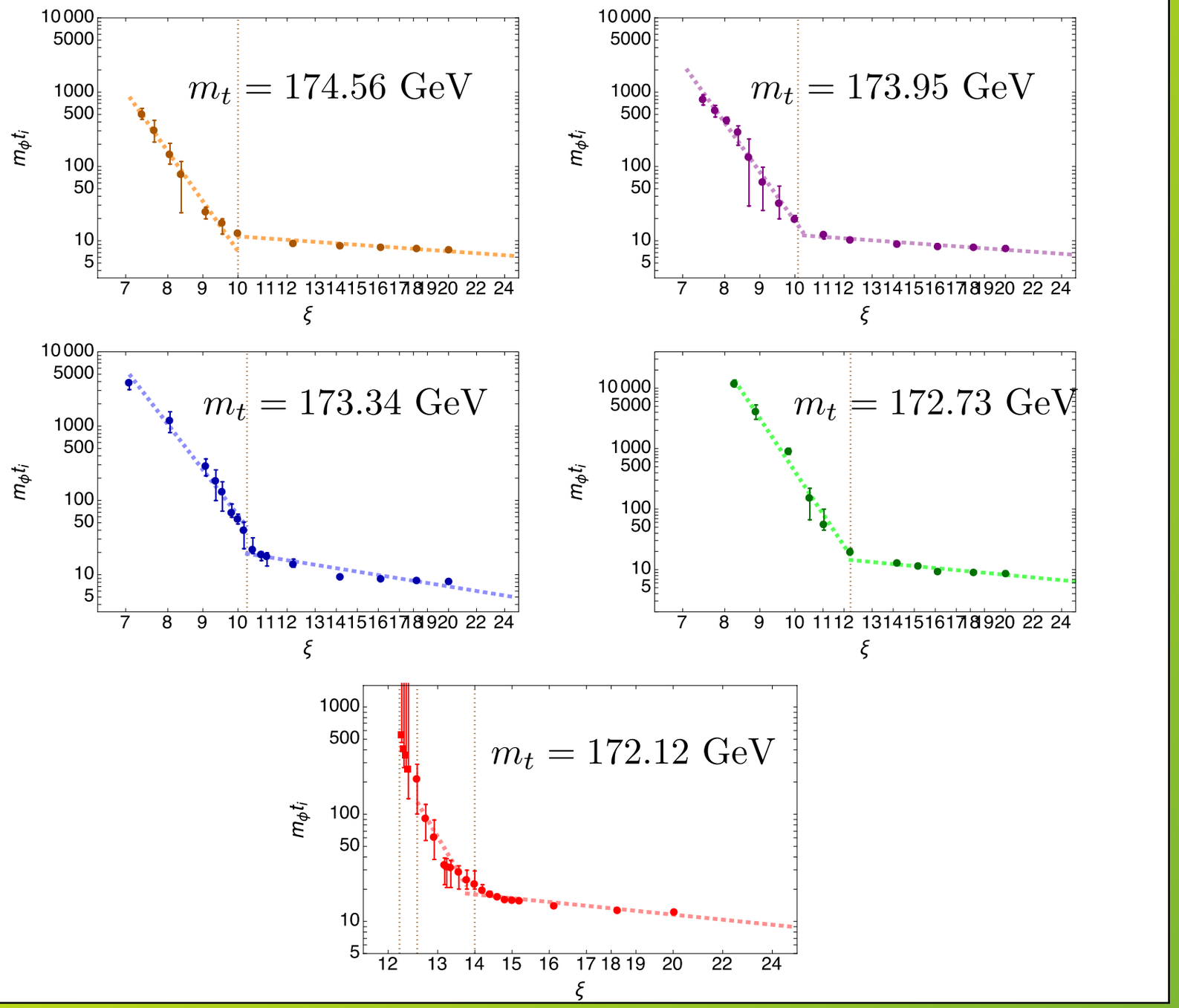
$$- -\mathscr{L}_{\rm int}(\phi, h) = \frac{1}{2}\underbrace{\xi R}_{mass^2} h^2$$



Problem for Chaotic Inflation ?

Inflaton oscillating —> Curvature Oscillating

Instability time scale after Chaotic Inflation



[DGF, Torrenti, Rajantie, 2016, Work in Progress]

Summary:

* Universal Mechanism to produce the SM !

DGF & Byrnes 2016

*** If Kination-Domination: SM species dominate!**

(eventually)

Reheating the Universe into the SM !

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* Inflaton Oscillations —> Curvature Oscillations

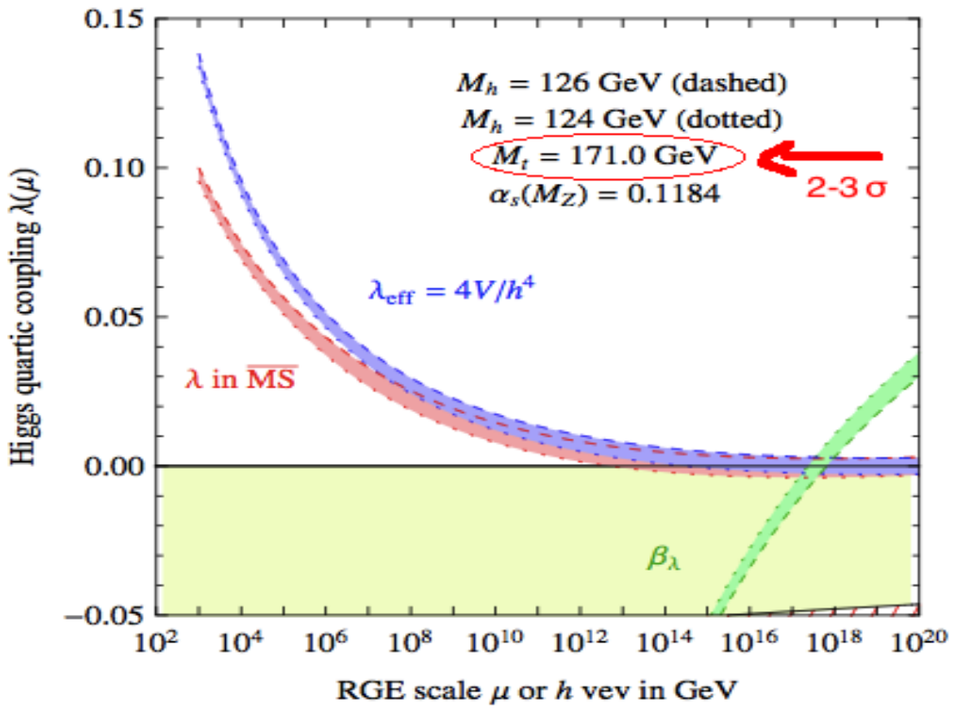
If $\xi \gg 1$, Reheating into SM / Instability Constraints

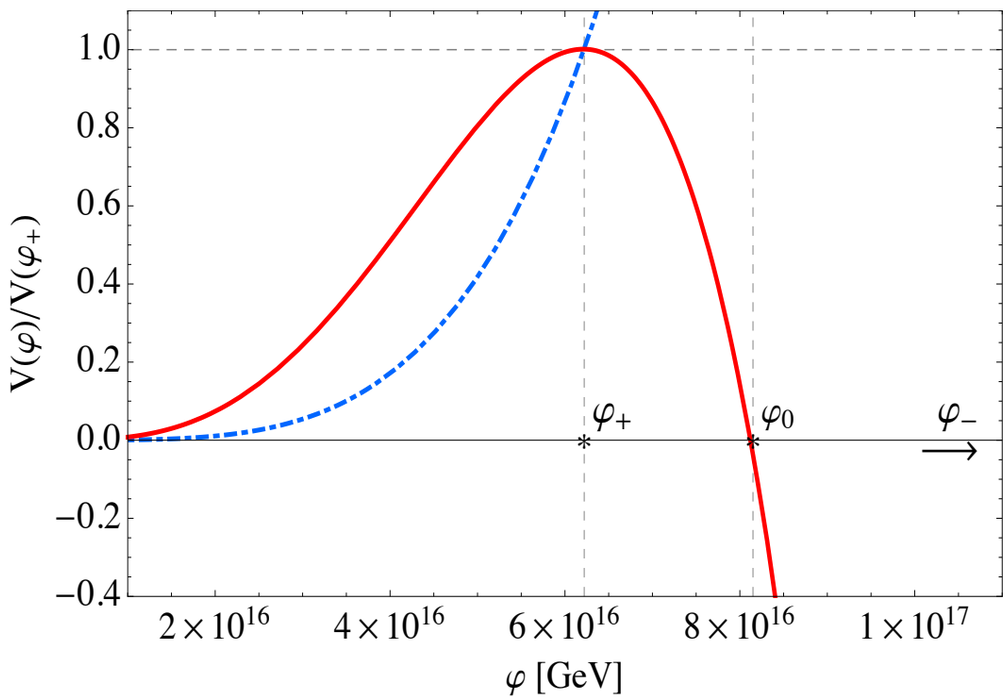
DGF, Rajantie, Torrenti

Merci Beaucoup !

Stability of the SM ?

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





(Degrassi et al 2012, Bezrukov and Shaposhnikov 2012)

CERN CINECLUB

Tonight 8:00pm,

@ Council Chamber
(Here!)

Dinner + Beers 7:00pm,
@ R1 restaurant