SM Higgs origin of the hot Big Bang

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The Problem: \( (p)\)Reheating into a Thermal Plasma
Successful Reheating: (p)Reheating into the Standard Model

\[ \mathcal{L} = \mathcal{L}(\phi, \varphi_i, \psi_j, A_\mu, h_{\mu\nu}, \ldots) \]
Successful Reheating: \( (p)\text{Reheating into the Standard Model} \)

\[ \mathcal{L} = \mathcal{L}(\phi, \varphi_i, \psi_j, A_\mu, h_{\mu\nu}, \ldots) \]

Connection between SM and Inflationary Sector ???

- SM
- SM
- BBN \((p, n, \gamma)\)
- SM
- SM
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 ???

Higgs-Portal ?

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

Mediator fields ?

\[ h^2 \phi^2 \chi^2 + f^2 \chi^2 |\mathcal{H}|^2 \]

\[ g^2 \phi^2 |\mathcal{H}|^2 \]
Successful Reheating:

(p)Reheating into the Standard Model

\[ L = L(\phi, \varphi_i, \psi_j, A_\mu, h_{\mu\nu}, \ldots) \]

- INFLATION
- Reheating
- SM
- BBN \((p, n, \gamma)\)
- Thermal Plasma

\[ a \sim e^{Ht} \]
\[ a \sim t^0(t) \]
\[ a \sim t^{1/2} \]

\[ 10^x \text{ s} \]
\[ \sim 1 \text{ s} \]

Connection between SM and Inflationary Sector ???

No coupling ?

\[ g^2 \phi^2 |H|^2 \]
\[ (g^2 \ll 1) \]
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 ???

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

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\[ 10^x \text{ s} \quad \sim 1 \text{ s} \]
(p)Reheating into the Standard Model

No Coupling to Inflaton

1) LIGHT

During Inflation ...

\[ m_\varphi^2 < H_*^2 \]

2) HEAVY

\[ m_\varphi^2 > H_*^2 \]
(p)Reheating into the Standard Model

(No Coupling to Inflaton)

1) LIGHT @ Inflation

\[ m_\varphi^2 < H_*^2 \]
Reheating into the Standard Model

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\[ m_\varphi^2 < H_*^2 \]

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

- **End of Inflation**: \( \varphi_* = \alpha H_*/\lambda_*^{1/4} \quad \alpha \in [0.001, 1] \) (99.9 %)
(p)Reheating into the Standard Model
(No Coupling to Inflaton)

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@ Inflation

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2) HEAVY @ Inflation
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(p)Reheating into the Standard Model
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\[ m_\varphi^2 > H_*^2 \]

\[ \frac{\lambda}{4} (|\varphi|^2 - v^2)^2 + \frac{\xi}{2} R |\varphi|^2 \]
(p)Reheating into the Standard Model
(No Coupling to Inflaton)

2) HEAVY
@ Inflation

\[ m_2^2 > H^2 \]

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

* 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
(p)Reheating into the Standard Model
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Equation of State

Higgs-Excitation !!!

\[ \langle \varphi^2 \rangle = \mathcal{O}(10^{-3}) \left( 1 - \frac{m_1}{m_2} \right)^2 \frac{H_*^2}{\sqrt{\xi}} \]
No Coupling to Inflaton

1) LIGHT

2) HEAVY

\[ \langle \varphi^2 \rangle \sim \mathcal{O}(0.1) H_*^2 \]
No Coupling to Inflaton

1) LIGHT

2) HEAVY

Higgs Condensate

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Higgs Condensate

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Higgs Condensate Oscillates!
1) LIGHT

No Coupling to Inflaton

2) HEAVY

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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

\[ \kappa = k/H_* \]

\[ \kappa^3 |B_k|^2 \]

\[ q = 9 \]

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

DGF 2014
No Coupling to Inflaton

Higgs @ Inflation

1) LIGHT
2) HEAVY

After Inflation

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

Higgs Condensate Oscillates!

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

SM species always created due to Non-Perturb effects!
No Coupling to Inflaton

1) LIGHT
2) HEAVY

Higgs @ Inflation

After Inflation

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

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

Higgs Condensate Oscillates!

UNiVERSAL SM Excitation !!
UNIVERSAL SM Excitation !!

[ Both: LIGHT & HEAVY ]
Initially: $\langle \lambda \varphi_*^4 \rangle \ll H_* m_p^2$

SM produced! but subdominant

UNiVERSEAL SM Excitation !!

[ Both: LIGHT & HEAVY ]
Initially: $\langle \lambda \varphi^4 \rangle \ll H^2_m^2$

SM produced! but subdominant

UNiVERSAL SM Excitation !!

[ Both: LIGHT & HEAVY ]
Initially: $\langle \lambda \varphi^4_\star \rangle \ll H^2_\star m^2_p$

SM produced! but subdominant
Initially: $\langle \chi \varphi^4 \rangle \ll H_*^2 m_p^2$

SM produced! but subdominant

Kination-Domination

Energy $\propto \frac{1}{\alpha^6}$
Initially: $\langle \lambda \varphi_4^4 \rangle \ll H_*^2 m_p^2$

SM Excitation

SM produced! and dominates

Kination-Domination

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

Inflaton

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

Higgs + SM species

$\propto \frac{1}{a^4}$

Higgs + SM Dominate !!!
 Initially: $\langle \lambda \phi_*^4 \rangle \ll H_*^2 m_p^2$

**SM Excitation**

SM produced! and dominates

**Kination-Domination**

$E \propto \frac{1}{\alpha^6}$

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

$\phi_e \sim O(10^{12}) \frac{\alpha^6}{\xi^2} \propto \Phi^{-\alpha^6}$

Energy

Time

Higgs + SM species

Higgs + SM Dominate !!!

Inflaton

(Data)
Case HEAVY

\[ T_{RH} \sim \mathcal{O}(10^{10}) \left( \frac{\xi^2}{\lambda} \right)^{\frac{3}{4}} \left( \frac{H_\ast}{H_{\text{max}}^\ast} \right)^2 \] (GeV)

Higgs @ Inflation

1) LIGHT

No Coupling to Inflaton

2) HEAVY

After Inflation

1) \( P_\xi \sim 0.1\sqrt{\lambda} \gg 2 \cdot 10^{-9} \)

@ CMB scales

2) \( P_\xi \sim 0.01/\sqrt{\xi} \)

@ Very Small Scales
Case HEAVY

\[ T_{RH} \sim O(10^{10}) \left( \frac{\xi^2}{\lambda} \right)^{\frac{3}{4}} \left( \frac{H_*}{H_{\text{max}}^*} \right)^2 (\text{GeV}) \]

1) LIGHT
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Higgs @ Inflation

1) \( P_\xi \sim 0.1\sqrt{\lambda} \gg 2 \cdot 10^{-9} \)

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@ Very Small Scales

After Inflation

✓

✓
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

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

**Gravitational Wave Amplitude**

\[ \Theta_{GW} \]

**Gravitational Wave Generation**

**Explosive Particle Production!**

**Universal Production!**

**Gravitational Wave Amplitude**

\[ \Theta_{GW} \]

GW Today: \( h^2 \Omega_{GW}^{(P)} \mid_t \sim 10^{-29} \left( \frac{0.01}{\lambda} \right) \left( \frac{H_*}{H_*^c} \right)^4 \left( \frac{\alpha_{RD}}{\alpha_*} \right)^{|3w-1|} \)

Running Self-Coupling 

Hubble Rate 

Equation of State 

\(~ ? ~\)
Gravitational Waves from Higgs decay Products

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

Gravitational Wave Amplitude

GW Today: \( h^2\Omega^{(p)}_{GW} \big|_t \sim 10^{-29} \left( \frac{0.01}{\lambda} \right)^3 \left( \frac{H_*}{H_{\text{crit}}} \right)^4 \left( \frac{a_{RD}}{a_*} \right)^{|3w - 1|} \) \( \sim 10^{-16} \) @ \( f_* \sim 10^{10} \text{Hz} \)
If there is Kination-Domination ...

Consequences:

1) Reheating the Universe

2) GW from Higgs decay products

3) Inflationary GW - blue tilted!
Gravitational Waves from Inflation

(Kination Domination)

(DGF, Torrenti 2016)

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

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

Observable?
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 $\rightarrow$ irrelevant? (baryogenesis, magnetogensis, DM ???)

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

Reheating the Universe into the SM!

+ (Observable ?) blue-shift Inflationary-GW

Kusenko et al '14-15

DGF & Byrnes '16
Cảm ơn !
Stability of the SM during Inflation?

\[ V(\varphi) = \frac{\lambda(\varphi)}{4} \varphi^4 \]

\[ \lambda \sim 10^{-5} - 10^{-2} \]

(Degrassi et al 2012, Bezrukov and Shaposhnikov 2012)