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Preheating with L-R neutrino oscillation

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Higgs inflation for νMSM
as a working example

Why Higgs Inflation?

Planck 2015 results. XX. Constraints on inflation

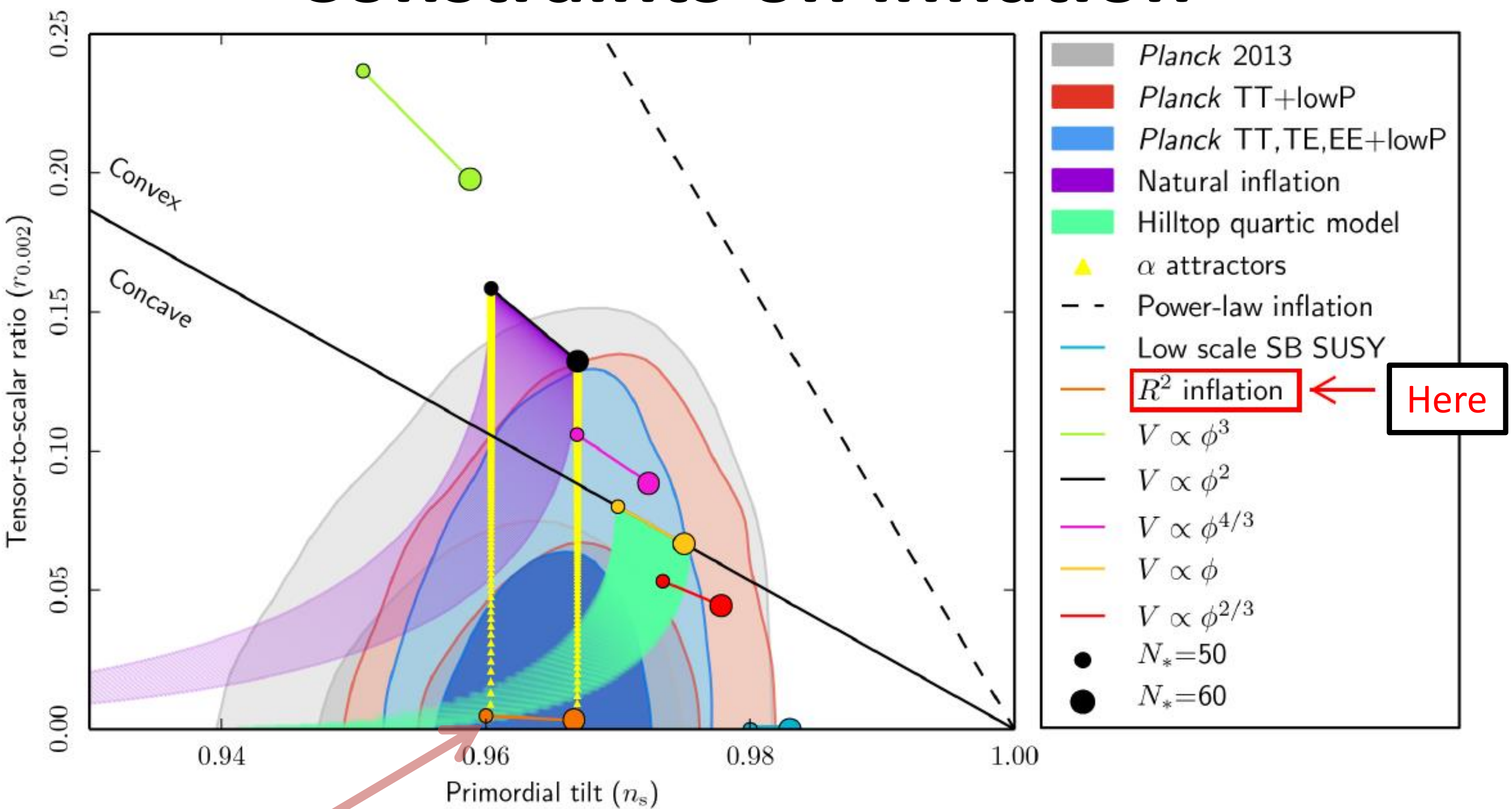


Fig. 12. Marginalized joint 68 % and 95 % CL regions for n_s and $r_{0.002}$ from *Planck* in combination with other data sets, compared to the theoretical predictions of selected inflationary models.

In good agreement with the Data sets

Planck 2015 results. XX. Constraints on inflation

Higgs inflation = Non-minimally coupled inflation
= R^2 (Starobinsky) Inflation (?)

Non-minimally coupled inflaton

Inflationary predictions are quite sensitive to a non-minimal coupling, $\xi R\phi^2$, of the inflaton to the Ricci scalar. One of the most interesting effects due to $\xi \neq 0$ is to reconcile the quartic potential $V(\phi) = \lambda\phi^4/4$ with *Planck* observations, even for $\xi \ll 1$.

The Higgs inflation model (Bezrukov & Shaposhnikov, 2008), in which inflation occurs with $V(\phi) = \lambda(\phi^2 - \phi_0^2)^2/4$ and $\xi \gg 1$ for $\phi \gg \phi_0$, leads to the same predictions as the R^2 model to lowest order in the slow-roll approximation at tree level (see

Reheating process is not the same <= our focus

Why νMSM?

*usually assume $M_s < \Lambda_{EW}$
singlet fermion $\simeq \nu_R \simeq$ sterile neutrino

νMSM

The minimal extension of the SM by three right-handed singlet fermions

The Standard Model (SM) lacks

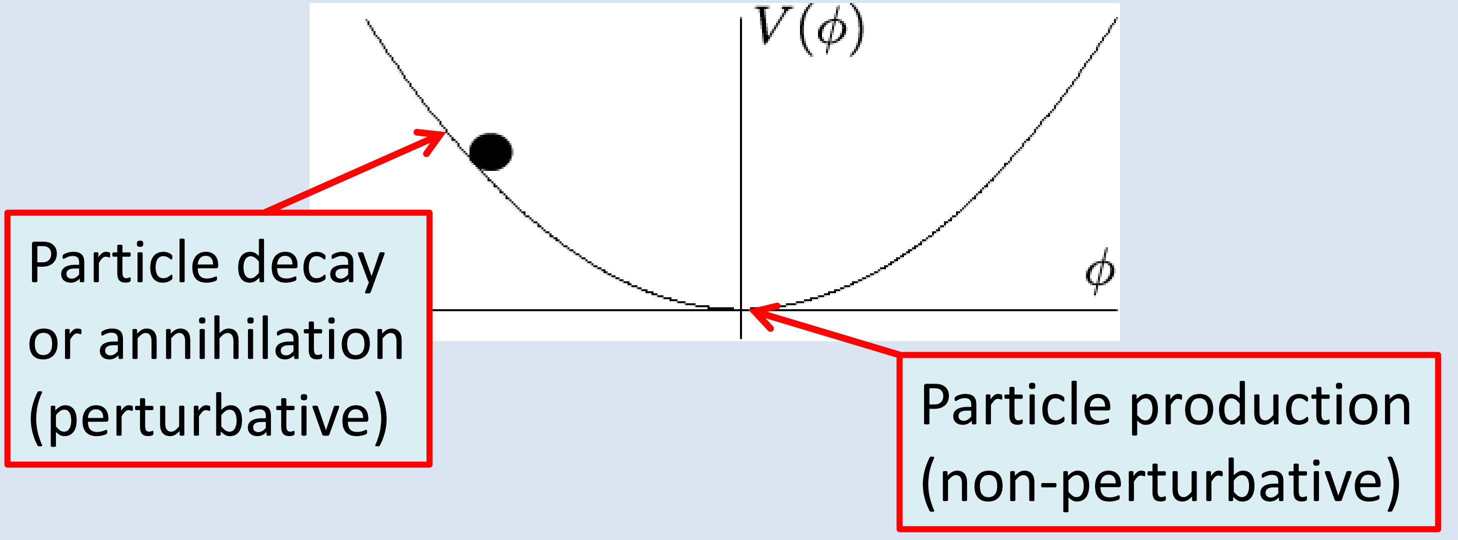
1. Neutrino Mass => See-Saw Mechanism
2. Baryogenesis => Leptogenesis
3. Dark Matter => Singlet fermion
4. Anomalies => Sterile neutrinos

For these solutions ν_R(Singlet fermion) is useful

The νMSM gives a minimal set of "beyond SM"
A good starting point

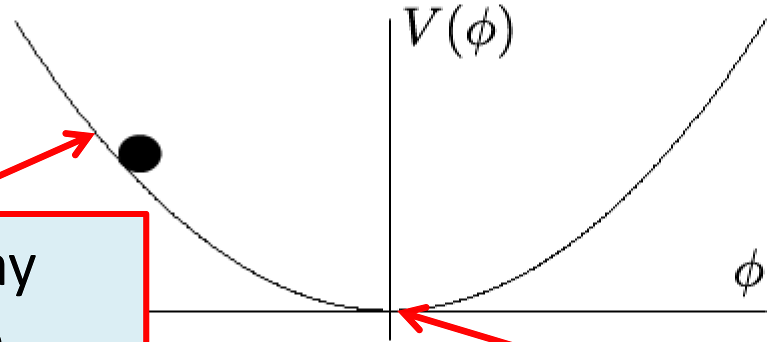
How Reheating goes along ?

1. Oscillation (Higgs field)
2. Preheating



3. Reheating

Our idea is very simple



$W^{\pm}, Z^0$ decay or annihilate into SM fermions

$W^{\pm}, Z^0$ production

Mixing at this moment

ν_L is generated,

mass matrix is not diagonal for (ν_L, ν_R)

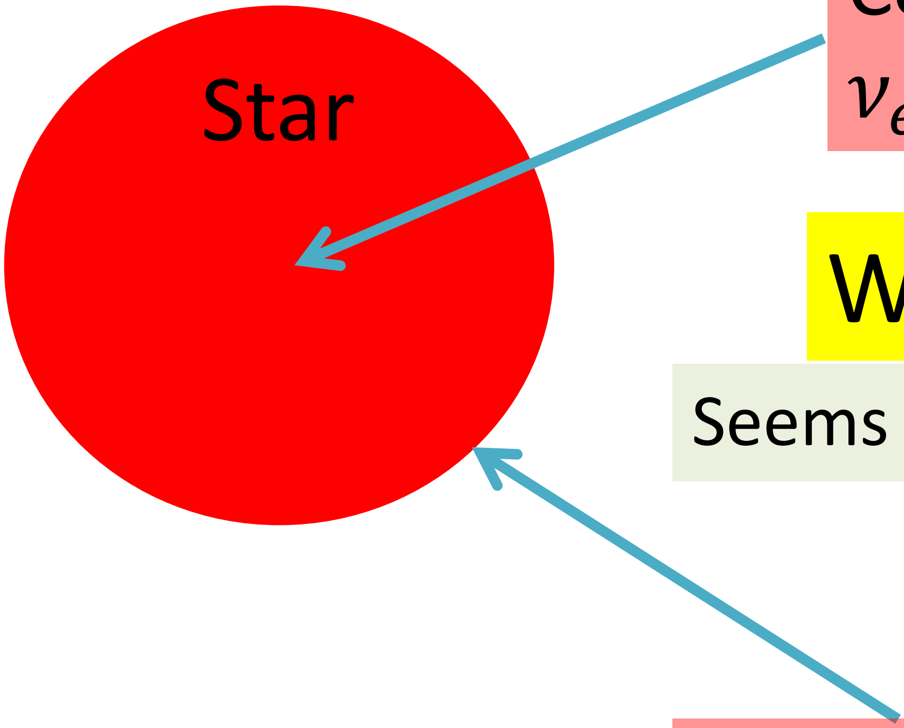
*We are not thinking about neutrino oscillation after reheating

Normally, singlet fermions are negligible because:

Direct production <= forbidden (by definition)

Secondary process <= suppressed by tiny coupling

Similar process in Astrophysics

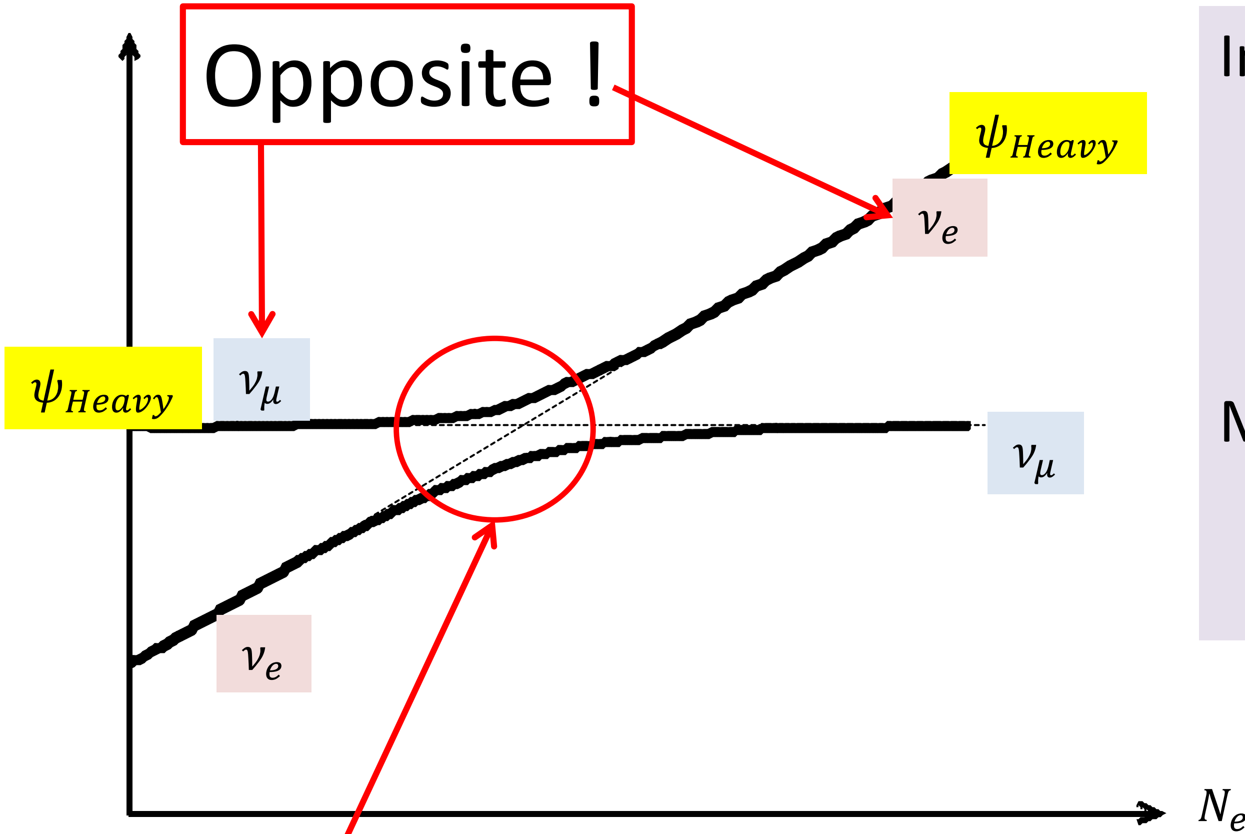


Core
ν_e production

WHY?

Seems strange in $\{\nu_e, \nu_\mu\}$ base

Surface
ν_μ emission



In the core (N_e is large)

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = H\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}$$

$$H \propto \begin{pmatrix} N_e & c_1 \\ c_2 & c_3 \end{pmatrix}$$

Mass eigenstates are

$$\psi_{heavy} \simeq \nu_e$$

$$\psi_{light} \simeq \nu_\mu$$

During the adiabatic process
“mass eigenstates” are separated
*definition changes

In our work
ν_L from W^+, Z^0 is
translated into ν_R

Calculation

Seesaw Mass matrix

$$M = \begin{bmatrix} 0 & m_D \\ m_D & M_R \end{bmatrix},$$

In terms of the mass eigenstates $[\psi_+, \psi_-]$, neutrinos are

$$\begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix} = \begin{bmatrix} cos\theta & -sin\theta \\ sin\theta & cos\theta \end{bmatrix} \begin{pmatrix} \psi_- \\ \psi_+ \end{pmatrix}$$

$\theta \rightarrow 0$ (No mixing) in the Vacuum

$\theta \rightarrow \frac{\pi}{4}$ (Maximal mixing) at the decay

$m_D \propto h$ (in the original frame)

**This must be seen in the Einstein frame

Conformal transformation => E-frame

h (original Higgs) => ϕ (E-frame)

$$\Omega^2(h) = 1 + \frac{\xi h^2}{M_p^2} = e^{\alpha\kappa\phi}$$

$$M_R = M_*^2 e^{-\alpha\kappa|\phi|}, \qquad m_D = \frac{y_\nu^2 M_p^2 \left(1 - e^{-\alpha\kappa|\phi|}\right)}{\xi}$$

1. ϕ is moving
2. Gauge bosons decay when ϕ is large
3. L-R Mixing at the decay is Maximal

   i.e. $\nu_L \sim \frac{1}{\sqrt{2}}(\psi_+ - \psi_-)$

Other quantities (E-frame)

$$V(\phi) = \frac{1}{2}M^2\phi^2,$$ Inflaton Potential

$$M = \frac{\sqrt{\lambda}M_p}{\sqrt{3}\xi},$$ Inflaton Mass

$$m_W^2 = \frac{g_2^2 M_p^2\left(1 - e^{-\alpha|\phi|}\right)}{4\xi}, \mathrm{m_Z^2} = \frac{\mathrm{m_W^2}}{\cos\theta_W}$$

Mass of the Gauge bosons

"Estimation" of the abundance is a simple task

Procedure

1. Calculate n_W and n_Z (conventional Preheating)
2. Find the branching ratio of $Z^0, W^\pm \to \nu_L$ from PDG
3. If the Mixing is Maximal at $Z^0, W^\pm \to \nu_L$,
   1/2 of ν_L is translated into ν_R

All these quantities are time-dependent and non-local (= integration of the past)

Exact calculation is very difficult

Fortunately this model is "nearly" local since until (just before) reheating gauge bosons decay rapidly preventing parametric resonance

Simple and intuitive estimation is possible

Estimation

<u>Simplifications (based on previous works)</u>

1. Main product of preheating is $Z^0, W^\pm$ since no resonance for fermions
2. Estimate quantities just before reheating (most ν_L are generated here)

no integration

3. $Z^0, W^\pm$ decays partially ($\epsilon_d \sim 0.1$)
4. Branching ratio ($\epsilon_{br} \sim 0.1$)

$$n_{\nu_L} \sim \epsilon_d \epsilon_{br} (n_{W^\pm} + n_{Z^0})$$

no resonance if $\epsilon_d = 1$
resonance starts
just before reheating

5. The mixing is maximal

$$n_{\psi_+} \sim n_L$$

This gives the abundance of the singlet fermions
$10^7 \times \epsilon_d\, \epsilon_{br} \sim 10^5$ times larger than the usual

Dark Matter Constraint is very severe

If ν_R is DM, usual result leads to

$$M_{\nu_R} < 3\text{MeV}\left(\frac{0.25}{\lambda}\right)^{\frac{1}{4}}$$

Because of the enhancement $10^7 \times \epsilon_d \, \epsilon_{br}$,
our result leads to

$$M_{\nu_R} < 0.1 \text{ eV}\frac{\left(\frac{0.25}{\lambda}\right)^{\frac{1}{4}}}{\epsilon_d \epsilon_{br}}$$

Conclusions and More

Neutrino oscillation during preheating
leads to significant enhancement of ν_R

If ν_R is essential for "beyond SM" scenarios,
Higgs inflation could be distinguishable
because of the significant ν_R-abundance
(especially when ν_R is stable)

We did not mention Leptogenesis with decaying ν_R
We found a small improvement (not significant)