The Seesaw Mechanism
--- 37 Years Later---

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Discovery of the Seesaw Mechanism

A Puzzle in the Weinberg-Salam model:

Gauge group = SU(3)xSU(2)xU(1)

1. U(1) hypercharges ?

$$q_L^i = \begin{pmatrix} u \\ d \end{pmatrix}_L^i \text{ (1/6)} \qquad u_R^i \text{ (2/3)} \qquad d_R^i \text{ (-1/3)}$$

$$l_L^i = \begin{pmatrix} \nu \\ e \end{pmatrix}_L^i \text{ (-1/2)} \qquad e_R^i \text{ (-1)}$$

The theory is anomaly free with these awkward charges !

An example; 6x(1/6)^3 + 3x(-2/3)^3 + 3x(1/3)^3 +2x(-1/2)^3 +(+1)^3 =0

The hypercharges are naturally explained in a grand unification

SU(3)xSU(2)xU(1) is embedded in **SU(5)**

Georgi, Glashow (1974)

All quarks and leptons belong to **5* + 10** of the SU(5) !
The hypercharges are given by an SU(5) generator

But, the quarks and leptons are not completely unified

SO(10) contains the SU(5) and is more attractive, since it unifies all quarks and leptons in 16

ν_R^i

16= $q_L^i = \begin{pmatrix} u \\ d \end{pmatrix}_L^i \quad \begin{matrix} u_R^i \\ d_R^i \end{matrix} \quad ; \quad l_L^i = \begin{pmatrix} \nu \\ e \end{pmatrix}_L^i \quad e_R^i$

We had a big problem

The neutrino has a large Dirac mass

$$y_\nu \bar{\nu}_R l_L \langle H \rangle \quad ; \quad y_t \bar{t}_R q_L \langle H \rangle$$

$y_\nu = y_t \longrightarrow$ m(neutrino) = m(top) ???

But, we found the right-handed neutrino get a huge Majorana mass when the SO(10) breaks down to the Standard Model

$$\frac{1}{2} M \bar{\nu}_R^C \nu_R$$

The neutrino mass becomes $m_\nu \simeq \frac{m^2}{M}$; $M_N \simeq M$

Yanagida (1979)
Gell-Mann, Ramond, Slansky (1979)

Seesaw Mechanism

Leptogenesis

Fukugita and Yanagida (1986)

N decays create the lepton asymmetry,
which is converted to baryon asymmetry

We can explain why our universe is made of baryons !

The right-handed neutrinos N play more roles in cosmology than I though

Mass scales of the N

The seesaw formula: $m_\nu = y^2 \langle H \rangle^2 / M$

$m_\nu = 0.05$ eV → $M = 10^{13-15}$ GeV ! for $y = 0.1-1$

The thermal leptogenesis

→ $M > 10^{10}$ GeV Buchmuller et al

Roughly, $M = 10^{10-15}$ GeV

Mass of Inflaton

High scale inflation (Chaotic inflation)

→ M~ 10^{13} GeV !

They are both gauge singlets

They may be indetical !!!

But, the N is a fermion and the inflaton is boson

Supersymmetry (SUSY)

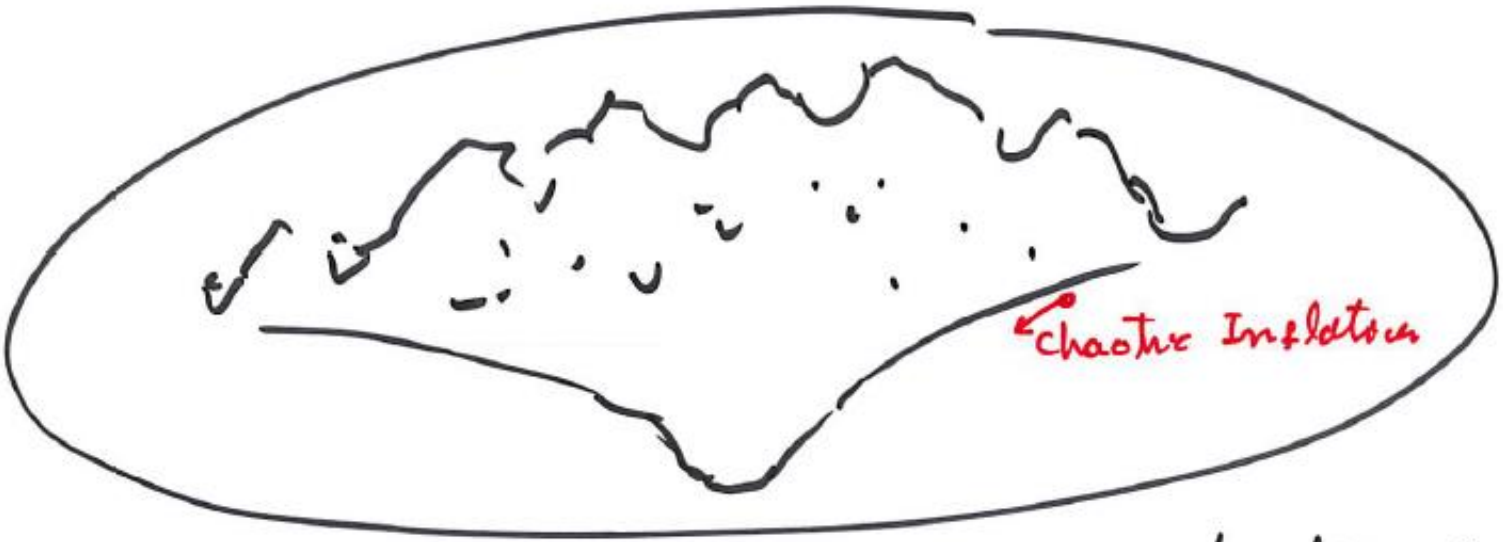
The leptogenesis requires two N's, but the inflaton is only one

However,
the chaotic inflation in supergravity requires another singlet

Kawasaki,Yamaguchi, Yanagida (2000)

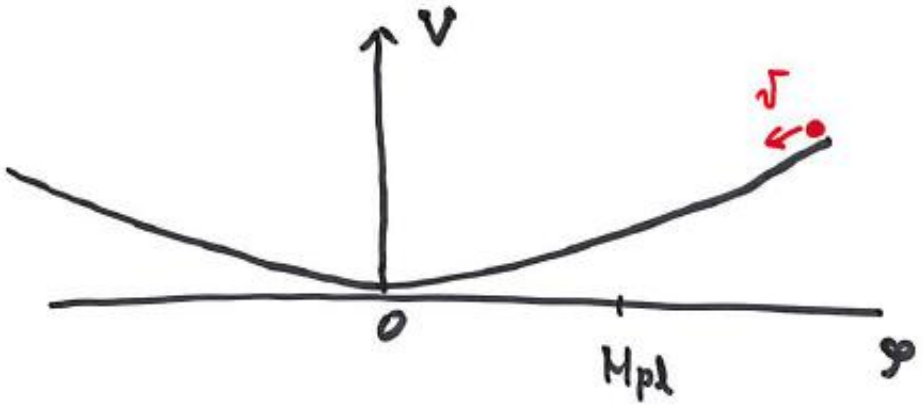
Chaotic Inflation

Linde (1983)



The chaotic Inflation is very simple.

$$V = \frac{1}{2} m^2 \varphi^2$$



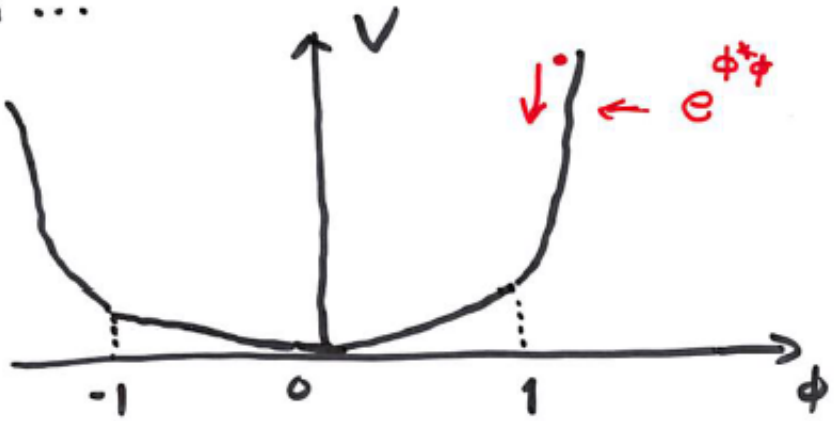
If $m < M_{pl}$, $|\varphi| > M_{pl}$. We have a slow roll inflation!

Linde (1983)

But. A Serious Problem in Supergravity :

$$V \simeq e^{K}\left\{|DW|^2 - 3|W|^2\right\}$$

$$K = \phi^*\phi + \cdots$$

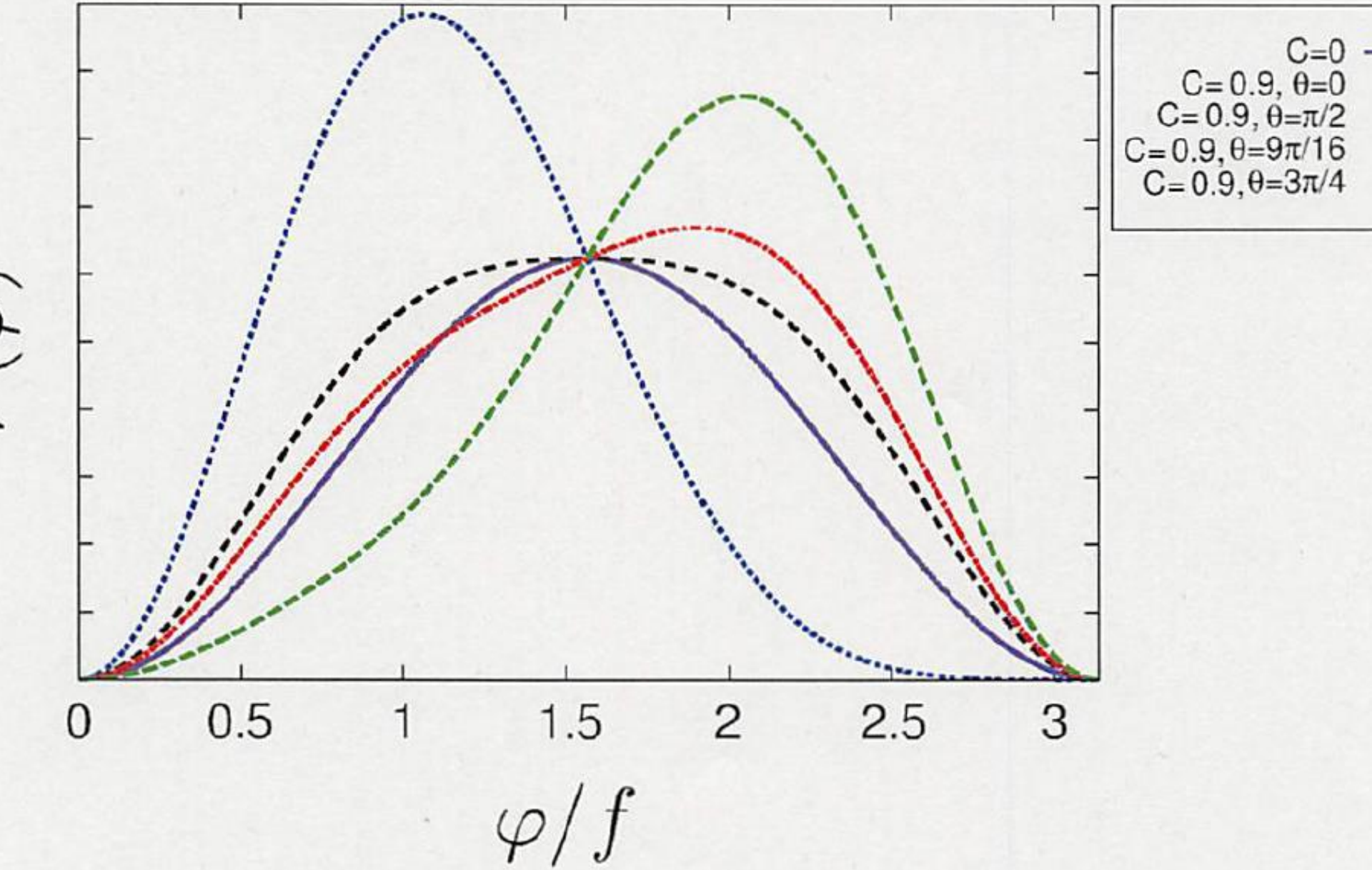


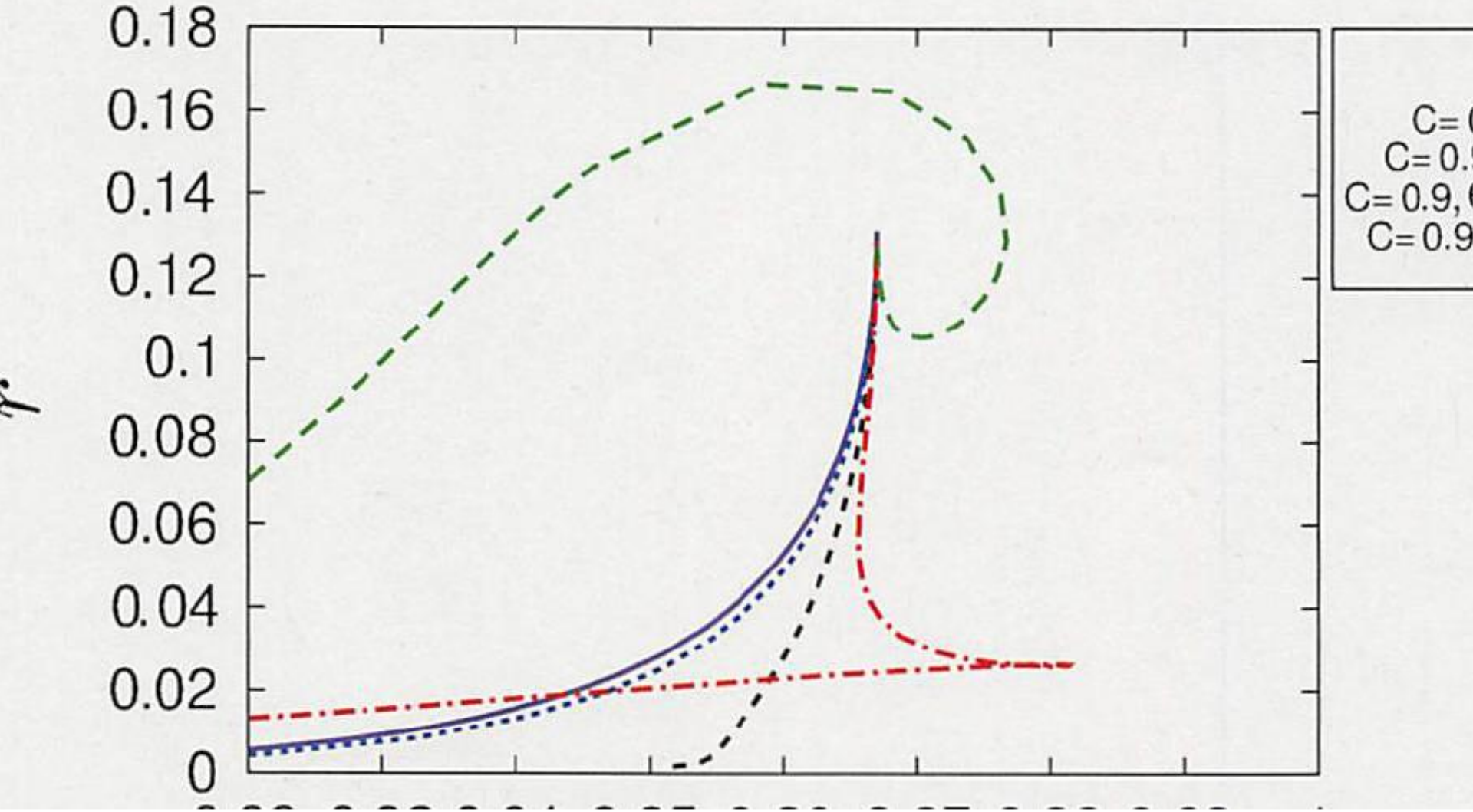
The potential is no longer flat above $M_{pl} = 1$.

No slow roll !!!

Chaotic Inflation is impossible !!!

Linde (1984)


C=0
C= 0.9, θ=0
C= 0.9, θ=π/2
C= 0.9, θ=9π/16
C= 0.9, θ=3π/4
0
0.5
1
1.5
2
2.5
3
φ/f


0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
C=
C= 0.
C= 0.9,
C= 0.9