

# Neutrino mass in the landscape of vacua

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# Neutrino mass

$$L_{\text{eff}} = (1/M_*) LLHH$$

Weinberg (1980)

Yanagida (1981)

$$m = 0.1 \text{ eV} \rightarrow M_* = 10^{15} \text{ GeV} \ll M_{\text{Planck}}$$

**GUT Seesaw**      Yanagida (1979) ; Gell-Mann, Ramond, Slansky (1979)

SO(10) GUT contains a singlet **N** in **16** and **N**  
exchange gives the effective operator  $L_{\text{eff}}$

$$M_* = M_N = \text{the GUT scale}$$

But, the observed large lepton mixing may be a problem

**TeV Seesaw**      Minkowski (1977) ; .....

$$M_* = (1/y^2) M_N ; M_N = \text{TeV scale}$$

But, we need a very small Yukawa coupling  $y$

*For  $y=0.01-1$ ,  $M_N = 10^{\{11-15\}}$  GeV*

**Who ordered the Ns and their masses ?**

# Inflation

- Chaotic inflation is the most attractive, since we have no initial fine tuning problem
- The mass of inflaton is  $10^{\{13\}}$  GeV !!!
- It coincides with the Seesaw mass scale

*What does it mean ?*

**Accidental or Fundamental**

- The right-handed neutrino  $N$  and the inflaton  $A$  are both singlets

**What is wrong to identify  $N$  with  $A$  ?**

## **Problems**

- 1.  $N$  is a fermion, but  $A$  is a scalar boson***
- 2. We need at least two  $N$ s to explain the neutrino masses and mixing but only one  $A$  is sufficient***

# Supersymmetry

- The  $N$  can be a fermion partner of the  $A$

Murayama, Yanagida, Yokoyama (1993)



**The second problem is also solved in Supergravity**

# Chaotic Inflation in Supergravity

$A$ : the inflaton chiral multiplet

The inflaton potential  $V$  is

$$V = \exp(AA^*) [\dots\dots]$$

The potential becomes **too steep** as  $A$  exceeds the Planck scale

**The chaotic inflation does not work at all !**

Then, we introduce a **shift symmetry** to get a flat potential

$$A \rightarrow A + i C$$

The Kahler potential is

$$K = (A + A^*)^2$$

The potential is now  $V = \exp\{(A + A^*)^2\}[\dots]$

The inflaton  $I$  is the imaginary part of  $A$  and the potential of  $I$  is completely flat beyond the Planck scale

Now let us introduce a mass term

$$W = (m/2)A^2$$

But, it does not work

$$V = \exp\{(A+A^*)^2\} [ |W_A|^2 - 3|W|^2 ]$$

$$[ \dots ] = m^2 |A|^2 - 3 | (m/2)A^2 |^2$$

The inflaton potential becomes **negative** for  $|A| >$  the Planck scale !

We introduce a stabilizer  $S$

Kawasaki, Yamaguchi, Yanagida (2000)

$$W = mAS$$

We obtain a desired potential for the inflaton  $V = m^2 |A|^2$

**We need two chiral multiplets  $A$  and  $S$  in supergravity !!!**

**They can be identified with two chiral multiplets of the right-handed neutrinos,  $N_1$  and  $N_2$**

We call the inflaton  $A$  as  $N$  and the stabilizer  $S$  as  $N'$

$$W = M NN' + yLNH + y'LN'H$$

This give us a quasi flat inflaton potential and small neutrino masses !

$$M = 10^{13} \text{ GeV}; \quad y=y'=O(0.1)$$

# Still a problem

*Now, the inflaton  $I$  is the imaginary part of the scalar  $N$*

During chaotic inflation the inflaton  $I$  has a large value,  
 $\langle I \rangle \gg O(10) M_{PL}$

**Then,  $L$  and  $H$  have an effective mass  $\gamma \langle I \rangle \gg M_{PL}$   
and they form Black Hole !!!**

A simple solution is given if the Yukawa couplings are functions of the inflaton field so that the effective mass of LH does not monotonically increase as Inflaton field increase beyond the Planck scale

***An intriguing possibility is that the system comes back to the SM as the inflaton field exceeds a critical value !!!***

This is simply realized in the case that the shift symmetry is not completely broken in the superpotential, but a ***discrete shift symmetry*** remains unbroken

$$I \text{ -----} \rightarrow I + 2\pi f$$

Nakayama, Takahashi, Yanagida (2016)

Now, the Yukawa coupling  $y = y_0 \{ \sin(I/f) + k \sin(2I/f) + \dots \}$

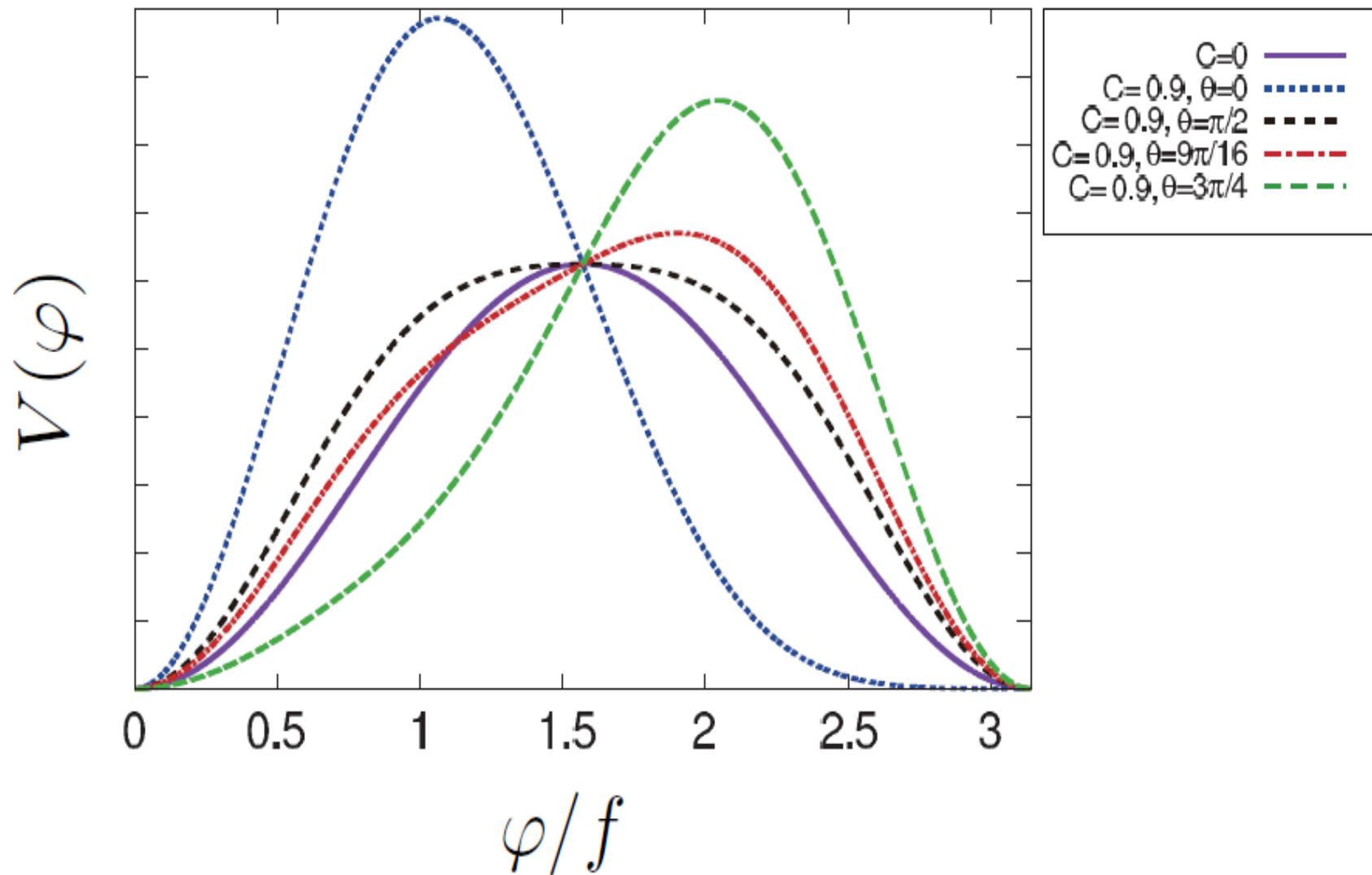
The Inflaton potential  $V$  is now

$$V = V_0 \left| \sin(I/f) + h \sin(2I/f) + \dots \right|^2$$

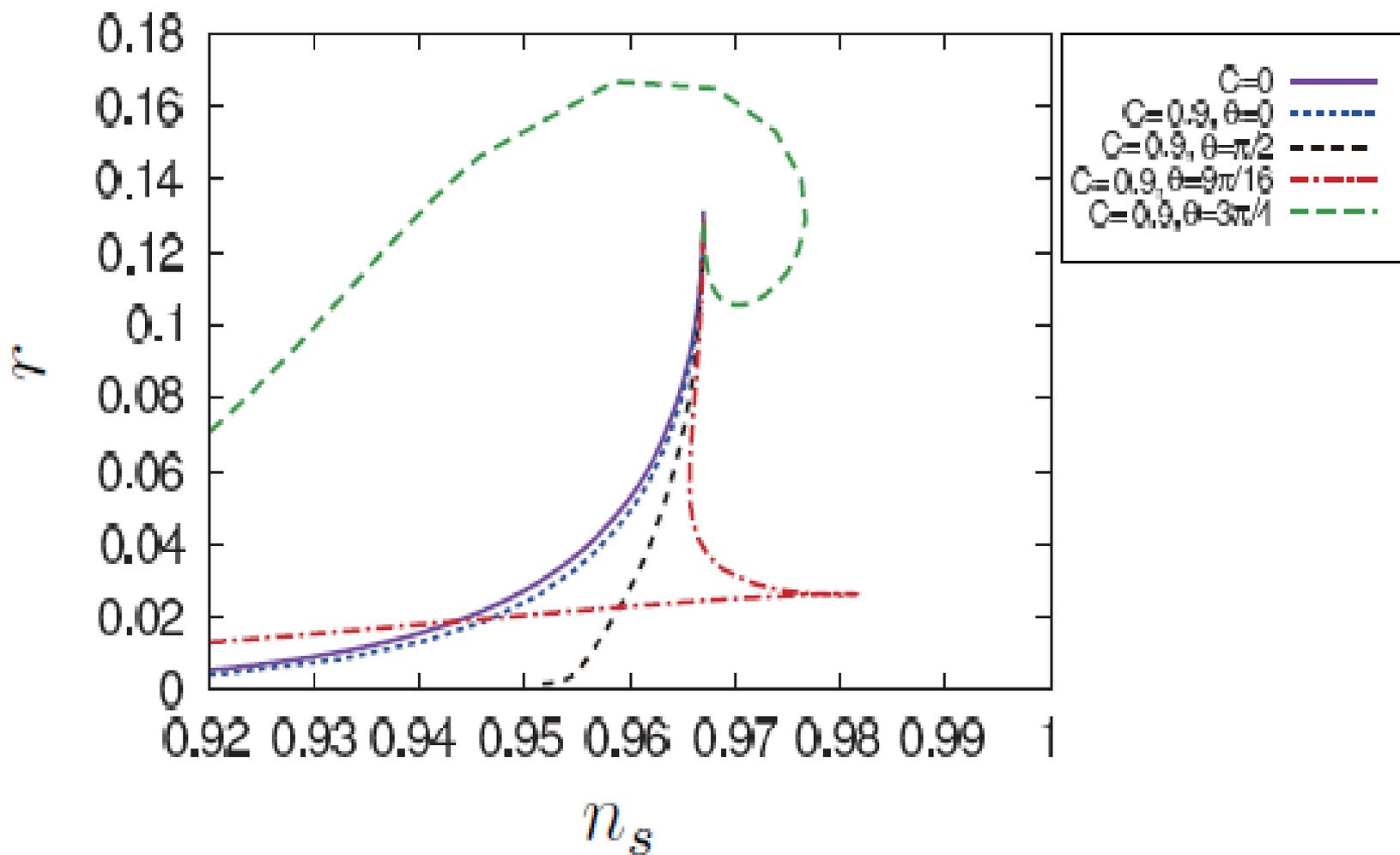
$I$  : the inflaton field

$f = O(10)$  x Planck scale

# Inflaton Potential



## The predictions of $n_s$ and $r$



$$W = M NN' + yLNH + y'LN'H$$

- $N$  causes a successful chaotic inflation
- The integration of  $N$  and  $N'$  generates small neutrino masses via the seesaw mechanism

If the Yukawa couplings  $y$  and  $y'$  have CP violating phases, the  $N$  and  $N'$  decays create Baryon asymmetry in the Universe

*Leptogenesis*

Fukugita, Yanagida (1986)

**But, the leptogenesis does not work !**

The asymmetry parameter  $\epsilon$  is

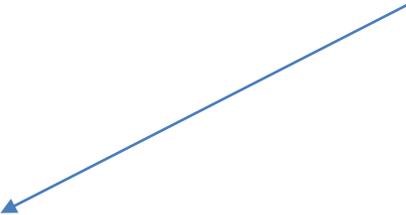
$$\epsilon_i^{\text{osc}} = \frac{\text{Im} \left\{ [(h^\dagger h)_{ij}]^2 \right\}}{(h^\dagger h)_{ii}(h^\dagger h)_{jj}} \frac{(M_i^2 - M_j^2) M_i \Gamma_j}{(M_i^2 - M_j^2)^2 + R_{ij}^2}.$$

We have the degenerate masses for two N's

$$M_1 = M_2 \rightarrow \text{vanishing asymmetry !!!}$$

But, the shift symmetry helps us again

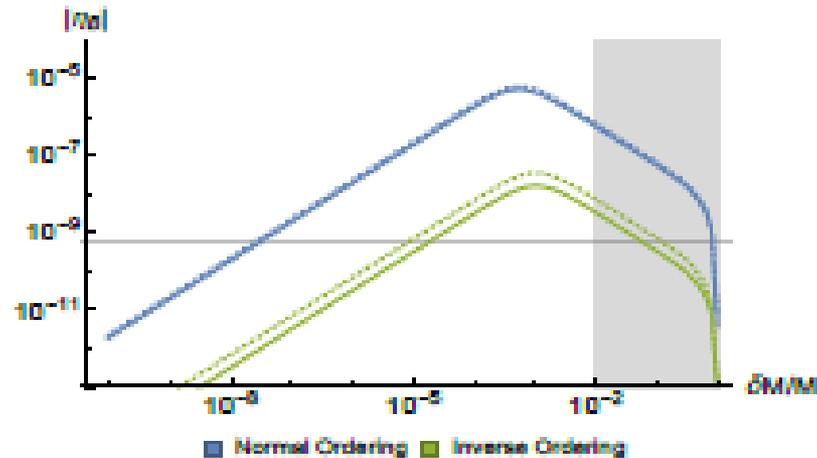
$$K = (1/2) (N+N^*)^2 + \dots = NN^* + (1/2)(NN + N^*N^*)$$


$$W = \exp(NN) W_0 = \exp(NN) \{ \dots + m_{3/2} \}$$
$$= \dots + m_{3/2} NN$$

Then, if the SUSY is broken, the mass degeneracy is resolved

$$W = MNN' + m_{3/2} NN$$

The lepton asymmetry is proportional to the gravitino mass  $m_{3/2}$



We predict  $m_{3/2} = O(100)$  TeV from the observed baryon asymmetry

Bjorkeroth, King, Schmitz, Yanagida (2016)

More Thinking .....

## Landscape of many vacua

Each vacuum is connected with many vacua by moduli  $X$

If the potential of  $X$  is sufficiently flat, we may have naturally **inflation**

The inflaton is most likely singlets and may have Yukawa coupling  
 $W = yXLH$

We call them as the right-handed neutrinos  **$N$**

They explain the observed small neutrino masses  
and the observed baryon asymmetry in the Universe

**$N$  are nothing but messengers from neighborhood vacua**

**What will we know about the neighborhood universe ?**

**If  $(n_s, r) = (0.96, 0.02)$ , the inflaton potential looks very symmetric**

**Our universe may be one of twin universes ???**

# Conclusion

$N$ 's are ordered by Landscape of vacua

$N$ 's are moduli connecting different vacua

$N$  produces the desired inflation

The decay of  $N$  creates the observed baryon asymmetry in the universe

The intergration of  $N$ 's explains the observed small neutrino masses