Anarchy and Leptogenesis

PPP2012 @YITP
2012年7月19日

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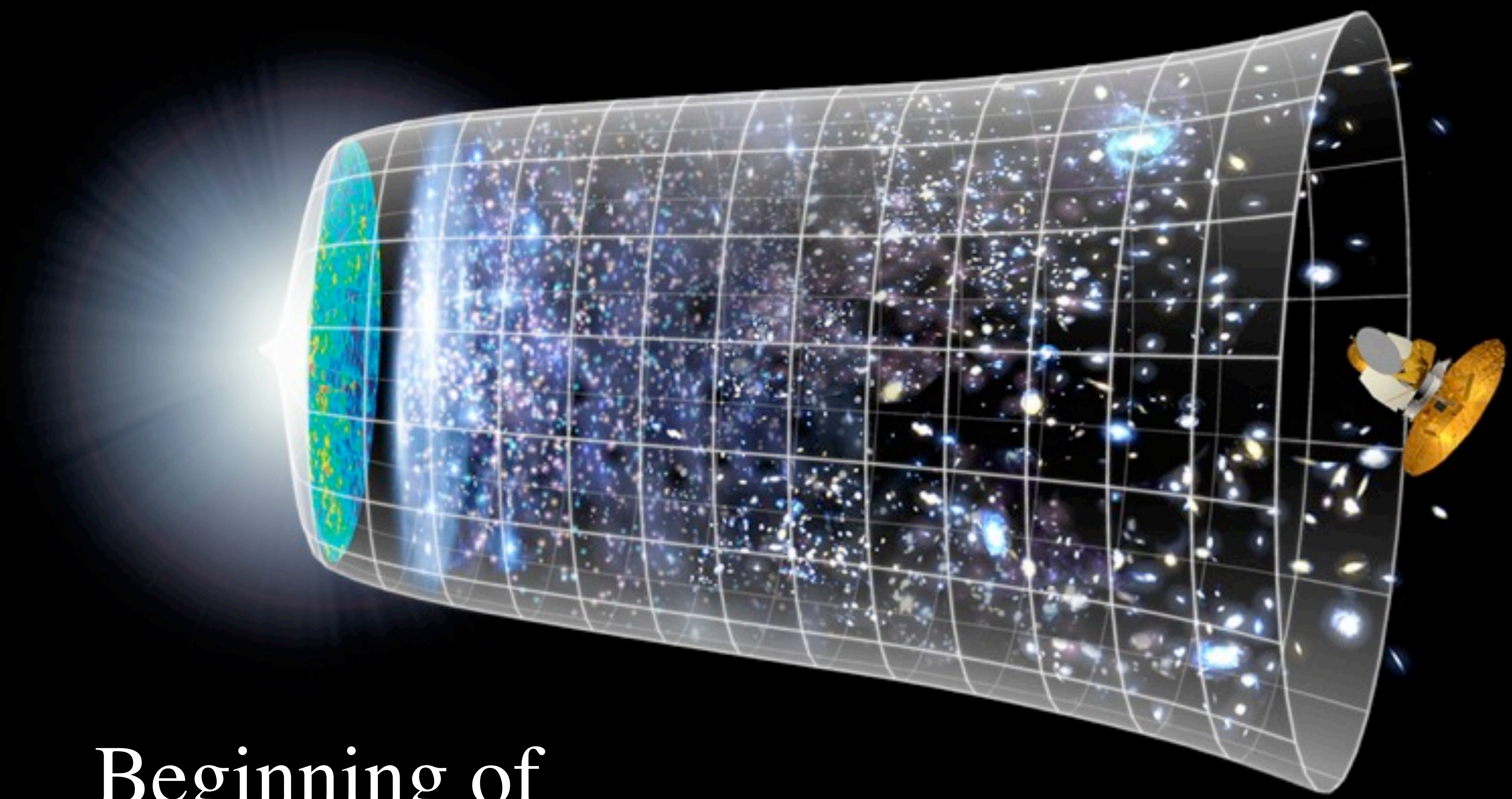
K-S. Jeong and FT, 1204.5453 (to appear in JHEP)

History of the Universe



Beginning of
the Universe

Present

NASA/WMAP Science Team

Time

We estimate T_R under 3 assumptions about neutrinos

1. Introduction

(1) Why is the neutrino mass so small?

Small but non-zero neutrino masses can be explained by the seesaw mechanism.

T. Yanagida `79, M.Gell-Mann, P.Ramond and R.Slansky `79, (Minkowski, `77)

1. Introduction

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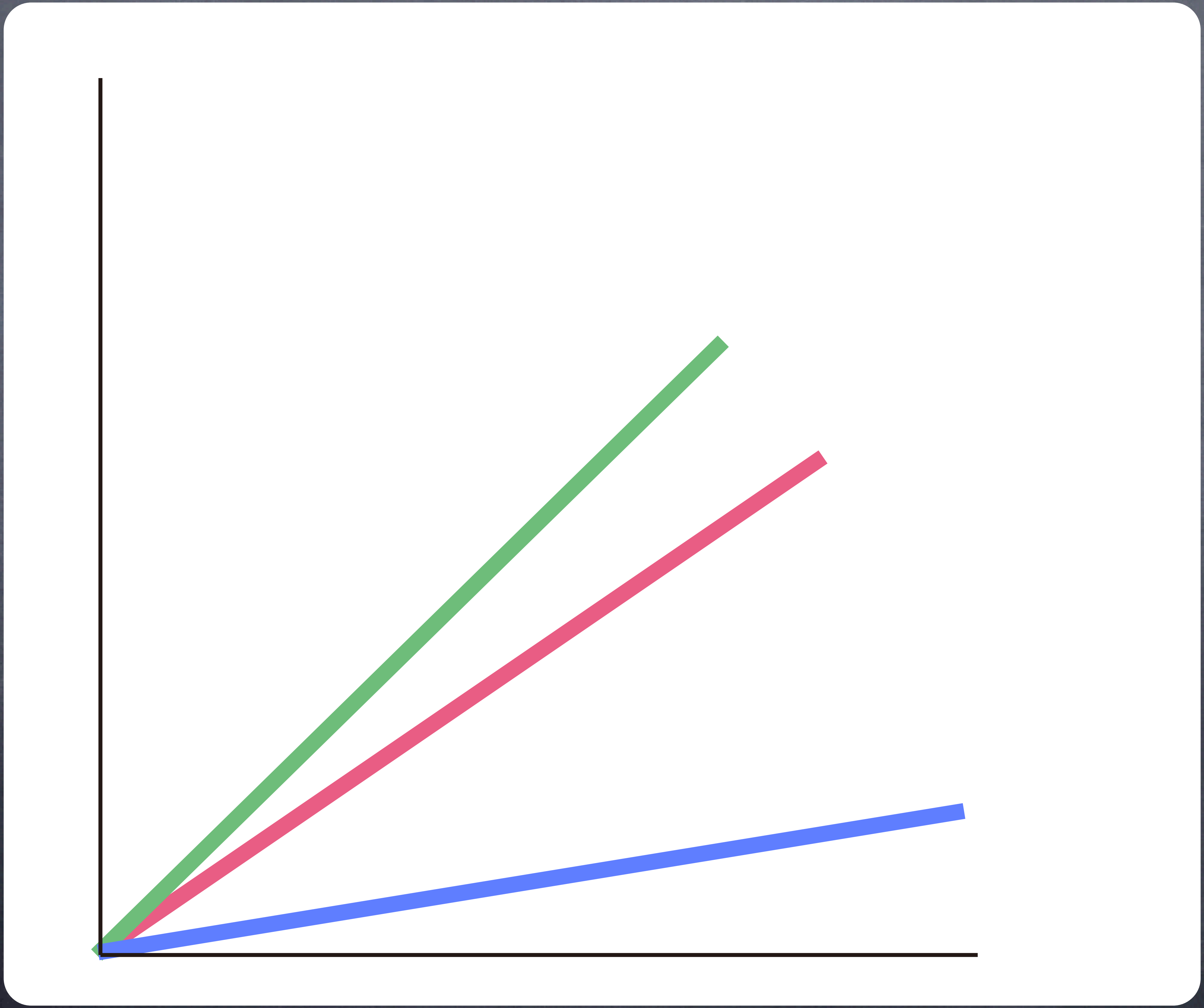
$$\mathcal{L} \supset h_{i\alpha}\bar{N}_i \ell_\alpha H - \frac{1}{2} M_{ij} \bar{N}_i \bar{N}_j + \mathrm{h.c.},$$

$$\Rightarrow \quad (m_\nu)_{\alpha\beta} = \left(h^T X^{-1} h\right)_{\alpha\beta} \frac{v^2}{M_0}$$

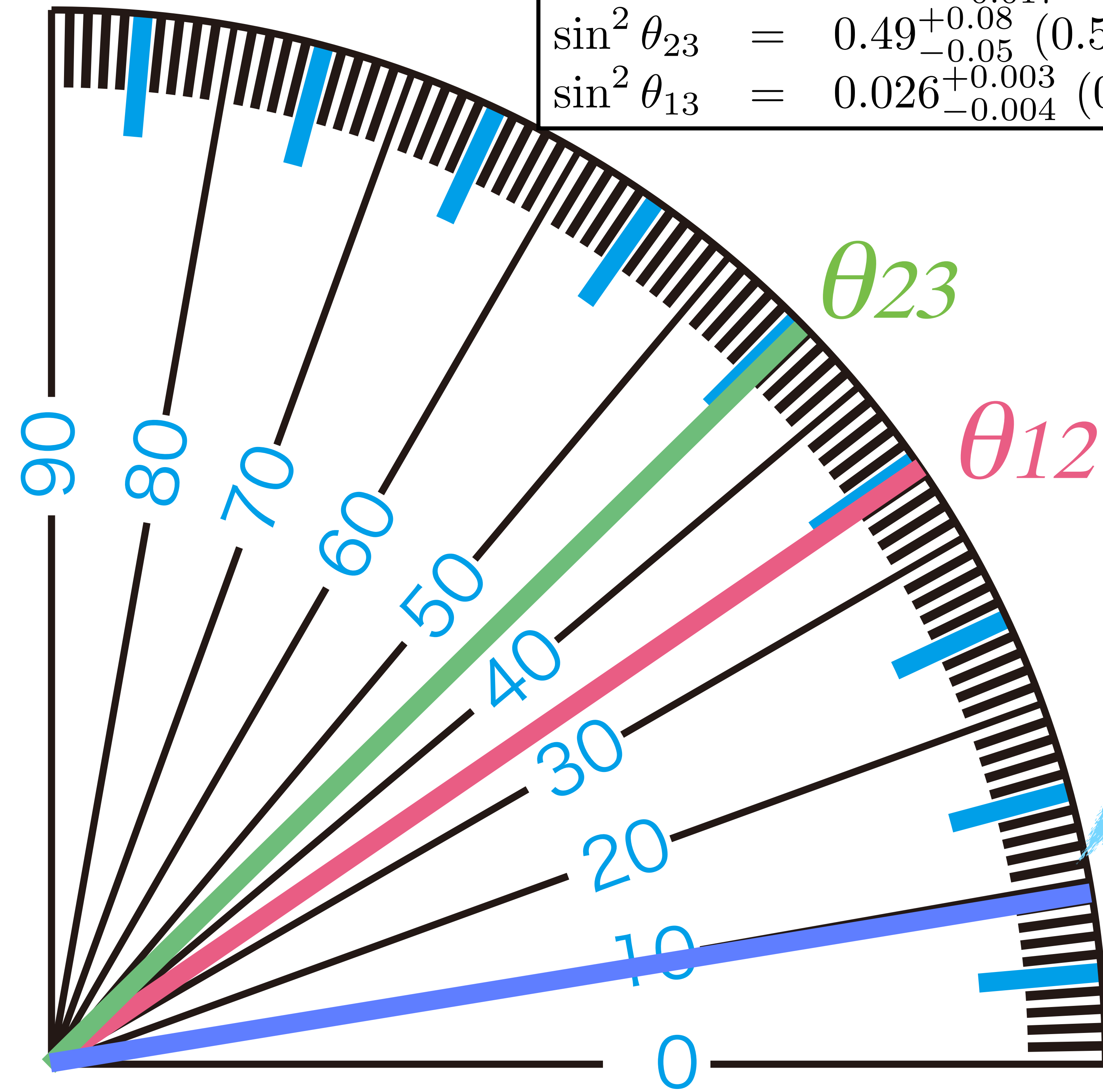
$M_{ij} \equiv M_0 X_{ij}$ M_0:typical RH neutrino mass scale

(2)



(2) Why are the neutrino mixing angles large?

$$\sin^2\theta_{12} = 0.320^{+0.015}_{-0.017},$$
$$\sin^2\theta_{23} = 0.49^{+0.08}_{-0.05}\ (0.53^{+0.05}_{-0.07}),$$
$$\sin^2\theta_{13} = 0.026^{+0.003}_{-0.004}\ (0.027^{+0.003}_{-0.004}),$$



Even the smallest one is not so small.

Neutrino Mass Anarchy

Hall, Murayama, Weiner, 99
Haba, Murayama, 00, Gouvea, Murayama, 03

Perhaps no quantum number to distinguish the neutrino flavor. If so, the neutrino Yukawa and RH Majorana mass matrices should be

1) structureless in the flavor space

They may be

2) subject to random distribution.

1) structureless in the flavor space

2) subject to random distribution.

The mixing angle and CP violation phase distributions are given by U(3) Haar distribution.

Also mild mass hierarchy realized.

$$R = \Delta m_{21}^2 / \Delta m_{32}^2 \approx 0.03$$

Random matrix and measure

$$\mathcal{L} \supset h_{i\alpha}\bar{N}_i \ell_\alpha H - \frac{1}{2}M_{ij}\bar{N}_i\bar{N}_j + \mathrm{h.c.},$$

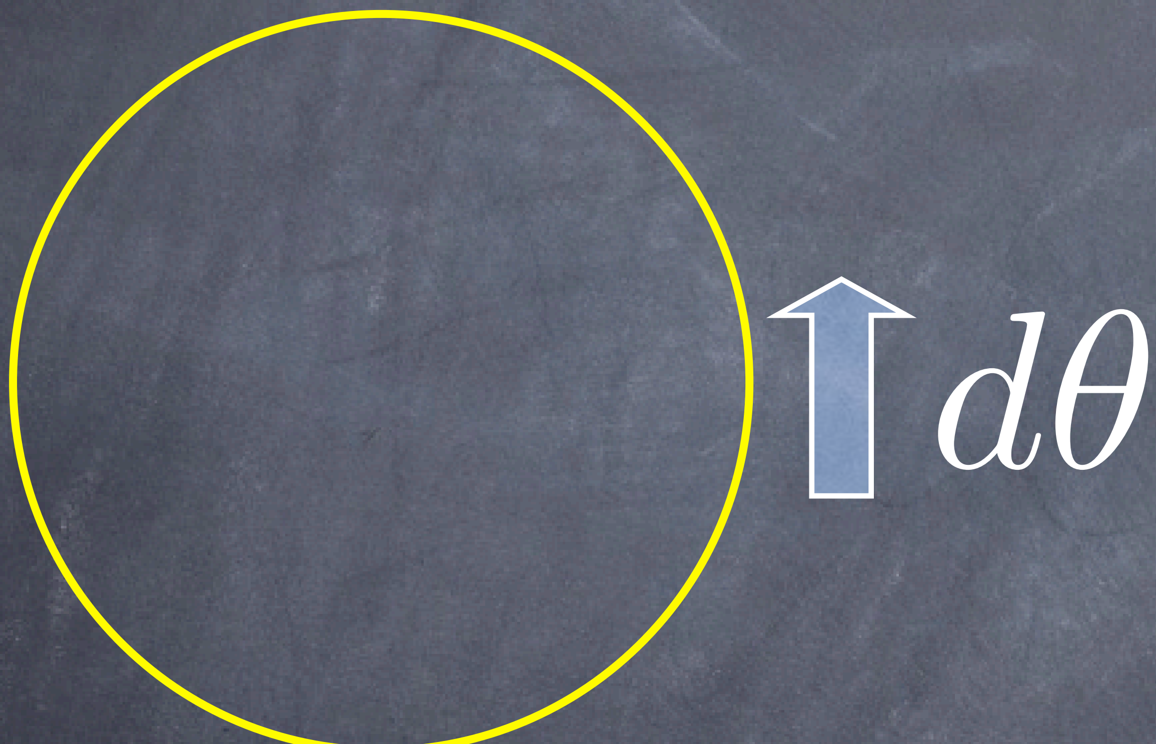
For each element, we generate a uniformly distributed random number satisfying

$$-1 \leq \mathrm{Re}[h_{ij}] \leq 1 \quad -1 \leq \mathrm{Im}[h_{ij}] \leq 1$$
$$\mathrm{Tr}[hh^\dagger] \leq 1$$

Similarly for $X_{ij} = M_{ij}/M_0$. We fix $M_0 = 10^{15}\,\mathrm{GeV}$

Haar measure

e.g.) the case of U(1)



$$dU = d\theta$$

e.g.) the case of U(3)

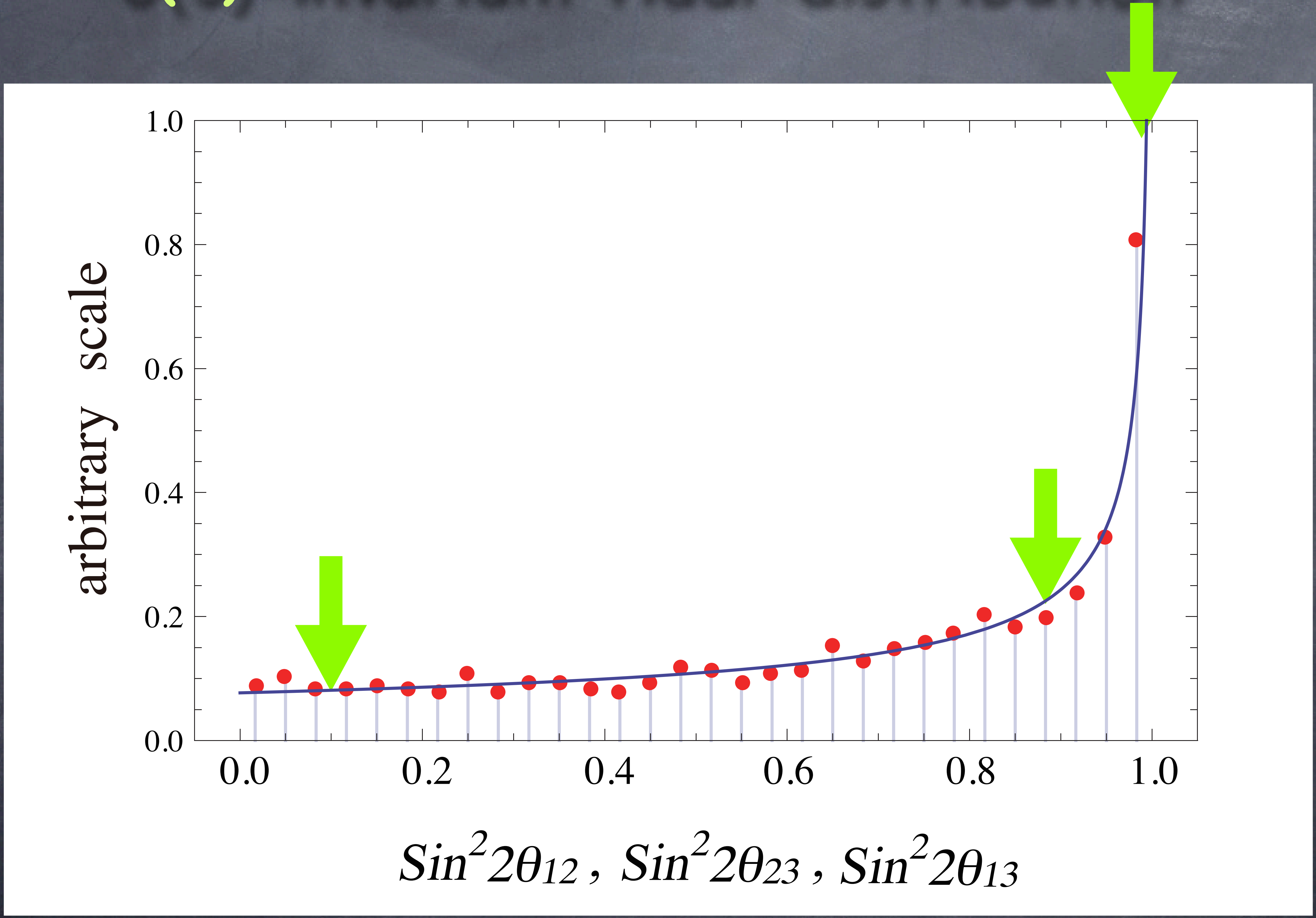
$$U_{MNS} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

$$\times \mathrm{diag}\left(1,\, e^{i\frac{\alpha_{21}}{2}},\, e^{i\frac{\alpha_{31}}{2}}\right),$$

$$dU_{MNS} = ds_{12}^2 dc_{13}^4 ds_{23}^2\, d\delta\, d\alpha_{21} d\alpha_{31}.$$

U(3)-invariant Haar distribution

U(3)-invariant Haar distribution



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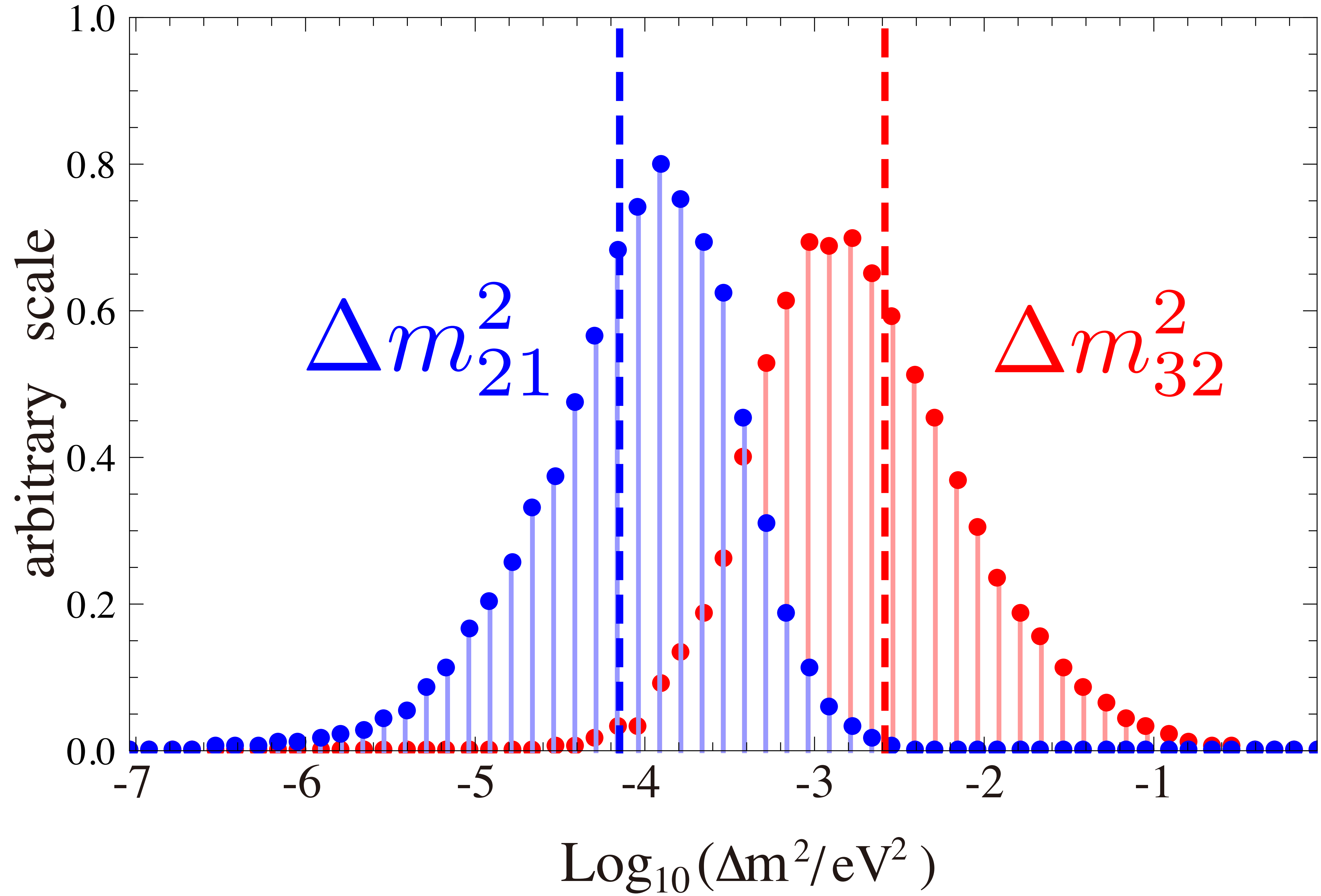
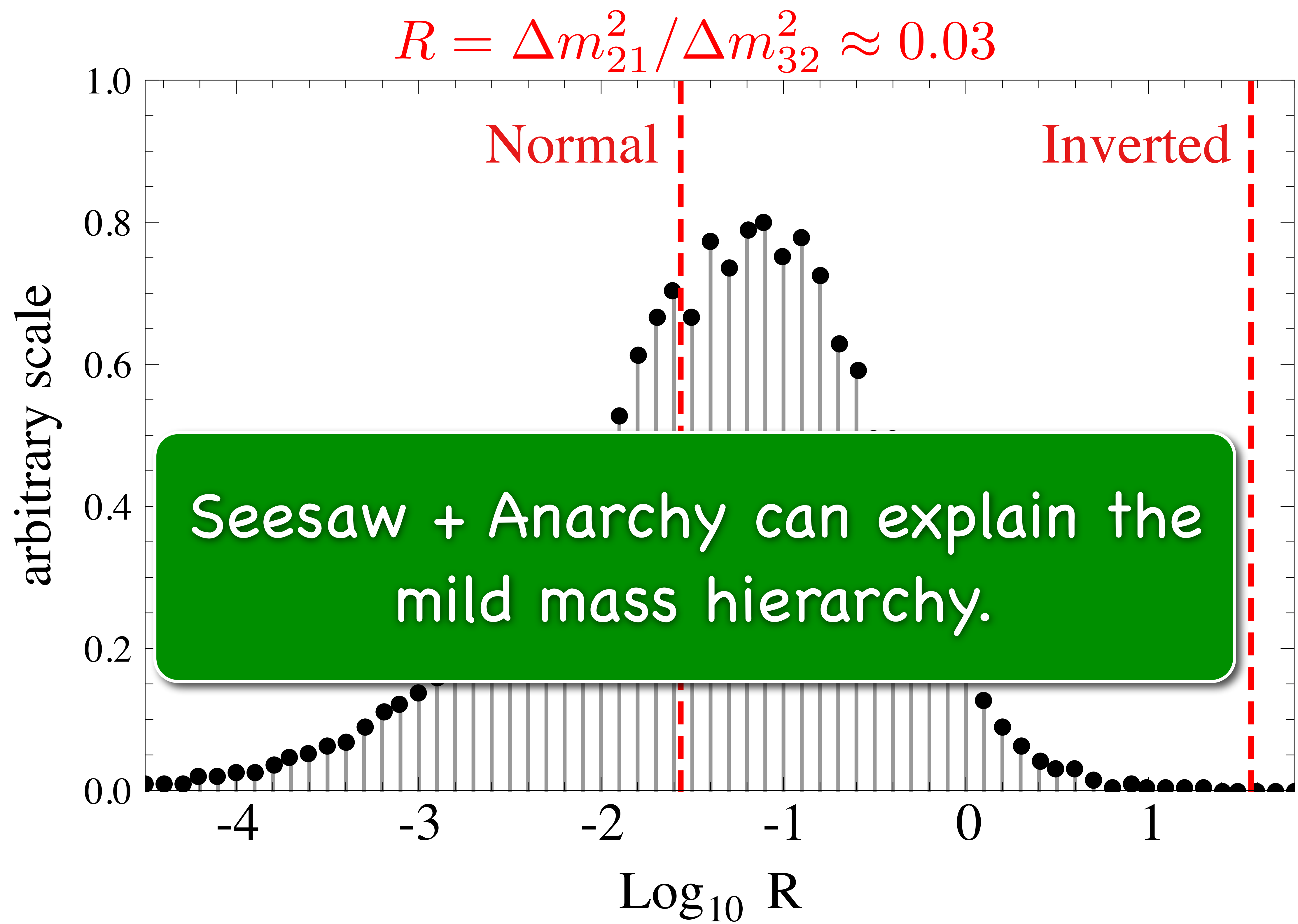
Probability distribution of Δm^2



Probability distribution of R

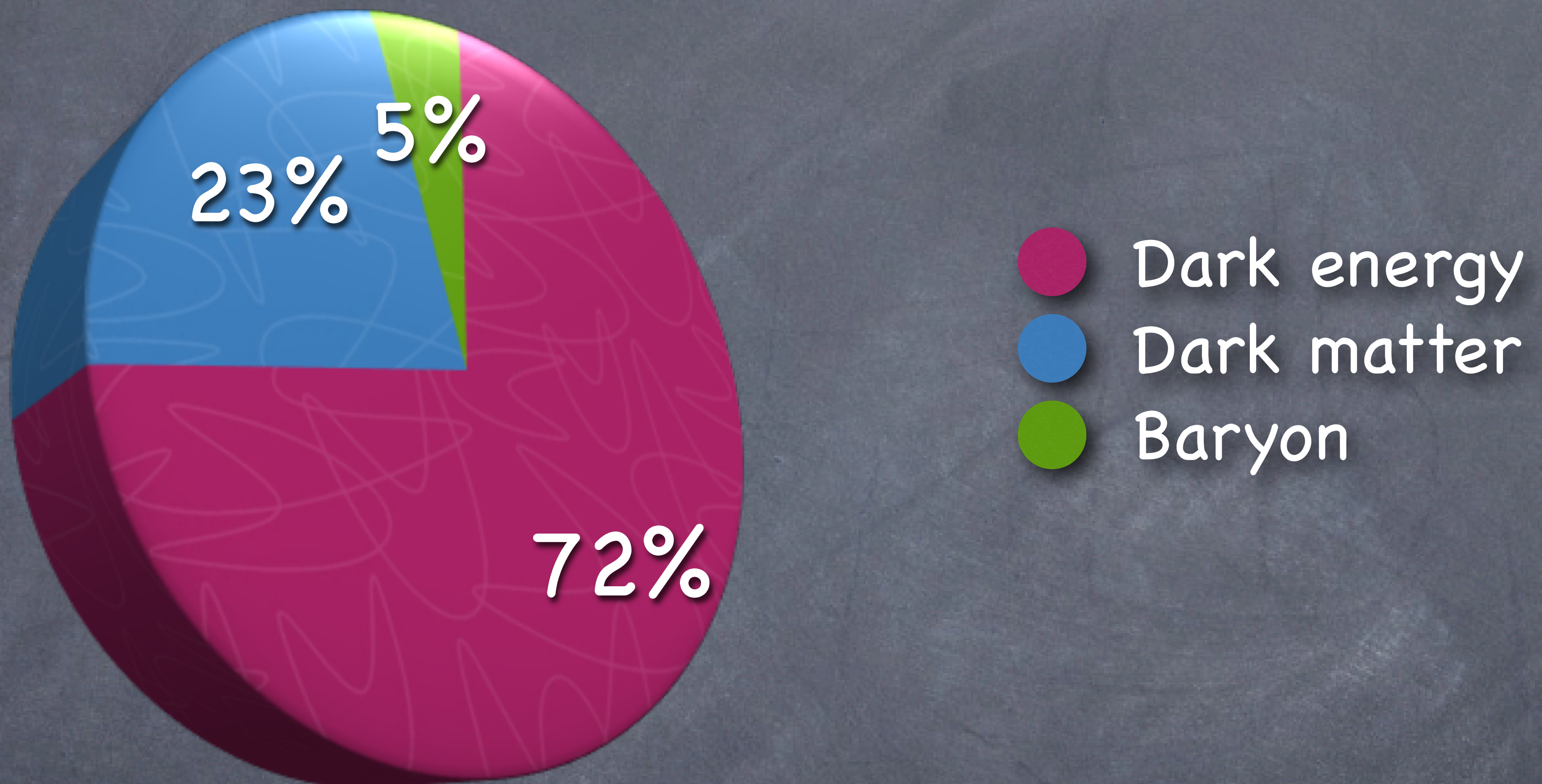


Seesaw + Anarchy can explain the mild mass hierarchy.

So far, so good.

Can seesaw + neutrino mass anarchy solve another important cosmological puzzle?

(3) What is the origin of matter?



Fukugita, Yanagida `86

Leptogenesis is one of the plausible candidates.
However, it may spoil the success of the neutrino mass anarchy.

What we did

We have studied if the neutrino mass anarchy hypothesis works together with leptogenesis

We have found that

1. the mixing angle and CP violation phase distributions are unchanged.

2. the neutrino mass distribution is modified, but can be consistent with obs. if $T_R = 10^9$-10^{11}GeV.

2. Set-up

We adopt a basis in which RH neutrino mass is diagonalized.

$$\mathcal{L} \supset h_{i\alpha} \bar{N}_i \ell_\alpha H - \frac{1}{2} M_i \bar{N}_i \bar{N}_i + \mathrm{h.c.},$$

We generate a random matrix for the neutrino Yukawa matrix $h_{i\alpha}$, and generate the RH neutrino masses following the linear measure,

$$dM = F_M(M_1, M_2, M_3) \prod_{i=1}^{3} dM_i \, dU_N$$

$$F_M(M_1, M_2, M_3) \equiv (M_1^2 - M_2^2)(M_2^2 - M_3^2)(M_3^2 - M_1^2) M_1 M_2 M_3,$$

Leptogenesis

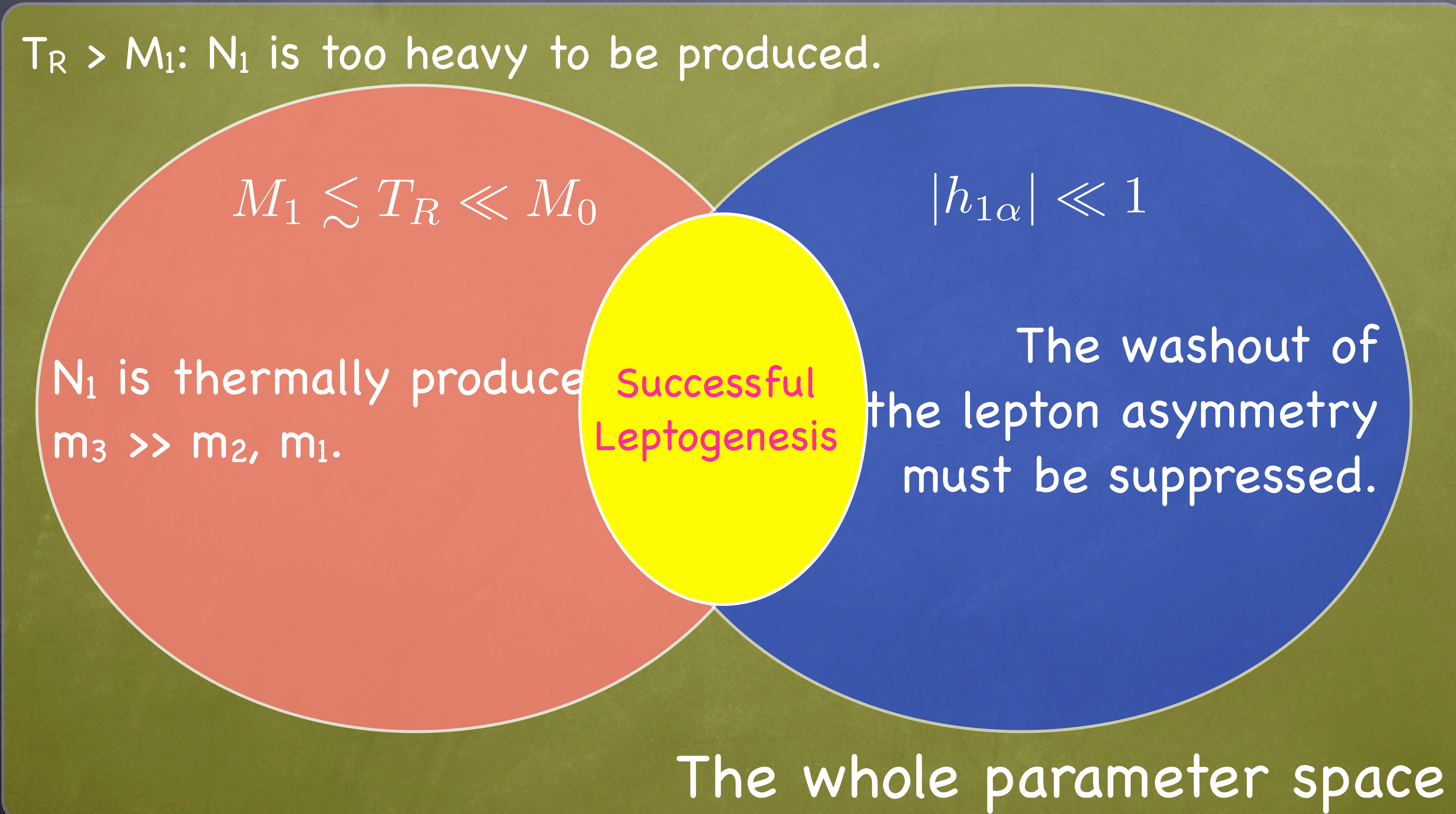
We assume the simplest thermal leptogenesis, in which the CP violating decay of the lightest N_1 creates the lepton asymmetry.

We impose the successful leptogenesis, namely,

$$5 \times 10^{-10} \leq \eta_B \leq 7 \times 10^{-10}.$$

We have generated (more than) 10^6 random matrices satisfying the above constraint for various reheating temperature T_R.

Leptogenesis requirement limits the parameter space

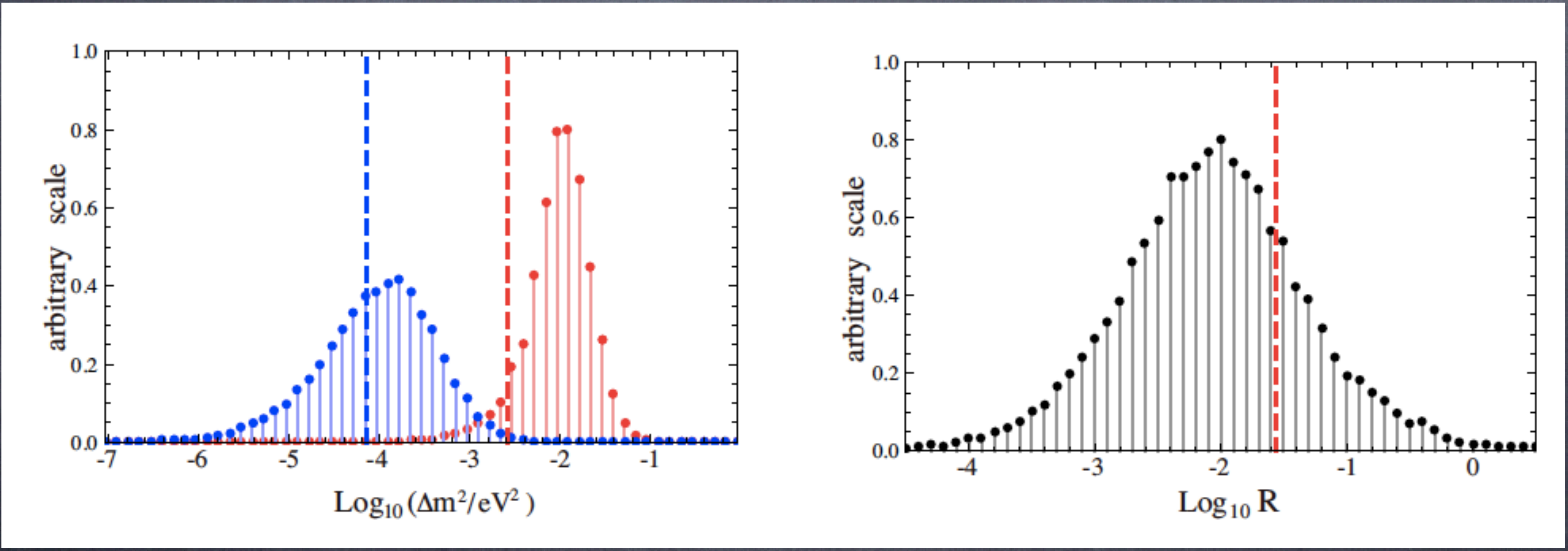


Rem. The flavor symmetry of RH N is emergent.

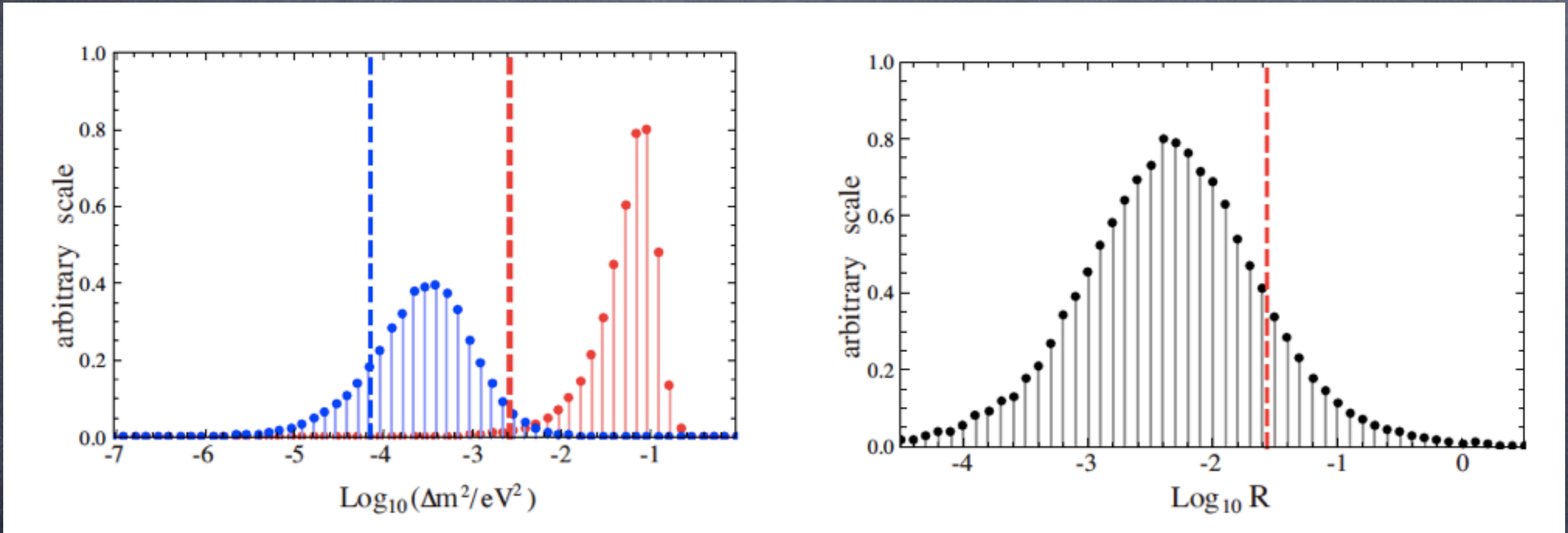
3. Neutrino mass distribution

If (seesaw + anarchy + leptogenesis) are correct, the observed neutrino mass squared difference should be typical in the distribution.

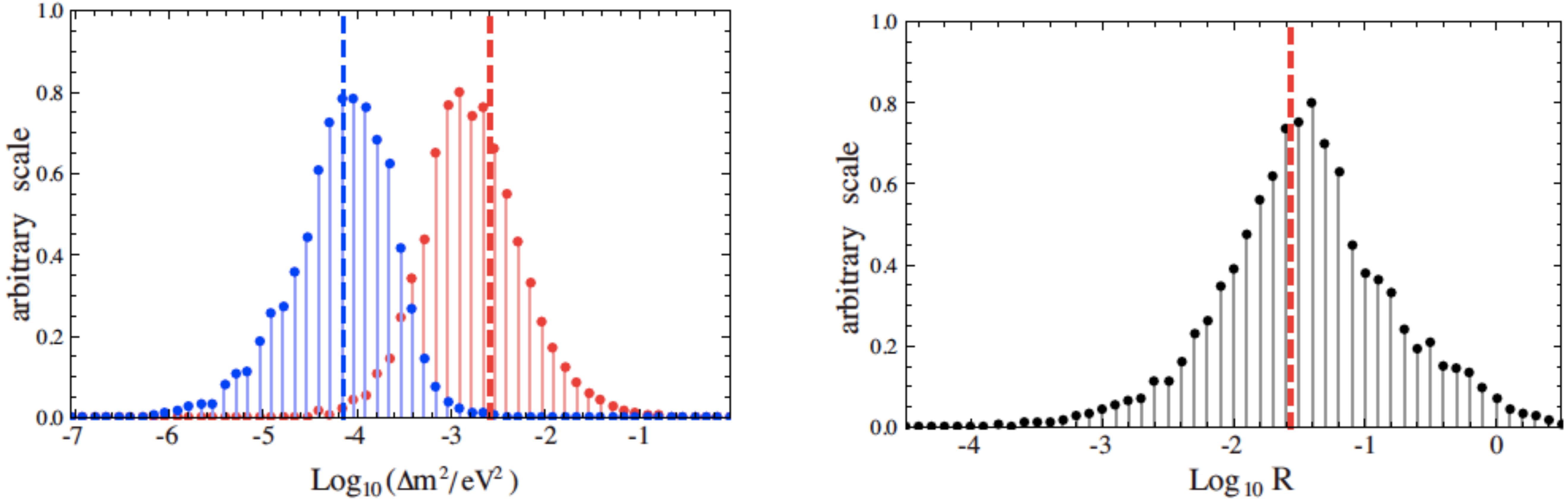
Case of $T_R \sim 10^{15}$GeV



Case of $T_R \sim 10^{13}$GeV



Case of T_R~5×10^{10}GeV



Mixing angle distributions

$$\ell_\alpha \rightarrow (U_L)_{\alpha\beta}\,\ell_\beta,$$

$$N_i \rightarrow (U_R)_{ij}N_j,$$

$$h \rightarrow U_R^\dagger\, h\, U_L = \begin{pmatrix} h_1 & 0 & 0 \\ 0 & h_2 & 0 \\ 0 & 0 & h_3 \end{pmatrix} \equiv D_h,$$

$$N_i \rightarrow (U_N)_{ij}N_j,$$

$$M \rightarrow U_N^\dagger\, M\, U_N^* = \begin{pmatrix} M_1 & 0 & 0 \\ 0 & M_2 & 0 \\ 0 & 0 & M_3 \end{pmatrix} \equiv D_M,$$

relevant for leptogenesis

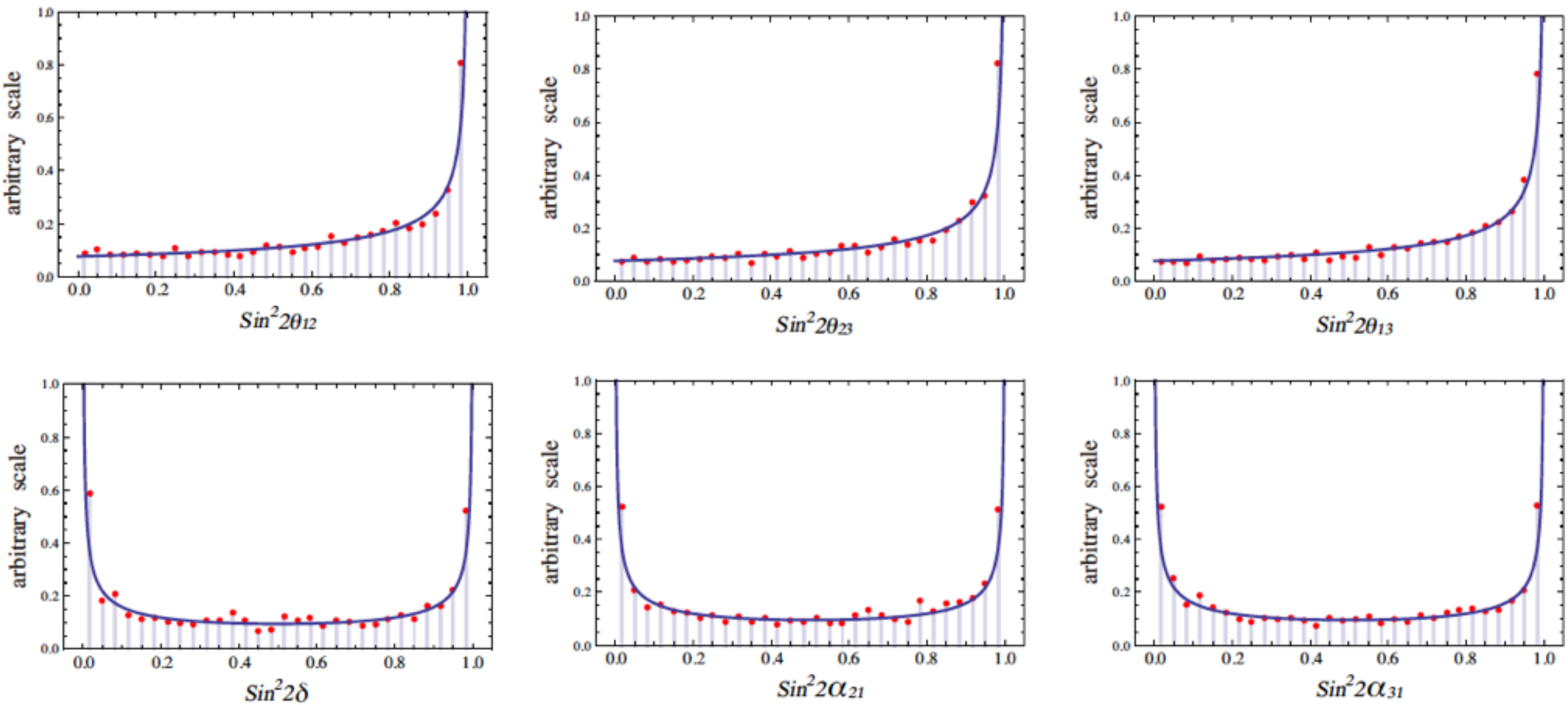
$$(m_\nu)_{\alpha\beta} = (h^T X^{-1} h)_{\alpha\beta} \frac{v^2}{M_0}$$
$$= \left(U_L^* D_h U_R^T U_N^* D_M^{-1} U_N^\dagger U_R D_h U_L^\dagger\right)_{\alpha\beta} v^2,$$

Lepton doublet mixing

$$(m_\nu)_{\alpha\beta} = U_{MNS}^* \begin{pmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{pmatrix} U_{MNS}^\dagger,$$

$$U_{MNS} = U_L U_h$$

Thus, U_{MNS} remains a random unitary matrix.



The red dots are distribution with the leptogenesis requirement.

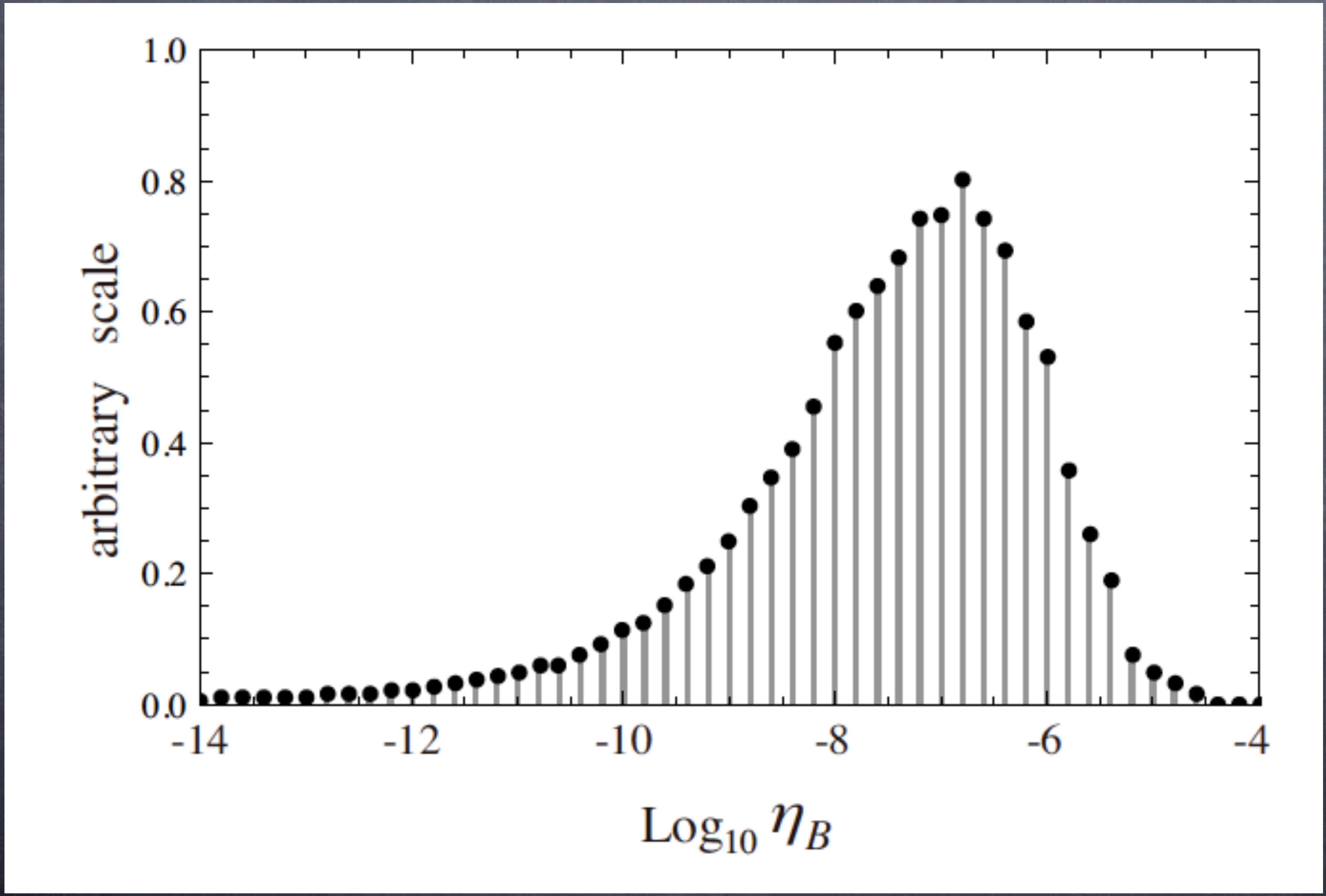
4. Summary

The neutrino mass anarchy hypothesis works together with thermal leptogenesis if $T_R = O(10^9\text{-}10^{11})$GeV.

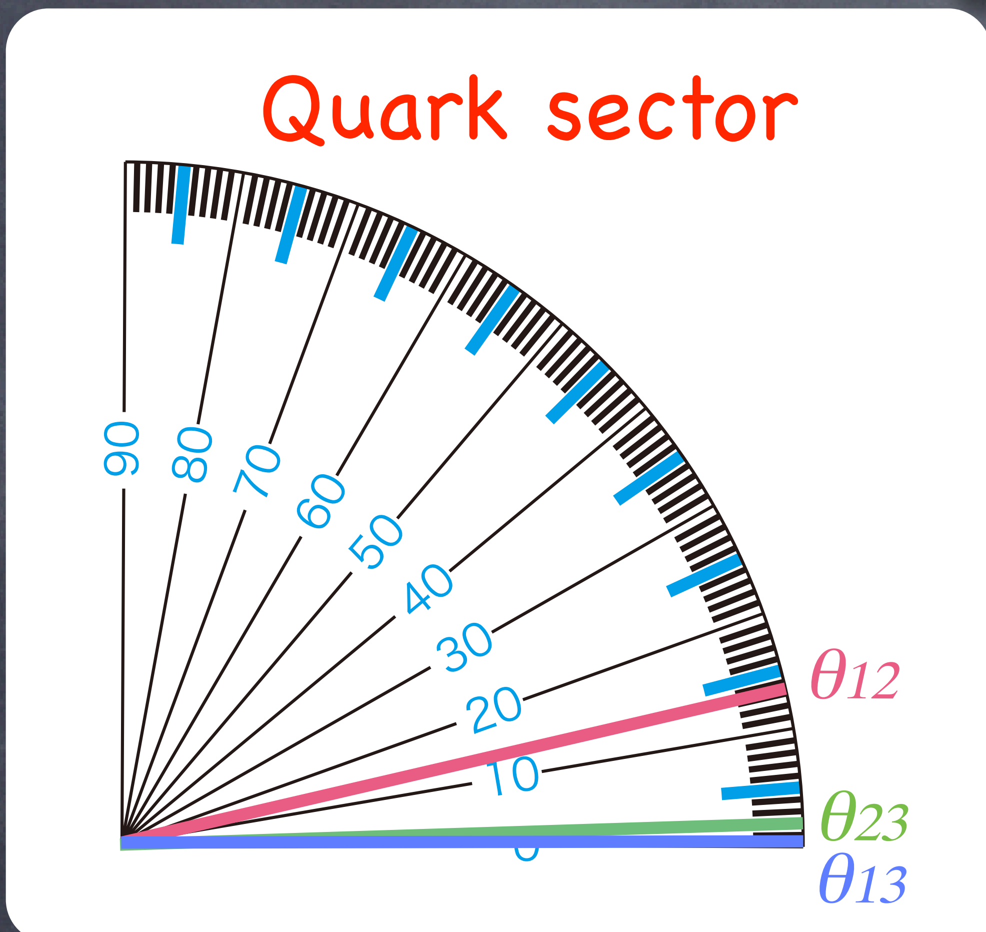
In the case of non-thermal leptogenesis, the inflaton mass needs to be heavier than the typical RH neutrino mass, 10^{15}GeV.

Back-up slides

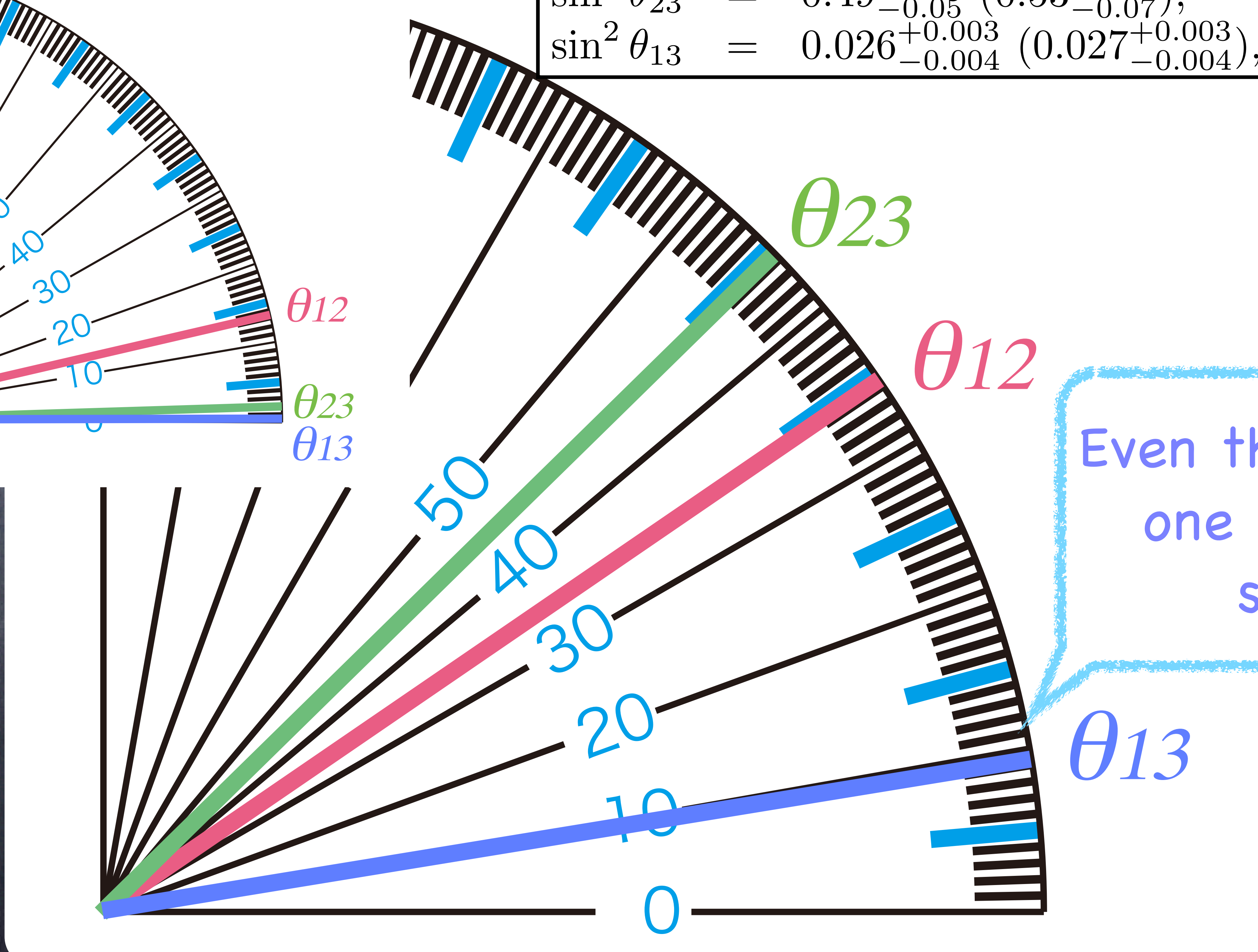
w/o leptogenesis requirement



(2) Why are the neutrino mixing angles large?

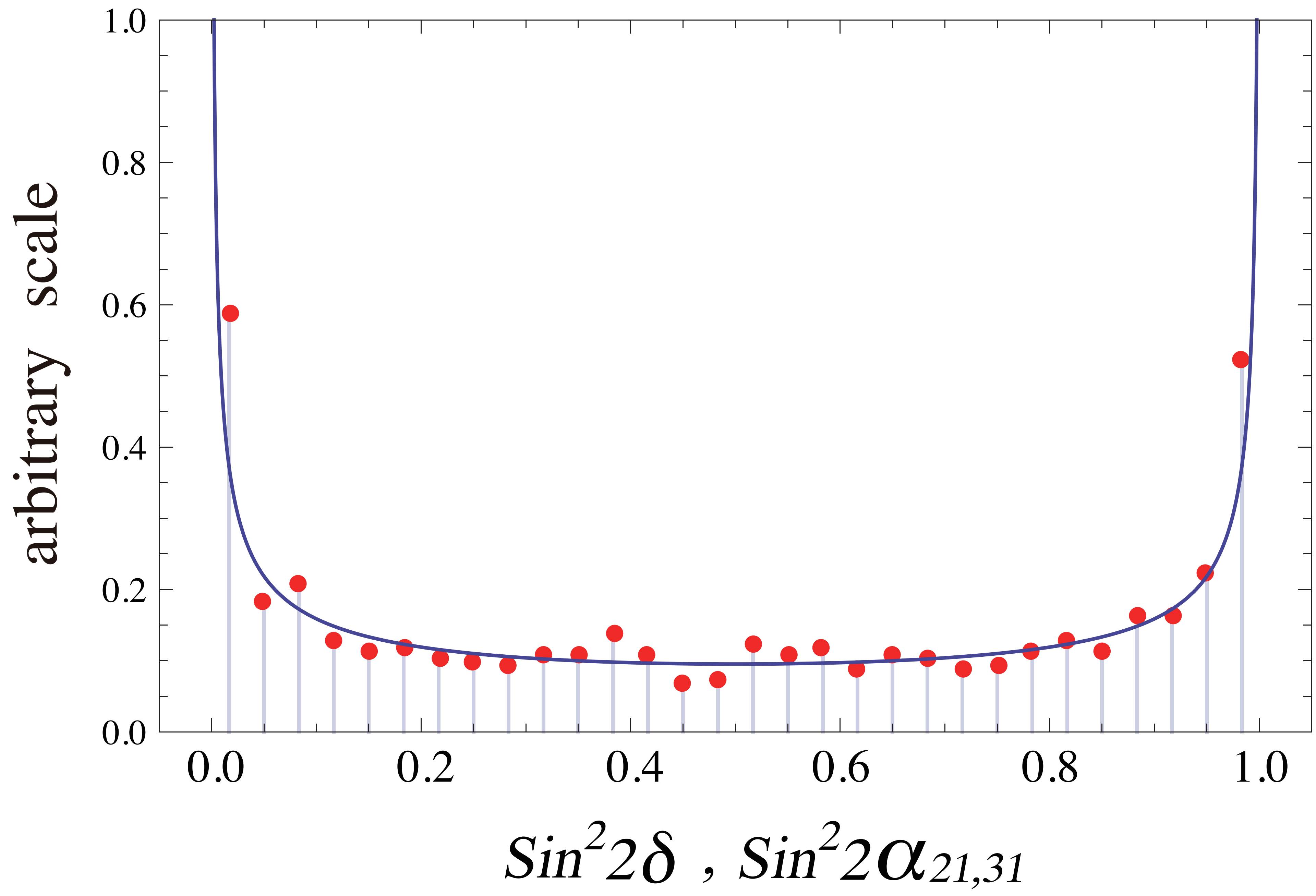


$$\begin{aligned}\sin^2\theta_{12} &= 0.320^{+0.015}_{-0.017},\\ \sin^2\theta_{23} &= 0.49^{+0.08}_{-0.05}\ (0.53^{+0.05}_{-0.07}),\\ \sin^2\theta_{13} &= 0.026^{+0.003}_{-0.004}\ (0.027^{+0.003}_{-0.004}),\end{aligned}$$



Even the smallest one is not so small.

U(3)-invariant Haar distribution



$$dU_{MNS} = ds_{12}^2 dc_{13}^4 ds_{23}^2 \, d\delta \, d\alpha_{21} d\alpha_{31}.$$