Neutrino mass anarchy and the origin of matter

特定領域「フレーバー物理の新展開」研究会

2012年7月7日

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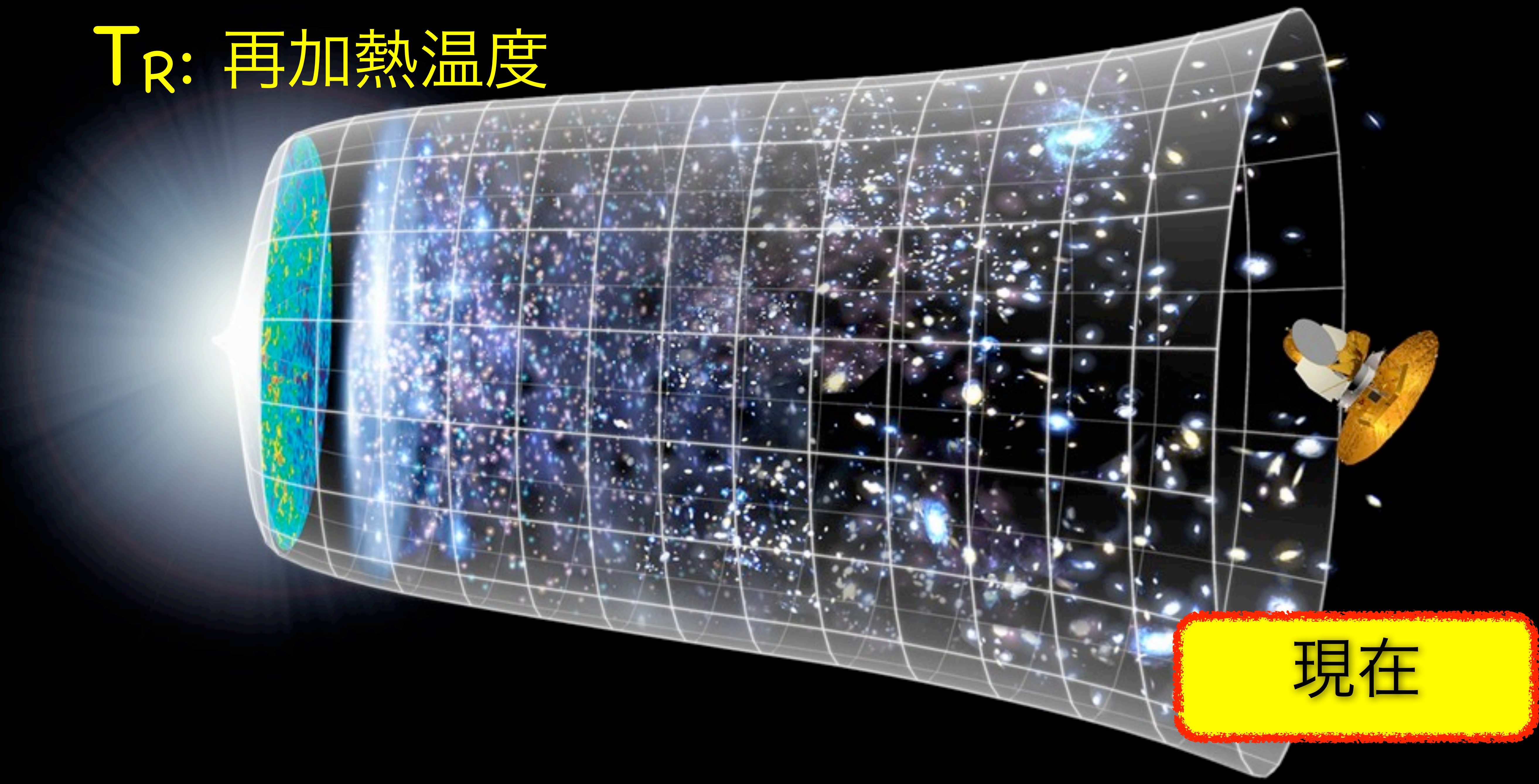
K-S. Jeong and FT, 1204.5453 (to appear in JHEP)

宇宙の歴史



→ 時間

NASA/WMAP Science Team

宇宙の歴史

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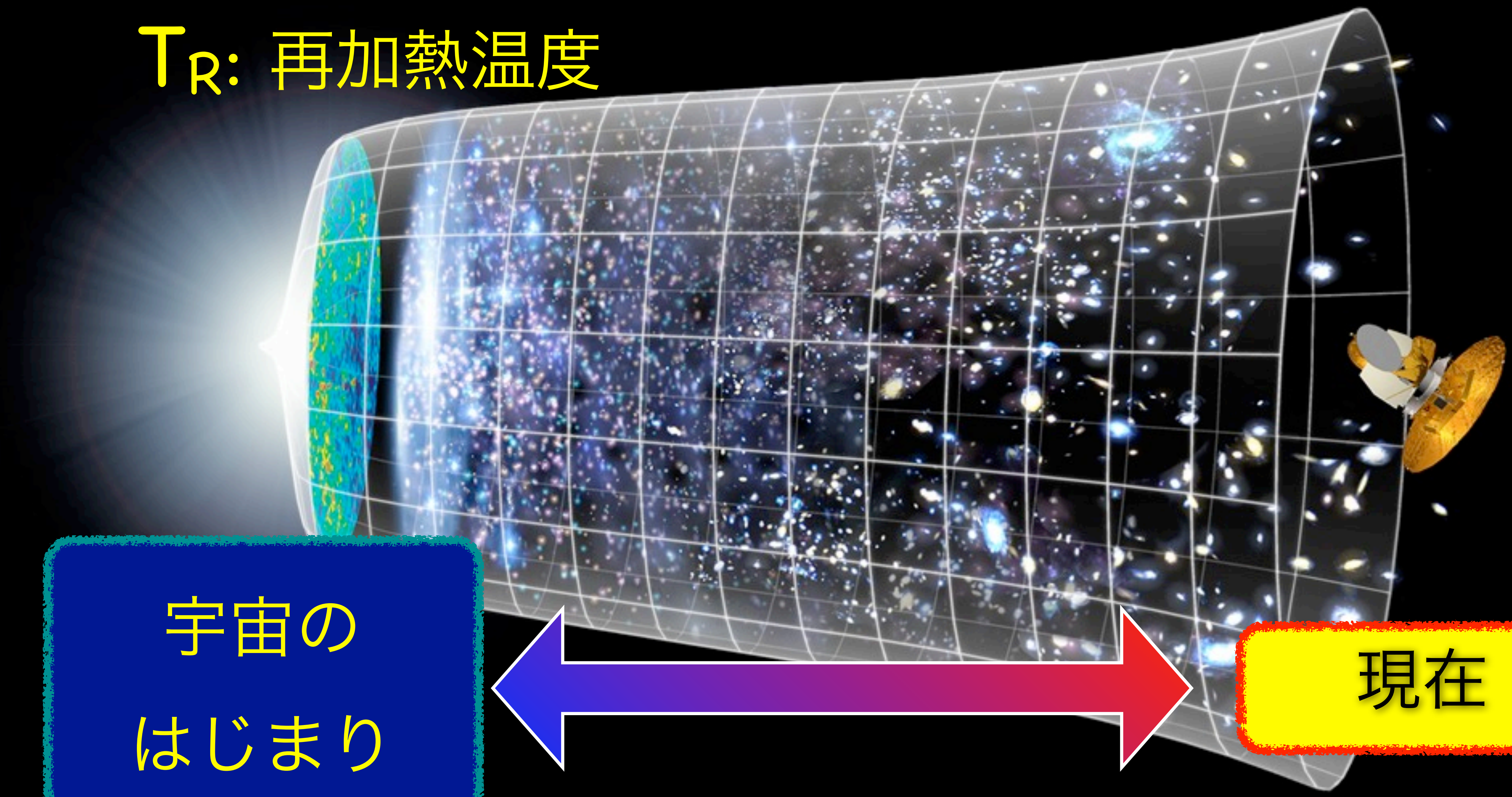

宇宙のはじまり

現在

時間

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1. Introduction

(1) Why is the neutrino mass so small?

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

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1. Introduction

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

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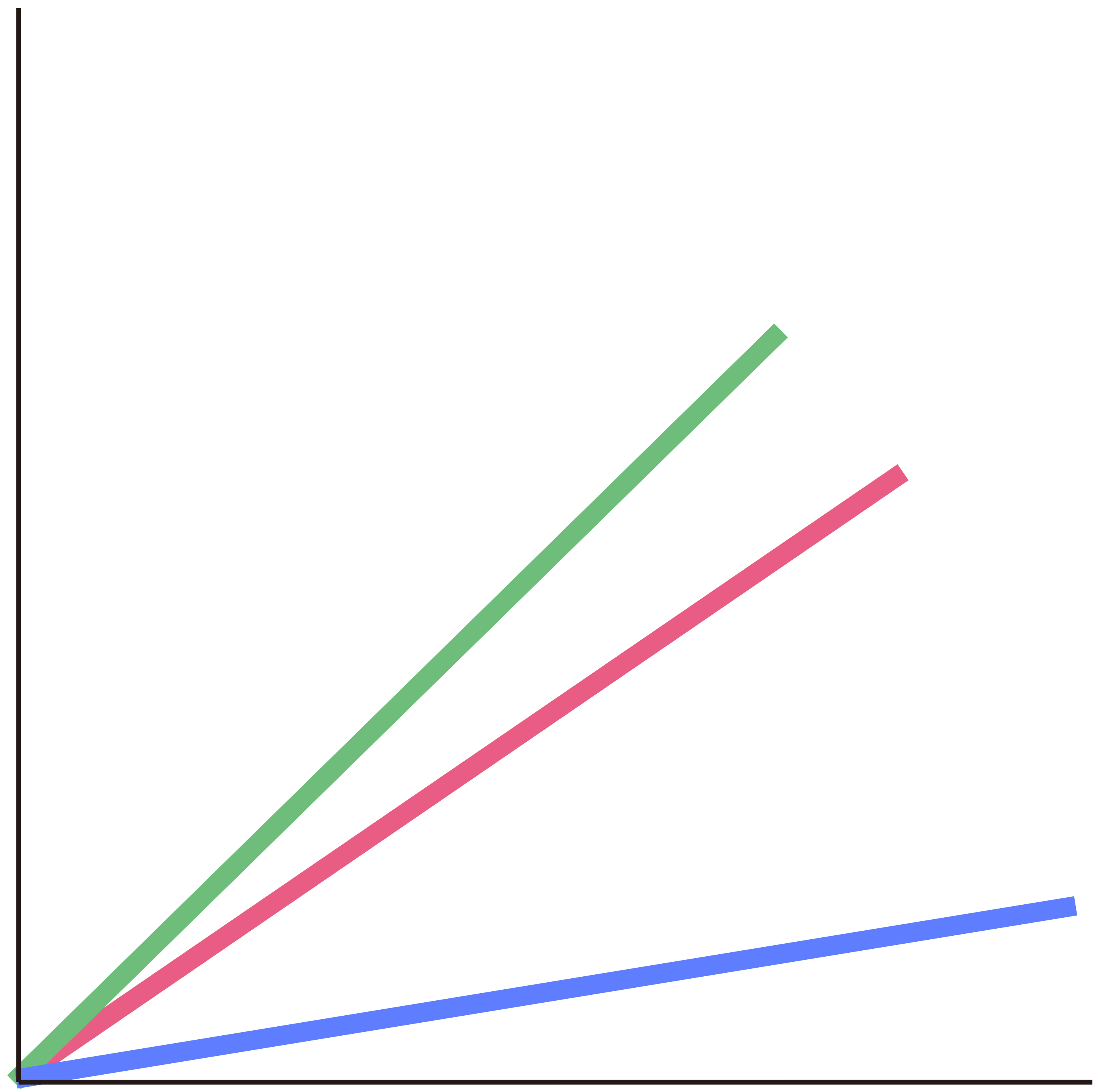
$$\mathcal{L} \supset h_{i\alpha}\bar{N}_i \ell_\alpha H - \frac{1}{2} M_{ij} \bar{N}_i \bar{N}_j + \text{h.c.},$$

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

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



(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}), \\
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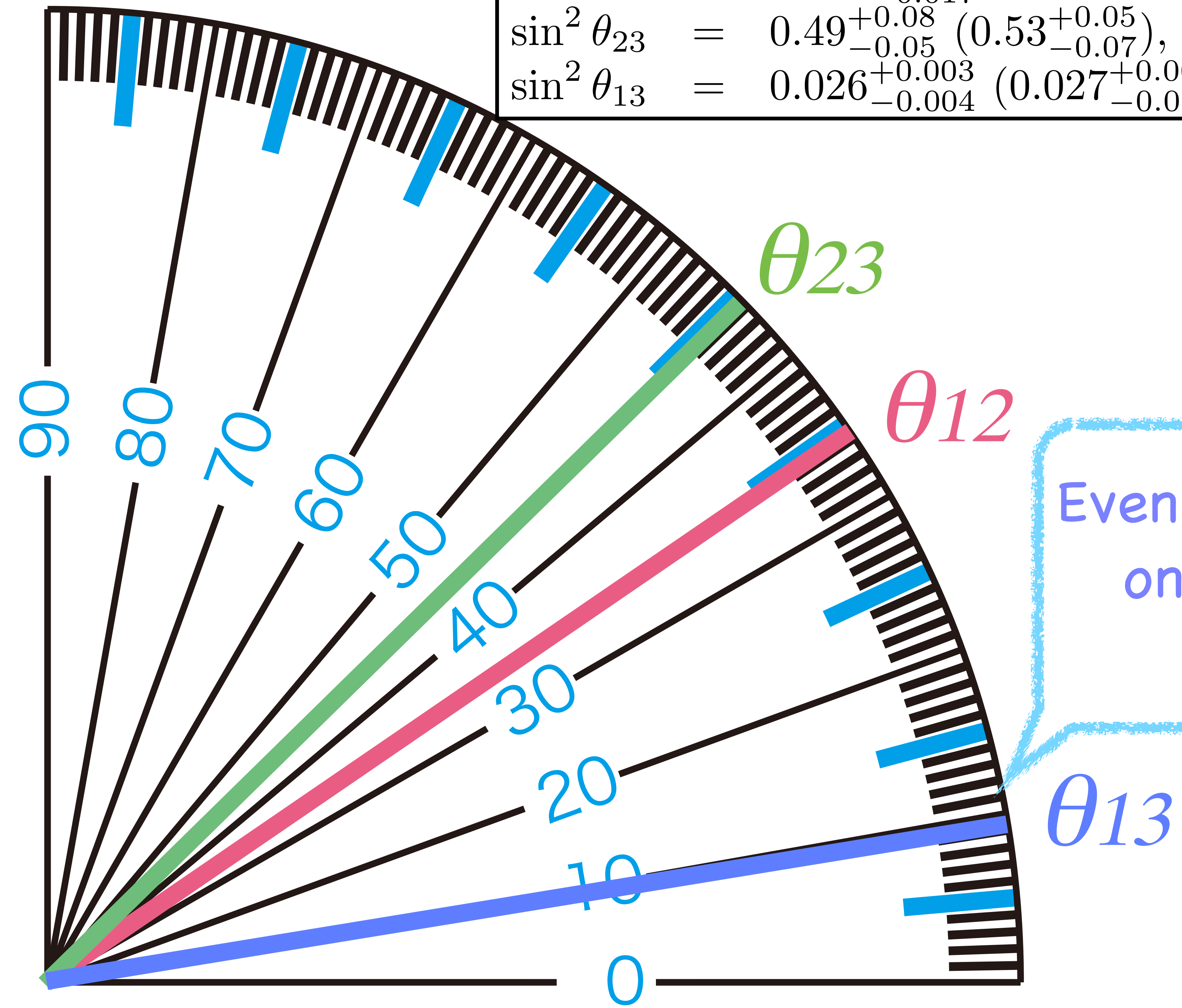

Even the smallest one is not so small.

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.

Random matrix and measure

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

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

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

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

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

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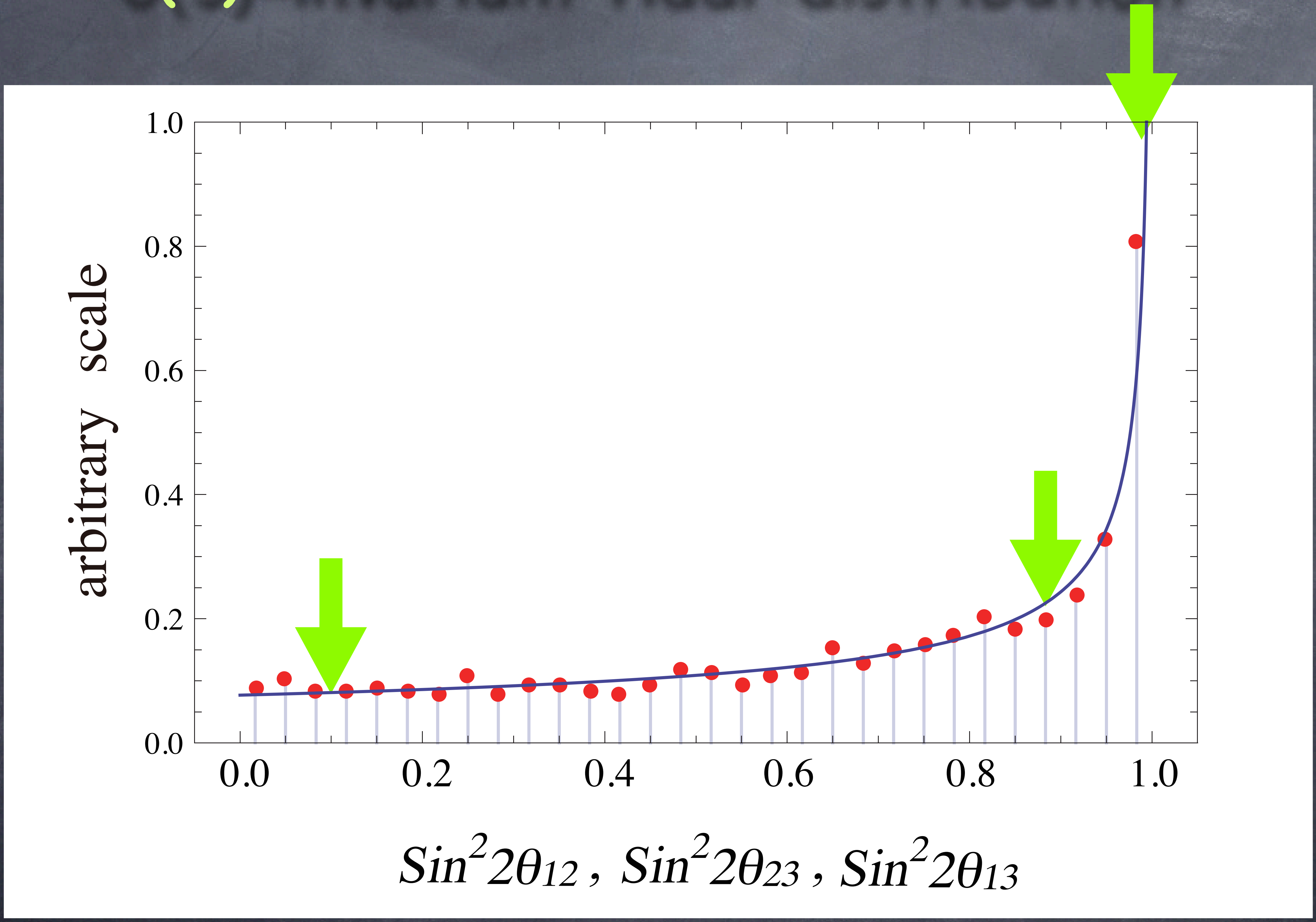

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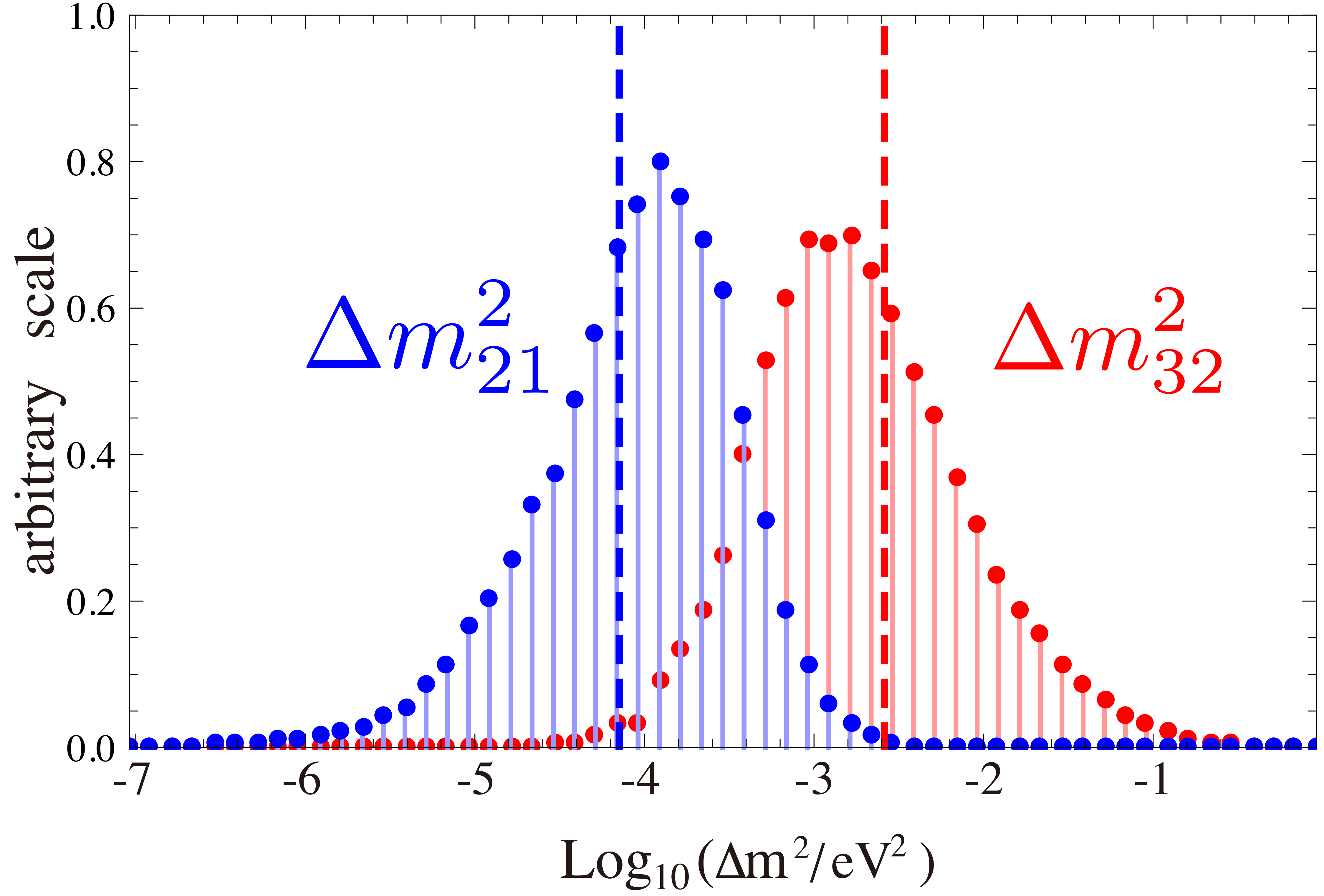
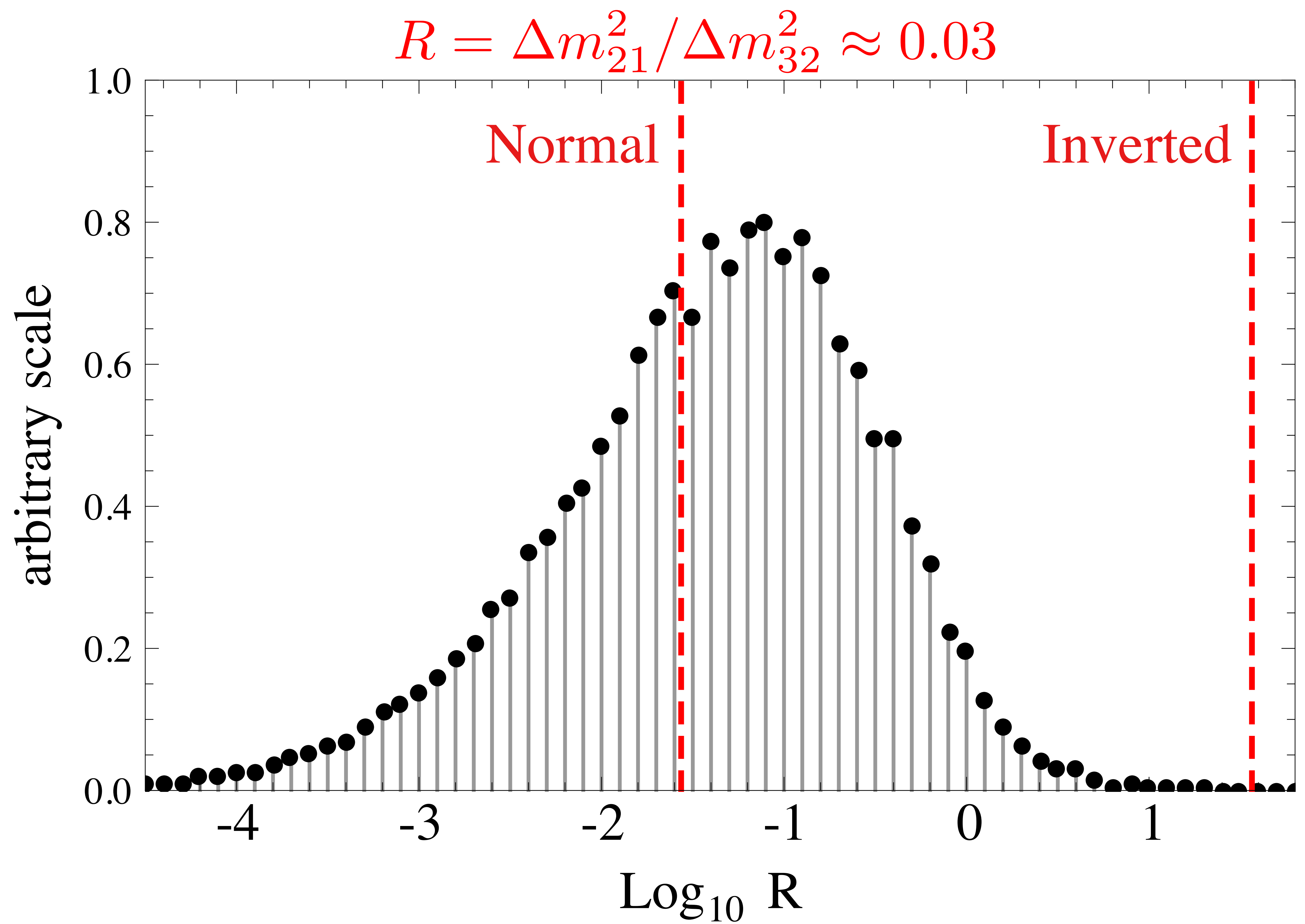
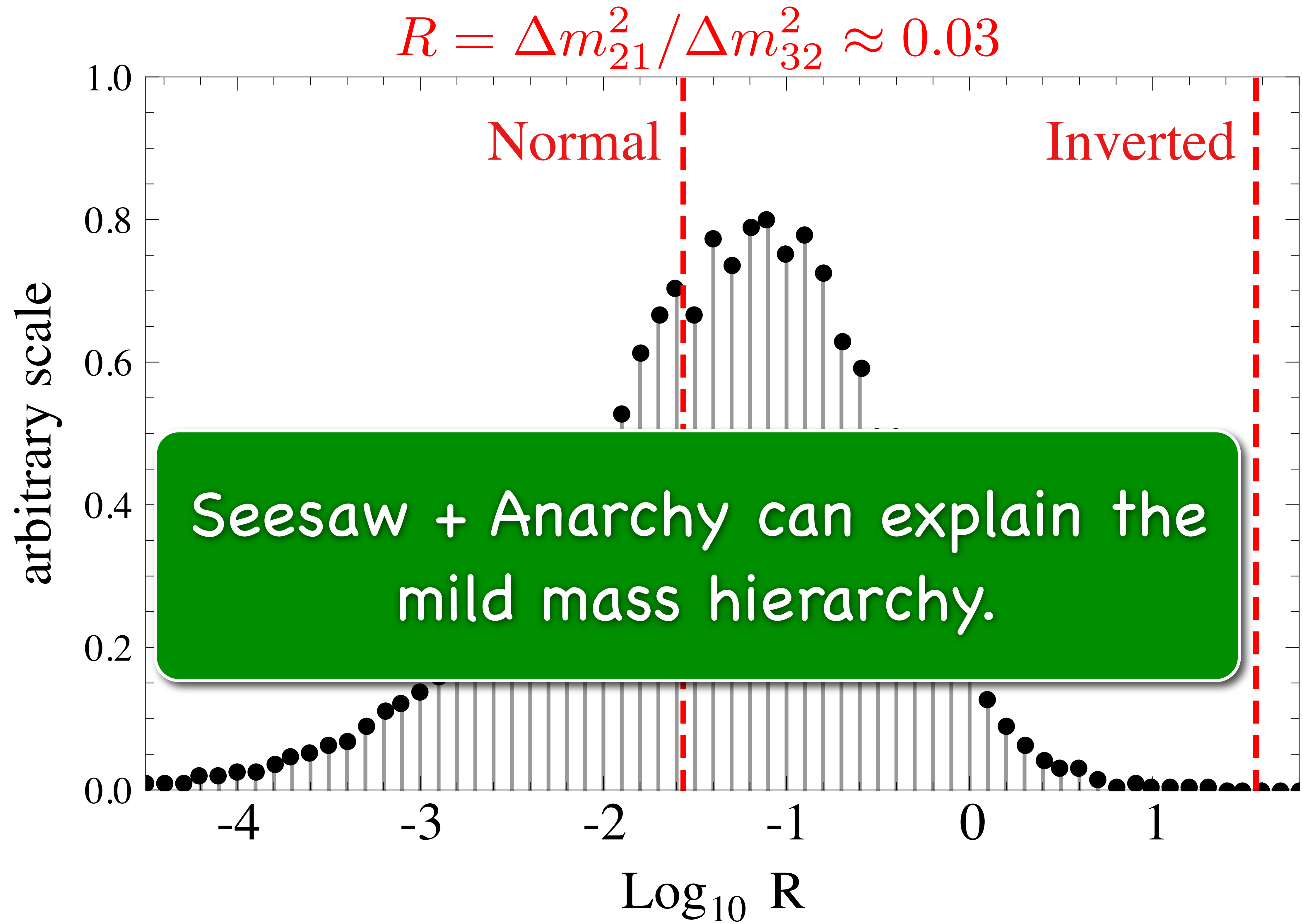
Probability distribution of Δm²



Probability distribution of R



Probability distribution of R



Seesaw + Anarchy can explain the mild mass hierarchy.

So far, so good.

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

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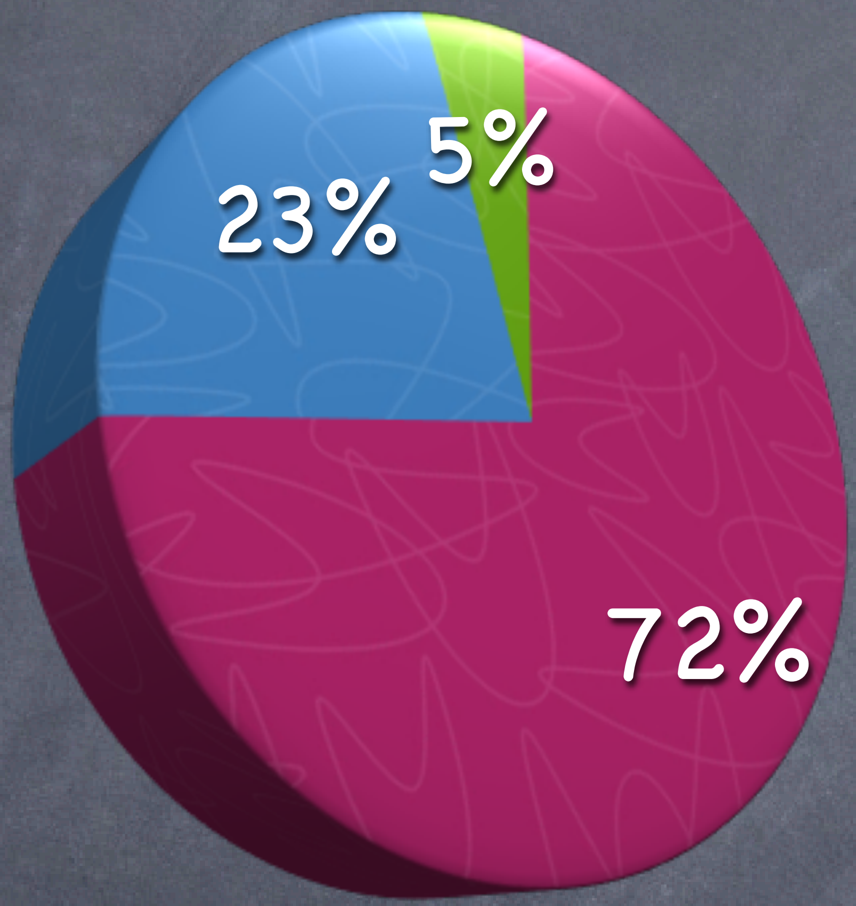

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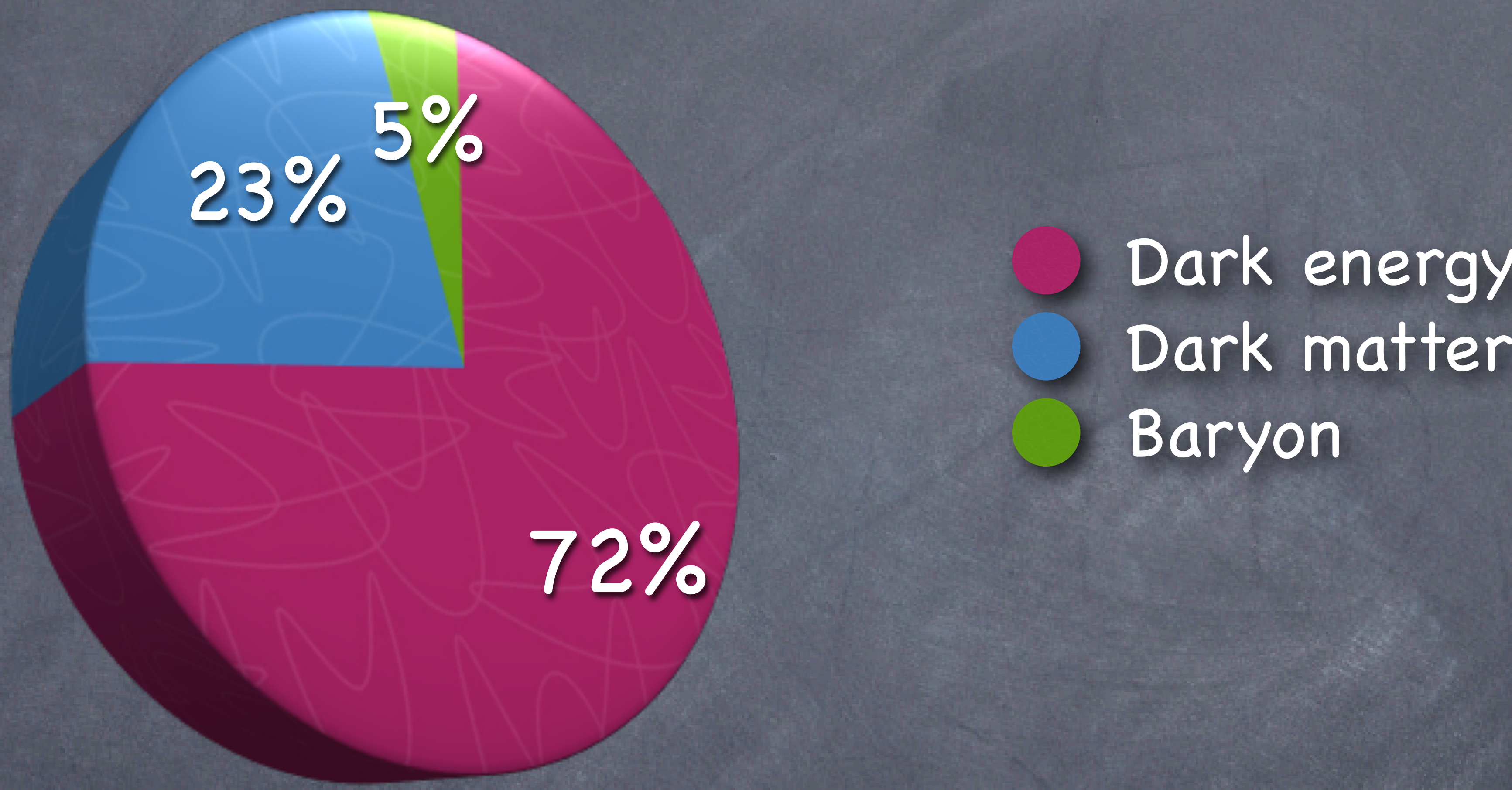

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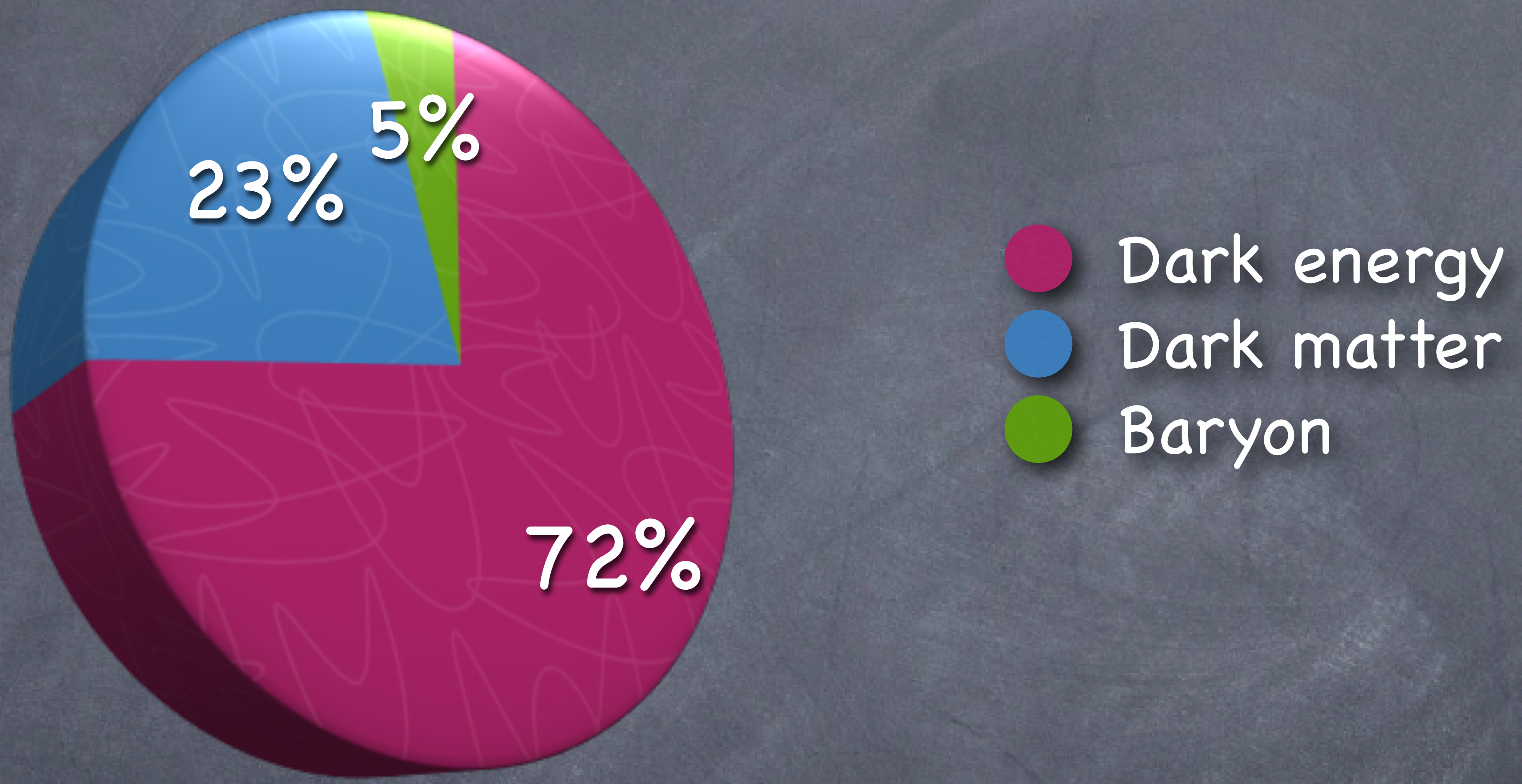

Fukugita, Yanagida `86

Leptogenesis is one of the plausible candidates. However, since it selects a certain subset of the parameter space, the success of the neutrino mass anarchy may be spoiled.

What we did

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

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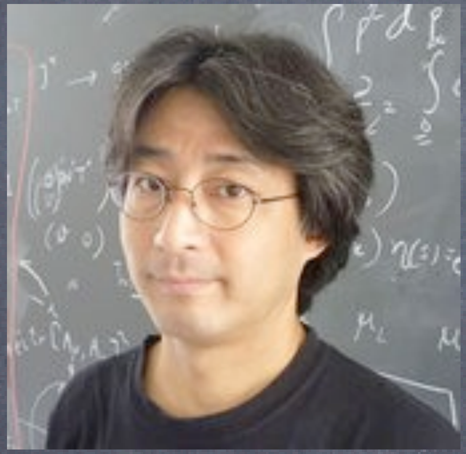

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We have found that

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 the basis in which the right-handed neutrino mass matrix 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

The whole parameter space

Leptogenesis requirement limits the parameter space

$T_R > M_1$: N_1 is too heavy to be produced.

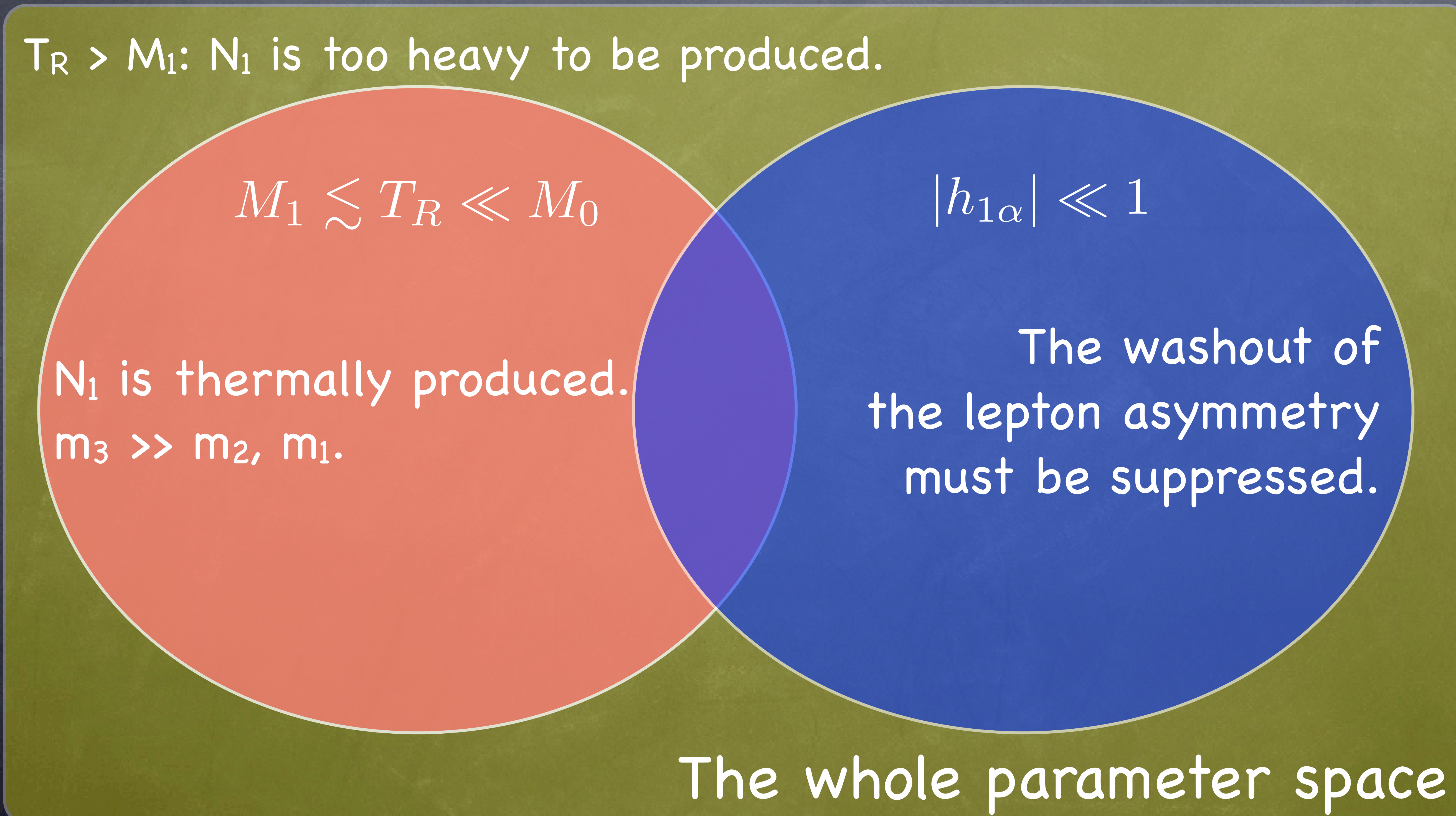
$$M_1 \lesssim T_R \ll M_0$$

N_1 is thermally produced.

$m_3 \gg m_2, m_1$.

The whole parameter space

Leptogenesis requirement limits the parameter space



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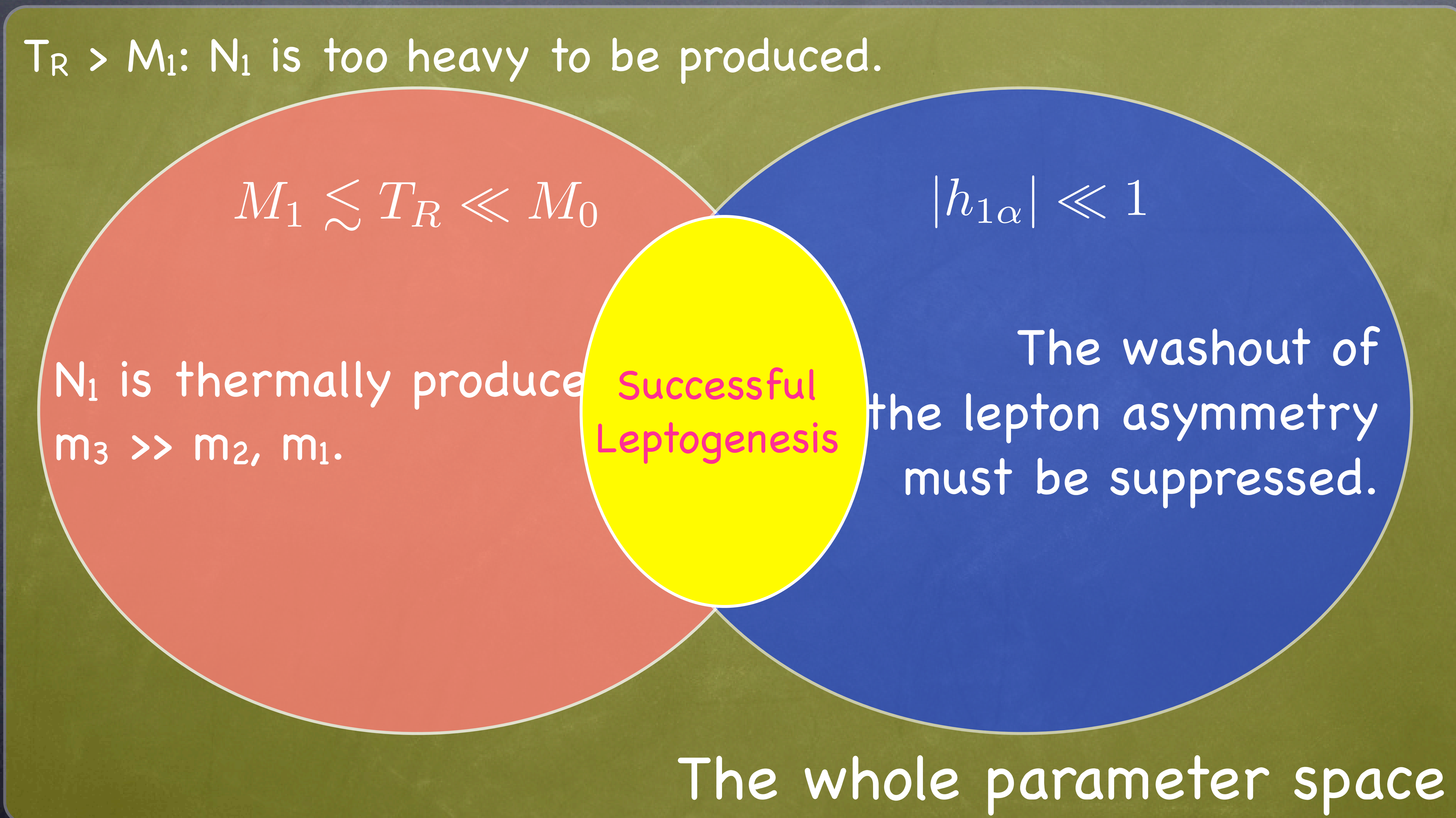
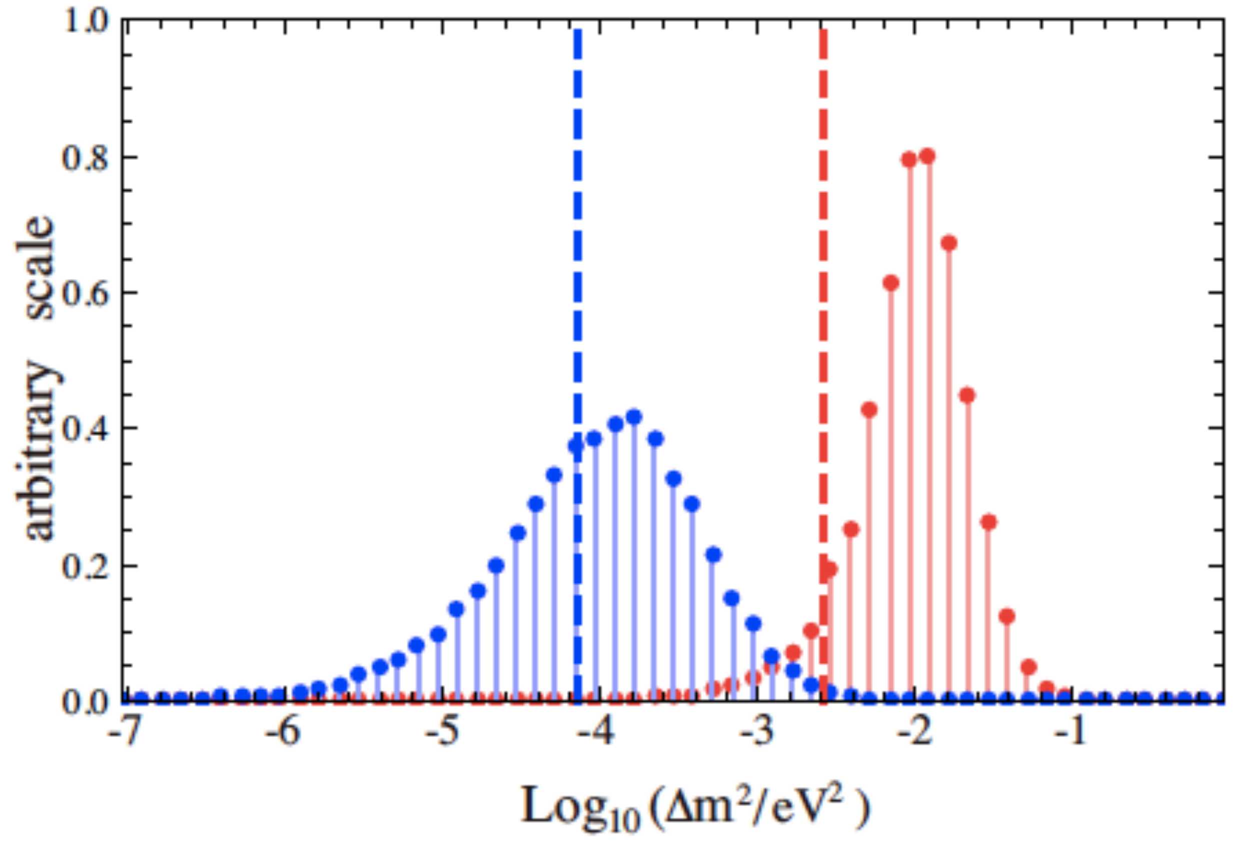
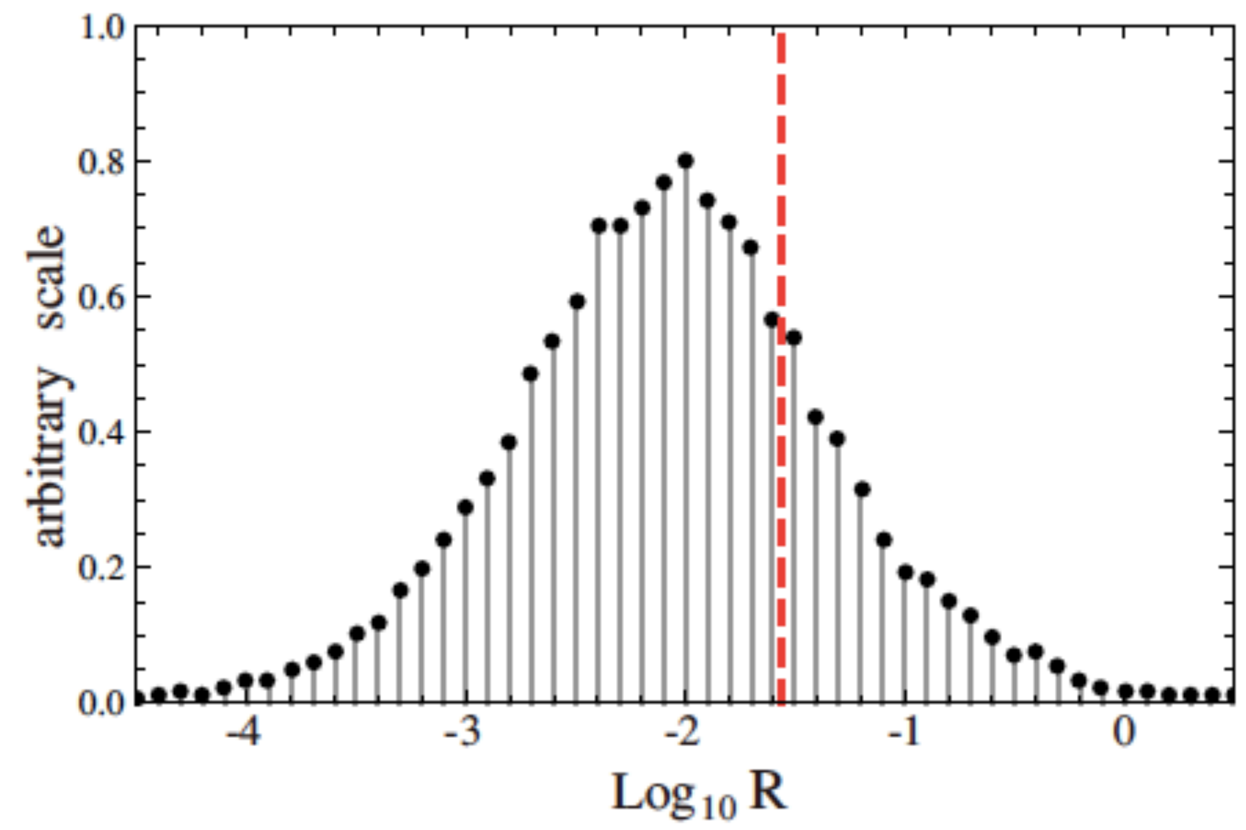


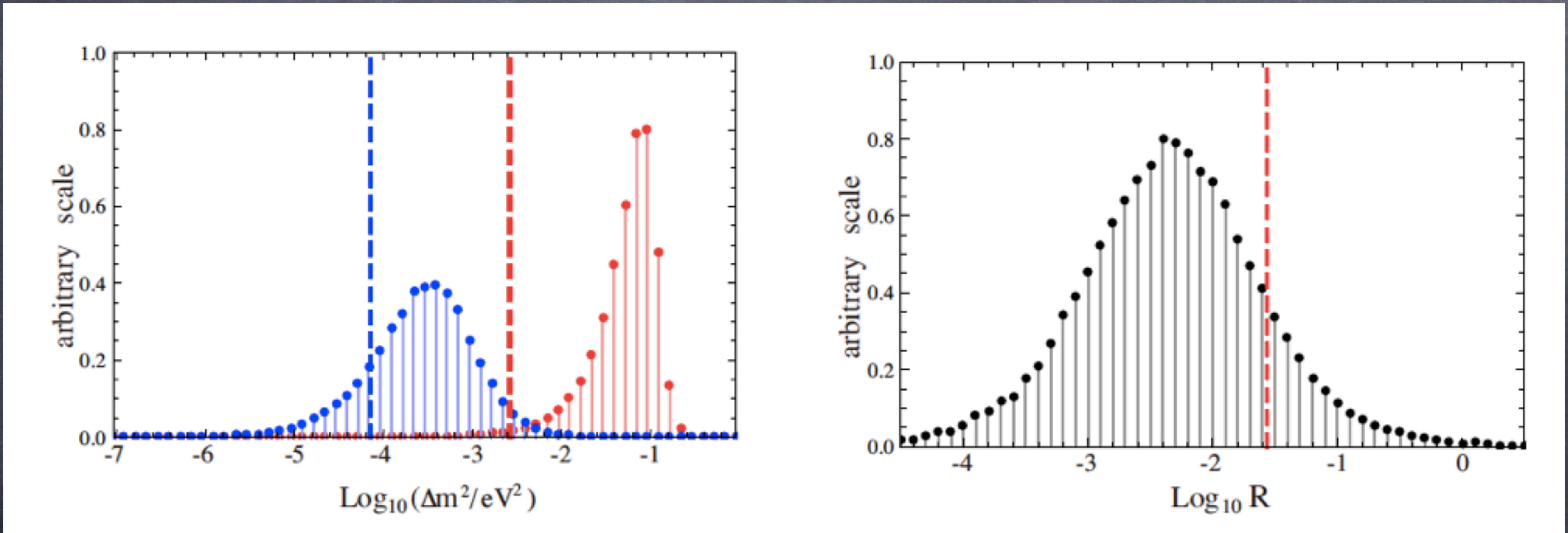
3. Neutrino mass distribution

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

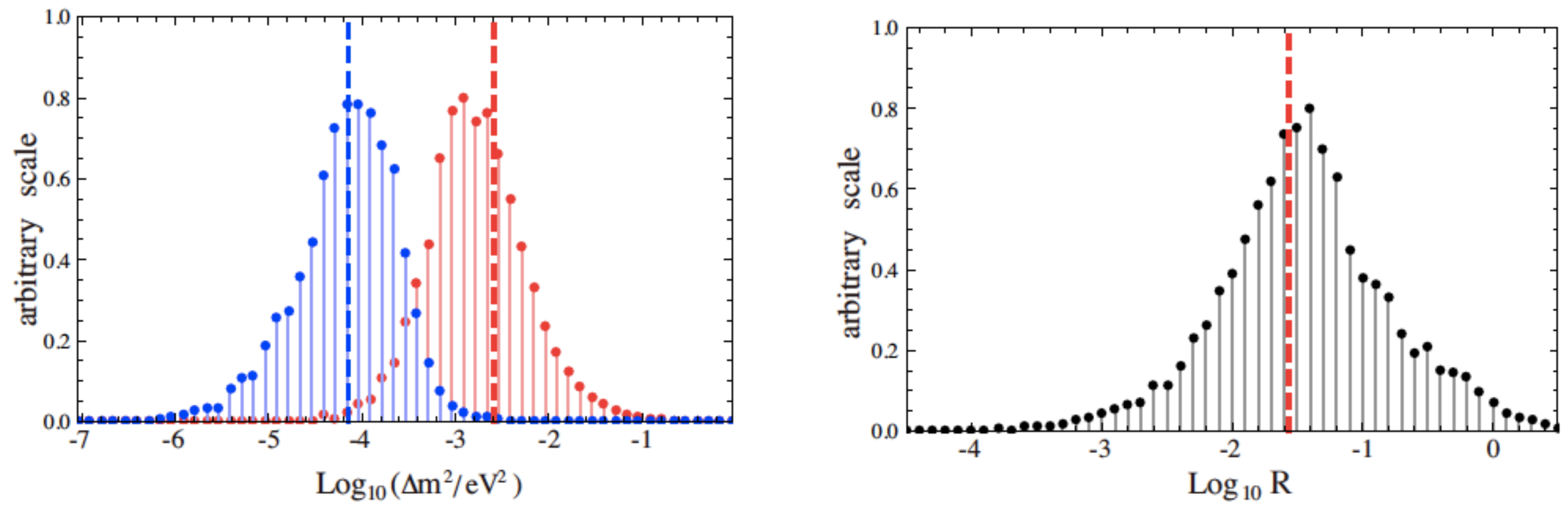




Case of $T_R \sim 10^{13}$GeV



Case of T_R~$5x10^{10}$GeV



Mixing angle distributions

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

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

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

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

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

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

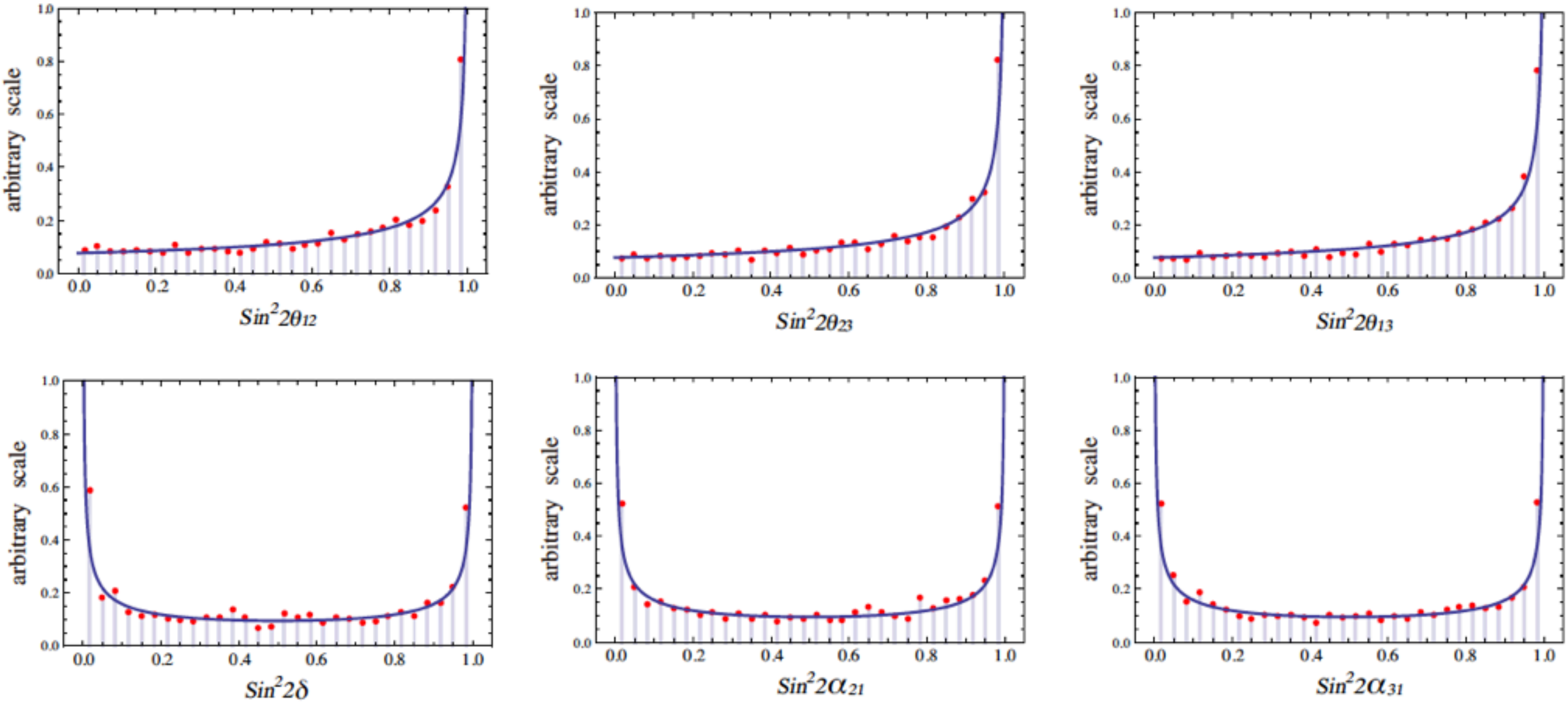
relevant for leptogenesis

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 only 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

(2) Why are the neutrino mixing angles large?

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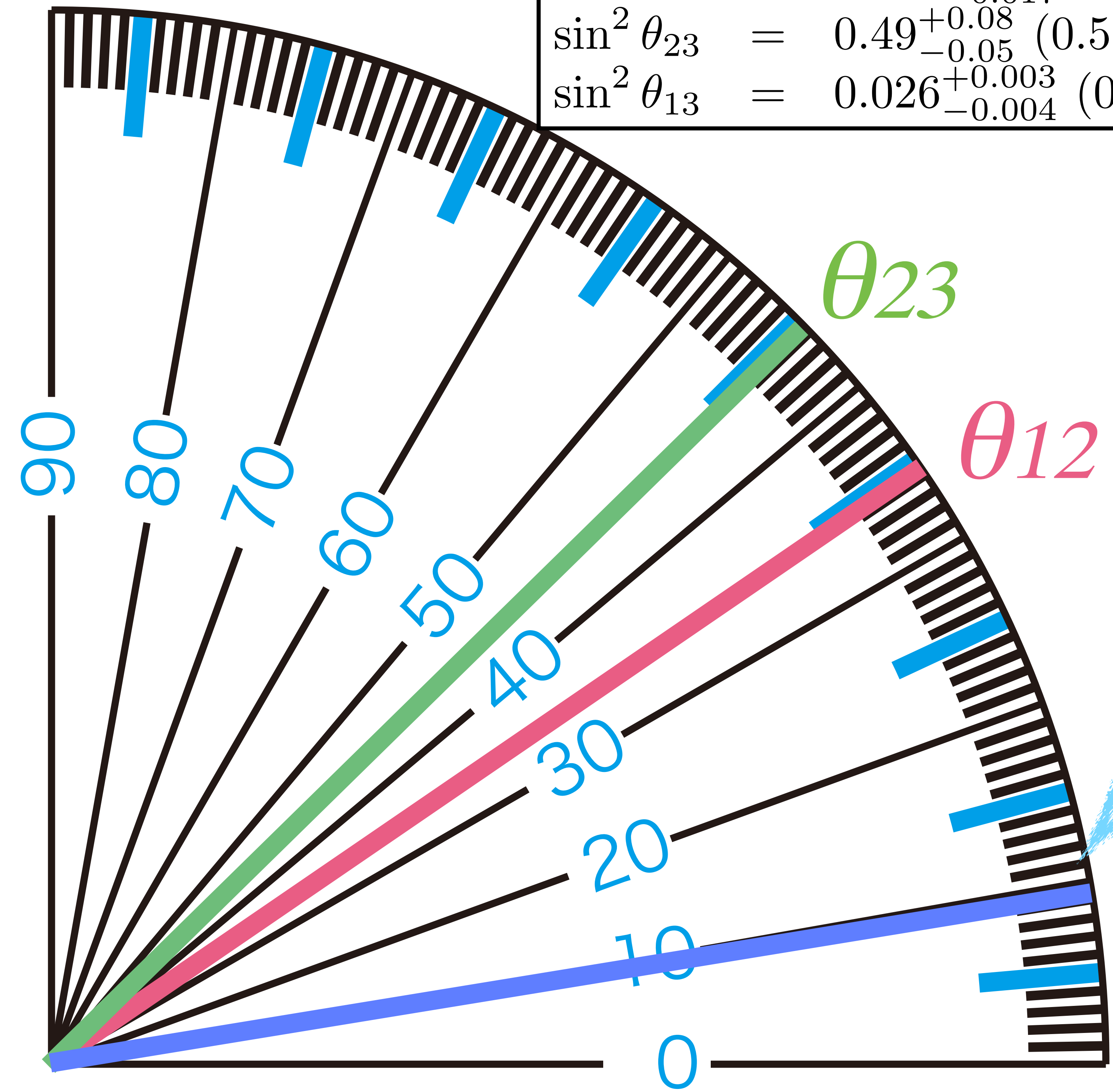

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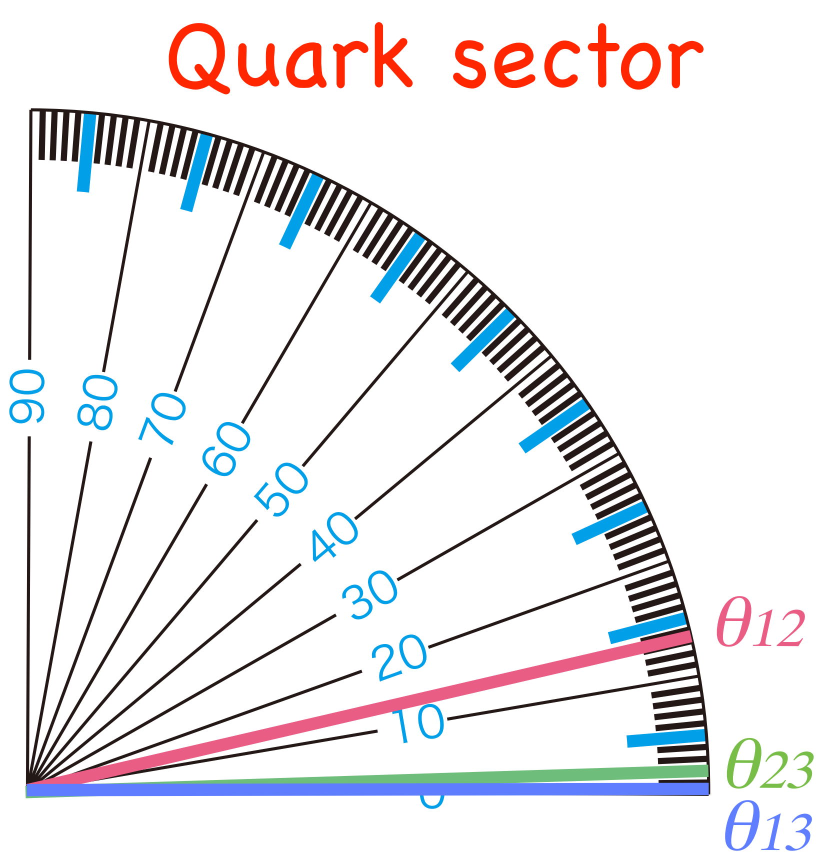

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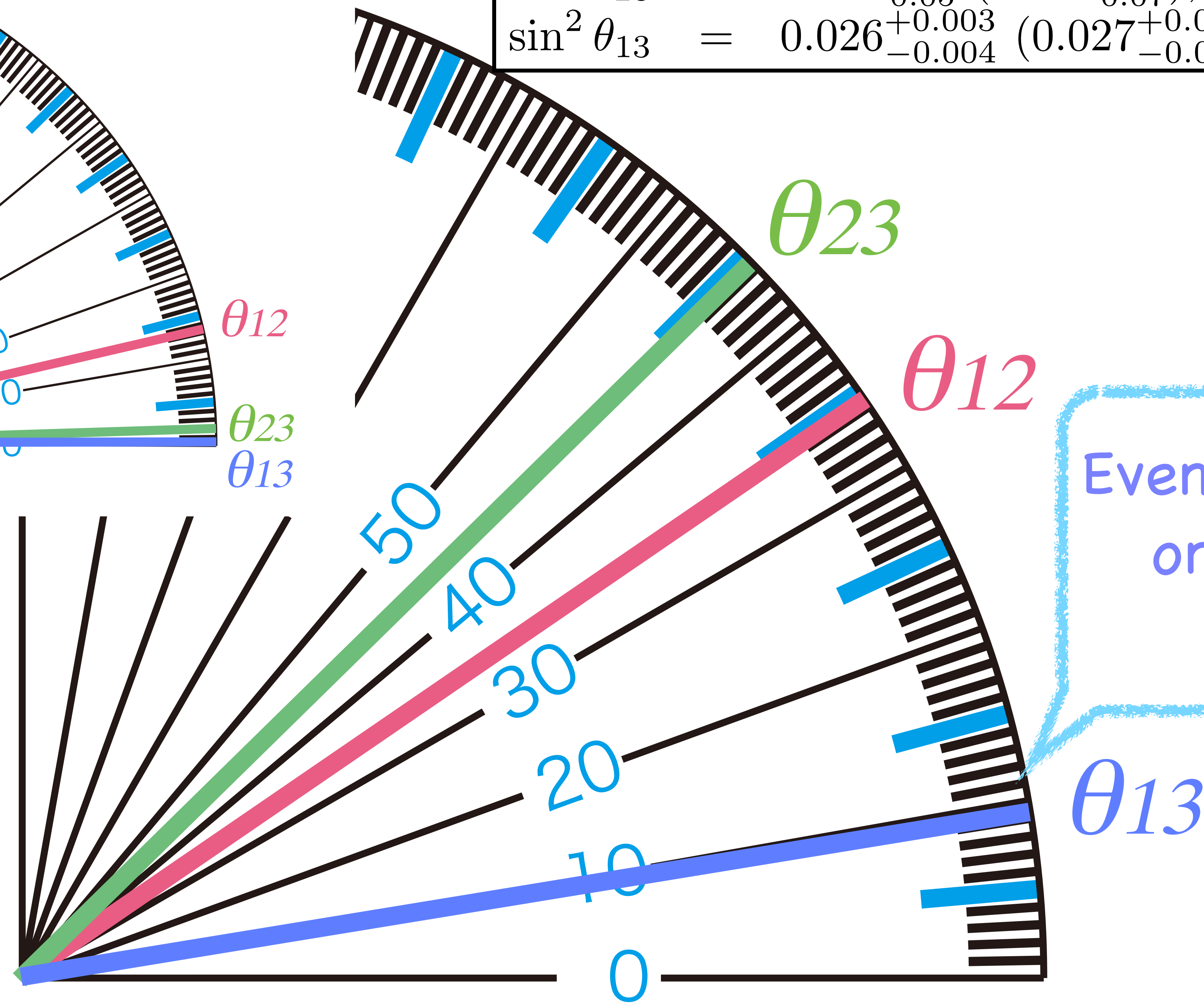

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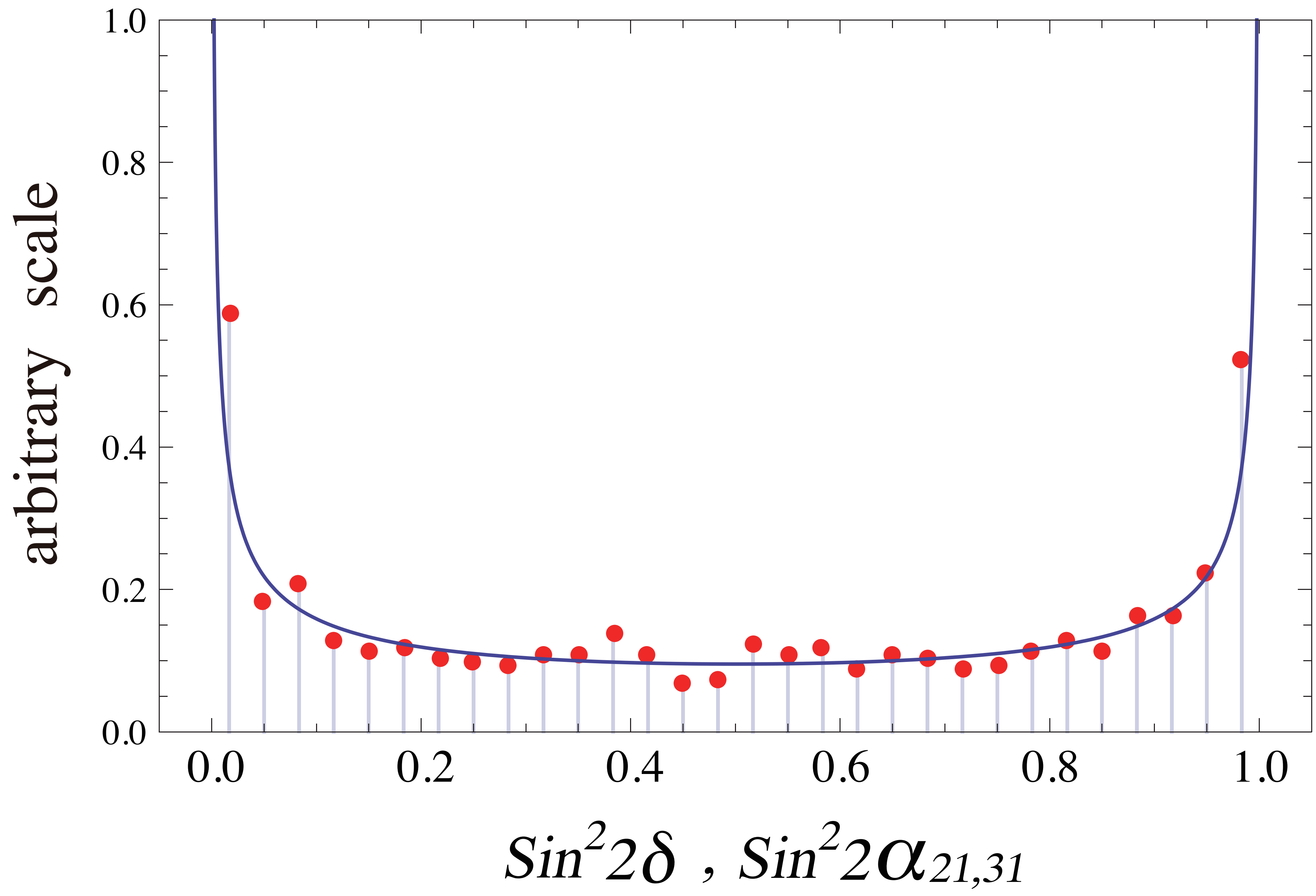
U(3)-invariant Haar distribution



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