

NEAR-CRITICALITY OF THE NEUTRINO SECTOR IN THE (AS)SM

IN COLLABORATION WITH A. EICHHORN, A. HELD AND D. BUCCIO

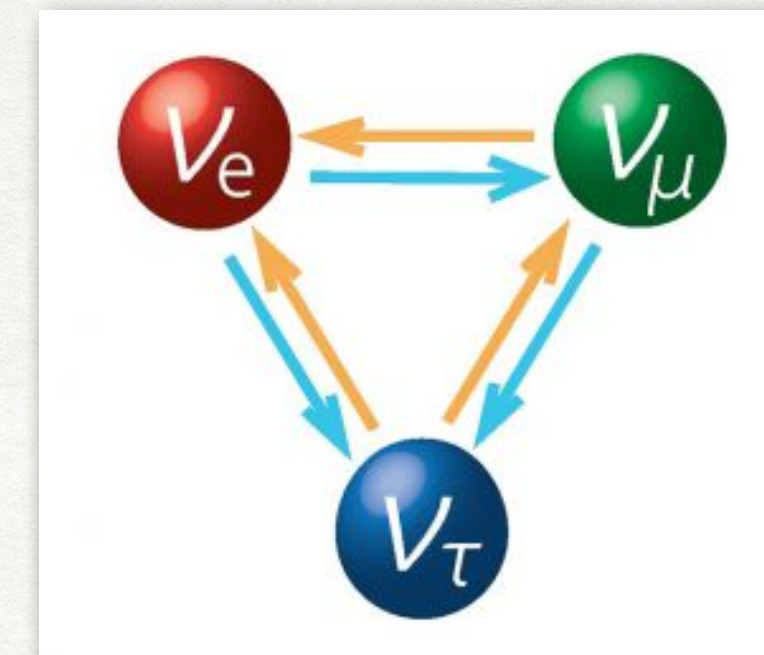
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ERG 2026 @ U. Sussex

What experiments tell us about neutrinos... so far

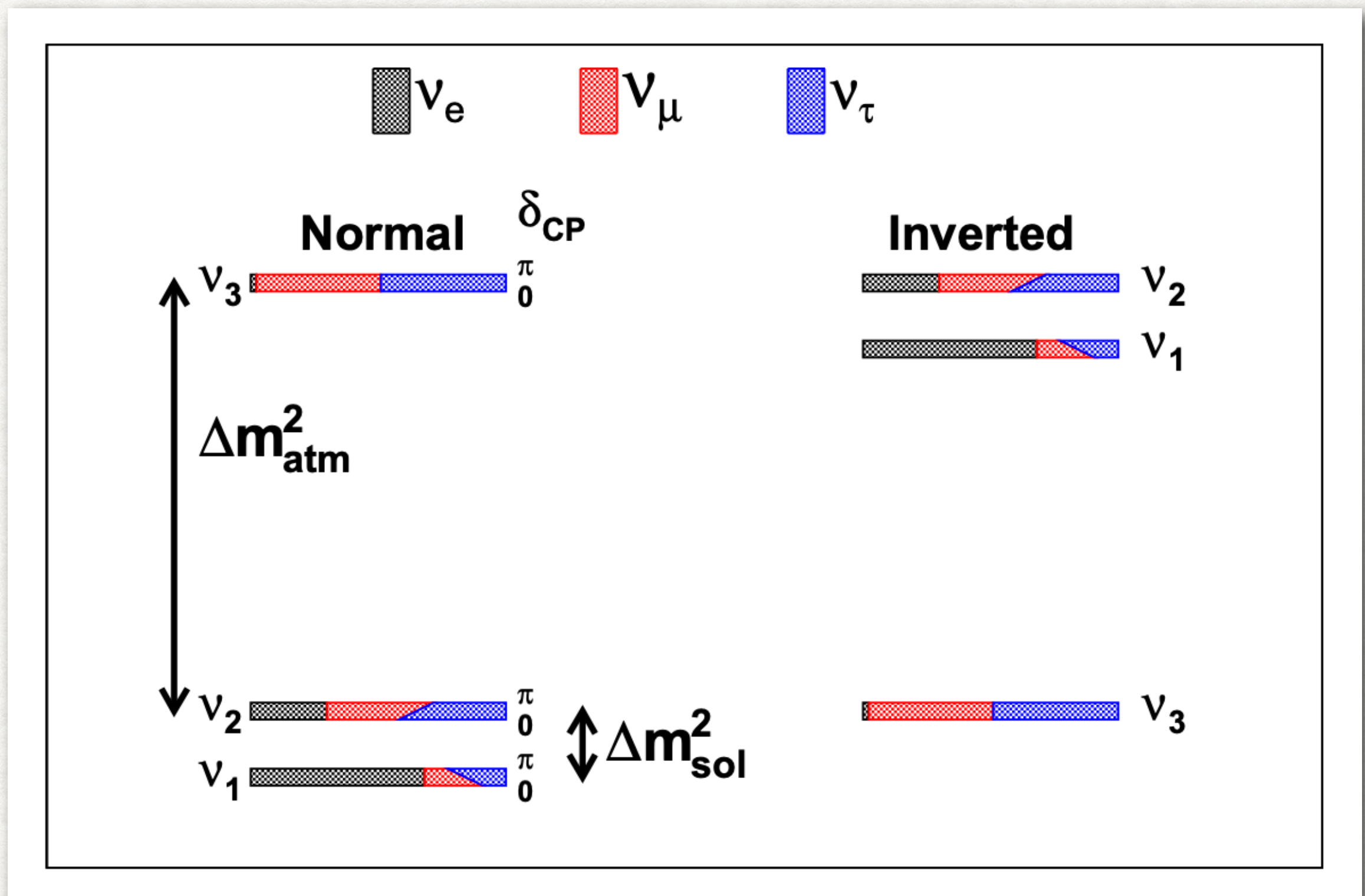


Mass Differences: [PDG '26]

- $\Delta m_{12}^2 \equiv \Delta m_{\text{sol}}^2 = (7.60 \pm 0.17) \cdot 10^{-5} \text{ eV}^2$
- NO : $\Delta m_{32}^2 \equiv \Delta m_{\text{atm}}^2 = (2.445 \pm 0.023) \cdot 10^{-3} \text{ eV}^2$
- IO : $\Delta m_{32}^2 \equiv (-2.52 \pm 0.04) \cdot 10^{-3} \text{ eV}^2$

$$m_{\nu_e} < 0.45 \text{ eV (KATRIN)}$$

$$\sum_i m_{\nu_i} < 0.072 \text{ eV (DESI)}$$



Lepton sector in the Standard Model + 3 flavors of right-handed neutrinos

$$\mathcal{L}_{\text{lepton}} = -\underbrace{Y_{ij}^l}_{\text{down-type Yukawa matrix}} \bar{L}^i H l_R^j - \underbrace{Y_{ij}^\nu}_{\text{up-type Yukawa matrix}} \bar{L}^i \tilde{H} \nu_R^j + \text{h.c.}$$

down-type Yukawa matrix

$$l_R^i = (e_R, \mu_R, \tau_R)$$

up-type Yukawa matrix

$$\nu_R^i = (\nu_{e,R}, \nu_{\mu,R}, \nu_{\tau,R})$$

From the Kinetic terms

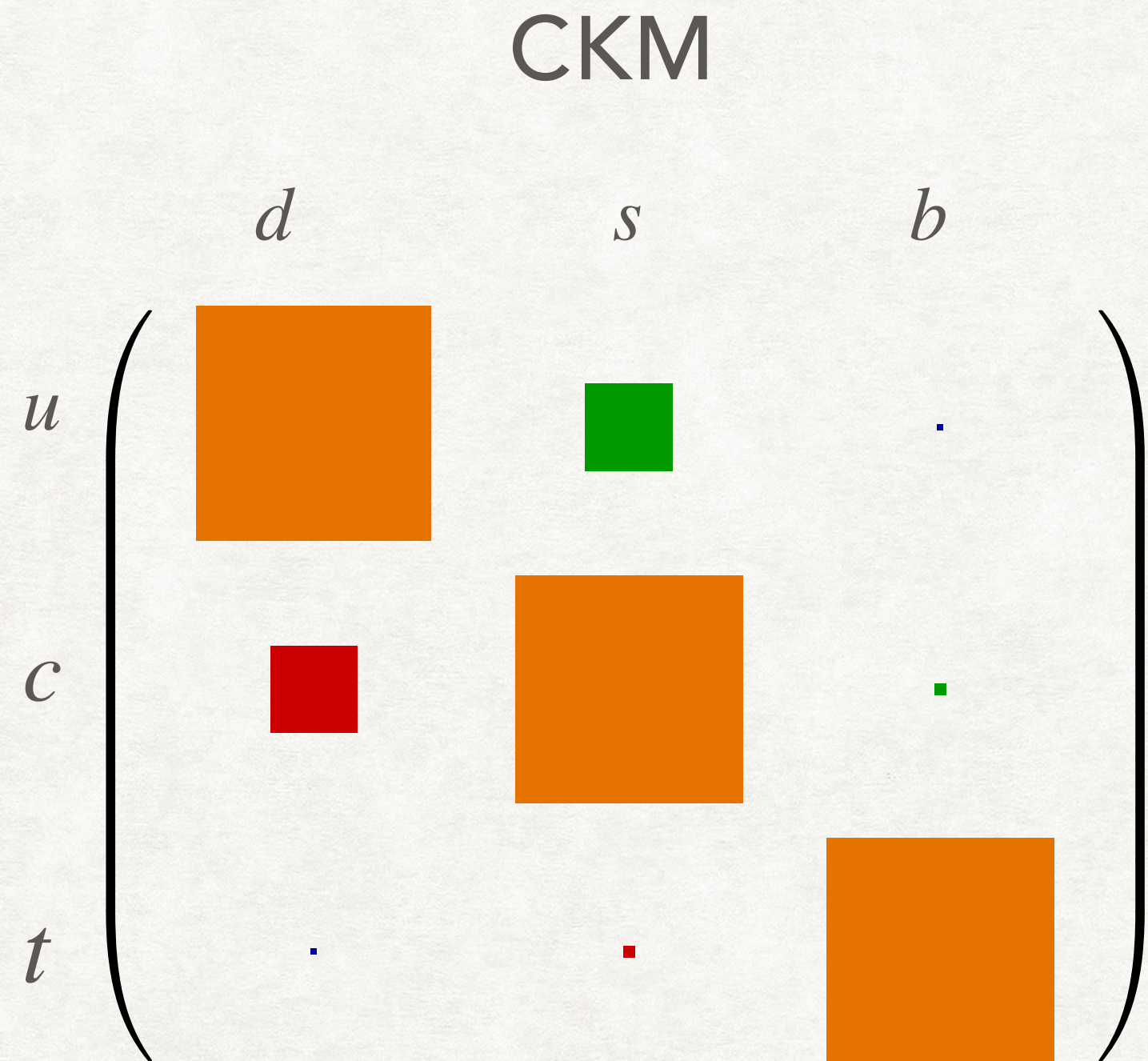
$$\mathcal{L}_{\text{SM}} \supset \bar{L}_l W(1 - \gamma_5) U_{li} \nu_i + \text{h.c.}$$

$$|U_{PMNS}|^2 = \begin{pmatrix} |U_{e1}|^2 & |U_{e2}|^2 & |U_{e3}|^2 \\ |U_{\mu1}|^2 & |U_{\mu2}|^2 & |U_{\mu3}|^2 \\ |U_{\tau1}|^2 & |U_{\tau2}|^2 & |U_{\tau3}|^2 \end{pmatrix}$$

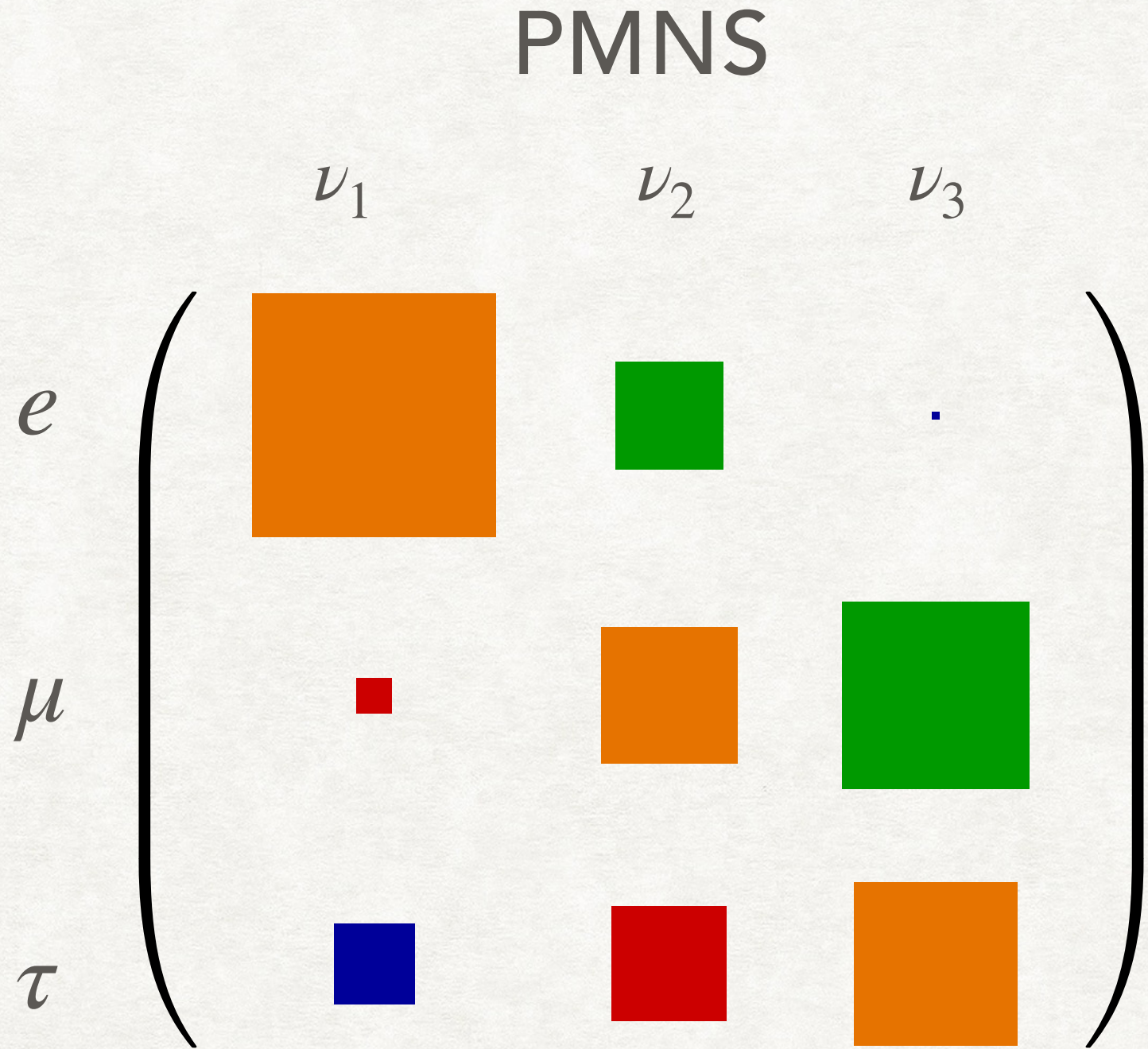
Lepton sector in the Standard Model

+

3 flavors of right-handed neutrinos
with no Majorana masses



vs

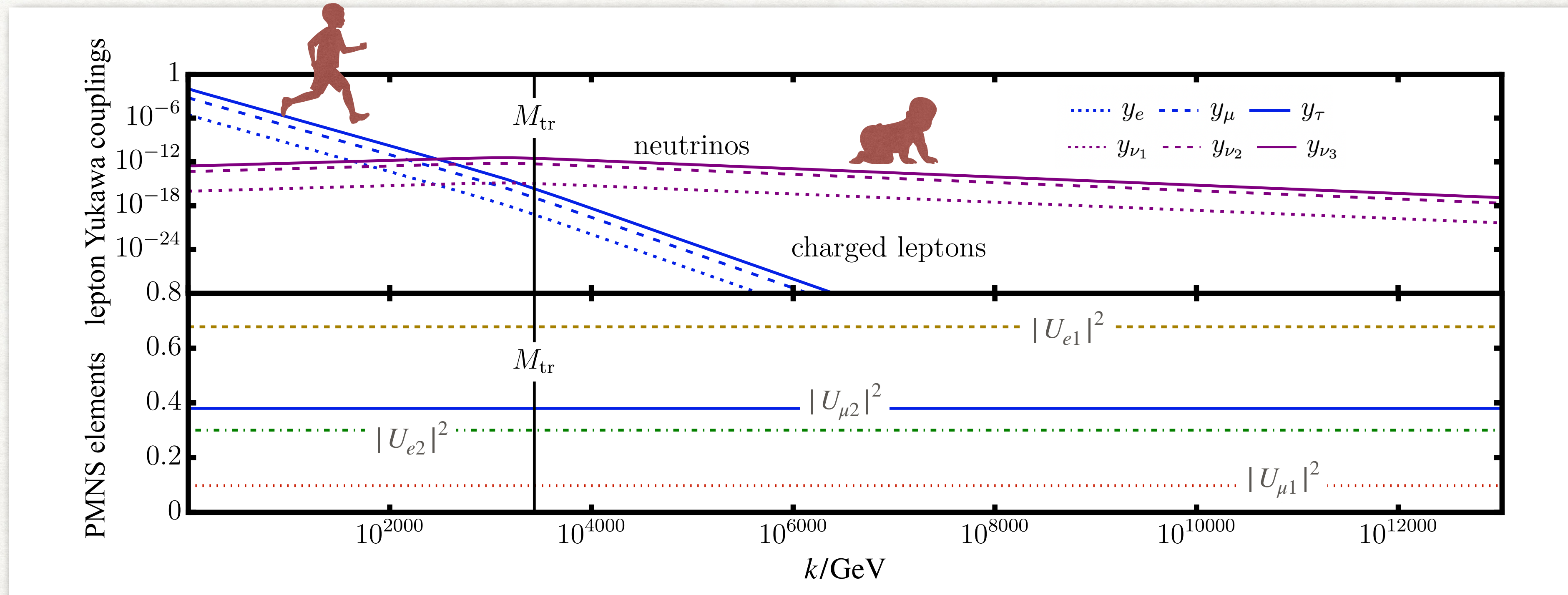


Can be explained through a QG-
induced fixed-point cascade, because it
is an IR attractive configuration

Alkofer, Eichhorn, Held, Nieto, Schröfl '20 ;
ZG, Eichhorn, Held '25; Dolan '26;

Large Mixing
and
no apparent structure

Including asymptotic safety corrections $\Rightarrow \beta_i = \beta_i^{SM} + f_i \theta(t - t_{M_p})$



[Z.G., A. Eichhorn, A. Held; '25]

1. y_e, y_μ, y_τ run quickly to tiny values

2. $y_{\nu_1}, y_{\nu_2}, y_{\nu_3}$ run slowly and remain tiny

[Eichhorn & Held '22; Kowalska, Pramanick and Sessolo '22]

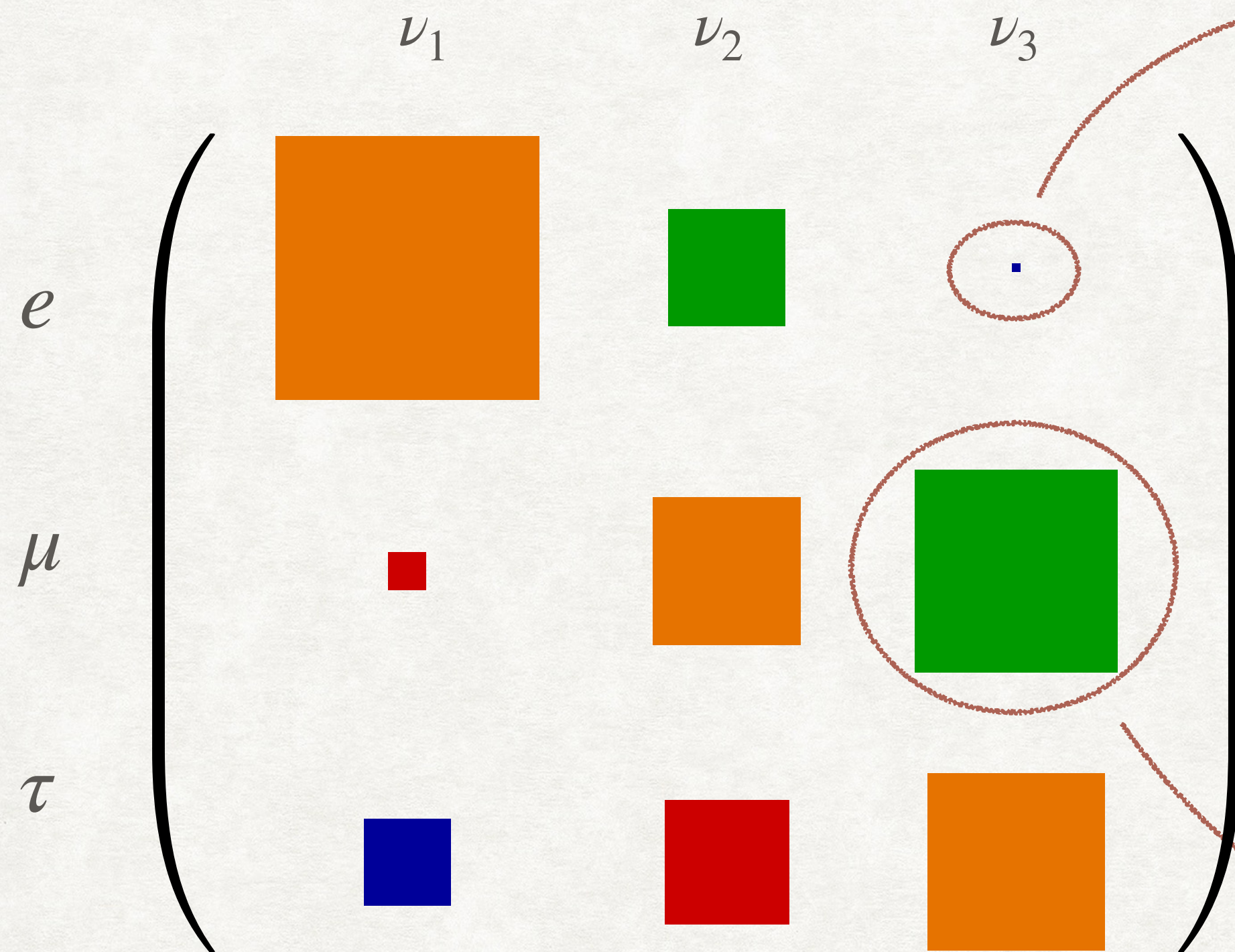


The PMNS matrix does not run



No emerging structure from
the RG flows!

PMNS matrix



$$\beta_{|U_{e3}|^2} = \frac{3y_\tau^2}{16\pi^2} \left[\frac{y_{\nu_3}^2 + y_{\nu_2}^2}{y_{\nu_3}^2 - y_{\nu_2}^2} \right] |U_{e3}|^2 + \dots$$

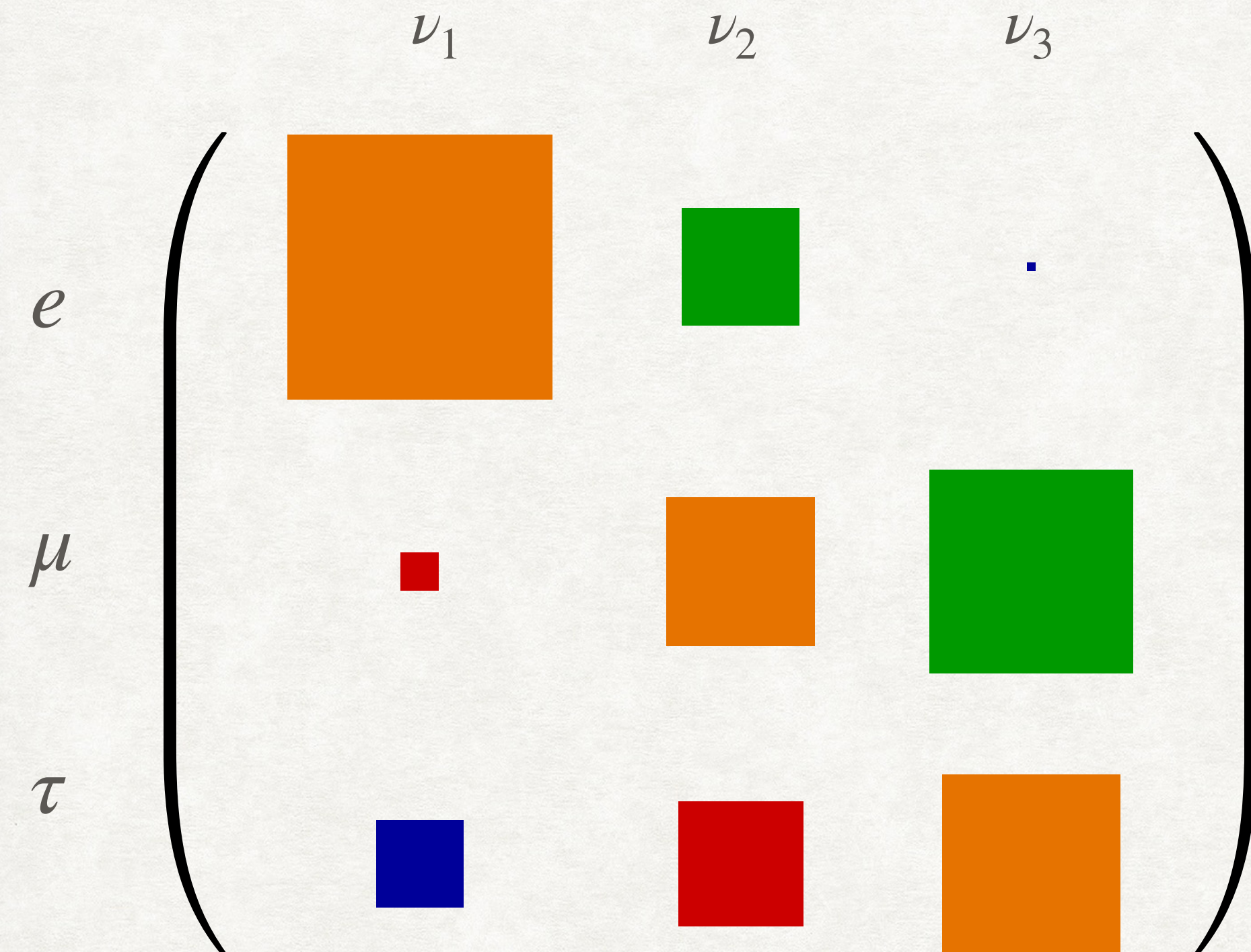
Quasi-degenerate case

$$m_{\nu_1} \approx m_{\nu_2} \approx m_{\nu_3}$$

$\Rightarrow$ Significant PMNS running!

$$\beta_{|U_{\mu 2}|^2} = \frac{3y_\tau^2}{16\pi^2} \left[\frac{y_{\nu_3}^2 + y_{\nu_2}^2}{y_{\nu_3}^2 - y_{\nu_2}^2} \right] |U_{\mu 2}|^2 + \dots$$

PMNS matrix



Quasi-degenerate case

$$m_{\nu_1} \approx m_{\nu_2} \approx m_{\nu_3}$$

$\implies$ Significant PMNS running!



For fixed Δm_{21}^2 , Δm_{23}^2

Imposing (nearly) no PMNS running

$\implies$

$$m_\nu^2 \lesssim M$$

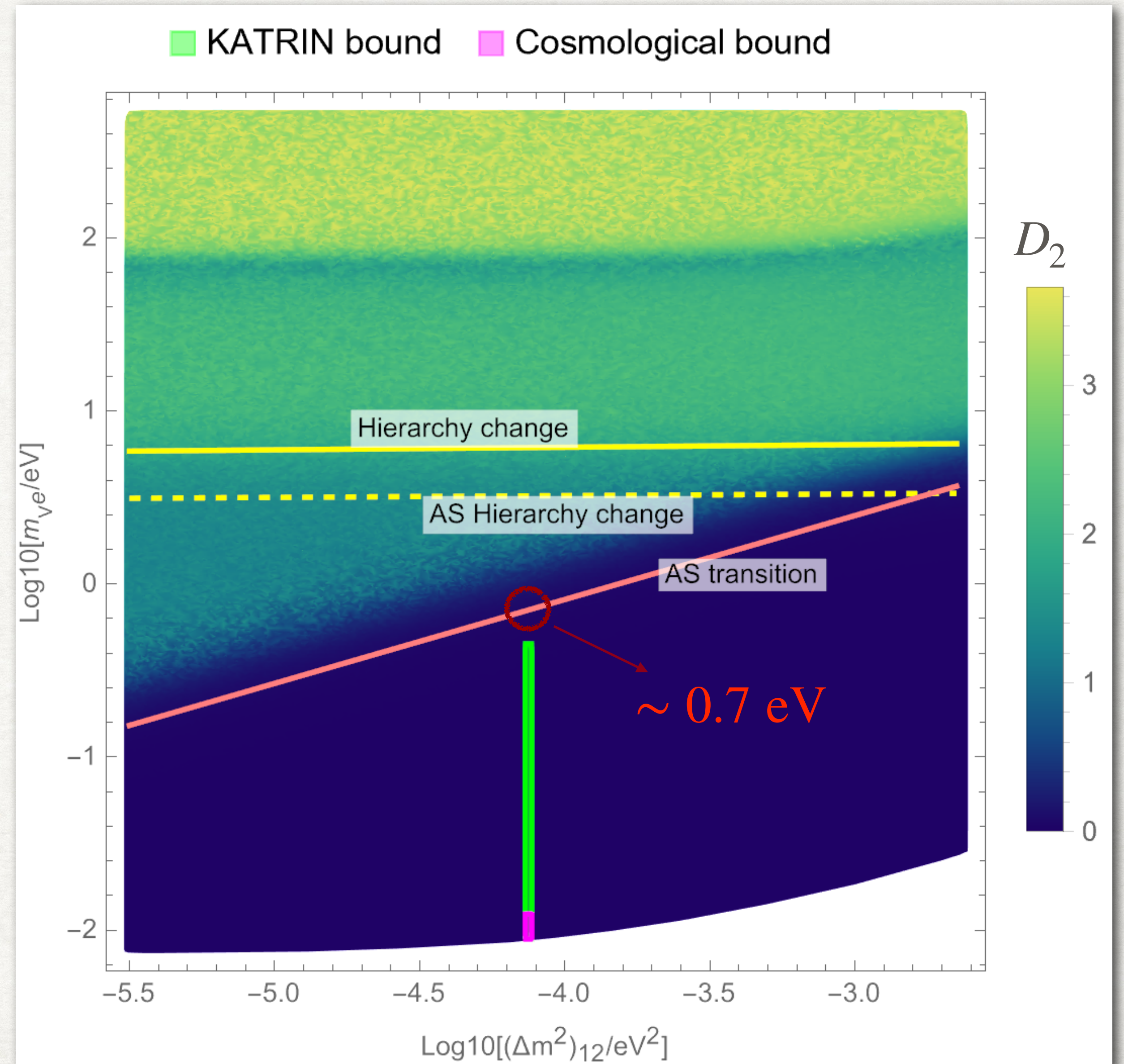
The bound M changes from SM to ASSM!

$$D_2 = \sum_i \left(|U_{i,\text{UV}}|^2 - |U_{i,\text{IR}}|^2 \right)^2$$

Region of PMNS
instability $UV \neq IR$

Asymptotic Safety pushes
the crossover region even
closer to the Standard Model

Region of PMNS
stability $UV \approx IR$



Another Question

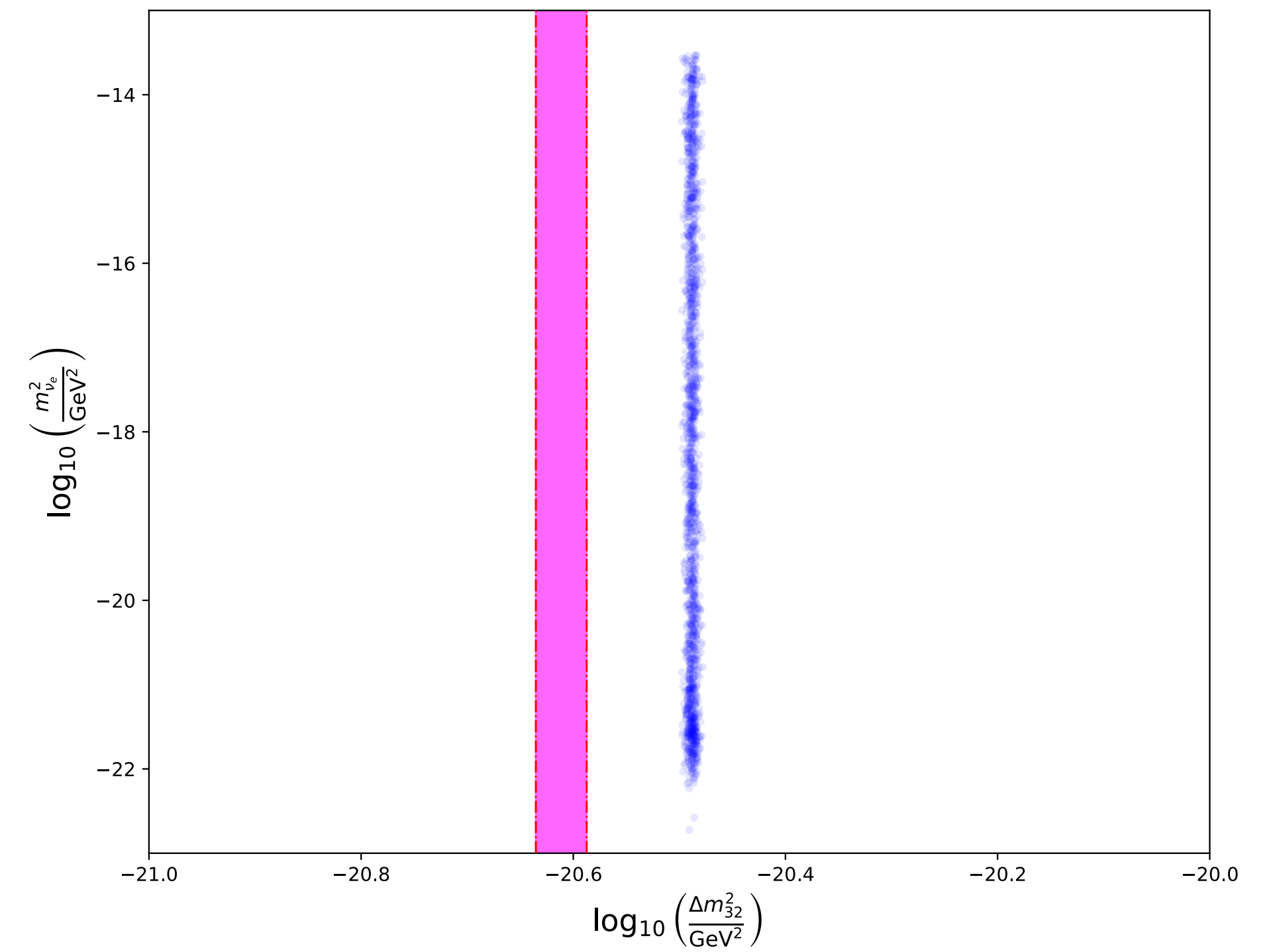
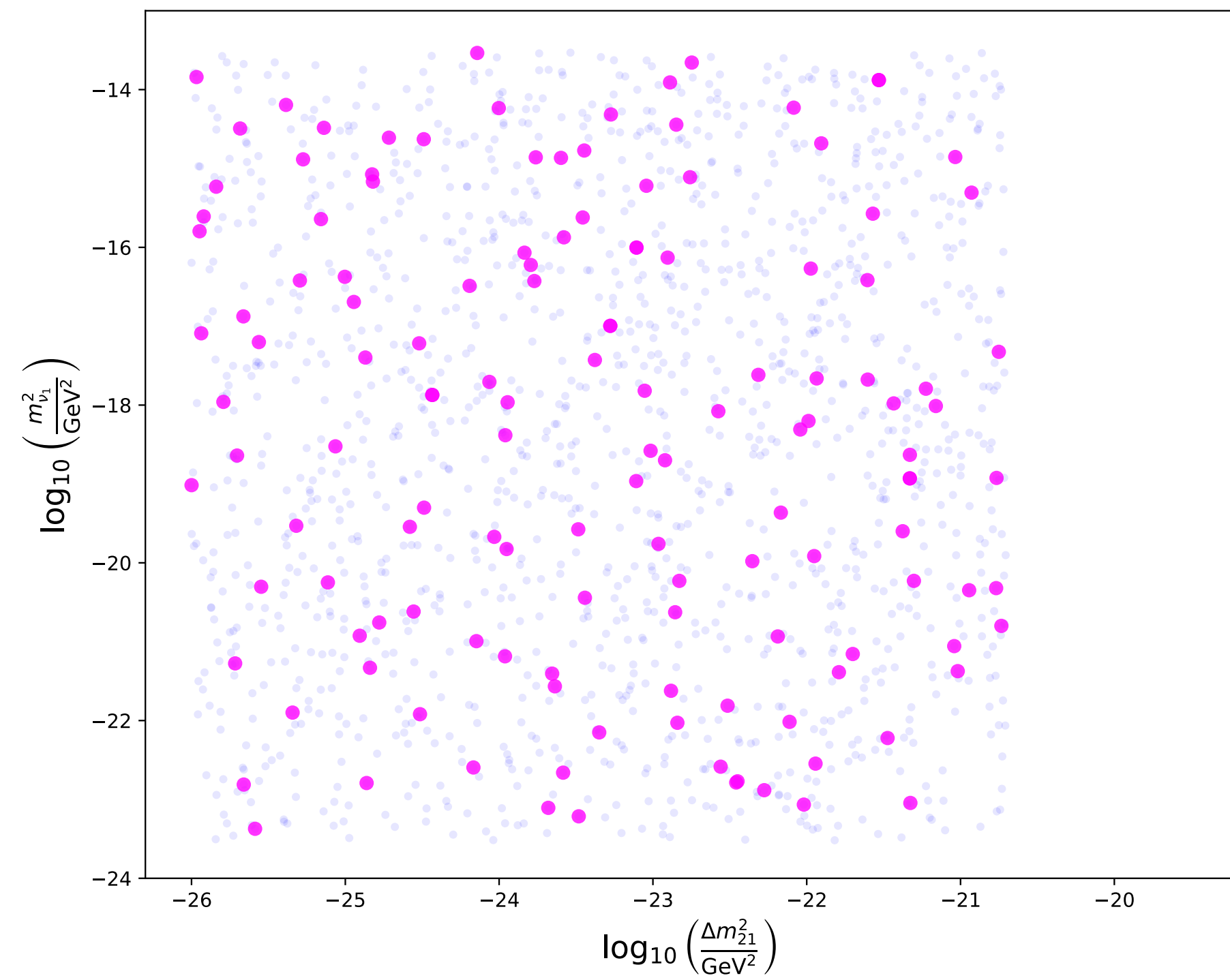
Given the experimental observations of mass differences, is there a preferred neutrino mass value for the (AS)SM?

Starting from an (fairly) ignorant prior, we want to compute the posterior distribution $\Rightarrow P\left(m_{\nu_e} \mid \Delta m_{12}^2, \Delta m_{23}^2 = \text{experiment}\right)$

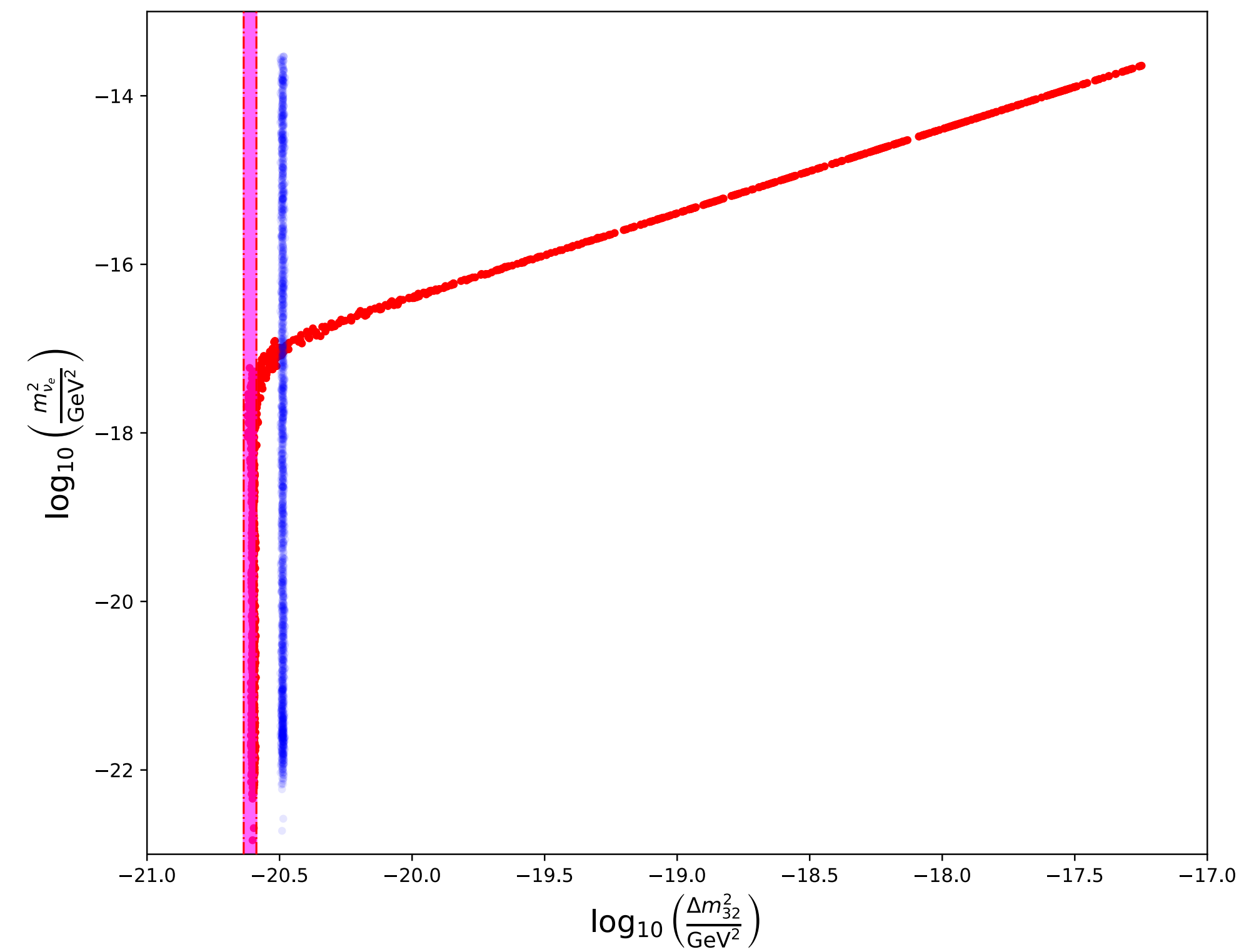
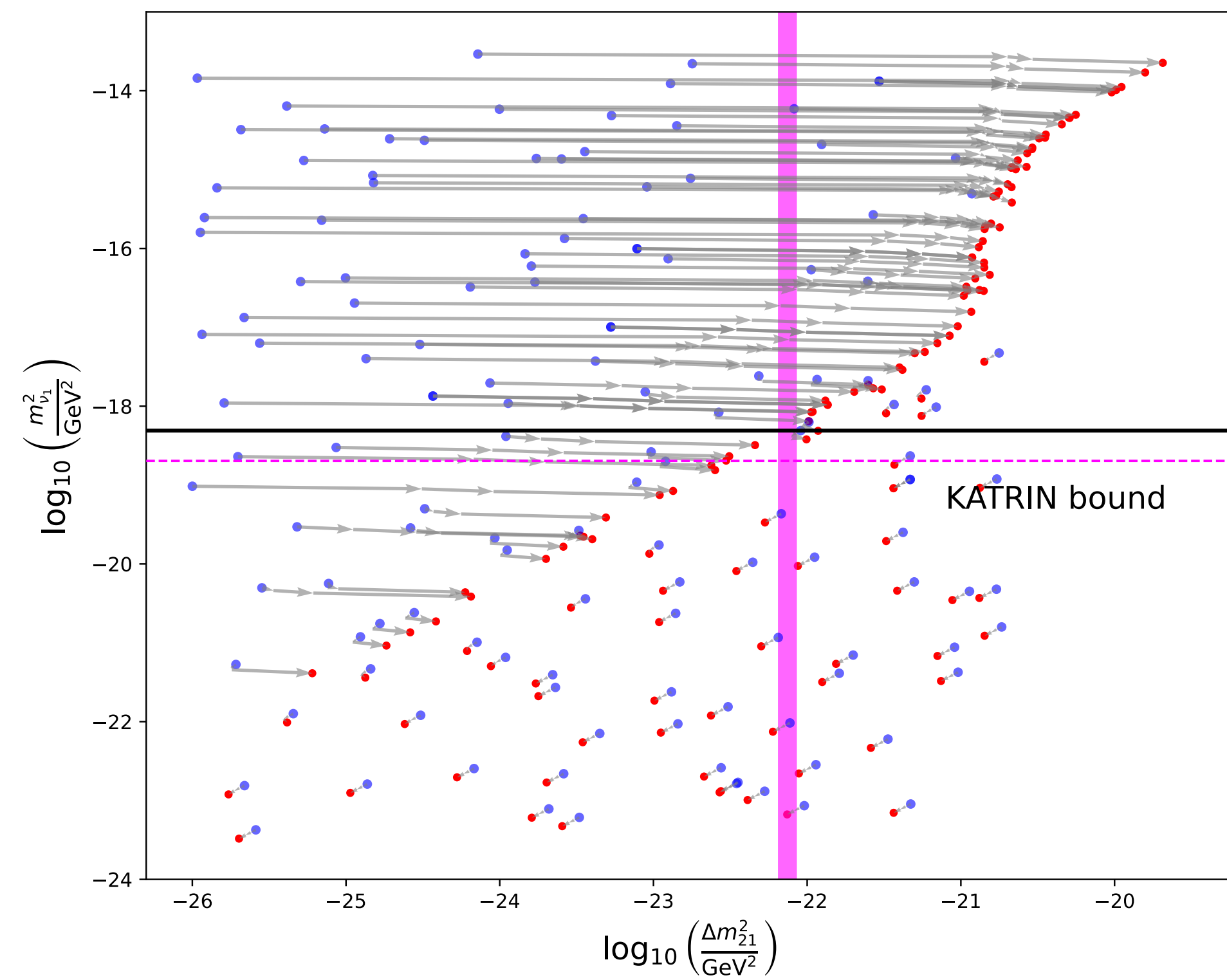
UV prior assumptions {

- PMNS: Uniform + constraints
- Δm_{32}^2 : Gaussian in the UV
- $y_{\min}, \Delta m_{12}^2$: Log - uniform

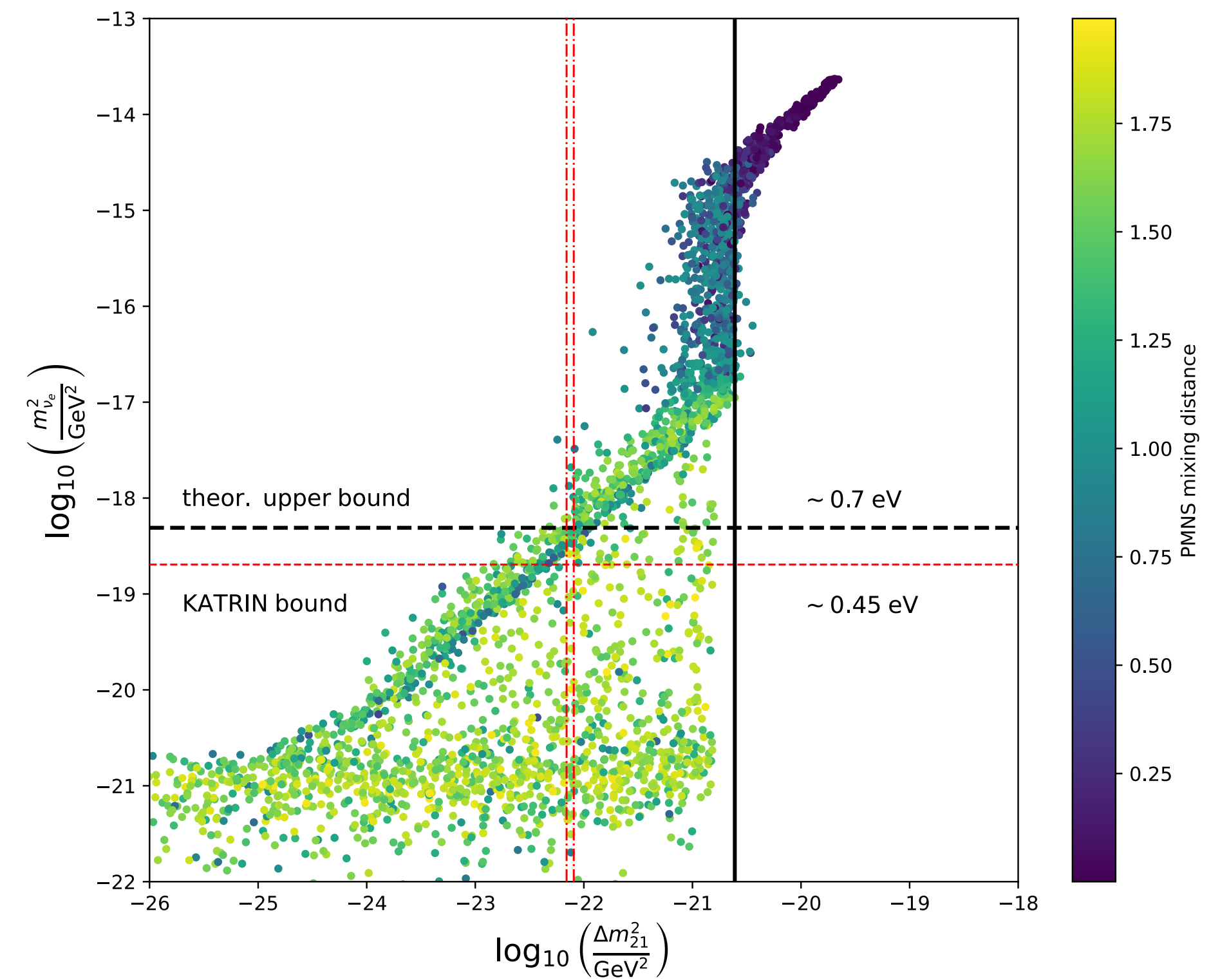
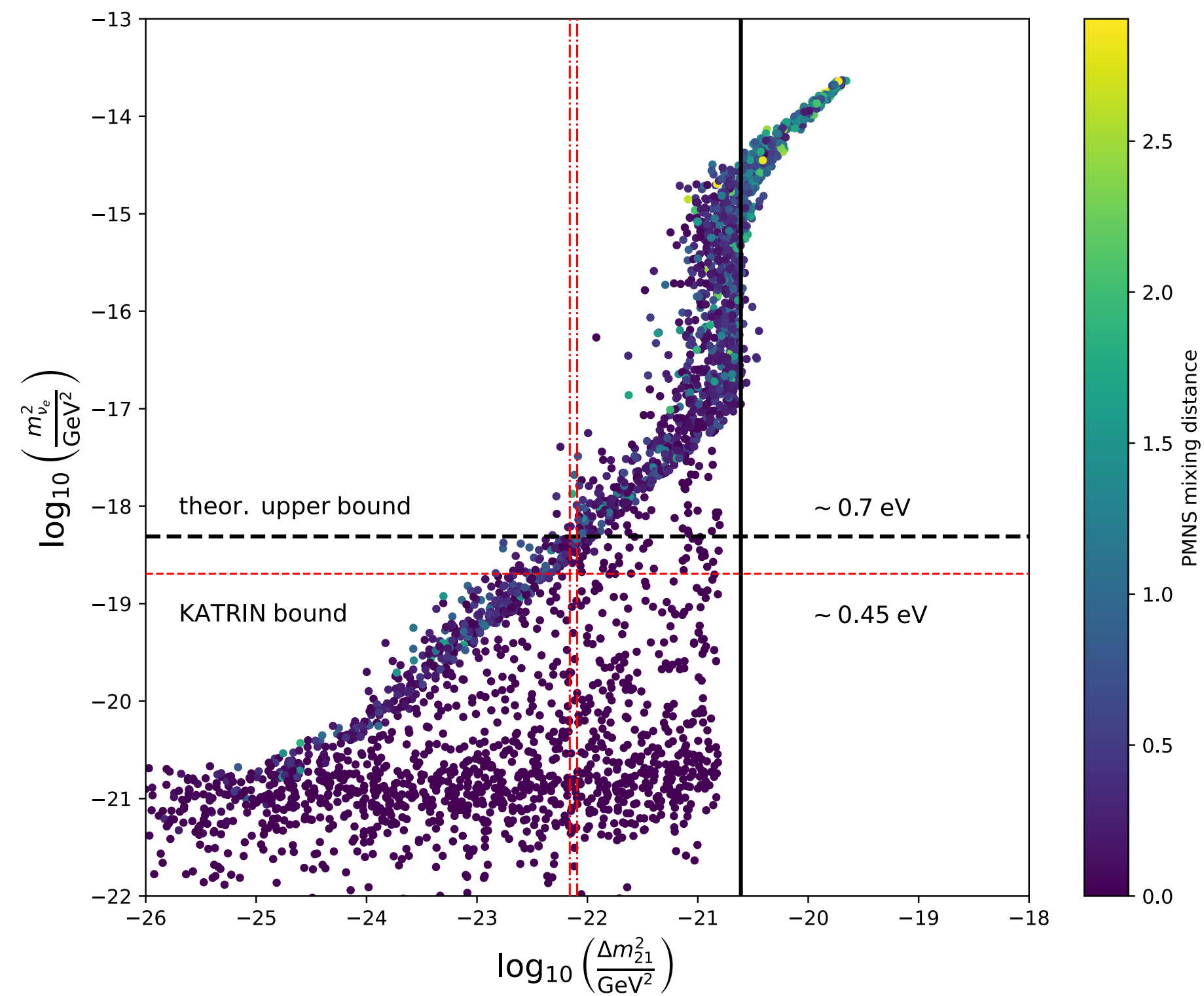
Scanning UV conditions



Scanning UV conditions



Tracking the behaviour of the mixing measure

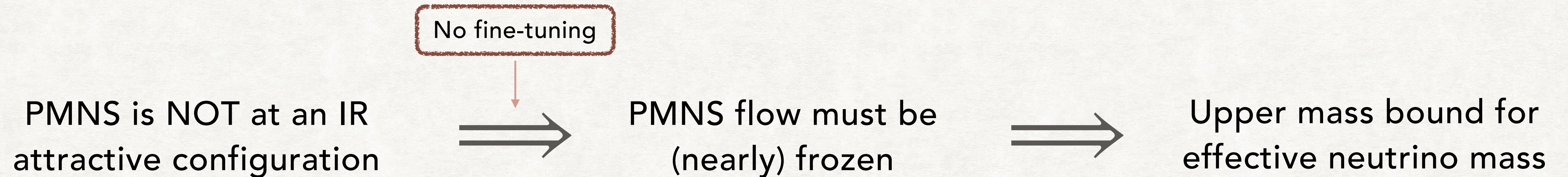


$$D_2 = \sum_i \left(|U_{i,\text{UV}}|^2 - |U_{i,\text{IR}}|^2 \right)^2$$

$$D = 3 - \sum_{i,j} |U_{ij}|^4$$

Conclusions/Summary

In the SM, small neutrinos are necessary for large mixing ("naturally")!



$$m_{\nu_e} \lesssim 1 \text{ eV (SM)}$$



KATRIN bound close to a crossover between regions with large and small mixing

$$m_{\nu_e} \lesssim 0.7 \text{ eV (ASSM)}$$

ASQG pushes the crossover region lower!

Favored mass due to the IR attractor

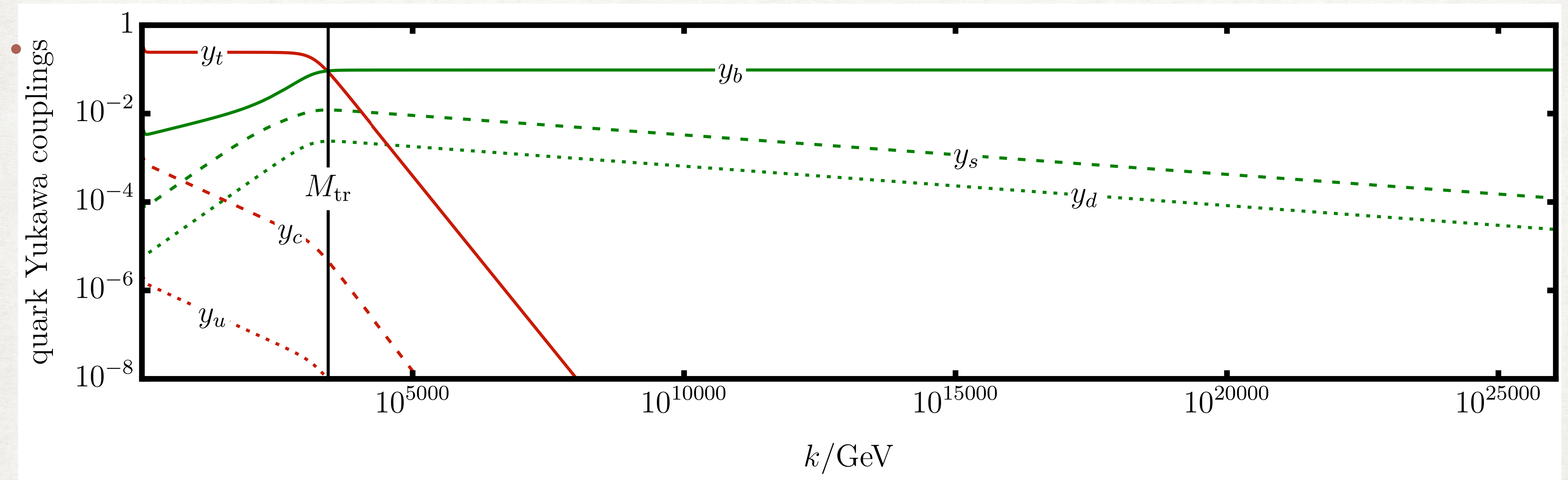
Thank you very much!



Extra slides

Including asymptotic safety corrections $\Rightarrow \beta_i = \beta_i^{SM} + f_i \theta(t - t_{M_p})$

- Asymptotically Safe Quantum Gravity allows for a cascading UV completions



All couplings have been fixed to their PDG values at $k_{IR} = 171.1$ GeV with a two-loop matching procedure [Huang, Zhou '21]. For this, we fixed the gravitational parameters to $f_g = 9.749 \times 10^{-3}$ and $f_y = -3.27 \times 10^{-4}$.

What happens to the PMNS matrix for a quasi-degenerate spectrum?

UV $\longrightarrow$ IR

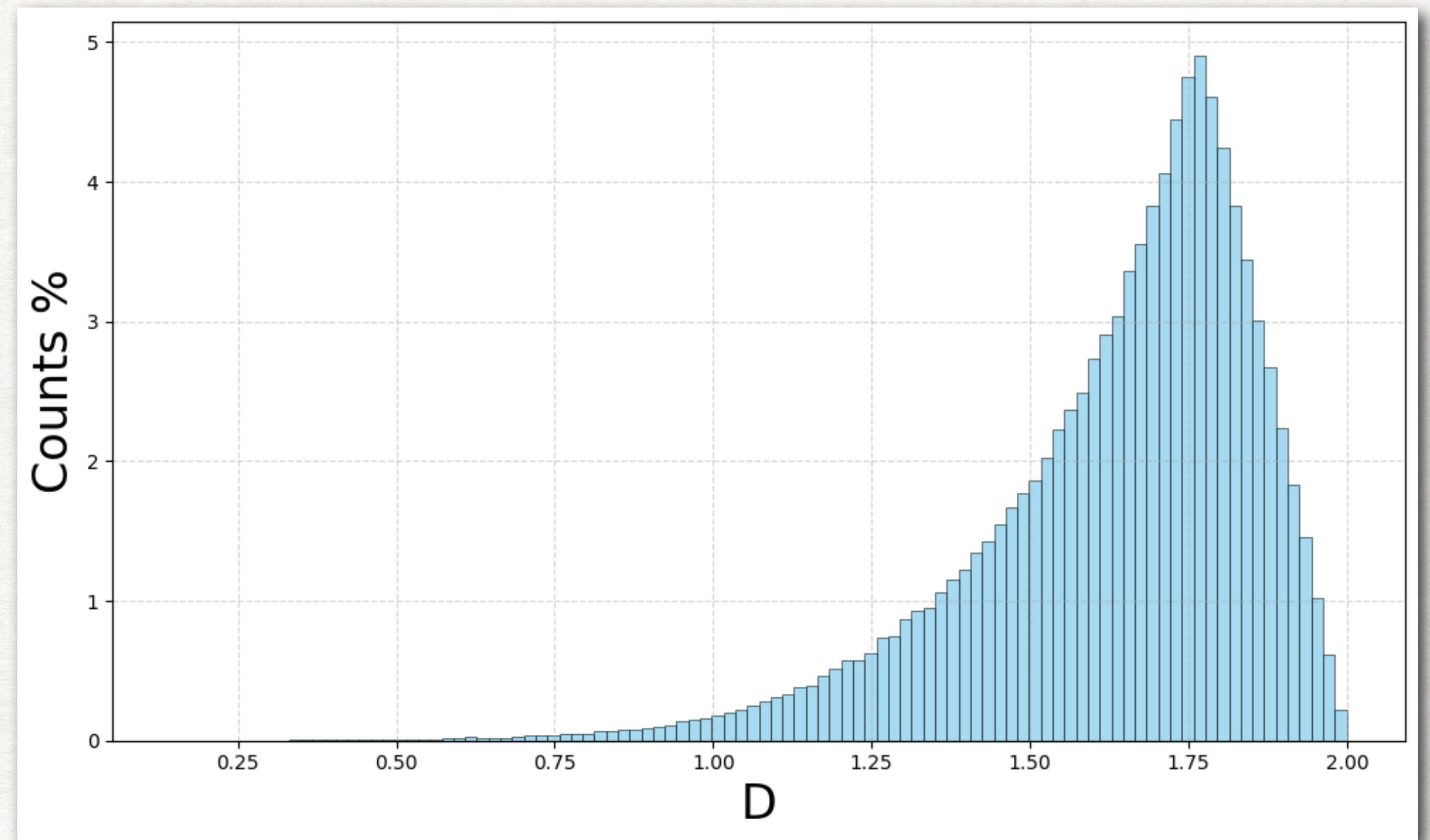
UV distribution

Ordering Invariant Mixing measure

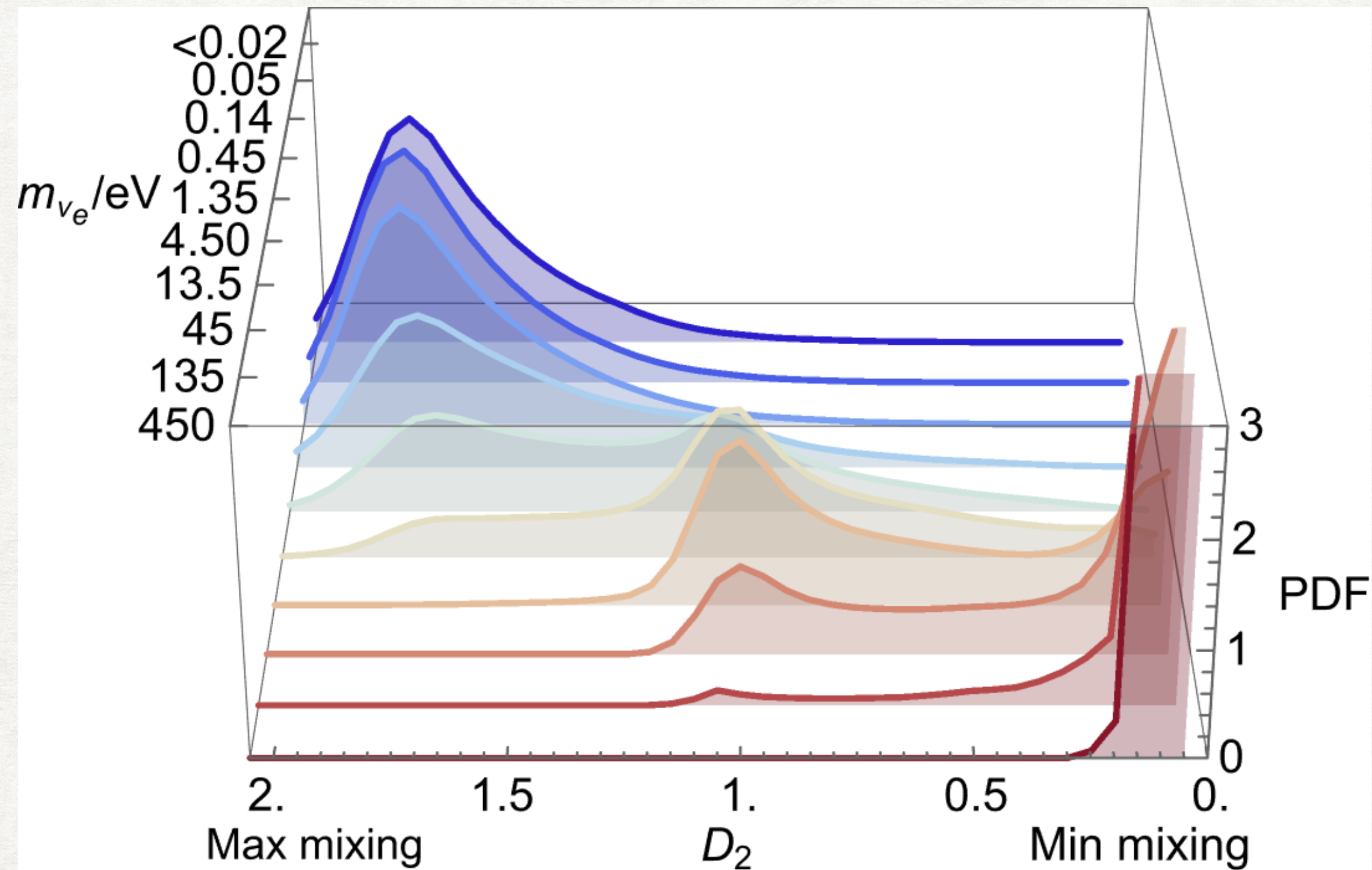
$$D = 3 - \sum_{i,j} |U_{ij}|^4$$

$D = 0$
no mixing

$D = 2$
maximal mixing



IR distribution for D

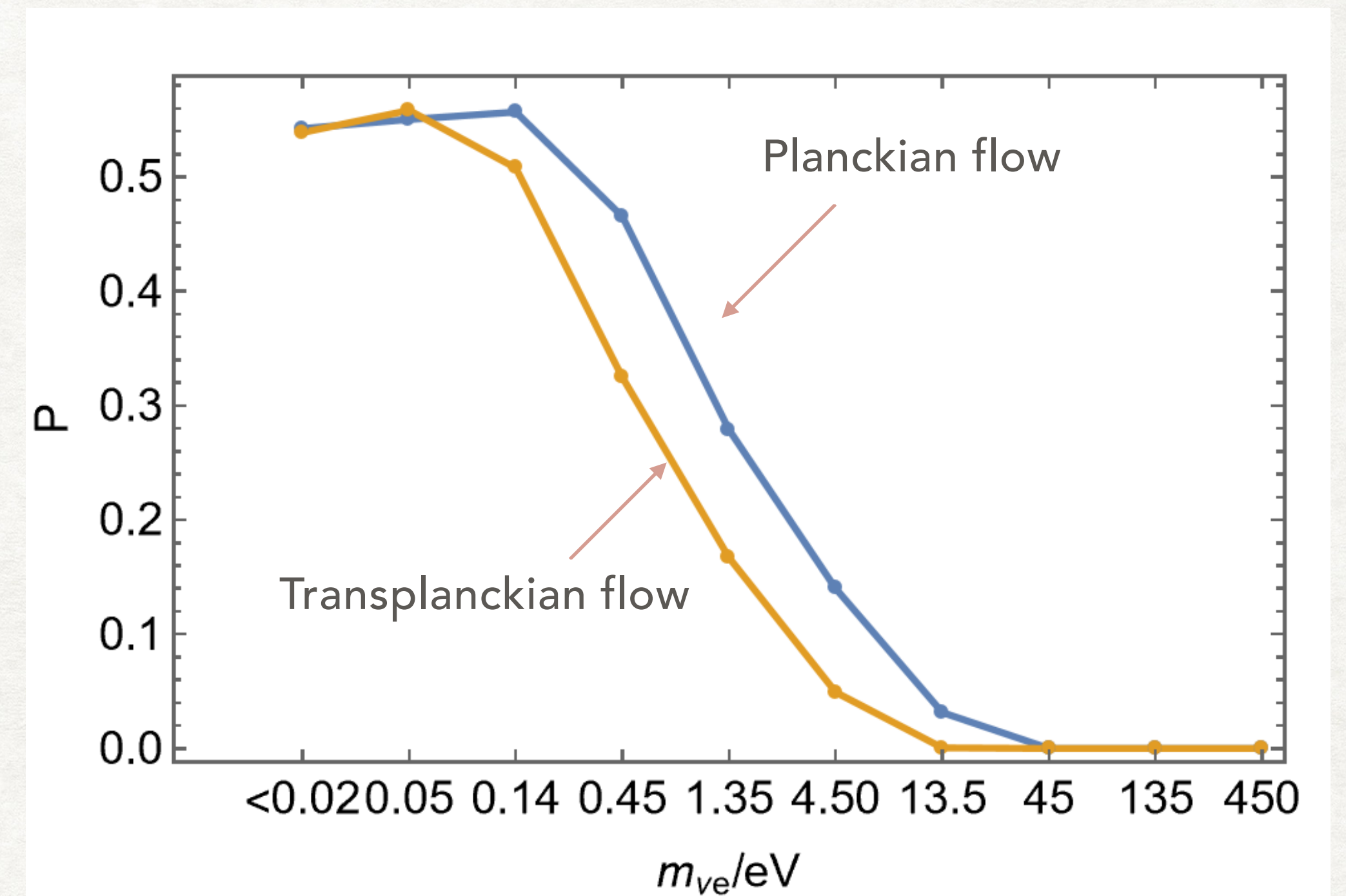


D

Phenomenological viability $\implies$ Neutrinos CANNOT be too large!

$$\text{SM: } m_{\nu_e} \lesssim 13 \text{ eV}$$

Probability for $D \gtrsim 1.7$



$$\text{ASQG + SM: } m_{\nu_e} \lesssim 4 \text{ eV}$$

RG flow toward the IR

Hierarchical case

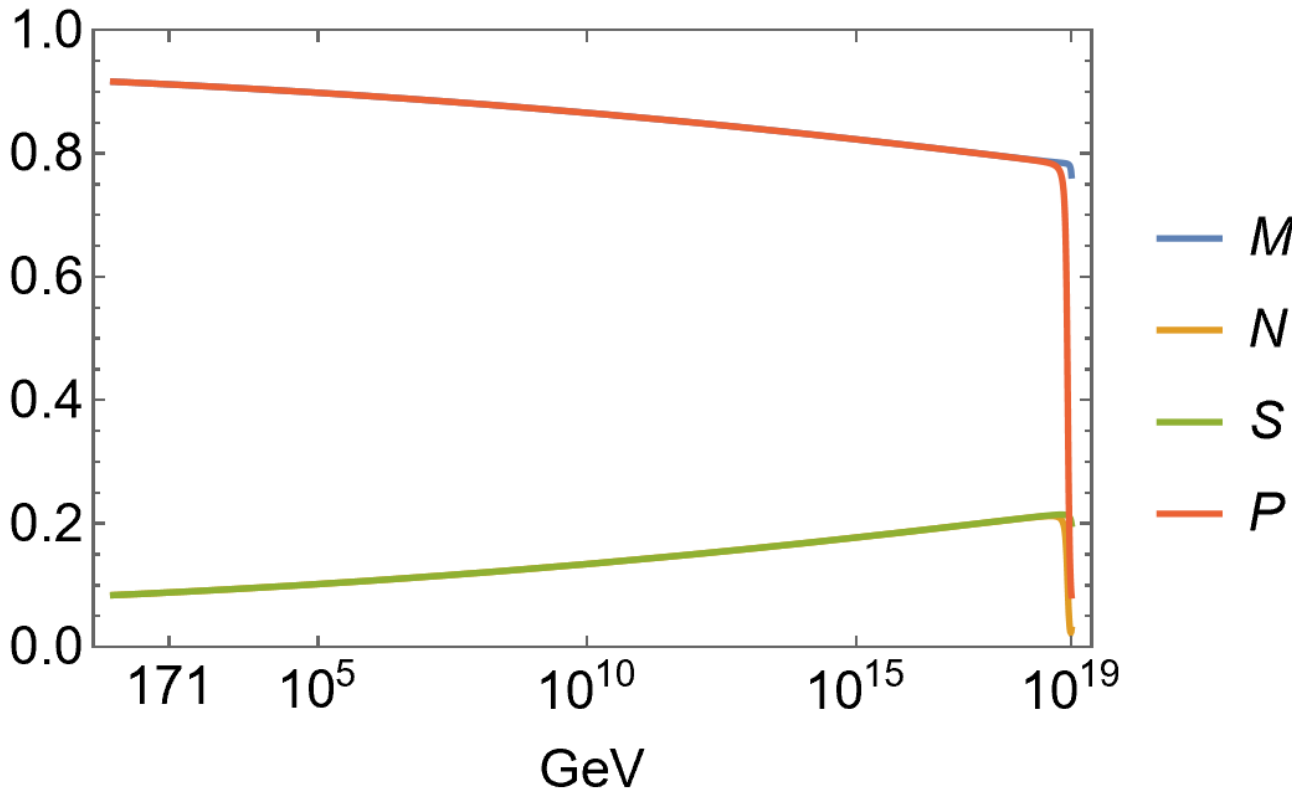
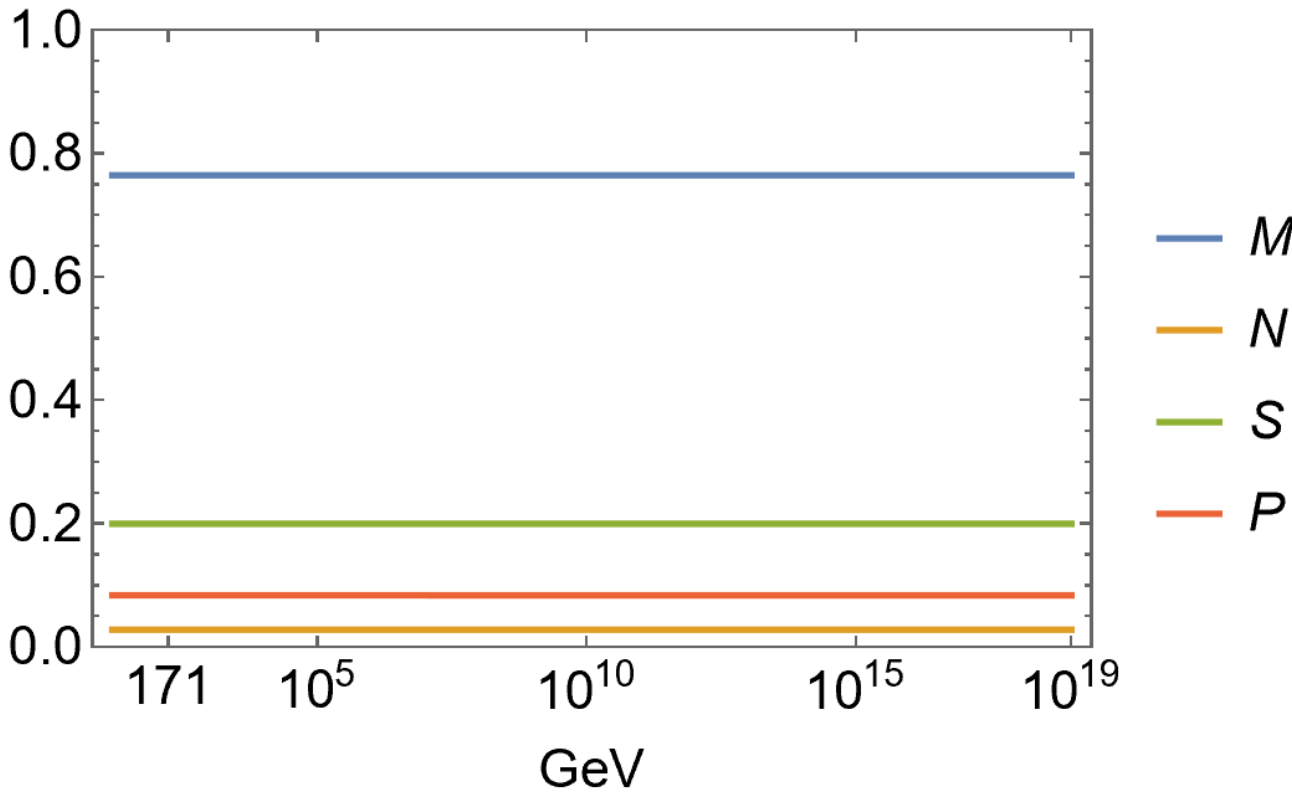
$$\frac{m_i^2 + m_j^2}{\Delta m_{ij}^2} \sim 1$$

Degenerate case

$$\frac{m_i^2 + m_j^2}{\Delta m_{ij}^2} \gg 1$$

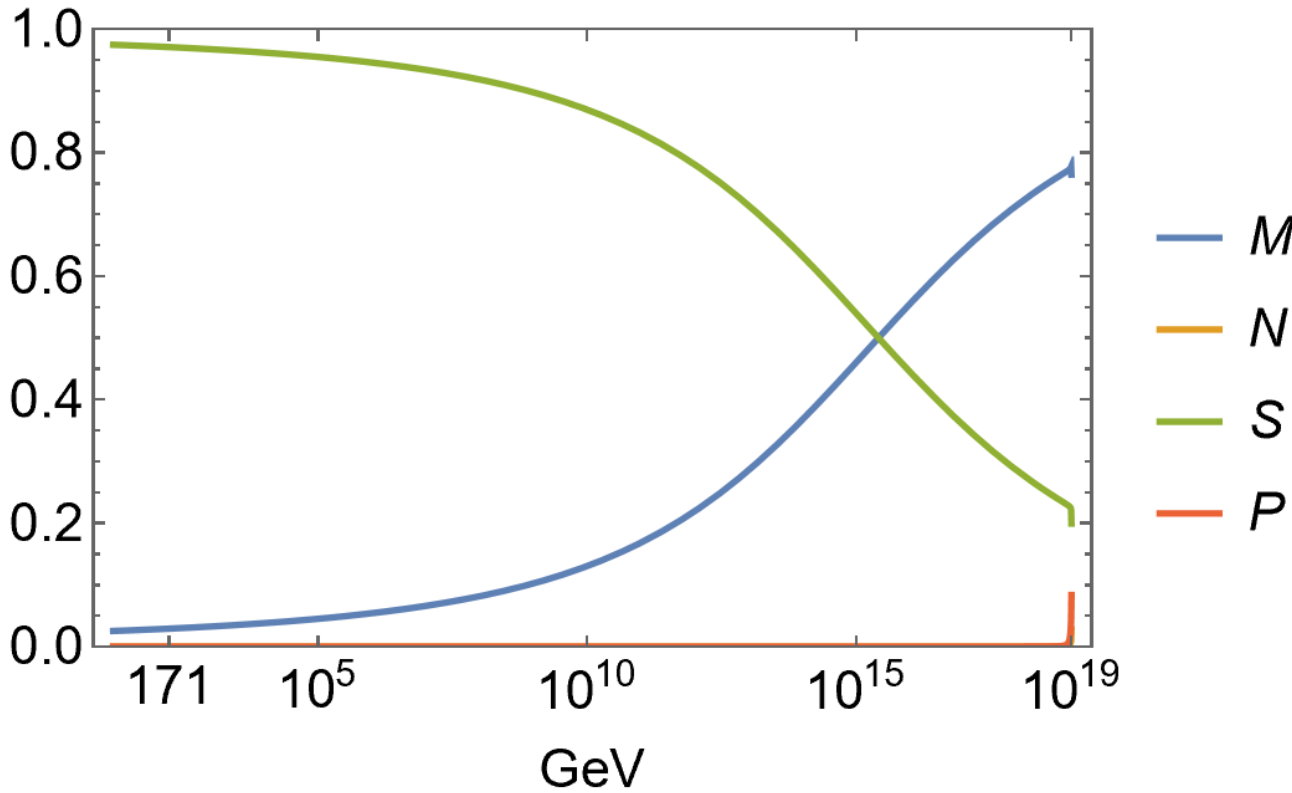
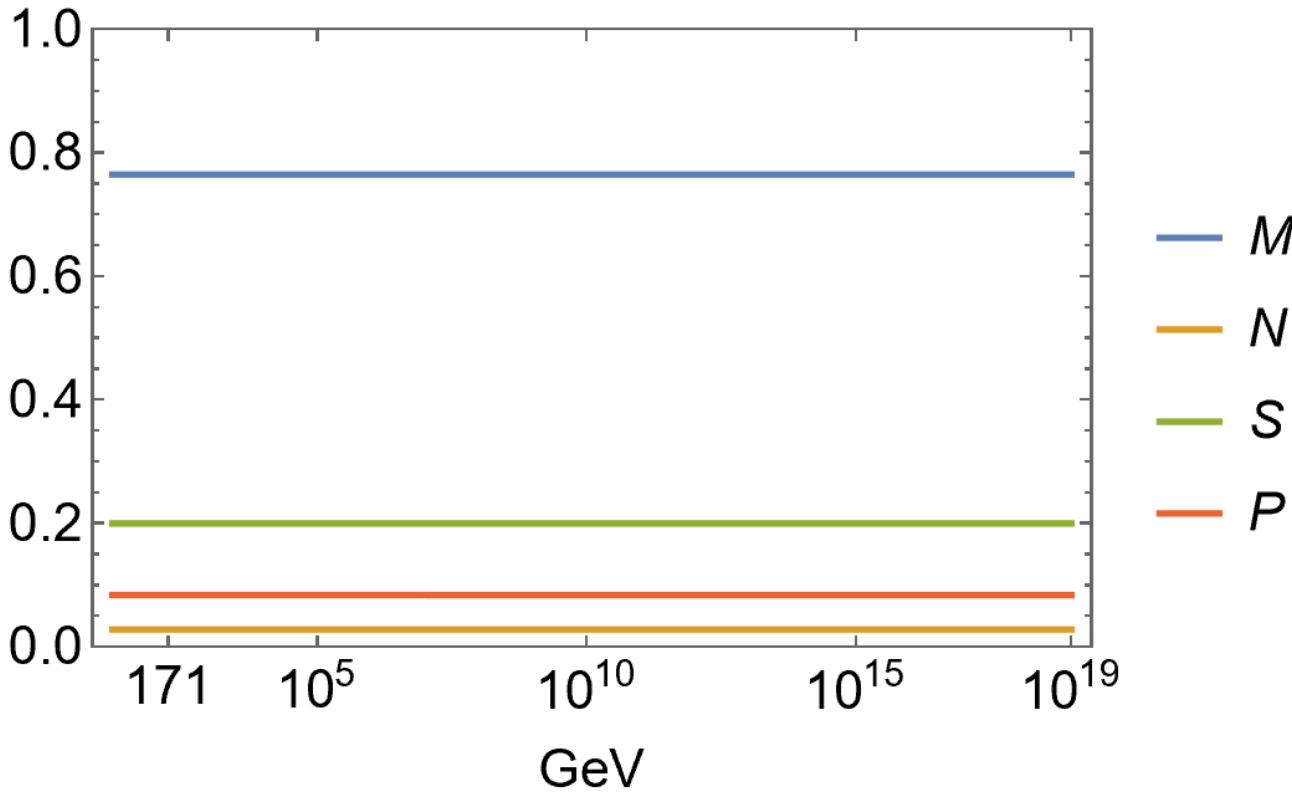
IR attractive FP

NO



$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

IO



$$\begin{pmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{pmatrix}$$

RG flow toward the UV

Hierarchical case

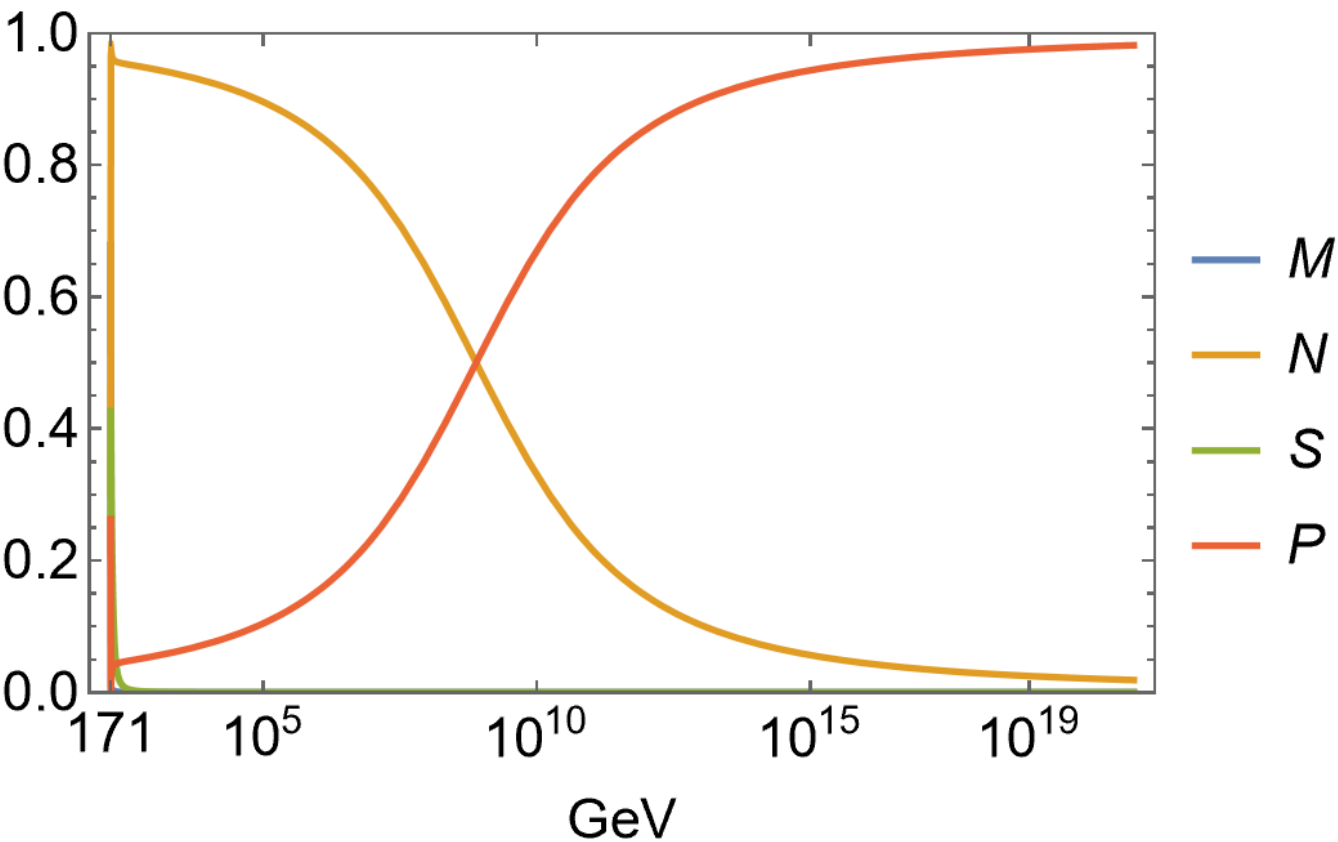
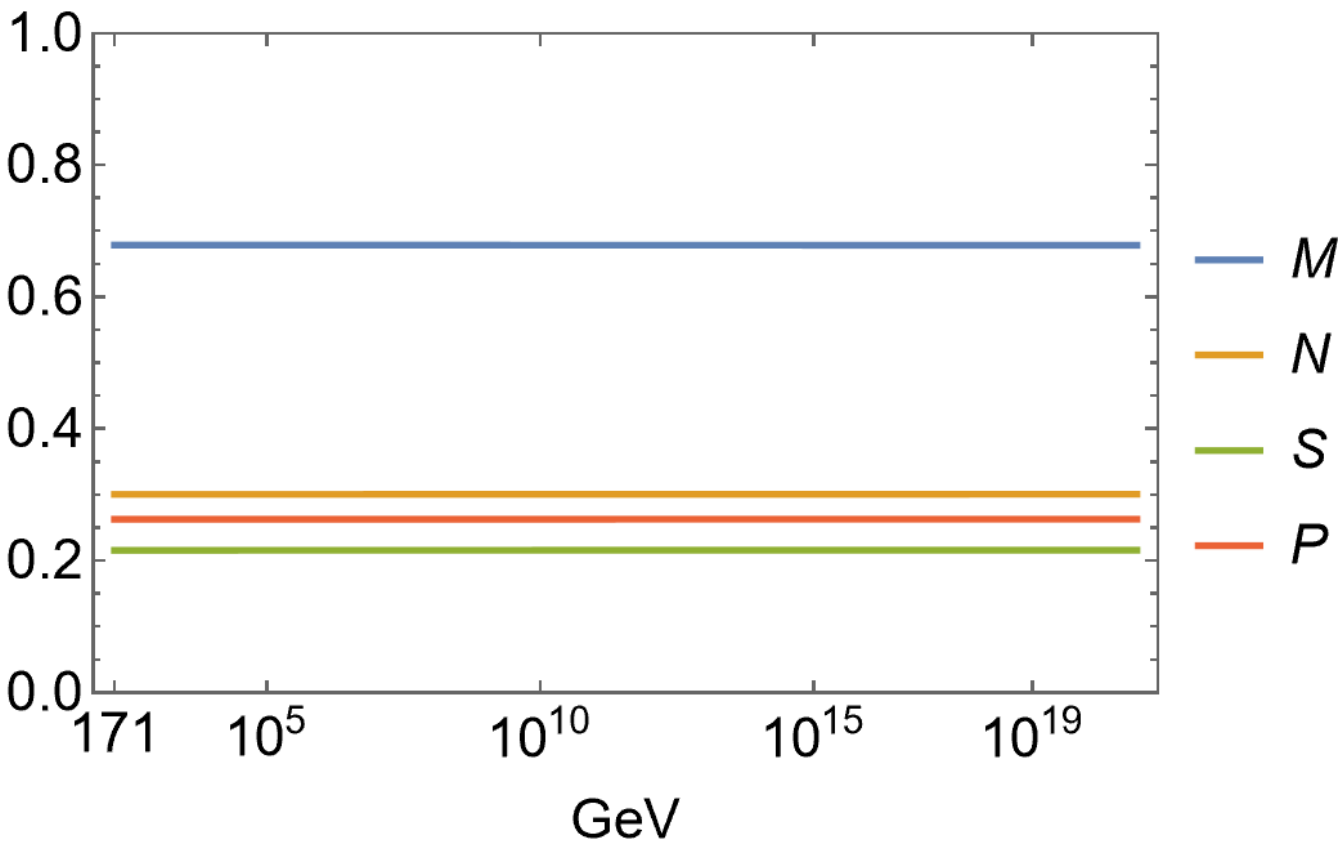
$$\frac{m_i^2 + m_j^2}{\Delta m_{ij}^2} \sim 1$$

Degenerate case

$$\frac{m_i^2 + m_j^2}{\Delta m_{ij}^2} \gg 1$$

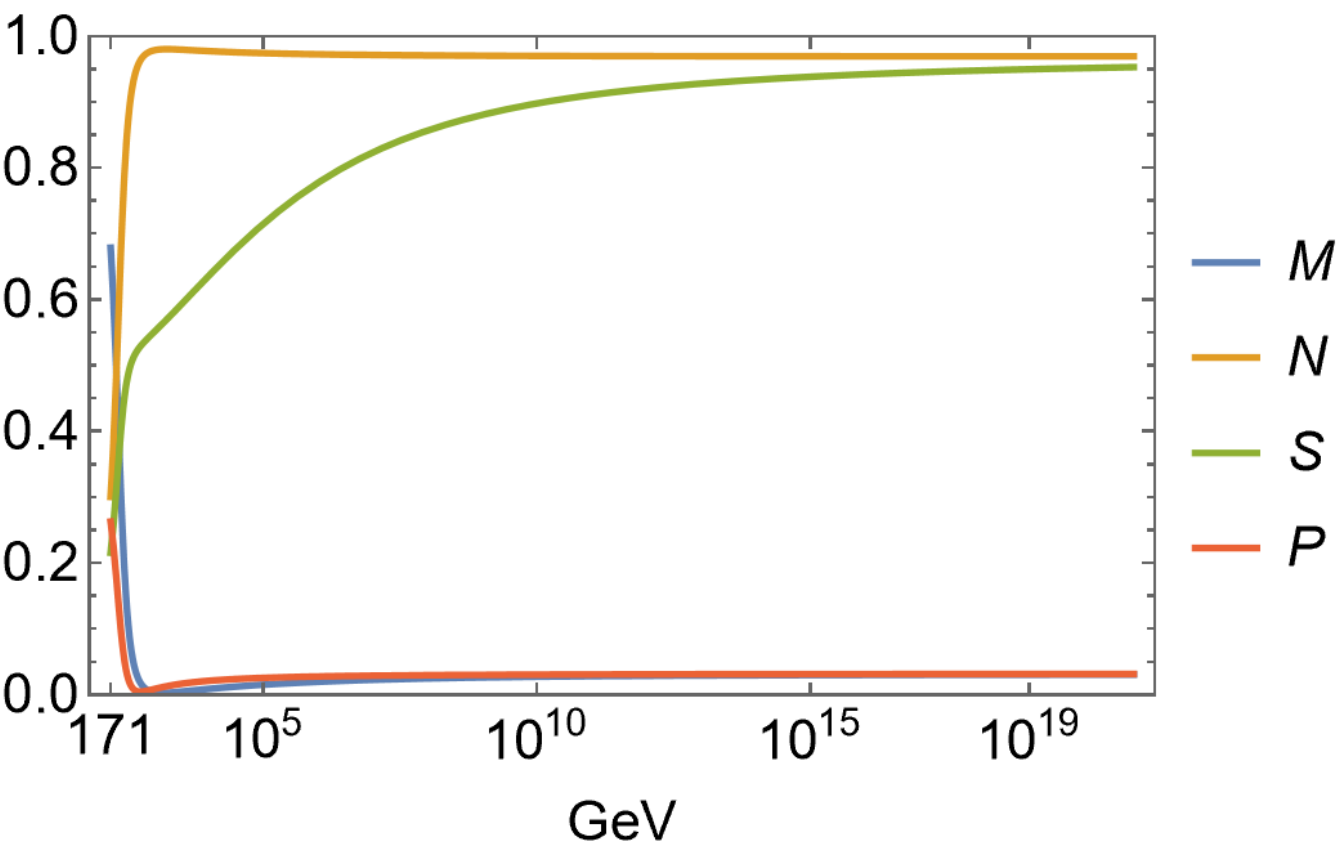
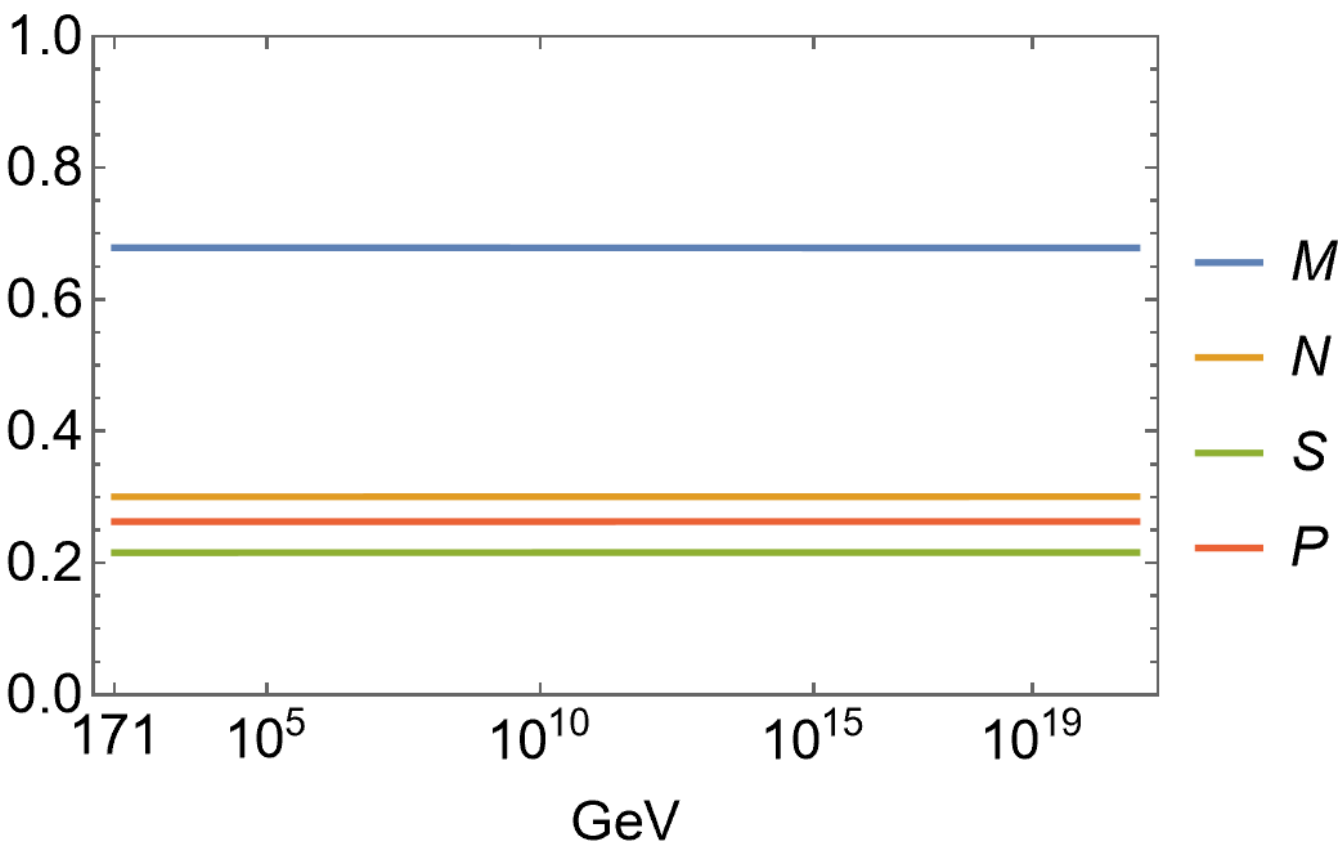
UV attractive FP

NO



$$\begin{pmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \\ 1 & 0 & 0 \end{pmatrix}$$

IO



$$\begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

QUARK MIXING IN THE STANDARD MODEL

$$\mathcal{L}_{\text{quark}} = - Y_{ij}^d \bar{Q}^i H d_R^j - Y_{ij}^u \bar{Q}^i \tilde{H} u_R^j + \text{h.c.}$$

Spontaneous symmetry breaking

$$H \rightarrow \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix} \text{ and } \tilde{H} \rightarrow \begin{pmatrix} \frac{v}{\sqrt{2}} \\ 0 \end{pmatrix}$$


$$= - \frac{v}{\sqrt{2}} \left[\bar{d}_L \cdot Y_d \cdot d_R + \bar{u}_L \cdot Y_u \cdot u_R \right] + \text{h.c.}$$

To extract the mass terms we need to diagonalize the Yukawa matrices

QUARK MIXING IN THE STANDARD MODEL

- Y_u and Y_d are not hermitian $\rightarrow$ but $Y_u Y_u^\dagger$ and $Y_d Y_d^\dagger$ are hermitian

Diagonalization via unitaries:

$$\left\{ \begin{array}{l} \text{diag}(y_u, y_c, y_t)^2 = U_u^\dagger Y_u Y_u^\dagger U_u = (U_u^\dagger Y_u K_u) (K_u^\dagger Y_u^\dagger U_u) \\ \text{diag}(y_d, y_s, y_b)^2 = U_d^\dagger Y_d Y_d^\dagger U_d = (U_d^\dagger Y_d K_d) (K_d^\dagger Y_d^\dagger U_d) \end{array} \right.$$

- We can write the Lagrangian via unitary transformation: $q_R \rightarrow K_q q_R$, $q_L \rightarrow U_q q_L$

$$\mathcal{L}_{\text{Yukawa}} = -\frac{y_{d^i} v}{\sqrt{2}} (\bar{d}_L^i d_R^i + \bar{d}_R^i d_L^i) - \frac{y_{u^i} v}{\sqrt{2}} (\bar{u}_L^i u_R^i + \bar{u}_R^i u_L^i)$$