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

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

Zois Gyftopoulos
Heidelberg University

UNIVERSITÄT
HEIDELBERG
ZUKUNFT
SEIT 1386

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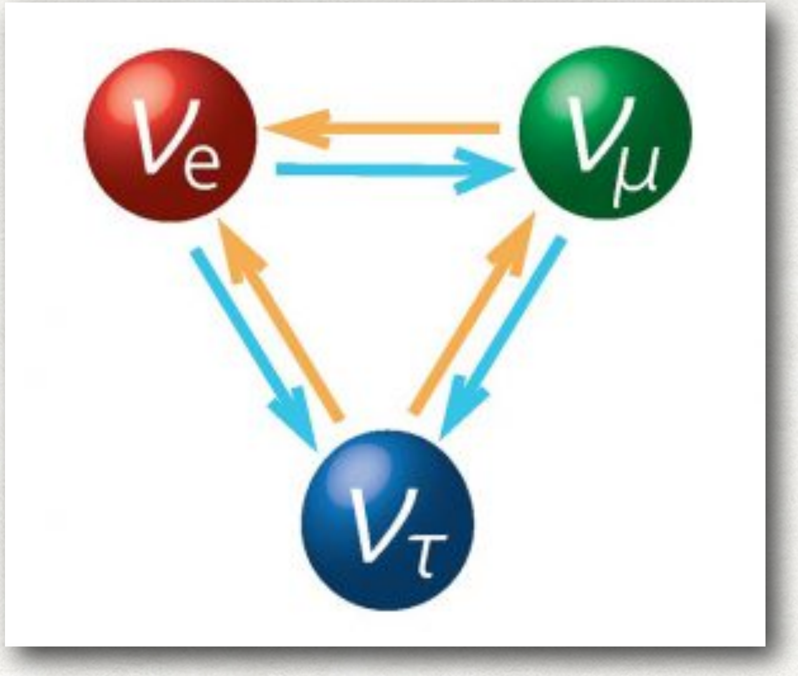
What experiments tell us about neutrinos… so far

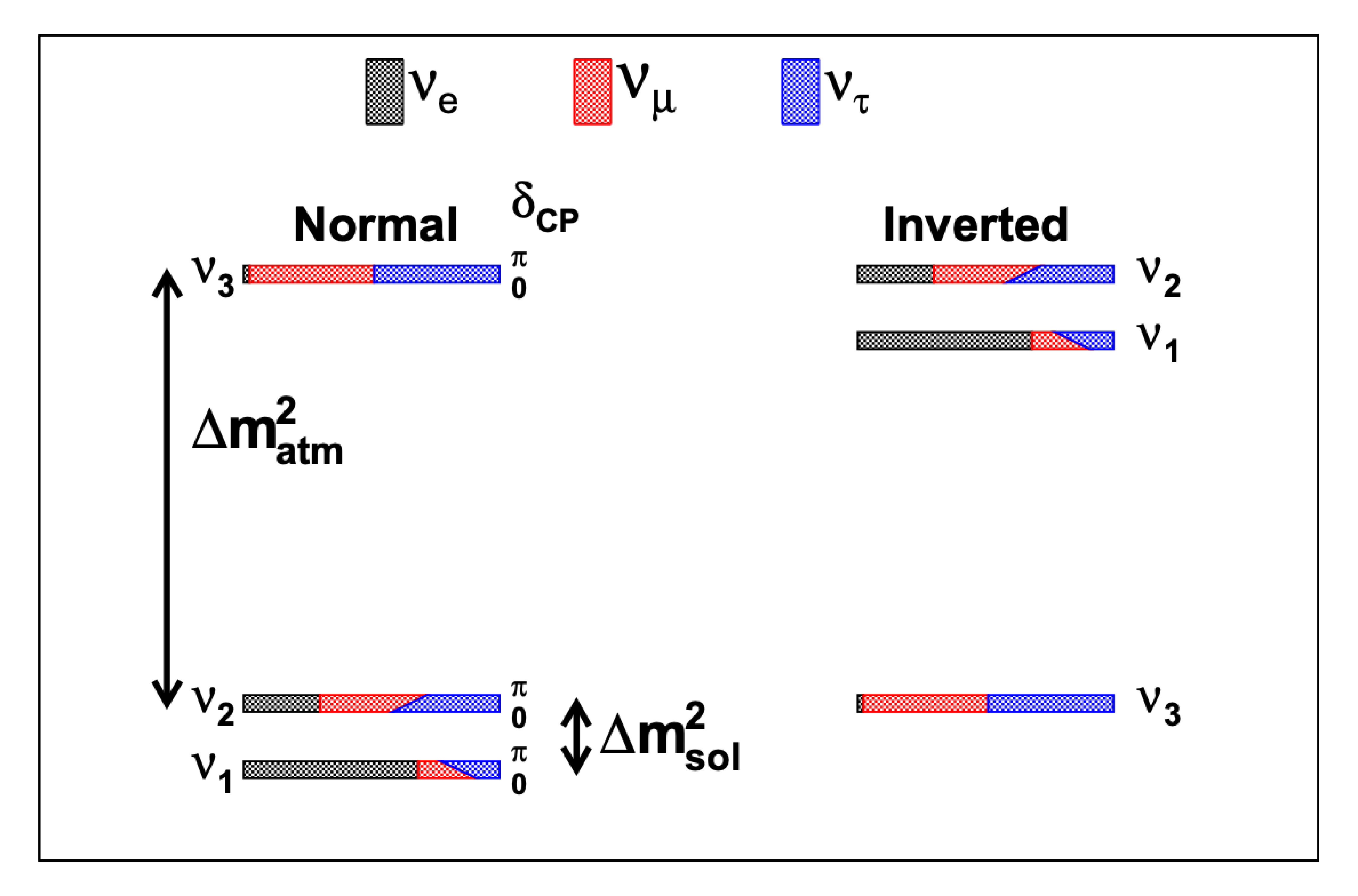


Mass Differences: [PDG '26]

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

$$\boxed{m_{\nu_e} < 0.45\ \mathrm{eV} \quad (\mathrm{KATRIN})}$$

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



X. Qian, P. Vogel et. al.(2015)

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

$$\mathscr{L}_{\text{lepton}} = -Y^l_{ij}\bar{L}^i H l^j_R - Y^\nu_{ij}\bar{L}^i \tilde{H}\nu^j_R + \text{h.c.}$$

down-type Yukawa matrix

$$l^i_R = (e_R, \mu_R, \tau_R)$$

up-type Yukawa matrix

$$\nu^i_R = (\nu_{e,R}, \nu_{\mu,R}, \nu_{\tau,R})$$

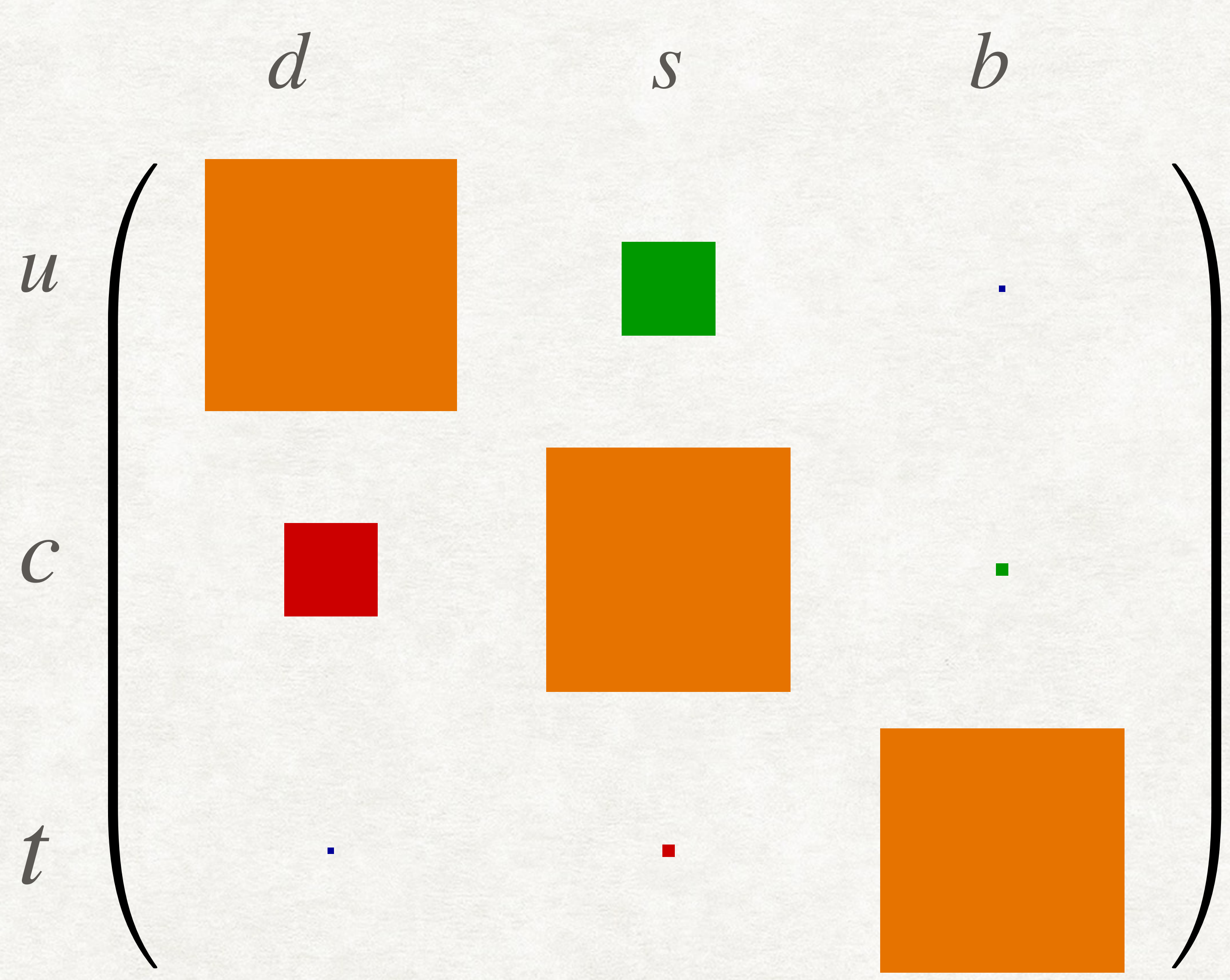
From the Kinetic terms

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

$$|U_{PMNS}|^2 = \begin{pmatrix} |U_{e1}|^2 & |U_{e2}|^2 & |U_{e3}|^2 \\ |U_{\mu 1}|^2 & |U_{\mu 2}|^2 & |U_{\mu 3}|^2 \\ |U_{\tau 1}|^2 & |U_{\tau 2}|^2 & |U_{\tau 3}|^2 \end{pmatrix}$$

Lepton sector in the Standard Model + 3 flavors of right-handed neutrinos with no Majorana masses

CKM

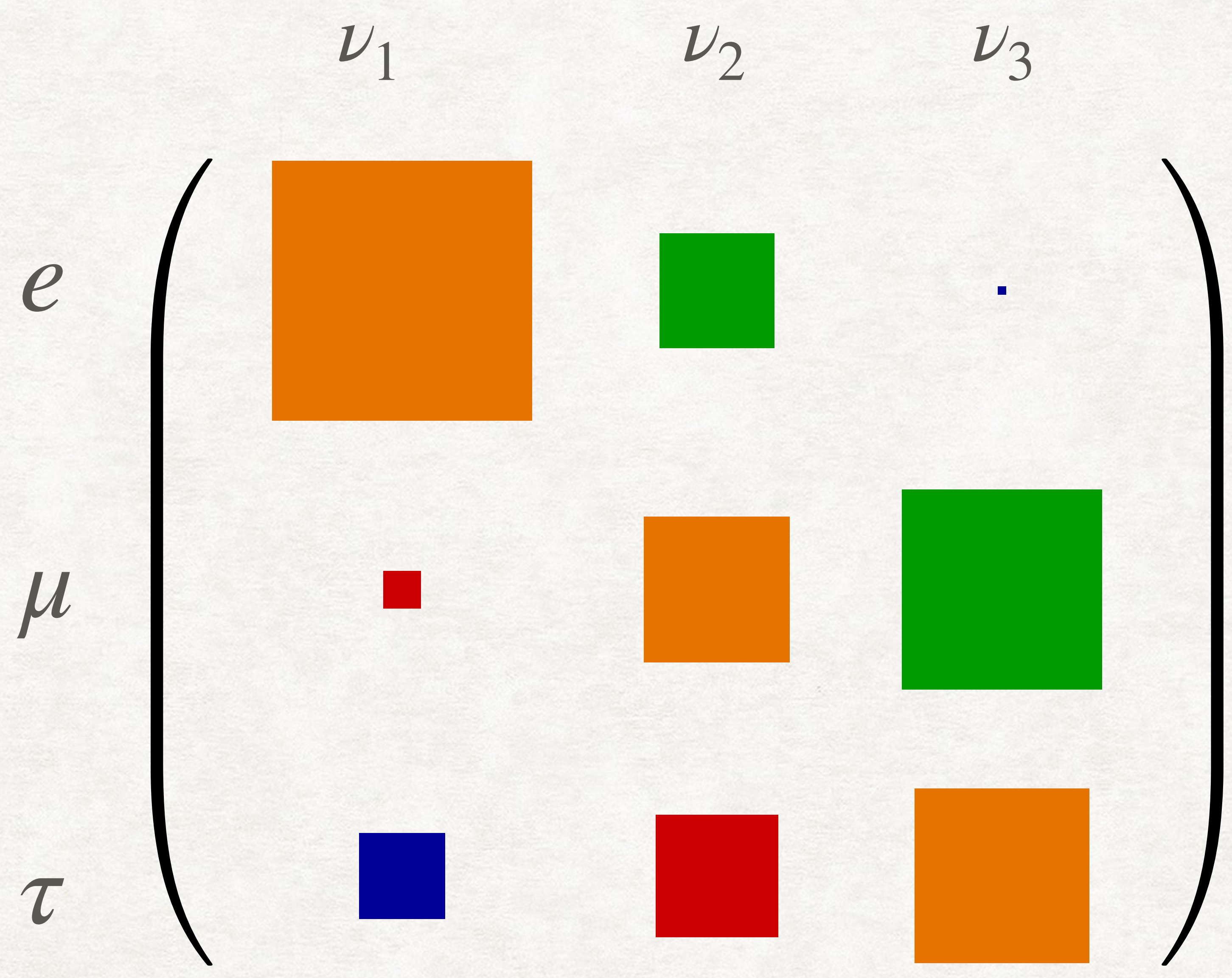


Can be explained through a QG-induced fixed-point cascade, because it is an IR attractive configuration

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

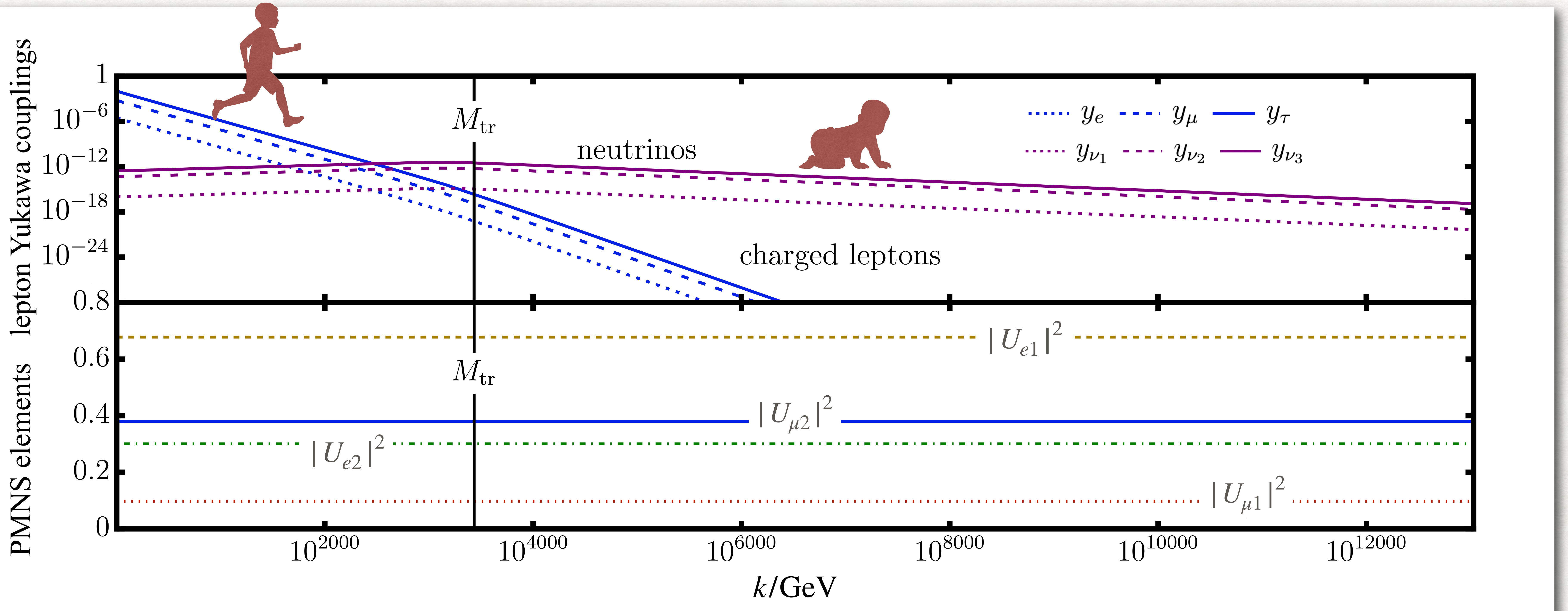
vs

PMNS



Large Mixing
and
no apparent structure

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



[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

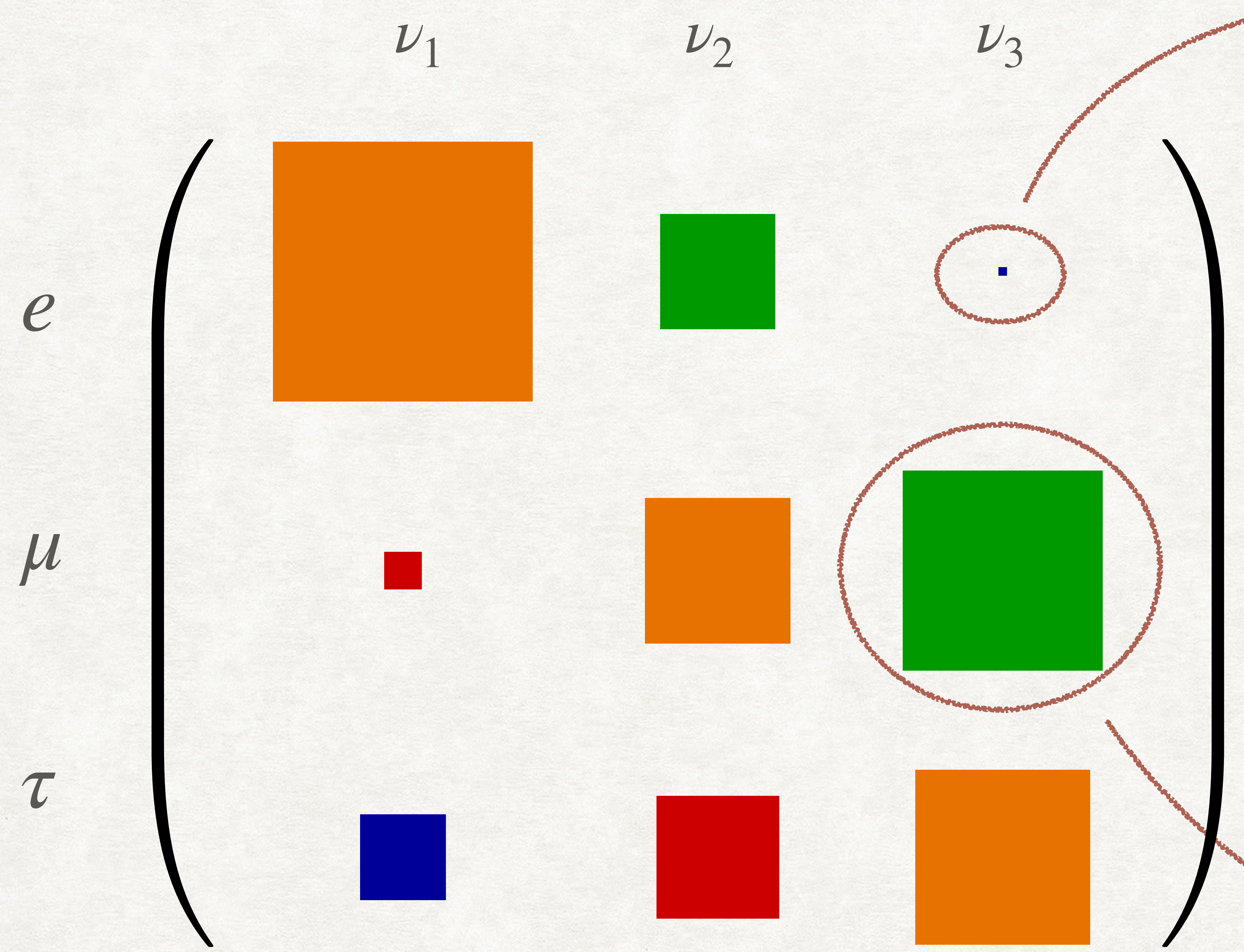
[Eichhorn & Held '22; Kowalska, Pramanick and Sessolo '22]

$\Longrightarrow$

The PMNS matrix <u>does not run</u>

No emerging structure from the RG flows!

PMNS matrix



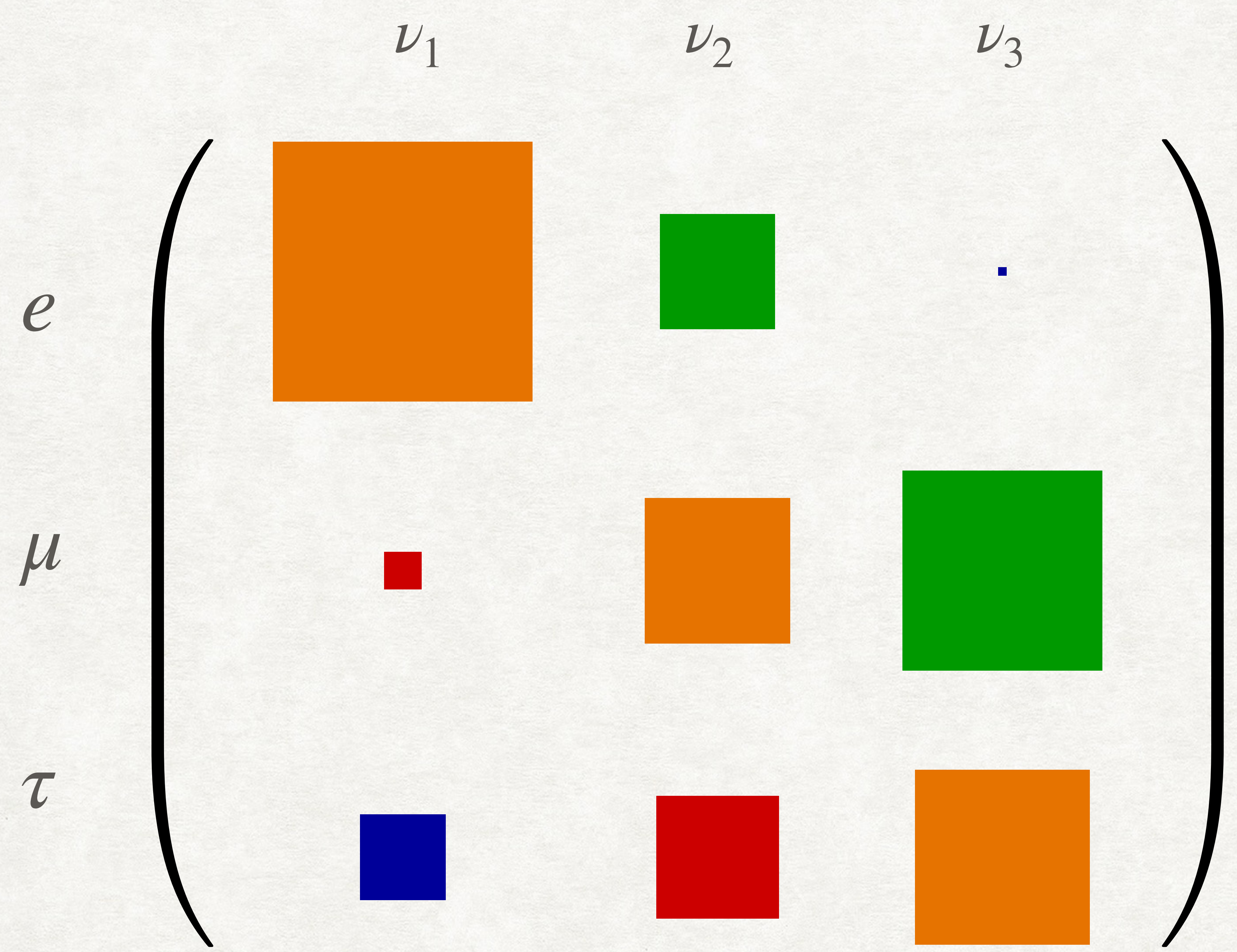
$$\beta_{|U_{e3}|^2} = \frac{3y_\tau^2}{16\pi^2}\boxed{\frac{y_{\nu_3}^2 + y_{\nu_2}^2}{y_{\nu_3}^2 - y_{\nu_2}^2}}|U_{e3}|^2 + \ldots$$

Quasi-degenerate case

$m_{\nu_1} \approx m_{\nu_2} \approx m_{\nu_3}$ $\Longrightarrow$ Significant PMNS running!

$$\beta_{|U_{\mu 2}|^2} = \frac{3y_\tau^2}{16\pi^2}\boxed{\frac{y_{\nu_3}^2 + y_{\nu_2}^2}{y_{\nu_3}^2 - y_{\nu_2}^2}}|U_{\mu 2}|^2 + \ldots$$

PMNS matrix



Quasi-degenerate case

$m_{\nu_1} \approx m_{\nu_2} \approx m_{\nu_3}$ $\Longrightarrow$ Significant PMNS running!

For fixed Δm^2_{21} , Δm^2_{23}

Imposing (nearly) no PMNS running $\Longrightarrow$ $\boxed{m^2_\nu \lesssim M}$

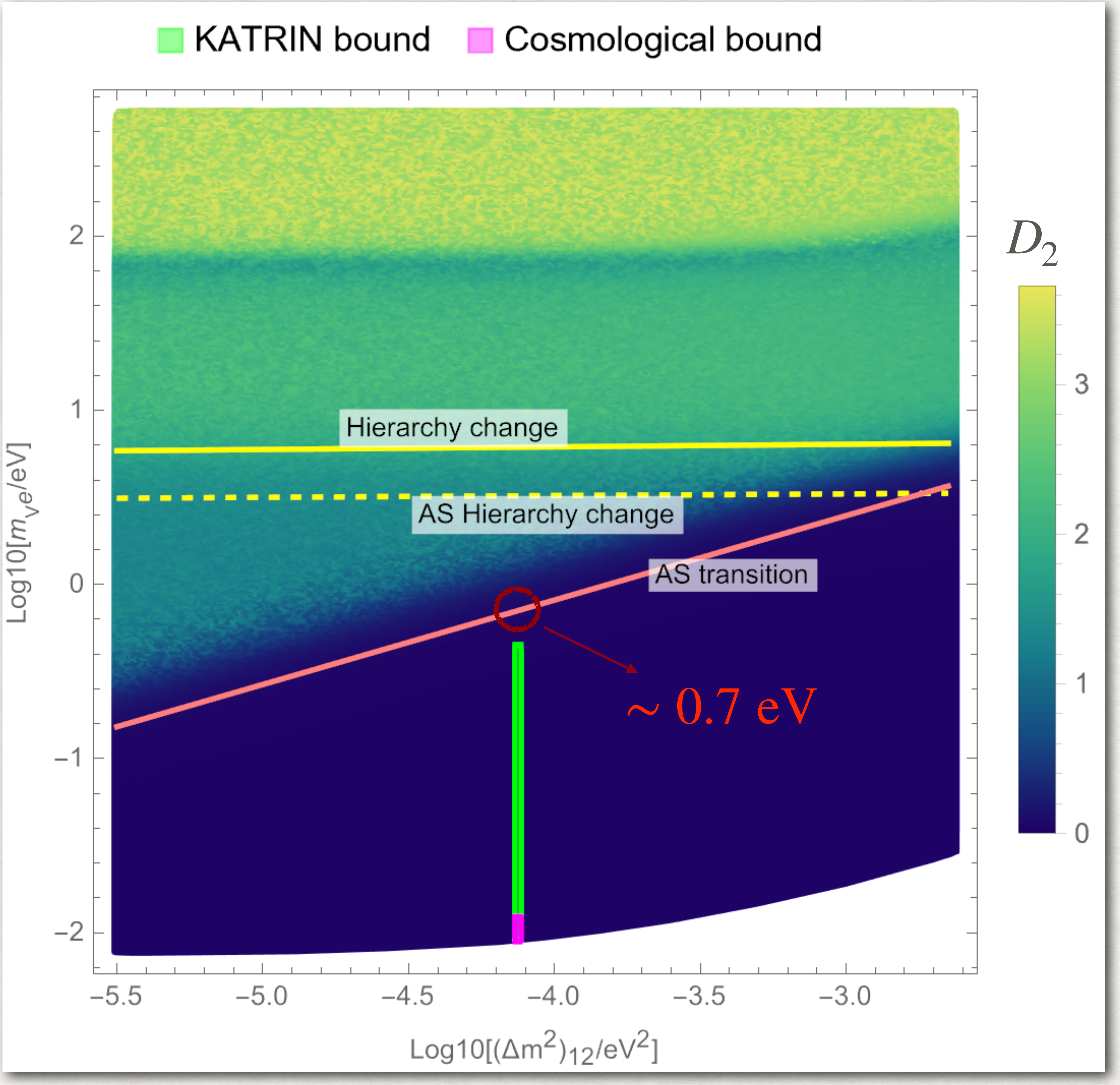
The bound M changes from SM to ASSM!

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

Region of PMNS instability $UV \neq IR$

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

Region of PMNS stability $UV \approx IR$



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

UV $\longrightarrow$ IR

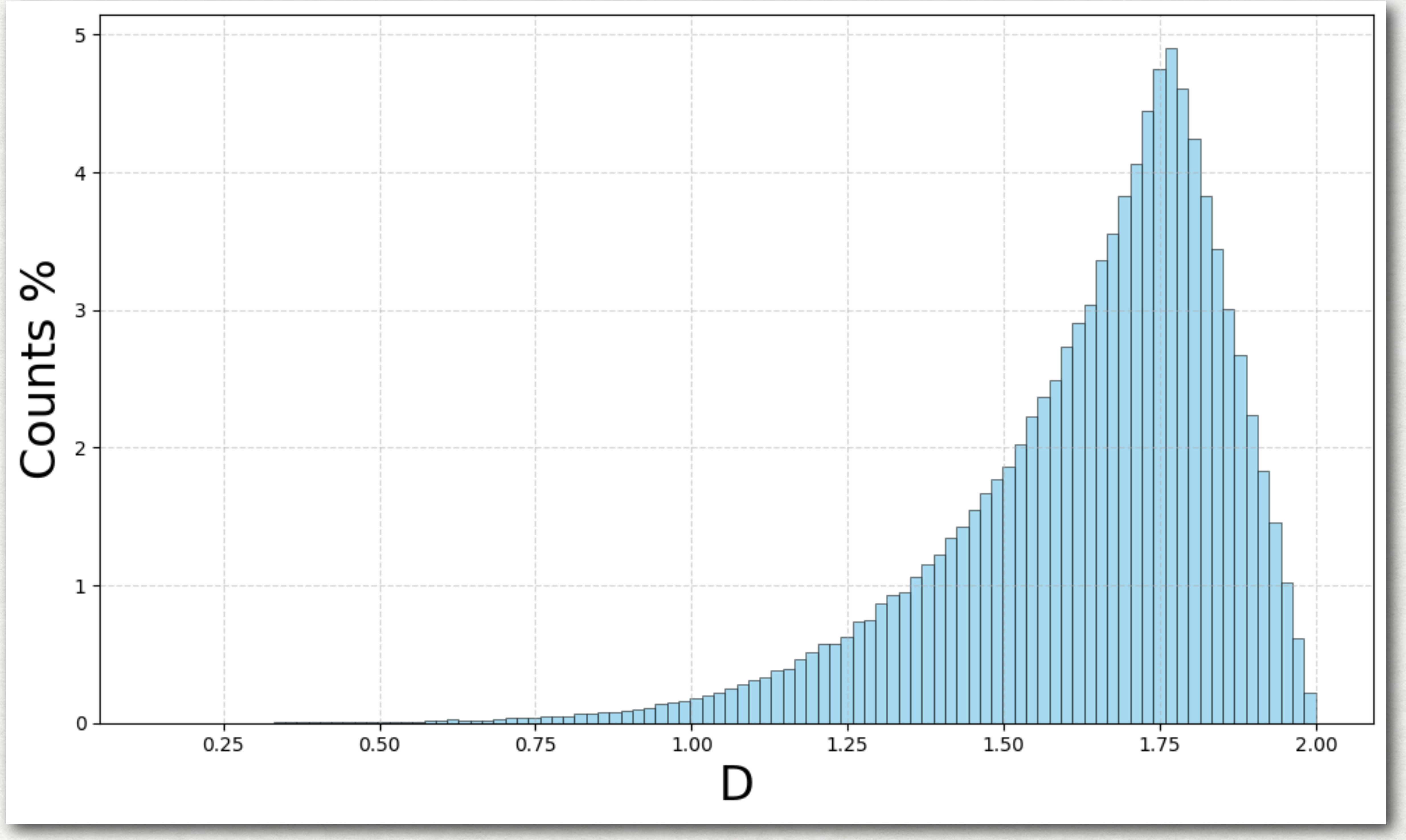
Ordering Invariant Mixing measure

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

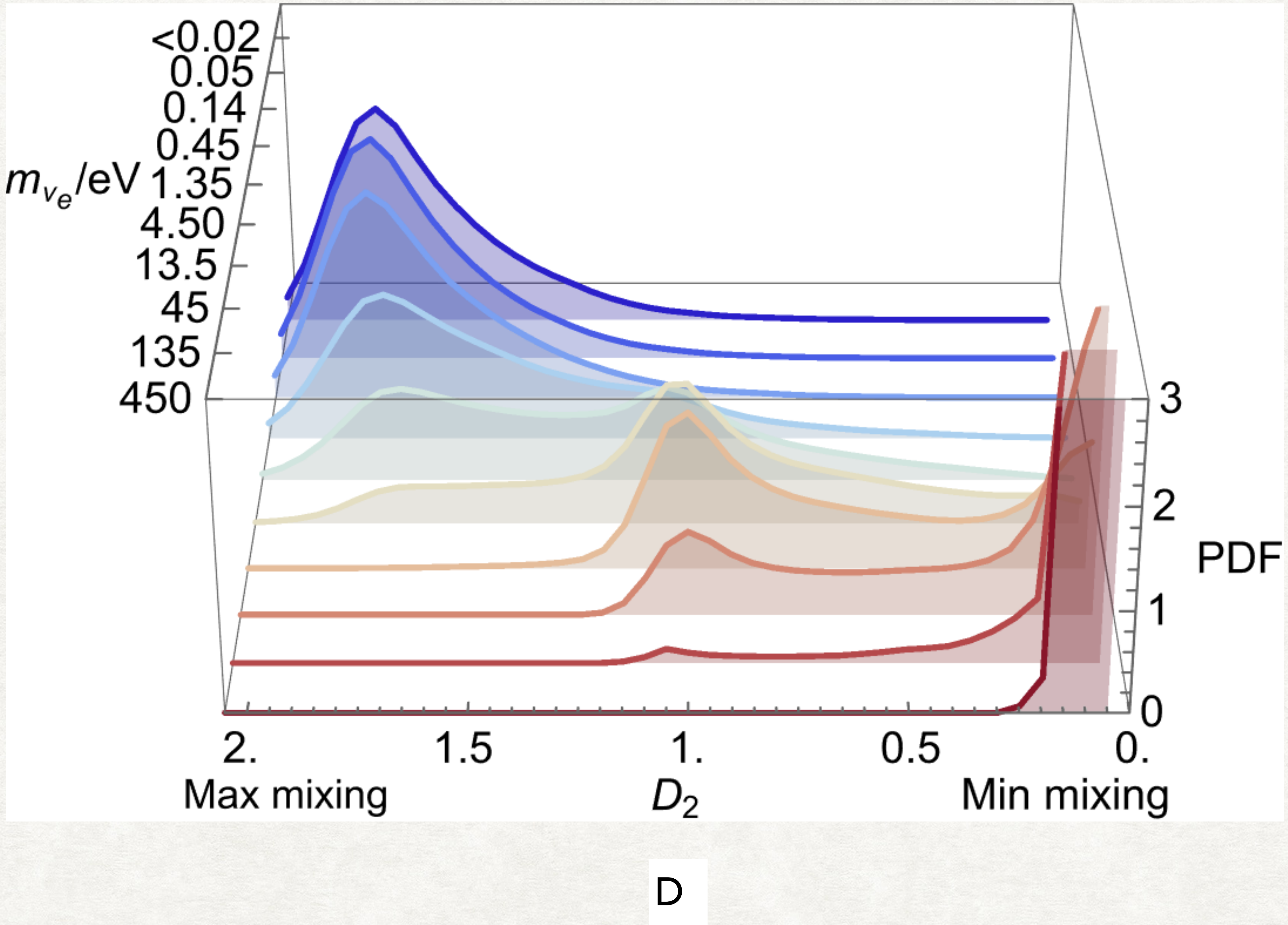
$D = 0$
no mixing

$D = 2$
maximal mixing

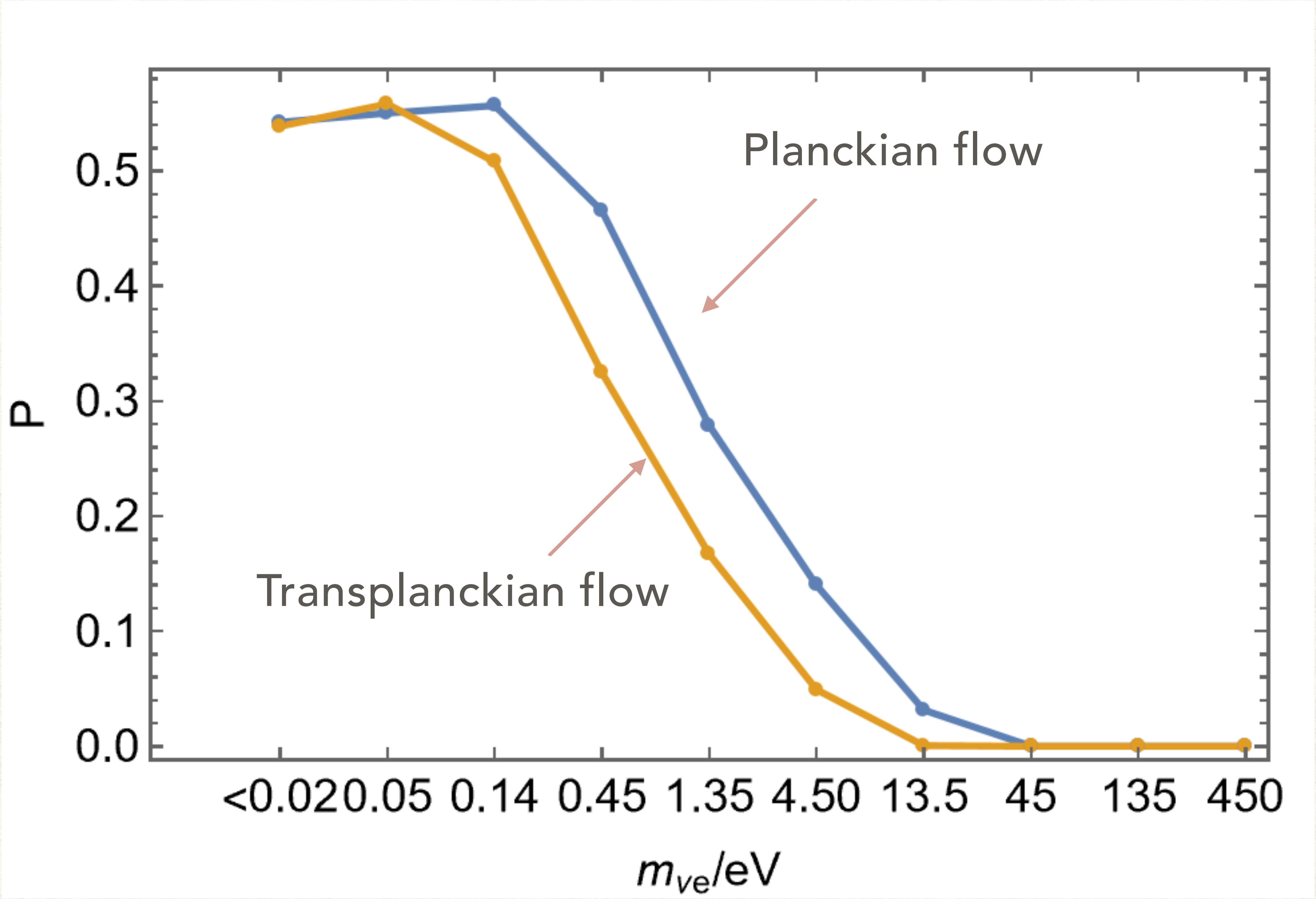
UV distribution



IR distribution for D



Probability for $D \gtrsim 1.7$



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

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

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

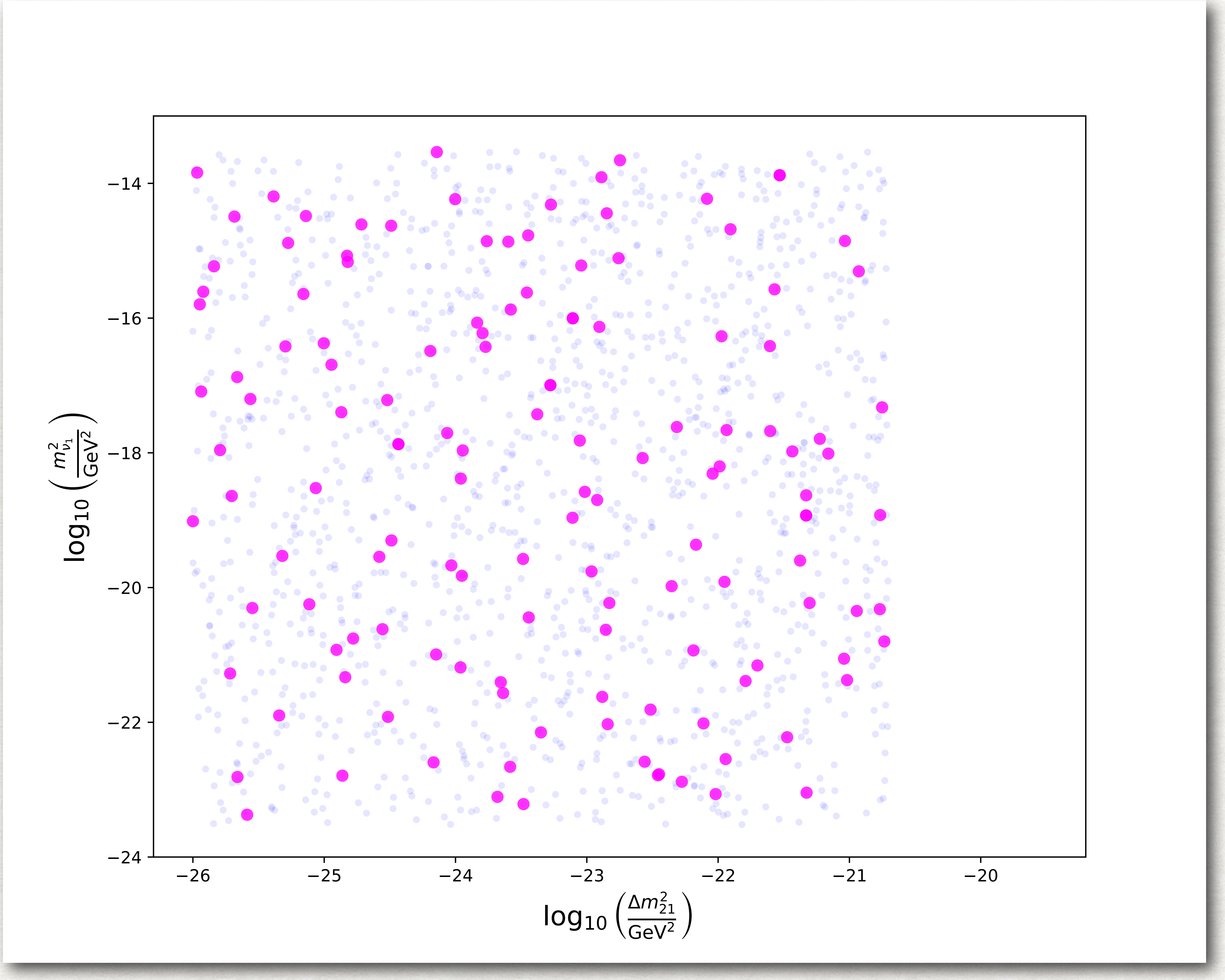
Another Question

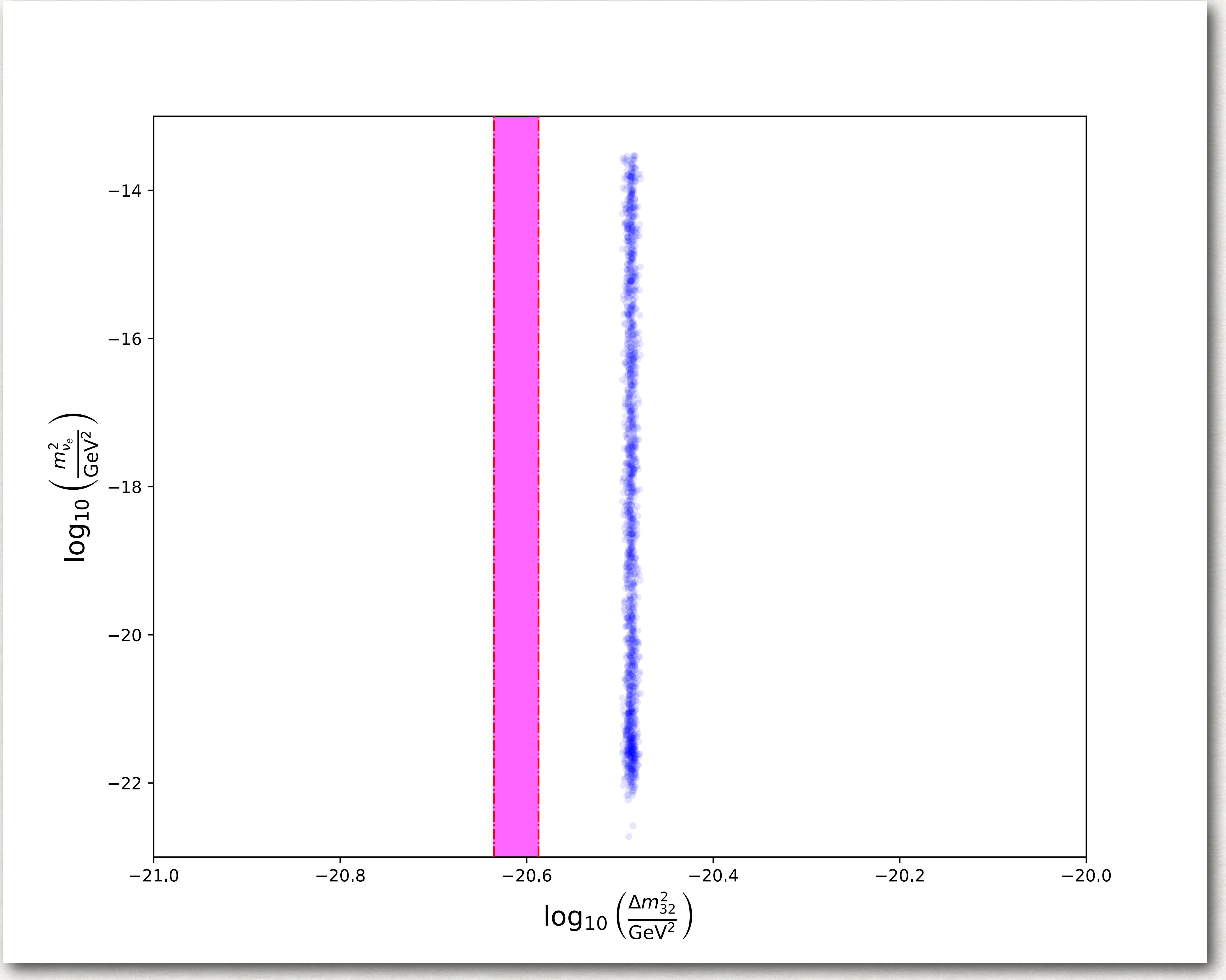
Given the experimental observations of mass differences, is there a preferred neutrino mass value for the (AS)SM?

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

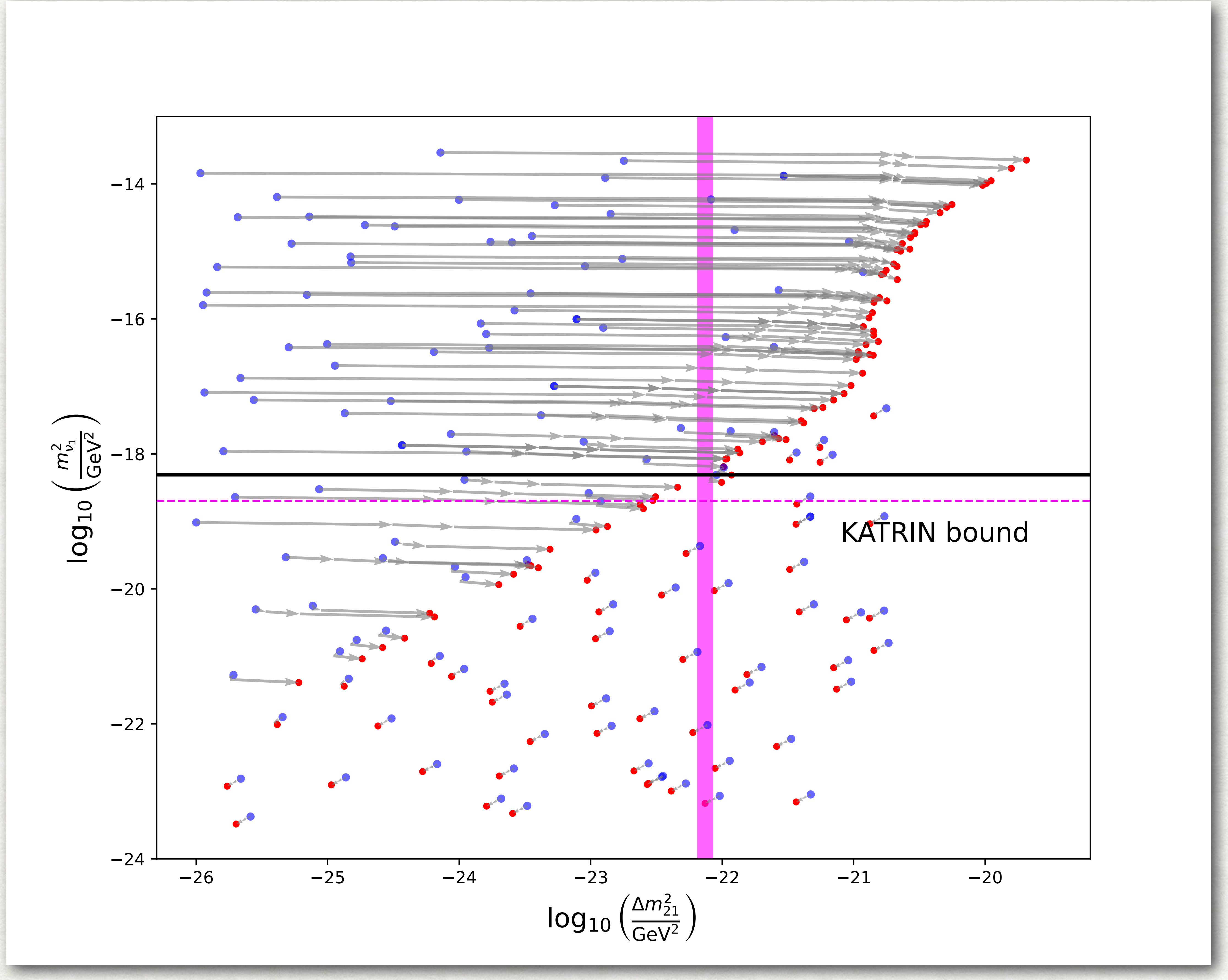
UV prior assumptions
$$\left\{\begin{array}{l} \text{PMNS: Uniform + constraints} \\ \Delta m^2_{32}\text{: Gaussian in the UV} \\ y_{\min}, \Delta m^2_{12}\text{: Log - uniform} \end{array}\right.$$

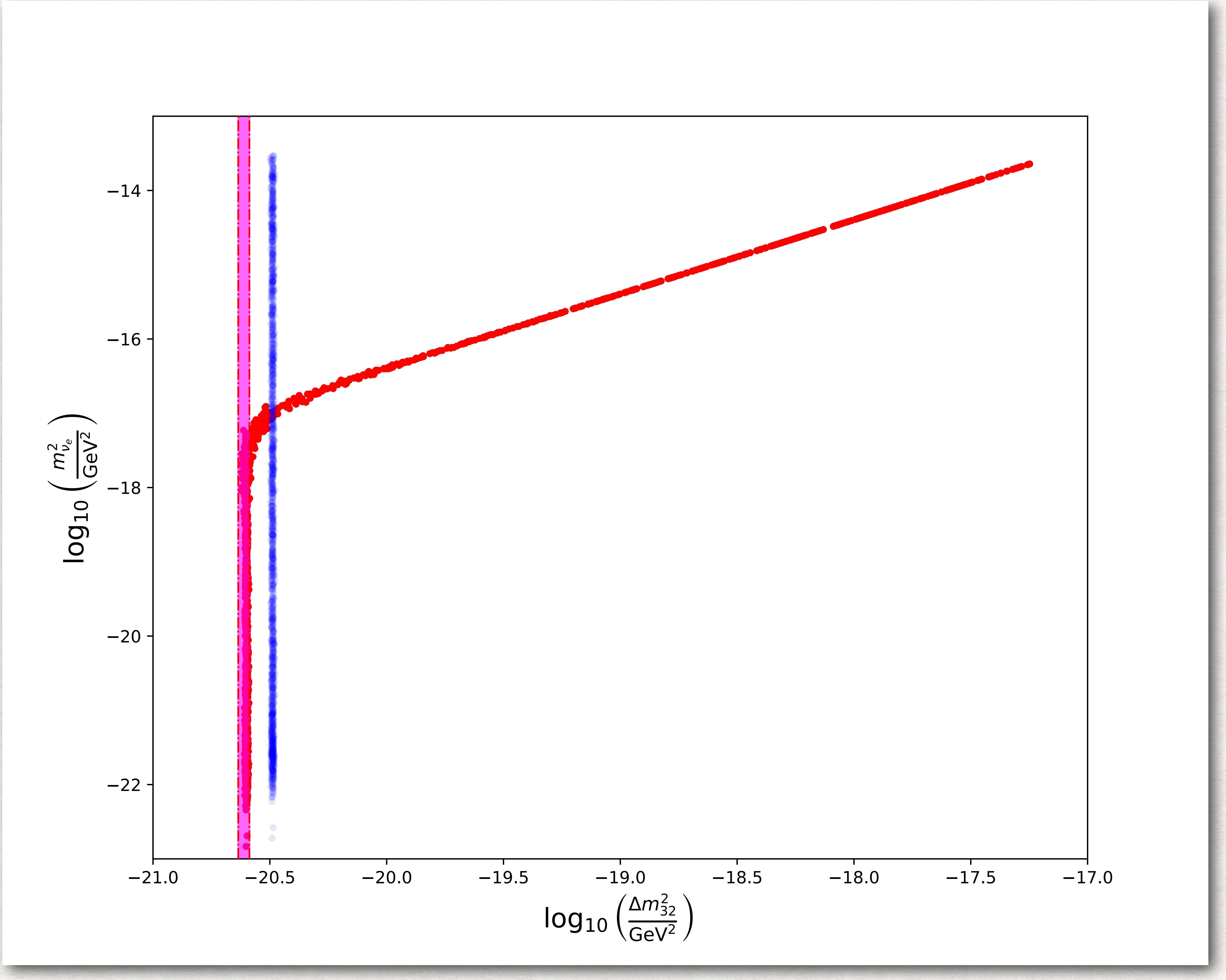
Scanning UV conditions



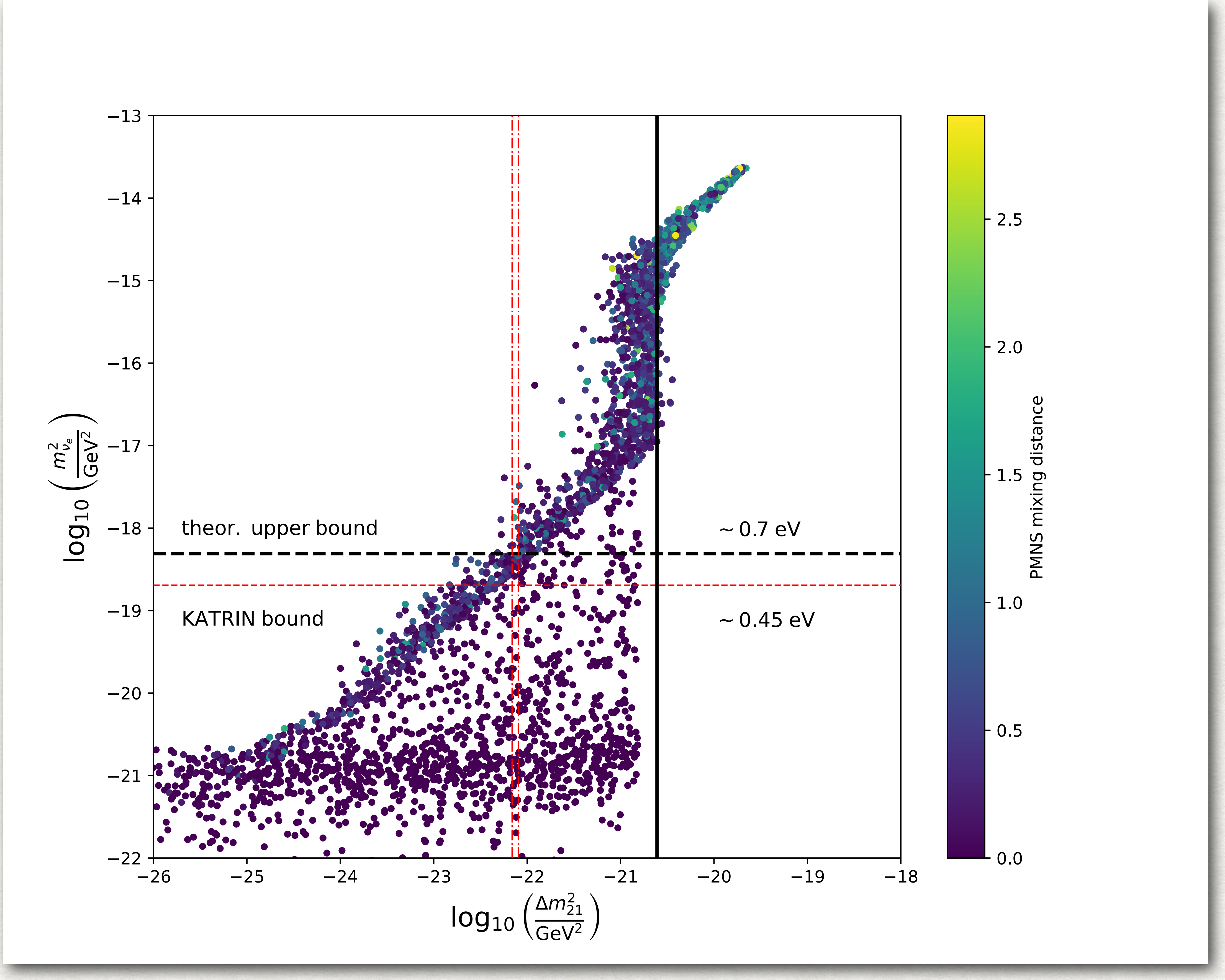


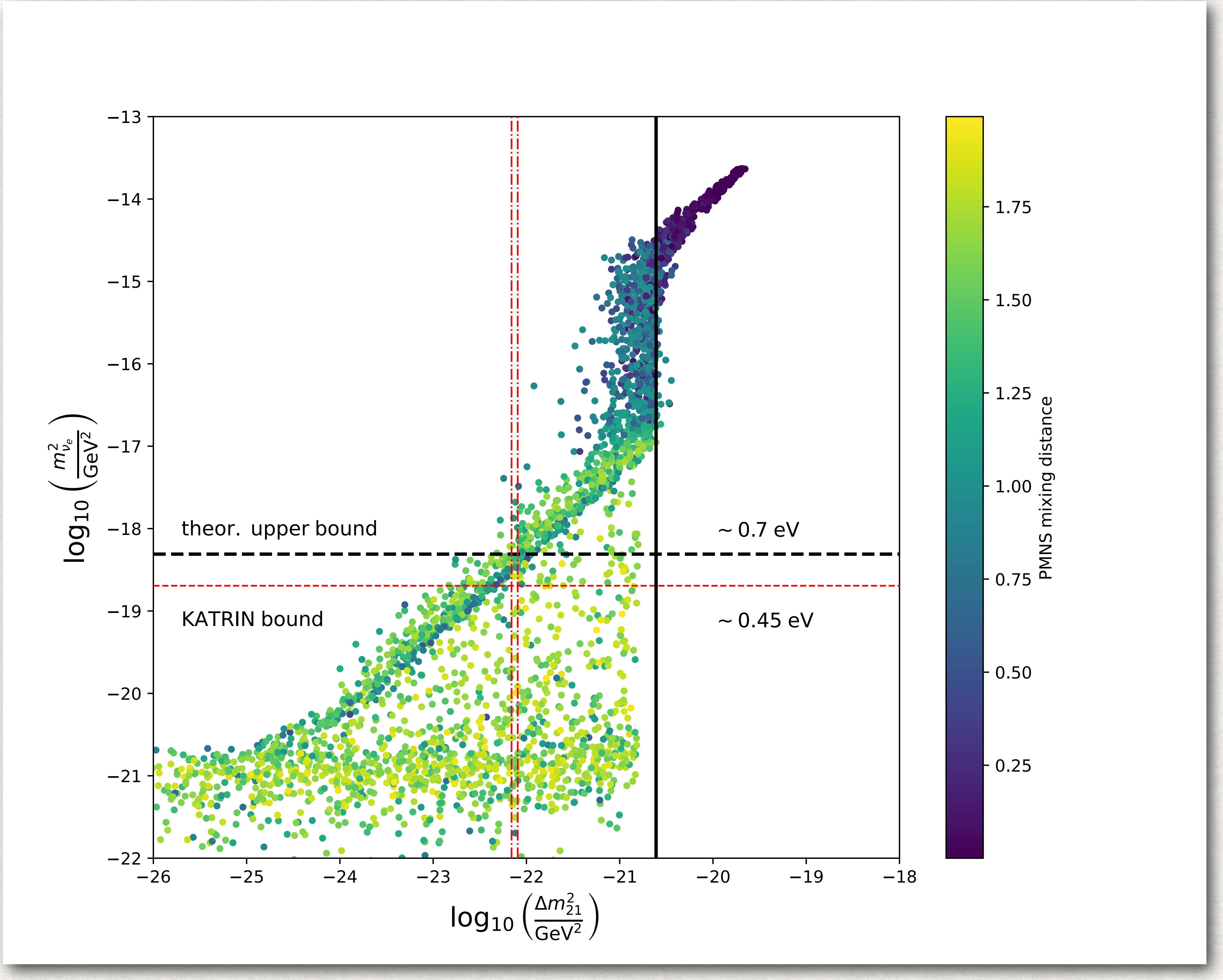
Scanning UV conditions





Tracking the behaviour of the mixing measure





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

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

Conclusions/Summary

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

No fine-tuning

PMNS is NOT at an IR attractive configuration $\Longrightarrow$ PMNS flow must be (nearly) frozen $\Longrightarrow$ Upper mass bound for effective neutrino mass

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

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

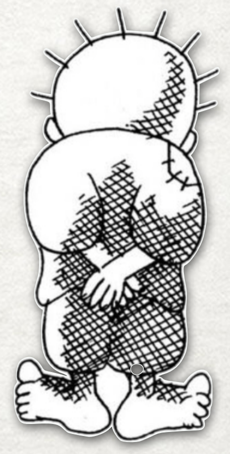
$\Longrightarrow$

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

ASQG pushes the crossover region lower!

Favored mass due to the IR attractor

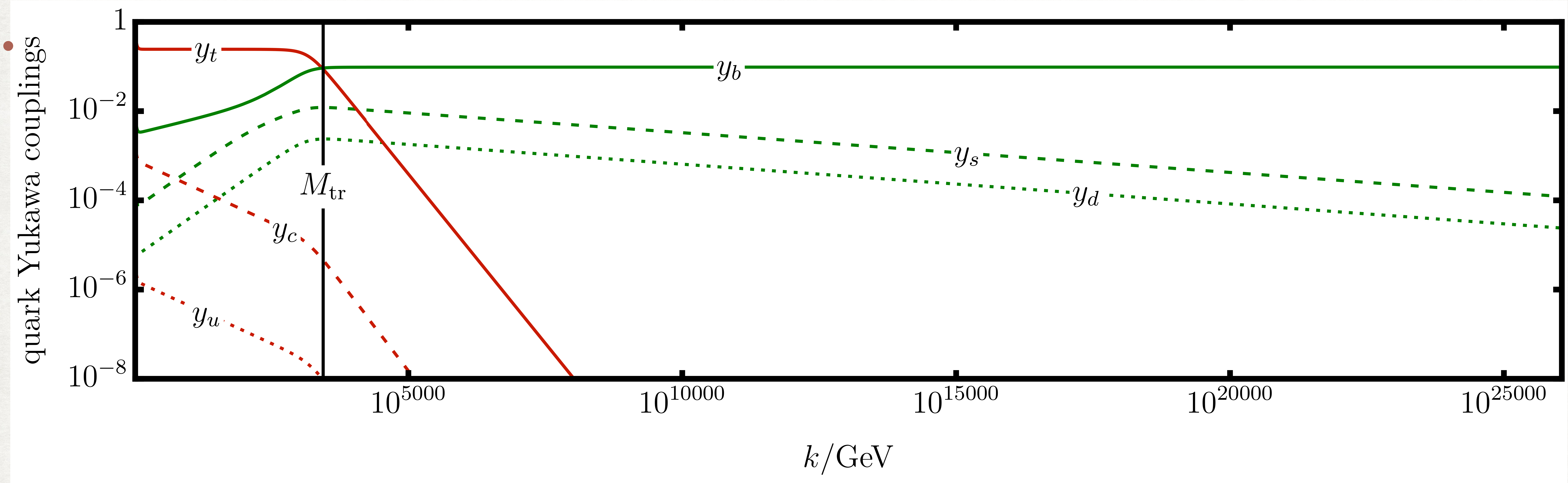
Thank you very much!



Extra slides

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

- 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 $f_y = -3.27 \times 10^{-4}$.

RG flow toward the IR

Hierarchical case

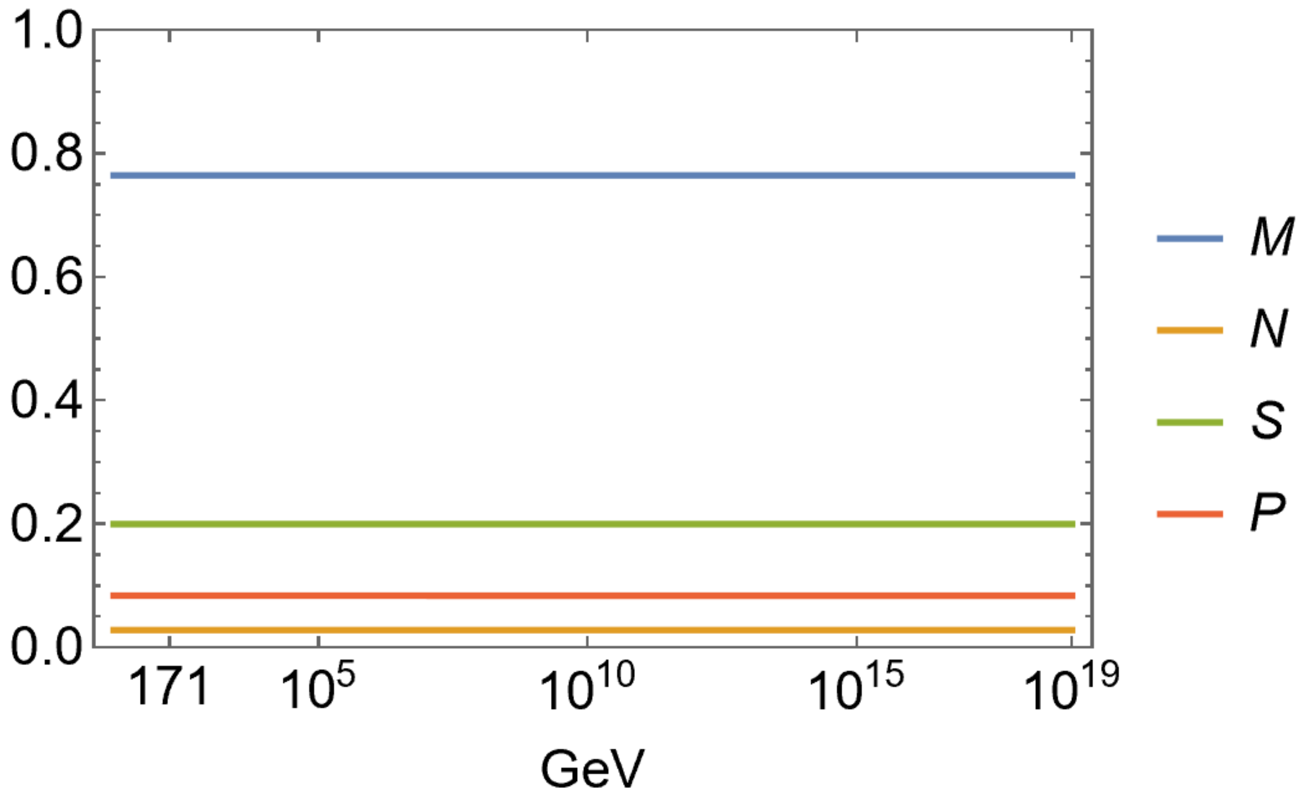
$$\frac{m_i^2 + m_j^2}{\Delta m_{ij}^2} \sim 1$$

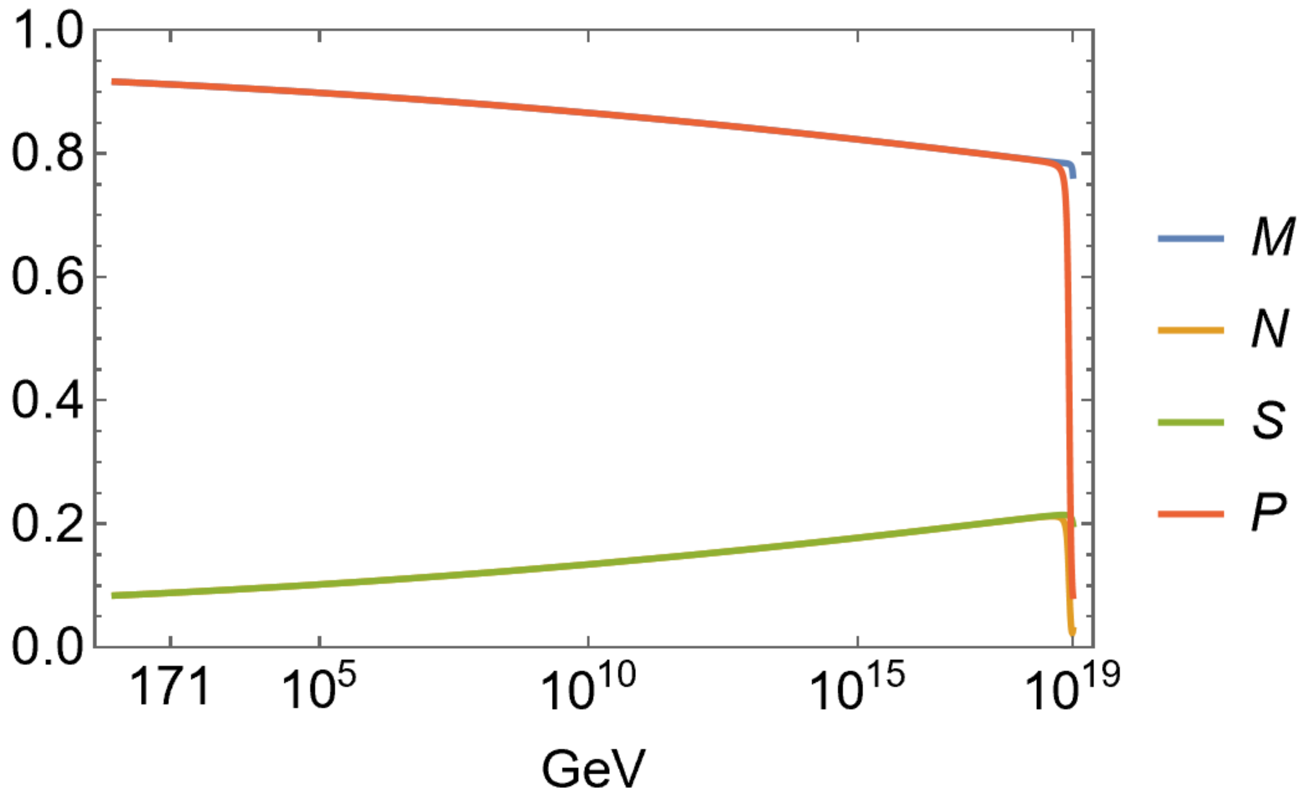
Degenerate case

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

IR attractive FP

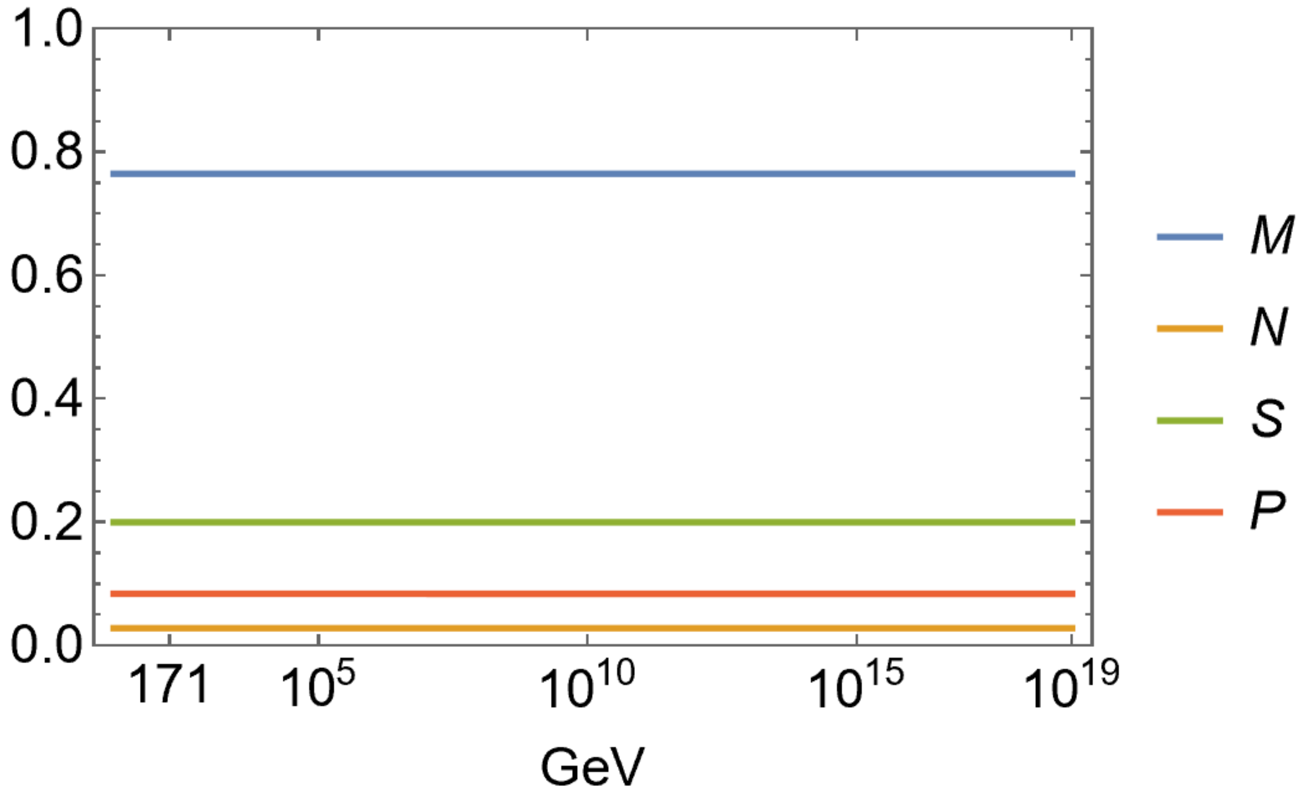
NO

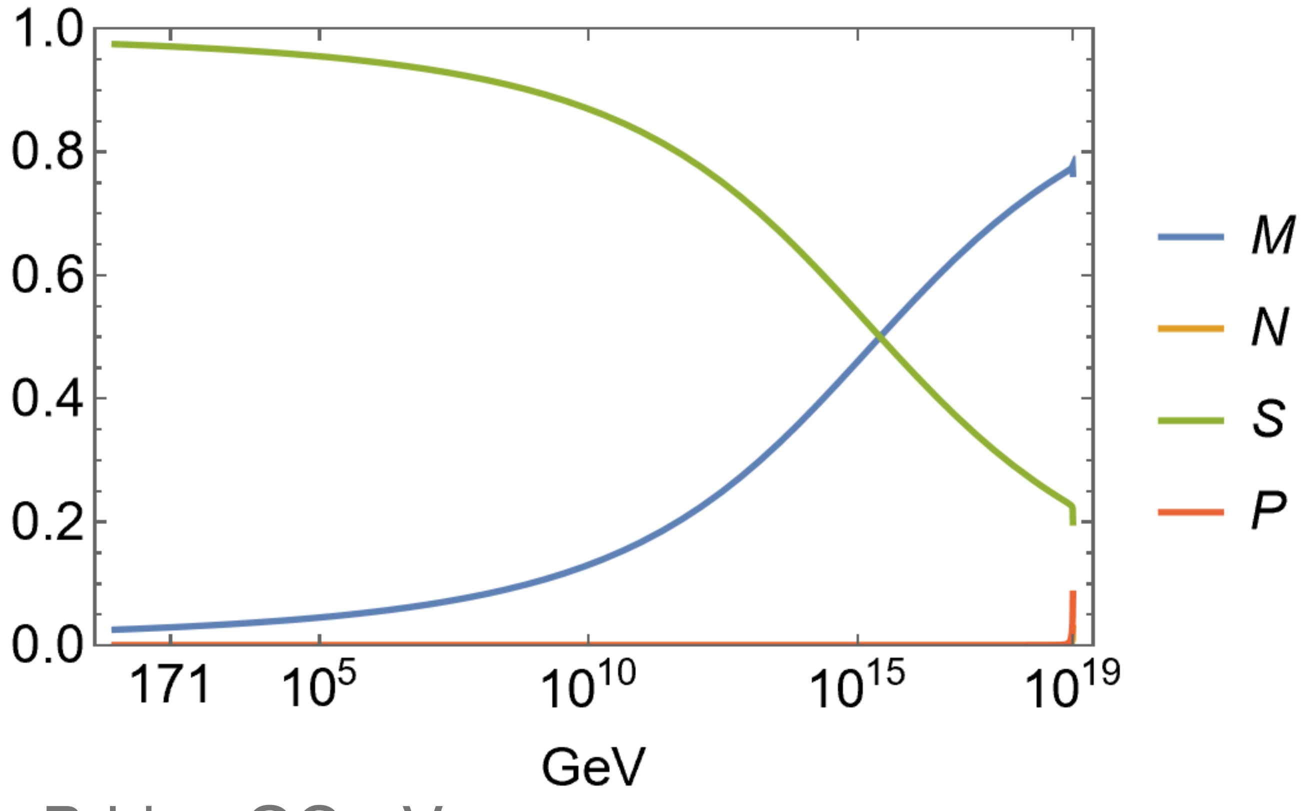




$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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

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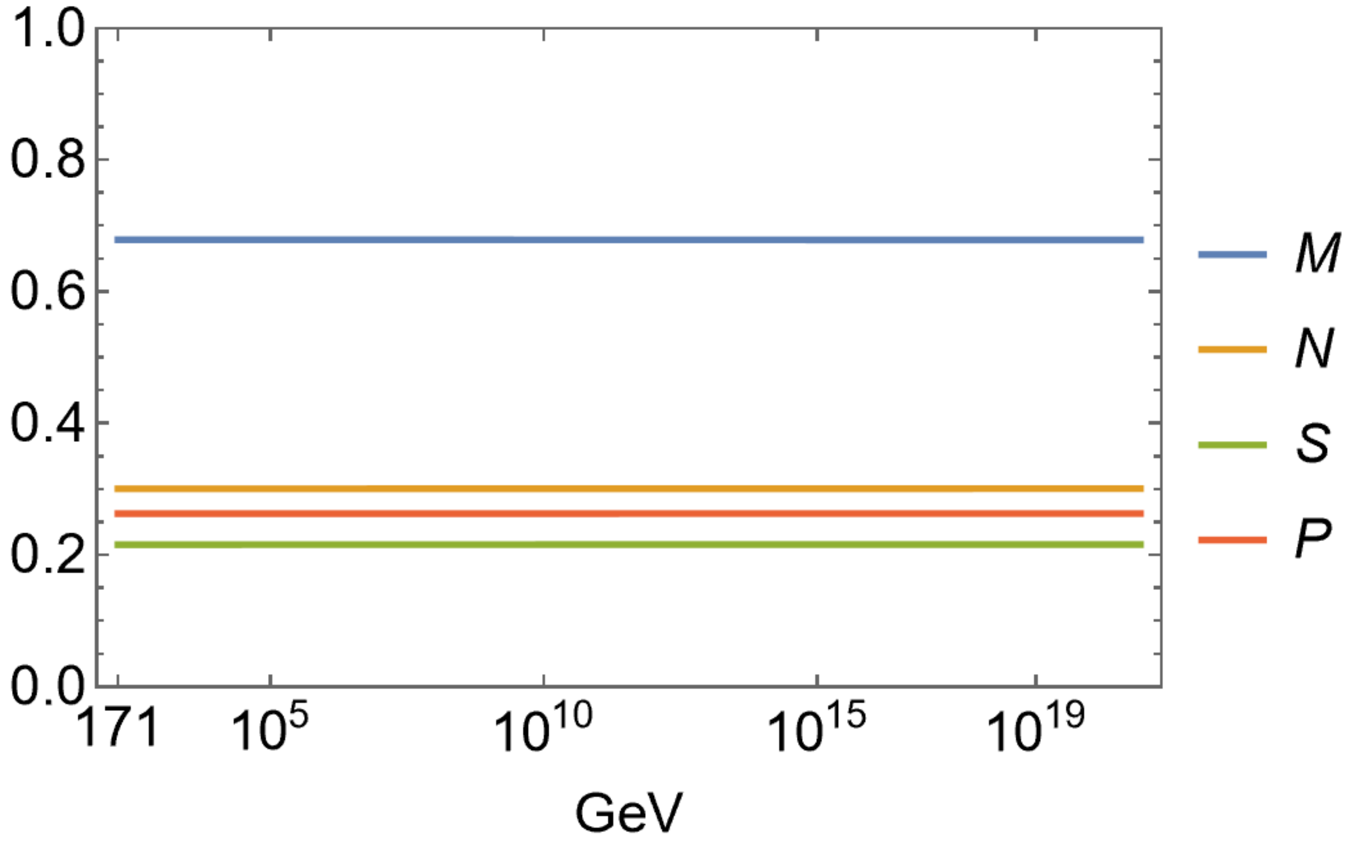
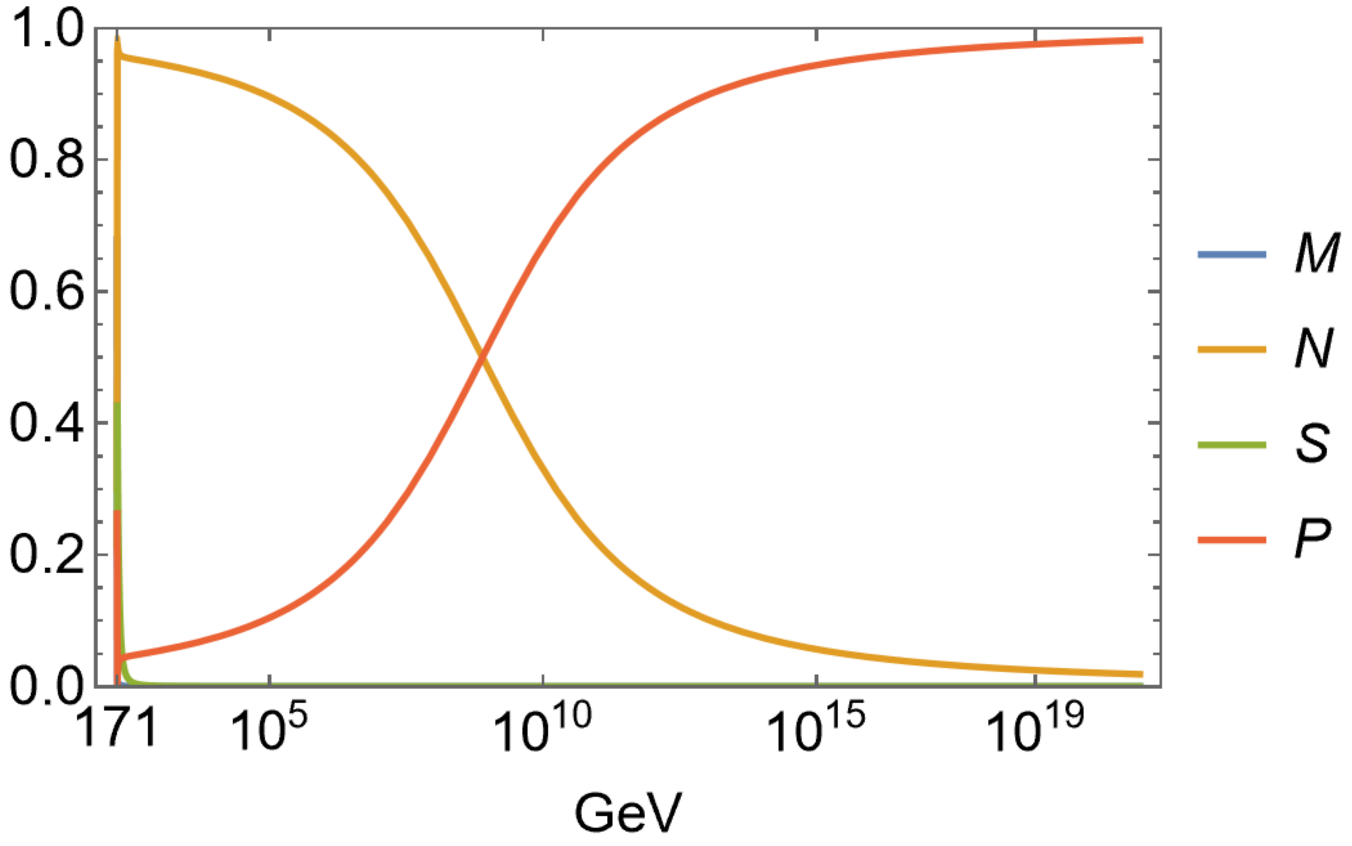
UV attractive FP

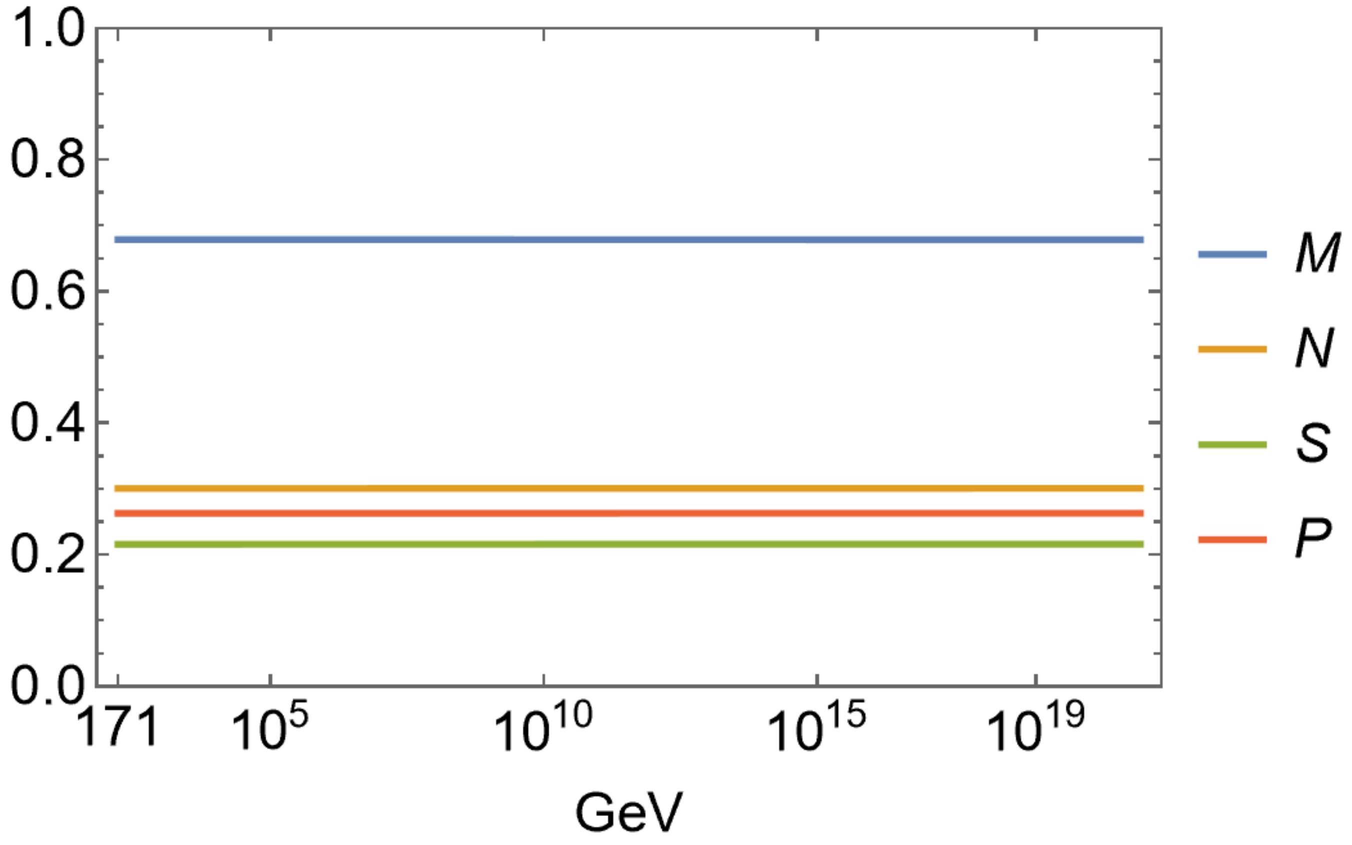
NO

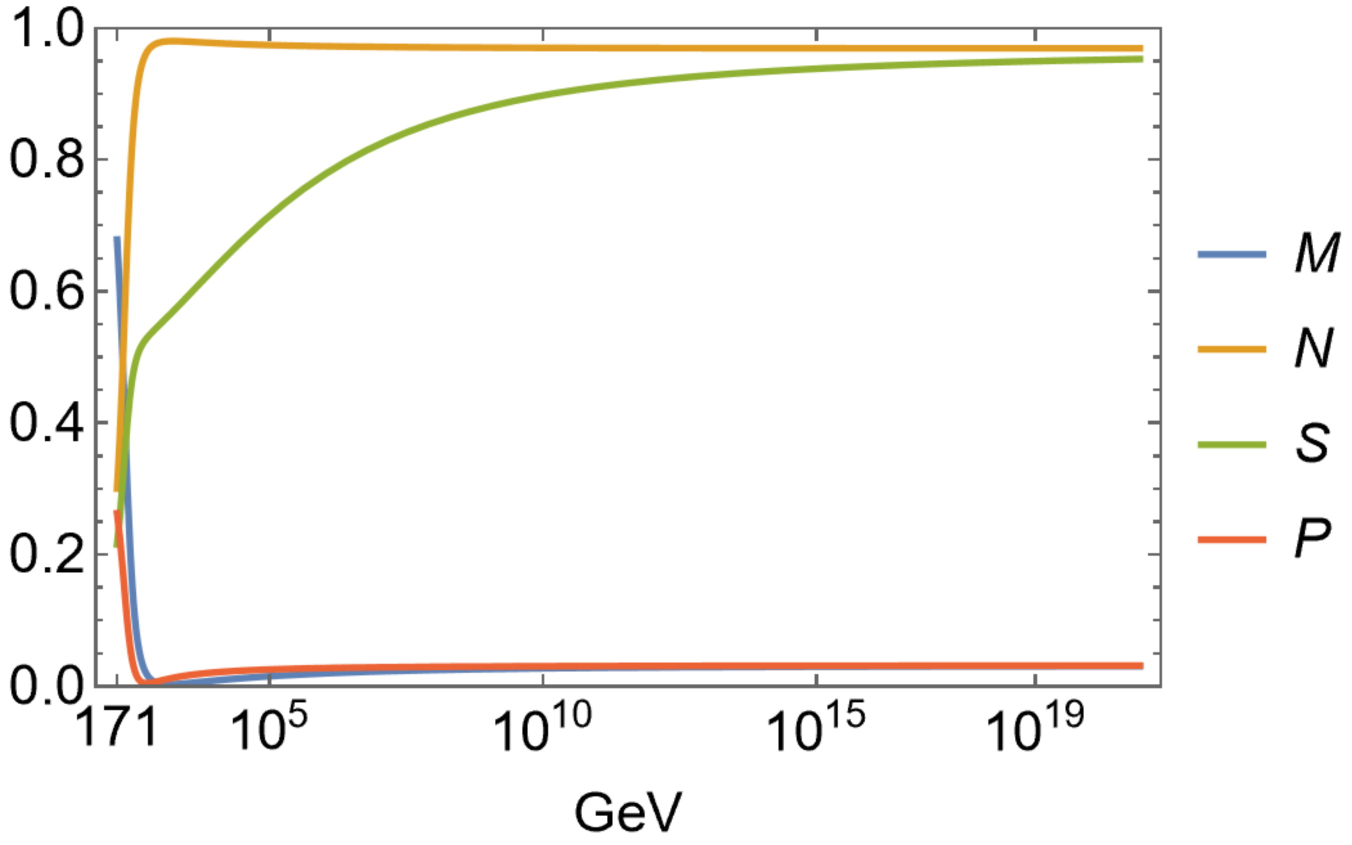




$$\begin{pmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \\ 1 & 0 & 0 \end{pmatrix}$$

IO





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

QUARK MIXING IN THE STANDARD MODEL

$$\mathscr{L}_{\text{quark}} = -\,Y^d_{ij}\,\bar{Q}^i\,H\,d^j_R - Y^u_{ij}\,\bar{Q}^i\,\tilde{H}\,u^j_R + \text{ h.c.}$$

$$\Big\downarrow \text{ Spontaneous symmetry breaking}$$

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

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

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 → but $Y_u Y_u^\dagger$ and $Y_d Y_d^\dagger$ are hermitian

Diagonalization via unitaries:
$$\begin{cases} \mathrm{diag}(y_u, y_c, y_t)^2 = U_u^\dagger Y_u Y_u^\dagger U_u = \left(U_u^\dagger Y_u K_u\right)\left(K_u^\dagger Y_u^\dagger U_u\right) \\ \\ \mathrm{diag}(y_d, y_s, y_b)^2 = U_d^\dagger Y_d Y_d^\dagger U_d = \left(U_d^\dagger Y_d K_d\right)\left(K_d^\dagger Y_d^\dagger U_d\right) \end{cases}$$

- We can write the Lagrangian via unitary transformation: $\boxed{q_R \to K_q q_R}$, $\boxed{q_L \to U_q q_L}$

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