Beyond the N_1-dominated leptogenesis with the smallest modular finite group

MATEMATICA E FISICA
DIPARTIMENTO DI ECCELLENZA

ROMA TRE
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Minimal seesaw and leptogenesis with the smallest modular finite group
JHEP 05 (2024), 020

S. Marciano D. Meloni M. Parriciatu

Prague, 19/07/2024

Outline

- Motivations
- The smallest modular finite group
- Leptogenesis: N_1-dominated scenario
- Results
- Conclusions and comments

Neutrino masses: who ordered that?

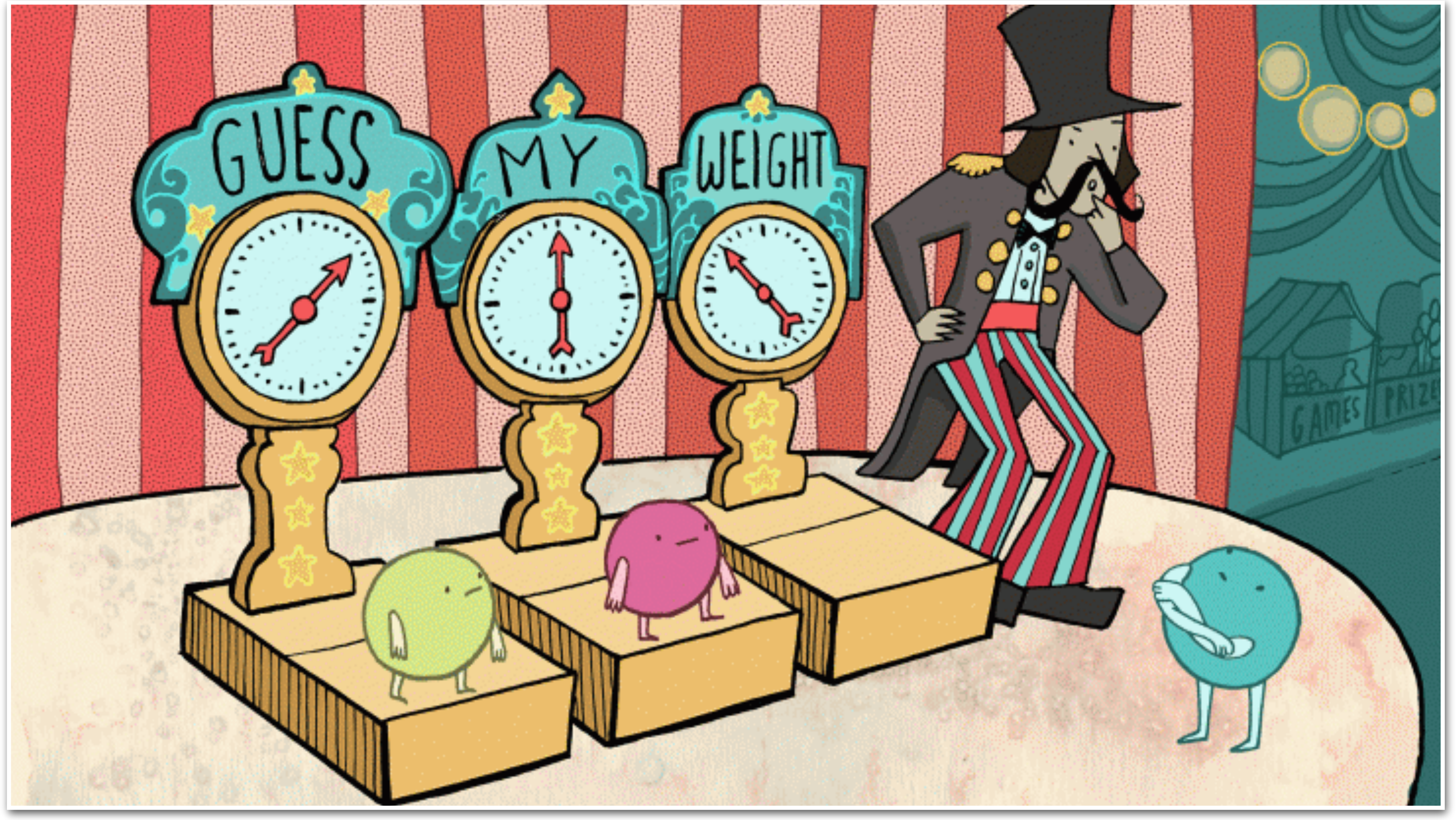
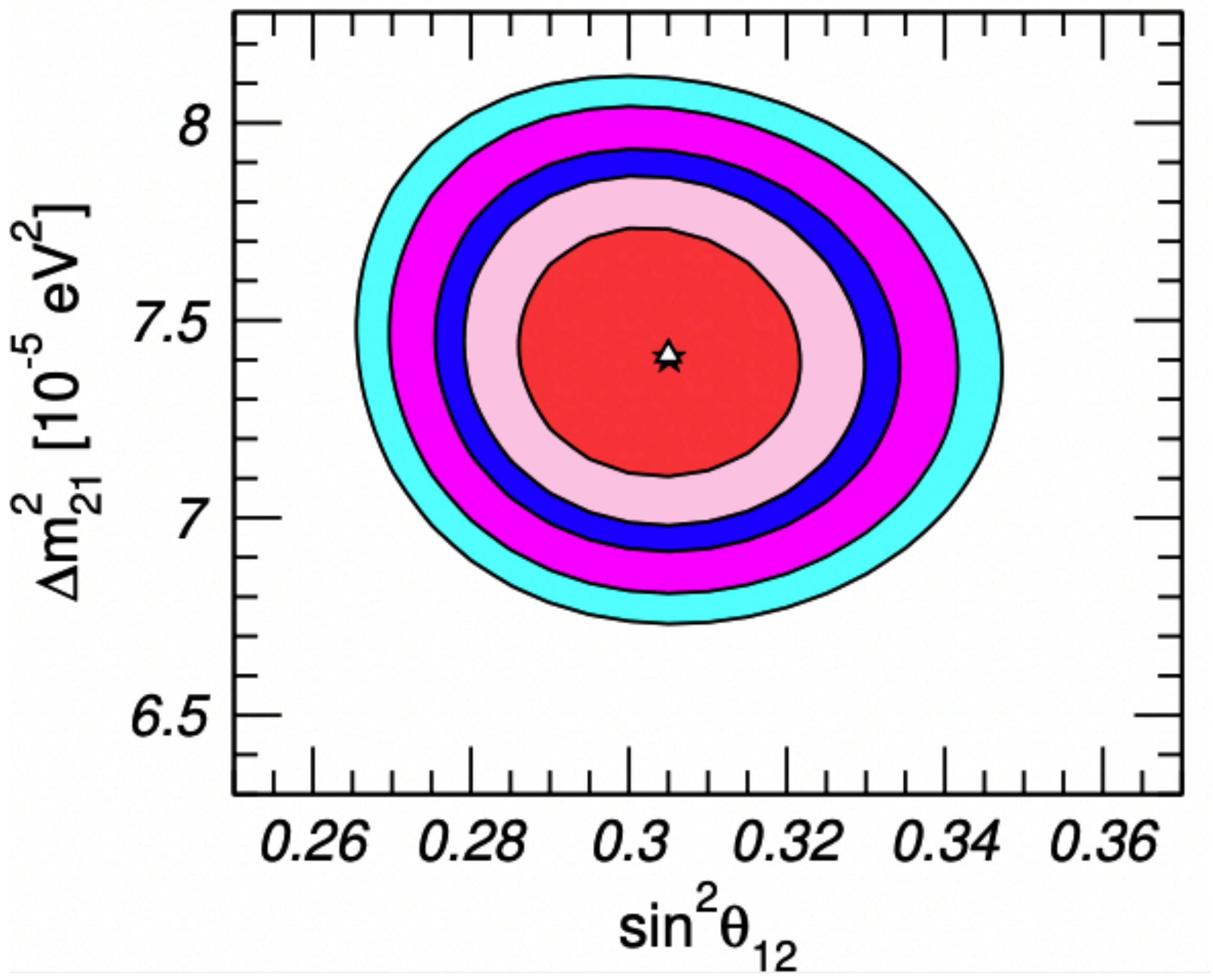
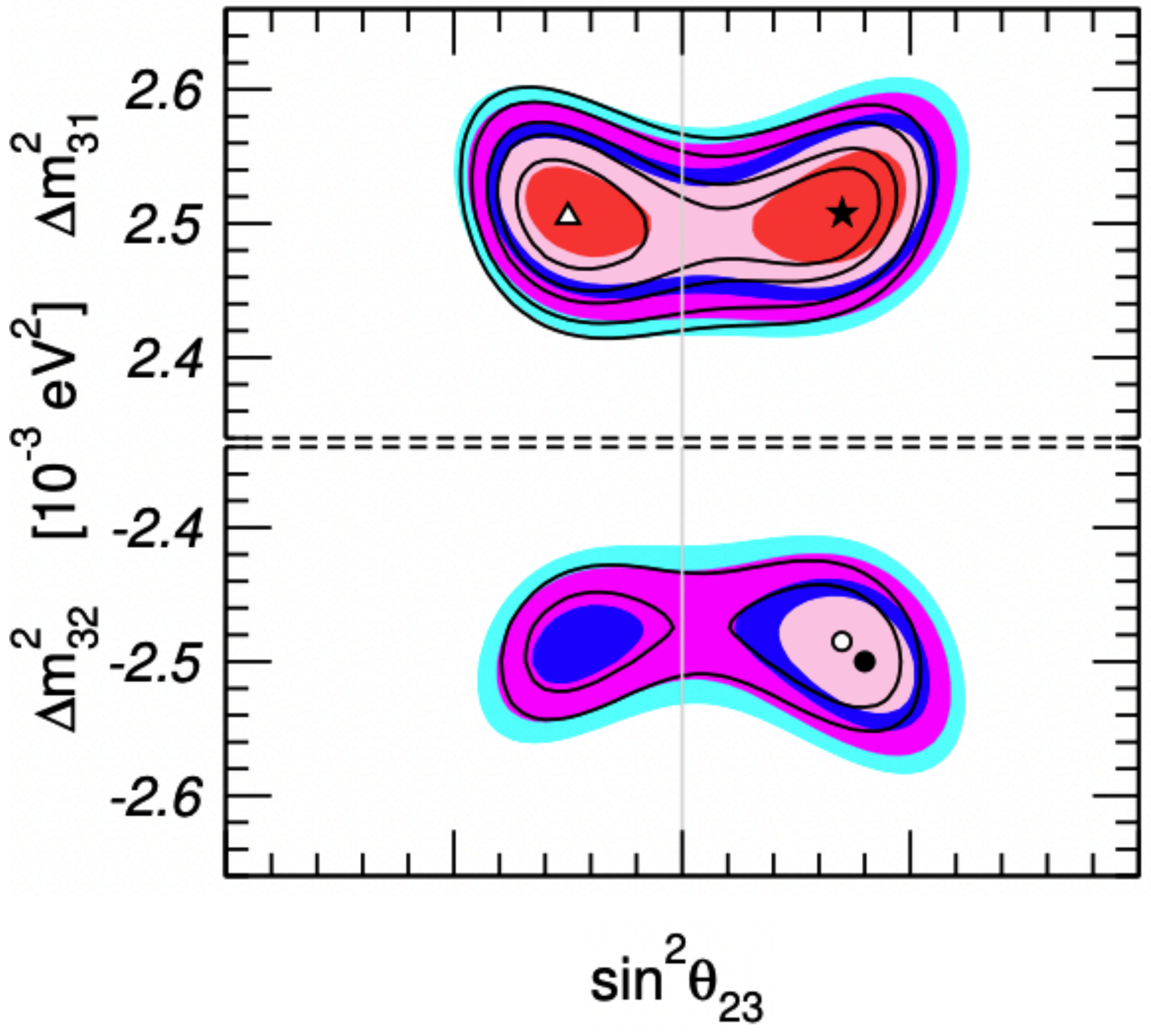


Illustration by Sandbox Studio, Chicago





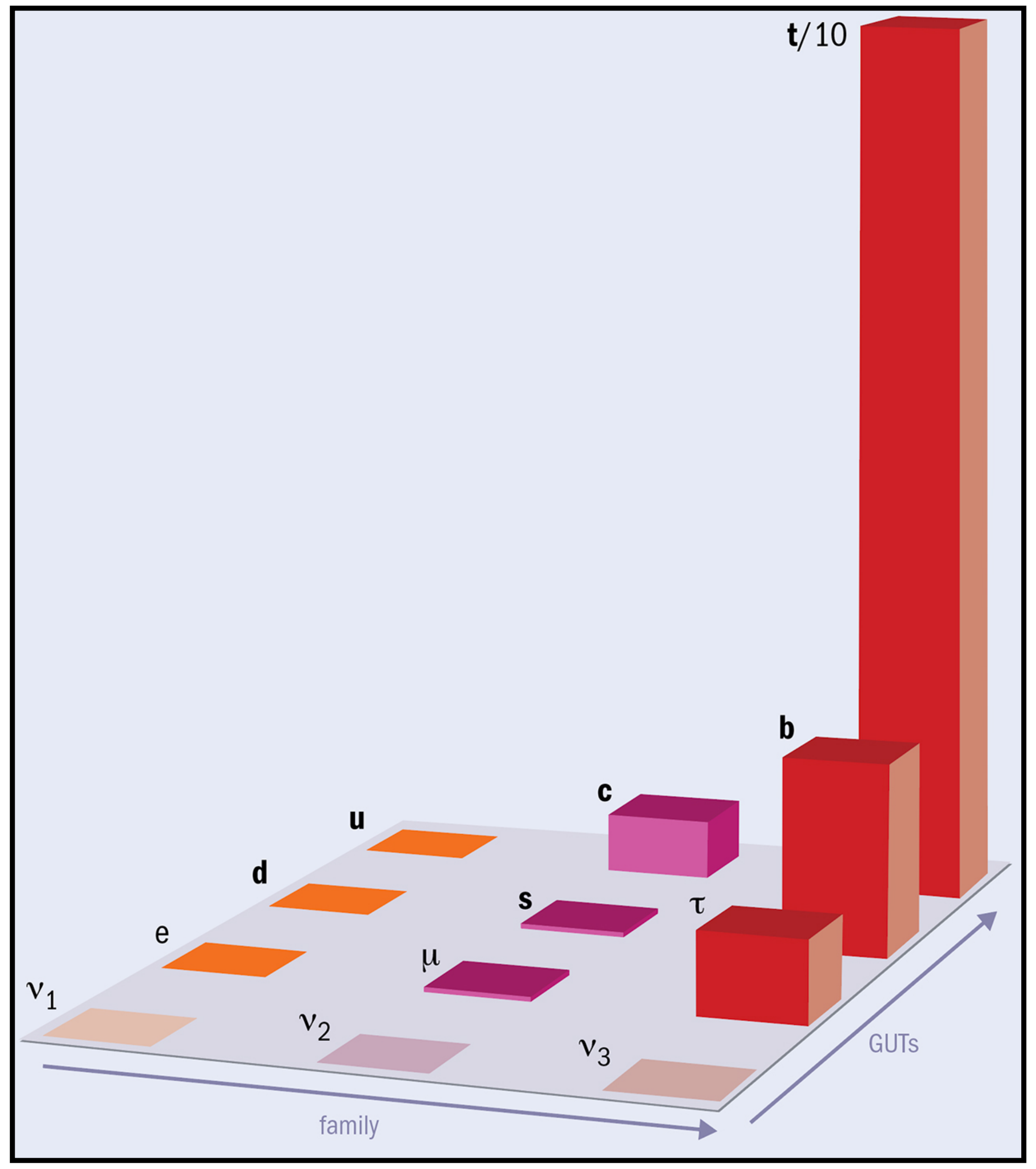
NuFIT 5.2 (2022)

		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 2.3$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
without SK atmospheric data	$\sin^2\theta_{12}$	$0.303^{+0.012}_{-0.011}$	$0.270 \to 0.341$	$0.303^{+0.012}_{-0.011}$	$0.270 \to 0.341$
	$\theta_{12}/^\circ$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$
	$\sin^2\theta_{23}$	$0.572^{+0.018}_{-0.023}$	$0.406 \to 0.620$	$0.578^{+0.016}_{-0.021}$	$0.412 \to 0.623$
	$\theta_{23}/^\circ$	$49.1^{+1.0}_{-1.3}$	$39.6 \to 51.9$	$49.5^{+0.9}_{-1.2}$	$39.9 \to 52.1$
	$\sin^2\theta_{13}$	$0.02203^{+0.00056}_{-0.00059}$	$0.02029 \to 0.02391$	$0.02219^{+0.00060}_{-0.00057}$	$0.02047 \to 0.02396$
	$\theta_{13}/^\circ$	$8.54^{+0.11}_{-0.12}$	$8.19 \to 8.89$	$8.57^{+0.12}_{-0.11}$	$8.23 \to 8.90$
	$\delta_{CP}/^\circ$	197^{+42}_{-25}	$108 \to 404$	286^{+27}_{-32}	$192 \to 360$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.511^{+0.028}_{-0.027}$	$+2.428 \to +2.597$	$-2.498^{+0.032}_{-0.025}$	$-2.581 \to -2.408$
		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 6.4$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
with SK atmospheric data	$\sin^2\theta_{12}$	$0.303^{+0.012}_{-0.012}$	$0.270 \to 0.341$	$0.303^{+0.012}_{-0.011}$	$0.270 \to 0.341$
	$\theta_{12}/^\circ$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$
	$\sin^2\theta_{23}$	$0.451^{+0.019}_{-0.016}$	$0.408 \to 0.603$	$0.569^{+0.016}_{-0.021}$	$0.412 \to 0.613$
	$\theta_{23}/^\circ$	$42.2^{+1.1}_{-0.9}$	$39.7 \to 51.0$	$49.0^{+1.0}_{-1.2}$	$39.9 \to 51.5$
	$\sin^2\theta_{13}$	$0.02225^{+0.00056}_{-0.00059}$	$0.02052 \to 0.02398$	$0.02223^{+0.00058}_{-0.00058}$	$0.02048 \to 0.02416$
	$\theta_{13}/^\circ$	$8.58^{+0.11}_{-0.11}$	$8.23 \to 8.91$	$8.57^{+0.11}_{-0.11}$	$8.23 \to 8.94$
	$\delta_{CP}/^\circ$	232^{+36}_{-26}	$144 \to 350$	276^{+22}_{-29}	$194 \to 344$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.507^{+0.026}_{-0.027}$	$+2.427 \to +2.590$	$-2.486^{+0.025}_{-0.028}$	$-2.570 \to -2.406$

JHEP 09 (2020) 178 [arXiv:2007.14792]

Neutrino masses and mixing

Mass hierarchies

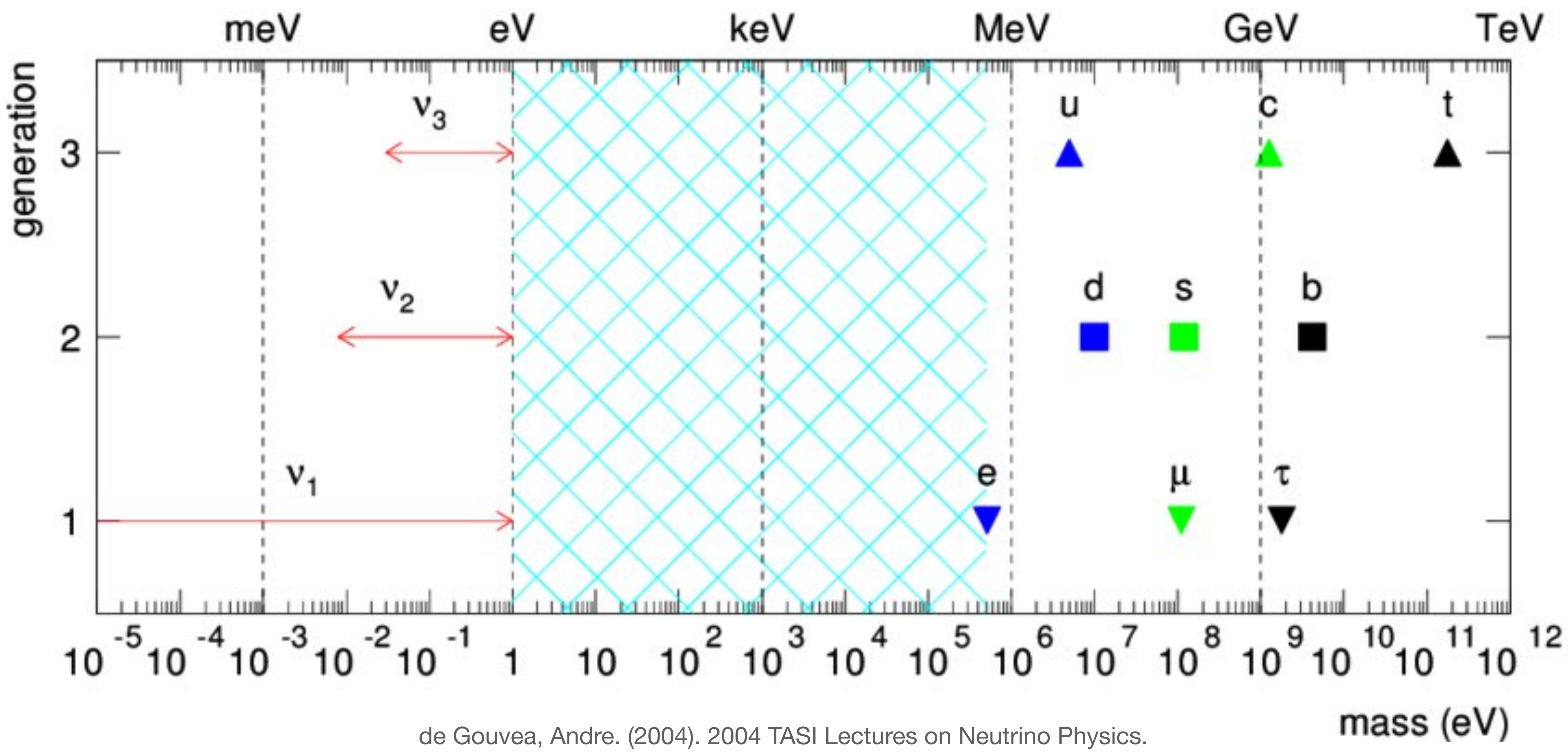


$$m_d \ll m_s \ll m_b \,, \quad \frac{m_d}{m_s} = 5.02 \times 10^{-2} \,,$$

$$m_u \ll m_c \ll m_t \,, \quad \frac{m_u}{m_c} = 1.7 \times 10^{-3} \,,$$

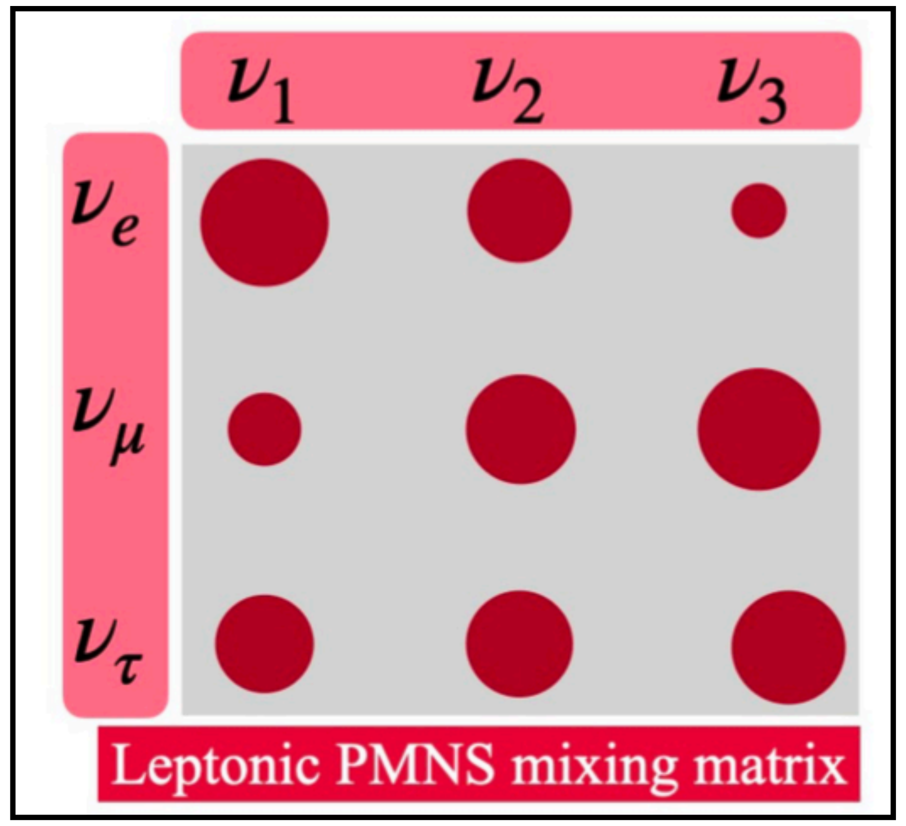
$$\frac{m_s}{m_b} = 2.22 \times 10^{-2} \,, \quad m_b = 4.18 \ \text{GeV};$$

$$\frac{m_c}{m_t} = 7.3 \times 10^{-3} \,, \quad m_t = 172.9 \ \text{GeV};$$



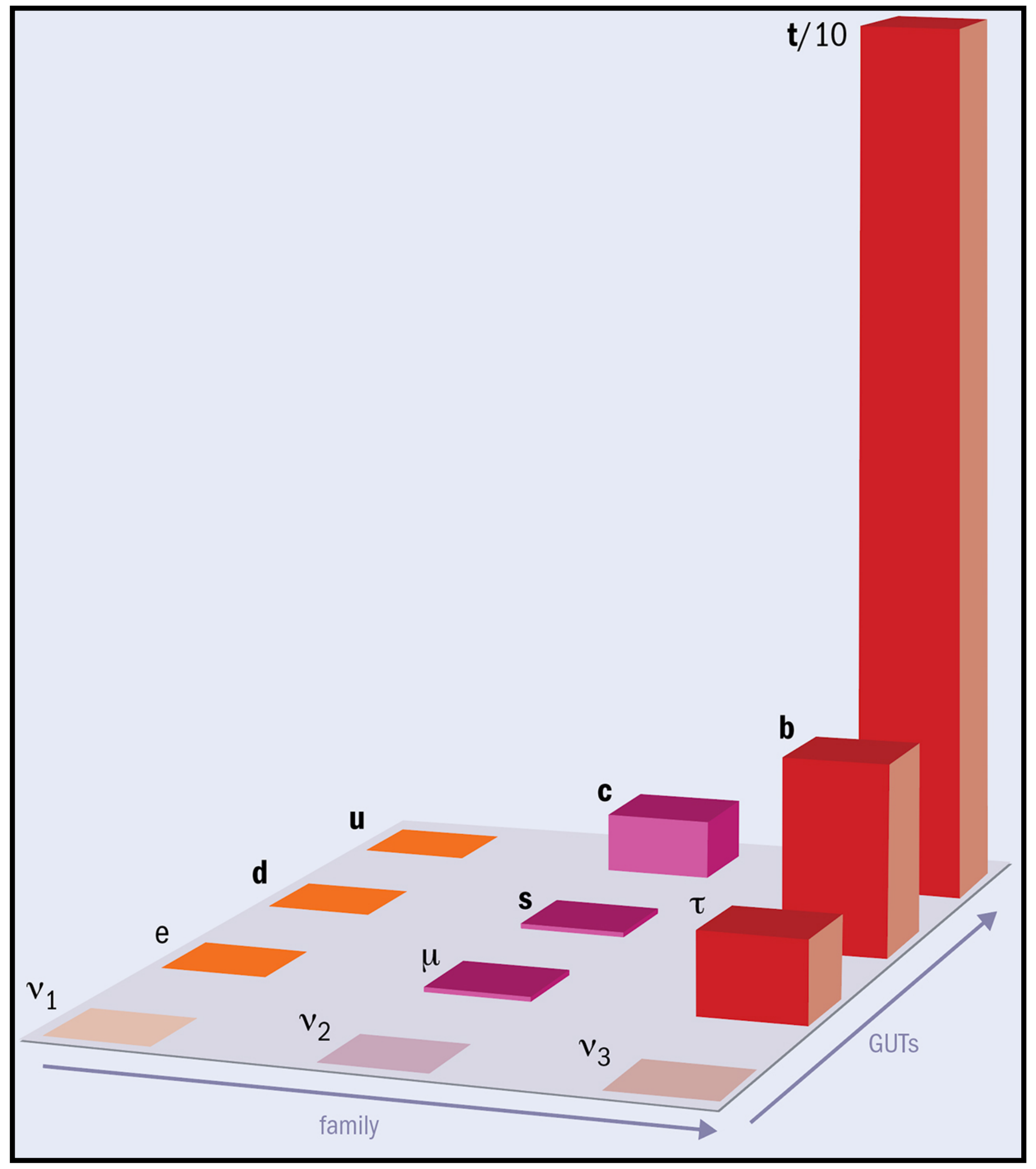
de Gouvea, Andre. (2004). 2004 TASI Lectures on Neutrino Physics.

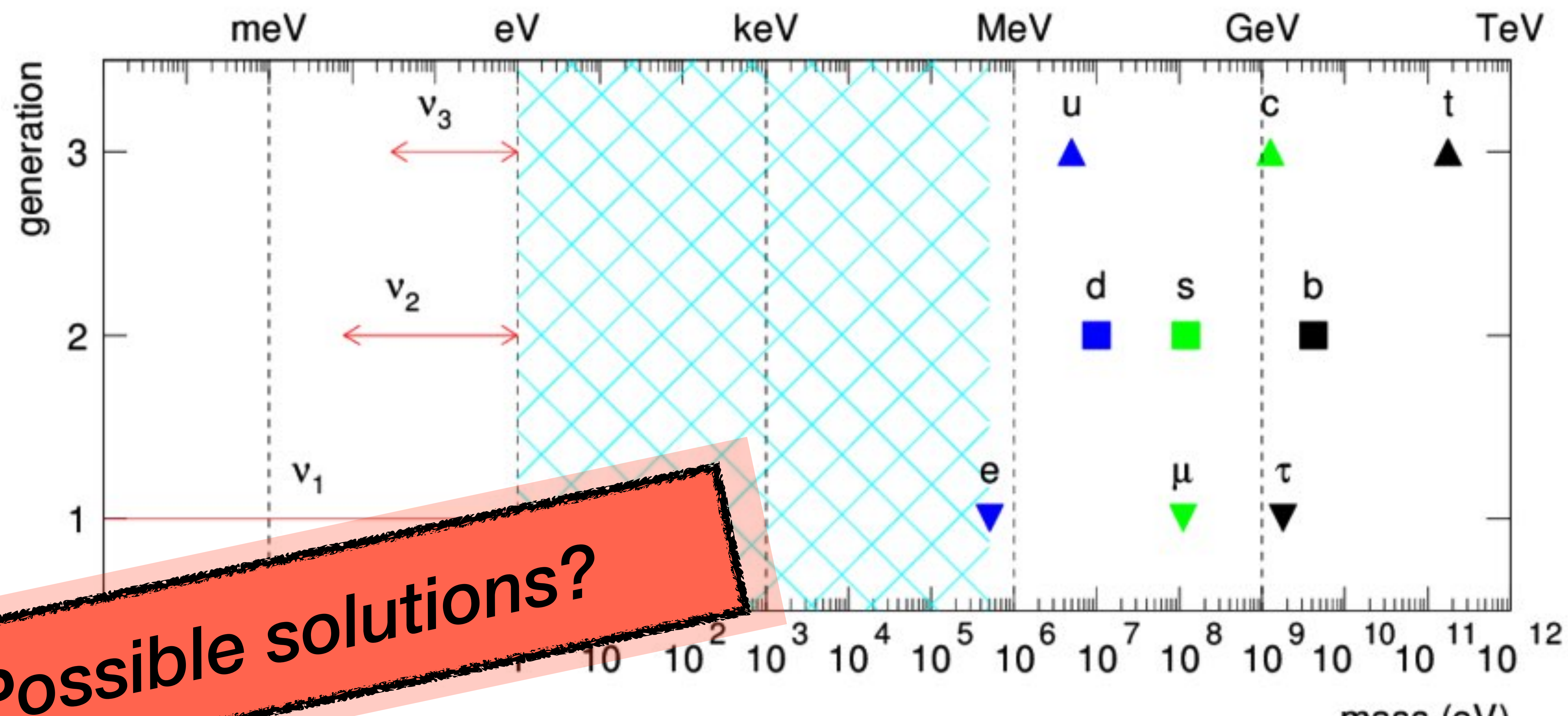
Fermion mixing



All mixing are large but the 13 element

Mass hierarchies





de Gouvea, Andre. (2004). 2004 TASI Lectures on Neutrino Physics.

Possible solutions?

$$m_d \ll m_s \ll m_b\,, \quad \frac{m_d}{m_s} = 5.02 \times 10^{-2}\,,$$

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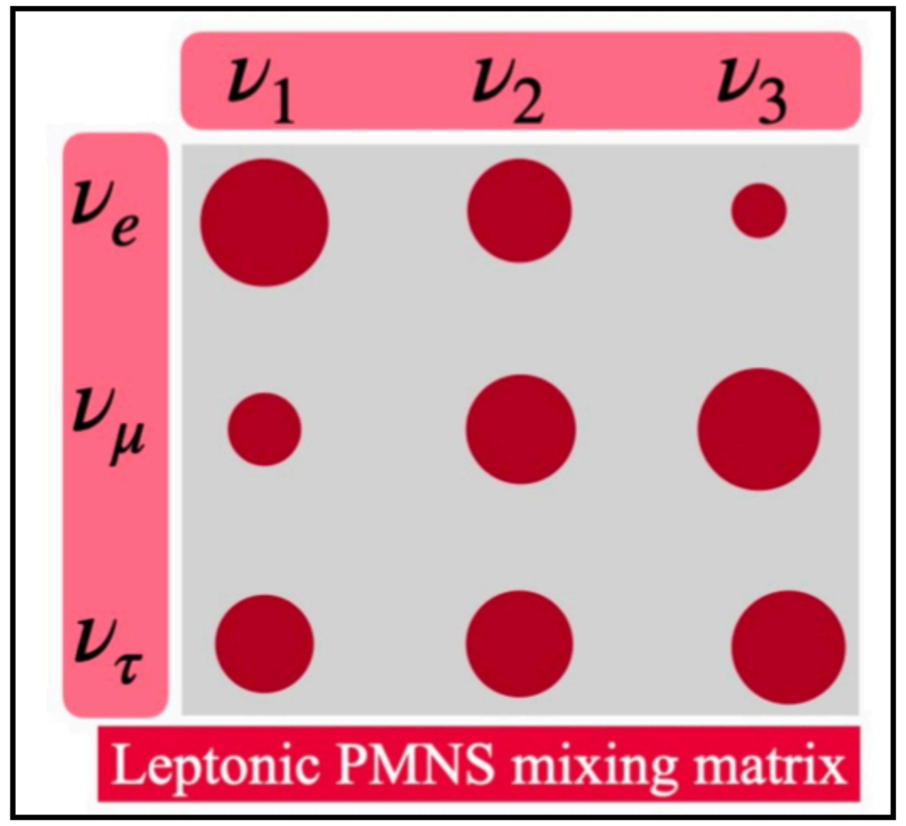
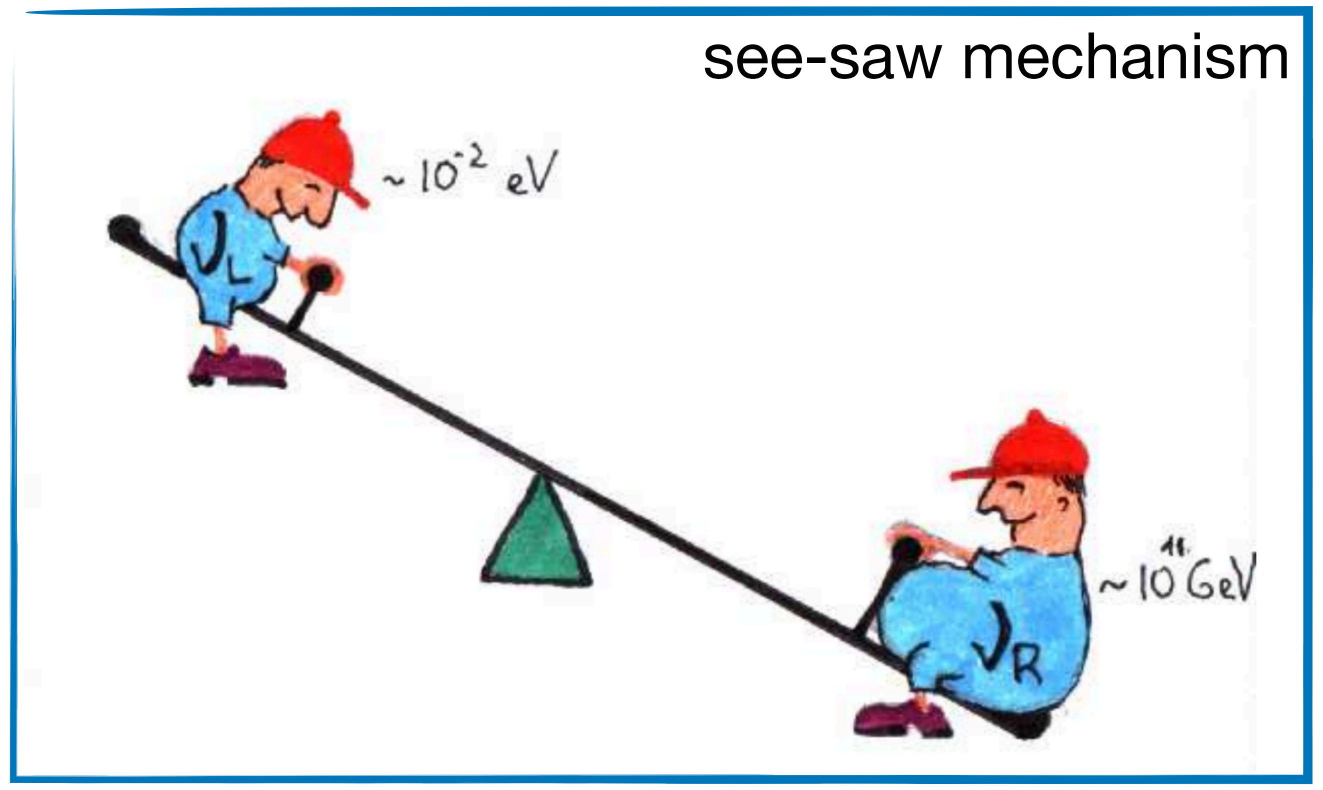


→ All mixing are large but the 13 element

Smallness of neutrino masses

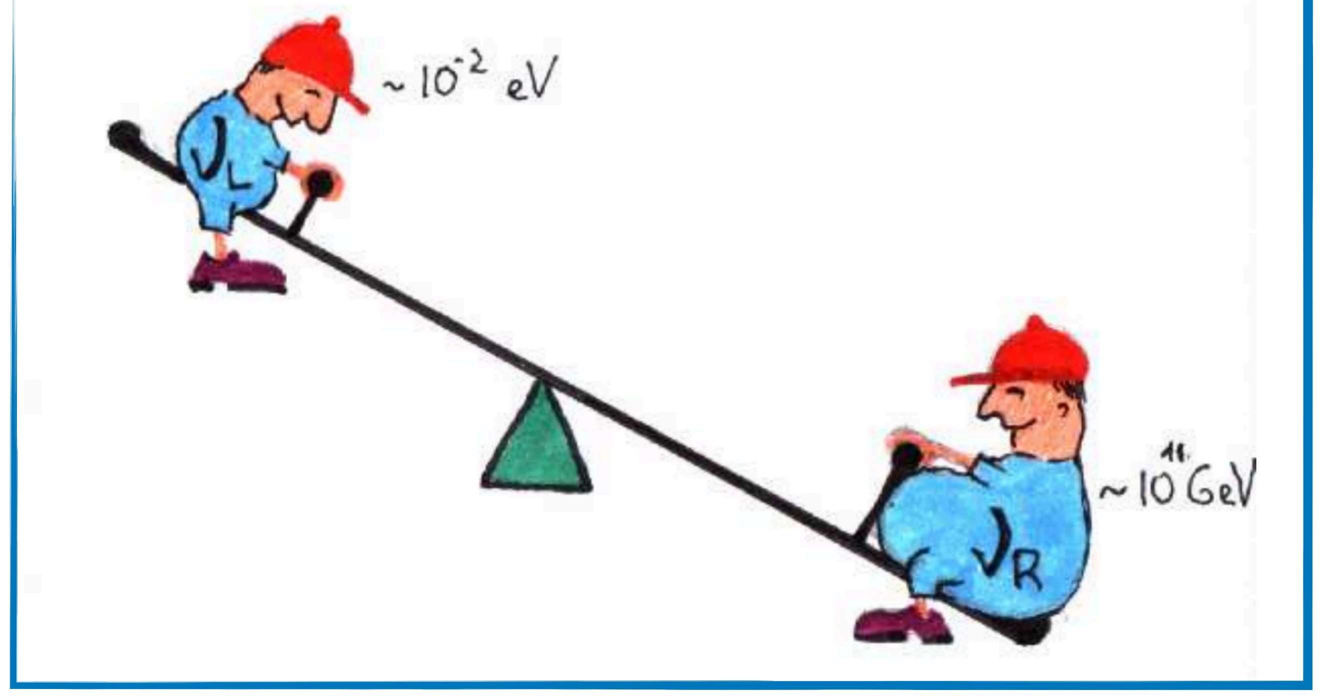


$$M_\nu = \begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix}$$

$$m_{light} \approx \frac{m_D^2}{M_R}$$

Suggested solutions

Smallness of neutrino masses



see-saw mechanism

$$M_\nu = \begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix}$$

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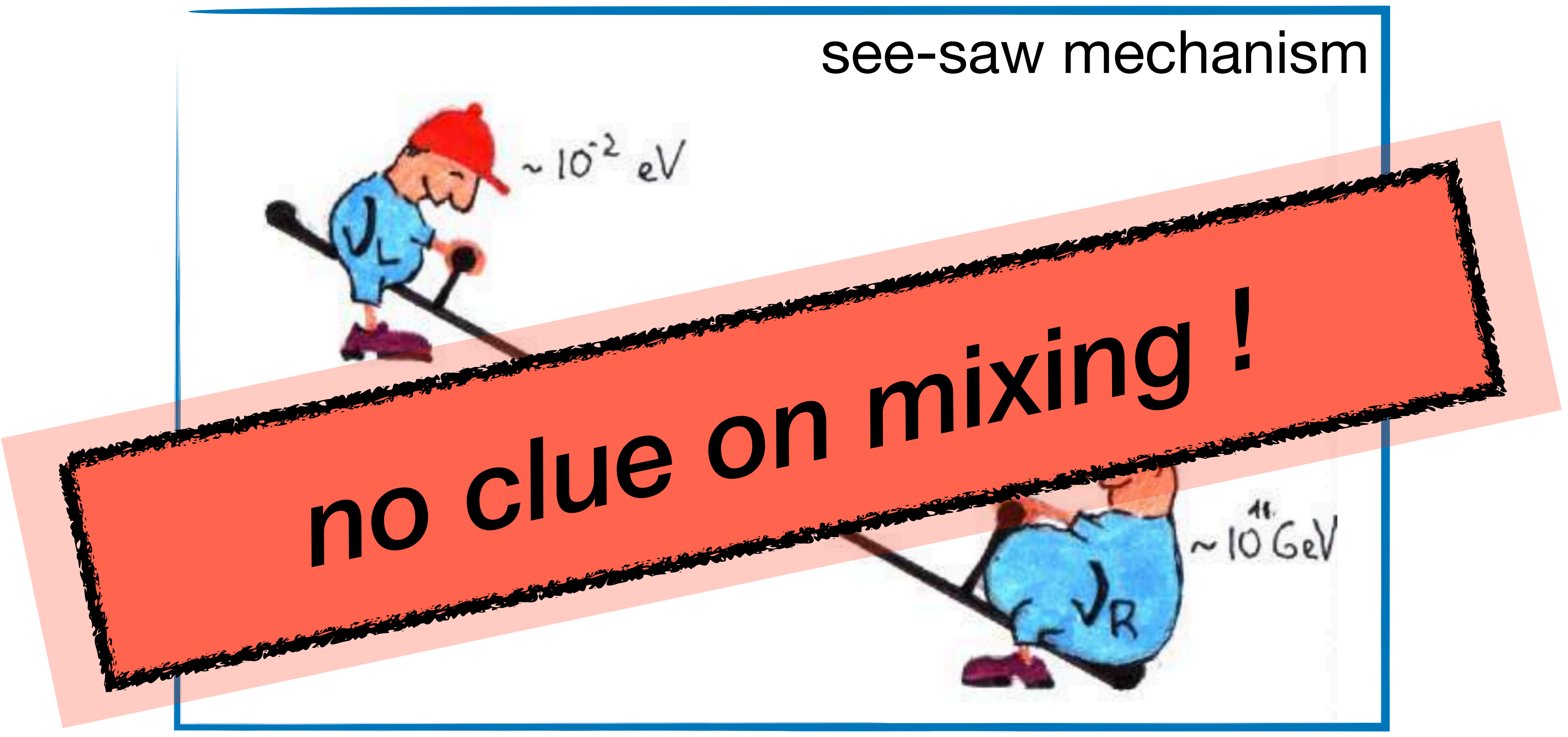
see also the talk by D. Vatsyayan on novel Weinberg-like operators

Neutrino masses from new seesaw models: Low-scale variants and phenomenological implications, [arXiv:2312.14119 [hep-ph]]

Neutrino masses from new Weinberg-like operators: phenomenology of TeV scalar multiplets JHEP 05 (2024), 055

A. Giarnetti, J. Herrero-Garcia, S. Marciano, D. Meloni and D. Vatsyayan

Smallness of neutrino masses



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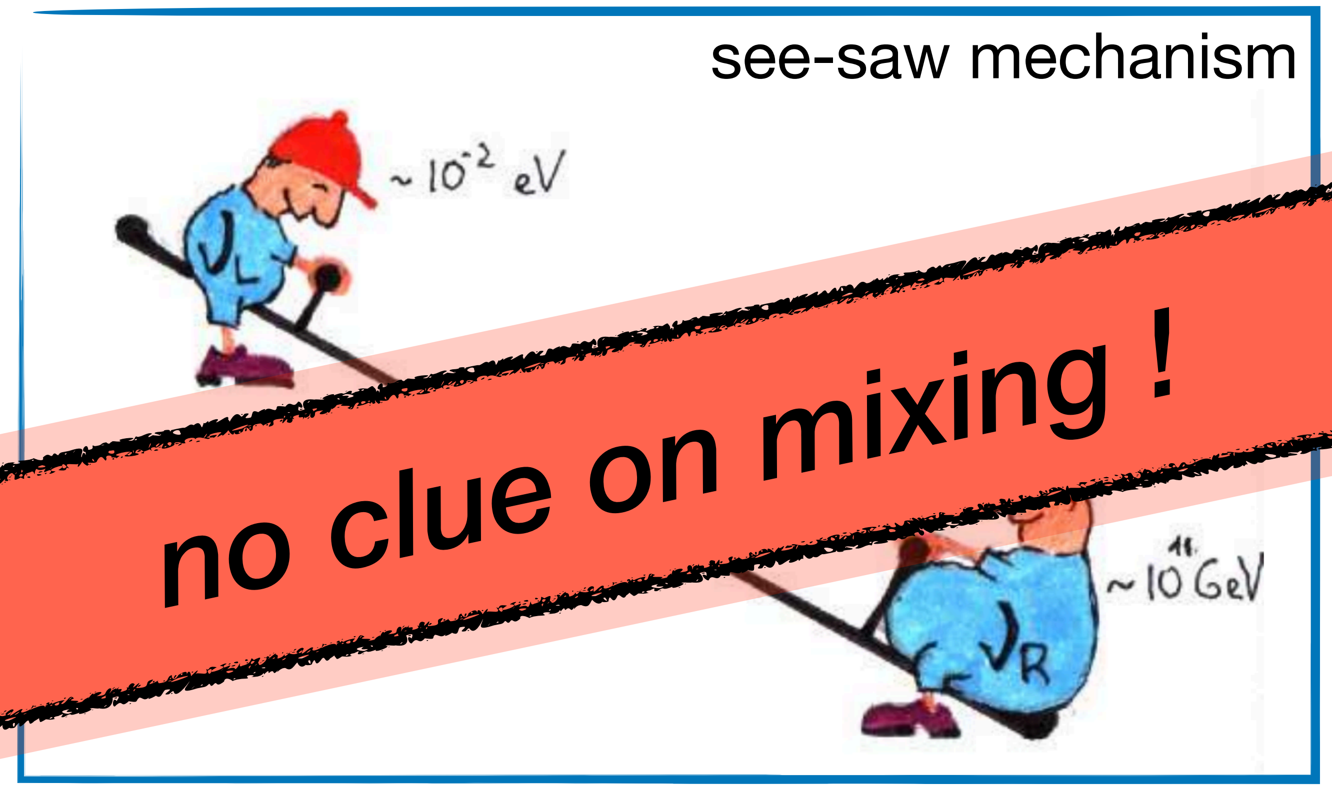


no clue on mixing !

$$M_\nu = \begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix}$$

$$m_{light} \approx \frac{m_D^2}{M_R}$$

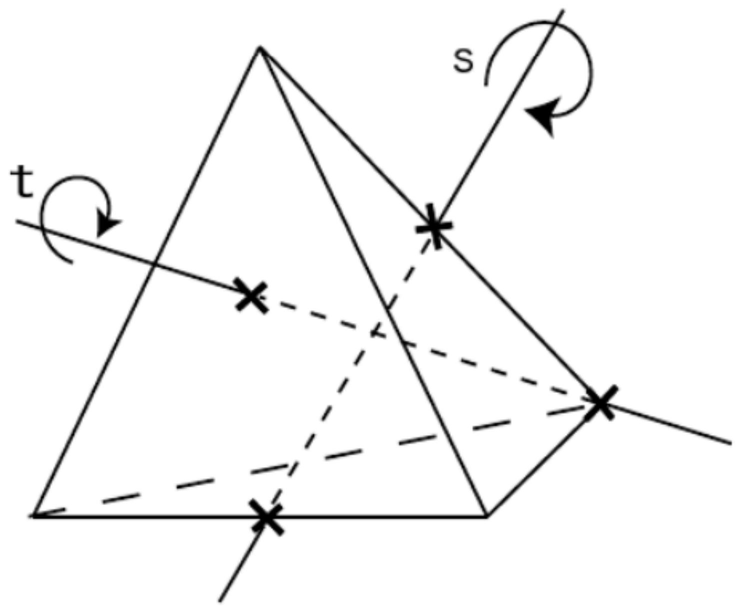
Hierarchical pattern and mixing angles

Froggatt-Nielsen mechanim

$$L \sim \overline{\Psi}_L H \Psi_R \left(\frac{\Theta}{\Lambda}\right)^n$$

too many $\mathcal{O}(1)$ coefficients

non-Abelian discrete flavor symmetries



complicated scalar sector

Modular symmetry ?

Feruglio, 1706.08749

Modular finite group

The modular group $\overline{\Gamma} = \mathrm{SL}(2,\mathbb{Z})/\{\pm\mathbb{1}\}$ acts on the modulus τ restricted to the upper-half complex plan through the transformation $\gamma \ : \ \tau \to \gamma(\tau)$

$$\gamma(\tau) = \frac{a\tau + b}{c\tau + d} \quad , \quad a, b, c, d \in \mathbb{Z} \quad , \quad ad - bc = 1\,,$$

$$S \,:\, \tau \to -\frac{1}{\tau} \qquad\qquad T \,:\, \tau \to \tau + 1 \qquad\qquad S^2 = (ST)^3 = \mathbb{1}$$

A modular form is a holomorphic function of τ such that:

$$f(\gamma(\tau)) = (c\tau + d)^k f(\tau)\,,$$

$$\Gamma(N) = \left\{ \begin{pmatrix} a & b \\ c & d \end{pmatrix} \in \mathrm{SL}(2,\mathbb{Z}) \middle| \begin{pmatrix} a & b \\ c & d \end{pmatrix} \equiv \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} (\mathrm{mod}\ N) \right\},$$

Feruglio ([1]) has shown that it is always possible to find a basis where modular forms of a given level N transform in unitary representations of the finite groups which, for N<6, are isomorphic to the non-Abelian discrete groups

$$\Gamma_2 \simeq S_3 \qquad \Gamma_3 \simeq A_4 \qquad \Gamma_4 \simeq S_4 \qquad \Gamma_5 \simeq A_5$$

for further details, see
the talk by M. Parriciatu

[1] F. Feruglio. "Are neutrino masses modular forms?", 1706.08749 [hep-ph]

The Model in a nutshell

The modular group $\overline{\Gamma} = \mathrm{SL}(2,\mathbb{Z})/\{\pm\mathbb{1}\}$ acts on the modulus τ restricted to the upper-half complex plan through the transformation $\gamma \; : \; \tau \to \gamma(\tau)$

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[1] F. Feruglio. "Are neutrino masses modular forms?", 1706.08749 [hep-ph]

$$\Gamma_2 \simeq S_3 \qquad \begin{pmatrix} Y_1(\tau) \\ Y_2(\tau) \end{pmatrix}_{\mathbf{2}} = \begin{pmatrix} \frac{7}{100} + \frac{42}{25}q + \frac{42}{25}q^2 + \frac{168}{25}q^3 + \ldots \\ \frac{14\sqrt{3}}{25}q^{1/2}(1 + 4q + 6q^2 + \ldots) \end{pmatrix} ,$$

SUSY framework

$$\Phi(\tau, \varphi) \qquad \varphi^{(I)} \to (c\tau + d)^{-k_I} \rho^{(I)}(\gamma) \varphi^{(I)}$$

chiral superfields — matter supermultiplets

Superpotential

$$\mathscr{W}(\Phi) = \sum (Y_{I_1 \ldots I_n}(\tau) \, \varphi^{(I_1)} \ldots \varphi^{(I_n)})_{\mathbf{1}} \, ,$$

Yukawa Couplings as modular forms

$$Y_{I_1 \ldots I_n}(\gamma(\tau)) = (c\tau + d)^{k_Y} \rho(\gamma) Y_{I_1 \ldots I_n}(\tau) \, ,$$

The novelty compared to classic non-Abelian discrete groups model building is that the invariance is achieved by satisfying not only the existence of a singlet contraction between all the irreps involved, but also that every operator must be *weightless*

Smallest modular finite group

The Model in a nutshell

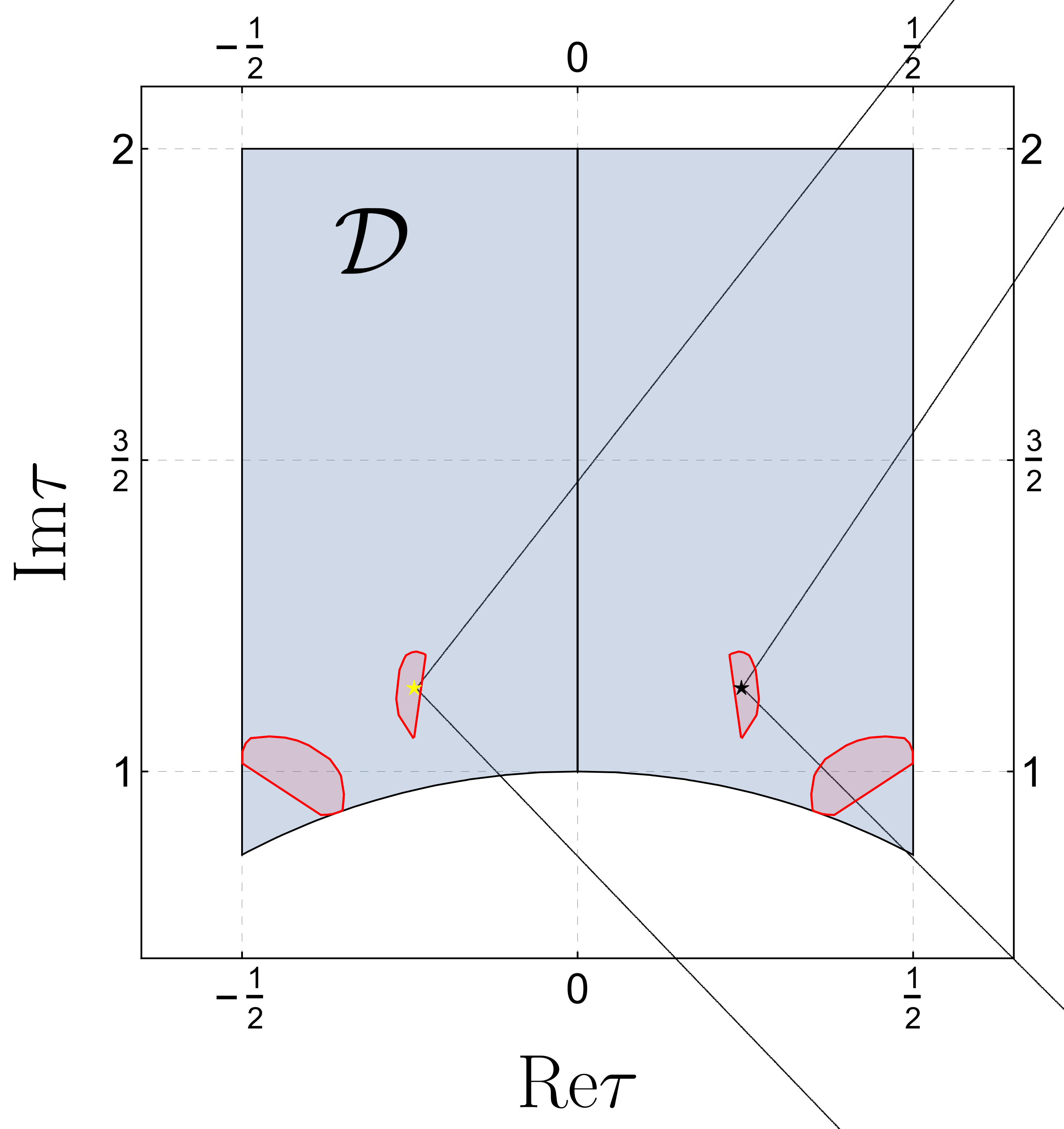
	E_1^c	E_2^c	E_3^c	D_ℓ	ℓ_3	$H_{d,u}$	N^c
$SU(2)_L\times U(1)_Y$	$(1,+1)$	$(1,+1)$	$(1,+1)$	$(2,-1/2)$	$(2,-1/2)$	$(2,\mp1/2)$	$(1,0)$
$\Gamma_2 \cong S_3$	1	$1'$	$1'$	2	$1'$	1	2
k_I	4	0	−2	2	2	0	2

$$\mathscr{W}_e^H = \alpha E_1^c H_d (D_\ell Y_2^{(3)})_1 + \beta E_2^c H_d (D_\ell Y_2)_{1'} + \gamma E_3^c H_d \ell_3 + \alpha_D E_1^c H_d \ell_3 Y_{1'}^{(3)},$$

$$\mathscr{W}_\nu = g H_u N^c D_\ell Y_2^{(2)} + g' H_u (N^c Y_2^{(2)})_{1'} \ell_3 + g'' H_u (N^c D_\ell)_1 Y_1^{(2)} + $$
$$+ \Lambda[(N^c N^c)_2 Y_2^{(2)} + \lambda (N^c N^c)_1 Y_1^{(2)}]$$

Parameter	Best-fit value and 1σ range	
$\Delta m^2_{\rm sol}/(10^{-5}\ {\rm eV}^2)$	$7.41^{+0.21}_{-0.20}$	
	NO	**IO**
$\lvert\Delta m^2_{\rm atm}\rvert/(10^{-3}\ {\rm eV}^2)$	$2.507^{+0.026}_{-0.027}$	$2.486^{+0.025}_{-0.028}$
$r \equiv \Delta m^2_{\rm sol}/\lvert\Delta m^2_{\rm atm}\rvert$	0.0295 ± 0.0008	0.0298 ± 0.0008
$\sin^2\theta_{12}$	$0.303^{+0.012}_{-0.012}$	$0.303^{+0.012}_{-0.011}$
$\sin^2\theta_{13}$	$0.02225^{+0.00056}_{-0.00059}$	$0.0223^{+0.00058}_{-0.00058}$
$\sin^2\theta_{23}$	$0.451^{+0.019}_{-0.016}$	$0.569^{+0.016}_{-0.021}$
m_e/m_μ	0.0048 ± 0.0002	
m_μ/m_τ	0.0565 ± 0.0045	

I. Esteban, M. C. Gonzalez-Garcia, M. Maltoni, T. Schwetz, and A. Zhou, "The fate of hints: updated global analysis of three-flavor neutrino oscillations," KHEP 09 (2020) 178, 2007.14792 [hep-ph]



★(-) ★(+)	Best-fit and 1σ range
${\rm Re}\,\tau$	$\pm0.244^{+0.012}_{-0.067}$
${\rm Im}\,\tau$	$1.132^{+0.027}_{-0.297}$
β/α	$0.92^{+0.85}_{-0.03}$
γ/α	$-1.20^{+0.06}_{-2.14}$
$\log_{10}(\alpha_D/\alpha)$	$-13.4^{+13.2}_{-76.3}$
g'/g	$2.76^{+0.21}_{-0.23}$
g''/g	$-2.53^{+0.13}_{-0.03}$
$\log_{10}(\lvert\lambda\rvert)$	$-12.2^{+10.9}_{-59.2}$
$v_d\,\alpha$, [GeV]	$1.08^{+0.06}_{-0.69}$
$v_u^2\, g^2/\Lambda$ [eV]	$3.46^{+0.55}_{-1.65}$
$\sin^2\theta_{12}$	$0.305^{+0.011}_{-0.011}$
$\sin^2\theta_{13}$	$0.0221^{+0.0006}_{-0.0005}$
$\sin^2\theta_{23}$	$0.448^{+0.014}_{-0.016}$
r	$0.0296^{+0.0006}_{-0.0008}$
m_e/m_μ	$0.0048^{+0.0001}_{-0.0002}$
m_μ/m_τ	$0.0574^{+0.0032}_{-0.0050}$
Ordering	**NO**
$J_{\rm CP}$	$-0.018^{+0.002}_{-0.002}$
α_1/π	0
α_2/π	$\pm0.112^{+0.792}_{-0.014}$
m_1 [meV]	0
m_2 [meV]	$8.620^{+0.095}_{-0.123}$
m_3 [meV]	$50.806^{+0.016}_{-0.021}$
$\sum_i m_i$ [eV]	$0.0594^{+0.0001}_{-0.0001}$
$\lvert m_{\beta\beta}\rvert$ [meV]	$3.61^{+0.09}_{-0.09}$
$m_\beta^{\rm eff}$ [meV]	$8.90^{+0.10}_{-0.09}$
$d_{\rm FT}$	3.03
$\chi^2_{\rm min}$	0.98

Thermal Leptogenesis

“Baryogenesis Without Grand Unification”, Phys.Lett.B174:45,1986, by Fukugita and Yanagida.

Volume 174, number 1 PHYSICS LETTERS B 26 June 1986

BARYOGENESIS WITHOUT GRAND UNIFICATION

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and

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and Deutsches Elektronen-Synchrotron DESY, D-2000 Hamburg, Fed. Rep. Germany

Received 8 March 1986

A mechanism is pointed out to generate cosmological baryon number excess without resorting to grand unified theories. The lepton number excess originating from Majorana mass terms may transform into the baryon number excess through the unsuppressed baryon number violation of electroweak processes at high temperatures.

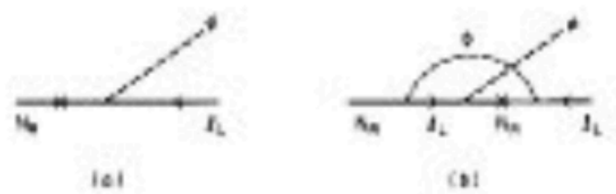


Fig. 1. The simplest diagram giving rise to a net lepton number production. The cross denotes the Majorana mass insertion.

Thermal Leptogenesis

"Baryogenesis Without Grand Unification", Phys.Lett.B174:45,1986, by Fukugita and Yanagida.

Sakharov Conditions

Baryon Number violation

C and CP violation

Departure from thermal eq.

C and CP violation

if C or CP are conserved,

$$\Gamma(X \to Y + B) = \Gamma(\overline{X} \to \overline{Y} + \overline{B})$$

No net effect

Departure from thermal eq.

In thermal equilibrium,
the production rate of baryons
is equal to the destruction rate:

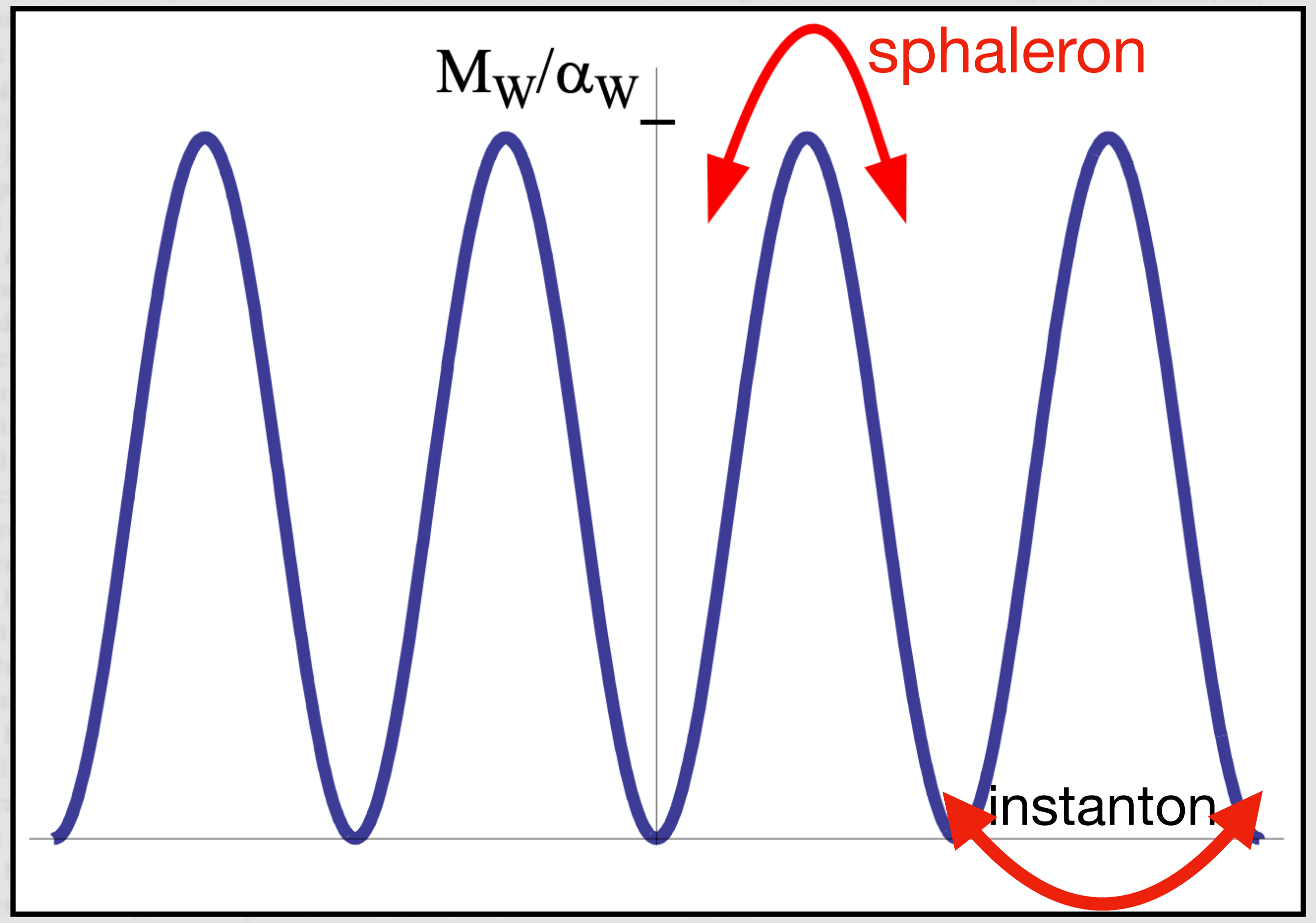
$$\Gamma(X \to Y + B) = \Gamma(Y + B \to X)$$

No net effect

Baryon Number violation

if baryon asymmetry is conserved,
then no baryon number can be
dynamically generated.

$$X^{B=0} \to Y^{B=0} + B^{\neq 0}$$



$\Delta B = \Delta L = 3$

At high temperatures, transitions violating B+L (and preserving B-L) occur very often

$$T < T_{EW} \quad \frac{\Gamma}{V} \sim \text{Exp}[-M_W/(\alpha k T)]$$

$$T > T_{EW} \quad \frac{\Gamma}{V} \sim \alpha^5 (\ln \alpha^{-1}) T^4$$

$$N^f_{B-L} = \sum_i \epsilon_i \, k^f_i \quad , \quad i = 1{,}2$$

$$k^f_i = k_i(z=\infty) = -\int_{z_{in}\to 0}^{z_{fin}\to\infty} \frac{\mathrm{d}N_i}{\mathrm{d}z'} \mathrm{Exp}\left[\sum_i \int_{z'}^{z} W_i(z'')\mathrm{d}z''\right] \mathrm{d}z'$$

$$N^f_{B-L} = \sum_i \epsilon_i k^f_i \quad , \quad i = 1,2$$

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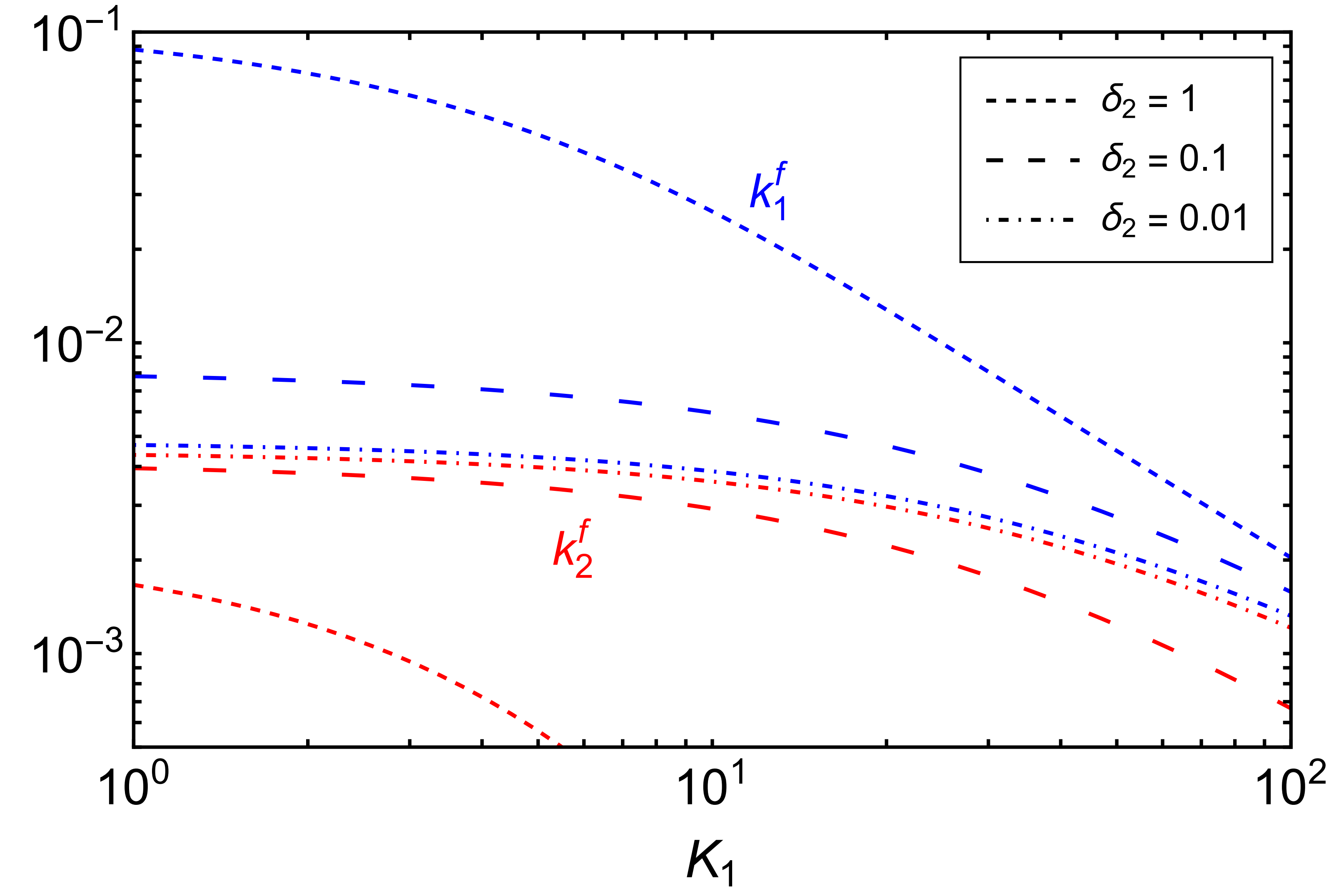
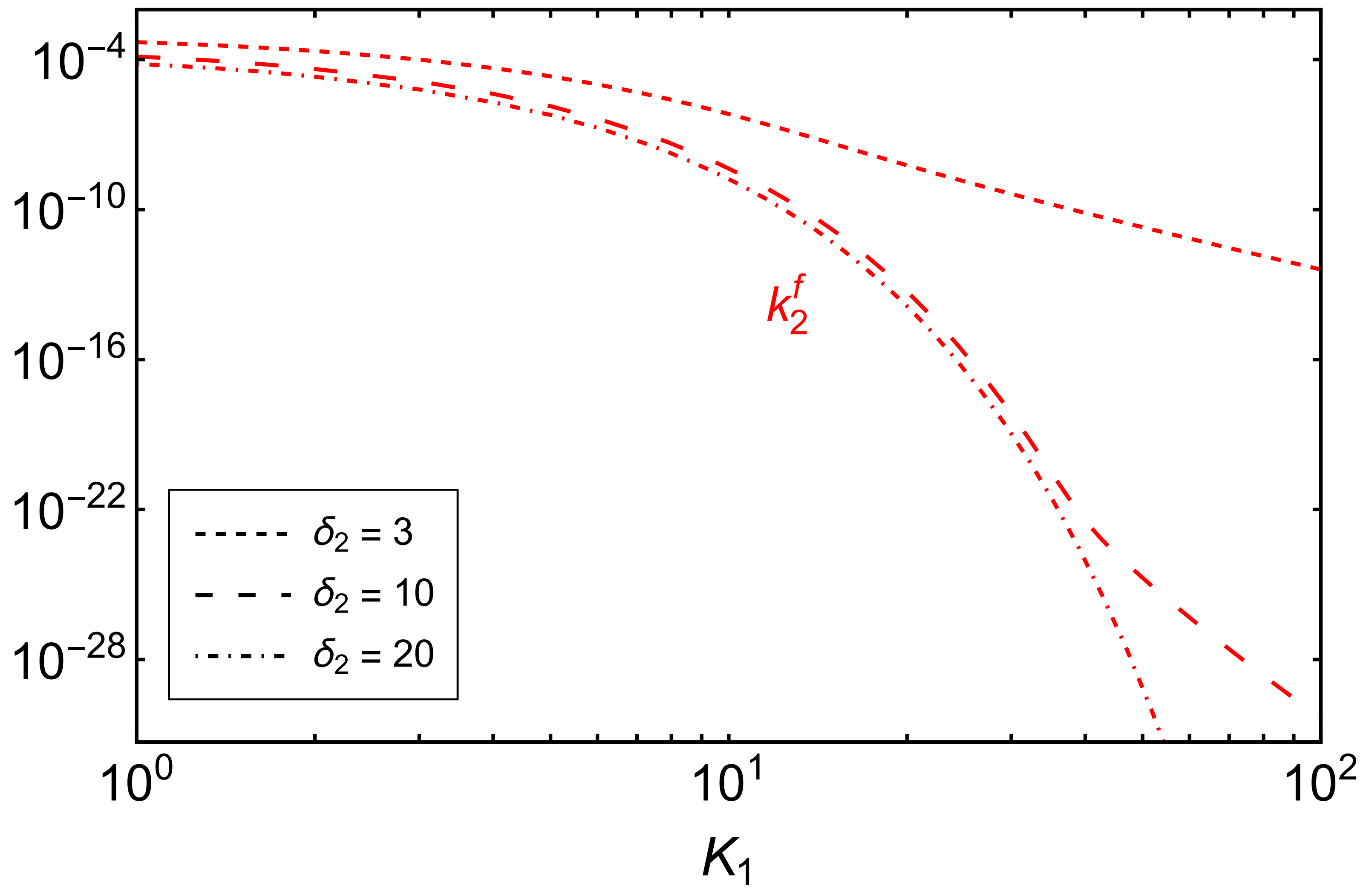


Strong dependence on

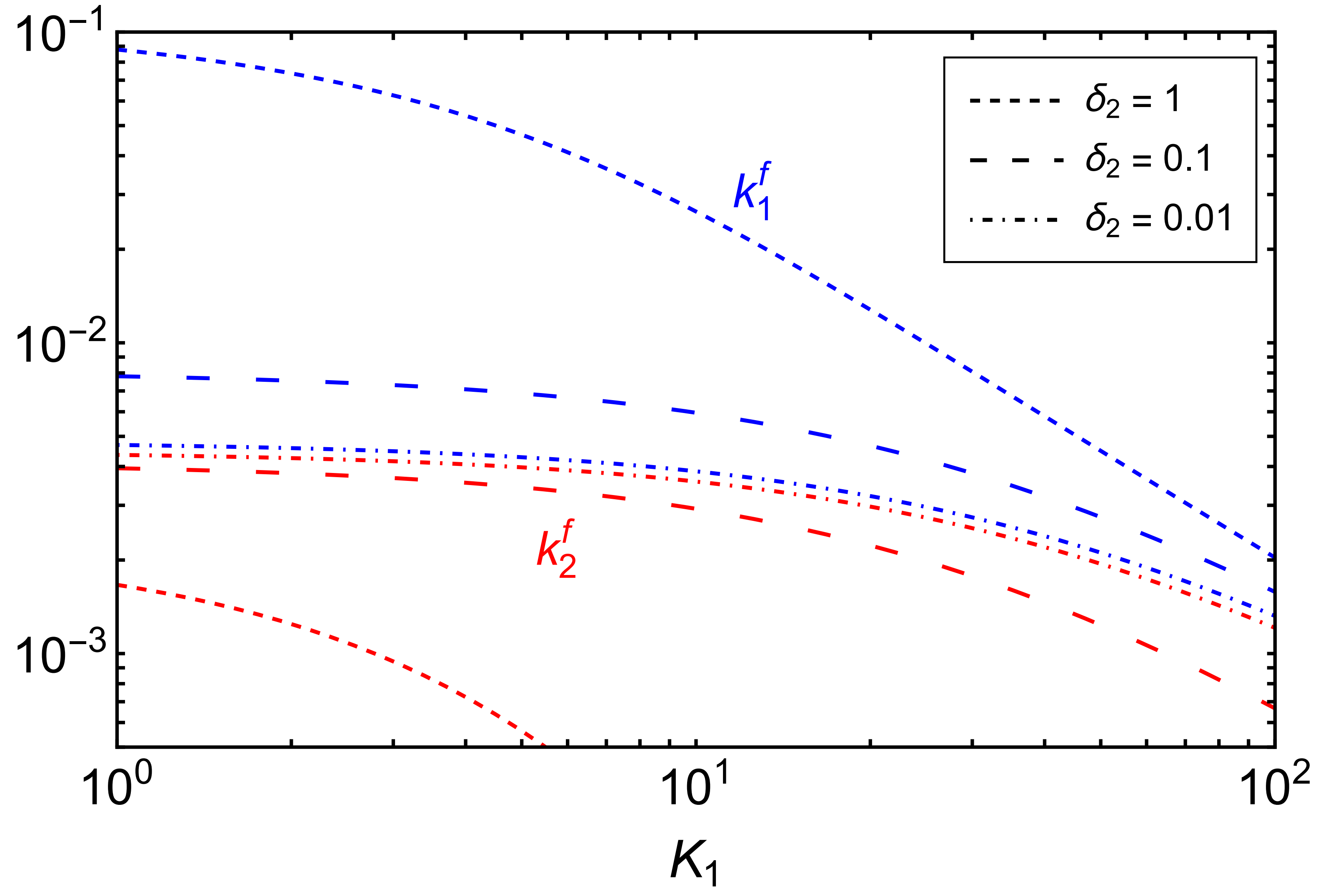
$$\delta_2 = \frac{M_2 - M_1}{M_1}$$



N_1 - dominated scenario?

$$N^f_{B-L} = \sum_i \epsilon_i k^f_i \quad , \quad i = 1,2$$

$$k^f_i = k_i(z = \infty) = -\int_{z_{in}\to 0}^{z_{fin}\to\infty} \frac{\mathrm{d}N_i}{\mathrm{d}z'} \mathrm{Exp}\left[\sum_i \int_{z'}^{z} W_i(z'')\mathrm{d}z''\right] \mathrm{d}z'$$



Strong dependence on

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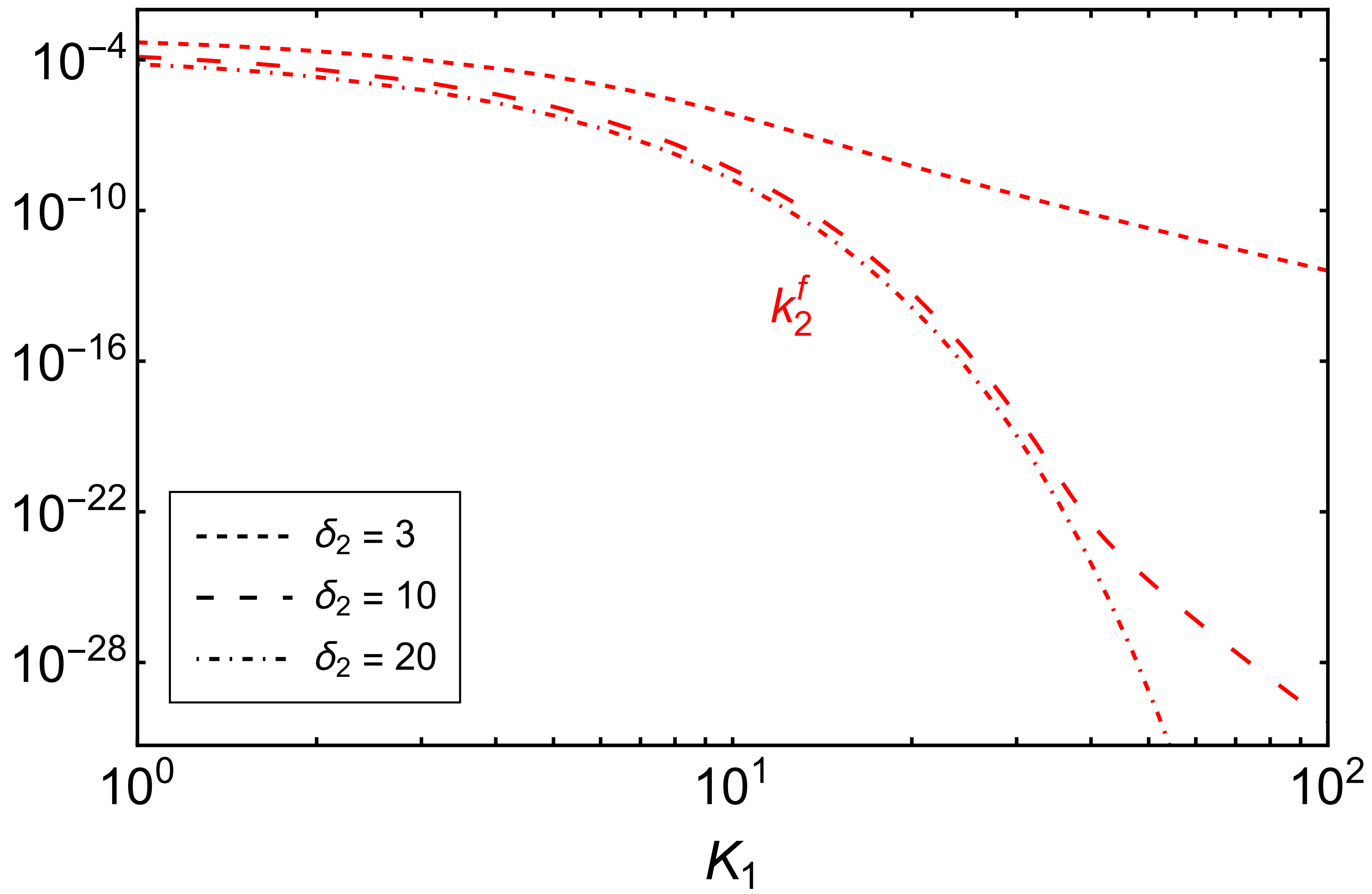
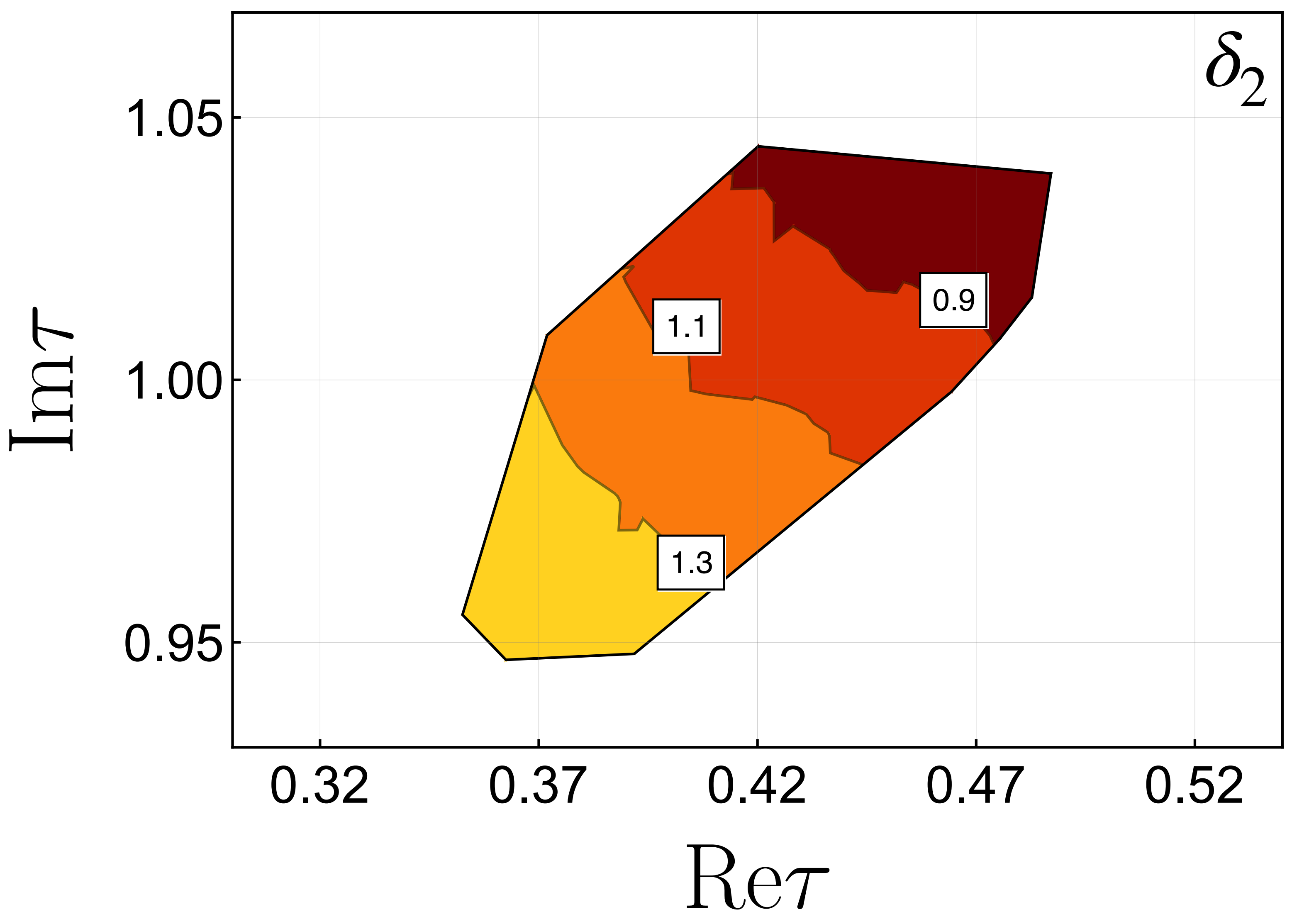
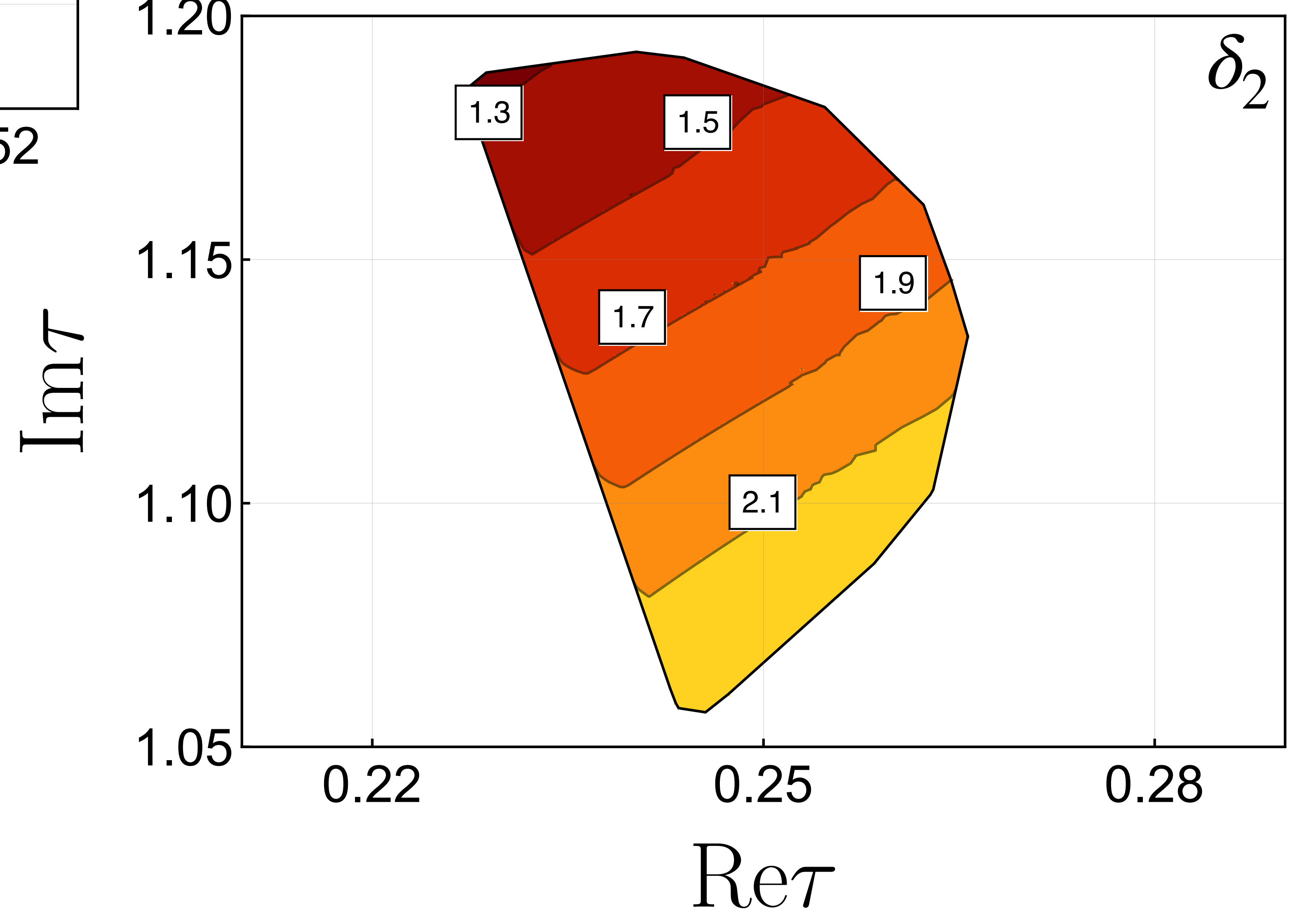
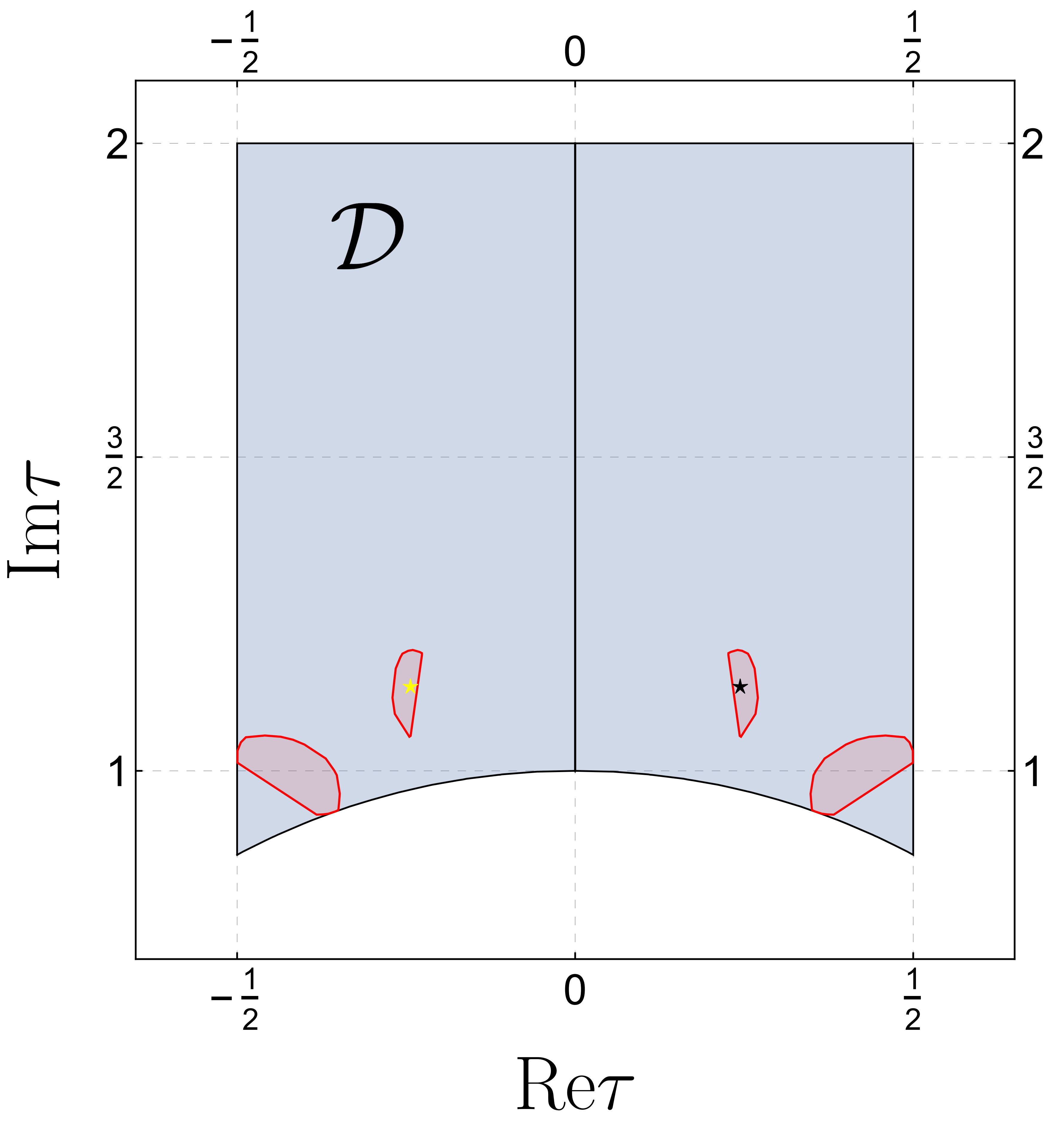


N_1 - dominated scenario?





3σ points



N_1 - dominated scenario?

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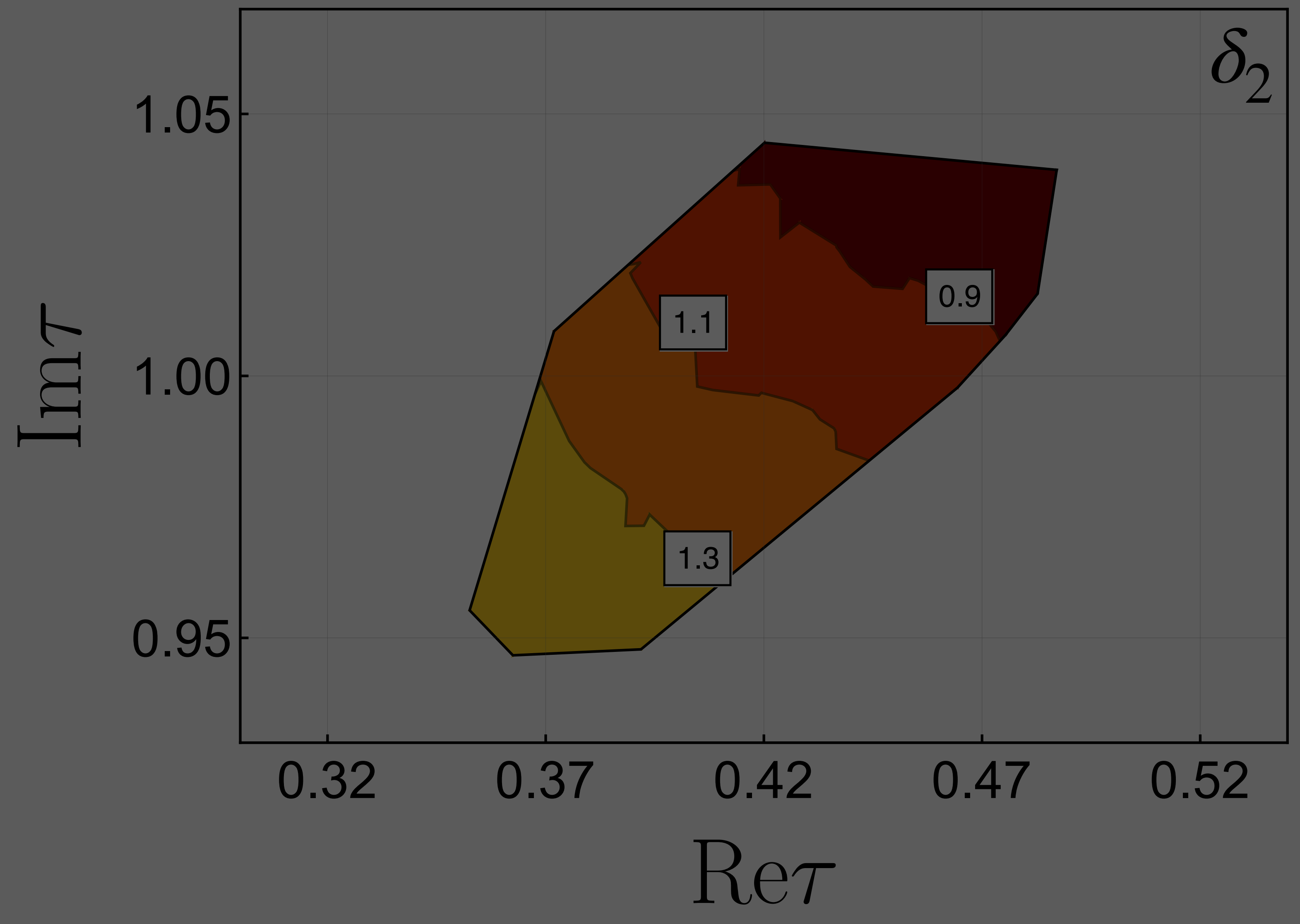
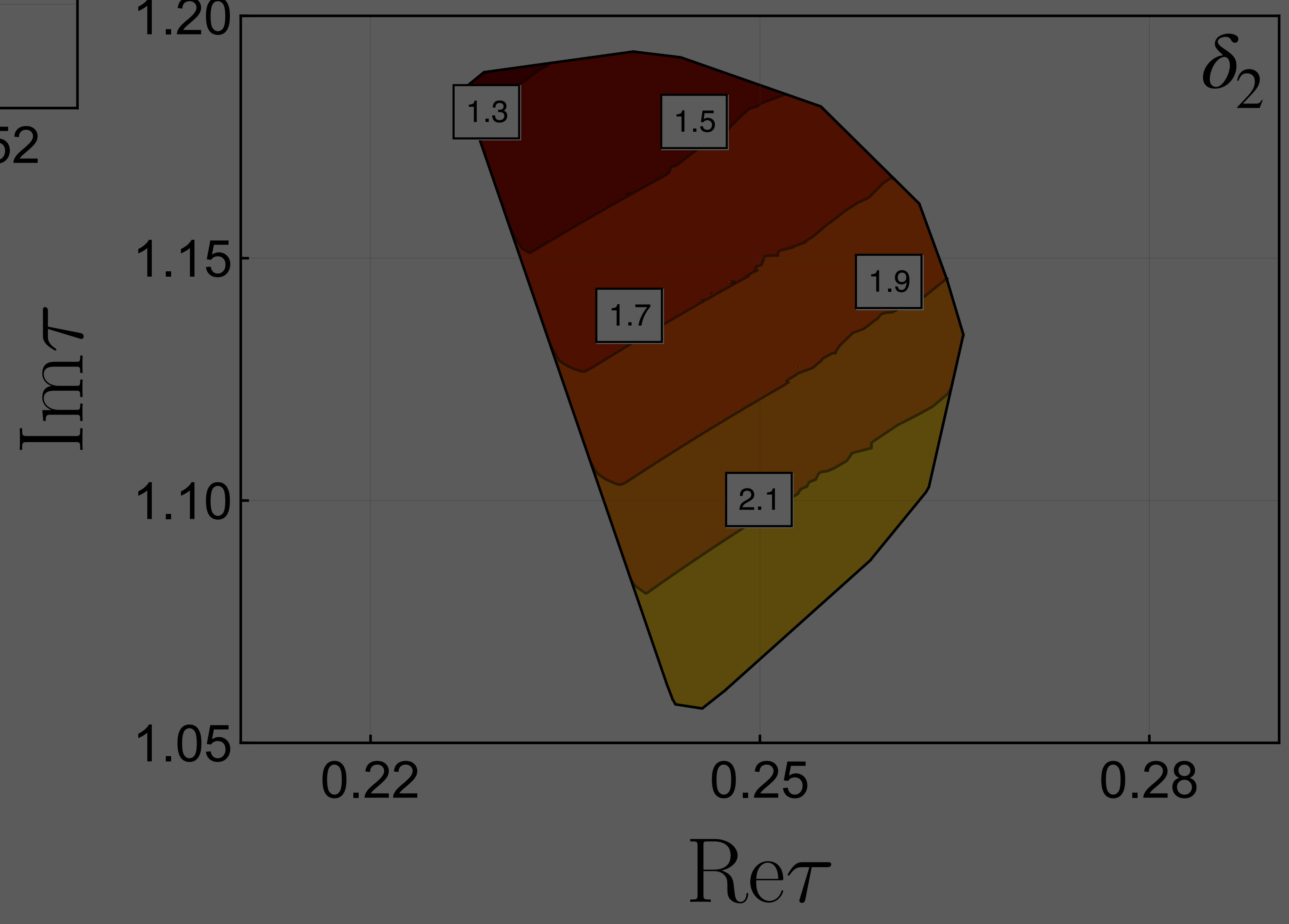
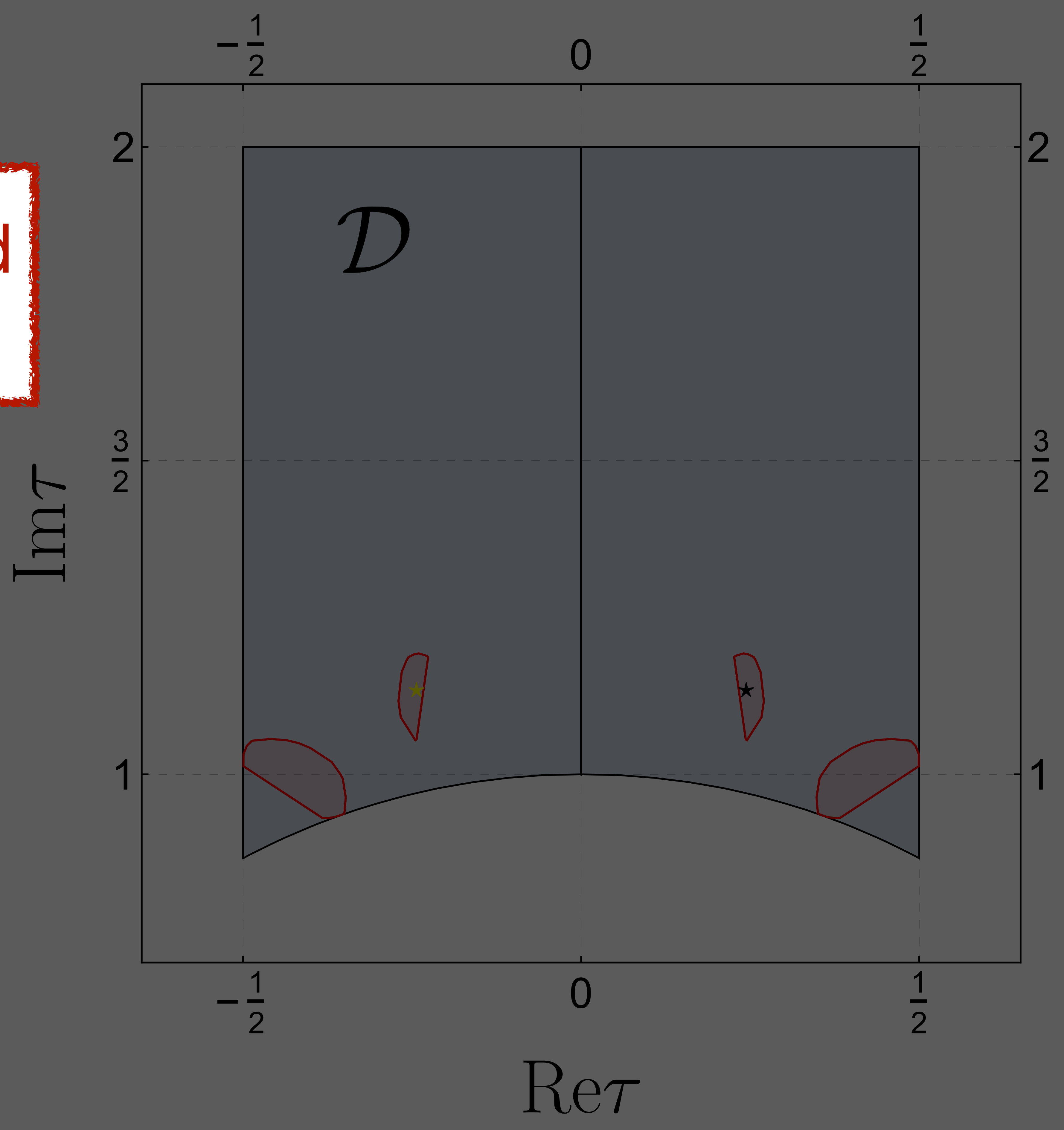


"Mild" N_1 - dominated scenario





Results

$$M_D = g v_u \begin{pmatrix} -(Y_2^2 - Y_1^2) + \frac{g''}{g}(Y_1^2 + Y_2^2) & 2Y_1Y_2 & \frac{g'}{g}(2Y_1Y_2) \\ 2Y_1Y_2 & (Y_2^2 - Y_1^2) + \frac{g''}{g}(Y_1^2 + Y_2^2) & -\frac{g'}{g}(Y_2^2 - Y_1^2) \end{pmatrix}_{\mathrm{RL}}$$

$$\mathscr{M}_R = \Lambda \begin{pmatrix} -(Y_2^2 - Y_1^2) + \lambda(Y_1^2 + Y_2^2) & 2Y_1Y_2 \\ 2Y_1Y_2 & (Y_2^2 - Y_1^2) + \lambda(Y_1^2 + Y_2^2) \end{pmatrix}_{\mathrm{RR}}$$

$$m_\nu = -M_D^T \mathscr{M}_R^{-1} M_D$$

Low-energy neutrino mixing and mass splittings will be mainly dictated by 5 parameters:

$g^2 v_u^2/\Lambda$, Reτ, Imτ, g'/g, g''/g, λ

Results

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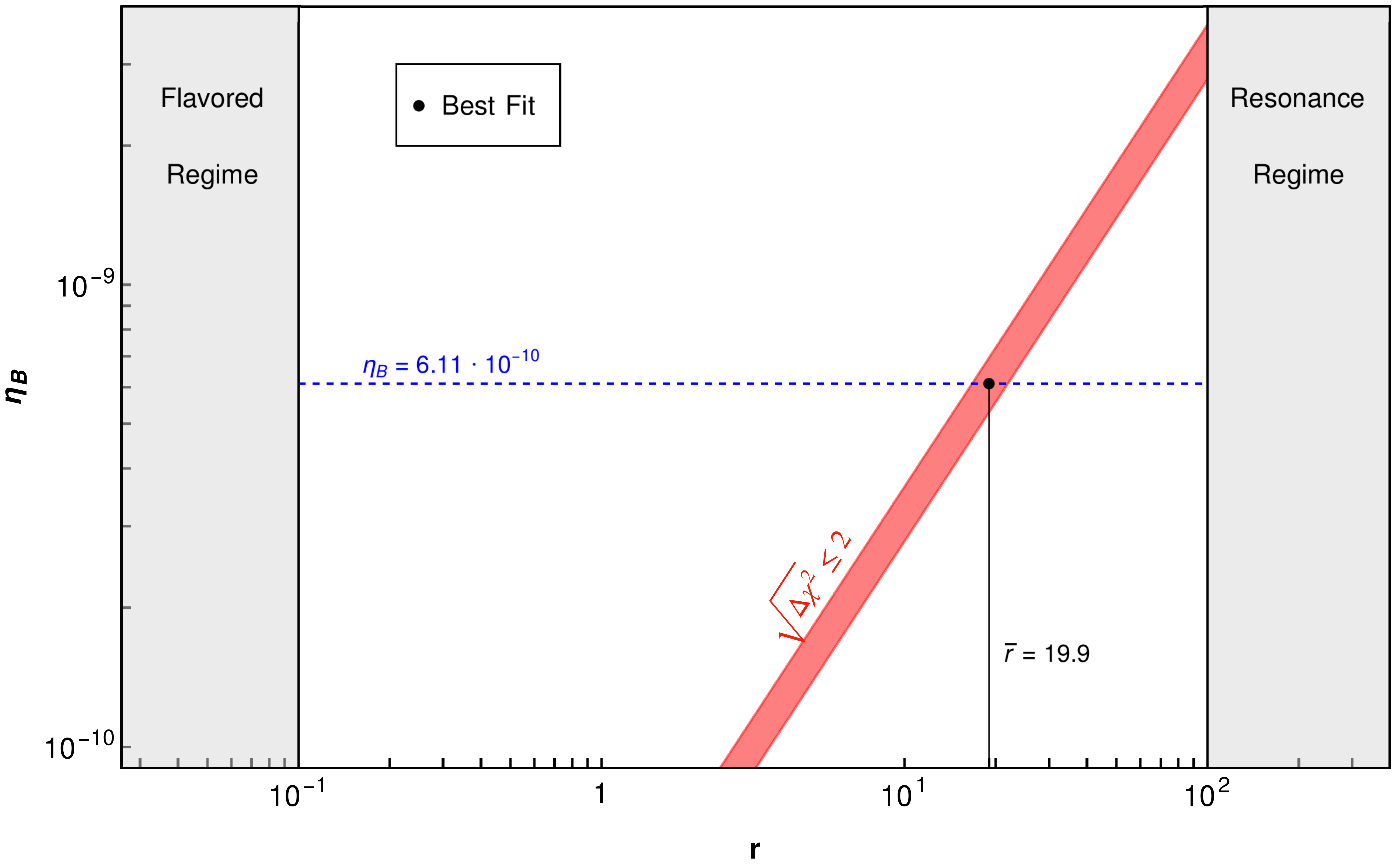

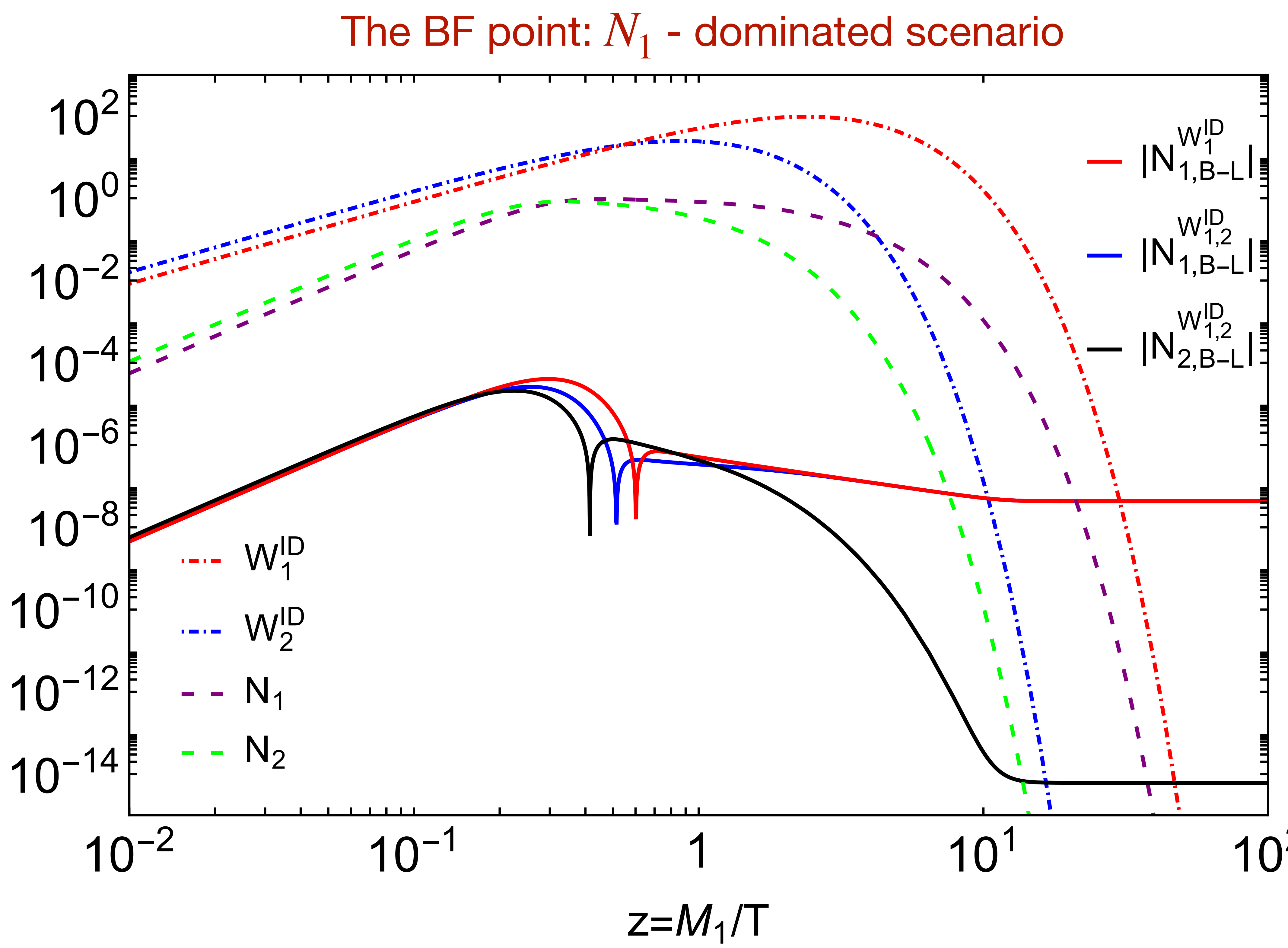

Conclusions and comments

Minimalist approach:

despite a small number of modular parameters and fields, the model provides the charged lepton masses, the neutrino masses as well the other low energy observables in great agreement with the measured values, without invoking *ad hoc* assignments

Boltzmann Equations:

a detailed analysis of the leptogenesis scenario is provided. The results are obtained solving numerically the full Boltzmann Equations, finding a realization for which the BAU is predicted inside the 3σ of the observed value. Such a realization, with $\bar{r} = 19.9$, preserve the *naturalness* of the model since it does not imply any further fine-tuning on the other parameters

MATEMATICA E FISICA
DIPARTIMENTO
DI ECCELLENZA

ROMA TRE
UNIVERSITÀ DEGLI STUDI

INFN
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Thank you!

Minimal seesaw and leptogenesis with the smallest modular finite group
JHEP 05 (2024), 020

S. Marciano D. Meloni M. Parriciatu

Prague, 19/07/2024

BACKUP SLIDES

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Smallest modular finite group

The Model in a nutshell

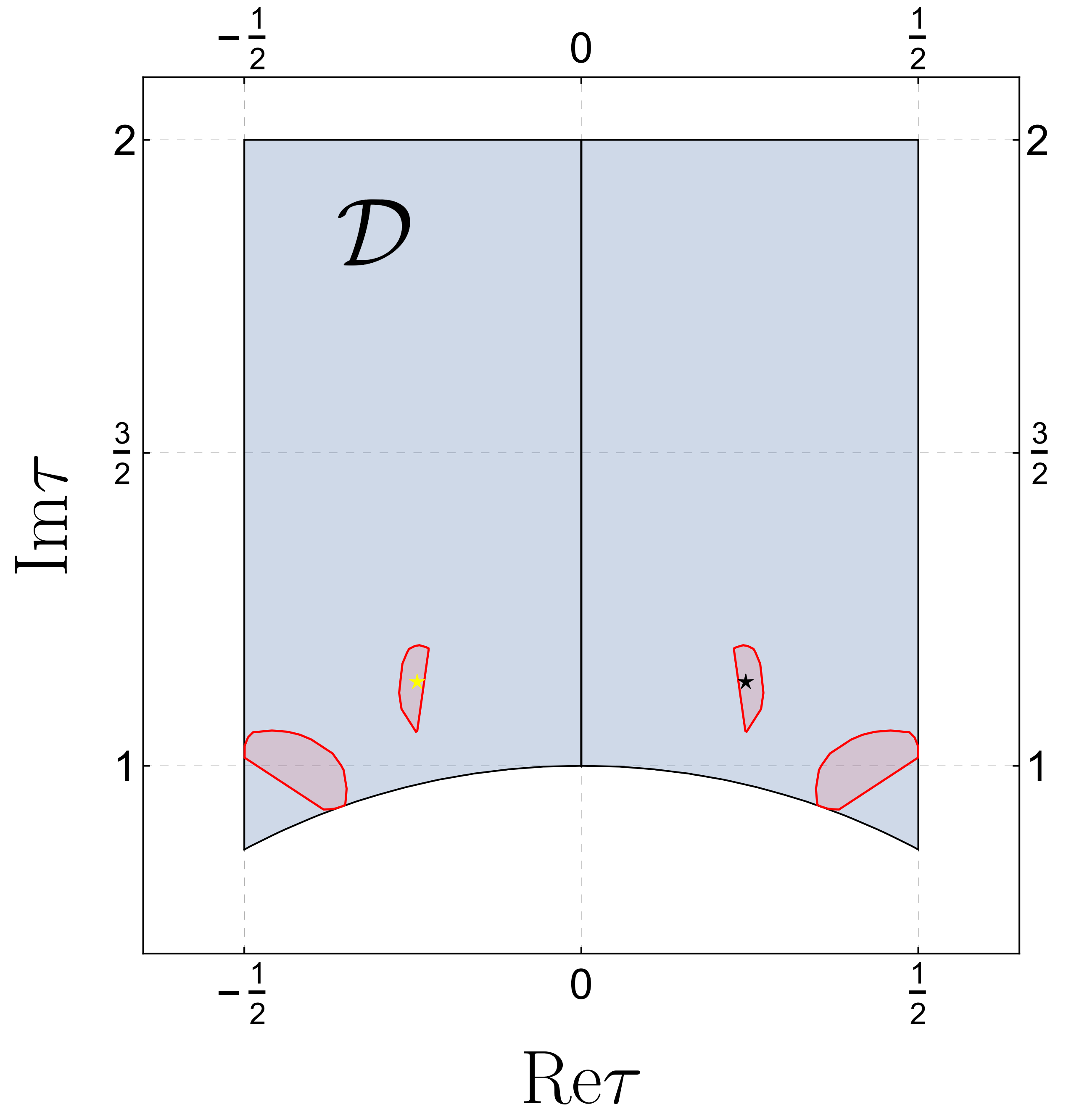
	E_1^c	E_2^c	E_3^c	D_ℓ	ℓ_3	$H_{d,u}$	N^c
$SU(2)_L\times U(1)_Y$	$(\mathbf{1},+1)$	$(\mathbf{1},+1)$	$(\mathbf{1},+1)$	$(\mathbf{2},-1/2)$	$(\mathbf{2},-1/2)$	$(\mathbf{2},\mp 1/2)$	$(\mathbf{1},0)$
$\Gamma_2 \cong S_3$	$\mathbf{1}$	$\mathbf{1'}$	$\mathbf{1'}$	$\mathbf{2}$	$\mathbf{1'}$	$\mathbf{1}$	$\mathbf{2}$
k_I	4	0	-2	2	2	0	2

$$\mathscr{W}_e^H = \alpha E_1^c H_d (D_\ell Y_{\mathbf{2}}^{(3)})_{\mathbf{1}} + \beta E_2^c H_d (D_\ell Y_{\mathbf{2}})_{\mathbf{1'}} + \gamma E_3^c H_d \ell_3 + \alpha_D E_1^c H_d \ell_3 Y_{\mathbf{1'}}^{(3)},$$

$$\mathscr{W}_\nu = g H_u N^c D_\ell Y_{\mathbf{2}}^{(2)} + g' H_u (N^c Y_{\mathbf{2}}^{(2)})_{\mathbf{1'}} \ell_3 + g'' H_u (N^c D_\ell)_{\mathbf{1}} Y_{\mathbf{1}}^{(2)} +$$
$$+ \Lambda[(N^c N^c)_{\mathbf{2}} Y_{\mathbf{2}}^{(2)} + \lambda (N^c N^c)_{\mathbf{1}} Y_{\mathbf{1}}^{(2)}]$$

Parameter	Best-fit value and 1σ range	
$\Delta m^2_{\rm sol}/(10^{-5}\ {\rm eV}^2)$	$7.41^{+0.21}_{-0.20}$	
	NO	**IO**
$\lvert\Delta m^2_{\rm atm}\rvert/(10^{-3}\ {\rm eV}^2)$	$2.507^{+0.026}_{-0.027}$	$2.486^{+0.025}_{-0.028}$
$r \equiv \Delta m^2_{\rm sol}/\lvert\Delta m^2_{\rm atm}\rvert$	0.0295 ± 0.0008	0.0298 ± 0.0008
$\sin^2\theta_{12}$	$0.303^{+0.012}_{-0.012}$	$0.303^{+0.012}_{-0.011}$
$\sin^2\theta_{13}$	$0.02225^{+0.00056}_{-0.00059}$	$0.0223^{+0.00058}_{-0.00058}$
$\sin^2\theta_{23}$	$0.451^{+0.019}_{-0.016}$	$0.569^{+0.016}_{-0.021}$
m_e/m_μ	0.0048 ± 0.0002	
m_μ/m_τ	0.0565 ± 0.0045	

I. Esteban, M. C. Gonzalez-Garcia, M. Maltoni, T. Schwetz, and A. Zhou, "The fate of hints: updated global analysis of three-flavor neutrino oscillations," KHEP 09 (2020) 178, 2007.14792 [hep-ph]



Altarelli-Blankenburg

$$d_{\rm FT} = \frac{\sum_i \left|\frac{{\rm par}_i}{\delta {\rm par}_i}\right|}{\sum_i \left|\frac{{\rm obs}_i}{\sigma_i}\right|}$$

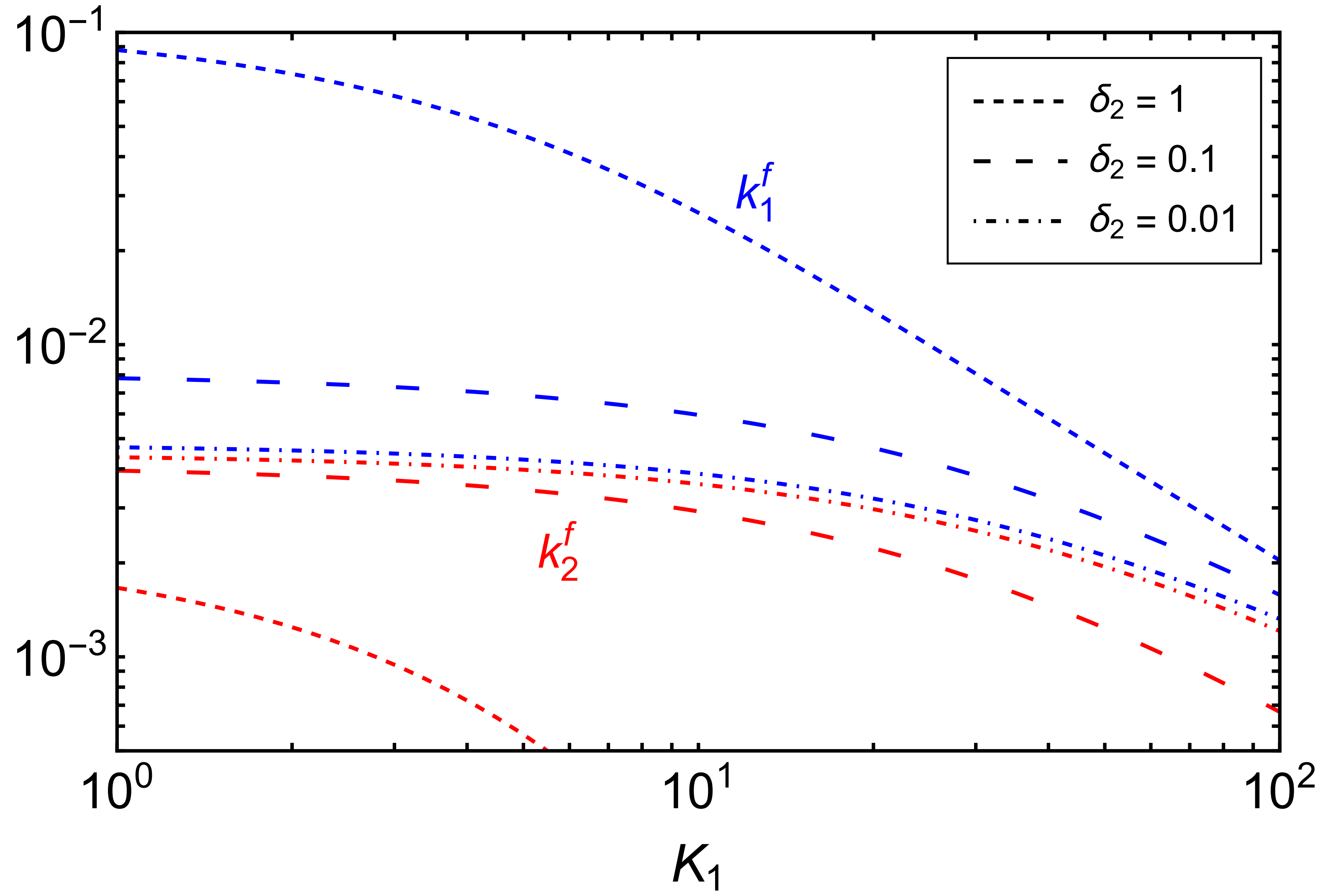
★(-) ★(+)	Best-fit and 1σ range
${\rm Re}\,\tau$	$\pm 0.244^{+0.012}_{-0.067}$
${\rm Im}\,\tau$	$1.132^{+0.027}_{-0.297}$
β/α	$0.92^{+0.85}_{-0.03}$
γ/α	$-1.20^{+0.06}_{-2.14}$
$\log_{10}(\alpha_D/\alpha)$	$-13.4^{+13.2}_{-76.3}$
g'/g	$2.76^{+0.21}_{-0.23}$
g''/g	$-2.53^{+0.13}_{-0.03}$
$\log_{10}(\lvert\lambda\rvert)$	$-12.2^{+10.9}_{-59.2}$
$v_d\,\alpha$, [GeV]	$1.08^{+0.06}_{-0.69}$
$v_u^2\,g^2/\Lambda$ [eV]	$3.46^{+0.55}_{-1.65}$
$\sin^2\theta_{12}$	$0.305^{+0.011}_{-0.011}$
$\sin^2\theta_{13}$	$0.0221^{+0.0006}_{-0.0005}$
$\sin^2\theta_{23}$	$0.448^{+0.014}_{-0.016}$
r	$0.0296^{+0.0006}_{-0.0008}$
m_e/m_μ	$0.0048^{+0.0001}_{-0.0002}$
m_μ/m_τ	$0.0574^{+0.0032}_{-0.0050}$
Ordering	**NO**
$J_{\rm CP}$	$-0.018^{+0.002}_{-0.002}$
α_1/π	0
α_2/π	$\pm 0.112^{+0.792}_{-0.014}$
m_1 [meV]	0
m_2 [meV]	$8.620^{+0.095}_{-0.123}$
m_3 [meV]	$50.806^{+0.016}_{-0.021}$
$\sum_i m_i$ [eV]	$0.0594^{+0.0001}_{-0.0001}$
$\lvert m_{\beta\beta}\rvert$ [meV]	$3.61^{+0.09}_{-0.09}$
$m_\beta^{\rm eff}$ [meV]	$8.90^{+0.10}_{-0.09}$
$d_{\rm FT}$	3.03
$\chi^2_{\rm min}$	0.98

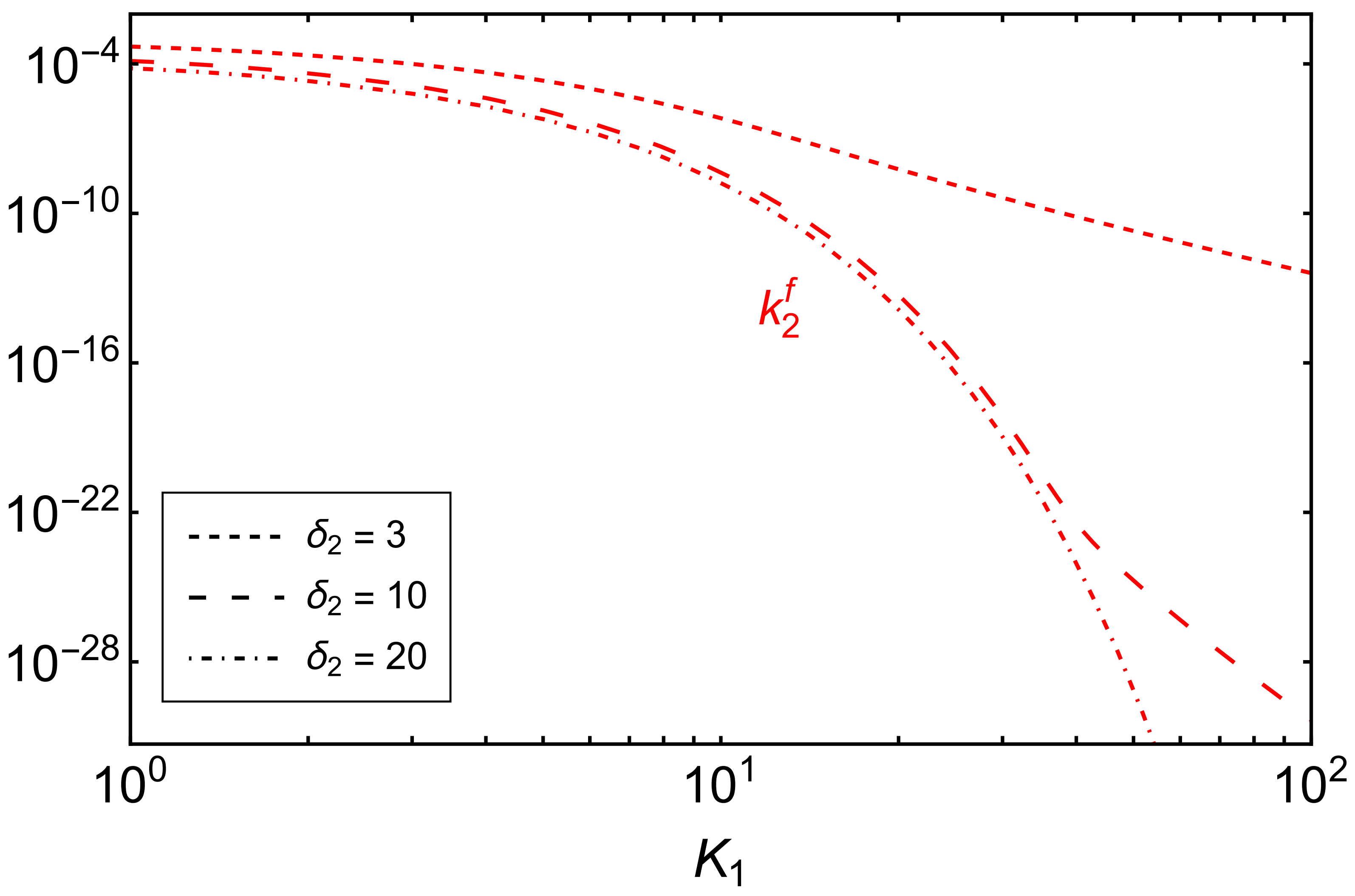
N_1 - dominated scenario?

$$N^f_{B-L} = \sum_i \epsilon_i k^f_i \quad , \quad i = 1,2$$

$$k^f_i = k_i(z=\infty) = -\int_{z_{in}\to 0}^{z_{fin}\to\infty} \frac{\mathrm{d}N_i}{\mathrm{d}z'} \mathrm{Exp}\left[\sum_i \int_{z'}^{z} W_i(z'')\mathrm{d}z''\right] \mathrm{d}z'$$

Strong dependence on $\delta_2 = \dfrac{M_2 - M_1}{M_1}$





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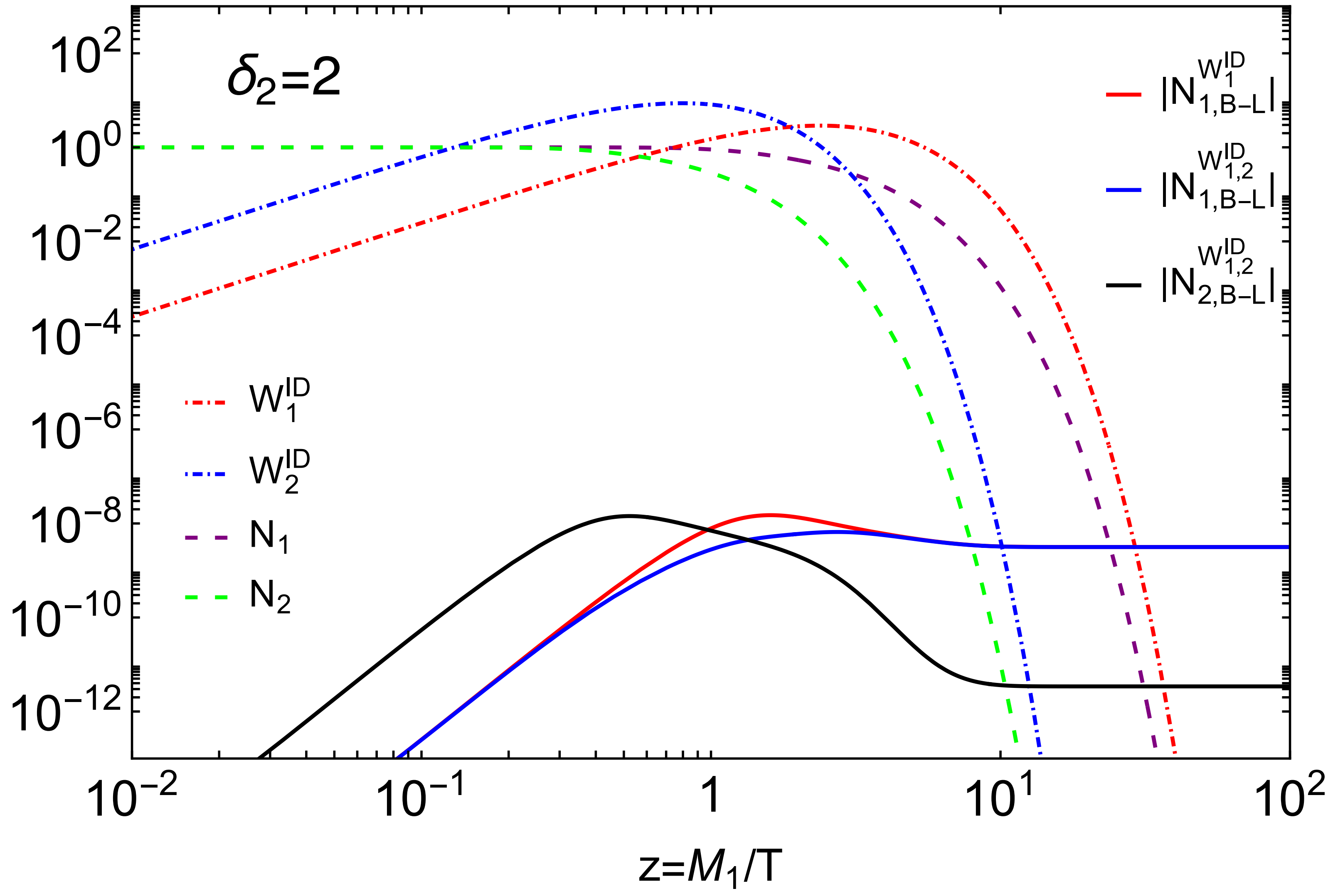

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