



# DATA DRIVEN FLAVOUR MODEL

Luca Merlo

Based on: Arias-Aragón, Bouthelier-Madrid, Cano & Merlo,  
Data Driven Flavour Model, arXiv: 2003.05941

**ICHEP 2020 | PRAGUE**

40<sup>th</sup> INTERNATIONAL CONFERENCE  
ON HIGH ENERGY PHYSICS

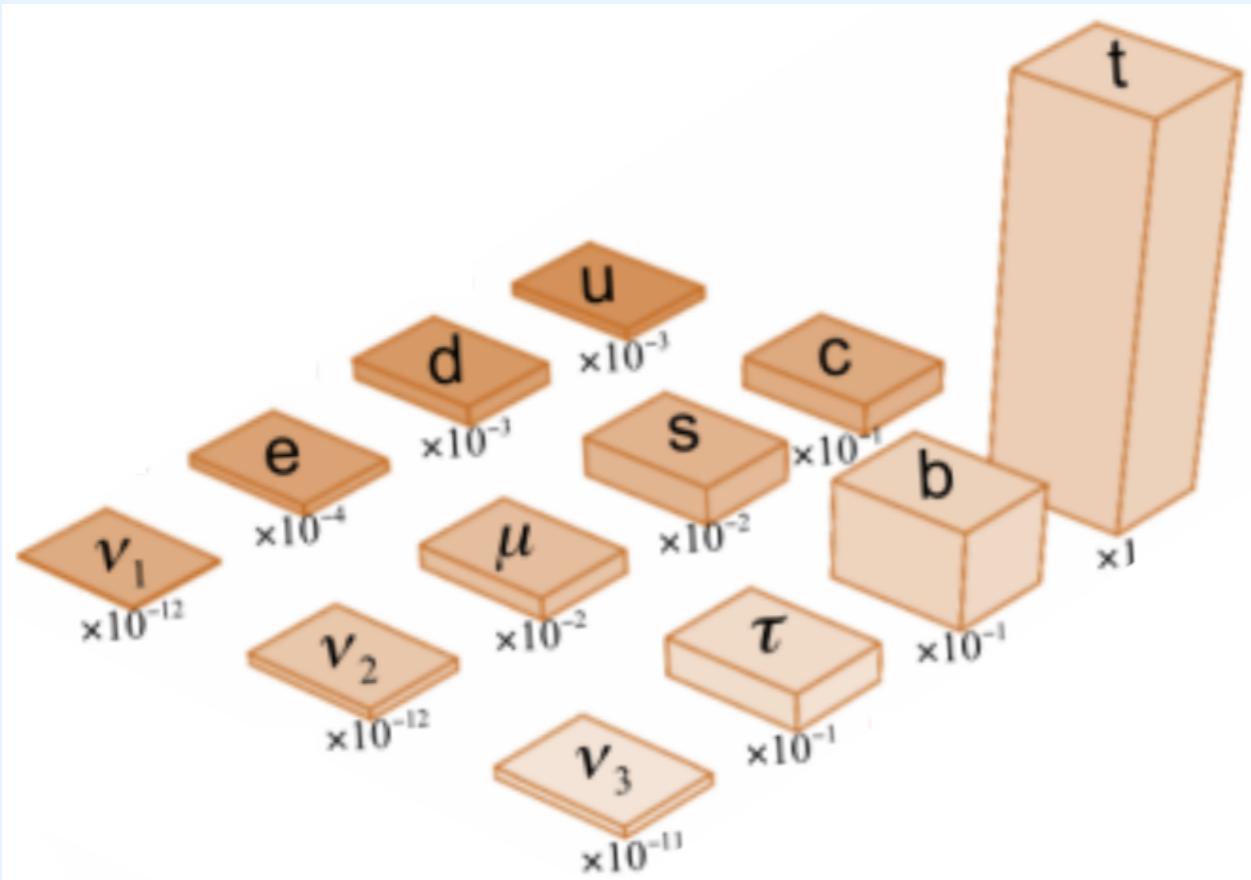
VIRTUAL  
CONFERENCE

28 JULY - 6 AUGUST 2020

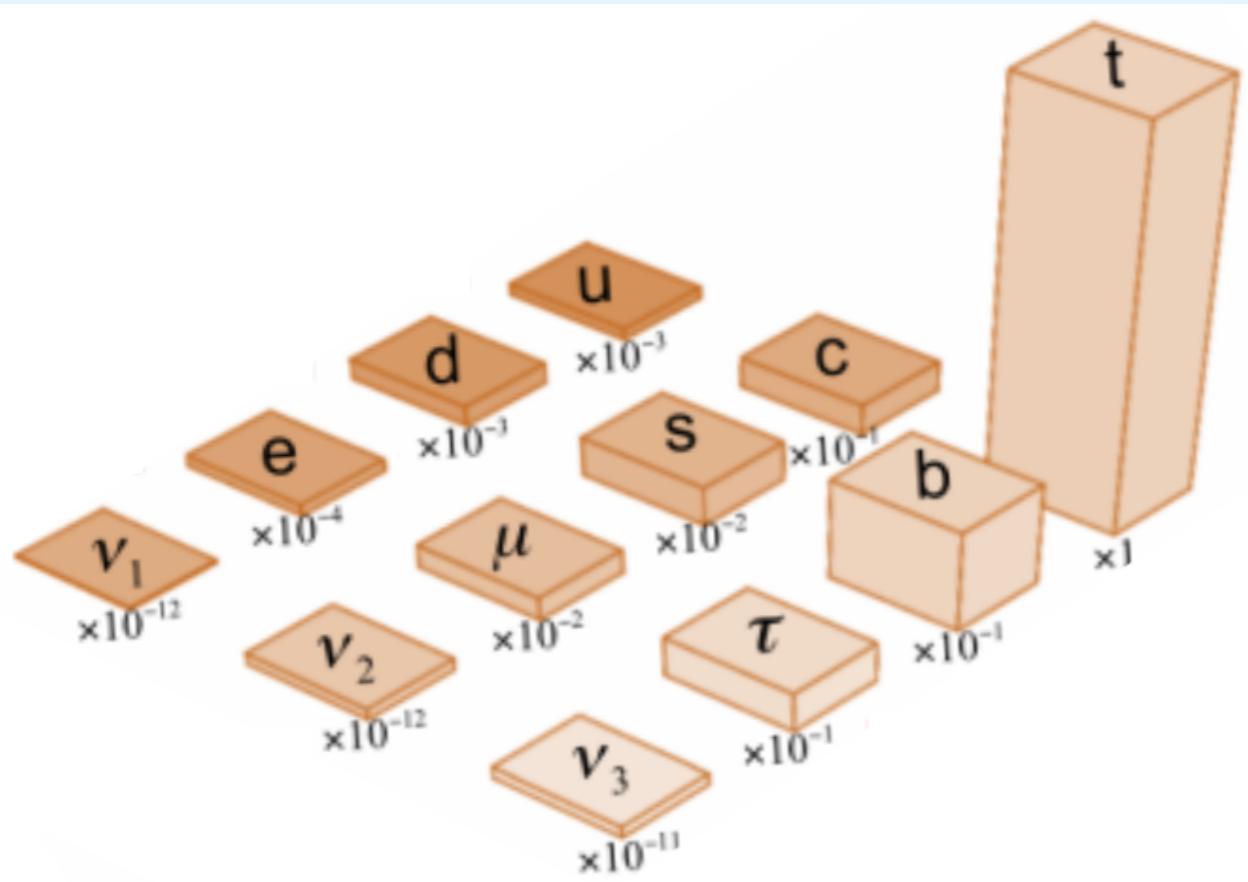
PRAGUE, CZECH REPUBLIC



# The Flavour Puzzle



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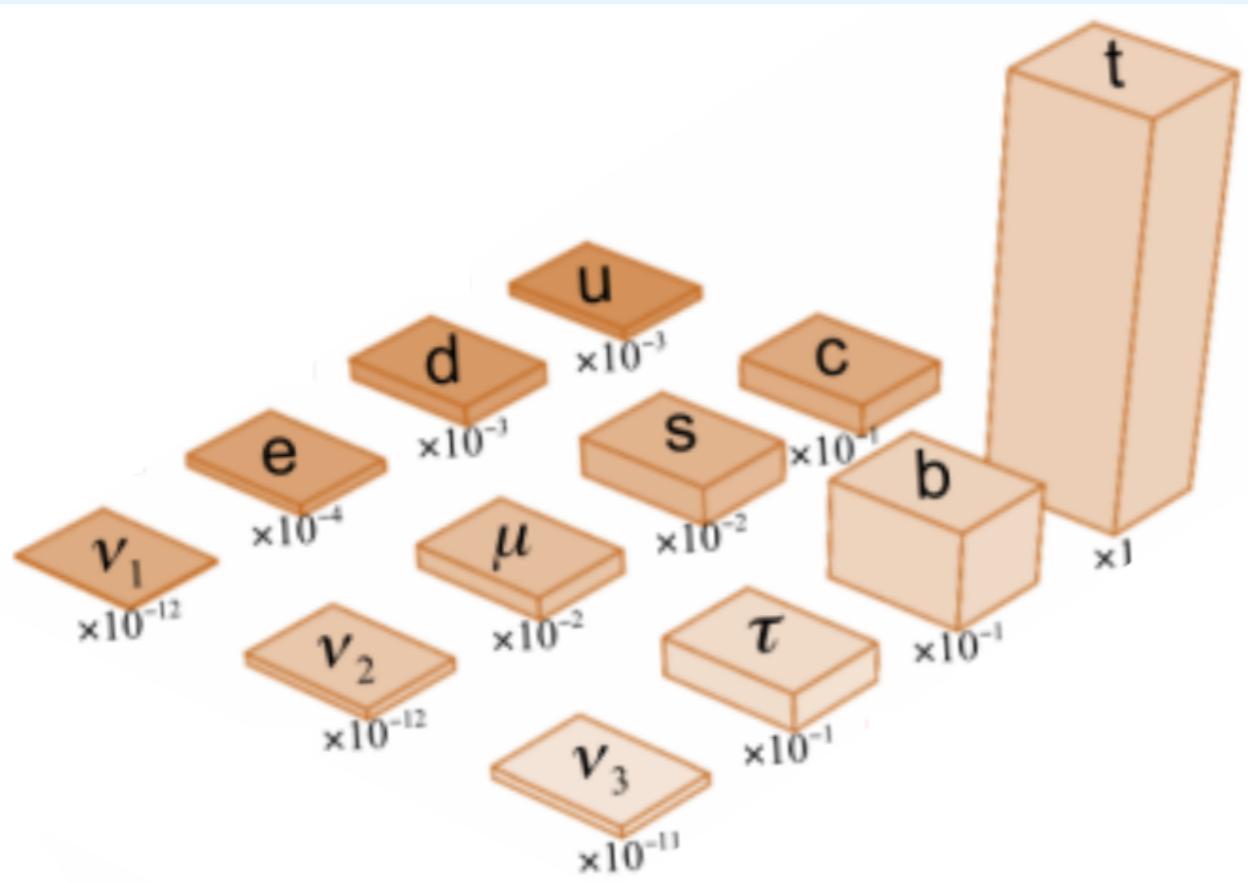


$$|V_{CKM}| \simeq \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$



$$|U_{PMNS}| \simeq \begin{pmatrix} 0.8 & 0.5 & 0.2 \\ 0.4 & 0.5 & 0.7 \\ 0.4 & 0.5 & 0.7 \end{pmatrix}$$

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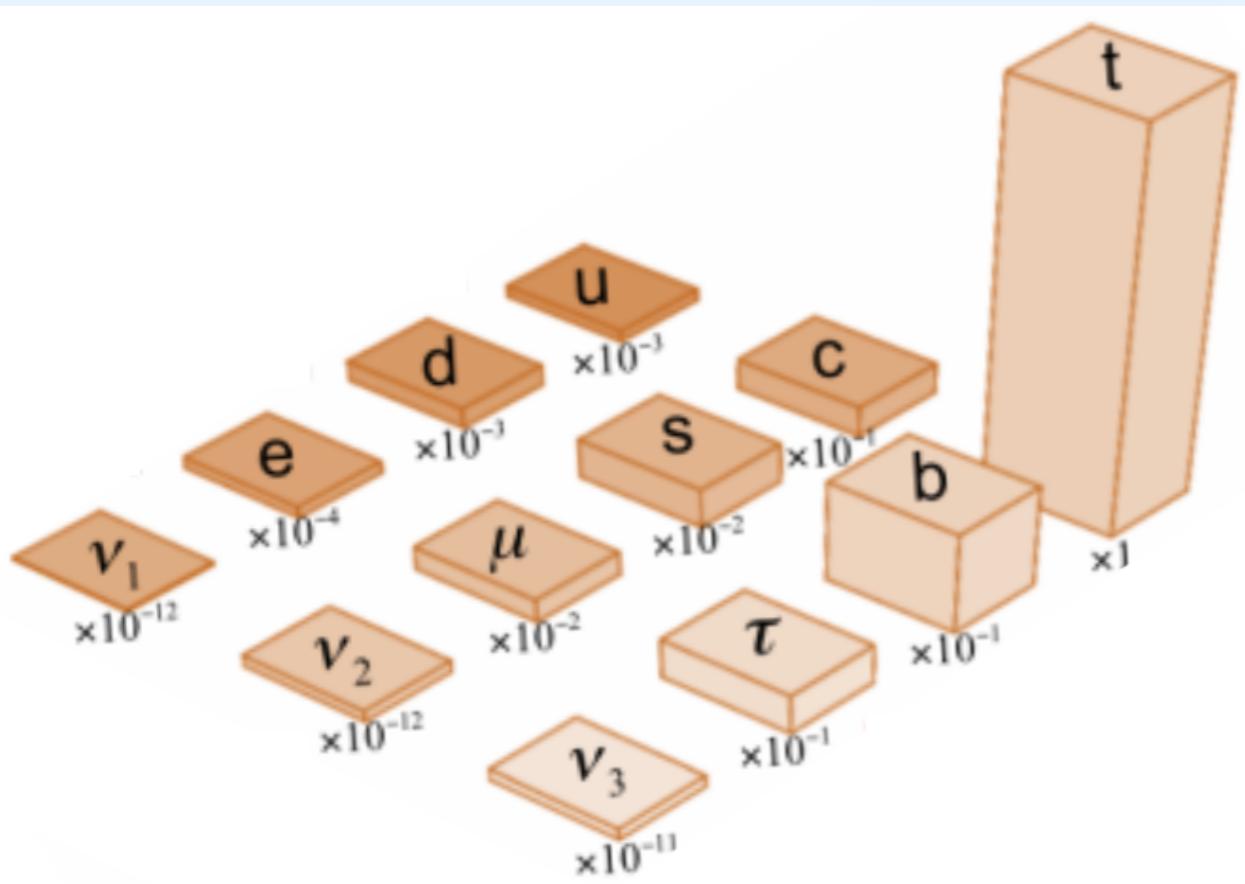
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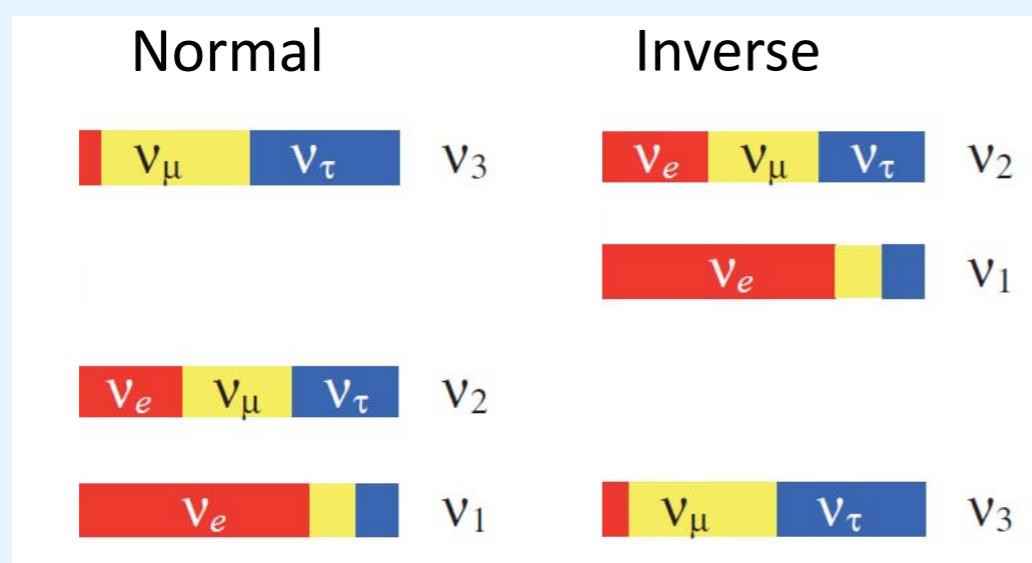
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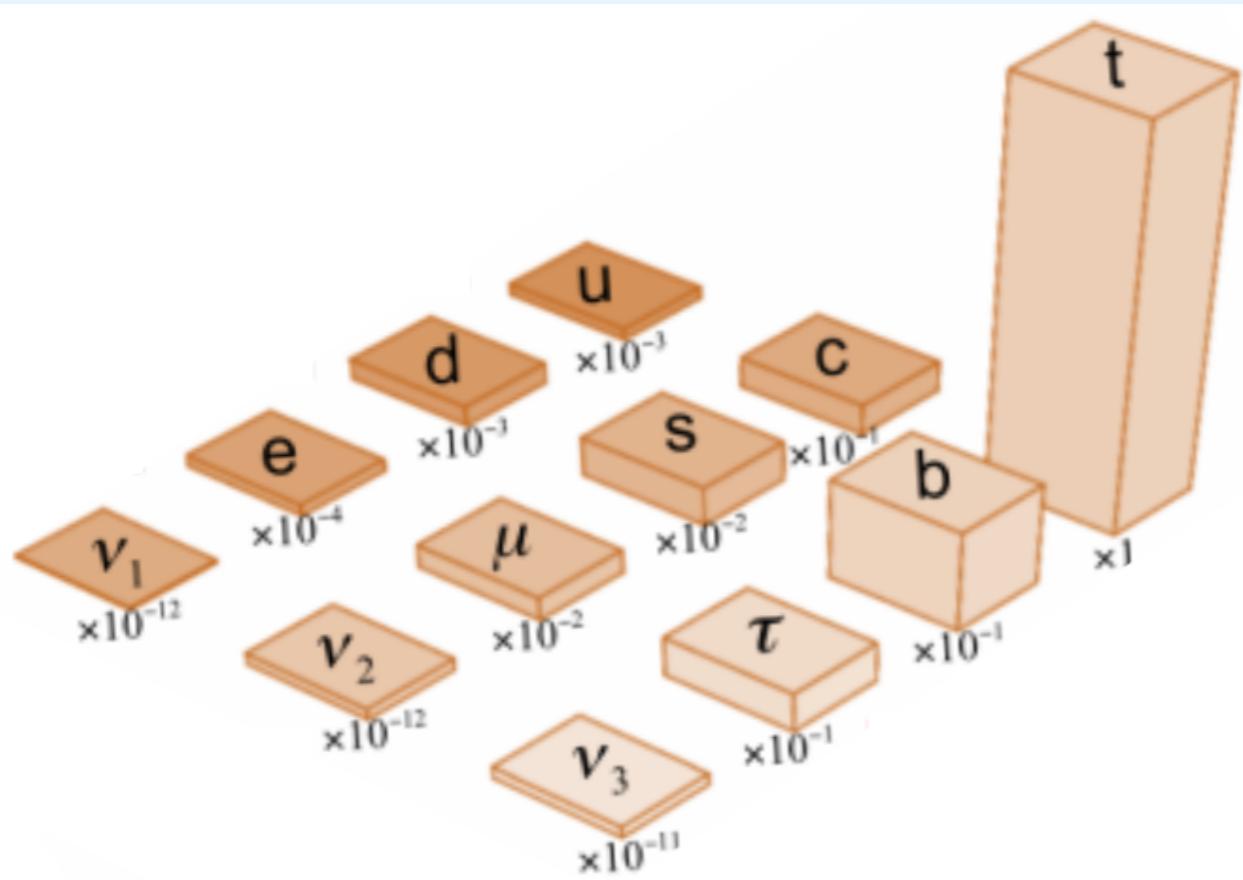
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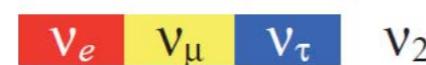
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Normal



Inverse



Nature of Neutrinos:

Majorana  $\nu^C = \nu$

Dirac  $\nu^C \neq \nu$

# Solutions?

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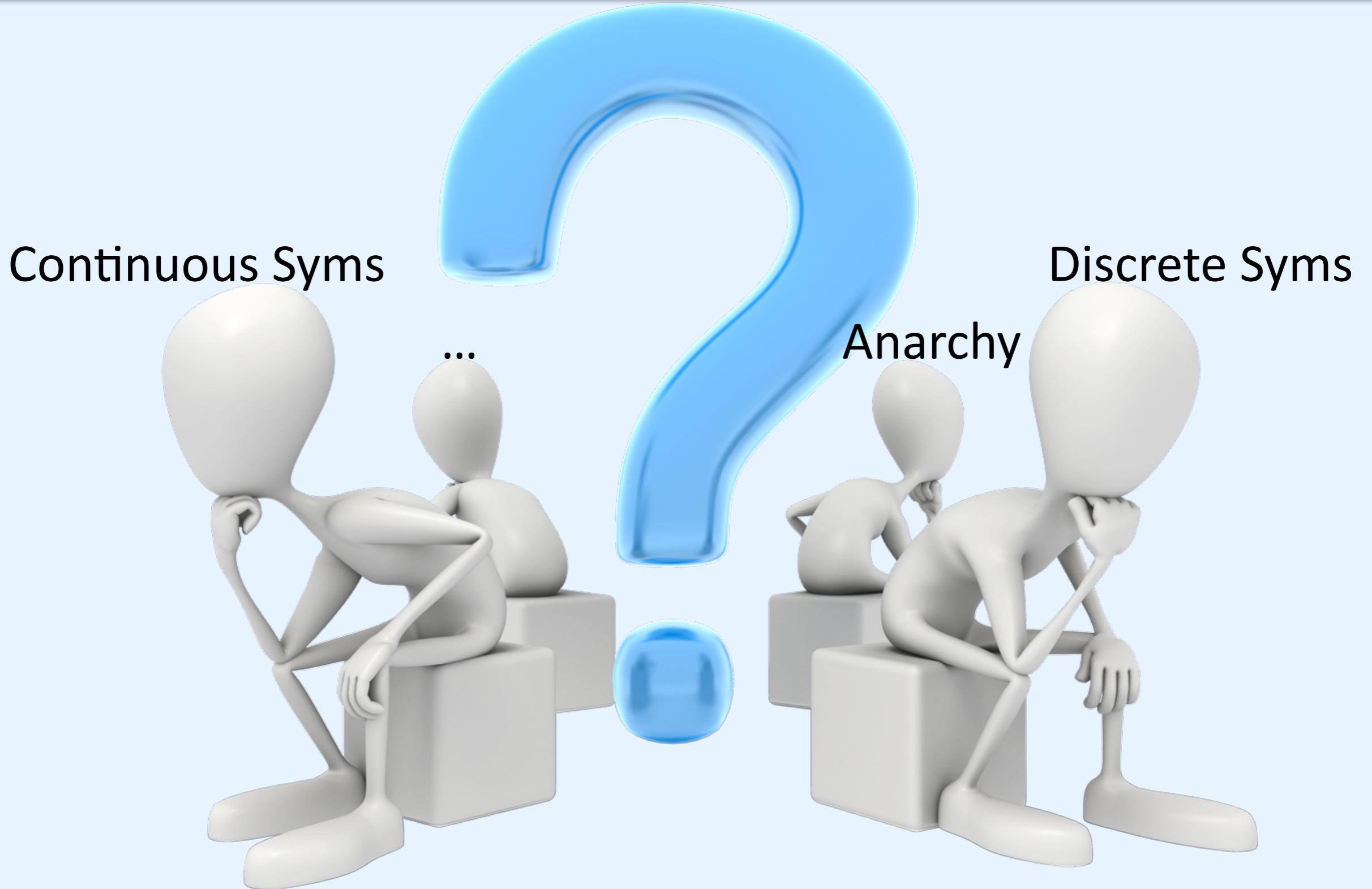
Continuous Syms

Discrete Syms

Anarchy



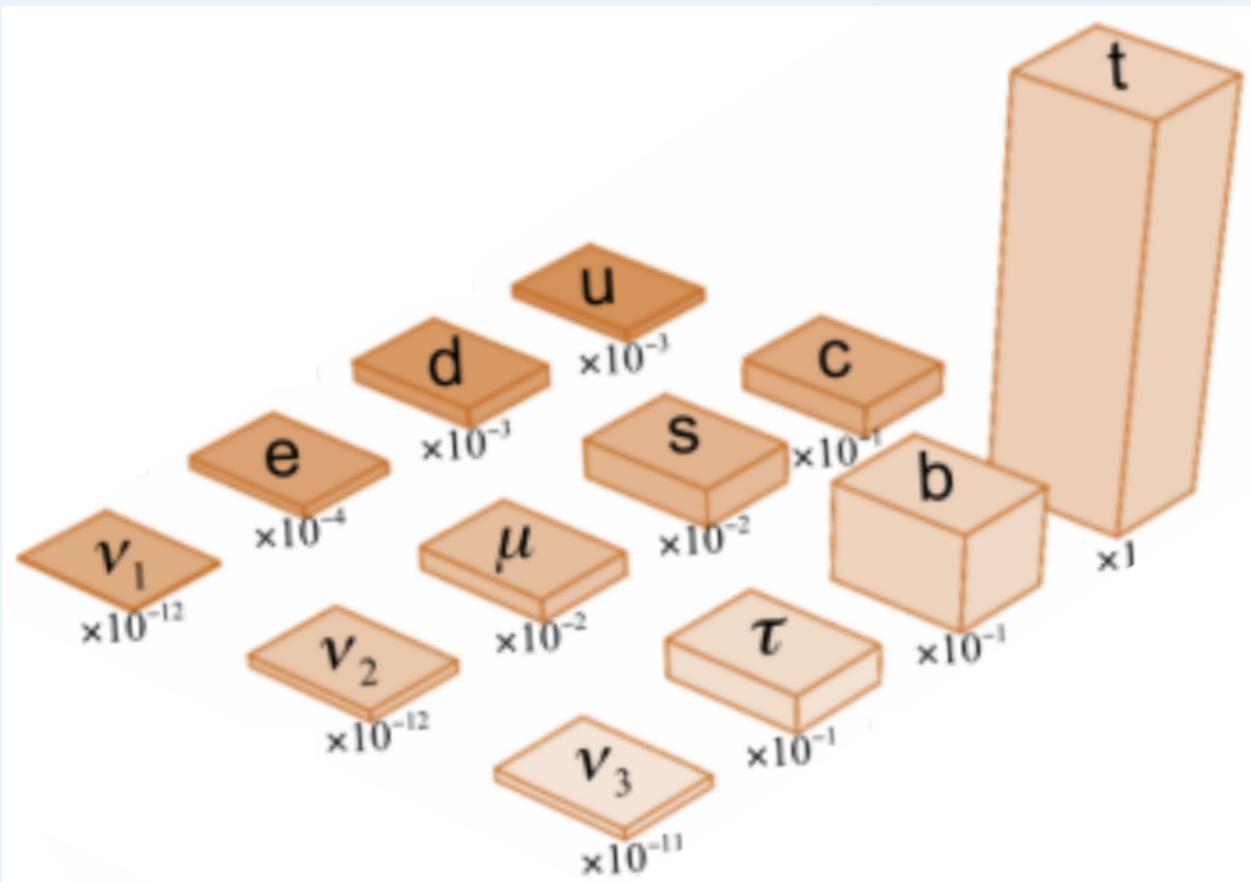
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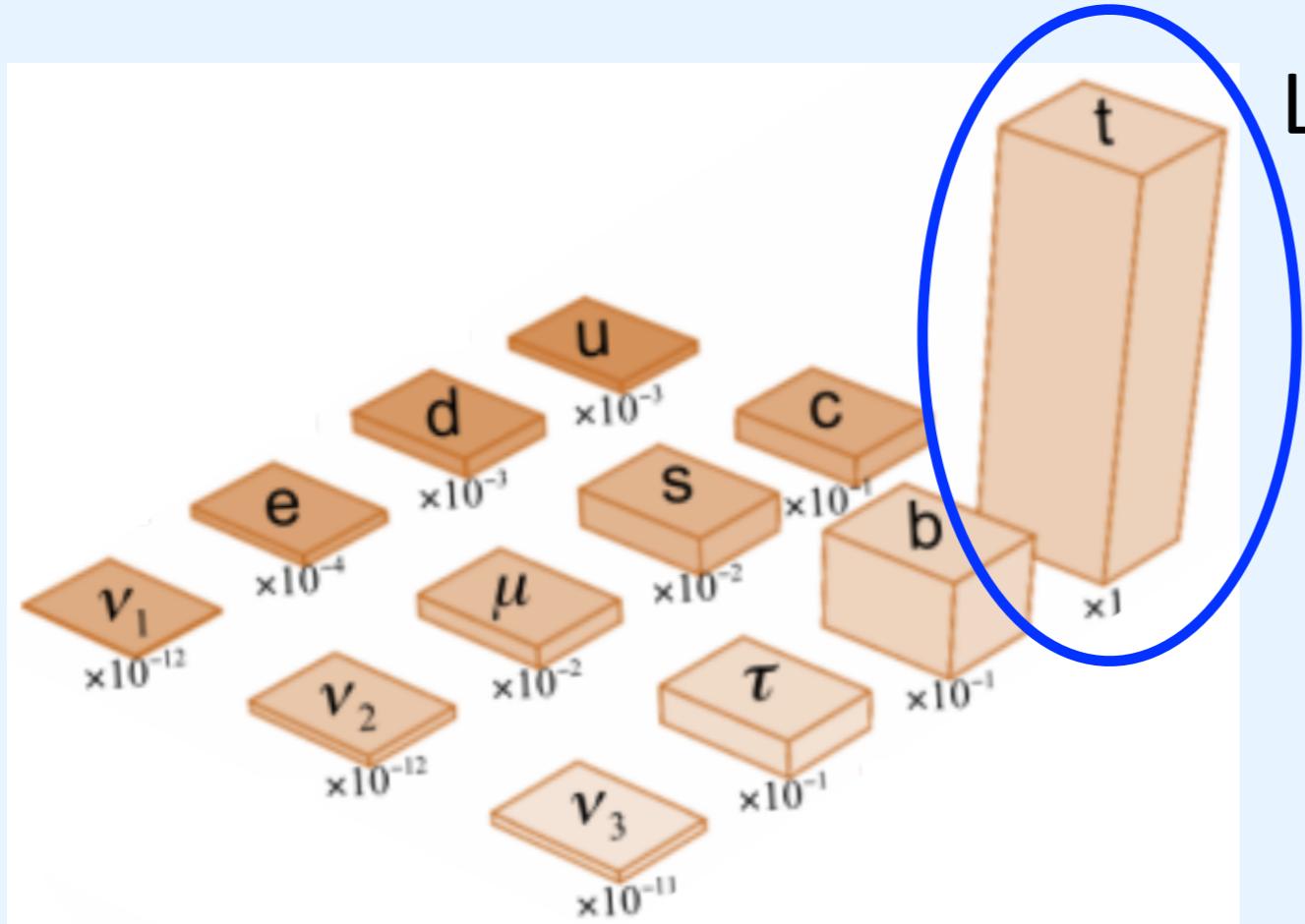
Common aspect: top-down approach!

# Bottom-up Approach

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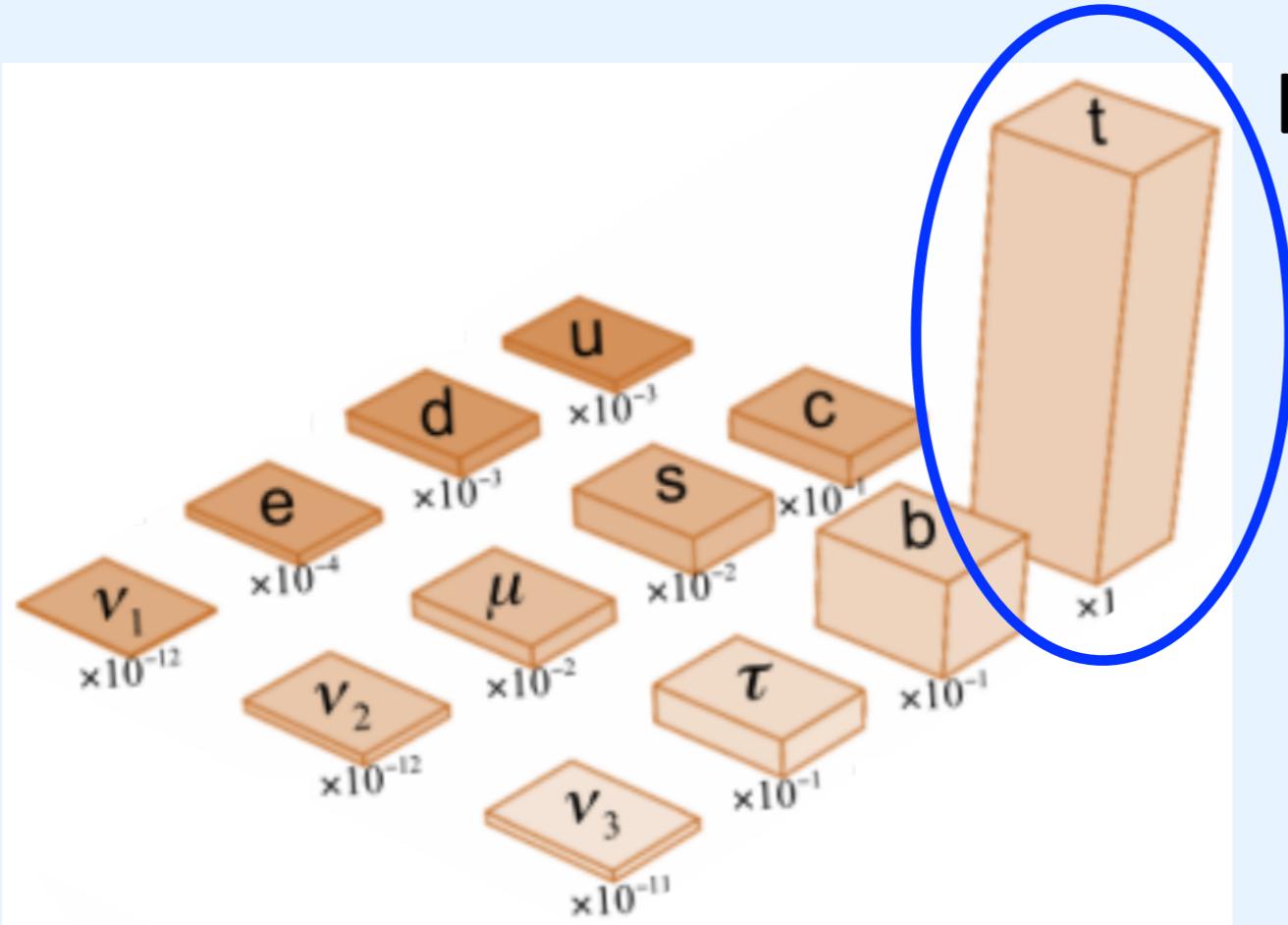


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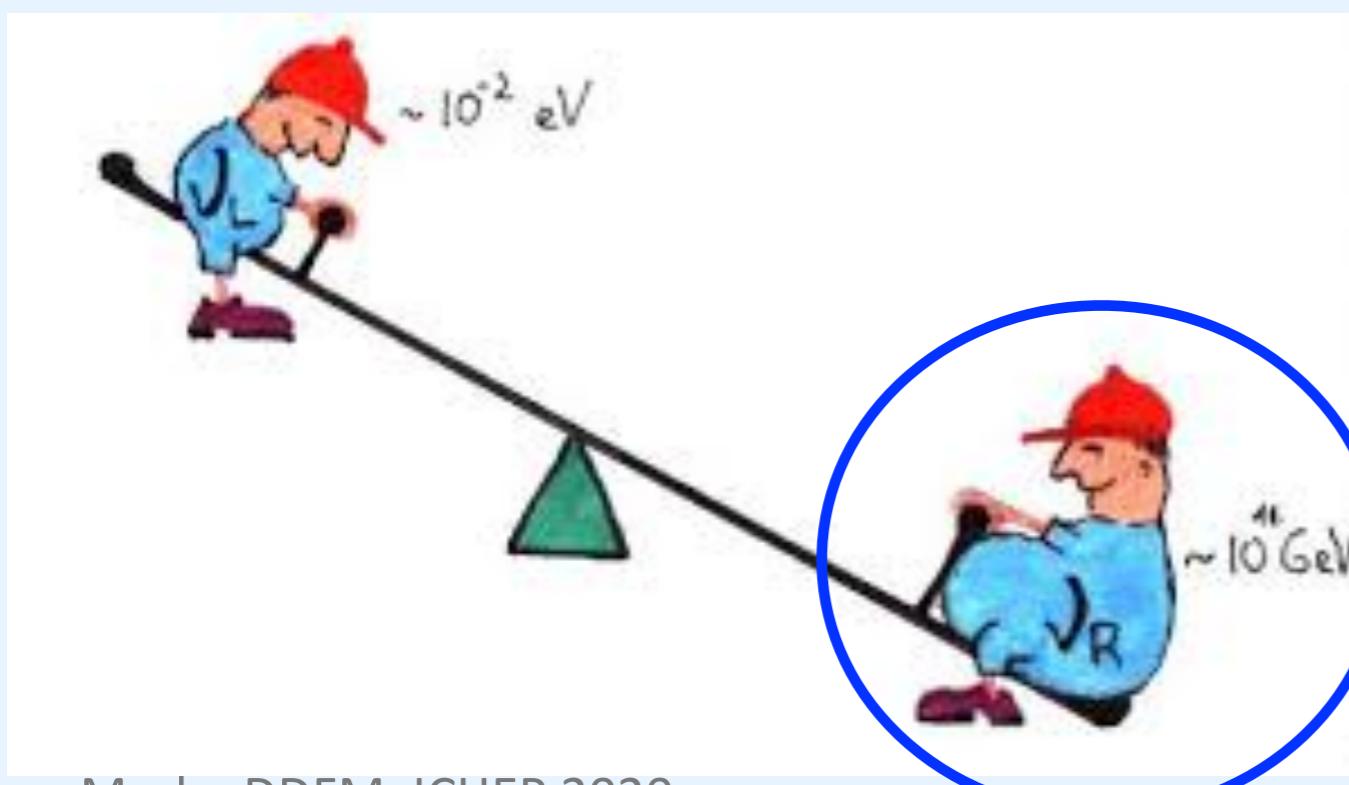


Largest breaking

# Bottom-up Approach

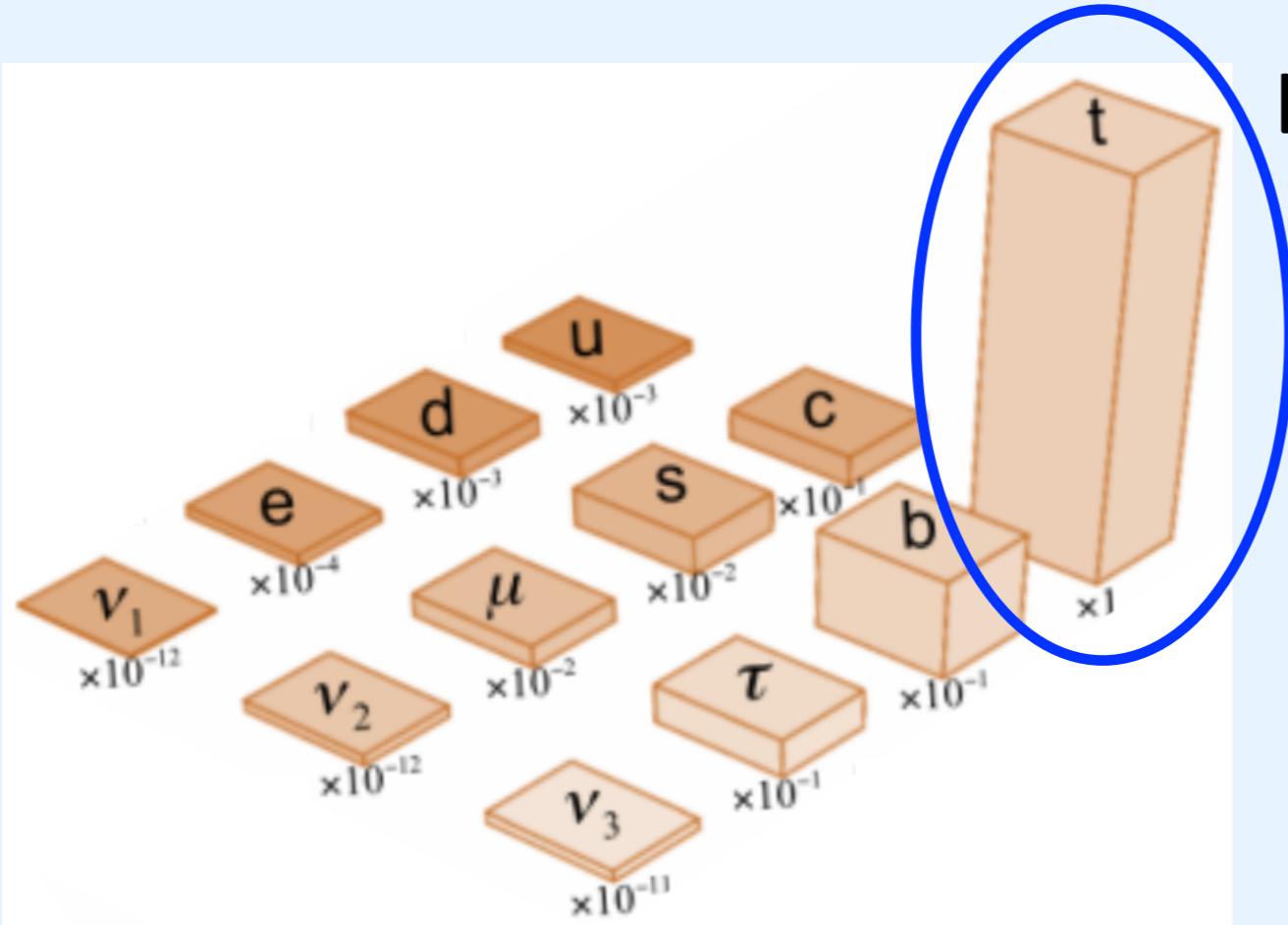


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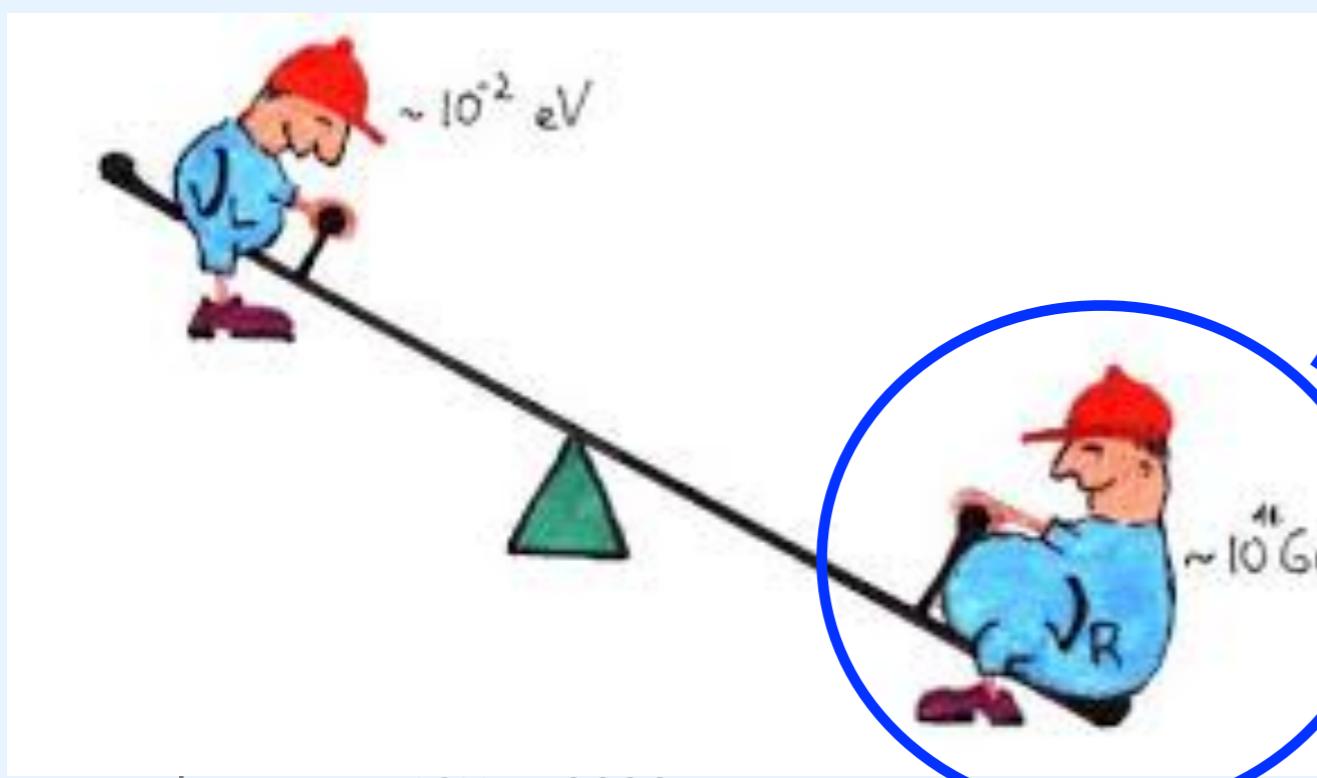
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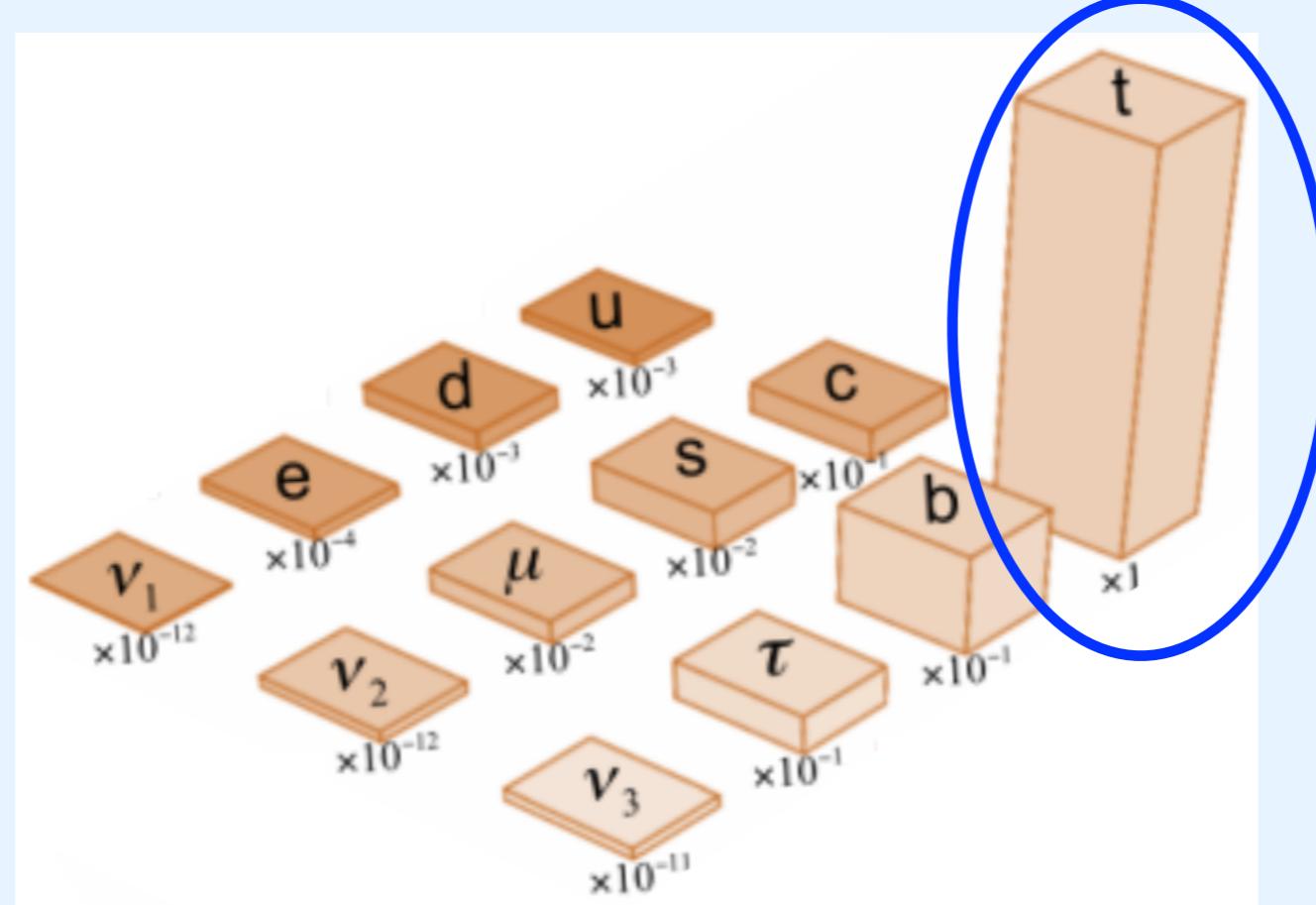
Largest breaking

These terms should be renormalisable in the Lag



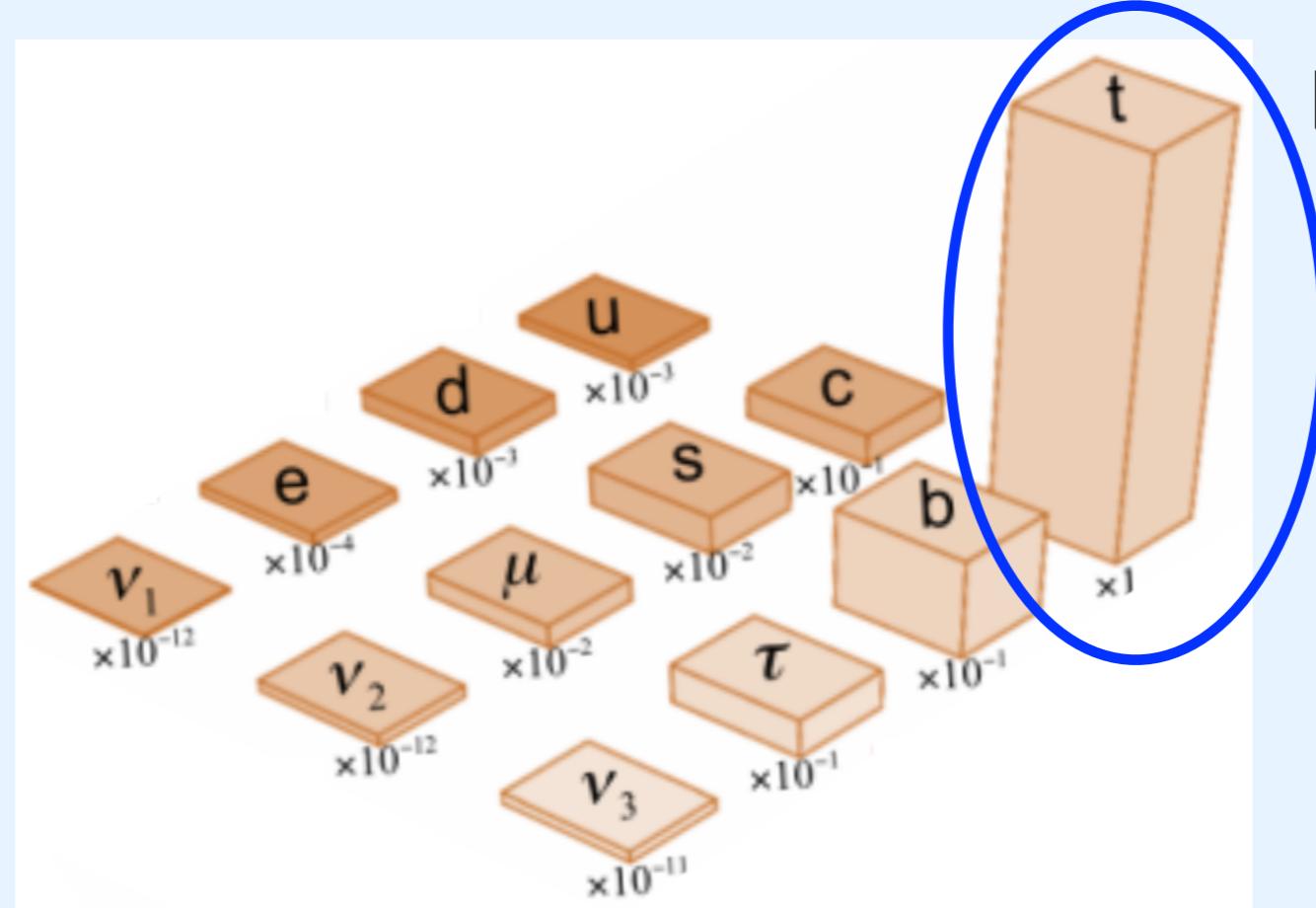
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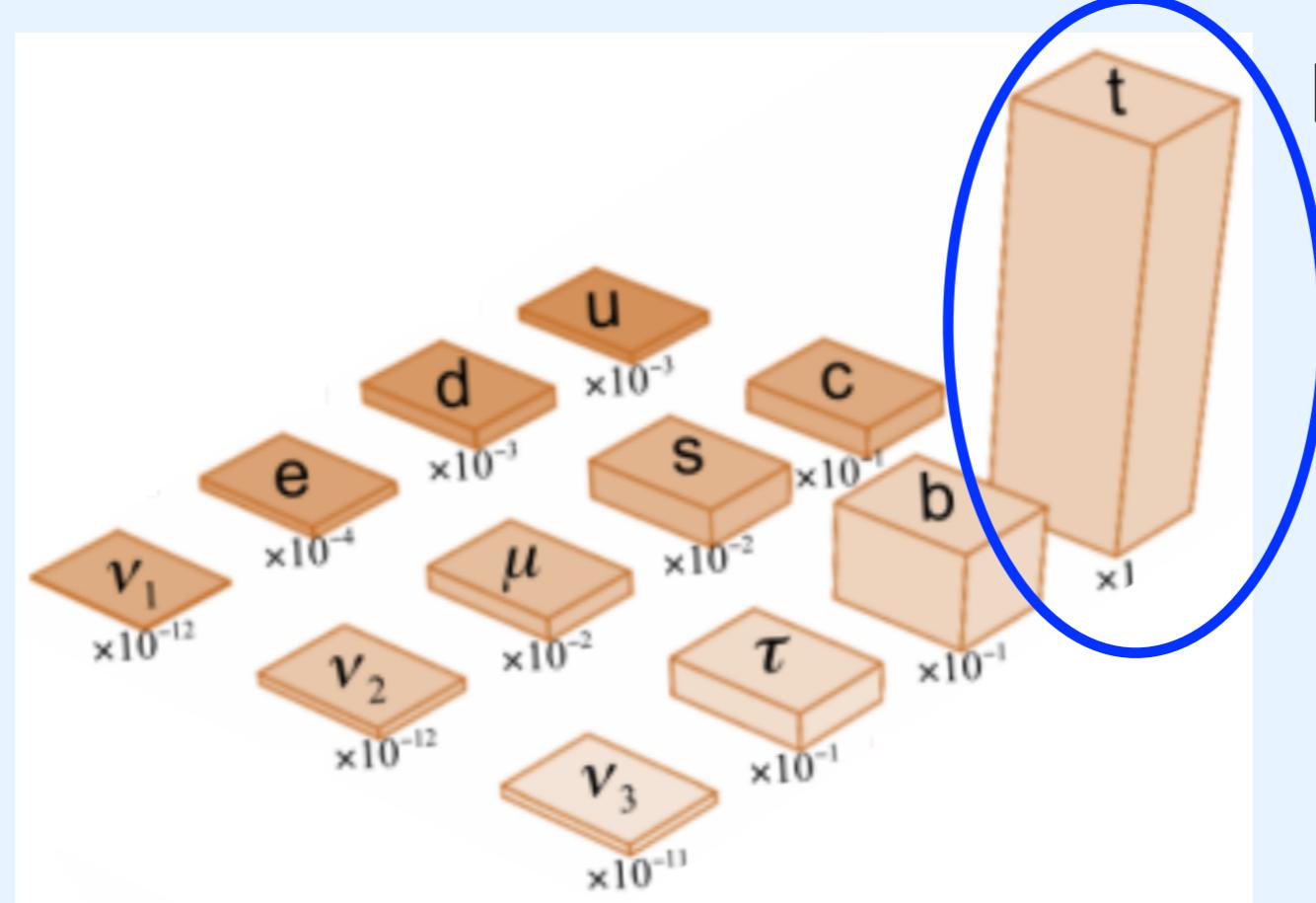


Largest breaking

$$q'_{3L} \sim \text{singlet}$$

$$t'_R \sim \text{singlet}$$

# Quark Sector



# Largest breaking

$q'_{3L} \sim$  singlet

$t'_R \sim$  singlet

$$\xrightarrow{\hspace{1cm}} -\mathcal{L}_Y^q = y_t \bar{q}'_{3L} \phi t'_R + \Delta \mathcal{L}_Y^q + \text{h.c.}$$

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$$Q'_L = \{q'_{1L}, q'_{2L}\} \sim \text{doublet}$$

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$$D'_R = \{d'_R, s'_R, b'_R\} \sim \text{triplet}$$

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→ The corresponding largest flavour symmetry is

$$\mathcal{G}_q = SU(2)_{q_L} \times SU(2)_{u_R} \times SU(3)_{d_R}$$

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Kinetic terms are invariant under  $\mathcal{G}_q$

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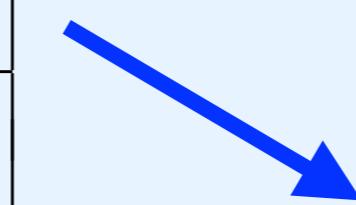
	$SU(2)_{q_L}$	$SU(2)_{u_R}$	$SU(3)_{d_R}$
$Q'_L$	<b>2</b>	1	1
$q'_{3L}$	1	1	1
$U'_R$	1	<b>2</b>	1
$t'_R$	1	1	1
$D'_R$	1	1	<b>3</b>
$\Delta\mathcal{Y}_U$	<b>2</b>	<b>2̄</b>	1
$\Delta\mathcal{Y}_D$	<b>2</b>	1	<b>3̄</b>
$\mathbf{y}_D$	1	1	<b>3̄</b>

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$$Y_U = \left( \begin{array}{cc|c} x & x & 0 \\ x & x & 0 \\ \hline 0 & 0 & 1 \end{array} \right)$$

$$Y_D = \left( \begin{array}{ccc} x & x & x \\ x & x & x \\ \hline y & y & y \end{array} \right)$$

# Quark Sector

$$\langle \Delta \mathcal{Y}_U \rangle \equiv \Delta Y_U = \begin{pmatrix} y_u & 0 \\ 0 & y_c \end{pmatrix}$$

$$\langle \Delta \mathcal{Y}_D \rangle \equiv \Delta Y_D = \begin{pmatrix} y_d V_{11} & y_s V_{12} & y_b V_{13} \\ y_d V_{21} & y_s V_{22} & y_b V_{23} \end{pmatrix}$$

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$$\longrightarrow Y_U = \begin{pmatrix} \Delta Y_U & 0 \\ 0 & 1 \end{pmatrix} \qquad \qquad Y_D = \begin{pmatrix} \Delta Y_D \\ y_D \end{pmatrix}$$

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$$\xrightarrow{\hspace{1cm}} Y_U = \begin{pmatrix} \Delta Y_U & 0 \\ 0 & 1 \end{pmatrix} \quad Y_D = \begin{pmatrix} \Delta Y_D \\ y_D \end{pmatrix}$$

$$\text{diag}(y_d, y_s, y_b) = V^\dagger Y_D$$

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$$\mathcal{O}_3 = (\bar{Q}'_L \gamma_\mu \sigma^a Q'_L) (\bar{Q}'_L \gamma^\mu \sigma^a Q'_L)$$

$$\mathcal{O}_5 = (\bar{Q}'_L \gamma_\mu T^a Q'_L) (\bar{Q}'_L \gamma^\mu T^a Q'_L)$$

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$$\mathcal{O}_{15} = (\bar{Q}'_L \gamma_\mu T^a Q'_L) (\bar{U}'_R \gamma^\mu T^a U'_R)$$

$$\mathcal{O}_2 = (\bar{q}'_{3L} \gamma_\mu q'_{3L}) (\bar{q}'_{3L} \gamma^\mu q'_{3L})$$

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$$\mathcal{O}_8 = (\bar{q}'_{3L} \gamma_\mu T^a \sigma^b q'_{3L}) (\bar{q}'_{3L} \gamma^\mu T^a \sigma^b q'_{3L})$$

$$\mathcal{O}_{10} = (\bar{q}'_{3L} \gamma_\mu q'_{3L}) (\bar{D}'_R \gamma^\mu D'_R)$$

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$$\mathcal{O}_{14} = (\bar{q}'_{3L} \gamma_\mu q'_{3L}) (\bar{U}'_R \gamma^\mu U'_R)$$

$$\mathcal{O}_{16} = (\bar{q}'_{3L} \gamma_\mu T^a q'_{3L}) (\bar{U}'_R \gamma^\mu T^a U'_R)$$

# Phenomenology in the Quark Sector

Operators	Bound on $\Lambda/\sqrt{a_i}$	Observables
$\mathcal{O}_1, \mathcal{O}_2$	5.9 TeV	$\epsilon_K, \Delta m_{B_d}, \Delta m_{B_s}$
$\mathcal{O}_{17}, \mathcal{O}_{18}$	4.1 TeV	$B_s \rightarrow \mu^+ \mu^-, B \rightarrow K^* \mu^+ \mu^-$
$\mathcal{O}_{21}, \mathcal{O}_{22}$	3.4 TeV	$B \rightarrow X_s \gamma, B \rightarrow X_s \ell^+ \ell^-$
$\mathcal{O}_{25}, \mathcal{O}_{26}$	6.1 TeV	$B \rightarrow X_s \gamma, B \rightarrow X_s \ell^+ \ell^-$
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$Br(B_s \rightarrow \mu^+ \mu^-) \neq Br(B_s \rightarrow \tau^+ \tau^-)$  DDFM

# Lepton Sector

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Very similar to the MLFV with type-I Seesaw!

Cirigliano et al. 2005

Davidson et al. 2006

Alonso et al. 2011

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$$\longrightarrow -\mathcal{L}_Y^\ell = \frac{1}{2} \Lambda_{LN} \bar{N}_R'^c Y_N N'_R + \Delta \mathcal{L}_Y^\ell + \text{h.c.}$$

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	$SU(3)_{\ell_L}$	$SU(2)_{e_R}$	$SO(3)_{N_R}$
$L'_L$	<b>3</b>	1	1
$E'_R$	1	<b>2</b>	1
$\tau'_R$	1	1	1
$N'_R$	1	1	<b>3</b>
$\Delta \mathcal{Y}_E$	<b>3</b>	<b>2</b>	1
$\mathbf{y}_E$	<b>3</b>	1	1
$\mathcal{Y}_\nu$	<b>3</b>	1	<b>3</b>

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$\Delta \mathcal{Y}_E$	<b>3</b>	<b>2</b>	1
$\mathbf{y}_E$	<b>3</b>	1	1
$\mathcal{Y}_\nu$	<b>3</b>	1	<b>3</b>

$$Y_E = \left( \begin{array}{cc|c} x & x & y \\ x & x & y \\ x & x & y \end{array} \right)$$

$$m_\nu = \left( \begin{array}{ccc} z & z & z \\ z & z & z \\ z & z & z \end{array} \right)$$

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$$\Delta \mathcal{L}_Y^\ell = \bar{L}'_L \phi \Delta \mathcal{Y}_E E'_R + \bar{L}'_L \phi \mathbf{y}_E \tau'_R + \bar{L}'_L \tilde{\phi} \mathcal{Y}_\nu N'_R$$

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→  $\langle \Delta \mathcal{Y}_E \rangle \equiv \Delta Y_E = \begin{pmatrix} y_e & 0 \\ 0 & y_\mu \\ 0 & 0 \end{pmatrix}$

$$\langle \mathbf{y}_E \rangle \equiv y_E = \begin{pmatrix} 0 & 0 & y_\tau \end{pmatrix}^T$$

$$\langle \mathcal{Y}_\nu \rangle \langle \mathcal{Y}_\nu^T \rangle \equiv Y_\nu Y_\nu^T = \frac{2\Lambda_{LN}}{v^2} U \text{diag}(m_{\nu_1}, m_{\nu_2}, m_{\nu_3}) U^T$$

# Lepton Sector

$$\Delta \mathcal{L}_Y^\ell = \bar{L}'_L \phi \Delta \mathcal{Y}_E E'_R + \bar{L}'_L \phi \mathbf{y}_E \tau'_R + \bar{L}'_L \tilde{\phi} \mathcal{Y}_\nu N'_R$$

→  $\langle \Delta \mathcal{Y}_E \rangle \equiv \Delta Y_E = \begin{pmatrix} y_e & 0 \\ 0 & y_\mu \\ 0 & 0 \end{pmatrix}$

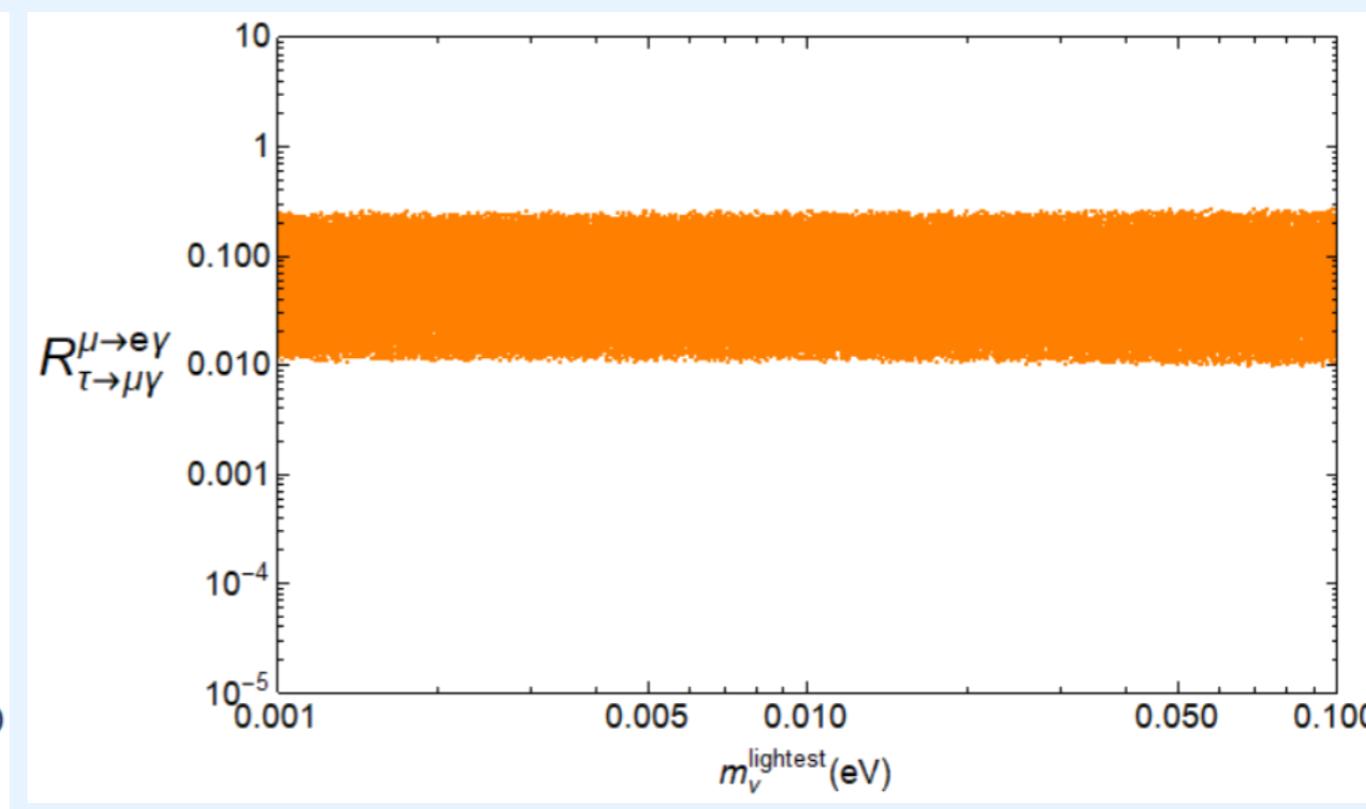
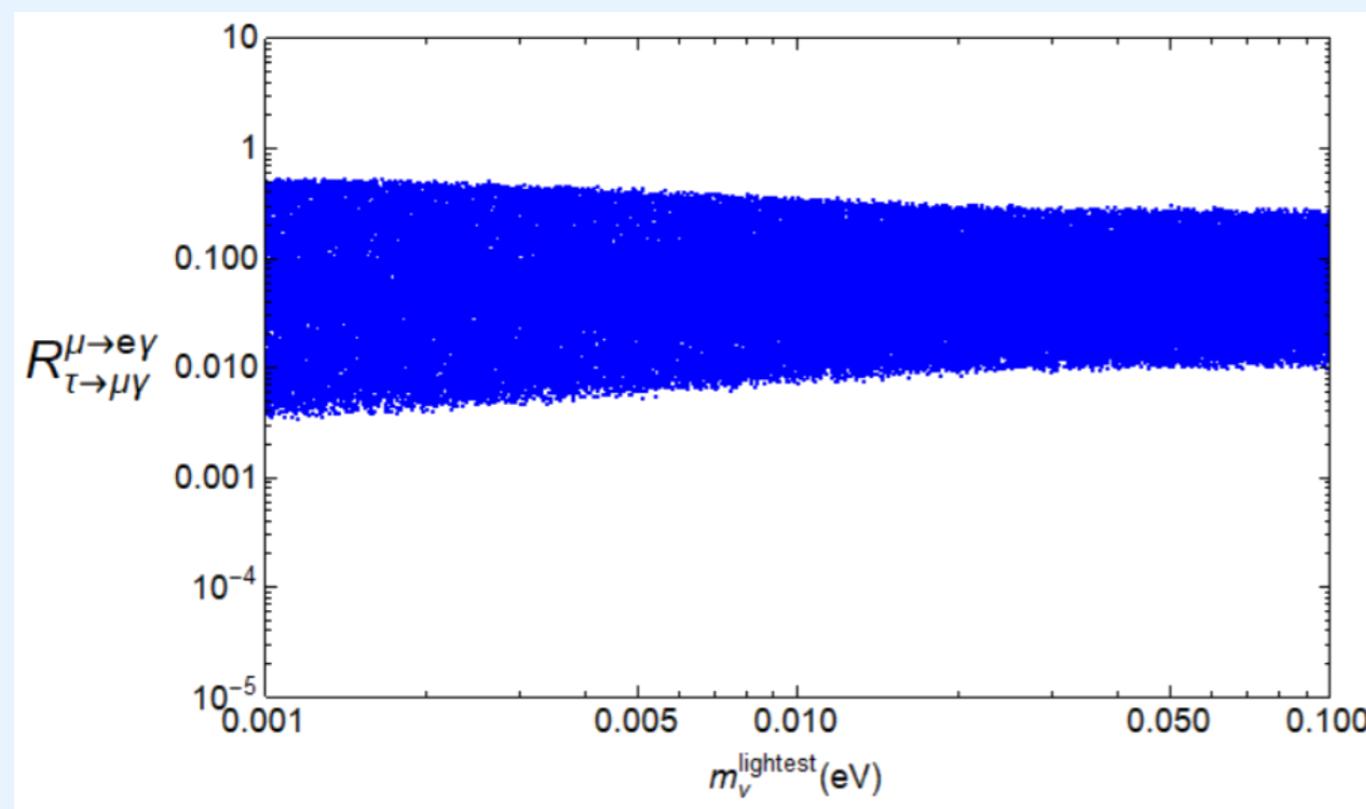
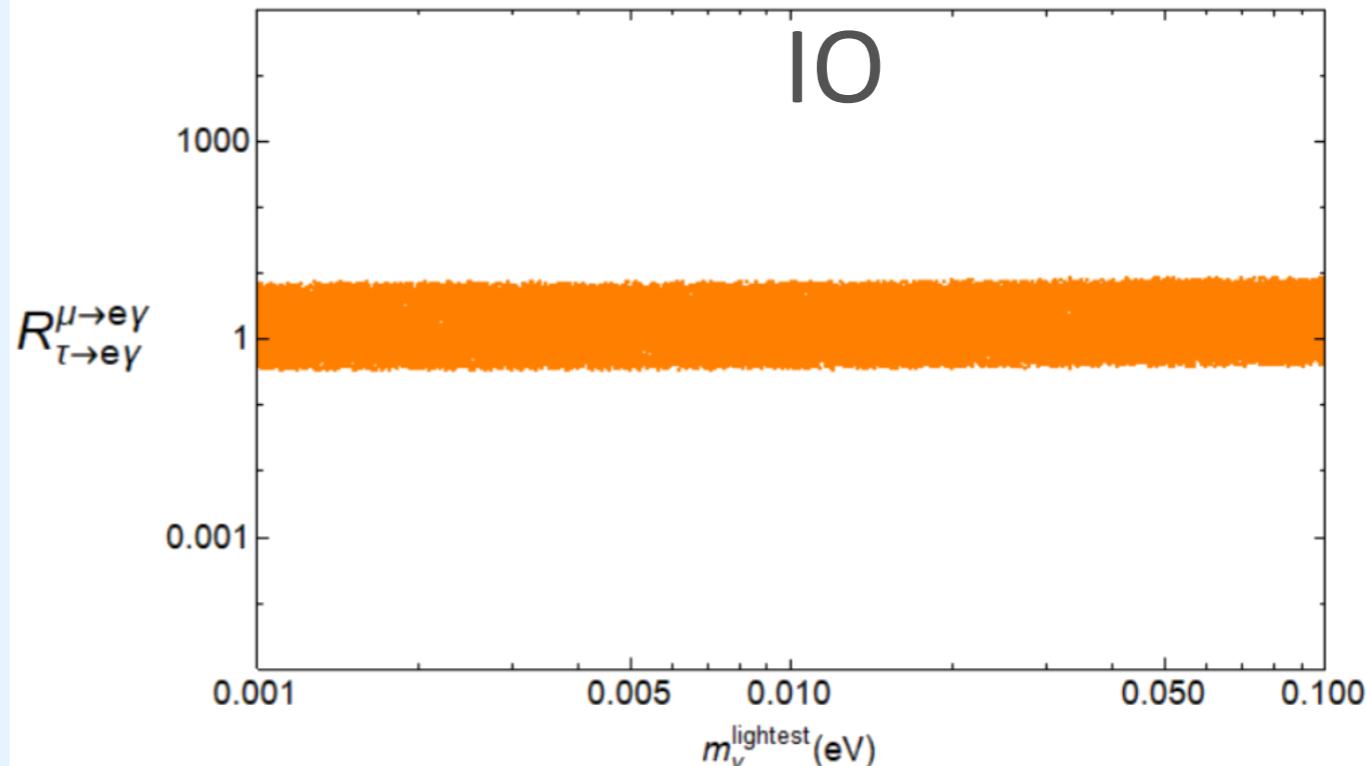
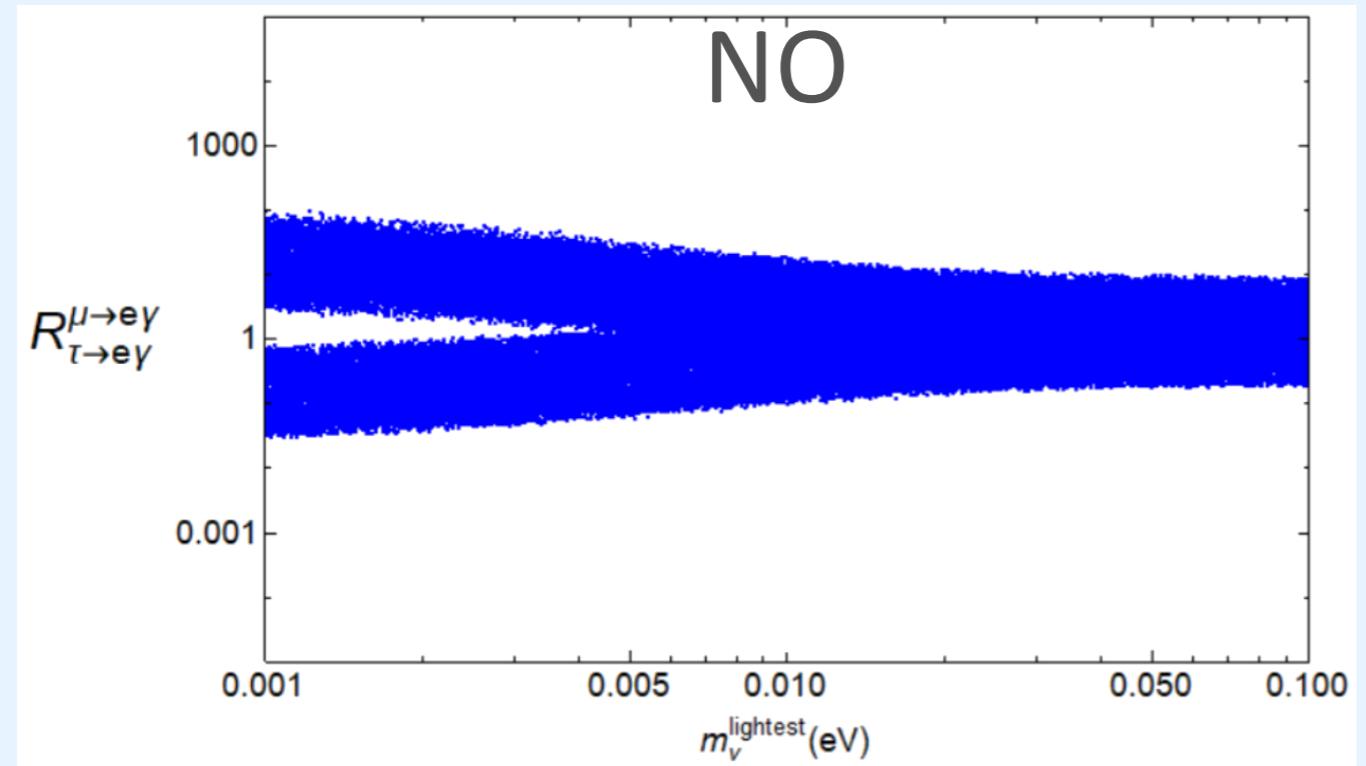
$$\langle \mathbf{y}_E \rangle \equiv y_E = \begin{pmatrix} 0 & 0 & y_\tau \end{pmatrix}^T$$

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→  $Y_E = \begin{pmatrix} \Delta Y_E & y_E \end{pmatrix} \quad m_\nu = \frac{v^2}{2\Lambda_{LN}} Y_\nu^* Y_\nu^\dagger$

$$\text{diag}(m_{\nu_1}, m_{\nu_2}, m_{\nu_3}) = U^T m_\nu U$$

# Phenomenology in the Lepton Sector



In MLFV, these ratios are all close to 1! Dihl et al. 2017

# Justify the Flavour Alignment

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In MFV there is no final explanation of the flavour alignments!

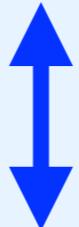
Alonso et al. 2011

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→ Promote the spurions to be dynamical scalar fields

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$$A_D = \text{Tr} (\Delta \mathcal{Y}_D \Delta \mathcal{Y}_D^\dagger)$$

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$$A_{DD} = \text{Tr} (\Delta \mathcal{Y}_D \Delta \mathcal{Y}_D^\dagger \Delta \mathcal{Y}_D \Delta \mathcal{Y}_D^\dagger)$$

$$A_{UD} = \text{Tr} (\Delta \mathcal{Y}_U \Delta \mathcal{Y}_U^\dagger \Delta \mathcal{Y}_D \Delta \mathcal{Y}_D^\dagger)$$

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$$A_{EE} = \text{Tr} (\Delta \mathcal{Y}_E \Delta \mathcal{Y}_E^\dagger \Delta \mathcal{Y}_E \Delta \mathcal{Y}_E^\dagger)$$

$$A_{\nu\nu 1} = \text{Tr} (\mathbf{y}_\nu \mathbf{y}_\nu^\dagger \mathbf{y}_\nu \mathbf{y}_\nu^\dagger)$$

$$A_{E\nu} = \text{Tr} (\Delta \mathcal{Y}_E \Delta \mathcal{Y}_E^\dagger \mathbf{y}_\nu \mathbf{y}_\nu^\dagger)$$

$$A_{\nu\nu 2} = \text{Tr} (\mathbf{y}_\nu \mathbf{y}_\nu^T \mathbf{y}_\nu^* \mathbf{y}_\nu^\dagger)$$

$$B_E = \mathbf{y}_E \mathbf{y}_E^\dagger$$

$$B_{EE} = \mathbf{y}_E^\dagger \Delta \mathcal{Y}_E \Delta \mathcal{Y}_E^\dagger \mathbf{y}_E$$

$$B_{E\nu} = \mathbf{y}_E^\dagger \mathbf{y}_\nu \mathbf{y}_\nu^\dagger \mathbf{y}_E$$

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- It is possible to find a solution compatible with quark masses and mixing, although at the price of tuning the parameters of the scalar potential

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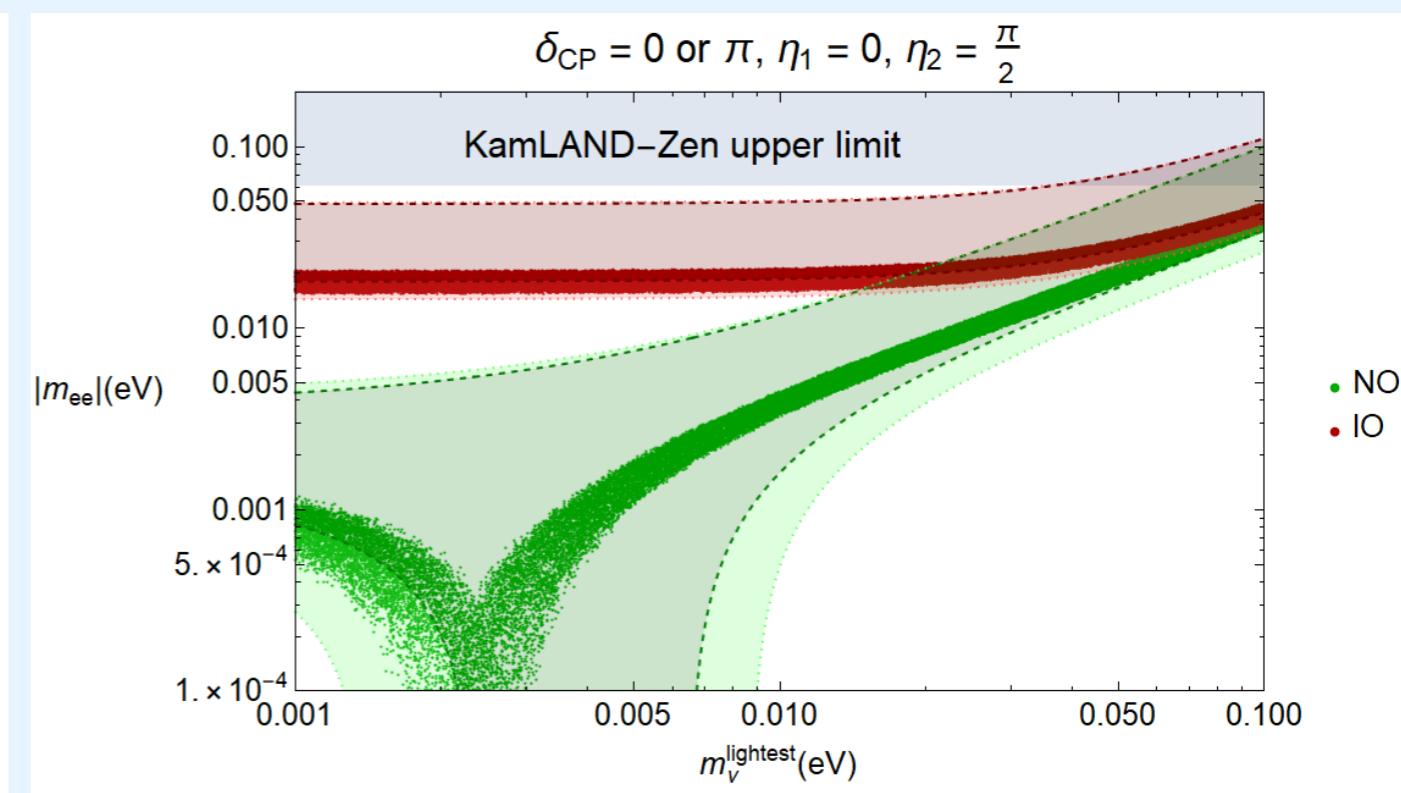
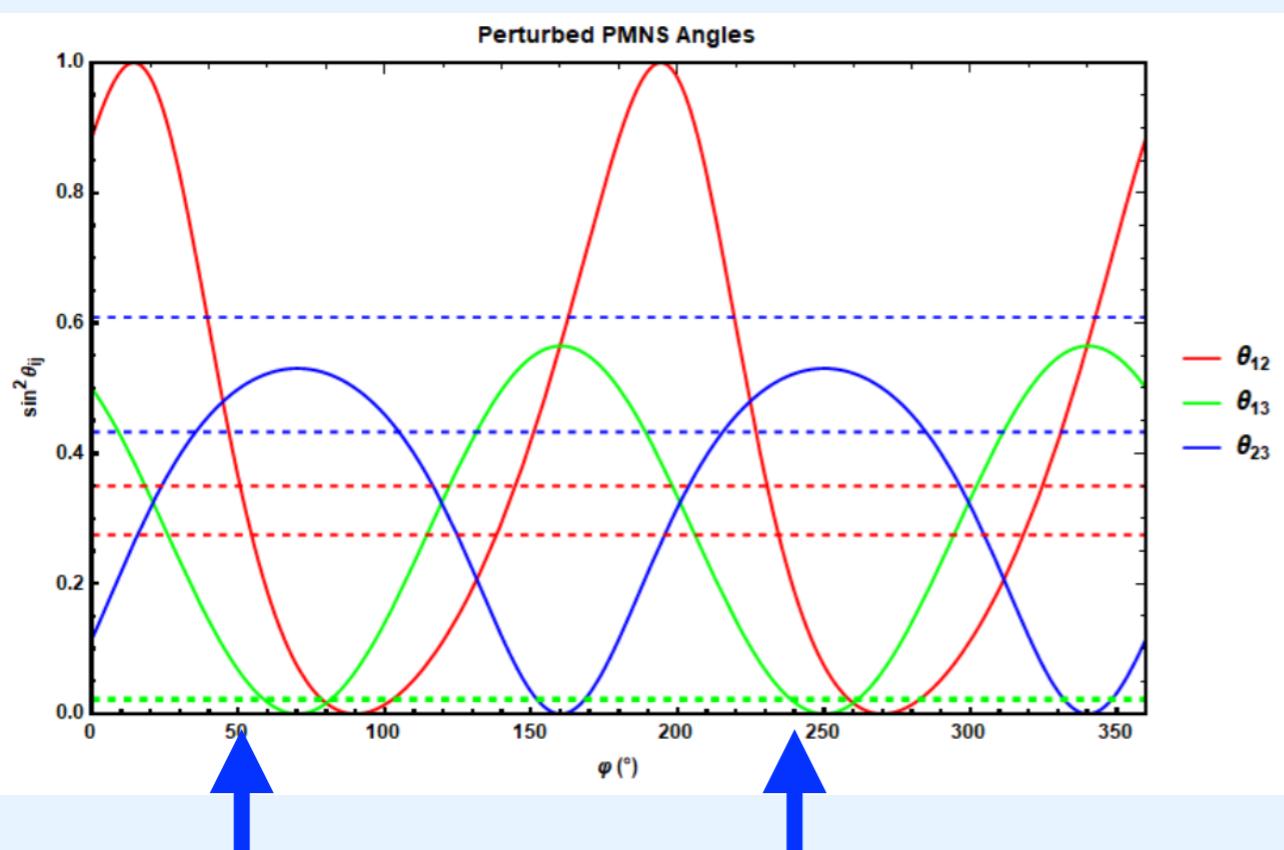
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# Thanks!

# U(2) Models



$$\mathcal{G}_q = SU(2)_{q_L} \times SU(2)_{u_R} \times SU(2)_{d_R}$$

Barbieri et al. 2011

$$Y_U = y_t \begin{pmatrix} x & x & | & y \\ x & x & | & y \\ \hline 0 & 0 & | & 1 \end{pmatrix}$$

$$Y_D = y_b \begin{pmatrix} x & x & | & y' \\ x & x & | & y' \\ \hline 0 & 0 & | & 1 \end{pmatrix}$$

No explanation of  $y_b/y_t$  SUSY or at least 2HDM

No explanation of flavour alignments

Alonso et al. 2011



$$\mathcal{G}_\ell = SU(2)_{\ell_L} \times SU(2)_{e_R} \times SO(2)_{N_R}$$

Blankenburg et al. 2012

No description of neutrino mixing  $SU(3)_{\ell_L} \times SO(3)_{N_R}$

No explanation of flavour alignments

Alonso et al. 2012

Alonso et al. 2013