Radiative neutrino mass models

Avelino Vicente
IFIC – CSIC / U. Valencia

BLV 2019

Some...
Radiative neutrino mass models
...face flavor constraints

Avelino Vicente
IFIC – CSIC / U. Valencia

BLV 2019

There are MANY Majorana neutrino mass models...

Tree-level

Radiative: 1-loop, 2-loop, 3-loop, ...

High scale

Low scale

Dimension-5: Weinberg operator

Higher dimensions: dim-7, dim-9, ...

There are MANY
Majorana neutrino mass models...

Review: [Cai, Herrero-García, Schmidt, AV, Volkas, 2017]

Tree-level

Radiative: 1-loop, 2-loop, 3-loop, ...

Loop suppression

Dark matter candidate

High scale

Low scale

Dimension-5: Weinberg operator

Higher dimensions: dim-7, dim-9, ...

Outline

Introduction

Finished already!

LFV in the Scotogenic model

How LFV constrains the parameter space in the fermion DM scenario

3-loop minimal models and flavor

Minimal models only survive in very fine-tuned regions of the parameter space

LFV in the Scotogenic model

Work in collaboration with

Takashi Toma [1312.2840] and **Carlos Yaguna** [1412.2545]

The scotogenic model

[Ma, 2006]

σκότος

skotos = darkness

	gen	$\mathrm{SU}(2)_L$	$\mathrm{U}(1)_Y$	$\mathbb{Z}_2$
η	1	$\mathbf{2}$	$1/2$	$-$
N	3	$\mathbf{1}$	0	$-$

Inert (or dark) doublet

Dark Matter!

$$\mathcal{L}_N = \overline{N_i} \not{\partial} N_i - \frac{M_{R_i}}{2} \overline{N_i^c} N_i + y_{i\alpha} \eta \overline{N_i} \ell_\alpha + \text{h.c.}$$

$$\begin{aligned}\mathcal{V} = \quad & m_\phi^2 \phi^\dagger \phi + m_\eta^2 \eta^\dagger \eta + \frac{\lambda_1}{2} \left(\phi^\dagger \phi\right)^2 + \frac{\lambda_2}{2} \left(\eta^\dagger \eta\right)^2 + \lambda_3 \left(\phi^\dagger \phi\right) \left(\eta^\dagger \eta\right) \\ & + \lambda_4 \left(\phi^\dagger \eta\right) \left(\eta^\dagger \phi\right) + \frac{\lambda_5}{2} \left[\left(\phi^\dagger \eta\right)^2 + \left(\eta^\dagger \phi\right)^2\right]\end{aligned}$$

Radiative neutrino masses

[Ma, 2006]

Tree-level:
Forbidden by the Z_2 symmetry

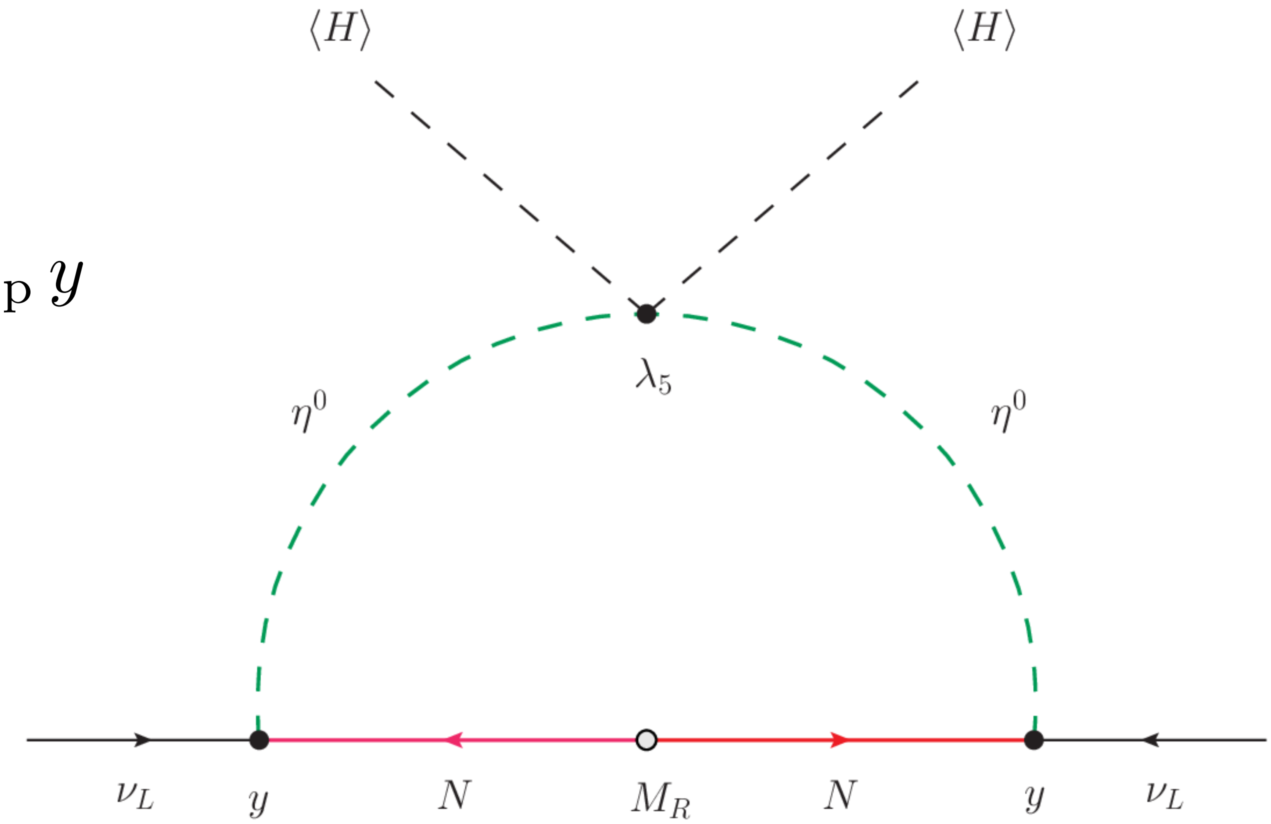
Radiative generation of neutrino masses

$$m_\nu = \frac{\lambda_5 v^2}{32\pi^2} \, y^T \, M_R^{-1} f_{\rm loop} \, y$$

Dark particles in the loop

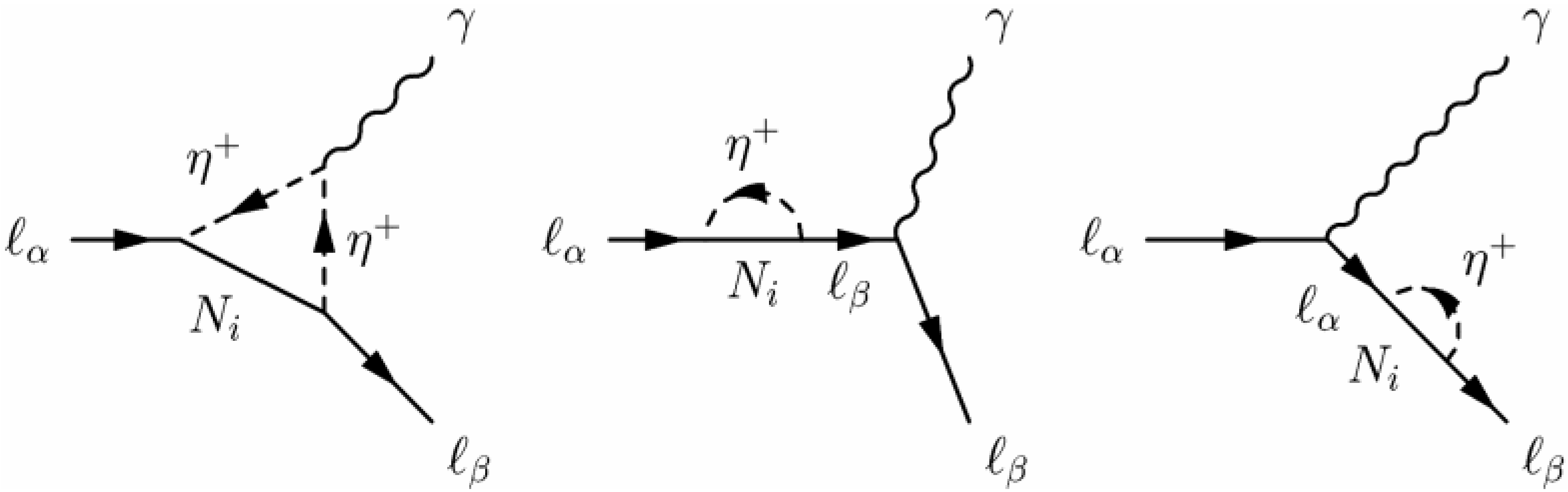
[Other variations in Restrepo et al, 2013]

1-loop neutrino masses



$\ell_\alpha \to \ell_\beta \gamma$

[Kubo et al, 2006]
[Ma, Raidal, 2001]



$$\mathcal{L}_{\rm eff} = \left(\frac{\mu_{\beta\alpha}}{2}\right) \overline{\ell_\beta} \sigma^{\mu\nu} \ell_\alpha F_{\mu\nu}$$

$$\mu_{\beta\alpha} = e m_\alpha A_D / 2$$

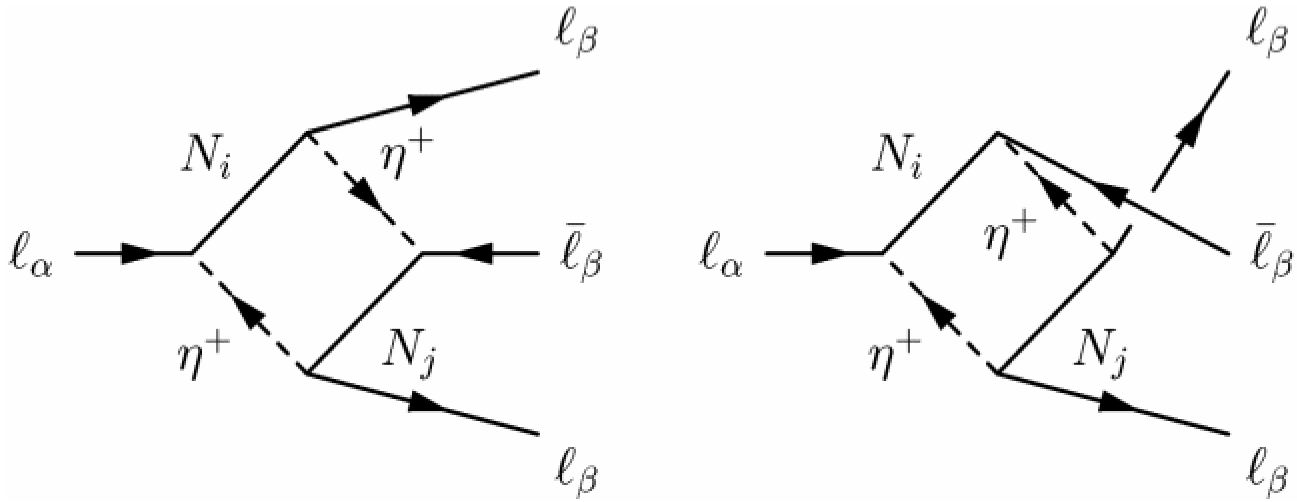
Transition magnetic moment

$$A_D = \sum_{i=1}^{3} \frac{y_{i\beta}^* y_{i\alpha}}{2(4\pi)^2} \frac{1}{m_{\eta^+}^2} F_2\left(\xi_i\right)$$

$$(\xi_i \equiv m_{N_i}^2 / m_{\eta^+}^2)$$

$\ell_\alpha \to 3\,\ell_\beta$

$\ell_\alpha(p) \to \ell_\beta(k_1)\bar{\ell}_\beta(k_2)\ell_\beta(k_3)$ [Toma, Vicente, 2013]



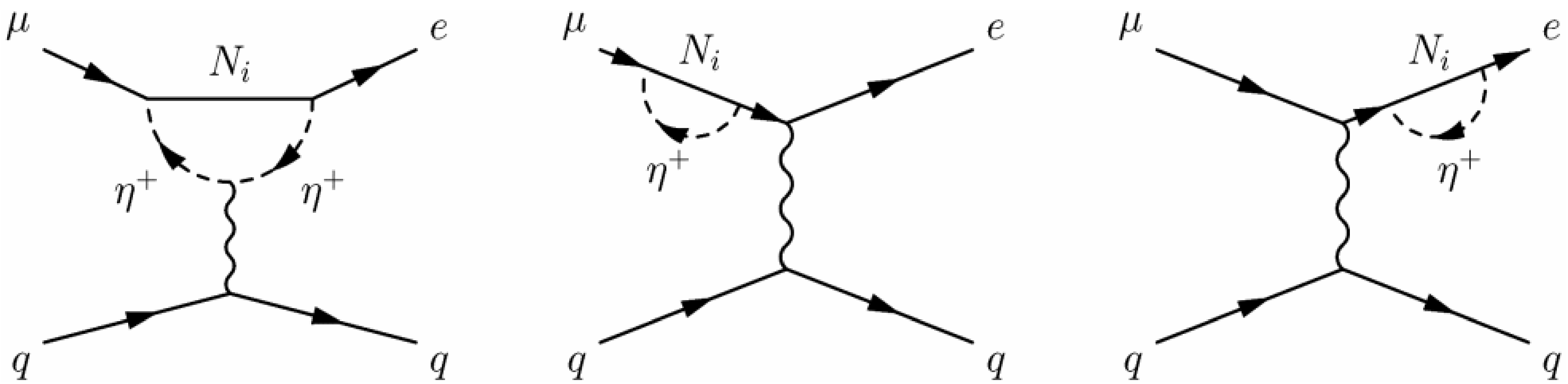
Boxes

$$i\mathcal{M}_{\rm box} = ie^2\, B\, \left[\bar{u}(k_3)\gamma^\mu P_L v(k_2)\right]\left[\bar{u}(k_1)\gamma_\mu P_L u(p)\right]$$

$$e^2 B = \frac{1}{(4\pi)^2 m_{\eta^+}^2}\sum_{i,\,j=1}^{3}\left[\frac{1}{2}D_1(\xi_i,\xi_j)y_{j\beta}^* y_{j\beta} y_{i\beta}^* y_{i\alpha} + \sqrt{\xi_i\xi_j}\,D_2(\xi_i,\xi_j)y_{j\beta}^* y_{j\beta}^* y_{i\beta} y_{i\alpha}\right]$$

$\mu - e$ conversion in nuclei

[Toma, Vicente, 2013]



- No box contributions from the inert doublet (they do <u>not</u> couple to the quark sector)

- The phenomenology is determined by photon penguin diagrams (Z penguins are negligible)

LFV and fermionic DM

Fermionic DM

Requires large
Yukawa couplings

Possible clash (?)

LFV bounds

Require small
Yukawa couplings

DM production
via Yukawa
couplings

$$\Omega_{\rm DM} h^2 \simeq 0.12$$

$$\mathrm{BR}(\mu \to e\gamma) < 4.2 \cdot 10^{-13}$$

$$\mathrm{BR}(\tau \to \mu\gamma) < 4.4 \cdot 10^{-8}$$

$$\mathrm{BR}(\mu \to 3\,e) < 1.0 \cdot 10^{-12}$$

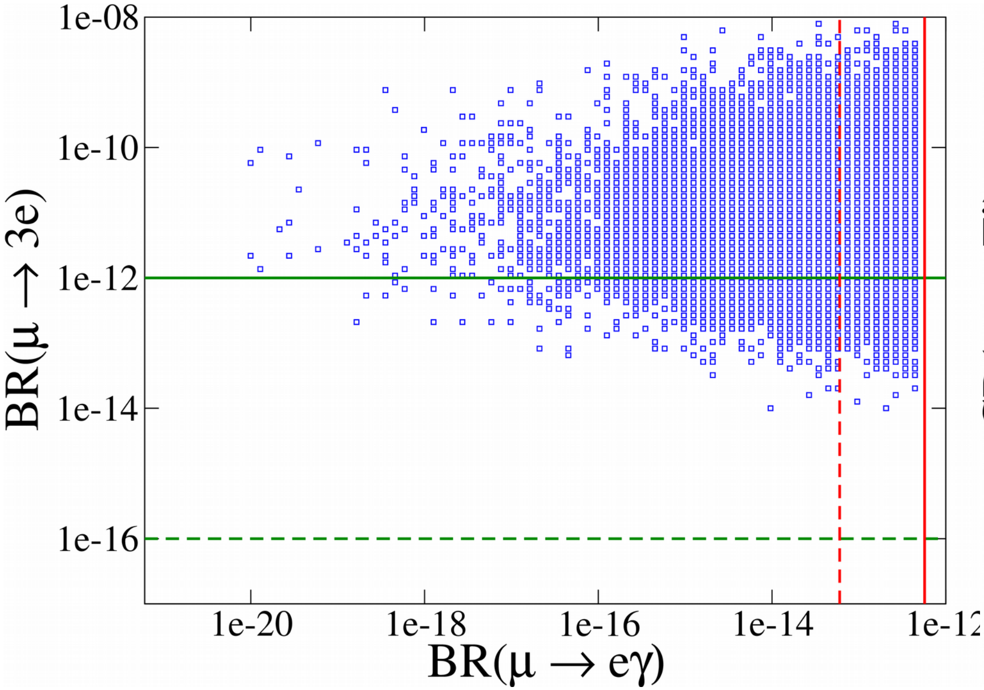
$$\mathrm{CR}(\mu - e, \mathrm{Au}) < 7.0 \cdot 10^{-13}$$

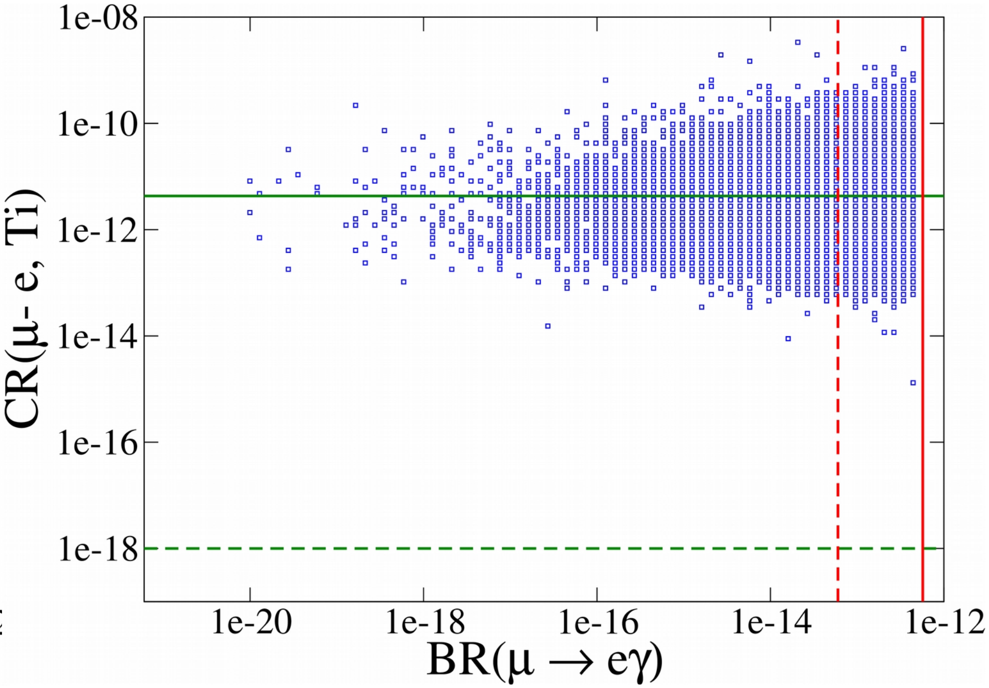
...

LFV and fermionic DM

[Vicente, Yaguna, 2014]

N_1 – N_1 annihilation





- Scenario still alive (although strongly constrained)
- The complete parameter space will be probed in the next round of experiments

3-loop minimal models and flavor

Work in progress in collaboration with

Ricardo Cepedello, Martin Hirsch and **Paulina Rocha-Morán**

[1912.XXXXX]

3-loop neutrino mass models

3-loop Majorana neutrino mass models
can actually be very simple

Minimal models

KNT model: Krauss, Nasri & Trodden, 2002

AKS model: Aoki, Kanemura & Seto, 2008

Cocktail model: Gustafsson, No & Rivera, 2012

[Full classification in Cepedello et al, 2018]

3-loop neutrino mass models

3-loop Majorana neutrino mass models
can actually be very simple

Minimal models

KNT model: Krauss, Nasri & Trodden, 2002

AKS model: Aoki, Kanemura & Seto, 2008

Cocktail model: Gustafsson, No & Rivera, 2012

Focus on AKS...

... but similar (qualitative) conclusions hold for the other two

[Full classification in Cepedello et al, 2018]

The AKS model

[Aoki, Kanemura, Seto, 2008]

	gen	$SU(2)_L$	$U(1)_Y$	$\mathbb{Z}_2$
Φ	1	**2**	1/2	+
φ	1	**1**	0	−
S	1	**1**	1	−
N	3	**1**	0	−

← 2nd Higgs doublet

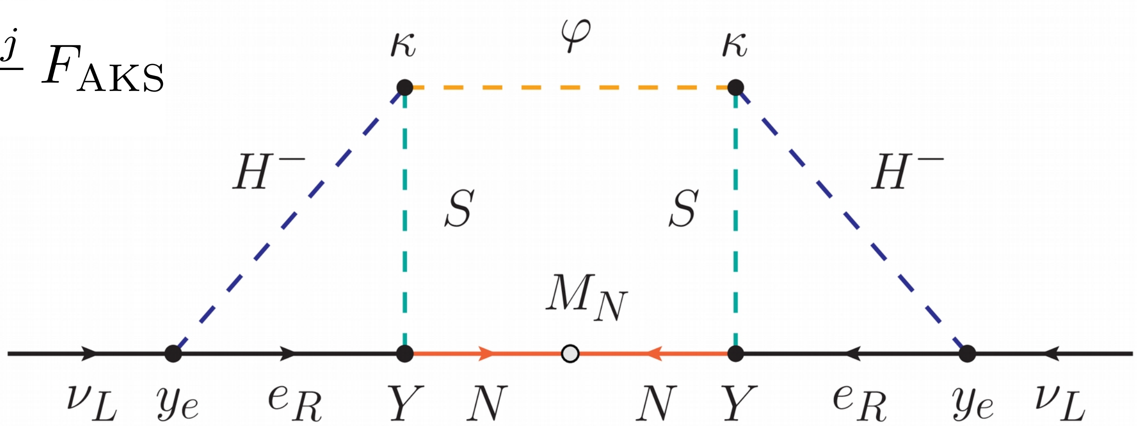
← real

Conserved $\mathbb{Z}_2$ parity

Dark Matter!

$$-\mathcal{L} \supset Y\, \overline{e_R^c}\, N S^* + \frac{1}{2} M_N \overline{N^c} N + \kappa\, \phi\, \Phi S^* \varphi + \text{h.c.}$$

$$(m_\nu)_{ij} = C_{\text{AKS}} \frac{\kappa^2}{(16\pi^2)^3} \frac{m_i\, Y_{i\alpha}\, Y_{j\beta}\, m_j}{(M_N)_{\alpha\beta}} F_{\text{AKS}}$$



(+ diagram with crossed S lines)

Y : parametrized à *la* Casas-Ibarra

Master parametrization

[Cordero-Carrión, Hirsch, AV, 2018]

Neutrino mass in the AKS model

$$(m_\nu)_{ij} = C_{\text{AKS}} \, \frac{\kappa^2}{(16\pi^2)^3} \, \frac{m_i \, Y_{i\alpha} \, Y_{j\beta} \, m_j}{(M_N)_{\alpha\beta}} \, F_{\text{AKS}}$$

Fit to oscillation data

Simple estimate

$$\xrightarrow{\hspace{2cm}}$$

$R = \mathbb{I}$

$m_\nu \sim 0.1$ eV

$$Y \sim \left(\begin{array}{ccc} 100 & 1 & 0.1 \\ 100 & 1 & 0.1 \\ 100 & 1 & 0.1 \end{array} \right)$$

LFV constraints

Perturbativity

Neutrino mass in the AKS model

$$(m_\nu)_{ij} = C_{\text{AKS}} \, \frac{\kappa^2}{(16\pi^2)^3} \, \frac{m_i \, Y_{i\alpha} \, Y_{j\beta} \, m_j}{(M_N)_{\alpha\beta}} \, F_{\text{AKS}}$$

Fit to oscillation data

Simple estimate

$$\xrightarrow{\hspace{2cm}}$$

$R = \mathbb{I}$

$m_\nu \sim 0.1$ eV

$$Y \sim \begin{array}{c} \begin{array}{ccc} 1/m_e & 1/m_\mu & 1/m_\tau \end{array} \\ \begin{pmatrix} 100 & 1 & 0.1 \\ 100 & 1 & 0.1 \\ 100 & 1 & 0.1 \end{pmatrix} \end{array}$$

LFV constraints

Perturbativity

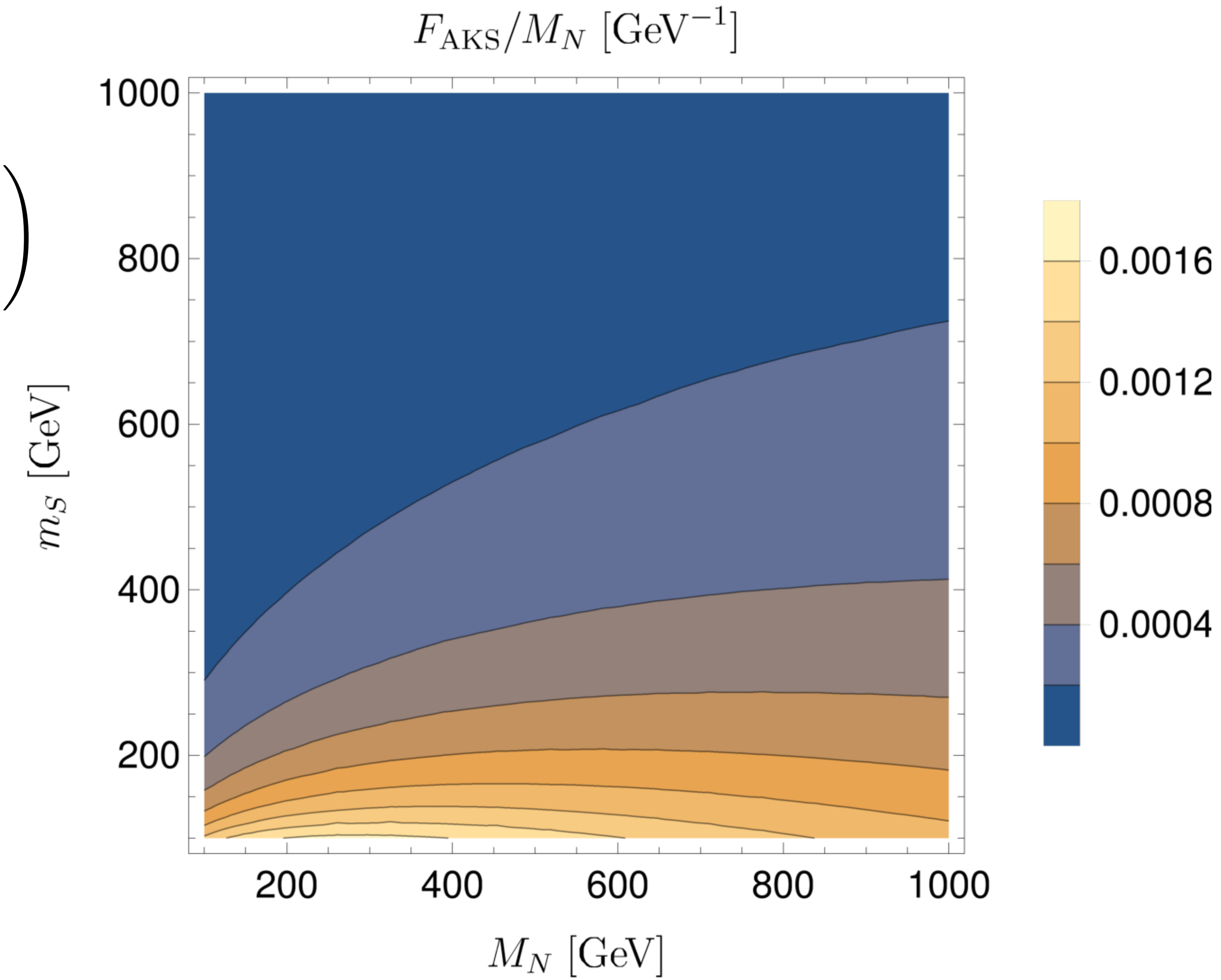
AKS loop function

Loop function

$$F_{\rm AKS}\left(\frac{M_S^2}{M_N^2},\frac{M_\varphi^2}{M_N^2},\frac{M_{H^\pm}^2}{M_N^2}\right)$$

Common scalar mass

$$M_S = M_\varphi = M_{H^\pm} \equiv m_S$$



AKS loop function

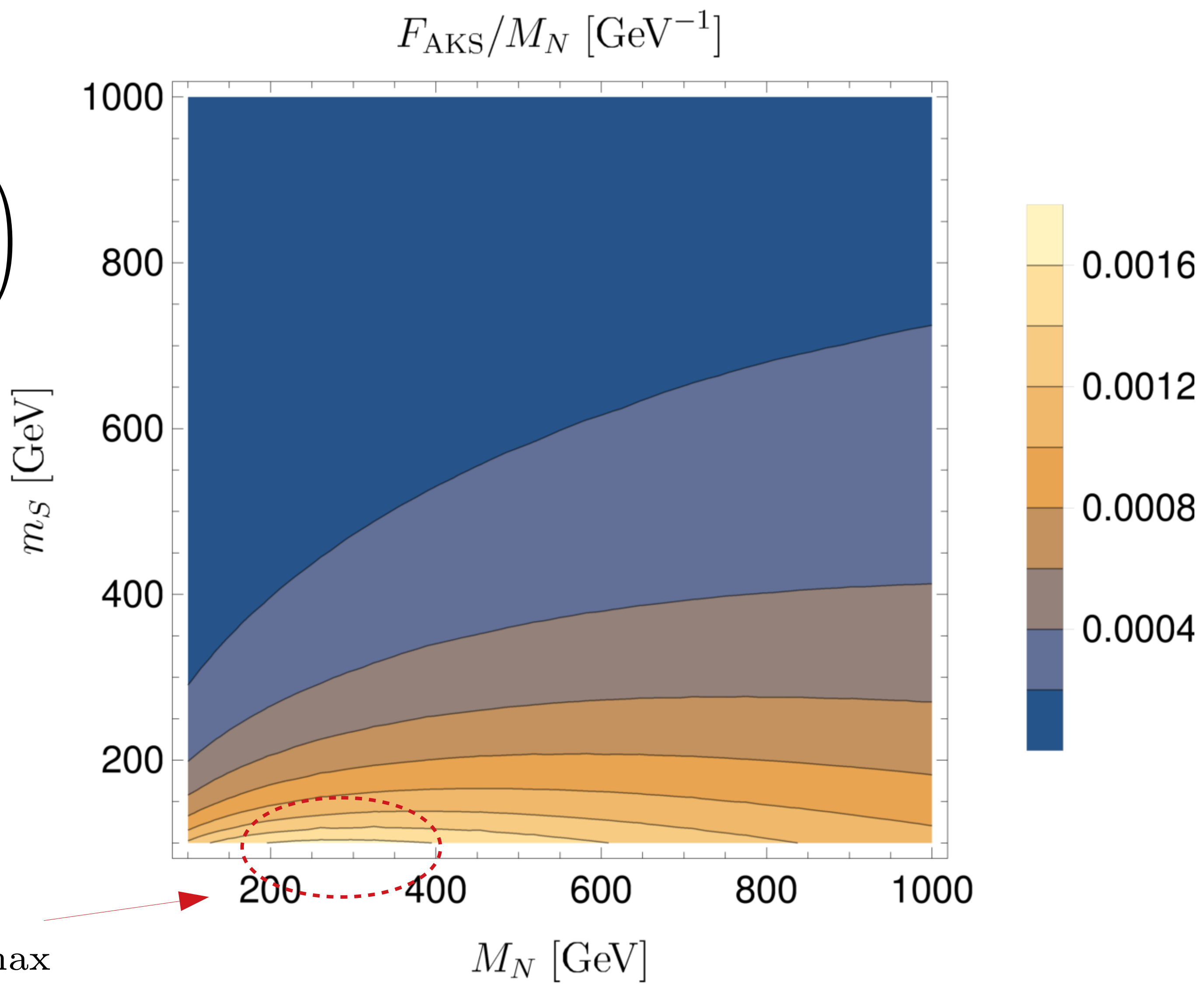
Loop function

$$F_{\rm AKS}\left(\frac{M_S^2}{M_N^2}, \frac{M_\varphi^2}{M_N^2}, \frac{M_{H^\pm}^2}{M_N^2}\right)$$

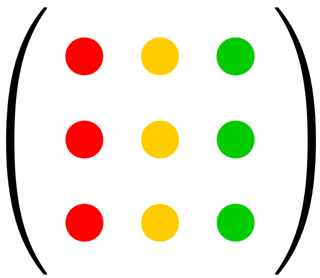
Common scalar mass

$$M_S = M_\varphi = M_{H^\pm} \equiv m_S$$

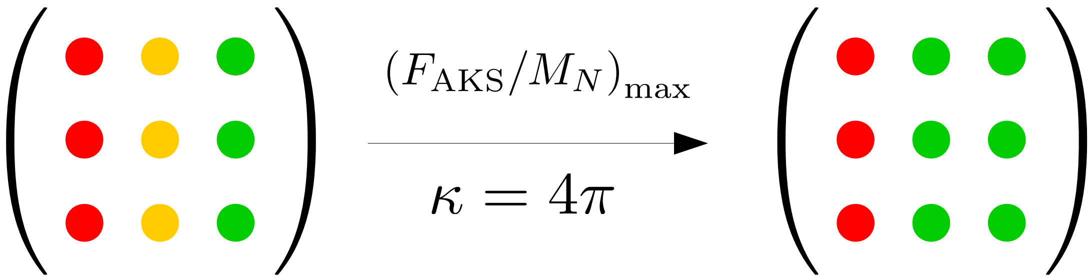
$$(F_{\rm AKS}/M_N)_{\rm max}$$



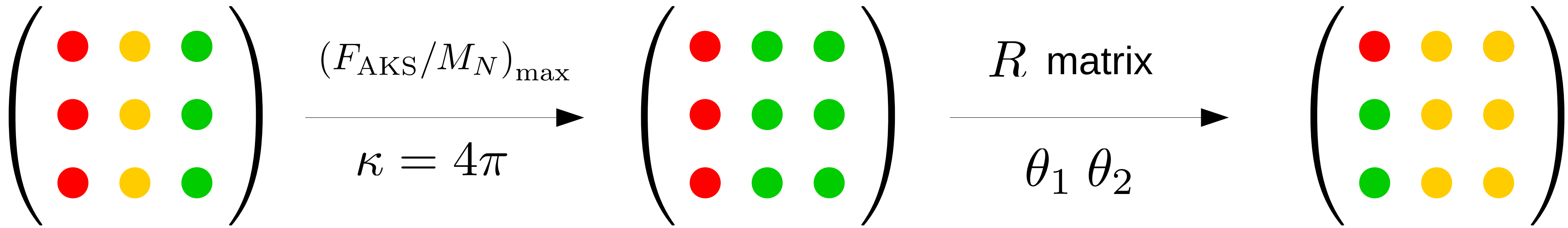
Fine-tuning Y in the AKS model



Fine-tuning Y in the AKS model



Fine-tuning Y in the AKS model

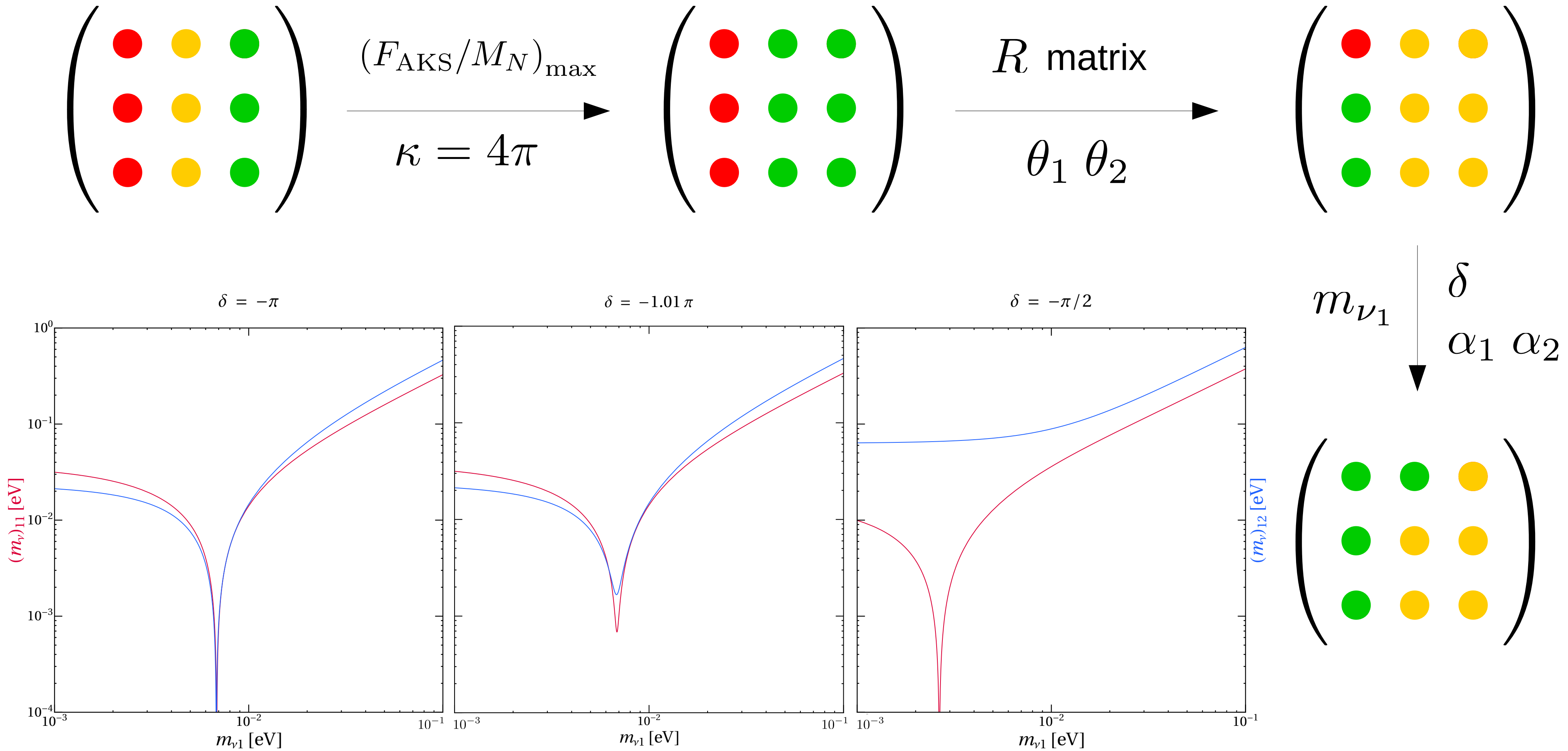


$$R = R(\theta_1, \theta_2, \theta_3)$$

θ_i : complex angles

$$\theta_1 \; \theta_2 \;\; \Rightarrow \;\; Y_{21,31} \to 0$$

Fine-tuning Y in the AKS model



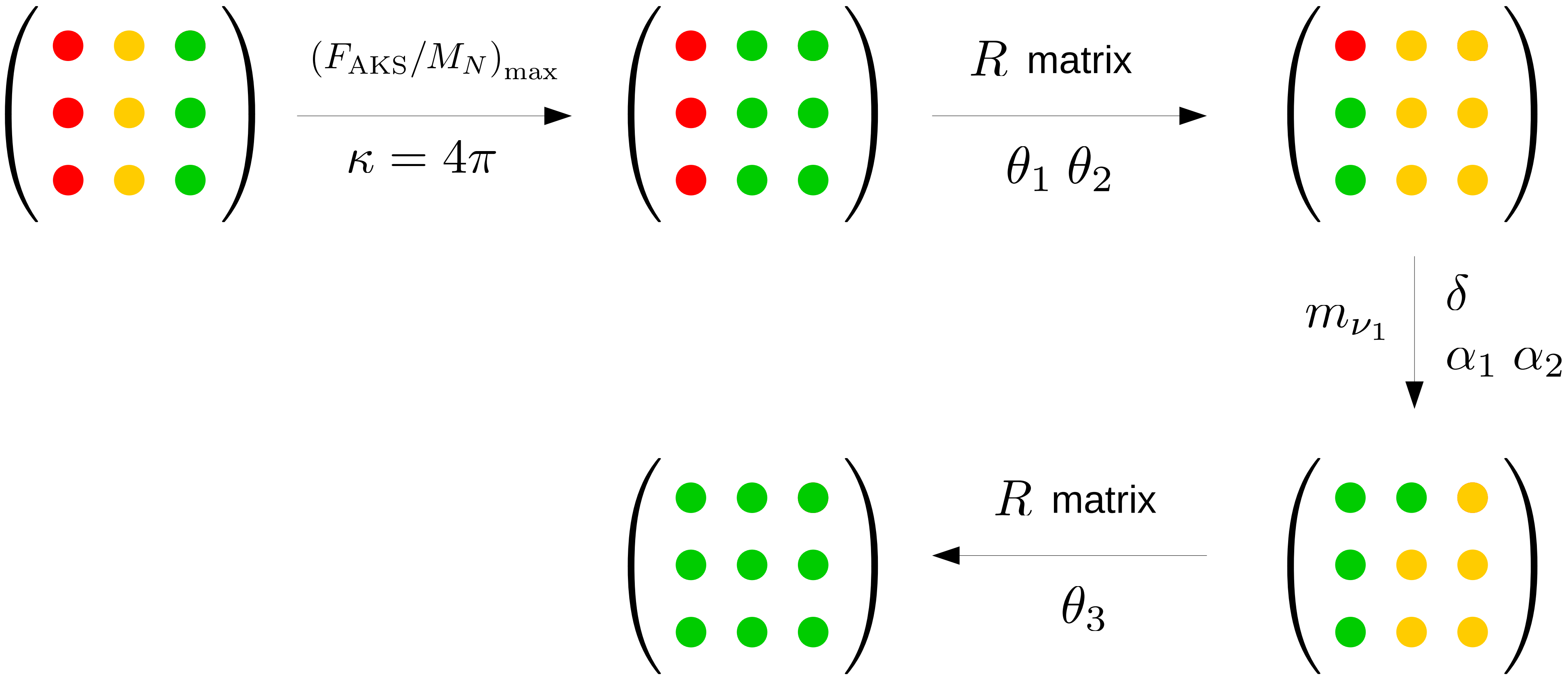
2σ tension with fits

[De Salas et al, 2018]

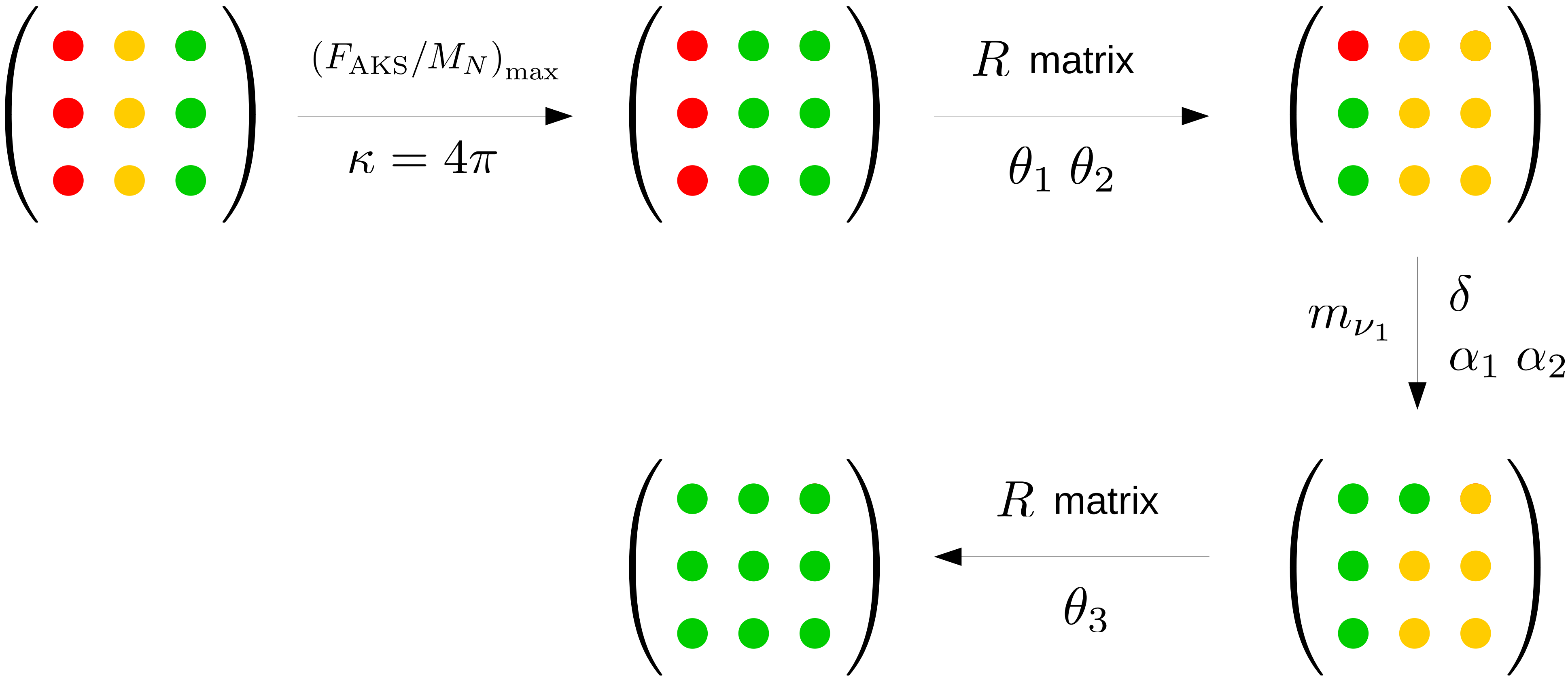
Fine-tuned

Partially working for $\delta = -\dfrac{\pi}{2}$

Fine-tuning Y in the AKS model



Fine-tuning Y in the AKS model



Perturbativity + flavor = (fine-tuning)^{4}

\+
largish LFV
effects

Final discussion

Final discussion

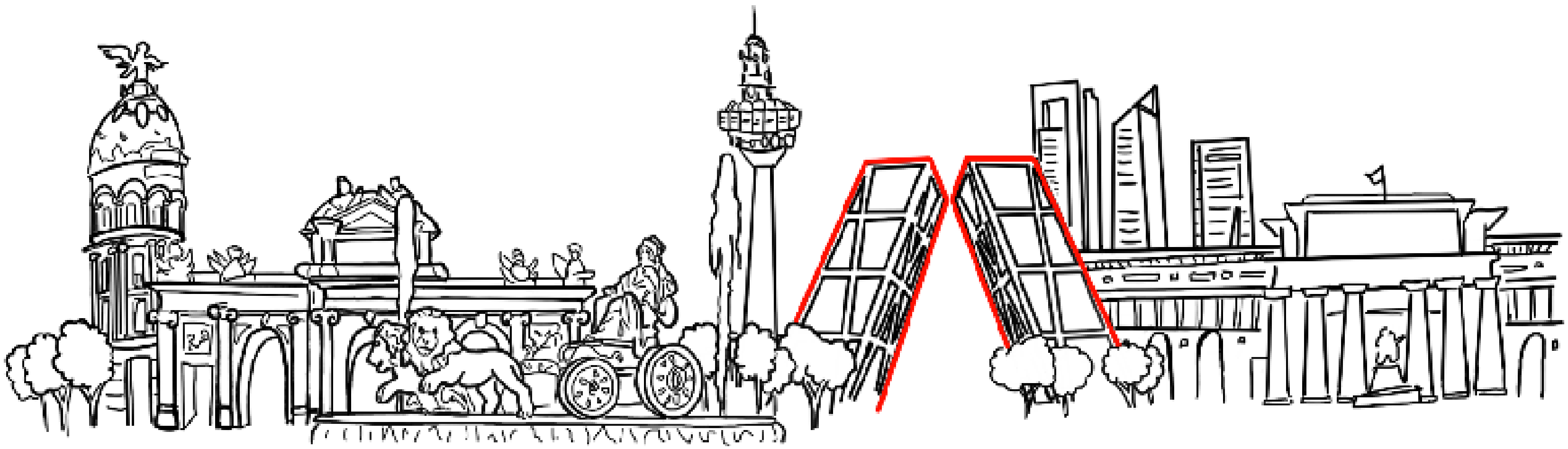
Radiative neutrino mass models constitute a simple yet predictive class of models, often including a dark matter candidate

Two possible issues:

Scotogenic model with fermion DM: restricted parameter space due to clash between flavor and DM production

3-loop minimal models: strong fine-tuning required to fit oscillation data with perturbative Yukawa couplings

Thanks for your attention!



And congratulations to Clara Murgui for a very artistic drawing!

Backup slides

LFV and fermionic DM

[Vicente, Yaguna, 2014]

Random scan of the parameter space

- Free parameters: $M_{N_i}, m_R, m_{\eta^+}, \lambda_5, R$
- Neutrino oscillation parameters in agreement with data (at 3σ)
- Impose MEG bound: $\mathrm{Br}(\mu \to e\gamma) < 5.7 \cdot 10^{-13}$
- DM relic density (computed with **micrOMEGAs**) in agreement with observations

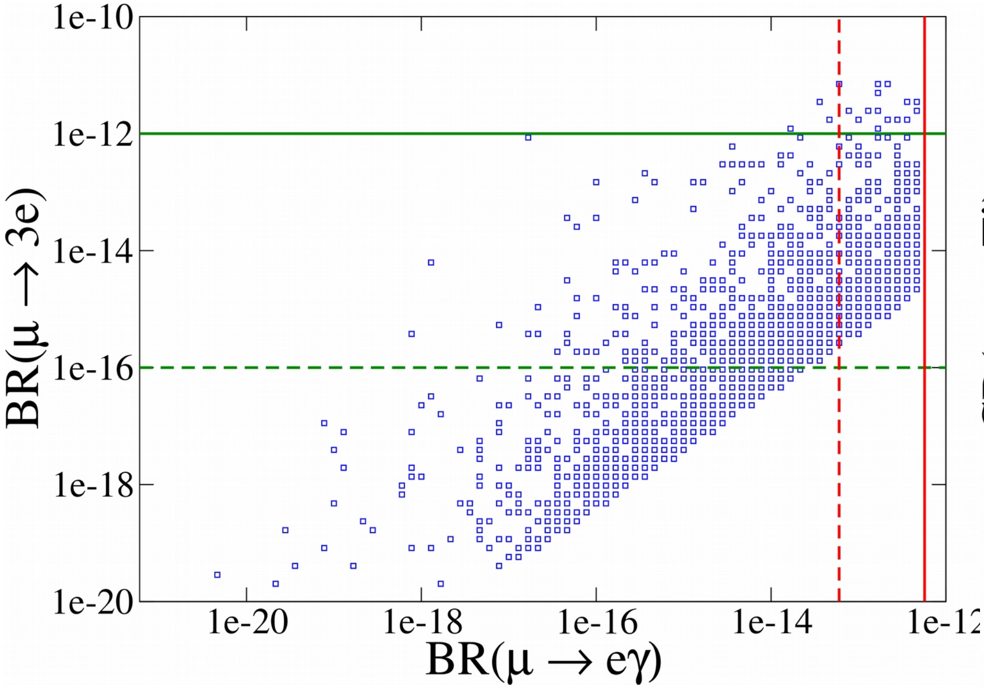
Two scenarios

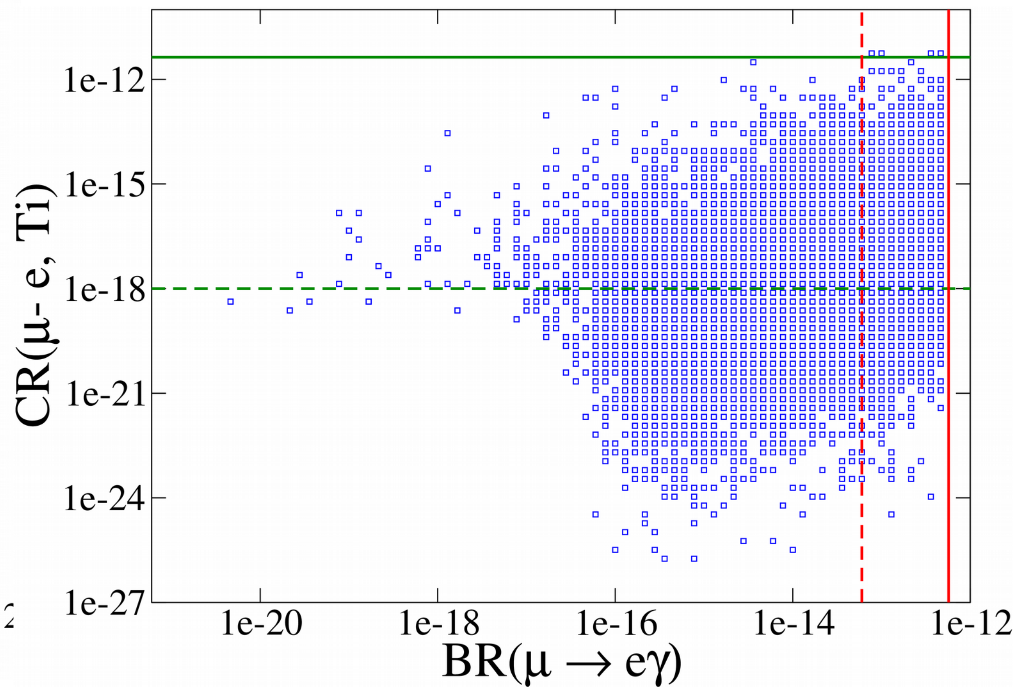
- **N_1 – N_1 annihilation:** large Yukawa couplings, most favorable case for LFV processes
- **N_1 – η coannihilation:** the Yukawa couplings can be smaller, lower LFV rates

[See Molinaro et al, 2014, for a FIMP realization of the scotogenic model]

[Vicente, Yaguna, 2014]

N_1 – η coannihilation





- Scenario with relaxed constraints
- The next round of experiments will not cover the whole parameter space

The KNT model

[Krauss, Nasri, Trodden, 2002]

	gen	$SU(2)_L$	$U(1)_Y$	$\mathbb{Z}_2$
h	1	$\mathbf{1}$	1	+
S	1	$\mathbf{1}$	1	−
N	3	$\mathbf{1}$	0	−

Singly charged scalars

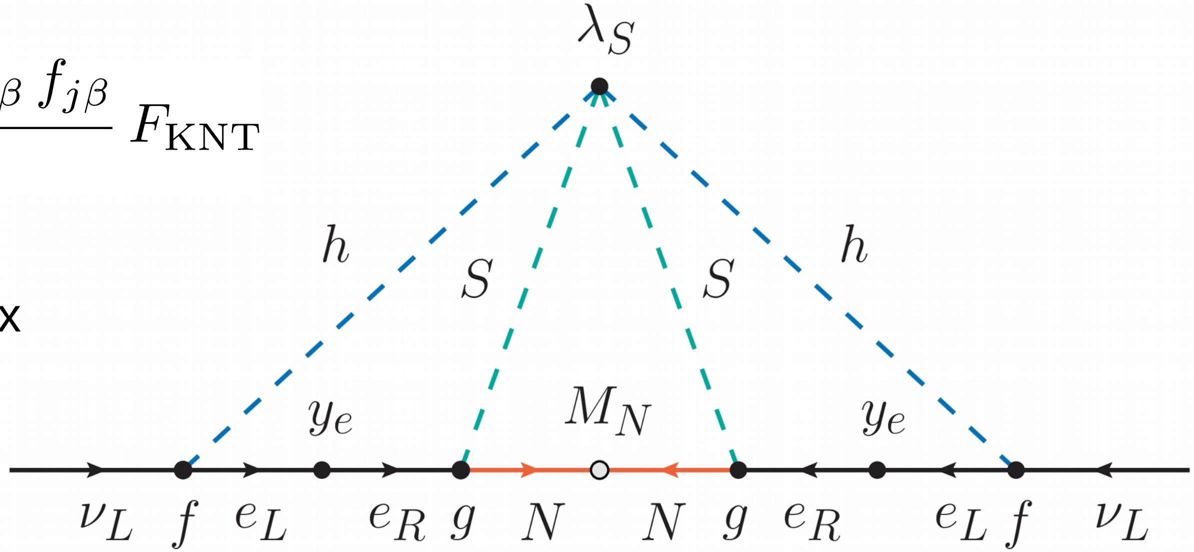
Conserved $\mathbb{Z}_2$ parity

Dark Matter!

$$-\mathcal{L} \supset f\,\overline{\ell^c}\,\ell\,h + g\,\overline{N^c}\,e_R\,S + \frac{1}{2}M_N\overline{N^c}N + \lambda_S\,(hS^*)^2 + \text{h.c.}$$

$$(m_\nu)_{ij} = \frac{\lambda_S}{(16\pi^2)^3}\,\frac{f_{i\alpha}\,m_\alpha\,g^*_\alpha\,g^*_\beta\,m_\beta\,f_{j\beta}}{(M_N)_{\alpha\beta}}\,F_{\text{KNT}}$$

f : antisymmetric Yukawa matrix



[Gustafsson, No, Rivera, 2012]

	gen	$\mathrm{SU}(2)_L$	$\mathrm{U}(1)_Y$	$\mathbb{Z}_2$
S	1	**1**	1	$-$
ρ	1	**1**	2	$+$
η	1	**2**	$1/2$	$-$

← Inert doublet

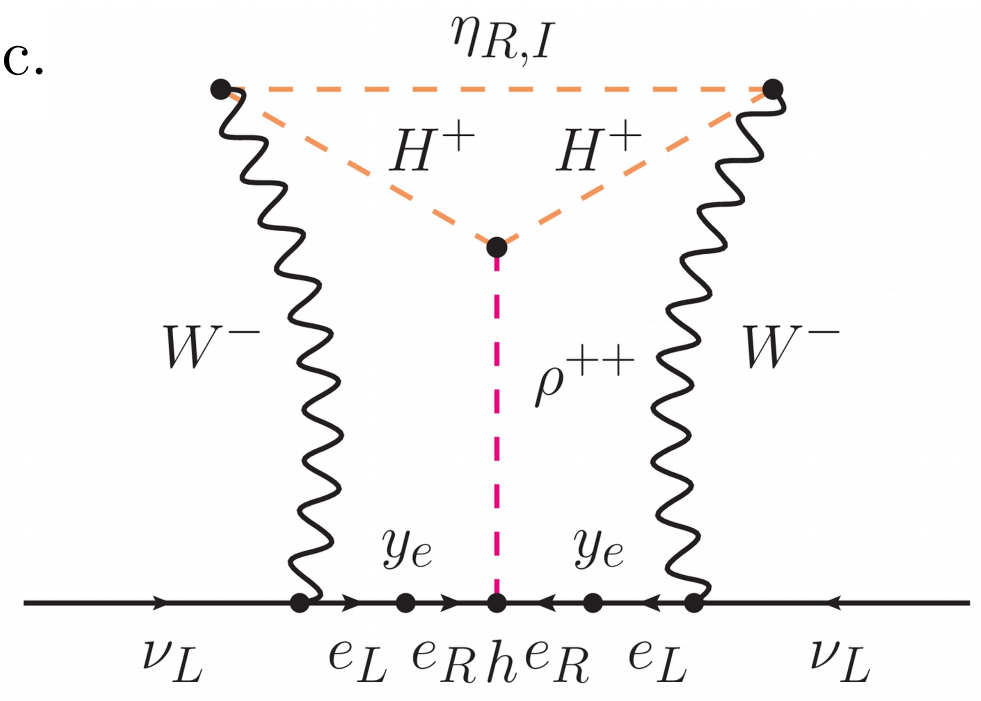
Conserved $\mathbb{Z}_2$ parity

Dark Matter!

$$-\mathcal{L} \supset h\, \overline{e_R^c} e_R\, \rho + \frac{1}{2}\, \lambda_5\, (\phi \eta^*)^2 + \text{h.c.}$$

$$(m_\nu)_{ij} = \frac{\lambda_5}{(16\pi^2)^3}\, \frac{m_i\, h_{ij}\, m_j}{v}\, F_{\text{Cocktail}}$$

h : symmetric Yukawa matrix
(type-II seesaw-like)



The master parametrization

[Cordero-Carrión, Hirsch, AV, 2018]

$$\boxed{m = f \, \left(y_1^T \, M \, y_2 + y_2^T \, M^T \, y_1 \right)}$$

$$y_1 = \frac{1}{\sqrt{2\,f}} \, V_1^\dagger \begin{pmatrix} \Sigma^{-1/2} \, W \, A \\ X_1 \\ X_2 \end{pmatrix} \bar{D}_{\sqrt{m}} \, U^\dagger$$

$$y_2 = \frac{1}{\sqrt{2\,f}} \, V_2^\dagger \begin{pmatrix} \Sigma^{-1/2} \, \widehat{W}^* \, \widehat{B} \\ X_3 \end{pmatrix} \bar{D}_{\sqrt{m}} \, U^\dagger$$

A philosophical moment

Occam’s razor:

The simplest explanation is the correct one

Occam’s laser:

The most awesome explanation is the correct one

Occam’s hammer:

My explanation is the correct one

All credit goes to
Alberto Aparici