Neutrino Model Building & keV sterile neutrino Dark Matter

Alexander Merle
Royal Institute of Technology (KTH)
Stockholm, Sweden

Based on: JCAP 1101: **034**, 2011 (Lindner, **AM**, Niro)
1105.5136 [hep-ph] (**AM** & Niro)

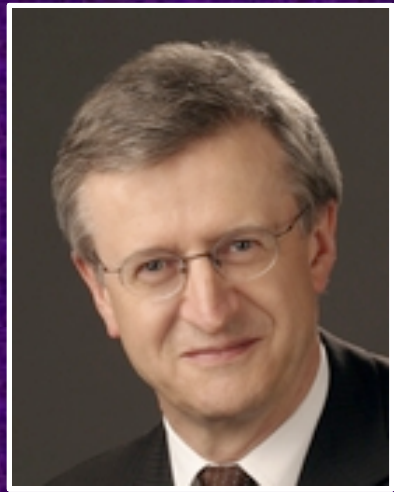
"Ecole Internationale d'Astrophysique Daniel Chalonge"

09 June 2011

<u>Don‘t forget to say:</u> **THANK YOU!!!**

Don't forget to say: **THANK YOU!!!**

- **to my collaborators:**



Manfred Lindner

Viviana Niro

Don‘t forget to say: **THANK YOU!!!**

- **to my collaborators:**

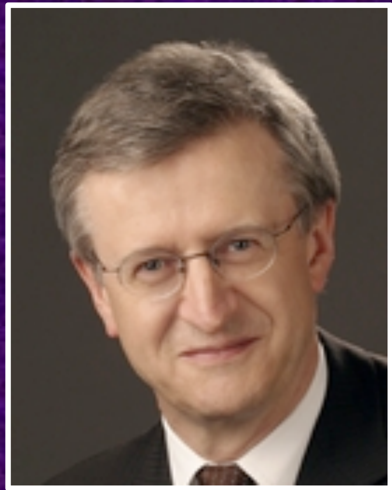
Manfred Lindner

Viviana Niro

- **and in particular to Norma and Hector for inviting me to this great workshop!!!**

Don‘t forget to say: **THANK YOU!!!**

• **to my collaborators:**



Manfred Lindner

Viviana Niro

• **and in particular to Norma and Hector for inviting me to this great workshop!!!**

THANK YOU!!!

Contents:

1. Introduction

1. Introduction

The Standard Model of Elementary Particle Physics does not solve everything:

1. Introduction

The Standard Model of Elementary Particle Physics does not solve everything:

- Hierarchy problem

1. Introduction

The Standard Model of Elementary Particle Physics does not solve everything:

- Hierarchy problem
- Neutrino masses & mixings

1. Introduction

The Standard Model of Elementary Particle Physics does not solve everything:

- Hierarchy problem
- Neutrino masses & mixings
- Dark Matter

1. Introduction

The Standard Model of Elementary Particle Physics does not solve everything:

- Hierarchy problem
- Neutrino masses & mixings
- Dark Matter
- Dark Energy

1. Introduction

The Standard Model of Elementary Particle Physics does not solve everything:

- Hierarchy problem
- Neutrino masses & mixings
- Dark Matter
- Dark Energy
- …

1. Introduction

<u>The Standard Model of Elementary Particle Physics does not solve everything:</u>

- Hierarchy problem
- Neutrino masses & mixings
- Dark Matter
- Dark Energy
- …

⇨ *Physics beyond the SM needed!!*

2. Neutrino pheno & models

2. Neutrino pheno & models

Prime example: *models for neutrino masses*

2. Neutrino pheno & models

<u>Prime example</u><u>:</u> *models for neutrino masses*

- experimental facts:

2. Neutrino pheno & models

Prime example: *models for neutrino masses*

- experimental facts:

MAINZ/Toitsk ➔ $m_\beta<2.2$eV ➔ **KATRIN**

2. Neutrino pheno & models

Prime example: *models for neutrino masses*

- experimental facts:

MAINZ/Toitsk → m_β<2.2eV → **KATRIN**

Heidelberg-Moscow → $|m_{ee}|$<1eV → **GERDA**

2. Neutrino pheno & models

Prime example: *models for neutrino masses*

- experimental facts:

MAINZ/Toitsk → m_β<2.2eV → **KATRIN**

Heidelberg-Moscow → $|m_{ee}|$<1eV → **GERDA**

WMAP 7 years + BAO + SN → Σ<0.7eV → **Planck**

2. Neutrino pheno & models

<u>Prime example</u>: *models for neutrino masses*

- experimental facts:

MAINZ/Toitsk ➔ $m_\beta<2.2$eV ➔ **KATRIN**

Heidelberg-Moscow ➔ $|m_{ee}|<1$eV ➔ **GERDA**

WMAP 7 years + BAO + SN ➔ $\Sigma<0.7$eV ➔ **Planck**

oscillations ➔ $\Delta m^2_S=7.6\times10^{-5}\text{eV}^2$, $\Delta m^2_A=2.4\times10^{-3}\text{eV}^2$

2. Neutrino pheno & models

Prime example: *models for neutrino masses*

- experimental facts:

MAINZ/Toitsk → m_β<2.2eV → **KATRIN**

Heidelberg-Moscow → $|m_{ee}|$<1eV → **GERDA**

WMAP 7 years + BAO + SN → Σ<0.7eV → **Planck**

oscillations → $\Delta m^2_S=7.6\times10^{-5}\text{eV}^2$, $\Delta m^2_A=2.4\times10^{-3}\text{eV}^2$

→ conclusion: m_ν < 1eV, but non-zero!

2. Neutrino pheno & models

Prime example: *models for neutrino masses*

- experimental facts:

  MAINZ/Toitsk ➔ $m_\beta<2.2eV$ ➔ **KATRIN**

  Heidelberg-Moscow ➔ $|m_{ee}|<1eV$ ➔ **GERDA**

  WMAP 7 years + BAO + SN ➔ $\Sigma<0.7eV$ ➔ **Planck**

  oscillations ➔ $\Delta m^2_S=7.6\times10^{-5}eV^2$, $\Delta m^2_A=2.4\times10^{-3}eV^2$

  ➔ conclusion: m_ν < 1eV, but non-zero!
- BUT: Standard Model ➔ $m_\nu=0$

2. Neutrino pheno & models

Prime example: *models for neutrino masses*

- experimental facts:

MAINZ/Toitsk → $m_\beta<2.2$eV → **KATRIN**

Heidelberg-Moscow → $|m_{ee}|<1$eV → **GERDA**

WMAP 7 years + BAO + SN → $\Sigma<0.7$eV → **Planck**

oscillations → $\Delta m^2_S=7.6\times10^{-5}\mathrm{eV}^2$, $\Delta m^2_A=2.4\times10^{-3}\mathrm{eV}^2$

→ conclusion: m_ν < 1eV, but non-zero!

- BUT: Standard Model → $m_\nu=0$

with N_R → m_ν should be around v=174 GeV

2. Neutrino pheno & models

Possible explanations:

2. Neutrino pheno & models

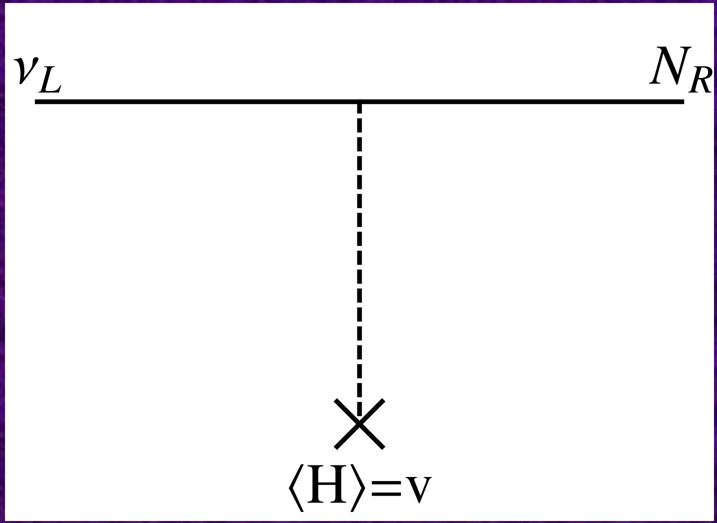
Possible explanations:

- seesaw mechanism type I: at least 2 N_R needed

2. Neutrino pheno & models

Possible explanations:

- seesaw mechanism type I: at least 2 N_R needed

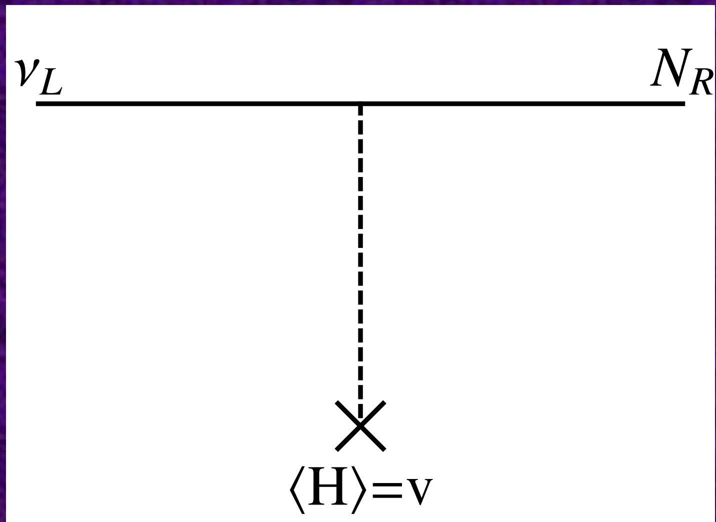


Dirac mass:
~100 GeV

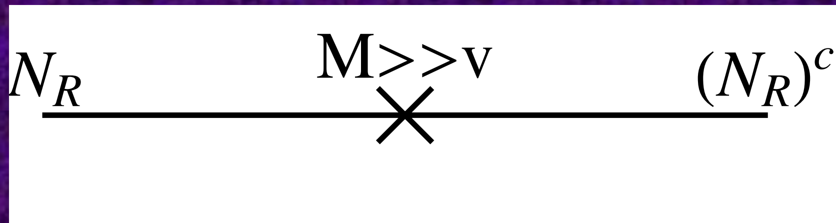
2. Neutrino pheno & models

Possible explanations:

- seesaw mechanism type I: at least 2 N_R needed



Dirac mass:
~100 GeV

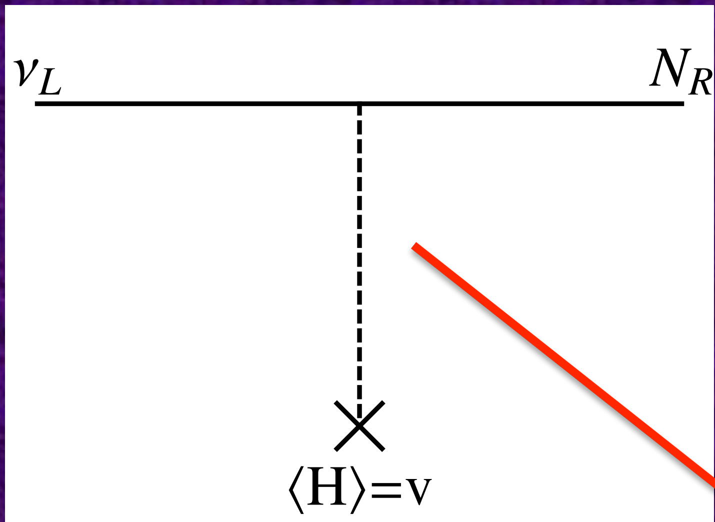


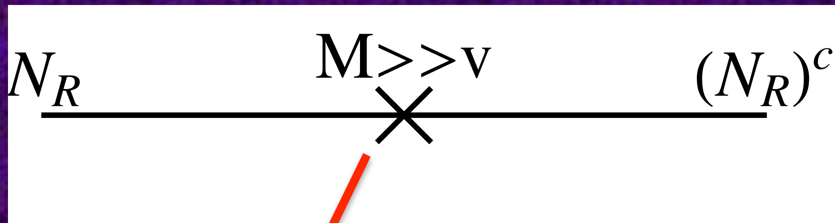
RH-Majorana mass:
~10^{13} GeV

2. Neutrino pheno & models

Possible explanations:

- seesaw mechanism type I: at least 2 N_R needed





RH-Majorana mass:
~10^{13} GeV

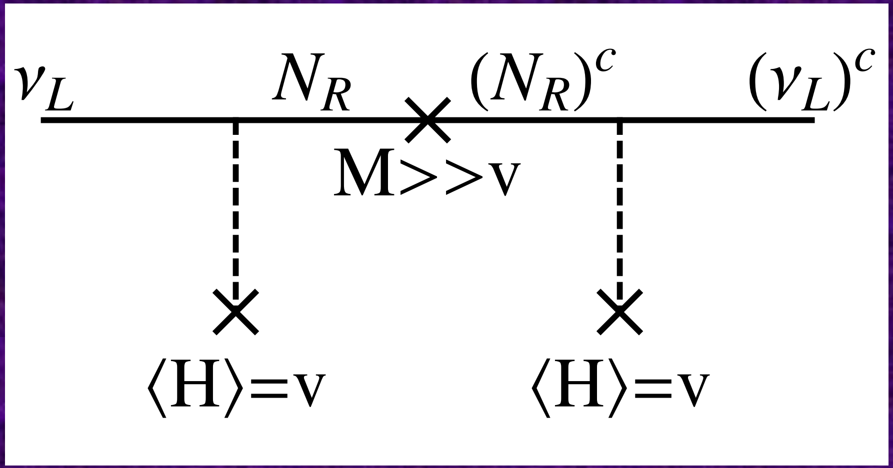
Dirac mass:
~100 GeV

SEESAW TYPE I

2. Neutrino pheno & models

Possible explanations:

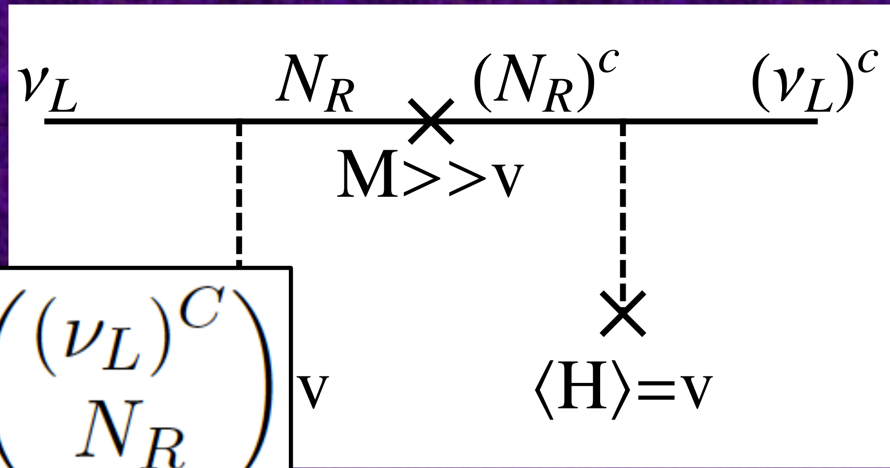
- seesaw mechanism type I:



2. Neutrino pheno & models

Possible explanations:

- seesaw mechanism type I:

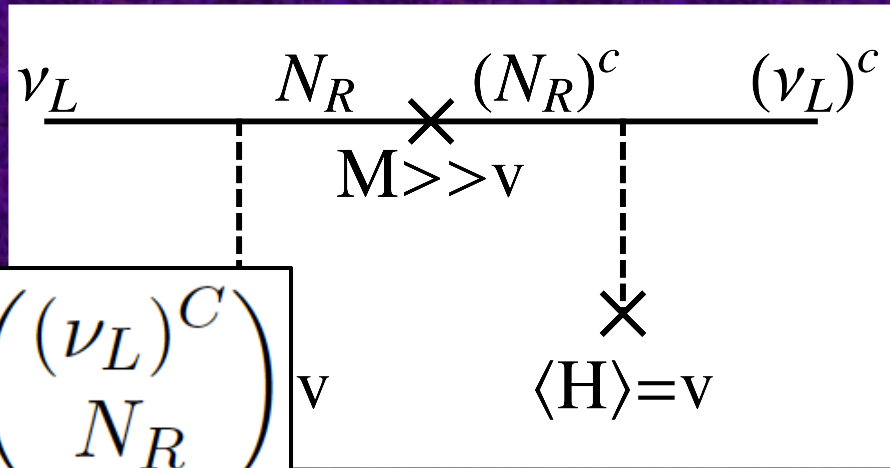


$$(\overline{\nu_L}, \overline{(N_R)^C}) \left(\begin{array}{c|c} 0 & m_D \\ \hline m_D^T & M_R \end{array}\right) \begin{pmatrix} (\nu_L)^C \\ N_R \end{pmatrix}$$

2. Neutrino pheno & models

Possible explanations:

- seesaw mechanism type I:



$$(\overline{\nu_L}, \overline{(N_R)^C}) \left(\begin{array}{c|c} 0 & m_D \\ \hline m_D^T & M_R \end{array} \right) \begin{pmatrix} (\nu_L)^C \\ N_R \end{pmatrix}$$

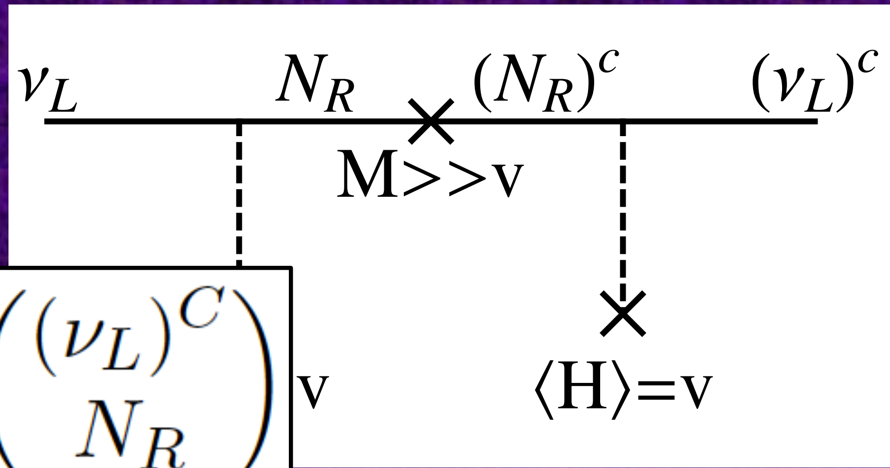
➔ light neutrino mass matrix:

$$- m_D^T M_R^{-1} m_D$$

2. Neutrino pheno & models

Possible explanations:

- seesaw mechanism type I:



$$\left(\overline{\nu_L}, \overline{(N_R)^C}\right) \left(\begin{array}{c|c} 0 & m_D \\ \hline m_D^T & M_R \end{array}\right) \begin{pmatrix} (\nu_L)^C \\ N_R \end{pmatrix}$$

➔ light neutrino mass matrix:

$$-\, m_D^T \, M_R^{-1} \, m_D$$

➔ suppression due to large M_R ➔ eV-scale mass!

2. Neutrino pheno & models

Possible explanations:

- seesaw mechanism type II:

2. Neutrino pheno & models

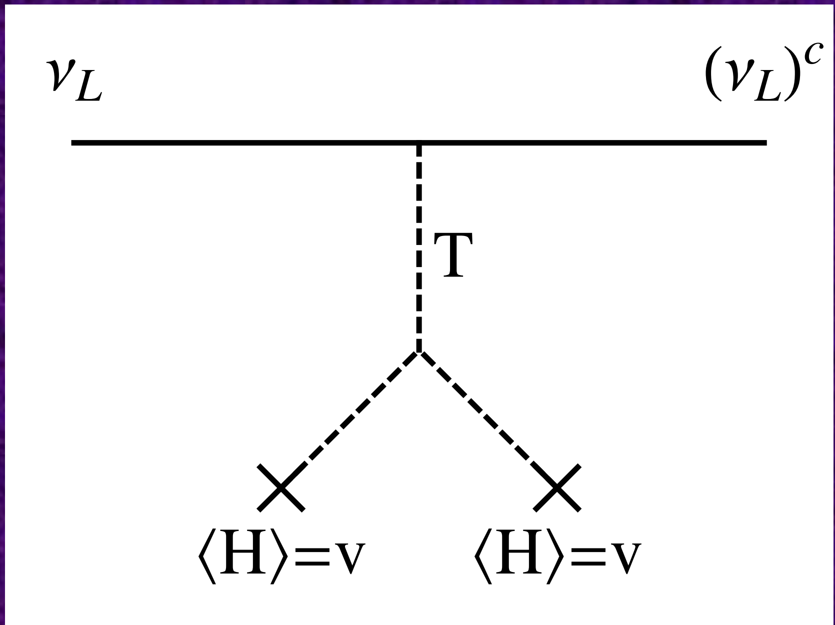
Possible explanations:

- seesaw mechanism type II: Higgs triplet needed

2. Neutrino pheno & models

Possible explanations:

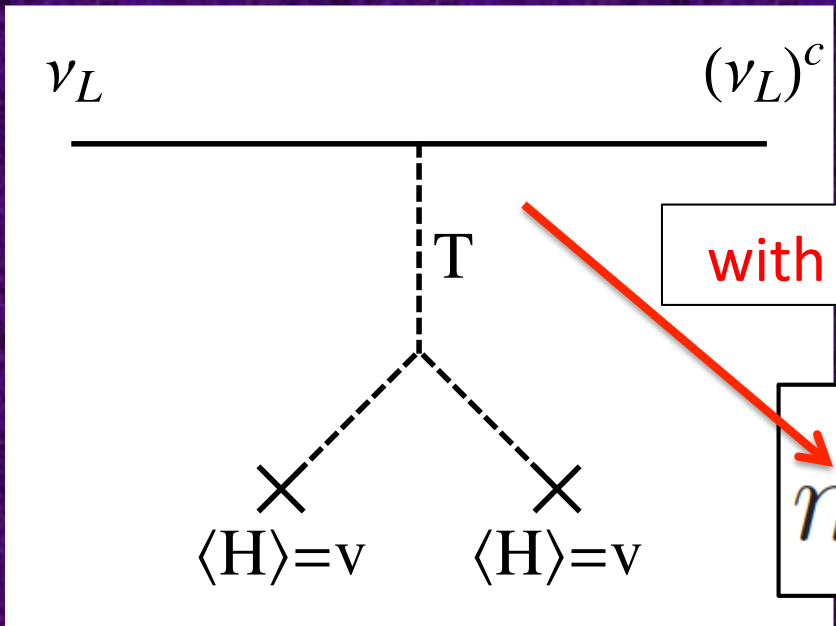
- seesaw mechanism type II: Higgs triplet needed



2. Neutrino pheno & models

Possible explanations:

- seesaw mechanism type II: Higgs triplet needed



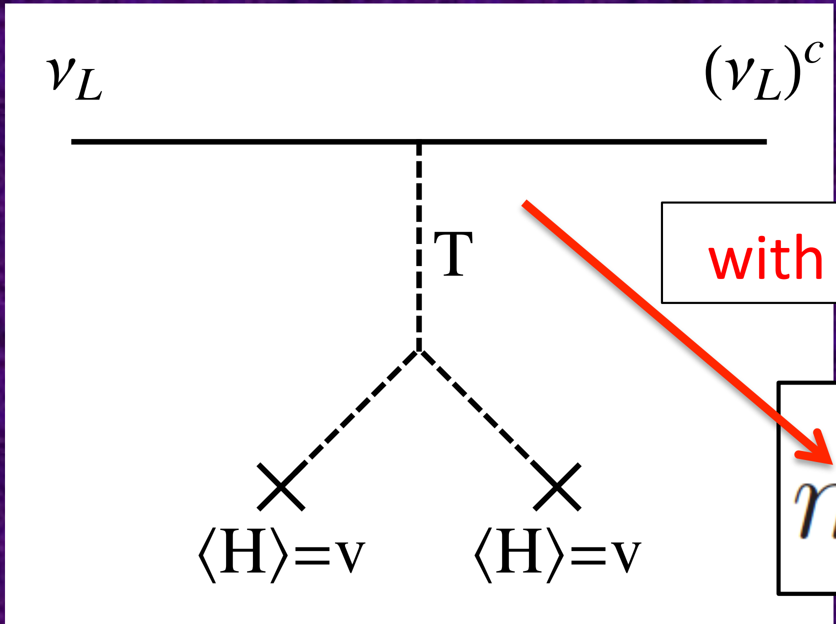
with N_R

$$m_L - m_D^T M_R^{-1} m_D$$

2. Neutrino pheno & models

Possible explanations:

- seesaw mechanism type II: Higgs triplet needed



with N_R

$$m_L - m_D^T M_R^{-1} m_D$$

→ suppression due to $M_{T,R}$ & possible cancellation!

2. Neutrino pheno & models

Possible explanations:

- radiative mass:

2. Neutrino pheno & models

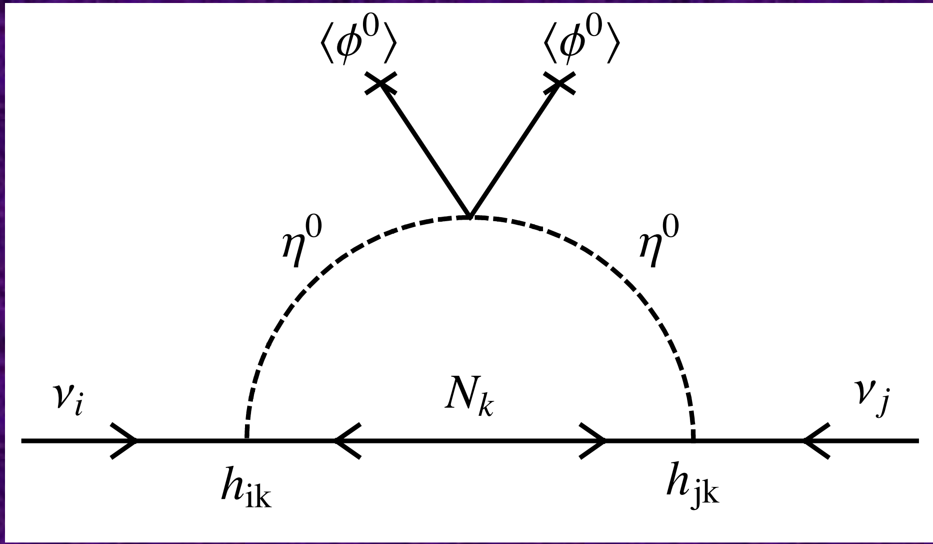
Possible explanations:

- radiative mass: e.g. scotogenic model

2. Neutrino pheno & models

Possible explanations:

- radiative mass: e.g. scotogenic model

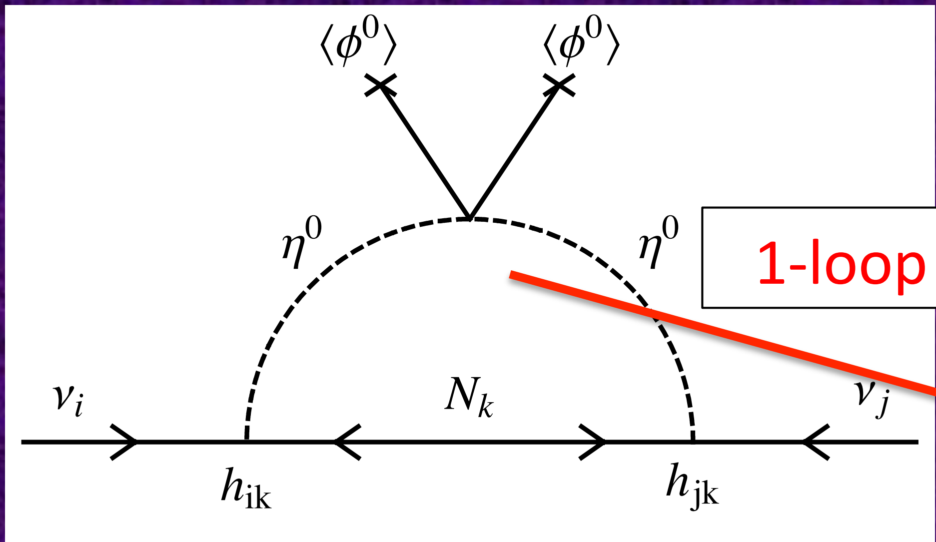


Ma: Phys. Rev. **D73** (2006) 077301

2. Neutrino pheno & models

Possible explanations:

- radiative mass: e.g. scotogenic model



Ma: Phys. Rev. **D73** (2006) 077301

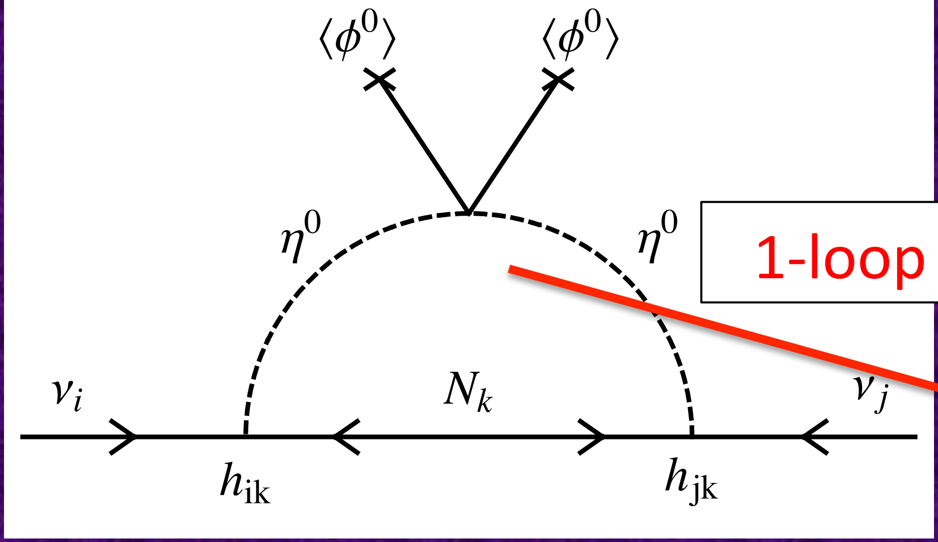
1-loop computation

$$(\mathcal{M}_\nu)_{ij} = \sum_{k=1}^{3} h_{ik} h_{jk} \Lambda_k$$

2. Neutrino pheno & models

Possible explanations:

- radiative mass: e.g. scotogenic model



Ma: Phys. Rev. **D73** (2006) 077301

1-loop computation

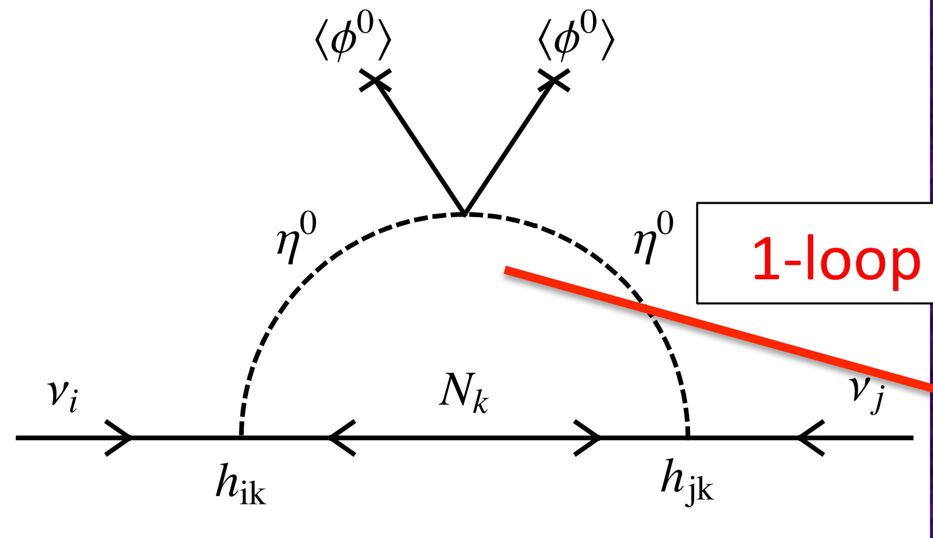
$$(\mathcal{M}_\nu)_{ij} = \sum_{k=1}^{3} h_{ik} h_{jk} \Lambda_k$$

$$\Lambda_k = \frac{M_k}{16\pi^2}\left[\frac{m^2(H^0)}{m^2(H^0)-M_k^2}\ln\left(\frac{m^2(H^0)}{M_k^2}\right) - \frac{m^2(A^0)}{m^2(A^0)-M_k^2}\ln\left(\frac{m^2(A^0)}{M_k^2}\right)\right]$$

2. Neutrino pheno & models

Possible explanations:

- radiative mass: e.g. scotogenic model



Ma: Phys. Rev. **D73** (2006) 077301

1-loop computation

$$(\mathcal{M}_\nu)_{ij} = \sum_{k=1}^{3} h_{ik} h_{jk} \Lambda_k$$

$$\Lambda_k = \frac{M_k}{16\pi^2}\left[\frac{m^2(H^0)}{m^2(H^0)-M_k^2}\ln\left(\frac{m^2(H^0)}{M_k^2}\right) - \frac{m^2(A^0)}{m^2(A^0)-M_k^2}\ln\left(\frac{m^2(A^0)}{M_k^2}\right)\right]$$

➔ Loop-suppression with M_R~1TeV!

2. Neutrino pheno & models

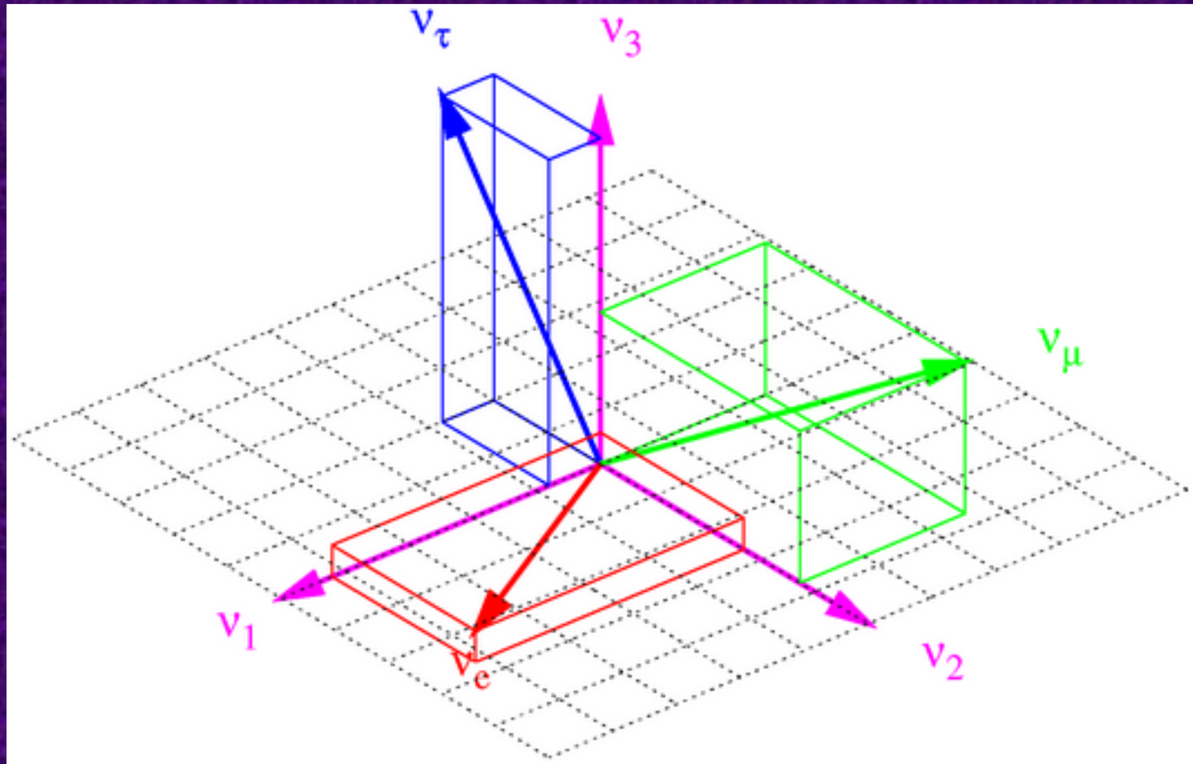
- Neutrino mixing:

2. Neutrino pheno & models

- Neutrino mixing: mass basis ≠ flavour basis

2. Neutrino pheno & models

- Neutrino mixing: mass basis ≠ flavour basis



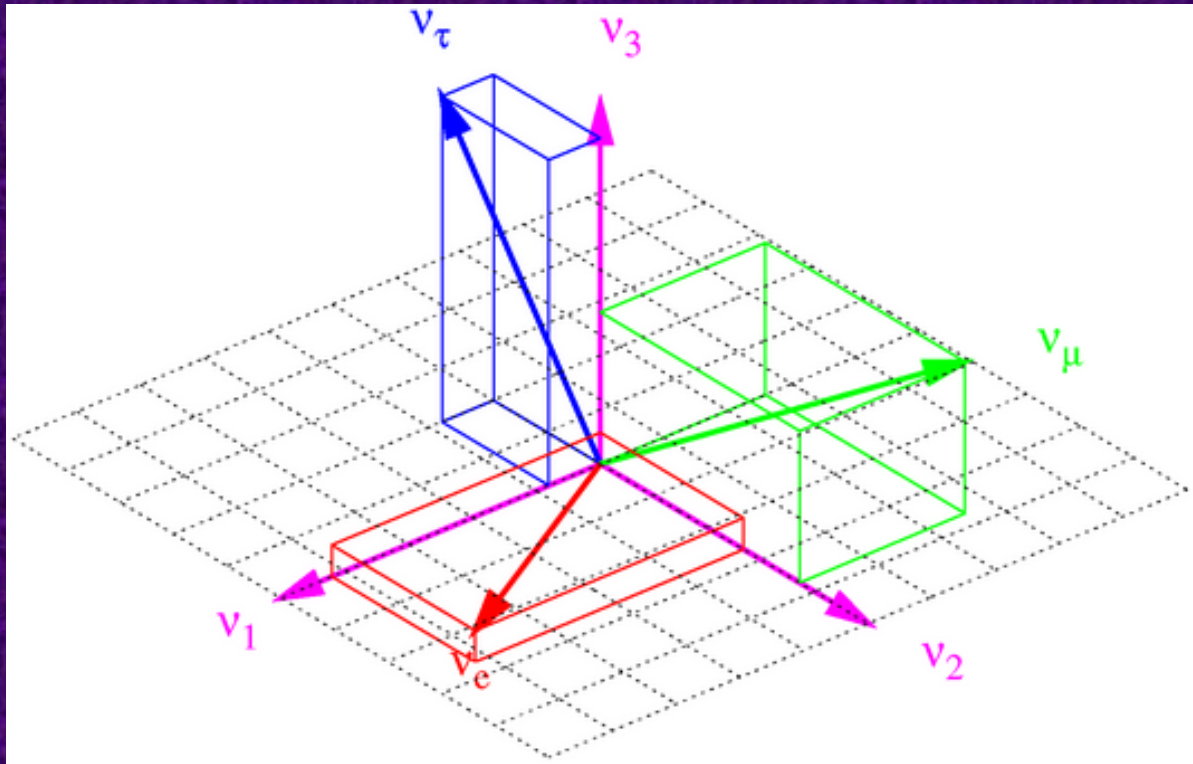
http://nu.phys.laurentian.ca/~fleurot/oscillations/

2. Neutrino pheno & models

- Neutrino mixing: mass basis ≠ flavour basis

$\theta_{12}=34°$
$\theta_{23}=45°$
$\theta_{13}<11°$

Schwetz, Tórtola Vallé
1103.0734 [hep-ph]



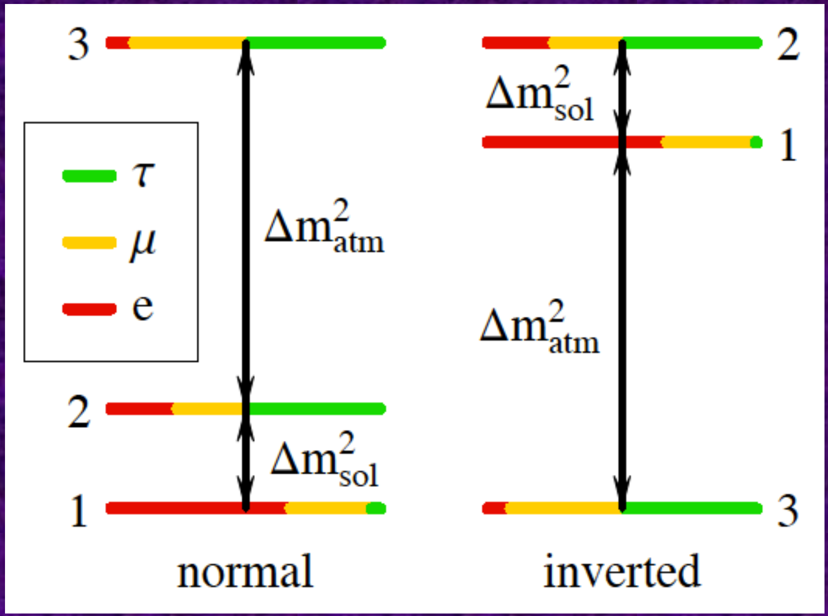
http://nu.phys.laurentian.ca/~fleurot/oscillations/

2. Neutrino pheno & models

- further puzzles in neutrino physics:

2. Neutrino pheno & models

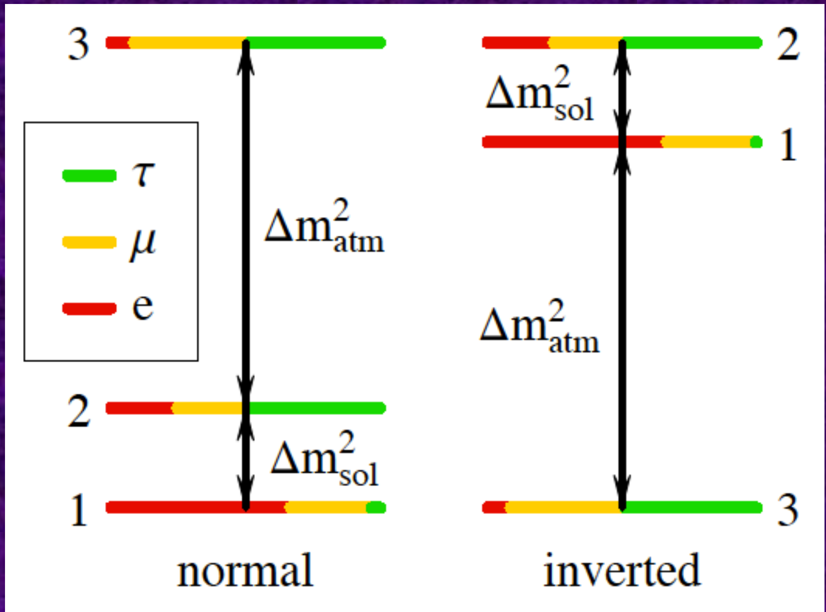
- further puzzles in neutrino physics:

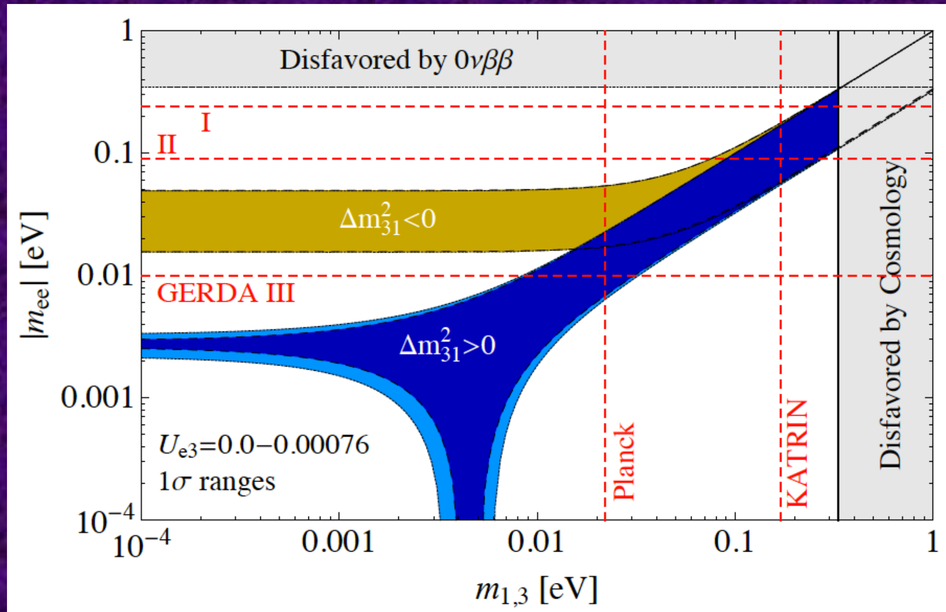


Normal or inverted ordering?

2. Neutrino pheno & models

- further puzzles in neutrino physics:



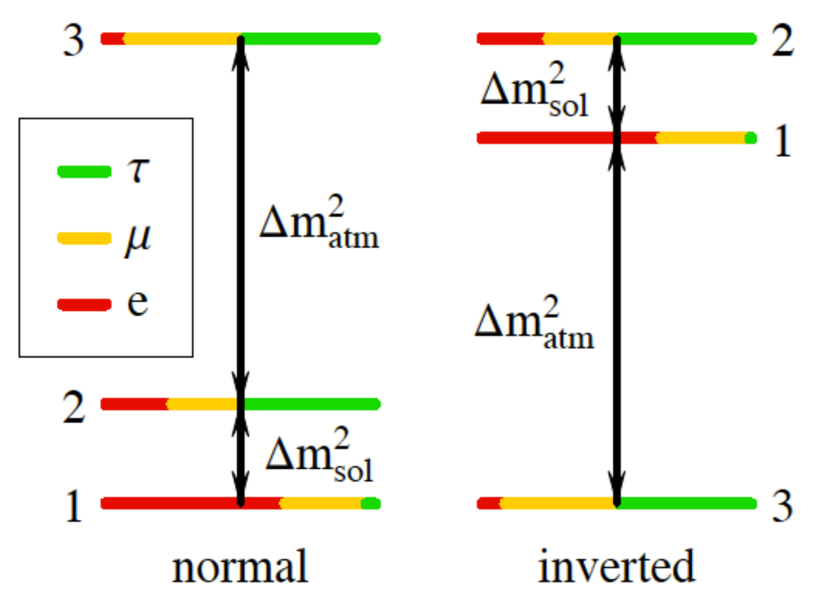


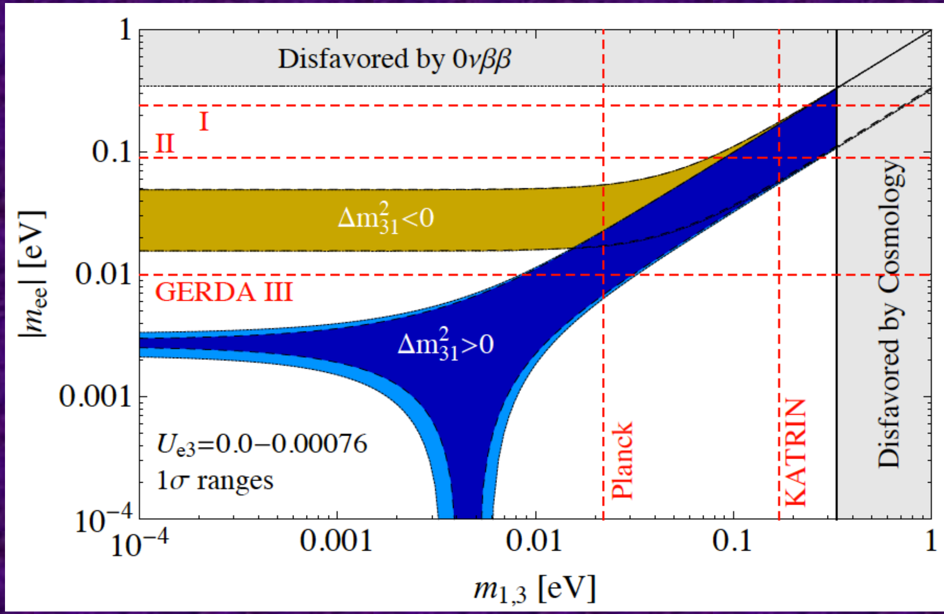
Normal or inverted ordering?

Dirac or Majorana?

2. Neutrino pheno & models

- further puzzles in neutrino physics:





Normal or inverted ordering?

Dirac or Majorana?

To be explained by models!!

2. Neutrino pheno & models

- **BE CAREFUL WITH TERMINOLOGY:**

2. Neutrino pheno & models

- **BE CAREFUL WITH TERMINOLOGY:**

SCENARIO

MODEL

2. Neutrino pheno & models

- **BE CAREFUL WITH TERMINOLOGY:**

SCENARIO

Provides a framework that includes keV sterile neutrinos

examples: νMSM, gauge extensions,...

→ provide all features needed for phenomenological calculations

MODEL

2. Neutrino pheno & models

- **BE CAREFUL WITH TERMINOLOGY:**

SCENARIO

Provides a framework that includes keV sterile neutrinos

examples: νMSM, gauge extensions,...

➔ provide all features needed for phenomenological calculations

MODEL

Explains the appearance and the mass pattern of keV ν's

examples: to be discussed here ➔ provide an "explanation" for what is measured

2. Neutrino pheno & models

- **QUESTION**: Can we also build models that involve one sterile neutrino with a keV-scale mass?!?

2. Neutrino pheno & models

- **QUESTION**: Can we also build models that involve one sterile neutrino with a keV-scale mass?!?

→ explanation of the keV mass scale

2. Neutrino pheno & models

- **QUESTION**: Can we also build models that involve one sterile neutrino with a keV-scale mass?!?

→ explanation of the keV mass scale

→ connection between neutrino flavour sector and Dark Matter

2. Neutrino pheno & models

- **QUESTION**: Can we also build models that involve one sterile neutrino with a keV-scale mass?!?

→ explanation of the keV mass scale

→ connection between neutrino flavour sector and Dark Matter

→ strong constraints for seesaw mechanism (keV too light?!?)

2. Neutrino pheno & models

- **QUESTION**: Can we also build models that involve one sterile neutrino with a keV-scale mass?!?

→ explanation of the keV mass scale

→ connection between neutrino flavour sector and Dark Matter

→ strong constraints for seesaw mechanism (keV too light?!?)

→ splitting of N_i-masses cries for a flavour symmetry

2. Neutrino pheno & models

- **QUESTION**: Can we also build models that involve one sterile neutrino with a keV-scale mass?!?

→ explanation of the keV mass scale

→ connection between neutrino flavour sector and Dark Matter

→ strong constraints for seesaw mechanism (keV too light?!?)

→ splitting of N_i-masses cries for a flavour symmetry

→ sterile ν models can be probed with light ν experiments

2. Neutrino pheno & models

- **QUESTION**: Can we also build models that involve one sterile neutrino with a keV-scale mass?!?

→ explanation of the keV mass scale

→ connection between neutrino flavour sector and Dark Matter

→ strong constraints for seesaw mechanism (keV too light?!?)

→ splitting of N_i-masses cries for a flavour symmetry

→ sterile ν models can be probed with light ν experiments

<u>up to now:</u> only 3 existing classes of models that give an explanation for the mass pattern keV-heavy-heavy (to my knowledge)

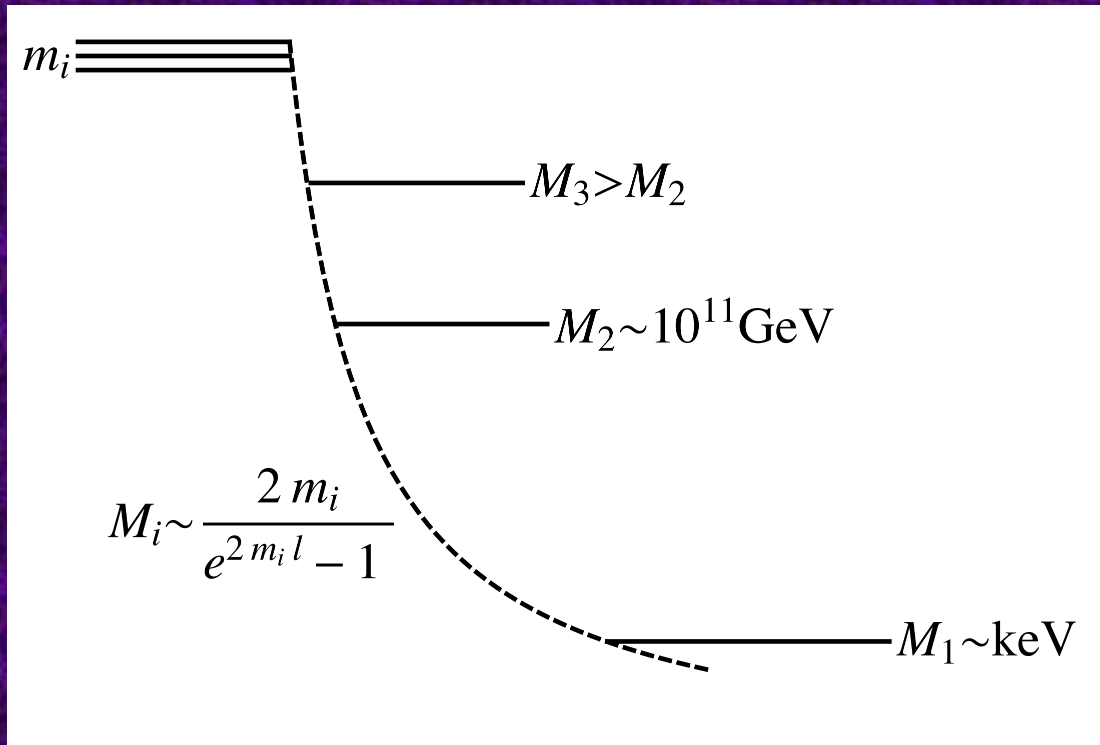
3. A Randall-Sundrum Model

3. A Randall-Sundrum Model

first strong model for keV sterile ν DM: "Dark Matter from Split Seesaw" (Kusenko, Takahashi, Yanagida: Phys. Lett. **B693** (2010) 144)

3. A Randall-Sundrum Model

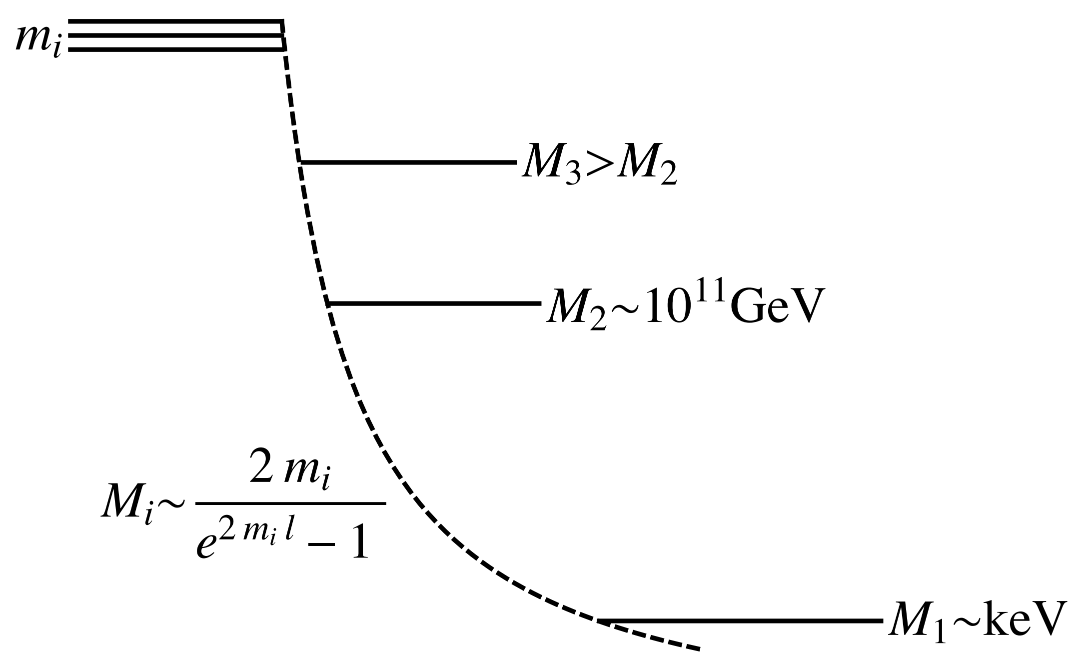
first strong model for keV sterile ν DM: “Dark Matter from Split Seesaw“ (Kusenko, Takahashi, Yanagida: Phys. Lett. **B693** (2010) 144)



3. A Randall-Sundrum Model

first strong model for keV sterile ν DM: "Dark Matter from Split Seesaw" (Kusenko, Takahashi, Yanagida: Phys. Lett. **B693** (2010) 144)

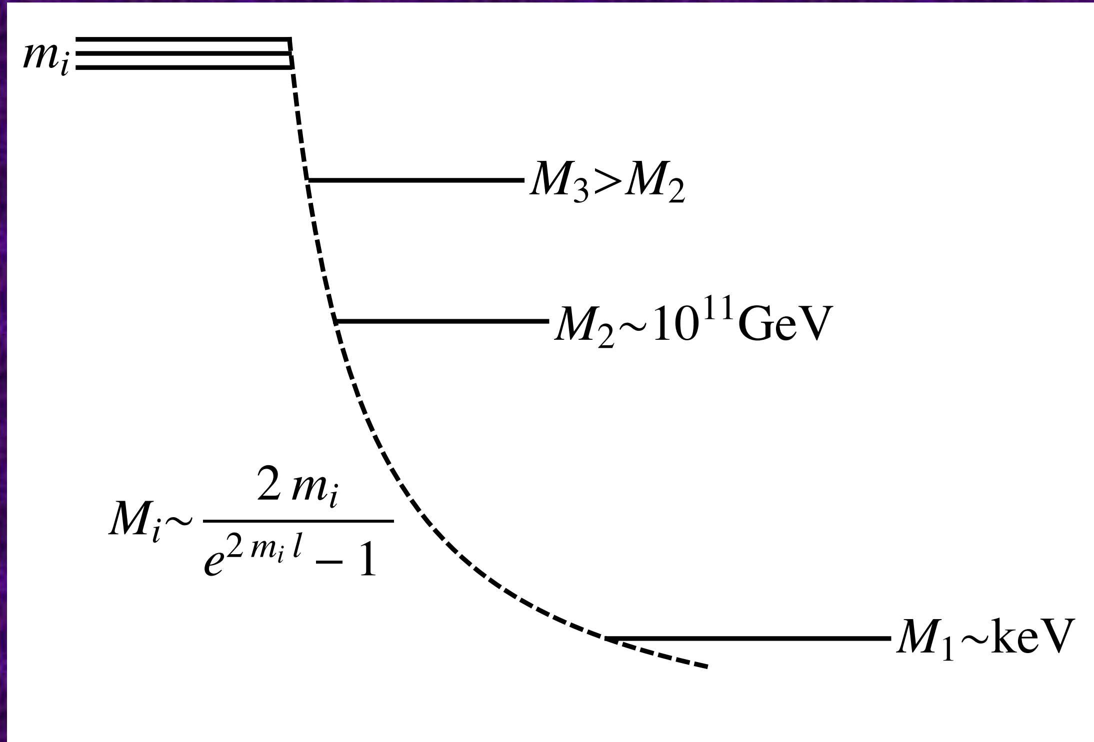
• idea: use the splitting between SM brane and hidden brane



3. A Randall-Sundrum Model

first strong model for keV sterile ν DM: “Dark Matter from Split Seesaw“ (Kusenko, Takahashi, Yanagida: Phys. Lett. **B693** (2010) 144)

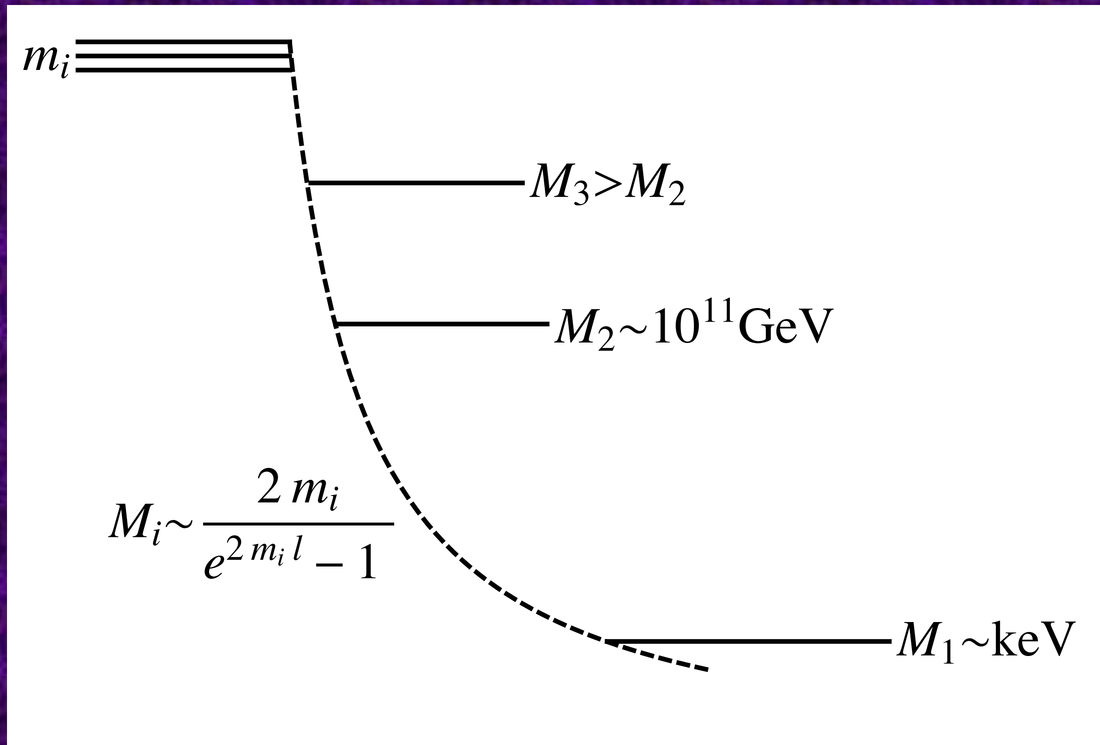
• idea: use the splitting between SM brane and hidden brane
• heavy neutrinos on hidden brane, only exponentially suppressed effect on SM brane



3. A Randall-Sundrum Model

first strong model for keV sterile ν DM: "Dark Matter from Split Seesaw" (Kusenko, Takahashi, Yanagida: Phys. Lett. **B693** (2010) 144)

- idea: use the splitting between SM brane and hidden brane
- heavy neutrinos on hidden brane, only exponentially suppressed effect on SM brane
- explains M_1~keV << M_2~10^{11} GeV < M_3



3. A Randall-Sundrum Model

• ansatz:

$$S = \int d^4x \, dy \, M \left(i\bar{\Psi}\Gamma^A \partial_A \Psi + m\bar{\Psi}\Psi \right)$$

3. A Randall-Sundrum Model

• ansatz:

$$S = \int \underbrace{d^4x}_{\text{standard 4D part}} \, dy \, M \left(i\bar{\Psi}\Gamma^A \partial_A \Psi + m\bar{\Psi}\Psi \right)$$

3. A Randall-Sundrum Model

- ansatz:

$$S = \int \underbrace{d^4x}_{\text{standard 4D part}} \, \underbrace{dy}_{\text{5th dimension integrated out}} \, M \left(i\bar{\Psi}\Gamma^A \partial_A \Psi + m\bar{\Psi}\Psi \right)$$

standard 4D part

5th dimension integrated out

3. A Randall-Sundrum Model

• ansatz:

$$S = \int d^4x \, dy \, M \left(i\bar{\Psi}\Gamma^A \partial_A \Psi + m\bar{\Psi}\Psi \right)$$

standard 4D part

5th dimension integrated out

• zero mode fermion (n=0):

$$(i\Gamma^5 \partial_5 + m)\Psi^{(0)} = 0$$

3. A Randall-Sundrum Model

• ansatz:

$$S = \int \underbrace{d^4x}_{\text{standard 4D part}} \, \underbrace{dy}_{\text{5th dimension integrated out}} \, M \left(i\bar{\Psi}\Gamma^A \partial_A \Psi + m\bar{\Psi}\Psi \right)$$

• zero mode fermion (n=0):

$$(i\Gamma^5 \partial_5 + m)\Psi^{(0)} = 0$$

➔ bulk profile:

$$\exp(\mp m y)$$

3. A Randall-Sundrum Model

• ansatz:

$$S = \int d^4x \, dy \, M \left(i\bar{\Psi}\Gamma^A\partial_A\Psi + m\bar{\Psi}\Psi \right)$$

standard 4D part

5th dimension integrated out

• zero mode fermion (n=0):

$$(i\Gamma^5\partial_5 + m)\Psi^{(0)} = 0$$

➔ bulk profile: $\exp(\mp my)$

➔ Z_2-parity for LH & RH spinors to obtain chiral fermions in 4D:

Z_2 parity -1 and $+1$ to χ and ψ

3. A Randall-Sundrum Model

• ansatz:

$$S = \int d^4x\, dy\, M \left(i\bar{\Psi}\Gamma^A\partial_A\Psi + m\bar{\Psi}\Psi\right)$$

standard 4D part

5th dimension integrated out

• zero mode fermion (n=0):

$$(i\Gamma^5\partial_5 + m)\Psi^{(0)} = 0$$

➔ bulk profile: $\exp(\mp my)$

➔ Z_2-parity for LH & RH spinors to obtain chiral fermions in 4D:

$$Z_2 \text{ parity } -1 \text{ and } +1 \text{ to } \chi \text{ and } \psi$$

➔ then, only ψ has a zero mode in the bulk (with exp-profile)

3. A Randall-Sundrum Model

- we want a canonically normalized right-handed fermion in 4D:

$$\Psi_R^{(0)}(y,x) \;=\; \sqrt{\frac{2m}{e^{2m\ell}-1}}\frac{1}{\sqrt{M}}e^{my}\psi_R^{(4D)}(x)$$

3. A Randall-Sundrum Model

- we want a canonically normalized right-handed fermion in 4D:

$$\Psi_R^{(0)}(y,x) \;=\; \sqrt{\frac{2m}{e^{2m\ell}-1}}\frac{1}{\sqrt{M}}e^{my}\psi_R^{(4D)}(x)$$

exponential suppression

3. A Randall-Sundrum Model

• we want a canonically normalized right-handed fermion in 4D:

$$\Psi_R^{(0)}(y,x) = \sqrt{\frac{2m}{e^{2m\ell}-1}}\frac{1}{\sqrt{M}}e^{my}\psi_R^{(4D)}(x)$$

exponential suppression

separation of branes

3. A Randall-Sundrum Model

• we want a canonically normalized right-handed fermion in 4D:

$$\Psi_R^{(0)}(y,x) = \sqrt{\frac{2m}{e^{2m\ell}-1}}\frac{1}{\sqrt{M}}e^{my}\psi_R^{(4D)}(x)$$

exponential suppression

separation of branes

bulk profile (SM at y=0)

3. A Randall-Sundrum Model

• we want a canonically normalized right-handed fermion in 4D:

$$\Psi_R^{(0)}(y,x) \;=\; \sqrt{\frac{2m}{e^{2m\ell}-1}}\frac{1}{\sqrt{M}}e^{my}\psi_R^{(4D)}(x)$$

exponential suppression

separation of branes

bulk profile (SM at y=0)

4D fermion

3. A Randall-Sundrum Model

• we want a canonically normalized right-handed fermion in 4D:

$$\Psi_R^{(0)}(y,x) = \sqrt{\frac{2m}{e^{2m\ell}-1}}\frac{1}{\sqrt{M}}e^{my}\psi_R^{(4D)}(x)$$

exponential suppression

4D fermion

separation of branes

bulk profile (SM at y=0)

• integrating out the 5th dimension:

$$S = \int d^4x\,dy\left\{M\left(i\bar{\Psi}_{iR}^{(0)}\Gamma^A\partial_A\Psi_{iR}^{(0)} + m_i\bar{\Psi}_{iR}^{(0)}\Psi_{iR}^{(0)}\right)\right.$$
$$\left.+\delta(y)\left(\frac{\kappa_i}{2}v_{\mathrm{B-L}}\bar{\Psi}_{iR}^{(0)c}\Psi_{iR}^{(0)} + \tilde{\lambda}_{i\alpha}\bar{\Psi}_{iR}^{(0)}L_\alpha\,\phi + \mathrm{h.c.}\right)\right\}$$

3. A Randall-Sundrum Model

- we obtain:

3. A Randall-Sundrum Model

- we obtain:

$$M_{Ri} = \kappa_i v_{\mathrm{B-L}} \frac{2m_i}{M(e^{2m_i \ell} - 1)}$$

3. A Randall-Sundrum Model

• we obtain:

$$M_{Ri} = \kappa_i v_{\mathrm{B-L}} \frac{2m_i}{M(e^{2m_i\ell} - 1)}$$

4D RH-mass

3. A Randall-Sundrum Model

• we obtain:

$$M_{Ri} = \kappa_i v_{\mathrm{B-L}} \frac{2m_i}{M(e^{2m_i \ell} - 1)}$$

4D RH-mass

v_{B-L} determines the natural size of the N_R mass

3. A Randall-Sundrum Model

- we obtain:

$$M_{Ri} = \kappa_i v_{\mathrm{B-L}} \frac{2m_i}{M(e^{2m_i \ell} - 1)}$$

4D RH-mass

$v_{B\text{-}L}$ determines the natural size of the N_R mass

exponential suppression due to bulk profile

3. A Randall-Sundrum Model

• we obtain:

$$M_{Ri} = \kappa_i v_{\mathrm{B-L}} \frac{2m_i}{M(e^{2m_i \ell} - 1)}$$

4D RH-mass

$v_{B\text{-}L}$ determines the natural size of the N_R mass

exponential suppression due to bulk profile

➔ Extreme splitting between N_R-masses!!! ✔

3. A Randall-Sundrum Model

• we obtain:

$$M_{Ri} = \kappa_i v_{\mathrm{B-L}} \frac{2m_i}{M(e^{2m_i \ell} - 1)}$$

4D RH-mass

v_{B-L} determines the natural size of the N_R mass

exponential suppression due to bulk profile

➔ Extreme splitting between N_R-masses!!! ✔

• light neutrinos:

$$(m_\nu)_{\alpha\beta} = \sum_i \lambda_{i\alpha} \lambda_{i\beta} \frac{\langle \phi^0 \rangle^2}{M_{Ri}}$$

3. A Randall-Sundrum Model

• we obtain:

$$M_{Ri} = \kappa_i v_{\mathrm{B-L}} \frac{2m_i}{M(e^{2m_i\ell} - 1)}$$

4D RH-mass

v_{B-L} determines the natural size of the N_R mass

exponential suppression due to bulk profile

➔ Extreme splitting between N_R-masses!!! ✔

• light neutrinos:

$$(m_\nu)_{\alpha\beta} = \sum_i \lambda_{i\alpha}\lambda_{i\beta} \frac{\langle \phi^0 \rangle^2}{M_{Ri}}$$

seesaw works: $(e^{2ml}-1)$-terms cancel between λ^2 and M_R

4. Soft breaking of L_e-L_μ-L_τ symmetry

4. Soft breaking of L_e-L_μ-L_τ symmetry

first model explaining keV sterile ν DM with L_e-L_μ-L_τ symmetry: Lindner, **AM**, Niro; JCAP 1101: **034,** 2011

4. Soft breaking of L_e-L_μ-L_τ symmetry

first model explaining keV sterile ν DM with L_e-L_μ-L_τ symmetry: Lindner, **AM**, Niro; JCAP 1101: **034,** 2011

Grimus & Lavoura [JHEP 0009: **007**, 2000]: L_e-L_μ-L_τ for 3 light & 2 heavy neutrinos ➔ already shows the desired spectrum for light neutrinos

4. Soft breaking of L_e-L_μ-L_τ symmetry

first model explaining keV sterile ν DM with L_e-L_μ-L_τ symmetry: Lindner, **AM**, Niro; JCAP 1101: **034,** 2011

Grimus & Lavoura [JHEP 0009: **007**, 2000]: L_e-L_μ-L_τ for 3 light & 2 heavy neutrinos ➔ already shows the desired spectrum for light neutrinos

Our model: application of the same symmetry to the heavy sector ➔ generates just the splitting that is desired

4. Soft breaking of L_e-L_μ-L_τ symmetry

first model explaining keV sterile ν DM with L_e-L_μ-L_τ symmetry: Lindner, **AM**, Niro; JCAP 1101: **034,** 2011

Grimus & Lavoura [JHEP 0009: **007**, 2000]: L_e-L_μ-L_τ for 3 light & 2 heavy neutrinos ➔ already shows the desired spectrum for light neutrinos

Our model: application of the same symmetry to the heavy sector ➔ generates just the splitting that is desired

$\mathcal{F}=L_e$-L_μ-L_τ: global U(1)-symmetry, f_k transforms as $e^{i\Phi} f_k$ with Φ=const.

	L_{eL}	$L_{\mu L}$	$L_{\tau L}$	e_R	μ_R	τ_R	N_{1R}	N_{2R}	N_{3R}	ϕ	Δ
$\mathcal{F}$	1	-1	-1	1	-1	-1	1	-1	-1	0	0

4. Soft breaking of L_e-L_μ-L_τ symmetry

first model explaining keV sterile ν DM with L_e-L_μ-L_τ symmetry: Lindner, **AM**, Niro; JCAP 1101: **034,** 2011

Grimus & Lavoura [JHEP 0009: **007**, 2000]: L_e-L_μ-L_τ for 3 light & 2 heavy neutrinos ➔ already shows the desired spectrum for light neutrinos

Our model: application of the same symmetry to the heavy sector ➔ generates just the splitting that is desired

$\mathcal{F}$=L_e-L_μ-L_τ: global U(1)-symmetry, f_k transforms as $e^{i\Phi}$ f_k with Φ=const.

	L_{eL}	$L_{\mu L}$	$L_{\tau L}$	e_R	μ_R	τ_R	N_{1R}	N_{2R}	N_{3R}	ϕ	Δ
$\mathcal{F}$	1	-1	-1	1	-1	-1	1	-1	-1	0	0

➔ only symmetry-preserving combinations of fields are allowed!

4. Soft breaking of L_e-L_μ-L_τ symmetry

- then, only certain contributions to the mass terms are allowed:

4. Soft breaking of L_e-L_μ-L_τ symmetry

• then, only certain contributions to the mass terms are allowed:

➔ right-handed Majorana mass:

$$\mathcal{L}_{\mathrm{mass}} = -M_R^{12}\,\overline{(N_{1R})^C}\,N_{2R} - M_R^{13}\,\overline{(N_{1R})^C}\,N_{3R}$$

4. Soft breaking of L_e-L_μ-L_τ symmetry

• then, only certain contributions to the mass terms are allowed:

→ right-handed Majorana mass:

$$\mathcal{L}_{\rm mass} = -M_R^{12}\ \overline{(N_{1R})^C}\, N_{2R} - M_R^{13}\ \overline{(N_{1R})^C}\, N_{3R}$$

→ Dirac mass term through Higgs doublet Yukawa couplings:

$$\begin{aligned}\mathcal{L}_{\rm mass} \quad = \quad & -Y_D^{e1}\ \overline{L_{eL}}\,\tilde{\phi}\,N_{1R} - Y_D^{\mu 2}\ \overline{L_{\mu L}}\,\tilde{\phi}\,N_{2R} - Y_D^{\mu 3}\ \overline{L_{\mu L}}\,\tilde{\phi}\,N_{3R} - \\ & -Y_D^{\tau 2}\ \overline{L_{\tau L}}\,\tilde{\phi}\,N_{2R} - Y_D^{\tau 3}\ \overline{L_{\tau L}}\,\tilde{\phi}\,N_{3R} + h.c.\end{aligned}$$

4. Soft breaking of L_e-L_μ-L_τ symmetry

• then, only certain contributions to the mass terms are allowed:

➔ right-handed Majorana mass:

$$\mathcal{L}_{\rm mass} = -M_R^{12}\, \overline{(N_{1R})^C}\, N_{2R} - M_R^{13}\, \overline{(N_{1R})^C}\, N_{3R}$$

➔ Dirac mass term through Higgs doublet Yukawa couplings:

$$\begin{aligned}\mathcal{L}_{\rm mass} \quad = \quad & -Y_D^{e1}\, \overline{L_{eL}}\, \tilde{\phi}\, N_{1R} - Y_D^{\mu 2}\, \overline{L_{\mu L}}\, \tilde{\phi}\, N_{2R} - Y_D^{\mu 3}\, \overline{L_{\mu L}}\, \tilde{\phi}\, N_{3R} - \\ & -Y_D^{\tau 2}\, \overline{L_{\tau L}}\, \tilde{\phi}\, N_{2R} - Y_D^{\tau 3}\, \overline{L_{\tau L}}\, \tilde{\phi}\, N_{3R} + h.c.\end{aligned}$$

➔ type II term through Higgs triplet Yukawa coupling:

$$\mathcal{L}_{\rm mass} = -Y_L^{e\mu}\, \overline{(L_{eL})^C}\, (i\sigma_2 \Delta)\, L_{\mu L} - Y_L^{e\tau}\, \overline{(L_{eL})^C}\, (i\sigma_2 \Delta)\, L_{\tau L}$$

4. Soft breaking of L_e-L_μ-L_τ symmetry

• total Majorana mass term:

$$\mathcal{L}_{\text{mass}} = -\frac{1}{2}\overline{\Psi^C}\mathcal{M}_\nu\Psi + h.c.$$

4. Soft breaking of L_e-L_μ-L_τ symmetry

• total Majorana mass term:

$$\mathcal{L}_{\text{mass}} = -\frac{1}{2}\overline{\Psi^C}\mathcal{M}_\nu\Psi + h.c.$$

$$\Psi \equiv \left((\nu_{eL})^C, (\nu_{\mu L})^C, (\nu_{\tau L})^C, N_{1R}, N_{2R}, N_{3R}\right)^T$$

4. Soft breaking of L_e-L_μ-L_τ symmetry

• total Majorana mass term:

$$\mathcal{L}_{\text{mass}} = -\frac{1}{2}\overline{\Psi^C}\mathcal{M}_\nu \Psi + h.c.$$

$$\Psi \equiv \left((\nu_{eL})^C, (\nu_{\mu L})^C, (\nu_{\tau L})^C, N_{1R}, N_{2R}, N_{3R}\right)^T$$

➔ mass matrix:

$$\mathcal{M}_\nu = \left(\begin{array}{ccc|ccc} 0 & m_L^{e\mu} & m_L^{e\tau} & m_D^{e1} & 0 & 0 \\ m_L^{e\mu} & 0 & 0 & 0 & m_D^{\mu 2} & m_D^{\mu 3} \\ m_L^{e\tau} & 0 & 0 & 0 & m_D^{\tau 2} & m_D^{\tau 3} \\ \hline m_D^{e1} & 0 & 0 & 0 & M_R^{12} & M_R^{13} \\ 0 & m_D^{\mu 2} & m_D^{\tau 2} & M_R^{12} & 0 & 0 \\ 0 & m_D^{\mu 3} & m_D^{\tau 3} & M_R^{13} & 0 & 0 \end{array}\right)$$

4. Soft breaking of L_e-L_μ-L_τ symmetry

• total Majorana mass term:

$$\mathcal{L}_{\text{mass}} = -\frac{1}{2}\overline{\Psi^C}\mathcal{M}_\nu\Psi + h.c.$$

$$\Psi \equiv \left((\nu_{eL})^C, (\nu_{\mu L})^C, (\nu_{\tau L})^C, N_{1R}, N_{2R}, N_{3R}\right)^T$$

→ mass matrix:

$$m_L^{\alpha\beta} = v_\Delta Y_L^{\alpha\beta}$$

$$\mathcal{M}_\nu = \left(\begin{array}{ccc|ccc} 0 & m_L^{e\mu} & m_L^{e\tau} & m_D^{e1} & 0 & 0 \\ m_L^{e\mu} & 0 & 0 & 0 & m_D^{\mu 2} & m_D^{\mu 3} \\ m_L^{e\tau} & 0 & 0 & 0 & m_D^{\tau 2} & m_D^{\tau 3} \\ \hline m_D^{e1} & 0 & 0 & 0 & M_R^{12} & M_R^{13} \\ 0 & m_D^{\mu 2} & m_D^{\tau 2} & M_R^{12} & 0 & 0 \\ 0 & m_D^{\mu 3} & m_D^{\tau 3} & M_R^{13} & 0 & 0 \end{array}\right)$$

$$m_D^{\alpha i} = v_\phi Y_D^{\alpha i}$$

4. Soft breaking of L_e-L_μ-L_τ symmetry

• eigenvalues of $\mathcal{M}_\nu$:

$$\begin{pmatrix} \lambda_+ & 0 & 0 & 0 & 0 & 0 \\ 0 & \lambda_- & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \Lambda_+ & 0 & 0 \\ 0 & 0 & 0 & 0 & \Lambda_- & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

4. Soft breaking of L_e-L_μ-L_τ symmetry

• eigenvalues of $\mathcal{M}_\nu$:

$$\lambda_{\pm} = \pm\sqrt{2}\left[m_L - \frac{m_D^2}{M_R}\right]$$

$$\Lambda_{\pm} = \pm\sqrt{2} M_R$$

$$\begin{pmatrix} \lambda_+ & 0 & 0 & 0 & 0 & 0 \\ 0 & \lambda_- & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \Lambda_+ & 0 & 0 \\ 0 & 0 & 0 & 0 & \Lambda_- & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

4. Soft breaking of L_e-L_μ-L_τ symmetry

• eigenvalues of $\mathcal{M}_\nu$:

$$\lambda_\pm = \pm \sqrt{2} \left[m_L - \frac{m_D^2}{M_R} \right]$$

$$\Lambda_\pm = \pm \sqrt{2} M_R$$

$$\begin{pmatrix} \lambda_+ & 0 & 0 & 0 & 0 & 0 \\ 0 & \lambda_- & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \Lambda_+ & 0 & 0 \\ 0 & 0 & 0 & 0 & \Lambda_- & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

➔ light neutrino spectrum: (0,m,m) ➔ nearly okay (degeneracy...)

4. Soft breaking of L_e-L_μ-L_τ symmetry

- eigenvalues of $\mathcal{M}_\nu$:

$$\lambda_\pm = \pm\sqrt{2}\left[m_L - \frac{m_D^2}{M_R}\right]$$

$$\Lambda_\pm = \pm\sqrt{2}M_R$$

$$\begin{pmatrix} \lambda_+ & 0 & 0 & 0 & 0 & 0 \\ 0 & \lambda_- & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \Lambda_+ & 0 & 0 \\ 0 & 0 & 0 & 0 & \Lambda_- & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

➔ light neutrino spectrum: (0,m,m) ➔ nearly okay (degeneracy...)

➔ heavy neutrino spectrum: (0,M,M) ➔ N_1 massless instead of keV

4. Soft breaking of L_e-L_μ-L_τ symmetry

• eigenvalues of $\mathcal{M}_\nu$:

$$\lambda_\pm = \pm\sqrt{2}\left[m_L - \frac{m_D^2}{M_R}\right]$$

$$\Lambda_\pm = \pm\sqrt{2}M_R$$

$$\begin{pmatrix} \lambda_+ & 0 & 0 & 0 & 0 & 0 \\ 0 & \lambda_- & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \Lambda_+ & 0 & 0 \\ 0 & 0 & 0 & 0 & \Lambda_- & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

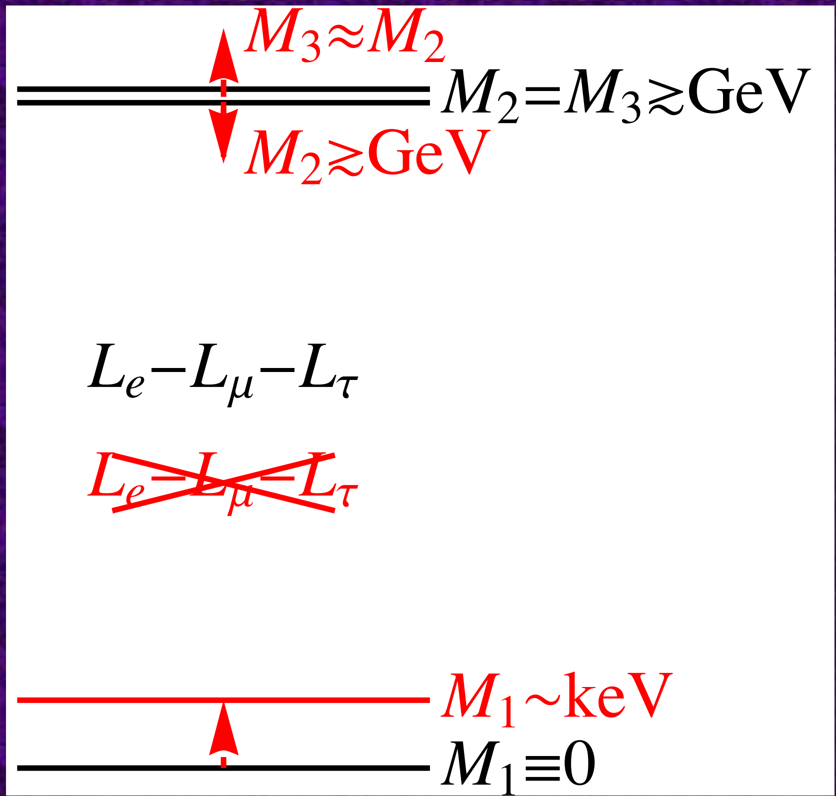
→ light neutrino spectrum: (0,m,m) → nearly okay (degeneracy...)

→ heavy neutrino spectrum: (0,M,M) → N_1 massless instead of keV

HOWEVER: flavour symmetries must always be broken for phenomenological reasons → this will lift the massless states and destroy the degeneracy
(similar idea: Shaposhnikov, Nucl. Phys. **B763** (2007) 49)

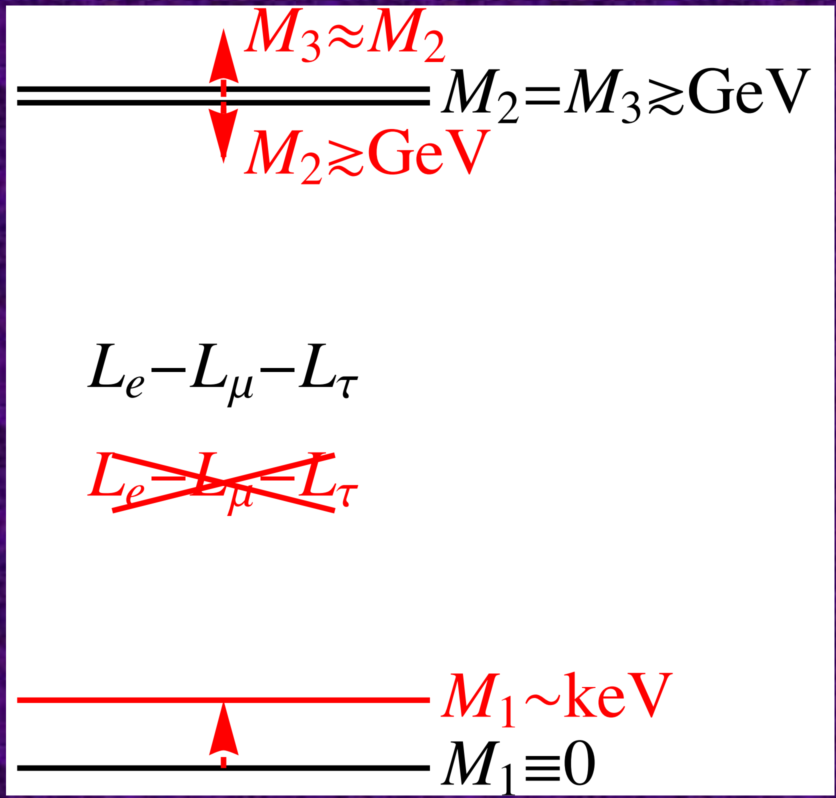
4. Soft breaking of L_e-L_μ-L_τ symmetry

- scheme:



4. Soft breaking of L_e-L_μ-L_τ symmetry

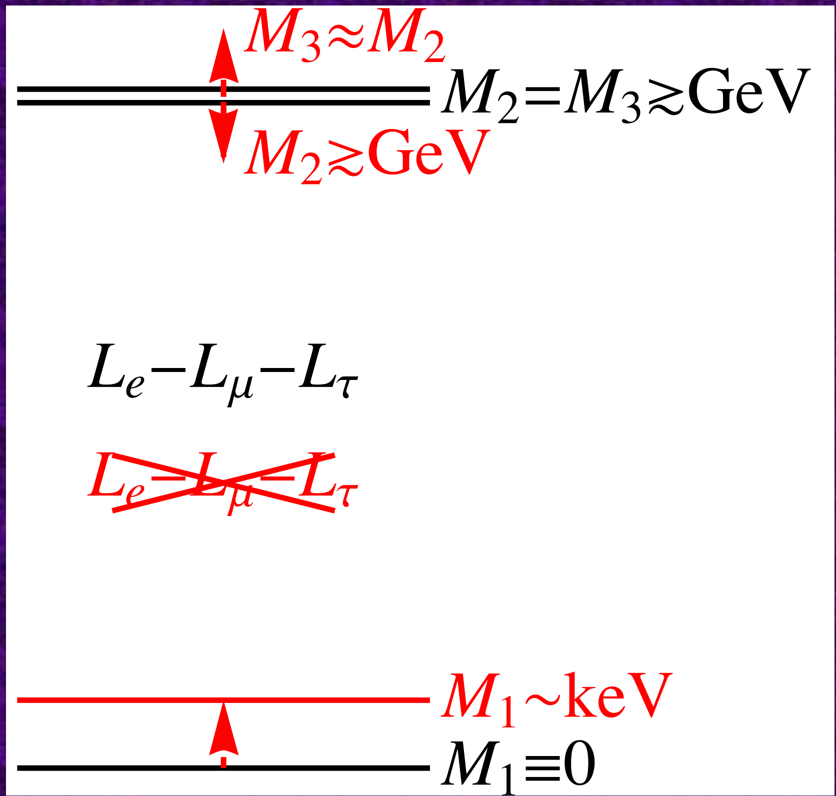
• scheme:



IDEA: since the symmetry is not phenomenologically valid, it must be broken

4. Soft breaking of L_e-L_μ-L_τ symmetry

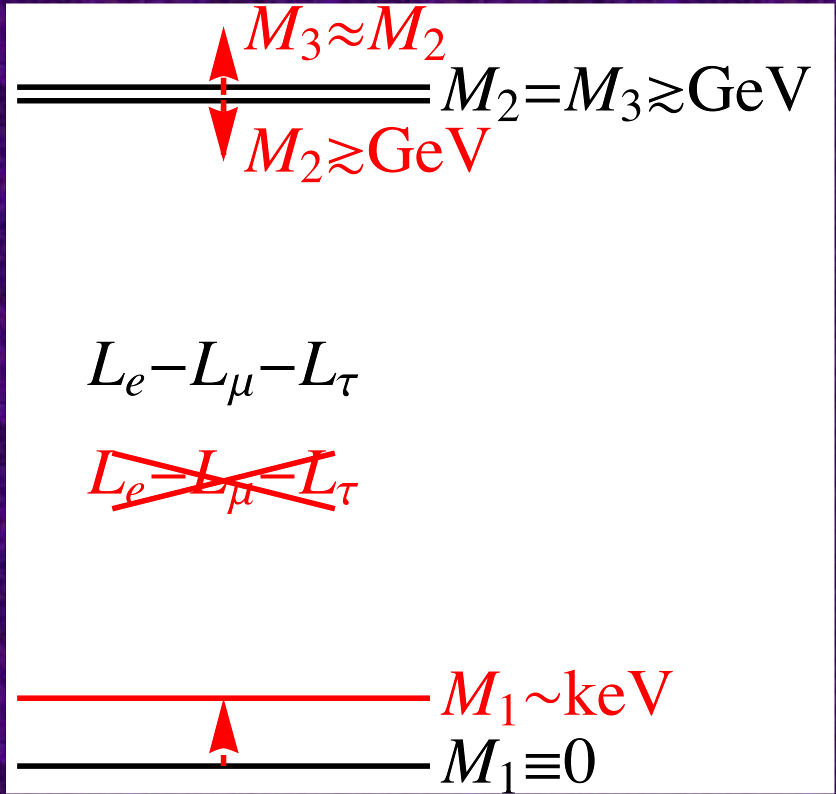
• scheme:



IDEA: since the symmetry is not phenomenologically valid, it must be broken ➔ *"soft breaking terms"* (no Λ^2-divergences) that must be SMALLER than the symmetry-preserving terms

4. Soft breaking of L_e-L_μ-L_τ symmetry

• scheme:



IDEA: since the symmetry is not phenomenologically valid, it must be broken ➔ *"soft breaking terms"* (no Λ^2-divergences) that must be SMALLER than the symmetry-preserving terms

EFFECT: these terms will give the previously massless state N_1 a small mass, and the will also lift the degeneracy between N_2 & N_3 ➔ just what was desired!

4. Soft breaking of L_e-L_μ-L_τ symmetry

• problem: one can choose the soft-breaking terms more or less arbitrarily, but any choice will only have a small effect

4. Soft breaking of L_e-L_μ-L_τ symmetry

• problem: one can choose the soft-breaking terms more or less arbitrarily, but any choice will only have a small effect

➔ example:

$$\left(\begin{array}{ccc|ccc}
s_L^{ee} & m_L^{e\mu} & m_L^{e\tau} & m_D^{e1} & 0 & 0 \\
m_L^{e\mu} & s_L^{\mu\mu} & 0 & 0 & m_D^{\mu 2} & m_D^{\mu 3} \\
m_L^{e\tau} & 0 & s_L^{\tau\tau} & 0 & m_D^{\tau 2} & m_D^{\tau 3} \\
\hline
m_D^{e1} & 0 & 0 & S_R^{11} & M_R^{12} & M_R^{13} \\
0 & m_D^{\mu 2} & m_D^{\tau 2} & M_R^{12} & S_R^{22} & 0 \\
0 & m_D^{\mu 3} & m_D^{\tau 3} & M_R^{13} & 0 & S_R^{33}
\end{array}\right)$$

4. Soft breaking of L_e-L_μ-L_τ symmetry

• problem: one can choose the soft-breaking terms more or less arbitrarily, but any choice will only have a small effect

➔ example:

$$\left(\begin{array}{ccc|ccc} s_L^{ee} & m_L^{e\mu} & m_L^{e\tau} & m_D^{e1} & 0 & 0 \\ m_L^{e\mu} & s_L^{\mu\mu} & 0 & 0 & m_D^{\mu 2} & m_D^{\mu 3} \\ m_L^{e\tau} & 0 & s_L^{\tau\tau} & 0 & m_D^{\tau 2} & m_D^{\tau 3} \\ \hline m_D^{e1} & 0 & 0 & S_R^{11} & M_R^{12} & M_R^{13} \\ 0 & m_D^{\mu 2} & m_D^{\tau 2} & M_R^{12} & S_R^{22} & 0 \\ 0 & m_D^{\mu 3} & m_D^{\tau 3} & M_R^{13} & 0 & S_R^{33} \end{array}\right)$$

➔ eigenvalues:

$$\Lambda_s = S \qquad \Lambda'_\pm = S \pm \sqrt{2} M_R$$

$$\lambda_s = s \qquad \lambda'_\pm = s \pm \sqrt{2}\left[m_L - \frac{m_D^2}{M_R}\right] + \frac{5 m_D^2 S}{4 M_R^2}$$

4. Soft breaking of L_e-L_μ-L_τ symmetry

• problem: one can choose the soft-breaking terms more or less arbitrarily, but any choice will only have a small effect

→ example:

$$\left(\begin{array}{ccc|ccc}
s_L^{ee} & m_L^{e\mu} & m_L^{e\tau} & m_D^{e1} & 0 & 0 \\
m_L^{e\mu} & s_L^{\mu\mu} & 0 & 0 & m_D^{\mu 2} & m_D^{\mu 3} \\
m_L^{e\tau} & 0 & s_L^{\tau\tau} & 0 & m_D^{\tau 2} & m_D^{\tau 3} \\
\hline
m_D^{e1} & 0 & 0 & S_R^{11} & M_R^{12} & M_R^{13} \\
0 & m_D^{\mu 2} & m_D^{\tau 2} & M_R^{12} & S_R^{22} & 0 \\
0 & m_D^{\mu 3} & m_D^{\tau 3} & M_R^{13} & 0 & S_R^{33}
\end{array}\right)$$

keV neutrino

→ eigenvalues:

$$\Lambda_s = S \qquad \Lambda'_\pm = S \pm \sqrt{2} M_R$$

$$\lambda_s = s \qquad \lambda'_\pm = s \pm \sqrt{2}\left[m_L - \frac{m_D^2}{M_R}\right] + \frac{5 m_D^2 S}{4 M_R^2}$$

4. Soft breaking of L_e-L_μ-L_τ symmetry

- conditions:

$s \ll m_L - m_D^2/M_R$ & $S \ll M_R$

4. Soft breaking of L_e-L_μ-L_τ symmetry

- conditions:

$s \ll m_L - m_D^2/M_R$ & $S \ll M_R$

➔ perfectly possible to have $M_1 \sim$ keV and $M_{2,3} \geq$ GeV!!!

4. Soft breaking of L_e-L_μ-L_τ symmetry

• conditions:

$s \ll m_L - m_D^2/M_R$ & $S \ll M_R$

➔ perfectly possible to have $M_1 \sim$ keV and $M_{2,3} \geq$ GeV!!!

• simplifications:

$$s_L^{\alpha\alpha} \simeq s \qquad S_R^{ii} \simeq S$$

$$M_R^{12} \simeq M_R^{13} \sim M_R$$

4. Soft breaking of L_e-L_μ-L_τ symmetry

• conditions: $s \ll m_L - m_D^2/M_R$ & $S \ll M_R$

➔ perfectly possible to have $M_1 \sim$ keV and $M_{2,3} \geq$ GeV!!!

• simplifications: $s_L^{\alpha\alpha} \simeq s$ $S_R^{ii} \simeq S$

$$M_R^{12} \simeq M_R^{13} \sim M_R$$

➔ masses: $m_1 = s + b, \; m_2 = s - b, \text{ and } m_3 = s$

$$b \equiv m_L - \frac{m_D^2}{M_R} > 0$$

4. Soft breaking of L_e-L_μ-L_τ symmetry

• conditions: $s \ll m_L - m_D^2/M_R$ & $S \ll M_R$

➔ perfectly possible to have $M_1 \sim$ keV and $M_{2,3} \geq$ GeV!!!

• simplifications: $s_L^{\alpha\alpha} \simeq s$ $\quad S_R^{ii} \simeq S$

$$M_R^{12} \simeq M_R^{13} \sim M_R$$

➔ masses: $m_1 = s + b,\ m_2 = s - b,\ \text{and}\ m_3 = s$

$$b \equiv m_L - \frac{m_D^2}{M_R} > 0$$

$$|m_1| = 0.0486\ \text{eV}$$
$$|m_2| = 0.0494\ \text{eV}$$
$$|m_3| = 0.0004\ \text{eV}$$

4. Soft breaking of L_e-L_μ-L_τ symmetry

• conditions: $s \ll m_L - m_D^2/M_R$ & $S \ll M_R$

→ perfectly possible to have $M_1 \sim$ keV and $M_{2,3} \geq$ GeV!!!

• simplifications: $s_L^{\alpha\alpha} \simeq s$ $\quad S_R^{ii} \simeq S$

$$M_R^{12} \simeq M_R^{13} \sim M_R$$

→ masses: $m_1 = s + b, \; m_2 = s - b, \; \text{and} \; m_3 = s$

$$b \equiv m_L - \frac{m_D^2}{M_R} > 0$$

$$|m_1| = 0.0486 \text{ eV}$$
$$|m_2| = 0.0494 \text{ eV}$$
$$|m_3| = 0.0004 \text{ eV}$$

→ we predict inverted mass ordering (in fact the exact spectrum)!

4. Soft breaking of L_e-L_μ-L_τ symmetry

- problem: we predict bimaximal instead of tri-bimaximal mixing

$$\mathcal{U}_\nu = \begin{pmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 \\ -\frac{1}{2} & \frac{1}{2} & \frac{1}{\sqrt{2}} \\ \frac{1}{2} & -\frac{1}{2} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

4. Soft breaking of L_e-L_μ-L_τ symmetry

- problem: we predict bimaximal instead of tri-bimaximal mixing

$$\mathcal{U}_\nu = \begin{pmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 \\ -\frac{1}{2} & \frac{1}{2} & \frac{1}{\sqrt{2}} \\ \frac{1}{2} & -\frac{1}{2} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

➔ $\theta_{13}=0°$ & $\theta_{23}=45°$: okay ✓

4. Soft breaking of L_e-L_μ-L_τ symmetry

- problem: we predict bimaximal instead of tri-bimaximal mixing

$$\mathcal{U}_\nu = \begin{pmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 \\ -\frac{1}{2} & \frac{1}{2} & \frac{1}{\sqrt{2}} \\ \frac{1}{2} & -\frac{1}{2} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

➔ $\theta_{13}=0°$ & $\theta_{23}=45°$: okay ✓

➔ $\theta_{12}=45°$: excluded at > 6σ... ☹

4. Soft breaking of L_e-L_μ-L_τ symmetry

• problem: we predict bimaximal instead of tri-bimaximal mixing

$$\mathcal{U}_\nu = \begin{pmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 \\ -\frac{1}{2} & \frac{1}{2} & \frac{1}{\sqrt{2}} \\ \frac{1}{2} & -\frac{1}{2} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

➔ $\theta_{13}=0°$ & $\theta_{23}=45°$: okay ✓

➔ $\theta_{12}=45°$: excluded at > 6σ... ☹

• *way out*: this mixing can come from the charged lepton sector

4. Soft breaking of L_e-L_μ-L_τ symmetry

• problem: we predict bimaximal instead of tri-bimaximal mixing

$$\mathcal{U}_\nu = \begin{pmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 \\ -\frac{1}{2} & \frac{1}{2} & \frac{1}{\sqrt{2}} \\ \frac{1}{2} & -\frac{1}{2} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

➔ $\theta_{13}=0°$ & $\theta_{23}=45°$: okay ✓

➔ $\theta_{12}=45°$: excluded at > 6σ... ☹

• *way out*: this mixing can come from the charged lepton sector

➔ we must assume one term in M_e to be small

4. Soft breaking of L_e-L_μ-L_τ symmetry

• problem: we predict bimaximal instead of tri-bimaximal mixing

$$\mathcal{U}_\nu = \begin{pmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 \\ -\frac{1}{2} & \frac{1}{2} & \frac{1}{\sqrt{2}} \\ \frac{1}{2} & -\frac{1}{2} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

➔ $\theta_{13}=0°$ & $\theta_{23}=45°$: okay ✓

➔ $\theta_{12}=45°$: excluded at > 6σ... ☹

• *way out*: this mixing can come from the charged lepton sector

➔ we must assume one term in M_e to be small

➔ actually somehow natural due to larger radiative corrections for charged leptons, but nevertheless only an assumption

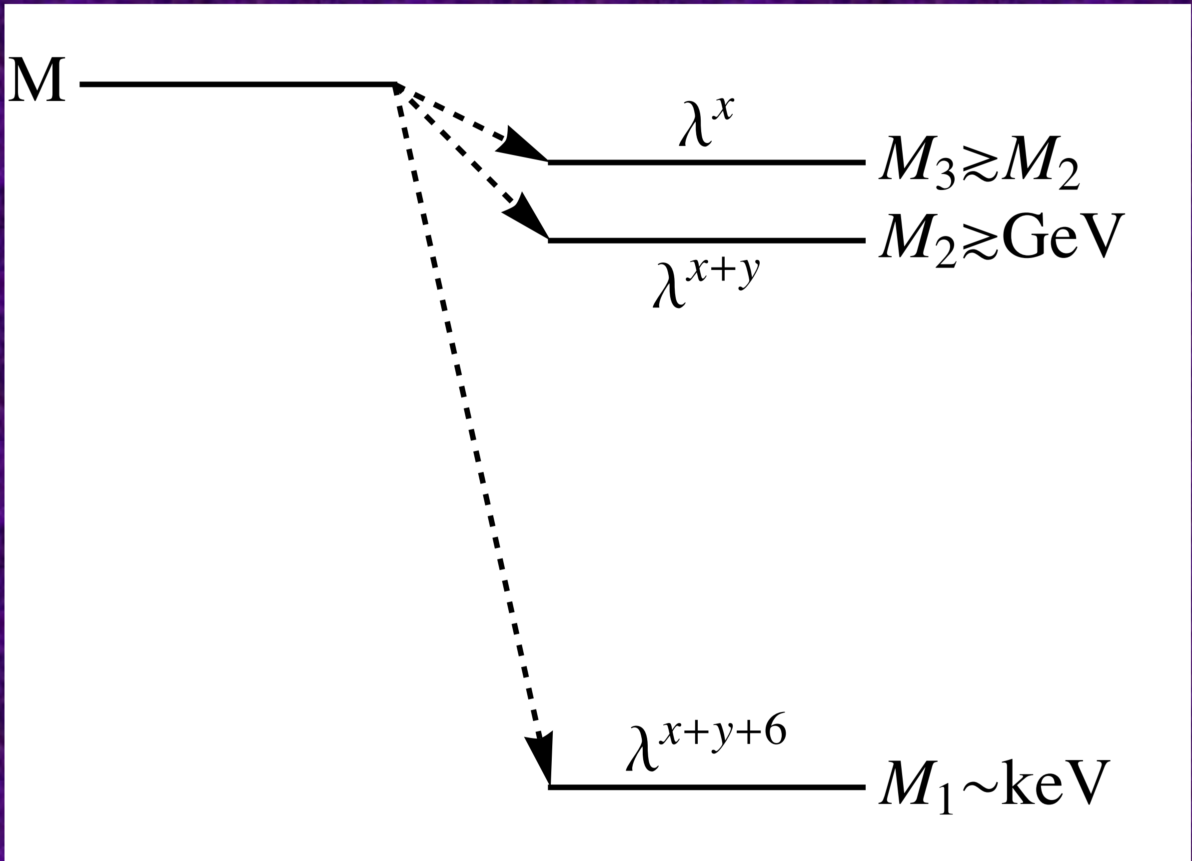
5. A Froggatt-Nielsen Model

5. A Froggatt-Nielsen Model

Froggatt-Nielsen mechanism to explain the spectrum:
AM & Niro; 1105.5136[hep-ph]

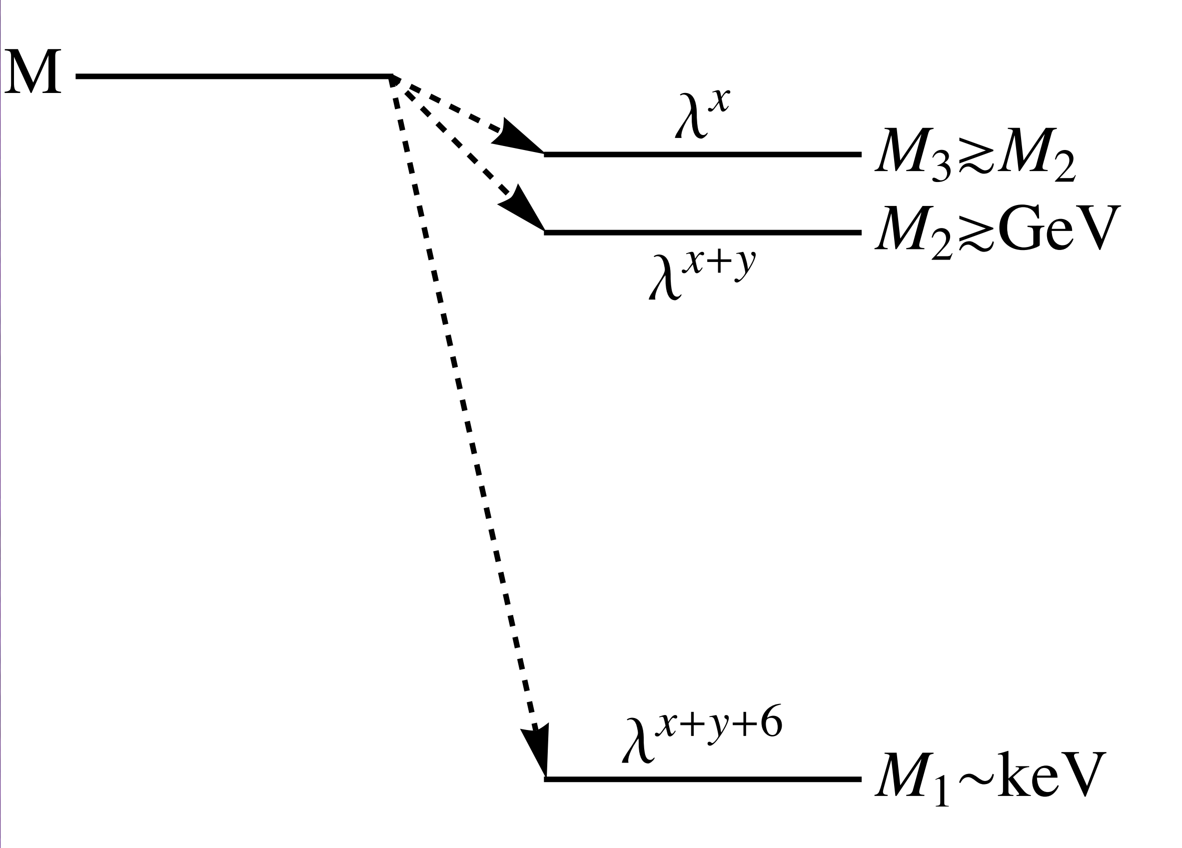
5. A Froggatt-Nielsen Model

Froggatt-Nielsen mechanism to explain the spectrum:
AM & Niro; 1105.5136[hep-ph]



5. A Froggatt-Nielsen Model

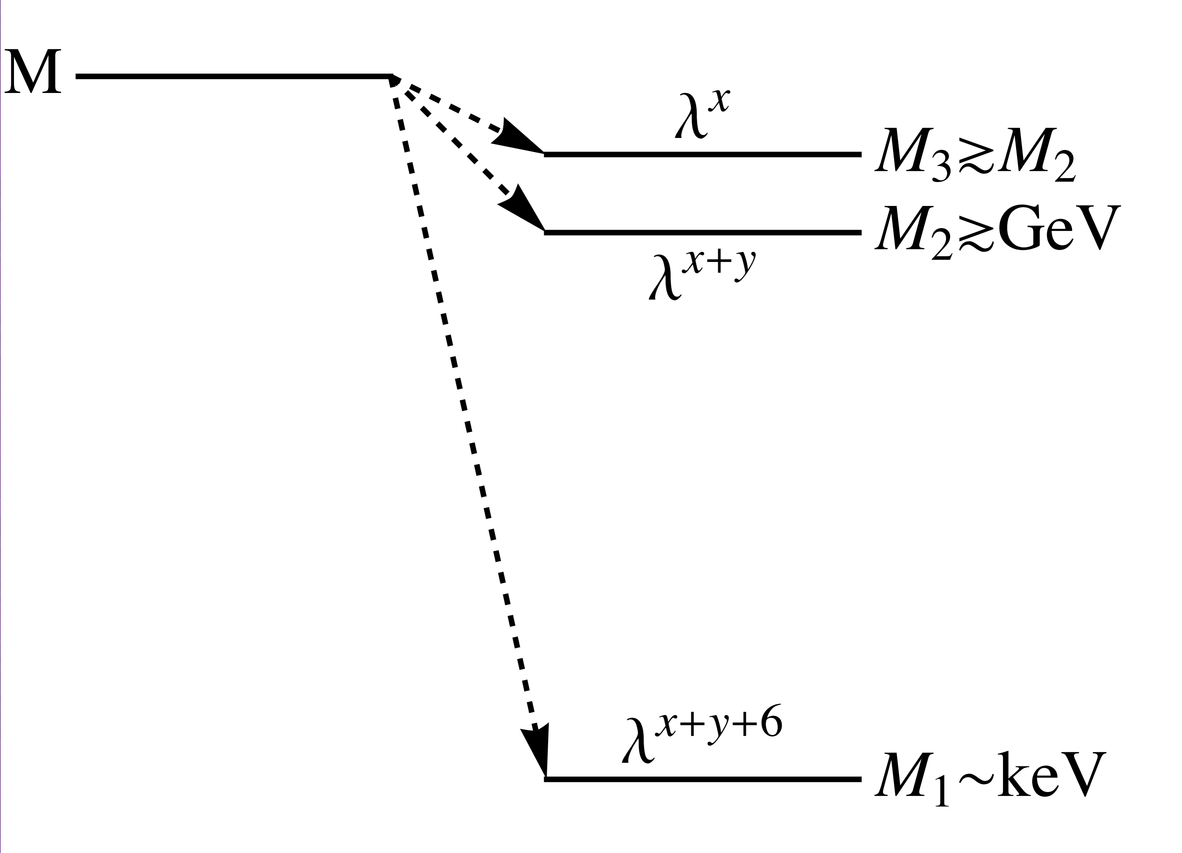
Froggatt-Nielsen mechanism to explain the spectrum:
AM & Niro; 1105.5136[hep-ph]



IDEA:

5. A Froggatt-Nielsen Model

Froggatt-Nielsen mechanism to explain the spectrum:
AM & Niro; 1105.5136[hep-ph]



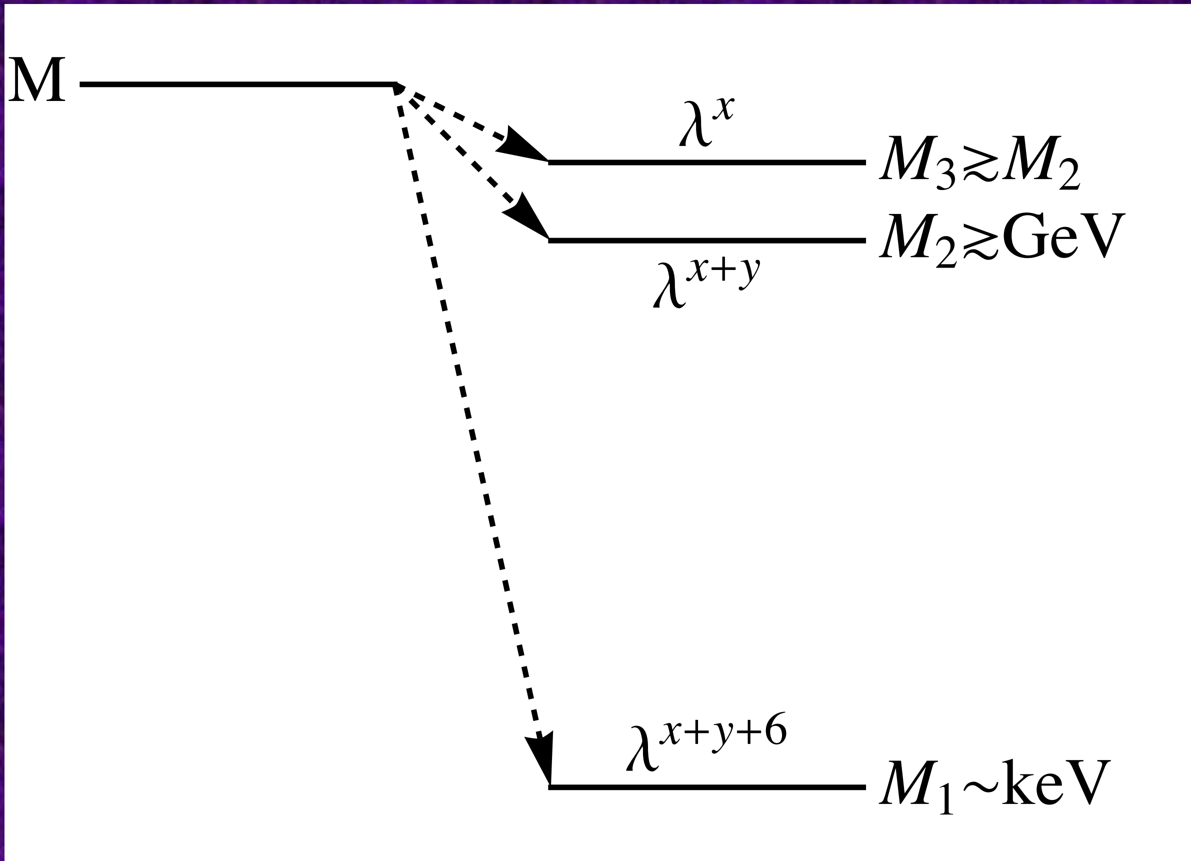
IDEA:

- we can use the Froggatt-Nielsen mechanism to suppress a higher mass scale

5. A Froggatt-Nielsen Model

Froggatt-Nielsen mechanism to explain the spectrum:

AM & Niro; 1105.5136[hep-ph]

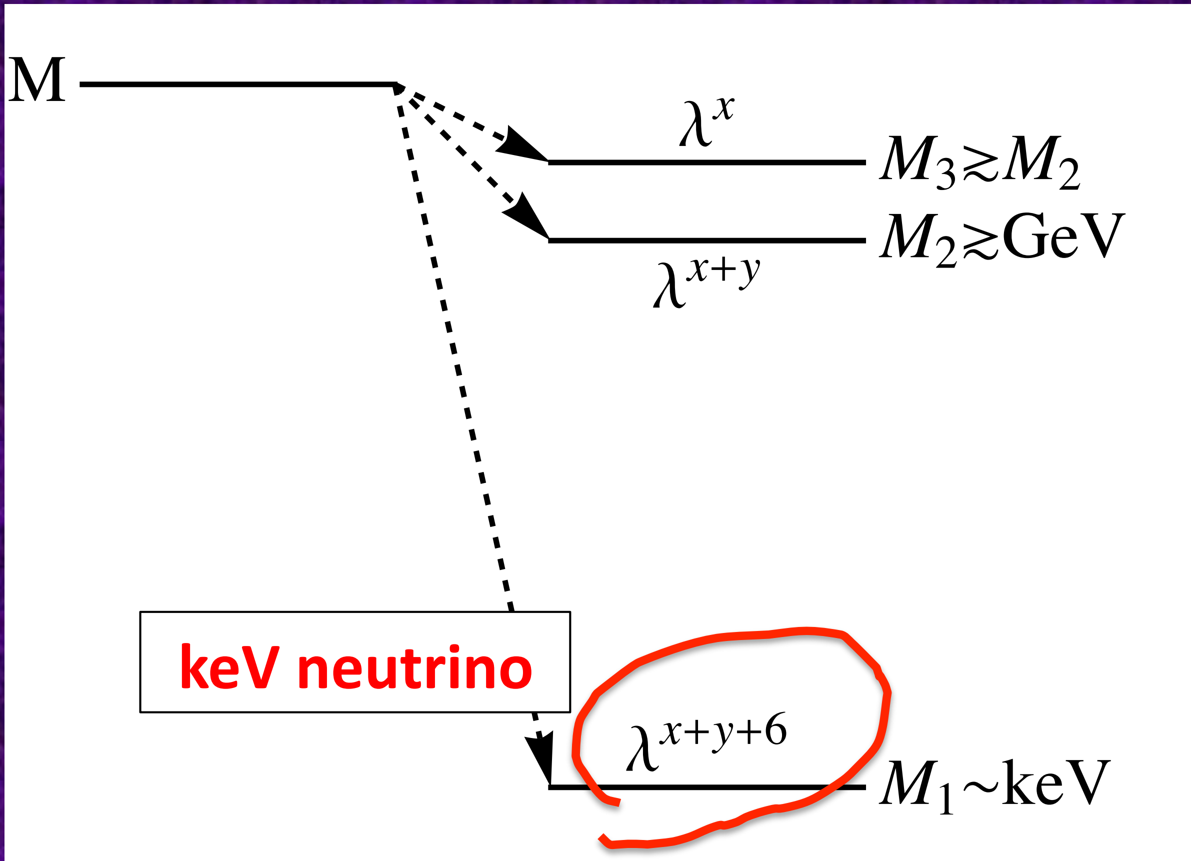


IDEA:

- we can use the Froggatt-Nielsen mechanism to suppress a higher mass scale
- leads naturally to a split mass spectrum

5. A Froggatt-Nielsen Model

Froggatt-Nielsen mechanism to explain the spectrum:
AM & Niro; 1105.5136[hep-ph]



IDEA:

- we can use the Froggatt-Nielsen mechanism to suppress a higher mass scale
- leads naturally to a split mass spectrum

5. A Froggatt-Nielsen Model

Froggatt & Nielsen: Nucl. Phys. **B147**, 277 (1979)

5. A Froggatt-Nielsen Model

Froggatt & Nielsen: Nucl. Phys. **B147**, 277 (1979)

- idea: the different generations are differently charged under a new $U(1)_{FN}$ symmetry

5. A Froggatt-Nielsen Model

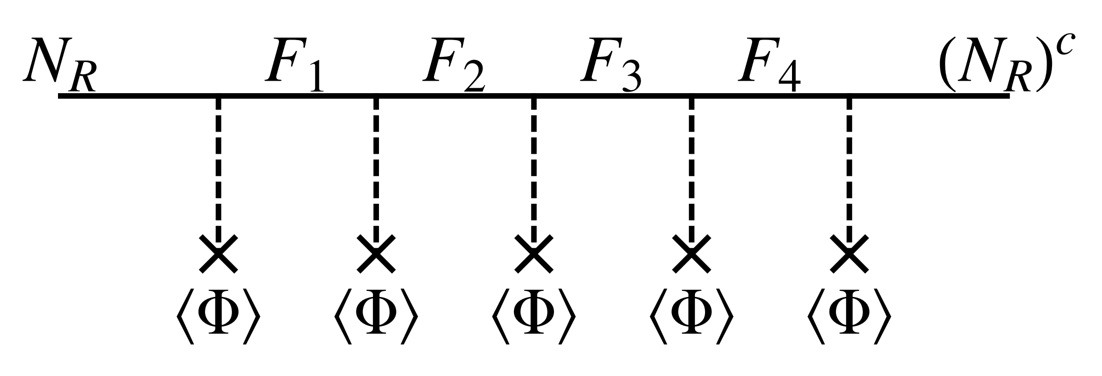
Froggatt & Nielsen: Nucl. Phys. **B147**, 277 (1979)

- idea: the different generations are differently charged under a new $U(1)_{FN}$ symmetry
- in addition, there is a high energy sector of fermions and scalars; the latter develop VEVs to break the symmetry

5. A Froggatt-Nielsen Model

Froggatt & Nielsen: Nucl. Phys. **B147**, 277 (1979)

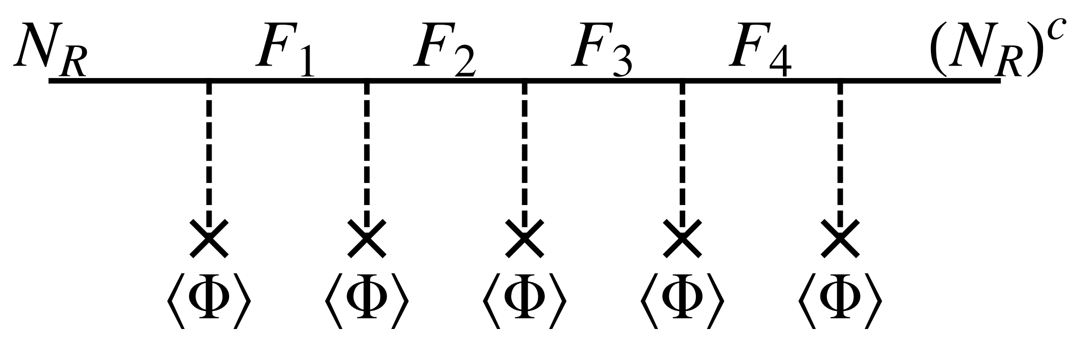
- idea: the different generations are differently charged under a new $U(1)_{FN}$ symmetry
- in addition, there is a high energy sector of fermions and scalars; the latter develop VEVs to break the symmetry
- this leads to multiple seesaw-like diagrams:



5. A Froggatt-Nielsen Model

Froggatt & Nielsen: Nucl. Phys. **B147**, 277 (1979)

- idea: the different generations are differently charged under a new $U(1)_{FN}$ symmetry
- in addition, there is a high energy sector of fermions and scalars; the latter develop VEVs to break the symmetry
- this leads to multiple seesaw-like diagrams:



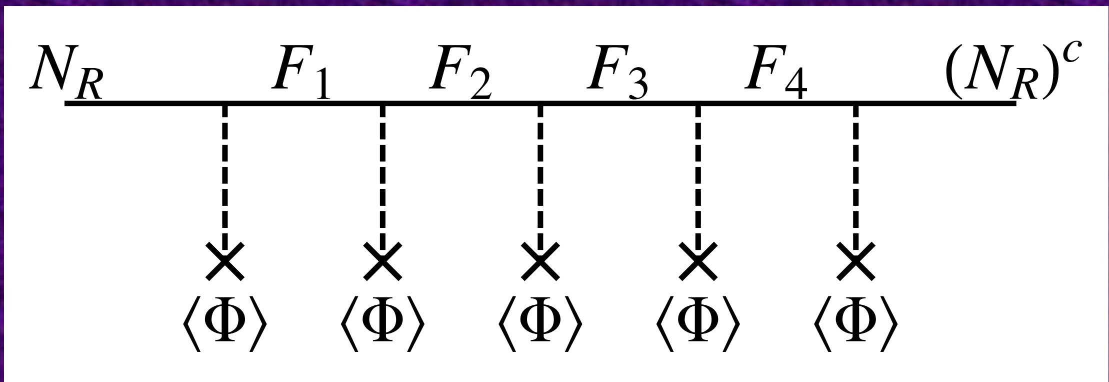
➔ integrating out the heavy fermions leads to:

$m \sim M \lambda^{f+g}$, where $\lambda = \langle\Theta\rangle/\Lambda$

5. A Froggatt-Nielsen Model

Froggatt & Nielsen: Nucl. Phys. **B147**, 277 (1979)

- idea: the different generations are differently charged under a new $U(1)_{FN}$ symmetry
- in addition, there is a high energy sector of fermions and scalars; the latter develop VEVs to break the symmetry
- this leads to multiple seesaw-like diagrams:



➔ integrating out the heavy fermions leads to:

$m \sim M \lambda^{f+g}$, where $\lambda = \langle\Theta\rangle/\Lambda$

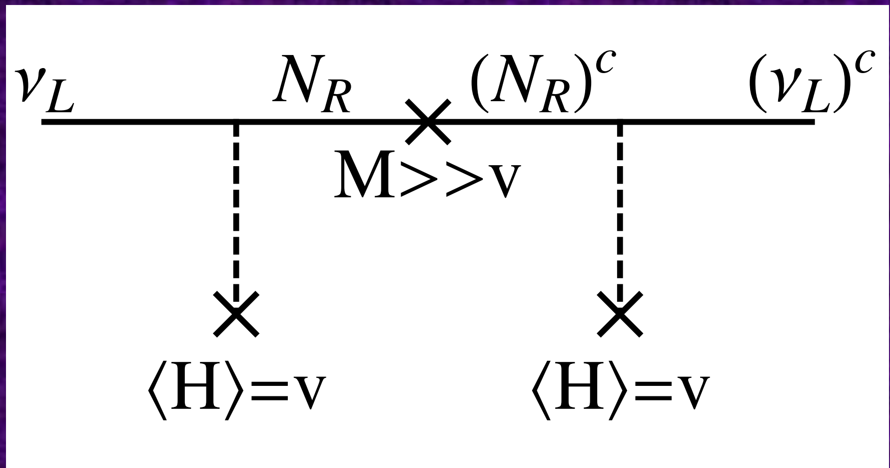
➔ *suppression!!!*

5. A Froggatt-Nielsen Model

crucial point: the FN-charges of the RH-neutrinos drop out in the seesaw formula, like any global U(1)

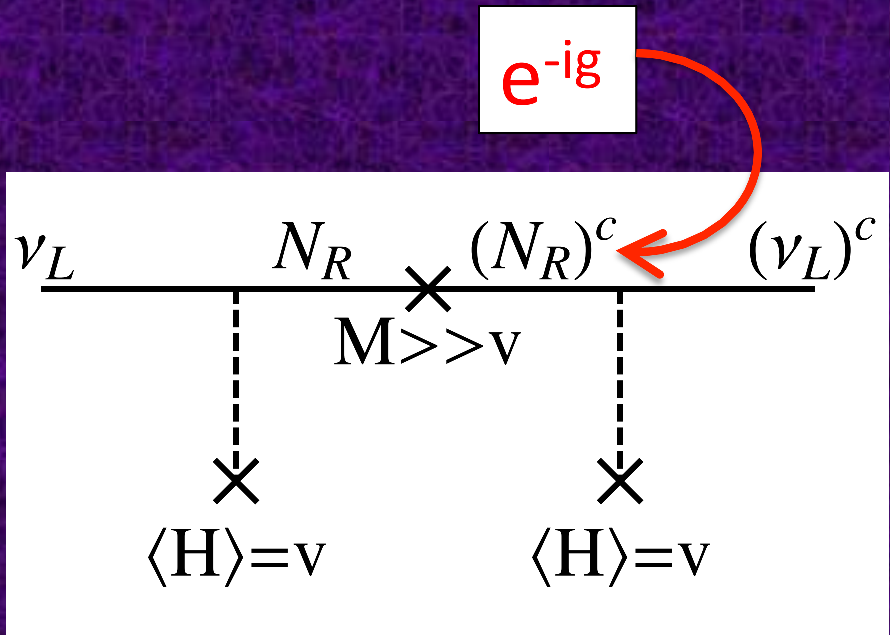
5. A Froggatt-Nielsen Model

crucial point: the FN-charges of the RH-neutrinos drop out in the seesaw formula, like any global U(1)



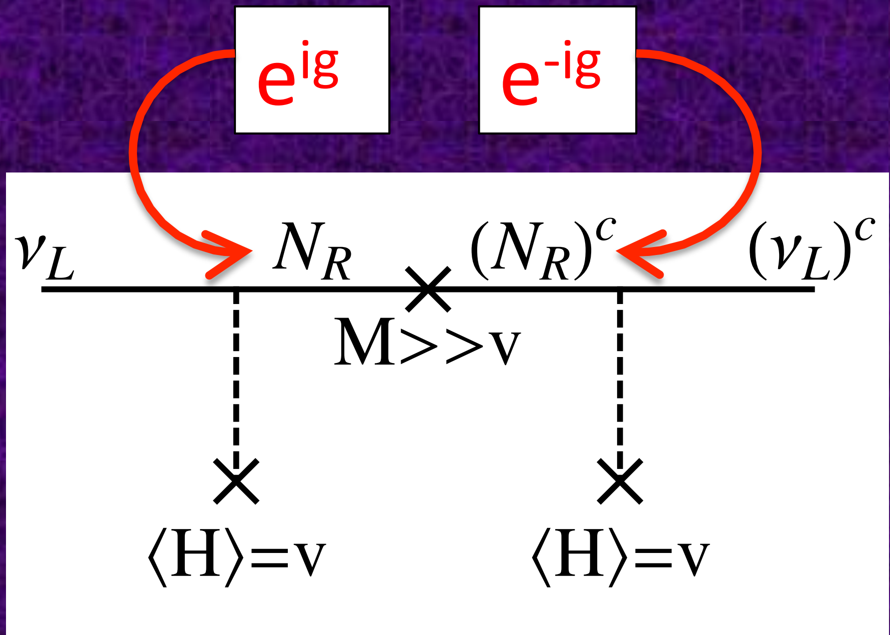
5. A Froggatt-Nielsen Model

crucial point: the FN-charges of the RH-neutrinos drop out in the seesaw formula, like any global U(1)



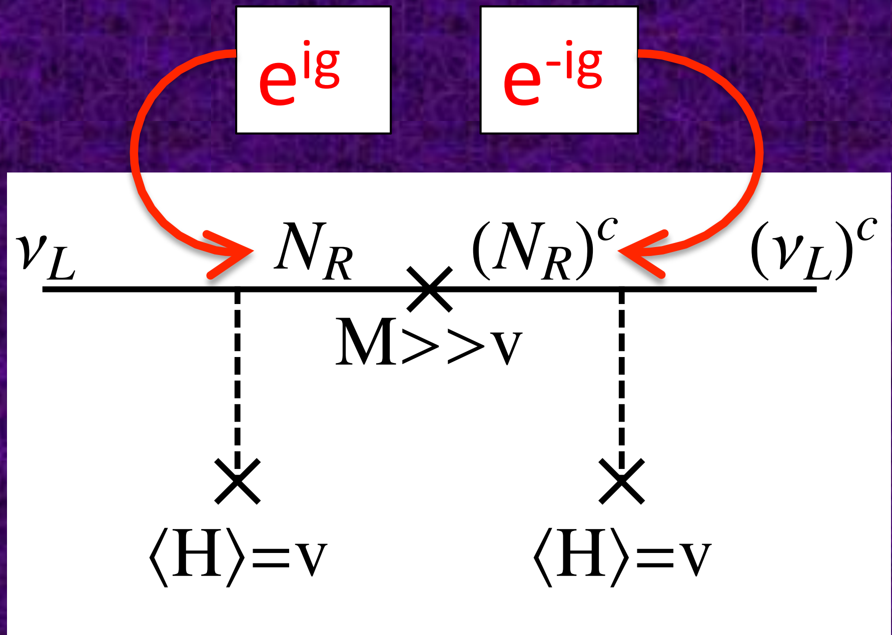
5. A Froggatt-Nielsen Model

crucial point: the FN-charges of the RH-neutrinos drop out in the seesaw formula, like any global U(1)



5. A Froggatt-Nielsen Model

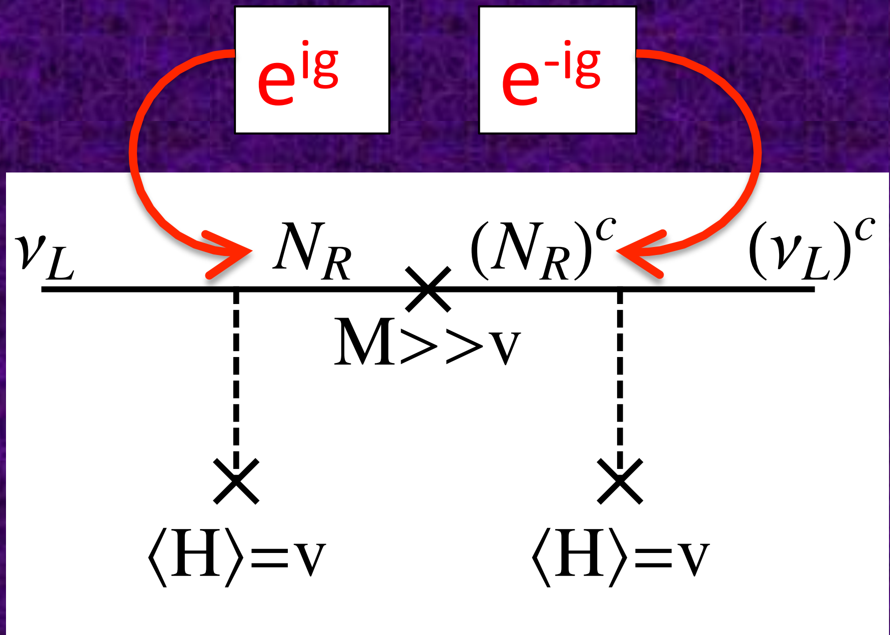
crucial point: the FN-charges of the RH-neutrinos drop out in the seesaw formula, like any global U(1)



➔ seesaw mechanism guaranteed to work (no keV problem)!

5. A Froggatt-Nielsen Model

crucial point: the FN-charges of the RH-neutrinos drop out in the seesaw formula, like any global U(1)



➔ seesaw mechanism guaranteed to work (no keV problem)!

➔ light neutrino mass matrix only depends on the charges of ν_L

5. A Froggatt-Nielsen Model

Goal: find MINIMAL assignments for RH-neutrinos

5. A Froggatt-Nielsen Model

Goal: find MINIMAL assignments for RH-neutrinos

- key point: for the charges (g_1,g_2,g_3), we need at least $g_2 \geq g_3+3$ in order to create the required hierarchy

5. A Froggatt-Nielsen Model

Goal: find MINIMAL assignments for RH-neutrinos

- key point: for the charges (g_1,g_2,g_3), we need at least $g_2 \geq g_3+3$ in order to create the required hierarchy
- two example scenarios: A=(3,0,0) & B=(4,1,0)

5. A Froggatt-Nielsen Model

Goal: find MINIMAL assignments for RH-neutrinos

- key point: for the charges (g_1,g_2,g_3), we need at least $g_2 \geq g_3+3$ in order to create the required hierarchy
- two example scenarios: A=(3,0,0) & B=(4,1,0)

$$M_R^{(\mathrm{A,B})} = \begin{pmatrix} \tilde{M}_R^{11} B_{6,8} \lambda^{6,8} & \tilde{M}_R^{12} B_{2,4} \lambda^{3,5} & \tilde{M}_R^{13} R B_2 \lambda^{3,4} \\ \bullet & \tilde{M}_R^{22} B_{0,2} \lambda^{0,2} & 0,\ \tilde{M}_R^{23} R \lambda \\ \bullet & \bullet & \tilde{M}_R^{33} \end{pmatrix}$$

5. A Froggatt-Nielsen Model

Goal: find MINIMAL assignments for RH-neutrinos

- key point: for the charges (g_1,g_2,g_3), we need at least $g_2 \geq g_3+3$ in order to create the required hierarchy
- two example scenarios: A=(3,0,0) & B=(4,1,0)

$$M_R^{(\mathrm{A,B})} = \begin{pmatrix} \tilde{M}_R^{11} B_{6,8} \lambda^{6,8} & \tilde{M}_R^{12} B_{2,4} \lambda^{3,5} & \tilde{M}_R^{13} R B_2 \lambda^{3,4} \\ \bullet & \tilde{M}_R^{22} B_{0,2} \lambda^{0,2} & 0,\ \tilde{M}_R^{23} R \lambda \\ \bullet & \bullet & \tilde{M}_R^{33} \end{pmatrix}$$

➔ scenario A: $M_1=M_0\,\lambda^6\,O(1)$, $M_2=M_0$, $M_3=M_0\,[1+\lambda^6\,O(1)]$

5. A Froggatt-Nielsen Model

Goal: find MINIMAL assignments for RH-neutrinos

- key point: for the charges (g_1,g_2,g_3), we need at least $g_2 \geq g_3+3$ in order to create the required hierarchy
- two example scenarios: A=(3,0,0) & B=(4,1,0)

$$M_R^{(\mathrm{A},\mathrm{B})} = \begin{pmatrix} \tilde{M}_R^{11} B_{6,8} \lambda^{6,8} & \tilde{M}_R^{12} B_{2,4} \lambda^{3,5} & \tilde{M}_R^{13} R B_2 \lambda^{3,4} \\ \bullet & \tilde{M}_R^{22} B_{0,2} \lambda^{0,2} & 0, \;\; \tilde{M}_R^{23} R \lambda \\ \bullet & \bullet & \tilde{M}_R^{33} \end{pmatrix}$$

→ scenario A: $M_1 = M_0 \lambda^6 O(1)$, $M_2 = M_0$, $M_3 = M_0 [1 + \lambda^6 O(1)]$

→ scenario B: $M_1 = M_0 \lambda^8 O(1)$, $M_2 = M_0 \lambda^2$, $M_3 = M_0 [1 + \lambda^2 O(1)]$

5. A Froggatt-Nielsen Model

Goal: find MINIMAL assignments for RH-neutrinos

- key point: for the charges (g_1,g_2,g_3), we need at least $g_2 \geq g_3+3$ in order to create the required hierarchy
- two example scenarios: A=(3,0,0) & B=(4,1,0)

$$M_R^{(\mathrm{A,B})} = \begin{pmatrix} \tilde{M}_R^{11} B_{6,8} \lambda^{6,8} & \tilde{M}_R^{12} B_{2,4} \lambda^{3,5} & \tilde{M}_R^{13} R B_2 \lambda^{3,4} \\ \bullet & \tilde{M}_R^{22} B_{0,2} \lambda^{0,2} & 0, \ \tilde{M}_R^{23} R \lambda \\ \bullet & \bullet & \tilde{M}_R^{33} \end{pmatrix}$$

→ scenario A: $M_1=M_0 \lambda^6 O(1)$, $M_2=M_0$, $M_3=M_0 [1 + \lambda^6 O(1)]$

→ scenario B: $M_1=M_0 \lambda^8 O(1)$, $M_2=M_0 \lambda^2$, $M_3=M_0 [1 + \lambda^2 O(1)]$

→ yield just the required spectra of the sterile neutrinos!!

5. A Froggatt-Nielsen Model

Froggatt-Nielsen charge assignment is not as arbitrary as it may look, when combined with other requirements (in the context of keV neutrinos!):

5. A Froggatt-Nielsen Model

Froggatt-Nielsen charge assignment is not as arbitrary as it may look, when combined with other requirements (in the context of keV neutrinos!):

- needs two FN-fields to combine predictivity and ~~CP~~

5. A Froggatt-Nielsen Model

Froggatt-Nielsen charge assignment is not as arbitrary as it may look, when combined with other requirements (in the context of keV neutrinos!):

- needs two FN-fields to combine predictivity and $\not{CP}$
- incompatible with left-right symmetry

5. A Froggatt-Nielsen Model

Froggatt-Nielsen charge assignment is not as arbitrary as it may look, when combined with other requirements (in the context of keV neutrinos!):

- needs two FN-fields to combine predictivity and ~~CP~~
- incompatible with left-right symmetry
- excludes bimaximal mixing from neutrino sector

5. A Froggatt-Nielsen Model

Froggatt-Nielsen charge assignment is not as arbitrary as it may look, when combined with other requirements (in the context of keV neutrinos!):

- needs two FN-fields to combine predictivity and ~~CP~~
- incompatible with left-right symmetry
- excludes bimaximal mixing from neutrino sector
- GUTs: favors SU(5), disfavors SO(10)

5. A Froggatt-Nielsen Model

Froggatt-Nielsen charge assignment is not as arbitrary as it may look, when combined with other requirements (in the context of keV neutrinos!):

- needs two FN-fields to combine predictivity and ~~CP~~
- incompatible with left-right symmetry
- excludes bimaximal mixing from neutrino sector
- GUTs: favors SU(5), disfavors SO(10)
- disfavors democratic Yukawa couplings

5. A Froggatt-Nielsen Model

Froggatt-Nielsen charge assignment is not as arbitrary as it may look, when combined with other requirements (in the context of keV neutrinos!):

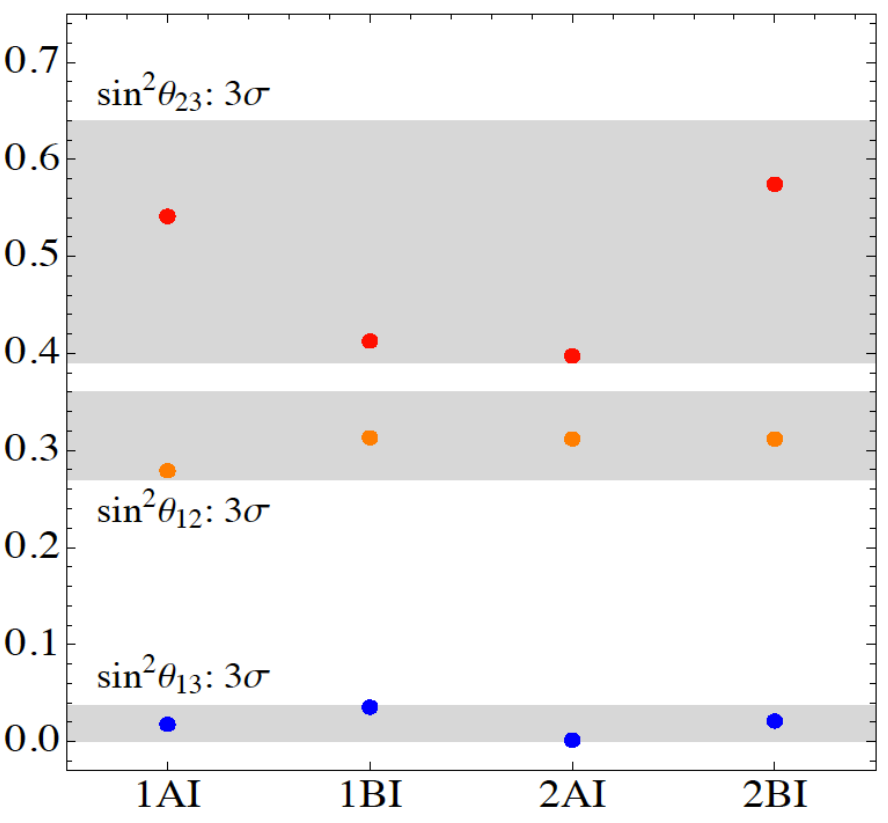
- needs two FN-fields to combine predictivity and $\not{CP}$
- incompatible with left-right symmetry
- excludes bimaximal mixing from neutrino sector
- GUTs: favors SU(5), disfavors SO(10)
- disfavors democratic Yukawa couplings
- nice feature: RGE-effects negligible (due to tiny y_D)

5. A Froggatt-Nielsen Model

We could show: with mild deviations from democratic assignments, one can find fully working models

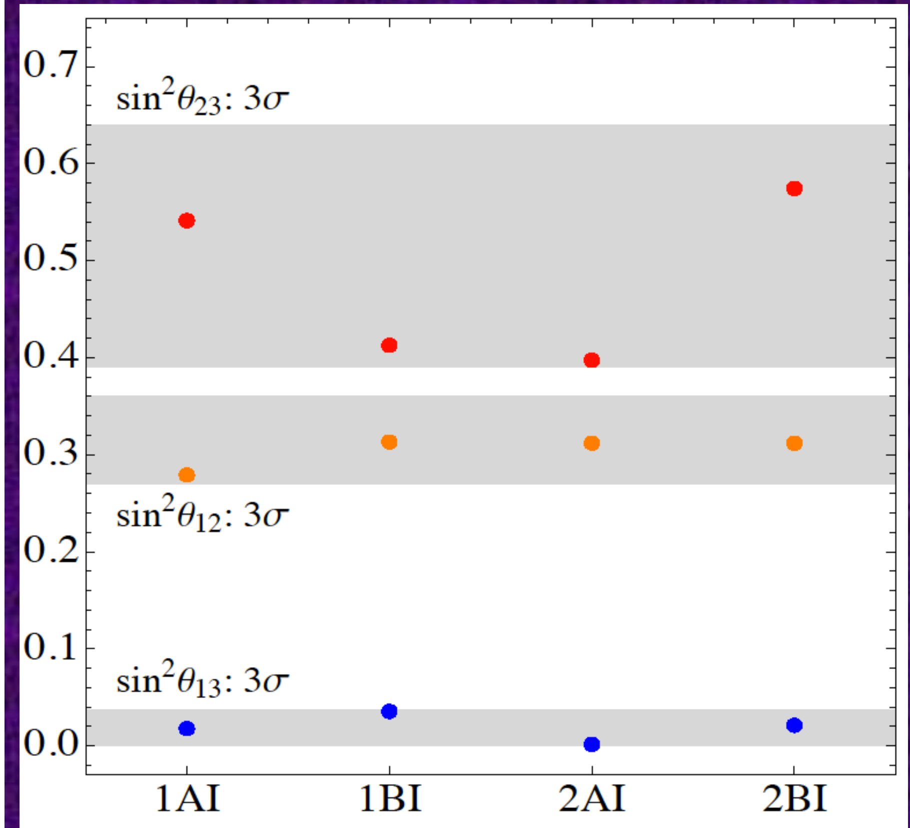
5. A Froggatt-Nielsen Model

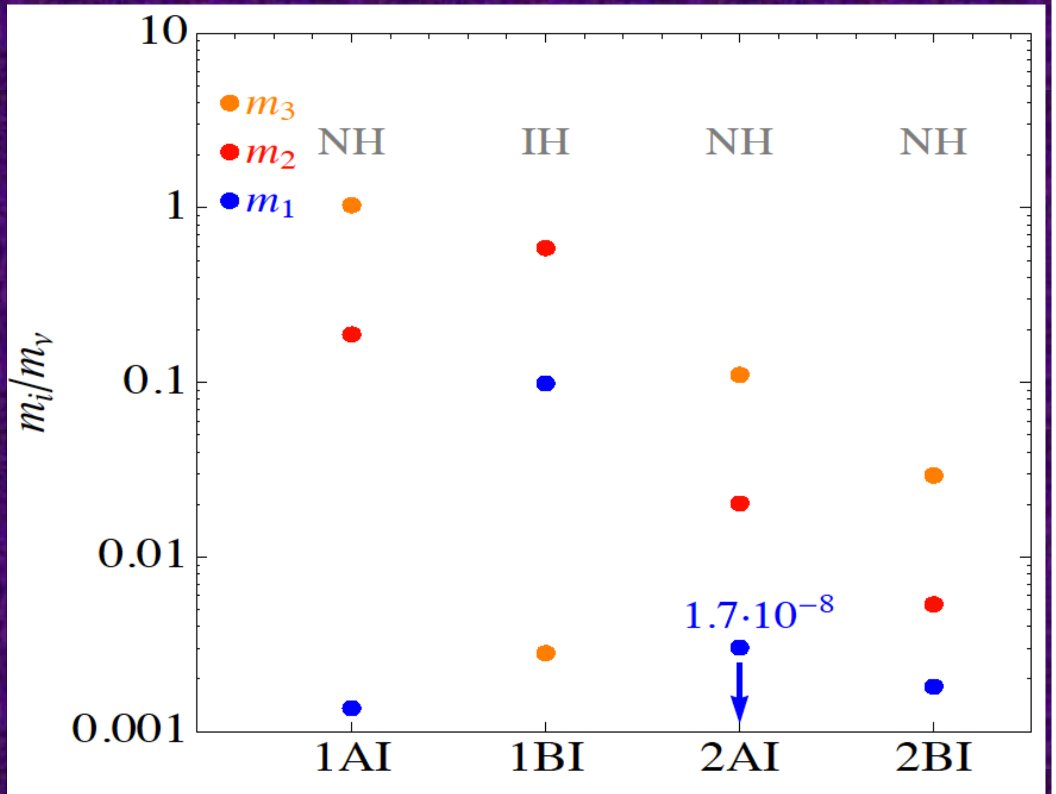
We could show: with mild deviations from democratic assignments, one can find fully working models



5. A Froggatt-Nielsen Model

We could show: with mild deviations from democratic assignments, one can find fully working models





6. Conclusions

6. Conclusions

- no need to say here: keV sterile neutrinos are an interesting candidate for Warm Dark Matter ☺

6. Conclusions

- no need to say here: keV sterile neutrinos are an interesting candidate for Warm Dark Matter ☺
- up to now: *scenarios* rather than *models*

6. Conclusions

- no need to say here: keV sterile neutrinos are an interesting candidate for Warm Dark Matter ☺
- up to now: *scenarios* rather than *models*
- Randall-Sundrum model: exp-suppression

6. Conclusions

- no need to say here: keV sterile neutrinos are an interesting candidate for Warm Dark Matter ☺
- up to now: *scenarios* rather than *models*
- Randall-Sundrum model: exp-suppression
- L_e-L_μ-L_τ: soft breaking makes massless N_R massive

6. Conclusions

- no need to say here: keV sterile neutrinos are an interesting candidate for Warm Dark Matter ☺
- up to now: *scenarios* rather than *models*
- Randall-Sundrum model: exp-suppression
- L_e-L_μ-L_τ: soft breaking makes massless N_R massive
- Froggatt-Nielsen: multiple seesaw-like diagrams

6. Conclusions

- no need to say here: keV sterile neutrinos are an interesting candidate for Warm Dark Matter ☺
- up to now: *scenarios* rather than *models*
- Randall-Sundrum model: exp-suppression
- L_e-L_μ-L_τ: soft breaking makes massless N_R massive
- Froggatt-Nielsen: multiple seesaw-like diagrams
- all models: deep connections between Dark Matter and light neutrino sector

6. Conclusions

- no need to say here: keV sterile neutrinos are an interesting candidate for Warm Dark Matter ☺
- up to now: *scenarios* rather than *models*
- Randall-Sundrum model: exp-suppression
- L_e-L_μ-L_τ: soft breaking makes massless N_R massive
- Froggatt-Nielsen: multiple seesaw-like diagrams
- all models: deep connections between Dark Matter and light neutrino sector

➔ ***We can look forward to more interesting ideas!!!***

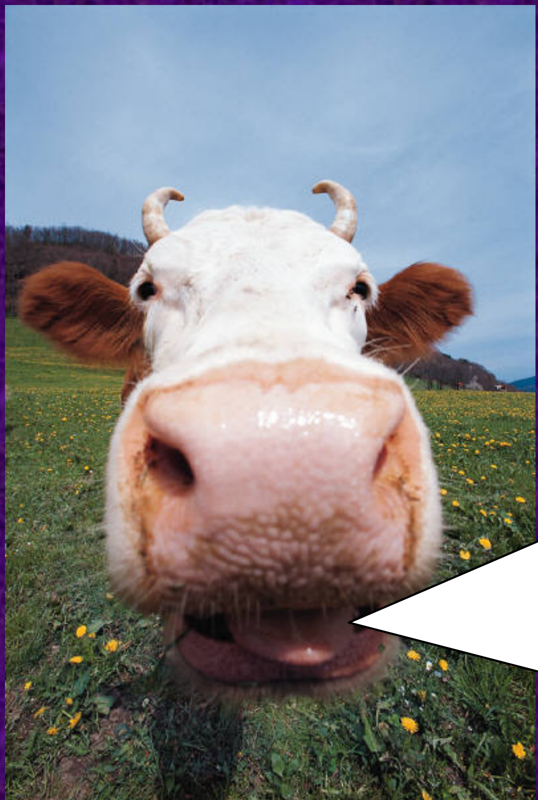
I am currently thinking about many other interesting possibilities....

I am currently thinking about many other interesting possibilities....

➔ Interested?!?

I am currently thinking about many other interesting possibilities....

→ Interested?!?



Ecole Internationale d'Astrophysique Daniel Chalonge **2012** ;-)

THANK YOU!!!