keV Neutrino Model Building

Alexander Merle

University of Southampton, U.K.

E-mail: A.Merle (AT) soton.ac.uk

Based on:

AM, Niro: JCAP **1107** (2011) 023

Lindner, **AM**, Niro: JCAP **1101** (2011) 034

King, **AM**: JCAP **1208** (2012) 016

AM: J. Phys. Conf. Ser. 375 (2012) 012047

AM: Phys. Rev. **D86** (2012) 121701(R)

AM, Niro: 1302.2032

AM: 1302.2625

GK-Get-Together, Würzburg, 23-05-2013

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MARIE CURIE ACTIONS

SEVENTH FRAMEWORK PROGRAMME

<u>*Based on:*</u>

AM, Niro: JCAP **1107** (2011) 023

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AM: 1302.2625 **Pedagogical Review**

GK-Get-Together, Würzburg, 23-05-2013

Contents:

1. Introduction
2. keV and/or Warm Dark Matter
3. Model building for keV neutrinos
4. Example models
5. Conclusions and Outlook

1. Introduction

Many things are not understood in neutrino physics...

$|m_{ee}| < 0.\ 140\text{-}0.\ 380$ eV
[EXO-200: Phys. Rev. Lett. **109** (2012) 032505]
$m_\beta < 2.3$ eV
[MAINZ, Eur. Phys. J. **C40** (2005) 447-468]
$\Sigma < 0.23$ eV
[Planck, 1303.5076 [astro-ph] (2013)]

$\theta_{12} \approx 34.4°$
$\theta_{13} \approx 9.1°$
$\theta_{23} \approx 51.1°$
$\Delta m^2_{21} \approx 7.6\times10^{-5}\,eV^2$
$|\Delta m^2_{31}| \approx 2.5\times10^{-3}\,eV^2$

Forero,Tórtola,Valle:
Phys. Rev. **D86** (2012) 073012

$\Omega_{DM}h^2 = 0.12038$
[Planck, 1303.5076 [astro-ph] (2013)]

BUT: We don‘t understand these values!!!

(http://brainstunts.blogspot.co.uk/2011/02/angry.html)

1. Introduction

We have to think about solutions!!!

- ***lepton mixing***: **flavour symmetries, anarchy, radiative transmission, GUTs,...**
- ***neutrino mass***: **seesaw(s), loop masses, R-parity violation, broken symmetries, Dark Energy connection,...**
- ***Dark Matter***: **WIMPs, FIMPs, EWIPs, WIMPzillas, keVins,...**
- **...**

Ambitious goal:

Try to solve all at once!!!

☺ appeal, testability, missing links,...
☹ difficult, sometimes complicated,...

(http://www.duckipedia.de/images/e/e9/Danield%C3%BCsentrieb.jpg)

2. keV and/or Warm Dark Matter

A big battle in astrophysics: Is Dark Matter...???

HOT
- highly relativistic
- light neutrinos
- only DM within SM (Higgs is unstable) ✓
- ruled out by structure formation ✖

WARM/COOL
- hardly relativistic
- gravitino, axino, sterile keV neutrino,...
- exotic ✗
- Dwarf galaxies ✓ (?)
- model building ✓

COLD
- non-relativistic
- WIMP paradigm
- good for SUSY, etc. ✓
- no direct detection so far (**XENON**) ✗
- Dwarf problem ✗ (?)

HOT: **EXCLUDED!!!**

WARM/COOL and COLD: **Still okay.**

I don't wanna enter that debate... ***<u>NOBODY KNOWS IT FOR SURE!!!</u>***
➔ ***As long as something is not exclued, I do not see any problem in thinking about it. Maybe we can exclude it with particle physics.***

2. keV and/or Warm Dark Matter

Hints for WDM/keV scale:

- Dwarf sattelite galaxies [Boyarsky,Ruchayski,Iakubovskyi: JCAP **0903** (2009) 005; Gorbunov,Khmelnitsky,Rubakov: JCAP **0810** (2008) 041]: we see less then predicted with CDM
  ➔ could be washed out by WDM (**or: astrophysics**)
- Model-independent surveys point at keV scale: e.g. [ALFALFA: Astrophys. J. **739** (2011) 38]
- Some model-independent data analysis point towards the keV scale [de Vega, Sanchez: Mon. Not. Roy. Astron. Soc. **404** (2010) 085; de Vega,Salucci,Sanchez: New Astron. **17** (2012) 653]

BUT: *No clear signal either...*

2. keV and/or Warm Dark Matter

Simple framework: **νMSM** [Asaka,Blanchet, Shaposhnikov: Phys. Lett. **B631** (2005) 151]

- SM + 3 RH neutrinos at (keV, GeV-ε, GeV+ε)

➔ can accommodate for ν-oscillations, BAU, and WDM

- *BUT:* **keV mass NOT explained**

  GeV-degeneracy NOT explained

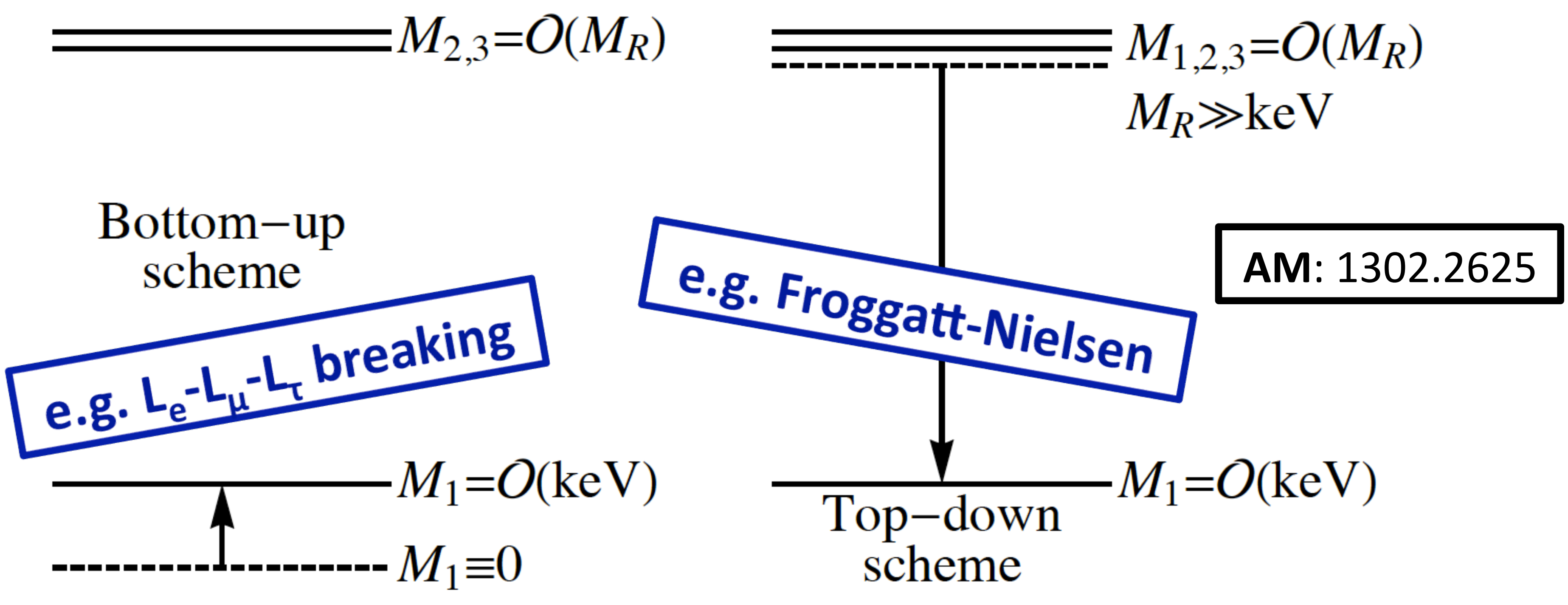
  ν-masses NOT explained

  HARDLY testable

➔ *Model building needed...*

3. Model building for keV neutrinos

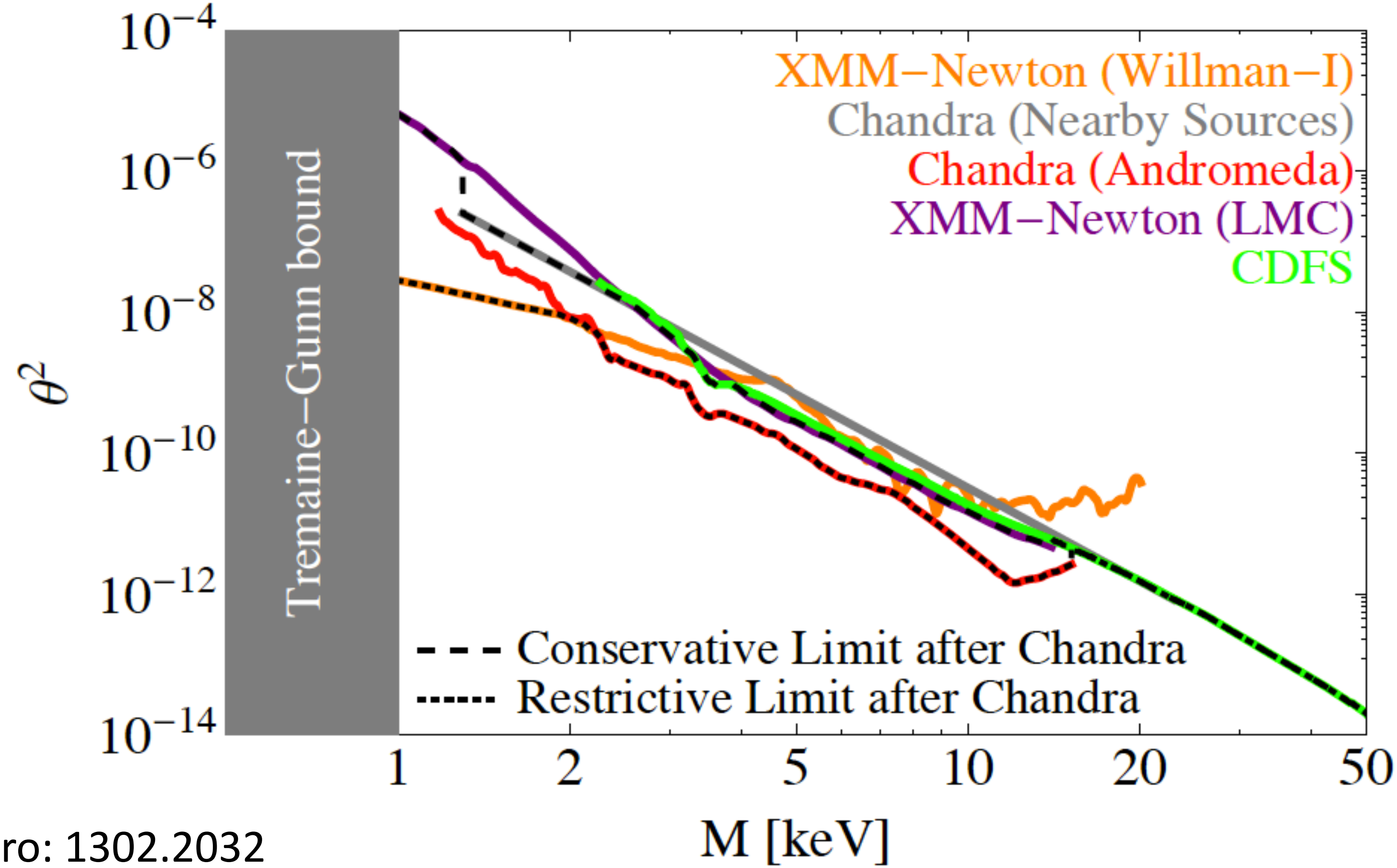
- ***Explanation for the keV scale needed***:



→ **Most models are in one or the other category!**

3. Model building for keV neutrinos

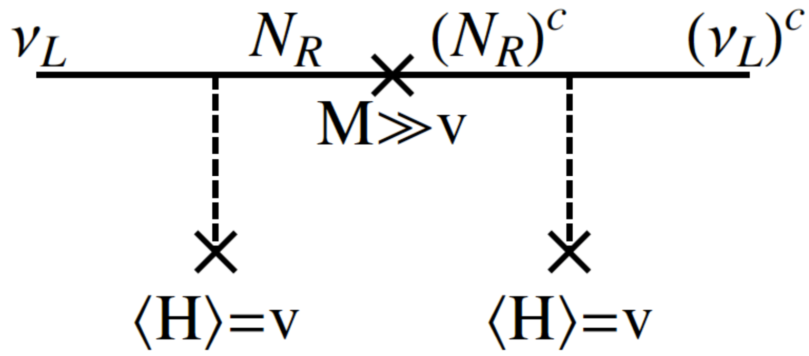
- ***Differences to "ordinary" model building***:
  - we need to respect the X-ray bound: $N_1 \rightarrow \nu\gamma$



AM,Niro: 1302.2032

3. Model building for keV neutrinos

- ***seesaw with keV scale?!?***



  - guaranteed to work for models based on the split seesaw or Froggatt-Nielsen mechanisms
    [Kusenko,Takahashi,Yanagida: Phys. Lett. **B693** (2010) 144]
    [**AM**,Niro: JCAP **1107** (2011) 023]

  - all models that respect the X-ray bound have no problems with the seesaw mechanism
    [**AM**: Phys. Rev. D86 (2012) 121701(R)]

→ ***Actually okay in most of the cases!***

3. Model building for keV neutrinos

Production Mechanisms for keV ν's (ordinary thermal production would lead to overclosure of the Universe):

- **thermal production by mixing** ("Dodelson-Widrow")
  [Dodelson,Widrow: Phys. Rev. Lett. **72** (1994) 17]
  ➔ excluded if no lepton asymmetry present
- **non-thermal resonant production** ("Shi-Fuller")
  [Shi,Fuller: Phys. Rev. Lett. **82** (1999) 2832]
  ➔ needs larger enough asymmetry to be efficient
- **primordial abundance by scalar (e.g. inflaton) decays**
  [Asaka,Shaposhnikov,Kusenko: Phys. Lett. **B638** (2006) 401]
  [Anisimov,Bartocci,Bezrukov: Phys. Lett. **B671** (2009) 211]
  [Bezrukov,Gorbunov: JHEP **1005** (2010) 010] [**AM**, Niro, Schmidt: *work in progress*]
- **thermal overproduction with entropy dilution**
  [Bezrukov,Hettmansperger,Lindner: Phys. Rev. **D81** (2010) 085032]
  [Nemevsek,Senjanovic,Zhang: JCAP **1207** (2012) 006]

4. Example Models

4. Example Models

- *probably the most intuitive*: $\mathcal{F}$**=L$_e$-L$_\mu$-L$_\tau$**
  - original: [Petcov: Phys. Lett. **B110** (1982) 245]
  - 2 RH neutrinos: [Grimus,Lavoura: JHEP **0009** (2000) 007]
  - 3 RH neutrinos:

    [Barbieri,Hall,Tucker-Smith,Strumia,Weiner: JHEP **9812** (1998) 017]

    [Mohapatra: Phys. Rev. **D64** (2001) 091301]
  - *application to keV sterile neutrinos*:

    [Shaposhnikov: Nucl. Phys. **B763** (2007) 49]

    [Lindner,**AM**,Niro: JCAP **1101** (2011) 034]
  - general features:
    - ***symmetry*** ➔ patterns: (0,m,m) & (0,M,M)
    - ***broken*** ➔ small mass, degeneracy lifted

4. Example Models

- *probably the most intuitive*: $\mathcal{F}$=L_e-L_μ-L_τ
  - charge assignment under global U(1) [or: Z_4]:

	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

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$\mathcal{F}$	1	-1	-1	1	-1	-1	1	-1	-1	0	0

  - then, only symmetry preserving terms are allowed:
    ➔ mass matrix:

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

  - mass patterns:
    - light ν's: (0,m,m) ➔ okay up to degeneracy
    - heavy N's: (0,M,M) ➔ 0 << M, but still 0≠keV

4. Example Models

- *probably the most intuitive*: $\mathcal{F}$**=L$_e$-L$_\mu$-L$_\tau$**
  - softly broken symmetry: [Lindner,**AM**,Niro: JCAP **1101** (2011) 034]
    - ➔ new mass matrix:

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

  - breaking terms are ***naturally*** assumed to be small **(like p-n isospin symmetry)**
  - eigenvalues: (s,m-δm,m+δm)

    (S,M-ΔM,M+ΔM)

4. Example Models

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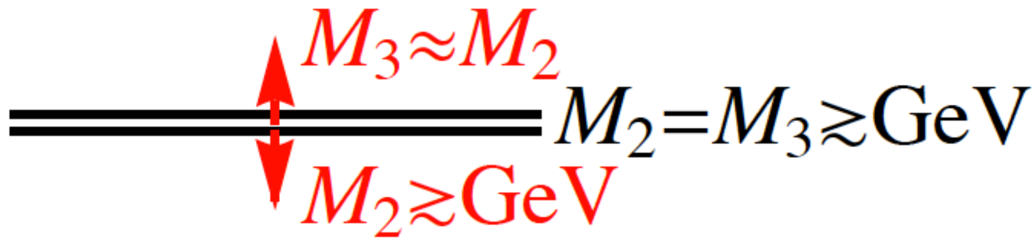
  - eigenvalues: (s,m-δm,m+δm)
    (S,M-ΔM,M+ΔM)

➔ motivates S=O(keV), due to S<<M

4. Example Models

- *probably the most intuitive*: $\mathcal{F}$=$\mathbf{L_e\text{-}L_\mu\text{-}L_\tau}$
    - mass shifting scheme:



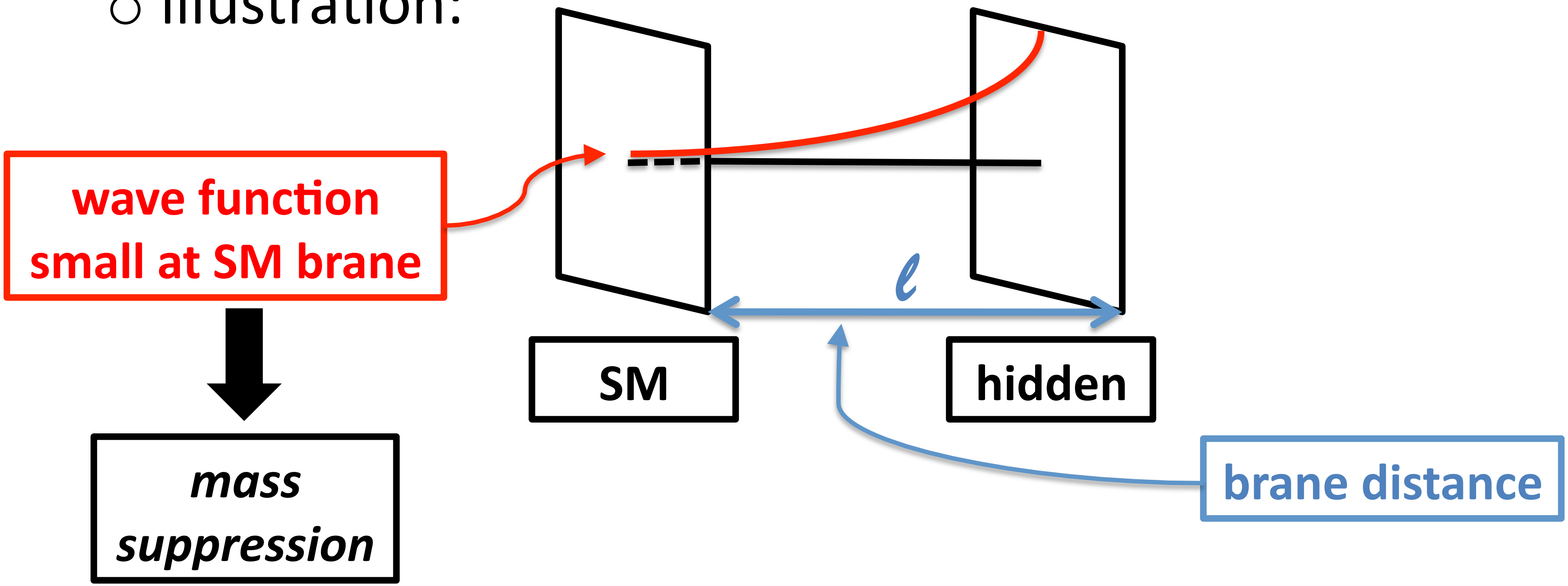
$L_e - L_\mu - L_\tau \,\&\, \mu - \tau$

~~$L_e - L_\mu - L_\tau$~~ $\&\, \mu - \tau$

➔ **clear bottom-up type scheme**

4. Example Models

- *probably the most effective*: **Split Seesaw**
  - *idea*: brane-splitting in etxra dimensions is known to lead to mass scale suppressions
  - this can be used to get a keV mass
    [Kusenko,Takahashi,Yanagida: Phys. Lett. **B693** (2010) 144]
  - illustration:



4. Example Models

- *probably the most effective*: **Split Seesaw**
  - 5D action:

$$S = \int d^4x \int dy \left[M_0 \left(\overline{\Psi_{iR}^{(0)}} i\Gamma^A \partial_A \Psi_{iR}^{(0)} - m_i \overline{\Psi_{iR}^{(0)}} \Psi_{iR}^{(0)} \right) \right.$$

$$\left. -\delta(y) \left(\frac{\kappa_i}{2} v_{B-L} \overline{(\Psi_{iR}^{(0)})^c} \Psi_{iR}^{(0)} + \tilde{\lambda}_{i\alpha} \overline{\Psi_{iR}^{(0)}} L_\alpha H \right) \right]$$

  - in 4D: bulk profile (ED w.f.) ➔ mass suppressions

$$\boxed{M_i = \kappa_i \frac{v_{B-L}}{M_0} \frac{2m_i}{e^{2m_i l} - 1}}$$

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5D mass of the sterile N_i's

  - in 4D: bulk profile (ED w.f.) ➔ mass suppressions

$$\boxed{M_i = \kappa_i \frac{v_{B-L}}{M_0} \frac{2m_i}{e^{2m_i l} - 1}}$$

5D masses get strongly split

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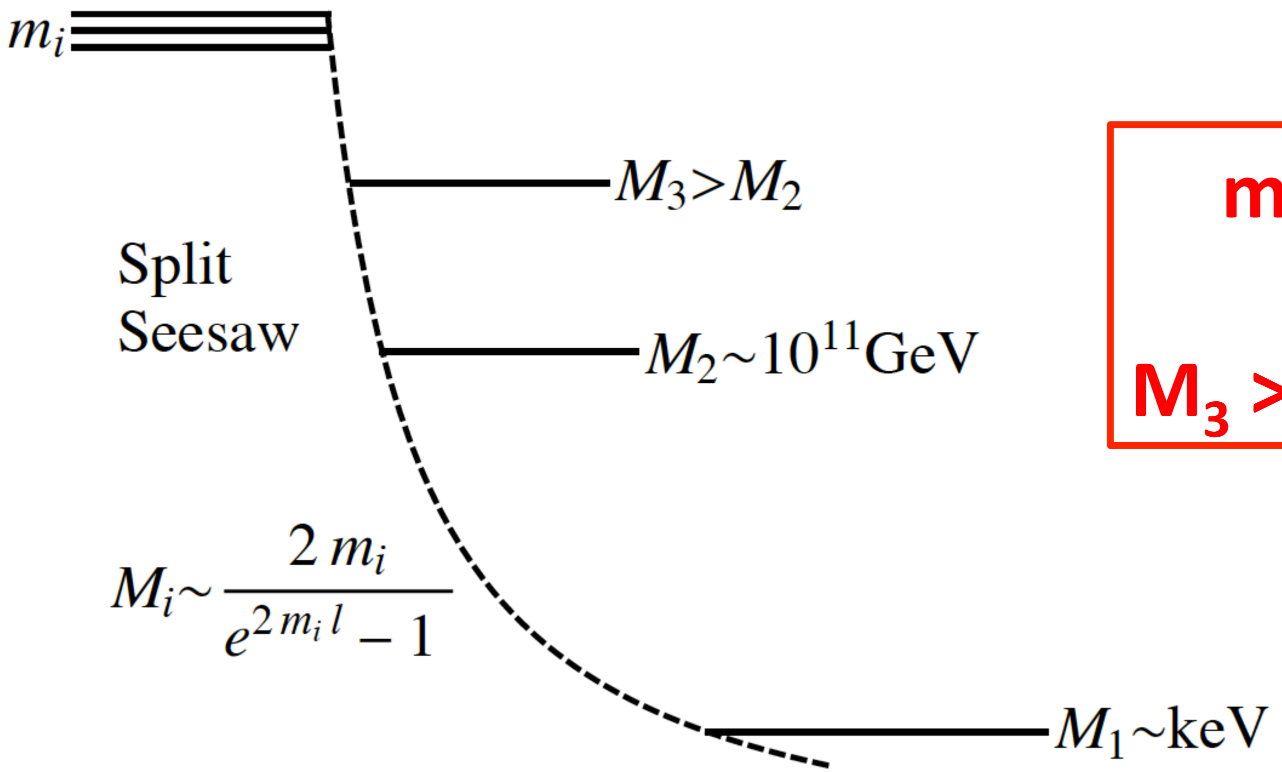


$m_3 < m_2 < m_1$

↓

$M_3 >> M_2 >> M_1$!!!

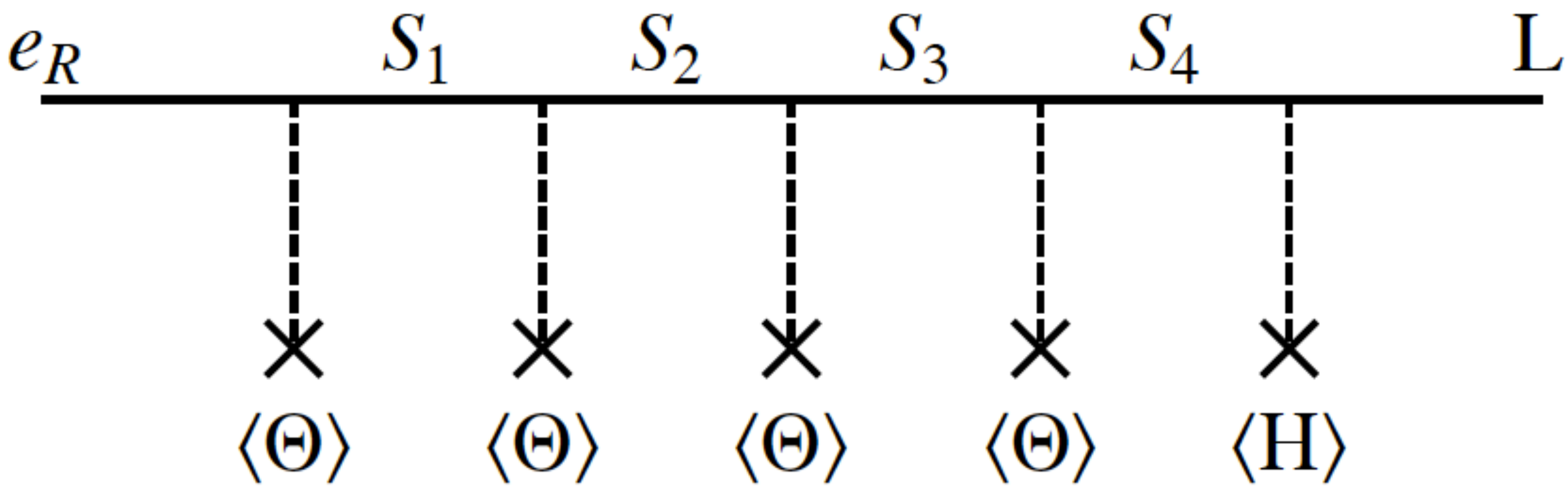
Can generate very strong hierarchies!!!

4. Example Models

- *probably the most simple*: **Froggatt-Nielsen** (FN)
  - original idea [Froggatt,Nielsen: Nucl. Phys. **B147** (1979) 277]
  - application to keV sterile neutrinos:
    - pure FN models [**AM**,Niro: JCAP **1107** (2011) 023]
    - mixed with flavour symmetry [Barry,Rodejohann,Zhang: JHEP **1107** (2011) 091, JCAP **1201** (2012) 052]
  - some features:
    - suppression maybe as strong as for split seesaw
    - more predictive than one would naively expect
    - seesaw guaranteed to work

4. Example Models

- *<u>probably the most simple</u>*: **Froggatt-Nielsen** (FN)
  - *Froggatt-Nielsen mechanism*:



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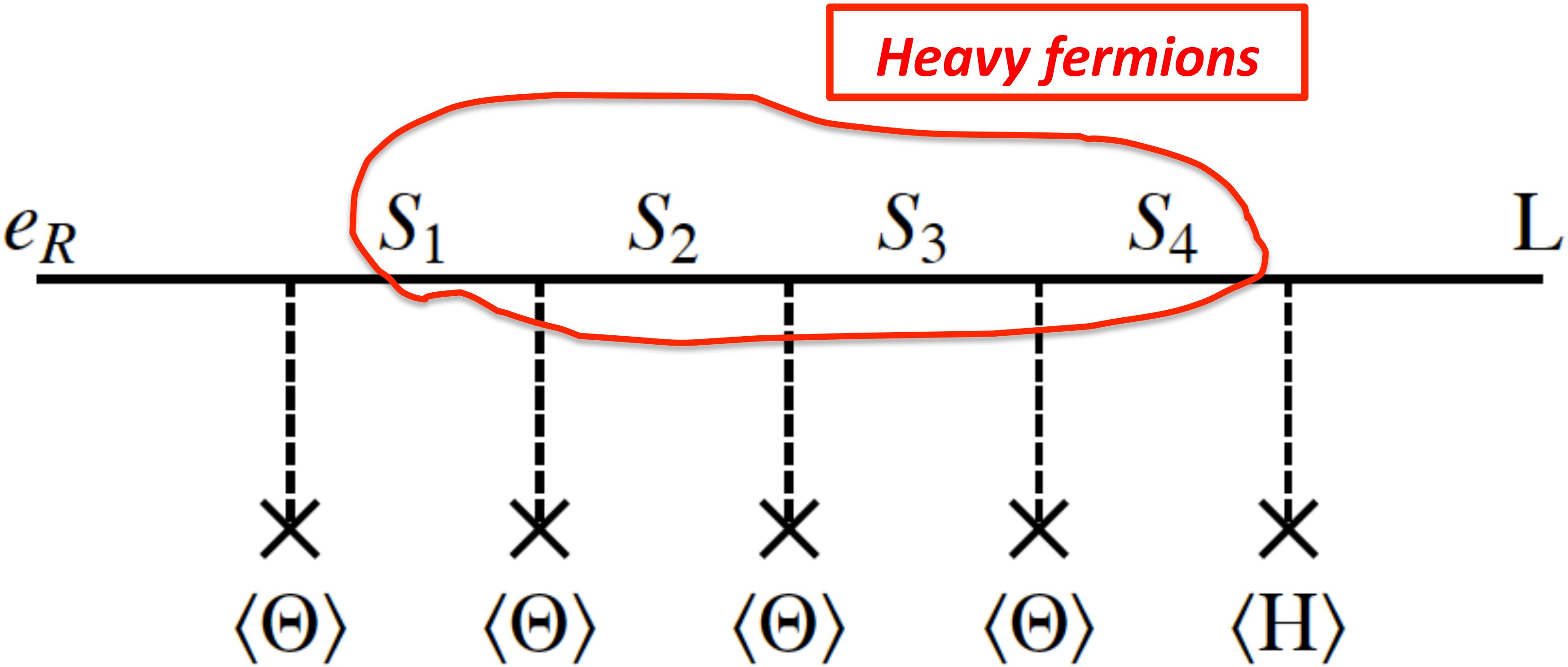

➔ suppress light fermion masses when integrated out!!!

(like in the seesaw mechanism)

4. Example Models

- *probably the most simple*: **Froggatt-Nielsen** (FN)
  - this leads to generation-dependent suppressions
    ➔ e.g. Yukawa couplings:

Generation-dependent $U(1)_{FN}$ charges

$$Y_{ij} = Y_{ij}^{\rm nat} \lambda^{a_i + b_j}$$

“natural“ Yukawa coupling: O(1)

$\lambda = \langle\Theta\rangle/\Lambda$: suppression factor

➔ ***Physical Yukawa coupling can be small!***

  - **HOWEVER**: some issues swept under carpet

4. Example Models

- *probably the most simple*: **Froggatt-Nielsen** (FN)
  - application to keV sterile neutrinos: $U(1)_{FN} \times Z_{2,aux}$

$$\Theta_{1,2}: \ (\theta_1, \theta_2; +, -)$$
$$L_{1,2,3}: \ (f_1, f_2, f_3; +, +, -)$$
$$\overline{e_{1,2,3}}: \ (k_1, k_2, k_3; +, +, -)$$
$$\overline{N_{1,2,3}}: \ (g_1, g_2, g_3; +, +, -)$$

$$\lambda = \frac{\langle \Theta_1 \rangle}{\Lambda}, \quad R = \frac{\langle \Theta_1 \rangle}{\langle \Theta_2 \rangle} = R_0 e^{i\alpha_0}$$

  - example model: $(g_1, g_2, g_3) = (3,0,0)$

$$M_1 = M_0 \lambda^6 \, 2R_0^2 \sqrt{1 + R_0^4 + 2R_0^2 \cos(2\alpha_0)}$$
$$M_2 = M_0$$
$$M_3 = M_0 \left(1 + \lambda^6 [1 + R_0^2 (3\cos(2\alpha_0) + 3R_0^2 \cos(4\alpha_0) + R_0^4 \cos(6\alpha_0)]\right)$$

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$$\Theta_{1,2}: \ (\theta_1, \theta_2; +, -)$$

Have to be chosen such that a strong hierarchy is generated!!

$$\overline{e}_{1,2,3}: \ (k_1, k_2, k_3; +, +, -)$$

$$\overline{N}_{1,2,3}: \ (g_1, g_2, g_3; +, +, -)$$

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Small mass

$$M_2 = M_0$$

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Small mass

$$M_2 = M_0$$

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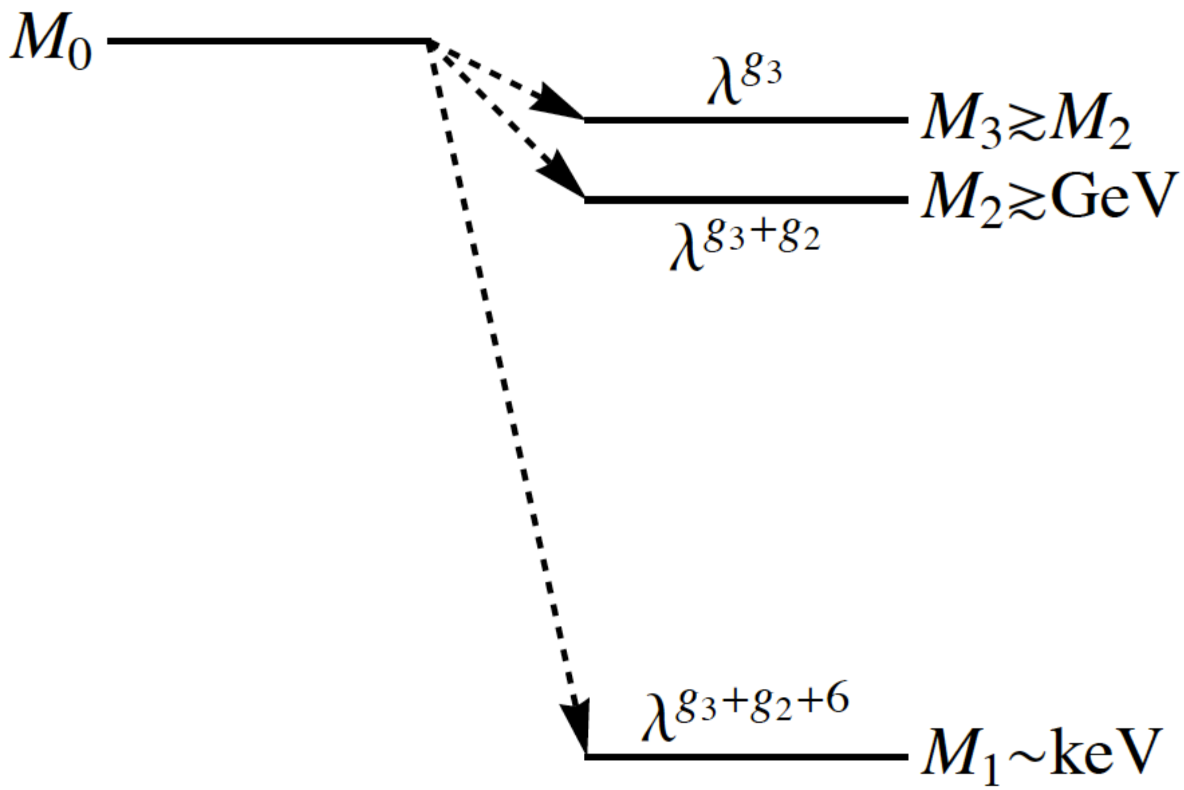
Quasi-Degeneracy

4. Example Models

- *probably the most simple*: **Froggatt-Nielsen** (FN)
  - mass shifting scheme:



➔ large mass scale gets suppressed

➔ ***top-down***

4. Example Models

- *probably the most versatile*: **<u>M</u>inimal <u>E</u>xtended <u>S</u>eesaw**
  - first proposed for solar ν problem
    [Chun,Joshipura,Smirnov: Phys. Lett. **B357** (1995) 608]
  - later on mentioned in the context of keV neutrinos
    [Barry,Rodejohann,Zhang: JHEP **1107** (2011) 091]
  - more detailed investigation + A4-extension
    [Zhang: Phys. Lett. **B714** (2012) 262]
  - anomaly-free U(1)-extension
    [Heeck,Zhang: 1211.0538]
  - important features:
    - necessarily goes beyond 3 sterile neutrinos
    - not justified by itself ➔ needs framework
    - structural implications (one massless ν, only possible for certain numbers of sterile ν's)

4. Example Models

- *probably the most versatile*: **Minimal Extended Seesaw**
  - idea: introduce another singlet fermion S_R and **assume** the following Lagrangian

$$\mathcal{L}_{\rm ES} = -\overline{\nu_L} m_D N_R - \overline{(S_R)^c} M_S^T N_R - \frac{1}{2}\overline{(N_R)^c} M_R N_R + h.c.$$

➔ *problem*: Majorana mass term for S_R **assumed** not to exist, but for no reason

  - assuming $m_D << M_S << M_R$ (**BUT**: unjustified!!!) and applying the seesaw formula twice

➔ there is an intermediate mass eigenvalue:

$$m_s = M_S M_R^{-1} M_S^T$$

➔ **keV neutrino**

4. Example Models

- *<u>probably the most versatile</u>*: **<u>M</u>inimal <u>E</u>xtended <u>S</u>eesaw**
  - *<u>problem</u>*: there is no reason for the structure of extended seesaw

    ➔ this can be enforced by a symmetry:

    – A_4 extension [Zhang: Phys. Lett. **B714** (2012) 262]:

    ➔ yields tri-bimaximal leptonic mixing

    ➔ excluded by new data!

    – U(1) extension [Heeck,Zhang: 1211.0538]:

    ➔ more complicated (addition singlets needed)

    ➔ okay with new data
  - *<u>general</u>*: although the mechanism cannot stand alone, it may be resembled in more concrete models

4. Example Models

- *other possibilities* (more or less all I know):
  - Q_6 symmetry at NLO [Araki,Li: Phys. Rev. **D85** (2012) 065016]
  - *composite Dirac neutrinos* [Grossmann,Robinson: JHEP **1101** (2011) 132; Robinson,Tsai: JHEP **1208** (2012) 161]
  - *type II seesaw in 331-models* [Dias,Peres,Silva: Phys. Lett. **B628** (2005) 85; Cogollo,Diniz,Peres: Phys. Lett. **B677** (2009) 338]
  - ~~*U(1)*~~ *symmetries close to* M_P [Allison, JHEP **1305** (2013) 009]
  - *Dark GUTs* [Babu,Seidl: Phys. Rev. **D70** (2004) 113014]
  - *many EDs* [Ioannision,Valle: Phys. Rev. **D63** (2001) 073002]
  - *MRISM* [Dev,Pilaftsis: Phys. Rev. **D87** (2013) 053007]
  - *Exotic Loops* [Ma: Phys. Rev. **D80** (2009) 013013]
  - global symmetries [Sayre,Wiesenfeldt,Willenbrock: Phys. Rev. **D72** (2005) 015001]
  - gravitational torsions [Mavromatos,Pilaftsis: Phys. Rev. D86 (2012) 124038]

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KEV NEUTRINO MODEL BUILDING

ALEXANDER MERLE

Physics and Astronomy, University of Southampton,
Highfield, Southampton, SO17 1BJ, United Kingdom
A.Merle@soton.ac.uk

Received Day Month Year
Revised Day Month Year

We review the model building aspects for keV sterile neutrinos as Dark Matter candidates. After giving a brief discussion of some cosmological and astrophysical aspects, we first discuss the currently known neutrino data and observables. We then explain the purpose and goal of neutrino model building, and review some generic methods used. Afterwards certain aspects specific for keV neutrino model building are discussed, before reviewing the bulk of models in the literature. We try to keep the discussion on a pedagogical level, while nevertheless pointing out some finer details where necessary and useful. Ideally, this review should enable a grad student or an interested colleague from cosmology or astrophysics with some prior experience to start working on the field.

Keywords: Neutrinos; Dark Matter; Model Building.

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Okay, it's 90 pages, but I tried to put in some jokes... ;-)

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