Particle Physics Models for keV Neutrinos

Alexander Merle

University of Southampton, U.K.

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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, accepted by IJMPD
AM, Niro, Schmidt: 1306.xxxx

WDM-Workshop, Meudon, 06-06-2013

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Contents:

1. Introduction

Every talk about physics starts with problems...

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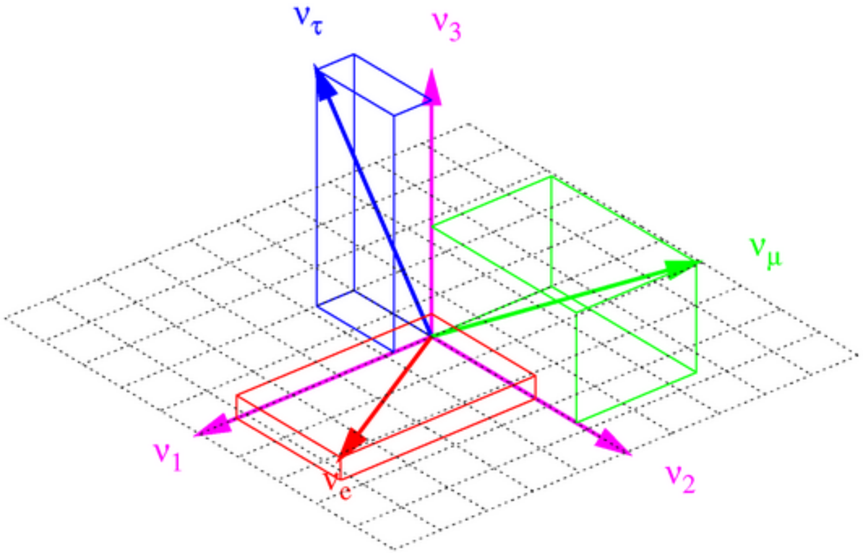
- **Neutrinos do mix:**



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

$\theta_{12} \approx 34.4°$
$\theta_{13} \approx 9.1°$
$\theta_{23} \approx 51.1°$
$\Delta m^2_{21} \approx 7.6 \times 10^{-5} eV^2$
$|\Delta m^2_{31}| \approx 2.5 \times 10^{-3} eV^2$

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Phys. Rev. **D86** (2012) 073012

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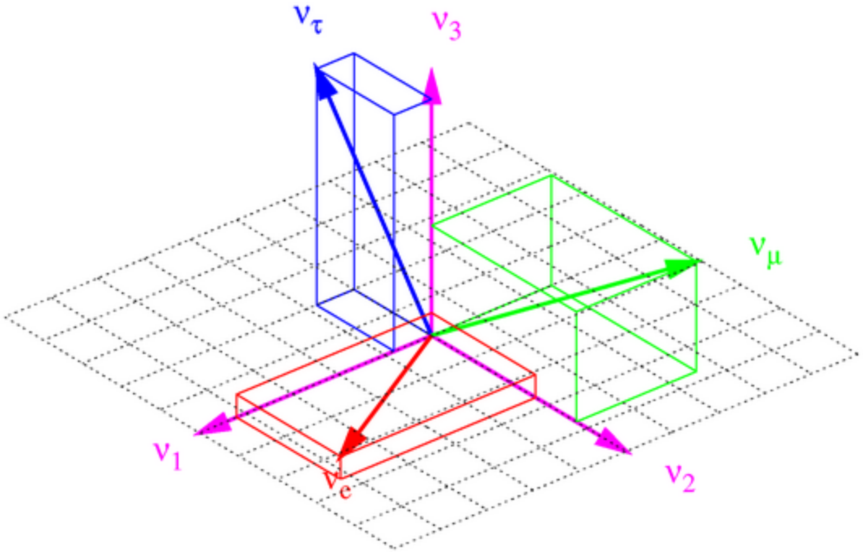

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BUT: We don't understand these values!!!

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

1. Introduction

Every talk about physics starts with problems...

- **Neutrinos have a tiny mass:**

$|m_{ee}|< 0.3\text{-}0.6$ eV [KamLAN-Zen: Phys. Rev. **C85** (2012) 045504]
$|m_{ee}|< 0.\ 140\text{-}0.\ 380$ eV [EXO-200: Phys. Rev. Lett. **109** (2012) 032505]
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$\Sigma < 0.23$ eV [Planck, 1303.5076 [astro-ph] (2013)]

BUT: We don't know why it is so small!!!

(http://imprinttrainingcenter.blogspot.co.uk/2010/12/understanding-and-controlling-anger.html)

1. Introduction

Every talk about physics starts with problems...

- **We know that Dark Matter is there:**

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

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- **We know that Dark Matter is there:**

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BUT: We don't know what it is!!!

(http://2.bp.blogspot.com/-WTeCZueCvFI/T5fSKtzDwOI/AAAAAAAAAf8/3zpFpaUaHUI/s1600/hulk-marvel-uk.jpg)

1. Introduction

We have to think about solutions!!!

- **<u>lepton mixing</u>: flavour symmetries, anarchy, radiative transmission, GUTs,...**
- **<u>neutrino mass</u>: seesaw(s), loop masses, R-parity violation, broken symmetries, Dark Energy connection,...**
- **<u>Dark Matter</u>: 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. Neutrino Model Building

2. Neutrino Model Building

What is model building good for?!?
Why all the effort?!?

We try to understand ***TWO MAIN PROPERTIES*** of neutrinos:

- **Why is the neutrino mass so small (<< all other fermions)???**

➔ *mass suppressions (seesaw, radiative mass generation, smallness enforced by symmetries,...)*

- **Why are the mixing angles so large (one may even be maximal)???**

➔ *structure in the mass matrices (symmetries, anarchy, radiative transmission, GUTs,...)*

2. Neutrino Model Building

Example: ***How to get neutrino masses small?!?***

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- **Dirac neutrinos** (like SM fermions):
  - Yukawa coupling with Higgs field:

$$\mathcal{L}_Y \supset -\overline{L}\tilde{H}y_\nu \nu_R + h.c.$$

  - Higgs obtains vaccuum expectation value v=<H>:

$$-\overline{L}\langle\tilde{H}\rangle y_\nu \nu_R + h.c.$$

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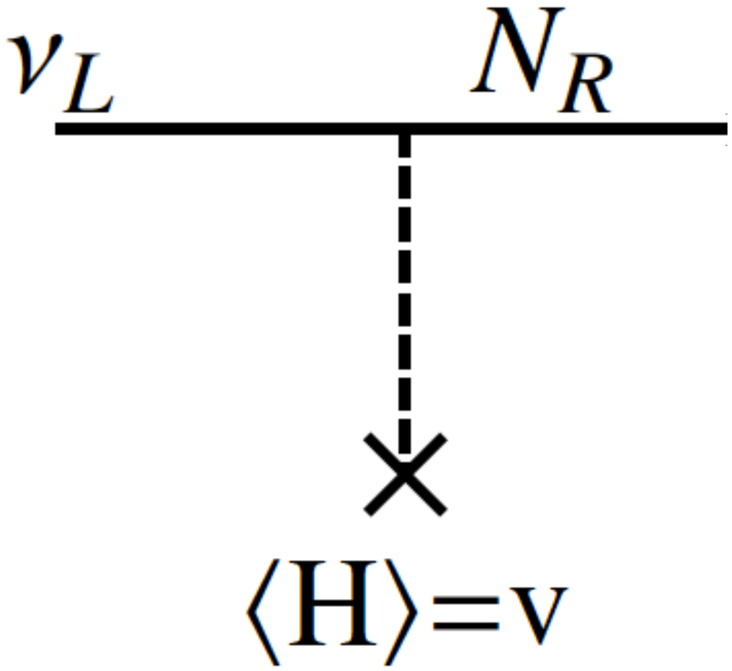
$=y_\nu v = m_D$, with v=174 GeV

➔ TOO LARGE TO EXPLAIN THE NEUTRINO MASS!!!

2. Neutrino Model Building

Example: ***How to get neutrino masses small?!?***

- **Dirac neutrinos** (like SM fermions):
    - Feynman diagram:



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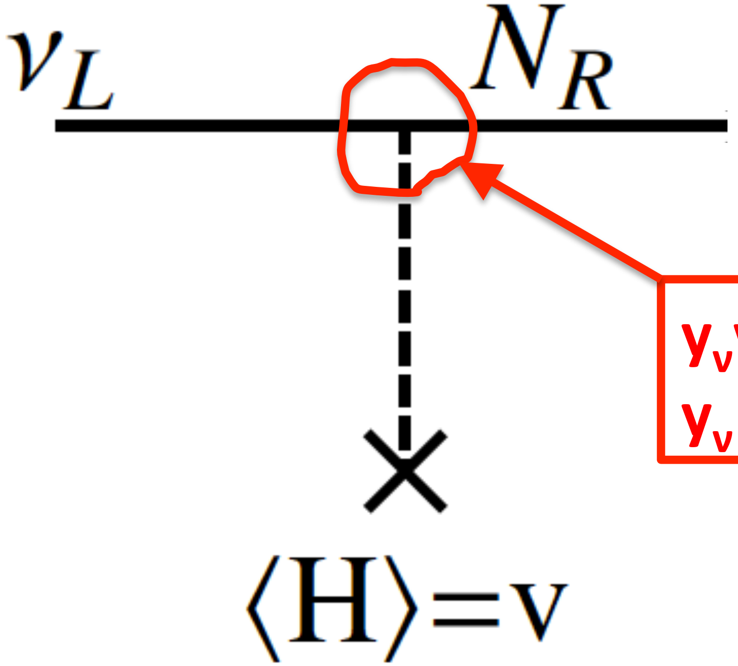

y_vv=m_D >> 1 eV (unless y_v is unnaturally small)

2. Neutrino Model Building

Example: ***How to get neutrino masses small?!?***

- **Seesaw type I** (Gell-Mann, Minkowski, Mohapatra, Ramond, Slansky, Senjanovic, Yanagida):
  - ○ Yukawa coupling **PLUS** heavy neutrino mass term:

$$-\overline{L}\tilde{H}y_\nu\nu_R + h.c. - \frac{1}{2}\overline{(\nu_R)^c}M_R\nu_R + h.c.$$

  - ○ this can be written as one big mass matrix:

$$\mathcal{L}_\nu = -\frac{1}{2}(\overline{\nu_L}, \overline{(N_R)^c})\begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix}\begin{pmatrix} (\nu_L)^c \\ N_R \end{pmatrix} + h.c.$$

2. Neutrino Model Building

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Example: ***How to get neutrino masses small?!?***

- **Seesaw type I** (Gell-Mann, Minkowski, Mohapatra, Ramond, Slansky, Senjanovic, Yanagida):
  - ○ light neutrino mass matrix:

$$m_\nu = -m_D M_R^{-1} m_D^T$$

  - ○ if M_R is large enough, the neutrino mass can be very small:

$$m_\nu \sim \frac{(100\ \mathrm{GeV})^2}{10^{14}\ \mathrm{GeV}} = 10^{-10}\ \mathrm{GeV} = 0.1\ \mathrm{eV}$$

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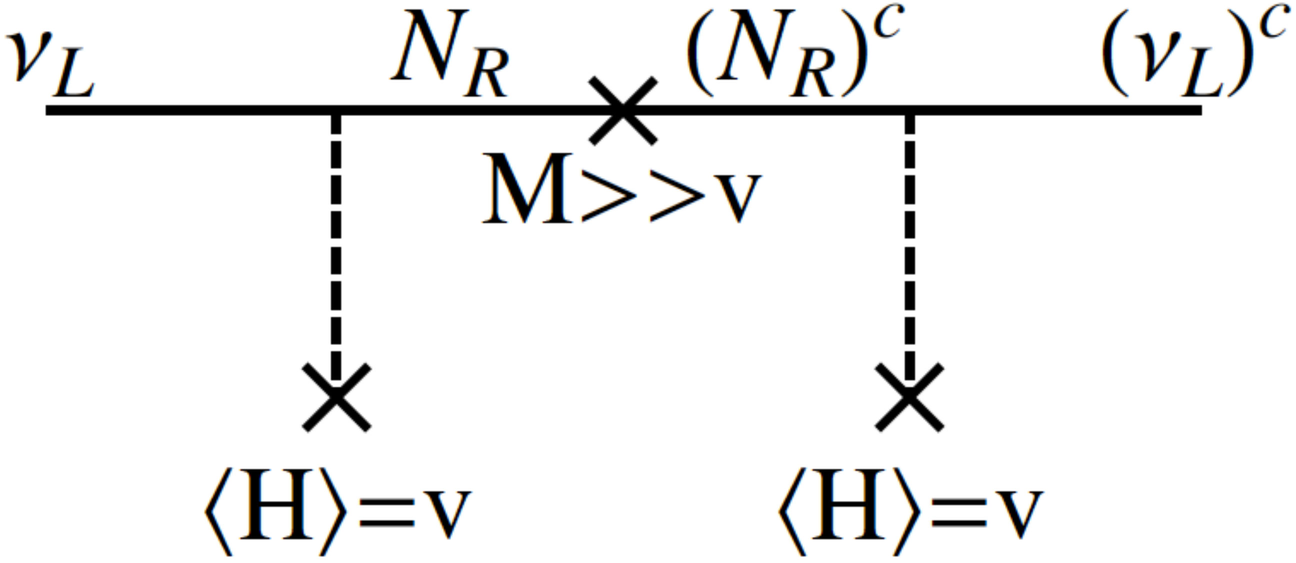

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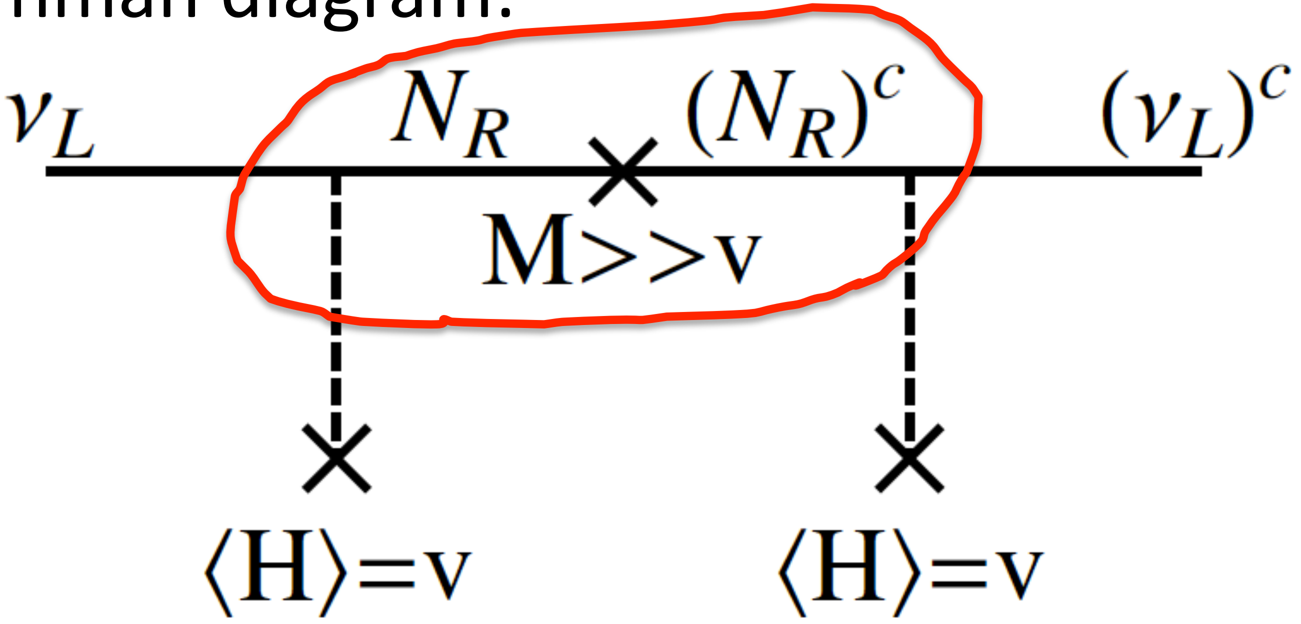

heavy right-handed neutrinos suppress the masses of the ordinary neutrinos ➔ explanation for small m_ν found!!!

2. Neutrino Model Building

Example: ***How to get leptonic mixing angles large?!?***

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- **Diagonal mass matrices**: NO MIXING!!!
  - the leptonic mixing matrix parametrizes the **mismatch** between the charged lepton and the neutrino mass bases:

$$U_{\mathrm{PMNS}} = U_e^\dagger U_\nu$$

  - if both are diagonal, the basis rotations are unit matrices:

M_e= diag(m_e,m_μ,m_τ) ➔ U_e=**1**

m_ν=diag(m_1,m_2,m_3) ➔ U_ν=**1**

➔ U_{PMNS}=1 ➔ θ_{ij}=0!!

2. Neutrino Model Building

Example: ***How to get leptonic mixing angles large?!?***

- **Non-diagonal matrices**: MIXING SWITCHED ON!!!
  - e.g. a model based on an A_4-symmetry:

$$M_e = v\alpha_S \begin{pmatrix} k_e & k_\mu & k_\tau \\ k_e & k_\mu & k_\tau \\ k_e & k_\mu & k_\tau \end{pmatrix} \quad m_\nu = \frac{v^2}{\Lambda} \begin{pmatrix} \alpha_0 + 2\alpha_S & -\alpha_S & -\alpha_S \\ -\alpha_S & 2\alpha_S & \alpha_0 - \alpha_S \\ -\alpha_S & \alpha_0 - \alpha_S & 2\alpha_S \end{pmatrix}$$

  - this yields a “tri-bimaximal“ mixing matrix:

$$U_{\rm TBM} = \begin{pmatrix} \frac{2}{\sqrt{6}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

➔ θ_{12}=35.3°, θ_{13}=0°, θ_{23}=45°: non-trivial mixing angles

3. Connection to keV neutrinos

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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

- provides fundamental connections between two clear signs for BSM physics: neutrinos & Dark Matter
- very minimalistic extension of the SM: only singlet (RH) neutrinos and lepton number violation
- *BUT:* **keV mass not explained**
  GeV-degeneracy not explained
  ν-masses & mixings not explained
  hardly testable

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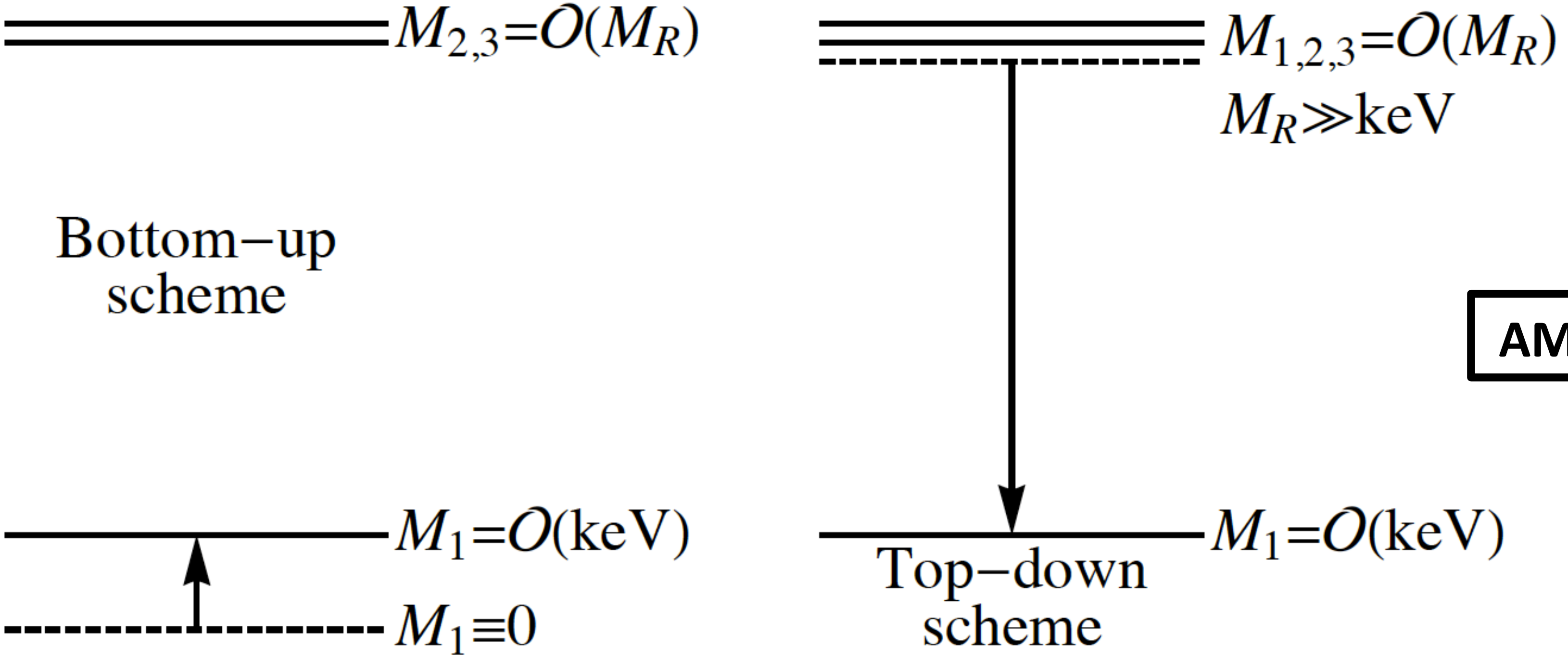
hardly testable ➔ **MODEL BUILDING NEEDED!!!**

3. Connection to keV neutrinos

- ***<u>Differences to “ordinary“ model building</u>***:
  - o we need an explanation for the keV scale:
    - – not considered to be “fundamental“
    - – need some mechanism ➔ two generic schemes:



AM: 1302.2625

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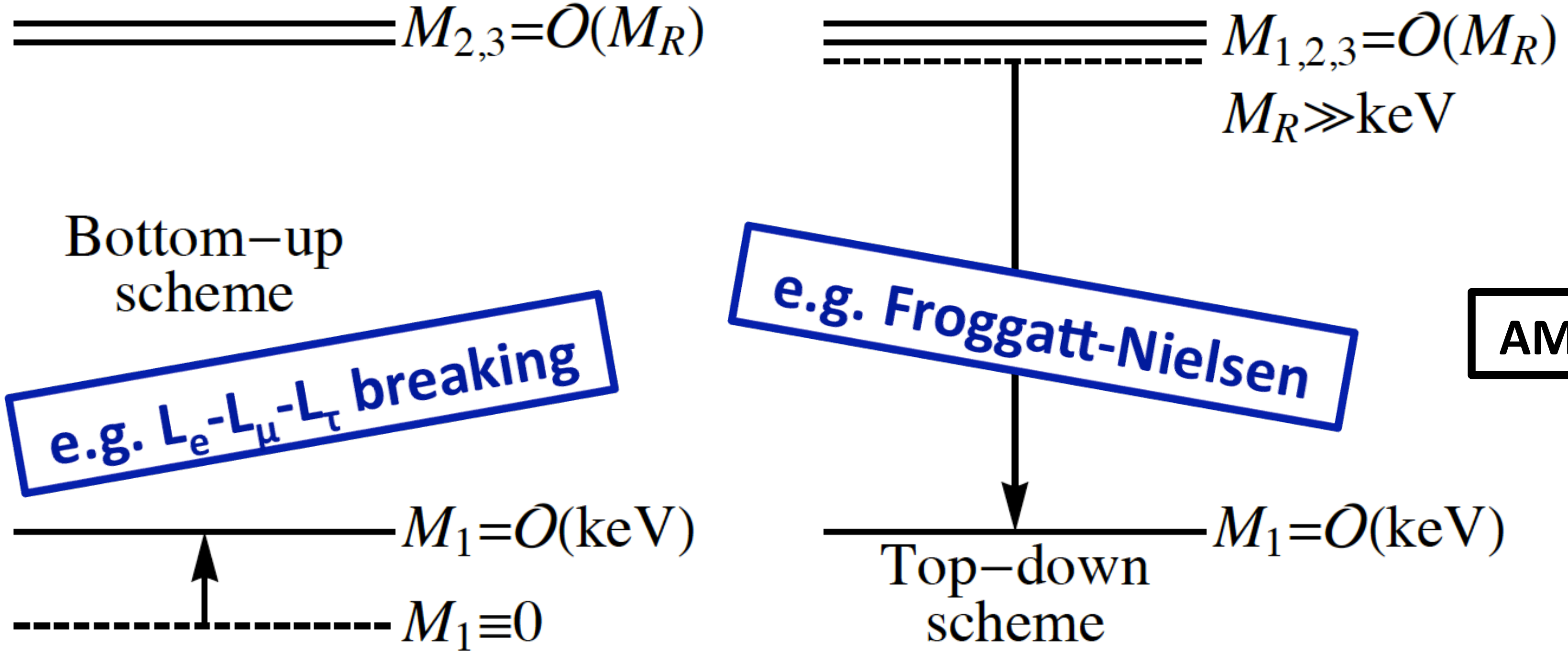


$M_{2,3}=\mathcal{O}(M_R)$

Bottom–up scheme

e.g. L_e-L_μ-L_τ breaking

$M_1=\mathcal{O}(\text{keV})$

$M_1\equiv 0$

$M_{1,2,3}=\mathcal{O}(M_R)$

$M_R \gg \text{keV}$

e.g. Froggatt-Nielsen

$M_1=\mathcal{O}(\text{keV})$

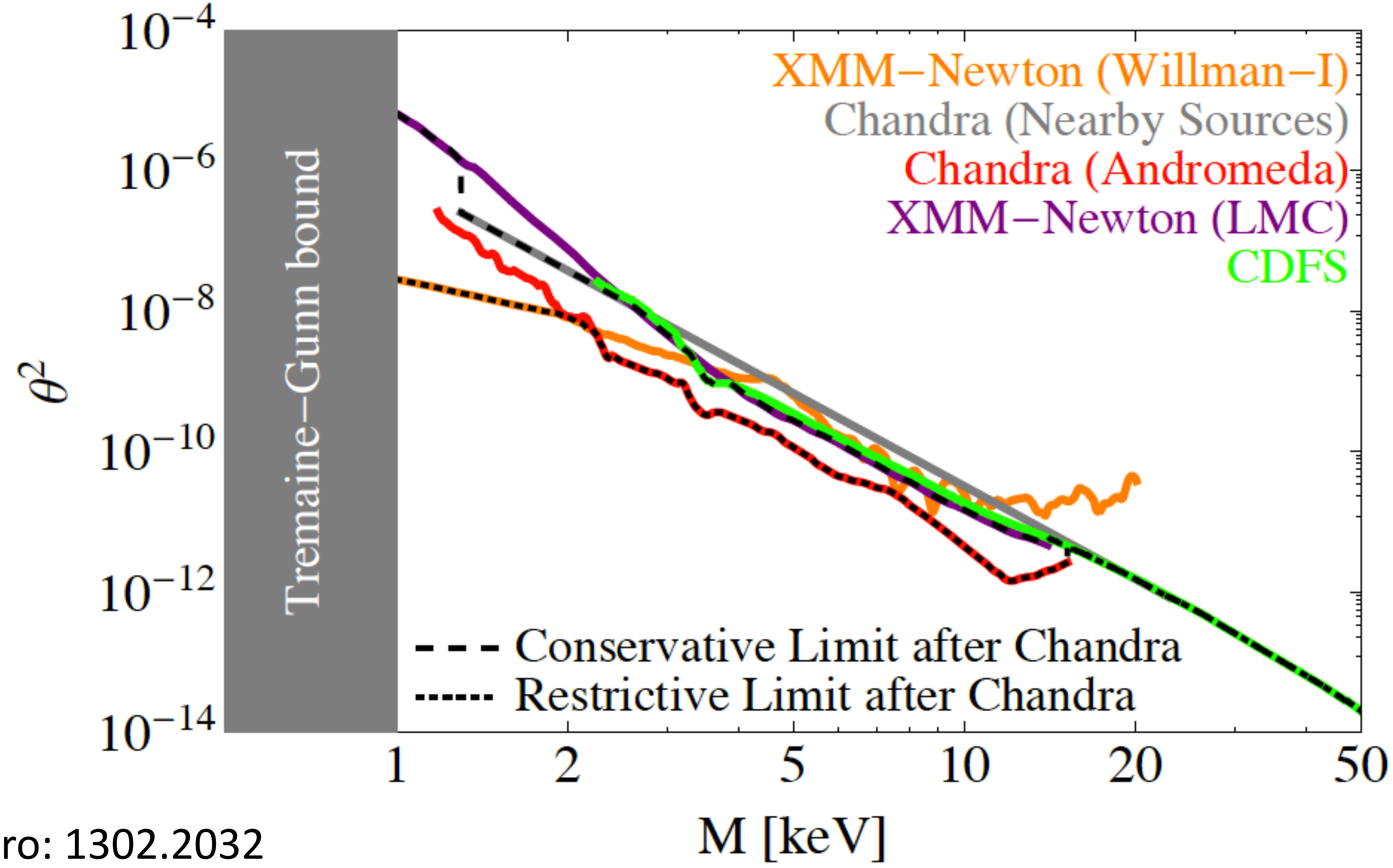
Top–down scheme

AM: 1302.2625

➔ Most models are in one or the other category!

3. Connection to keV neutrinos

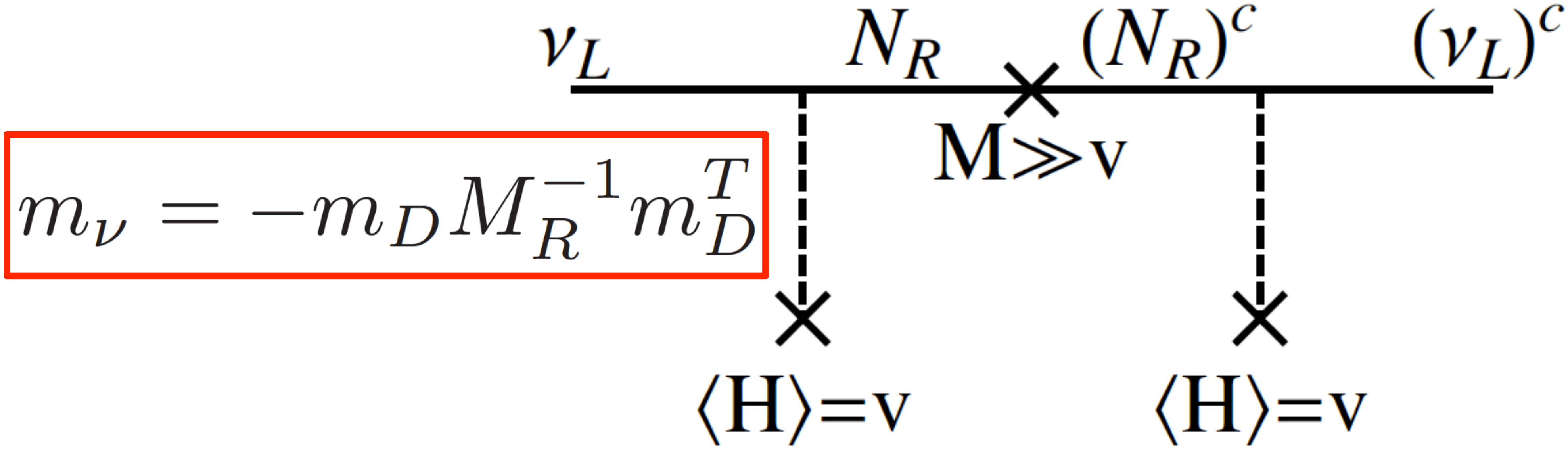
- ***Differences to "ordinary" model building***:
  - ○ we need to respect the X-ray bound: $N_1 \;\to\; \nu\gamma$



AM,Niro: 1302.2032

3. Connection to keV neutrinos

- ***Differences to "ordinary" model building***:
    - reminder: seesaw mechanism for eV neutrinos:



$$\boxed{m_\nu = -m_D M_R^{-1} m_D^T}$$

Inventors in alphabetical order:
Gell-Mann, Glashow, Minkowski, Ramond, Senjanovic, Slansky, Yanagida

➔ ***Does that also work when "dividing by keV mass"?!?***

3. Connection to keV neutrinos

- ***<u>Differences to "ordinary" model building</u>***:
  - seesaw mechanism for keV neutrinos:
    - 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. Connection to 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: 1306.xxxx]
- **thermal overproduction with entropy dilution**

  [Bezrukov,Hettmansperger,Lindner: Phys. Rev. **D81** (2010) 085032]
  [Nemevsek,Senjanovic,Zhang: JCAP **1207** (2012) 006]

3. Connection to keV neutrinos

New Production Mechanism:

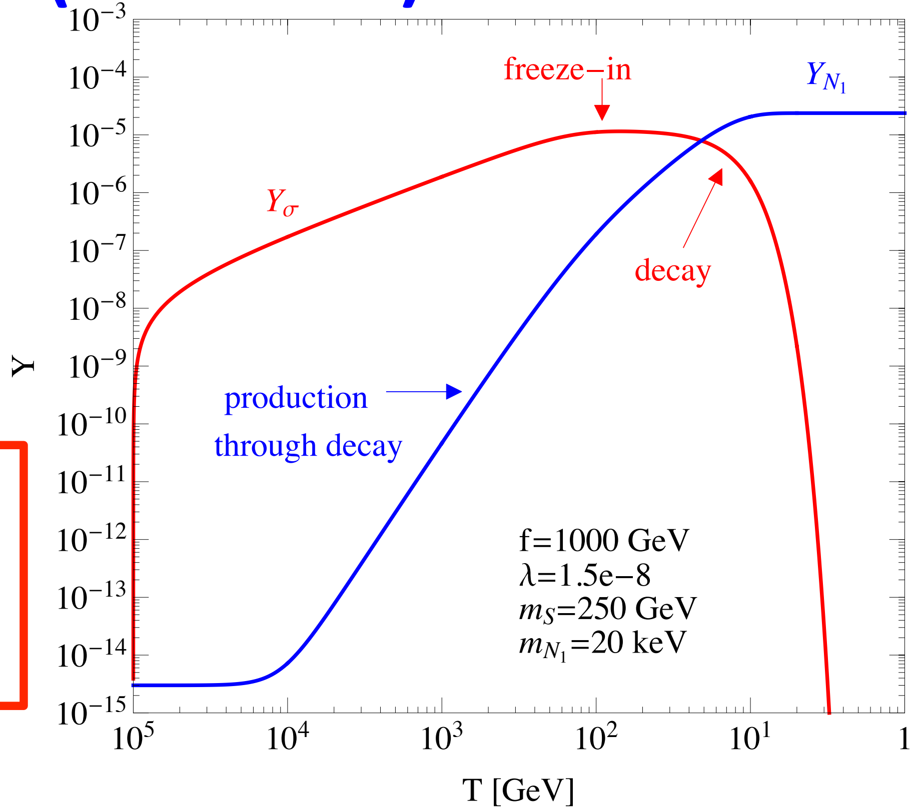
- *known*: **freeze-out of a singlet scalar (via a Higgs portal $\lambda \geq 10^{-6}$) which decays to keV ν's**
  [Kusenko,Petraki: Phys. Rev. **D77** (2008) 065014]
- *variant*: **use freeze-in instead (for $\lambda \approx 10^{-8}$)**
  [**AM**,Niro,Schmidt: 1306.xxxx]

Opens up a new window in the parameter space (for small λ)!

Production in the very early Universe

↓

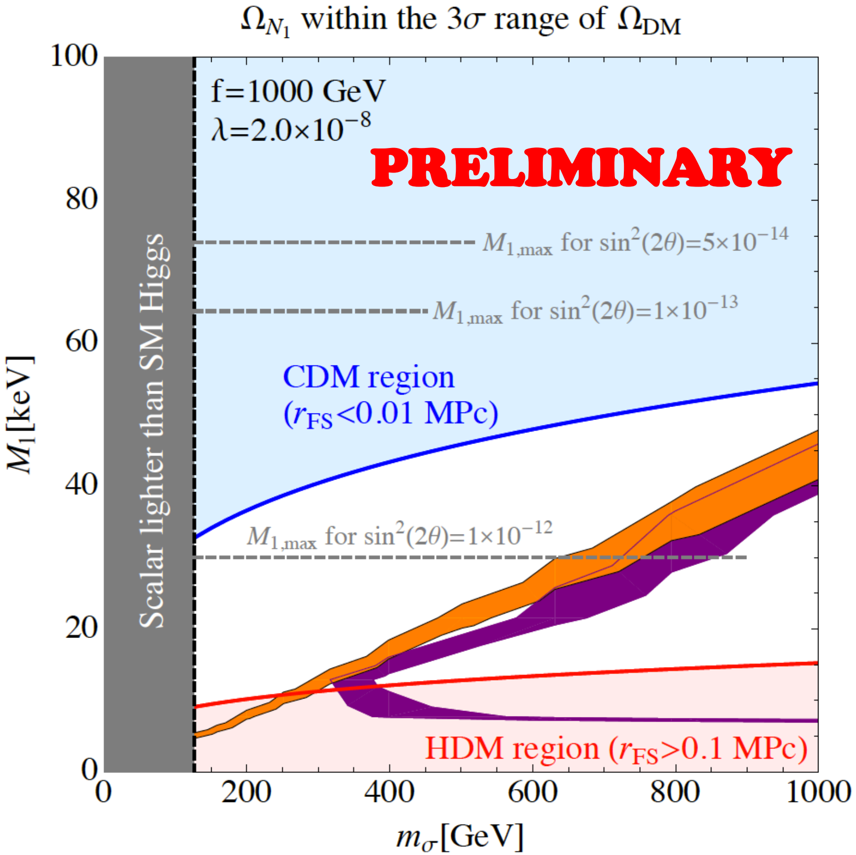
Dark Matter has time to cool down



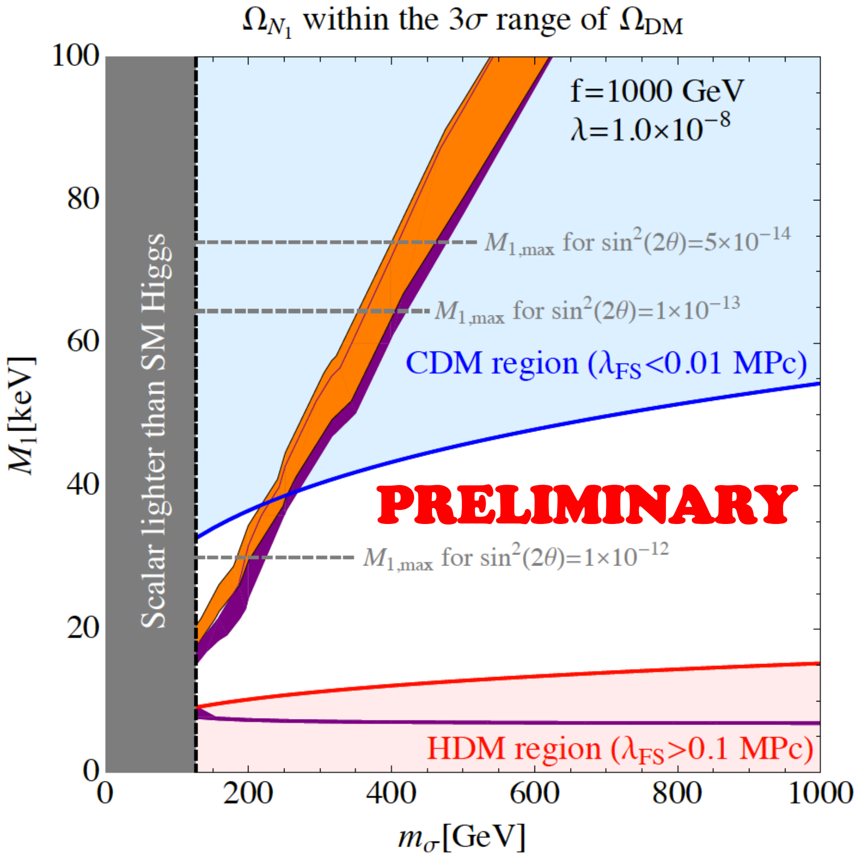
3. Connection to keV neutrinos

New Production Mechanism:

- depending on the parameters, we could have warm or cold Dark Matter of keV-scale mass:



WARM: $\lambda=2.0\times10^{-8}$



COLD: $\lambda=1.0\times10^{-8}$

4. Example Models

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- ***Pick your poison***: most probably, I will by now have run a bit late... ***Which model do you wanna hear about?***

  ○ flavour symmetry: $\mathcal{F}$**=L$_e$-L$_\mu$-L$_\tau$** (**AM**)

  ○ heavy sector: **Froggatt-Nielsen mechanism** (**AM**)

  ○ extra singlets: **extended seesaw mechanism**

  ○ extra dimensions: **split seesaw mechanism**

certainly covered by Alex Kusenko

We have time for one or two... *Make your choice!!*

4. Example Models

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

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- *probably the most intuitive*: $\mathcal{F}$**=L_e-L_μ-L_τ**
  - ○ 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**
  - o 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

  - o then, only symmetry preserving terms are allowed:

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

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

➔ 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. Example Models

- *probably the most intuitive*: $\mathcal{F}$=**L_e-L_μ-L_τ**
  - ○ eigenvalues of $\mathcal{M}_\nu$ (with μ-τ symmetry):
    - light neutrinos: $(\lambda_+,\lambda_-,0)$
    - heavy neutrinos: $(\Lambda_+,\Lambda_-,0)$
    - with: $\lambda_\pm = \pm\sqrt{2}\left[m_L - \frac{m_D^2}{M_R}\right]$ $\Lambda_\pm = \pm\sqrt{2}M_R$
  - ○ mass patterns:
    - light ν's: $(0,\lambda_+,\lambda_-)$ ➔ okay up to degeneracy
    - heavy N's: $(0,\Lambda_+,\Lambda_-)$ ➔ 0 << M, but still 0≠keV
  - ○ WAY OUT: **broken symmetry**
    - ➔ will remedy the above issues
    - ➔ important: no matter how the breaking is achieved, the results will always look similar

4. Example Models

- *probably the most intuitive*: **$\mathcal{F}$=L$_e$-L$_\mu$-L$_\tau$**
  - pragmatic: *soft breaking* [Lindner,**AM**,Niro: JCAP **1101** (2011) 034]
  - we assumed ***small*** breaking terms and worked out their consequences:

    ➔ new mass matrix:

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

    ➔ new eigenvalues: $\Lambda_s = S \quad \Lambda'_\pm = S \pm \sqrt{2} M_R$

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

4. Example Models

- *probably the most intuitive*: $\mathcal{F}$**=L$_e$-L$_\mu$-L$_\tau$**
  - ○ pragmatic: *soft breaking* [Lindner,**AM**,Niro: JCAP **1101** (2011) 034]
  - ○ we assumed ***small*** breaking terms and worked out their consequ

natural assumption: like p-n isospin symmetry

➔ new mass matrix:

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

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keV neutrino

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4. Example Models

- *probably the most intuitive*: **$\mathcal{F}$=L$_e$-L$_\mu$-L$_\tau$**
  - mixings also require soft breaking:

$$\mathcal{M}_l \mathcal{M}_l^\dagger \simeq \begin{pmatrix} m_e^2 + m_\mu^2 \lambda^2 & m_\mu^2 \lambda & 0 \\ m_\mu^2 \lambda & m_\mu^2 & 0 \\ 0 & 0 & m_\tau^2 \end{pmatrix}$$

$$\boxed{\begin{aligned} \tan^2\theta_{12} \simeq 1 - 2\sqrt{2}\lambda + 4\lambda^4 - 2\sqrt{2}\lambda^3 \quad &\rightarrow \quad \theta_{12} \simeq 33.4^\circ \\ |U_{e3}| \simeq \frac{\lambda}{\sqrt{2}} \quad &\rightarrow \quad \theta_{13} \simeq 8^\circ\,, \\ \sin^2 2\theta_{23} \simeq 1 - 4\lambda^4 \quad &\rightarrow \quad \theta_{23} \simeq 45^\circ\,. \end{aligned}}$$

$\boxed{\lambda=\theta_{12}-\pi/4}$

  - prediction for the masses (under assumptions):

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

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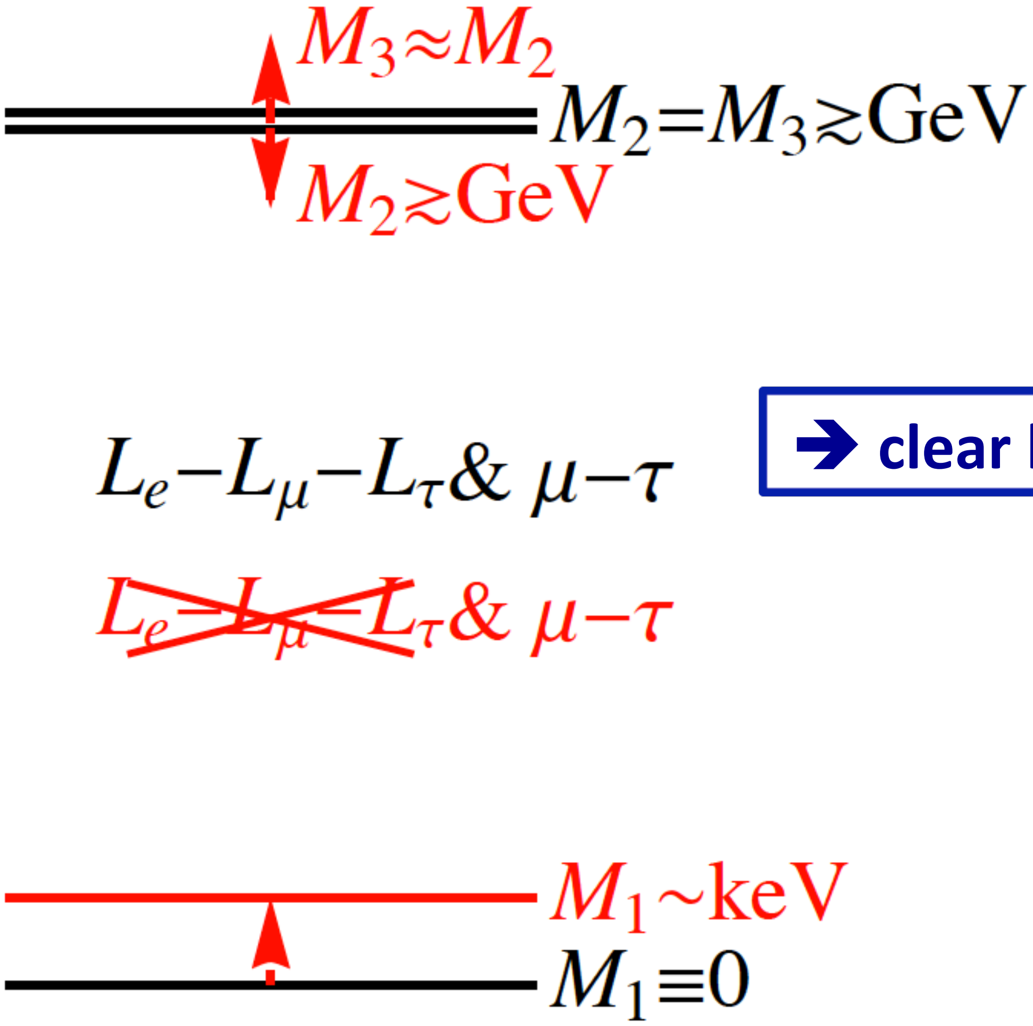

$M_3 \approx M_2$

$M_2 = M_3 \gtrsim \mathrm{GeV}$

$M_2 \gtrsim \mathrm{GeV}$

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

$\xcancel{L_e - L_\mu - L_\tau} \,\&\, \mu - \tau$

$M_1 \sim \mathrm{keV}$

$M_1 \equiv 0$

→ **clear bottom-up type scheme**

4. Example Models

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

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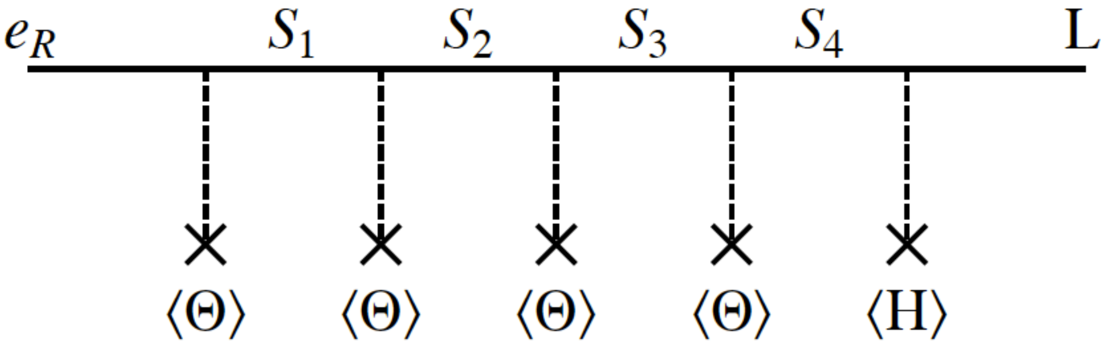
- *probably the most simple*: **Froggatt-Nielsen** (FN)
  - original idea [Froggatt,Nielsen: Nucl. Phys. **B147** (1979) 277]
    - ➔ used to explain the quark mass pattern
    - ➔ very well suited to predict hierarchies
  - application to keV sterile neutrinos:
    - pure FN models [**AM**,Niro: JCAP **1107** (2011) 023]
    - mixed with flavour symmetry [Barry,Rodejohann,Zhang: JHEP **1107** (2011) 091, JCAP **1201** (2012) 052]
  - features:
    - suppression maybe as strong as for split seesaw
    - *stronger* enhancement of active-sterile mixing
    - more predictive than one would naively expect
    - seesaw guaranteed to work

4. Example Models

- *probably the most simple*: **Froggatt-Nielsen** (FN)
  - ○ *Froggatt-Nielsen mechanism*:
    - – assume new (mostly global) $U(1)_{FN}$ symmetry with generation-dependent charges
    - – assume *flavons* (=SM-singlet scalars charged under $U(1)_{FN}$, which obtain VEVs)
    - – assume a suitable heavy fermion sector (note: this assumption is often *not* stated)
  - ○ then, one can draw seesaw-like diagrams:



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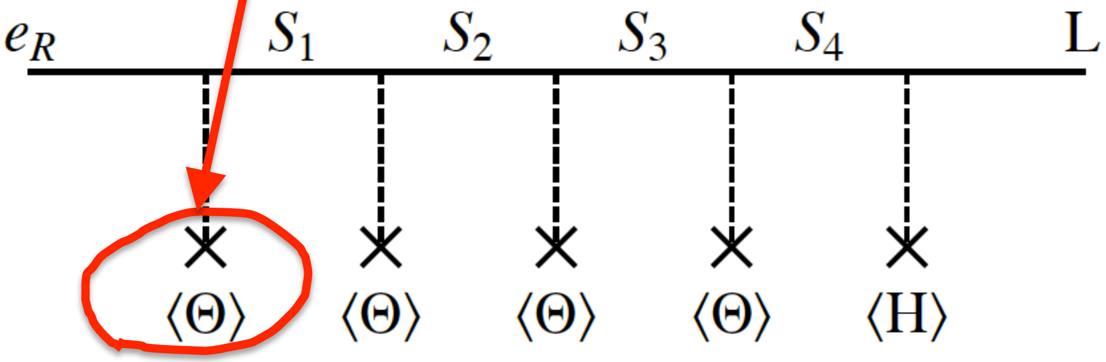

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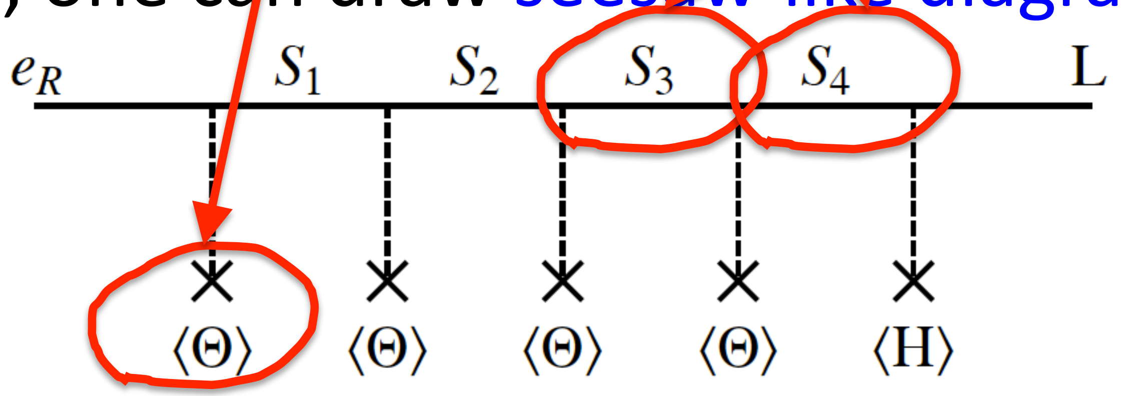

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    - ➔ e.g. Yukawa couplings:

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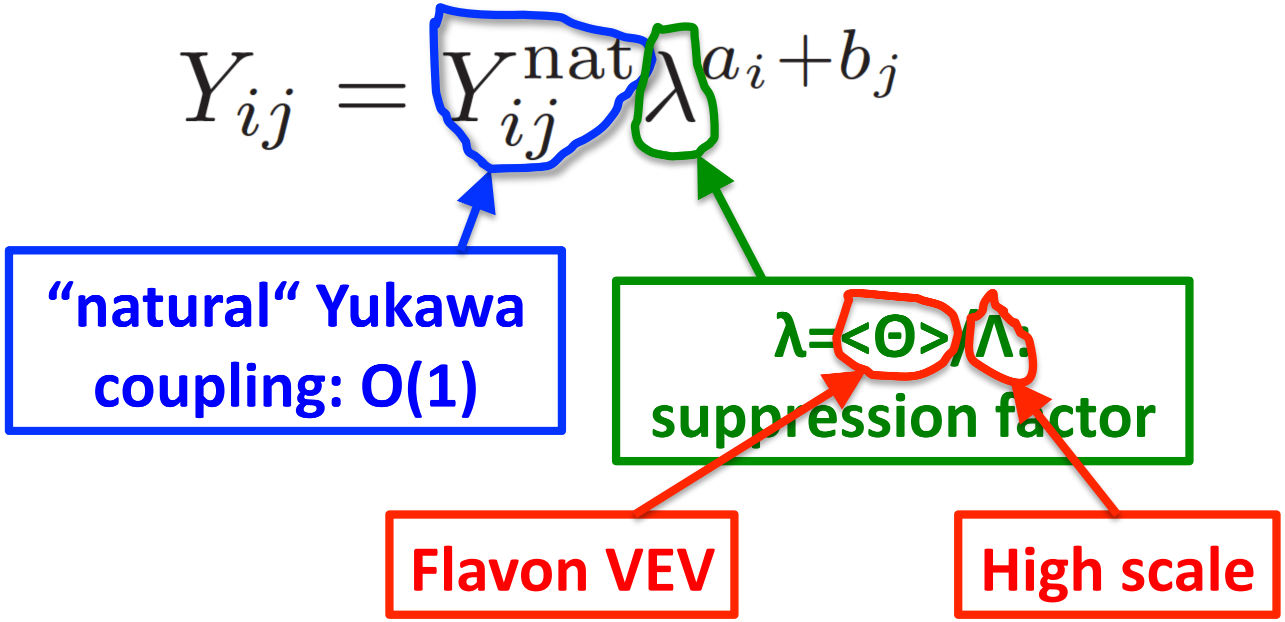

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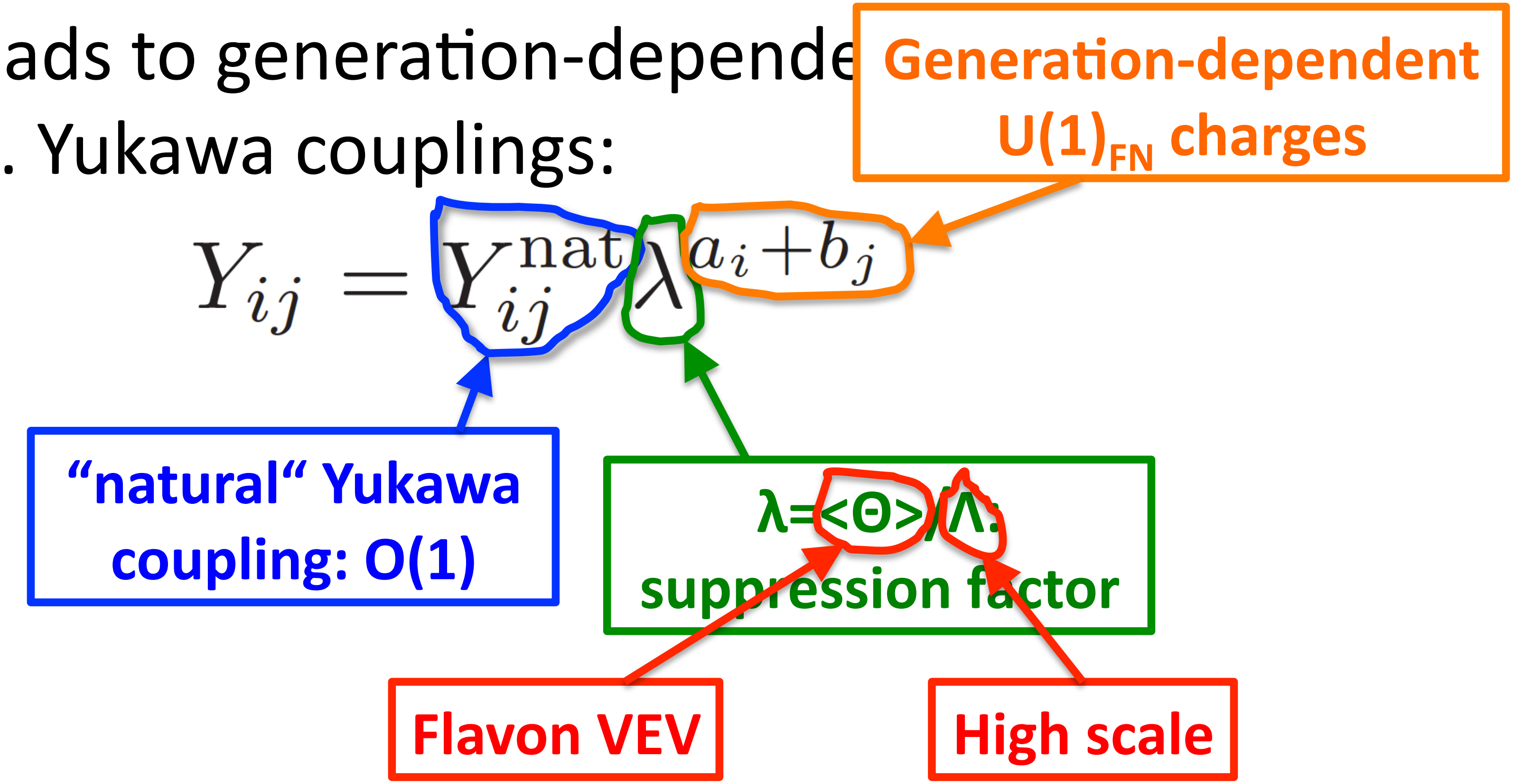

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Generation-dependent U(1)$_{FN}$ charges

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

Physical Yukawa coupling can be small!

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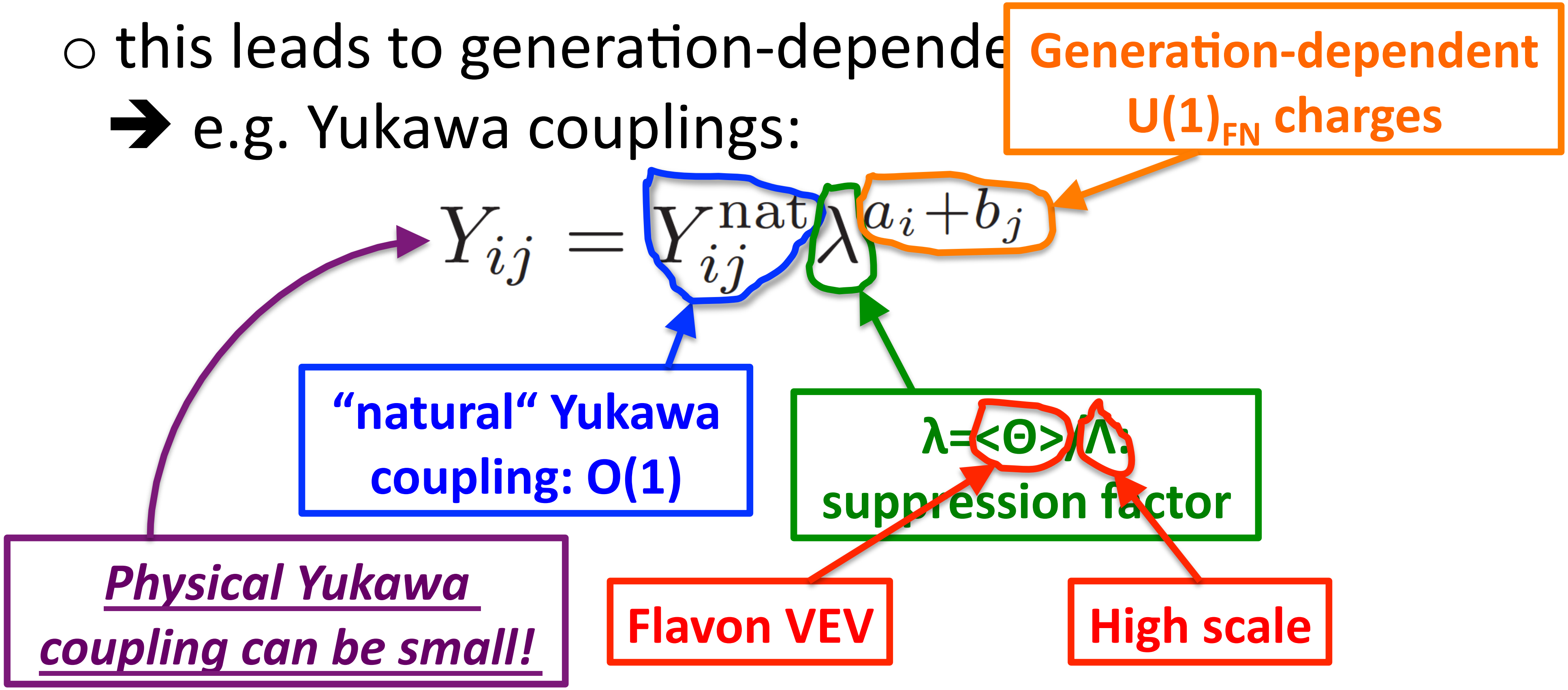

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  - **HOWEVER**: several problems are swept under the carpet (UV-completion, U(1)-breaking,...)

4. Example Models

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

$$
\begin{aligned}
\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; +, +, -)
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Have to be chosen such that a strong hierarchy is generated!!

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  - full Lagrangian:

$$\mathcal{L} = -\sum_{a,b,i,j}^{a+b=k_i+f_j} Y_e^{ij}\, \overline{e_{iR}}\, H\, L_{jL}\, \lambda_1^a \lambda_2^b + h.c. - \sum_{a,b,i,j}^{a+b=g_i+f_j} Y_D^{ij}\, \overline{N_{iR}}\, \tilde{H}\, L_{jL}\, \lambda_1^a \lambda_2^b + h.c.$$

$$- \sum_{a,b,i,j}^{a+b=f_i+f_j} \frac{1}{2} \overline{(L_{iL})^c}\, \tilde{m}_L^{ij}\, L_{jL}\, \lambda_1^a \lambda_2^b + h.c. - \sum_{a,b,i,j}^{a+b=g_i+g_j} \frac{1}{2} \overline{(N_{iR})^c}\, \tilde{M}_R^{ij}\, N_{jR}\, \lambda_1^a \lambda_2^b + h.c.$$

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    ➔ 3 real parameters: $\lambda = \frac{\langle\Theta_1\rangle}{\Lambda}, \quad R = \frac{\langle\Theta_1\rangle}{\langle\Theta_2\rangle} = R_0 e^{i\alpha_0}$
  - o two example scenarios: A(3,0,0) & B(4,1,0)

$$\begin{aligned}
\mathrm{A}(3,0,0): \quad & 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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Small mass

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Quasi-Degeneracy

$$\mathrm{B}(4,1,0): \quad M_1 = M_0\lambda^8\ 2R_0^4$$

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Hierarchy

4. Example Models

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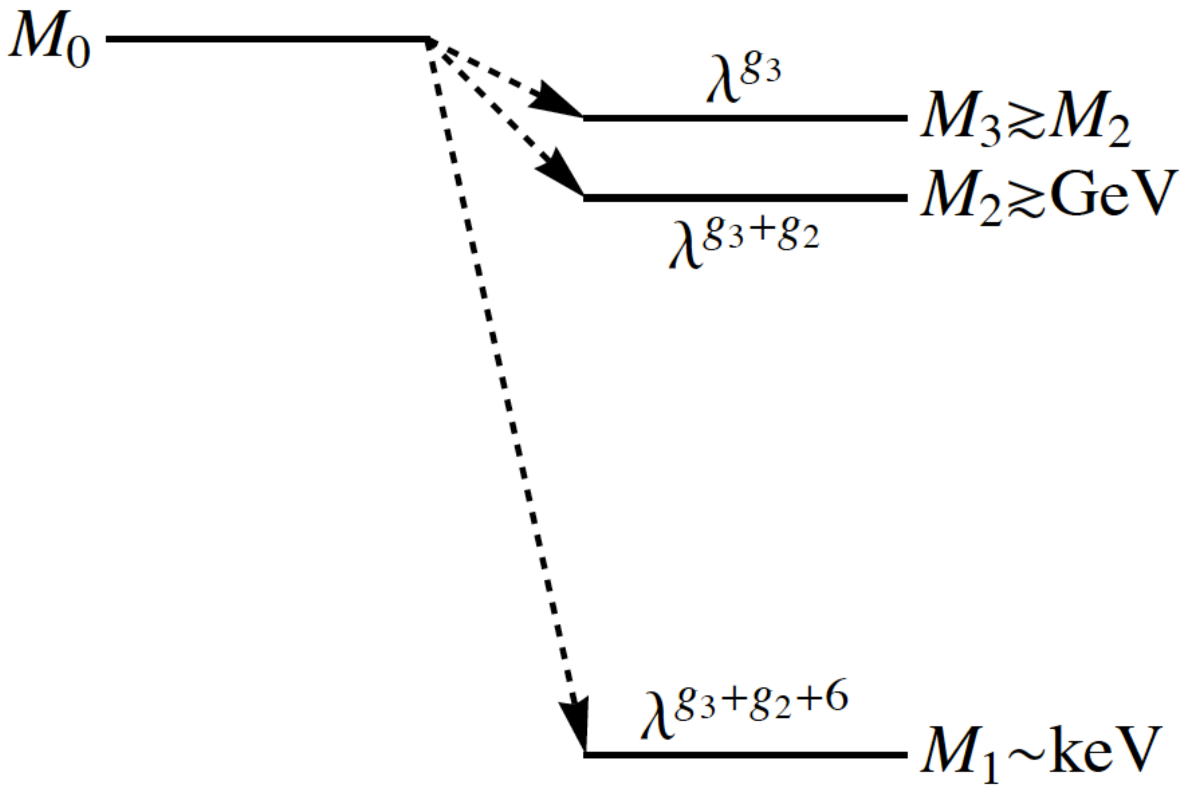
  - mass shifting scheme:

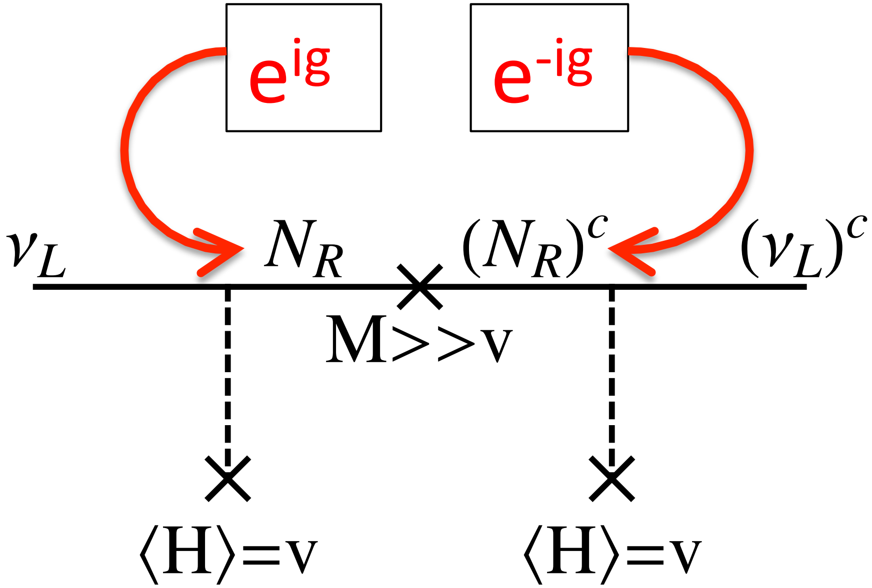


➔ large mass scale gets suppressed

➔ ***top-down***

4. Example Models

- *probably the most simple*: **Froggatt-Nielsen** (FN)
  - important point: seesaw guaranteed to work



➔ $U(1)_{FN}$ is a global U(1), just like lepton number, which gets broken by the seesaw-diagram!

➔ the charges (g_1,g_2,g_3) drop out of the light neutrino mass matrix ✓

4. Example Models

- *probably the most simple*: **Froggatt-Nielsen** (FN)
  - ○ **interesting to note**: FN not as arbitrary as it looks!
    - – does not work with Left-Right symmetry
      - ➔ disfavours one production mechanism
    - – favours SU(5) compared to SO(10)
      - ➔ reason: g_i unconstrained for singlet N_i
      - ➔ BUT: associated problems with p^+ decay...
    - – Renormalization Group Running negligible
    - – excludes bimaximal *neutrino* mixing (for the diagonalization of the light neutrino mass matrix)
    - – disfavours democratic Yukawa couplings
    - – no anomalies within SU(5)

4. Example Models

- *probably the most versatile*: **Minimal Extended Seesaw**

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  - 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

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

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

  - we can nevertheless rewrite the Lagrangian:

$$\mathcal{L}_{\text{ES}} = -\frac{1}{2}(\overline{\nu_L}, \overline{(S_R)^c}, \overline{(N_R)^c}) \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & M_R & M_S^T \\ 0 & M_S & 0 \end{pmatrix} \begin{pmatrix} (\nu_L)^c \\ S_R \\ N_R \end{pmatrix} + h.c.$$

  - one now assumes a hierarchy: $m_D << M_S << M_R$

4. Example Models

- *probably the most versatile*: **Minimal Extended Seesaw**
  - ○ the hierarchy allows to apply the seesaw formula:

$$M_\nu^{4\times 4} = \begin{pmatrix} m_D M_R^{-1} m_D^T & m_D M_R^{-1} M_S^T \\ M_S \left(M_R^{-1}\right)^T m_D^T & M_S M_R^{-1} M_S^T \end{pmatrix}$$

➔ det=0 ➔ one zero eigenvalue ➔ hierarchy!

  - ○ applying the seesaw formula one more time:

$$M_\nu^{3\times 3} = m_D M_R^{-1} M_S^T \left(M_S M_R^{-1} M_S^T\right)^{-1} M_S M_R^{-1} m_D^T - m_D M_R^{-1} m_D^T$$

➔ this is non-zero (M_S is 1x3 ➔ cannot be inverted)

➔ there is an intermediate mass eigenvalue:

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

➔ keV neutrino

4. Example Models

- *probably the most versatile*: **Minimal Extended Seesaw**
  - ○ ***problem***: 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
  - ○ *general*: although the mechanism cannot stand alone, it may be resembled in more concrete models

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- *<u>other possibilities</u>* (more or less all I know):

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 broken 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], type III seesaw [Dürr, Lindner, Fileviez Perez: 1306.0568]

5. The generalization: ***keVins***

- *the generalization*: **keV inert fermions**

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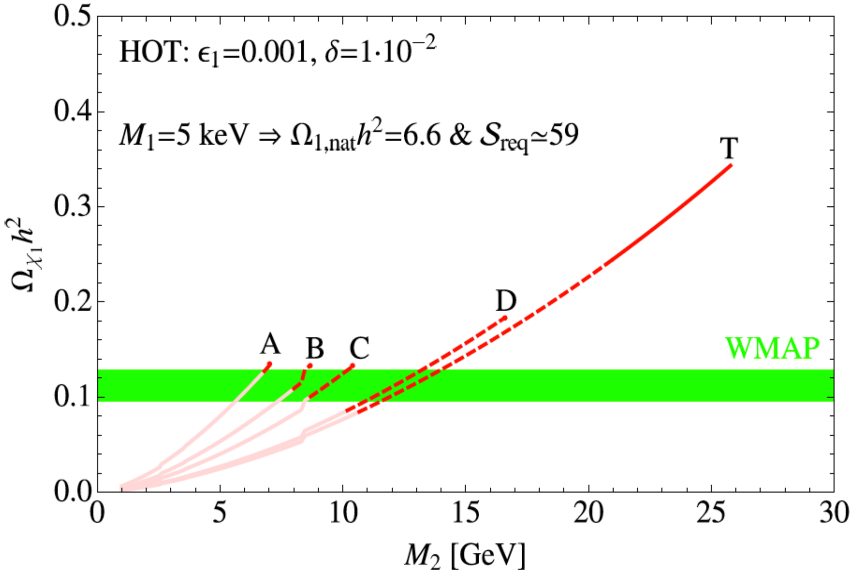
- *the generalization*: **keV inert fermions**
  - ○ we have many fermions at the keV-scale which could play the role of Dark Matter:
    - gravitinos [Gorbunov,Khmelnitsky,Rubakov: JHEP **0812** (2008) 055; Jedamzik,Lemoine,Moultaka: JCAP **0607** (2006) 010; Baltz,Murayama: JHEP **0305** (2003) 067]
    - axinos [Jedamzik,Lemoine,Moultaka: JCAP **0607** (2006) 010]
    - singlinos [McDonald,Sahu: Phys. Rev. **D79** (2009) 103523]
    - modulino [Dvali,Nir: JHEP **9810** (1998) 014; Benakli,Smirnov: Phys. Rev. Lett. **79** (1997) 3669]
  - ○ ***idea***: just like WIMPs (Weakly Interacting Massive Particles) do, the *keV inert fermions* form a general class of Dark Matter ➔ **keVins** [**AM**,King: **JCAP** 1208 (2012) 016]

5. The generalization: ***keVins***

- *the generalization*: **keV inert fermions**
  - setting: χ_1 at O(keV) to be Dark Matter, χ_2 at O(GeV)
  - proposed mechanism: thermal overproduction of χ_1 plus subseqent dilution by entropy production
  - can produce the correct abundance:



  - other production mechanisms and more or less model-independent studies possible

6. Conclusions and Outlook

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- Warm and/or keV Dark Matter is not worse than Cold Dark Matter ➔ motivation to study it

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  ➔ can be made testable in concrete models
- in principle: fundamental connections between neutrinos and Dark Matter possible
- long term goal, if the considerations survive: collaborative effort between particle physics, astrophysics, and cosmology
  ➔ <u>*synergies needed:*</u> **ASTROPARTICLE PHYSICS**

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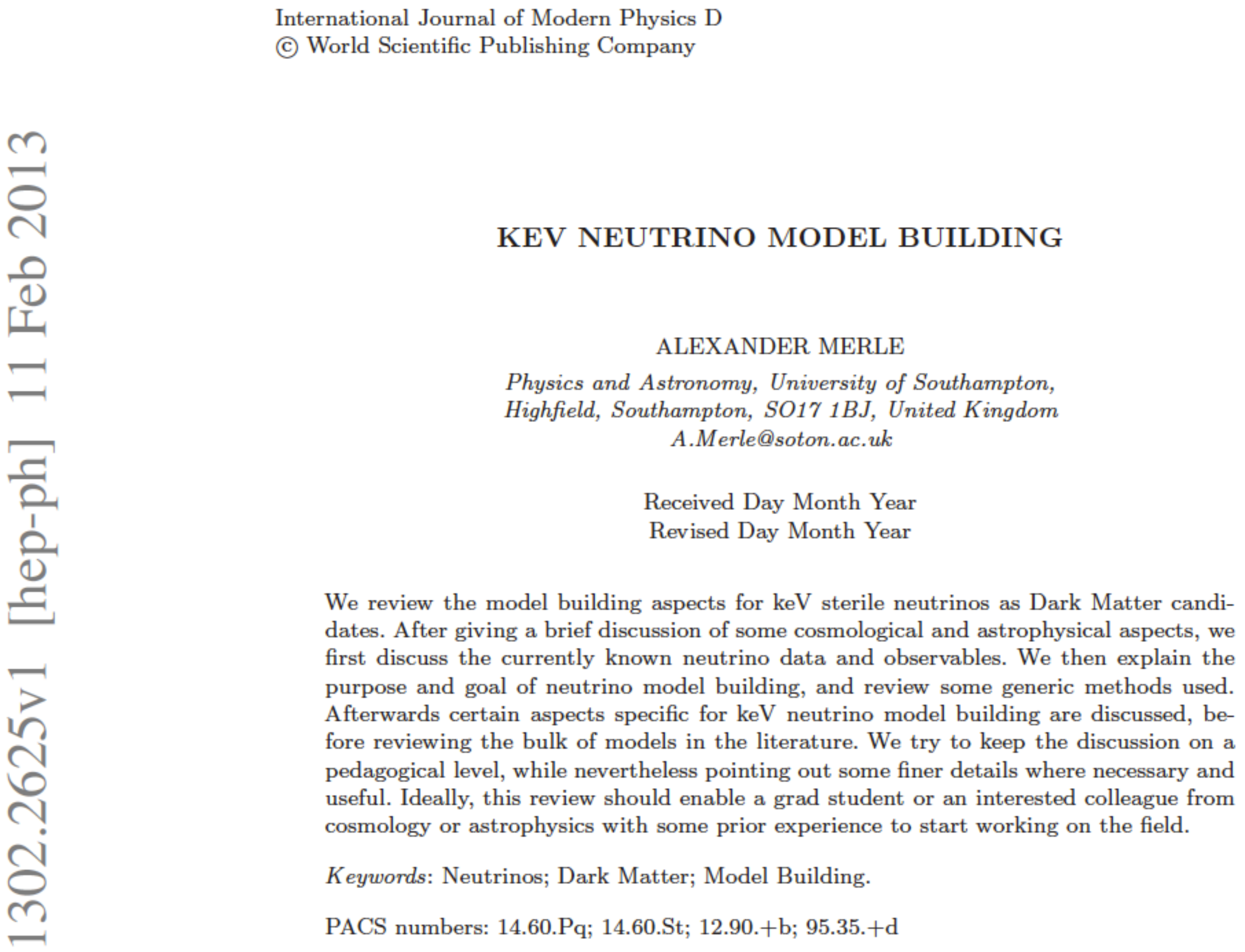

International Journal of Modern Physics D

KEV NEUTRINO MODEL BUILDING

ALEXANDER MERLE
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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.

PACS numbers: 14.60.Pq; 14.60.St; 12.90.+b; 95.35.+d

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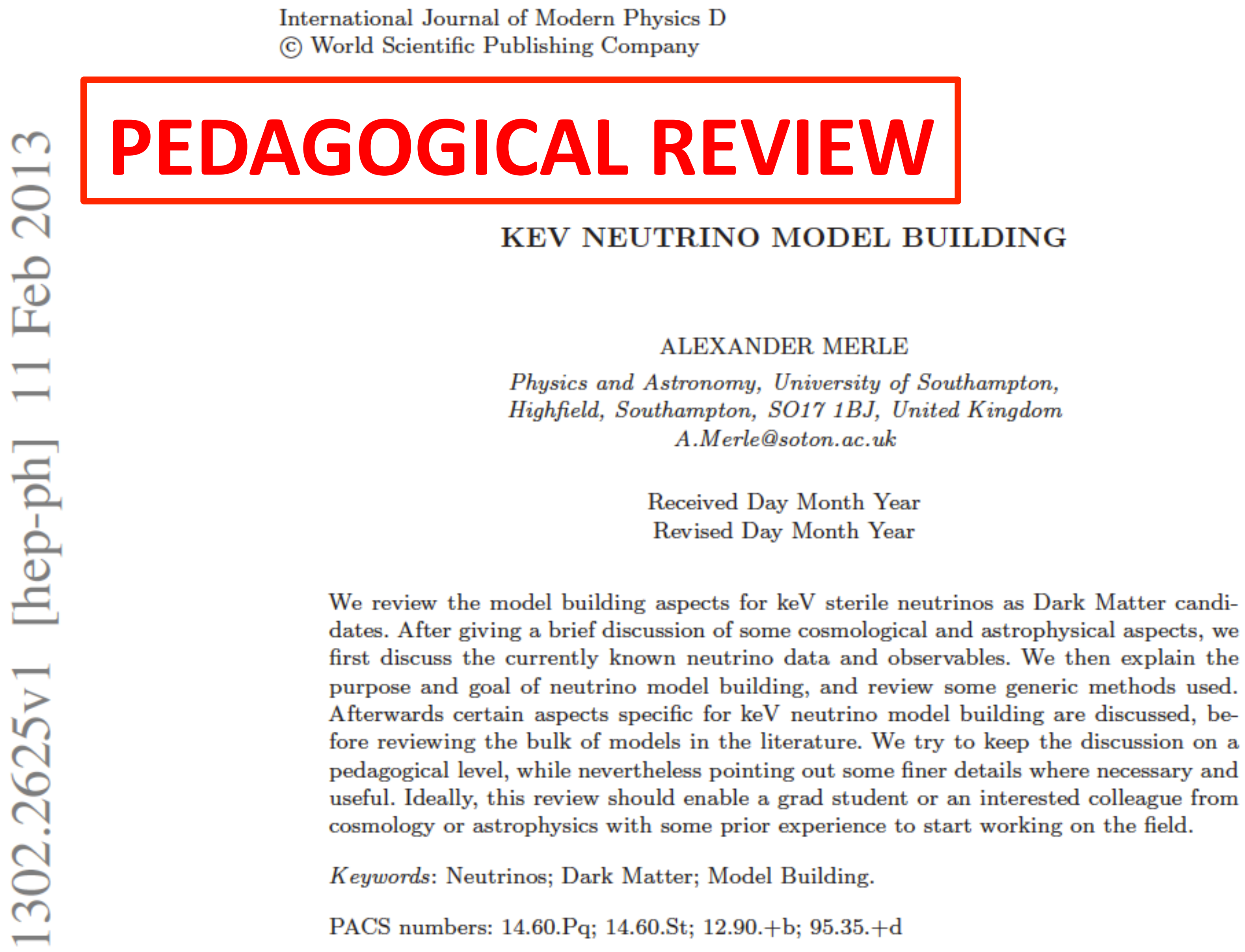

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PEDAGOGICAL REVIEW

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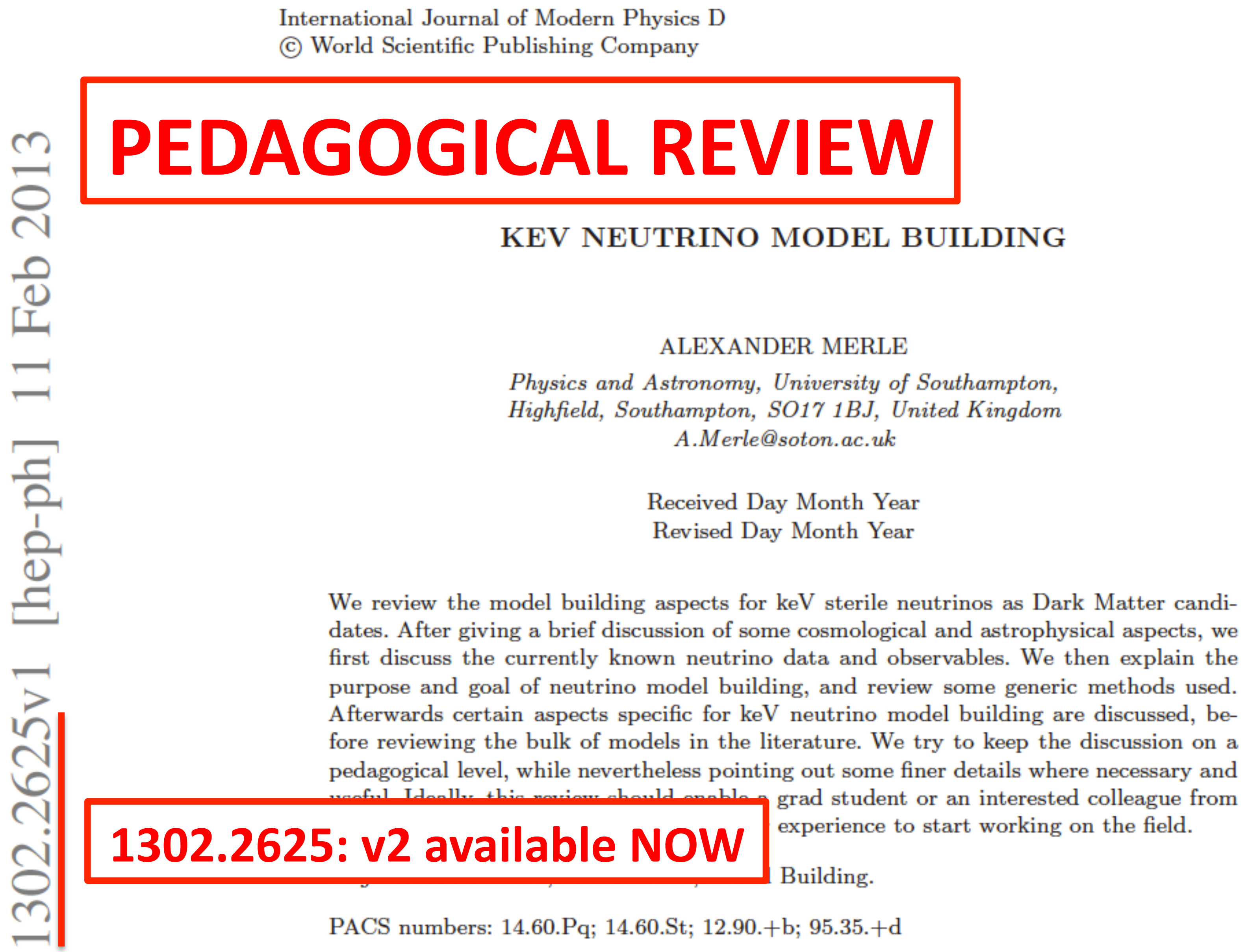

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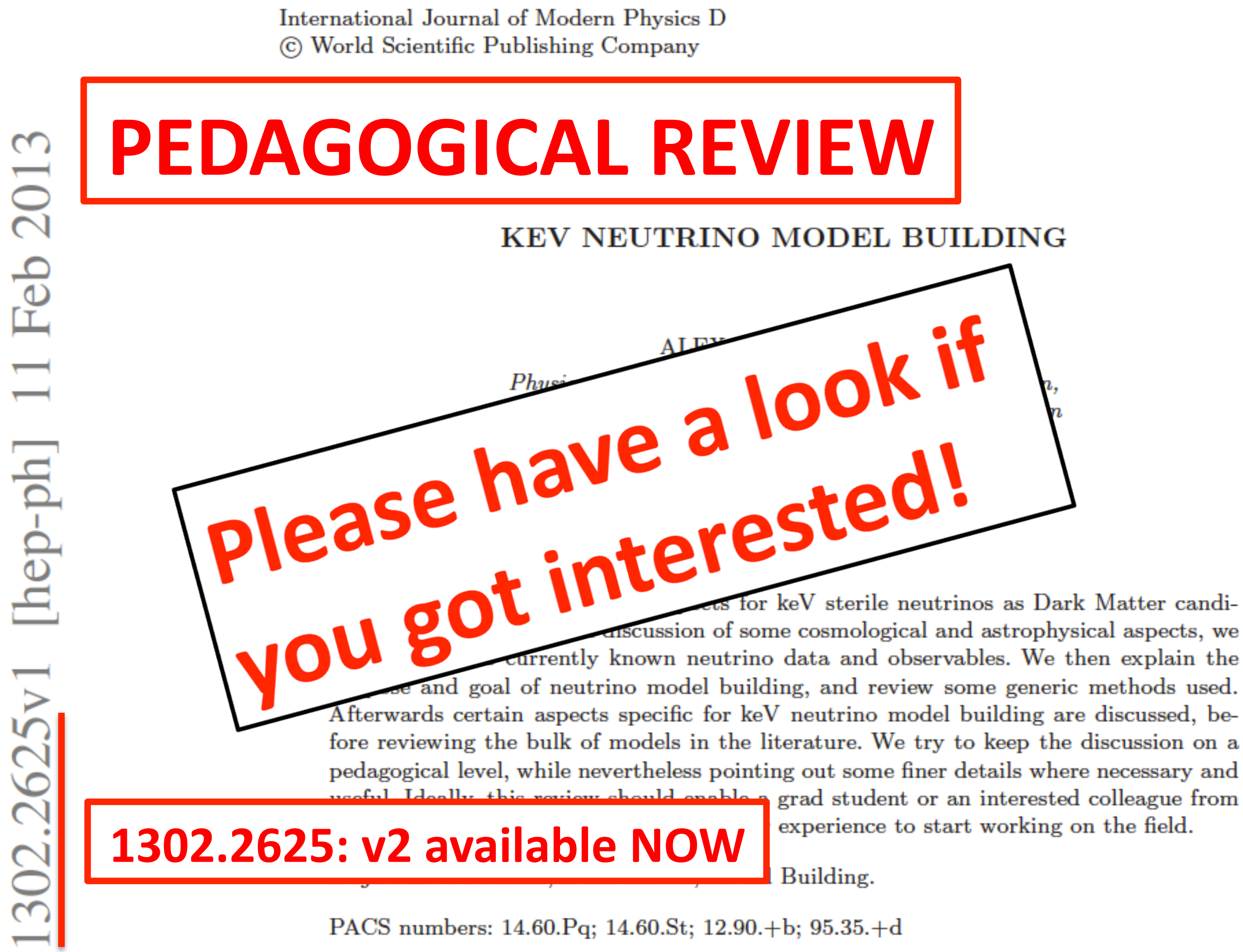

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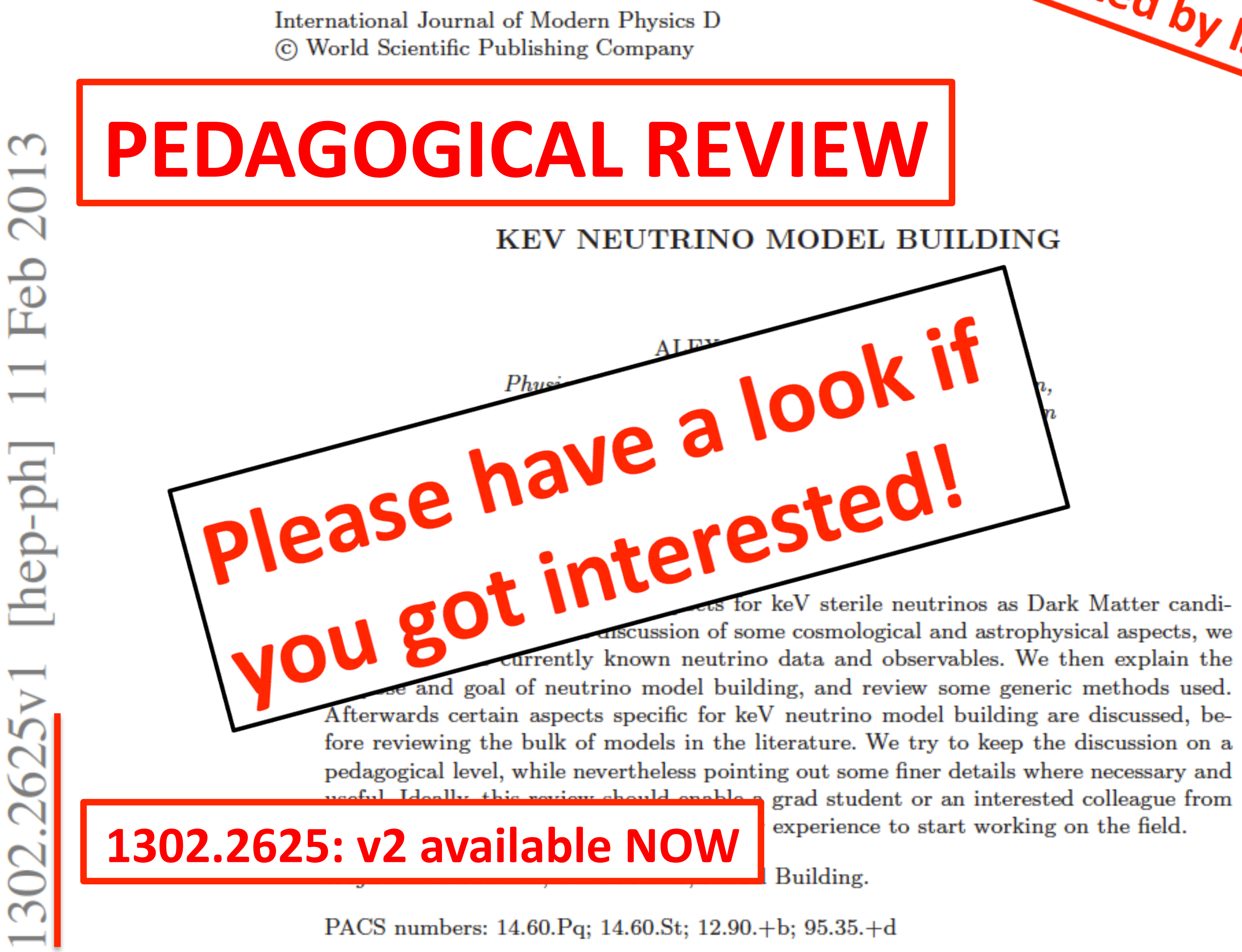

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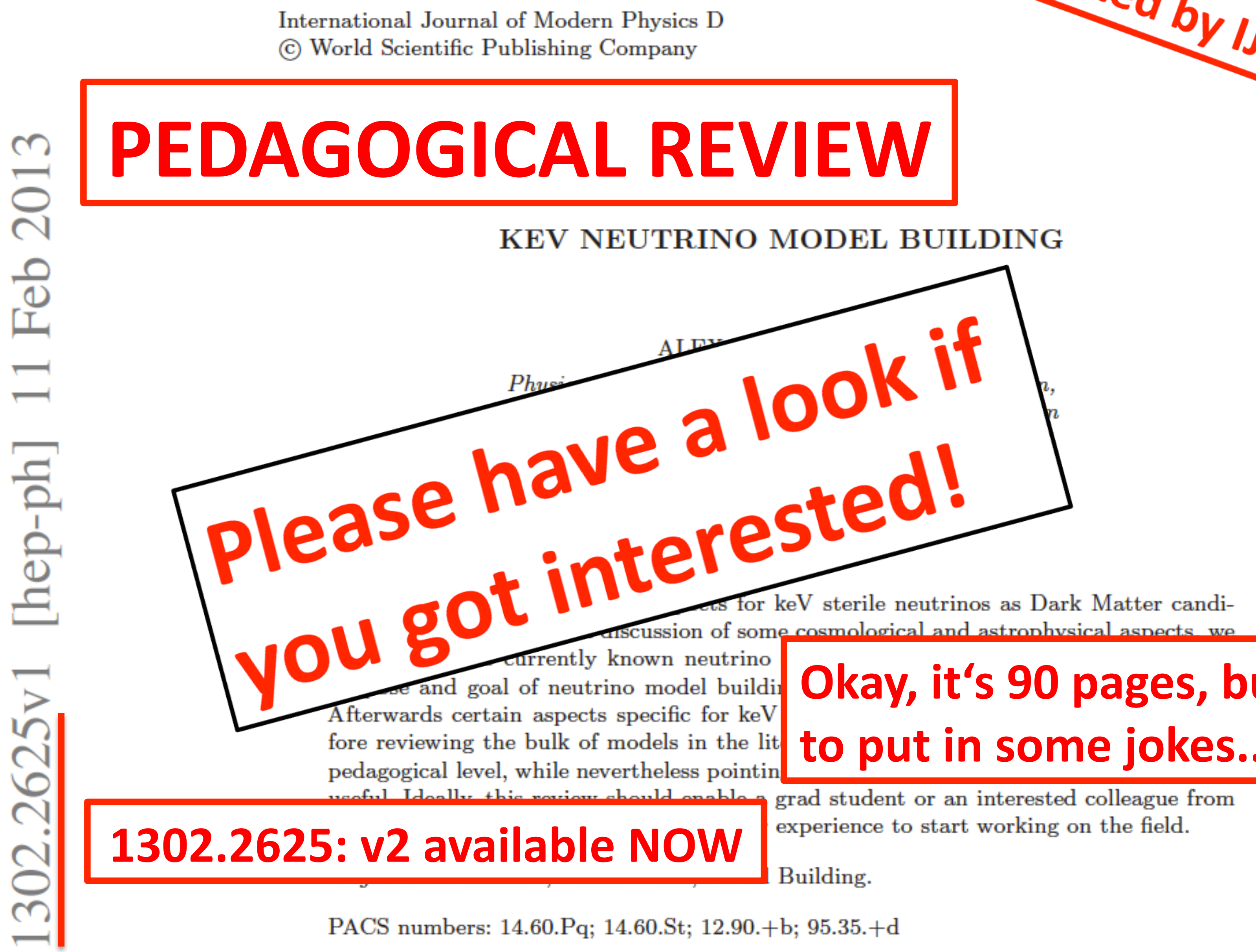

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Okay, it's 90 pages, but I tried to put in some jokes... ;-)

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THANK YOU!!!

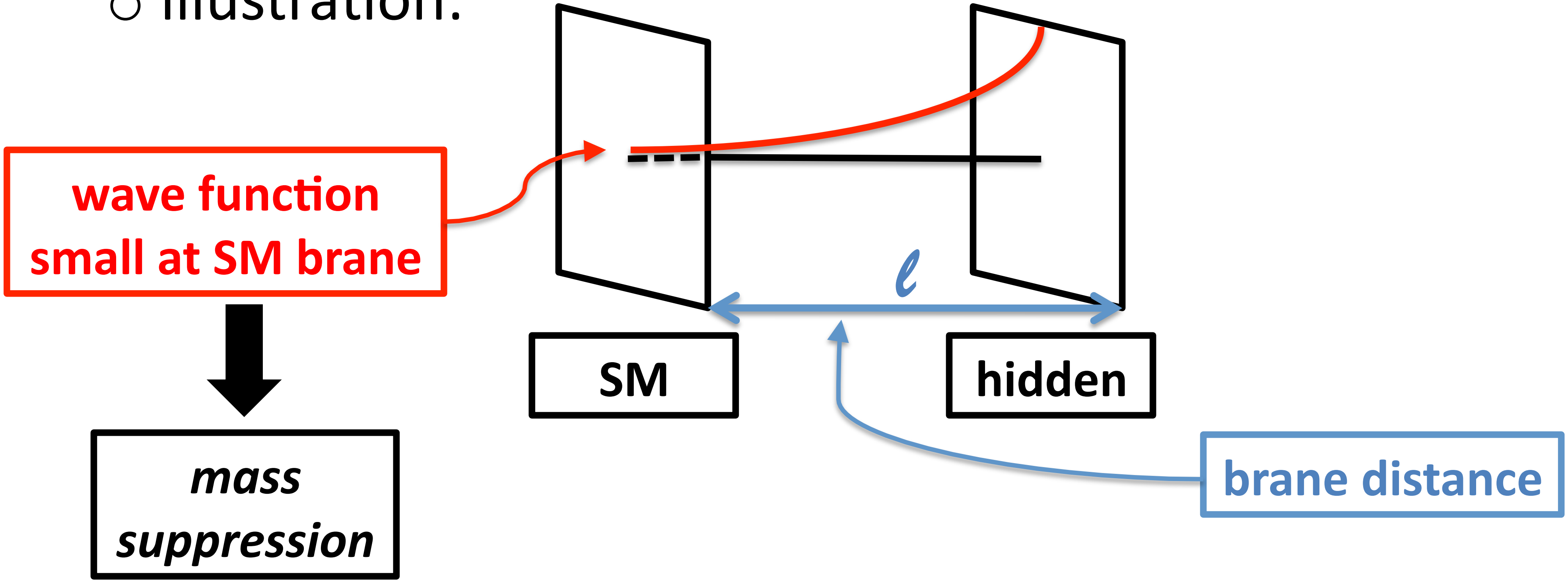
BACK-UP
SLIDES

4. Example Models

- *probably the most effective*: **Split Seesaw**

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**
  - starting point: 5D action

$$S = \int d^4x \int_0^l dy\ M_0\ (i\overline{\Psi}\Gamma^A \partial_A \Psi - m\overline{\Psi}\Psi)$$

  - Fourier expansion of the field:

$$\Psi_{L,R}(x^\mu, y) = \sum_n \psi^{(n)}_{L,R}(x^\mu)\ f^{(n)}_{L,R}(y)$$

➔ equation of motion in the Extra Dimension:

$$(\pm\partial_y - m) f^{(n)}_{L,R}(y) = m_n f^{(n)}_{L,R}(y)$$

  - solution ("**bulk profile**") for the zero mode: m_n=0

$$\boxed{f^{(0)}_{L,R}(y) = Ce^{\mp my}} \qquad C = \sqrt{\frac{2m}{e^{2ml}-1}}\frac{1}{\sqrt{M_0}}$$

4. Example Models

- *probably the most effective*: **Split Seesaw**
  - for a more complicated action, this leads to strong mass suppression and hierarchy enhancement:

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

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

  - the bulk profile leads to suppressions of masses AND Yukawa couplings:

$$\boxed{M_i = \kappa_i \frac{v_{B-L}}{M_0} \frac{2m_i}{e^{2m_i l} - 1}} \quad \boxed{\lambda_{i\alpha} = \frac{\tilde{\lambda}_{i\alpha}}{\sqrt{M_0}} \sqrt{\frac{2m_i}{e^{2m_i l} - 1}}}$$

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5D mass of the sterile N_i's

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$$-\delta(y) \left(\frac{1}{2} v_{B-L} (\overline{\Psi^{(0)}_{iR}})^c \Psi^{(0)}_{iR} + \lambda_{i\alpha} \overline{\Psi^{(0)}_{iR}} L_\alpha H \right) \Big]$$

$e^{-2m_i l} \ll 1$ for $m_i l \gg 1$ → **STRONG SUPPRESSION!!!**

  - the bulk profile leads to suppressions of masses AND Yukawa couplings:

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

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4. Example Models

- *probably the most effective*: **Split Seesaw**
  - in particular: exponential enhances hierarchies

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

$m_3 < m_2 < m_1$ ➔ $M_3 >> M_2 >> M_1$!!!

➔ this mechanism is very well suited to generate strong mass hierachies!

  - additional enhancement: $v_{B-L} << M_0$ (M_0: fundamental Planck scale in 5D)
  - bonus: seesaw *guaranteed* to work, due to conspiracy between the suppressions

4. Example Models

- *probably the most effective*: **Split Seesaw**
  - ○ issue #1: slight enhancement of active-sterile mixing

$$\theta_1 \propto M_1^{-1/2} \text{ instead of } \theta_1 \sim \frac{m_D}{M_R} \propto M_1^{-1}$$

➔ not a very big problem

  - ○ issue #2: we do not have an explanation for having $m_1 > m_2 > m_3$ in the first place

➔ can be cured by A_4 extension:

$m_1 > m_2 = m_3$ ➔ $M_1 << M_2 = M_3$

[Adulpravitchai,Takahashi: JHEP **1109** (2011) 127]

BUT: $\theta_{13}=0$, $\theta_{23}=\pi/4$, excluded by X-ray bound!

➔ needs seesaw type II situation to work