keV Neutrino Model Building

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

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.xxxx

Seminar, University of Sussex, 11-02-2013

Contents:

1. Introduction

Every talk about physics starts with problems...

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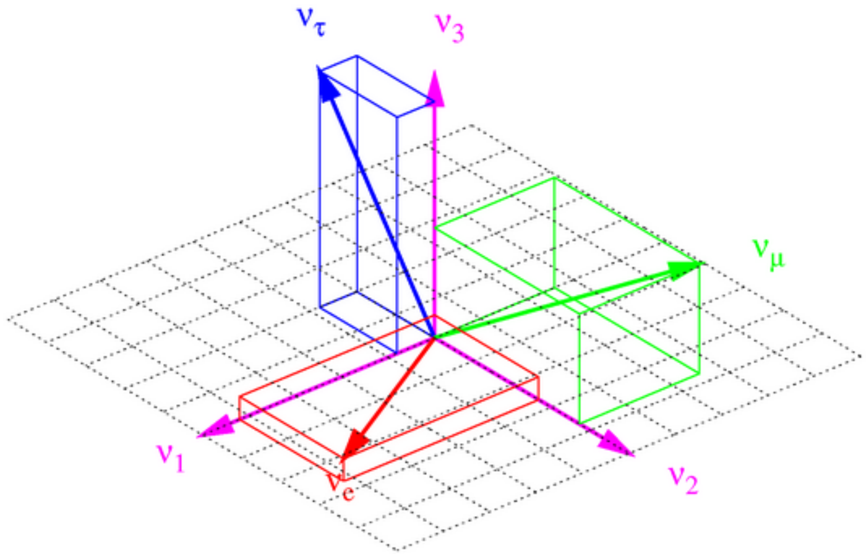
• Neutrinos do mix:



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

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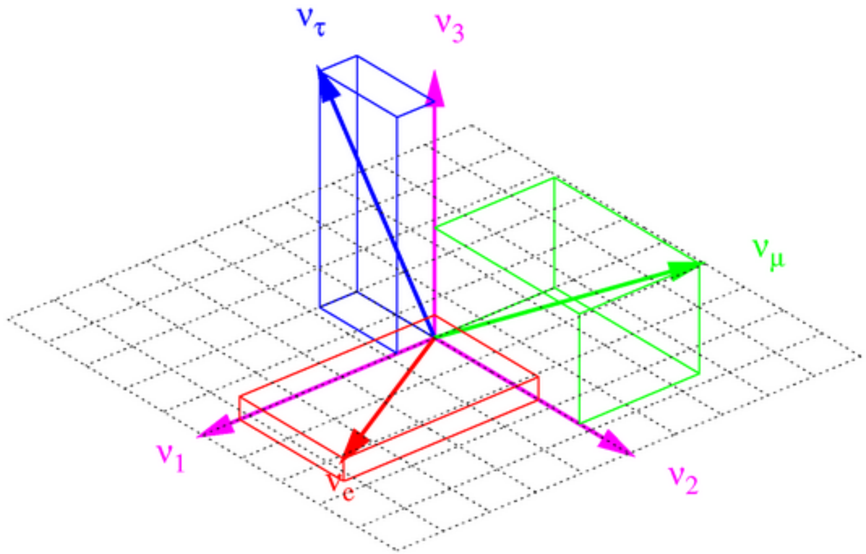

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$\theta_{12} \approx 34.4°$
$\theta_{13} \approx 9.1°$
$\theta_{23} \approx 51.1°$
$\Delta m_{21}^2 \approx 7.6\times10^{-5}\mathrm{eV}^2$
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Forero,Tórtola,Valle:
Phys. Rev. **D86** (2012) 073012

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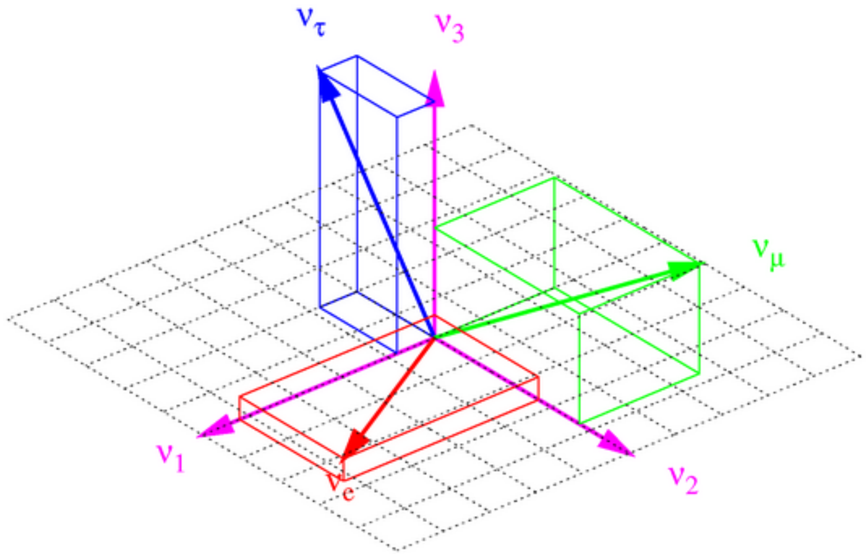

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BUT: We don't understand these values!!!

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

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

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

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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!!!

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

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

2. keV and/or Warm Dark Matter

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- only DM within SM (Higgs is unstable) ✓
- ruled out by structure formation ✖

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- no direct detection so far (**XENON**) ✗
- Dwarf problem ✗ (?)

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

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Still okay.

I don't wanna enter that debate... ***NOBODY KNOWS IT FOR SURE!!!***

➔ ***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.***

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- Some model-independent data analysis (however, by WDM fans...) 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]

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ν-masses not explained

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- ***METHODS*:** use what is known from light neutrino models to explain the desired structure ➔ flavour symmetries, mass suppression mechanisms, ...

- ***LINK*:** be careful to accommodate the information from astrophysics/cosmology DM-production mechnism, correct abundance, X-ray bound, structure formation, ...

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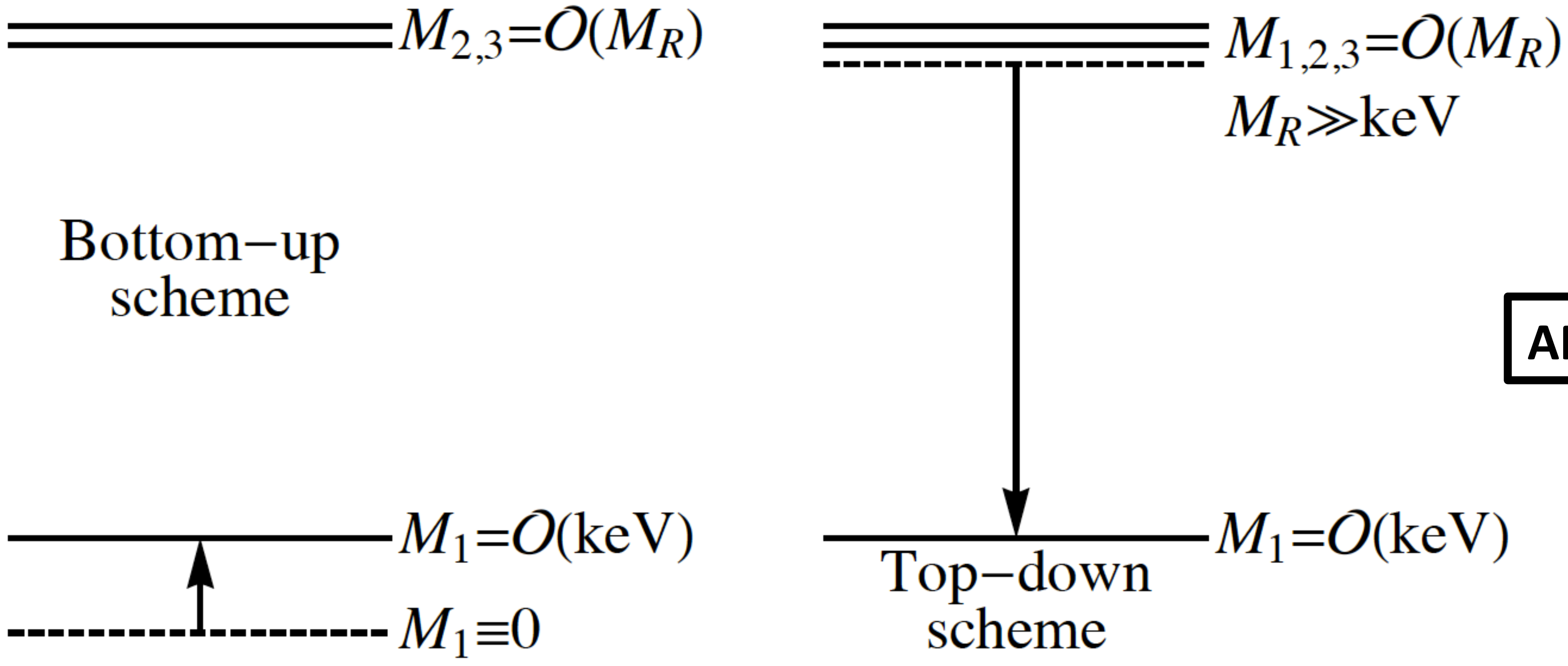

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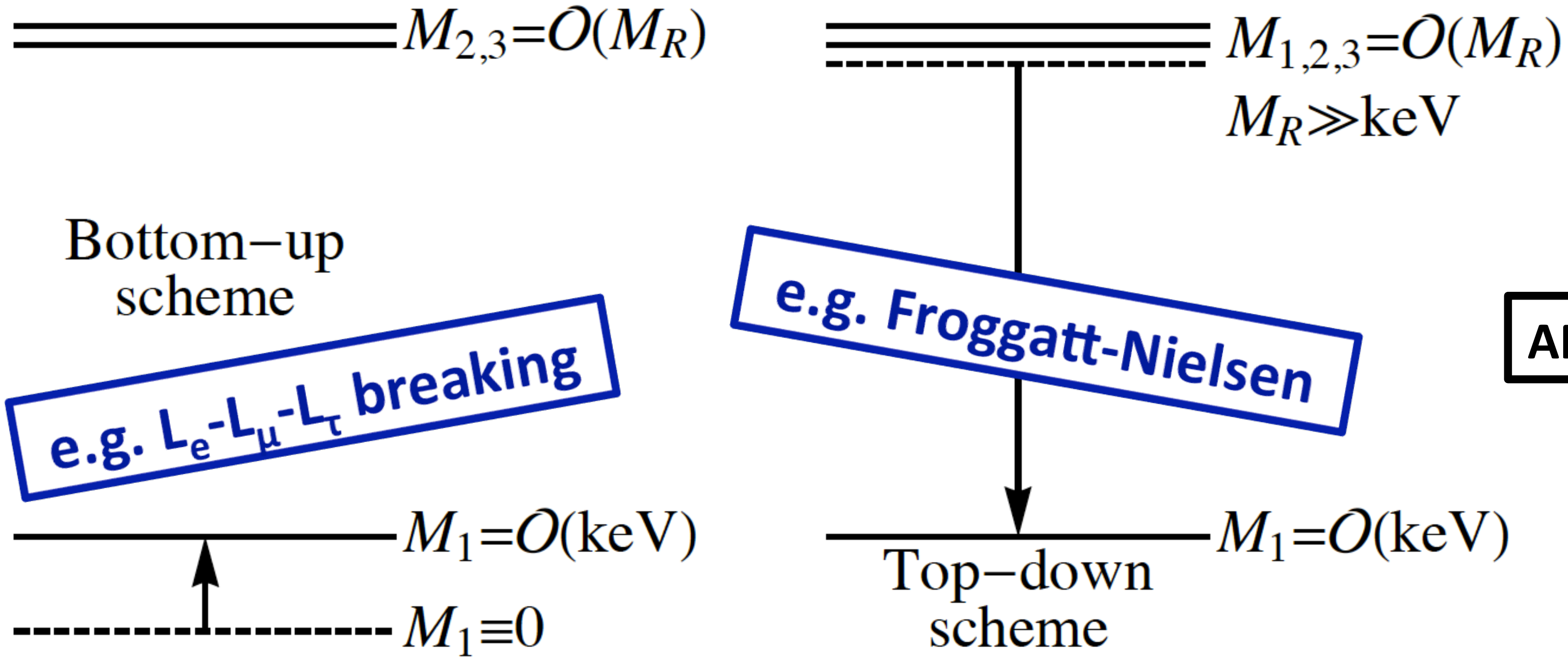

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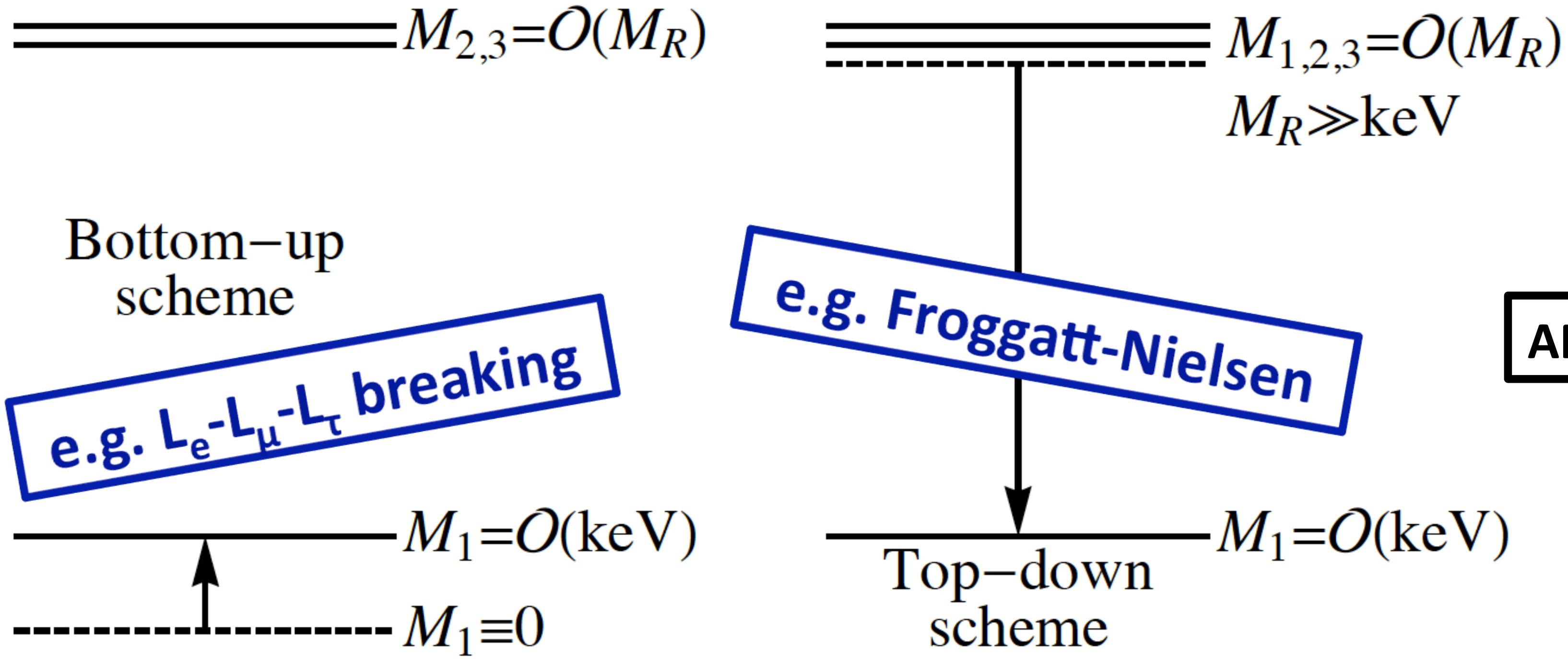

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➔ Most models are in one or the other category!

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    - HOWEVER: this line is **NOT** observed

      ➔ strong bound on active-sterile mixing $\theta_i^2 = \Sigma_\alpha |\theta_{\alpha i}|^2$ with the keV neutrino:

$$\theta_1^2 \lesssim 1.8 \cdot 10^{-5} \left(\frac{1 \text{ keV}}{M_1} \right)^5$$

Boyarsky,Ruchayskiy,Shaposhnikov:
Ann. Rev. Nucl. Part. Sci. **59** (2009) 191

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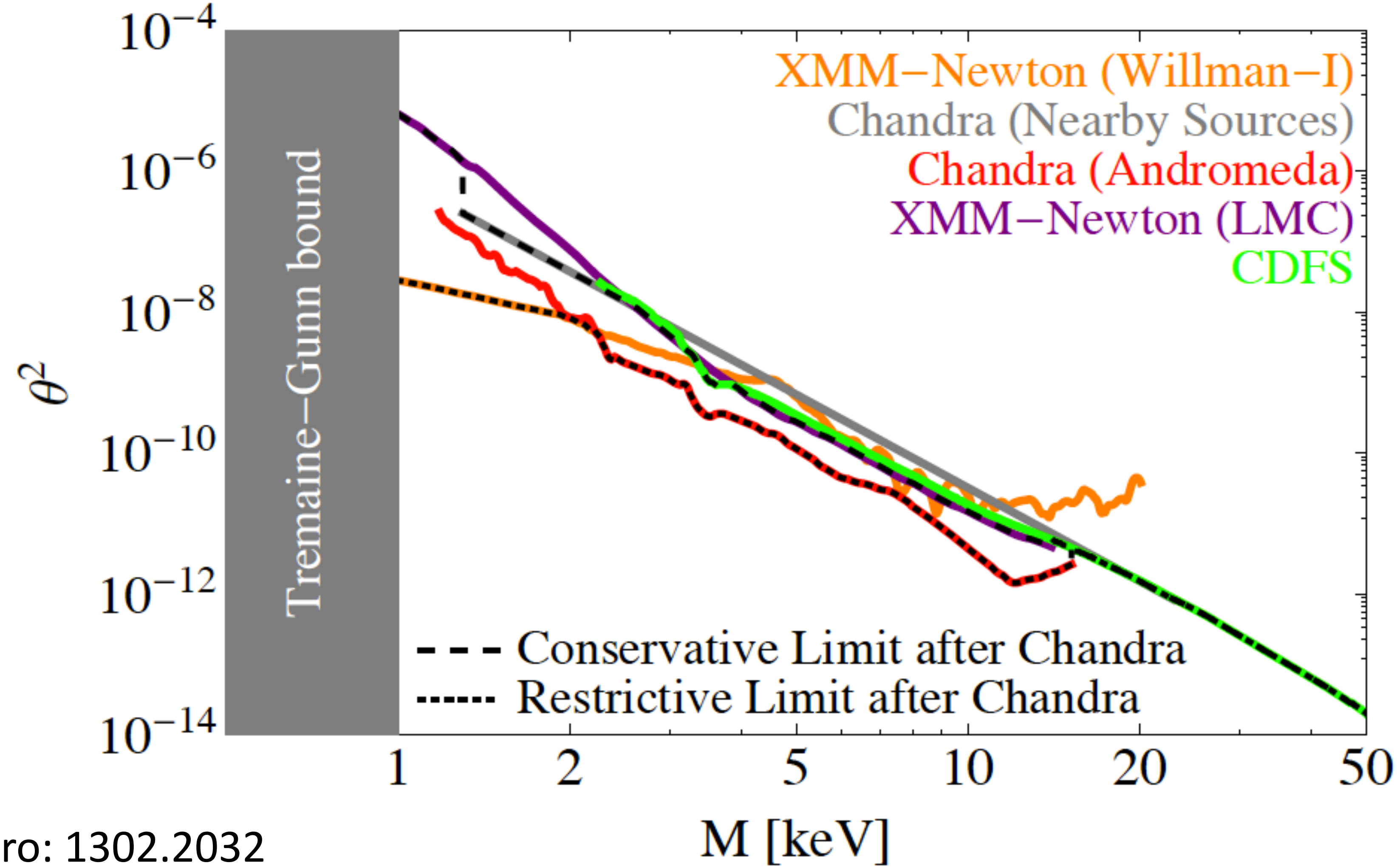

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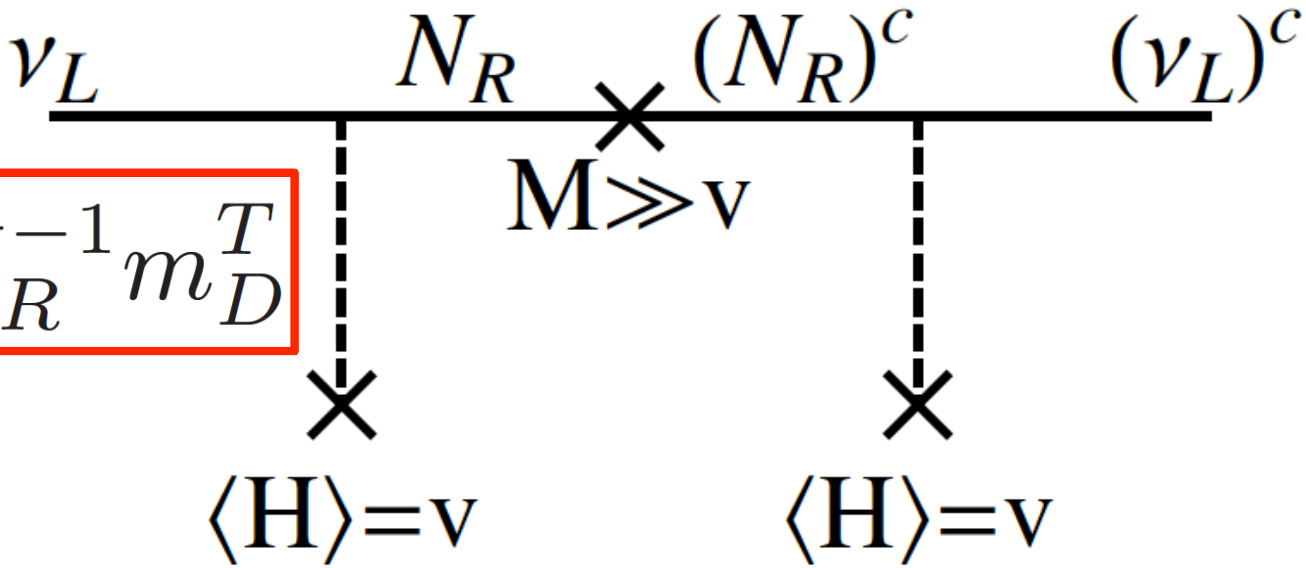

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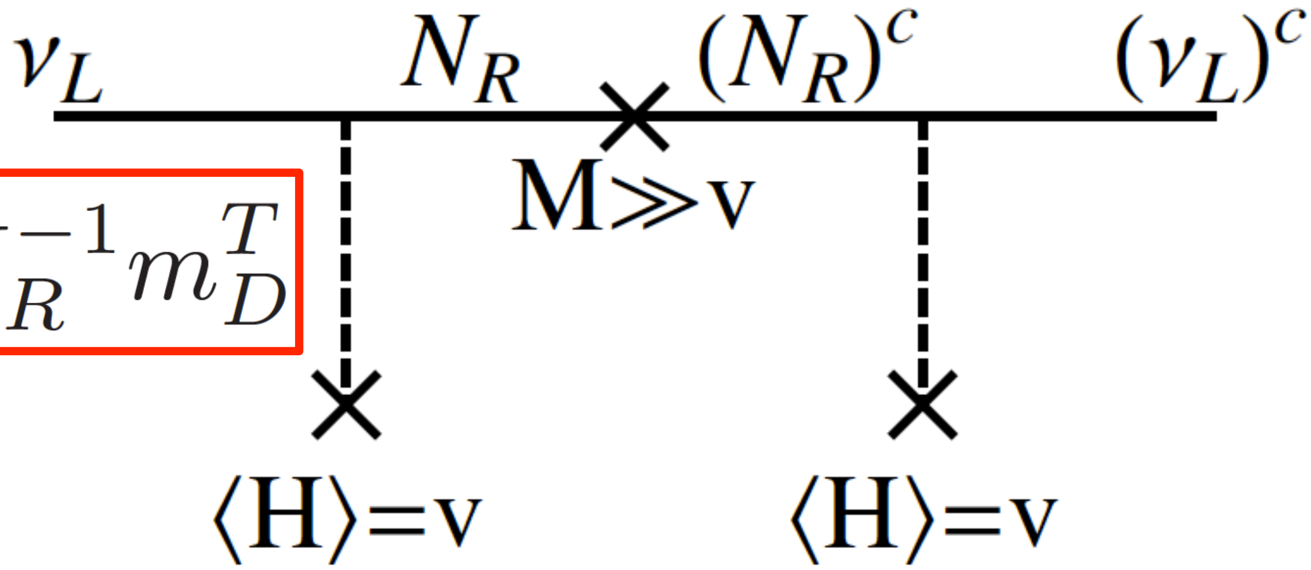

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➔ ***Does that also work when "dividing by keV mass"?!?***

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      [Kusenko,Takahashi,Yanagida: Phys. Lett. **B693** (2010) 144]

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

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

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

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  [Asaka,Shaposhnikov,Kusenko: Phys. Lett. **B638** (2006) 401]
  [Anisimov,Bartocci,Bezrukov: Phys. Lett. **B671** (2009) 211]
  [Bezrukov,Gorbunov: JHEP **1005** (2010) 010]

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  [Anisimov,Bartocci,Bezrukov: Phys. Lett. **B671** (2009) 211]
  [Bezrukov,Gorbunov: JHEP **1005** (2010) 010]
- **thermal overproduction with entropy dilution**
  [Bezrukov,Hettmansperger,Lindner: Phys. Rev. **D81** (2010) 085032]
  [Nemevsek,Senjanovic,Zhang: JCAP **1207** (2012) 006]

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  - *note*: there are not many such models
    ➔ there is still a lot to do!!!

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  - *note*: there are not many such models
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  - ... Now let's start!

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  - 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]

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  - general features:
    - ***symmetry*** ➔ patterns: (0,m,m) & (0,M,M)
    - ***broken*** ➔ small mass, degeneracy lifted

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  - 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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  - WAY OUT: broken symmetry
    - ➔ will remedy the above issues
    - ➔ important: no matter how the breaking is achieved, the results will always look similar

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  - mixings also require soft breaking:

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  - prediction for the masses (under assumptions):

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

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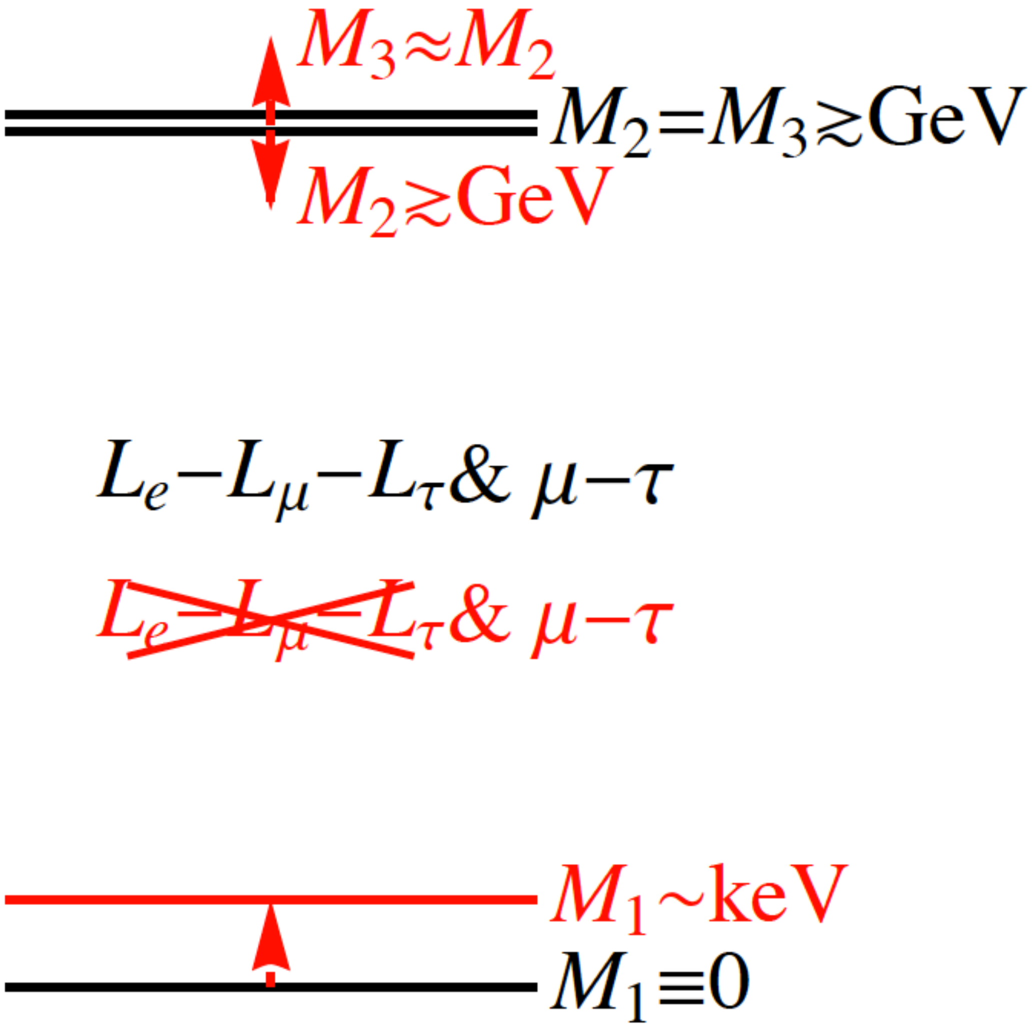

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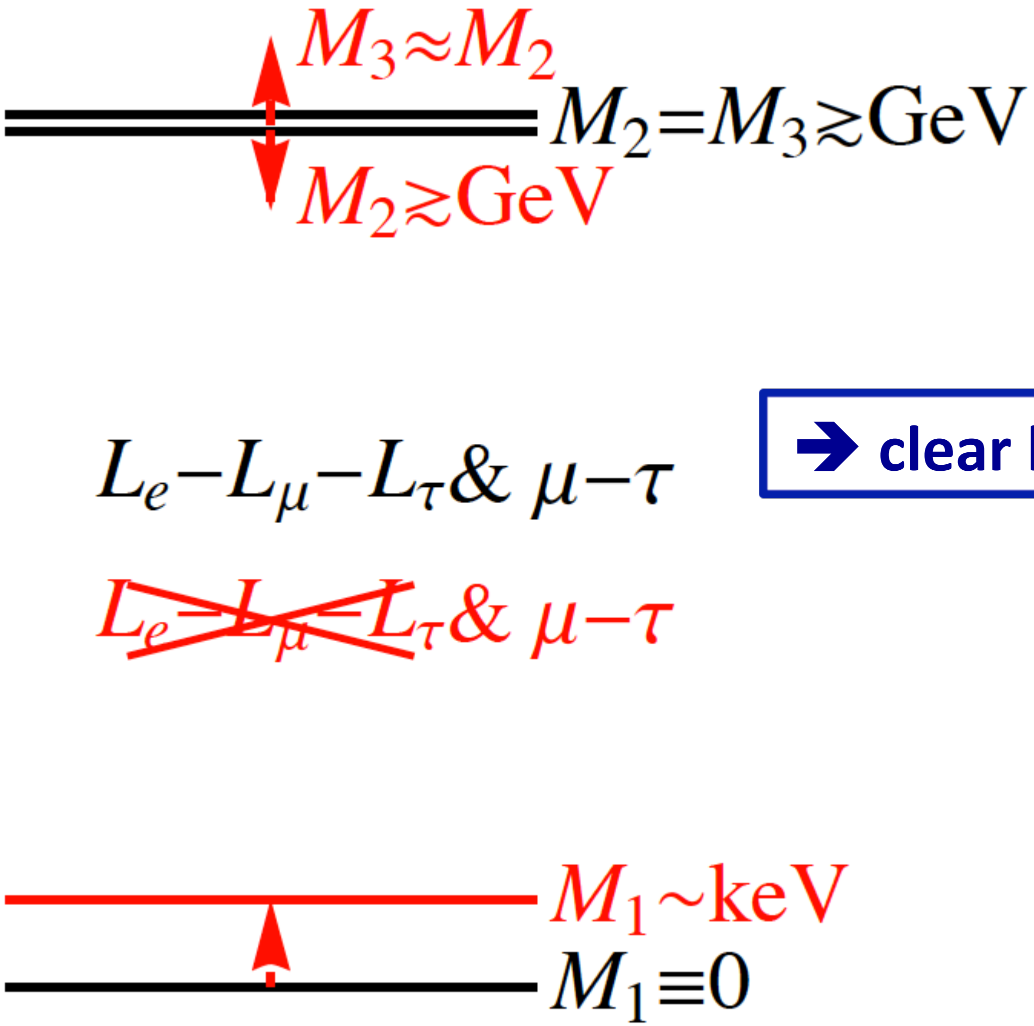

➔ **clear bottom-up type scheme**

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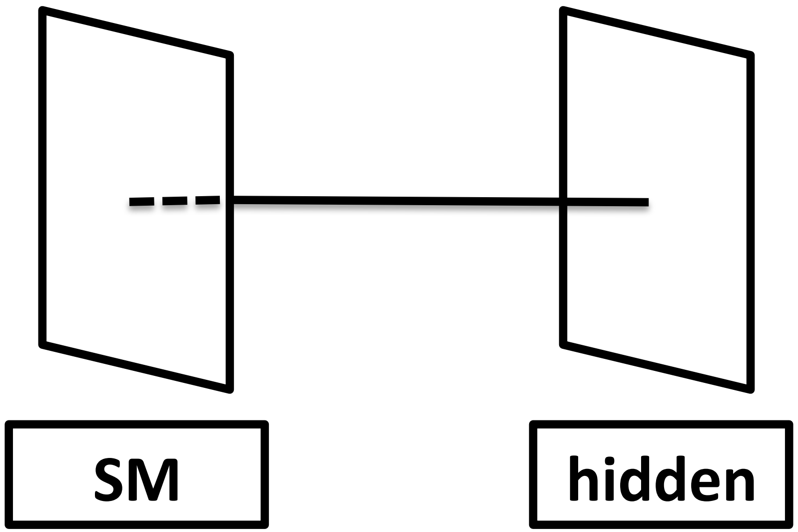

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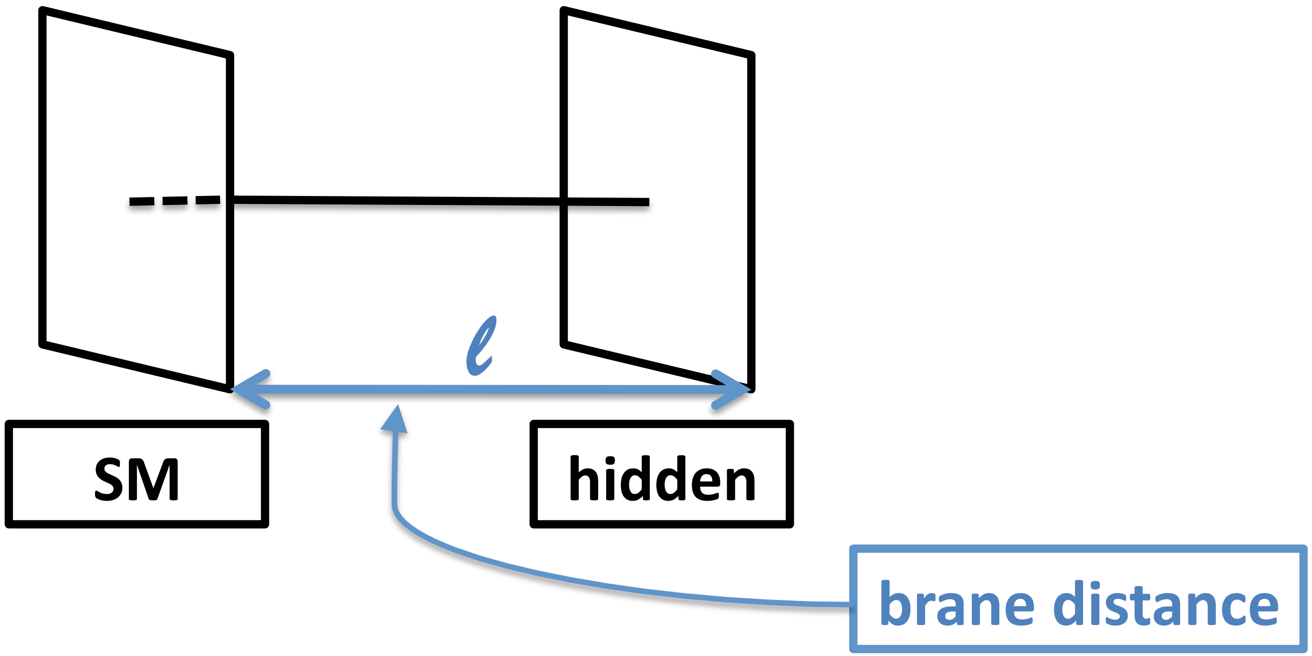

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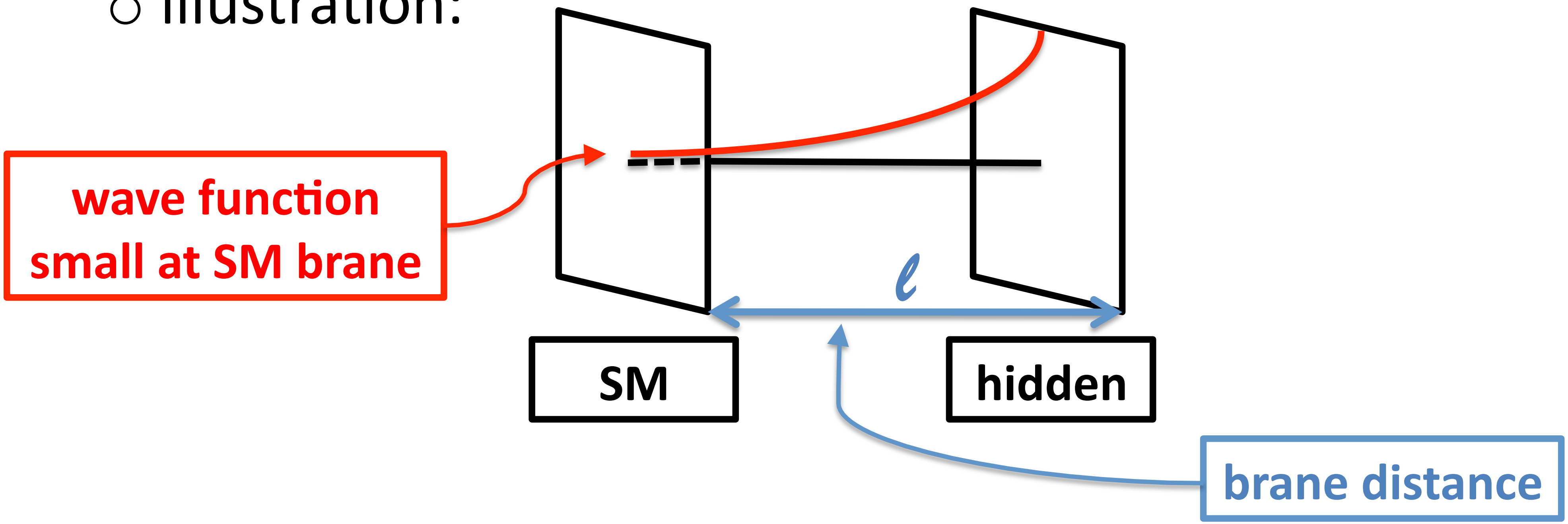

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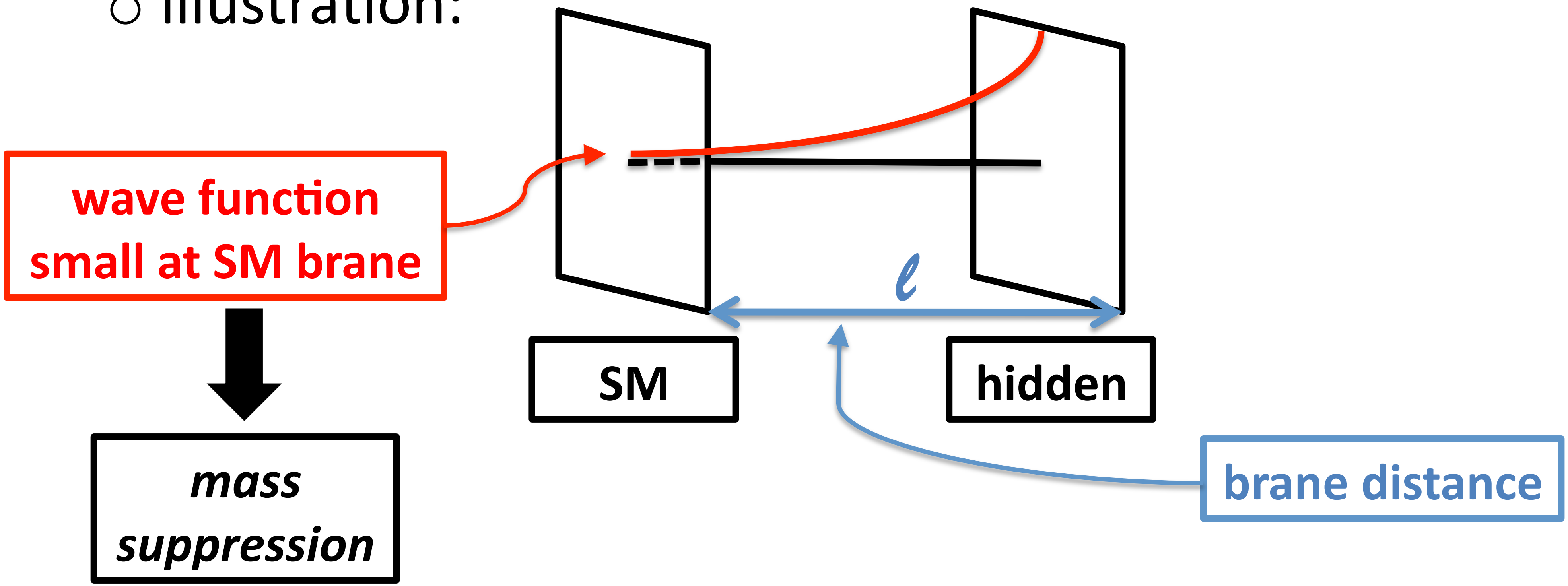

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$$\Psi_{L,R}(x^\mu, y) = \sum_n \psi_{L,R}^{(n)}(x^\mu) \; f_{L,R}^{(n)}(y)$$

➔ equation of motion in the Extra Dimension:

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

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

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$e^{-2m_i l} << 1$ for $m_i l >> 1$

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

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

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

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

$$\lambda_{i\alpha} = \frac{\tilde{\lambda}_{i\alpha}}{\sqrt{M_0}} \sqrt{\frac{2m_i}{e^{2m_il} - 1}}$$

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

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  - bonus: seesaw *guaranteed* to work, due to conspiracy between the suppressions

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    ➔ can be cured by A_4 extension:

    $m_1 > m_2 = m_3$ ➔ $M_1 \ll M_2 = M_3$

    [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

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  - o 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

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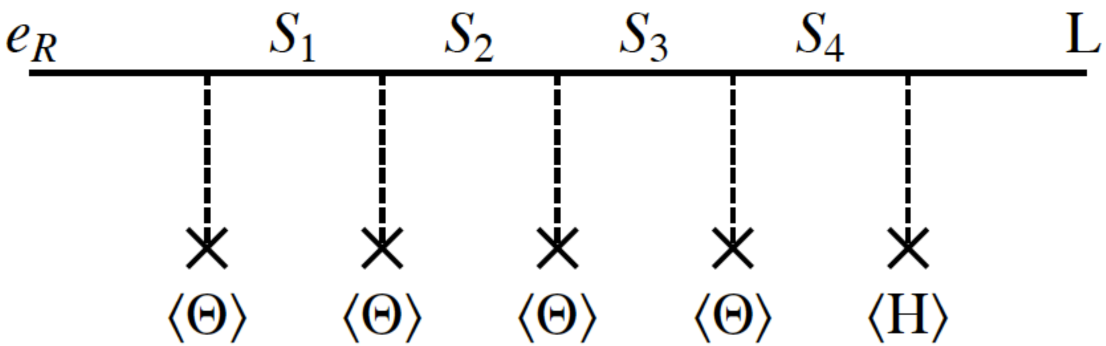

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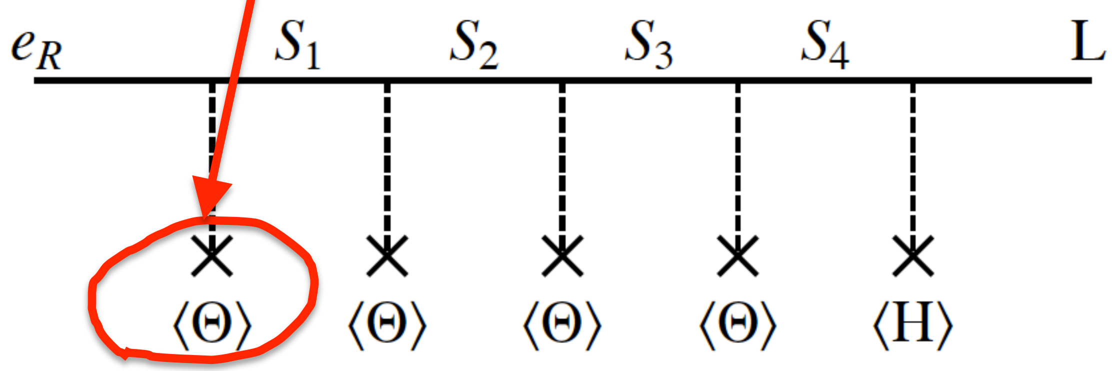

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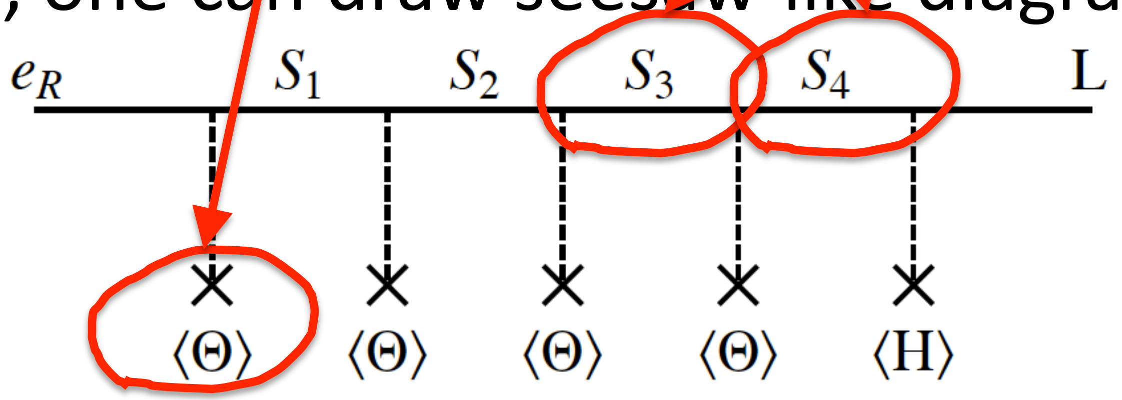

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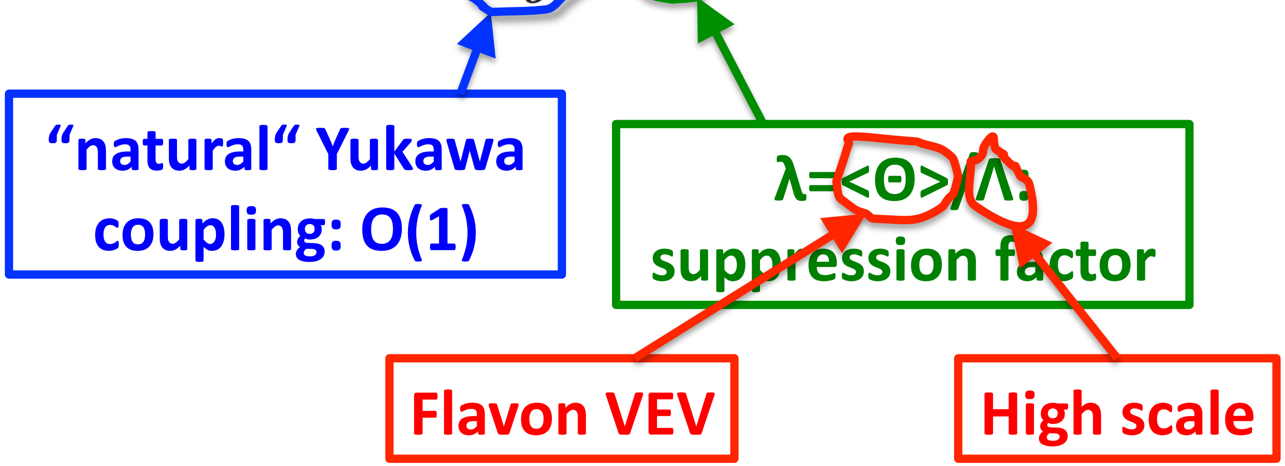

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  - **HOWEVER**: several problems are swept under the carpet (UV-completion, U(1)-breaking,...)

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  - application to keV sterile neutrinos: $U(1)_{FN} \times Z_{2,aux}$

$$
\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; +, +, -) \\
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  - ○ full Lagrangian:

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

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  - two example scenarios: A(3,0,0) & B(4,1,0)

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\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)} \\
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Hierarchy

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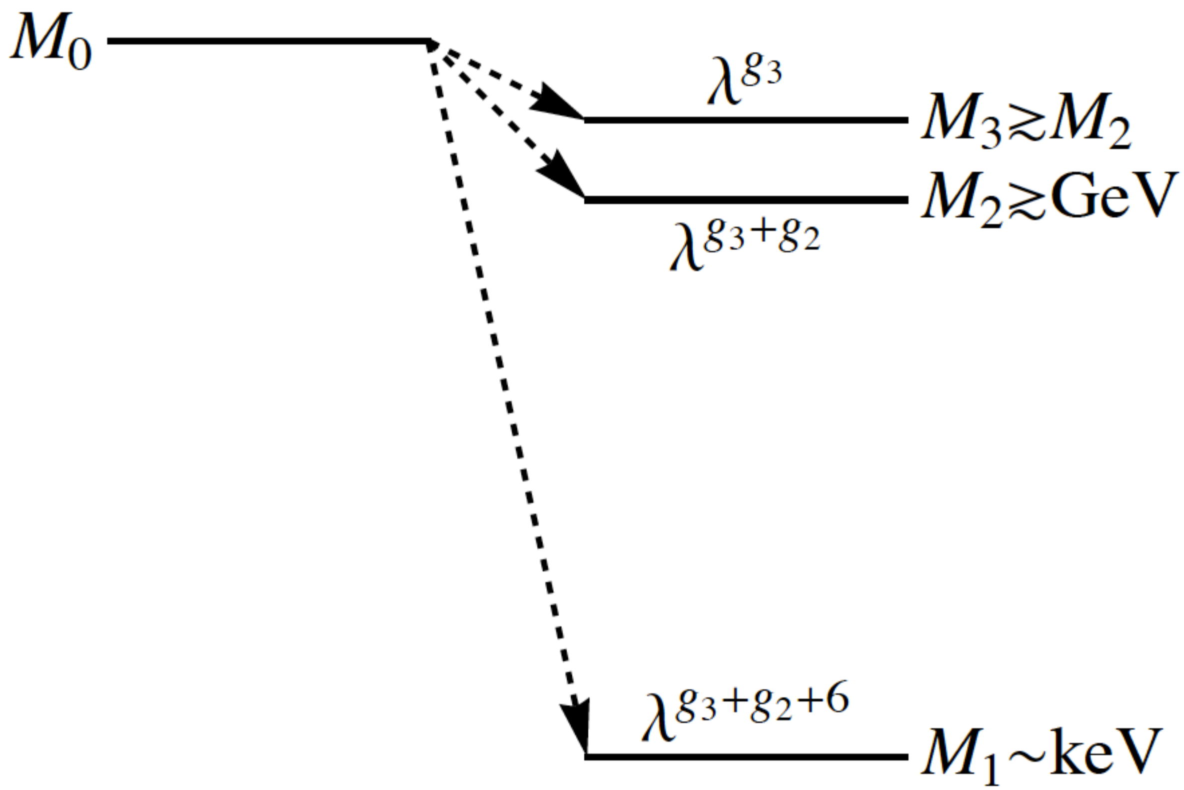

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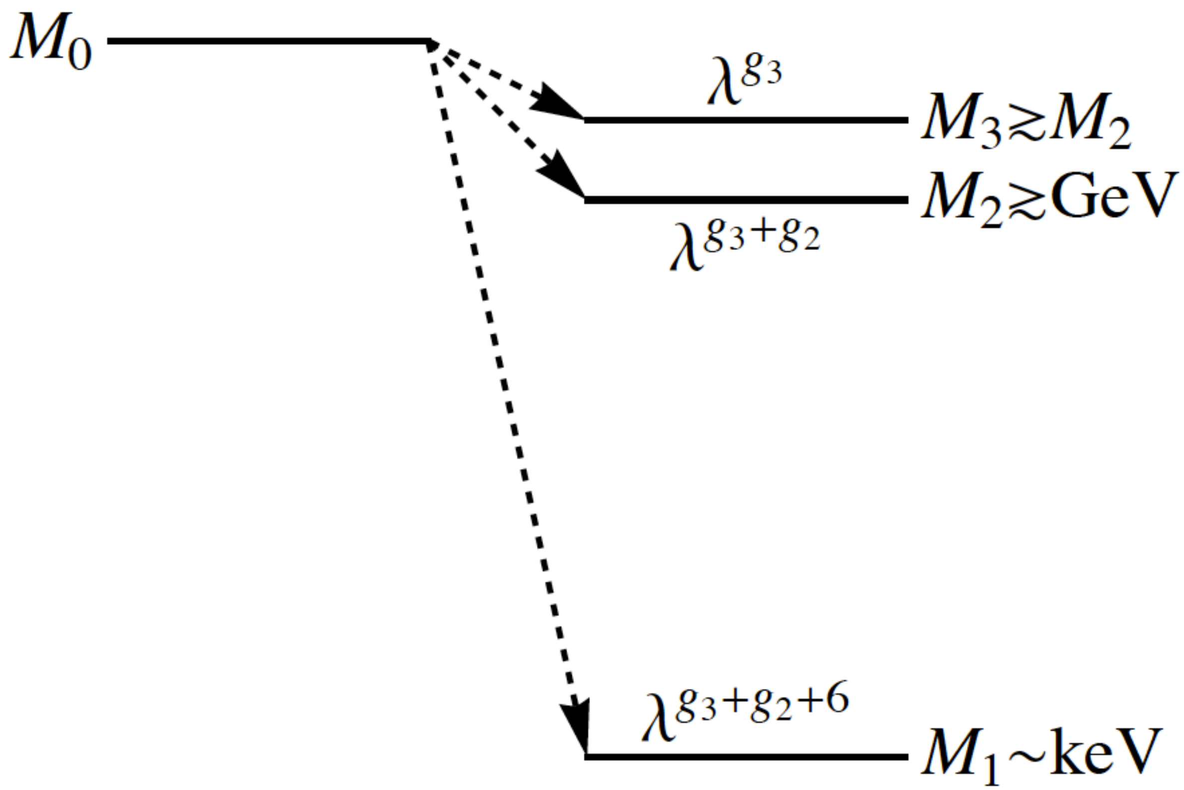

➔ large mass scale gets suppressed

➔ ***top-down***

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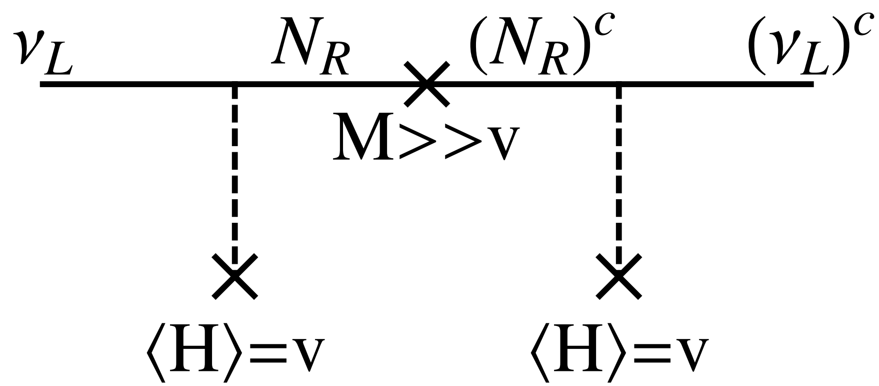

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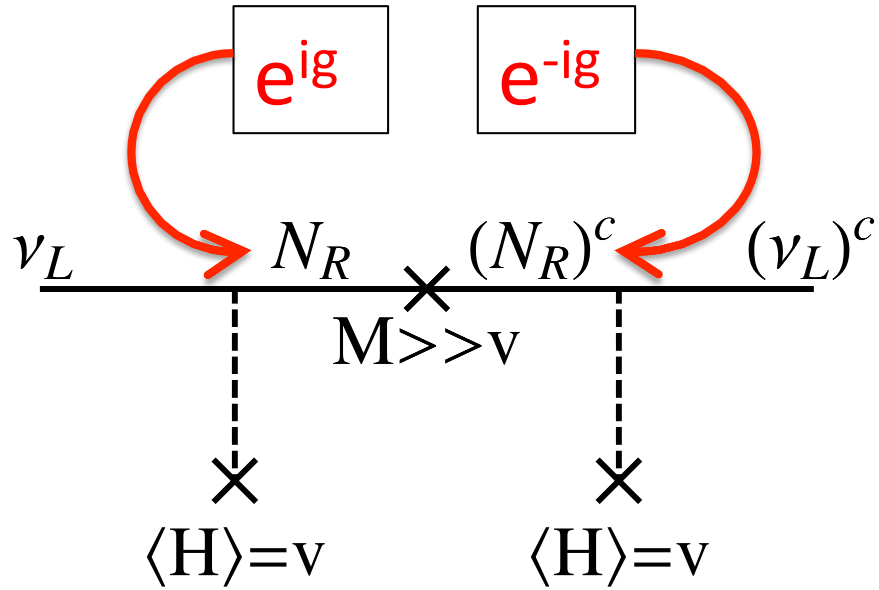

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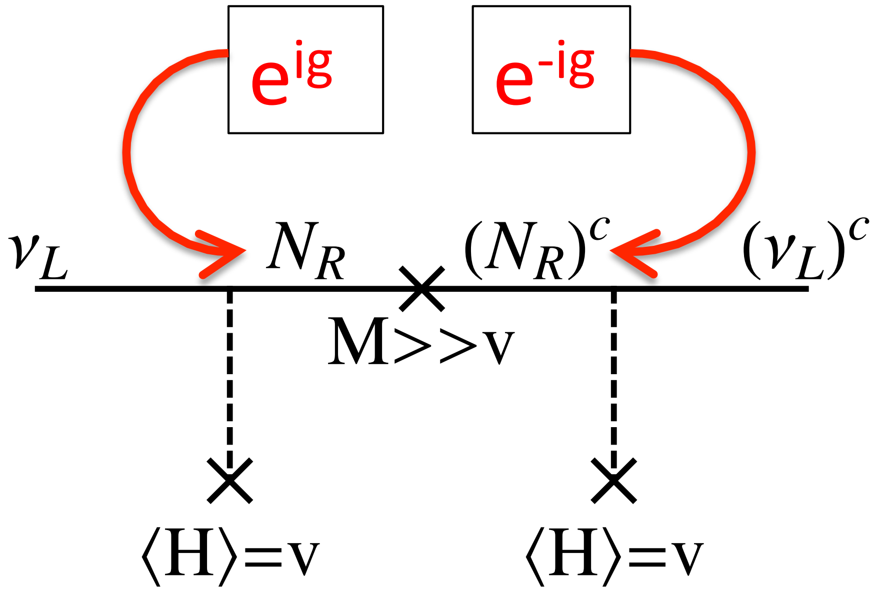

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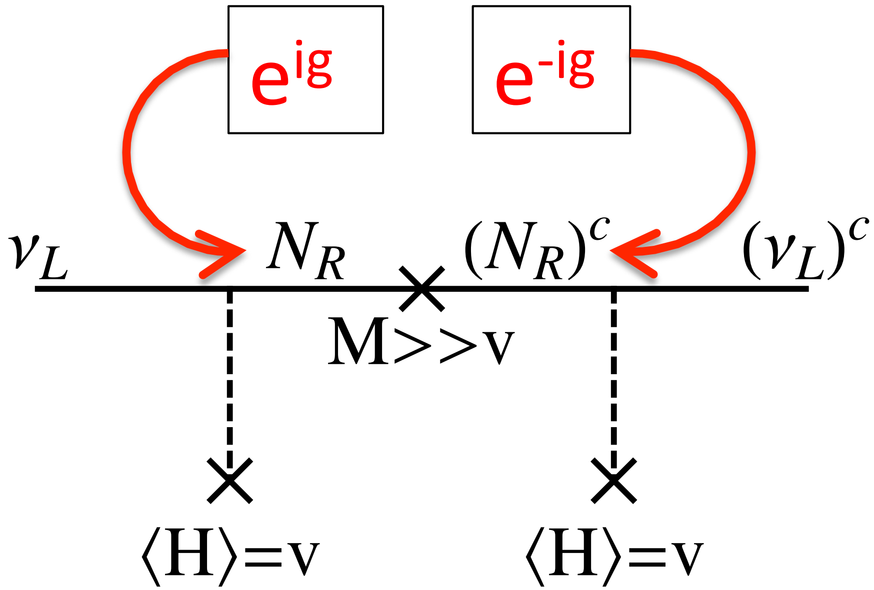

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      ➔ disfavours one production mechanism
    - favours SU(5) compared to SO(10)
      ➔ reason: g_i unconstrained for singlet N_i
      ➔ BUT: associated problems with p^+ decay...
    - Renormalization Group Running negligible
    - excludes bimaximal *neutrino* mixing (for the diagonalization of the light neutrino mass matrix)
    - disfavours democratic Yukawa couplings

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  - 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)

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  - idea: introduce another singlet fermion S_R and ***<u>assume</u>*** the following Lagrangian

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

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  - *general*: although the mechanism cannot stand alone, it may be resembled in more concrete models

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- plus many ***scenarios*** (=frameworks without explanation for scale): Left-Right symmetry, scotogenic model, ...

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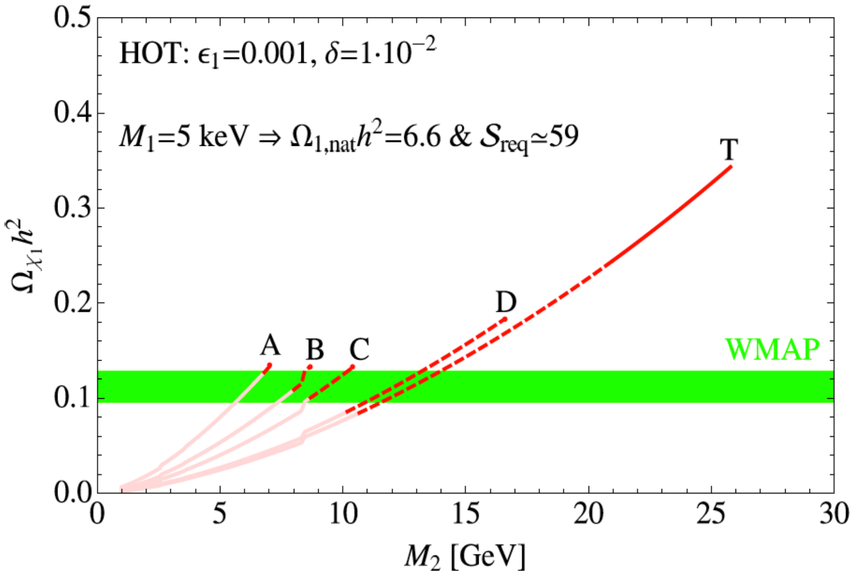

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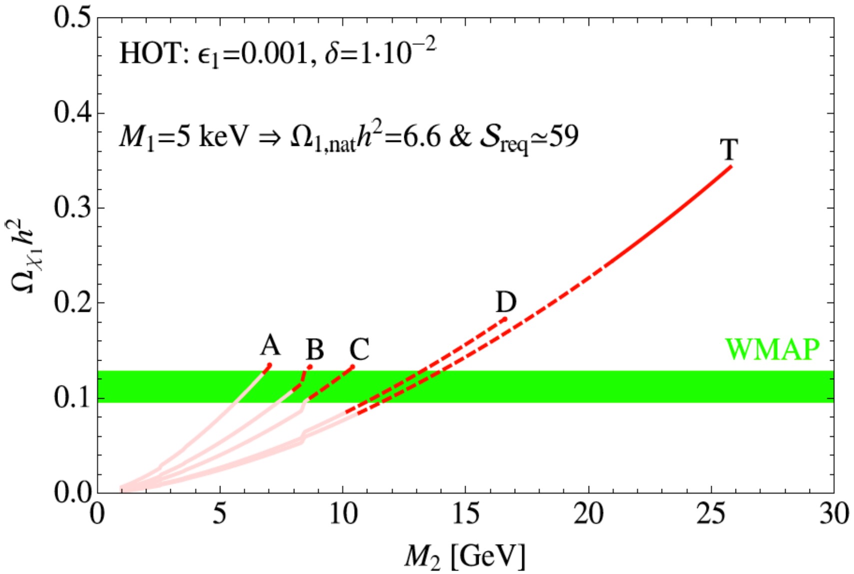

  - other production mechanisms and more or less model-independent studies possible

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  ➔ *synergies needed*

THANK YOU!!!