

keV Neutrino Model Building



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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: 1210.6035, PRD (Rapid Communication) acc.

AM: *in preparation*

Seminar on Particle Physics, Vienna, 29-11-2012

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1. Introduction
2. keV and/or Warm Dark Matter
3. Model building for keV neutrinos
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5. The generalization: keVins
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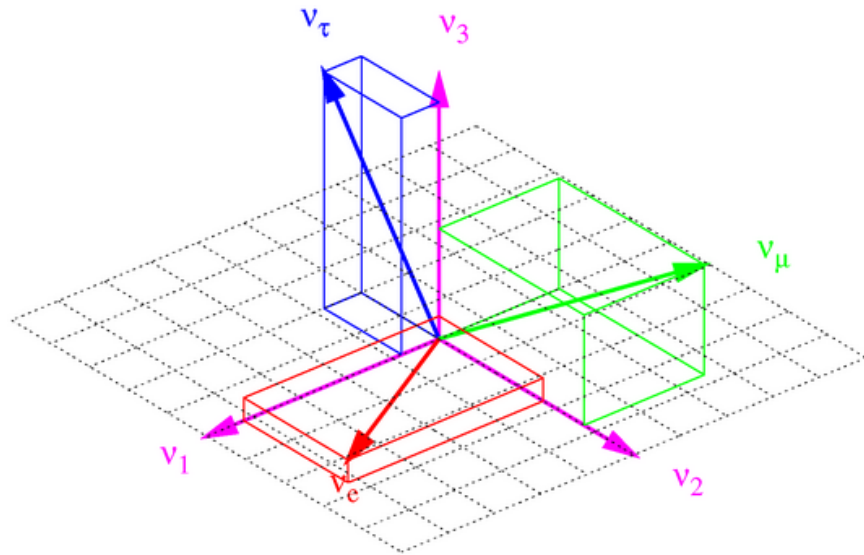
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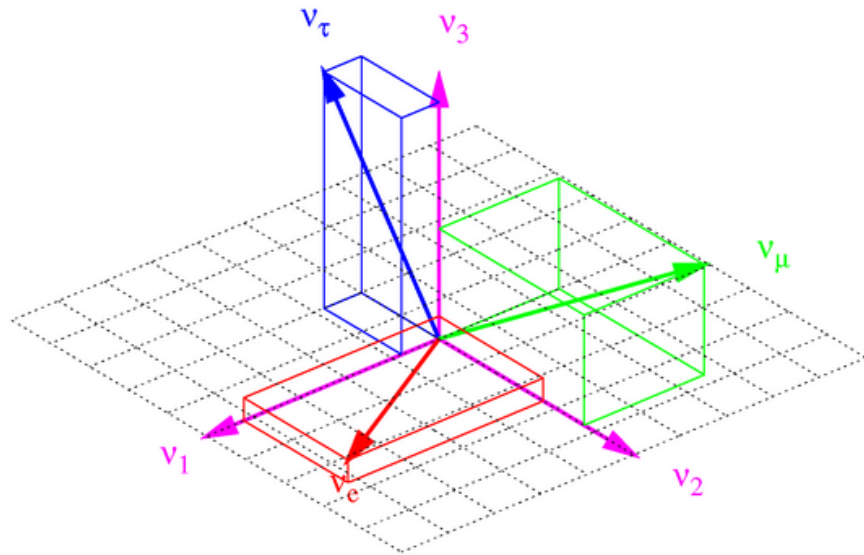


(<http://nu.phys.laurentian.ca/~fleurot/oscillations/>)

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$$\theta_{12} \approx 34.4^\circ$$

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$$\theta_{23} \approx 51.1^\circ$$

$$\Delta m_{21}^2 \approx 7.6 \times 10^{-5} \text{eV}^2$$

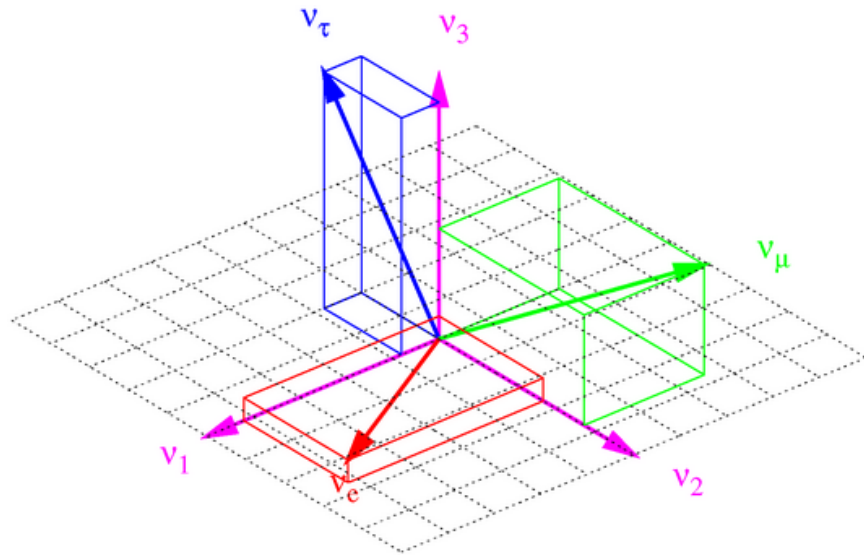
$$|\Delta m_{31}^2| \approx 2.5 \times 10^{-3} \text{eV}^2$$

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

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

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

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$|m_{ee}| < 0.3\text{-}0.6 \text{ eV}$ [KamLAN-Zen: Phys. Rev. **C85** (2012) 045504]

$|m_{ee}| < 0.140\text{-}0.380 \text{ eV}$ [EXO-200: Phys. Rev. Lett. **109** (2012) 032505]

$|m_{ee}| < 0.300\text{-}0.710 \text{ eV}$ [CUORECINO: Astropart. Phys. **34** (2011) 822-831]

$m_\beta < 2.3 \text{ eV}$ [MAINZ, Eur. Phys. J. **C40** (2005) 447-468]

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

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

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

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We have to think about solutions!!!



(<http://www.duckipedia.de/images/e/e9/Daniel%C3%BCsentrrieb.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,...



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- Dwarf galaxies ✓ (?)
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Still okay.

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

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we see less than predicted with CDM
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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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Simple framework: **ν MSM** [Asaka,Blanchet,
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hardly testable ➔ **model building needed!!!**

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- **GOAL**: make a vMSM testable by tightly linking it to low energy neutrino data → even though the vMSM itself is hard to exclude, such models are predictive
- **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 mechanism, correct abundance, X-ray bound, structure formation, ...

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

Bottom–up
scheme

$$\text{-----} \uparrow \text{----- } M_1 = O(\text{keV})$$

$$\text{-----} M_1 \equiv 0$$

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

$M_R \gg \text{keV}$

$$\text{-----} \downarrow \text{----- } M_1 = O(\text{keV})$$

Top–down
scheme

AM: in preparation

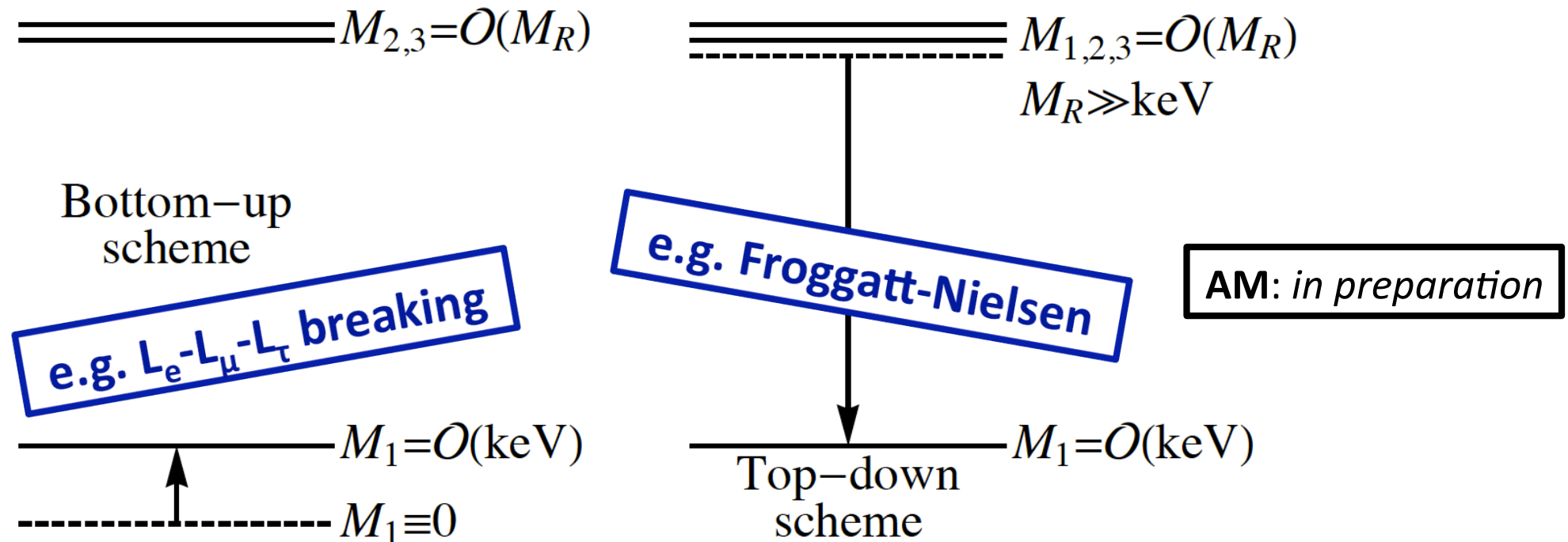
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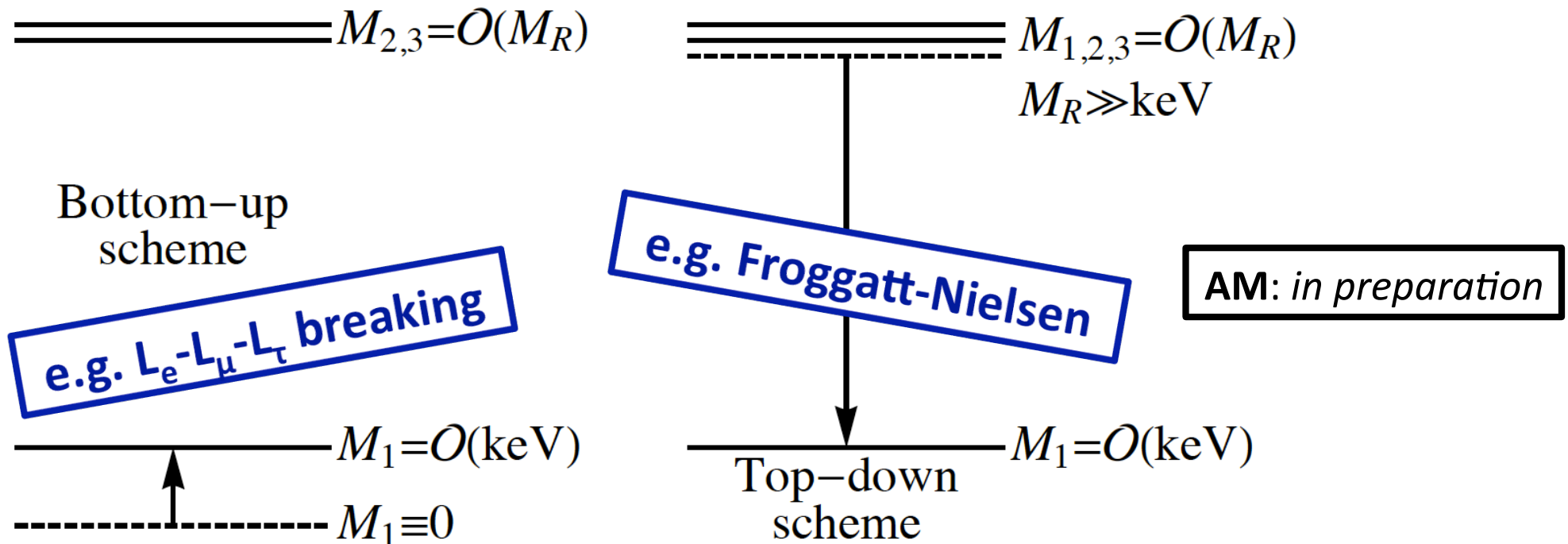
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→ Most models are in one or the other category!

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 - a sterile neutrino N_1 can decay: $N_1 \rightarrow \nu\gamma$
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 - ➔ this produces a monoenergetic X-ray line with $E = M_1/2$ ($N_1 = \text{DM} \rightarrow$ many around)
 - HOWEVER: this line is **NOT** observed
 - ➔ strong bound on active-sterile mixing $\theta_i^2 = \sum_\alpha |\theta_{\alpha i}|^2$ with the keV neutrino:

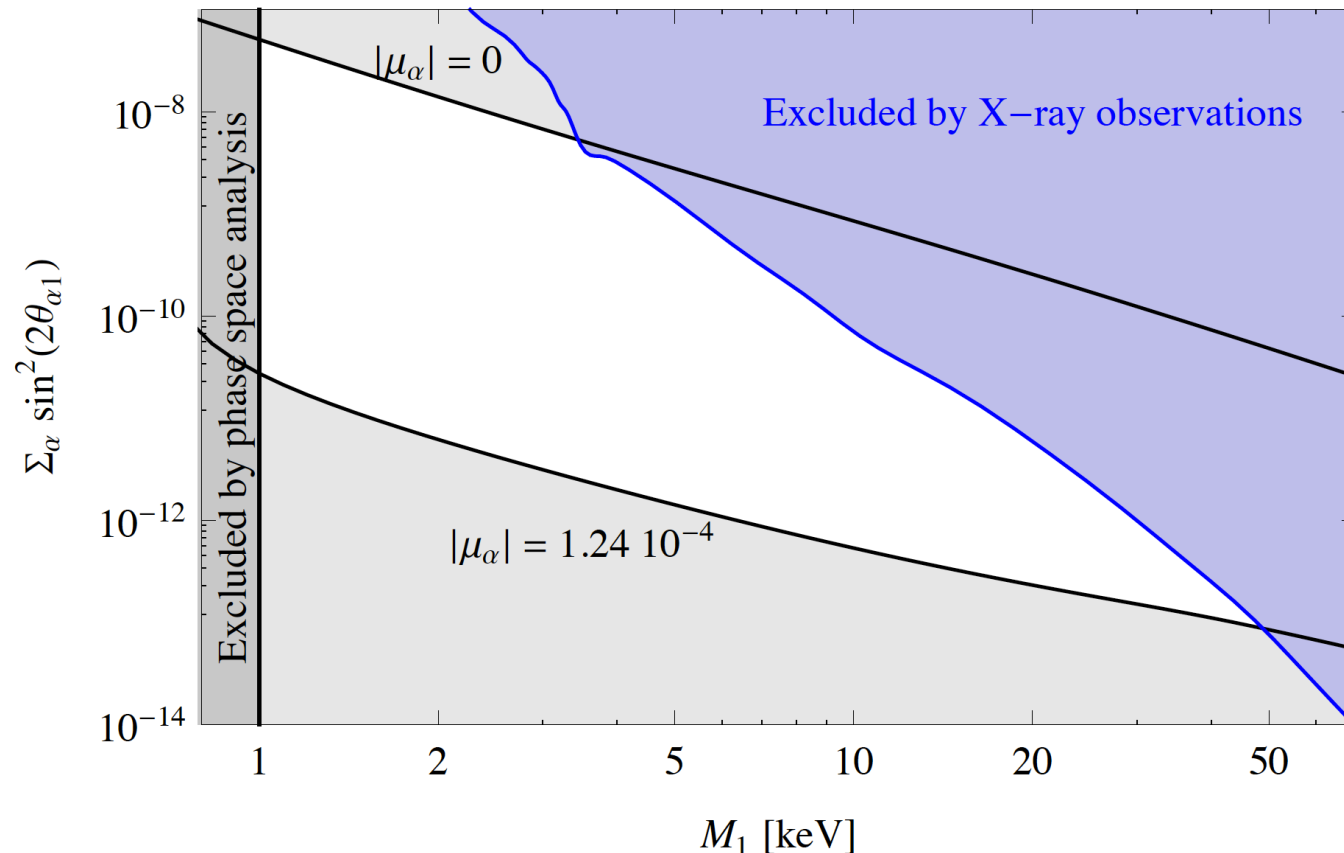
$$\theta_1^2 \lesssim 1.8 \cdot 10^{-5} \left(\frac{1 \text{ keV}}{M_1} \right)^5$$

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

3. Model building for keV neutrinos

- **Differences to “ordinary” model building:**

- we need to respect the X-ray bound:
 - more detailed version:



Canetti, Drewes,
Shaposhnikov:
1204.3902 [hep-ph]

Canetti, Drewes,
Frossard,
Shaposhnikov:
1208.4607 [hep-ph]

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- Differences to “ordinary” model building:

- seesaw mechanism for eV neutrinos:

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

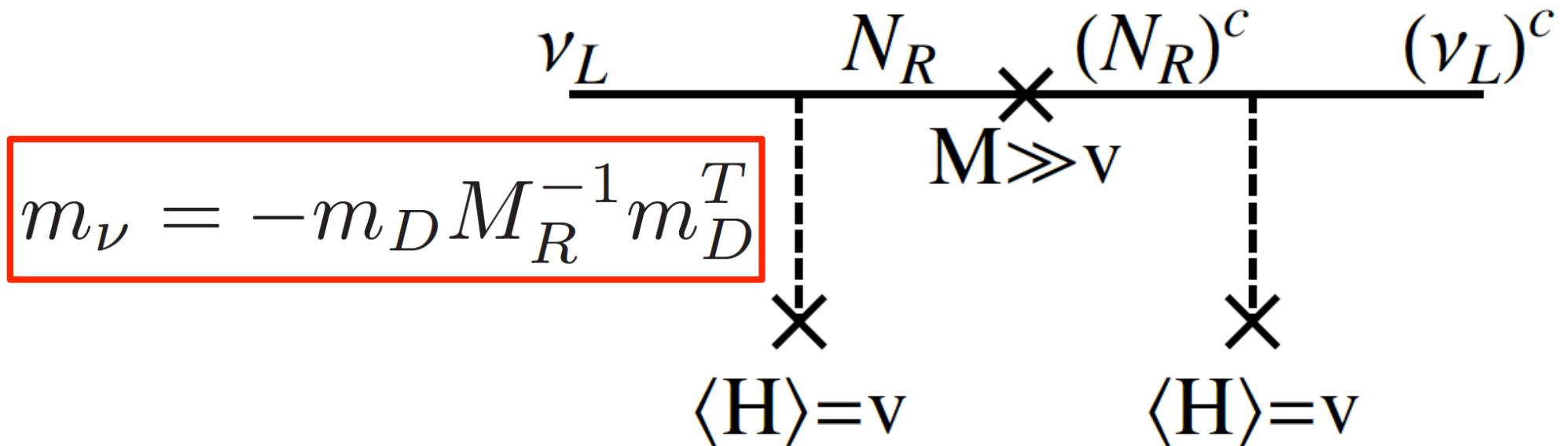
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→ Does that also work when “dividing by keV mass“?!?

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[Kusenko,Takahashi,Yanagida: Phys. Lett. **B693** (2010) 144]
[AM,Niro: JCAP **1107** (2011) 023]

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

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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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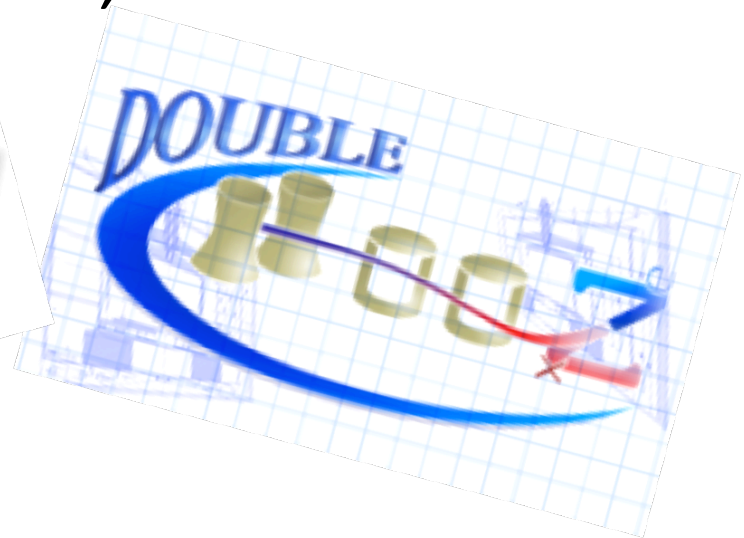
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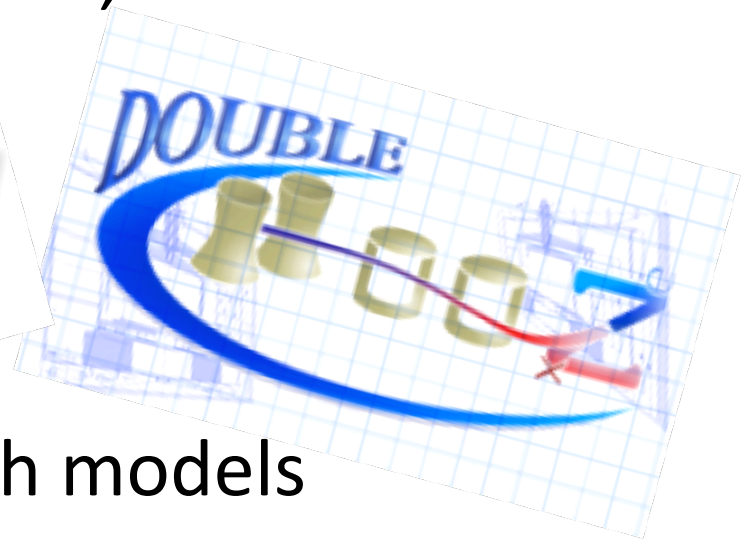
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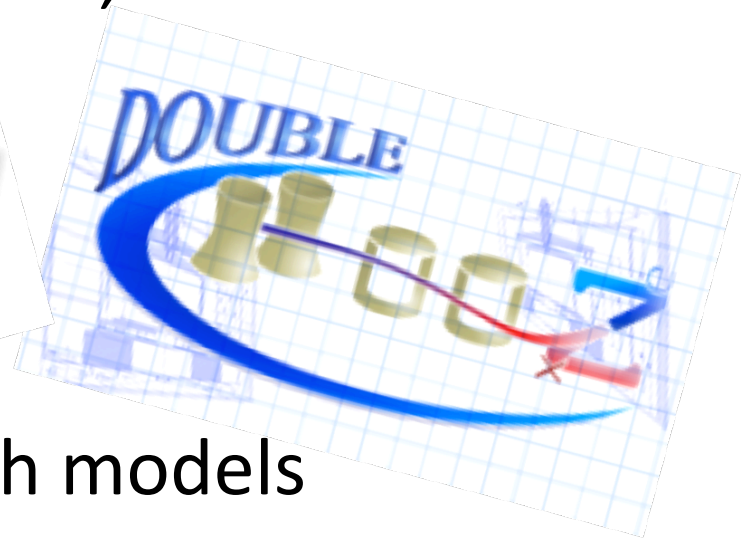


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- ... Now let's start!

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 - 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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 - [Mohapatra: Phys. Rev. **D64** (2001) 091301]
 - *application to keV sterile neutrinos*:
 - [Shaposhnikov: Nucl. Phys. **B763** (2007) 49]
 - [Lindner, **AM**, Niro: JCAP **1101** (2011) 034]

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* $\rightarrow$ patterns: $(0, m, m)$ & $(0, M, M)$
 - *broken* $\rightarrow$ 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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- then, only symmetry preserving terms are allowed:

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

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

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→ mass matrix:

$$\mathcal{M}_\nu = \left(\begin{array}{ccc|ccc} 0 & m_L^{e\mu} & m_L^{e\tau} & m_D^{e1} & 0 & 0 \\ m_L^{e\mu} & 0 & 0 & 0 & m_D^{\mu2} & m_D^{\mu3} \\ m_L^{e\tau} & 0 & 0 & 0 & m_D^{\tau2} & m_D^{\tau3} \\ \hline m_D^{e1} & 0 & 0 & 0 & M_R^{12} & M_R^{13} \\ 0 & m_D^{\mu2} & m_D^{\tau2} & M_R^{12} & 0 & 0 \\ 0 & m_D^{\mu3} & m_D^{\tau3} & M_R^{13} & 0 & 0 \end{array} \right)$$

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 - light neutrinos: $(\lambda_+, \lambda_-, 0)$
 - heavy neutrinos: $(\Lambda_+, \Lambda_-, 0)$
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 - WAY OUT: **broken symmetry**
 - $\rightarrow$ will remedy the above issues
 - $\rightarrow$ important: no matter how the breaking is achieved, the results will always look similar

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

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$$\tan^2 \theta_{12} \simeq 1 - 2\sqrt{2}\lambda + 4\lambda^4 - 2\sqrt{2}\lambda^3 \rightarrow \theta_{12} \simeq 33.4^\circ$$

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

$$|U_{e3}| \simeq \frac{\lambda}{\sqrt{2}} \rightarrow \theta_{13} \simeq 8^\circ,$$

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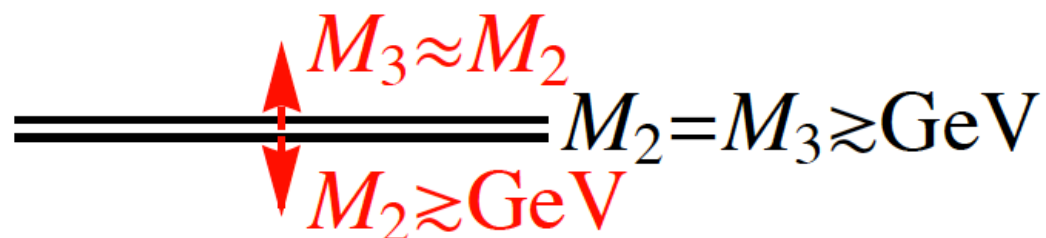
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- prediction for the masses (under assumptions):

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

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 - mass shifting scheme:



$$M_3 \approx M_2$$

$$M_2 \approx M_3 \gtrsim \text{GeV}$$

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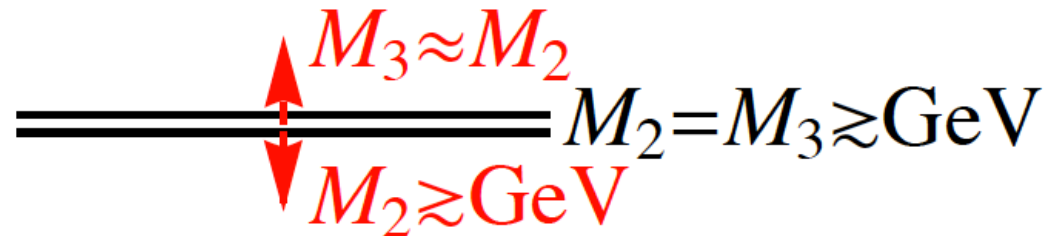
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→ clear bottom-up type scheme

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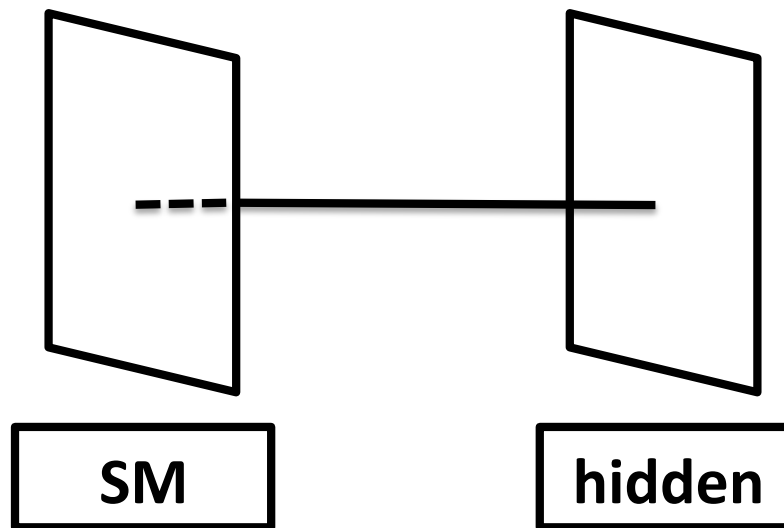
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[Kusenko,Takahashi,Yanagida: Phys. Lett. **B693** (2010) 144]

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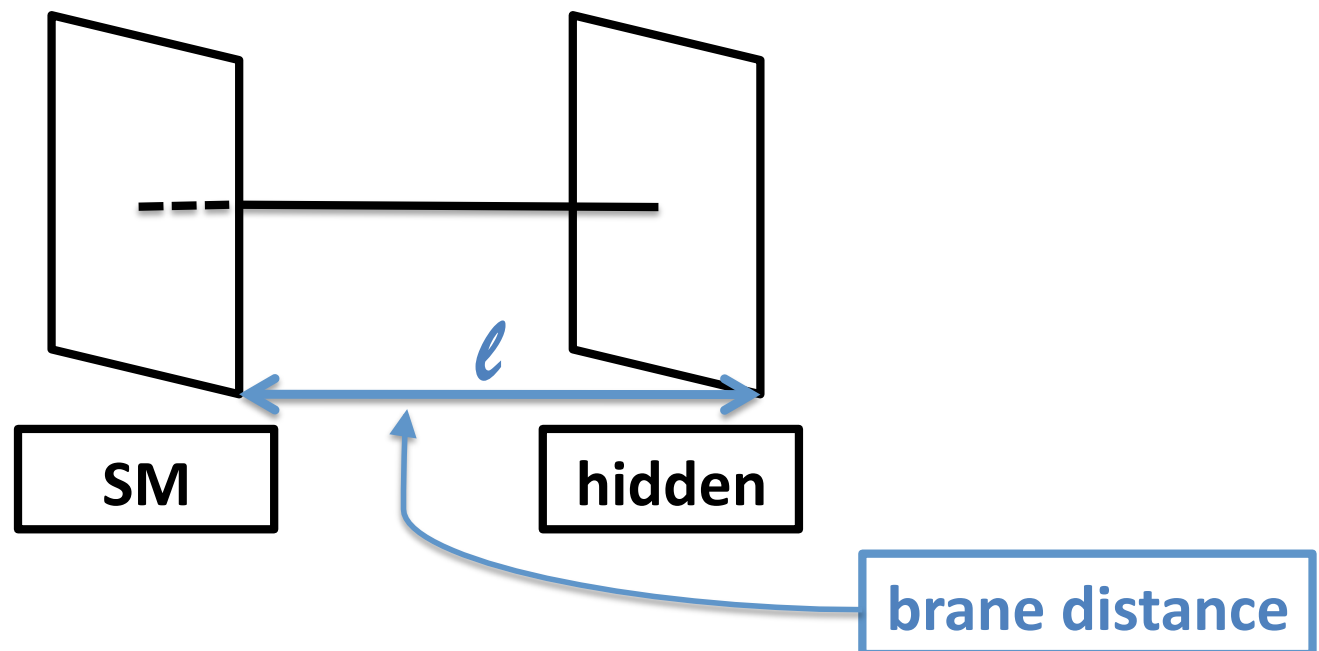


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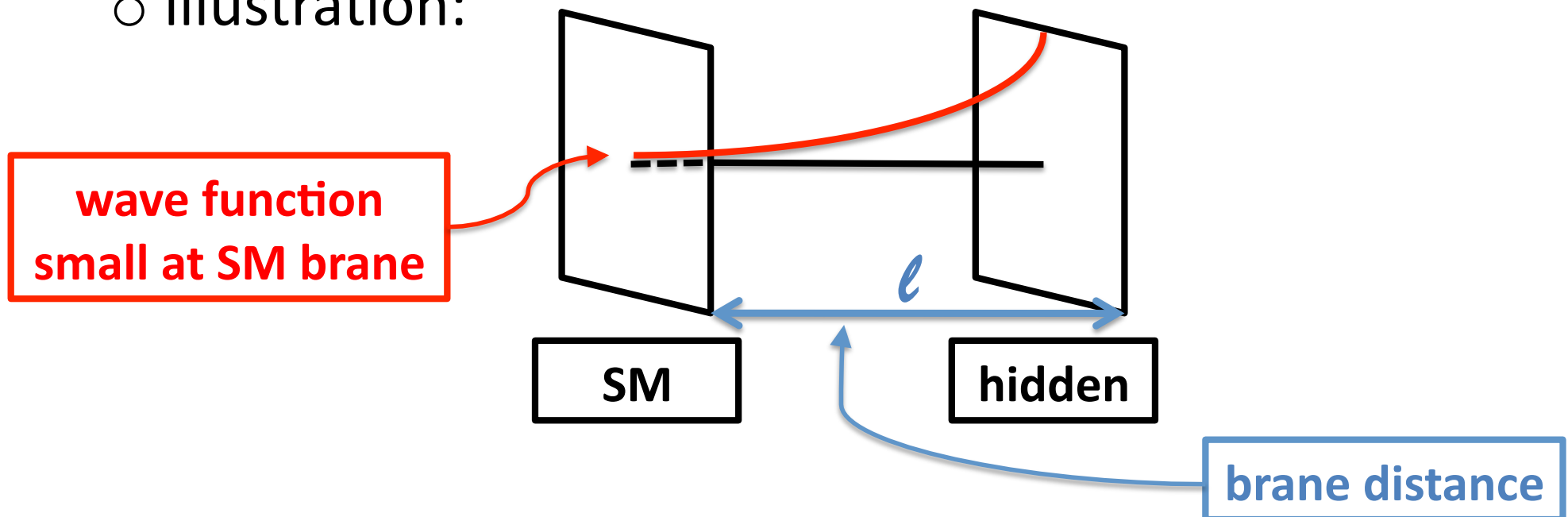


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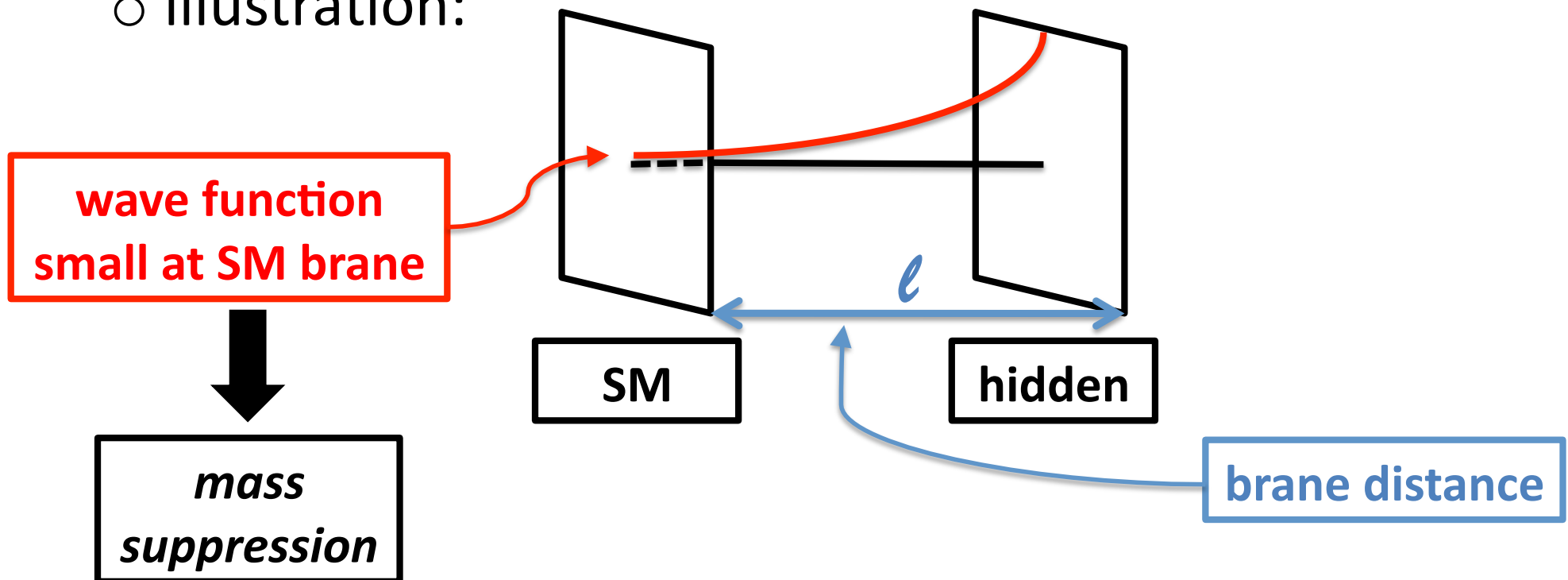


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- starting point: 5D action

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

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- Fourier expansion of the field:

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➔ equation of motion in the Extra Dimension:

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

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- solution (“**bulk profile**”) for the zero mode: $m_n=0$

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

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- for a more complicated action, this leads to strong mass suppression and hierarchy enhancement:

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STRONG SUPPRESSION!!!

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$$m_3 < m_2 < m_1 \Rightarrow M_3 \gg M_2 \gg M_1!!!$$

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

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- **issue #1**: slight enhancement of active-sterile mixing

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

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→ can be cured by A_4 extension:

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

[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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 - 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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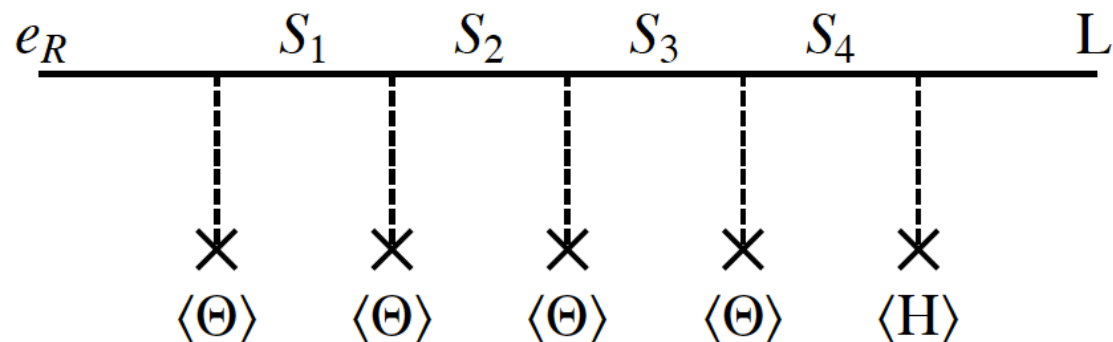
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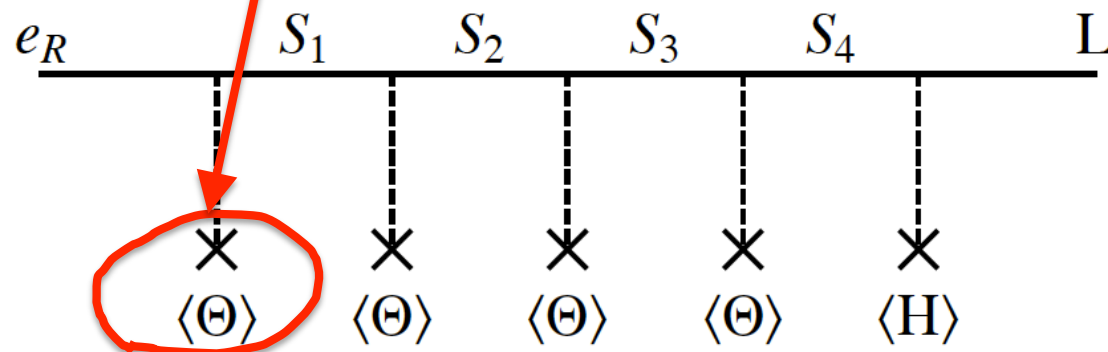
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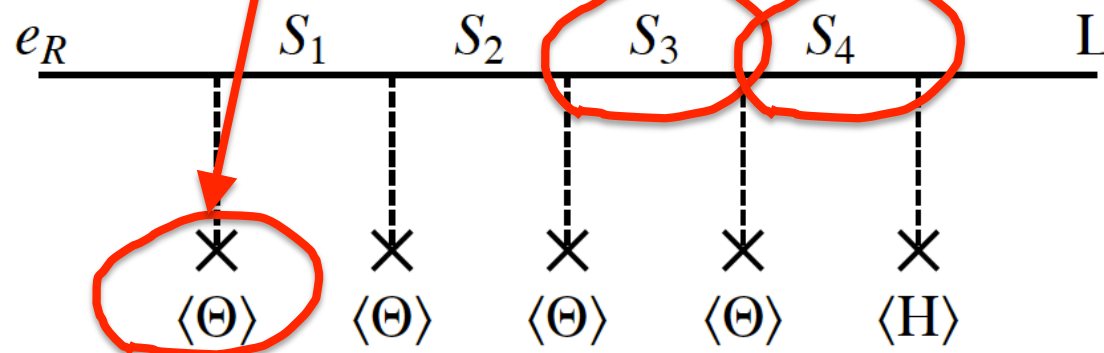
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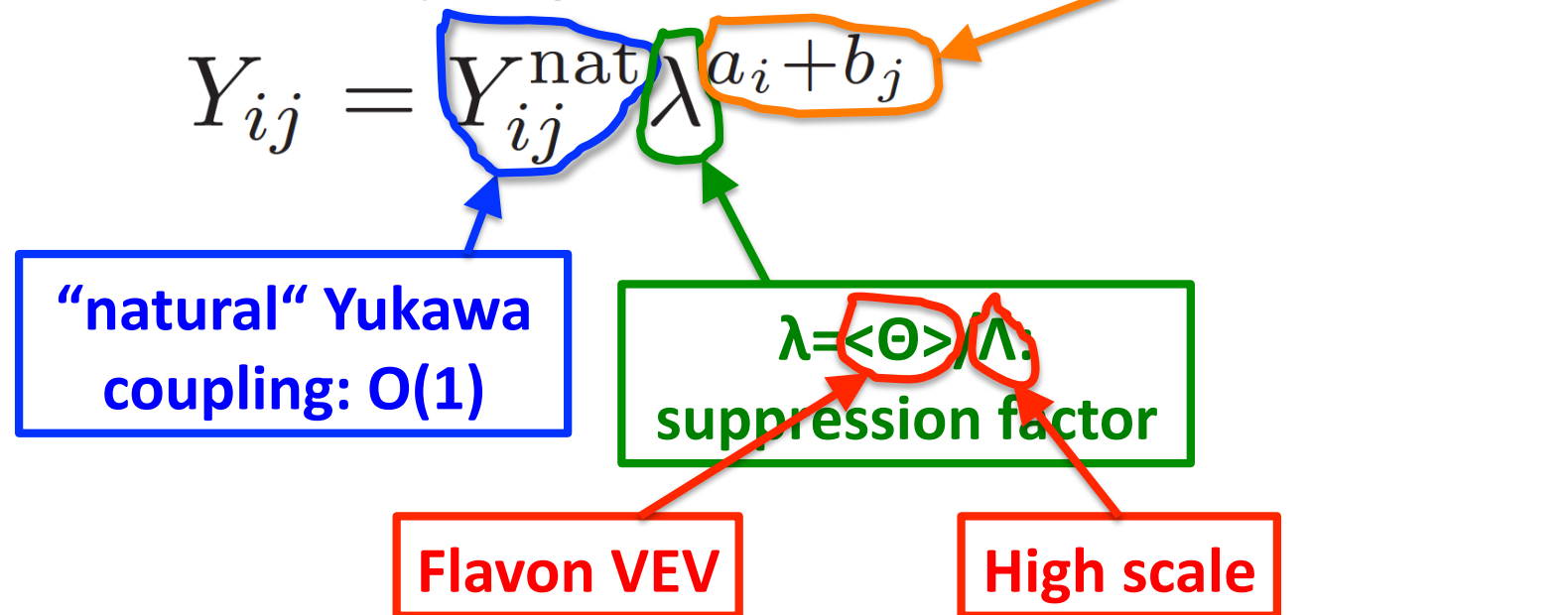
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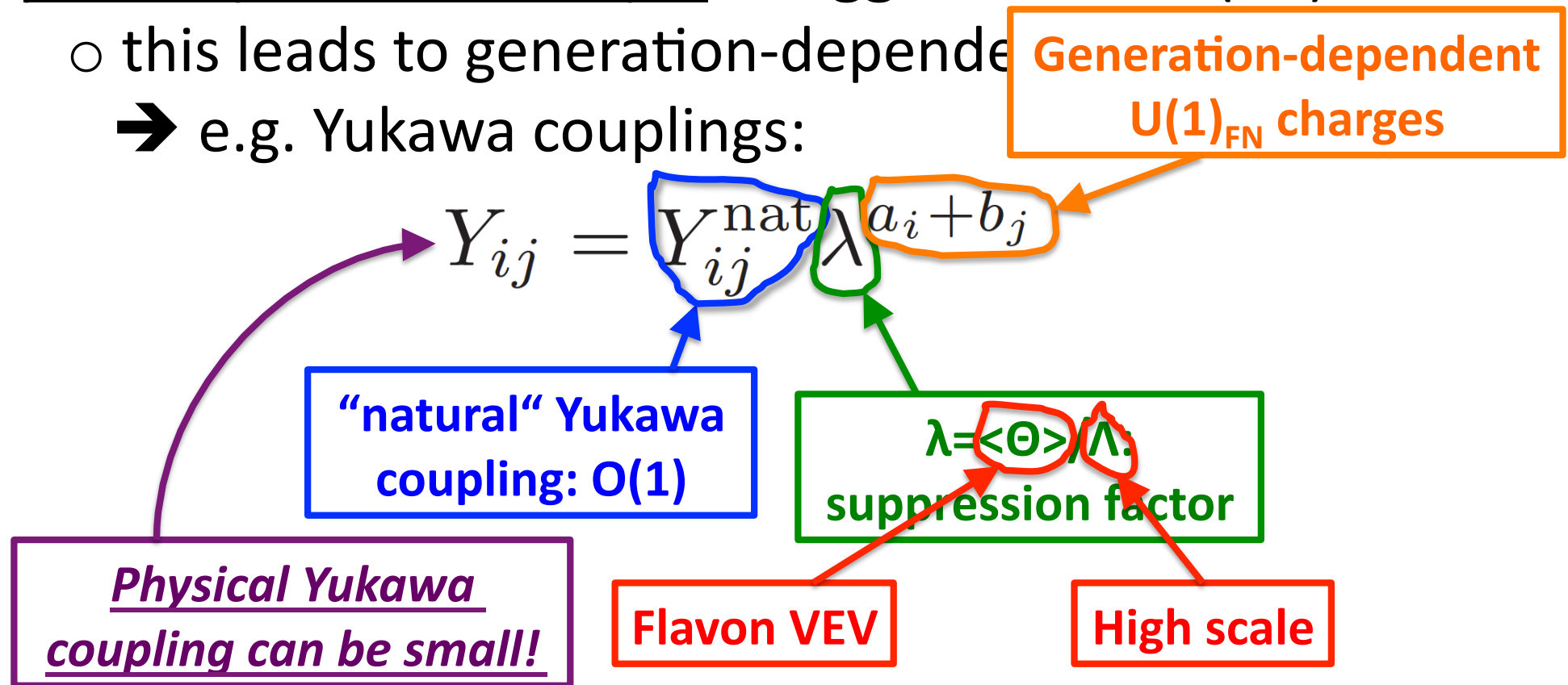


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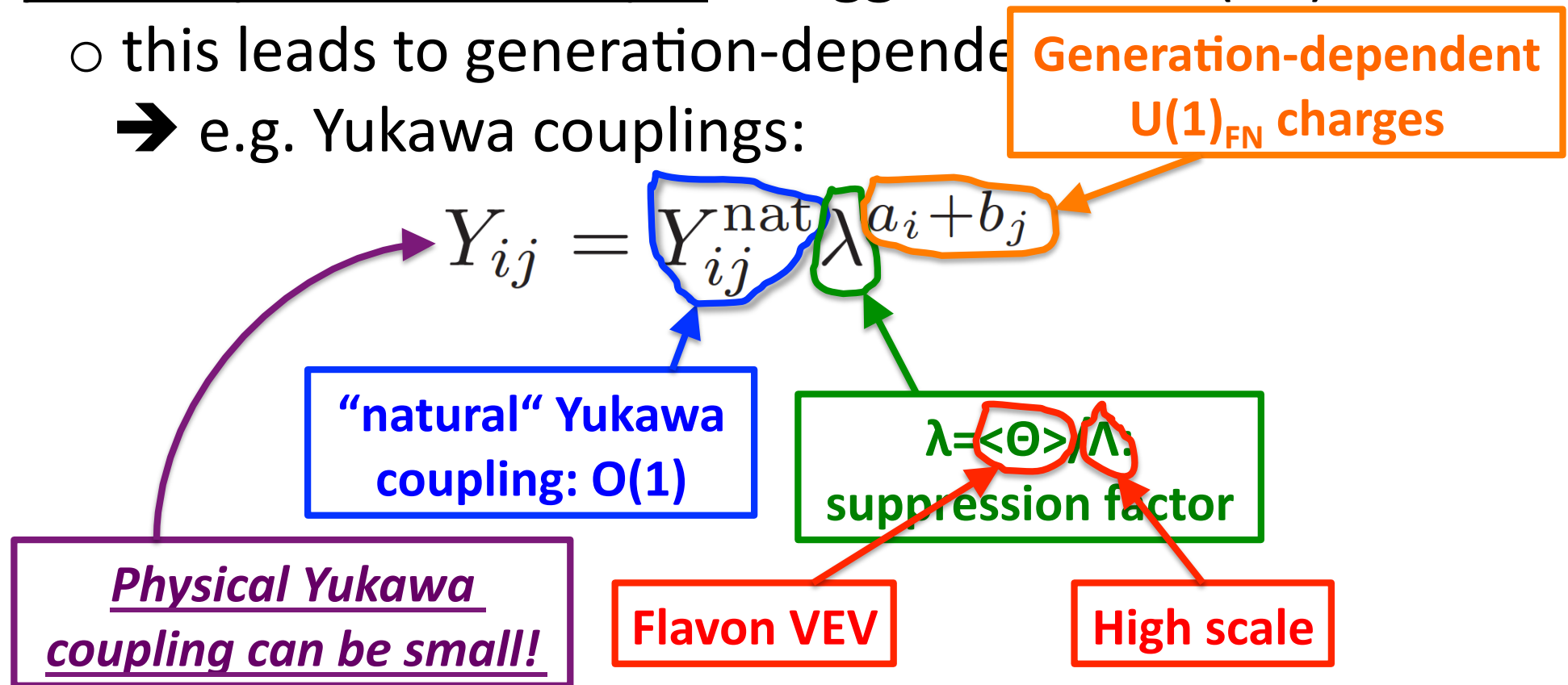


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- **HOWEVER**: several problems are swept under the carpet (UV-completion, $U(1)$ -breaking,...)

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

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$$L_{1,2,3} : (f_1, f_2, f_3; +, +, -)$$

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Quasi-Degeneracy

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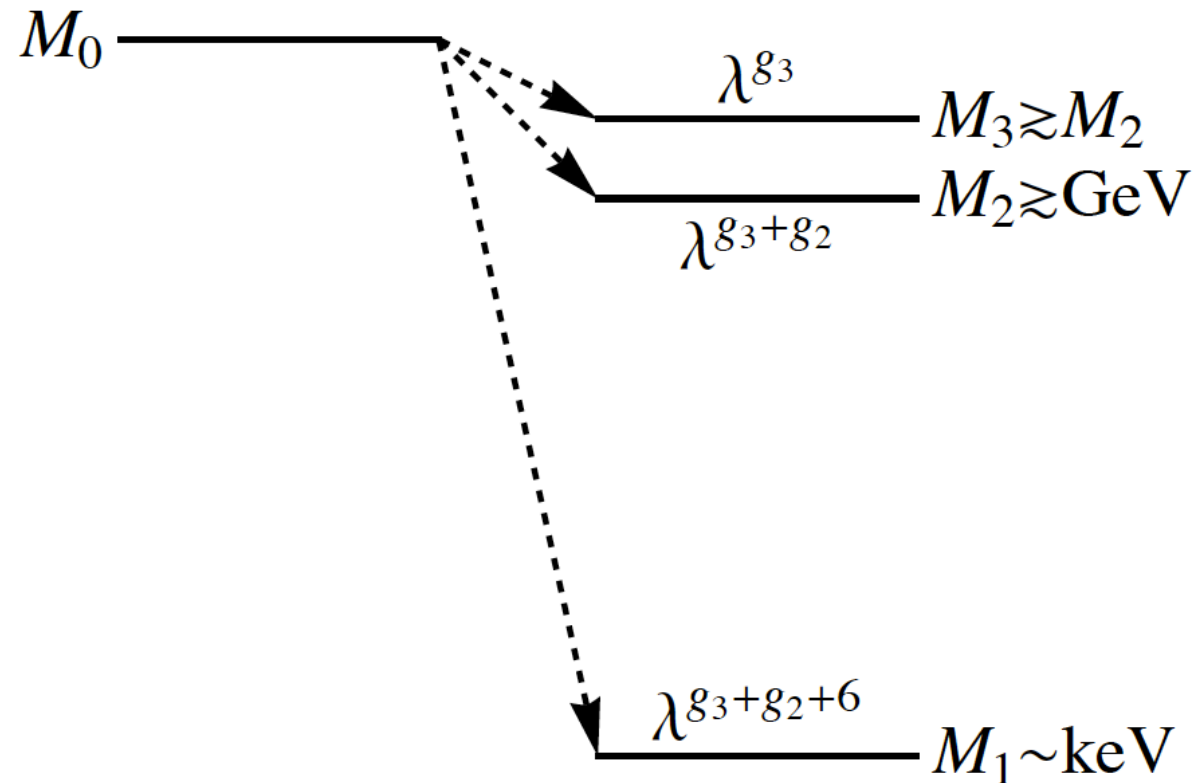
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Hierarchy

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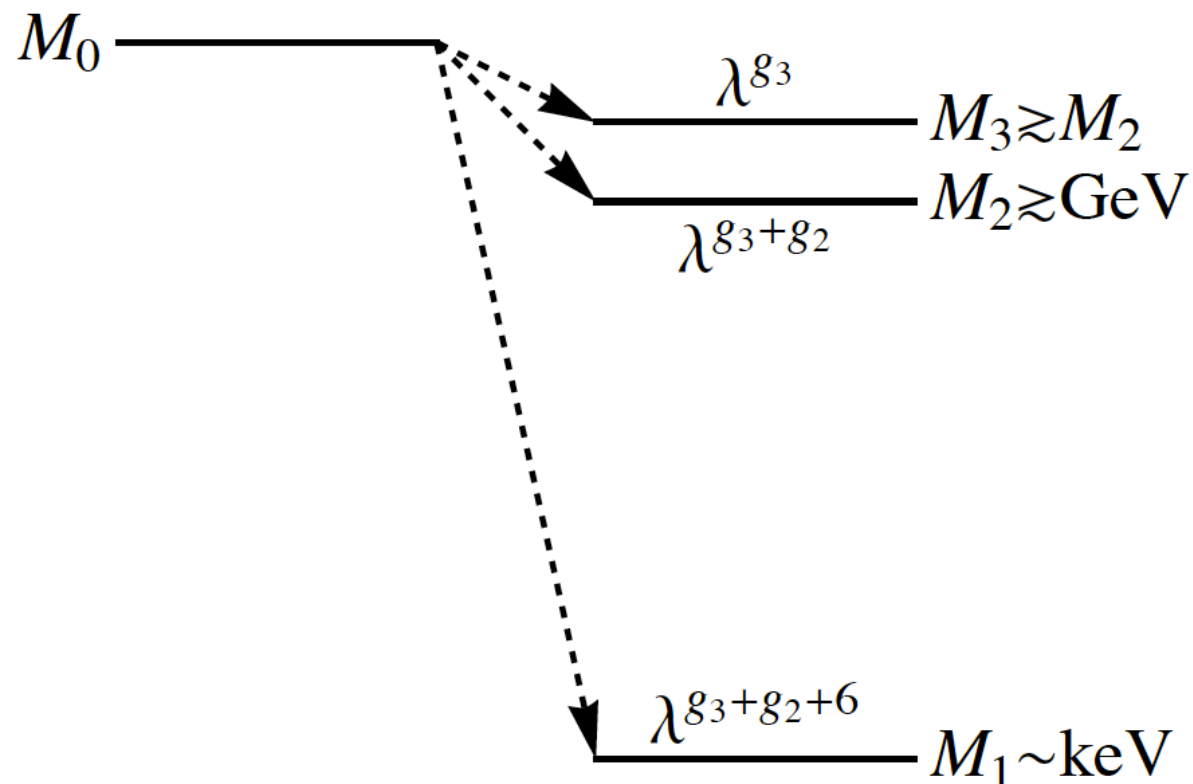
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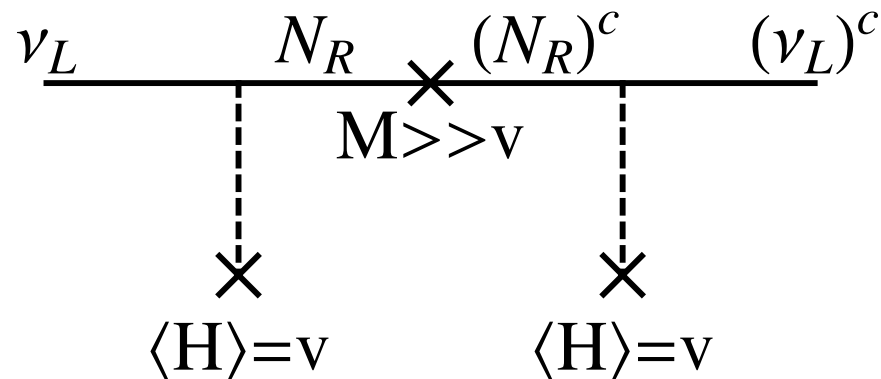


→ large mass scale gets suppressed

→ *top-down*

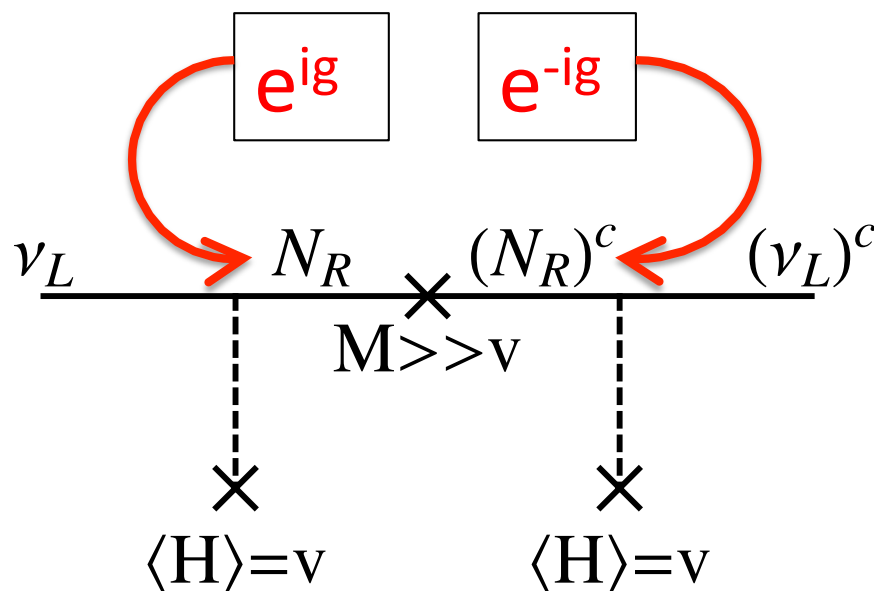
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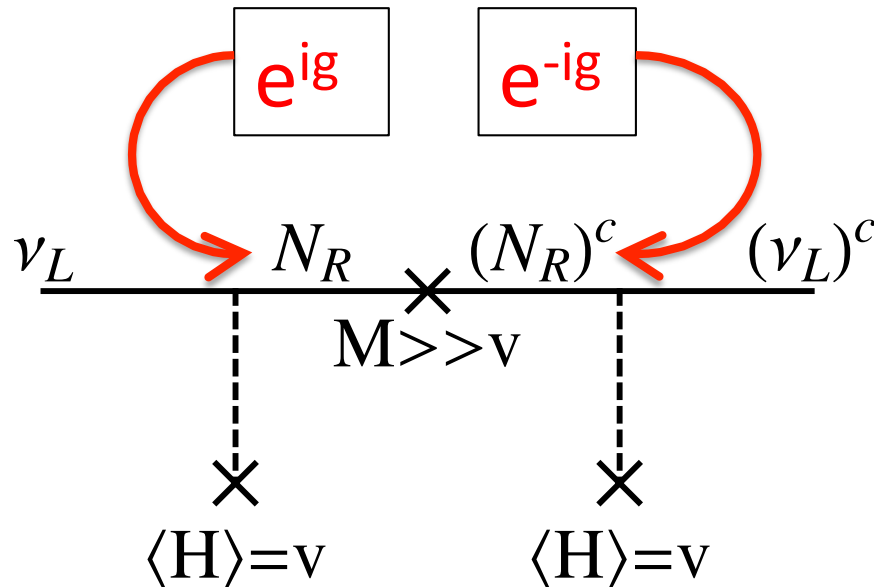
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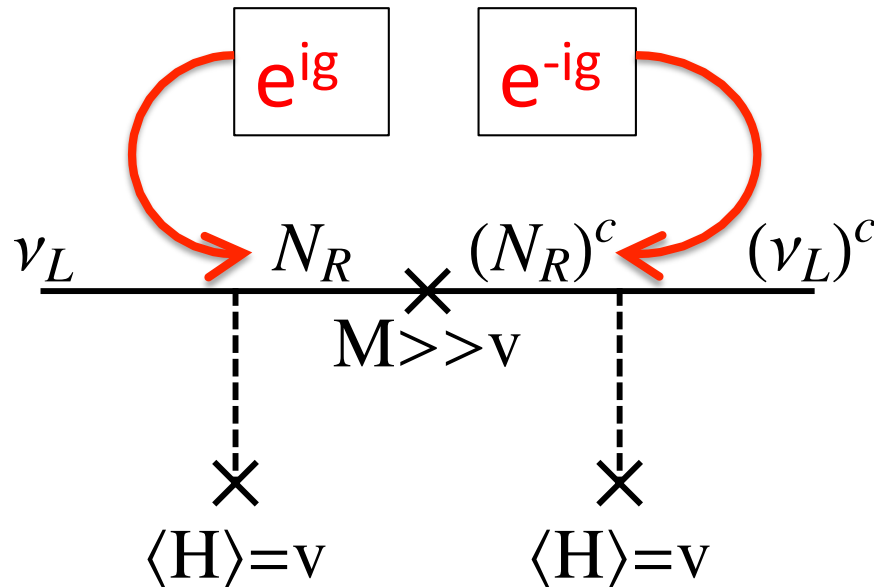
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- ➔ $U(1)_{\text{FN}}$ is a global $U(1)$, just like lepton number, which gets broken by the seesaw-diagram!
- ➔ the charges (g_1, g_2, g_3) drop out of the light neutrino mass matrix ✓

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 - **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)

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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 **assume** the following Lagrangian

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

- one now assumes a hierarchy: $m_D \ll M_S \ll M_R$

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 - the hierarchy allows to apply the seesaw formula:

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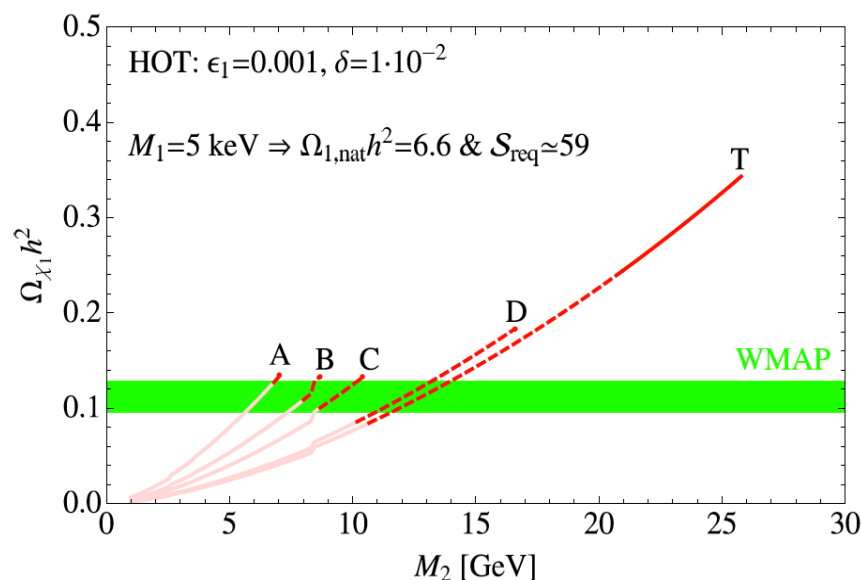
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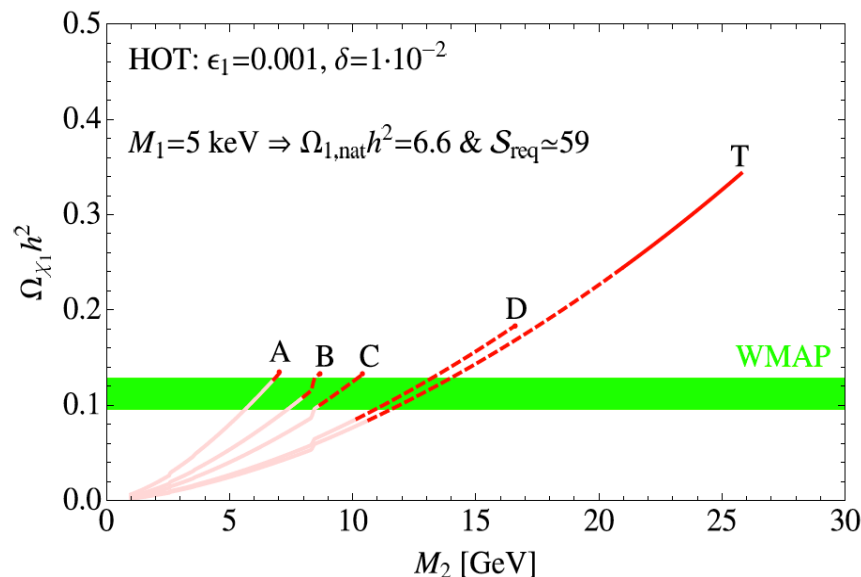
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- other production mechanisms and more or less model-independent studies possible

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