Beyond the Standard Model from a Neutrino Perspective

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DESY THEORY WORKSHOP
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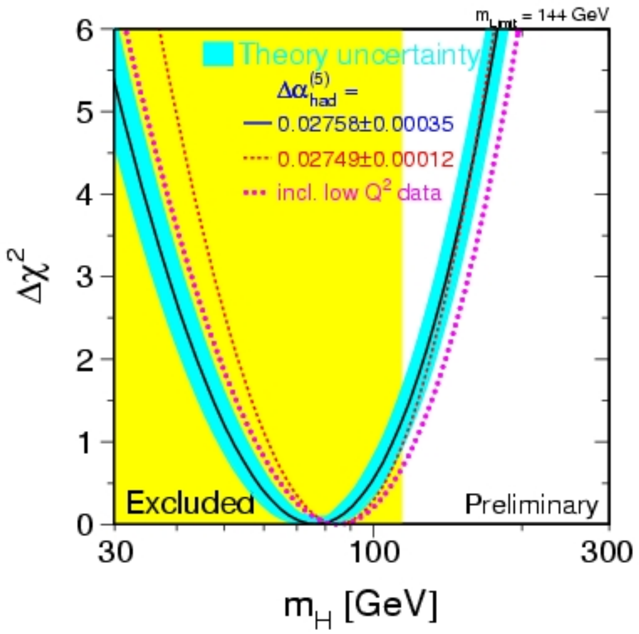
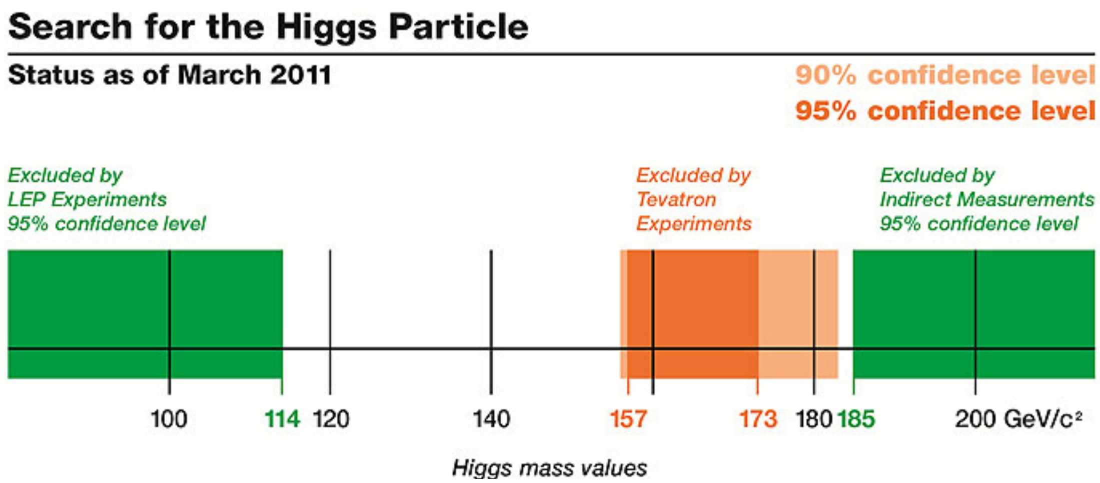
Lessons from the first phase of the LHC

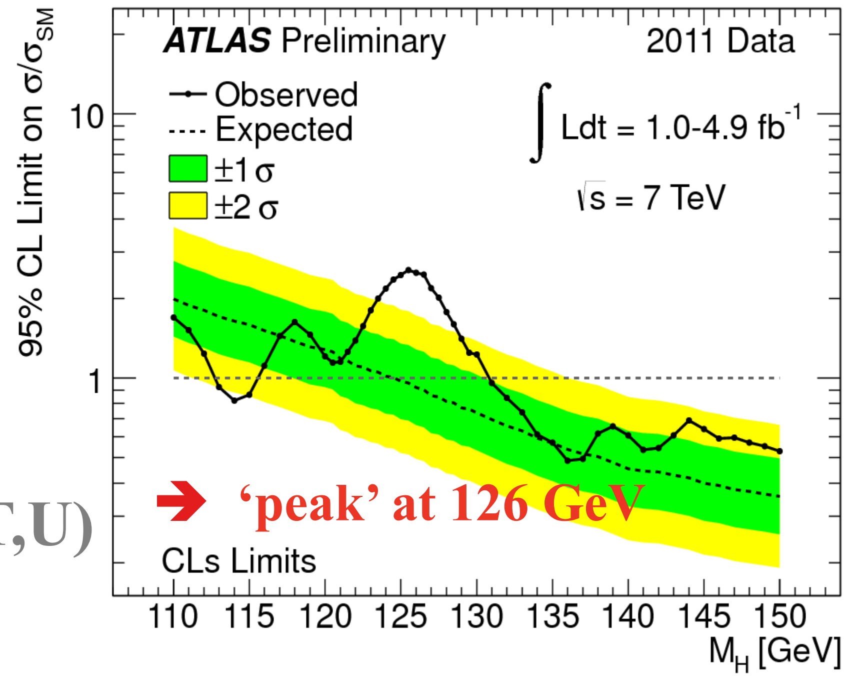
HELMHOLTZ ASSOCIATION

DESY

The SM works perfectly







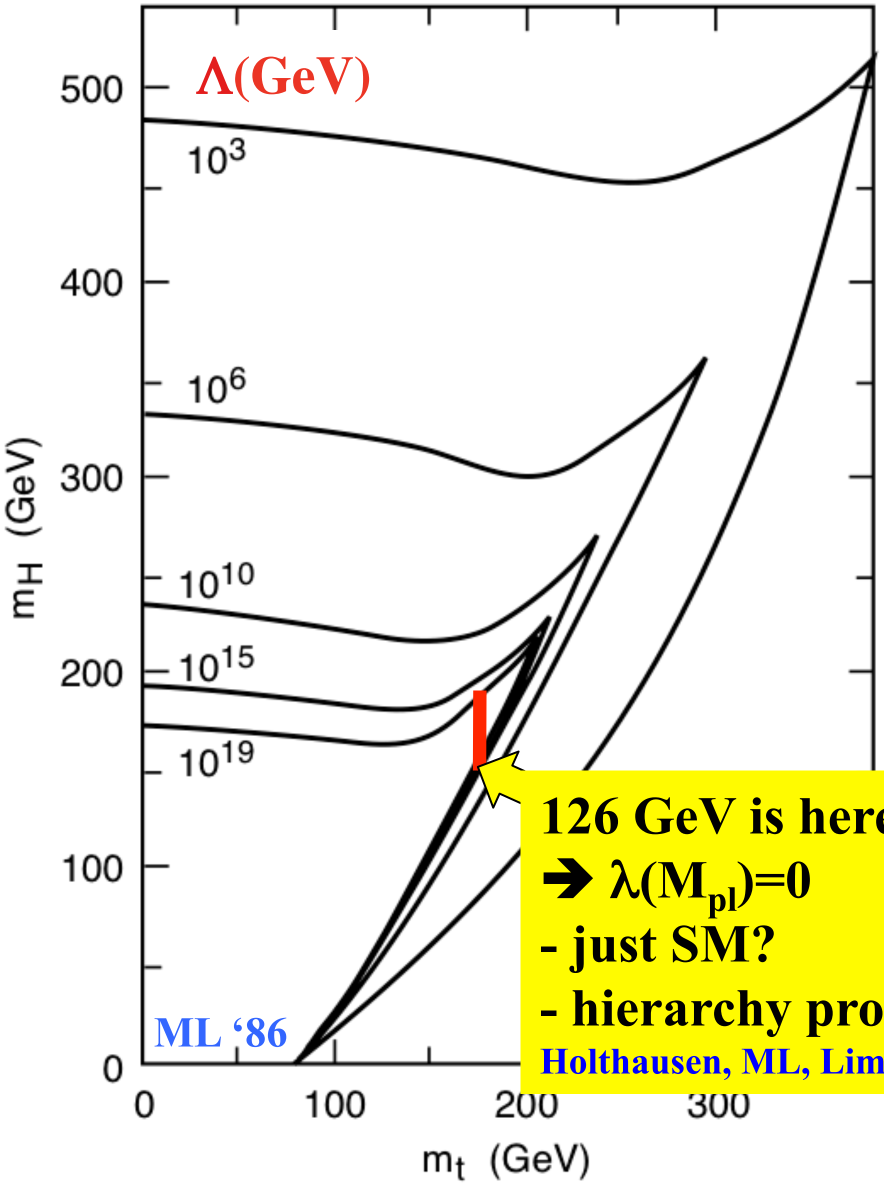
➔ 'peak' at 126 GeV

mass range was shrinking…

- if SM Higgs → light
- no (clear) sign for anything else
- no signs in quantum effects (S,T,U)

➔ just the SM?

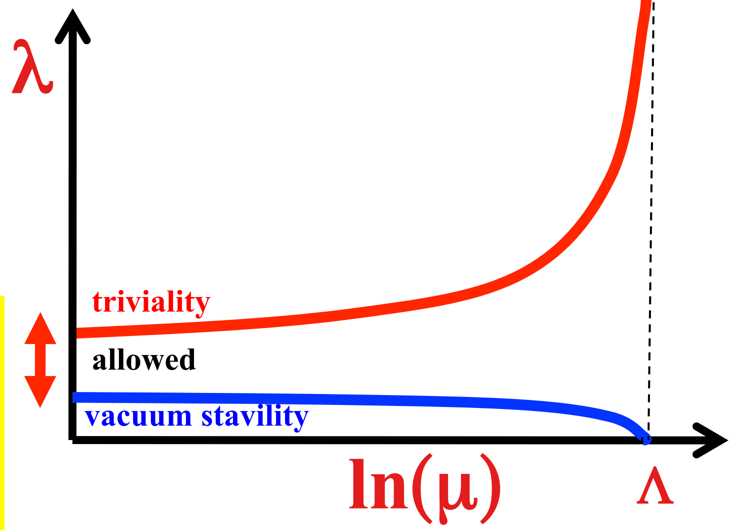
Triviality and Vacuum Stability



126 GeV is here!
➔ $\lambda(M_{pl})=0$
- just SM?
- hierarchy problem
Holthausen, ML, Lim

126 GeV < m_H < 174 GeV

SM does not exist w/o embedding
- U(1) copling , Higgs self-coupling



➔ RGE arguments seem to work
➔ we need some embedding

The SM works perfect but must be extended….

- **Many theoretical reasons for BSM physics…**
  - **Hierarchy problem:** separation of two scalar scales is unstable
  - SUSY, DSB, gauge extensions, new ideas, Planck scale physics?
  - ???

- **Experimental facts:**
  - **SM must be amended by neutrino masses ➔ SM+**
  - **SM cannot explain Baryon Asymmetry of the Universe**

    neutrinos ➔ leptogenesis = one of the best BAU explanations
  - **Dark Matter**
    - an extra particle is needed which is DM
    - particles connected to the hierarchy problem, strong CP, …

  } ???

➔ massive neutrinos require new physics ➔ BSM ➔ connections?

The Standard 3 Neutrino Framework

Mass & mixing parameters: m_1 , Δm^2_{21}, $|\Delta m^2_{31}|$, sign(Δm^2_{31})

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \mathrm{diag}(e^{i\alpha}, e^{i\beta}, 1)$$

Questions:

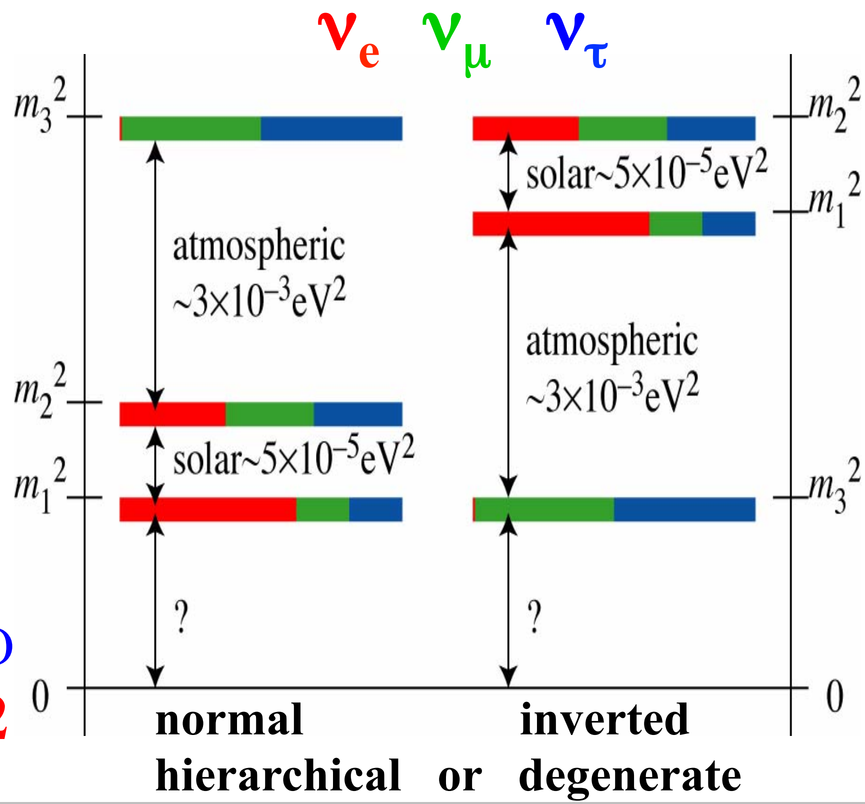
- ➔ Dirac / Majorana,
- ➔ mass scale & ordering: m_1, sgn(Δm^2_{31})
- ➔ θ_{23} maximal?
- ➔ leptonic CP violation
- ➔ 3 flavour unitarity?
- ➔ why 3 generations ? ←→ steriles?

➔ **Recent improvements:**

θ_{13} is determined: ➔ $\theta_{13} \simeq 9 \pm 1°$

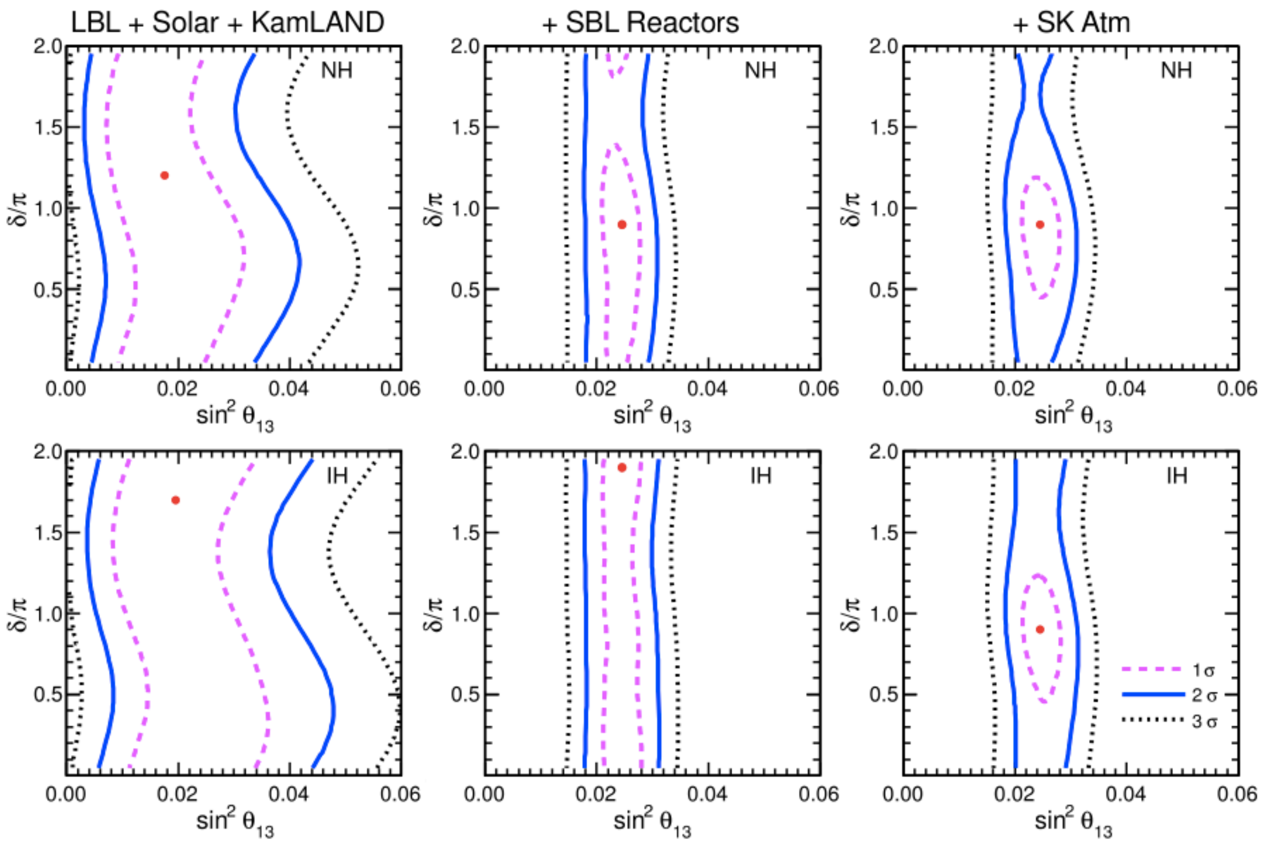
T2K, MINOS, Double Chooz, Daya Bay, RENO

θ_{23}: Indications for deviation from $\pi/2$



normal hierarchy

inverted hierarchy



~ 1σ preference for δ ~ π   Fogli et al. , others ➔ first glimpse?

➔ enhances the interference oscillation term and gives extra electron appearance for atmospheric events O(GeV), "explaining" part of the persisting SK electron excess.

New Physics: Neutrino Mass Terms

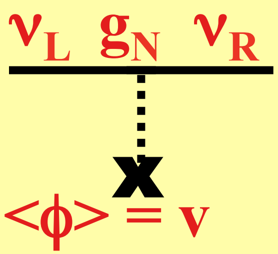
SM ~$m\bar{L}\phi R$ = (2,1)

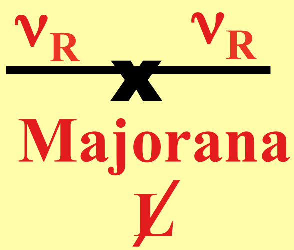
→ new fields

→

1) Simplest possibility:
add 3 right handed neutrino fields

Field	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
$L_Q = \begin{pmatrix} l_u \\ l_d \end{pmatrix}$	3	2	1/3
r_u	3	1	4/3
r_d	3	1	-2/3
$L_L = \begin{pmatrix} l_\nu \\ l_e \end{pmatrix}$	1	2	-1
r_ν ???	1	1	0
r_e	1	1	-2





→

$$\begin{pmatrix} \nu_L & \nu_R^c \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix}$$

like quarks and charged leptons → Dirac mass terms (including NMS mixing)

New ingredients:
1) Majorana mass (explicit)
2) lepton number violation

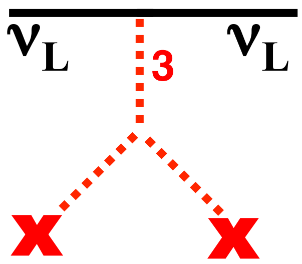
6x6 block mass matrix
block diagonalization
M_R heavy → 3 light ν's

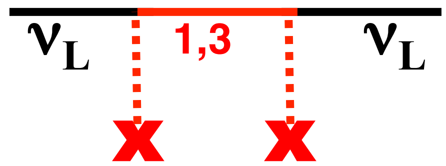
NEW ingredients, 9 parameters → SM+ and sea-saw

2) Maybe 3+N right handed neutrino fields

→ (6+N) x (6+N) mass matrix
→ how many of the 6+N eigenvalues are light (also for N=0)

3) new: scalar tripelts (3_L) or fermionic 1_L ro 3_L





→left-handed Majorana mass term:

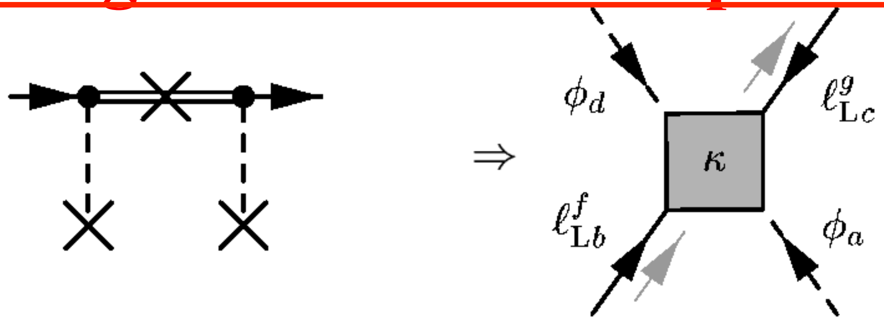
→ $M_L \overline{L} L^c$

4) Both ν_R and new singlets / triplets:

→ see-saw type II, III

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

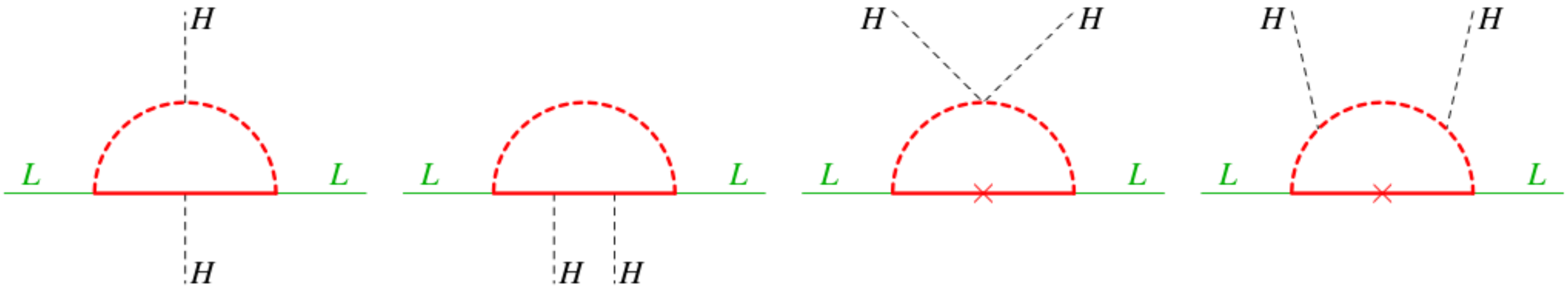
5) Higher dimensional operators: d=5, …



$\Leftrightarrow$ $\mathcal{L}_{mass} = \kappa \cdot \overline{\nu}_L^C \nu_L \Phi^T \Phi$

$\rightarrow M_L \overline{L} L^c$

6) Radiative neutrino mass generation



- Lagrangians where neutrino masses are forbidden at tree level ←→ symmetries
- interactions induce neutrino mass terms

7) GUT's (and SUSY GUTs)

Gauge unification suggests that some GUT exists

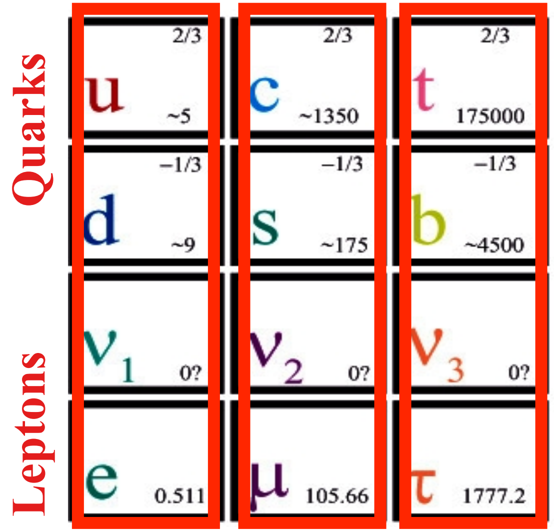
Requirements:

gauge unification

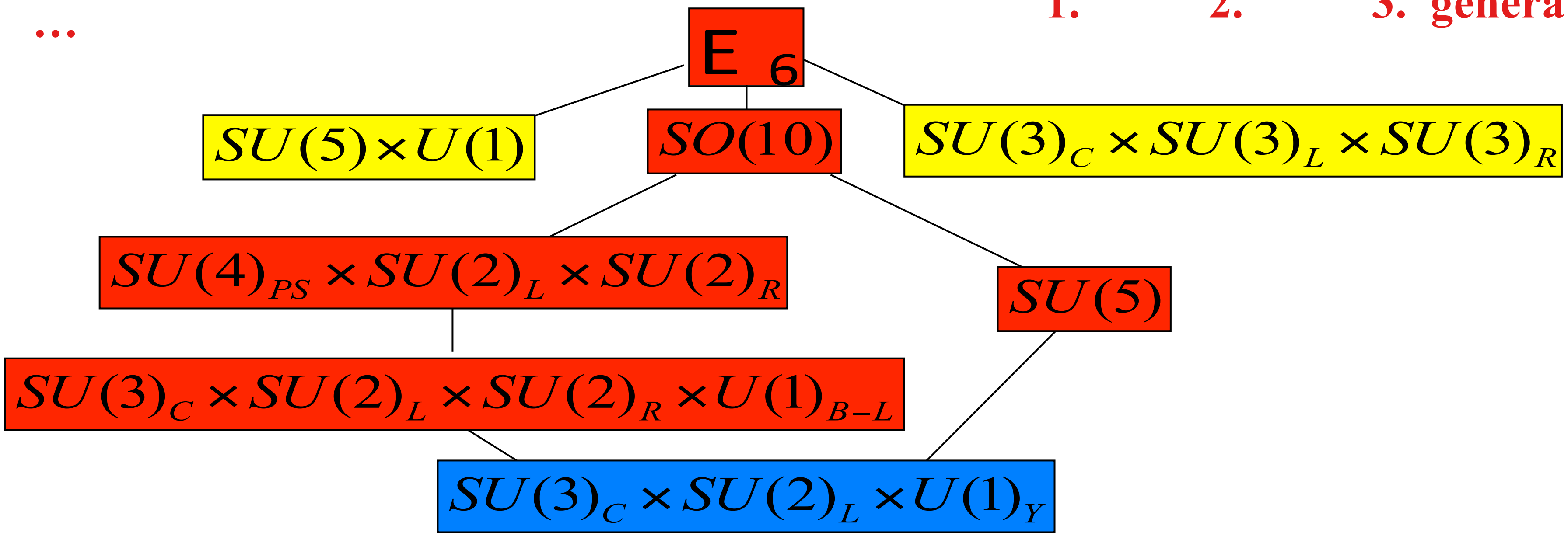
particle multiplets ⇔ ν_R

proton decay

…



1. 2. 3. generation



many possibilities…

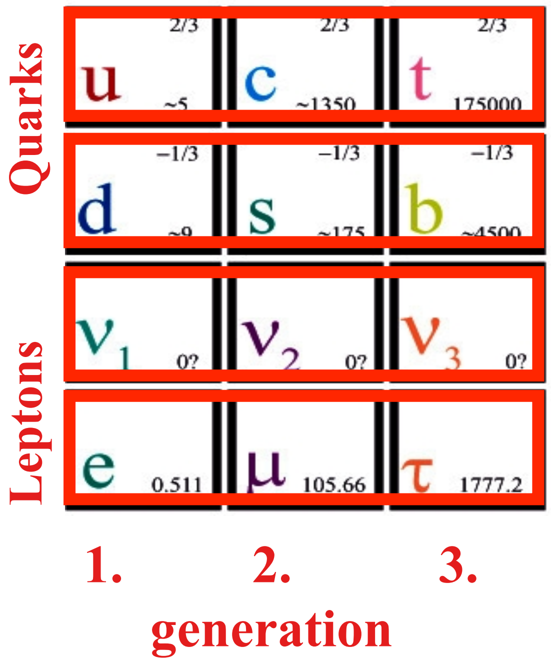
7) Flavour Symmetries

- so far **no understanding of flavour, 3 generations**
- apparant regularities in quark and lepton parameters

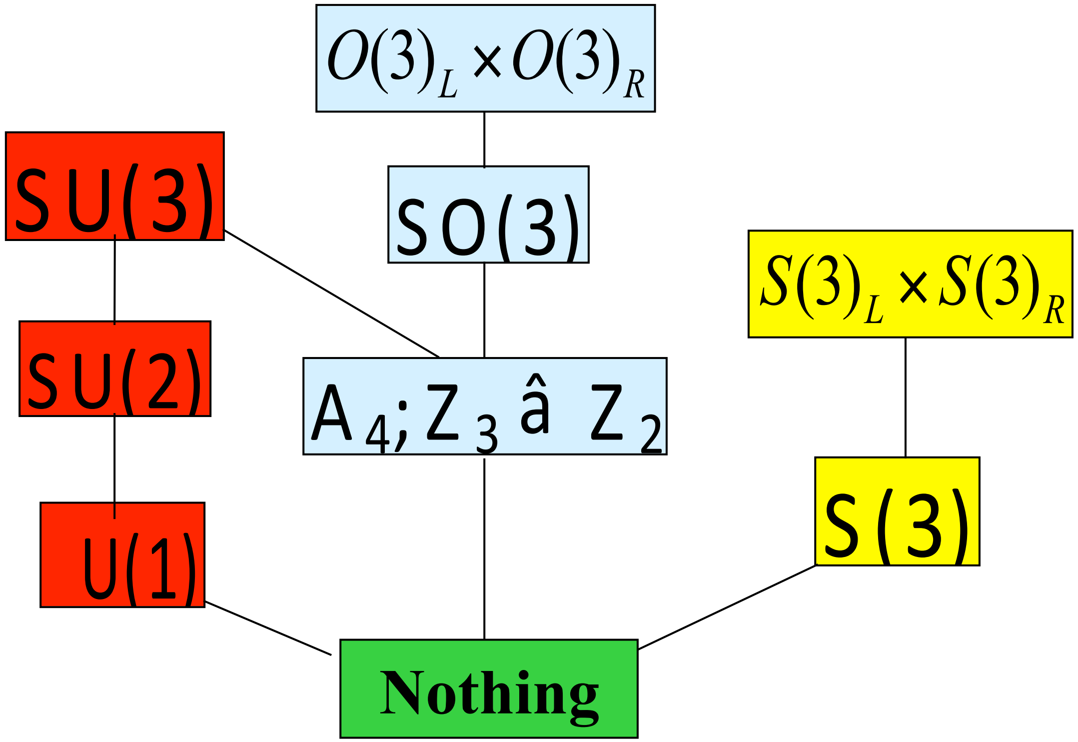
➔ flavour symmetries (finite number for limited rank)

➔ symmetry not texture zeros

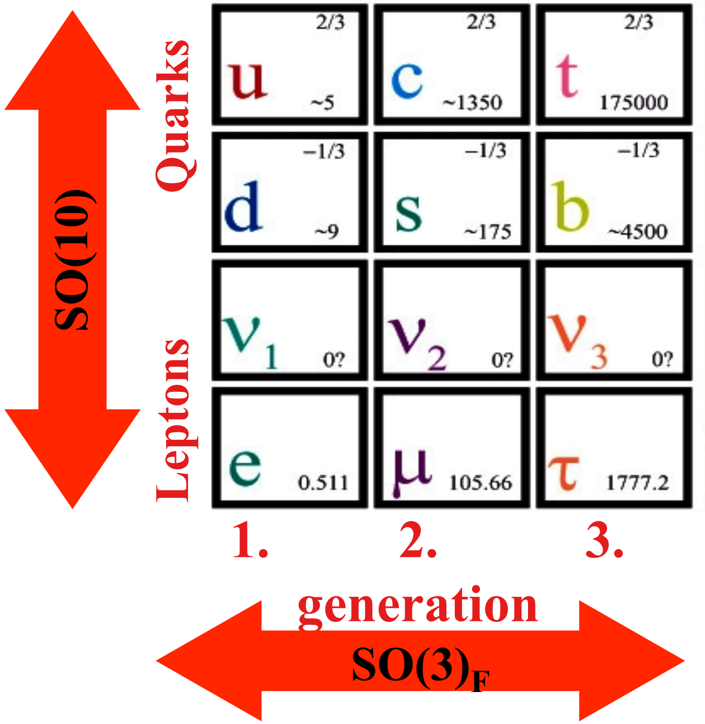
➔ Breaking sequences...



Examples:



8) GUTs x Flavour Symmetries



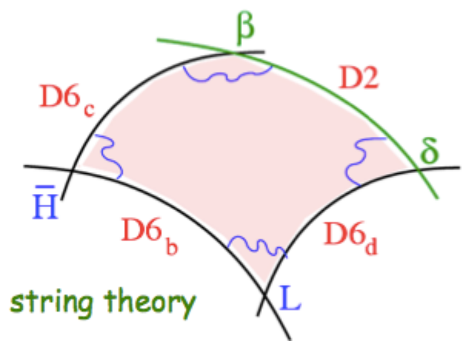
➔ GUT group ⊗ flavour group

example: SO(10) ⊗ $SU(3)_F$

- SSB of $SU(3)_F$ between Λ_{GUT} and Λ_{Planck}
- all flavour Goldstone Bosons eaten
- discrete sub-groups survive ⟵⟶ SSB
  e.g. Z2, S3, D5, A4
  ➔ structures in flavour space
  ➔ compare with data
  ➔ rather restricted… few solutions

9) extra dimensions, strings, …

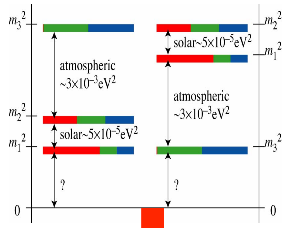
➔ many options ➔ different secondary effects



Suggestive Seesaw Features

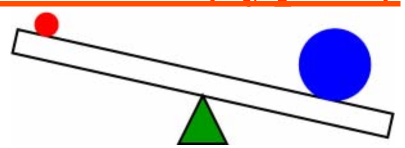
QFT: natural value of mass operators ⇔ scale of symmetry

$m_D \sim$ electro-weak scale
$M_R \sim$ L violation scale ⇐?⇒ embedding (GUTs, …)



? → EW scale

See-saw (type I)



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

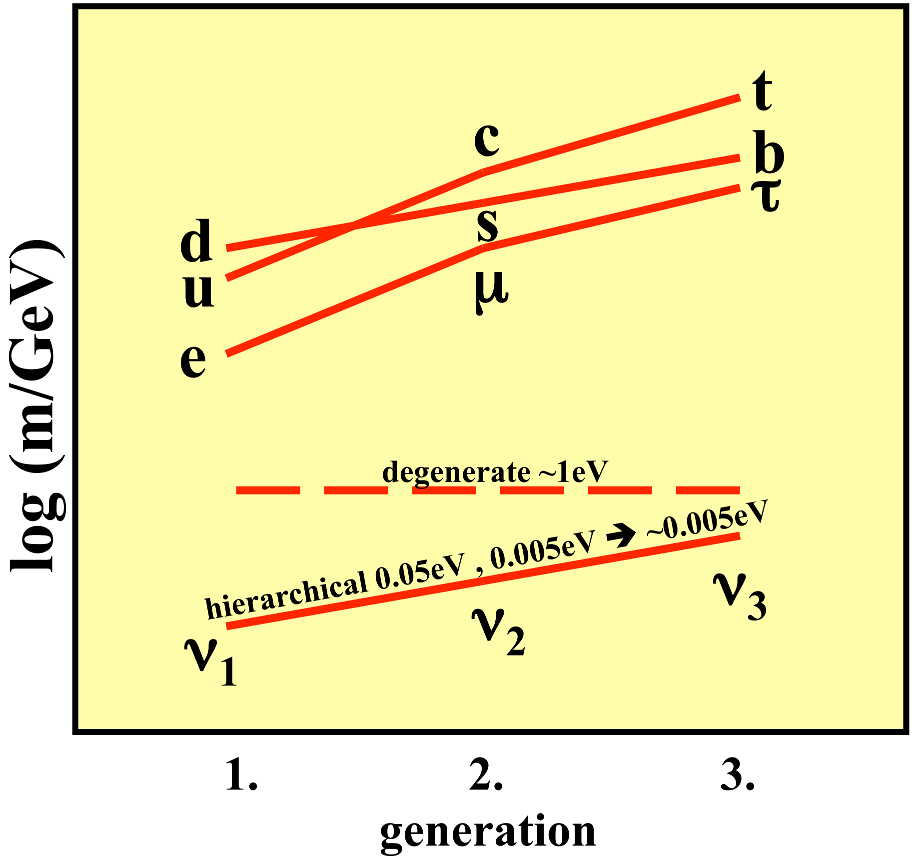
$m_h = M_R$

Numerical hints:

For $m_3 \sim (\Delta m^2_{atm})^{1/2}$, $m_D \sim$ leptons ⇒ $M_R \sim 10^{11} - 10^{16}$GeV
⇒ ν's are Majorana particles , m_ν probes ~ GUT scale physics!
⇒ smallness of m_ν ⇔ high scale of L̸, symmetries of m_D ,M_R

2nd Look Questions

Quarks & charged leptons ➔ hierarchical masses ➔ neutrinos?



Quarks and charged leptons:

$m_D \sim H^n$; n = 0,1,2 ➔ $H \geq 20...200$

Neutrinos: $m_\nu \sim H^n$ ➔ $H \leq \sim 10$

See-saw:

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

	m_ν	m_D^T	M_R^{-1}	m_D
H	~10	≥20	?	≥20

- less hierarchy in m_D or corr. hierarchy in M_R? ➔theoretically not connected!
- Dirac masses
- other version of see-saw? ➔ type II, III, … ➔

The Double Seesaw

- Assume right handed neutrinos N and singlets S → (ν, N, S)
- Assign quantum numbers such that mass matrix is

$$\mathcal{M} = \begin{pmatrix} 0 & Y_\nu \langle\phi\rangle & 0 \\ Y_\nu^T \langle\phi\rangle & 0 & Y_N^T \langle\sigma\rangle \\ 0 & Y_N \langle\sigma\rangle & M_S \end{pmatrix}$$

M_S = O(Planck scale) $\simeq 10^{19}$ GeV

$Y_N\langle\sigma\rangle$ = O(GUT scale) $\simeq 10^{16}$ GeV

$Y_\nu\langle\phi\rangle$ = O(EW scale) $\simeq 10^{2}$ GeV

1st seesaw → eigenvalues M_S and $Y_N^T (M_S)^{-1} Y_N \langle\sigma\rangle^2$ = O(10^{16} GeV)

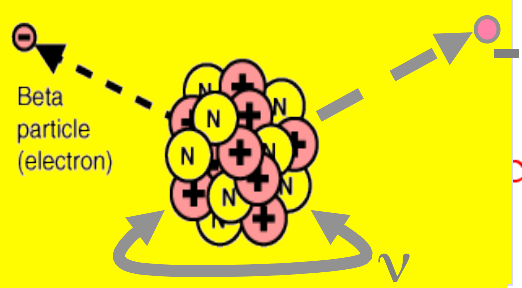
2nd seesaw

→ $m_\nu^0 = \left[\frac{\langle\phi\rangle}{\langle\sigma\rangle}\right]^2 Y_\nu \left(Y_N\right)^{-1} M_S \left(Y_N^T\right)^{-1} Y_\nu^T$ **= O(eV)**

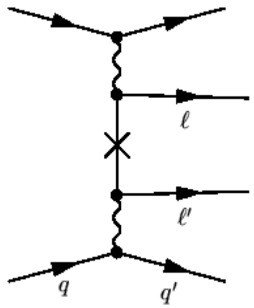
Possibility: $Y_N \sim Y_\nu$ → structure of m_ν from M_S ML, Schmidt, Smirnov

Is the Picture complete? Correct?

$0\nu\beta\beta$ Beta Decay



Majorana ν ➔ 0ν2β decay

$\propto$ 

$\propto |\langle m_{ee} \rangle| = |\sum m_i U_{ei}^2|$ **$\leq$ 0.35 eV ?**

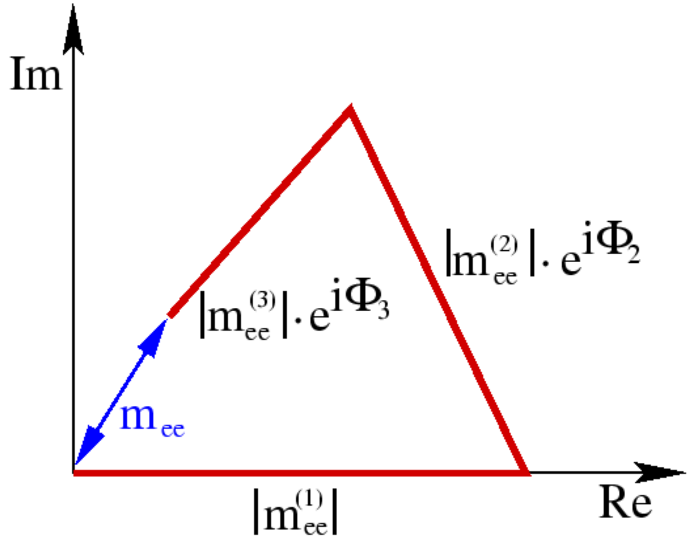
Heidelberg-Moscow experiment

$$m_{ee} = |m_{ee}^{(1)}| + |m_{ee}^{(2)}| \cdot e^{i\Phi_2} + |m_{ee}^{(3)}| \cdot e^{i\Phi_3}$$

$$|m_{ee}^{(1)}| = |U_{e1}|^2 m_1$$

$$|m_{ee}^{(2)}| = |U_{e2}|^2 \sqrt{m_1^2 + \Delta m_{21}^2}$$

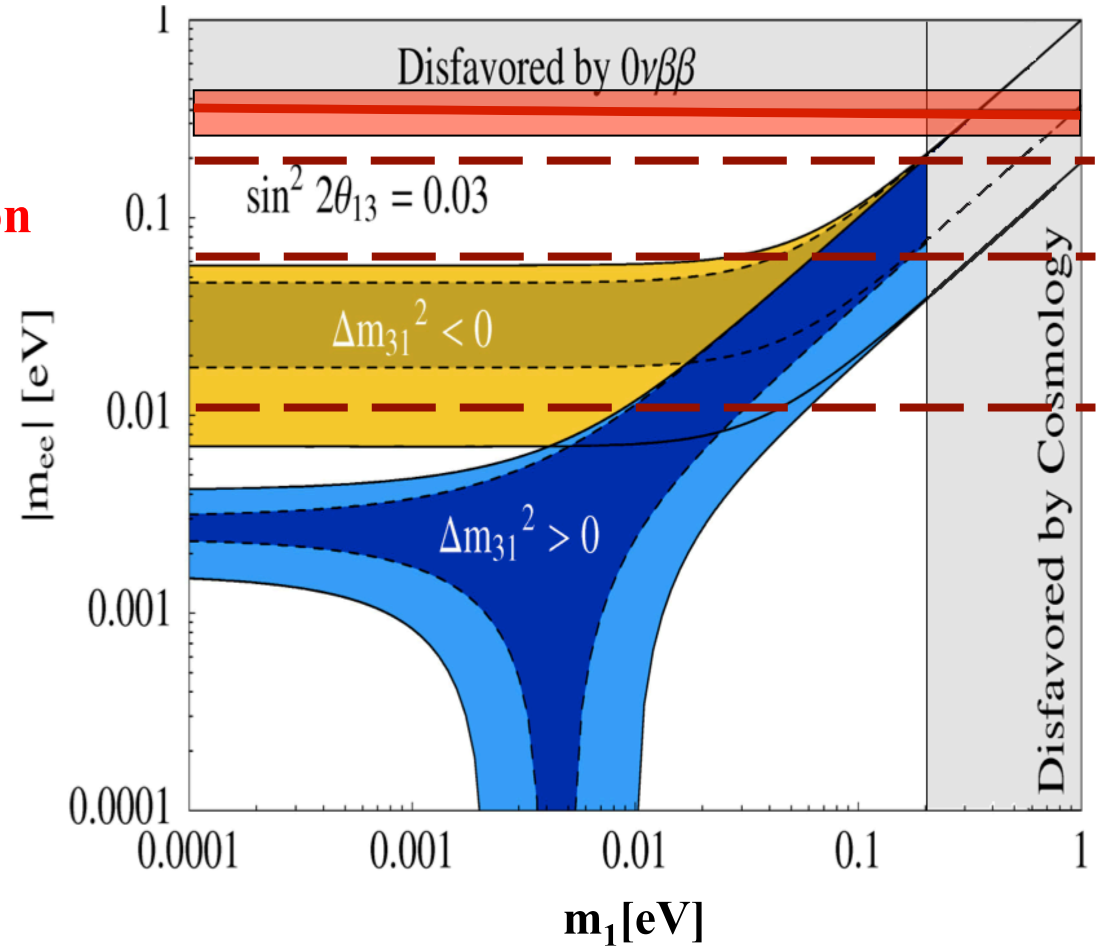
$$|m_{ee}^{(3)}| = |U_{e3}|^2 \sqrt{m_1^2 + \Delta m_{31}^2}$$



solar $\Rightarrow$ $|U_{e1}|^2, |U_{e2}|^2, \Delta m_{21}^2$ atmosph. $\Rightarrow$ $|\Delta m_{31}^2|$ CHOOZ $\Rightarrow$ $|U_{e3}|^2 < 0.05$

➔ free parameters: m_1 , sign(Δm^2_{31}) , CP-phases Φ_2, Φ_3

Claim of part of the original Heidelberg-Moscow collaboration ⇔ cosmology ➔ ‚tension'



<u>aims of new experiments:</u>

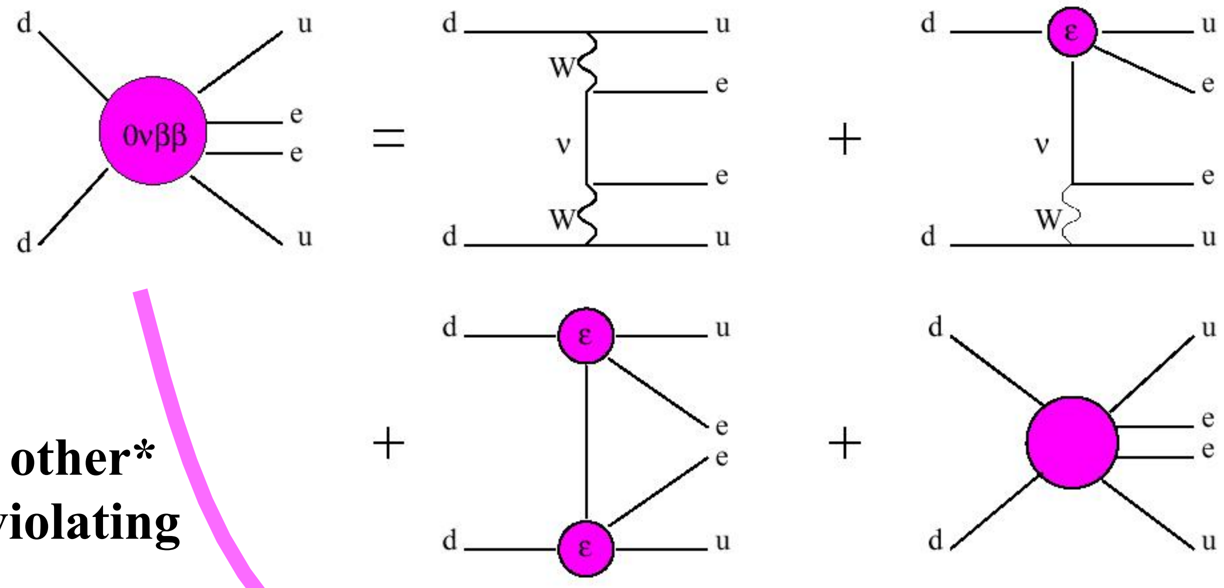
- **test HM claim**
- **$(\Delta m_{31}^2)^{1/2} \simeq 0.05$eV ± errors**
  - ➔ **reach 0.01eV**
  - ➔ **CUORE**
  - ➔ **GERDA phases I, II, (III)**

<u>Comments:</u>

- **cosmology: limitation by systematical errors ➔ ~ another factor 5-10?**
- **$0\nu\beta\beta$ nuclear matrix elements ~factor 1.3-2 theoretical uncertainty in m_{ee}**
- **$\Delta m^2 > 0$ allows complete cancellation**
  - ➔ **$0\nu\beta\beta$ signal not guaranteed, but cancelation appears unlikely**

0νββ from Alternative ΔL=2 Operators

Various possibilities:
- LR symmetry
- SUSY (RPV)
- …



➔0νββ signal from *some other* new BSM lepton number violating operator

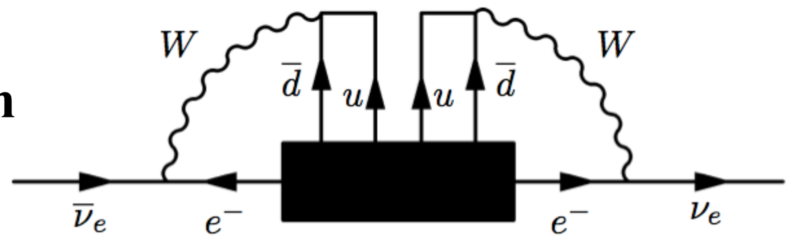
➔ very promising interplay of neutrino mass determinations, cosmology, LHC, LVF experiments and theory

Schechter + Valle: Any ΔL=2 violating operator

➔ radiative generation of Majorana mass term

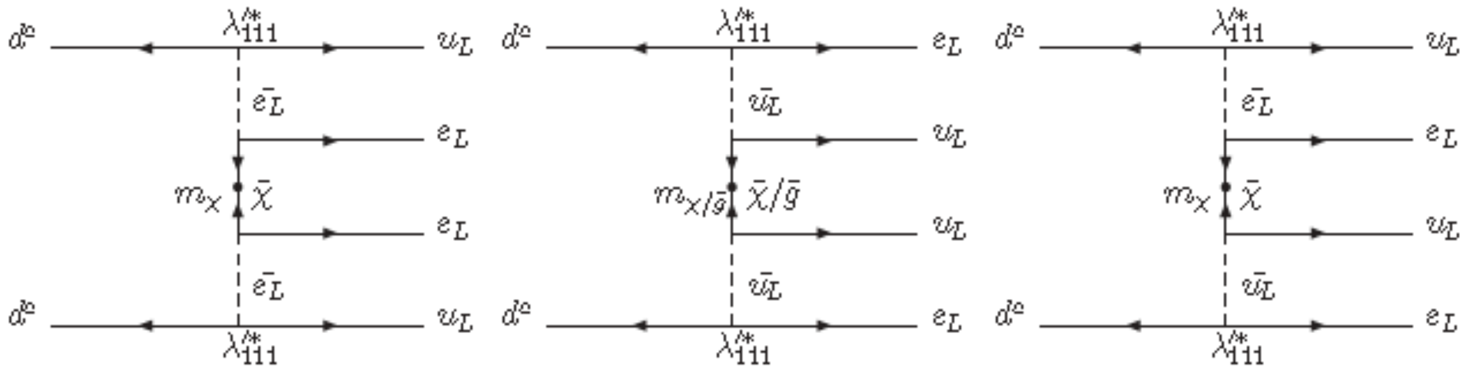
➔ Majorana nature of ν's guaranteed

➔ but how big is the mass?



SUSY Example

Direct, TeV scale short range mediation w/o intermediate light ν, e.g.



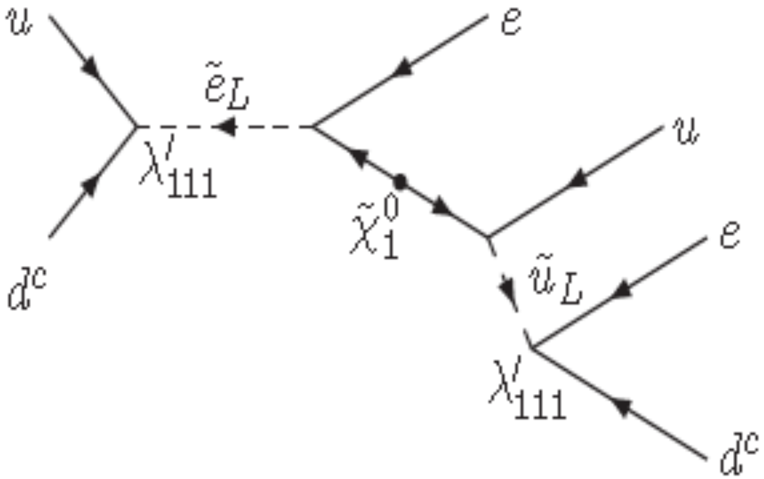
$$\mathcal{L}^{eff,\,\Delta L_e=2}_{\lambda'_{111}\lambda'_{111}}(x) = \frac{G_F^2}{2} m_p^{-1} [\bar{e}(1+\gamma_5)e^c]$$

$$\times \left[(\epsilon_{\tilde{g}} + \epsilon_\chi)(J_{PS}J_{PS} - \frac{1}{4} J_T^{\mu\nu} J_{T\mu\nu}) + (\epsilon_{\chi\tilde{e}} + \epsilon'_{\tilde{g}} + \epsilon_{\chi\tilde{f}}) J_{PS}J_{PS} \right]$$

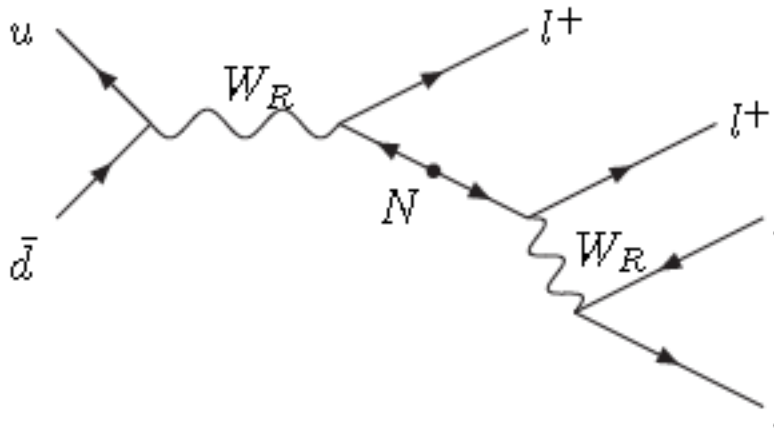
$$\epsilon_i \sim \pi\alpha_{(\mathrm{Strong,EW})} \frac{\lambda'^2_{111}}{G_F^2} \frac{m_P}{m_{(\tilde{g},\tilde{\chi})}} \frac{1}{m^4_{(\tilde{u},\tilde{d},\tilde{e})}}.$$

ΔL=2 Operators and TeV Scale Physics

SUSY: direct test of λ'_{111}

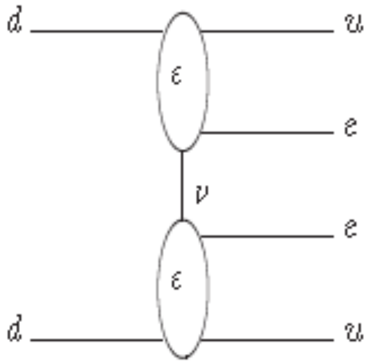


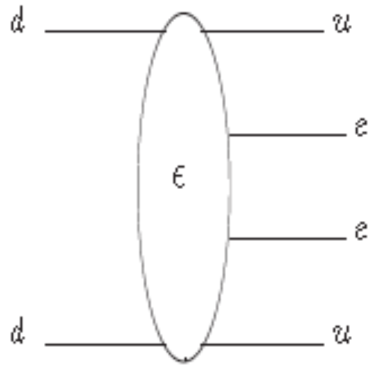
L-R symmetry: heavy N's



Relative strength of 'light' and 'heavy' $0\nu\beta\beta$ amplitudes:

$$M_{\rm light} \sim G_F^2 \frac{m_{\beta\beta}}{\langle k^2 \rangle}$$





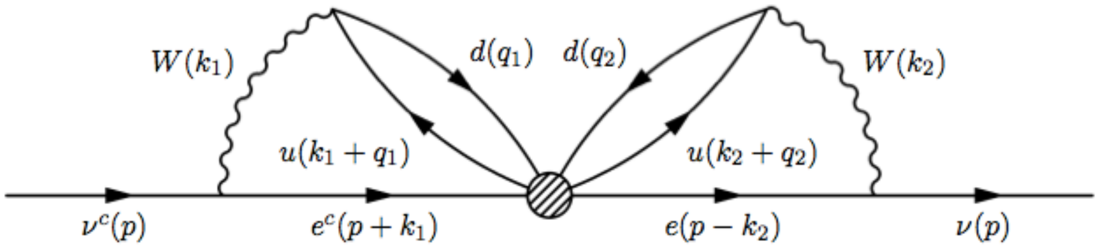
$$M_{\rm heavy} \sim G_F^2 \left(\frac{\lambda}{g_2}\right)^4 \frac{M_W^4}{\Lambda^5}$$

SV-induced Neutrino Masses

General Lorentz-invariant Lagrangian for 0νββ (point operator)

$$\mathcal{L} = \frac{G_F^2}{2} m_p^{-1} \left(\epsilon_1 J J j + \epsilon_2 J^{\mu\nu} J_{\mu\nu} j + \epsilon_3 J^{\mu} J_{\mu} j + \epsilon_4 J^{\mu} J_{\mu\nu} j^{\nu} + \epsilon_5 J^{\mu} J j_{\mu}\right)$$

$$J = \overline{u}\left(1 \pm \gamma_5\right) d, \;\; J^{\mu} = \overline{u}\gamma^{\mu}\left(1 \pm \gamma_5\right) d \text{ etc.}$$



Outcome: **M. Dürr, ML, A. Merle, arXiv:1105.0901**

If other ΔL=2 physics drives 0νββ ➔ SV gives $\delta m_\nu = 10^{-24}$ eV

➔ mass correction too small to explain observed masses and splittings

➔ other explicit neutrino mass operators required

Dirac: 0νββ essentially unrelated to neutrino masses ⇐⇒ other BSM

Majorana: dominates over SV contribution

0νββ may be a mixture of Majorana mass and other ΔL=2 physics

➔ mimics higher Majorana neutrino mass

Non Standard Interactions (NSIs)

Effective Operators Beyond the SM

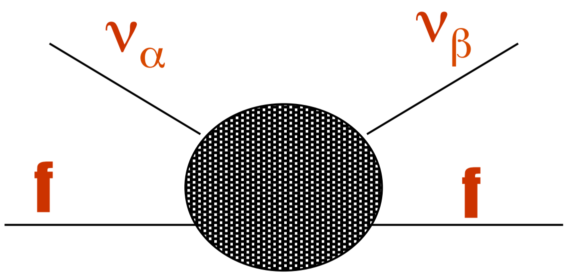
➔ **effects beyond 3 flavours**

➔ **Non Standard Interactions = NSIs ➔ effective 4f opersators**

$$\mathcal{L}_{NSI} \simeq \epsilon_{\alpha\beta} 2\sqrt{2} G_F (\bar{\nu}_{L\beta}\ \gamma^\rho\ \nu_{L\alpha})(\bar{f}_L \gamma_\rho f_L)$$

- **integrating out heavy physics (c.f. G_F ⇔ M_W)**

$$|\epsilon| \simeq \frac{M_W^2}{M_{NSI}^2}$$

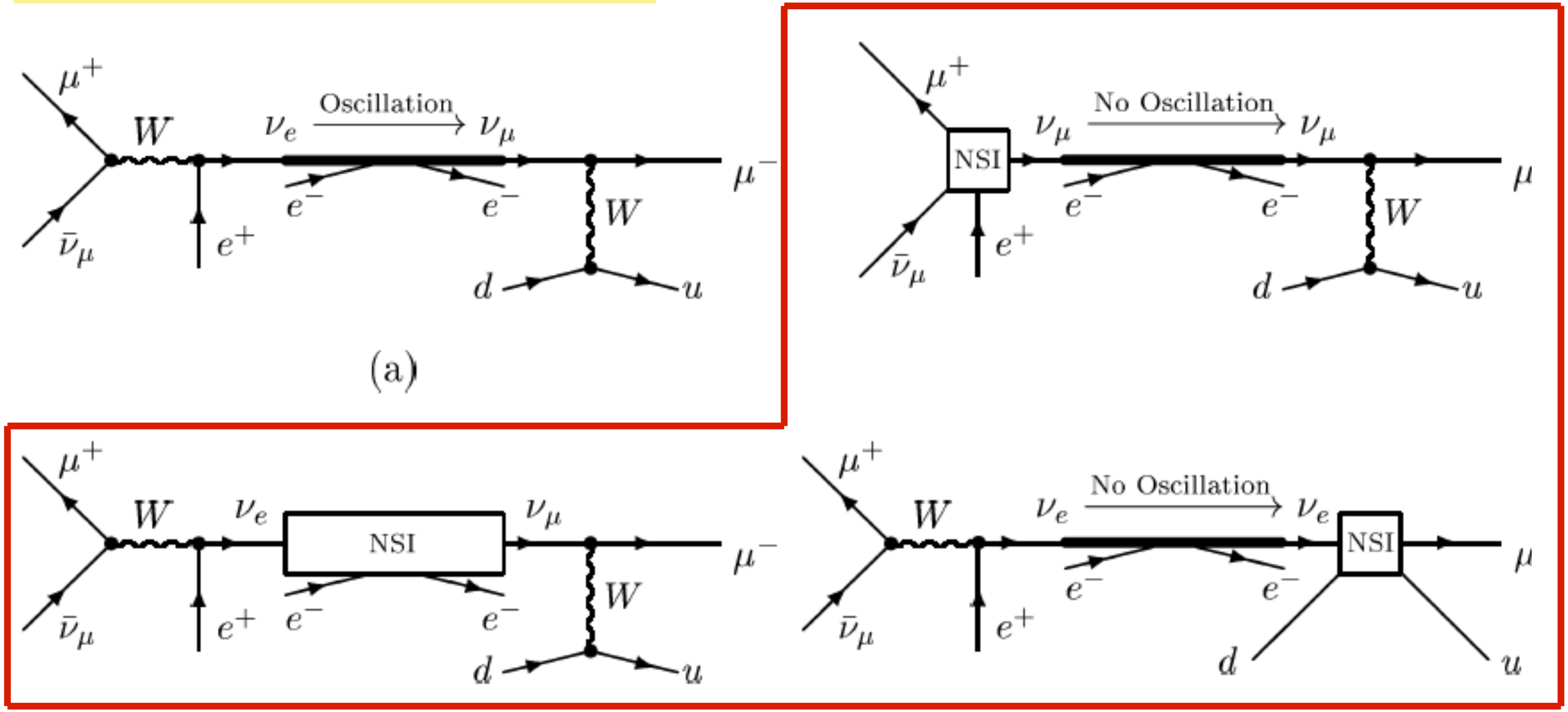


Grossman, Bergmann+Grossman, Ota+Sato, Honda et al., Friedland+Lunardini, Blennlow +Ohlsson+Skrotzki, Huber+Valle, Huber+Schwetz+Valle, Campanelli+Romanino, Bueno et al., Barranco+Miranda+Rashba, Kopp+ML+Ota, …

NSIs interfere with Oscillations

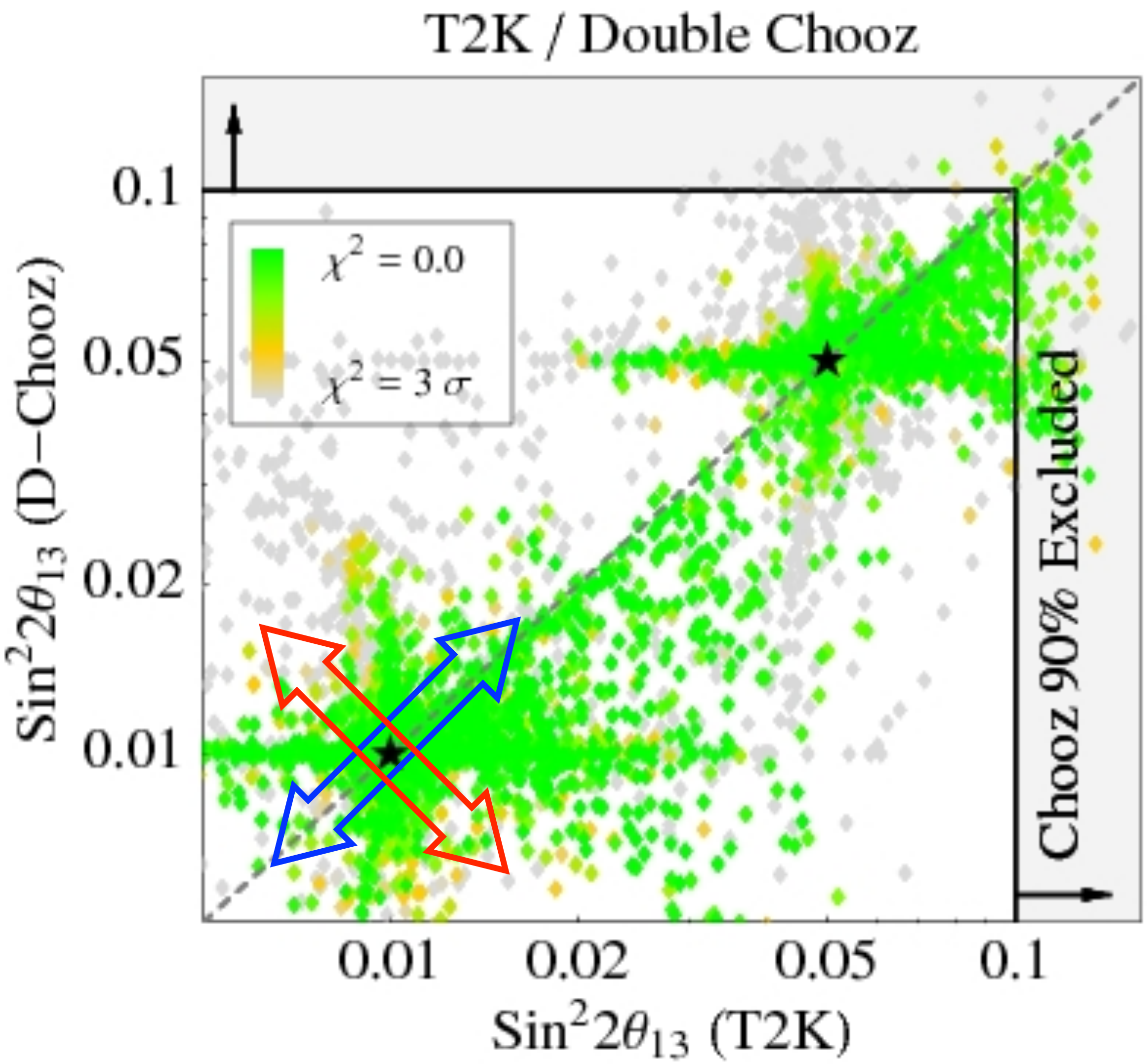
the "golden" oscillation channel

NSI contributions to the "golden" channel



note: interference in oscillations ~ε ⇔ FCNC effects ~ε^2

NSI: Offset and Mismatch in θ_{13}



Kopp, ML, Ota, Sato

Redundant measurements:

Double Chooz + T2K

***=assumed 'true' values of θ_{13}**

scatter-plot: ε values random

- below existing bounds

- random phases

NSIs can lead to:

- offset

- mismatch

➔ redundancy

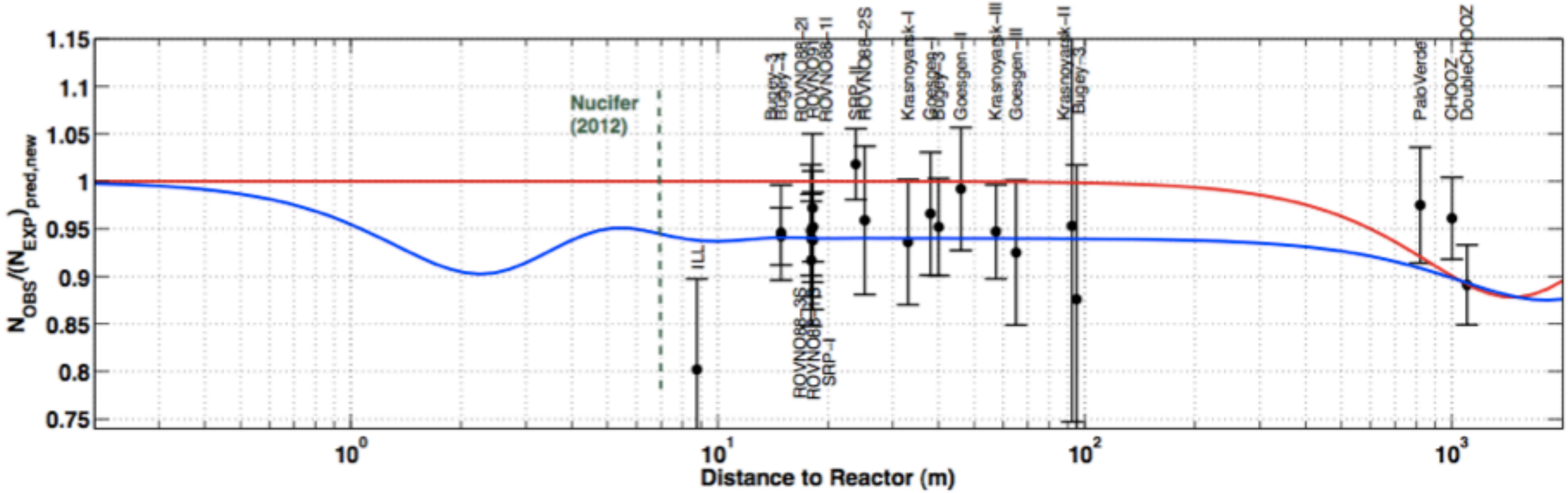
➔ interesting potential

➔ might first show up as tension in global fits

Sterile Neutrinos

The Reactor Anomaly

New reactor fluxes and global reactor data: Mention et al.



θ_{13} can reduce flux at L $\geq$ 1 km, but not at shorter baselines
Sterile neutrino with $\Delta m^2 \sim$ eV can nicely account for reduction
➔ 3+1 fits ; all evidences for eV scale ➔ 3+2, …
See e.g. T. Schwetz at NEUTRINO 2012

➔ will be tested by new experiments (e.g. NUCIFER @ few meters)

Evidences for Light Sterile Neutrinos

Particle Physics:

Reactor anomaly, LSND, MiniBooNE, MINOS, Gallex…

➔ **New and better data / experiments are needed to clarify the situation**

➔ **maybe something exciting around the corner?**

➔ **would hint at eV scale and sizable percentage type mixings**

CMB: Extra eV-ish neutrinos possible J. Hamann et al. , …

BBN: Extra ν's possible: $N_\nu \underline{\sim} 3.7 \underline{+} 1$

E. Aver, K. Olive, E. Skillman (2010), Y. Izotov, T. Thuan(2010)

Astrophysics: keV-ish sterile neutrinos could exp,ain pulsar kicks

Kusenko, Segre, Mocioiu, Pascoli, Fuller et al., Biermann & Kusenko, Stasielak et al., Loewenstein et al., Dodelson, Widrow, Dolgov, …

My believe: Most likely not all of them are correct

➔ **but any one has far reaching consequences!**

The Neutrino Spectrum

<u>The standard picture:</u>

3 heavy sterile neutrinos typ. $\geq 10^{13}$ GeV

➔ leptogenesis, role in GUTs, …

Some mechanism which makes 1, 2, … heavy states light?

➔ light sterile neutrino(s)

➔ tiny heavy-light mixing expected $\theta^2 < O(m_\nu/m_s)$

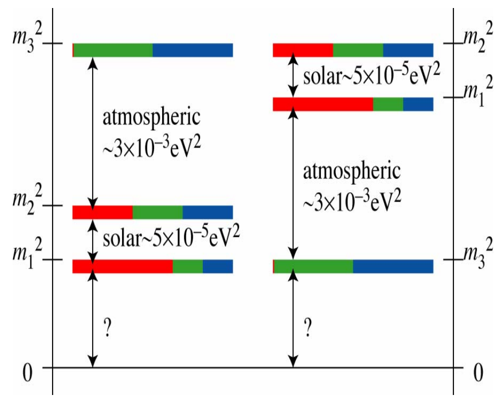
3 light active neutrinos

➔ this cold easily be wrong

- more than 3 N_R states, …

- M_R may have special eigenvalues, …

➔ light sterile neutrinos ?!



keV sterile Neutrinos as WDM

Could Neutrinos be Dark Matter?

- **Active neutrinos would be perfect Hot Dark Matter**
  → ruled out:
  - destroys small scale structures in cosmological evolution
  - measured neutrino masses too small → maybe HDM component

- **keV sterile neutrinos: Warm Dark Matter**
  → workes very well:
  → relativistic at decoupling
  → non-relativistic at radiation to matter dominance transition
  - **OK for $M_X \simeq$ few keV with very tiny mixing**
    ←→ tiny active – sterile mixings $O(m_\nu/M_R)$ expected
  - **reduced small scale structure → smoother profile, less dwarf satellites**

Note: Right-handed neutrinos exist probably anyway

The νMSM

Asaka, Blanchet, Shaposhnikov, Asaka, Shaposhnikov

Particle content:

- Gauge fields of $SU(3)_c$ x $SU(2)_W$ x $U(1)_Y$: **γ, $W_{\pm}$, Z, g**
- Higgs doublet: **Φ=(1,2,1)**
- Matter

	$SU(3)_c$	$SU(2)_W$	$U(1)_Y$	$U(1)_{em}$
$\begin{pmatrix} u \\ d \end{pmatrix}_L$	3	2	+1/3	$\begin{pmatrix} +2/3 \\ -1/3 \end{pmatrix}$
u_R	3	1	+4/3	+2/3
d_R	3	1	-2/3	-1/3
$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	1	2	-1	$\begin{pmatrix} 0 \\ -1 \end{pmatrix}$
e_R	1	1	-2	-1
N	1	1	0	0

x3 generations

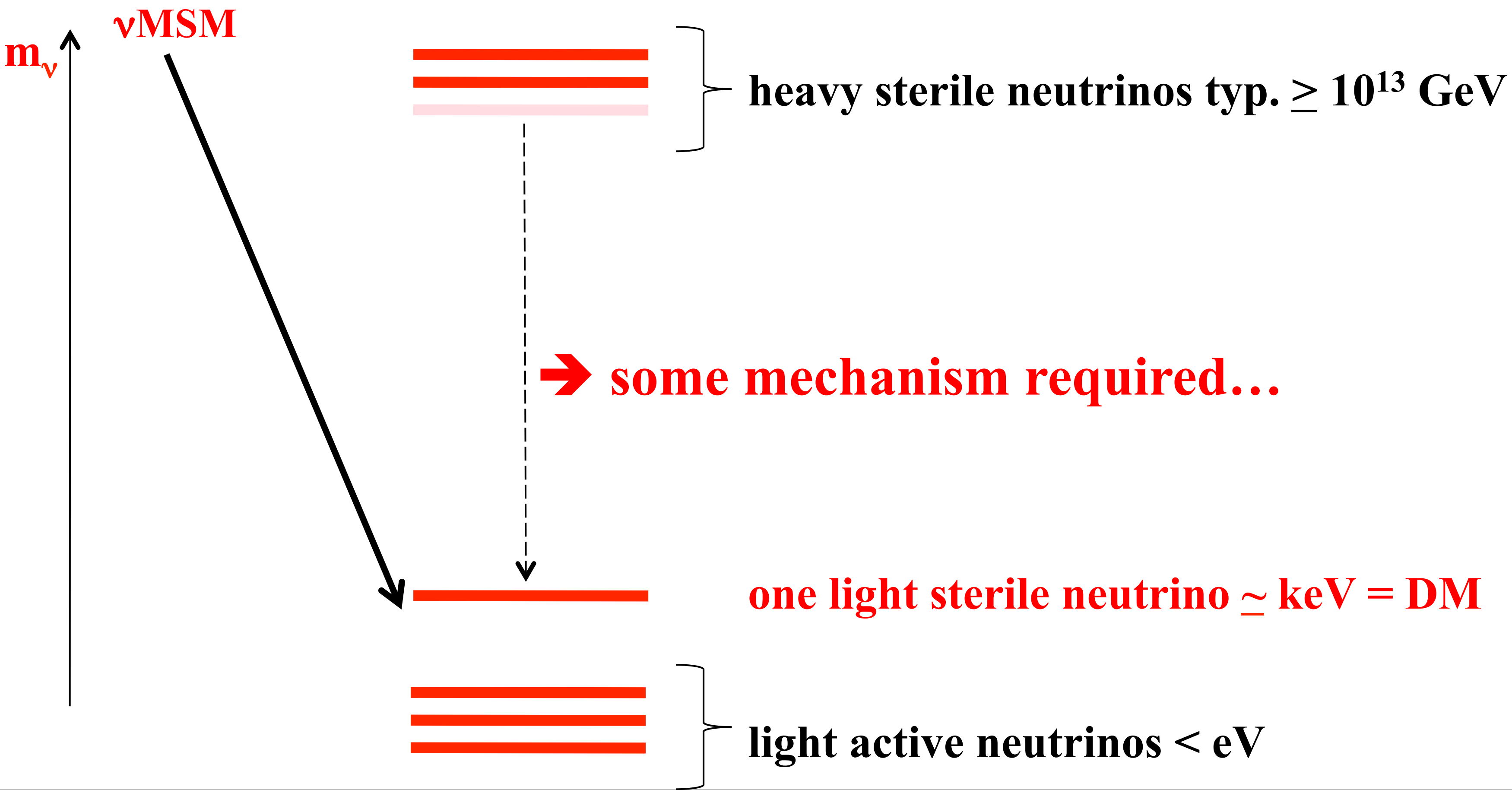
➔ lepton sector more symmetric to the quark sector

➔ Majorana masses for N

➔ choose for one sterile ν ~keV mass ➔ exceeds lifetime of Universe

Virtue and Problem of the νMSM

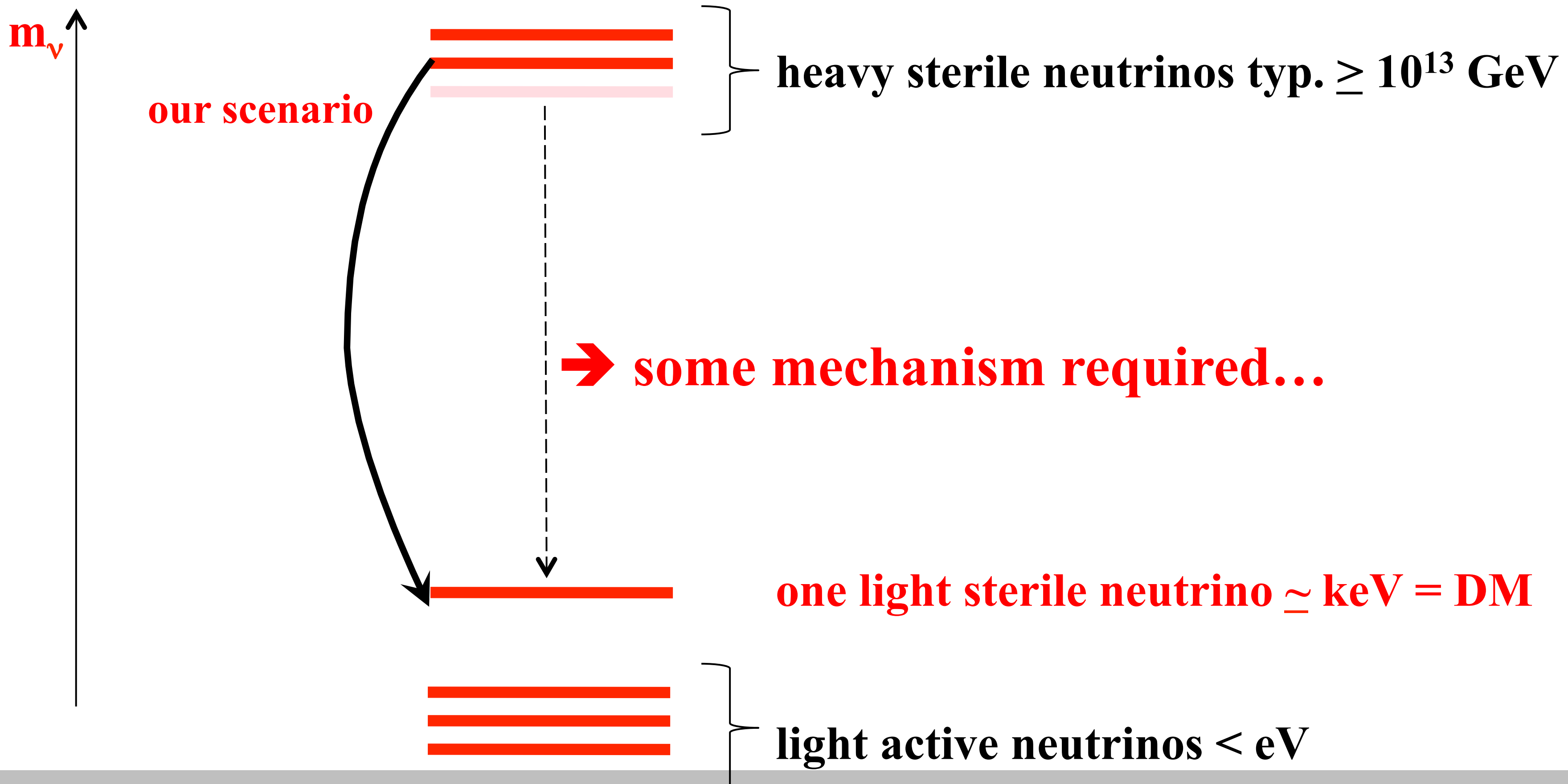
νMSM: Scenario with sterile ν and tiny mixing ➔ never enters thermal equilibrium
➔ requires non-thermal production from other particles (avoid over-closure)
➔ new physics before the beginning of the thermal evolution sets abundance



Alternative Scenario with Thermal Abundance

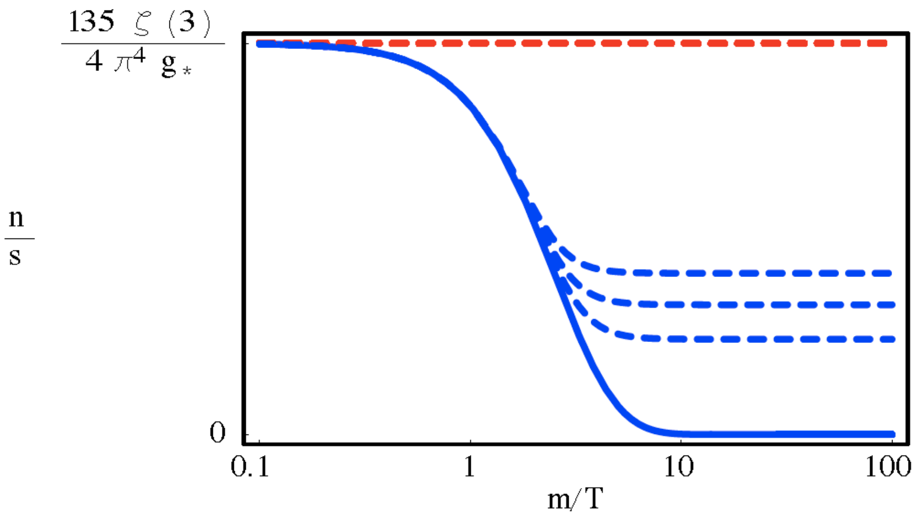
- **Three right-handed neutrinos N_1, N_2, N_3, Dirac and Majorana mass terms**
- **N Charged under some (BSM) gauge group ➔ scale M (~sterile)**
  ➔ thermal production of DM abundance
- **Specific example: LR-symmetry** $SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

Bezrukov, Hettmannsperger, ML



Obtaining the correct Abundance

Usual thermal WIMP case:



$$\frac{\Omega}{\Omega_{DM}} \simeq \left(\frac{10}{g_{*f}}\right)\left(\frac{M}{10\,eV}\right)$$

Decoupled relativistic

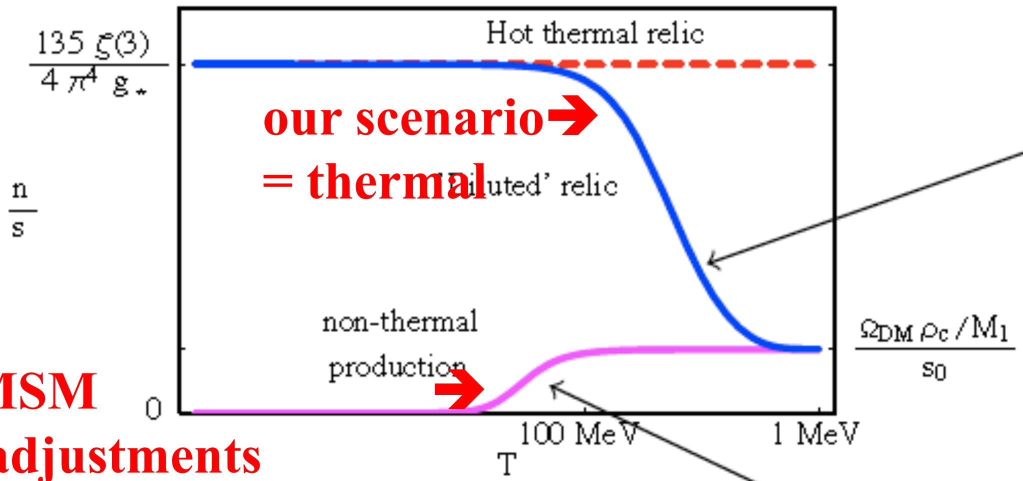
CDM:
(M>>MeV)

$$\Omega \sim \Omega_{DM}$$

Decoupled

nonrelativistic

keV sterile neutrinos:



νMSM
= adjustments

Diluted after decoupling
(entropy generated by other
particle decay)

$$\Omega \sim \Omega_{DM}$$

Never entered thermal equilibrium

Entropy Generation by out-of Equilibrium Decay

Heavy particle (here: N_3) dropping out of thermal equilibrium while relativistic $T_f > M_2$: ➔ bounds gauge scale from below

$$M > \frac{1}{g_{*f}^{1/8}} \left(\frac{M_2}{\text{GeV}} \right)^{3/4} (10 \div 16)\ \text{TeV}$$

➔ **sufficiently long lived ➔ become non-relativistic**

➔ **dominates expansion of Universe during its decay**

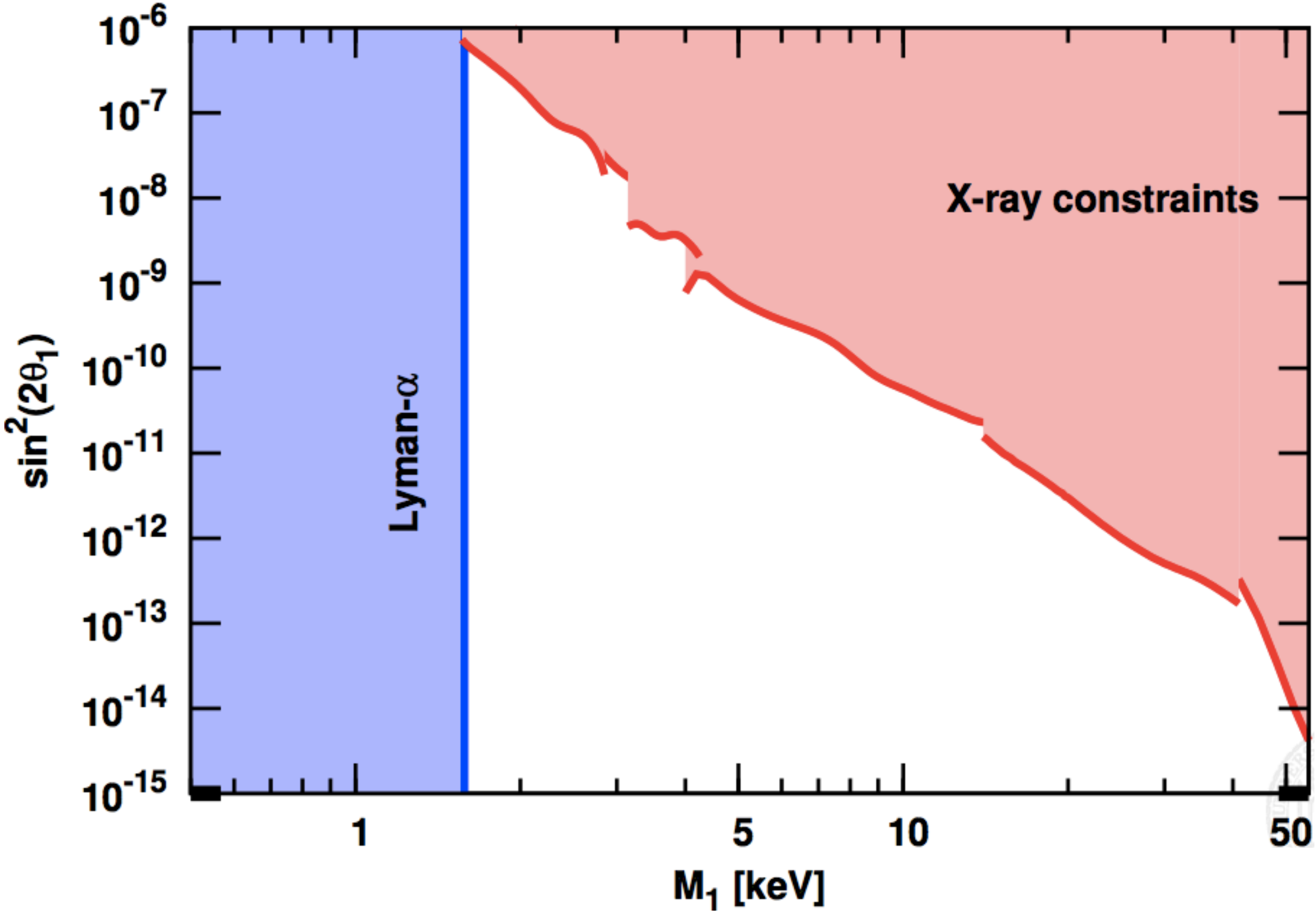
➔ **entropy generation factor ➔**

$$\frac{S_{\text{after}}}{S_{\text{before}}} = S \frac{a^3_{\text{before}}}{a^3_{\text{after}}}$$

$$S \simeq 0.76 \frac{\bar{g}_*^{1/4} M_2}{g_* \sqrt{\Gamma_2 M_{\text{Pl}}}}$$

➔ **fixes decay width Γ_2**

Allowed Parameter Range



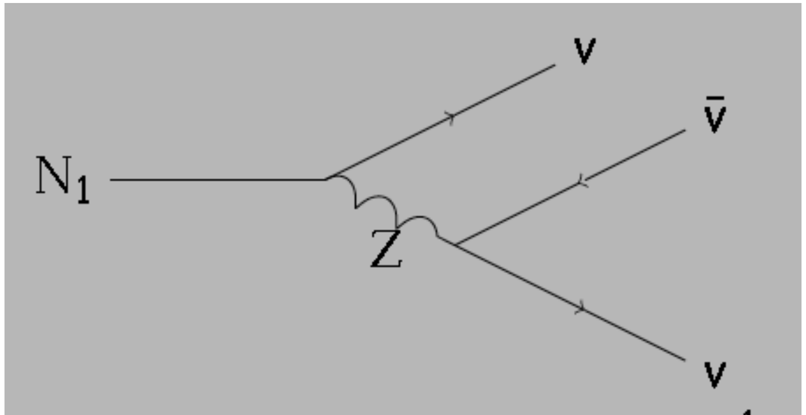
Observing keV-ish Neutrino DM

- **LHC**
  - sterile neutrino DM is not observable
  - WIMP-like particles still possible – but not DM
- **direct searches**
  - sterile ν DM extremely difficult; maybe in β-decay (MARE)
- **astrophysics/cosmology ➔ at some level: keV X-rays**

➔ sterile neutrino DM is decaying into active neutrinos

- decay $N_1 \rightarrow \nu\bar{\nu}\nu$, $N_1 \rightarrow \nu\bar{\nu}\bar{\nu}$

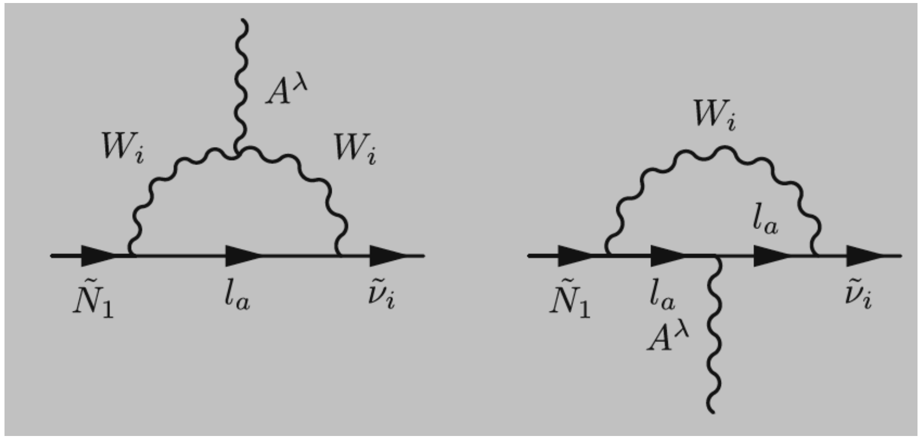
- not very constraining since
  $\tau >> \tau_{Universe}$



$$\tau = 5 \times 10^{23}\,\text{sec} \left(\frac{M_1}{1\text{keV}}\right)^{-5} \left(\frac{\theta_1^2}{10^{-5}}\right)^{-1}$$

- - radiative decays $N_1 \rightarrow \nu\gamma$

➔ photon line $E_\gamma = m_s/2$



- so far: observational limit on active-sterile mixing angle

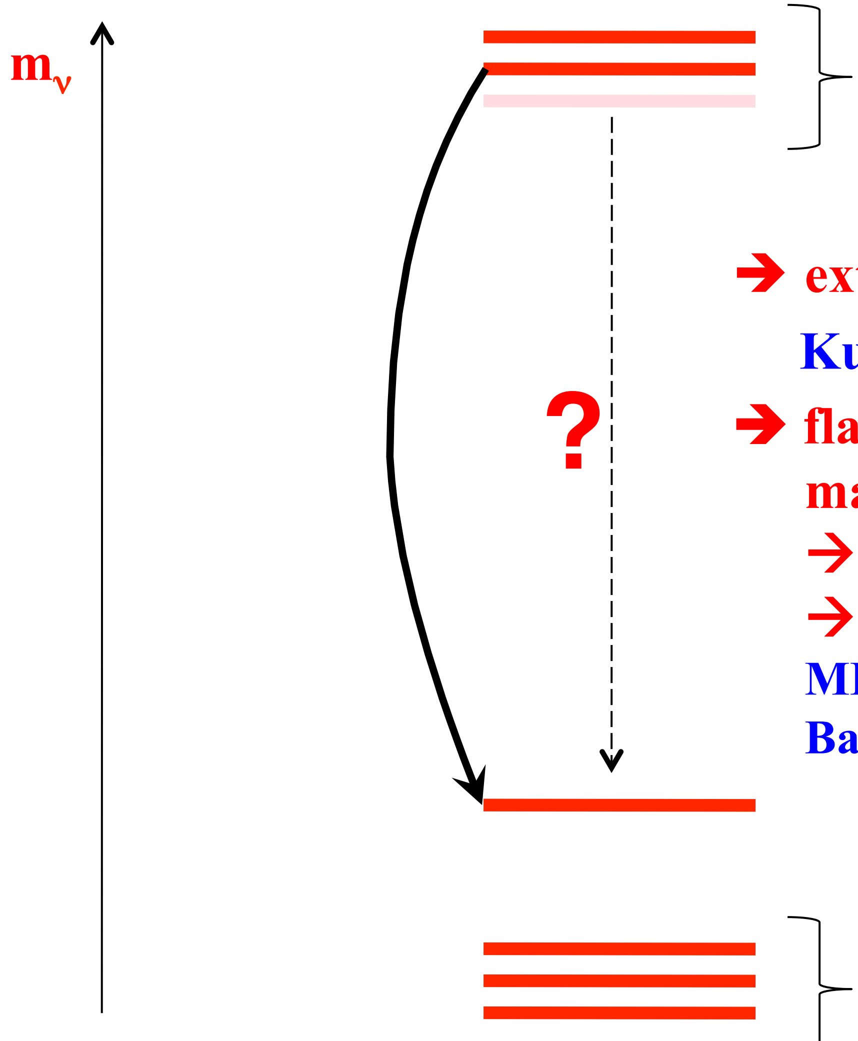
$$\Gamma_{N_1 \to \nu\gamma} \simeq 5.5 \times 10^{-22} \theta_1^2 \left(\frac{M_1}{1 \text{ keV}} \right)^5 \text{s}^{-1}$$

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

- mixing tiny, but naturally expected to be tiny: O(scale ratio)

Explaining keV-ish Sterile Neutrinos

Possible scenario: See-saw + a reason why 1 sterile ν is light



heavy sterile neutrinos typ. $\geq 10^{13}$ GeV

→ extra dimensional physics → 'split see-saw'

Kusenko, Takahashi, Yanagida,

→ flavour symmetries explaining active neutrino masses + charged leptons + quarks

→ consequences for heavy mass matrix

→ L_e-L_μ-L_τ DM ←→ flavour problem

ML, Merle, Niro ; Merle, Niro,

Barry, Rodejohann, Zhang

one light sterile neutrino $\simeq$ keV = DM

light active neutrinos < eV

Light Sterile Neutrinos from L_e-L_μ-L_τ

- Flavour symmetries have been studied to explain apparent regularities of masses and mixing: A4, S3, D5, …
  ➔ implications for sterile sector?
  ➔ could the same symmetries explain a keV-ish sterile ν?

Model with **L_e-L_μ-L_τ** symmetry:

by Lavoura & Grimus ➔ extended: ML, Merle, Niro

SM + ν_{iR} + softly broken U(1) ←→ $\mathcal{F} \equiv L_e - L_\mu - L_\tau$

type II see-saw ➔ +Higgs triplet $\Delta = \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{pmatrix}$

	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

- **Mass matrix for right-handed neutrinos:**

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

- **Dirac masses**

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

- **In addition: Triplet masses**

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

Neutrino mass matrix:

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

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

det(M_{ij}) =0 ➔ M_1=0

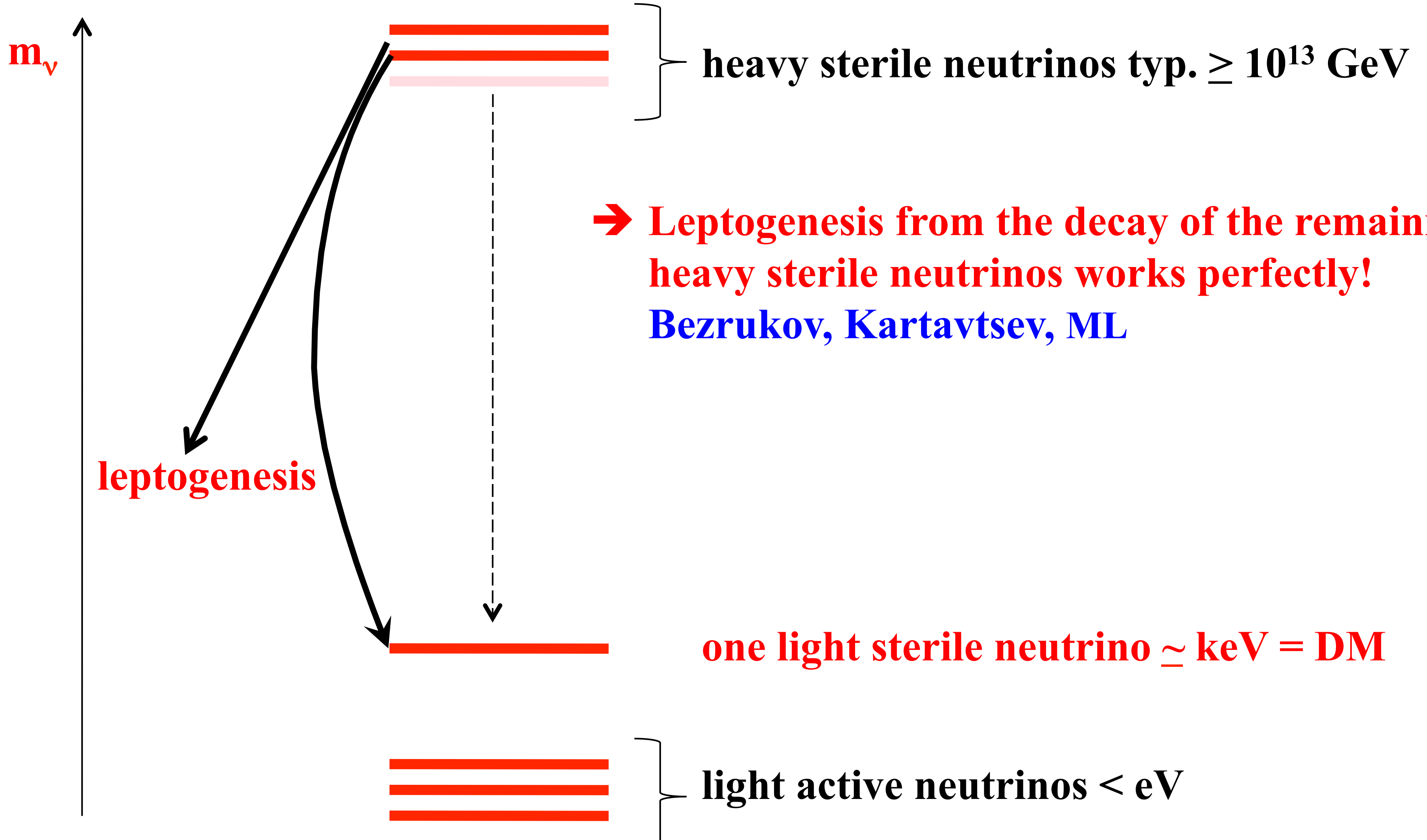
➔ massless sterile state + soft breaking

➔ naturally light sterile ν

➔ mechanism possible in models

Leptogenesis

…there still exist heavy sterile states …



➔ **Leptogenesis from the decay of the remaining heavy sterile neutrinos works perfectly!**
Bezrukov, Kartavtsev, ML

Conclusions

- **Neutrinos are physics a little bit beyond the SM**
- **Interesting features & unique insights**
- **Models: Many possibilities ←→ experiment**
- **Ways to get fooled: 0nbb, NSIs, …**
- **A keV-ish sterile neutrino is a very well motivated and good working Warm Dark Matter candidate ←→ finite ν-masses**
- **Right handed neutrinos probably exist**
  → requires only some mechanism for light sterile mass O(keV)

→ Combination with Leptogenesis possible → BAU

→ More general scenarios: any mechanism which 'naturally' explains light sterile neutrinos