TeV-Scale Sterile Neutrinos

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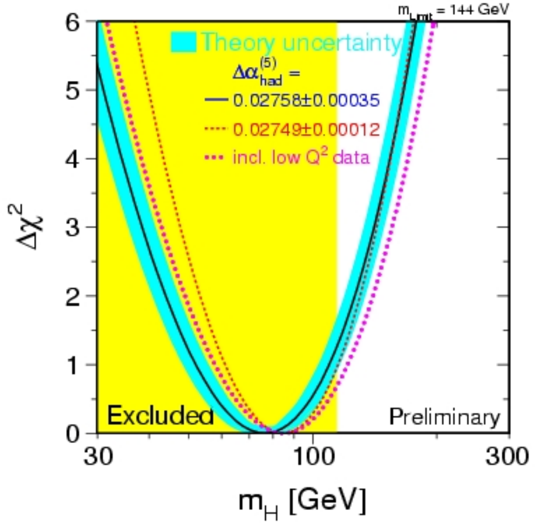
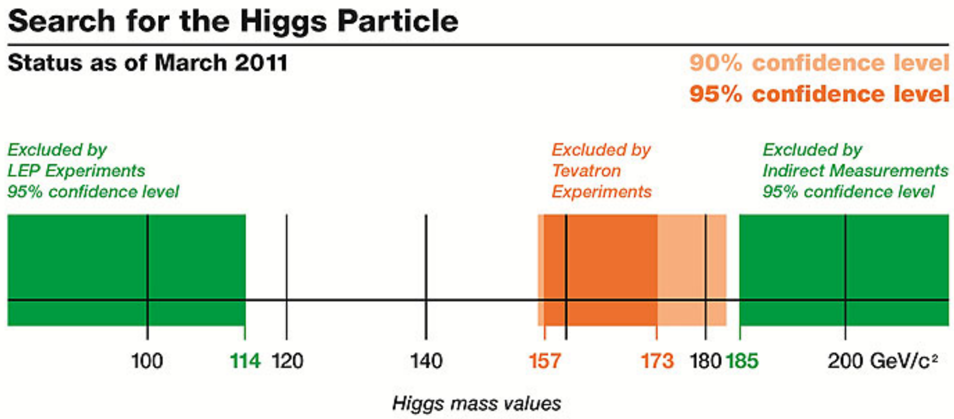
SM works perfectly & Higgs seems to be there



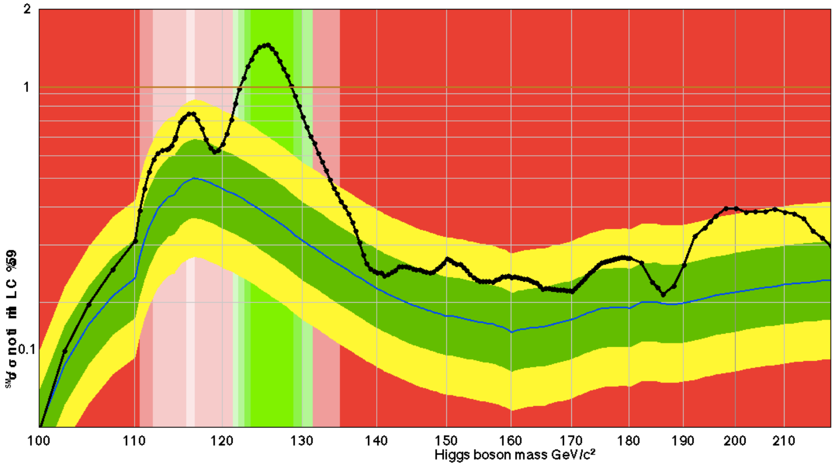


- mass range was shrinking…

… and is now rather precisely known

- no signs for anything else

➔ just the SM?



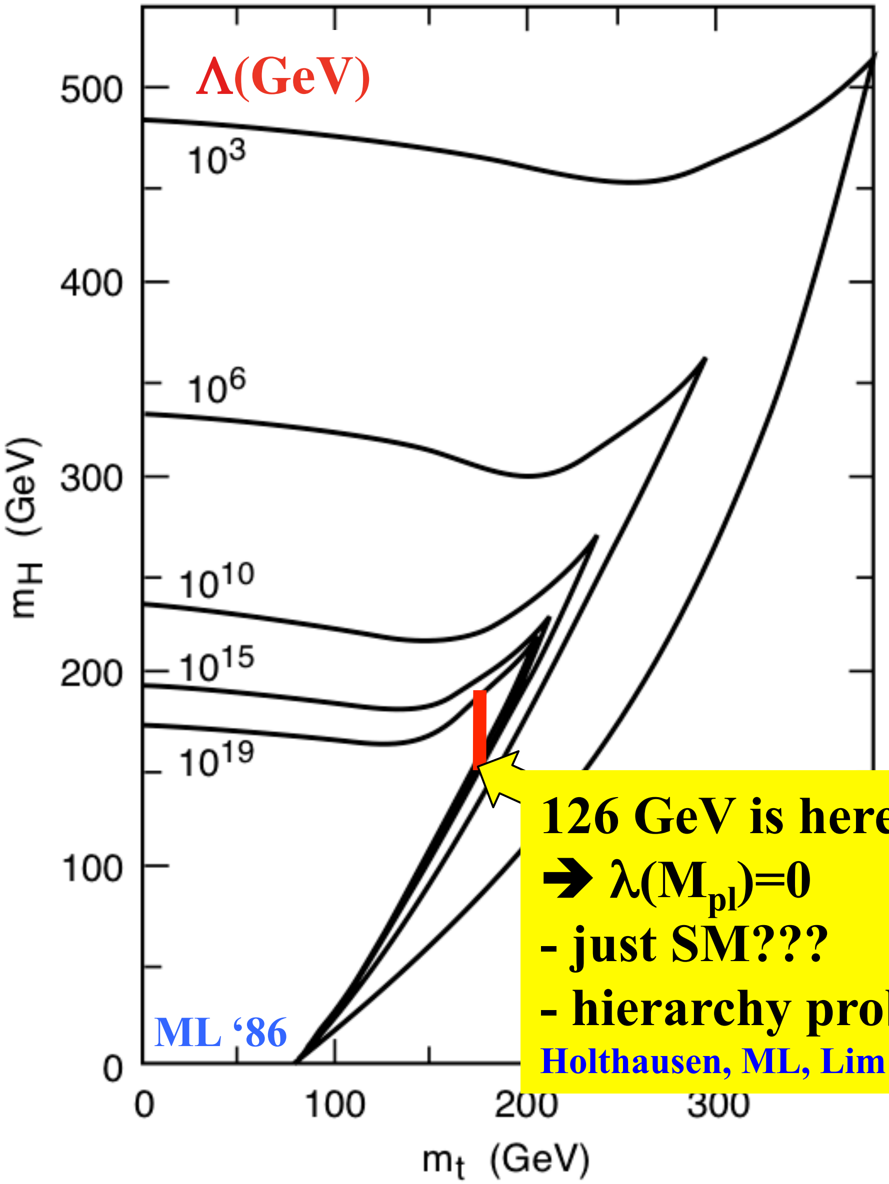
- It's a well defined QFT
- just like QED, QCD, …

→ 18+1 parameters → experimental input

→ tests by over-constraining (S,T,U, running α's, …)

→ per se no hierarchy problem! ←→ embedding QFT self-consistency ➔

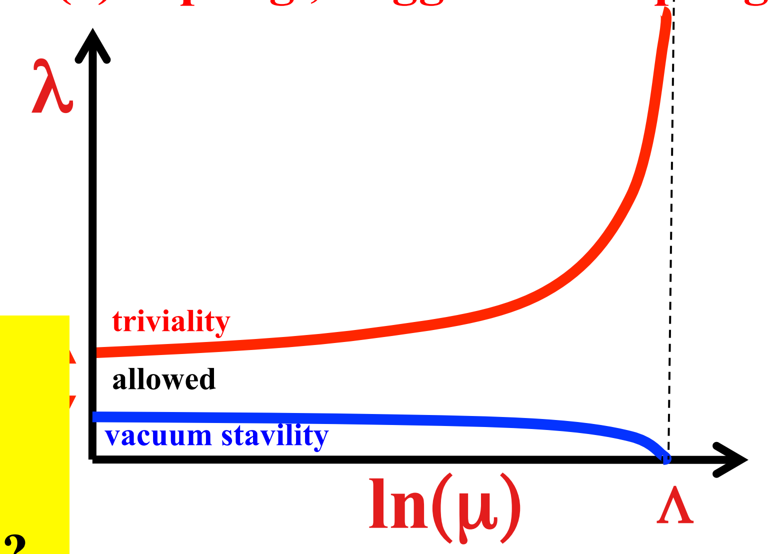
Triviality and Vacuum Stability



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

$$126 \text{ GeV} < m_H < 174 \text{ GeV}$$

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 perfectly but it must be extended….

- **Many theoretical reasons for BSM physics:**
  - Flavour problem … ←→ maybe insights via neutrinos
  - Hierarchy problem
    - only a problem once the SM is embedded… → GUTs, …
    - separation of two scalar scales: SM Higgs and some other scalar at Λ
    - Planck scale physics → new concepts, spin 2, no new scalars?
    - ➔ no 2nd scalar for direct embeddings at the Planck scale?
    - ➔ SM boundary conditions that point to Λ_{Planck} → vacuum stability line!

- **Experimental facts:**
  - SM cannot explain Baryon Asymmetry of the Universe
    - BUT: neutrino masses require SM extension ➔ SM+➔
    - leptogenesis = one of the best BAU explanations
  - Dark Matter
    - some extra particle is required which is DM
    - particles connected to the hierarchy problem, strong CP, … → neutrinos
  - Neutrino Masses and maybe evidences for sterile neutrinos

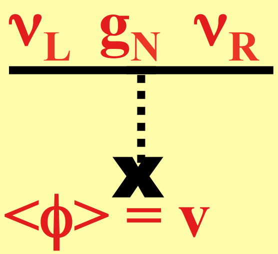
New Physics: Neutrino Mass Terms

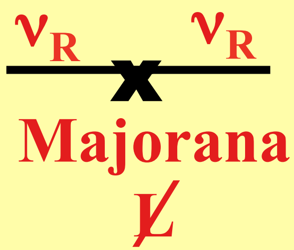
SM ~m$\phi\bar{L}R$ = (2,1)

→ new fields

→ **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

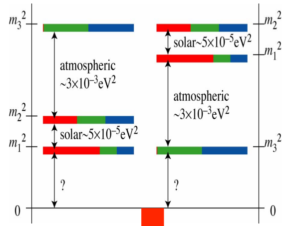
NEW ingredients, 9 parameters → SM+ and sea-saw

Suggestive Seesaw Features

QFT: natural value of mass operators ⟷ scale of symmetry

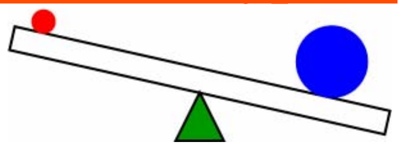
$m_D \sim$ electro-weak scale

$M_R \sim$ 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 $\not{L}$, symmetries of m_D ,M_R

The Neutrino Spectrum

The standard picture:

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 $\theta^2 < O(m_\nu/m_s)$**

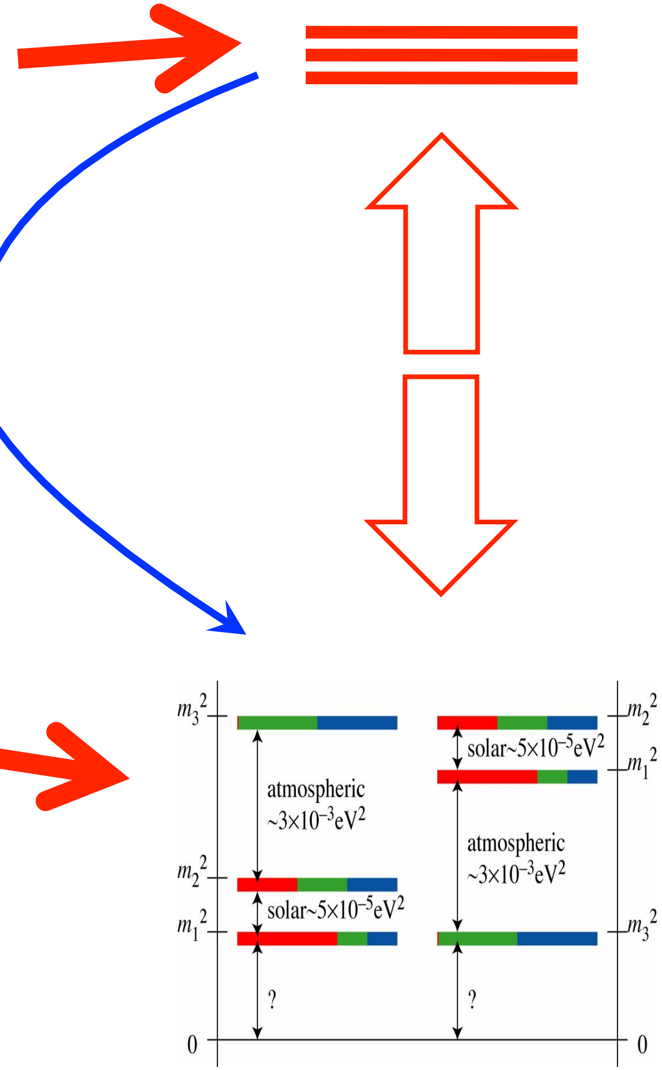
3 light active neutrinos

➔ this cold easily be wrong

- more than 3 N_R states, …

- M_R may have special eigenvalues, …

➔ light sterile neutrinos ?!



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: $N_\nu \simeq 3.7 \pm 1$

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

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

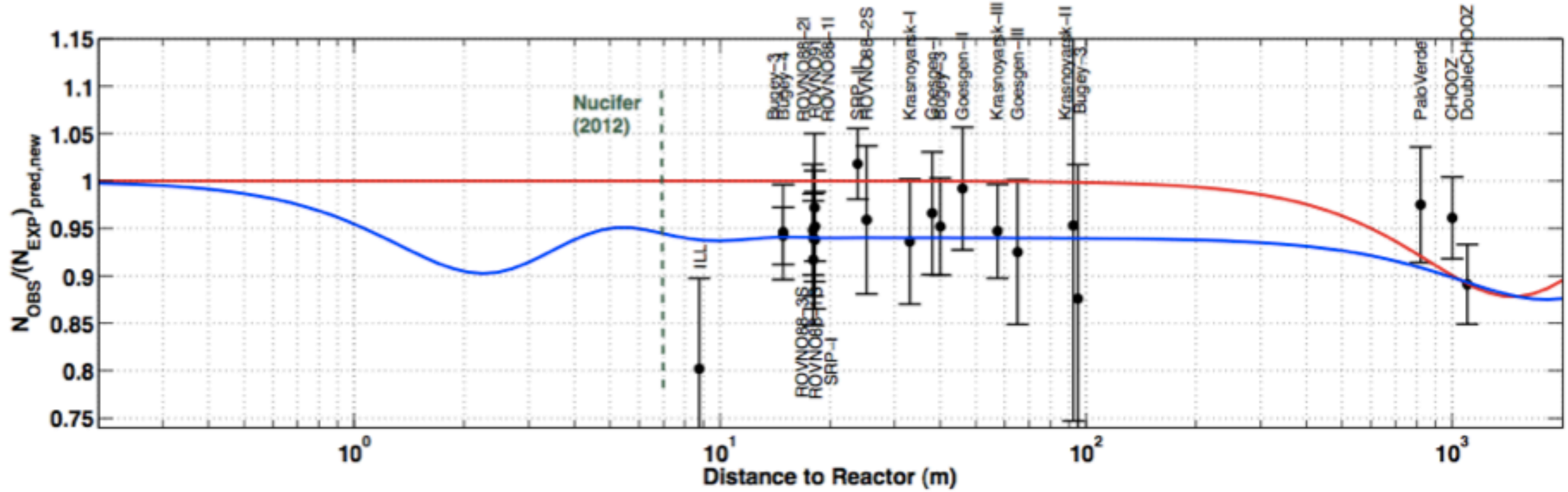
Kusenko, Segre, Mocioiu, Pascoli, Fuller et al., Biermann & Kusenko, Stasielak et al., Loewenstein et al., Dodelson, Widrow, Dolgov, …

My believe: Most likely not all of them are correct

➔ but any one has far reaching consequences!

The Reactor Anomaly

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

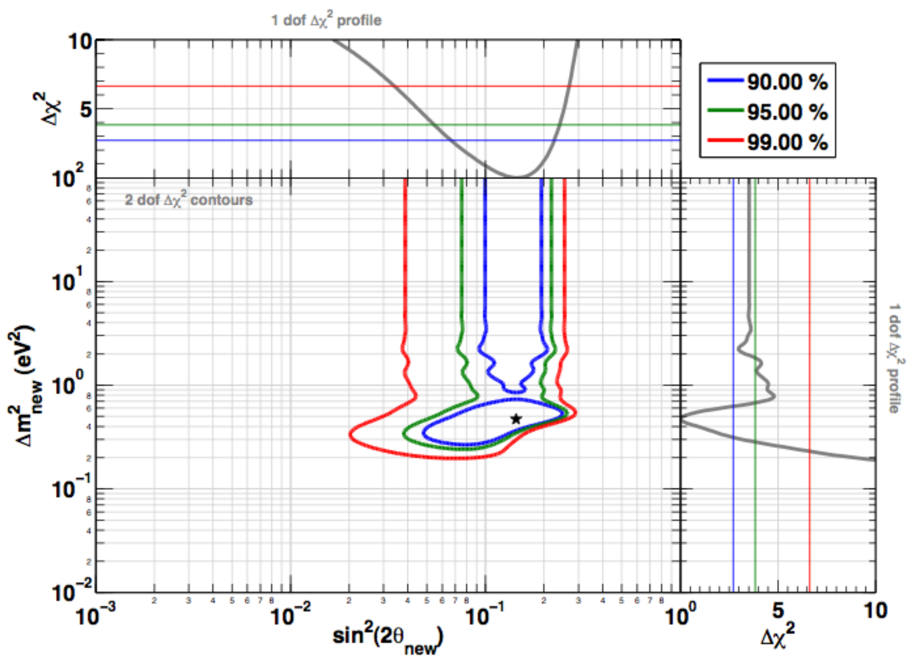


θ_{13} can reduce flux at L $\geq$ 1 km, but not at shorter baselines
Sterile neutrino with $\Delta m^2 \sim$ eV can nicely account for reduction
➔ 3+1 fits ; all evidences for eV scale ➔ 3+2, …
See e.g. T. Schwetz at NEUTRINO 2012

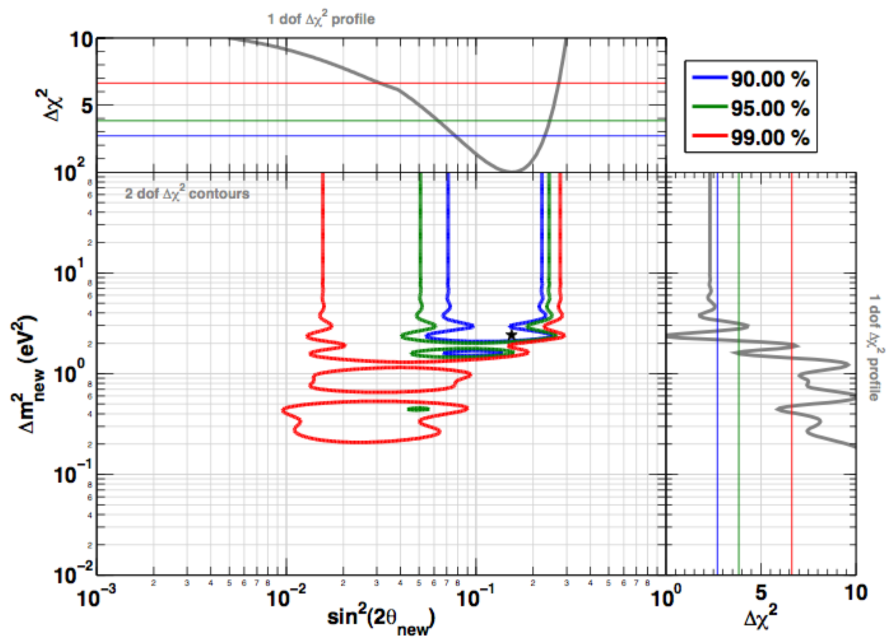
➔ will be tested by new experiments (e.g. NUCIFER @ few meters)

Reactor Anomaly

Rate only analysis



Rate + Shape (Bugey 3) analysis



- **Best fit: $\Delta m^2 = 2.4$ eV^2 ; $\sin^2(2\theta_{new}) = 0.14$**
- **2.9 sigma significance**

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**

• **reduced small scale structure ➔ smoother profile, less dwarf satellites**

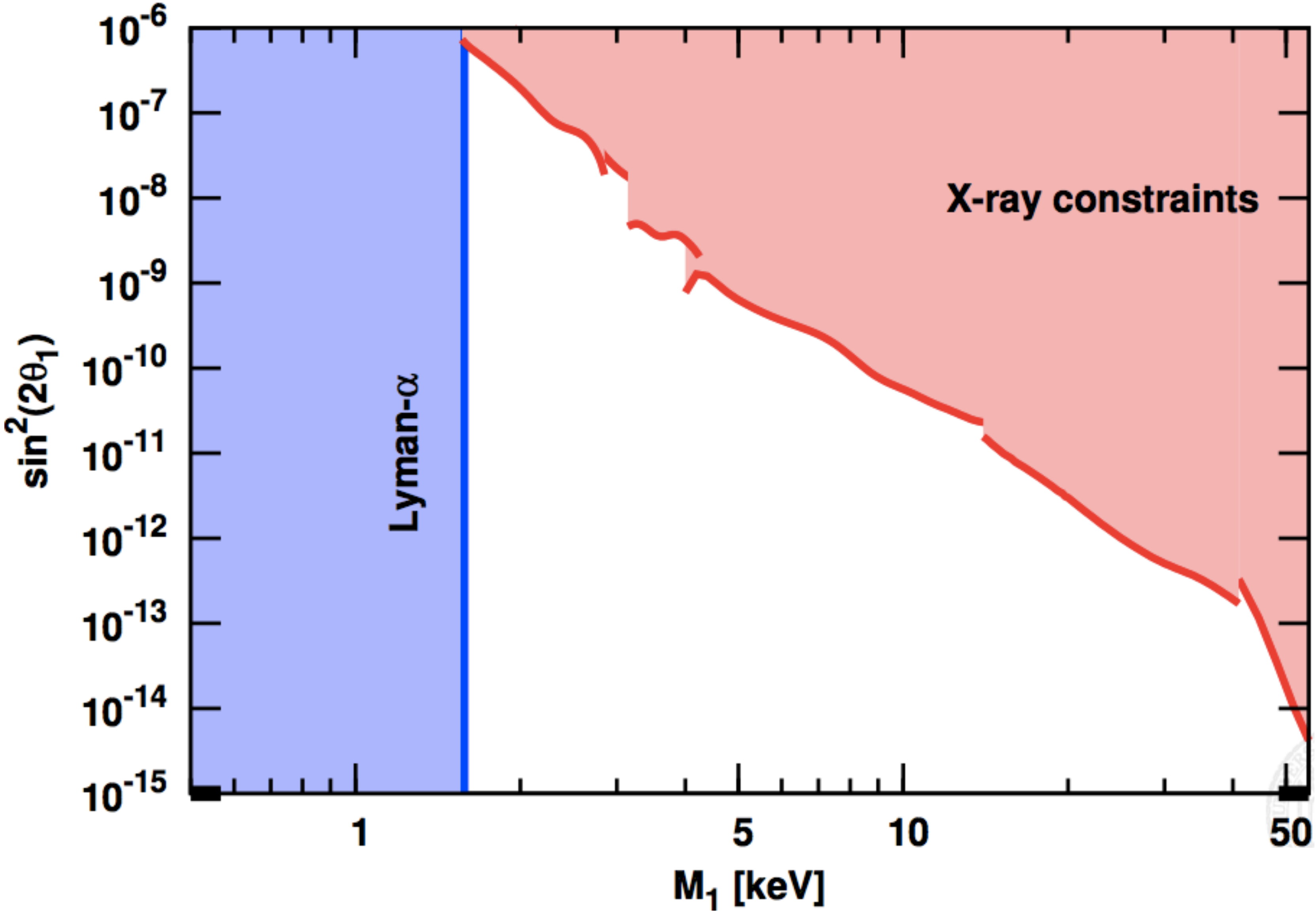
➔ **scenario where one sterile neutrino is keV-ish, the others heavy**

➔ **tiny active – sterile mixings $O(m_\nu/M_R)$**

Note: Right-handed neutrinos exist probably anyway – just make one light!

Asaka, Blanchet, Shaposhnikov, Asaka, Shaposhnikov; Kusenko, Segre, Mocioiu, Pascoli, Fuller et al., Biermann & Kusenko, Stasielak et al., Loewenstein et al., Dodelson, Widrow, Dolgov, … Bezrukov, Hettmannsperger, ML

Allowed Range for keV Sterile ν Dark Matter



Could TeV-Scale Sterile Neutrinos Exist?

E. Akhmedov, A. Kartavtsev, ML, L. Michaels and J. Smirnov
arXiv 1302.1872

Let's assume that TeV-scale sterile neutrinos exist.
- what are the limits?
- do they improve things or make them worse?

➔ improvements of over-all fits!

Simplest Extension of the SM

- Add 3 right-handed neutrinos (Majorana fields) $N_i = N_i^c$

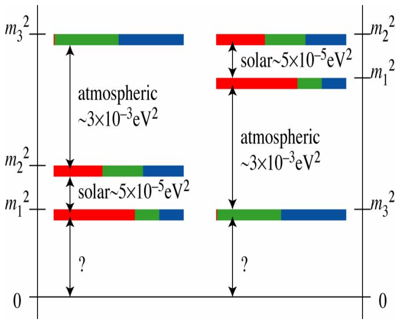
$$\mathscr{L} = \mathscr{L}_{SM} + \frac{1}{2}\bar{N}_i(i\partial\!\!\!/ - M_i)N_i \quad - h_{\alpha i}\bar{\ell}_\alpha\tilde{\phi}N_i - h_{i\alpha}^\dagger\bar{N}_i\tilde{\phi}^\dagger\ell_\alpha$$

- This can solve experimentally required facts :
  - small neutrino masses via type I see-saw
  - baryon asymmetry of the Universe via leptogenesis
  - eV-ish sterile neutrinos (reactor anomaly)
  - keV sterile neutrinos (dark matter)
  - …
- Explaining the sterile spectrum …???
- Study effects of sterile neutrinos with any mass ➔ TeV

N=3 sterile Neutrinos

sterile neutrinos $\nu_{4,5,6}$
spectrum ???

active neutrinos $\nu_{4,5,6}$



Global fits of active neutrino data usually assume 3x3 unitarity!
→ unconstraint fits ≃ up to 4% changes Antusch et al.

6x6 mixing matrix:

$$\mathbf{U} = \begin{pmatrix} \mathscr{U} & \mathscr{R} \\ \mathscr{W} & \mathscr{V} \end{pmatrix}$$

(3×3) PMNS matrix $\mathscr{U}$
is not exactly unitary
→ deviations

$$\epsilon_\alpha \equiv \sum_{i \geq 4} |\mathbf{U}_{\alpha i}|^2$$

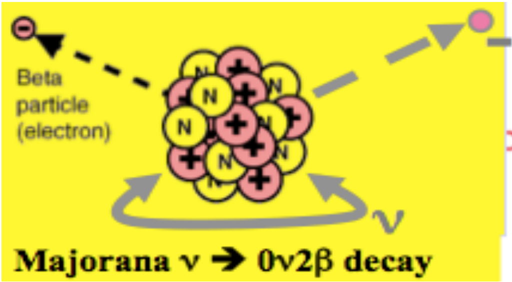
$$\epsilon_e - \epsilon_\mu = 0.0022 \pm 0.0025$$

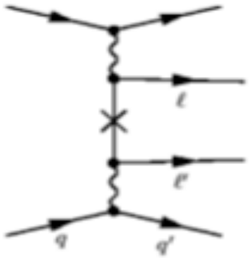
$$\epsilon_\mu - \epsilon_\tau = 0.0017 \pm 0.0038$$

$$\epsilon_e - \epsilon_\tau = 0.0039 \pm 0.0040$$

Consequences of sterile Neutrinos

- Shifts in active neutrino parameters in global analyses
- L-violating admixture in light ν's →0νββ Beta Decay





$$\propto |\langle \mathbf{m_{ee}} \rangle| = |\sum \mathbf{m_i U_{ei}^2}|$$

- Effective mass including all states:

$$|\langle m_{ee} \rangle| \approx |\sum_{i=1}^{3} \mathbf{U}_{ei}^2 m_i - \sum_{i=4}^{3+n} F(A, M_i) \mathbf{U}_{ei}^2 m_i|$$

$$F(A, m_i) \approx (m_a/m_i)^2 f(A)$$

f(A) depends on the decaying isotope

today $|\langle m_{ee} \rangle| < 0.4$ eV → will improve in next years!

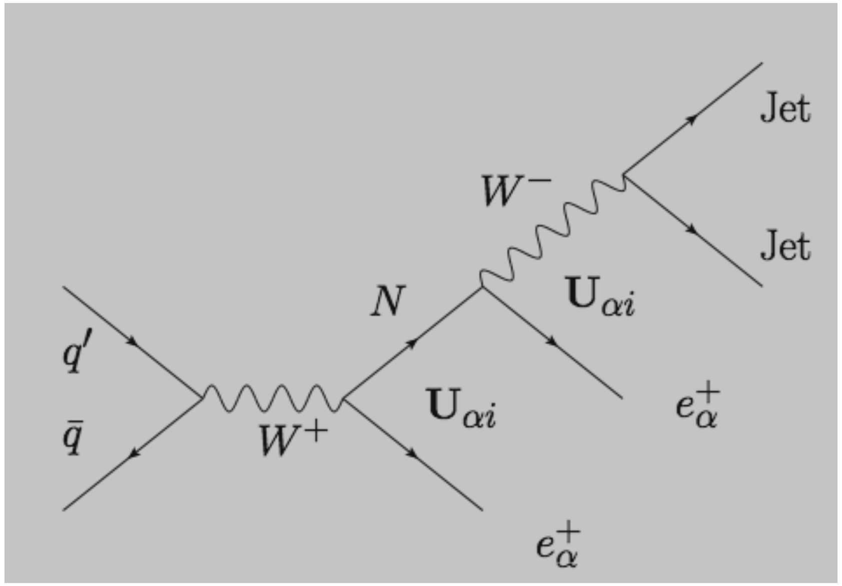
- **Additional interactions of W and Z:**

$$\mathscr{L}_{\text{int}} = -\frac{e}{2c_w s_w} Z_\mu \sum_{i,j=1}^{3+n} \sum_{\alpha=e,\mu,\tau} \bar{\nu}_i \mathbf{U}^\dagger_{i\alpha} \gamma^\mu P_L \mathbf{U}_{\alpha j} \nu_j$$
$$- \frac{e}{\sqrt{2} s_w} W_\mu \sum_{i=1}^{3+n} \sum_{\alpha=e,\mu,\tau} \bar{\nu}_i \mathbf{U}^\dagger_{i\alpha} \gamma^\mu P_L e_\alpha + \text{h.c.}$$

→L-violating processes

e.g. production of heavy neutrino at LHC as intermediate state

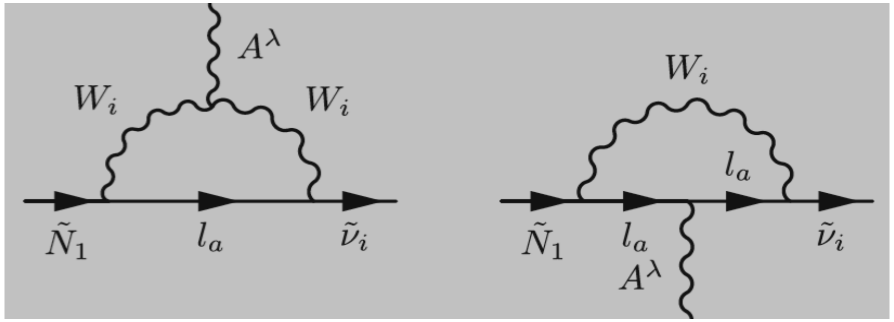
→ after upgrade to 14TeV with 100 fb^{-1} expected limit



$$|\sum_i \mathbf{U}^2_{\alpha i}\, m_i^{-1}| \simeq 6.5 \cdot 10^{-3}\ \text{TeV}^{-1}$$

sensitivity to 800 GeV sterile neutrinos!

- **L-violating decays;**
  e.g. : μ→ eγ



$$\mathrm{BR}(\mu \to e\gamma) = \frac{\Gamma(\mu \to e\gamma)}{\Gamma(\mu \to e\nu\bar{\nu})} = \frac{3\alpha}{32\pi}|\delta_\nu|^2$$

$$\delta_\nu = 2\sum_i \mathbf{U}^*_{ei}\mathbf{U}_{\mu i}\, g\left(m_i^2/M_W^2\right)$$

$$g(x) = \int_0^1 \frac{(1-\alpha)d\alpha}{(1-\alpha)+\alpha x}[2(1-\alpha)(2-\alpha)+\alpha(1+\alpha)x].$$

→ $$\delta_\nu = 2\sum_{i=4}^{3+n}\mathbf{U}^*_{ei}\mathbf{U}_{\mu i}\left[g\left(m_i^2/M_W^2\right) - 5/3\right]$$

MEG bound: $\mathrm{BR}(\mu^+ \to e^+\gamma) \leq 2.4 \cdot 10^{-12}$

- **Non-unitarity in neutrino oscillations**
  → zero distance effec in addtion to oscillations

$$P_{\alpha\beta}(L=0) = \frac{\delta_{\alpha\beta}\,(1-2\epsilon_\alpha) + \epsilon_\alpha\epsilon_\beta}{(1-\epsilon_\alpha)(1-\epsilon_\beta)}$$

- not easy to detect ←→ normalization
- note that this cannot explain the reactor anomaly!

- **Electro-weak precision observables**
  - tree level mixing and loop effects (S,T,U)
  → may explain some `deviations'
  → fix SM definition → predict other observables

EWPO	Theory (Standard Model)	Experiment
$\Gamma_{\rm lept}$ (MeV)	84.005 ± 0.015	83.984 ± 0.086
$\Gamma_{\rm inv}/\Gamma_{\rm lept}$	5.9721 ± 0.0002	5.942 ± 0.016
$\sin^2\theta_{\rm W}$	0.23150 ± 0.0001	0.2324 ± 0.0012
$g_{\rm L}^2$	0.3040 ± 0.0002	0.3026 ± 0.0012
$g_{\rm R}^2$	0.0300 ± 0.0002	0.0303 ± 0.0010
$M_{\rm W}$ (GeV)	80.359 ± 0.011	80.385 ± 0.015

- **Z-width very precisely known $\simeq 2\sigma$ too low**
- **NuTeV anomaly**

- **Sterile neutrinos lead to modifcations**
  → may explain some `deviations'

$$\Gamma_{\rm inv}/\left[\Gamma_{\rm inv}\right]_{\rm SM} = \tfrac{1}{3}\sum_\alpha (1-\epsilon_\alpha)^2$$

CC and NC scatering ←→ mixing

$$\sigma_\alpha^{\rm CC} = \sigma_{\alpha,\rm SM}^{\rm CC}(1-\epsilon_\alpha)\,,$$
$$\sigma_\alpha^{\rm NC} = \sigma_{\alpha,\rm SM}^{\rm NC}(1-\epsilon_\alpha)^2$$

definition of G_μ:

$$G_\mu^2 = G_F^2\,(1-\epsilon_\mu)(1-\epsilon_e)$$

Corrections due to heavy sterile ν's:

- Both tree level (ε's) and loop (S,T,U) effects
- U is tiny
- identical or almost identical parameter combinations

→ cancellations

→ some observables don't change

→ some do ←→ data

$$\frac{\Gamma_{\rm lept}}{[\Gamma_{\rm lept}]_{\rm SM}} = 1 + 0.6\,(\epsilon_e + \epsilon_\mu + 0.0145\,T) - 0.0021\,S\,,$$

$$\frac{\Gamma_{\rm inv}/\Gamma_{\rm lept}}{[\Gamma_{\rm inv}/\Gamma_{\rm lept}]_{\rm SM}} = 1 - 0.67\,(\epsilon_e + \epsilon_\mu + \epsilon_\tau) + 0.0021\,S - 0.0015\,T\,,$$

$$\frac{\sin^2\theta_{\rm w}^{\rm lept}}{[\sin^2\theta_{\rm w}^{\rm lept}]_{\rm SM}} = 1 - 0.72\,(\epsilon_e + \epsilon_\mu + 0.0145\,T) + 0.0016\,S\,,$$

$$\frac{g_L^2}{[g_L^2]_{\rm SM}} = 1 + 0.41\,\epsilon_e - 0.59\,\epsilon_\mu - 0.0090\,S + 0.0022\,T\,,$$

$$\frac{g_R^2}{[g_R^2]_{\rm SM}} = 1 - 1.4\,\epsilon_e - 2.4\,\epsilon_\mu + 0.031\,S - 0.0067\,T\,,$$

$$\frac{M_{\rm W}}{[M_{\rm W}]_{\rm SM}} = 1 + 0.11\,\epsilon_e + 0.11\,\epsilon_\mu - 0.0036\,S + 0.0056\,T + 0.0042\,U$$

• Details…

$$T_{\rm tot} = T_N + T_{\rm SM} = -\frac{1}{8\pi s_w^2 M_W^2}$$
$$\times \Big[\sum_{i,j=1}^{3+n}\sum_{\alpha\beta} \mathbf{U}^\dagger_{i\alpha}\mathbf{U}_{\alpha j}\mathbf{U}^\dagger_{j\beta}\mathbf{U}_{\beta i}\, Q(0,m_i^2,m_j^2)$$
$$+ \sum_{i,j=1}^{3+n}\sum_{\alpha\beta} \mathbf{U}^\dagger_{i\alpha}\mathbf{U}_{\alpha j}\mathbf{U}^\dagger_{i\beta}\mathbf{U}_{\beta j} m_i m_j B_0(0,m_i^2,m_j^2)$$
$$- 2\sum_{i=1}^{3+n}\sum_{\alpha} \mathbf{U}^\dagger_{i\alpha}\mathbf{U}_{\alpha i}\, Q(0,m_i^2,m_\alpha^2)$$
$$+ \sum_\alpha m_\alpha^2 B_0(0,m_\alpha^2,m_\alpha^2)\Big]\,, \quad (1$$

$$S_{\rm tot} = S_N + S_{\rm SM} = -\frac{1}{2\pi M_Z^2}$$
$$\times \Big[\sum_{i,j=1}^{3+n}\sum_{\alpha\beta} \mathbf{U}^\dagger_{i\alpha}\mathbf{U}_{\alpha j}\mathbf{U}^\dagger_{j\beta}\mathbf{U}_{\beta i}\, \Delta Q(M_Z^2,m_i^2,m_j^2)$$
$$+ \sum_{i,j=1}^{3+n}\sum_{\alpha\beta} \mathbf{U}^\dagger_{i\alpha}\mathbf{U}_{\alpha j}\mathbf{U}^\dagger_{i\beta}\mathbf{U}_{\beta j} m_i m_j \Delta B_0(M_Z^2,m_i^2,m_j^2)$$
$$+ \sum_\alpha m_\alpha^2 B_0(0,m_\alpha^2,m_\alpha^2) + \sum_\alpha Q(M_Z^2,m_\alpha^2,m_\alpha^2)$$
$$- 2\sum_\alpha m_\alpha^2 B_0(M_Z^2,m_\alpha^2,m_\alpha^2)\Big]\,, \quad (20)$$

$$U_{\rm tot} = U_N + U_{\rm SM} = \frac{1}{2\pi M_Z^2}$$
$$\times \Big[\sum_{i,j=1}^{3+n}\sum_{\alpha\beta} \mathbf{U}^\dagger_{i\alpha}\mathbf{U}_{\alpha j}\mathbf{U}^\dagger_{j\beta}\mathbf{U}_{\beta i}\, \Delta Q(M_Z^2,m_i^2,m_j^2)$$
$$+ \sum_{i,j=1}^{3+n}\sum_{\alpha\beta} \mathbf{U}^\dagger_{i\alpha}\mathbf{U}_{\alpha j}\mathbf{U}^\dagger_{i\beta}\mathbf{U}_{\beta j} m_i m_j \Delta B_0(M_Z^2,m_i^2,m_j^2)$$
$$+ \sum_\alpha m_\alpha^2 B_0(0,m_\alpha^2,m_\alpha^2) - \sum_\alpha Q(M_Z^2,m_\alpha^2,m_\alpha^2)$$
$$- 2\sum_\alpha m_\alpha^2 B_0(M_Z^2,m_\alpha^2,m_\alpha^2)$$
$$- 2(M_Z/M_W)^2\sum_\alpha \mathbf{U}^\dagger_{i\alpha}\mathbf{U}_{\alpha i}\Delta Q(M_W^2,m_i^2,m_\alpha^2)\Big]\,. \quad (21)$$

$$Q(q^2,m_1^2,m_2^2) \equiv (D-2)B_{22}(q^2,m_1^2,m_2^2) + q^2\left[B_1(q^2,m_1^2,m_2^2) + B_{21}(q^2,m_1^2,m_2^2)\right]$$

B_0, B_1, B_{21} and B_{22}

are the he usual loop functions

Results of global Fits to all Data

- **Assume Lagrangian including see-saw type I ←→ parameter relations**
- **All data: LFV, LHC, EWPO and active neutrinos and consider 3 tyical mass spectra**

$$\sin^2\theta_{12} = 0.30 \pm 0.013\,,$$
$$\sin^2\theta_{23} = 0.41^{+0.037}_{-0.025}\,,$$
$$\sin^2\theta_{13} = 0.023 \pm 0.0023\,,$$
$$\delta_{CP} = 300^{+66}_{-138}\,,$$

	NH	IH	QD
m_1 (eV)	~ 0	$4.85 \cdot 10^{-2}$	~ 0.1
m_2 (eV)	$8.660 \cdot 10^{-3}$	$4.93 \cdot 10^{-2}$	~ 0.1
m_3 (eV)	$4.97 \cdot 10^{-2}$	~ 0	~ 0.1

- **Quality of fit:**

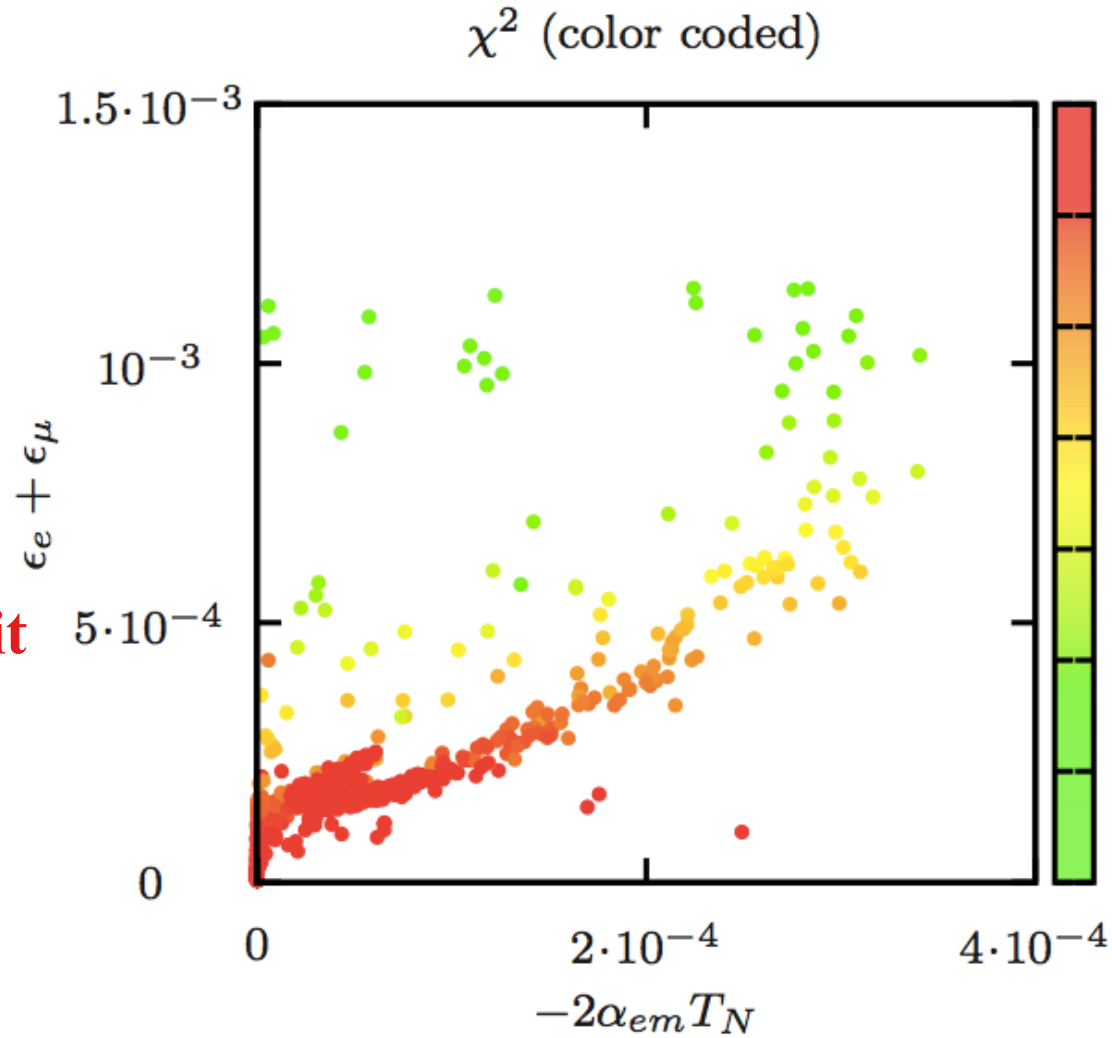
$$\chi^2_{\mathrm{EWPO}} = \sum_i \frac{(O_i - O_{i,\mathrm{SM}})^2}{(\delta O_i)^2 + (\delta O_{i,\mathrm{SM}})^2}$$

Some Examples

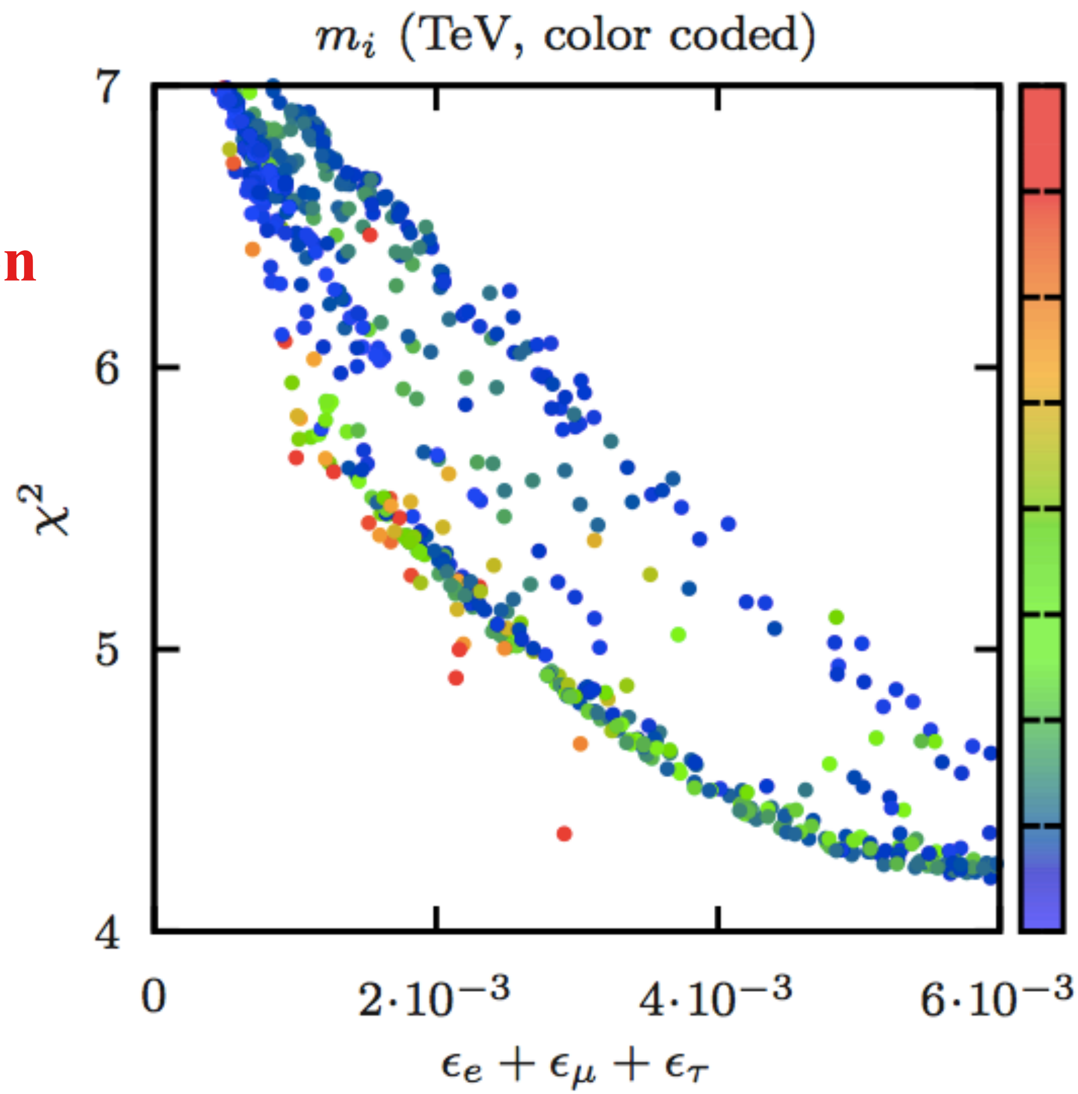
NH, $\chi 2$ for 4 d.o.f.
fit to all EWPOs

→ overall $\chi 2$/dof goes
from $\underline{\sim}$ 2 to $\underline{\sim}$1
for $\varepsilon_e + \varepsilon_\mu \sim 10^{-3}$

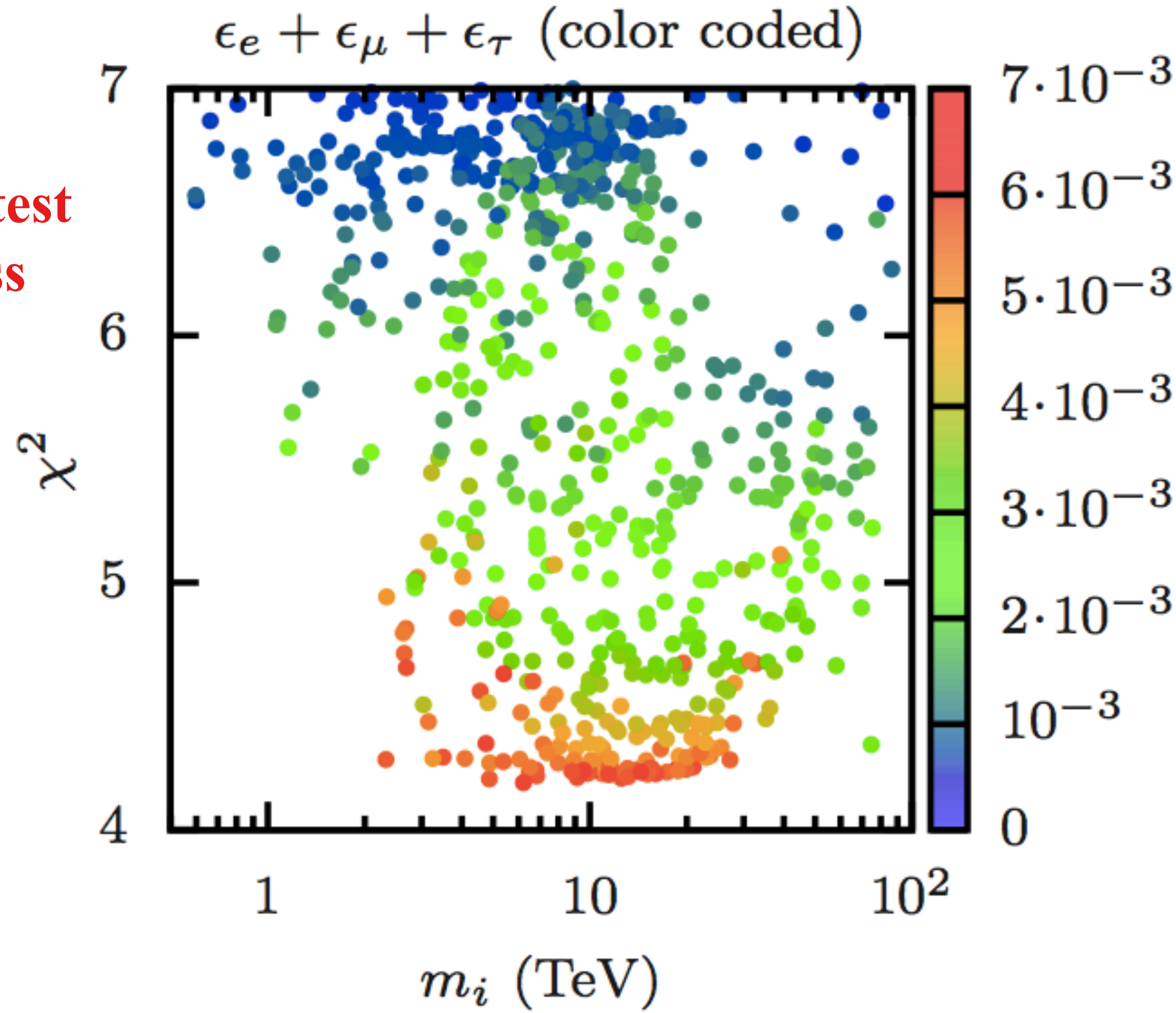
→ sterile ν's improve fit



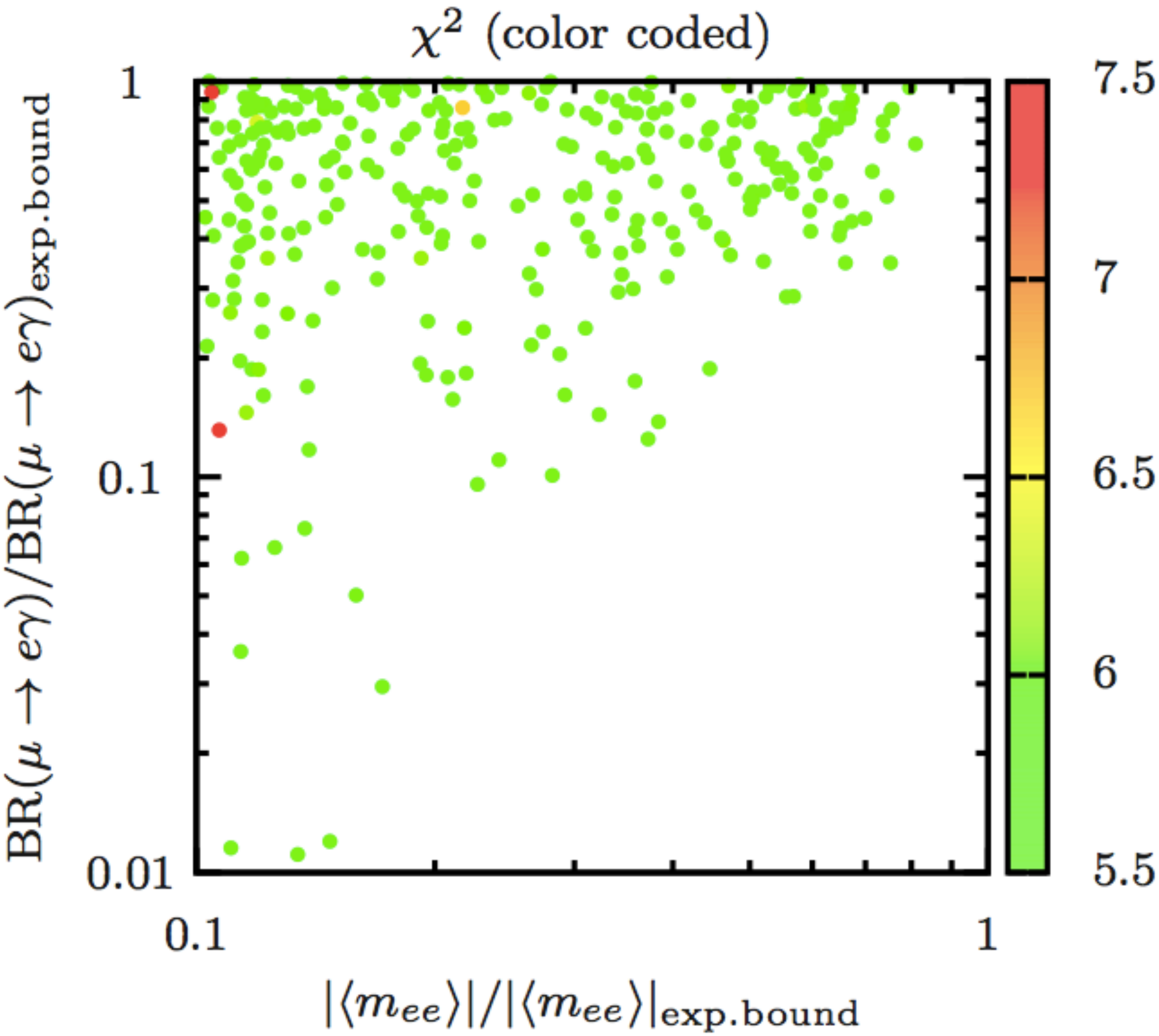
NH, the lightest heavy neutrino mass as function of $\chi 2$ and $\varepsilon_e + \varepsilon_\mu + \varepsilon_\tau$ for 4dof



NH, $\varepsilon_e + \varepsilon_\mu + \varepsilon_\tau$ as a function of the lightest heavy neutrino mass for 4dof



IH,
double beta decay
and μ→ eγ limits
for 4dof



Which Improvements

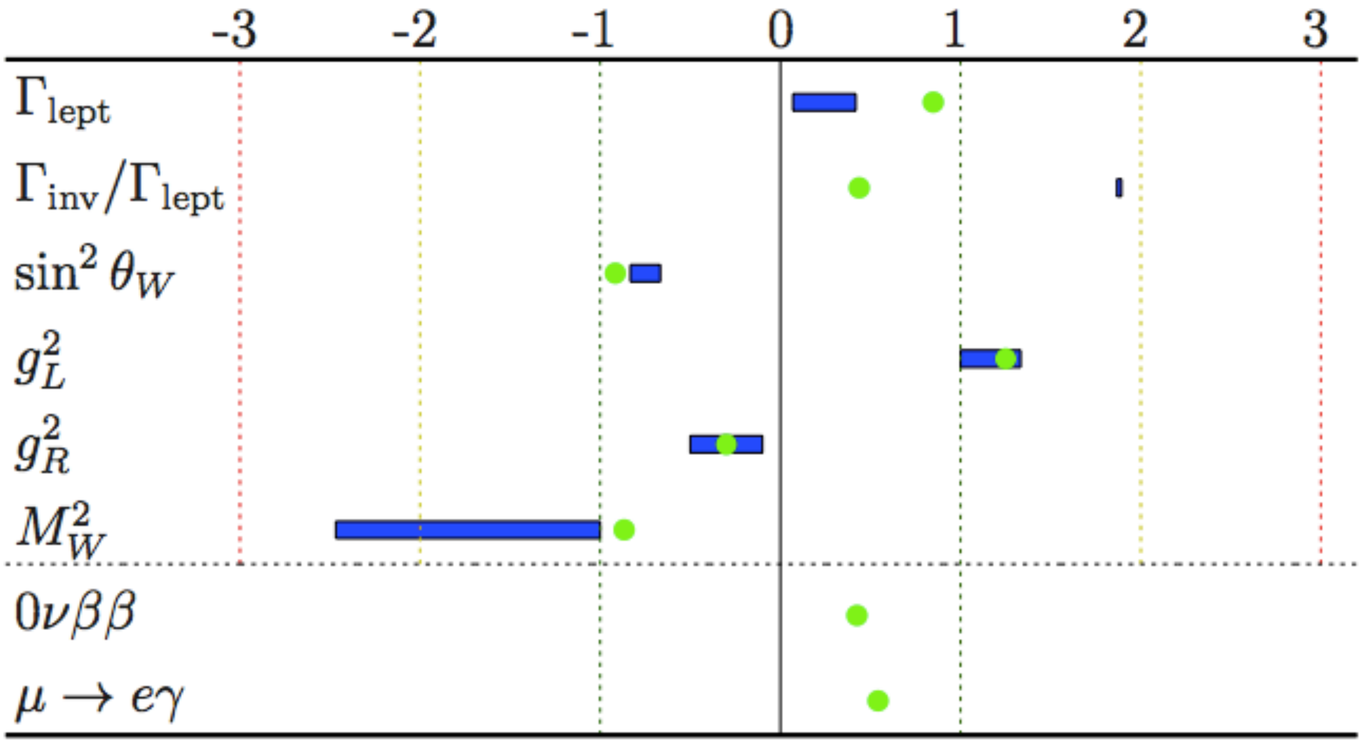
Agreement with data=0 + 1,2,3 σ ; assumed scenario: NH

SM best fit → blue bars

best fit with steril n's → green points

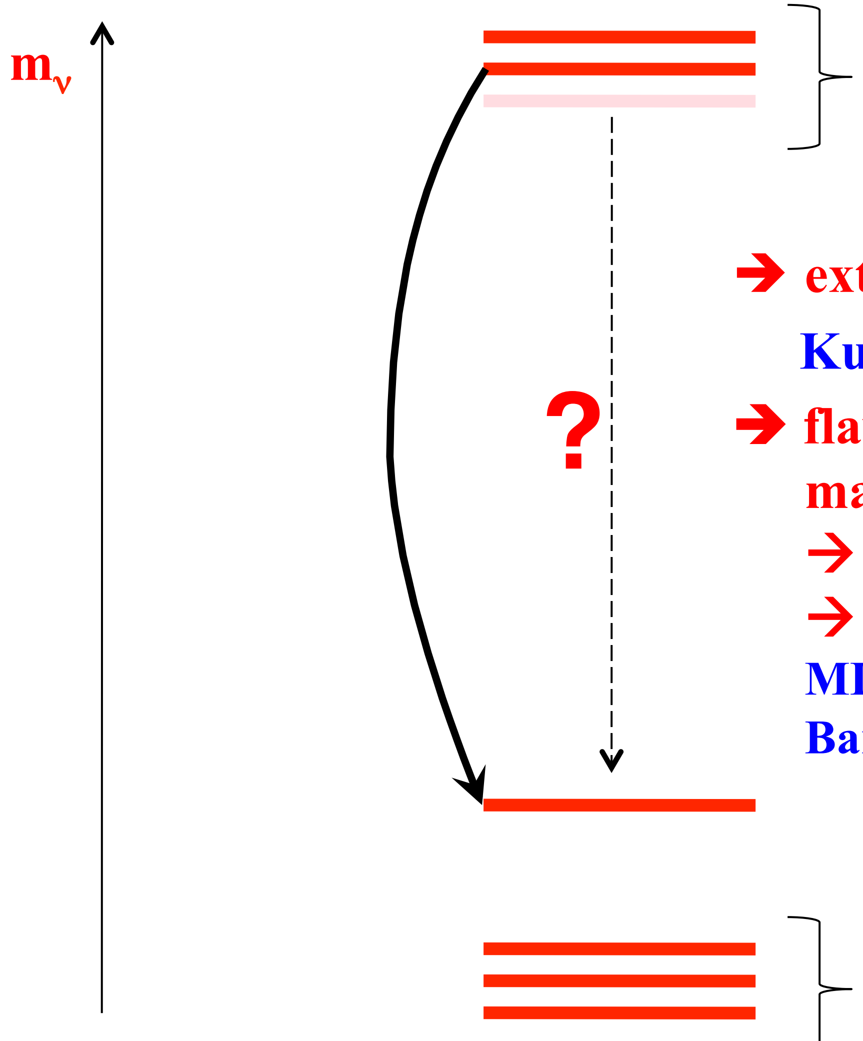
M_1 = 20.3 TeV, M_2 = 14.1 TeV, M_3 = 21.0 TeV,

$\varepsilon_e = 2.1\cdot10^{-3}$, $\varepsilon_\mu = 3.0\cdot10^{-6}$ and $\varepsilon_\tau = 4.5\cdot10^{-3}$



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

Conclusions

- Different indications / motivations for sterile neutrinos
  → what about masses O(TeV)?
- Interesting cancellations between tree and loop effects of heavy sterile neutrinos
- Heavy sterile neutrinos improve global fits to all data and reduces tensions: deviation of Z-width, NuTeV, global
- Mass range from a few hundred GeV to 100 TeV
- $O(10^{-3})$ mixings
- Natural theoretical explanation of the spectrum required
  → eV and keV states might also be explained
  → interesting possibilities / combinations