Sterile neutrinos from low energy to the GUT scale

Max-Planck-Institut
für Kernphysik

Werner Rodejohann

Erice

17/09/13

ν

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

erc

MANITOP
Massive Neutrinos: Investigating their
Theoretical Origin and Phenomenology

Outline

- General aspects and phenomenology
  - What is a sterile neutrino?
  - What is its mass?
  - 3 (4) well motivated scales and some phenomenology
    - eV
    - keV
    - (TeV)
    - heavy
- Models for light sterile neutrinos: 3 ways to make them light

What is a sterile neutrino?

SM contains 3 active neutrinos with isospin $\frac{1}{2}$

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L , \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L , \quad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L$$

their CP-partners are also active:

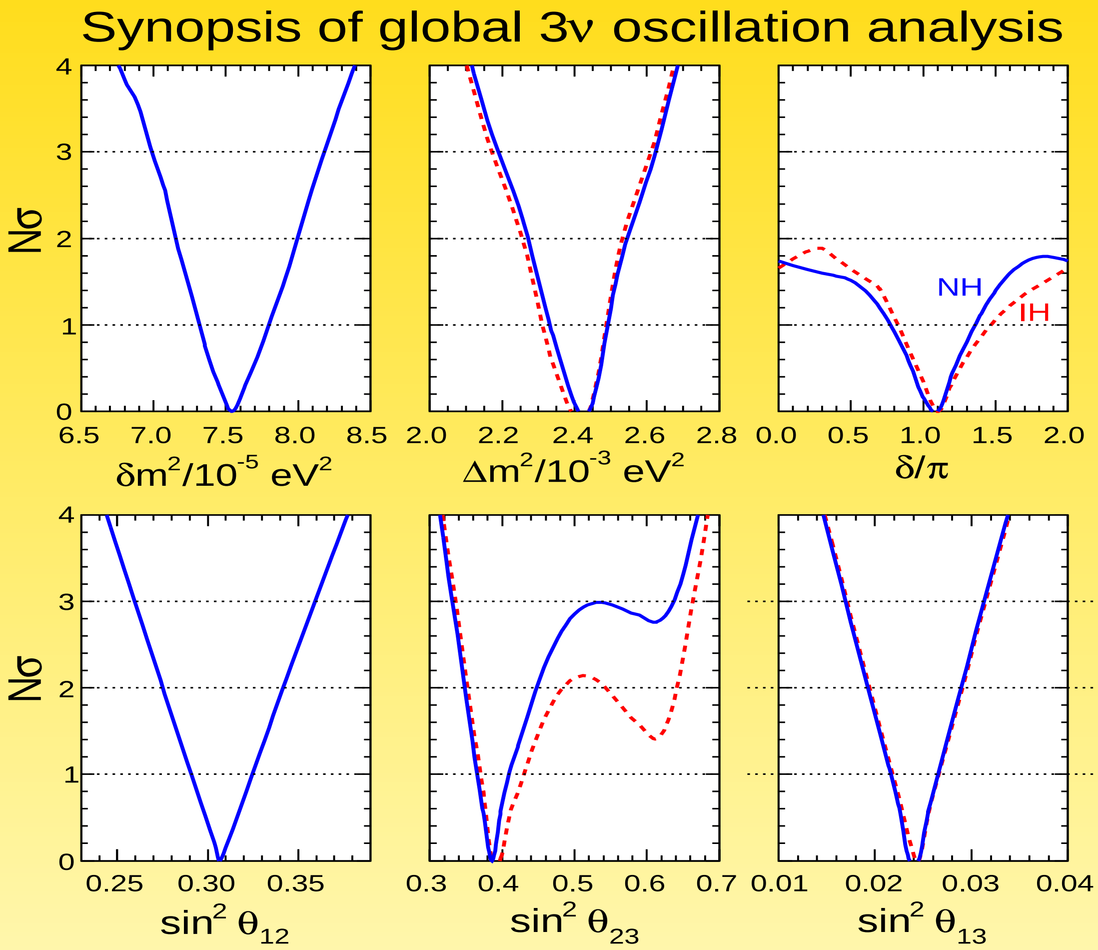
$$\begin{pmatrix} e^+ \\ \bar{\nu}_e \end{pmatrix}_R , \quad \begin{pmatrix} \mu^+ \\ \bar{\nu}_\mu \end{pmatrix}_R , \quad \begin{pmatrix} \tau^+ \\ \bar{\nu}_\tau \end{pmatrix}_R$$

the $(\nu_{e,\mu,\tau})_L$ and $(\bar{\nu}_{e,\mu,\tau})_R$ take part in weak interactions = couple to W, Z

What is a sterile neutrino?

- add a fourth state to the game, but don't give it isospin!
  $\Rightarrow$ **a sterile neutrino** ν_s
- a sterile neutrino ν_s does NOT take part in weak interactions = does NOT couple to W, Z
- can mix with active neutrinos
- can couple to Higgs
- can couple to BSM physics

Neutrino Physics: Status of global fits



`Fogli, Lisi` *et al.*`, June 2012`

Lessons

- consistent picture emerging
- there are 3 generation effects!
- about 2σ hint for $\theta_{23} < \pi/4$
- about 1σ hint for $\delta \neq 0$
- no hint for hierarchy
- future program of LBL experiments to pin down, make more precise
- all is well…?

Light Sterile Neutrinos

$\leftrightarrow$ is there an additional **sterile** state at $\Delta m^2 \sim$ eV^2 and mixing $\mathcal{O}(0.1)$?

- LSND ($\overline{\nu}_\mu \to \overline{\nu}_e$) 3.8σ
- MiniBooNE ($\overline{\nu}_\mu \to \overline{\nu}_e$ and $\nu_\mu \to \nu_e$) 3.8σ
- Gallium anomaly ($\nu_e \to \nu_e$) 2.9σ
- reactor anomaly ($\overline{\nu}_e \to \overline{\nu}_e$) 2.8σ
- cosmology and astroparticle physics

Sterile Neutrinos: Disappearance vs. Appearance

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

$$P(\nu_\mu \to \nu_e) = 4\,|U_{e4}|^2\,|U_{\mu 4}|^2\,\sin^2 \tfrac{\Delta m_{41}^2}{4E} L$$

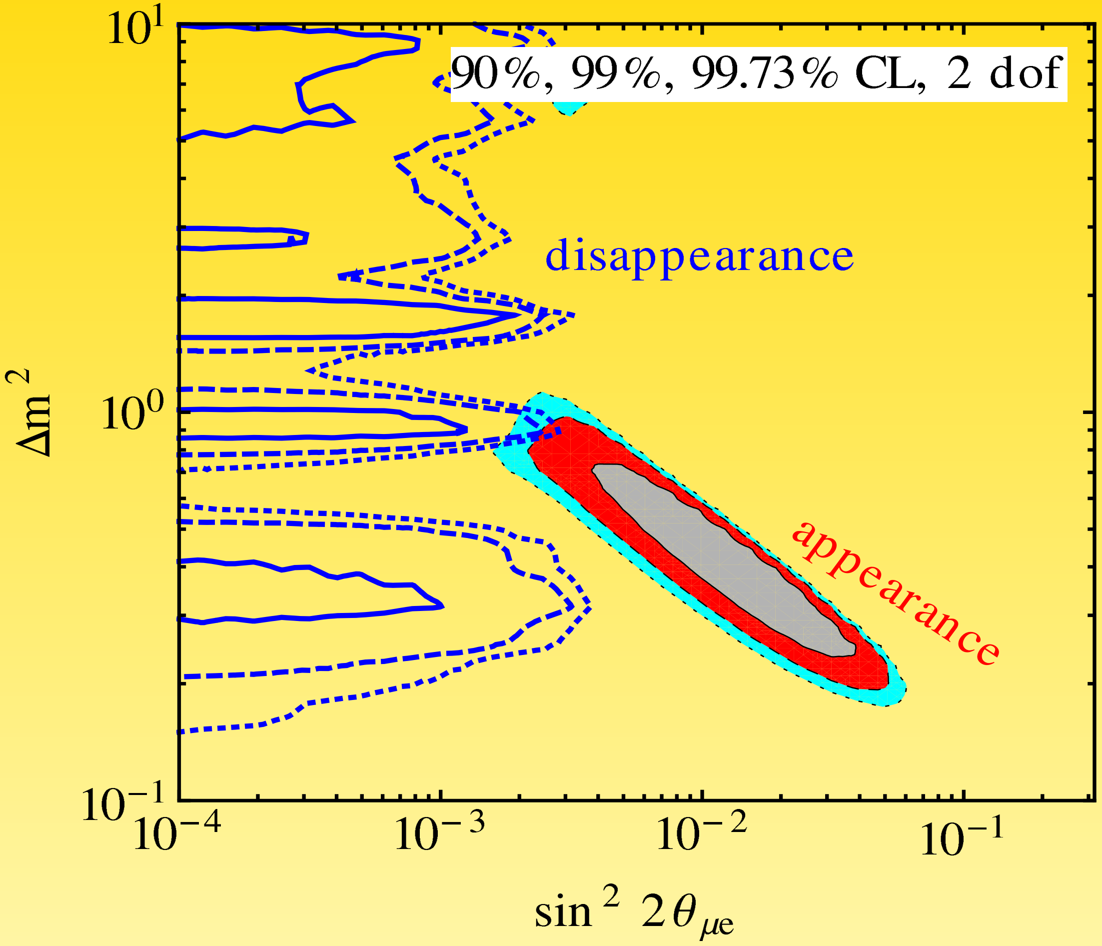
$$P(\nu_e \to \nu_e) = 1 - 4\,|U_{e4}|^2 (1 - |U_{e4}|^2)\,\sin^2 \tfrac{\Delta m_{41}^2}{4E} L$$

$$P(\nu_\mu \to \nu_\mu) = 1 - 4\,|U_{\mu 4}|^2 (1 - |U_{\mu 4}|^2)\,\sin^2 \tfrac{\Delta m_{41}^2}{4E} L$$

$\Rightarrow$ if $\nu_\mu \to \nu_e$, then there should be $\nu_e \to \nu_e$ and $\nu_\mu \to \nu_\mu$

$\Leftrightarrow$ tension between appearance and disappearance data…

Sterile Neutrinos: Disappearance vs. Appearance

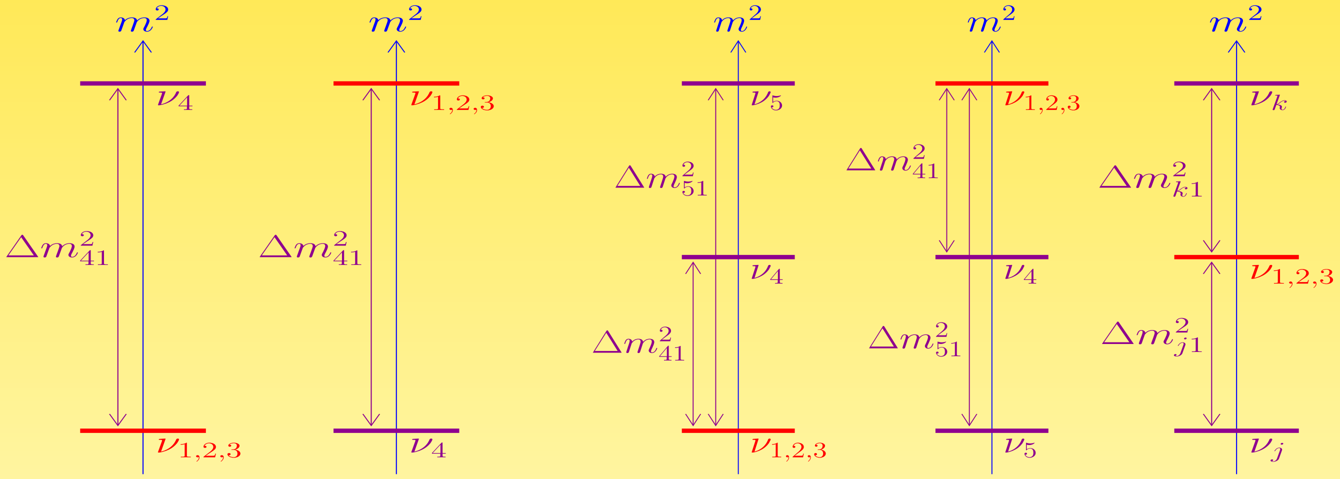


some overlap at 99 % CL, consistency has p-value $\simeq 10^{-4} \ldots$

Kopp, Machado, Maltoni, Schwetz, 1303.3031

Sterile Neutrinos: more than one?

- does not help much for tension between appearance and disappearance
- mass ordering? 3+2 or 1+3+1



Sterile Neutrinos: Typical Values

	Δm^2_{41}	$\lvert U_{e4}\rvert$	$\lvert U_{\mu4}\rvert$	Δm^2_{51}	$\lvert U_{e5}\rvert$	$\lvert U_{\mu5}\rvert$	$\gamma_{\mu e}$	p(app./dis.)
3+1	0.93	0.15	0.17					1.2×10^{-4}
3+2	0.47	0.13	0.15	0.87	0.14	0.13	-0.15π	3.4×10^{-5}
1+3+1	-0.87	0.15	0.13	0.47	0.13	0.17	0.06π	2.1×10^{-3}

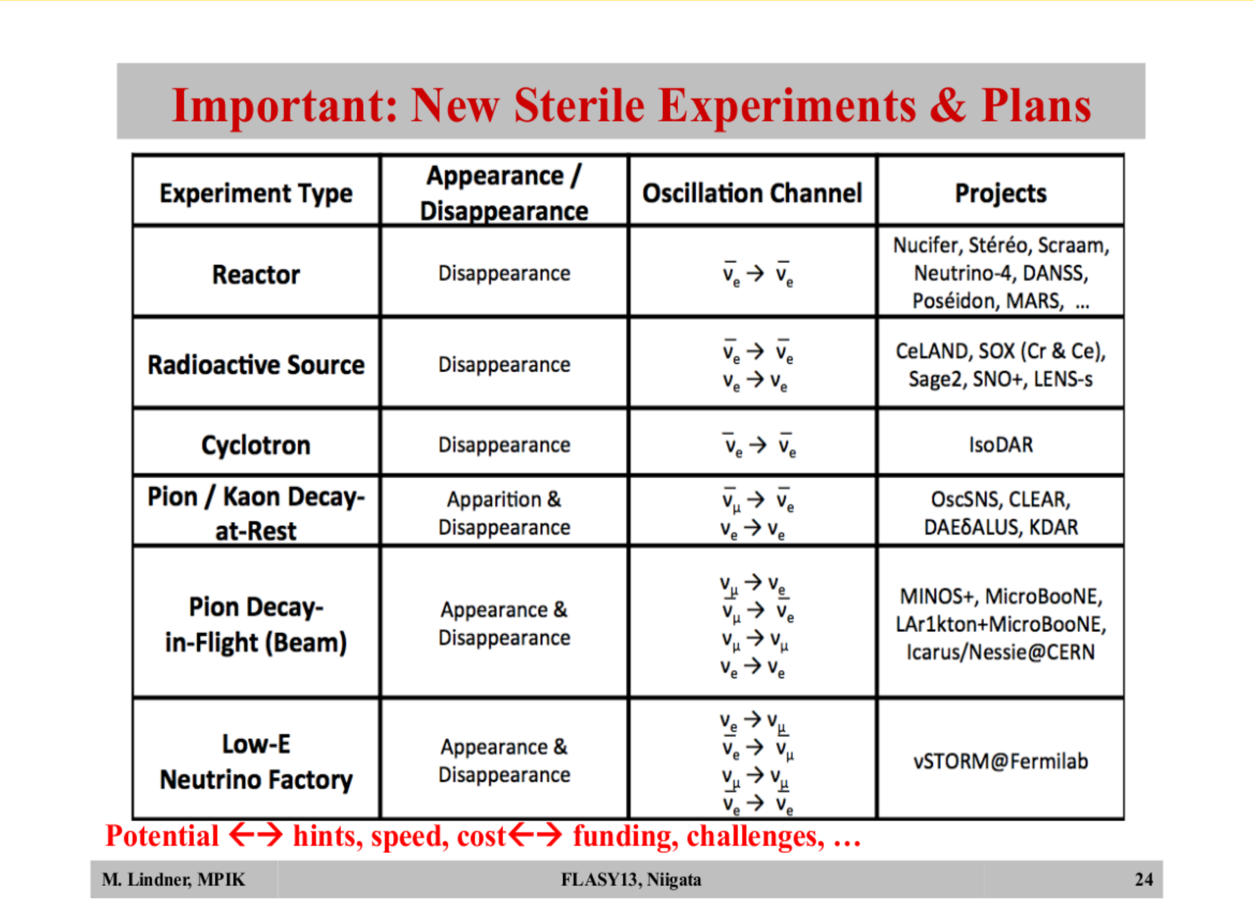
Kopp, Machado, Maltoni, Schwetz, 1303.3031

$$\begin{aligned} P^{\rm SBL}_{\nu_\alpha\to\nu_\beta} = {} & 4\,|U_{\alpha4}|^2|U_{\beta4}|^2\,\sin^2\phi_{41} + 4\,|U_{\alpha5}|^2|U_{\beta5}|^2\,\sin^2\phi_{51} \\ & + 8\,|U_{\alpha4}U_{\beta4}U_{\alpha5}U_{\beta5}|\,\sin\phi_{41}\sin\phi_{51}\cos(\phi_{54}-\gamma_{\alpha\beta}) \end{aligned}$$

$$\phi_{ij} \equiv \frac{\Delta m^2_{ij} L}{4E}\,, \qquad \gamma_{\alpha\beta} \equiv \arg\left(I_{\alpha\beta54}\right)\,, \qquad I_{\alpha\beta ij} \equiv U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}$$

experimental tests: talk by Karsten Heeger...

Experiments. . .



Important: New Sterile Experiments & Plans

Experiment Type	Appearance / Disappearance	Oscillation Channel	Projects
Reactor	Disappearance	$\bar{\nu}_e \rightarrow \bar{\nu}_e$	Nucifer, Stéréo, Scraam, Neutrino-4, DANSS, Poséidon, MARS, ...
Radioactive Source	Disappearance	$\bar{\nu}_e \rightarrow \bar{\nu}_e$ $\nu_e \rightarrow \nu_e$	CeLAND, SOX (Cr & Ce), Sage2, SNO+, LENS-s
Cyclotron	Disappearance	$\bar{\nu}_e \rightarrow \bar{\nu}_e$	IsoDAR
Pion / Kaon Decay-at-Rest	Apparition & Disappearance	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ $\nu_e \rightarrow \nu_e$	OscSNS, CLEAR, DAEδALUS, KDAR
Pion Decay-in-Flight (Beam)	Appearance & Disappearance	$\nu_\mu \rightarrow \nu_e$ $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ $\nu_\mu \rightarrow \nu_\mu$ $\nu_e \rightarrow \nu_e$	MINOS+, MicroBooNE, LAr1kton+MicroBooNE, Icarus/Nessie@CERN
Low-E Neutrino Factory	Appearance & Disappearance	$\nu_e \rightarrow \nu_\mu$ $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$ $\nu_\mu \rightarrow \nu_\mu$ $\bar{\nu}_e \rightarrow \bar{\nu}_e$	νSTORM@Fermilab

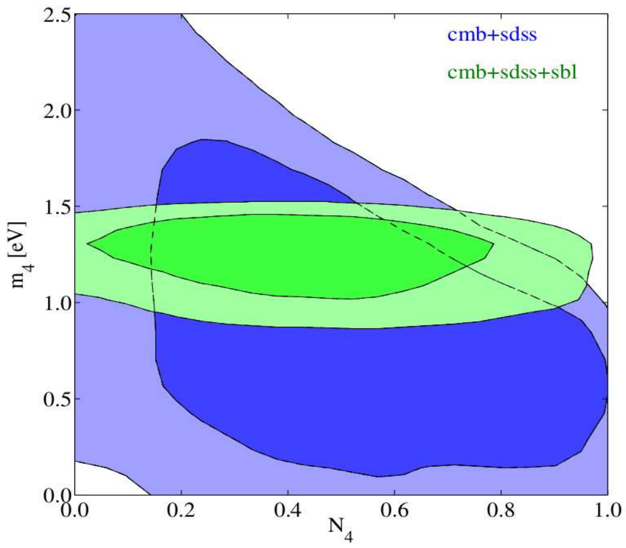
Potential ←→ hints, speed, cost←→ funding, challenges, …

M. Lindner, MPIK FLASY13, Niigata 24

See also `Light Sterile Neutrinos: A White Paper, 1204.5379`

Motivation for Sterile Neutrinos: Cosmology

- CMB and power matter spectrum prefer $N_{\text{eff}} > 3$
- BBN prefers $N_{\text{eff}} > 3$
- Planck: $N_{\text{eff}} = 3.5 \pm 0.5$



`Giunti, Hannestad` *et al.*, `1302.6720, talk by Steen Hannestad`

model-dependent, inconsistent data sets?

can be avoided by asymmetries, new interactions,. . .

Phenomenology of eV steriles: β-decays

with non-zero U_{e4} and m_4:

- Kurie-plot experiments:

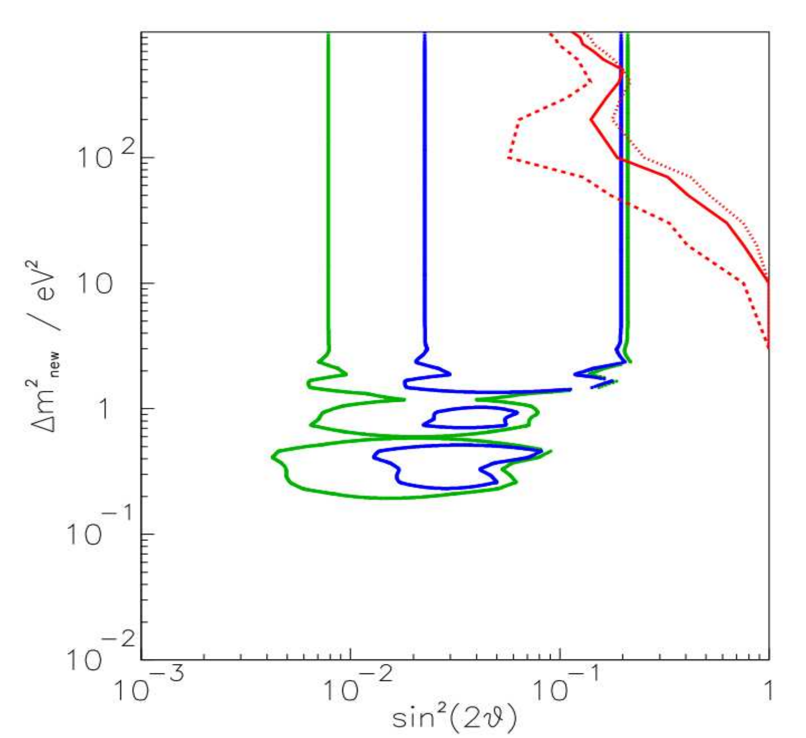
$$m_\beta^2 = |U_{e1}|^2\, m_1^2 + |U_{e2}|^2\, m_2^2 + |U_{e3}|^2\, m_3^2 + |U_{e4}|^2\, m_4^2 \leq (2.2\,\mathrm{eV})^2$$

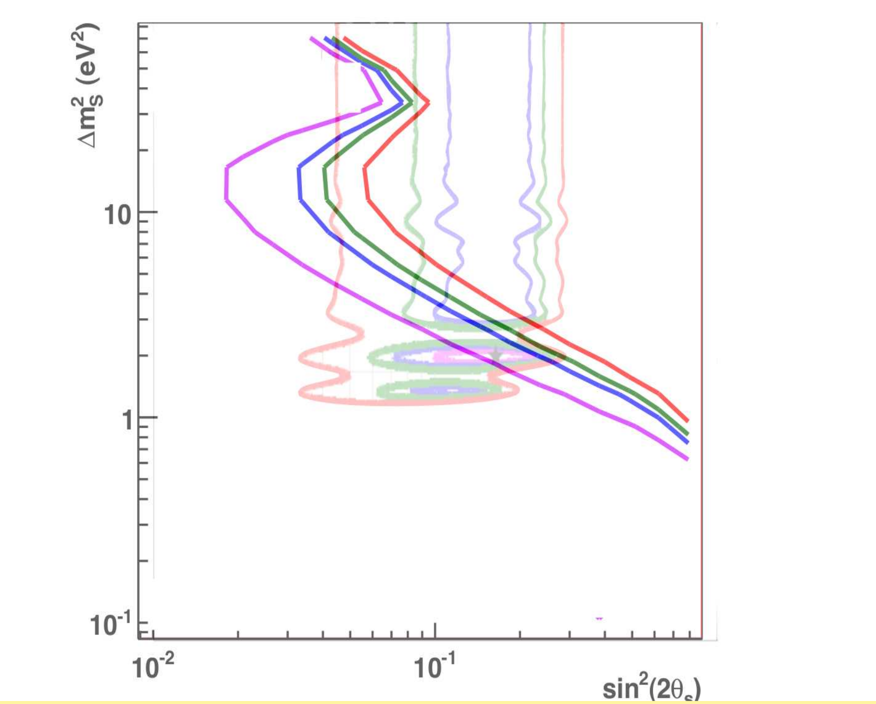
- neutrinoless double beta decay experiments:

$$|m_{ee}| = \left|U_{e1}^2\, m_1 + U_{e2}^2\, m_2 + U_{e3}^2\, m_3 + U_{e4}^2\, m_4\right| \leq 0.3\,\mathrm{eV}$$

Phenomenology of eV steriles

Neutrino mass observables: β decays



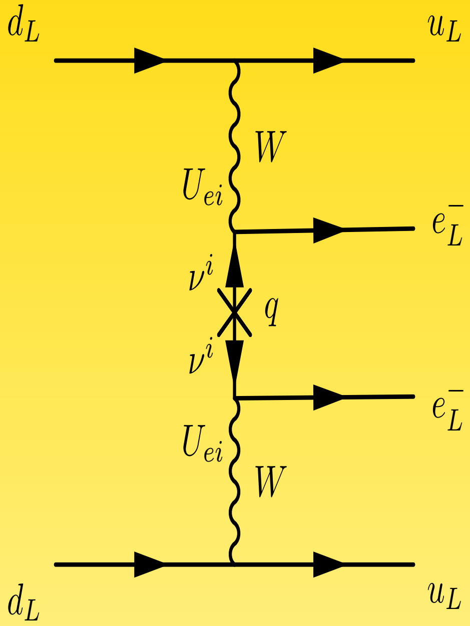


Mainz

Sejersen Riis, Hannestad;

Formaggio, Barret

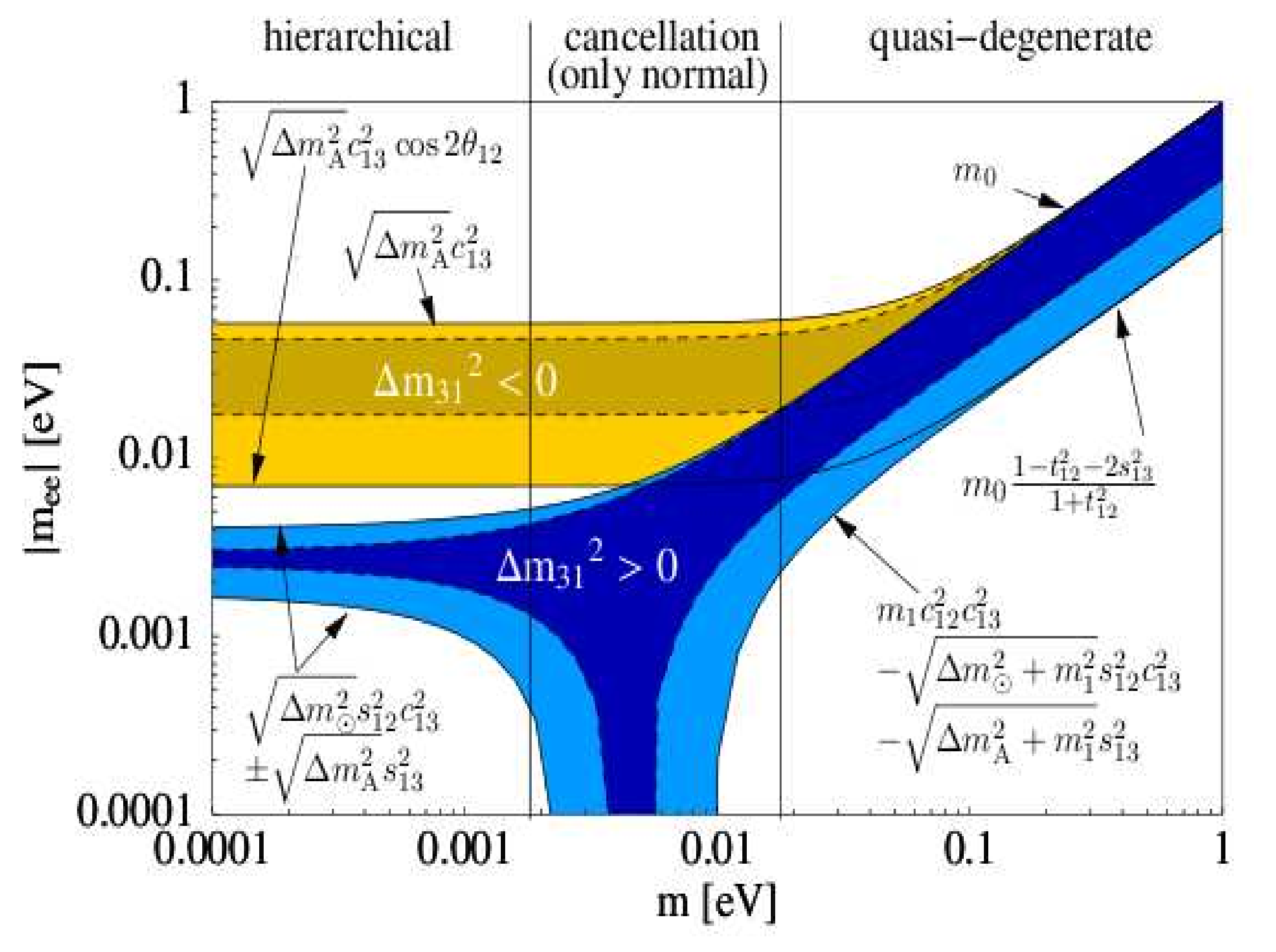
Neutrinoless double beta decay: $nn \rightarrow pp\, e^- e^-$



Amplitude proportional to

$$\frac{U_{ei}^2\, m_i}{q^2 - m_i^2} \propto \begin{cases} U_{ei}^2\, m_i & \text{for light neutrinos} \quad q^2 \gg m_i^2 \\ \dfrac{U_{ei}^2}{m_i} & \text{for heavy neutrinos} \quad q^2 \ll m_i^2 \end{cases}$$

The usual plot for double beta decay. . .



Sterile Neutrinos and $0\nu\beta\beta$

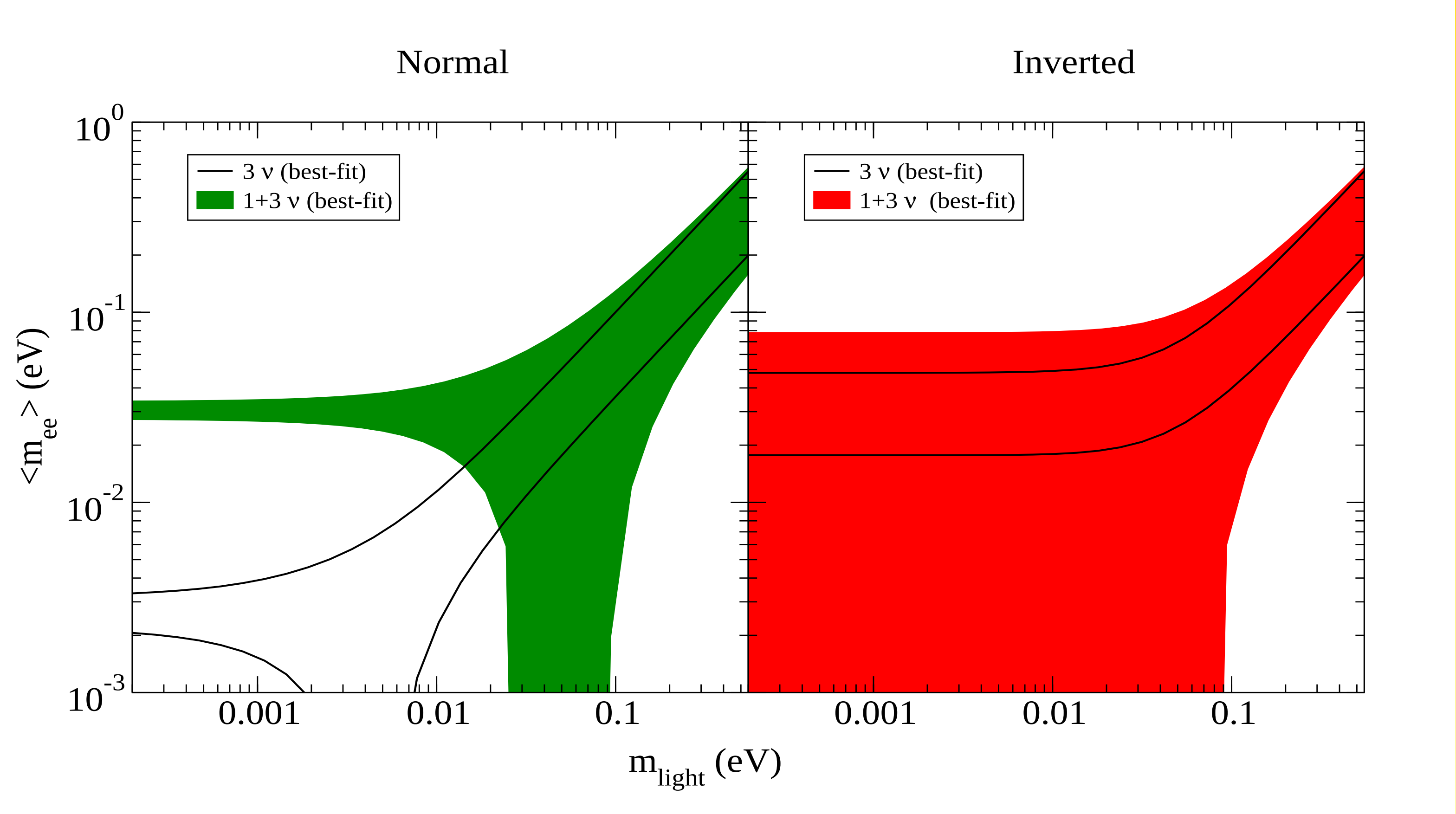
- recall $|m_{ee}|^{\rm act}_{\rm NH}$ can vanish and $|m_{ee}|^{\rm act}_{\rm IH}$ cannot vanish
- $|m_{ee}| = |\underbrace{|U_{e1}|^2 m_1 + |U_{e2}|^2 m_2\, e^{2i\alpha} + |U_{e3}^2| m_3\, e^{2i\beta}}_{m_{ee}^{\rm act}} + \underbrace{|U_{e4}|^2 m_4\, e^{2i\Phi_1}}_{m_{ee}^{\rm st}}|$
- sterile contribution to $0\nu\beta\beta$:

$$|m_{ee}|^{\rm st} \simeq \sqrt{\Delta m^2_{\rm st}}\, |U_{e4}|^2 \left\{ \begin{array}{l} \gg |m_{ee}|^{\rm act}_{\rm NH} \\ \simeq |m_{ee}|^{\rm act}_{\rm IH} \end{array} \right.$$

- $\Rightarrow$ $|m_{ee}|_{\rm NH}$ cannot vanish and $|m_{ee}|_{\rm IH}$ can vanish!

`Barry, W.R., Zhang, JHEP 1107; Giunti` *et al.*`, PRD` **87**`; Girardi, Meroni, Petcov, 1308.5802`

The usual plot for double beta decay. . .
. . . gets completely turned around!



Barry, W.R., Zhang, JHEP 1107; Giunti *et al.*, PRD **87**; Girardi, Meroni, Petcov, 1308.5802

Other Sterile Neutrinos

- very light $\ll$ eV ($\leftrightarrow$ missing upturn of $P_{ee}^{\odot}$)
- keV ($\leftrightarrow$ Warm Dark Matter)
- $10^{10} \ldots 10^{15}$ GeV ($\leftrightarrow$ GUTs, leptogenesis)
- [TeV ($\leftrightarrow$ LHC)]

What is a sterile neutrino?

- add a fourth state to the game, but don't give it isospin!

  $\Rightarrow$ **a sterile neutrino** ν_s
- a sterile neutrino ν_s does NOT take part in weak interactions = does NOT couple to W, Z
- can mix with active neutrinos
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- can couple to BSM physics

we discuss N_R, the right-handed neutrino of the seesaw mechanism, and assume that it is Majorana, and assume that no other New Physics is there

Seesaw: Formalism

$$\mathcal{L} = \frac{1}{2}(\bar{\nu}_L, \, \bar{N}_R^c) \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix} \begin{pmatrix} \nu_L^c \\ N_R \end{pmatrix}$$

6×6 mass matrix diagonalized by

$$\mathcal{U}_\nu \simeq \begin{pmatrix} 1 - \frac{1}{2}BB^\dagger & B \\ -B^\dagger & 1 - \frac{1}{2}B^\dagger B \end{pmatrix} \begin{pmatrix} U & 0 \\ 0 & V_R \end{pmatrix} \quad \text{with } B = m_D M_R^{-1}$$

light neutrino mass matrix:

$$m_\nu = -m_D \, M_R^{-1} \, m_D^T = U \, \mathrm{diag}(m_1, m_2, m_3) \, U^T$$

heavy neutrino mass matrix:

$$M_R = V_R \, \mathrm{diag}(M_1, M_2, M_3) \, V_R^T$$

N_R is a *sterile neutrino*

What is the mass of a Sterile Neutrino?

total mass term for active neutrinos and sterile neutrino(s):

$$\mathcal{L} = \frac{1}{2}(\bar{\nu}_L,\, \bar{N}_R^c) \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix} \begin{pmatrix} \nu_L^c \\ N_R \end{pmatrix}$$

Question: WHAT IS THE SCALE OF M_R?

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two good ideas for M_R:

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- SM singlet, not protected by v, hence GUT-scale, or $B - L$ breaking scale, or Planck-scale ⇒ naturally large
-

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- if M_R is zero, symmetry of the Lagrangian is enlarged ⇒ naturally small

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so, what now?

What is the mass of a Sterile Neutrino?

$$\mathcal{L} = \frac{1}{2}(\bar{\nu}_L,\, \bar{N}_R^c) \left(\begin{array}{cc} 0 & m_D \\ m_D^T & M_R \end{array} \right) \left(\begin{array}{c} \nu_L^c \\ N_R \end{array} \right)$$

special cases:

- $m_D = 0$; **pure Majorana case**
- $M_R = 0$; **pure Dirac case**
- $M_R \gg m_D$; **seesaw case**
- $m_D \gg M_R$; **pseudo-Dirac case**
- $M_D \sim M_R$; **ugly case**

What is the mass of a Sterile Neutrino?

The seesaw limit $M_R \gg m_D$

$$m_\nu = \frac{m_D^2}{M_R}$$

does this fix everything?

No, multiply m_D with x and M_R with x^2: leaves m_ν invariant

Formalism

$$\mathcal{L} = \frac{1}{2}(\bar{\nu}_L,\, \bar{N}_R^c) \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix} \begin{pmatrix} \nu_L^c \\ N_R \end{pmatrix}$$

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3 active neutrinos mix with each other through

$\boxed{N \equiv U\left(1 - \frac{1}{2}BB^\dagger\right)}$ with $B = m_D M_R^{-1}$

3 active neutrinos mix with sterile neutrinos via

$$\boxed{\theta_{\alpha i} = (m_D\, M_R^{-1}\, V_R)_{\alpha i} = \frac{[m_D V_R^*]_{\alpha i}}{M_i} = \mathcal{O}(\sqrt{m_\nu/M_R})}$$

Consequences

- unitarity violation of PMNS matrix of order $(m_D/M_R)^2$

$$\epsilon_\alpha \equiv \sum_{i\geq 4} |\,(\mathcal{U}_\nu)_{\alpha i}\,|^2 \;\Rightarrow \left\{ \begin{array}{lcl} \epsilon_e - \epsilon_\mu & = & 0.0022 \pm 0.0025 \\ \epsilon_\mu - \epsilon_\tau & = & 0.0017 \pm 0.0038 \\ \epsilon_e - \epsilon_\tau & = & 0.0039 \pm 0.0040 \end{array} \right.$$

`Loinaz` *et al.*, `PRD` **70**

- Lepton flavor violation

$$\mathrm{BR}(\mu \to e\gamma) \propto \left| N^*_{\mu i}\, N_{ei}\, f(m_i/m_W) + \theta^*_{\mu i}\, \theta_{ei}\, g(M_i/m_W) \right|^2 \lesssim 1.1 \times 10^{-8}$$

- neutrinoless double beta decay

$$\sum N^2_{ei}\, m_i \lesssim 0.3 \text{ eV and } \sum \frac{\theta^2_{ei}}{M_i} \lesssim 2 \times 10^{-8} \text{ GeV}^{-1}$$

Sterile Neutrinos, Seesaw and $0\nu\beta\beta$

- if the eV-steriles are from seesaw: individual cancellations in flavor symmetry models, e.g.:

$$U_{e2}^2\, m_2 + U_{e4}^2\, m_4 = 0$$

`Barry, W.R., Zhang, JCAP 1201`

- if seesaw scale is below 100 MeV: No double beta decay!

$$\sum_{i=1}^{6} U_{ei}^2\, m_i = 0 \text{ since } \mathcal{M} = \left(\begin{array}{cc} 0 & m_D \\ m_D^T & M_R \end{array} \right) = U \left(\begin{array}{cc} m_\nu^{\rm diag} & 0 \\ 0 & M_R^{\rm diag} \end{array} \right) U^T$$

`de Gouvea, Jenkins, Vasudevan, PRD` **75**

keV steriles as Warm Dark Matter

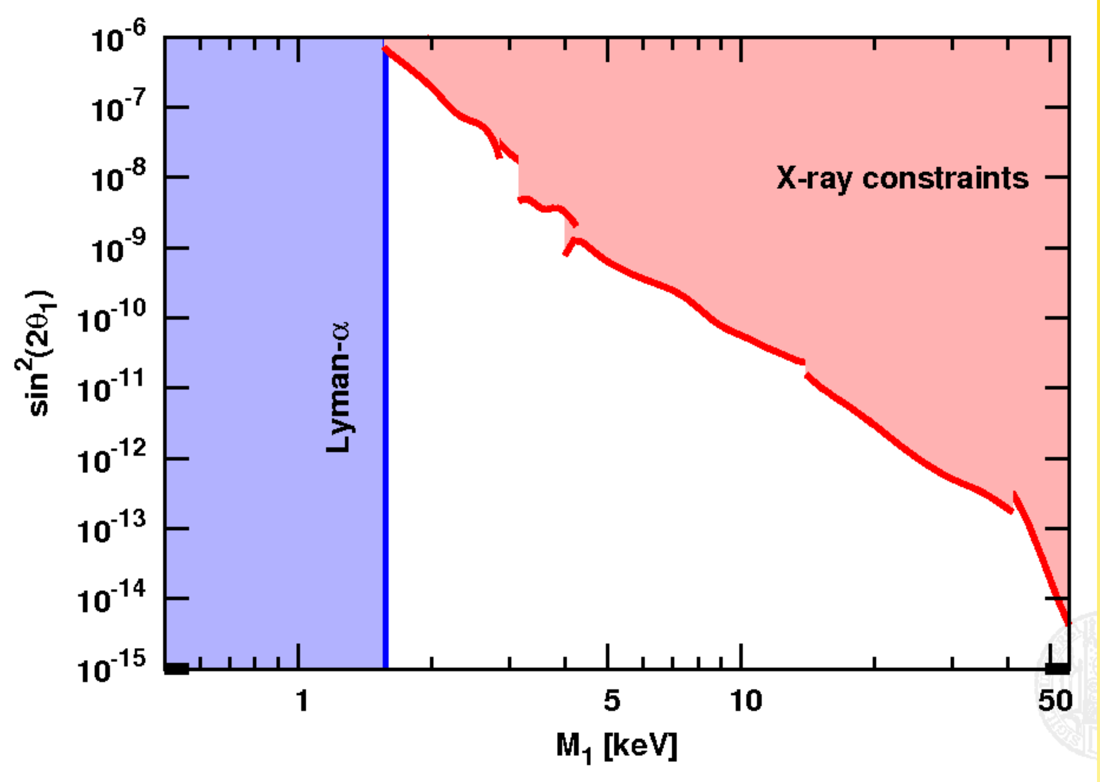
$\rightarrow$ WDM has same large scale structure formation as CDM, but suppresses small scale formations

$\Rightarrow$ predicts less cuspy (=smoother) DM profiles, and less dwarf satellites

keV sterile is excellent candidate

parameters: mass M_1 and mixing θ

- X-ray searches $\Gamma \sim G_F^2 \, M_1^5 \, \theta^2$
- Ly-α: structure formation at low scales $\sim$ MPc
- Tremaine-Gunn
- $\tau \sim \tau_{\rm U}$
- etc.



$m_\nu = \theta^2 M \Rightarrow$ one massless active neutrino! (unless strong cancellations)

`talk by Viollier`

TeV seesaw

naively, $m_\nu = m_D^2/M_R$ and mixing m_D/M_R

$\Rightarrow$ TeV neutrinos have mixing of order 10^{-7}

But, matrices are involved. . .e.g. (`Kersten, Smirnov`)

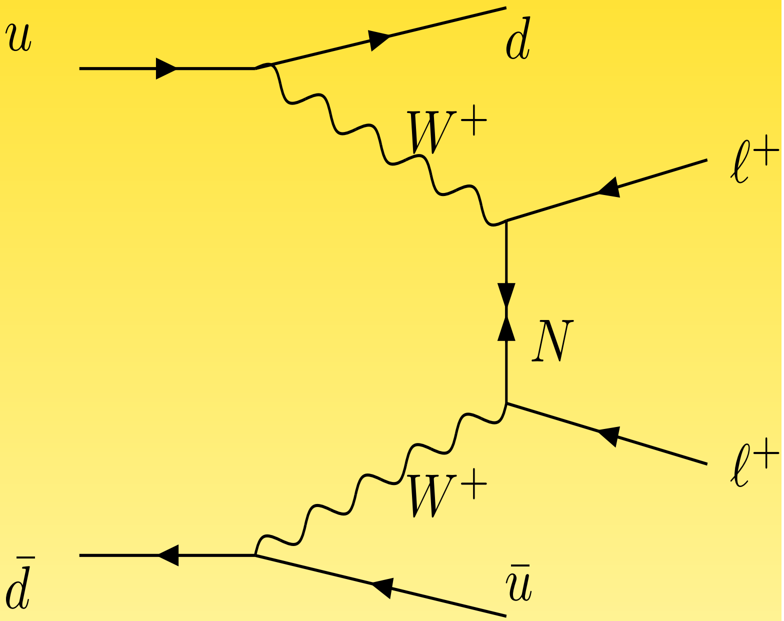
$$m_D = v \begin{pmatrix} h_1 & h_2 & h_3 \\ \omega\, h_1 & \omega\, h_2 & \omega\, h_3 \\ \omega^2\, h_1 & \omega^2\, h_2 & \omega^2\, h_3 \end{pmatrix} = \mathcal{O}(v) \text{ and } M_R = M_0 \mathbb{1} = \mathcal{O}(\mathrm{TeV})$$

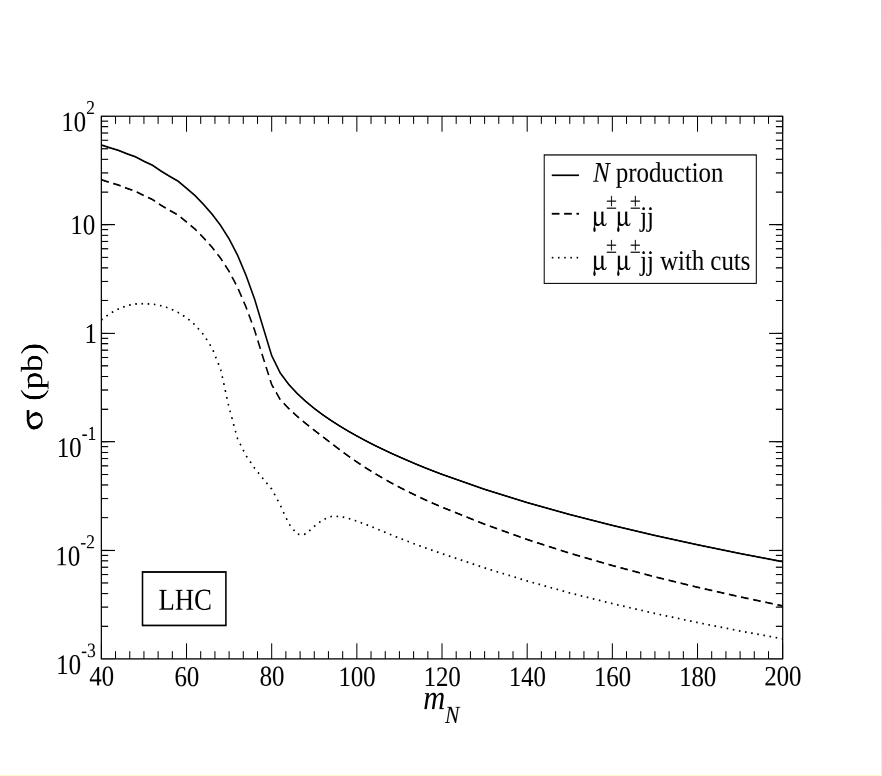
gives $m_\nu = 0$, add (very) small corrections

first pointed out: `Korner, Pilaftsis, Schilcher (1993)`

works with $Y_\nu = \mathcal{O}(1)$, mixing $m_D/M_R = \mathcal{O}(0.1)$ and $M_0 \lesssim$ TeV!

TeV seesaw



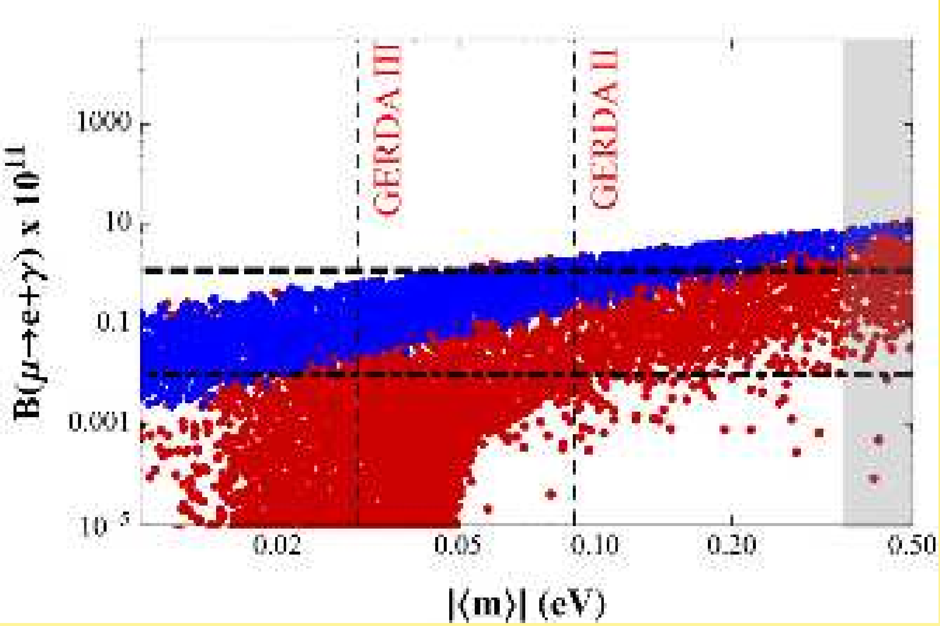


at most $M_i \lesssim 400$ GeV

Han, Zhang; del Aguila, Aguilar-Saavedra, Pittau

TeV scale seesaw with sizable mixing

can saturate LFV and LNV



`Ibarra, Molinaro, Petcov`

TeV scale seesaw with sizable mixing

$$m_D = m \begin{pmatrix} f\epsilon^2 & 0 & 0 \\ 0 & g\epsilon & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad \text{and} \quad M_R^{-1} = M^{-1} \begin{pmatrix} a & b & k \\ b & c & d\epsilon \\ k & d\epsilon & e\epsilon^2 \end{pmatrix}$$

M/GeV	m/MeV	ϵ	a	k	b	c	d	e	f	g
5.00	0.935	0.02	1.00	1.35	0.90	1.4576	0.7942	0.2898	0.0948	0.485

gives successful m_ν and for double beta decay:

$$\frac{T_{1/2}(\text{light})}{T_{1/2}(\text{heavy})} \simeq 10^4$$

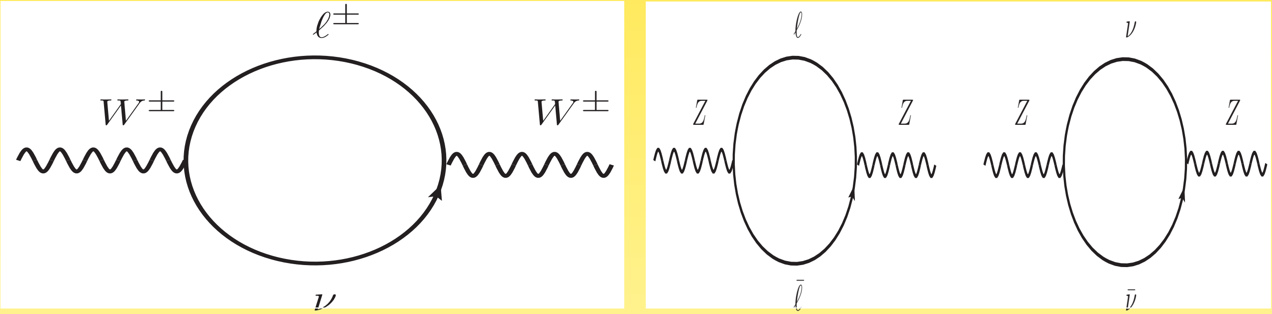
`Mitra, Senjanovic, Vissani`

New motivation for TeV neutrinos?

$$\Gamma_{\rm inv} = \tfrac{1}{3}\Gamma_{\rm inv}^{\rm SM} \sum (1-\epsilon_\alpha)^2$$

$$\sigma(\nu_\alpha q)_{\rm CC} = \sigma(\nu_\alpha q)_{\rm CC}^{\rm SM}\,(1-\epsilon_\alpha)$$

$$\sigma(\nu_\alpha q)_{\rm NC} = \sigma(\nu_\alpha q)_{\rm NC}^{\rm SM}\,(1-\epsilon_\alpha)^2$$



Fit to EWPO: TeV-scale neutrinos with $\epsilon \lesssim 10^{-3}$

`Akhmedov, Kartavtsev, Michaels, Lindner, Smirnov, 1302.1872`

Seesaw with not too diverse mass scales

if m_D/M_R is sizable, NLO corrections to seesaw become relevant:

$$\tilde{m}_\nu = -m_D^T\, M_R^{-1}\, m_D + \tfrac{1}{2} m_D^T\, M_R^{-1}\, X\, M_R^{-1}\, m_D$$
$$\tilde{M}_R = M_R + \tfrac{1}{2} X$$

with $X = A + A^T$ where $A = m_D\, m_D^\dagger\, (M_R^*)^{-1}$

`Grimus, Lavoura, JHEP 0011; Hettmansperger, Lindner, W.R., JHEP 1104`

Examples:

- no correction to $U_{e3} = 0$ and $\theta_{23} = \pi/4$ for μ-τ symmetry
- no correction to $U_{\alpha i}$ if one light neutrino m_i massless
- relevant for inverse, linear, double seesaw

Phenomenology of heavy singlets

recall: for small quartic Higgs coupling $\lambda = m_h/(v\sqrt{2})$ is driven to negative values by top Yukawa:

$$\beta_\lambda \propto -24\,\mathrm{Tr}\left(Y_u^\dagger Y_u\right)^2 \Rightarrow m_h \geq f(\Lambda)$$

vacuum stability bound

currently unclear situation:

- could be $\lambda(M_{\mathrm{Pl}}) = 0$
- vacuum could be stable
- vacuum could be unstable
- vacuum could be metastable

(`Holthausen, Lim, Lindner; Bezrukov` *et al.*; `Strumia` *et al.*; `Masina`)

strong dependence on top mass, threshold corrections, α_s

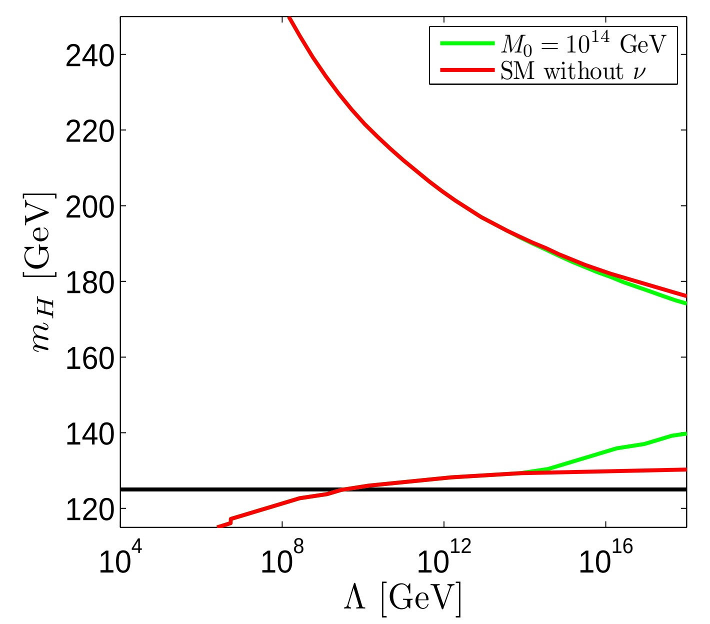
Phenomenology of heavy singlets

often overlooked: Dirac Yukawa $\bar{\nu}_L\, Y_\nu\, N_R$ contribution to λ:

$$\Delta\beta_\lambda = -8\,\mathrm{Tr}\left(Y_\nu^\dagger Y_\nu\right)^2$$

`Casas` *et al.*; `Strumia` *et al.*; `W.R., Zhang`

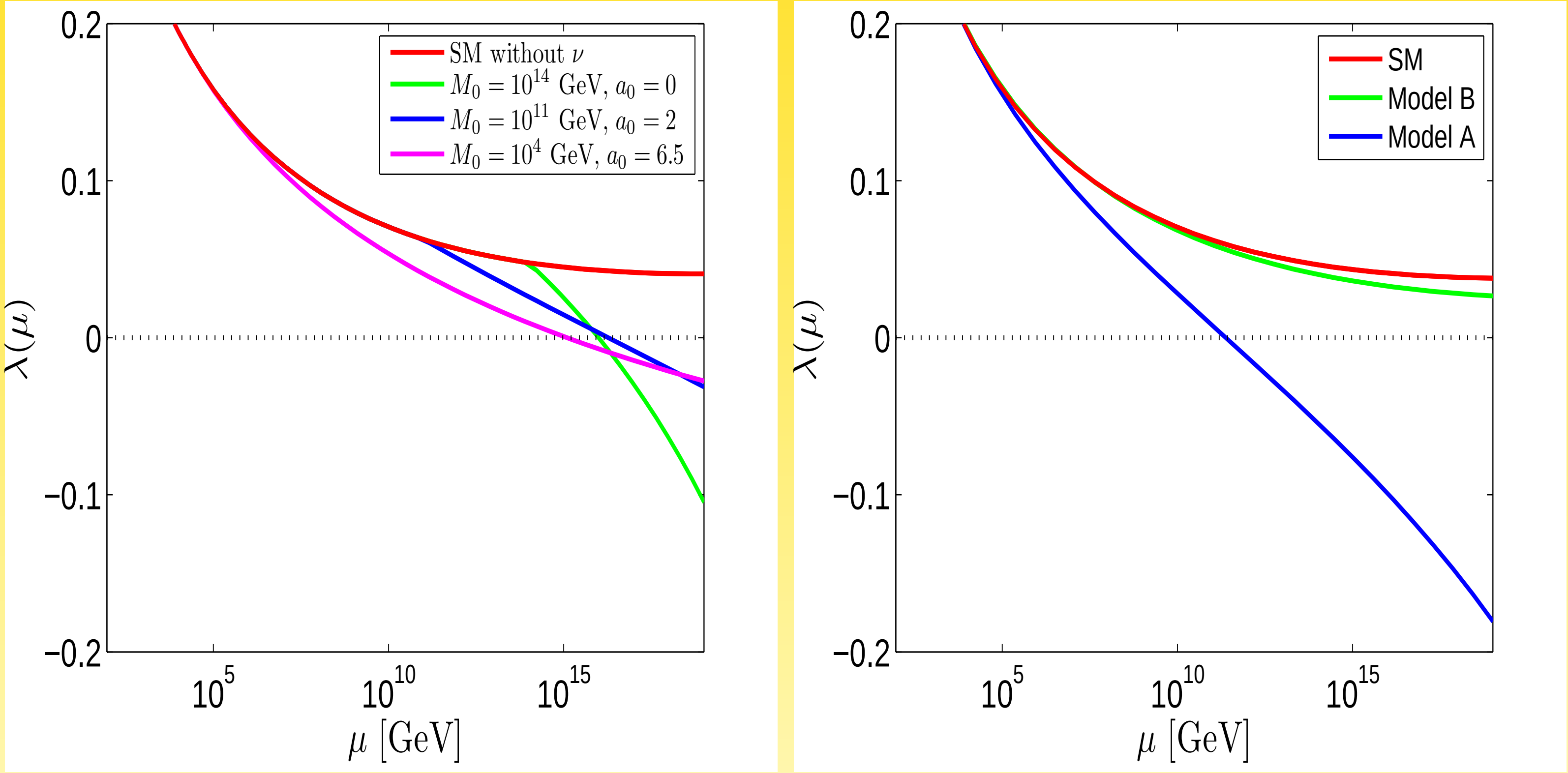
makes vacuum stability condition worse!



naively, if M_R goes down, Y_ν goes down and effect is negligible

Higgs physics and sterile neutrinos

if neutrinos are made accessible at colliders, Dirac Yukawa is large even for TeV neutrinos $\Rightarrow$ influences vacuum stability bound



W.R., Zhang, JHEP 1206

$10^9 \ldots 10^{15}$ GeV: The case of very heavy $M_R \ldots$

…gives correct neutrino masses for $m_D \simeq v$

…gives successful thermal leptogenesis

…is a generic GUT prediction

this is the scale where one would expect M_R

$10^9 \dots 10^{15}$ GeV: The case of very heavy $M_R \dots$

…gives correct neutrino masses for $m_D \simeq v$

…gives successful thermal leptogenesis (`lecture by Ibarra`)

…is a generic GUT prediction

this is the scale where one would expect M_R

Recall: theorists also expected small neutrino mixing…

Predictions of $SO(10)$ theories

Model	Fit	M_3 [GeV]	M_2 [GeV]	M_2 [GeV]	χ^2
$10_H + \overline{126}_H$	NH	3.6×10^{12}	2.0×10^{11}	1.2×10^{11}	23.0
$10_H + \overline{126}_H$ + SS	NH	1.1×10^{12}	5.7×10^{10}	1.5×10^{10}	3.29
$10_H + \overline{126}_H + 120_H$	NH	9.9×10^{14}	7.3×10^{13}	1.2×10^{13}	11.2
$10_H + \overline{126}_H + 120_H$ + SS	NH	4.2×10^{13}	4.9×10^{11}	4.9×10^{11}	6.9×10^{-6}
$10_H + \overline{126}_H + 120_H$	IH	1.1×10^{13}	3.5×10^{12}	5.5×10^{11}	13.3
$10_H + \overline{126}_H + 120_H$ + SS	IH	1.2×10^{13}	3.1×10^{11}	2.0×10^{03}	0.6

Fit to SO(10) models including θ_{13}, Higgs, seesaw RG, etc.

`Dueck, W.R., 1306.4468`

Phenomenology of (high scale) Leptogenesis

little

(would expect leptonic CP violation and neutrinoless double beta decay)

But note:

- bread and butter leptogenesis requires $M_1 \gtrsim 10^9$ GeV
- *resonant* leptogenesis works even at weak scale
- *flavor oscillation* of sterile neutrinos with mass around few GeV

3 well motivated scales

there are three well-motivated mass values of M_R:

- eV
- keV
- $\gtrsim 10^9$ GeV

what if all three are there?

N_1	N_2	N_3	BAU	eV-anomalies	DM
eV	GUT	GUT	✓	✓	–
eV	keV	GUT	–	✓	✓
keV	GUT or GeV	GUT or GeV	✓	–	✓

(last row is called νMSM, `Shaposhnikov` *et al.*)

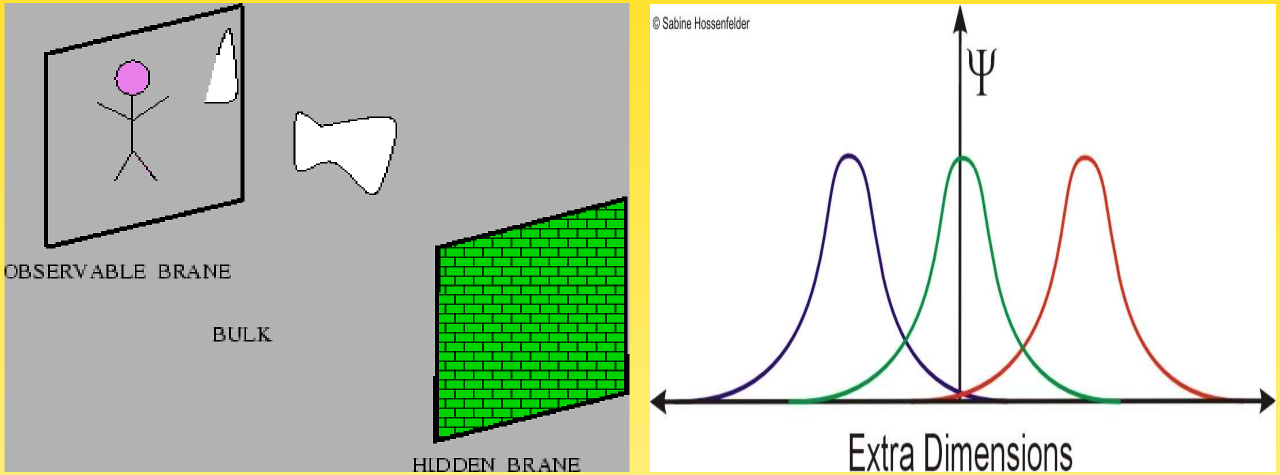
Models for light sterile neutrinos

how to bring one (or all) of the singlet neutrinos down to (k)eV ?

- extra dimensions (`Kusenko, Takahashi, Yanagida`)
- zero mass plus corrections (`Mohapatra; Shaposhnikov; Lindner, Merle, Niro; Araki, Li`)
- Froggatt-Nielsen (`Merle, Niro; Barry, W.R., Zhang`)

Light sterile neutrinos from extra dimensions

localize one heavy neutrino N_1 on distant brane, separated from the SM brane, where we live



small wave function overlap between this field and the other ones

$$M_s \propto e^{-2m\,l}\ , \quad m_D \propto e^{-m\,l} \Rightarrow m_D^2/M_R = \mathrm{const}$$

(m mass of 5D spinor, l size of ED)

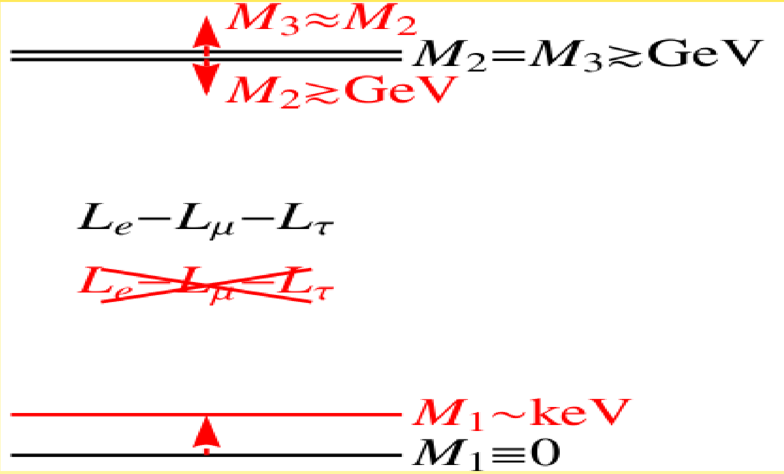
“Split seesaw”

Kusenko, Takahashi, Yanagida

Light sterile neutrinos from slightly broken flavor symmetry

introduce flavor symmetry leading to one massless neutrino, e.g.

$$M_R^{L_e-L_\mu-L_\tau} = \begin{pmatrix} 0 & a & b \\ \cdot & 0 & 0 \\ \cdot & \cdot & 0 \end{pmatrix} \Rightarrow M_1 = 0\,, \quad M_{2,3} = \pm\sqrt{a^2+b^2}$$



small breaking to lift M_1

Mohapatra; Shaposhnikov; Lindner, Merle, Niro; Araki, Li

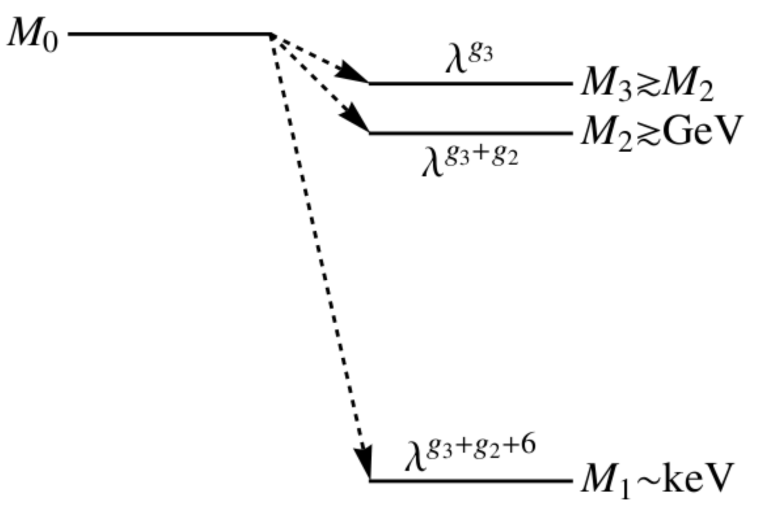
Light sterile neutrinos from Froggatt-Nielsen

introduce new $U(1)$ and field Θ with charge -1

N_R has charge m and ν_L has charge n:

$$m_D\,\bar{\nu}_L\,N_R\,\left(\frac{\Theta}{\Lambda}\right)^{n+m} + M_R\,\bar{N}_R^c\,N_R\,\left(\frac{\Theta}{\Lambda}\right)^{2m}\,, \qquad \frac{\Theta}{\Lambda} \simeq \lambda$$

$\Rightarrow$ FN charge of N_R drops out in m_D^2/M_R



`Merle, Niro; Barry, W.R., Zhang`

Flavor Symmetries

add ν_s to bread and butter A_4 model and use FN to control mass:

	l	e^c	μ^c	τ^c	ν^c	$h_{u,d}$	ν_s
A_4	3	1	1"	1'	3	1	1
Z_3	ω	ω^2	ω^2	ω^2	ω^2	1	1
$U(1)$	0	4	2	0	0	0	6 (8)

active neutrino terms of order $llhh(\xi, \varphi')/\Lambda^2$

active-sterile terms of order $l\xi\varphi' h \nu_s \lambda^6/\Lambda^2$

sterile-sterile terms of order $\varphi^2 \nu_s \nu_s \lambda^{12}/\Lambda$

generate tri-bimaximal mixing and mixing of order 0.1 with eV-steriles
(or 10^{-4} with keV)

Barry, W.R., Zhang, JHEP 1107

Flavor Symmetries

$$M_\nu^{4\times 4} = \begin{pmatrix} a+\frac{2d}{3} & -\frac{d}{3} & -\frac{d}{3} & e \\ \cdot & \frac{2d}{3} & a-\frac{d}{3} & e \\ \cdot & \cdot & \frac{2d}{3} & e \\ \cdot & \cdot & \cdot & m_s \end{pmatrix} \quad \text{with} \quad \begin{array}{cc} a, d \simeq 10^{-2}\,\mathrm{eV} & \\ e/m_s \simeq 0.1 & (10^{-4}) \\ m_s \simeq \mathrm{eV} & (\mathrm{keV}) \end{array}$$

diagonalized by

$$U \simeq \begin{pmatrix} \frac{2}{\sqrt{6}} & \frac{1}{\sqrt{3}} & 0 & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} + \begin{pmatrix} 0 & 0 & 0 & \frac{e}{m_s} \\ 0 & 0 & 0 & \frac{e}{m_s} \\ 0 & 0 & 0 & \frac{e}{m_s} \\ 0 & -\frac{\sqrt{3}e}{m_s} & 0 & 0 \end{pmatrix} + \begin{pmatrix} 0 & -\frac{\sqrt{3}e^2}{2m_s^2} & 0 & 0 \\ 0 & -\frac{\sqrt{3}e^2}{2m_s^2} & 0 & 0 \\ 0 & -\frac{\sqrt{3}e^2}{2m_s^2} & 0 & 0 \\ 0 & 0 & 0 & -\frac{3e^2}{2m_s^2} \end{pmatrix}$$

A_4 Seesaw Model with light steriles (`Barry, W.R., Zhang, JCAP 1201`)

Field	L	e^c	μ^c	τ^c	$h_{u,d}$	φ	φ'	φ''	ξ	ξ'	ξ''	Θ	ν_1^c	ν_2^c	ν_3^c
$SU(2)_L$	2	1	1	1	2	1	1	1	1	1	1	1	1	1	1
A_4	$\underline{3}$	$\underline{1}$	$\underline{1}''$	$\underline{1}'$	$\underline{1}$	$\underline{3}$	$\underline{3}$	$\underline{3}$	$\underline{1}$	$\underline{1}'$	$\underline{1}$	$\underline{1}$	$\underline{1}$	$\underline{1}'$	$\underline{1}$
Z_3	ω	ω^2	ω^2	ω^2	1	1	ω	ω^2	ω^2	ω	1	1	ω^2	ω	1
$U(1)$	-	3	1	0	-	-	-	-	-	-	-	-1	F_1	F_2	F_3

various possibilities for the FN-charges:

	F_1, F_2, F_3	**Mass spectrum**	$\lvert U_{\alpha 4}\rvert$	$\lvert U_{\alpha 5}\rvert$	m_{ee} **NO**	 **IO**	**Phenomenology**
I	9, 10, 10	$M_{2,3} = \mathcal{O}(\text{eV})$	$\mathcal{O}(0.1)$	$\mathcal{O}(0.1)$	**0**	**0**	$3+2$ **mixing**
IIA	9, 10, 0	$M_2 = \mathcal{O}(\text{eV})$ $M_3 = \mathcal{O}(10^{11}\text{ GeV})$	$\mathcal{O}(0.1)$	$\mathcal{O}(10^{-11})$	**0**	$\frac{2\sqrt{\Delta m_{\text{A}}^2}}{3}$	$3+1$ **mixing**
IIB	9, 0, 10	$M_2 = \mathcal{O}(10^{11}\text{ GeV})$ $M_3 = \mathcal{O}(\text{eV})$	$\mathcal{O}(10^{-11})$	$\mathcal{O}(0.1)$	$\frac{\sqrt{\Delta m_{\odot}^2}}{3}$	$\frac{\sqrt{\Delta m_{\text{A}}^2}}{3}$	
III	9, 5, 5	$M_{2,3} = \mathcal{O}(10\,\text{GeV})$	$\mathcal{O}(10^{-6})$	$\mathcal{O}(10^{-6})$	$\frac{\sqrt{\Delta m_{\odot}^2}}{3}$	$\sqrt{\Delta m_{\text{A}}^2}$	**Leptogenesis**

Final Remarks

Steriles have a number of consequences:

- oscillations
- astrophysics
- cosmology
- beta decays, neutrinoless double beta decay
- Higgs physics
- Lepton flavor violation
- . . .

would be extraordinary discovery!

Summary

- Are there sterile neutrinos?
-
-
-

Summary

- Are there sterile neutrinos? Maybe!
-
-
-

Summary

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- if there are steriles, are they light?
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Summary

- Are there sterile neutrinos? Maybe!
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- experimental input necessary
-

Summary

- Are there sterile neutrinos? Maybe!
- if there are steriles, are they light? Maybe!
- experimental input necessary
- if (light) steriles necessary, we know what to do

EXTRA SLIDES FROM HERE ON

Predictions of $SO(10)$ theories

Yukawa structure of $SO(10)$ models depends on Higgs representations

10_H ($\leftrightarrow H$), $\overline{126}_H$ ($\leftrightarrow F$), 120_H ($\leftrightarrow G$)

Gives relation for mass matrices:

$$\begin{aligned} m_{\rm up} &\propto r(H + sF + it_u\, G) \\ m_{\rm down} &\propto H + F + iG \\ m_D &\propto r(H - 3sF + it_D\, G) \\ m_\ell &\propto H - 3F + it_l\, G \\ M_R &\propto r_R^{-1} F \end{aligned}$$

Numerical fit including RG, Higgs, θ_{13}

`Dueck, W.R., 1306.4468`

Froggatt-Nielsen mechanism

effective theory

introduce new scalar field θ with charge -1 under new $U(1)$; acquires VEV $\langle\theta\rangle$

L_e and Φ have charge 0, e_R has charge 4, thus the term

$$\overline{L_e}\,\Phi\,e_R\,\frac{\theta^4}{\Lambda^4} \to \overline{L_e}\,\Phi\,e_R\,\frac{\langle\theta\rangle^4}{\Lambda^4}$$

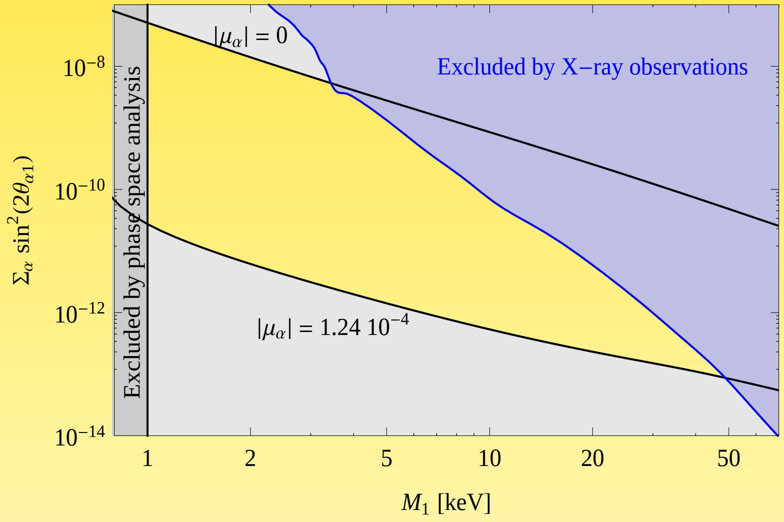
is allowed

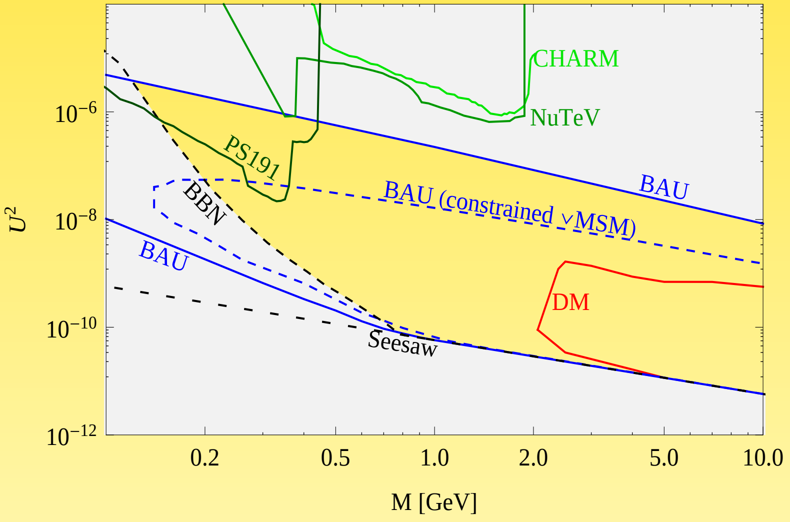
tau mass can go as $\overline{L_\tau}\,\Phi\,\tau_R$

With $\langle\theta\rangle/\Lambda \simeq \lambda$: $m_e \simeq \lambda^4\,m_\tau$

νMSM

- no new scale beyond v and Planck scale
- no new particles except 3 right-handed neutrinos
  - one is keV and is Warm Dark Matter
  - two are few GeV, almost degenerate, and do leptogenesis via oscillations





Shaposhnikov *et al.*; Shaposhnikov *et al.*; Shaposhnikov *et al.*; Shaposhnikov *et al.*; Shaposhnikov *et al.*; Shaposhnikov *et al.*,...

νMSM

- $N_{2,3}$ produced thermally at $T \gtrsim T_{\rm EW}$
- oscillate and generate lepton asymmetry
- $\mu \simeq 10^{-10}$ at $T = T_{\rm EW}$
- $N_{2,3}$ freeze out, decay at $T \lesssim$ GeV and generate lepton asymmetry $\mu \simeq 10^{-7}$ at $T \simeq 100$ MeV
- resonant WDM production at $T \simeq 100$ MeV

Higgs physics and sterile neutrinos (`W.R., Zhang`)

$$m_\nu = v^2 Y_\nu^T M_R^{-1} Y_\nu \quad \text{with} \quad Y_\nu = \frac{1}{v}\sqrt{M_R^{\rm diag}}\, R \sqrt{m_\nu^{\rm diag}}\, U^\dagger$$

useful parametrization:

$$R = O e^{\mathrm{i}A} \quad \text{with} \quad A = \begin{pmatrix} 0 & a & b \\ -a & 0 & c \\ -b & -c & 0 \end{pmatrix}$$

degenerate heavy and light neutrinos:

$$\mathrm{tr}\left(Y_\nu^\dagger Y_\nu\right) \simeq \frac{M_0 m_0}{v^2}\left(1 + 2\cosh r\right) \quad \text{with} \quad r = 2\sqrt{a^2+b^2+c^2}$$

for instance, $M_0 = 1\ \mathrm{TeV}$, $m_0 = 0.1\ \mathrm{eV}$, $r = 25$ gives $\mathrm{tr}\left(Y_\nu^\dagger Y_\nu\right) = \mathcal{O}(0.1)$

(compare to naive estimate $Y_\nu \simeq m_0 M_0 / v^2 \sim 10^{-11}$)

Seesaw parameters and sterile neutrinos: eV scale

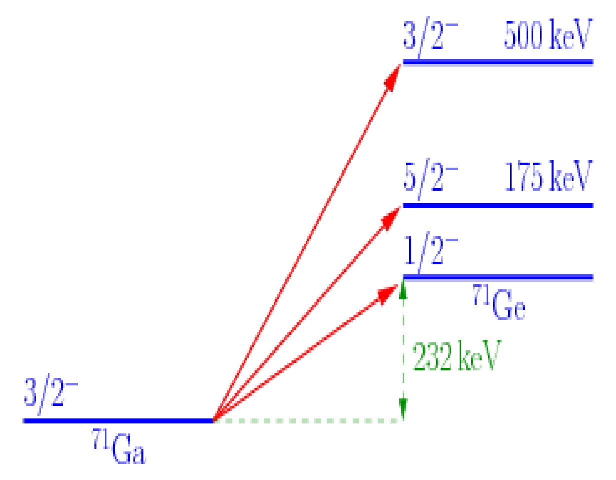
- 3+2 scenario: m_ν is 5×5 matrix, with a total of 5 masses, 9 mixing angles, 6 Dirac and 4 Majorana phases, 24 parameters
- seesaw with 2 singlet neutrinos has 11 parameters

But: no problem, seesaw fits work as well

`Donini` *et al.*; `Blennow, Fernandez-Martinez; Fan, Langacker`

Motivation for Sterile Neutrinos: Gallium Anomaly

- overestimate of detection process $\sigma(\nu_e + {}^{71}\mathrm{Ga} \to e^- + {}^{71}\mathrm{Ge})$?



- small contributions of excited states confirmed by $^{71}\mathrm{Ga}(^3\mathrm{He},\mathrm{t})^{71}\mathrm{Ge}$ measurements

Motivation for Sterile Neutrinos: Reactor Anomaly

- 200 MeV energy per fission, 6 neutrinos generated in β-decay chain
  $\Rightarrow 2 \times 10^{20}\,\nu$/s per GW thermal power
- U and Pu chains have $\mathcal{O}(10^2)$ nuclei, with $\mathcal{O}(10)$ branches each
- high energy part (shortest lifetime, i.e. least known) most important
- $\Leftrightarrow$ measurement of e^- spectrum at ILL
- sophisticated translation into $\overline{\nu}_e$ spectra, taking into account
  - new neutron lifetime ($\sigma_{\text{fission}} \propto 1/\tau_n$)
  - corrections to Fermi theory
    - nuclear charge distribution **(↔ QED corrections)**
    - weak magnetism **(↔ magn. moment and axial current interference)**
    - off-equilibrium effects **(↔ evolution of reactor)**
    - radiative corrections
    - more branches

$$S_\beta(Z,A,E_e) \quad = \quad \underbrace{K}_{\text{Norm.}} \times \underbrace{\mathcal{F}(Z,A,E_e)}_{\text{Fermi function}} \times \underbrace{p_e E_e (E_e - E_0)^2}_{\text{Phase space}} \times \underbrace{\Big(1 + \delta(Z,A,E_e)\Big)}_{\text{Correction}}$$

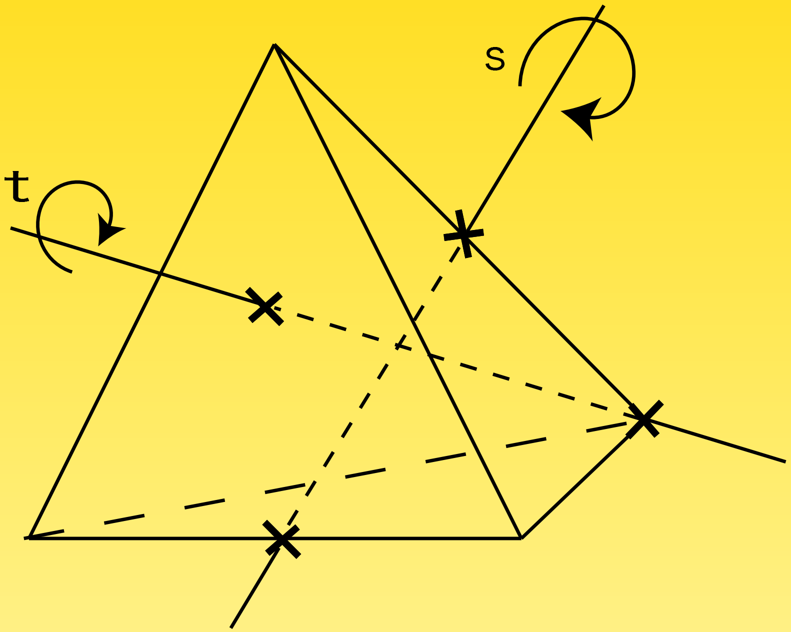
Origin of m_ν

$\mathcal{L}_M = \frac{1}{2}\,\overline{\nu_L}\,m_\nu\,\nu_L^c$ or $\mathcal{L}_D = \overline{\nu_L}\,m_\nu\,\nu_R$ are necessarily BSM

Ansatz	content	$\mathcal{L}$	m_ν	scale
“SM” (Dirac mass)	singlet	$y\overline{L}HN_R$	yv	$y = \mathcal{O}(10^{-12})$
“effective” (dim 5 operator)	new scale + LNF	$\frac{1}{\Lambda}\overline{L}HH^TL^c$	$\frac{v^2}{\Lambda}$	$\Lambda = \left(\frac{0.1\text{ eV}}{m_\nu}\right)10^{14}$ GeV
“direct” (Type II See-Saw)	Higgs triplet + LNV	$y\overline{L}\Delta L^c + \mu HH\Delta$	yv_T	$\Lambda = \frac{1}{y\mu}M_\Delta^2$
“indirect 1” (Type I see-saw)	Singlet + LNV	$y\overline{L}HN_R + \overline{N_R^c}M_RN_R$	$\frac{(yv)^2}{M_R}$	$\Lambda = \frac{1}{y}M_R$
“indirect 2” (Type III see-saw)	Fermion triplet + LNV	$y\overline{L}\,\Sigma H + \mathrm{Tr}\overline{\Sigma}M_\Sigma\Sigma$	$\frac{(yv)^2}{M_\Sigma}$	$\Lambda = \frac{1}{y}M_\Sigma$

focus here on type I see-saw mechanism

How to generate lepton mixing: Flavor Symmetries…

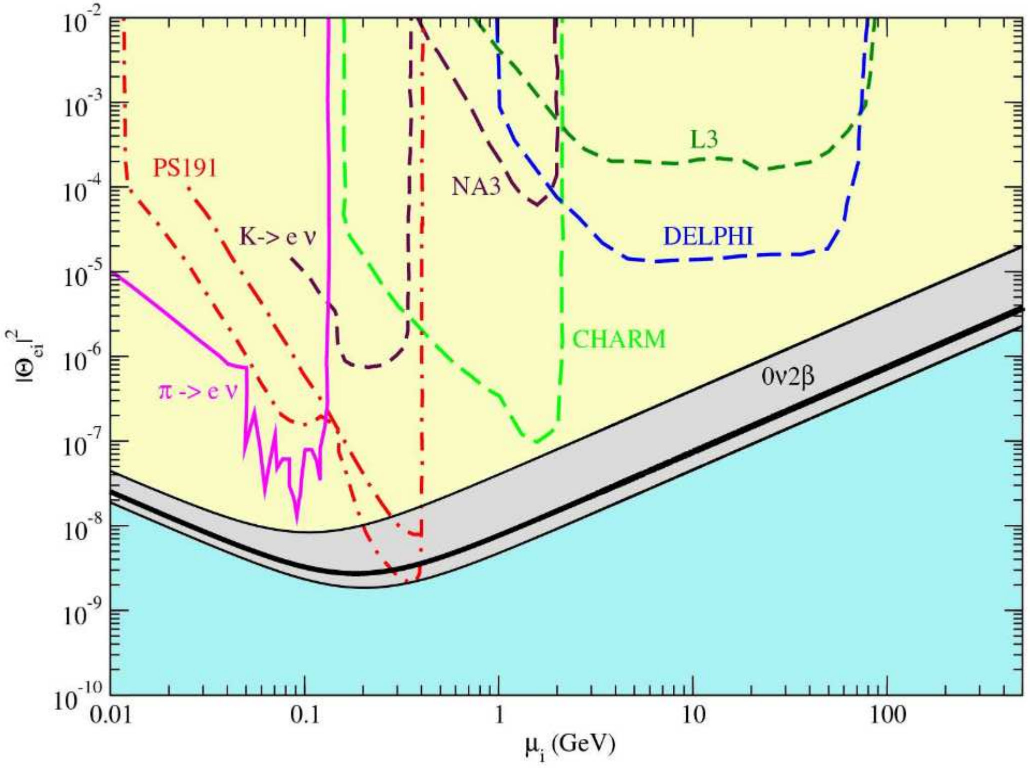


A_4 smallest group with irreducible $3 \leftrightarrow 3$ generations

$$3 \times 3 = 1 + 1' + 1'' + 3 + 3$$

$$1 \times 1 = 1,\ 1' \times 1'' = 1,\ 1'' \times 1' = 1,\ 1' \times 1' = 1'',\ 1'' \times 1'' = 1',\ 3 \times 1 = 3, \ldots$$

Heavy neutrinos



Mitra, Senjanovic, Vissani