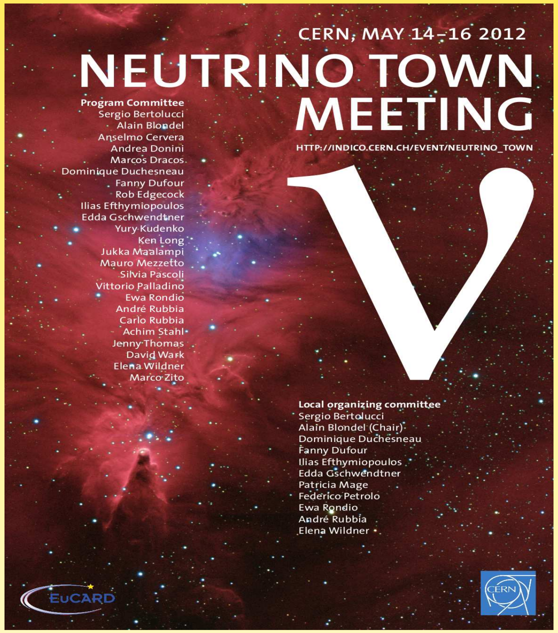
Sterile neutrinos from the low energy to the GUT scale

Werner Rodejohann
(MPIK, Heidelberg)

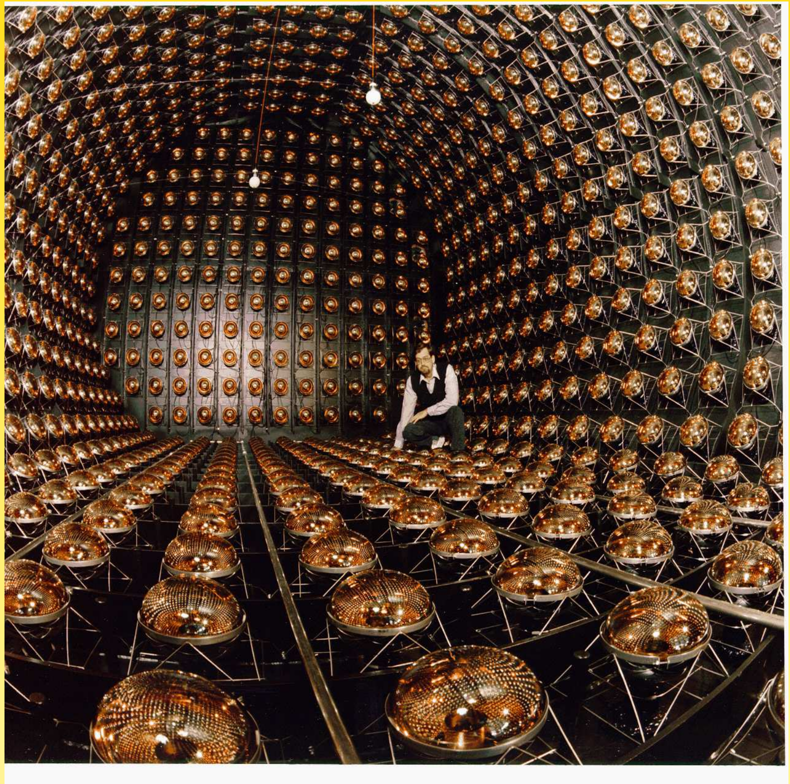
14/05/12



Outline

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

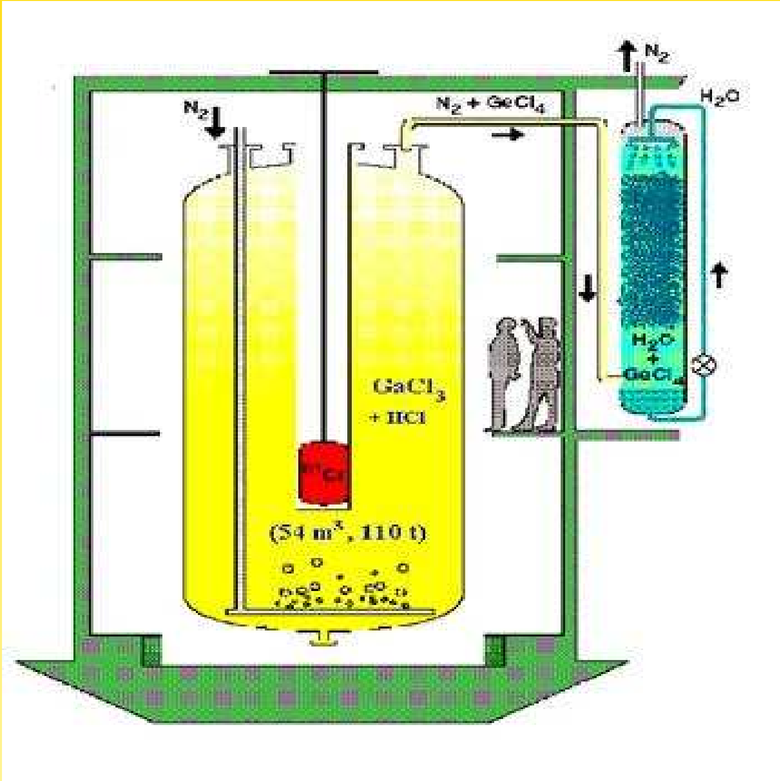
Motivation



LSND/MiniBooNE

(talk by Thierry Lasserre)

Motivation



calibration of Gallium experiments

(talk by Thierry Lasserre)

Motivation

reactor anomaly

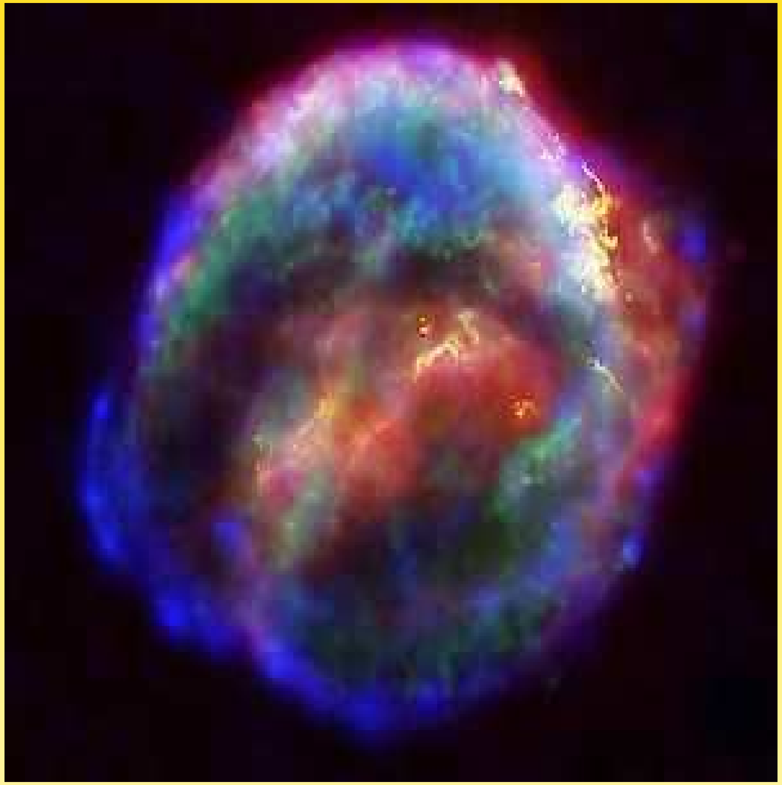
(`talk by Thierry Lasserre`)

Motivation

cosmology

(`talk by Yvonne Wong`)

Motivation



supernova

Light Sterile Neutrinos: A White Paper

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Remarks

Steriles have a number of consequences:

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

would be extraordinary discovery!

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 anti-particles (CP-partners; $\nu \to \nu^c$) 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

- example: N_R with CP-partner N_R^c

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

What is its mass?

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?

What is its mass?

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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 $\Rightarrow$ naturally large
-

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so, what now?

What is its mass?

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

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 its mass?

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

stay in the seesaw limit $M_R \gg m_D$ from now on

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

$$\mathcal{U}_\nu \simeq \begin{pmatrix} 1 - \frac{1}{2}BB^\dagger & B \\ -B^\dagger & 1 - \frac{1}{2}B^\dagger B \end{pmatrix} \begin{pmatrix} U & 0 \\ 0 & V_R \end{pmatrix}$$

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:

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

Formalism

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3 active neutrinos mix with each other through

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

3 active neutrinos mix with sterile neutrinos via

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

Formalism

Immediate consequences:

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

$$\left|\frac{1}{2}BB^\dagger\right| < \begin{pmatrix} 4.0\times10^{-3} & 1.2\times10^{-5} & 3.2\times10^{-3} \\ \cdot & 1.6\times10^{-3} & 2.1\times10^{-3} \\ \cdot & \cdot & 5.3\times10^{-3} \end{pmatrix}$$

- Lepton flavor violation

$$\mathrm{BR}(\mu\to e\gamma) \propto \left| N^*_{\mu i}\, N_{ei}\, f(m_i/m_W) + \theta^*_{\mu i}\, \theta_{ei}\, f(M_i/m_W)\right|^2 \lesssim 1.1\times10^{-8}$$

- neutrinoless double beta decay

$$\sum N^2_{ei}\, m_i \lesssim 0.5 \text{ eV} \text{ and } \sum \frac{\theta^2_{ei}}{M_i} \lesssim 2\times10^{-8} \text{ GeV}$$

3 (4) well motivated scales

there are three well-motivated mass values of M_R:

- eV
- keV
- $\gtrsim 10^9$ GeV
- (TeV)

The case of very heavy $M_R \ldots$

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

$\ldots$ gives successful thermal leptogenesis

$\ldots$ is a generic GUT prediction

this is the scale where one would expect M_R

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…is a generic GUT prediction

this is the scale where one would expect M_R

Recall: theorists also expected small neutrino mixing…

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

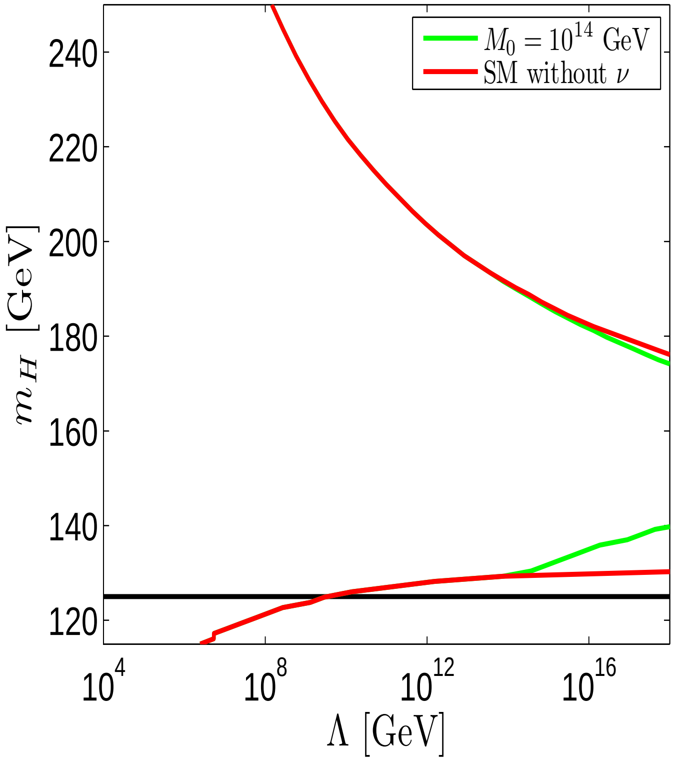
often overlooked: Dirac Yukawa $\bar{\nu}_L\, Y_\nu\, N_R$ contribution to λ:

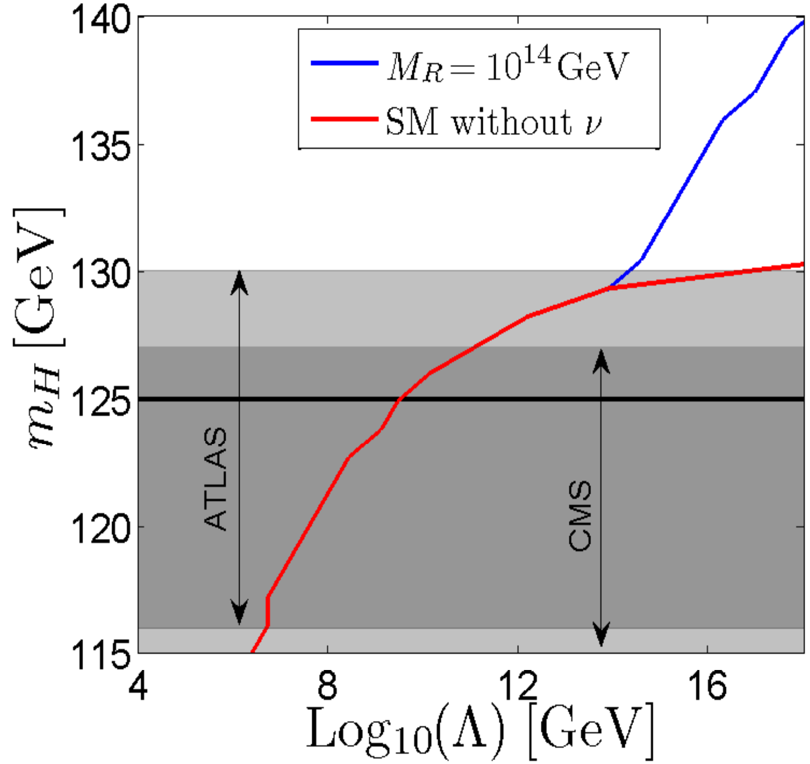
$$\Delta\beta_\lambda = -8\,\mathrm{Tr}\left(Y_\nu^\dagger Y_\nu\right)^2$$

`Casas, Di Clemente, Ibarra, Quiros; Miro, Espinosa, Giudice, Isidori, Riotto, Strumia`

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

Higgs physics and sterile neutrinos





W.R., Zhang

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

keV steriles as Warm Dark Matter particles

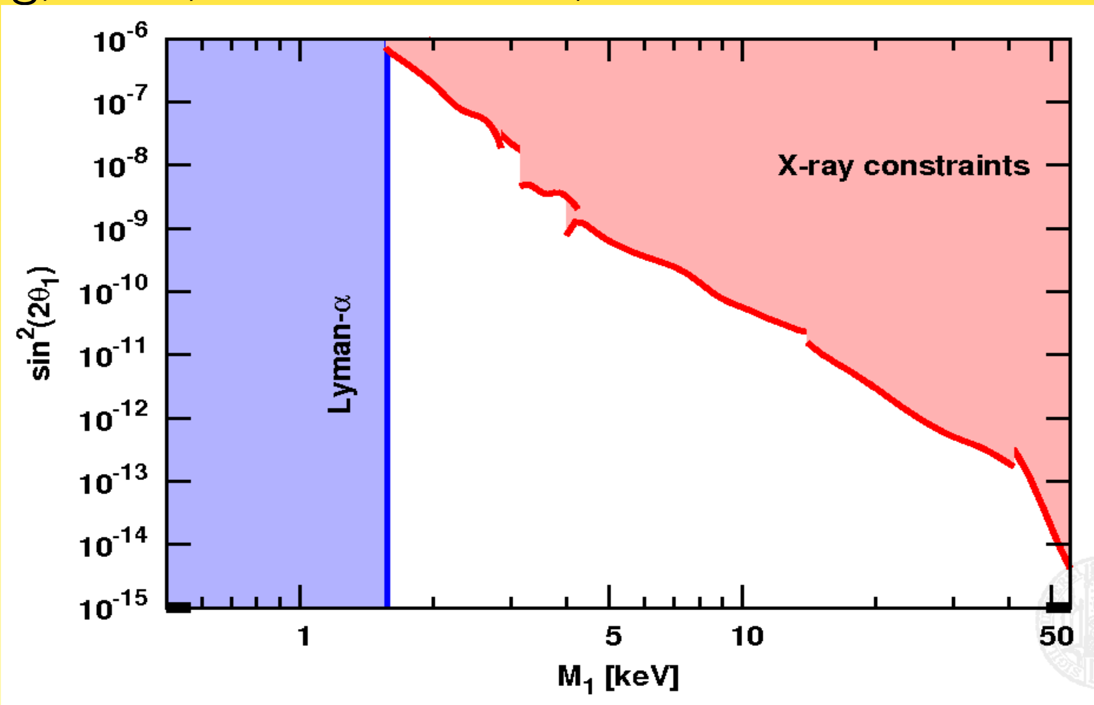
Warm Dark Matter predicts less cuspy (=smoother) DM profiles, and less dwarf satellites than Cold Dark Matter

keV sterile is excellent candidate

- produced from non-resonant (Dodelson-Widrow) or resonant + μ_α (Shi-Fuller) mixing with SM neutrinos
- thermally produced and then diluted
- non-thermally produced from BSM physics

keV WDM is constrained by

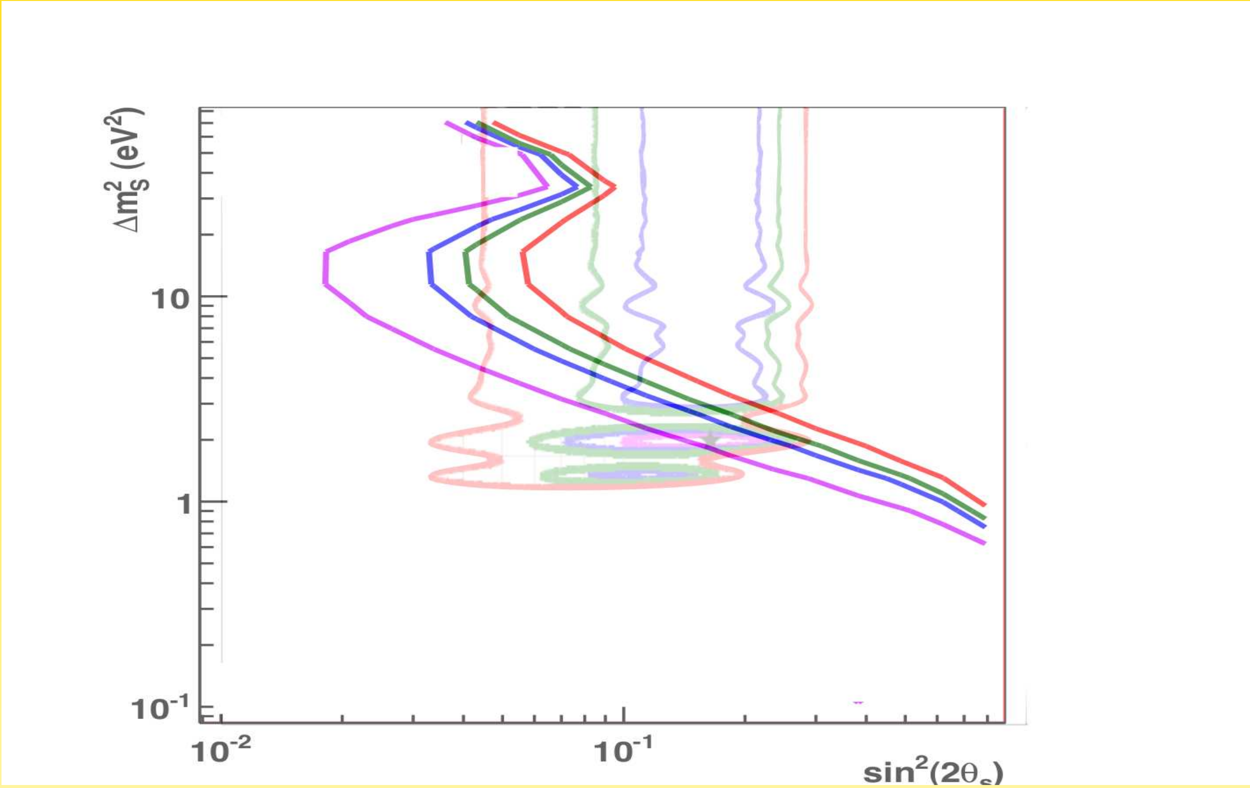
- X-ray searches $\Gamma \sim G_F^2 M_1^5\,\theta^2$
- Ly-α structure formation: $M_1 \gtrsim 1$ keV
- free streaming, BBN, Tremaine-Gunn,...



$m_\nu = \theta^2\,M \Rightarrow$ one massless active neutrino!

Phenomenology of eV steriles

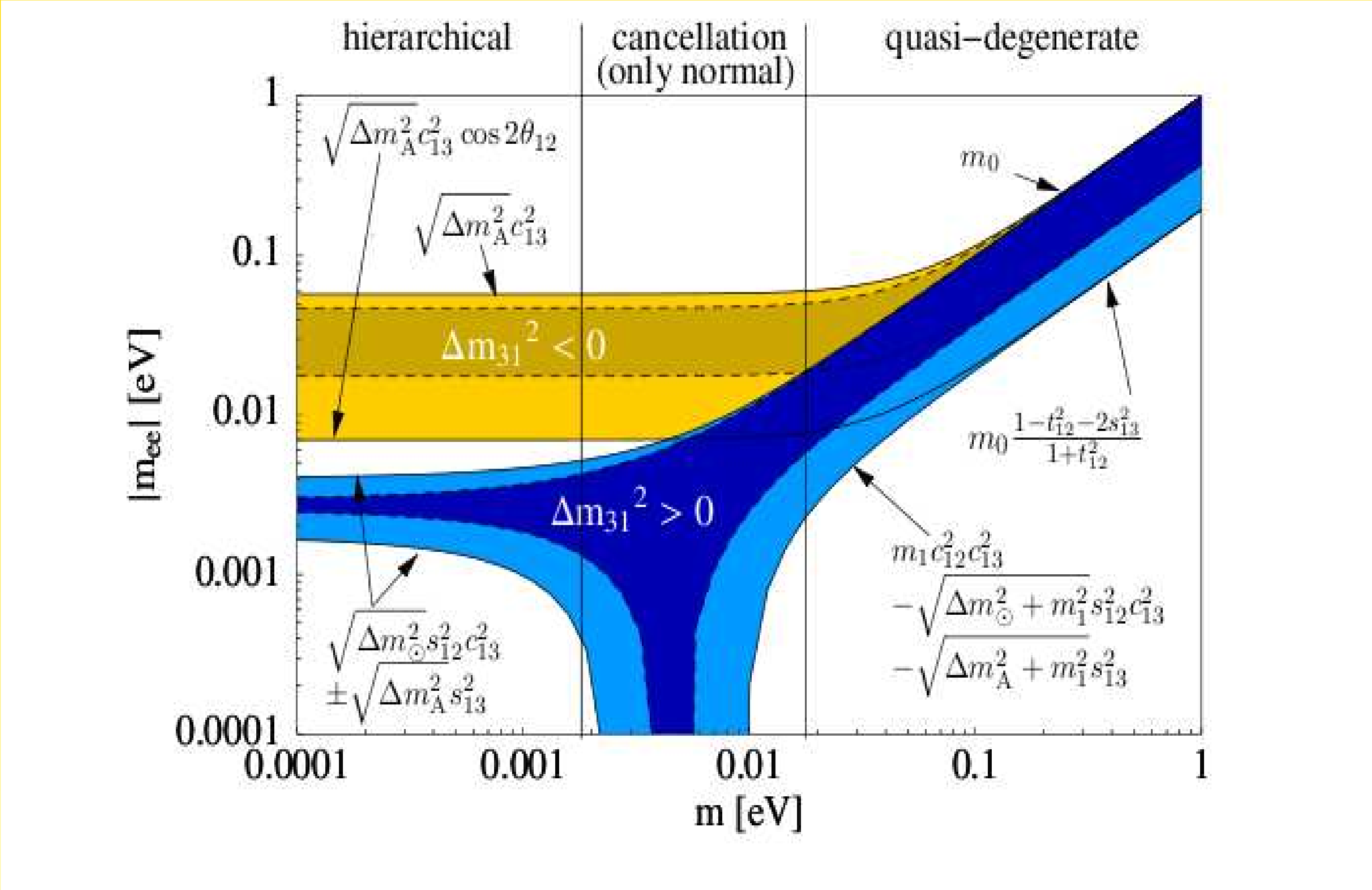
Neutrino mass observables: KATRIN



Sejersen Riis, Hannestad; Formaggio, Barret

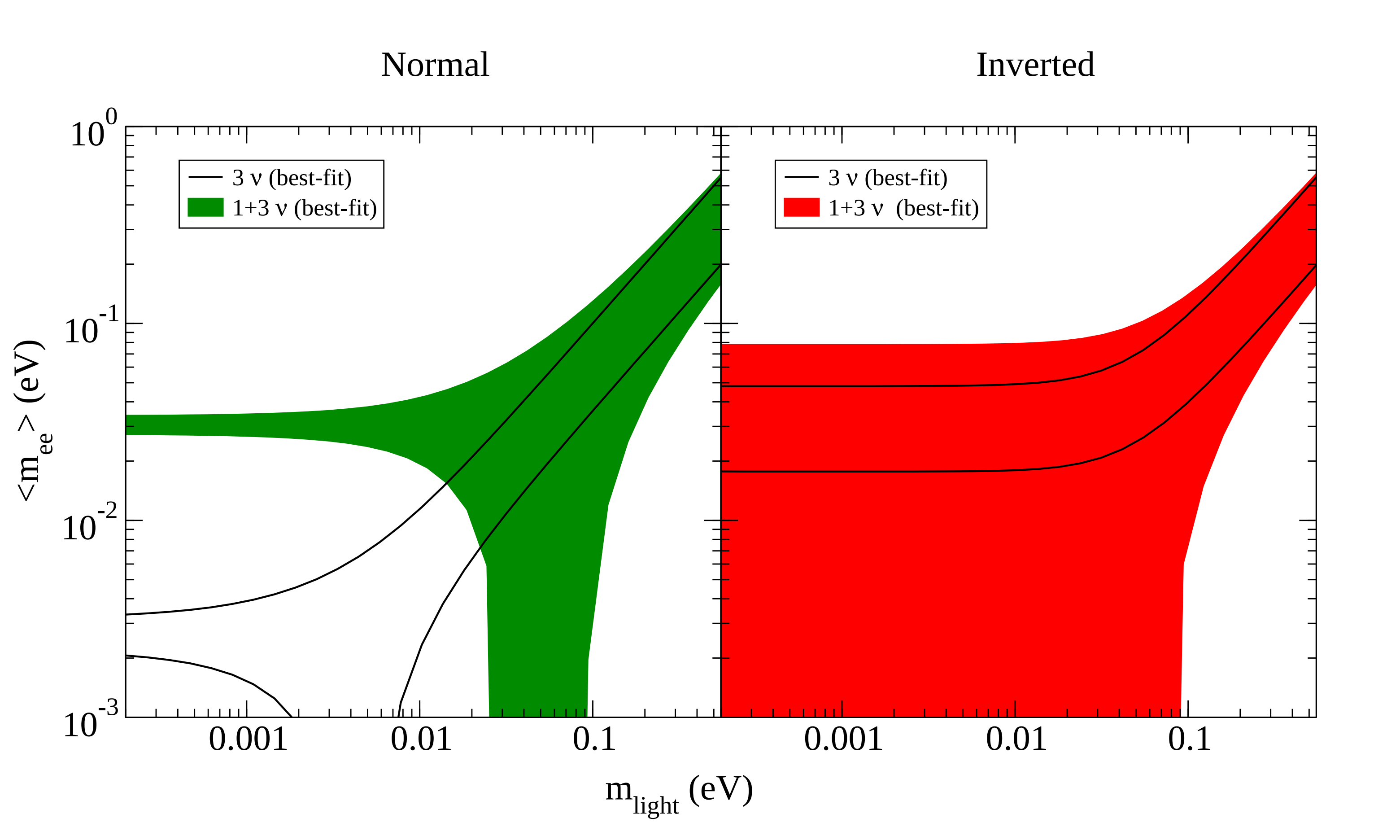
(talk by Carlo Giunti)

The usual plot for double beta decay...



The usual plot for double beta decay. . .

. . . gets completely turned around!



Barry, W.R., Zhang

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

- recall $|m_{ee}|^{\rm act}_{\rm NH}$ can vanish and $|m_{ee}|^{\rm act}_{\rm IH} \sim 0.02$ eV cannot vanish
- $|m_{ee}| = |\underbrace{|U_{e1}|^2 m_1 + |U_{e2}|^2 m_2\, e^{2i\alpha} + |U_{e3}^2| m_3\, e^{2i\beta}}_{m_{ee}^{\rm act}} + \underbrace{|U_{e4}|^2 m_4\, e^{2i\Phi_1}}_{m_{ee}^{\rm st}}|$
- $\Delta m^2_{\rm st} \simeq 1$ eV^2 and $|U_{e4}| \simeq 0.15$
- sterile contribution to $0\nu\beta\beta$:

$$|m_{ee}|^{\rm st} \simeq \sqrt{\Delta m^2_{\rm st}}\, |U_{e4}|^2 \simeq 0.02 \text{ eV} \left\{ \begin{array}{c} \gg |m_{ee}|^{\rm act}_{\rm NH} \\ \simeq |m_{ee}|^{\rm act}_{\rm IH} \end{array} \right.$$

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

Barry, W.R., Zhang

Remarks

- majority of experiments does not require sterile neutrinos
- oscillation experiments: $\Delta m^2 \simeq 1$ eV^2 vs. cosmology: $m_s \lesssim 1$ eV
- appearance-disappearance tension
- all anomalies explained by the same thing?
- are they all real?

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	✓	–	✓

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)

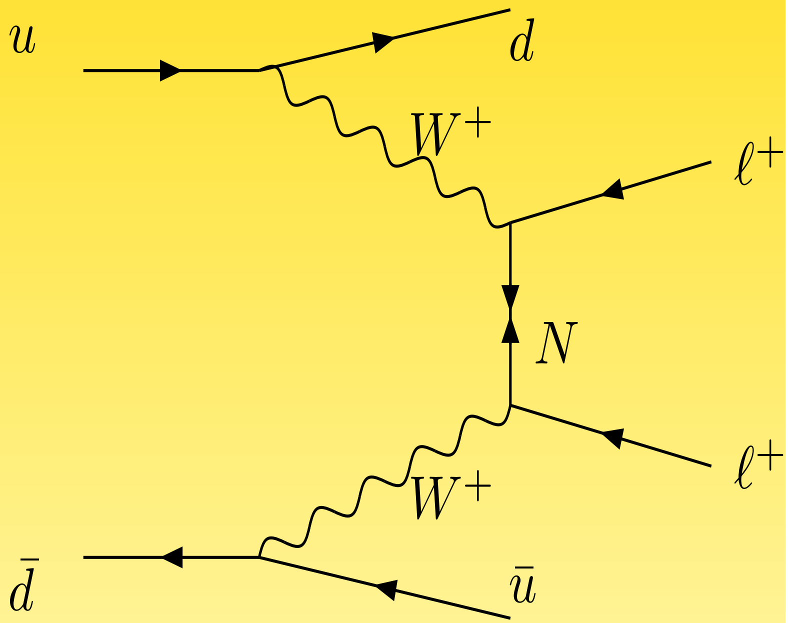
$$m_D = v \begin{pmatrix} h_1 & h_2 & h_3 \\ \omega\, h_1 & \omega\, h_2 & \omega\, h_3 \\ \omega^2\, h_1 & \omega^2\, h_2 & \omega^2\, h_3 \end{pmatrix} \text{ and } M_R = M_0 \mathbb{1}$$

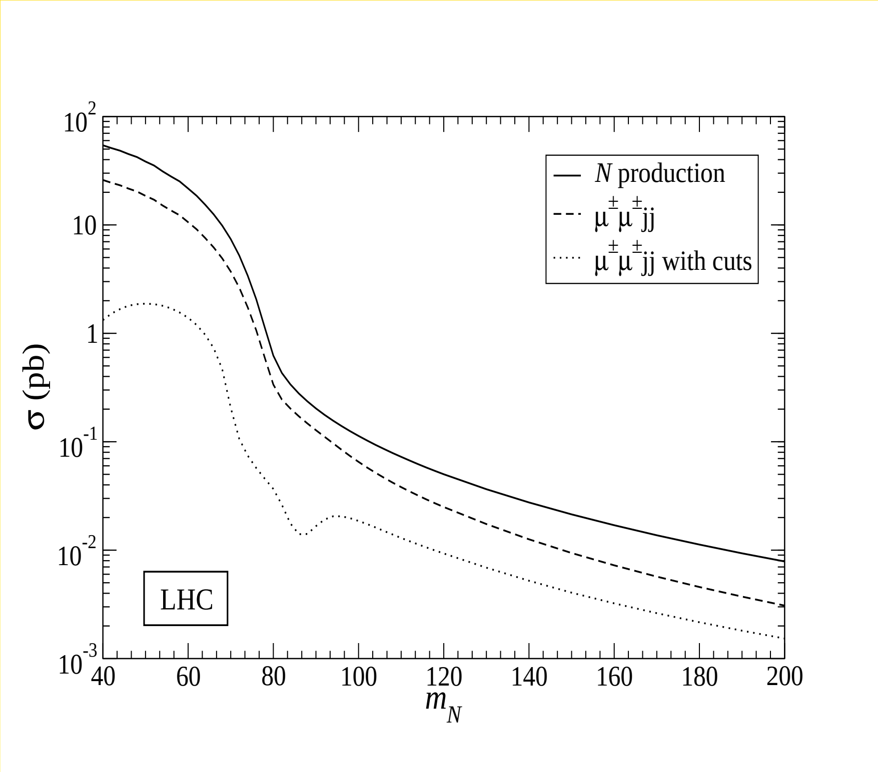
gives $m_\nu = 0$, add (very) small corrections

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

works with $Y = \mathcal{O}(1)$ and $M_0 \lesssim$ TeV!

TeV seesaw





at most $M_i \leq 400$ GeV

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

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:

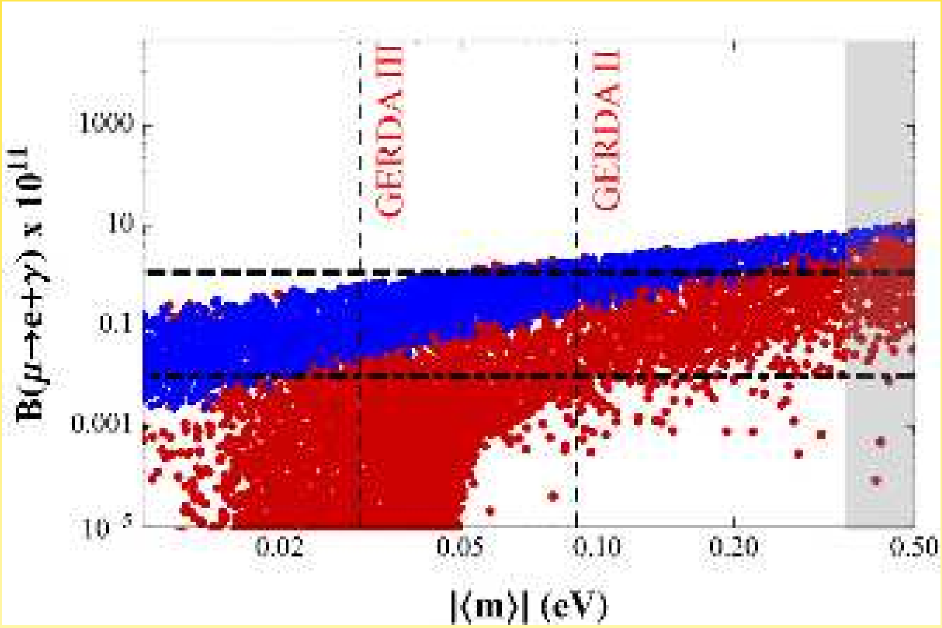
$$\frac{T_{1/2}(\text{light})}{T_{1/2}(\text{heavy})} \simeq 10^4$$

Mitra, Senjanovic, Vissani

TeV scale seesaw with sizable mixing

Casas-Ibarra Parametrization

$$m_D = iU\sqrt{m_\nu^{\rm diag}}\,R\,\sqrt{M_R^{\rm diag}}\,V_R^T$$



Ibarra, Molinaro, Petcov

Higgs physics and sterile neutrinos

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

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

vacuum stability bound

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

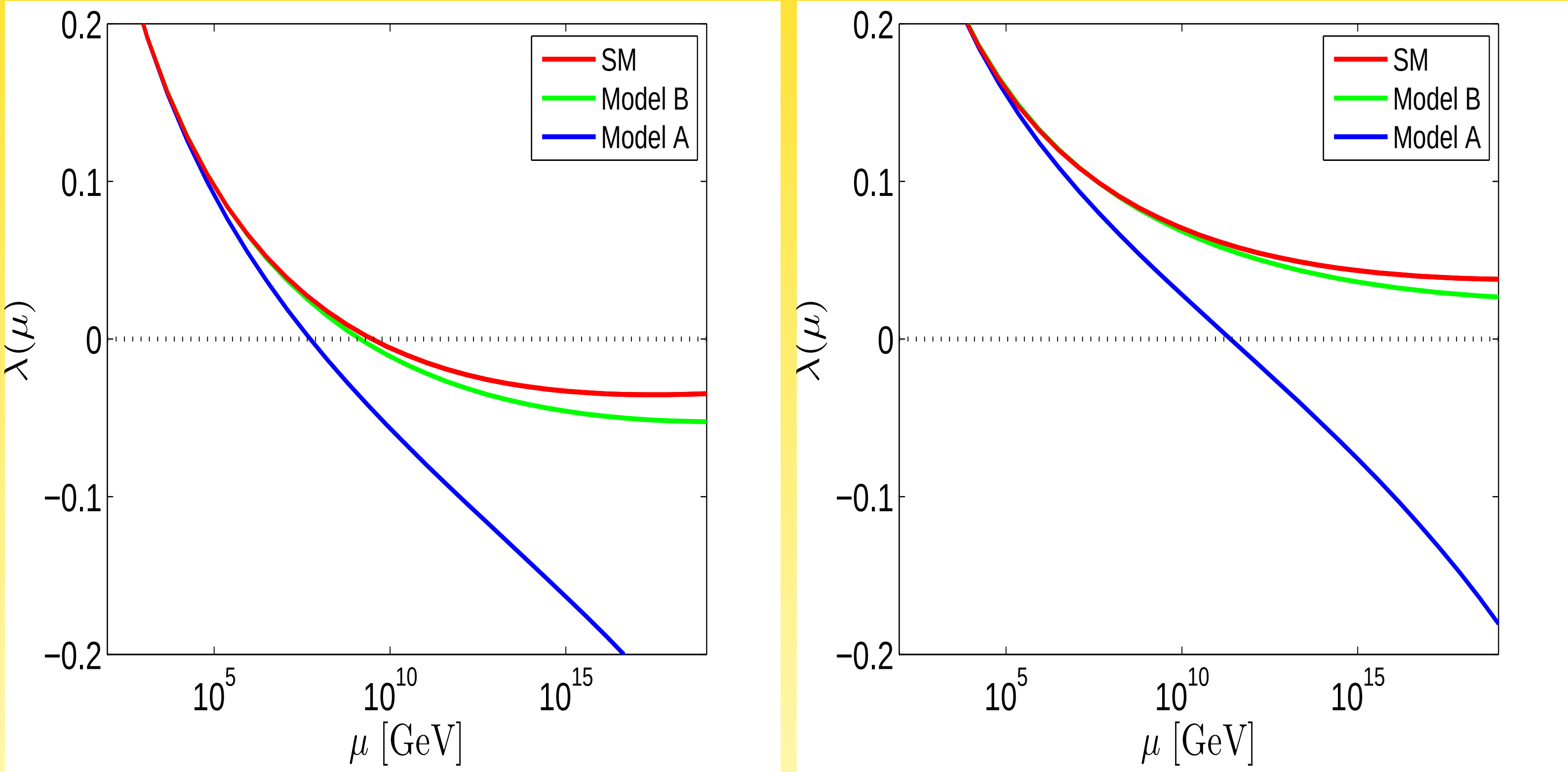
$$\Delta\beta_\lambda = -8\,\mathrm{Tr}\left(Y_\nu^\dagger Y_\nu\right)^2$$

Casas, Di Clemente, Ibarra, Quiros; Miro, Espinosa, Giudice, Isidori, Riotto, Strumia

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

Higgs physics and sterile neutrinos

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



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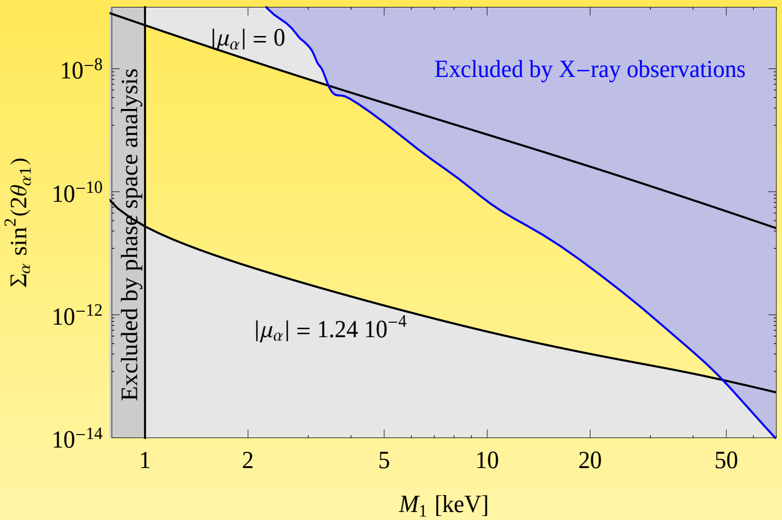
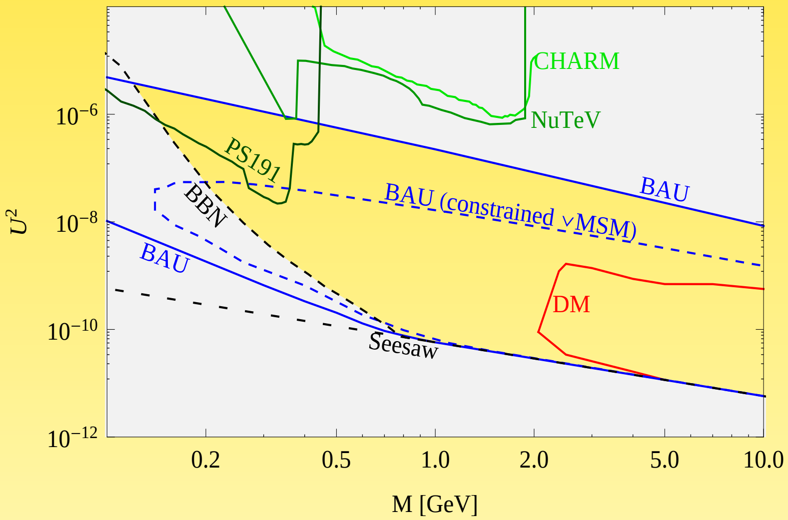
νMSM

- 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.*,...

Mini-seesaw

M_R very small but $\gg m_D$

immediate and important consequence: no neutrinoless double beta decay!

$$\frac{1}{2}(\bar{\nu}_L,\, \bar{N}^c_R)\begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix}\begin{pmatrix} \nu^c_L \\ N_R \end{pmatrix} \to \mathrm{diag}(m_{\nu_1}, m_{\nu_2}, m_{\nu_3}, m_{\nu_4}, m_{\nu_5}, m_{\nu_6})$$

6×6 mass matrix diagonalized by $\mathcal{U}_\nu$

$$\sum_{i=1}^{6} (\mathcal{U}_\nu)^2_{ei}\, m_{\nu_i} = 0$$

if all 6 masses are below 100 MeV:

$$\mathcal{A}_{0\nu\beta\beta} \simeq G_F^2 \frac{(\mathcal{U}_\nu)^2_{ei}\, m_{\nu_i}}{q^2 - m^2_{\nu_i}} = G_F^2 \frac{(\mathcal{U}_\nu)^2_{ei}\, m_{\nu_i}}{q^2} = 0$$

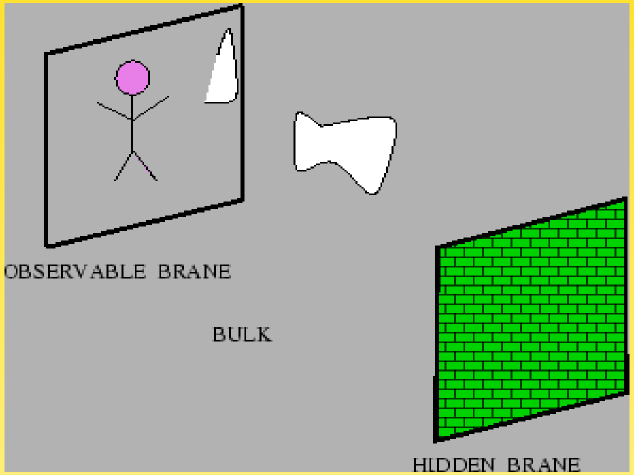
Models for light sterile neutrinos

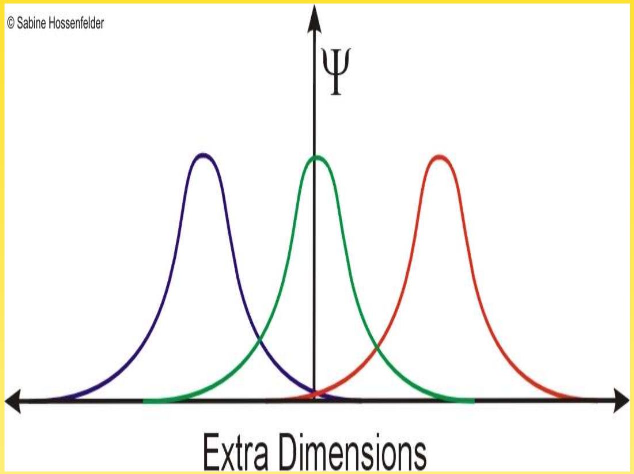
how to bring one (or all) of the singlet neutrinos down to (k)eV ?

- extra dimensions
- zero mass plus corrections
- Froggatt-Nielsen

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

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

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

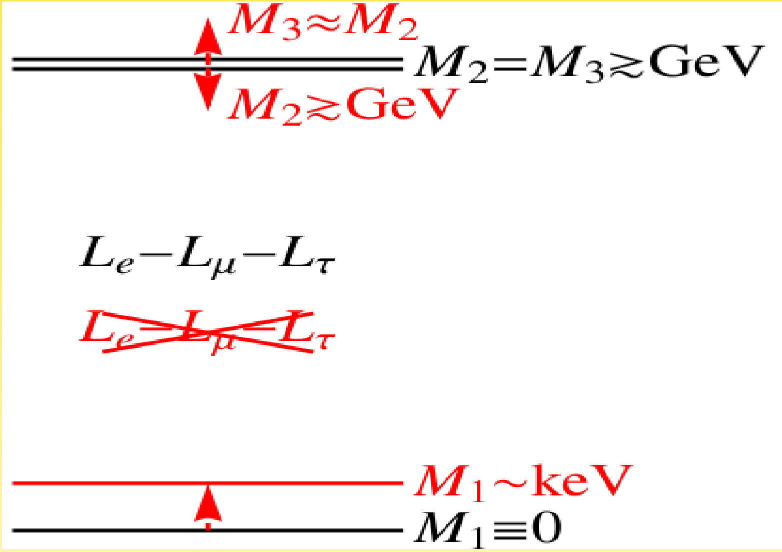
"Split seesaw"

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

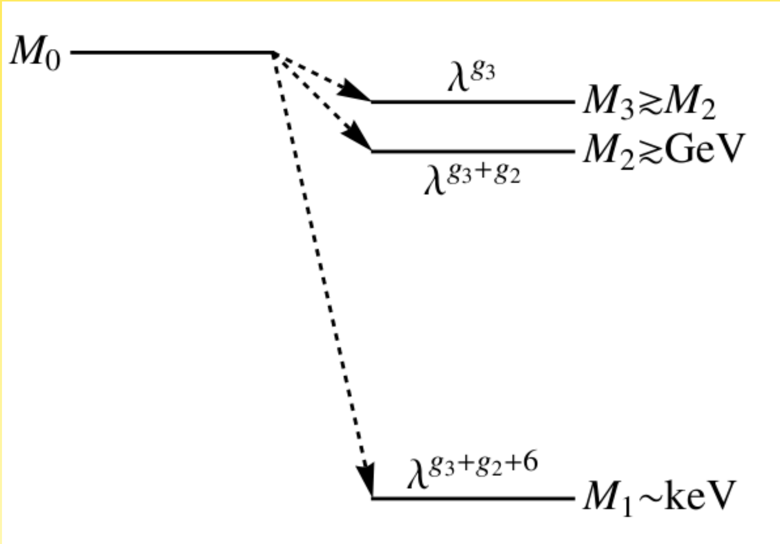
Light sterile neutrinos from Froggatt-Nielsen

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

	l	e^c	μ^c	τ^c	ν^c	$h_{u,d}$	θ	φ_T	φ_S	ξ	φ_0^T	φ_0^S	ξ_0
A_4	3	1	1"	1'	3	1	1	3	3	1	3	3	1
Z_3	ω	ω^2	ω^2	ω^2	ω^2	1	1	1	ω^2	ω^2	1	ω^2	ω^2
$U(1)$	0	4	2	0	0	0	-1	0	0	0	0	0	0

Froggatt-Nielsen $U(1)$ to get charged lepton hierarchy

Altarelli, Feruglio

add ν_s and use FN to control magnitude of its mass

A_4 Seesaw Model with light steriles

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**	m_{ee} **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**	$\frac{2\sqrt{\Delta m_A^2}}{3}$	$3+1$ **mixing**
IIB	9, 0, 10	$M_2 = \mathcal{O}(10^{11}\ \text{GeV})$ $M_3 = \mathcal{O}(\text{eV})$	$\mathcal{O}(10^{-11})$	$\mathcal{O}(0.1)$	$\frac{\sqrt{\Delta m_\odot^2}}{3}$	$\frac{\sqrt{\Delta m_A^2}}{3}$	
III	9, 5, 5	$M_{2,3} = \mathcal{O}(10\,\text{GeV})$	$\mathcal{O}(10^{-6})$	$\mathcal{O}(10^{-6})$	$\frac{\sqrt{\Delta m_\odot^2}}{3}$	$\sqrt{\Delta m_A^2}$	**Leptogenesis**

Barry, W.R., Zhang

Summary

- Are there sterile neutrinos?
-
-
-

Summary

- Are there sterile neutrinos? Maybe!
-
-
-

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-

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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

Seesaw parameters and sterile neutrinos: eV scale

usual fit procedure for two eV-scale steriles:

make m_ν a 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 physical parameters

seesaw with 3 singlet neutrinos has 18 physical parameters

But: no problem, seesaw fits work as well

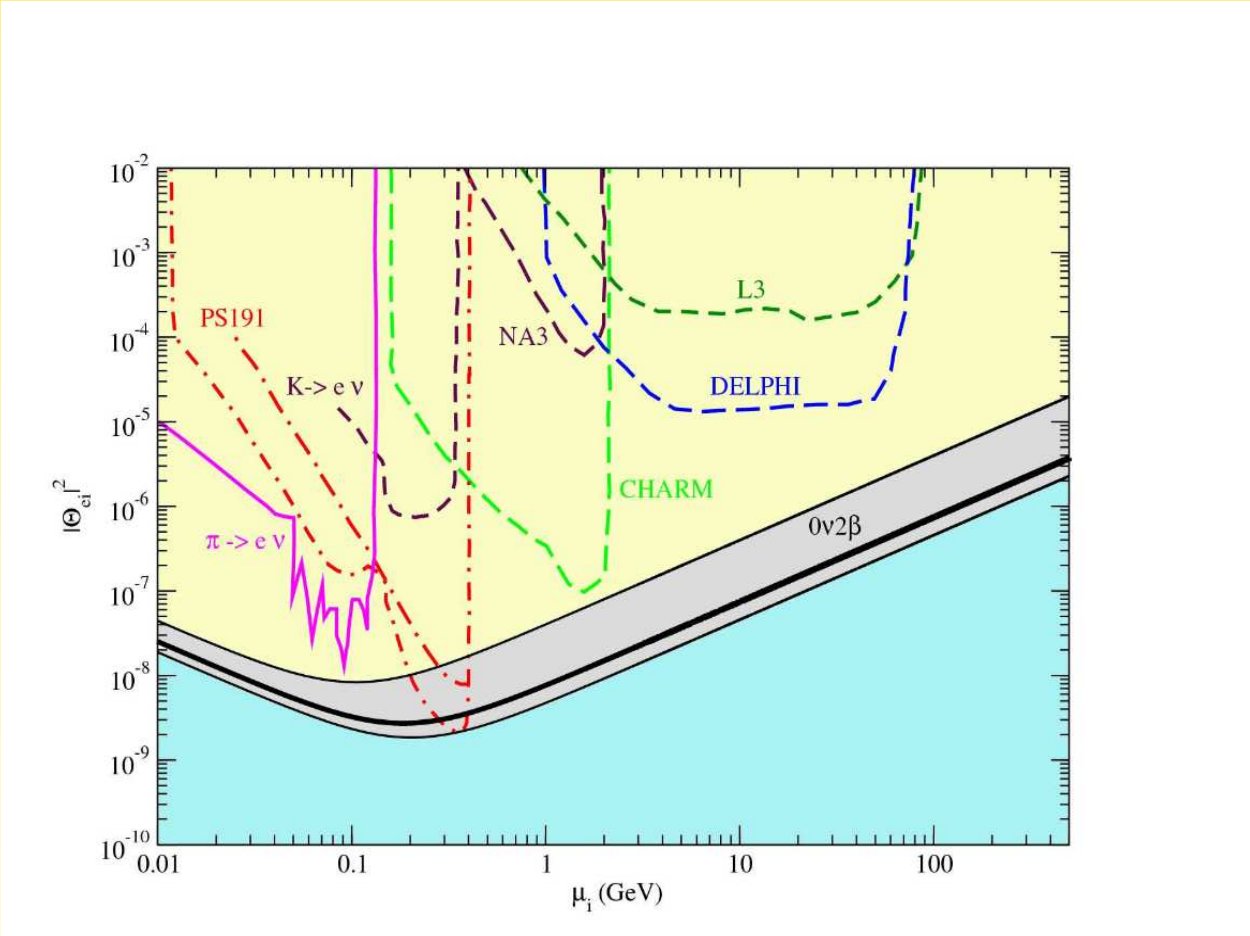
Donini *et al.*; Blennow, Fernandez-Martinez; Fan, Langacker

Confused?

there are different transformations:

$(\nu_e)_L \xrightarrow{C} (\nu_e)_R$	charge conjugation
$(\nu_e)_L \xrightarrow{P} (\nu_e)_R$	parity conjugation
$(\nu_e)_L \xrightarrow{CP} (\bar{\nu}_e)_R$	CP transformation
$(\nu_e)_L \xrightarrow{\hat{\mathcal{C}}} (\bar{\nu}_e)_R$	particle-antiparticle transformation $\nu \to \nu^c$

Heavy neutrinos



Mitra, Senjanovic, Vissani