Theoretical Implications of Neutrino Masses

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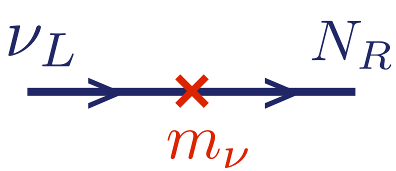
Neutrino masses $\Longrightarrow$ new physics

$\hookrightarrow$ in the particle physics Standard Model ν are massless

$\Downarrow$

ν are neutral $\Rightarrow$ 2 different possible types of neutrino masses

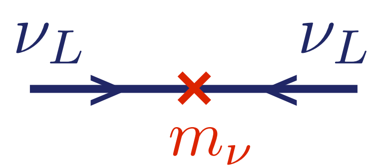
Dirac mass:



$$\mathcal{L} \ni -m_\nu \, \bar{N}_R \, \nu_L$$

not in SM: no N_R in SM

Majorana mass:



$$\mathcal{L} \ni -\frac{1}{2} m_\nu \, \bar{\nu}_L^c \, \nu_L$$

not in SM: breaks the L symmetry

$\Rightarrow$ ν masses require new physics beyond the SM

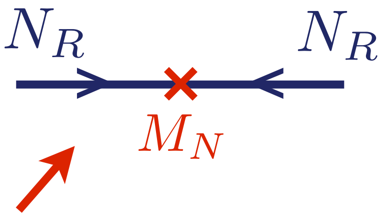
Neutrino masses: Dirac or Majorana?

→ very important for ν mass origin model building

→ both are possible but theoretically clear preference for Majorana masses: if we add N_R to the SM we can have Dirac masses but:

- why m_ν observed so small then?

- a N_R is singlet of SM ⇒ we expect a Majorana mass for N_R ⇒ gives a Majorana mass for ν_L too

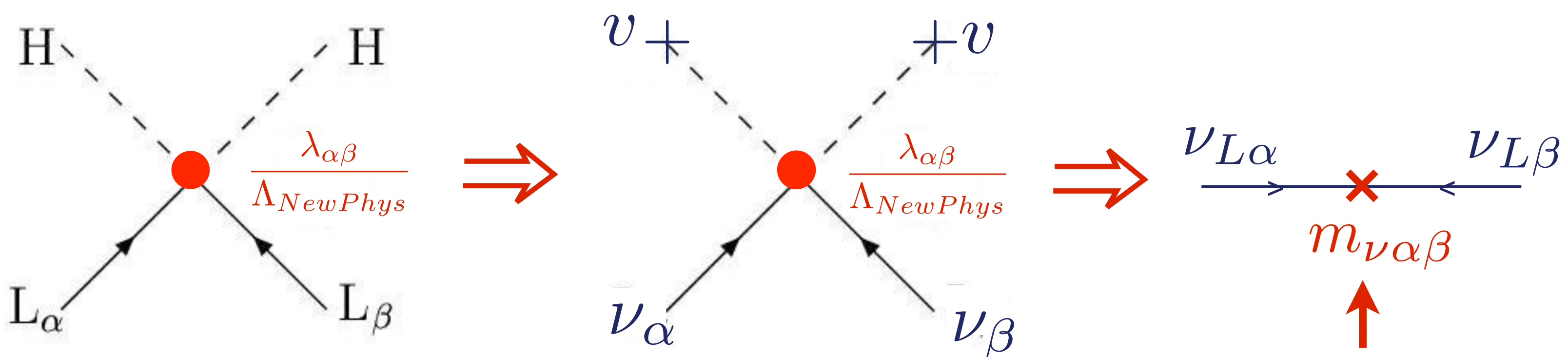


Unique status of neutrino masses

If we write down the possible low energy interactions between SM fermions which could be induced by any kind of new physics at a heavy scale $\Lambda_{NewPhys}$:

- all interactions are suppressed by $1/\Lambda^2_{NewPhys}$, $1/\Lambda^3_{NewPhys}$, ...

- except one in $1/\Lambda_{NewPhys}$: $\mathcal{L}_{eff} \ni \frac{\lambda_{\alpha\beta}}{\Lambda_{NewPhys}} L_\alpha L_\beta H H$



$$m_{\nu\alpha\beta} \sim \frac{\lambda_{\alpha\beta}}{\Lambda_{NewPhys}} v^2$$

⇒ ν masses: first BSM effect expected and first seen!

argument for Majorana masses

ν masses can probe new physics up to 10^{16} GeV

$$m_{\nu\alpha\beta} \sim \frac{\lambda_{\alpha\beta}}{\Lambda_{NewPhys}} v^2$$

$\Downarrow$

if $\lambda_{\alpha\beta} \sim 1$, $m_\nu \sim 0.1\,\mathrm{eV}$ requires $\Lambda_{NewPhys} \sim 10^{15-16}\,\mathrm{GeV}$

$\Rightarrow$ unique way to probe high scale new physics and GUT in particular

$\Rightarrow$ provides a natural explanation for the tinyness of ν masses:

if $\Lambda_{NewPhys}$ is large, m_ν is small: seesaw mechanism

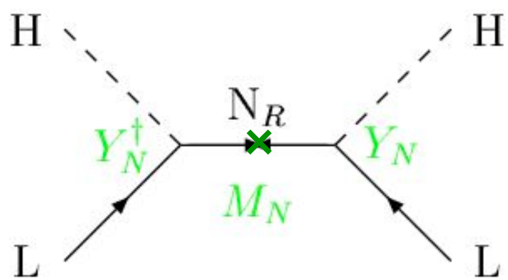
→ yet another argument for Majorana masses

Seesaw Models

The 3 basic seesaw models

i.e. tree level ways to generate the dim 5 $\frac{\lambda}{M} LLHH$ operator

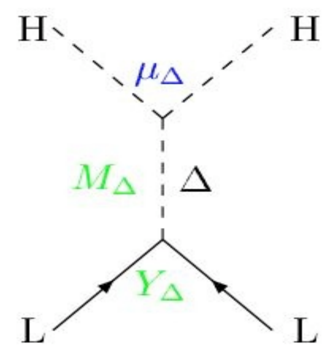
Right-handed singlet:
(type-I seesaw)



$$m_\nu = Y_N^T \frac{1}{M_N} Y_N v^2$$

m_ν small if M_N large
(or if Y_ν small)

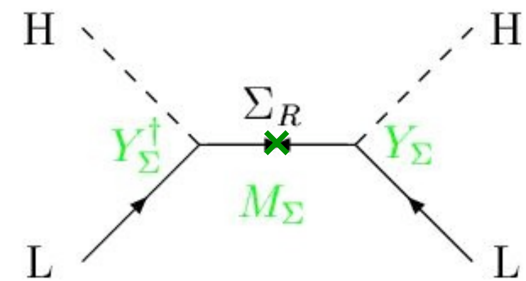
Scalar triplet:
(type-II seesaw)



$$m_\nu = Y_\Delta \frac{\mu_\Delta}{M_\Delta^2} v^2$$

m_ν small if M_Δ large
(or if Y_Δ, μ small)

Fermion triplet:
(type-III seesaw)



$$m_\nu = Y_\Sigma^T \frac{1}{M_\Sigma} Y_\Sigma v^2$$

m_ν small if M_Σ large
(or if Y_Σ small)

Can we fit ν flavour structure in all seesaw models?

yes: easily

in particular the main features of ν data

2 large mixing angles θ_{23}, θ_{12} larger than for quarks and one small θ_{13}

2 $\neq$ squared mass differences leading to a milder hierarchy between 2 ν than for quarks

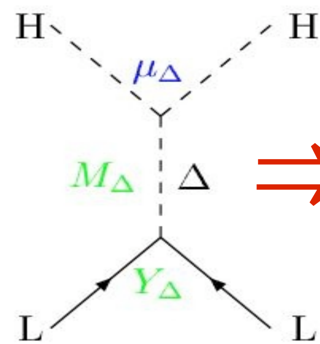
$$\frac{\Delta m^2_{atm}}{\Delta m^2_{sol}} \sim 32$$

$$\frac{m_{\nu_3}}{m_{\nu_2}} < \sim 6$$

$\Longrightarrow$ the seesaw models can fit the data even too easily: can give any ν mass matrix which could be observed

Access to the seesaw parameters from ν mass matrix data

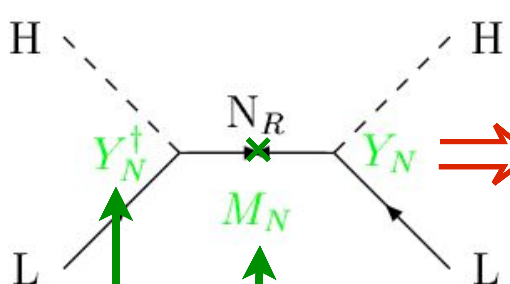
- Type II seesaw:



$$\Longrightarrow \quad m_{\nu ij} = Y_{\Delta ij} \frac{\mu_\Delta}{M_\Delta^2} v^2 \quad \Longrightarrow$$

ν mass matrix data gives full access to type II flavour structure

- Type I or III seesaw model:



$$\Longrightarrow \quad m_{\nu ij} = Y^T_{Nik} \frac{1}{M_{Nk}} Y_{Nkj} v^2 \quad \Longrightarrow$$

ν mass matrix data: gives access to 9 parameter combinations of Y_N and M_N

3 masses of the N

15 parameters in Yukawa matrix → 9 real parameters, 6 phases

} **18 parameters**

How could we distinguish experimentally the 3 seesaw models?

several possibilities:

	$\mu \to eee$	
$\mu \to e\gamma$	$\tau \to eee$	$Z \to \mu e$
$\tau \to e\gamma$	$\tau \to \mu ee$	$Z \to \tau e$
$\tau \to \mu\gamma$	$\tau \to \mu\mu e$	$Z \to \tau\mu$
	$\tau \to \mu\mu\mu$	....

- combining the ν mass matrix data with other data
  - → rare lepton processes
  - → colliders: LHC, ...
  - → cosmology: baryogenesis, ...

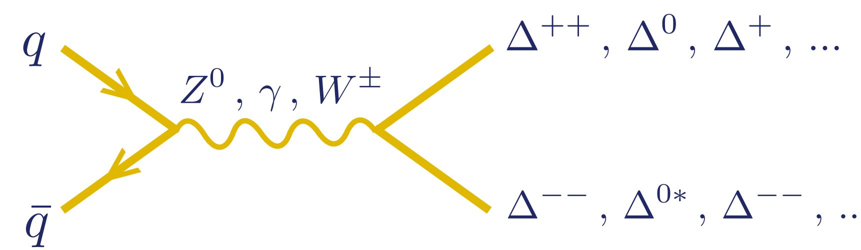
and/or

- embedding the seesaw models in broader frameworks
  - → supersymmetry
  - → $U(1)_{B-L}$ model
  - → L-R model
  - → Grand Unified Theories

......

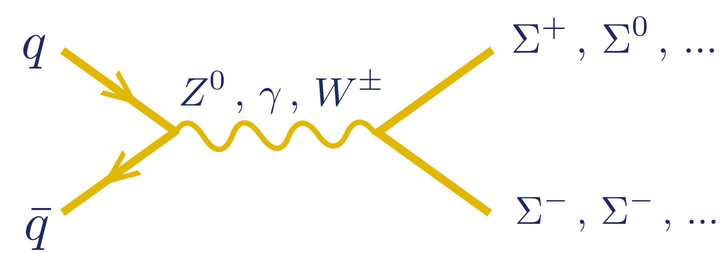
Seesaw at colliders

→ if seesaw states are around TeV



- Type-II and type-III are the most promising because have gauge interactions

→ can be Drell-Yan pair produced



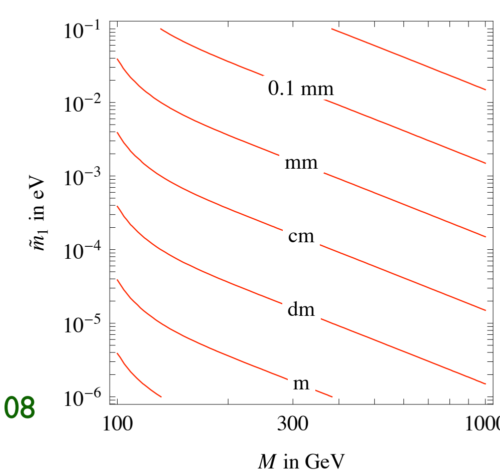
⇒ at LHC up to $M_\Delta \sim 1.5\,\mathrm{TeV}$, $M_\Sigma \sim 1.5\,\mathrm{TeV}$

Chun et al. 03'; Akeroyd, Aoki 05'; Hektor et al. 07'; Chun, Lee, Park 07'; Garayoa, Schwetz 08'; Fileviez Perez et al. 08', 09'; del Aguila et al 09'; ......

Bajc, Senjanovic 06'; Bajc, Nemvesek, Senjanovic 07'; Franceschini, TH, Strumia 08'; Arhrib et al. 09'; del Aguila et al 09, ...'

⇒ allow to reconstruct the Yukawa coupling structure from decay branching ratios

given the tiny neutrino masses one e.g. expect couplings sufficiently small to lead to observable displaced vertices



Franceschini, TH, Strumia 08

Seesaw at colliders

- Type-I seesaw model: the N_R have no SM gauge interactions $\Rightarrow$ can be produced only through Yukawas $\leftarrow$ e.g. small if $M_{N_R} \sim \mathrm{TeV}$

see e.g. del Aguila et al 06', 09', Kersten, Smirnov 07'

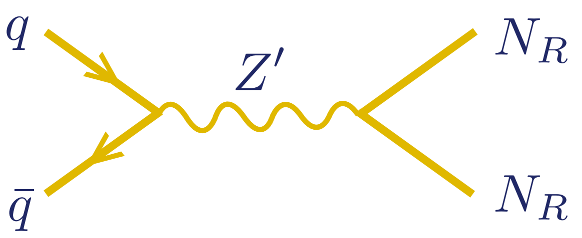
$\Rightarrow$ 2 possibilities: - inverse seesaw models allow larger Yukawas

→ production cross section limited by upper bounds on Yukawas from $\mu \to e\gamma$, ...

- extra production interactions

see e.g. Abbas et al. 08'; Fileviez-Perez, Han, Li 09'

→ pair production through a Z'



$U(1)_{B-L}$ seesaw models

- the SM accidentally conserved B-L ← global $U(1)_{B-L}$
- it is tempting to gauge $U(1)_{B-L}$

↓

require to introduce the N_R

⇒ M_{N_R} not anymore an ad hoc scale: $M_{N_R} \propto v_{B-L}$

- can justify TeV scale N_R ← linking e.g. v_{B-L} to susy breaking scale

Barger, Fileviez-Perez, Spinner 09';
Fileviez-Perez, Spinner 08', 09'

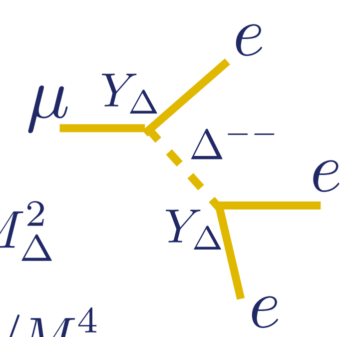
If $U(1)_{B-L}$ is ungauged but spontaneously broken: Majoron models

- other example of consequence at LHC: invisible Higgs decay to Majorons

Seesaw models with approximately conserved lepton number

rare lepton processes such as $\mu \to e\gamma$ are e.g. expected very suppressed $\propto Y_N^4/\Lambda^4_{NewPhys}$ ← come from dim-6 operator in $1/\Lambda^2_{NewPhys}$

if $\Lambda_{NewPhys}$ is as low as $\sim 1\,\mathrm{TeV}$ they remain e.g. very suppressed but not necessarily:



- Type II model with a TeV scale scalar triplet:

$$m_\nu = Y_\Delta \mu_\Delta v^2/M_\Delta^2$$

$$\Gamma(\mu \to e\gamma) \propto Y_\Delta^4/M_\Delta^4$$
$$\Gamma(\mu \to eee) \propto Y_\Delta^4/M_\Delta^4$$
....

⇒ 2 step mechanism:

- we start from a L conserved situation: Y_Δ large $\to$ $\mu \to e\gamma$, $\mu \to e\,e\,e$

  $\mu_\Delta = 0 \quad \to \quad m_\nu = 0$

  ....

- we introduce a small L breaking: $\mu_\Delta \neq 0 \quad \to \quad m_\nu \neq 0$

Bounds on Type-II seesaw Yukawa couplings

Process	Constraint on	Bound $(\times (\frac{M_\Delta}{1\,\mathrm{TeV}})^2)$
M_W	$\lvert Y_{\Delta_{\mu e}}\rvert^2$	$< 7.3 \times 10^{-2}$
$\mu^- \to e^+e^-e^-$	$\lvert Y_{\Delta_{\mu e}}\rvert\lvert Y_{\Delta_{ee}}\rvert$	$< 1.2 \times 10^{-5}$
$\tau^- \to e^+e^-e^-$	$\lvert Y_{\Delta_{\tau e}}\rvert\lvert Y_{\Delta_{ee}}\rvert$	$< 1.3 \times 10^{-2}$
$\tau^- \to \mu^+\mu^-\mu^-$	$\lvert Y_{\Delta_{\tau\mu}}\rvert\lvert Y_{\Delta_{\mu\mu}}\rvert$	$< 1.2 \times 10^{-2}$
$\tau^- \to \mu^+e^-e^-$	$\lvert Y_{\Delta_{\tau\mu}}\rvert\lvert Y_{\Delta_{ee}}\rvert$	$< 9.3 \times 10^{-3}$
$\tau^- \to e^+\mu^-\mu^-$	$\lvert Y_{\Delta_{\tau e}}\rvert\lvert Y_{\Delta_{\mu\mu}}\rvert$	$< 1.0 \times 10^{-2}$
$\tau^- \to \mu^+\mu^-e^-$	$\lvert Y_{\Delta_{\tau\mu}}\rvert\lvert Y_{\Delta_{\mu e}}\rvert$	$< 1.8 \times 10^{-2}$
$\tau^- \to e^+e^-\mu^-$	$\lvert Y_{\Delta_{\tau e}}\rvert\lvert Y_{\Delta_{\mu e}}\rvert$	$< 1.7 \times 10^{-2}$
$\mu \to e\gamma$	$\lvert\Sigma_{l=e,\mu,\tau} Y^\dagger_{\Delta_{l\mu}} Y_{\Delta_{el}}\rvert$	$< 4.7 \times 10^{-3}$
$\tau \to e\gamma$	$\lvert\Sigma_{l=e,\mu,\tau} Y^\dagger_{\Delta_{l\tau}} Y_{\Delta_{el}}\rvert$	< 1.05
$\tau \to \mu\gamma$	$\lvert\Sigma_{l=e,\mu,\tau} Y^\dagger_{\Delta_{l\tau}} Y_{\Delta_{\mu l}}\rvert$	$< 8.4 \times 10^{-1}$

Barger e tal 82'; Pal '83; Bernabeu et al '84, '86; Bilenky, Petcov'87; Gunion et al '89, '06; Swartz '89; Mohapatra '92

Abada, Biggio, Bonnet, Gavela, T.H. '07

Combined bounds		
Process	Yukawa	Bound $\left(\times (\frac{M_\Delta}{1\,\mathrm{TeV}})^4\right)$
$\mu \to e\gamma$	$\lvert Y^\dagger_{\Delta_{\mu\mu}} Y_{\Delta_{\mu e}} + Y^\dagger_{\Delta_{\tau\mu}} Y_{\Delta_{\tau e}}\rvert$	$< 4.7 \times 10^{-3}$
$\tau \to e\gamma$	$\lvert Y^\dagger_{\Delta_{\tau\tau}} Y_{\Delta_{\tau e}}\rvert$	< 1.05
$\tau \to \mu\gamma$	$\lvert Y^\dagger_{\Delta_{\tau\tau}} Y_{\Delta_{\tau\mu}}\rvert$	$< 8.4 \times 10^{-1}$

$\Longrightarrow$ rare processes could be seen for M_Δ up to $\sim 1000\,\mathrm{TeV}$

↑ $\mu \to eee$

Inverse seesaw models (type-I or type-III models)

- Type-I model with TeV scale N_R : same 2 steps mechanism is possible

Gonzalez-Garcia, Valle '89
.....
Kersten, Smirnov '07
Abada, Biggio, Bonnet, Gavela, T.H. '07

- we start from a L conserved situation:

$$\begin{array}{c} \\ \nu_L \\ N_1 \\ N_2 \end{array} \begin{array}{c} \begin{array}{ccc} \nu_L & N_1 & N_2 \end{array} \\ \begin{pmatrix} 0 & Y_N \frac{v}{\sqrt{2}} & 0 \\ Y_N \frac{v}{\sqrt{2}} & 0 & M_N \\ 0 & M_N & 0 \end{pmatrix} \end{array} \Longrightarrow \begin{array}{l} m_\nu = 0 \\ Y_N \text{ large} \rightarrow \quad \mu \rightarrow e\gamma \end{array}$$

- we introduce a small L breaking:

see S. Antusch talk

$$\begin{array}{c} \\ \nu_L \\ N_1 \\ N_2 \end{array} \begin{array}{c} \begin{array}{ccc} \nu_L & N_1 & N_2 \end{array} \\ \begin{pmatrix} 0 & Y_N \frac{v}{\sqrt{2}} & 0 \\ Y_N \frac{v}{\sqrt{2}} & 0 & M_N \\ 0 & M_N & \mu \end{pmatrix} \end{array} \Longrightarrow m_\nu \neq 0$$

$\Longrightarrow$ together with ν mass matrix data we could in principle reconstruct the full seesaw model

$\Longrightarrow$ some of these models are of Minimal Flavour type: all flavour structure is in ν mass matrix

Gavela, T.H., Hernandez, Hernandez, 09'

Bounds on Type-I and Type-III seesaw Yukawa couplings

- Type-I seesaw:

Antusch, Biggio, Fernandez-Martinez, Lopez-Pavon, Gavela '06

$$\frac{v^2}{2}|c^{d=6}|_{\alpha\beta} = \frac{v^2}{2}|Y_N^\dagger \frac{1}{|M_N|^2} Y_N|_{\alpha\beta} \lesssim \begin{pmatrix} 10^{-2} & 7.2\cdot 10^{-5} & 1.6\cdot 10^{-2} \\ 7.2\cdot 10^{-5} & 10^{-2} & 1.1\cdot 10^{-2} \\ 1.6\cdot 10^{-2} & 1.1\cdot 10^{-2} & 10^{-2} \end{pmatrix}$$

Abada, Biggio, Bonnet, Gavela, T.H. '07

- Type-III seesaw:

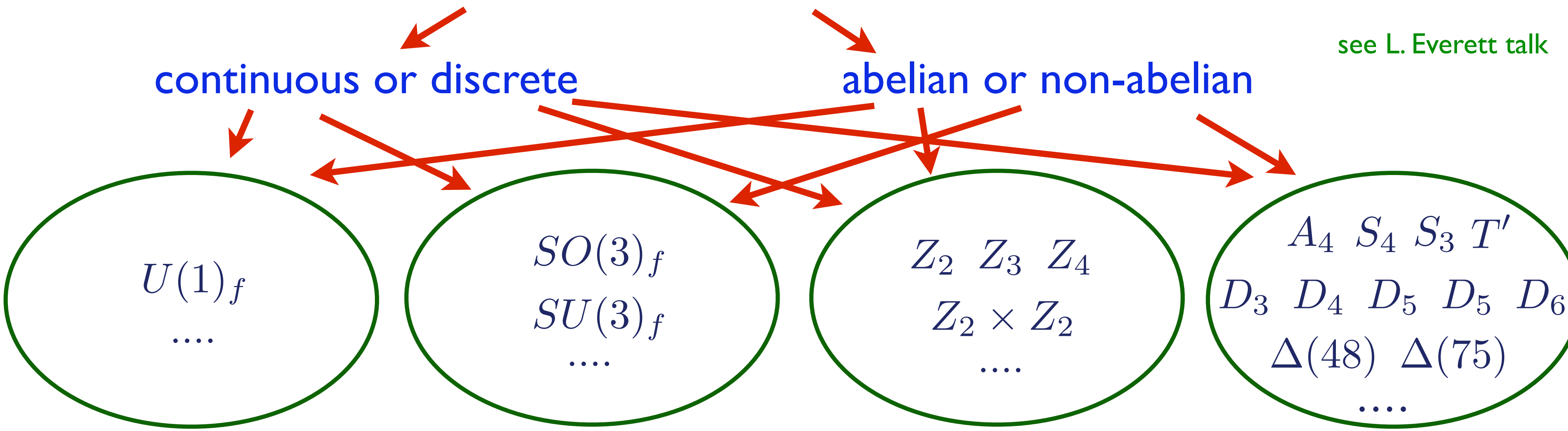
$$\frac{v^2}{2}|c^{d=6}|_{\alpha\beta} = \frac{v^2}{2}|Y_\Sigma^\dagger \frac{1}{M_\Sigma^\dagger} \frac{1}{M_\Sigma} Y_\Sigma|_{\alpha\beta} \lesssim \begin{pmatrix} 3\cdot 10^{-3} & 1.1\cdot 10^{-6} & 1.2\cdot 10^{-3} \\ 1.1\cdot 10^{-6} & 4\cdot 10^{-3} & 1.2\cdot 10^{-3} \\ 1.2\cdot 10^{-3} & 1.2\cdot 10^{-3} & 4\cdot 10^{-3} \end{pmatrix}$$

Abada, Biggio, Bonnet, Gavela, T.H. '07

Flavour symmetries

- seesaw models have no flavour symmetries in se
- we can assume flavour symmetries at level of Yukawa coupling matrices

see L. Everett talk



Froggatt, Nielsen 79',
Altarelli, Feruglio 04',
Leontaris et al 04',
....

King, Ross 01',
King, Malinski '06,
de Medeiros Varzielas, King, Ross 05',
Antusch, King '07,
.....

Low, Volkas 03',
Mohapatra, Rodejohann 03'
......

Pakvasa, Sugarawa 78, Harari, Haut, Weyers 78', Wyler 79', Ma 91', 00', 06', Lee, Mohapatra 94', Chou, Wu 97', Ma, Rajasekaran 01', Grimus, Lavoura 03', Babu, Ma, Valle 03', Altarelli, Feruglio 05', Zee 05', Keum, Volkas '06, Chen, Frigerio, Ma 04', Dermisek, Raby 05', Caravaglios, Morisi 05' Kubo, Mandragon et al 03', 05', Kobayashi et al 03', Haba, Yoshioka 05', Hagerdorn, Lindner, Mohapatra 06', Hagedorn, Lindner, Plentiger 06',
.....

Flavour symmetries

some of these symmetries lead to the interesting tri-bimaximal mixing pattern

$$A_4\,,\,S_4\,,\,SO(3)\,,\,SU(3)\,,\,\ldots$$

$$U=\begin{pmatrix}\sqrt{\frac{2}{3}} & \sqrt{\frac{1}{3}} & 0\\ -\sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & \sqrt{\frac{1}{2}}\\ \sqrt{\frac{1}{6}} & -\sqrt{\frac{1}{3}} & \sqrt{\frac{1}{2}}\end{pmatrix} \leftarrow \theta_{13}=0\,,\,\theta_{23}=\frac{\pi}{4}\,,\,\sin^2\theta_{12}=\frac{1}{3}$$

Altarelli, Feruglio 05', Babu, He 05', de Medeiros Varzielas, Ross 06',

Ma 05', 09', Carr, Frampton 06', Koide 07', Bazzochi et al 08',

Adhikary, Ghosal, Roy 09', Ciafolini et al 09'

Plentinger, Rodejohann 05' Pakvasa, Rodejohann, Weiler 08', ...

Flavour symmetries

the striking observables for flavour models are:

- the absolute scale: $0\nu2\beta$, Katrin, ...
- the mass hierarchy: expts sensitive to matter effects, ...
- θ_{13} : how close to 0?
- θ_{23} : how close to maximal?
- δ_{CP} : how large is it?

Supersymmetric seesaw models

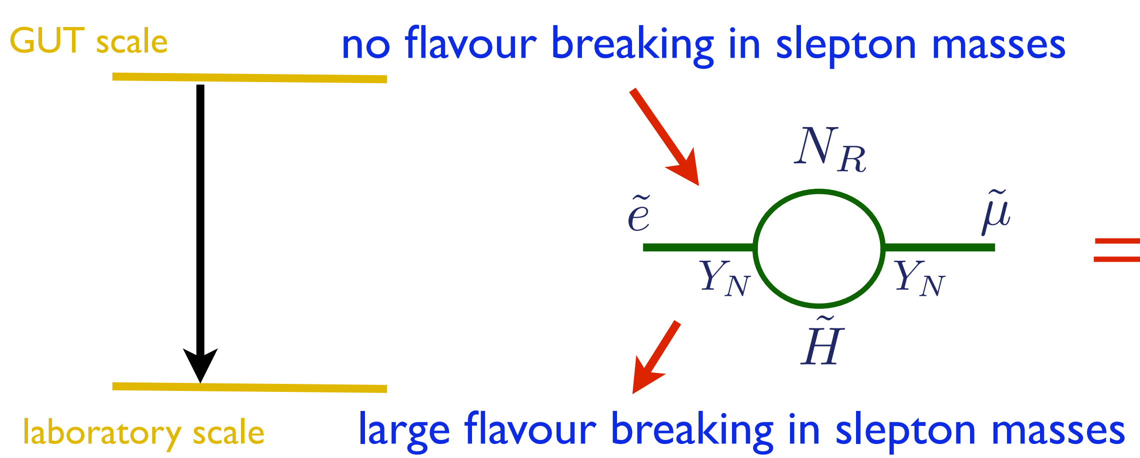
to supersymmetrize the seesaw model:

- doesn't alterate the successful features of seesaw models

- brings new possibilities of seesaw tests even for very high seesaw scale

Yukawa couplings can induce large $\mu \to e\gamma$, ... rates through their effects on the running of slepton masses

see e.g. Ellis et al 03'



$\Longrightarrow$ $Br(\mu \to e\gamma)$ up to $\sim 10^{-12}$

reachable experimentally

Davidson, Ibarra 03'

combined with ν data in principle we could reconstruct the full seesaw lagrangian

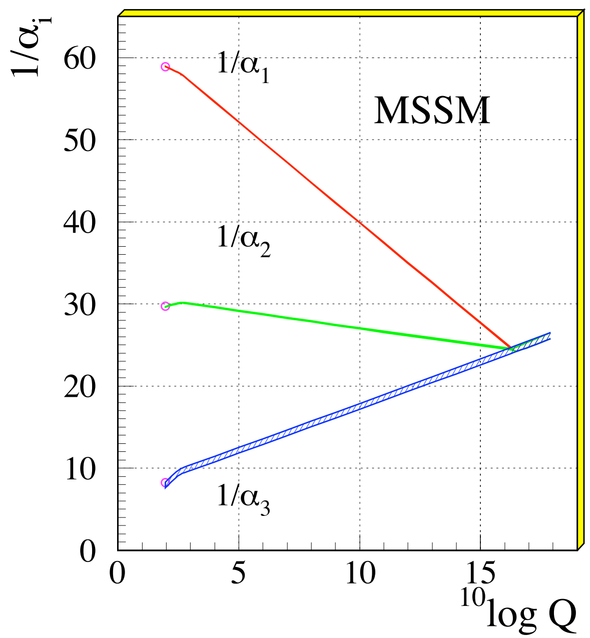
Grand-Unified-Theories

$$\mathcal{L}_{eff} \ni \frac{\lambda_{\alpha\beta}}{\Lambda_{NewPhys}} L_\alpha L_\beta H H$$

Majorana ν masses requires a new physics scale $\Lambda_{NewPhys}$ which could be as large as $10^{16}\,\mathrm{GeV}$ and give ν masses with right order of magnitude for couplings of order unity

if $\Lambda_{NewPhys} \sim 10^{15-16}\,\mathrm{GeV}$

cannot be the Planck scale but is just around the GUT scale



ν masses and seesaw fit very well in GUT

- most GUT models predicted ν masses prior their discovery
- in particular SO(10) GUT

$\nu_L, \, l_L^-, \, l_R^-,$

$u_{L_{1,2,3}}, \, u_{R_{1,2,3}},$

$d_{L_{1,2,3}}, \, d_{R_{1,2,3}}$

all 15 fermions of a SM generation can be put in a single SO(10) representation, 16_F, and the 16th fermion is the N_R

"explains" the particle content of the SM and its charge quantization

leads to ν masses

Close relation between tiny ν masses and distinction between left and right in SM

why parity is broken in SM and why maximally?

Pati, Salam 75', Mohapatra, Senjanovic 75'

in SO(10) or its left-right subgroup $SU(3)_c \times SU(2)_R \times SU(2)_L \times U(1)_{B-L}$ parity is restored at high energies and one finds a one to one relation between the fact that parity is maximally broken in SM and the fact that ν masses are tiny

Mohapatra, Senjanovic 80'

What ν data teach us on GUT

- ν data point towards particular GUT groups: $SO(10)$, E_6 , $(SU(5))$

- ν data has ruled out various pre-1998 GUT models

  → predicted large ν mixing angles as for quarks

What ν data teach us on GUT

"Minimal" SO(10) model: renormalizable model with only 2 Yukawa flavour structures

from $10_H : Y_{10}$ from $126_H : Y_{126}$

$$
\begin{aligned}
m_u &= Y_{10} v_{10}^u + Y_{126} v_{126}^u \\
m_d &= Y_{10} v_{10}^d + Y_{126} v_{126}^d \\
m_l &= Y_{10} v_{10}^d - 3 Y_{126} v_{126}^d \\
m_D &= Y_{10} v_{10}^u - 3 Y_{126} v_{126}^u \\
M_N &= Y_{126} v_R \\
m_\nu &= Y_{126} v_L + m_D^T M_N^{-1} m_D
\end{aligned}
$$

type-II contribution type-I contribution

Babu, Mohapatra 93'
Lee, Mohapatra 95', Lavoura '93,
....
Bajc, Senjanovic, Vissani 03', Goh, Mohapatra, Ng 03', Bertolini, Malinski 05', Bertolini, Schwetz, Malinski 06'

type-I and type-II contributions can be disentangled in general SO(10) models Akhmedov, Frigerio 06', 07'

⟹ close link between the fact that θ_{23} is measured close to maximal and $b-\tau$ unification,....

But: a detailed fit of fermion masses with RGE equations shows that this model cannot fit all masses and give unification at the same time Bertolini, Schwetz, Malinski 06'

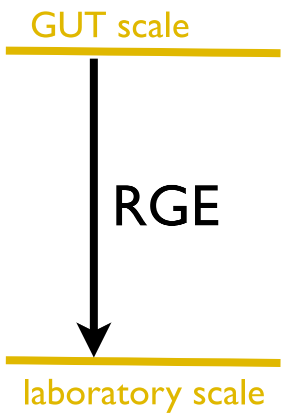
⟹ need for a more complicated Higgs structure and/or more sources of Yukawa flavour

Babu, Barr 02'; Dutta, Mimura, Mohapatra 04'; Bertolini, Schwetz, Malinski 06'; Dermisek, Haraba, Raby 06'; Aulakh, Garg 06'; Calibbi, Frigerio et al. 09',...

Renormalization group equations for neutrinos

→ full RGE'S have been determined for seesaw models

Babu, Leung, Pantaleone 93'; Chankowski, Plucieniek 93'; Antusch, Drees, Kersten, Lindner, Ratz 01'; Casas, Espinosa, Ibarra, Navaro 00' Chankowski, Pokorski 02'; Lindner 05'; Antusch, Kersten, Lindner, Ratz, Schmidt 05'; Hagedorn, Kersten, Lindner 04'; Ellis, Lola 99'; Chankowski et al. 01'; Balaji et al 00'; Mohapatra et al.04'; Chun 01'; Bhattacharyya et al 03'; Joshipura et al03'; Antusch, Kersten, Lindner, Ratz 03'; Antusch, Huber, Kersten, Schwetz, Winter 04; Antusch, Kersten, Ratz 02'; Antusch, Ratz 02'



↓

important for GUT and flavour models:

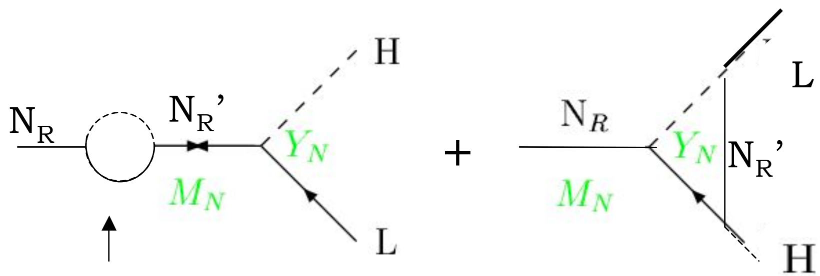
- especially if ν are quasi-degenerate
- especially for θ_{12} because associated to small Δm^2_{sol}
- induce deviation from maximal for θ_{23}
- interesting phenomenons for model building ← mixing angle magnification through running

→ will become mandatory at the level of precision of new ν data

Matter-antimatter asymmetry of the universe

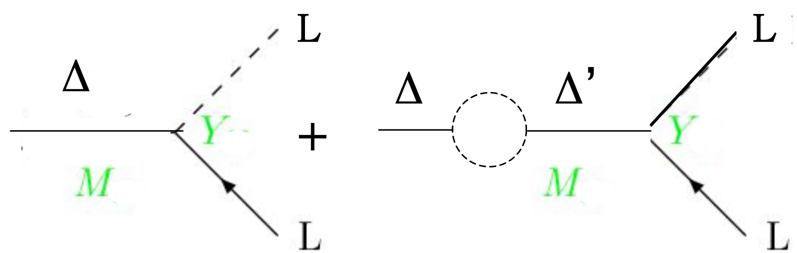
from the seesaw interactions responsible for neutrino masses one can also explain baryogenesis via leptogenesis

- type-I:



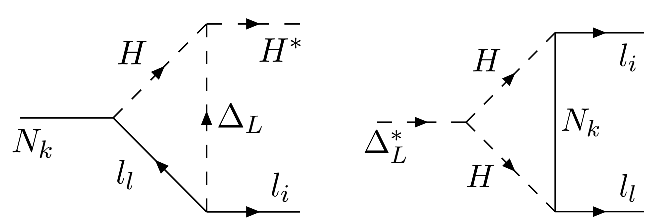
Fukugita, Yanagida 86', Buchmüller, Plumacher 97', ...

- type-II:



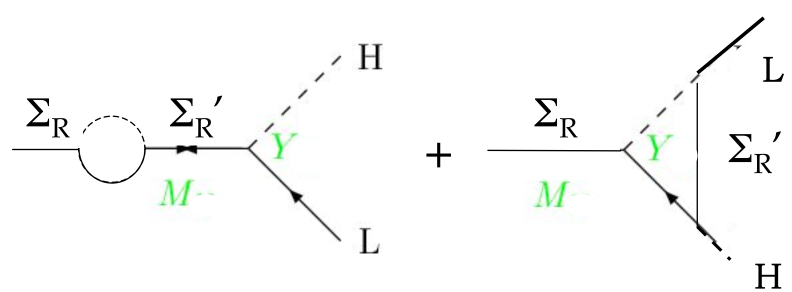
Ma, Sarkar 98', ...

- type-I+ type II:



O'Donnell, Sarkar 94', TH, Senjanovic 04'; Antusch, King 04', ...

- type-III:



TH, Lin, Notari, Papucci, Strumia 04'; ...

Non seesaw neutrino mass origins

ν masses from R-parity breaking

masses can be induced in the MSSM without any new field at the price of breaking R-parity

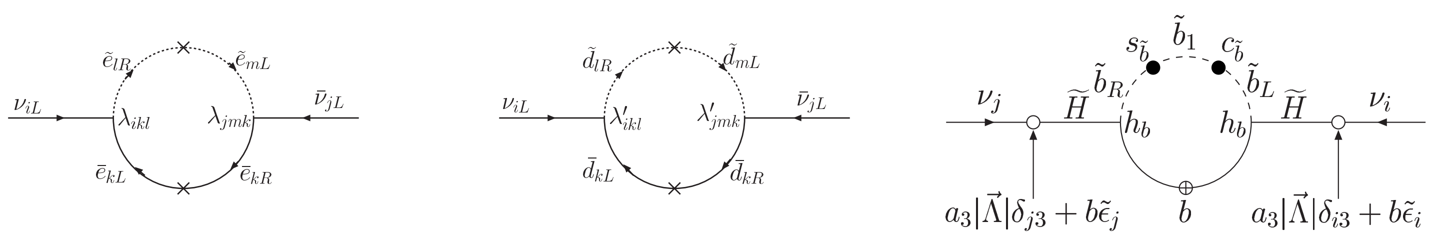
$$W \ni \epsilon_i \hat{L}_i \hat{H}_u + \lambda_{ijk} \hat{L}_i \hat{L}_j \hat{e}_{Rk} + \lambda'_{ijk} \hat{L}_i \hat{Q}_j \hat{d}_{Rk}$$

see e.g. Romao et al 08'

$$V_{soft} \ni B_i^S \tilde{L}_i H_u$$

⇒ gives one m_ν at tree level from neutrino Higgsino mixing
gives 2 m_ν at one loop

} tends to give a ν hierarchy larger than data



doesn't explain the tinyness of ν masses in se

ν masses from supersymmetry breaking

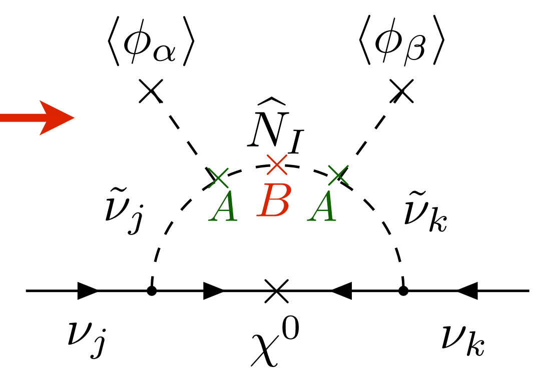
in the MSSM with extra N_R the soft susy breaking terms involving right-handed sneutrinos $\tilde{N}_R$ bring new sources of L violation:

Grossman, Haber 96'
Boubekeur '02

$$\mathcal{L}_{\widetilde{N}} = (m^2_{\widetilde{N}})_{ij}\widetilde{N}_i^*\widetilde{N}_j + B_{ij}\widetilde{N}_i\widetilde{N}_j + A^U_{ij}\widetilde{L}_i H_U \widetilde{N}_j$$

lead to ν masses at one loop

naturally suppressed ν masses



Arkani-Hamed et al;. 01'.
Borzumati, Nomura,01'
Borzumati, Hamagushi, Yanagida 01'
March-Russell, West '03
TH, March-Russell, West '04

Using the Giudice-Masiero mechanism one can:

- forbid the seesaw Y_N and M_{N_R}
- induce them subsequently from F and D terms giving
  - $M_{N_R} \sim M_{\tilde{N}_R} \sim \mathrm{TeV}$
  - $Y_N \sim 10^{-8}$
- induce L violating soft A and B terms giving rise to 1-loop ν mass:

$$m_\nu^{\rm loop} \sim \mu \equiv \frac{\alpha_w}{96\pi}\frac{m_I^9 v^2}{M^5 m_{\rm susy}^5} \simeq 10^{-2}\,\mathrm{eV} - 10^{-1}\,\mathrm{eV}$$

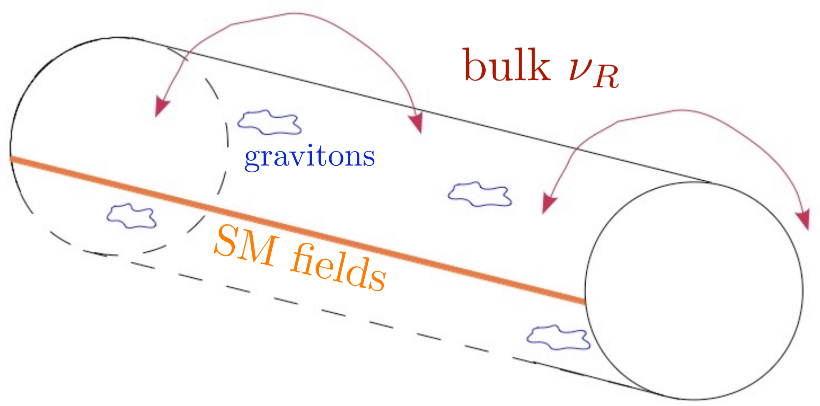
$\Longrightarrow$ testable TeV scale model

ν masses from extra dimensions: large extra dimension

Hierarchy problem: why gravity so weak % electroweak force? $M_{Planck} >> v_{EW}$

↪ if gravity propagates in 3+1+d dimensions whereas we live in 3 +1 dimensions

⇓ Arkani-Hamed,Dimopoulos, Dvali 98'



gravity is weak in 3+1 dim.: volume suppression

$$M^2_{Planck} = M_G^{2+d} V_d \quad V_d = (2\pi R)^d$$

but is similar to weak force in 3+1+d dim.

↪ fundamental gravity scale: $M_G \sim TeV \sim v_{EW}$

⇒ if the N_R propagates in the 3+1+d dim. as graviton: suppression of m_ν

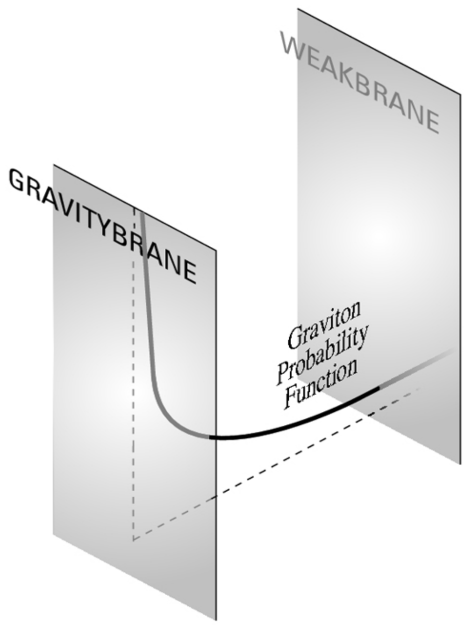
↪ lead to tiny Dirac m_ν e.g. 10^{2-3} too small % data in minimal version but OK in non minimal versions

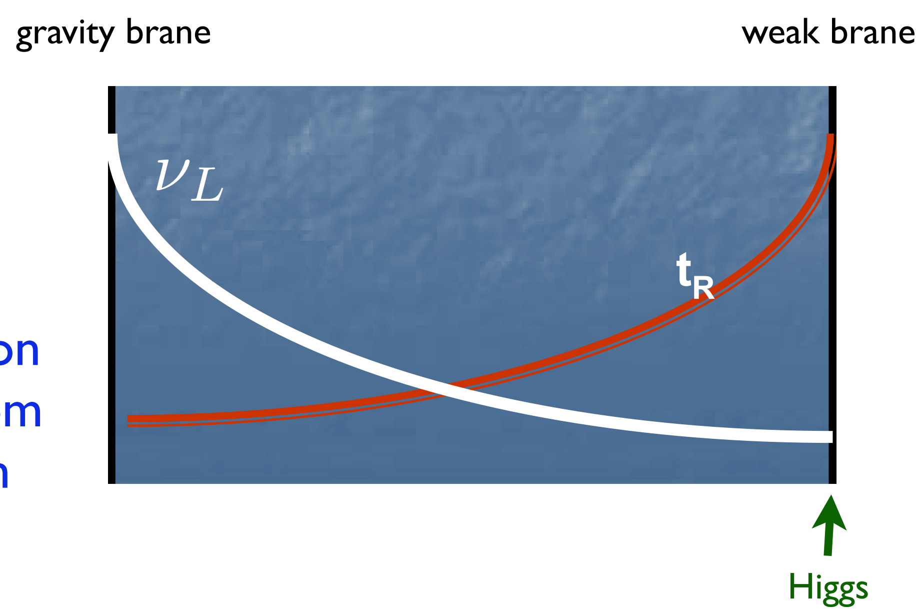
Dienes, Dudas, Gerghetta 99'
Arkani-Hamed, Dimopoulos, Dvali, March-Russell 00'
Dvali, Smirnov 99'

⇒ interesting phenomenology at TeV scale, effects of Kaluza-Klein N_R (supernovae,...), large $\mu \to e\gamma$,........

ν masses from extra dimensions: Randall-Sundrum scenario

↪ suppression of gravity on weak brane if there is an extra curved (warped) dimension with graviton wave function peaked on a distant UV Planck brane





⇒ naturally suppressed m_ν if the wave function of the ν is peaked on the UV brane far from the weak brane where sits the Higgs boson

ν mass varying with their environment

Fardon, Nelson, Weiner 03', Peccei 04'

- 73% of universe energy content is due to dark energy
- 2 coincidences between ν and dark energy:
  - dark energy scale $V^{1/4} \sim 10^{-3}\,\mathrm{eV}$ of order ν masses
  - universe energy densities, ρ_ν and ρ_Λ, are within 3 orders of magnitudes today

$\Longrightarrow$ idea: the scalar field ϕ responsible for ν masses is the dark energy field

$\Downarrow$

ϕ contributes in 2 ways to universe energy density

$$V(\phi) = V_0(\phi) + n_\nu m_\nu$$

$V_0(\phi)$: usual scalar potential

$n_\nu m_\nu$: ϕ contribution to m_ν it induces

$\Longrightarrow$ early universe (high ν density): $n_\nu m_\nu$ large $\rightarrow$ ϕ small $\rightarrow$ m_ν small

today universe (high ν density): $n_\nu m_\nu$ small $\rightarrow$ ϕ large $\rightarrow$ m_ν larger

$\Longrightarrow$ varying m_ν : - ρ_ν keeps track of ρ_Λ

- $m_\nu \sim V^{1/4}$ because $T \sim m_\nu$ today

$(\rho_\nu \sim T^3 m_\nu$ and $\rho_\Lambda \sim V)$

Short conclusion for long talk

ν data:

- provides a unique tool to probe beyond standard model physics up to very high scales
- has and will open the door to a large variety of theoretical works related to very fundamental questions