LPT-Orsay

Neutrino Physics: theory and phenomenology

Cargese 2018 International Summer School

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inνisiblesPlus elusiνes

two lectures

- Basics: history and basic concepts
- Oscillation phenomena and searches from many fronts
- Properties and Nature
- Theoretical frameworks and (Minimal) New Physics Models
- Effective approach and some applications

Some references

- C. Giunti, C.W. Kim, “Fundamentals of Neutrino Physics and Astrophysics, Oxford University Press.
- R. N. Mohapatra and P. Pal, “Massive Neutrinos in Physics and Astrophysics, World Scientific
- M. Fukugita, T. Yanagida, “Physics of Neutrinos: and Application to Astrophysics (Theoretical and Mathematical Physics) ", Springer

Part 1

- Neutrino Problem: brief chronology
- Oscillation phenomena
- Searches from many fronts: present situation
- Theoretical frameworks and Minimal New Physics Models

Neutrinos are the most elusive particles of the Standard Model

$$Q_{em} = 0, \quad Q_{color} = 0.$$

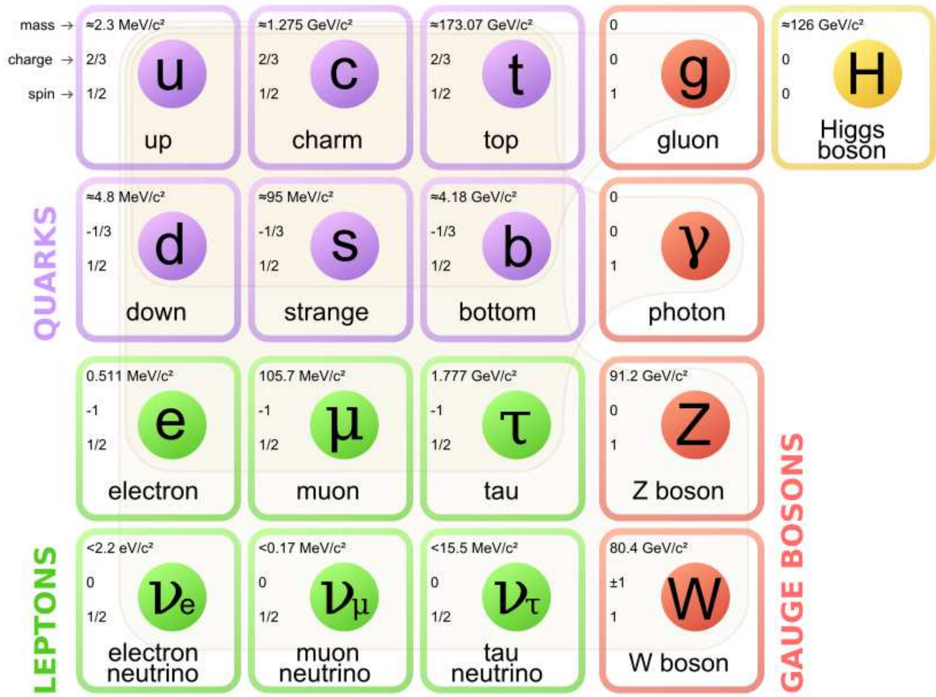
- **Provide informations on the essential features of the SM:**
  "left" nature of the weak interaction and family structure

- **more importantly, they call for physics beyond the Standard Model**

The Standard Model of particle physics

- **Standard Model:** renormalisable QFT formulation based on $SU(3)_c \times SU(2)_L \times U(1)_Y$

  $\Rightarrow$ **successful description** of (most) elementary particles and their interactions



- **Gauge bosons** ⇝ **strong, weak, electromagnetic** interactions
- **Quarks** (strong, weak, electric);
  charged leptons (weak, electric);
  neutral leptons (weak)
- **Higgs boson:** EW symmetry breaking;
  elementary particle masses

☞ Despite its *remarkable success*, is the **SM the ultimate description of Nature?**

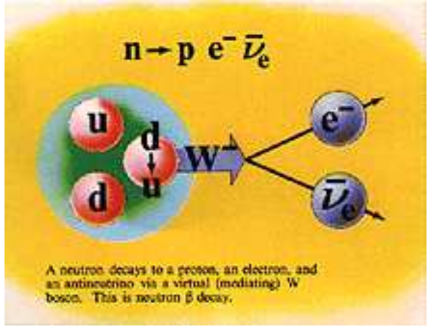
Theoretical caveats (hierarchy problem, choice of gauge group, family/flavour puzzle, ...)

Observational problems: dark matter candidate, baryon asymmetry of the Universe,

massive neutrinos!

Brief history of the neutrinos ν

- ν **birth:** **"Rescue" conservation of energy** in nucleus beta decay $\quad n \to p + e^- + \bar{\nu}_e$



"Dear Radioactive Ladies and Gentlemen,

... because of the wrong statistics of the N and Li^6 nuclei...and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" of statistics and the law of conservation of energy. ... electrically neutral particles, that I wish to call neutrons, which have spin 1/2 and obey the exclusion principle ...

...The continuous beta spectrum would then become understandable..."

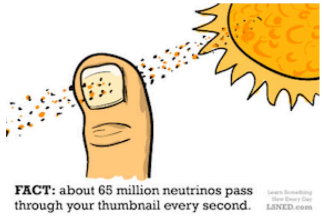
Pauli, 1930

- **Fermi Theory for β decay** (Named **"neutrino"** 1934), following)
  the "neutron" discovery by **Chadwick** (1933), assumed **massless**
- **(Anti)Electron neutrino:** detected in **1956** by **Cowan** and **Reines**; so they come **in flavours!**
- **Muon neutrino:** $\pi^- \to \mu^- \bar{\nu}_\mu$ discovery in **1962** by **Lederman, Schwartz** and **Steinberger**
- **3 neutrino families:** Z boson **decay width, CERN 1989**
- **Tau neutrino:** $\tau^- \to \pi^-\pi^-\pi^+\pi^-\pi^+\nu_\tau$ direct evidence in **2000** by **DONUT at Fermilab**

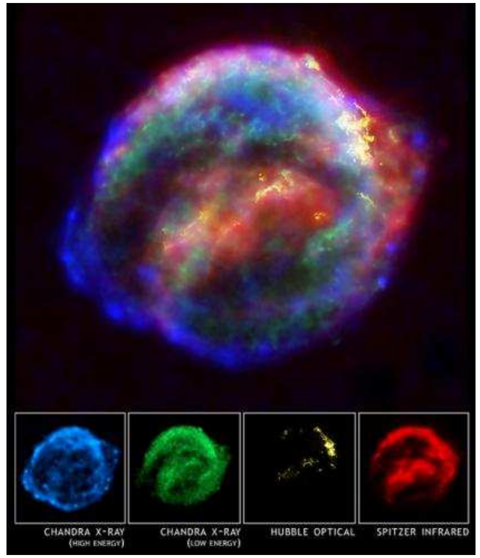
☞ **Neutrinos in the SM:** 3 **massless** states! $\quad \nu_e,\ \nu_\mu$ and ν_τ

Studying neutrinos: rich sources in Nature & hand-made

- About $\sim 10^{11}$ **neutrinos** cross a cm^2 of our skin!



- About $\sim 10^{8}$ **neutrinos** from natural radioactivity,
- even $\sim 10^{11}$ **relic neutrinos** from the Big-Bang



- Supernova, e.g., SN1987A $\sim 10^{11}$ **neutrinos** similar as solar flux during few seconds

→ **Neutrino Astronomy era!**

Studying neutrinos: sources & detectors

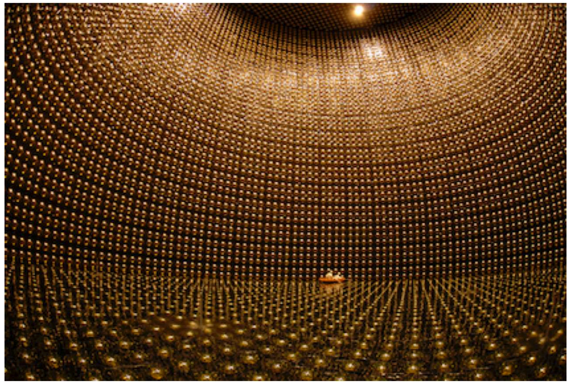
- **Neutrino sources** have been experimentally and observationally explored,
  huge impact for particle & astroparticle physics and astronomy!

- A **world-wide effort** to detect and study ν's
  from different sources, using distinct methods...

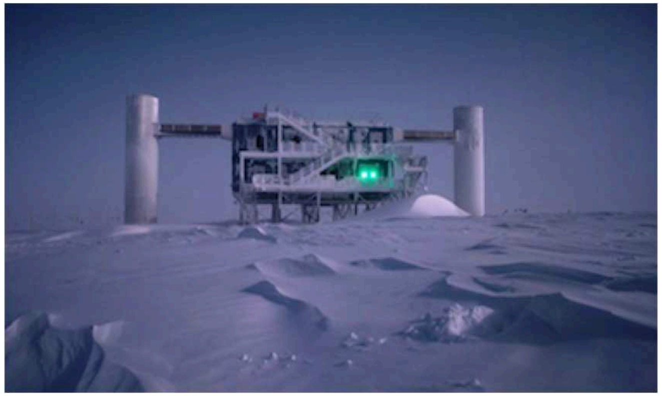
Laboratory: reactors, accelerators

Cosmic rays: atmospheric neutrinos (ν_{atm}), ultra-high energy neutrinos

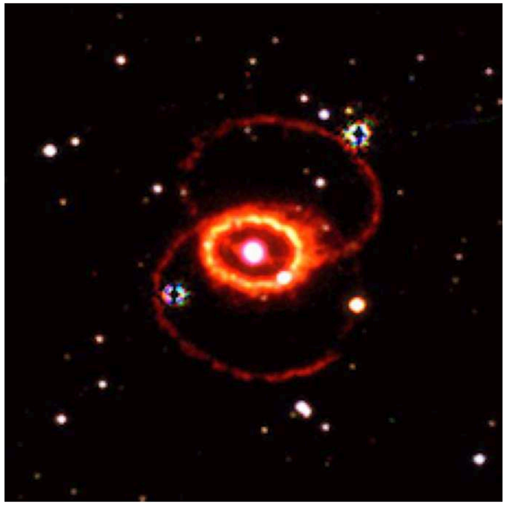
Astrophysical: solar neutrinos (ν_{sol}), supernovae



Super-Kamokande



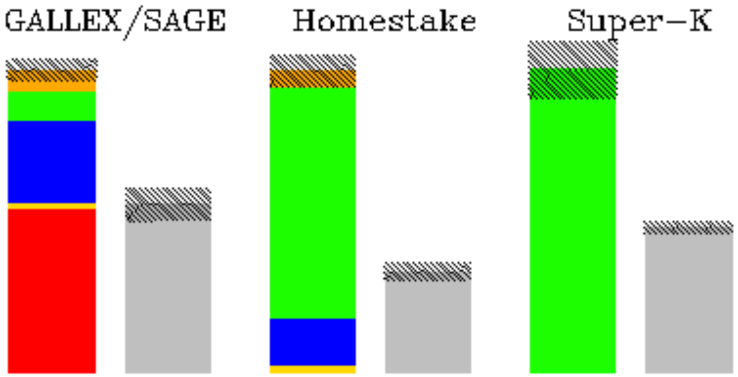
IceCube Neutrino Observatory

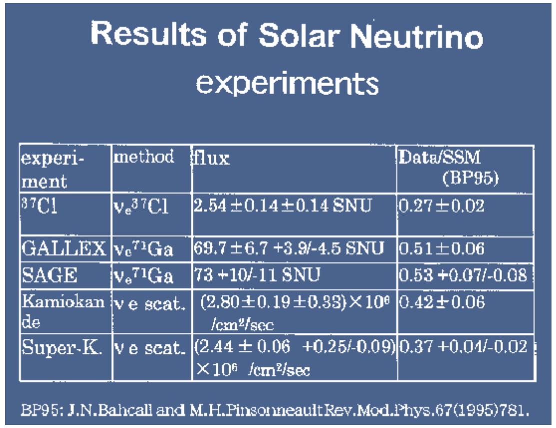


SN1987A

Studying neutrinos: unexpected news

A puzzling and surprising discovery: the solar ν_e and atmospheric ν_μ fluxes...





Results of Solar Neutrino experiments

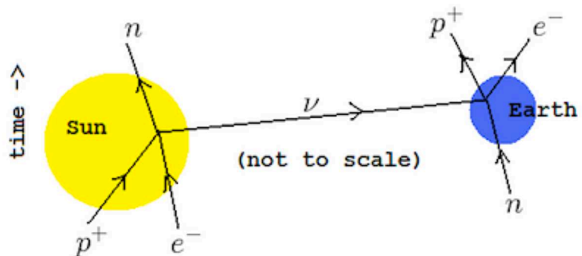
experi-ment	method	flux	Data/SSM (BP95)
^{37}Cl	$\nu_e{}^{37}$Cl	2.54±0.14±0.14 SNU	0.27±0.02
GALLEX	$\nu_e{}^{71}$Ga	69.7±6.7 +3.9/-4.5 SNU	0.51±0.06
SAGE	$\nu_e{}^{71}$Ga	73 +10/-11 SNU	0.53 +0.07/-0.08
Kamiokande	ν e scat.	(2.80±0.19±0.33)×10^6 /cm^2/sec	0.42±0.06
Super-K.	ν e scat.	(2.44 ± 0.06 +0.25/-0.09)×10^6 /cm^2/sec	0.37 +0.04/-0.02

BP95: J.N.Bahcall and M.H.Pinsonneault Rev.Mod.Phys.67(1995)781.

- **Solar neutrino problem:** detection of **only 1/3 of expected flux of solar ν_e's**
- **Atmospheric neutrino problem:** detection of $\#\nu_e \sim \#\nu_\mu$, expected $\#\nu_\mu \sim 2\#\nu_e$

$$\pi^\pm\ ,\ K^\pm \to \quad \mu^\pm \quad +\nu_\mu(\overline{\nu}_\mu)$$
$$\mu^\pm \quad \to e^\pm \ +\ \nu_e(\overline{\nu}_e)\ +\ \overline{\nu}_\mu(\nu_\mu)$$

- **"Unexpected" production of ν_α:** *do charged currents violate lepton flavours?*
- **"Disappearance" of propagating ν_α:** *do neutrinos oscillate?*
- **Standard Solar model** predictions: *to be challenged?*



→ **Massive implications:** *Propagating neutrinos are not weak interaction eigenstates!*

Neutrino oscillations $\rightarrow$ massive states, leptonic mixing!

- Illustrative 2-family example

  2 **massive states** ($\nu_2, \nu_3 : \ \Delta m_\nu = \sqrt{|m_2^2 - m_3^2|}$) related to 2 flavour states $\nu_\alpha = U^*_{\alpha i}\,\nu_i$

$$\begin{pmatrix} \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_2 \\ \nu_3 \end{pmatrix}$$

- Consider **a relativistic neutrino**, produced (e.g.) in muon decay??

  (i) Production of weak eigenstate: $|\nu(t=0)\rangle = |\nu_\mu\rangle = \cos\theta\,|\nu_2\rangle + \sin\theta\,|\nu_3\rangle$

  (ii) Travel distance L to the **detector**, during which it *oscillates*

$$|\nu(t)\rangle = \cos\theta e^{-iE_2 t}|\nu_2\rangle + \sin\theta e^{-iE_3 t}|\nu_3\rangle, \quad \text{with } t \simeq L \text{ and } E \sim \sqrt{p^2 + m^2}$$

  (using wave packet formalism we arrive to the same expressions)

  (iii) At the detector, it produces μ in **charged current** scattering, with probability

$$\mathcal{P}^{2\nu}_{\mu\to\mu}(L,t) = |\langle\nu_\mu|\nu(t)\rangle|^2 = 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m_\nu^2 L}{4E}\right) \quad \neq 1$$

☞ **Indisputable:** Oscillations hold if and only if νs are massive and mix

→ The minimal SM is incomplete!

Charged current interaction not diagonal in flavour space

$$\mathcal{L}_{int} = -\frac{g}{\sqrt{2}} \bar{\ell}^i_L \gamma^\mu \nu^j_L \boldsymbol{U}_{ij} W^+_\mu + h.c. \ ,$$

For $n = 3$ ➡ Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix

$$U = \begin{pmatrix} c_{12}\ c_{13} & s_{12}\ c_{13} & s_{13} e^{-i\delta} \\ -s_{12}\ c_{23} - c_{12}\ s_{23}\ s_{13} e^{i\delta} & c_{12}\ c_{23} - s_{12}\ s_{23}\ s_{13} e^{i\delta} & s_{23}\ c_{13} \\ s_{12}\ s_{23} - c_{12}\ c_{23}\ s_{13} e^{i\delta} & -c_{12}\ s_{23} - s_{12}\ c_{23}\ s_{13} e^{i\delta} & c_{23}\ c_{13} \end{pmatrix} \mathrm{Diag}\left\{ e^{i\alpha_1}, e^{i\alpha_2}, 1 \right\}$$

[Chau-Keung parametrisation]

δ Dirac phase, $\alpha_{1,2}$ Majorana[a], $\theta_{12}, \theta_{23}, \theta_{13}$

m_1, m_2, m_3 mass eingenvalues, if $m_3 > 0$, $m_{1,2} = |m_{1,2}| e^{i\alpha_{1,2}}$

[a] We will discuss the Nature Majorana or Dirac later

Transition Probabilities

$$P(\nu_\alpha \to \nu_\beta; L) = \delta_{\alpha\beta} - 4 \sum_{j<k} \mathrm{Re}\left(U_{\alpha j} U^*_{\beta j} U^*_{\alpha k} U_{\beta k}\right) \sin^2\left(\frac{\Delta m^2_{jk} L}{4E}\right)$$
$$\pm \quad 2 \sum_{j<k} \mathrm{Im}\left(U_{\alpha j} U^*_{\beta j} U^*_{\alpha k} U_{\beta k}\right) \sin\left(\frac{\Delta m^2_{jk} L}{2E}\right), \quad \Delta m^2_{jk} = m^2_j - m^2_k$$

- ☞ $\pm$ ➞ $-$ for neutrinos, $+$ for antineutrinos
- ☞ Appearance (Desappearance) oscillation probability: $\alpha \neq \beta$ ($\alpha = \beta$)
- ☞ Oscillation experiments do not give the nature : Dirac or Majorana : $\overline{\nu} \equiv \nu$!
- ☞ oscillations arise when $L \sim L_{\text{osc}} \Rightarrow \frac{\Delta m^2 L}{4\pi E} \sim 1 \Leftrightarrow \Delta m^2(\mathrm{eV}^2) \sim \frac{E(\mathrm{GeV})}{L(\mathrm{km})}$
- ☞ e.g., $n = 2$: $P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2\left(\frac{L}{L_{\text{osc}}}\pi\right)$, $L_{\text{osc}} = \frac{4\pi E}{\Delta m^2} \simeq 2.48\mathrm{km}\left(\frac{E(\mathrm{GeV})}{\Delta m^2(\mathrm{eV}^2)}\right)$

⬇

Accessible Δm^2

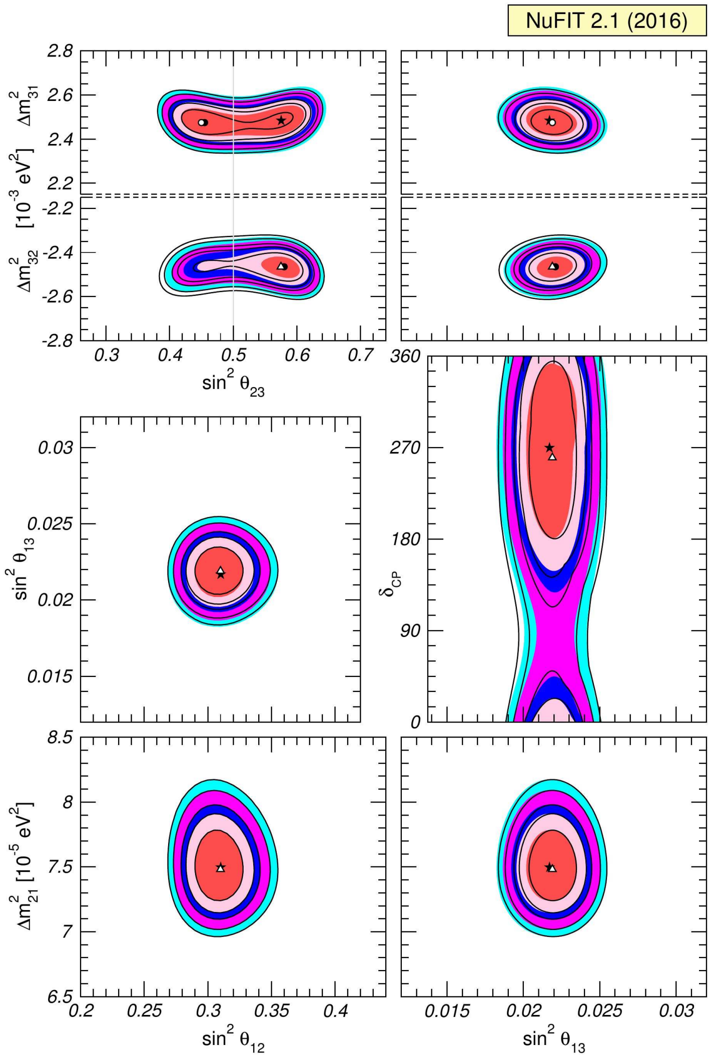
Depending on ν sources (E) and positions L of the detector :

L(km)	E(GeV)	Δm^2(eV^2)	Source
10^8	10^{-3}	10^{-11}	solar ν
10^4	1	10^{-4}	atmospheric ν
10^3	10	10^{-2}	ν from accelerators (long distance)
0.1	1	10	ν from accelerators (short distance)
0.1	10^{-3}	10^{-2}	ν from reactors

☞ **Facts:** ν change flavours after propagating a finite distance

Solar $\nu_e \to \nu_{\mu,\tau}$	$\Delta m^2_{\text{sol}} \simeq 7.6 \times 10^{-5}\ \text{eV}^2$ $\sin^2\theta_{\text{sol}} \simeq 0.30$	SNO, BOREXino, Super-Kamiokande, GALLEX/GNO, SAGE, Homestake, Kamiokande
Atmospheric $\nu_\mu \to \nu_\tau$		IMB, MAcro, Soudan-2, Kamiokande, Super-Kamiokande
LBL Accelerator ν_μ disappearance	$\Delta m^2_{\text{atm}} \simeq 2.4 \times 10^{-3}\ \text{eV}^2$ $\sin^2\theta_{\text{atm}} \simeq 0.50$	K2K, T2K, MINOS
LBL Accelerator $\nu_\mu \to \nu_\tau$		Opera
LBL Accelerator $\nu_\mu \to \nu_e$	Δm^2_{atm}	T2K, MINOS
LBL Reactor $\overline{\nu}_e$ disappearance	$\sin^2\theta_{\text{Chooz}} \simeq 0.023$	Daya Bay, RENO Double Chooz
SBL Accelerator $\nu_\mu(\overline{\nu}_\mu) \to \nu_e(\overline{\nu}_e)$	$\Delta m^2 \simeq 1\text{eV}^2$ (?)	LSND, MiniBooNE
SBL Reactor $\overline{\nu}_e$ disappearance	$\sin^2\theta \simeq 0.1$ (?)	++ Solar: GALLEX, SAGE++ Bugey, ILL, Rovno,...

Lepton mixing & neutrino data: current status



$\Rightarrow$

NuFIT 2.1 (2016)

LEM	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 0.97$)		Any Ordering
$\sin^2\theta_{12}$	$0.308^{+0.013}_{-0.012}$	$0.273 \to 0.349$	$0.308^{+0.013}_{-0.012}$	$0.273 \to 0.349$	$0.273 \to 0.349$
$\theta_{12}/^\circ$	$33.72^{+0.79}_{-0.76}$	$31.52 \to 36.18$	$33.72^{+0.79}_{-0.76}$	$31.52 \to 36.19$	$31.52 \to 36.18$
$\sin^2\theta_{23}$	$0.574^{+0.026}_{-0.144}$	$0.390 \to 0.639$	$0.579^{+0.022}_{-0.029}$	$0.400 \to 0.637$	$0.390 \to 0.639$
$\theta_{23}/^\circ$	$49.3^{+1.5}_{-8.3}$	$38.6 \to 53.1$	$49.6^{+1.3}_{-1.7}$	$39.2 \to 53.0$	$38.6 \to 53.1$
$\sin^2\theta_{13}$	$0.0217^{+0.0013}_{-0.0010}$	$0.0187 \to 0.0250$	$0.0221^{+0.0010}_{-0.0010}$	$0.0190 \to 0.0251$	$0.0187 \to 0.0250$
$\theta_{13}/^\circ$	$8.47^{+0.24}_{-0.20}$	$7.86 \to 9.11$	$8.54^{+0.19}_{-0.20}$	$7.93 \to 9.12$	$7.86 \to 9.11$
$\delta_{CP}/^\circ$	272^{+61}_{-64}	$0 \to 360$	256^{+43}_{-43}	$131 \to 381$	$0 \to 360$
$\dfrac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.49^{+0.19}_{-0.17}$	$7.02 \to 8.08$	$7.49^{+0.19}_{-0.17}$	$7.02 \to 8.08$	$7.02 \to 8.08$
$\dfrac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.484^{+0.045}_{-0.048}$	$+2.351 \to +2.618$	$-2.467^{+0.041}_{-0.042}$	$-2.595 \to -2.341$	$\begin{bmatrix}+2.351 \to +2.618\\ -2.588 \to -2.348\end{bmatrix}$

- ▶ **"Precision era"** for **neutrino physics**
- ▶ Only **three** oscillation **parameters unknown...**

  $\boldsymbol{\theta_{23}}$ octant; $\boldsymbol{\delta_{CP}}$; $\boldsymbol{\nu}$-mass ordering

- ▶ Exciting **experimental roadmap** ahead!

Lepton mixing & neutrino data: Leptonic CP Asymmetry

$$\Delta_{CP}(\alpha\beta) \equiv P(\nu_\alpha \to \nu_\beta) - P(\overline{\nu_\alpha} \to \overline{\nu_\beta})$$
$$= 4\sum_{j>k} \mathrm{Im}\left(U_{\alpha j}U^*_{\beta j}U^*_{\alpha j}U_{\beta k}\right)^* \sin\left(\Delta m^2_{jk}\frac{L}{2E}\right)$$

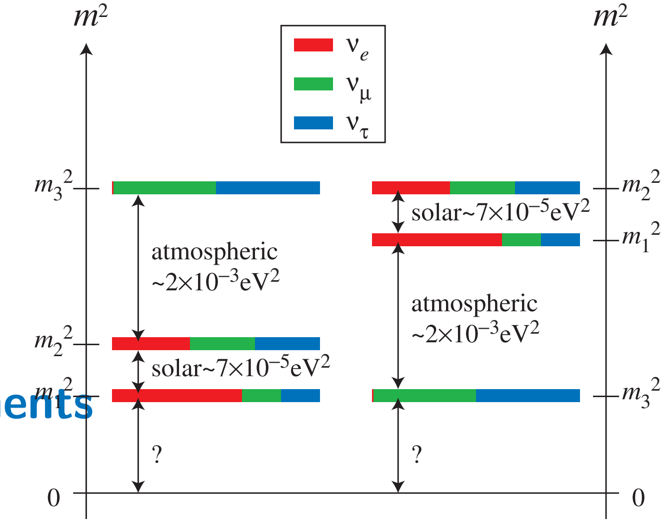
- ☞ Cannot be observed in **appearance experiments**

$$CPT \to \Delta_{CP}(e\mu) = \Delta_{CP}(\mu\tau) = \Delta_{CP}(\tau e) \equiv 16\mathcal{J}\ell_{12}\ell_{23}\ell_{31}$$

- ☞ $\mathcal{J} \equiv \mathrm{Im}\left(U_{e3}U^*_{e1}U^*_{\mu 3}U_{\mu 1}\right) \simeq \sin 2\theta_{23}\sin 2\theta_{12}\sin\theta_{13}\sin\delta$
  (Jarlskog Invariant)
- ☞ $\ell_{ij} \equiv \sin\left(1.27\Delta m^2_{ij}(\mathrm{eV})^2\frac{L(\mathrm{km})}{E(\mathrm{GeV})}\right)$
- ☞ θ_{23} large (OK) and also Δm^2_{13}.
- ☞ θ_{12} large (OK) and also Δm^2_{12}.
- ☝ θ_{13} conditions the measurement of CPV phase: $\theta_{13} \sim 8.5^0$

▶ **What about (absolute) neutrino masses?**

Lepton mixing & neutrino data: Absolute ν masses



- ▶ **Oscillation data:** only **two squared-mass differences**

  Undetermined mass ordering:

  normal $[m_{\nu_1} < m_{\nu_2} \ll m_{\nu_3}]$

  inverted $[m_{\nu_3} \ll m_{\nu_1} \lesssim m_{\nu_2}]$

  Unknown absolute mass scale: need direct experiments

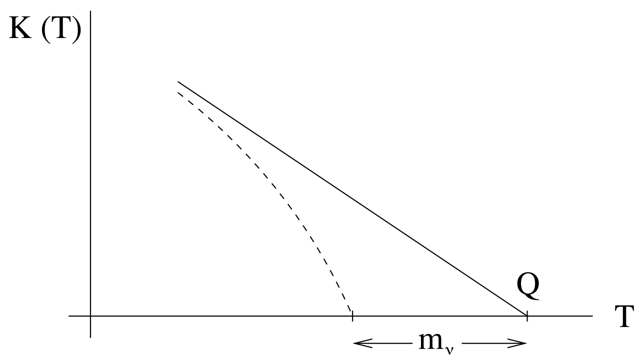
- ▶ **Resolving** the absolute mass scale

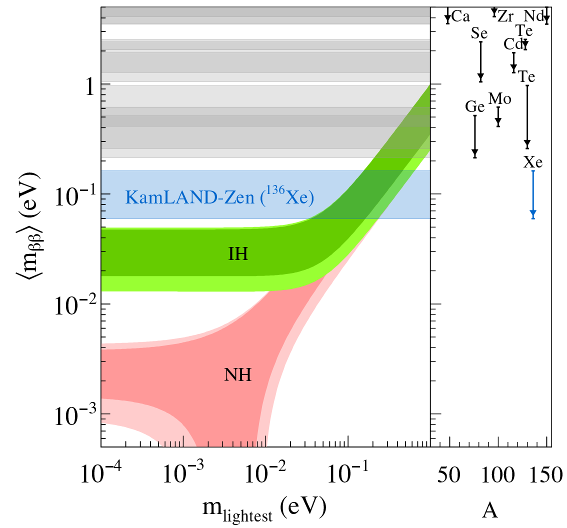
  - **Tritium decays** $({}^3\text{H} \to {}^3\text{He} + \overline{\nu}_e + e^-)$: $\boldsymbol{m_{\nu_e} \lesssim 2.1}$ **eV** [Troitsk]

    ☝ June 11 2018, the KATRIN experiment has been inaugurated!

  - **$0\nu2\beta$ decays** (if Majorana ν): $\boldsymbol{|m_{ee}| \lesssim 0.3}$ **eV** [GERDA, KamLAND-Zen]

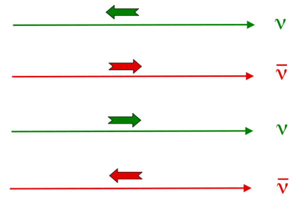
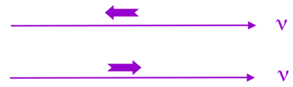
  - **Cosmology** (CMB, LSS, Lyα): $\boldsymbol{\sum_i m_{\nu_i} \lesssim 0.23 \to 0.12}$ **eV**





[KamLAND-Zen Coll., '15]

What about the nature: Dirac or Majorana?

Dirac spinor	Majorana spinor
	
Collection of 4 states	2 states
$\psi = \psi_L + \psi_R$	$\psi = \psi_L + (\psi_L)^c$, $(\psi_L)^c = (\psi)^c_R$
Conservation of L	Non-conservation of L

▶ both descriptions are possible for neutrinos

$$-\mathcal{L}_m^{\text{Dirac}} = m\overline{\psi}\psi = m(\overline{\psi_L + \psi_R})(\psi_L + \psi_R) = m(\overline{\psi_L}\psi_R + \overline{\psi_R}\psi_L)$$ ← all fermions

$$-\mathcal{L}_m^{\text{Majorana}} = \frac{m}{2}\overline{\psi^c}\psi + \frac{m}{2}\overline{\psi}\psi^c = \frac{m}{2}\psi^T C\psi + \frac{m}{2}\overline{\psi}C\overline{\psi}^T,\ \psi^c = C\gamma_0\psi^*,\ C = i\gamma_2\gamma_0$$ ← only for ν

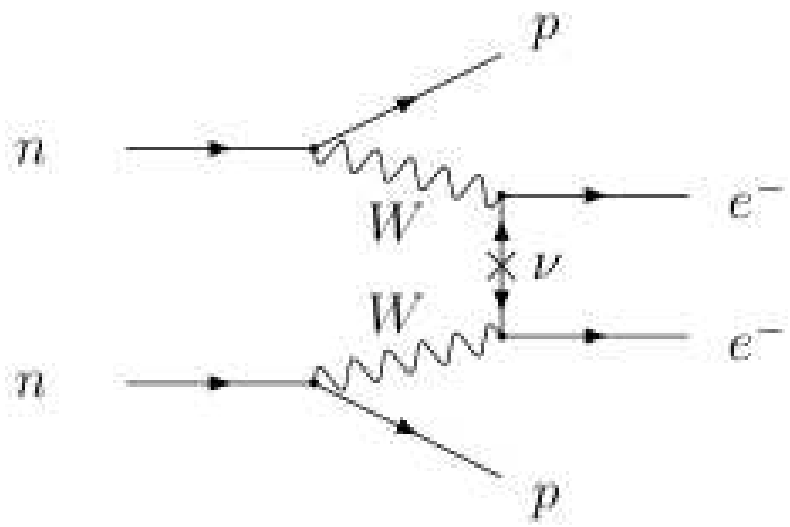
- ☞ Both break gauge invariance (need SSB)
- ☞ $\mathcal{L}_m^{\text{Majorana}}$ violates Lepton number symmetry
- ☞ Lepton number symmetry is accidental in the SM
- ☞ To distinguish them: mass observables and not kinematical observables

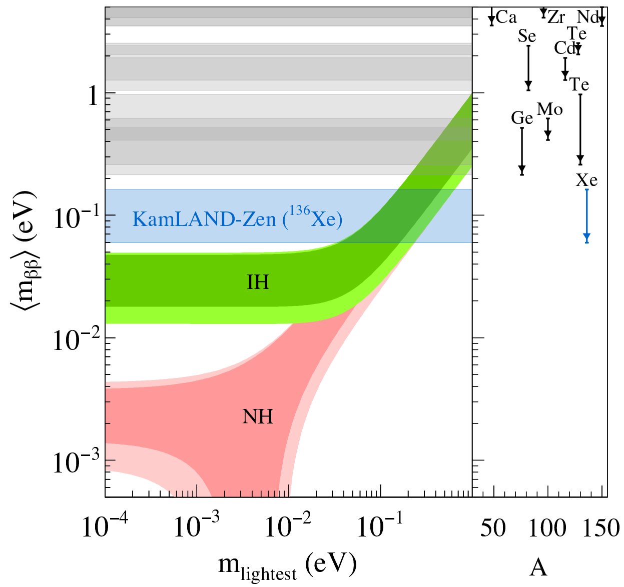
Experimental test for Lepton Number violation ($0\nu\beta\beta$)

$$(A,Z) \longrightarrow (A,Z+2) + e^- + e^- + \overline{\nu_e} + \overline{\nu_e}$$

Furry ➞ $(A,Z) \longrightarrow (A,Z+2) + e^- + e^-$

$$\overline{\nu_e} \equiv \nu_e$$





- $\Delta L = 2$ ➞ Majorana
- ($0\nu\beta\beta$) Amplitude proportional to effective Majorana mass :$|m_{ee}| = |\sum_i U_{ei}^2 m_i|$
- m_{ee} depend on m_i, Dirac and Majorana CP phases and mixings angles
- A signal **($0\nu\beta\beta$)** ➞absolute mass, prove LNV, thus the Majorana nature for ν

☞ **Indisputable:** νs are massive and mix

↓

The minimal SM is incomplete!

↓

An observational Caveat that is also theoretical one!

▶ ν mixings "add fuel to the fire": add to the fermion flavour puzzle!

$$U_{CKM} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}, \lambda \sim 0.2, A \simeq 0.8, \rho \simeq 0.1, \eta \simeq 0.4$$

$\rightarrow$ Quarks: small mixing angles, 1 Dirac CPV phase

$$U_{PMNS} = \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{23}s_{13}c_{12}e^{i\delta} & c_{23}c_{12} - s_{23}s_{13}s_{12}e^{i\delta} & -s_{23}c_{13} \\ s_{23}s_{12} - c_{23}s_{13}c_{12}e^{i\delta} & -s_{23}c_{12} - c_{23}s_{13}s_{12}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \times \mathrm{diag}\left(e^{i\alpha_1}, e^{i\alpha_2}, 1\right)$$

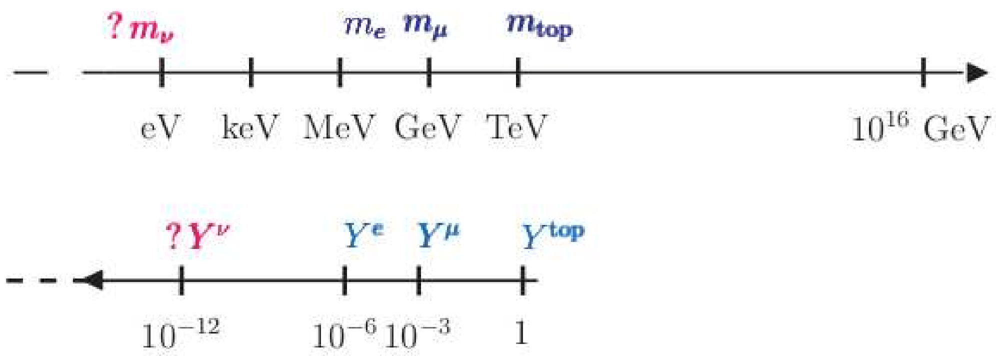
Leptons: 2 large mixing angles, 1 Dirac + 2 Majorana CPV phases

$\Rightarrow$ Very different mixing pattern for Leptons and Quarks

➡ Is this related to different mass generation mechanisms?

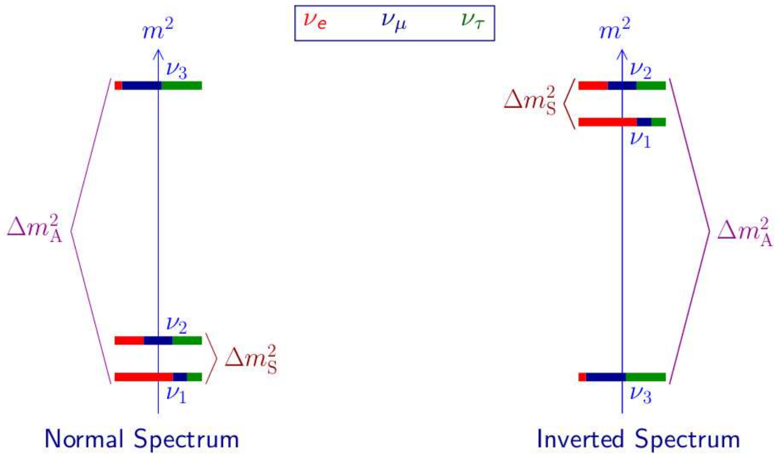
- ν data worsens fermion hierarchy problem!

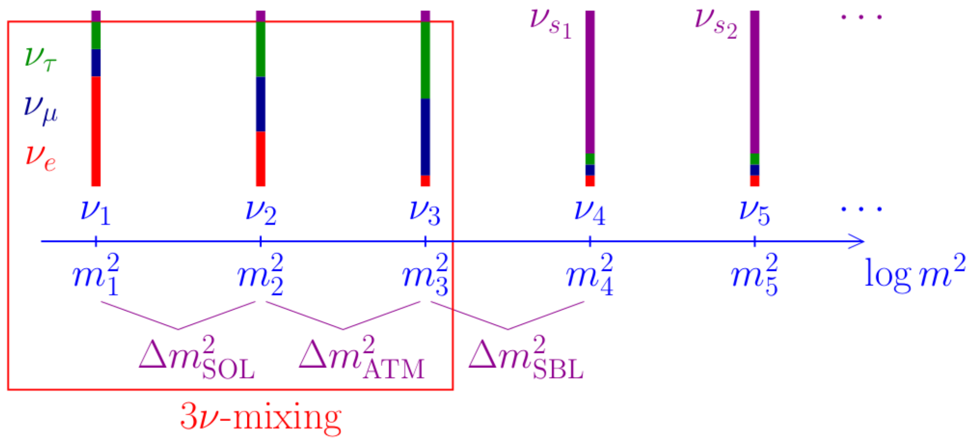
→ Why are ν so light?



→ What is the absolute neutrino mass scale?

▶ **Are there some extra fermionic gauge singlets (steriles)?**





3-ν mixing scheme

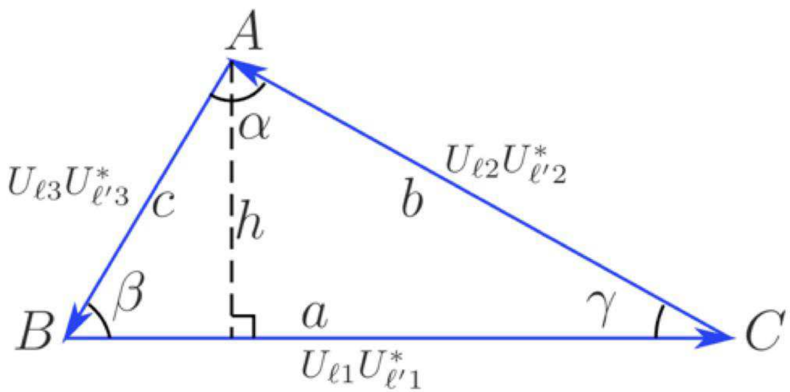
3+?-ν mixing schemes

➞ Does this mean that U_{PMNS} is incomplete? Non-Unitary ?

▶ Strong Potential for CP violation

☞ Unitarity triangle surface $\propto J_{\text{CP}}^{\text{lepton}}$: $J_{\text{CP,max}}^{\text{lepton}} \simeq 1000 \times J_{\text{CP}}^{\text{quark}}$

$$J_{\text{CP}}^{\text{quark}} = 2.96 \times 10^{-5}, \quad J_{\text{CP,max}} \simeq 3.29 \times 10^{-2}$$



$$\mathcal{J} \equiv \text{Im}\left(U_{e3}U^*_{e1}U^*_{\mu 3}U_{\mu 1}\right)$$

$$\mathcal{J} = \sin 2\theta_{23} \sin 2\theta_{12} \sin\theta_{13} \sin\delta$$

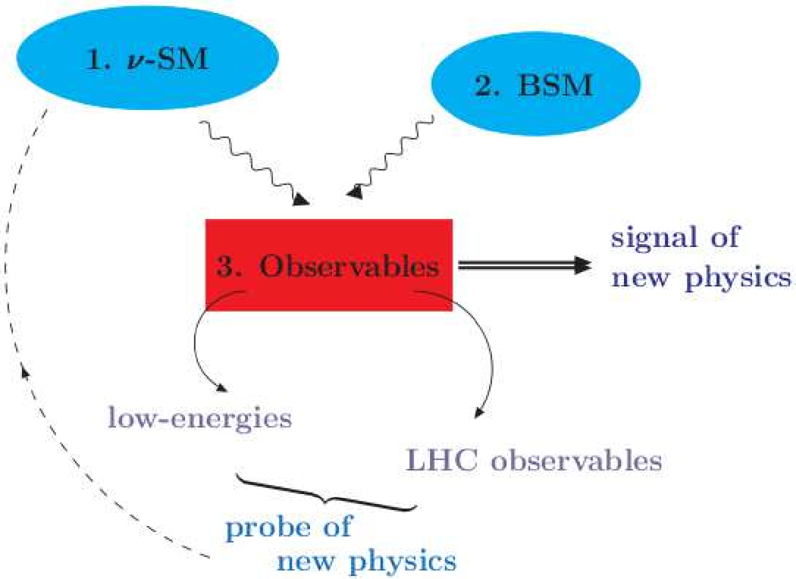
Unitarity Triangle (in e, μ)

Jarlskog Invariant

→ New possibility for having Baryogenesis from Leptogenesis ?

Lepton mixing & massive neutrinos: a gateway to NP

- ν-SM = New Physics just to explain ν masses and mixings
- ν-SM will allow for many new phenomena
- SM has other issues that call for BSM



➞ Determination of ν-SM/BSM model requires combinations of $\neq$ observables

$m_\nu \neq 0 \Rightarrow$ New Physics Scale

Standard Model

- ν_L and no ν_R $\Longrightarrow$ No Dirac mass term: $\mathcal{L}_{m_D} = m_D\,(\overline{\nu_L}\nu_R + \overline{\nu_R}\nu_L)$

- No Higgs triplet $\Longrightarrow$ No Majorana mass term: $\mathcal{L}_{m_M} = \frac{1}{2} M \overline{\nu_L^c}\nu_L + h.c.$

Majorana field: $\Psi_\nu = \nu_L + \nu_L^c$ ➞ $\Psi_\nu = \Psi_\nu^c$ ➞ $\overline{\nu_L^c}\nu_L = \nu_L^T C \nu_L$, $C = i\gamma^2\gamma^0$

- Lepton number symmetry is accidental $\Longrightarrow$ Non-renormalisable operators dim 5, 6 ..

SM $\equiv$ Effective theory of a larger one valid at a scale Λ

↓

$$\delta\mathcal{L}^{d=5} = c^{d=5}\mathcal{O}^{d=5}, \quad \mathcal{O}^{d=5} = \frac{1}{\Lambda}\left\{(\phi\ell)^{\mathrm{T}}(\phi\ell) + h.c.\right\} \xrightarrow{\langle\phi\rangle = v} m_\nu \sim v^2/\Lambda$$

$m_\nu \sim \sqrt{\Delta m^2_{\mathrm{atm}}} \sim \sqrt{2\times 10^{-3}\mathrm{eV}^2} \Rightarrow \Lambda \sim 10^{15}$ GeV (Remarkably near Λ_{GUT} !)

Beyond the Standard Model

Typically 3 possible ways to generate $m_\nu \neq 0$:

- Seesaw mechanism can be achieved via
  1. type I with RH neutrino exchange
  2. type II with scalar triplet exchange
  3. type III with fermionic triplet exchange
- Radiative corrections → MSSM extended $+\not{R}_p$, Zee model, $\cdots$
- Extra dimensions → alternative to the seesaw

Neutrino masses at Tree-Level

Example: SM $+\nu_R$

ν_R (massive and Majorana) : gauge singlet ➔ does not break gauge invariance!!

$$\mathcal{L}_{\text{SM}} \to \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{type-I}}$$

$$\mathcal{L}_{\text{type-I}} = -\sum_{ij}^{a} \left(Y_\nu^{ij} \overline{L_i} \tilde{\phi} \nu_{Rj} + \frac{1}{2} M_R^{ij} \nu_{Rj} \nu_R + h.c. \right)$$

General mass term Dirac+Majorana[a]

($+\nu_L$ with or without Majorana mass[b])

$$\mathcal{L}_M^{(\nu)} = -\frac{1}{2} (\overline{\nu}_L \ \overline{\nu^c}_R) \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix} + h.c.$$

---

[a] Minkowski, Ramond, Yanagida, Mohapatra, Senjanovic, Gell Mann, ...

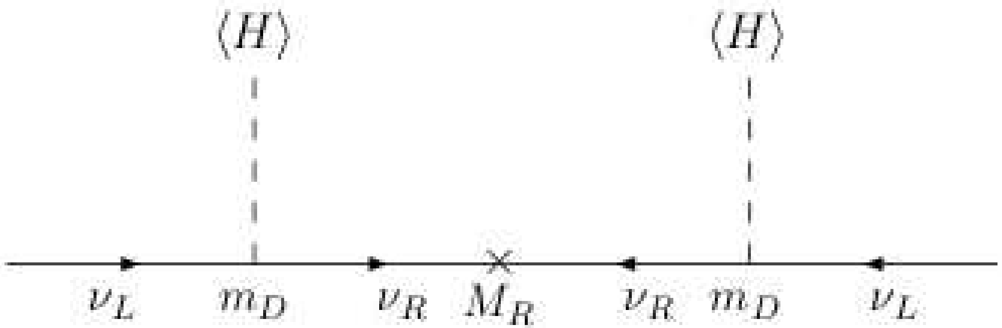
[b] such a term $\overline{\nu_L^c} m_L \nu_L$ ➔ Isospin Triplet

Diagonalisation : $\mathcal{L}_M^{(\nu)} = \frac{1}{2} \left(\overline{L} \; \overline{R^c}\right) \begin{pmatrix} m_L & 0 \\ 0 & M_R \end{pmatrix} \begin{pmatrix} L^c \\ R \end{pmatrix} + h.c.$

mass eigenstates: [in the limit $m_D \ll M_R$]

$$\nu \simeq L + L^c = \nu^c \,, \quad \rightarrow \quad \tilde{m}_L \sim -m_D \frac{1}{M_R} m_D^T$$

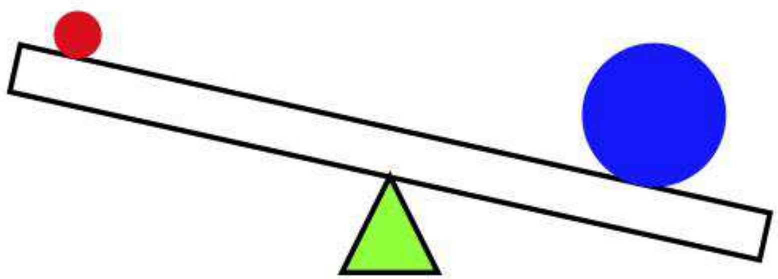
$$N \simeq R + R^c = N^c \,, \quad \rightarrow \quad \tilde{M}_R \sim M_R$$



$$M_R \sim \Lambda$$

One generation case:

$$\tilde{m}_L \sim \frac{m_D^2}{M_R} \ll M_R$$
$$\tilde{M}_R \sim M_R$$



$$\begin{cases} m_D \sim 200\text{GeV} \quad \rightarrow \geq \text{heaviest fermion} \\ M_R \sim 10^{15}\text{GeV} \rightarrow \text{close to GUT} \end{cases}$$

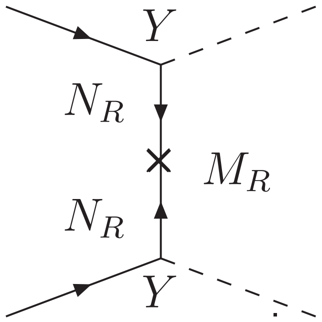
↓

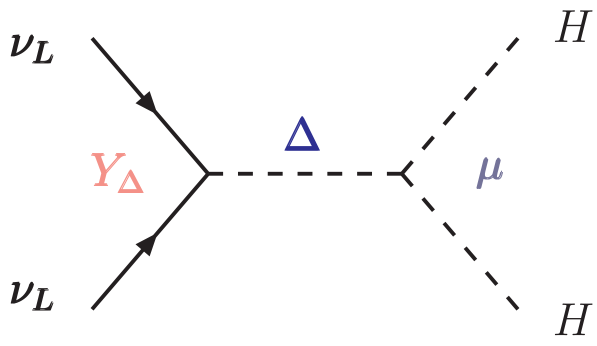
$$m_\nu \propto \sqrt{\Delta m^2_{\text{atm}}} \sim (10^{-2} \; - \; 10^{-1})\text{eV}$$

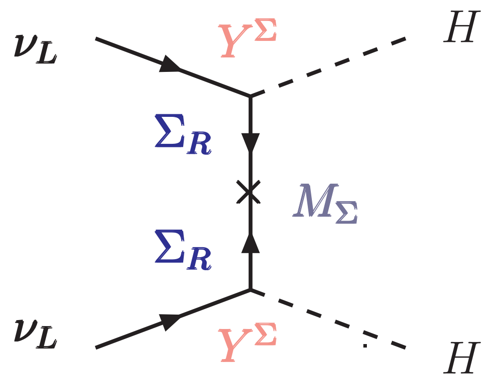
☞ **Neutrino mass generation mechanism at tree-level, other options?**

➡ Other Seesaw Mechanisms

Seesaw I, II, III







type I (fermionic singlet)

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

Minkowski, Gell-Man,

Ramond, Slansky

Yanagida, Glashow

Mohapatra, Senjanovic

type II (scalar triplet)

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

Magg, Wetterich,

Nussinov

Mohapatra, Senjanovic

Schechter, Valle

Ma, Sarkar

type III (fermionic triplet)

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

Ma, Hambye et al.

Bajc, Senjanovic, Lin

A.A., Biggio, Bonnet, Gavela,

Notari, Strumia, Papucci, Dorsner

Fileviez-Perez, Foot, Lew...

☞ **How to disentangle among the different possibilities (BSM)?**

→ Use first the effective approach

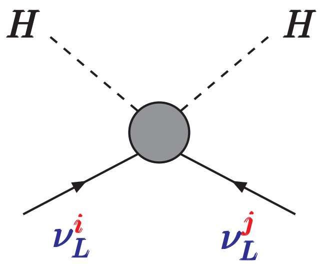
☞ **Neutrino masses require the addition of new fields**

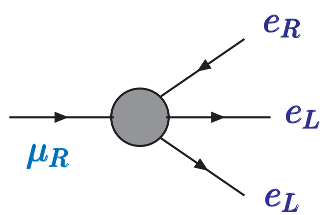
▶ Effects at low energy: effective theorie approach

☞ heavy fermion: $\frac{1}{\not{D}-M} \sim -\frac{1}{M} - \frac{1}{M}\not{D}\frac{1}{M} + \ldots$

☞ heavy scalar : $\frac{1}{D^2-M^2} \sim -\frac{1}{M^2} - \frac{D^2}{M^4} + \ldots$

➙ $$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{1}{M} c^{d=5} \mathcal{O}^{d=5} + \frac{1}{M^2} c^{d=6} \mathcal{O}^{d=6} + \cdots$$

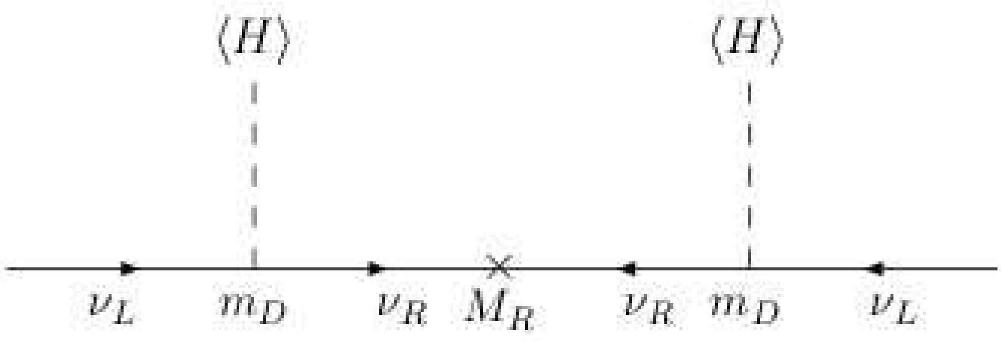
$\Delta \mathcal{L}^{d\geq 5} = \frac{c^{d=5}}{M} \times$ 

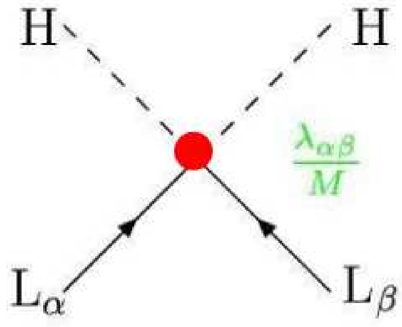
$+ \frac{c^{d=6}_{\mu eee}}{M^2} \times$ 

$+ \frac{c^{d=6}_{\ell_i \ell_j \gamma}}{M^2} \ldots$

Dimension 5

$$\delta\mathcal{L}^{d=5} = \frac{1}{2}\, c^{d=5}_{\alpha\beta} \left(\overline{\ell^c_{L\alpha}}\tilde{\phi}^*\right)\left(\tilde{\phi}^\dagger\, \ell_{L\beta}\right) + \text{h.c.}\,,$$





$$m_\nu = \frac{v^2 Y^\dagger Y}{M_R}$$

$$m_\nu = c^{d=5} v^2, \quad c^{d=5} = \frac{Y^\dagger Y}{M_R}$$

- ☞ $Y \sim 1$ ➙ $M_R \sim M_{\rm GUT}$
- ☞ $Y \sim 10^{-6}$ ➙ $M_R \sim \text{TeV}$

$\mathcal{O}^{d=5}$ Operator violates lepton number L ➙ Majorana neutrinos

- ▶ $\mathcal{O}^{d=5}$ **is common to all models of Majorana neutrinos**

Higher order operators

☞ $\mathcal{O}^{d=5}$ operator: same for all SM extensions incorporating massive MAJORANA

☞ $\mathcal{O}^{d=6}$: 3 "types" of Dimension 6 operators relevant for **cLFV (dipole and 3-body)**

2 lepton-Higgs-photon: $\mathcal{O}^6_{\ell_i\ell_j\gamma} \sim L_i \sigma^{\mu\nu} e_j H F_{\mu\nu}$

$\mathcal{O}^6_{\ell_i\ell_i\gamma}$ ➞ anomalous magnetic or electric moments $(\propto$ Re or Im $\mathcal{C}^6_{\ell_i\ell_i\gamma}/\Lambda^2)$

$\mathcal{O}^6_{\ell_i\ell_j\gamma}$ ➞ **radiative decays** $\ell_i \to \ell_j \gamma$ $(\propto \mathcal{C}^6_{\ell_i\ell_j\gamma}/\Lambda^2)$

4 lepton: $\mathcal{O}^6_{\ell_i\ell_j\ell_k\ell_l} \sim (\ell_i \gamma_\mu P_{L,R} \ell_j)(\ell_k \gamma^\mu P_{L,R} \ell_l) \rightsquigarrow$ **3-body decays** $\ell_i \to \ell_j \ell_k \ell_l$, ...

2 lepton-2 quarks: $\mathcal{O}^6_{\ell_i\ell_j q_k q_l} \sim (\ell_i \gamma_\mu P_{L,R} \ell_j)(q_k \gamma^\mu P_{L,R} q_l)$ **$\mu - e$ in Nuclei, meson decays,**

(Higher order $\mathcal{O}^{d=7,8,..}$: ν (transitional) magnetic moments, NSI, unitarity violation, ...)

☞ **A specific example: Seesaw models**

Dimension 6 operators

Model	Effective Lagrangian $\mathcal{L}_{eff} = c_i \mathcal{O}_i$			
	$c^{d=5}$	$c_i^{d=6}$	$\mathcal{O}_i^{d=6}$	
Fermionic Singlet	$Y_N^T \frac{1}{M_N} Y_N$	$\left(Y_N^\dagger \frac{1}{M_N^\dagger} \frac{1}{M_N} Y_N\right)_{\alpha\beta}$	$\left(\overline{\ell_{L\alpha}} \widetilde{\phi}\right) i \partial\!\!\!/ \left(\widetilde{\phi}^\dagger \ell_{L\beta}\right)$	LFV
Scalar Triplet	$4 Y_\Delta \frac{\mu_\Delta}{M_\Delta^2}$	$\frac{1}{M_\Delta^2} Y_{\Delta\alpha\beta} Y^\dagger_{\Delta\gamma\delta}$	$\left(\overline{\widetilde{\ell_{L\alpha}}} \vec{\tau} \ell_{L\beta}\right)\left(\overline{\ell_{L\gamma}} \vec{\tau} \widetilde{\ell_{L\delta}}\right)$	LFV
		$\frac{\lvert\mu_\Delta\rvert^2}{M_\Delta^4}$	$\left(\phi^\dagger \vec{\tau} \widetilde{\phi}\right)\left(\overleftarrow{D_\mu} \overrightarrow{D^\mu}\right)\left(\widetilde{\phi}^\dagger \vec{\tau} \phi\right)$	Higgs-Gauge
		$-2\left(\lambda_3 + \lambda_5\right) \frac{\lvert\mu_\Delta\rvert^2}{M_\Delta^4}$	$\left(\phi^\dagger \phi\right)^3$	Higgs
Fermionic Triplet	$Y_\Sigma^T \frac{1}{M_\Sigma} Y_\Sigma$	$\left(Y_\Sigma^\dagger \frac{1}{M_\Sigma^\dagger} \frac{1}{M_\Sigma} Y_\Sigma\right)_{\alpha\beta}$	$\left(\overline{\ell_{L\alpha}} \vec{\tau} \widetilde{\phi}\right) i D\!\!\!\!/ \left(\widetilde{\phi}^\dagger \vec{\tau} \ell_{L\beta}\right)$	LFV

Fermions: if $Y \sim \mathcal{O}(1)$, $c^{d=6} \sim (c^{d=5})^2$ and the smallness m_ν would preclude observable effects from $\mathcal{O}_i^{d=6}$. Not the case for scalars!

- d=6 operators allow to discriminate among models of Majorana ν
- d=5 operator violates B-L but all d=6 operators conserve it

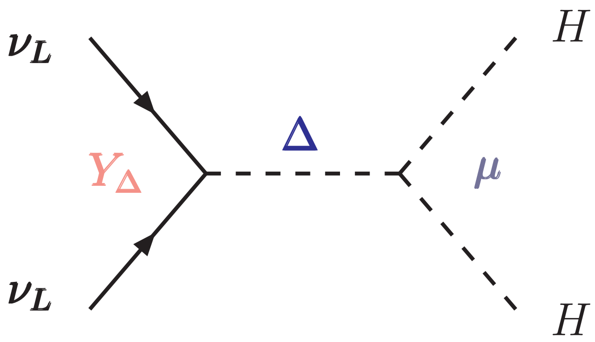
➡ Direct Lepton Violation pattern:

d=5 operator supressed by a small scale and not the d=6 operators

Natural with scalar triplet, not in fermionic case (way out: inverse seesaw)

- Rich phenomenology associated to TeV seesaw : LFV, ...

Case of scalar triplet (type II)



$$\Delta = \begin{pmatrix} \Delta^{++} \\ \Delta^{+} \\ \Delta^{0} \end{pmatrix} \sim (1,3,2) \qquad L_\Delta = -2$$

Yukawa couplings:

$$Y_{\Delta ij} \overline{(l_L)^c}_{ia} (l_L)_{jb} (i\tau_2 \tau_\alpha)_{ab} \Delta^\alpha + h.c.$$

Scalar coupling:

$$\mu \, \phi_a^t \phi_b (i\tau_2\tau_\alpha) \left(\Delta^\dagger\right)^\alpha + h.c.$$

$$-M_\Delta{}^2 \Delta^\dagger \Delta - \tfrac{1}{2}\lambda_2 \left(\Delta^\dagger \Delta\right)^2$$

$$-\lambda_3 \left(\phi^\dagger \phi\right) \left(\Delta^\dagger \Delta\right) + \ldots$$

d=5 Operator (Mass)

$$m_\nu = v^2 \, Y_\Delta \, \frac{\mu}{M_\Delta{}^2}$$ ➜ 2 different scales μ, M_Δ

possible to have $Y_\Delta \sim \mathcal{O}(1)$ $\quad M_\Delta \sim 1\,\text{TeV}$ ($\mu \sim 100$ eV)

Low energy effects of dimension 6 operators:

$$\frac{1}{2M_\Delta^2} Y_{\Delta ij} Y^\dagger_{\Delta kl} \left(\overline{l_{Li}} \gamma^\mu l_{Lk}\right) \left(\overline{l_{Lj}} \gamma_\mu l_{Ll}\right) \rightarrow$$ **LFV**, $g-2$, EDMs

constraints not suppressed by μ

$$\left.\begin{array}{l} -2\frac{\mu^2}{M_\Delta^4} \partial_\mu \left(\phi^\dagger \phi\right) \partial^\mu \left(\phi^\dagger \phi\right) \\ 2\lambda_3 \frac{\mu^2}{M_\Delta^4} \left(\phi^\dagger \phi\right)^3 \\ 4\frac{\mu^2}{M_\Delta^4} \left[\phi^\dagger D_\mu \phi\right]^\dagger \left[\phi^\dagger D_\mu \phi\right] \end{array}\right\} \rightarrow$$ EW precision data, couplings to gauge bosons

$$-2\frac{\mu^2}{M_\Delta^4} \left(\phi^\dagger \phi\right) \left\{Y_e \bar{l} e_R \phi + Y_d \bar{q} d \phi - Y_u \bar{q} i \tau_2 u \phi + h.c.\right\} \rightarrow$$ top physics...

Constraining the type II seesaw

★ Scalar triplet: bounds from low energy constraints

☞ $Y_\Delta \lesssim 10^{-1} \times \left(\frac{M_\Delta}{1\,\mathrm{TeV}}\right)$ or stronger

☞ If observation of $\mu \to e\gamma$ at MEG (sensitivity of 10^{-13})

- for $Y_\Delta \sim \mathcal{O}(1)$ ➞ $15\ \mathrm{TeV} < M_\Delta < 50\ \mathrm{TeV}$
- for $Y_\Delta \sim \mathcal{O}(10^{-2})$ ➞ $0.15\ \mathrm{TeV} < M_\Delta < 0.50\ \mathrm{TeV}$

★ Scalar triplet: bounds from LHC

☞ If M_Δ turns out to be as low as $\mathcal{O}(\mathrm{TeV})$ ➞ possibility of clean signals in colliders (LHC)

LHC constraints on scalar triplet

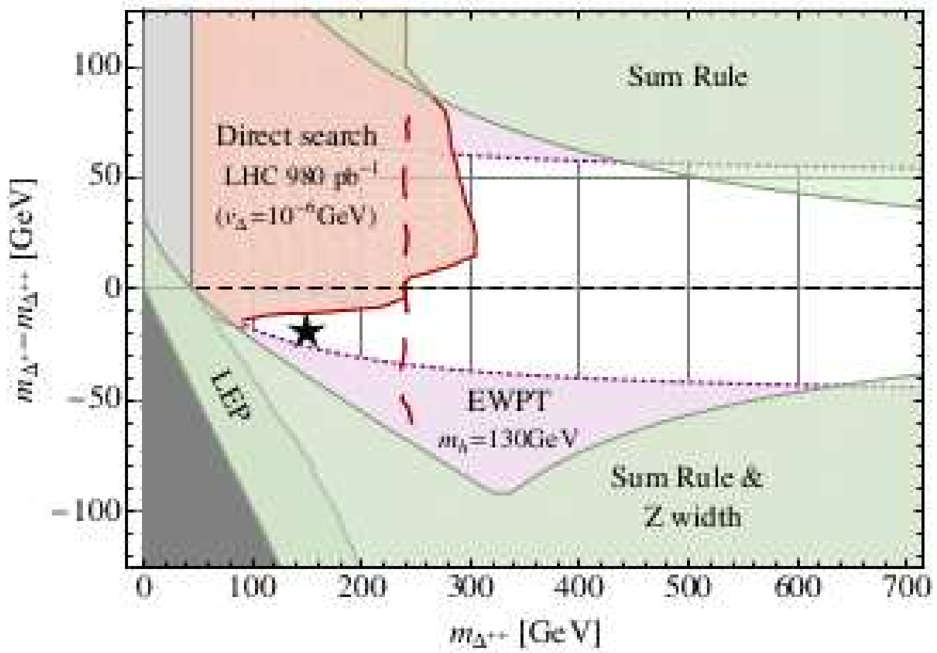
★ Production of Δ^{++} and Δ^{--}, decaying into pairs of same-sign leptons

➞ striking signals, free from SM backgrounds

★ Drell-Yann Production
$$\begin{cases} M_{\Delta^{++}} \sim 200 \text{ GeV} \Rightarrow \sigma(\gamma^*, Z^* \to \Delta^{++}\Delta^{--}) \sim 100 \text{ fb} \\ M_{\Delta^{++}} \sim 900 \text{ GeV} \Rightarrow \sigma(\gamma^*, Z^* \to \Delta^{++}\Delta^{--}) \sim 0.1 \text{ fb} \end{cases}$$

★ Decay product
$$\begin{cases} \Gamma(\Delta^{\pm\pm} \to W^{\pm}W^{\pm}) \sim \mu^2 M_\Delta^3 \\ \Gamma(\Delta^{\pm\pm} \to \ell_i^{\pm}\ \ell_j^{\pm}) \sim Y_{\Delta ij} M_\Delta \end{cases}$$

➞ **LHC:** so far, only **negative search** results $\Rightarrow$ **constraints on parameter space** $(M_\Delta, \mu, Y_\Delta)$



Melfo et.al., arXiv:1108.4416

Summary

Up to now, we have seen

- ☞ **Indisputable:** νs are massive and mix
- ☞ **Majorana and Dirac nature :** both are possible
- ☞ **SM$_{m_\nu}$:** strong potential for CP violation
- ☞ **The SM must be extended:** extended Higgs sector, New particles, ...
- ☞ **The Seesaw mechanism:** fermionic and/or scalar new fields
  ➞ Seesaw type I, II, III
- ☞ **The effective approach:** Dim 5 operator common to all NP extensions
- ☞ **The effective approach:** Dimension 6 operatorw may help in disentangling among NP scenarios

Where is the scale of NP?

Part 2

- Focus on extension with Fermionic singlets
- Lowering the scale, different models
- Sterile fermions

Extension of the SM with Sterile fermions

☞ **Extending the SM with sterile fermions**: **singlets** under $\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$

Interactions with SM fields: through **mixings** with **active neutrinos**

A priori, **no bound** on the **number** of sterile states, **no limit** on their **mass scale(s)**

Present in **several theoretical models** accounting for $\boldsymbol{\nu}$ **masses and mixings**

▶ **Interest & phenomenological implications** - strongly dependent on their **mass!**

eV scale $\leftrightarrow$ extra neutrinos suggested by reactor (& short baseline?) ν-oscil. anomalies

keV scale $\leftrightarrow$ warm dark matter candidates; explain pulsar velocities (kicks); 3.5 keV line..

MeV - TeV scale $\leftrightarrow$ experimental testability! (and BAU, DM, m_ν generation...)

Beyond 10^9 GeV $\leftrightarrow$ theoretical appeal: standard seesaw, BAU, GUTs

m_{ν_s}	Motivation	ν-oscillations	laboratory searches
$\lesssim$ eV	ν-oscil. anomalies, dark radiation	massses by seesaw, explain anomalies	oscillation anomalies, β-decays
keV	DM	no if DM	direct searches? , nuclear decays?
MeV	testability	masses by seesaw	intensity frontier, $0\nu\beta\beta$
GeV	testability, minimality	masses by seesaw	intensity frontier, EW precision data, $0\nu\beta\beta$
TeV	minimality, testability	masses by seesaw	LHC
$\gtrsim 10^9$ GeV	grand unification, "naturality"	masses by seesaw	–

m_{ν_s}	CMB	BBN	DM	Leptogenesis
$\lesssim$ eV	explain $N_{\mathrm{eff}} > 3$	may explain $N_{\mathrm{eff}} > 3$	no	no
keV	act as DM, no effect on N_{eff}	effect on N_{eff} too small if DM	good candidate	no
MeV	unaffected	constrains $m_{\nu_s} \gtrsim 200$ MeV	no	possible (finetuning)
GeV	unaffected	unaffected	no	possible
TeV	unaffected	unaffected	no	possible
$\gtrsim 10^9$ GeV	unaffected	unaffected	no	natural

☞ **Extending the SM with sterile fermions**: (testable!) **theoretical frameworks**

▶ **Incorporating ν_R - low scale seesaws: type I seesaw [TeV]** ➔ small Y_ν

type I seesaw variants ➔ "large" Y_ν

νMSM [GeV] ➔ tiny Y_ν

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & v\,Y_\nu^T \\ v\,Y_\nu & M_R \end{pmatrix}$$

$$\boxed{m_\nu \approx -v^2 Y_\nu^T \frac{1}{M_R} Y_\nu}$$

▶ **Incorporating ν_R and additional steriles ν_S: Inverse seesaw (ISS)** ➔ sizeable Y_ν

Linear seesaw (LSS) ➔ sizeable Y_ν

[in the basis $\left(\nu_L, \nu_R^c, \nu_S\right)^T$]

$$\mathcal{M}_{\text{ISS}} = \begin{pmatrix} 0 & Y_\nu^T v & 0 \\ Y_\nu v & 0 & M_R \\ 0 & M_R^T & \mu_X \end{pmatrix}$$

$$\boxed{m_\nu \approx \frac{(Y_\nu v)^2}{M_R} \mu_X}$$

$$\mathcal{M}_{\text{LSS}} = \begin{pmatrix} 0 & Y_\nu^T v & M_L^T \\ Y_\nu v & 0 & M_R \\ M_L & M_R^T & 0 \end{pmatrix}$$

$$\boxed{= m_\nu \approx (vY_\nu)\,(M_L {M_R}^{-1})^T + (M_L {M_R}^{-1})\,(vY_\nu)^T}$$

☞ **Extending the SM with sterile fermions**: phenomenological consequences

▶ **Modified charged ($W^\pm$) and neutral (Z^0) current interactions:**

$$\mathcal{L}_{W^\pm} \sim -\frac{g_w}{\sqrt{2}} W^-_\mu \sum_{\alpha=e,\mu,\tau} \sum_{i=1}^{3+N_S} \mathbf{U}_{\alpha i}\, \bar{\ell}_\alpha\, \gamma^\mu\, P_L\, \nu_i$$

$$\mathcal{L}_{Z^0} \sim -\frac{g_w}{2\cos\theta_w} Z_\mu \sum_{i,j=1}^{3+N_S} \bar{\nu}_i\, \gamma^\mu \left[P_L\, (\mathbf{U}^\dagger \mathbf{U})_{ij} - P_R\, (\mathbf{U}^\dagger \mathbf{U})^*_{ij}\right] \nu_j$$

$\mathbf{U}_{\alpha i}$ ➞ modified lepton mixing - now encodes also active-sterile mixings

(for $N_s = 0$, $\mathbf{U}_{\alpha i} = U_{\text{PMNS}}$)

▶ If sufficiently light, sterile ν_S can be **produced as final states**

☞ **Huge impact for numerous observables**: high-intensity and colliders (and cosmology, ...)
But also abundant constraints!!

☞ **Illustrate these phenomenological consequences via simple bottom-up extensions**:

SM + N_s sterile fermions

☞ **Extending the SM with sterile fermions**: (testable!) **simple "ad-hoc models"**

First phenomenological studies can be carried for SM $+ \#\nu_s$ ➔ "$3 + N_s$"

No hypothesis on mechanism of neutrino mass generation (seesaw, ...)

Physical parameters: masses **[3 light (mostly active)** + N_s **heavier (mostly sterile)** states]

mixing matrix (angles and CPV phases)

$$U_{(3+N_s)\times(3+N_s)} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} & \cdots \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} & \cdots \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} & \cdots \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} & \cdots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

Left-handed lepton mixing $U_{\alpha 1-3}$:

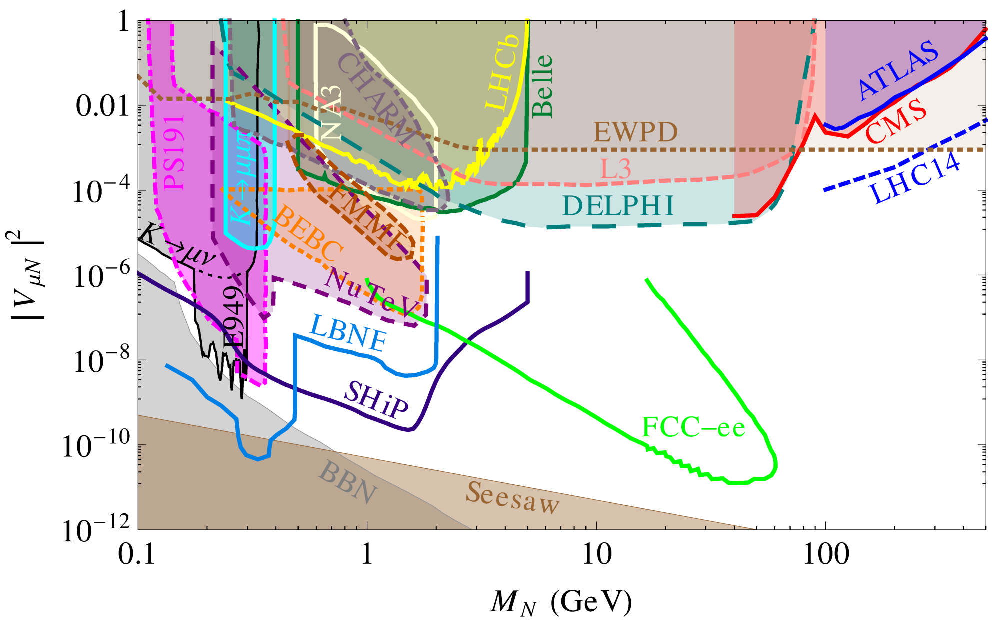
$\tilde{U}_{\text{PMNS}}$ (non-unitary)

Active-sterile mixing: $\mathbf{U}_{\alpha i}$

$\mathbf{U} = U|_{3\times(3+N_s)}$

☞ **Heavily constrained**

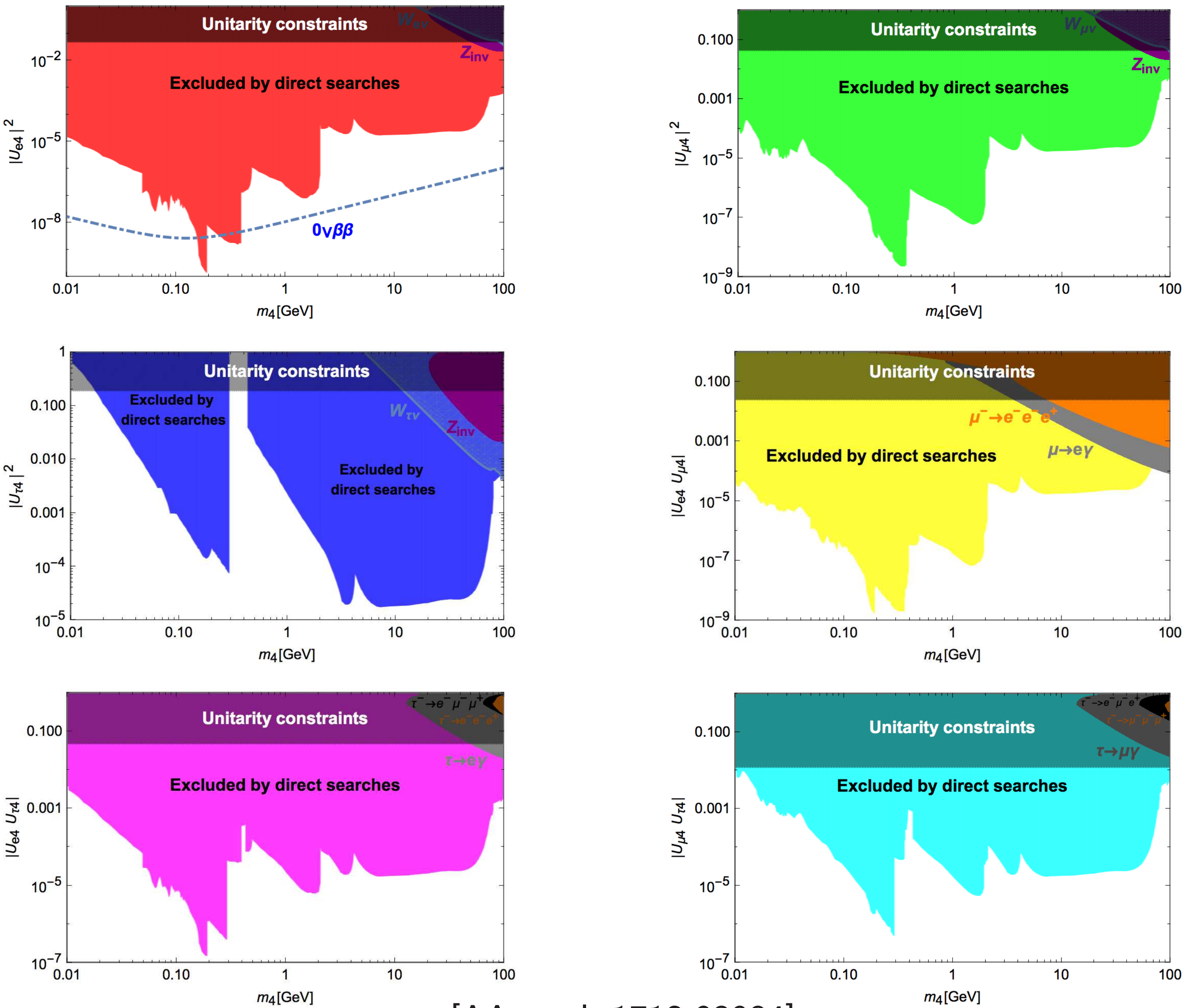
sterile masses and mixings



[Deppisch et al, '15,]

[updated 2018: AA et al, 1712.03984]

☞ Updated constraints on the sterile neutrino parameter space



[AA et al, 1712.03984]

☞ Constraints on sterile fermions

- **Neutrino oscillation parameters:** $\tilde{U}_{\text{PMNS}}$ comply with observed mixings

- **Electroweak precision tests:** invisible Z width; leptonic Z width; Weinberg angle...
  [Del Aguila et al, '08; Atre et al, '09; ...
  Antusch et al, '09-'14; Fernandez-Martinez et al, '16; ...]

- **Searches at the LHC:** invisible Higgs decays $H \to \nu_L \nu_R$; direct searches, ...
  [Dev et al, '12-'15; Bandyopadhyay et al, '12; Cely et al, '14;
  Arganda et al, '14-'15; Deppisch et al, '15; ...]

- **Peak searches in meson decays:** monochromatic lines in $\ell^\pm$ spectrum from $X_M^\pm \to \ell^\pm \nu_s$
  [Shrock, '80-'81; Atre et al, '09; Kusenko et al, '09; Lello et al,'13]

- **Beam dump experiments:** ν_s decay products (light mesons, $\ell^\pm$) from $X_M^\pm$ decays
  [PS191, CHARM, NuTeV, ...]

☞ Constraints on sterile fermions (contd.)

- **Neutrinoless double beta decays - $|m_{ee}|$:** [EXO-200, KamLAND-Zen, GERDA,...]
  [Blenow et al, '10; Lopez-Pavon et al, '13;
  [AA et al, '14, ..., Giunti et al]

- **Rare meson decays:** **Lepton Number Violating (LNV)** e.g. $K^+ \to \ell^+ \ell^+ \pi^-$
  [see e.g., AA et al, 1712.03984]

  Lepton Universality Violating (LUV) e.g. R_{X_M}, $R(D)$, R_τ
  [CLEO, Belle, BaBar, NA62, LHCb, BES III, ...]
  [Shrock, '81; Atre et al, '09; AA et al, '13-'15, ...]

- **Lepton Flavour Violation:** **3 body decays among most stringent...**
  [Gronau et al, '85; Ilakovac & Pilaftsis, '95 - '14;
  Deppisch et al, '05; Dinh et al, '12; Alonso et al, '12; ...]

- **Cosmology:** large scale structures, Lyman-α, BBN, CMB, X-ray, SN1987a, ...
  [Smirnov et al, '06; Kusenko, '09; Gelmini, '10;
  Donini et al, '14; Hernández et al, '15-'16; ...]

☞ Sterile fermions: contributions to observables

➡ Cosmology and astroparticle

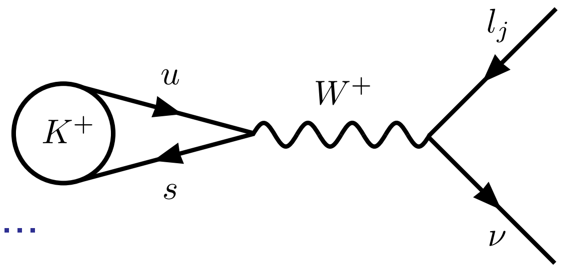
⇒ BAU from leptogenesis

⇒ (Warm) dark matter candidates [See White paper: Drewes et al, '16; Merle; AA, Lucente, Arcadi, '14, ...

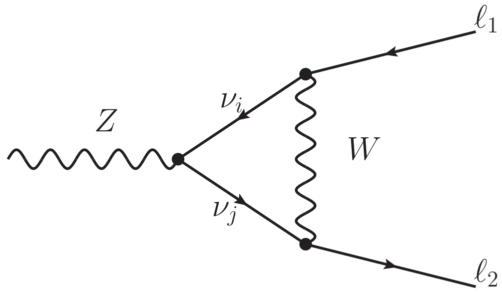
⇒ Astrophysical puzzles: pulsar kicks, ... [e.g. Kusenko, '04 & '09]

➡ Particle physics

Lepton properties:
- Electric and magnetic moments
- Neutrinoless double beta decay (LNV)
- Violation of flavour universality (e.g. Δr_K), ...



Rare decays:
- Lepton number violation
- Violation of lepton flavour
- cLFV Z decays
- cLFV and invisible H decays
- Collider signatures, ...



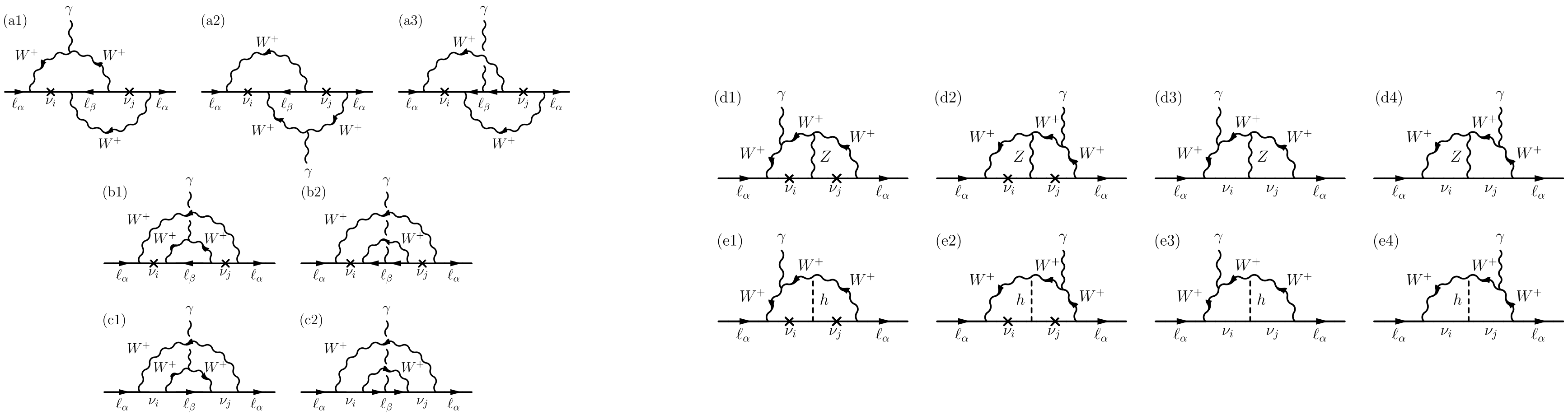
☞ Sterile fermions & CPV: contributions to EDMs

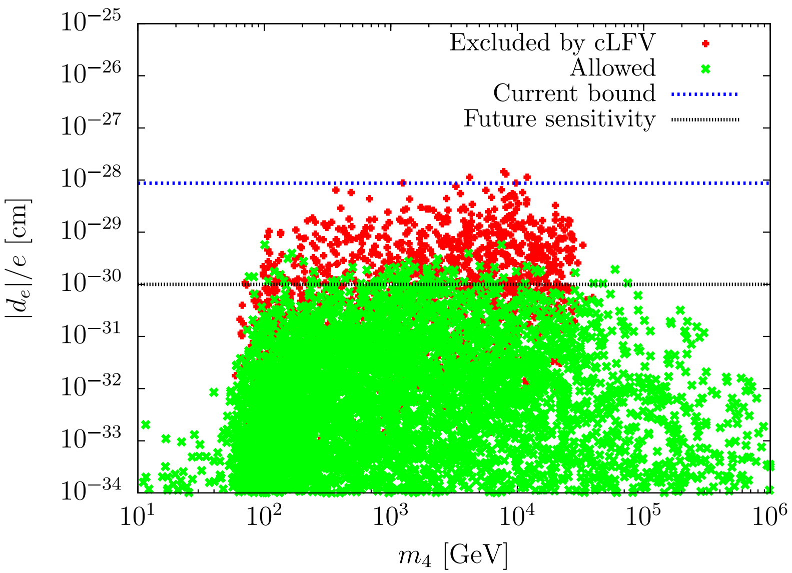
- Majorana (and Dirac) phases ⇒ **lepton EDMs**:

$$d_e = -\frac{g_2^4\, e\, m_e}{4(4\pi)^2 m_W^2} \sum_\beta \sum_{i,j} \Big[J^M_{ije\beta} I_M(x_i, x_j) + J^D_{ije\beta} I_D(x_i, x_j) \Big],$$

$$J^M_{ij\alpha\beta} \equiv \mathrm{Im}\left(U_{\alpha j} U_{\beta j} U^*_{\beta i} U^*_{\alpha i}\right), \qquad J^D_{ij\alpha\beta} \equiv \mathrm{Im}\left(U_{\alpha j} U^*_{\beta j} U_{\beta i} U^*_{\alpha i}\right)$$

- Many new (2-loop) contributions!



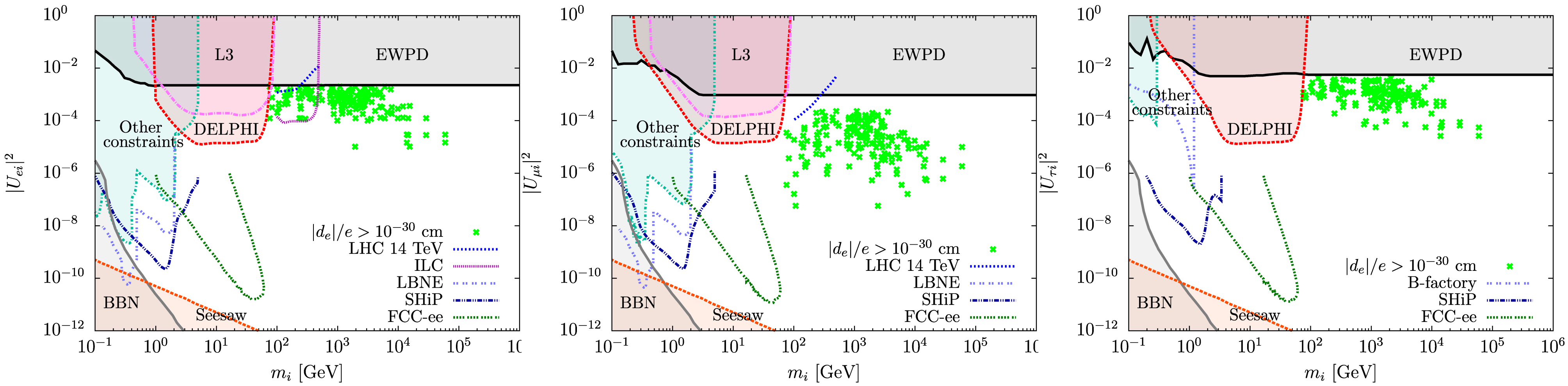


- **Non-vanishing** contributions: at least **two sterile ν**
- $|d_e|/e \geq 10^{-30}$ **cm** for $m_{\nu_{4,5}} \sim$ **[100 GeV, 100 TeV]**

  Within ACME reach

[AA and Toma, '15, '16]

☞ Sterile neutrino parameter space for EDM within ACME



[AA and Toma, '15, '16]

- Significant contributions are obtained only if sterile neutrinos are of **Majorana** nature
- green points : $|d_e|/e \geq 10^{-30}$ cm
- $m_{\nu_{4,5}} \sim$ **[100 GeV, 100 TeV]**
- Large regime for $|U_{ei}|^2$, some points can be marginally tested by LHC 14 TeV run data
- Better prospects for future ILC

☞ Sterile fermions: lepton number violation

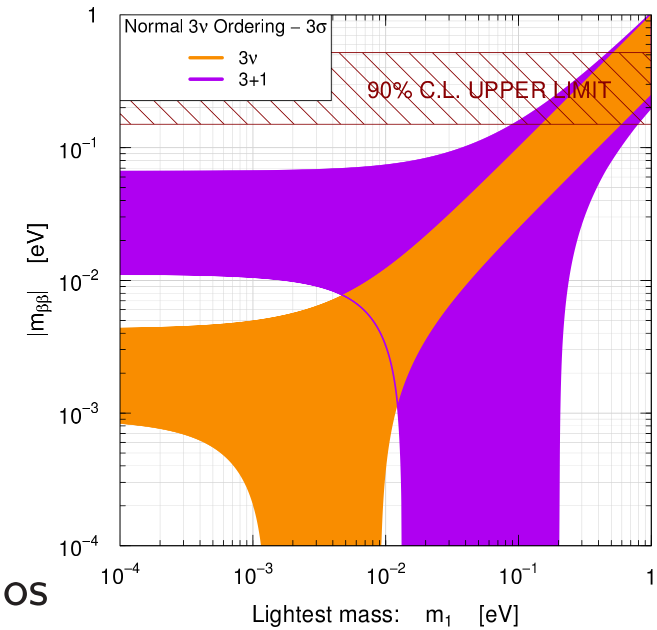
▶ Lepton number violation: $0\nu 2\beta$ decays

▶ ν_s can strongly impact **predictions for $|m_{ee}|$**

$\Rightarrow$ **augmented ranges** for effective mass *(IH and NH)*

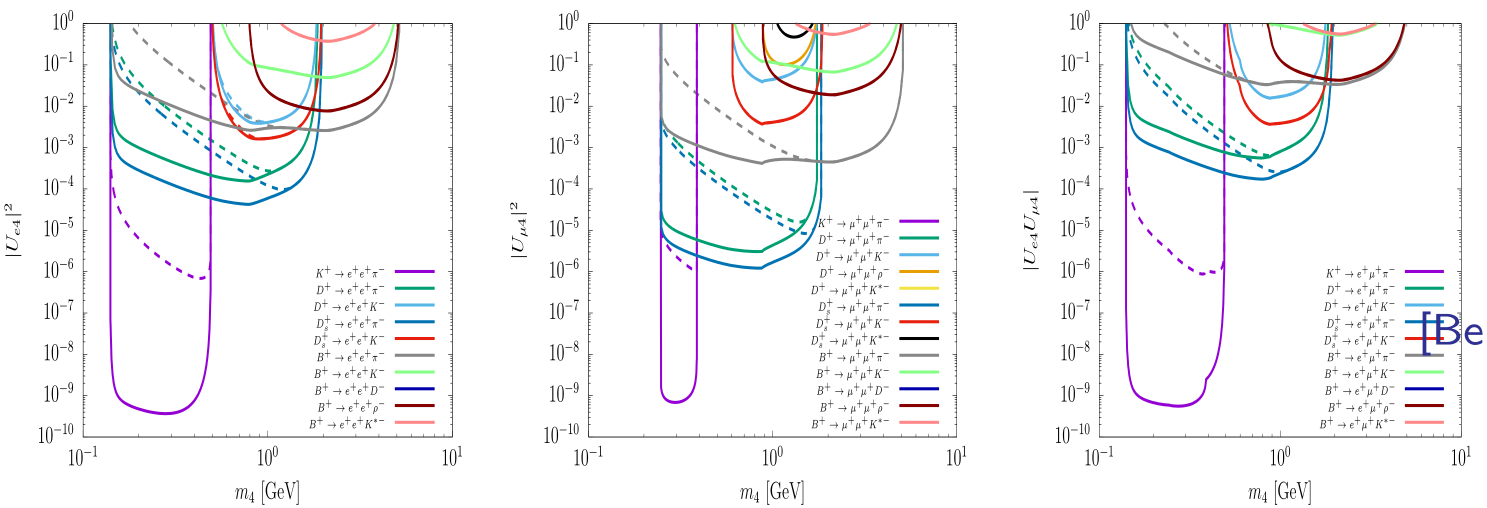
▶ **Observation of $0\nu 2\beta$ signal** in future experiments

does not imply **Inverted Ordering** for light neutrinos



[AA, De Romeri and Teixeira, '14; Lopez-Pavon et al. '13, Girardi, Meroni, Petcov, '13,...; Giunti et al, '15 ↖]

▶ Lepton number violation in meson and τ decays



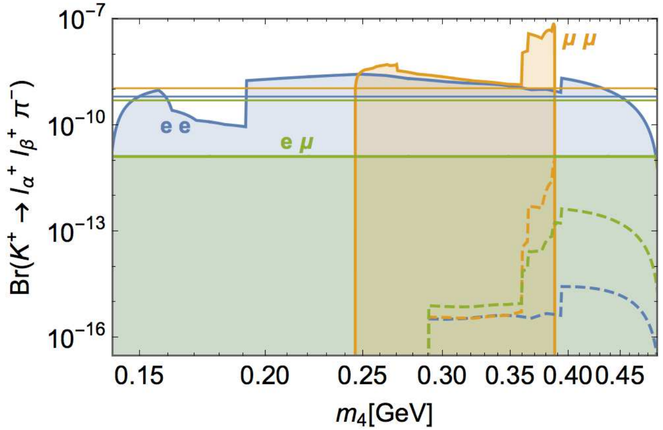
$$\tau^- \to \ell^+ \pi^- \pi^- (K^- K^-)$$
$$\tau^- \to \ell^+ \pi^- K^-$$
$$D^-_{(s)} \to \ell^- \ell'^- \pi^+ (K^+)$$
$$B^- \to \ell^- \ell'^- \pi^+ (K^+, D^+)$$

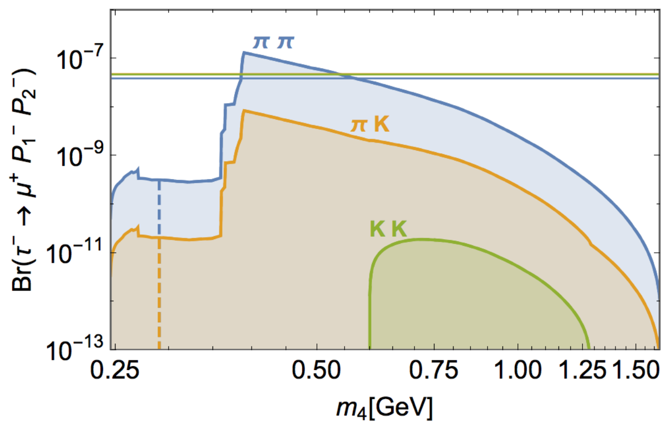
[Belle, BaBar, LHCb - NA62, ...]

[AA et al, 1712.03984]

☞ Lepton number violation in meson and τ decays

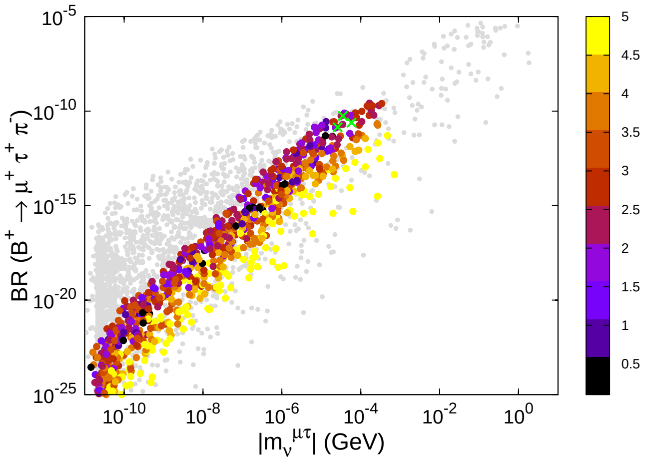
- **Resonant enhancement if sterile neutrino is produced on-shell**

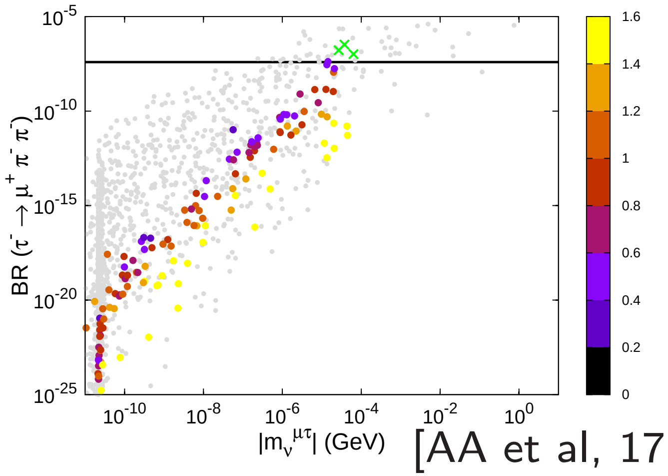




- **Reconstructing the effective Majorana mass $m_\nu^{\alpha\beta}$**

$$M \to M' \ell_\alpha \ell_\beta \; ; \; \tau \to M M^{(\prime)} \ell \quad \longleftrightarrow \quad m_\nu^{\alpha\beta} = \sum_{j=1}^{n} \frac{U_{\alpha j}\, m_j\, U_{\beta j}}{1 - m_j^2/q^2 + i\; m_j\, \Gamma_j/q^2}$$





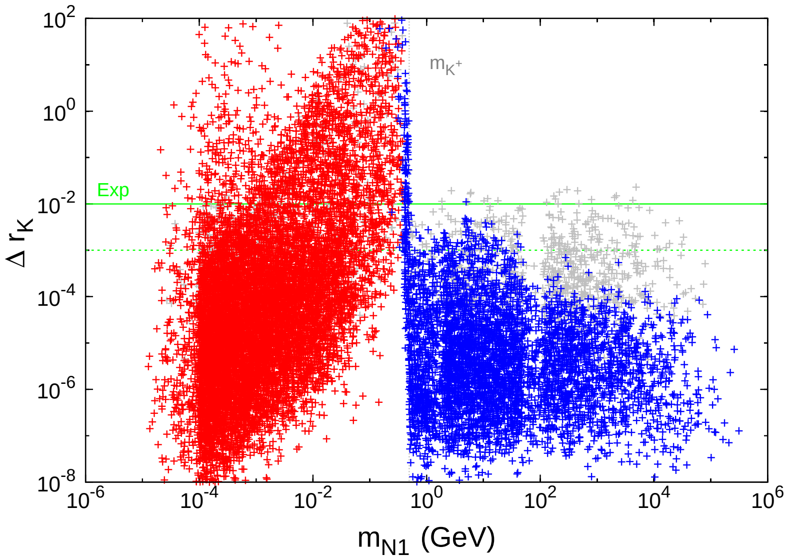
[AA et al, 1712.03984]

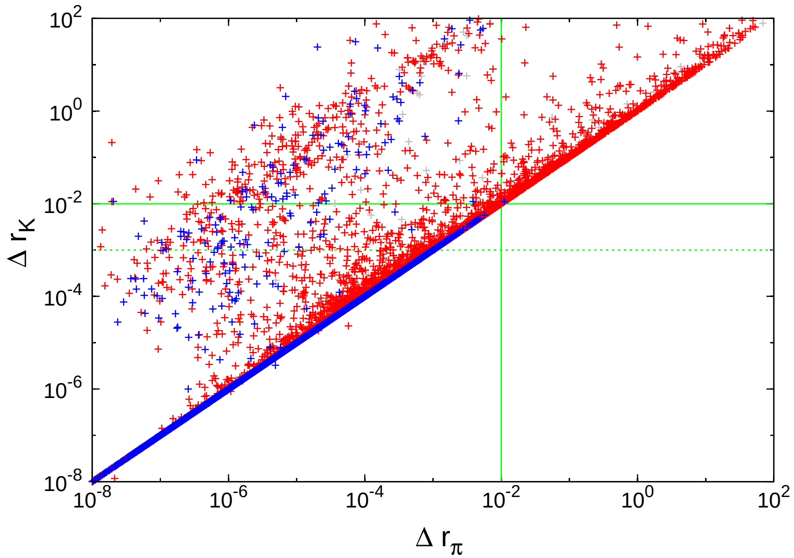
- **bounds: $m_\nu^{\alpha\beta} < 10^{-4} - 10^{-3}$ eV**

☞ Sterile fermions: violation of lepton flavour universality

Lepton Universality Violation in K and π decays: tree level effect

$$R_K = \frac{\Gamma(K \to e\nu)}{\Gamma(K \to \mu\nu)} \quad \text{comparison with } \textbf{SM th predictions} \quad \Delta r_K = \frac{R_K^{exp}}{R_K^{SM}} - 1$$

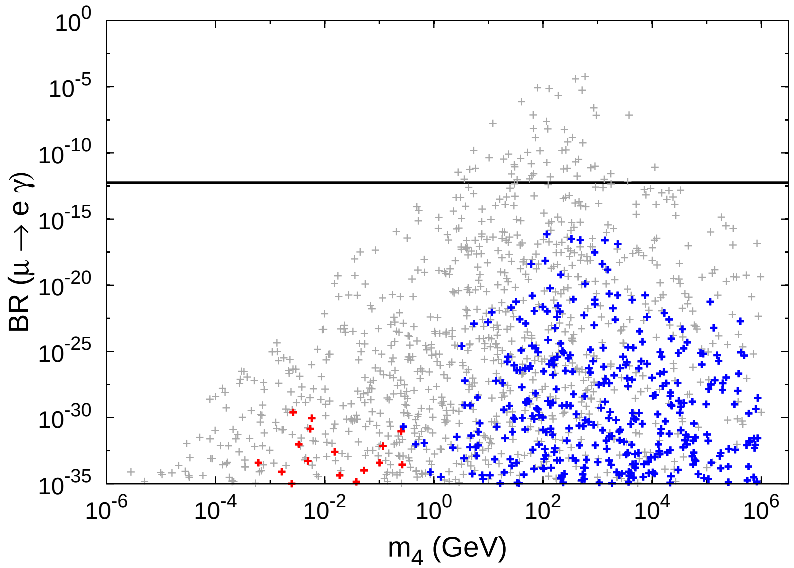




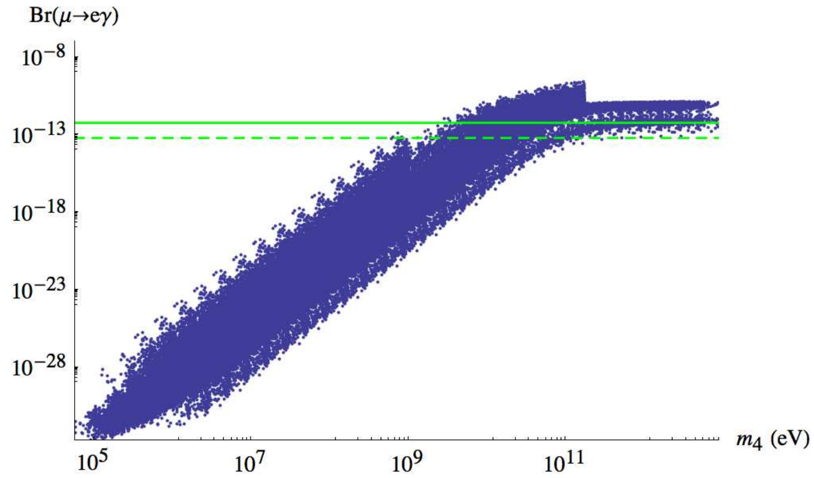
[*"ISS (3,3)"*: AA, Teixeira, Vicente and Weiland, '11-'13]

- **Sterile neutrino contributions:** $\Delta r_{K,\pi} \gtrsim \mathcal{O}(10^{-2})$
- $\Delta r_{K,\pi} \sim \mathcal{O}(1) \Rightarrow$ one of the **strongest constraints in SM + ν_s models!**

☞ Sterile fermions: cLFV in radiative decays $\ell_i \to \ell_j \gamma$ and 3-body decays $\ell_i \to 3\ell_j$



"3+1" toy model, [AA, De Romeri and Teixeira, '15]



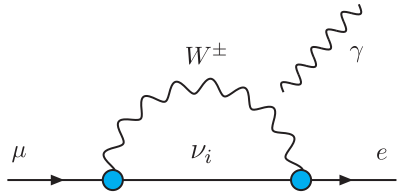
"(2,2) ISS realisation" [AA and Lucente, '14]

- Consider $\mu \to e\gamma$:

  for $m_s \gtrsim 10 - 100$ GeV sizeable ν_s contributions

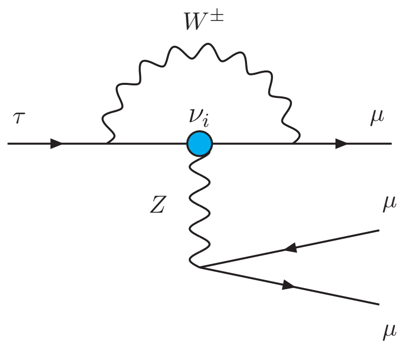
  ... but precluded by invisible Z width

  And by other cLFV observables!



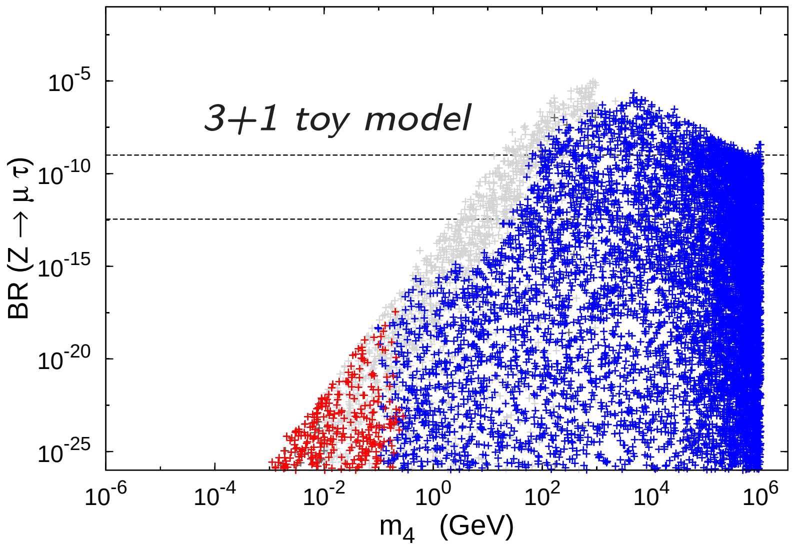
- **Particularly constraining: BR($\mu \to 3e$), CR($\mu - e$, N)**

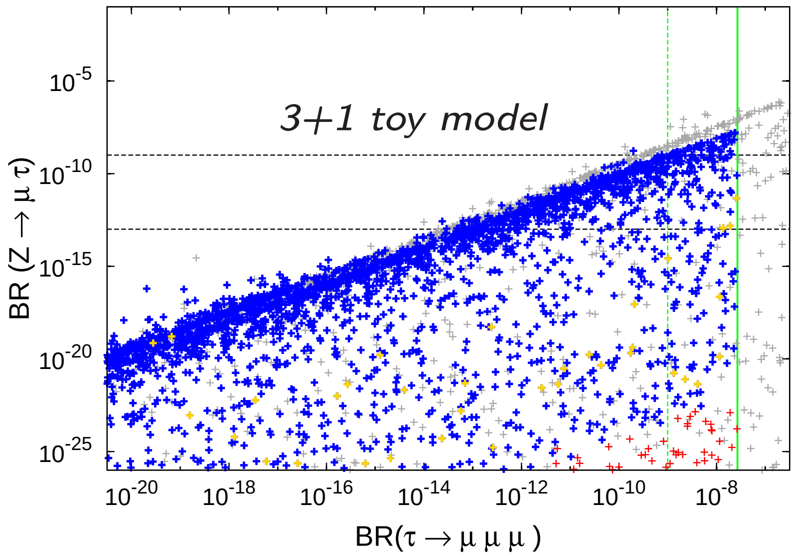
  Dominated by Z penguin contributions for $m_s \gtrsim M_Z$

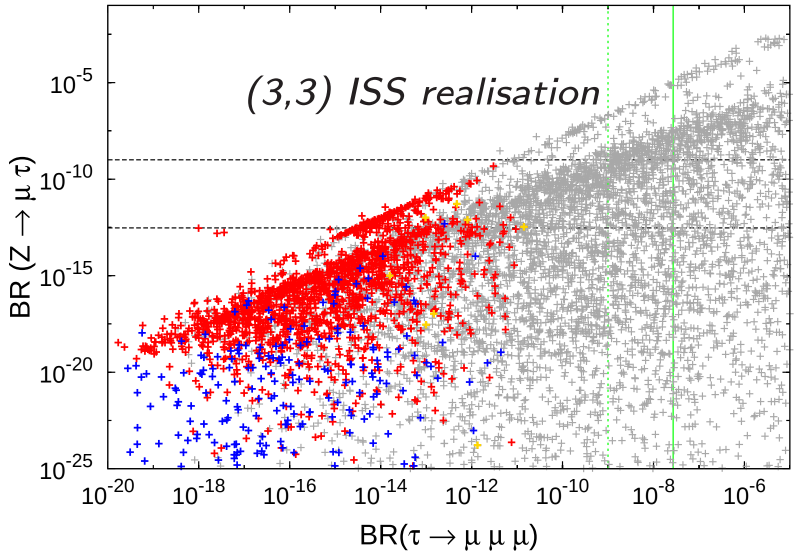


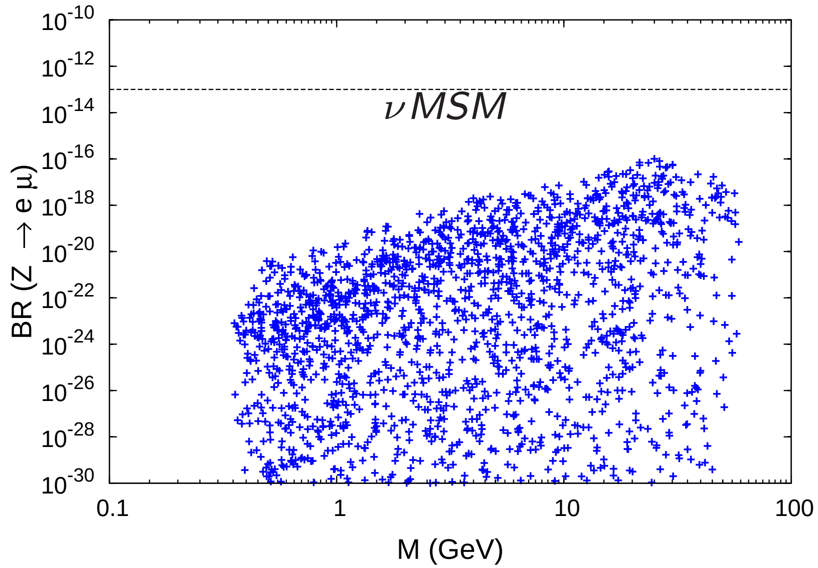
☞ Sterile fermions: cLFV at high- and low-energies

[AA, De Romeri, Monteil, Orloff, Teixeira, '15]









- ▶ **Complementarity probes** of ν_s **cLFV** at **low- and high energies!** (and in LNV...)
- ▶ $Z \to \mu\tau$ at FCC-ee: allows to **probe $\mu - \tau$ cLFV** beyond **SuperBelle reach**

[see also AA, Becirevic, Lucente, Sumensari '15, and De Romeri et al, '16]

☞ Sterile fermions: cLFV in muonic atoms

- **Muonic atoms:** 1s bound state formed when μ^- stopped in target

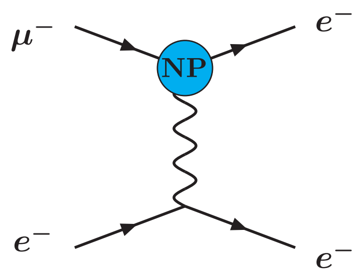
  Interesting laboratory to study cLFV! $\boldsymbol{\mu - e}$ conversion

- **Muonic atom decay:** $\boldsymbol{\mu^- e^- \to e^- e^-}$ [Koike et al, '10]

  Initial μ^- and e^-: 1s state bound in Coulomb field of the muonic atom's nucleus

- **Experimental status: New observable!**

  Hopefully included in Physics programmes of **COMET** & **Mu2e** (?)



- **Coulomb interaction** increases overlap between

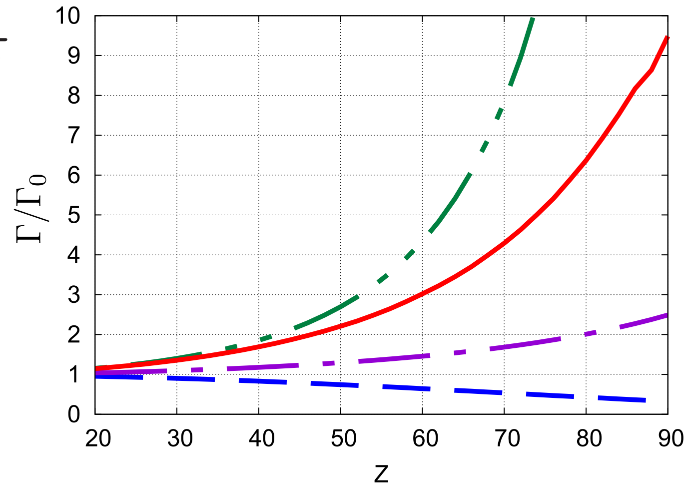
  Ψ_{μ^-} and Ψ_{e^-} wave functions

  $$\Gamma(\mu^- e^- \to e^- e^-,\ \mathrm{N}) \propto \sigma_{\mu e \to ee} v_{\mathrm{rel}} \left[(Z-1)\,\alpha\, m_e\right]^3/\pi$$

- **Rate strongly enhanced** in **large Z atoms**

  $\boldsymbol{\Gamma/\Gamma_0 \gtrsim 10\times(Z-1)^3}$ [Uesaka et al, '15-'16]

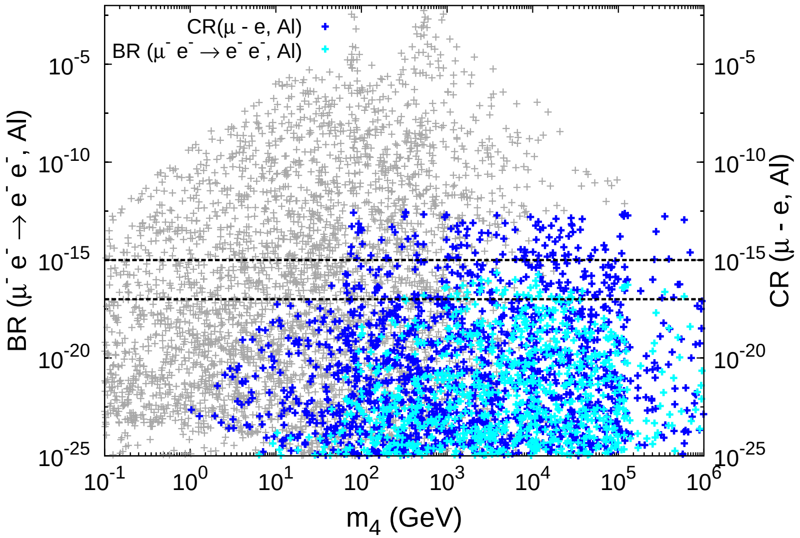
  Consider experimental setups for **Pb, U !?**

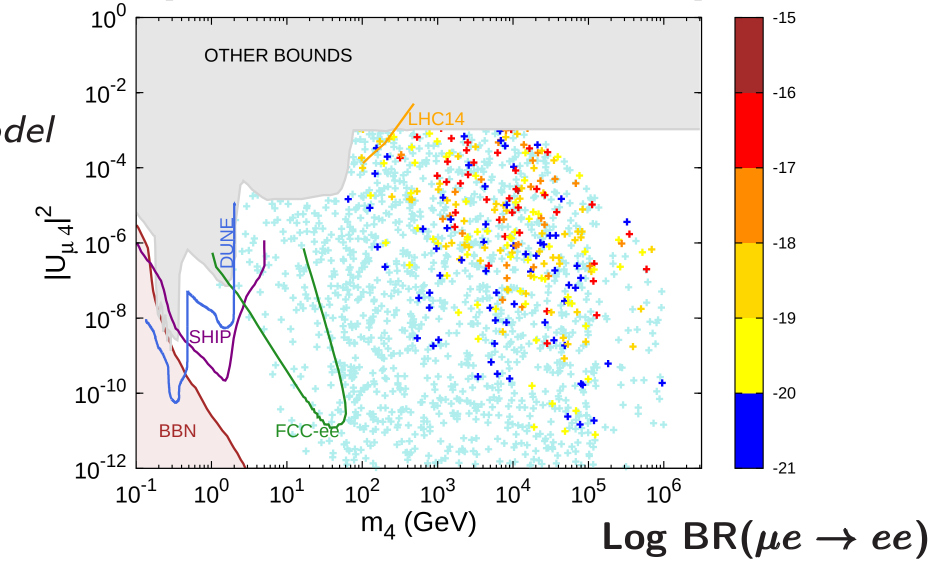


☞ Sterile fermions: cLFV muonic atom decays

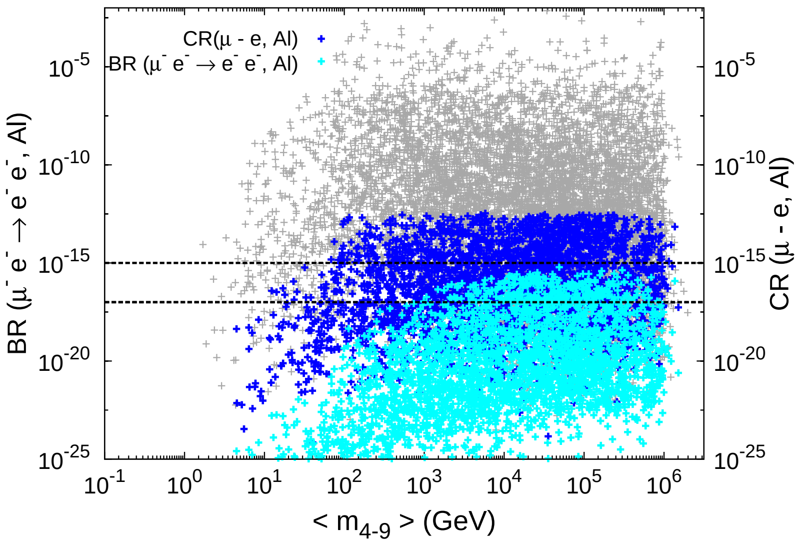
[AA, De Romeri, Teixeira, '15]

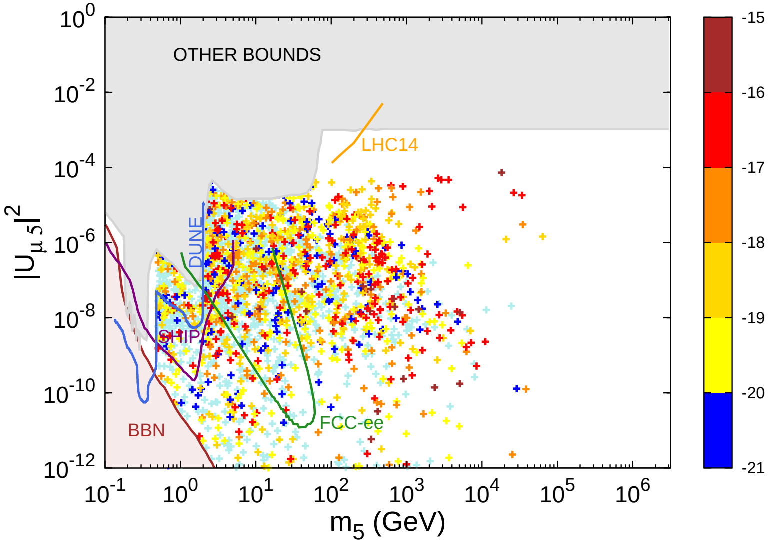
3+1 toy model





(3,3) ISS

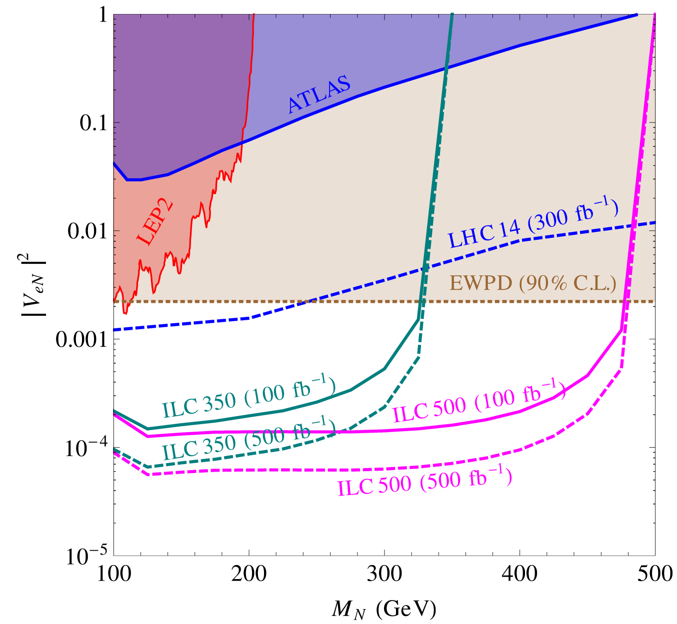




- ▶ **Sizeable values** for BR($\mu^- e^- \to e^- e^-$) - potentially within **experimental reach!**
- ▶ For **Aluminium**, CR($\mu - e$) appears to have **stronger experimental potential**

.. consider **"heavy" targets** to probe BR($\mu^- e^- \to e^- e^-$)

☞ Sterile fermions: searches at the LHC and beyond



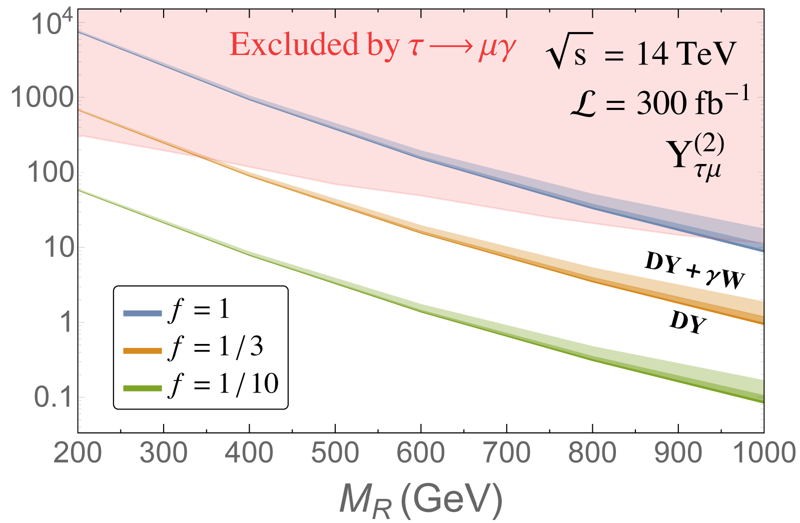
- Searches for ν_s by ATLAS and CMS "smoking-gun" (LNV) channel: $p\,p \to W^* \to N\,\ell^\pm \to \ell^\pm + \ell^\pm + 2\,\text{jets}$
- Promising prospects for FCC-ee, ILC, CEPC... [Banerjee et al, 1503.05491]
- Further searches carried for LFV final states and/or other exotic channels

▶ cLFV exotic events at the LHC

- Searches for **heavy** $\boldsymbol{N}$ at the LHC

  $q\,q' \to \tau\,\mu + 2$ **jets** (no missing E^T!)

- After cuts, **significant number of events!**



[Arganda et al, 1508.05074]

▶ Resonant mono-Higgs production at FCC-ee

$N \to H\,\nu \rightsquigarrow$ sizeable deviations from SM mono-Higgs

- Sensitive probe of ν_s at high-energies! [Antusch et al, '15]