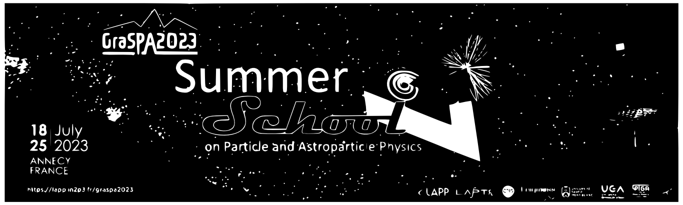
Neutrino Physics: theory

GraSPA Summer School 2023



Asmaa Abada

LPT - IJCLAB

two lectures

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

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
- Why neutrino physics is challenging

Neutrinos are the most elusive particles of the Standard Model

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

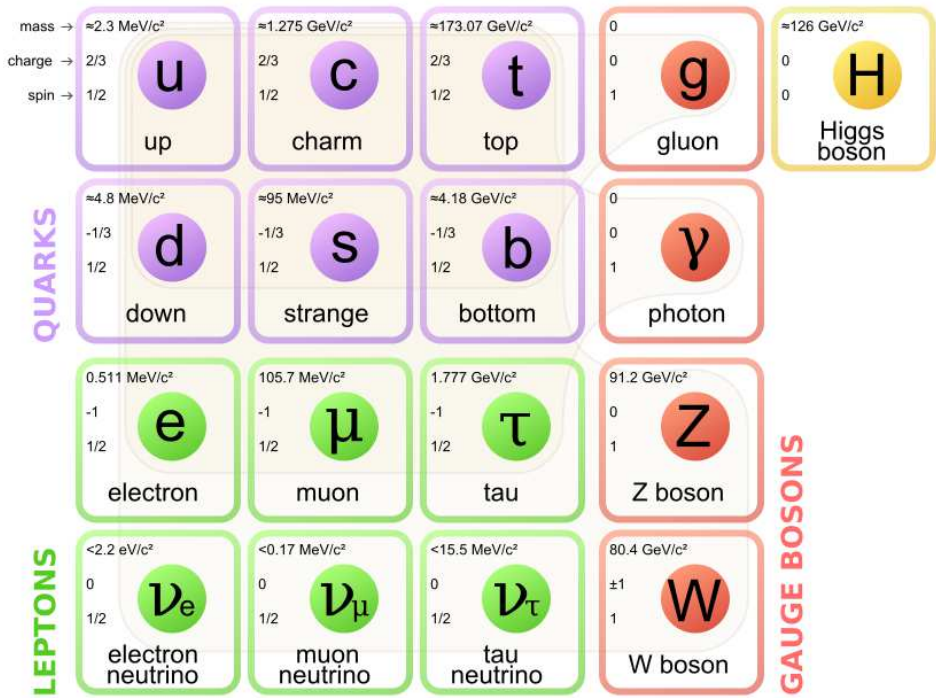
- **Provide informations on the essential features of the SM:**
  "left" nature of the weak interaction and family structure

- **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?**

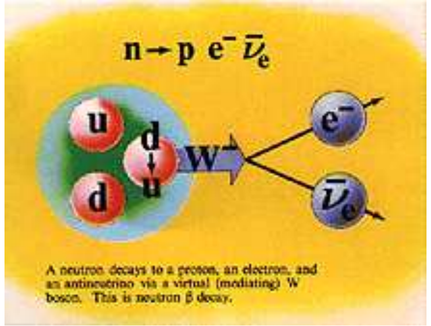
Theoretical caveats (hierarchy problem, choice of gauge group, family/flavour puzzle, ...)

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 $n \to p + e^- + \bar{\nu}_e$



"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 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

- **Enter the "neutrino":** following the discovery of the "neutron" in 1933 by Chadwick, Pauli postulates the **existence of a "massless neutrino"**

- **Electron neutrino:** detected in **1956** by **Cowan** and **Reines**

- **Muon neutrino:** discovery in **1962** by **Lederman, Schwartz** and **Steinberger**

- **3 neutrino families:** Z boson **decay width, CERN 1989**

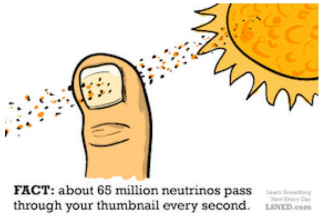
- **Tau neutrino:** direct evidence in **2000** by **DONUT** team

- **Neutrinos in the SM:** 3 **massless** states! ν_e, ν_μ and ν_τ

Studying neutrinos: sources & detectors

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

- At every second, **70 $\times 10^9$ neutrinos** cross a cm^2 !

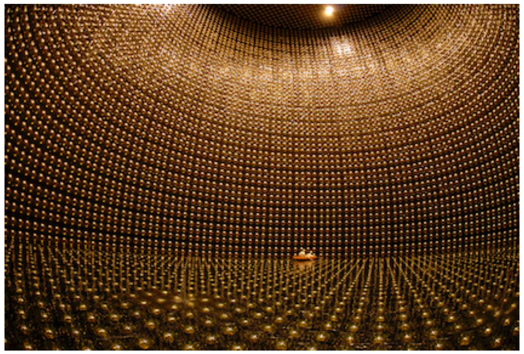


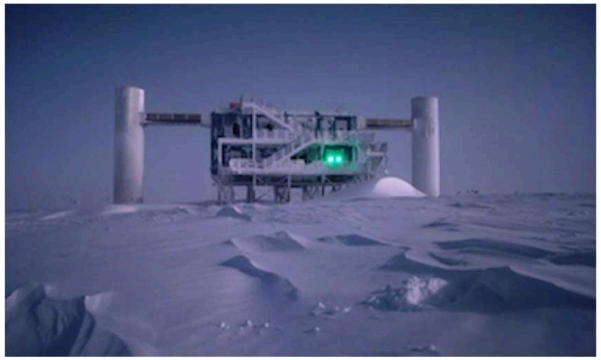
- A *world-wide effort* to detect and study ν's
  from different sources, using distinct methods...

Laboratory: reactors, accelerators

Cosmic rays: atmospheric neutrinos ($\nu_{@}$), ultra-high energy neutrinos

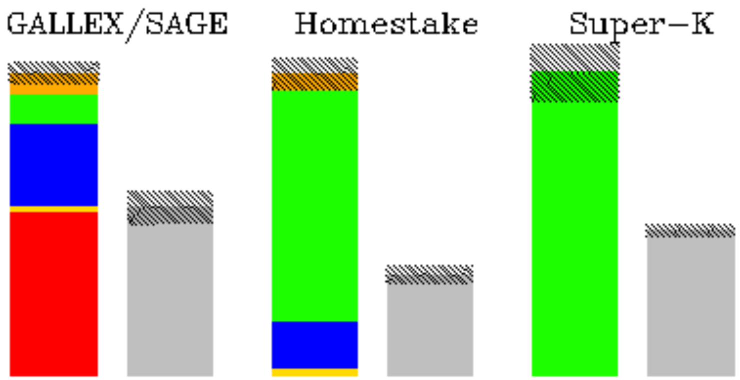
Astrophysical: solar neutrinos ($\nu_{\odot}$), supernovae





Studying neutrinos: unexpected news

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



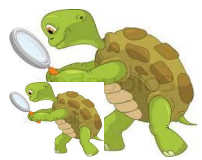
Results of Solar Neutrino experiments

experi-ment	method	flux	Data/SSM (BP95)
^{37}Cl	$\nu_e{}^{37}$Cl	$2.54 \pm 0.14 \pm 0.14$ 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.	$(2.80 \pm 0.19 \pm 0.33) \times 10^6$ /cm²/sec	0.42 ± 0.06
Super-K.	ν e scat.	$(2.44 \pm 0.06$ +0.25/-0.09) $\times 10^6$ /cm²/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 $\nu_e \sim 2\,\nu_\mu$)

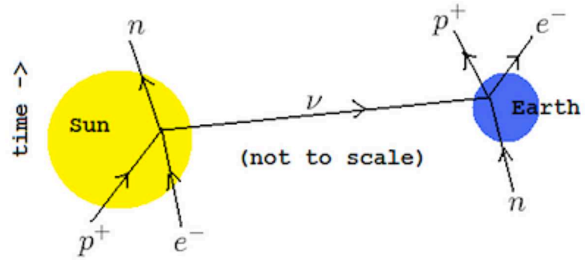


- **Hypotheses:**

  "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?*



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

Solar $\nu_e \to \nu_{\mu,\tau}$	$\Delta m^2_{\text{sol}} \simeq 7.4 \times 10^{-5}\ \text{eV}^2$ $\sin^2\theta_{\text{sol}} \simeq 0.30$	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	$\Delta m^2_{\text{atm}} \simeq 2.5 \times 10^{-3}\ \text{eV}^2$ $\sin^2\theta_{\text{atm}} \simeq 0.58$	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 $\bar{\nu}_e$ disappearance	$\sin^2\theta_{\text{Chooz}} \simeq 0.022$	Daya Bay, RENO Double Chooz
SBL Accelerator $\nu_\mu(\bar{\nu}_\mu) \to \nu_e(\bar{\nu}_e)$	$\Delta m^2 \simeq 1\text{eV}^2$ (?)	LSND, MiniBooNE ++ Solar: GALLEX, SAGE++
SBL Reactor $\bar{\nu}_e$ disappearance	$\sin^2\theta \simeq 0.1$ (?)	Bugey, ILL, Rovno,...

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

→ The minimal SM is incomplete!

Neutrino oscillations: massive states, leptonic mixing!

- A simple solution to both problems!   Illustrative 2-family example

  Two **massive states** ($\Delta m_\nu \neq 0$) related to flavour eigenstates as $\nu_\alpha = U_{\alpha i}\,\nu_i$

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

- What happens to a relativistic neutrino, e.g. a ν_μ produced in the atmosphere?

  Production of **weak eigenstate** at $t = 0$:

$$|\nu_{t=0}\rangle = |\nu_\mu\rangle = \cos\theta\,|\nu_2\rangle + \sin\theta\,|\nu_3\rangle$$

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

$$|\nu(t)\rangle = \cos\theta e^{-iE_2 t}|\nu_2\rangle + \sin\theta e^{-iE_3 t}|\nu_3\rangle$$

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

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

- **Oscillations are possible if and only if** neutrinos are **massive** and **mix!**

☞ **this is not accounted for by the SM!**

Parametrisation with 3 flavours

The charged current interaction is not diagonal in flavour space:

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

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 phases, $\theta_{12}, \theta_{23}, \theta_{13}$ $(\nu = \bar{\nu})$

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

Transition Probabilities

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

- Oscillations are possible if ν are massive ($\Delta m^2_{jk} \neq 0$) and mix ($U_{\alpha j}U_{\beta j} \neq 0$)
- Oscillation experiments do not give the nature : Dirac or Majorana : $\bar{\nu} \equiv \nu$!
- $n = 2$:
  $P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2\left(\frac{L}{L_{vac}}\pi\right), \quad L_{vac} = \frac{4\pi E}{\Delta m^2} \simeq 2.48\mathrm{km}\left(\frac{E(\mathrm{GeV})}{\Delta m^2(\mathrm{eV}^2)}\right)$

↓

- oscillations arise when $L \sim L_{vac} \Rightarrow \frac{\Delta m^2 L}{4\pi E} \sim 1 \Leftrightarrow \Delta m^2(\mathrm{eV}^2) \sim \frac{E(\mathrm{GeV})}{L(\mathrm{km})}$

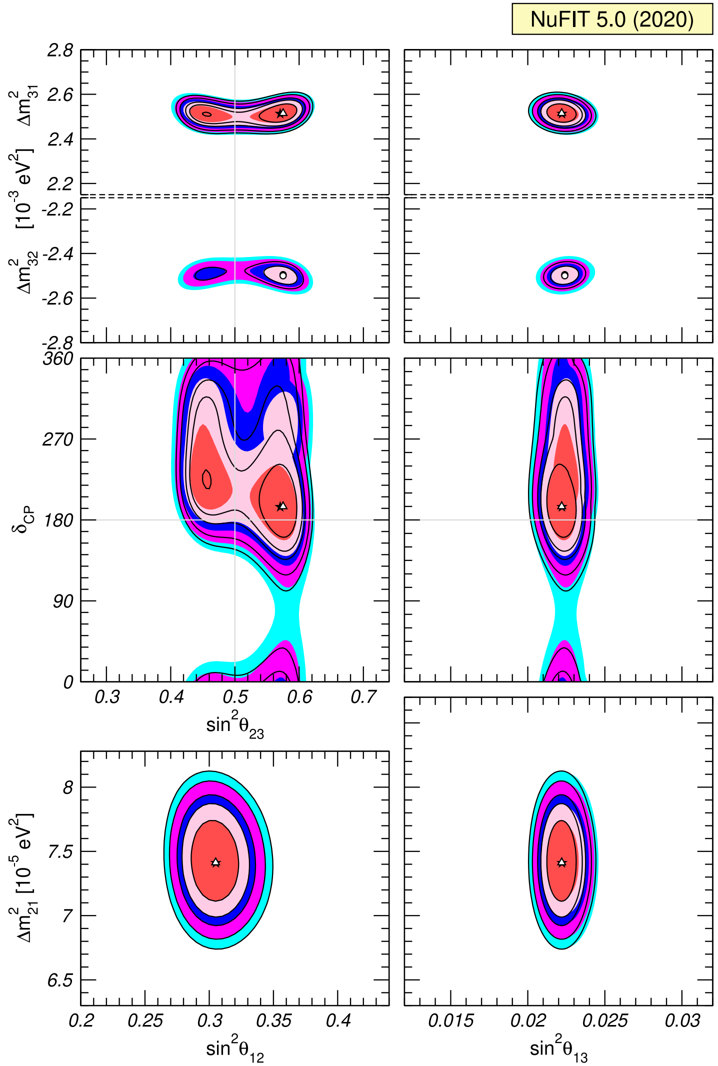
Accessible Δm^2

Depending on L and E neutrino sources:

i.e. ν source and position 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

Lepton mixing & neutrino data: current status



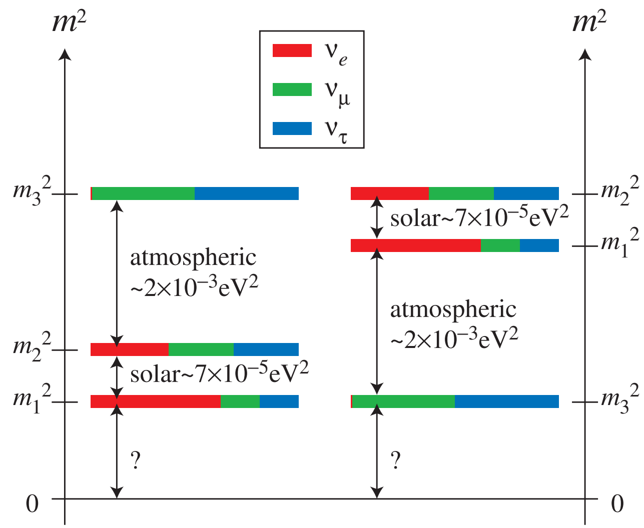
		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 7.1$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
with SK atmospheric data	$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
	$\theta_{12}/°$	$33.44^{+0.77}_{-0.74}$	$31.27 \to 35.86$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
	$\sin^2\theta_{23}$	$0.573^{+0.016}_{-0.020}$	$0.415 \to 0.616$	$0.575^{+0.016}_{-0.019}$	$0.419 \to 0.617$
	$\theta_{23}/°$	$49.2^{+0.9}_{-1.2}$	$40.1 \to 51.7$	$49.3^{+0.9}_{-1.1}$	$40.3 \to 51.8$
	$\sin^2\theta_{13}$	$0.02219^{+0.00062}_{-0.00063}$	$0.02032 \to 0.02410$	$0.02238^{+0.00063}_{-0.00062}$	$0.02052 \to 0.02428$
$\Rightarrow$	$\theta_{13}/°$	$8.57^{+0.12}_{-0.12}$	$8.20 \to 8.93$	$8.60^{+0.12}_{-0.12}$	$8.24 \to 8.96$
	$\delta_{CP}/°$	197^{+27}_{-24}	$120 \to 369$	282^{+26}_{-30}	$193 \to 352$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.517^{+0.026}_{-0.028}$	$+2.435 \to +2.598$	$-2.498^{+0.028}_{-0.028}$	$-2.581 \to -2.414$

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

  θ_{23} octant; δ_{CP}; ν-mass ordering
- **Exciting and rich experimental program ahead!**

So far, only Δm^2_{ij}, but ....what about absolute neutrino masses?

Lepton mixing & neutrino data: current status



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

  Undetermined mass ordering:

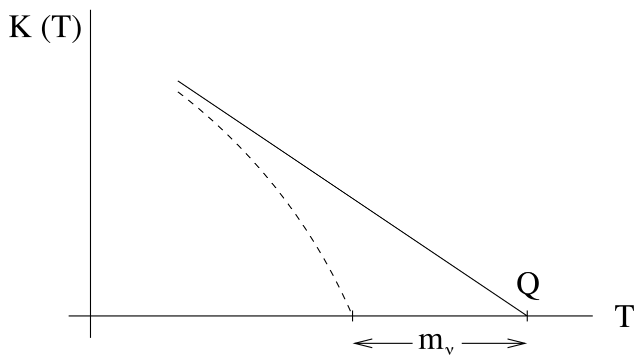
  normal $[m_{\nu_1} < m_{\nu_2} \ll m_{\nu_3}]$

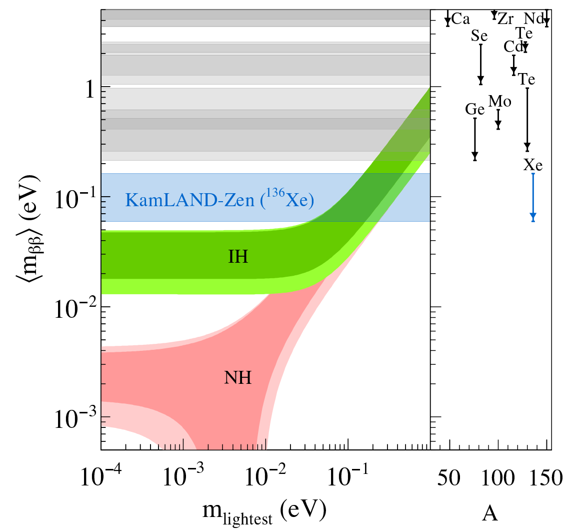
  inverted $[m_{\nu_3} \ll m_{\nu_1} \lesssim m_{\nu_2}]$

  Unknown absolute mass scale

- **Resolving** the absolute mass scale m_{lightest}

  - **Tritium decays** (^{3}H $\to$ ^{3}He $+\bar{\nu}_e + e^-$): $m_{\nu_e} \lesssim 0.8$ eV [KATRIN'22] the only direct mass determination
  - **$0\nu2\beta$ decays** - if Majorana nature: $|m_{ee}| \lesssim 0.06 - 0.16$ eV [KamLAND-Zen]
  - **Cosmology** (CMB, LSS, Lyα): $\sum_i m_{\nu_i} \lesssim 0.26 \to 0.39$ eV





[KamLAND-Zen Coll., '16]

Leptonic CP Asymmetry

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

- Cannot be observed in **appearance experiments**

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

- $\mathcal{J} \equiv \text{Im}\left(U_{e3}U^*_{e1}U^*_{\mu 3}U_{\mu 1}\right) \simeq \sin 2\theta_{23} \sin 2\theta_{12} \sin\theta_{13} \sin\delta$
  (Jarlskog Invariant)
- $\ell_{ij} \equiv \sin\left(1.27\Delta m^2_{ij}(\text{eV})^2 \frac{L(\text{km})}{E(\text{GeV})}\right)$
- 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: $\theta_{13} \sim 8.5^0$

☞ **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

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

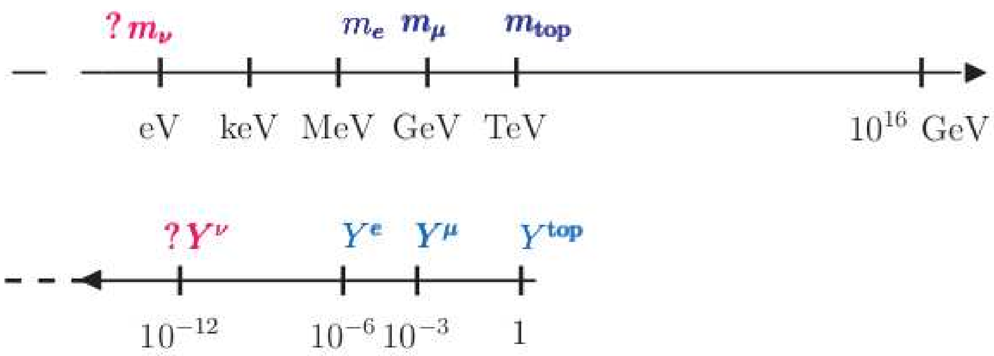
Leptons: 2 large mixing angles, 1 Dirac + 2 Majorana CPV phases

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

➞ Is this related to different mass generation mechanisms?

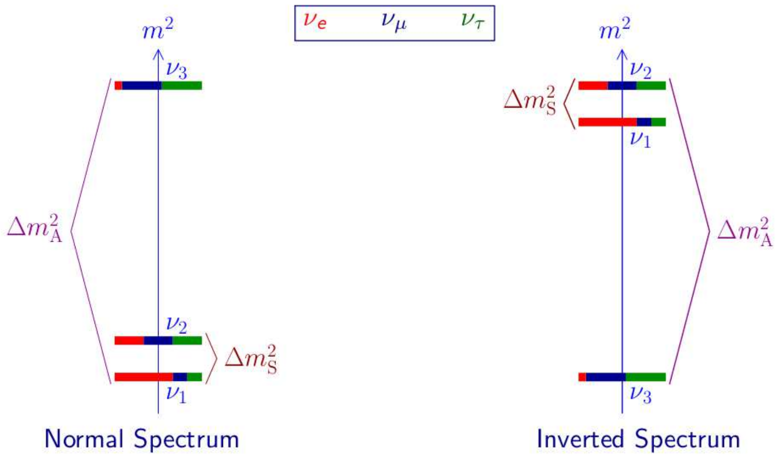
- ν data worsens fermion hierarchy problem!

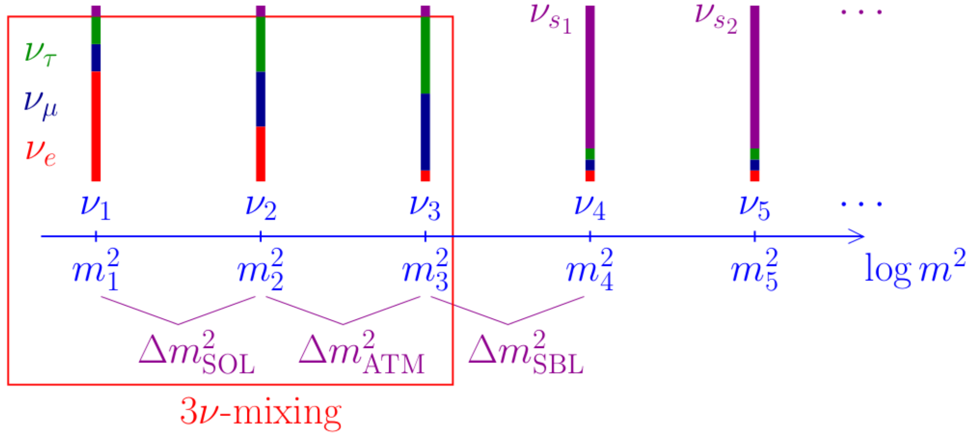
→ **Why are ν so light?**



→ **What is the absolute neutrino mass scale?**

Are there some extra fermionic gauge singlets (steriles)?





3-ν mixing scheme

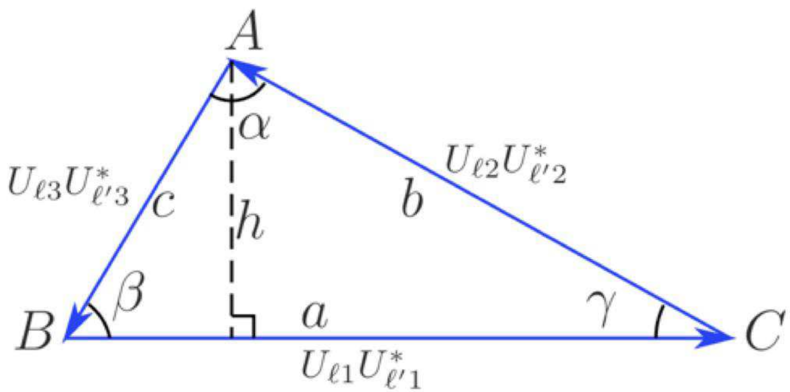
3+?-ν mixing schemes

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

- Need other d.o.f, for instance Right-Handed Neutrinos, $m_\nu \leftarrow H\, Y^\nu\, \nu_L\, \nu_R + \ldots$
  - What is the neutrino mass generation mechanism?
    - $\nu \leftrightarrow \bar{\nu}$ the **only particle** that can have *both* **Dirac or Majorana** descriptions
      - If ν has Majorana nature ➞ **New physics scale ($\neq$ EW scale)**

☞ ν-SM will allow for many new phenomena

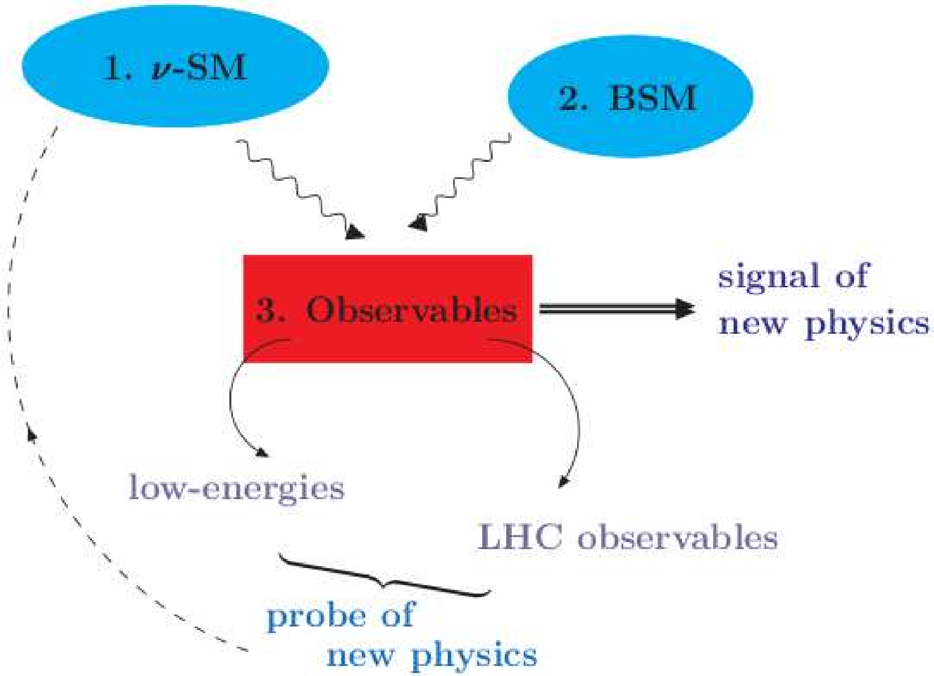
- Lepton flavour violation in neutral sector, not in the charged one? $\ell_i \to \ell_j \ell_k \ell_l$, $\ell_i \to \ell_j \gamma$, ...
  - Contributions to other observables like $g-2$, Lepton EDMs
    - Collider searches for new heavy states ...

☞ SM has other issues that call for larger BSM frameworks

- observational problems (ν masses & mixings): BAU and Dark Matter
  - theoretical caveats: fine-tuning, hierarchy and flavour problems ....

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

☞ How to proceed?



- Ingredients:
  1. mass generation mechanism (seesaw, radiative corrections, extra dim, ...)
  2. extension of SM: SM + new d.o.f, or BSM (extend Higgs and/or gauge sectors, e.g. SUSY, ...)
- Observables (peculiar to these extensions):
  - Produce directly new d.o.f at LHC (if accessible)
  - or study impact of 1. (and 1. + 2.) on observables at low-energy/high-intensity experiments (MEG, ...) and high-energy (LHC)
- Probe New Physics:  interplay between low- and high-energy observables