# Theory Outlook:
# the high precision era of neutrinos


**Neutrino2022**
**Virtual Seoul**

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HIDDeν
Hunting Invisibles: Dark sectors, Dark matter and Neutrinos
Horizon2020
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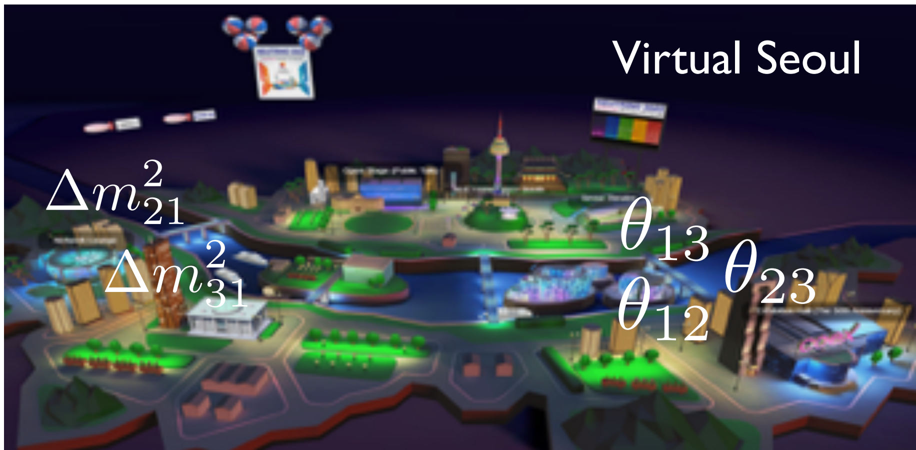
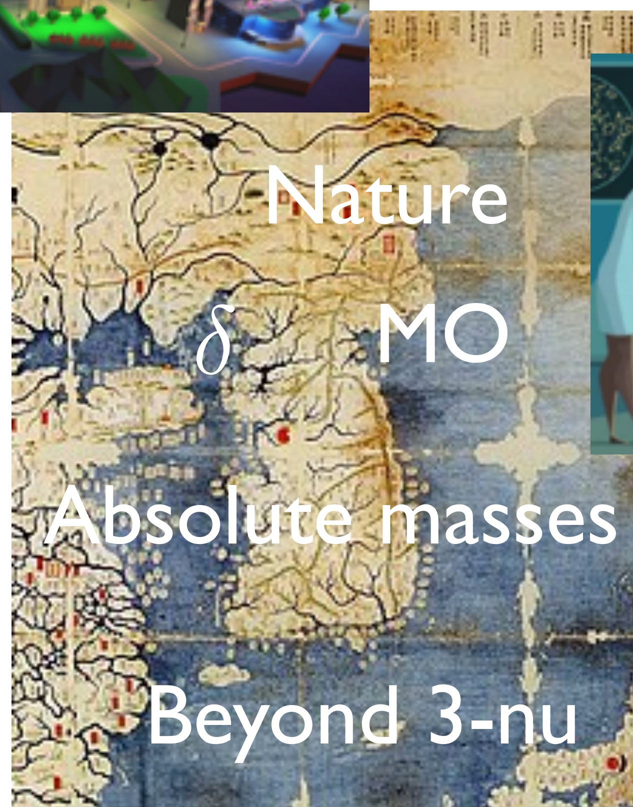
CERN

# Neutrinos: the most elusive particle & a window BSM

**Current landscape:** Known neutrino properties

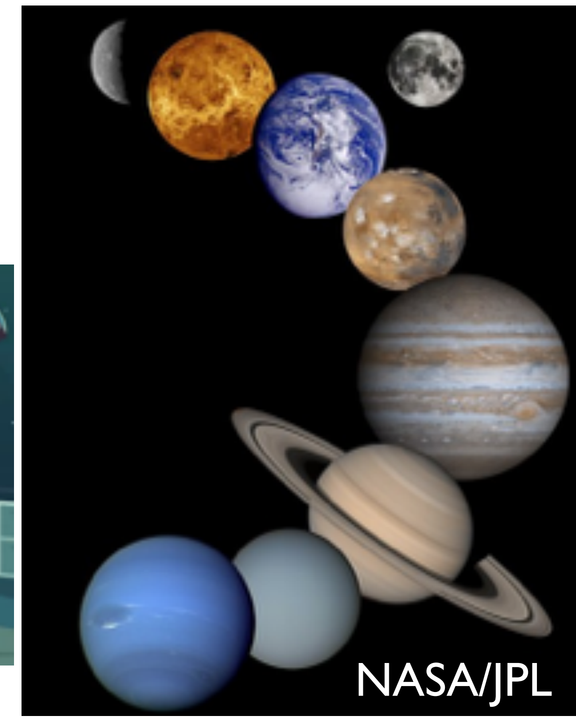



**Land in exploration:** Open questions to complete our understanding of neutrino properties



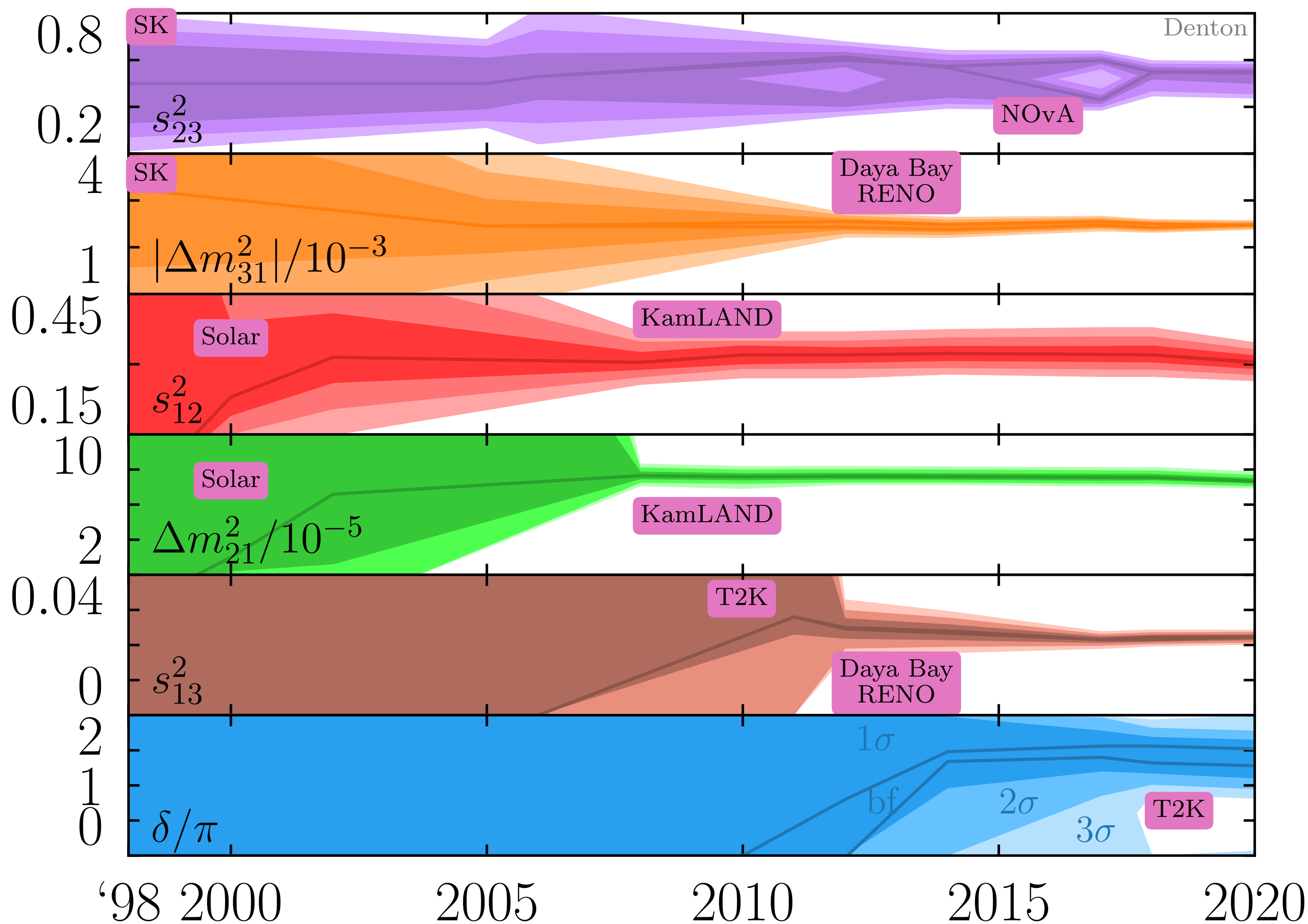

Honil Gangni Yeokdae Gukdo Ji Do


**Uncharted territory:** New physics BSM




Neutrino can guide us in unveiling the New SM.

# *Current status of neutrino parameters: the era of very precise neutrino physics*




*See P. Denton's talk*

The past 20 years have seen a remarkable progress in determining neutrino properties!

http://www.nu-fit.org/

| with SK atmospheric data | Normal Ordering (best fit) | | Inverted Ordering ($\Delta\chi^2 = 7.0$) | |
|---|---|---|---|---|
| | bfp $\pm1\sigma$ | $3\sigma$ range | bfp $\pm1\sigma$ | $3\sigma$ range |
| $\sin^2\theta_{12}$ | $0.304^{+0.012}_{-0.012}$ | $0.269 \to 0.343$ | $0.304^{+0.013}_{-0.012}$ | $0.269 \to 0.343$ |
| $\theta_{12}/^\circ$ | $33.45^{+0.77}_{-0.75}$ | $31.27 \to 35.87$ | $33.45^{+0.78}_{-0.75}$ | $31.27 \to 35.87$ |
| $\sin^2\theta_{23}$ | $0.450^{+0.019}_{-0.016}$ | $0.408 \to 0.603$ | $0.570^{+0.016}_{-0.022}$ | $0.410 \to 0.613$ |
| $\theta_{23}/^\circ$ | $42.1^{+1.1}_{-0.9}$ | $39.7 \to 50.9$ | $49.0^{+0.9}_{-1.3}$ | $39.8 \to 51.6$ |
| $\sin^2\theta_{13}$ | $0.02246^{+0.00062}_{-0.00062}$ | $0.02060 \to 0.02435$ | $0.02241^{+0.00074}_{-0.00062}$ | $0.02055 \to 0.02457$ |
| $\theta_{13}/^\circ$ | $8.62^{+0.12}_{-0.12}$ | $8.25 \to 8.98$ | $8.61^{+0.14}_{-0.12}$ | $8.24 \to 9.02$ |
| $\delta_{CP}/^\circ$ | $230^{+36}_{-25}$ | $144 \to 350$ | $278^{+22}_{-30}$ | $194 \to 345$ |
| $\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$ | $7.42^{+0.21}_{-0.20}$ | $6.82 \to 8.04$ | $7.42^{+0.21}_{-0.20}$ | $6.82 \to 8.04$ |
| $\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$ | $+2.510^{+0.027}_{-0.027}$ | $+2.430 \to +2.593$ | $-2.490^{+0.026}_{-0.028}$ | $-2.574 \to -2.410$ |

Esteban et al., 2007.14792, See also Capozzi et al., de Salas et al.

*See T. Schwetz's talk*

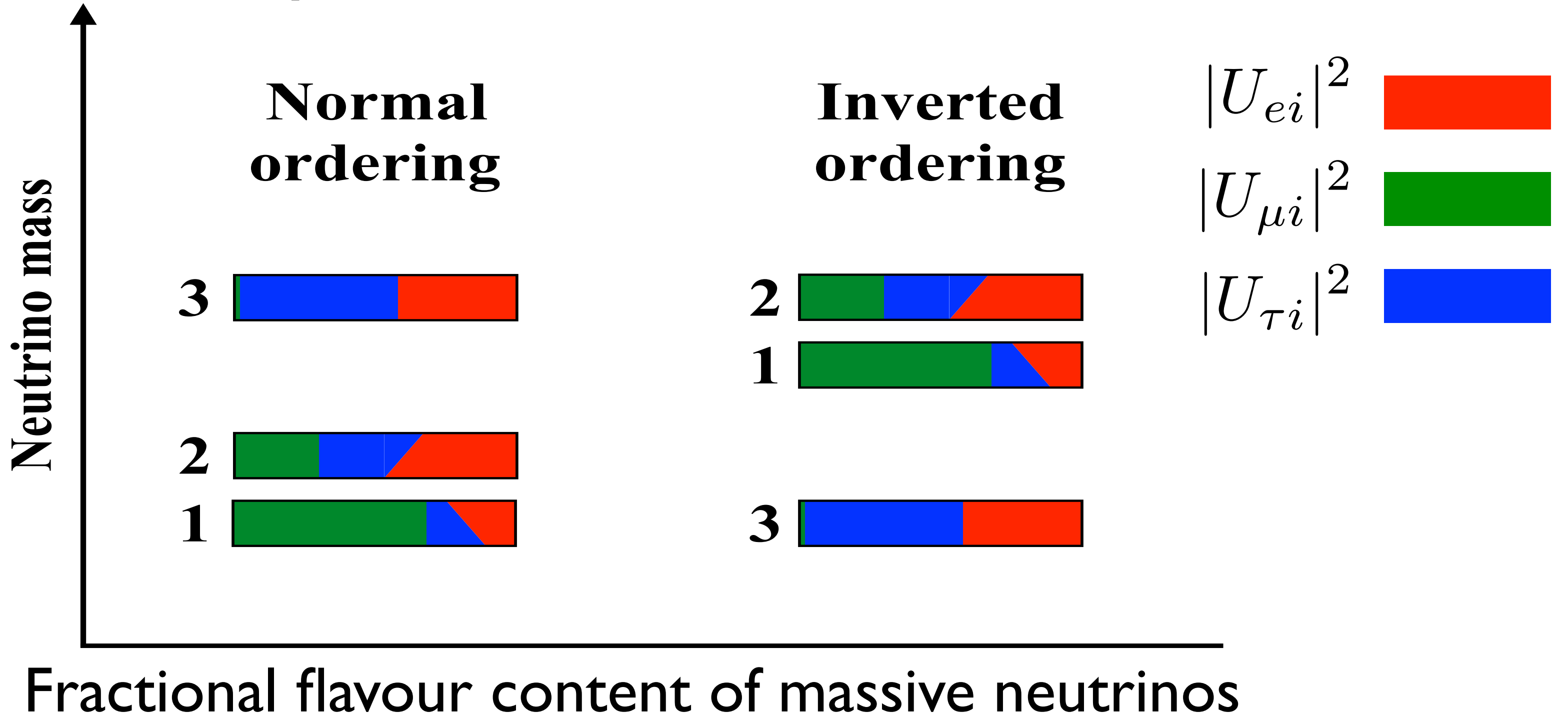
*Also, K.-B. Luk, K. K. Joo, C. Bronner, J. Hartnell, L. Wan, T. Stuttard, Y. Koshio*

Current status:

- 2 mass squared differences
- 3 sizable mixing angles (one not too well known)
- mild hints of CPV (not robust)
- mild indications in favour of NO (?)

# Neutrino masses

$\Delta m_s^2 \ll \Delta m_A^2$ implies at least 3 massive neutrinos.




$$m_1 = m_{\rm min}$$
$$m_2 = \sqrt{m_{\rm min}^2 + \Delta m_{\rm sol}^2}$$
$$m_3 = \sqrt{m_{\rm min}^2 + \Delta m_{\rm A}^2}$$

$$m_3 = m_{\rm min}$$
$$m_1 = \sqrt{m_{\rm min}^2 + \Delta m_{\rm A}^2 - \Delta m_{\rm sol}^2}$$
$$m_2 = \sqrt{m_{\rm min}^2 + \Delta m_{\rm A}^2}$$

Measuring the masses requires:

- the mass scale: $m_{\rm min}$
- the mass ordering.

# Leptonic Mixing and CP-violation

The Pontecorvo-Maki-Nakagawa-Sakata matrix

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_{21}/2} & 0 \\ 0 & 0 & e^{i\alpha_{31}/2} \end{pmatrix}$$

CPV?

- $\theta_{23}$ maximal or close to maximal
- $\theta_{12}$ large but significantly different from maximal
- $\theta_{13}$ quite large: challenge to flavour models
- Mixings very different from those in the quark sector
- Possibly, large leptonic CPV. This is a fundamental question, possibly related to the origin of the baryon asymmetry and to the origin of the flavour structure.

# What do we still need to know?

1. **What is the nature of neutrinos?**

2. **What are the values of the masses?** Absolute scale and the ordering.

3. **Is there CP-violation?**

4. **What are the precise values of mixing angles?**

5. **Is the standard picture correct?** Are there NSI? Sterile neutrinos? Non-unitarity? Other effects?

**Very exciting experimental programme now and for the future.**

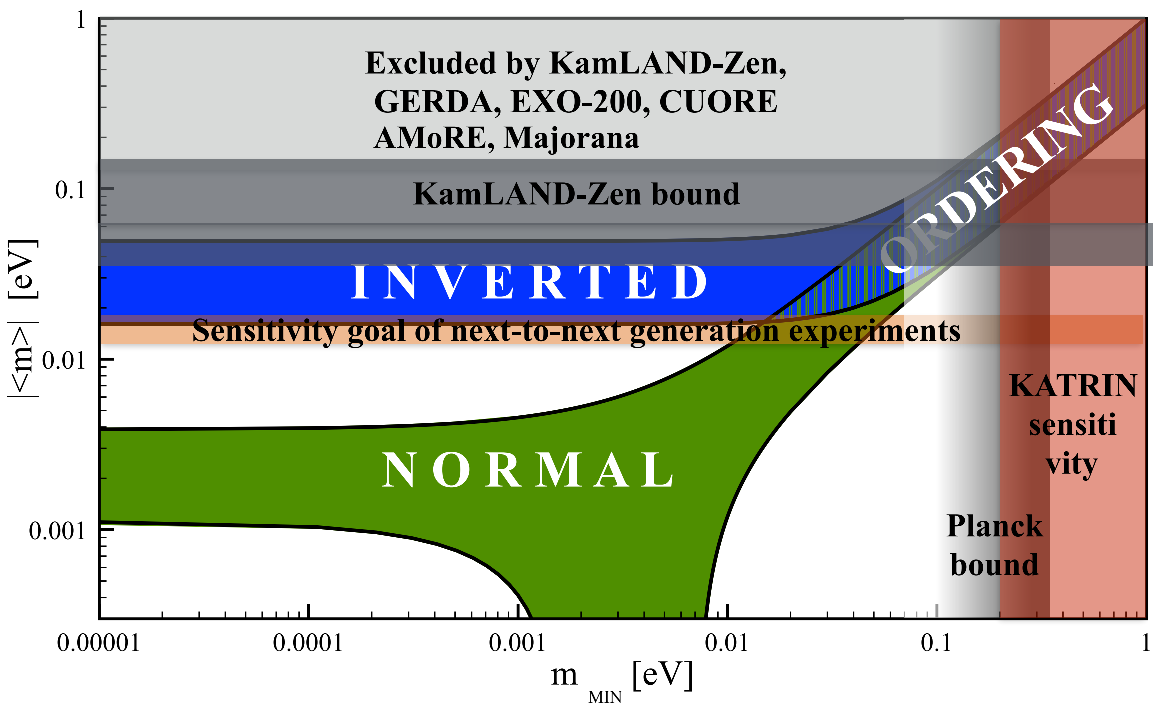
# 1. What is the nature of neutrinos?

Neutrinos can be **Majorana** or **Dirac** particles: $\nu = \nu^c$

Nature of neutrinos <=> Lepton number

**Key symmetry for physics BSM and necessary condition for Leptogenesis.**

- Most sensitive test of LNV: neutrinoless DBD. Crucial issue for interpretation: NME computation. *F. Simkovic's talk*




A very exciting programme of current and near-future searches.

*See A. Gando, I. Nutini, A. Zolotarova, Y. Oh, M. Sorel, J. Gruszko, S. Schoenert's talks*

# 2. What are the values of the masses?

- **Mass ordering** via **neutrino oscillations in matter** (DUNE, atmospheric neutrinos) or **in vacuum** (JUNO).

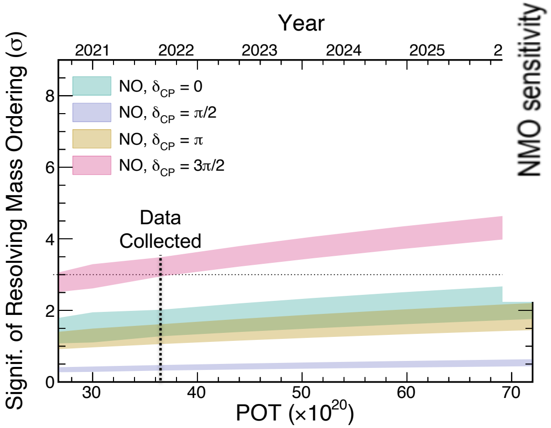
1. NOvA and T2K both prefer NO over IO
2. NOvA+T2K prefers IO over NO
3. SK still prefers NO over IO
4. NOvA+T2K+SK still prefers NO over IO
5. + Daya Bay & RENO ⇒ slight preference NO

*See P. Denton's talk*

*Also, T. Schwetz's, O. Yasuda's talk*

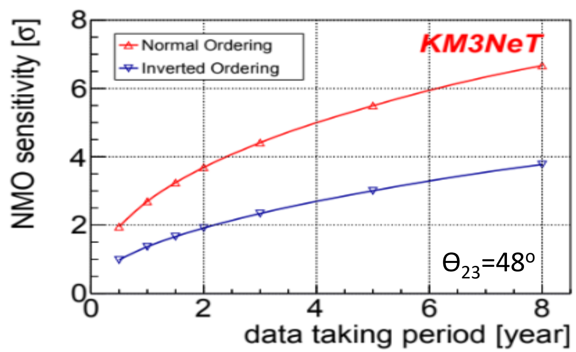
Good news: Discovery expected within ~a decade.

NOvA



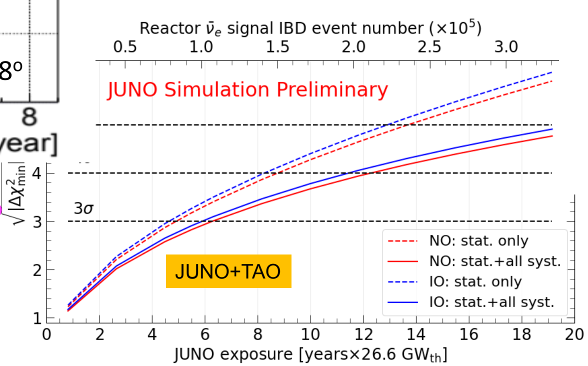

*J. Hartnell's talk*

SK, HK, IceCube



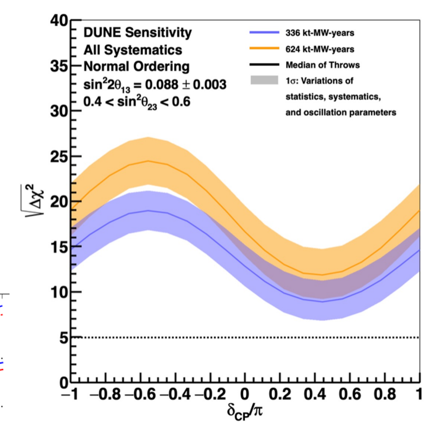

*A. Heijboer's talk, Also L. Wan, T. Stuttard, J. Wilson, H. Kim*

JUNO




*J. Zhao's talk*

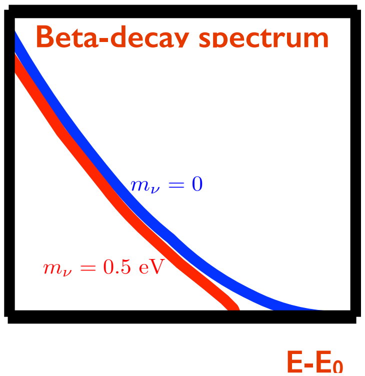
DUNE




*M. Muether's talk*

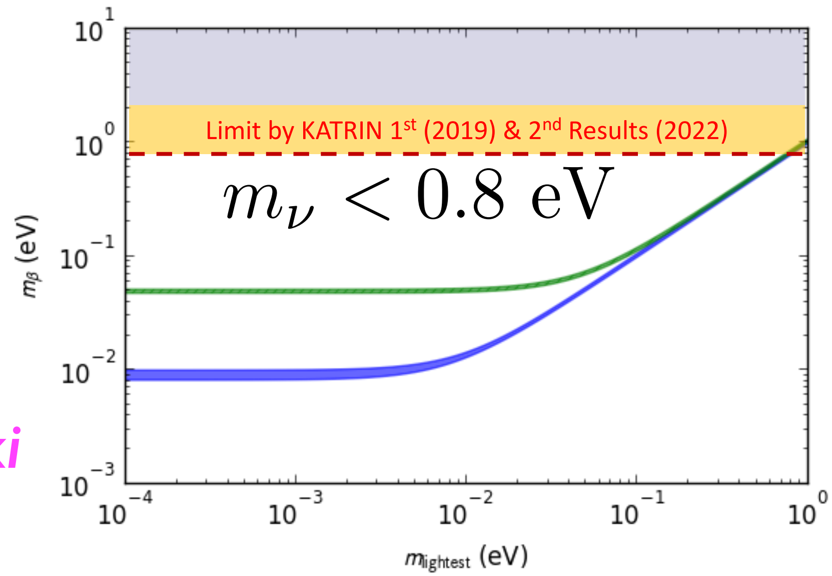
# 2. What are the values of the masses?

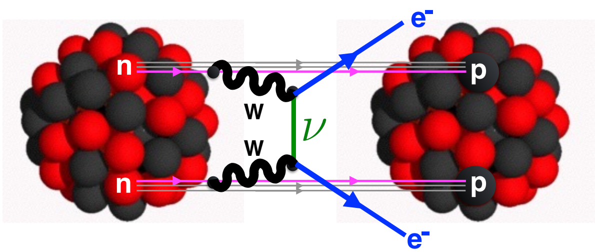
- Absolute mass scale.



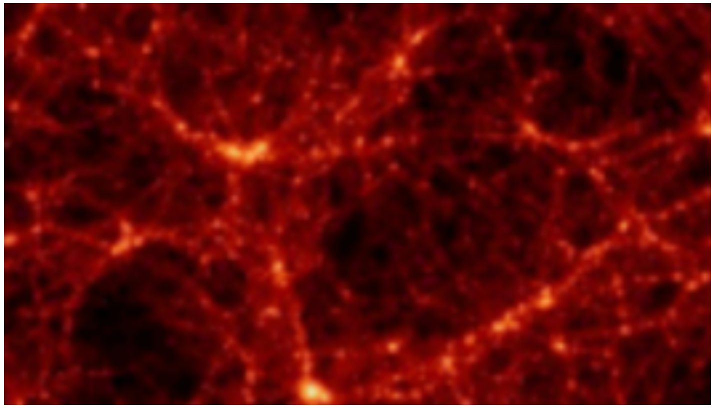

Beta decay (KATRIN, Project 8)

*See T. Lasserre's talk,*
*Also L. Gastaldo, E. Novitski*




Neutrinoless double beta decay: interplay with CPV phases.



Cosmology: assume underlying cosmological model. Dependence on priors assumed.

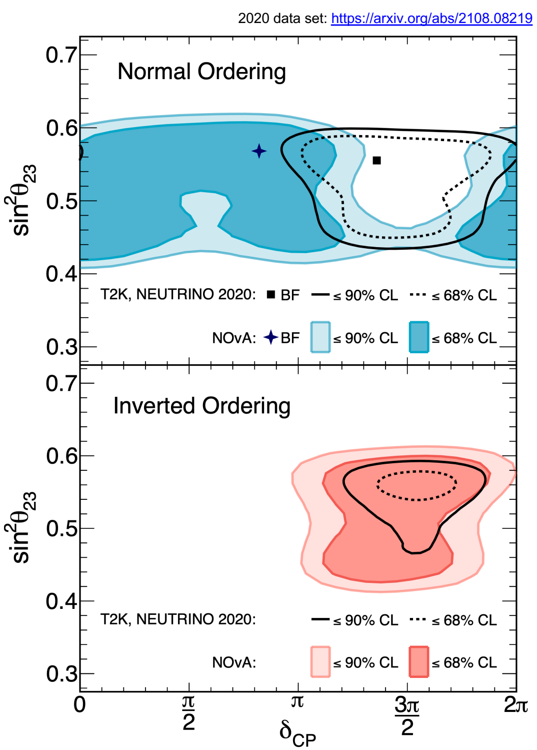
*See J. Lesgourgues', O. Mena's talk*

# 3. Is there CP-violation?

*T. Schwetz's, P. Denton's, O. Yasuda's talks*

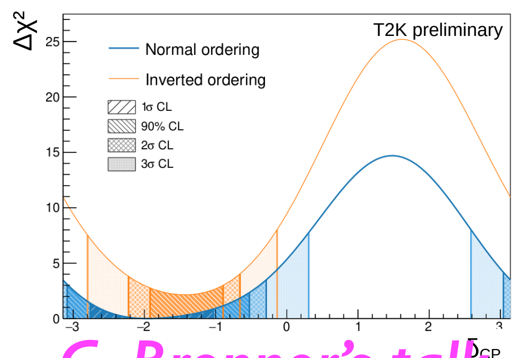
Hints of leptonic CPV? Situation remains unclear. Expect soon T2K-NOvA joint analysis. DUNE and T2HK will get to 5 sigma for a large range of delta.

NOvA



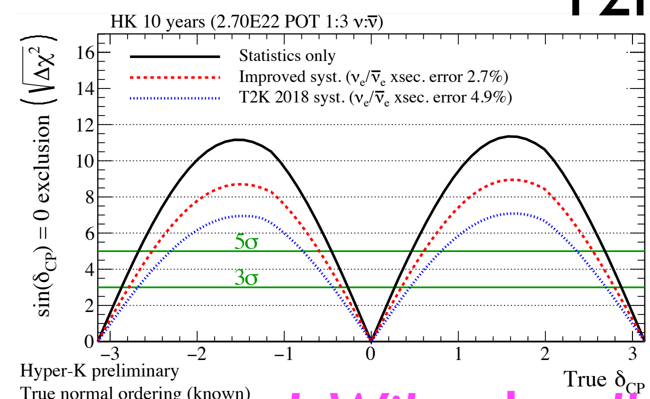

*J. Hartnell's talk*

T2K



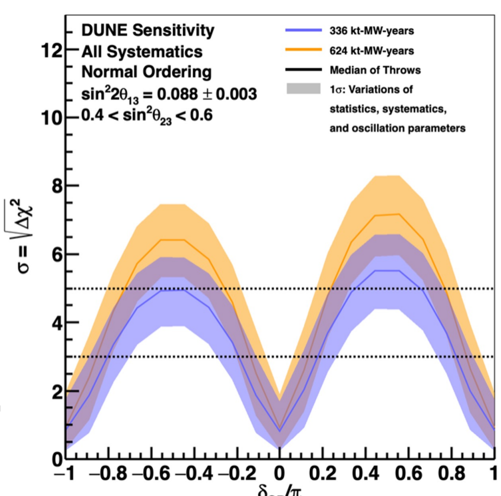

*C. Bronner's talk*

T2HK



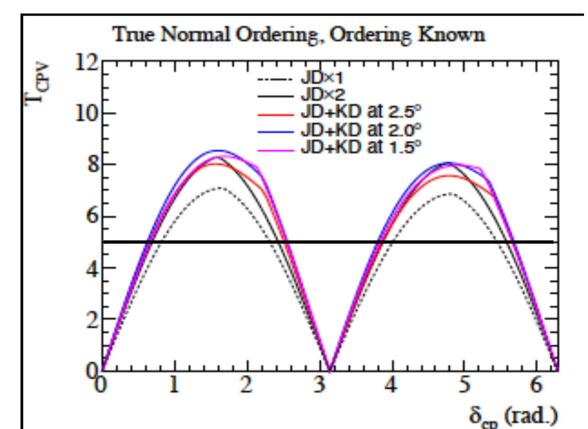

*J. Wilson's talk*

DUNE




*M. Muether's talk*

T2HKK/KNO

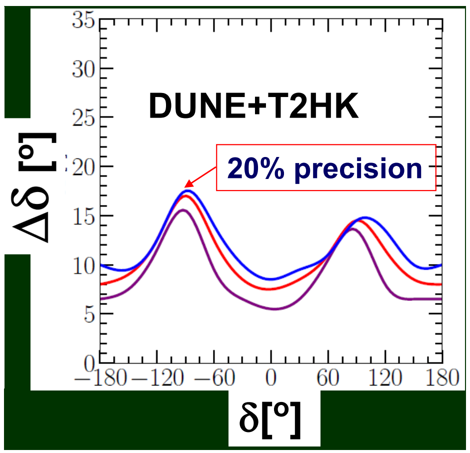



*H. Kim's talk*

# 4. What are the precise values of the mixing parameters?

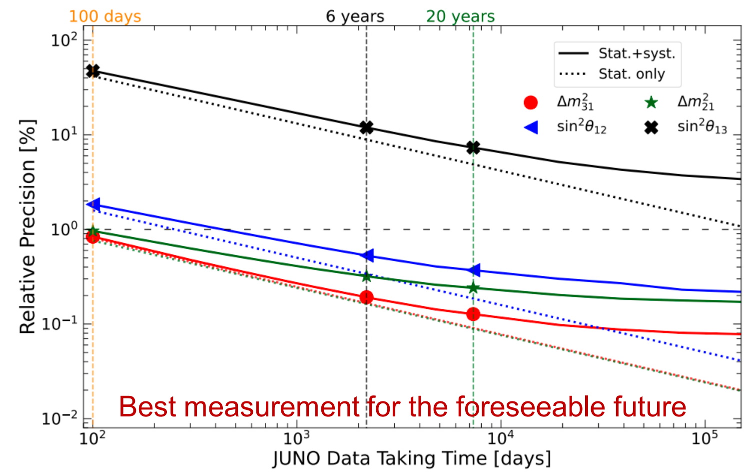
The angle $\theta_{23}$ is still not know very well.

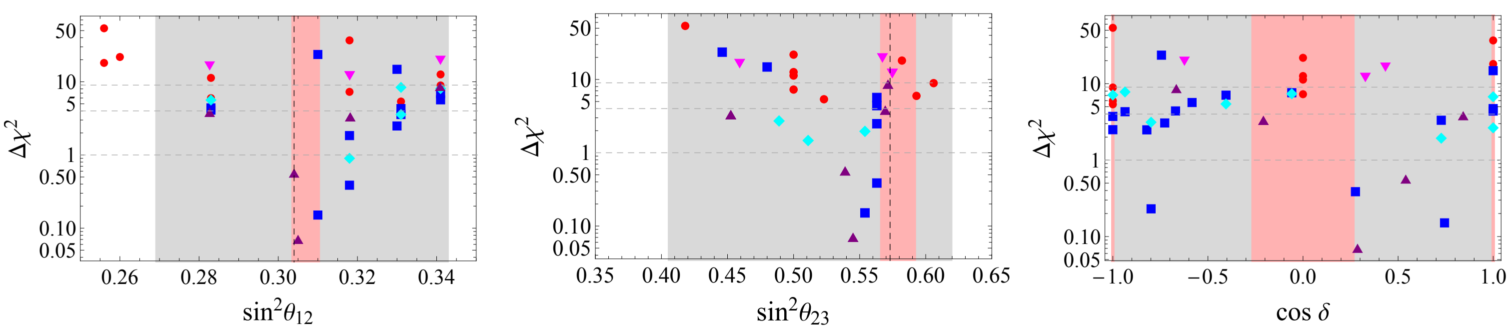
JUNO




See O. Yasuda's talk

See J. Zhao's talk




See e.g. J. Gehrlein et al., 2203.06219, Snowmass

See P. Denton's talk

Once we see CPV, the key issue will be the precise measurement of $\theta_{23}, \theta_{12}, \delta$ . Should we start thinking about the following step? Upgrades? ESSnuSB, Nu factory?

# *5. Is the standard 3-neutrino picture correct?*

Neutrinos are the least known of the SM fermions and could provide a privileged window on new physics BSM.

With great precision of neutrino properties, the search for beyond 3-nu mixing becomes very compelling:

Neutrino 2002: 5 talks mainly on sterile neutrinos
Neutrino 2012: 4 talks mainly on sterile neutrinos
Neutrino 2022: 10 talks with many new results and theory developments

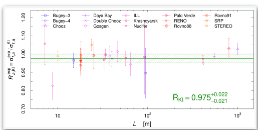
- Non standard interactions, non-unitarity.

*See e.g. Y. Farzan, P. Denton's talk*

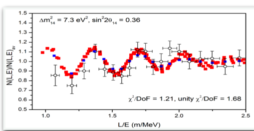
- Dark sector connection (with dark photons, FIPs, DM) and other exotic effects (decoherence, Lorentz viol…)

*See e.g. C. Arguelles', C. Giunti's talks*

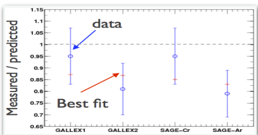
- **Sterile neutrinos:** Hints for eV sterile neutrinos are present but controversial. SBL oscillations (MicroBooNE, SBN, reactor neutrino exp, BEST…) are testing it.



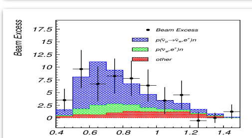
reactor flux anomaly
resolved with new input data to flux calculation



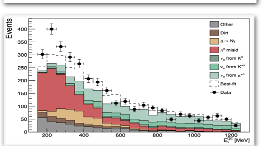
reactor spectra
is there really an anomaly?



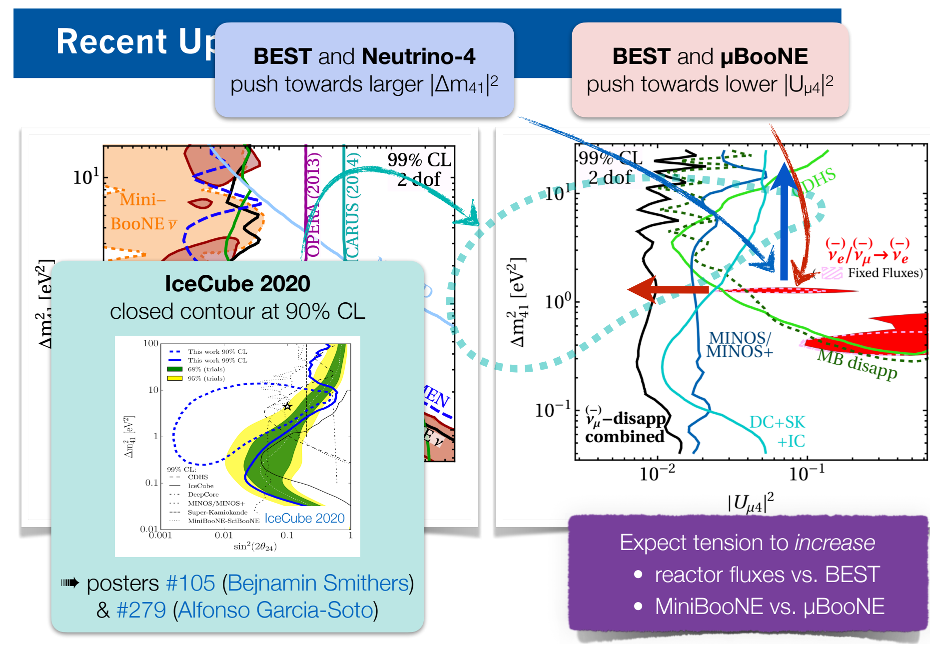

gallium anomaly
unresolved, recently reinforced



LSND
unresolved



MiniBooNE
unresolved




*See J. Kopp's talk, and M. Licciardi, J. Kim, J. Park, H. Wei, A. Schukraft, S. Elliott, C. Arguelles-Delgado, K. Leach, D. Winklehner&J. Spitz*

The discovery of any signature beyond 3-neutrinos, would be game-changing for experiments and theory.

# Other important theory developments

- Great emphasis on very precise evaluation of experimental quantities, such as neutrino fluxes, neutrino cross sections, nuclear effects and nuclear matrix elements. Study of neutrino coherent scattering.

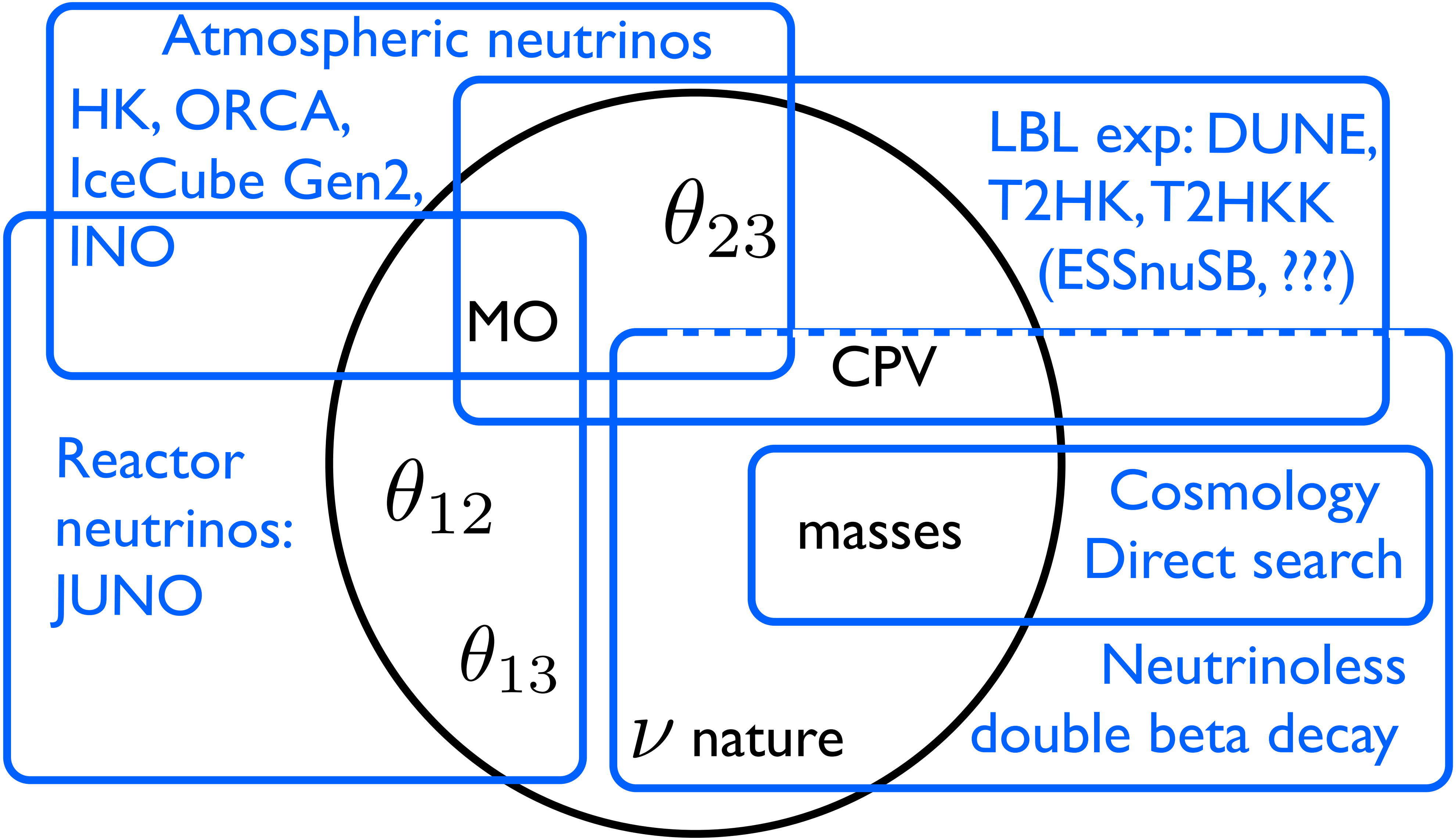
*See M. Friend, K. Sato, A. Fedynitch, P. Vogel, N. Jachowicz's, C. Giunti's talk*
*Also L. Fields, X. Lu, C. Bonifazi, D. Pershey, S. Gardiner, N. Bowden, O. Hen*

- Neutrinos in astrophysics and multimessenger astronomy: SN, solar and HE neutrinos as a tool to study stars and extreme environments in the Universe. Connection with GW and HE cosmic ray searches.

*See B. Caccianiga, A. Mastbaum, J. Tjus, I. Bartos, M.-R. Wu*
*Also, N. Park, A. Heijboer, Z. Dzhilkibayev*

- Neutrinos for security. *See P. Huber's talk*

# Complementarity

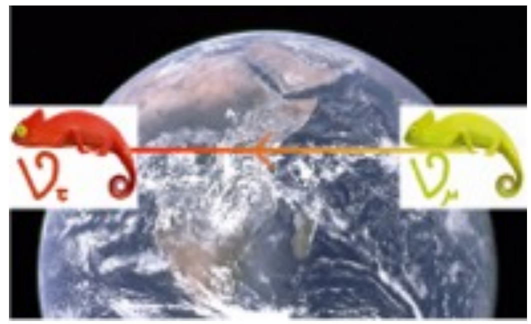



Tests of standard neutrino paradigm: SBL oscillations (SBN, reactor exp), LBL/atm oscillations, neutrino less DBD, beta decays, cosmology (BBN, CMB, LSS), dedicated searches.

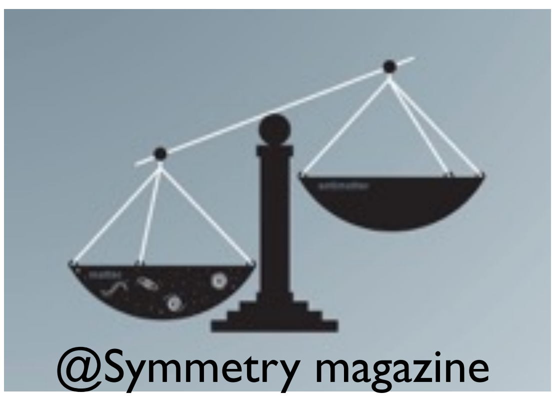
# *Evidence beyond the SM*

There is experimental/observational evidence that the Standard Model is incomplete: neutrinos play a key role.

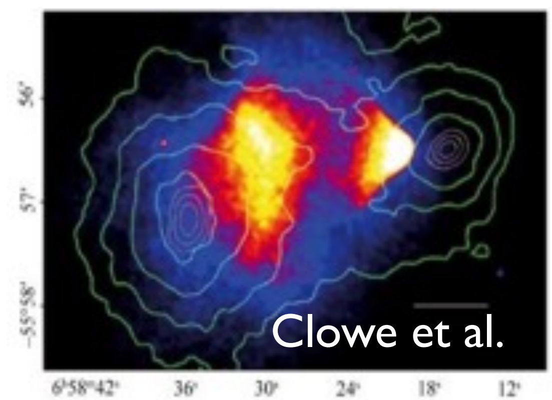
*Neutrino masses*



*Dark Matter*




*Baryon asymmetry*



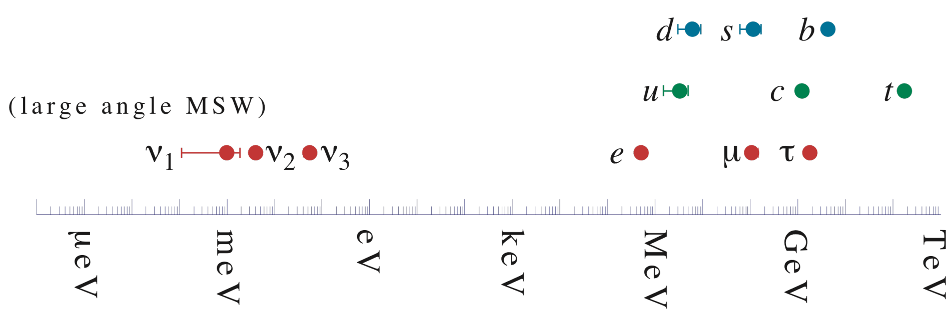

The ultimate goal is to understand

- where do neutrino masses come from?
- what is the origin of leptonic mixing?

# Neutrinos: Open window on Physics BSM

Neutrinos give a new perspective on physics BSM.

## 1. Origin of masses




Why neutrinos have mass?
and why are they so much lighter than the other fermions?
and why their hierarchy is at most mild?
Can it be related to the Majorana nature?

## 2. Problem of flavour

$$\begin{pmatrix} \sim 1 & \lambda & \lambda^3 \\ \lambda & \sim 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & \sim 1 \end{pmatrix} \quad \lambda \sim 0.2$$

$$\begin{pmatrix} 0.8 & 0.5 & 0.16 \\ -0.4 & 0.5 & -0.7 \\ -0.4 & 0.5 & 0.7 \end{pmatrix}$$

Why leptonic mixing is so different from quark mixing?

*See e.g. F. Feruglio's talk*

# Neutrino masses Beyond SM

In the SM, neutrinos do not acquire mass and mix.

## Dirac Masses

If we introduce a right-handed neutrino, then an interaction with the Higgs boson emerges.

$$\mathcal{L} = -y_\nu \bar{L} \cdot \tilde{H} \nu_R + \mathrm{h.c.} \longrightarrow m_D = y_\nu v = V m_{\mathrm{diag}} U^\dagger$$

This term is SU(2) invariant and respects lepton number.

$$y_\nu \sim \frac{\sqrt{2} m_\nu}{v_H} \sim \frac{0.2\ \mathrm{eV}}{200\ \mathrm{GeV}} \sim 10^{-12}$$

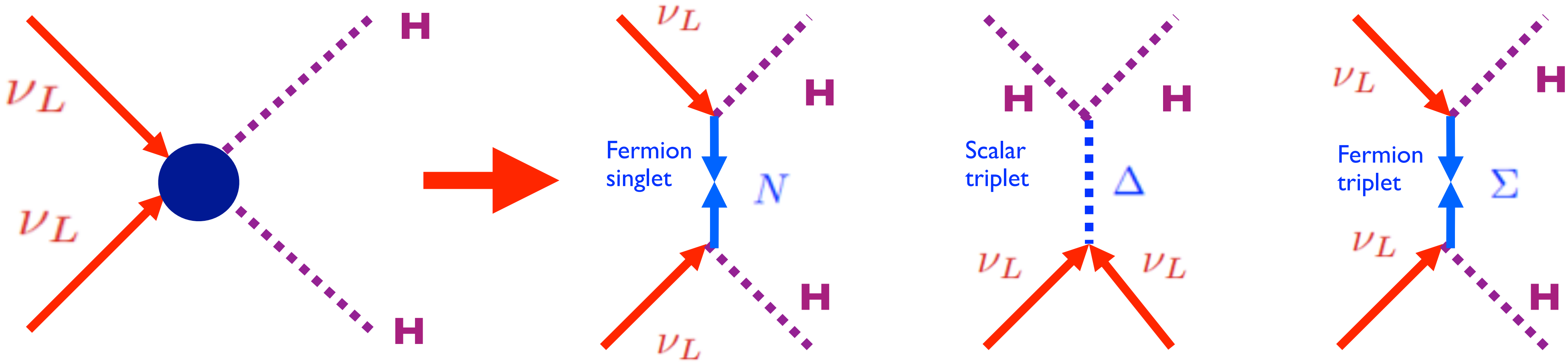
- why the coupling is so small???
- why the leptonic mixing angles are large?
- why neutrino masses have at most a mild hierarchy?
- why no Majorana mass term for RH neutrinos? We need to impose L as a fundamental symmetry (BSM).

# Majorana Masses

In order to have an SU(2) invariant Majorana mass term for neutrinos, it is necessary to introduce a Dimension 5 operator (or to allow new scalar fields, e.g. a triplet):

$$-\mathcal{L} = \lambda \frac{L \cdot H L \cdot H}{M} = \frac{\lambda v_H^2}{M} \nu_L^T C^\dagger \nu_L$$

Weinberg operator, PRL 43




Minkowski, Yanagida, Glashow, Gell-Mann, Ramond, Slansky, Ma, Mohapatra, Senjanovic, Magg, Wetterich, Lazarides, Shafi, Schecter, Valle, Hambye…

This term breaks lepton number and induces Majorana masses and Majorana neutrinos. It can be induced by a high energy theory (see-saw mechanism).

# *Neutrino masses BSM:*
# *"vanilla" see saw mechanism type I*


Symmetry magazine

- Introduce a right handed neutrino **N**
- It couples to the Higgs and has a Majorana mass

$$\mathcal{L} = -Y_\nu \bar{N} L \cdot H - 1/2 \bar{N}^c M_R N$$

$$\begin{pmatrix} 0 & m_D \\ m_D^T & M_N \end{pmatrix}$$

$$m_\nu = \frac{Y_\nu^2 v_H^2}{M_N} \sim \frac{1\ \mathrm{GeV}^2}{10^{10}\mathrm{GeV}} \sim 0.1\ \mathrm{eV}$$

Minkowski; Yanagida; Glashow; Gell-Mann, Ramond, Slansky; Mohapatra, Senjanovic

As a result, neutrinos can have naturally small masses and are Majorana particles.

# The baryon asymmetry of the Universe

There is evidence of the baryon asymmetry:

$$\eta_B \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} = (6.23 \pm 0.03) \times 10^{-10}$$

Planck, 1807.06209

In order to generate it dynamically in the Early Universe, the Sakharov's conditions need to be satisfied:

- B (or L) violation;
- C, CP violation;
- departure from thermal equilibrium.

$$X^c \to \bar{q}q \qquad X \to \bar{q}q$$

$$X \to \ell q \qquad X^c \to \bar{\ell}\bar{q}$$

$$X \to \bar{q}q \qquad X \to \ell q$$

The Standard Model cannot generate the necessary amount of baryon asymmetry: BSM physics, e.g. electroweak baryogegesis and leptogenesis.

# *Leptogenesis*

- At T>M, N are in equilibrium:

$$N \leftrightarrow \ell H \quad N \leftrightarrow \ell H \quad N \leftrightarrow \ell H$$
$$N \leftrightarrow \ell H \quad N \leftrightarrow \ell H$$

- At T<M, N drops out of equilibrium:

$$N \to \ell H \quad N \to \ell^c H^c \quad N \to \ell H$$
$$N \to \ell^c H^c \quad N \to \ell^c H^c$$


- A lepton asymmetry can be generated if

$$\Gamma(N \to \ell H) \neq \Gamma(N \to \ell^c H^c)$$

- $$\Delta L \xrightarrow{sphalerons} \Delta B$$

*The observation of L violation and of CPV in the lepton sector would be a strong indication (even if not a proof) of leptogenesis as the origin of the baryon asymmetry.*

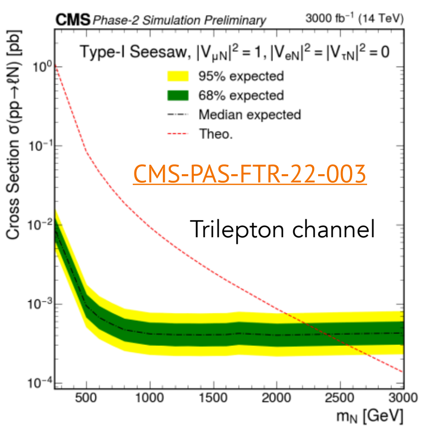
*What is the new physics scale?*

*Are there new:*
*symmetries?*
*particles?*
*interactions?*

# New physics scale? Going to high energy

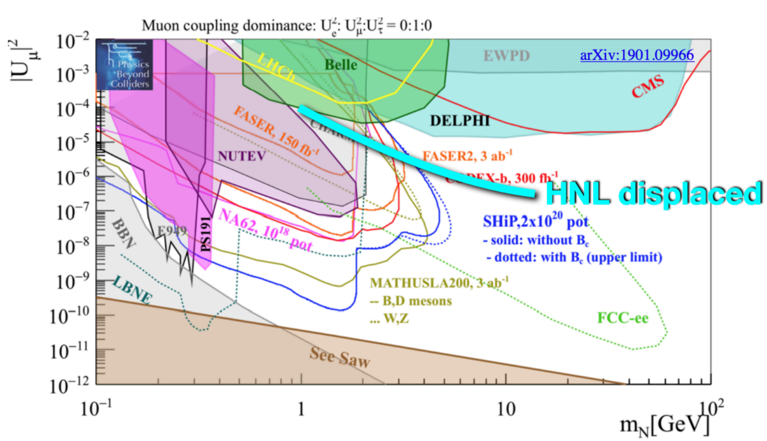
eV keV MeV GeV **TeV** **Intermediate scale** **GUT scale**

*TeV see-saw I, see-saw II, see-saw III, extended-type seesaws, radiative models, extra-D, R-parity V SUSY...*




**LHC searches**

*See J. Xiao's talk*

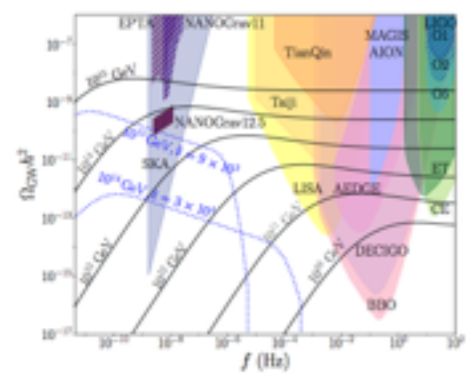



**Leptogenesis**

**CLFV**

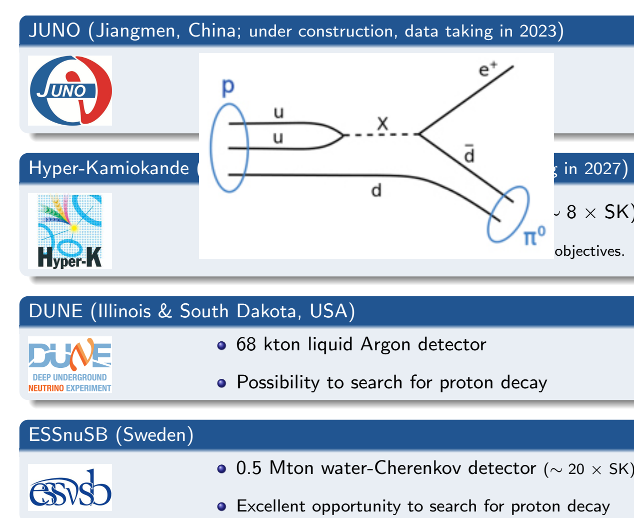
**Proton decay**

*See T. Ohlsson's talk*




**GW**

S. King et al., PRL 126 (2021)



# *Going low in energy: Dark sectors*

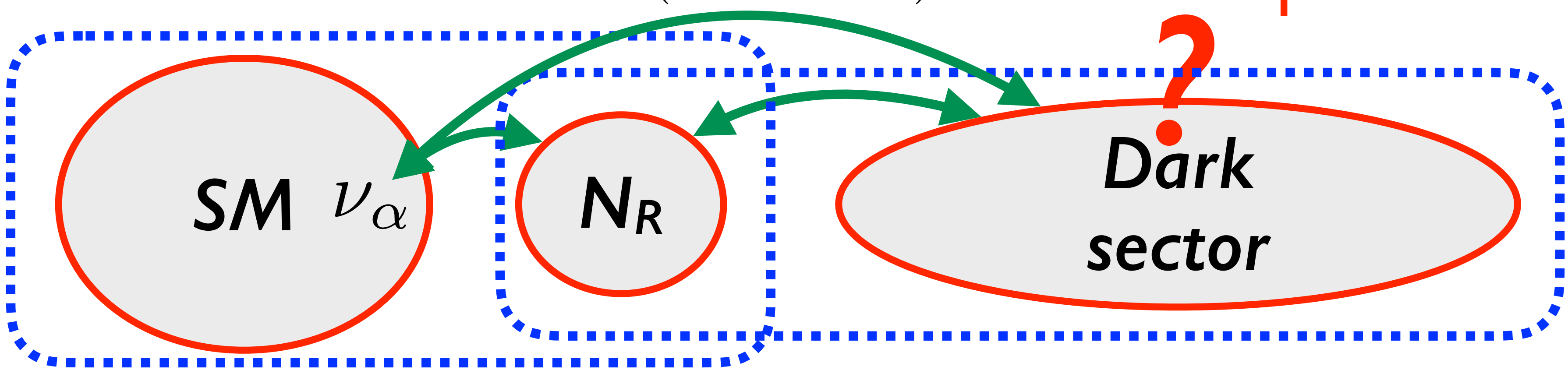
eV keV MeV GeV TeV Intermediate scale GUT scale

*Low E See-saw models, NuMSM, extended see-saw…*

Sterile nu oscillations    DM    Leptogenesis    HNL searches: peak, kinks, decays,

Neutrino can play a unique role in searching for Dark Sectors.

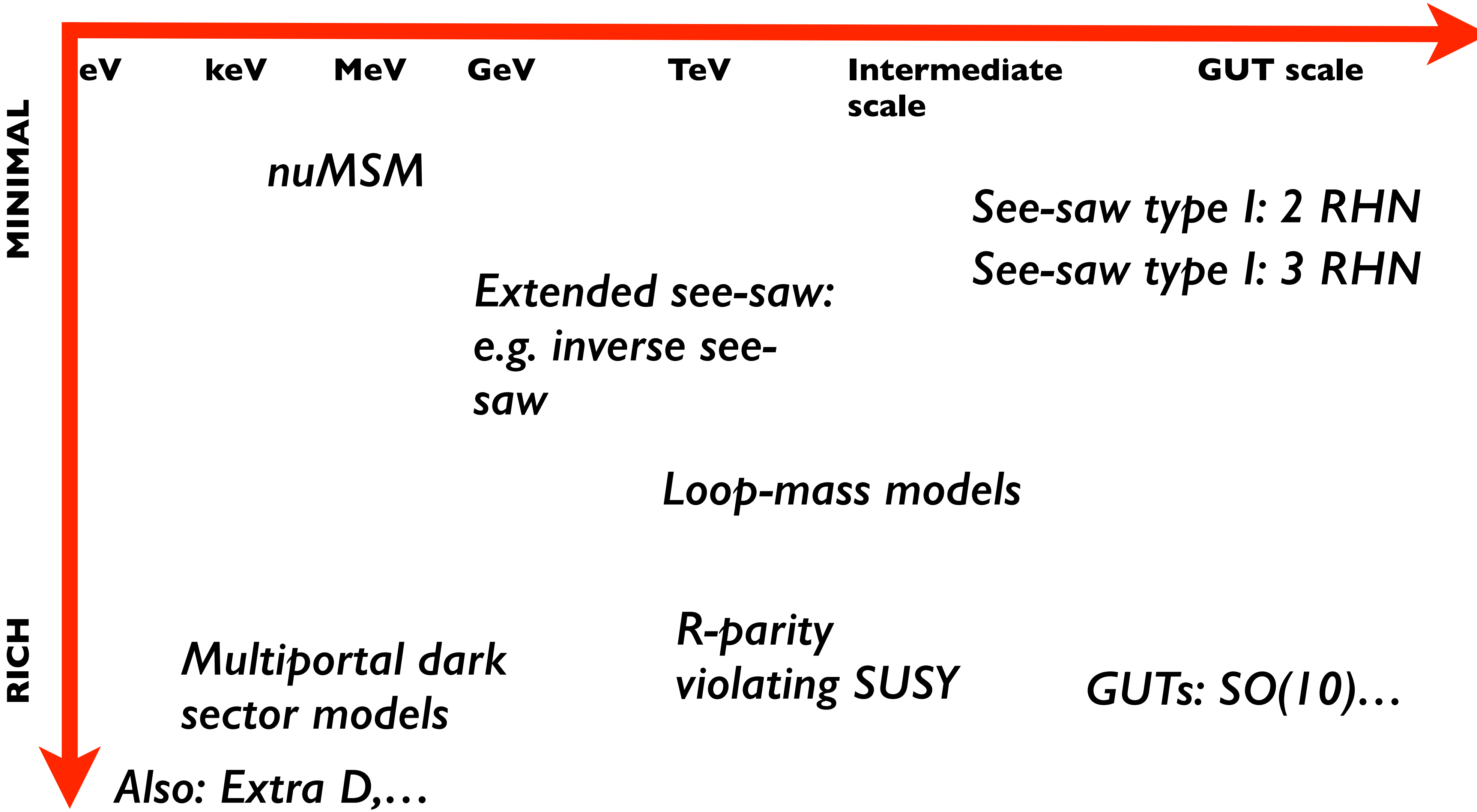
$\bar{L}\cdot HN_R \quad (+...\overline{N_R}N_S)$ Neutrino portal




Have we seen already some glimpses??? If a signal in future, this would lead to a major change in the BSM paradigm.

*See C. Giunti's, Y. Farzan's and C. Arguelles' talks*

# From minimality to richness




Two contrasting approaches can be taken:

Minimality: the fewest ingredients -> predictivity

Richness (theory-motivated): connections, new signatures

# The problem of leptonic flavour

$$\boxed{M_M = (U^\dagger)^T m_{\rm diag} U^\dagger} \quad \Rightarrow \quad \boxed{n_L = U^\dagger \nu_L}$$

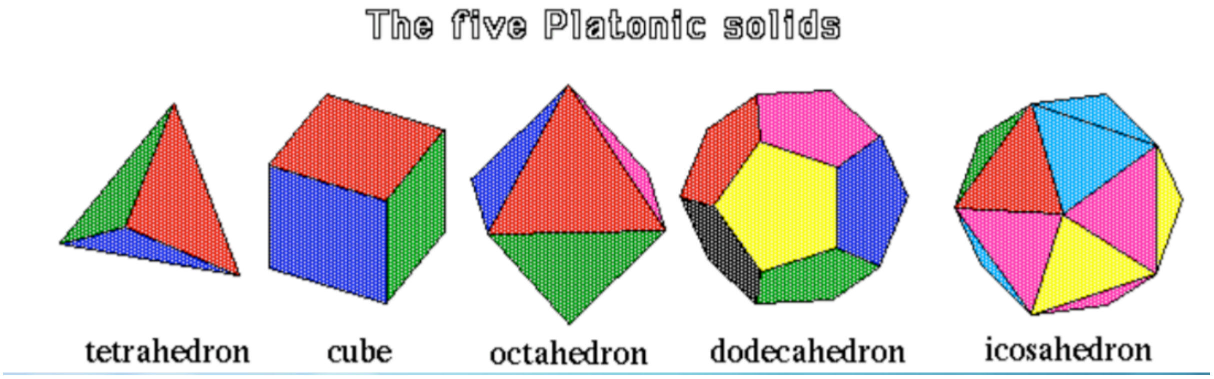
Theory

Experiments

$$\mathcal{L}_{CC} = \frac{g}{\sqrt{2}} (\bar{e}_L, \bar{\mu}_L, \bar{\tau}_L) \gamma^\mu U_{\rm osc} \begin{pmatrix} \nu_{1L} \\ \nu_{2L} \\ \nu_{3L} \end{pmatrix} W_\mu$$

**with** $U_{\rm osc} = V_L^\dagger U_\nu$

Symmetry approach (not unique) to understand observed pattern: use of traditional and new (modular) symmetries. Need more precise values of oscillation parameters.




*See F. Feruglio's talk*

# Conclusions

**Neutrinos are the most elusive and mysterious of the known particles. Neutrino masses are the only particle physics evidence BSM to date.**

Current status: precise knowledge of most of neutrino properties. Key questions open (nature, CPV, MO) due to be answered in the next ~decade. Thriving experimental programme.

Surprises in store? Several SBL anomalies remain unexplained.

Neutrino masses require to extend the SM to a new theory (energy scale? symmetries? particles?). Are neutrinos pointing to a new BSM paradigm: dark sector?


*Thank you very much to the Chairs Yeongduk Kim and Sunny Seo, the Neutrino2022 Secretariat and to all for an amazing virtual conference!!!*