

# Neutrinos: the Big Questions

22 November 2022  
**UKHeP Forum 2022**

**Silvia Pascoli**

# Evidence beyond the SM

There is experimental/observational evidence that the Standard Model is incomplete.

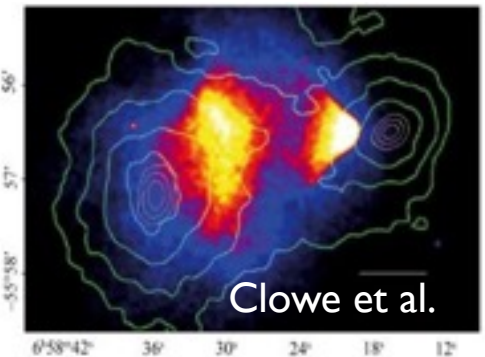
*Neutrino masses*



*Dark Matter*



*Baryon asymmetry*



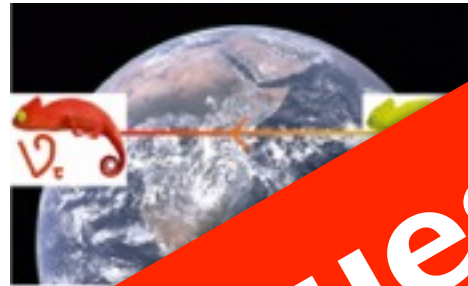
The ultimate goal is to understand

- what origin for neutrino masses and leptonic mixing?
- what is DM made of and how does it interact?
- what is the origin of the baryon asymmetry?

# Evidence beyond the SM

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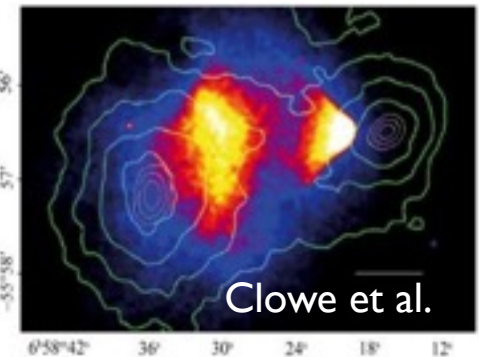
Neutrino  
masses



Dark Matter



Baryon  
asymmetry



# The Big Questions

- The ultimate goal is to understand
- what is the origin for neutrino masses and leptonic mixing?
- what is DM made of and how does it interact?
- what is the origin of the baryon asymmetry?

I will focus on neutrinos.

*Question 1:  
What do we still need  
to know about  
neutrino properties?*

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

NuFIT 5.1 (2021)

		Normal Ordering (best fit)		Inverted Ordering ( $\Delta\chi^2 = 2.6$ )	
		bfp $\pm 1\sigma$		bfp $\pm 1\sigma$	
		$3\sigma$ range		$3\sigma$ range	
without SK atmospheric data	$\sin^2 \theta_{12}$	$0.304^{+0.013}_{-0.012}$	$0.269 \rightarrow 0.343$	$0.304^{+0.012}_{-0.012}$	$0.269 \rightarrow 0.343$
	$\theta_{12}/^\circ$	$33.44^{+0.77}_{-0.74}$	$31.27 \rightarrow 35.86$	$33.45^{+0.77}_{-0.74}$	$31.27 \rightarrow 35.87$
	$\sin^2 \theta_{23}$	$0.573^{+0.018}_{-0.023}$	$0.405 \rightarrow 0.620$	$0.578^{+0.017}_{-0.021}$	$0.410 \rightarrow 0.623$
	$\theta_{23}/^\circ$	$49.2^{+1.0}_{-1.3}$	$39.5 \rightarrow 52.0$	$49.5^{+1.0}_{-1.2}$	$39.8 \rightarrow 52.1$
	$\sin^2 \theta_{13}$	$0.02220^{+0.00068}_{-0.00062}$	$0.02034 \rightarrow 0.02430$	$0.02238^{+0.00064}_{-0.00062}$	$0.02053 \rightarrow 0.02434$
	$\theta_{13}/^\circ$	$8.57^{+0.13}_{-0.12}$	$8.20 \rightarrow 8.97$	$8.60^{+0.12}_{-0.12}$	$8.24 \rightarrow 8.98$
	$\delta_{CP}/^\circ$	$194^{+52}_{-25}$	$105 \rightarrow 405$	$287^{+27}_{-32}$	$192 \rightarrow 361$
	$\frac{\Delta m_{21}^2}{10^{-5} \text{ eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \rightarrow 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \rightarrow 8.04$
	$\frac{\Delta m_{3\ell}^2}{10^{-3} \text{ eV}^2}$	$+2.515^{+0.028}_{-0.028}$	$+2.431 \rightarrow +2.599$	$-2.498^{+0.028}_{-0.029}$	$-2.584 \rightarrow -2.413$

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

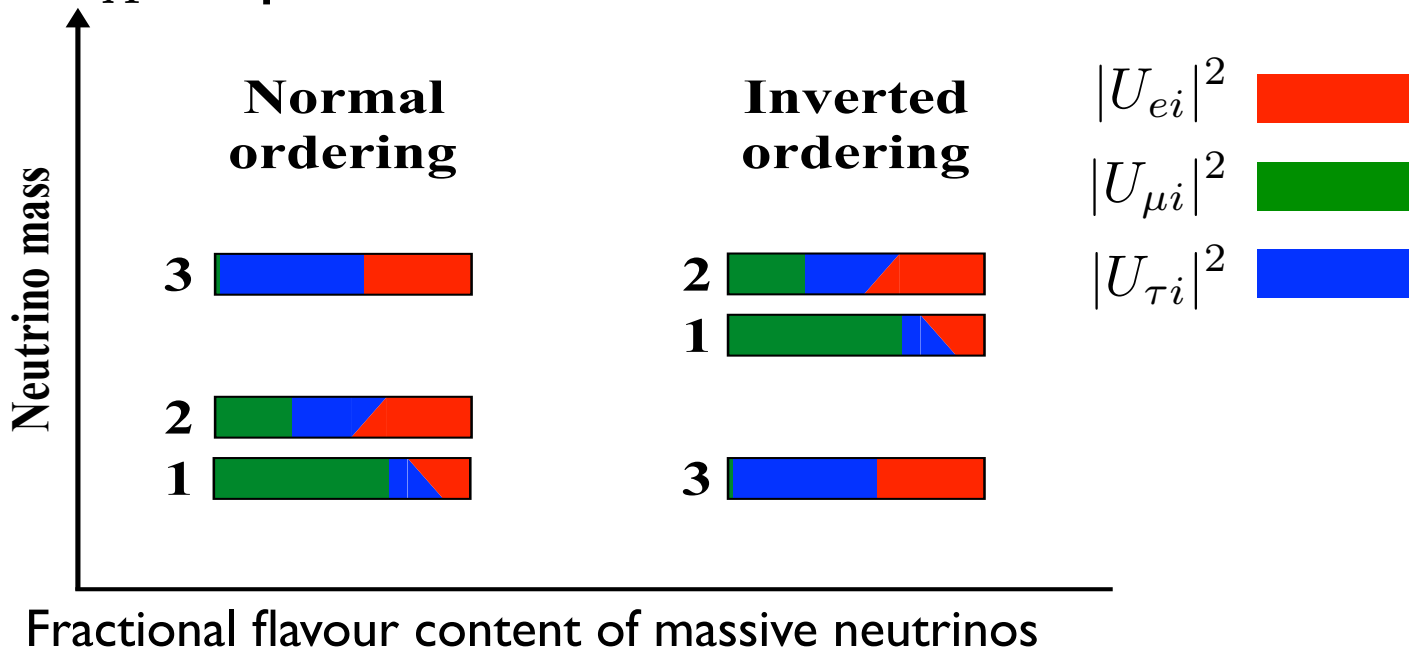
<http://www.nu-fit.org/>

- 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 (?)

The past 20 years have seen a remarkable progress in determining neutrino properties! How about the next 20?

# Neutrino masses

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



$$\begin{aligned} m_1 &= m_{\min} \\ m_2 &= \sqrt{m_{\min}^2 + \Delta m_{\text{sol}}^2} \\ m_3 &= \sqrt{m_{\min}^2 + \Delta m_A^2} \end{aligned}$$

$$\begin{aligned} m_3 &= m_{\min} \\ m_1 &= \sqrt{m_{\min}^2 + \Delta m_A^2 - \Delta m_{\text{sol}}^2} \\ m_2 &= \sqrt{m_{\min}^2 + \Delta m_A^2} \end{aligned}$$

Measuring the masses requires:

- the mass scale:  $m_{\min}$
- 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?

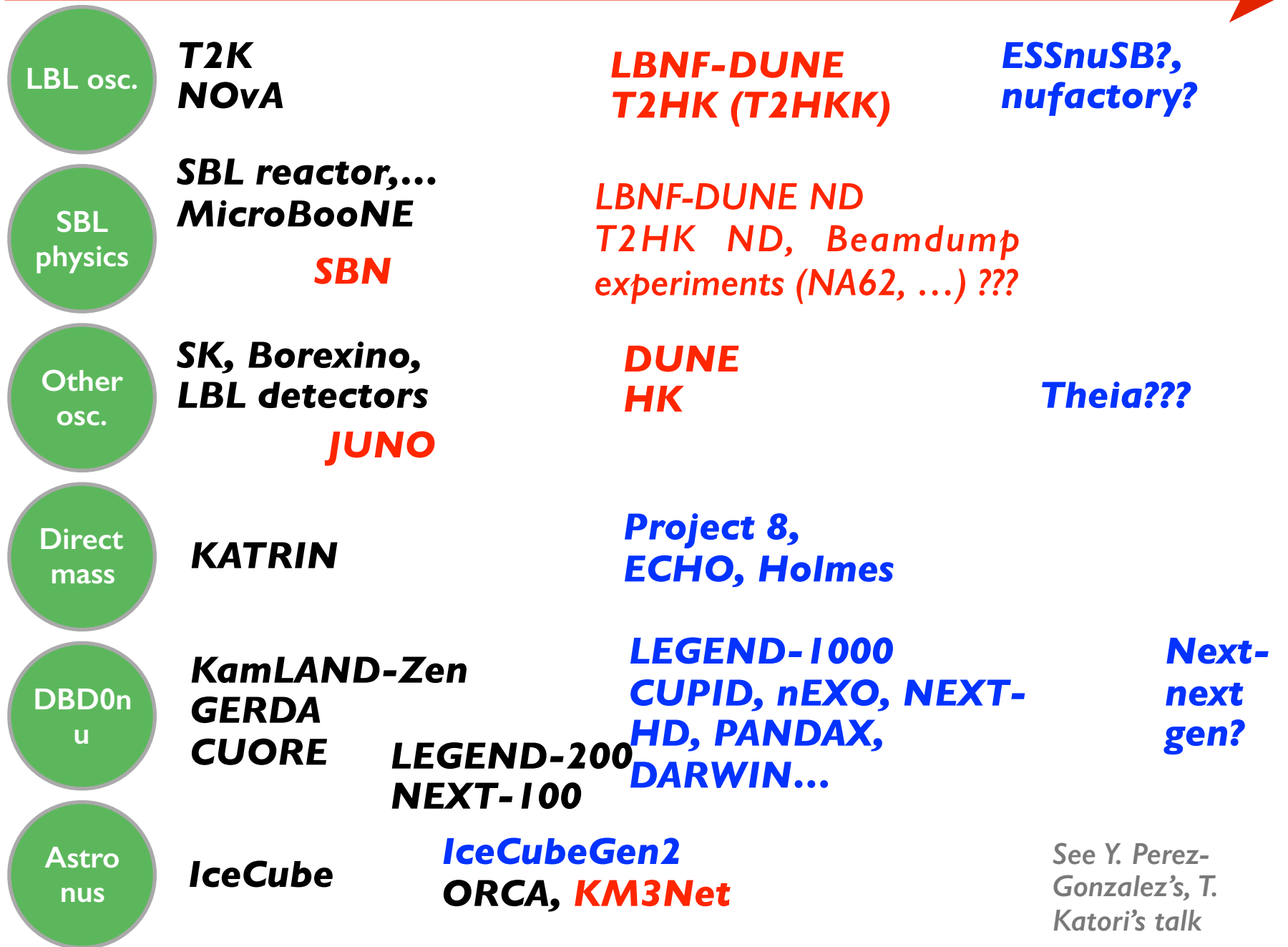
**Very exciting experimental programme.**

2020

2025

2030

2035



# I. What is the nature of neutrinos?

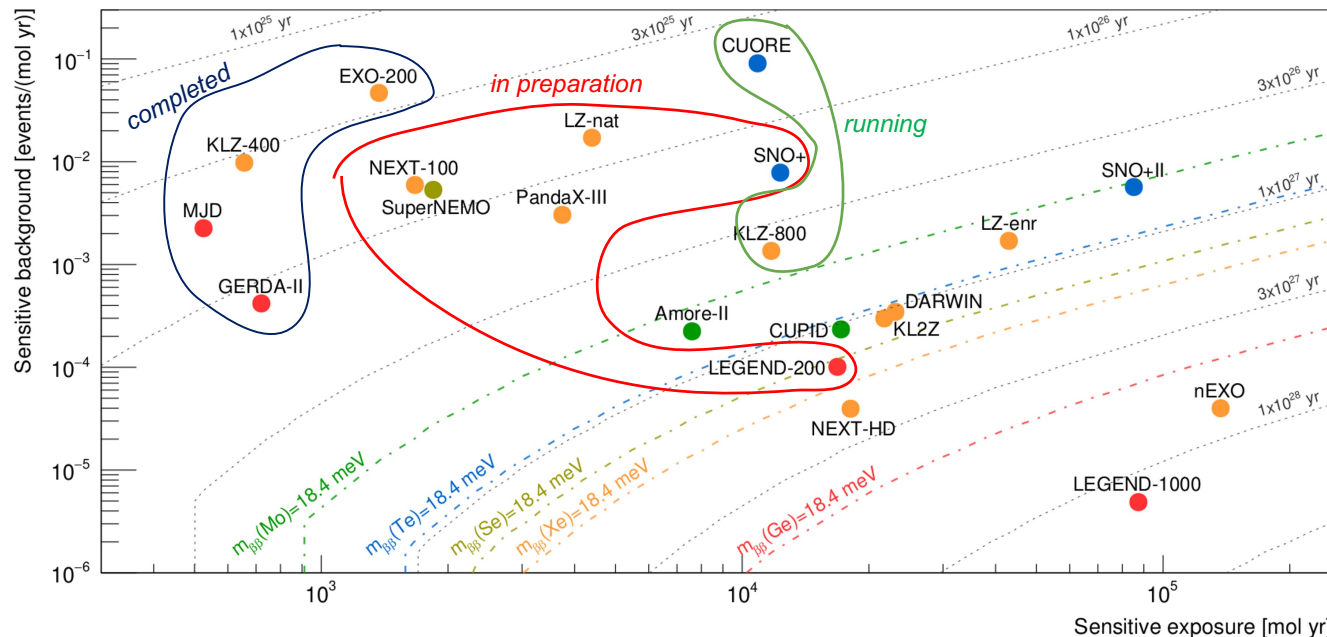
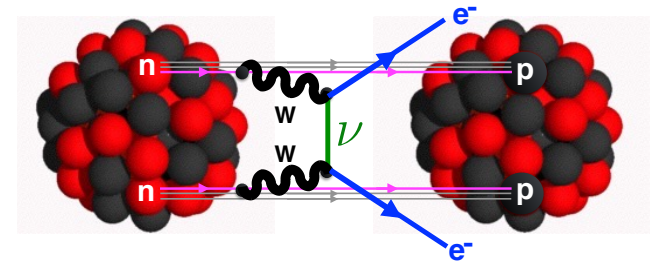
See C. Patrick's talk

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

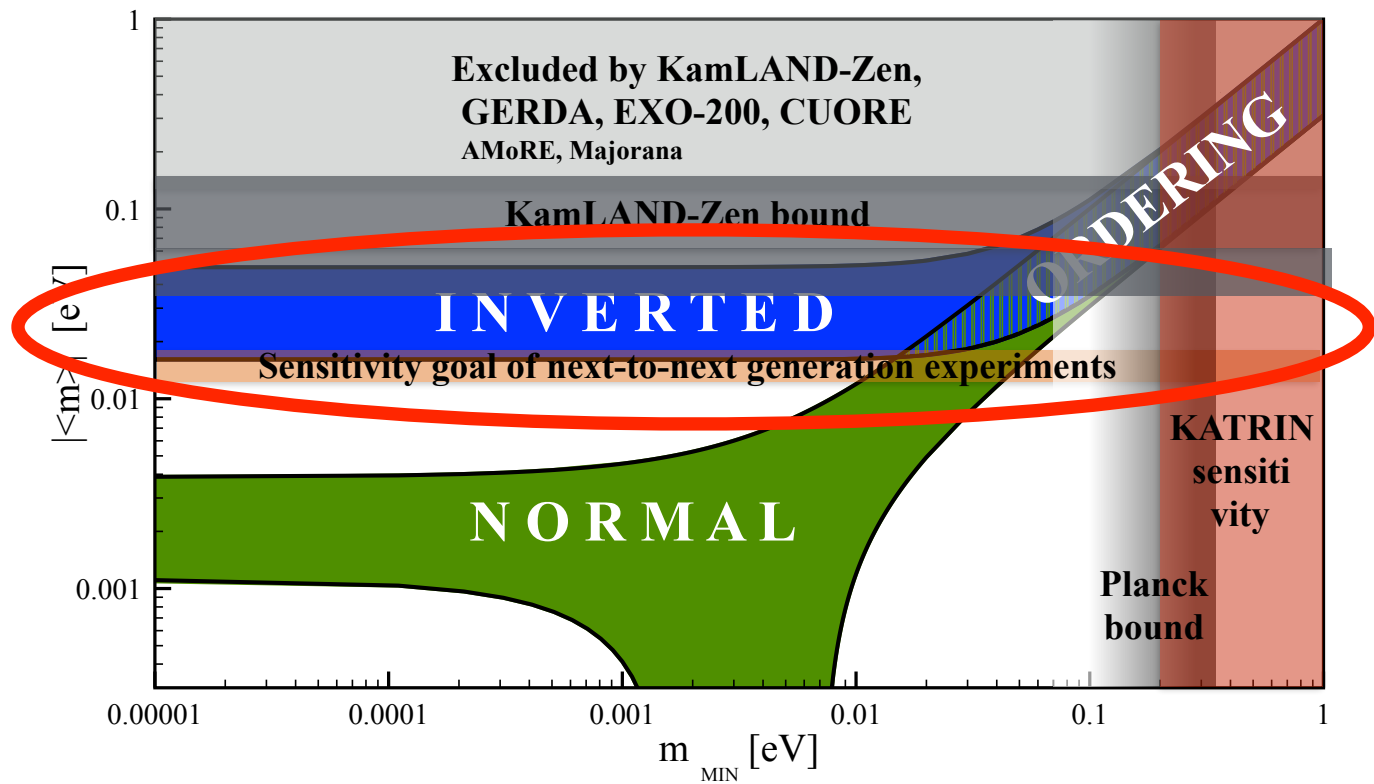
**Nature of neutrinos  $\Leftrightarrow$  Lepton number**

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

- Most sensitive test of LNV: neutrinoless double beta decay.



R. Saakyan's  
talk at FIPs  
2022,  
M. Agostini et  
al., 2202.01787



The answer might be around the corner..... (or not).

If the ordering is inverted, then we should be close to it.

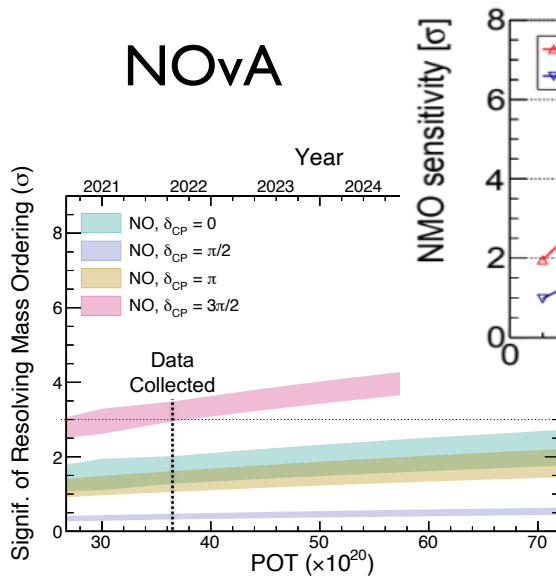
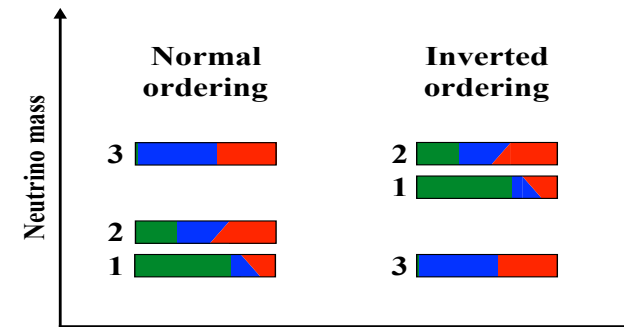
If the ordering is normal, then we cannot predict when and if we will find a positive signal.

## 2. What are the values of neutrino masses?

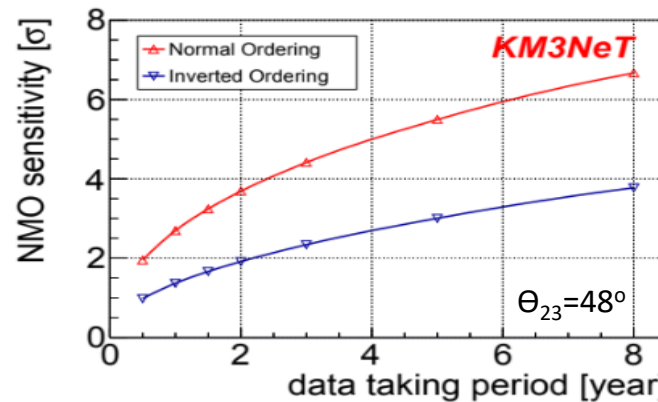
See L. Cremonesi's talk

The current situation is still rather uncertain but we should know the answer in  $\sim$ a decade.

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



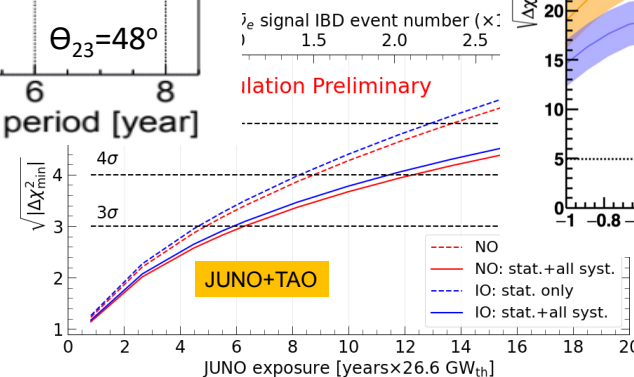
J. Hartnell's talk at Neutrino 2022



A. Heijboer's talk at Neutrino 2022

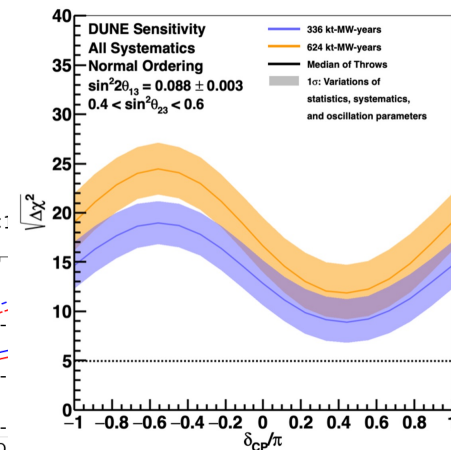
SK, HK, IceCube

JUNO



J. Zhao's talk at Neutrino 2022

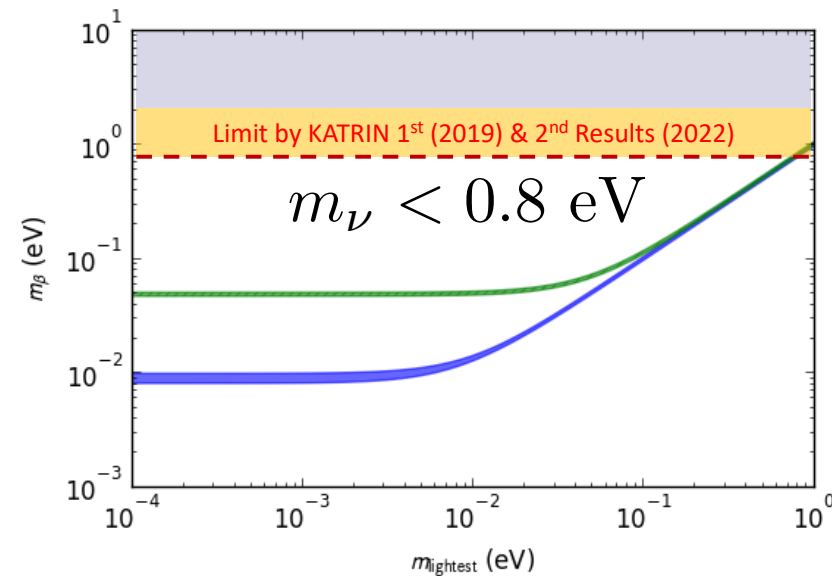
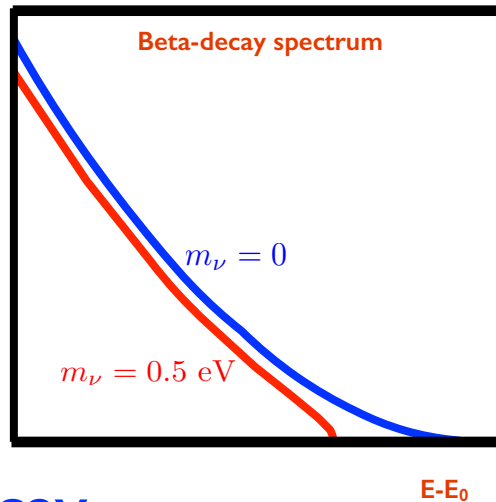
DUNE



DUNE Coll., 2006.16043

## 2. What are the values of the masses?

Absolute mass scale.

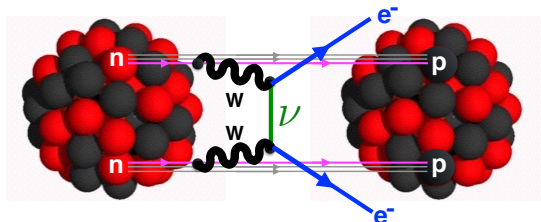


Beta decay  
(KATRIN, Project 8, Ptolemy)

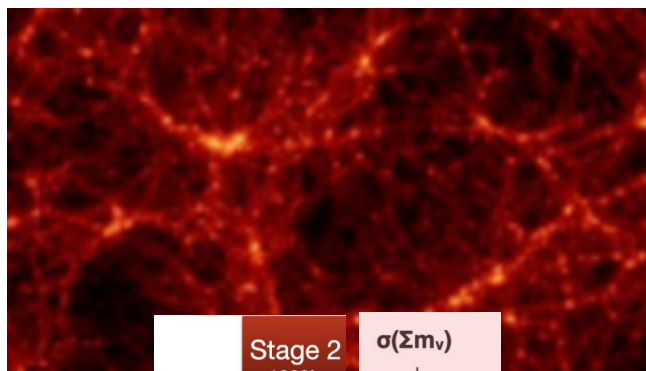
*T. Lassere's talk at Neutrino 2022*

New results from KATRIN in the quasi-degenerate mass region. Direct mass measurement is a crucial piece of information to confront with cosmology and for neutrinoless double beta decay.

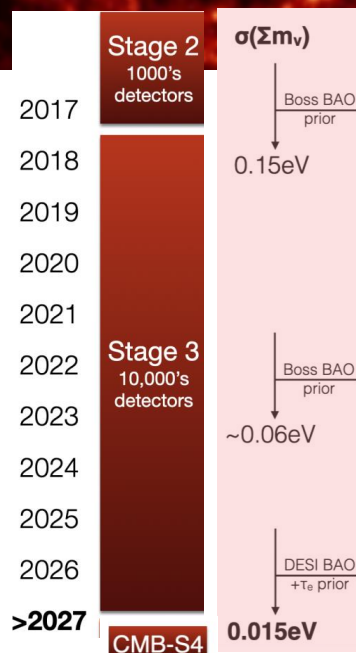
See J.  
Canning's  
talk



**Neutrinoless double beta decay:** interplay with CPV phases. It might be possible to hunt for Majorana CPV in the far future.



**Cosmology:** it provides the most stringent bound:  $\sum m_i < 0.12 - 0.13 \text{ eV}$ . Assumes an underlying cosmological model, standard neutrinos and combines different sets of data.



See E. Di Valentino's talk



ESA Euclid

2024



LSST

2024

$1\sigma$  sensitivity to  $\sum m_\nu$

0.011 – 0.02 eV

0.015 eV

Y. Y. Y. Wong's talk at FIPs 2022

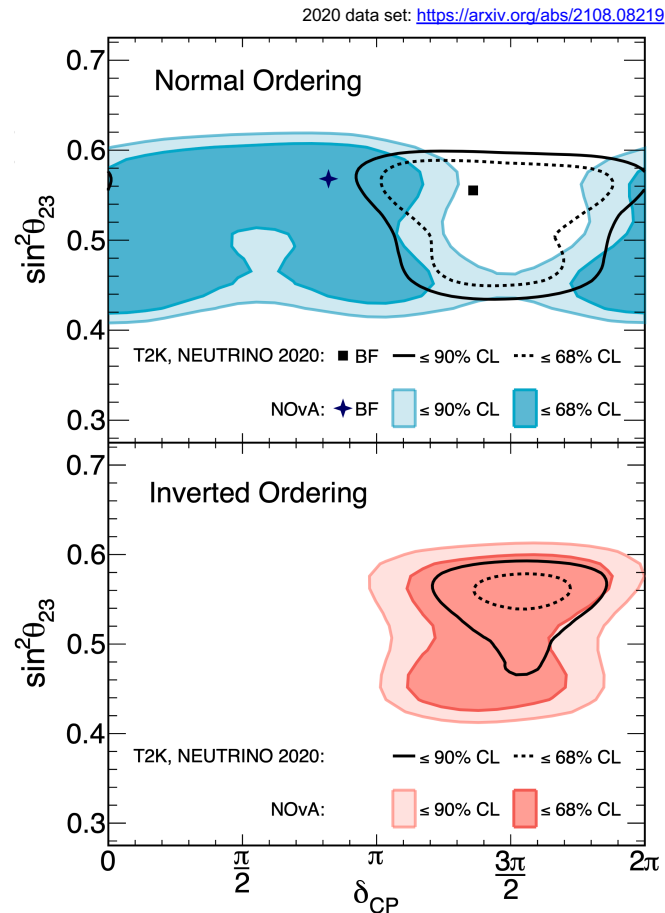
# 3. Is there CP-violation?

Hints of leptonic CPV?

Situation remains unclear.

Expect soon T2K-NOvA joint analysis.

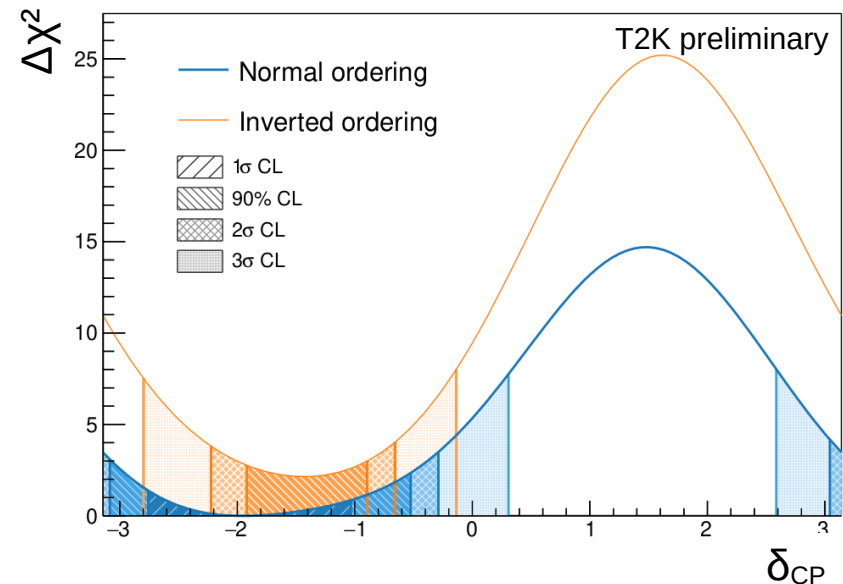
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix}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



NOvA

See F. Di Lodovico's,  
L. Cremonesi's talks

T2K

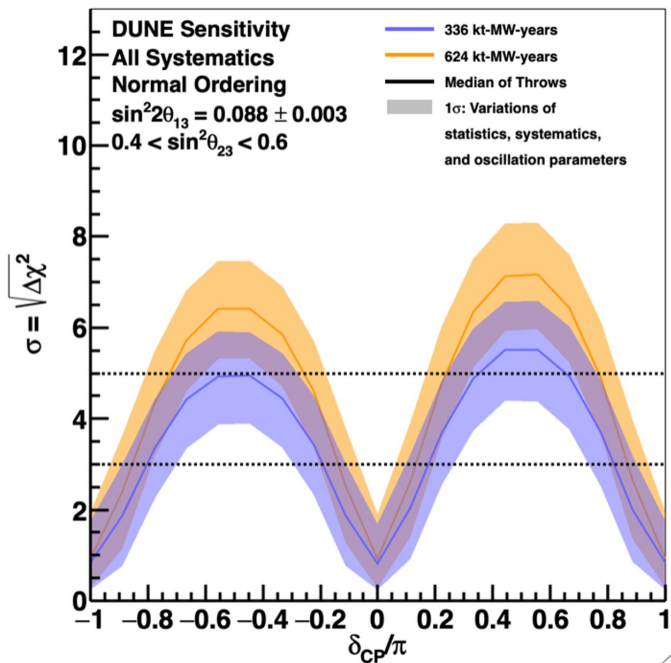


C. Bronner's talk at Neutrino 2022

J. Hartnell's talk at Neutrino 2022

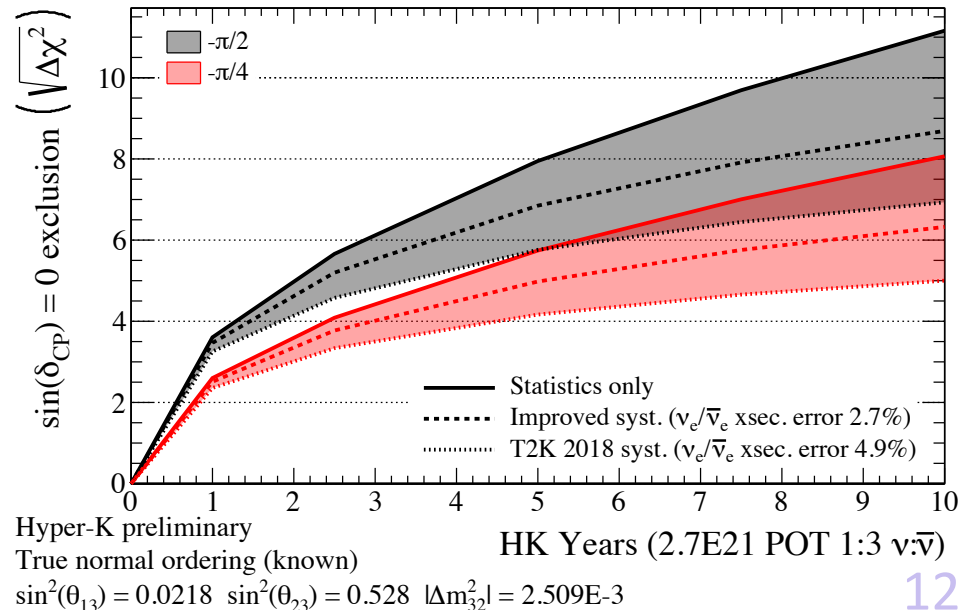
DUNE and T2HK will get to 5 sigma for a large range of values of delta by the end of the next decade. Whether we discover it or not depends on the true value of delta.

## DUNE



DUNE Coll., 2006.16043

## T2HK



J. Wilson's talk at Neutrino 2022

12

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

Remarkable progress has been seen in the past 10 years. The angle  $\theta_{23}$  is still not known very well.

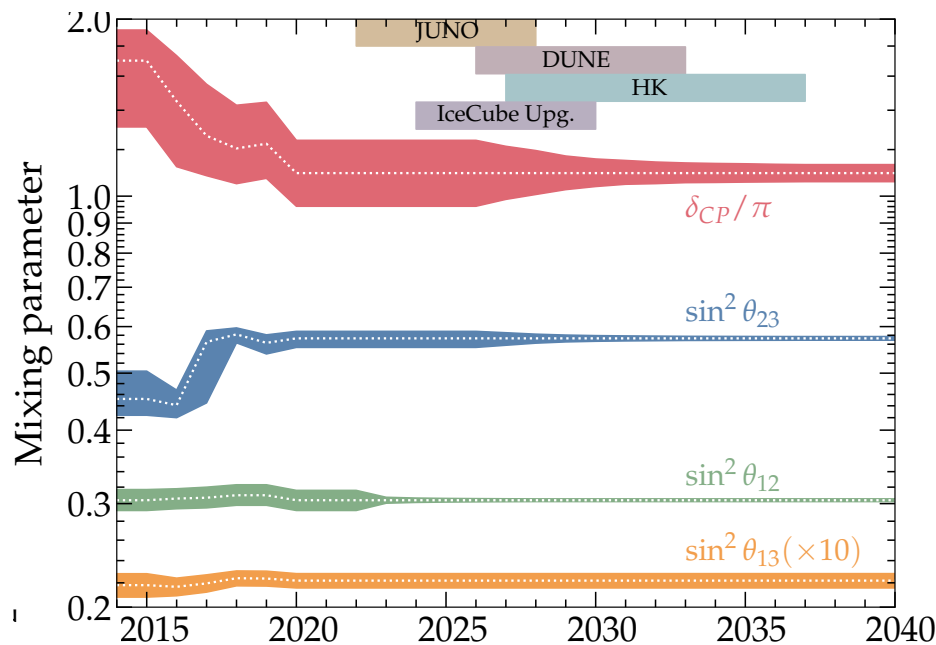
	2012	2014	2016	2018	2021
	NuFIT 1.0	NuFIT 2.0	NuFIT 3.0	NuFIT 4.0	NuFIT 5.1
$\theta_{12}$	15%	14%	14%	14%	14%
$\theta_{13}$	30%	15%	11%	8.9%	9.0%
$\theta_{23}$	43%	32%	32%	27%	27%
$\Delta m_{21}^2$	14%	14%	14%	16%	16%
$ \Delta m_{3\ell}^2 $	17%	11%	9%	7.8%	6.7% [6.5%]
$\delta_{\text{CP}}$	100%	100%	100%	100% [92%]	100% [83%]
$\Delta\chi_{\text{IO-NO}}^2$	$\pm 0.5$	$-0.97$	$+0.83$	$+4.7$ [+9.3]	$+2.6$ [+7.0]

w/o [w] SK atm data

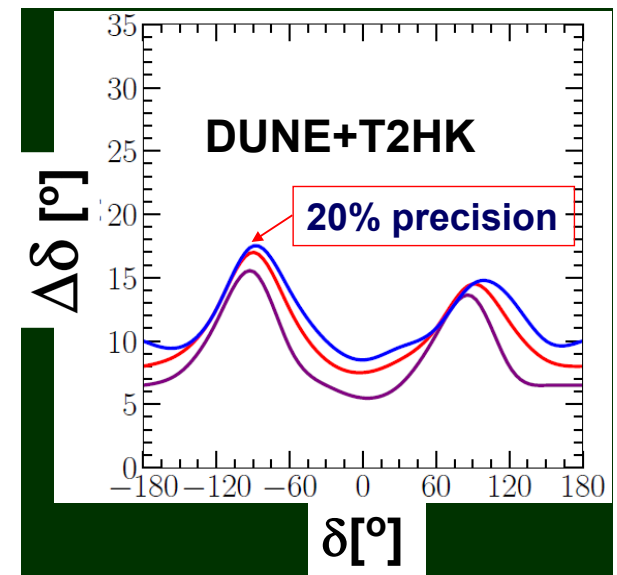
Gonzalez-  
Garcia et al.,  
2111.03086

	Central Value	PDG2020	100 days	6 years	20 years
$\Delta m_{31}^2$ ( $\times 10^{-3}$ eV <sup>2</sup> )	2.5283	$\pm 0.034$ (1.3%)	$\pm 0.021$ (0.8%)	$\pm 0.0047$ (0.2%)	$\pm 0.0029$ (0.1%)
$\Delta m_{21}^2$ ( $\times 10^{-5}$ eV <sup>2</sup> )	7.53	$\pm 0.18$ (2.4%)	$\pm 0.074$ (1.0%)	$\pm 0.024$ (0.3%)	$\pm 0.017$ (0.2%)
$\sin^2 \theta_{12}$	0.307	$\pm 0.013$ (4.2%)	$\pm 0.0058$ (1.9%)	$\pm 0.0016$ (0.5%)	$\pm 0.0010$ (0.3%)
$\sin^2 \theta_{13}$	0.0218	$\pm 0.0007$ (3.2%)	$\pm 0.010$ (47.9%)	$\pm 0.0026$ (12.1%)	$\pm 0.0016$ (7.3%)

JUNO Coll., 2204.13249



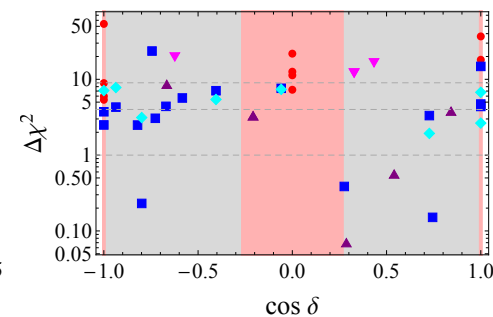
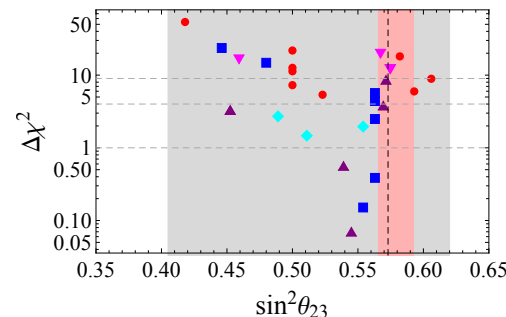
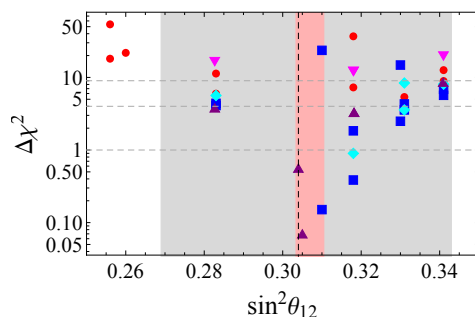
*N. Song et al., 2012.12893*



*See O. Yasuda's talk at Neutrino 2022*

This information is crucial to understand the problem of leptonic mixing.

*See S. King's talk*



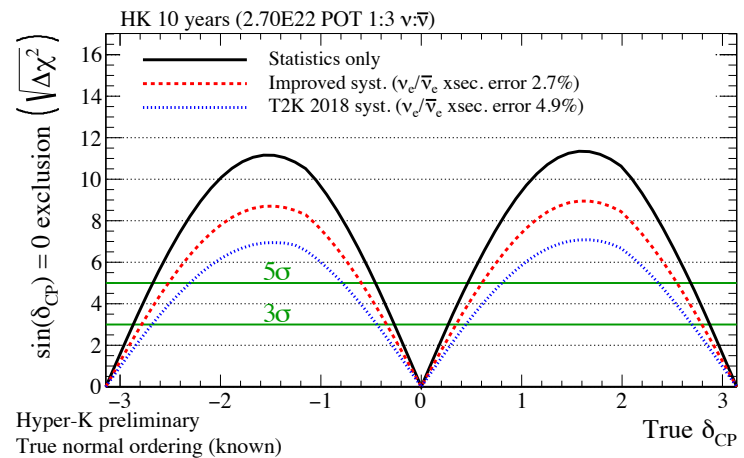
- discrete symmetries w/ CP
- discrete symmetries w/o CP (NO)
- ◆ discrete symmetries w/o CP (IO)
- ▲ modular symmetries (NO)
- ▼ modular symmetries (IO)

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

Do we have sufficient control on the experimental quantities to achieve the precision required to discover CPV and measure the angles/delta with sufficient precision?

- Need to pursue **precise determination** of neutrino fluxes, neutrino cross sections, nuclear effects. Study of neutrino coherent scattering.

*See N. Jachowicz's talk*

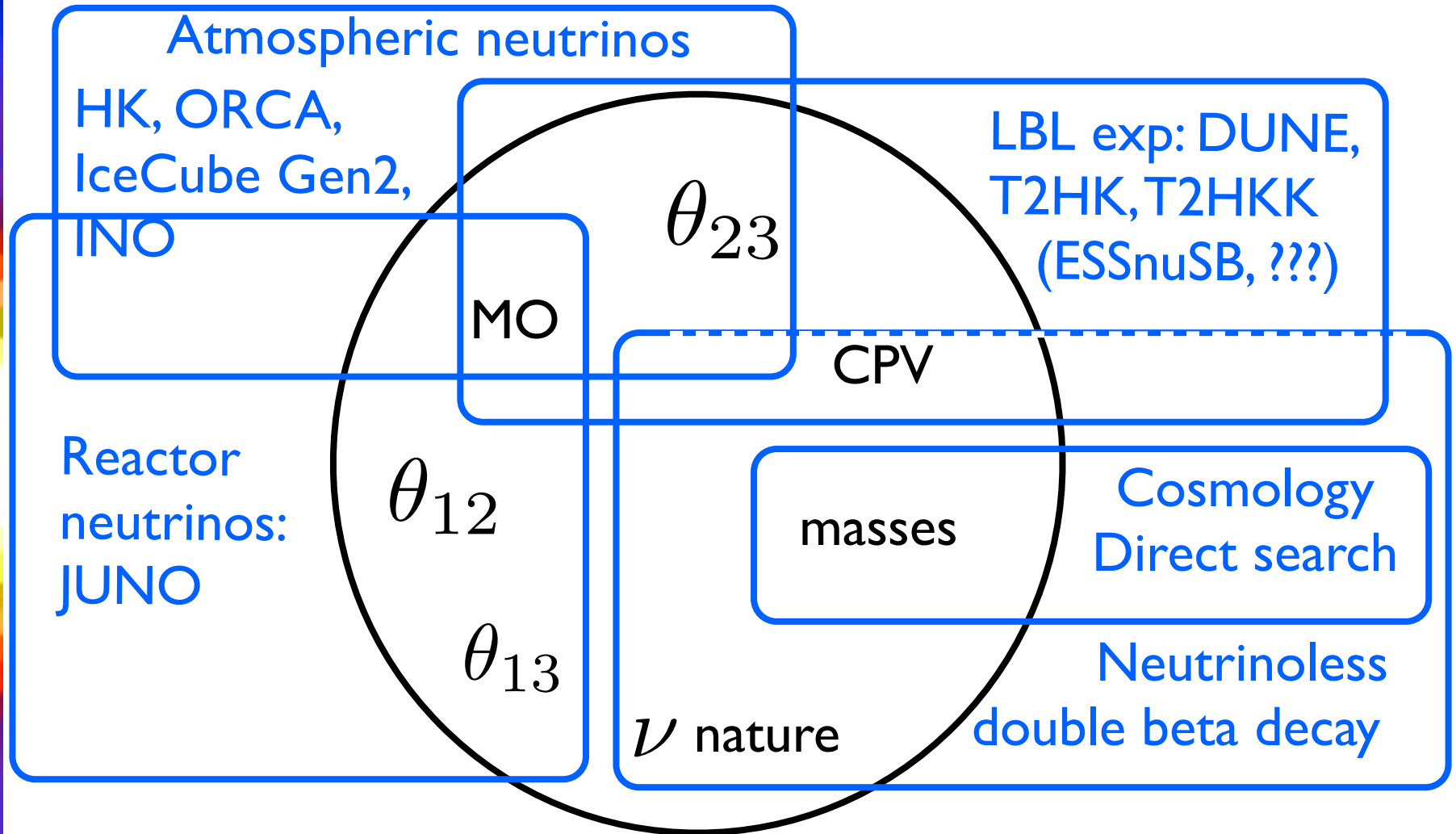


*J. Wilson's talk at Neutrino 2022*

- Should we start thinking about the **following step going beyond 2035?** Upgrades of DUNE/T2K? ESSnuSB? Neutrino factory (possibly in connection with a muon collider effort)?

*See C. Rogers', J. Hartnell's and G. Burton's, K. Dixon's, J. Gao's, M. Malek's, J. Paton's talks*

# Complementarity



Tests of standard neutrino paradigm: SBL oscillations (SBN, reactor exp), LBL/atm oscillations,  $0\nu\text{DBD}$ , beta decays, cosmology (BBN, CMB, LSS), dedicated searches.

## 5. *Is the standard 3-neutrino picture correct?* See J. Evans' talk

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

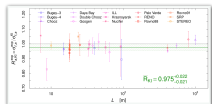
Neutrino 2022: 10 talks with many new results and theory developments

Neutrino 2032: ?????

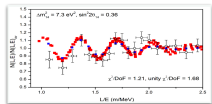
- Non standard interactions, non-unitarity.
- Dark sector connection (with dark photons, FIPs, DM)
- Exotic properties: decays, decoherence, CPT and Lorentz violation...

- **Sterile neutrinos: Current hints** for eV sterile neutrinos (LSND, MiniBooNE, BEST?) have not yet been confirmed or disproven. **SBL oscillation experiments** (SBN, reactor neutrino exp, BEST...) are testing them and will provide a definitive (???) answer by the end of this decade.

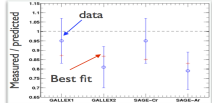
See J. Evans', W. Pei's talks



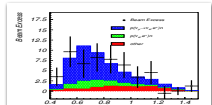
reactor flux anomaly  
resolved with new input data  
to flux calculation



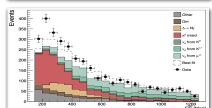
reactor spectra  
is there really an anomaly?



gallium anomaly  
unresolved, recently reinforced

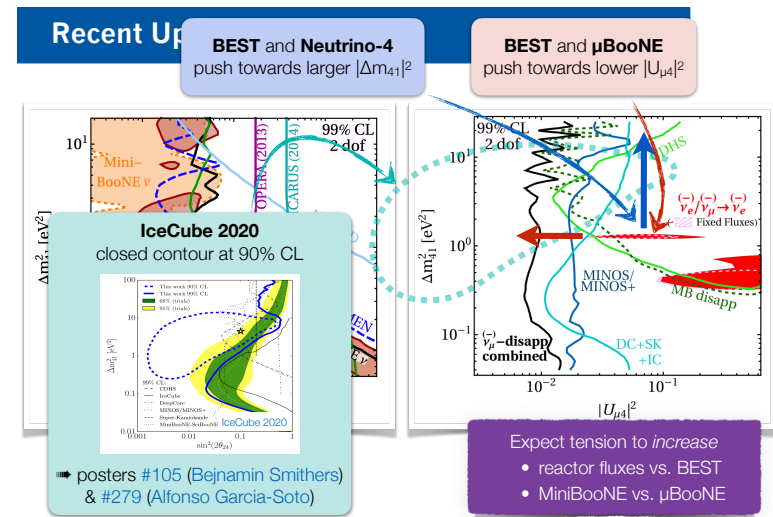


LSND  
unresolved



MiniBooNE  
unresolved

See J. Kopp's  
talk at  
Neutrino 2022



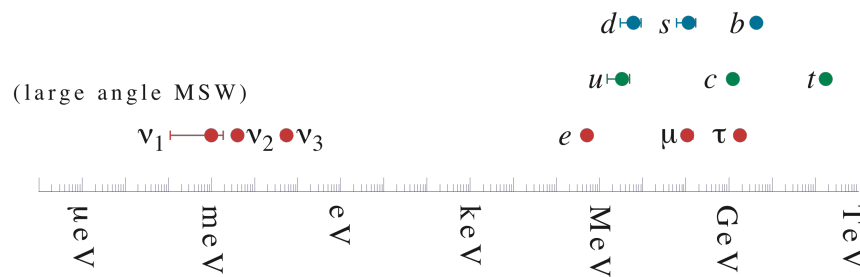
The discovery of any signature beyond 3-neutrinos, would be game-changing for experiments and theory. Need to continue the search even for negative results.

**Question 2:**  
**Where do**  
***neutrino masses***  
***and***  
***leptonic mixing***  
***arise from?***

# 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?

## 2. Problem of flavour

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

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

Why leptonic  
mixing is so  
different from  
quark mixing?

See S. King's, B. Fu's talks

# 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.

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

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

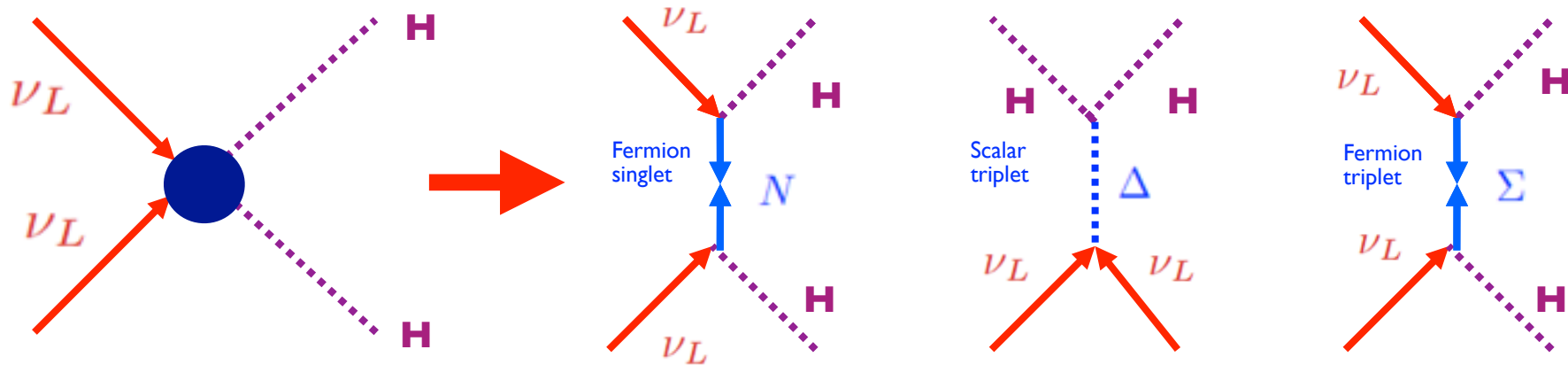
- why the coupling is so small???
  - why the leptonic mixing angles are large?
  - why neutrino masses have at most a mild hierarchy?
  - why no Majorana mass term for RH neutrinos? We need to impose L as a fundamental symmetry.
- $$y_\nu \sim \frac{\sqrt{2}m_\nu}{v_H} \sim \frac{0.2 \text{ eV}}{200 \text{ GeV}} \sim 10^{-12}$$

# 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):

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

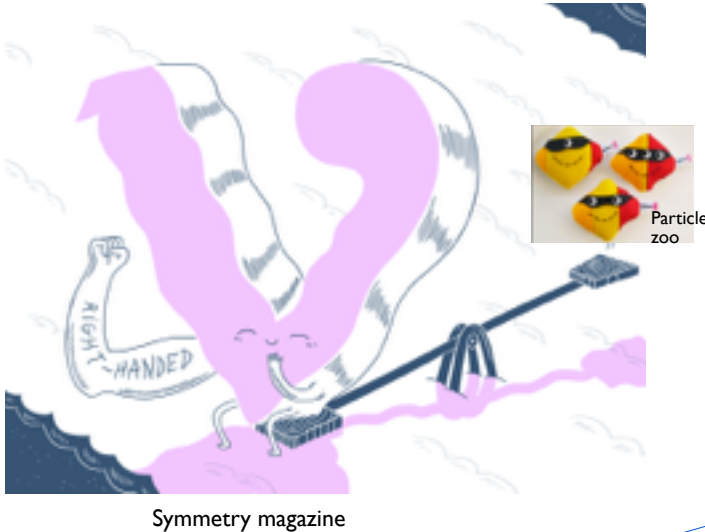
Weinberg operator, PRL 43



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



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

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

$$\begin{pmatrix} 0 & m_D \\ m_D^T & M_N \end{pmatrix} \rightarrow m_\nu = \frac{Y_\nu^2 v_H^2}{M_N} \sim \frac{1 \text{ GeV}^2}{10^{10} \text{ GeV}} \sim 0.1 \text{ eV}$$

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*

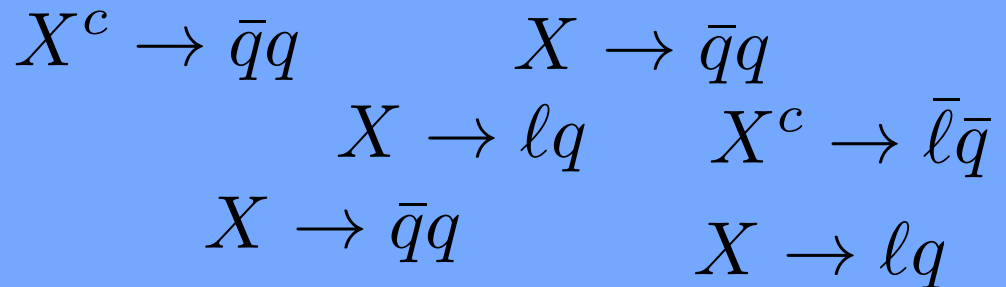
There is evidence of the **baryon asymmetry**:

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

*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;



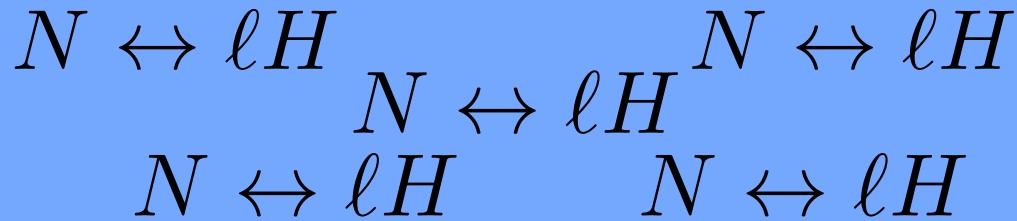
- C, CP violation;

- departure from thermal equilibrium.

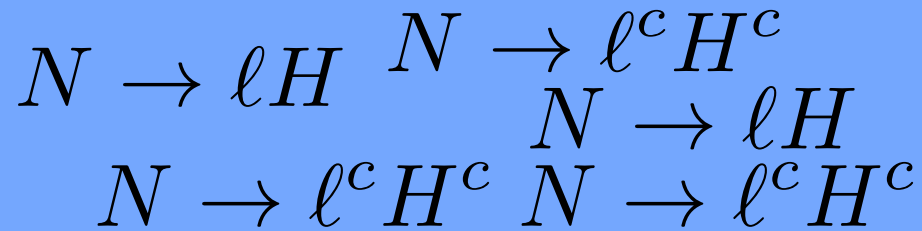
The Standard Model cannot generate the necessary amount of baryon asymmetry: BSM physics, e.g. electroweak baryogenesis and leptogenesis.

# Leptogenesis

- At  $T > M$ ,  
N are in  
equilibrium:



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



- A lepton asymmetry can be generated if

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

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

$T = 100$   
GeV

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.

*Question 2a: What is the  
new physics scale?*

*Question 2b: Are there new:  
symmetries?  
particles?  
interactions?*

## ***New physics scale? Going to high energy***

keV

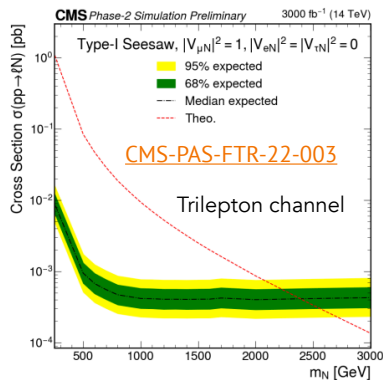
GeV

## 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...*

See *B. Fu's talk*

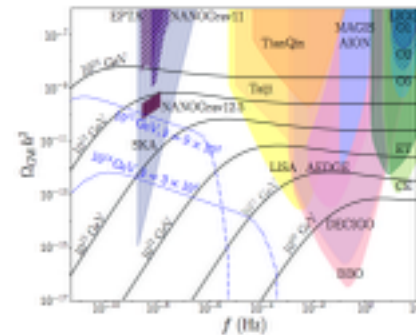


## LHC searches

## J. Xiao's talk at Neutrino2022

# Leptogenesis

CLFV

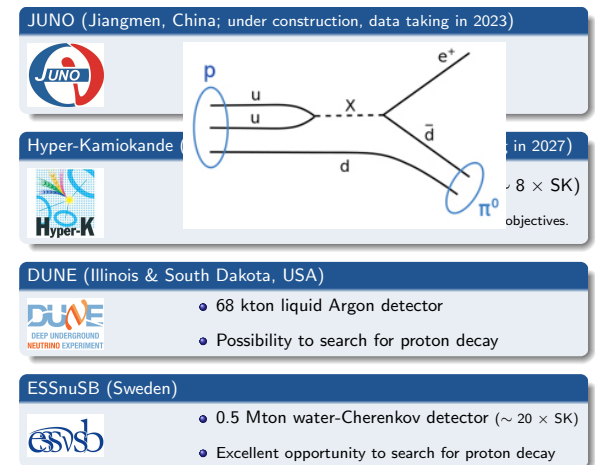
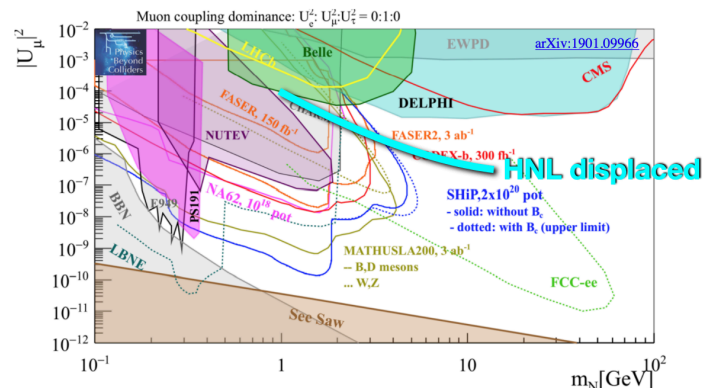


GW

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

## Proton decay

T. Ohlsson's  
talk at  
Neutrino2022



# Going low in energy: Dark sectors

eV

keV

MeV

GeV

TeV

Intermediate scale

GUT scale

Sterile nu

Leptogenesis

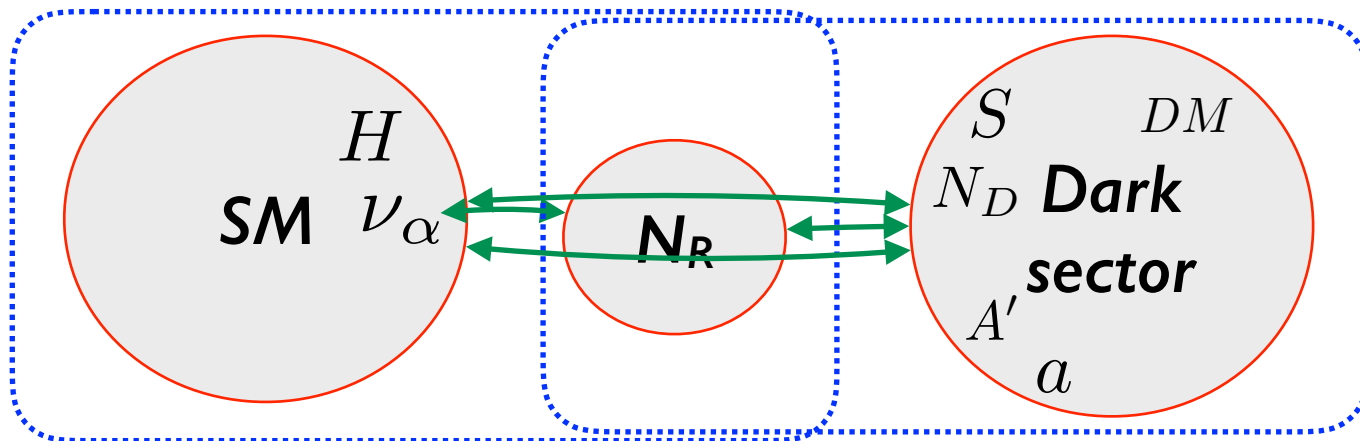
Light thermal and non-thermal DM

HNL

dark photons

dark scalars

Dark sectors can account for neutrino masses, the baryon asymmetry, dark matter.



They can be classified via the connection to SM: **neutrino**, **scalar**, **vector portals**. **Rich DS** have multiple portals.

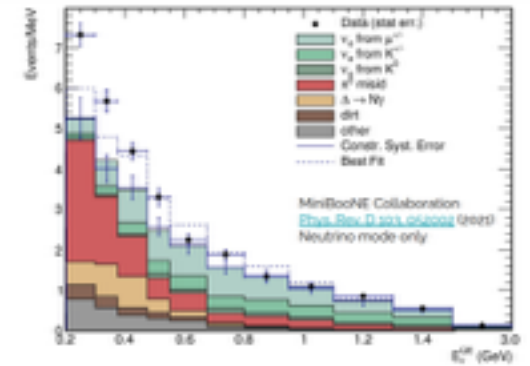
# Are there hints of darks sectors????

The longstanding MiniBooNE LEE is being tested at SBN. Explanations due to SM photons seem disfavoured.

## Electrons? Or Photons?

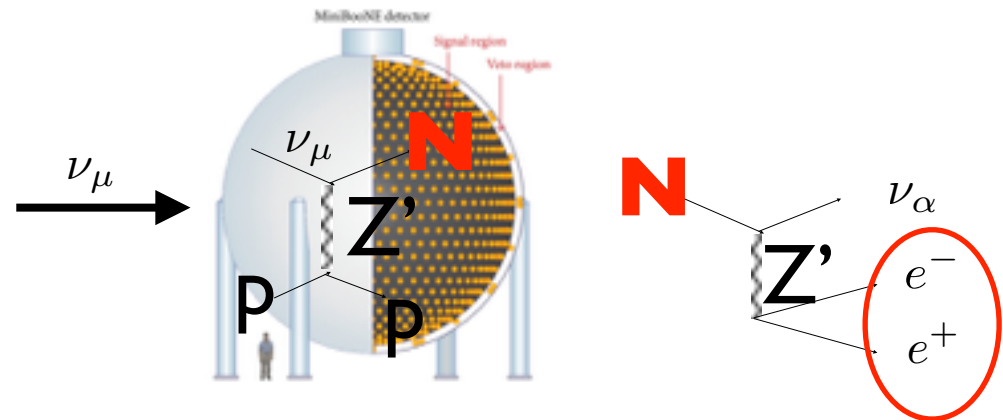
Several sources of photons in MiniBooNE backgrounds:

- $NC \pi^0 \rightarrow \pi^0 \gamma$  (Neutral Current  $\pi^0$  radiative decay) **MEASURED IN-SITU**
- **BEAM TIMING** DIRT (events from outside)
- $NC \Delta \rightarrow N \gamma$  (Neutral Current  $\Delta$  radiative decay)



M. Ross-Lonergan's talk at Fermilab, 04/10/2021  
MicroBooNE Coll., 2110.00409

A viable explanation is provided by the **up-scattering of HNL** in the detector and **its decay into  $ee$   $N_s$** .



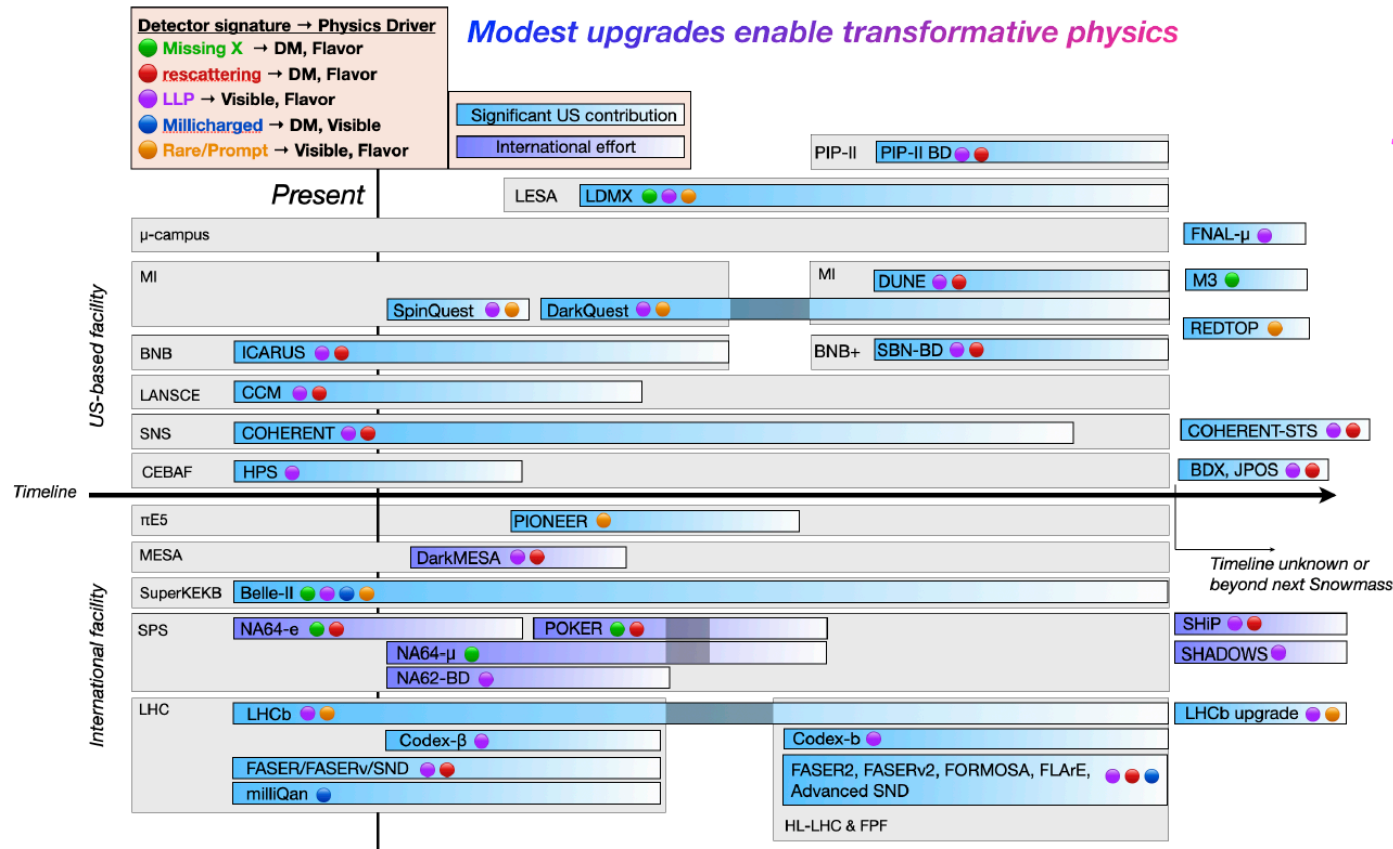
P. Ballett, S. Pascoli, M. Ross-Lonergan, PRD 99 (2019)

These same models can also explain the value of muon  $g-2$ , via a dark photon with large kinetic mixing.

A. Abdullahi, M. Hostert, SP, 2007.11813

# What can expect in the coming years?

“Unexpectedly” wide experimental programme is ongoing and planned. Hints could pile up, maybe discoveries.



See S. Gori's talk  
at FIPs 2022

Ilten, Tran et al,  
2206.04220

See K. J.  
Plows', Z.  
Zhang's, J.  
Franklin's  
talks

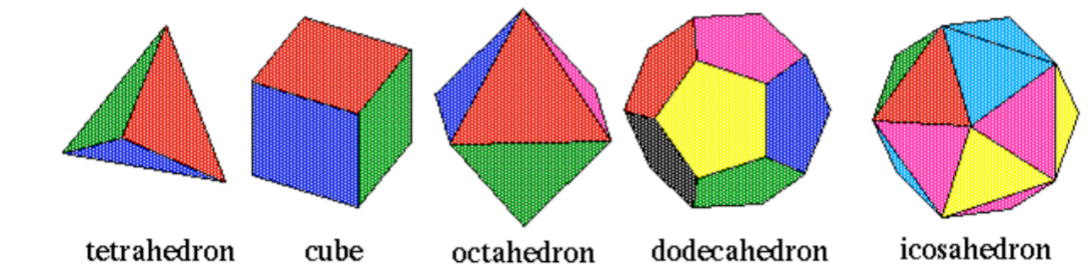
A discovery would be a major departure from “traditional” BSM and open a very exciting experimental landscape.

# The problem of leptonic flavour

$$\begin{array}{ccc}
 \boxed{M_M = (U^\dagger)^T m_{\text{diag}} U^\dagger} & \Rightarrow & \boxed{n_L = U^\dagger \nu_L} \\
 \text{Theory} & & \text{Experiments} \\
 \mathcal{L}_{CC} = \frac{g}{\sqrt{2}} (\bar{e}_L, \bar{\mu}_L, \bar{\tau}_L) \gamma^\mu U_{\text{osc}} \begin{pmatrix} \nu_{1L} \\ \nu_{2L} \\ \nu_{3L} \end{pmatrix} W_\mu & & \text{with } U_{\text{osc}} = V_L^\dagger U_\nu
 \end{array}$$

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

The five Platonic solids



# Conclusions

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

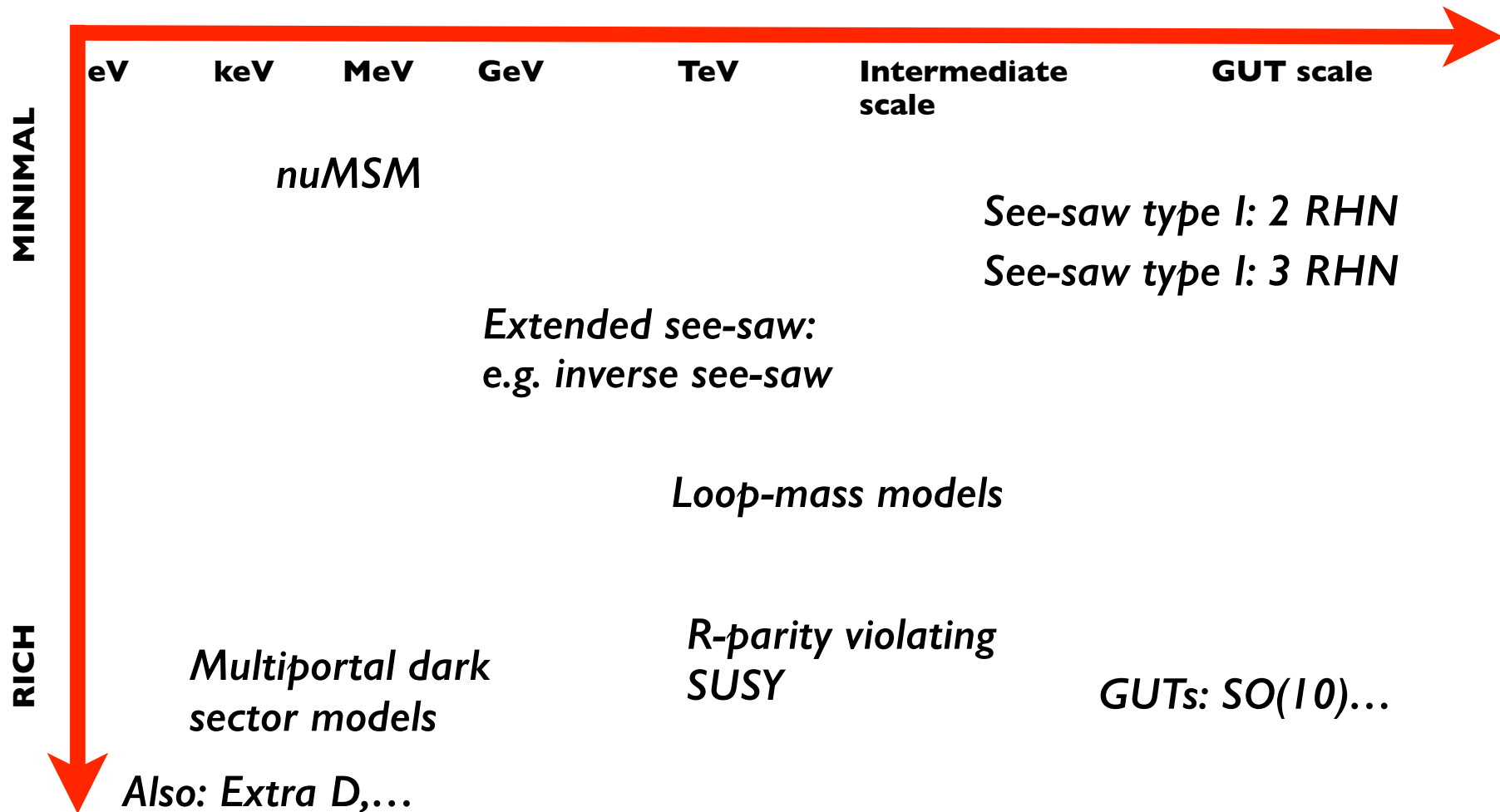
**Current status:** precise knowledge of most of neutrino properties. Key questions open (nature, CPV, MO) due to be answered in the next ~decade. Thriving experimental programme.

**Surprises in store?** Several SBL anomalies 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?**

**See D.Wark's talk.**

# From minimality to richness



Two contrasting approaches can be taken:

Minimality: the fewest ingredients -> predictivity

Richness (theory-motivated): connections, new signatures

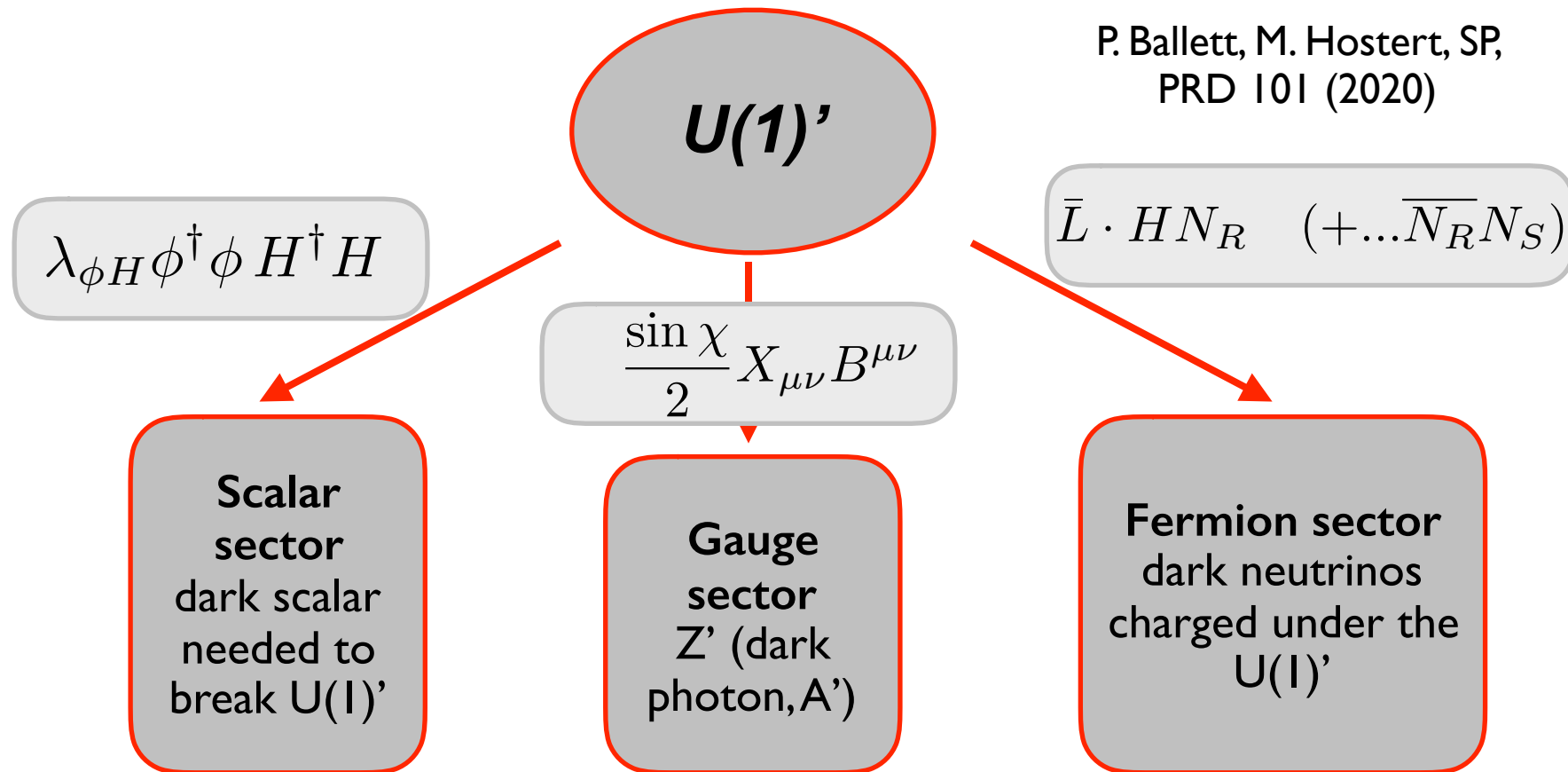
*What is the new physics  
scale? Is it low???*

*An application of  
rich dark sectors*

# A dark sector scenario

We extend the gauge sector via **new  $U(1)'$** .

P. Ballett, M. Hostert, SP,  
PRD 101 (2020)



The phenomenology of this type of models can be very different from the standard case.

## A specific 3-portal model

The Lagrangian is given by

$$\begin{aligned} \mathcal{L} \supset \mathcal{L}_{\text{SM}} &- \frac{1}{4} X_{\mu\nu} X^{\mu\nu} - \frac{\sin \chi}{2} X_{\mu\nu} B^{\mu\nu} \\ &+ (D_\mu \Phi)^\dagger (D^\mu \Phi) - V(\Phi) - \lambda_{\Phi H} |H|^2 |\Phi|^2 \\ &+ \overline{\widehat{\nu}}_N i \not{D} \widehat{\nu}_N + \overline{\widehat{\nu}}_D i \not{D}_X \widehat{\nu}_D - \left[ (\overline{L} \widetilde{H}) Y \widehat{\nu}_N^c + \overline{\widehat{\nu}}_N Y_L \widehat{\nu}_{D_L}^c \Phi \right. \\ &\left. + \overline{\widehat{\nu}}_N Y_R \widehat{\nu}_{D_R} \Phi^* + \frac{1}{2} \overline{\widehat{\nu}}_N M_N \widehat{\nu}_N^c + \overline{\widehat{\nu}}_{D_L} M_X \widehat{\nu}_{D_R} + \text{h.c.} \right] \end{aligned}$$

A. Abdullahi, M. Hostert, SP, 2007.11813

The model is **anomaly free** thanks to the inclusion of two dark neutrinos with opposite charges. Other possibilities can also be considered (DM).

We focus on a scale of GeV:  $v_\phi, m_{Z'} \sim \text{GeV}.$

# New particles

**Z'/A'**

: mass  $m_{Z'} = 1.25$  GeV.

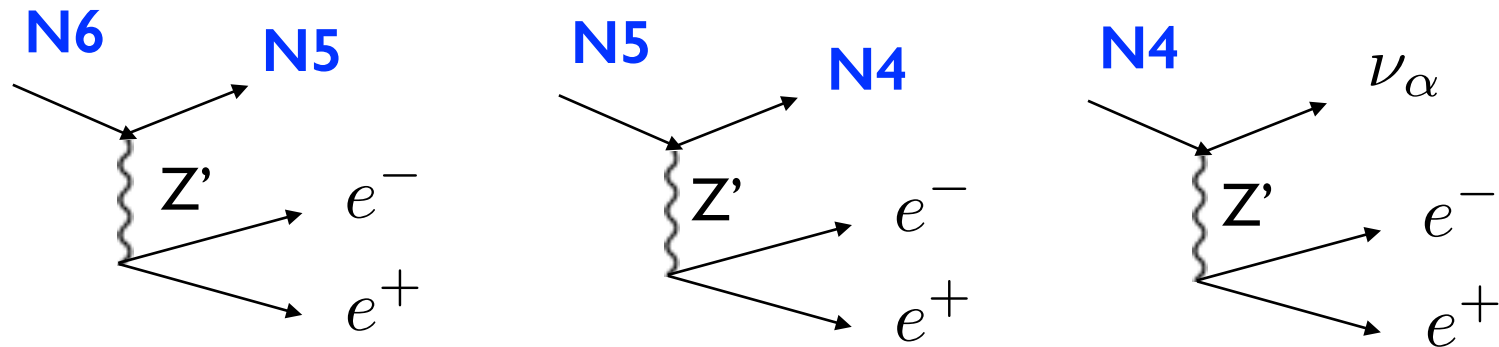
Z' decays predominantly into heavy neutrinos.

$\mathcal{B}(Z' \rightarrow N_i N_j)/\%$					
44	45	46	55	56	66
0.15	11	0.48	1.6	86	0.59

**N6, N5, N4**

: with 100s MeV masses.

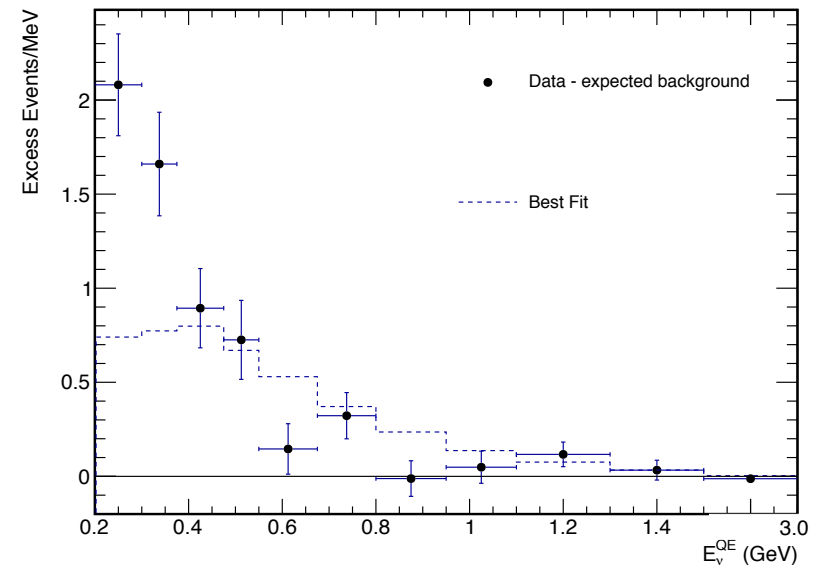
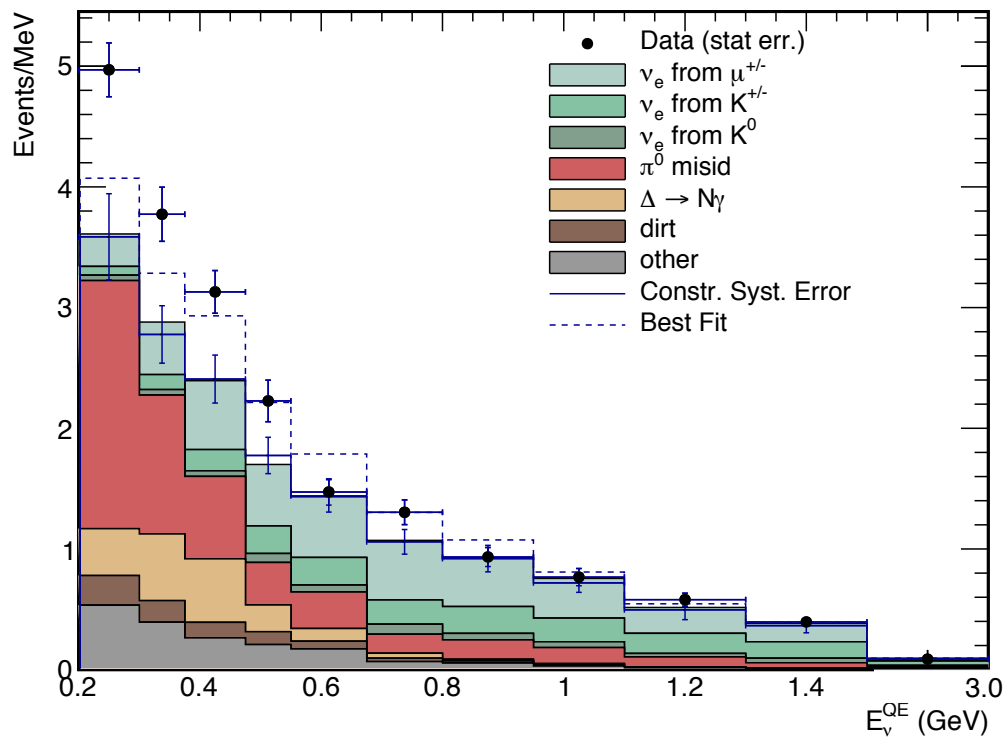
They decay via the new Z' into ee and neutrinos.



The decays are much faster than in the SM.

# The MiniBooNE low-E excess

MiniBooNE reports a low-E excess which has increased in significance in the past couple of years ( $\sim 3\sigma \rightarrow 4.7\sigma \rightarrow 4.8\sigma$ ).

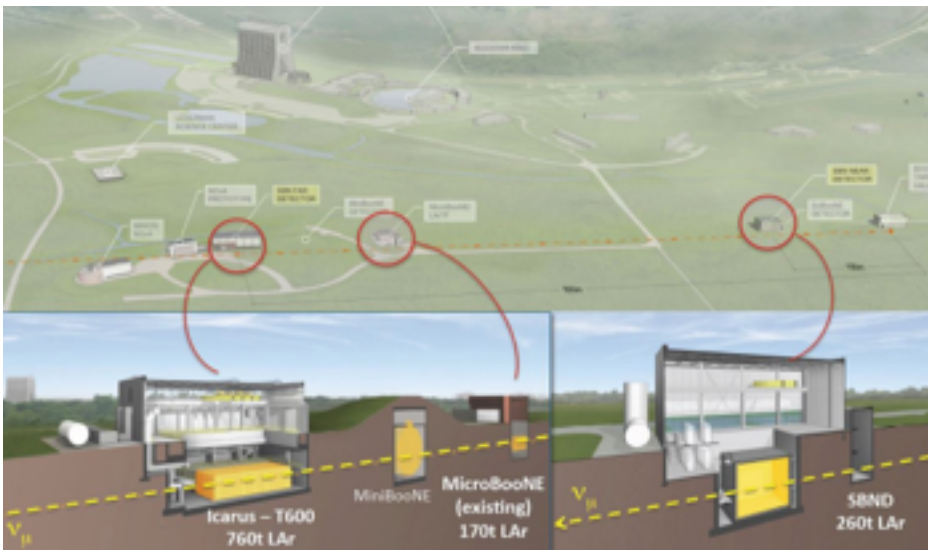


MiniBooNE Coll., PRL 121 (2018)

# MicroBooNE and SBN at Fermilab

They use accelerator neutrinos with  $L \sim 100-600\text{m}$  and  $E \sim 700-800\text{ MeV}$ .

<https://www.bo.infn.it/gruppo2/sbn-it/>



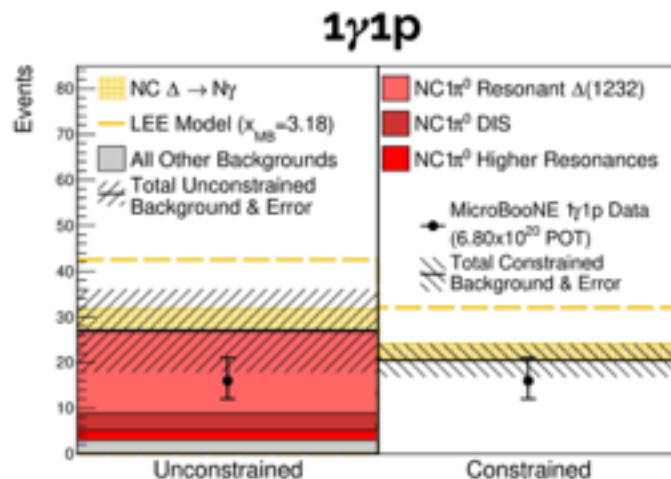
MicroBooNE detector



Accelerator neutrino experiments should provide the definitive answer and can check both the appearance and disappearance channels.

# First results from MicroBooNE.

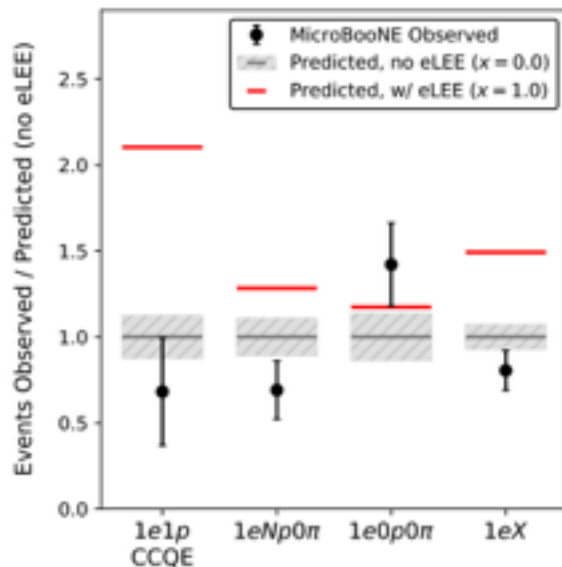
- Is the MiniBooNE LEE is due to SM photons?



*My take:  
Most likely not.*

MicroBooNE Coll., 2110.00409

- Is the MiniBooNE LEE is due to electrons?



Electrons would come from  $\nu_e$  scattering, and would signal neutrino oscillations.

*My take: Most likely not.*

# BSM explanations for MB LEE

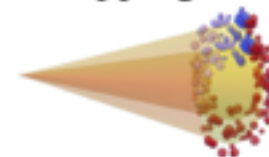
Due to the WC nature of MB, single electrons can be mimicked by photons and by electron-positron pairs (if overlapping or asymmetric).

Electrons? Or Photons? .....Or Neither?

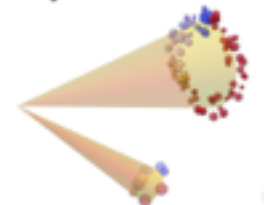
**Rich phenomenology** developing in recent years around the possibility of the MiniBooNE excess being due to  $e^+e^-$  pairs from decays of new exotic particles.

- Decays of **new dark gauge bosons** ( $Z'$ )
  - E. Bertuzzo, S. Jana, P. A.N. Machado, R.Zukanovich Funchal [Phys.Rev.Lett. 121 24, 241801\(2018\)](#)
  - P. Ballett, S. Pascoli, M. RL [Phys. Rev. D 99, 071701 \(2019\)](#)
  - A. Abdollahi, M. Hostert, S. Pascoli [Phys.Lett.B 820 136531\(2021\)](#)
- General **Extended higgs sectors + Decay**
  - B. Dutta, S. Ghosh, T. Li Phys. [Rev. D 102, 055017 \(2020\)](#)
  - W. Abdallah, R. Gandhi, S. Roy [Phys. Rev. D 104, 055028 \(2021\)](#)
- Decays of **leptophilic axion-like** particles
  - C. V. Chang, C. Chen, S. Ho, S. Tseng [Phys. Rev. D 104, 015030 \(2021\)](#)

Overlapping  $e^+e^-$

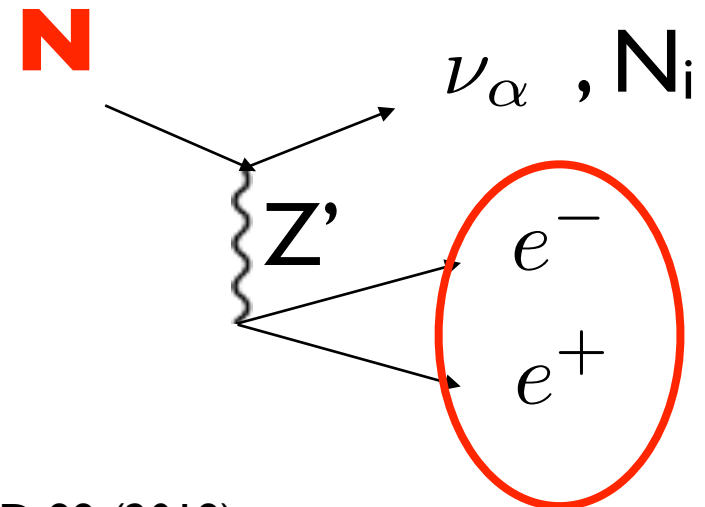
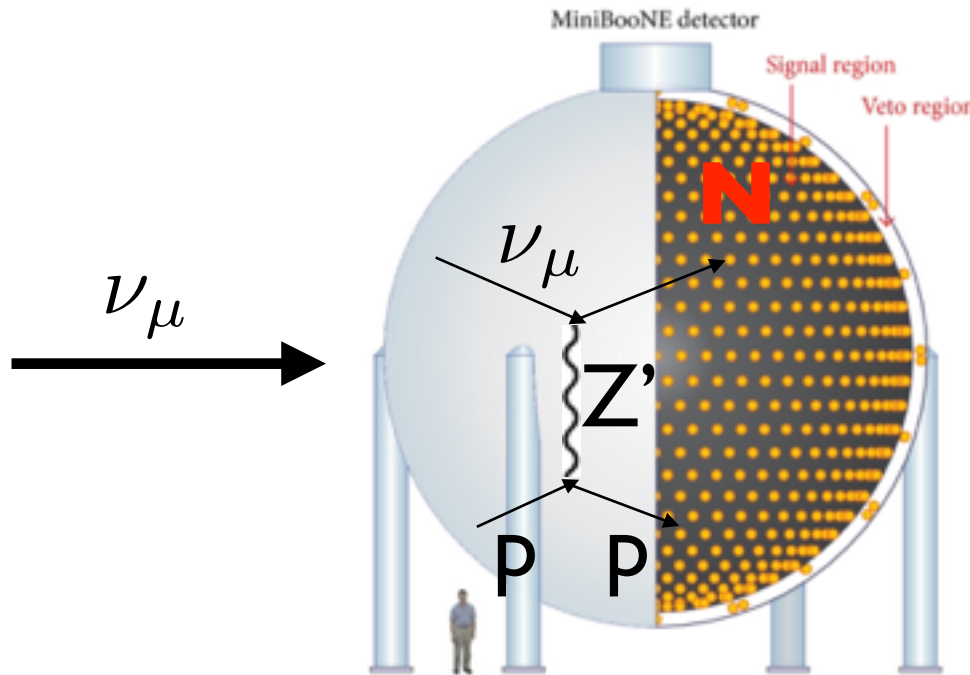


Highly Asymmetric  $e^+e^-$

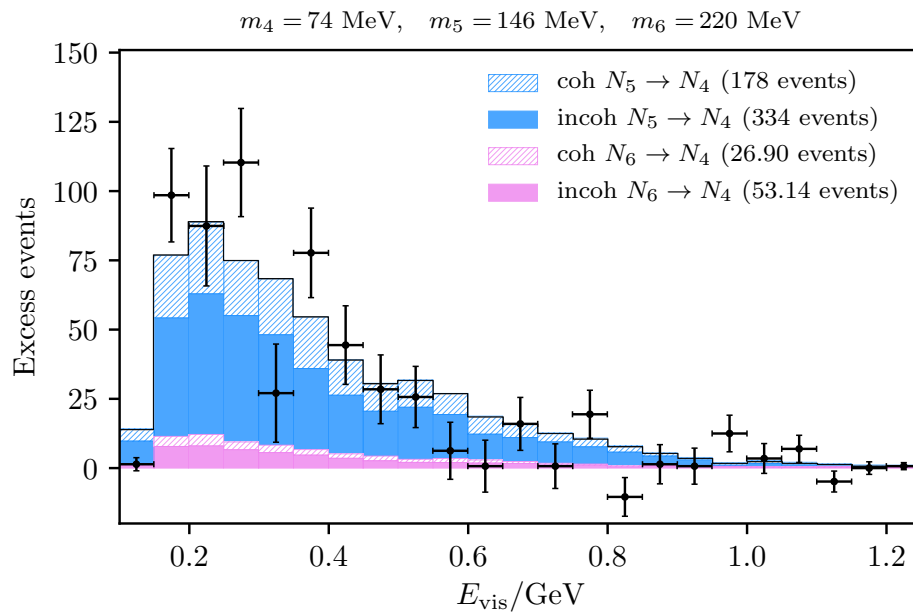


A viable explanation of the MiniBooNE low-E excess is provided by the **up-scattering of an HNL  $N$**  in the detector and **its decay into  $ee \nu$** .

It builds on a decay explanation of MiniBooNE by S. Gninenko, PRL 103 (2009). A similar analysis appeared at the same time but with light  $Z'$  by E. Bertuzzo et al., PRL 121 (2018).

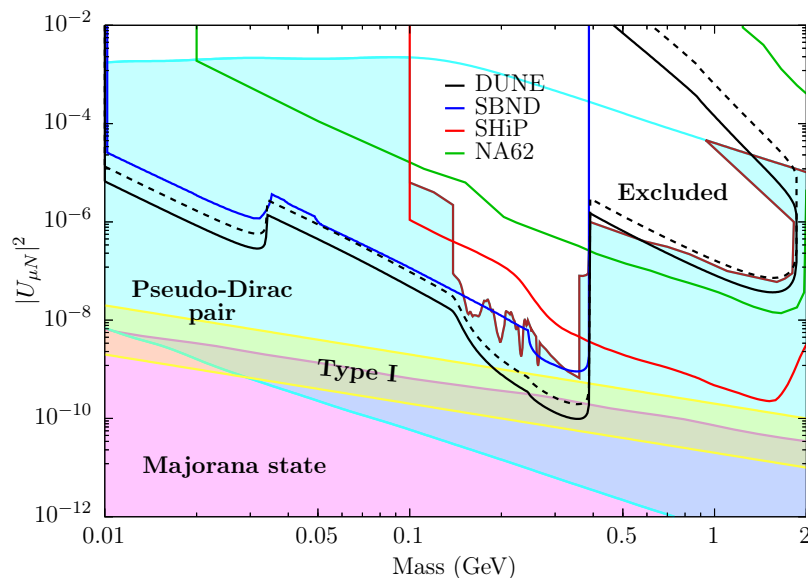


P. Ballett, S. Pascoli, M. Ross-Lonergan, PRD 99 (2019)



The  $N_5$ ,  $N_6$  produced in up scatterings of beam neutrinos decay in ee and missing energy mimicking the signal.

A. Abdullahi, M. Hostert, SP, 2007.11813



Bounds change if additional interactions are allowed, (HNL can decay invisibly or semivisibly).

Potentially, strong bounds from ND280 in T2K.

Ballett, Boschi, SP, 1905.00284

See V. Brdar et al., 2007.14411, C. Argüelles et al., 2205.12273

# A host of other signatures

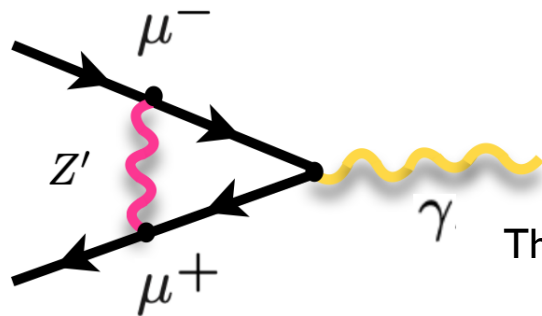
There is a longstanding discrepancy between the measured value of  $a_\mu$  and the theoretical prediction, at 4.2 sigma.

See Keshavarzi, Marciano, Passera, Sirlin.

$$\Delta a_\mu \equiv a_\mu^{exp} - a_\mu^{th} = (274 \pm 73) \times 10^{-11}$$

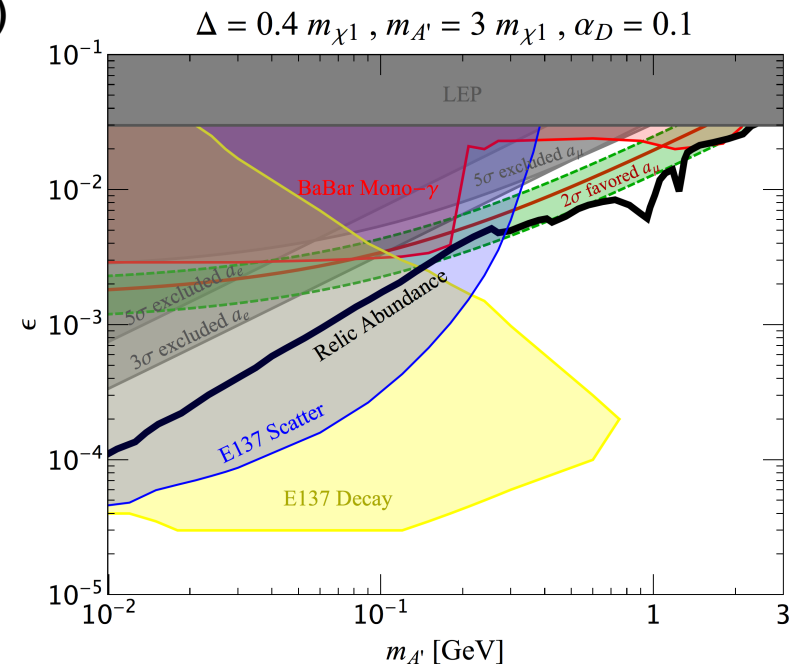
Kinetic mixing and light  $Z'$  can explain the anomaly,...

P. Fayet, PRD75 (2007), M. Pospelov, PRD80 (2009)



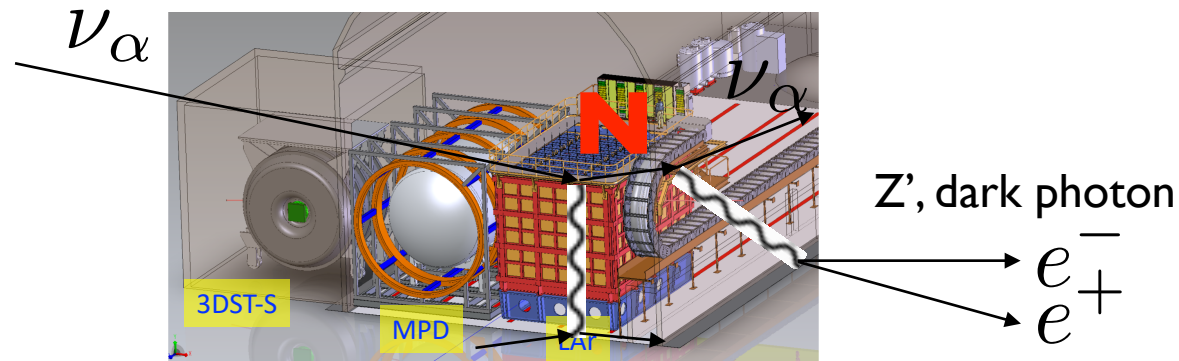
Thanks to A. Abdullahi

as far as  $Z'$  decays mainly semi-visibly ( $Z' \rightarrow N N$  and  $N$  decay fast).



# Unique signatures and future tests

The model has key signatures which can be tested.



One can expect **displaced vertices**, decay chains and unique HNL and dark photon phenomenology (typically, semivisible decays):

- MicroBooNE, T2K ND, DUNE-ND;
- NA62&SHADOWS;
- Nu@LHC programme;
- NA64;
- BelleII and BESIII.

Some possible scenarios by 2035.

- DUNE discovers IO. No signal in  $0\nu$  DBD.

Simplest conclusion: Dirac neutrinos. Check low scale see-saw. Other possible strongly fine-tuned models.

- DUNE discovers IO or KATRIN measures neutrino masses. No signal in cosmology.

Modify cosmological model or advocate non-standard neutrino properties (decays, ...). In both cases, non trivial.

- Neutrino oscillation exp show some tension.

Non standard neutrino properties? New matter effects?

- Establish NO and mbb precisely known. Compatible cosmological measurement of neutrino masses.

Test the light Majorana neutrino explanation of  $0\nu$ DBD.