Neutrinos: a window on the physics BSM

13 November 2019

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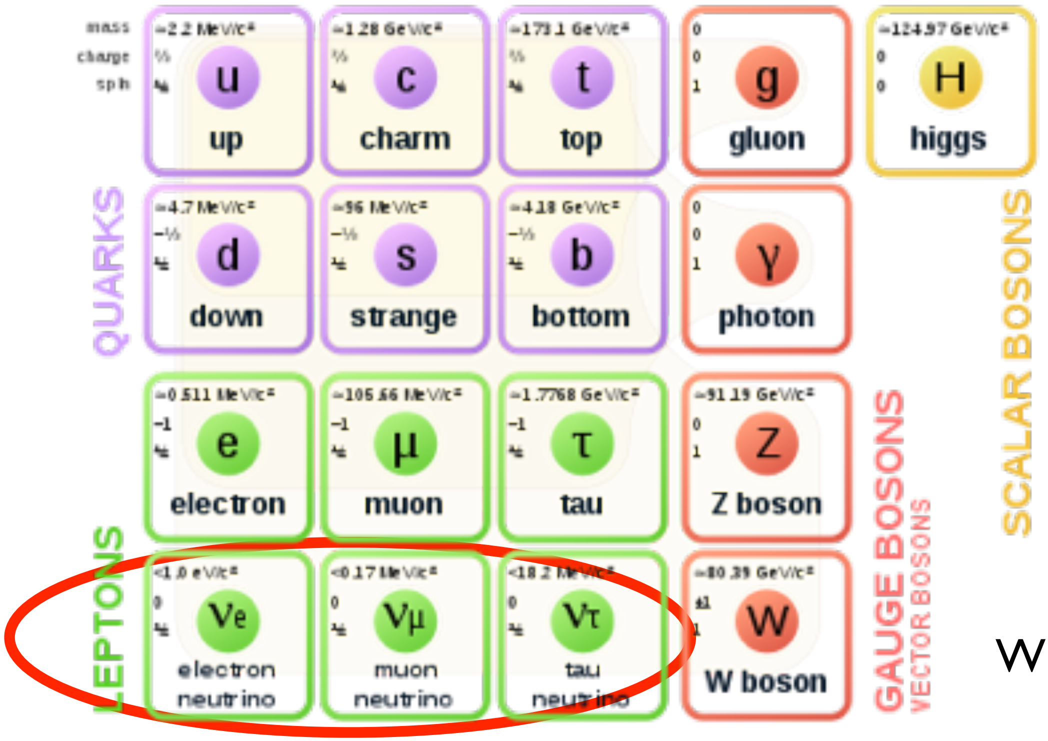
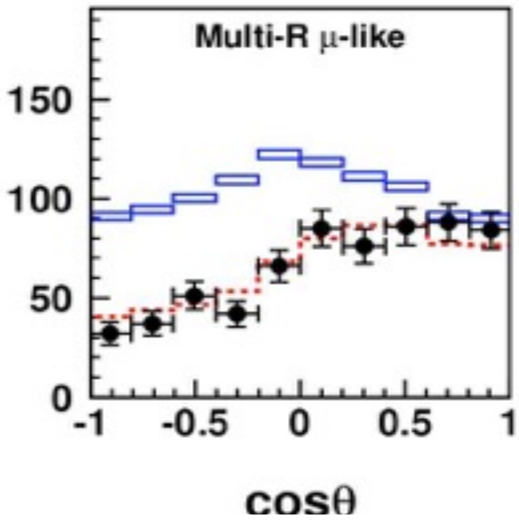
Neutrinos in the Standard model of particle physics

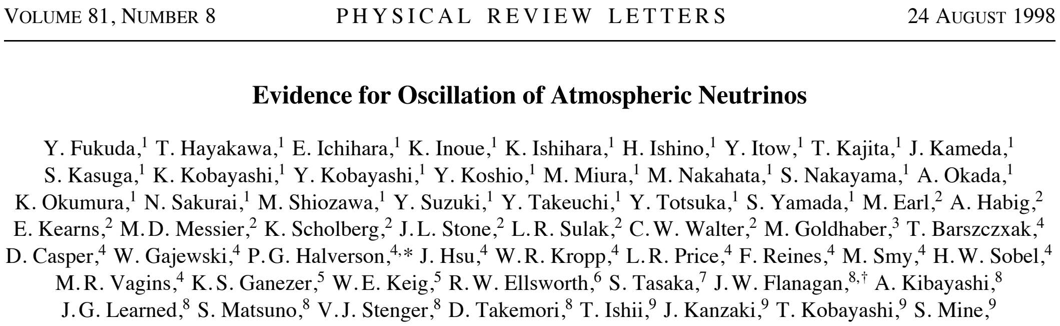


Wikipedia

The Standard Model describes the particles which exist in Nature (fermions and bosons) and explains their interactions. Neutrinos are the most elusive of the SM particles.

The discovery of neutrino oscillations




VOLUME 81, NUMBER 8 PHYSICAL REVIEW LETTERS 24 AUGUST 1998

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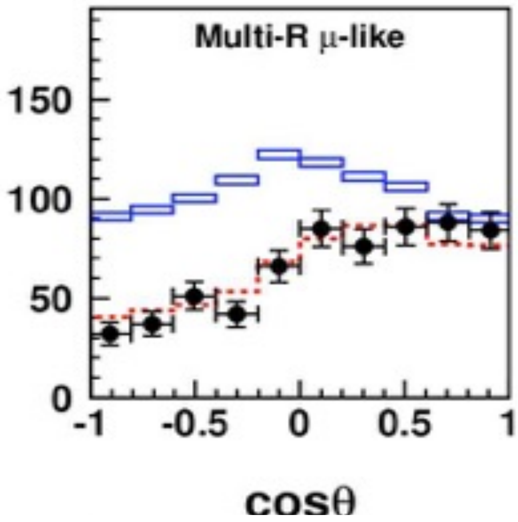
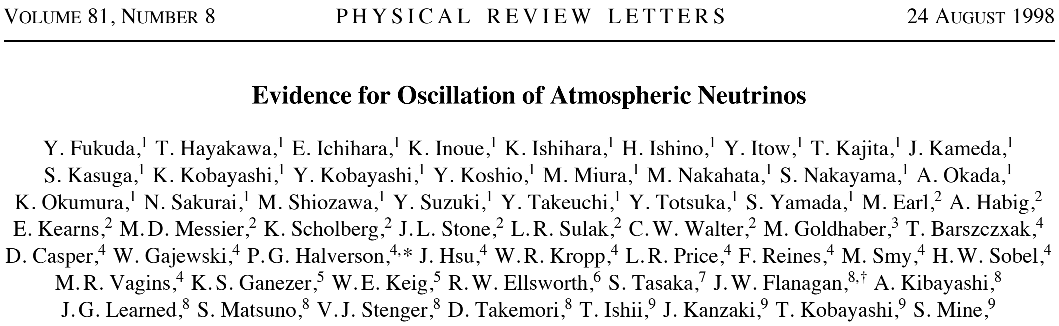
- Atmospheric neutrinos 1998: Super-Kamiokande
- Solar neutrinos: In 2002, SNO
- Reactor neutrinos: KamLAND observed the disappearance of electron anti-neutrinos.

The discovery of neutrino oscillations

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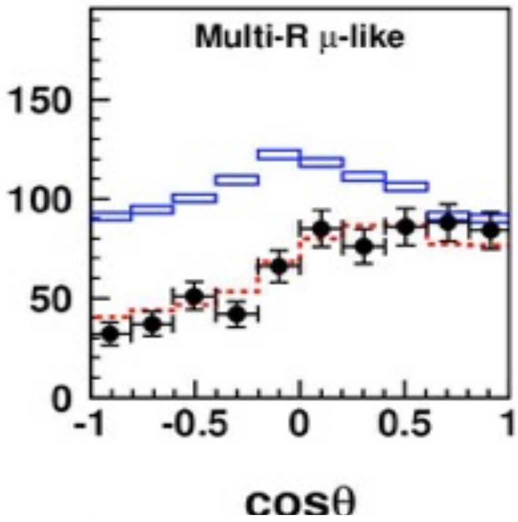
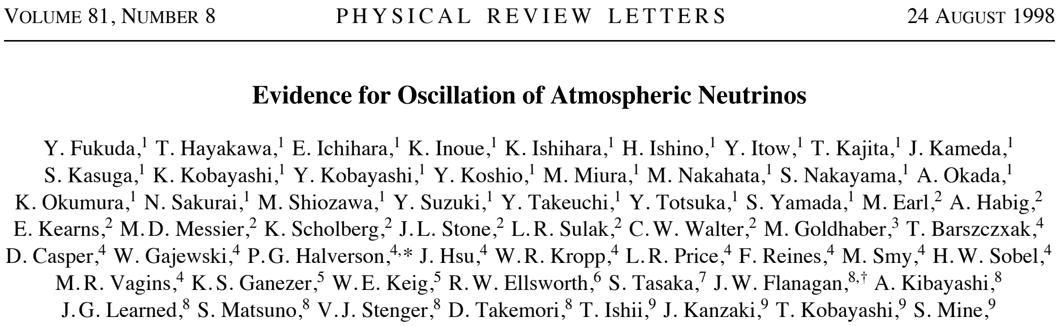
The SNO Detector


T. Kajita *A. McDonald*

Nobel Prize in Physics 2015
"for the discovery of neutrino oscillations, which shows that neutrinos have mass"

The discovery of neutrino oscillations

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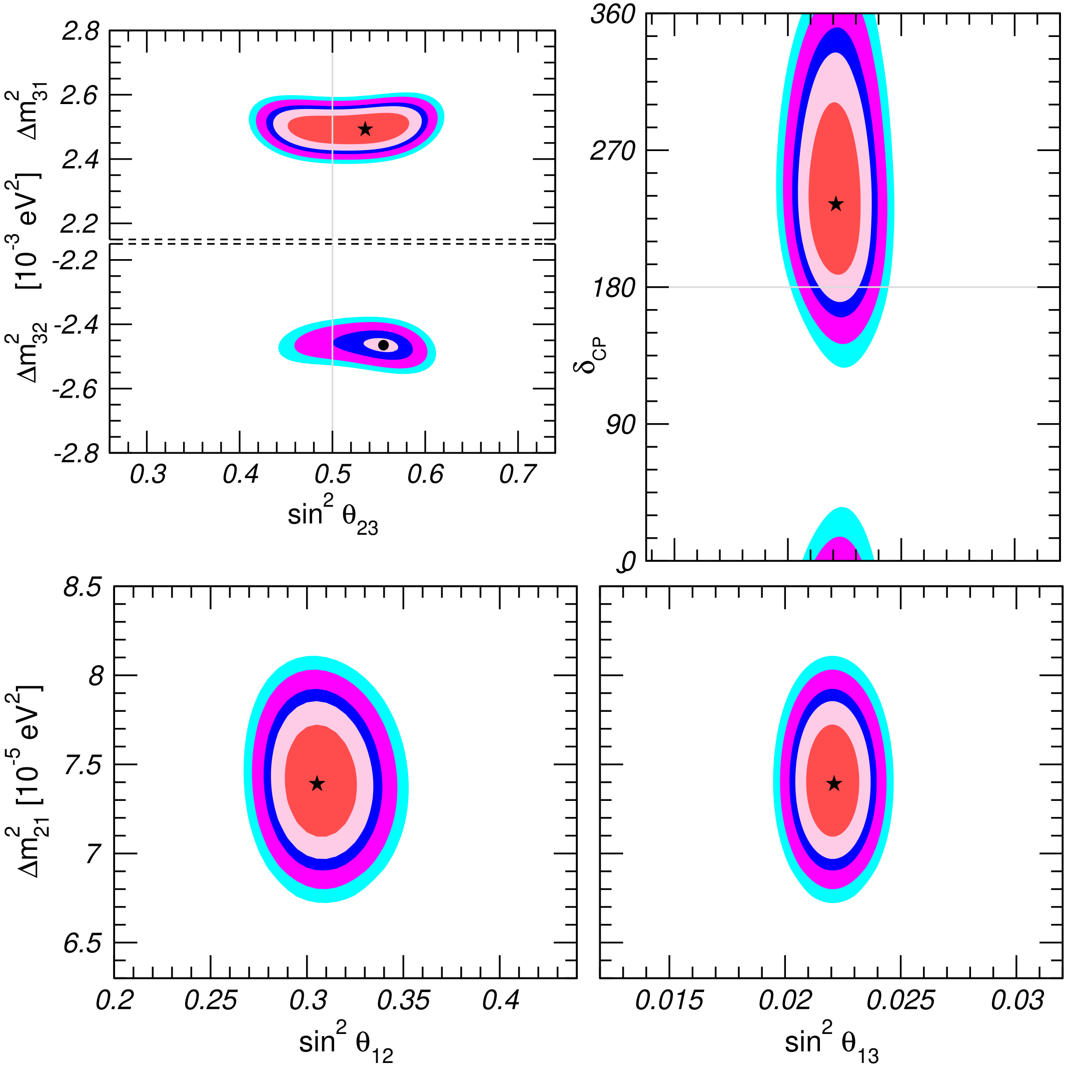
The SNO Detector


T. Kajita

Advert:
NuPhys 2019
Cavendish
Conference
Centre, London
Dec 16-18 2019

Neutrino properties after Neutrino 2018

NuFIT 4.0 (2018)



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

M. C. Gonzalez-Garcia et al., 1811.05487

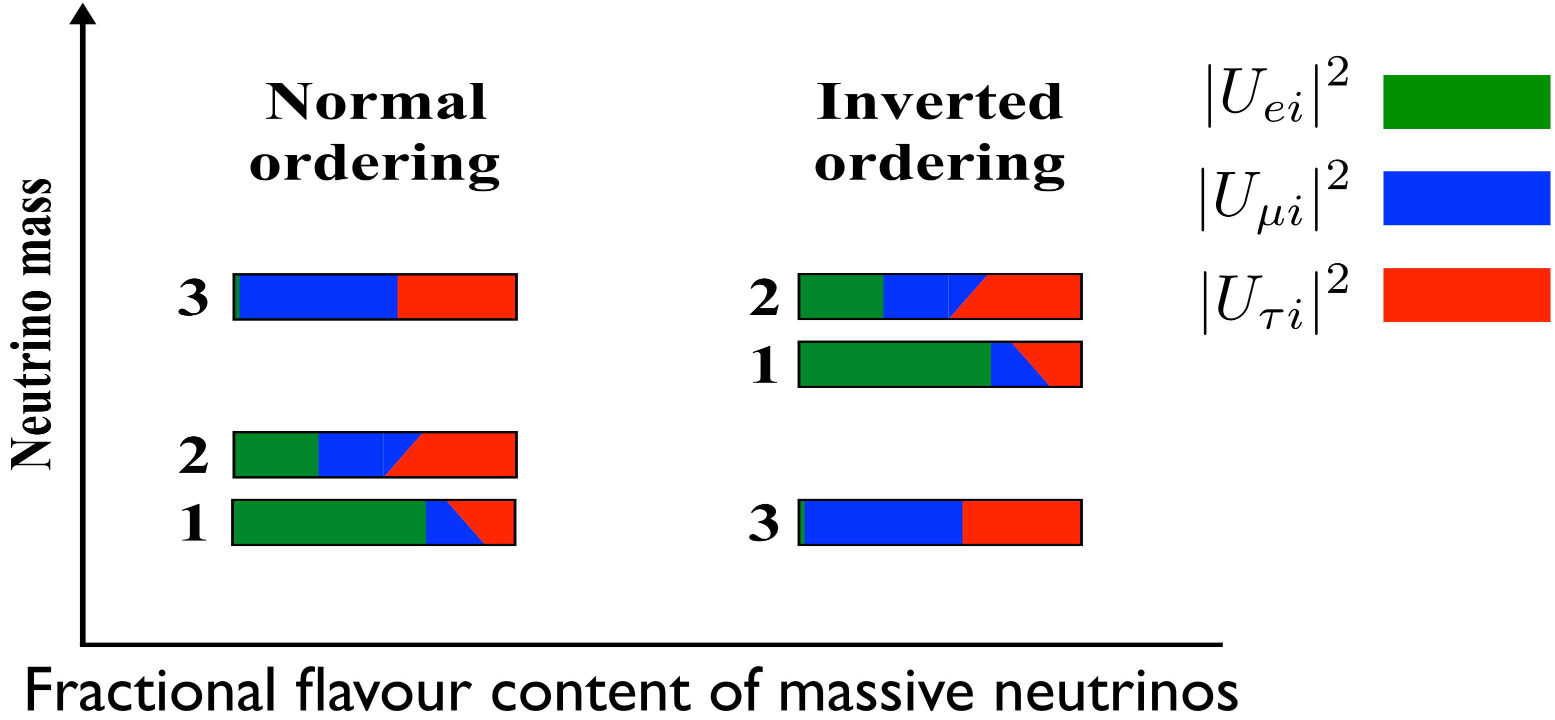
Neutrinos have masses and mix!

Current knowledge of neutrino properties:

- 2 mass squared differences
- 3 sizable mixing angles,
- some hints of CPV
- indications in favour of NO

Neutrino masses

$\Delta m^2_{\rm s} \ll \Delta m^2_{\rm A}$ implies at least 3 massive neutrinos.



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

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

Measuring the masses requires:

- the mass scale: $m_{\rm min}$
- the mass ordering. Some preference for NO ($\Delta\chi^2 \sim 4$).

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?

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

Phenomenology questions for the future

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? Other effects?

Very exciting experimental programme now and for the future.

Neutrino nature

Neutrinos can be **Majorana or Dirac particles**. In the SM only neutrinos can be Majorana as they are neutral.

Majorana condition $\nu = C\bar{\nu}^T$

The **nature** of neutrinos is linked to the conservation of **Lepton number (L)**.

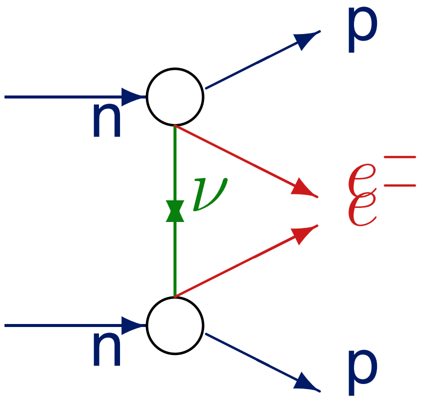
- This is crucial information to unveil the **Physics BSM: with or without L-conservation**? Lepton number violation is a necessary condition for **Leptogenesis**.

- Tests of LNV:

 - At low energy, neutrinoless double beta decay,
 - LNV tau and meson decays, collider searches.

Neutrinoless double beta decay

Neutrinoless double beta decay, (A, Z) → (A, Z+2) + 2e, will test the nature of neutrinos.



The half-life time depends on neutrino properties

$$\left[T_{0\nu}^{1/2}(0^+ \to 0^+)\right]^{-1} \propto |M_F - g_A^2 M_{GT}|^2 \, |<m>|^2$$

- The effective Majorana mass parameter:

$$\boxed{|<m>| \equiv |\, m_1|U_{e1}|^2 + m_2|U_{e2}|^2 e^{i\alpha_{21}} + m_3|U_{e3}|^2 e^{i\alpha_{31}} \,|\,,}$$

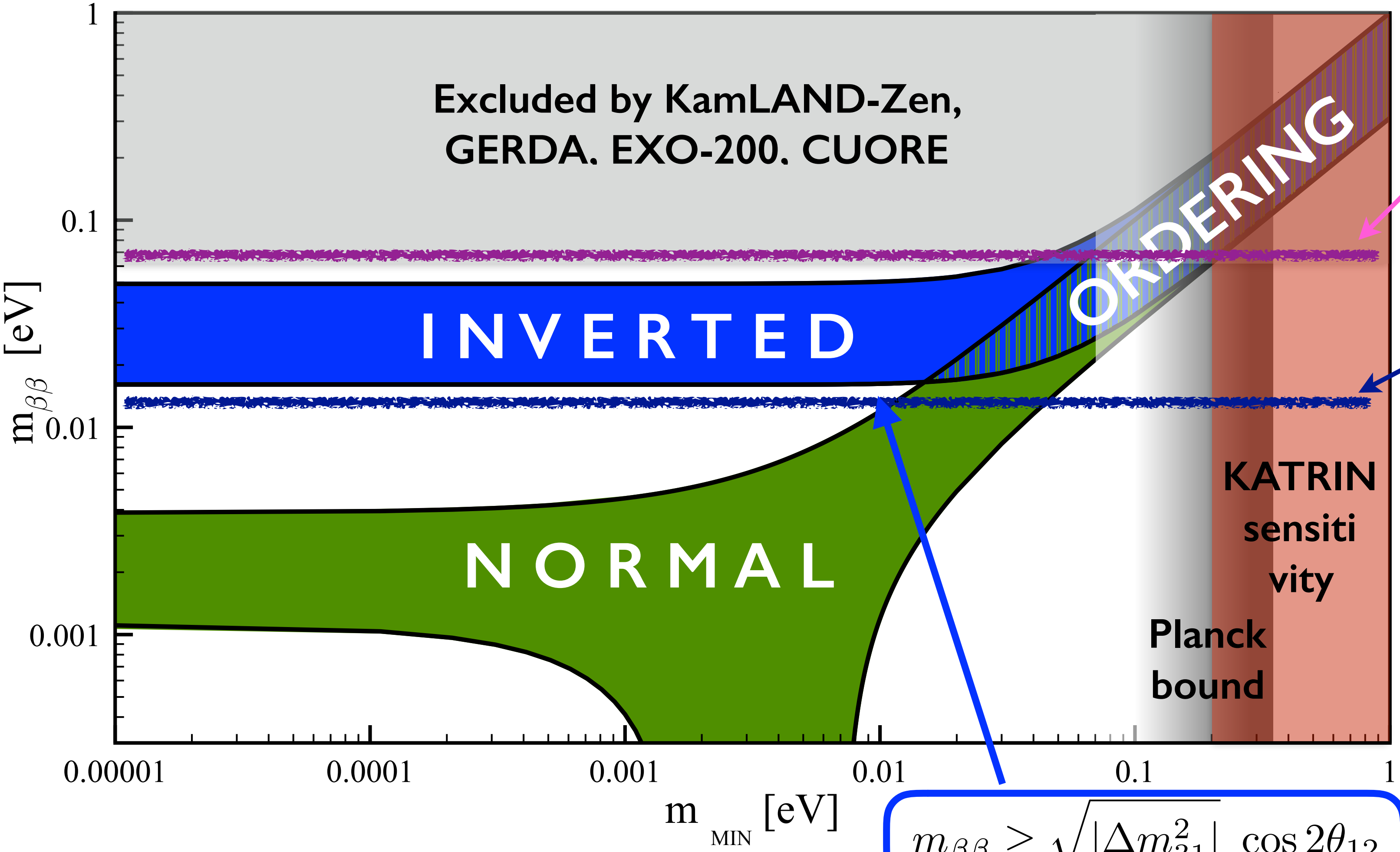
Mixing angles (known)

CPV phases (unknown)

- $|M_F - g_A^2 M_{GT}|^2$ the nuclear matrix elements

Predictions for betabeta decay

The predictions for m_{bb} depend on the neutrino masses:



Present bounds:
GERDA-II, CUORE,
KamLAND-Zen

Goals of Next
generation exp:
LEGEND-1K, CUPID,
NEXT-HD, nEXO,
SNO+, PANDAX,
DARWIN…

R&D for future exp

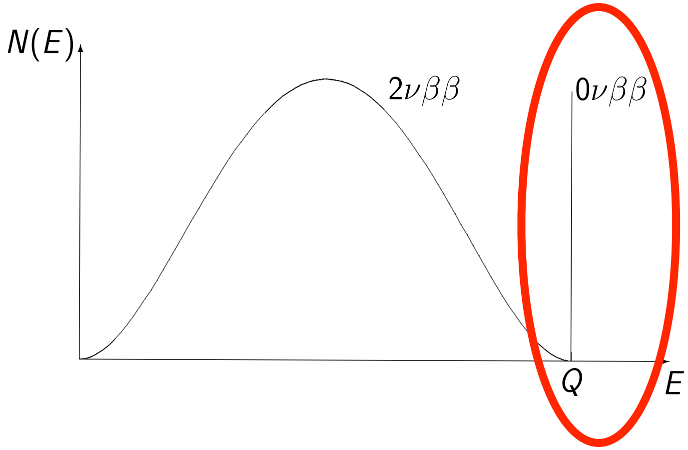
$$\boxed{m_{\beta\beta} \geq \sqrt{|\Delta m^2_{31}|}\ \cos 2\theta_{12}}$$

Wide experimental program which is ongoing. The next generation is well into planning and R&D for future.

A positive signal would indicate L violation!

Experimental searches of betabeta decay

Neutrinoless double beta decay can be tested in nuclei in which single beta decay is kinematically forbidden (^{76}Ge, ^{100}Mo, ^{130}Te, ^{136}Xe…).



Very rare process which requires
- very low backgrounds (<1 cts / (yrs ton ROI));
- excellent energy resolution (<1% at Q_{bb});
- large active isotope mass (ton-scale).

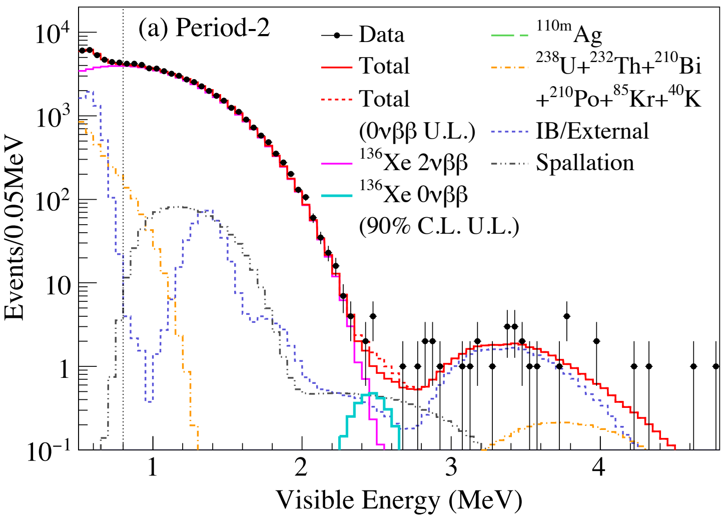
KamLAND-Zen Loaded LSc with 380 kg ^{136}Xe, $T_{1/2} > 1.07\text{x}10^{26}$ yrs (90% C.L.), $m_{bb} <$ 61-165 meV

EXO-200 ~75 kg LXe TPC, $T_{1/2} > 3.7\text{x}10^{25}$ yrs

GERDA 31 kg (enriched) ^{76}Ge, $T_{1/2} > 0.9\text{x}10^{26}$ yrs

MAJORANA 26.0 kg yrs, $T_{1/2} > 0.27\text{x}10^{26}$ yrs

CUORE ^{130}Te, ~206 kg, $T_{1/2} > 1.5\text{x}10^{25}$ yrs



KamLAND-Zen, PRL 117 (2016)

Scalability	**Fluid embedded source**	Xe-based TPC	EXO-200 NEXT-10	NEXT-100 PandaX-III	nEXO NEXT-HD PandaX-III 1t
		Liquid scintillator as a matrix	KamLAND-Zen 800 SNO+ phase I		KamLAND2-Zen SNO+ phase II
High ΔE and ε	**Crystal embedded source**	Germanium diodes	GERDA-II MJD	LEGEND 200	LEGEND 1000
		Bolometers	AMoRE pilot, I CUORE CUPID-0, CUPID-Mo	AMoRE II	CUPID

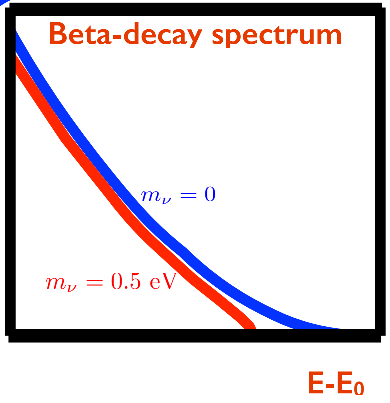
A. Giuliani, Neutrino 2018

The ultimate goal of next generation is m_{bb}~15-20 meV.

Measuring neutrino masses

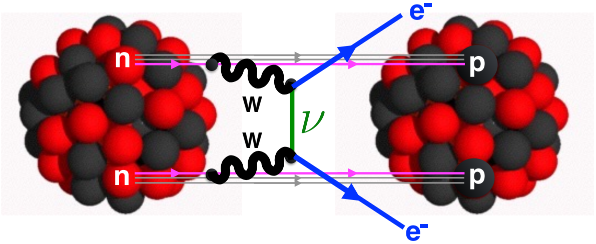
- Mass ordering via neutrino oscillation in matter (NOvA, DUNE, atmospheric neutrinos) or in vacuum (JUNO). Discovery expected within 10 years.

- Absolute mass scale.



Beta decay

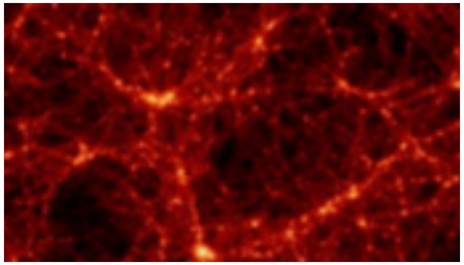
$$m_\beta \equiv \sqrt{\sum_i U_{ei}^2 m_i}$$



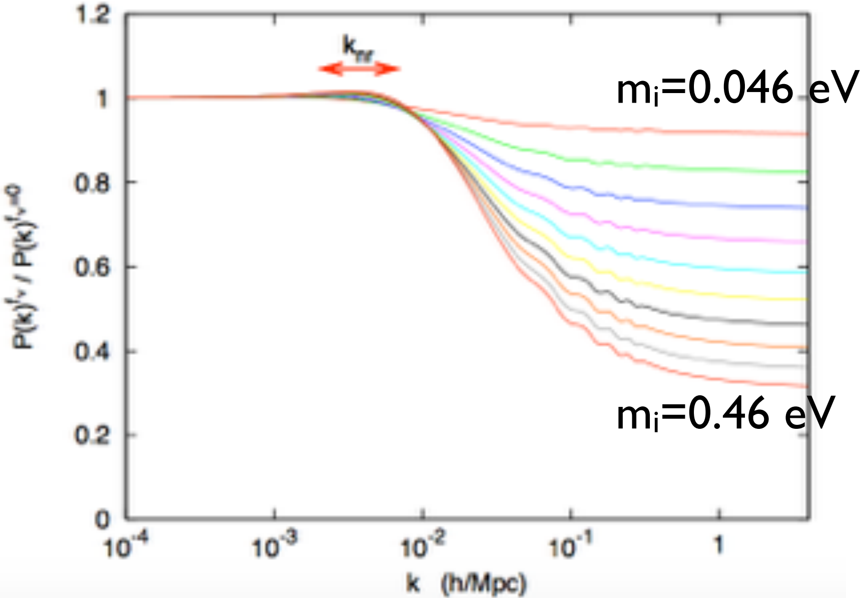
Neutrinoless dbeta decay

$$m_{\beta\beta} = f(m_i, \alpha_{21}, \alpha_{31}, \delta)$$

Cosmology

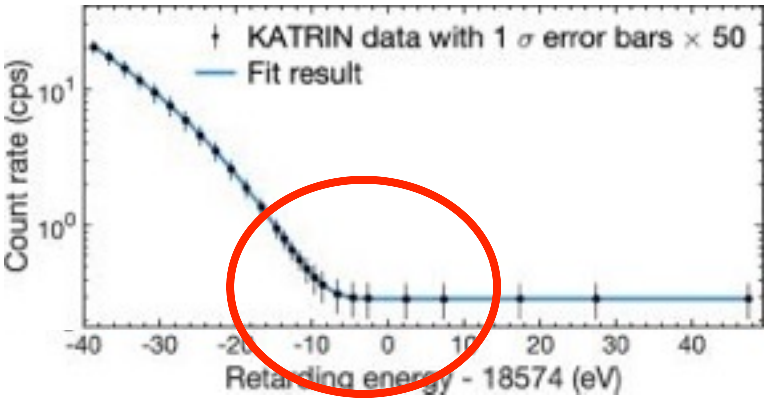


$$\sum_i m_i$$

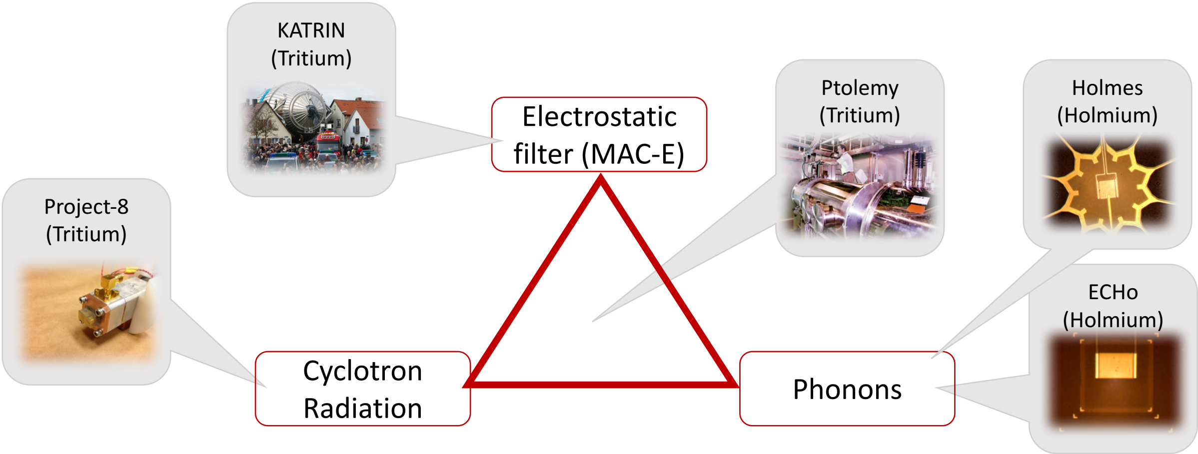


J. Lesgourgues and S. Pastor, Phys. Rep. 429

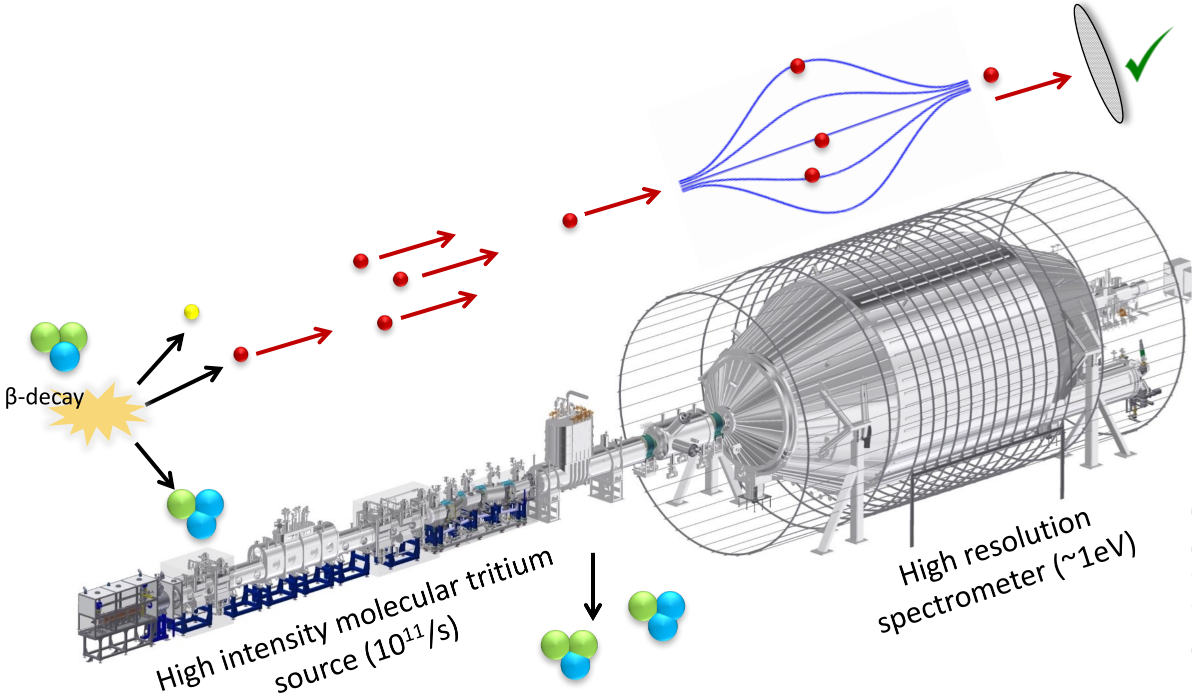
Direct mass searches



KATRIN coll., KIT press release



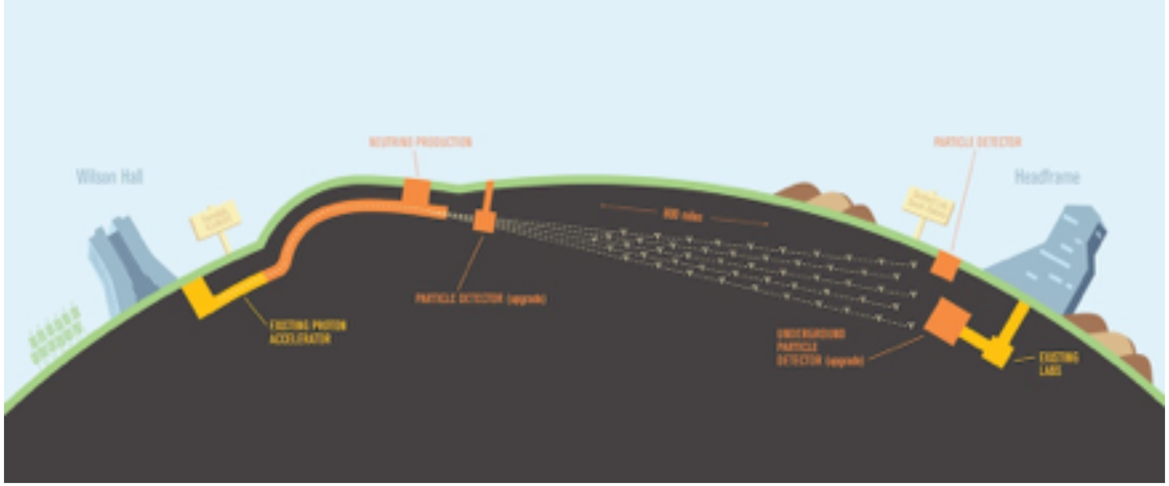
S. Mertens, Granada Open Symposium ESPP



KATRIN has released the first data in Sep 2019: $m_b < 1$ eV. The ultimate sensitivity is to $m_b < 0.2$ eV.

Long-baseline oscillations, MO and CPV

- In LBL experiments, accelerator neutrinos travel for 100s-1000s km before being detected. Experiment aim at detecting the subdominant $P(\nu_\mu \to \nu_e) \equiv P_{\mu e}$.



Credit: Symmetry magazine

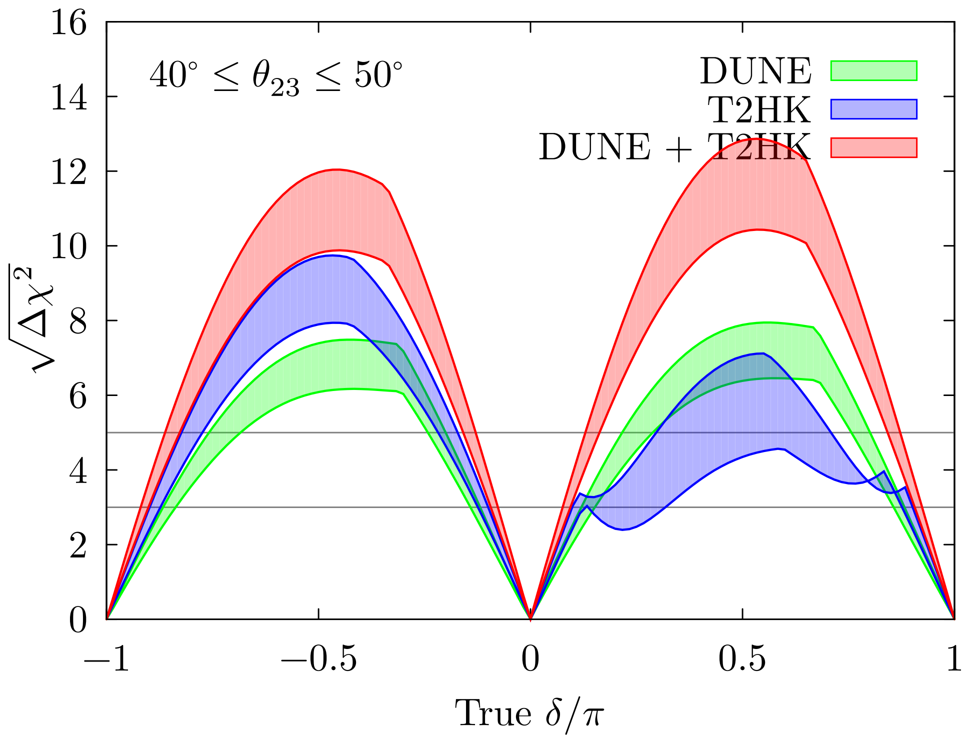
- Thanks to 3-nu mixing effects, the probability for neutrinos and antineutrinos can be different due to CPV.
- Due to their interactions with the background of e, p, n, they get an effective mass which changes the oscillation probabilities differently for neutrinos and antineutrinos (as the background is CP/CPT violating).

$$P_{\mu e} \simeq 4 s_{23}^2 s_{13}^2 \frac{1}{(1-r_A)^2} \sin^2 \frac{(1-r_A)\Delta_{31} L}{4E}$$

$$+ \sin 2\theta_{12} \sin 2\theta_{23} s_{13} \frac{\Delta_{21} L}{2E} \sin \frac{(1-r_A)\Delta_{31} L}{4E} \cos\left(\delta - \frac{\Delta_{31} L}{4E}\right) + \ldots$$

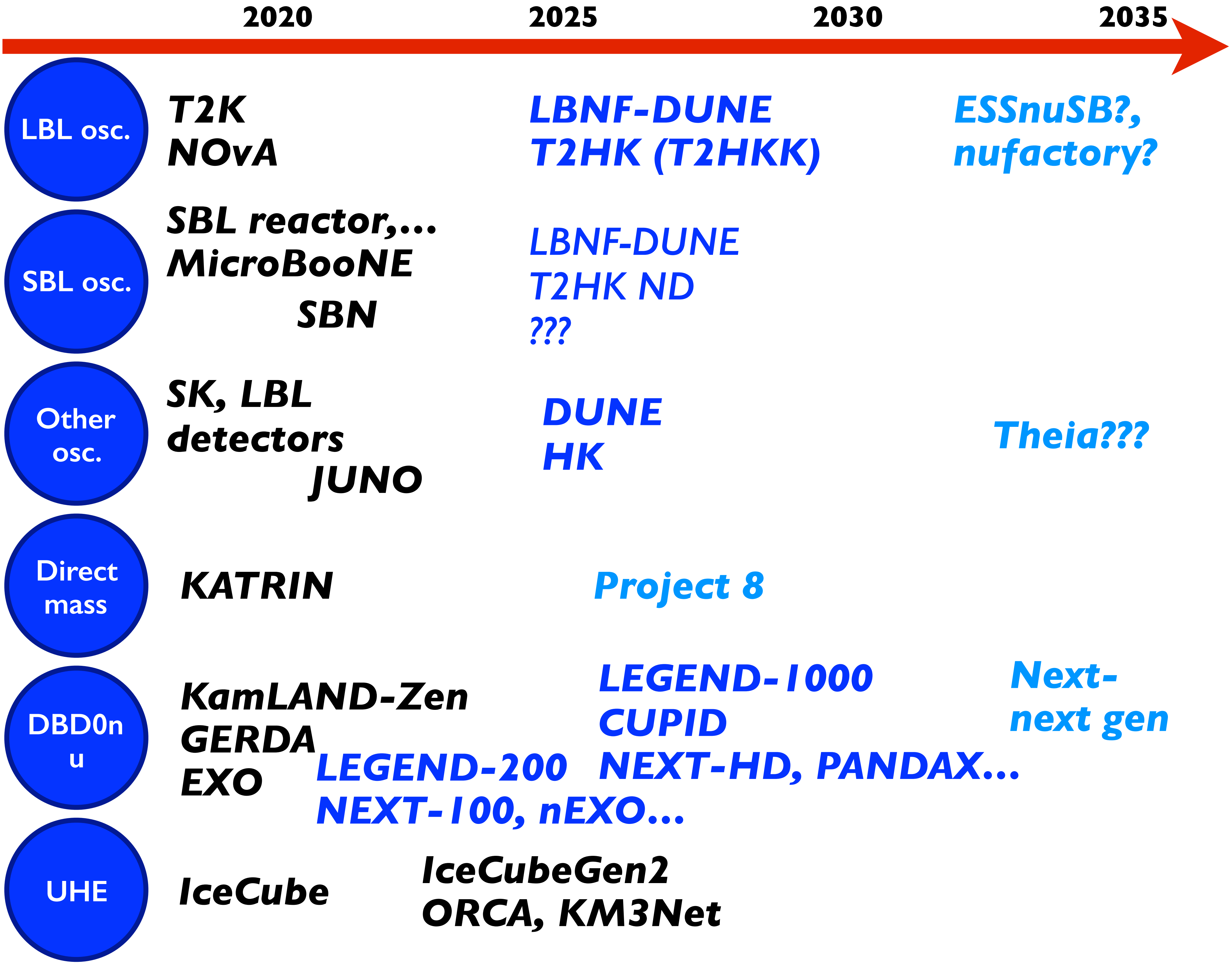
with $r_A \equiv A/\Delta_{31},$ $\Delta_{i1} \equiv \Delta m_{i1}^2$

e.g. A. Cervera et al., hep-ph/0002108; Denton at al, 1806.01277; and many others, for a recent comparison see Parke et al., 1902.00517



Ballett et al., PRD96 (2017)

These experiments are the tool of choice to determine the mass ordering and CPV.



2020 2025 2030 2035

LBL osc.

T2K
NOvA

LBNF-DUNE
T2HK (T2HKK)

ESSnuSB?,
nufactory?

SBL osc.

SBL reactor,…
MicroBooNE
SBN

LBNF-DUNE
T2HK ND
???

Other osc.

SK, LBL detectors
JUNO

DUNE
HK

Theia???

Direct mass

KATRIN

Project 8

DBD0nu

KamLAND-Zen
GERDA
EXO

LEGEND-200
NEXT-100, nEXO…

LEGEND-1000
CUPID
NEXT-HD, PANDAX…

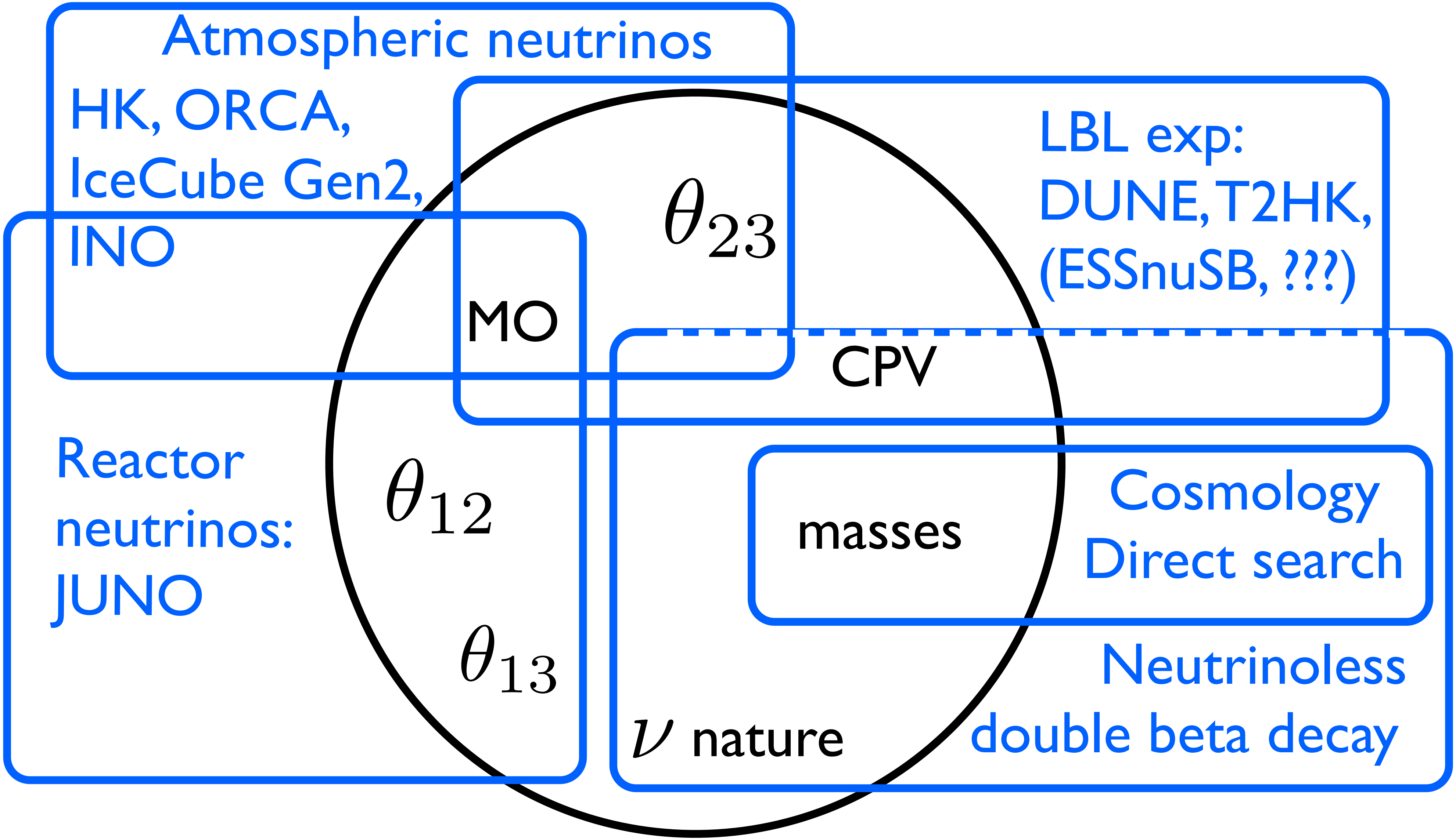
Next-next gen

UHE

IceCube

IceCubeGen2
ORCA, KM3Net

Complementarity



Atmospheric neutrinos

HK, ORCA,
IceCube Gen2,
INO

LBL exp:
DUNE, T2HK,
(ESSnuSB, ???)

θ_{23}

MO

CPV

Reactor
neutrinos:
JUNO

θ_{12}

θ_{13}

masses

Cosmology
Direct search

Neutrinoless
double beta decay

ν nature

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

Neutrino oscillations imply that neutrinos have mass and mix.

First evidence of physics beyond the SM.

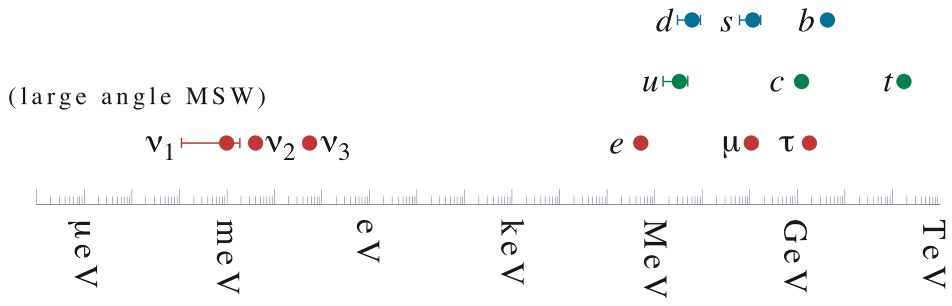
The ultimate goal is to understand

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

Open window on the Physics BSM

Neutrinos give a different perspective on physics BSM.

1. Origin of masses



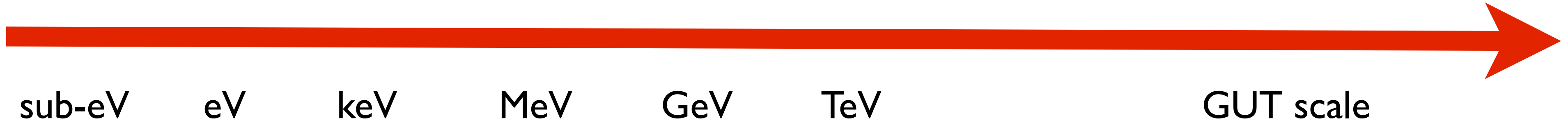
Why neutrinos have mass? and why are they so light? and why their hierarchy is at most mild?

2. Problem of flavour

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

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

Why leptonic mixing is so different from quark mixing?
Is there CPV?



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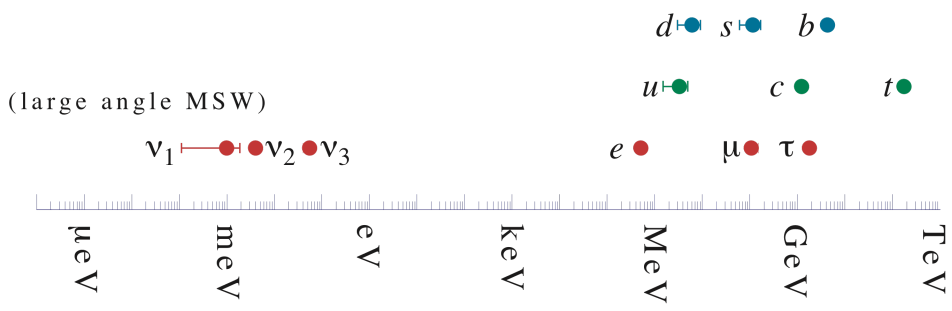

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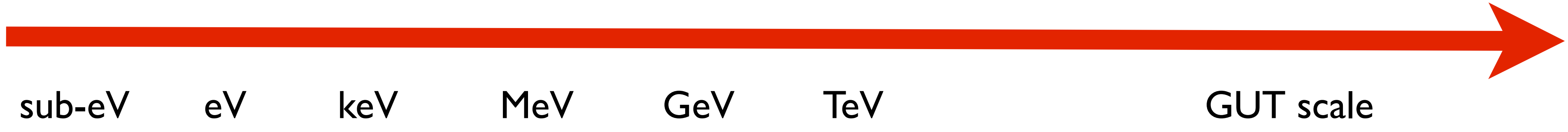


Neutrino Masses in the SM and beyond

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

- Dirac masses do not arise as there are no right-handed neutrinos.

$$m_e \bar{e}_L e_R \qquad\qquad m_\nu \bar{\nu}_L \cancel{\nu_R}$$

If there are RH neutrinos, lepton number would have to be a fundamental symmetry to avoid RH Majorana mass.

- They do not have a Majorana mass term

$$M \nu_L^T C \nu_L$$

as this term breaks the SU(2) gauge symmetry.
This term breaks Lepton Number.

Dirac Masses

If we introduce a right-handed neutrino, then an interaction with the Higgs boson is allowed. We need to impose L as a fundamental symmetry (BSM).

$$\boxed{\mathcal{L} = -y_\nu \bar{L} \cdot \tilde{H} \nu_R + \text{h.c.}}$$

This conserves lepton number!

$$\downarrow$$

$$\boxed{m_D = y_\nu v = V m_{\text{diag}} U^\dagger}$$

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

Tiny couplings!

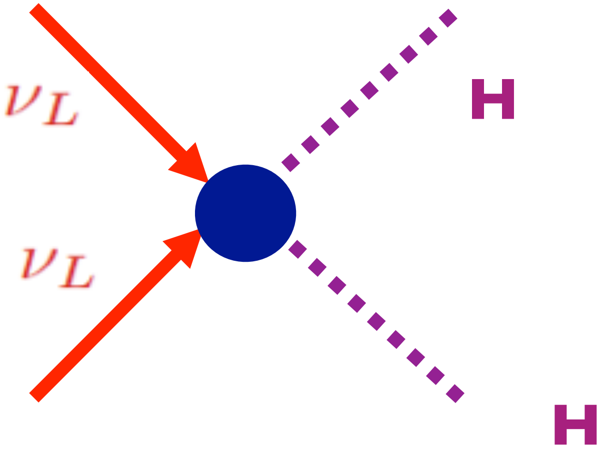
- why no Majorana mass term for RH neutrinos?
- why the coupling is so small????
- why the leptonic mixing angles are large?
- why neutrino masses have at most a mild hierarchy?

Majorana Masses

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

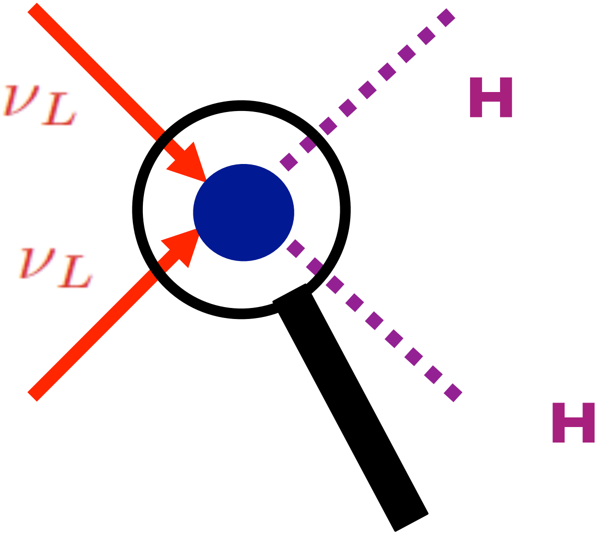
$$-\mathcal{L} = \lambda \frac{L \cdot H L \cdot H}{M} = \frac{\lambda v_H^2}{M} \nu_L^T C^\dagger \nu_L$$

Weinberg operator, PRL 43



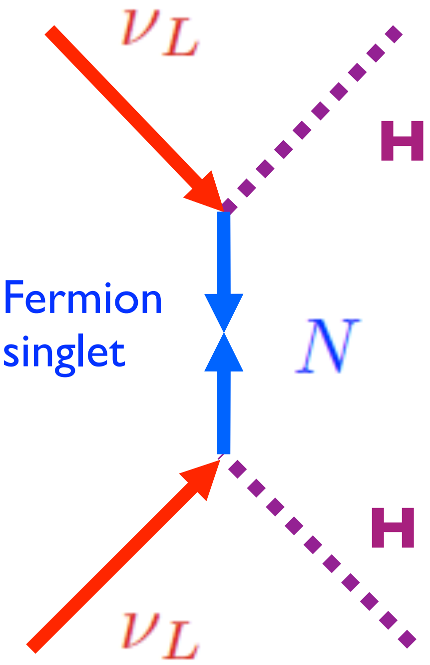
Only D=5 term allowed for the SM

This term breaks lepton number and induces Majorana masses and Majorana neutrinos.



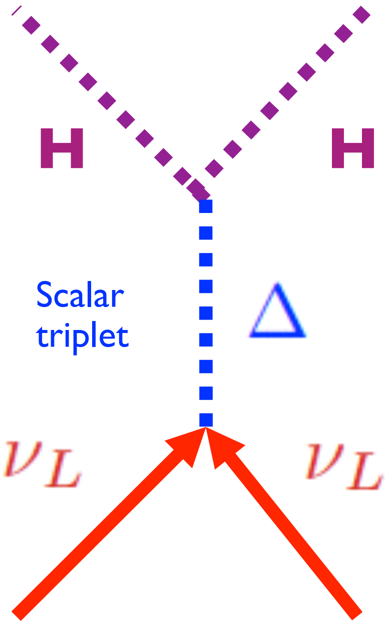
A **Majorana mass** can arise as the low energy realisation of a higher energy theory (new mass scale!).

See-saw Type I



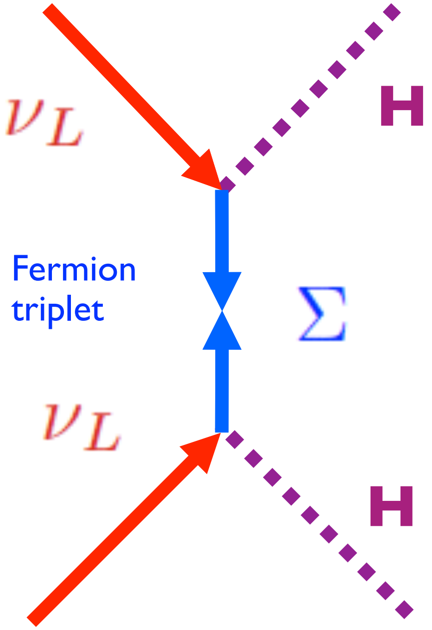
Minkowski, Yanagida, Glashow, Gell-Mann, Ramond, Slansky, Mohapatra, Senjanovic…

See-saw Type II



Magg, Wetterich, Lazarides, Shafi. Mohapatra, Senjanovic, Schecter, Valle…

See-saw Type III



Ma, Roy, Senjanovic, Hambye…

Neutrino masses BSM: “vanilla” see saw mechanism type I

Particle zoo

Symmetry magazine

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

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

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

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

See-saw type I models can be embedded in GUT and explain the baryon asymmetry via leptogenesis.
HNL masses can go from eV to GUT scale.

Pros:

- they explain "naturally" the smallness of masses
- they can be embedded in GUT theories!
- leptogenesis
- they can have many phenomenological signatures

Cons:

- if M very heavy the new particles cannot be tested directly or the mixing with the new states is tiny
- many more parameters than measurable

Many other testable models:

- TeV scale see-saw (II and III)
- Inverse, extended, linear s.-saw
- R-parity violating SUSY
- radiative neutrino masses...

$$\begin{pmatrix} 0 & Y v_H & \epsilon Y v_H \\ Y v_H & \mu' & \Lambda \\ \epsilon Y v_H & \Lambda & \mu \end{pmatrix}$$

Leptogenesis in see-saw models

There is evidence of the baryon asymmetry:

$$\eta_B \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} = (6.18 \pm 0.06) \times 10^{-10}$$

Planck, 1502.01589, AA 594

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;

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

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

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

- departure from thermal equilibrium.

- At T>M, N are in equilibrium:

$$N \leftrightarrow \ell H \qquad N \leftrightarrow \ell H$$
$$N \leftrightarrow \ell H$$
$$N \leftrightarrow \ell H \qquad N \leftrightarrow \ell H$$

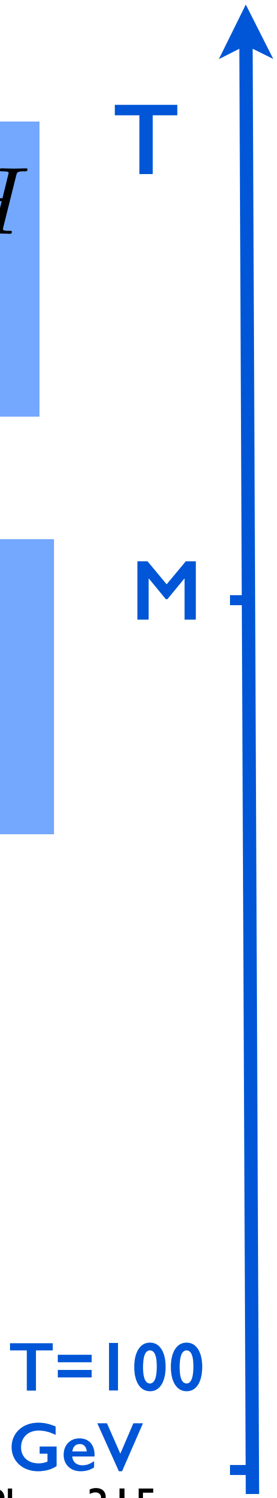
- At T<M, N drops out of equilibrium:

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

- A lepton asymmetry can be generated if

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

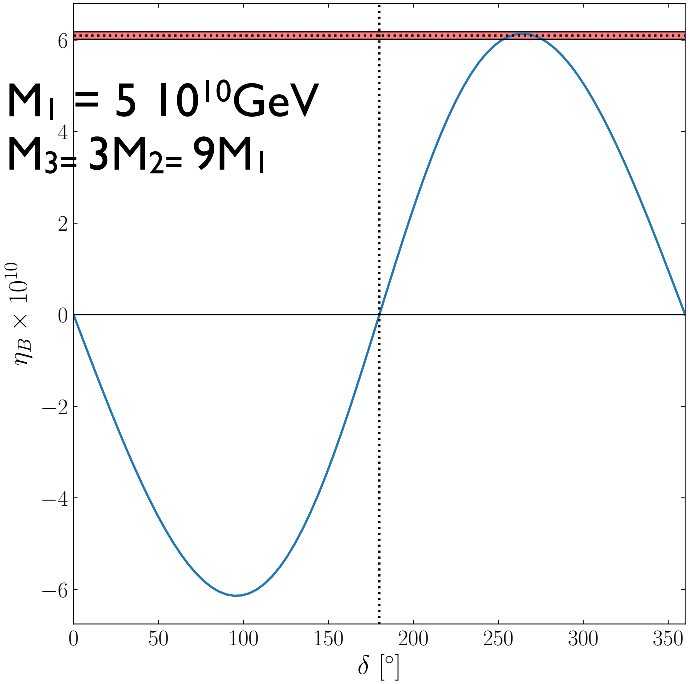
- $$\Delta L \xrightarrow{sphalerons} \Delta B$$



Fukugita, Yanagida, PLB 174; Covi, Roulet, Vissani PLB 384; Buchmuller, Plumacher, Annal. Phys. 315, ...

- Has leptogenesis anything to do with the low energy delta phase? Generically, NO. Many models, lots of parameters…

An interesting example. Vanilla high-energy see-saw type I:

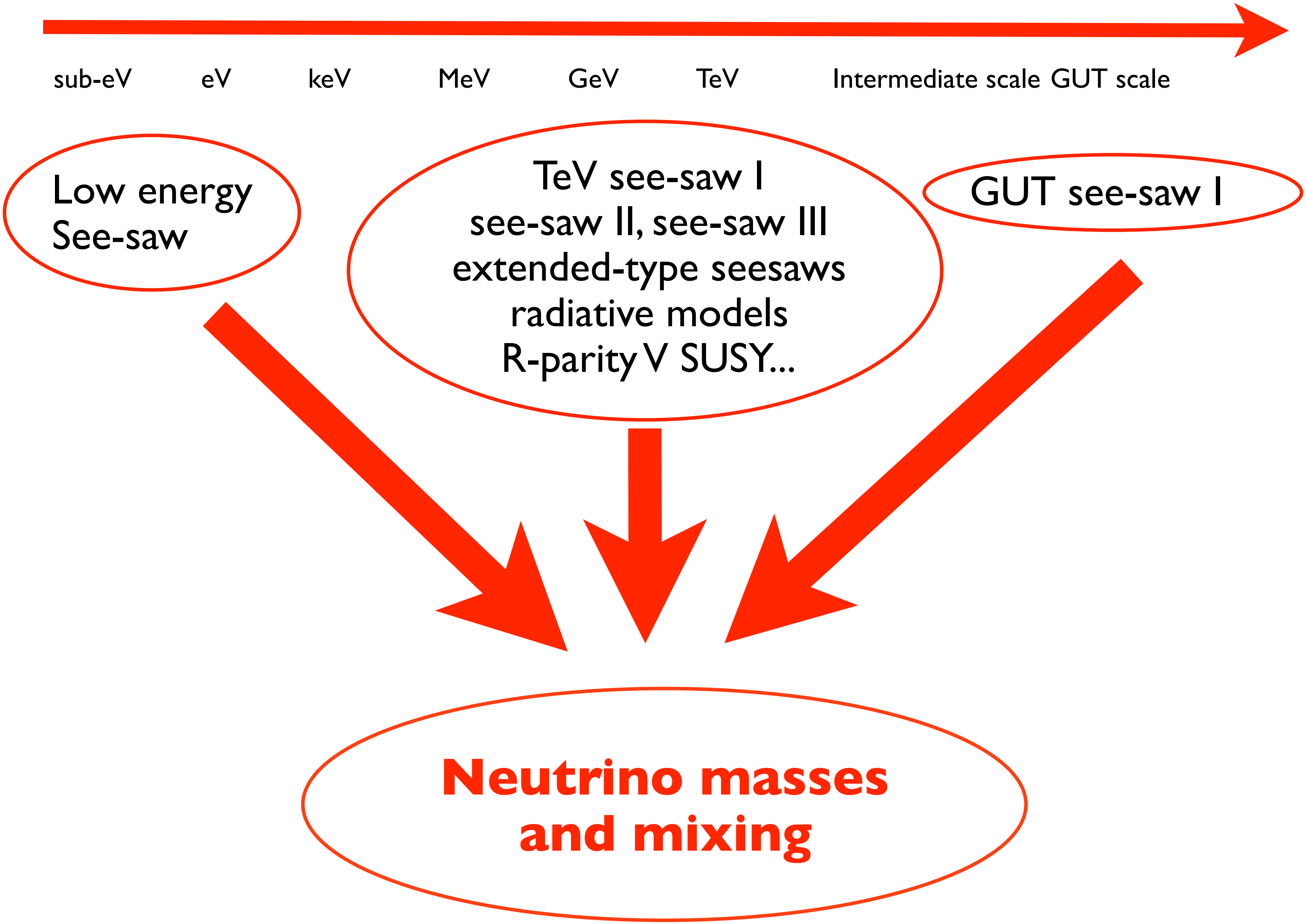

$M_1 = 5\ 10^{10}$GeV
$M_3 = 3M_2 = 9M_1$

A detailed study shows that delta can give an important (even dominant) contribution to the baryon asymmetry. For Majorana CPV, effects enhanced by a factor of ~10.

Moffat, SP, Petcov, Turner, PRD 98, JHEP 1903

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?



sub-eV eV keV MeV GeV TeV Intermediate scale GUT scale

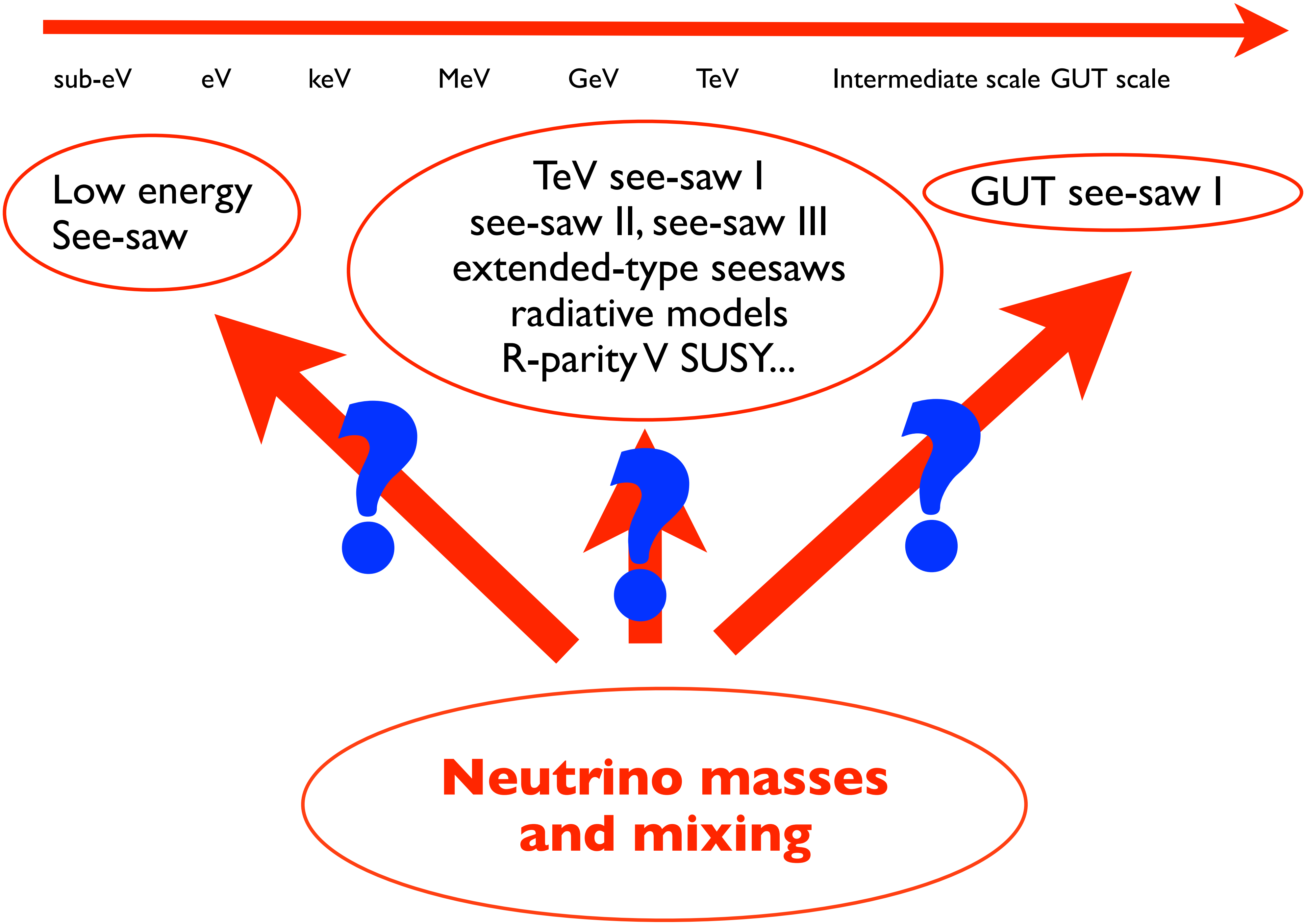
Low energy
See-saw

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

GUT see-saw I

**Neutrino masses
and mixing**

What is the new physics scale?



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TeV see-saw I
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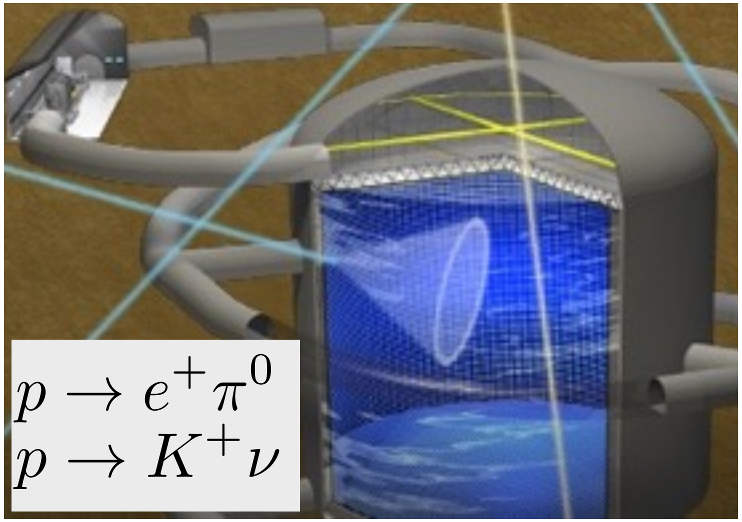
**Neutrino masses
and mixing**

What is the new physics BSM?

sub-eV eV keV MeV GeV TeV GUT scale



$p \to e^+ \pi^0$

$p \to K^+ \nu$

Proton decay

Charged lepton flavour violation, in SUSY models

Neutrino masses

Leptogenesis

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

$N \to \ell H$

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

What is the new physics?

sub-eV eV keV MeV GeV TeV GUT scale

Neutrino masses

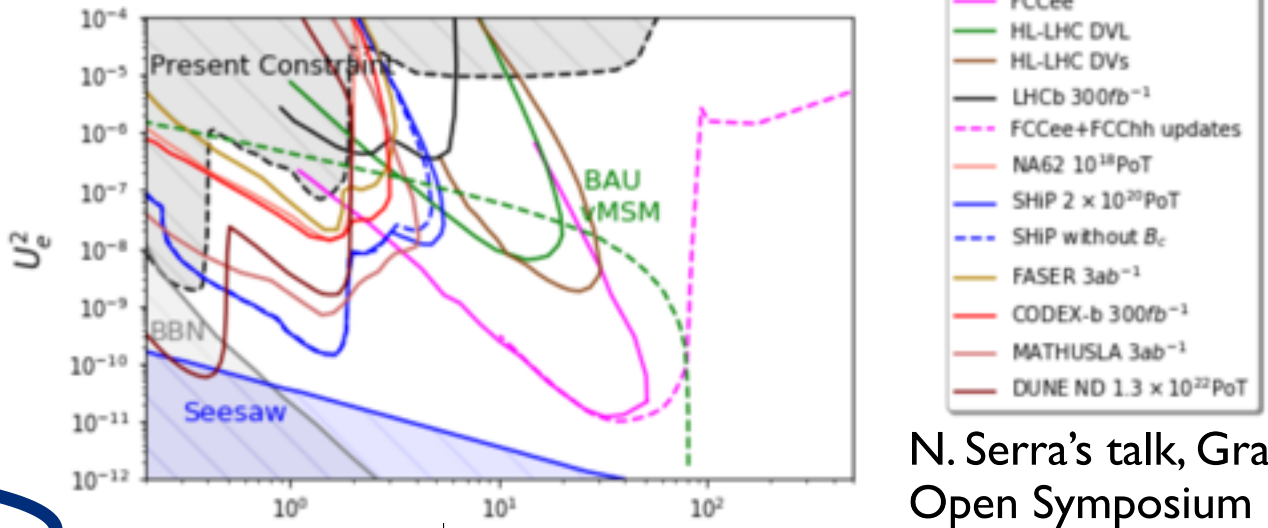
DBD0nu

Colliders

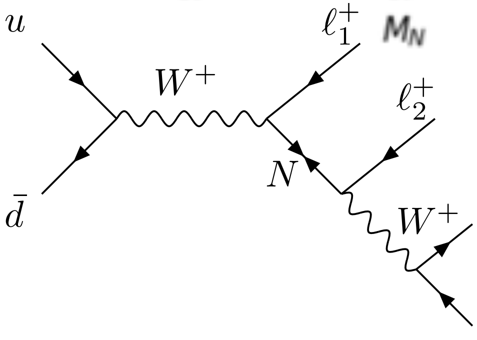
Charged lepton flavour violation

Decays in beam dump exp

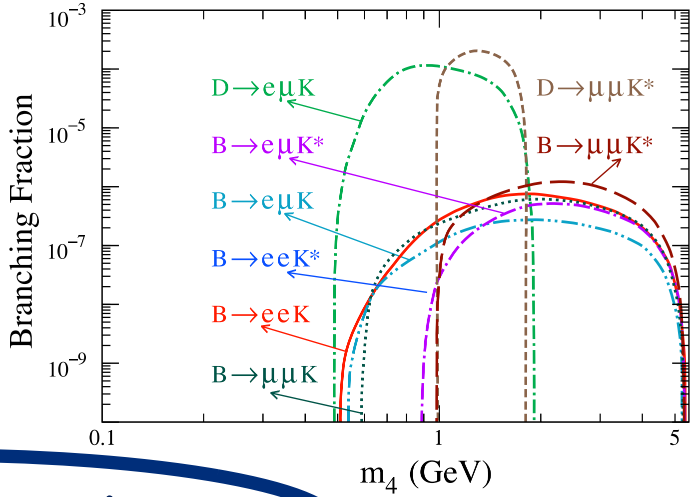
Leptogenesis



N. Serra's talk, Granada Open Symposium ESPP



Atre et al., JHEP0905 (2009)



What is the new physics BSM?

sub-eV eV keV MeV GeV TeV GUT scale

Neutrino masses

Peak searches

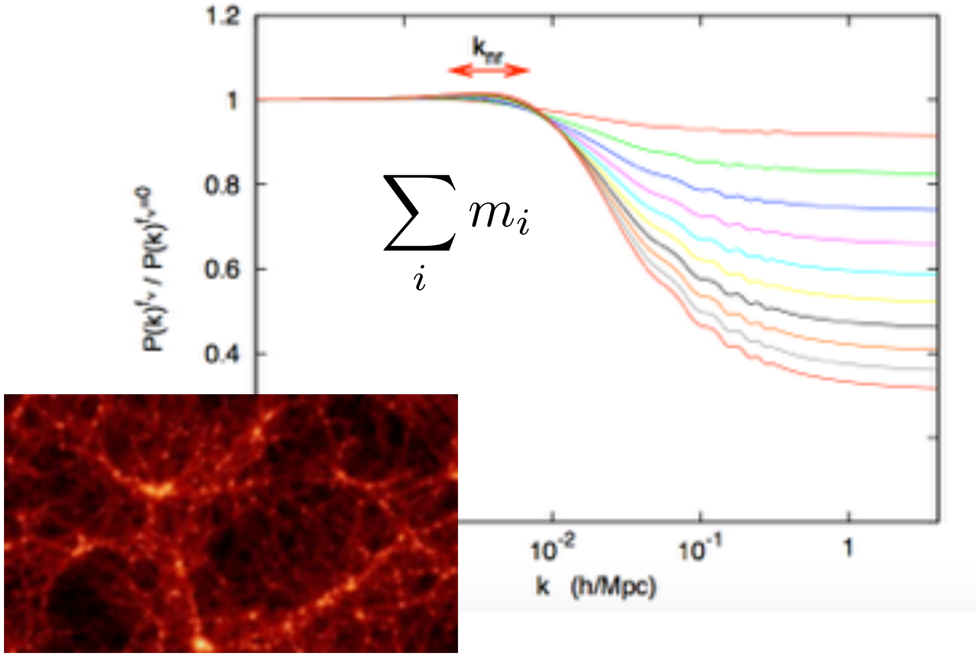
Decays

DM

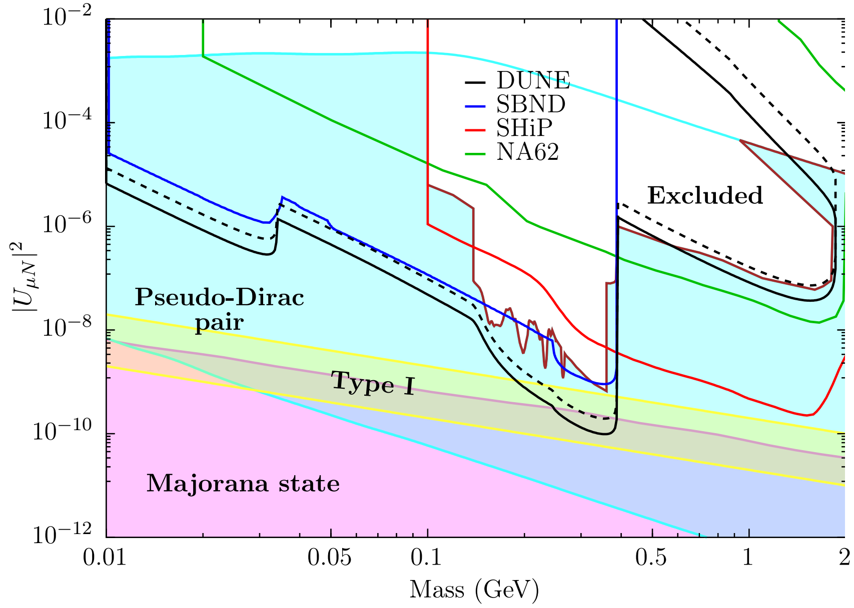
Neutrino oscillations

Rare tau and meson decays

Neutrinoless double beta decay



J. Lesgourgues and S. Pastor, Phys. Rep. 429

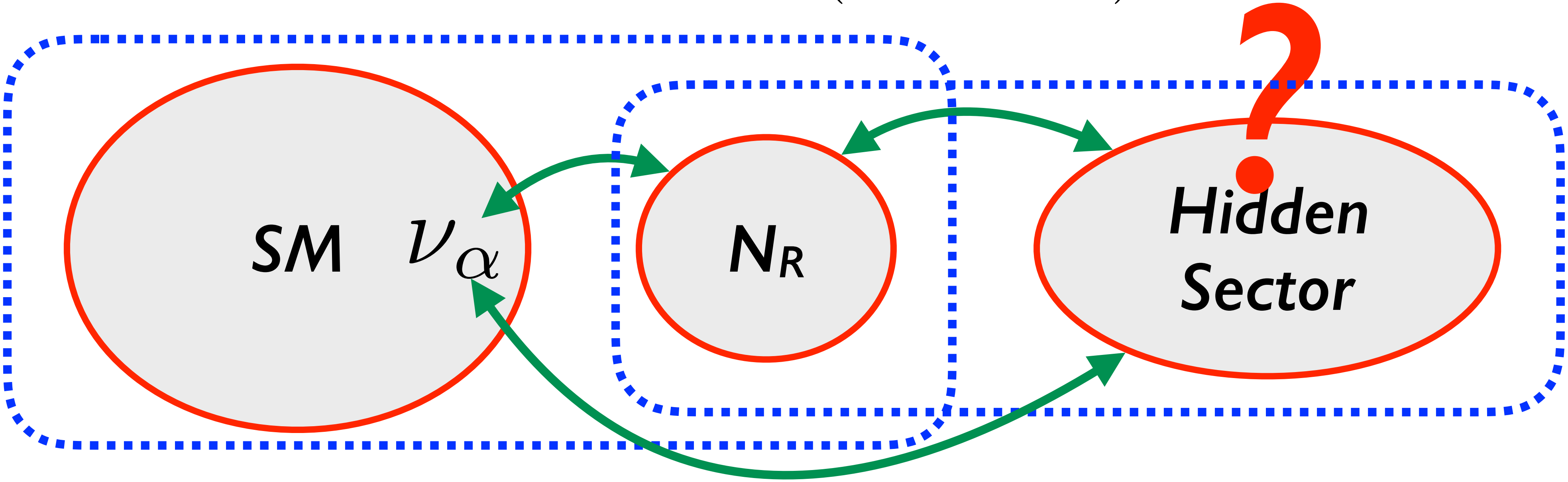


Ballett et al., 1905.00284

Neutrinos: a window on the dark sector?

Neutrinos are one of the key portals to new physics (together with scalar and vector ones). Neutrinos are the least know fermions

$$\bar{L} \cdot H N_R \quad (+ \ldots \overline{N_R} N_S)$$



The dark sector could include new gauge interactions (e.g. dark photons), new scalars and new fermions.
There is a possible connection between neutrinos and dark photon/Z', dark scalars, dark matter studies.

A low energy BSM model

We consider a model in which we introduce a new U(1) gauge interaction under which the SM is neutral but new fermions are charged. In order to break the symmetry a new scalar is introduced.

$$\begin{aligned}\mathscr{L} \supset & \left(D_\mu \Phi\right)^\dagger \left(D^\mu \Phi\right) - V(\Phi, H) \\ & - \frac{1}{4} X^{\mu\nu} X_{\mu\nu} + \overline{N} i \partial\!\!\!/ N + \overline{\nu_D} i \not{D} \nu_D \\ & - \left[y_\nu^\alpha (\overline{L_\alpha} \cdot \widetilde{H}) N^c + \frac{\mu'}{2} \overline{N} N^c + y_N \overline{N} \nu_D^c \Phi + \text{h.c.} \right]\end{aligned}$$

Ballett et al., 1903.07589

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& - \frac{1}{4} X^{\mu\nu} X_{\mu\nu} + \overline{N} i \partial\!\!\!/ N + \overline{\nu_D} i D\!\!\!\!/\, \nu_D \\
& - \left[y_\nu^\alpha (\overline{L_\alpha} \cdot \widetilde{H}) N^c + \frac{\mu'}{2} \overline{N} N^c + y_N \overline{N} \nu_D^c \Phi + \mathrm{h.c.} \right]
\end{aligned}
$$

Ballett et al., 1903.07589

After symmetry breaking, the theory contains:

- heavy neutral fermions which mix with the neutrinos;

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Ballett et al., 1903.07589

After symmetry breaking, the theory contains:

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- a dark photon, which generically mixes via a vector portal;

A low energy BSM model

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$$\lambda_{\Phi H}\, H^\dagger H \, |\Phi|^2$$

$$\mathscr{L} \supset (D_\mu \Phi)^\dagger (D^\mu \Phi) - V(\Phi, H)$$

Ballett et al., 1903.07589

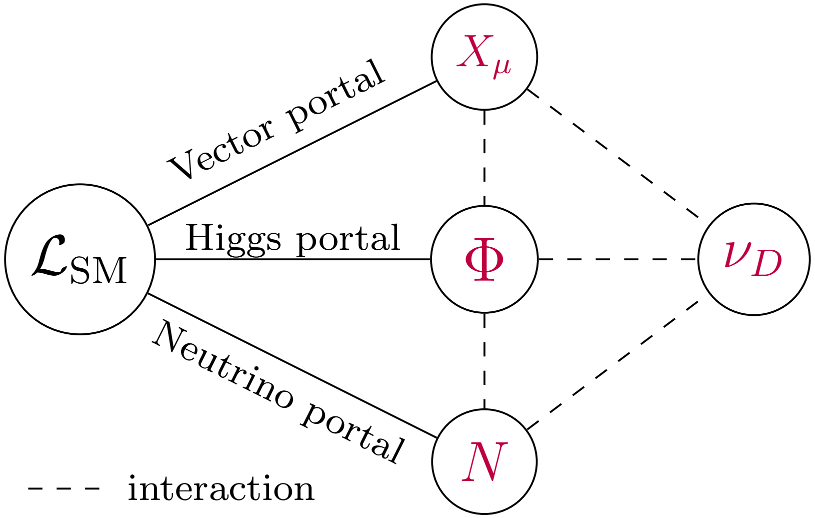
$$- \frac{1}{4} X^{\mu\nu} X_{\mu\nu} + \overline{N} i \not{\partial} N + \overline{\nu_D} i \not{D} \nu_D - \frac{\sin\chi}{2} X_{\mu\nu} B^{\mu\nu}$$

$$- \left[y_\nu^\alpha (\overline{L_\alpha} \cdot \widetilde{H}) N^c + \frac{\mu'}{2} \overline{N} N^c + y_N \overline{N} \nu_D^c \Phi + \text{h.c.} \right]$$

After symmetry breaking, the theory contains:

- heavy neutral fermions which mix with the neutrinos;
- a dark photon, which generically mixes via a vector portal;
- a massive scalar which generically mixes with the Higgs.

This model has naturally three portals to the SM



Ballett et al.,
1903.07589

Ballett et al., PRD 99 (2019)

with a very distinct phenomenology which can be very different from the standard case.

I focus on a new energy scale below the EW symmetry breaking one, ~MeV—GeV, controlled by the vev of Phi.

Fermionic sector

The theory contains two heavy fermions (per generation):

$$m_\nu = \begin{pmatrix} 0 & Y v_H & \cancel{\epsilon Y v_H} \\ Y v_H & \mu' & \Lambda \\ \cancel{\epsilon Y v_H} & \Lambda & \cancel{\mu} \end{pmatrix}$$

ISS: $\Lambda \gg \mu'$

$$m_5 \simeq -m_4 \simeq \Lambda \ , \ m_5 - |m_4| = \mu'$$

$$U_{\alpha 5} \simeq U_{\alpha 4} \simeq \frac{m_D}{\sqrt{2}\Lambda}$$

A pseudoDirac HNL.

Large mixing with nus.

ESS: $\Lambda \ll \mu'$

$$m_4 \simeq -\frac{\Lambda^2}{\mu'} \ , \ m_5 \simeq \mu'$$

$$U_{\alpha 4} \simeq U_{\alpha 5} \sqrt{\frac{m_5}{|m_4|}} \simeq \frac{m_D}{\Lambda}$$

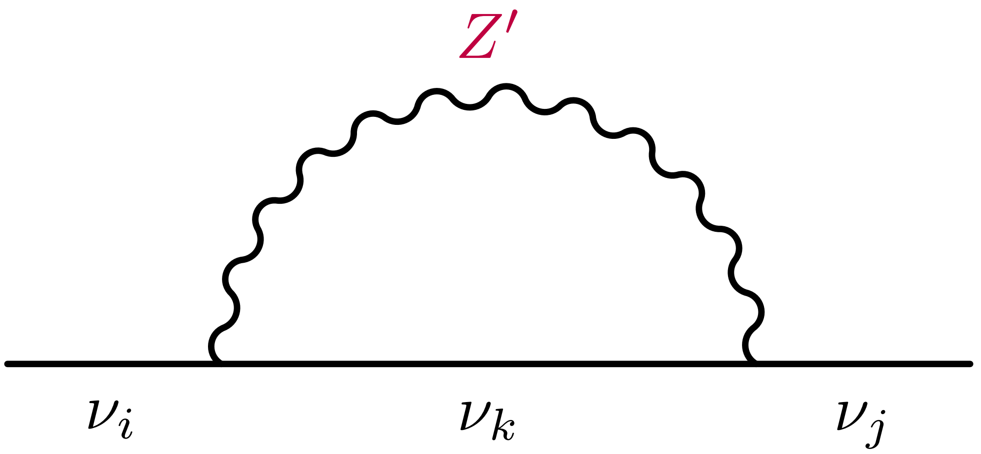
HNL see saw.

Large mixing with nus.

At tree-level neutrino remain massless:

$$\begin{pmatrix} 0 & m_D & 0 \\ m_D & \mu' & \Lambda \\ 0 & \Lambda & 0 \end{pmatrix} \qquad Det(m_\nu) = 0$$

Neutrino masses arise from the exchange of virtual Z'.



Ballett et al., PRD 99 (2019)

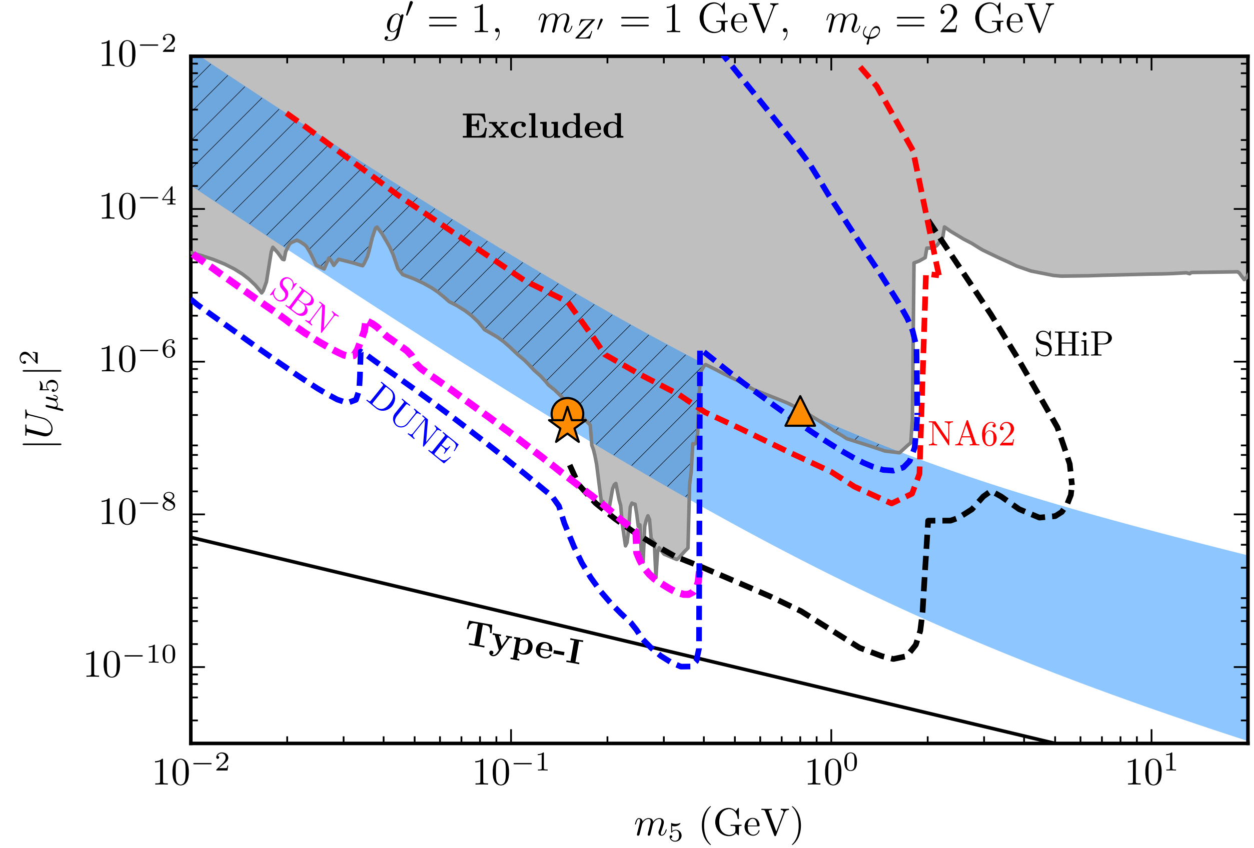
It depend on the LNV parameters:

$$\frac{1}{2}\begin{pmatrix}\overline{\nu_\alpha} & \overline{N} & \overline{\nu_D}\end{pmatrix}\begin{pmatrix}0 & m_D & 0\\ m_D & \mu' & \Lambda\\ 0 & \Lambda & 0\end{pmatrix}\begin{pmatrix}\nu_\alpha^c\\ N^c\\ \nu_D^c\end{pmatrix}$$

- charging N and nu and nuD: μ',
- charging nu: m_D
- charging nu and N: μ', Λ,

For ISS and heavy bosons:

$$m_3 \simeq \frac{g'^2}{16\pi^2}\underbrace{\frac{m_D^2}{\Lambda^2}}_{U_{\mu4}^2}\mu'\,\mathcal{O}(1)$$

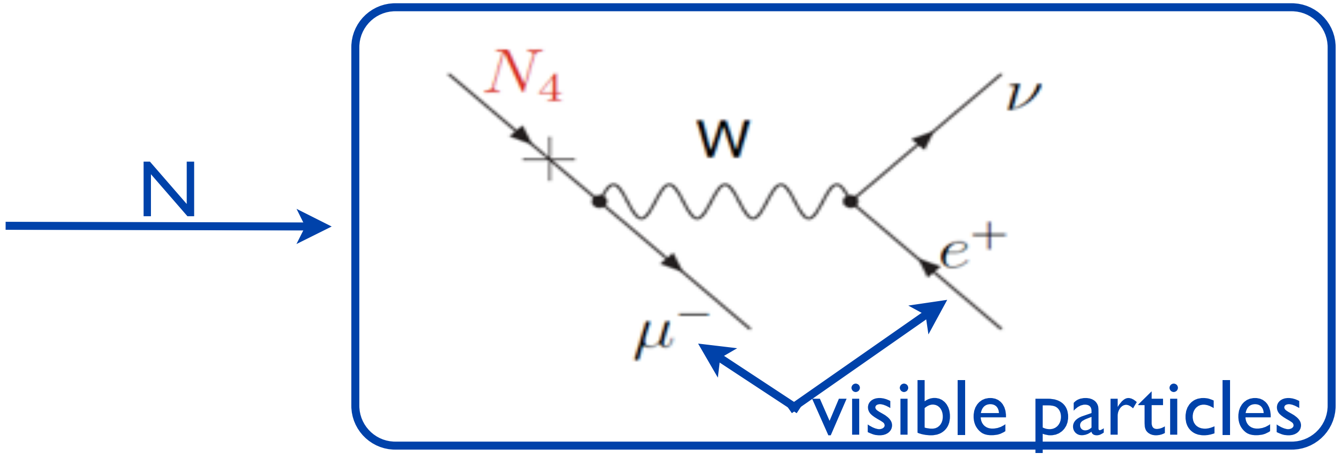


Ballett et al., PRD 99 (2019)

Because of the simultaneous presence of the three portals, the phenomenology can be very different from the case in which only one portal is considered.
As a notable example, let’s consider neutrino mixing and searches for HNLs.

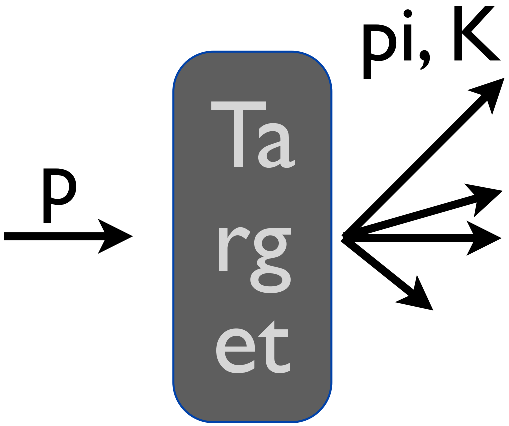
Decay Searches

HNLs can decay in visible particles inside a detector (electrons, muons, pions....).



There are two main exp strategies:

- **beam dump experiments:**



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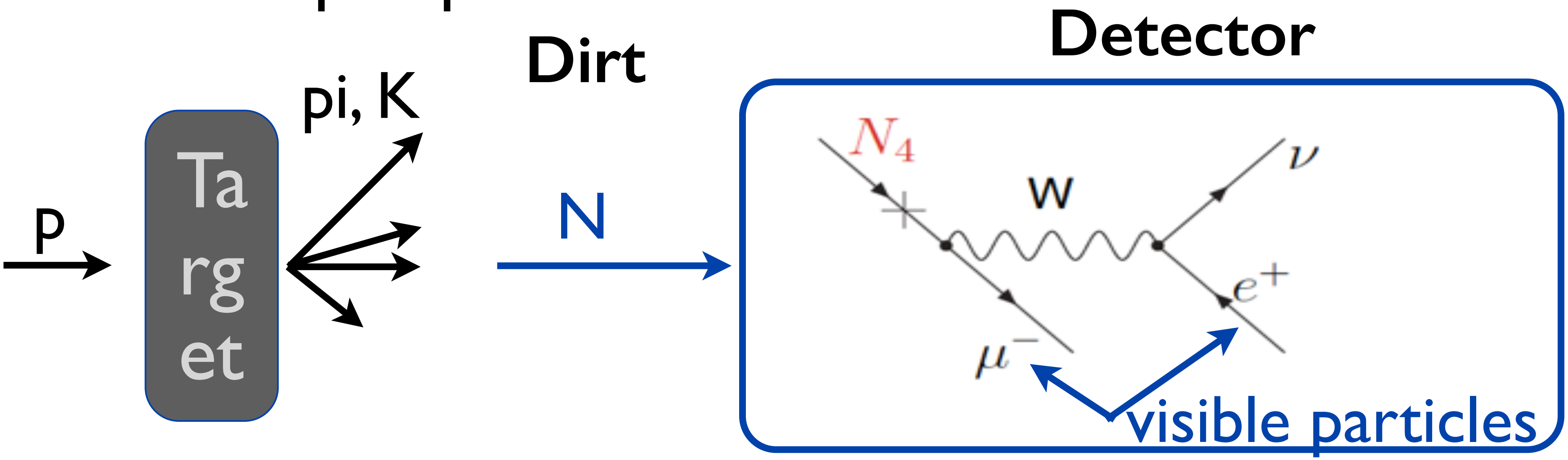


p

Target

pi, K

Dirt

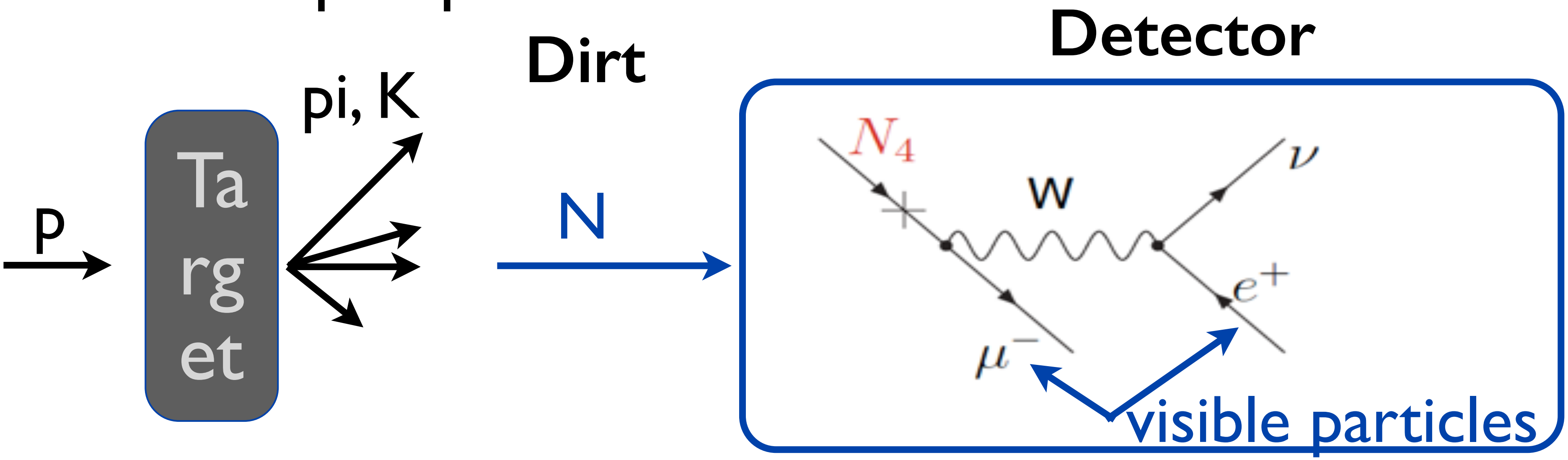
N

Detector

visible particles

There are two main exp strategies:

- beam dump experiments:



Dirt

Detector

p

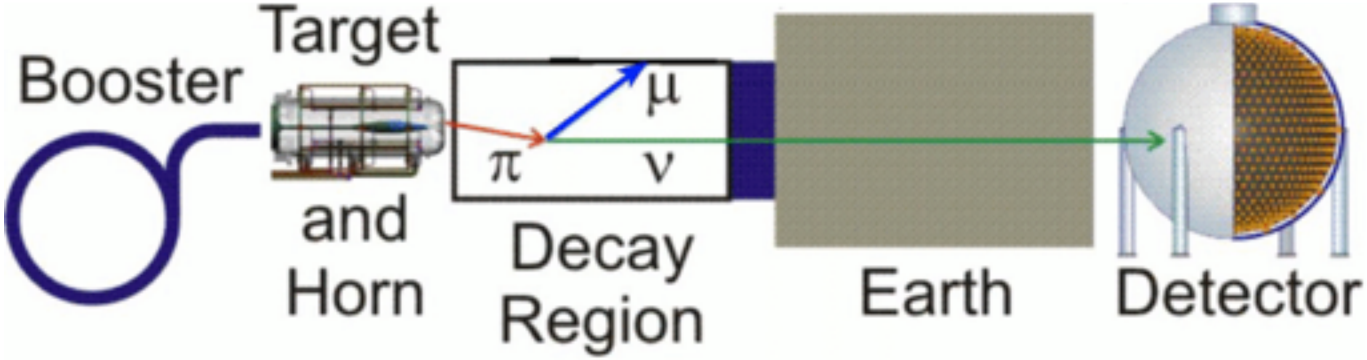
Target

pi, K

N

visible particles

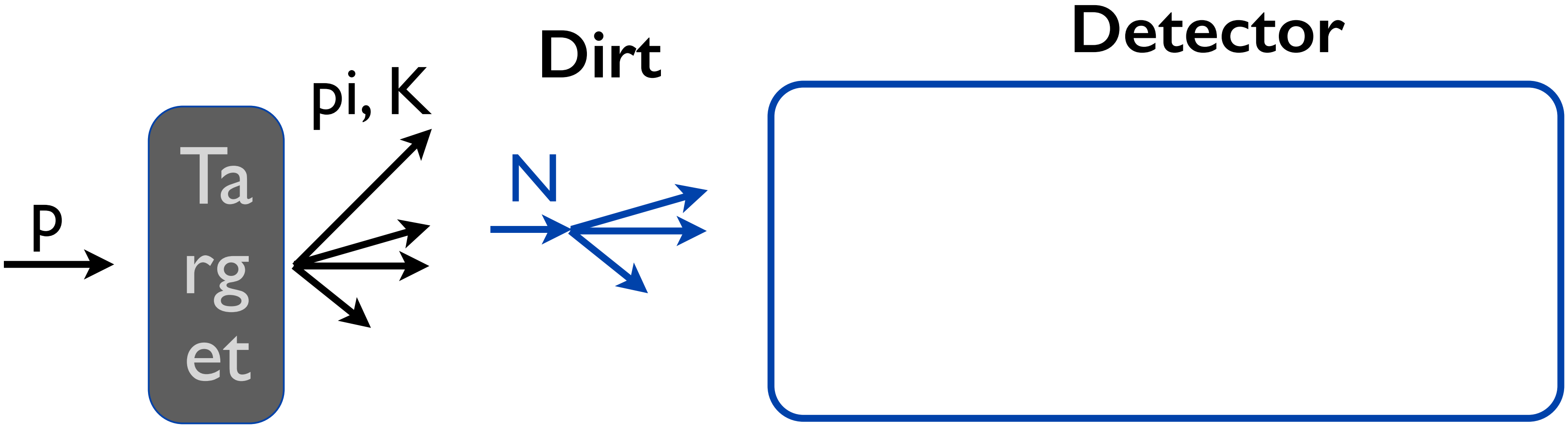
A part from the exp in the 90', in particular PS191, current neutrino experiments and NA62 can search in this mode. An example is MiniBooNE:

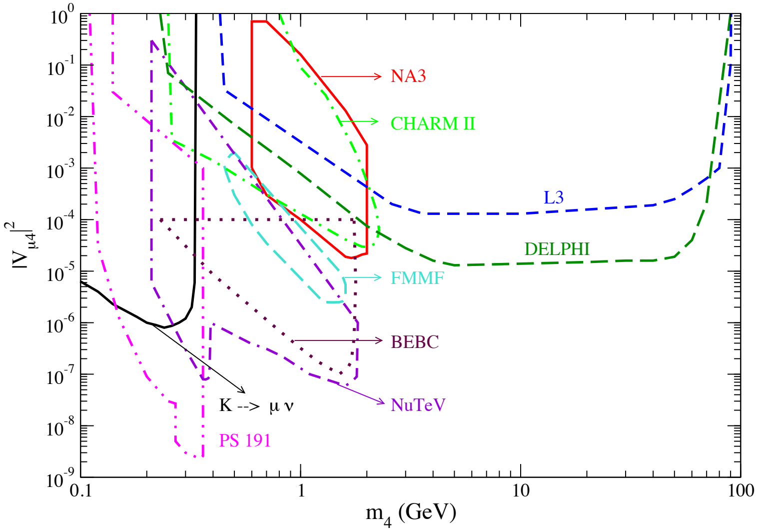


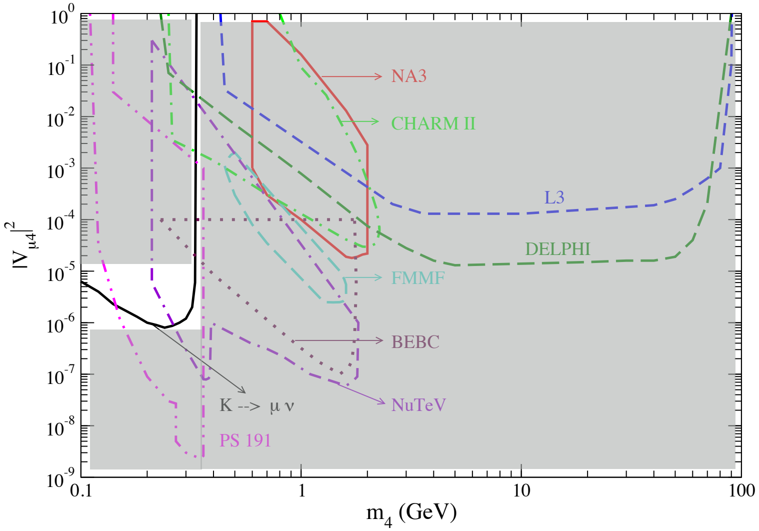
A crucial caveat

If the HNL decays rapidly, before reaching the detector, because of the new interactions

- no signal in beam dump experiments
- the bounds in scattering experiments would be weakened by the Br into visible particles.







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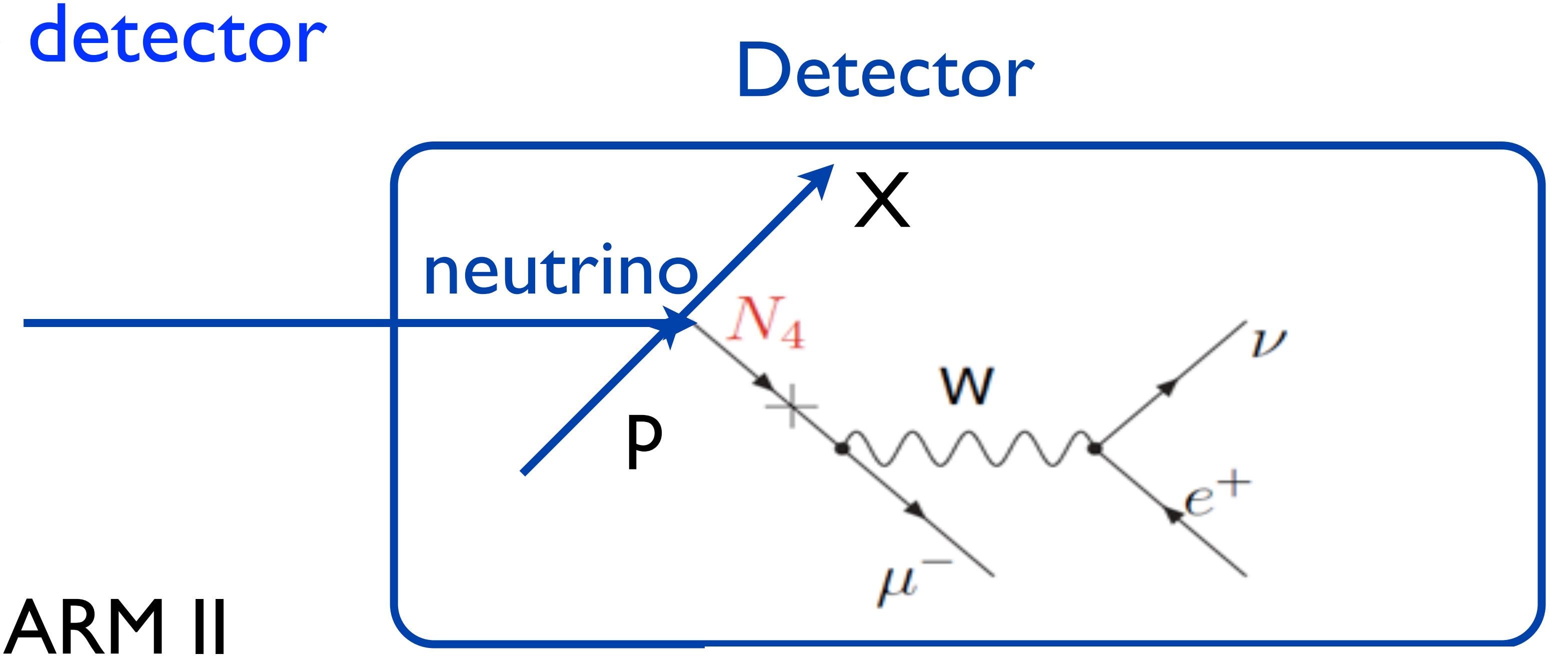
- production (e.g. via NC) and detection in the same detector



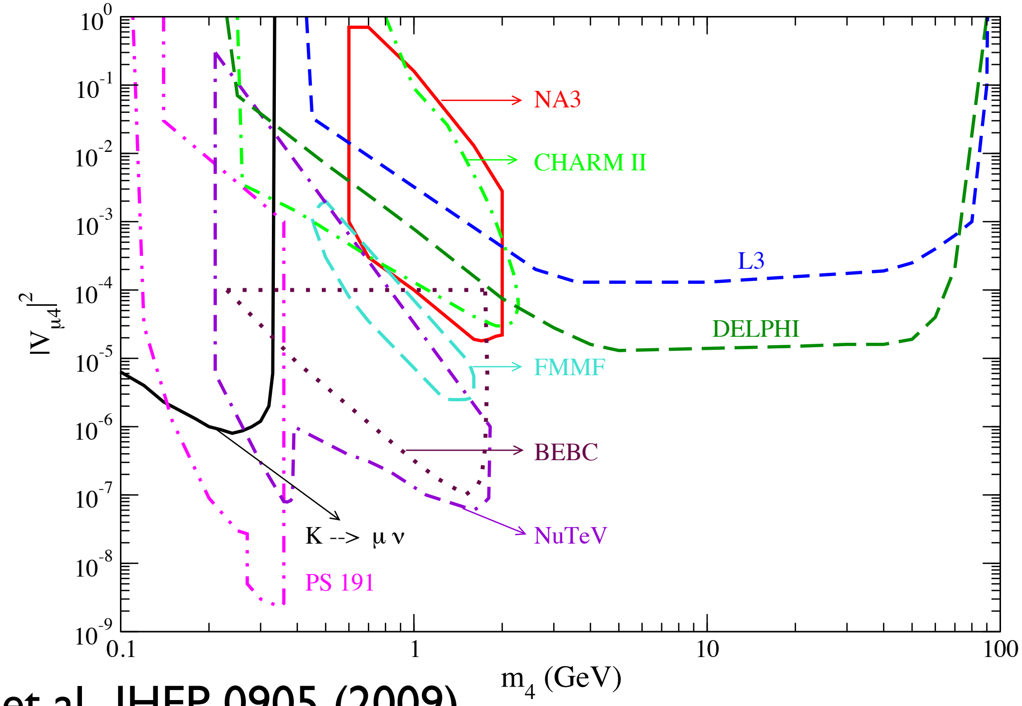
Detector

neutrino

X

p

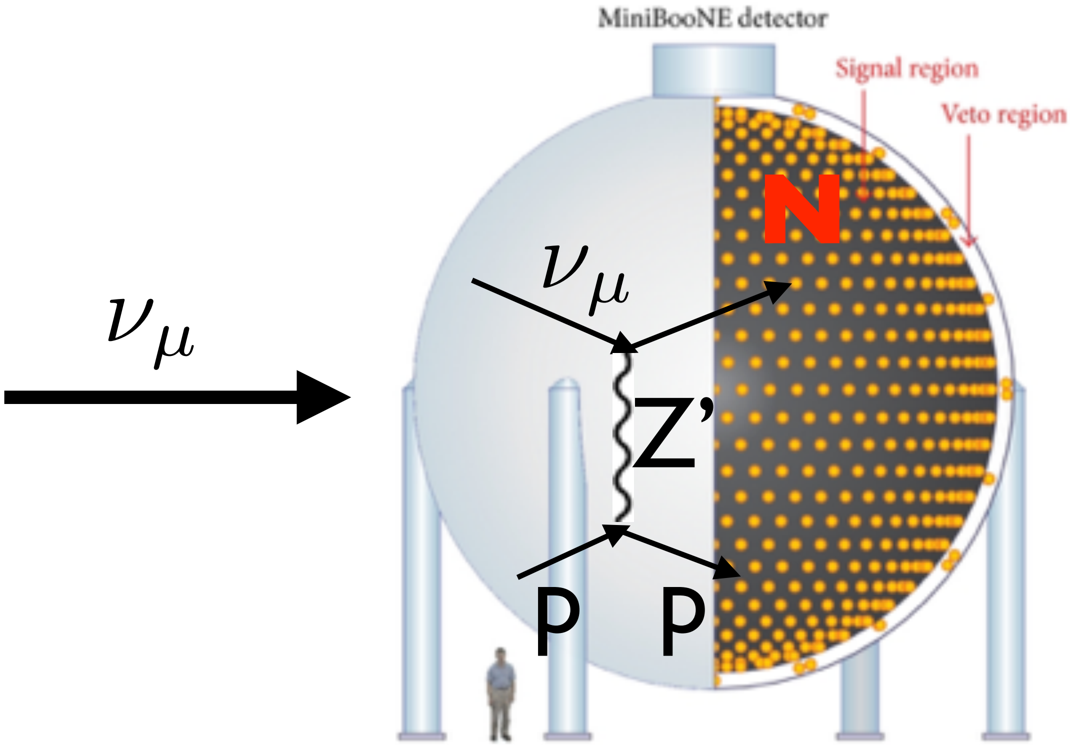
CHARM II

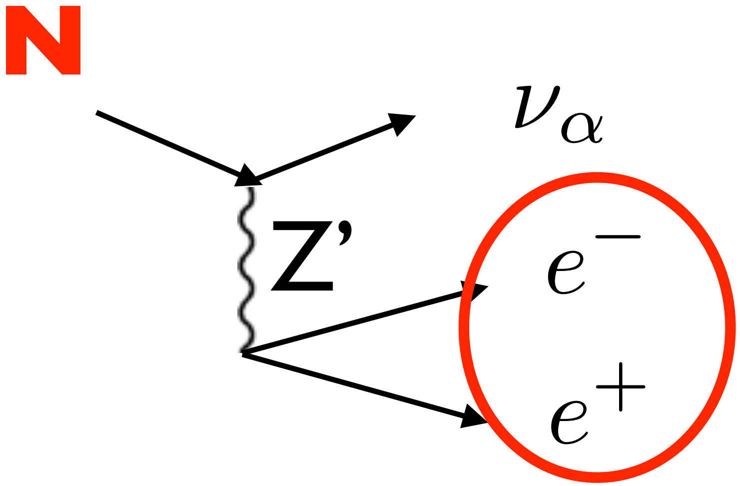


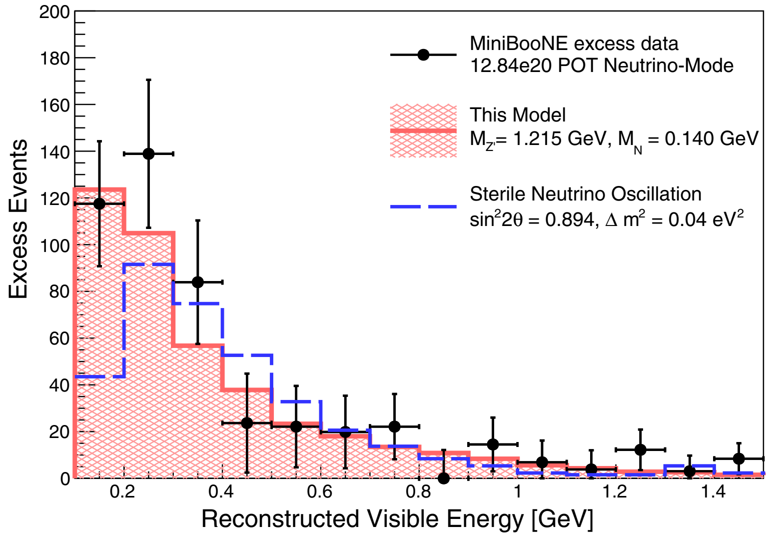
Atre et al., JHEP 0905 (2009)

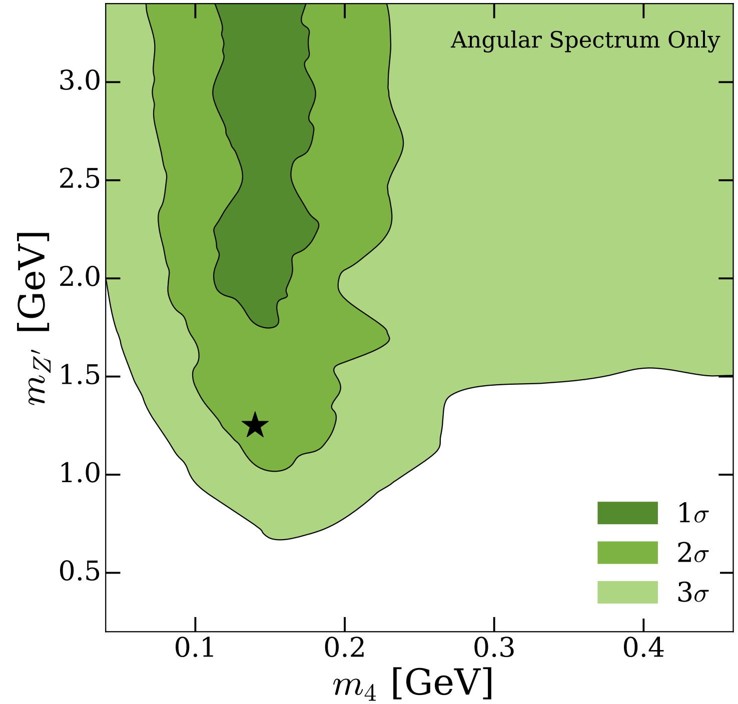
A new MiniBooNE low-E excess explanation

Ballett et al., PRD 99 (2019)









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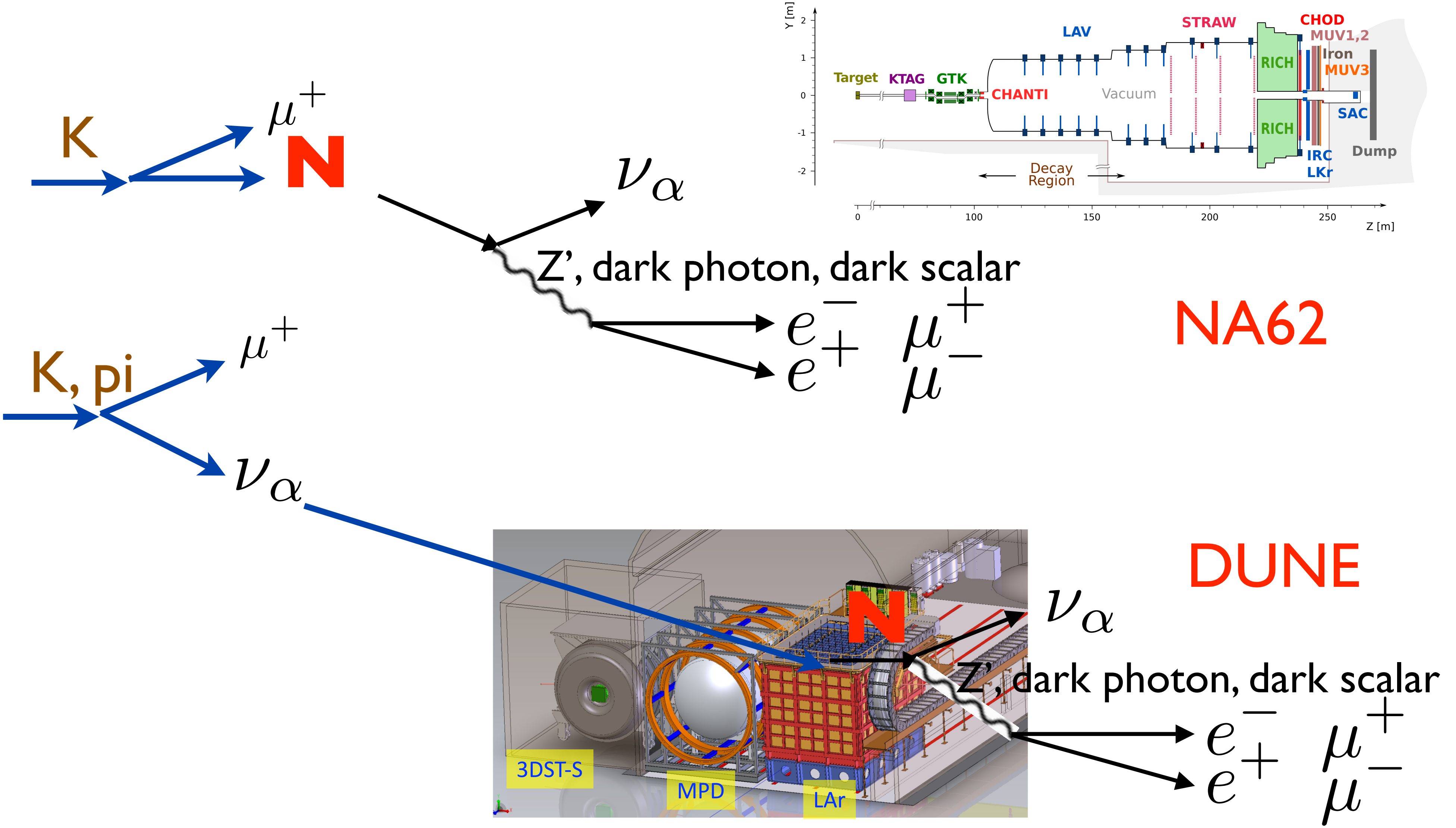
A unique signature

Typically one can expect the HNLs to decay dominantly via new NC interactions into pairs of leptons, possibly with displaced vertices…



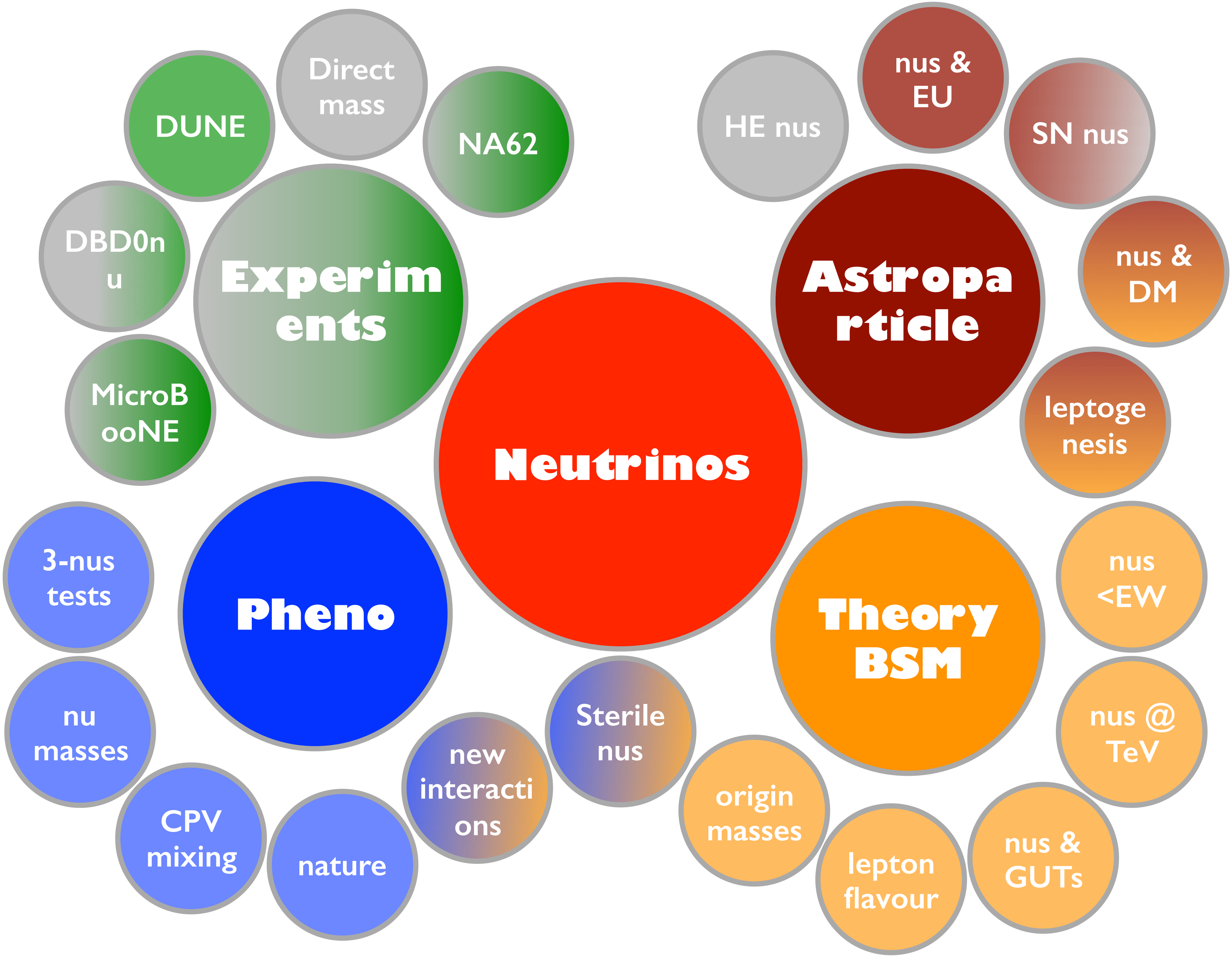
Conclusions

- Neutrino masses are the first particle physics evidence of Physics Beyond the Standard Model. Neutrinos provide a new complementary window w.r.t. collider and flavour physics searches.

- Determining the New Standard Model, responsible also for neutrino masses, is the ultimate goal. It requires complementary information: CLFV, leptogenesis, direct searches at TeV scale and below, low energy probes (e.g. SBL experiments).

- Neutrinos offer a unique portal on models below the EW scale. They can also explain neutrino masses and have a very distinct phenomenology.

My research activity



Neutrinos

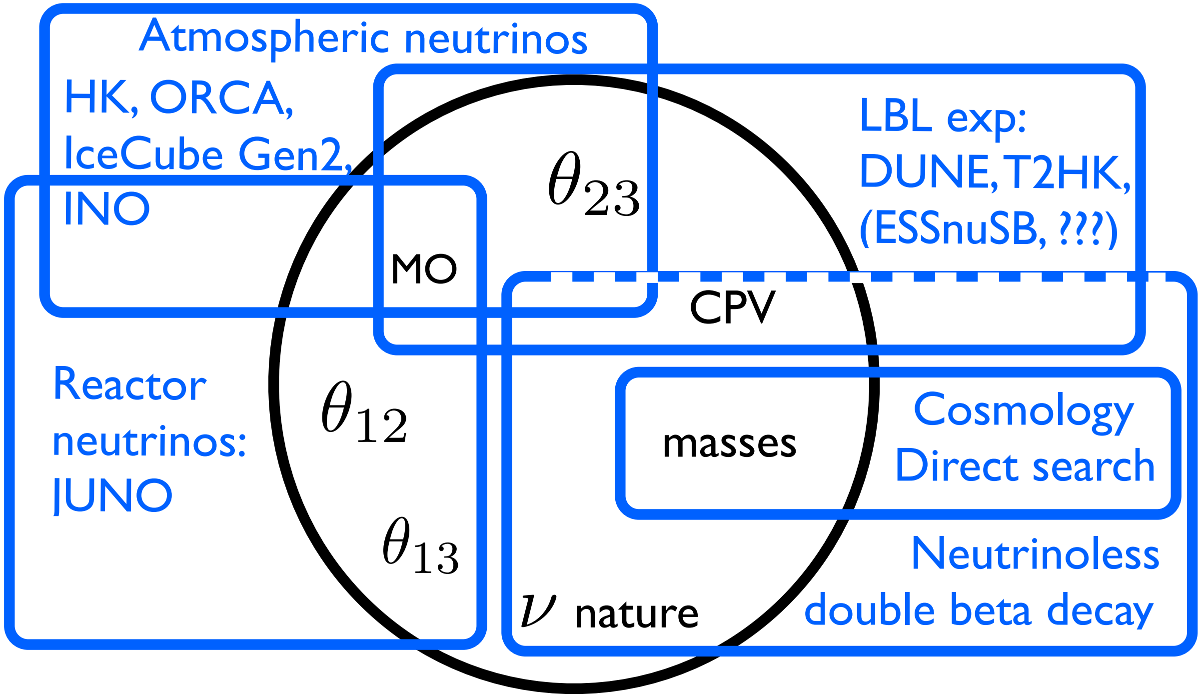
Experiments
- DUNE
- Direct mass
- NA62
- DBD0nu
- MicroBooNE

Astroparticle
- HE nus
- nus & EU
- SN nus
- nus & DM
- leptogenesis

Pheno
- 3-nus tests
- nu masses
- CPV mixing
- nature
- new interactions
- Sterile nus

Theory BSM
- nus <EW
- nus @ TeV
- nus & GUTs
- lepton flavour
- origin masses

Complementarity and synergy of exp searches



Atmospheric neutrinos
HK, ORCA, IceCube Gen2, INO

LBL exp: DUNE, T2HK, (ESSnuSB, ???)

Reactor neutrinos: JUNO

θ_{23}

MO

CPV

θ_{12}

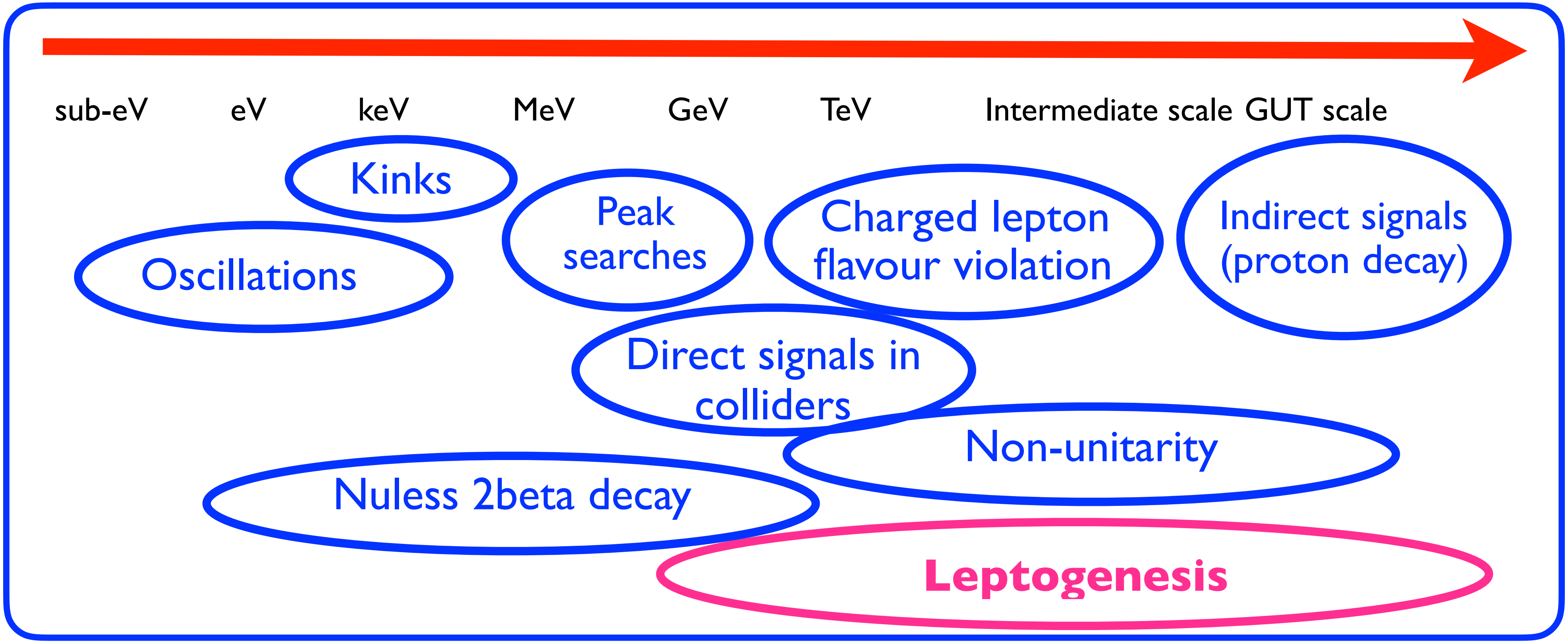
θ_{13}

masses

Cosmology
Direct search

Neutrinoless double beta decay

ν nature



sub-eV | eV | keV | MeV | GeV | TeV | Intermediate scale | GUT scale

Kinks

Oscillations

Peak searches

Charged lepton flavour violation

Indirect signals (proton decay)

Direct signals in colliders

Non-unitarity

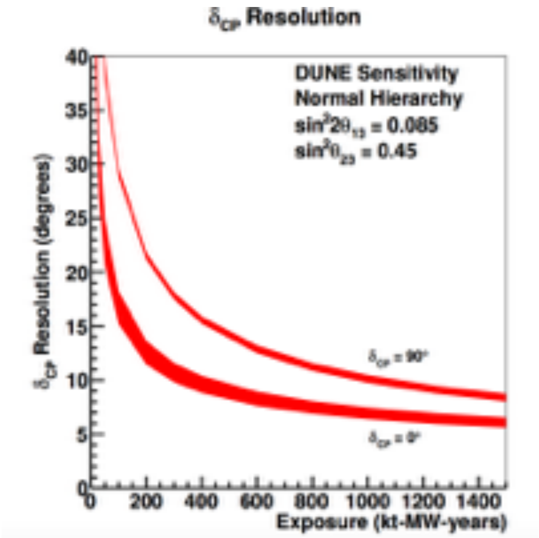
Nuless 2beta decay

Leptogenesis

3. Is there CP-violation?

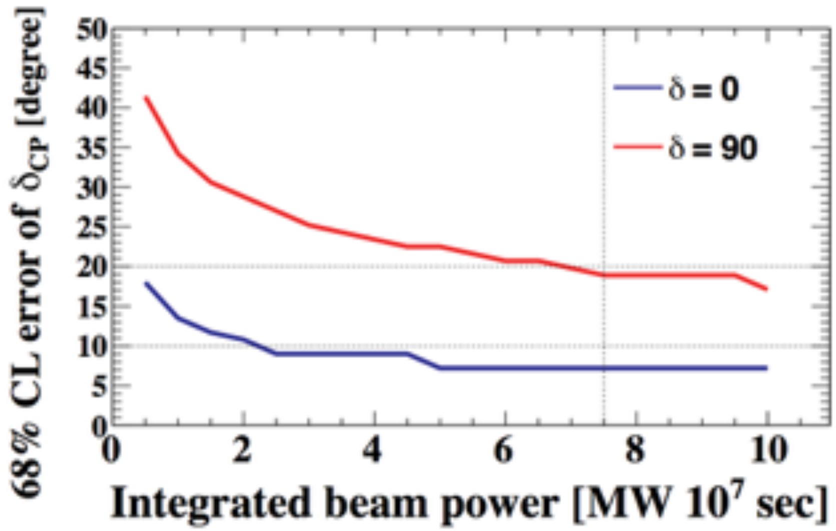
4. What are the precise values of the mixing parameters?

Hints of leptonic CPV have already been found. T2K and NOvA have been approved for extended running. DUNE and T2HK will get to 5 sigma for a large range of delta.



DUNE CDR

T2HK, PTEP 2015



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 3neutrino mixing picture correct?

Neutrinos are the least known of the SM fermions.

Sterile neutrinos: The experimental strategy depends on their mass. Hints for sterile neutrinos are present but controversial. At the eV, SBL oscillations (MicroBooNE, SBN, reactor neutrino exp…) can test.

Non standard interactions: brief introduction later.

Dark sector connection (with dark photons, FIPs): neutrino facilities, cosmology, astrophysics.

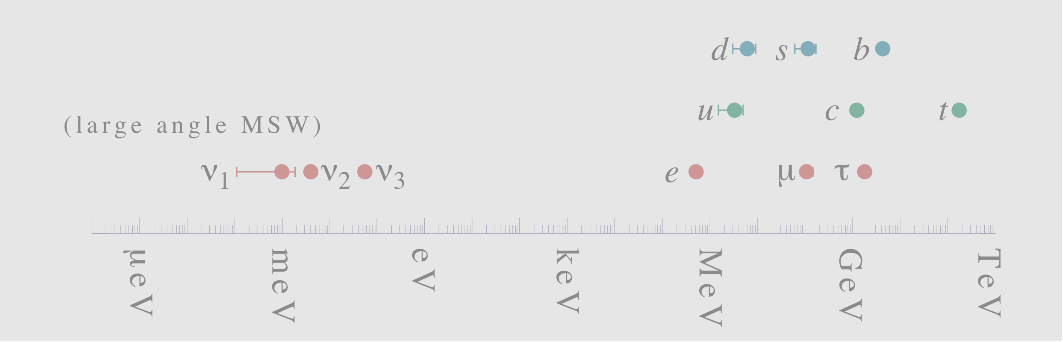
Other exotic effects (decoherence, Lorentz violation…)

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

Open window on Physics beyond the SM

Neutrinos give a different perspective on physics BSM.

1. Origin of masses



Why neutrinos have mass?
and why are they so lighter?
and why their hierarchy is at most mild?

2. Problem of flavour

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

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

Why leptonic mixing is so different from quark mixing?
Is there CPV?

Masses and mixing from the mass matrix

Neutrino masses and the mixing matrix arises from the diagonalisation of the neutrino mass matrix

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

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

Example. In the diagonal basis for the leptons

$$\mathcal{M}_\nu = \begin{pmatrix} a & b \\ b & c \end{pmatrix}$$

the angle is $\tan 2\theta = \dfrac{2b}{a-c} \gg 1 \quad \text{for} \quad a \sim c \text{ and, or } a, c \ll b$

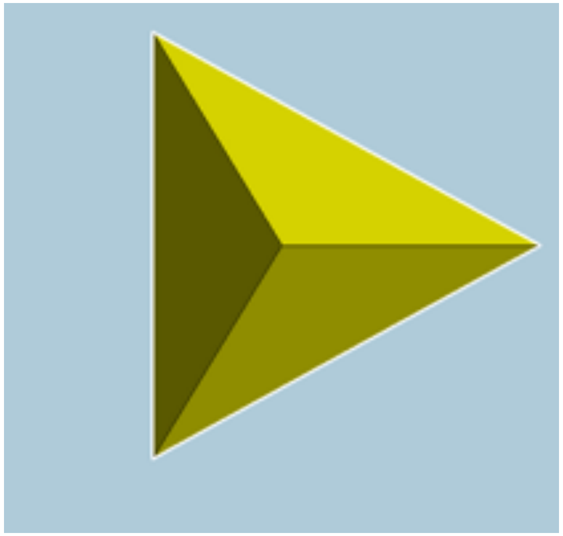
Various strategies and ideas can be employed to understand the observed pattern (many many models!): anarchy, texture zeros, symmetry approach, …

Symmetry approach

- Choose a leptonic symmetry (e.g. A4, S4, A5, $\mu - \tau$ …)

- Use the fact that one can arrange for $U_\nu \neq V_L$

- Obtain the mixing matrix (possibly invoking corrections).



$$\begin{pmatrix} |U_{e1}|^2 & |U_{e2}|^2 & |U_{e3}|^2 \\ |U_{\mu1}|^2 & |U_{\mu2}|^2 & |U_{\mu3}|^2 \\ |U_{\tau1}|^2 & |U_{\tau2}|^2 & |U_{\tau3}|^2 \end{pmatrix} = \begin{pmatrix} 2/3 & 1/3 & 0 \\ 1/6 & 1/3 & 1/2 \\ 1/6 & 1/3 & 1/2 \end{pmatrix}$$

E.g. Tribimaximal mixing

@Silvia Pascoli

Typically, there are relations between masses, mixing angles and CPV phase. E.g. the so-called sumrules:

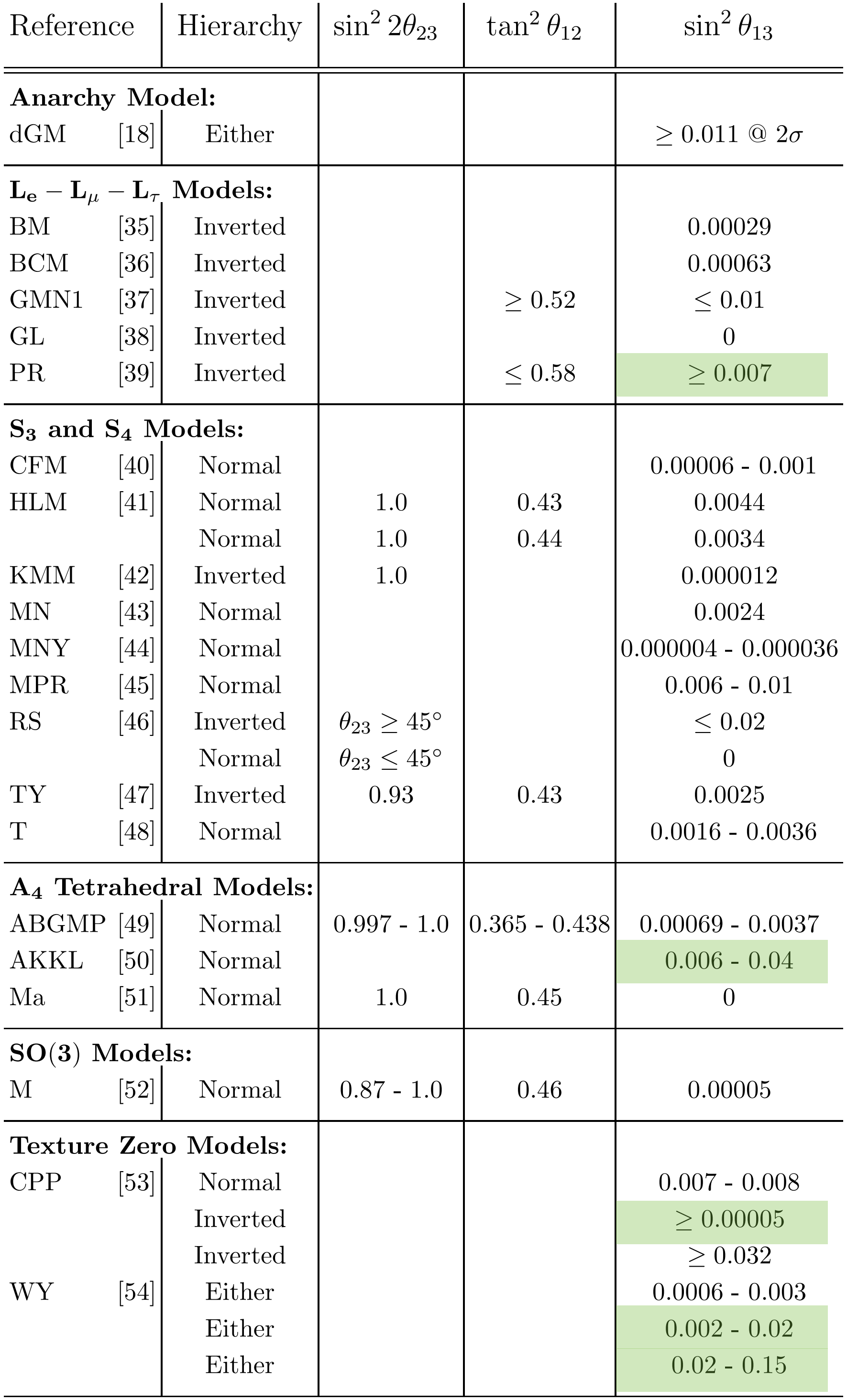
$$\sin\theta_{23} - \frac{1}{\sqrt{2}} = \sin\theta_{13}\cos\delta$$

$$\cos\delta = \frac{t_{23}s_{12}^2 + s_{13}^2 c_{12}^2/t_{23} - s_{12}^{\nu 2}(t_{23} + s_{13}^2/t_{23})}{\sin 2\theta_{12} s_{13}}$$

Ballet et al., Girardi et al.

Needed:

- A precise measurements of the oscillation parameters (including the delta phase).
- Mass ordering and neutrino mass spectrum.



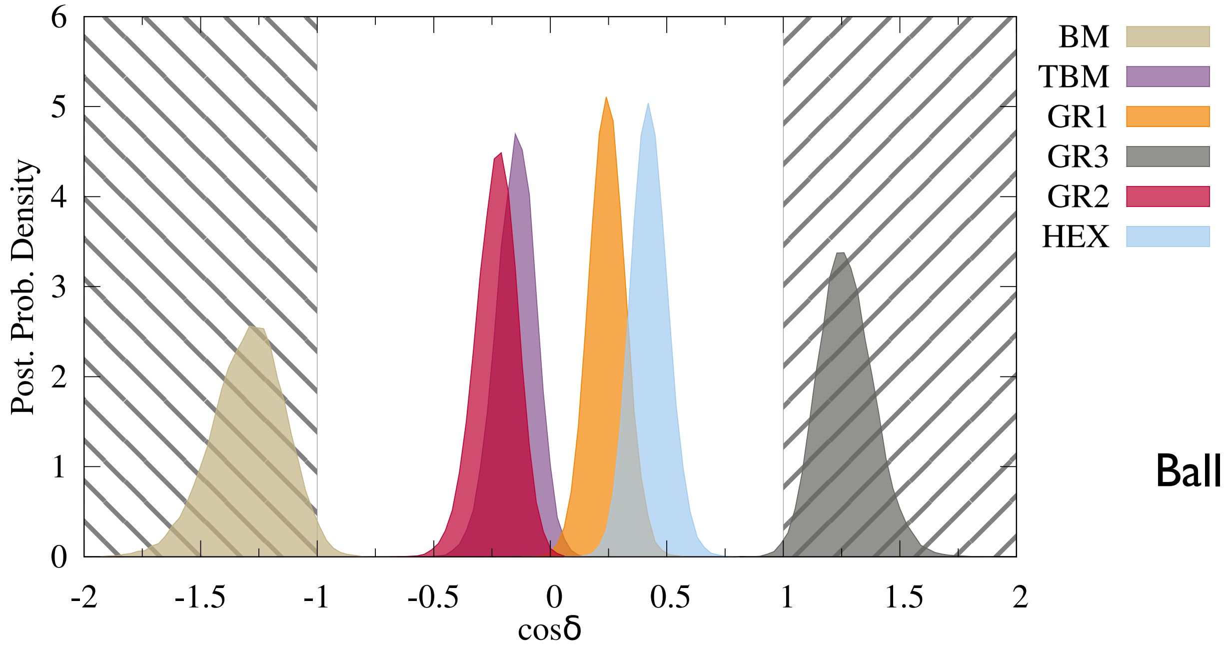
Reference	Hierarchy	$\sin^2 2\theta_{23}$	$\tan^2\theta_{12}$	$\sin^2\theta_{13}$
Anarchy Model:				
dGM [18]	Either			≥ 0.011 @ 2σ
$L_e - L_\mu - L_\tau$ Models:				
BM [35]	Inverted			0.00029
BCM [36]	Inverted			0.00063
GMN1 [37]	Inverted		≥ 0.52	≤ 0.01
GL [38]	Inverted			0
PR [39]	Inverted		≤ 0.58	≥ 0.007
S_3 and S_4 Models:				
CFM [40]	Normal			0.00006 - 0.001
HLM [41]	Normal	1.0	0.43	0.0044
	Normal	1.0	0.44	0.0034
KMM [42]	Inverted	1.0		0.000012
MN [43]	Normal			0.0024
MNY [44]	Normal			0.000004 - 0.000036
MPR [45]	Normal			0.006 - 0.01
RS [46]	Inverted	$\theta_{23} \geq 45°$		≤ 0.02
	Normal	$\theta_{23} \leq 45°$		0
TY [47]	Inverted	0.93	0.43	0.0025
T [48]	Normal			0.0016 - 0.0036
A_4 Tetrahedral Models:				
ABGMP [49]	Normal	0.997 - 1.0	0.365 - 0.438	0.00069 - 0.0037
AKKL [50]	Normal			0.006 - 0.04
Ma [51]	Normal	1.0	0.45	0
SO(3) Models:				
M [52]	Normal	0.87 - 1.0	0.46	0.00005
Texture Zero Models:				
CPP [53]	Normal			0.007 - 0.008
	Inverted			≥ 0.00005
	Inverted			≥ 0.032
WY [54]	Either			0.0006 - 0.003
	Either			0.002 - 0.02
	Either			0.02 - 0.15

Albright, Chen, PRD 74 (2006)

Tests of flavour models

Typically, the models considered have a reduced number of parameters, leading to relations between the masses and/or mixing angles and CPV phase.

Examples are the so-called sumrules, e.g.:



Ballet at al., JHEP 1412