# Neutrino physics beyond oscillation measurements

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# Outline

1. Current knowledge of neutrino parameters

2. Present status of neutrino physics

3. Direct mass searches

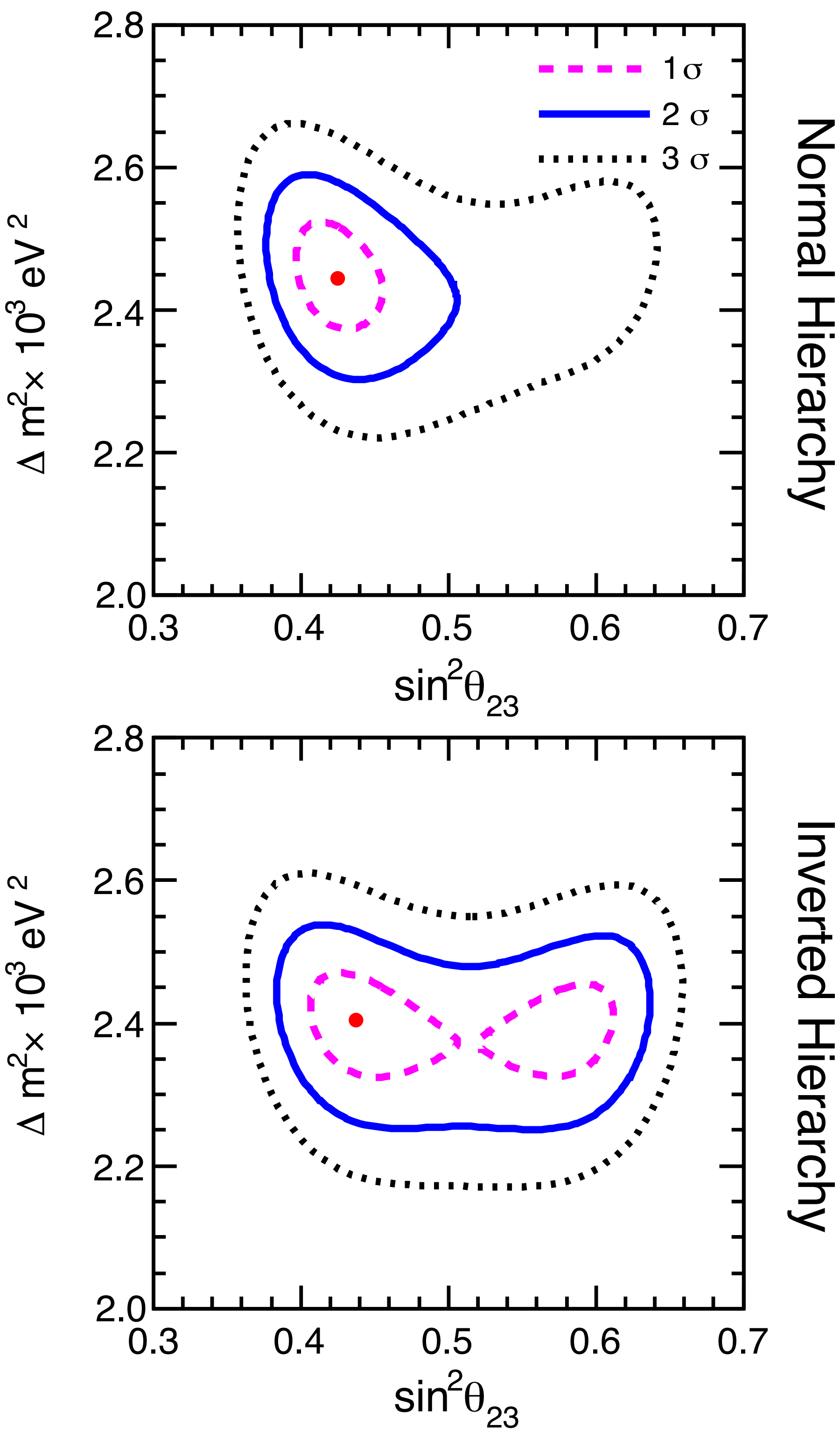
4. Neutrinoless double beta decay

5. Neutrino physics as a window on the physics BSM

6. Conclusions

# Present knowledge of neutrino parameters

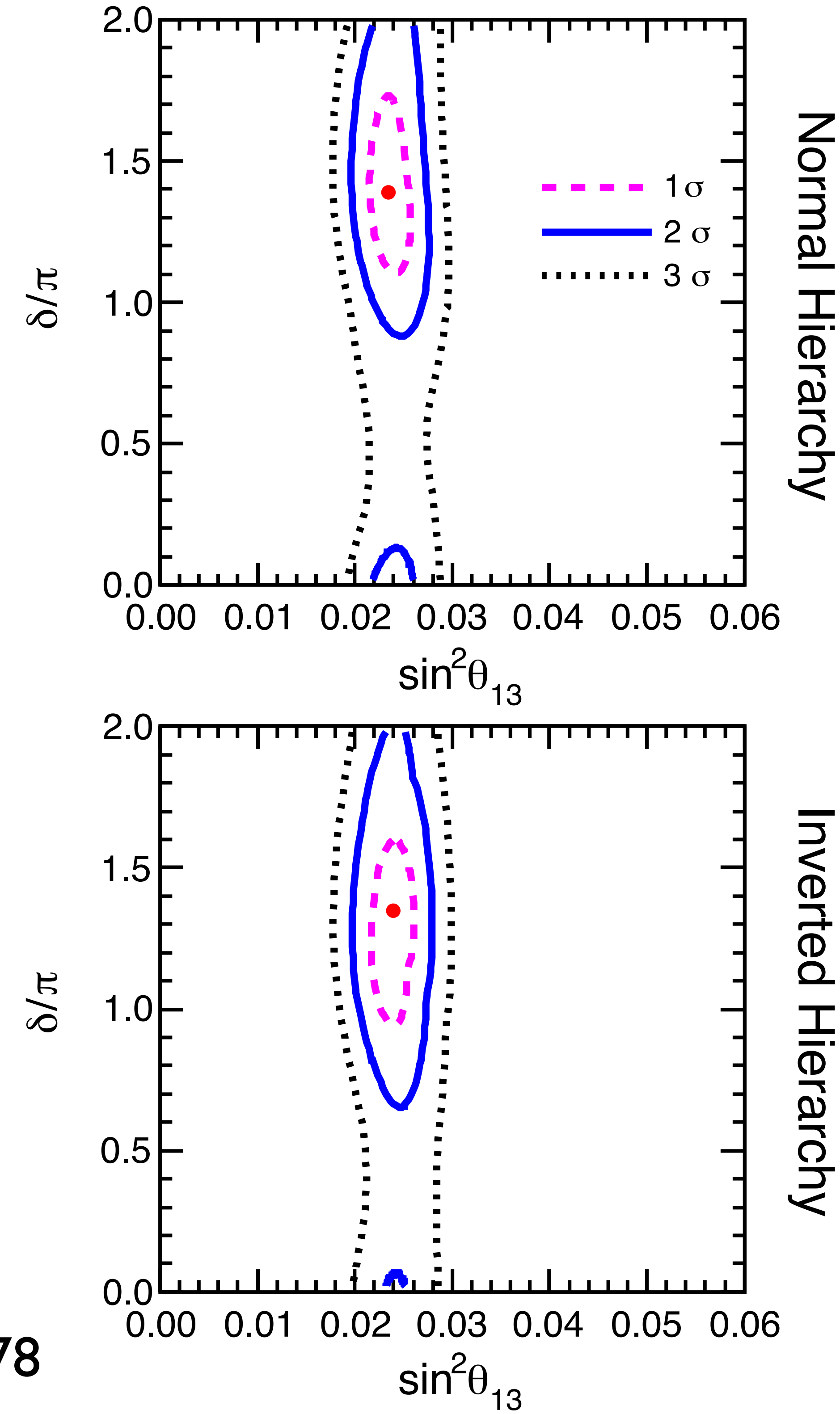
See Meloni's talk




We have determined

2 mass squared differences

3 mixing angles.




F. Capozzi et al., 1312.2878

| Parameter | Best fit | $1\sigma$ range |
|---|---|---|
| $\delta m^2/10^{-5}$ eV$^2$ (NH or IH) | 7.54 | 7.32 – 7.80 |
| $\sin^2\theta_{12}/10^{-1}$ (NH or IH) | 3.08 | 2.91 – 3.25 |
| $\Delta m^2/10^{-3}$ eV$^2$ (NH) | 2.44 | 2.38 – 2.52 |
| $\Delta m^2/10^{-3}$ eV$^2$ (IH) | 2.40 | 2.33 – 2.47 |
| $\sin^2\theta_{13}/10^{-2}$ (NH) | 2.34 | 2.16 – 2.56 |
| $\sin^2\theta_{13}/10^{-2}$ (IH) | 2.39 | 2.18 – 2.60 |
| $\sin^2\theta_{23}/10^{-1}$ (NH) | 4.25 | 3.98 – 4.54 |
| $\sin^2\theta_{23}/10^{-1}$ (IH) | 4.37 | 4.08 – 4.96 $\oplus$ 5.31 – 6.10 |
| $\delta/\pi$ (NH) | 1.39 | 1.12 – 1.72 |
| $\delta/\pi$ (IH) | 1.35 | 0.96 – 1.59 |

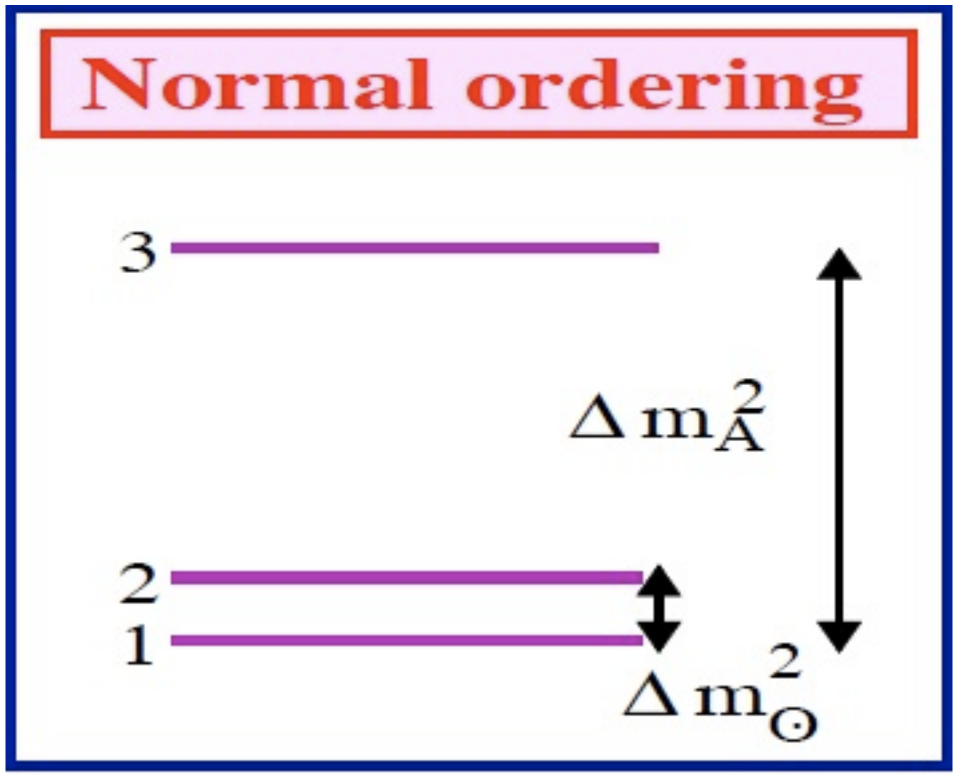
F. Capozzi et al., 1312.2878

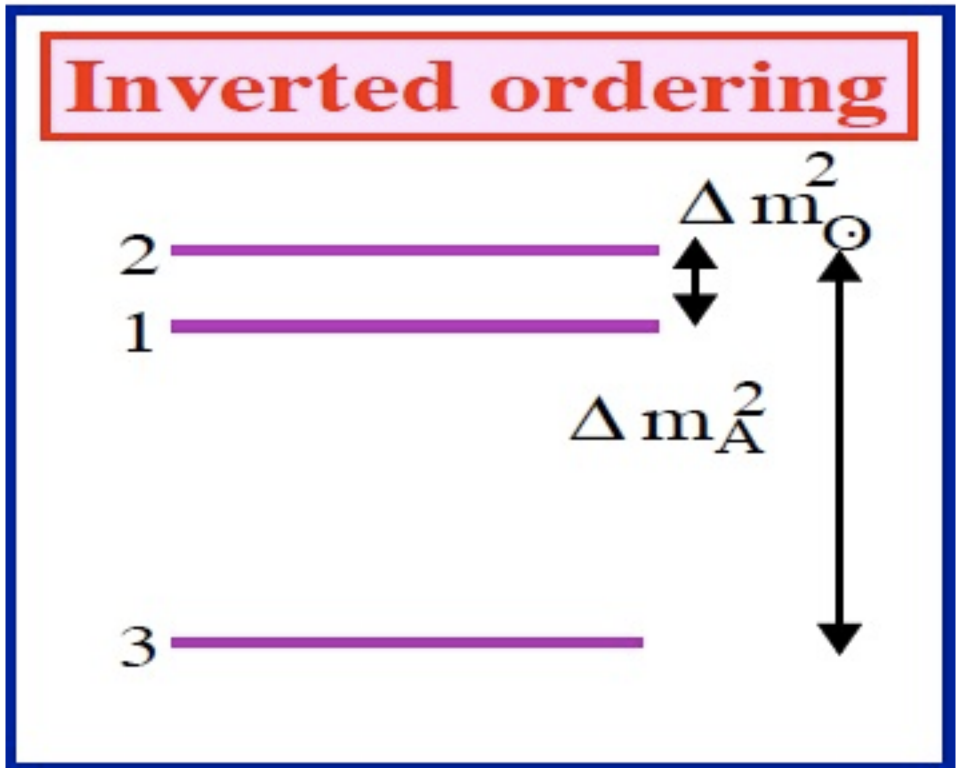
With the discovery of theta13 and its subsequent accurate measurement, all oscillation parameters are known with very good precision, except for the mass hierarchy and the delta phase.

One needs also to check the 3-neutrino paradigm (not discussed) in view of LSND, MiniBooNE and the reactor anomaly.

# Present status of (standard) neutrino physics

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




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

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

Measuring the masses requires: $m_{\min}$ and the ordering .

# Neutrino mixing

Mixing is described by the Pontecorvo-Maki-Nakagawa-Sakata matrix, which enters in the CC interactions

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i}|\nu_i\rangle$$

$$\mathcal{L}_{CC} = -\frac{g}{\sqrt{2}}\sum_{k\alpha}\left(U^*_{\alpha k}\bar{\nu}_{kL}\gamma^\rho l_{\alpha L}W_\rho + \text{h.c.}\right)$$

Large angles

$$U = \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Solar, reactor } \theta_\odot \sim 30^o} \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{Atm, Acc. } \theta_A \sim 45^o}$$

CPV?

$$\underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{-i\delta} \end{pmatrix}}_{\text{CPV phase}} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix}}_{\text{Reactor, Acc. } \theta_{13} \sim 9^o} \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{-i\alpha_{21}/2} & 0 \\ 0 & 0 & e^{-i\alpha_{31}/2+i\delta} \end{pmatrix}}_{\text{CPV Majorana phases}}$$

CPV is a fundamental question to answer, possibly related to the origin of the baryon asymmetry.

# Nature of Neutrinos: Majorana vs Dirac

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

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

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

- This is crucial information to understand the **Physics BSM: with or without L-conservation**?

- Lepton number violation is a necessary condition for **Leptogenesis**.

# Phenomenology questions for the future

- **1. What is the nature of neutrinos?**
- **2. What are the values of the masses?** Absolute scale (KATRIN, ...?) and the ordering.
- **3. Is there CP-violation?** Its discovery in the next generation of LBL depends on the value of delta.
- **4. What are the precise values of mixing angles?** Do they suggest a underlying pattern?
- **5. Is the standard picture correct?** Are there NSI? Sterile neutrinos? Other effects?

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Neutrino oscillation experiments



@Silvia Pascoli

# Absolute values of neutrino masses

Neutrino oscillations are not sensitive to the absolute mass scale. However, via matter effects they can establish the mass ordering.

- Direct mass searches in beta decays: model-independent but feasible only for QD spectrum.

- Neutrinoless double beta decay: if dominant mechanism is light neutrino masses.

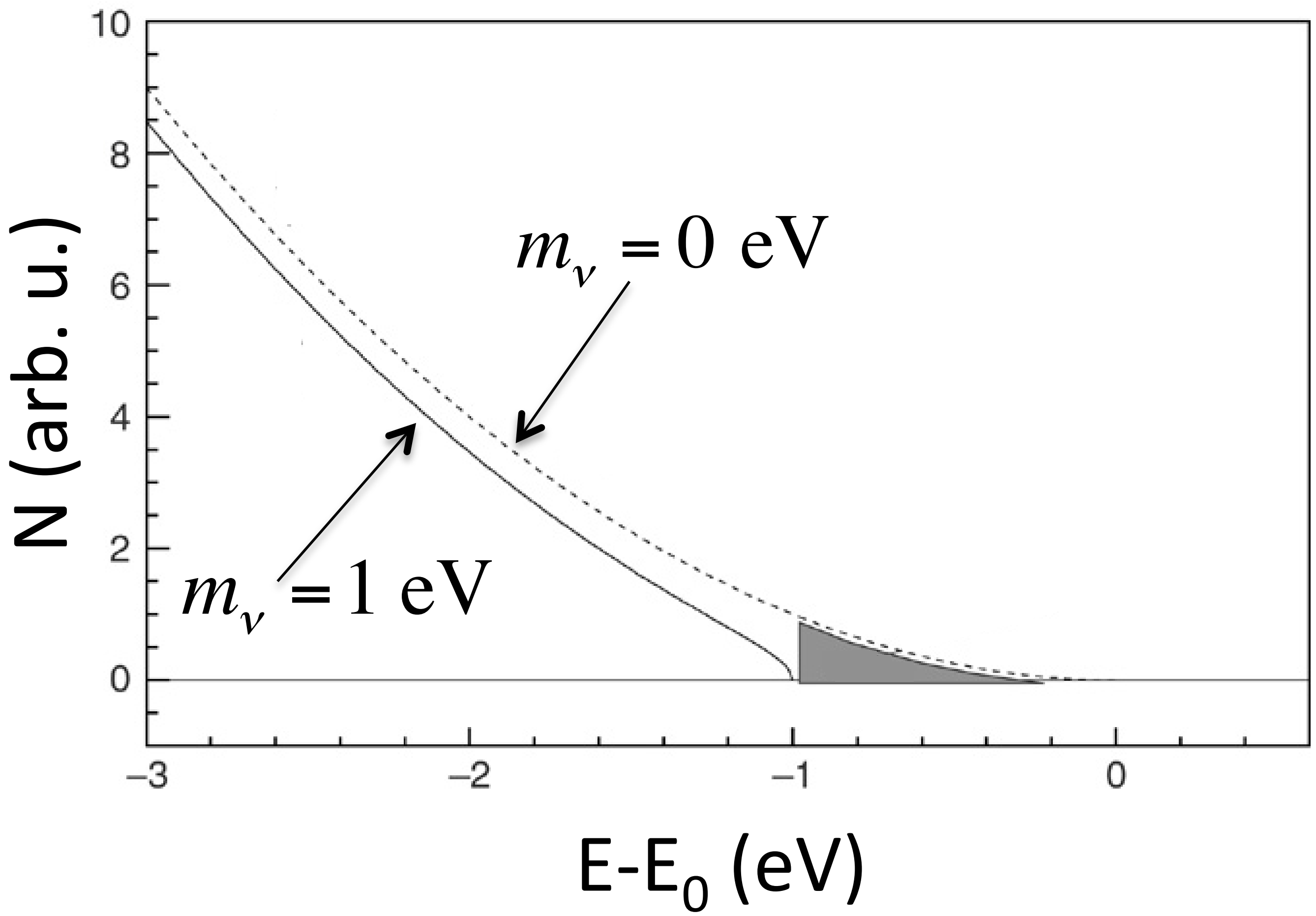
- Neutrino masses from cosmology by probing the DM distribution (observing the distribution of biased tracers and/or gravitational lensing)

# Direct mass measurements

The electron spectrum in beta decays depends on neutrino masses as

$$\frac{d\Gamma}{dE_e} = \sum_i |U_{ei}|^2 \frac{d\Gamma_i}{dE_e}(m_i)$$ with

$$\frac{d\Gamma_i}{dE_e} = \mathcal{C}|M|^2 p_e(E_e + m_e)(E_e - E_0)\sqrt{(E_e - E_0)^2 - m_i^2}\, F(E_e)$$




$$m_\beta \sim \sqrt{|U_{ei}|^2 m_i^2} \sim m_0$$

C. Weinheimer, PNPP 2006

- $^3H$ beta decay experiments: Troitsk and Mainz.

  Use of tritium beta decay
  $E_0$ = 18.58 keV
  t = 12.3 yrs

They provide the most stringent limit (95% CL):

$m_0 < 2.3$ eV

Kraus et al., EPJC 40

$m_0 < 2.05$ eV

Aseev et al., PRD 84

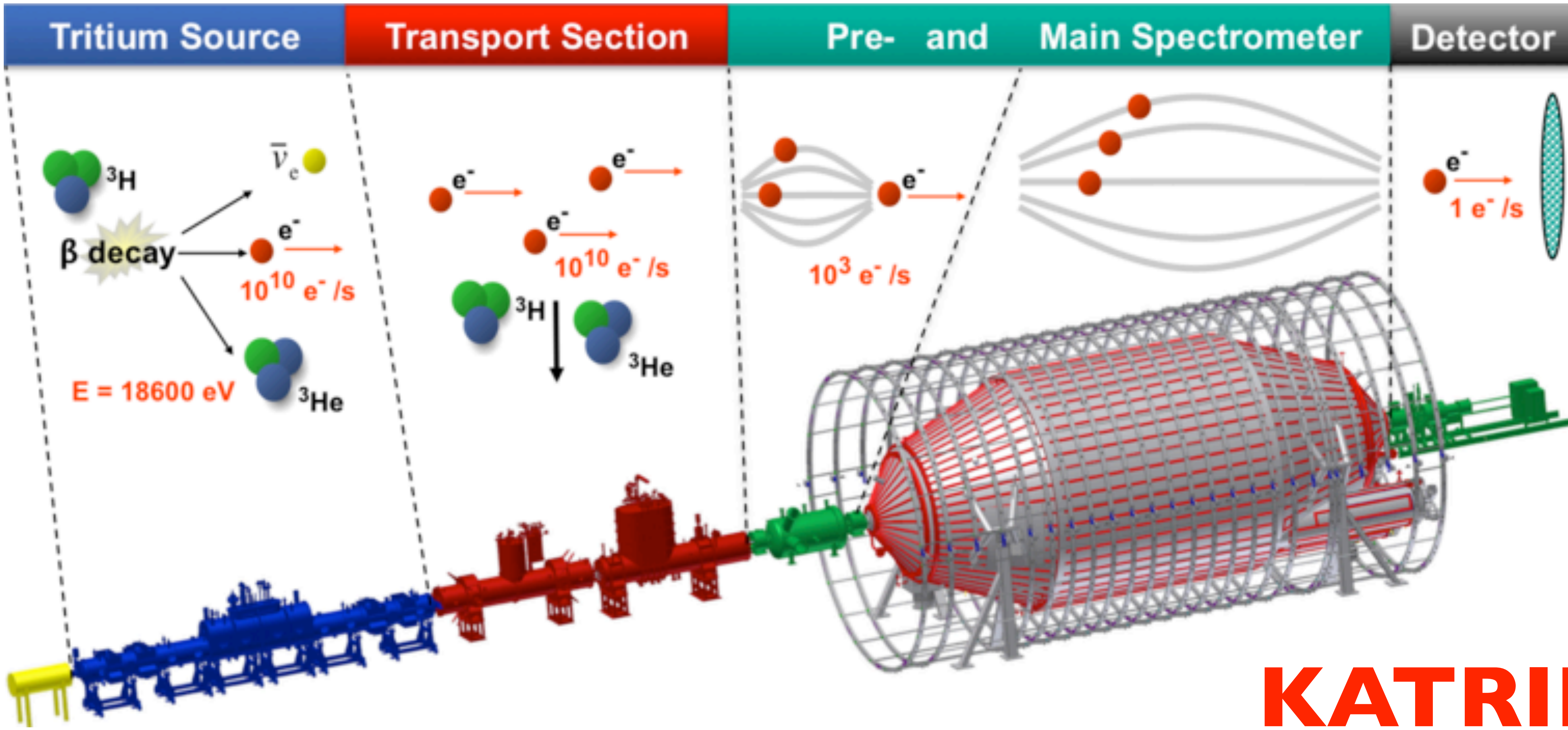
- Searches with cryogenic bolometers using $^{187}Re$

MIBETA (Milano/Como): $m_0 < 15.6$ eV at 90% C.L.

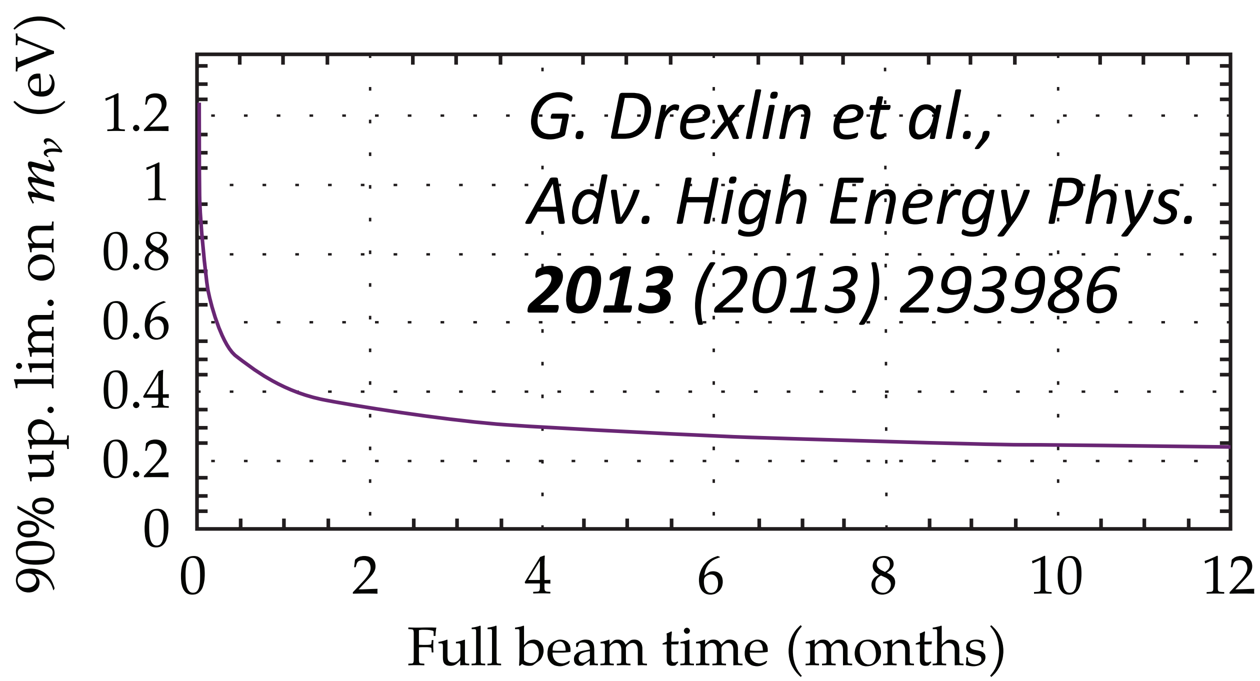
Sisti et al., NIMA 520

MANU: $m_0 < 26$ eV Gatti, NPB91

MARE-1 and MARE-2



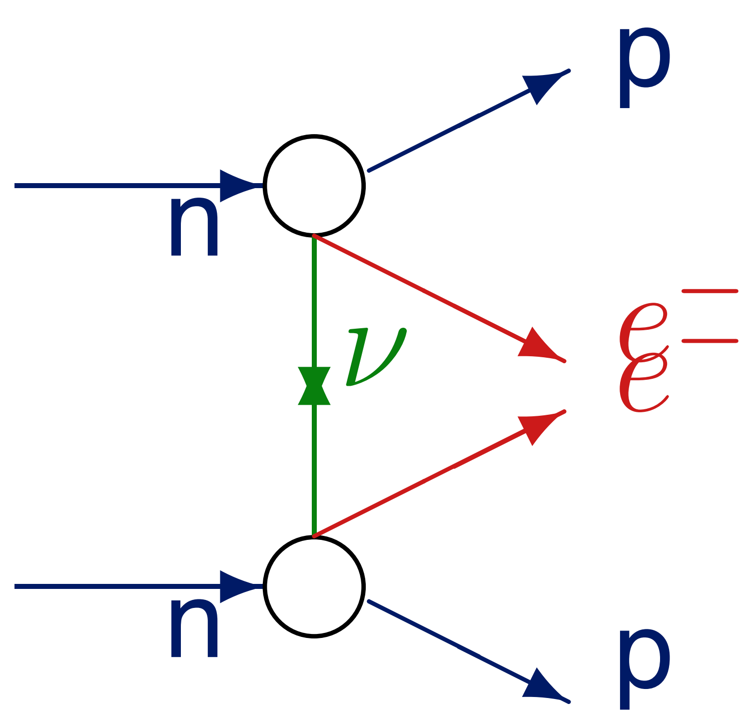

# KATRIN




KATRIN is in the commissioning phase. Data taking will start in late 2015. It will reach a sensitivity down to m<0.2 eV and a 5-sigma discovery of m=0.35 eV.

# Neutrinoless double beta decay

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




This process has a special role in the study of neutrino properties as it probes lepton number violation and can provide information on neutrino masses and (possibly) on CP-violation.

## The half-life time depends on neutrino properties

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

- $|\langle m \rangle| = m_{ee}$ : 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. They need to be computed theoretically.

# Predictions for betabeta decay

The predictions for |<m>| depend on the neutrino mass spectrum

- NH (m1<<m2<<m3): |<m>| ~ 2.5-3.9 meV

$$|{<}m{>}| \simeq \left| \sqrt{\Delta m^2_\odot} \cos^2\theta_{13} \sin^2\theta_\odot + \sqrt{\Delta m^2_{\rm atm}} \sin^2\theta_{13} e^{i\alpha_{32}} \right|$$

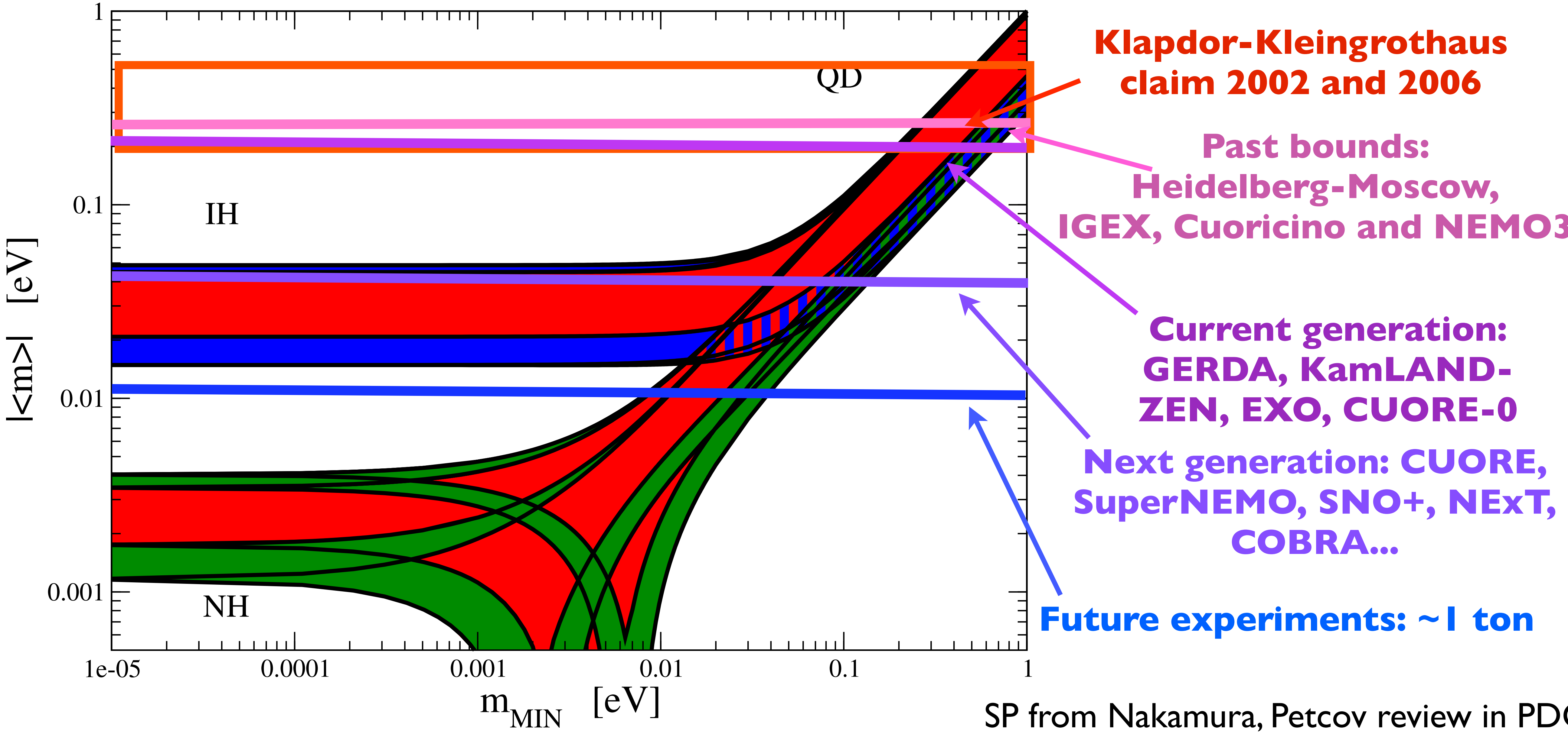
- IH (m3<<m1~m2): 10 meV < |<m>| < 50 meV

$$\sqrt{\Delta m^2_{\rm atm}} \cos 2\theta_\odot \leq |{<}m{>}| \simeq \sqrt{\left(1 - \sin^2 2\theta_\odot \sin^2 \frac{\alpha_{21}}{2}\right) \Delta m^2_{\rm atm}} \leq \sqrt{\Delta m^2_{\rm atm}}$$

- QD (m1~m2~m3): 44 meV < |<m>| < m1

$$|{<}m{>}| \simeq m_{\bar\nu_e} \left| \left( \cos^2\theta_\odot + \sin^2\theta_\odot e^{i\alpha_{21}} \right) \cos^2\theta_{13} + \sin^2\theta_{13} e^{i\alpha_{31}} \right|$$

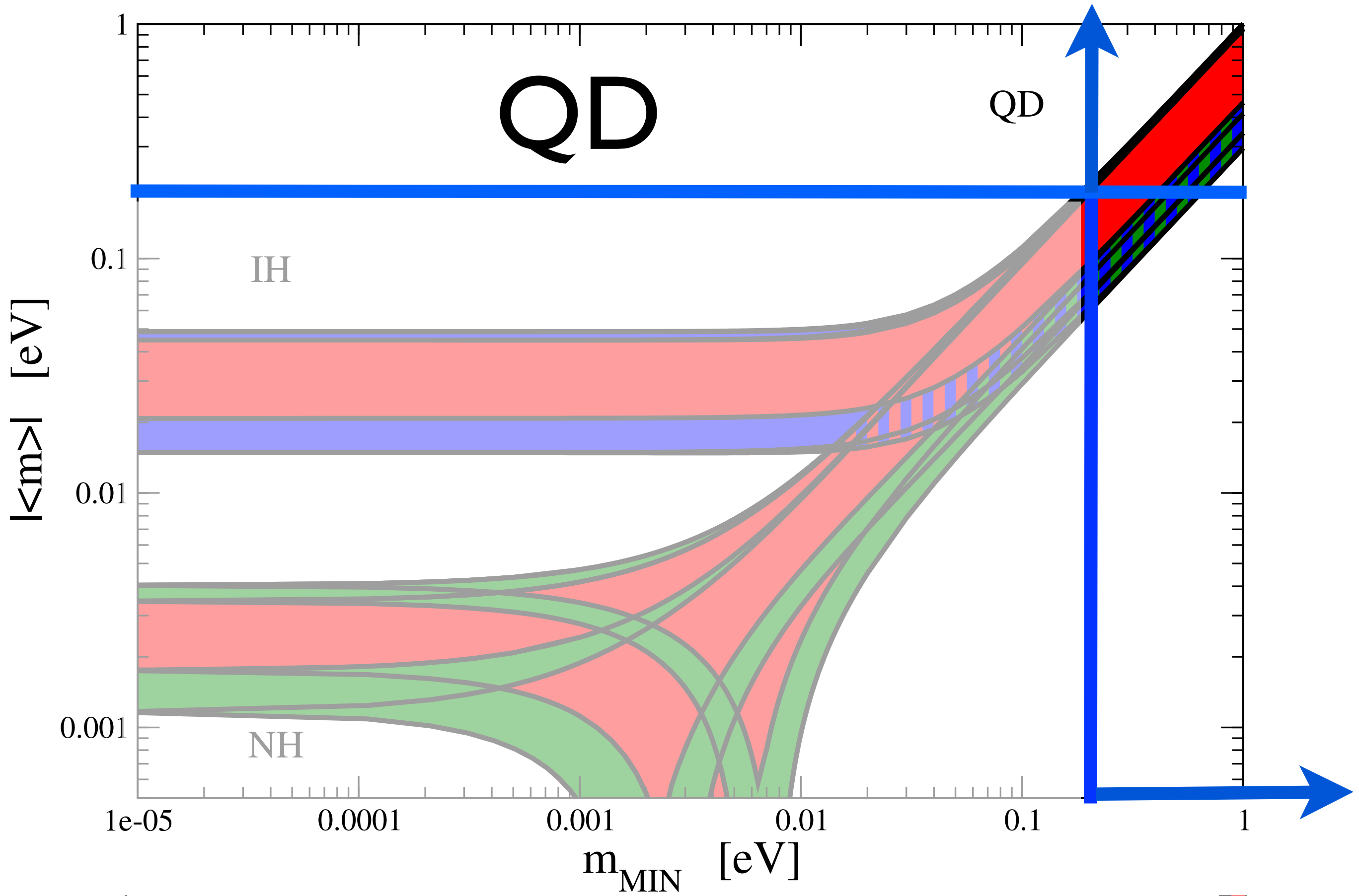
$$|\langle m\rangle| \sim |m_1 \cos^2\theta_{12} + m_2 \sin^2\theta_{12} e^{i\alpha_{21}} + m_3 \sin^2\theta_{13} e^{i\alpha_{31}}|$$



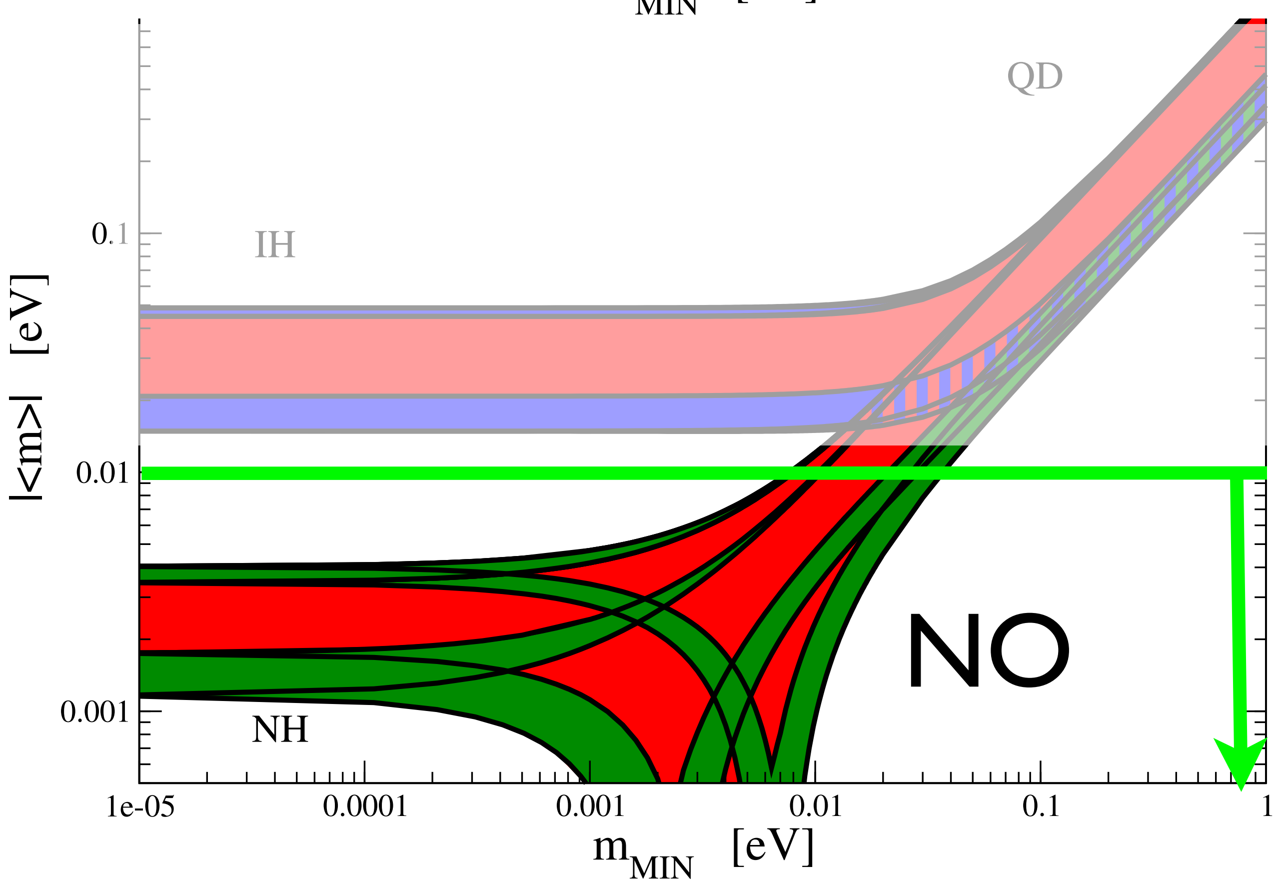

SP from Nakamura, Petcov review in PDG

**Wide experimental program** for the future: **a positive signal would indicate that L is violated!**

# Determining neutrino masses with neutrinoless dbeta decay




- If |<m>| > 0.2 eV, then the neutrino spectrum is QD. The measurement of m1 is entangled with the value of the Majorana phase.

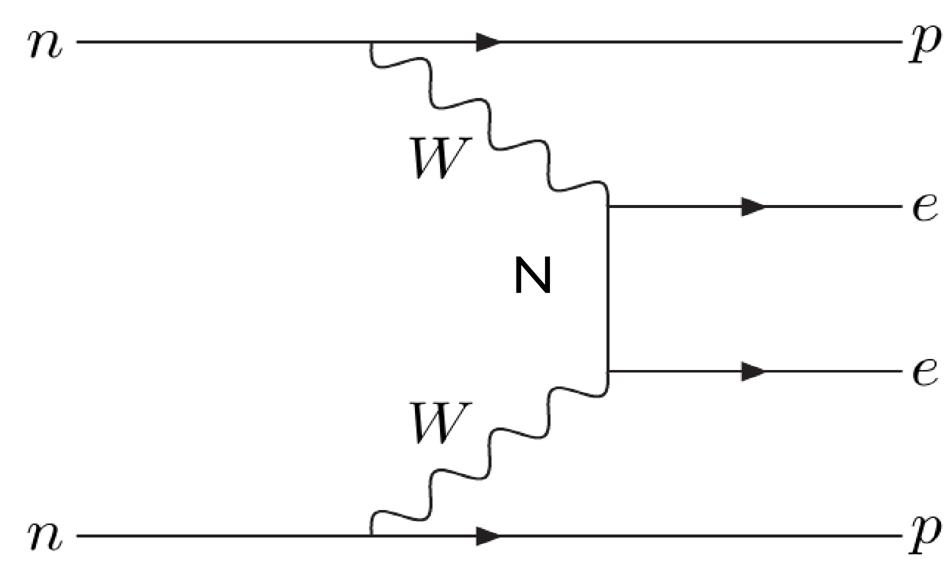


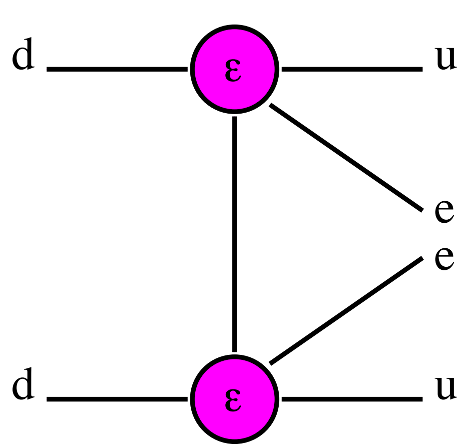

- • If no signal for |<m>| ~10 meV, then only NO is allowed.
  • If LBL experiments find IO, neutrino are Dirac particles (without fine-tuned cancellations).

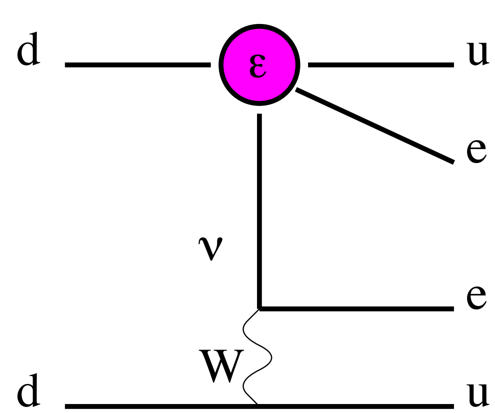
# Other mechanisms

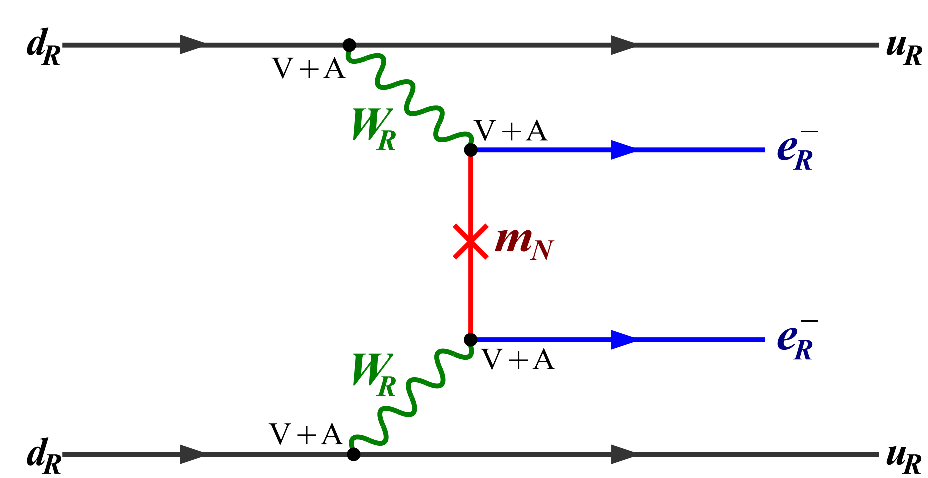
Neutrinoless double beta decay can also be mediated by other LNV mechanisms.

- Light sterile neutrinos
- Heavy sterile neutrinos
- R-parity violating SUSY
- Extra dimensional models
- Left-Right models



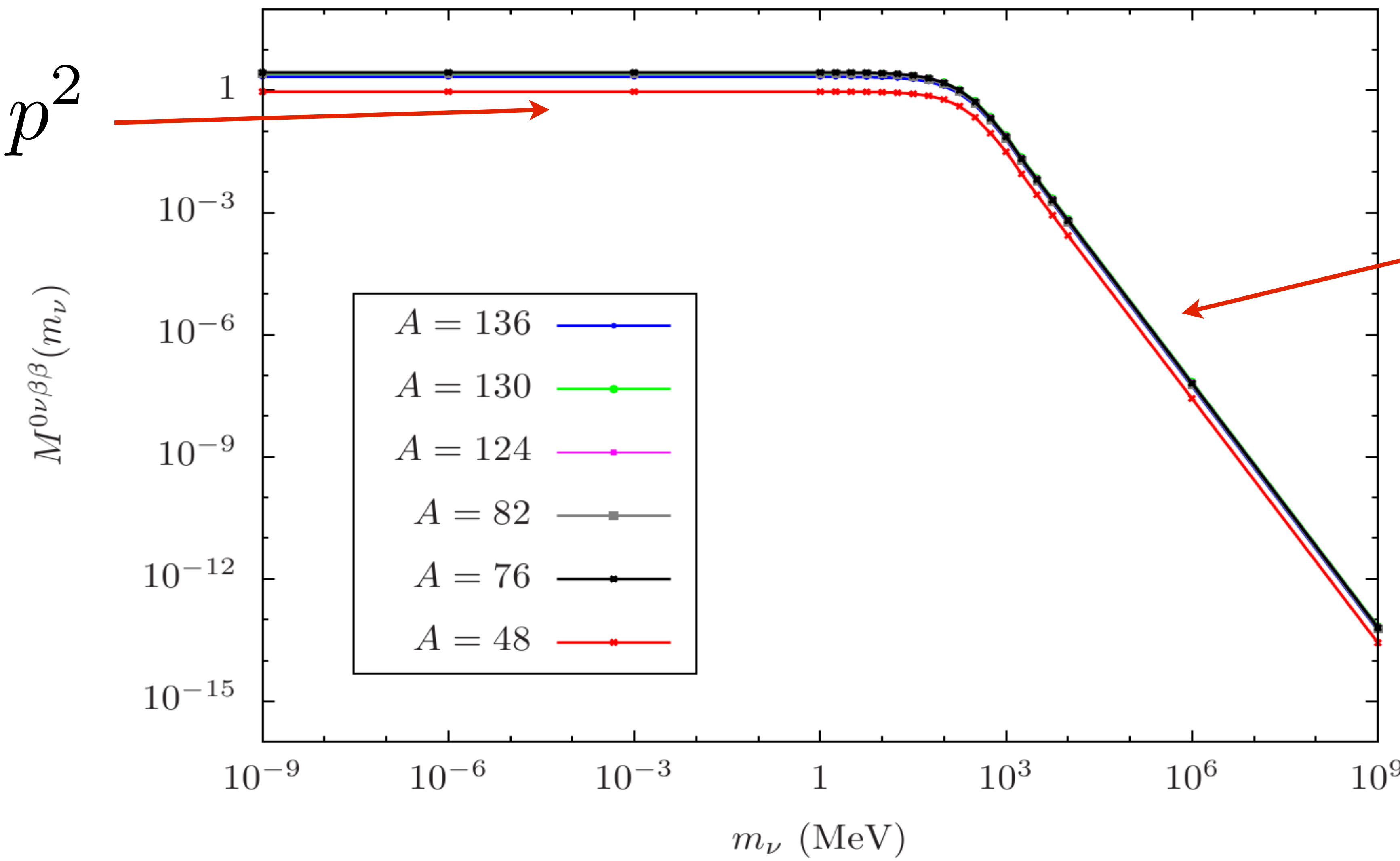

Deppisch, Hirsch, Pas, 1208.0727

In most cases the new mechanisms (with heavy particles) are subdominant as the NME for heavy particles suppress their contribution.

http://www.th.mppmu.mpg.de/members/blennow/nme_mnu.dat

$m_i^2 \ll p^2$

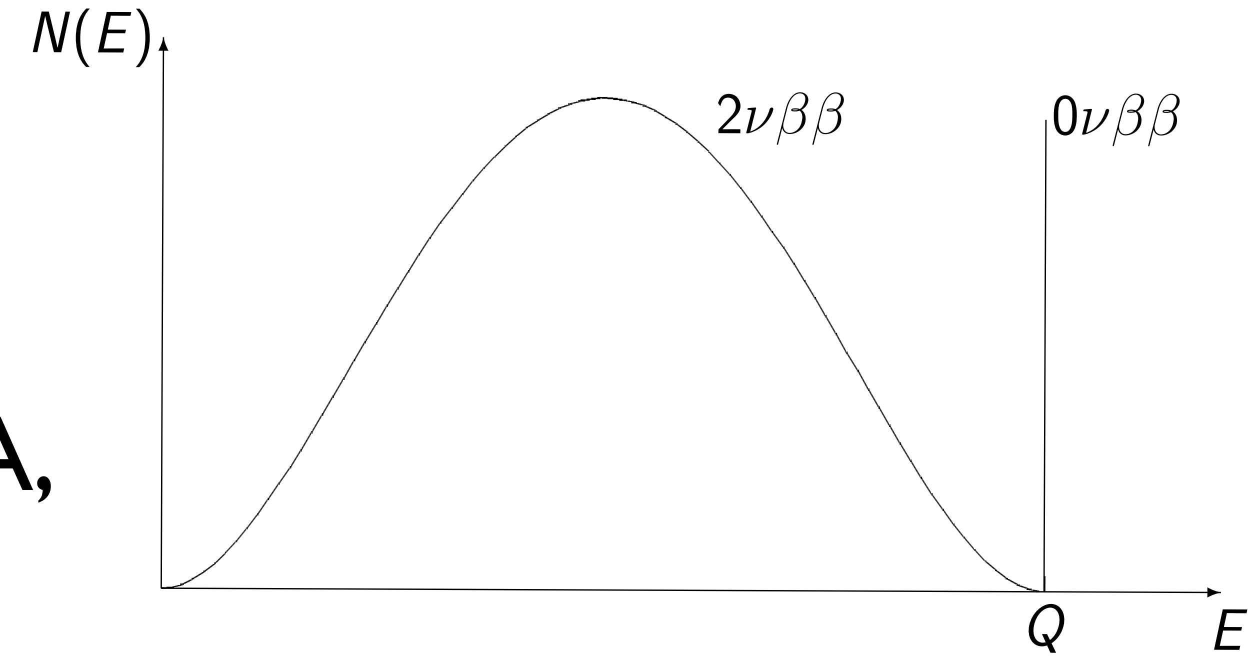
$M_i^2 \gg p^2$




The NME behaviour changes at p~100 MeV, the scale of the process.

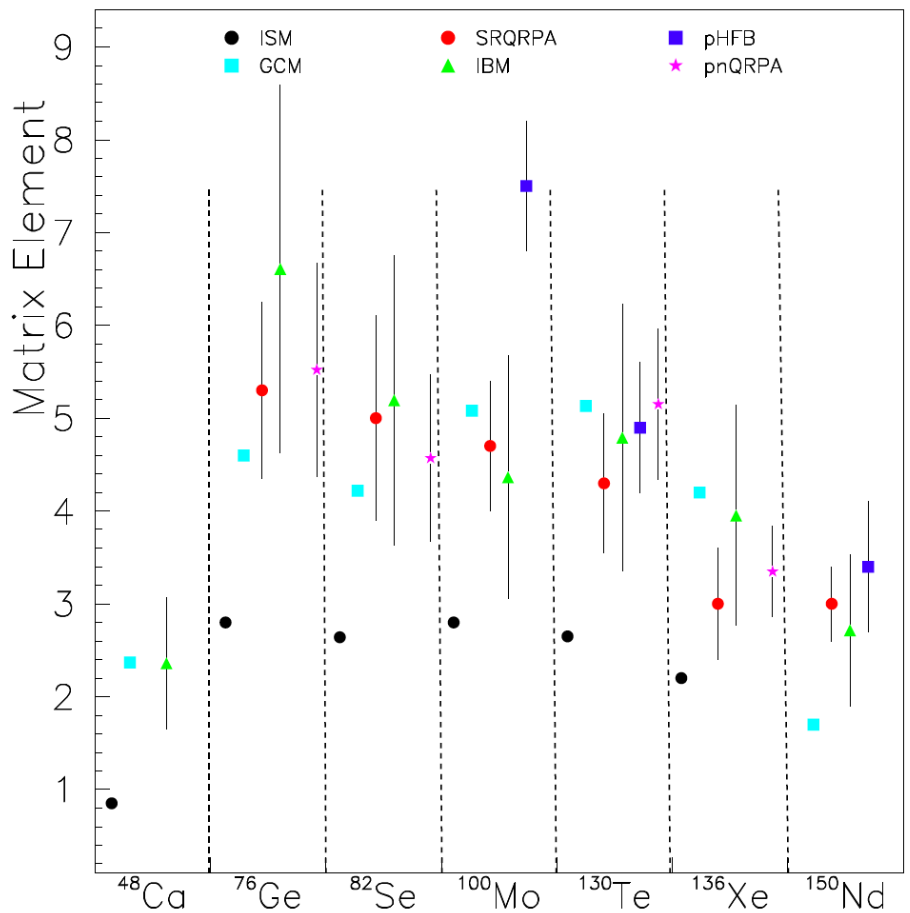
# Experimental searches of betabeta decay

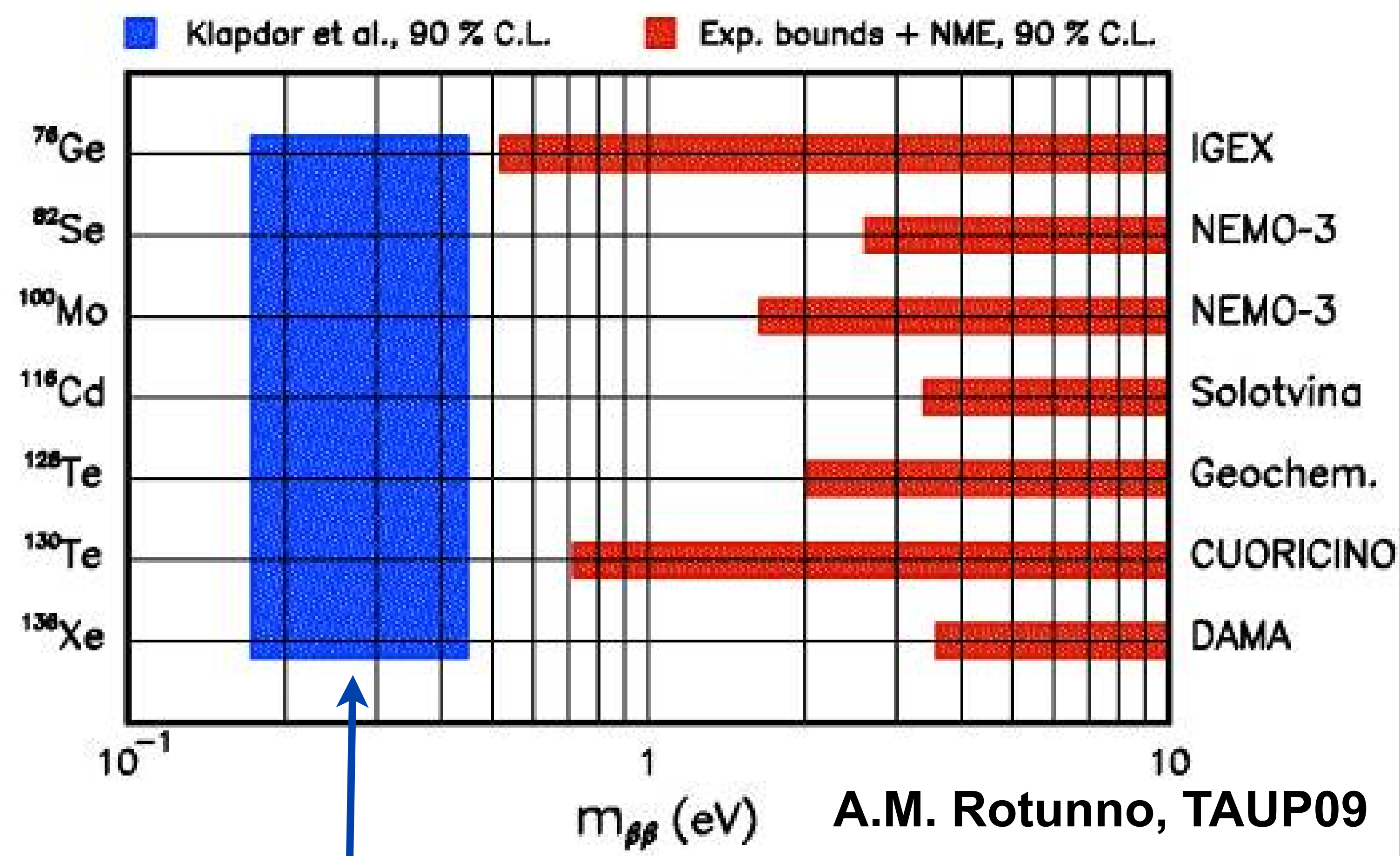
Neutrinoless double beta decay proceeds in nuclei in which single beta decay is kinematically forbidden but double beta decay (A, Z) → (A, Z+2) + 2 e + 2 v is allowed.




NMEs

B. Schwingenheuer, Annalen der Physik, 2012

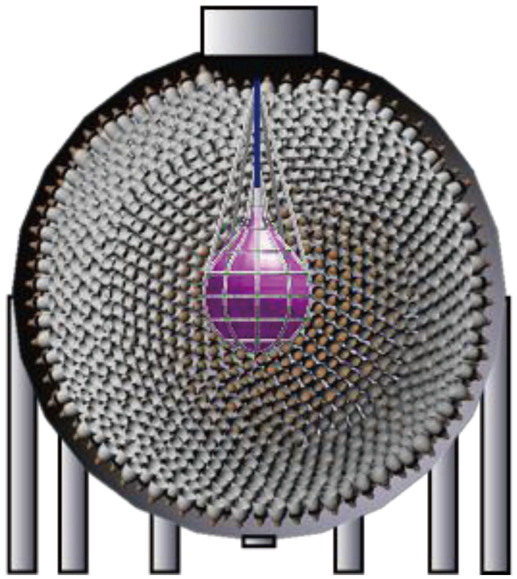



A.M. Rotunno, TAUP09

Depending on treatment of background, from 4.2 to 1.3 sigma

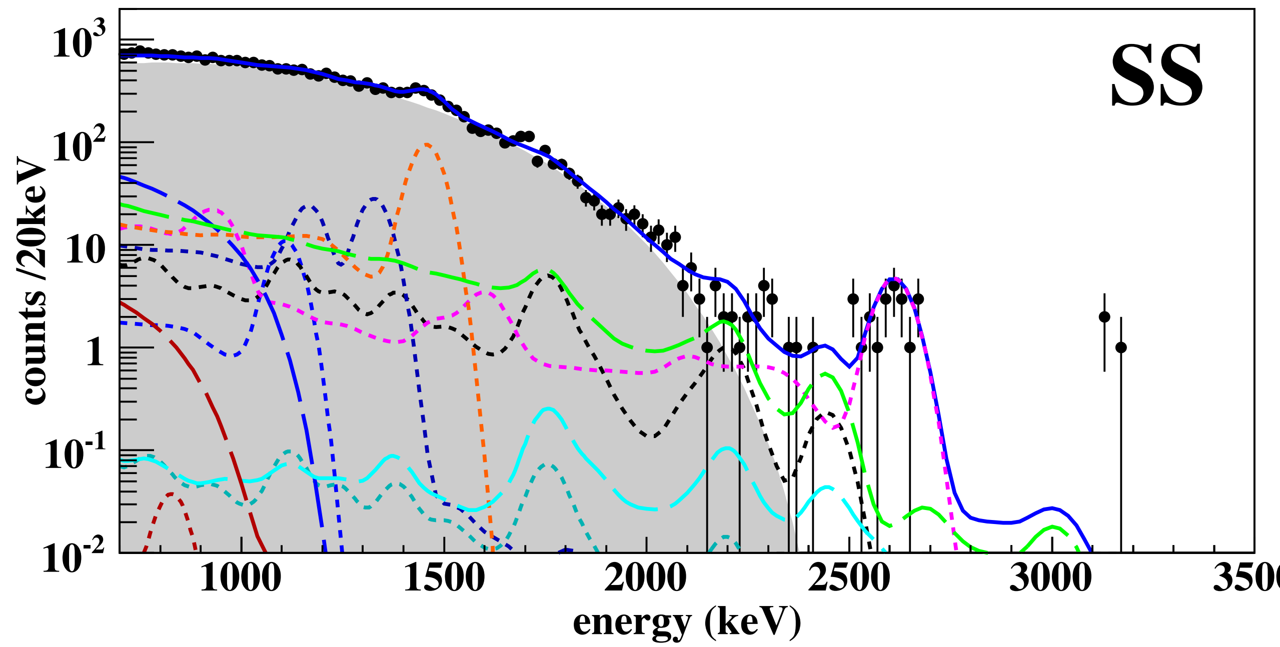
GERDA



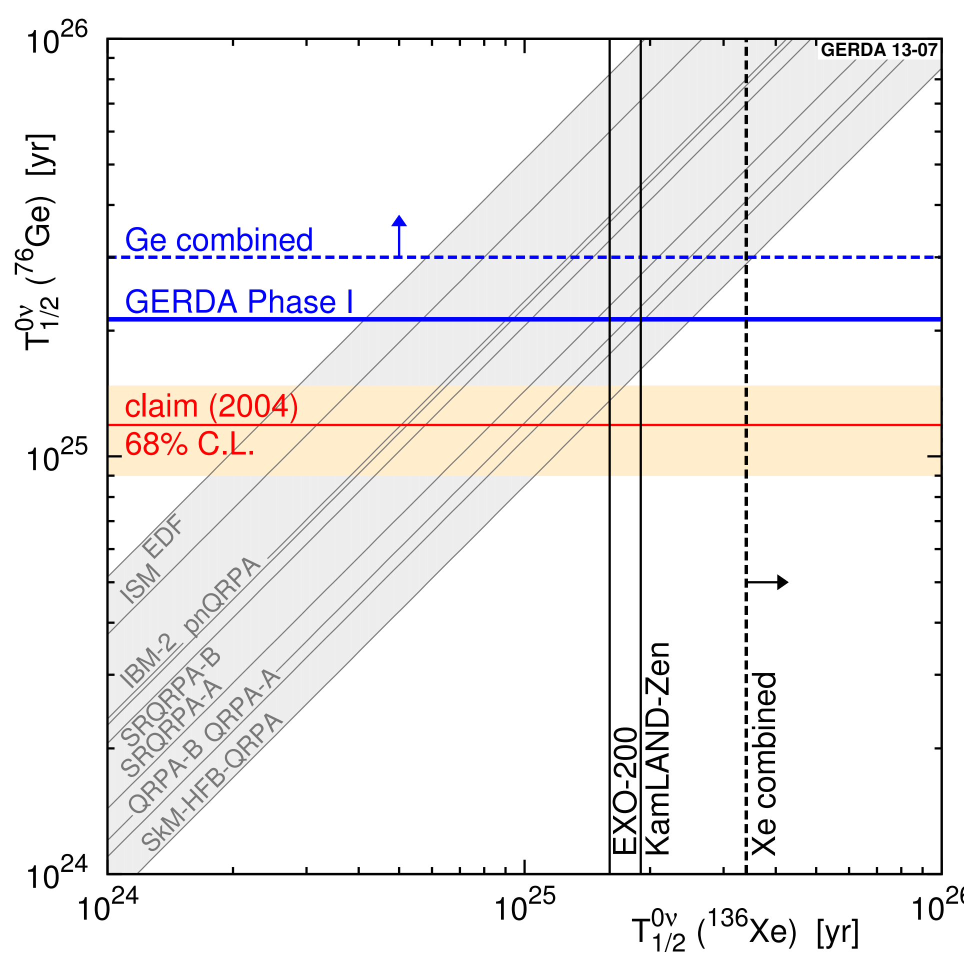
KamLAND-Zen


EXO-200 location, at the WIPP Site, USA, 1585 m.w.e.

See talks by Agostini, di Domizio.




EXO-200 reported the first results summer 2012, T(0nu) >1.6 10^25 yrs for Xe136.
First GERDA results: July 2013 1307.4720.



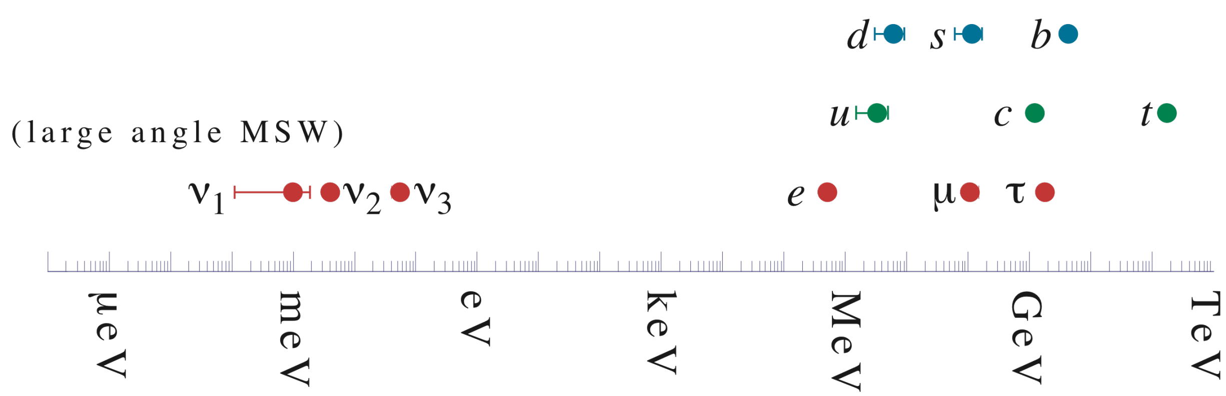

The new generation of experiments is already taking data (EXO, KamLAND-ZEN, CUORE, GERDA,...) and more powerful ones are planned (e.g., NExT, SNO+, SuperNEMO, COBRA,...)!!

**The ultimate goal is to understand**
**- where do neutrino masses come from?**
**- why is there leptonic mixing? and what is at the origin of the observed structure?**

# Open window on Physics beyond the SM

Neutrino physics gives a new perspective on physics BSM.

## 1. Origin of masses




Why do neutrinos have mass? and why are they so much lighter?

## 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?

This information is **complementary** with the one which comes from flavour physics experiments and from colliders.

# What is the new physics scale?

sub-eV eV keV MeV GeV TeV GUT scale

Thanks also to P. Hernandez

The **new Standard Model** will contain

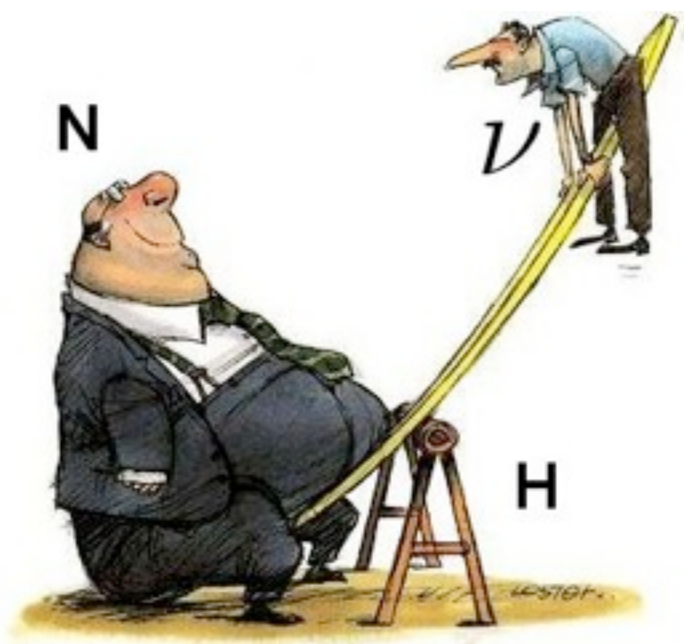
- new particles at a new physics scale
- new interactions.

Coupling with the dark sector. Neutrinos can be a portal to new physics:

$$\mathcal{L}_\nu = y \, \bar{L} \cdot H \; \text{new}$$

# What is the new physics scale?

sub-eV eV keV MeV GeV TeV GUT scale




## See-saw mechanism type I

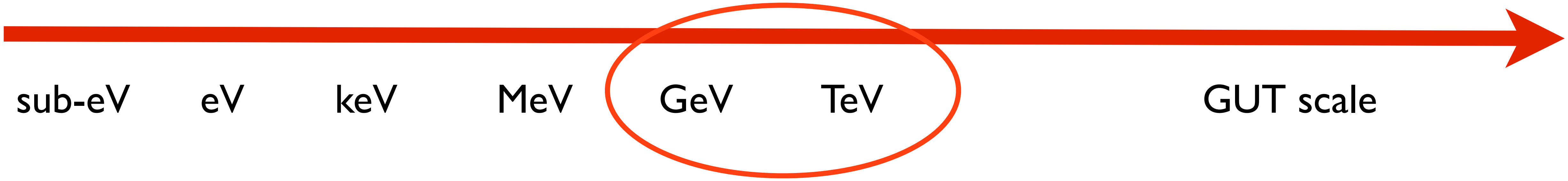
- Introduce a right handed neutrino **N**
- Couple it to the Higgs

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

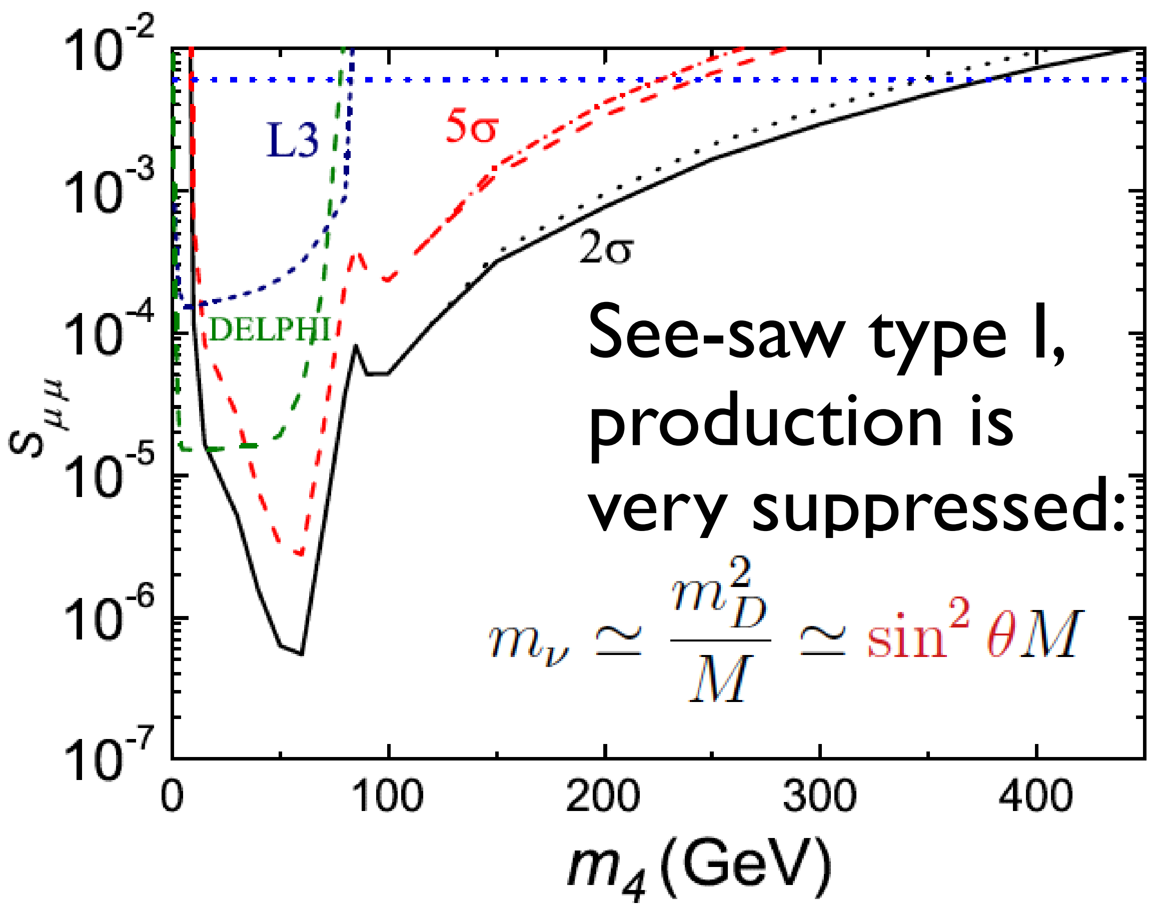
$$\begin{pmatrix} 0 & m_D \\ m_D^T & M_N \end{pmatrix} \Rightarrow m_\nu = \frac{Y_\nu^2 v_H}{M_N} \sim \frac{1 \text{ GeV}^2}{10^{10}\text{GeV}} \sim 0.1 \text{ eV}$$

See-saw type I models can be embedded in GUT theories and can also explain the baryon asymmetry via leptogenesis.

# What is the new physics scale?




For smaller Yukawa couplings or cancellations, small masses can arise from new physics at the TeV scale: in principle testable at the LHC by looking at same-sign dileptons.




See-saw type I, production is very suppressed:

$$m_\nu \simeq \frac{m_D^2}{M} \simeq \sin^2\theta M$$

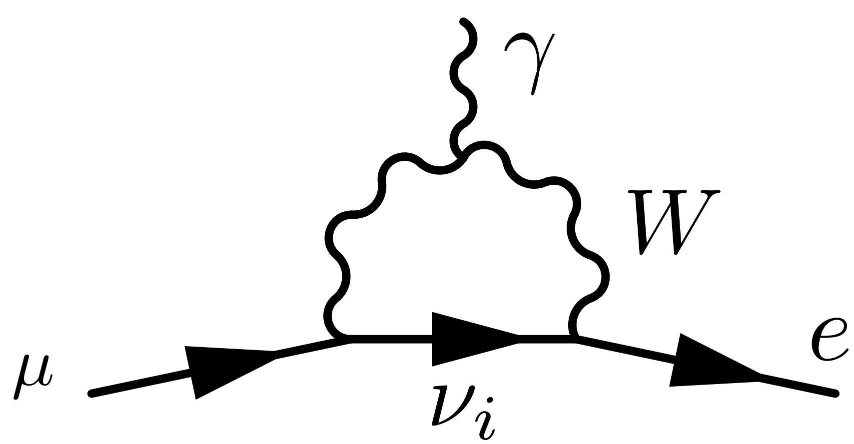
Atre et al., 0901.3589

- Gauge B-L: pp → Z' → N N
- See-saw type II: Scalar Triplets
- Triplet see-saw.
- Left-Right models via $W_R$
- Inverse or extended see-saw models
- R-parity violating SUSY

# What is the new physics scale?

sub-eV eV keV MeV GeV TeV GUT scale

Establishing the origin of neutrino masses requires to have as much information as possible about the masses and to combine it with other signatures of the models (proton decay, LHC searches...). CLFV plays a special role.




$$Br(\mu \to e\gamma)$$

$$\sim \frac{3\alpha}{32\pi}\left(\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta^2 m_{i1}}{m_W^2}\right)^2 \sim 10^{-53}$$

Many models of neutrino masses give raise to sizable LFV: models at the TeV scale with large mixing (e.g. Inverse seesaw), Radiative neutrino mass models, SUSY GUT see-saw models, Extra D, extra Higgs etc.

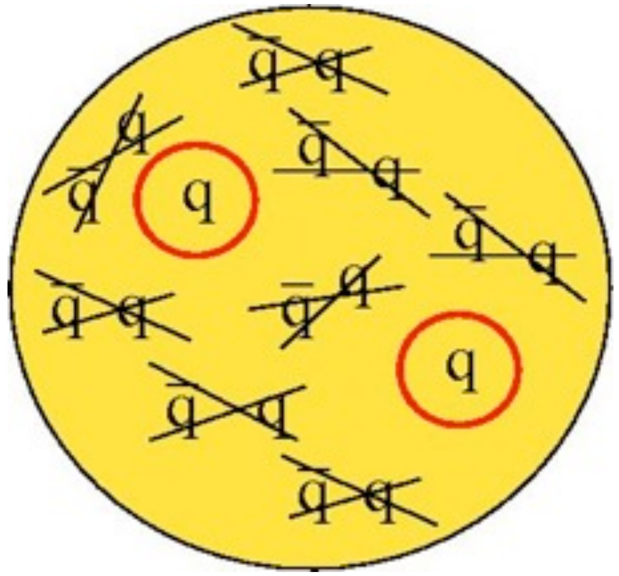
# Conclusions


The discovery of neutrino oscillations has opened a new perspective: neutrino have masses and mix implying new physics beyond the Standard Model of Particle Physics.

A wide experimental programme is taking place: in addition to oscillation experiments, direct mass searches and neutrinoless double beta decay experiments.

The ultimate goal is to understand the origin of neutrino masses (and the new physics scale) and of mixing.

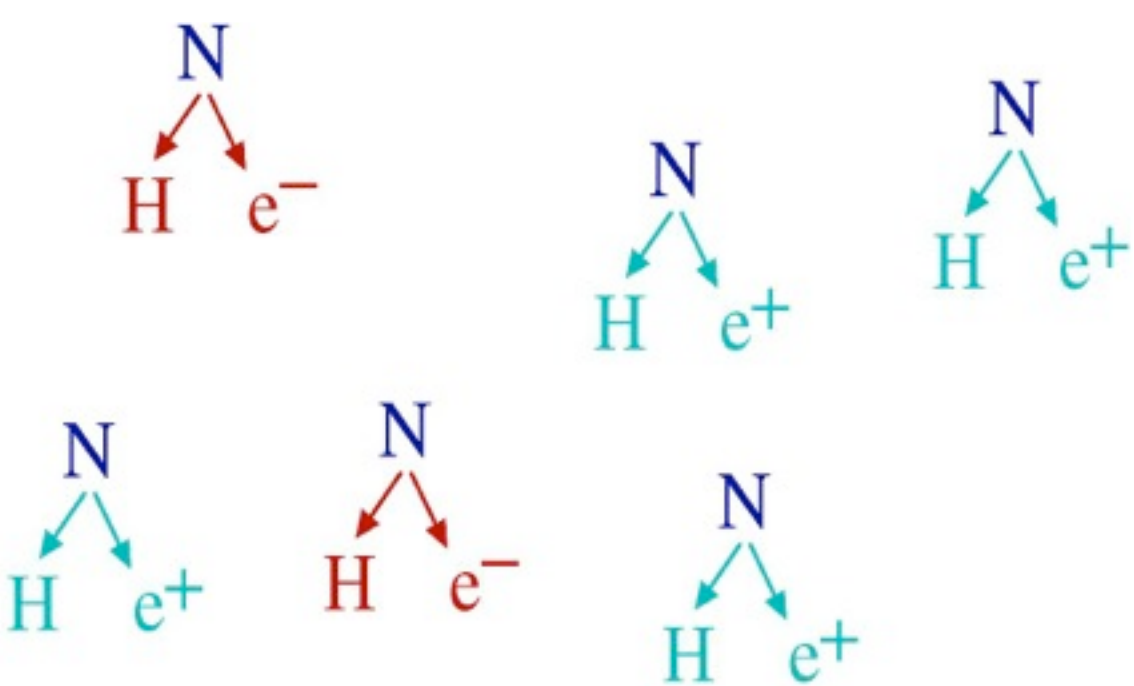
In the Early Universe



As the temperature drops, only quarks are left:

$$Y_B = \frac{n_B}{n_\gamma} = (6.0 \pm 0.2) \times 10^{-10}$$

The excess of quarks can be explained by **Leptogenesis** (Fukugita, Yanagida): the heavy N responsible for neutrino masses generate a lepton asymmetry.

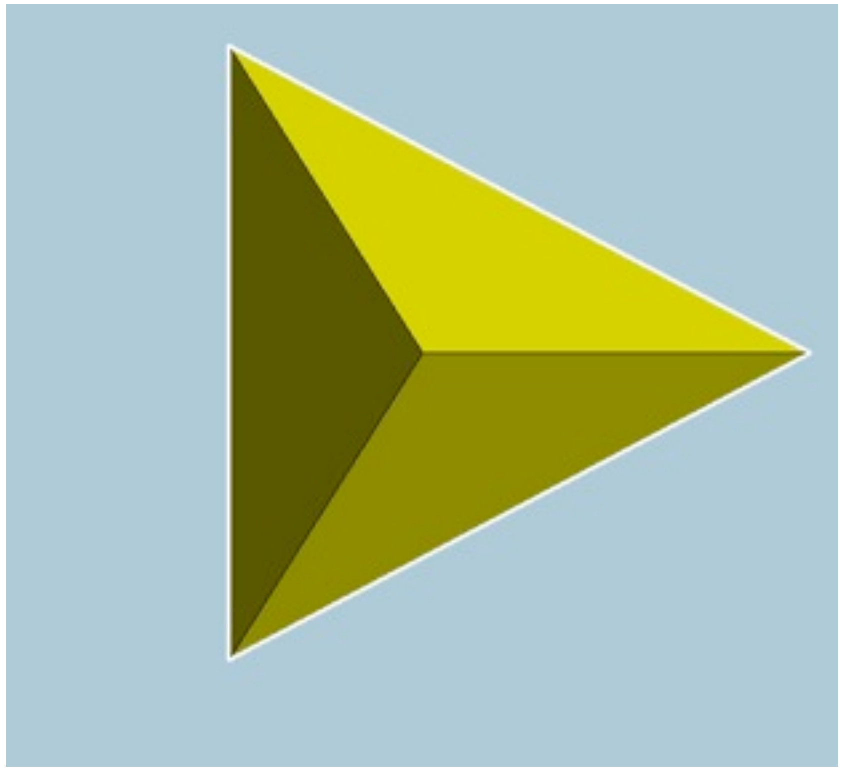



Excess of $e^+ \longrightarrow$ excess of $q$ over $\bar{q}$

**Observing L violation and CPV** would constitute a **strong hint in favour of leptogenesis as the origin of the baryon asymmetry**.

# The problem of flavour

Mixing in the leptonic sector is very different from the quark one: angles are large (even $\theta_{13}$ !) and there can be new sources of CP-violation. Neutrinos provide a different perspective on the flavour problem.



Why three generations?

Why the angles have the values measured?

What is the origin of CPV?

Various approaches can be adopted: Flavour symmetries; Anarchy; Quark-lepton complementarity...
It is crucial to measure with precision the mixing parameters to unveil any underlying pattern.