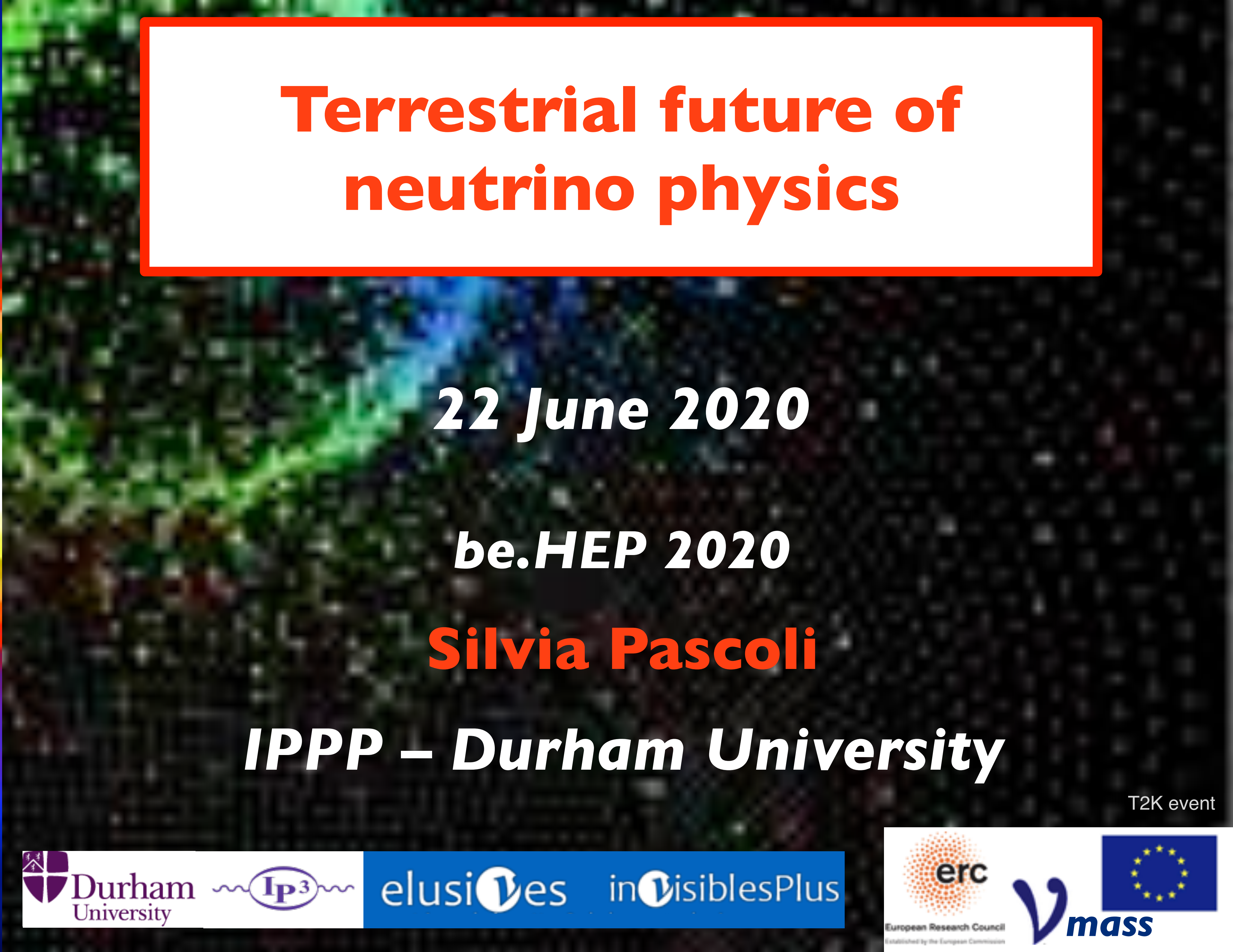
# Terrestrial future of neutrino physics



T2K event

*22 June 2020*

*be.HEP 2020*

**Silvia Pascoli**

*IPPP – Durham University*

Durham University

IP3

elusives

invisiblesPlus

erc

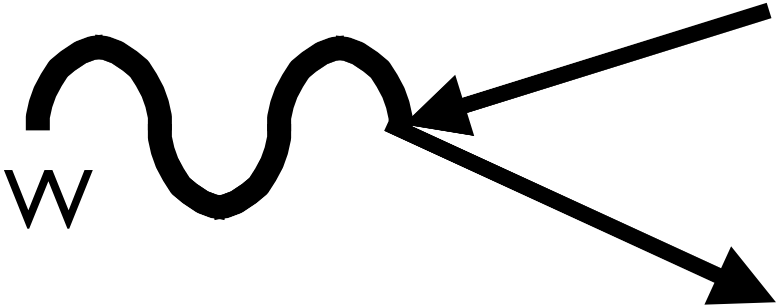
European Research Council

Established by the European Commission

νmass

# *Neutrinos in the SM*

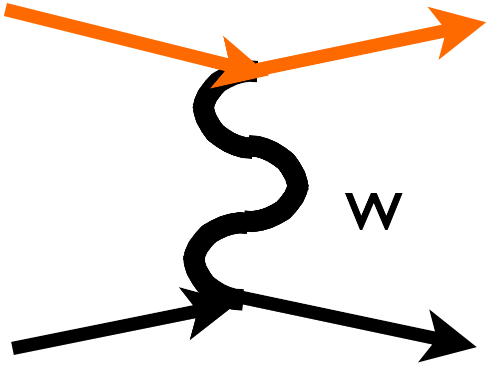
- They belong to SU(2) doublets: $\begin{pmatrix} \nu_e \\ e \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$


W

positron

electron neutrino

- Neutrinos can be produced and detected:


electron neutrino

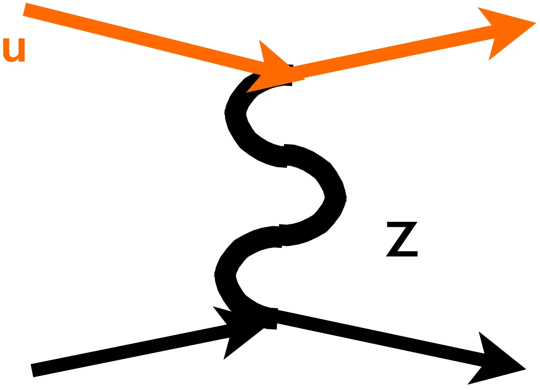
electron

W

n

p

charge current int.


electron, muon, tau neutrino

electron, muon, tau neutrino

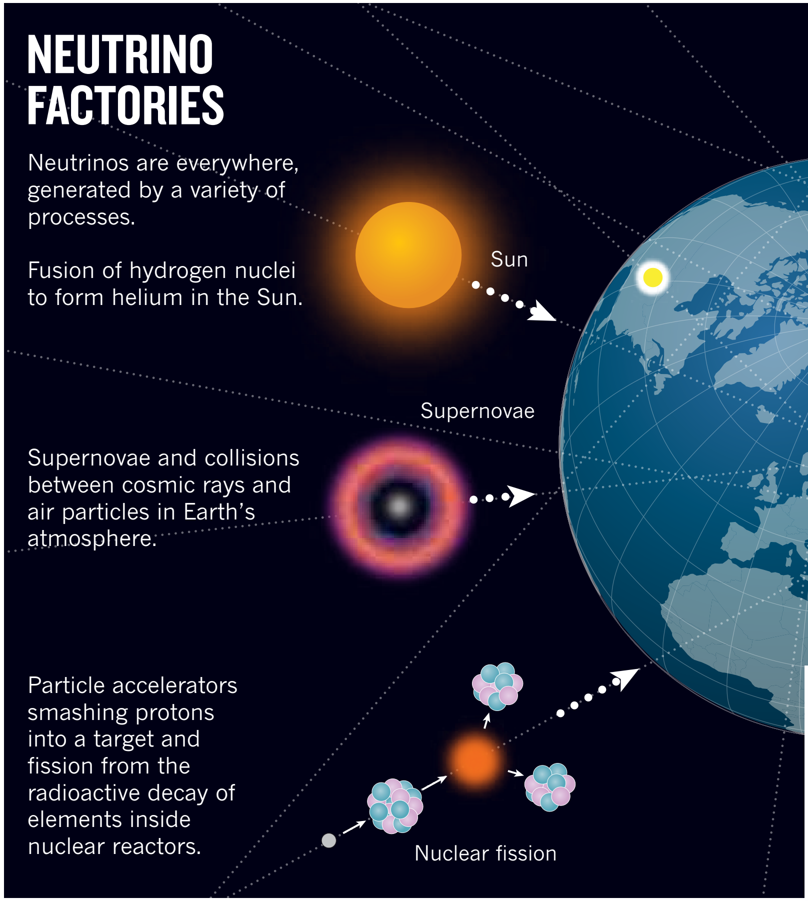
Z

n, p, e

n, p, e

neutral current int.

@Silvia Pascoli



**NEUTRINO FACTORIES**

Neutrinos are everywhere, generated by a variety of processes.

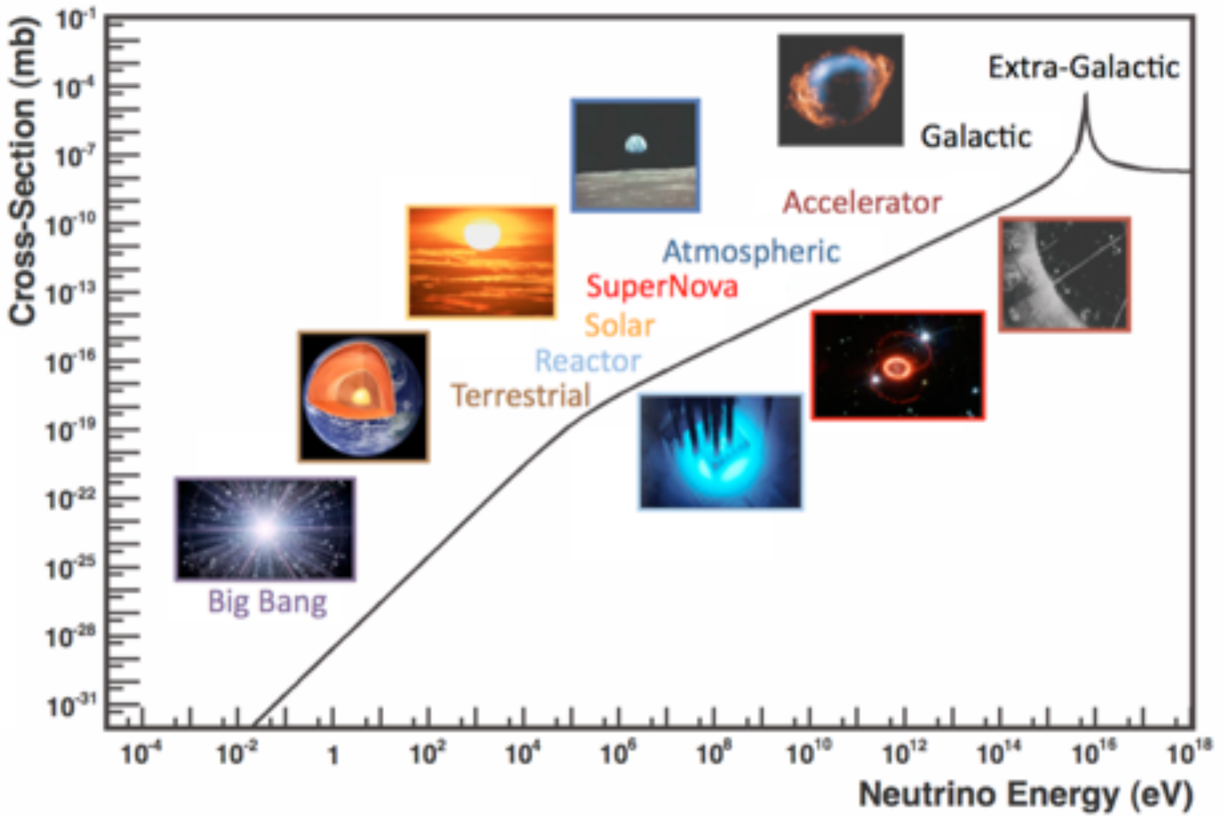
Fusion of hydrogen nuclei to form helium in the Sun.

Supernovae and collisions between cosmic rays and air particles in Earth's atmosphere.

Particle accelerators smashing protons into a target and fission from the radioactive decay of elements inside nuclear reactors.

@Nature, 2015

Neutrinos are produced in many processes with energy that go from sub-eV to 10^18 eV.



J. Formaggio and S. Zeller, 1305.7513

**NeutrinoScope** 4+

Bring neutrinos alive with AR!

Cambridge Consultants

★★★★★ 5.0, 7 Ratings

Free

Free App to "visualise" neutrinos around us.

# *BSM: Neutrino mixing and oscillations*

Mixing is described by the *Pontecorvo-Maki-Nakagawa-Sakata* matrix:

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

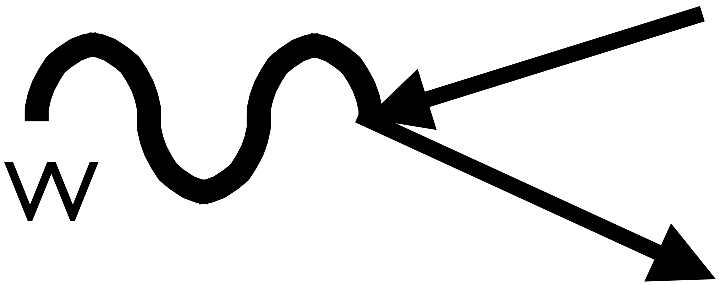
Flavour states

Mass states

which enters in the CC interactions

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

This implies that in an interaction with an electron, the corresponding (anti-)neutrino will be produced as a superposition of different mass eigenstates.



Positron

electron neutrino $= \sum_i U_{ei} \nu_i$

Let’s assume that at t=0 a muon neutrino is produced

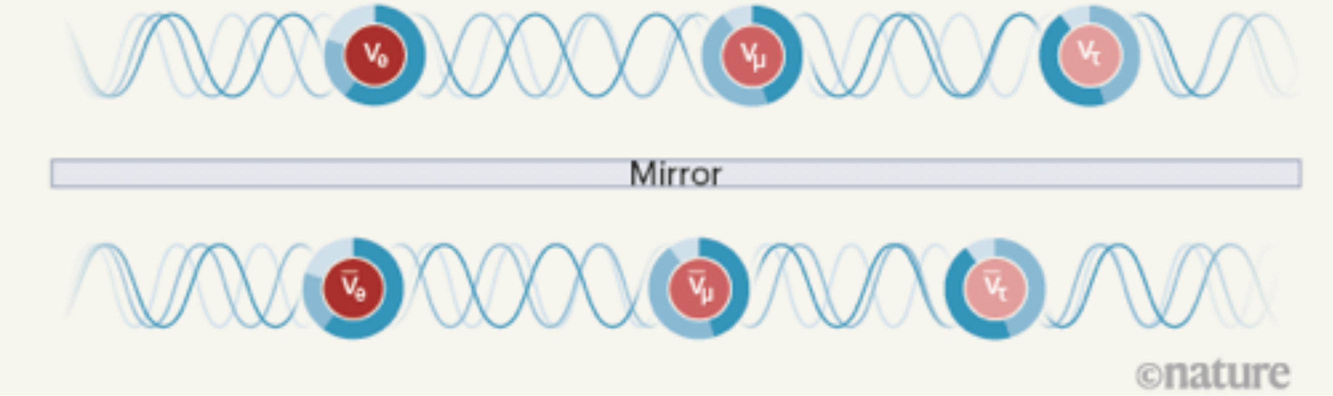
$$|\nu, t=0\rangle = |\nu_\mu\rangle = \sum_i U_{\mu i} |\nu_i\rangle$$

The time-evolution is given by the solution of the Schroedinger equation with free Hamiltonian:

$$|\nu, t\rangle = \sum_i U_{\mu i} e^{-iE_i t} |\nu_i\rangle$$

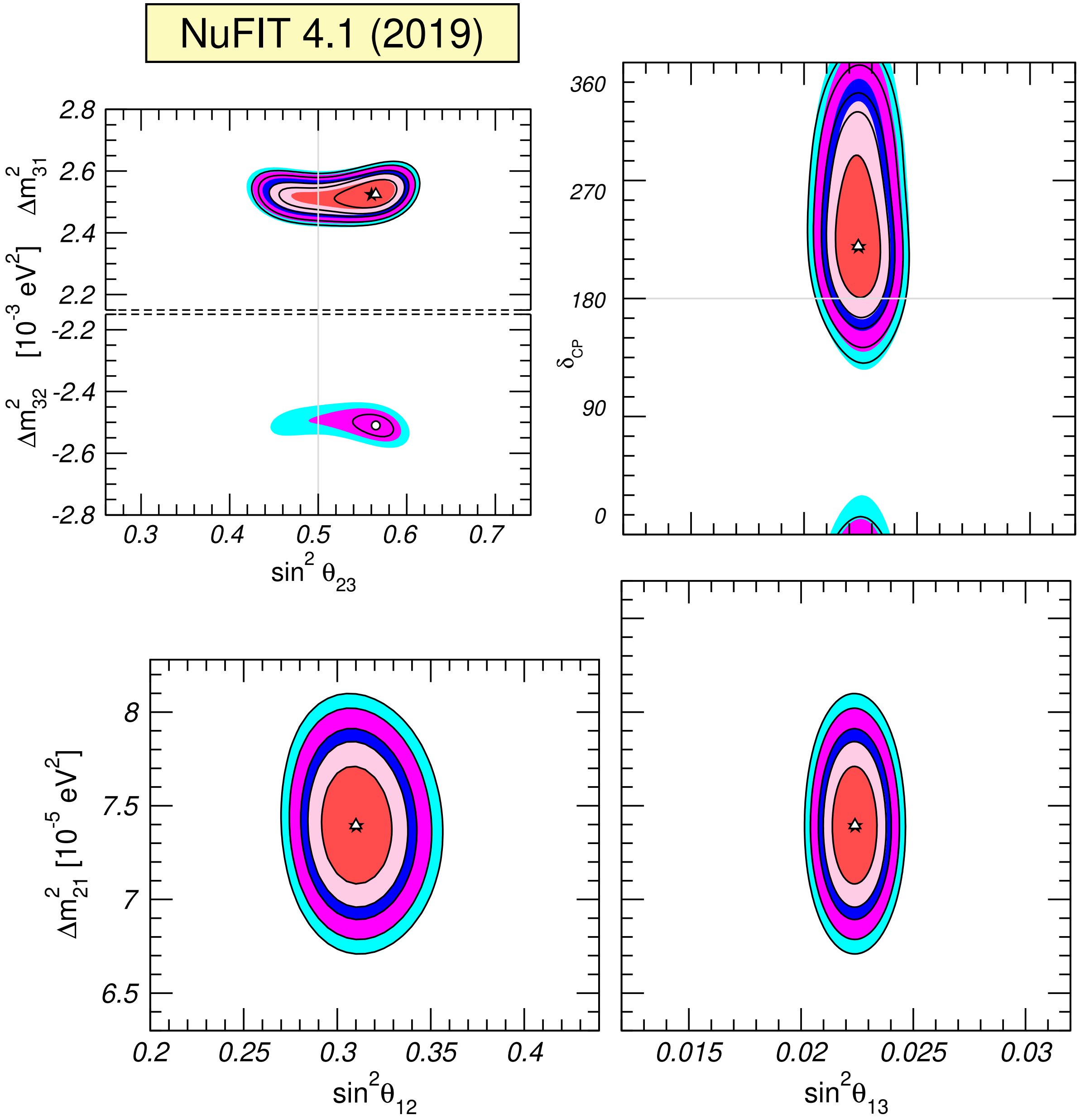
At detection, projecting over the flavour state :

$$P(\nu_\alpha \to \nu_\beta) \quad = \quad \left| \sum_i U_{\alpha 1} U^*_{\beta 1} e^{-i \frac{\Delta m^2_{i1}}{2E} L} \right|^2 \overset{2\nu}{=} \sin^2 2\theta \ \sin^2 \frac{\Delta m^2 L}{4E_\nu}$$



Nature, SP and J. Turner, News and views, 15 April 2020

# *Neutrino properties after July 2019*



http://www.nu-fit.org/ M. C. Gonzalez-Garcia et al., 1811.05487

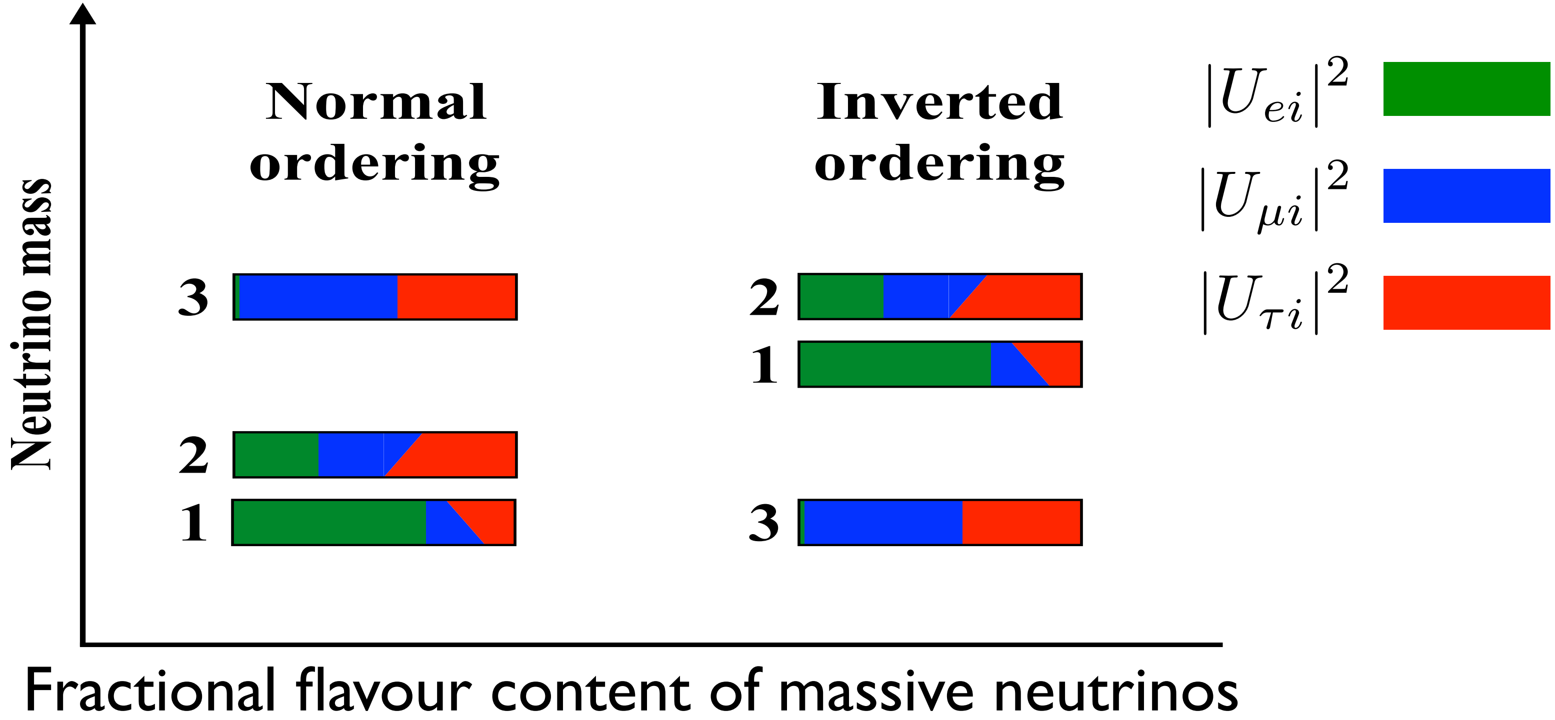
**Neutrinos have masses and mix!**

Current knowledge of neutrino properties:

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

# Neutrino masses

$\Delta m^2_{21} \ll \Delta m^2_{31}$ implies at least 3 massive neutrinos.



$$m_1 = m_{\rm min}$$
$$m_2 = \sqrt{m_{\rm min} + \Delta m^2_{21}}$$
$$m_3 = \sqrt{m_{\rm min} + \Delta m^2_{31}}$$

$$m_3 = m_{\rm min}$$
$$m_1 = \sqrt{m_{\rm min} + |\Delta m^2_{32}| - \Delta m^2_{21}}$$
$$m_2 = \sqrt{m_{\rm min} + |\Delta m^2_{32}|}$$

Measuring the masses requires:

- the mass scale: $m_{\rm min}$
- the mass ordering: preference for NO ($\Delta\chi^2 \sim 4.7(9.3)$).

# *Leptonic Mixing and CP-violation*

The Pontecorvo-Maki-Nakagawa-Sakata matrix

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

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

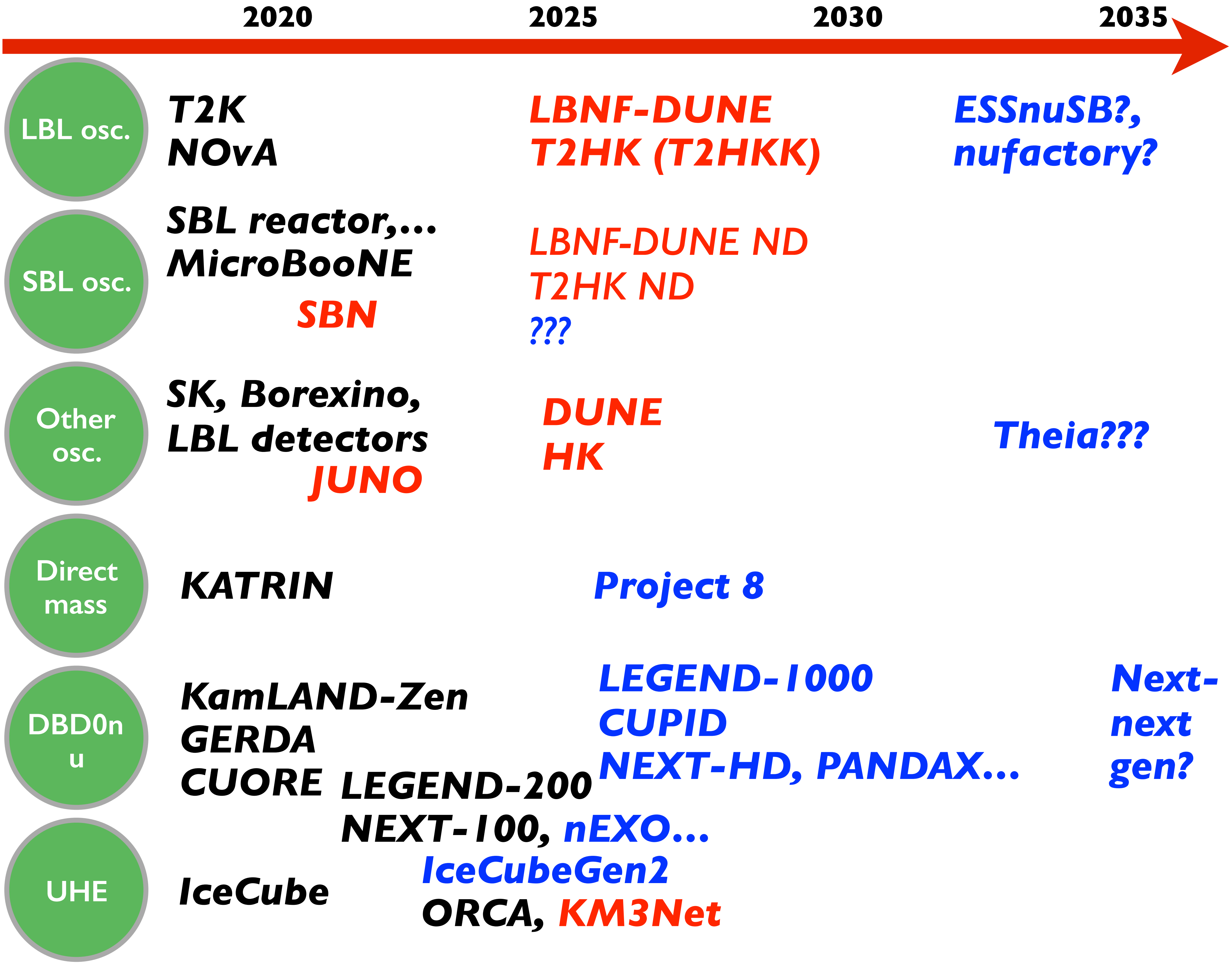
CPV?

- 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 leptonic 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.**



2020
2025
2030
2035

LBL osc.
T2K
NOvA
LBNF-DUNE
T2HK (T2HKK)
ESSnuSB?,
nufactory?

SBL osc.
SBL reactor,...
MicroBooNE
SBN
LBNF-DUNE ND
T2HK ND
???

Other osc.
SK, Borexino,
LBL detectors
JUNO
DUNE
HK
Theia???

Direct mass
KATRIN
Project 8

DBD0nu
KamLAND-Zen
GERDA
CUORE
LEGEND-200
NEXT-100, nEXO...
LEGEND-1000
CUPID
NEXT-HD, PANDAX...
Next-next gen?

UHE
IceCube
IceCubeGen2
ORCA, KM3Net

# *Phenomenology questions for the future*

1. What is the nature of neutrinos?

**Neutrinoless double beta decay**

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

3. Is there leptonic CP-violation?

**Long baseline neutrino oscillation experiments**

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

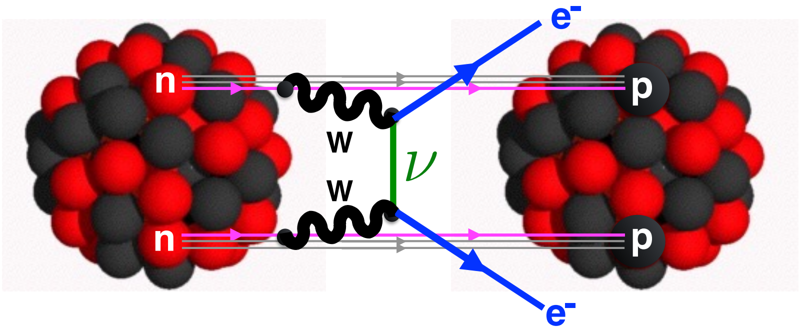
The **nature** of neutrinos is linked to the conservation of **Lepton number (L).**

- 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.



SP, CERN Courier, Jul 2016

The half-life time depends on neutrino properties

$$(T_{0\nu}^{1/2})^{-1} \propto |M_{NME}|^2 |m_{\beta\beta}|^2$$

- The effective Majorana mass parameter:

$$\boxed{|m_{\beta\beta}| \equiv \left| m_1|U_{e1}|^2 + m_2|U_{e2}|^2 e^{i\alpha_{21}} + m_3|U_{e3}|^2 e^{i\alpha_{31}} \right|}$$

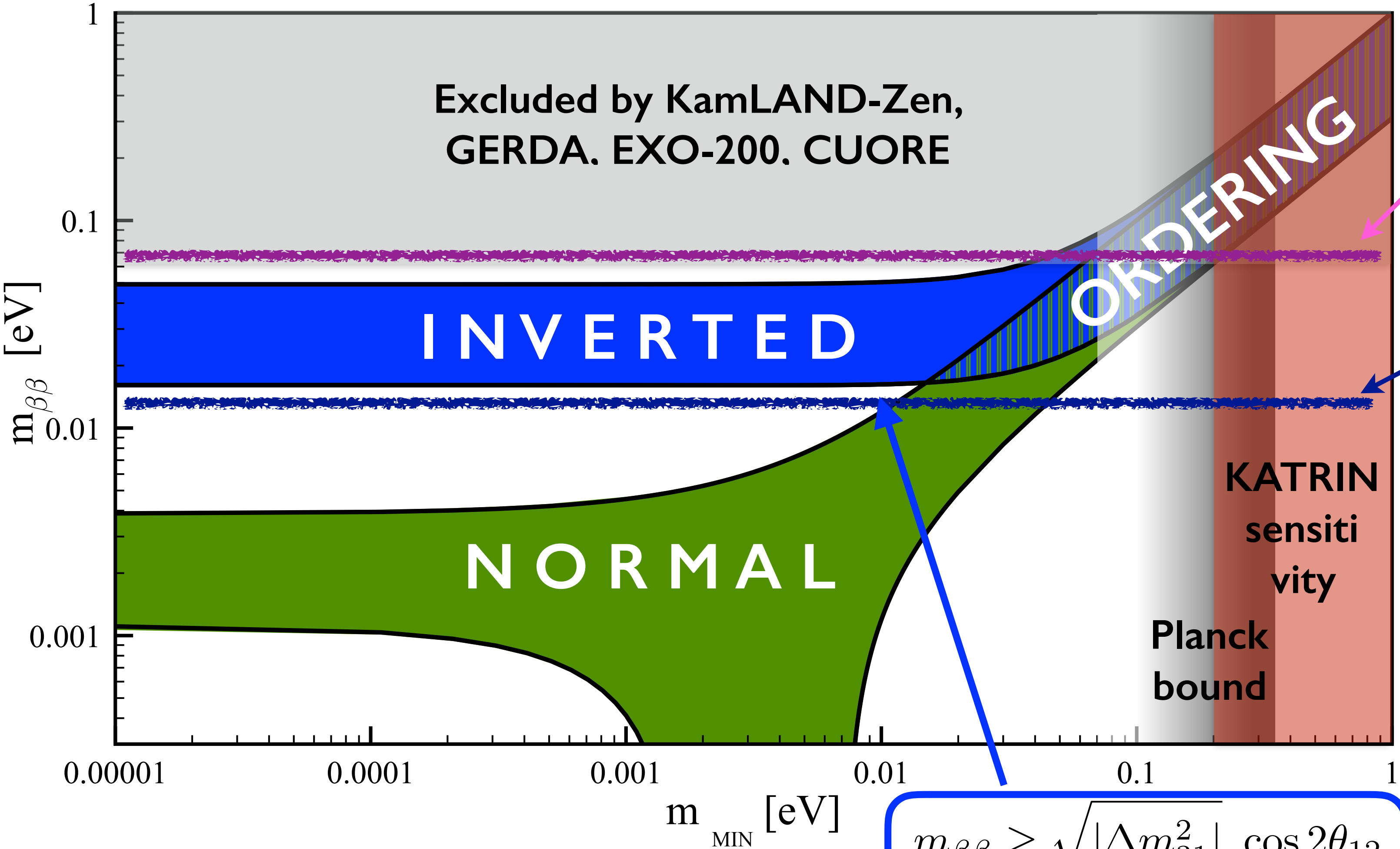
Mixing angles (known)

CPV phases (unknown)

- $|M_{NME}|$ are the nuclear matrix elements

# Predictions for betabeta decay

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



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

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

APPEC DBD
committee
1910.04688

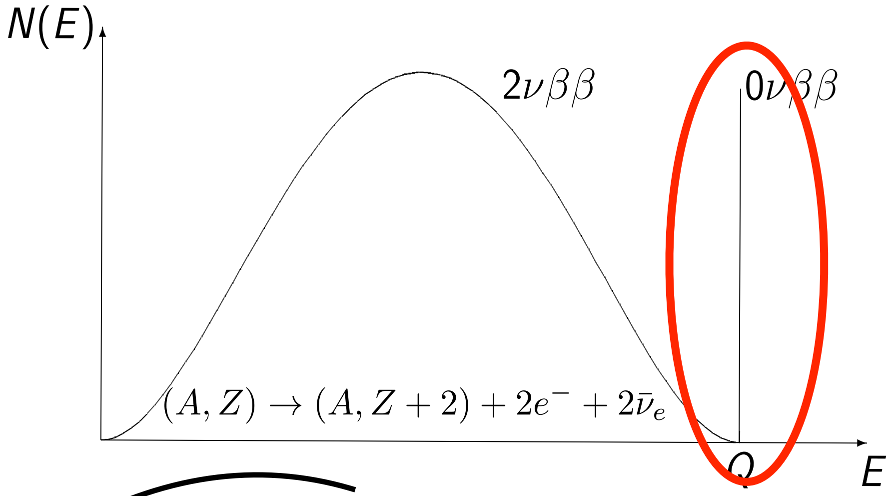
**Wide experimental program** which is ongoing. The next generation is well into planning and R&D for future.

**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…).

It is a very rare process:



$$T_{0\nu} \propto \sqrt{\frac{M\ t}{B\ \Delta E}}$$

ton-scale

<1% at $Q_{bb}$

<1 cts/yr/ton/ROI

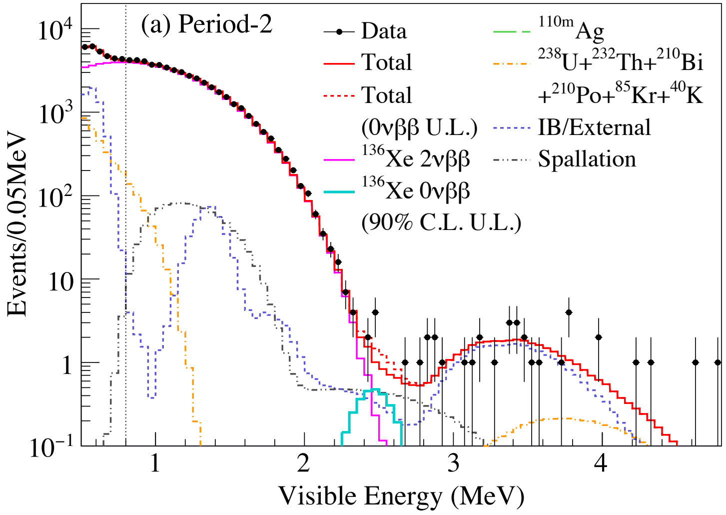
**KamLAND-Zen** Loaded LSc with 380 kg $^{136}$Xe, $T_{1/2} > 1.07\times10^{26}$ yrs (90% C.L.), $m_{bb} <$ 61-165 meV

**EXO-200** ~75 kg LXe TPC, $T_{1/2} > 3.7\times10^{25}$ yrs

**GERDA** 31 kg (enriched) $^{76}$Ge, $T_{1/2} > 0.9\times10^{26}$ yrs

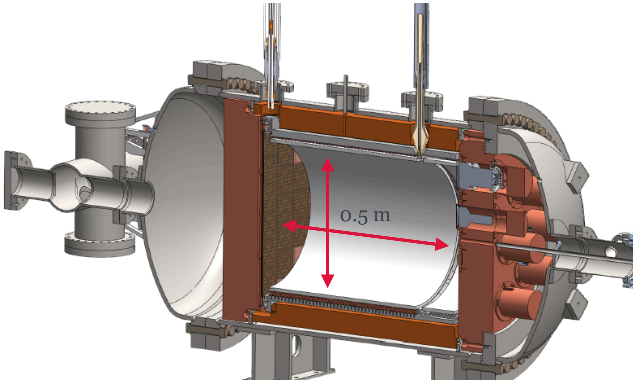
**MAJORANA** 26.0 kg yrs, $T_{1/2} > 0.27\times10^{26}$ yrs

**CUORE** $^{130}$Te, ~206 kg, $T_{1/2} > 1.5\times10^{25}$ yrs



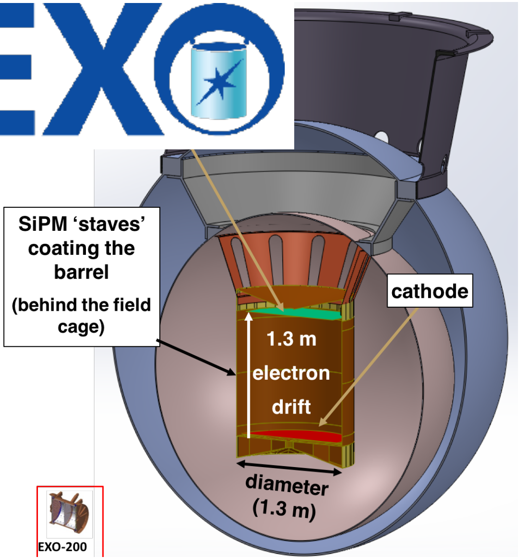
KamLAND-Zen, PRL 117 (2016)

**SNO+**



## NEXT-HD

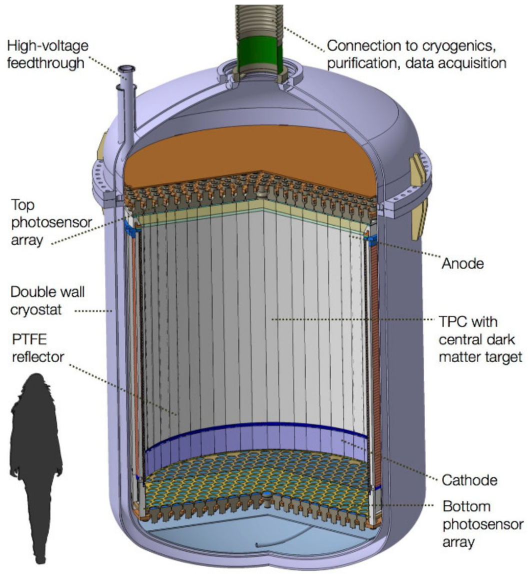
**nEXO**

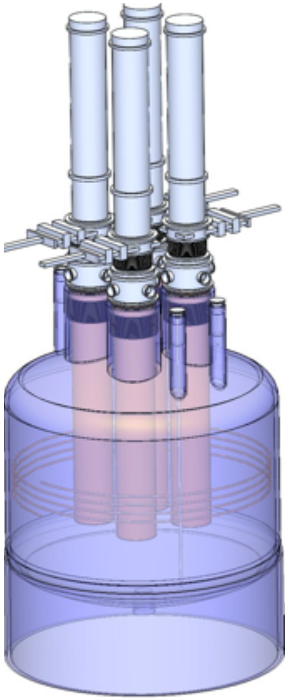


5 ton LSc Xe

## DARWIN

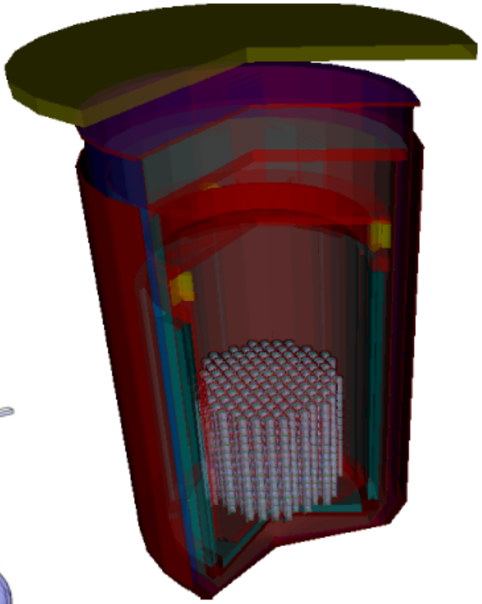
40 t liquid Xe TPC
(with 8.9% $^{136}$Xe → 3.6 t of $^{136}$Xe)



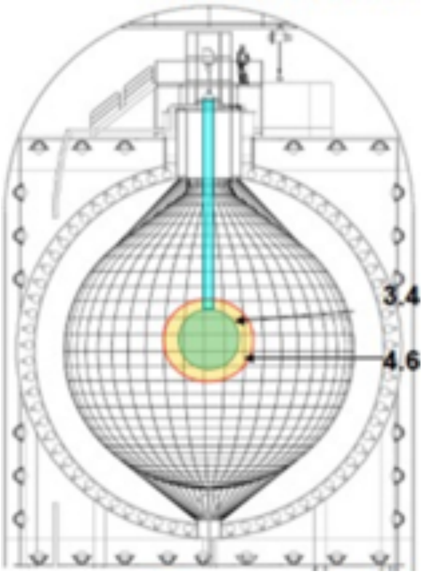


**LEGEND**

Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay



## CUPID

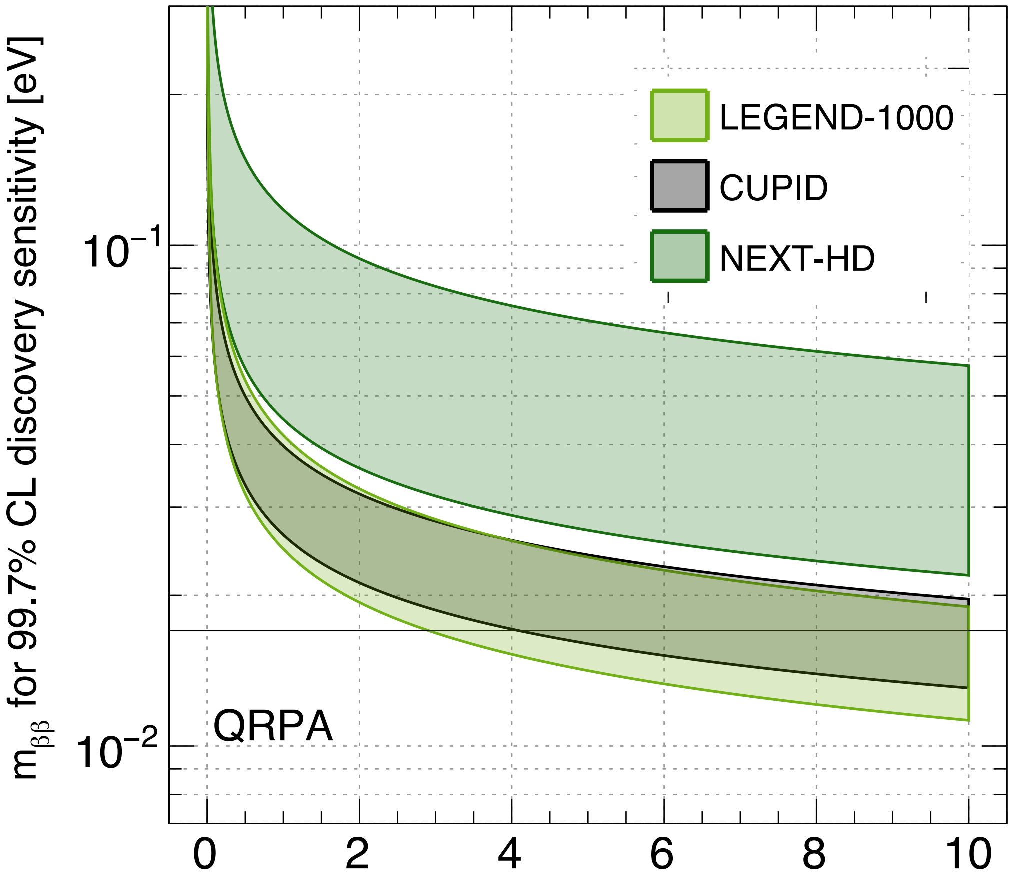


## KamLAND2-Zen

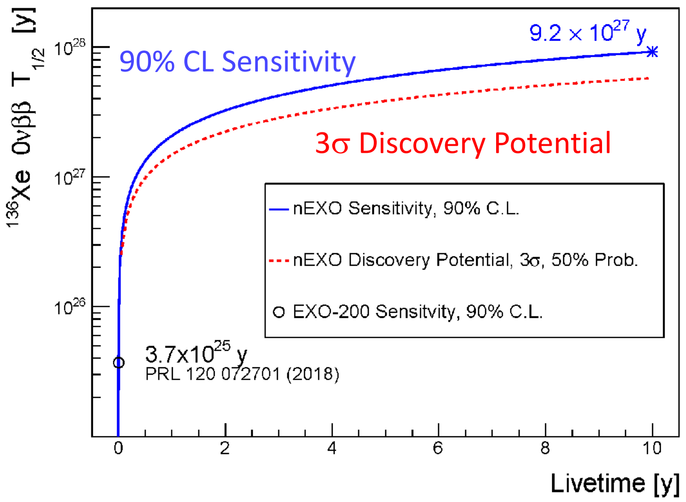
HPXe: PANDAX-III
Bolometers: AMoRE

| | | |
|---|---|---|
| Scalability | **Fluid embedded source** | Xe-based TPC |
| | | Liquid scintillator as a matrix |
| High ΔE and ε | **Crystal embedded source** | Germanium diodes |
| | | Bolometers |

A. Giuliani, Neutrino 2018



APPEC DBD committee 1910.04688



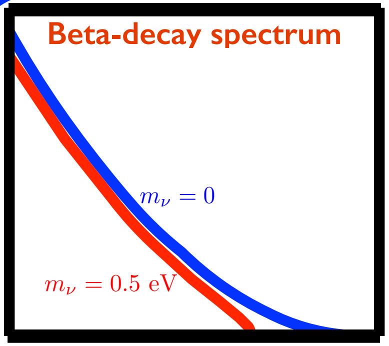
nEXO Coll.

$m_{\beta\beta} < 5.7 - 17.7$ eV

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

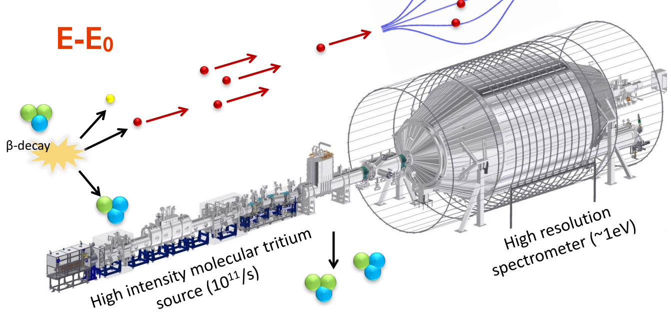
# Measuring neutrino masses

- Absolute mass scale.



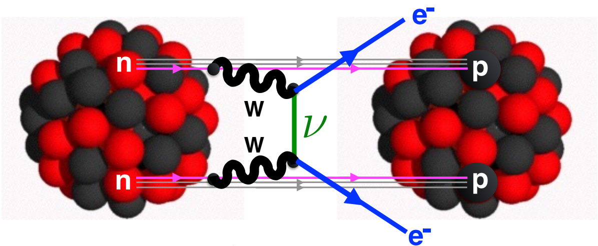
## Beta decay

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



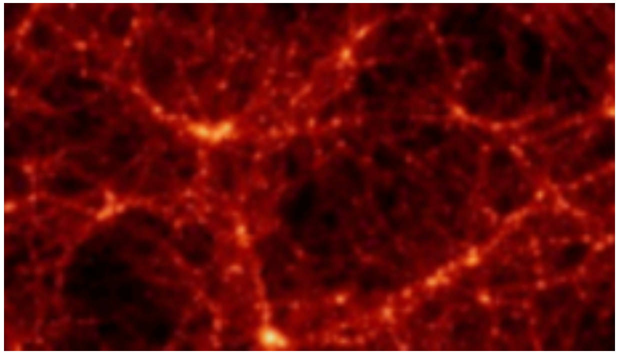
**KATRIN**

## Neutrinoless dbeta decay

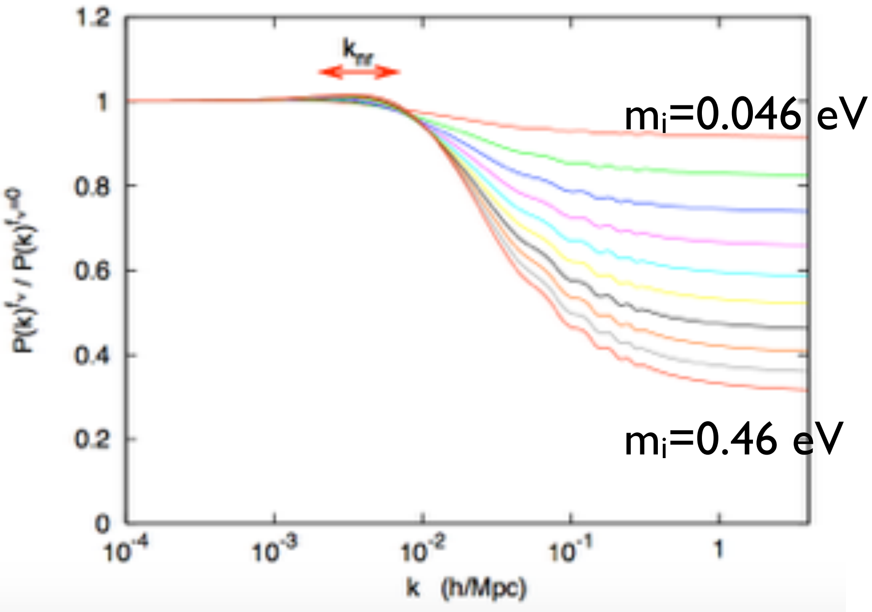


$$m_{\beta\beta} = f(m_i, \alpha_{21}, \alpha_{31}, \delta)$$

## Cosmology



$$\sum_i m_i$$



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

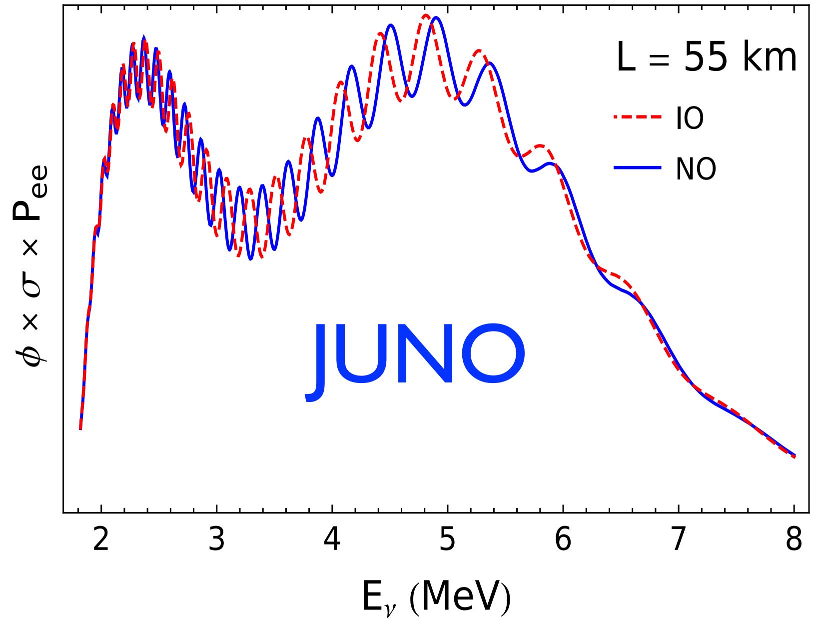
# Neutrino mass ordering

- Mass ordering via neutrino oscillation in matter or in vacuum (JUNO). Discovery expected within 10 years thanks to relatively large $\theta_{13}$.

## Atm neutrinos

Exploit the matter effects in Earth. Without detector magnetisation, require large mass (multi Mton) and excellent angular and energy resolution (ORCA, IceCube Gen 2, HK, INO).

Long baseline neutrino oscillation experiments



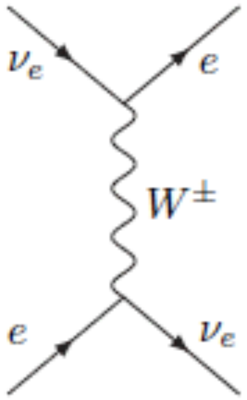
P. Coloma and SP, World Scientific

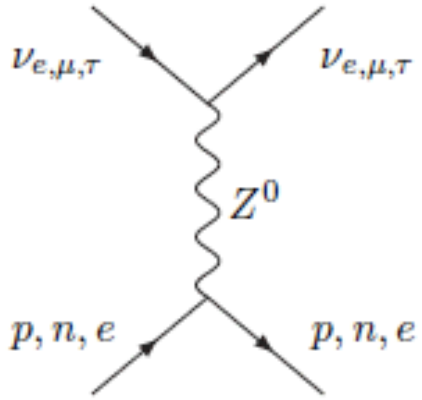
Petcov, Piai, hep-ph/0112074

Uses reactor neutrinos with detectors at ~60 km. Excellent energy resolution is needed.

# *Neutrino oscillations in matter and the ordering*

- When neutrinos travel through a medium, they interact with the background of electron, proton and neutrons and acquire an effective mass.





MWS effect

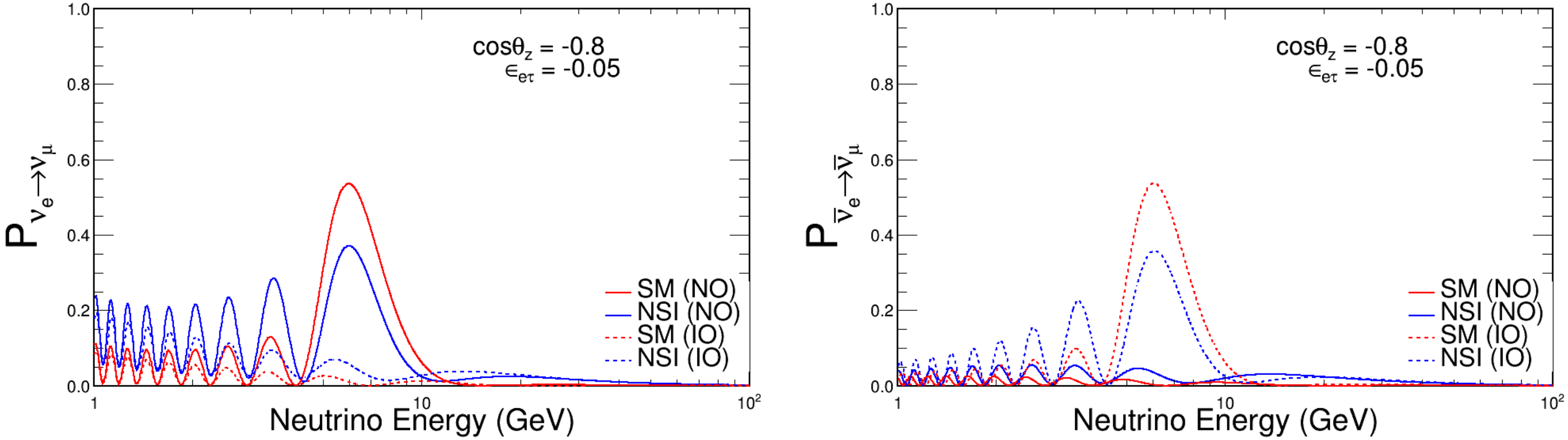
- Typically the background is CP and CPT violating, e.g. the Earth and the Sun contain only electrons, protons and neutrons, and the resulting oscillations are CP and CPT violating.

# The mixing angle becomes (for constant density)

$$\sin^2(2\theta_m) = \frac{\left(\frac{\Delta m^2}{2E}\sin(2\theta)\right)^2}{\left(\frac{\Delta m^2}{2E}\cos(2\theta) \mp \sqrt{2}G_F N_e\right)^2 + \left(\frac{\Delta m^2}{2E}\sin(2\theta)\right)^2}$$

- If $\boxed{\sqrt{2}G_F N_e = \frac{\Delta m^2}{2E}\cos 2\theta}$ : resonance $\boxed{\theta_m = \pi/4}$
- The resonance condition can be satisfied for

$$\boxed{\begin{array}{l}\text{- neutrinos if } \Delta m^2 > 0 \\ \text{- antineutrinos if } \Delta m^2 < 0\end{array}}$$



KM3Net, ORCA Coll., 2004.05004

# *Long baseline oscillations: mass ordering & CPV*

Long baseline neutrino oscillation experiments (T2K, NOvA, DUNE, T2HK) study the subdominant channels

A. Cervera et al., hep-ph/0002108;
K. Asano, H. Minakata, 1103.4387;
S. K. Agarwalla et al., 1302.6773...

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

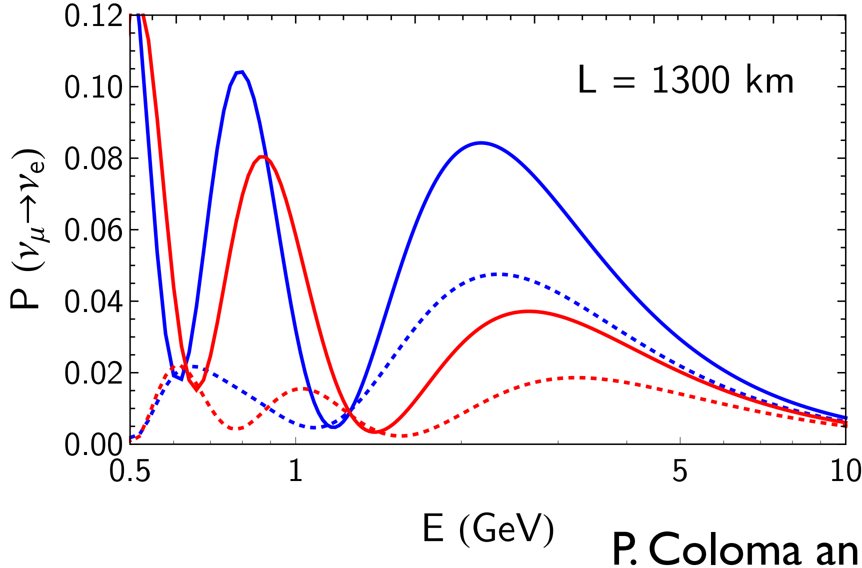
$$+ \sin 2\theta_{12} \sin 2\theta_{23} s_{13} \frac{\Delta_{21} L}{2E} \sin \frac{(1-r_A)\Delta_{31} L}{4E} \cos\left(\delta - \frac{\Delta_{31} L}{4E}\right)$$

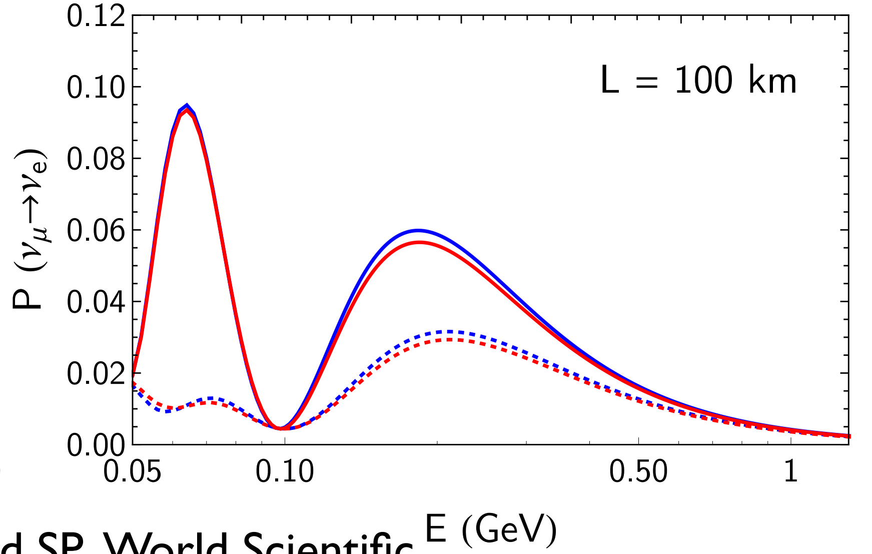
$$+ s_{23}^2 \sin^2 2\theta_{12} \frac{\Delta_{21}^2 L^2}{16 E^2} - 4 c_{23}^2 s_{13}^4 \sin^2 \frac{(1-r_A)\Delta_{31} L}{4E}$$

with

$$\Delta_{31} \equiv \Delta m_{31}^2/(2E_\nu)$$

$$r_A \simeq \frac{\sqrt{2} G_F N_e}{\Delta m_{31}^2/(2E_\nu)}$$





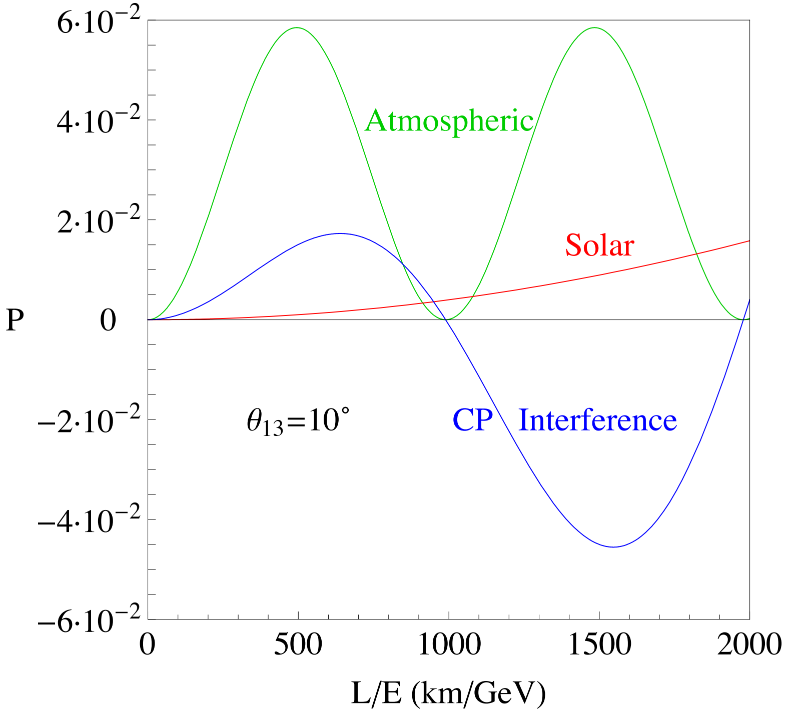
P. Coloma and SP, World Scientific

# CPV needs to be searched for in long baseline neutrino experiments which have access to 3-neutrino oscillations.

$$
\begin{aligned}
P_{\mu e} \simeq & 4c_{23}^2 \boxed{s_{13}^2} \frac{1}{(1-r_A)^2} \sin^2 \frac{(1-r_A)\Delta_{31}L}{4E} \\
& + \sin 2\theta_{12} \sin 2\theta_{23} \boxed{s_{13}} \frac{\boxed{\Delta_{21}L}}{2E} \sin \frac{(1-r_A)\Delta_{31}L}{4E} \cos\left(\boxed{\delta} - \frac{\Delta_{31}L}{4E}\right) \\
& + s_{23}^2 \sin^2 2\theta_{12} \frac{\Delta_{21}^2 L^2}{16E^2} - 4c_{23}^2 s_{13}^4 \sin^2 \frac{(1-r_A)\Delta_{31}L}{4E}
\end{aligned}
$$

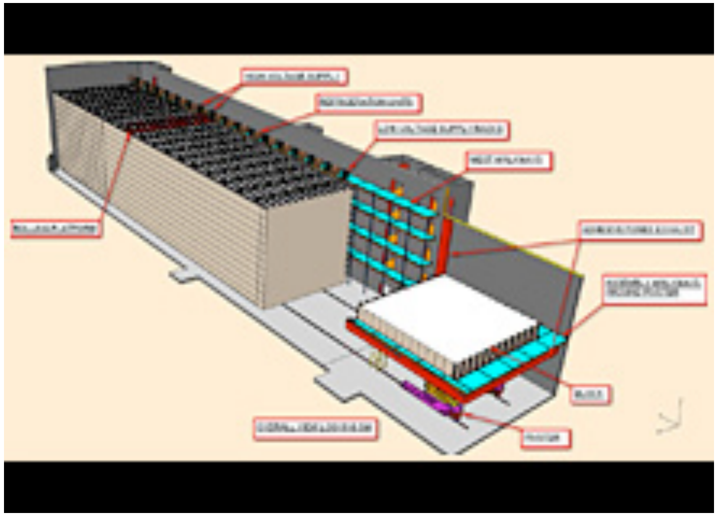
A. Cervera et al., hep-ph/0002108;
K. Asano, H. Minakata, 1103.4387;
S. K. Agarwalla et al., 1302.6773...

- The determination of CPV and of the mass ordering are entangled.
- Matter effects increase with energy and distance.
- CPV effects more pronounced at low energy.



P. Coloma, E. Fernandez-Martinez, JHEP1204

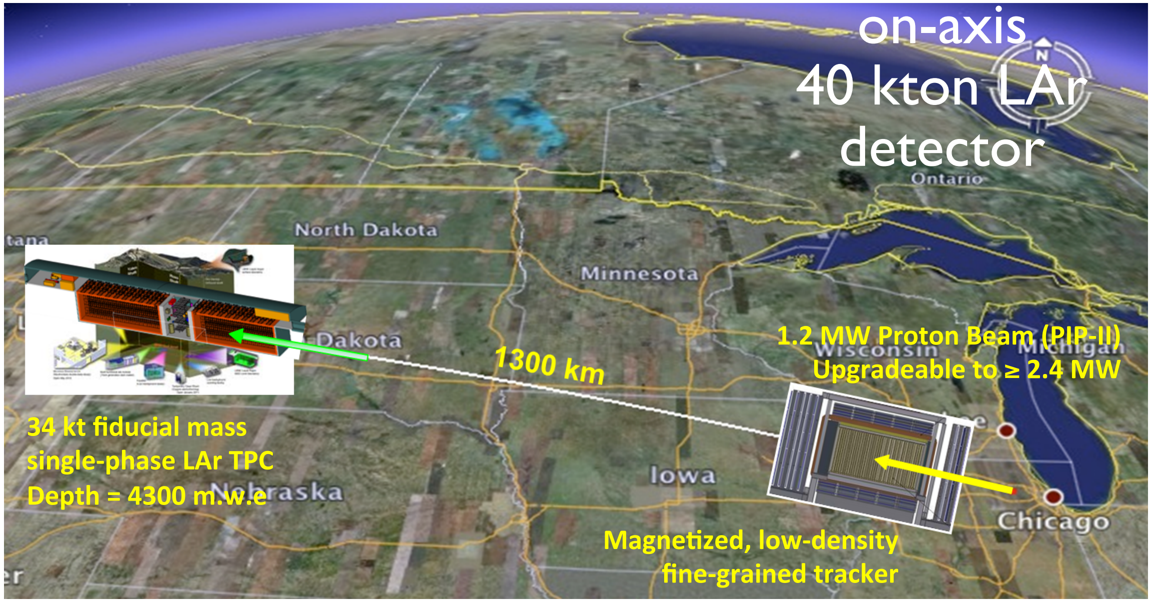
# Present/Future LBL exp

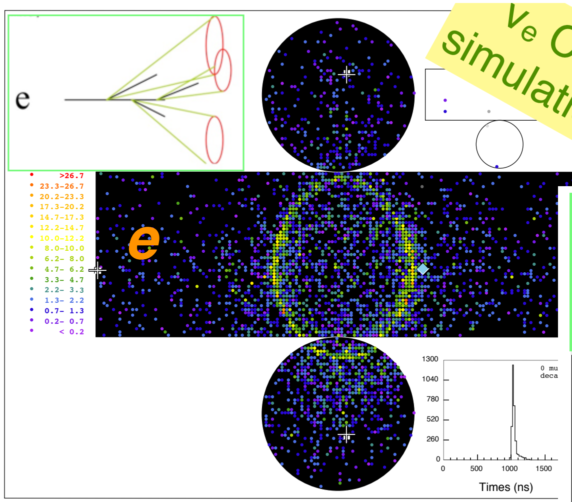


**NOvA**: 810 km off-axis
~14 kton plastic scintillator detector

**T2K**: 295 km off-axis
~22.5 kton WC detector

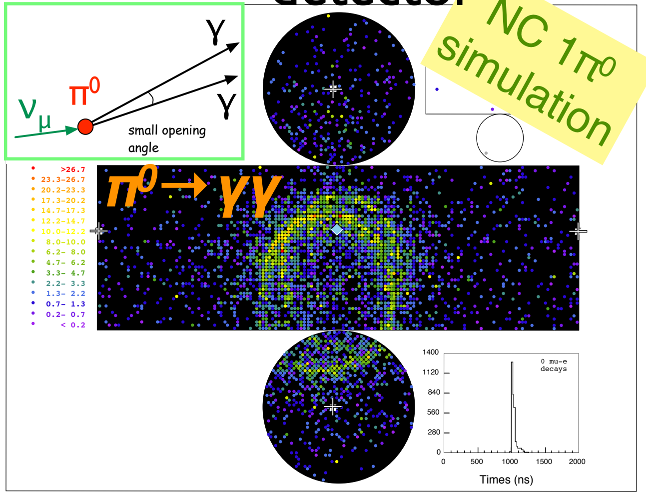
**DUNE**: 1300 km
on-axis
40 kton LAr detector

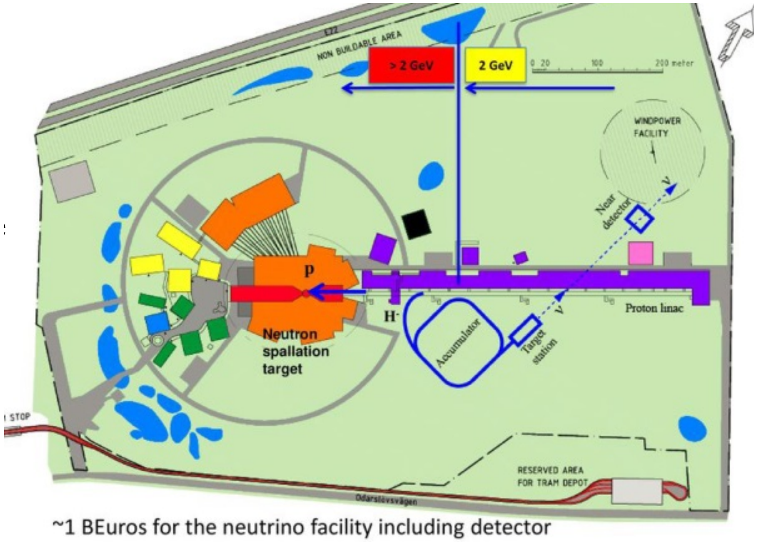




M. Shiozawa, for
T2HK coll., NuPhys
2014

**T2HK**: 295 km
off-axis
~1 Mton WC
detector

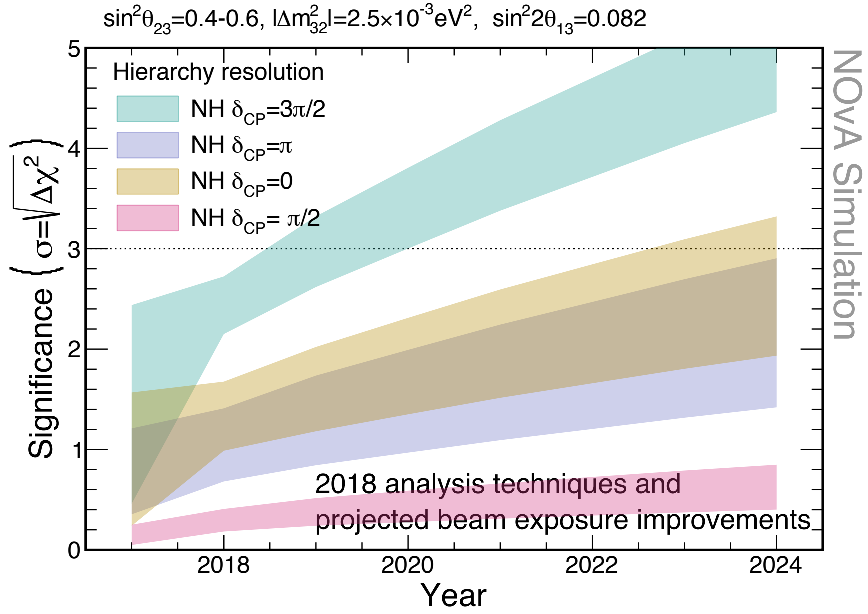




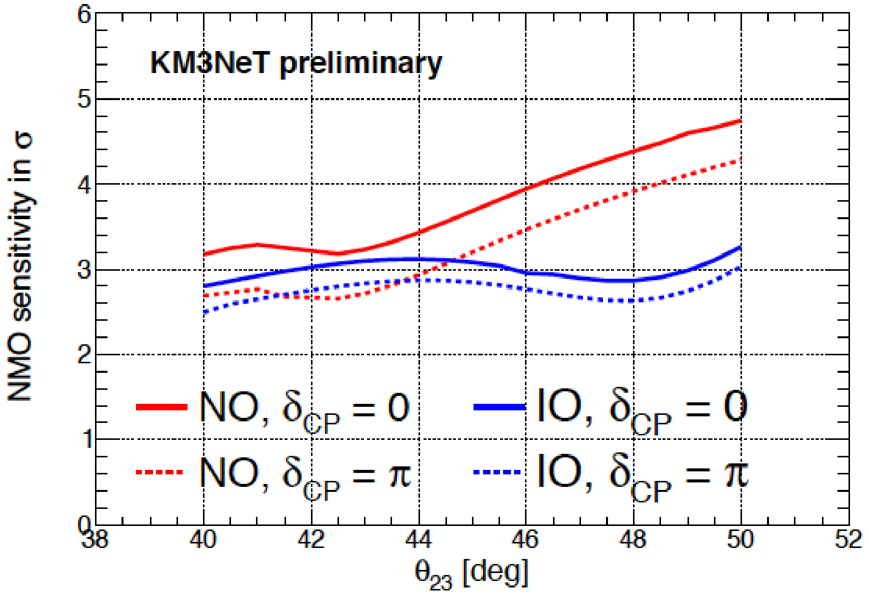
~1 BEuros for the neutrino facility including detector

***ESSnuSB**: 300-500 km*
*~0.5 Mton WC detector*
*second osc. maximum*

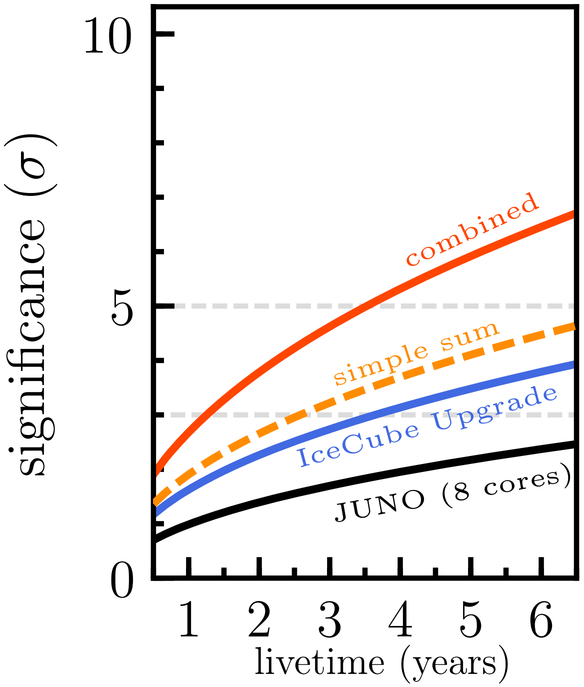
# *Mass ordering sensitivity*



M. Sanchez, Neutrino 2018

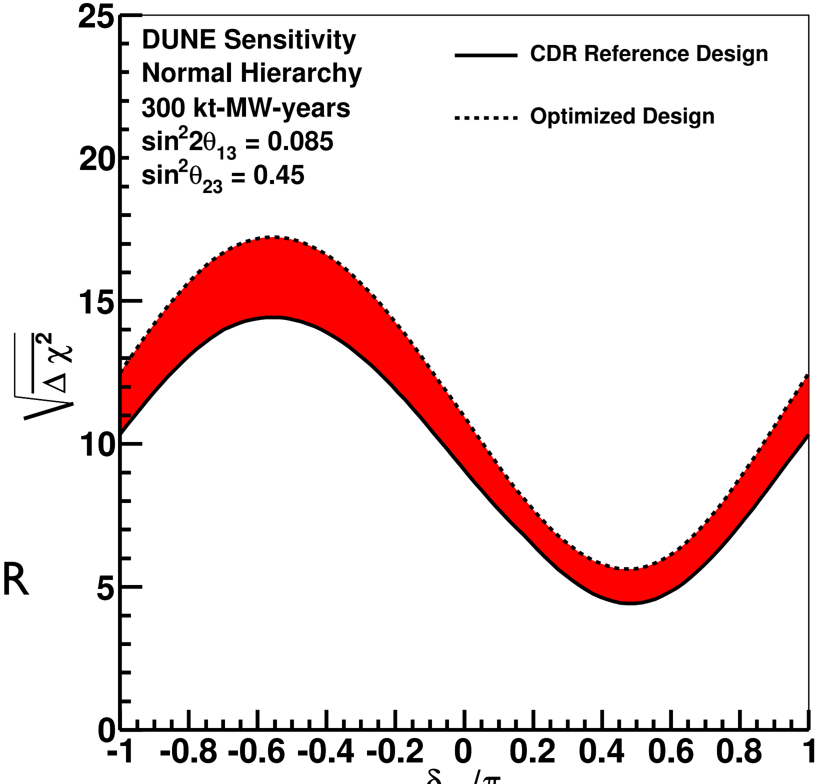


KM3Net, ORCA Coll., 2004.05004

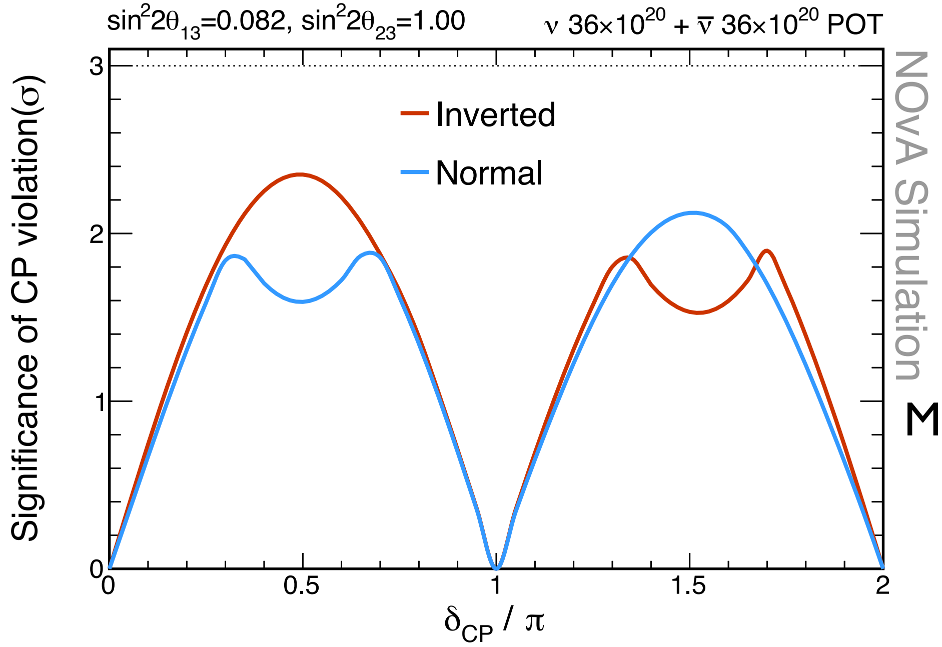


JUNO+PINGU,
PRD101 (2020)

DUNE CDR



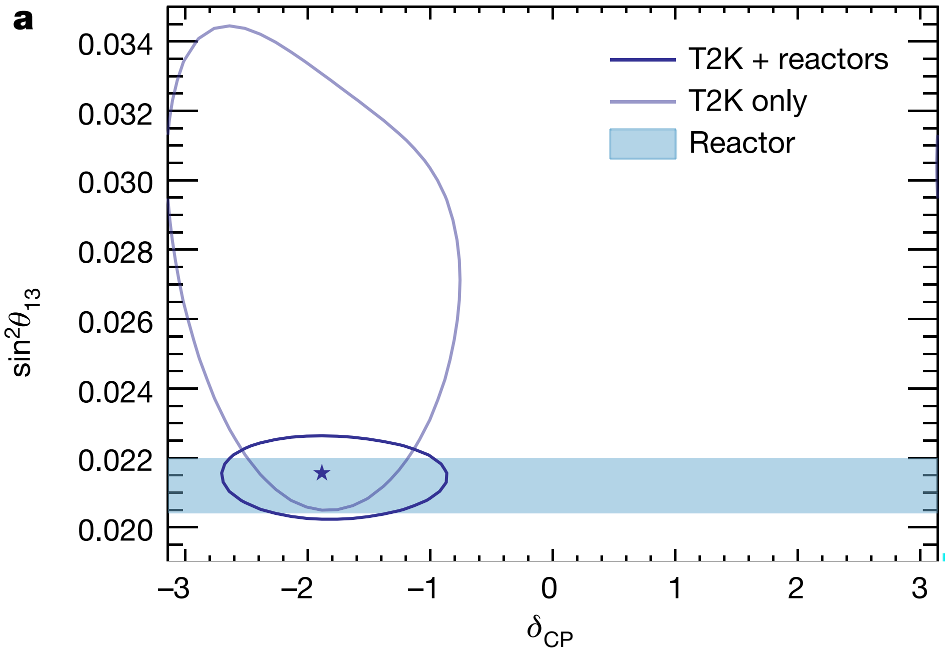
# *CPV sensitivity*



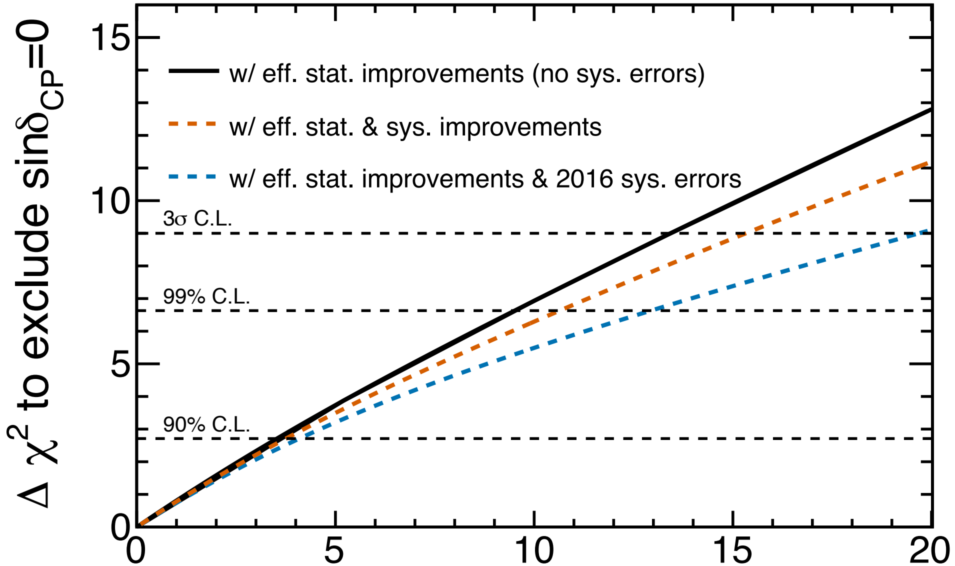
NOvA plans an extended run till 2024 (50% nu, 50% antinu) with further accelerator improvements.

M. Sanchez, Neutrino 2018

T2K phase 2 extension aims at reaching 1.3 MW by 2026 (20x10^21pot).

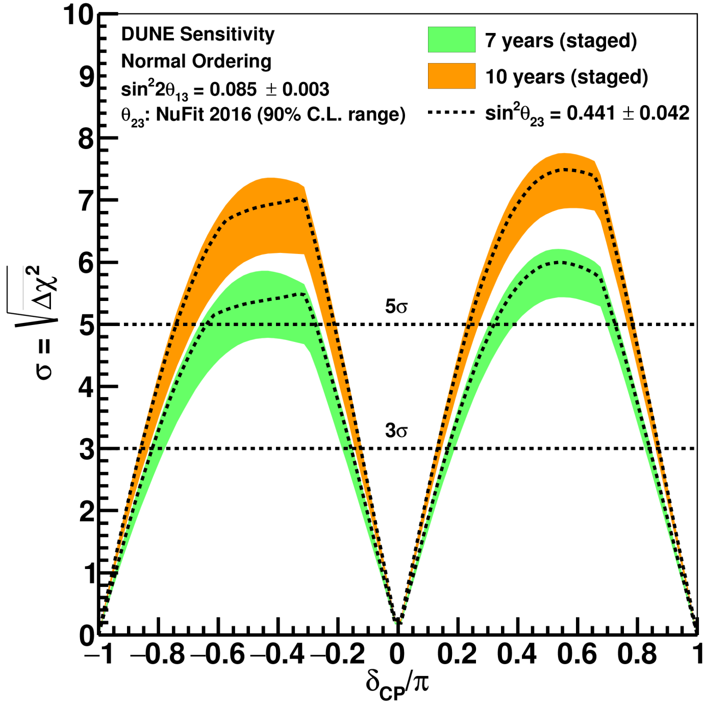


T2K Coll., Nature 580 (2020)



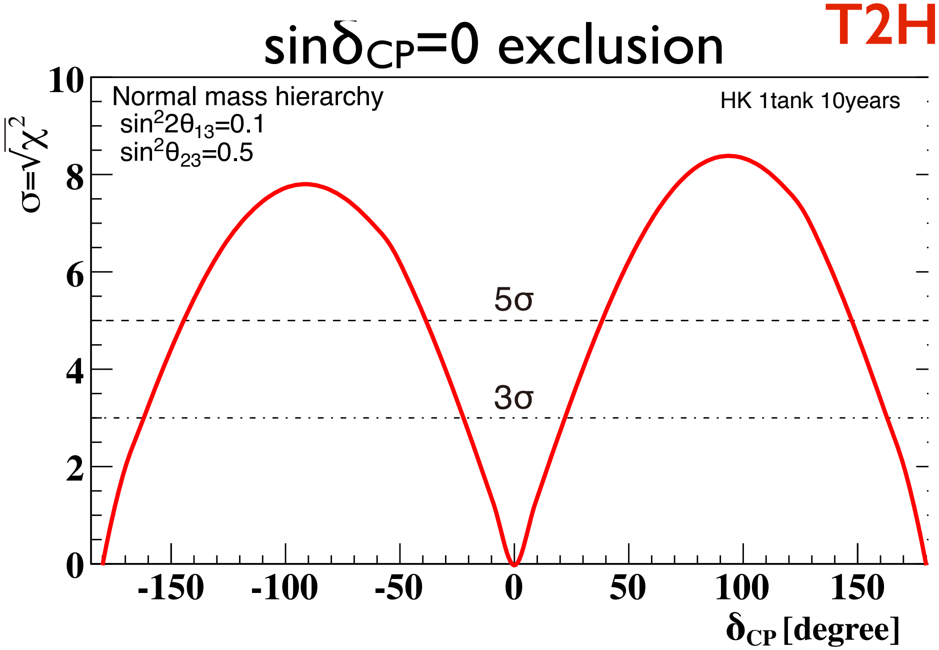
T2K, 1609.04111

**DUNE** CP Violation



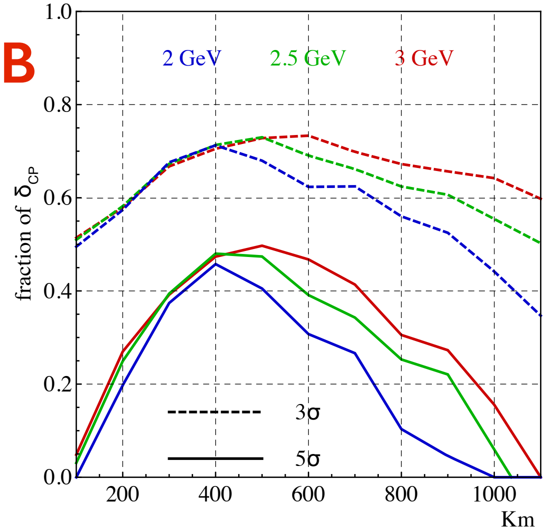
E. Worcester, for DUNE, Neutrino 2018

**T2HK**

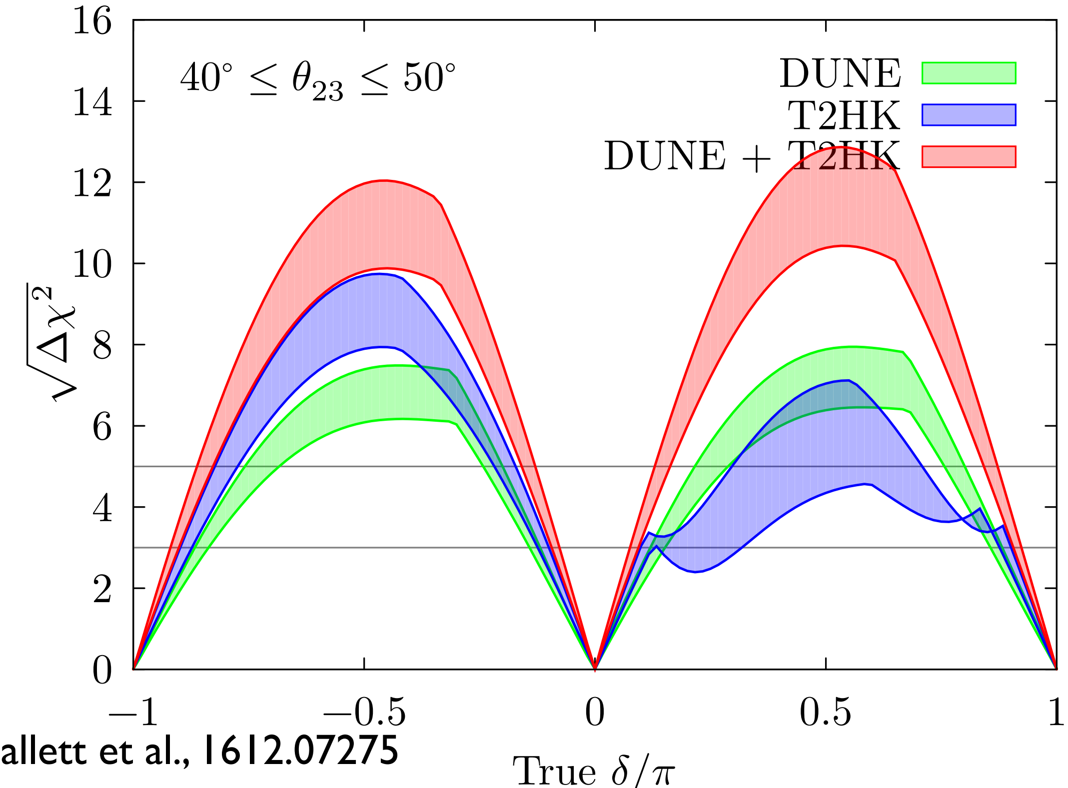


M. Shiozawa, for HK, Neutrino 2018

**ESSnuSB**

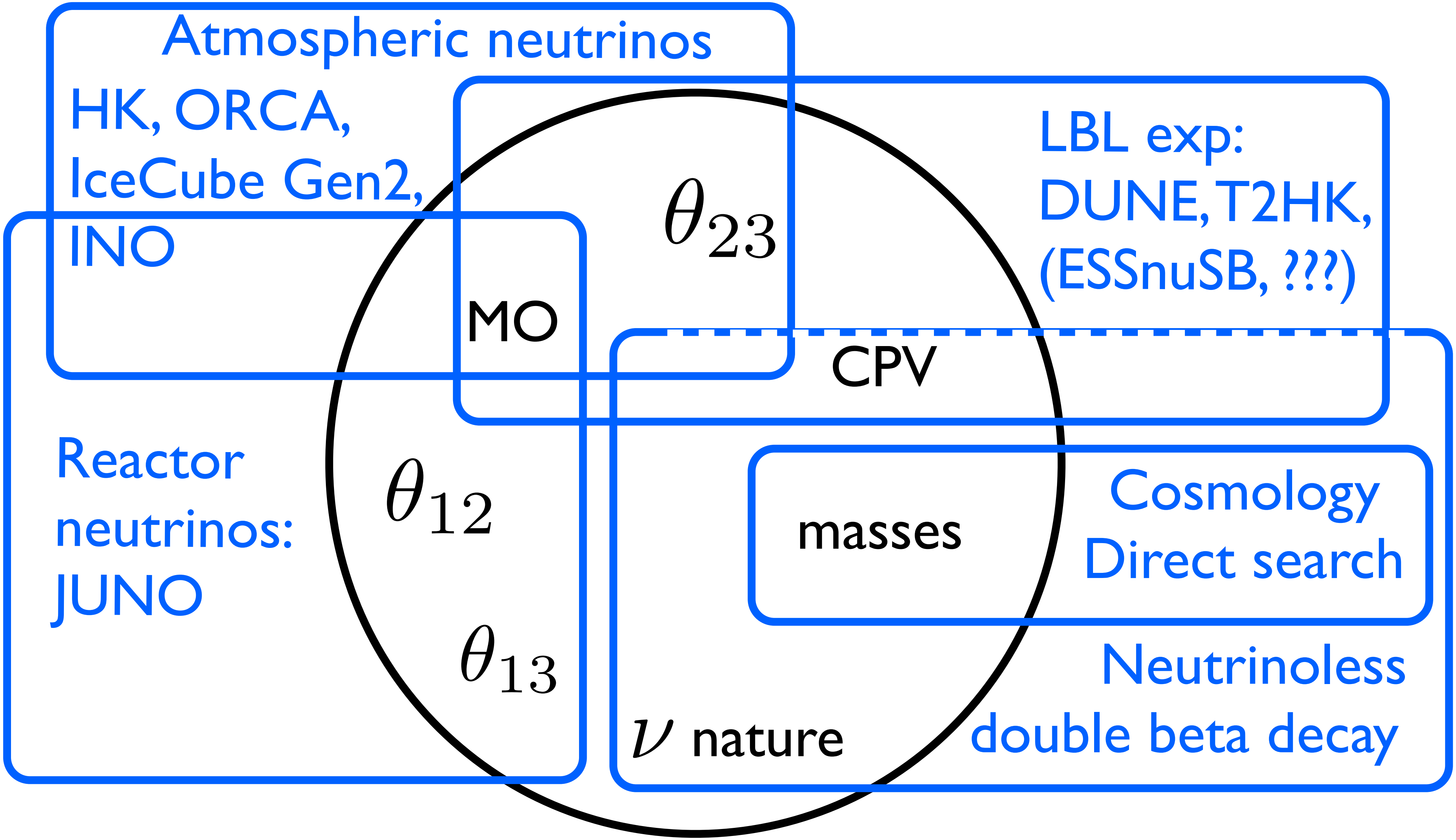


ESSnuSB, 1309.7022



Ballett et al., 1612.07275

# *Complementarity*



Atmospheric neutrinos
HK, ORCA,
IceCube Gen2,
INO

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

$\theta_{23}$

MO

CPV

Reactor
neutrinos:
JUNO

$\theta_{12}$

$\theta_{13}$

masses

Cosmology
Direct search

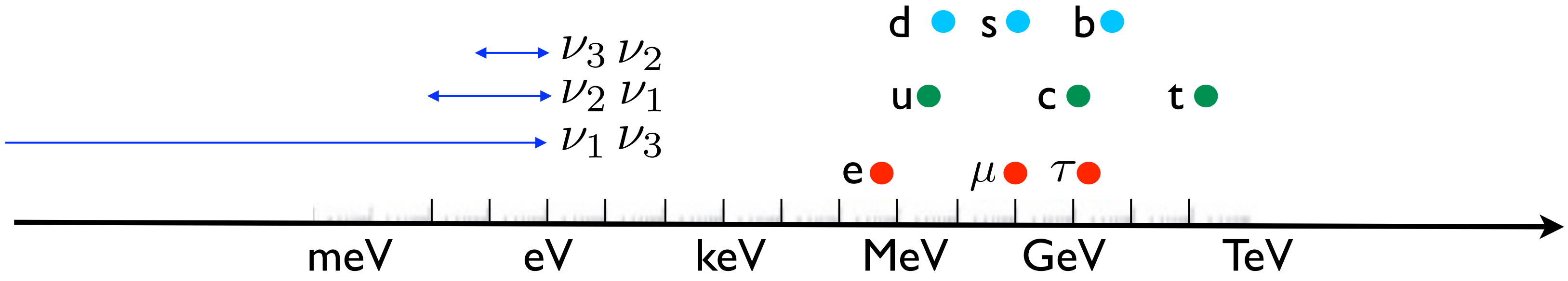
Neutrinoless
double beta decay

$\nu$ 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.

# Conclusions

- Neutrino oscillations imply that neutrinos have mass and mix: First particle physics evidence of physics beyond the SM. They provide a complementary window w.r.t. collider and flavour physics searches.



- The ultimate goal is to understand the origin of neutrino masses and leptonic mixing.

- It is necessary to known the values of the masses and of the mixing angles and CPV phase (with precision). An exciting experimental programme is under way.