Neutrino Physics
(accelerator and non-accelerator)
summary of the session

Conveners: Stan Bentvelsen, Marco Zito

ESPPU Open Symposium Granada
May 16, 2019

In the session we also covered astroparticle physics

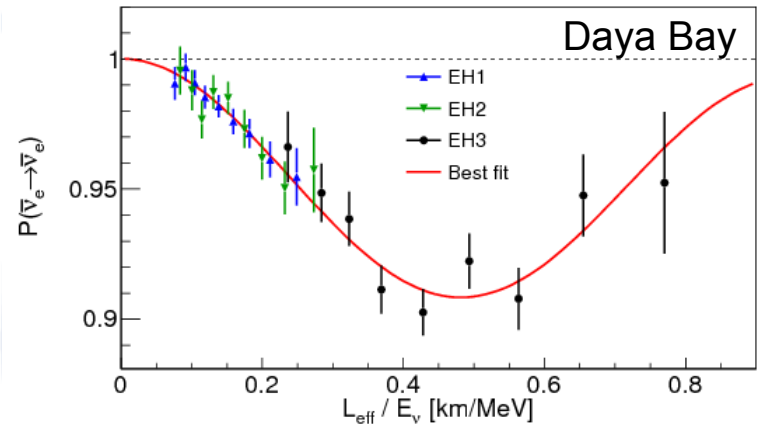
Neutrino masses are BSM!

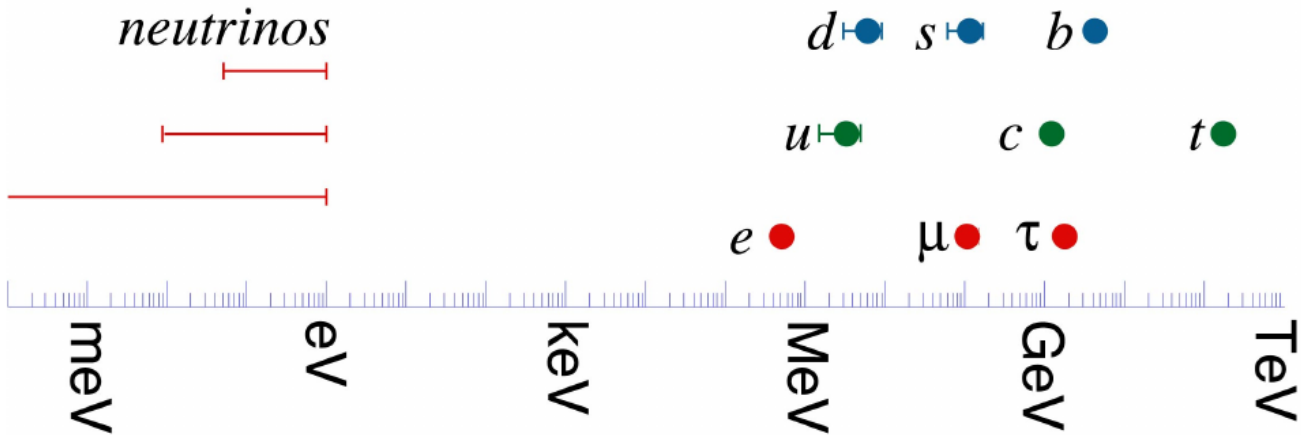
- Neutrino masses, firmly established by neutrino oscillations, are the first particle physics evidence of Physics BSM
- Why ? No right-handed neutrinos $m_\nu \bar{\nu}_L \nu_R$
- A tantalizing explanation is a Majorana term

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

Weinberg operator, PRL 43

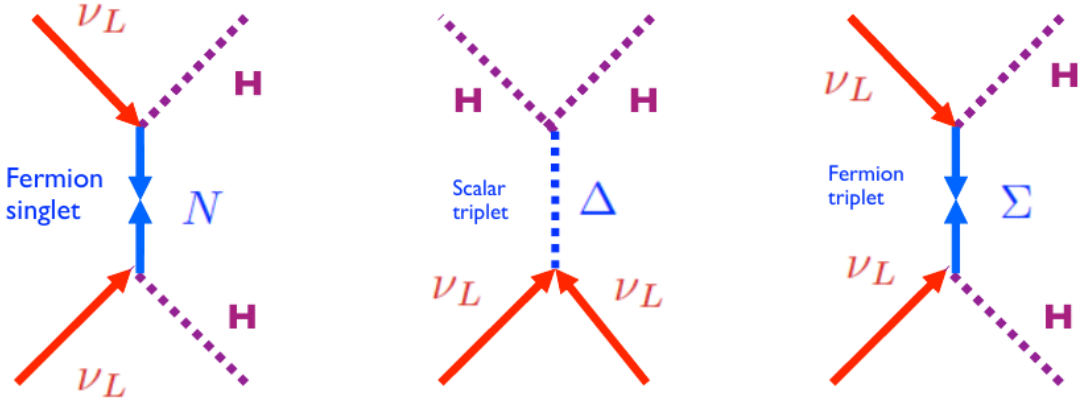
Lepton violation





Neutrino as a window to new physics

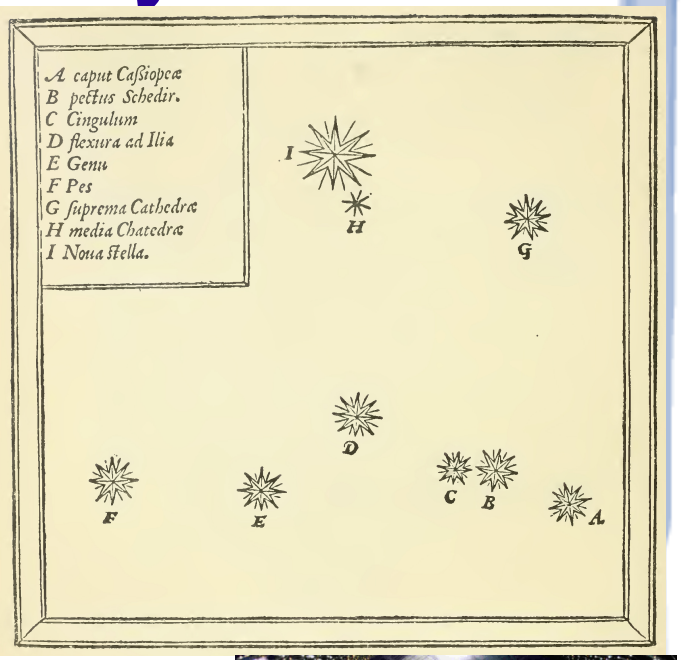
- The minimal extension is to have new elementary neutral fermions
- Neutrinos could have new interactions

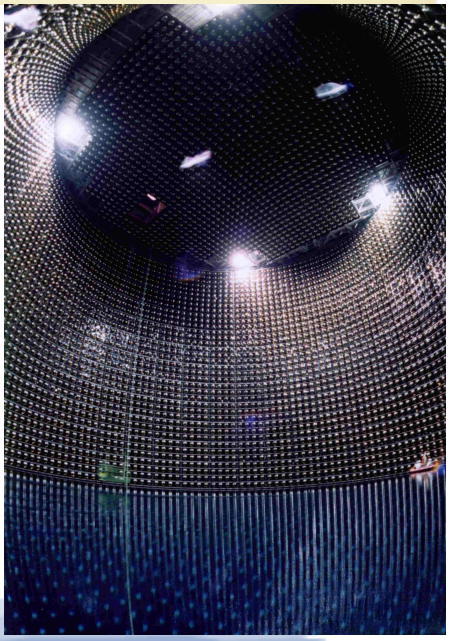


- A strong physics case for precisely measuring the mass and mixing parameters
- Determining the nature (Dirac or Majorana) of the neutrino is a crucial step
- The (possible) CP violation in the mixing could be related to the baryon asymmetry in the Universe
- We shoud also look for new states or new interactions (neutrino portal) : could be a ground-breaking discovery !

Discoveries in the sky

- 1572 Tycho Brahe measures a supernova
- 1610 Galileo observes Jupiter satellites, ...
- 1687 Newton unifies gravitation
- ….
- ….
- ….
- 1930-1950 e+,μ, π, K discovered in cosmic rays
- 1968-2001 neutrino oscillations discovered with solar and atmospheric neutrinos !
- 2017- New windows are opening up in gravitational waves and multimessenger physics !





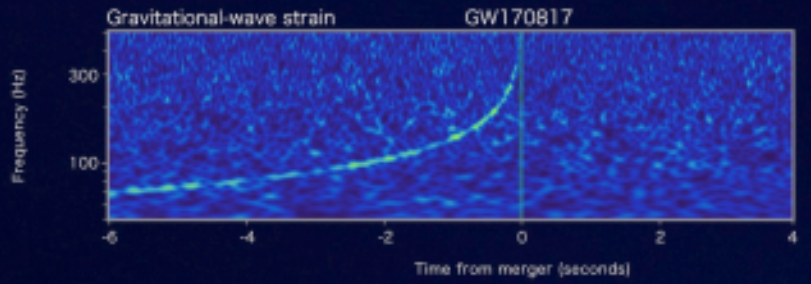
SPEED OF GRAVITATIONAL WAVES FROM GW170817 AND GRB170817A

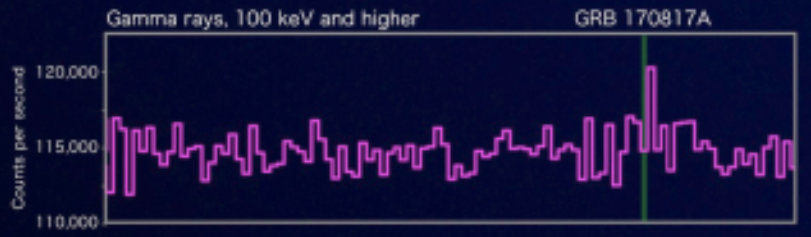
Abbott+ ApJ Letters, 848, L12 (2017)

Fermi
Reported 16 seconds after detection

LIGO-Virgo
Reported 27 minutes after detection

INTEGRAL
Reported 66 minutes after detection





$$-3 \times 10^{-15} \leq \frac{v_{\rm GW} - v_{\rm EM}}{v_{\rm EM}} \leq 7 \times 10^{-16}$$

3G network will improve this limit by three orders of magnitude

Thanks to the scientific secretaries!

Albert De Roeck (CERN) and Thomas Schwetz (KIT) who have helped us to organize the session and will assist us in the preparation of the Briefing Book

The team (speakers and scientific secretary)

Thanks to all the speakers!

1. Neutrino oscillations

Silvia Pascoli (Durham) Theories of neutrino masses and leptonic CP violation

Eligio Lisi (INFN Bari) Precision determination of neutrino mass-mixing parameters

Mauro Mezzetto (INFN Padova) Prospects for the measurement of the nu Mass ordering and leptonic CP violation

Federico Sanchez (Geneva U) Meas. of Nu-nucleus cross sections and nu flux

2. Neutrino mass and new states

Susanne Mertens (TUM) Measurements of the neutrino mass

Bonnie Fleming (Yale) Prospects for the search of sterile neutrinos

Nicola Serra (Zurich U) Prospects for the search of Heavy Neutral Leptons

3. Cosmic messengers

Andreas Haungs (Karlsruhe) Cosmic ray physics

Francis Halzen (Winsconsin) Neutrino astroparticle physics

B.S. Sathyaprakash (Penn State) Gravitational waves

Marek Kowalski (DESY) Multimessenger physics

Big questions

What is the origin of the neutrino masses ? And of the leptonic mixing ?

What is the optimal strategy towards a complete set of measurements of neutrino oscillation parameters and towards a precision global fit of the PMNS matrix ?

Is the existing experimental program (reactor, SBL) sufficient to confirm or exclude the existence of sterile neutrino states with masses in the eV/c^2 range ?

How to search for heavy neutral leptons with present and future facilities ?

Is gravity described by the Einstein theory of general relativity?

How do gravitational waves help to understand Dark Sector of the universe?

What is the proton-proton cross section at ultra-high energies?

How can cosmic neutrino’s help to pin-down their properties - oscillations and mass hierarchy?

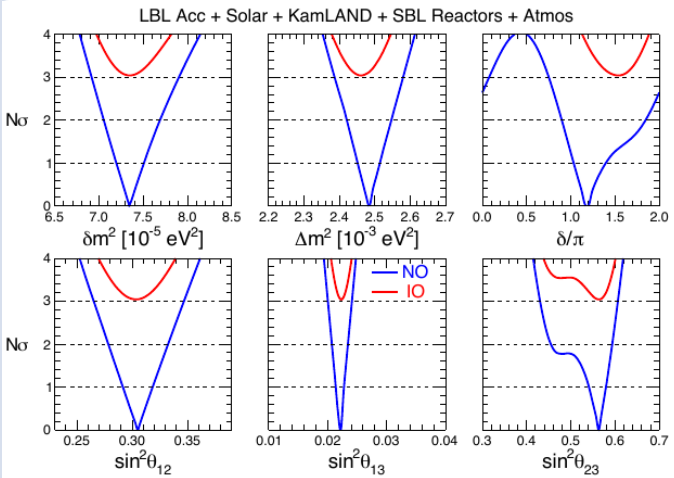
2013 Strategy

f) Rapid progress in neutrino oscillation physics, with significant European involvement, has established a strong scientific case for a long-baseline neutrino programme exploring CP violation and the mass hierarchy in the neutrino sector. CERN should develop a neutrino programme to pave the way for a substantial European role in future long-baseline experiments. Europe should explore the possibility of major participation in leading long-baseline neutrino projects in the US and Japan.

j) A range of important non-accelerator experiments take place at the overlap of particle and astroparticle physics, such as searches for proton decay, neutrinoless double beta decay and dark matter, and the study of high-energy cosmic-rays. These experiments address fundamental questions beyond the Standard Model of particle physics. The exchange of information between CERN and ApPEC has progressed since 2006. In the coming years, CERN should seek a closer collaboration with ApPEC on detector R&D with a view to maintaining the community's capability for unique projects in this field.

The study of neutrino properties

Today : few % precision on most of the parameters

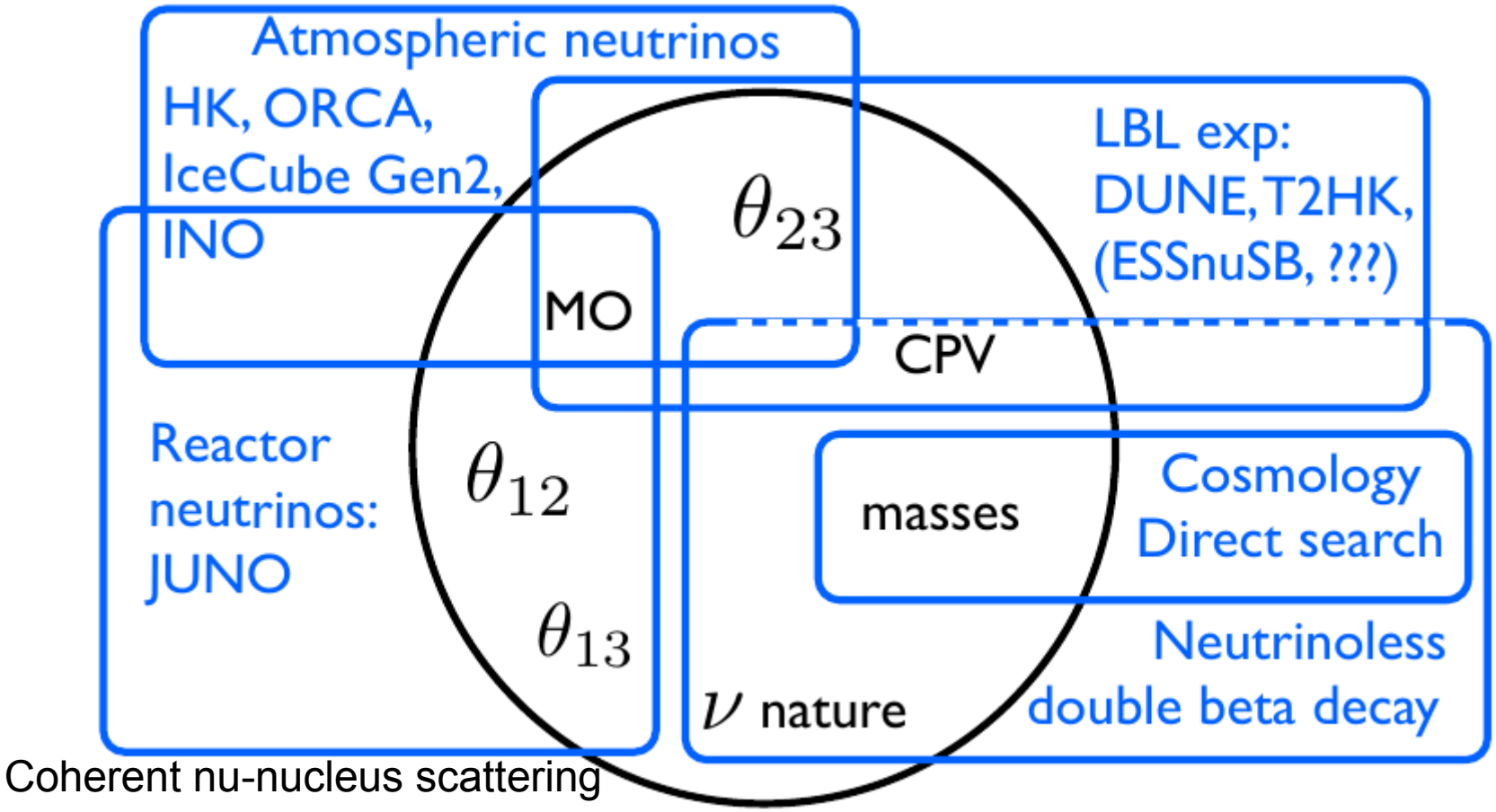


Oscillation parameter		Best-fit (NO)	Best-fit (IO)	"1σ" error
Δm^2	$/10^{-3}$ eV^2	2.49	2.47	1.3 %
δm^2	$/10^{-5}$ eV^2	7.34	7.34	2.2 %
$\sin^2\theta_{13}$	$/10^{-2}$	2.23	2.24	3.0 %
$\sin^2\theta_{12}$	$/10^{-1}$	3.04	3.03	4.4 %
$\sin^2\theta_{23}$		0.56	0.56	~ 5 %

E. Lisi Granada 2019

But there are still major unknowns : Dirac or Majorana, CP violation phase δ, mass ordering and θ_{23} octant, absolute mass

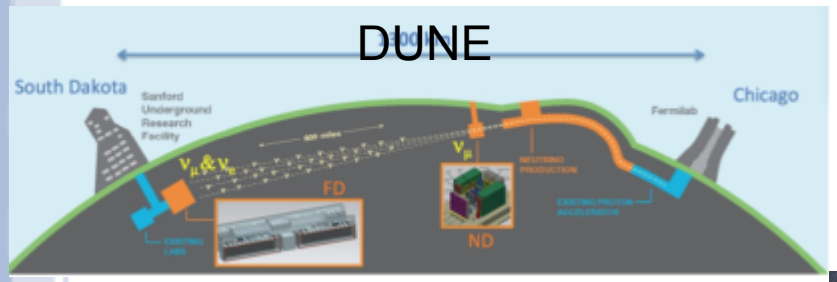
A very diverse experimental approach

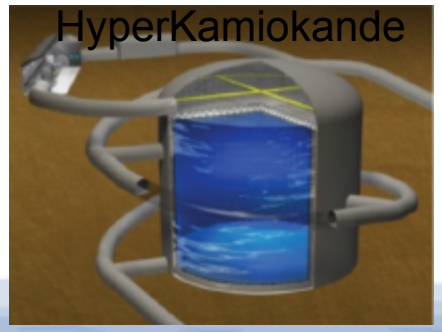


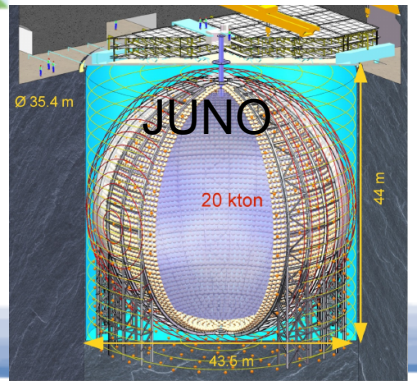
Motivation : necessary to get a complete picture, make the most out of every neutrino source, test at different L/E, possible existence of new neutrino states, of Non-Standard-Interactions

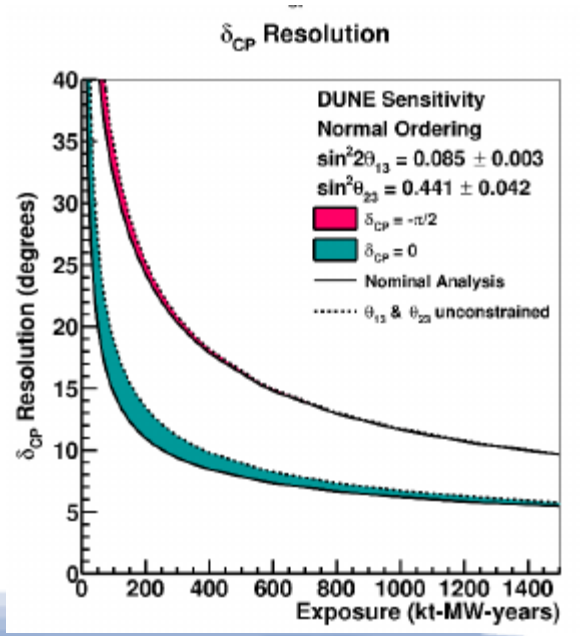
New long baseline projects

- Golden physics case for LBL: CP violation in PMNS would be a new source since 1964 discovery, possible link with leptogenesis, CP and MO linked to model building
- Since 2013 progress in the field had been faster than “rapid” convincing a growing community (>2000 worlwide) of physicists and the funding agencies to invest in these experiments
- Major players : DUNE, Hyper-Kamiokande, JUNO, ORCA



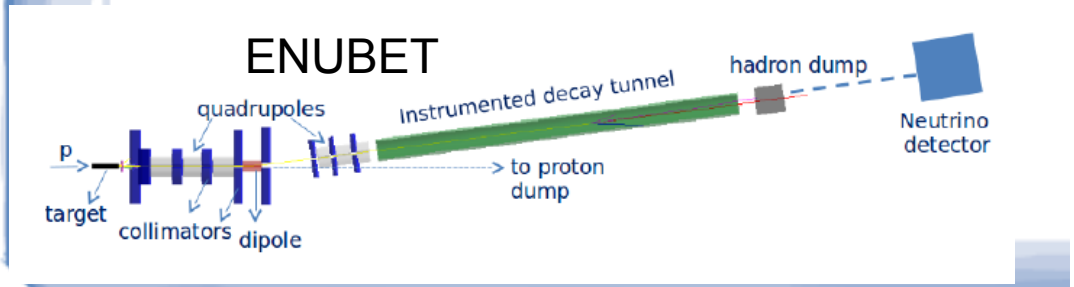


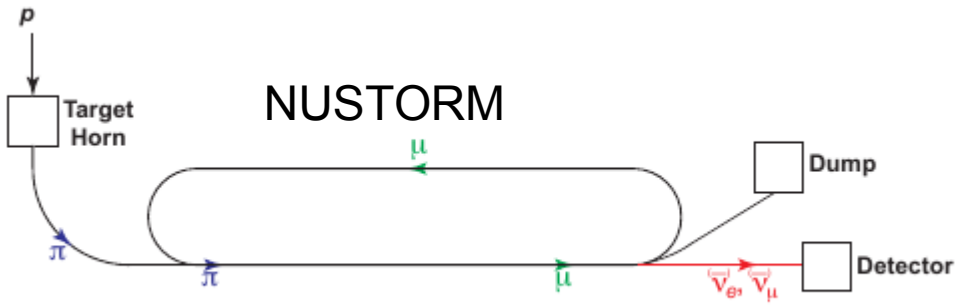




Precision program in Europe

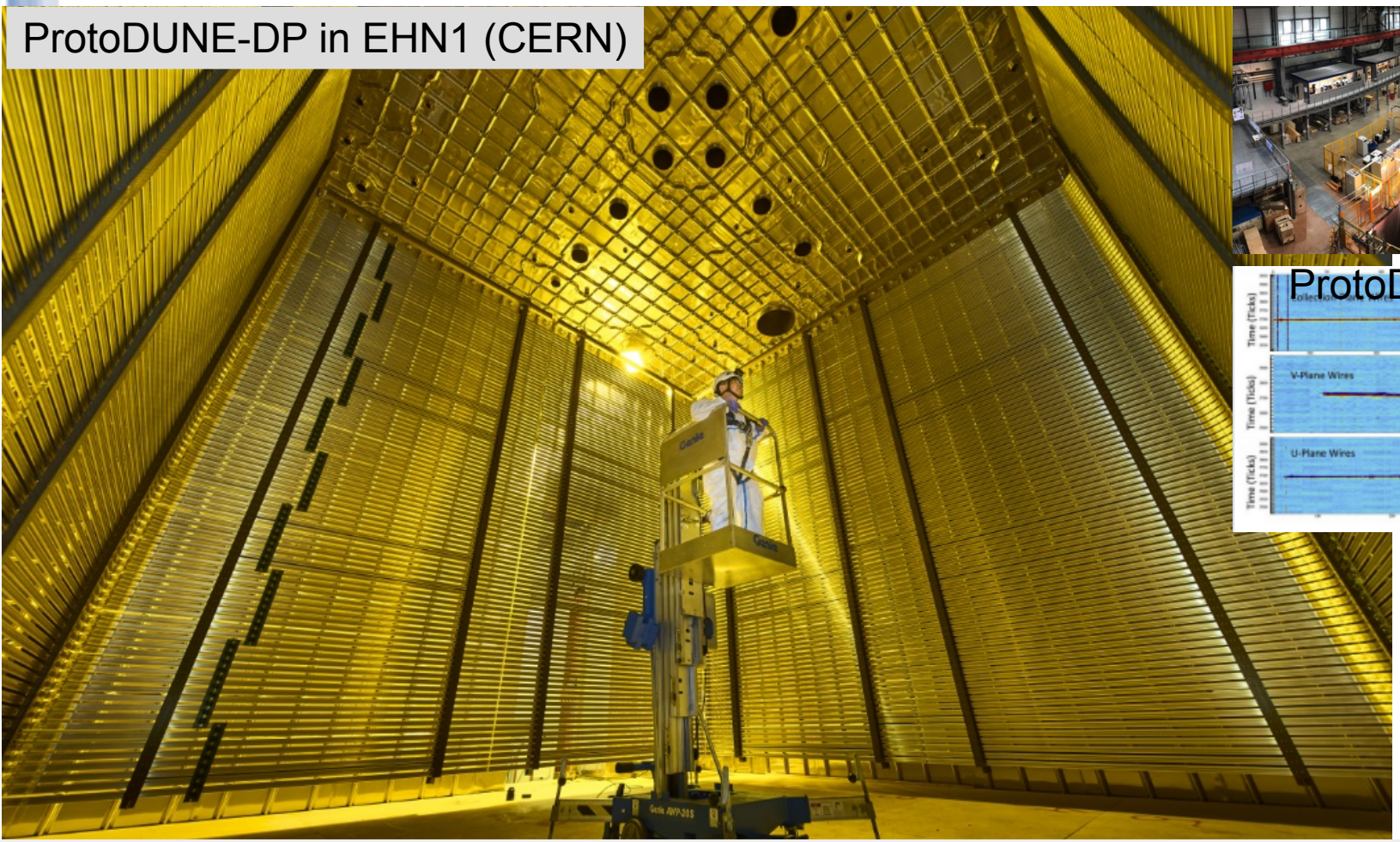
- Squeezing every bit of information out of the future experiments requires a complementary program (special rôle for Europe) to
  - Measure hadroproduction for the neutrino flux prediction (NA61)
  - Understand the neutrino-nucleus cross-section at the % level, both theoretically and with new facilities (Enubet, Nustorm)
  - Collaboration to be developed with nuclear physicists
- Next-to-next generation facilities (ESSnuSB, …) are also under study

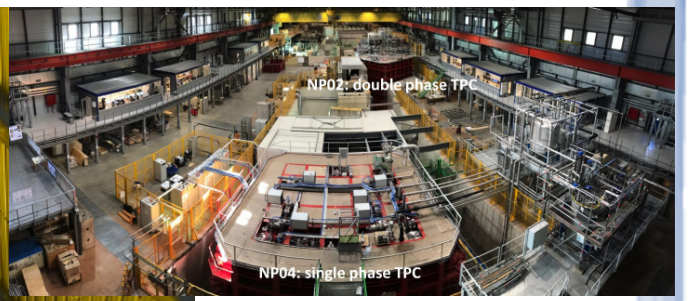




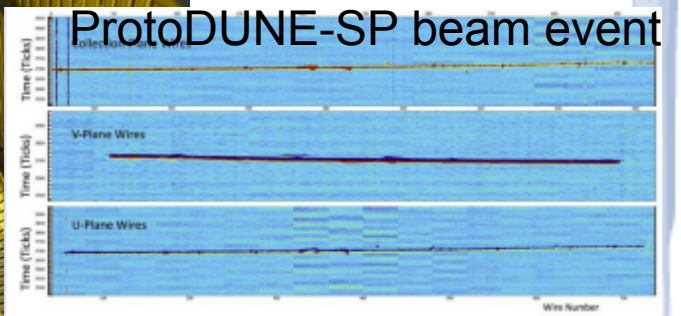
The CERN Neutrino Platform

ProtoDUNE-DP in EHN1 (CERN)





ProtoDUNE-SP beam event

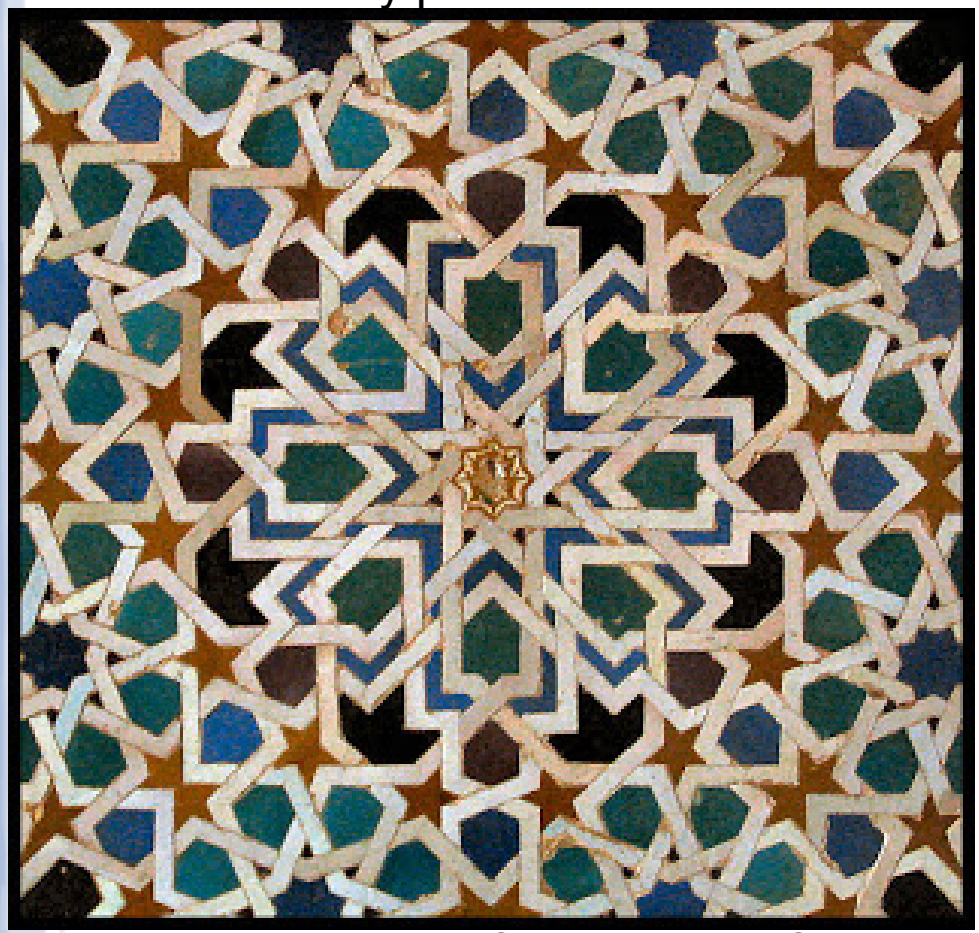


- Demonstration of membrane cryostats for LAr TPC
- ProtoDUNE-SP exposed to the SPS beam in 2018 and fully validated (purity, S/N, HV)
- ProtoDUNE-DP to be tested this summer
- Also T2K ND Upgrade, ENUBET, BabyMIND...

A game changer for the field worlwide !

The origin of leptonic mixing

One of the many patterns of Alhambra!



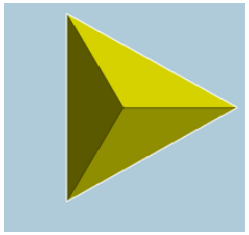
See also H. Weyl Symmetry

Aesthetically pleasing and possibly relevant for elementary particles !

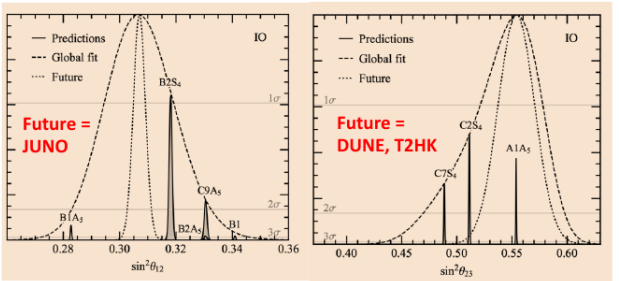
Is there a pattern behind the PMNS matrix ?

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

$$\begin{pmatrix} |U_{e1}|^2 & |U_{e2}|^2 & |U_{e3}|^2 \\ |U_{\mu 1}|^2 & |U_{\mu 2}|^2 & |U_{\mu 3}|^2 \\ |U_{\tau 1}|^2 & |U_{\tau 2}|^2 & |U_{\tau 3}|^2 \end{pmatrix} = \begin{pmatrix} 2/3 & 1/3 & 0 \\ 1/6 & 1/3 & 1/2 \\ 1/6 & 1/3 & 1/2 \end{pmatrix}$$



Various symmetries have been proposed (A4, S4, A5)

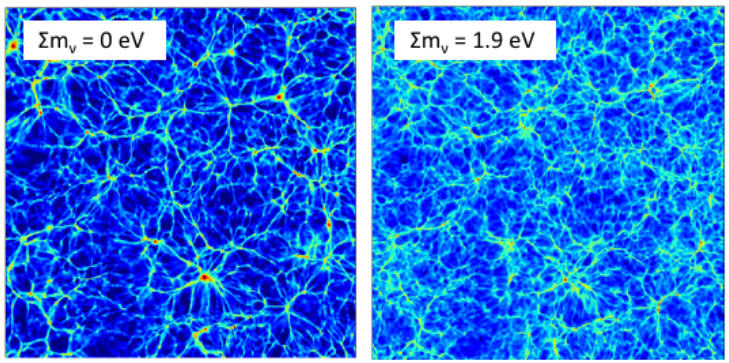


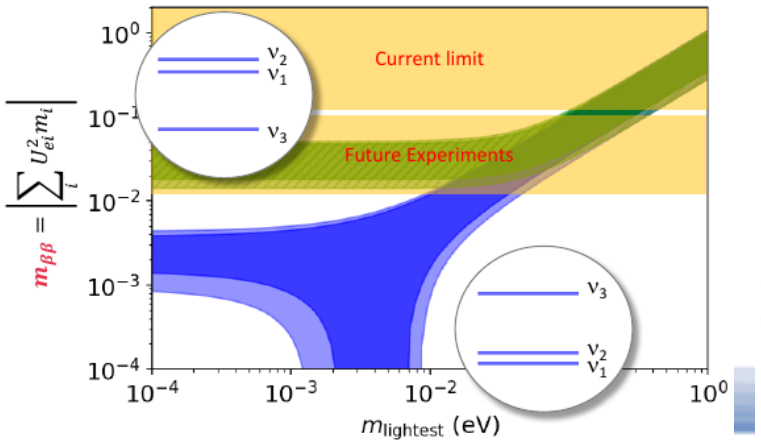
Petcov & Titov 1804.00182

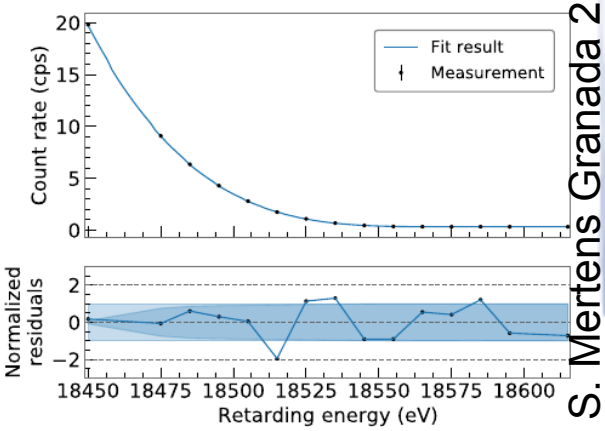
Precision might be the key to discriminate among different models

Measuring the neutrino masses

- Future cosmology missions (Euclid, DESI …) target the neutrino mass detection ! (only parameter in common between particle physics and cosmology)
- Neutrinoless double beta decay : key to determine the neutrino nature. IO covered with the next generation of experiments (strong program in Europe: LEGEND, CUPID, NEXT ...)
- Single beta decay : KATRIN taking data. New exp. methods (Project8, ECHo) under development.



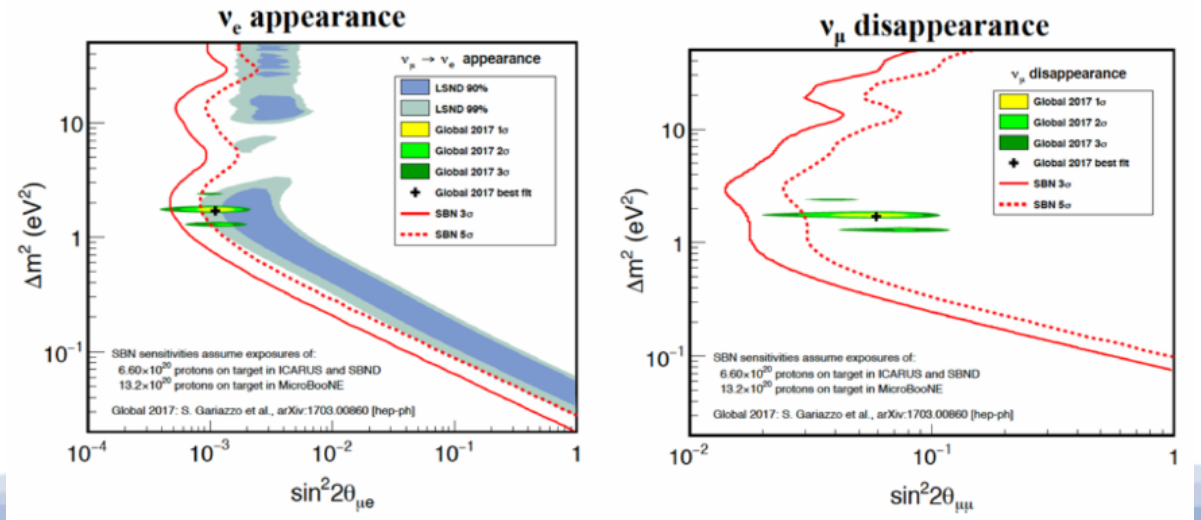




S. Mertens Granada 2019

Are there sterile neutrinos ?

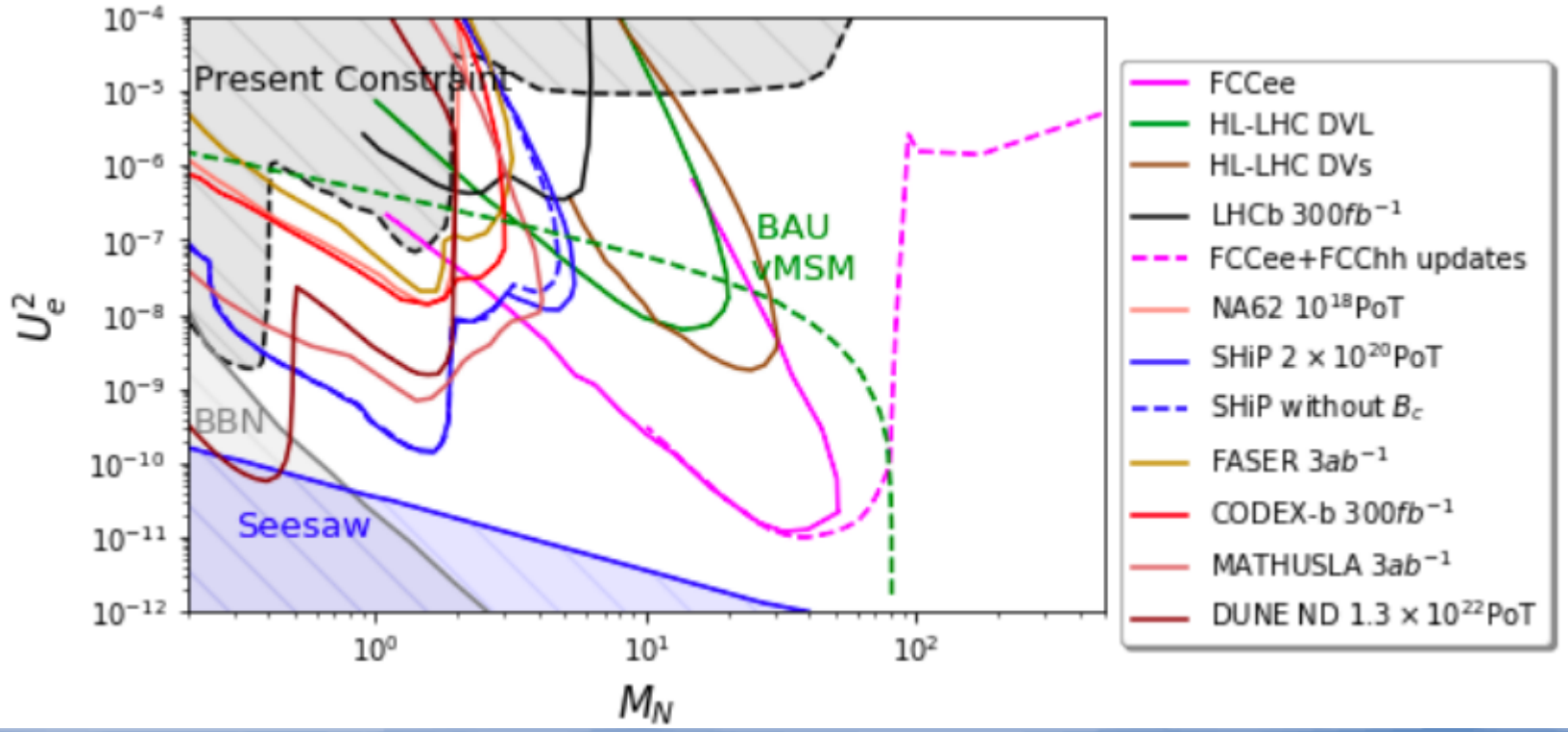
- Motivated by long standing anomalies (LSND, MiniBoone, Gallium, reactor anomaly)
- No successful model and strong tension with other results (MINOS+, IceCube)
- A very rich program developing with SBL reactor neutrino experiments (Prospect, Solid, Stereo, Neutrino4, DANSS, NEOS). The results are ambiguous.
- Fermilab SBN three detectors program (SBND, MicroBoone, Icarus). 2020 results from MicroBoone
- We will know a lot more in the next couple of years



B. Fleming Granada 2019

Hunting new states (HNL)

- New neutrino states (Heavy Neutral Leptons) possibly related to neutrino masses and baryon asymmetry
- Their masses could be anywhere between eV and GUT scales !
- Very active area : searches based on LBL near detectors, beam dump, colliders, « symbiotic » expt.
- Unique sensitivity at low masses for the beam dump facility

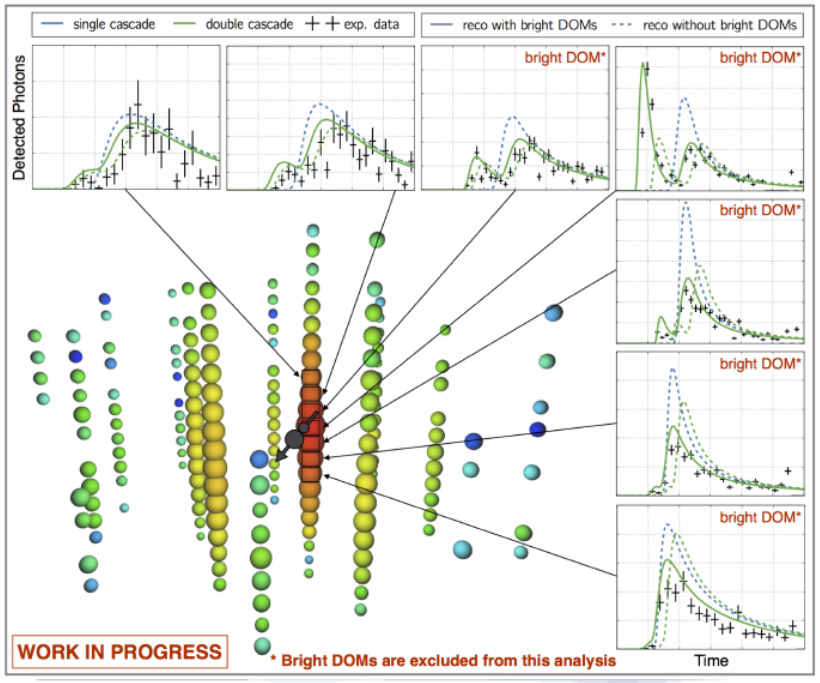


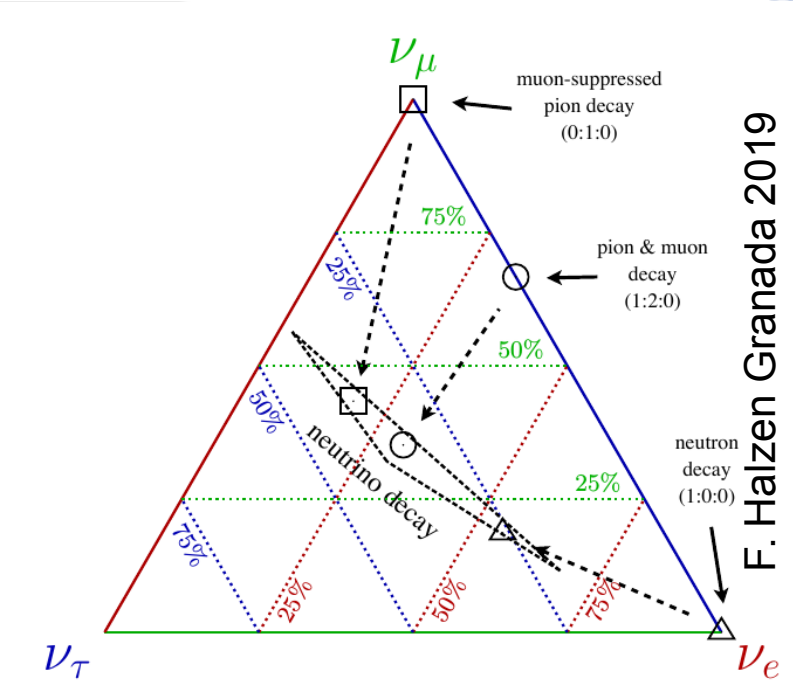
N. Serra Granada 2019

Cosmic neutrinos

- Cosmic neutrinos are complementary to accelerator-based experiments : mass ordering with KM3NeT/ORCA and IceCube/PINGU.
- But also neutrino properties and interactions, tau neutrino, PMNS unitarity...
-

a cosmic tau neutrino: livetime 17m

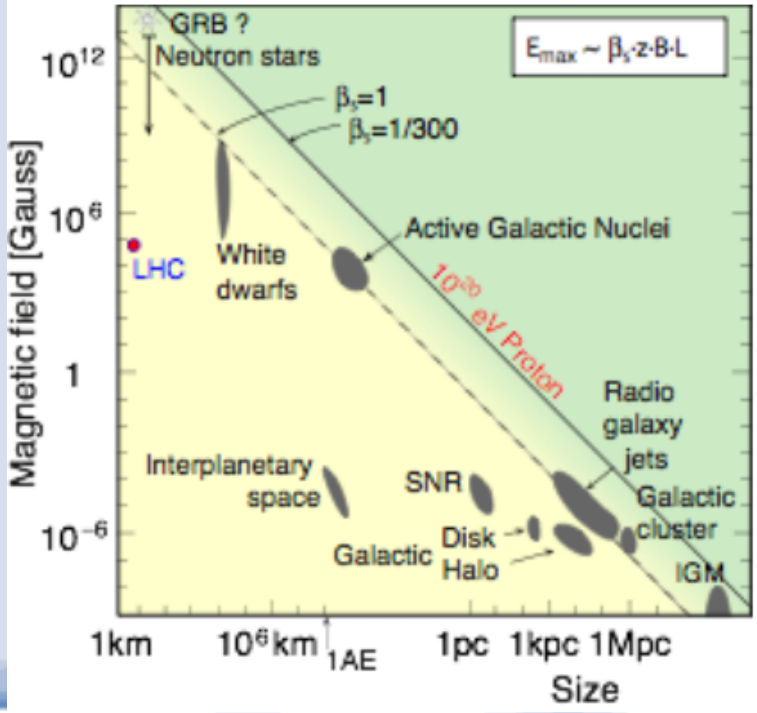


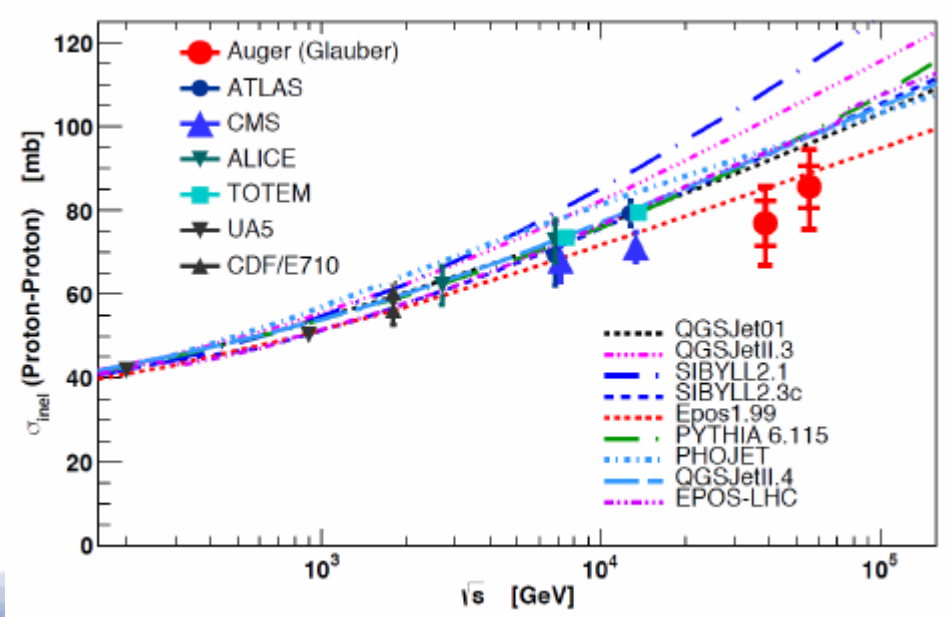


F. Halzen Granada 2019

UHE Cosmic Rays

- Flux suppression observed at ~10^{20} eV
- Dipole distribution observed above 8 EeV : extragalactic origin
- Most models of UHECR from exotic sources are ruled out (monopoles, cosmic strings…)
- Proton-proton cross-sections
- The first EeV-neutrino should be 'just around the corner'

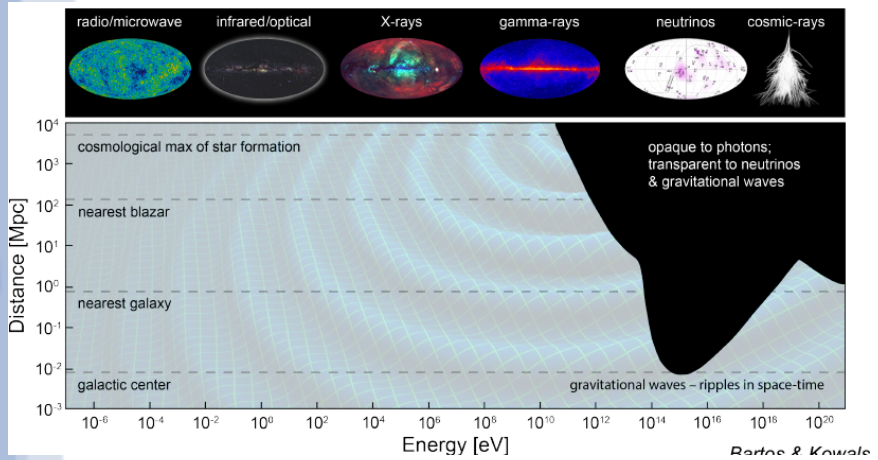


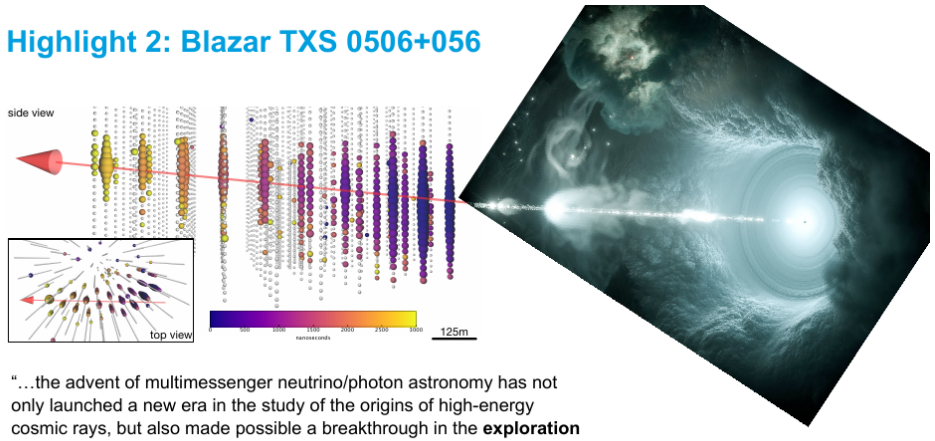


A. Haungs Granada 2019

Multimessengers

- Multimessenger : combining information from photons, neutrinos, CR, GW.
- Recent highlights : Neutron star merger (GW+photon), Blazar (neutrino's +photon)
- Many physics topics : dark matter searches, expansion history of the Universe, Lorentz symmetry, ...



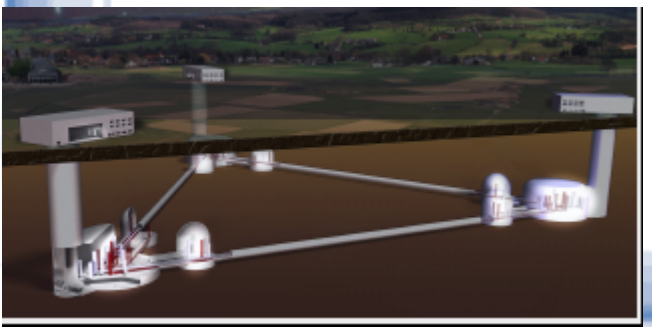


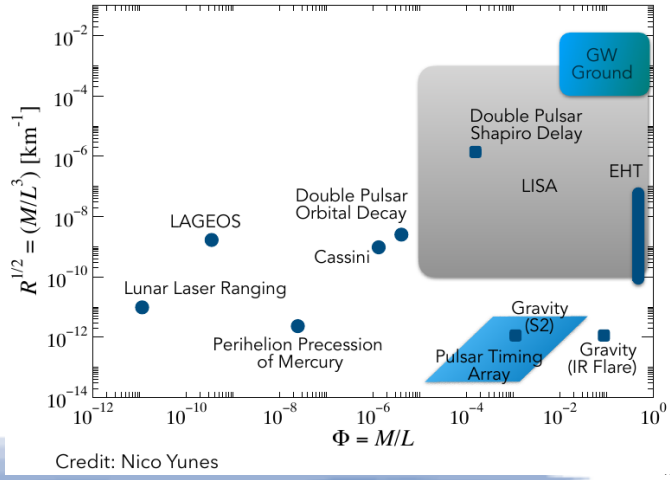
"…the advent of multimessenger neutrino/photon astronomy has not only launched a new era in the study of the origins of high-energy cosmic rays, but also made possible a breakthrough in the **exploration of Lorentz symmetry** using neutrinos."

M. Kowalski Granada 2019

Gravitational waves

- Gravitational waves open a new field of research
  - Testing General Relativity in extreme conditions
  - Probing Black hole as Dark Matter
  - Equation of state in neutron stars
  - Serendipity : exotic objects, new fields and phenomena
- Einstein Telescope : 3rd generation of interferometers. Ultimate facility to probe the entire universe in the 1-100 Hz frequency range
- ET has put on the table a request for CERN to help with
  - Underground infrastructure, cryogenics
  - Vacuum, material and surface science
  - Electronics and data acquisition, computing





Neutrino oscillations

- Vibrant program (DUNE, Hyper-Kamiokande, JUNO, ORCA) to fully measure the PMNS mixing matrix and especially the Mass Ordering and the CP violation phase delta, with strong European contribution. Perceived by the community as a priority.
- Neutrino experiments need cutting-edge detectors and % precision on the flux and cross-sections: leading rôle for Europe (NA61, Neutrino Platform). New facilities currently under study.
- Long term future for high precision LBL measurements with new techniques. Time to prepare for it !

Understanding the neutrino mass

- The absolute mass is still unknown (challenging task m<~0.1 eV!). Laboratory (Katrin) and cosmology missions ongoing.
- Is the neutrino a Dirac or a Majorana fermion ? Neutrinoless double beta decay searches can provide an answer to this crucial question
- The neutrino mass might require new neutral fermions with masses between eV and GUT scale (!)
  - Clarify eV scale anomalies (SBL program at FNAL, reactor neutrino experiments)
  - CERN could have a leading rôle for the Search for new states at the GeV-EW scale (beam dump and colliders)

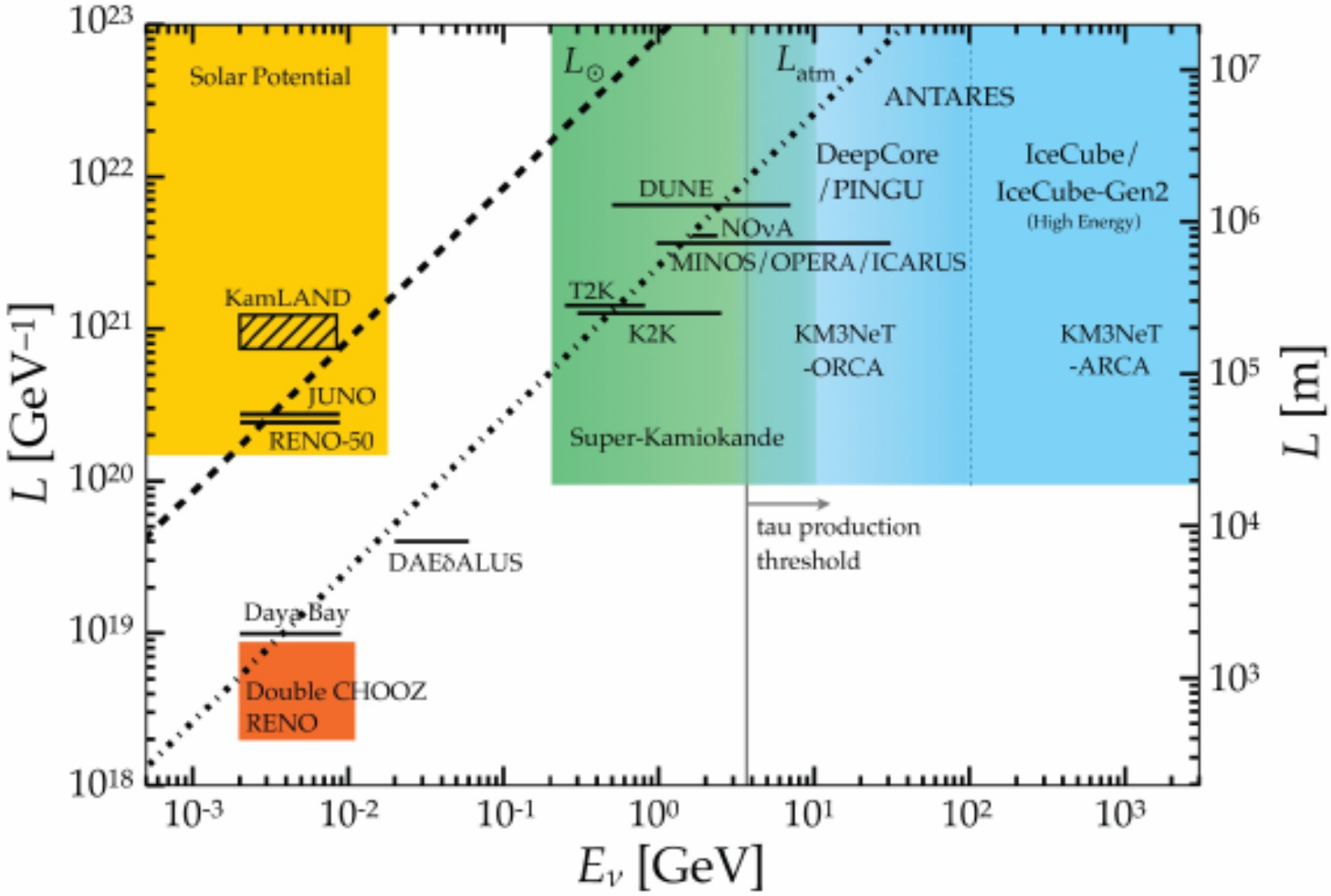
Astroparticle physics

- Gravitational waves and multimessenger physics open up a new window on the Universe. Very strong physics case.
- There is a very high impact on the field of particle physics (and fundamental interactions) (eg dark matter, neutrinos, general relativity, ...)
- There is clearly an opportunity for the particle physics community and laboratories to expand their involvement in this program

Backup

Complementarity: same L/E but different E

Any subleading non-oscillatory effect would violate L/E scaling.
Atmospheric/astrophysical neutrinos play a very important role (F. Halzen talk in this session)



What is the new physics scale?