Credit: symmetry magazine

Neutrino Physics – Experimental II

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TAE 2023 – International Workshop on High Energy Physics

Centro de Ciencias Pedro Pascual

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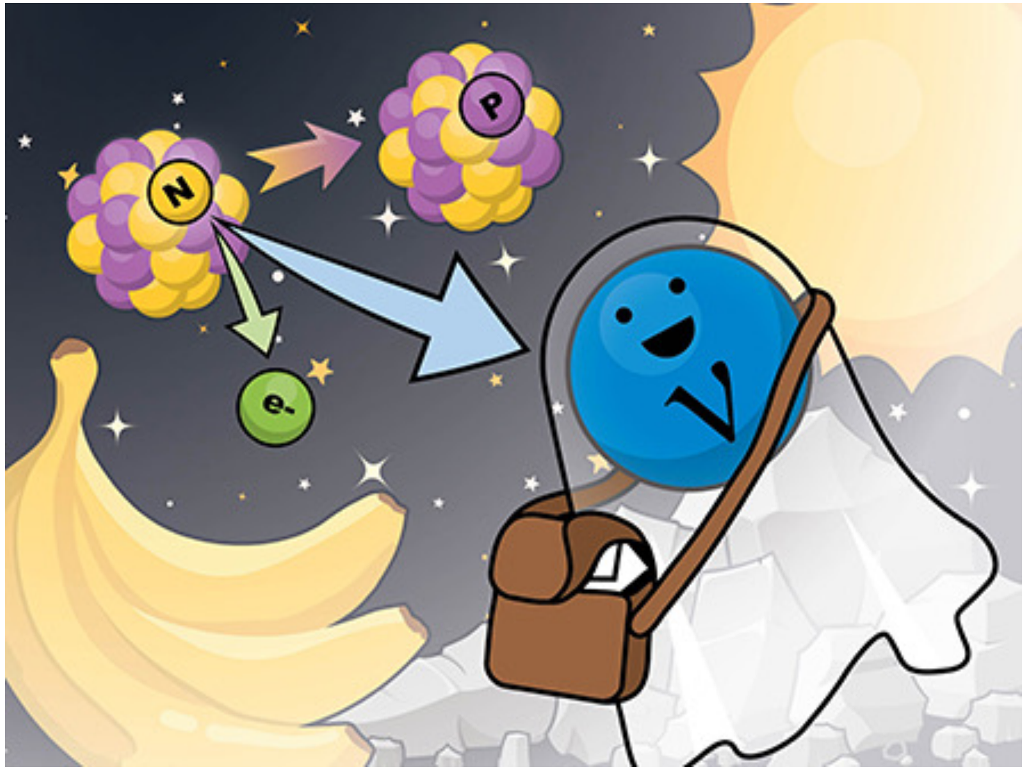
Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

Why do we study neutrinos?



Credit: symmetry magazine

Neutrinos are abundant, but the most elusive particles.

Enigmatic particles, not fully understood

Provide answers to our understanding of the universe

Q

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History highlights of neutrinos

1930 - Pauli proposed the ν.

1956 - The neutrino (ν_e) was directly observed by Cowan & Reines.

1962 - First experiment with accelerator ν's in Brookhaven (USA): ν_μ observation.

1968 - Solar ν detection by Davis $\rightarrow$ ν_e rate smaller tan expected.

- 1957 - Pontecorvo postulated oscillation theory of $\nu \rightarrow \bar{\nu}$.
- 1962 - Maki, Nakagawa y Sakata proposed a two-flavor mixing theory and latter built a general model.

1998: Super-K detected atmospheric neutrino oscillations

2001: SNO detected solar neutrino oscillation measuring the total neutrino flux.

2000-2020: Experimental measurement of oscillation parameters:

$$\theta_{12}, \Delta m^2_{12}, \theta_{23}, \theta_{13}, \Delta m^2_{31}$$

Reines - 1995

Lederman, Schwartz, Steinberger - 1988

Davis - 2002

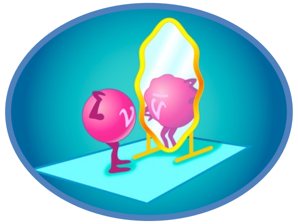
McDonald, Kajita -2015

Flavor oscillations imply that neutrinos are massive $\rightarrow$

Physics Beyond the Standard Model

Neutrino unknowns

1. **Neutrino mixing**
   Is the CP symmetry violated in the neutrino sector? CP-violation is one of the 'Sakharov conditions' to explain the matter-antimatter asymmetry in the Universe.



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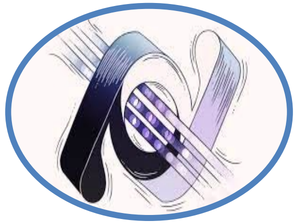

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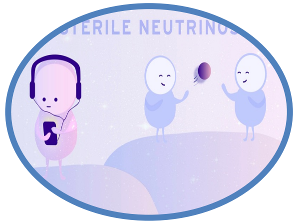

Powerful experimental program to answer these questions!

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NEUTRINO MIXING

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Neutrino unknowns

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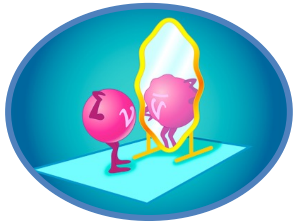

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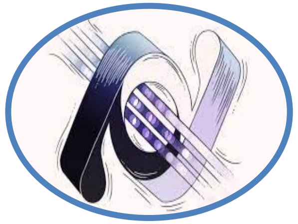

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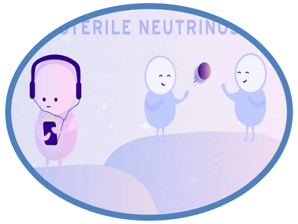


Credit: symmetry magazine

1. Neutrino mixing

The measurement of $\theta_{13} \neq 0$ allows

- Determination of the mass ordering
- Study of the existence of CP violation in the leptonic sector.

The goals of the future research in neutrino oscillation are:

1. To determine the status of the CP symmetry in the leptonic sector
2. To solve the octant θ_{23} degeneracy: $\sin^2(2\theta_{23}) \sim 1$, but the data are inconclusive whether θ_{23} is larger or smaller than 45°
3. To determine the mass ordering: There are 2 possibilities for the ordering of the neutrino masses $m_1 < m_2 < m_3$ "Normal ordering" and $m_3 < m_1 < m_2$ "Inverted ordering"

CP violation phase

Long baseline experiments can measure additionally CP violation using beam of neutrinos and anti-neutrinos

$\boldsymbol{P}\,(\bar{\nu}_{\mu} \to \bar{\nu}_{e})$ the same except that the sign of the second term has opposite sign

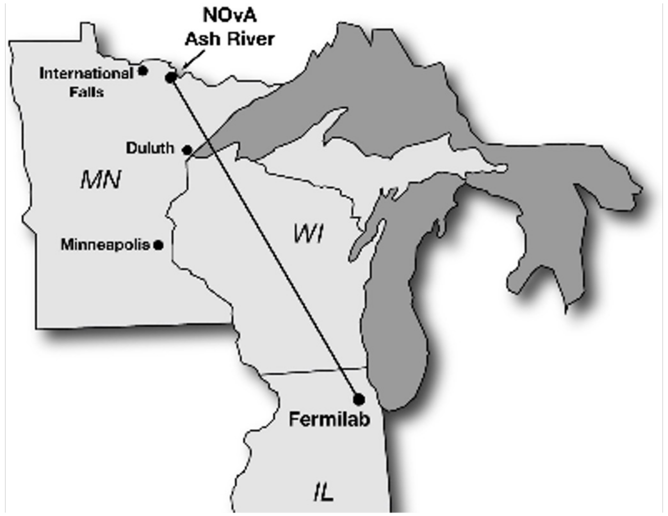
$$P_{\nu_\mu \to \nu_e} \sim \frac{1}{2}\sin^2 2\theta_{13} - 0.043 \sin 2\theta_{13} \sin 2\theta_{23} \sin\delta$$

$$P_{\bar{\nu}_\mu \to \bar{\nu}_e} \sim \frac{1}{2}\sin^2 2\theta_{13} + 0.043 \sin 2\theta_{13} \sin 2\theta_{23} \sin\delta$$

$$A_{CP} = \frac{P_{\mu e} - \bar{P}_{\mu e}}{P_{\mu e} + \bar{P}_{\mu e}} \sim 0.3 \sin\delta$$

T2k

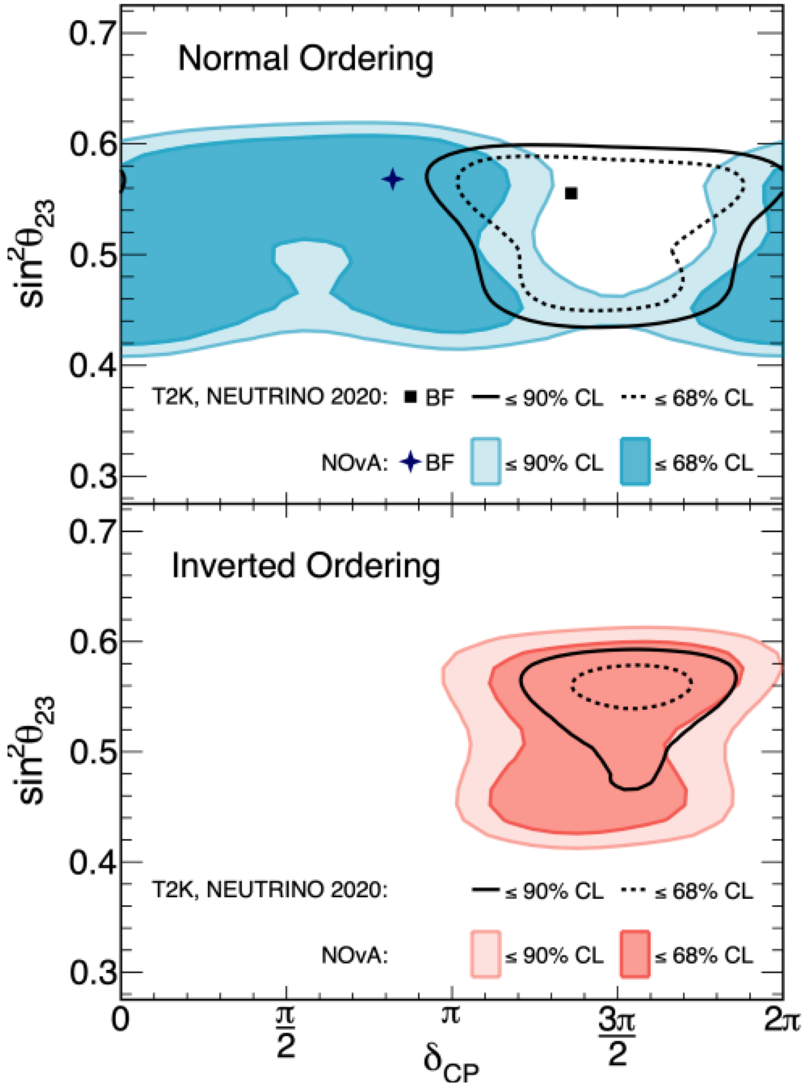
NoVA



CP violation phase

- Is there leptonic CP violation?
  - Hints from T2K and NOvA, but tension for normal ordering. Combined analysis may give more preference, but not stable yet.
  - Need next generation experiments: DUNE, T2HK
- Next experiments : DUNE, T2HK, JUNE will measure precisely mixing parameters.

2020 data set: https://arxiv.org/abs/2108.08219



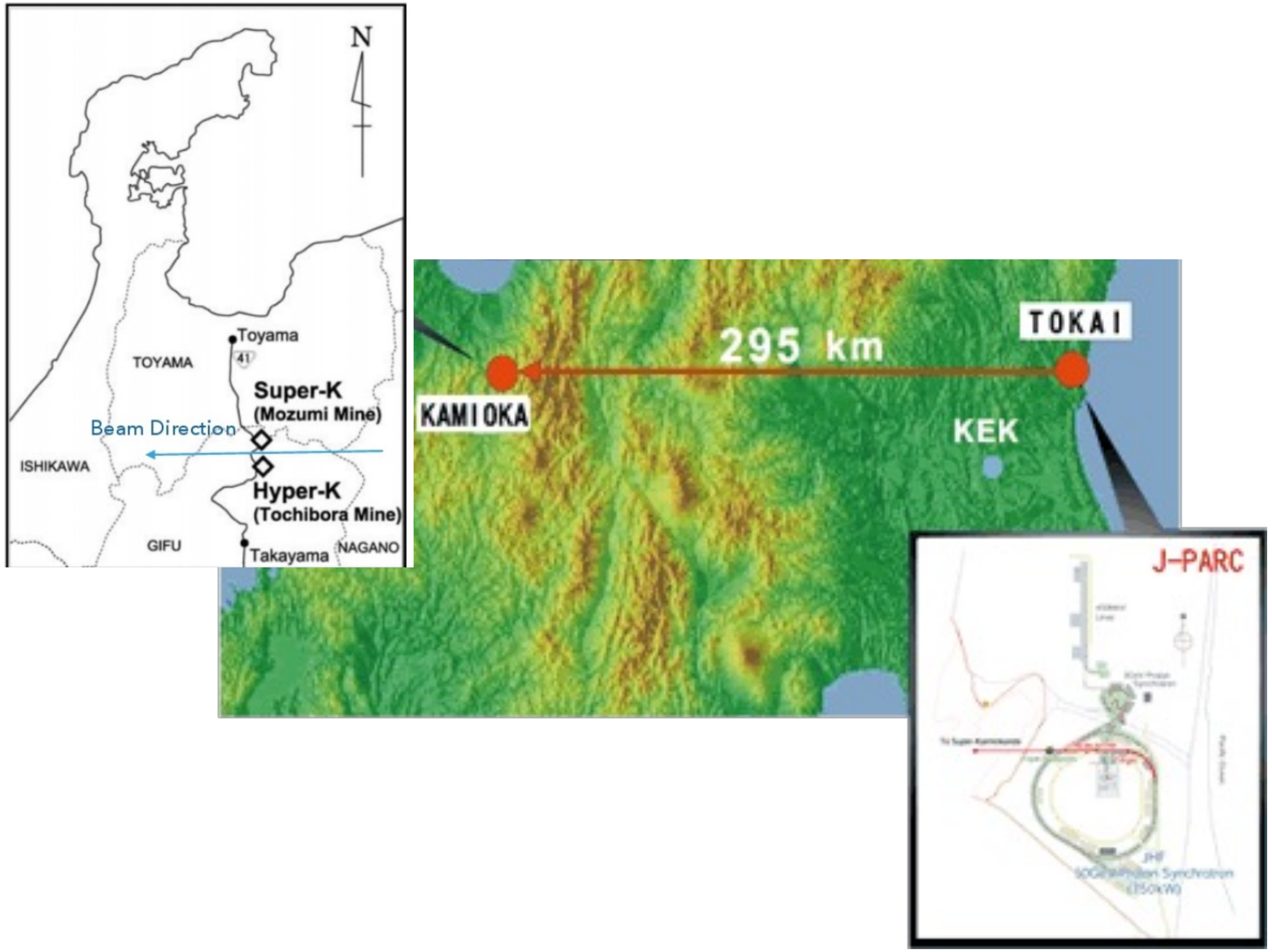
Hyper-Kamiokande experiment

Physics goals:

- Discovery of the difference between ν and $\bar{\nu}$ oscillations (CP violation) and precise measurements to elucidate the origin of matter in the universe.
- Further development of neutrino astronomy.
- Proof of "unification of elementary particles" and "unification of electromagnetic, weak and strong force" by the discovery of proton decay.

Tokai to Hyper-Kamiokande:

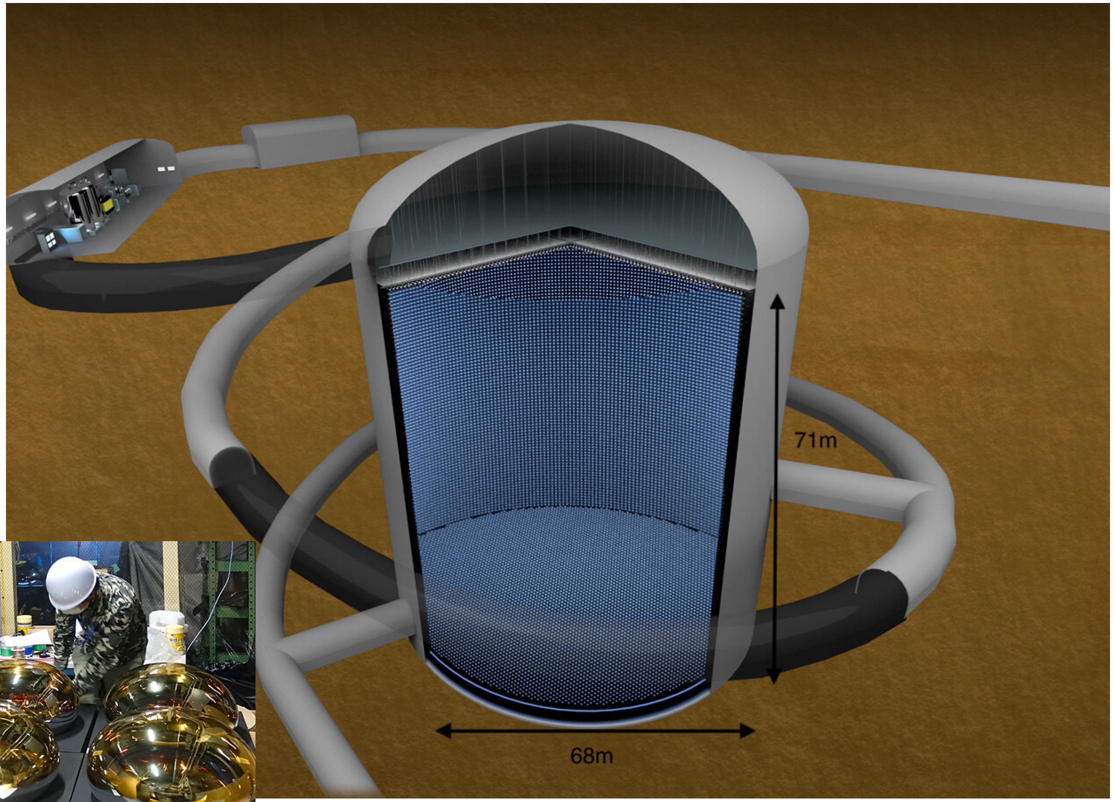
- Near detector ND280 to continue for Hyper-K use
- Upgraded J-PARC neutrino beam line (same as T2K) with expected beam power > 1.3MW



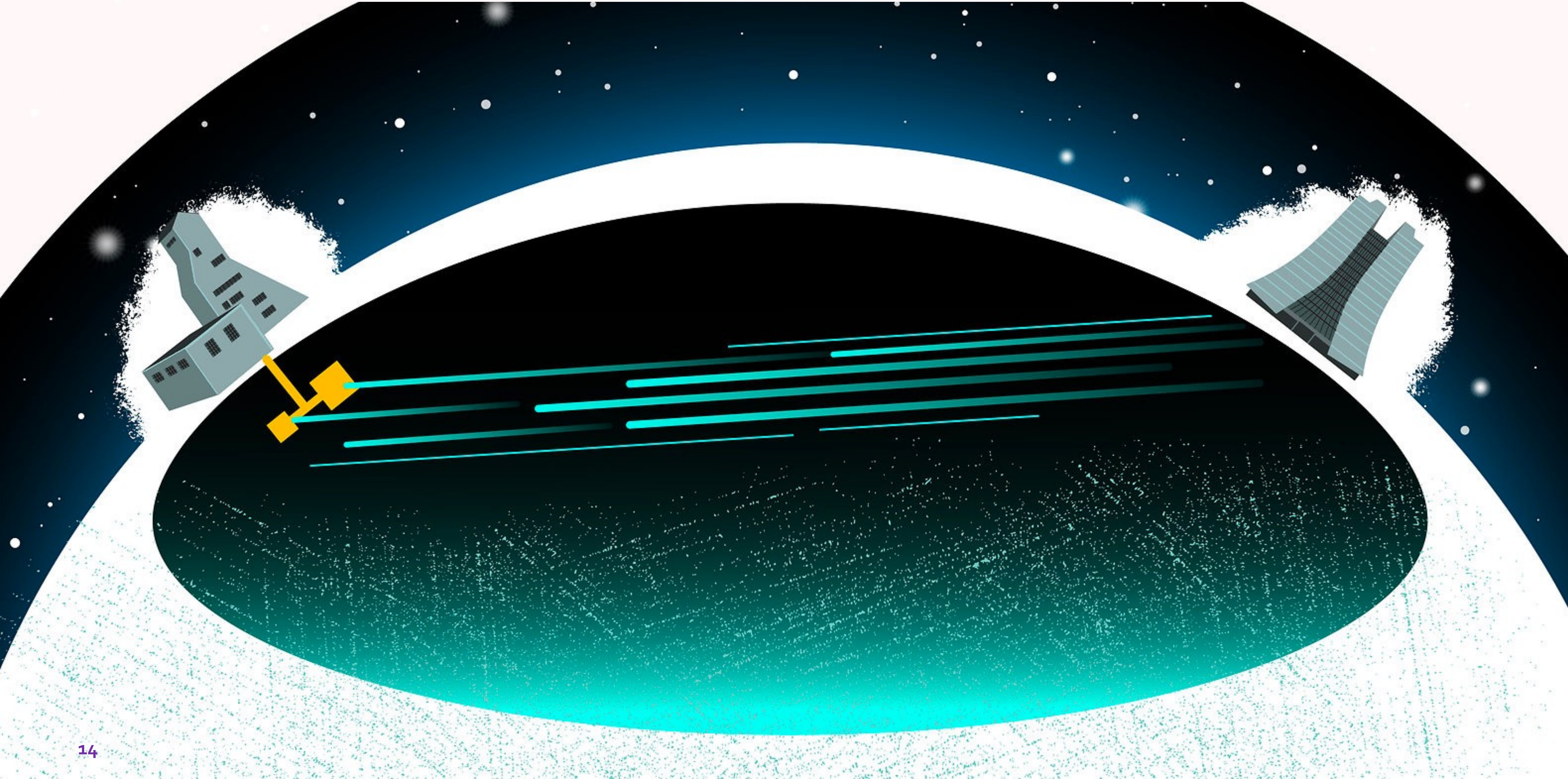
Hyper-Kamiokande experiment

Detector features:

- water Cherenkov detector.
  - 68 m diameter x 71 m height.
  - 260 kton (190 kton fiducial.
  - about 40000 PMTS of 50 cm diameter.



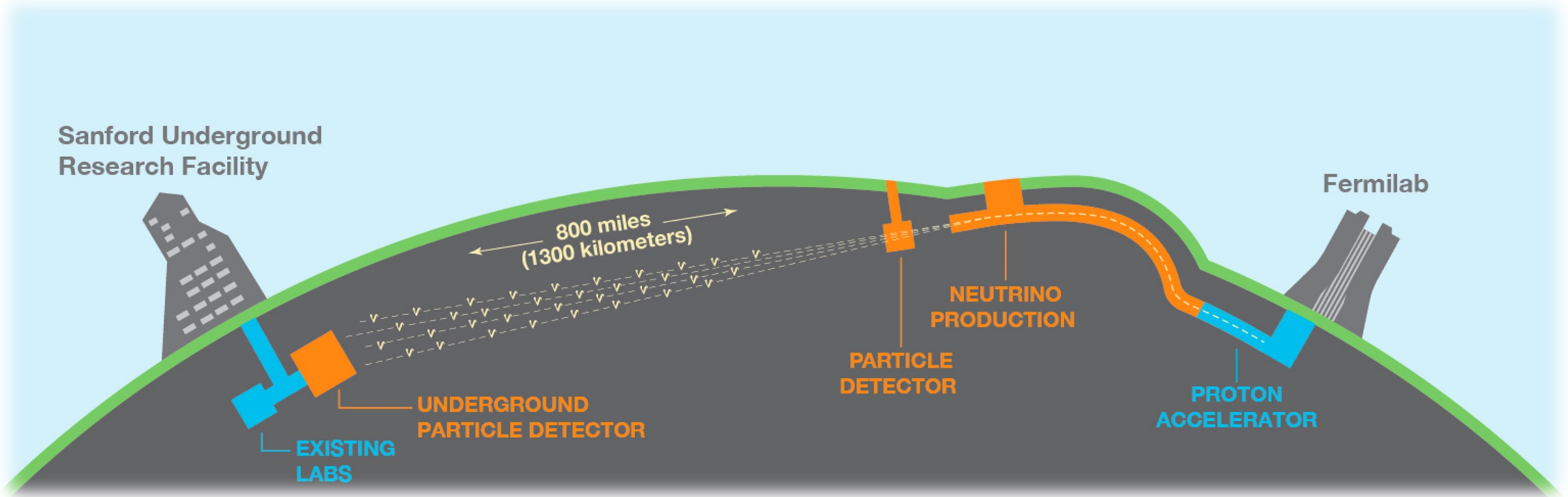
The Deep Underground Neutrino Experiment (DUNE)



Deep Underground Neutrino Experiment (DUNE)

DUNE aims at answering fundamental questions related to:

- The matter-antimatter asymmetry – Long baseline neutrino oscillations EPJC 80 (2020) 978
- The Grand Unification of forces – Physics beyond the Standard Model EPJC 81 (2021) 322
- The supernova explosion mechanism – Low energy physics EPJC 81 (2021) 423



- New neutrino (ν_μ or $\overline{\nu}_\mu$) beam facility at Fermilab (LBNF), US.
- A highly capable Near Detector at Fermilab to measure the unoscillated neutrino spectrum and flux constraints.
- 4 x 17 kton liquid argon time-projection chambers (LArTPC) modules deep underground at SURF (Lead, SD, 1300 km baseline).

Instruments 5 (2021) 31

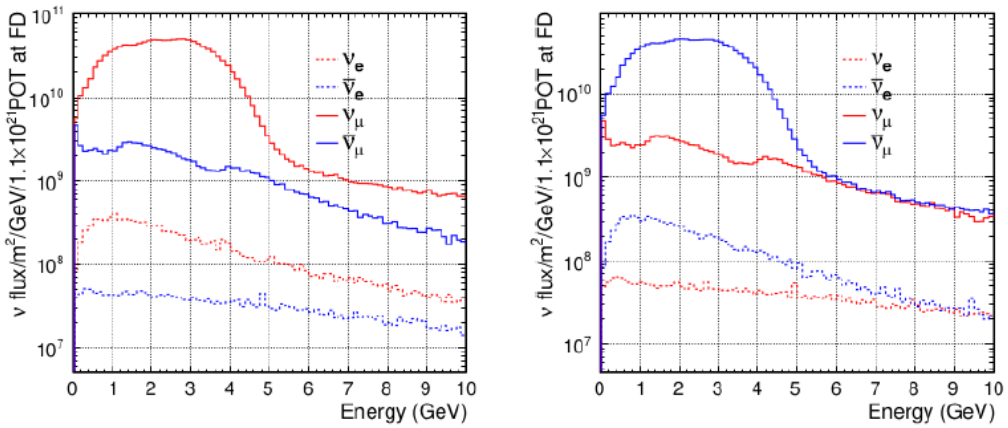
JINST 15 (2020) T08008
JINST 15 (2020) T08010

Long-baseline oscillations in DUNE

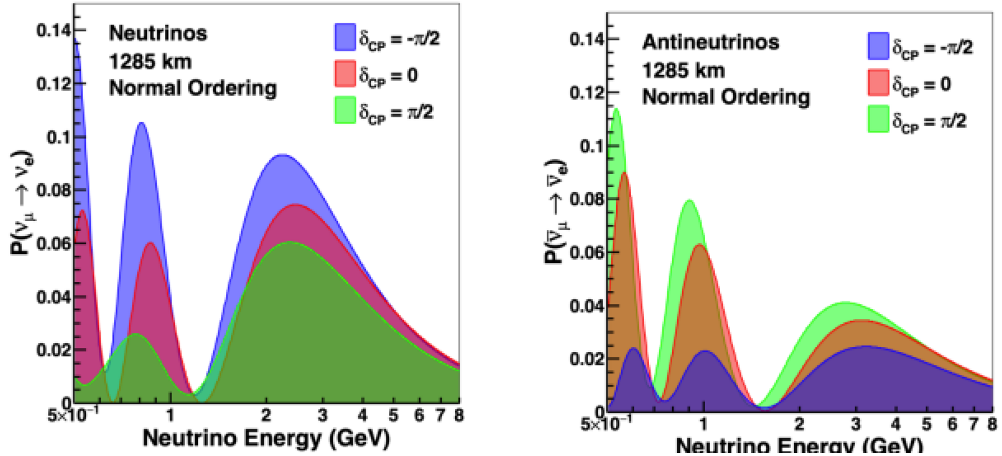
Precision measurement of the parameters that govern $\nu_\mu \rightarrow \nu_e$ and $\overline{\nu_\mu} \rightarrow \overline{\nu_e}$

- The LBNF neutrino beam will provide neutrinos and antineutrinos with energies from 0-5+ GeV
- At 1,300 km the oscillation probability has a strong dependence on the δ_{CP} and the mass ordering.
- The beam energy will cover two oscillation maxima improving the sensitivity.

Neutrino beam energy spectrum



Neutrino oscillation probability at a baseline of 1300 km



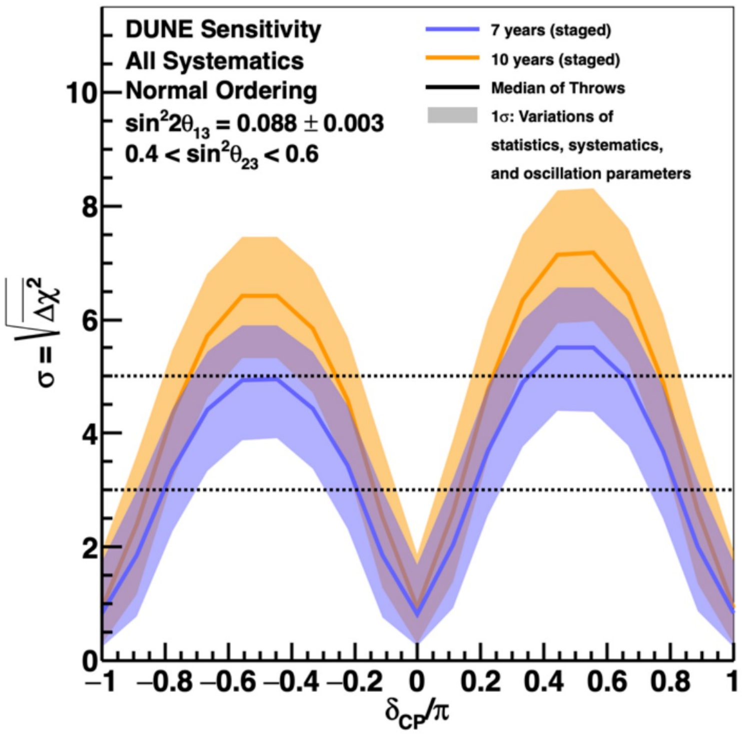
Long-baseline oscillations

Precision measurement of the parameters that govern $\nu_\mu \rightarrow \nu_e$ and $\overline{\nu_\mu} \rightarrow \overline{\nu_e}$ oscillations with the goal of

- Measuring the CP violating phase (δ_{CP})
- Determining neutrino mass ordering (Δm^2_{31} sign)
- Precision tests of the 3 flavor neutrino oscillation paradigm (θ_{23} and octant)

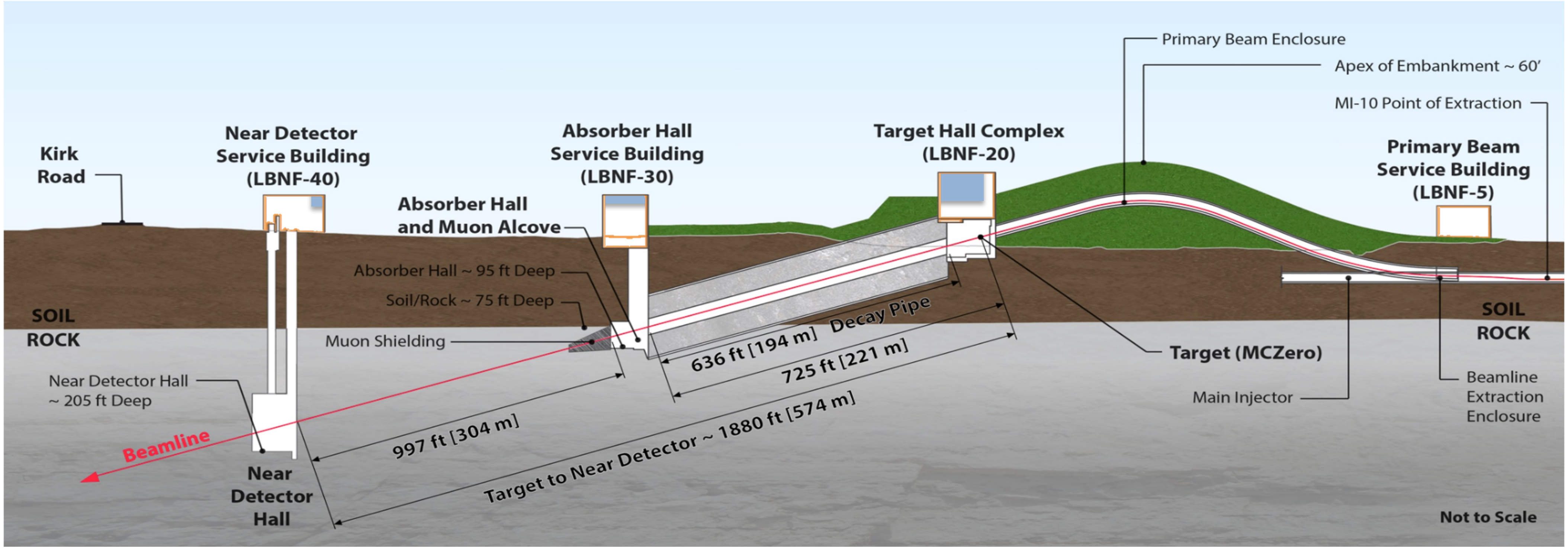
CP violation sensitivity of DUNE

Significance with which δ_{CP} can be determined



EPJC 80 (2020) 978

LBNF Beam



- 120 GeV main injector **proton beam**
- Initial 1.2 MW beam power, upgradable to 2.4 MW
- Embankment allows target complex to be at grade and neutrino beam to be aimed to SURF
- Decay region followed by absorber
- Four surface support buildings

Near Detector

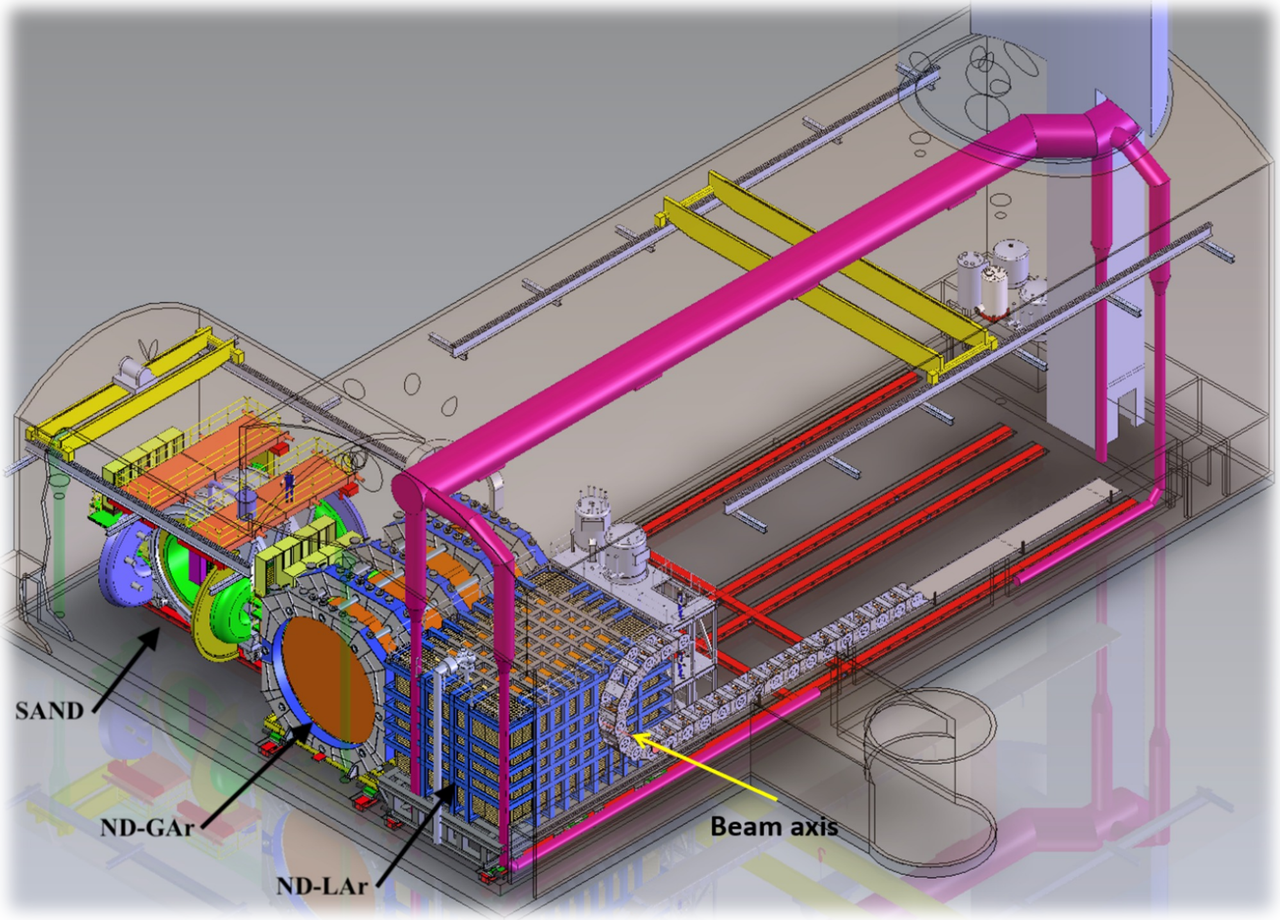
Roles:

- Characterization of the beam close to the source.
- Spectral beam monitor.
- Tuning the neutrino interaction model reducing systematics.
- Off-axis beam data to deconvolve beam and cross section models.

Located 574 m from the ν source.

Components:

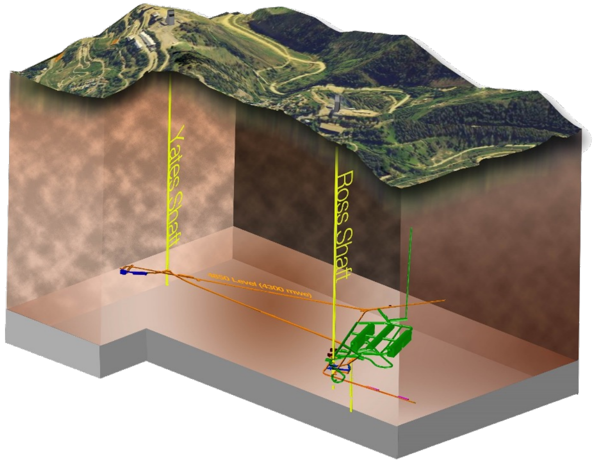
- Highly modular LArTPC (**ND-LAR**).
- Magnetized gaseous argon TPC (**ND-GAr**).
- Magnetized beam monitor (**SAND**).

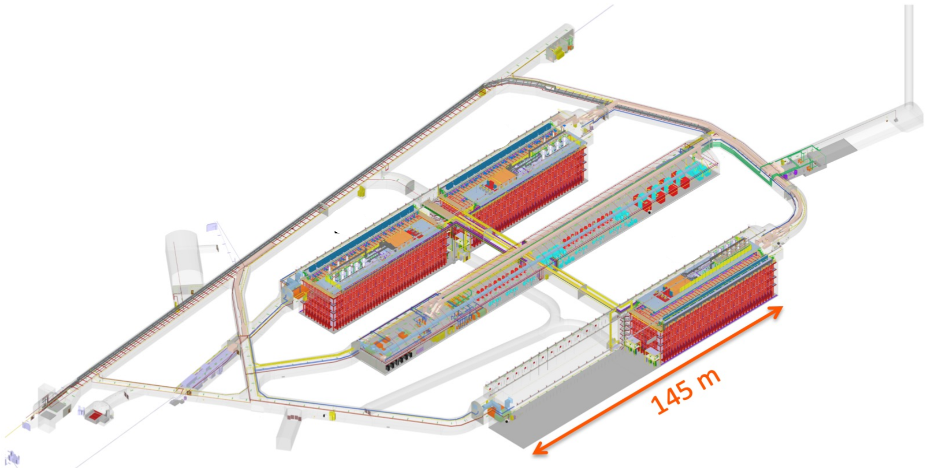


Instruments 5 (2021) 31

DUNE Far Detector

Located 1.48 km underground at Sanford Underground Research Facility in Lead, South Dakota (USA)





Four 17-kt LAr TPC modules

Phase I:

- FD-1 horizontal drift (HD)
- FD-2 vertical drift (VD)

Phase II:

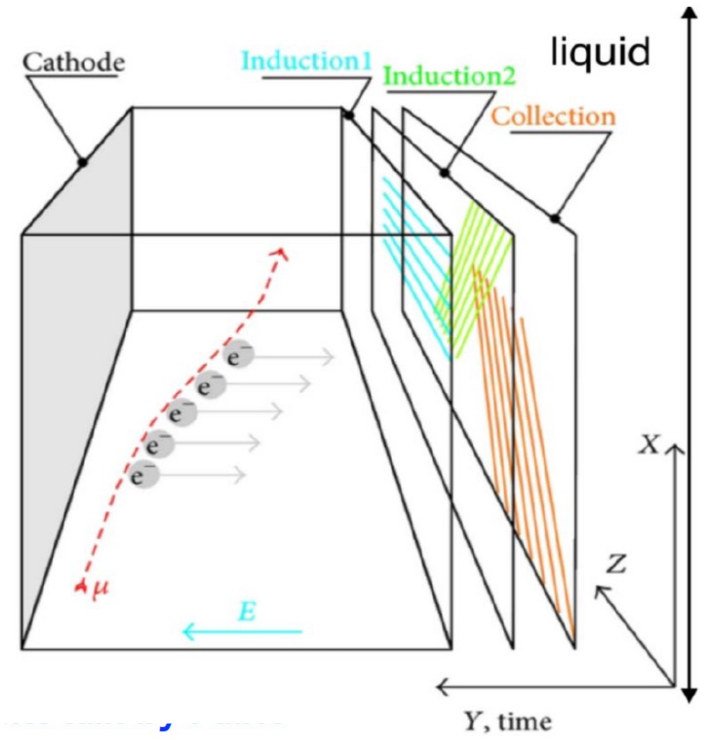
- Possibility of a module with enhanced low energy physics capabilities

ProtoDUNEs

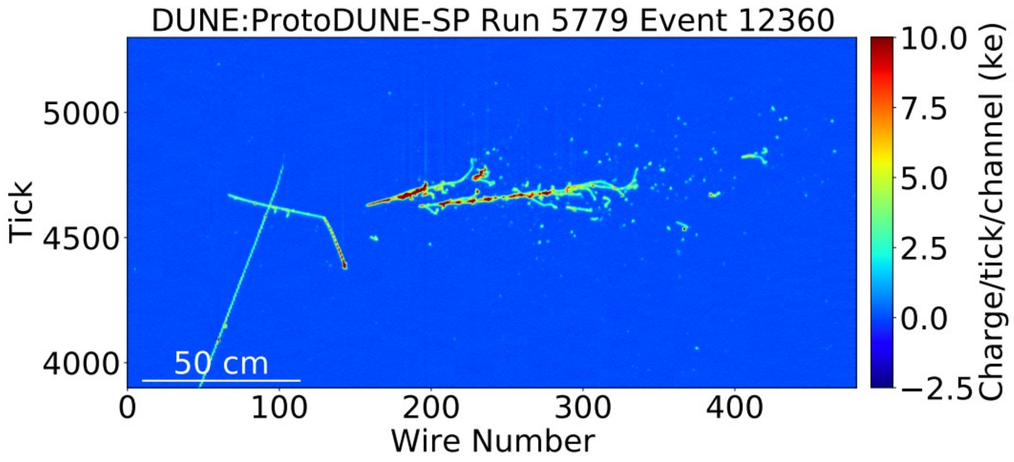
Construction and operation of 1 kton-scale prototypes at CERN, critical to demonstrate viability of technology

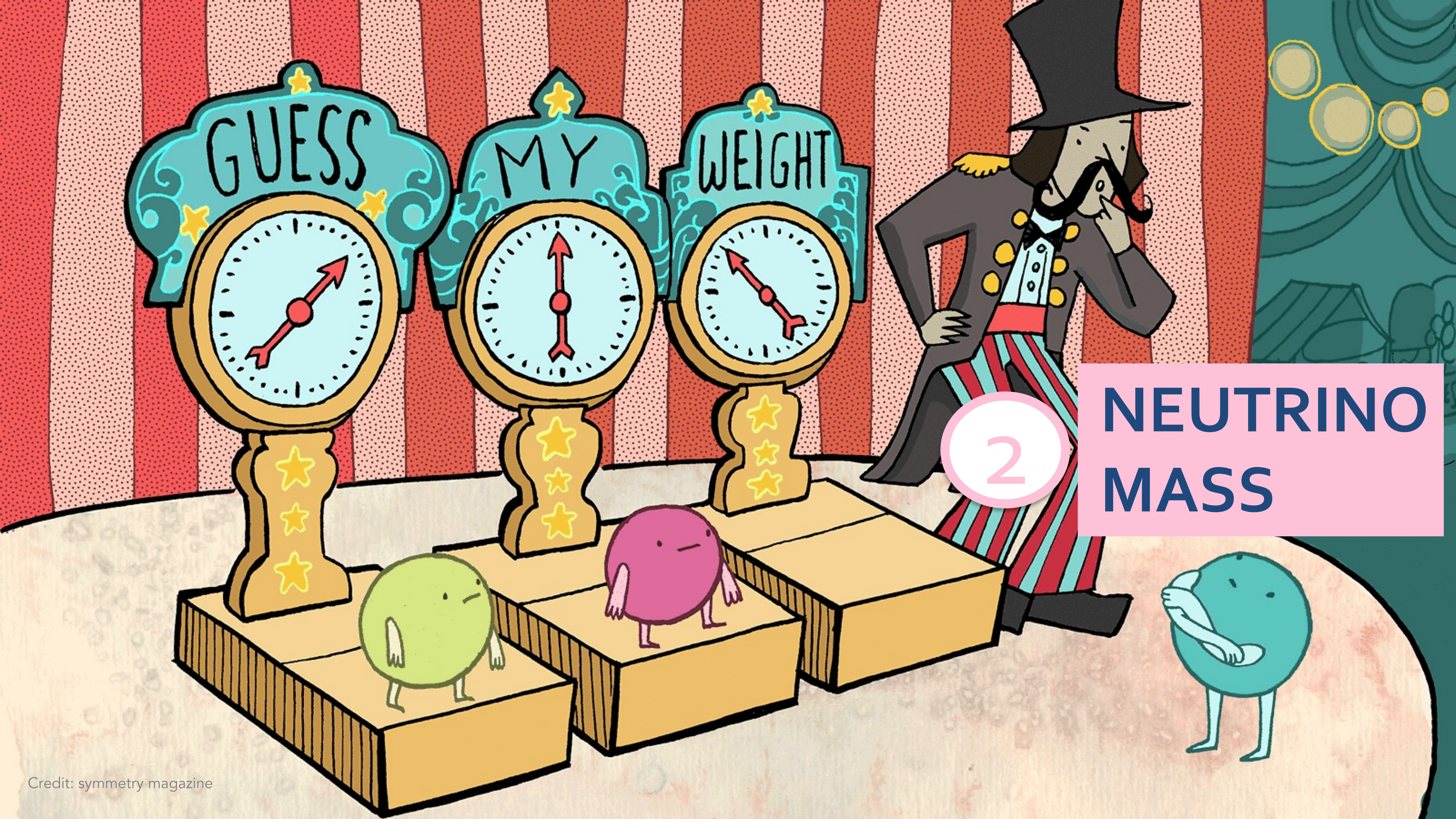
LAr TPC technology

- Liquid argon is inert, dense and naturally abundant.
- Strong electric field applied across the TPC to collect e⁻ produced by energy loss.
- LAr is transparent to its own scintillation light which can be used as an internal trigger and for complementary calorimetry measurement.



- Excellent **3D imaging** capabilities – few mm scale over large volume detector.
- Excellent energy measurement. capability – **totally active calorimeter.**
- **Particle ID** by dE/dx, range, event topology.





2

NEUTRINO MASS

Credit: symmetry magazine

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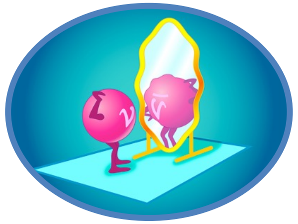

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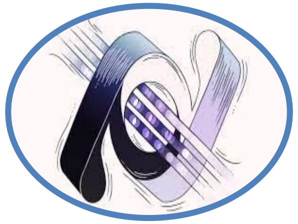

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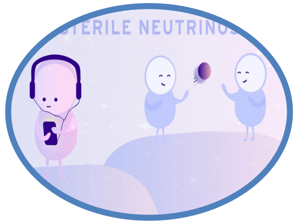

Powerful experimental program to answer these questions!

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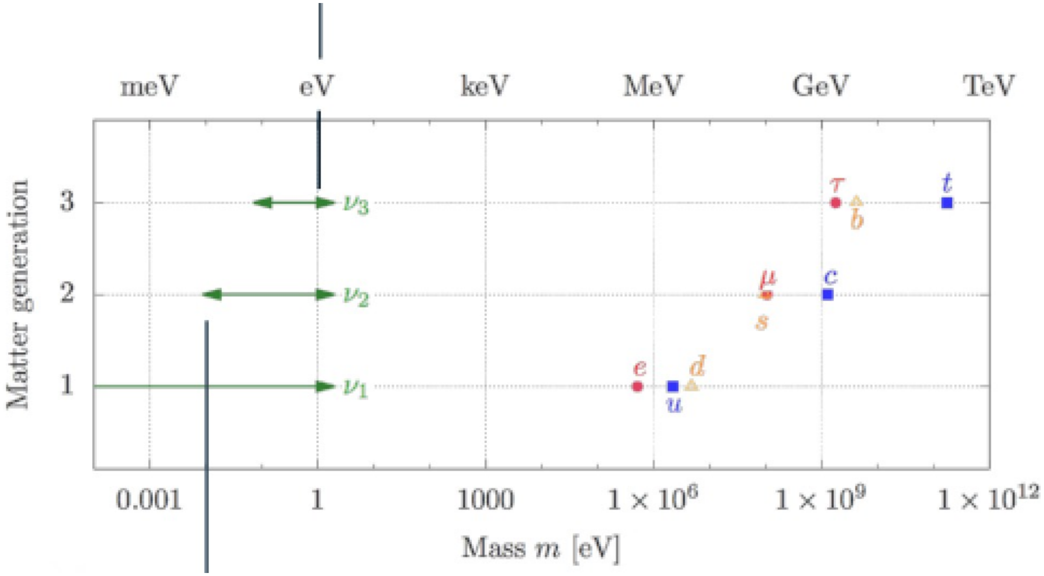
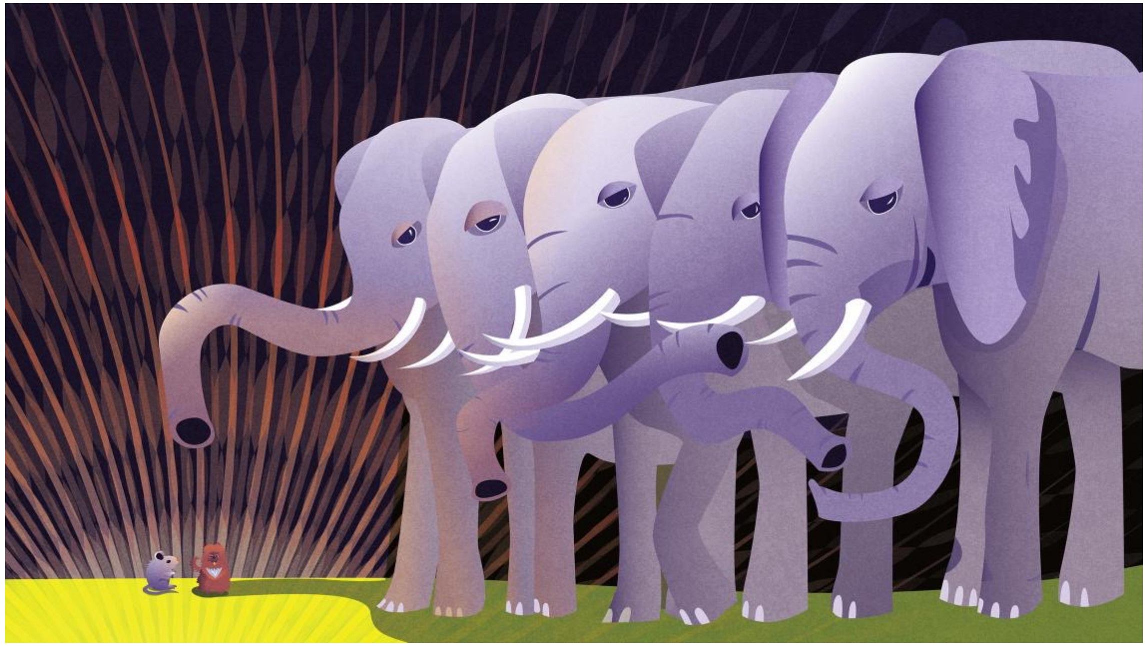
2. Neutrino mass

Measuring the masses requires:





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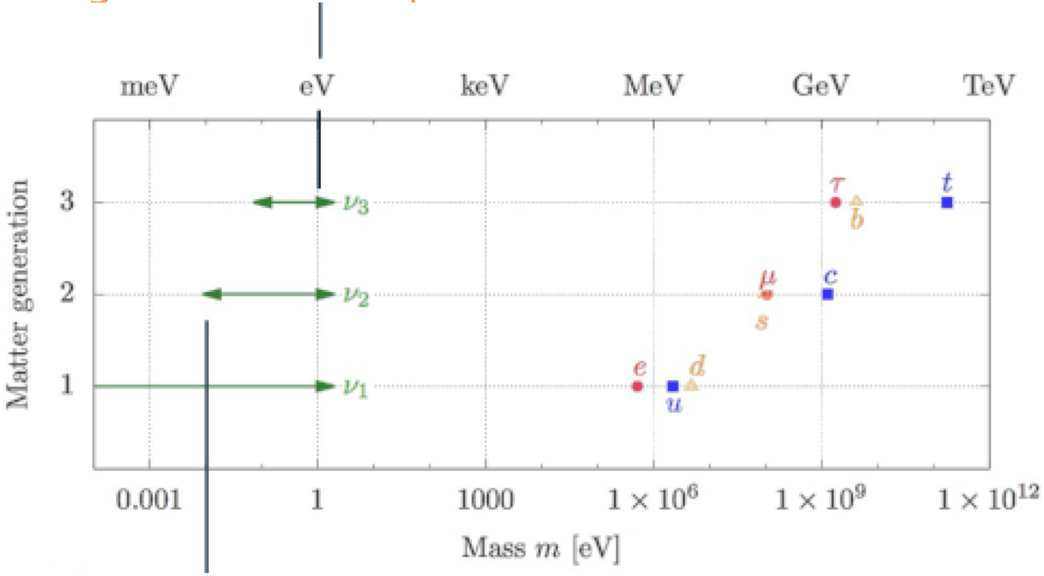
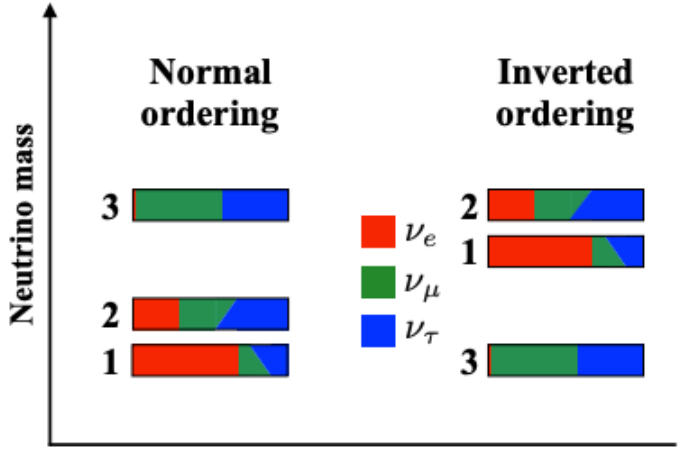


mass ordering → oscillation experiments



✓ Δm^2_{12} solar

? sing of Δm^2_{31}

- T2K and NOvA show mild preference for normal ordering
- Need next generation experiments: neutrino oscillations in matter (DUNE, atmospheric neutrinos) or in vacuum (JUNO)

Neutrino mass ordering

? sing of Δm^2_{31}

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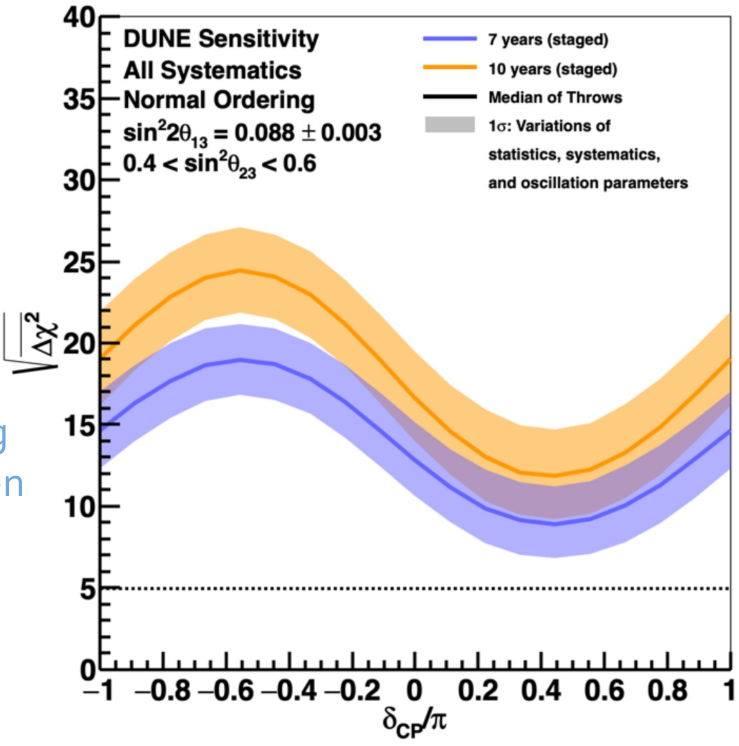
- Need next generation experiments: neutrino oscillations in matter (DUNE, atmospheric neutrinos) or in vacuum (JUNO)

Mass ordering sensitivity of DUNE

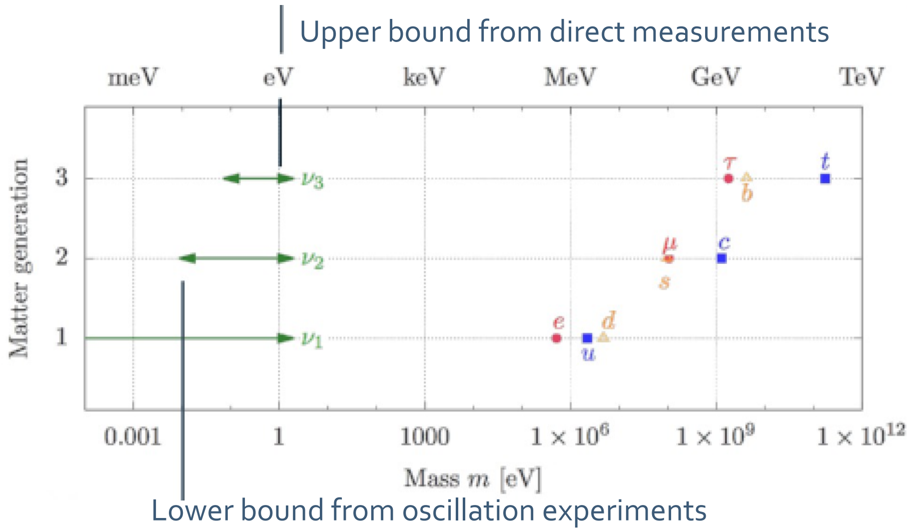
Discriminating power between the two mass ordering hypotheses



2. Neutrino mass

Measuring the masses requires:

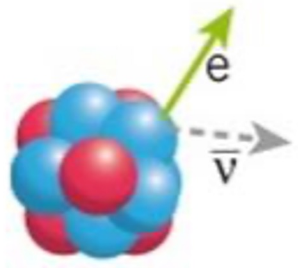
Absolute mass scale



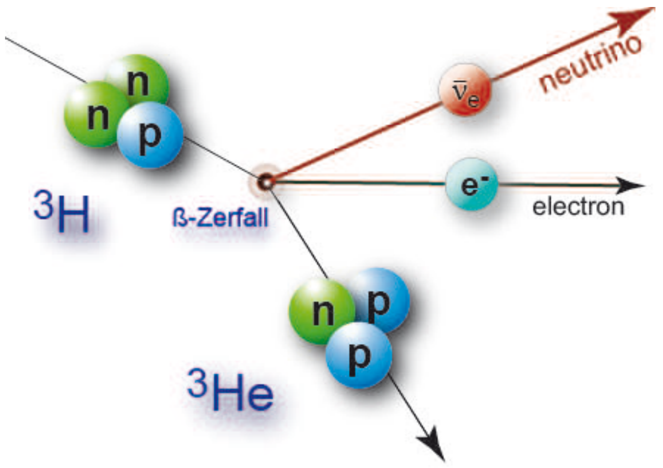
	Beta decay	0νββ	Cosmology
Observable	$m_{\nu_e}^2 = \sum_i \lvert U_{ei}\rvert^2 \cdot m_{\nu_i}^2$	$m_{\beta\beta} = \left\lvert \sum_i U_{ei}^2 \cdot m_{\nu_i} \right\rvert$	$\sum m_\nu$
Model dependence	Direct measurement	Neutrino nature Matrix elements	Cosmological model

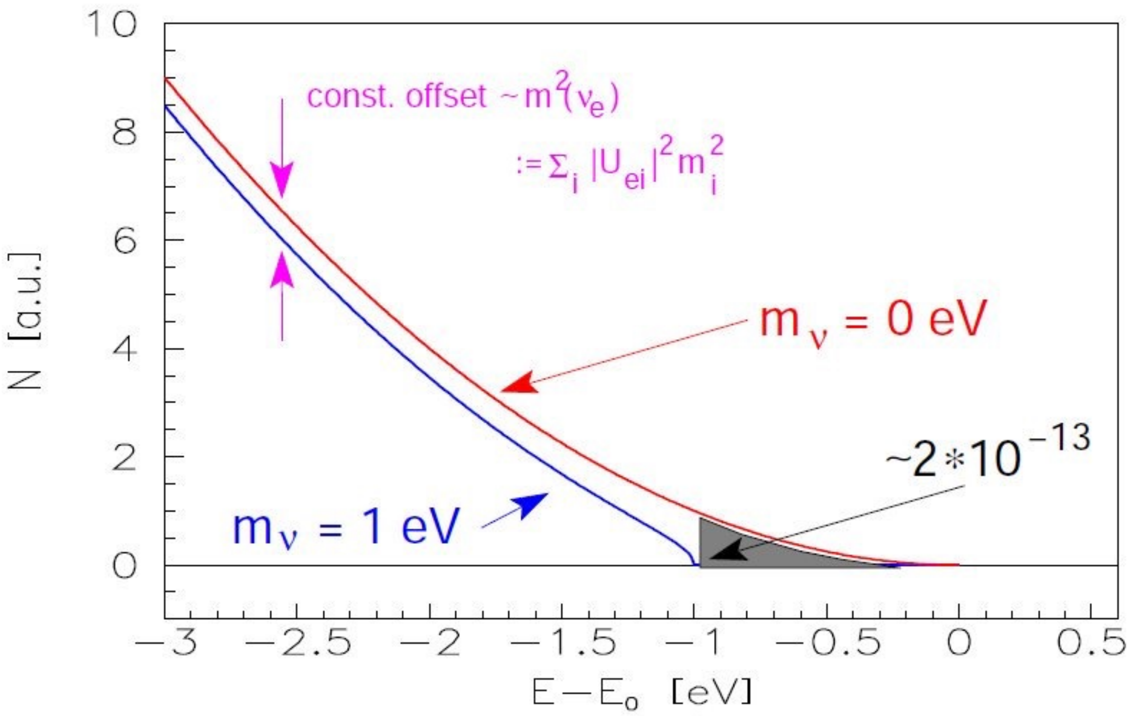
Absolute mass scale

Beta decay: the energy is distributed among: $(Z,A) \rightarrow (Z+1,A) + e^- + \bar{\nu}_e$

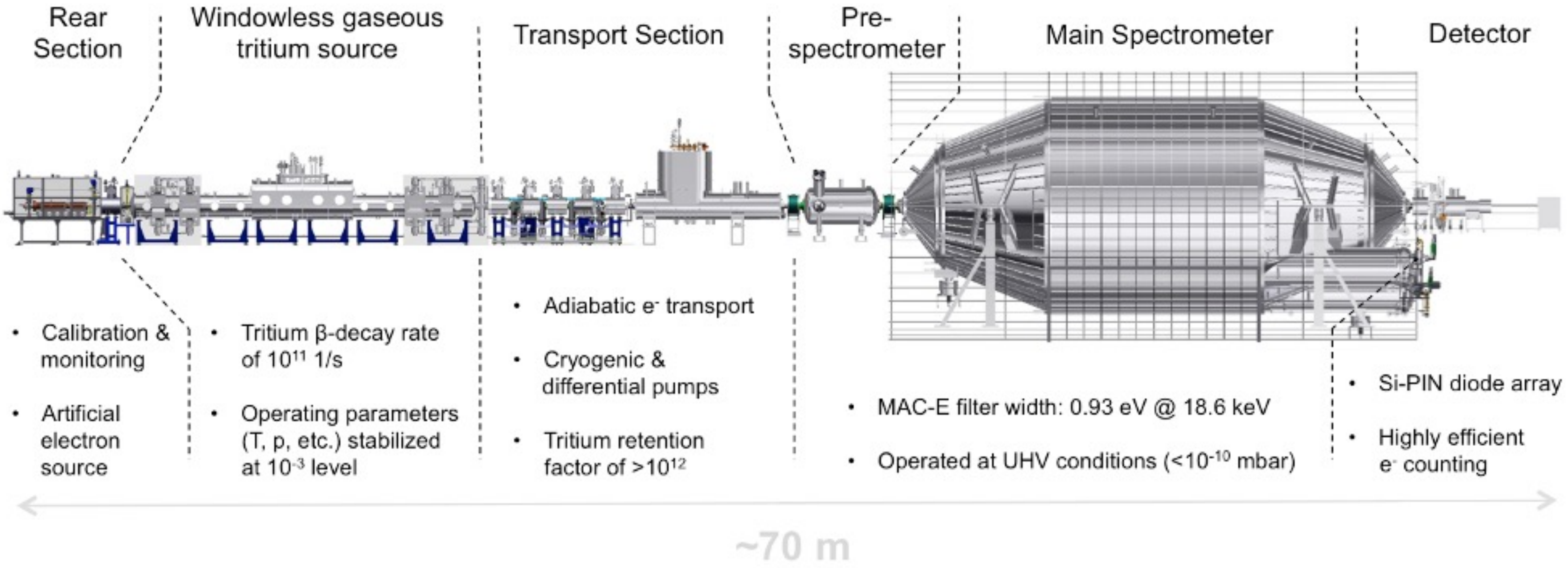


Tritium experiments:





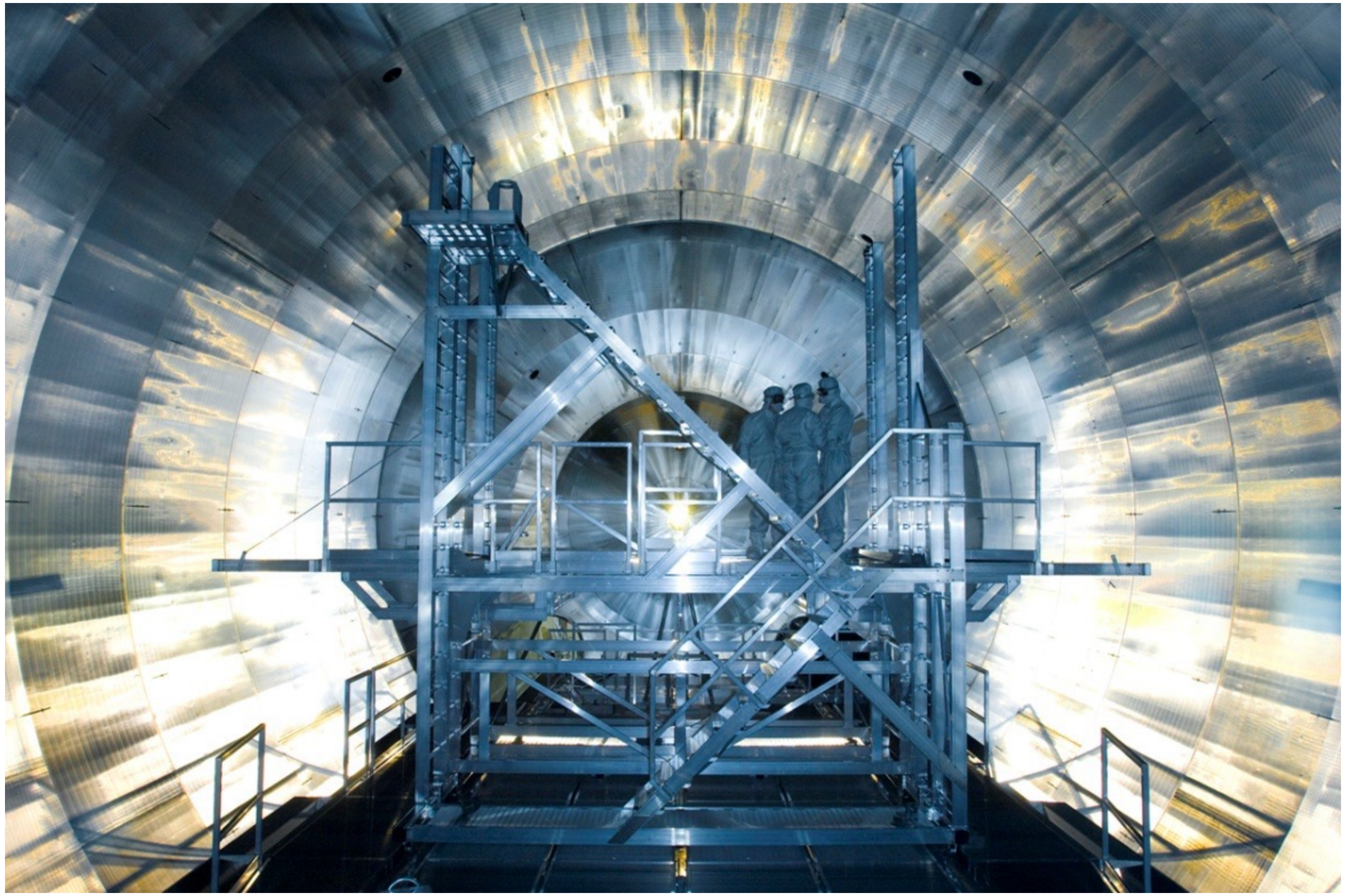
KATRIN experiment



KATRIN experiment

KATRIN (Karlsruhe Tritium Neutrino Experiment)

- Study of beta-decay spectrum with tritium.
- e^- must pass through an electric potential that stops all electrons below a certain threshold (few eV). Only electrons that have enough energy to pass through the potential are counted.
- Since $\Delta E/E = B_{min}/B_{max}$, to achieve an energy resolution 1:20000, the spectrometer needs to have a diameter of 10m
- Data taking since 2019



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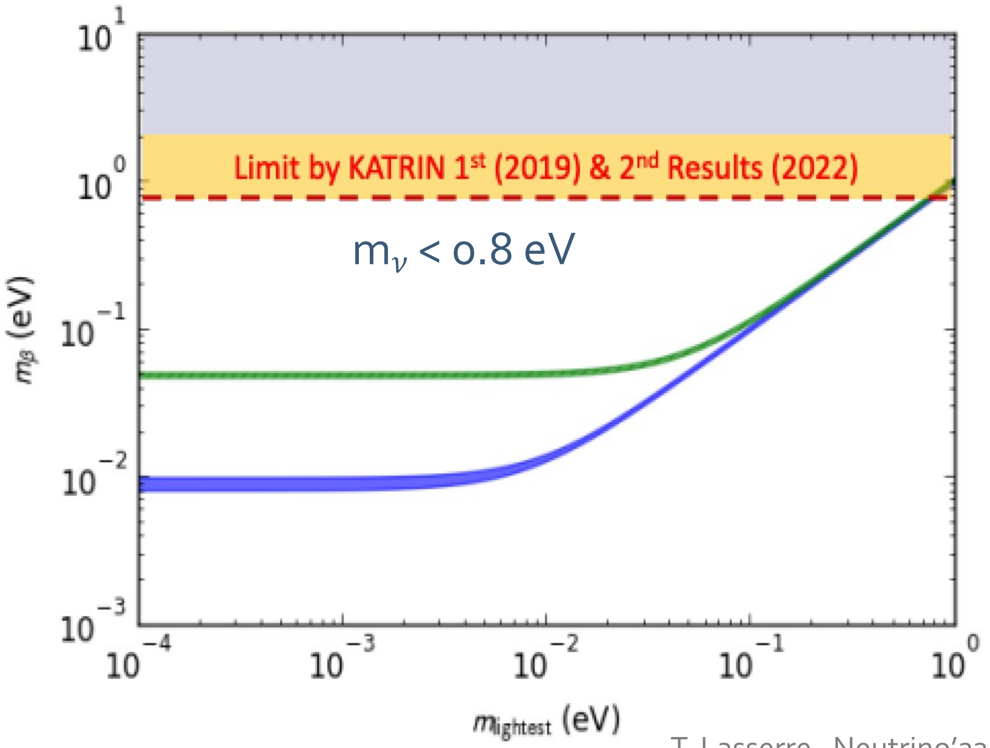
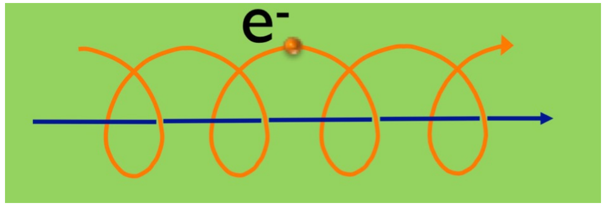
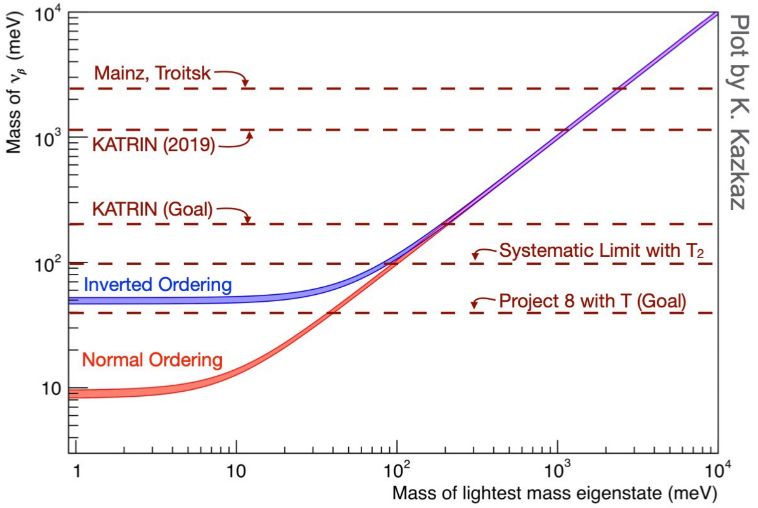


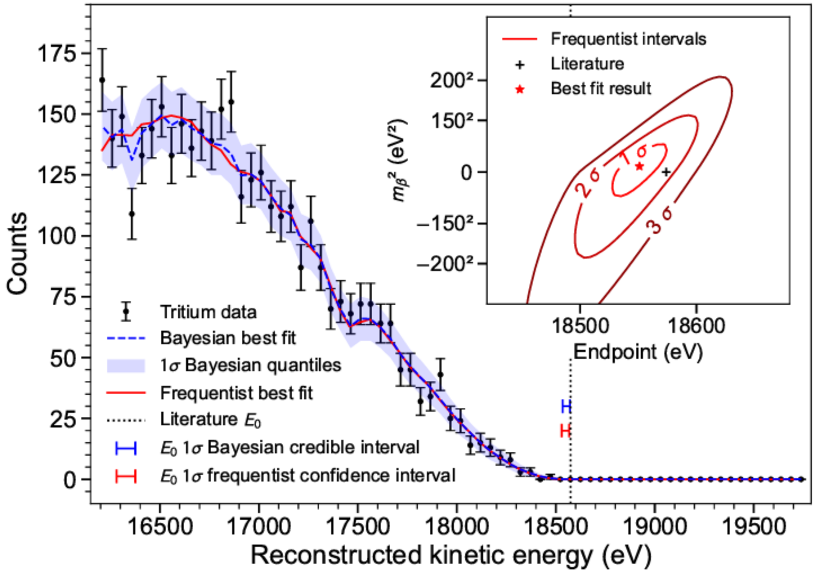
T. Lasserre , Neutrino'22

Project 8 experiment

- Beta decay tritium next generation experiment
- Cyclotron Radiation Emission Spectroscopy (CRES), first demonstrated by the collaboration in 2014
  - Tritium gas in an enclosed volume with a magnetic field
  - Decay electrons spiral around field lines
  - The frequency of the emitted cyclotron radiation depends on the relativistic boost (e- energy).



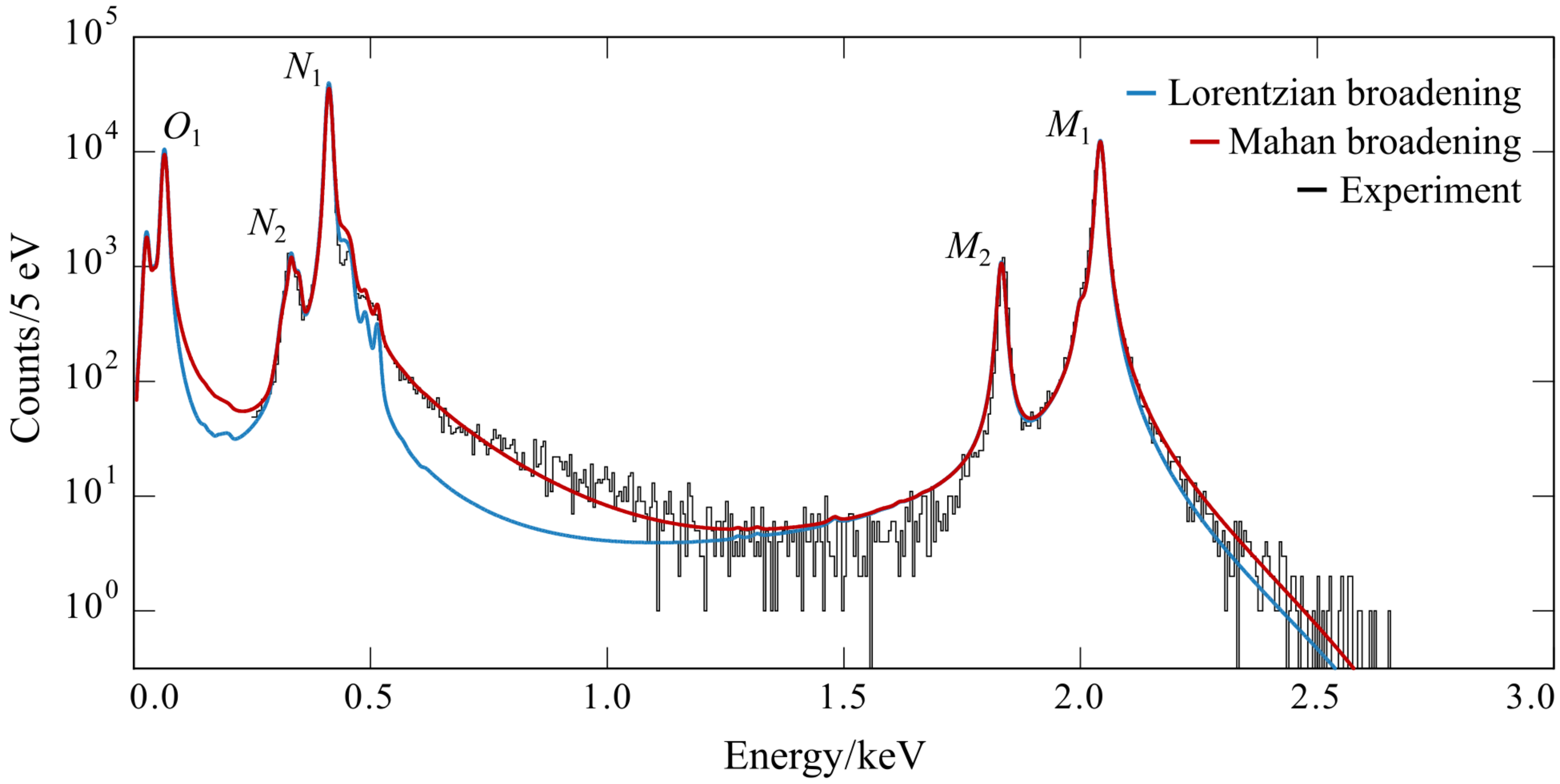




^{163}Ho experiments

Other experiments with ^{163}Ho using low temperature calorimeters

- Holmes
- ECHo

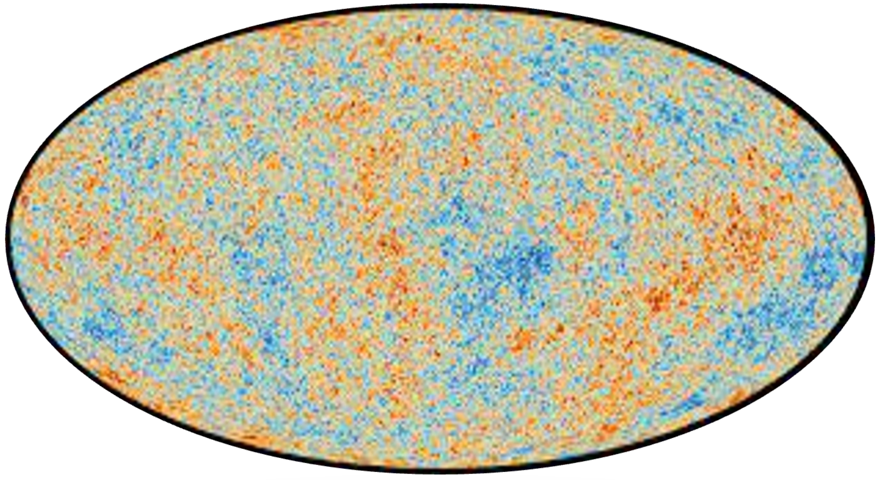



NEUTRINOS
IN COSMOLOGY

Neutrinos in cosmology

Neutrino masses have measurable effects in Cosmology:

- Anisotropies of the cosmic microwave background (CMB).
- The large-scale structure of the Universe.
- Abundances of the elements created in the nucleosynthesis of the Big Bang.



The sum of neutrino masses (DES + Planck 2021)is:

< 0.13 eV

- The fit depends on a model.
- It depends on the data used.

Cosmological measurements are also sensitive to the number of neutrinos.

$$N_{eff} = 3.046$$

Planck results are close to rule out the inverted ordering hypothesis but rely on cosmological assumptions.

An independent measurement would help cosmological models

3 NEUTRINO NATURE

Credit: symmetry magazine
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Q

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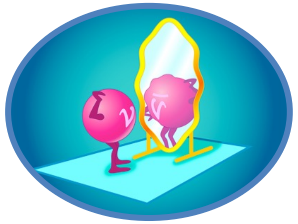
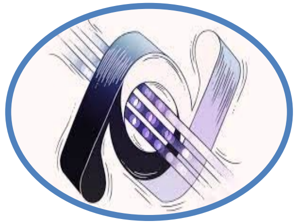
   Is the CP symmetry violated in the neutrino sector? CP-violation is one of the 'Sakharov conditions' to explain the matter-antimatter asymmetry in the Universe.

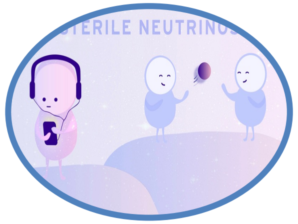


2. **Neutrino mass**
   How are the three neutrino mass states ordered from lightest to heaviest (neutrino "mass ordering")? What is the absolute scale of neutrino masses?

3. **Neutrino nature**
   Is the neutrino its own antiparticle? Are neutrinos Majorana particles?



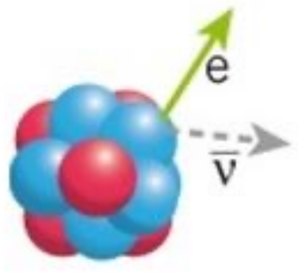
4. **Neutrino species**
   Are there sterile neutrino species in addition to the three active ones participating in the weak interactions?



Credit: symmetry magazine

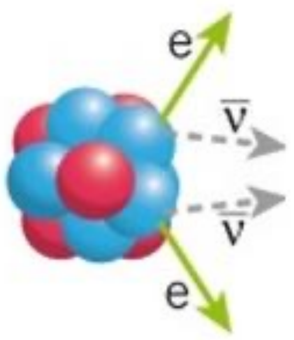
1. Neutrino nature

The experimental way to determine the neutrino nature is the discovery of **neutrinoless double beta decay (0νββ)**.



Standard β decay

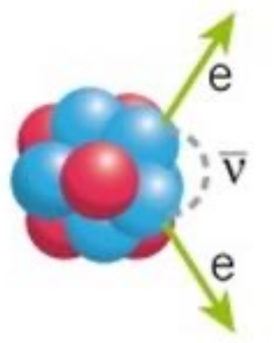
$$(Z,A) \rightarrow (Z+1,A) + e^- + \bar{\nu}_e$$



Double-β decay

$$(Z,A) \rightarrow (Z+2,A) + 2e^- + 2\bar{\nu}_e$$

Energetically favored
for some isotopes



Neutrino-less
double-β decay

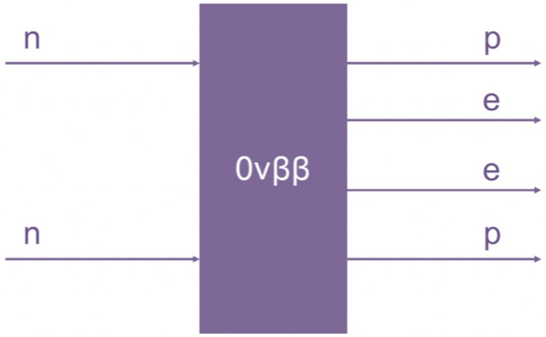
$$(Z,A) \rightarrow (Z+2,A) + 2e^-$$

Not discovered yet!

1. Neutrino nature

The experimental way to determine the neutrino nature is the discovery of **neutrinoless double beta decay (ονββ)**.

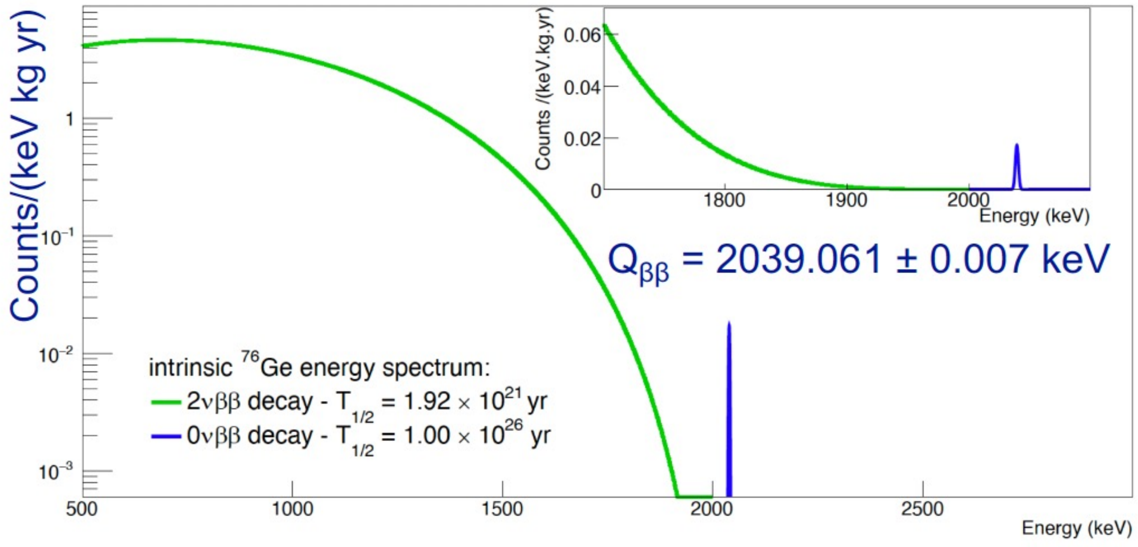
- Matter creation process!
- Lepton number is not conserved
- The neutrino is a fundamental Majorana particle



(A, Z) → (A, Z+2) +2e-

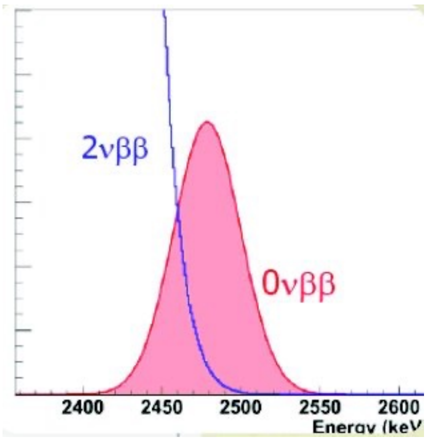
Neutrinoless double beta decay

Must measure summed electron kinetic energy to distinguish from Standard-model 2ν process



Need a good signal-to-background ratio to get statistical significance

- Very low background event rate
- The best possible energy resolution



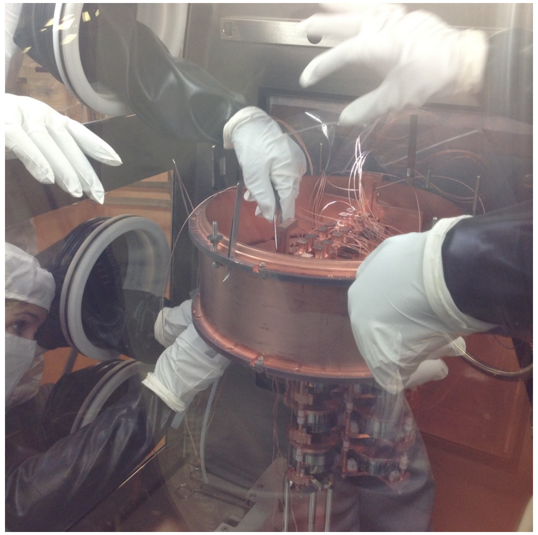
Isotope selection:

- The decay rates are similar.
- For $m_{\beta\beta}$~10 meV -> 1 decay/(ton.yr) in all isotopes.
- The choice is driven by easiness of isotope enrichment, half-life, scalability and modularity of the design

Experimental approach: source = detector

Low radioactive background

- Underground location to avoid cosmic rays
- Passive shielding, f.i. lead, copper
- Active shielding, f.i. plastic scintillators
- Material screening and selection
- Avoid surface exposure
- Clean room conditions for detector assembly
- Background rejection techniques at the analysis



Neutrinoless double beta decay

The experimental way to determine the neutrino nature is the discovery of **neutrinoless double beta decay (0νββ)**.

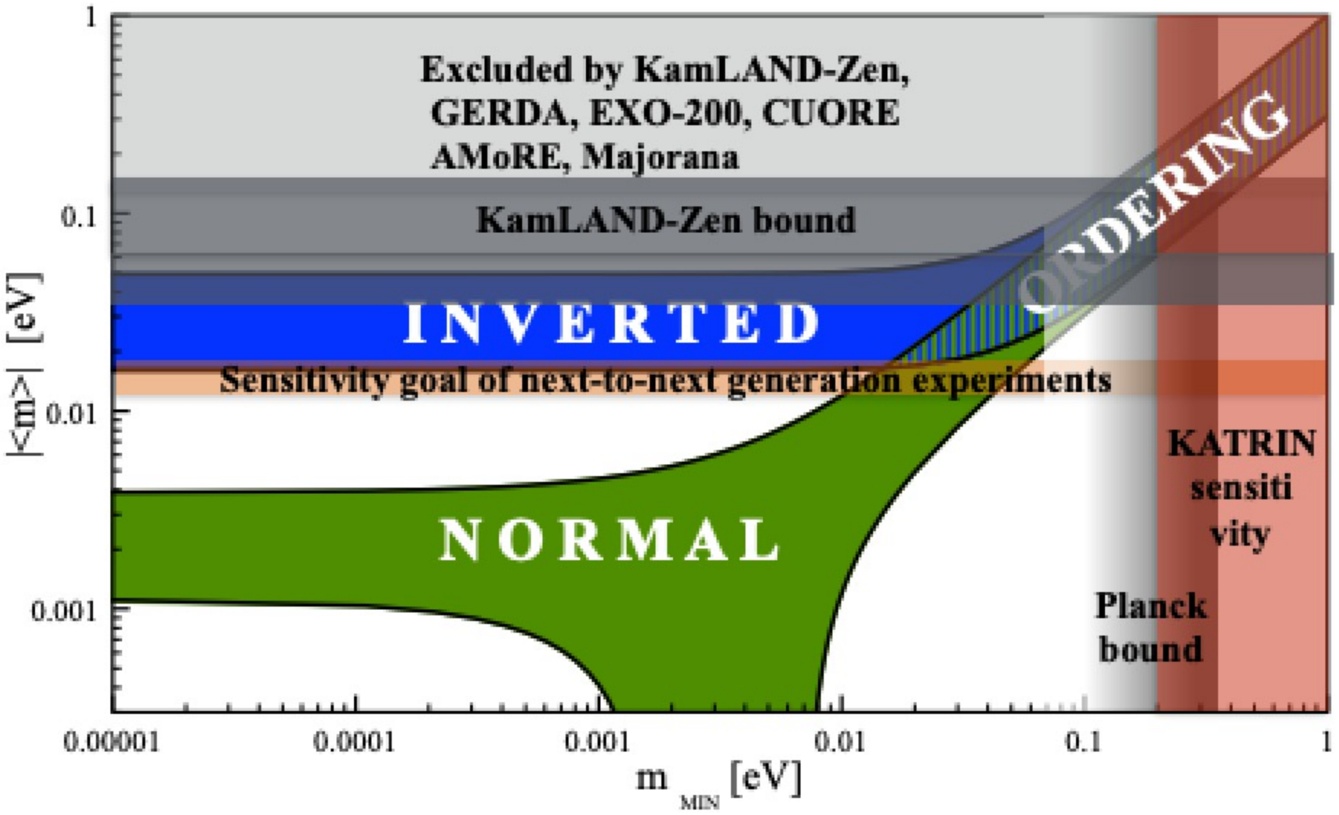
- Present best limits $T_{1/2} > 10^{26}$ y

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}|M_{0\nu}|^2 \left(\frac{\langle m_{\beta\beta}\rangle}{m_e}\right)^2$$

$G^{0\nu}$: Phase space

$M_{0\nu}$: Nuclear matrix elements

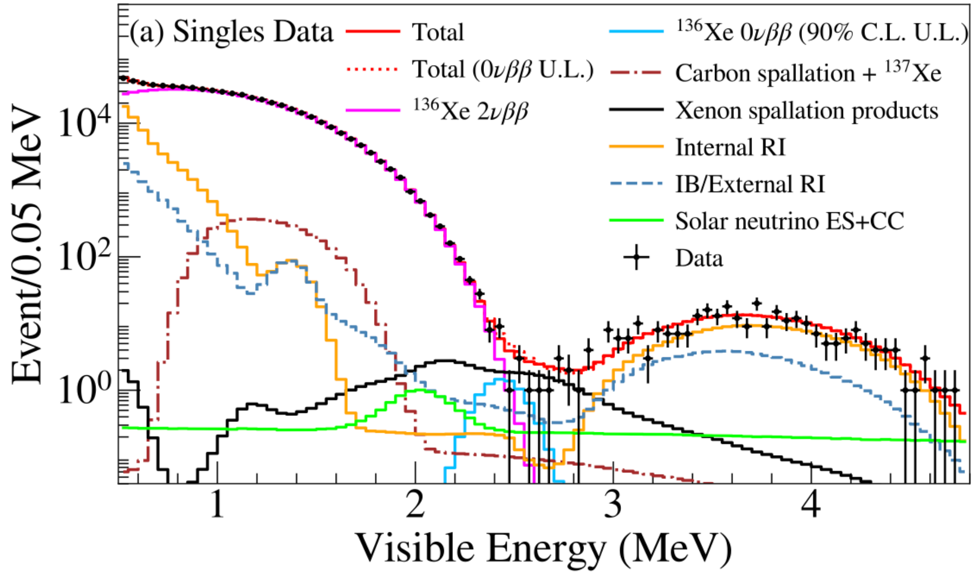
$$\langle m_{\beta\beta}\rangle = |\sum_{i=1}^{3} U_{ei}^2 m_i|$$

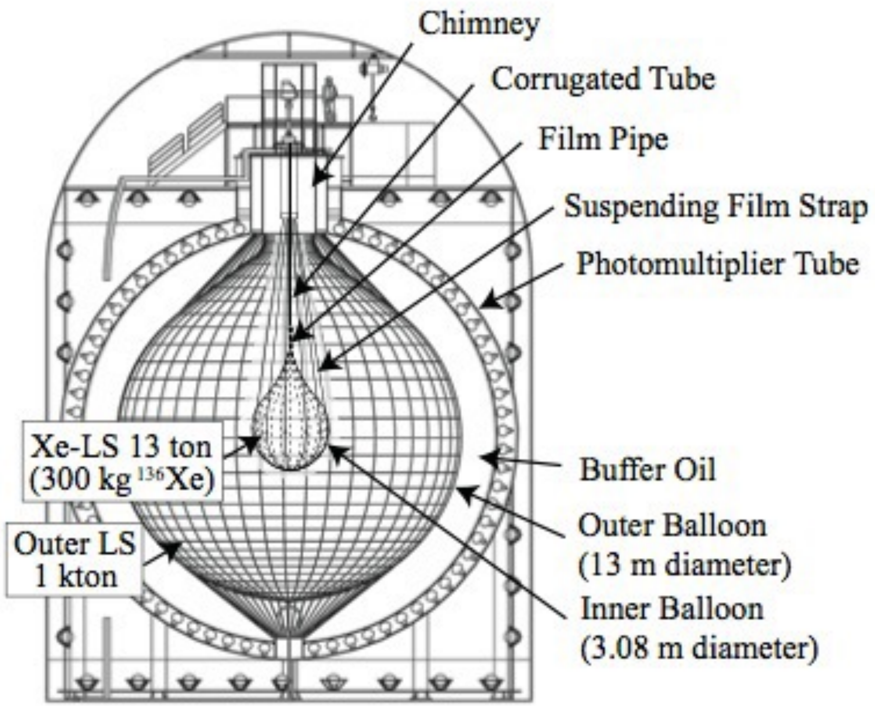


* PRD 96 (2017) 053001

KAMLAND-ZEN

- Xe-loaded liquid scintillator ~800 kg ^{136}Xe contained in a 3.08-m diameter transparent nylon based inner balloon suspended at t centre of the KamLAND detector by film straps.
- The balloon is surrounded by 1 kton of liquid scintillator contai in a 13-m diameter outer balloon.
- Event vertex and energy are reconstructed based on the timing and charge distributions of photoelectrons recorded by the PM





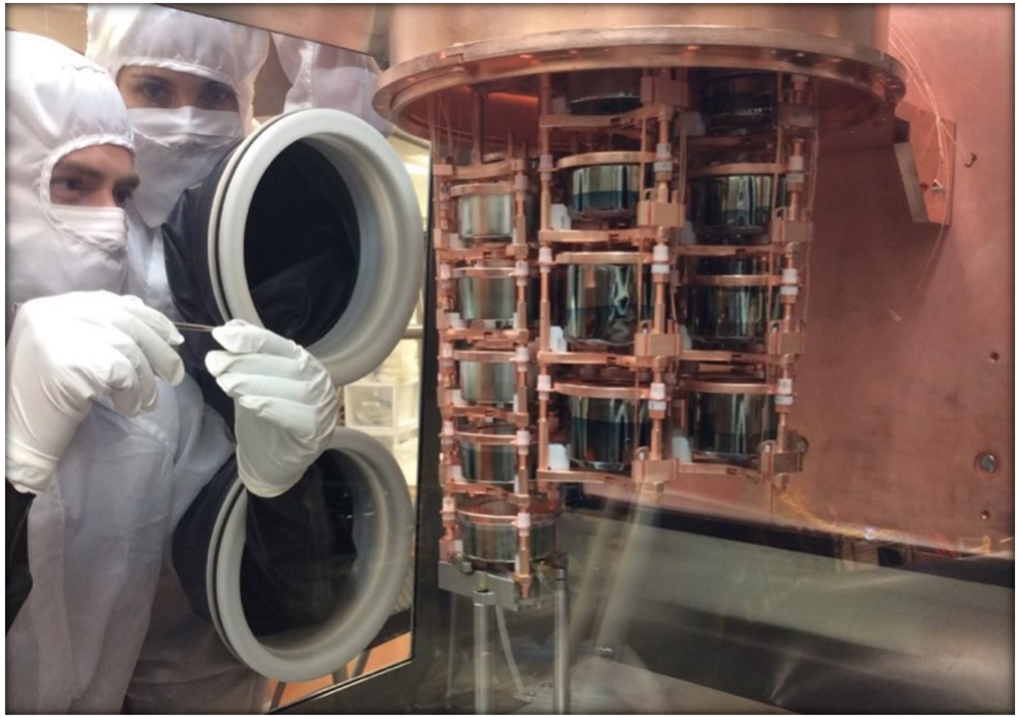
The experiment sets a lower limit at 90% C.L.

$T_{1/2} > 2.3\ 10^{26}$ yr

<mββ> < 36-156 meV

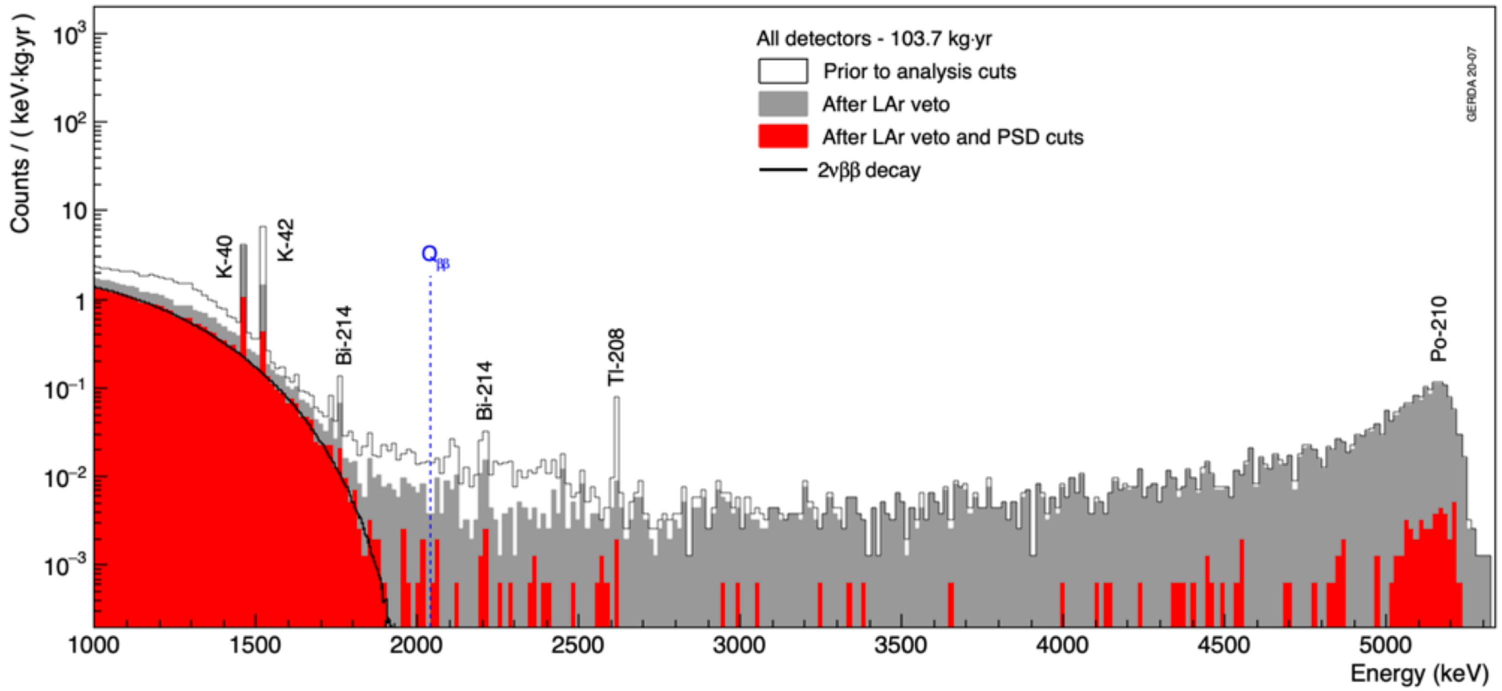
GERDA and MAJORANA

- Germanium detector isotopically enriched in ^{76}Ge
- Ge detectors are semiconductor diodes sensitive to ionizing radiation (γ spectrometry)
- The Ge detectors are deployed within vertical strings containing two or three elements each.



- Constructed with ultra-low radioactive materials
- The detector is enclosed in several active volumes to detect external radiation

GERDA and MAJORANA

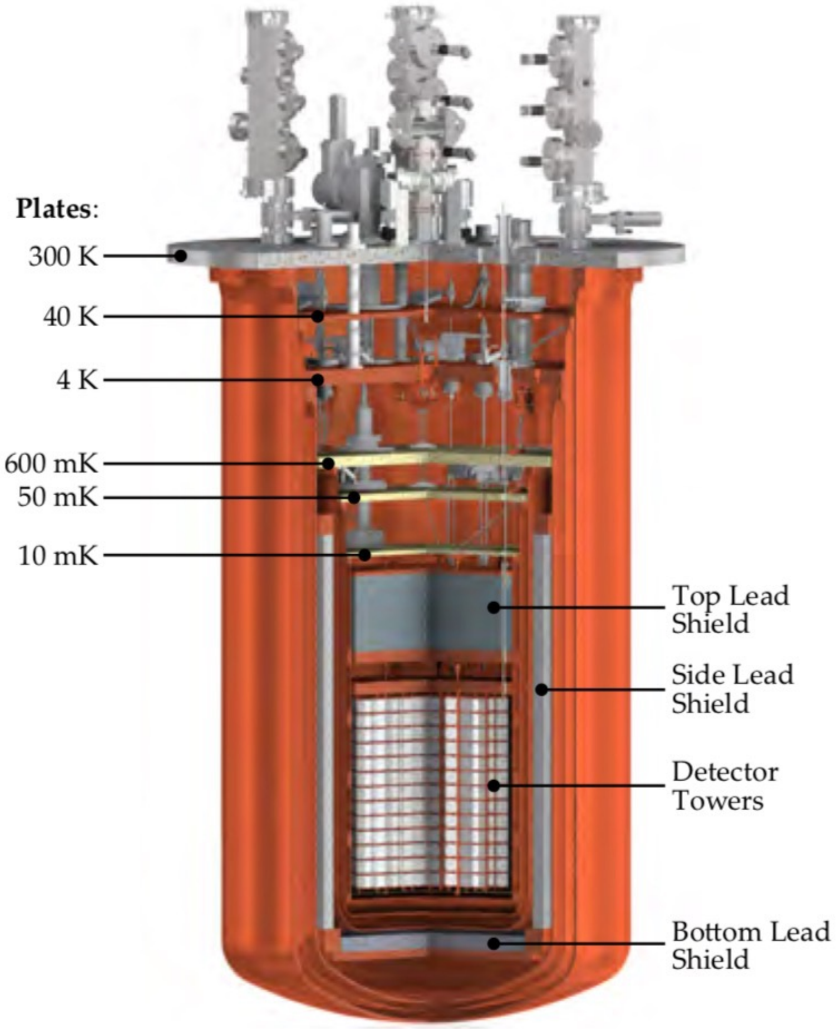


- GERDA: Lowest background
- MAJORANA: Best energy resolution
- LEGEND: next generation experiment combining efforts

GERDA sets a lower limit at 90% C.L.
$T_{1/2} > 1.8\ 10^{26}$ yr
<mββ> < 79-180 meV

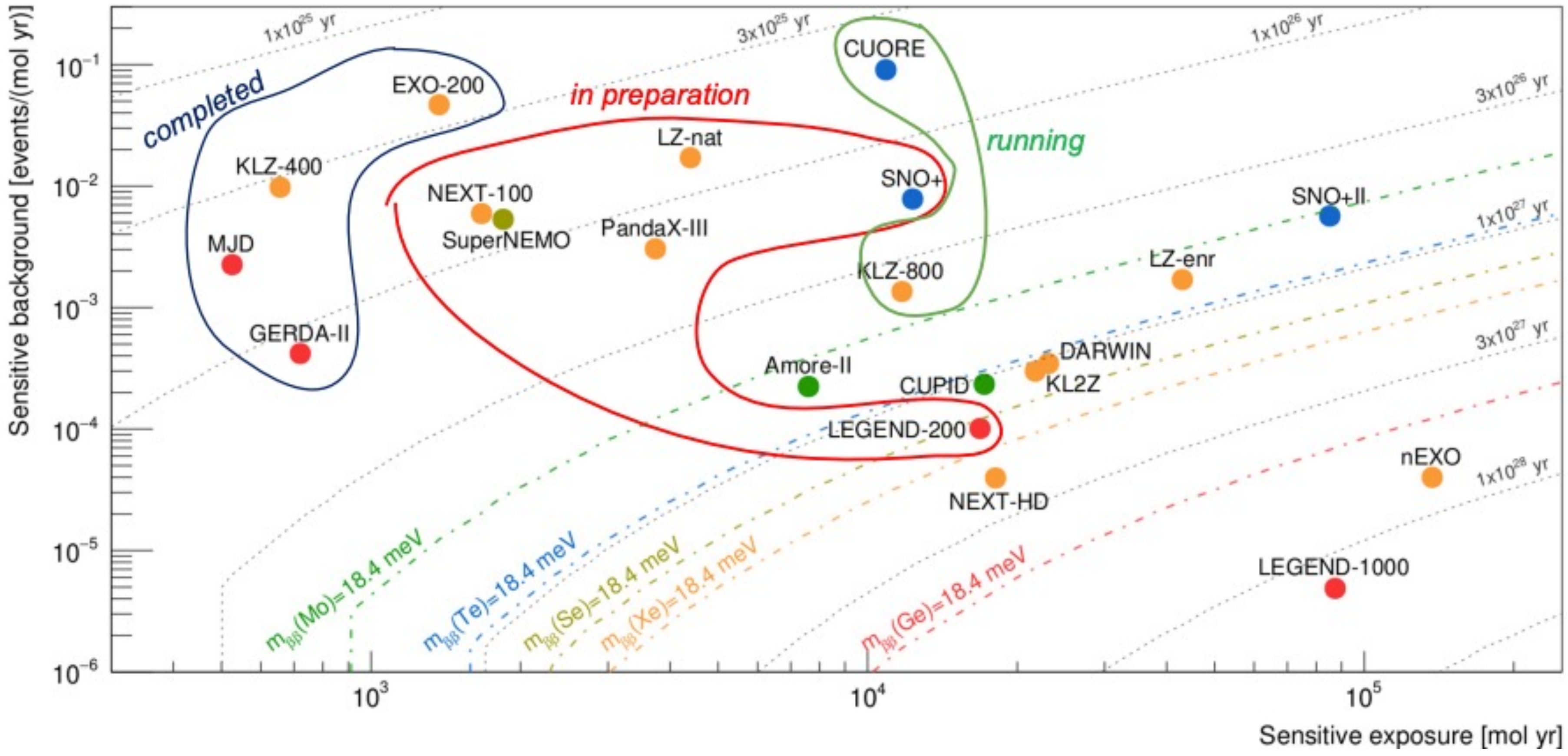
CUORE

- The detector consists of TeO_2 crystals (30% ^{130}Te, natural abundance)
- TeO_2 is a dielectric and diamagnetic material, providing that the temperature is extremely low (~10mK), a small energy release in the crystal results into a measurable temperature rise. This temperature change is recorded using a Neutron Transmutation Doped (NTD) Ge thermistors glued on the crystal surface.
- 988 5x5x5 cm^3 TeO_2 crystals (750 g) arranged in 19 towers.



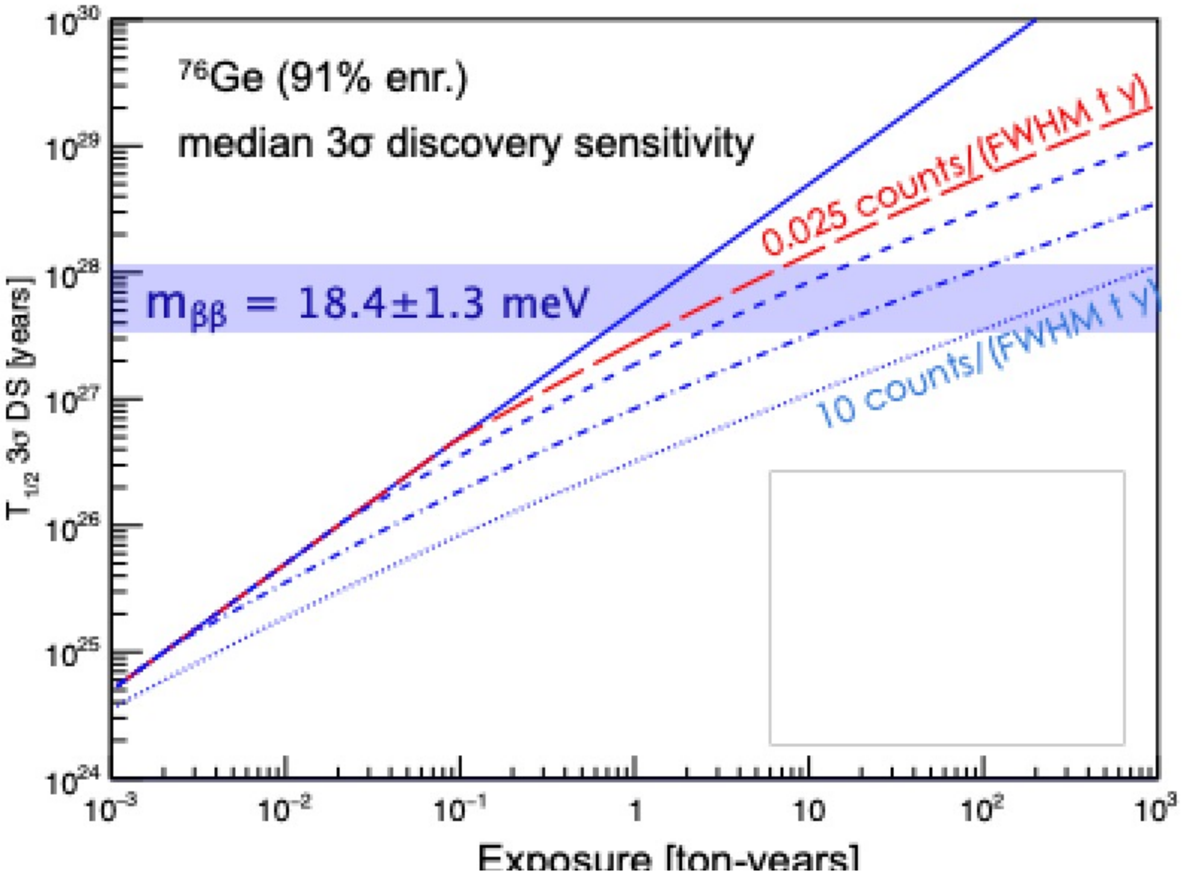
GERDA sets a lower limit at 90% C.L.
$T1/2 > 2.2\ 10^{25}$ yr
<mββ> < 90-305 meV

Neutrinoless double beta decay



Great experimental prospects

Neutrinoless double beta decay



- Future goal ~2 OoM improvement in $T_{1/2}$ covering Io and up to 50% NO*.
  - Only observable: energy
  - Sensitivity rises with exposure, but strongly depends on backgrounds

* PRD 96 (2017) 053001

4 NEUTRINO SPECIES

Credit: symmetry magazine

Neutrino unknowns

Q

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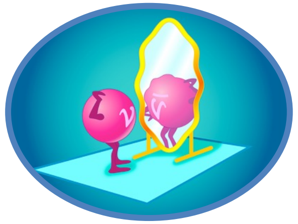
   Is the CP symmetry violated in the neutrino sector? CP-violation is one of the 'Sakharov conditions' to explain the matter-antimatter asymmetry in the Universe.



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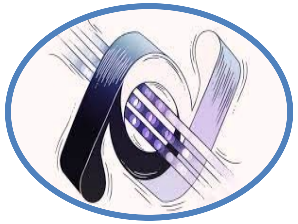

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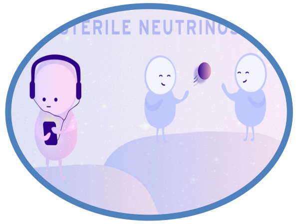
   Are there sterile neutrino species in addition to the three active ones participating in the weak interactions?



Credit: symmetry magazine

4. Neutrino species

Is the standard 3-neutrino picture correct?

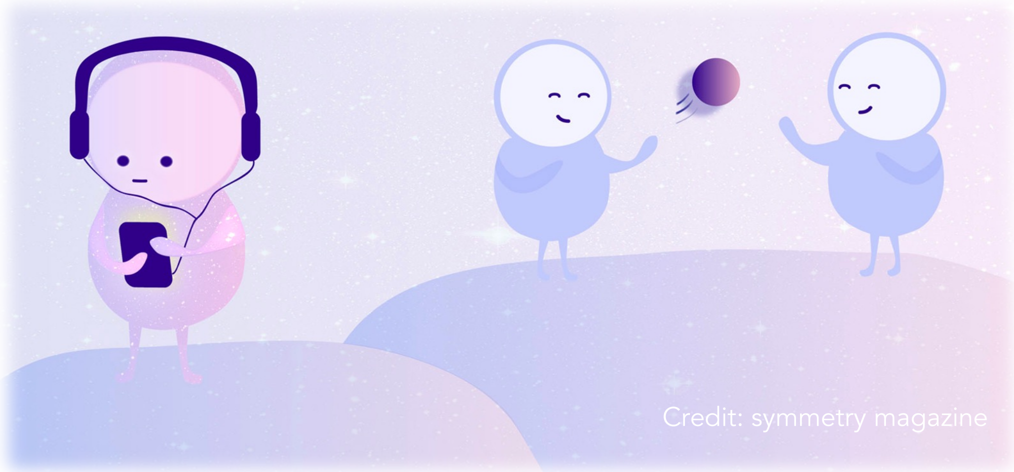
- An active area with a lot of experiments and anomalies:
  - ✓ **Reactor neutrino fluxes**
    - most likely solved

    Reactor spectra: NEUTRINO-4

    Gallium anomaly: BEST
    - recently confirmed

    LSND anomaly

    MiniBooNE excess, non explanation, non-confirmation by MicroBooNE. Short Baseline Neutrino Program (Fermilab) will solve it.



Sterile neutrinos? Simplest 3+1 model seems in tension to cover all anomalies.

- Some anomalies seems real, but maybe not related to sterile neutrinos.
- An extra neutrino species is in severe tension with cosmology.

Gallium anomaly

- Deployment of radioactive sources for detector calibration with mono-energetic ν_{e}:

$$e^- + {}^{51}Cr \longrightarrow {}^{51}V + \nu_e \ (0.82 \text{ MeV})$$

$$e^- + {}^{37}Ar \longrightarrow {}^{37}Cl + \nu_e \ (0.9 \text{ MeV})$$

- The neutrinos emitted were detected through the same reaction used for the solar neutrinos:

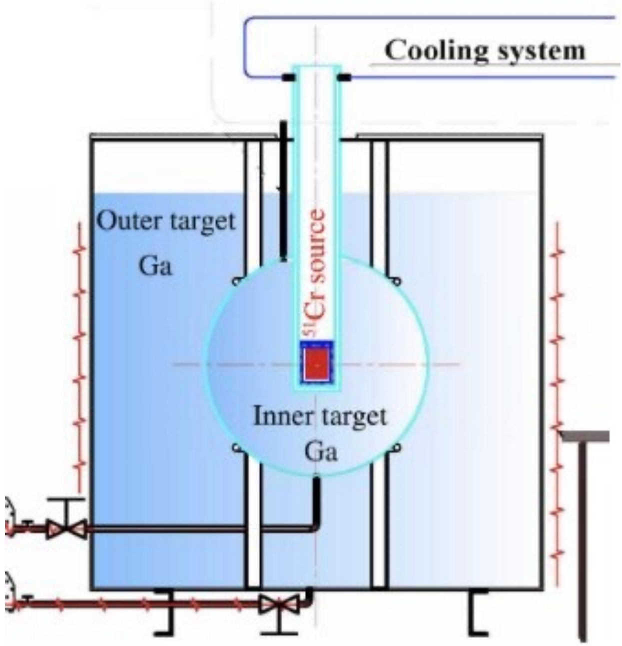
$$^{71}Ga + \nu_e \longrightarrow {}^{71}Ge + e^-$$

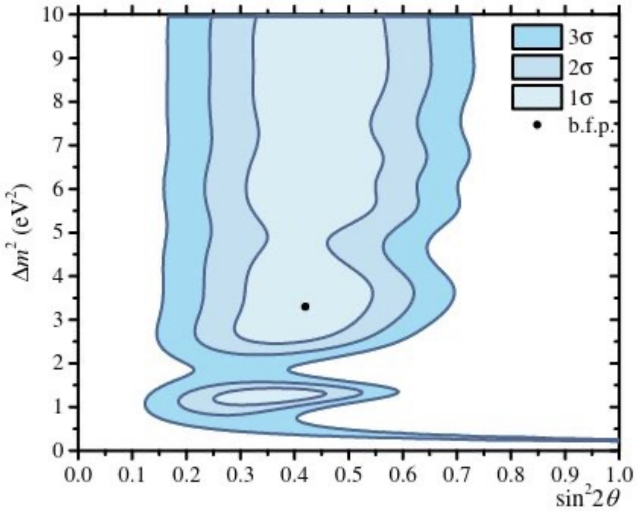
- ^{71}Ge production rate averaging results of Gallex and Sage:

$$0.84 \pm 0.05$$

- Recently confirmed by BEST Experiment

$$\text{Meas./Exp.} = 0.78 \pm 0.05$$

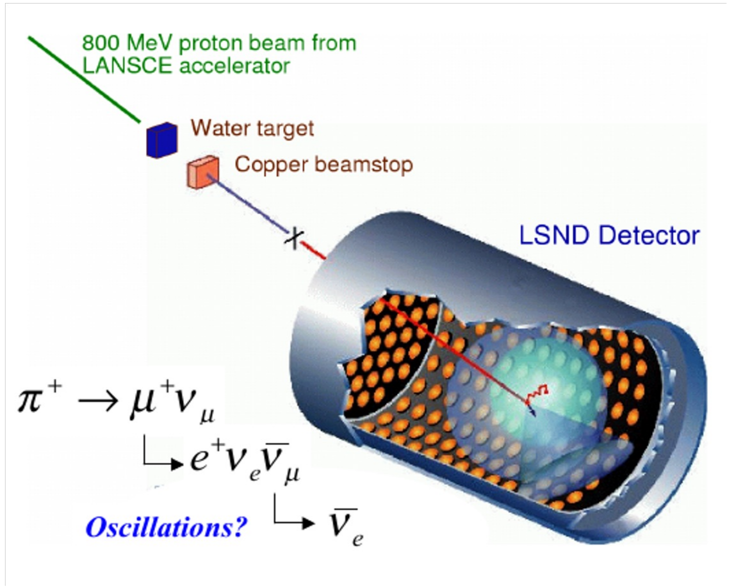


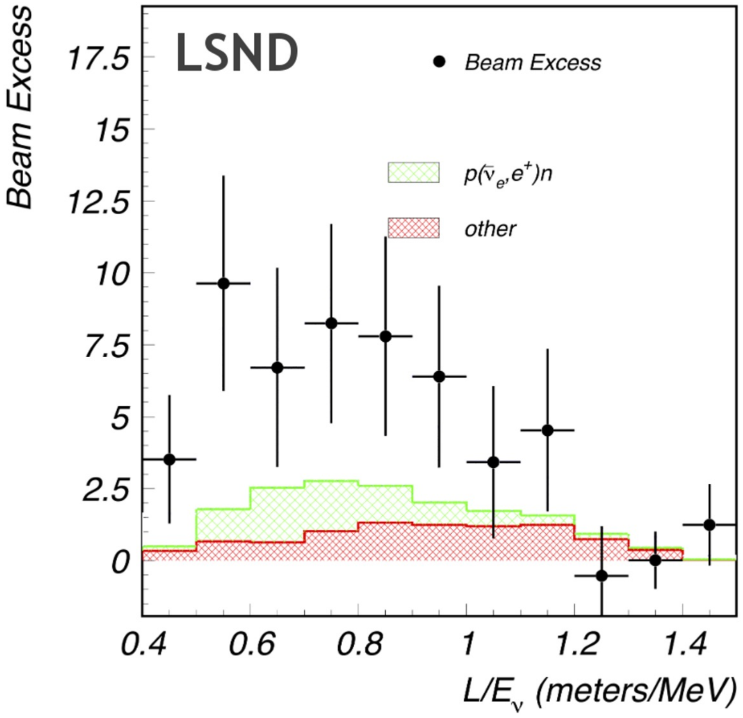


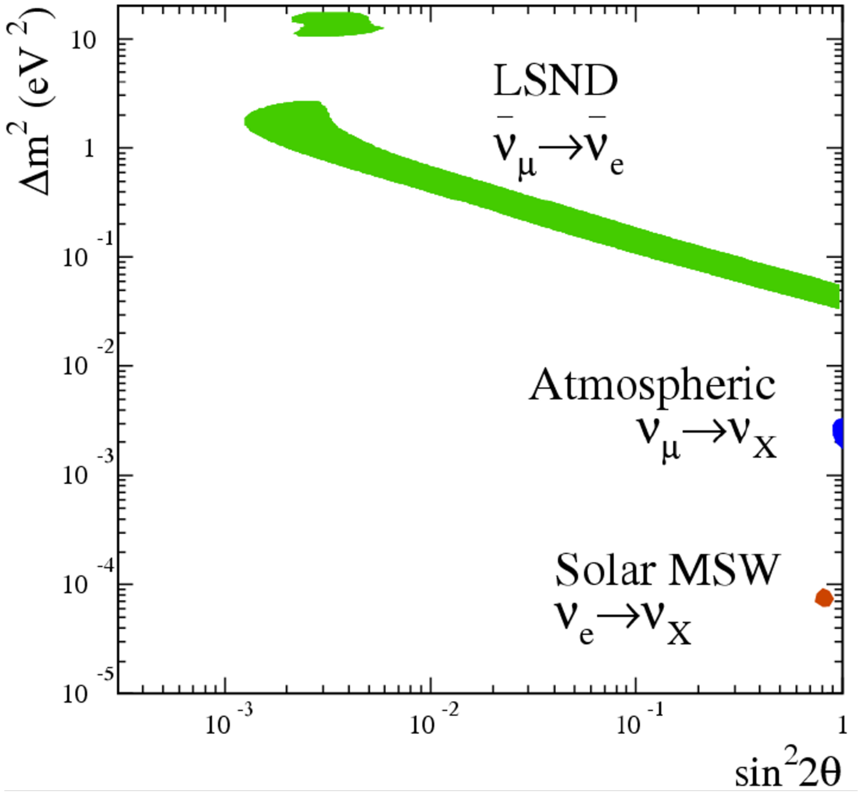
Robustness of these experiments proven by:
- Their sophisticated calibration
- Solar neutrino measurements in agreement with other experiments

LSND experiment

- Excess of $\bar{\nu}_e$ interpreted as $\bar{\nu}_e$ apparition at short distance.
- Δm^2 needed to explain the results is greater than the ones measured



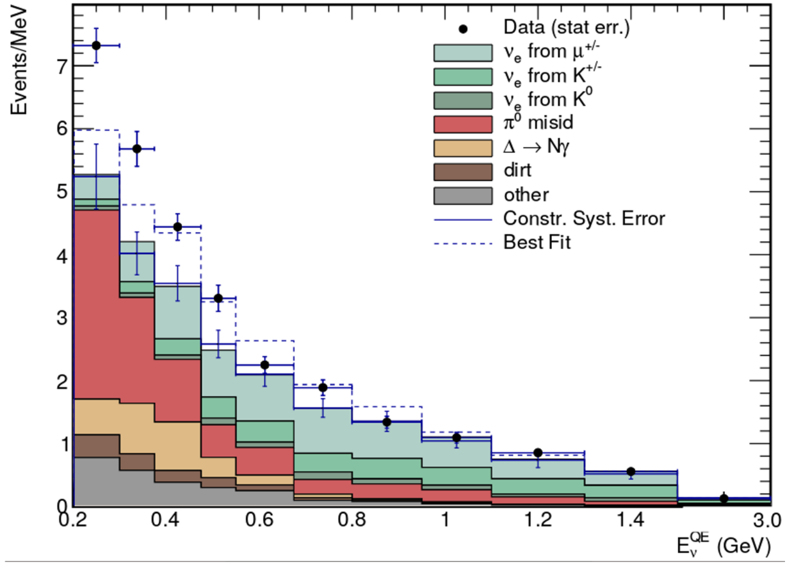


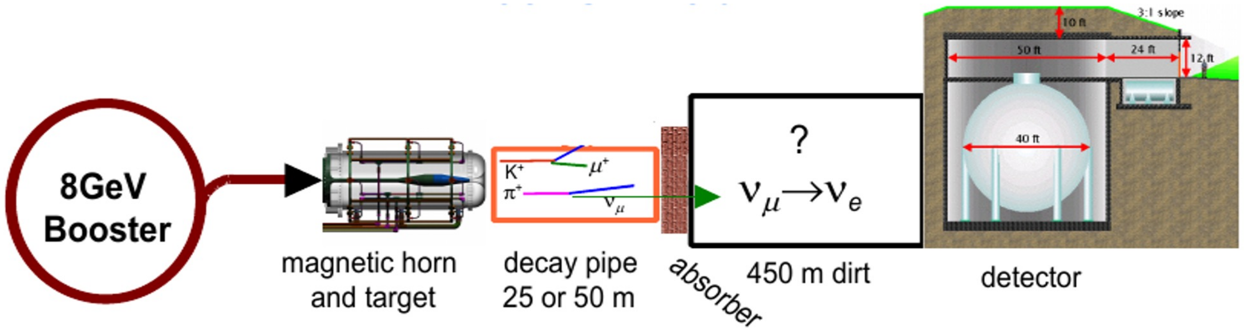


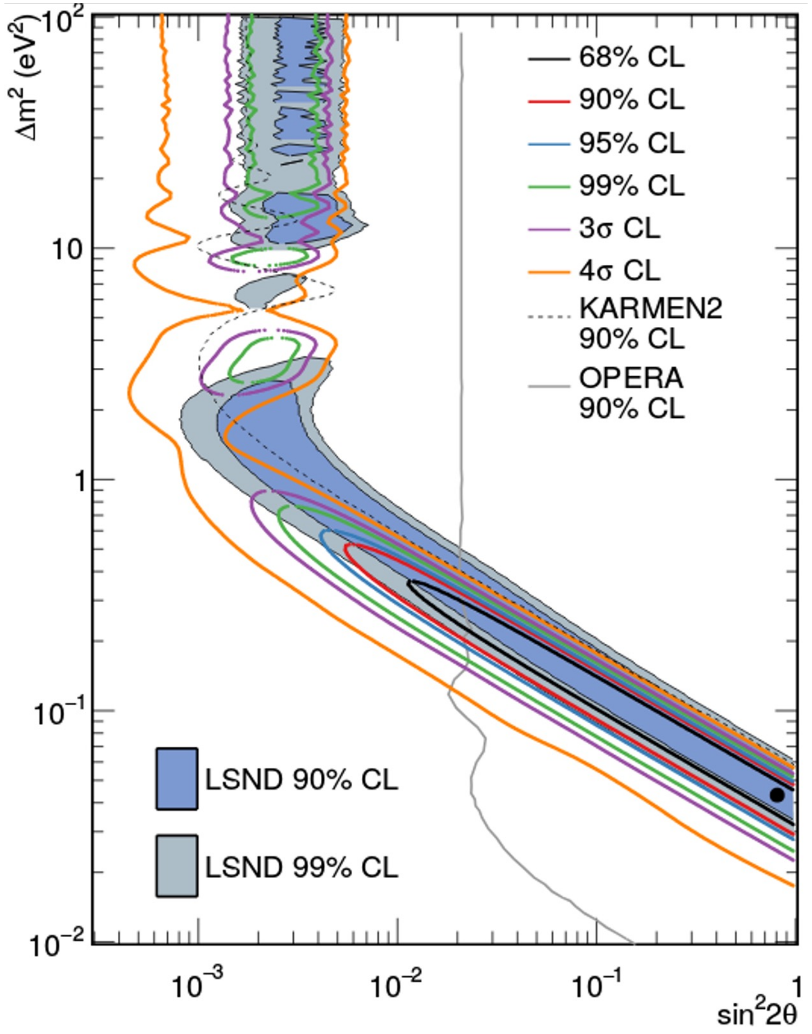
MiniBooNE experiment

Different beam and detector but same L/E.

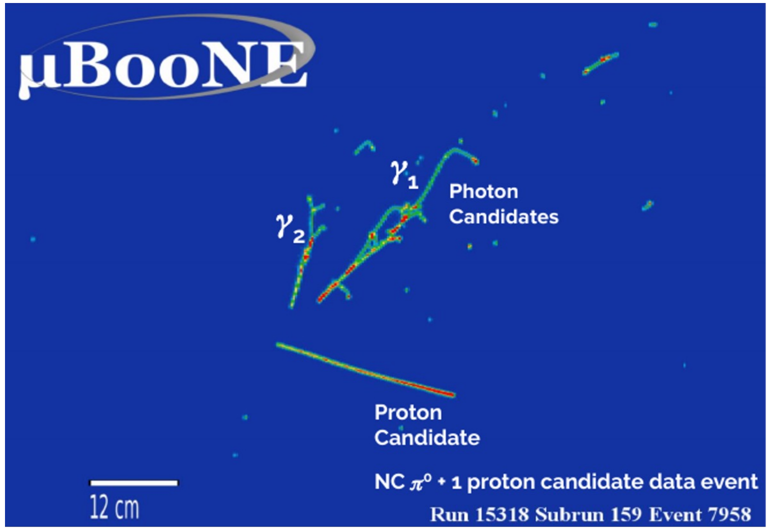
Excess in neutrinos and o antineutrinos.

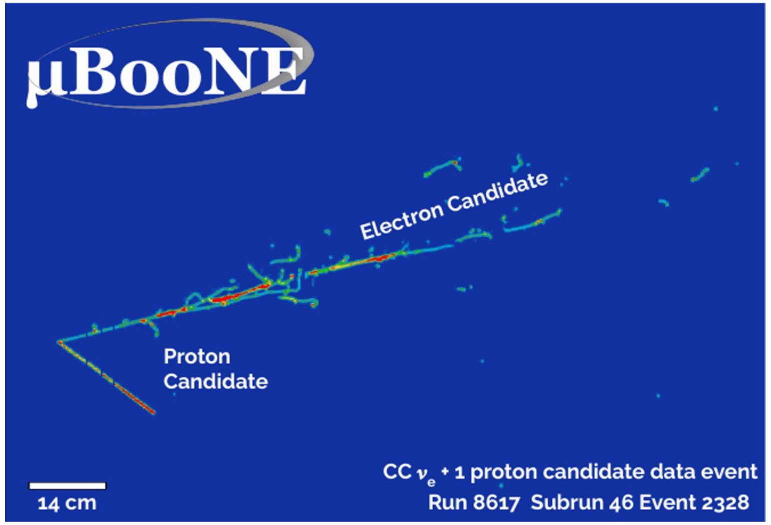




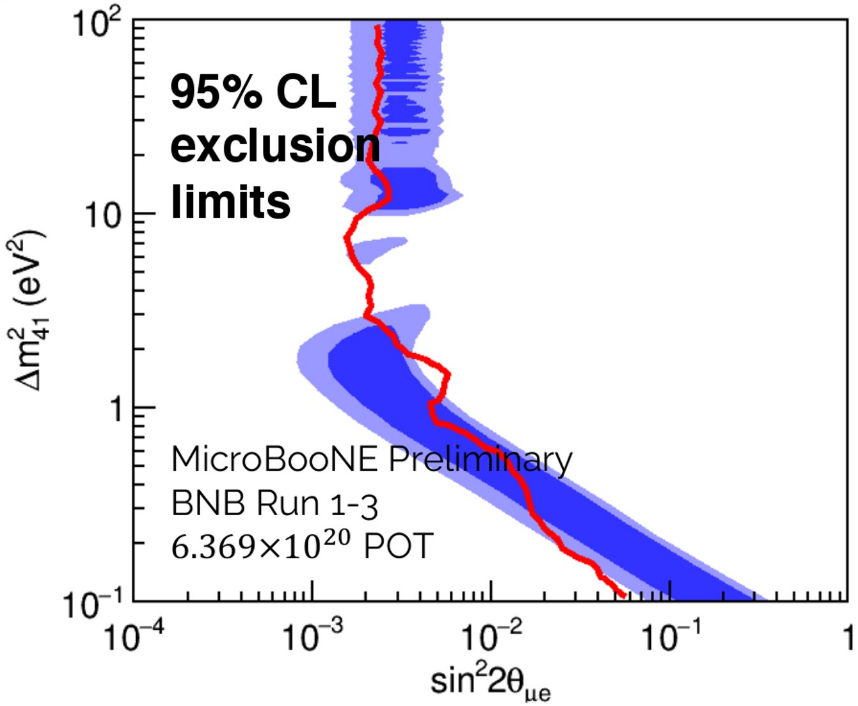


MicroBooNE experiment





New detector close MiniBooNE with a new technology (LAr TPC) able to distinguish the electromagnetic showers started by photons vs. electrons

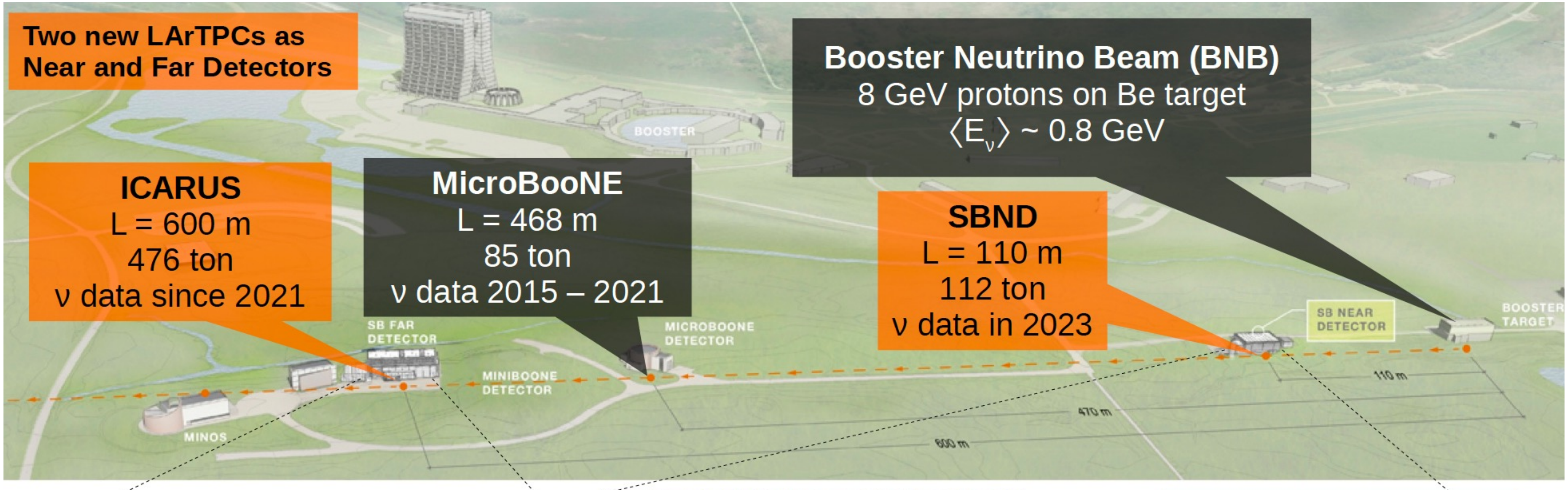


First results:

- No excess in photons
- No excess in electrons.
- LNSD and MiniBooNE anomaly still unexplained.

Short Baseline Neutrino Program

Goal: Perform sensitive searches for ν_e appearance and ν_μ disappearance
➜ search for light ($\Delta m^2 \sim 1\ eV^2$) sterile neutrino oscillations.



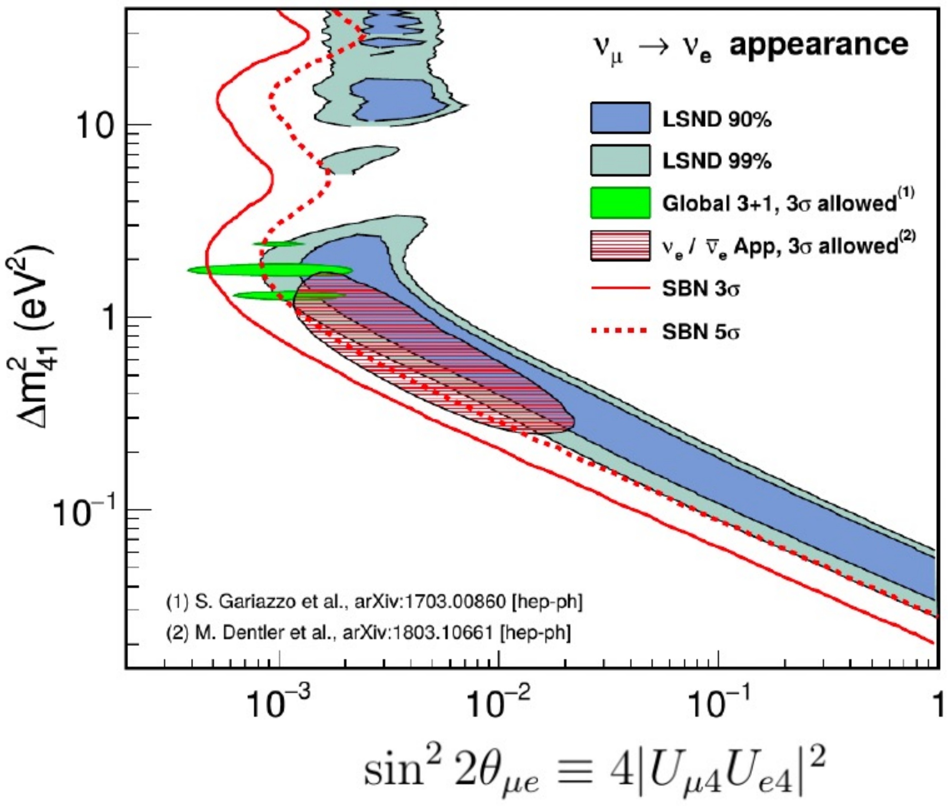
Short Baseline Neutrino Program

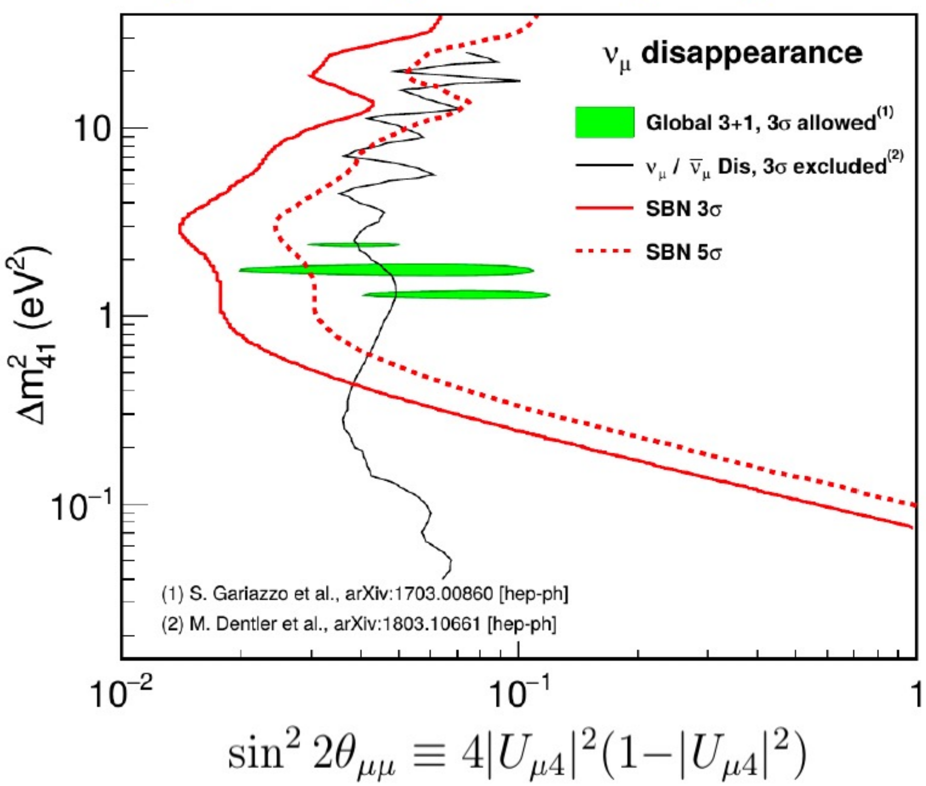
Goal: Perform sensitive searches for ν_e appearance and ν_μ disappearance
→ search for light ($\Delta m^2 \sim 1$ eV^2) sterile neutrino oscillations.

Detector assembly and installation in progress

Short Baseline Neutrino Program

Goal: Perform sensitive searches for ν_e appearance and ν_μ disappearance
→ search for light (Δm^2 ~1 eV^2) sterile neutrino oscillations.



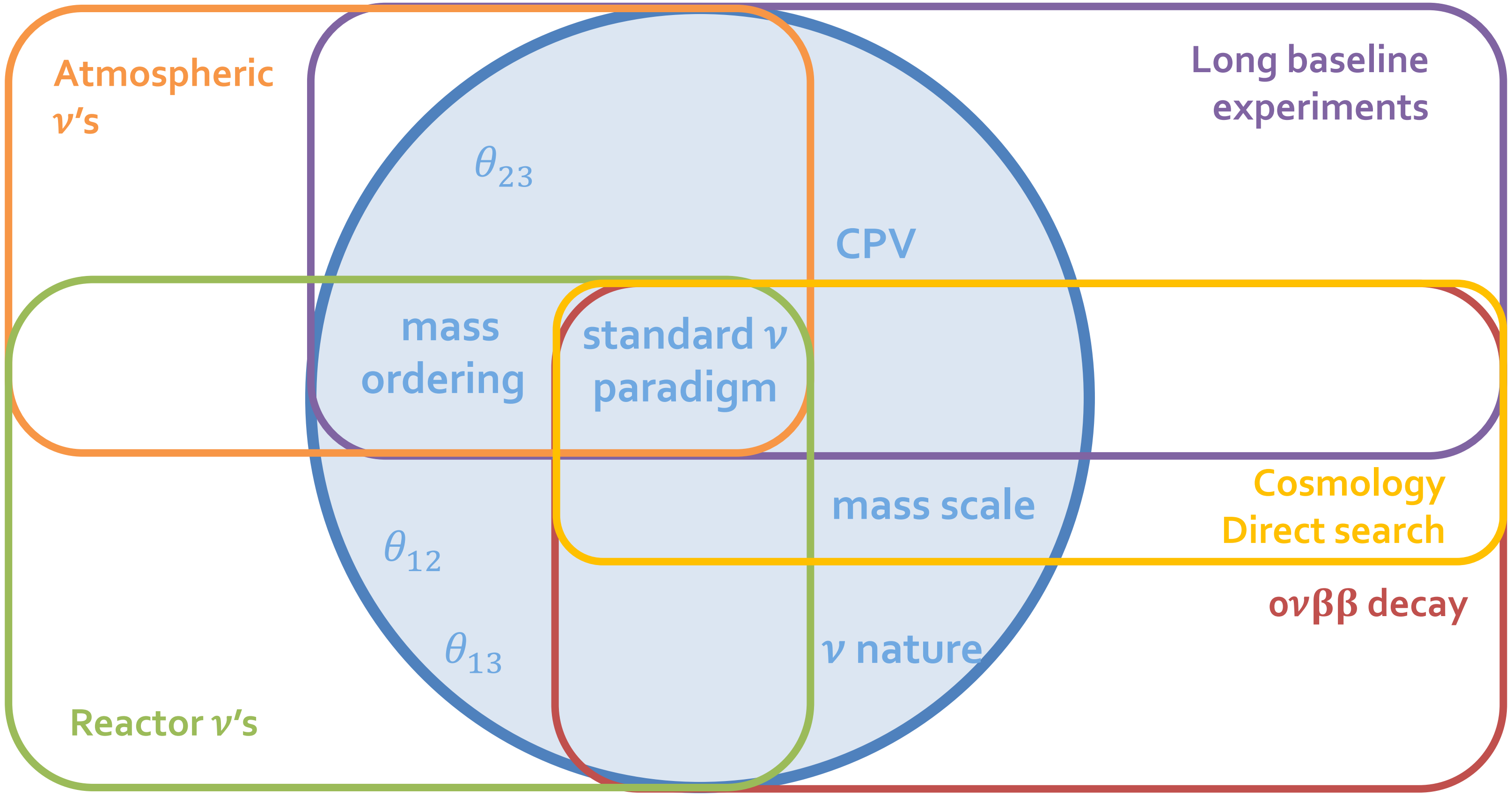


Ann. Rev. Nucl. Part. Sci. 69 (2019) 363-387

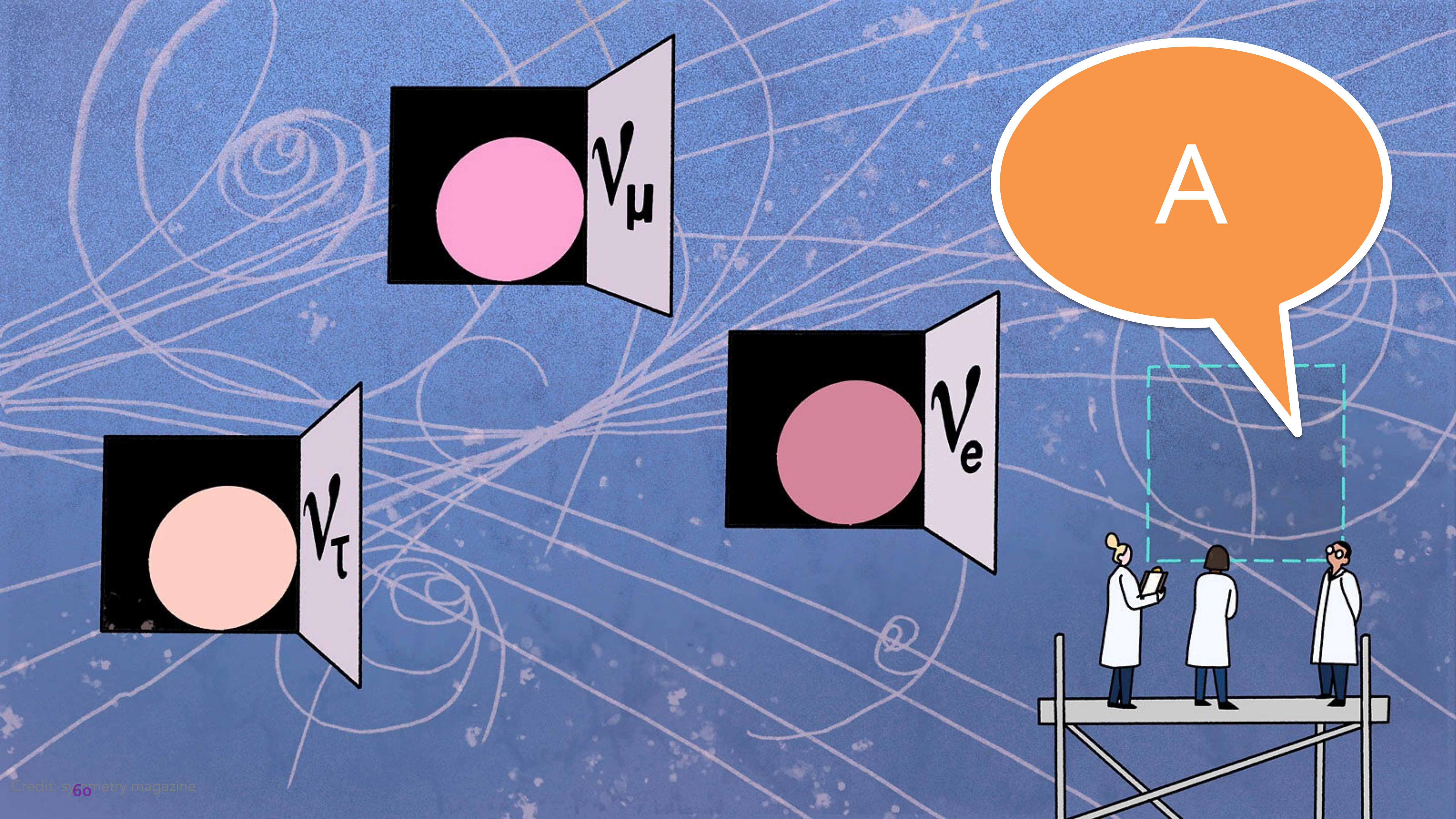
Complementarity

Next generation experiments able to answer ν unknowns!

ν's can answer fundamental questions



Adapted form S. Pascoli



Credit: symmetry magazine

Neutrinos also provide answers

A

Neutrinos and neutrino experiments are excellent probes to explore the Universe and provide insight of new Physics

- **Neutrino experiments** are such a powerful tools that allow to perform searches beyond the standard model: dark matter searches, proton decay, etc.

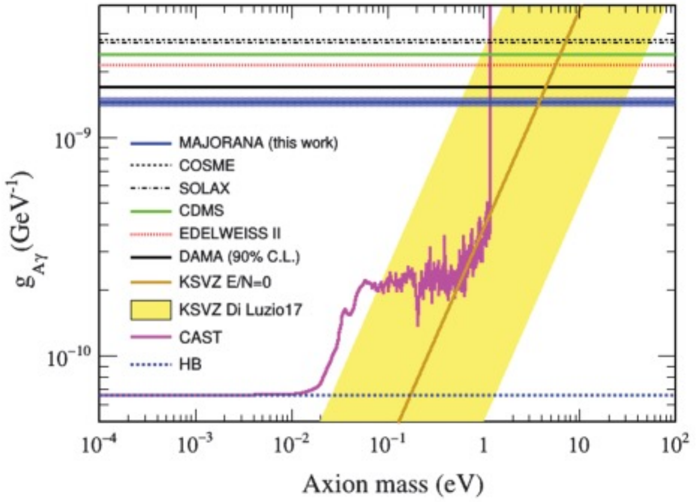
- **Neutrinos as messengers**
  - Neutrinos bring raw information from the source as barely interact along the way.
  - Multi-messenger astronomy provides complementary information from neutrino detector, gravitational waves, cosmic-rays, ɣ-rays, X-rays.
  - Bright new era coming!

BEYOND THE STANTARD MODEL

Searches beyond the Standard Model

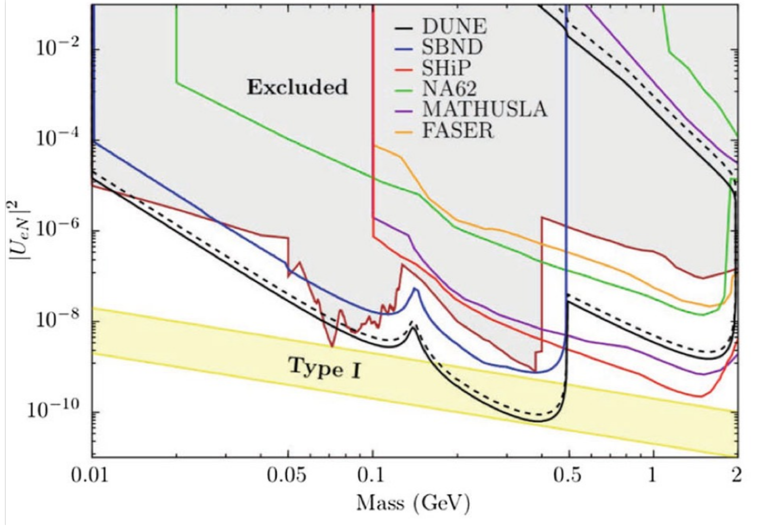
Neutrinos experiments are state-of-the-art detectors able to search for new physics as primary or complementary physics goals:

- Dark matter, including searches for axion-like particles and low-mass dark matter, and boosted dark matter.
- Non-standard neutrino interactions.
- Heavy neutral leptons: heavy right-handed singlets predicted in many extensions of the Standard Model
- CPT violation: Using beam neutrinos, we can look for Lorentz and CPT violation by Baryon number violating processes, like proton decay.



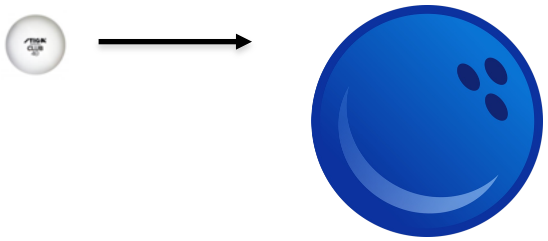
MAJORANA DEMONSTRATOR constraints on axions:

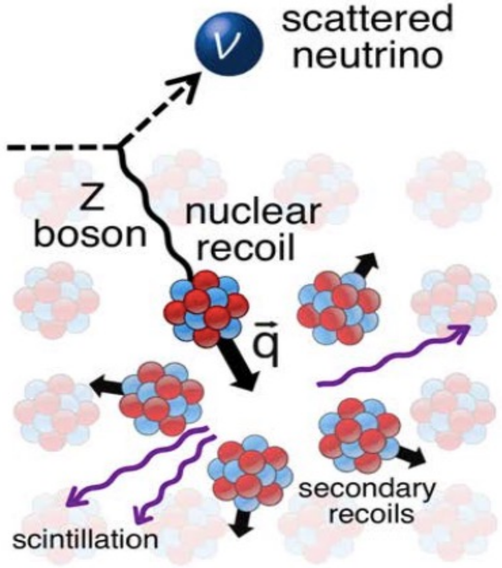
DUNE sensitivity for heavy neutral leptons



Coherent Elastic Neutrino-Nucleus Scattering

- CEνNS is Standard Model process predicted in 1974 because of Weak Neutral Curren
- Neutrino scatters on a target nucleus → amplitudes of individual nucleons add coher



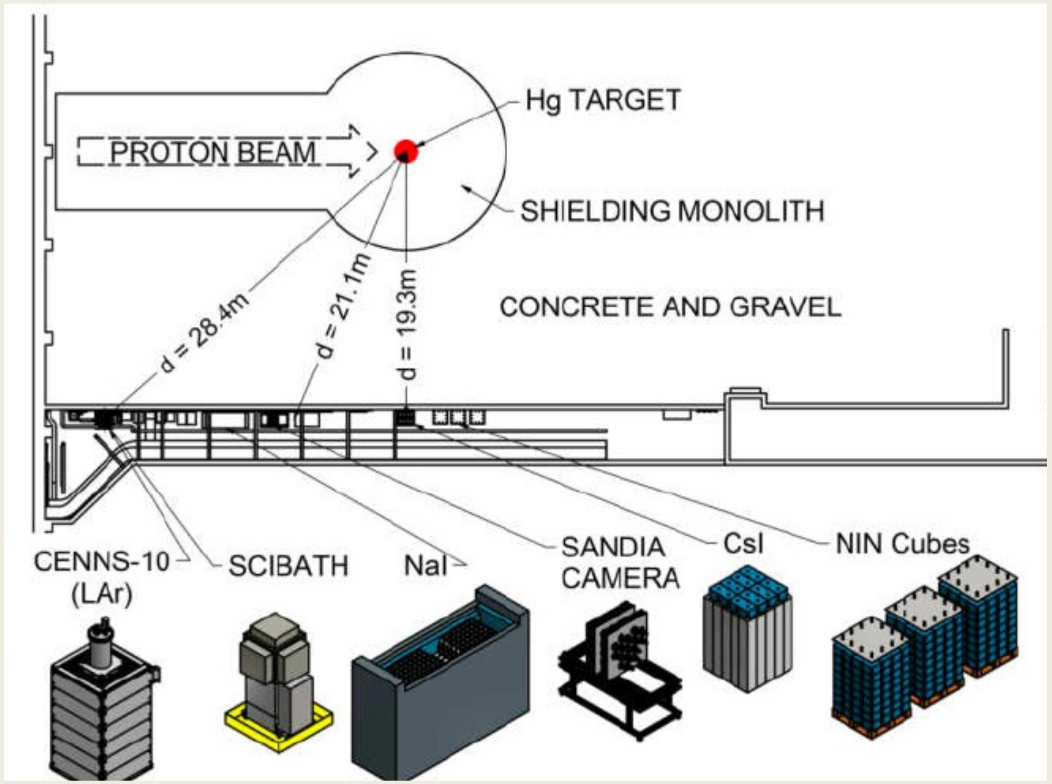


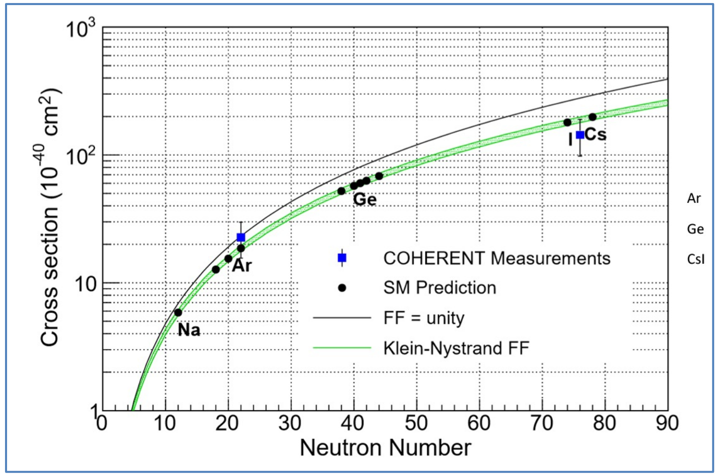
- The coherence imposes 2 requirements:
  1. The scattering must be elastic: only experimental observable a nuclear recoil.
  2. The wavelength of the momentum transfer must be of the size of the nucleus: the neutrino must be low energy ($E_\nu \leq 50$ MeV).

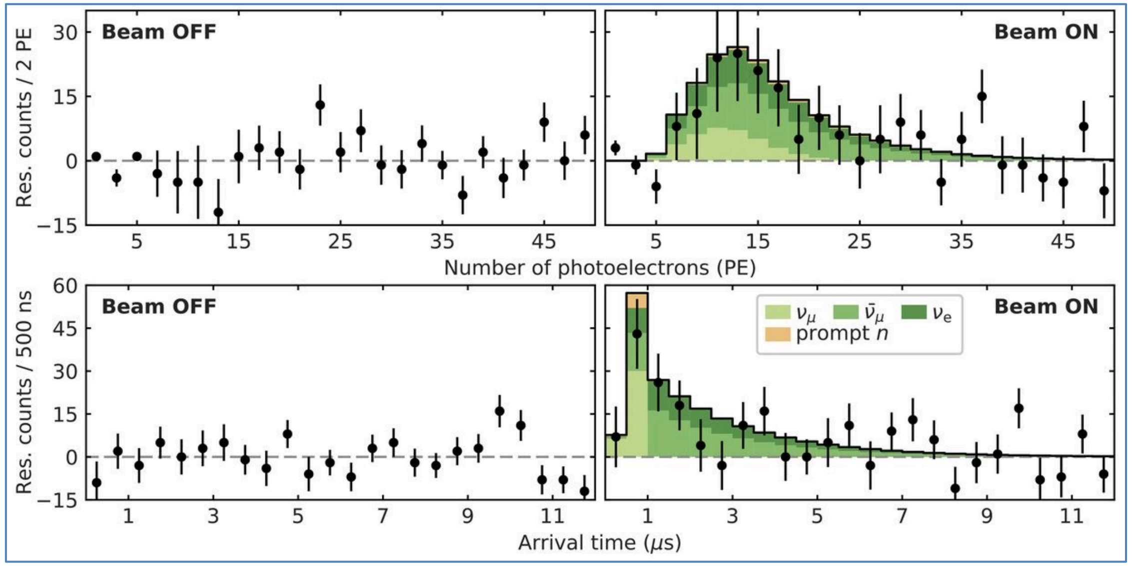
- Strategy: Measure N^2 dependence of CEvNS process with multiple targets/detector technologies:
  - (event rate)/kg is high, so relatively small (10-100 kg) detectors sufficient
  - Radiological background requirements fairly modest, because of pulsed beam
  - Need low E thresholds!

COHERENT experiments

First observation in 2017 of CEνNS with 14.6kg CsI(Na) detector and the Spallation Neutron Source (SNS) at Oak Ridge (USA)



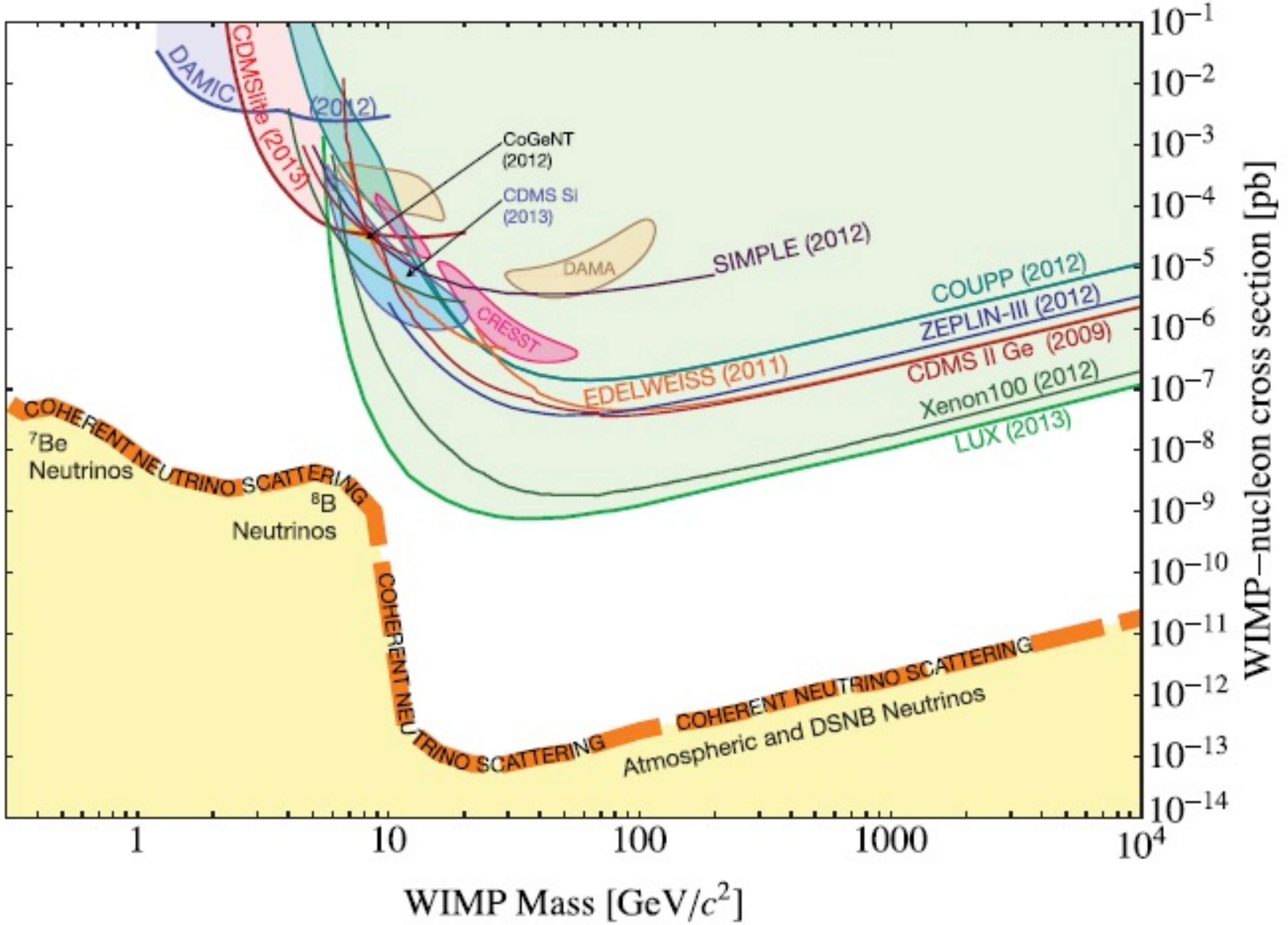




Coherent Elastic Neutrino-Nucleus Scattering

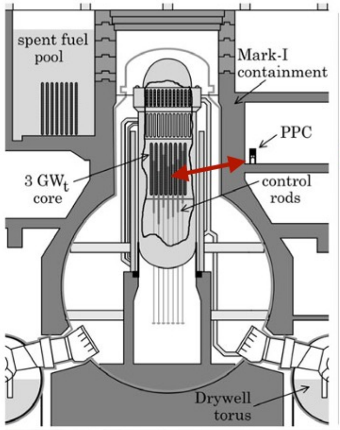
Physics impact:

- A simultaneous measurement on multiple targets can dramatically constrain available Non-Standard Neutrino Interactions parameter space.
- CEνNS is the largest cross-section in supernova dynamics → validate models.
- CEνNS is an irreducible background for wimp searches.
- Future expansions for sterile neutrinos, neutrino magnetic moment, θ_W, …



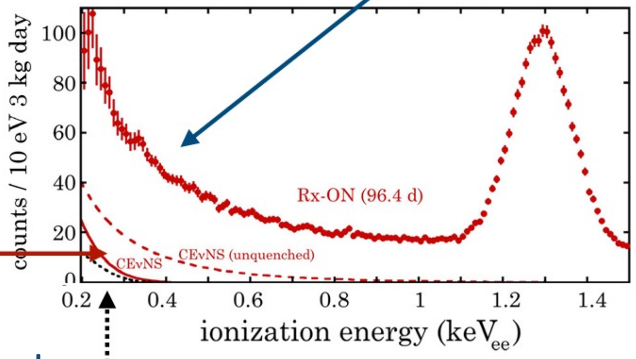
CEvNS with reactors

Dresden (Ge)



Detector baseline: 10.4 m
$4.8 \times 10^{13}\ \bar{\nu}/\mathrm{cm}^2\,\mathrm{s}$

Reactor-induced background from epithermal neutrons

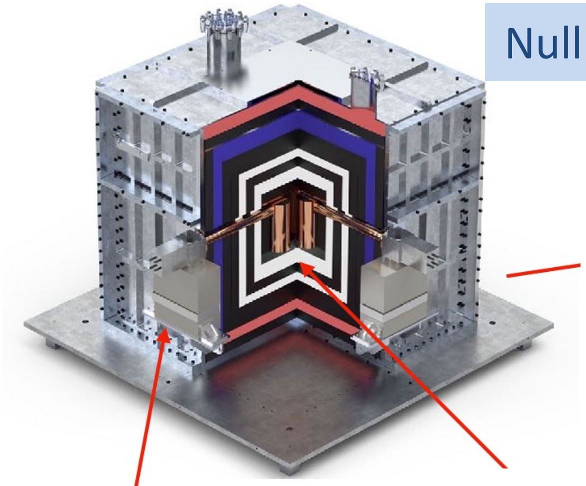


CEvNS?

background

CONUS (Ge)

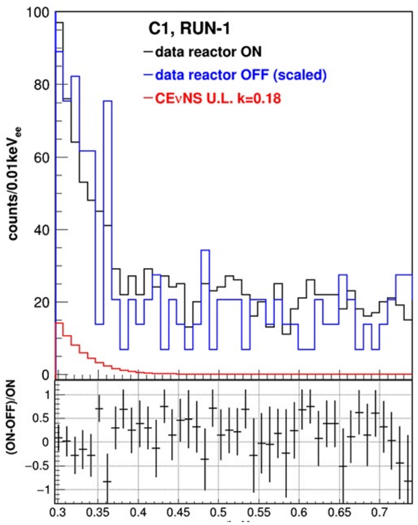
Null result



Brokdorf reactor in Germany

Shielding

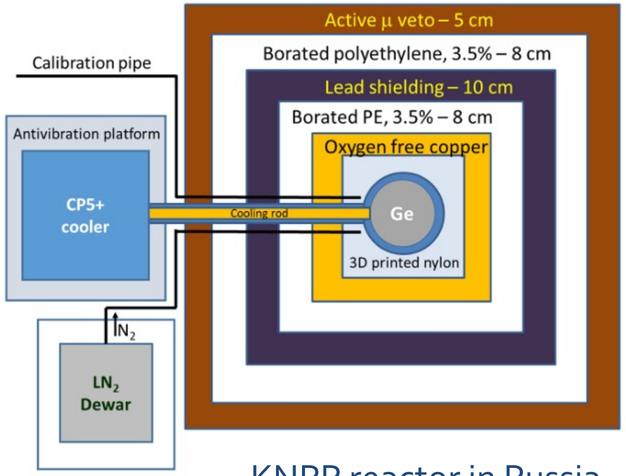
Ge



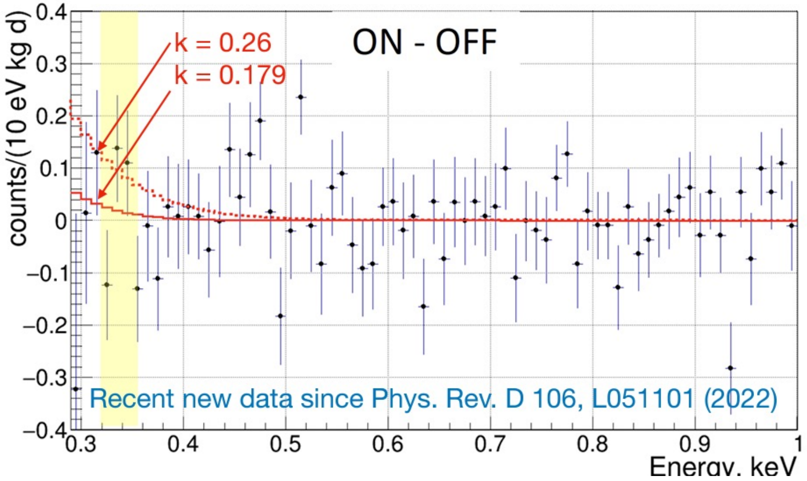
H. Bonet, et al, Phys. Rev. Lett. 12

CEvNS with reactors

νGEN (Ge)



KNPP reactor in Russia

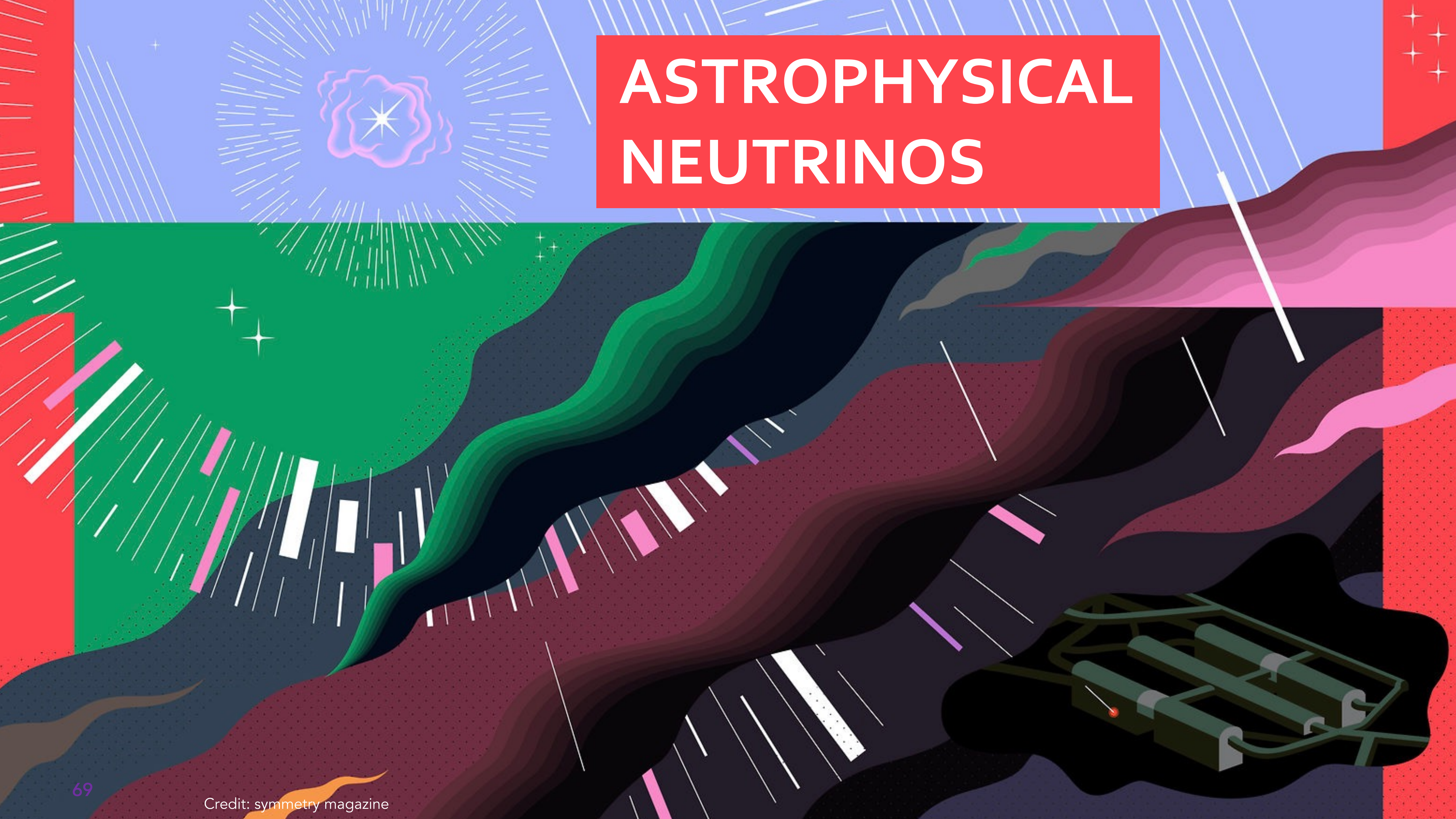


Null result

Other experimental approach: Cryodetectors -> no quenching

- **RICOCHET:** ILL reactor in France, Ge and Zn detectors
- **NUCLEUS:** Chooz nuclear plant in France, Al_2O_3 and $CaWO_4$

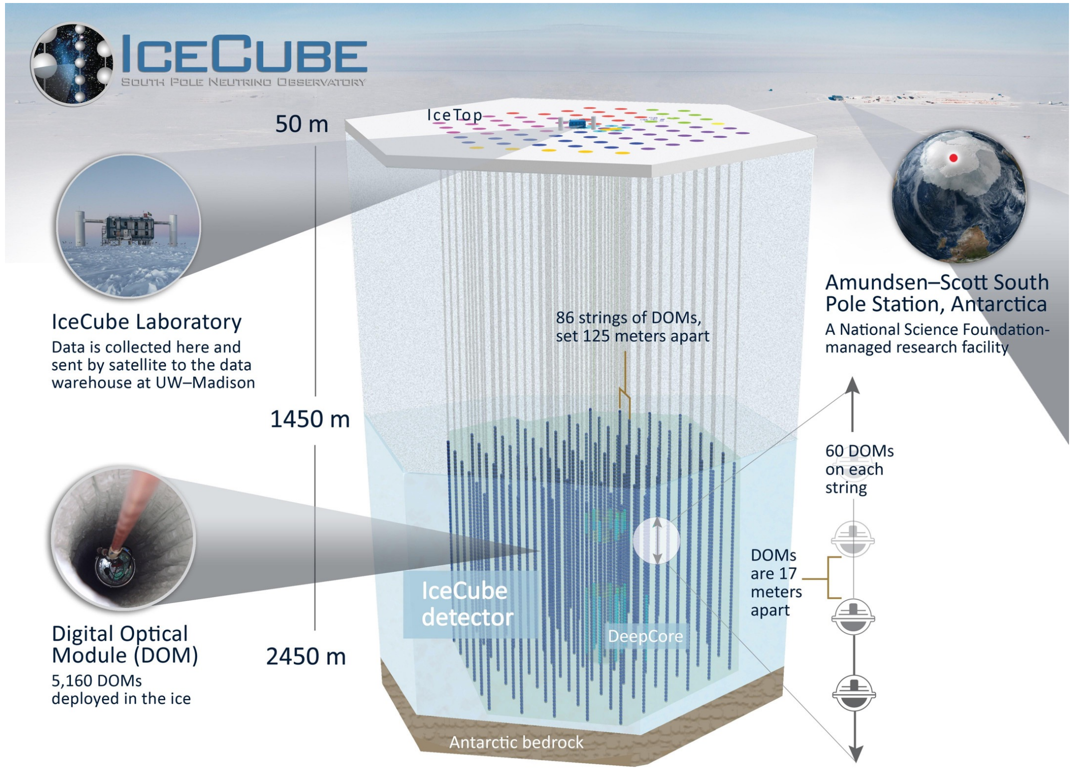
ASTROPHYSICAL NEUTRINOS

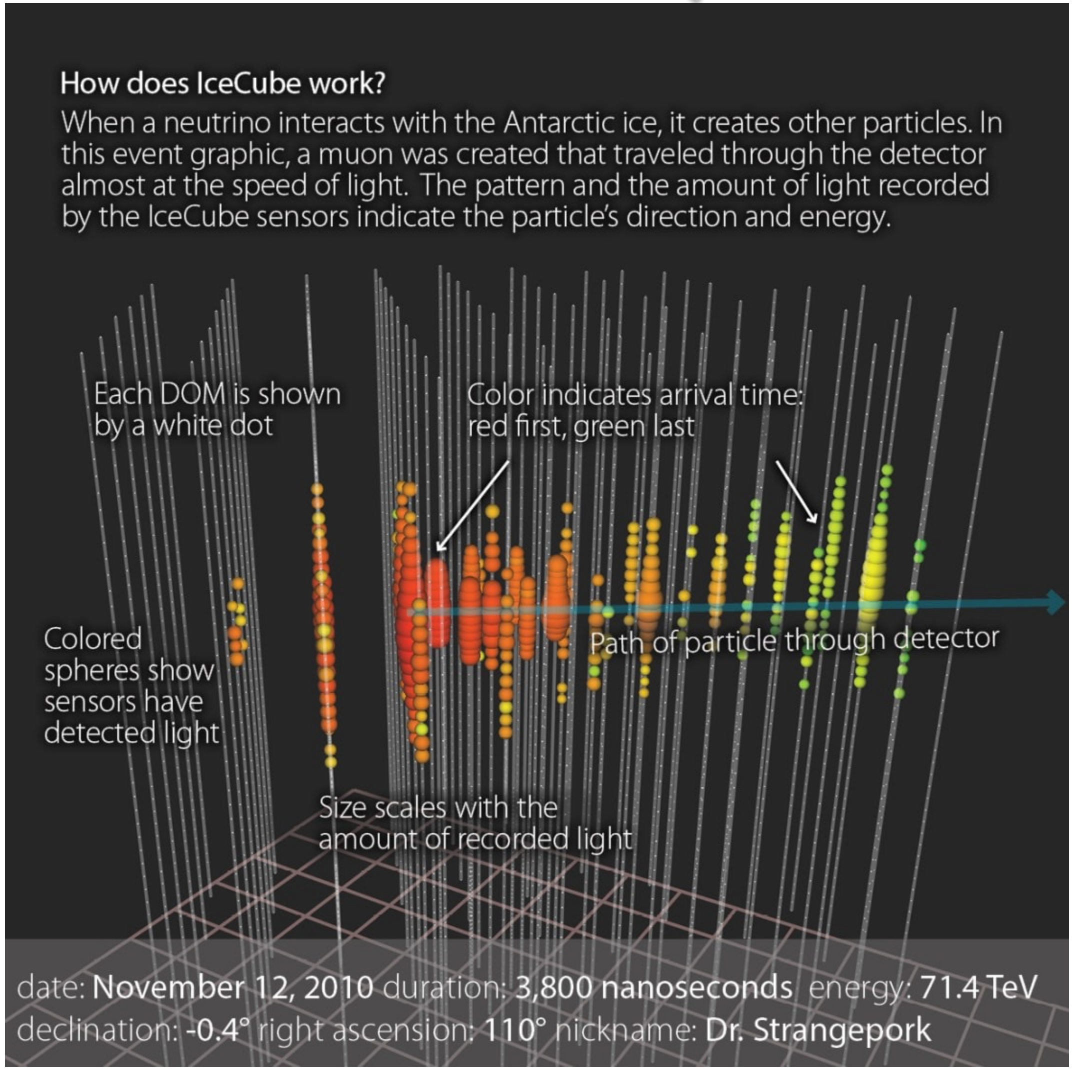


Credit: symmetry magazine

IceCube

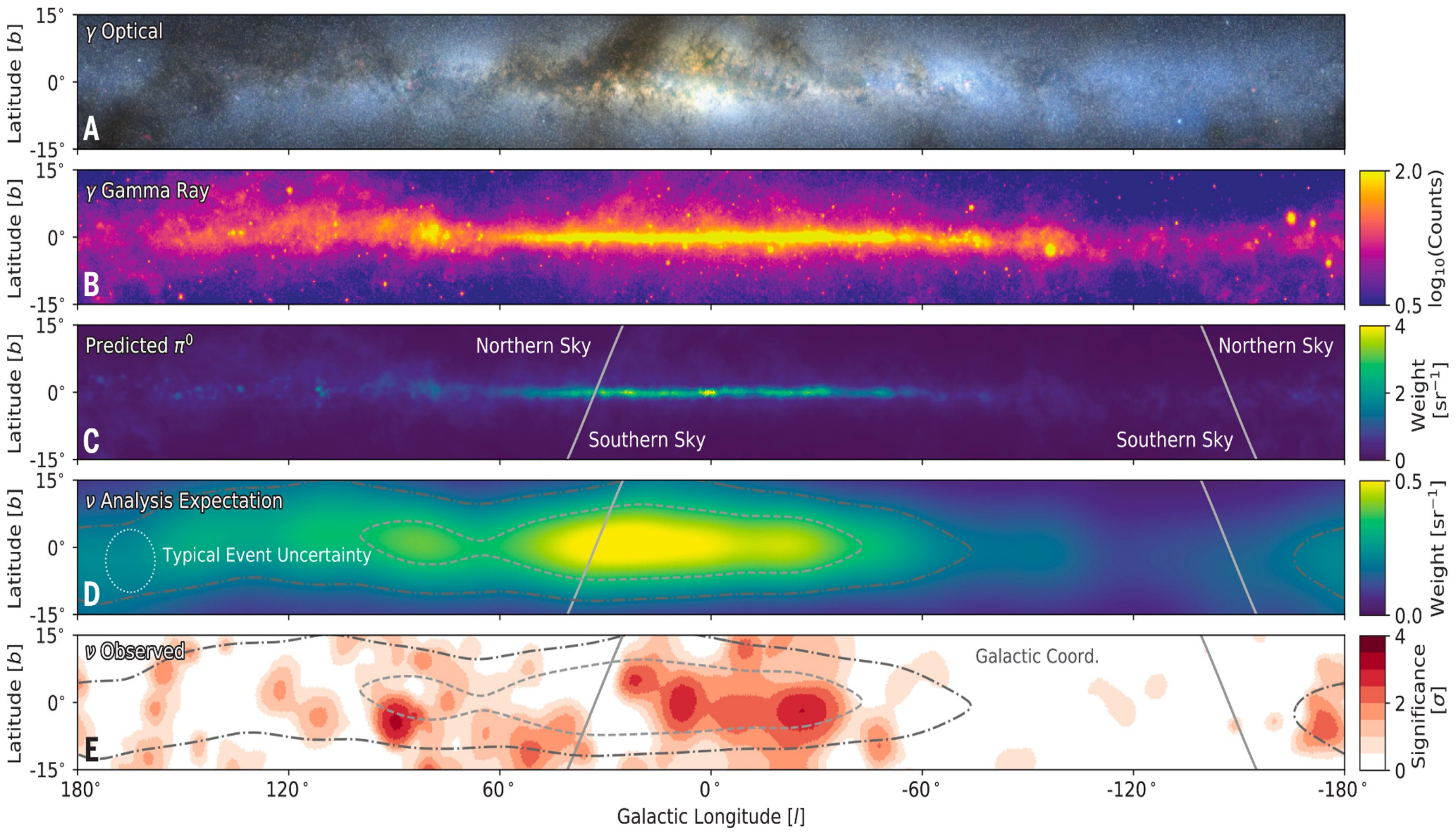
- 5.000 photosensors in 1km^3 ice at the South Pole.
- 1km^3 particle detector
- Very energetic extragalactic neutrinos detected (up to 10^{16} eV).





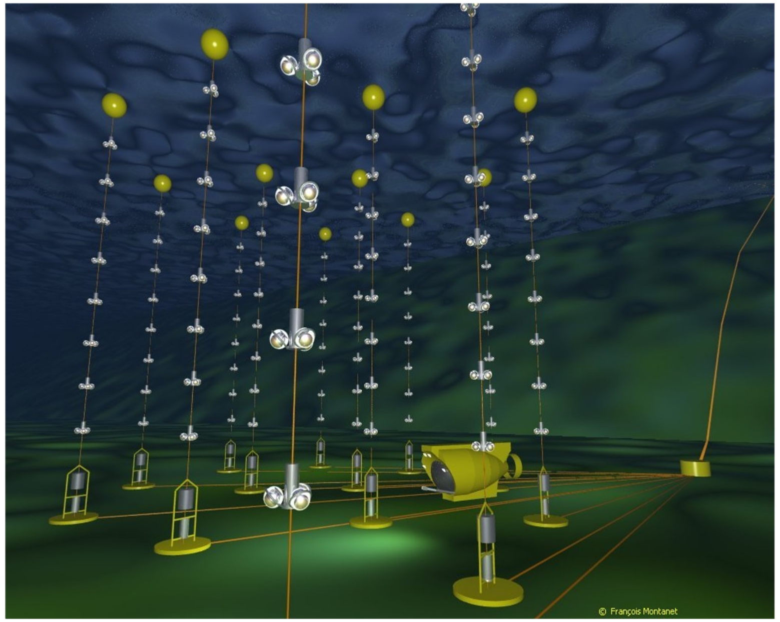
IceCube

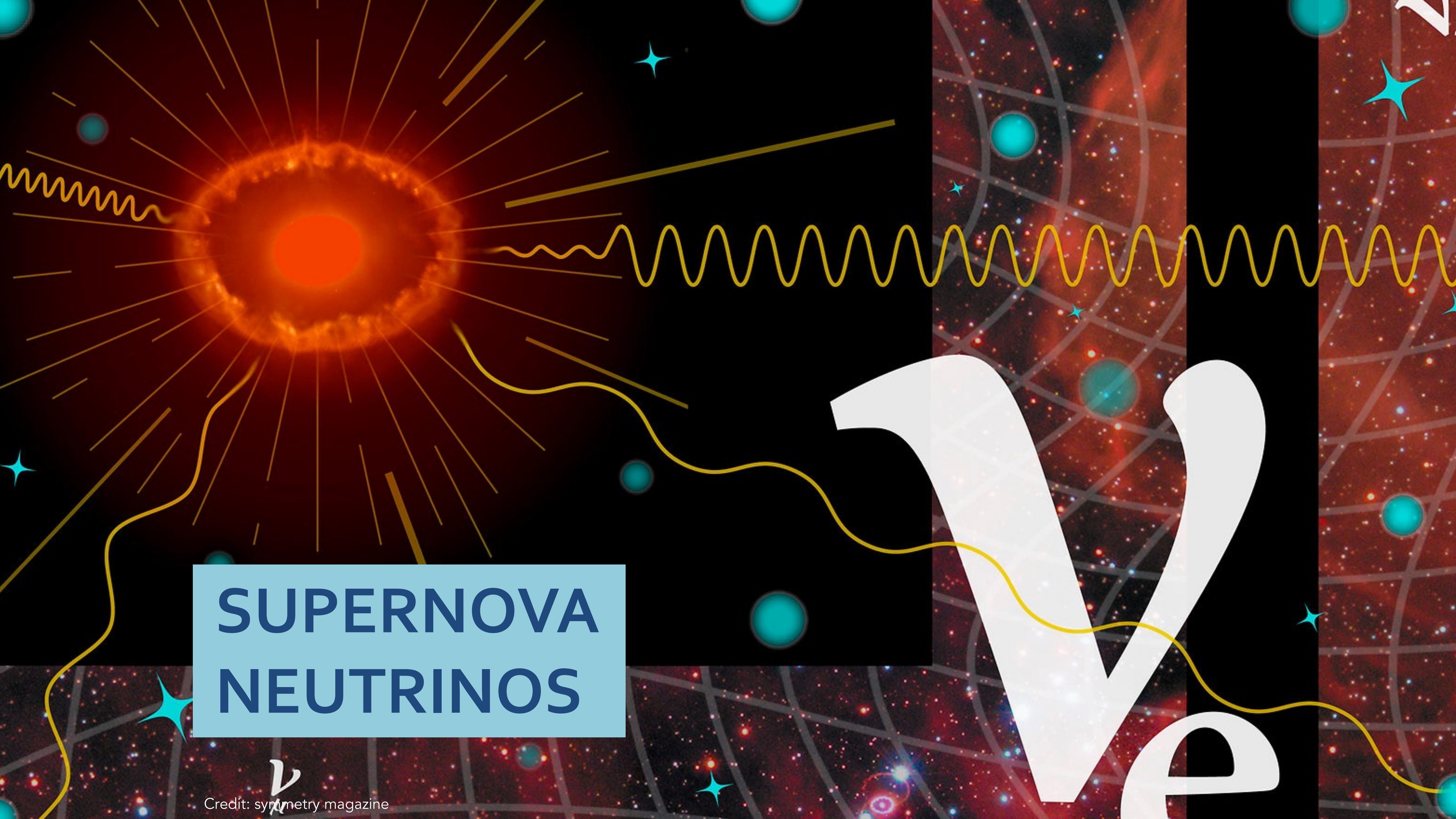
"Neutrinography" of our galaxy



Km3Net

- Next generation neutrino telescopes ($1km^3$)
- Volumes between megaton and several cubic kilometres of clear sea water in the Mediterranean.
  - With the ARCA telescope, KM3NeT scientists will search for neutrinos from distant astrophysical sources such as supernovae, gamma ray bursters or colliding stars.
  - The ORCA telescope is the instrument for KM3NeT scientists studying neutrino properties exploiting neutrinos generated in the Earth's atmosphere.





Credit: symmetry magazine

Supernova neutrinos

Infall

Core collapses, and a shock wave is formed. The medium is opaque even for neutrinos.

Neutronization

Primarily ν_e escape, as messengers of the shock front breaking.

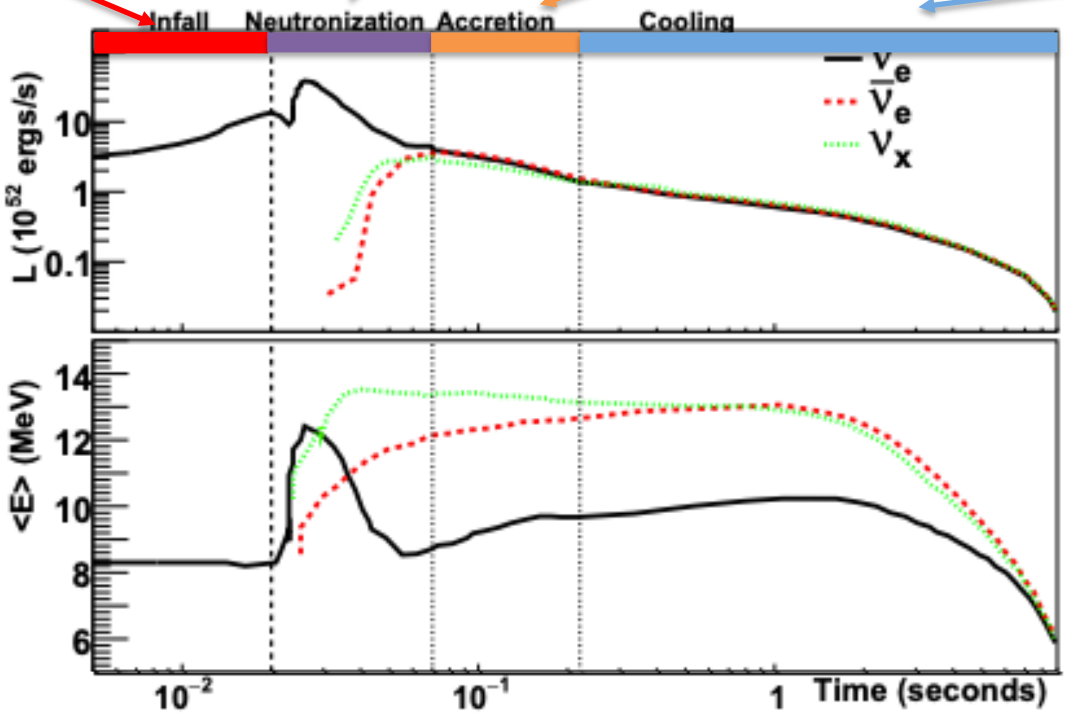
Accretion

(<1s) ν's powered by infalling matter.

Cooling

(~10s) main part of the signal, the proto-neutron star sheds its trapped energy.

For a supernova at 10 kpc from Earth.

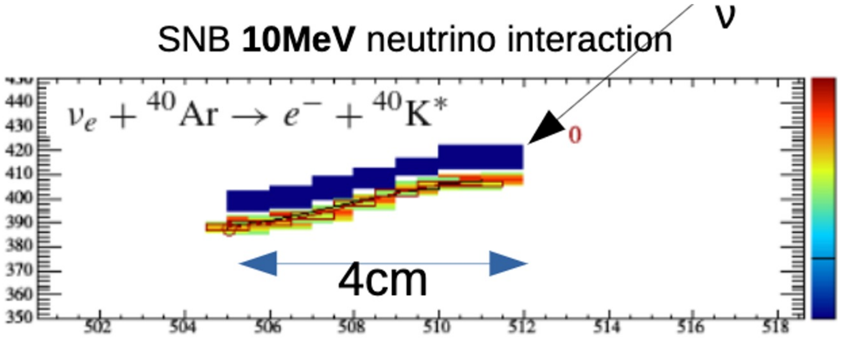


A lot of information about the supernova in this profile:
flavor content and spectra of the ν's emitted change throughout these phases, and the supernova's evolution can be followed with the ν signal.

Supernova neutrinos

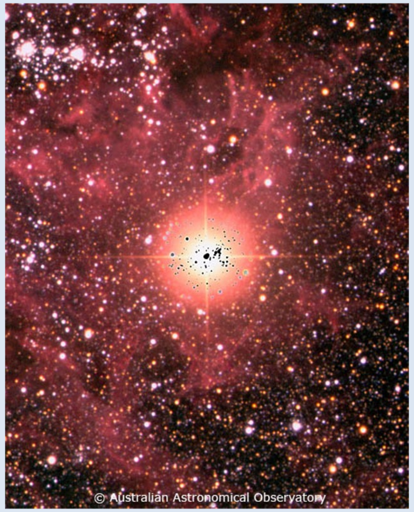
- **Core-collapse supernovae** are a huge source of ν's of all flavors in~10 sec.
  - 1-3 SN/century in our Galaxy (10 kpc).
  - Super Nova Early Warning System (SNEWS).
  - Measurement of the SN ν's will provide information about:
    - **Supernova physics**: Core collapse mechanism, SN evolution in time, black hole formation.
    - **Neutrino physics:** ν flavor transformation, ν absolute mass, other ν properties (sterile ν's, magnetic moments, extra dimensions…).
- **Diffuse background supernova ν's** are not detected yet.

Low energy signal (few MeV) to be distinguished from radiological backgrounds



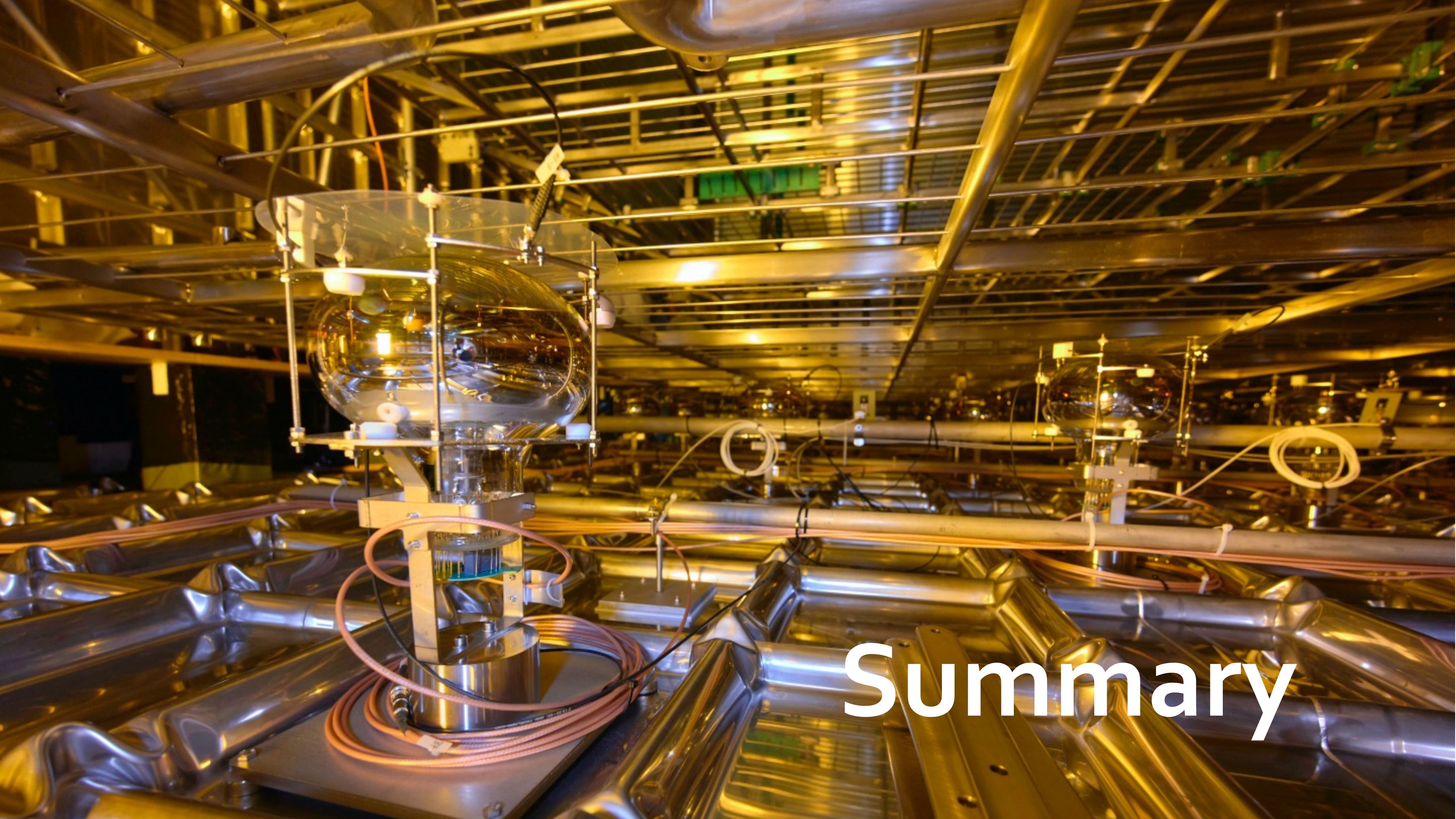
DUNE simulation

SN1987A



- ~25 neutrinos detected in Kamiokande, IMB, Baksan
- Confirmed baseline model
- Beginning of neutrino & multi-messenger astronomy

Summary



Summary

Neutrino oscillations show that neutrinos have mass.

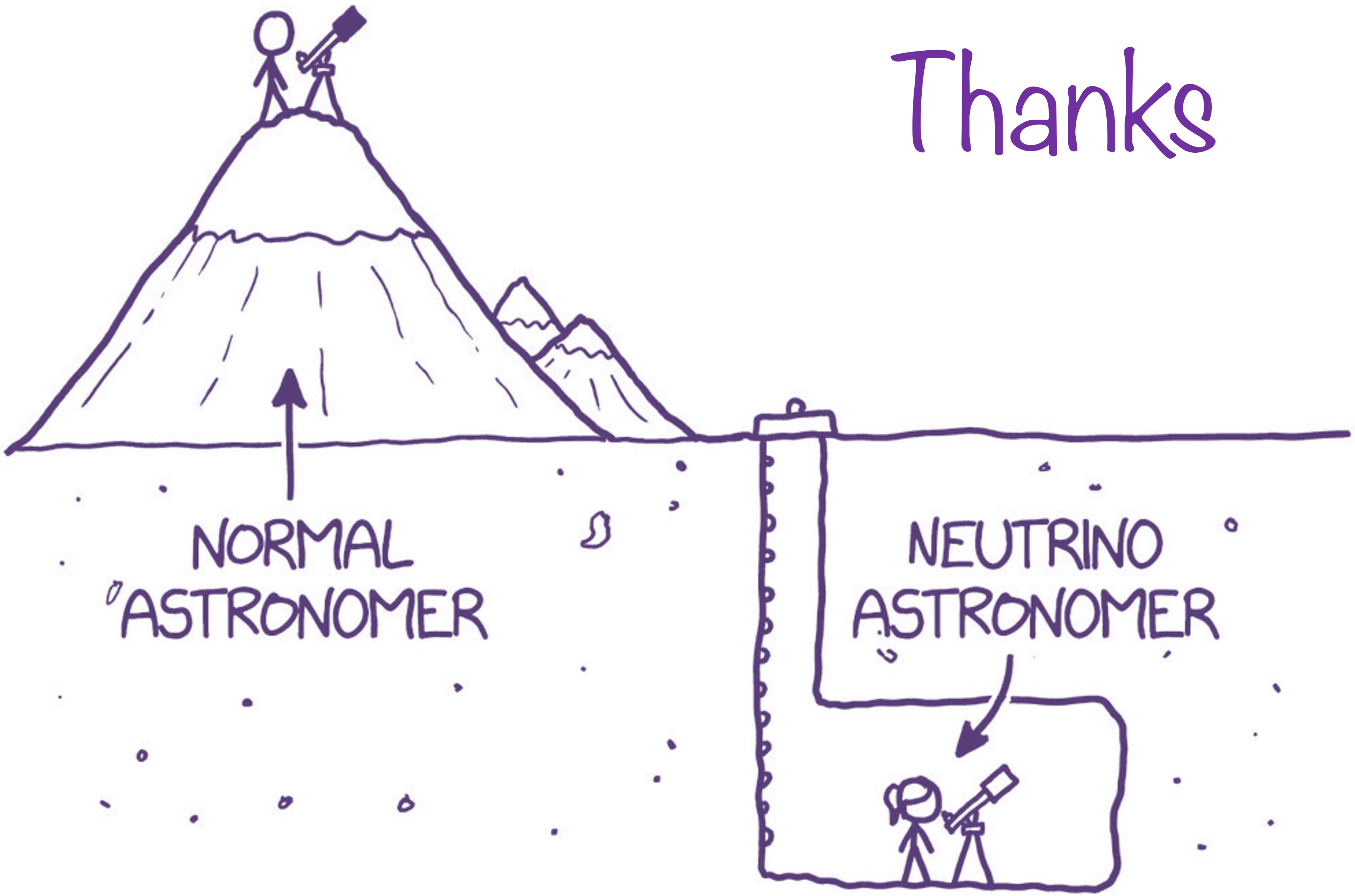
The mass scale of neutrinos is very different from other particles. It points to Physics Beyond the Standard Model.

There are still many questions to be solved:

- Do neutrinos and antineutrinos behave the same (CP violation in neutrinos)?
- What is the lightest neutrino (order of neutrino masses)?
- Does θ_{23} indicate a symmetry between the second and third generation of the Standard Model?
- Are there more than 3 neutrinos?
- What is the absolute mass of neutrinos?
- Are neutrinos their own antiparticles?
- Where do ultra-high energy cosmic neutrinos come from?
- How does a supernova explode?

Experimental prospects to answer them in the next decades. You can provide answers!

Thanks



Credit: Randall Munroe