Neutrino Physicist or Ghost Hunter?


Inside Proto-DUNE


Inside Super-Kamiokande


On top of ND280

International High School Teacher Programme

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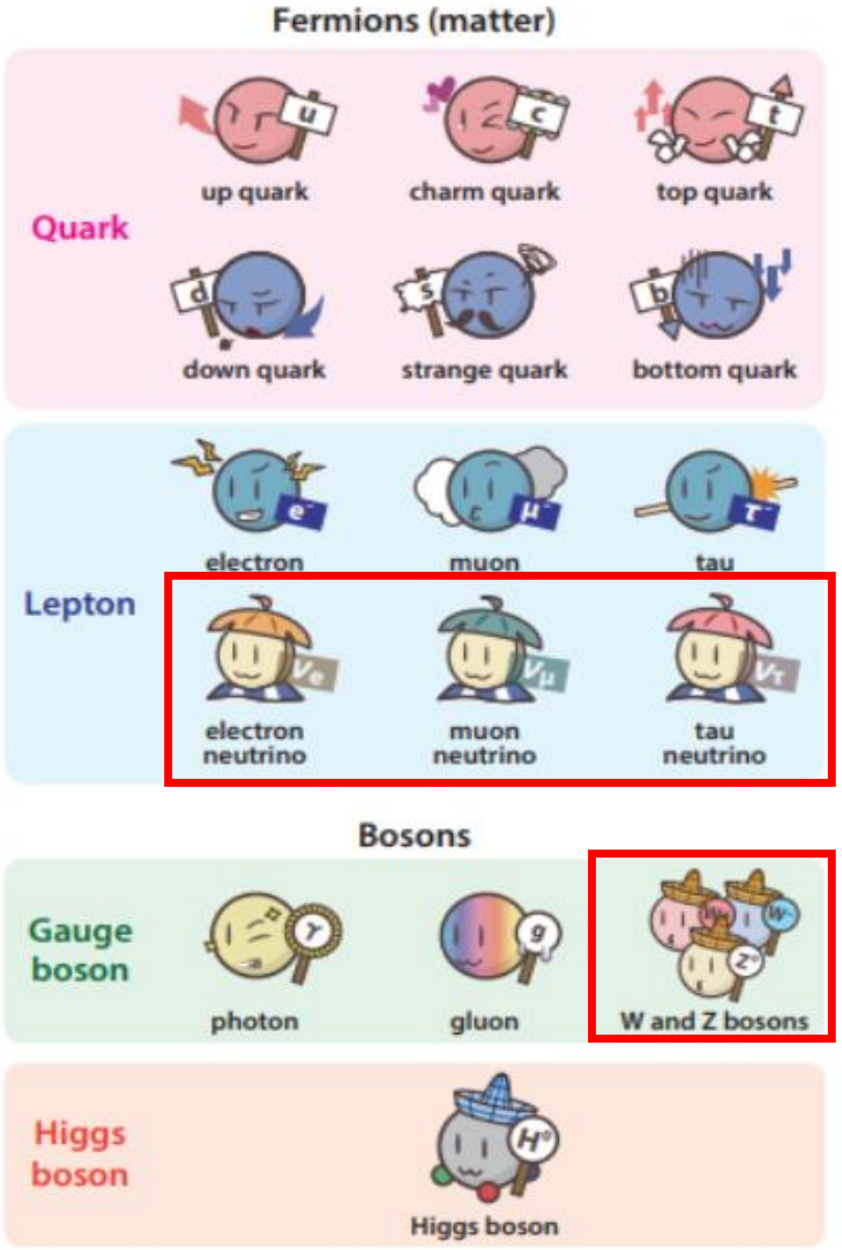
Neutrinos in the Standard Model

Neutrinos are elementary particles.

Facts:

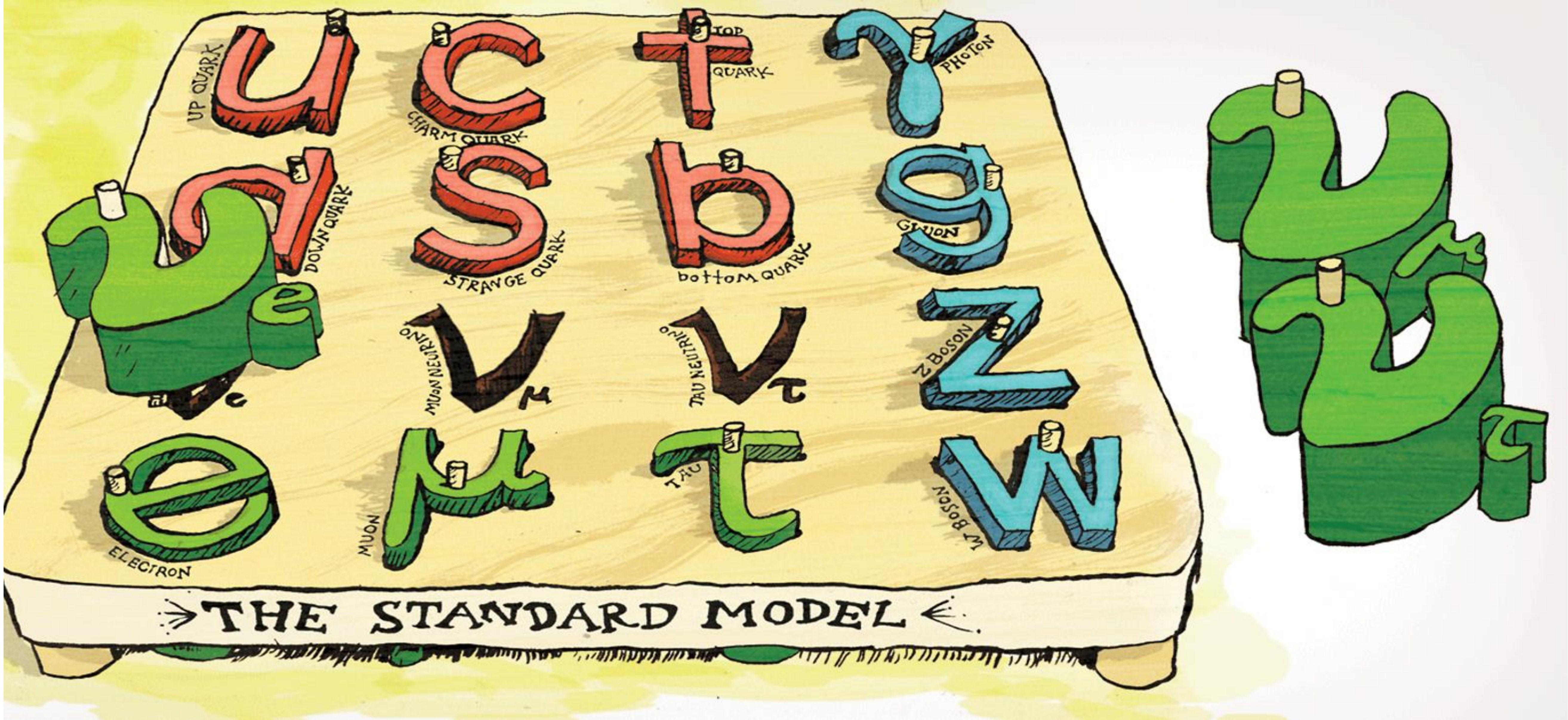
- There are 3 flavors (ν_e, ν_μ, ν_τ) matched to charged leptons (e, μ, τ)
- They have no charge
- They are ~~massless~~ nearly massless
- They are spin ½ leptons
- They only interact weakly trough $W^{\pm}$ and Z^0 bosons

All this makes them basically… INVISIBLE

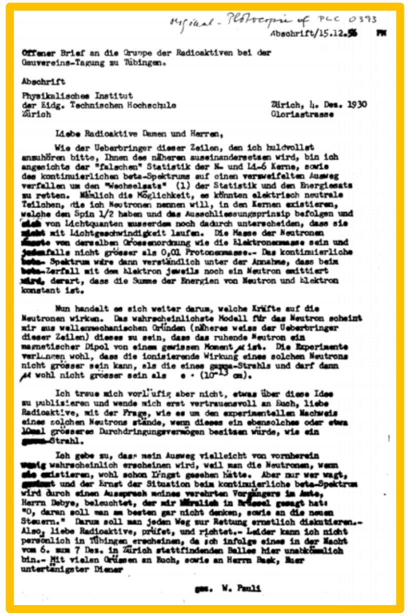


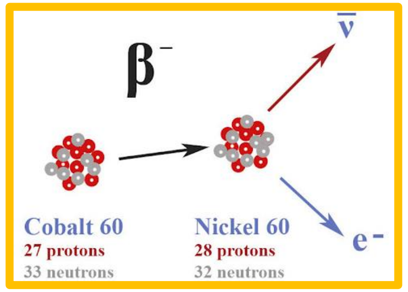
https://www-he.scphys.kyoto-u.ac.jp/nucosmos/en/

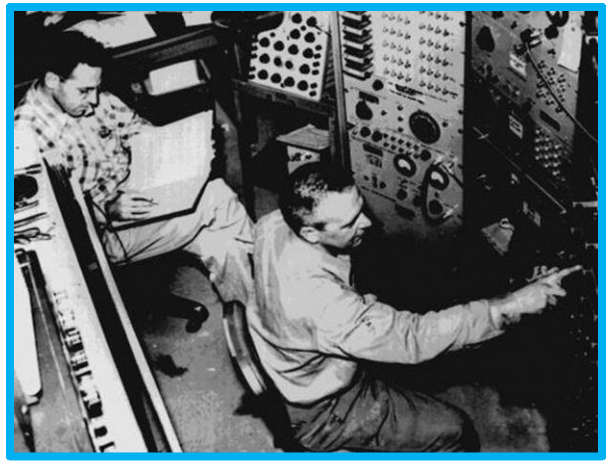
Neutrinos in the Standard Model

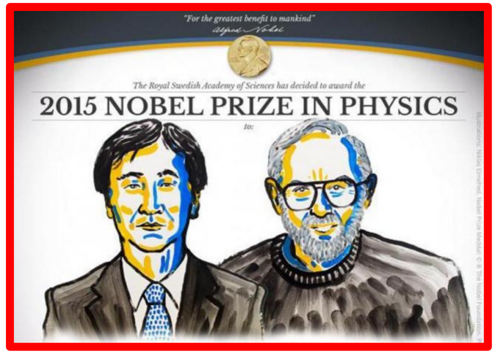


Neutrino physics history









1930

Wolfgang Pauli postulated the “neutron” to compensate for the apparent loss of energy and conserve the momentum of decay $\beta-$

1932

The Pauli neutron was renamed "neutrino" by Fermi when the real neutron was discovered by Chadwick

1956

Clyde Cowman and Federick Reines detected the neutrino experimentally from a reactor source

1962

Leon Max Lederman, Melvin Schwartz, and Jack Steinberger showed that more than one type of neutrino existed when the muon neutrino was first detected

2000

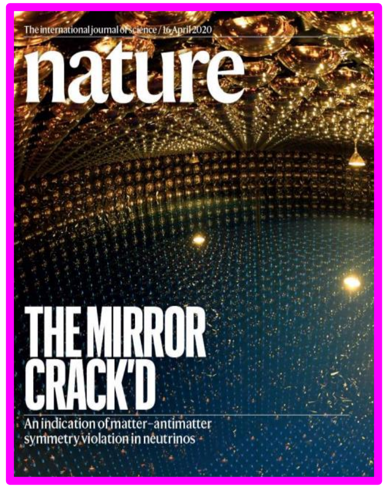
The DONUT collaboration at Fermilab announced the discovery of the tauonic neutrino

2015

Nobel Prize in Physics to Takaaki Kajita and Arthur B. McDonald "for the discovery of neutrino oscillations, which shows that neutrinos have mass.“

2020

Constraint on the Matter-Antimatter Symmetry-Violating Phase in Neutrino Oscillations



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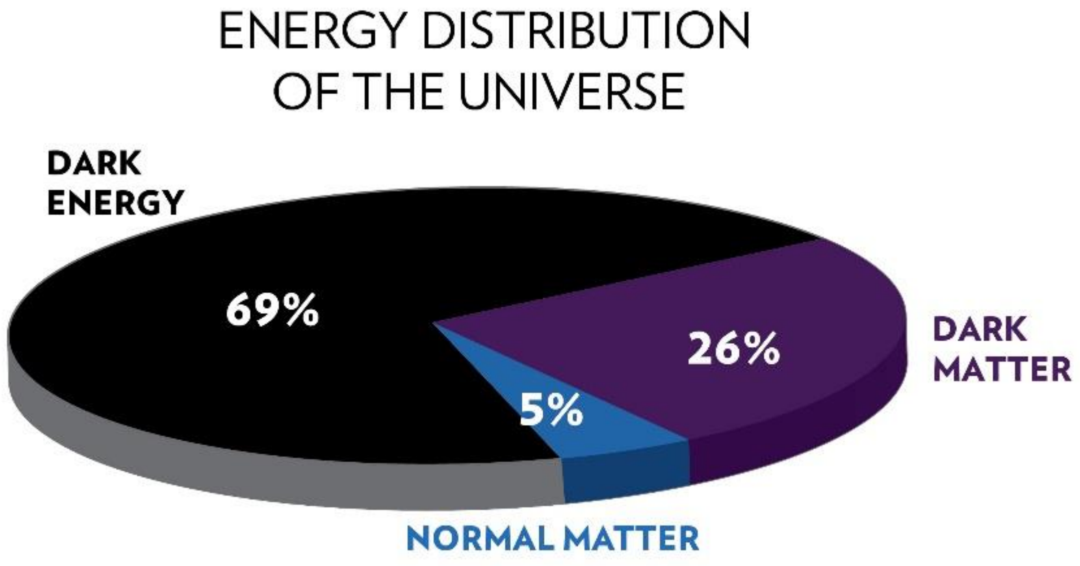
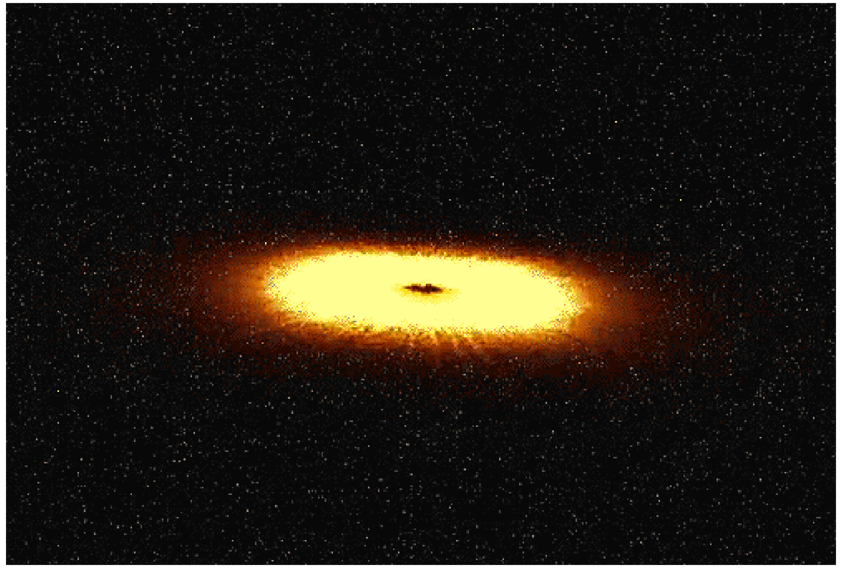
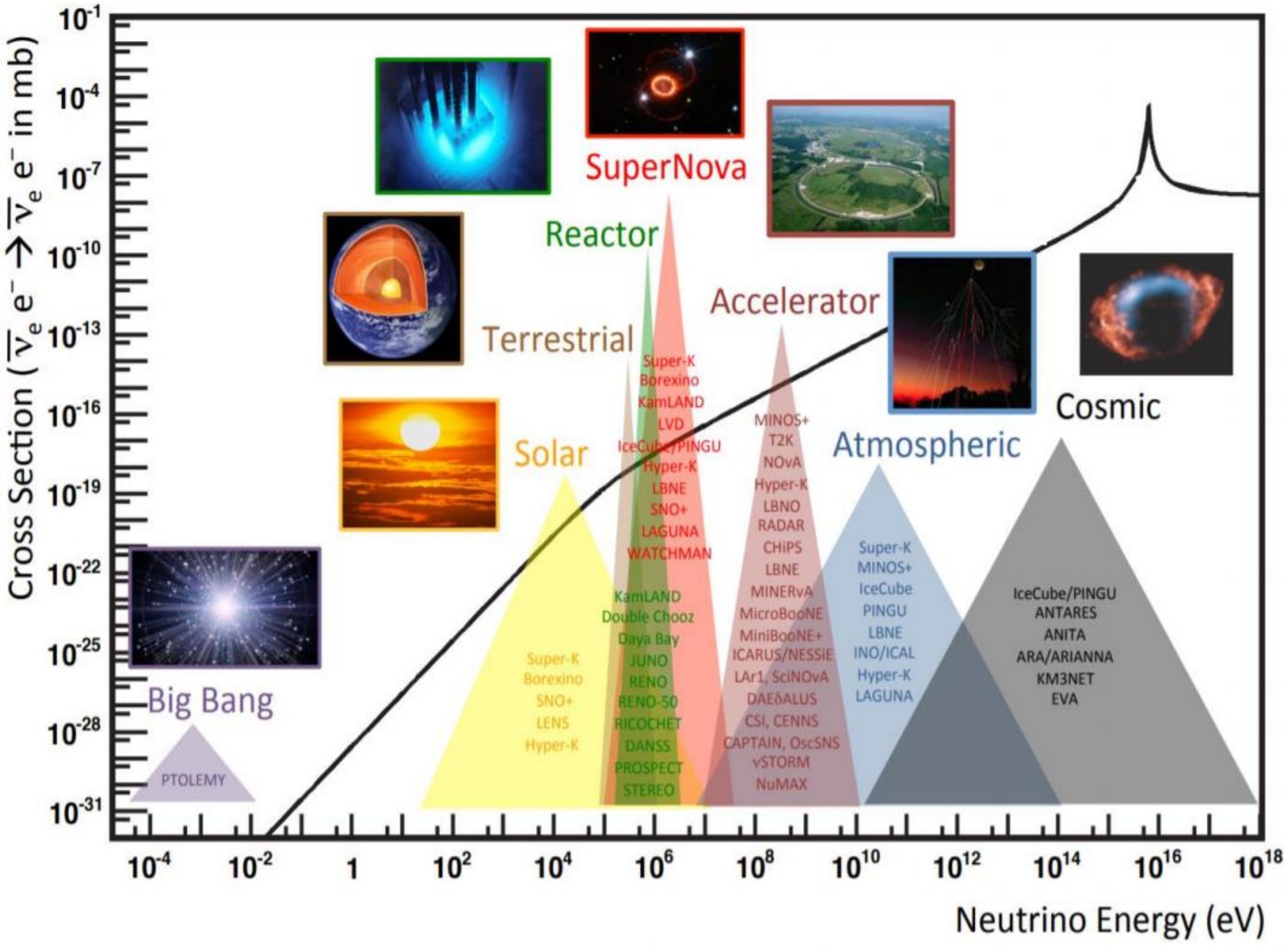
What's so interesting about neutrinos?

- Discover supernovae and other astrophysical events.
- We could explain the matter/antimatter asymmetry.
- They could help explain dark matter.
- Geologically study the interior of the earth.
- Monitor nuclear weapons on earth.
- Method of transmitting information (in the distant future).





Neutrino sources



There are two types of neutrino sources:

- Natural:
  - Sun (solar neutrinos)
  - Big Bang (relic neutrinos)
  - Supernova explosions (supernova neutrinos)
  - Cosmic rays interacting in the atmosphere (atmospheric neutrinos)
- Artificial:
  - Nuclear reactors (reactor neutrinos)
  - Particle accelerators (accelerator neutrinos)

Neutrinos cover a wide spectrum of energy and detecting them involves using different techniques and detectors.

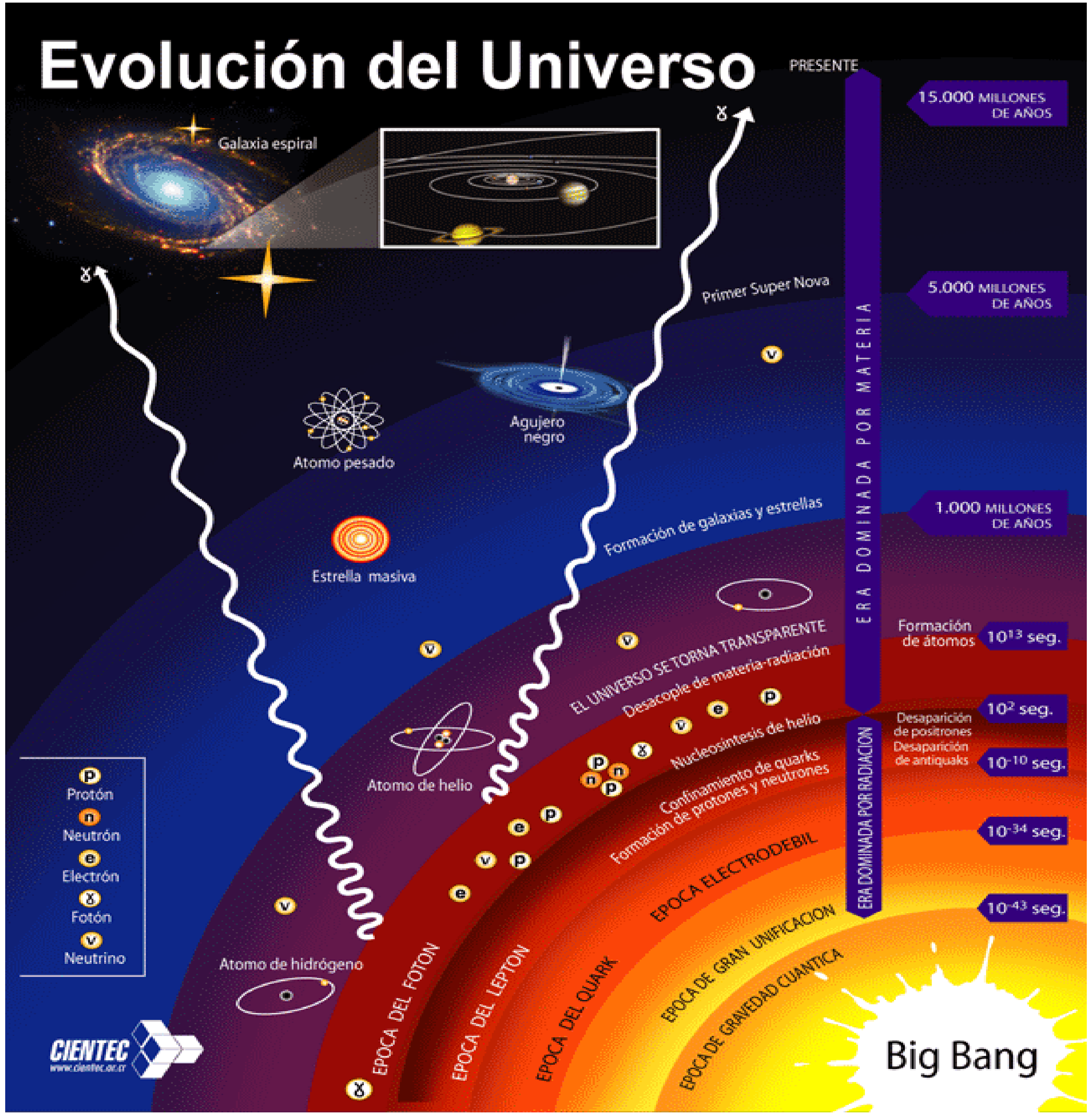
Relic neutrinos

- Relic neutrinos from the cosmic neutrino background (CNB) originating in the early Universe let us know:
  - The conditions of the early Universe (neutrino decoupling ~1 s after the Big Bang)

Could answer basic questions like:

- What is the absolute scale of the neutrino mass?
- Are neutrinos their own antiparticle?…

But they haven't been detected yet!!!



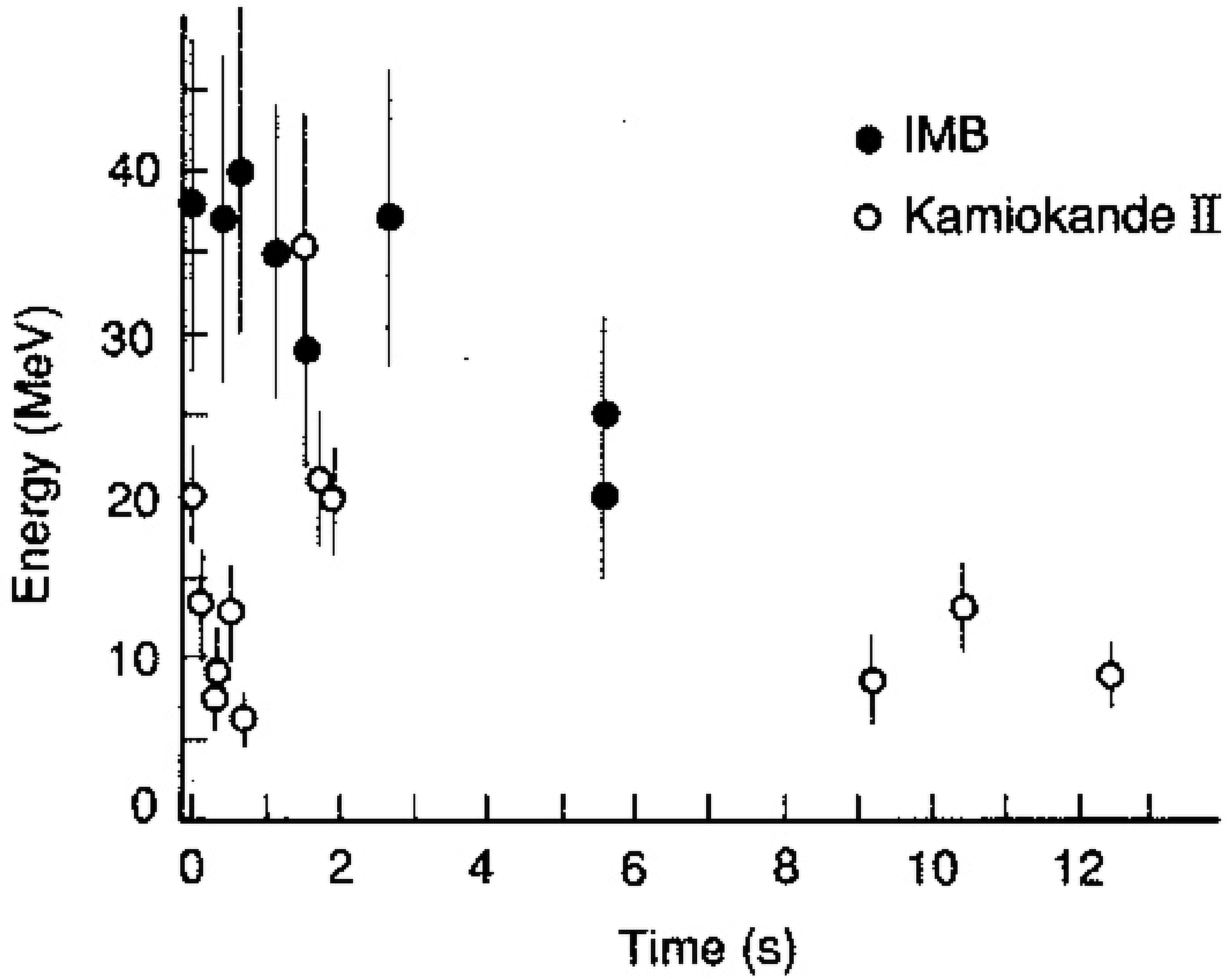
Supernova neutrinos (SN)

Supernovae bursts are a huge source of neutrinos of all flavors within ~12 sec.

- Measurement of SN neutrinos will provide information about:
  - Supernova physics: Core collapse mechanism, SN evolution in time, black hole formation, etc.
  - Neutrino physics: neutrino oscillation, neutrino absolute mass, etc.

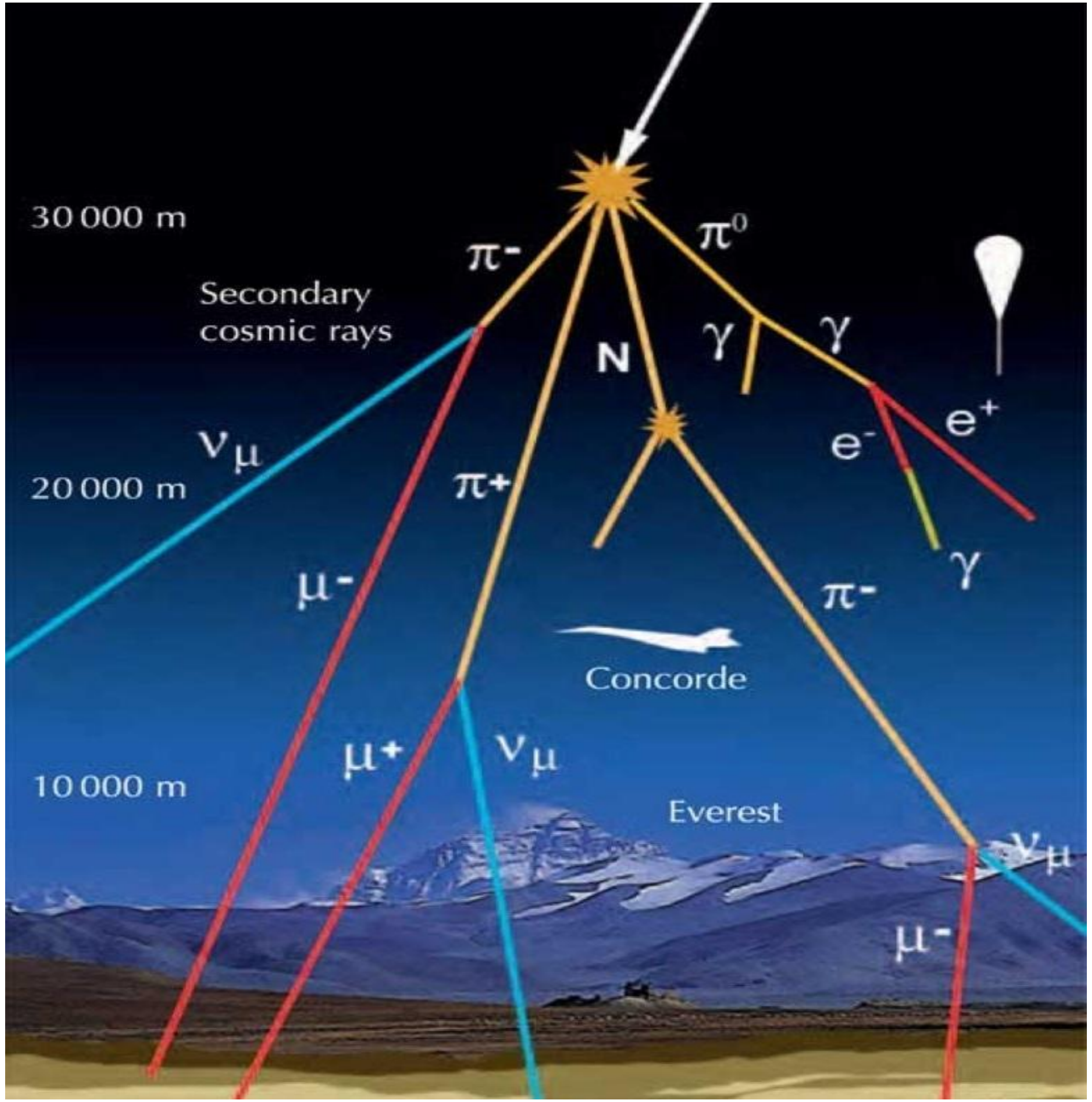
~20 supernova neutrino events were measured in Kamiokande and IMB from SN1987A.

- Beginning of using neutrinos for multi-messenger astronomy.



Atmospherics neutrinos

$$p + {}^{A}X \rightarrow \pi^{\pm} + {}^{A}X'$$
$$\hookrightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu})$$
$$\hookrightarrow e^{\pm} + \nu_{e}(\bar{\nu}_{e}) + \bar{\nu}_{\mu}(\nu_{\mu})$$
$$\hookrightarrow K^{\pm} + {}^{A}X'$$
$$\hookrightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu})$$
$$\hookrightarrow e^{\pm} + \nu_{e}(\bar{\nu}_{e}) + \bar{\nu}_{\mu}(\nu_{\mu})$$



- Experiments to observe atmospheric neutrinos are built underground:
  - To diminish the effects of cosmic rays and other sources of stellar noise.

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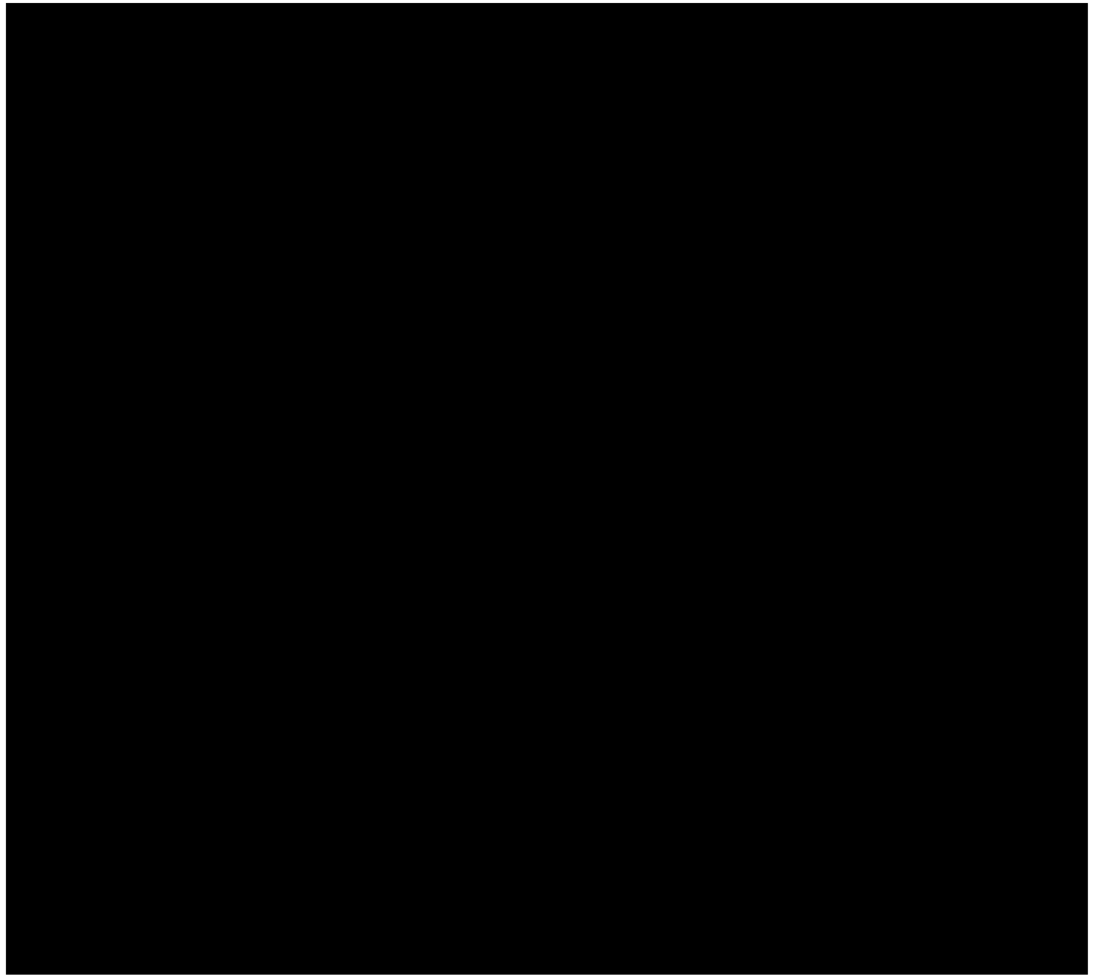
Solar neutrinos



- Most of the neutrinos that reach Earth are solar neutrinos.
- The sun produces electron neutrinos ($\sim 2 \times 10^{38}$ neutrinos/sec).

Why are neutrinos important in the sun?

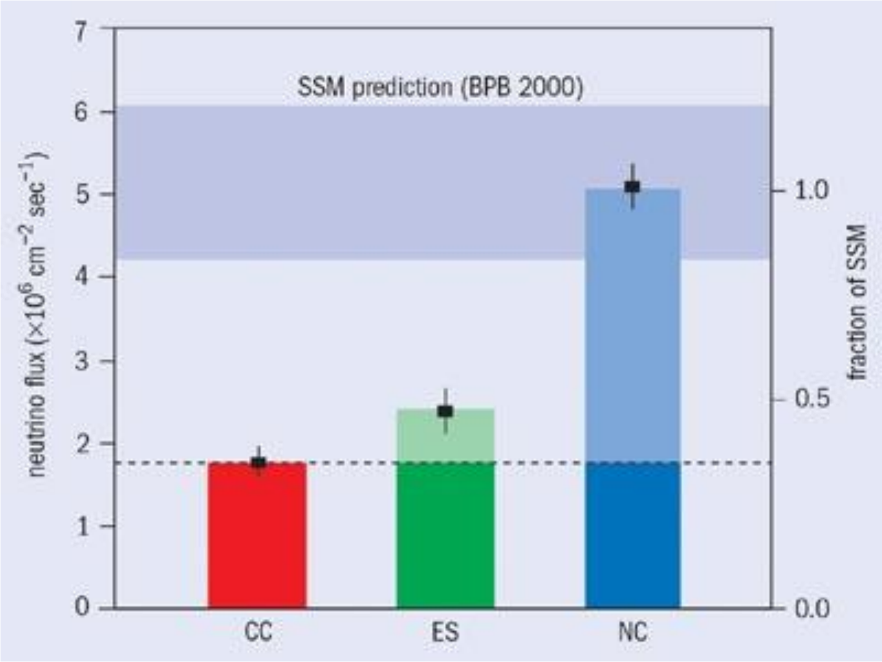
- The generation of energy in the sun begins with the reaction:

$$p^+ + p^+ \rightarrow \ ^2H + e^+ + \nu_e$$

- Without the neutrino, angular momentum would not be conserved.

Solar neutrinos

- John Bahcall predicted that the ratio ($R = \frac{N_{experimental}}{N_{theoretical}}$) should be equal to 1.
- Number of experimentally measured solar neutrinos is less than what is theoretically expected!



Charged Current (CC):

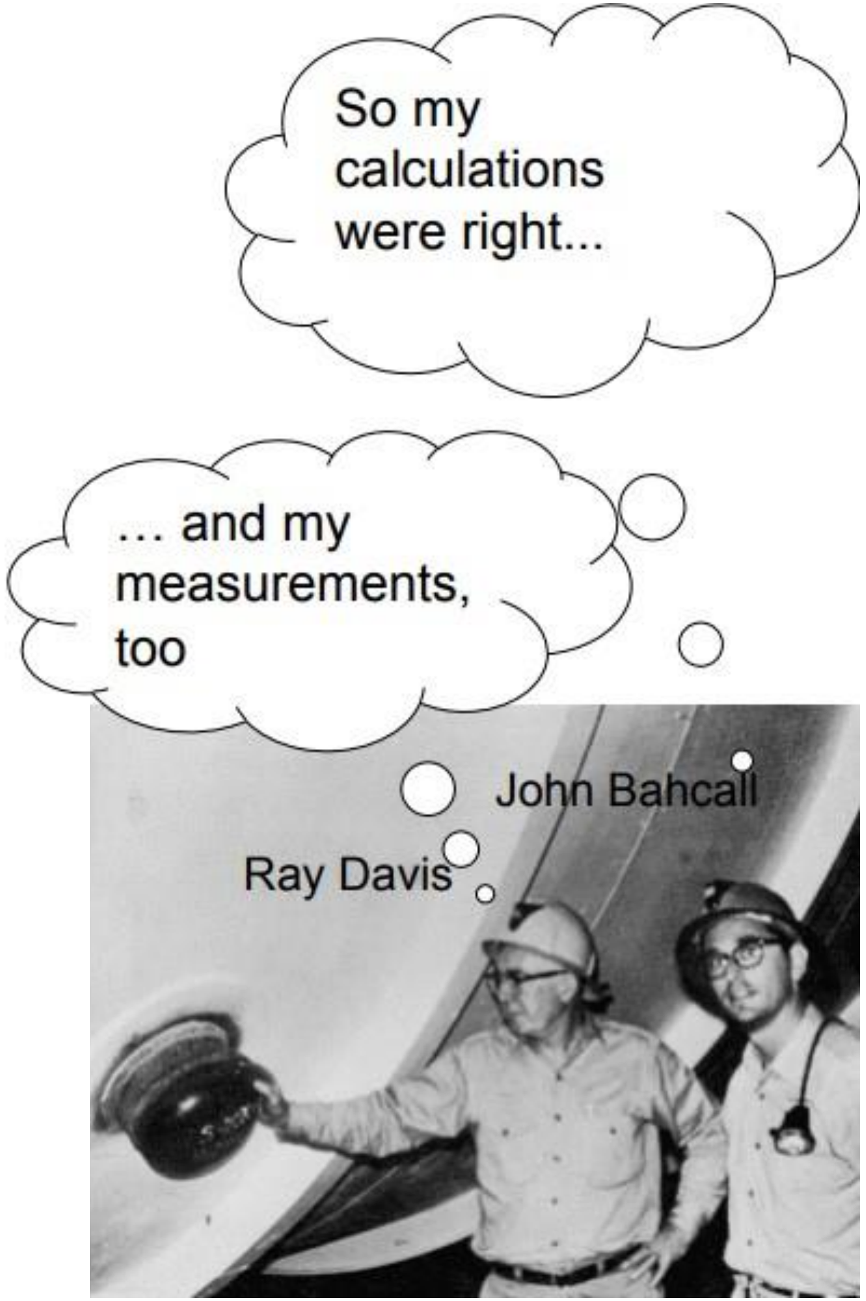
$$D + \nu_e \rightarrow p + p + e^-$$

Elastic Scattering (ES):

$$D + \nu_{e,\mu,\tau} \rightarrow p + p + e^-$$

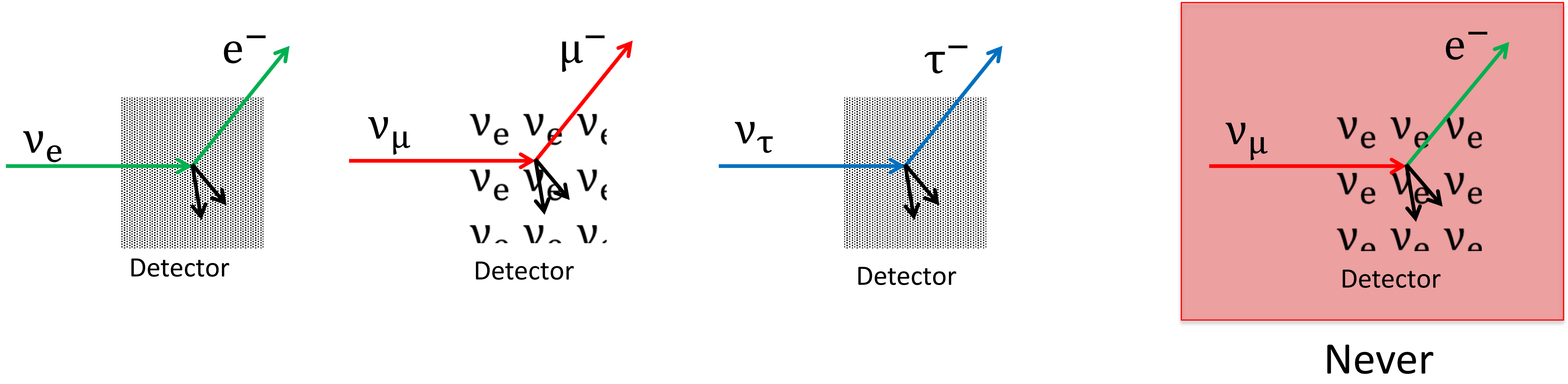
Neutral Current (NC):

$$e^- + \nu_{e,\mu,\tau} \rightarrow e^- + \nu_x$$

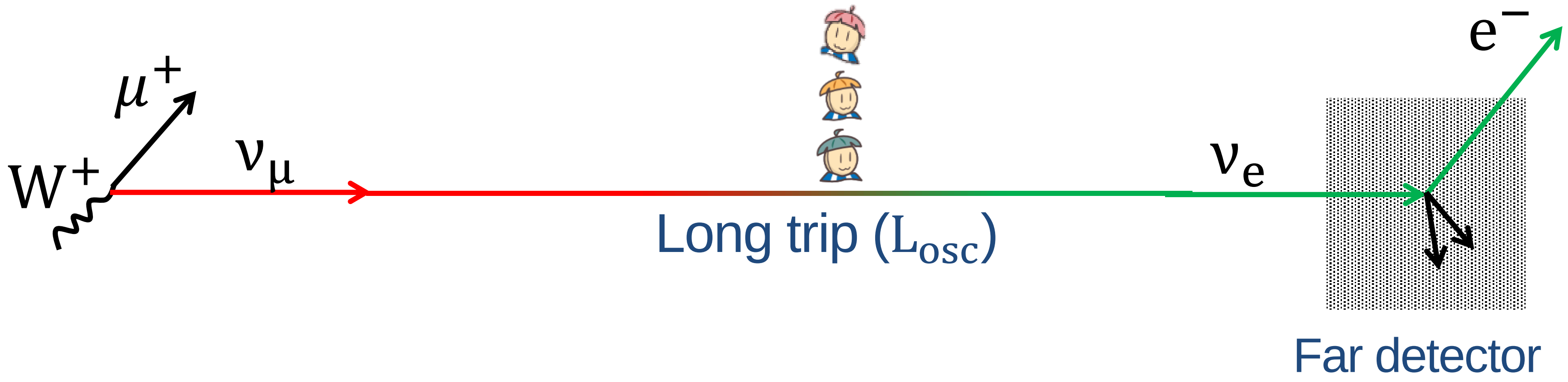


Neutrino oscillation

- Neutrinos interact with matter and produce a lepton of the same flavor as the neutrino.

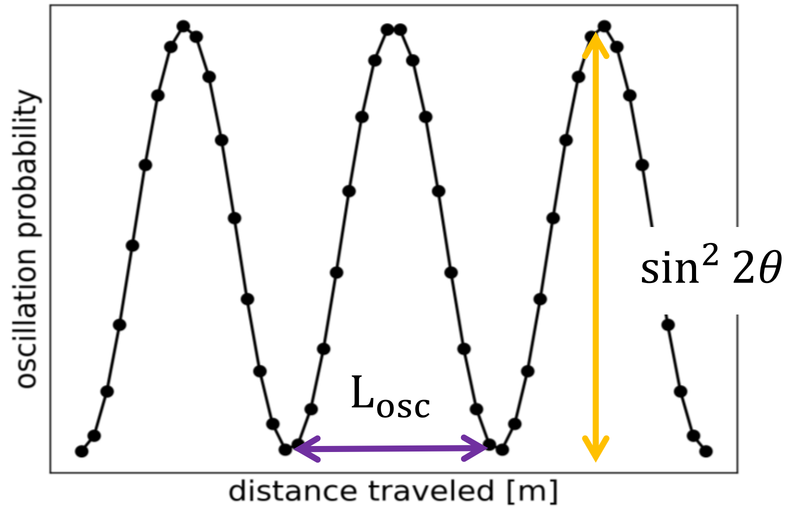


Neutrino two flavor oscillation



All oscillation experiments live in the 0.1-10 GeV transition region.

The oscillation is described by this equation:



We extract:
Rotation angle

$$P_{osc}(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L_{osc}}{4E_\nu}\right)$$

We know:
length of the neutrino's long journey

We calculate:
Probability of the oscillation

We calculate:
Neutrino flux energy

Note: Which means that at least one of them has to have mass for the oscillation to occur.

Neutrino three flavor oscillation

PNMS (Pontecorvo–Maki–Nakagawa–Sakata) rotation matrix.

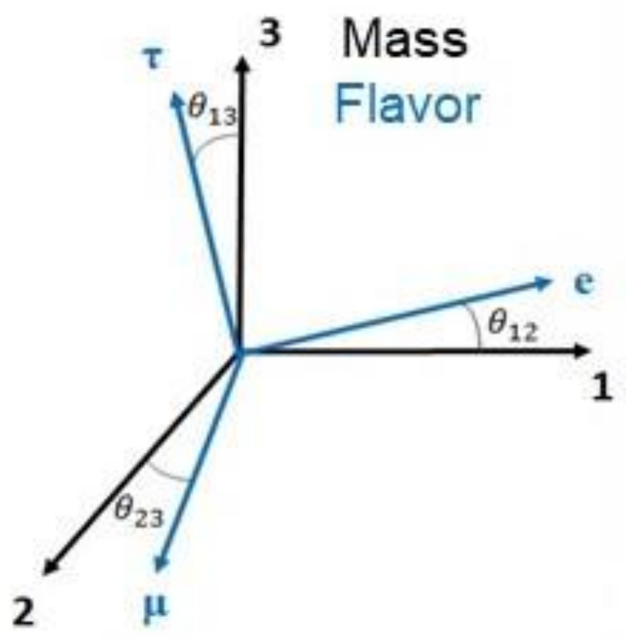
$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix} = \begin{bmatrix} \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \end{bmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}$$

Atmospheric Reactor Solar

Where $c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$ and $\Delta m^2_{ij} = m_i^2 - m_j^2$

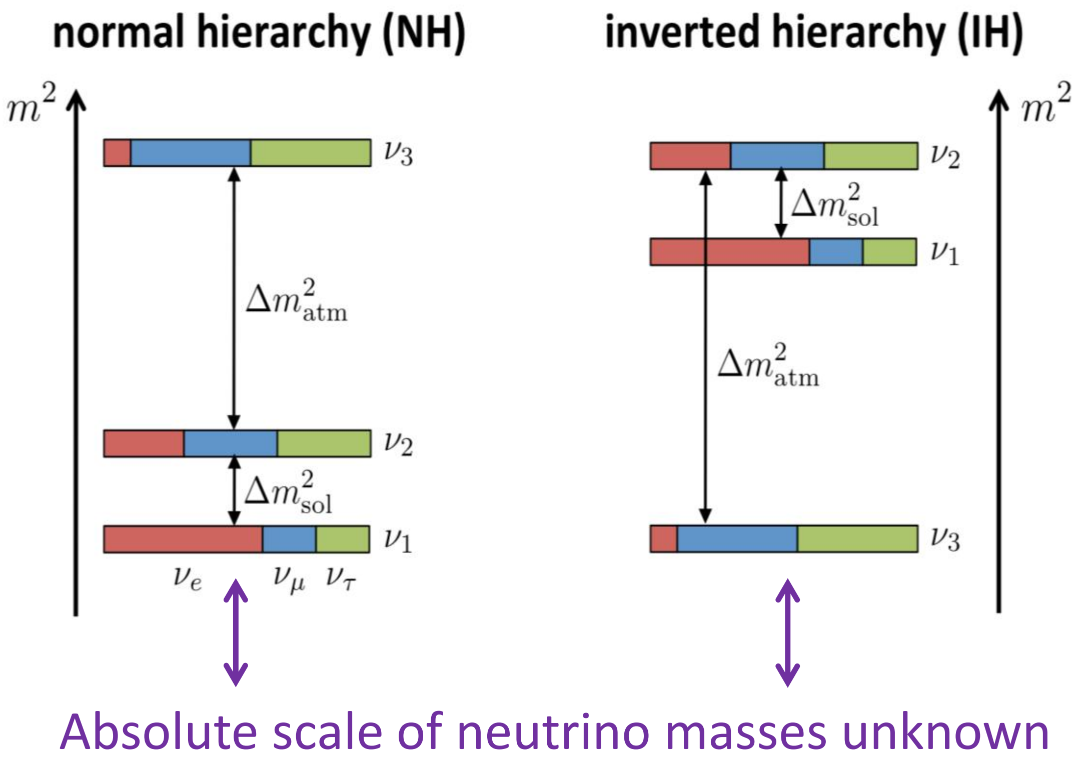
The oscillation depends of:

- 3 mixing angles: $\theta_{12}, \theta_{13}, \theta_{23}$
- 1 CP violating phase: δ_{CP} Value still unknown
- 2 mass differences: $\Delta m^2_{21}, \Delta m^2_{32}$ Sign still unknown



Mass hierarchy

A neutrino with a specific mass has no specific flavor
… a neutrino with a specific flavor has no specific mass



Hierarchy determines the ordering of the masses:

- Normal: $m_1 < m_2 < m_3$
- Inverted: $m_3 < m_1 < m_2$

The differences have been measured

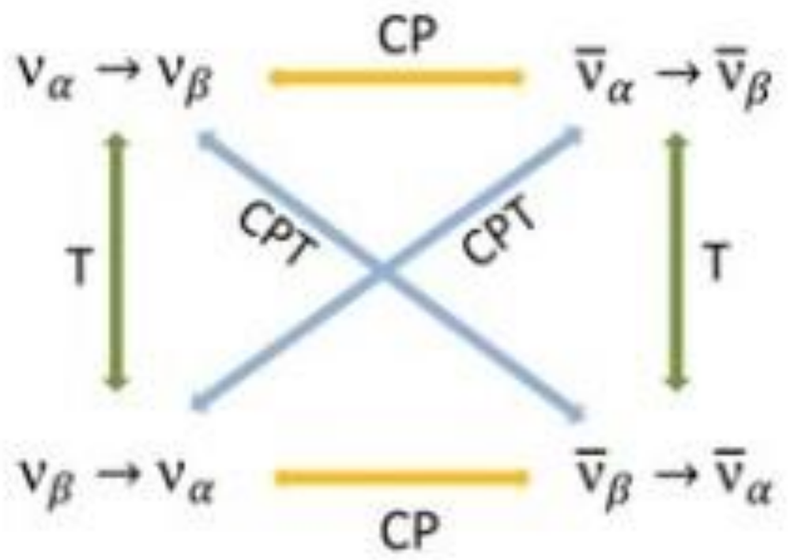
- atmospheric neutrino
  $\Delta m^2_{atm} \cong (2.453 \pm 0.033) \times 10^{-3}\ eV^2$
- solar neutrino
  $\Delta m^2_{sol} \cong (7.53 \pm 0.18) \times 10^{-5}\ eV^2$

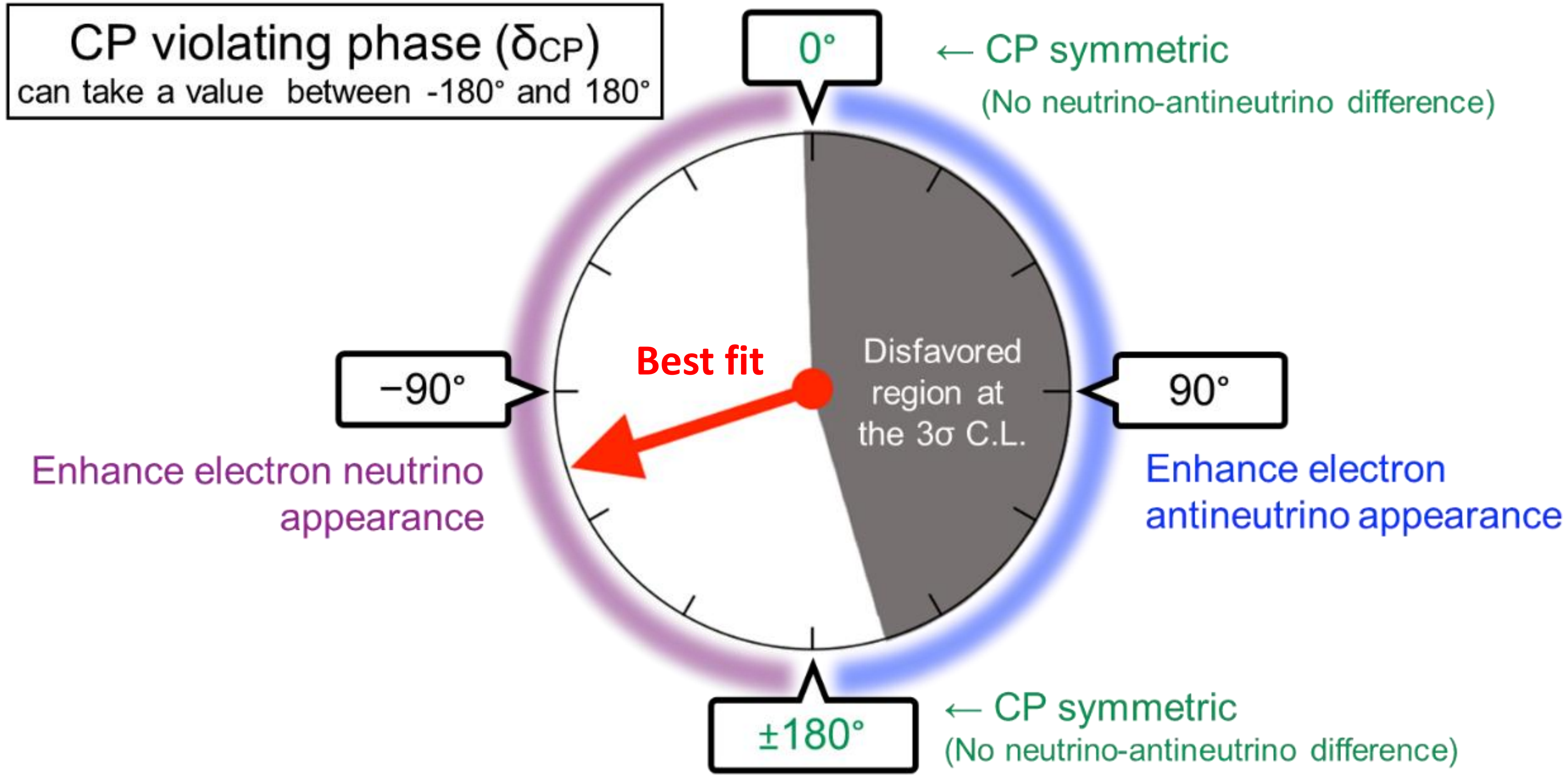
https://pdg.lbl.gov/2022/tables/contents_tables.html

CP violation

We assume the world is CPT invariant

- C: Particle → Antiparticle
- P: Parity → Reversed Parity
- T: Time → Reversed time





https://www.nature.com/articles/s41586-020-2177-0

T2K result excludes most of the δ_{CP} >0 values a 99.7% Confidence Level

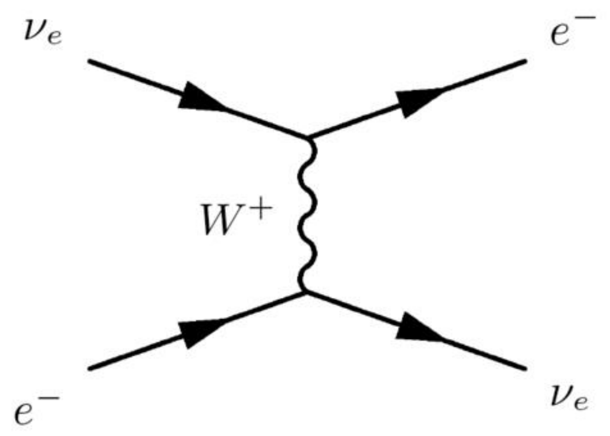
Why is it so hard to detect them?

- With $E_\nu = 11\ \mathrm{MeV}$ the mean free path in lead is 350 billion kilometer
- In earth ~3 out of 1 billion neutrinos would interact

Neutrino interactions

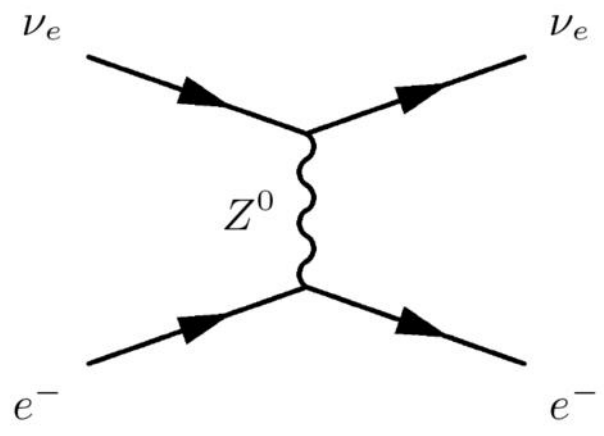
Charged current:

- The incident neutrino/antineutrino interacts through a $W^{\pm}$ boson,
- Changing its identity
- Does not change its flavor.



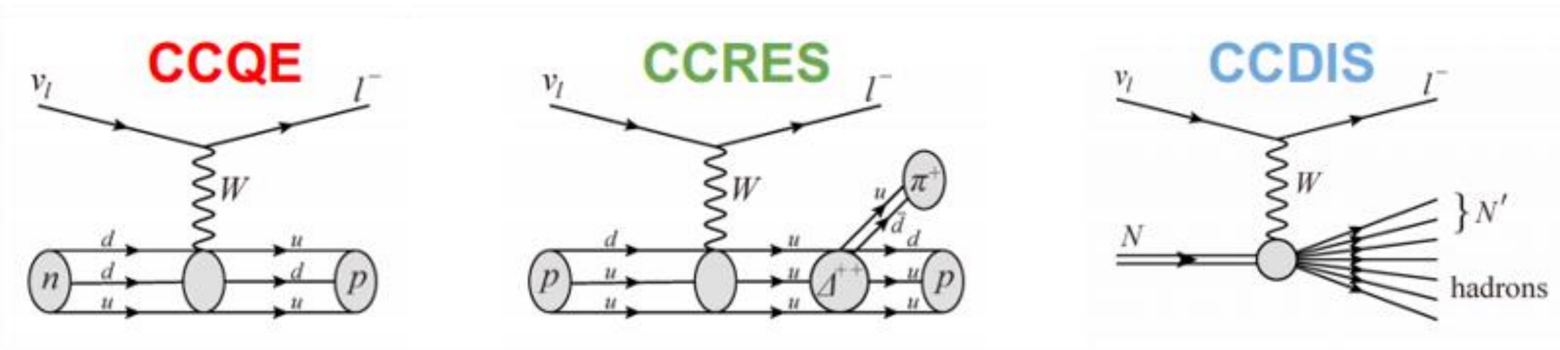
Neutral current:

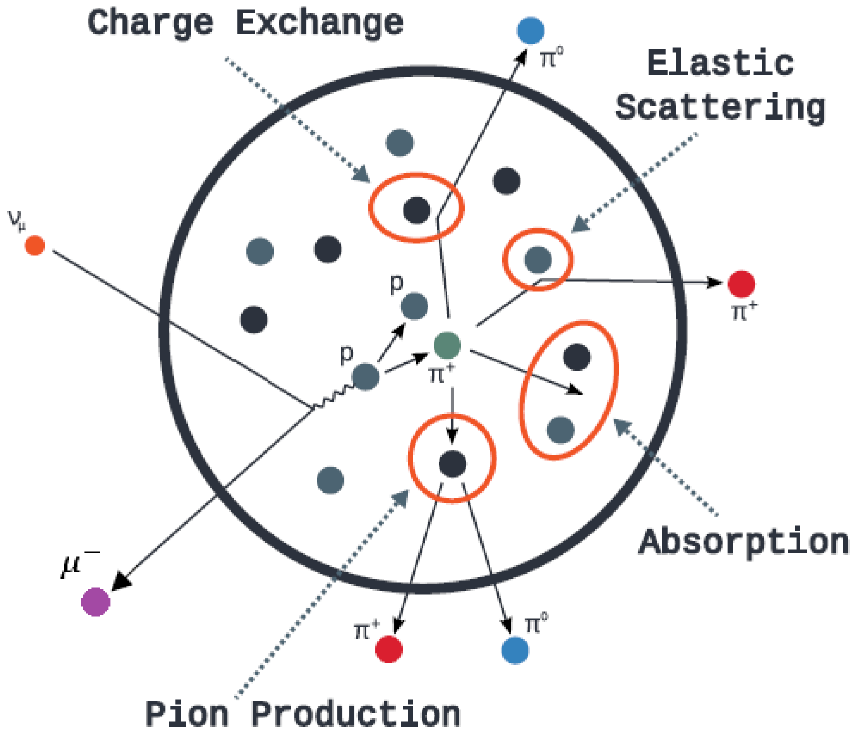
- The incident neutrino or antineutrino interacts through a Z^0 boson,
- Maintaining its identity
- Does not change its flavor.



Neutrino interactions

Interaction modes (nucleon level)



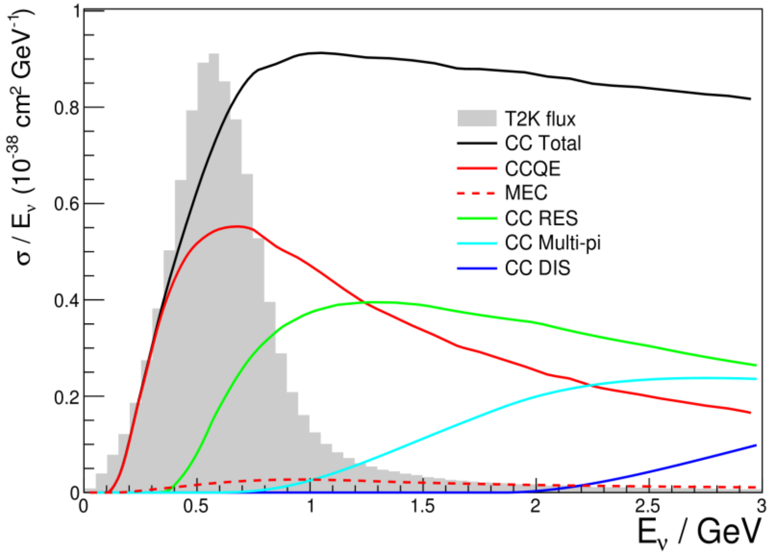


Three dominant scattering processes:

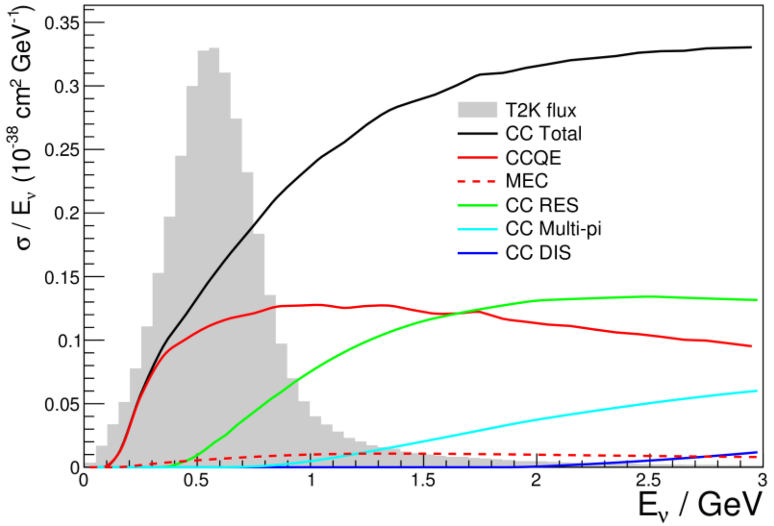
- Quasi Elastic,
- Resonant Pion Production,
- Deep Inelastic Scattering

As a consequence of this, the kinematics and/or interaction topology can be altered.

Neutrino

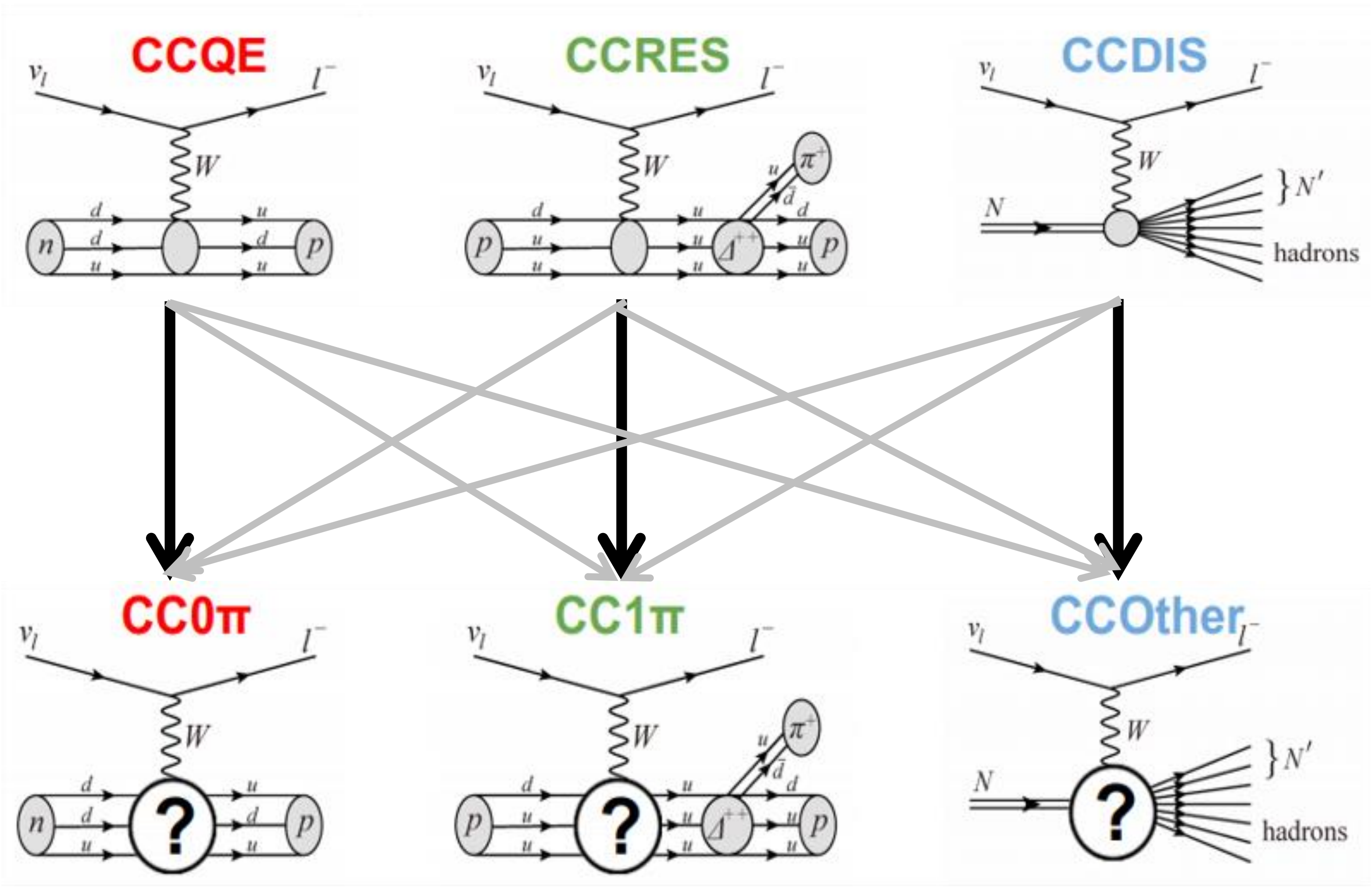


Antineutrino



Neutrino interactions

Interaction modes (nucleon level)



Interaction topologies (nucleus level)

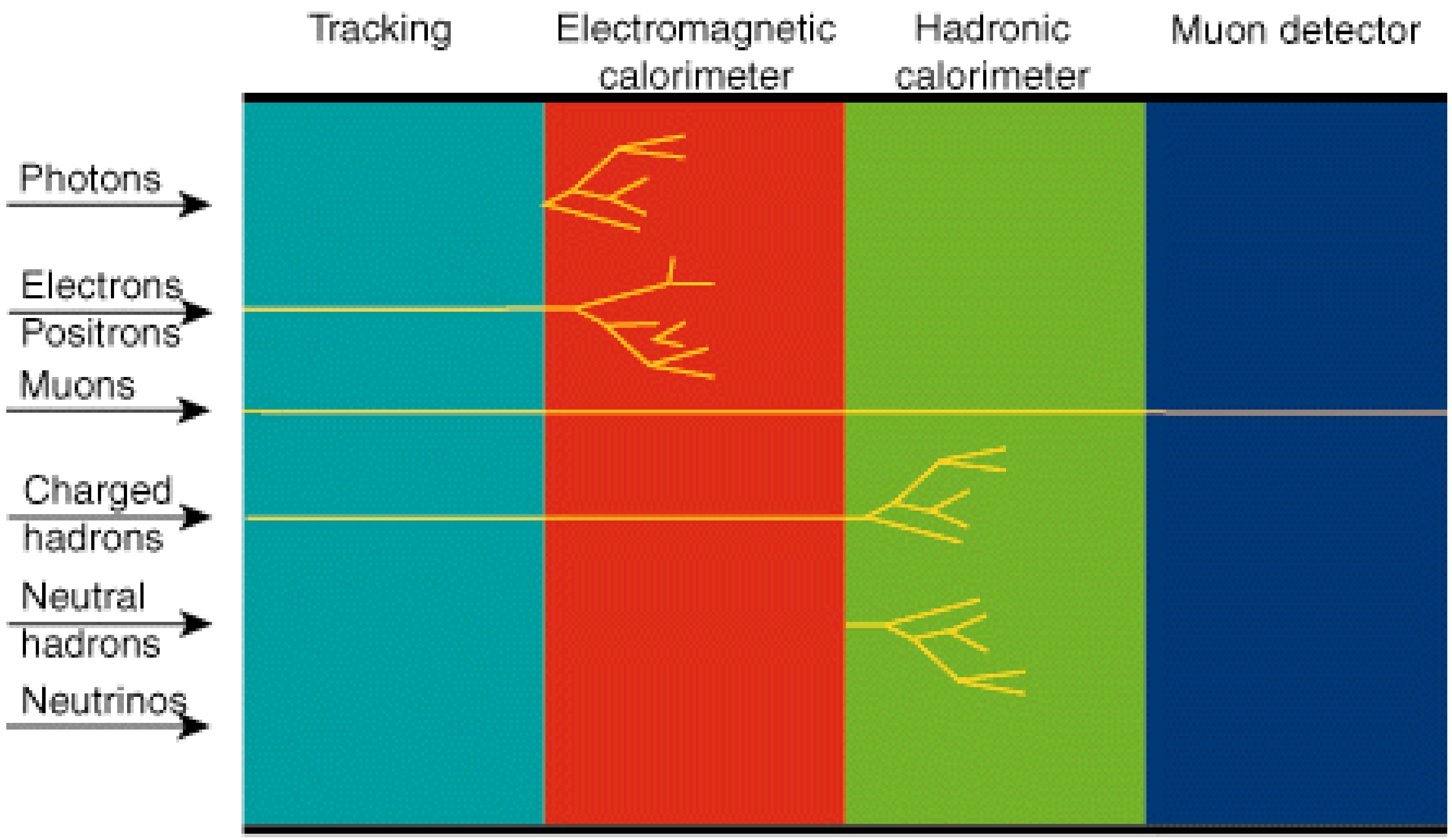
Nuclear Effects and Final State Interactions

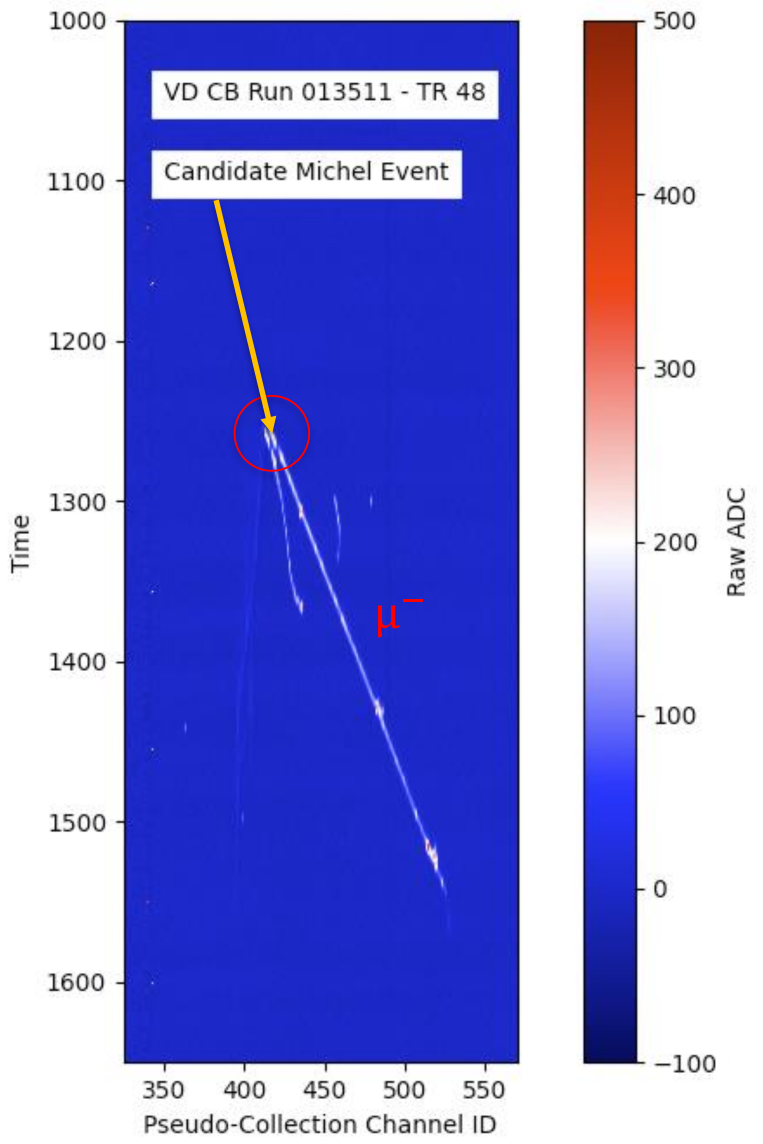
CCQE: $\nu_\mu + \mathrm{n} \rightarrow \mu^- + \mathrm{p}$

CCRES: $\nu_\mu + \mathrm{p} \rightarrow \mu^- + \pi^+ + \mathrm{p}$

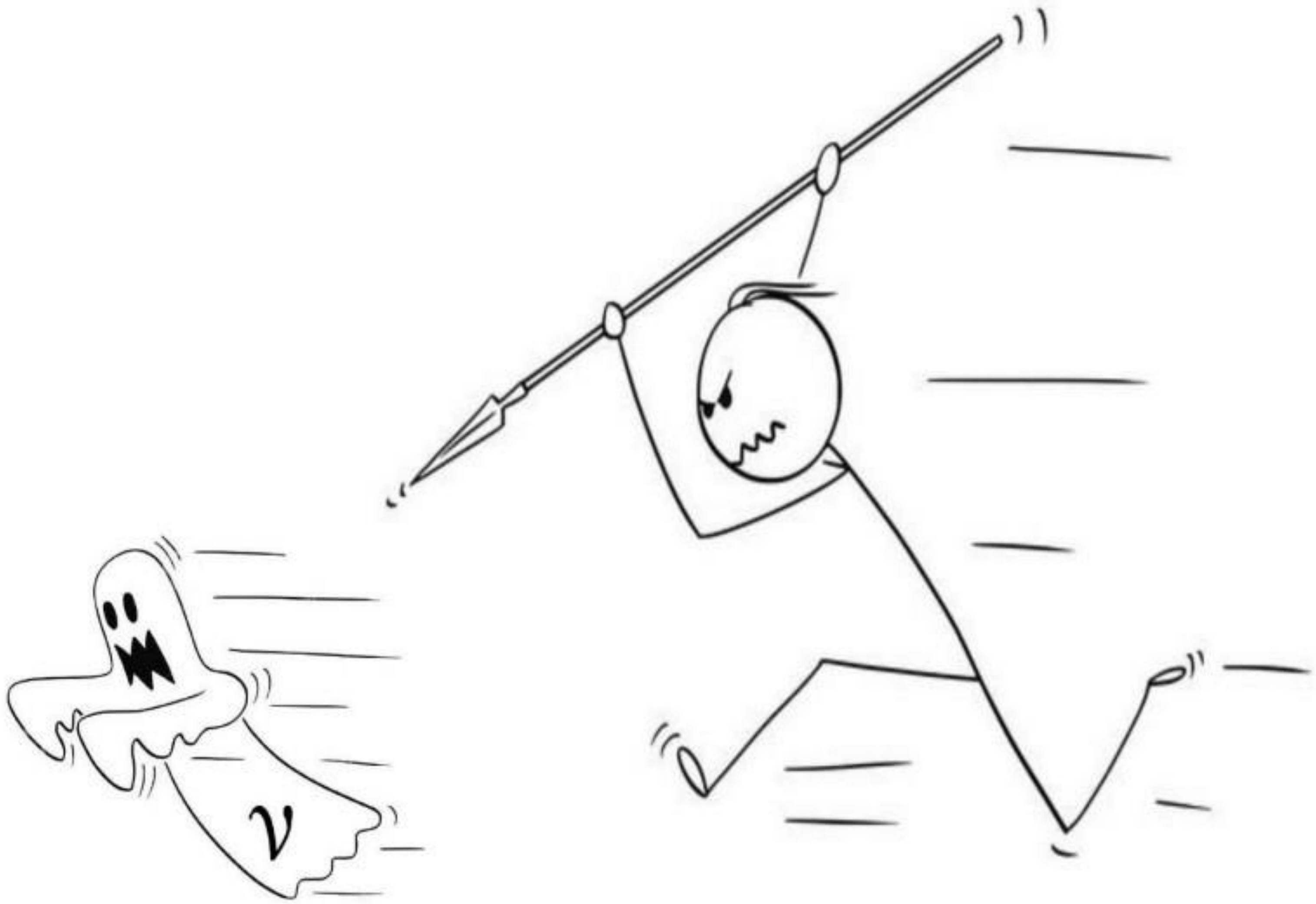
$\nu_\mu + \mathrm{n} \rightarrow \mu^- + \pi^+ + \mathrm{n}$

What do we see in the detector?

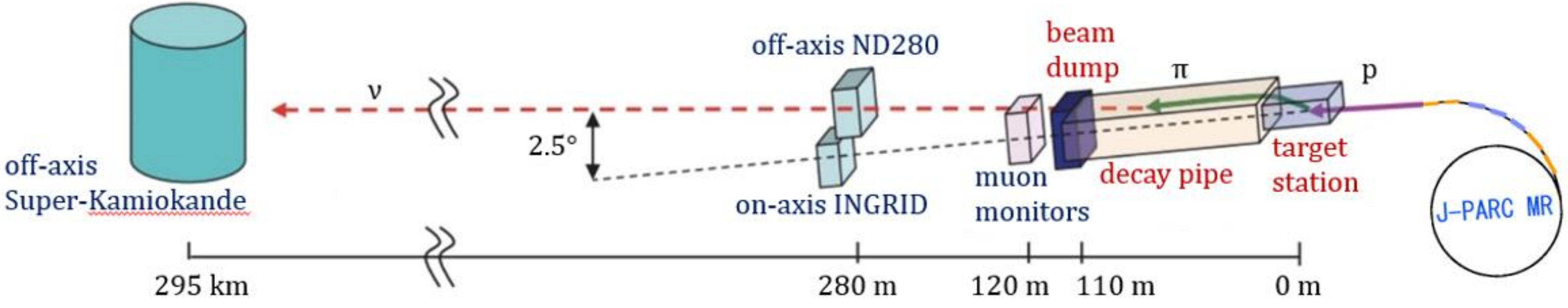




How do we ~~hunt~~ the neutrinos?
detect

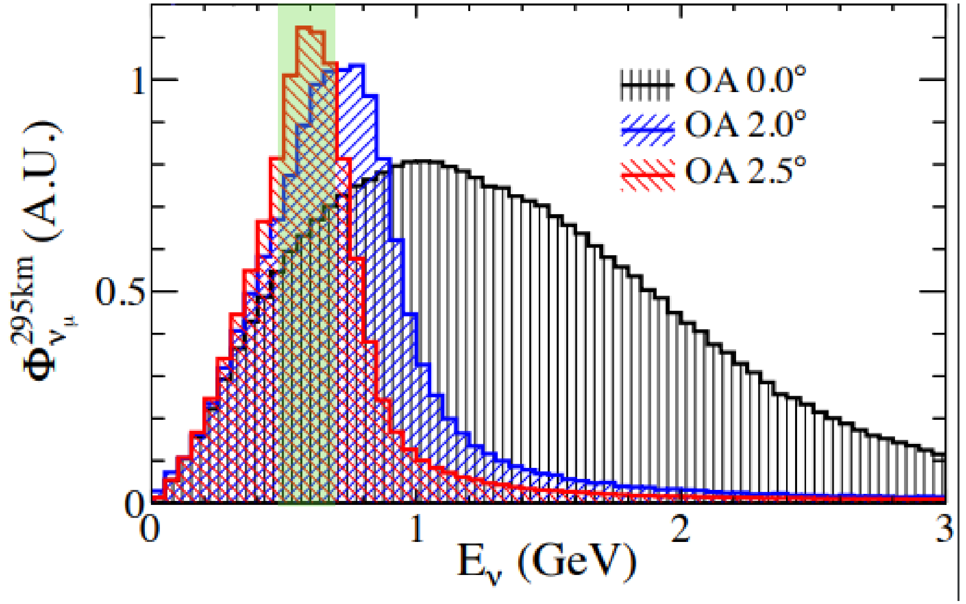


How do we produce the neutrino beam?



- 30 GeV protons collide with a graphite target and produce pions and kaons
- Magnetic horns will focus the pions:
  - Forward horn current (FHC): $\pi^+ \rightarrow \mu^+ + \nu_\mu$
  - Reverse horn current (RHC): $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$
- All particles except neutrinos stopped in beam dump

- Use off-axis beam for narrower energy spectrum.
- Off-axis angle flux peaked at 0.6 GeV, which is at an oscillation maximum.
- Only one oscillation maximum can be measured at a fixed distance.



What do we measure?

Number of neutrino-matter interactions

Detector efficiency

Near detector

Oscillation probability

$$N_x(E_\nu) = \phi(E_\nu)\,\sigma(E_\nu)\,\epsilon(E_\nu)\,P(\nu_\mu \rightarrow \nu_x)$$

Far detector

Neutrino flux

depends on the source

very energetic sources

Cross-section

It is very small and depends on the energy

go to higher energies

The neutrino energy is reconstructed:

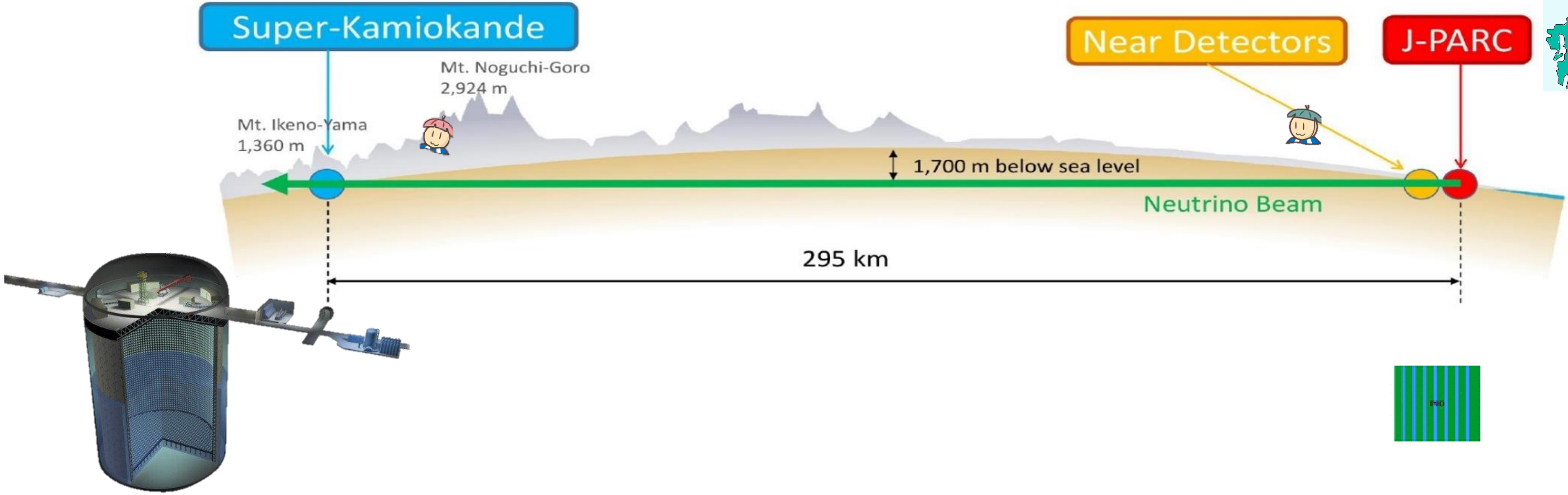
- using leptonic and hadronic kinematics,
- assuming stationary target (a nucleon)
- massless neutrino.

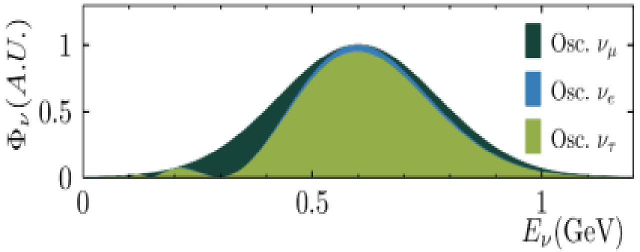
This introduces some biases:

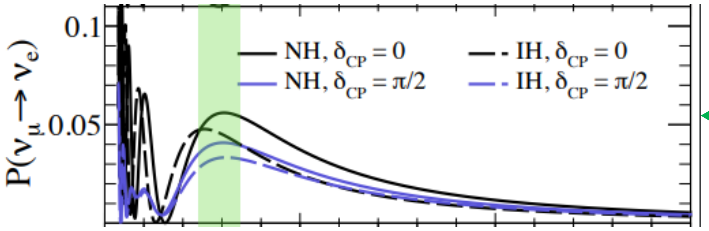
- Due to initial state interactions (Fermi motion),
- The detector misses neutral particles,

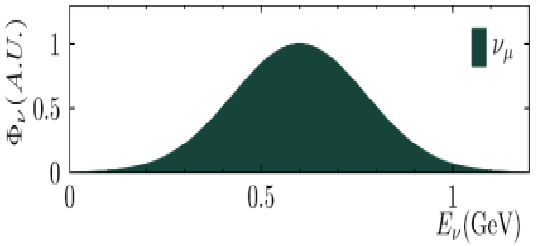
T2K experiment

- Measure neutrino oscillations: $\bar{\nu}_\mu/\nu_\mu$ disappearance and $\bar{\nu}_e/\nu_e$ appearance.
- Measure the oscillation parameters $\theta_{13}, \theta_{23}, \delta_{CP}$ and Δm^2_{32}



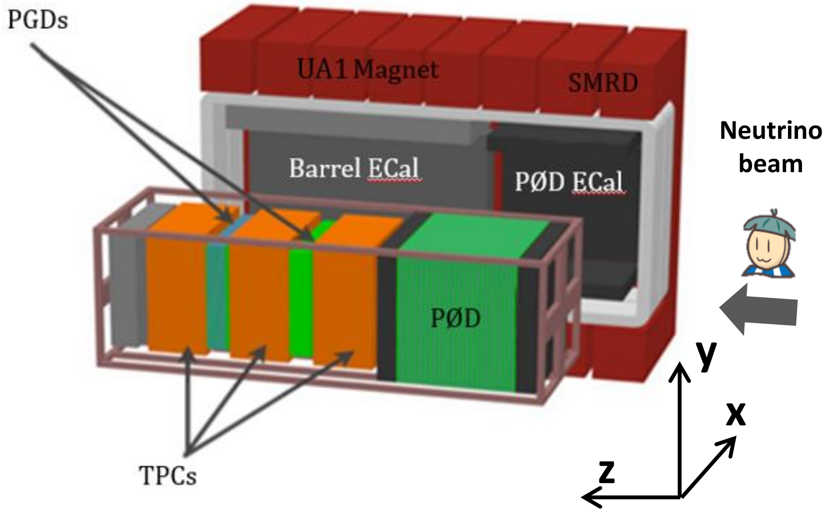






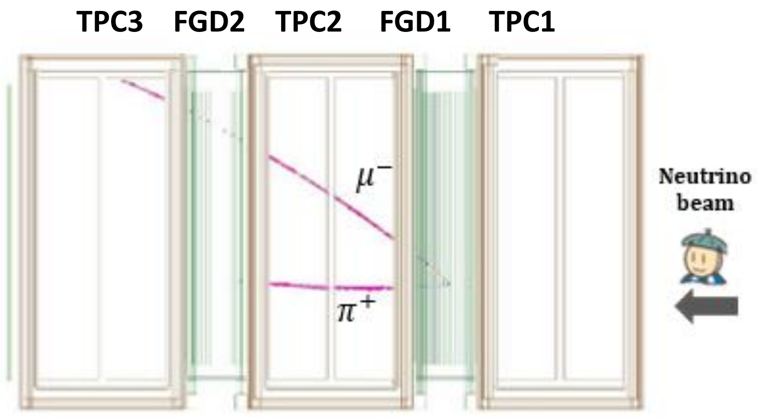
T2K experiment: near detector

- ND280 is used to:
- constrain the flux and cross section parameters.
- measure background processes to oscillation.



ND280 is formed by:

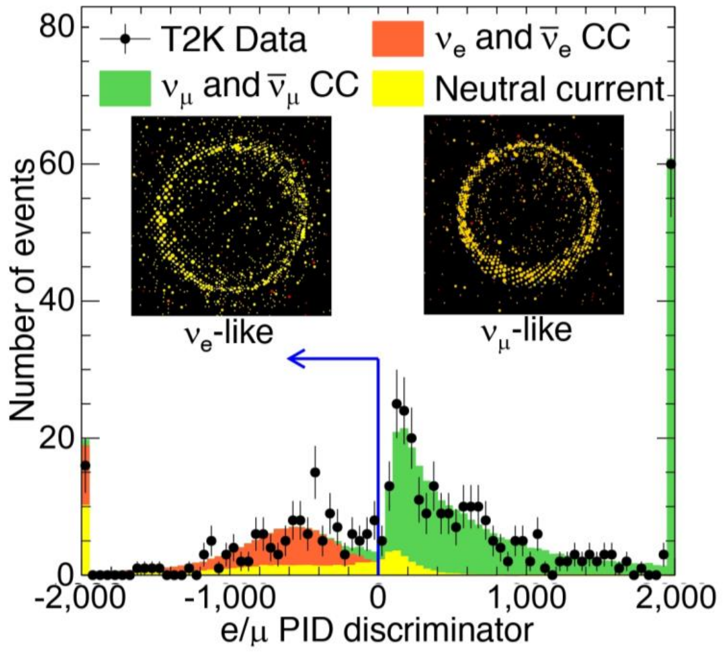
- Pion zero detector (PØD): neutral pion detector, optimized for NC interactions.
- Time Projection Chambers (TPCs): energy, angle and identification
- Fine grained detectors (FGDs): active target
  - FGD1: Hydrocarbon
  - FGD2: Hydrocarbon + Water
- Electromagnetic Calorimeters (ECals): separate tracks from showers and used as veto.
- Side Muon Range Detector (SMRD): energy of muons based on the range and as veto.
- Magnet: charge of the particles and momentum.



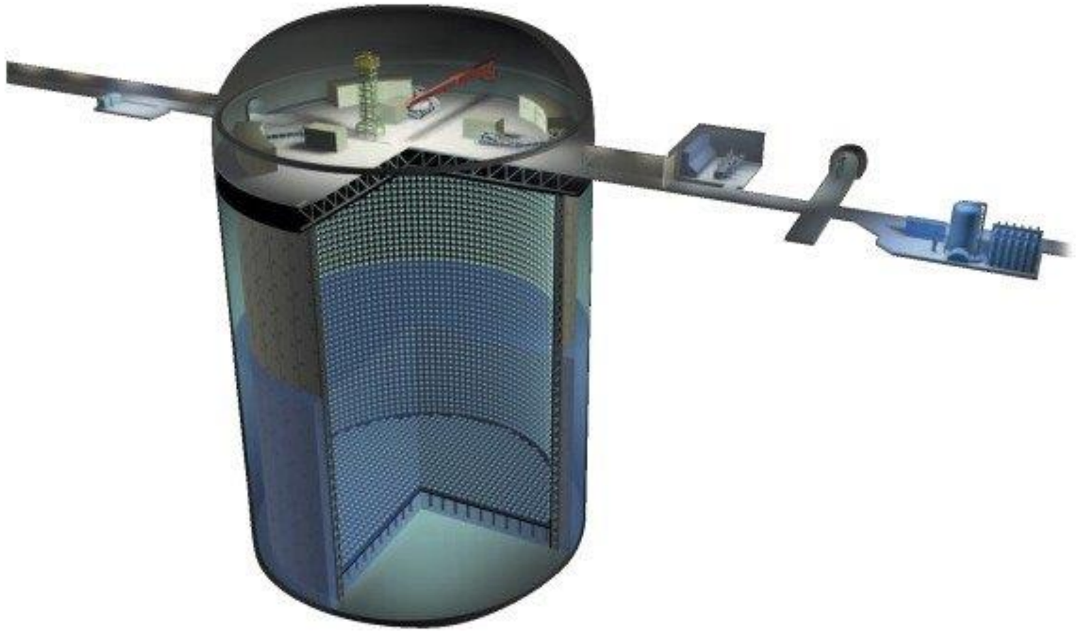
T2K experiment: far detector

Off-axis (2.5 degrees) Super-Kamiokande

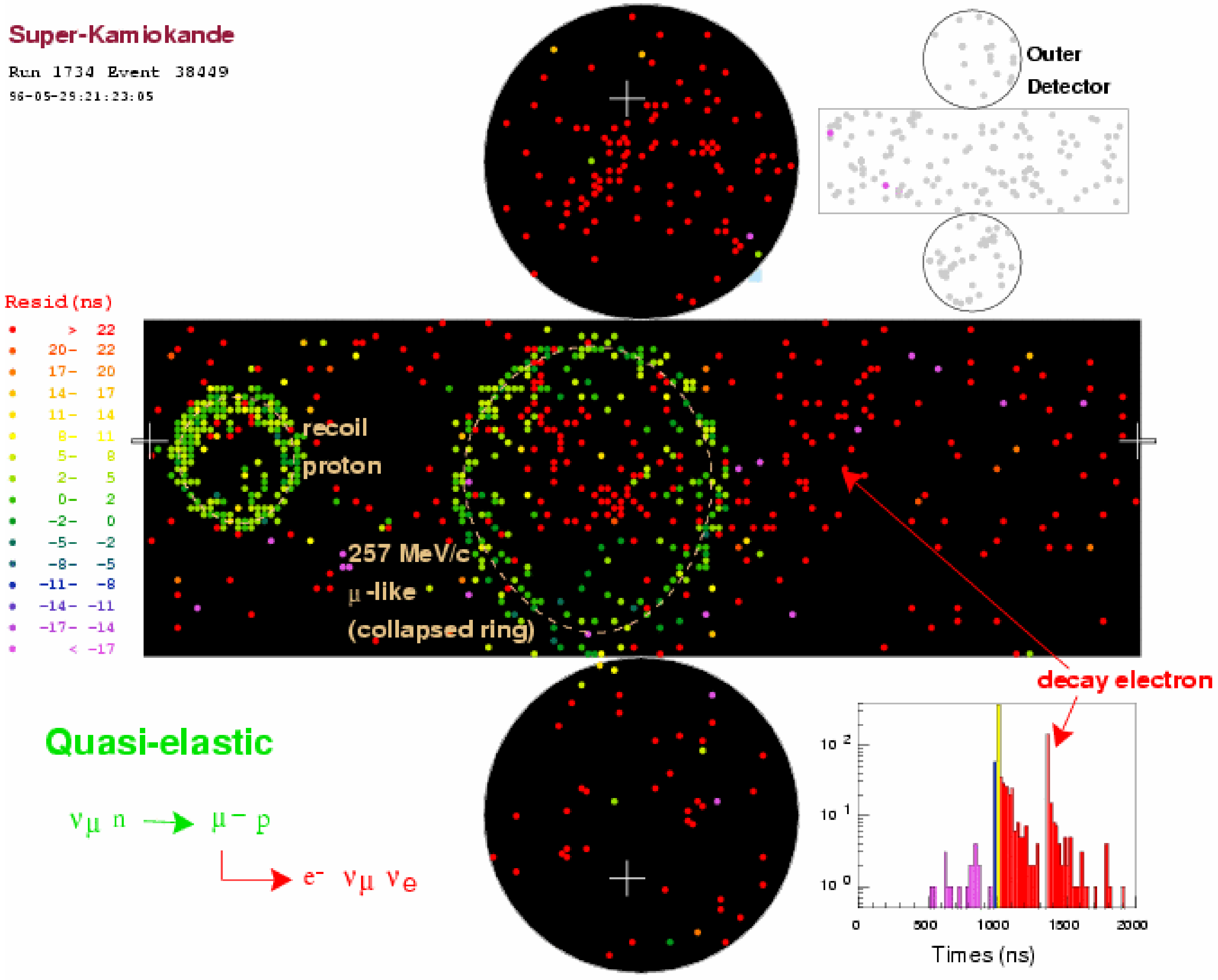
Water Cherenkov detector
- 50 kton of ultra-pure water
- 22.5 kt fiducial volume
- 40 m diameter and ~50 m deep
- ~11000 20 inch PMTs
- 1 km underground
- Operational since May 31,1996

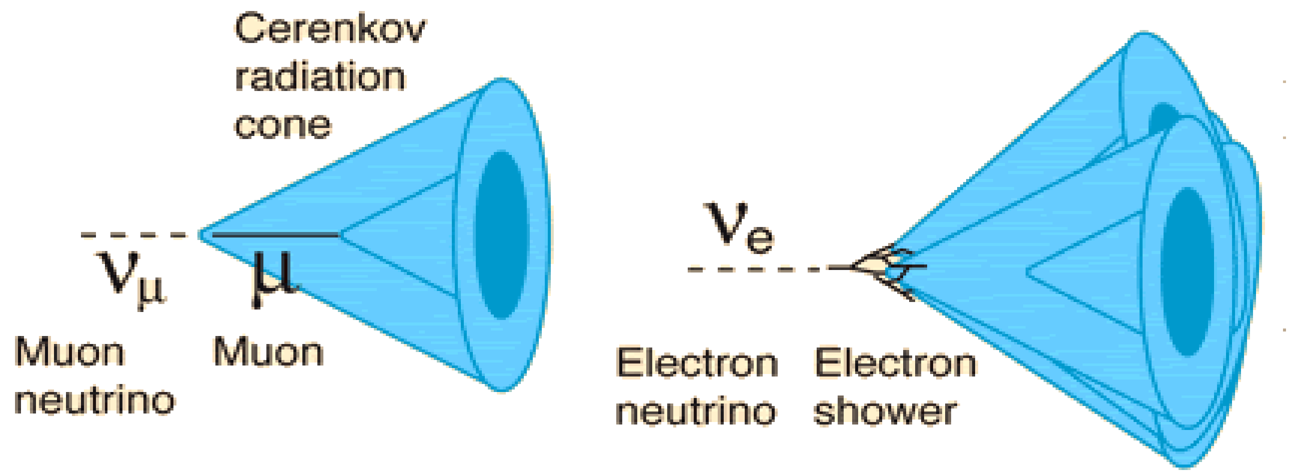


https://www.nature.com/articles/s41586-020-2177-0



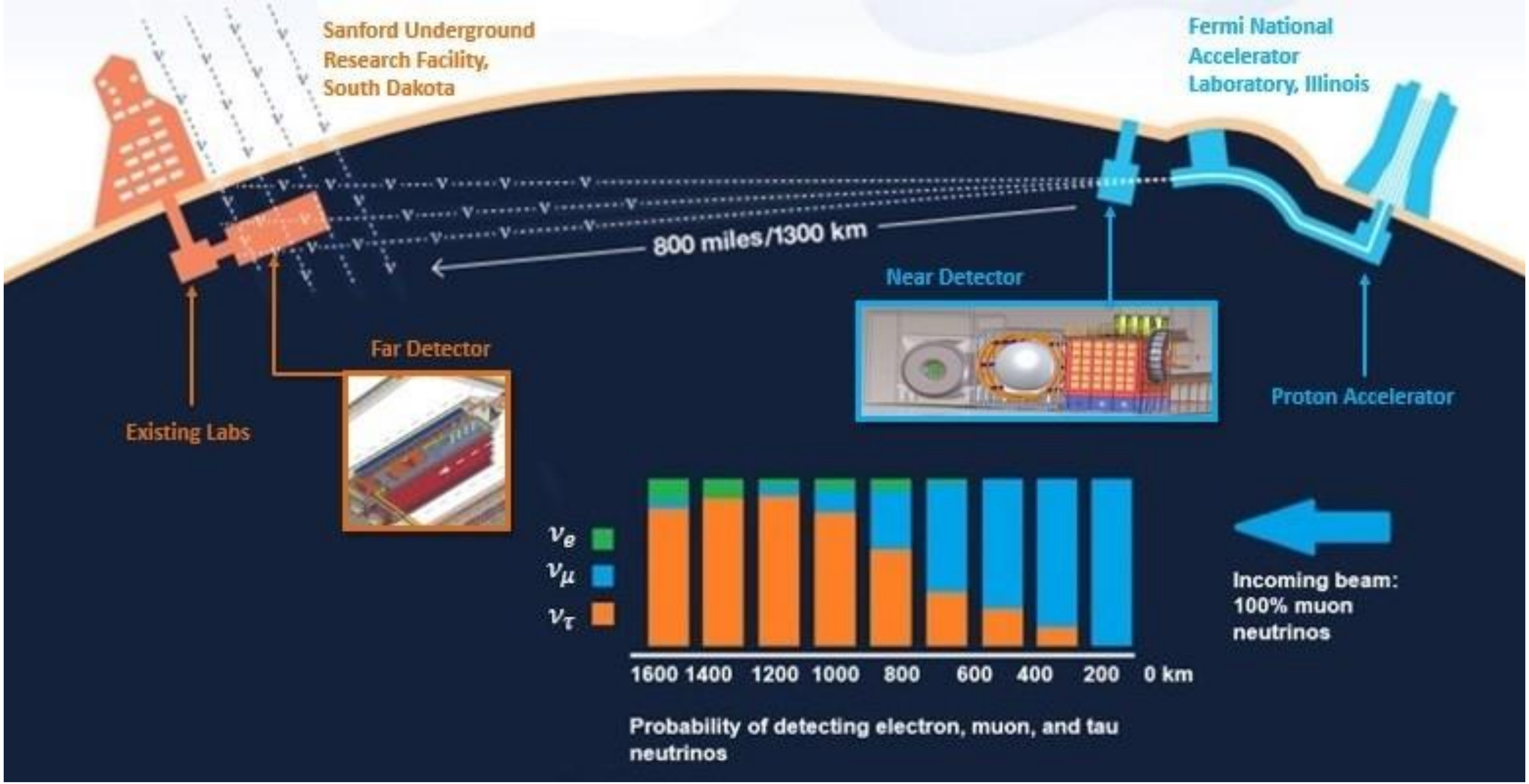
T2K experiment: far detector



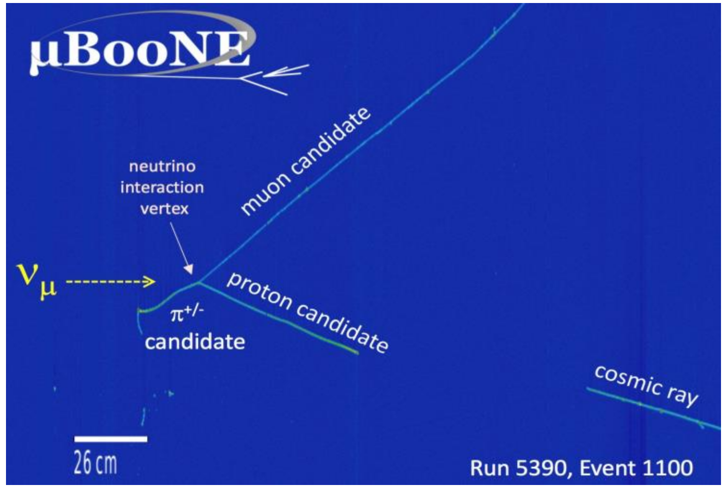


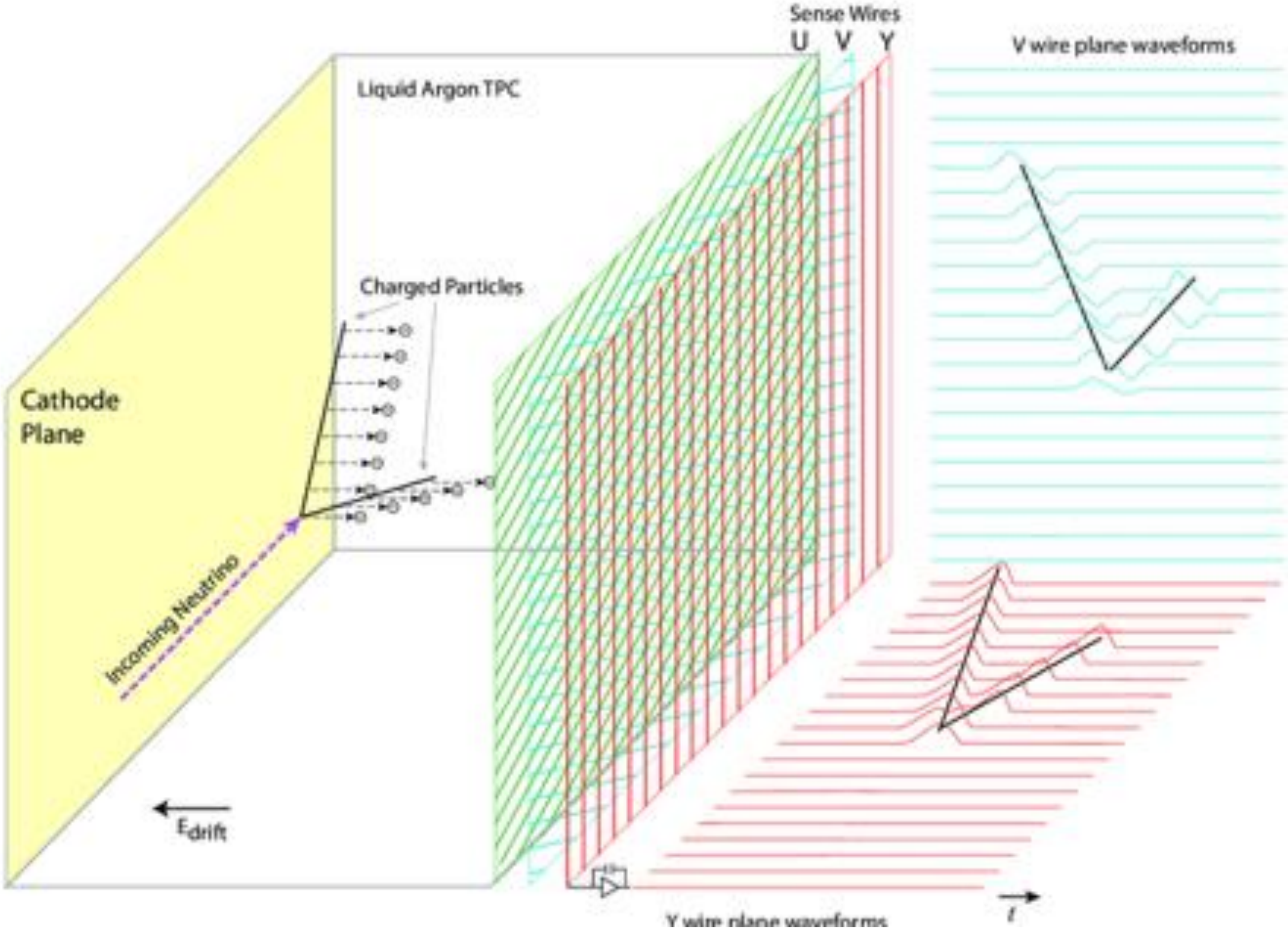
- Particle identification
- Particle range
- Interaction vertex reconstruction
- Electromagnetic energy reconstruction
- Track Multiplicity

DUNE experiment



LAr TPC working principle

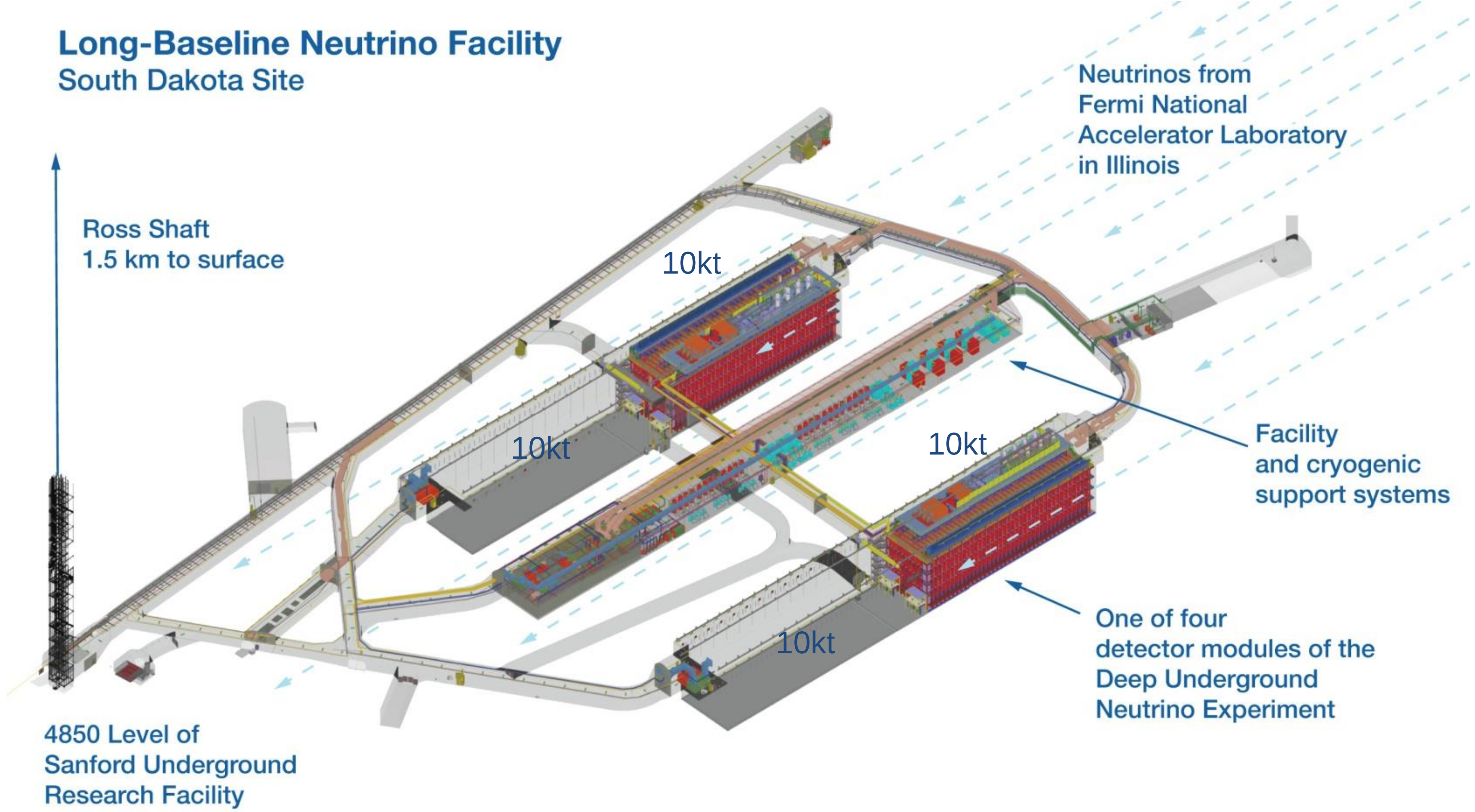




Liquid Argon Time Projection Chamber: technology capable of measuring with sub-centimeter precision ionization tracks and is sensitive to energies in the range 5MeV – 100GeV.

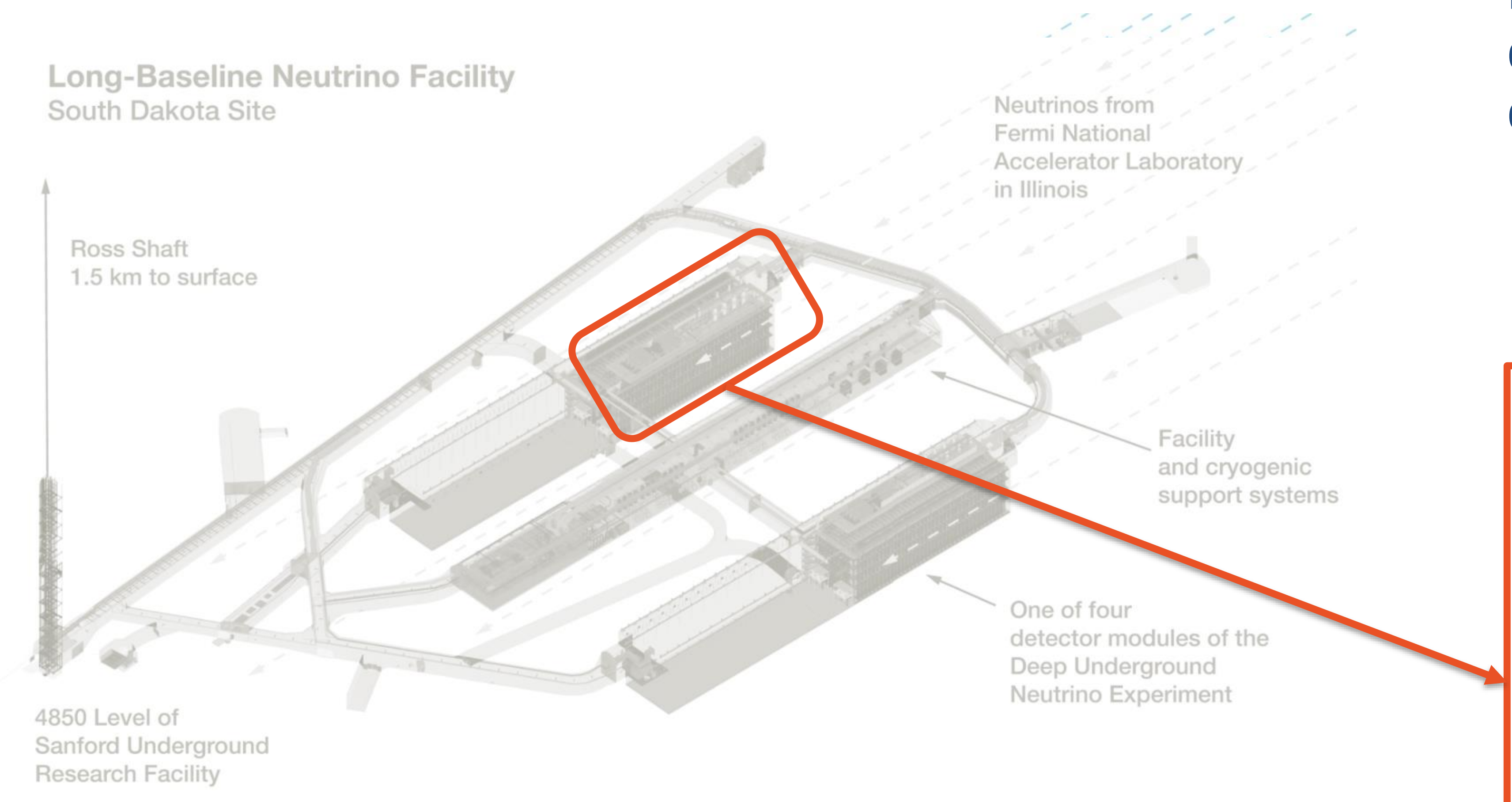
- detectors with large fiducial volumes,
- high imaging capabilities → excellent kinematic reconstruction with a mm-scale spatial resolution.

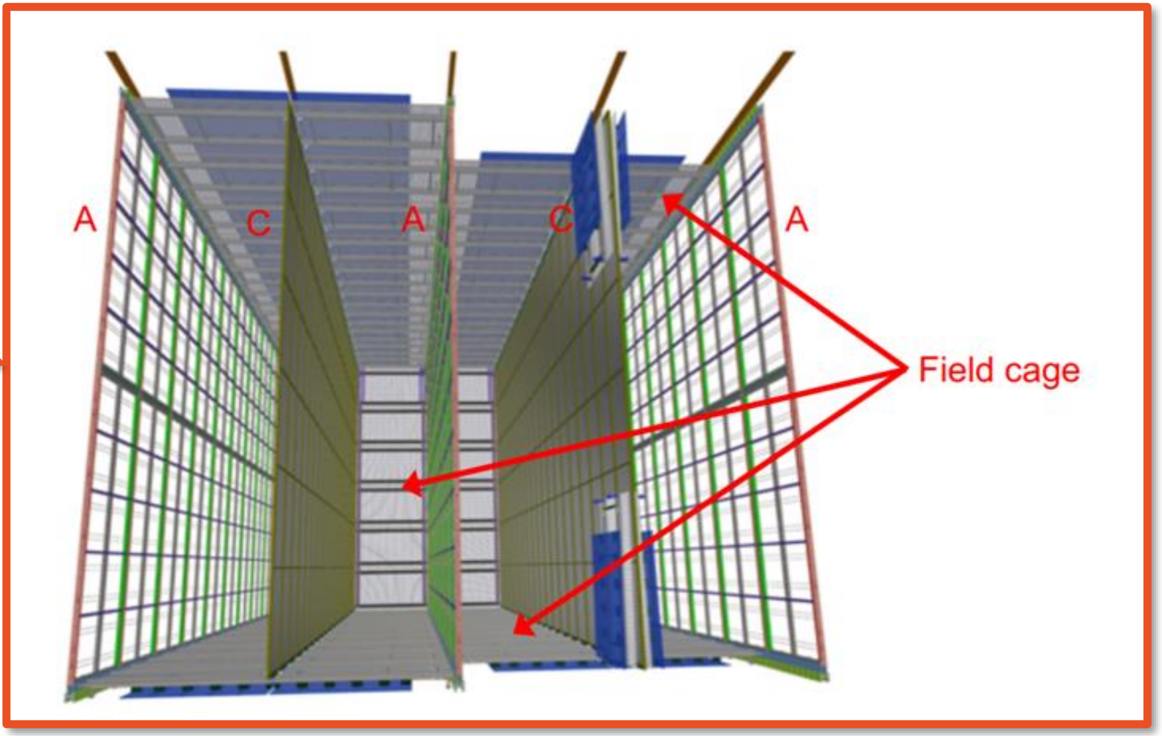
DUNE experiment: far detector



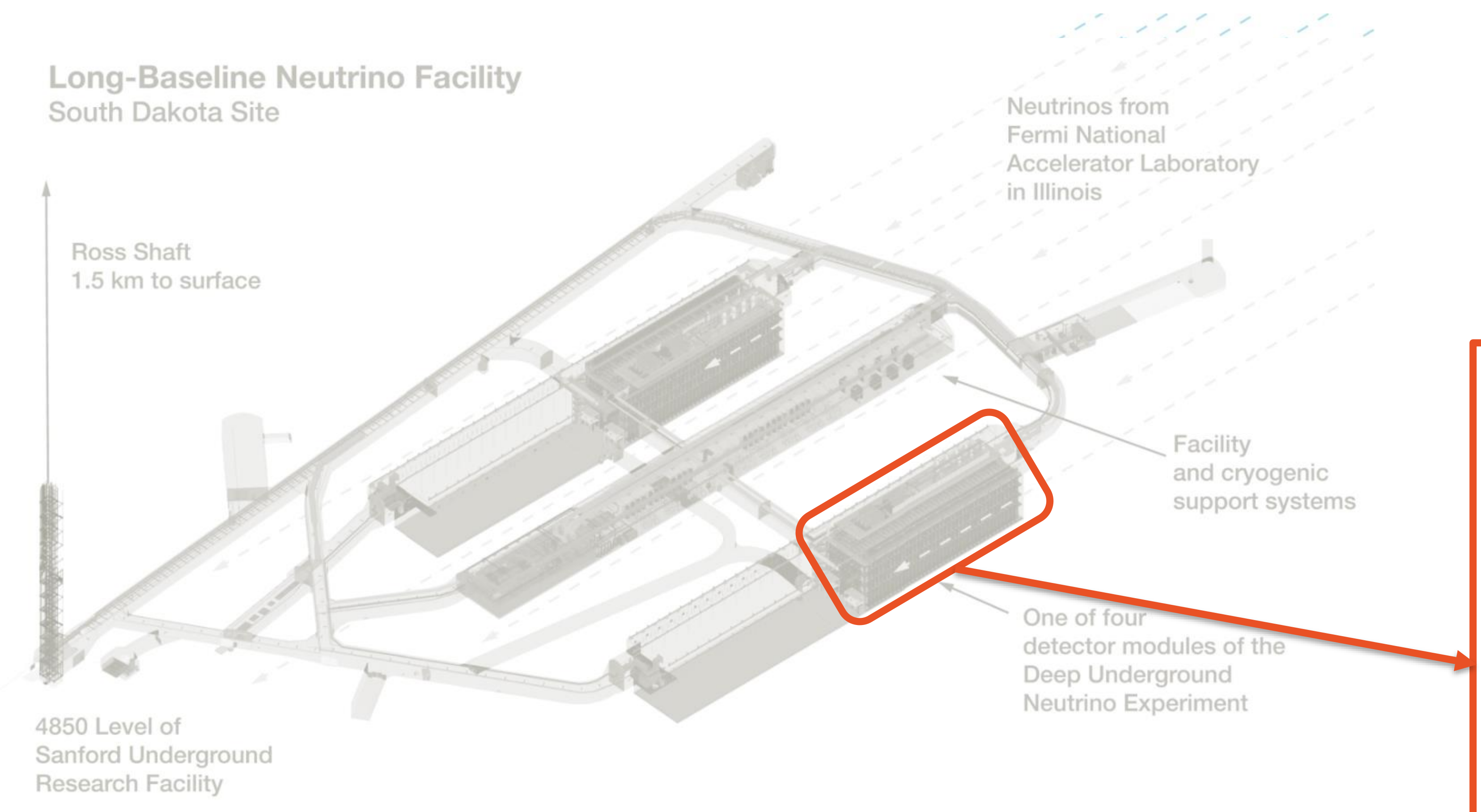
DUNE experiment: far detector

First 10 kt module will be Single Phase (SP) design with Horizontal Drift (HD), LArTPC divided into 4 drift volumes.

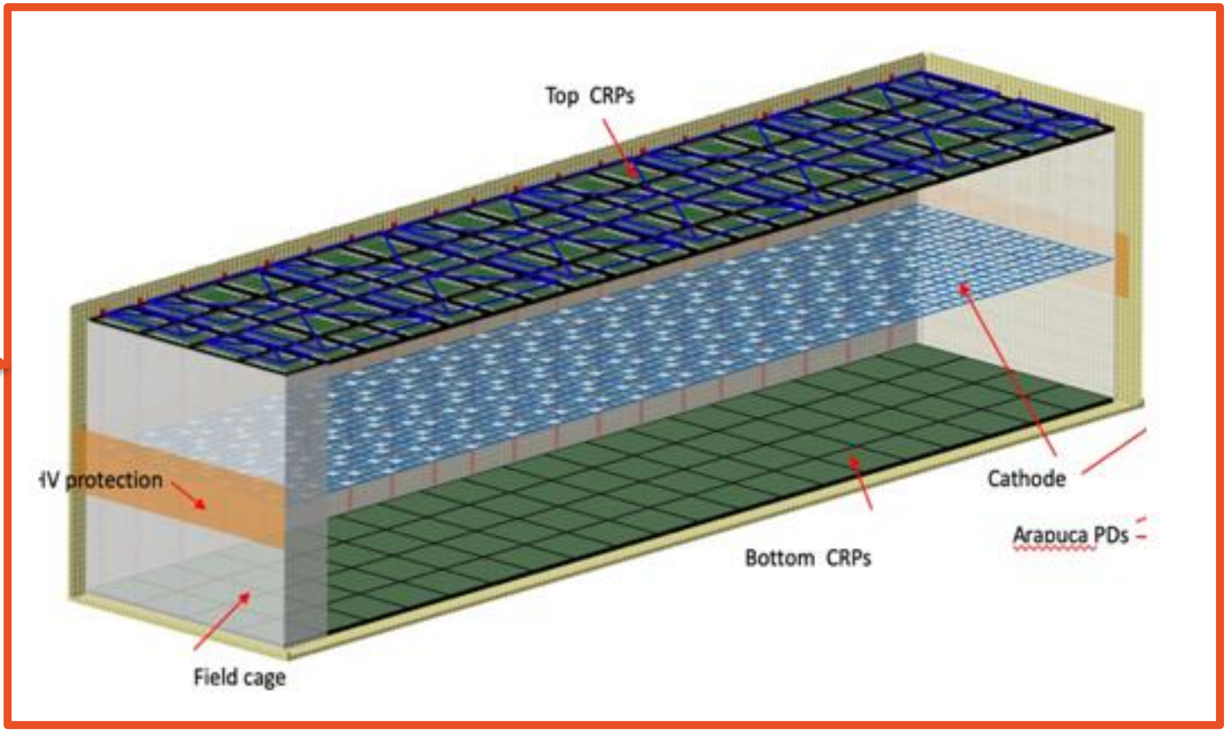




DUNE experiment: far detector



Second 10 kt module will be Single Phase (SP) design with Vertical Drift (VD), LArTPC divided into 2 drift volumes.



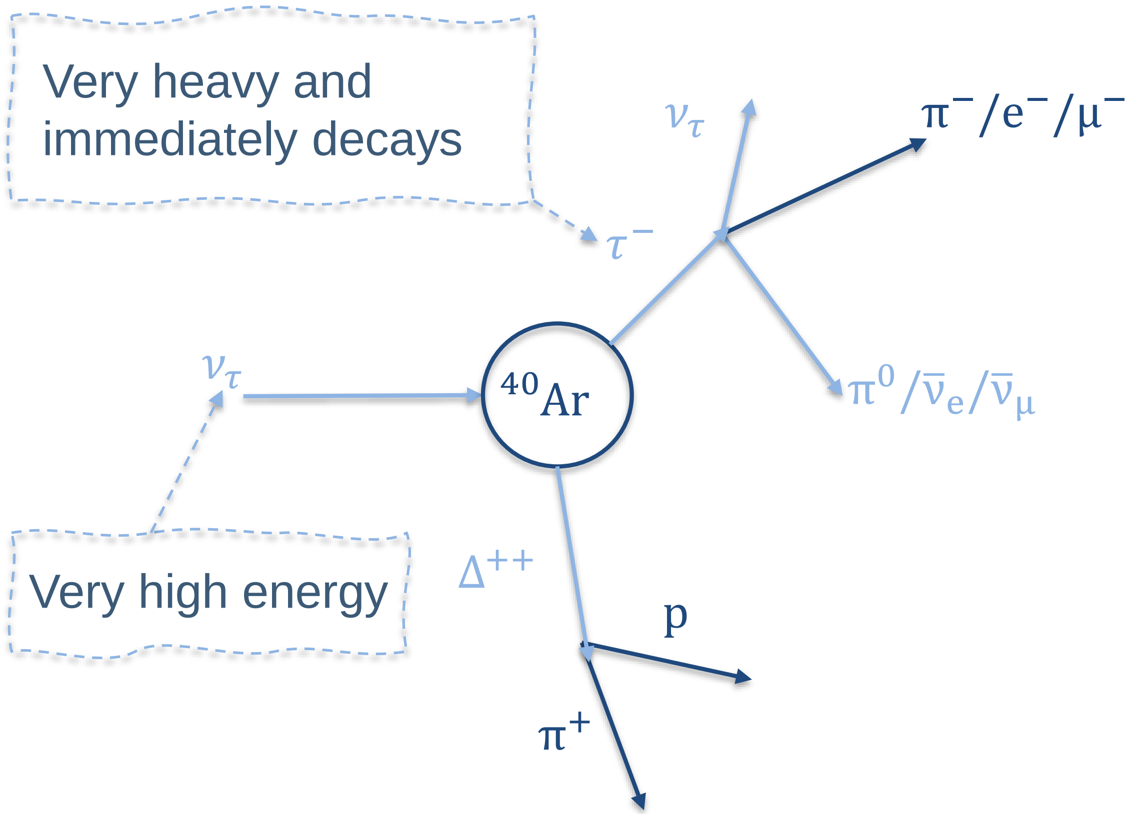
Tau neutrinos

- DUNE will be able to constrain the three-massive-neutrino paradigm by providing complementary measurements to:
  - ν_e -appearance channel
  - ν_μ-disappearance channel.

- Almost all knowledge of ν_τ comes from:
  - Lepton universality for cross-sections
  - PMNS unitarity for oscillations

These assumptions need to be tested!!!

- The τ production by ν_τCC-nucleus scattering requires neutrino energies $E_\nu \geq 3.5$ GeV.

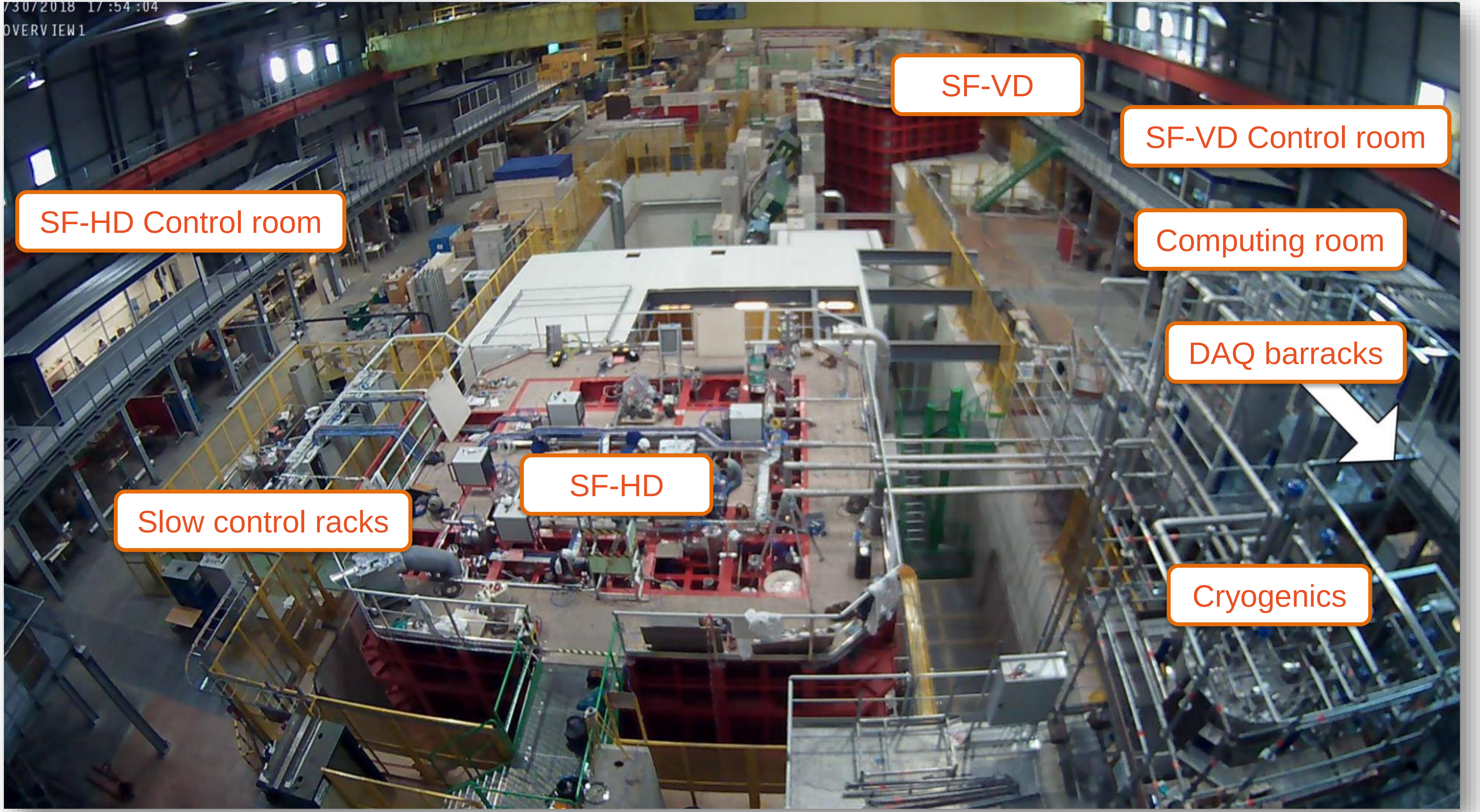


Physics Beyond the Standard Model (BSM)

- **Neutrinos are the first experimental observation of physics beyond the standard model.**

- **Most theories, explaining neutrino masses, need extra neutrinos and/or non-standard neutrino interactions (NSI)**

What are you going to see at the neutrino platform at CERN?



Summary

- Neutrino physics is entering the precision era.
  - Most of the parameters measured with <10% precision
  - θ_{23} mixing angle is known with 15% precision
  - Remaining parameters are δ_{CP} and mass hierarchy
  - T2K result excludes most of the δ_{CP} >0 values a 99.7% Confidence Level

- Beyond the Standard Model Physics is being studied in our experiments
  - PMNS non-unitarity

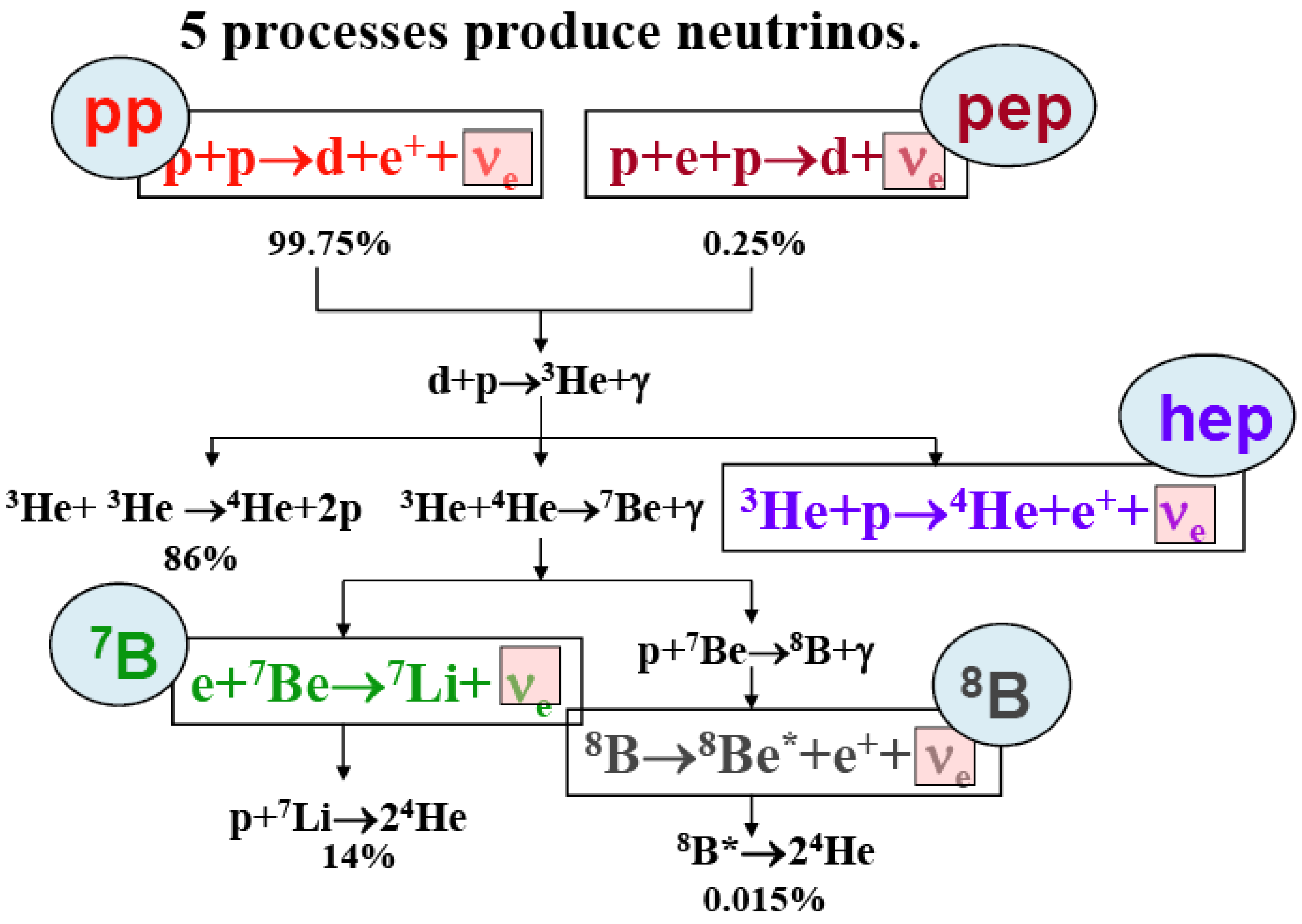
What are neutrinos?

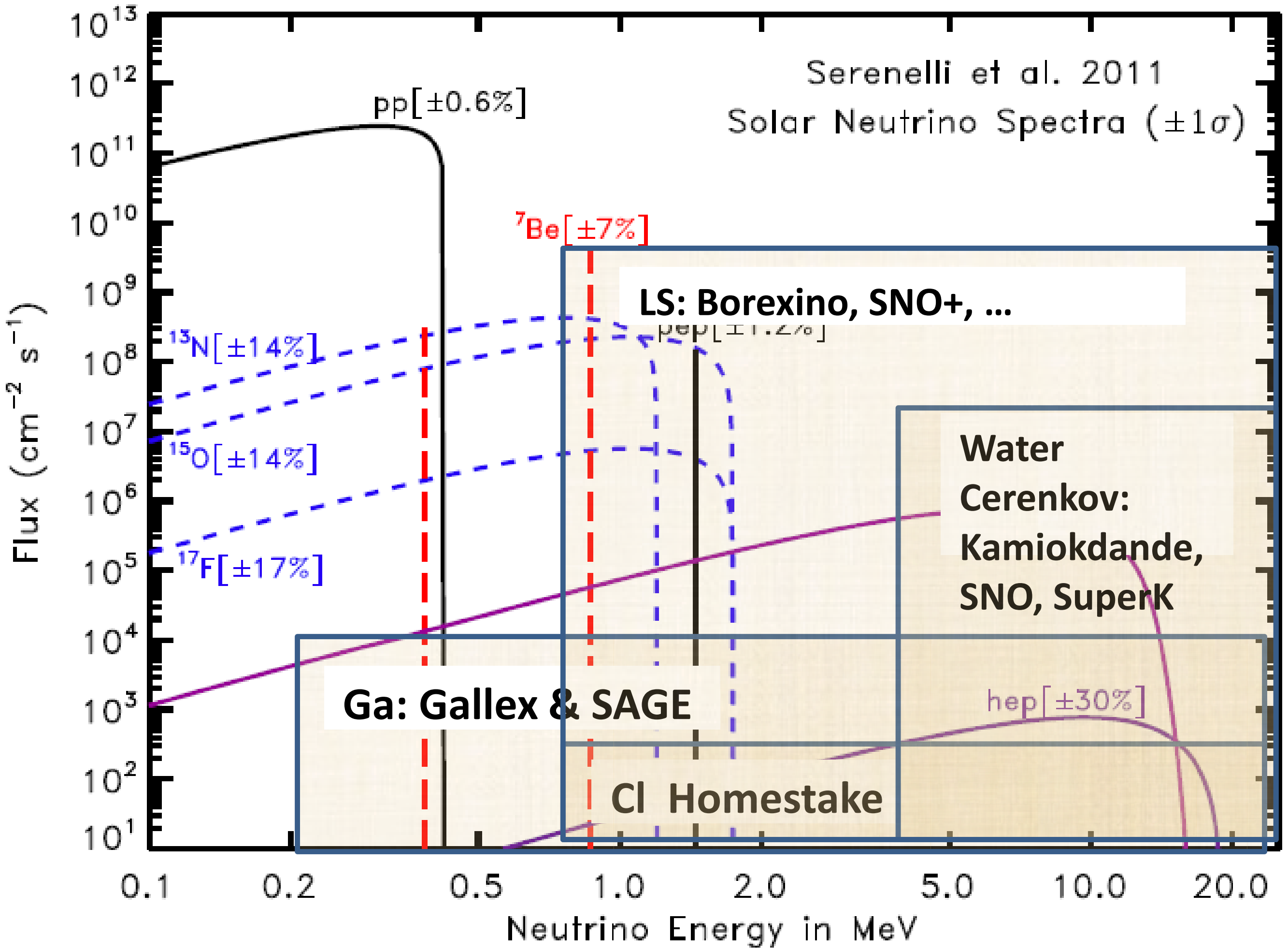
How do we detect them?

Why are they important?

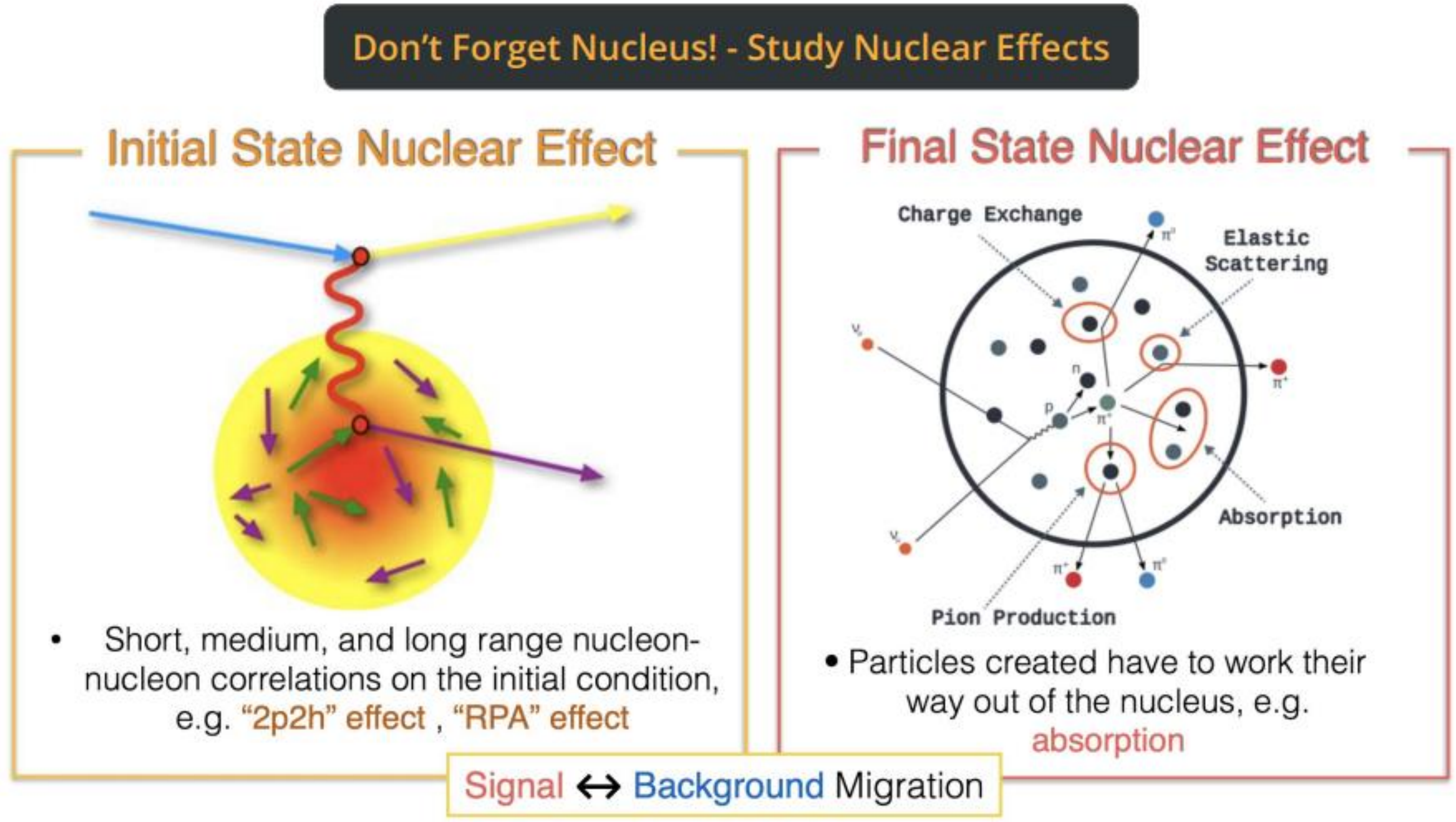

COMMUNITIES

Solar neutrinos



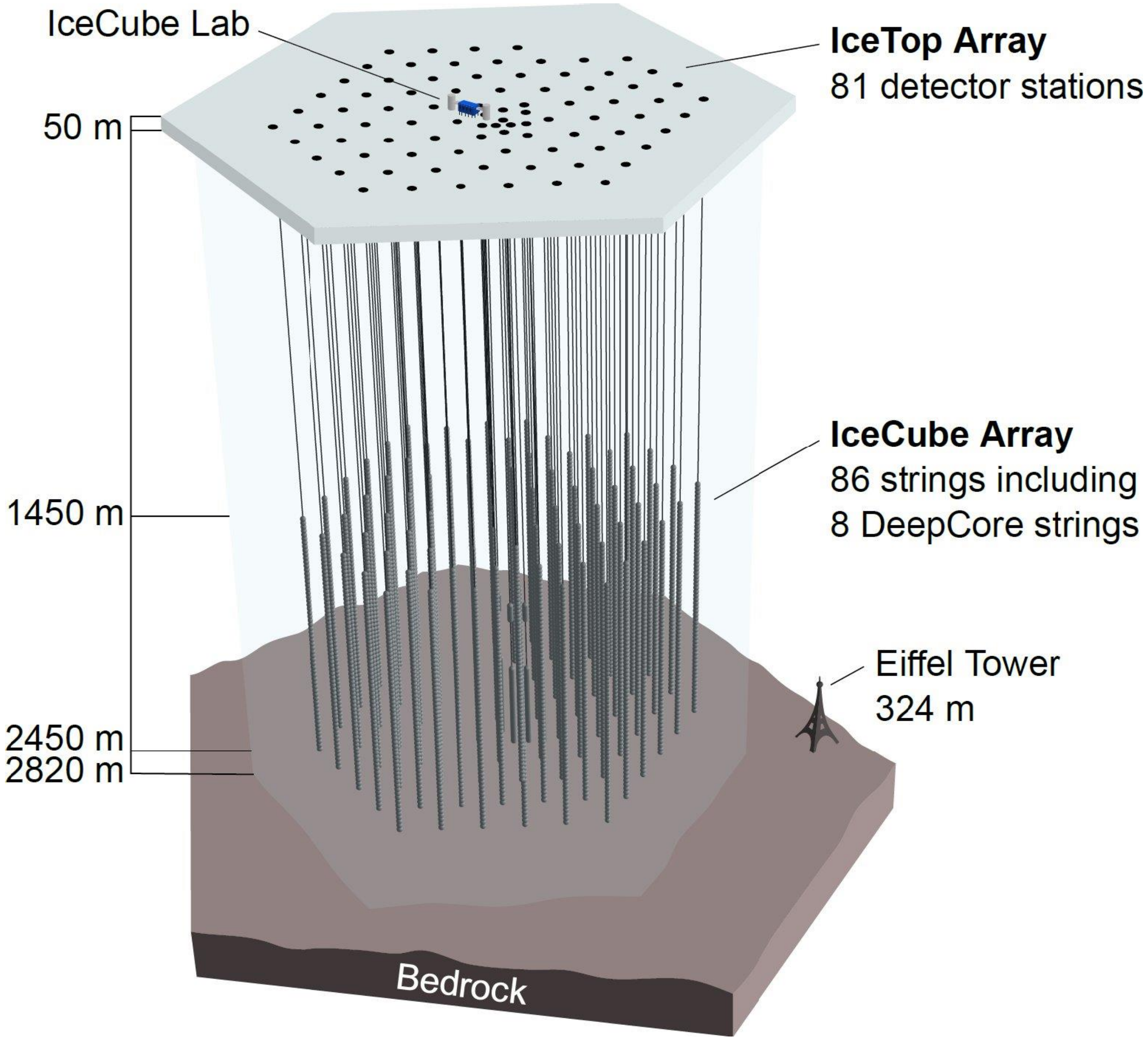


Neutrino interactions

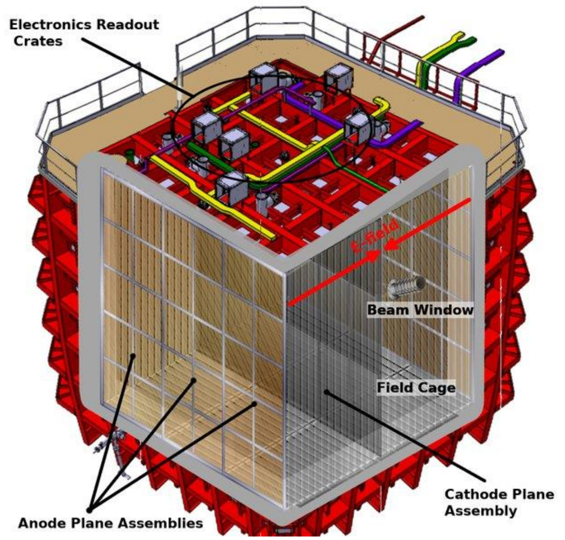


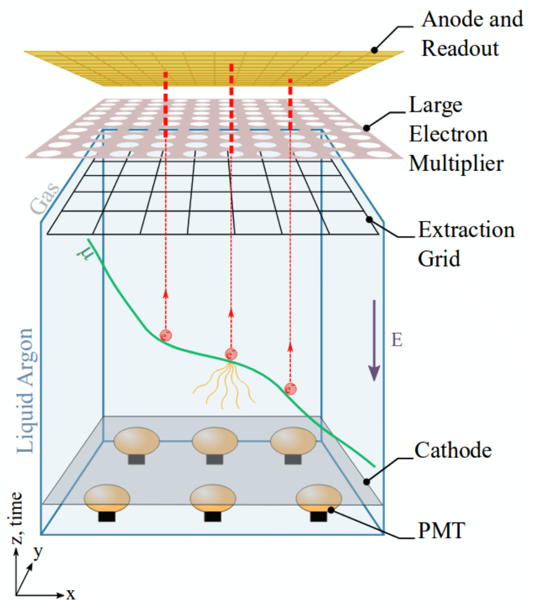
Icecube

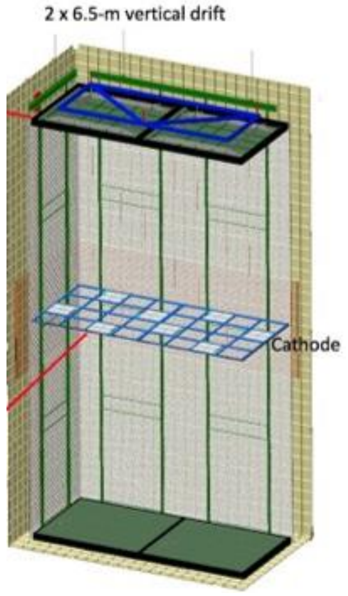
- Detect Cherenkov light from charged particles.
- Incoming neutrino produces the associated charged lepton through charged current.
  - Muon neutrinos leave a track + a hadronic shower
  - Electron and (low energy) tau neutrinos produce only a shower
- Neutral currents produces only the hadronic shower

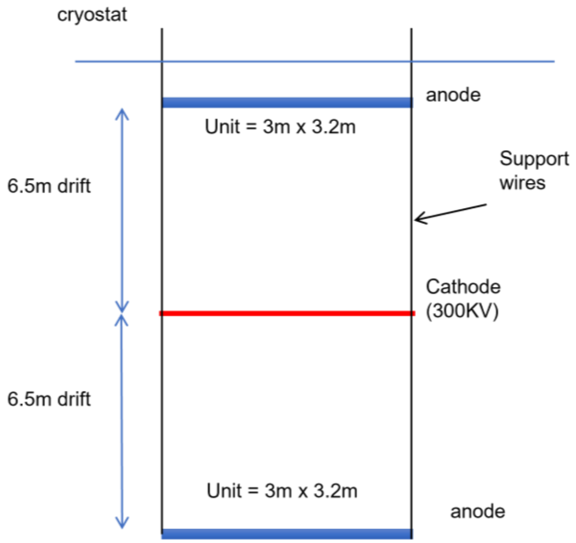


ProtoDUNE









ProtoDUNE-I (Sept 2018 to July 2020)

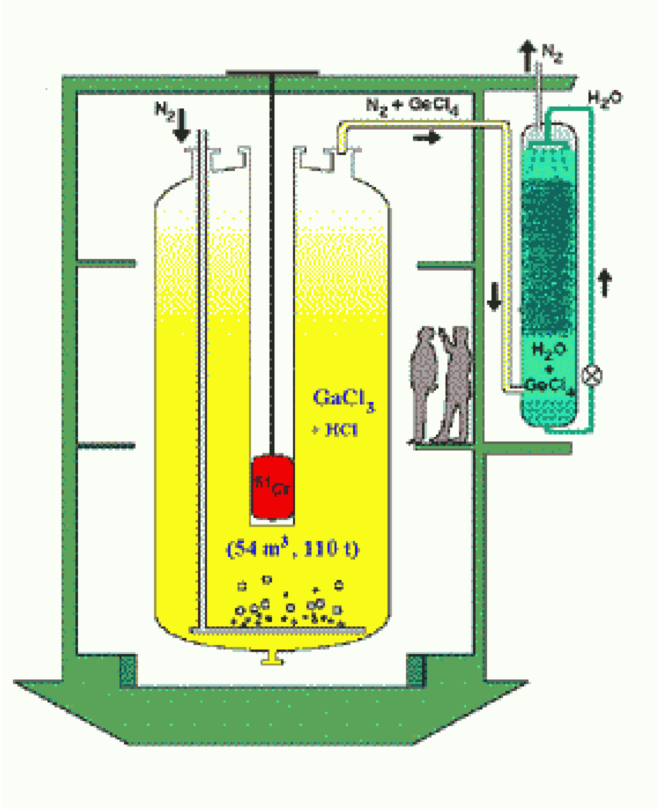
- Single Phase detector collected hadron data and cosmic ray data
- Dual Phase detector

ProtoDUNE- II (will start Aug or Sept 2022)

- Single Phase with Horizontal Drift
- Single Phase with Vertical Drift
  - Central Cathode Plane Assembly (CPA) hanging at mid-height
  - Field cage ensures E-field uniformity, 500 V/cm
  - Electrons drift vertically over 6.5m
  - Perforated PCB Anode Plane Assemblies (APAs) on the top and bottom of the detector
  - Photon sensors on cathode (provide the trigger and timestamp of the events)

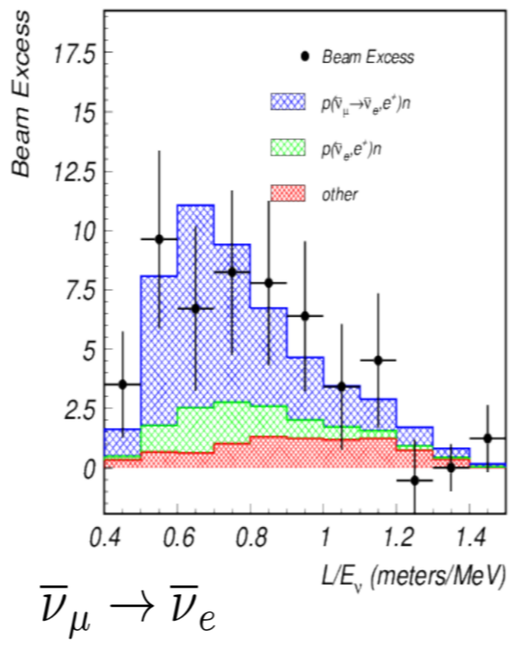
Anomalies in oscillations

Gallium anomaly: GALLEX and SAGE collaborations place detectors besides artificial radioactive sources producing high fluxes of electron neutrinos (ν_e) - 2.9 σ deficit of the ν_e.



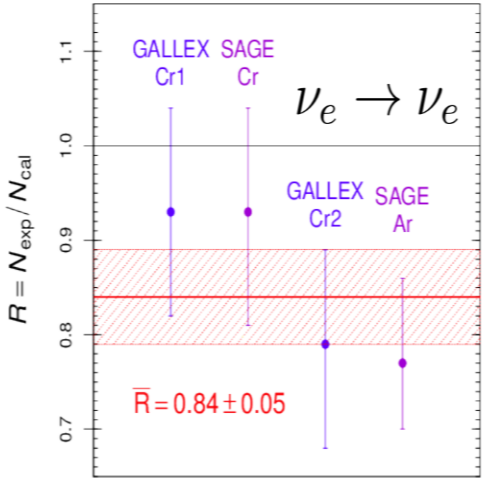
https://www.sciencedirect.com/science/article/pii/S0370269310000729
https://arxiv.org/abs/nucl-ex/0512041

- 3.8σ excess in **LSND**

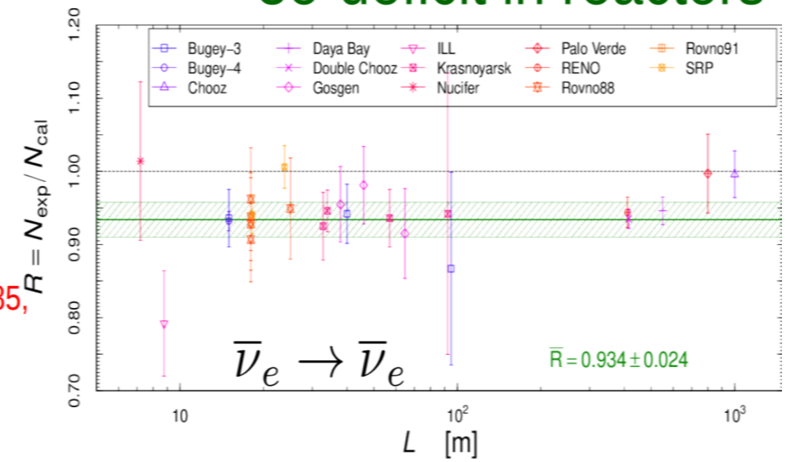


- No signal **@Karmen**

- ~3σ deficit in **Gallium**

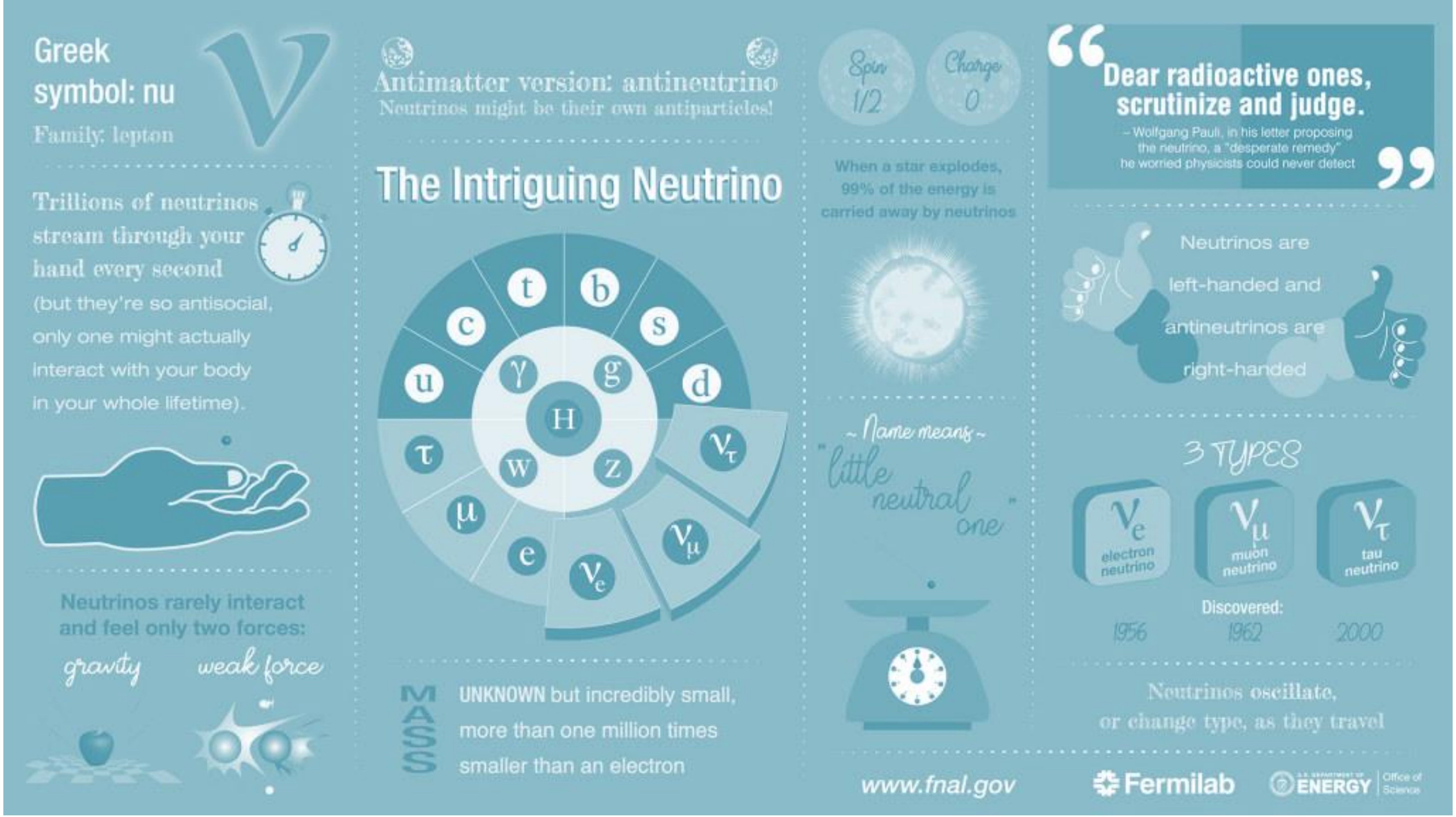


- ~3σ deficit in reactors



LSND: PRL 75 (1995) 2650, PRC 54 (1996) 2685, PRL 77 (1996) 3082, PRD 64 (2001) 112007
Karmen: PRD 65 (2002) 112001
Gallium: PRC 80 (2009) 015807, **SAGE,** Nucl.Phys.Proc.Suppl. 168 (2007) 344, Laveder et al, PRD 78 (2008) 073009 and PRC 83 (2011) 065504, C. Giunti et al
Reactor: PRD 83 (2011) 073006, Mention et al. PRC 83 (2011) 054615, Mueller et al. PRC 84 (2011) 024617, Huber

https://oglez.web.cern.ch/oglez/public/EPPSU-CMS-Week-v0.pdf



https://www.innovationnewsnetwork.com/dune-experiment-unlock-mysteries-neutrino/21061/