
Neutrino Physicist or Ghost Hunter?



Inside Proto-DUNE



Inside Super-Kamiokande



On top of ND280

International High School Teacher Programme

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UNIVERSITY OF
TORONTO



Neutrinos in the Standard Model

Neutrinos are elementary particles.

Facts:

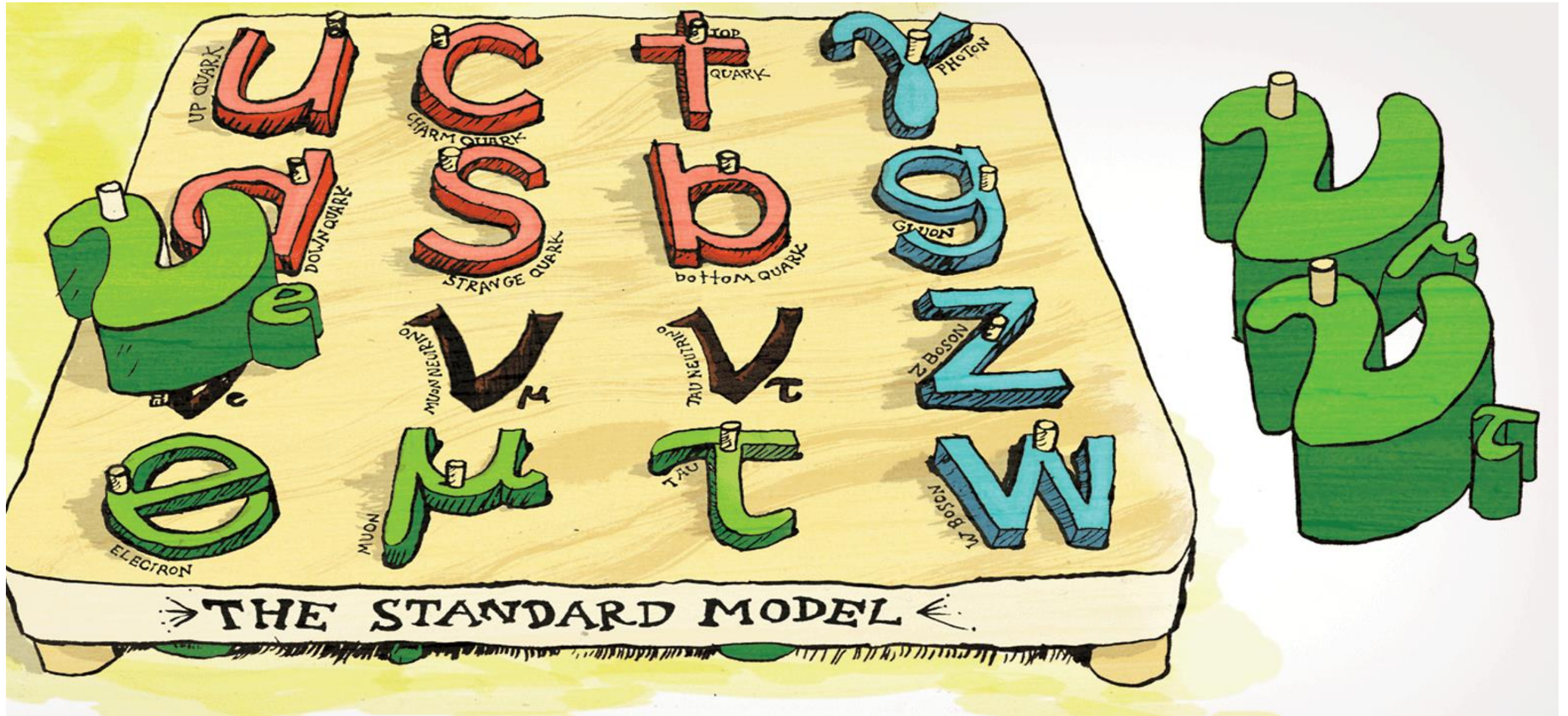
- There are 3 flavors (ν_e, ν_μ, ν_τ) matched to charged leptons (e, μ, τ)
- They have no charge
- They are ~~massless~~ nearly massless
- They are spin $\frac{1}{2}$ leptons
- They only interact weakly through W^\pm and Z^0 bosons

All this makes them basically... INVISIBLE



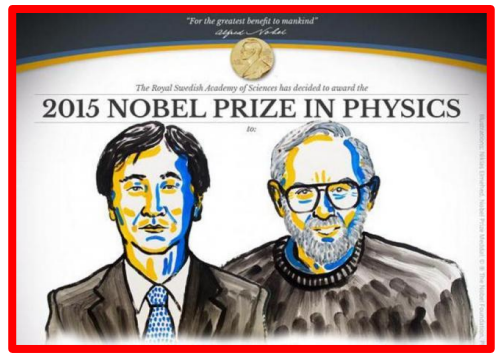
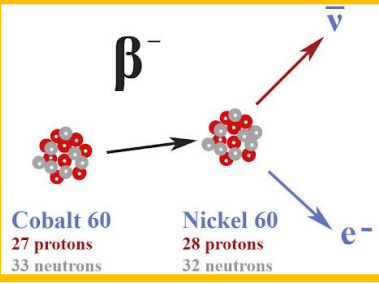
<https://www-he.scphys.kyoto-u.ac.jp/nucosmos/en/>

Neutrinos in the Standard Model



Neutrino physics history

Original: *Photocopy of PNC 0373*
 Abchrift/15.12.26
 OTTAWER Brief an die Gruppe der Radioaktiven bei der
 Gouvernements-Tagung zu Röhlingen.
 Abchrift
 Physikalisches Institut
 der Eidg. Technischen Hochschule
 Zürich
 Zürich, 14. Dez. 1930
 Gustav Weiss
 Liebe Radioaktive Damen und Herren,
 Wie der Heberbringer dieser Zeilen, dem ich herzlichst
 annehme, Ihnen das näherer auseinander wird, bin ich
 angesichts der "falschen" Statistik der α - und β -Kerne, sowie
 des kontinuierlichen β -Spektrums auf einen verwerflichen Ausweg
 verfallen um den "Neutrino" (1) der Statistik und dem Energiemass
 zu retten. Möchten die Möglichkeit, es könnten elektrisch neutrale
 Teilchen, die ich Neutrino nennen will, in den Kernen existieren,
 welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und
 sich von Lichtgeschwindigkeit unterscheiden, dass sie
 nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutrino
 würde von derselben Dimensionierung wie die Elektronenmasse sein und
 jedenfalls nicht grösser als 0,01 Protonenmasse. Das kontinuierliche
 β -Spektrum wäre dementsprechend unter der Annahme, dass beim
 β -Zerfall mit dem Elektron jeweils noch ein Neutrino emittiert
 würde, demart, dass die Summe der Energien von Neutron und Elektron
 konstant wäre.
 Nun handelt es sich weiter darum, welche Kräfte auf die
 Neutrino wirken. Das wahrscheinlichste Modell für das Neutron scheint
 mir aus wellenmechanischen Gründen (näheres siehe der Heberbringer
 dieser Zeilen) dieses zu sein, dass das ruhende Neutron ein
 magnetischer Dipol von einem gewissen Moment μ ist. Die Experimente
 verlaufen wohl, dass die Ionisationswirkung eines solchen Neutrino
 nicht grösser sein kann, als die eines gamma-Strahls und darf dann
 μ wohl nicht grösser sein als $e \cdot (10^{-27} \text{ cm})$.
 Ich brauche mich vorläufig aber nicht, etwas über diese Idee
 zu publizieren und werde mich erst verträglich an Sie, liebe
 Radioaktive, mit der Frage, wie es um den experimentellen Nachweis
 eines solchen Neutrino stünde, wenn dieses ein demotisches oder etwa
 lokal grösseres Durchdringungsvermögen besitzen würde, wie ein
 gamma-Strahl.
 Ich gebe zu, dass mein Ausweg vielleicht von vornherein
 wenig wahrscheinlich erscheinen wird, weil man die Neutrino, wenn
 sie existieren, wohl schon längst gesehen hätte. Aber nur wer sagt,
 gemäss und der Instet der Situation bei kontinuierliche β -Spektrum
 wird durch einen Ausweg andere verurteilen Vorgänger im Jahre,
 Herr Bohr, bezieht sich, der mir ebenfalls in diesem Zusammenhang
 "0", daraus soll man es besten gar nicht denken, wenn es die neuen
 Störern. Darum soll man jeden Weg zur Rettung ernstlich studieren.
 Also, liebe Radioaktive, mühen, und richtig. Leider kann ich nicht
 persönlich in Röhlingen erscheinen, da ich infolge eines in der Nacht
 von G. am 7. Dez. in Zürich stattfindenden Ballen mit dementsprechend
 bin. Mit vielen Grüßen an Sie, sowie an Herrn Neak, hier
 unterfertigter Diener
 gen. V. Pauli



1930
 Wolfgang Pauli postulated the "neutron" to compensate for the apparent loss of energy and conserve the momentum of decay β^-

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

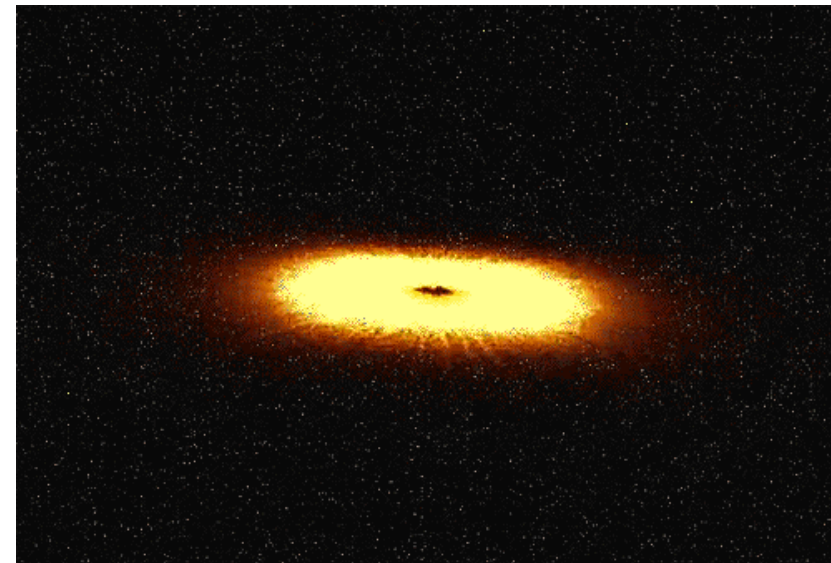
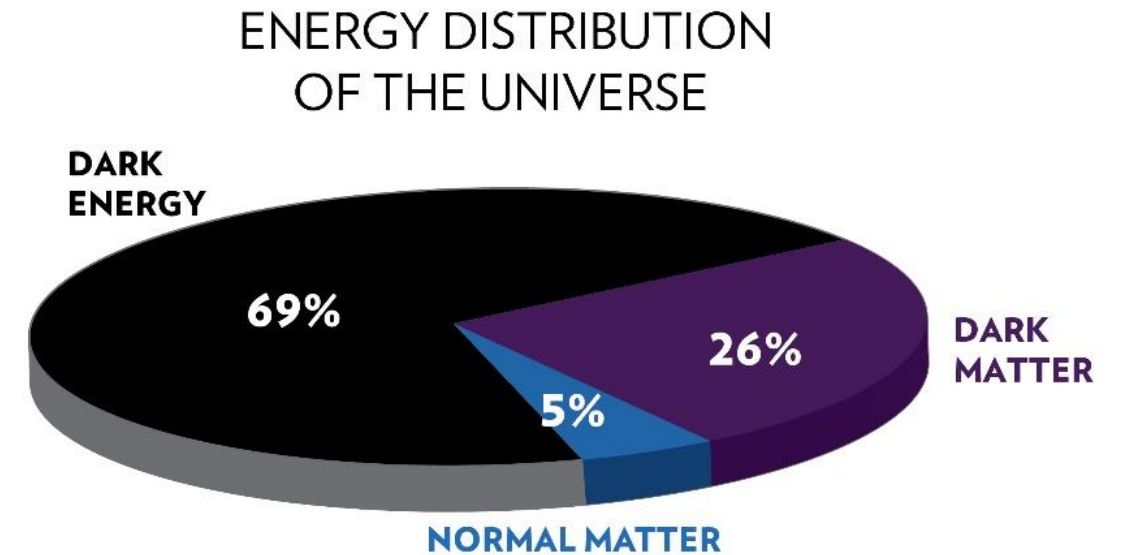
2015
 Nobel Prize in Physics to Takaaki Kajita and Arthur B. McDonald "for the discovery of neutrino oscillations, which shows that neutrinos have mass."

2020
 Constraint on the Matter-Antimatter Symmetry-Violating Phase in Neutrino Oscillations

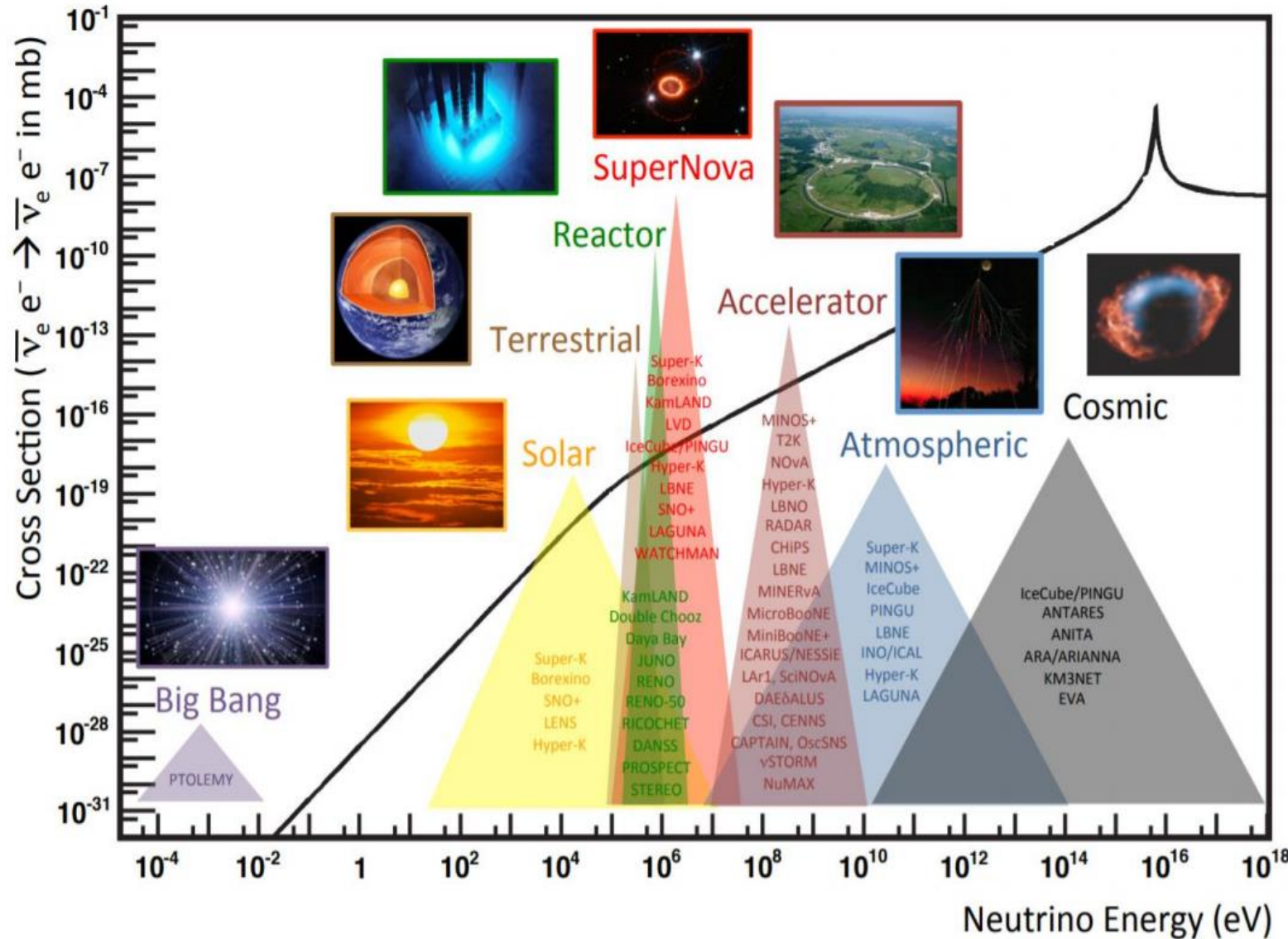


What's so interesting about neutrinos?

- 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.

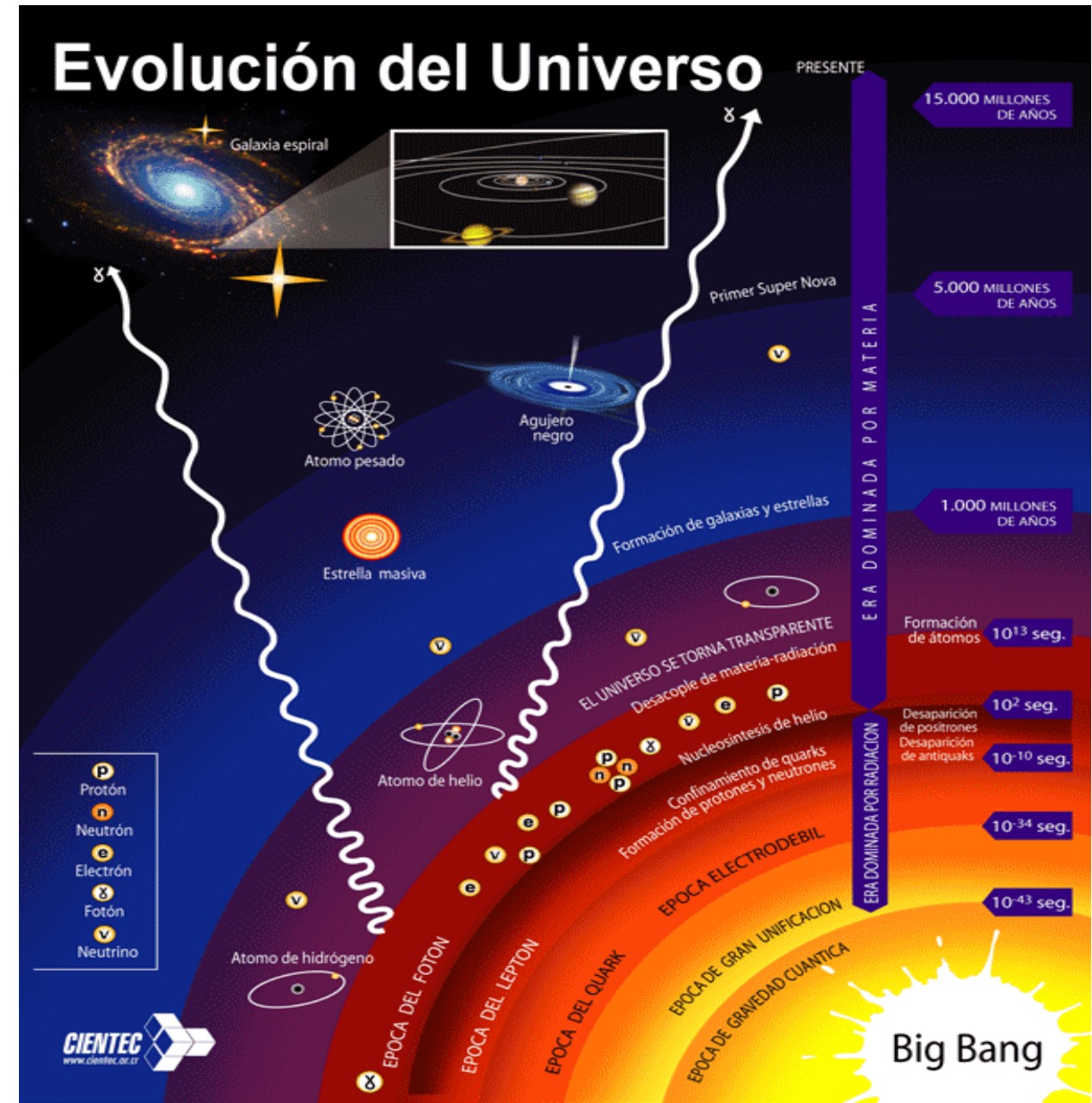
Relic neutrinos

- Relic neutrinos from the cosmic neutrino background (CMB) 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!!!



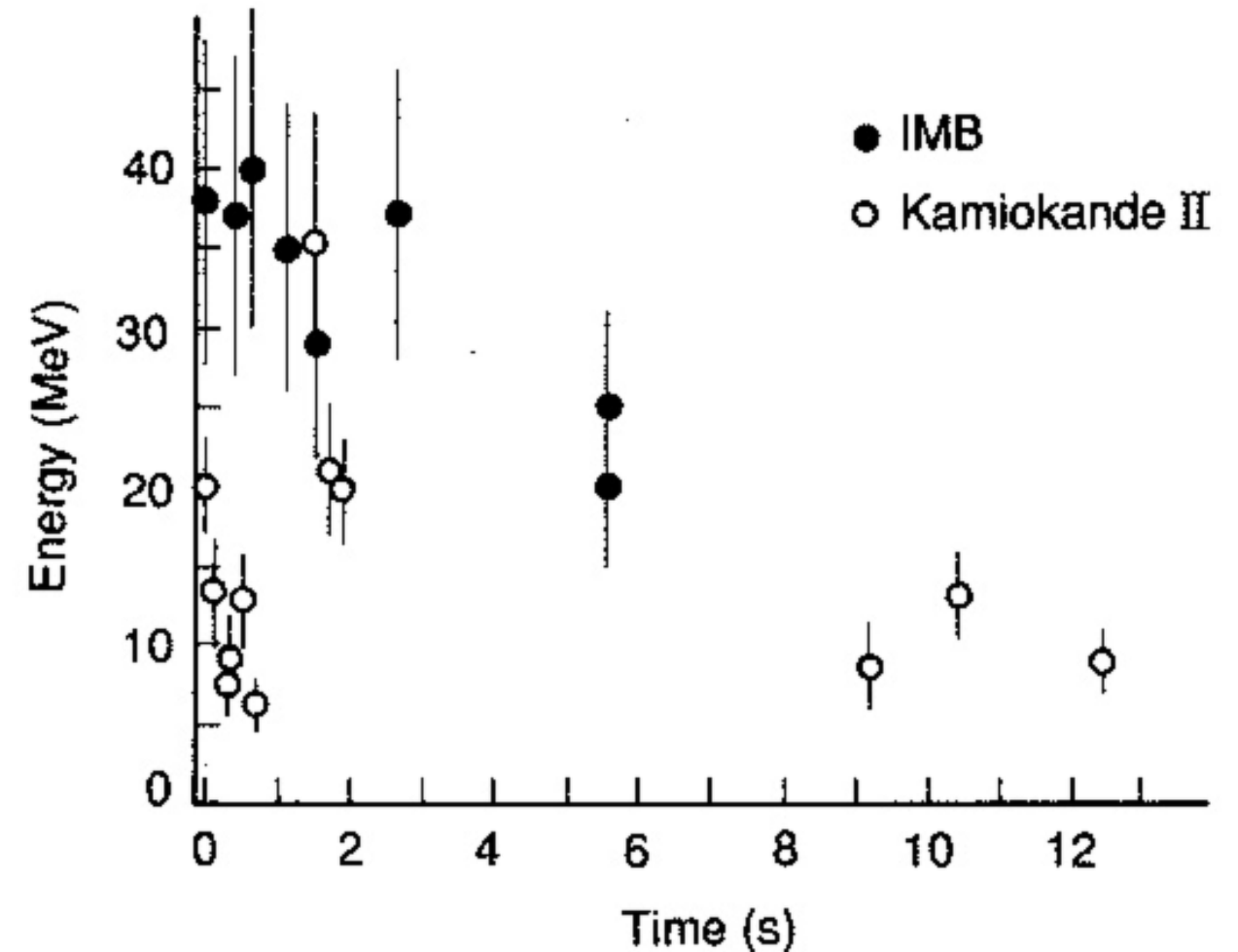
Supernova neutrinos (SN)

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

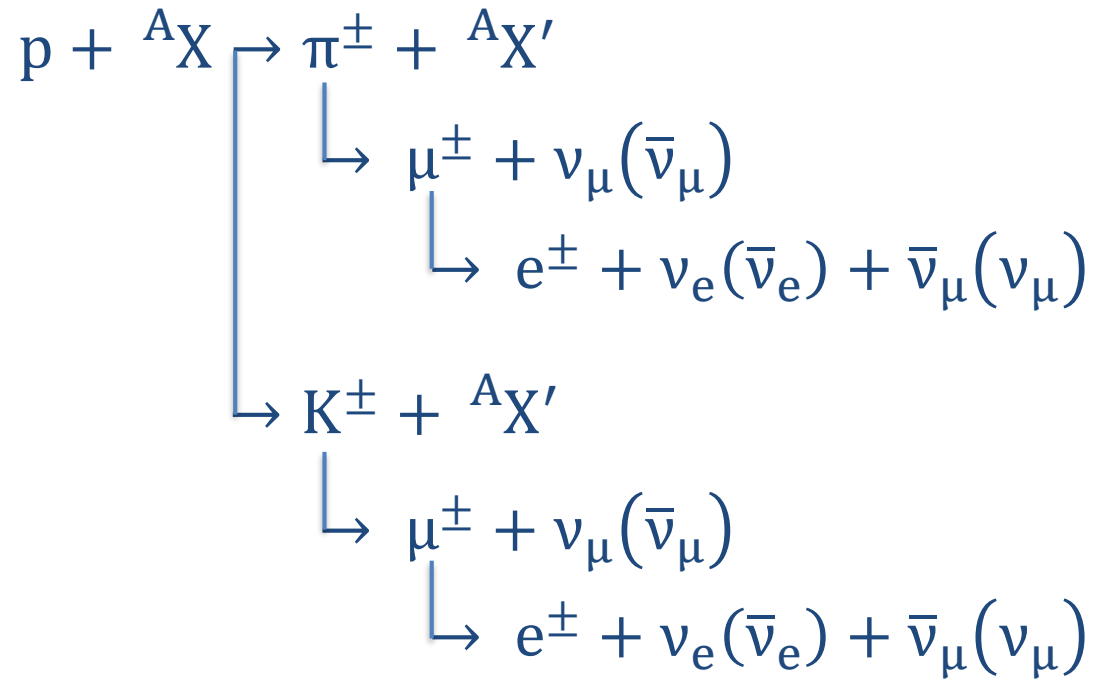
- Measurement of SN neutrinos will provide information about:
 - Supernova physics: Core collapse mechanism, SN evolution in time, black hole formation, etc.
 - Neutrino physics: neutrino oscillation, neutrino absolute mass, etc.

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

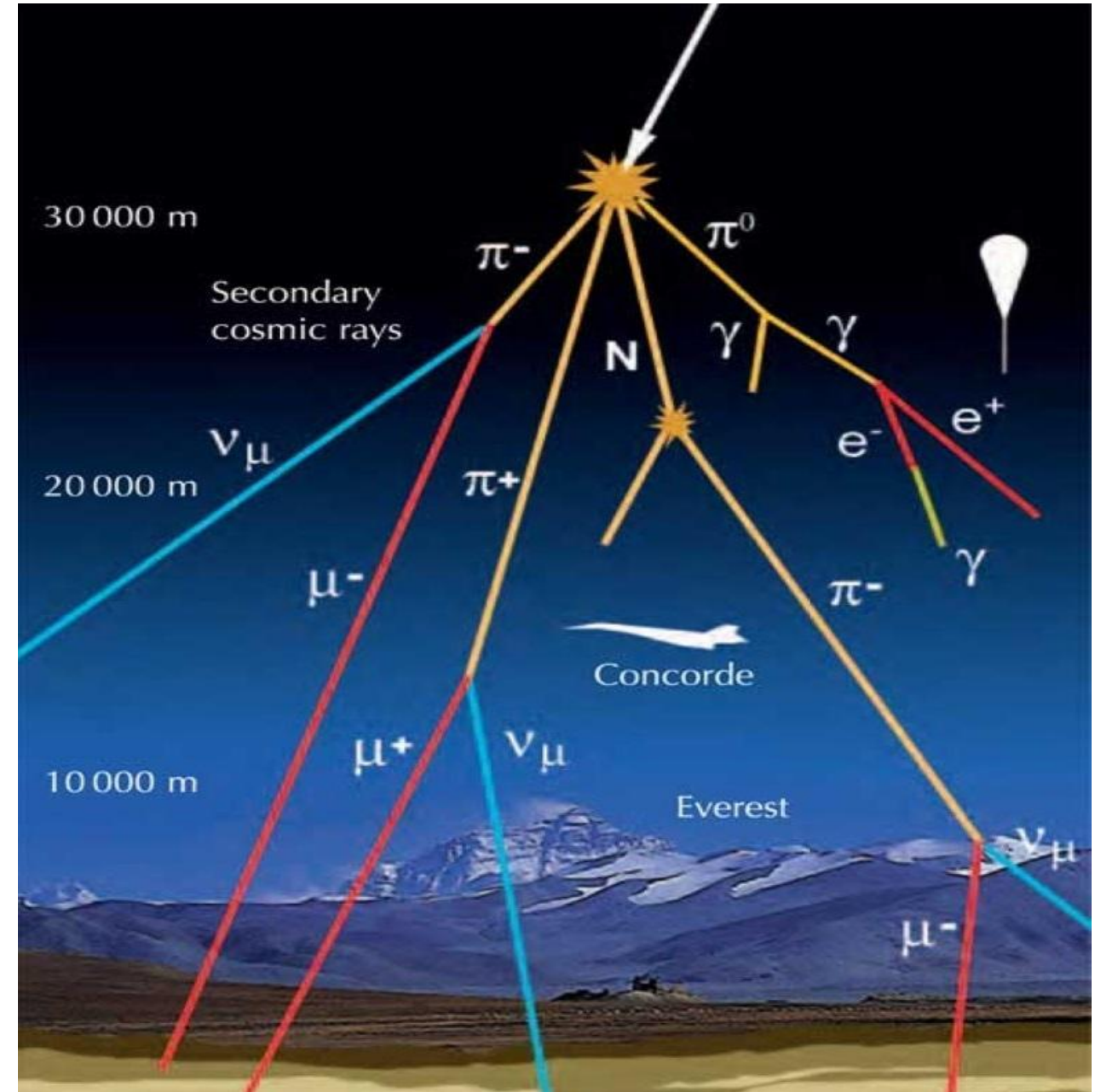
- Beginning of using neutrinos for multi-messenger astronomy.



Atmospheric neutrinos



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



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:

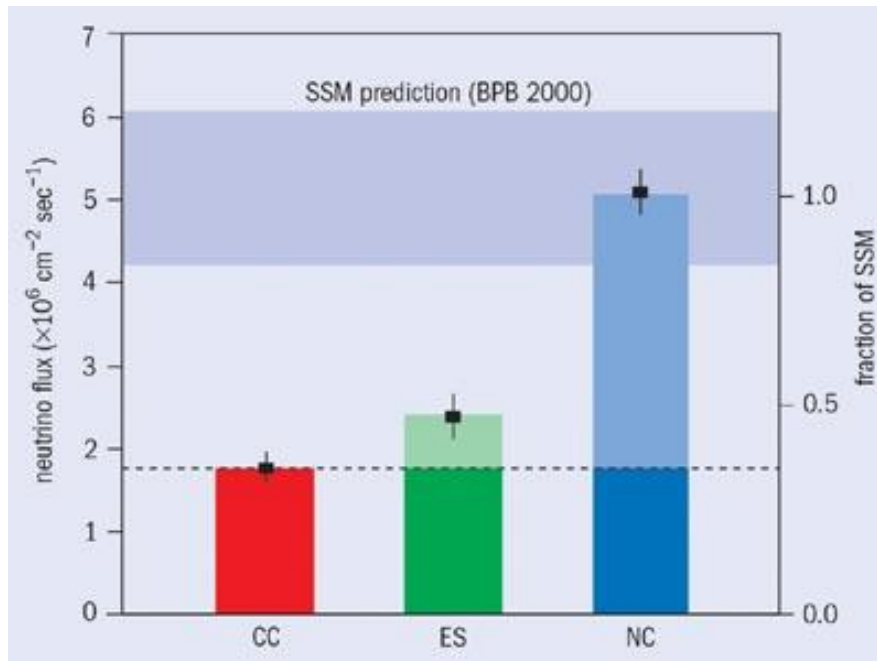


- Without the neutrino, angular momentum would not be conserved.



Solar neutrinos

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



Charged Current (CC):



Elastic Scattering (ES):

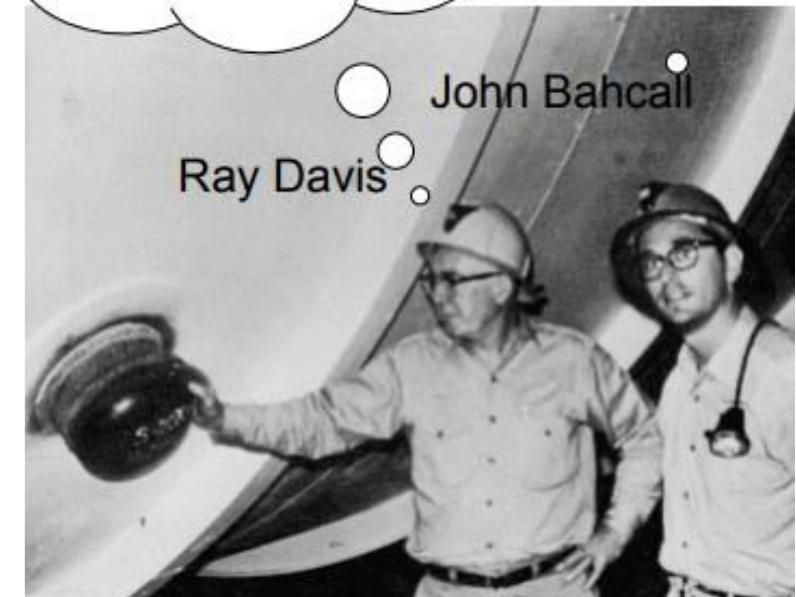


Neutral Current (NC):



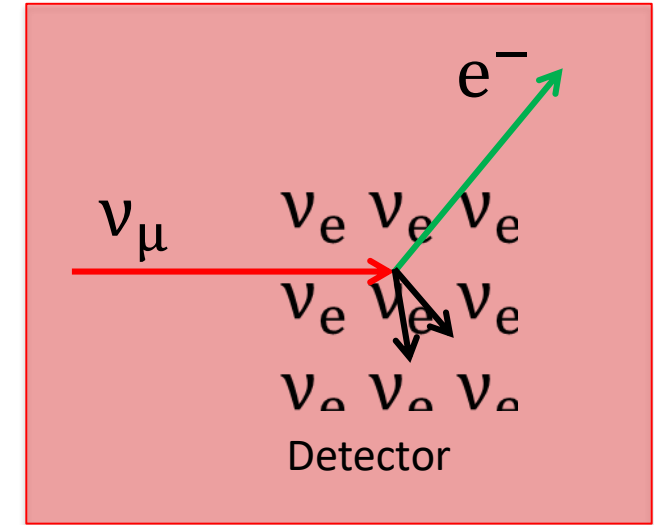
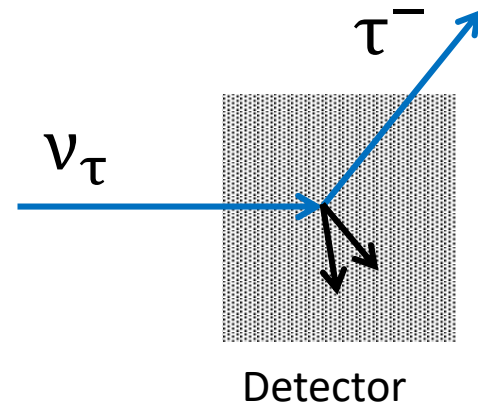
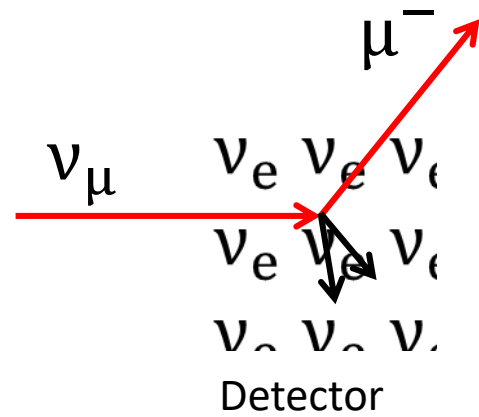
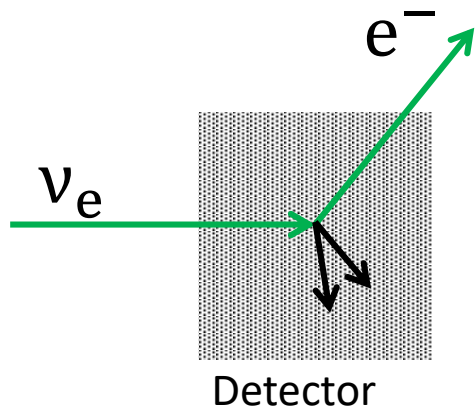
So my calculations were right...

... and my measurements, too



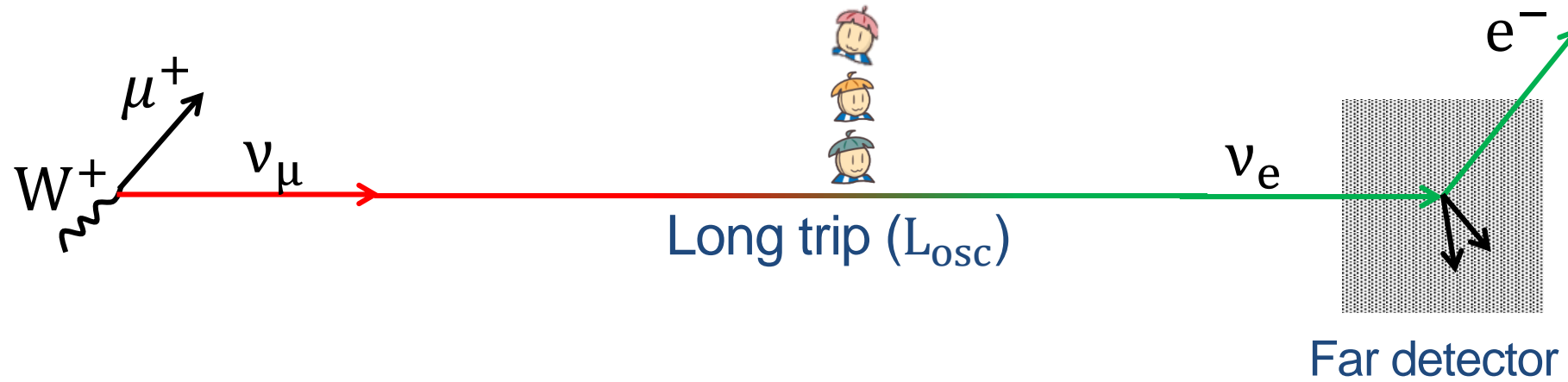
Neutrino oscillation

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



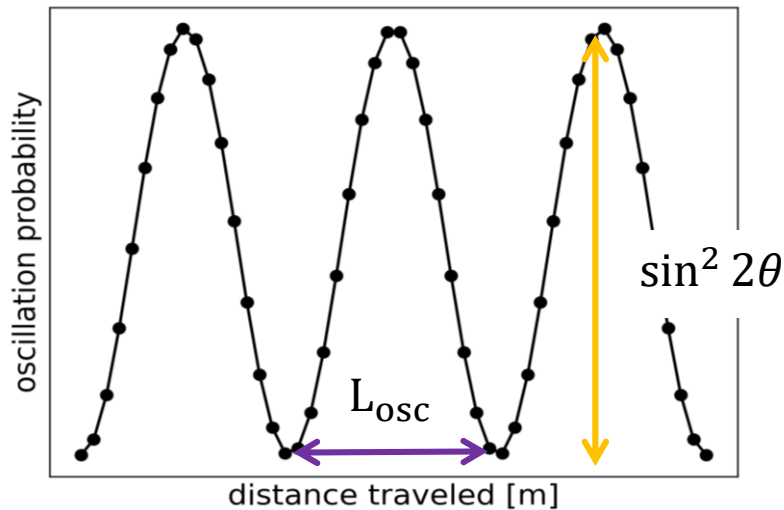
Never

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.

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

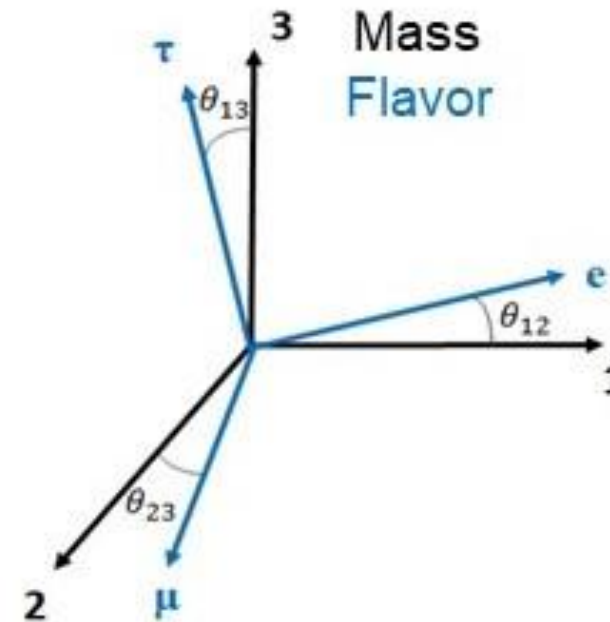
Atmospheric
Reactor
Solar



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

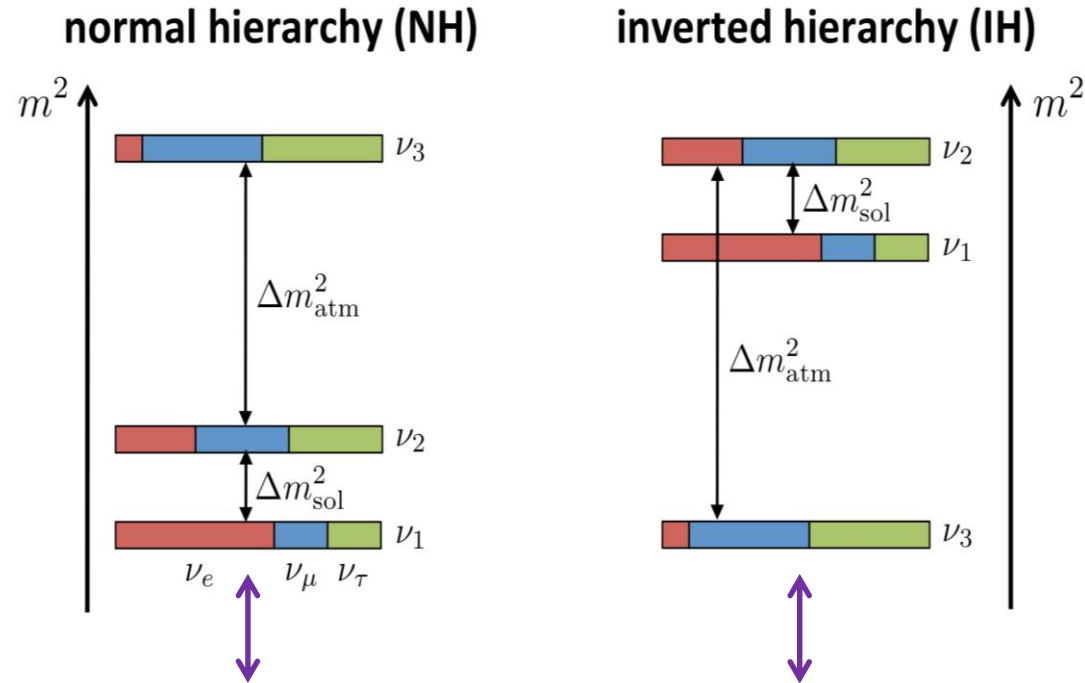
The oscillation depends of:

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



Absolute scale of neutrino masses unknown

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

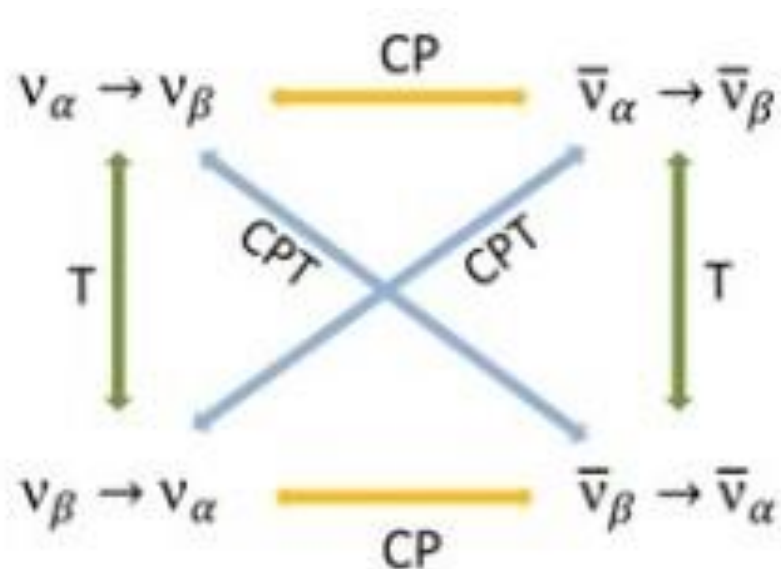
CP violation

We assume the world is CPT invariant

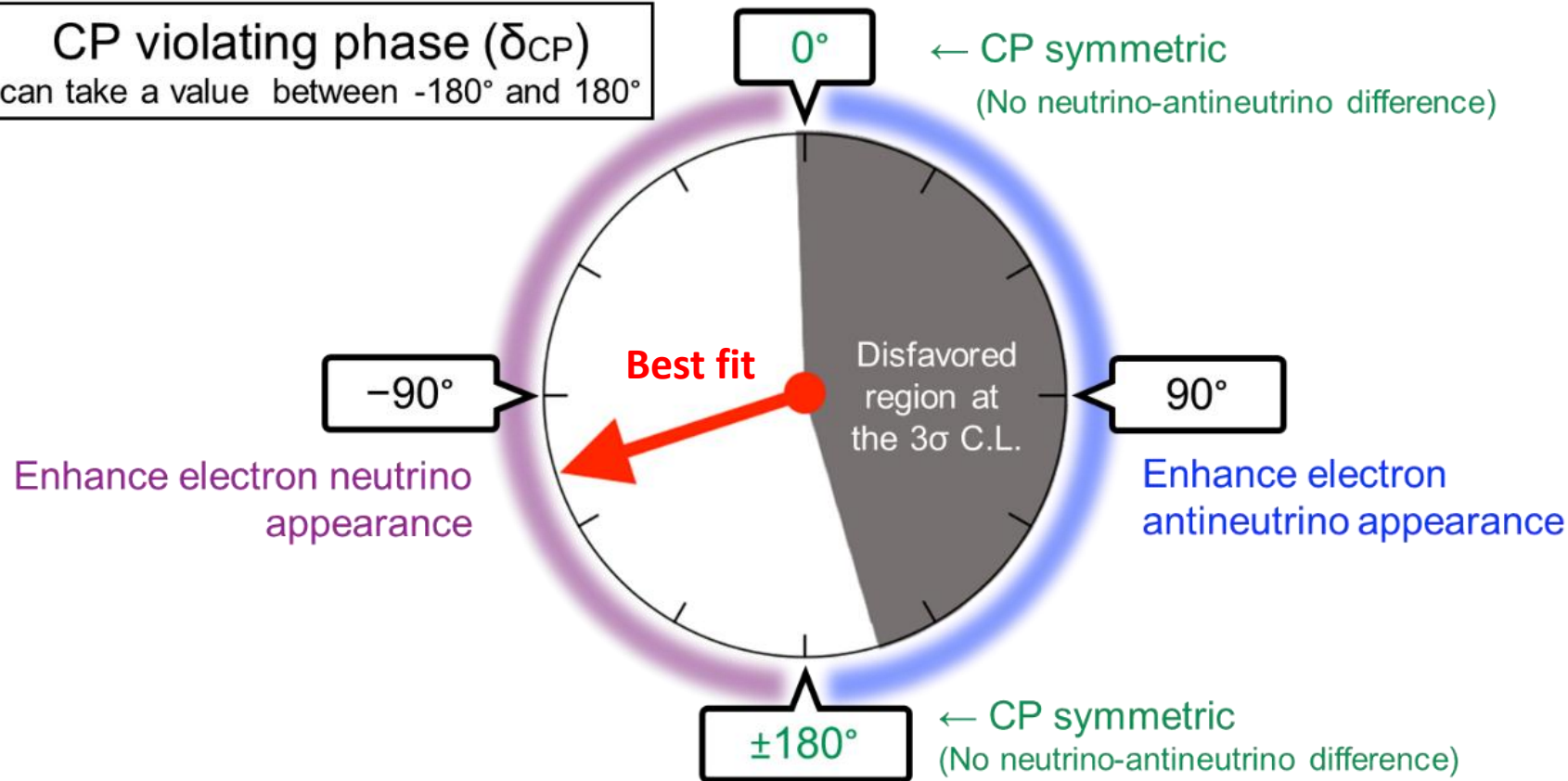
C: Particle → Antiparticle

P: Parity → Reversed Parity

T: Time → Reversed time



CP violating phase (δ_{CP})
can take a value between -180° and 180°



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

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

Why is it so hard to detect them?

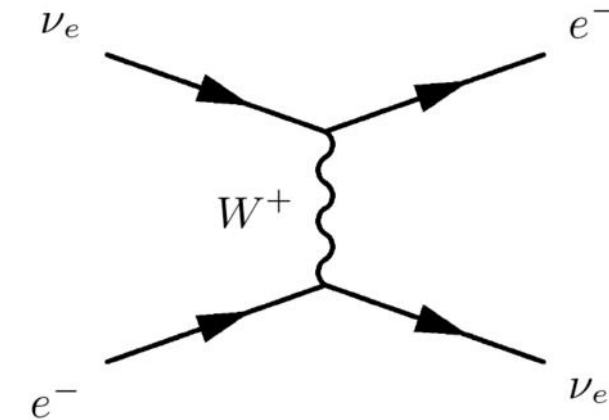


- With $E_\nu = 11$ MeV the mean free path in lead is 350 billion kilometers
- In earth ~3 out of 1 billion neutrinos would interact

Neutrino interactions

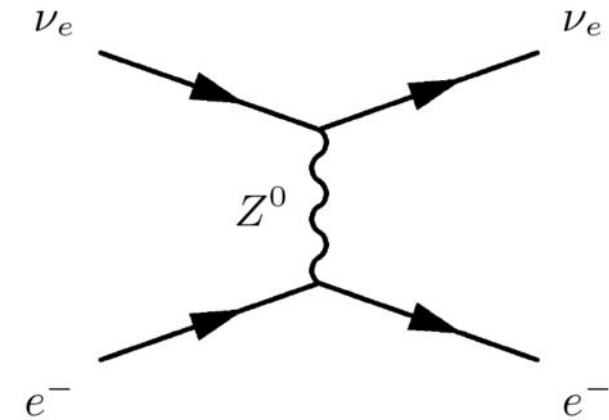
Charged current:

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



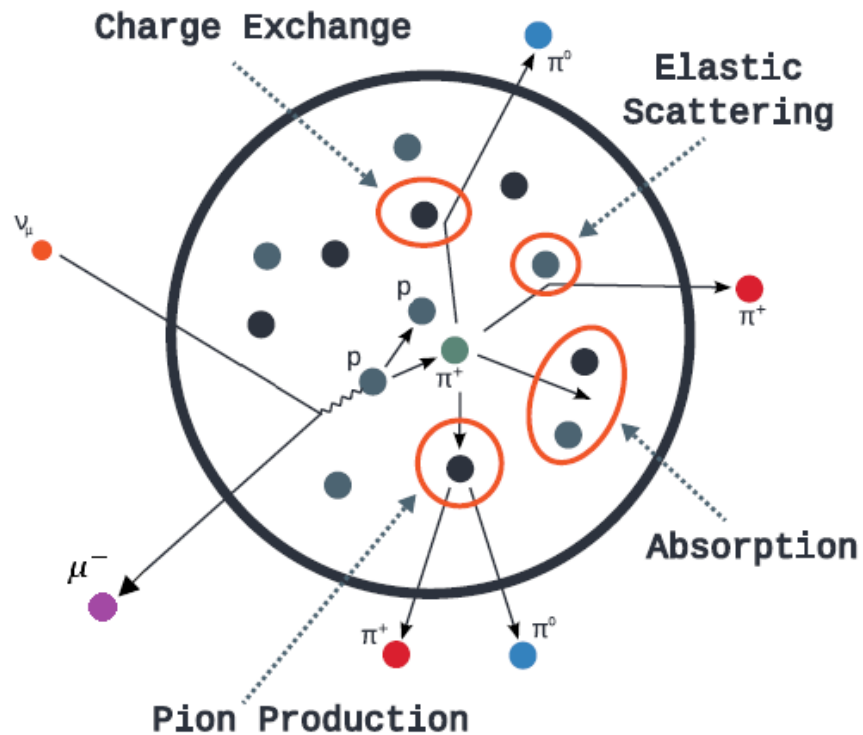
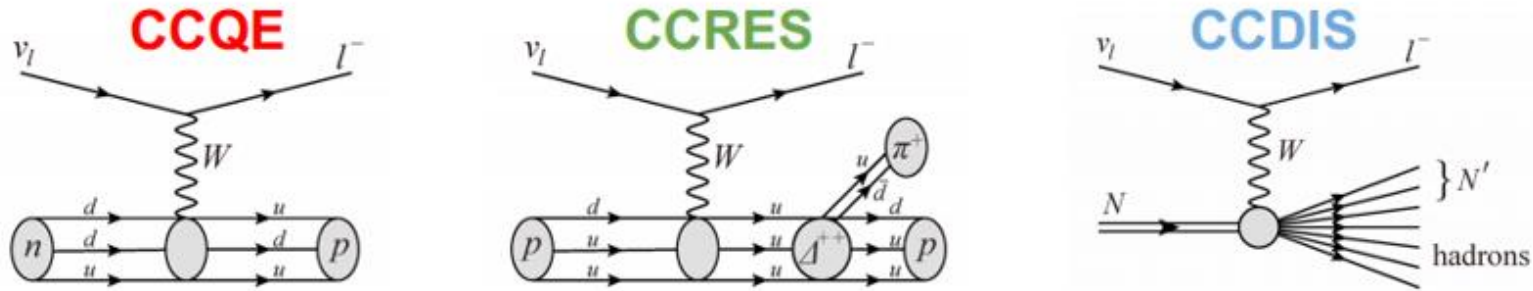
Neutral current:

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



Neutrino interactions

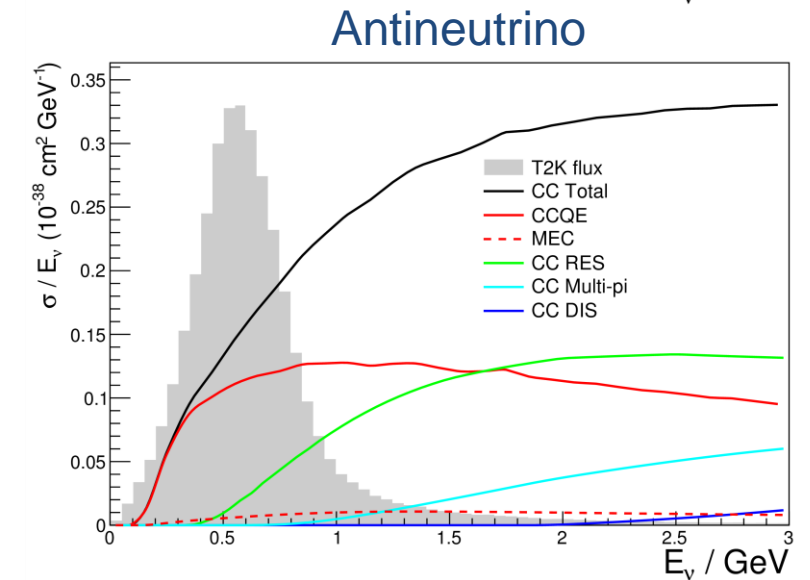
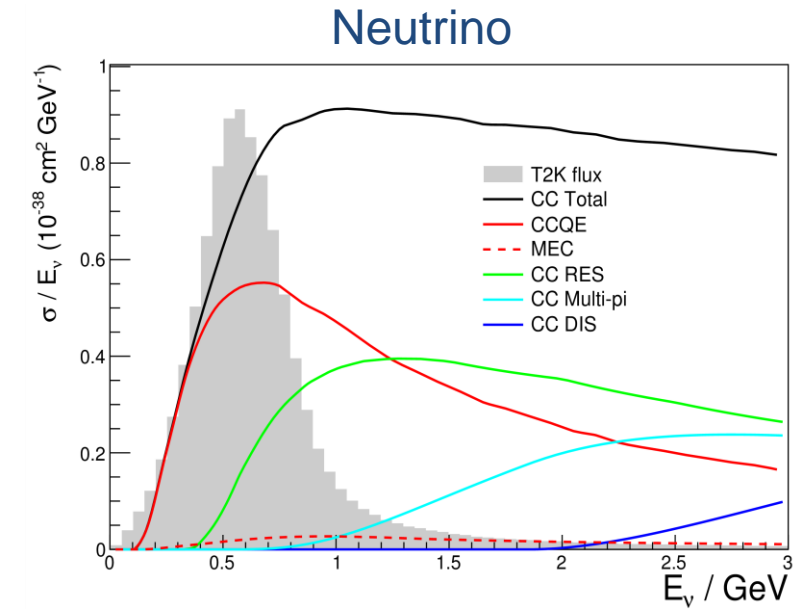
Interaction modes (nucleon level)



Three dominant scattering processes:

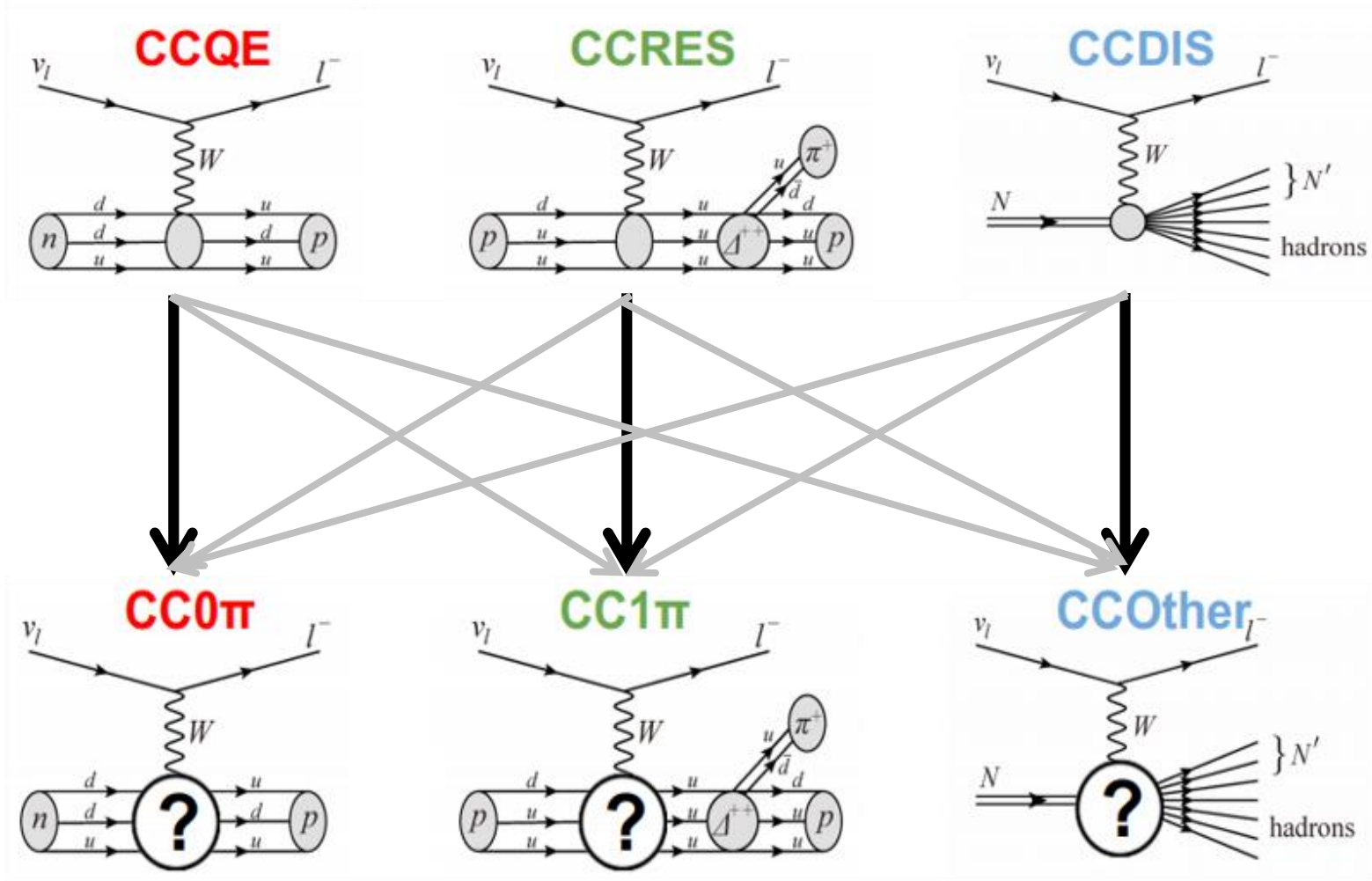
- Quasi Elastic,
- Resonant Pion Production,
- Deep Inelastic Scattering

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

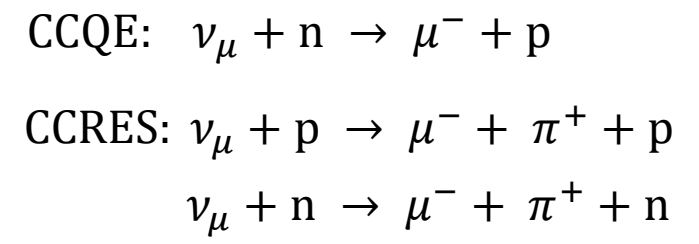


Neutrino interactions

Interaction modes (nucleon level)

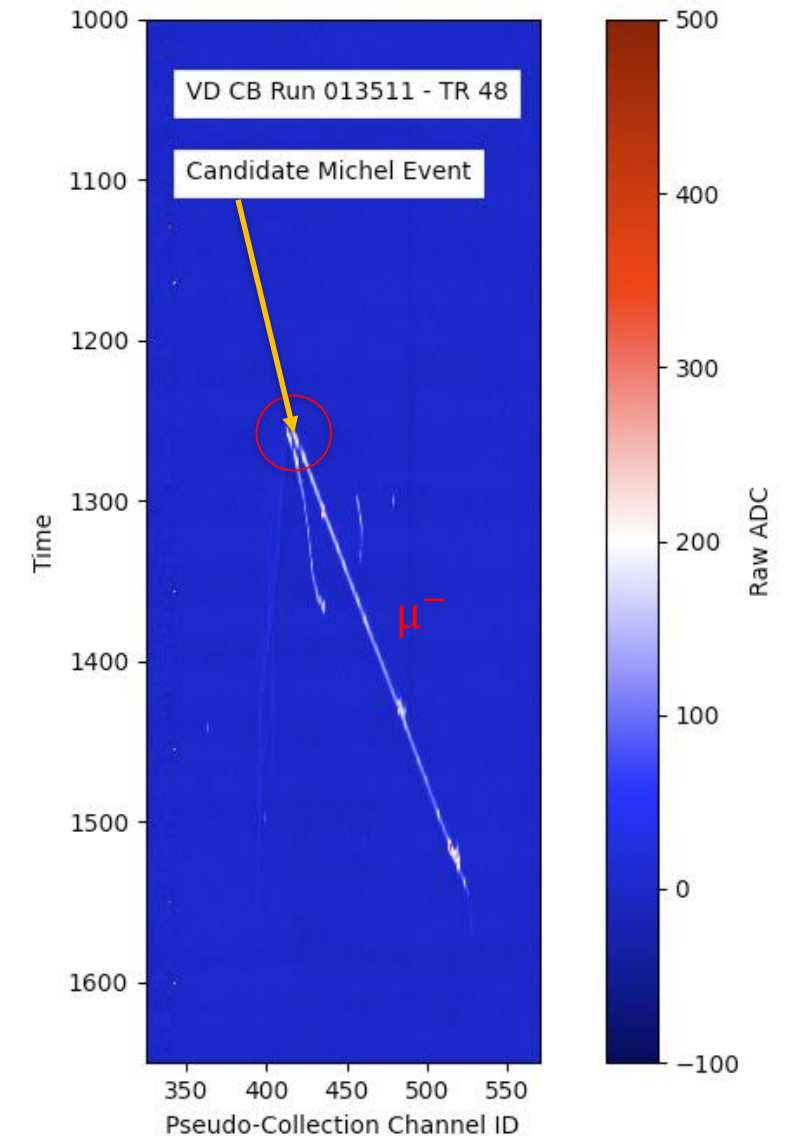
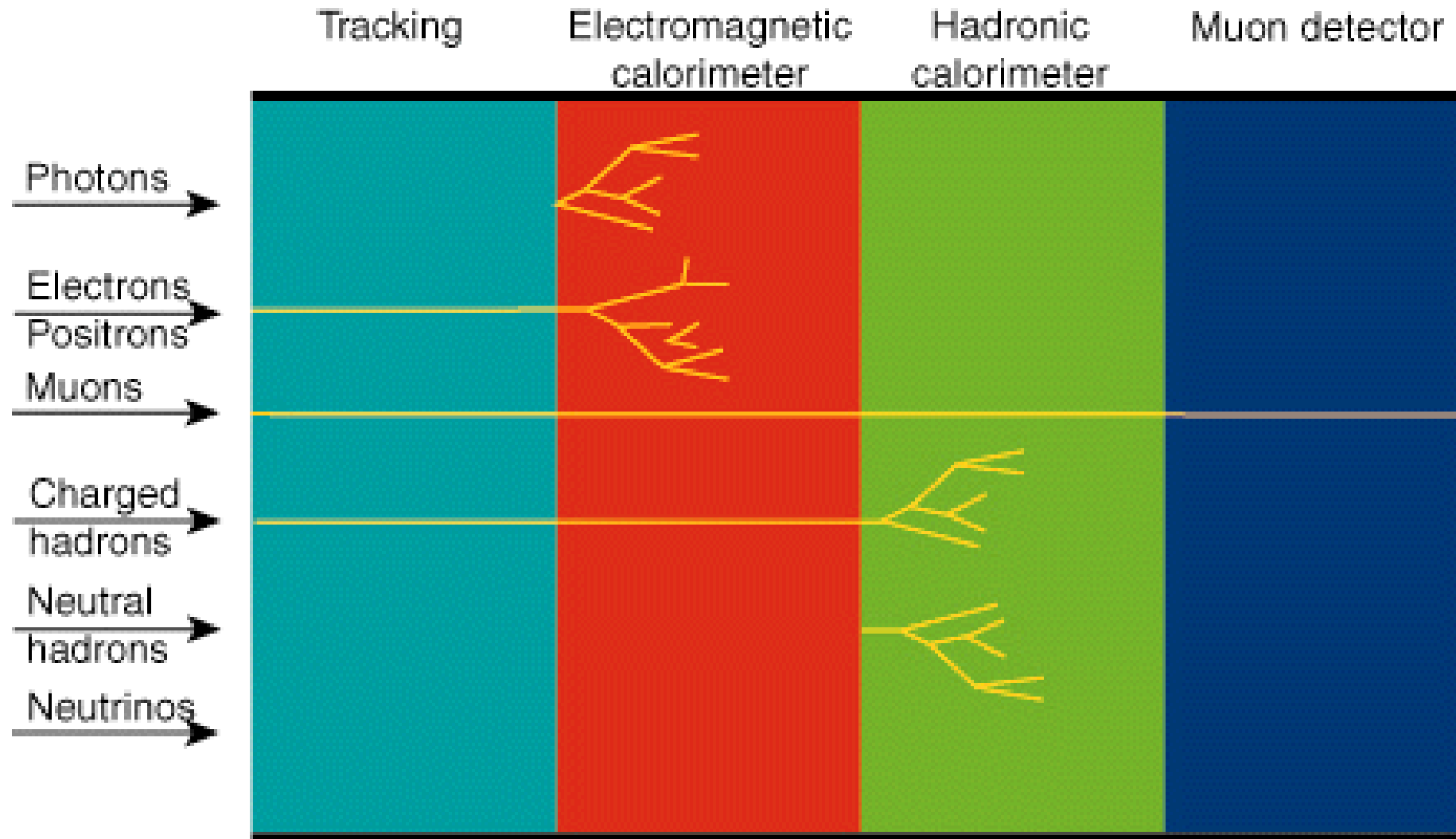


Nuclear Effects and Final State Interactions

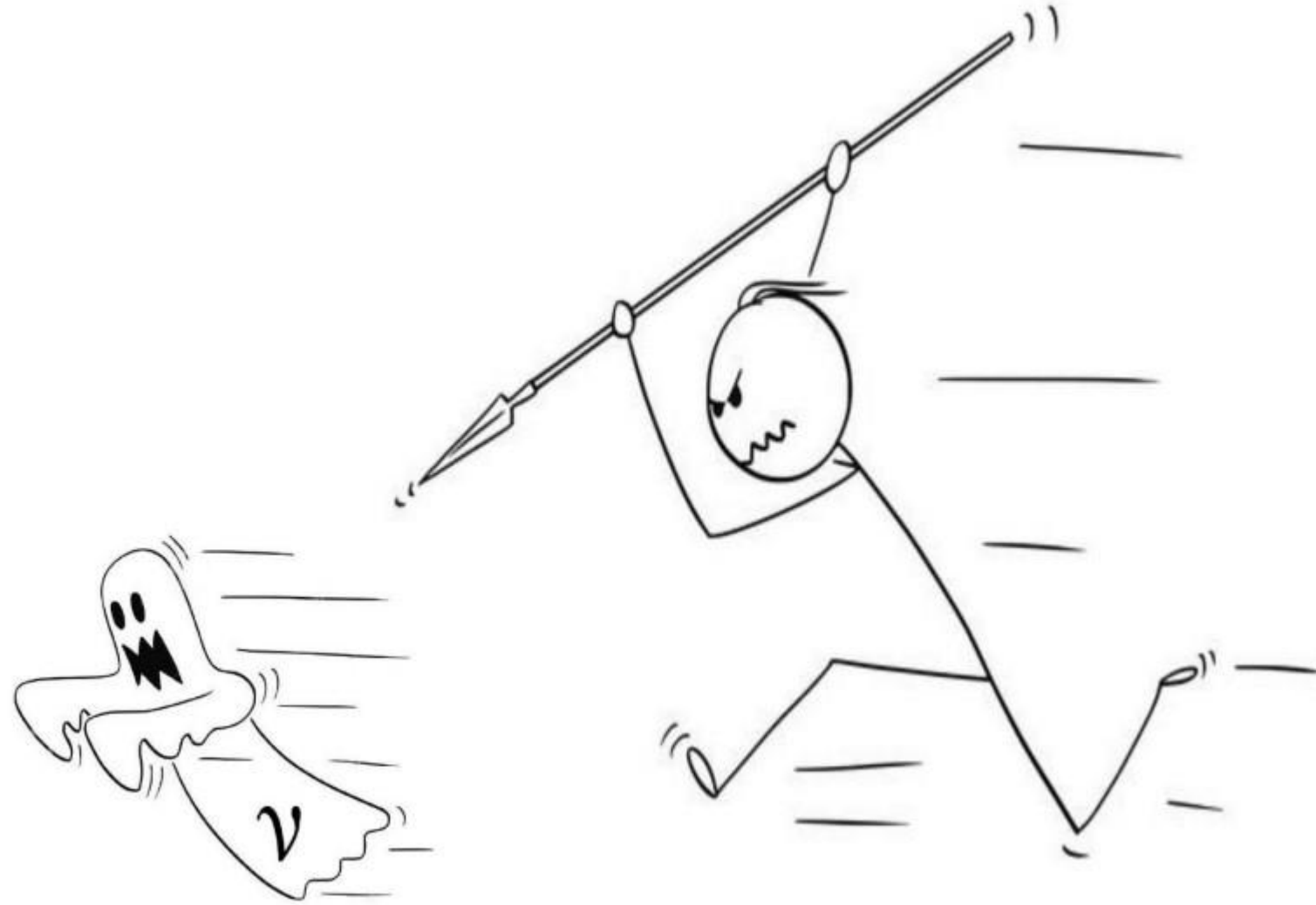


Interaction topologies (nucleus level)

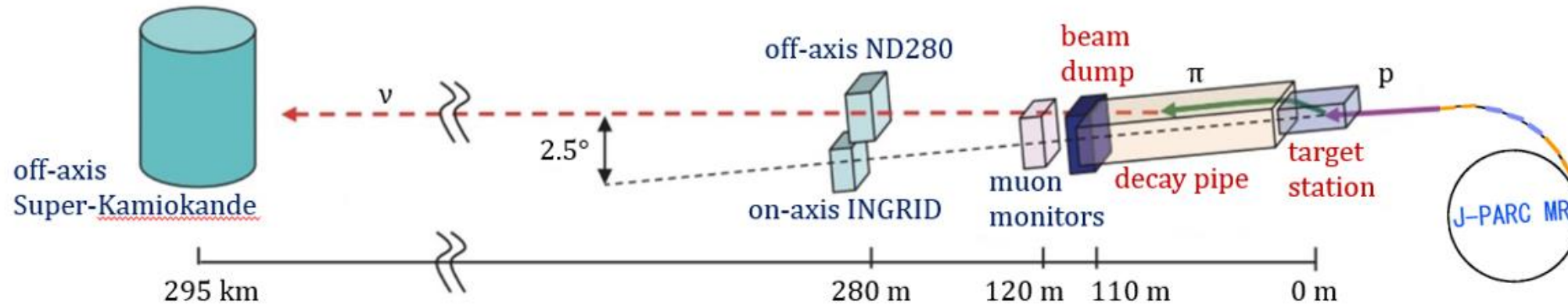
What do we see in the detector?



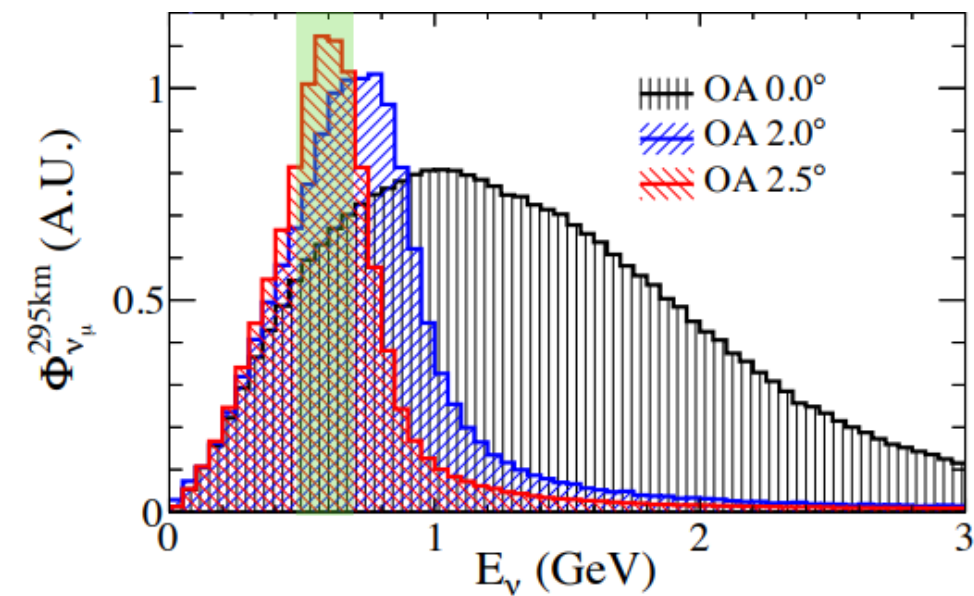
How do we ~~hunt~~ the neutrinos? detect



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

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

Neutrino flux

depends on the source

very energetic sources

Cross-section

It is very small and depends on the energy

go to higher energies

Far detector

The neutrino energy is reconstructed:

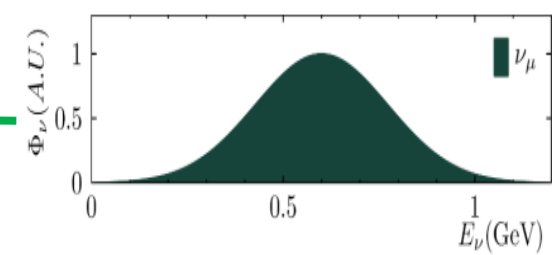
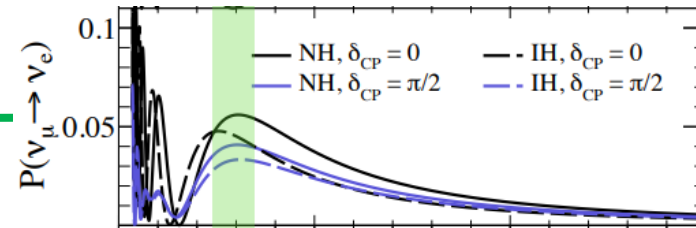
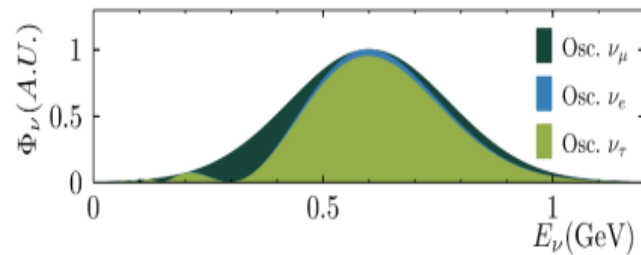
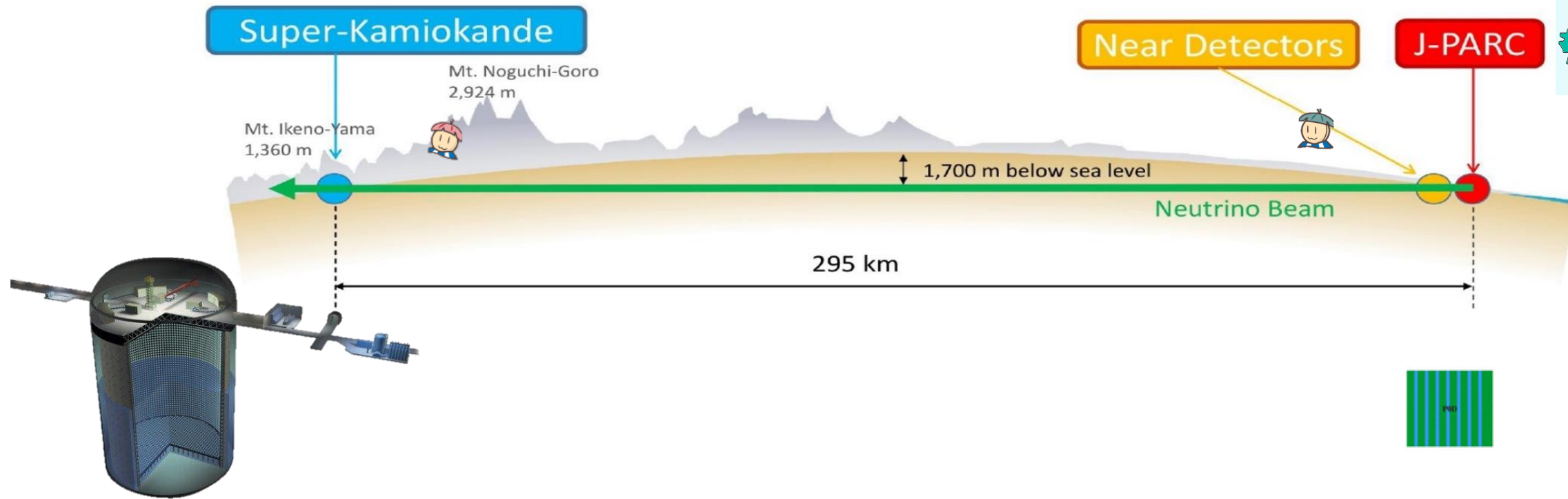
- using leptonic and hadronic kinematics,
- assuming stationary target (a nucleon)
- massless neutrino.

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 θ_{13} , θ_{23} , δ_{CP} and Δm_{32}^2

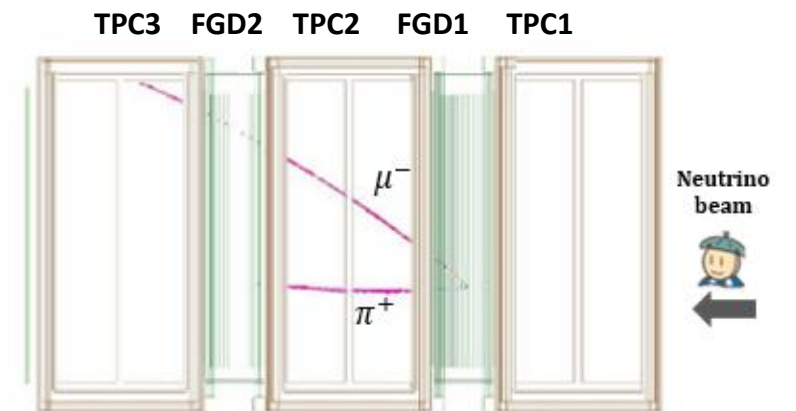
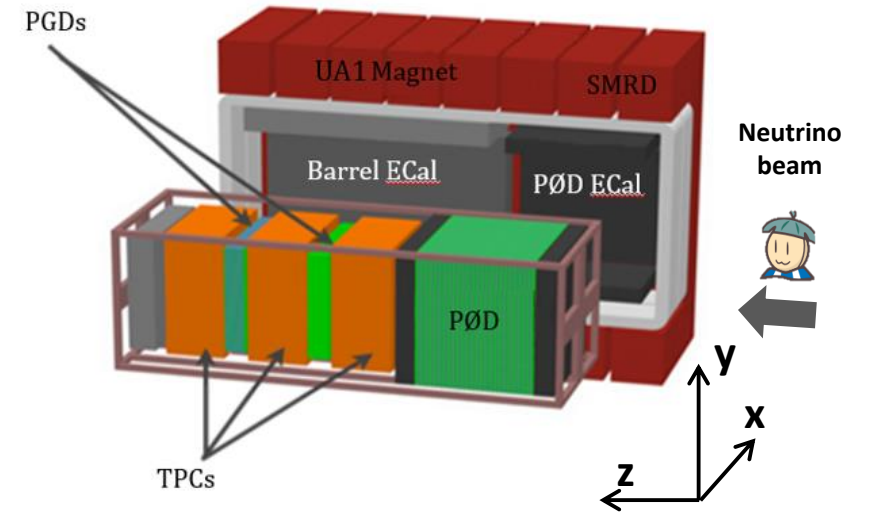


T2K experiment: near detector

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

ND280 is formed by:

- Pion zero detector (P \emptyset D): 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.

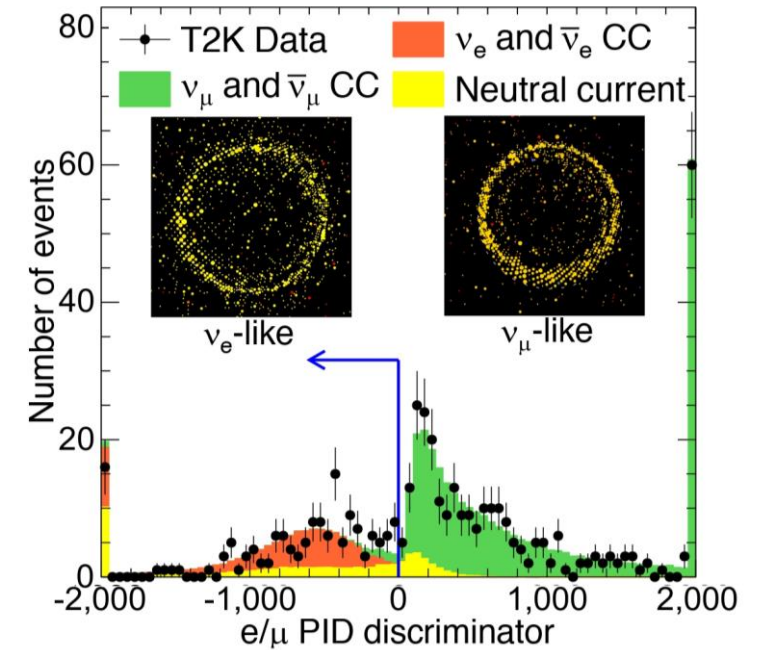
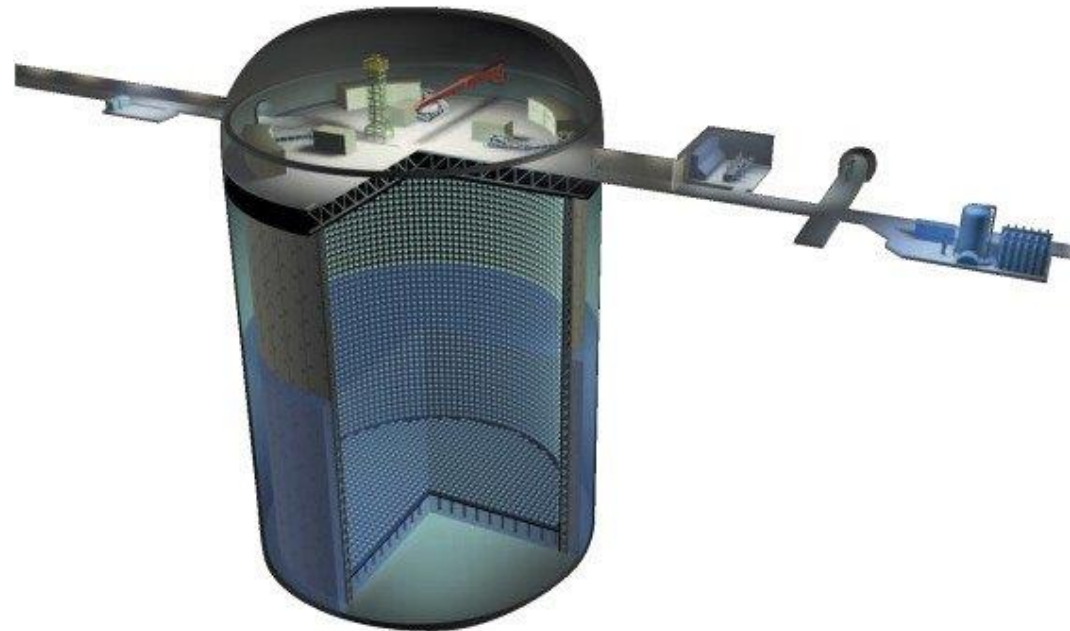


T2K experiment: far detector

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



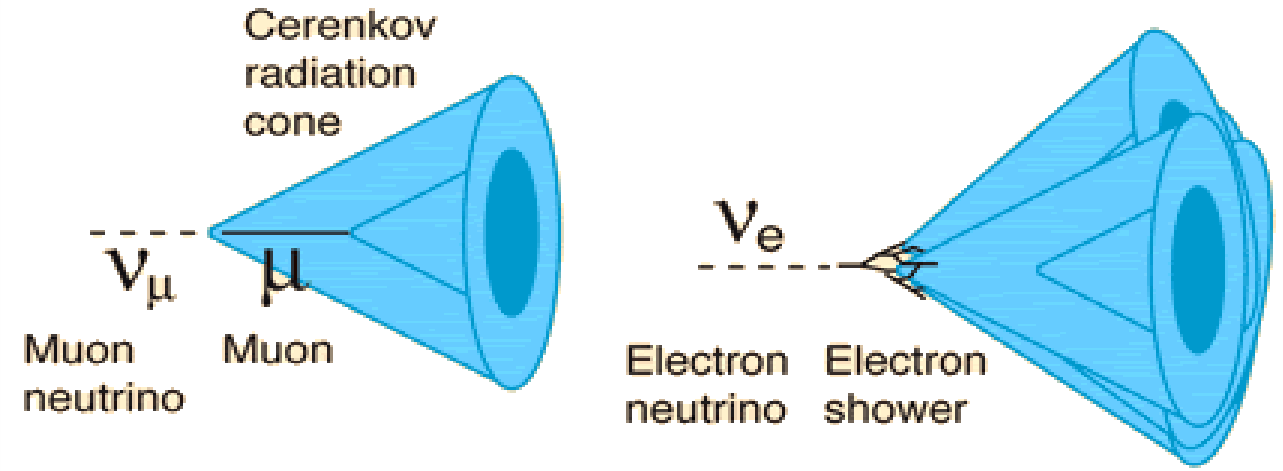
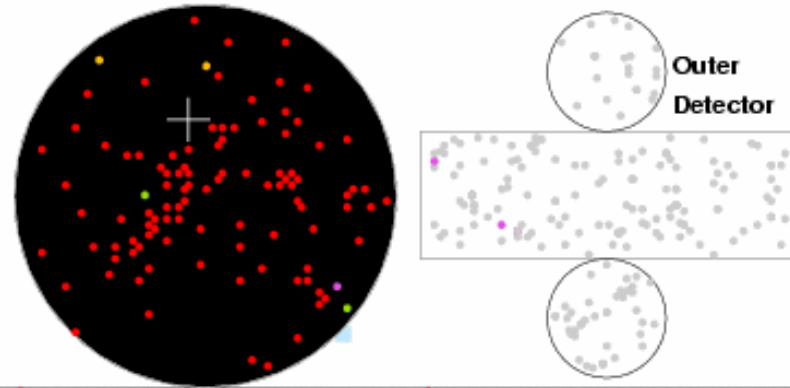
<https://www.nature.com/articles/s41586-020-2177-0>



T2K experiment: far detector

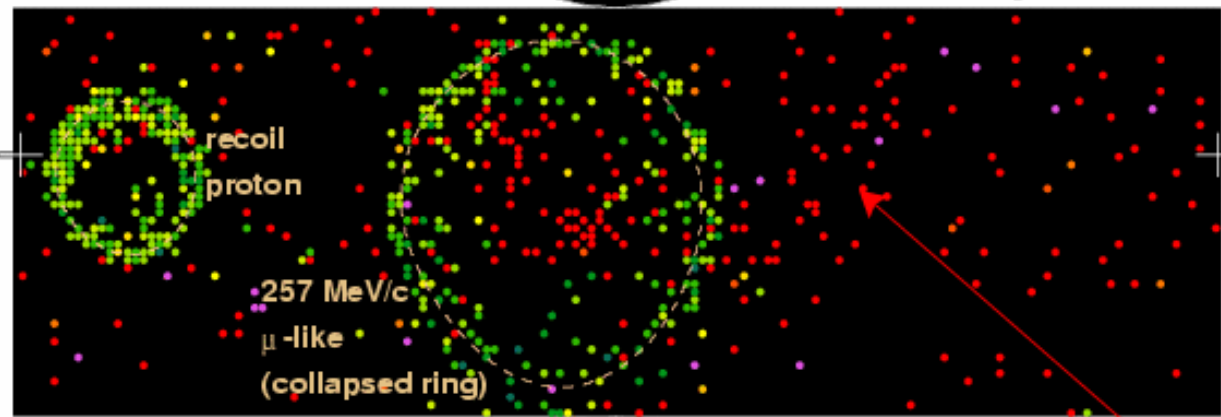
Super-Kamiokande

Run 1734 Event 38449
56-05-29:21:23:05

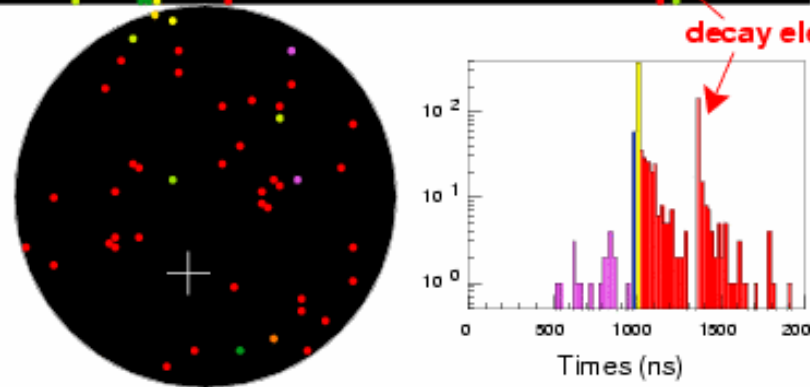
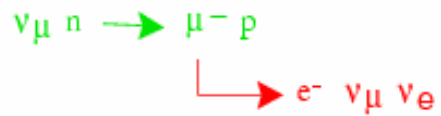


Resid (ns)

- > 22
- 20- 22
- 17- 20
- 14- 17
- 11- 14
- 8- 11
- 5- 8
- 2- 5
- 0- 2
- -2- 0
- -5- -2
- -8- -5
- -11- -8
- -14- -11
- -17- -14
- < -17

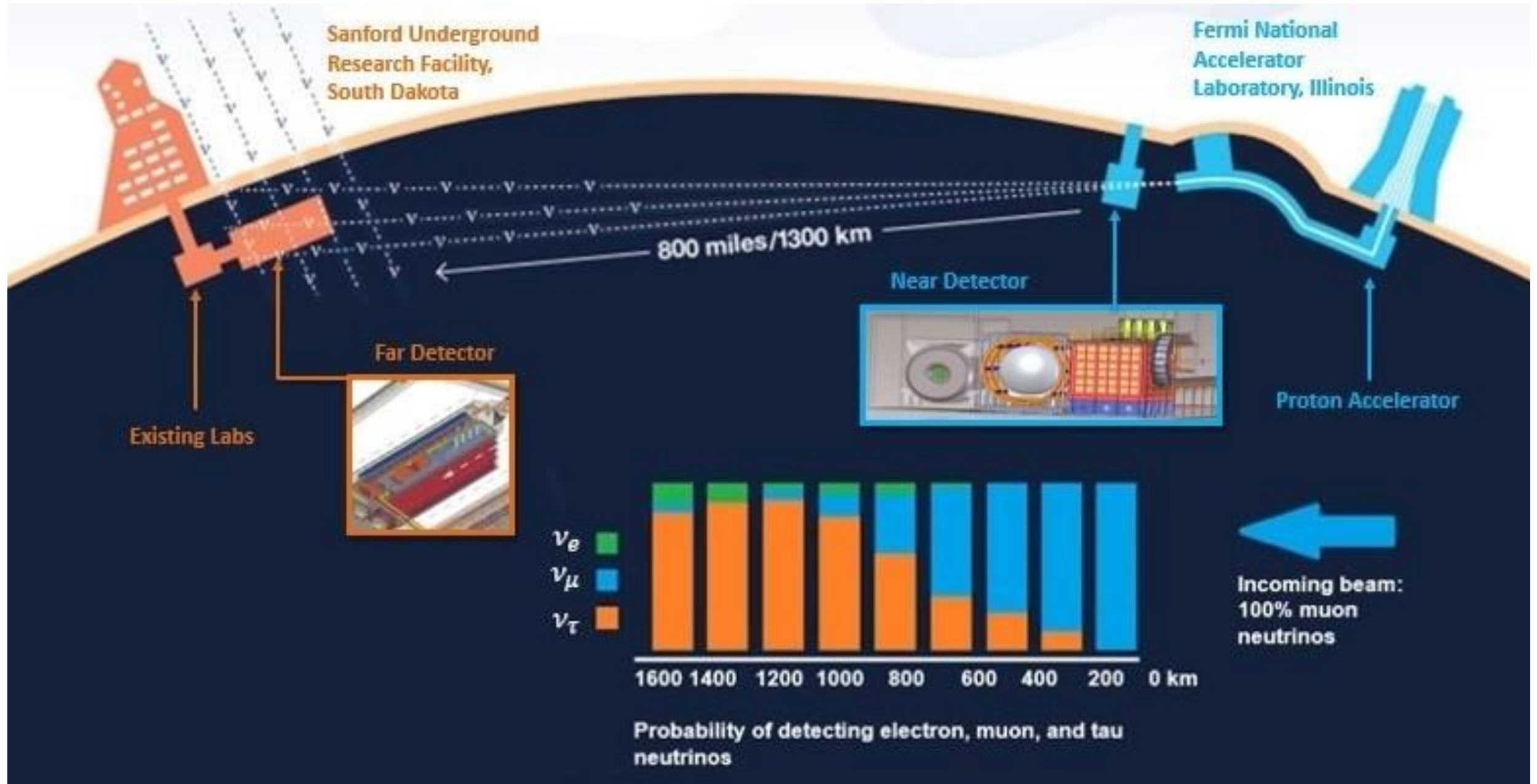


Quasi-elastic

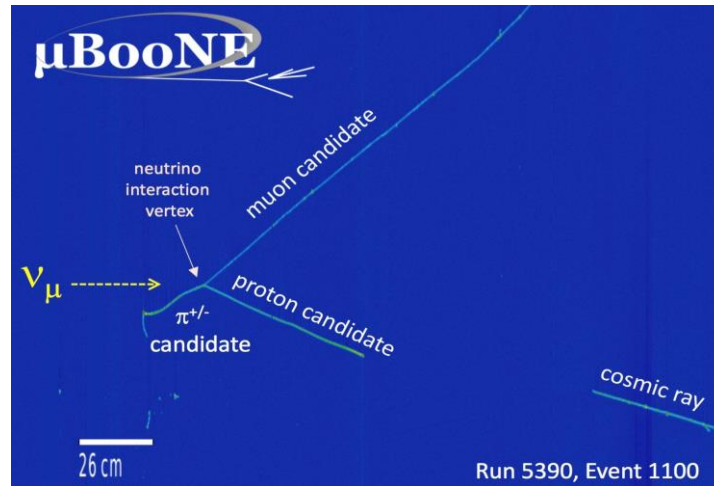


- Particle identification
- Particle range
- Interaction vertex reconstruction
- Electromagnetic energy reconstruction
- Track Multiplicity

DUNE experiment

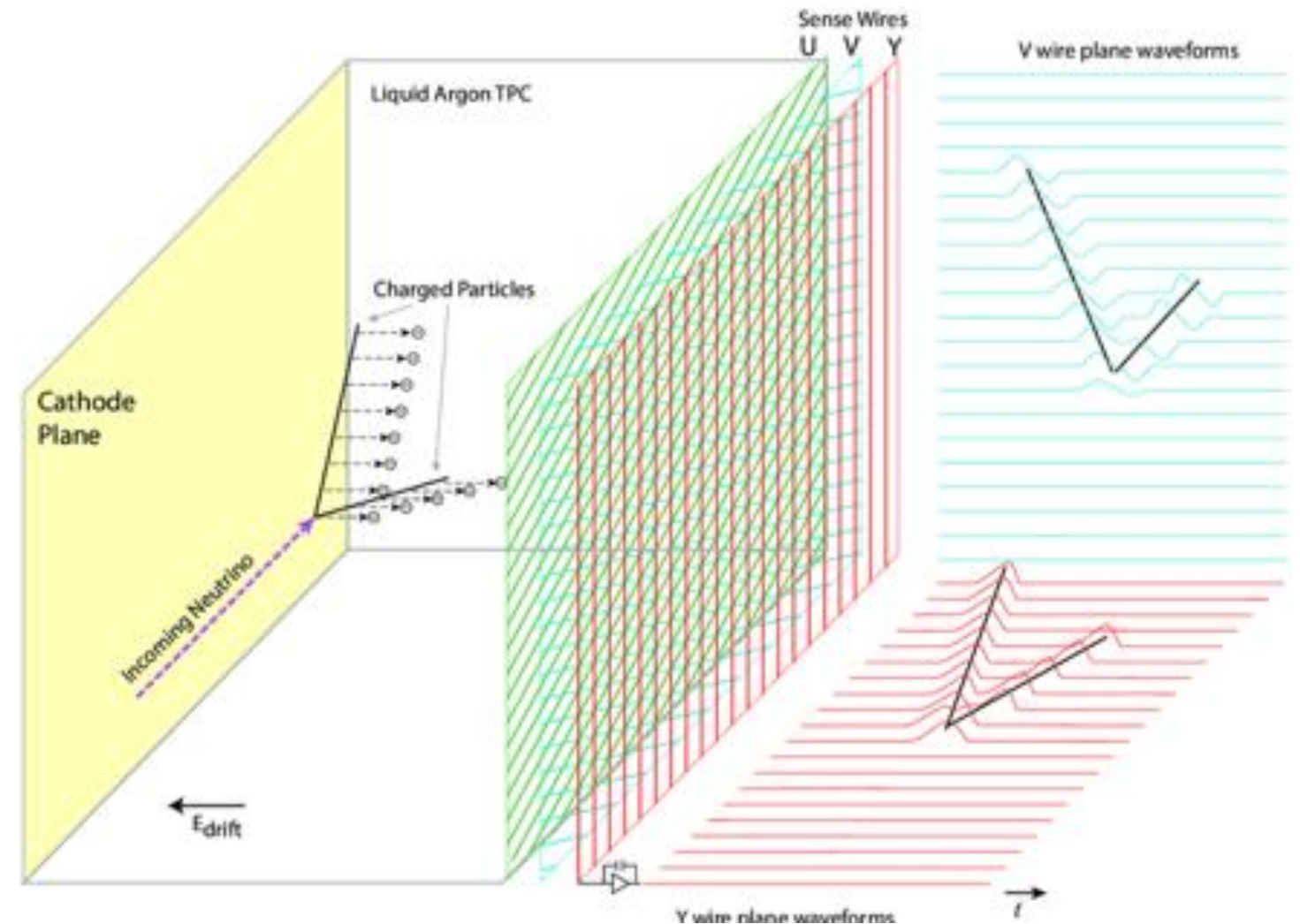


LAr TPC working principle



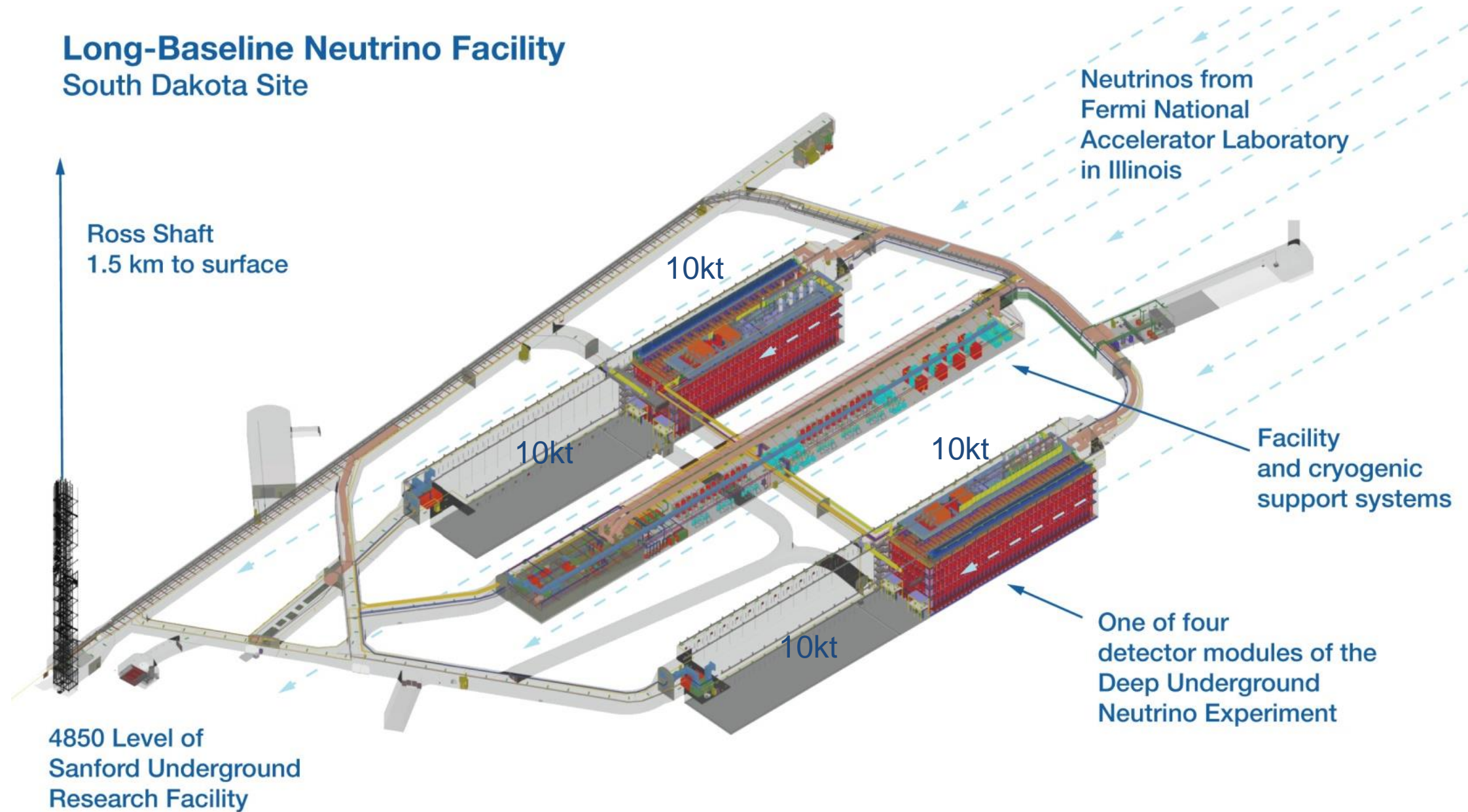
Liquid Argon Time Projection Chamber: technology capable of measuring with sub-centimeter precision ionization tracks and is sensitive to energies in the range 5MeV – 100GeV.

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



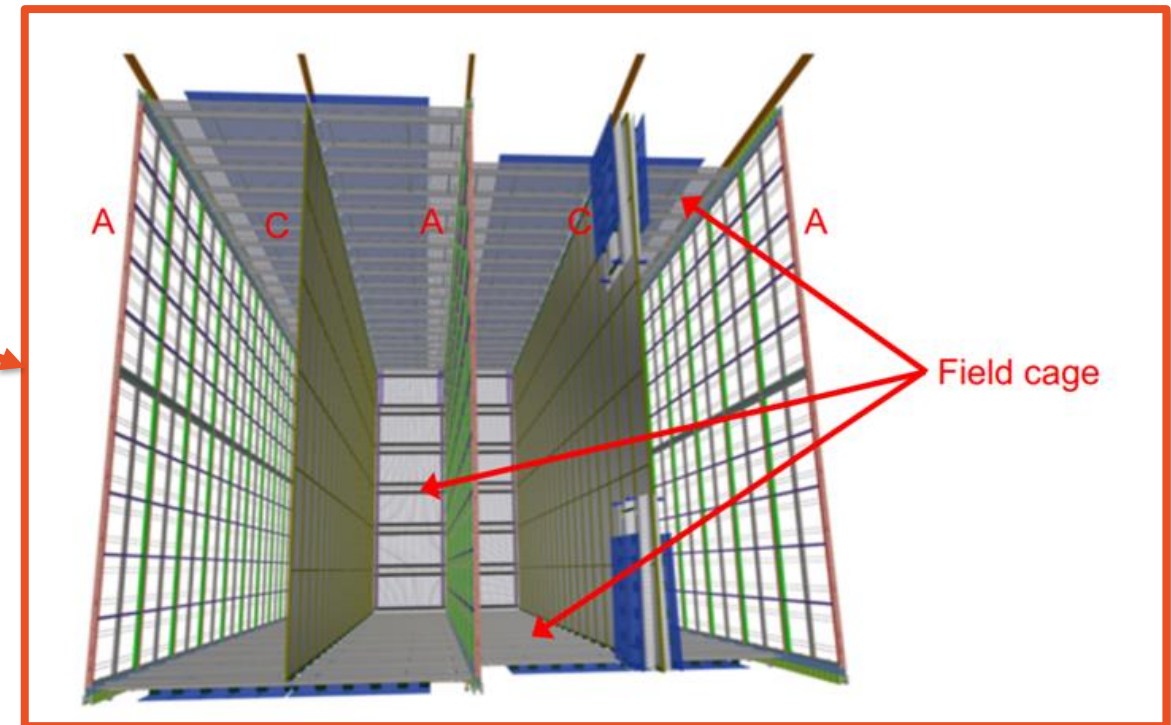
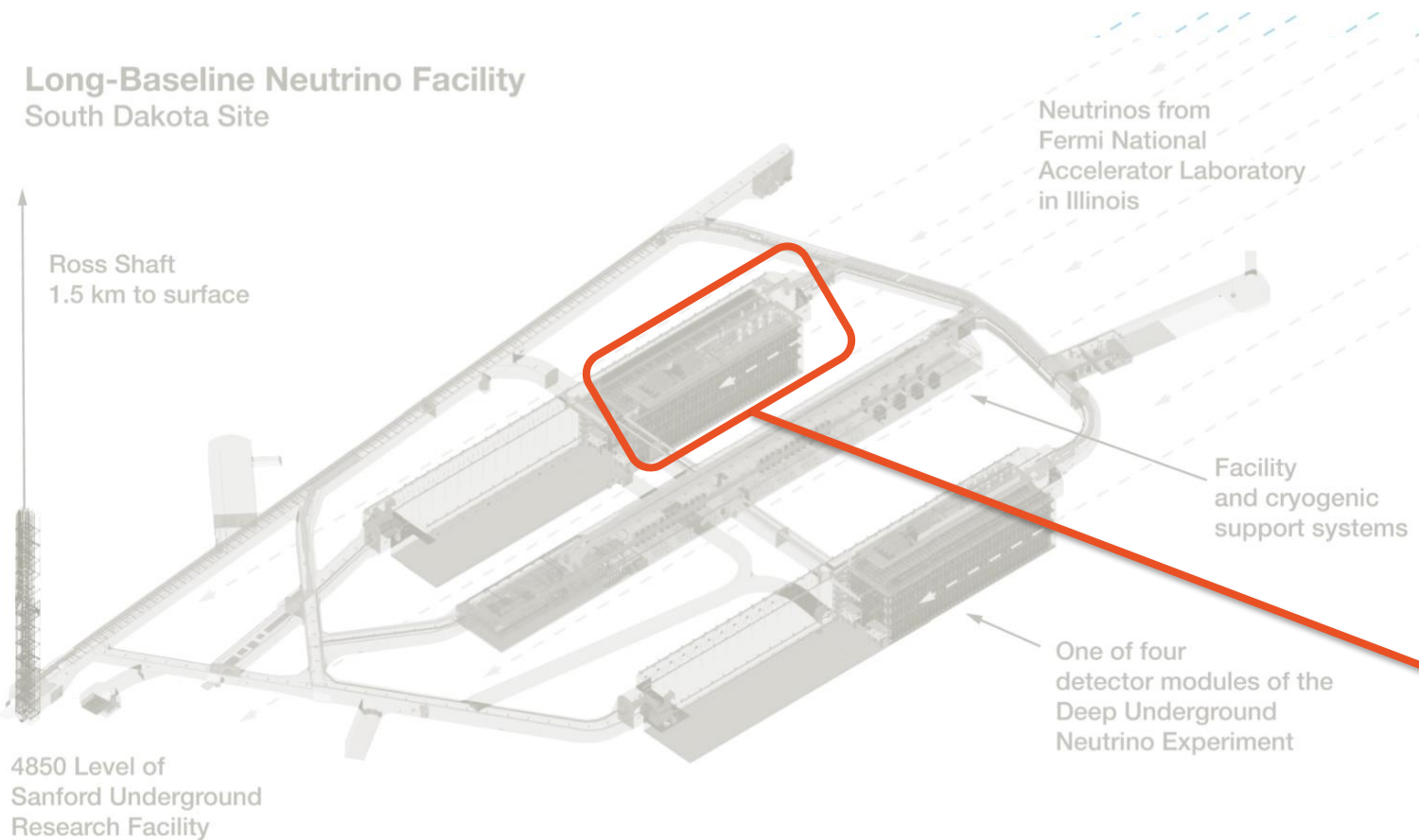
DUNE experiment: far detector

Long-Baseline Neutrino Facility
South Dakota Site



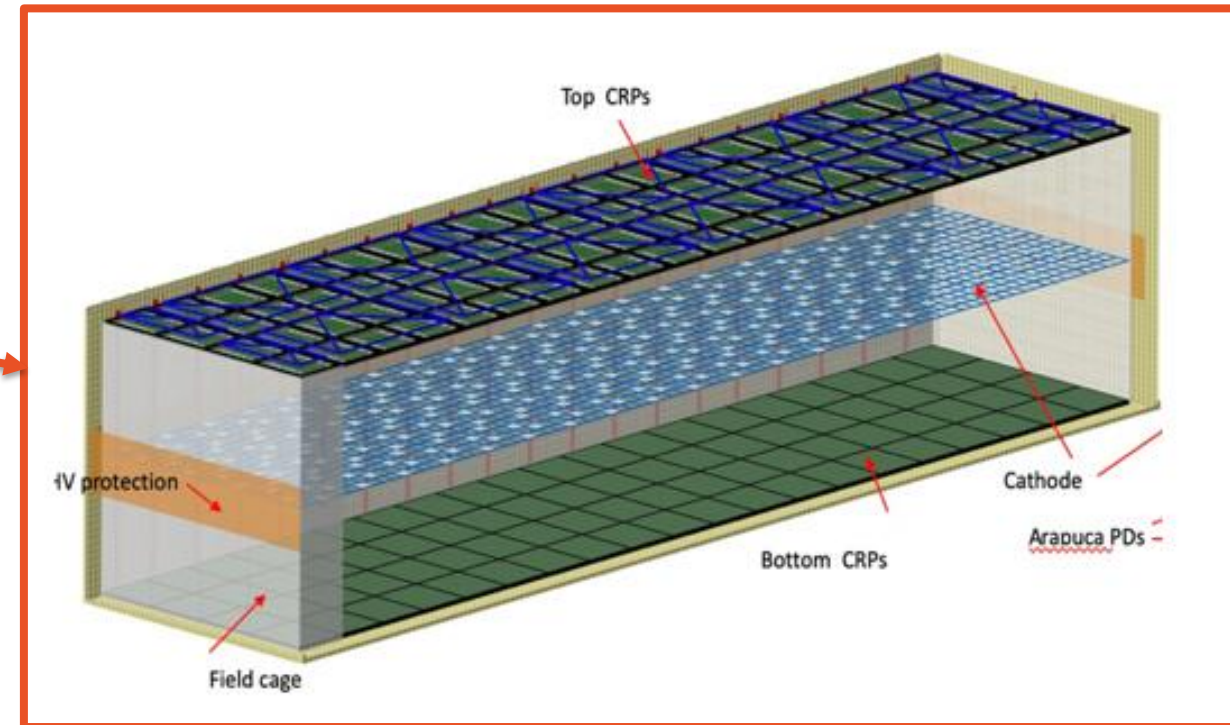
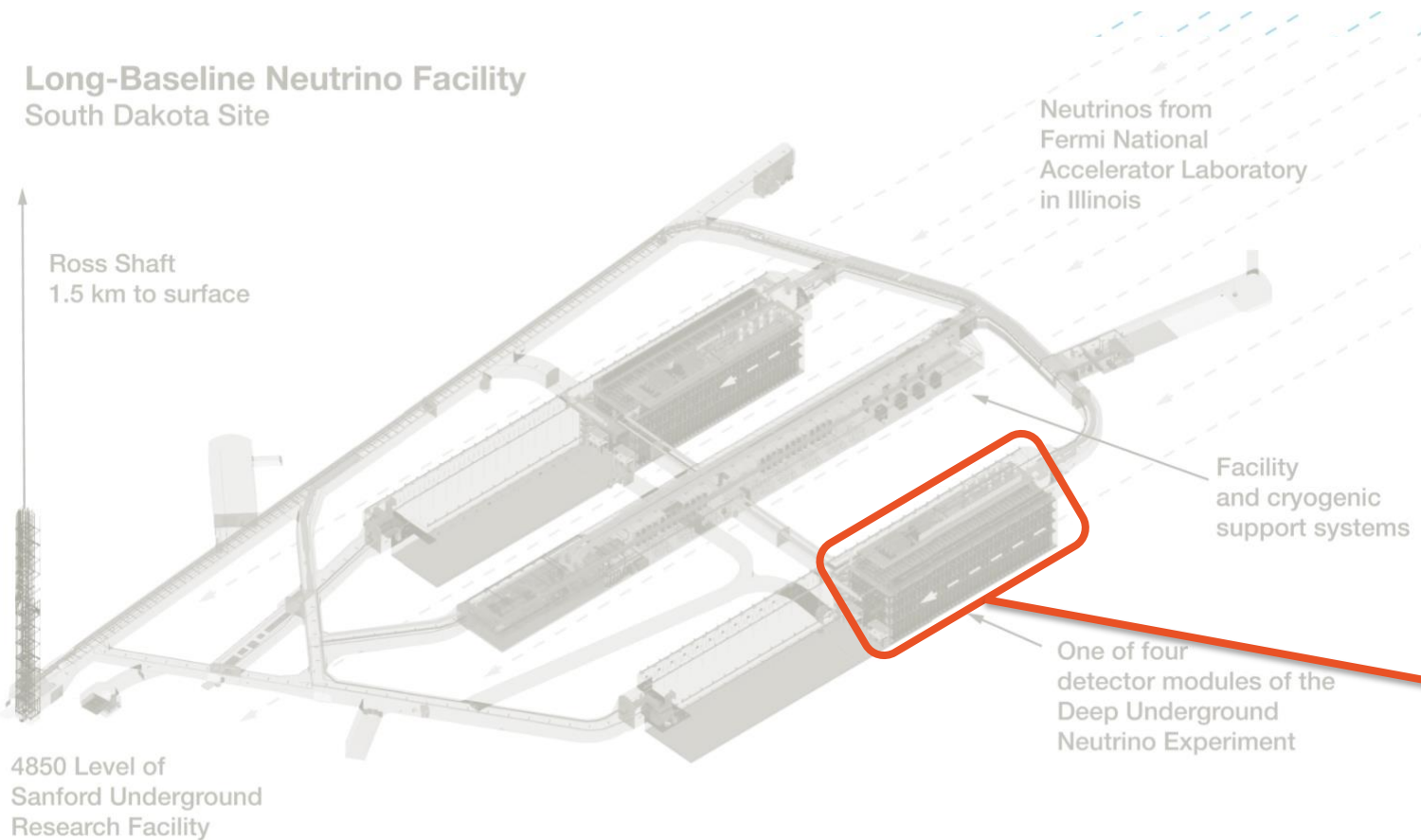
DUNE experiment: far detector

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



DUNE experiment: far detector

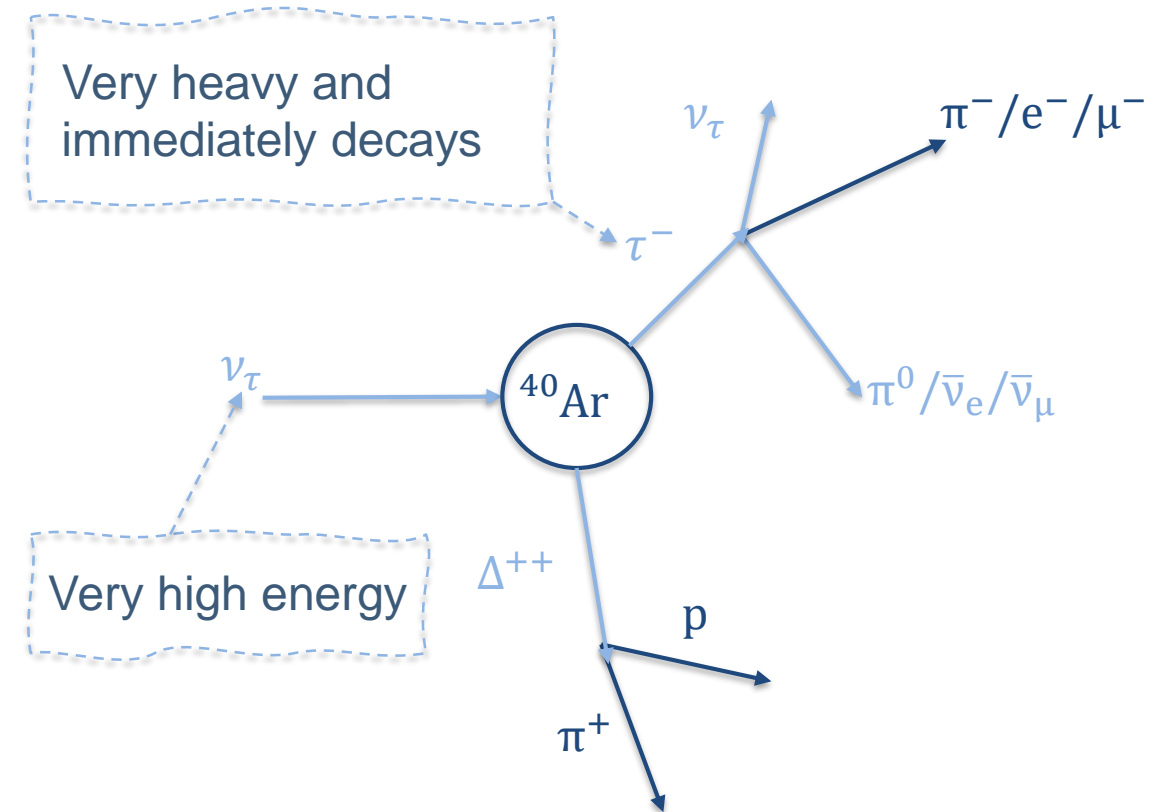
Second 10 kt module will be Single Phase (SP) design with Vertical Drift (VD), LArTPC divided into 2 drift volumes.



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

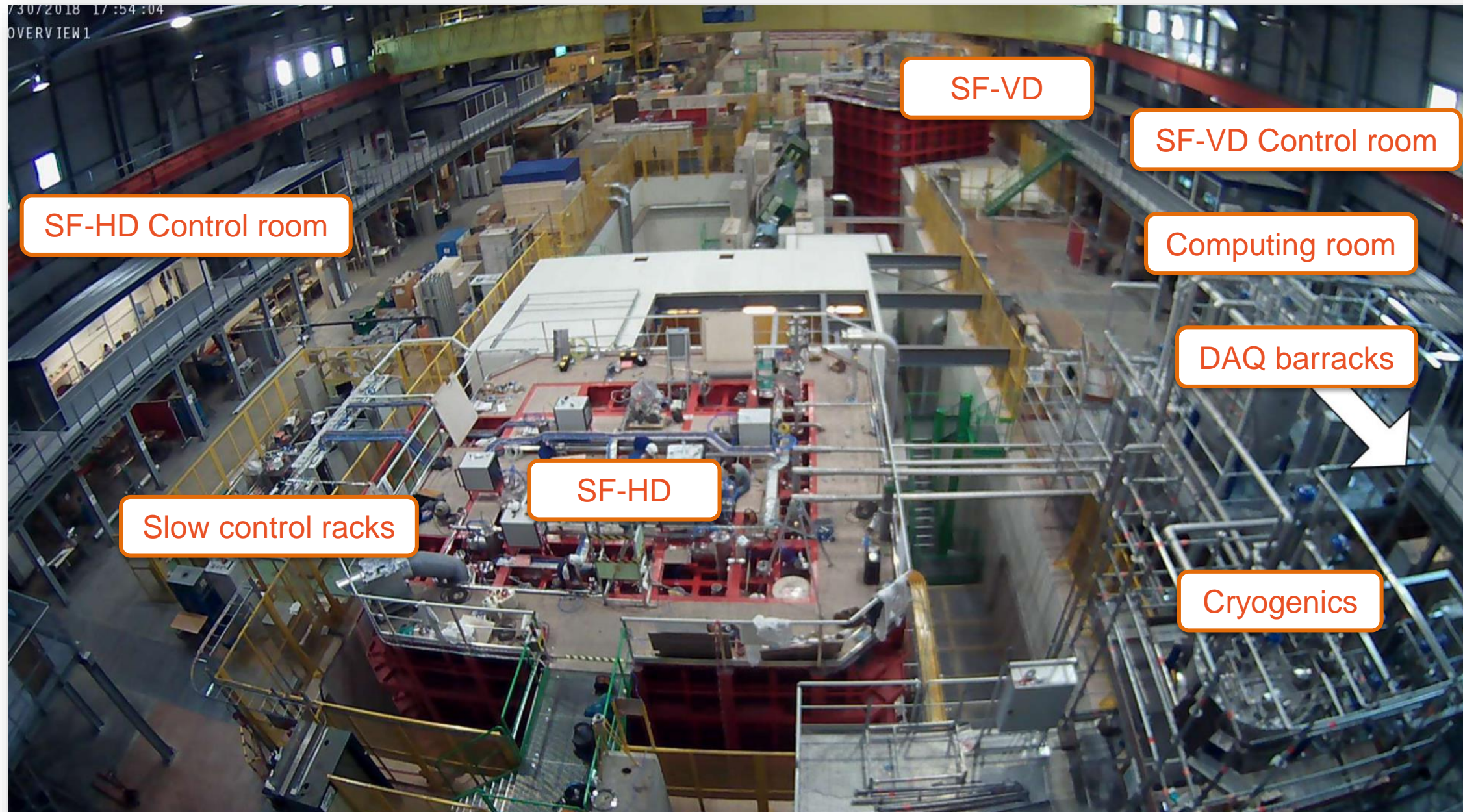
These assumptions need to be tested!!!



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 $\delta_{CP} > 0$ values a 99.7% Confidence Level
- Beyond the Standard Model Physics is being studied in our experiments
 - PMNS non-unitarity

What are neutrinos?

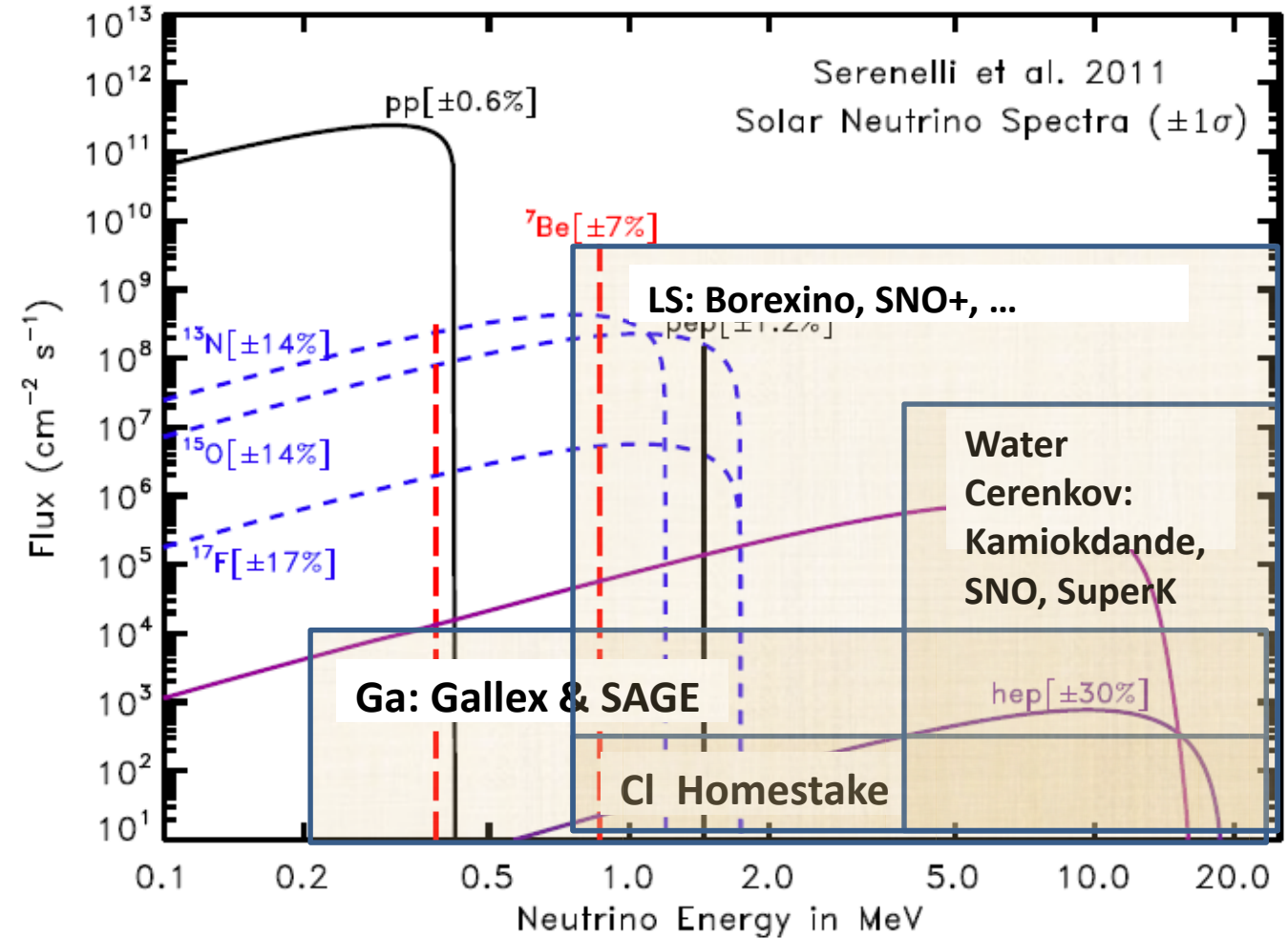
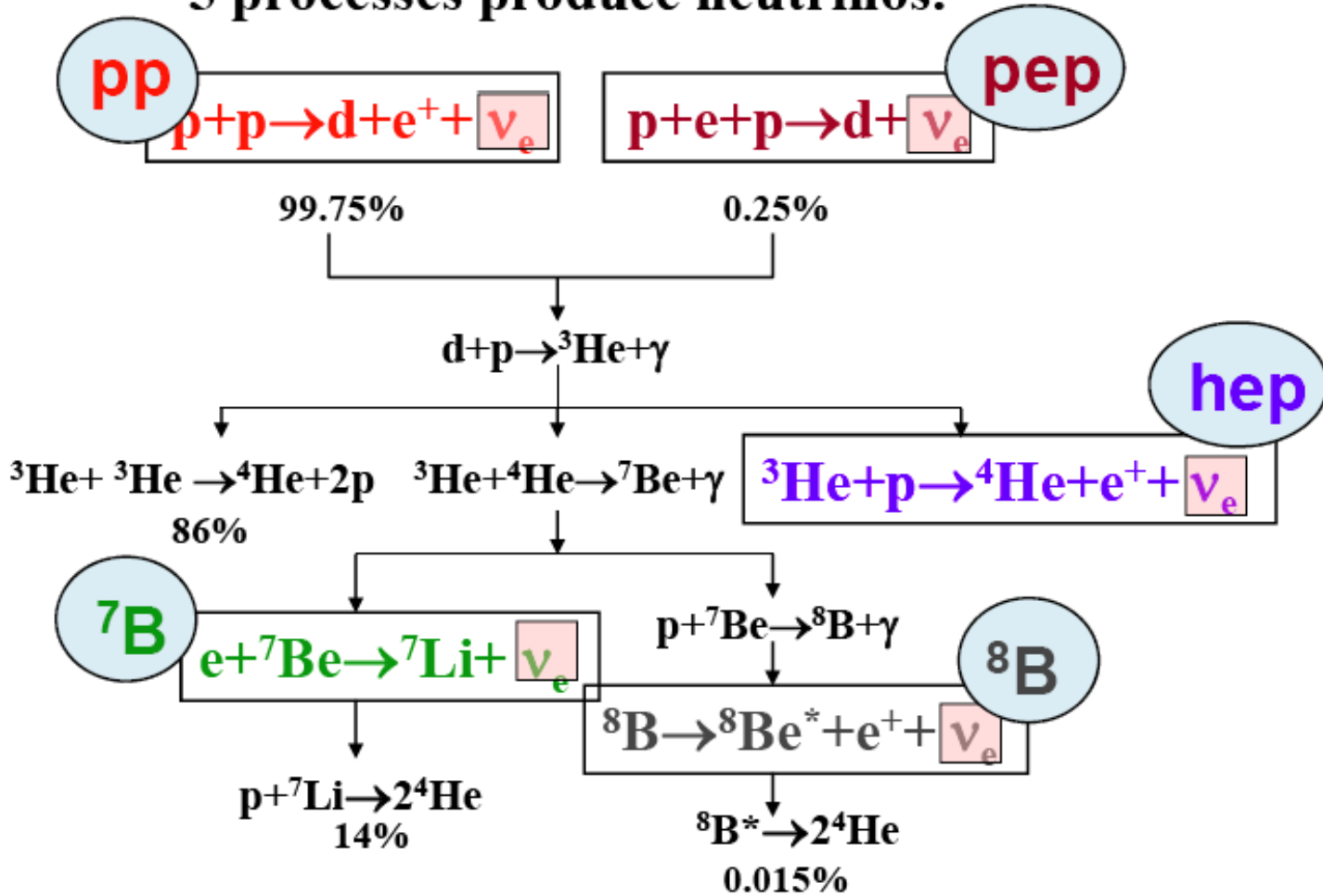
How do we detect them?

Why are they important?



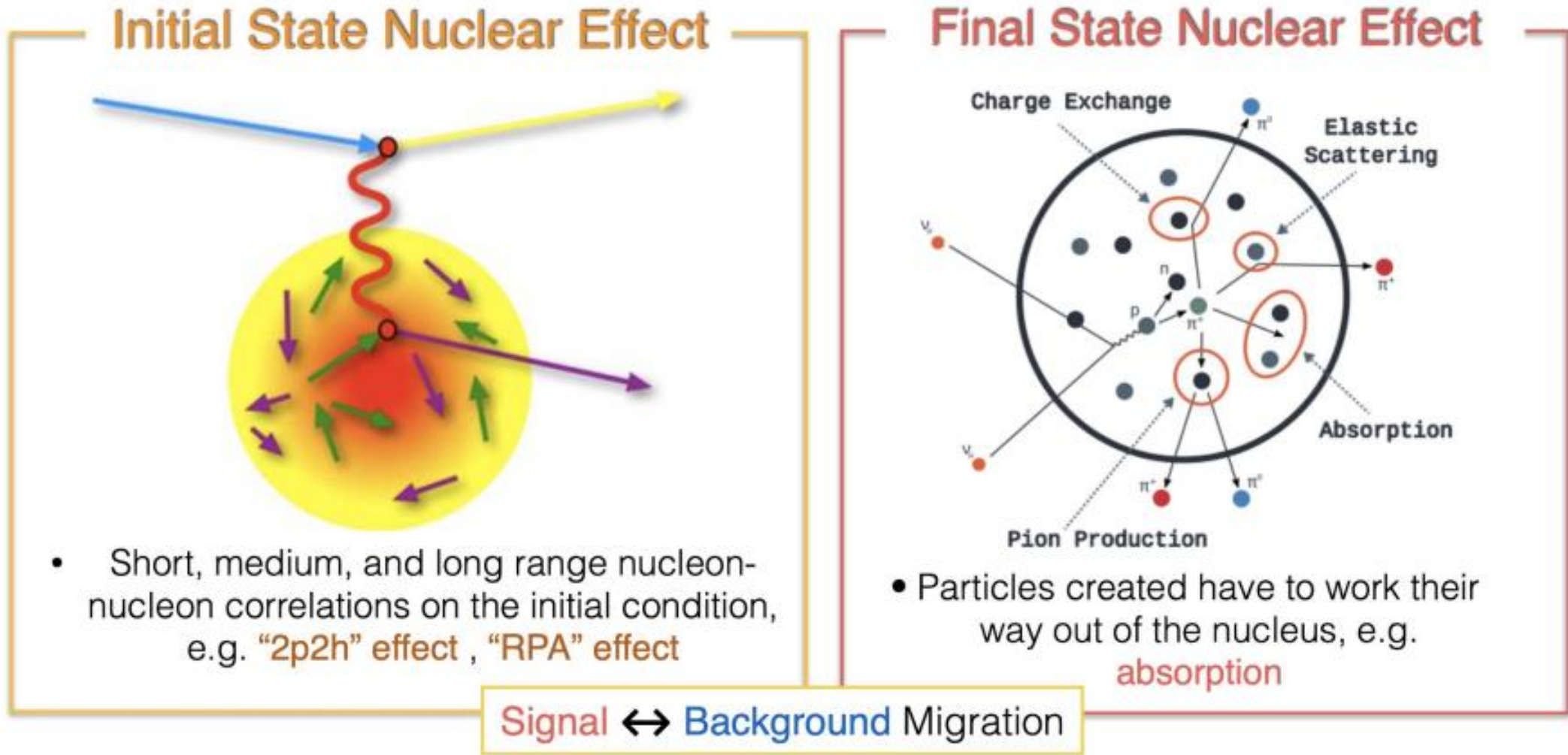
Solar neutrinos

5 processes produce neutrinos.



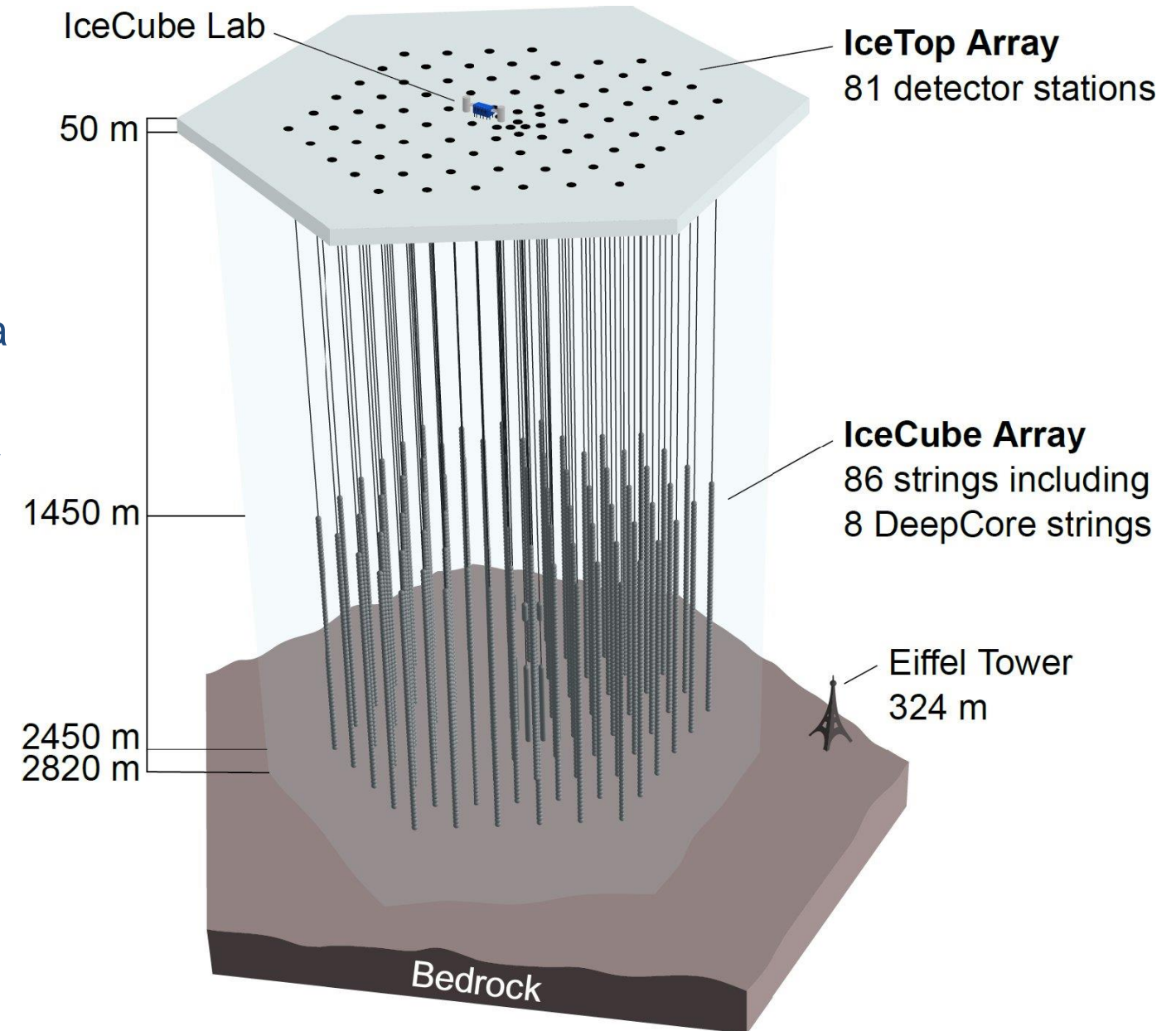
Neutrino interactions

Don't Forget Nucleus! - Study Nuclear Effects

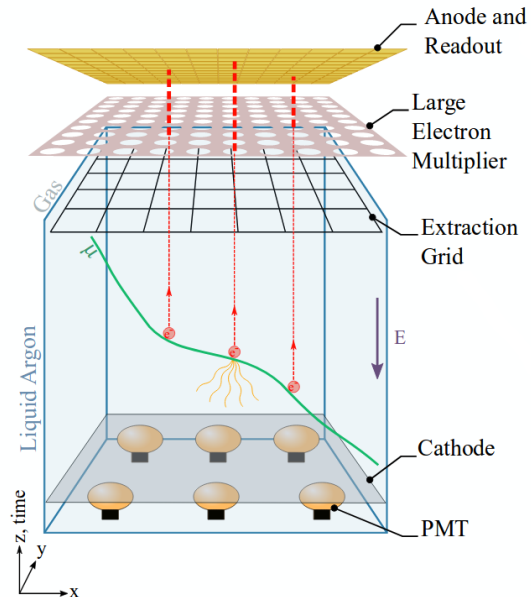
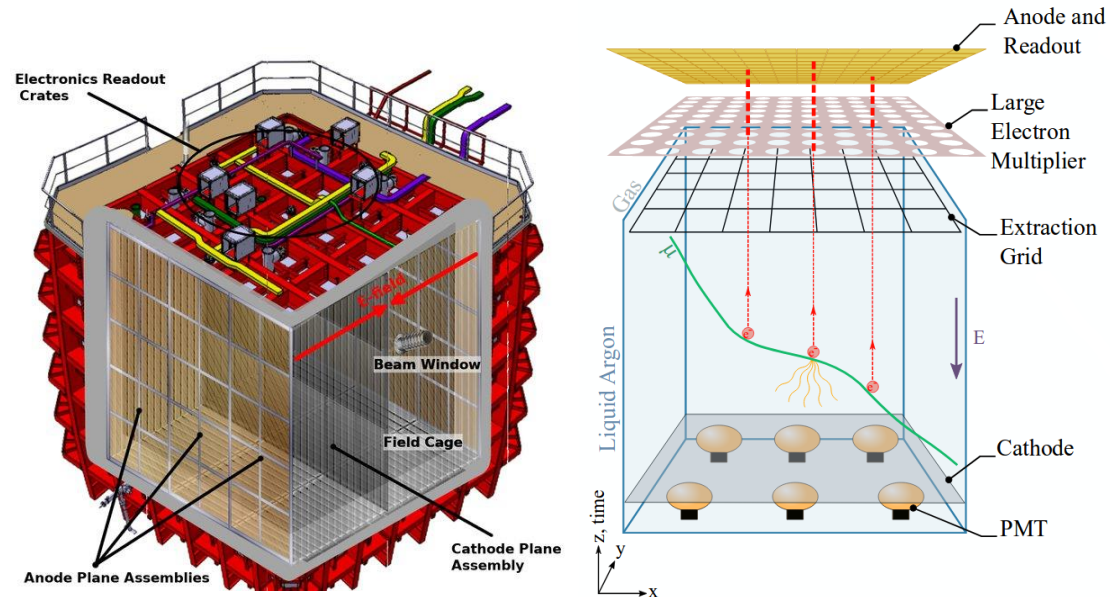


Icecube

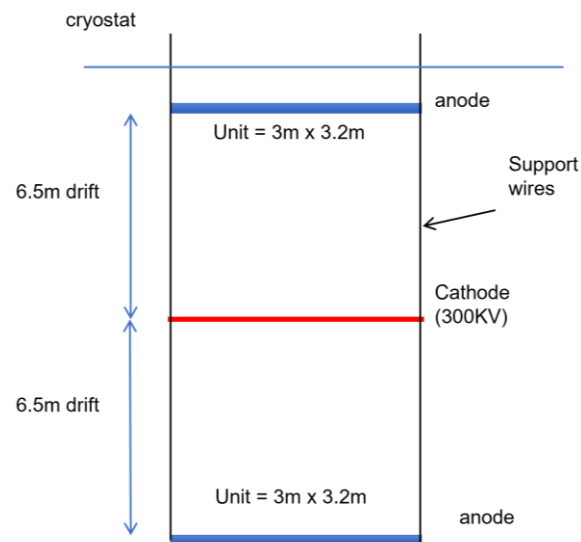
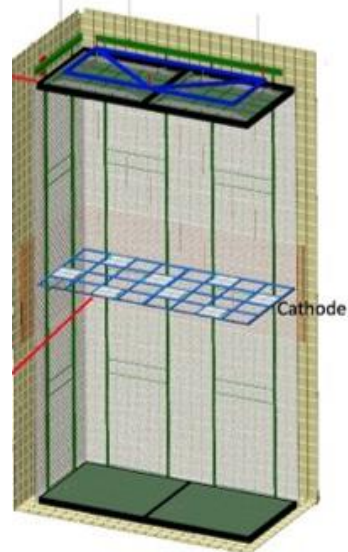
- Detect Cherenkov light from charged particles.
- Incoming neutrino produces the associated charged lepton through charged current.
 - Muon neutrinos leave a track + a hadronic shower
 - Electron and (low energy) tau neutrinos produce only a shower
- Neutral currents produces only the hadronic shower



ProtoDUNE



2 x 6.5-m vertical drift



ProtoDUNE-I (Sept 2018 to July 2020)

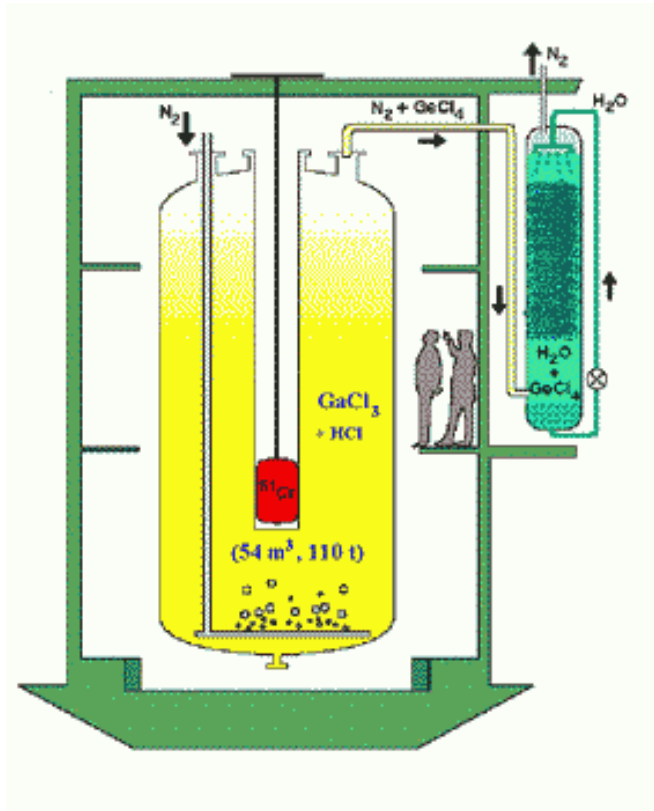
- Single Phase detector collected hadron data and cosmic ray data
- Dual Phase detector

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)

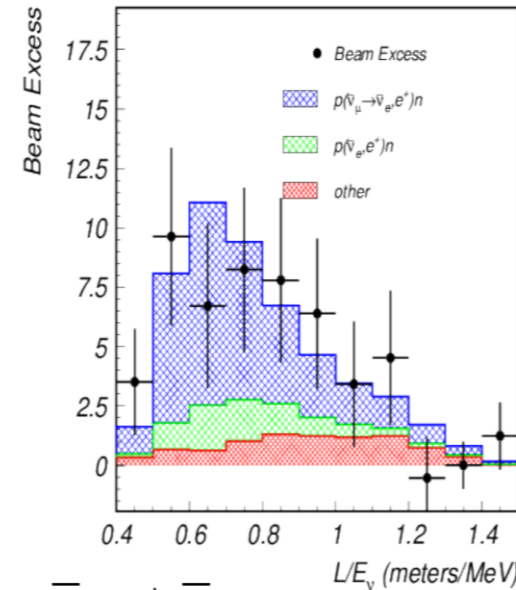
Anomalies in oscillations

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>

- 3.8 σ excess in LSND



$$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$$

- No signal @Karmen

LSND: PRL 75 (1995) 2650, PRC 54 (1996) 2685, PRL 77 (1996) 3082, PRD 64 (2001) 112007

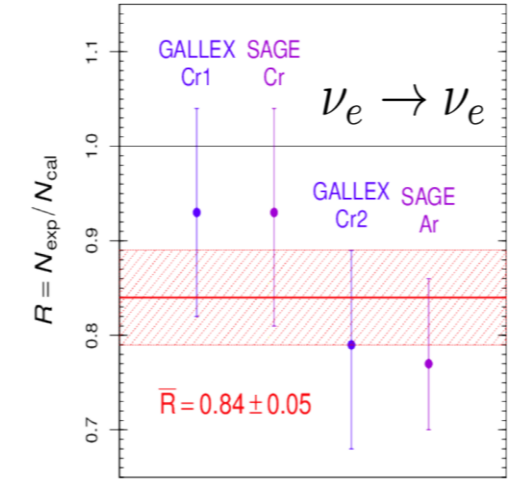
Karmen: PRD 65 (2002) 112001

Gallium: PRC 80 (2009) 015807, SAGE,

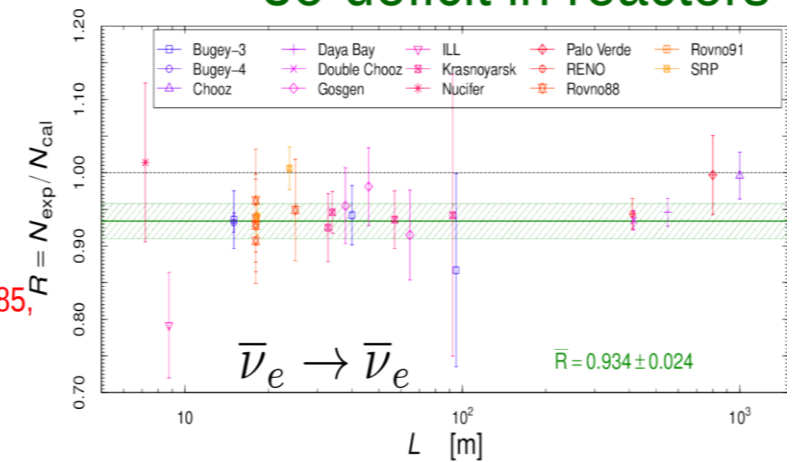
Nucl.Phys.Proc.Suppl. 168 (2007) 344, Laveder et al, PRD 78 (2008) 073009 and PRC 83 (2011) 065504, C. Giunti et al

Reactor: PRD 83 (2011) 073006. Mention et al. PRC 83 (2011) 054615. Mueller et al. PRC 84 (2011) 024617. Huber

- $\sim 3\sigma$ deficit in Gallium



- $\sim 3\sigma$ deficit in reactors



Greek symbol: ν



Family: lepton

Trillions of neutrinos stream through your hand every second



(but they're so antisocial, only one might actually interact with your body in your whole lifetime).



Neutrinos rarely interact and feel only two forces:

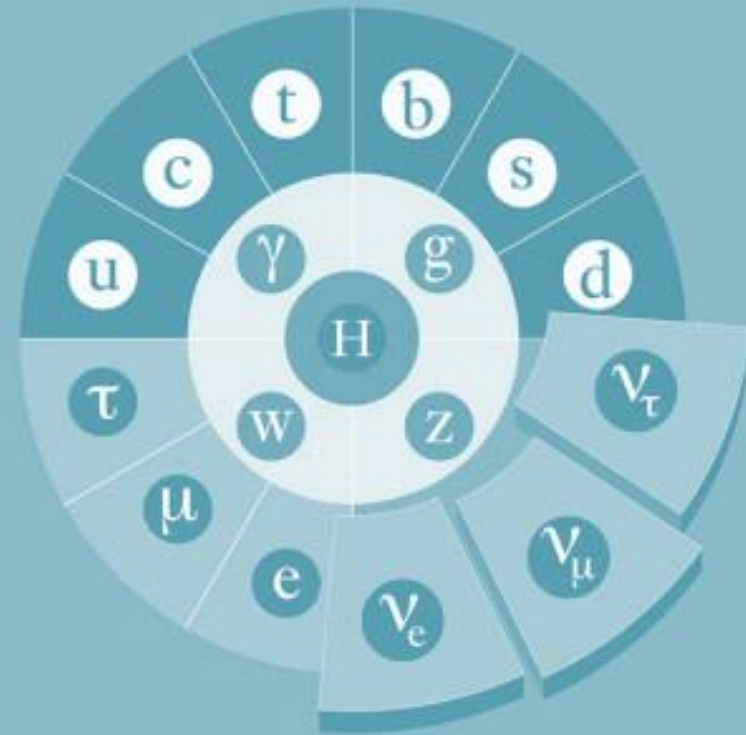
gravity

weak force



Antimatter version: antineutrino
Neutrinos might be their own antiparticles!

The Intriguing Neutrino



MASS

UNKNOWN but incredibly small, more than one million times smaller than an electron

Spin $1/2$ Charge 0

When a star explodes, 99% of the energy is carried away by neutrinos



~ Name means ~
"little neutral one"



www.fnal.gov

“Dear radioactive ones, scrutinize and judge.”
- Wolfgang Pauli, in his letter proposing the neutrino, a “desperate remedy” he worried physicists could never detect



Neutrinos are left-handed and antineutrinos are right-handed

3 TYPES



1956



Discovered: 1962



2000

Neutrinos oscillate, or change type, as they travel

