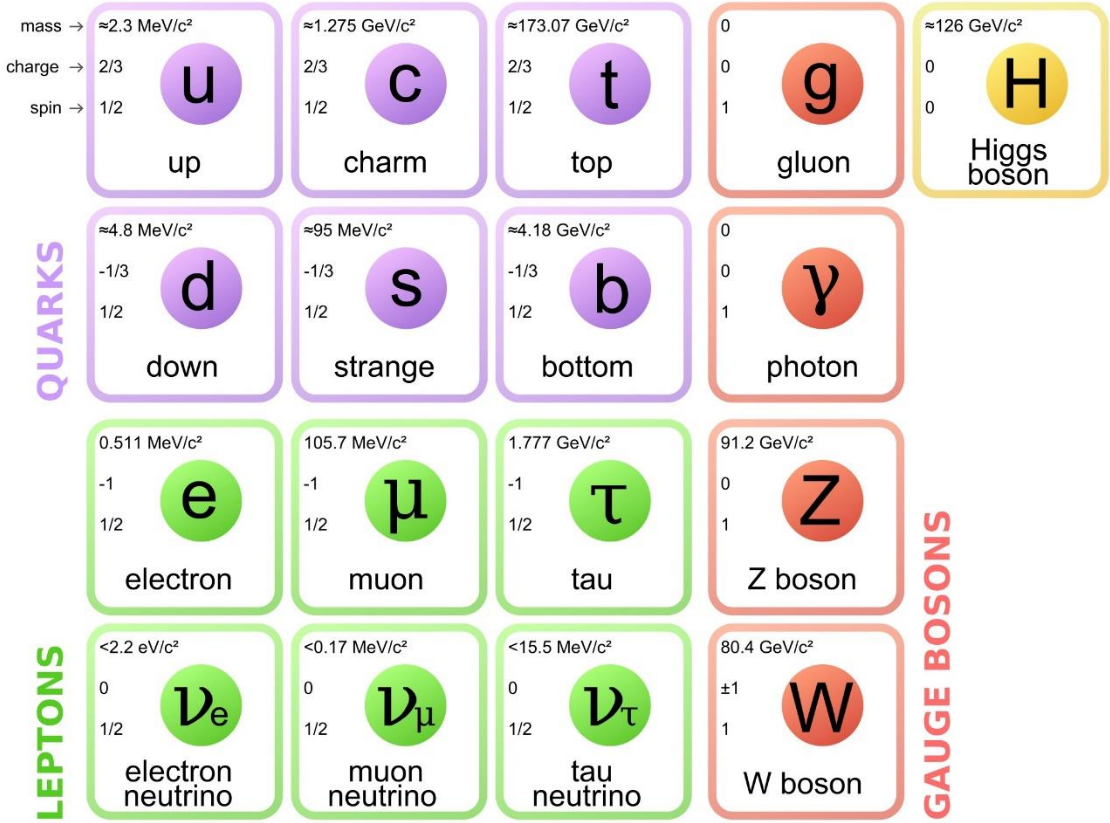
Neutrino detection

Loredana Gastaldo

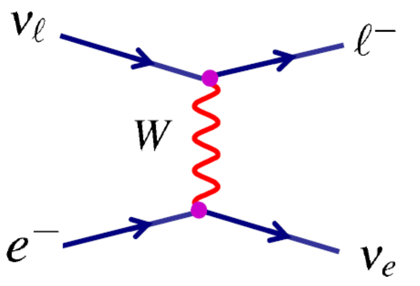
- short neutrino history up to the standard model
- planning a neutrino experiment
- neutrino oscillations in vacuum
- neutrino sources
- neutrino cross-sections
- experiments across the neutrino energy scale

Important concepts

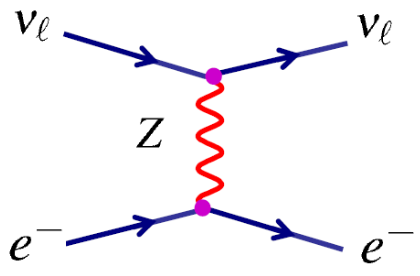


Neutrinos can undergo

- charged current (CC) interactions via the exchange of a W-boson



- neutral current (NC) interactions via the exchange of a Z-boson



History of neutrinos

- 1900 -1930	Observation of a continuous spectrum of electrons emitted in decay (A,Z) → (A,Z-1) + e-…
- 1930	Pauli postulation of a neutral spin ½ , quite light and quite penetrating particle
- 1934	Fermi wrote the first theory of beta decay – very small cross section
-1956	Reines and Cowan experiment at Savannah River nuclear reactor: First detection of neutrinos
-1957	Wu et al. experiment with polarized ^{60}Co: discovery of parity violation in beta decays
-1958	Goldhaber et al. experiment: neutrinos are left-handed particles
-1962	Brookhaven neutrino experiment: muon neutrinos are different from electron neutrinos
-1965	First detection of atmospheric neutrinos
-1970	First detection of solar neutrinos (Davis Chlorine experiment) starting of the solar neutrino problem
-1973	Gargamelle experiment at CERN discovered neutral current interactions
- ’90	The decay width of the Z-boson showed the existence of three neutrino flavor states
-1998	explanation deficit of detected atmospheric neutrinos by neutrino oscillation in SK experiment
-2000	the tau neutrino was discovered (DONUT experiment)
-2002	solution of solar neutrino problem through neutrino oscillations in the Sun

How to plan an experiment with neutrinos

In order to study the neutrino properties we need some ingredients:

- A proper description of the evolution of neutrino wavefunctions
- A proper understanding of neutrino sources
- A proper understanding of the neutrino cross-sections with matter
- A proper detector concept: which neutrino interactions can occur in the detector material? which final state particles can be detected?

Mass and flavor eigenstates

By definition ν_e is the neutrino state produced along with an electron. In the same way, charged current weak interactions of the state ν_e produce an electron. Same considerations are valid for ν_μ and ν_τ.

3 neutrino flavor eigenstates – weak eigenstates

$$\nu_\alpha = (\nu_e , \nu_\mu , \nu_\tau)$$

Each flavor eigenstate is a coherent linear combination of the three mass eigenstates:

$$\nu_i = (\nu_1 , \nu_2 , \nu_3)$$

Let‘s consider the case of two flavor eigenstates and two mass eigenstates

$$\nu_e = U_{e1}\nu_1 + U_{e2}\nu_2$$

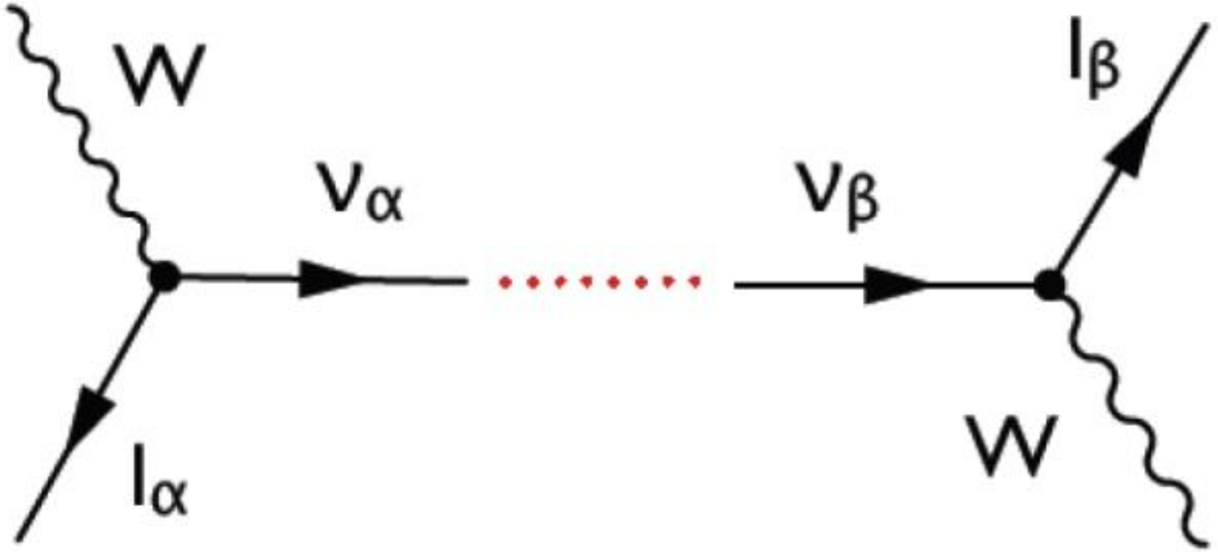
$$\nu_\mu = U_{\mu 1}\nu_1 + U_{\mu 2}\nu_2$$

ν_e represents the wave-function of the coherent state produced along with an electron in the weak interaction

Neutrino oscillations (2 states)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$|\nu_e\rangle = \cos\theta\, |\nu_1\rangle + \sin\theta\, |\nu_2\rangle$$



Production

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

Propagation

$$|\nu_1(t)\rangle = |\nu_1\rangle e^{i\vec{p}_1\cdot\vec{x} - iE_1 t}$$

$$|\nu_2(t)\rangle = |\nu_2\rangle e^{i\vec{p}_2\cdot\vec{x} - iE_2 t}$$

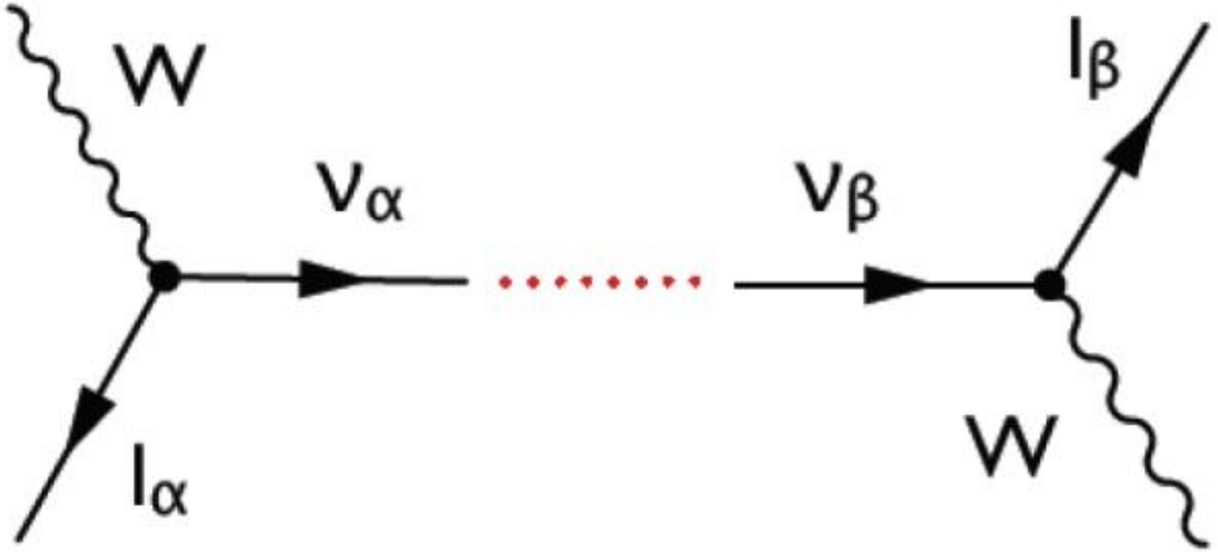
Detection

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

Neutrino oscillations (2 states)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$|\nu_e\rangle = \cos\theta\ |\nu_1\rangle \ + \ \sin\theta\ |\nu_2\rangle$$



$$P(\nu_e \to \nu_\mu) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2_{21}}{4E} L\right) \qquad \Delta m^2_{21} = m^2_2 - m^2_1$$

$$P(\nu_e \to \nu_e) = 1 - \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2_{21}}{4E} L\right) \qquad \frac{\Delta m^2_{21}}{4E} L = 1.27 \frac{\Delta m^2_{21}[\mathrm{eV}^2]}{E[\mathrm{GeV}]} L[\mathrm{km}]$$

3-neutrino scenario

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

$$U_{\alpha i} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{-i\alpha/2} & 0 \\ 0 & 0 & e^{-i\beta/2} \end{bmatrix}$$

2-3 rotation

1-3 rotation
+ CP Dirac phase

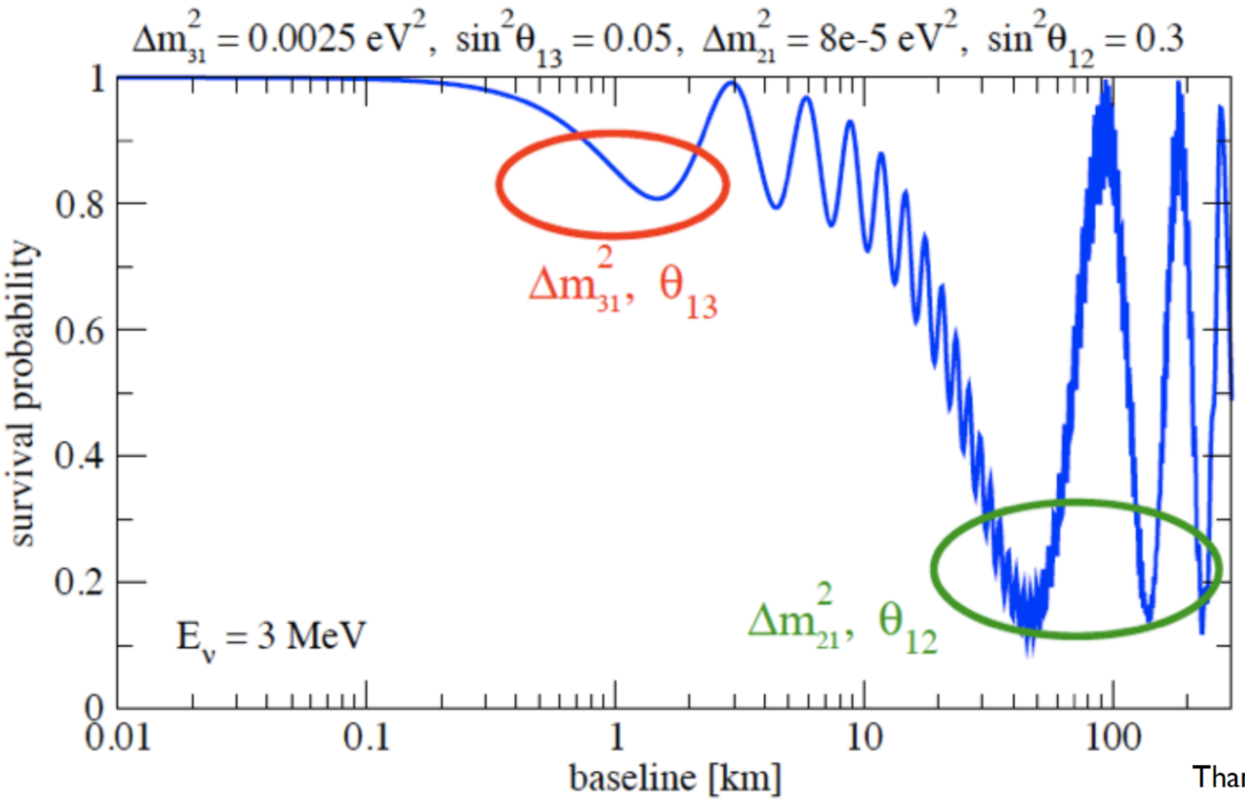
1-2 rotation

extra Majorana
phases

How to extract oscillation parameters

Disappearance: deficit in the detection rate for neutrinos having the same flavor as the neutrino at the source

Appearance: detection of neutrinos with a different flavor with respect to the flavor at the source



Thanks to T. Schwetz

$$P(\nu_e \rightarrow \nu_\mu) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2_{21}}{4E}L\right)$$

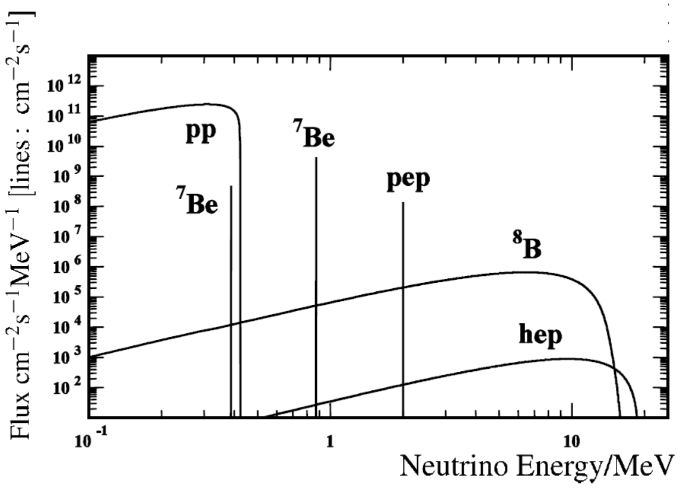
$$\frac{\Delta m^2_{21}}{4E}L = 1.27\frac{\Delta m^2_{21}\left[\mathrm{eV}^2\right]}{E\left[\mathrm{GeV}\right]}L\left[\mathrm{km}\right]$$

The neutrino source define the energy *E* of the neutrinos
The position of the experiment define the flying distance *L*
Experiments can be optimized to test given values of the oscillation parameters

Neutrino sources

Radioactive sources: electron anti-neutrinos from beta-decays, electron neutrinos from electron capture (beta+)
Energies up to MeV range

Solar neutrinos: electron neutrinos from nuclear reaction in the Sun
energy < 20 MeV
large flux of electron neutrinos ~2 × 10^{38} ν_e s^{-1}



Atmospheric neutrinos: electron and muon neutrinos and anti-neutrinos from the interaction of cosmic rays in the atmosphere CR → $\pi^+ \to \mu^+ \nu_\mu$ $\quad \mu^+ \to e^+ \nu_e \bar{\nu}_\mu$
Energy > 1 GeV $\quad \pi^- \to \mu^- \bar{\nu}_\mu$ $\quad \mu^- \to e^- \bar{\nu}_e \nu_\mu$

Reactor neutrinos: electron anti-neutrinos from the decay of the reactor fuel (mainly U-235, U-238,…)
Energy < 8 MeV

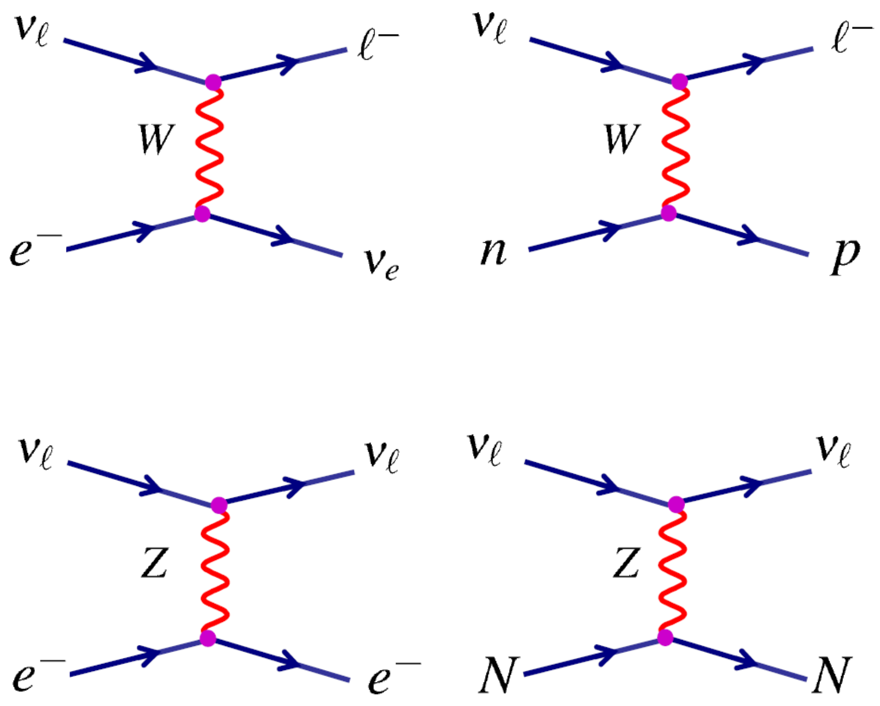
Neutrino beams from accelerators: muon neutrinos and anti-neutrinos from pions and kaons decay generated by high energy proton beams on light target
Energy ~ 1 GeV

Neutrino detection – interactions

In general we can consider the interaction with:

- atomic electrons
- nucleons within the nucleus

We can then consider both charged and neutral currents:



Charged current energy threshold

e$^-$

$E_{\nu e} > 0$

$E_{\nu\mu} > 11$ GeV

$E_{\nu\tau} > 3090$ GeV

n

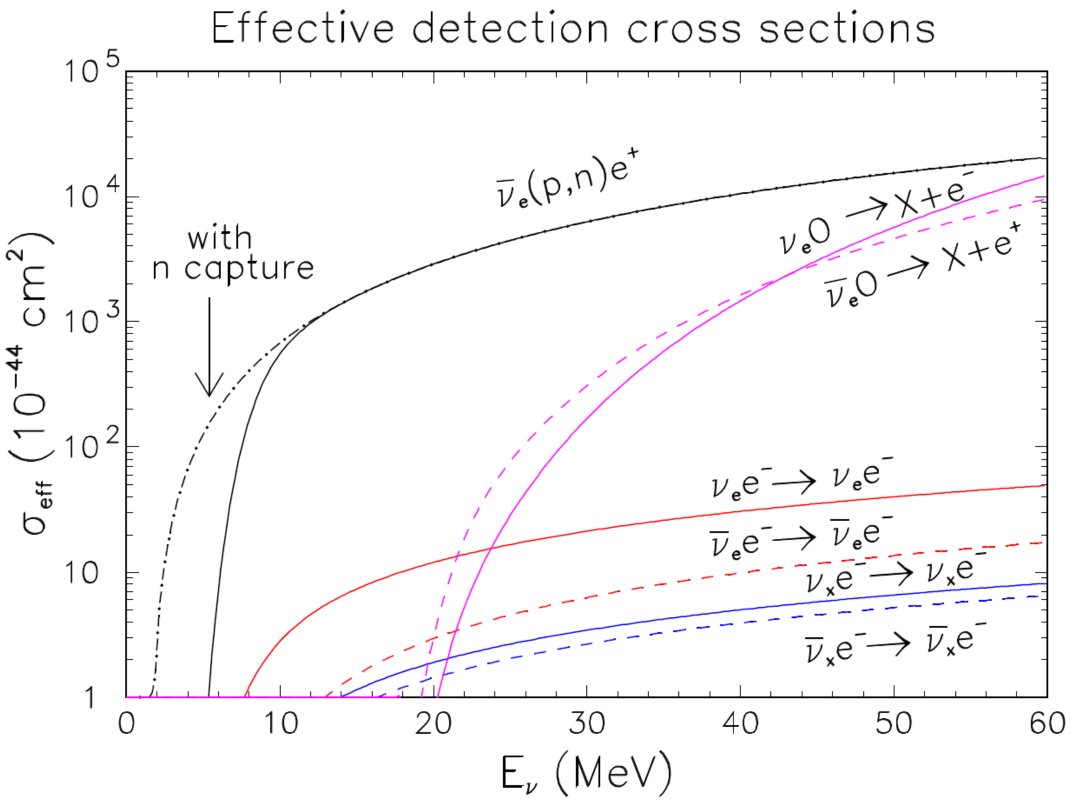
$E_{\nu e} > 0$

$E_{\nu\mu} > 110$ MeV

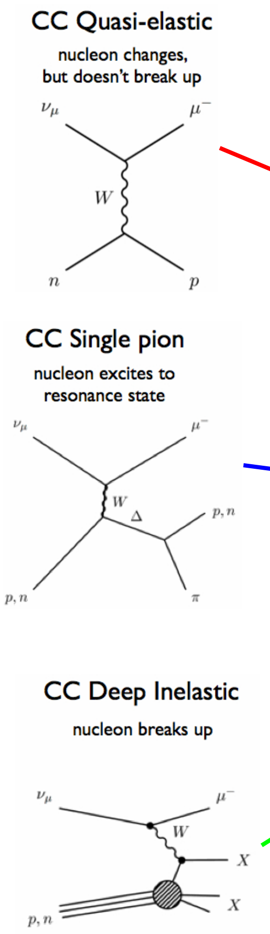
$E_{\nu\tau} > 3.5$ GeV

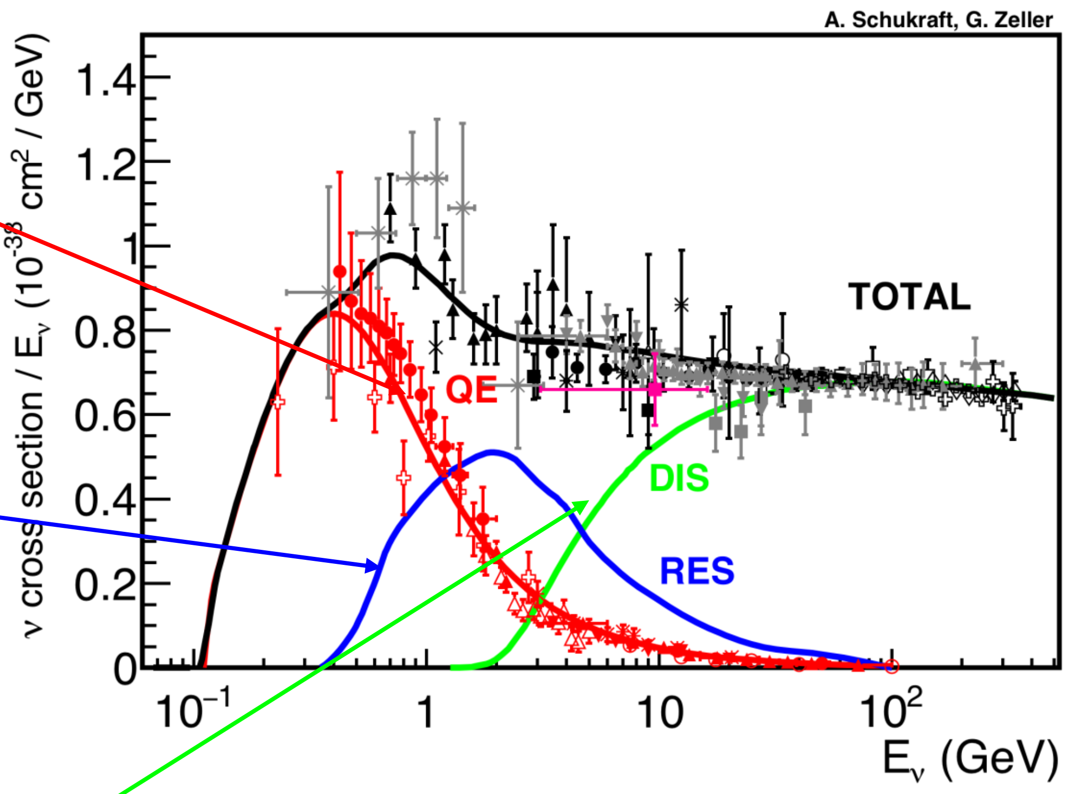
Neutrino cross-sections

The known reactions of neutrinos with matter fall completely within the Standard Model of particle physics. Therefore the cross-section of different process can be calculate (but not so easy….)



Fogli et al., JCAP 0504:002,2005



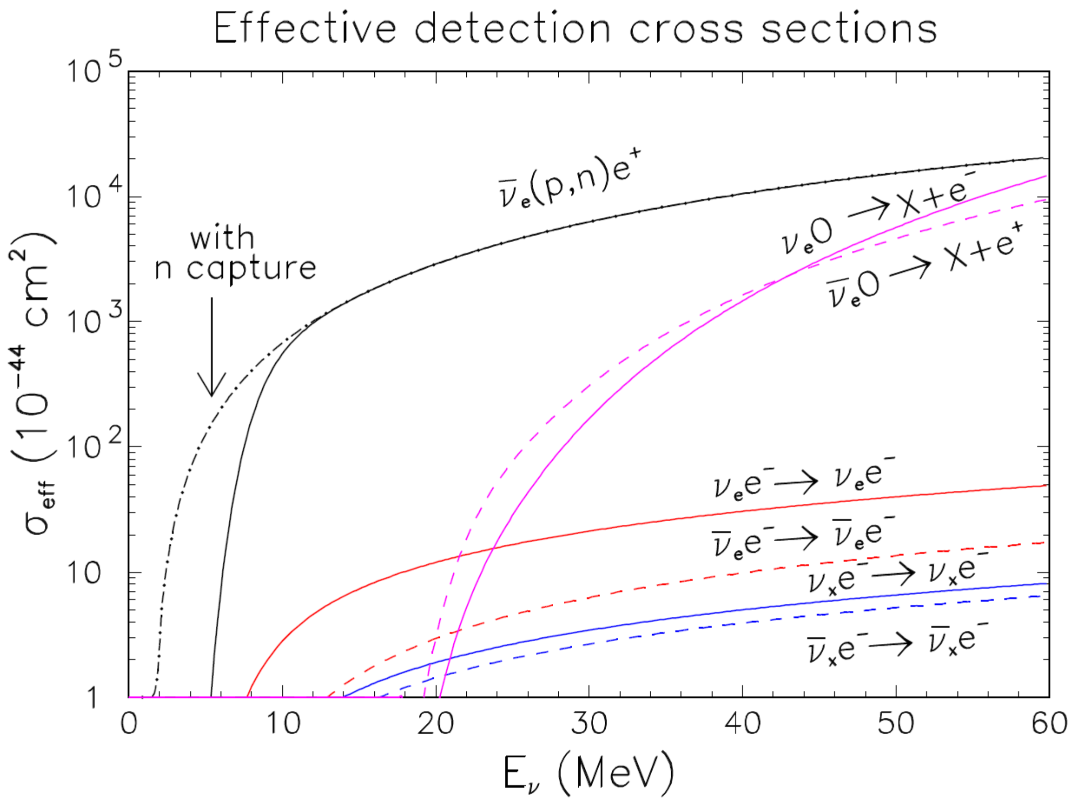


Total neutrino per nucleon CC cross sections

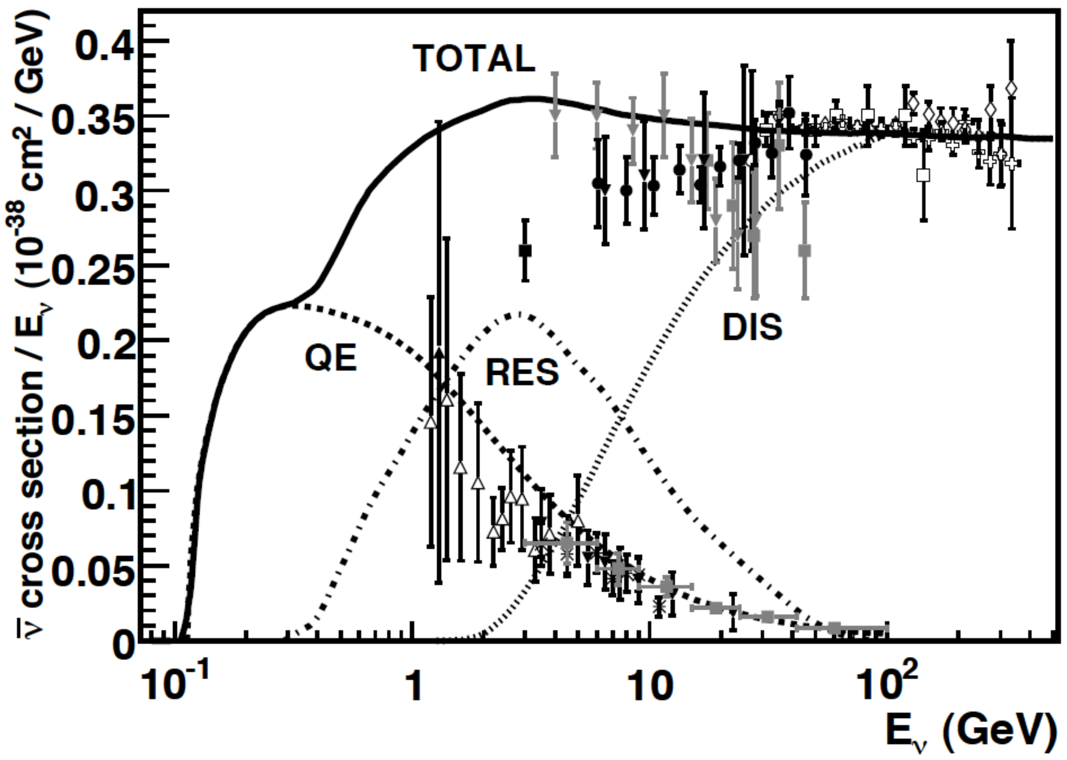
Formaggio, Zeller Rev. Mod. Phys. 84, 1307 (2012)

Neutrino cross-sections

The known reactions of neutrinos with matter fall completely within the Standard Model of particle physics. Therefore the cross-section of different process can be calculate (but not so easy….)



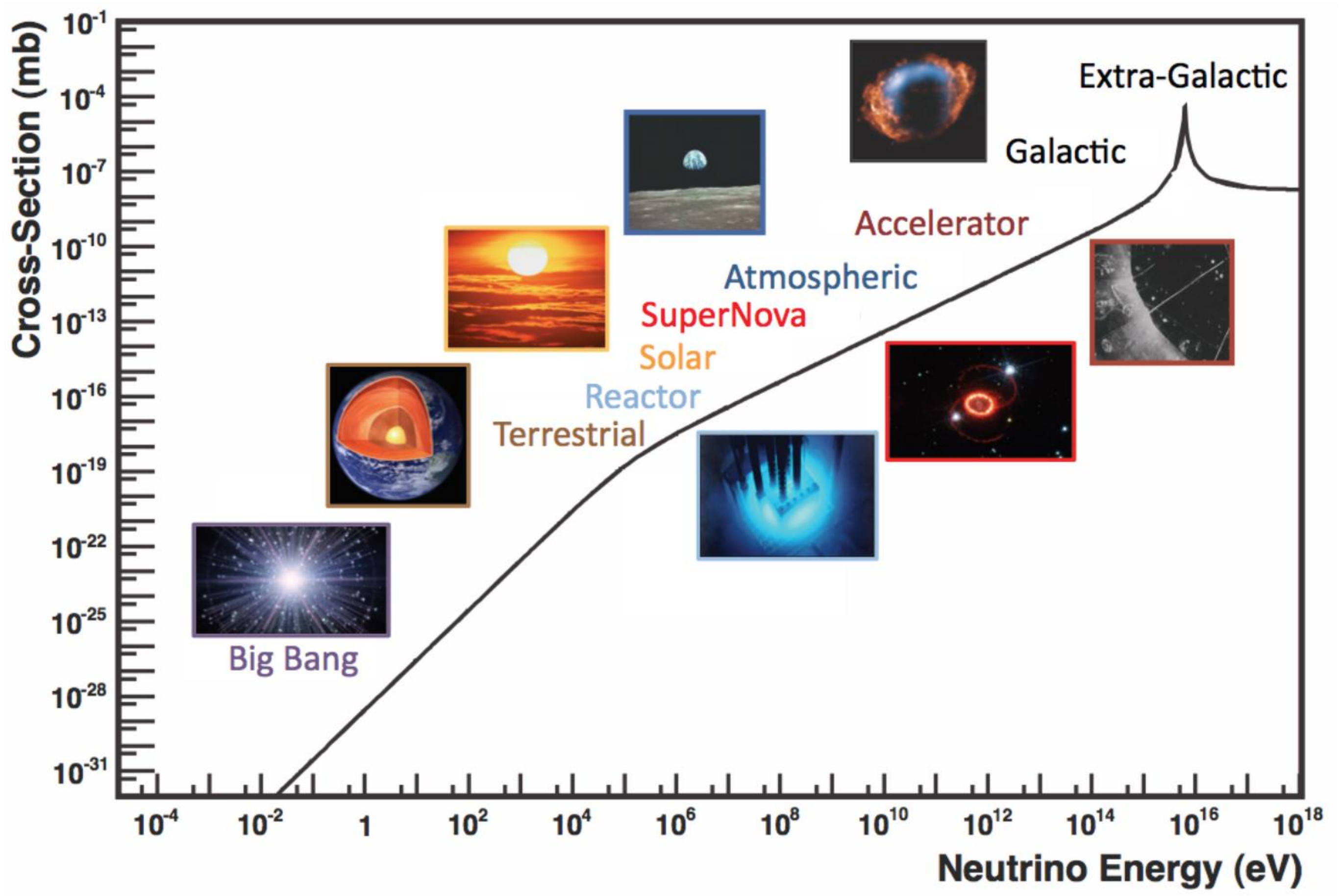
Fogli et al., JCAP 0504:002,2005



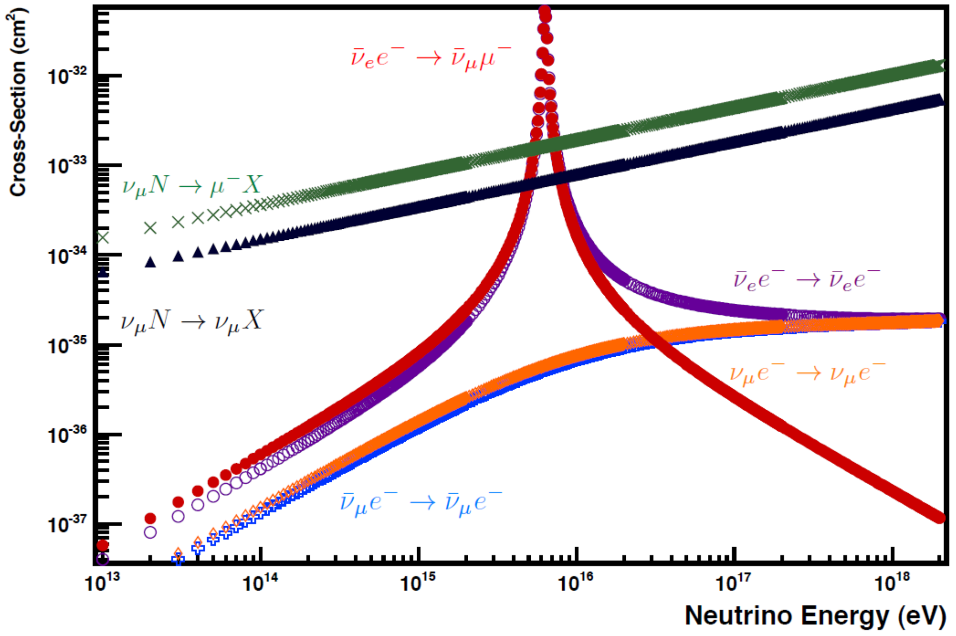
Total anti-neutrino per nucleon CC cross sections

Formaggio, Zeller Rev. Mod. Phys. 84, 1307 (2012)

Neutrino cross-sections



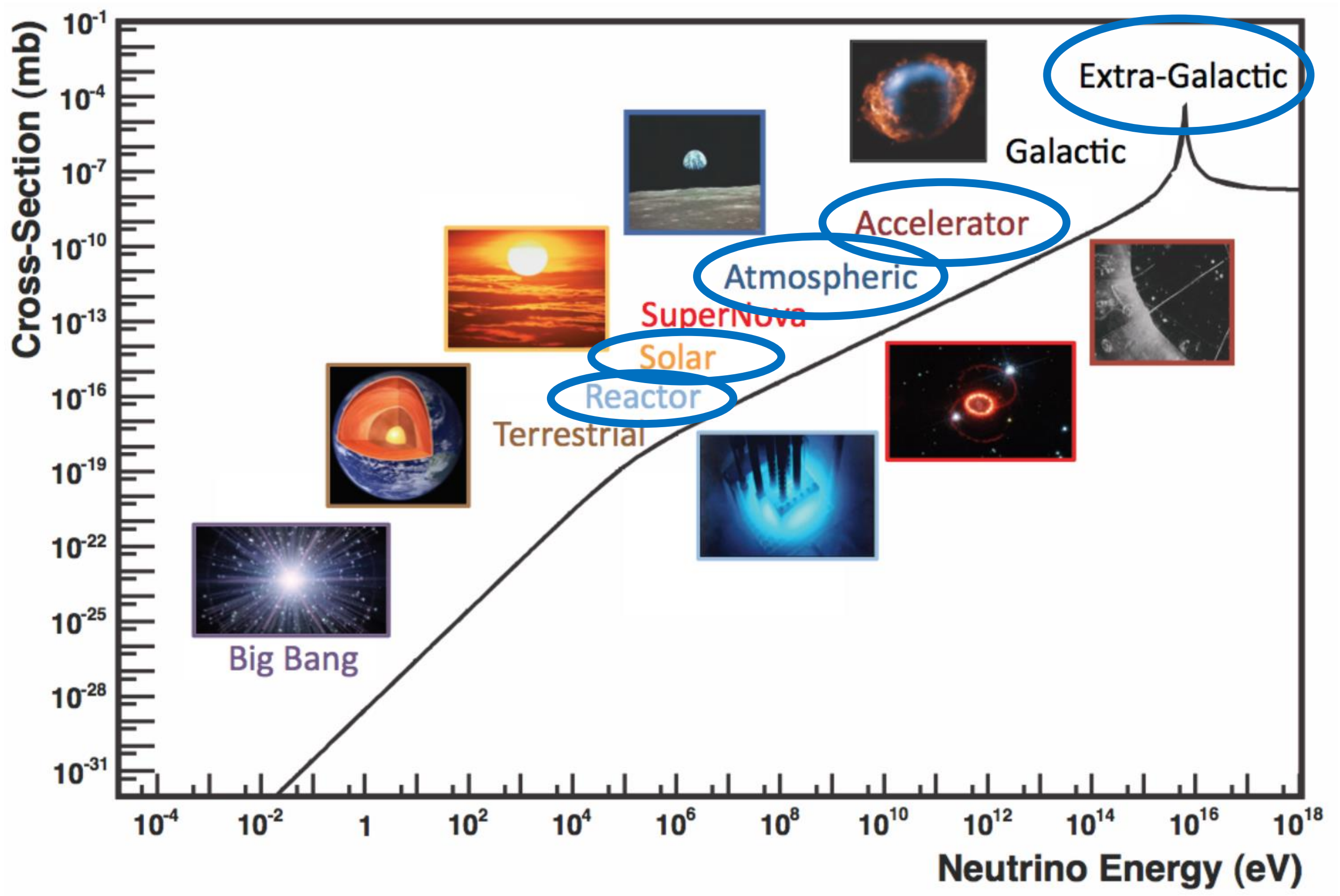
Representative example of various neutrino sources across decades of energy. The electroweak cross-section for $\overline{\nu}_e e^- \rightarrow \overline{\nu}_e e^-$ scattering on free electrons



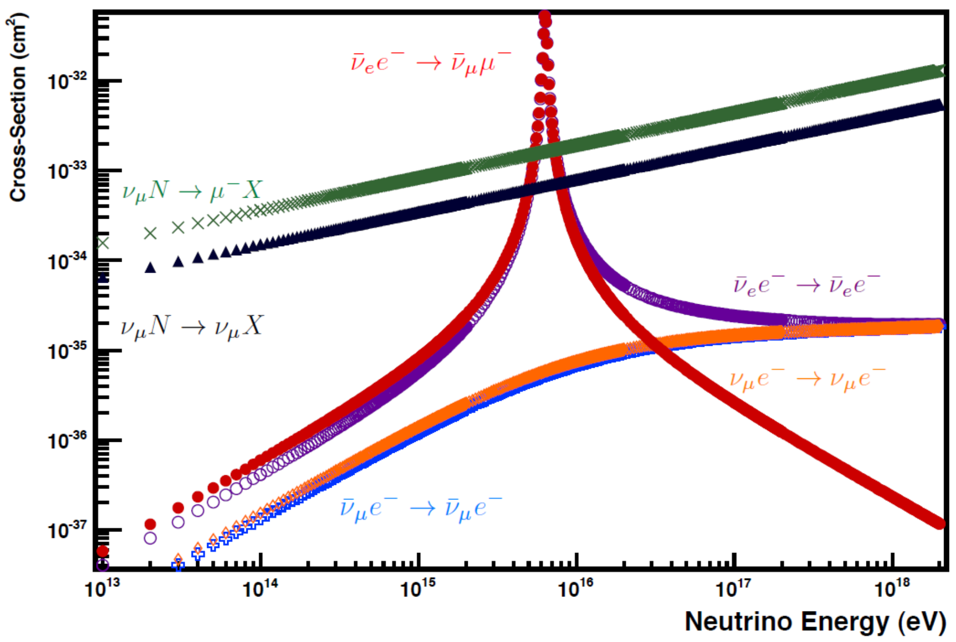
Neutrino electron and nucleon scattering in the ultra-high energy regime (E > 10^4 GeV).

Formaggio, Zeller Rev. Mod. Phys. 84, 1307 (2012)

Neutrino cross-sections



Representative example of various neutrino sources across decades of energy. The electroweak cross-section for $\overline{\nu}_e e^- \rightarrow \overline{\nu}_e e^-$ scattering on free electrons



Neutrino electron and nucleon scattering in the ultra-high energy regime ($E > 10^4$ GeV).

Formaggio, Zeller Rev. Mod. Phys. 84, 1307 (2012)

Neutrino detection techniques

- What is the energy of the neutrinos to be detected
- Which neutrino flavor and which kind of interactions (charged or neutral current) should be observed
- Which final state can be detect and what should be measured
- How many events should be acquired
- Which background is expected and how this can be eliminated

Solar Neutrinos

$E(\nu_e) < 20$ MeV
Radio-chemical experiments: Inverse beta decay $(A, Z) + \nu_e \rightarrow (A, Z+1) + e^-$
chemically extract produced isotopes and count decay
Water Cherenkov: Cherenkov light from electron produced in $\nu_e + e^- \rightarrow \nu_e + e^-$

Reactor Neutrinos

$E(\overline{\nu}_e) < 8$ MeV
Liquid scintillators: inverse beta decay $\overline{\nu}_e + p \rightarrow e^+ + n$

Atmospheric Neutrinos

$E(\nu_e, \nu_\mu, \overline{\nu}_e, \overline{\nu}_\mu) > 1$ GeV   Water Cherenkov

Neutrino Beams

Water Cherenkov
Calorimeters (Fe)
Scintillators

Solar neutrino detection and problem

Homestake (Ray Davis in 1968)

$\nu_e + {}^{37}Cl \rightarrow e^- + {}^{37}Ar$ E_{th} = 814 keV

${}^{37}Ar + e^- \rightarrow {}^{37}Cl + \nu_e$ τ = 35.04 days

615 tons of cleaning fluid C_2Cl_4(perchlorate-ethylene) 60 days exposure

SAGE, GALLEX

$\nu_e + {}^{71}Ga \rightarrow e^- + {}^{71}Ge$ E_{th} = 233 keV

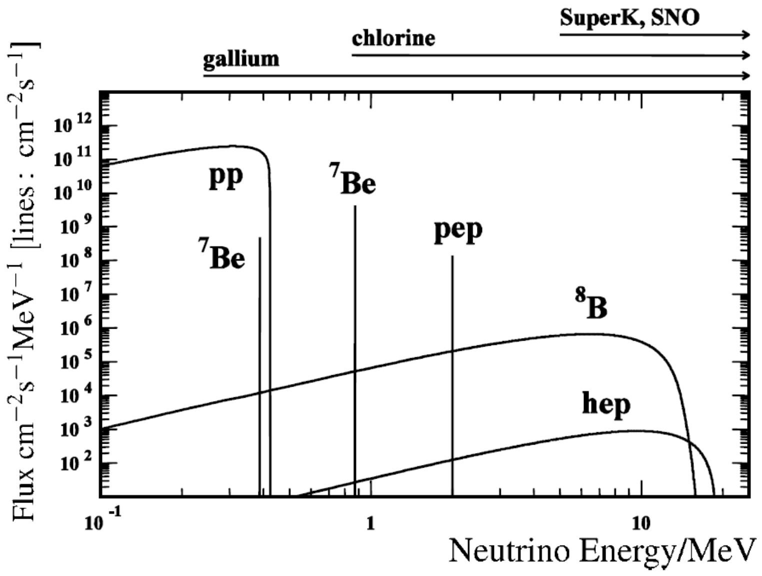
${}^{71}Ge + e^- \rightarrow {}^{37}Ga + \nu_e$ τ = 11.5 days

100 tons of gallium chloride $GaCl_3$ (~30 (12) tons Ga (${}^{71}Ga$)) 20 days exposure

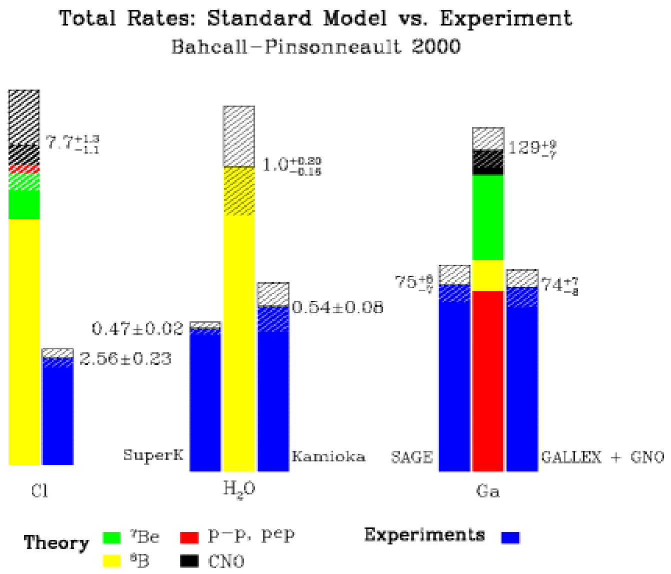
Superkamiokande

$\nu_e + e^- \rightarrow \nu_e + e^-$ E_{th} > 5 MeV (Cherenkov – background)

50000 ton water Cherenkov detector with 11146 Photo-multiplier tubes



Bahcall, solar neutrino problem

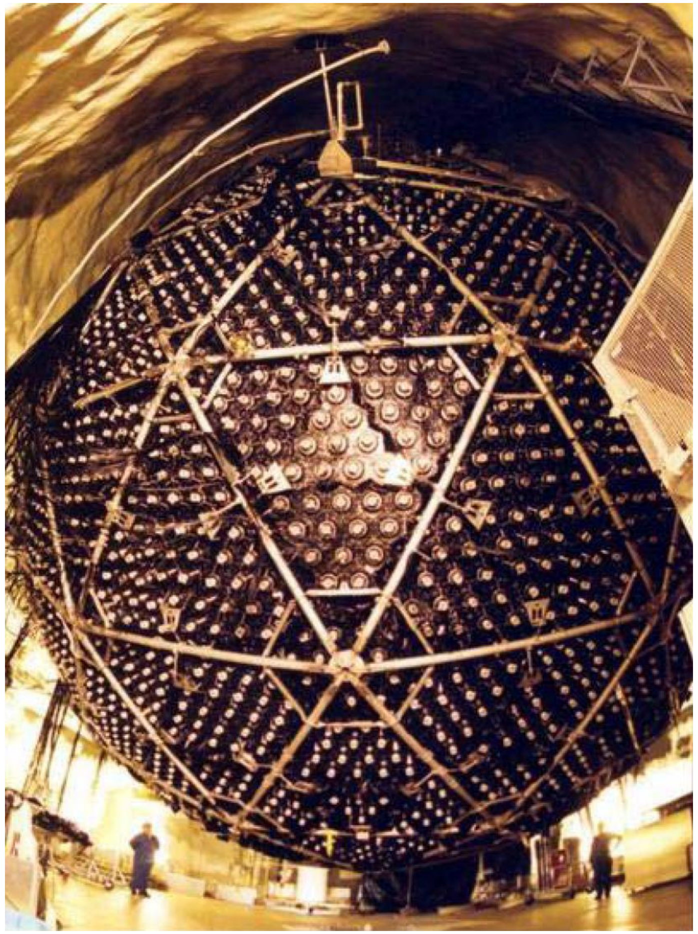


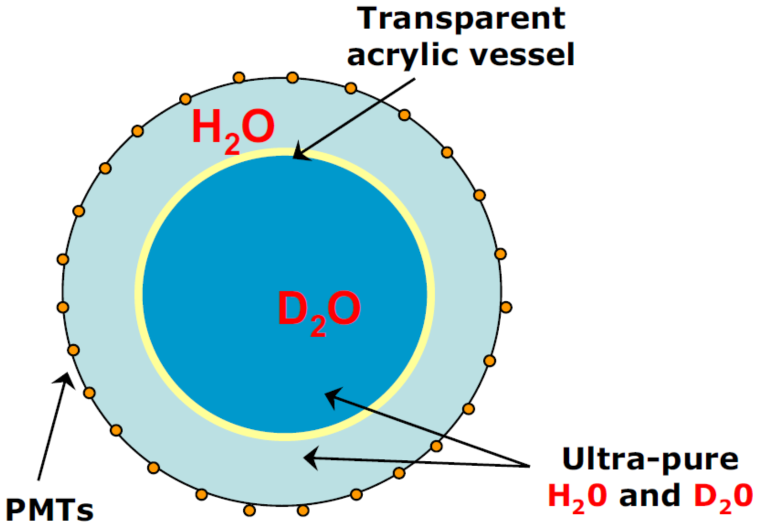
All the three applied methods to measure the solar neutrino flux showed a lower than expected rate

Solution of the solar neutrino problem – the SNO experiment

Sudbury Neutrino Observatory – SNO - located in a deep mine in Canada

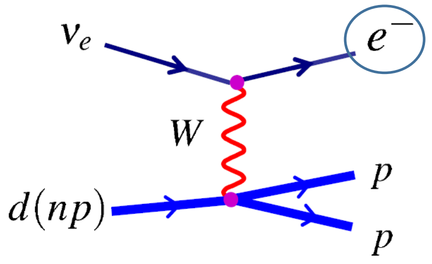
- 1000 ton heavy water (D_2O) Cherenkov detector inside a 12 m diameter acrylic vessel
- 3000 tons of normal water surround the heavy water target
- 9546 PMTs to monitor events





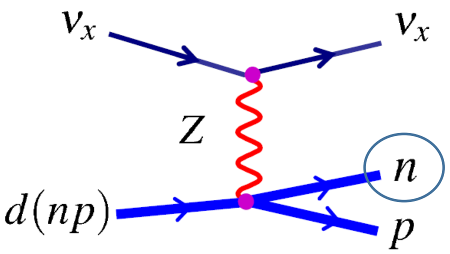
Solution of the solar neutrino problem – the SNO experiment

Three different reactions



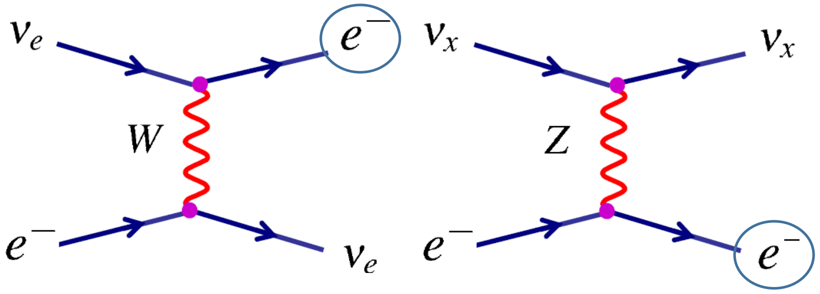
Charged current: Only sensitive to ν_e (threshold)
measure the ν_e flux

CC Rate $\propto \phi(\nu_e)$



Neutral current: sensitive to all neutrino flavors
measure the total neutrino flux

NC Rate $\propto$ $\phi(\nu_e)+ \phi(\nu_\mu)+ \phi(\nu_\tau)$



Elastic scattering: sensitive to all neutrino flavors, but with higher rate for ν_e

ES Rate $\propto$ $\phi(\nu_e)+ 0.154(\phi(\nu_\mu)+ \phi(\nu_\tau))$

Solution of the solar neutrino problem – the SNO experiment

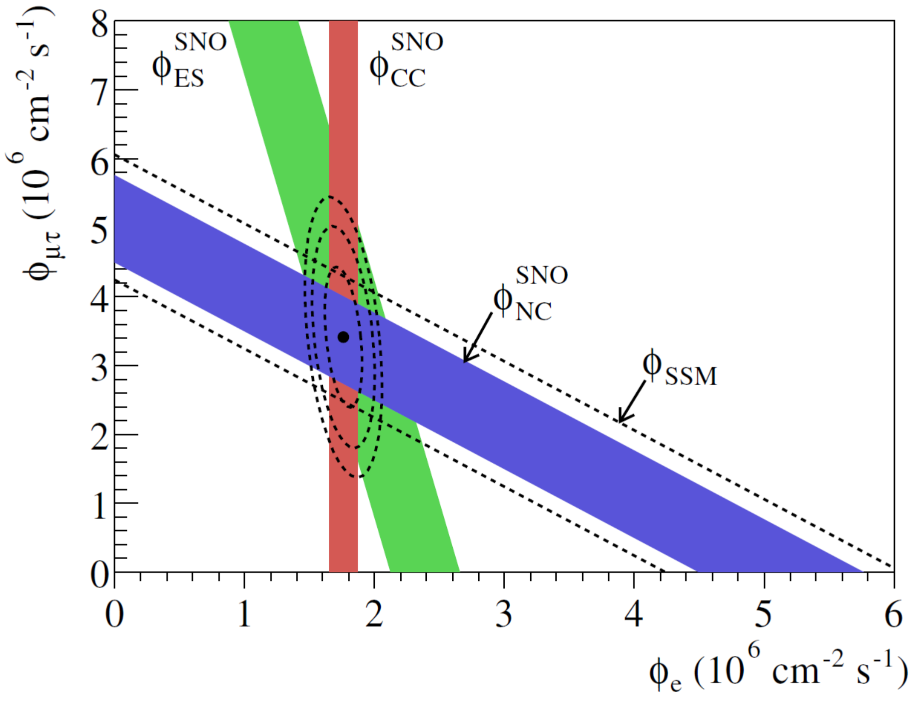
CC Rate $\propto \phi(\nu_e)$ → measured 1968 ± 61

NC Rate $\propto \phi(\nu_e) + \phi(\nu_\mu) + \phi(\nu_\tau)$ → measured 264 ± 26

ES Rate $\propto \phi(\nu_e) + 0.154(\phi(\nu_\mu) + \phi(\nu_\tau))$ → measured 576 ± 50

$\phi(\nu_e) = (1.8 \pm 0.1) \times 10^{-6}\ cm^{-2}\ s^{-1}$

$\phi(\nu_\mu) + \phi(\nu_\tau) = (3.4 \pm 0.6) \times 10^{-6}\ cm^{-2}\ s^{-1}$



SNO Collaboration, Q.R. Ahmad et al., Phys. Rev. Lett. 89:011301, 2002

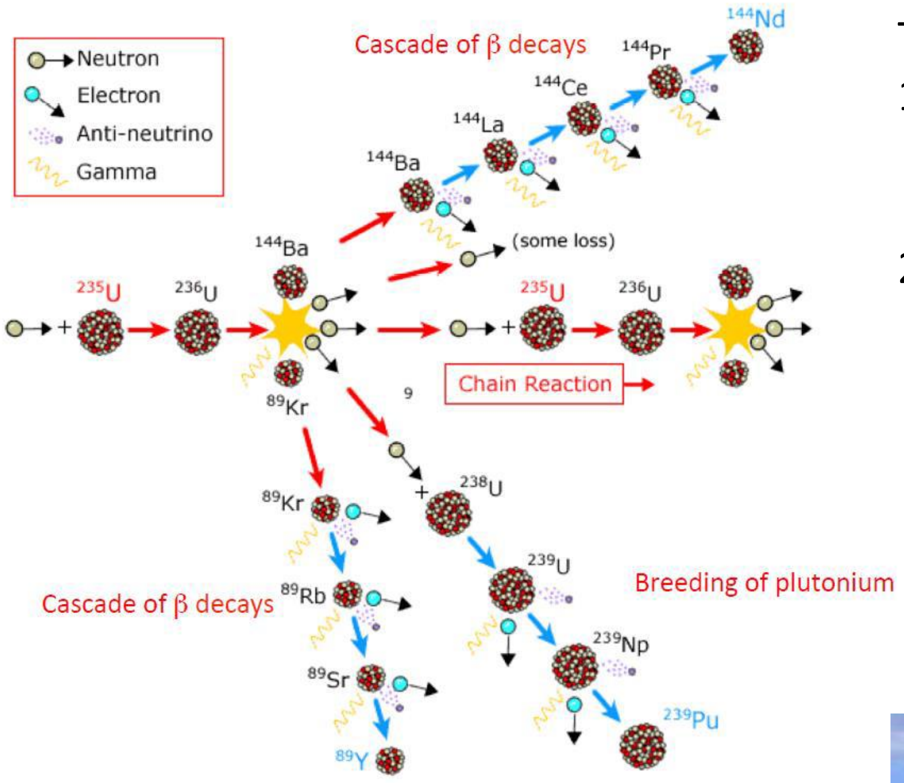
Expected electron neutrino flux from standard solar model:
$\phi(\nu_e) = 5.1 \times 10^{-6}\ cm^{-2}\ s^{-1}$

Clear evidence for a flux of ν_μ and/or ν_τ from the Sun

Total neutrino flux is consistent with expectation from SSM

Clear evidence of $\nu_e \rightarrow \nu_\mu$ and/or $\nu_e \rightarrow \nu_\tau$ neutrino transitions

Reactor neutrinos



Fission fragments are unstable
→ Decay through cascade of β decays

3 GW reactor ~ $10^{20}\ \nu_e/s$

Two antineutrino spectrum models

1) ILL + Vogel
   ILL model - ^{235}U, ^{239}Pu, ^{241}Pu
   Vogel's theoretical model - ^{238}U

2) Huber + Muller
   Huber's model - ^{235}U, ^{239}Pu , ^{241}Pu
   Muller's model - ^{238}U

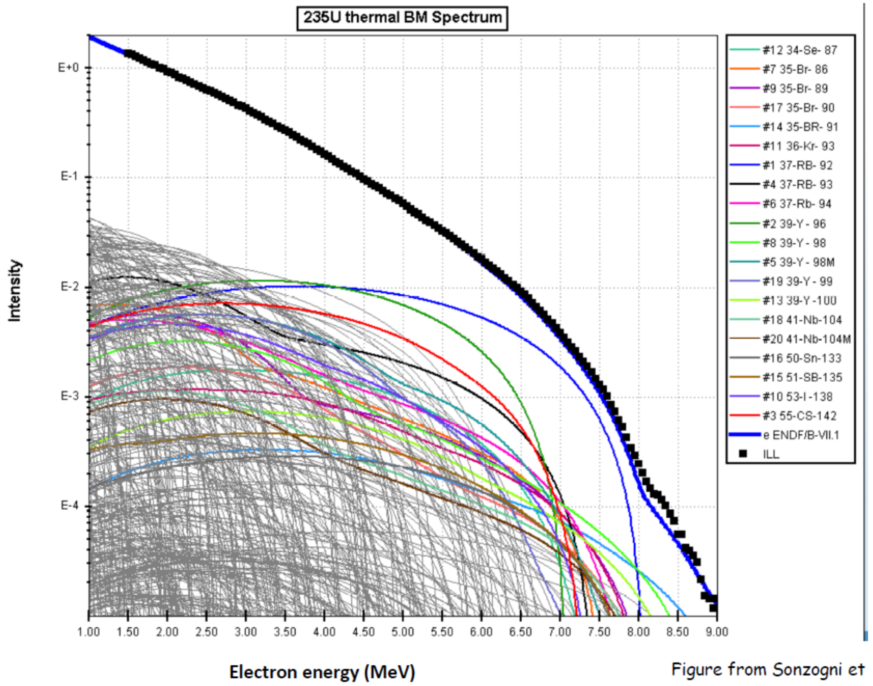
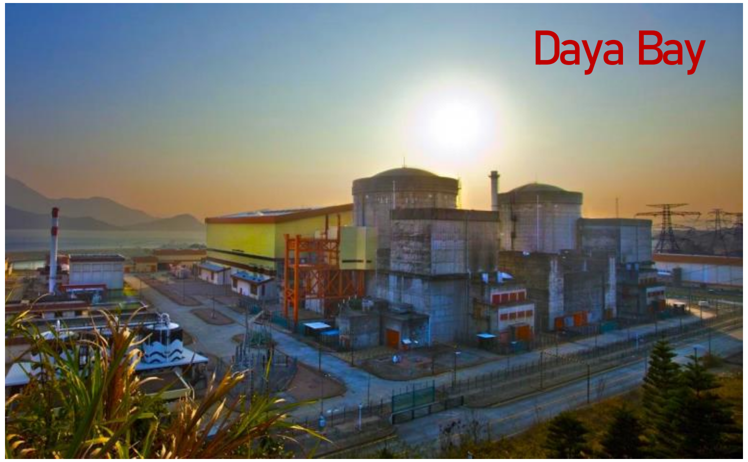


Figure from Sonzogni et



Reactor neutrinos

Reactor neutrino detection:

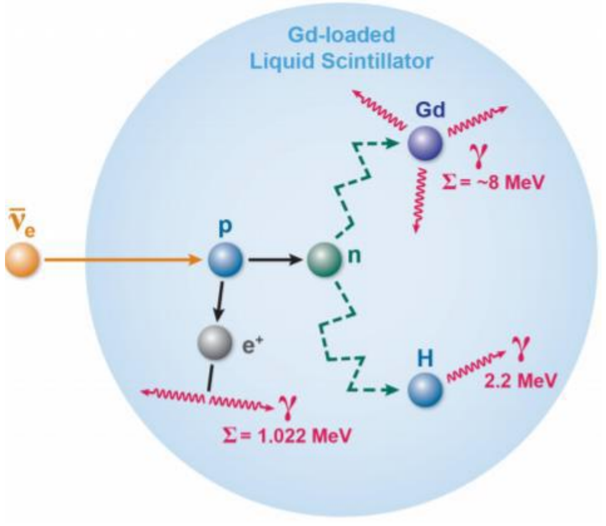
Inverse beta decay

$\bar{\nu}_e + p \rightarrow e^+ + n$ Threshold $E_{th} = 1.806\ MeV$

$e^+ + e^- \rightarrow \gamma\,\gamma$ (1.022 MeV) Prompt signal

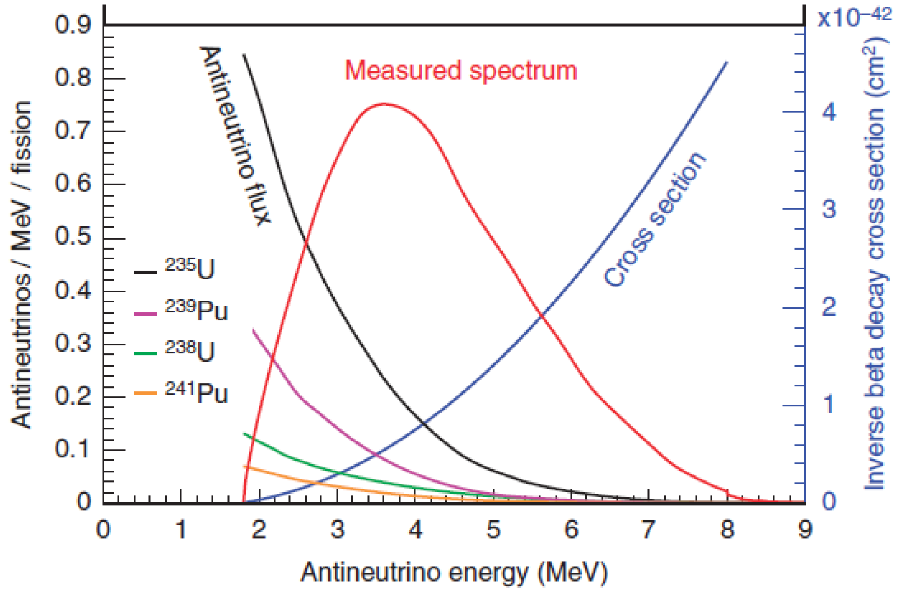
$n + p \xrightarrow{\tau \sim 200\ \mu s} D + \gamma(2.2\ \text{MeV})$ delayed signal

$n + \text{Gd} \rightarrow \text{Gd}^* \xrightarrow{\tau \sim 28\ \mu s} \text{Gd} + \gamma(8\ /\ 8.5\ \text{MeV})$ delayed signal

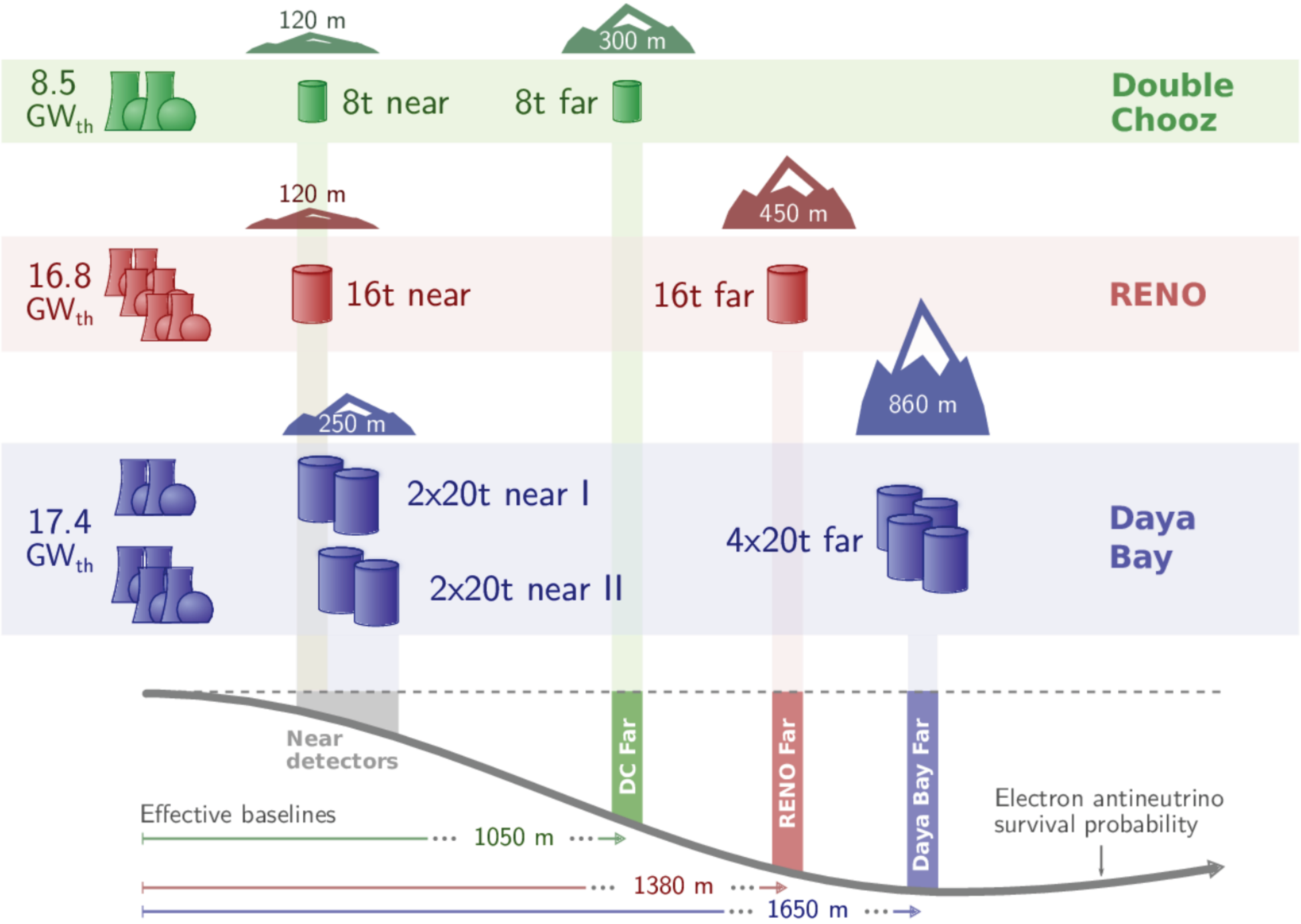


Liquid Scintillator Detectors

- High Light Yield
  Resolution & Energy Threshold
- Large Proton Abundance
  antineutrino target
- Doping capability
  improve background rejection
- Large Volumes
  compensate low cross section

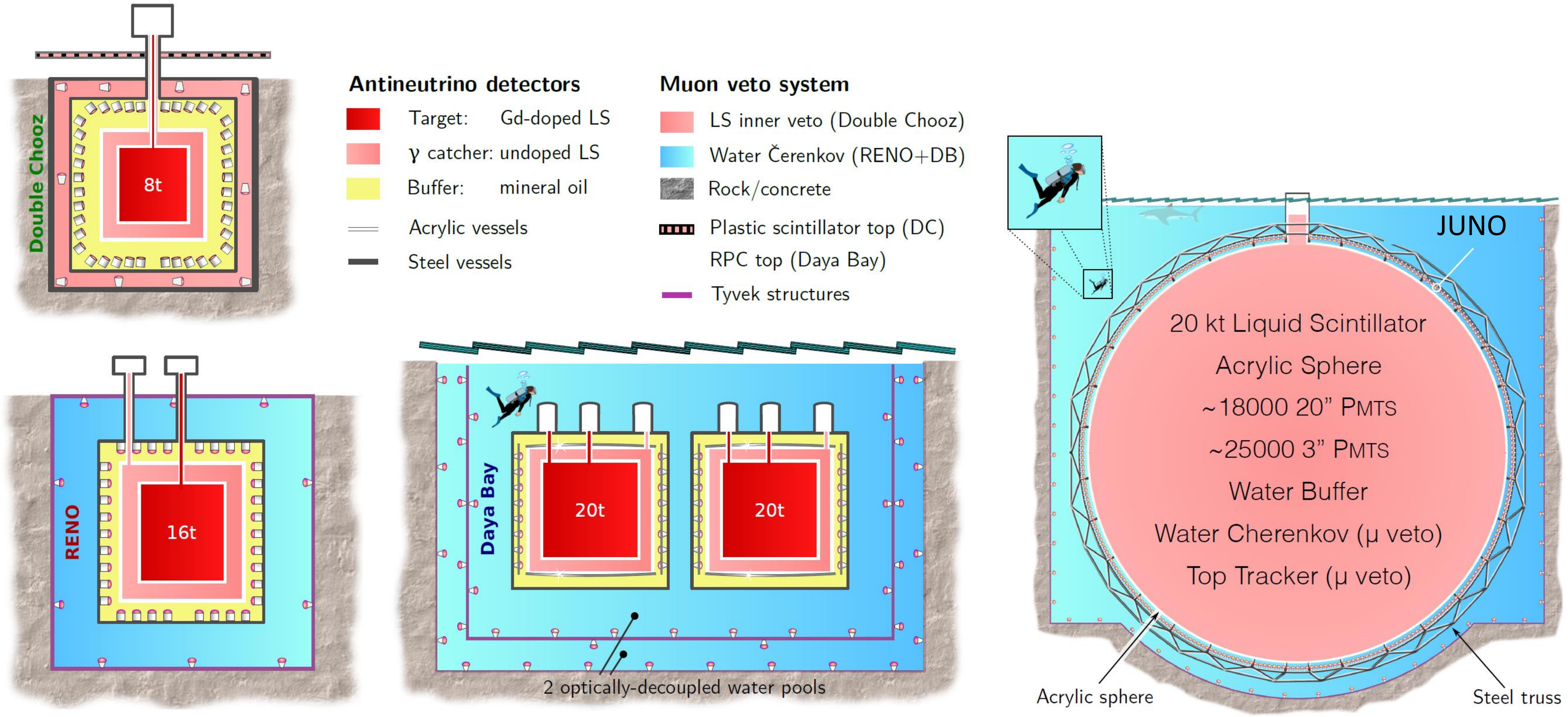


Reactor neutrino experiments



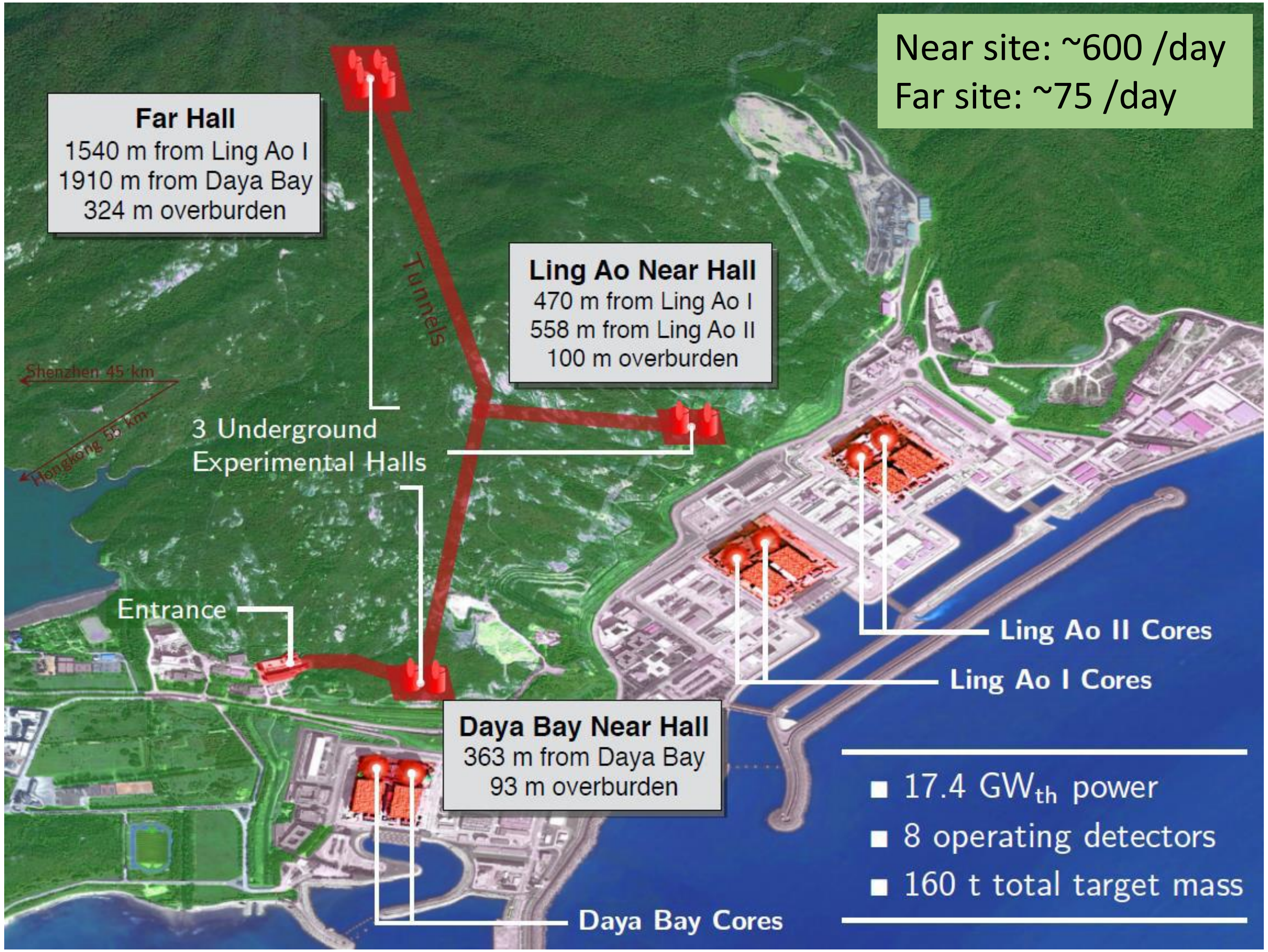
Jetter @ COSPA (2014)

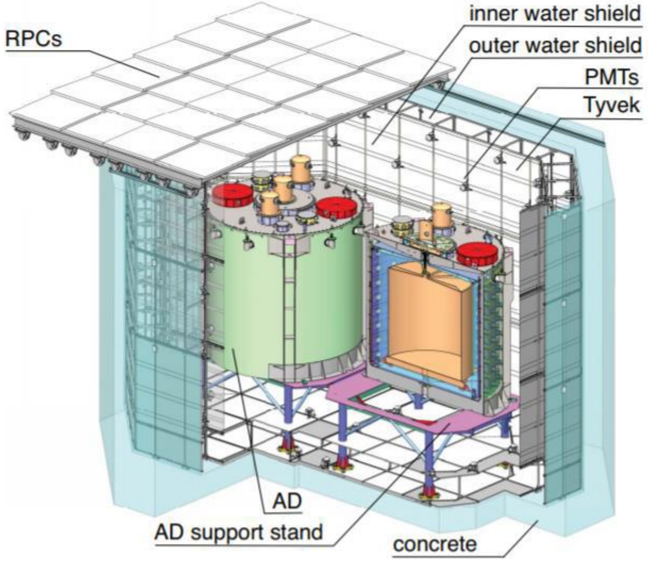
Reactor neutrino detectors



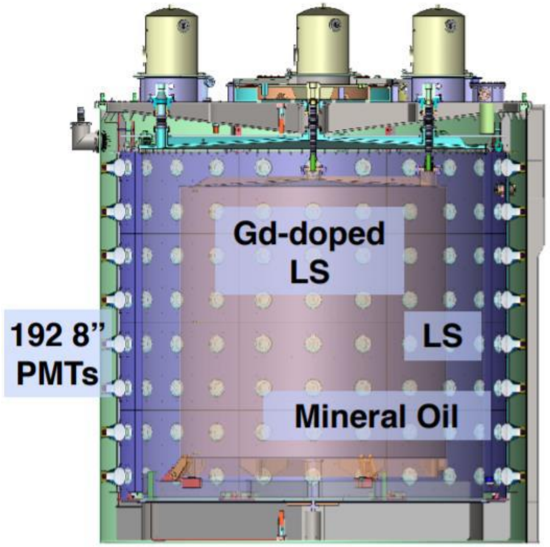
Jetter @ COSPA (2014)

Daya Bay





Double purpose: shield the ADs and veto cosmic ray muons



Energy resolution:
$\sigma_E/E \cong 8.5\%/\sqrt{E}$

Atmospheric neutrino detection and problem

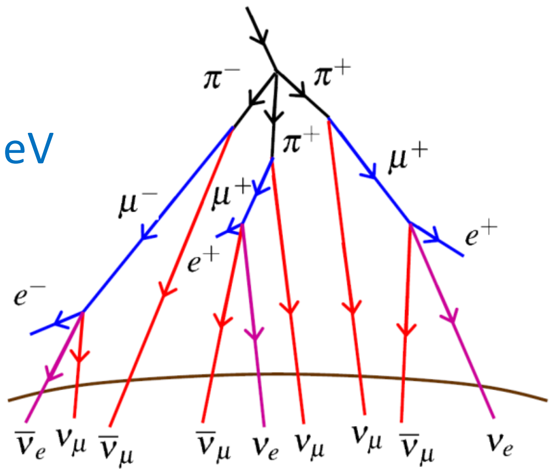
$$\pi^+ \to \mu^+ \nu_\mu \qquad \mu^+ \to e^+ \nu_e \bar{\nu}_\mu$$

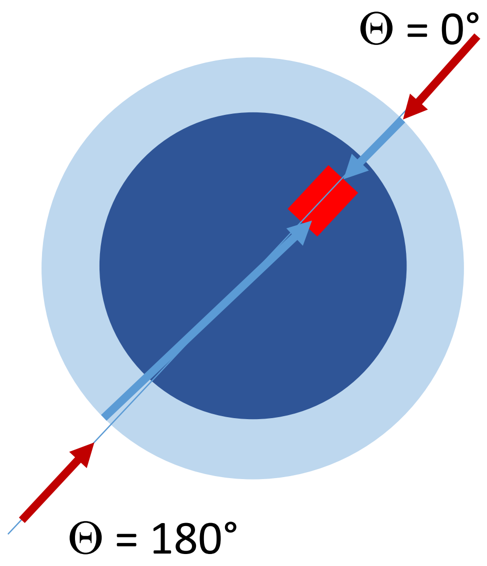
$$\pi^- \to \mu^- \bar{\nu}_\mu \qquad \mu^- \to e^- \bar{\nu}_e \nu_\mu$$

Therefore, there is a clear expectation for the rate:

$$R = \frac{(\nu_e + \bar{\nu}_e)}{(\nu_\mu + \bar{\nu}_\mu)} = \frac{1}{2}$$

$E > 1$ GeV





Smaller than expected ratio was measured by different experiments

Flavor identification in SK

Superkamiokande

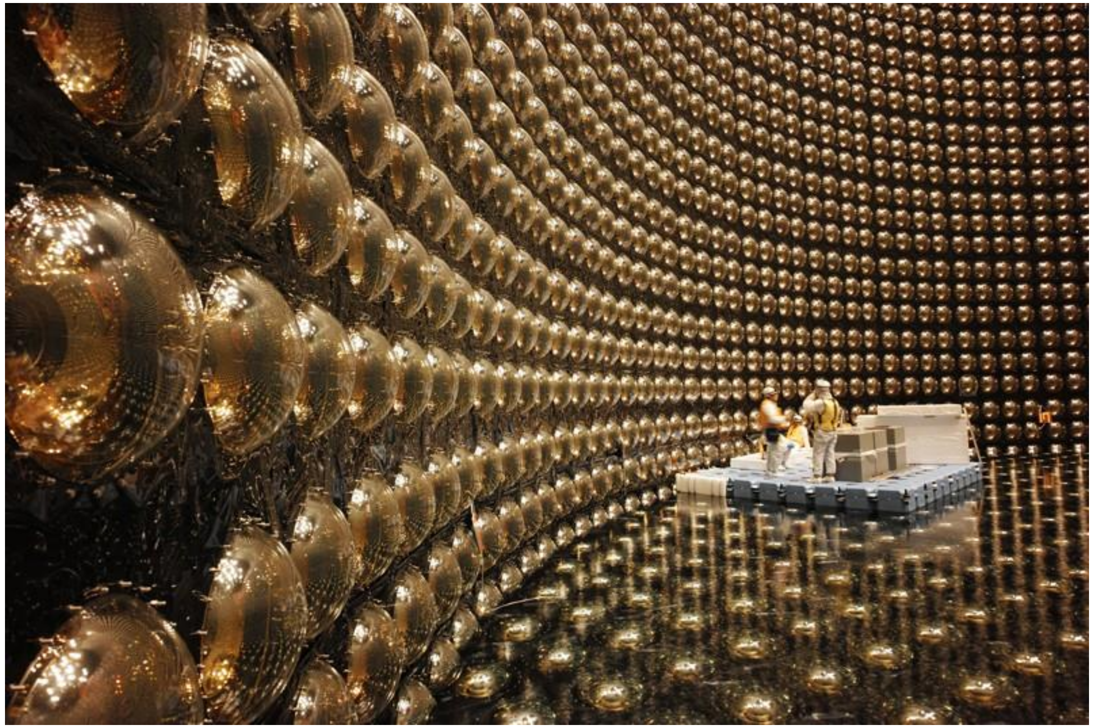
Water Cherenkov detector

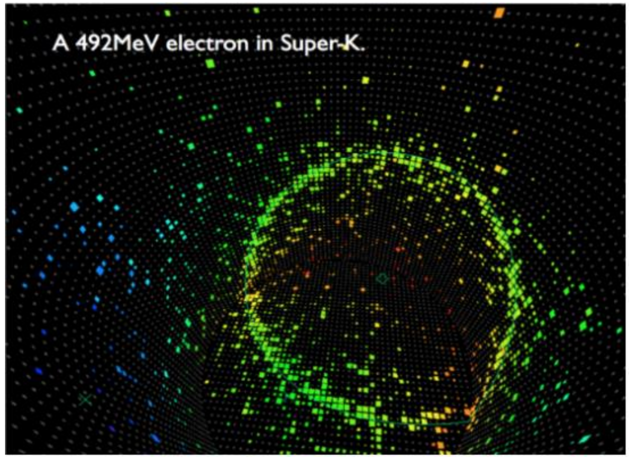
50000 ton water

11146 Photo-multiplier tubes

$\nu_l + e^- \rightarrow \nu_e + l^-$

Discrimination muon neutrino events from electron neutrino events





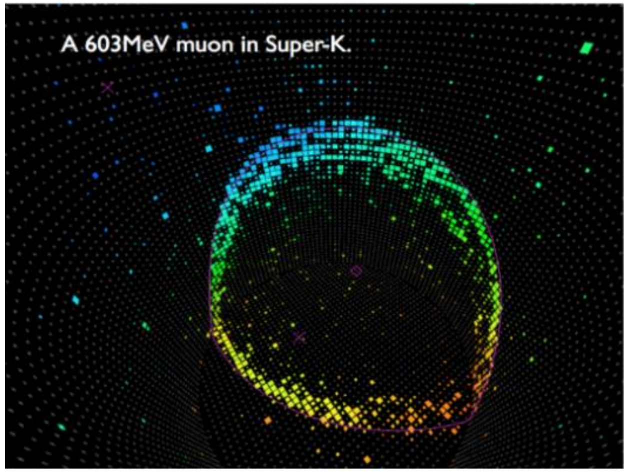
Example: 1 GeV muon created at 10 m from the bottom propagating along the SK axis:

Muons lose energy via ionization.

Consindering muon as MIP the full energy is lost in about 4.5 m

For 4.23 m the muon has enough energy to produce Cherenkov light

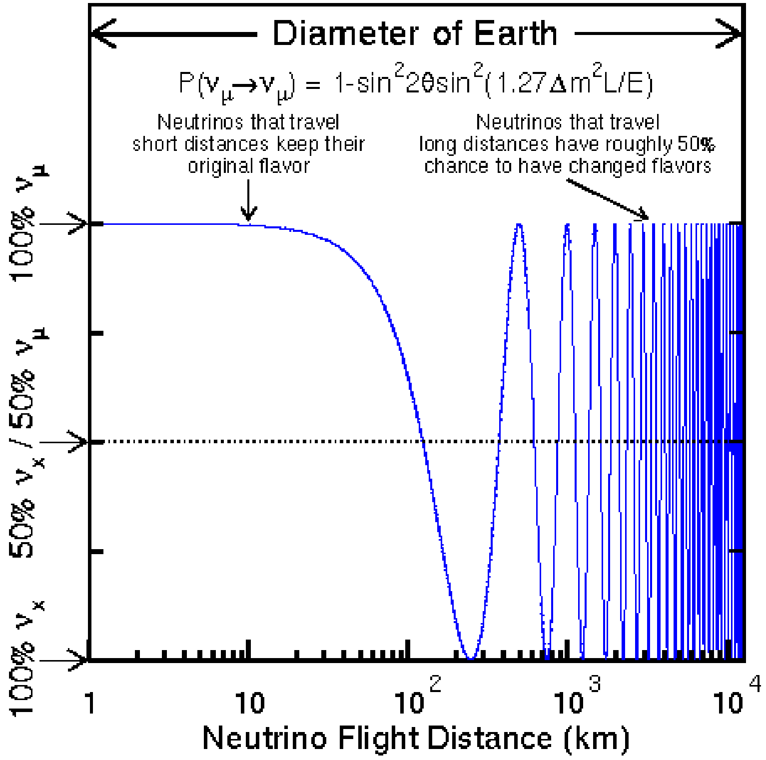
The Cherenkov ring at the bottom cover an area with R_{max} ~ 8.7 m and R_{min} ~ 5 m

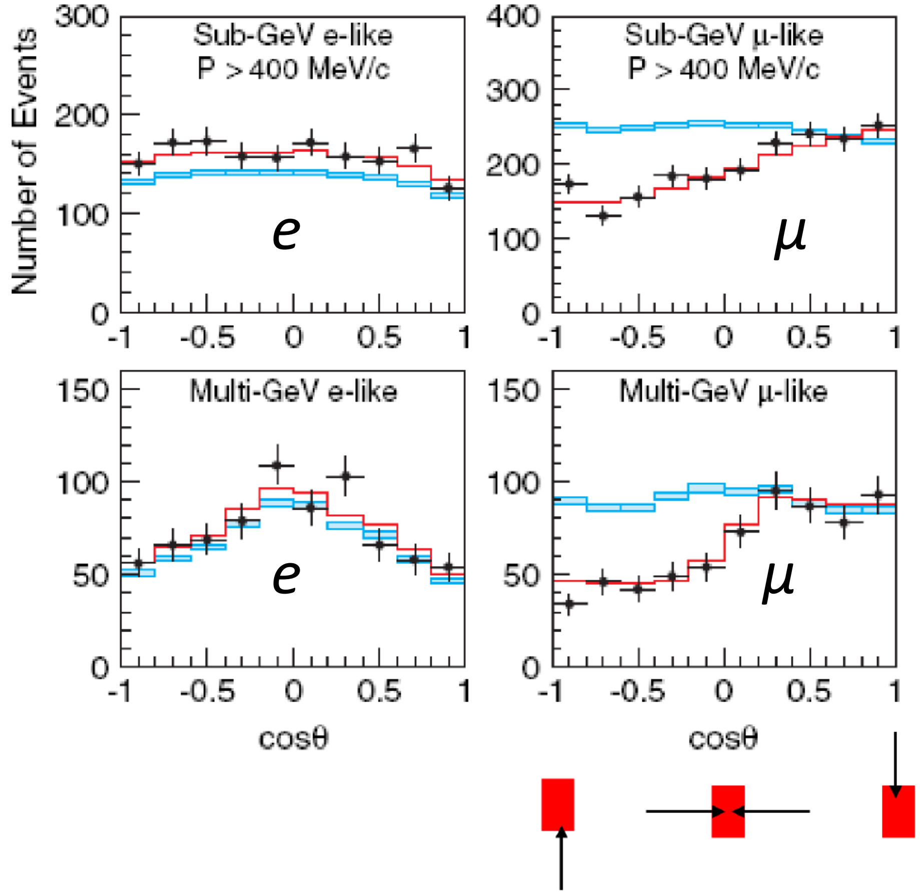


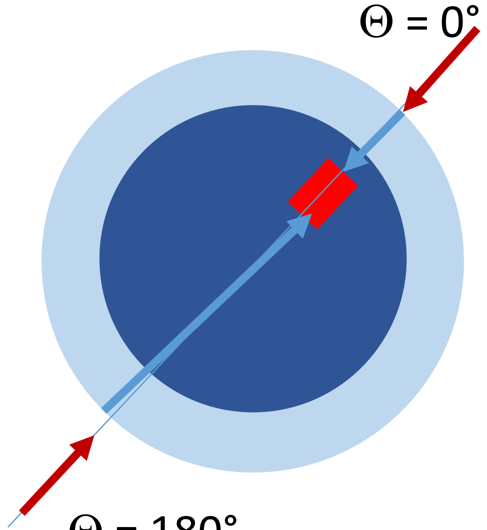
Simulation by SK Collaboration

Solution of the atmospheric neutrino problem

Flight distances for neutrinos detected can vary from 15 km for neutrinos coming "down" to more than 13,000 km for neutrinos coming from interactions in the atmosphere below the detector on the other side of the planet.







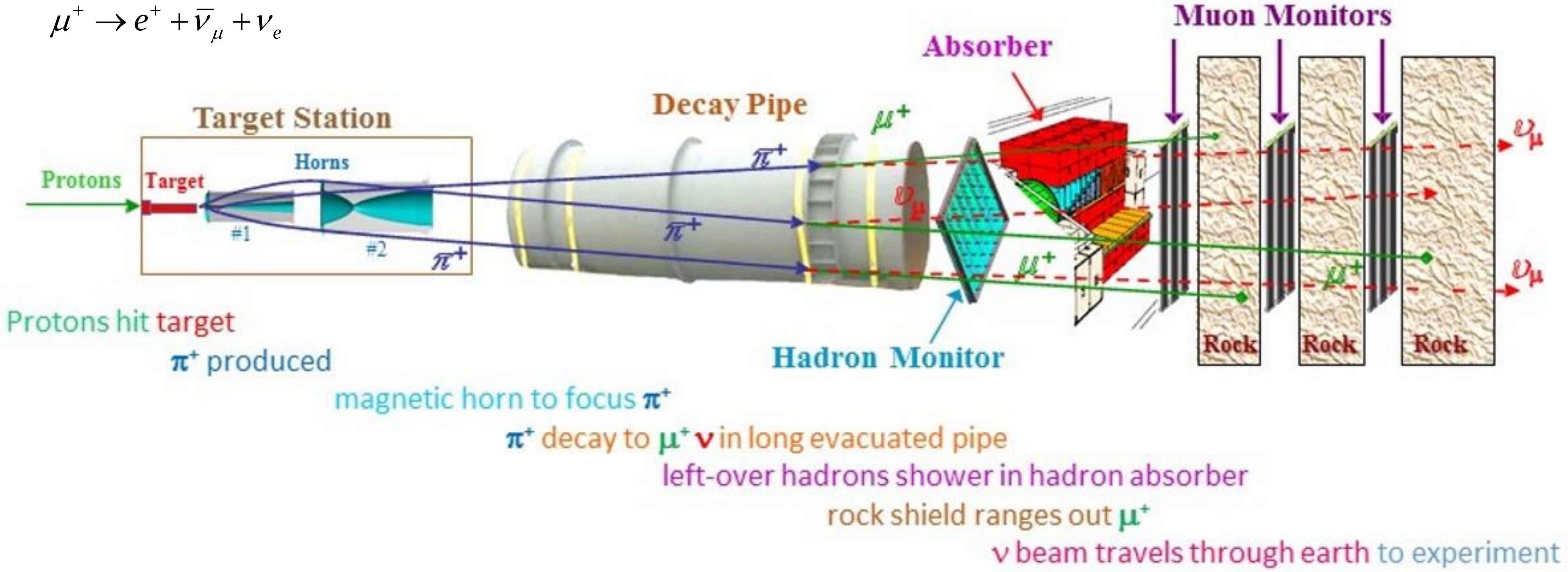
Super-Kamiokande Collaboration
Phys. Rev. Lett. 81, 1562

Neutrino beams

Mesons (pions, kaons) are produced in the interaction of high energy protons with a target

$$\pi^+ \to \mu^+ + \nu_\mu$$

$$\mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e$$



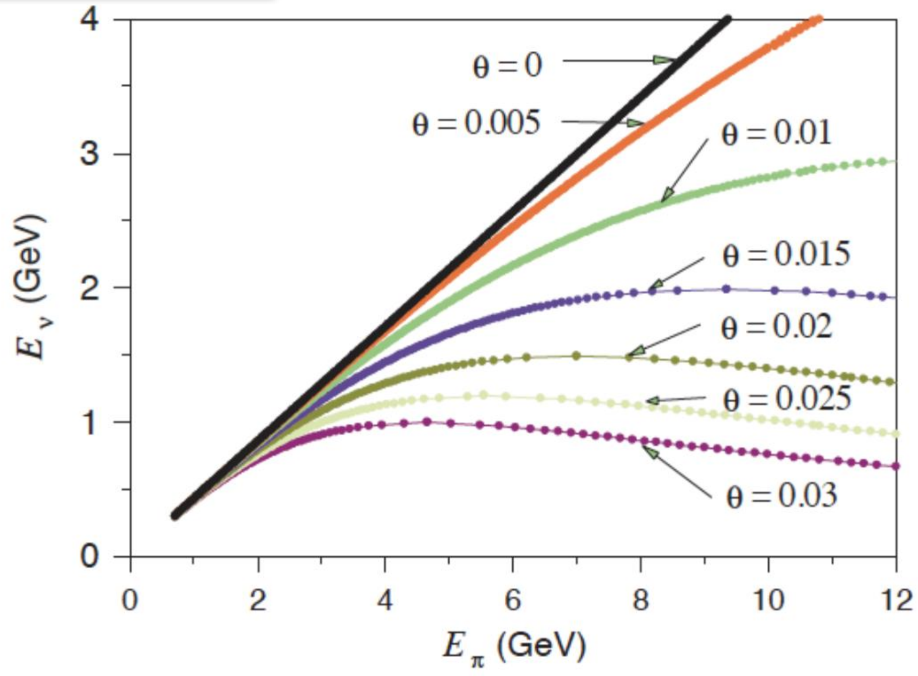
Fermilab, NuMI

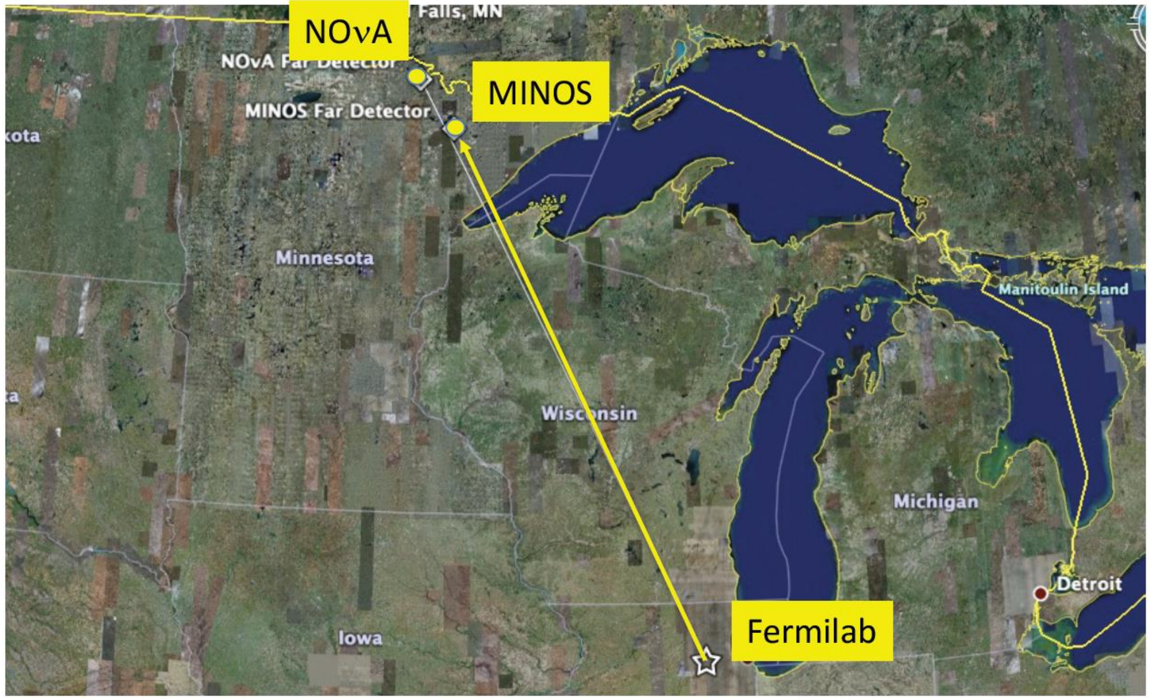
Neutrino beams – on-axis and off-axis beam

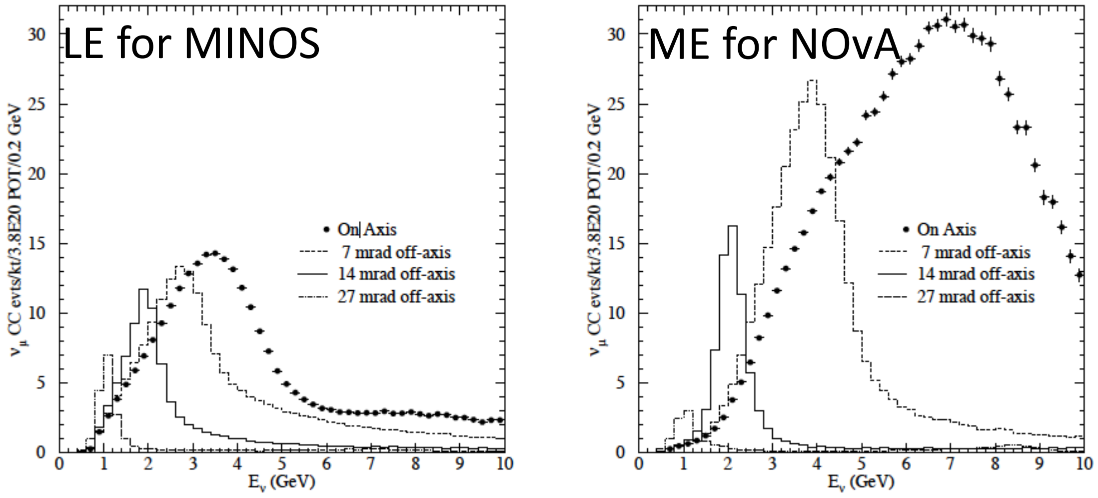
Two approaches to neutrino beams:

- **On**-axis (put detector on the axis of the neutrino beam)
  → $E_\nu = E_\nu^{max} \sim 0.43 E_\pi$
  → broad energy range and high flux

- **Off**-axis (put detector a few degrees off the beam axis)
  → E_ν/GeV = $\frac{0.03}{\Theta}$
  → narrow energy range and lower flux



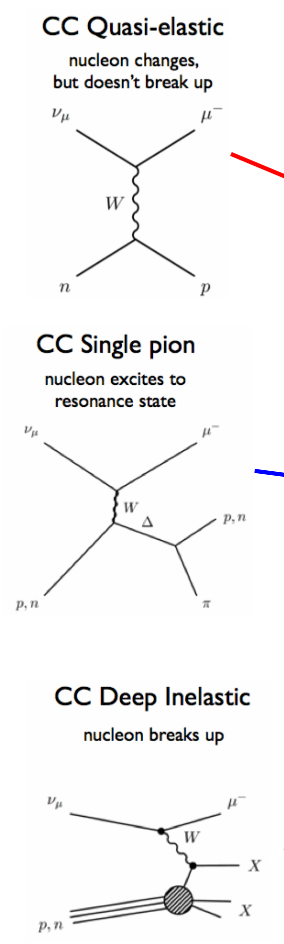


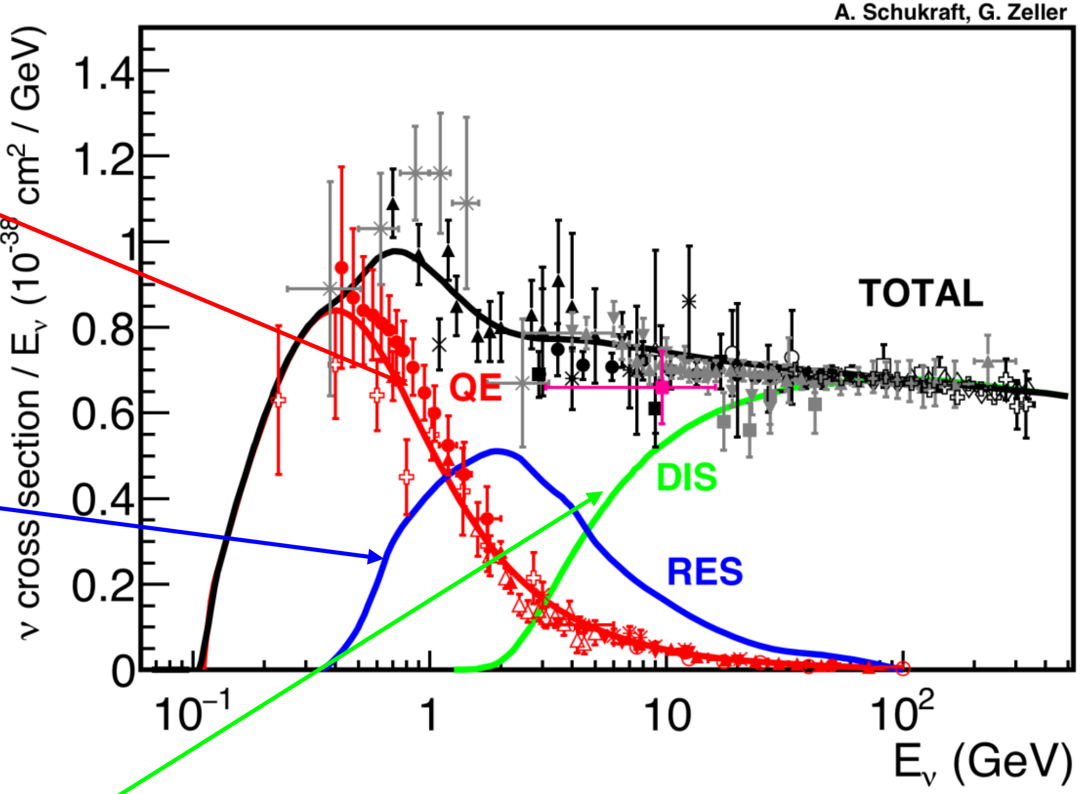


Nakaya and Plunkett 2016 *New J. Phys.* **18** 015009

Neutrino cross-sections

The known reactions of neutrinos with matter fall completely within the Standard Model of particle physics. Therefore the cross-section of different process can be calculate (some of them with more effort..)





Total neutrino per nucleon CC cross sections

Formaggio, Zeller Rev. Mod. Phys. 84, 1307 (2012)

- < 1 GeV QE dominates
- > 5 GeV DIS dominates
- 1 GeV < E < 5 GeV mixture of QE, RES, DIS

In all cases need to reconstruct the neutrino energy:

- QE simple topology
- DIS complex topology

Need dedicated experiments and theoretical models

Neutrino beam experiments

Experiment	data run	Peak energy	Baseline	Detector	Main results
K2K	1999-2004	1 GeV	250 km	Water Cherenkov	confirm atmospheric neutrino oscillations
MINOS(+)	2005-2015	3 GeV	735 km	Iron/scintillator	precise measurement of $\left|\Delta m_{23}^2\right|$ and θ_{23}
CNGS/OPERA	2008-2012	17 GeV	735 km	Emulsions	observe tau appearance in $\nu_\mu \rightarrow \nu_\tau$ oscillations
T2K	2010 -	0.7 GeV	295 km	Water Cherenkov	observe $\nu_\mu \leftrightarrow \nu_e$ oscillations, measure θ_{13}
NOνA	2014 -	2 GeV	810 km	Liquid scintillator	observe $\nu_\mu \leftrightarrow \nu_e$ at a longer baseline for mass ordering

Neutrino Detectors

arXiv:1710.02601v1

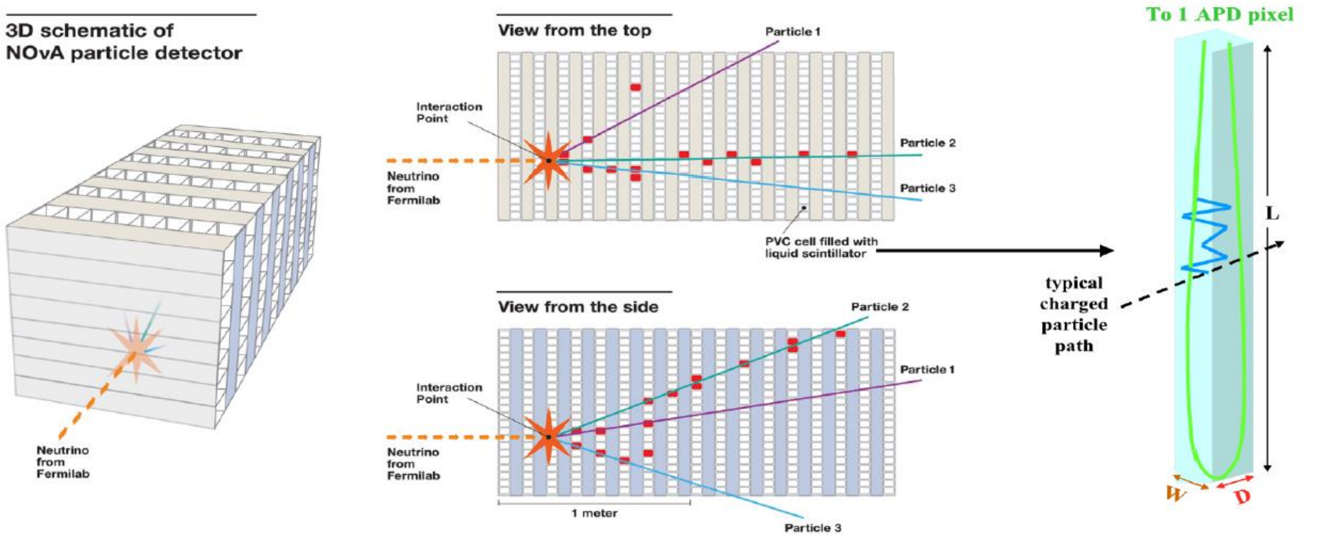
NOvA (NuMI off-axis ν_e appearance)
off-axis (14.8 milliradians) E = 2 GeV
Active segmented liquid scintillator detector

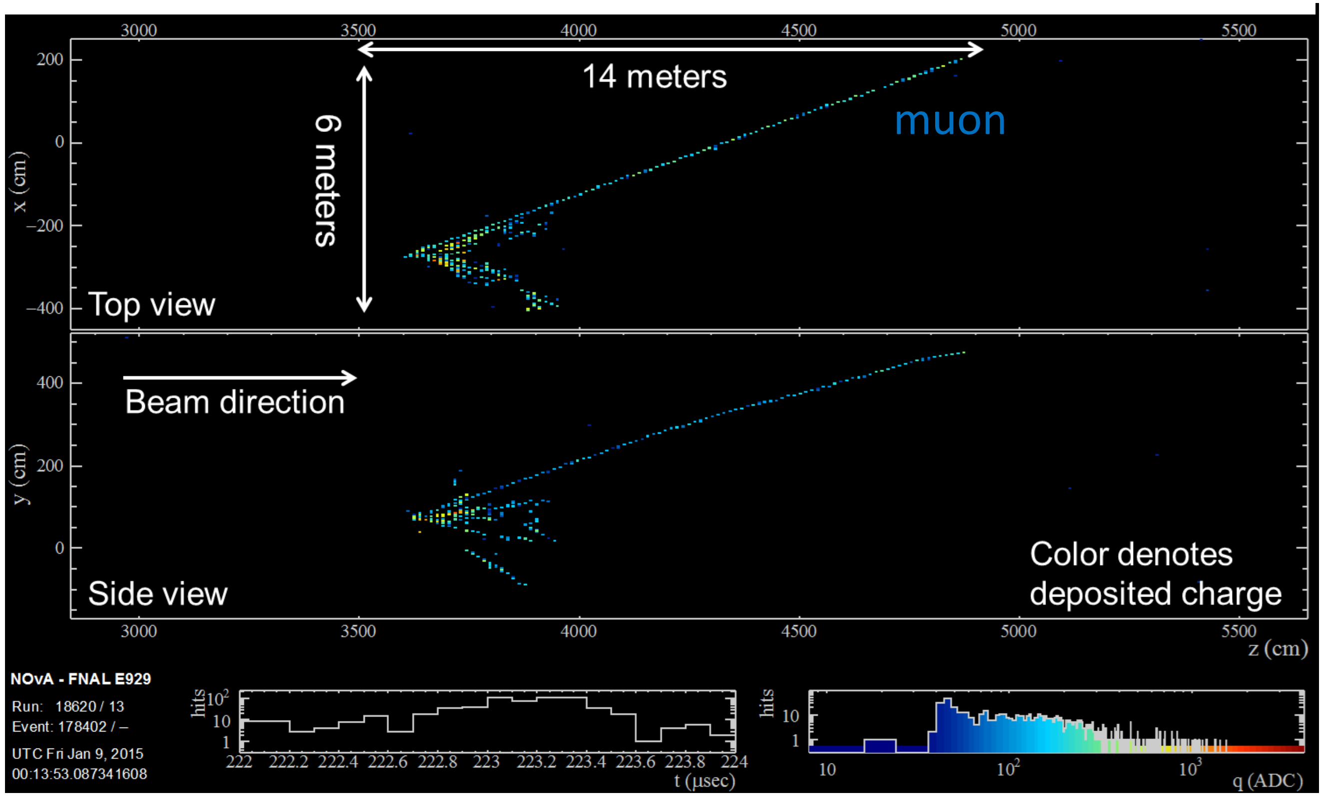
- Muon momentum from range
- Hadronic/EM energy from light yield

193 ton Near Detector has dimensions
3.9 m × 3.9 m × 12.67 m is located
100 m underground at Fermilab

14 kton Far Detector has dimensions
15.5 m × 15.5 m × 60 m is located approximately
810 km away on the surface in Ash River, Minnesota.

Neutrino energy from the sum of muon/electron energy and hadron energy





https://nusoft.fnal.gov/nova/public/neutrinos.html

DUNE

LBNF: the world's most intense high-energy ν beam

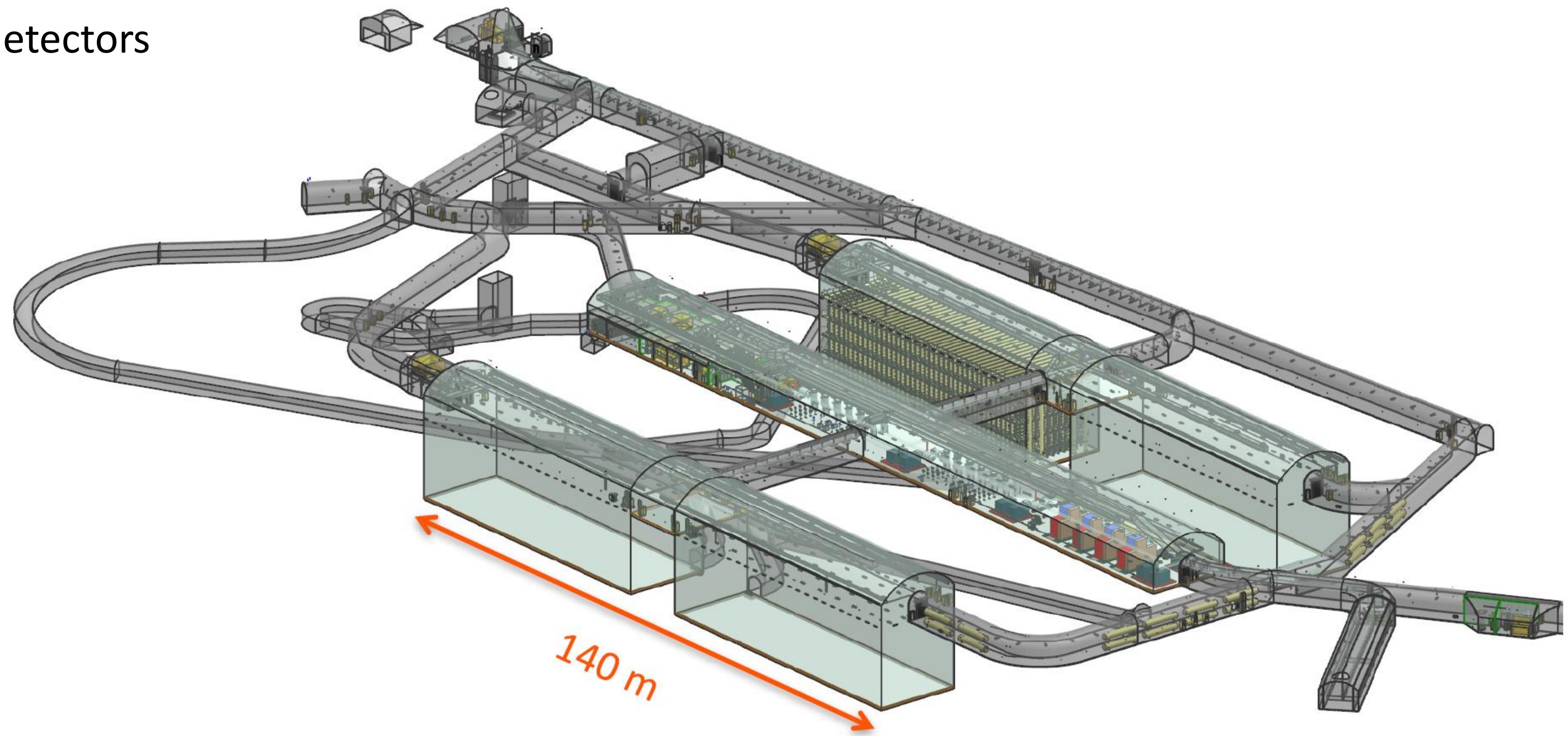
→ 1.2 MW from day one

→ upgradable to 2.4 MW

→~80 GeV proton beam

to be compared to NuMI (MINOS) <400 kW and NuMI (NOVA) 600 - 700 kW

Far detector: 70-kt LAr-TPC = 4 x 17 kt detectors



DUNE

Physics which can be done with the DUNE detector

1) Neutrino Oscillation Physics

– Discover CP Violation in the leptonic sector

– Mass ordering

– Precision Oscillation Physics:

- parameter measurement, θ_{23} octant
- testing the 3-flavor paradigm, steriles, NSI

2) Nucleon Decay

– e.g. targeting SUSY-favored modes, $p \rightarrow K^{+}\overline{\nu}$

3) Supernova burst physics & astrophysics

– Galactic core collapse supernova, sensitivity to ν_e

Long baseline:

→ Matter effects are large ~ 40%

Wide-band beam:

→ Measure νe appearance and $\nu\mu$ disappearance over range of energies

→ MO & CPV effects are separable

$$\nu_e + {}^{40}Ar \rightarrow e^{-} + {}^{40}K$$

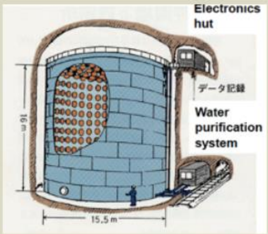
T2HK

Upgraded JPARC beam → Assume 1.3 MW at start of experiment

T2HK will run 6 years with one tank (260 kt)
4 years with two tanks (2 x 260 kt)

Hyper-K is off-axis Narrow-band beam, centered on first oscillation maximum
Baseline = 295 km matter effect is small

Kamiokande
(1983-1996)

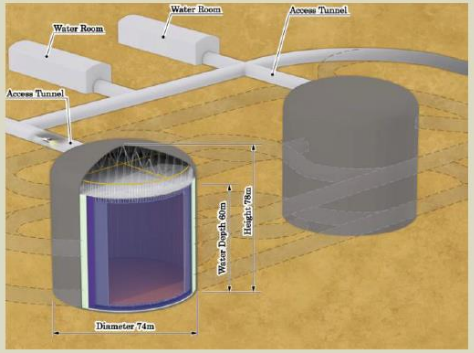


3 kton

Super-Kamiokande
(1996-)

50 kton

Hyper-Kamiokande
(2026?-)



0.52 Mton

T2HK

Physics cases for T2HK

1) Neutrino Oscillations

– CPV from J-PARC neutrino beam

– Mass Hierarchy from Atmospheric Neutrinos

– Solar neutrinos

2) Search for Proton Decay

– Particularly strong for decays with π^0

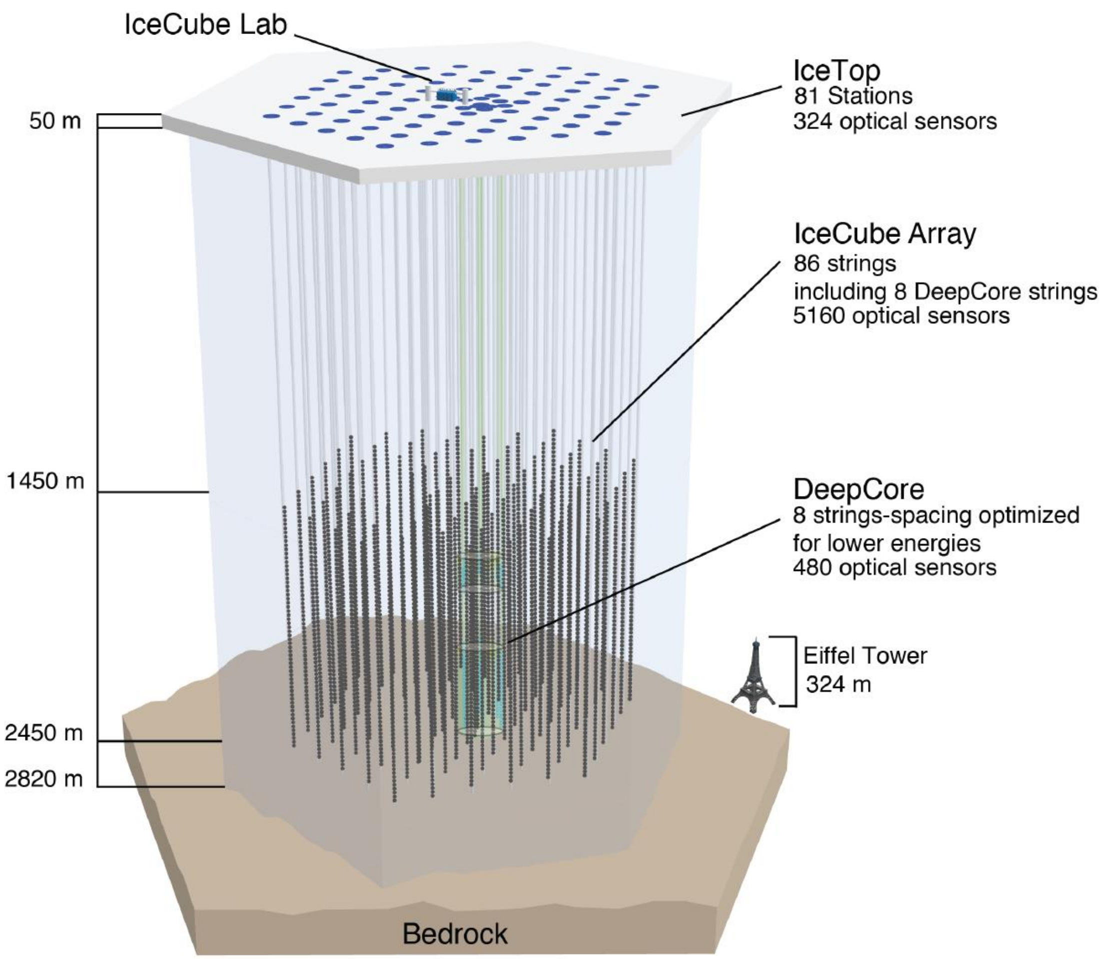
3) Supernova burst physics & astrophysics

– Galactic core collapse supernova – sensitivity to $\overline{\nu}_e$

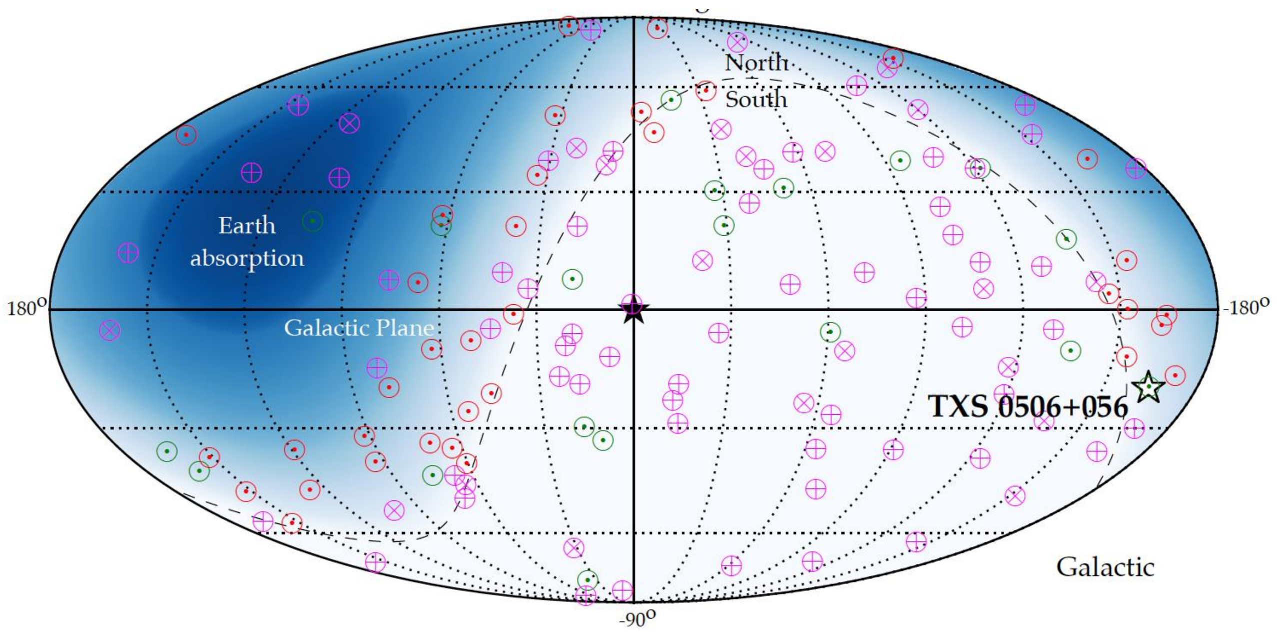
UHE neutrinos

www.quantamagazine.org/

Icecube

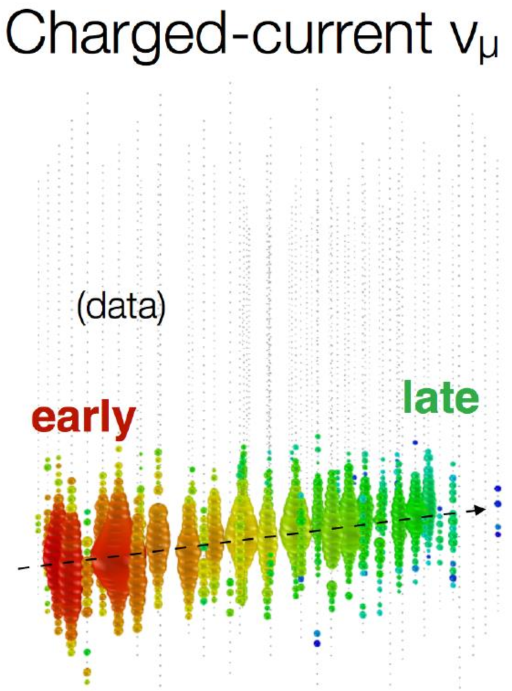


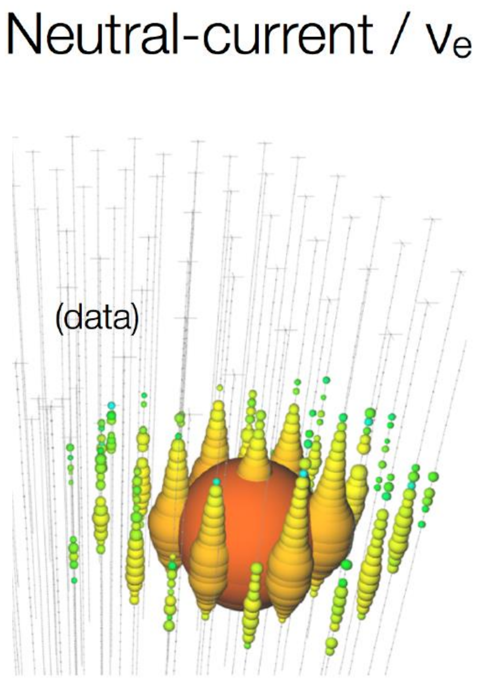
2013: Discovery of cosmic PeV neutrino flux
2018: Evidence for Blazars as neutrino sources
2020: Observation of first tau neutrino
Glashow resonance interaction

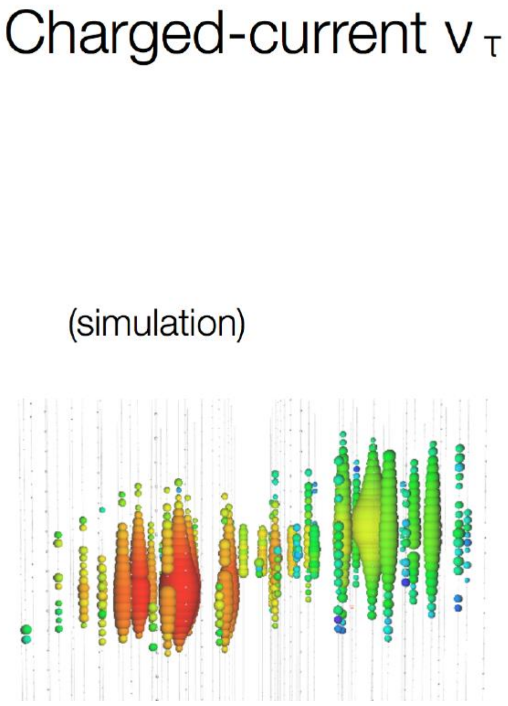


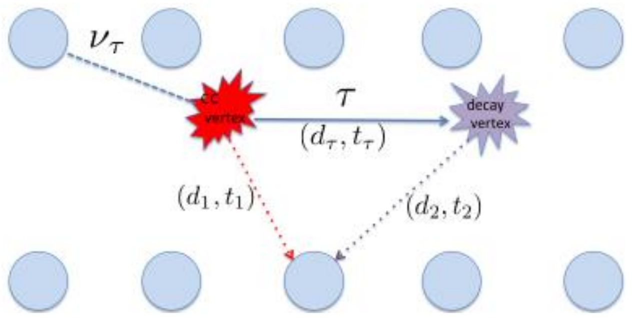
F. Halzen https://arxiv.org/abs/2110.01687
https://onlinelibrary.wiley.com/doi/10.1002/andp.202100309

Flavor identification in Icecube









Up-going track

Precise direction reconstruction 0.5°
factor 2 for energy determination

Cascade

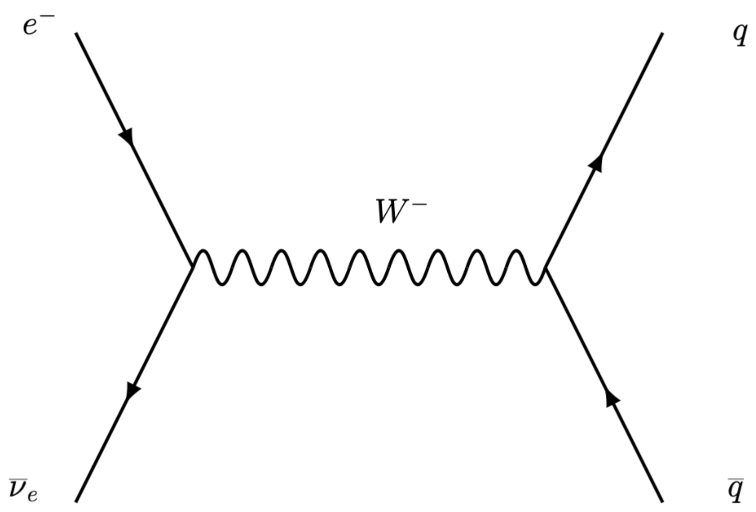
15% energy resolution
10° angular resolution (E>100TeV)

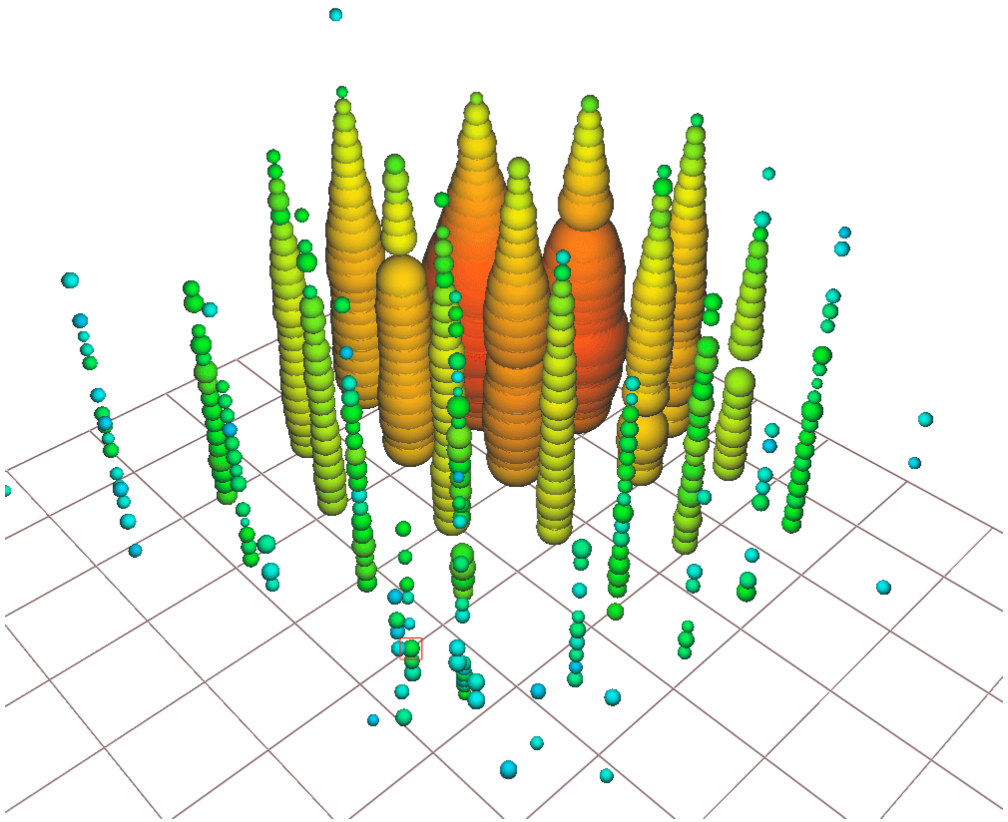
Double cascade

resolvable above ~ 100TeV

IceCube collaboration

Glashow resonance



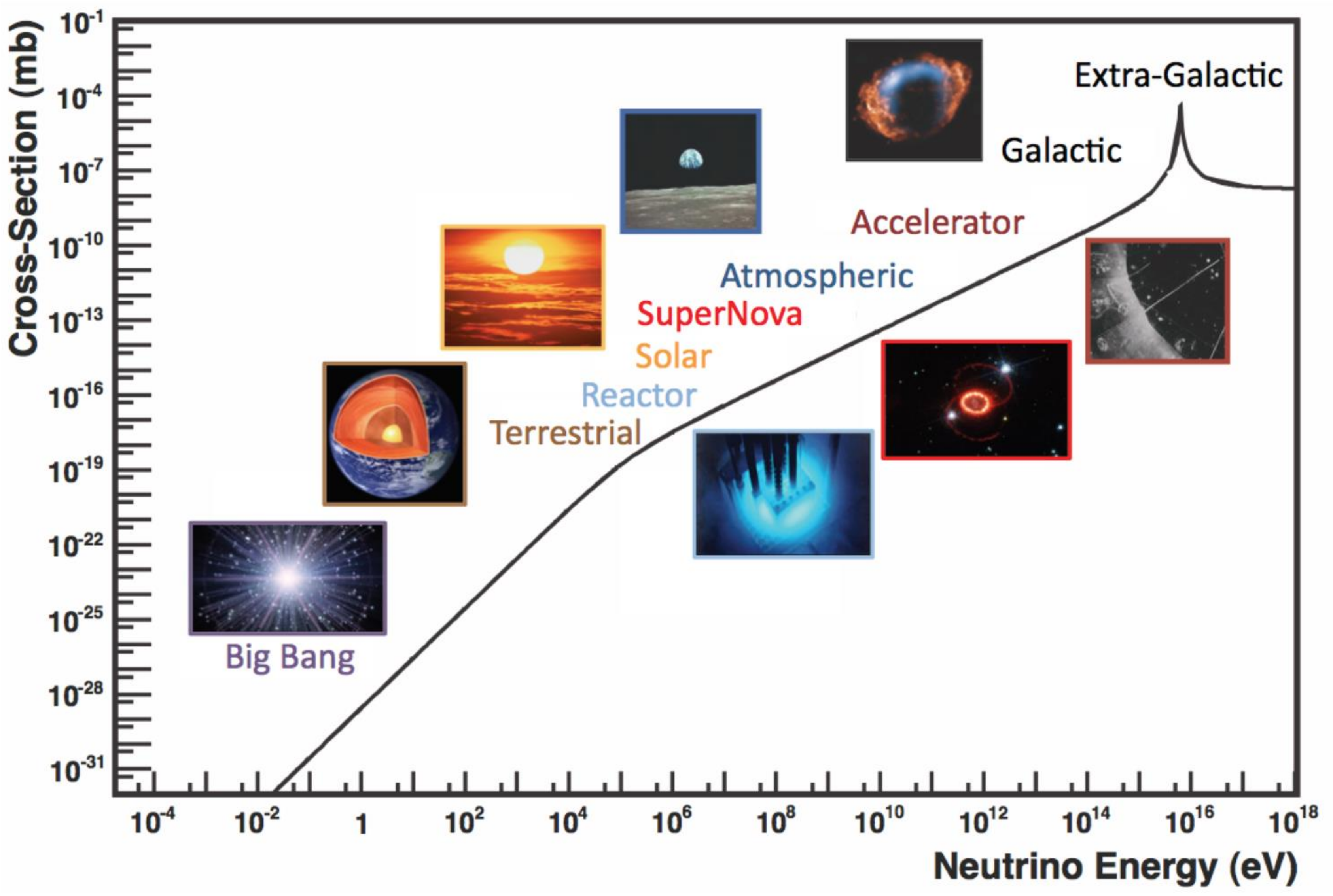


Glashow resonance expected at 6.4 PeV

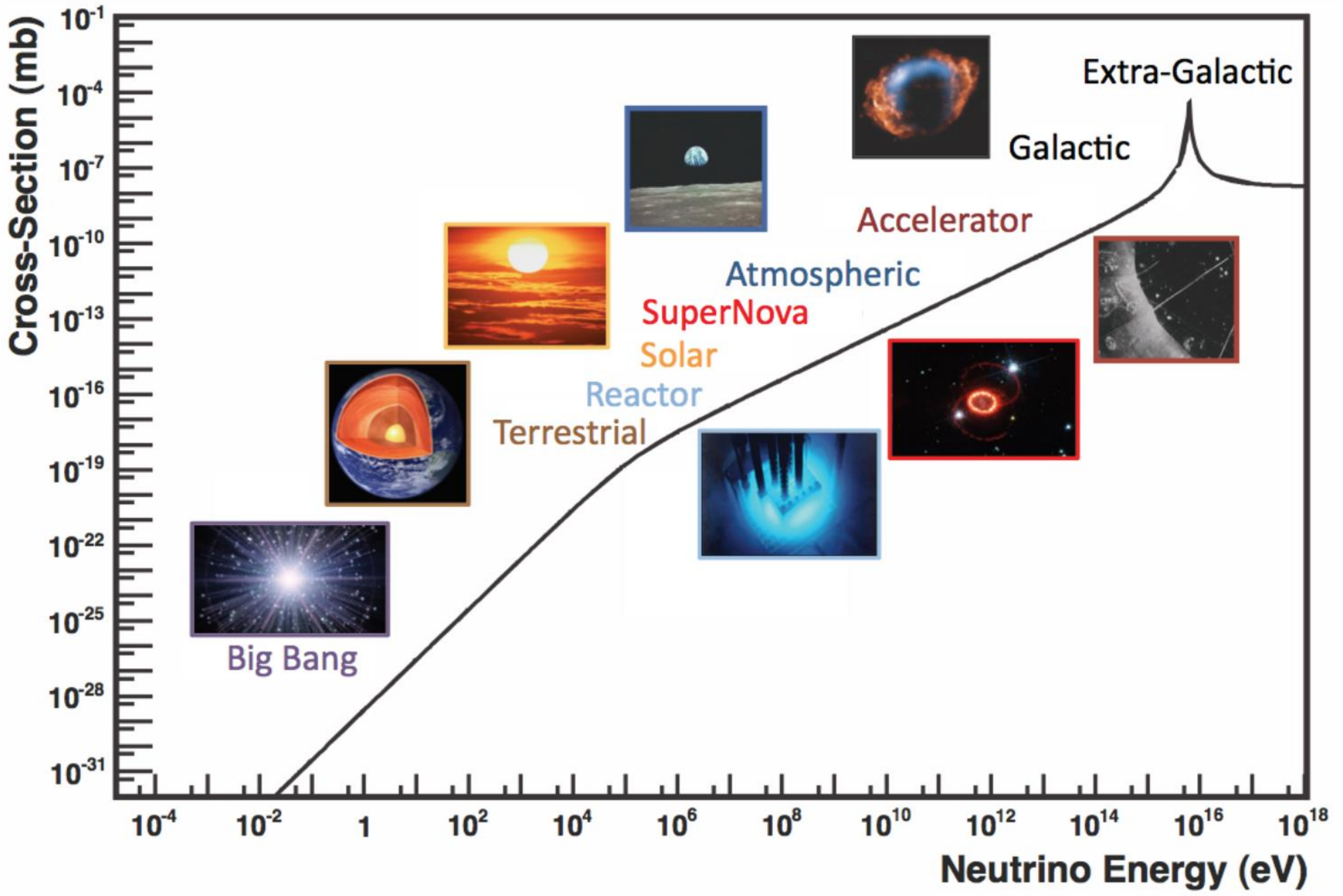
Measured energy ~ 6 PeV

https://icecube.wisc.edu/gallery/icecube-sees-a-glashow-resonance-event/

Conclusions



Conclusions



Any questions ???