NEUTRINO PHYSICS I (EXPERIMENTAL)

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CIEMAT

OUTLINE

1. Introduction
2. Neutrino detection
3. Neutrino oscillation

INTRODUCTION

Introduction to Experimental Neutrino Physics

- Experimental Neutrino Physics has contributed to the development of Electro-Weak theory in a decisive way.
- The Neutrino Discovery and Detection has been critical for:
  - Formulation of Fermi's Theory
  - Existence of Intermediate boson
  - Discovery of Neutral current
  - Discovery of Parity violation

DISCOVERY OF NEUTRINO

1956 Reines and Cowan

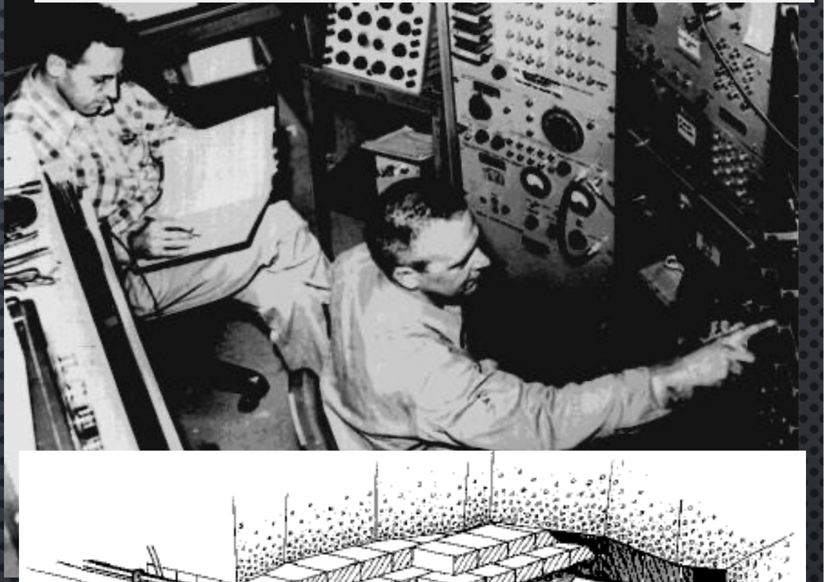
Source of an intense flux of neutrinos:
Nuclear fission bomb → **fission reactor** (1/1000 lower flux)
Very large detector
The newly discovered, **liquid, organic scintillators:**
Target for neutrino interaction (high proportion of hydrogen)
Detection medium from scintillation light.

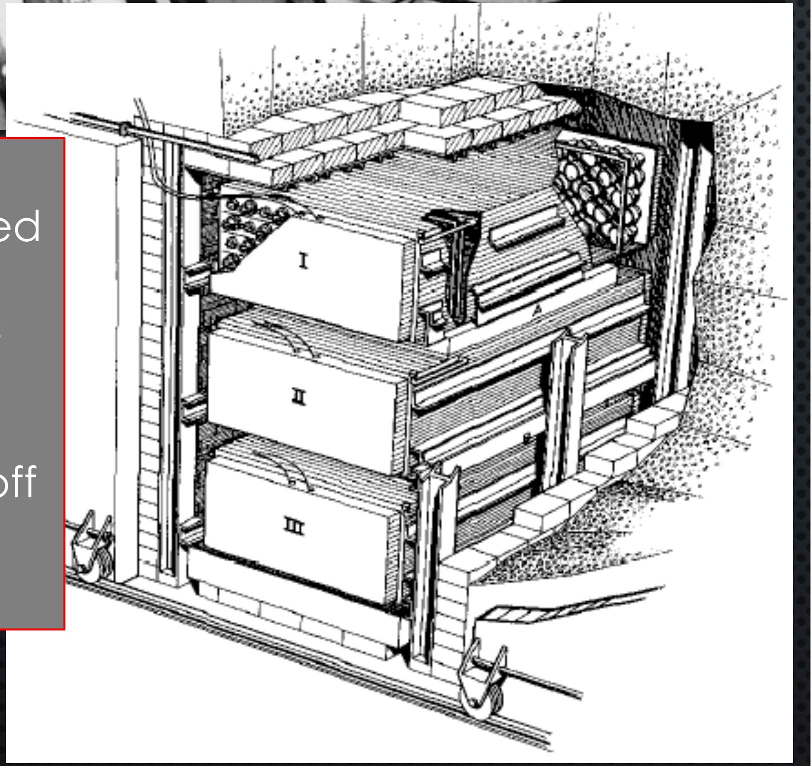
(1954) The Hanford Experiment:
The huge BG due to cosmic rays allowed just to observed a small increase of neutrino candidates when the reactor was on/off.
→ **Insufficient evidence to claim the neutrino discovery.**

(1956) The Savannah River Experiment
The detector was improved and segmented to distinguish from false signals induced by neutrons, gamma rays, and other particles from cosmic ray showers.
The rate of neutrino signals was
5 times greater when the reactor was on/off

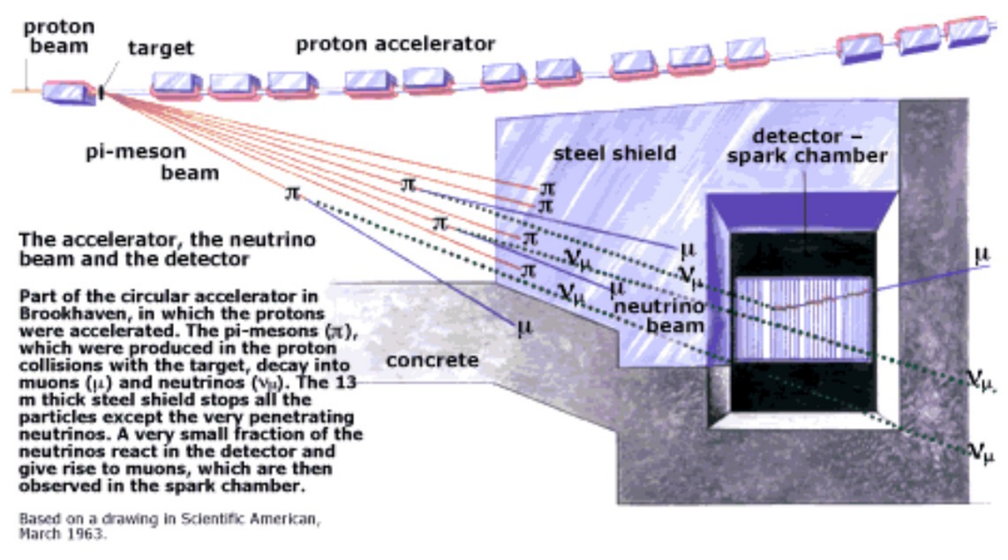
→ **Discovery !**

The Savannah River Experiment





BROOKHAVEN NEUTRINO BEAM (1962)



Generation: $\pi^{\pm} \rightarrow \mu^{\pm} + (\nu/\bar{\nu})$

Detection: $\nu + n \rightarrow p + e^{-}$ $\qquad$ $\nu + n \rightarrow p + \mu^{-}$

10 (1-ton) modules spark chambers after an iron shield wall of 13.5 m

Goals:

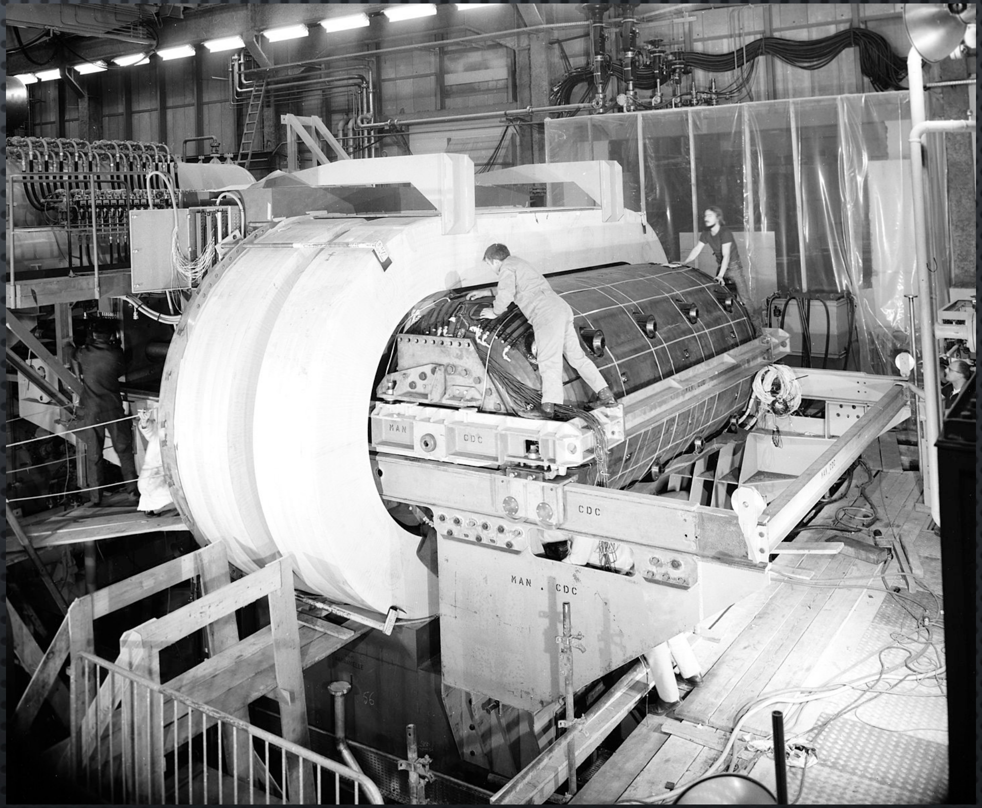
- Are there **two kinds of neutrinos**? Are these 2 reactions produced with the same rate?
- **Test of Fermi's theory**: The existence of an intermediate boson solves the Unitarity problem but implies the existence of reactions like $\mu \rightarrow e + \gamma$ (not observed) unless the two neutrinos are different (lepton number conservation)

Only muons were detected → Discovery of muon neutrino

$\nu_{\mu} \neq \nu_{e}$

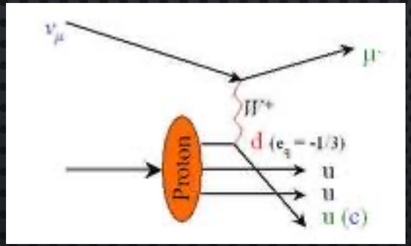
GARGAMELLE BUBBLE CHAMBER FOR NEUTRINO DETECTION AT CERN (1973)

Muon neutrino and anti-neutrino beams at the CERN PS
Gargamelle bubble chamber with freon CF3Br.
Fiducial volume 6.2 m^3.

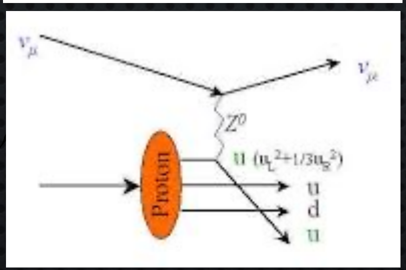


First direct evidence of the weak neutral current (Z boson)

Charged Current



Neutral Current



Only hadrons are produced

INTRODUCTION TO EXPERIMENTAL NEUTRINO PHYSICS

Experiments carried out in the last 20 years has shown:

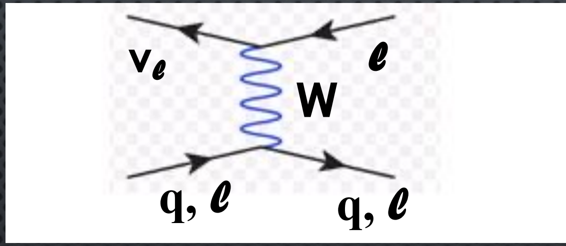
- THE NEUTRINO IS THE ONLY PARTICLE WHOSE BEHAVIOR IS **NOT WELL DESCRIBED BY THE STANDARD MODEL**
- IN MANY ASPECTS **IS DIFFERENT** FROM THE REST OF LEPTONS.
- THE PHENOMENA AROUND THE NEUTRINO COULD OPEN A WINDOW **TO NEW PHYSICS**. THE STUDY OF THEIR OSCILLATIONS AND INTERACTIONS COULD GIVE US INFORMATION ABOUT:
  - CP VIOLATION --> LEPTOGENESIS AND BARYON ASYMMETRY
  - THE EXISTENCE OF NEW PARTICLES (DARK MATTER)
  - NEW MASS GENERATION MECHANISM
  - SM UNITARITY
- **ITS DETECTION HAS BEEN A CHALLENGE FOR EXPERIMENTAL PARTICLE PHYSICS: VERY LOW PROBABILITY OF INTERACTIONS, LOW ENERGY SIGNALS, ETC….**

NEUTRINO DETECTION

NEUTRINO INTERACTION

Neutrinos cannot be detected by the current particle detectors but they can interact and produce new particles sensitive to electro-magnetic fields and, therefore, perceptible.

Charged Current (CC):



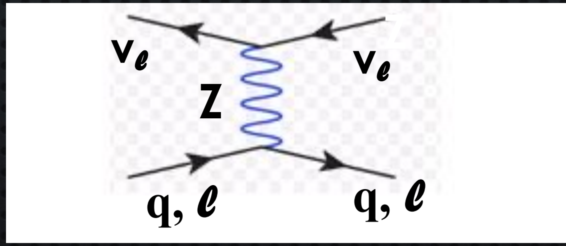
- Flavor of outgoing lepton tags flavor of incoming neutrino
- Charge of outgoing lepton determines whether ν or anti- ν

$\nu_e \rightarrow e^-$ $\quad \bar{\nu}_e \rightarrow e^+$

$\nu_\mu \rightarrow \mu^-$ $\quad \bar{\nu}_\mu \rightarrow \mu^+$

$\nu_\tau \rightarrow \tau^-$ $\quad \bar{\nu}_\tau \rightarrow \tau^+$

Neutral Current (NC):

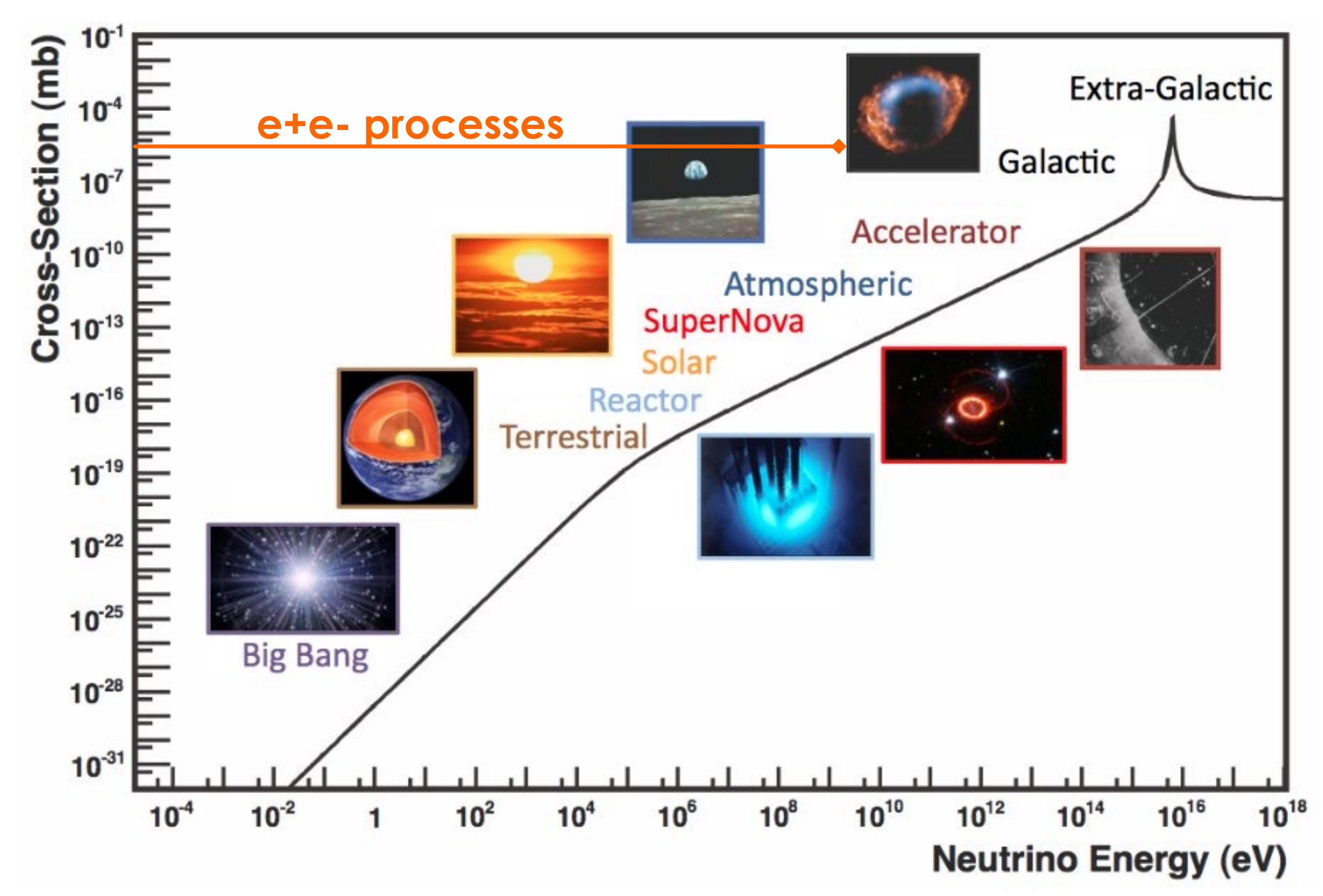


- Flavor of outgoing fermion is independent of incoming neutrino
- It is not possible to infer the neutrino flavor

NEUTRINO CROSS SECTION

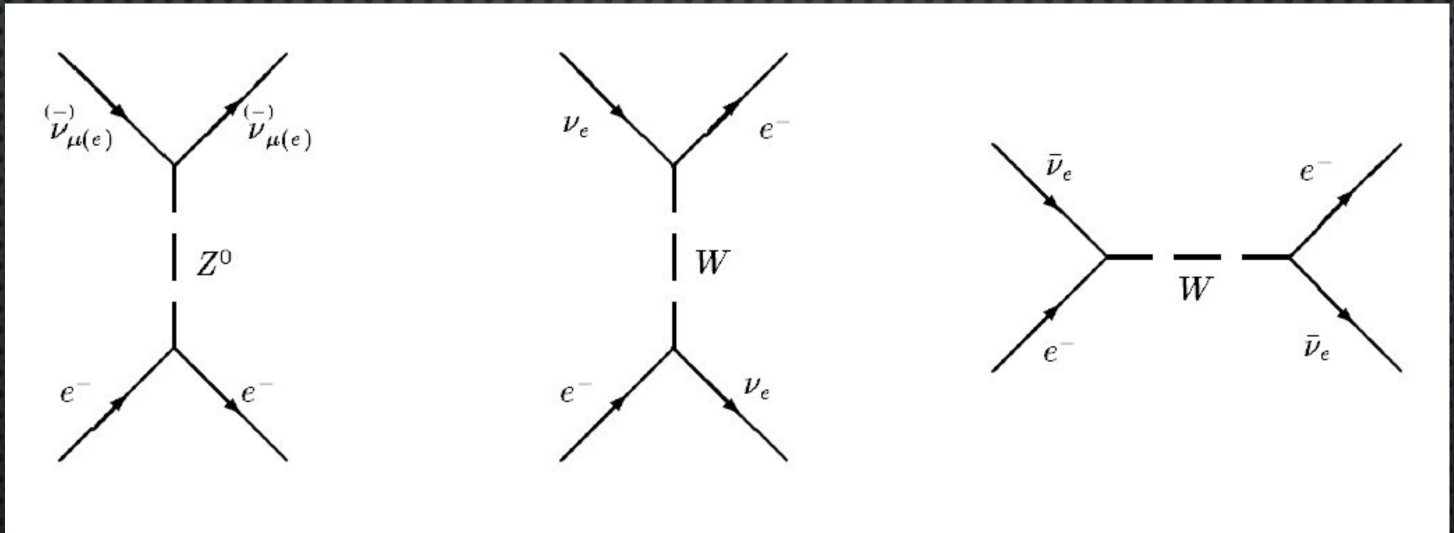
- ❑ Information needed in the interpretation of neutrino oscillation data
- ❑ Many experiments dedicated to the measurement of the different processes cross-section

(1 mb = 10^{-21} cm^2)



NEUTRINO ELECTRON SCATTERING

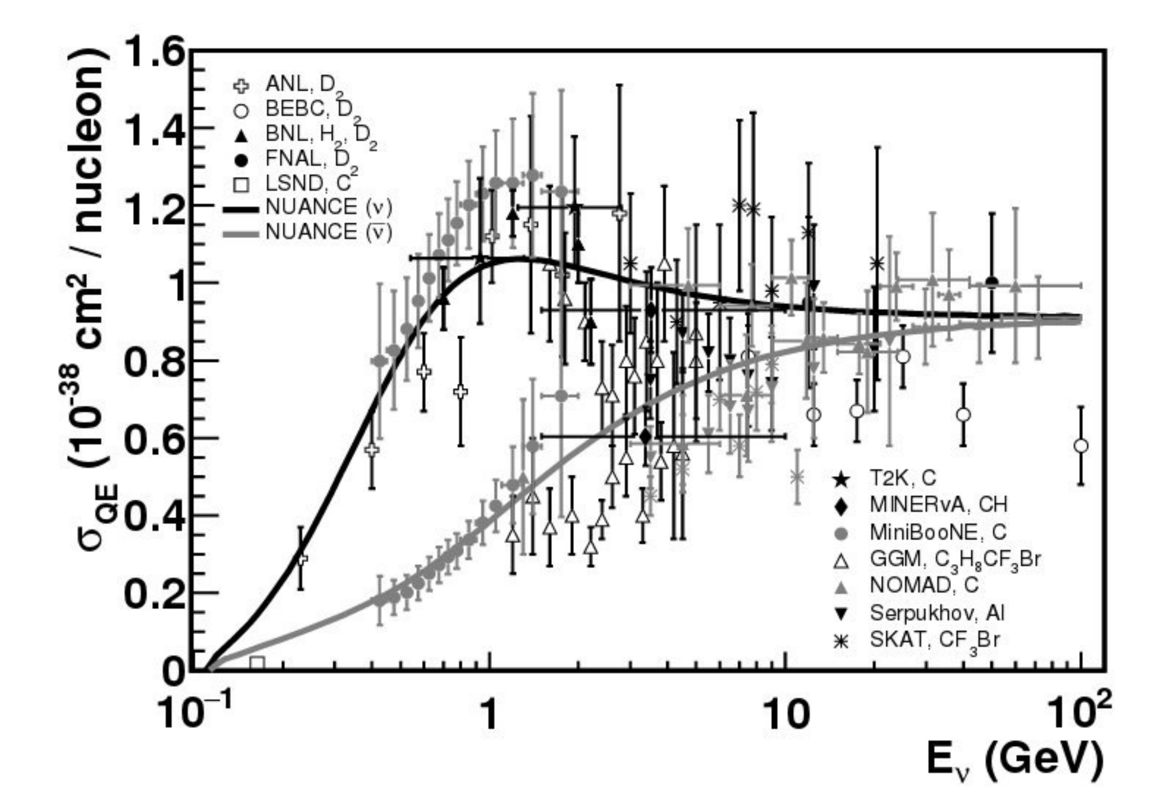
The neutrino is detected through the electron signal in the detector.
The electron scattered retains the information on the neutrino direction (and energy)



The cross-section is higher for ν_e than for ν_μ and ν_τ because they interact only via NC

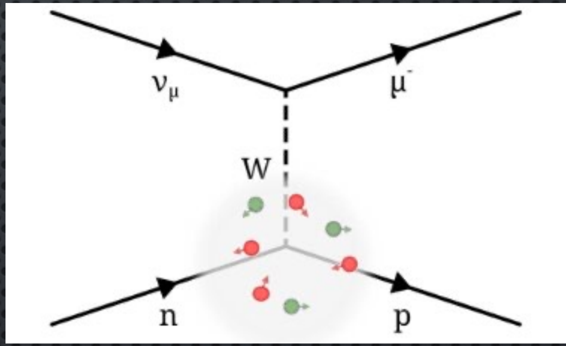
CHARGED-CURRENT QUASI-ELASTIC SCATTERING

Quasi-elastic scattering is the dominant neutrino interaction for E< 1GeV



$$\nu_\mu \, n \;\rightarrow\; \mu^- \, p$$

$$\bar{\nu}_\mu \, p \;\rightarrow\; \mu^+ \, n$$



QE: INVERSE BETA DECAY

$$\bar{\nu}_e\, p \;\rightarrow\; e^+\, n$$

IBD is largely used for $\bar{\nu}_e$ detection (from β decays: reactors, geo-neutrinos)

Detection through the time correlated signal of e^+ and neutron capture of some nuclei.
The neutron-capture cross-section and the energy of the released gammas depend on the type of nucleus.

Neutrino energy is directly obtained from the lepton (e^+) energy:

$$E_\nu = E_l + (M_n - M_p) + O\left({E_\nu}/{M_n}\right)$$

QE: NEUTRINO INTERACTION WITH DEUTERON

The binding energy of the deuteron is only 2.2 MeV, so any neutrino with E_ν>2.2 MeV is capable of initiating the first of these reactions:

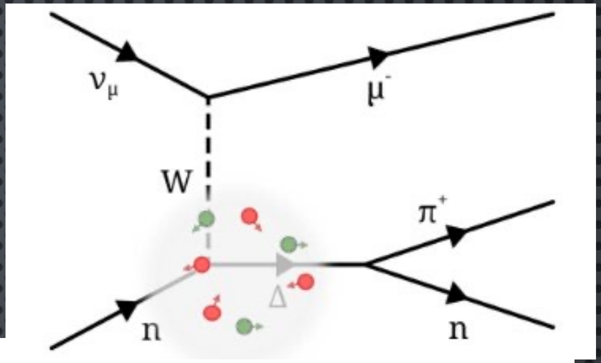
NC: $\nu_X + d \rightarrow \nu_X + p + n$

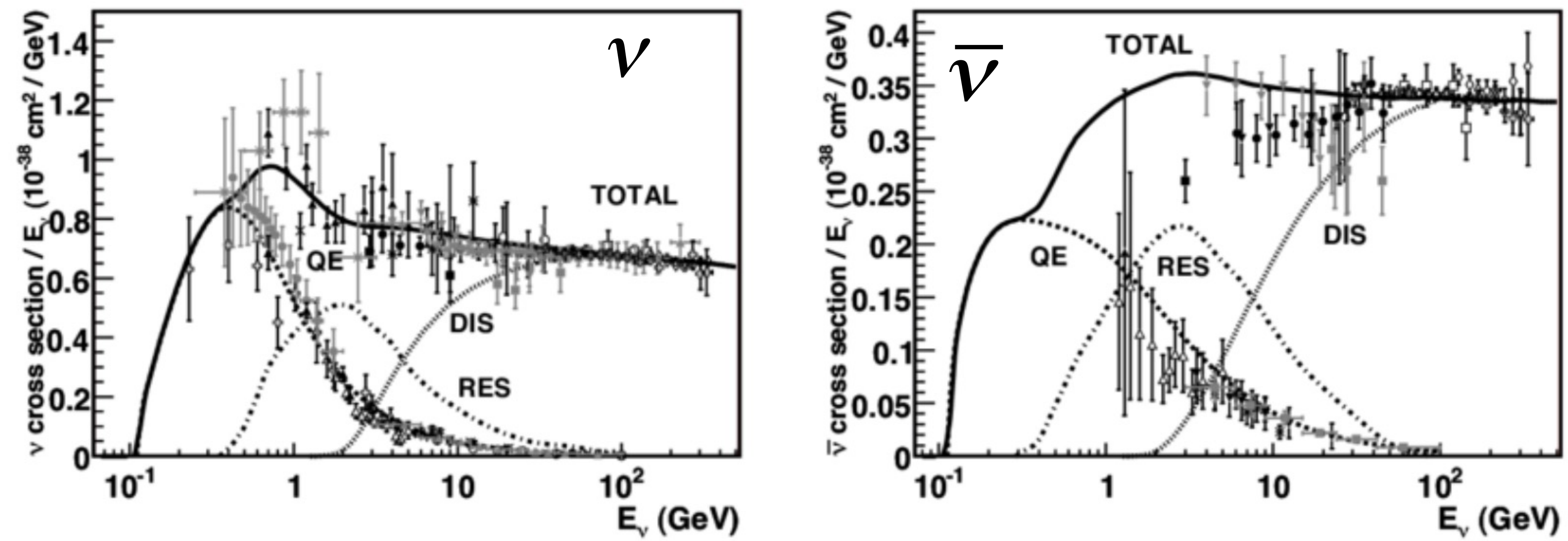
The neutrino is detected through the neutron capture signal

CC: $\boldsymbol{\nu_e + d \rightarrow e^- + p + p}$

The neutrino is detected through the electron signal

RESONANCE PRODUCTION
DEEP-INELASTIC SCATTERING

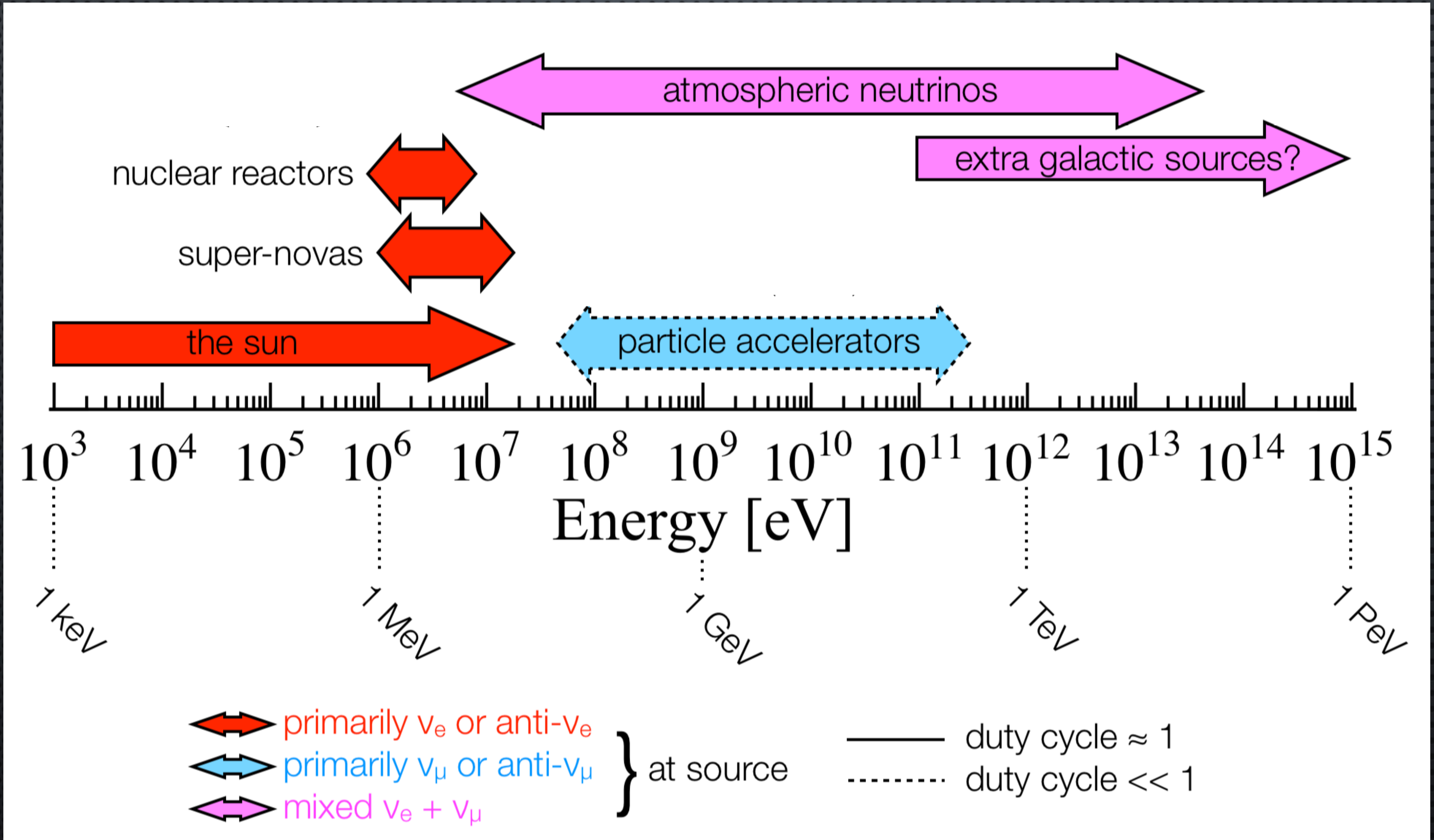




Resonance Production: $\nu_x(\bar{\nu}_x) + N \rightarrow \Delta + \mu^-(\mu^+)$, where $\Delta \rightarrow \pi + N'$

Deep-inelastic scattering on the quarks inside the nucleons
--> Production of hadronic showers

SOURCES OF NEUTRINOS



NEUTRINO DETECTION

The neutrino interaction cross-section VERY SMALL

MASSIVE DETECTORS needed.

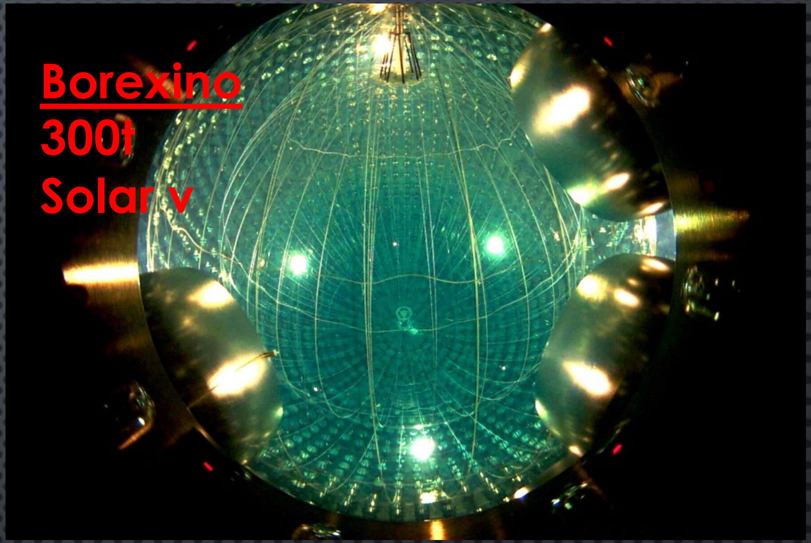
LIQUID SCINTILLATOR

Target: Organic compounds rich in H nuclei (p)

Interaction: IBD ($\bar{\nu}_e$) and ES (ν_e)

Detection: Charged particles (and γ-rays) produce light.
The light yield is proportional to particle energy.
The light is detected by large area photo-multipliers.

- ✓ Large and homogenous target
- ✓ Good energy and time resolution
- ❖ Not very accurate vertex reconstruction
  Directional information not preserved
- ❖ Particle identification from scintillation time profile
  (but difficult)



WATER CHERENKOV

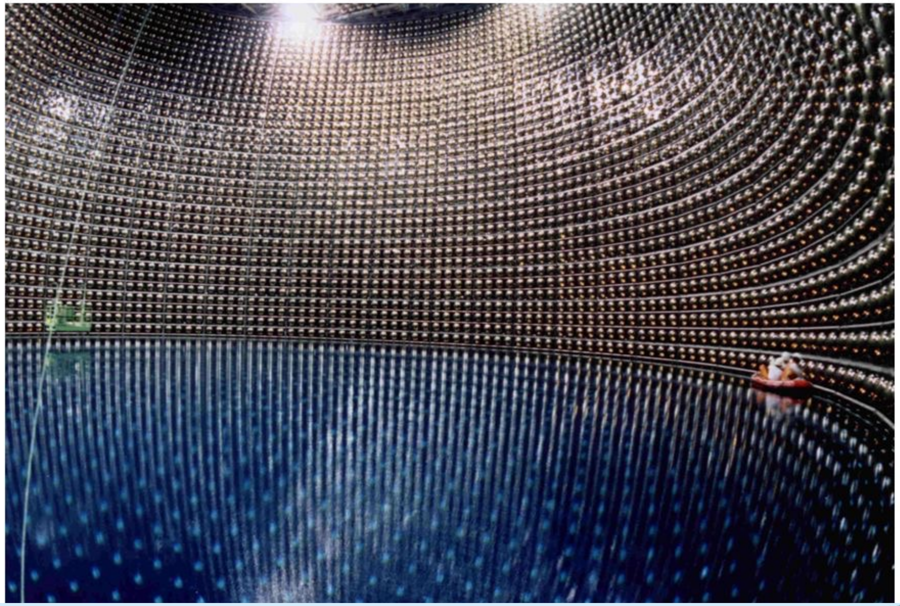
Target: Water (cheaper and easier to handle than LS)

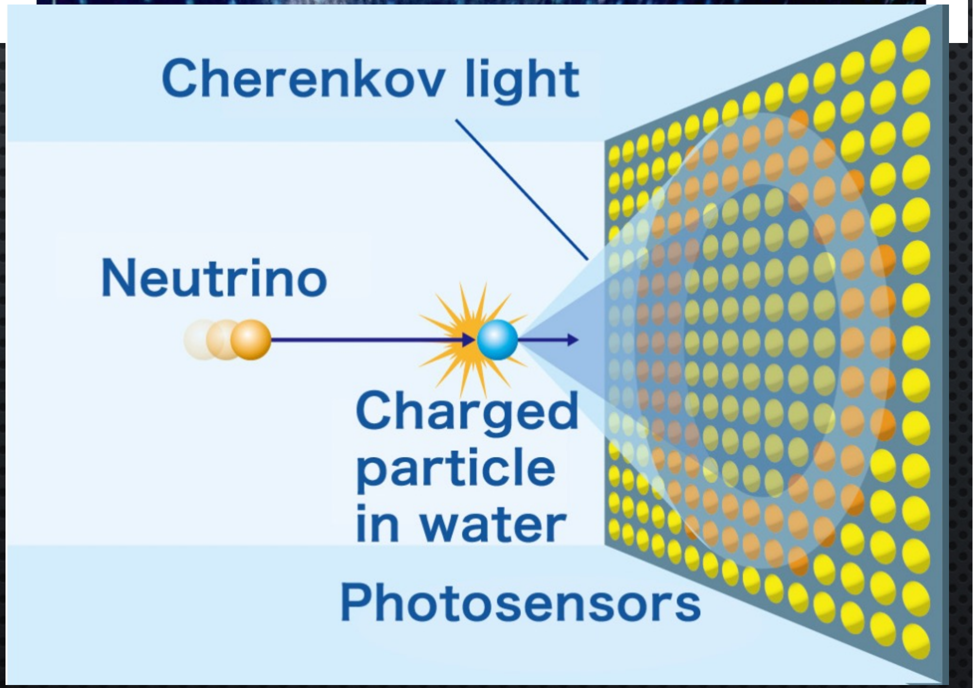
Interaction: ES and QE

Detection: **Cherenkov radiation**
Charged particles propagating in a medium with a speed exceeding that of light in that medium emit Cerenkov radiation.
Detected as a ring by large area photo-multipliers.

- ✓ Good energy and time resolution
- ✓ Directional information
- ✓ Particle identification from ring patten (e/μ)

Super-KamiokaNDE, 50ktons H_2O, 11,500PMTs





TRACKING DETECTORS

Target: Solid (liquid) plastic scintillator (expensive, so limited for very large detectors)

Interaction: ES and QE

Detection: Reconstruction of charged leptons tracks (ionization or deposited energy).
A magnetic field could bend the tracks
→ measurement of the momentum and sign(q).

- ✓ Very good energy and time resolution
- ❖ best suited to higher energy neutrinos (ν_μ beam)
- ✓ Good at separating μ,s from e⁻,s
- ✓ Good reconstructing events containing multiple particles.

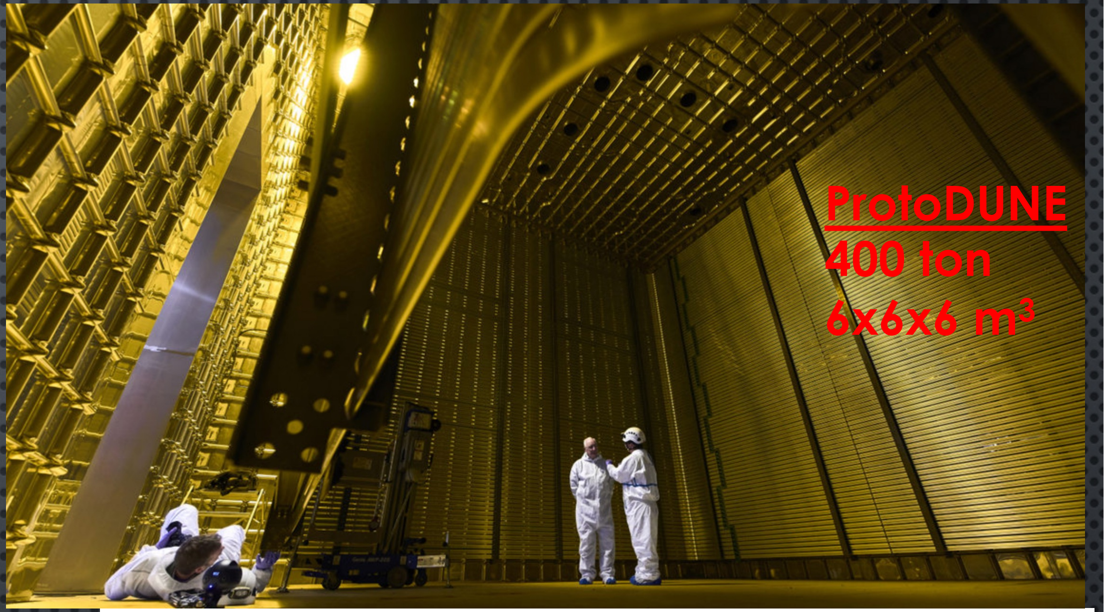
LIQUID ARGON TPC

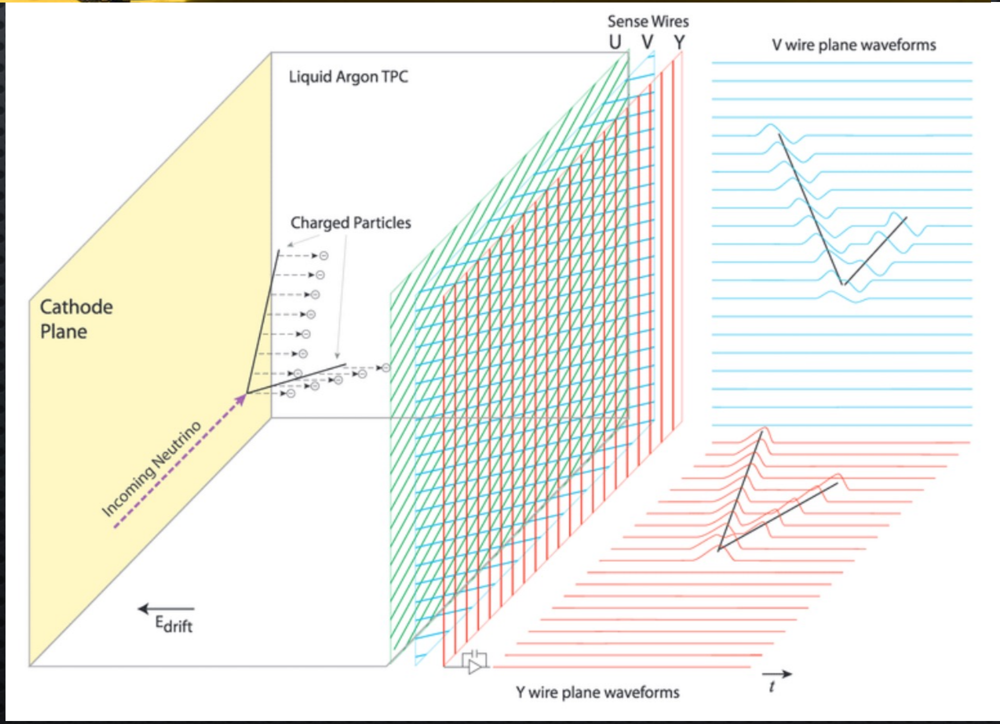
Target: Ar atoms (liquid) Higher atomic number and density than water and LS.
Requires cryogeny (-186 °C).

Interaction: QE

Detection: Reconstruction of charged particle tracks (ionization)

- ✓ Very good energy resolution
- ✓ Good tracking and calorimetric capability
- ✓ Good reconstructing events containing multiple particles
- ✓ Particle identification photon/electron separation





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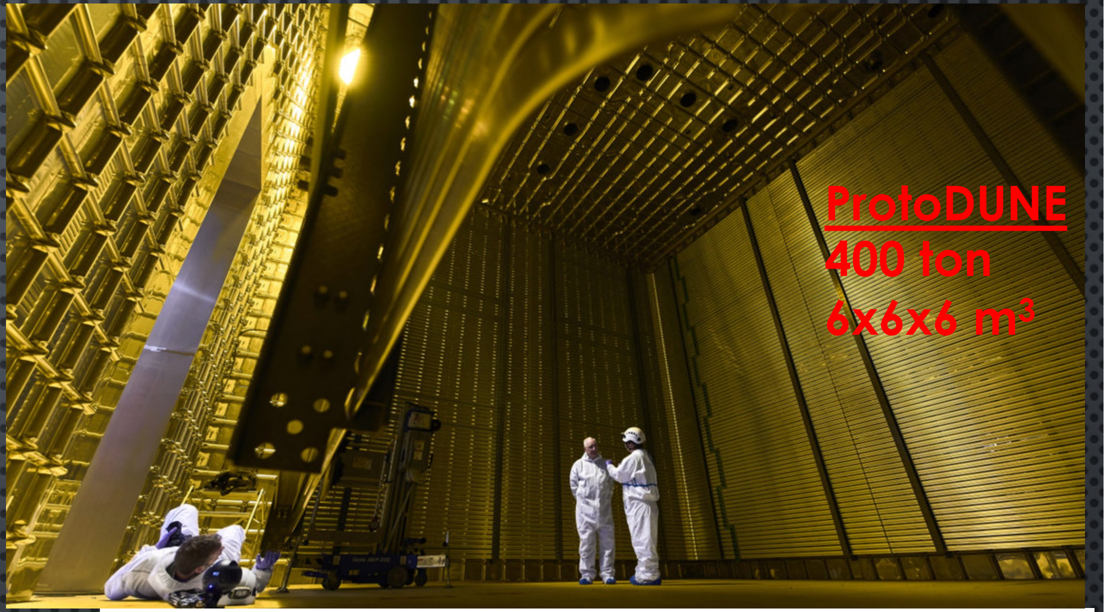
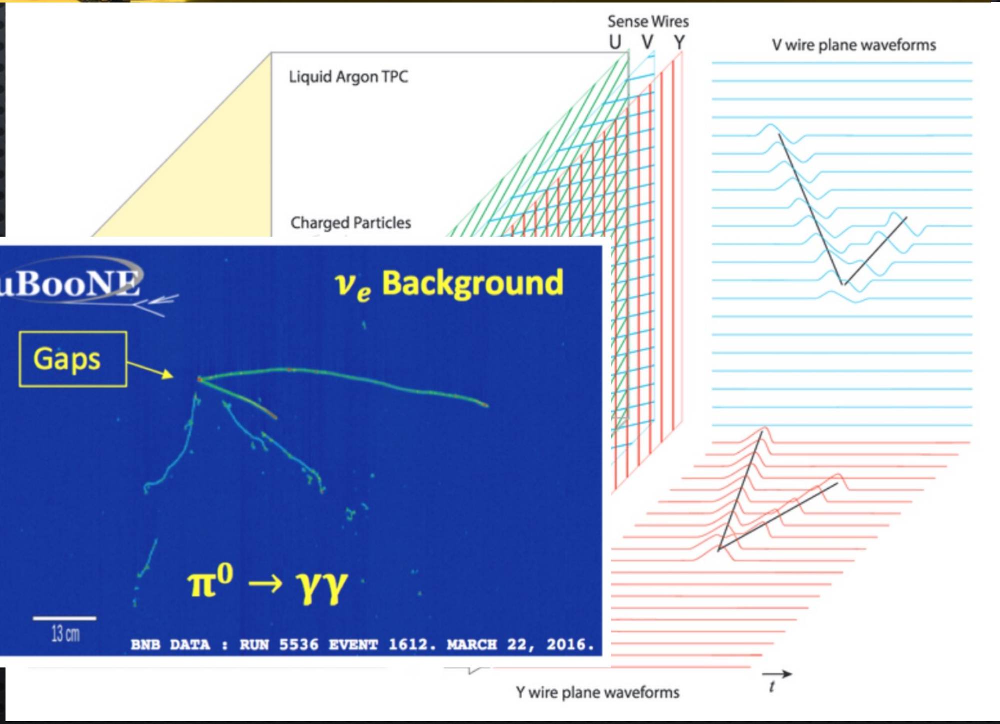
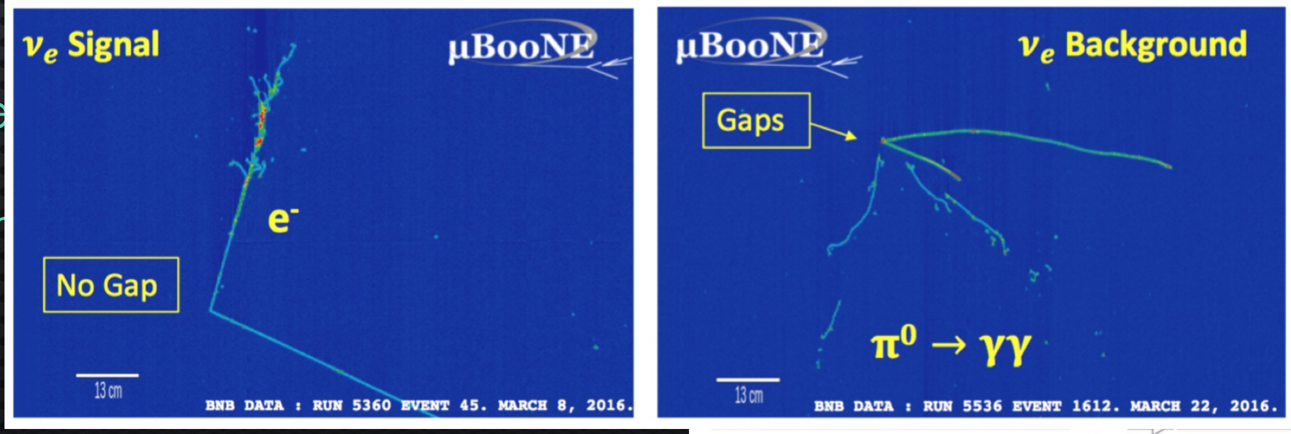


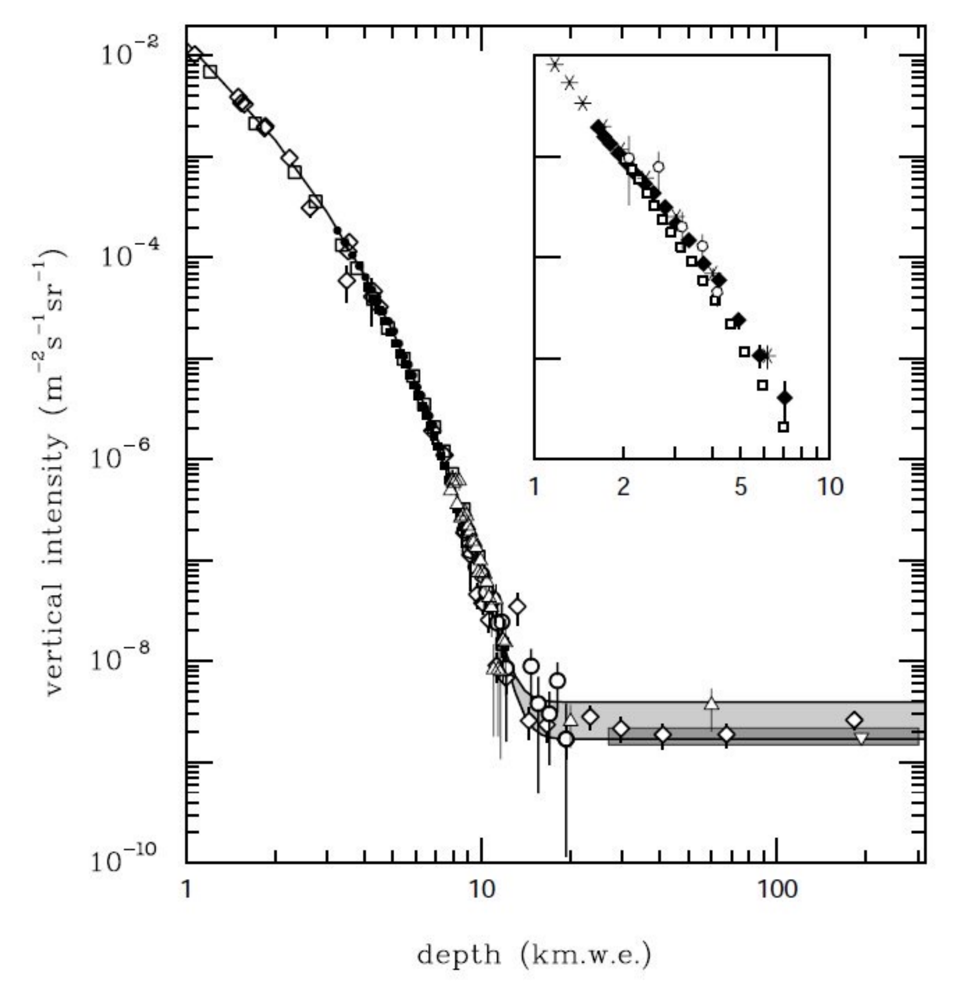


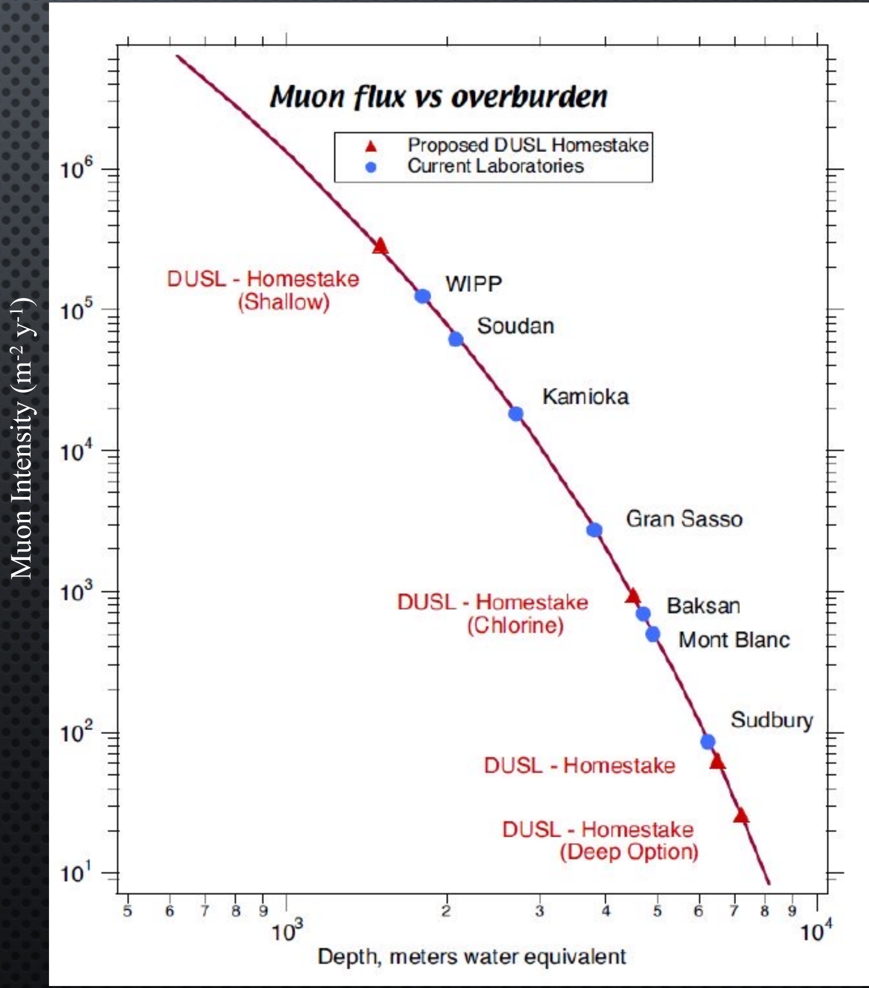


UNDERGROUND DETECTORS

The <u>main background</u> are cosmic muons and their products: *fast neutrons, β-emitters isotopes, Michel electrons, etc…*

The laboratories hosting neutrino experiments are always under ≥ 1000 m rock coverage



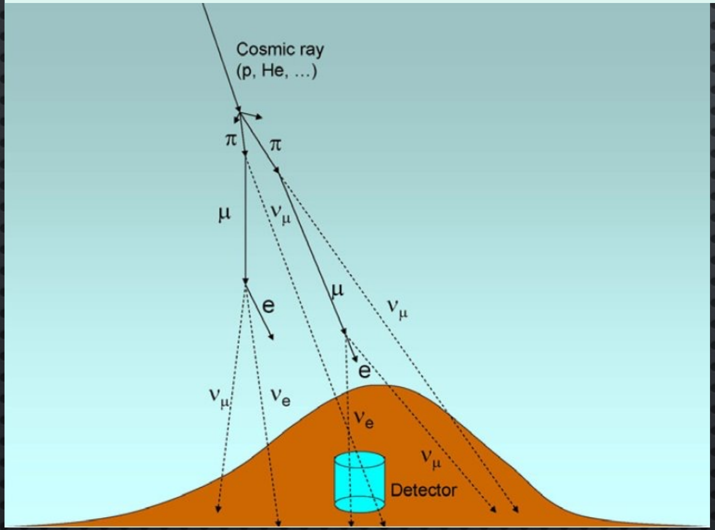


NEUTRINO OSCILLATION

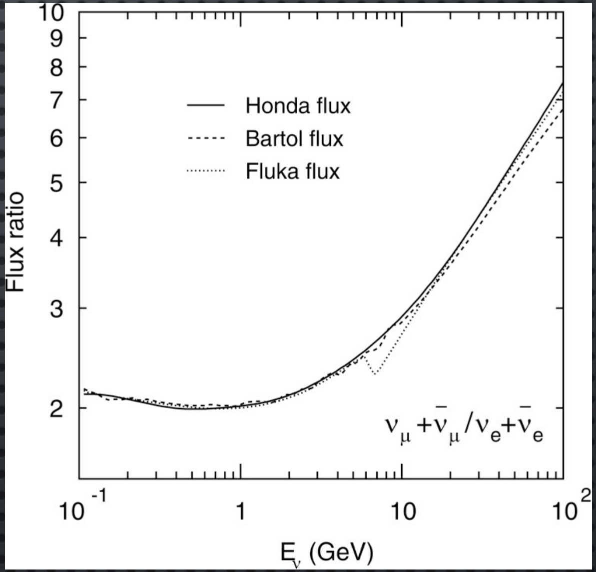
NEUTRINO OSCILLATION (MASSIVE NEUTRINO)

The atmospheric neutrinos: $\pi^{\pm} \rightarrow \mu^{\pm} + (\nu_{\mu} | \bar{\nu}_{\mu})$

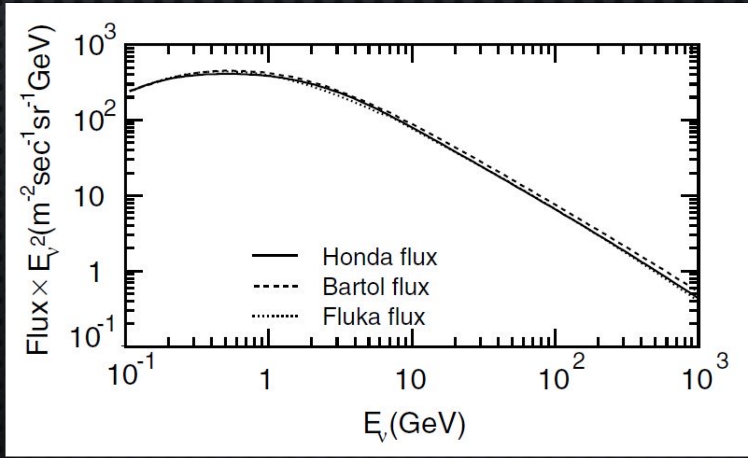
$$\mu^{\pm} \rightarrow e^{\pm} + (\nu_e | \bar{\nu}_e) + (\nu_{\mu} | \bar{\nu}_{\mu})$$



The flux ratio $\dfrac{(\nu_{\mu} | \bar{\nu}_{\mu})}{(\nu_e | \bar{\nu}_e)}$ **should be ~2**



The Kaimokande experiment.
Water Cerenkov detector of 4500 tons mass.
The Cerenkov rings are detected by 1000 20 inches PMTs.
Both ν_μ and ν_e are detected.



NEUTRINO OSCILLATION (MASSIVE NEUTRINO)

The Kaimokande experiment, which was initially created to study proton decay, did the first observation of ν_μ oscillation: detecting a deficit of ν_μ / ν_e .

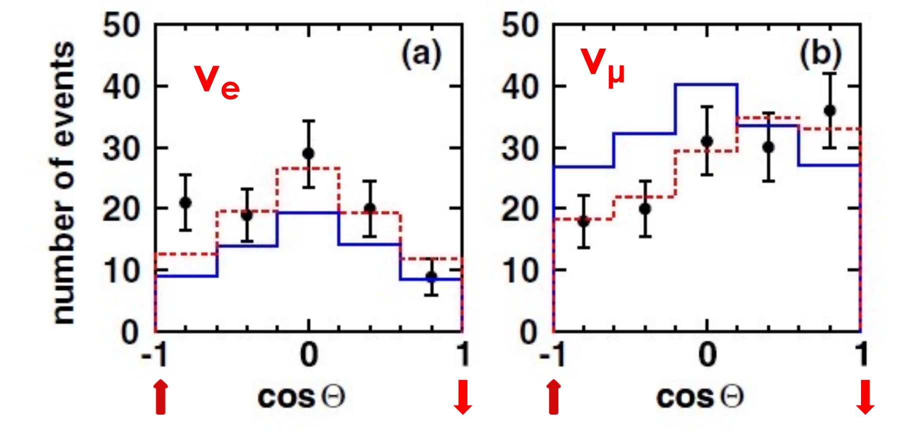
From the study of high energy (muti-GeV) atmospheric – ν data:

- Deficit of events in the upward going direction
- No deficit for downward going μ-like

However, the statistical significance was not conclusive.

	Data	Prediction
e-like events	93	88.5
μ-like events	85	144.0

Hirata K.S. et al.
Phys. Lett. B 205 416 (1988)

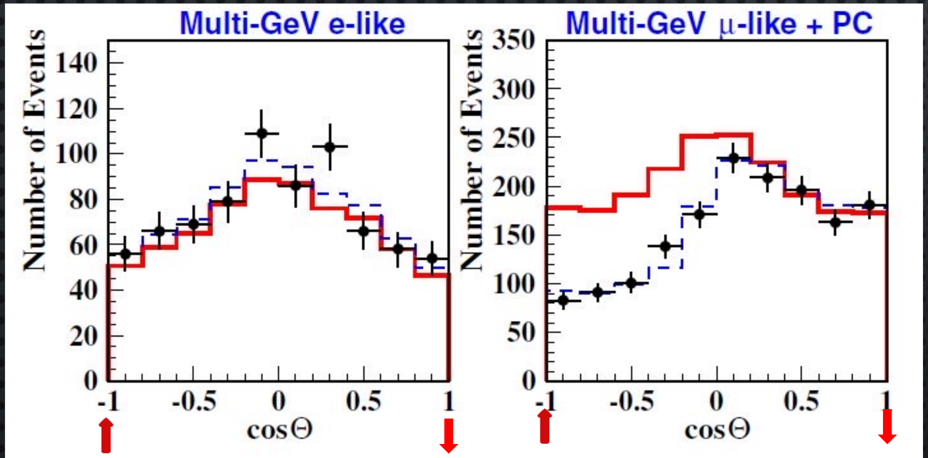


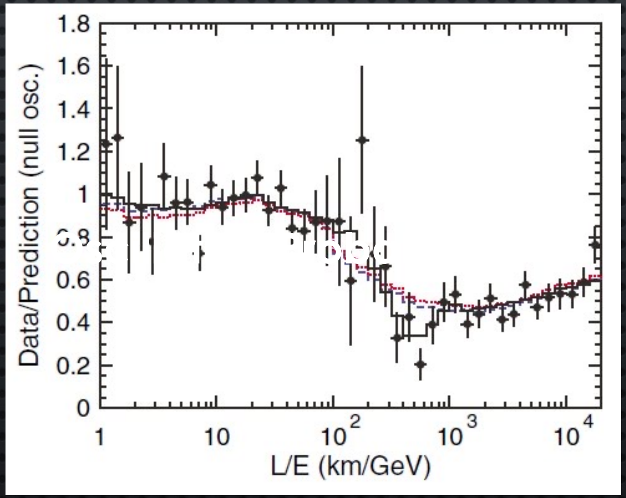
Evidence for Oscillation of Atmospheric Neutrinos
Phys.Rev.Lett..81 (1998)

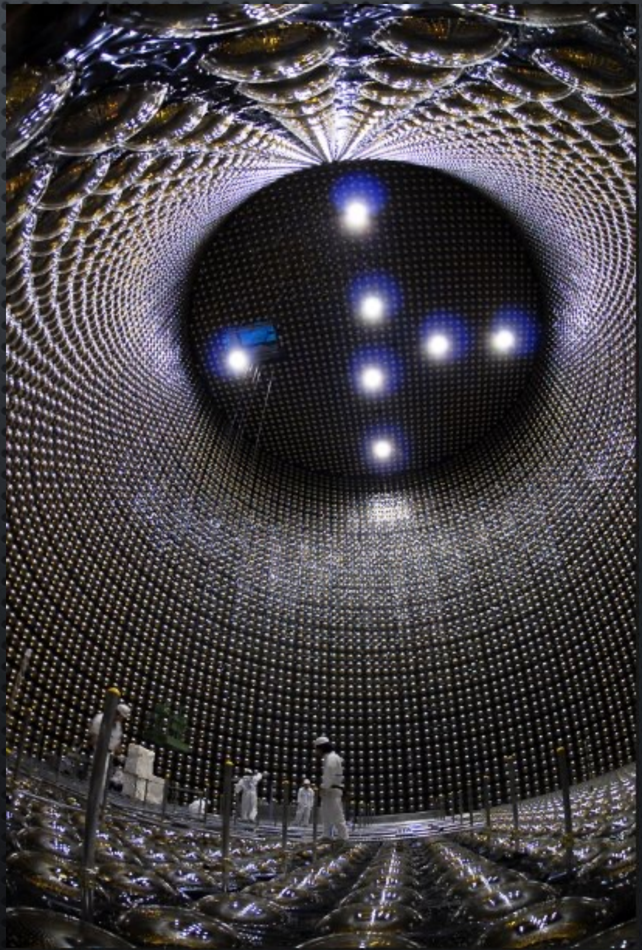
NEUTRINO OSCILLATION (MASSIVE NEUTRINO)

Super-Kamiokande:
Larger version of Kamiokande ~15m → ~40m
4.5k → 50k tons of water

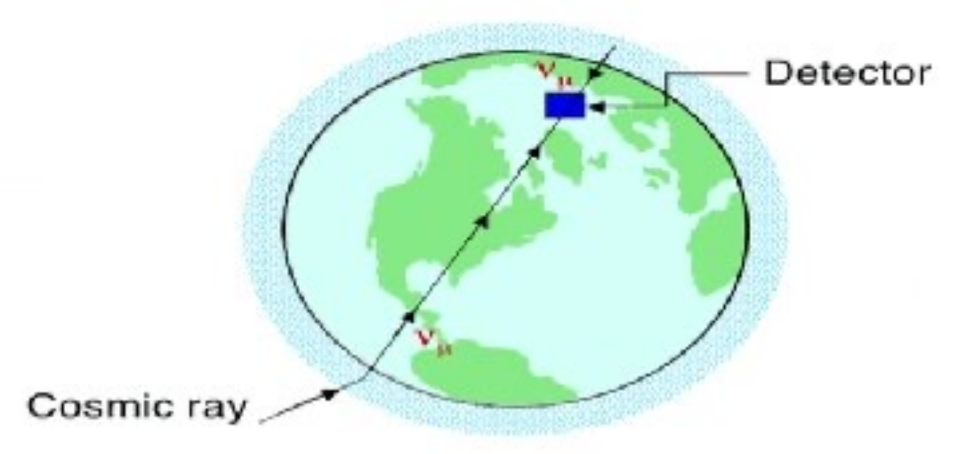
First observation of neutrino oscillation 1998







NEUTRINO OSCILLATION (MASSIVE NEUTRINO)



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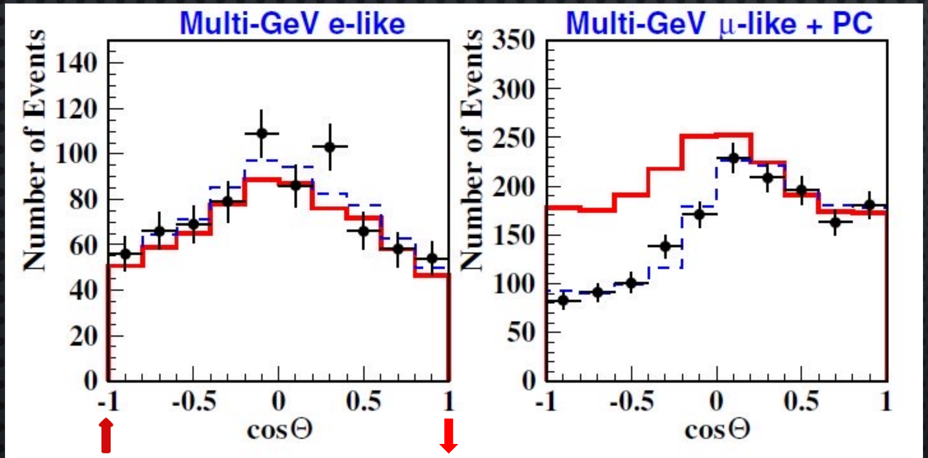
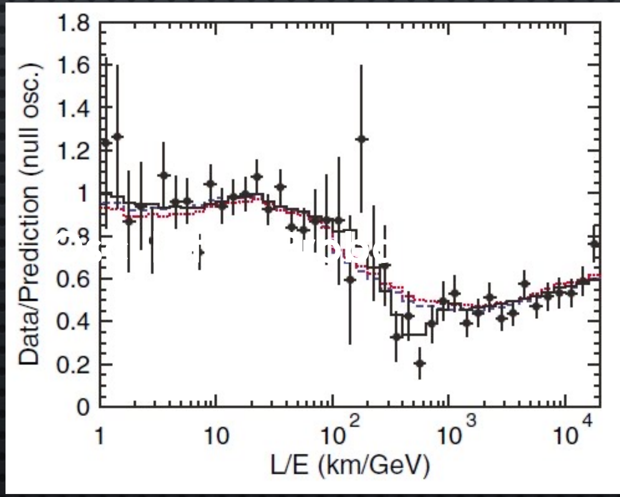


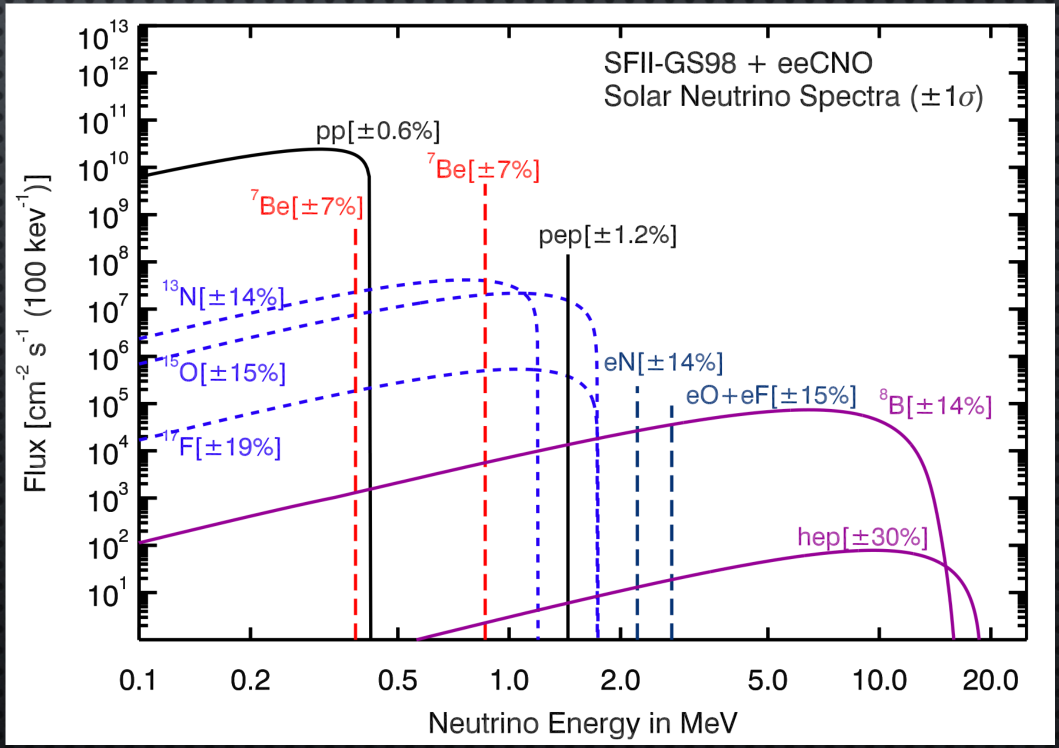


The "oscillation" $\nu_\mu \rightarrow \nu_\tau$ explains the atmospheric ν_μ deficit

NEUTRINO OSCILLATION: SOLAR NEUTRINOS

Neutrinos are the sole direct probes of the Sun's core
The measurement of ν_e flux is a direct way of testing Standard Solar Model
The first predictions of ν_e flux made by John Bahcall

ν flux	E_ν^{max} (MeV)	GS98-SFII	AGSS09-SFII	Solar	units
$p+p \to {}^2H+e^++\nu$	0.42	$5.98(1 \pm 0.006)$	$6.03(1 \pm 0.006)$	$6.05(1^{+0.003}_{-0.011})$	$10^{10}/cm^2s$
$p+e^-+p \to {}^2H+\nu$	1.44	$1.44(1 \pm 0.012)$	$1.47(1 \pm 0.012)$	$1.46(1^{+0.010}_{-0.014})$	$10^{8}/cm^2s$
${}^7Be+e^- \to {}^7Li+\nu$	0.86 (90%)	$5.00(1 \pm 0.07)$	$4.56(1 \pm 0.07)$	$4.82(1^{+0.05}_{-0.04})$	$10^{9}/cm^2s$
	0.38 (10%)				
${}^8B \to {}^8Be+e^++\nu$	~ 15	$5.58(1 \pm 0.14)$	$4.59(1 \pm 0.14)$	$5.00(1 \pm 0.03)$	$10^{6}/cm^2s$
${}^3He+p \to {}^4He+e^++\nu$	18.77	$8.04(1 \pm 0.30)$	$8.31(1 \pm 0.30)$	—	$10^{3}/cm^2s$
${}^{13}N \to {}^{13}C+e^++\nu$	1.20	$2.96(1 \pm 0.14)$	$2.17(1 \pm 0.14)$	≤ 6.7	$10^{8}/cm^2s$
${}^{15}O \to {}^{15}N+e^++\nu$	1.73	$2.23(1 \pm 0.15)$	$1.56(1 \pm 0.15)$	≤ 3.2	$10^{8}/cm^2s$
${}^{17}F \to {}^{17}0+e^++\nu$	1.74	$5.52(1 \pm 0.17)$	$3.40(1 \pm 0.16)$	$\leq 59.$	$10^{6}/cm^2s$
χ^2/P^{agr}		3.5/90%	3.4/90%		



W.C. Haxton et al.
Ann. Rev. Astron. Astrophys. 51 (2013)

HOMESTAKE EXPERIMENT

$^{37}Cl + \nu_e \rightarrow {}^{37}Ar + e^-$

Goal Measurement of the flux of solar neutrinos (1970-1994)

Detection mode based on the inverse beta reaction

$$^{37}Cl + \nu_e \rightarrow {}^{37}Ar + e^-$$

Threshold 814 keV → ^{8}B dominant contribution but ^{7}Be, pep, ^{13}N and ^{15}O neutrinos also contribute.

Results The flux measured is 1/3 of the solar model predictions

→ **"the solar neutrino problem"**

Possible causes:

- The theory was wrong
- The experiment was wrong
- Both are wrong

OTHER SOLAR EXPERIMENTS

GALLEX (1991-1997), another radiochemical experiment with lower threshold 233 keV

$$^{71}Ga + \nu_e \rightarrow {}^{71}Ge + \nu_e$$

- First pp solar neutrino observation in 1992
- The flux measured is 1/2 of the predicted one
- The response of the detector was tested with an intense man-made ν_e source ^{51}Cr

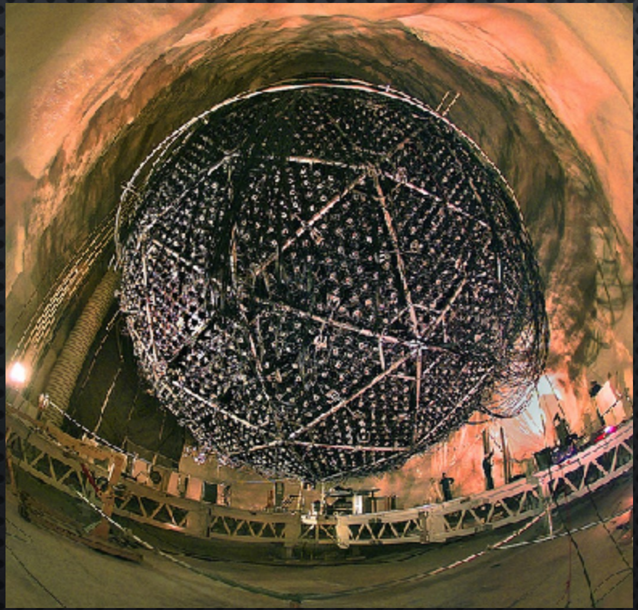
Kamiokande and Super-Kamiokande

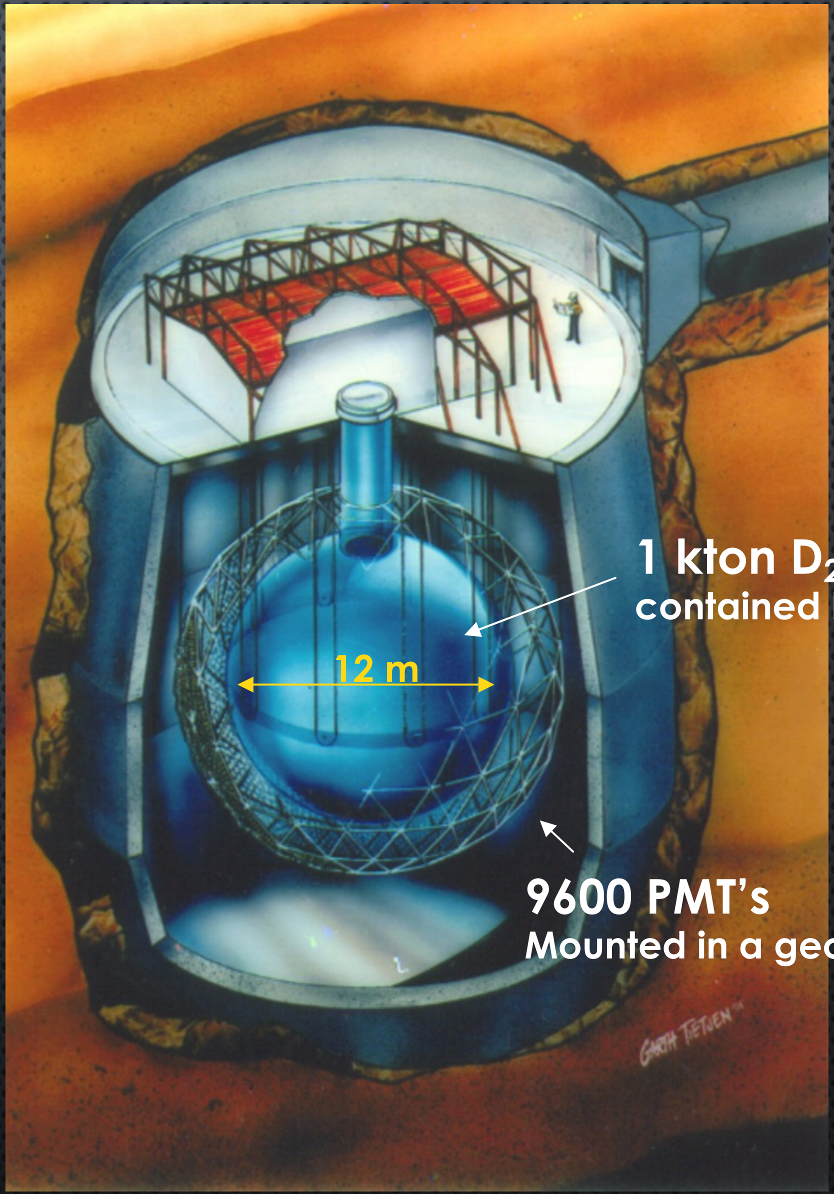
- Only sensitive to ^{8}B neutrinos
- Detection ES
- Directional information: first evidence Sun emits neutrinos
- The solar-ν flux was also below the prediction

SNO EXPERIMENT

Heavy-water Cherenkov detector
2 km underground
VALE's Creighton mine (Canada)

Only sensitive to ^{8}B neutrinos
E > 3 MeV





SNO EXPERIMENT

Evidence for Solar Neutrino Oscillation

Goal measurement of not only ν_e but also ν_μ and ν_τ

Detection mode:

$\boldsymbol{\nu_e + d \rightarrow e^- + p + p}$ (CC reaction sensitive only to ν_e) $\boxed{\phi_{CC} = \phi_e}$

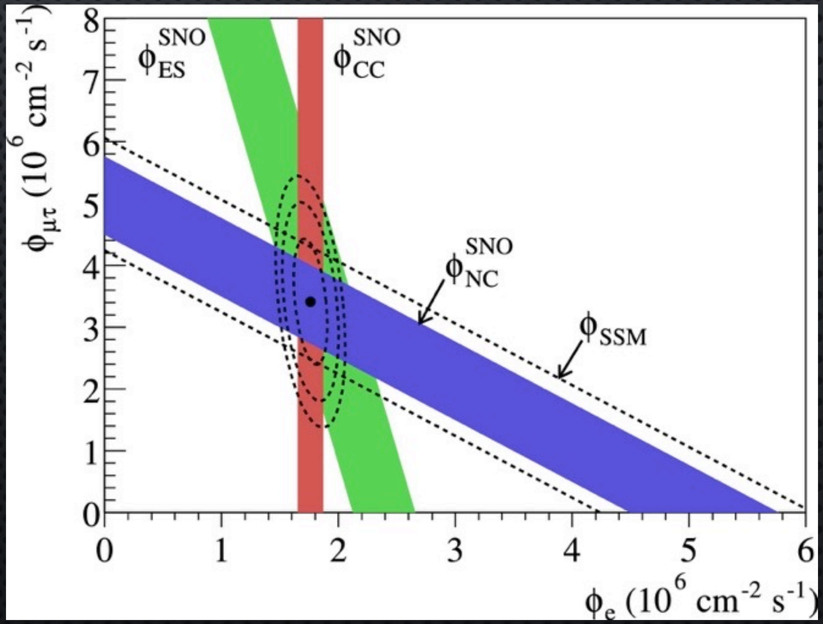
$\nu_X + d \rightarrow \nu_X + p + n$ (NC reaction sensitive to all active neutrinos) $\boxed{\phi_{NC} = \phi_e + \phi_{\mu,\tau}}$

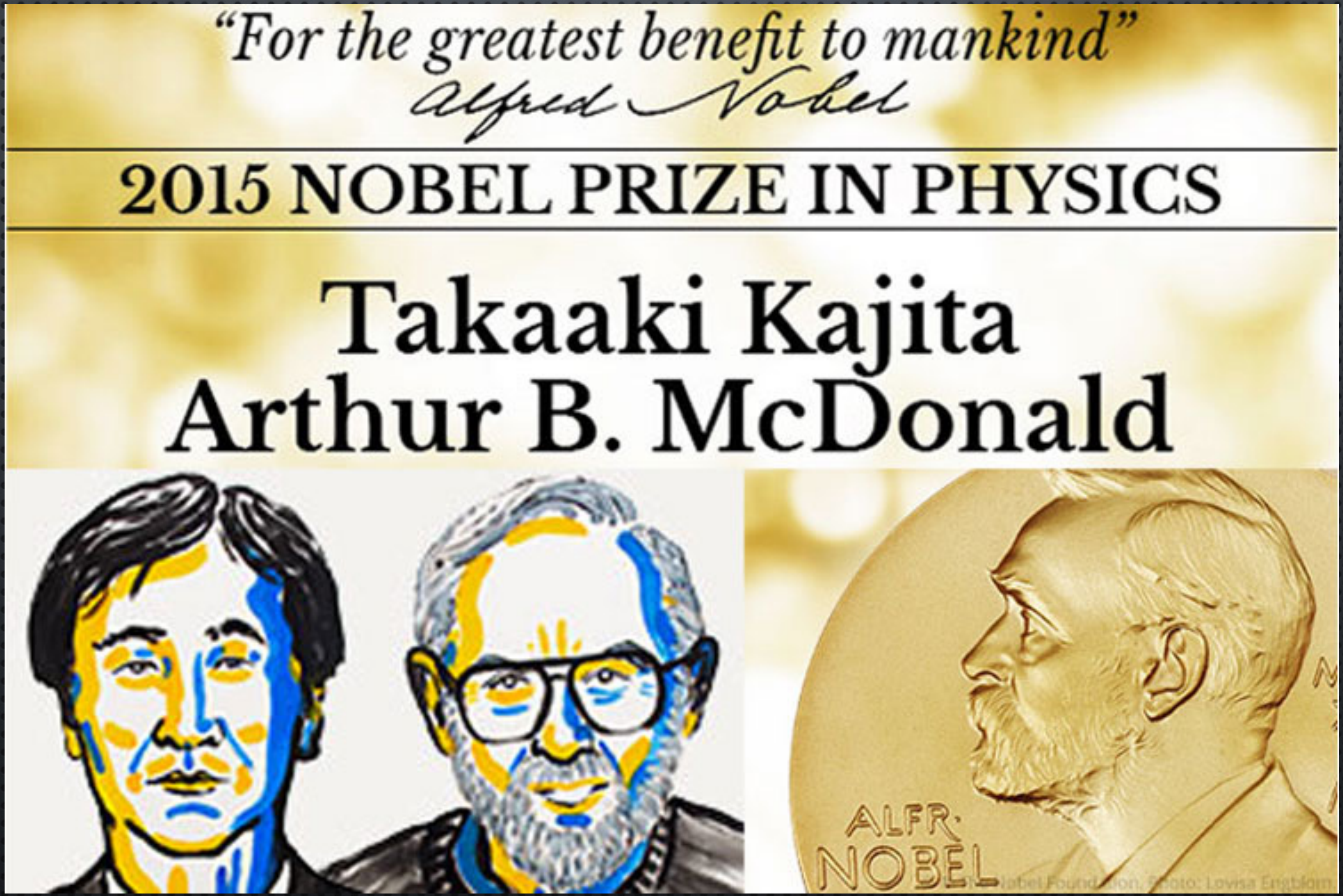
$\nu_X + e^- \rightarrow \nu_X + e^-$ (ES reaction sensitive to all but not in the same way) $\boxed{\phi_{ES} = \phi_e + 0.15 \cdot \phi_{\mu,\tau}}$

Results:

- **$\varphi^{CC}(\nu_e)$ = (1.76±0.06±0.09) x 10^6 / cm s**
- **$\varphi^{ES}(\nu_x)$ = (2.39±0.24±0.12) x 10^6 / cm s**
- **$\varphi^{NC}(\nu_x)$ = (5.09±0.44±0.44) x 10^6 / cm s** ***Agreement with solar predictions***

- **The spectral shape of the electron energy was consistent with expectations (no distortion is observed)**
- **No significant day-night flux asymmetries were observed**




"For the greatest benefit to mankind"
Alfred Nobel
2015 NOBEL PRIZE IN PHYSICS
Takaaki Kajita
Arthur B. McDonald
ALFR·
NOBEL

PROBABILITY OF NEUTRINO OSCILLATION (IN VACUUM)

Propagation of state ν_i in vacuum:

$$|\nu_\alpha(t)\rangle = \sum_\beta |\nu_\beta\rangle \left(\sum_i U^*_{\beta i} e^{-iE_i t} U_{\alpha i} \right)$$

Probability for neutrino oscillation in vacuum:

$$P(\nu_\alpha \to \nu_\beta) = |\langle \nu_\beta | \nu_\alpha(t)\rangle|^2 = |\sum_i U_{\beta i} e^{-iE_i t} U^*_{\alpha i}|^2$$

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} R(U^*_{\alpha i} U_{\beta i} U^*_{\alpha j} U_{\beta j}) \sin^2(\Delta m^2_{ij} \frac{L}{4E}) + 2\sum_{i>j} I(U^*_{\alpha i} U_{\beta i} U^*_{\alpha j} U_{\beta j}) \sin^2(\Delta m^2_{ij} \frac{L}{4E})$$

- **If all $\Delta m^2 = 0$ then** $P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta}$

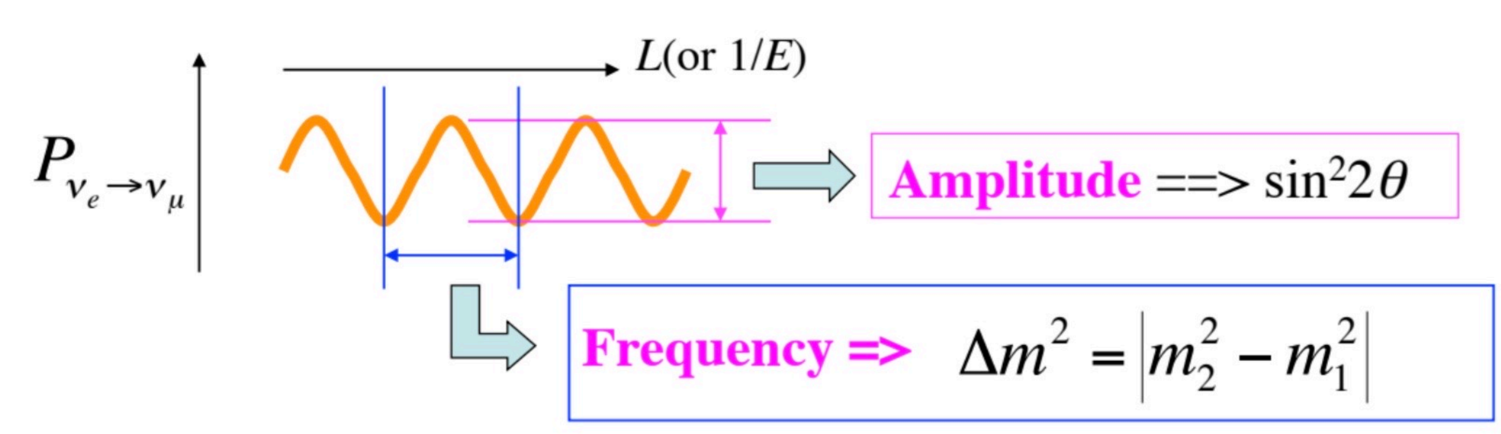
  Flavor change implies ν mass

- **If no mixing:** $U_{\alpha i} U^*_{\beta \neq \alpha, i} = 0$ **then** $P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta}$

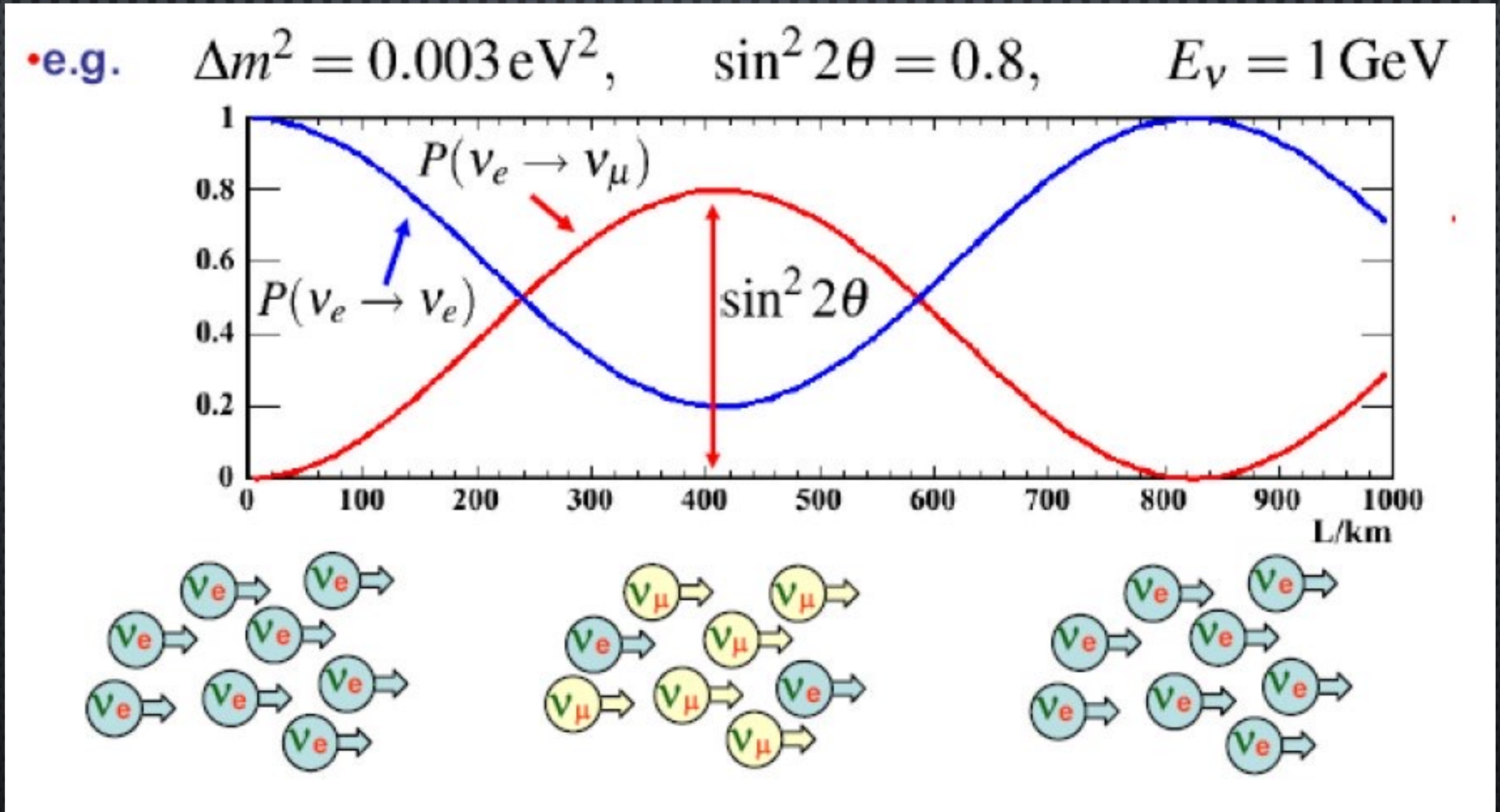
  Flavor change implies mixing

PROBABILITY OF 2-FLAVOUR NEUTRINO OSCILLATION

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



NEUTRINO OSCILLATION FOR A GIVEN ΔM² AND SIN²Θ



NEUTRINO OSCILLATION

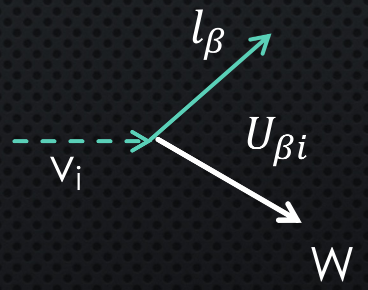
PMNS Matrix:

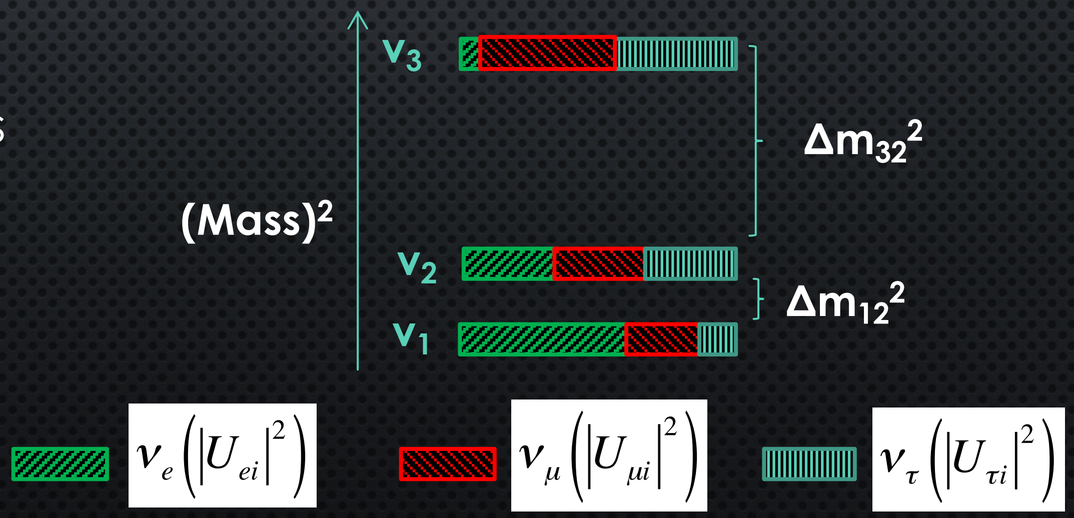
$$
\begin{array}{cccc}
 & \textbf{ATMOSPHERIC} & \textbf{REACTOR} & \textbf{SOLAR} \\
U = & \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \times & \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \times & \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}
\end{array}
$$

where $c_{ij} \equiv \cos\theta_{ij}$, $s_{ij} \equiv \sin\theta_{ij}$

δ would lead to $P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) \neq P(\nu_\alpha \to \nu_\beta)$ CP violation
But can be measured only if all mixing angles are ≠ 0

$|U_{\beta i}|^2$ gives the probability that a ν_i creates a charged lepton of flavor β



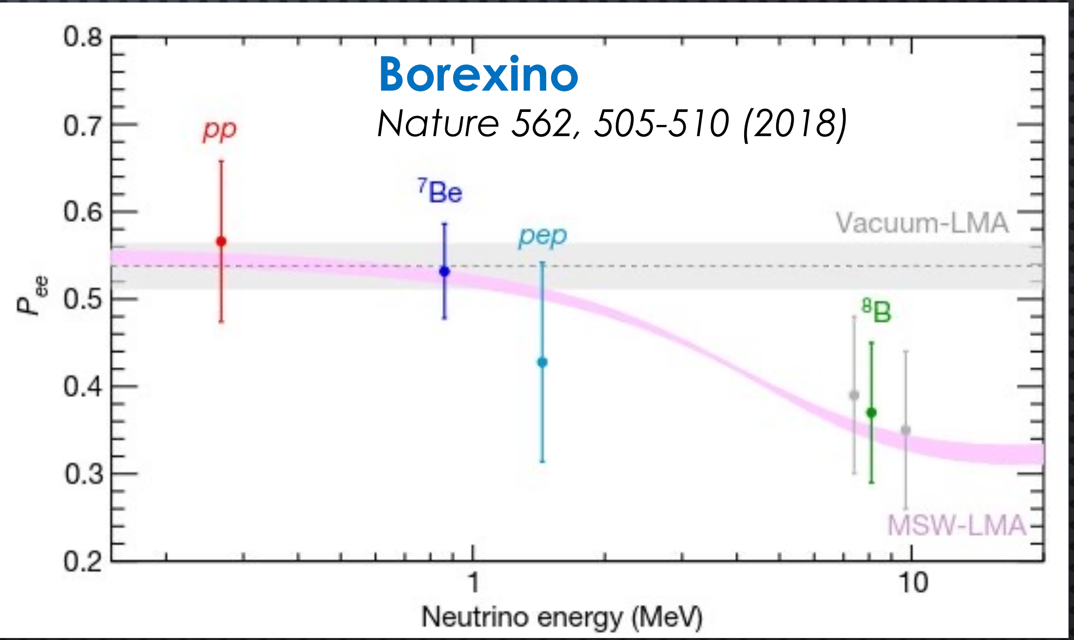


NEUTRINO FLAVOR CHANGE IN MATTER

Matter effects play a critical role in solar neutrino data

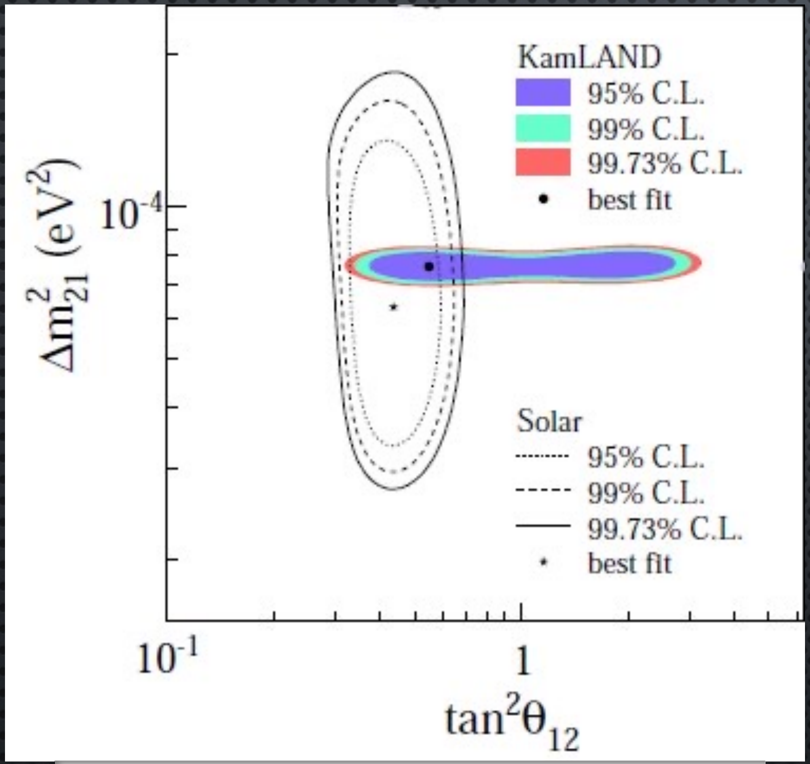
ES cross-section larger for ν_e than ν_μ and ν_τ in the Sun
+ Effective mass difference between states is modified
+ off-diagonal terms in the mixing matrix

- The sign of Δm^2_{21} can be determined
- Enhancement of vacuum oscillations (MSW effect)



NEUTRINO OSCILLATION RESULTS IN 2011

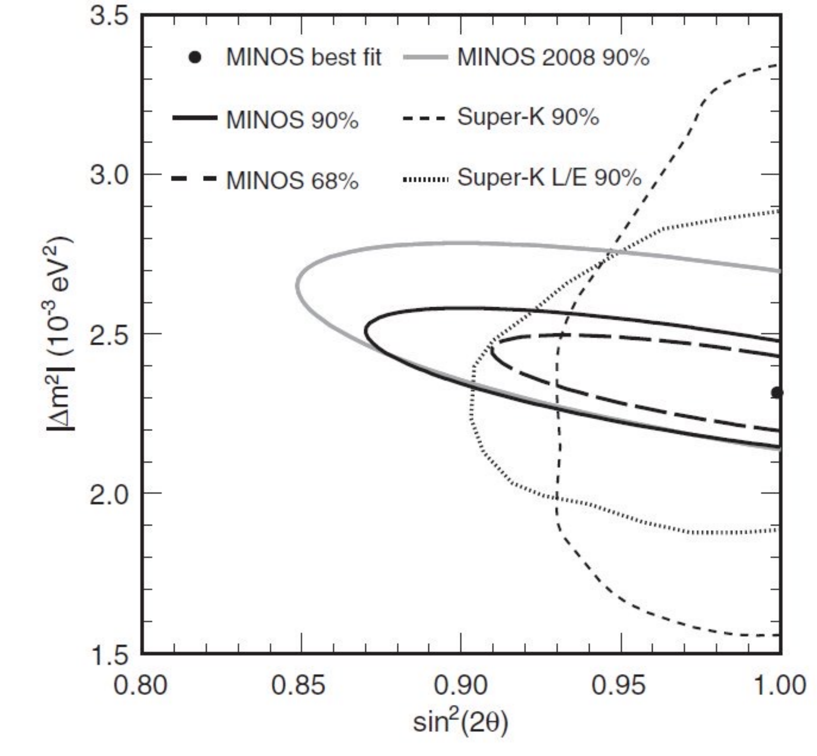
SOLAR SECTOR



$$\theta_{12} = 33.36^{+0.81}_{-0.78}\ \text{deg}$$

$$\Delta m^2_{12} = \begin{pmatrix} 7.50 & \begin{matrix} +0.18 \\ -0.19 \end{matrix} \end{pmatrix} \times 10^{-5}\, eV^2$$

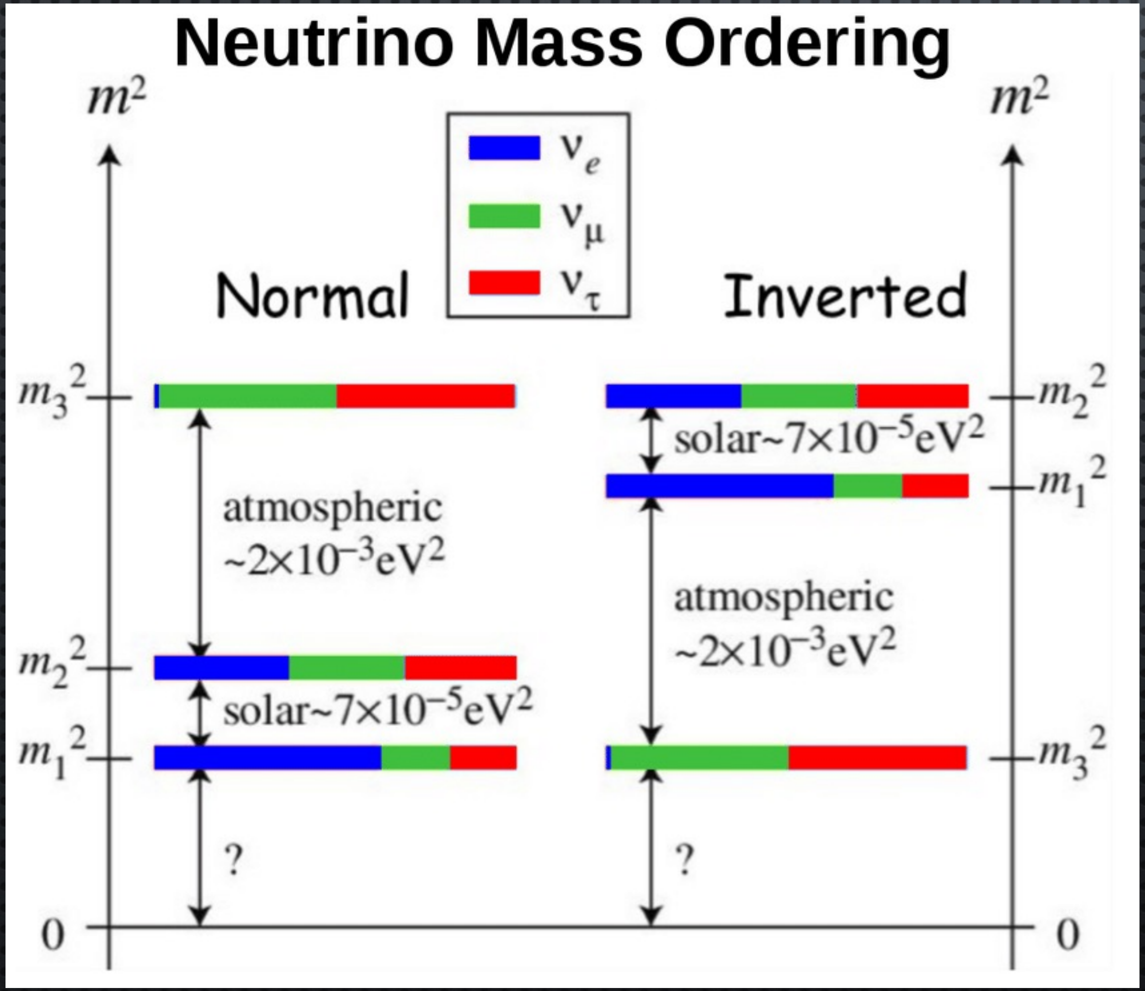
ATMOSPHERIC SECTOR



$$\theta_{23} = 40.0^{+2.1}_{-1.5} \oplus 50.4^{+1.3}_{-1.3}\ \text{deg}$$

$$\left|\Delta m^2_{23}\right| = \begin{pmatrix} 2.473 & \begin{matrix} +0.070 \\ -0.067 \end{matrix} \end{pmatrix} \times 10^{-3}\, eV^2$$

NEUTRINO MASS ORDERING

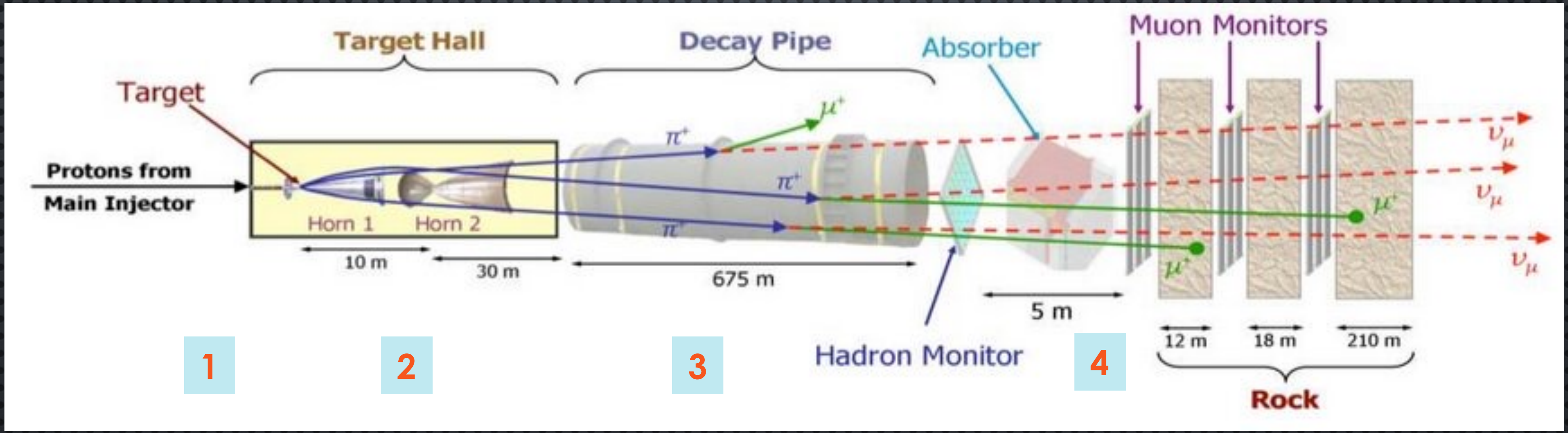


- Δm^2_{21}>0 from matter effects in solar neutrino oscillation
- The sign of Δm^2_{32} is still unknown.

Determination of Δm^2_{32}

- **The sign of Δm_{13}^2 can be measured by the study of the matter effect in transitions due to Δm_{13}^2**
- **MO can be determined through the remote detection of $\bar{\nu}_e$ from a nuclear reactor**

NEUTRINO BEAM EXPERIMENTS



1 A beam of protons (Fermilab and Tokai) impacts onto a target (carbon, graphite…) producing $\pi^{\pm}$ and $K^{\pm}$

2 These mesons are focused toward the beam axis by magnetic horns.

3 The mesons then decay into muons and neutrinos during their flight through a long decay tunnel.

4 A hadron absorber downstream of the decay tunnel removes the remaining hadronic particles from the beam. The muons are absorbed by the subsequent earth shield.

T2K EXPERIMENT

Near detectors (280m from the target): To measure ν-beam direction, spectrum and composition before oscillations and to measure ν-interaction cross-sections.

Far detector- Super-Kamiokande (295km from the target): To detect the oscillated neutrinos

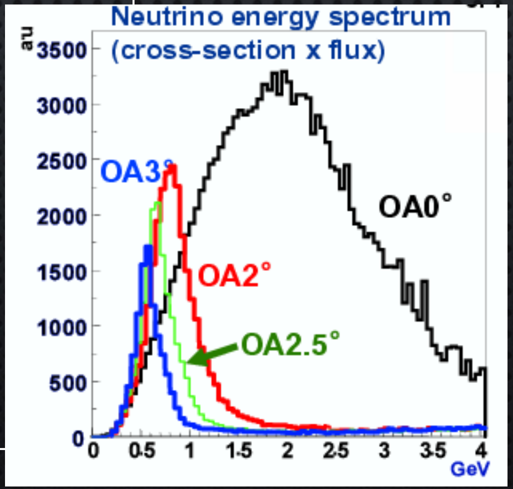
ν_μ Beam:

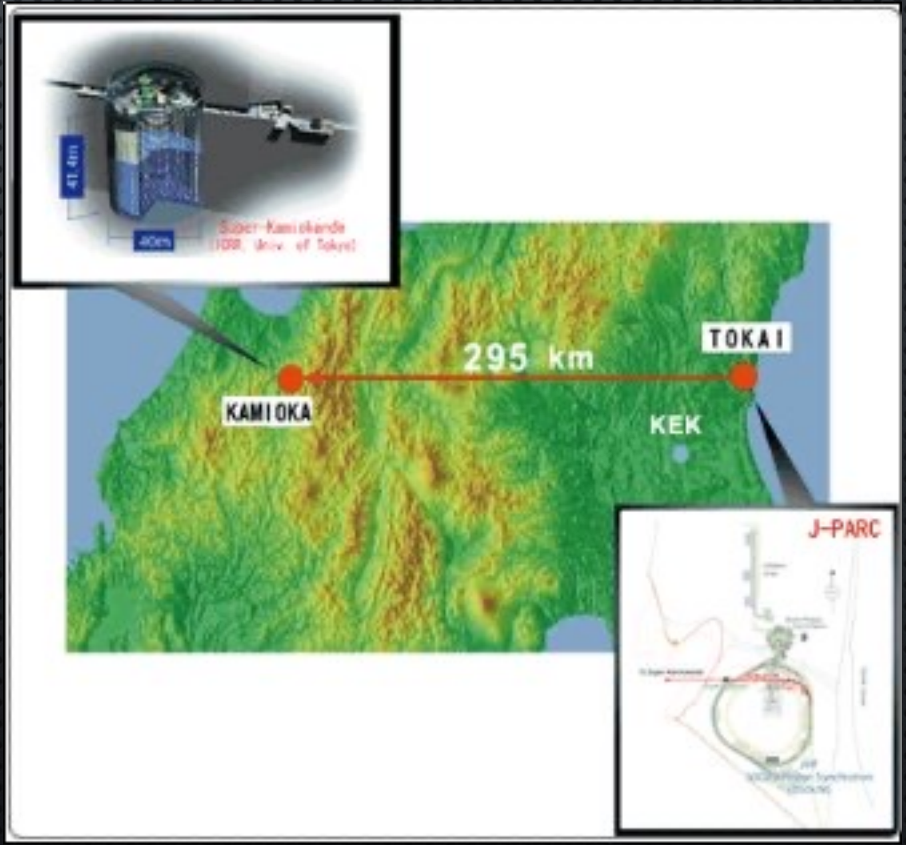
- T2K beam is 95% ν_μ, 4% $\bar{\nu}_\mu$, ν_e <1%
- Both detectors are 2.5° off ν beam axis

  ($E_{peak} \approx 600$ MeV)

By going off-axis, beam energy is reduced and spectrum becomes very sharp

- Energy → maximum oscillation signal
- Removes the high energy flux that contributes to background





T2K EXPERIMENT

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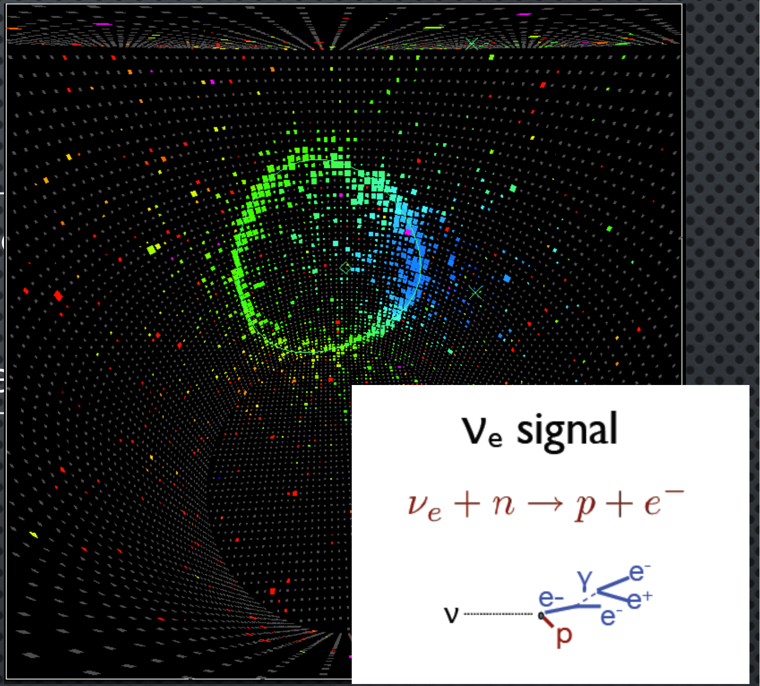

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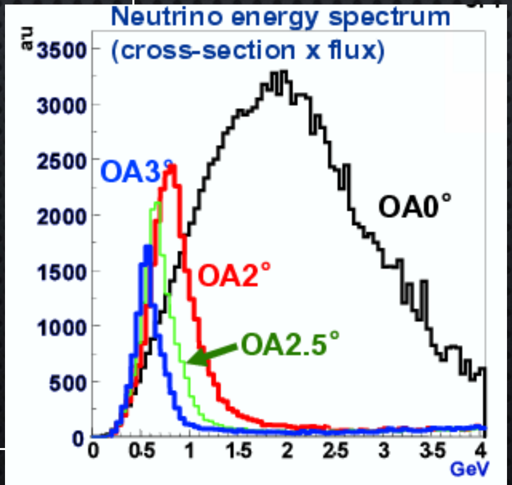
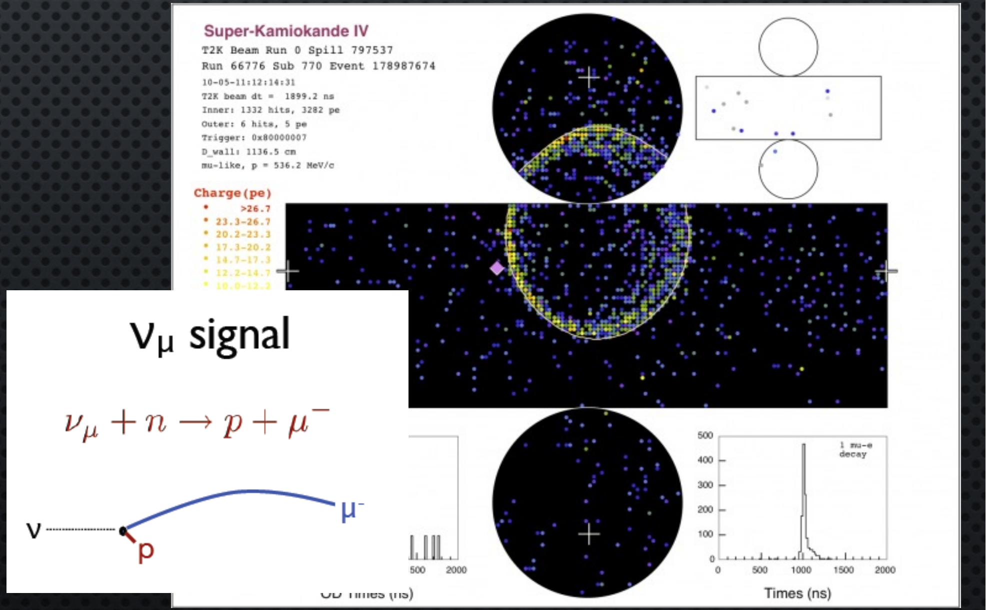




NOνA EXPERIMENT

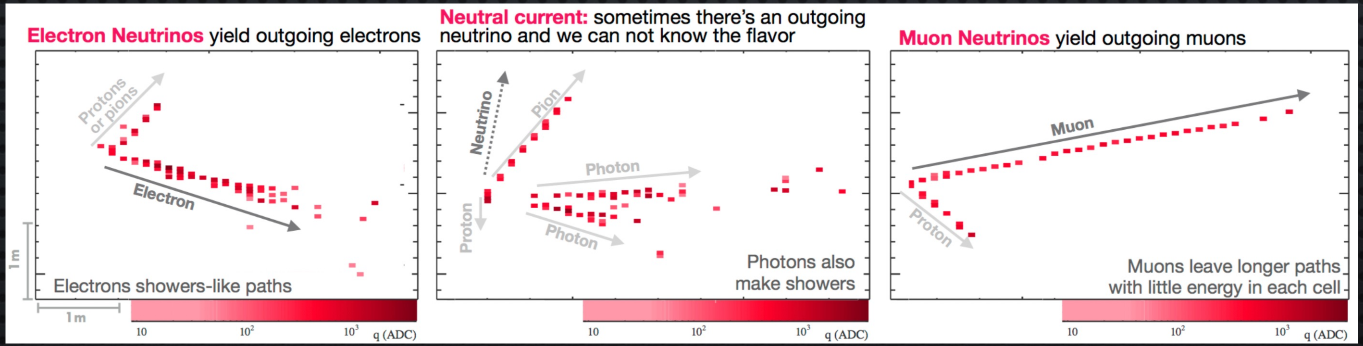
Near detector (1km from the source): To measure ν-beam spectrum before oscillations occur.

Far detector (810 km from the source): To detect the oscillated neutrinos

Beam:

- The beam is predominantly ν_μ, 1.8% $\bar{\nu}_\mu$, 0.7% ν_e
- $E_{peak} \approx$ 2 GeV (E:[1,3] GeV)
- 810 km baseline → Sensitive to matter effects

The 14-kton **detector** are made up of 344000 cells of PVC filled with liquid scintillator.

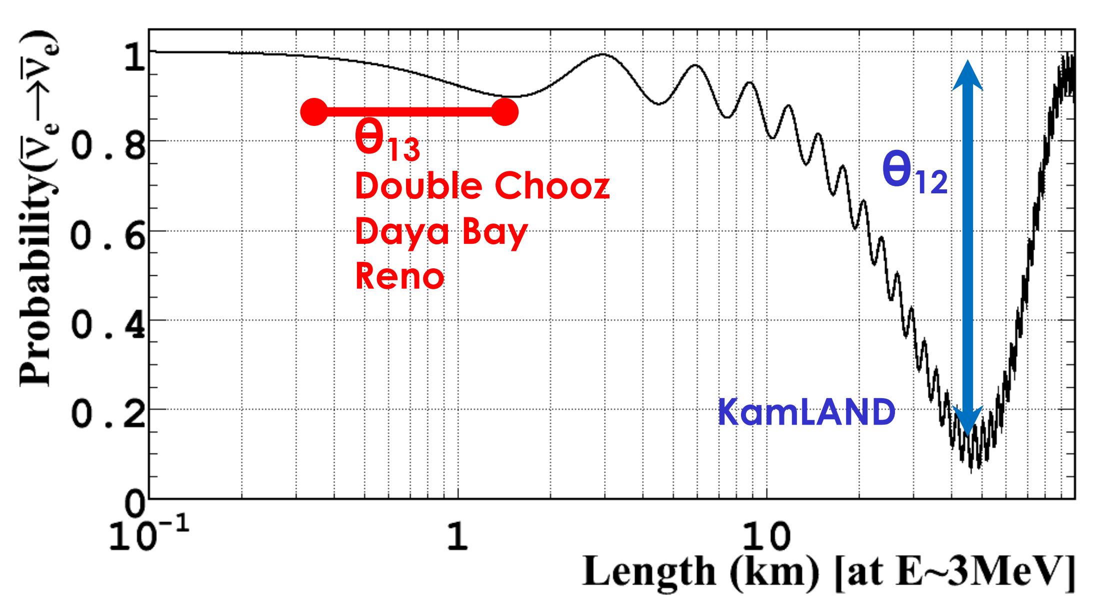


NUCLEAR REACTOR EXPERIMENTS

Neutrinos are produced by beta-decays of Fission products
Commercial nuclear reactors produces 10^{21} anti-ν_e/s of energies up to ~10 MeV

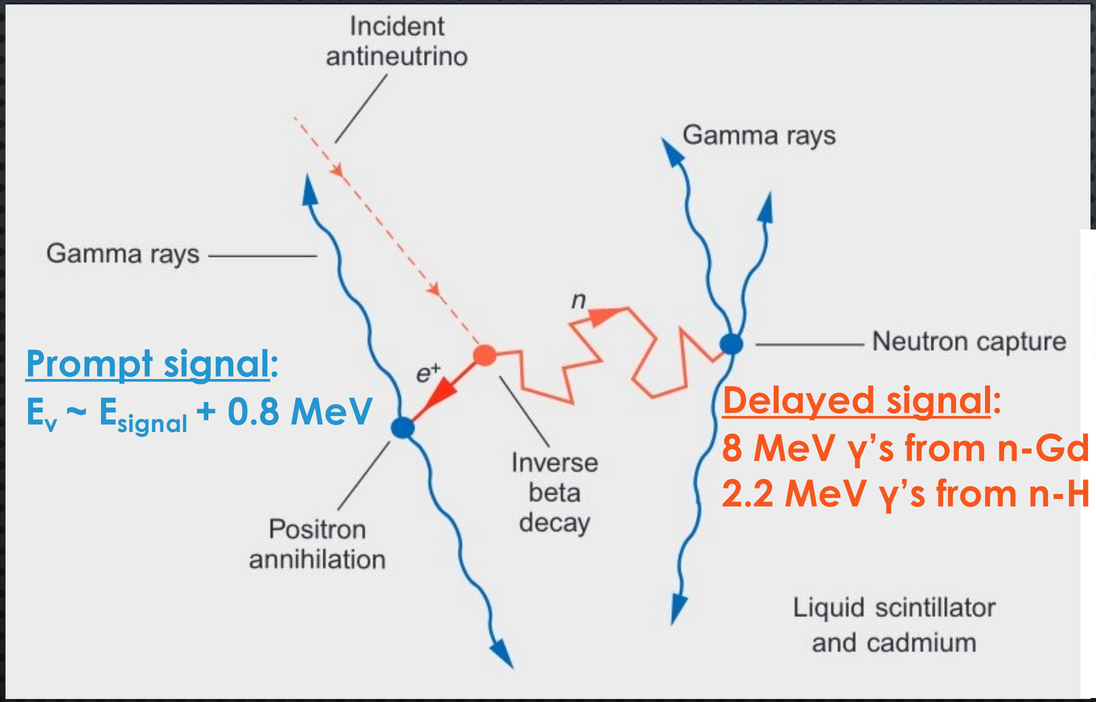
Disappearance Probability

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{4E}$$



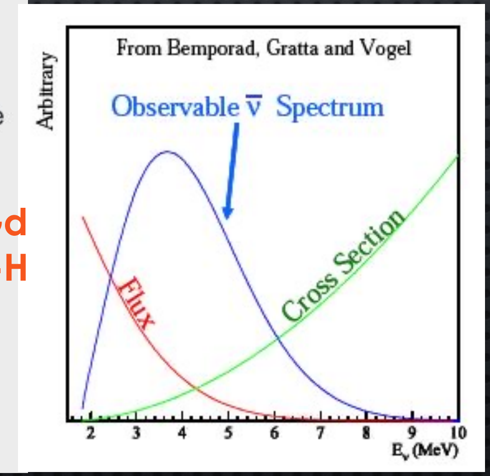
NUCLEAR REACTOR EXPERIMENTS

Detection **via inverse β-decay reaction $\bar{\nu}_e\, p \rightarrow e^+\, n$**

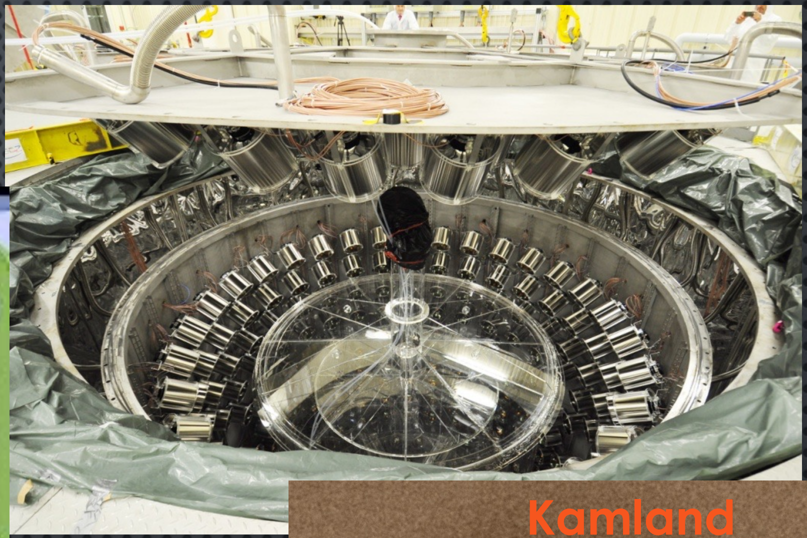


Prompt signal:
$E_\nu \sim E_{signal}$ + 0.8 MeV

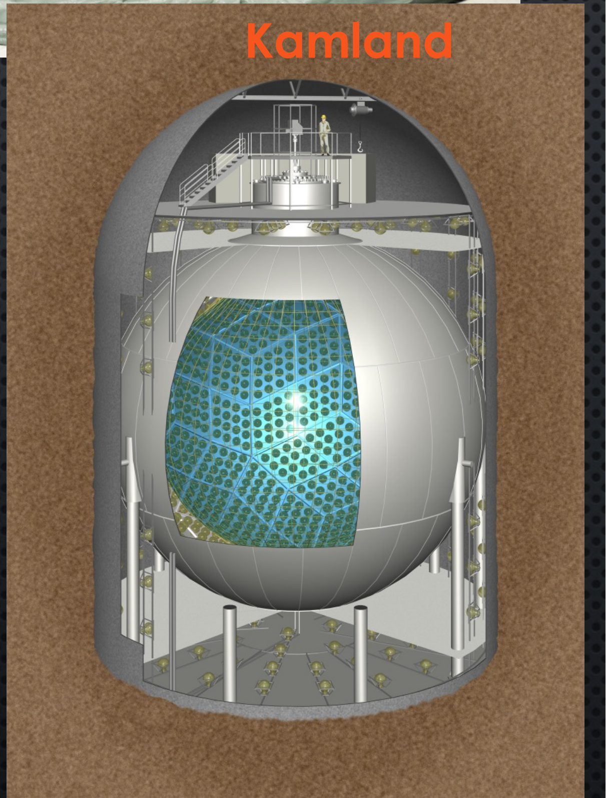
Delayed signal:
8 MeV γ's from n-Gd
2.2 MeV γ's from n-H



Double Chooz



Kamland



Θ_{13} MIXING ANGLE MEASUREMENT

θ_{13} was measured to be non zero at the end of 2011 by the Double Chooz experiment.

The determination of θ_{13} was one of the primary goals in neutrino physics until this date. Why?

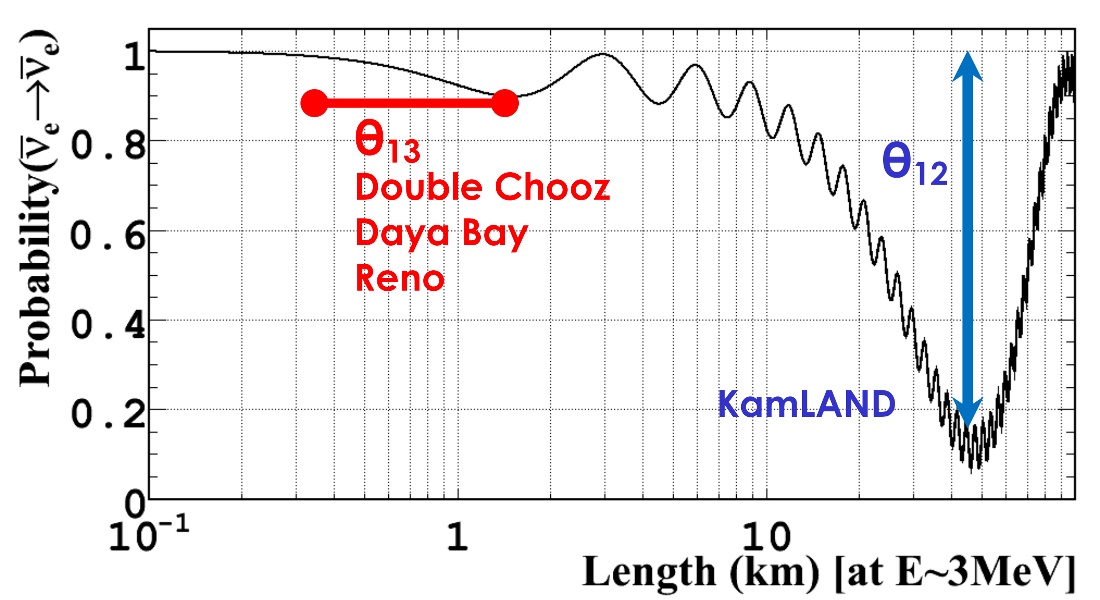
1. The possibility of CP violation in neutrino oscillations depends on a non-zero value of θ_{13}.
2. Any realistic possibility to determine the neutrino mass hierarchy (i.e. the sign of Δm_{13}^2) relies on a not too small θ_{13}.

The ways used to measure this parameter were:

1. Through the disappearance of $\bar{\nu}_e$ produced in a nuclear reactor
   → **Reactor neutrino experiments**
2. Through the appearance of ν_e in a beam of ν_μ
   → **Long baseline experiments**

MEASUREMENT OF Θ_{13} BY REACTOR EXPERIMENTS

$$P(\overline{\nu_e} \rightarrow \overline{\nu_e}) = 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m_{13}^2 L}{4E} + O(\frac{\Delta m_{21}^2}{\Delta m_{31}^2})$$



<u>*Reactor experiments*</u> provide an unambiguous measurement of θ_{13} :

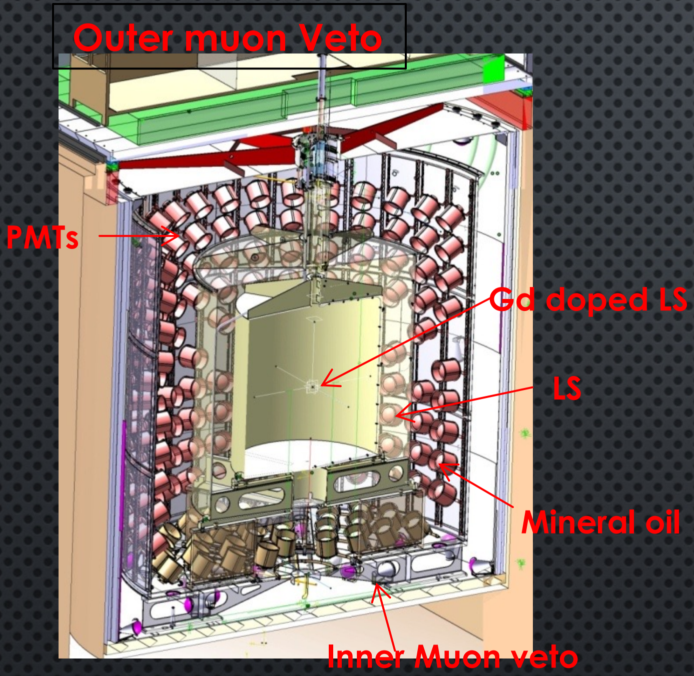
- **Insensitive to δ-CP phase and matter effects**
- **Weak dependence on Δm^2_{21}**

Small angle $\theta_{13} < 10.5$ deg
Its measurement requires:

- High statistics
- Extremely small systematic uncertainty

New generation of reactor experiments:
Daya Bay, **Reno** and **Double Chooz**.

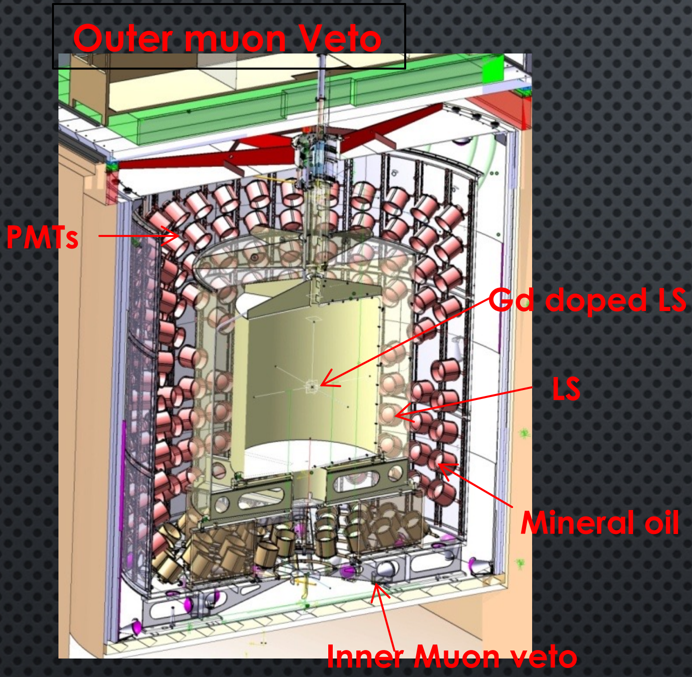
DOUBLE CHOOZ



- Larger detectors
- Less BG
- *2 identical reactors*
  - Reduction of flux uncertainty
  - Reduction of detection efficiency error

Reactors
Two N4-type PWRs
4.25 GWth each
10^{21} / s

DOUBLE CHOOZ / DAYA BAY



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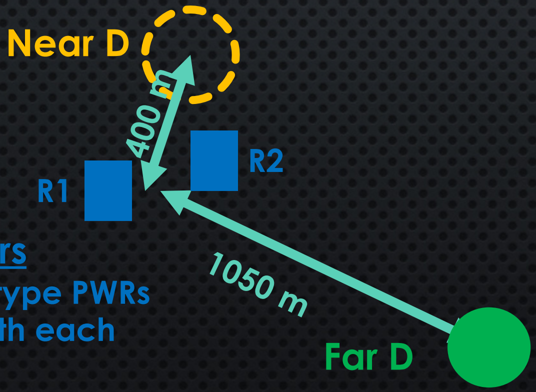

Reactors
Two N4-type PWRs
4.25 GWth each
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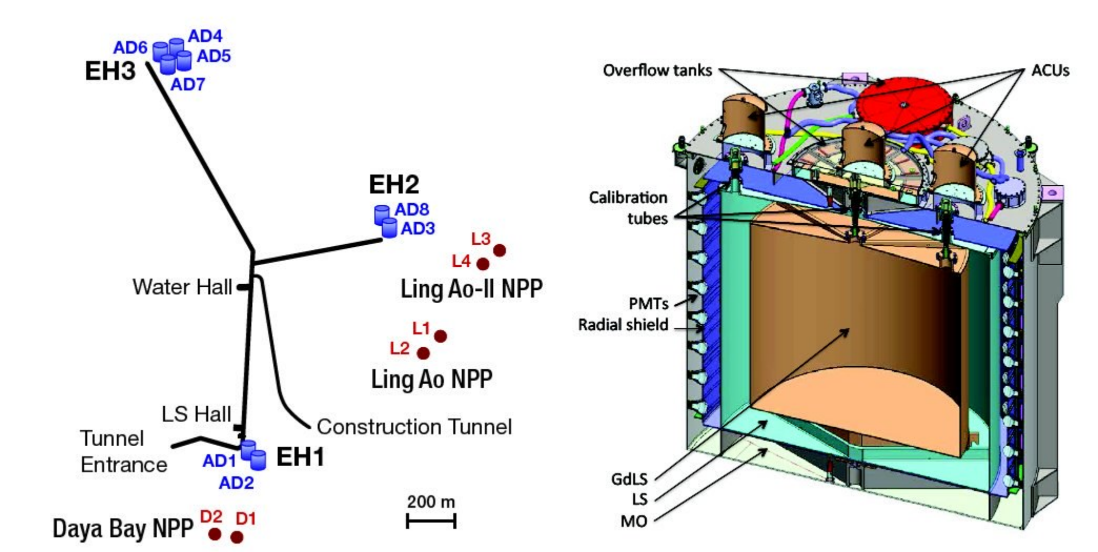
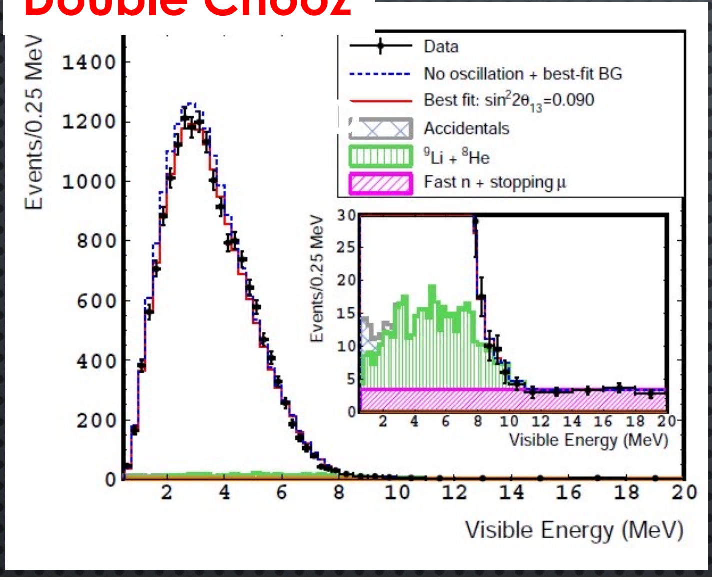
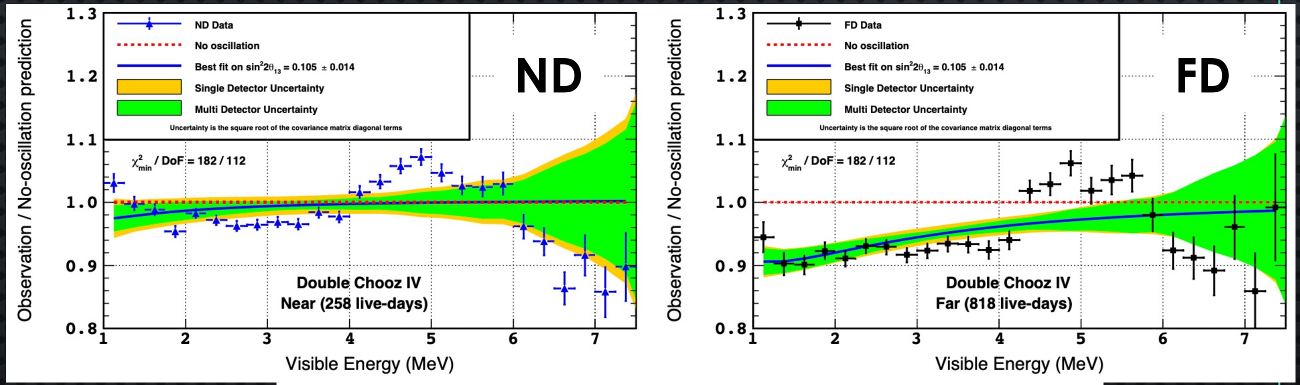


Daya Bay was designed to be able to measure extremely small values of θ_{13}
→ using multiple detectors in every site.

DOUBLE CHOOZ / DAYA BAY: RESULTS

Double Chooz

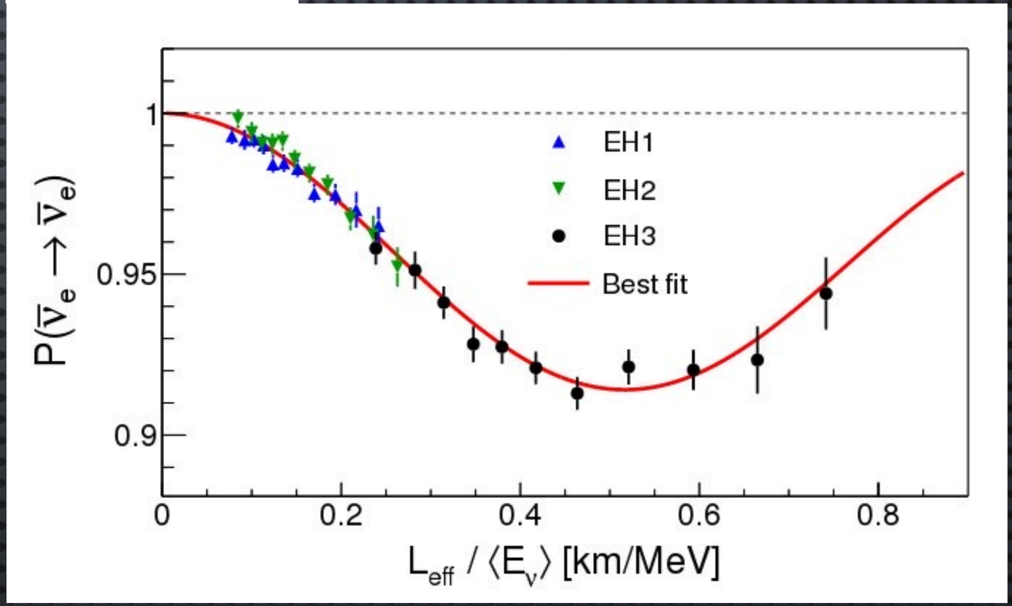




$$\sin^2 2\theta = 0.105 \pm 0.014(\text{stat.} + \text{syst})$$

Nature Phys. **16 (2020) 5, 558-564**

Daya Bay



Phys. Rev. D95 no.7 (2017)

$$\sin^2 2\theta_{13} = 0.0856 \pm 0.0029$$

Phys. Rev. Lett. 121 no.24. 241805 (2018)

MEASUREMENT OF Θ_{13} BY LONG BASELINE EXPERIMENTS

$$P(\nu_\mu \to \nu_e) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2(A-1)\Delta}{(A-1)^2}$$
$$+\alpha \sin 2\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \cos(\Delta+\delta) \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)}$$

The first term dominates (for large θ_{13})

The second term depends on the CP phase δ and is responsible for CP violation

where, $\Delta \equiv \frac{\Delta m_{31}^2 L}{4E}$ $A \equiv \frac{2E\sqrt{2}G_F N_e}{\Delta m_{31}^2}$ $\alpha \equiv \frac{\Delta m_{21}^2}{\Delta m_{31}^2}$

In this case, the oscillation probability depends not only on θ_{13} but also on:

- CP violation parameter δ
- sign of Δm_{31}^2 (matter effects)
- size of $\sin^2\theta_{23}$ (octant)

Examples of this kind of experiments are **NOνA** and **T2K**.

CP VIOLATION & LONG BASELINE EXPERIMENTS

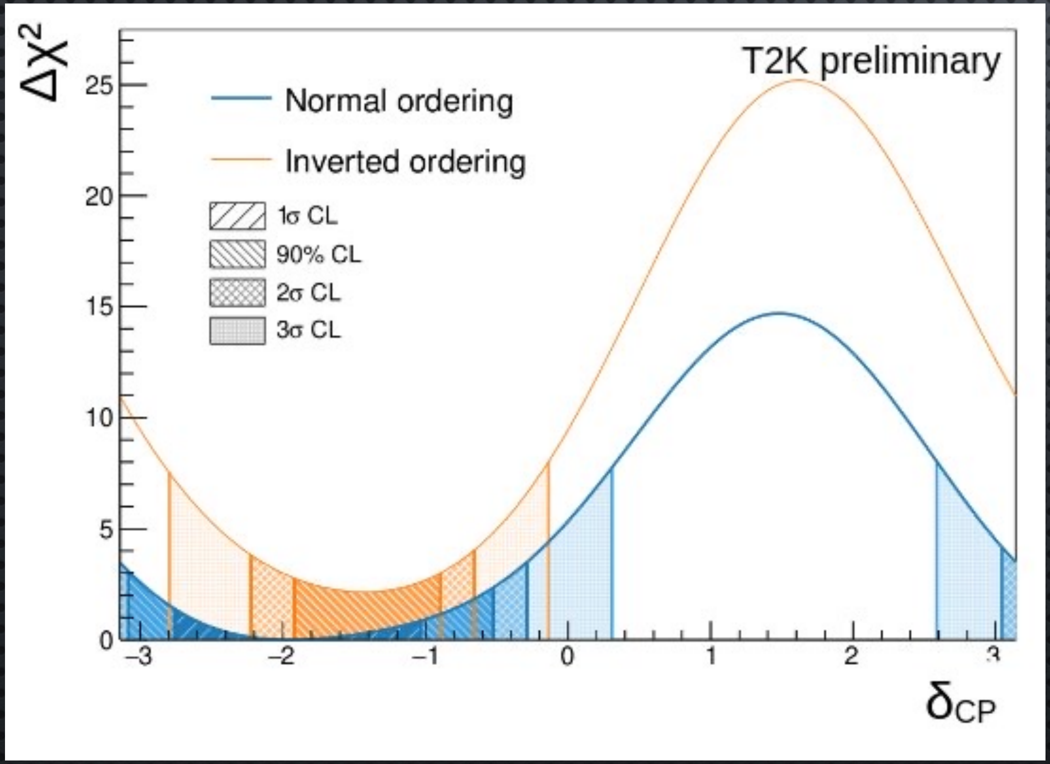
Long baseline experiments can measure additionally CP violation using beam of neutrinos and anti-neutrinos

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

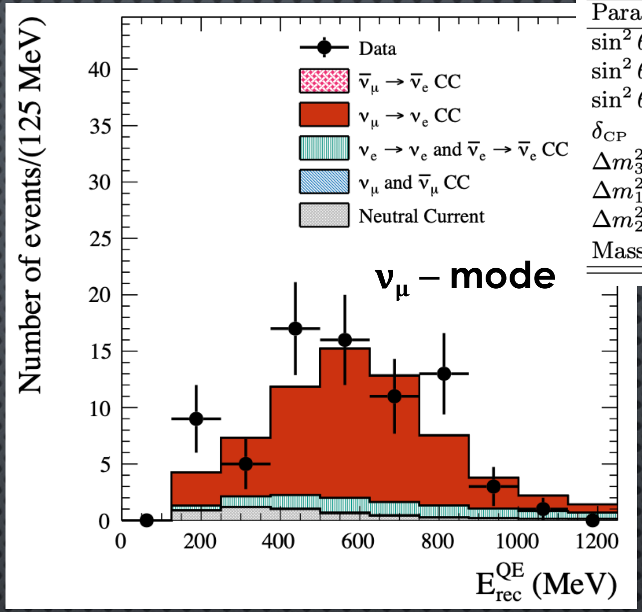
$$P_{\bar{\nu}_\mu \to \bar{\nu}_e} \sim \frac{1}{2}\sin^2 2\theta_{13} + 0.043\sin 2\theta_{13}\sin 2\theta_{23}\sin\delta$$

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

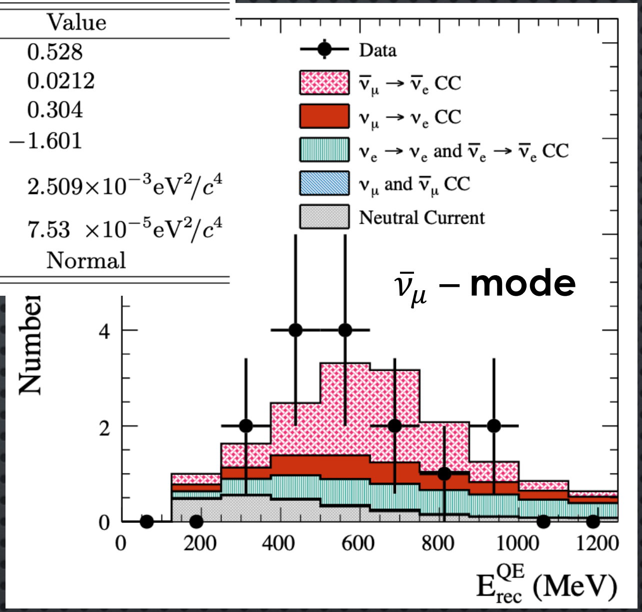
T2K EXPERIMENT

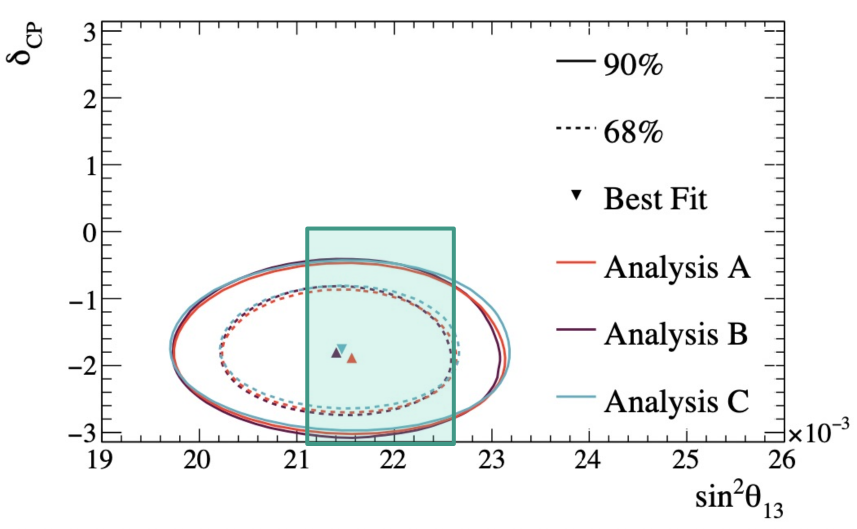


Presented at Neutrino2022



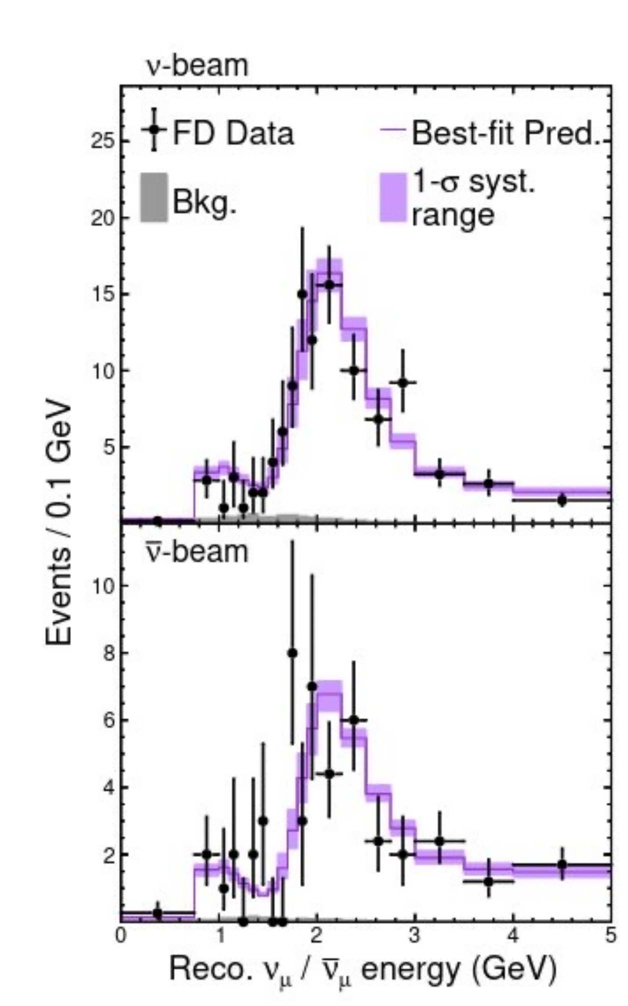
Parameter	Value
$\sin^2\theta_{23}$	0.528
$\sin^2\theta_{13}$	0.0212
$\sin^2\theta_{12}$	0.304
δ_{CP}	-1.601
Δm^2_{32} (NO) Δm^2_{13} (IO)	$2.509 \times 10^{-3} eV^2/c^4$
Δm^2_{21}	$7.53 \times 10^{-5} eV^2/c^4$
Mass Ordering	Normal

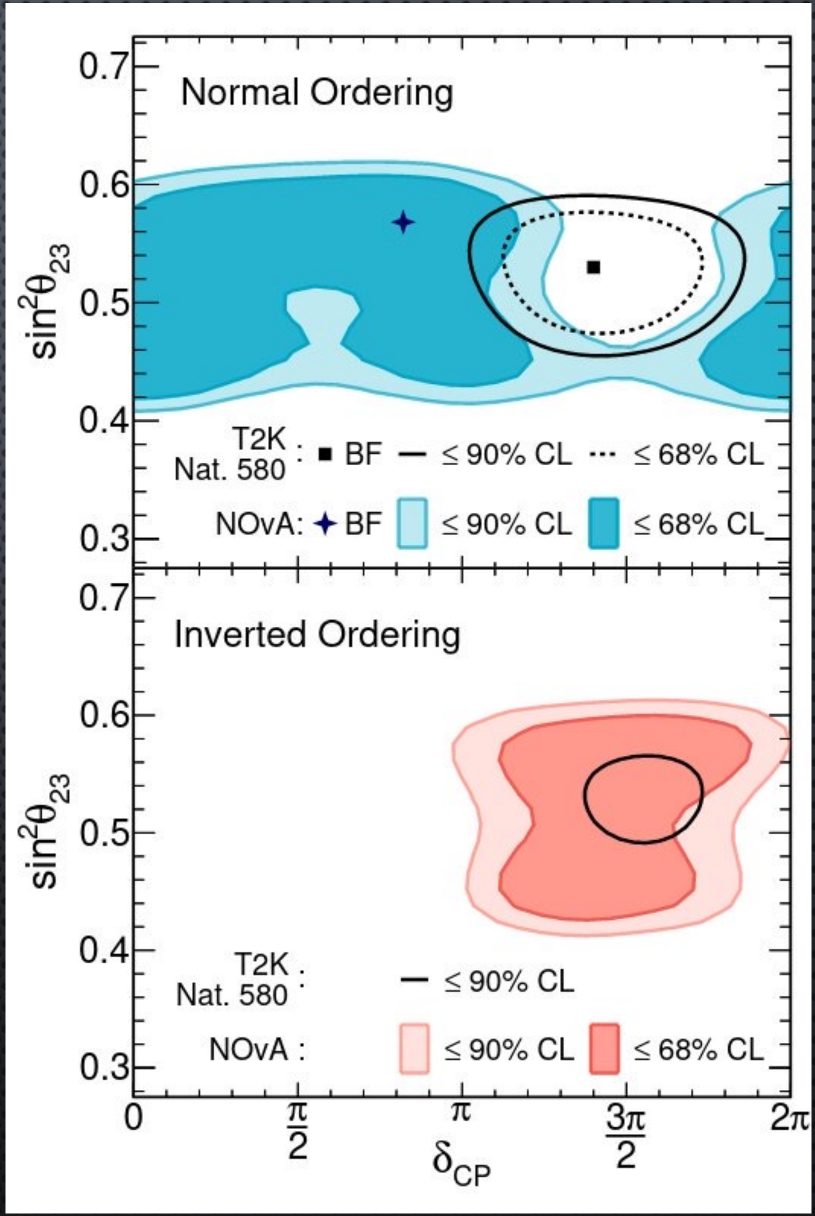




Improved constraints on neutrino mixing from the T2K experiment with 3.13 10^{21} protons on target. T2K Collab. K. Abe et al. *Phys. Rev. D* 103 (2021) 11, 112008

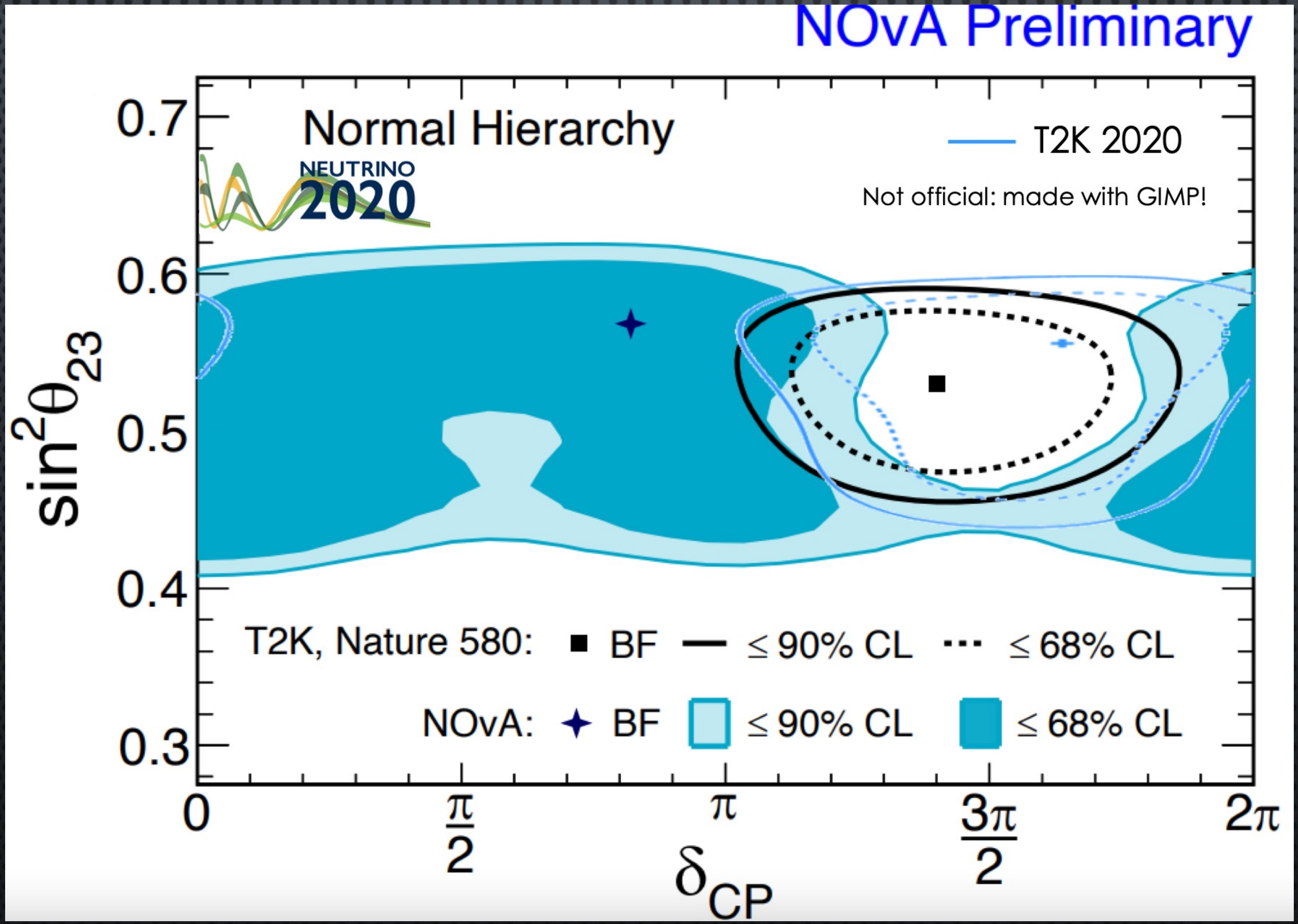
NOνA EXPERIMENT





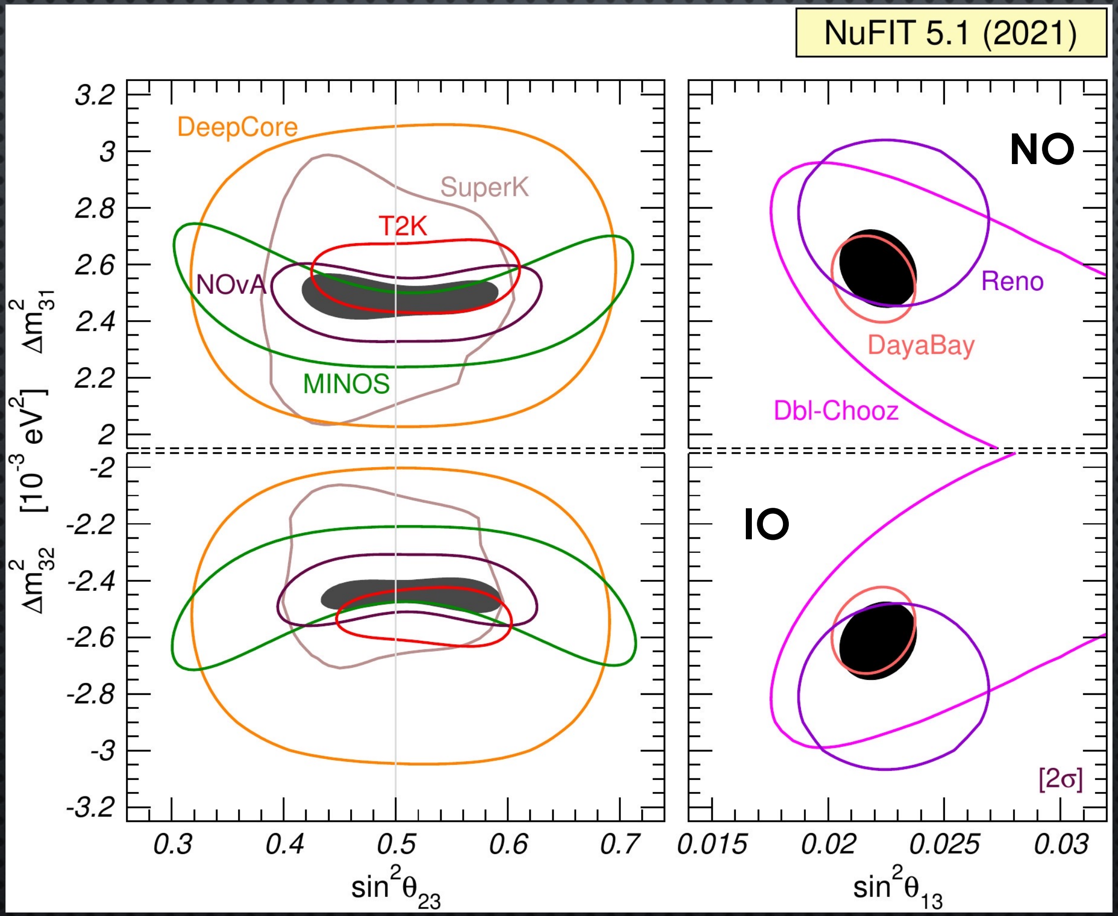
arXiv:2108.08219

δ_{CP} RESULTS T2K & NOvA



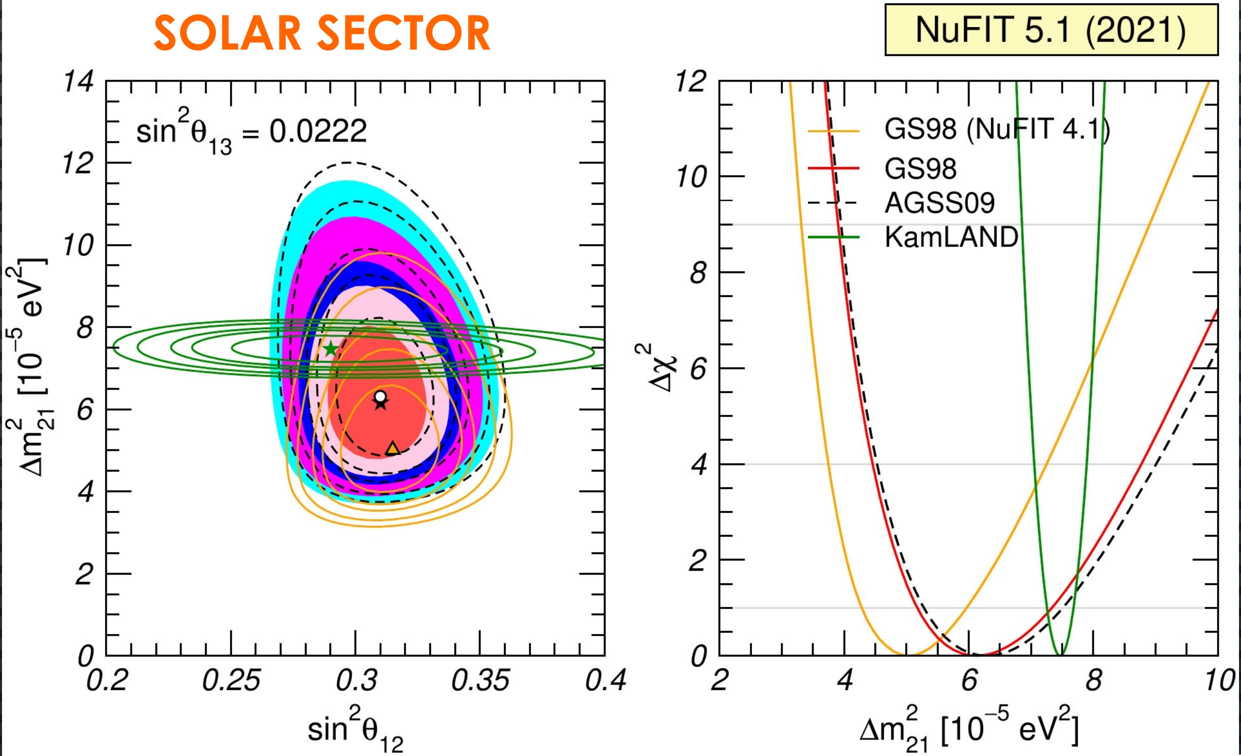
NEUTRINO OSCILLATION RESULTS (2021)

ATMOSPHERIC and REACTOR SECTORS



NEUTRINO OSCILLATION RESULTS (2021)

Tension between
Solar and KamLAND



NuFIT 5.1 (2021)

	θ_{12}	θ_{23}	θ_{13}	δ_{CP}	Δm_{12}^2	Δm_{32}^2
N.H.	33.5°	42.1°	8.62°	230°	7.42×10^{-5} eV^2	2.510×10^{-3} eV^2
I.H	33.5°	49.0°	8.61°	278°	7.39×10^{-5} eV^2	-2.490×10^{-3} eV^2
σ (%)	2.3	2.3	1.4	13*	2.8	1.1

Neutrino Physics II (Experimental)

Carmen Palomares

CIEMAT

OUTLINE

- Future Long-baseline Neutrino Oscillation Experiments
- Sterile neutrino
- Measurement of Neutrino mass

FUTURE NEUTRINO OSCILLATION EXPERIMENTS

OSCILLATION PARAMETERS

The measurement of $\theta_{13} \neq 0$ allows
- Determination of the mass ordering
- Study of the existence of CP violation in the leptonic sector.

The goals of the future research in neutrino oscillation are:

1. To determine the status of the CP symmetry in the leptonic sector
2. To solve the octant θ_{23} degeneracy. $\sin^2(2\theta_{23}) \sim 1$, but the data are inconclusive whether θ_{23} is larger or smaller than 45°
3. To determine the mass ordering. There are 2 possibilities for the ordering of the neutrino masses m1 < m2 < m3 "Normal hierarchy" and m3< m1< m2 "Inverted hierarchy"

CP VIOLATION PHASE

The CP violation in neutrino oscillation is a genuine three flavor effect, so it can be observed only when there is an interface between flavor oscillation involving at least 2 different Δm^2 and 3 mixing angles:

$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23}\frac{\sin^2 2\theta_{13}}{(\hat{A}-1)^2}\sin^2((\hat{A}-1)\Delta)$$

Atmospheric

$$+\alpha\frac{\sin\delta_{CP}\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}}{\hat{A}(1-\hat{A})}\sin(\Delta)\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)$$

Interference

$$+\alpha\frac{\cos\delta_{CP}\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}}{\hat{A}(1-\hat{A})}\cos(\Delta)\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)$$

$$+\alpha^2\frac{\cos^2\theta_{23}\sin^2 2\theta_{12}}{\hat{A}^2}\sin^2(\hat{A}\Delta)$$

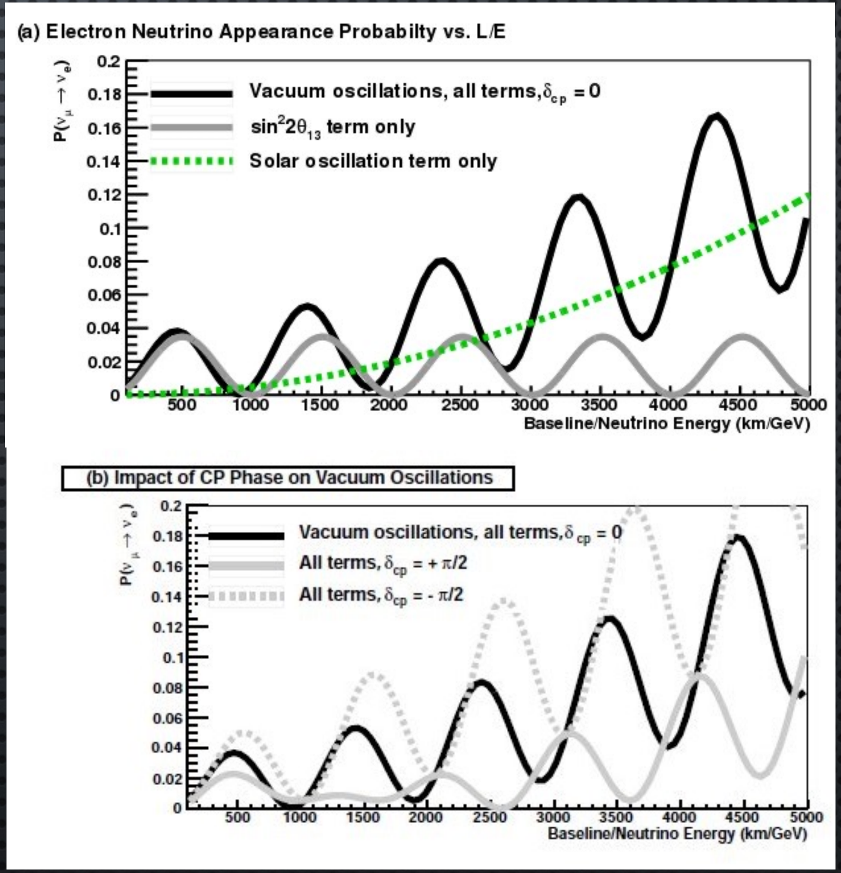
Solar

where $\alpha = \Delta m^2_{21}/\Delta m^2_{31}$, $\Delta = \Delta m^2_{31}L/4E_\nu$, $\hat{A} = 2VE_\nu/\Delta m^2_{31}$, $V = \sqrt{2}G_F n_e$,

$P(\overline{\nu}_\mu \to \overline{\nu}_e)$ **the same except that the sign of the second term is negative**

CP VIOLATION

M. Bass et al. arXiv:1311.0212



Maximum Oscillation Probabilities in vacuum:

$$L/E_n\,(Km/GeV) \approx (2n-1)\left(\frac{\pi}{2}\right)\frac{1}{1.27\times\Delta m_{23}^2}$$

Short-baselines: The n>1 maxima too low in energy for neutrino beams

Long-baselines: It is possible to observe multiple oscillation nodes if E_ν covers a wide range

CP VIOLATION

If δ≠0 and δ≠π → $P(\nu_\mu \to \nu_e) \neq P(\bar{\nu}_\mu \to \bar{\nu}_e)$

The CP asymmetry is defined as:

$$A_{CP}(E_\nu) = \left[\frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)} \right]$$

If δ=0 or δ=π

→ In vacuum $P(\nu_\mu \to \nu_e) = P(\bar{\nu}_\mu \to \bar{\nu}_e)$ and $A_{CP}=0$

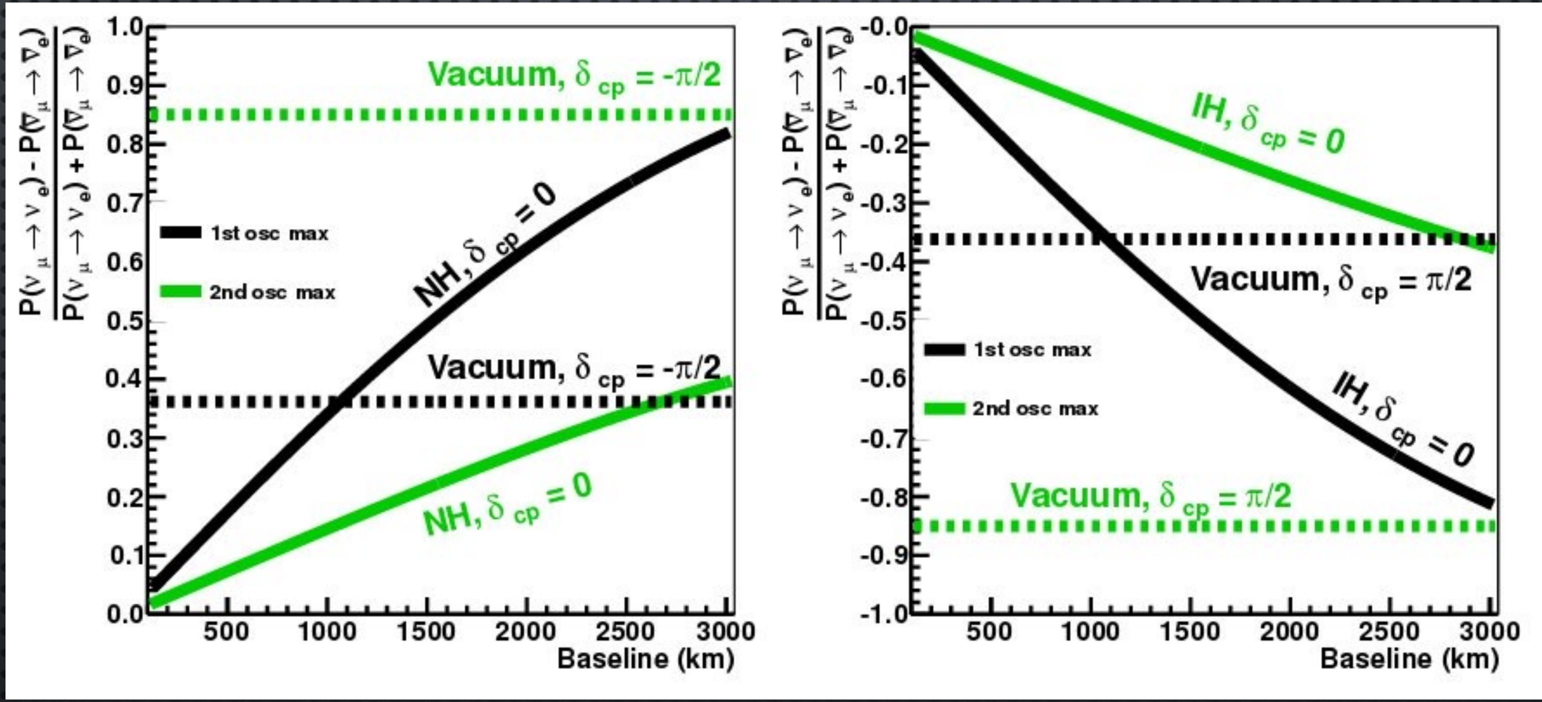
→ In matter $P(\nu_\mu \to \nu_e) \neq P(\bar{\nu}_\mu \to \bar{\nu}_e)$ $\bar{P}_{\mu e}(NH) = P_{\mu e}(IH)$

In matter there are two contributions to A_{CP}:

$$A_{CP}(E_\nu) \approx -0.3 \sin\delta \pm \underbrace{2L / L_0}_{\text{matter effects}}$$

CP VIOLATION

A_{CP} for different baselines



- The asymmetry due to $\delta \neq 0$ is constant as a function of L (at oscillation max.) while that due to matter effects increases with baseline, as expected.
- The measurement at the second node has better sensitivity but requires long-baselines

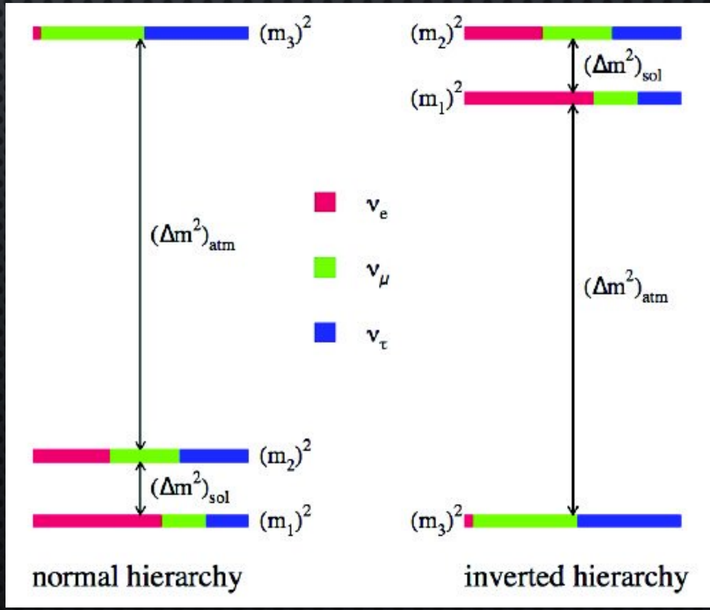
NEUTRINO MASS ORDERING

Once we understand the ordering of the neutrino mass states:

1. The uncertainty on the CP-violating phase measurement is significantly reduced.
2. MH knowledge would define the scope for future neutrino-less double beta decay experiments.
3. In combination with cosmological measurements, which are sensitive to the sum of neutrino masses, MH could also be used to determine the absolute mass scale of neutrinos

Determination:

- The sign of Δm_{13}^2 can be measured by the study of the matter effect in transitions due to Δm_{13}^2



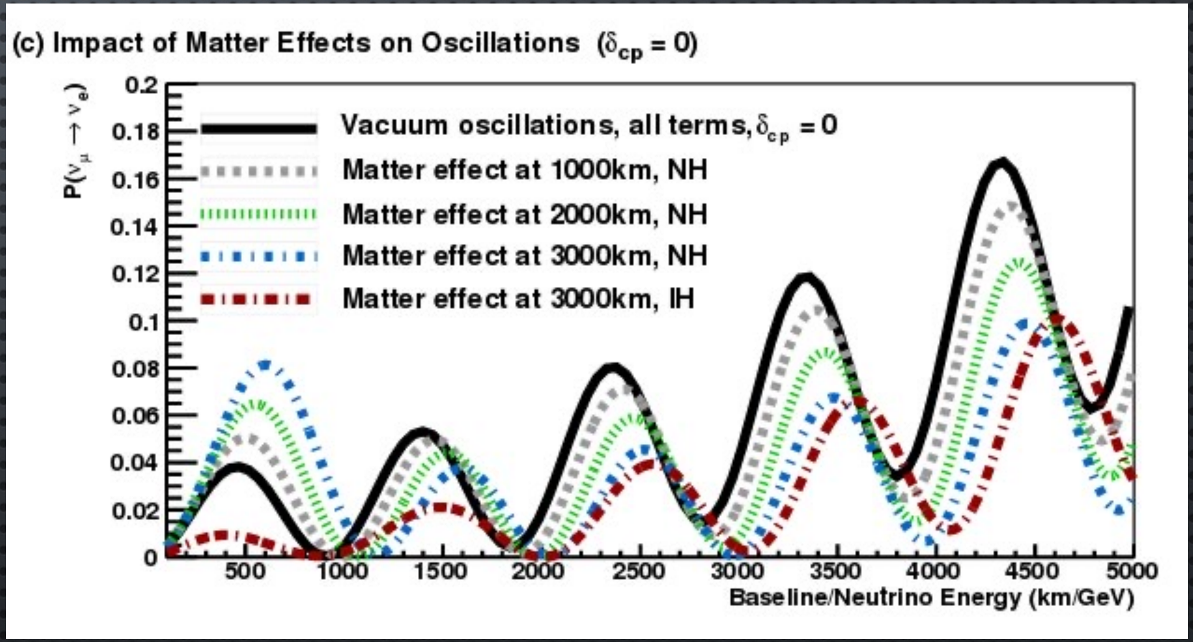
MASS ORDERING

Requirements of the experiment:

- L large enough – matter effects increase with L
- Distinction between ν and anti-ν

Future experiments:

- Long baseline experiments: DUNE (depends on δ)
- Atmospheric experiments: Hyper-K, PINGU,…

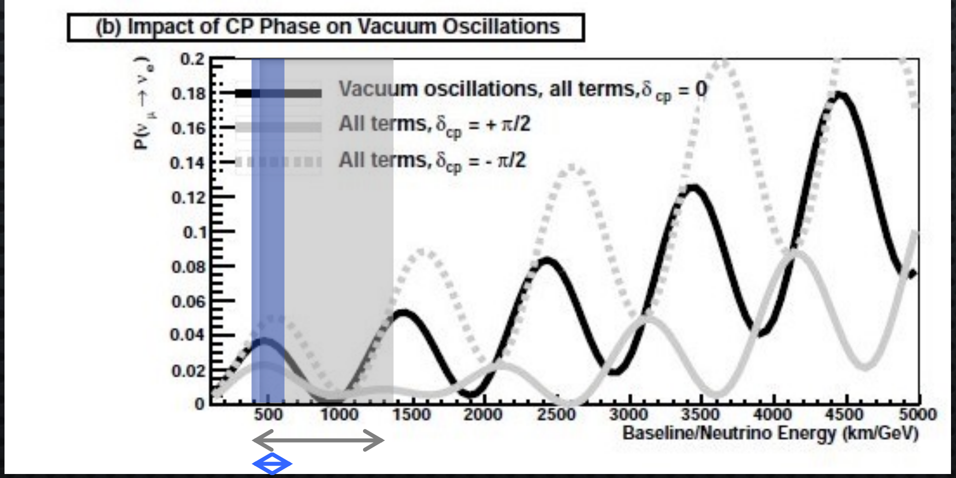


FUTURE LBL PROJECTS: DUNE AND HYPER-K

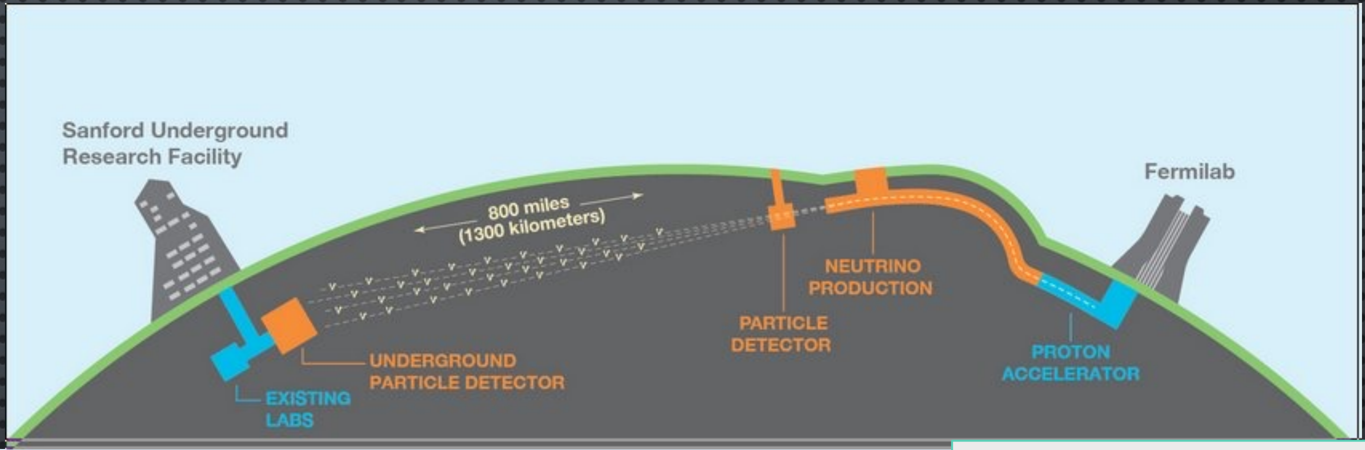
- Long-baseline accelerator neutrino projects:
  - **Hyper-K approach**: minimizes matter effects and measures CP (MH must be known by other means)

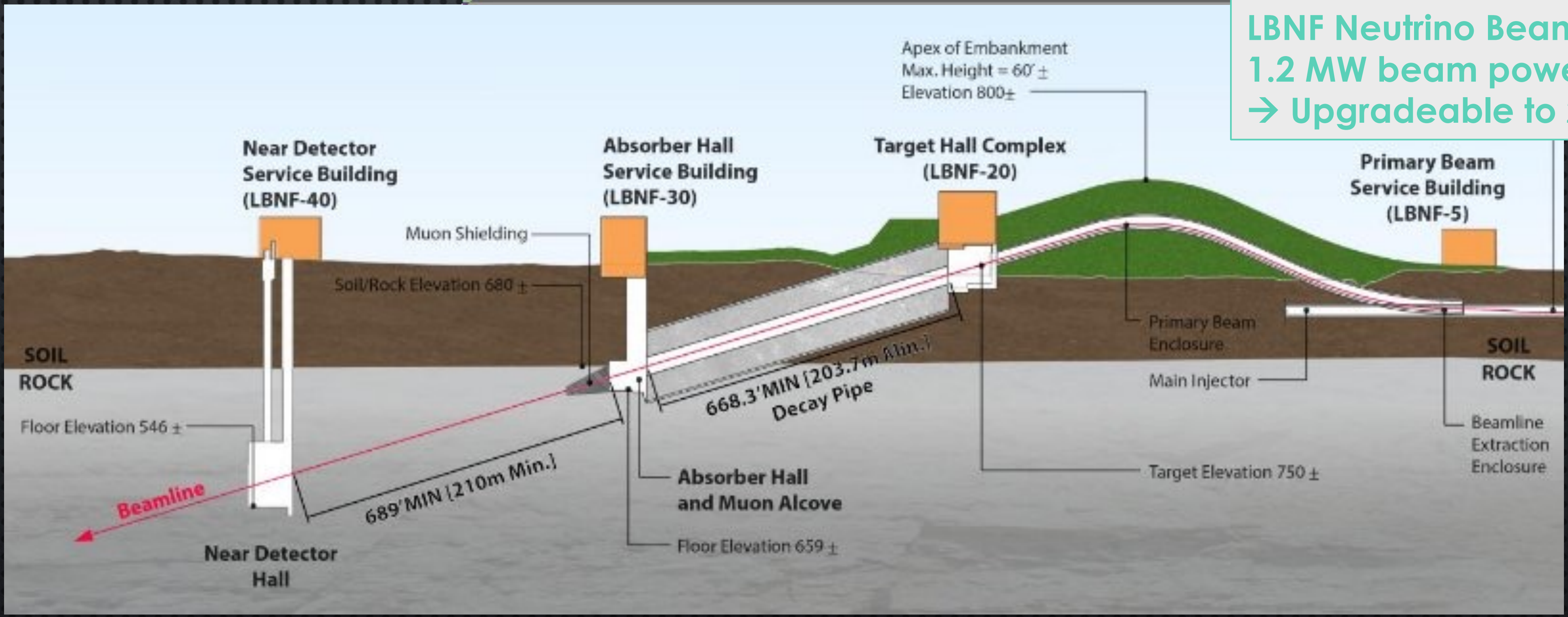
    L=295 km ,, E~0.6 GeV --> L/E ~ 492 (km/GeV)
  - **DUNE approach**: measure first and second oscillation maxima to disentangle CP and matter effects

    L = 1300 km ,, E~2 GeV (wide-band beam) --> L/E~500-1300 (km/GeV)



DUNE

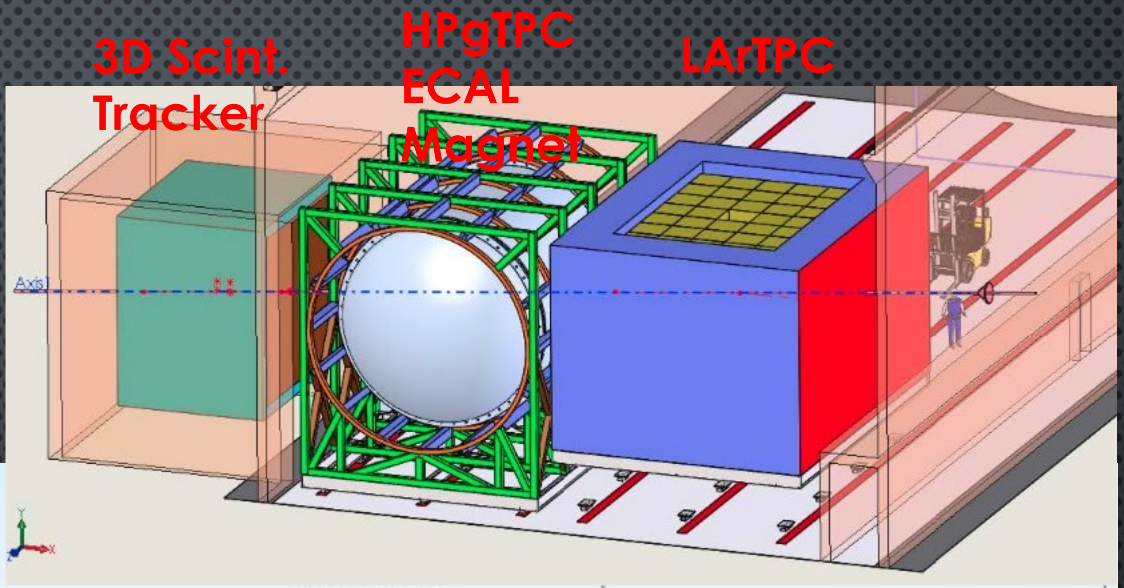


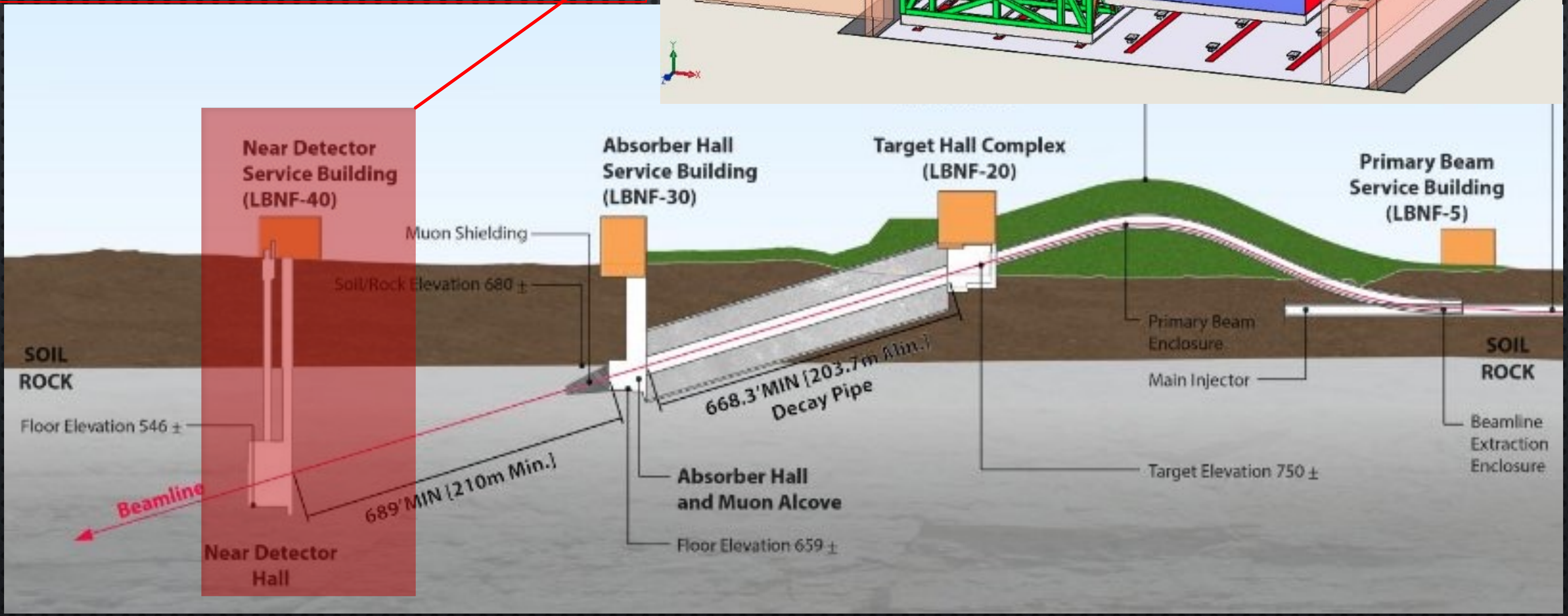


LBNF Neutrino Beam
1.2 MW beam power
→ Upgradeable to 2.4 MW

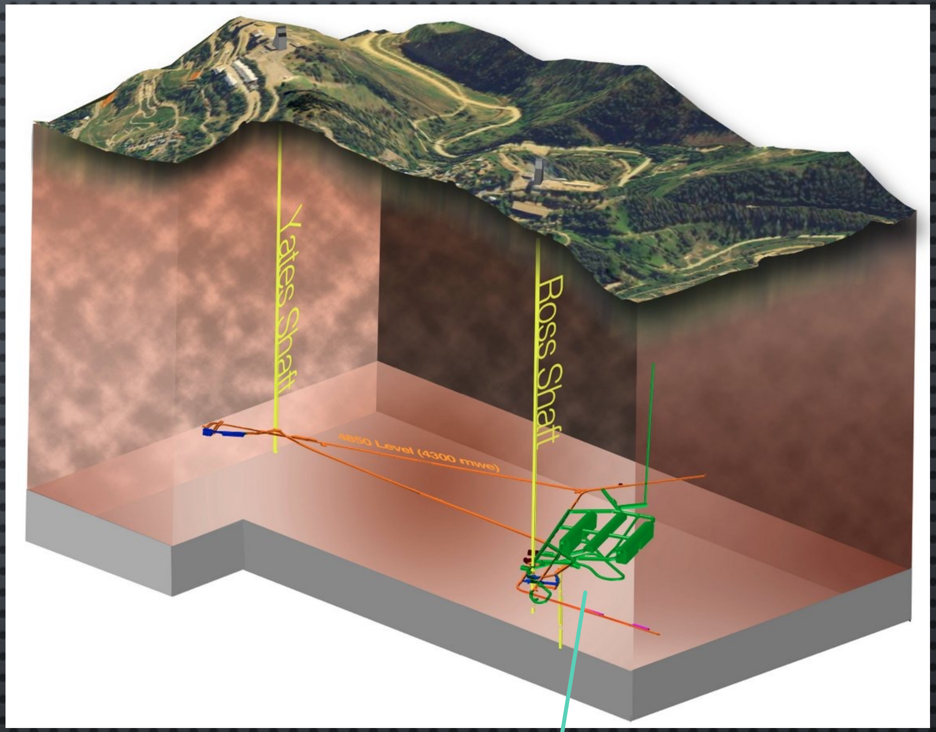
DUNE

Near Detector will reduce systematic errors by measuring:
- neutrino-argon interactions
- unoscillated neutrino spectra
- neutrino flux





DUNE FAR DETECTOR



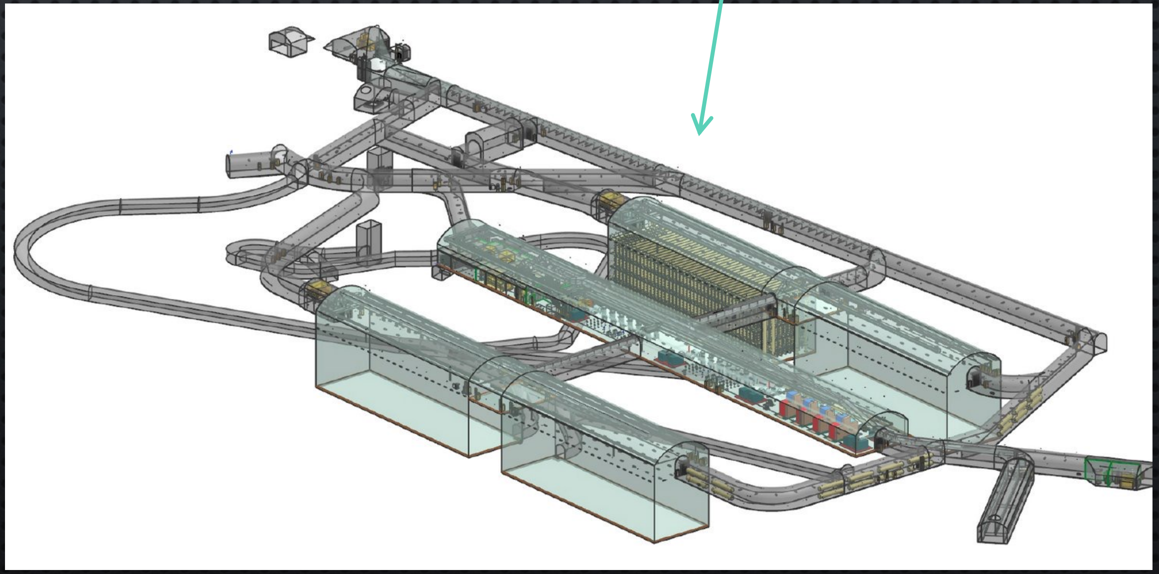
Detector

- Liquid Argon Time-Projection Chamber
- Four 17-kt separate modules

Detection mode:

1. Neutrino interaction produces charged particles
2. The charged particles will produce ionization electrons

That drift under a high-voltage electric field to the anode where the detection elements are installed



Schedule:

- Far site construction is underway
- Start of Modules 1-2 Installation: 2024
- Far detector physics data expected in late 20´s

DUNE FAR DETECTOR

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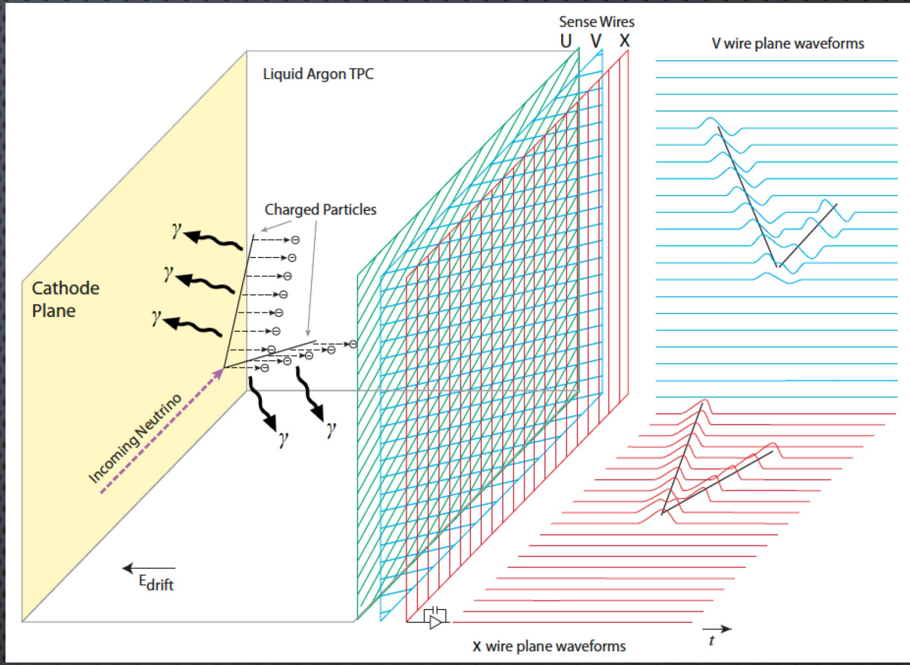

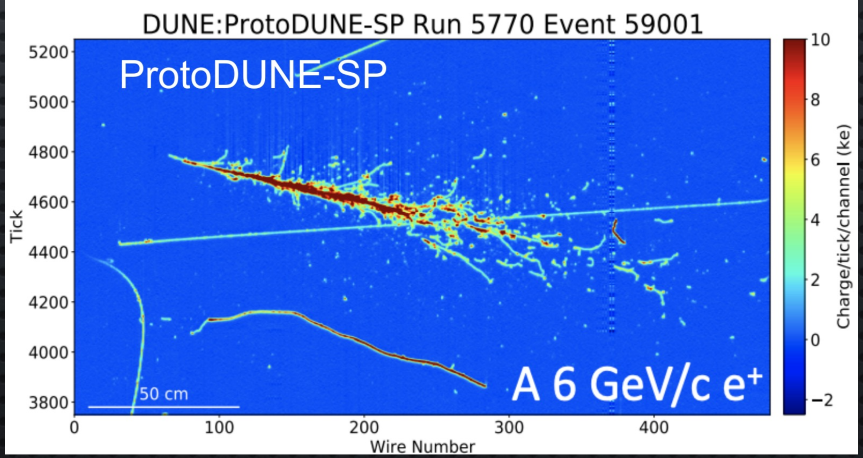

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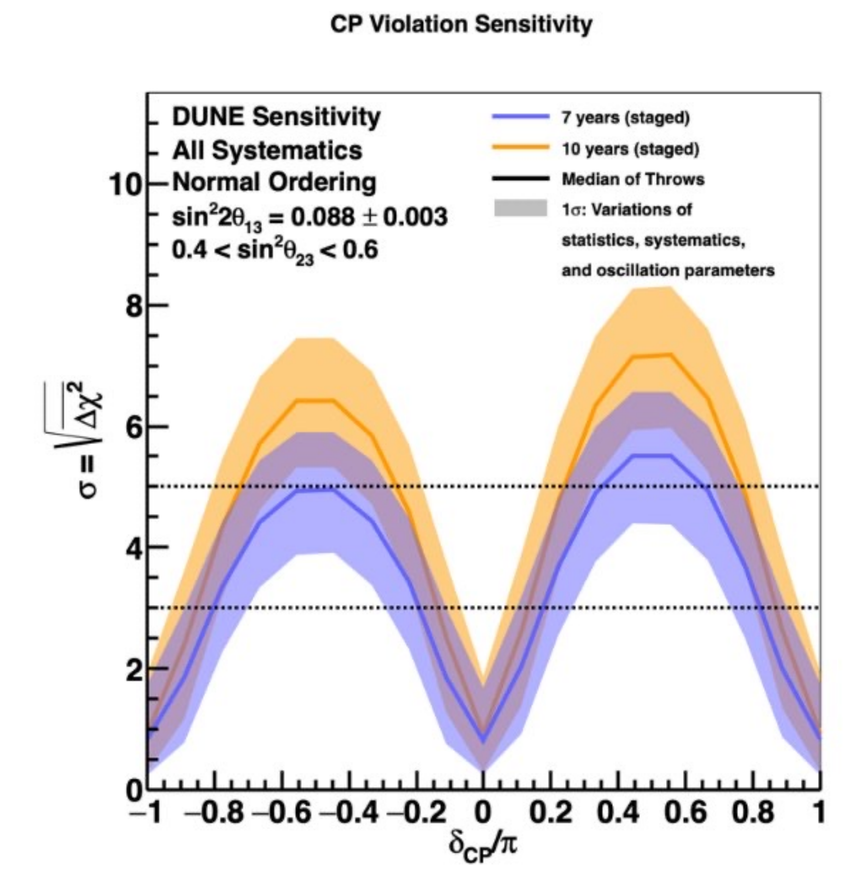
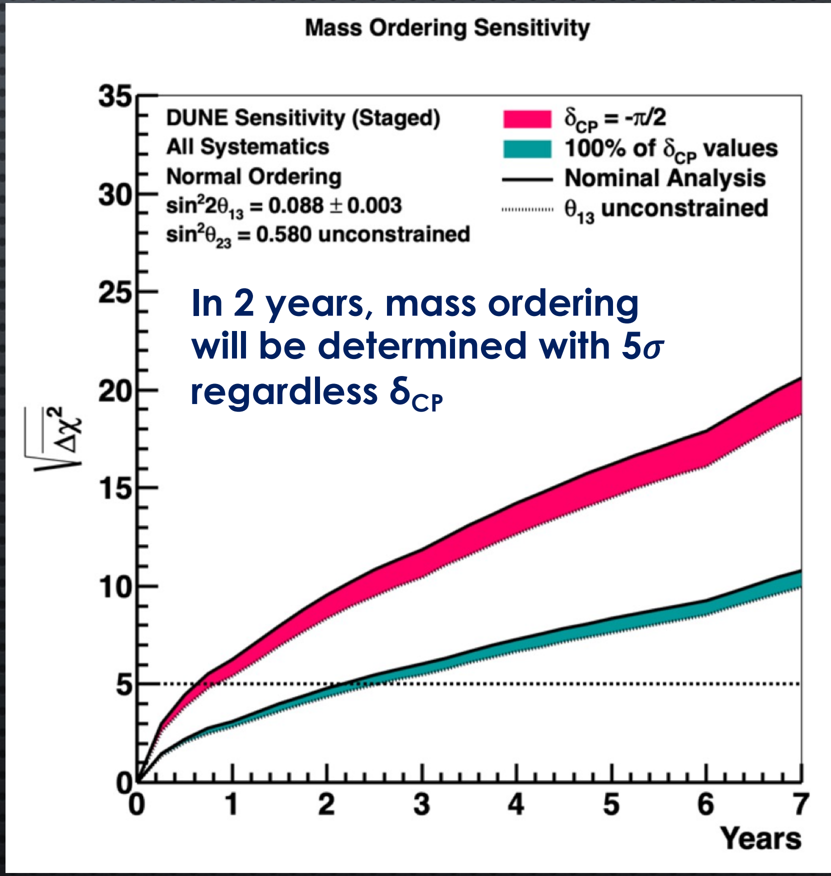
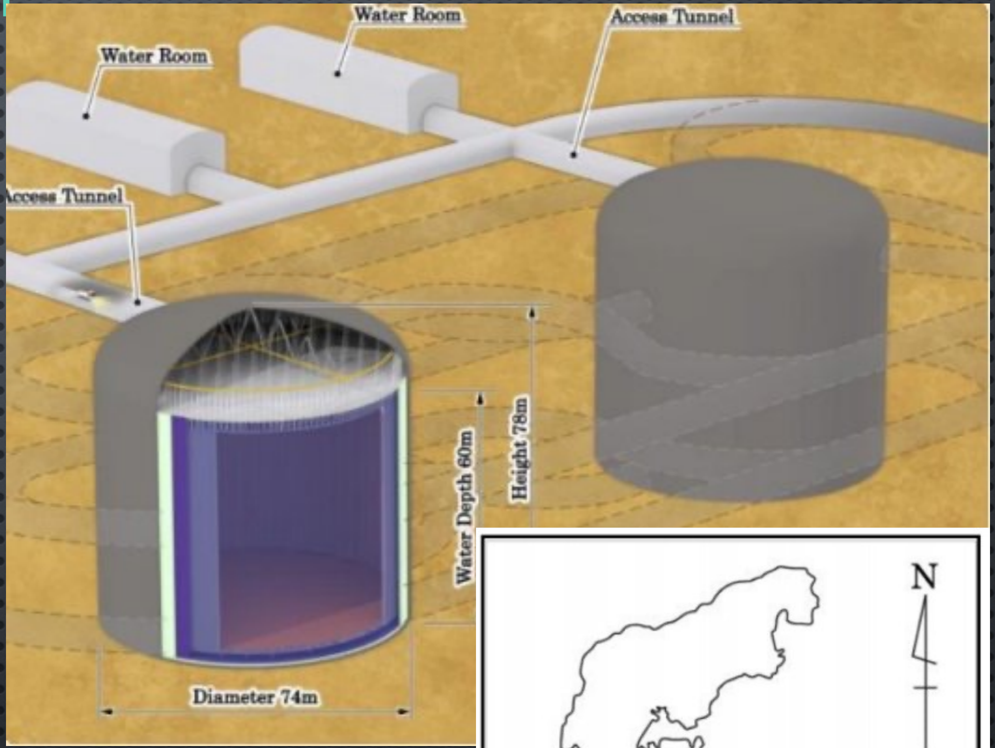
DUNE EXPECTED SENSITIVITY

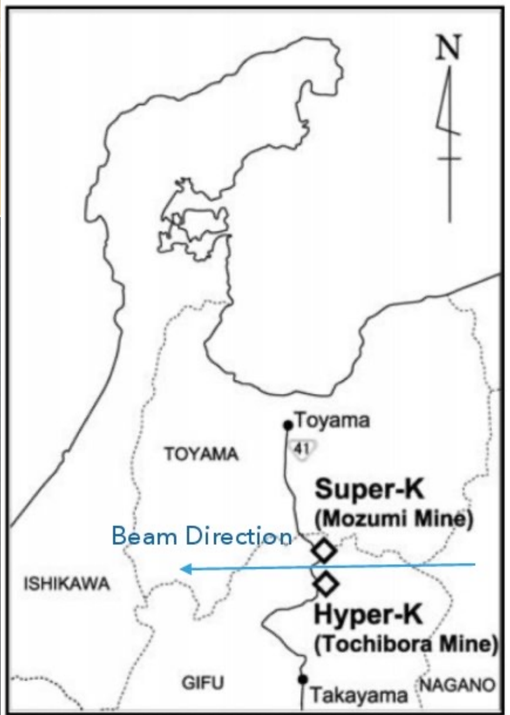




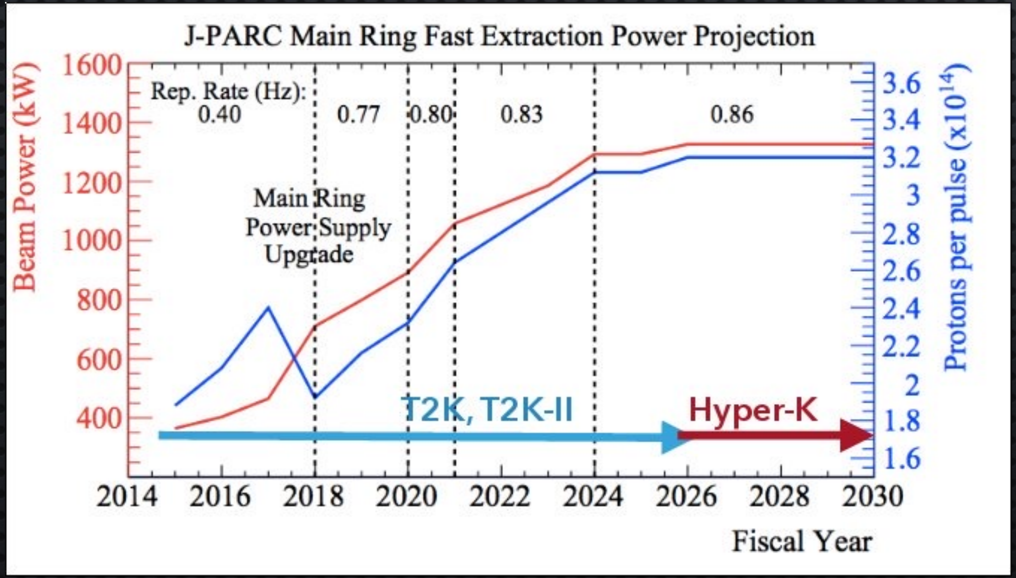
HYPER-KAMIOKANDE

Detector:
260 kton Water Cherenkov (187 kton FV) (10xSK)
2^{nd} tank 6 years after 1^{st} tank





The Neutrino Beam

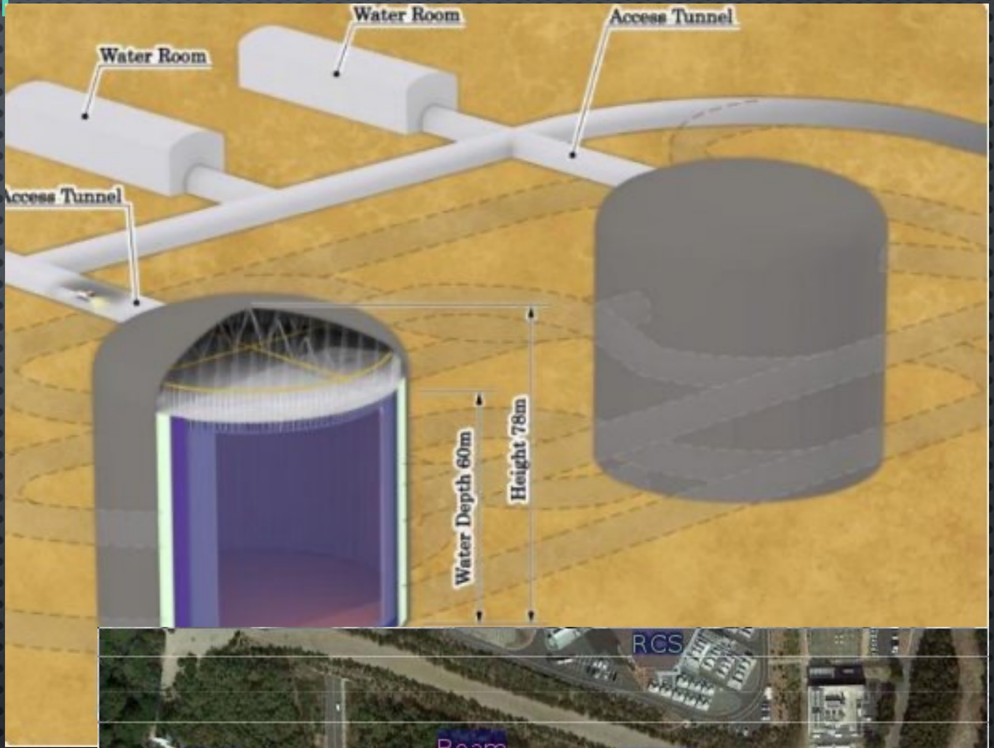


HYPER-KAMIOKANDE

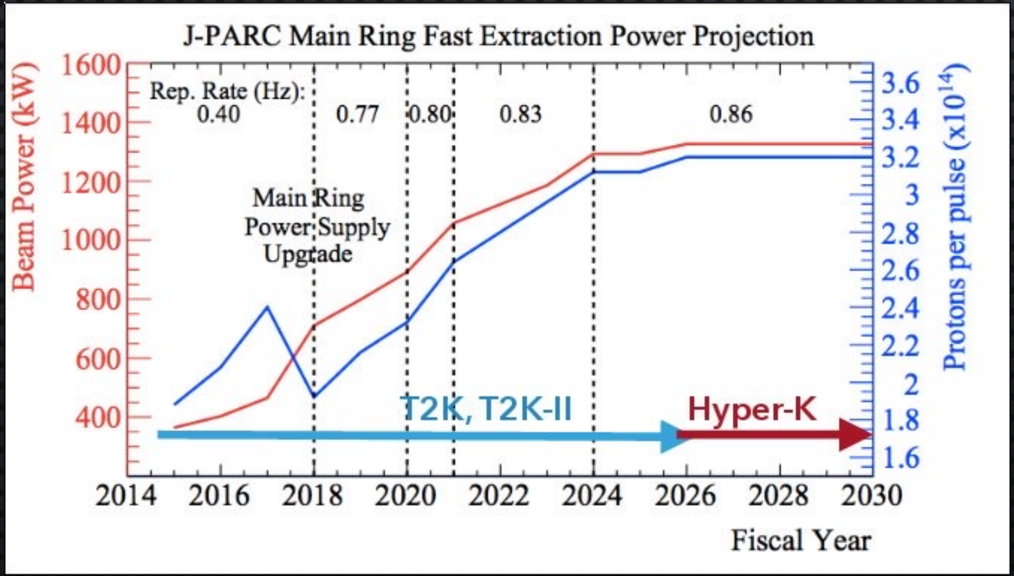
Detector:

260 kton Water Cherenkov (187 kton FV) (10xT2K)

2^{nd} tank 6 years after 1^{st} tank



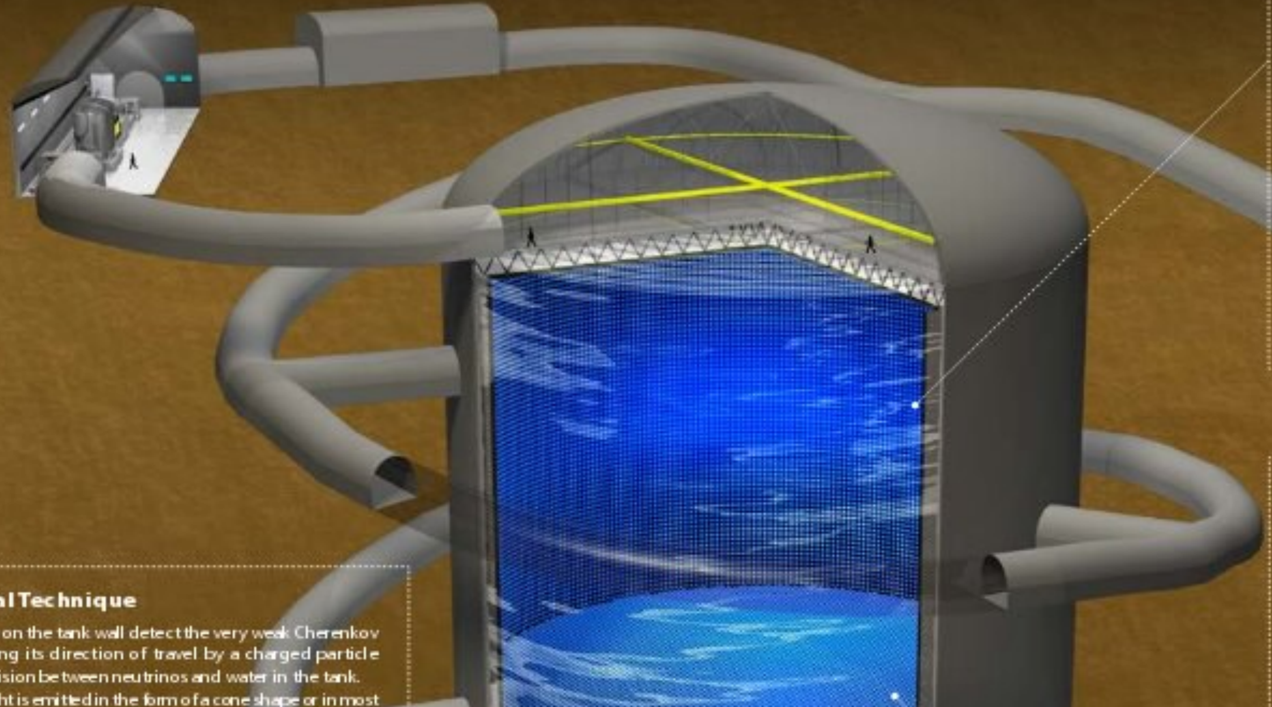
The Neutrino Beam



Hyper-Kamiokande

Peering into the Universe and its elementary particles from underground

The planned Hyper-Kamiokande detector will consist of an order of magnitude larger tank than the predecessor, Super-Kamiokande, and will be equipped with ultra high sensitivity photosensors. The Hyper-Kamiokande detector is both a "microscope," used to observe elementary particles, and a "telescope", used to study the Sun and supernovas through neutrinos. Hyper-Kamiokande aims to elucidate the Grand Unified Theory and explain the evolution of the Universe through the investigation of proton decay, CP violation (the difference between neutrinos and antineutrinos), and the observation of neutrinos from supernova explosions. The Hyper-Kamiokande experiment is an international research project aiming to become operational in the second half of the 2020s.

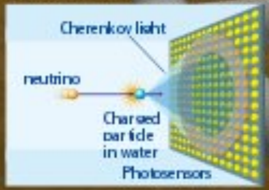


Ultrasensitive Photodetectors

We have been developing the world's largest photosensors, which exhibit a photodetection efficiency two times greater than that of the Super-Kamiokande photosensors. These new photosensors are able to perform light intensity and timing measurements with a much higher precision.
The new Large-Aperture High-Sensitivity Hybrid Photodetector (left), the new Large-Aperture High-Sensitivity Photomultiplier Tube (right). The bottom photographs show the electron multiplication component.

Experimental Technique

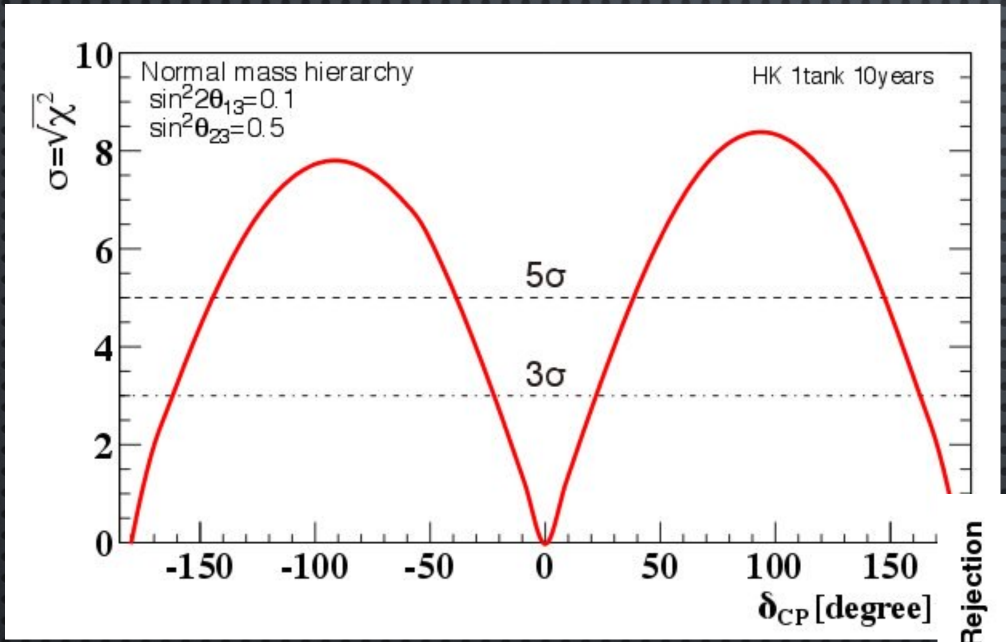
The photosensors on the tank wall detect the very weak Cherenkov light emitted along its direction of travel by a charged particle ejected in the collision between neutrinos and water in the tank. This Cherenkov light is emitted in the form of a cone shape or in most cases a ring as the charged particle is eventually absorbed. The energy, direction and type of neutrinos are determined using the information obtained from the photosensors, such as the quantity of light and the ring shape.

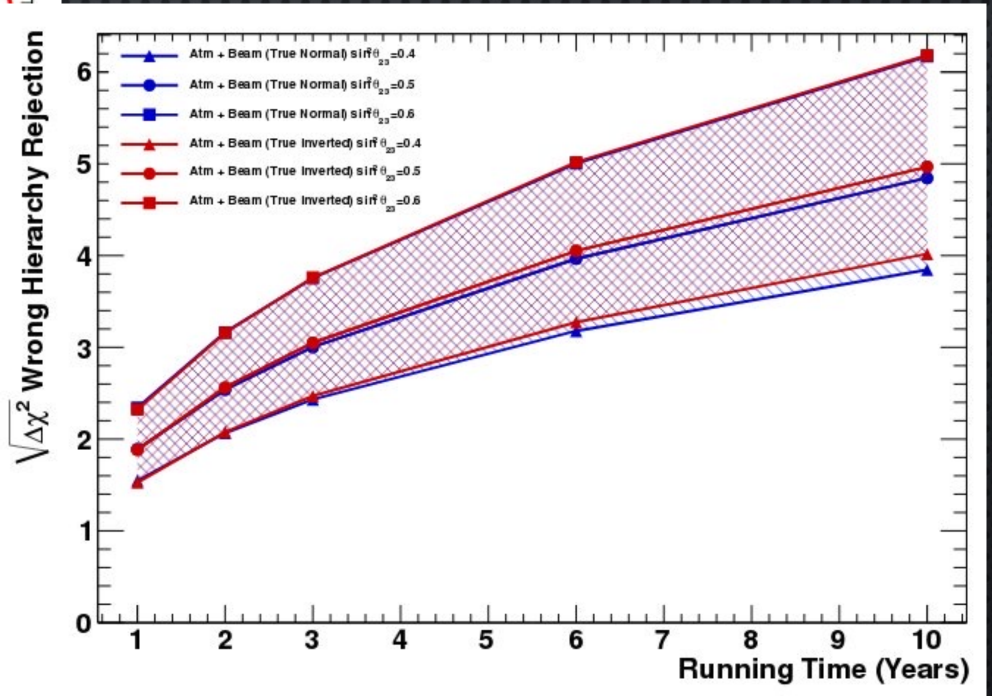


A megaton water tank

The huge Hyper-Kamiokande tank will be used in order to obtain in only 10 years an amount of data corresponding to 100 years of data collection time using Super-Kamiokande. This allows the observation of previously unrevealed rare phenomena and small values of CP violation.

HYPER-K EXPECTED SENSITIVITY





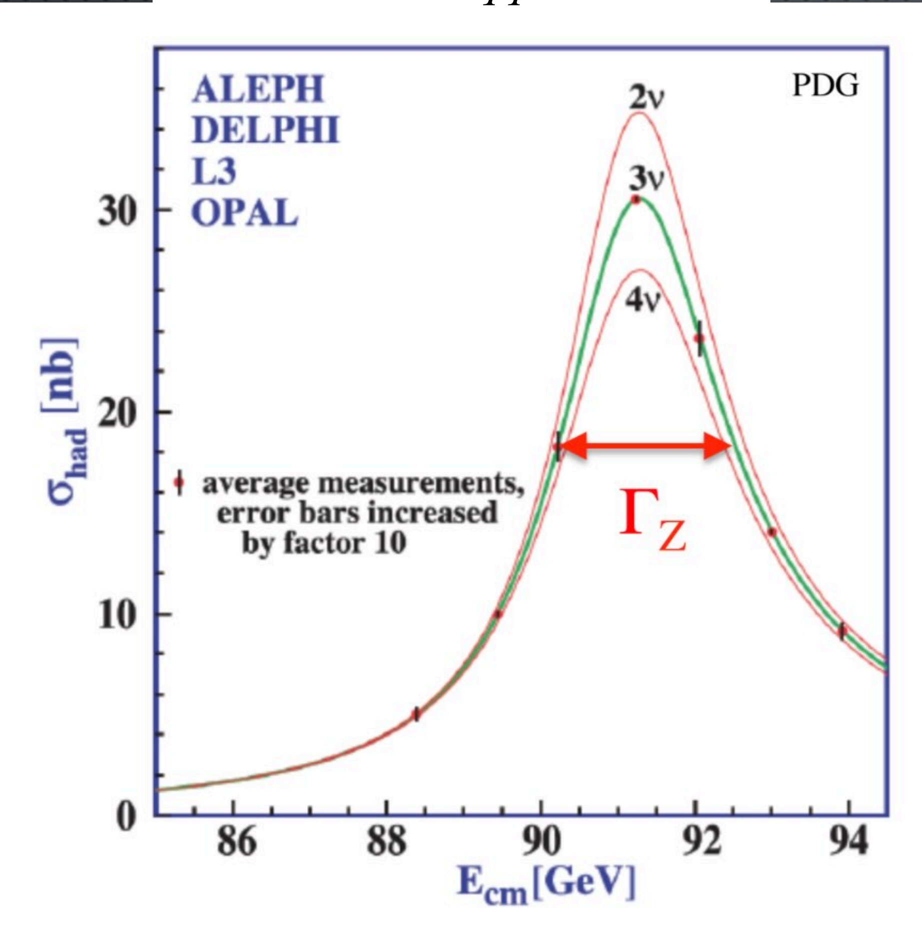
Schedule:

- Detector construction is underway
- Expected first data in 2027

STERILE NEUTRINOS

NUMBER OF NEUTRINO FLAVORS

$e^+ + e^- \rightarrow Z^0 \rightarrow q\bar{q} \rightarrow hadrons$



$$\Gamma_Z = n_\nu \Gamma_\nu + 3\Gamma_l + \Gamma_{had}$$

$$\boxed{n_\nu = 3.00 \pm 0.08}$$

If there is $Z^0 \rightarrow \nu_4 \bar{\nu}_4$:

- Z^0 lifetime ➔ shorter
- Z^0 width ➔ wider

However, if

- (1) $m_4 > m_Z/2 \sim 45$ GeV
- (2) ν_4 doesn't couple to Z^0

ν_4 can exist!

Indications of Sterile Neutrino (Anomalies)

- Reactor Neutrino Flux $\bar{\nu}_e \rightarrow \nu_x$
- Gallium Anomaly $\nu_e \rightarrow \nu_x$

Disappearance

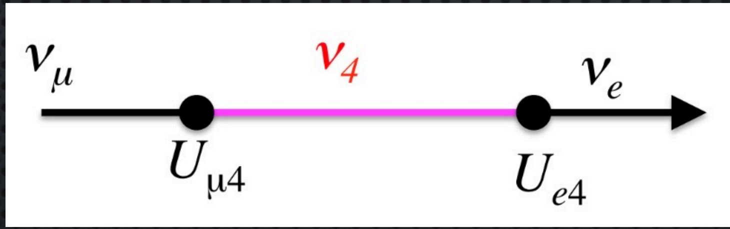
- LSND – MiniBoone $\nu_\mu \rightarrow \nu_e$

Appearance

EXTENSION OF ν MIXING MATRIX: 3 ν_a + 1 ν_s

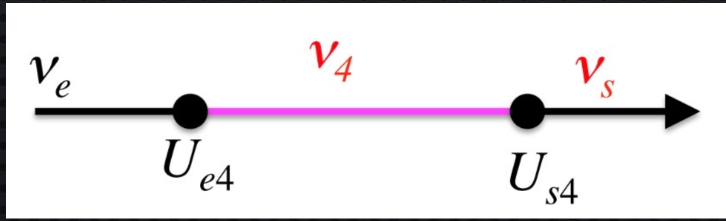
$$
\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}
$$

For m_4 >> $m_{1,3}$



Appearance

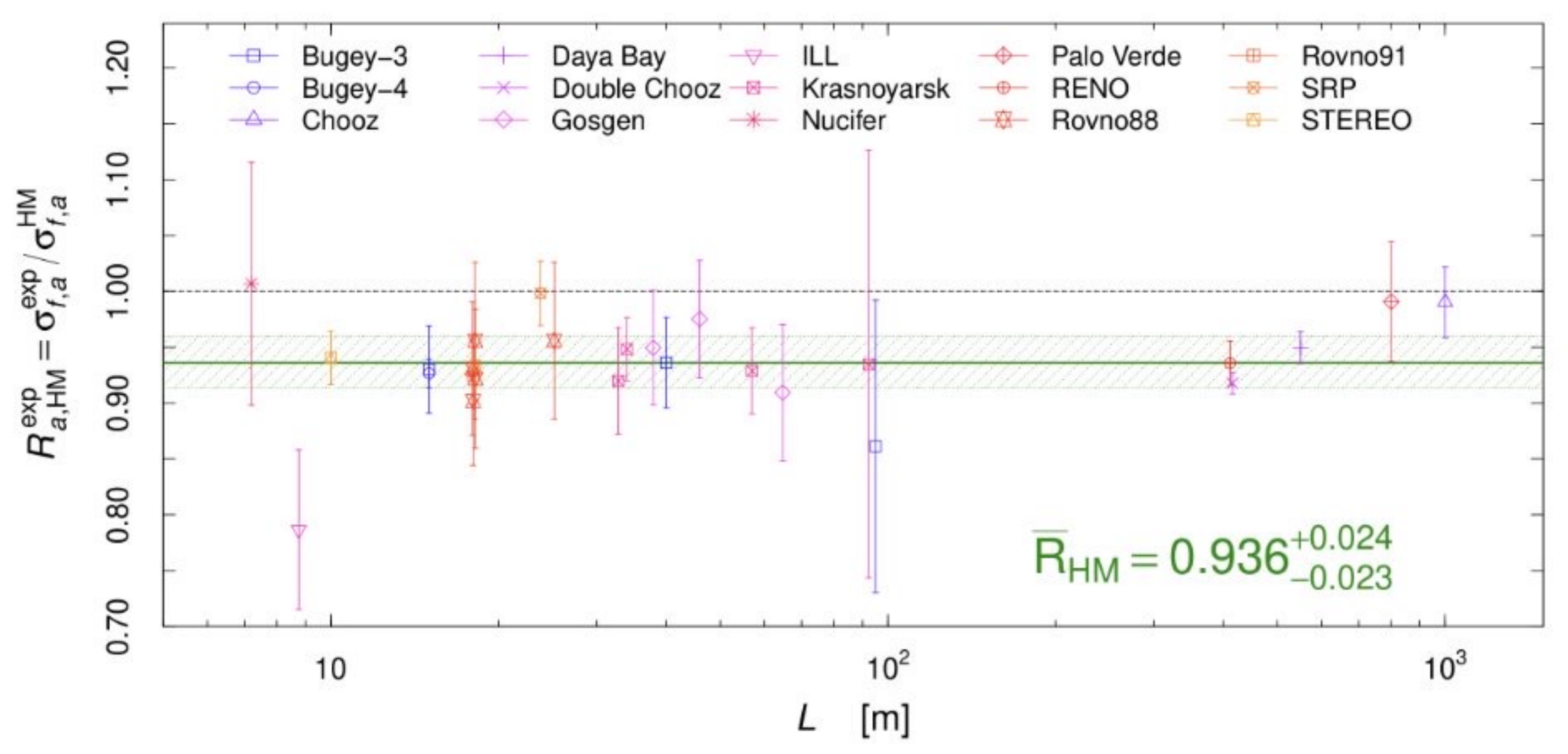
$$P(\nu_\mu \to \nu_e) \sim \left|U_{\mu 4} U_{e4}\right|^2 \sin^2\left(\frac{m_4^2}{4E} L\right)$$



Disappearance

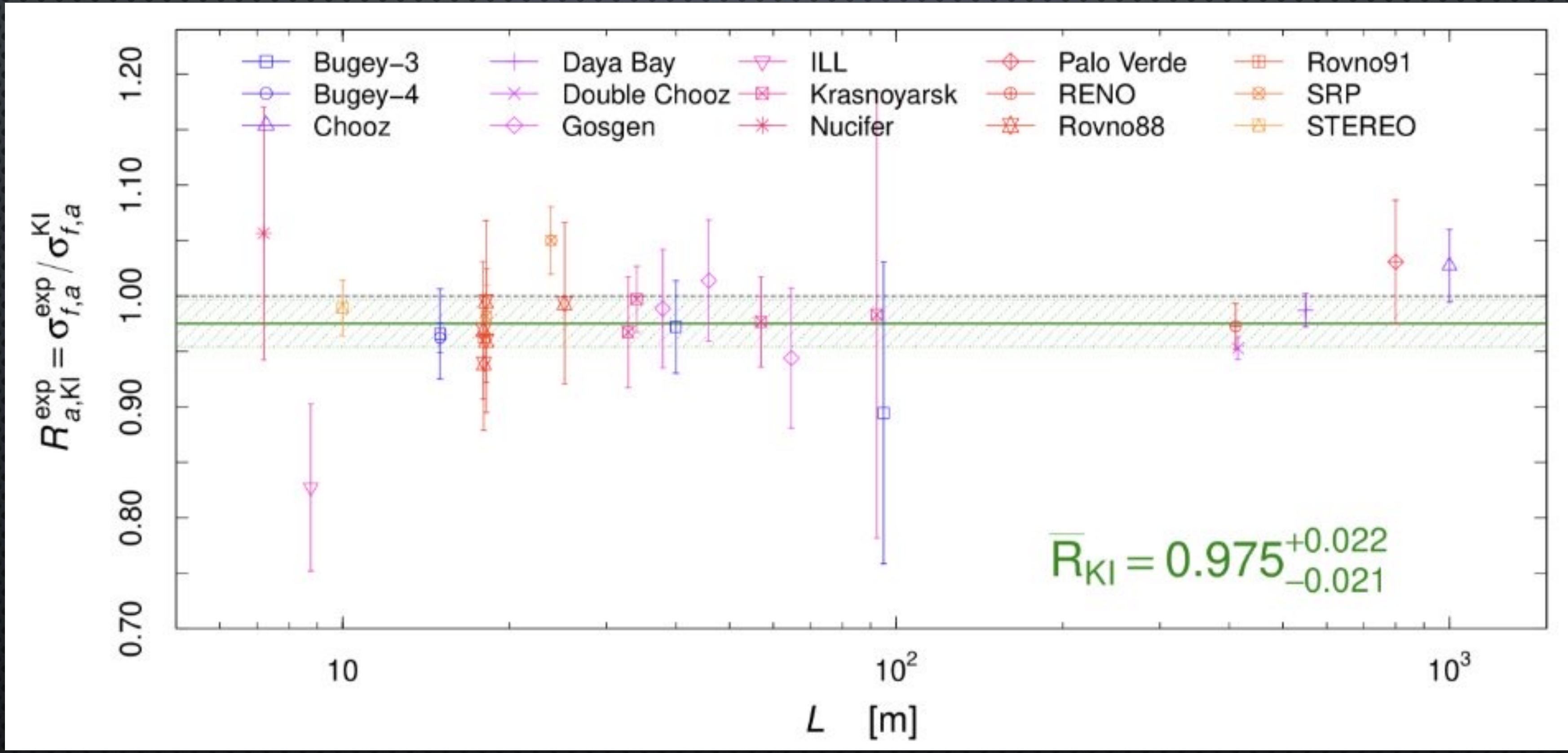
$$P(\nu_e \to \nu_e) \sim 1 - \left|U_{s4} U_{e4}\right|^2 \sin^2\left(\frac{m_4^2}{4E} L\right)$$

REACTOR NEUTRINO FLUX ANOMALY



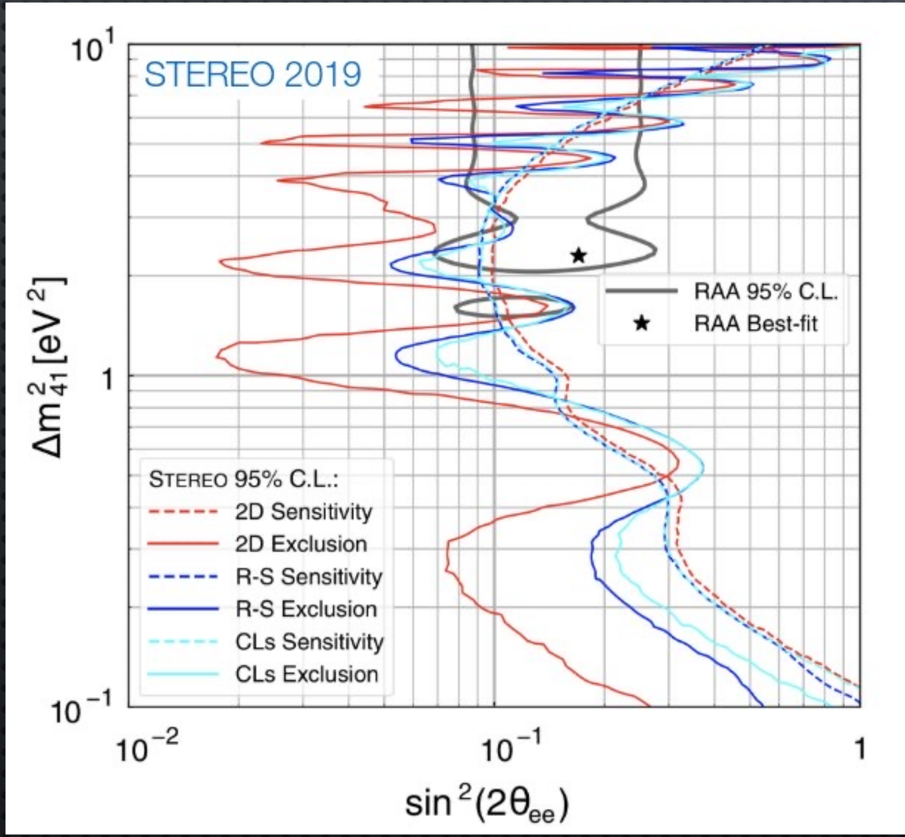
T. A. Muller et al. Phys. Rev. C 83 (2011)
P. Hubert Phys. Rev. C 84 (2011)

REACTOR NEUTRINO FLUX ANOMALY



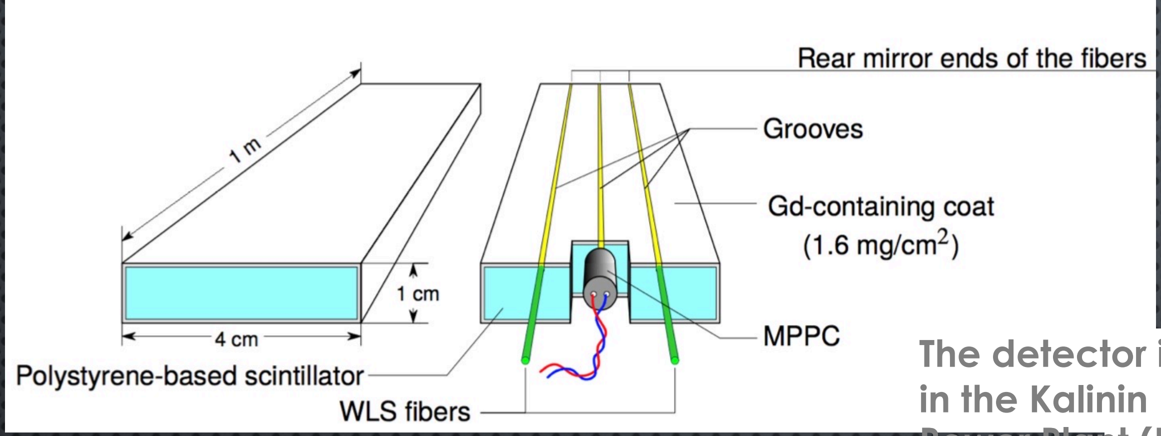
V. Kopeikin et al. Phys. Rev. D 104 (2021)

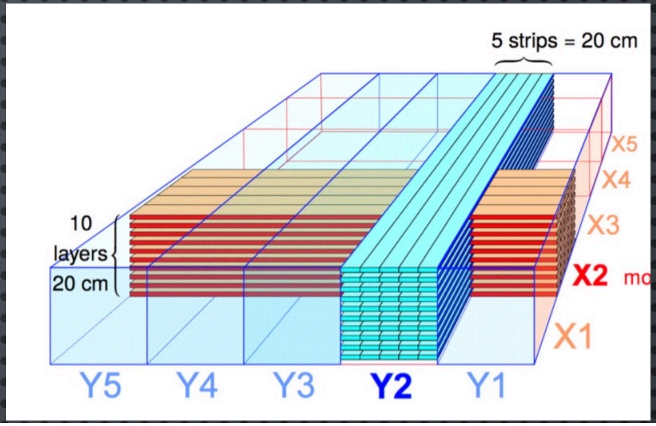
REACTOR NEUTRINO FLUX ANOMALY



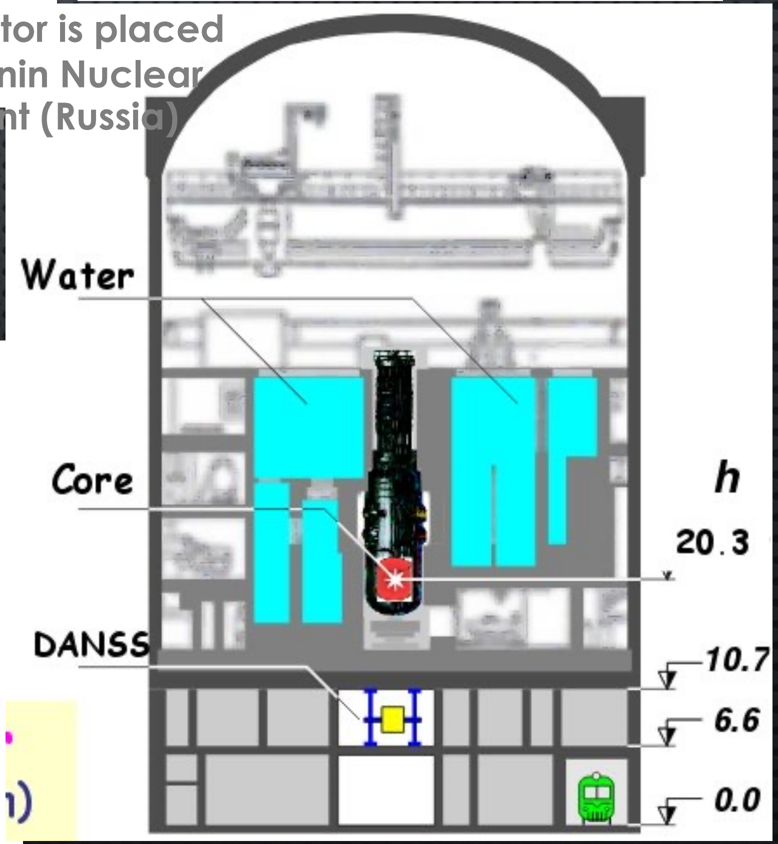
Strong constraints from very-short baseline experiments that compare flux rates at different distances

DANSS



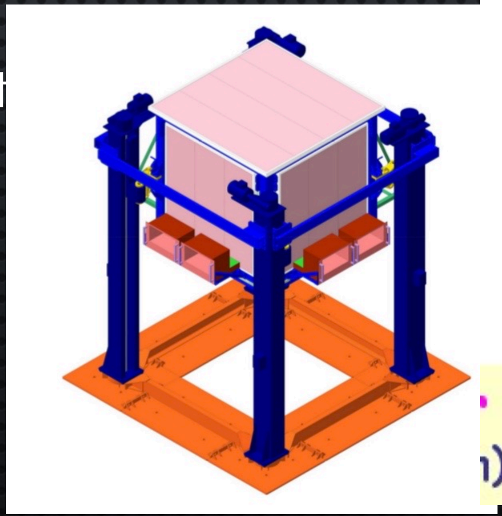


The detector is placed in the Kalinin Nuclear Power Plant (Russia)



The neutrino flux is measured at two distances from the reactor core: 10.7 m and 12.7

Very short baseline oscillat



THE GALLIUM ANOMALY

Deployment of radioactive sources for detector calibration with mono-energetic ν_e

$$e^- + {}^{51}Cr \rightarrow {}^{51}V + \nu_e \qquad E_\nu = 0.82\ \mathrm{MeV}$$

$$e^- + {}^{37}Ar \rightarrow {}^{37}Cl + \nu_e \qquad E_\nu = 0.90\ \mathrm{MeV}$$

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

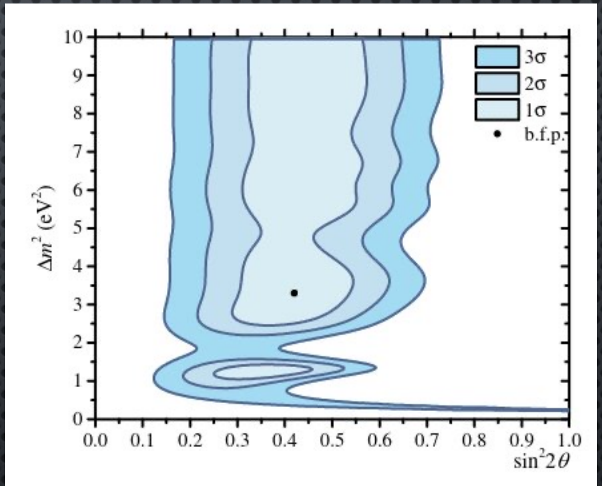
$$^{71}Ga + \nu_e \rightarrow {}^{71}Ge + e^-$$

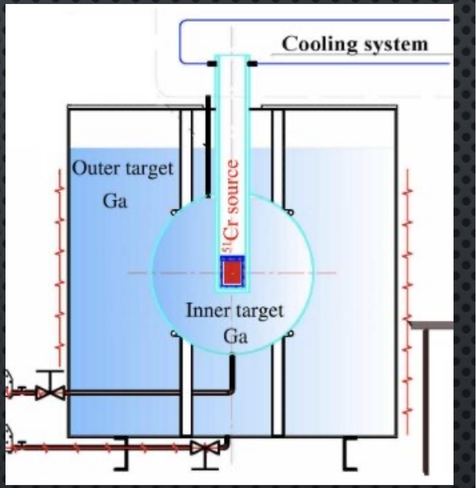
^{71}Ge production rates

Experiment	Source	Meas./Expected
Gallex	Cr1 Cr2	0.94±0.11 0.80±0.10
Sage	Cr Ar	0.93±0.12 0.77±0.08
Average		**0.84±0.05**

Recently confirmed by BEST Experiment **arXiv:2109.11482**

Meas./Exp. = 0.78 ± 0.05

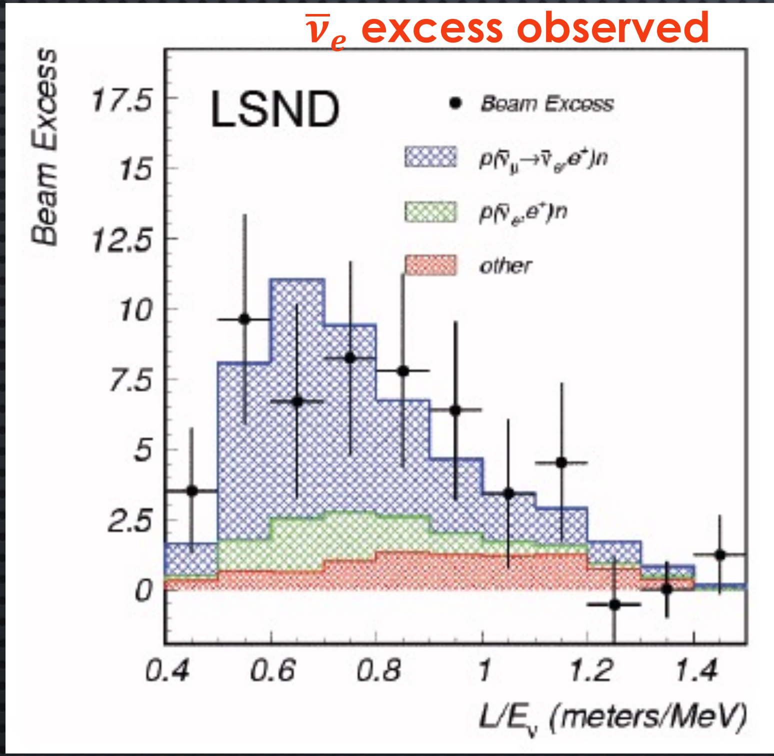




The robustness of these experiments proven by:

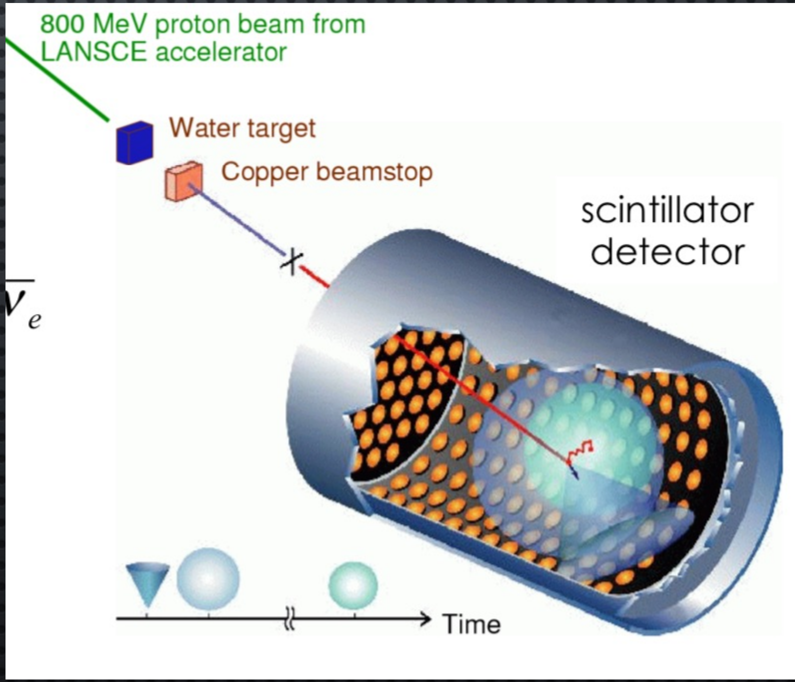
- Their sophisticated calibration
- Solar neutrino measurements in agreement with other experiments

LSND EXPERIMENT Los Alamos NL 1993-1998



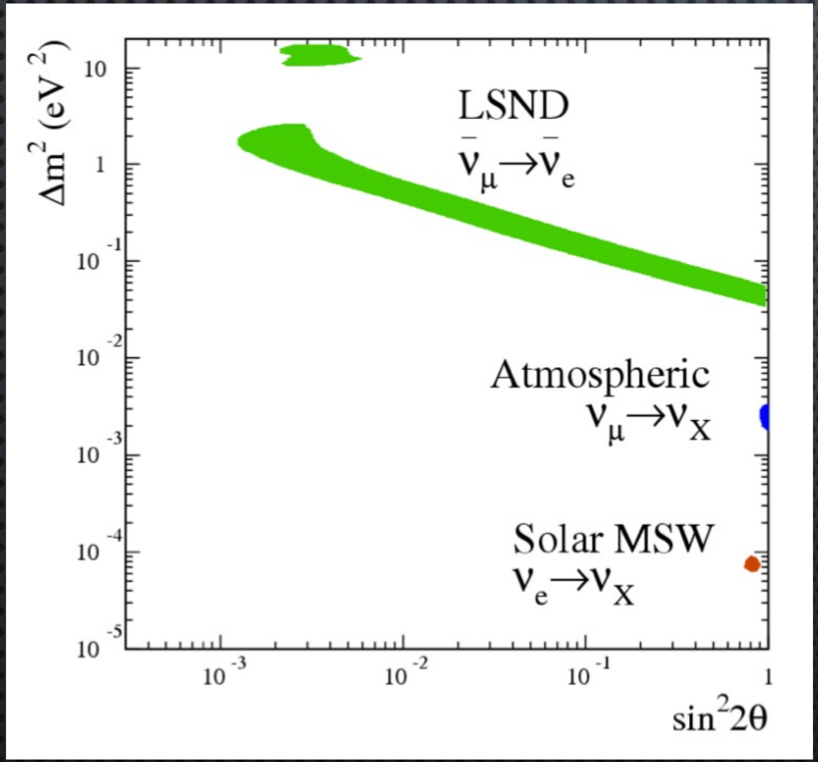
$$\pi^+ \to \mu^+ \nu_\mu$$
$$\hookrightarrow e^+ \nu_e \bar{\nu}_\mu$$

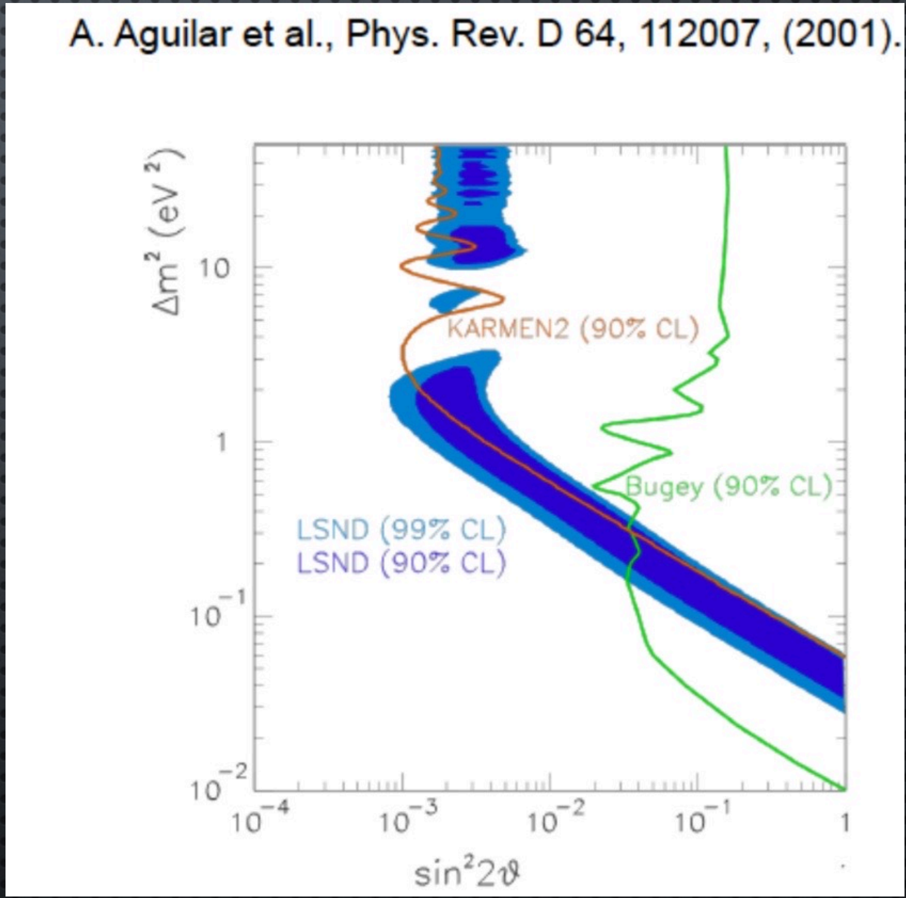
Decay at rest



Background were huge and analysis was complicate.
➔ Confirmation is necessary

LSND EXPERIMENT



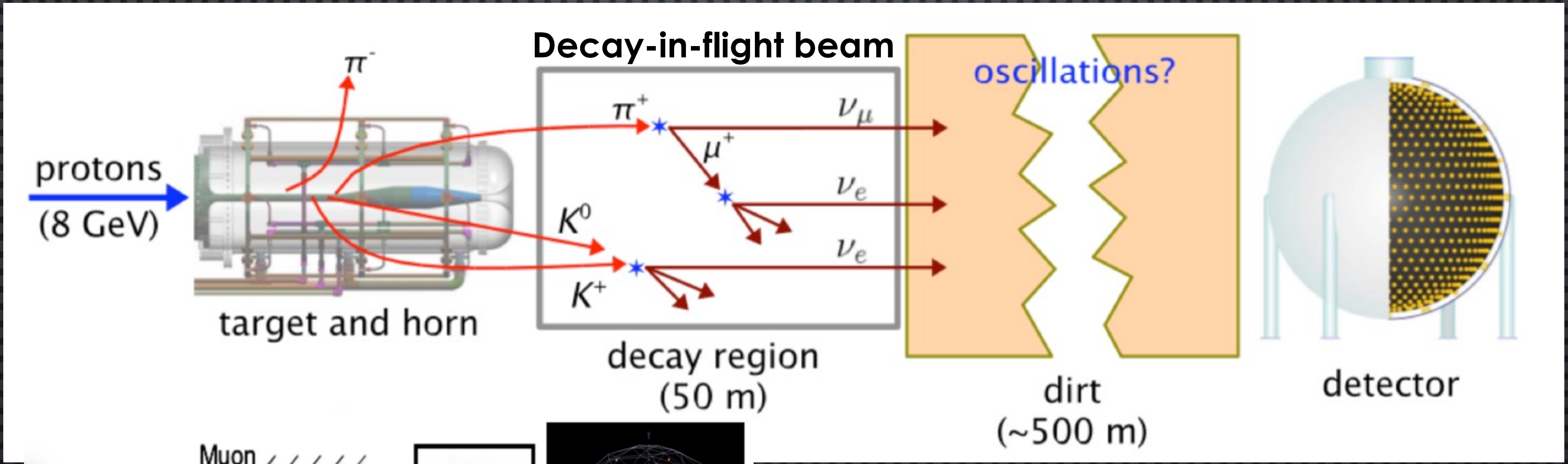


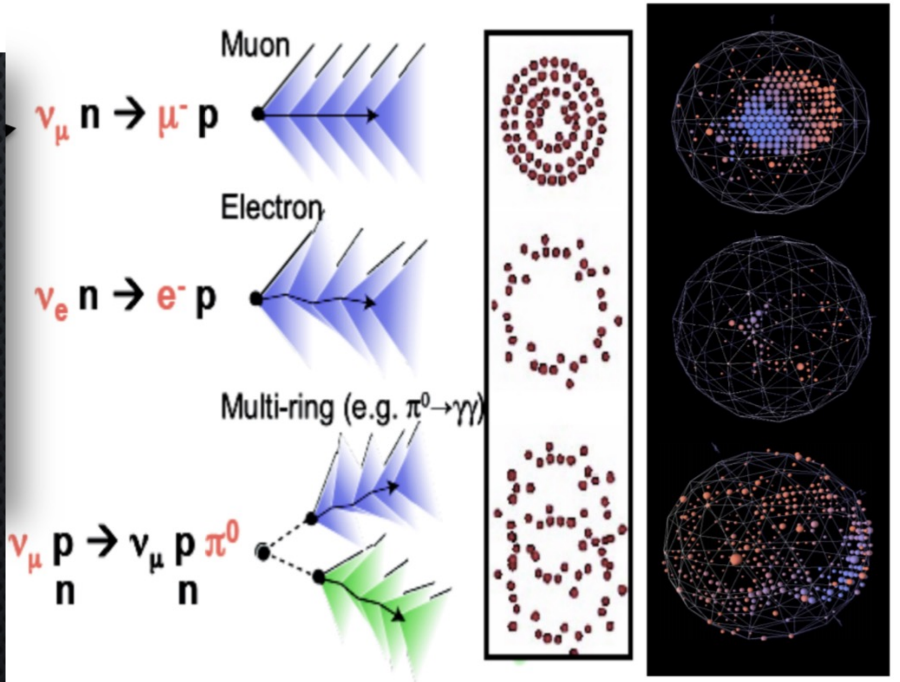
$\Delta m^2 > 0.03 eV^2$

➔ Different from known ν oscillations

➔ Sterile Neutrino is needed

MINIBOONE EXPERIMENT





Similar E/L as LSND but:

- Different energy, beam and detector systematics

- **Cherenkov detector**: Different event signatures and backgrounds

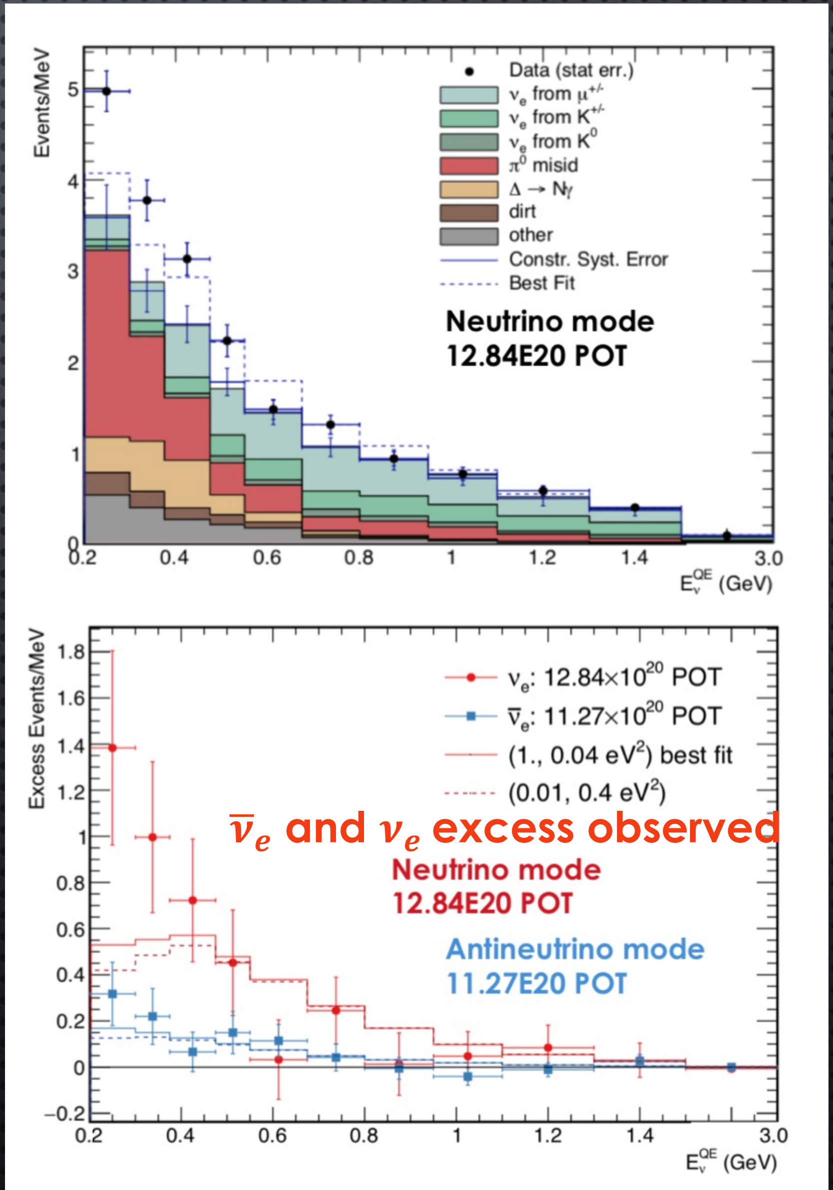
MINIBOONE EXPERIMENT Fermilab 2002-2018

MiniBooNE
2018 ν_e appearance results:

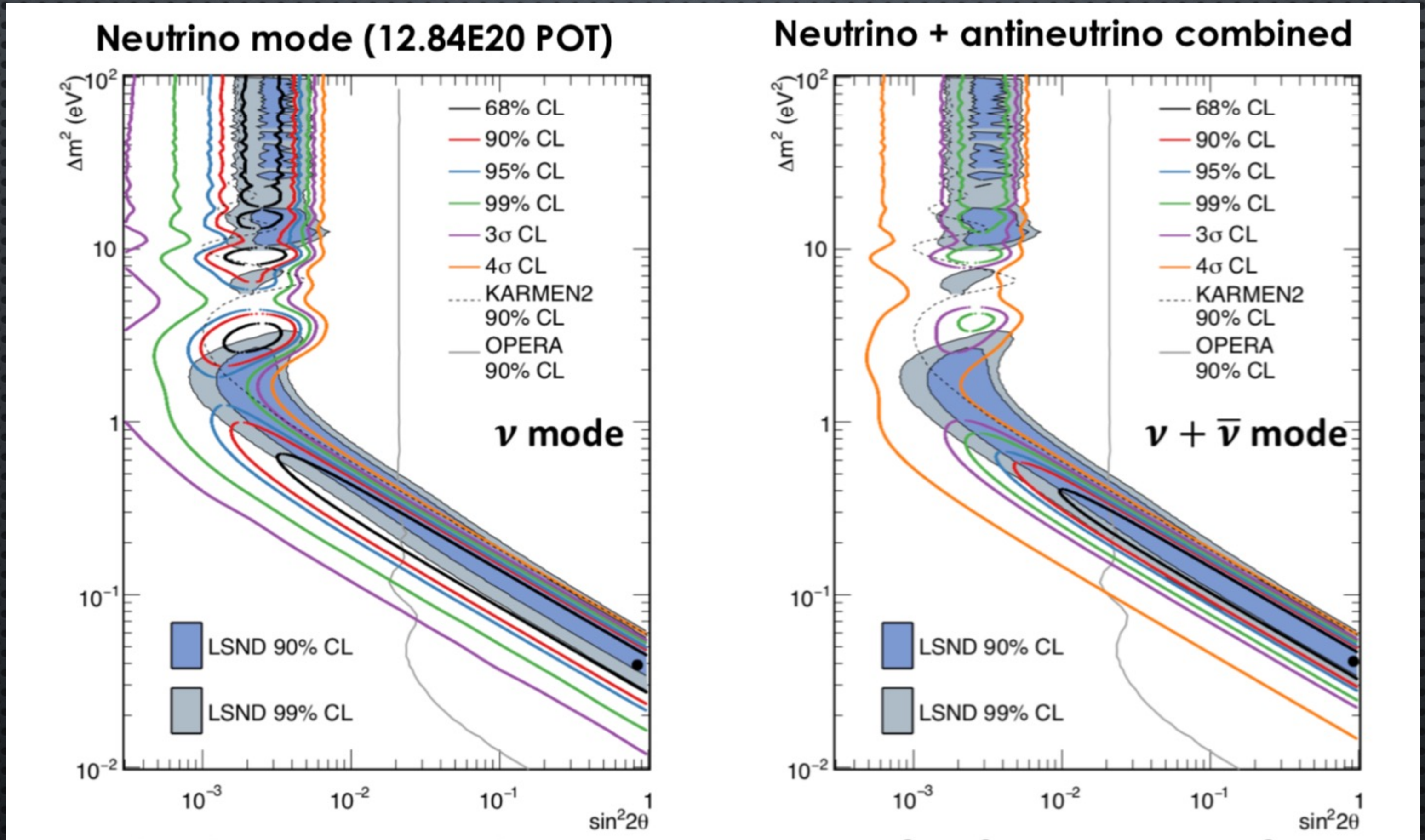
Total neutrino mode excess (12.84E20 POT):
381.2 +/- 85.2 excess events (**4.5σ**)
Best-fit χ^2-prob = 15%

Combined with antineutrino mode:
460.5 +/- 95.8 excess events (**4.8σ**)
Best-fit χ^2-prob = 20%

The electron signal might be N.C. γ signal mis-ID
➔Confirmation is necessary



MINIBOONE RESULTS VS LSND

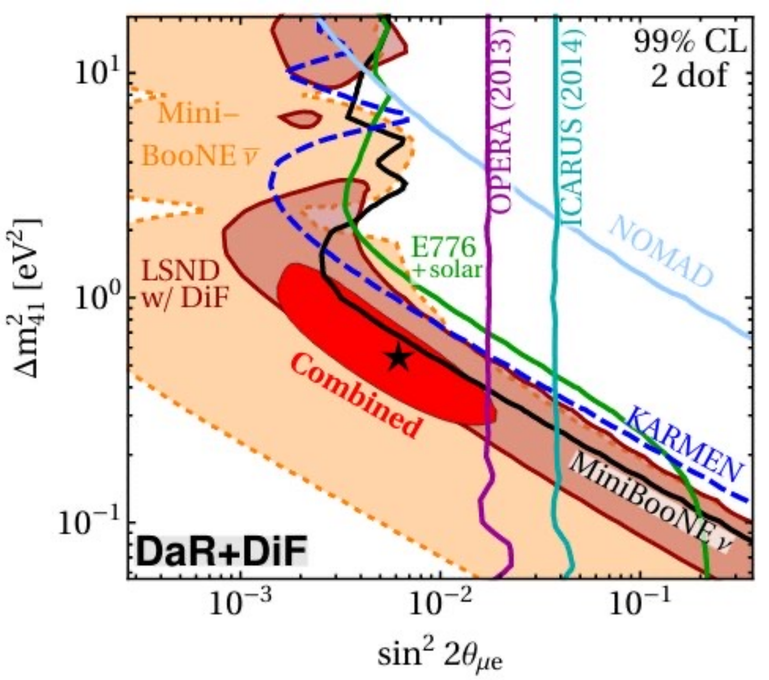


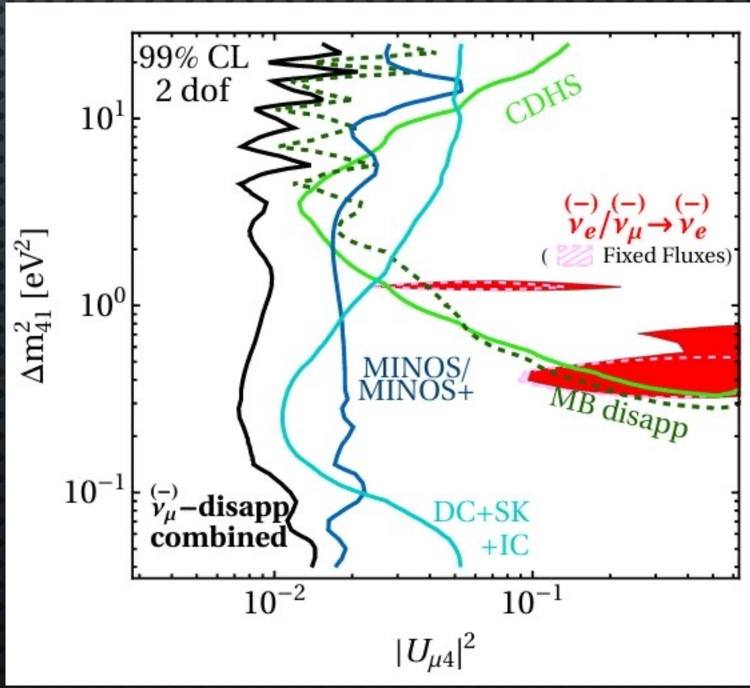
$(\Delta m^2, \sin^2 2\theta) = (0.037\ \mathrm{eV}^2, 0.958)$
$\chi^2/ndf = 10.0/6.6$ (prob = 15.4%)

$(\Delta m^2, \sin^2 2\theta) = (0.041\ \mathrm{eV}^2, 0.958)$
$\chi^2/ndf = 19.5/15.4$ (prob = 20.1%)

Neutrino and anti-neutrino results are consistent with LSND allowed regions and high-Δm^2 oscillation interpretation

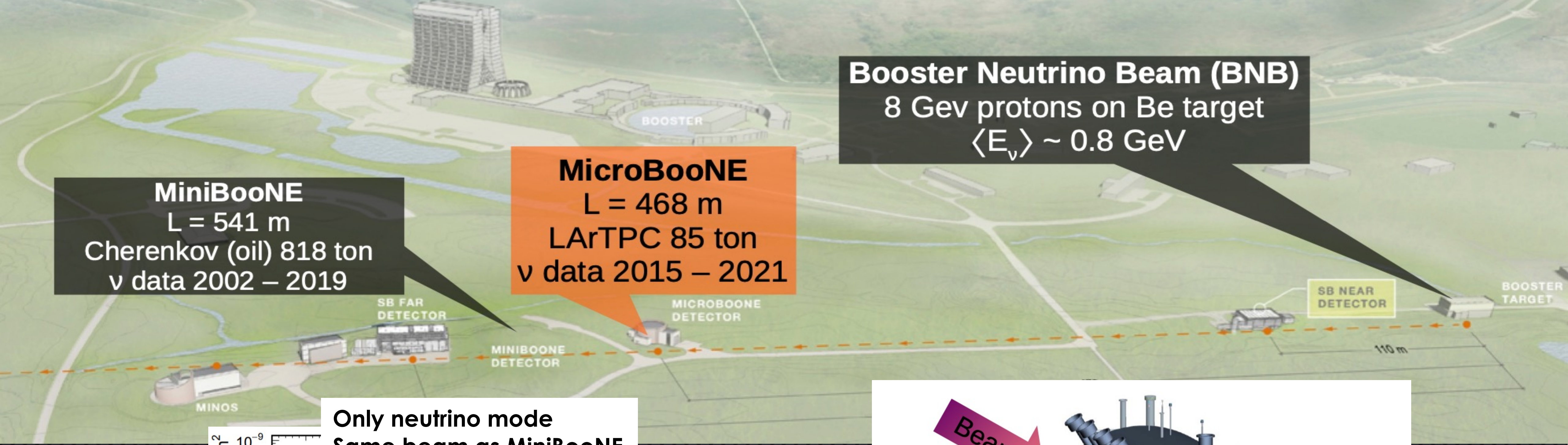
GLOBAL FIT RESULTS





arXiv:1803.10661 (2018)

The MicroBooNE experiment at Fermilab

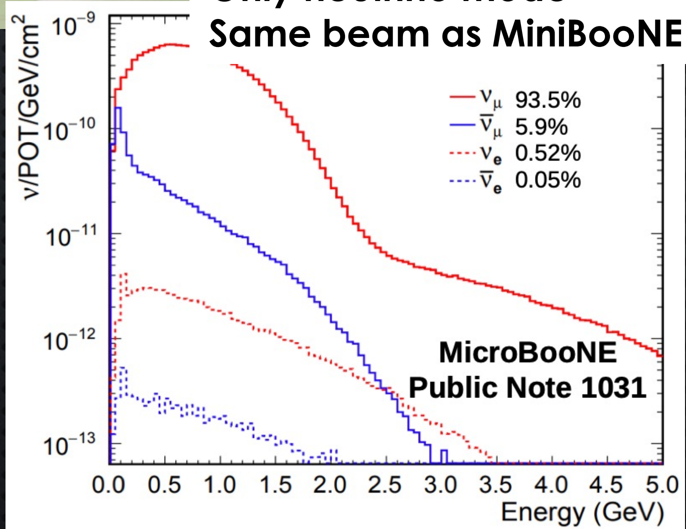


Booster Neutrino Beam (BNB)
8 Gev protons on Be target
$\langle E_\nu \rangle \sim 0.8$ GeV

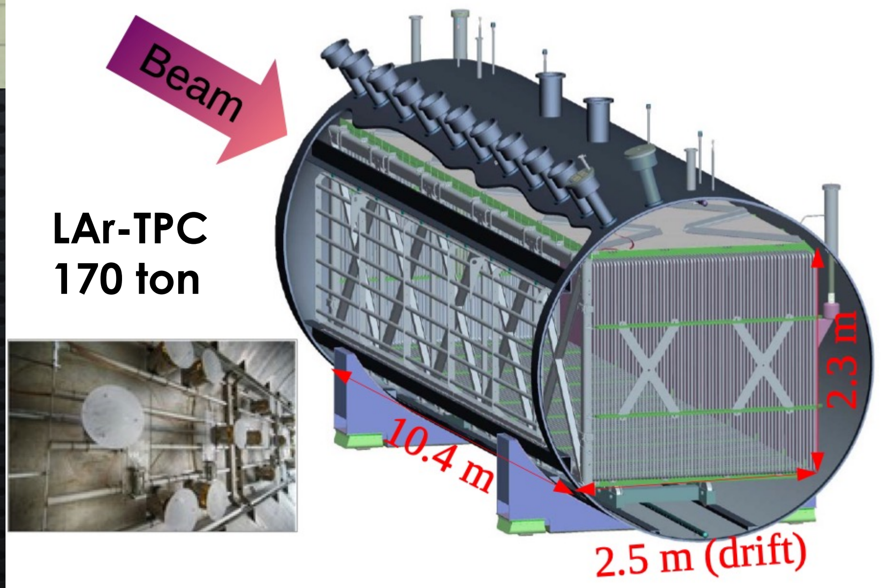
MiniBooNE
L = 541 m
Cherenkov (oil) 818 ton
ν data 2002 – 2019

MicroBooNE
L = 468 m
LArTPC 85 ton
ν data 2015 – 2021

Only neutrino mode
Same beam as MiniBooNE



LAr-TPC
170 ton



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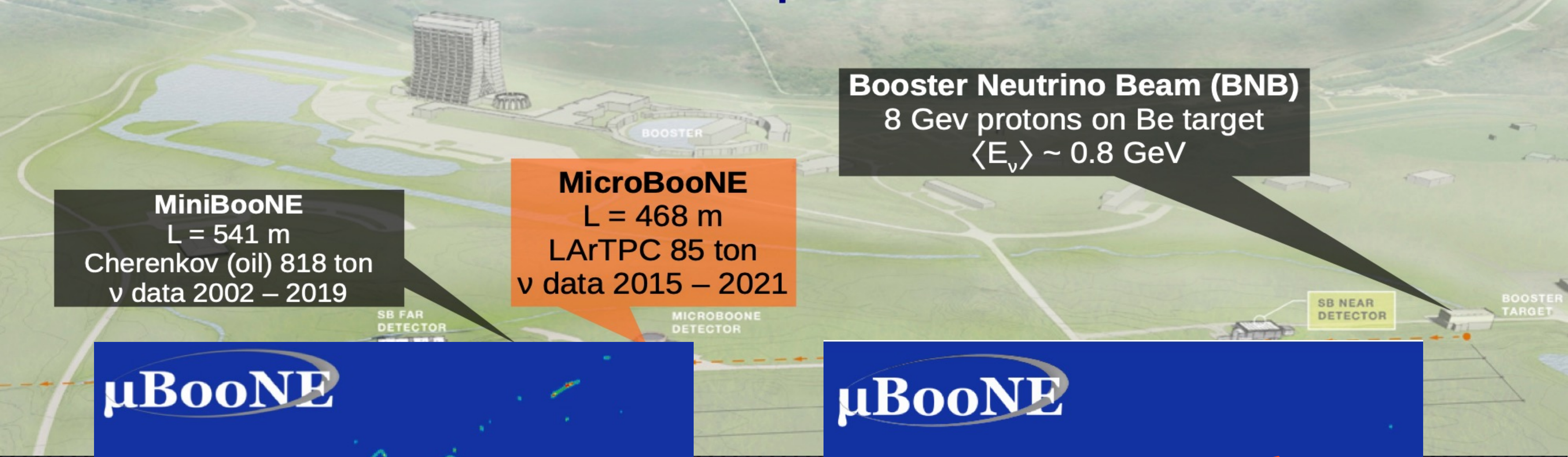
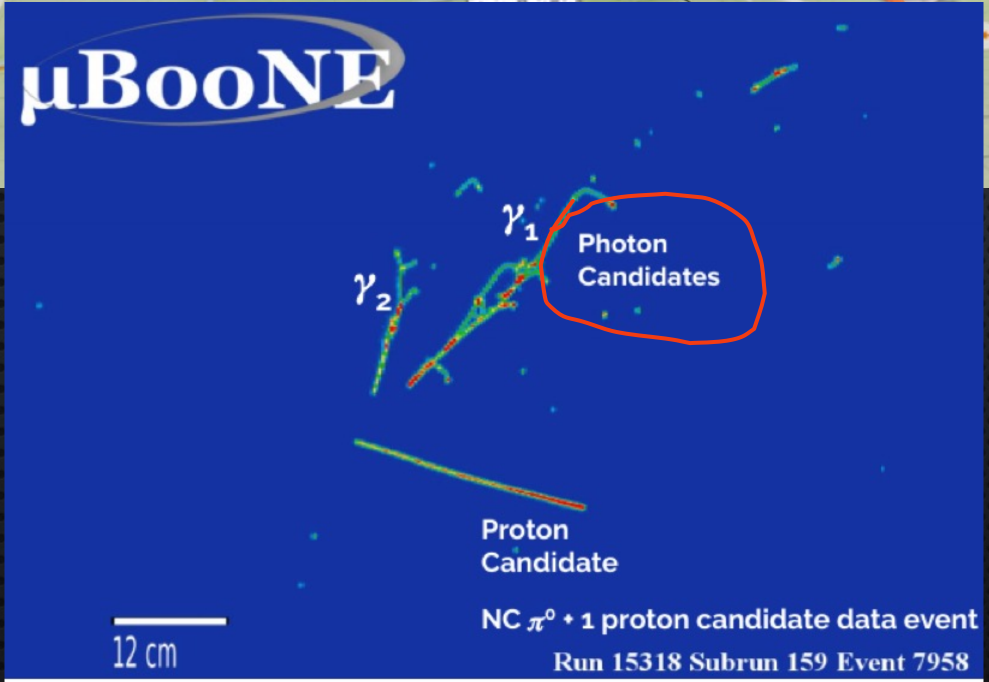
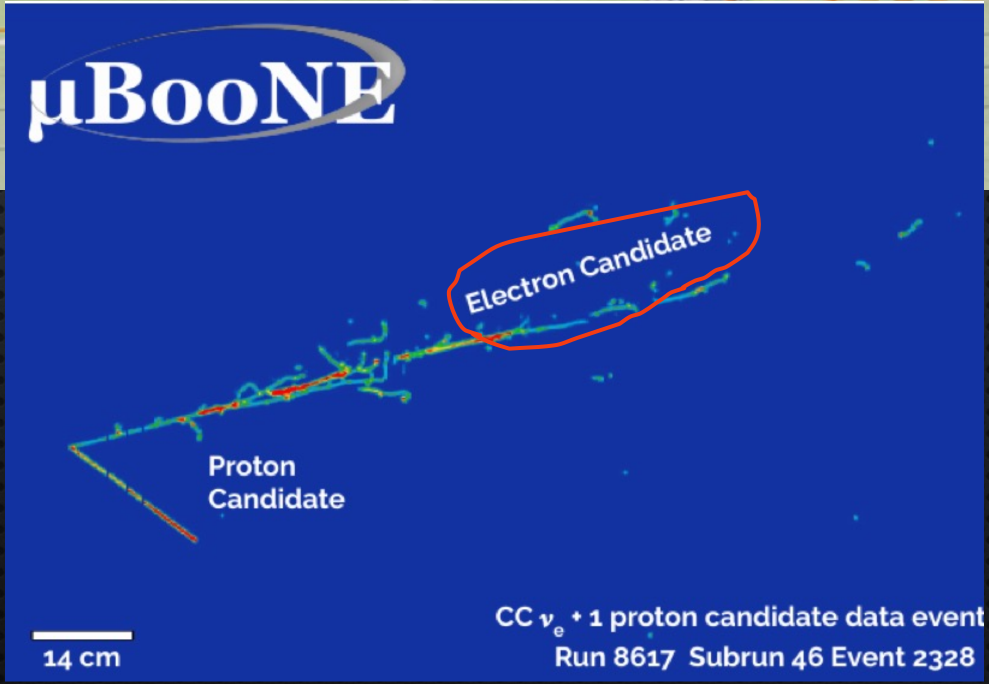
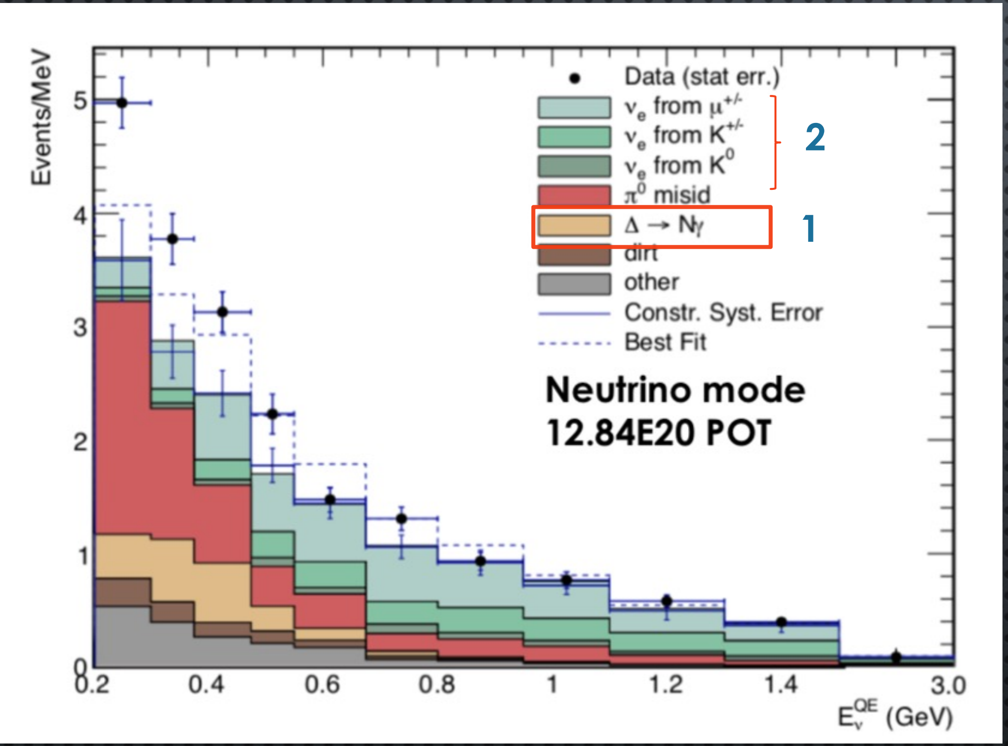






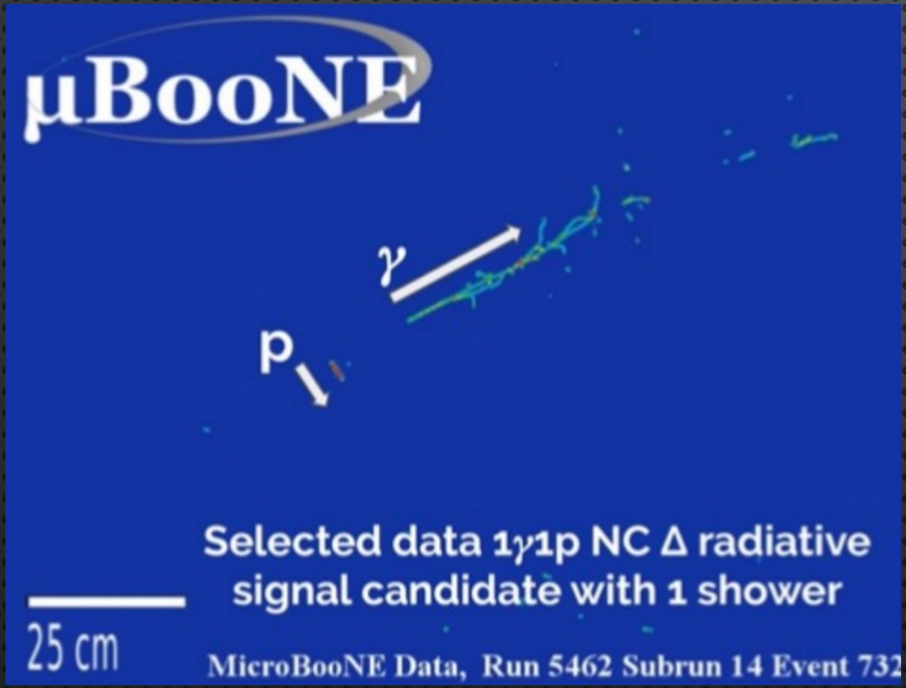
MICROBOONE



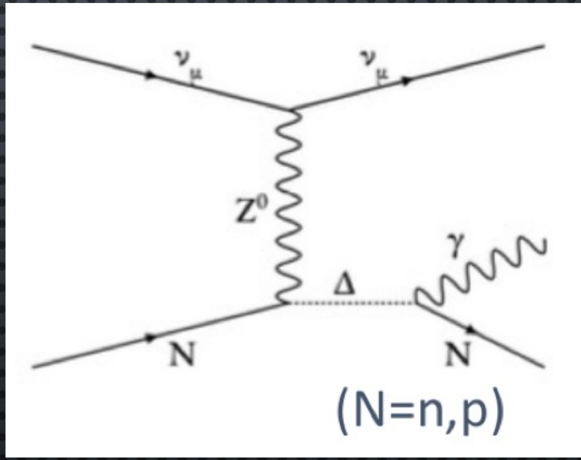
MiniBooNE cannot distinguish between e and γ.
We do not know the nature of the excess.

1. **Excess is an enhanced production of single photons from NC Δ radiative decay**
2. **Excess is due to electron neutrinos**

MICROBOONE



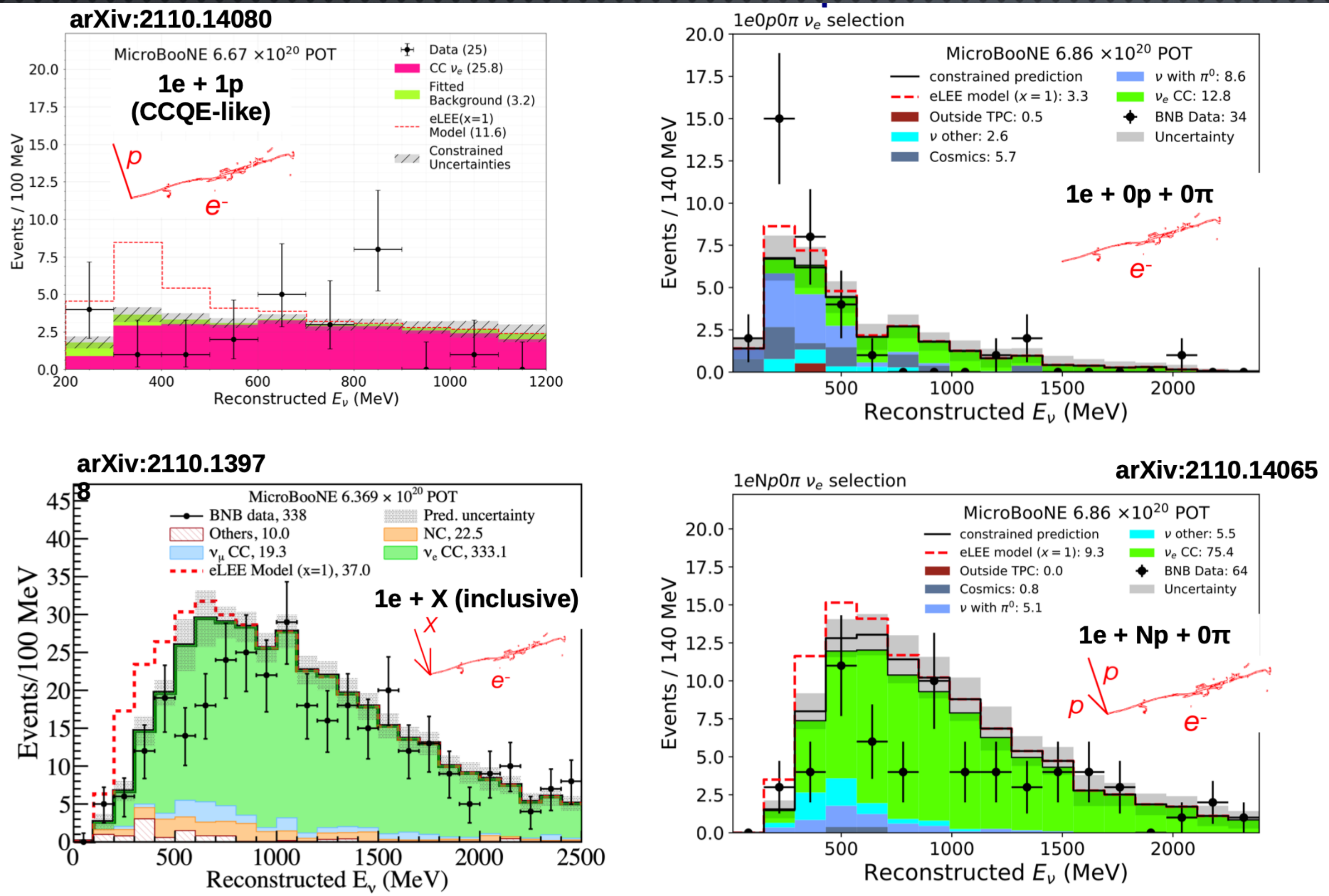
1. Excess is an enhanced production of single photons from NC Δ radiative decay



Result shows no excess with respect to SM.
NC $\Delta \to N\gamma$ explanation of the excess is disfavored at 94.8% CL.

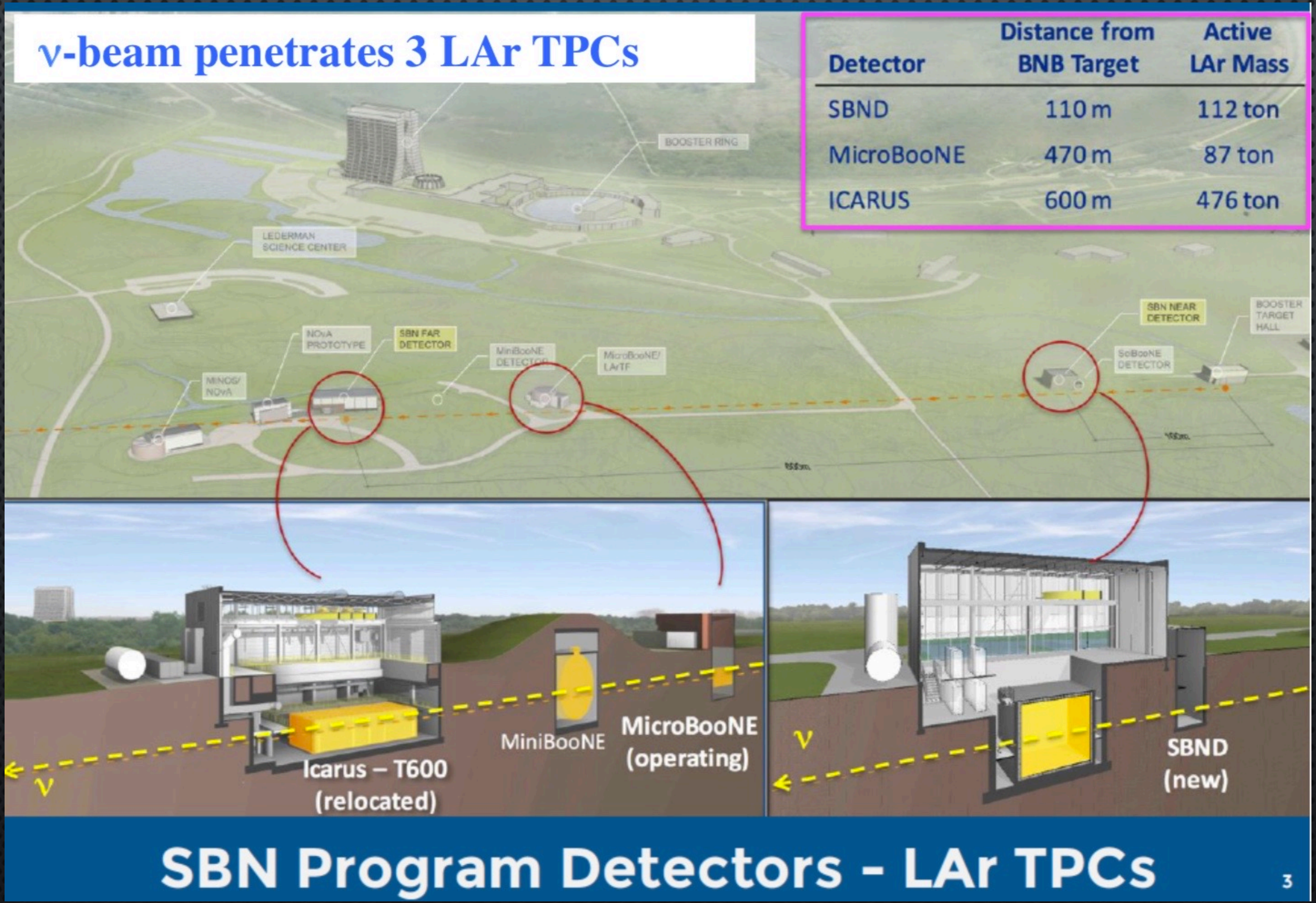
MICROBOONE

2. Excess is due to electron neutrinos



MicroBooNE rejects the hypothesis that ve CC interactions are fully responsible for the excess at > 97% CL

SHORT BASELINE NEUTRINO PROJECT AT FERMILAB



Detector	Distance from BNB Target	Active LAr Mass
SBND	110 m	112 ton
MicroBooNE	470 m	87 ton
ICARUS	600 m	476 ton

STERILE NEUTRINOS: SUMMARY

- TWO OF THE THREE ANOMALIES AFFECTING THE OSCILLATION DATA ARE STILL UNRESOLVED
- BUT NO FULLY CONSISTENT PICTURE HAS EMERGED SO-FAR.

NEUTRINO MASS

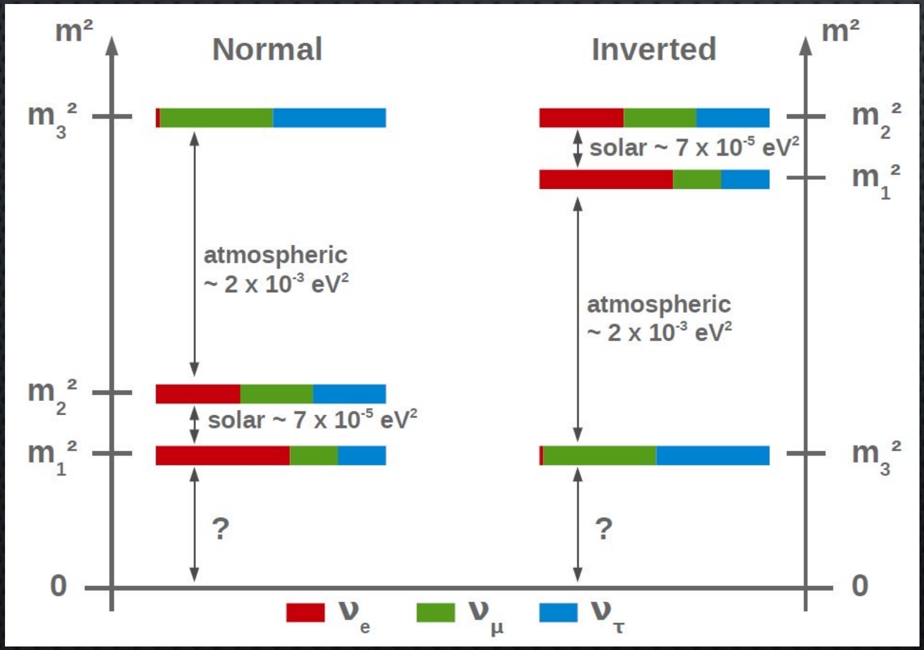
Neutrino mass

- Neutrino masses can be an evidence for <u>physics beyond the SM</u>
- We know that **$m_\nu \sim m_E/10^6 \lesssim 1$ eV**. The explanation of neutrino masses via Dirac mass terms alone requires neutrino **Yukawa coupling $\lesssim 10^{-12}$**
- The value of m_ν is very important for astrophysics and cosmology. Neutrinos may contribute significantly to the mass density of the universe.
- The neutrino mass can be determined directly by the measurement of the observable effect of m_ν over some phenomena as nuclei decay (Model independent).
- There are indirect ways to infer the neutrino mass through processes whose rate depends on the ν-mass (the neutrino-less double beta decay).
- The cosmological measurements provide also information about the neutrino mass.

NEUTRINO MASS FROM OSCILLATION

Neutrino oscillation experiments prove that neutrinos have masses but cannot determine their absolute value

NO: $\Sigma m_\nu > 0.06$ eV
IO: $\Sigma m_\nu > 0.1$ eV



Normal Ordering

$$m_2 = \sqrt{m_1^2 + \Delta m_{21}^2}$$

$$m_3 = \sqrt{m_1^2 + \Delta m_{21}^2 + \Delta m_{32}^2}$$

If $m_1^2 < \Delta m_{32}^2$ → Different masses

If $m_1^2 > \Delta m_{32}^2$ → quasi-degenerate masses

Inverted Ordering

$$m_1 = \sqrt{m_3^2 - \Delta m_{31}^2}$$

$$m_2 = \sqrt{m_3^2 - \Delta m_{31}^2 + \Delta m_{21}^2}$$

$$\forall m_3 \to m_1 \sim m_2$$

If $m_3^2 > \Delta m_{31}^2$ → quasi-degenerate masses

COSMOLOGICAL CONSTRAINTS ON NEUTRINO MASS

The large number of neutrinos and their non-zero mass have effect on cosmological observables

Planck 2018 results VI Cosmological parameters
***Astron. Astrophys.* 641, A6 (2020)**

Data sets	Σm_ν (eV) 95% CL
CMB alone: Planck '18 TT + lowE	< 0.54
Planck '18 TT + lowE + lensing	< 0.44
CMB + BAO: Planck '18 TT + lowE + BAO	< 0.16
Planck '18 TT + lowE + lensing + BAO	**< 0.12**
CMB + BAO + SN: Planck '18 TT + lowE + lensing + BAO + DES	< 0.14

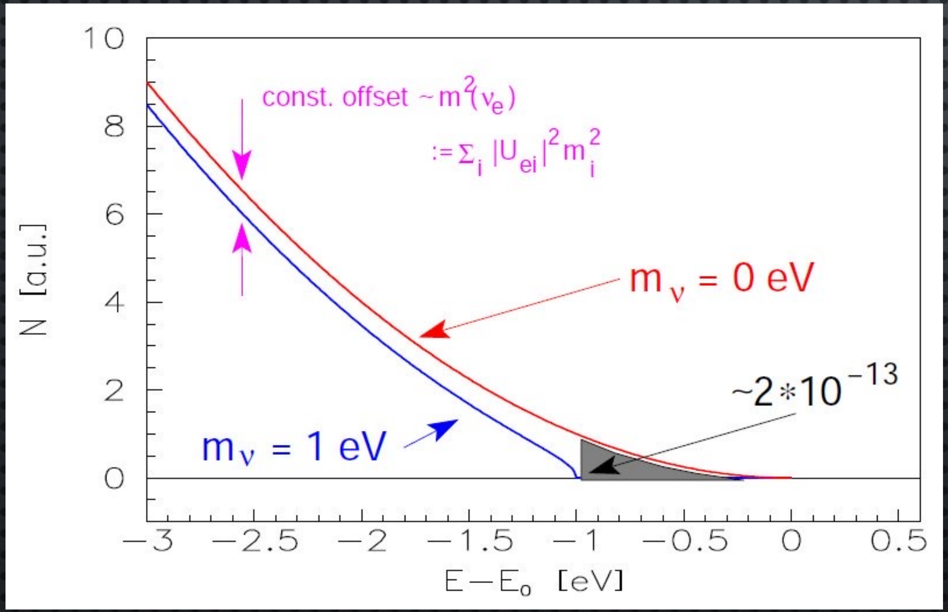
1. **Planck results are close to rule out the IO hypothesis** (rely on cosmological assumptions)
2. **An independent measurement of could help cosmological models**

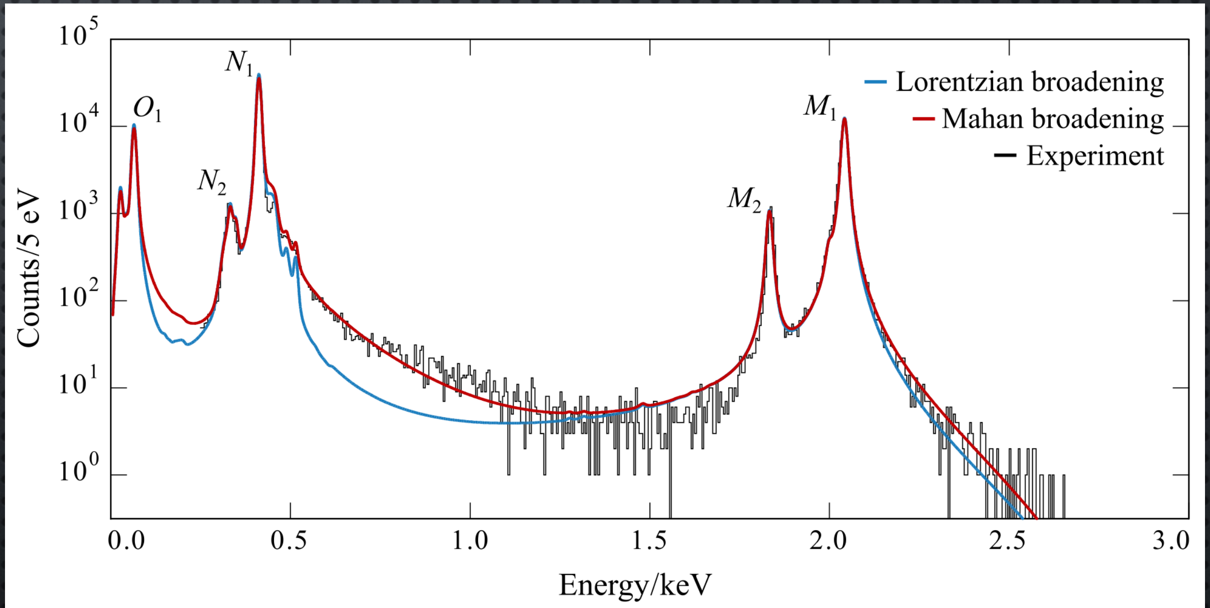
NEUTRINO MASS DIRECT MEASUREMENT

DIRECT MEASUREMENT OF NEUTRINO MASS

The most direct way is based on the kinematics of β-decay or electron capture processes

This method is independent of any cosmological model and of the mass nature of the neutrino

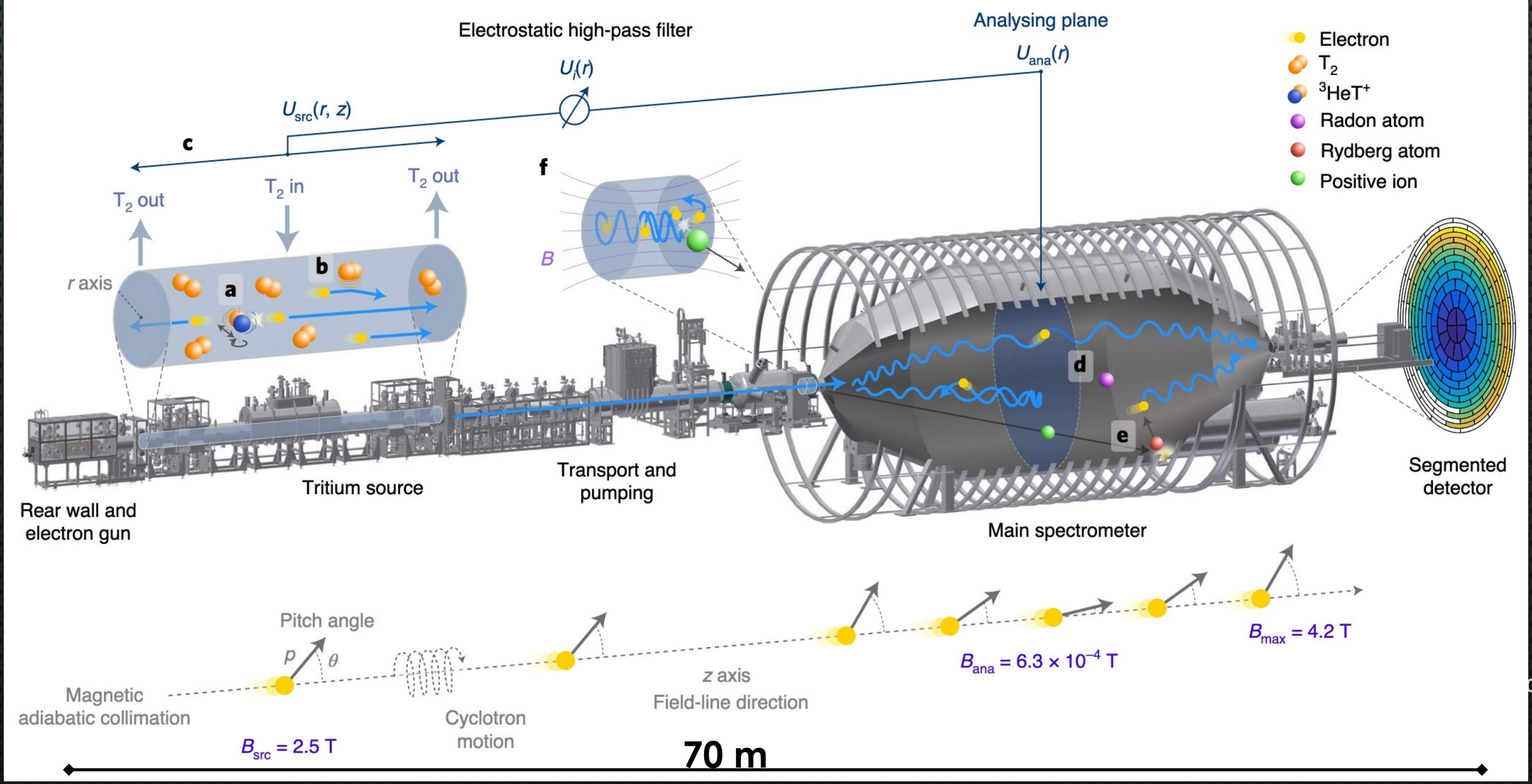




$$T_2 \rightarrow He^3T^+ + e^- + \bar{\nu}_e$$

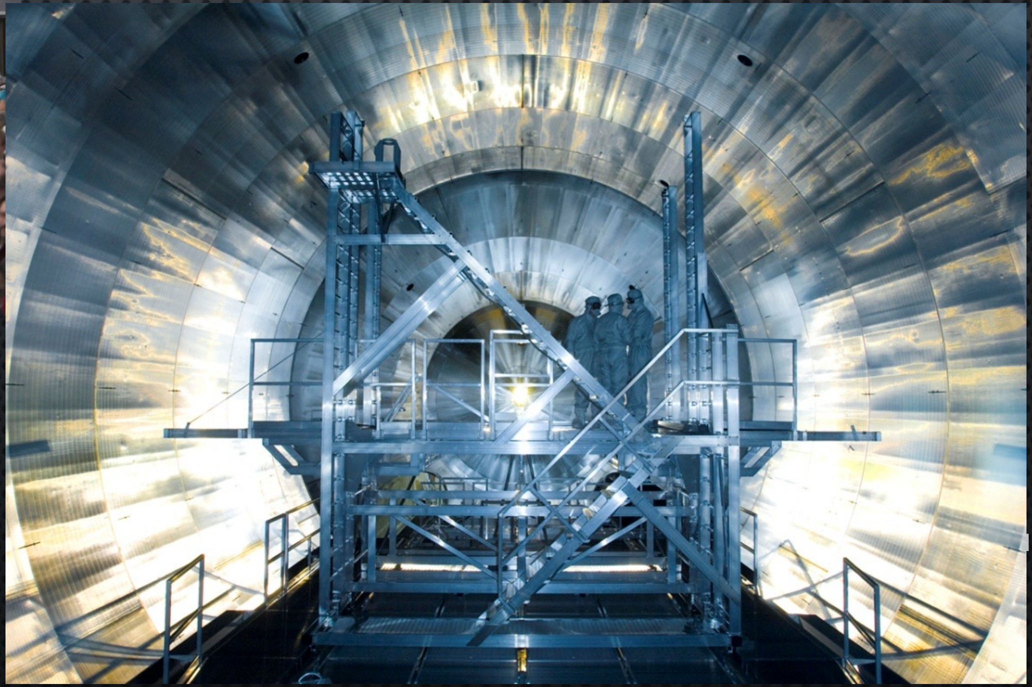
$$Ho^{163} + e^- \rightarrow Dy^{163} + \nu_e$$

TRITIUM BETA-DECAY EXPERIMENTS: KATRIN



KATRIN EXPERIMENT

Since $\frac{\Delta E}{E} = \frac{B_{min}}{B_{max}}$, in order to achieve an energy resolution 1:20000, the spectrometer needs to have a diameter of 10m

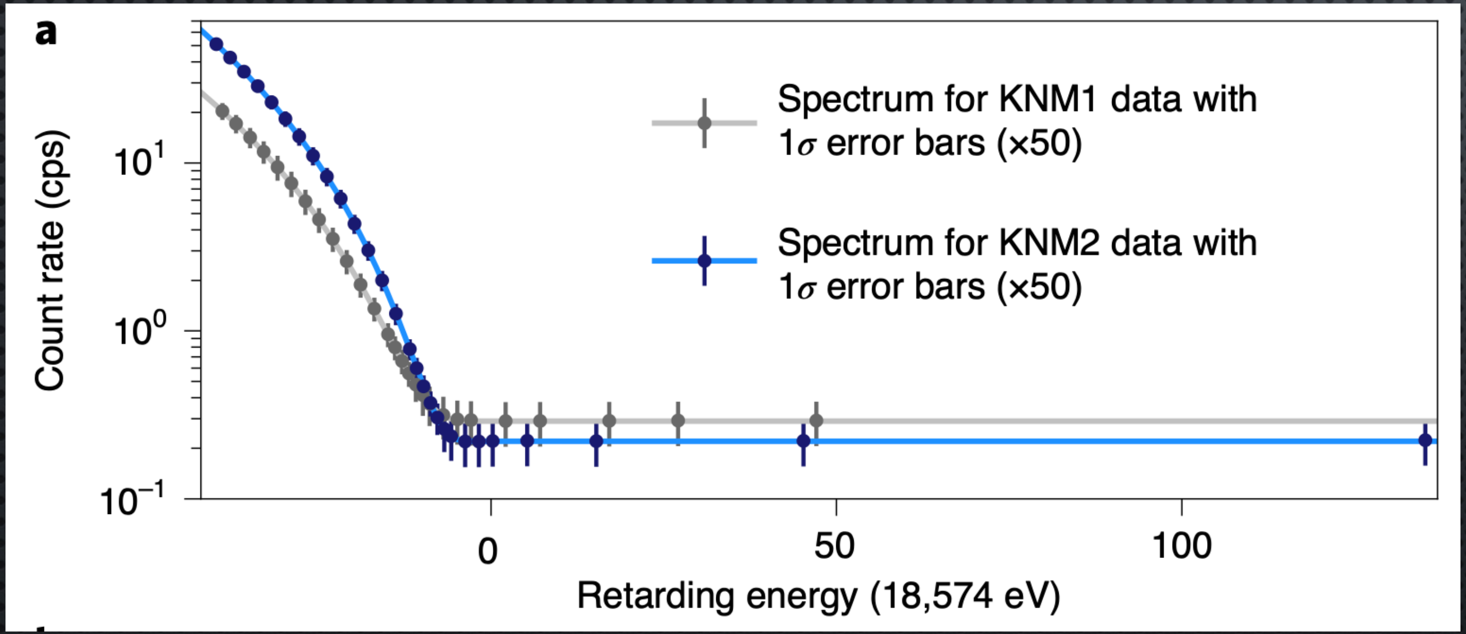


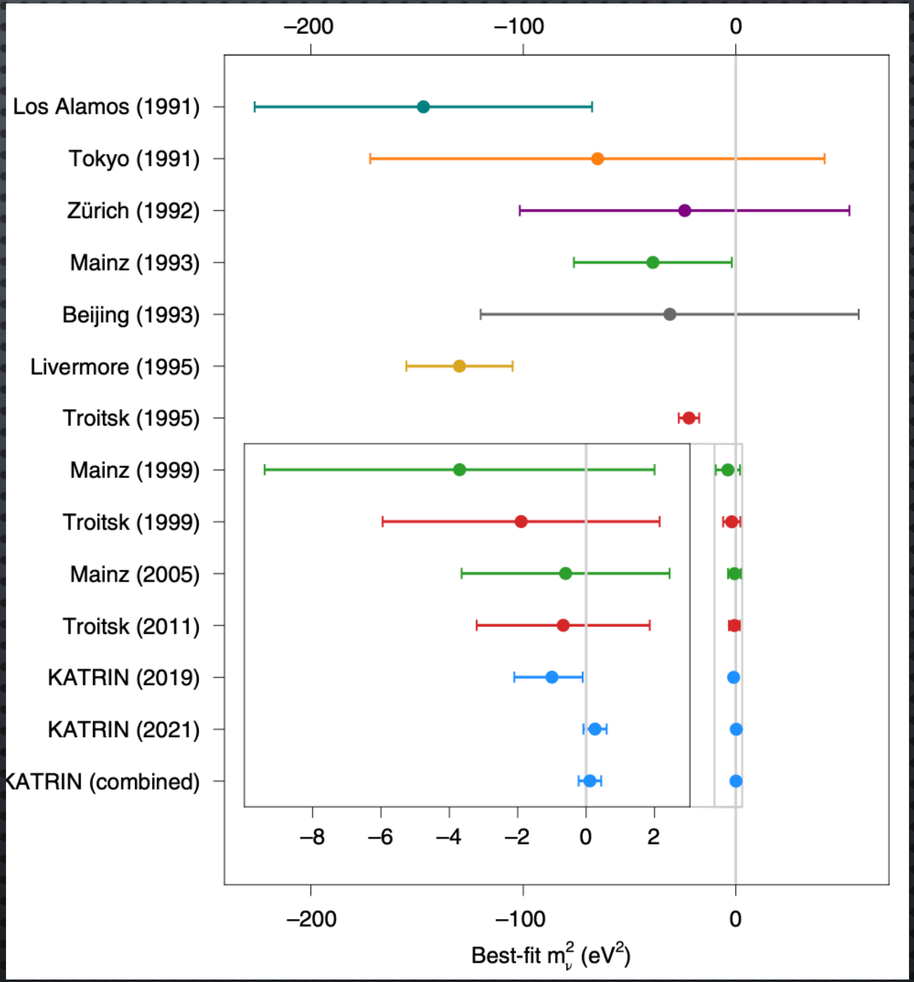
- The mass reachable by KATRIN allows to investigate the quasi-degenerate neutrino mass regime
- The experiment is also sensitive to the existence of additional sterile neutrinos at the keV mass scale.

KATRIN EXPERIMENT

Results 2019 - 2022

m_ν < 0.8 eV (90%C.L.)

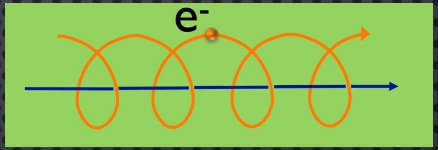


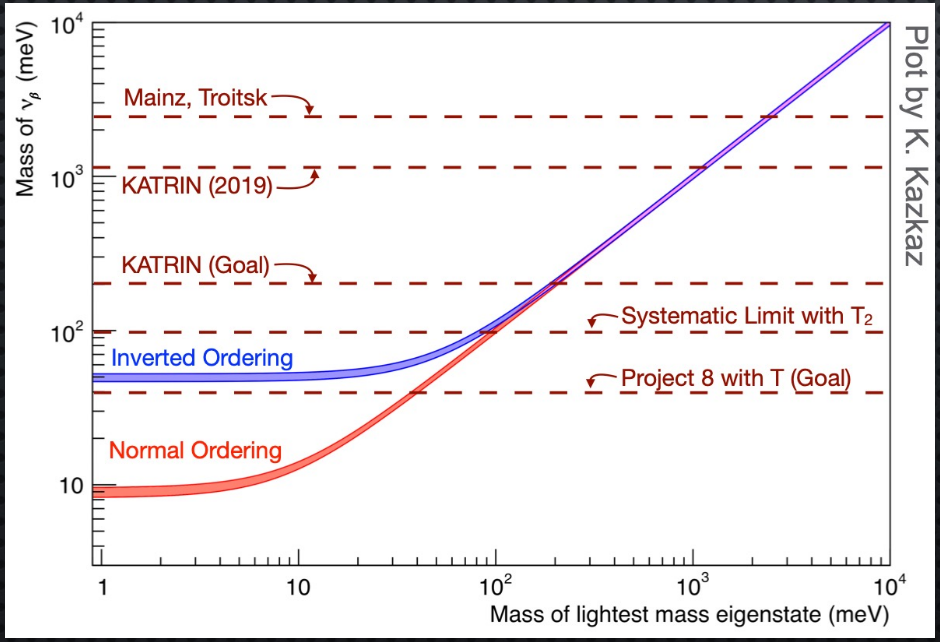


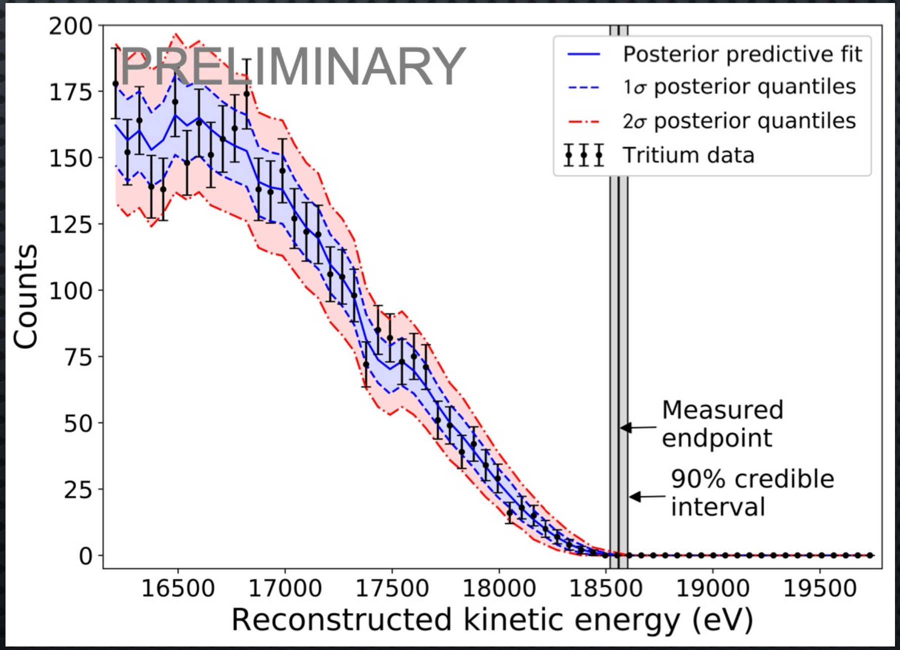
Nature Phys. Vol 18, 160-166 (2022)

PROJECT 8: CYCLOTRON RADIATION EMISSION SPECTROSCOPY

1. TRITIUM GAS IN AN ENCLOSED VOLUME WITH A MAGNETIC FIELD
2. DECAY ELECTRONS SPIRAL AROUND FIELD LINES
3. THE FREQUENCY OF THE EMITTED CYCLOTRON RADIATION DEPENDS ON THE RELATIVISTIC BOOST (E^- ENERGY).





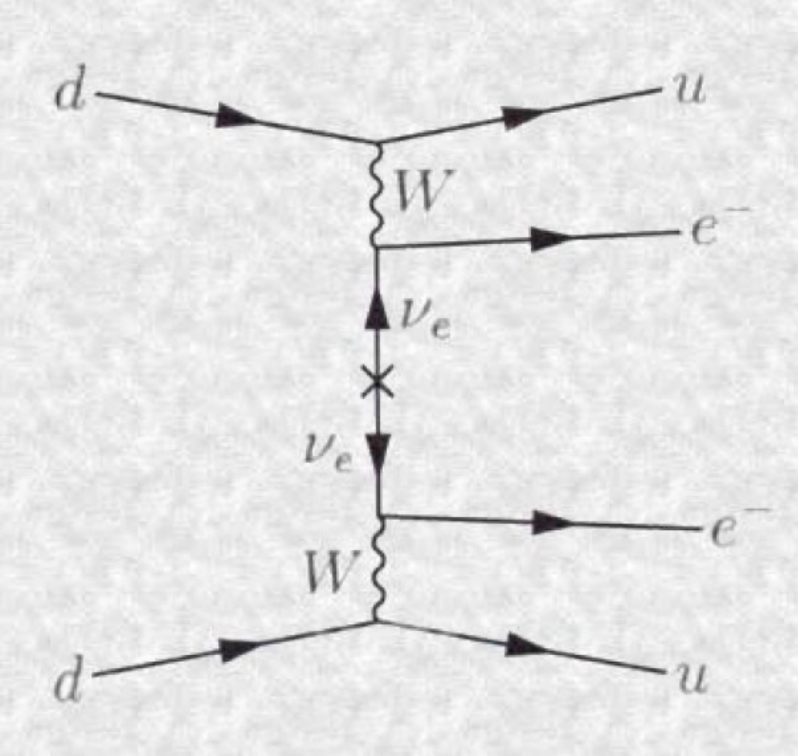


NEUTRINO MASS
INDIRECT MEASUREMENT

DIRAC OR MAJORANA NATURE

There is a way to distinguish between Dirac and Majorana neutrinos and to get information about the absolute value of the neutrino mass:

Neutrino-less double beta decay



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

Lepton number violating process

NEUTRINO-LESS DOUBLE BETA-DECAY

The rate of this decay depends on the neutrino mass

$$(T_{1/2}^{0\nu})^{-1} = (g_A^{eff,0\nu})^4 G^{0\nu}(Q_{\beta\beta}, Z) \left| M^{0\nu} \right|^2 \cdot \langle m_{\beta\beta} \rangle^2$$

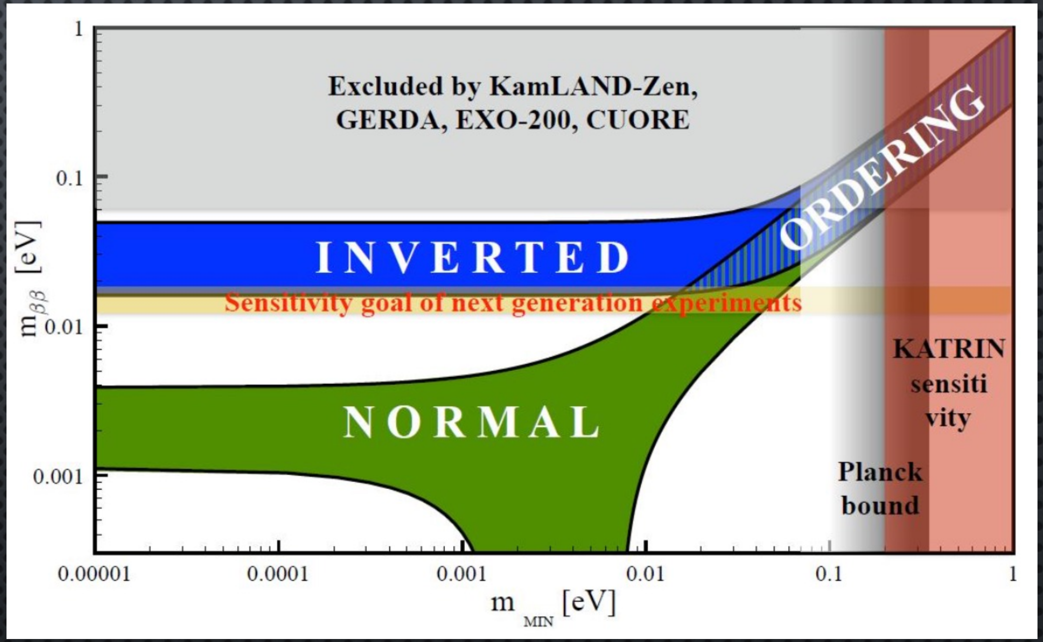
where

$g_A^{eff,0\nu}$ axial-vector coupling constant

$G^{0\nu}$ phase space

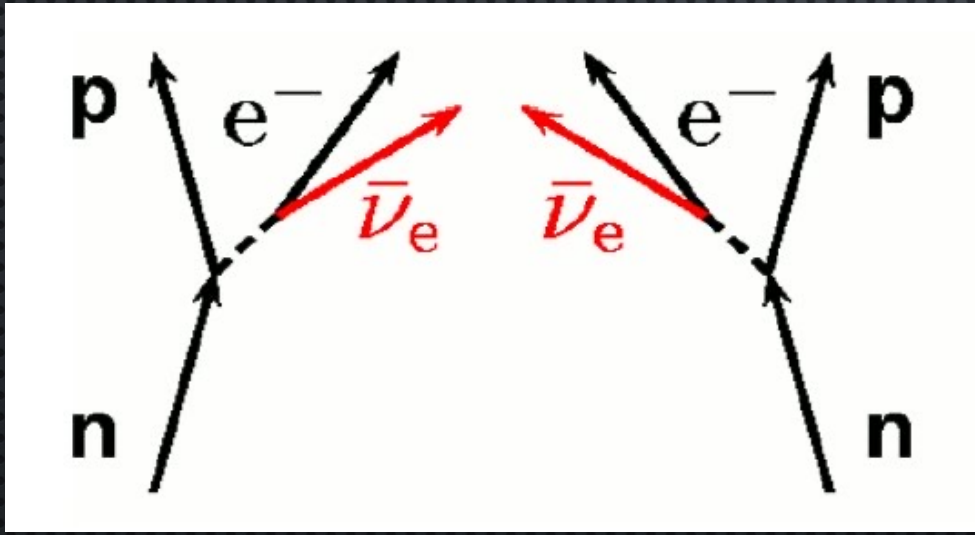
$M^{0\nu}$ nuclear matrix element

Effective Majorana mass: $\langle m_{\beta\beta} \rangle^2 = \left| \sum_i U_{ei}^2 m_i \right|^2$



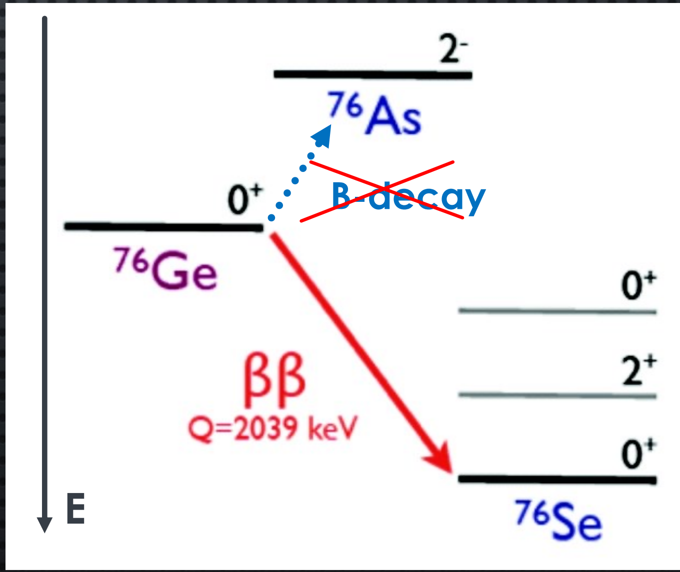
DOUBLE BETA-DECAY

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



Ordinary double β-decay Sum of two β-decays.

In order for (double) β-decay to be possible the final nucleus must have a larger binding energy than the original nucleus.



DOUBLE Β-DECAY: ISOTOPES

Isotope	Nat. abund. (%)	Q-value (keV)	Half-life 10^{21} years	Experiment
^{48}Ca	0.187	4267.98±0.32	0.064±0.007±0.011	NEMO-3
^{76}Ge	7.8	2039.006±0.050	1.926±0.094	GERDA
^{82}Se	9.2	2997.9±0.3	0.096±0.003±0.010	NEMO-3
^{96}Zr	2.8	3347.7±2.2	0.0235±0.0014±0.0016	NEMO-3
^{100}Mo	9.6	3034.40±0.17	$(6.93\pm0.04)\times10^{-3}$	NEMO-3
^{116}Cd	7.5	2813.50±0.13	$(2.74\pm0.04\pm0.18)\times10^{-2}$	NEMO-3
^{128}Te			7200±400	geochemical
^{130}Te	34.5	2527.518±0.013	0.82±0.02±0.06	CUORE-0
^{136}Xe	8.9	2457.83±0.37	2.165±0.016±0.059	EXO-200
^{150}Nd	5.6	3371.38±0.20	$(9.34\pm0.22\pm0.61)\times10^{-3}$	NEMO-3

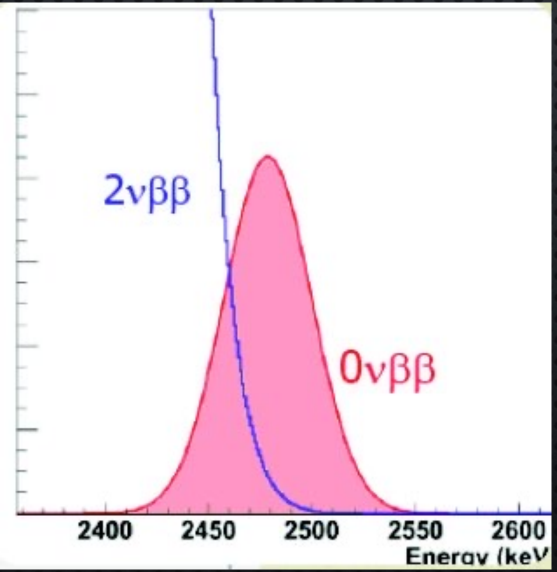
NEUTRINO-LESS DOUBLE BETA-DECAY EXPERIMENTS

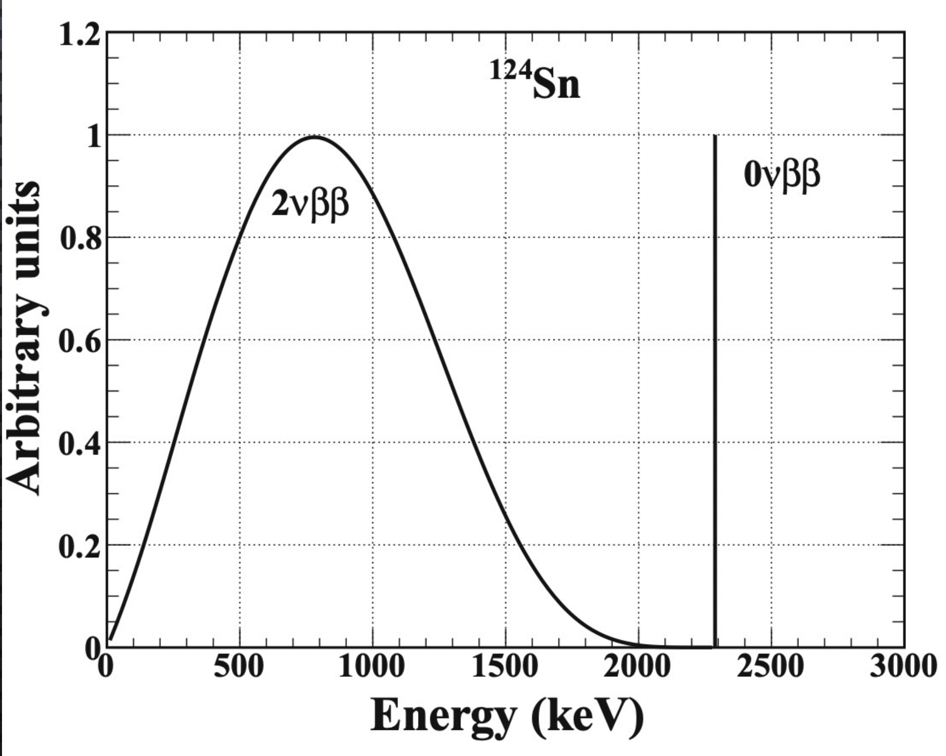
Signature: **Two and only two β-electrons with $E_{\beta\beta}$ = Q-value of the nuclear transition**

Despite the rare decay the signature is very clear

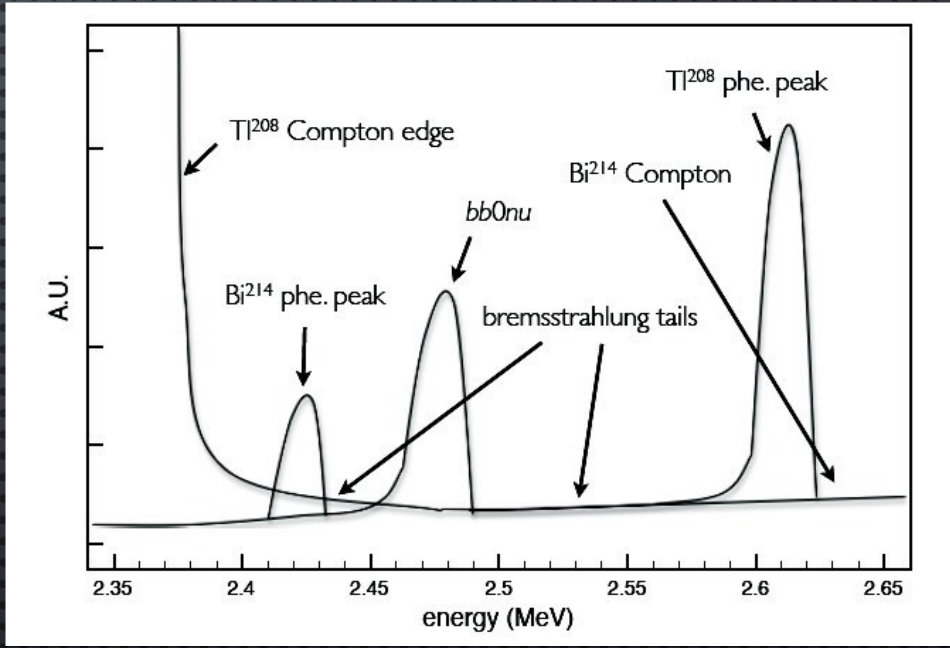
Requirements:

- **Identification of two β-electrons**
- **Large target mass**
- **Very good energy resolution**





NEUTRINO-LESS DOUBLE BETA-DECAY EXPERIMENTS



Requirements: Low background

- Ultrapure materials
- Passive and active shield
- Placed in an underground laboratory

Election of Isotope:

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

The observation of the 0νββ in different isotopes would be mandatory to confirm and certify a discovery.

NEUTRINO-LESS DOUBLE Β-DECAY EXPERIMENTS

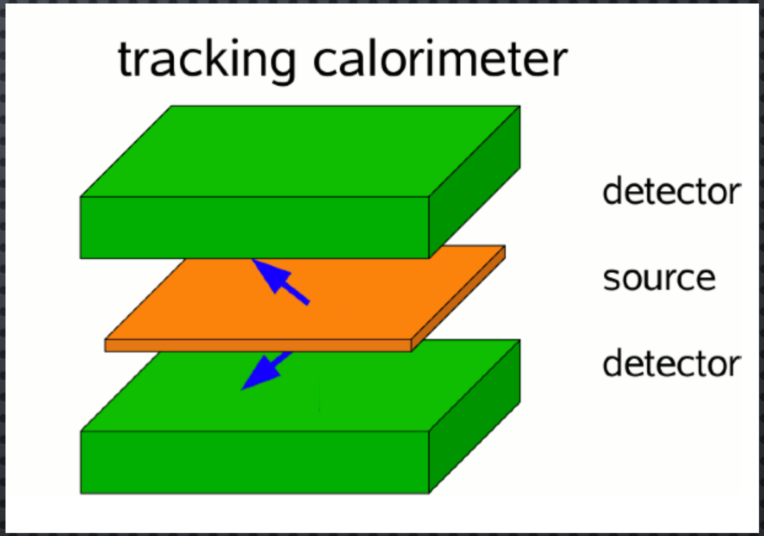
Two experimental approaches:

1/ source ≠ detector

Source surrounded by a tracking-calorimeter

Ex. NEMO

Pros: Detection of both β-electrons separately



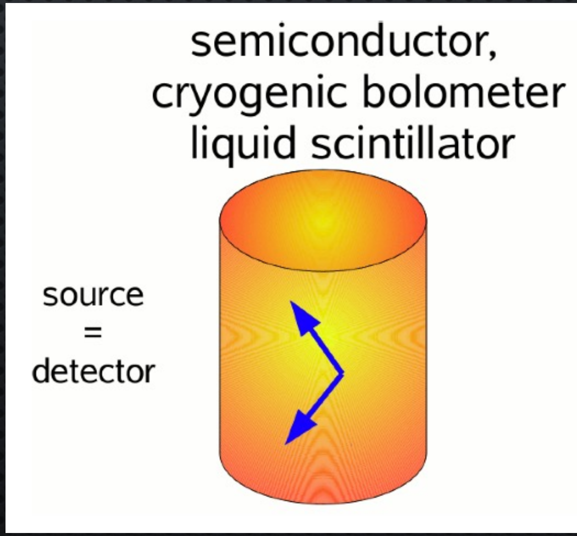
2/ source = detector

The double β-decay nuclei are part of the detector

Semiconductors, cryo-bolometers, GTPC, LiqTPC, liquid scintillator

Ex. Gerda, CUORE, EXO-200, KamLand-Zen

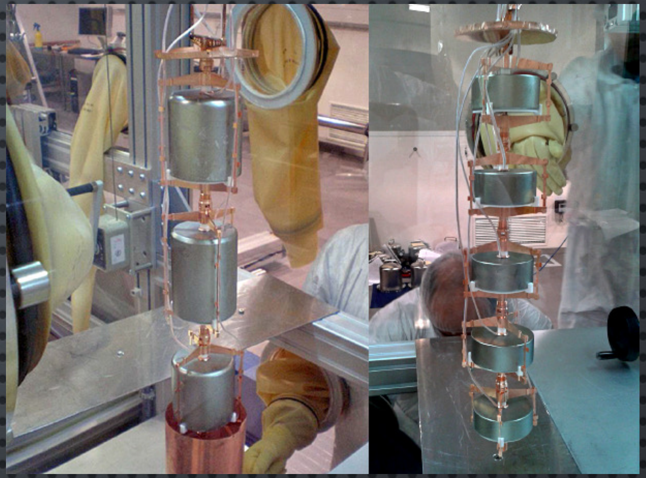
Pros. Larger target mass



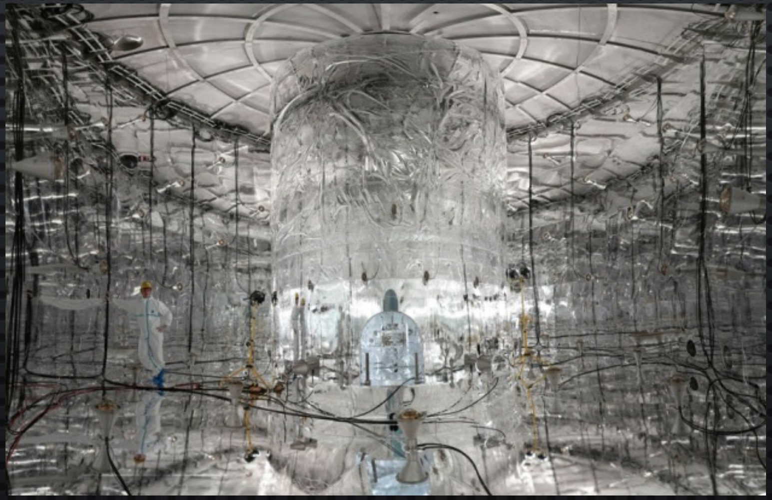
GERDA

Germanium detector isotopically enriched in ^{76}Ge
Ge detectors are semiconductor diodes sensitive to ionizing radiation (γ spectrometry)

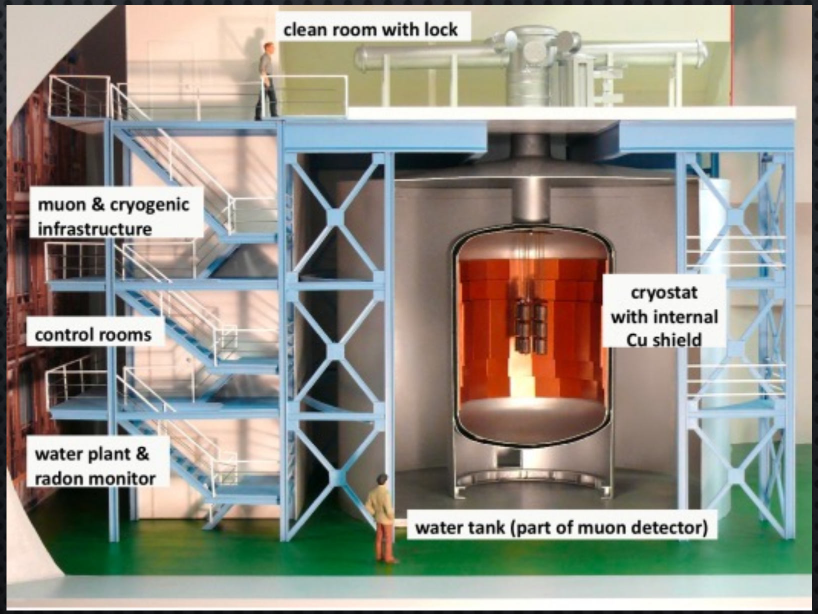
The Ge detectors are deployed within vertical strings containing two or three elements each.



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



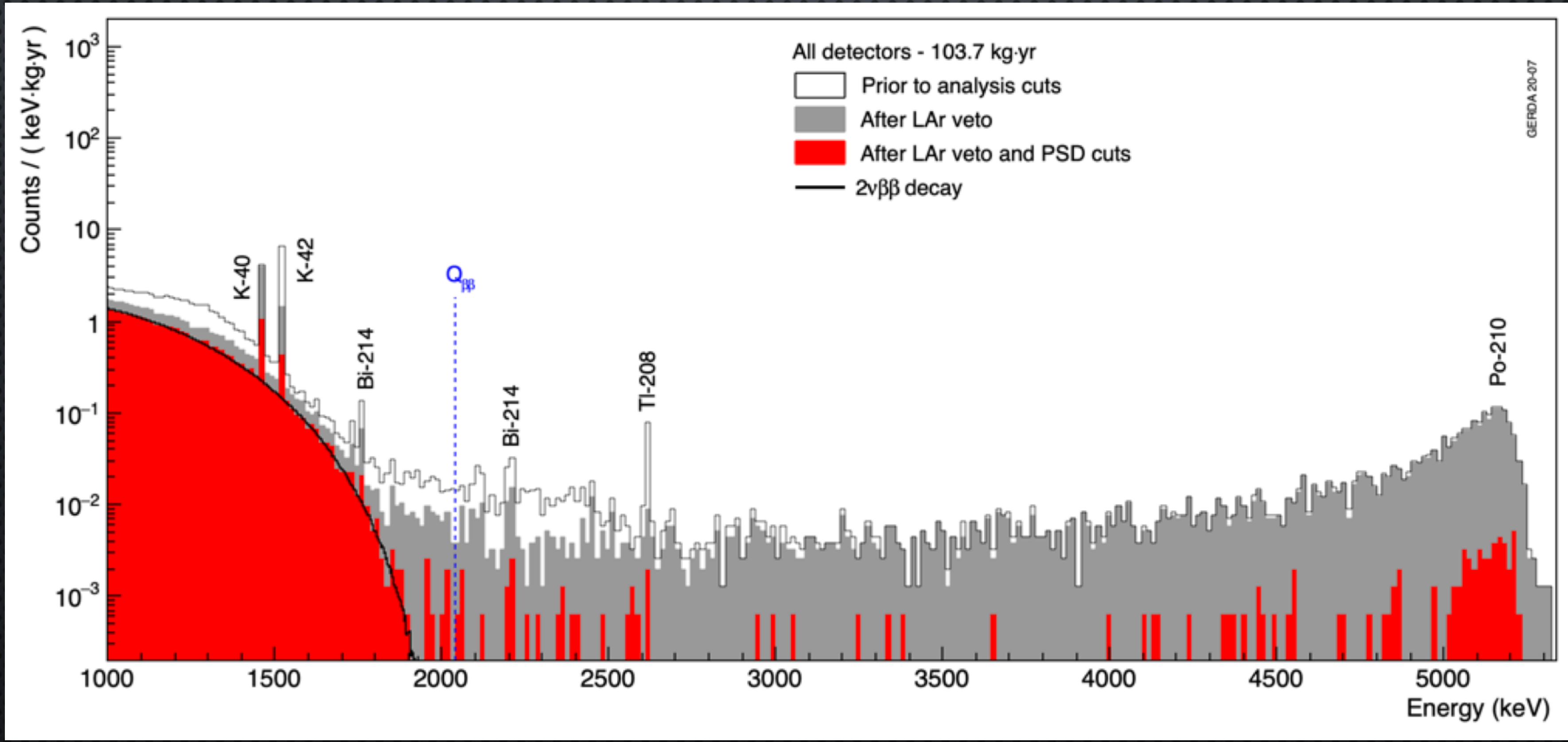
Gran Sasso lab



GERDA

Results

Exposure: 127.2 kg yr



GERDA

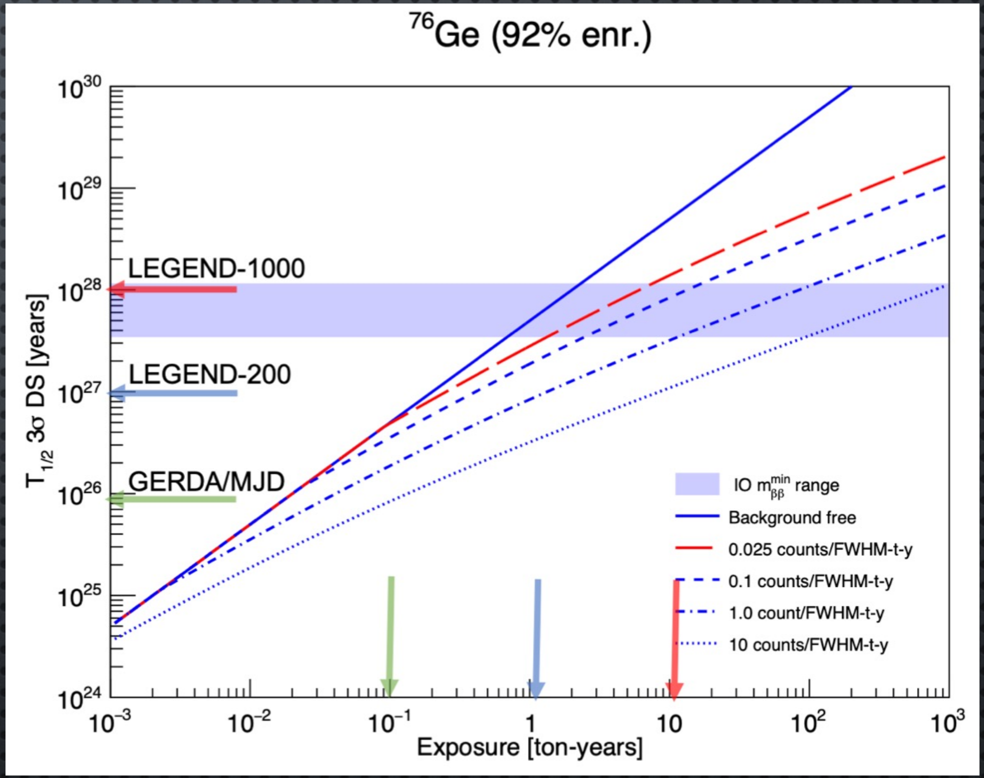
Results

Exposure: 127.2 kg yr

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

$$T_{1/2}^{0\nu}(Ge^{76}) > 1.8 \cdot 10^{26} \text{ yr}$$

$<m_{\beta\beta}> < 79\text{-}180$ meV



GERDA (+ MAJORANA) → LEGEND

^{76}Ge ~36kg → 200 kg → 1 ton

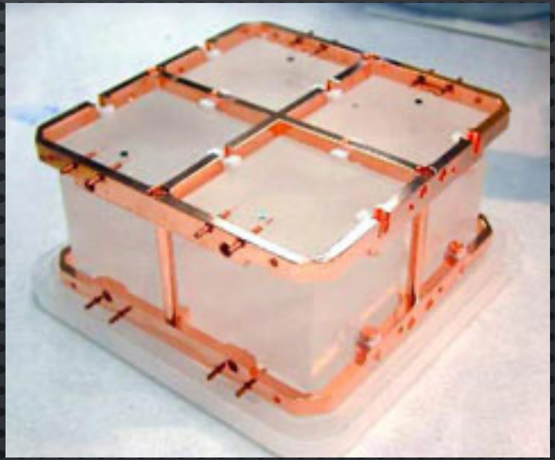
$T_{1/2}^{0\nu}(Ge^{76})$ $1.8 \cdot 10^{26}$ yr → 10^{27} yr → 10^{28} yr

CUORE

The detector consists of TeO_2 crystals (30% ^{130}Te, natural abundance)

TeO_2 cryogenic calorimeter

TeO_2 is a dielectric and diamagnetic material, providing that the temperature is extremely low (~10mK), a small energy release in the crystal results into a measurable temperature rise. This temperature change is recorded using a Neutron Transmutation Doped (NTD) Ge thermistors glued on the crystal surface.



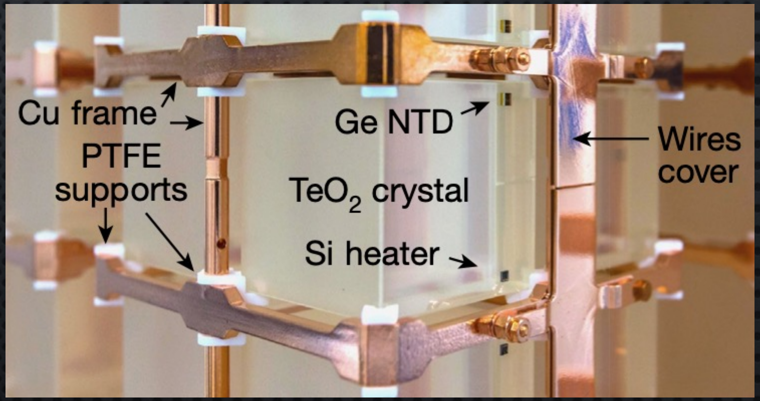
988 5x5x5 cm^3 TeO_2 crystals (750 g) ➔ ~200 kg ^{130}Te

Arranged in 19 towers Each tower ➔ 13 floors of 4 crystals

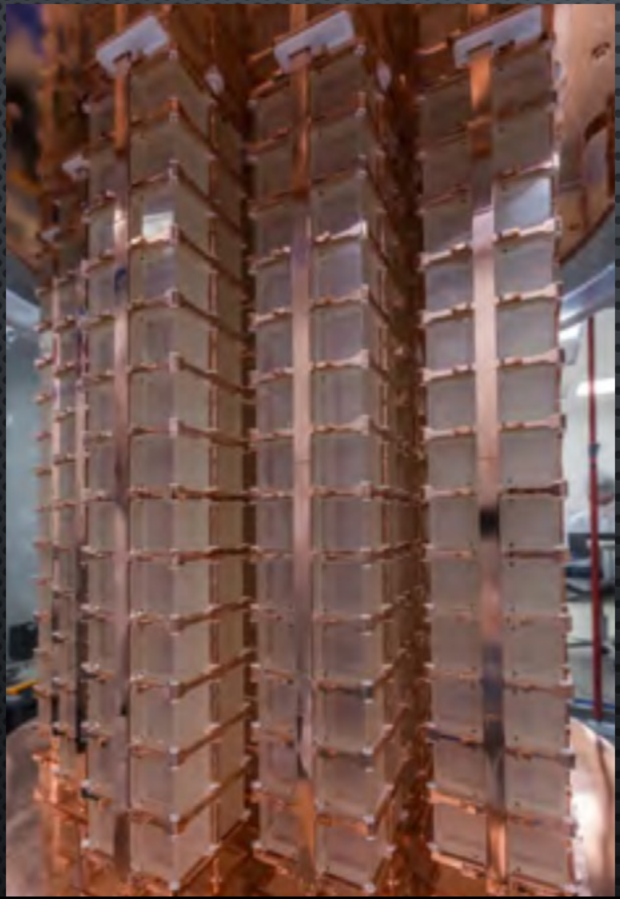
Taking science data since Spring 2017

BG: 0.01 cts/(keV · kg of TeO_2 · yr).

Energy resolution ~0.3%

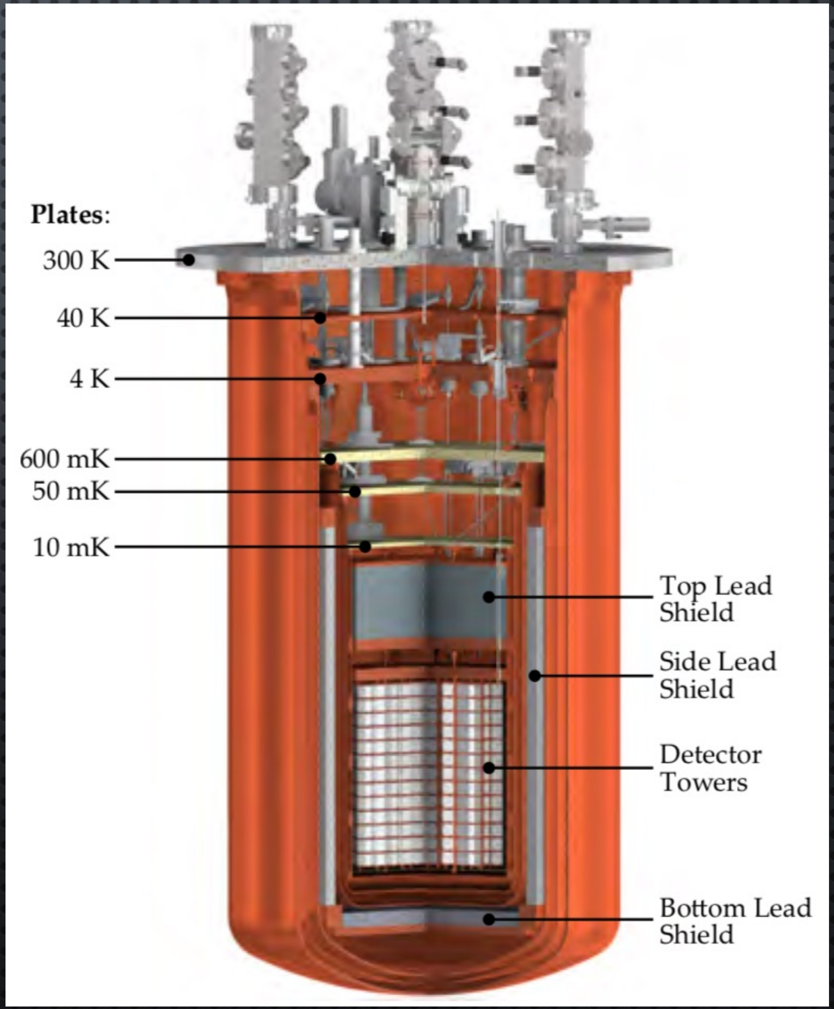


CUORE



19 towers Each tower ➔ 13 floors of 4 crystals

Gran Sasso lab



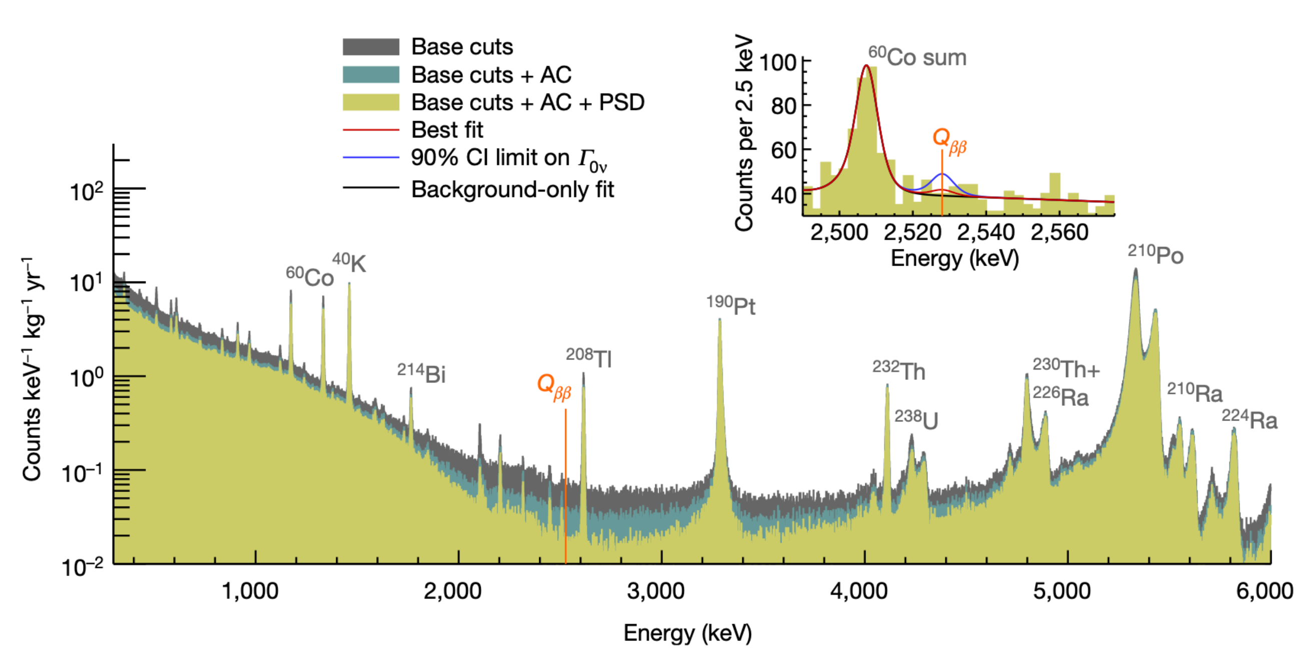
CUORE

Results
Exposure: 288.8 kg yr

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

$$T^{0\nu}_{1/2}(Te^{130}) > 2.2 \cdot 10^{25} \text{ yr}$$

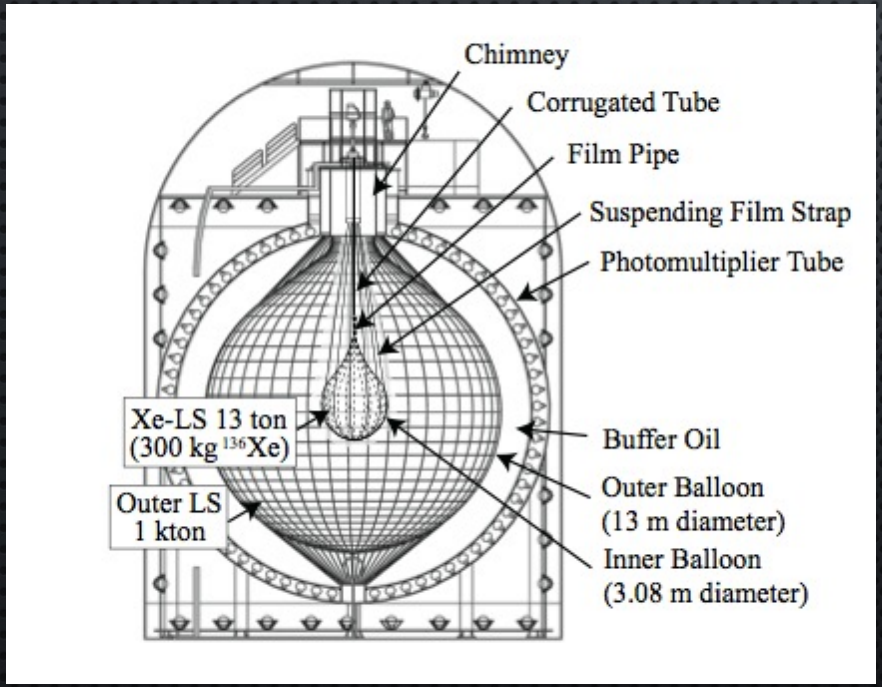
$$<m_{\beta\beta}> < 90\text{-}305 \text{ meV}$$



CUORE will take data until ^{130}Te exposure of 1000 kg yr ($T^{0\nu}_{1/2}(Te^{130}) \sim 1 \cdot 10^{26}$ yr)

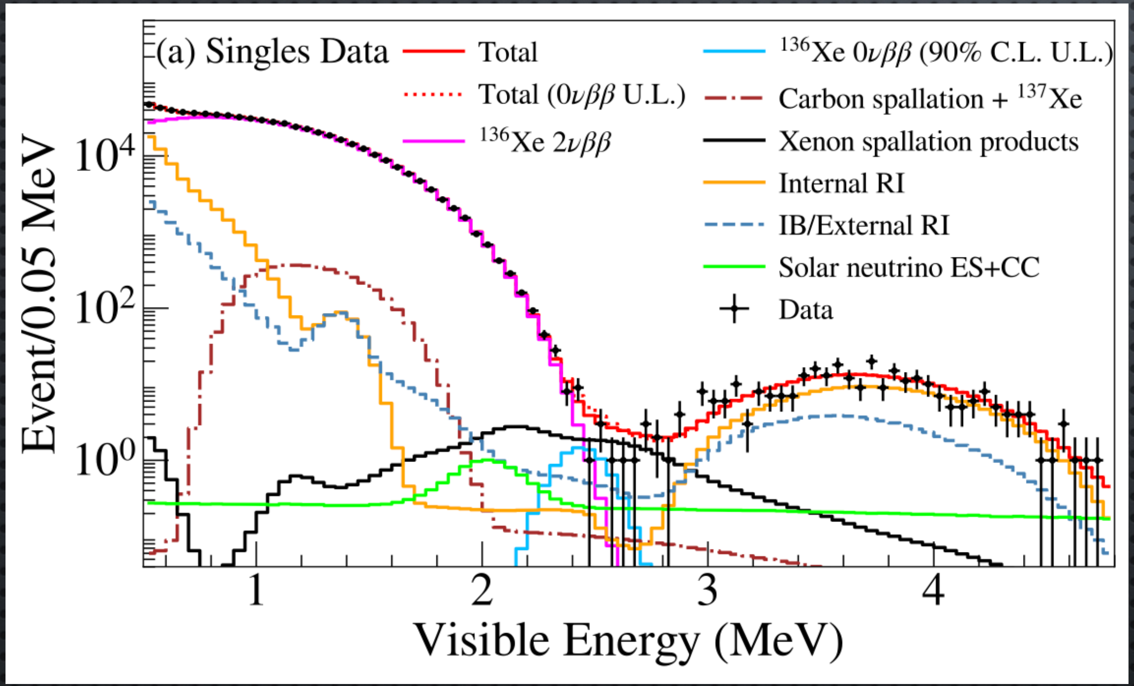
KAMLAND-ZEN

Xe-loaded liquid scintillator ~800 kg ^{136}Xe contained in a 3.08-m diameter transparent nylon-based inner balloon suspended at the center of the KamLAND detector by film straps.
The balloon is surrounded by 1 kton of liquid scintillator contained in a 13-m diameter outer balloon.



Event vertex and energy are reconstructed based on the timing and charge distributions of photoelectrons recorded by the PMTs.

KAMLAND-ZEN



arXiv: 2203.02139

Results

Exposure 970 kg yr

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

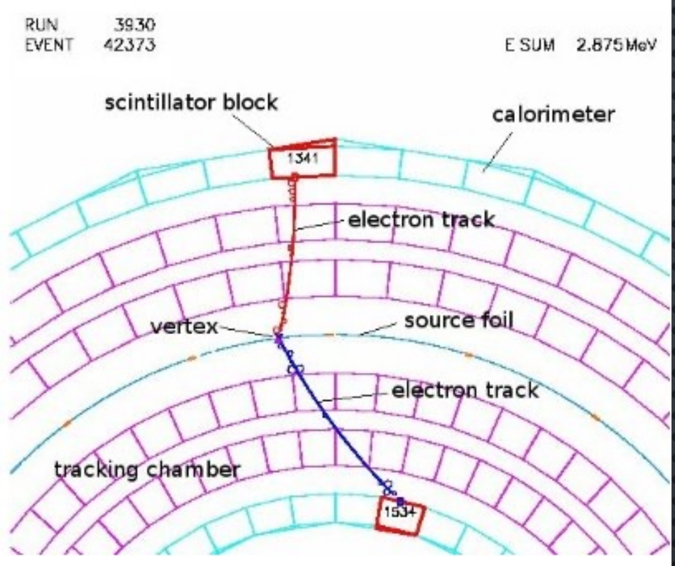
$T^{0\nu}_{1/2}(Xe^{136}) > 2.3 \cdot 10^{26}$ yr

$\langle m_{\beta\beta} \rangle < 36\text{-}156$ meV

SOURCE ≠ DETECTOR

NEMO-3 **(40-60 mg/cm²) source foils of ^{100}Mo**

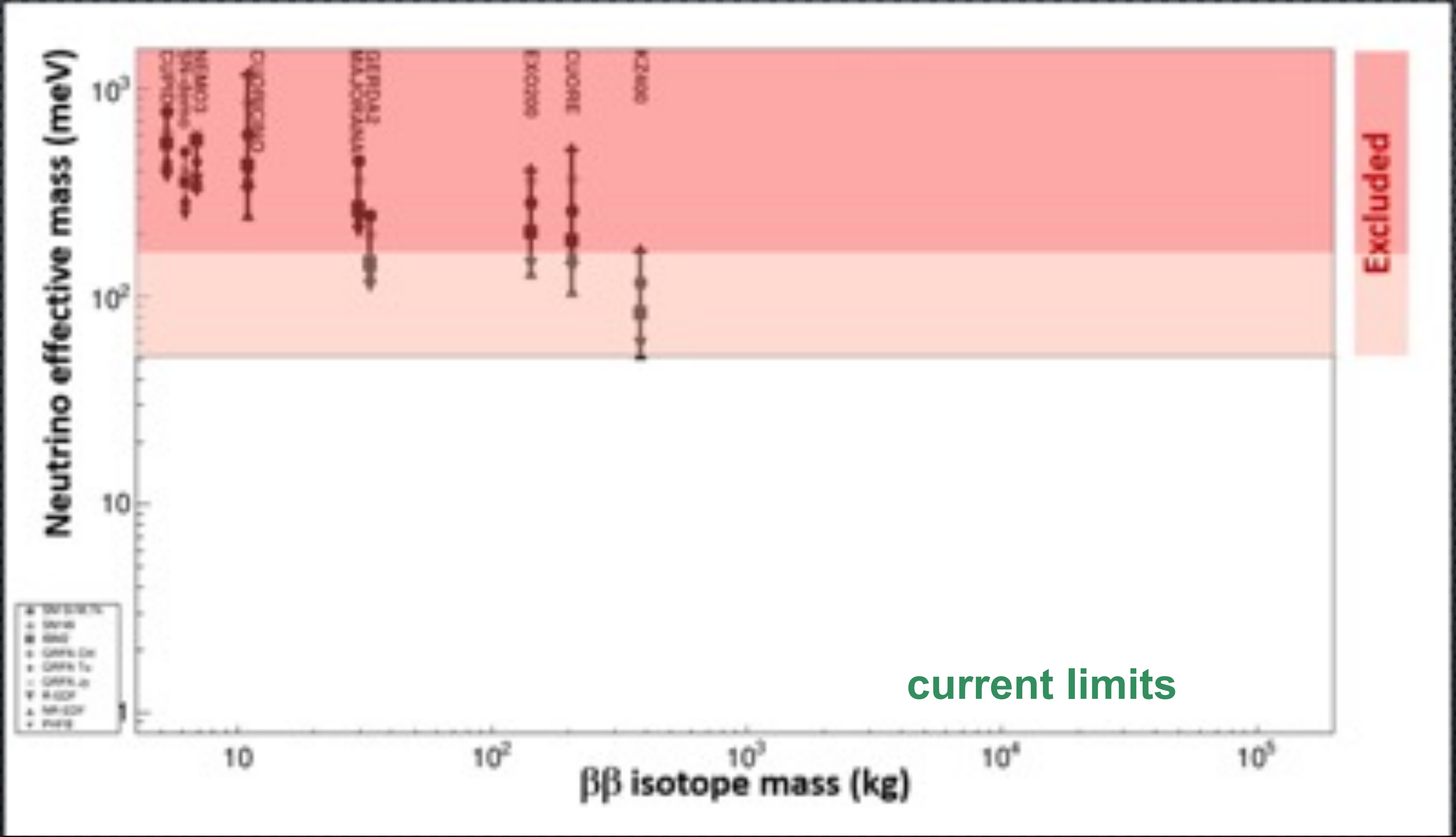
Exposure: 34.7 kg yr



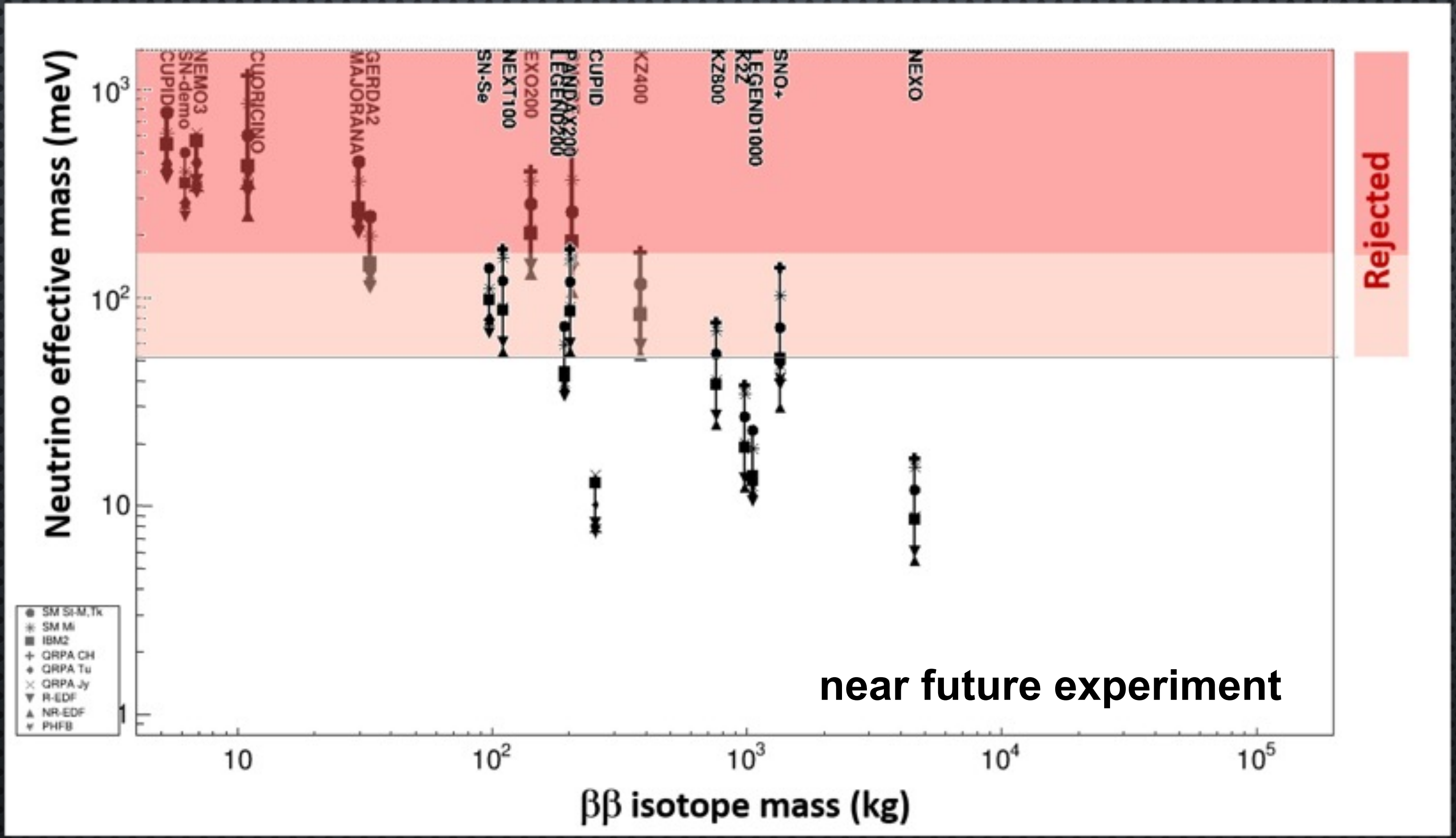
Full reconstruction with 3D-tracking and calorimetric information of the topology of the final state: 2 $e^{-}{}_{,s}$ simultaneously emitted from a common vertex.

The experiment sets a lower limit at 90% C.L.
$T^{0\nu}_{1/2}(Mo^{100}) > 1.1 \cdot 10^{24}$ yr

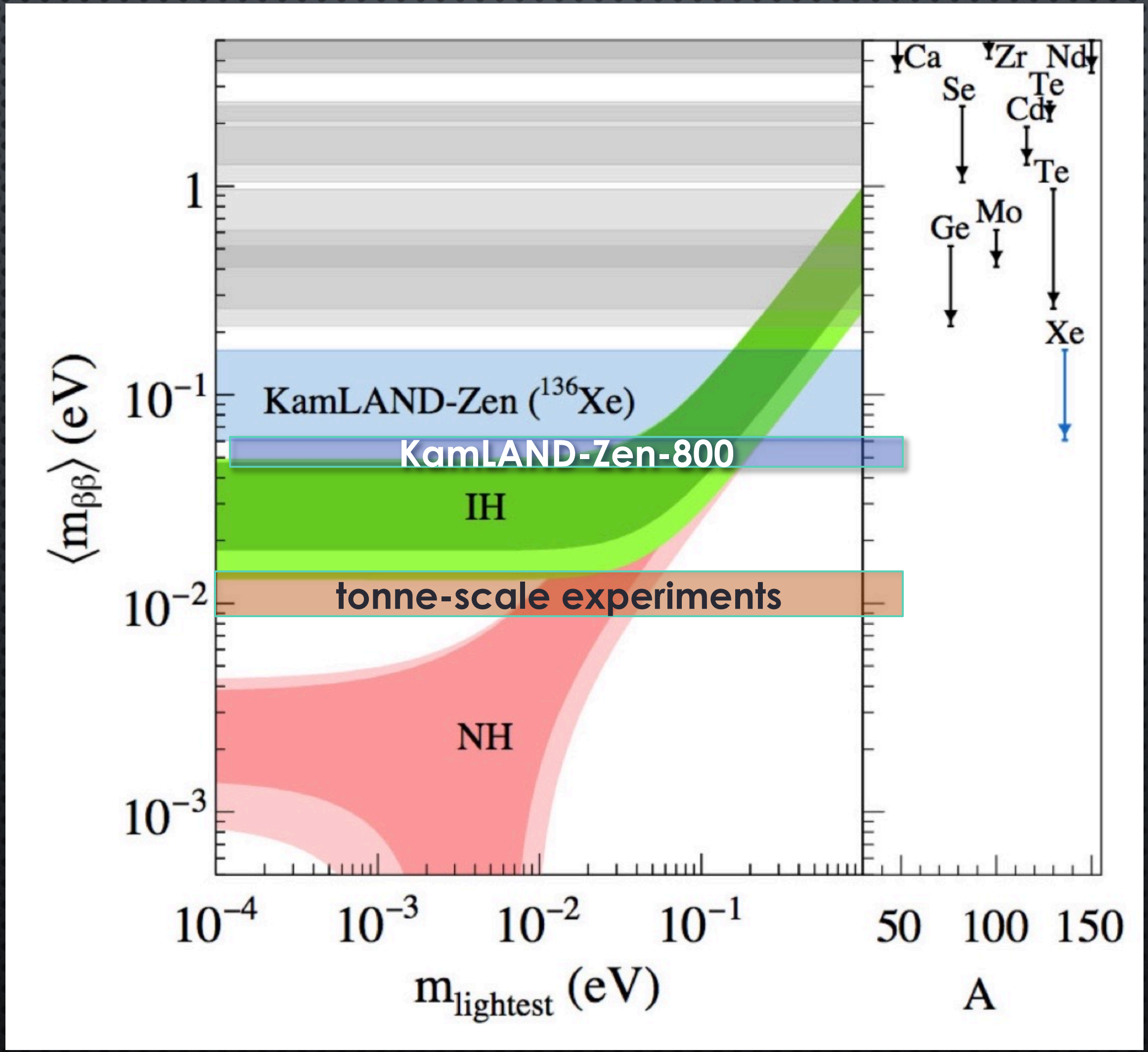
NEUTRINO-LESS DOUBLE Β-DECAY EXPERIMENTS



NEUTRINO-LESS DOUBLE B-DECAY EXPERIMENTS



NEUTRINO-LESS DOUBLE B-DECAY EXPERIMENTS



SUMMARY

- Future long baseline experiments are needed to determine the existence of CP violation in the leptonic sector
- Very long baseline experiments (>1000 km) can determine the mass neutrino ordering.
- In the next future the existence of a sterile neutrino will be established.
- The Neutrinos continue to be the key to extensions of the current particle model.