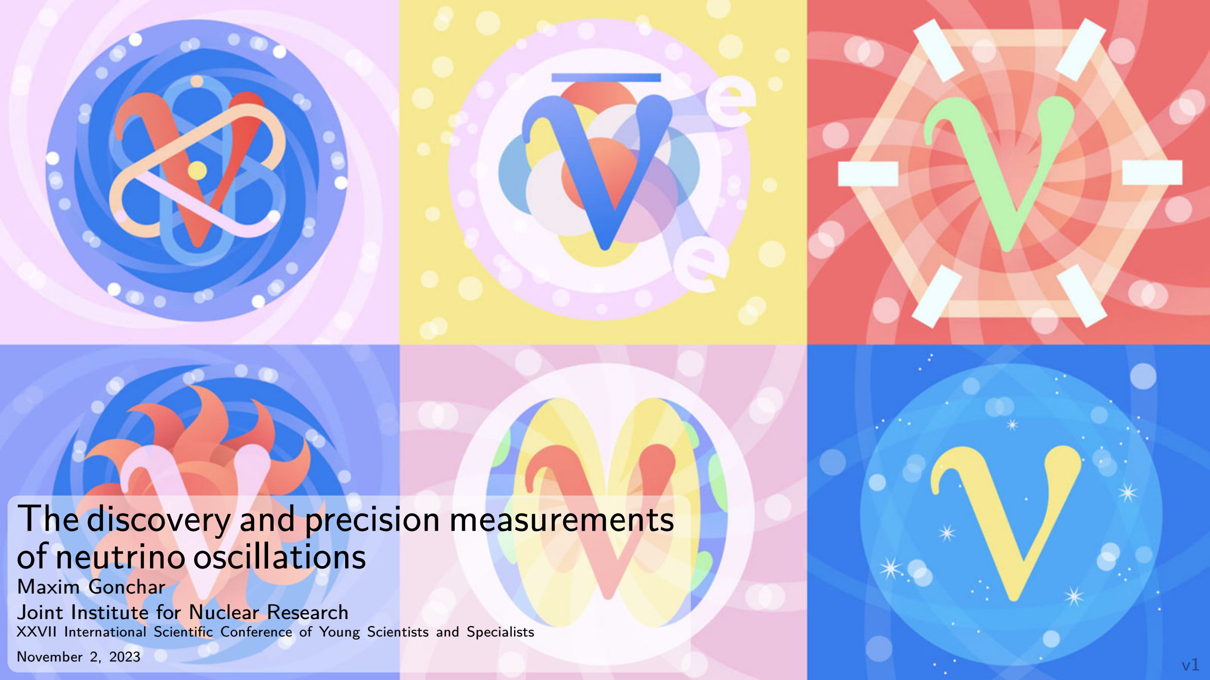


The discovery and precision measurements of neutrino oscillations

Maxim Gonchar
Joint Institute for Nuclear Research

XXVII International Scientific Conference of Young Scientists and Specialists

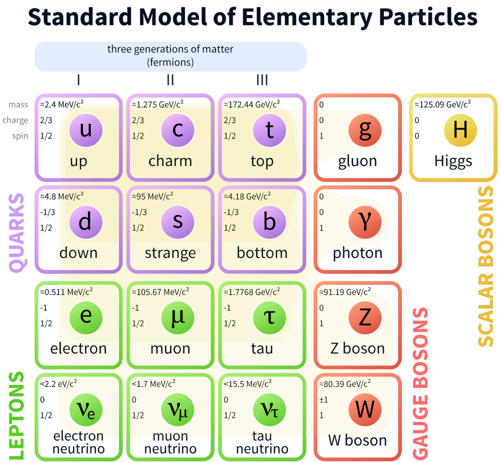
November 2, 2023

v1

Credits

- Book: "Fundamentals of Neutrino Physics and Astrophysics" by Carlo Giunti, Chung W. Kim
- "Neutrino. History of a unique particle" by S.M. Bilenky — Eur. Phys. J. H 38
- "Accelerator neutrinos" by L. Kolupaeva — lecture at Baikal school 2023
- "Introduction into neutrino physics" by D. Naumov — lecture at Baikal school 2023
- Plots from papers.
- Images from the Internet.
  - Title page picture: Sandbox Studio for Symmetry Magazine

Elementary particles



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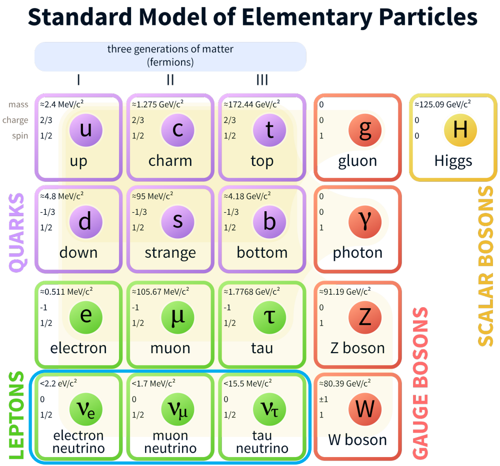
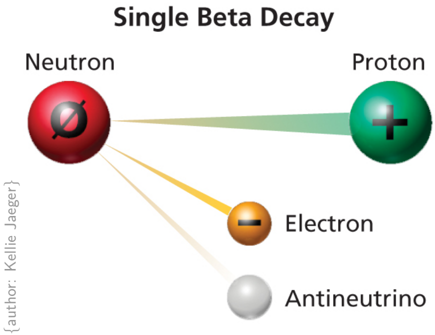


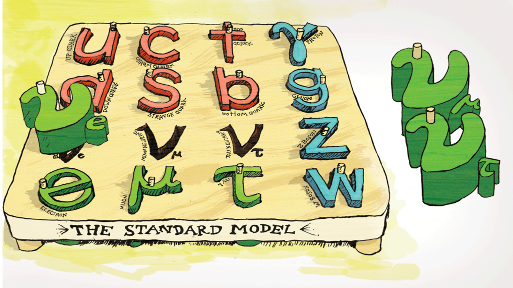
Neutrino



- Neutrino production (example): beta decay
- Neutrino flavor: neutrino interaction state

Elementary particles

Standard Model of Elementary Particles

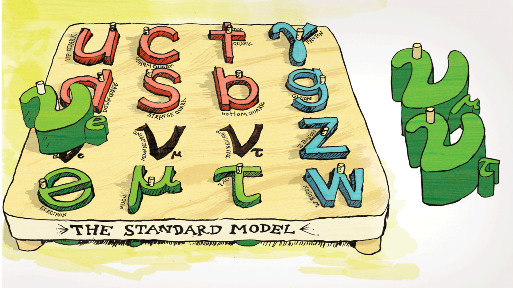


Neutrino

- Mass state $\neq$ interaction state.
- Flavor: how neutrino interacts.

Elementary particles

Standard Model of Elementary Particles



Neutrino

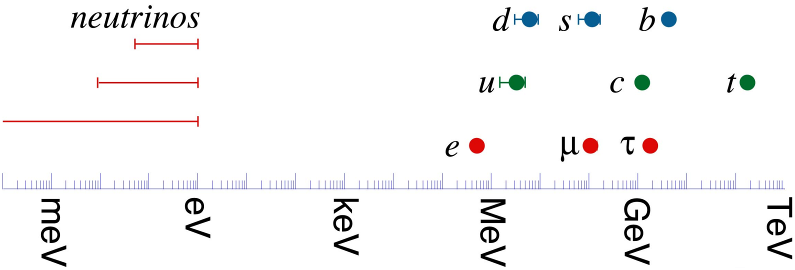
- Mass state $\neq$ interaction state.
- Flavor: how neutrino interacts.

Massive and flavored neutrinos

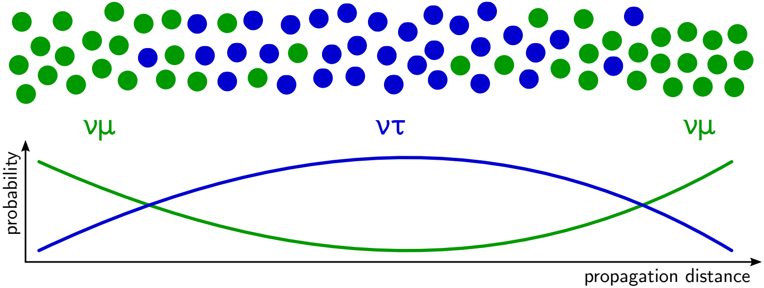
Neutrino properties

Properties

- Neutral, spin $1/2$
- Almost massless: $0 \lesssim m_\nu \lesssim 10^{-6} m_e$
- Interact only weakly
  - $\sim 1'000'000$ suns before interaction (1 MeV)
- Strongly mixes
- Oscillates (in an observable way)
- May be it's own antiparticle
  - only possible for neutrino



Neutrino mixing and oscillations



Mixing

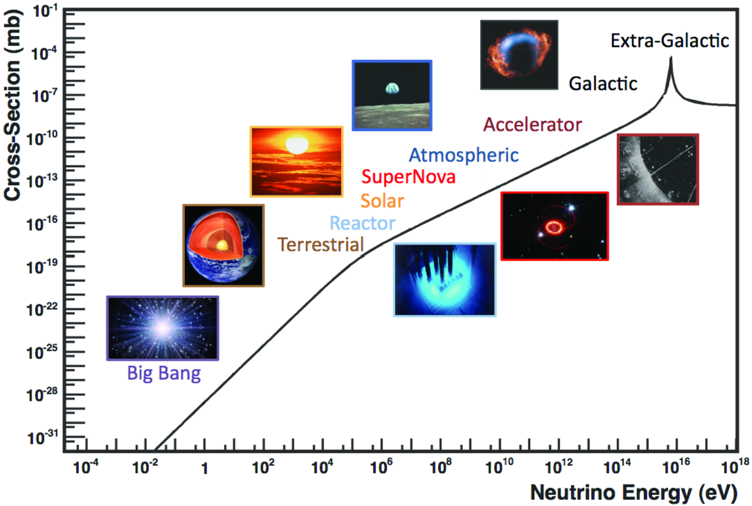
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}\text{3D rotation matrix}\\ \text{with 3 angles}^*:\\ \theta_{e2},\theta_{e3},\theta_{\mu3},\ i\delta_{\text{CP}}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Pontecorvo-Maki-Nakagawa-Sakata (PMNS)

Oscillations

- Mixing angles θ_{12}, θ_{23}, θ_{13}: flavor composition
- Mass splitting Δm^2_{32}, Δm^2_{21}: location of maximum
- At least two neutrinos have nonzero mass
- δ_{CP} differences neutrino/antineutrino

Neutrino sources



10^{14}

neutrinos are passing you per second at any given time at the speed of light.

($\sim$ 100 000 000 000 000 particles/second)

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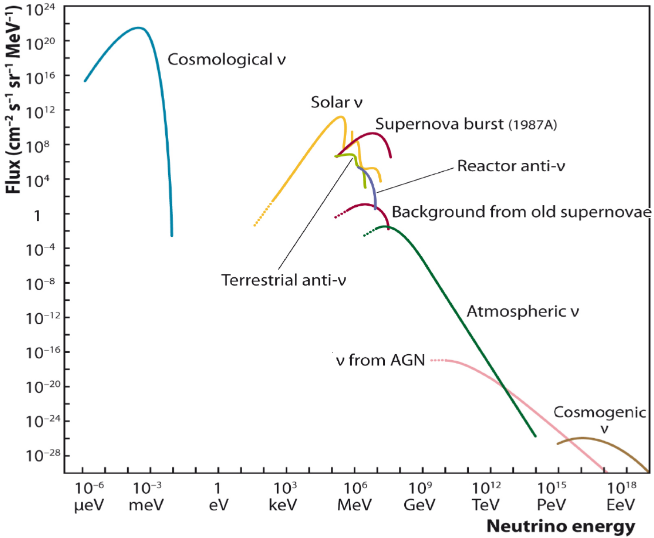

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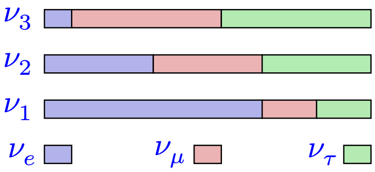
Mandatory slide I: Neutrino mixing



Weak and mass eigenstates differ:

$$|\nu_\alpha\rangle = \sum U^*_{\alpha i}|\nu_i\rangle$$

α — flavor states

i — mass states

Mixing parametrized by:

- three mixing angles: $\theta_{12}, \theta_{23}, \theta_{13}$,
- CP-violating phase: δ_{CP}.

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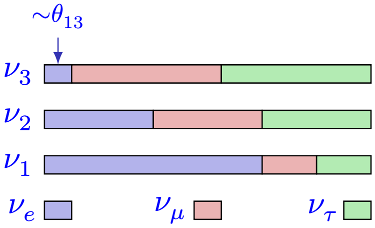

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Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix:

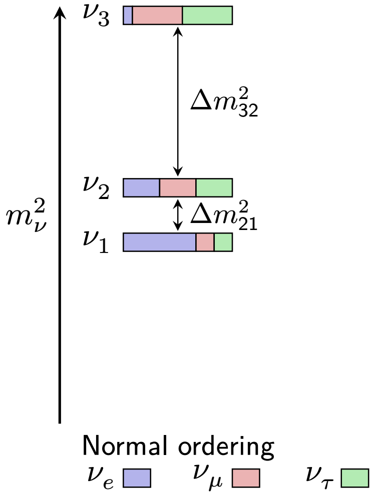
✓ $\theta_{23} \approx 45^\circ$ established through atmospheric and accelerator experiments: possibly maximal.

✓ $\theta_{12} \approx 34^\circ$ established through solar experiments and KamLAND: large, but not maximal.

✓ $\theta_{13} \approx 8^\circ$ established by reactor: **Daya Bay**, RENO, Double Chooz.

- δ_{CP} unknown: NOvA and T2K.

Mandatory slide II: Neutrino mass and ordering



Mass splitting: oscillations PDG2020

- $\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5}$ eV^2
- $\left|\Delta m^2_{32}\right|_{\text{NO}} = (2.453 \pm 0.033) \times 10^{-3}$ eV^2
- $\left|\Delta m^2_{32}\right| / \Delta m^2_{21} \sim 31$

Numbers updated: 2022.06.10

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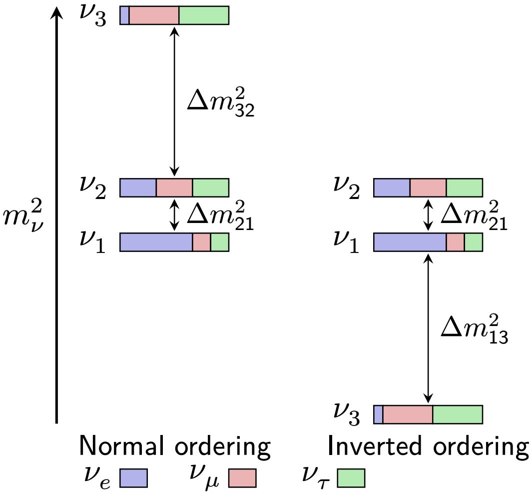

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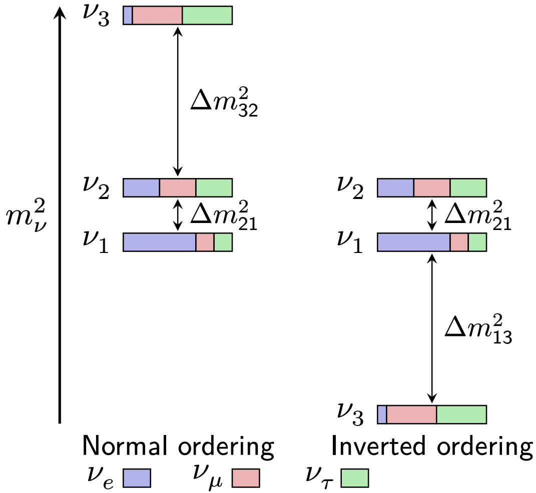

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Neutrino mass

- Mass limits, meV:

$m_2, m_3 > 0$	oscillations	
$\sum m_i \gtrsim 60$	oscillations	
$\sum m_i \lesssim 120$	cosmology	Planck
$m_\beta < 900$	direct	KATRIN [2105.08533]
$\langle m_{\beta\beta}\rangle < 156$	$0\nu\beta\beta$	Kamland-ZEN
$m_{\text{light}} \lesssim 500$	$0\nu\beta\beta$	[2203.02139]

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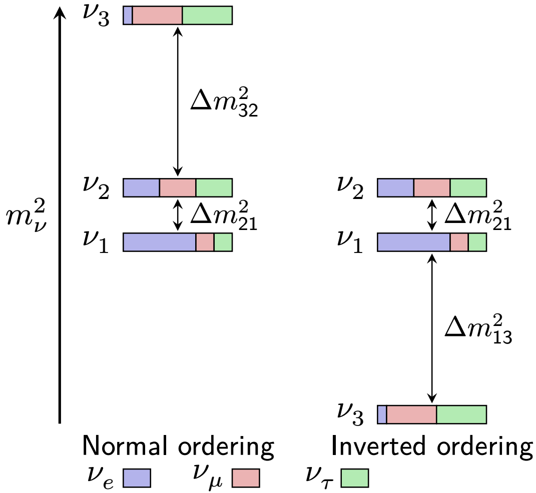

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Neut...

- Mas...

m_2,

$\sum$

$\sum$

$$m_\beta = \sqrt{\sum_i m_i^2 \left|U_{ei}\right|^2}$$

$$m_{\beta\beta} = \left|\sum_i m_i U_{ei}^2\right|$$

m_β<900	direct	KATRIN [2105.08533]
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Neutrino Physics

Physics of neutrino

- Number of neutrino types
- Absolute masses, relative masses
- Neutrino nature: Dirac or Majorana particle
- Neutrino mixing and oscillation parameters
- CP violation in leptonic sector
- Neutrino cross sections

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Physics with neutrino

- Reactor $\overline{\nu}_e$:
  - non-proliferation of nuclear weapons
  - spectrum
- Geo-$\overline{\nu}_e$: Earth radiogenic heat
- Atmospheric ν
- Solar ν_e: model, Solar metallicity
- Astrophysical ν:
  - SuperNova ν
  - Ultra high energy neutrino sources
- Cosmology:
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Physics with neutrino detectors

- Proton decay
- Invisible neutron decay
- Dark matter searches

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What do we know about neutrino oscillations

The particle

- neutral, spin $1/2$, $m = 0$

Mixing

ν

Timeline

- 1930 Pauli proposes neutrino

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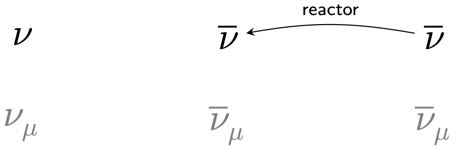

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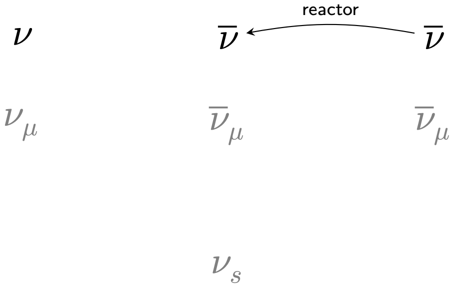

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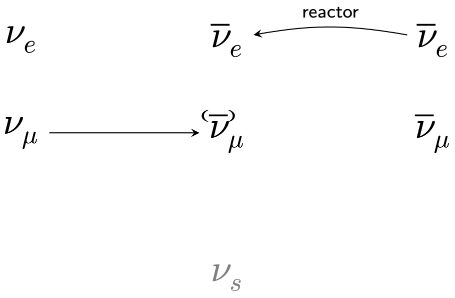

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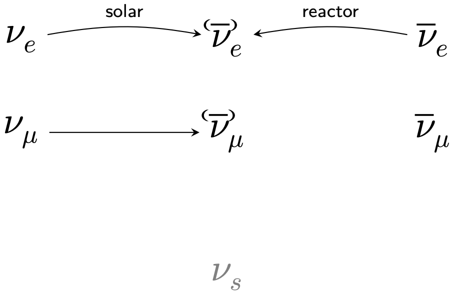

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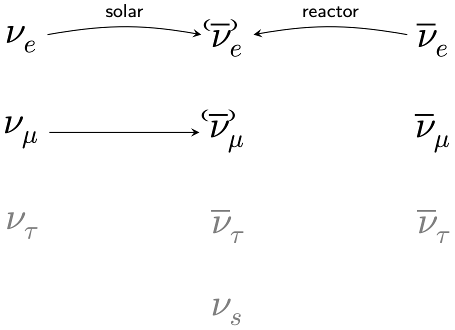

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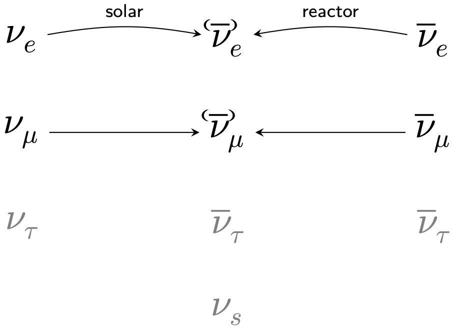

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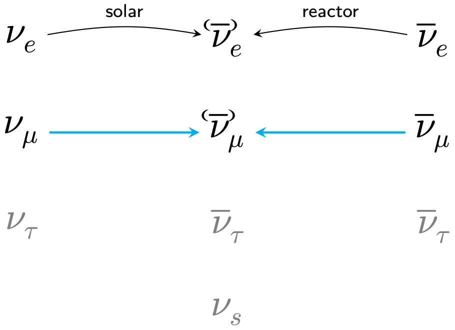

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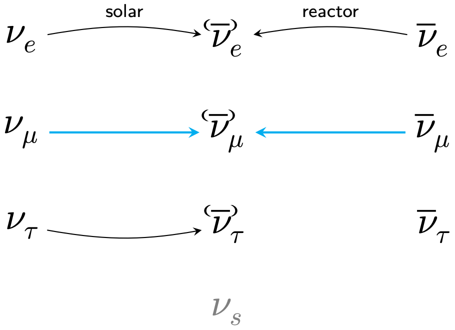

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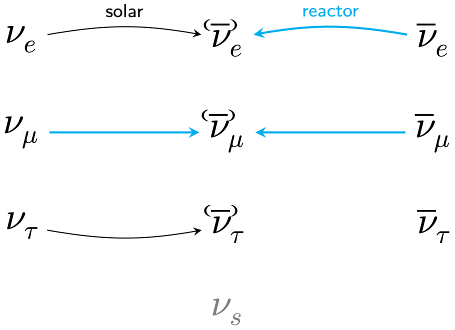

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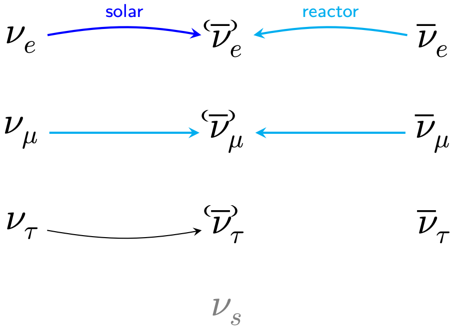

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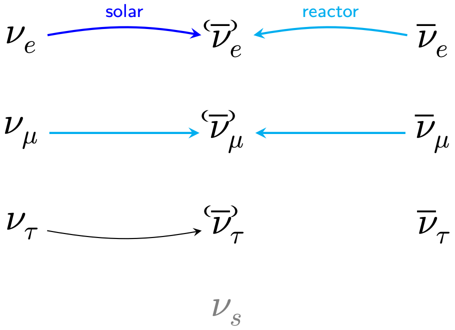

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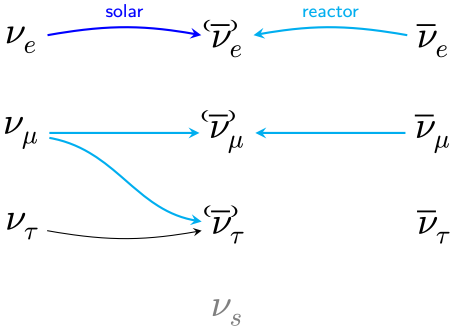

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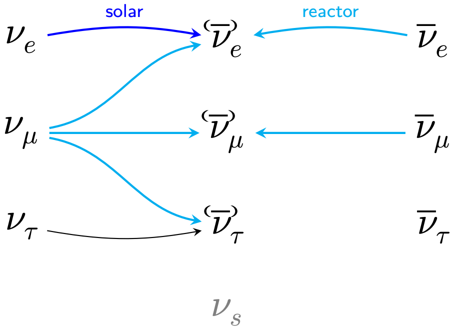

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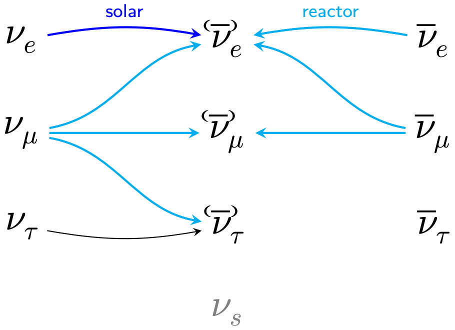

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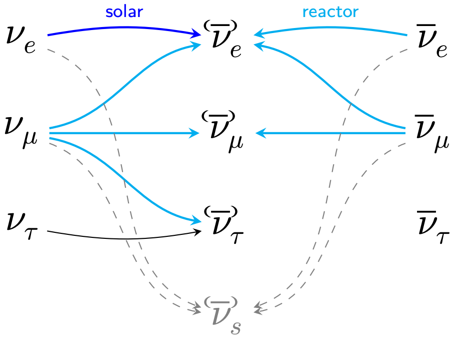

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- 2013 T2K, then NOvA: ν_e appearance
- 2018 T2K, then NOvA: $\overline{\nu}_e$ appearance
- Sterile ν_s actively searched for

Observation of $\overline{\nu}_e$

☢ $\overline{\nu}_e \longrightarrow \overline{\nu}_e$

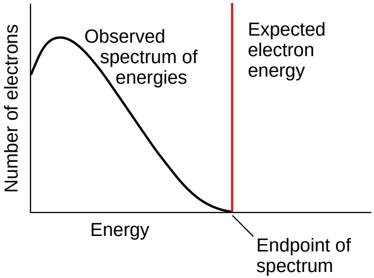
Pauli: proposal of the neutrino

Neutrino proposal

✗ Problem: in tritium (three body) decay

$$^3\text{T} \longrightarrow {}^3\text{He} + e^-$$

e^- should have definite energy.



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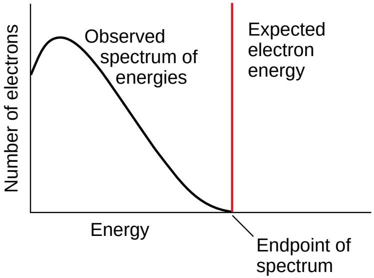

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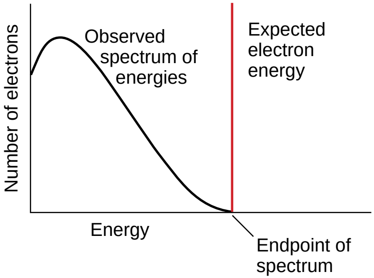

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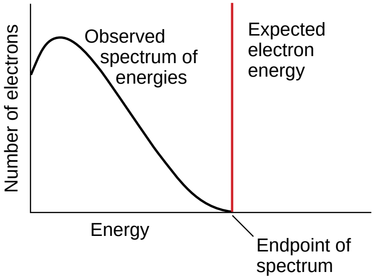
- ✗ Expected cross section: 10^{-44} cm^2

  ↪ impossible to detect



Reines and Cowan: neutrino detection experiment

Neutrino proposal

- ✗ Problem: tritium decay

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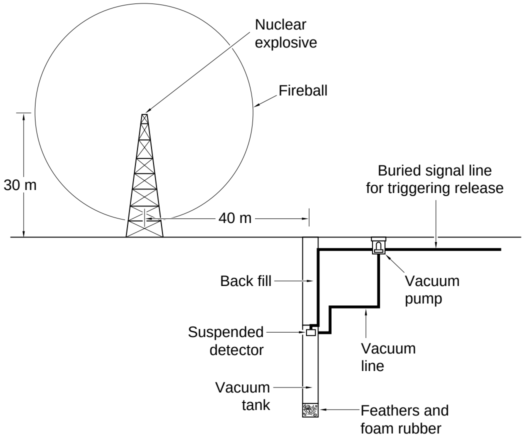
- Detect ν at 50 m from 20 kt nuclear explosion.



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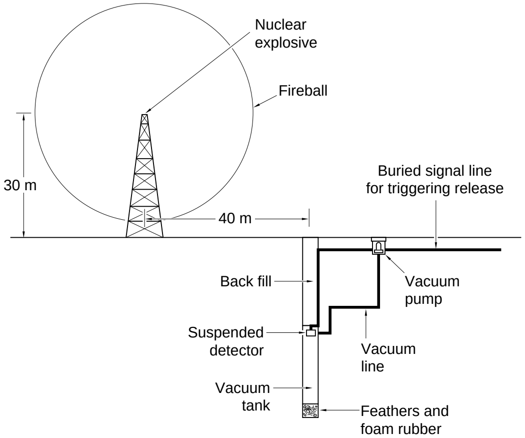

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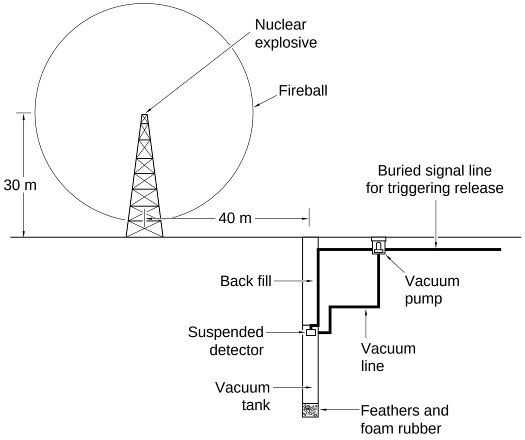

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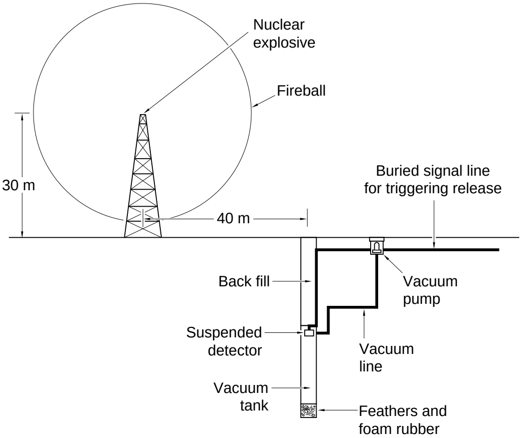

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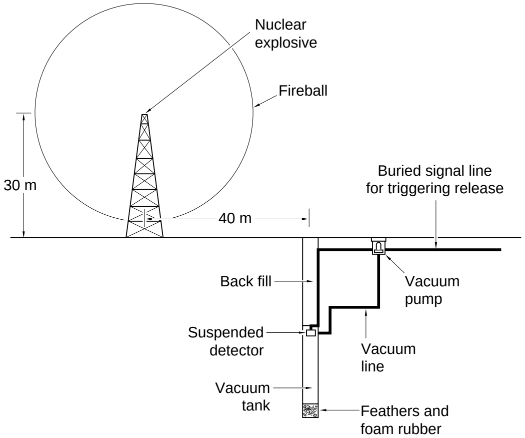
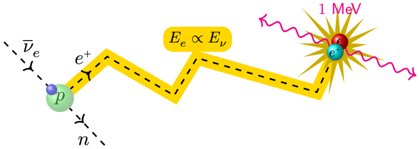
- ✓ With double signal: no need to use explosion.



Inverse beta decay and selection criteria



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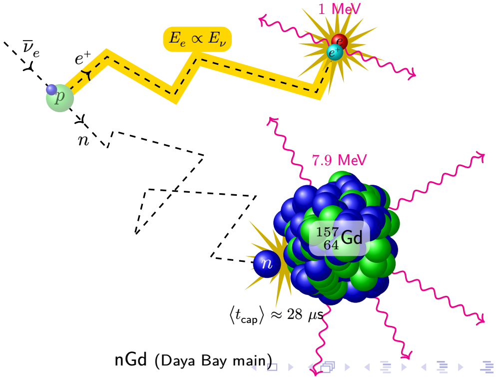

nGd (Daya Bay main)

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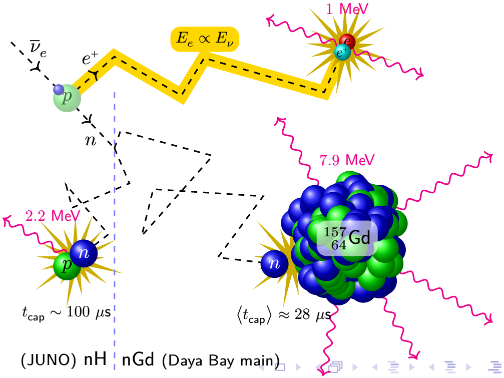

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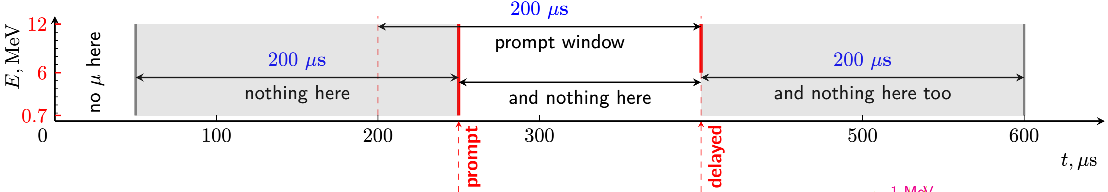

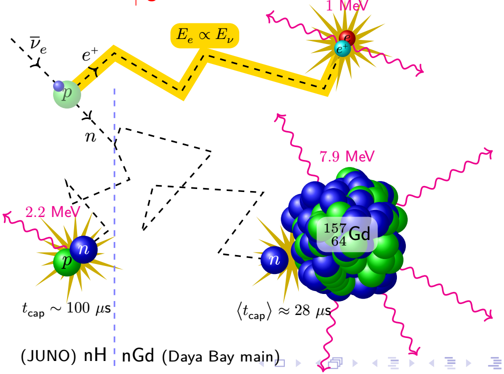

Plot: Daya Bay

Cherenkov: $< 5\%$

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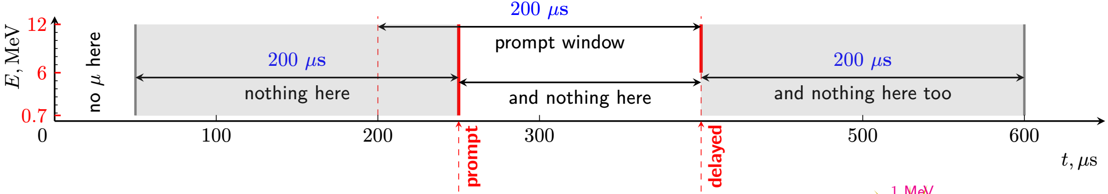

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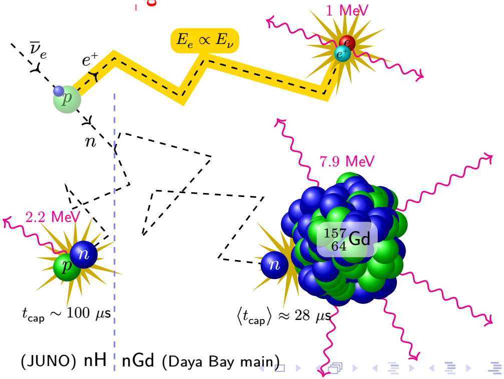
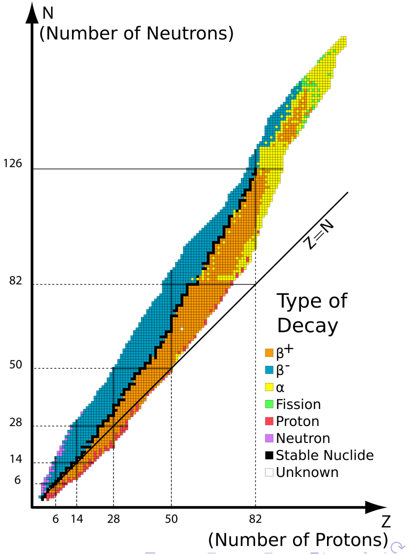
Tagged antineutrino signal

- Great background suppression
- Control over tag cross section and energy
- More complicated event selection procedure



Reactor $\overline{\nu}_e$ production and detection



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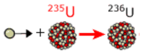

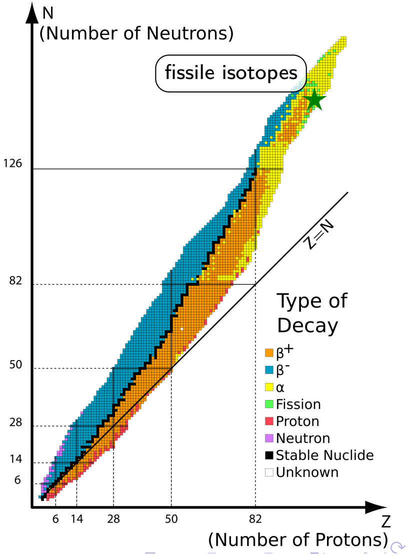

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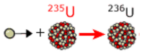

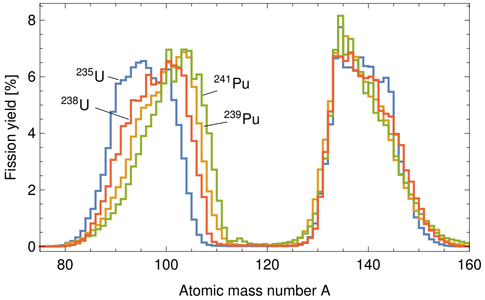

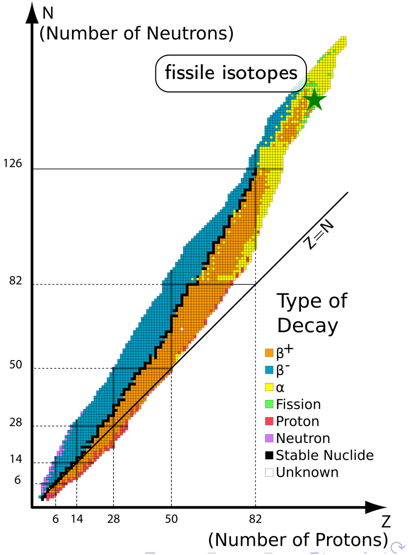

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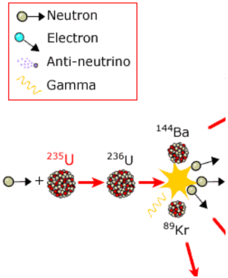

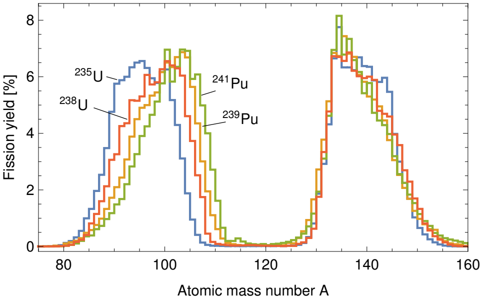

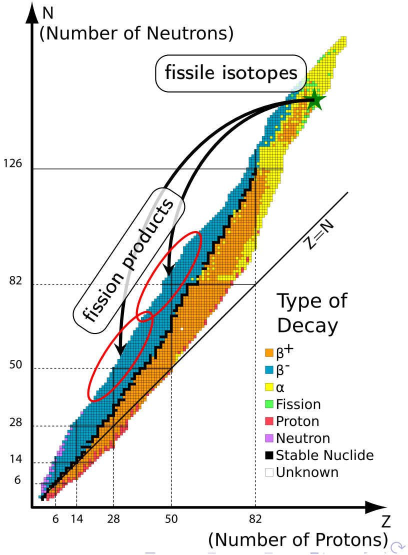

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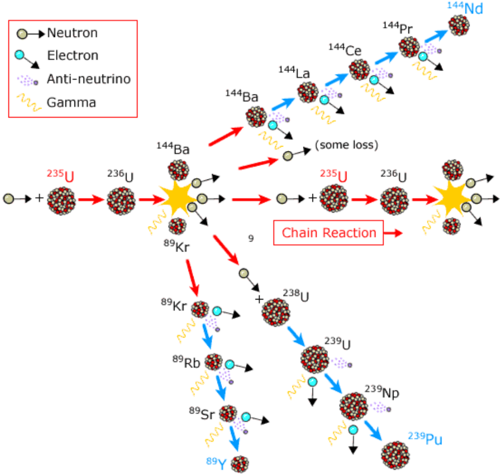

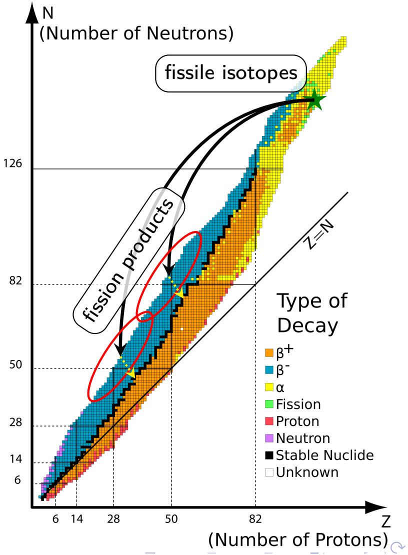

Reactor $\overline{\nu}_e$ production and detection

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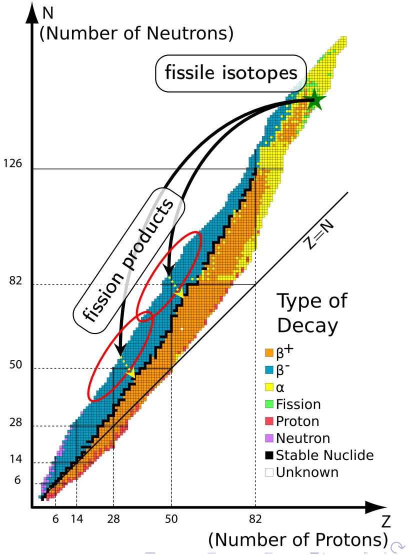

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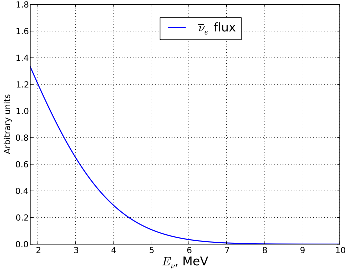
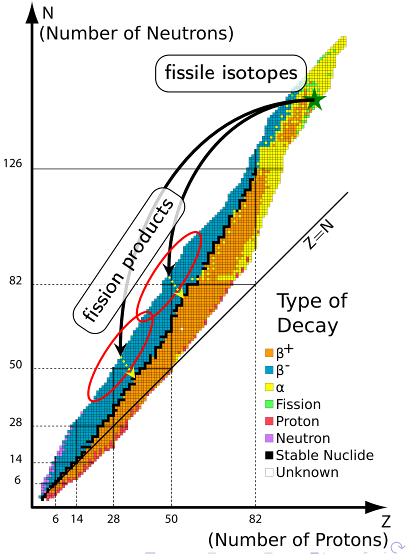


$\overline{\nu}_e$ detection



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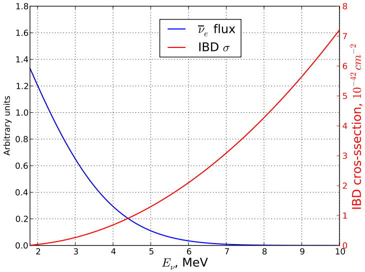

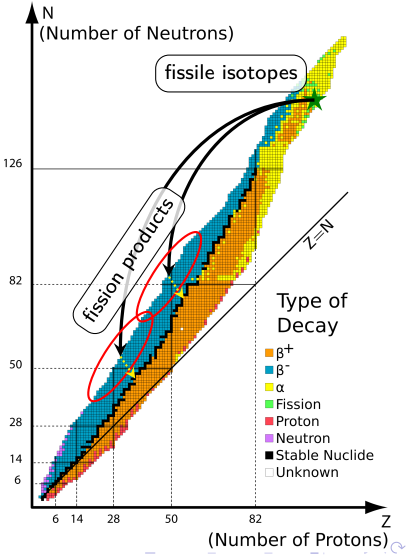

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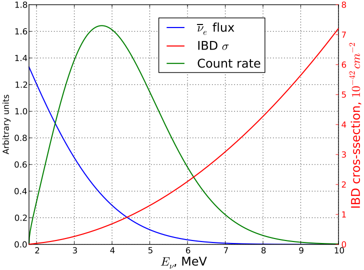
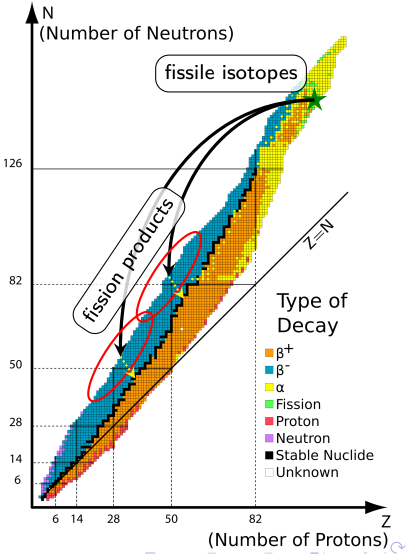
- Threshold: 1.8 MeV





Scintillation and Cherenkov light

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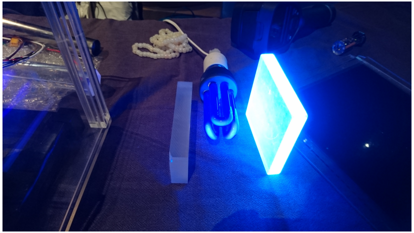
- Special material: scintillator
- Energy: "any"
- Light direction: isotropic
- Time distribution: exponential decay
  scintillator (de)excitation takes some time
  $\sim$ ns



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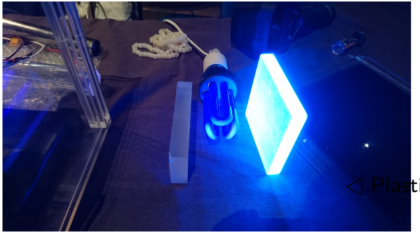
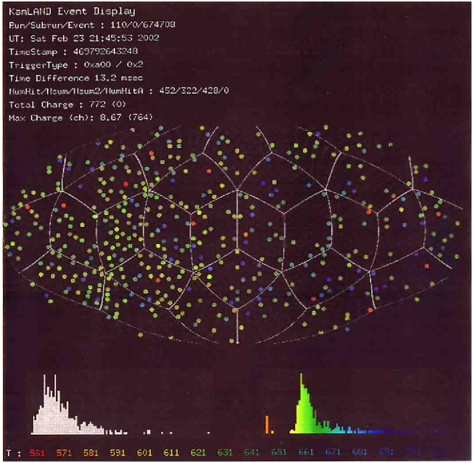


◁ Plastic scintillator in UV light

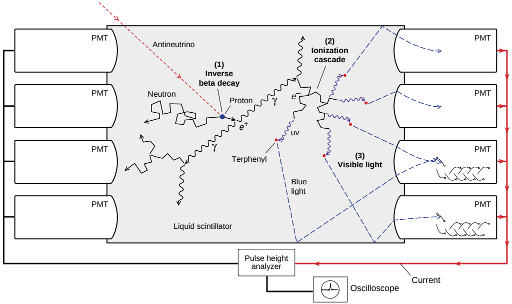


△ KamLAND first $\overline{\nu}_e$ event.

Hanford experiment: detector Herr Auge

First attempt 1953

- Cylindrical detector: ⌀71 cm, ↕ 76 cm, 300 L
- Target: liquid scintillator (LS) + ^{113}Cd
- 90 2" PMTs



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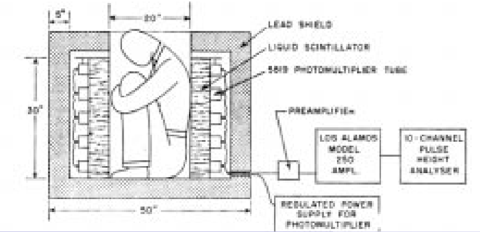

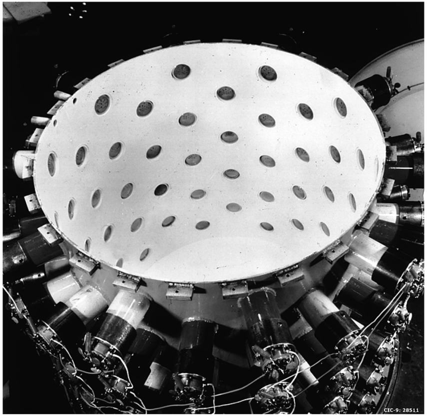

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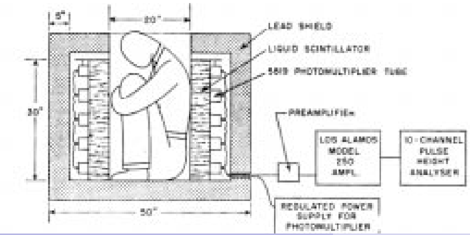

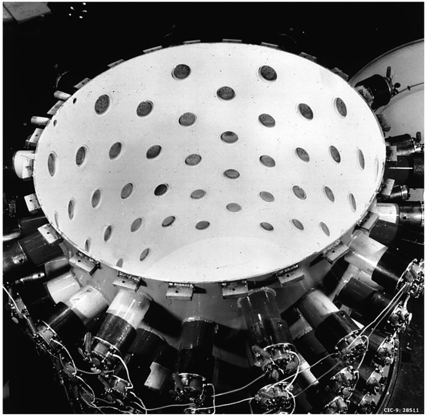

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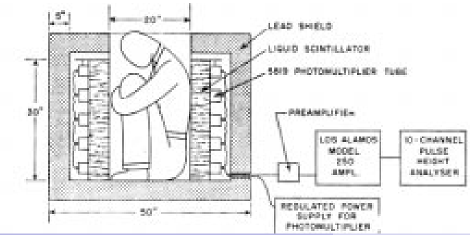

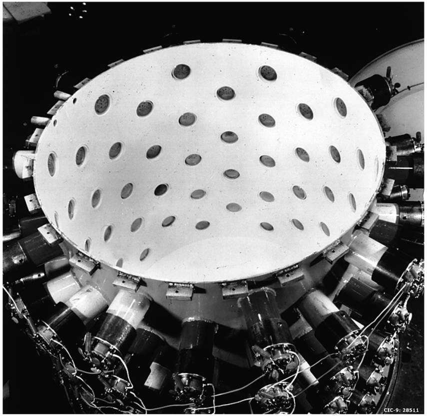

Savannah River experiment: observation

Second attempt 1955

- Sandwich detector: 3×1400 L LS
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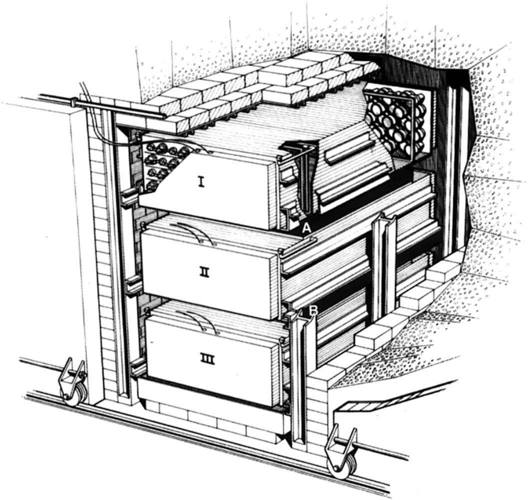

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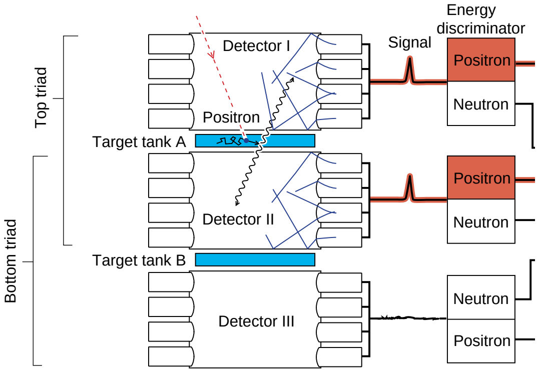

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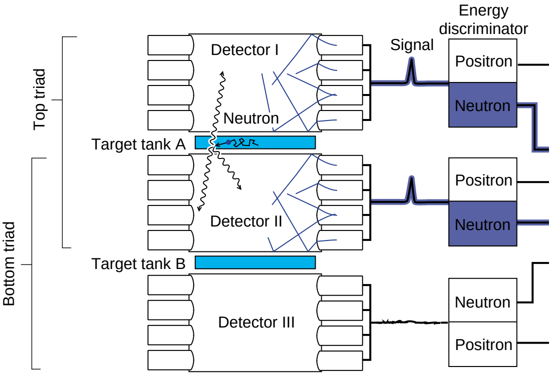

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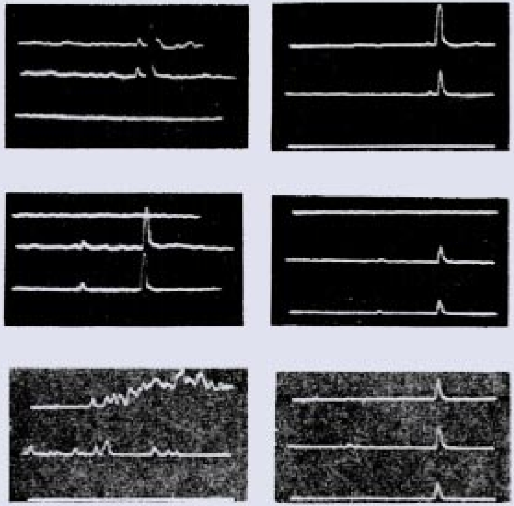

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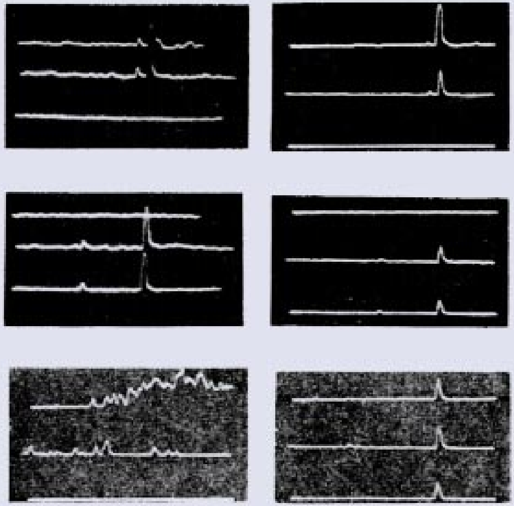

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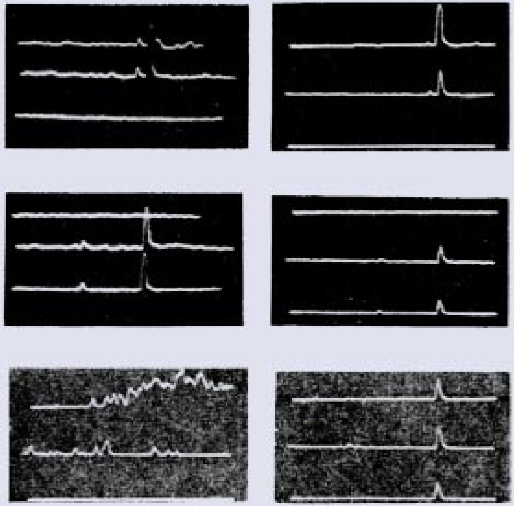

Neutrino detection with chemical method

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  - $\nu + {}^{37}\mathrm{Cl} \longrightarrow e^- + {}^{37}\mathrm{Ar}$
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  - ${}^{37}\mathrm{Ar}$ with half life of 35 days decays via electron capture
  - ${}^{37}\mathrm{Ar} + e^- \longrightarrow {}^{37}\mathrm{Cl} + \nu$, followed by Auger electron
  - Argon may be extracted and the decay may be observed

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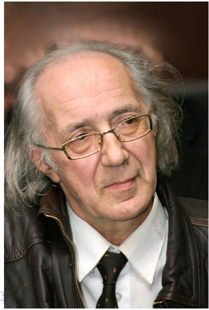
  - ${}^{37}\mathrm{Ar} + e^- \longrightarrow {}^{37}\mathrm{Cl} + \nu$, followed by Auger electron
  - Argon may be extracted and the decay may be observed



Gallium-germanium

- 1966 Kuzmin proposes gallium-germanium method
  - $\nu + {}^{71}\mathrm{Ga} \longrightarrow e^- + {}^{71}\mathrm{Ge}$
  - Threshold: 233 keV

Neutrino detection with chemical method

Chlorine-argon

- 1946 Pontecorvo proposes chlorine-argon method to detect reactor $\overline{\nu}_e$ neutrino   Report PD-205, Chalk River Laboratory, 1946
  - $\nu + {}^{37}\mathrm{Cl} \longrightarrow e^- + {}^{37}\mathrm{Ar}$
  - Threshold: 814 keV
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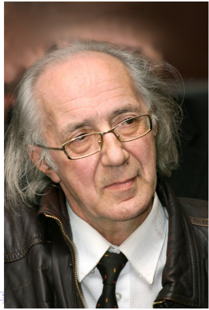

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  - Threshold: 233 keV
  - ${}^{71}\mathrm{Ge}$ half life of 11.3 days: electron capture
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In the mean time…

Reines and Cowan

- Reaction: $\overline{\nu}_e + p \longrightarrow e^+ + n$
- Threshold: 1.8 MeV
- Source: reactor

Davis

- Reaction: $\nu + {}^{37}\mathrm{Cl} \longrightarrow e^- + {}^{37}\mathrm{Ar}$
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- No signal...
- 1958 New measurements: ${}^{3}\mathrm{He} + \alpha \longrightarrow {}^{7}\mathrm{Be} + \gamma$ may contribute to the solar ν_e above Cl-Ar threshold
- Fowler and Cameron suggest Davis measuring solar $\overline{\nu}_e$

1957 Neutrino oscillations

Context

- Only reactor $\overline{\nu}_e$ observed, no (solar) ν_e, no $\nu_\mu/\overline{\nu}_\mu$.
- Davis has some candidates for reactor ν_e (not $\overline{\nu}_e$)
- $K^0 \rightleftarrows \overline{K}^0$ mixing and oscillation observed.

Oscillations

- Pontecorvo proposes the idea of $\nu_e \rightleftarrows \overline{\nu}_e$ oscillations

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- Transition probability: $P(\nu \to \overline{\nu}) = \frac{1}{2}\left(1 - \cos\frac{\Delta m^2 L}{E}\right)$

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- Theory of neutrino mixing and oscillations established by 1978:
  - Eliezer, Swift, Frietzsch, Minkowski, Bilenky and Pontecorvo
  - also Maki, Nakagawa, Sakata

Observation of ν_μ

$$\nu_\mu \longrightarrow \nu_\mu$$

Neutrino universality

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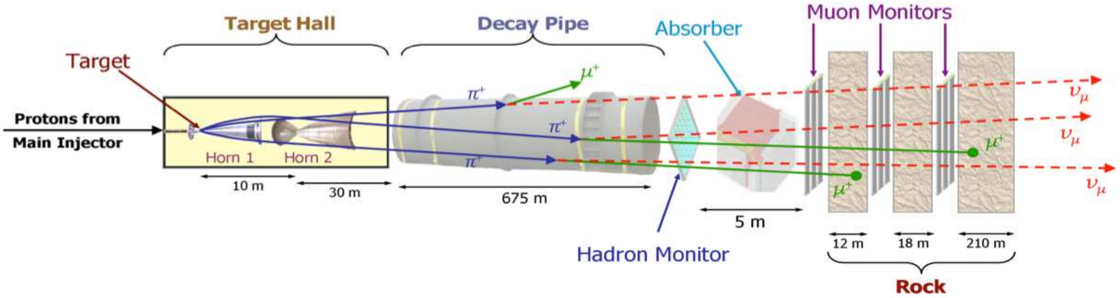
- The idea of accelerator neutrino experiments in 1959 Sov. Phys. JETP 10, 1236 (1960)
- Accelerator experiments proposed independently by M. Schwartz in 1960 Phys.Rev.Lett. 4 (1960)

Production of accelerator neutrinos



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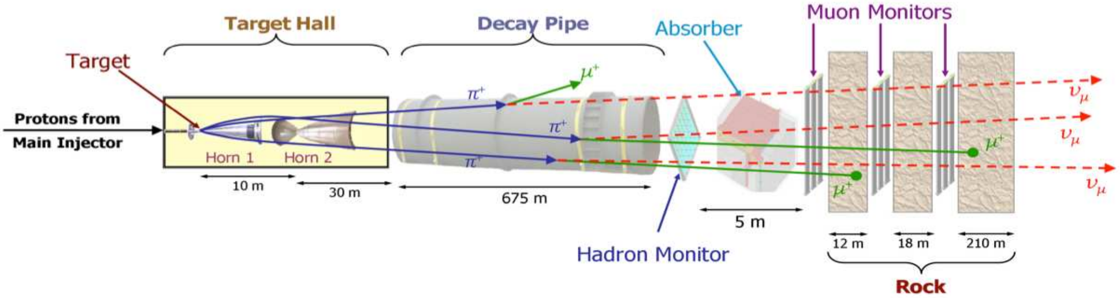

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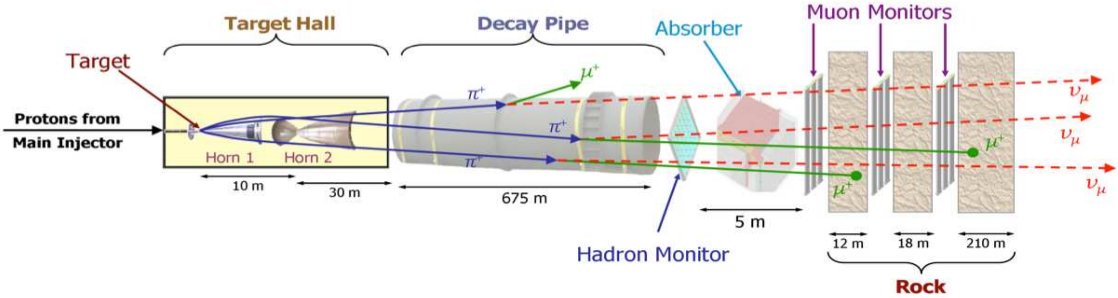

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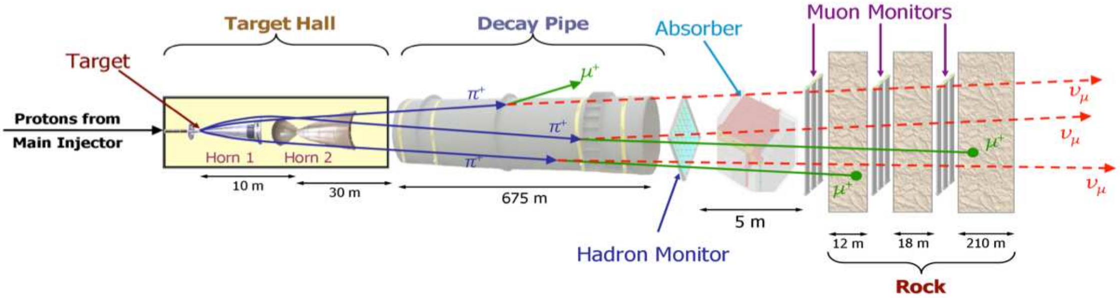

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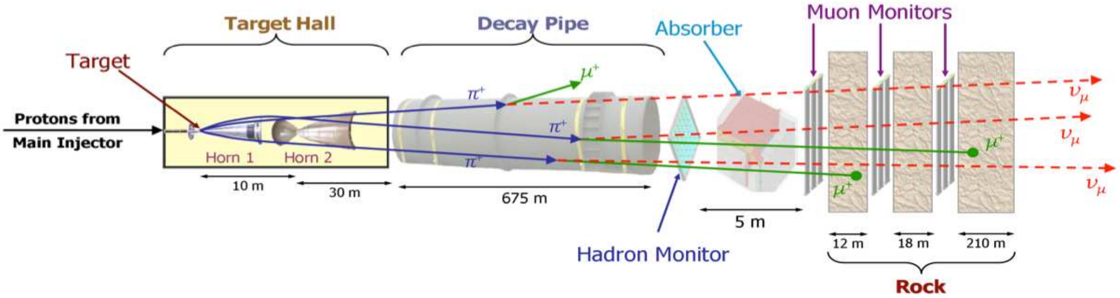

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- Absorb remaining hadrons

Accelerator neutrino beam types

Production method

- Beam dump:
  100 GeV at 1 km $\Rightarrow \Delta m^2 \gtrsim 100$ eV^2
  - ~100 GeV proton beam stops at thick target.
  - ν_e/ν_μ produced in decays of heavy hadrons

Accelerator neutrino beam types

Production method

- Beam dump
- Pion decay in flight (π-DIF)

  ~GeV at 1—1000 km
  $\Rightarrow \Delta m^2 \gtrsim 10^{-3}$ eV^2

  - Proton beam hits target, producing $\pi/$K
  - ν_e/ν_μ produced in decays of $\pi/$K
  - contains admixture of $\overline{\nu}_e/\overline{\nu}_\mu$

Accelerator neutrino beam types

Production method

- Beam dump
- Pion decay in flight (π-DIF)
- Muon decay at rest (μ-DAR):
  10 MeV at 10 m $\Rightarrow \Delta m^2 \gtrsim 1$ eV^2
  - Proton beam hits target, producing π/K
  - μ^+ produced in decays of π/K
  - ν_μ produced in decay of μ^+

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- Pion decay in flight (π-DIF)
  ~GeV at 1—1000 km
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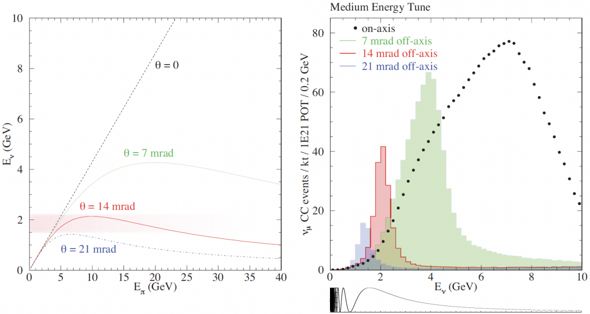
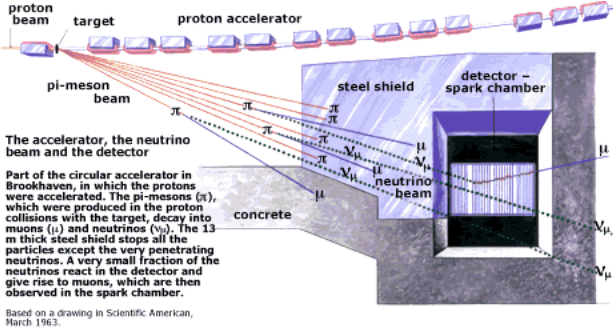
Energy spectrum

- On-axis:
  - Wide band: search for new signals
  - Narrow band: precision measurements
- Off-axis: based on wide band



1962 Observation of ν_μ from accelerator

- AGS Neutrino experiment at Brookhaven
- 15 GeV proton beam, Be target, π-DIF, on-axis
- Detector: 10 ton spark chamber



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- Lederman, Schwartz, Steinberger: Nobel Prize 1988

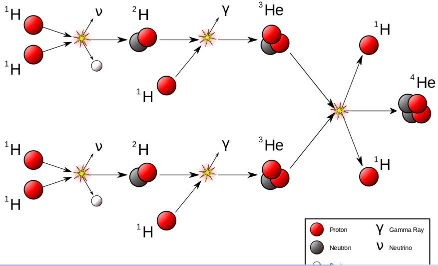
Observation of solar neutrino

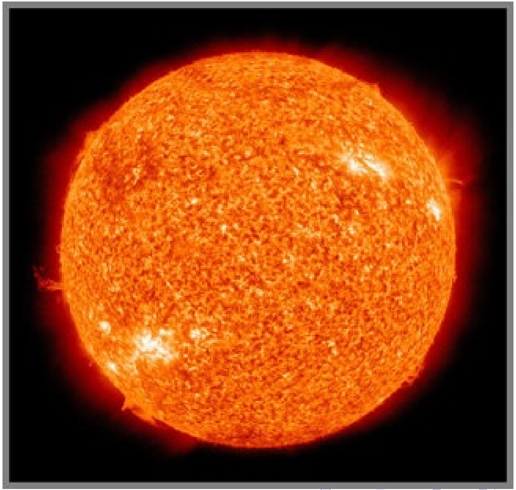
☼ $\nu_e \longrightarrow \nu_e$

Solar neutrinos

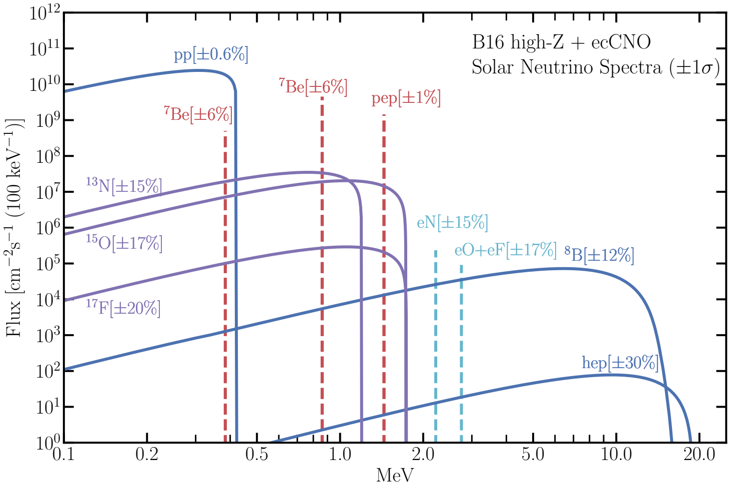
- Produced in fusion process in the Sun
- Produced: electron neutrino
- At Earth: all neutrino flavors
- Flux: $7 \times 10^{10}\ \nu_e/\mathrm{cm}^2/\mathrm{s}$
- Energies: < 20 MeV

▿ Dominant reaction





Solar ν_e spectrum



Solar ν_e observation

- Location: Homestake gold mine, South Dakota
- Target: tetrachlorethylene C_2Cl_4

  "dry-cleaning fluid"
- 390 000 l, ^{37}Cl fraction $\sim 1/4$
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  - 2.32 ± 0.22 Solar Neutrino Units (SNU)

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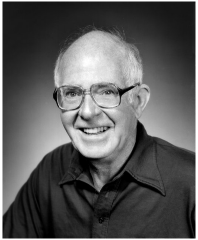

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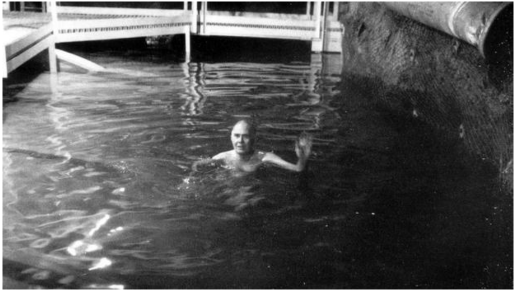
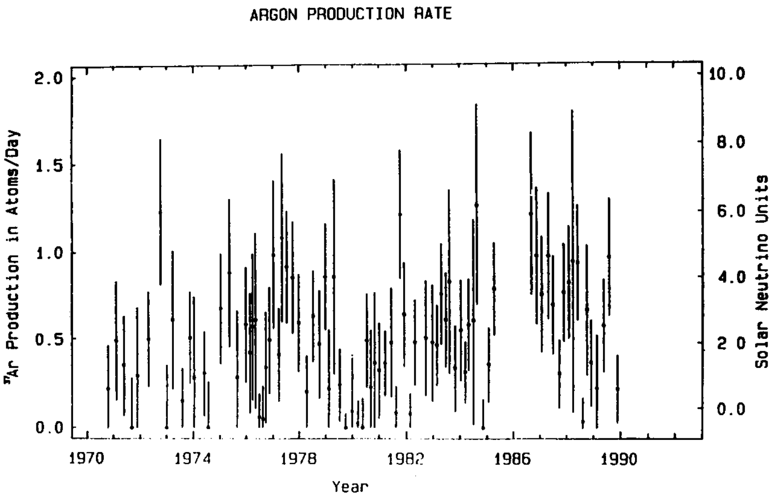
- Nobel Prize 2002: Raymond Davis Jr.



SOLAR ν_e OBSERVATION



Homestake experiment was taking data from March 1970 to February 1994.

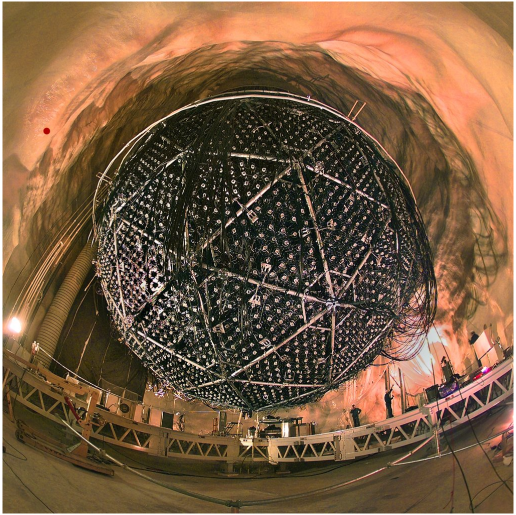
Solar mixing

☼ $\nu_e \longrightarrow \nu_e$

SNO: Sudbury Neutrino Observatory

Summary

- Location: Craighton mine, Sudbury, Canada
- Goal: Solar ν_e from $^8\mathrm{B}$
- Detector: $\varnothing$12 m acrylic sphere
- Target: 1 kt D_2O
- PMT + light concentrator: 9438 8"
- Resolution: $\sigma_E = 6\%$ at 1 MeV



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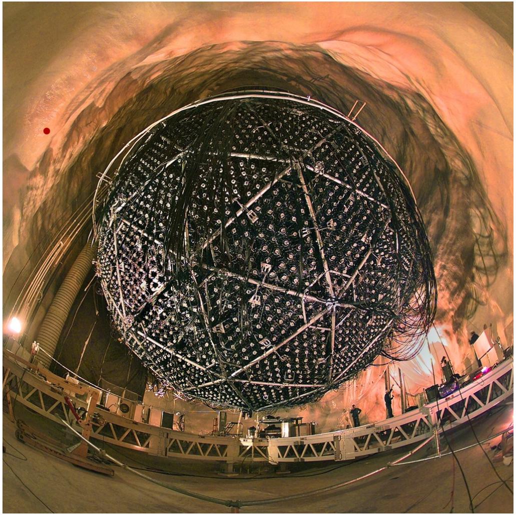

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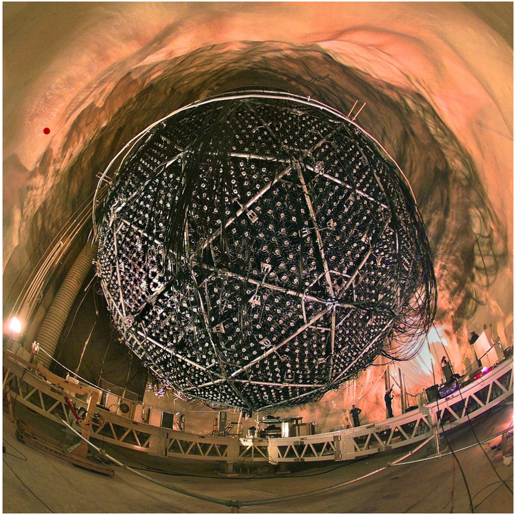

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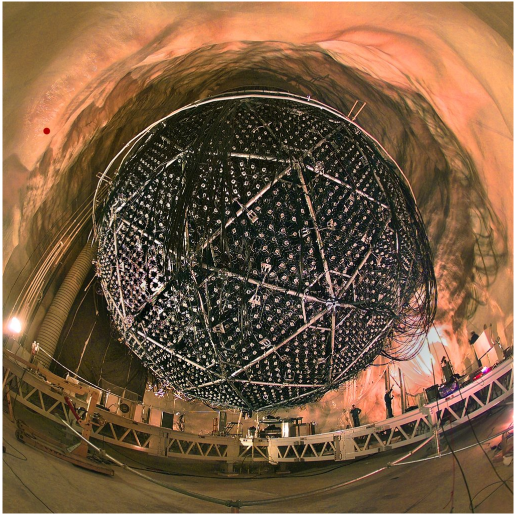

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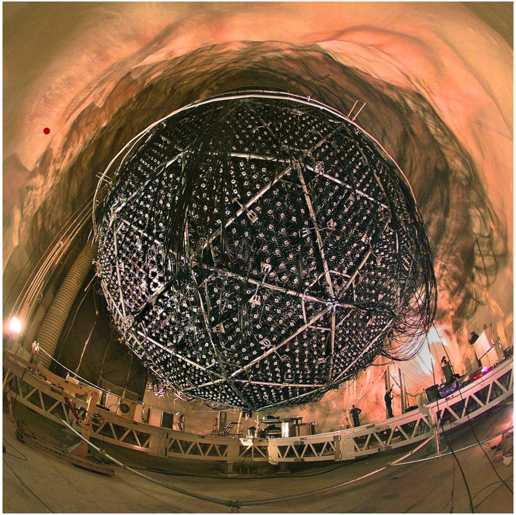
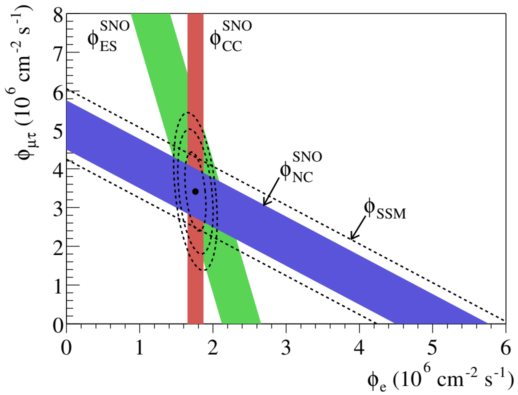
- Sensitive to all ν flavors from Sun

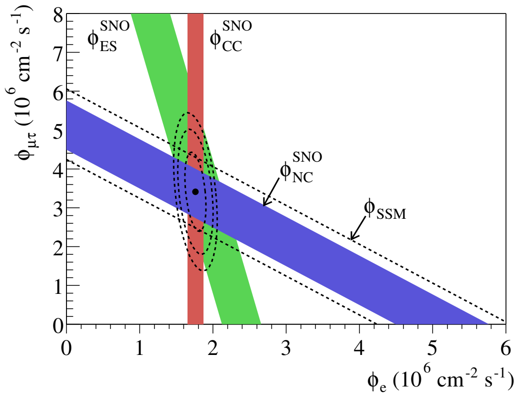


SNO RESULTS



- Observation of neutrino flavor change: $\nu_e \longrightarrow \nu_\mu + \nu_\tau$

SNO results



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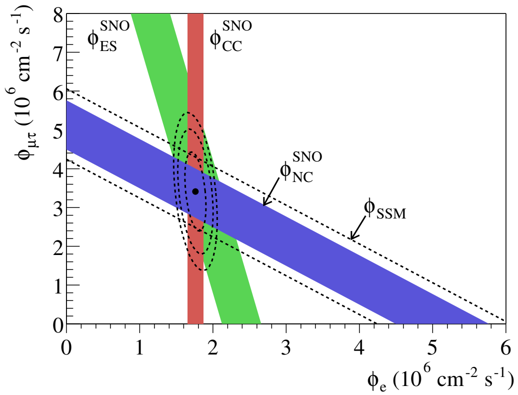
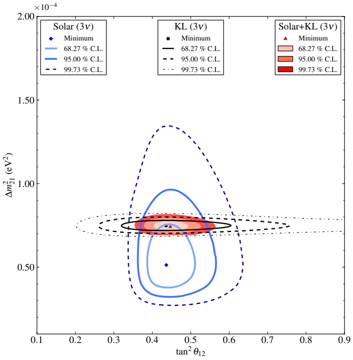


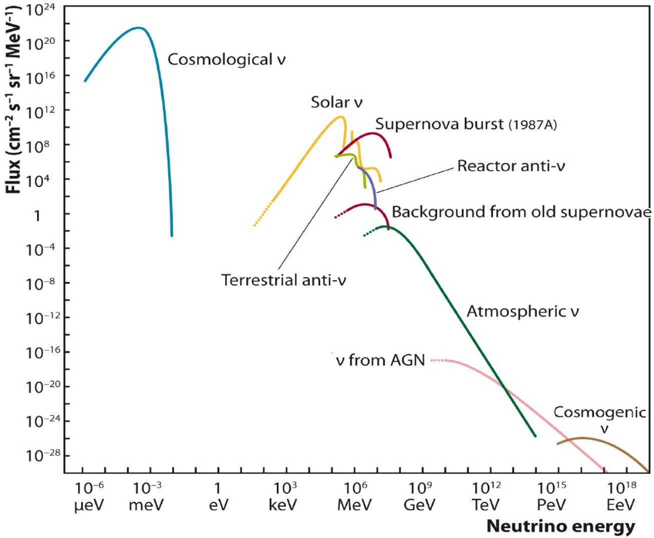


- Observation of neutrino flavor change: $\nu_e \longrightarrow \nu_\mu + \nu_\tau$
- Nobel Prize 2015: Arthur B. McDonald; Breakthrough Prize 2016: SNO collaboration
- Most precise θ_{12} measurement
- Homestake, GALLEX, SAGE, Borexino, Super-Kamiokande draw consistent picture: MSW osc.

Observation

$$\nu_e \longrightarrow \nu_\mu$$

Neutrino sources



10^{14}

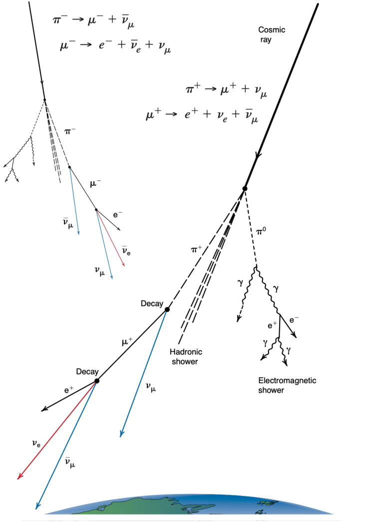
neutrinos are passing you per second at any given time at the speed of light.

($\sim$ 100 000 000 000 000 particles/second)

Atmospheric neutrino and oscillations

Production

- Interaction of cosmic ray particle in the atmosphere
- Evolution of hadronic shower: $\pi^\pm$, $K^\pm$



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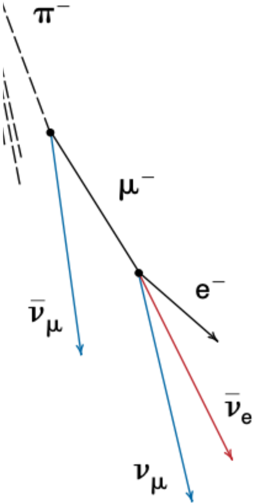
- Similar to accelerators:
  - $\pi^+ \longrightarrow \mu^+ + \nu_\mu$
  - $\mu^+ \longrightarrow e^+ + \nu_e + \overline{\nu}_\mu$
- At production area

$$R = \frac{\nu_\mu + \overline{\nu}_\mu}{\nu_e + \overline{\nu}_e} = 2$$



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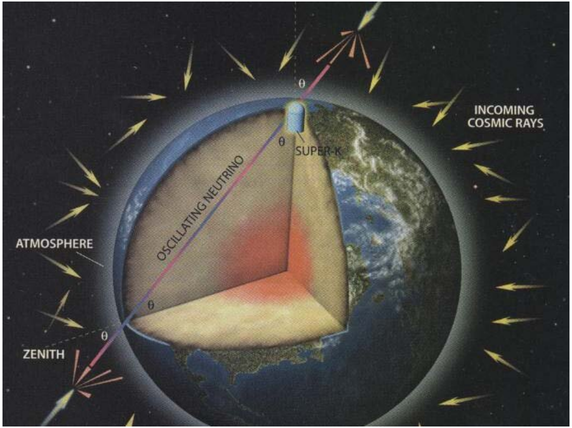

Detection

- Oscillations: distort R
- Source: whole atmosphere
- Downward: vacuum oscillations, short baseline
- Upward: matter oscillations, long baseline

High energy neutrino detection

Neutrino: Charged Current (CC)

- $\nu_\mu + n \longrightarrow \mu^- + p$ $\hookrightarrow$ Long muon track

Anti-neutrino: Charged Current (CC)

- $\overline{\nu}_\mu + p \longrightarrow \mu^+ + n$ $\hookrightarrow$ Long muon track

High energy neutrino detection

Neutrino: Charged Current (CC)

- $\nu_\mu + n \longrightarrow \mu^- + p$ ↪ Long muon track
- $\nu_e + n \longrightarrow e^- + p$ ↪ Electromagnetic shower

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High energy neutrino detection

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- $\overline{\nu}_\mu + p \longrightarrow \mu^+ + n$ — $\hookrightarrow$ Long muon track
- $\overline{\nu}_e + p \longrightarrow e^+ + n$ — $\hookrightarrow$ Electromagnetic shower

All neutrinos: Neutral Current (NC)

- eNC: $\nu_x + p \longrightarrow \nu_x + p$
- pNC: $\nu_x + e^- \longrightarrow \nu_x + e^-$ — $\hookrightarrow$ Hadronic shower, no muon

High energy neutrino detection

Neutrino: Charged Current (CC)

- $\nu_\mu + N \longrightarrow \mu^- + X$ ↪ Long muon track
- $\nu_e + N \longrightarrow e^- + X$ ↪ Electromagnetic shower

Anti-neutrino: Charged Current (CC)

- $\overline{\nu}_\mu + N \longrightarrow \mu^+ + X$ ↪ Long muon track
- $\overline{\nu}_e + N \longrightarrow e^+ + X$ ↪ Electromagnetic shower

All neutrinos: Neutral Current (NC)

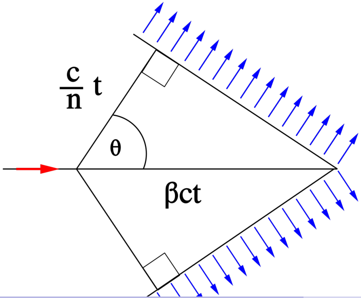
- eNC: $\nu_x + N \longrightarrow \nu_x + X$
- pNC: $\nu_x + e^- \longrightarrow \nu_x + e^-$ ↪ Hadronic shower, no muon

Scintillation and Cherenkov light

- Common scenario: neutrino interaction produces a single charged particle in a large volume

Cherenkov light

- Any transparent material
- Particle velocity > light velocity in matter
- Cherenkov cone
- Time distribution: 'immediate'



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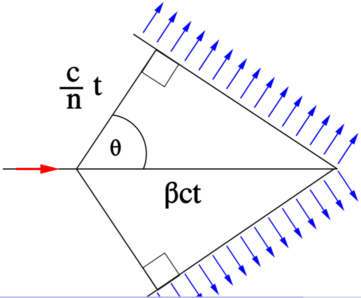
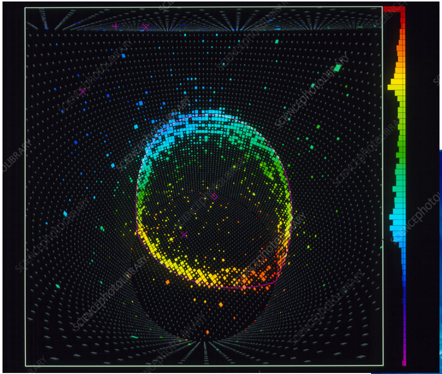
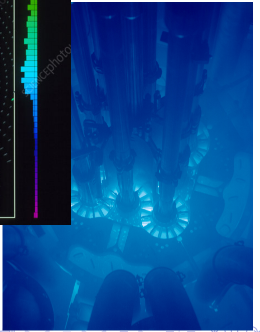




△ Super Kamiokande muon event.



ATR reactor Cherenkov light ▷

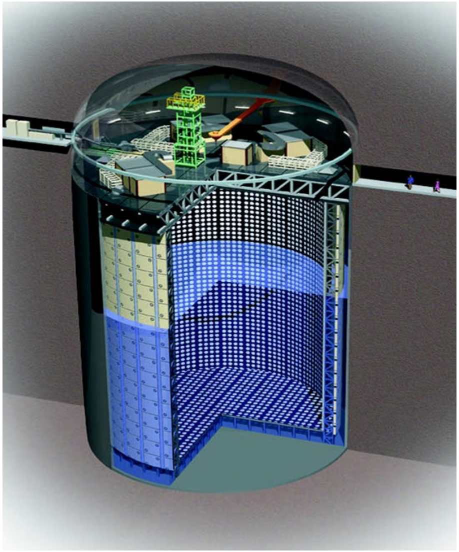
Atmospheric Neutrino Anomaly

First atmospheric neutrino measurements

- Kamiokande experiment
  - $R_{\mu/e}^{\text{multi-GeV}} = 0.60^{+0.07}_{-0.06} \pm 0.05$ Phys. Lett., B280, 1992
  - $R_{\mu/e}^{\text{multi-GeV}} = 0.57^{+0.08}_{-0.07} \pm 0.07$ Phys. Lett., B335, 1994
- IMB experiment: Irvine-Michigan-Brookhaven
  - $R_{\mu/e}^{\text{multi-GeV}} = 0.54 \pm 0.05 \pm 0.11$ Nucl. Phys. Proc. Suppl., 70, 1999
- where $R_{\mu/e}$ is double ratio: $R_{\text{DATA}}/R_{\text{MC}} = 1$ in case of no deviation.

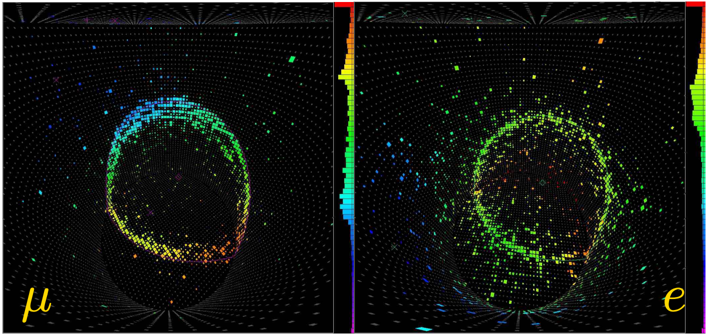
Super-KamiokaNDE experiment

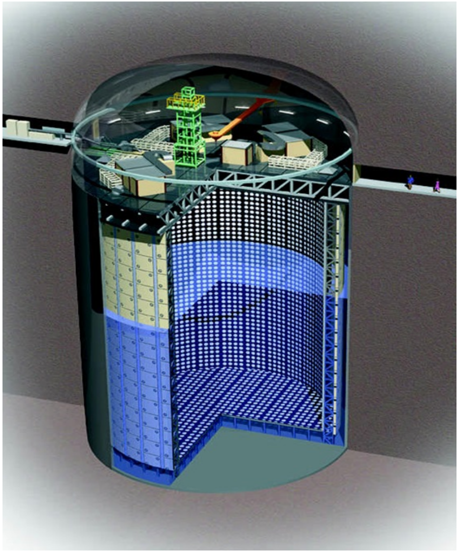
- Location: Kamioka mine, Japan
- Goals: ν_e/ν_μ
  - Solar ν_e from ^8B
  - Atmospheric ν_μ/ν_e
  - Proton decay (original)
- Operation: since 1996
- Detector: 40 m tank
- Target: 50 kt ultra-pure H_2O
- PMT: 11 146 8"

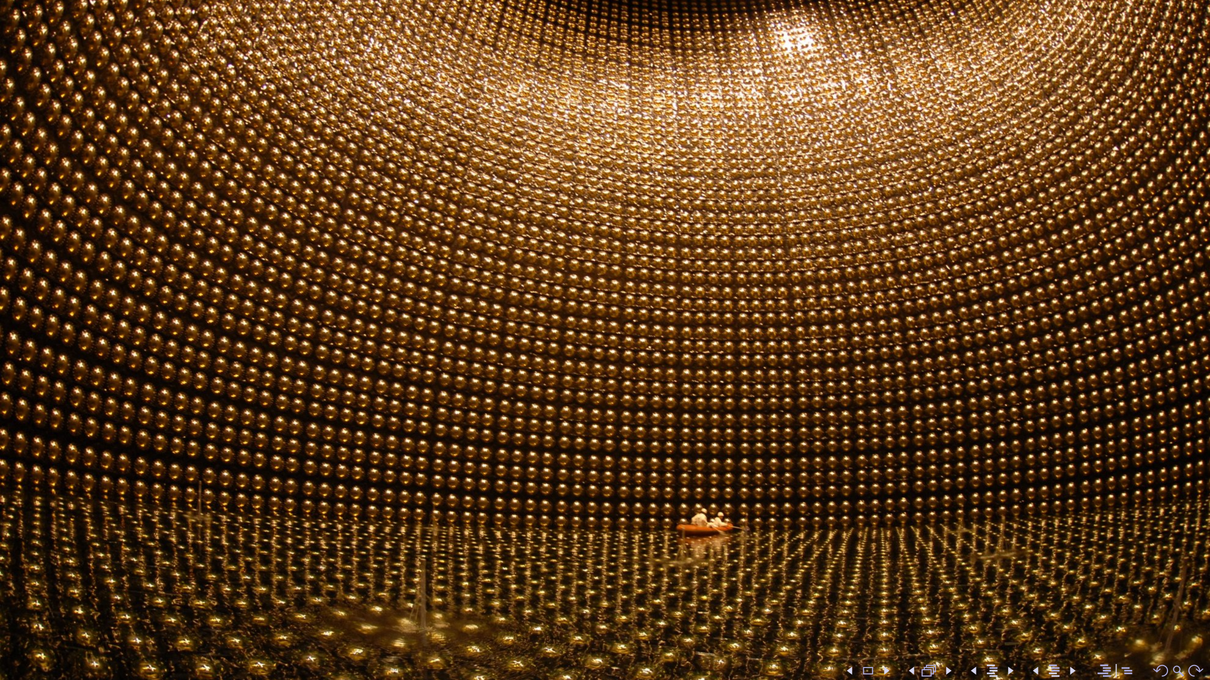


Super-KamiokaNDE experiment

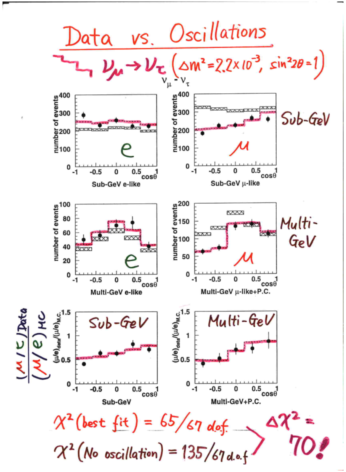
- Location: Kamioka mine, Japan
- Goals: ν_e/ν_μ
- Signal: Cherenkov "rings"
  - μ/e separation
  - no particle/antiparticle discrimination





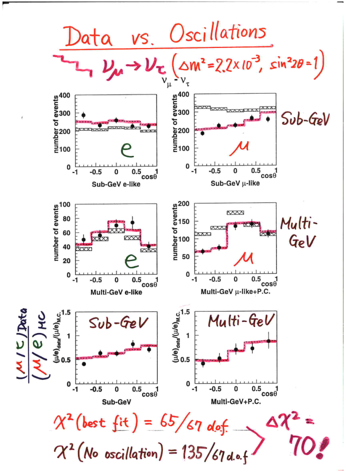


SuperK atmospheric results



Takaaki Kajita at Neutrino 1998

SuperK atmospheric results



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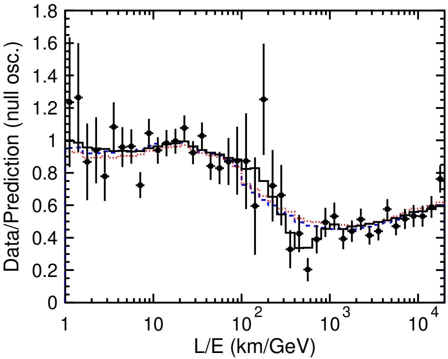

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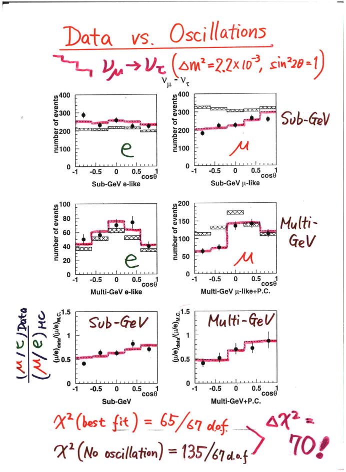

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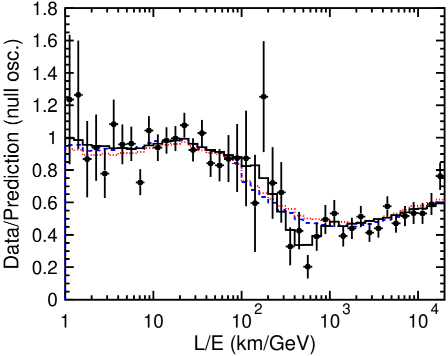


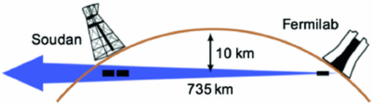
- Observation of ν_μ disappearance: $\nu_\mu \longrightarrow \nu_\tau$ (mostly)
- Nobel Prize 2015: Takaaki Kajita
- Breakthrough Prize 2016: SuperK collaboration

Accelerator ν_μ disappearance

 $\nu_\mu \longrightarrow \nu_\mu$

MINOS: Main Injector Neutrino Oscillation Search

- Location: Soudan mine, Northen Minnesota, US
- Beam: FNAL Main Injector, 735 km, E_ν=3.5 GeV
  π-DIF, on-axis
- Operation: 2005—2012
- Goal: ν_μ oscillations
- Target: 0.98 kton/5.4 kton (near/far)
- Detector: steel-scintillator, magnetic field



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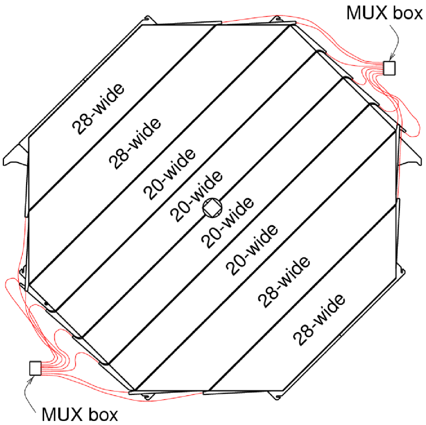

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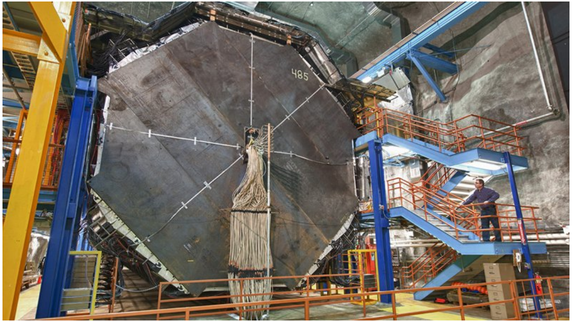
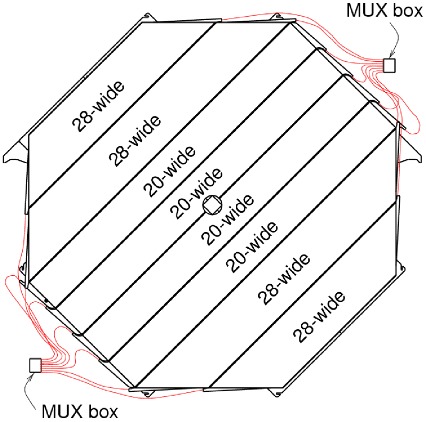
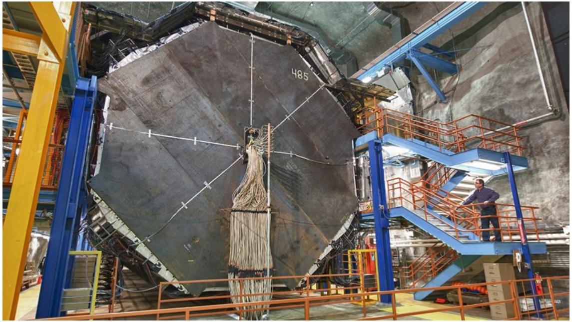
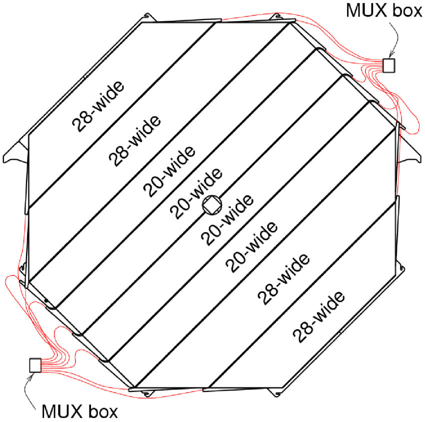




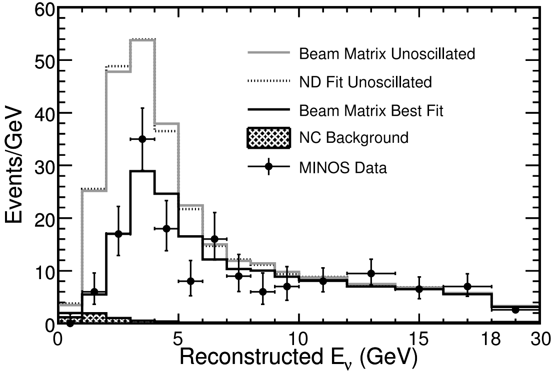
MINOS: Main Injector Neutrino Oscillation Search

- Operation: 2005—2012
- Goal: ν_μ oscillations
- Statistics, contained events:
  - 2579 ν_μ from ν_μ beam
  - 226 $\overline{\nu}_\mu$ from $\overline{\nu}_\mu$ beam
  - 905 $\nu_\mu/\overline{\nu}_\mu$ from atmosphere



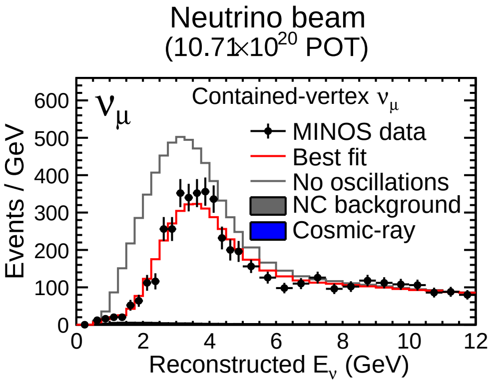


MINOS RESULTS



- 2006: Measurement of $\Delta m^2_{32} = 2.74^{+0.44}_{-0.26} \Longrightarrow$ baseline for reactor experiments

MINOS RESULTS



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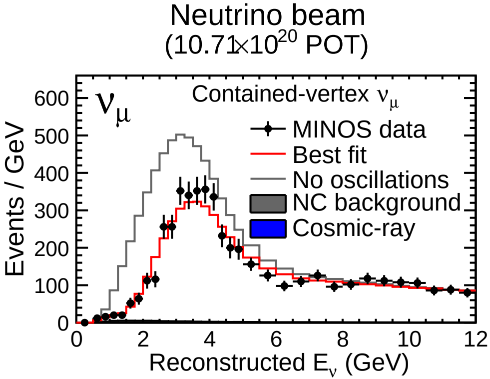
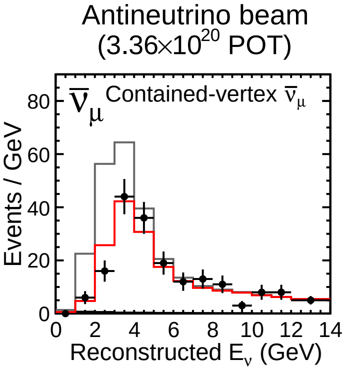
MINOS results





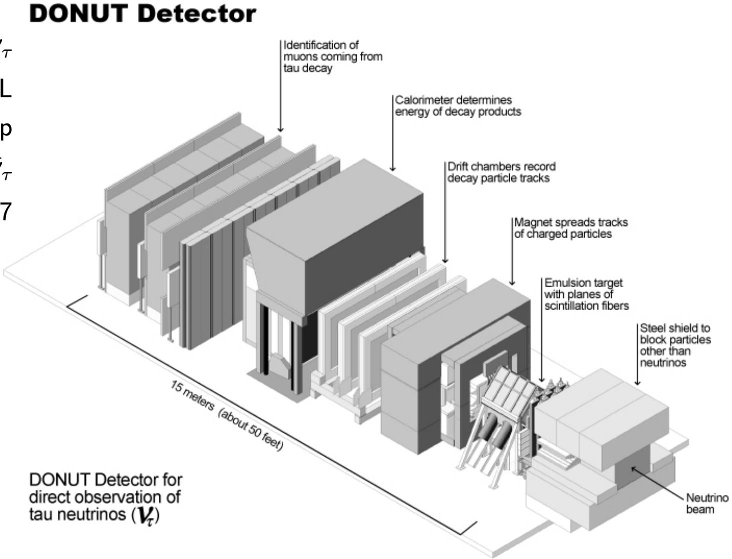
- 2006: Measurement of $\Delta m^2_{32} = 2.74^{+0.44}_{-0.26}$ $\Longrightarrow$ baseline for reactor experiments
- Final: evidence for $\overline{\nu}_e$ disappearance

ν_τ appearance

$$\nu_\mu \longrightarrow \nu_\tau$$

DONUT: Direct Observation of Nu-Tau

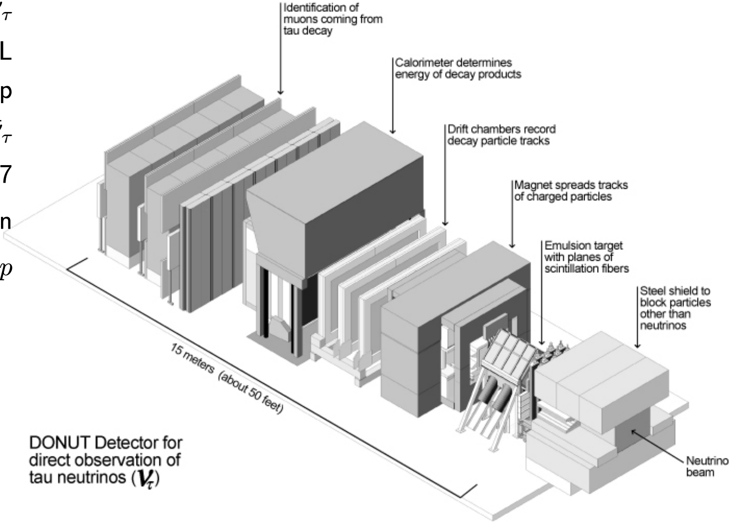
- Goal: observe ν_τ
- Beam: TeVatron at FNAL
  40 m, E_ν=∼50 GeV, beam dump
  $$D_s \longrightarrow \tau + \overline{\nu}_\tau$$
- Operation: 1997



DONUT: Direct Observation of Nu-Tau

- Goal: observe ν_τ
- Beam: TeVatron at FNAL
  40 m, $E_\nu = \sim 50$ GeV, beam dump
  $D_s \longrightarrow \tau + \overline{\nu}_\tau$
- Operation: 1997
- Target: 260 kg emulsion
- Detection $\nu_\tau + n \longrightarrow \tau + p$

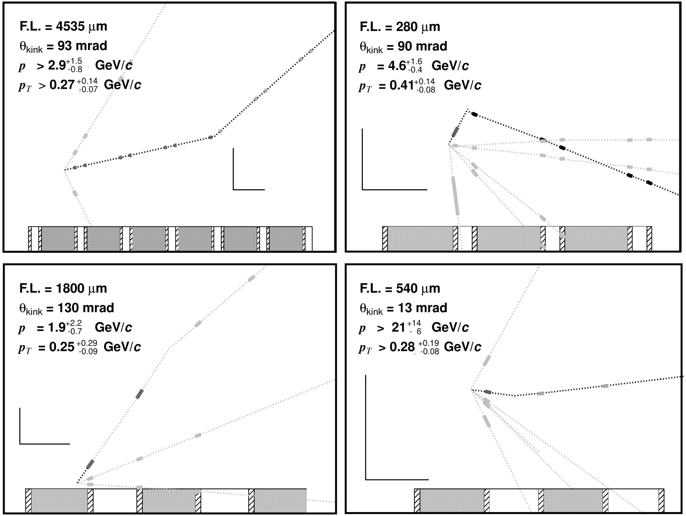
DONUT Detector



DONUT Detector for direct observation of tau neutrinos (ν_τ)

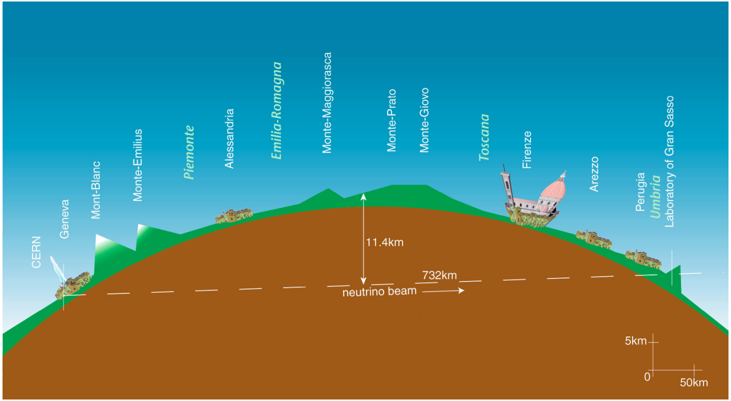
DONUT: Direct Observation of Nu-Tau

- Goal: observe ν_τ
- Beam: TeVatron at FNAL
  40 m, E_ν=∼50 GeV, beam dump
  $D_s \longrightarrow \tau + \overline{\nu}_\tau$
- Operation: 1997
- Target: 260 kg emulsion
- Detection $\nu_\tau + n \longrightarrow \tau + p$
- Results:
  - Observed: 9 ν_τ events
  - Expected background: 1.5



OPERA: Oscillation Project with Emulsion-tRacking Apparatus

- Goal: observe ν_τ appearence
- Beam: CERN to Gran-Sasso
  732 km, E_ν=17 GeV, π-DIF, on-axis
- Operation: 2008—2012



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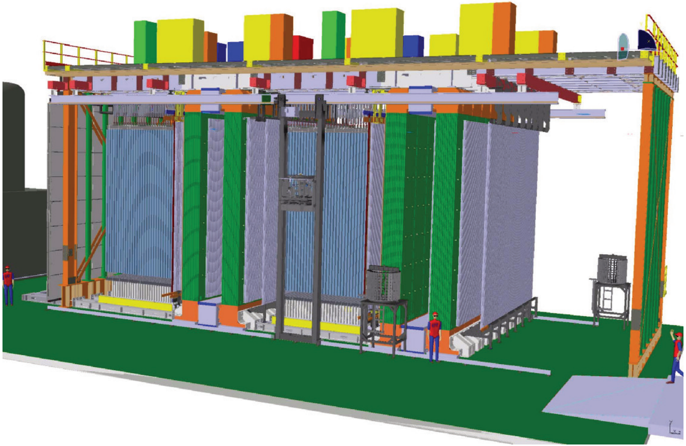
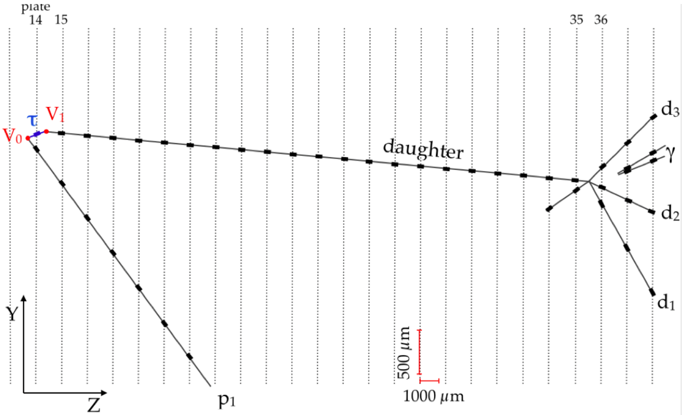
- Beam: CERN to Gran-Sasso
  732 km, E_ν=17 GeV, π-DIF, on-axis
- Operation: 2008—2012
- Target: 1.25 kt Lead
- Detection: emulsion layers
  observe "kink"



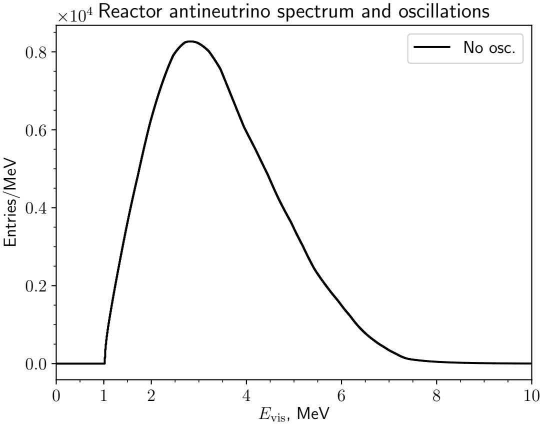
OPERA: Oscillation Project with Emulsion-tRacking Apparatus

- Results:
  - Observed: 10 ν_τ
  - Expected background: 2.0 ± 0.4

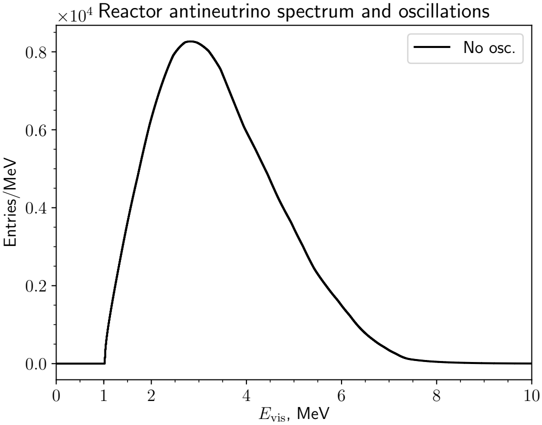


Disappearance of $\overline{\nu}_e$

☢ $\overline{\nu}_e \longrightarrow \overline{\nu}_e$



$E_{\text{vis}} \approx E_\nu - 0.78\,\text{MeV}$

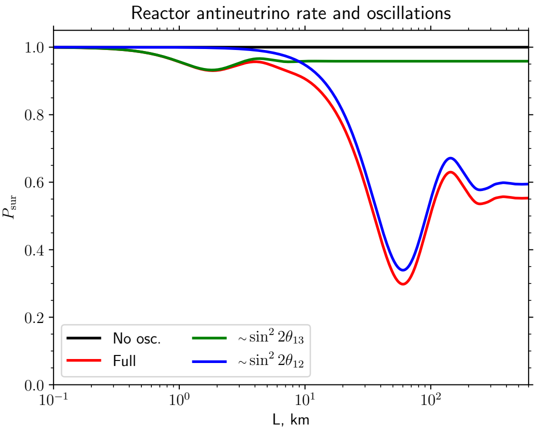


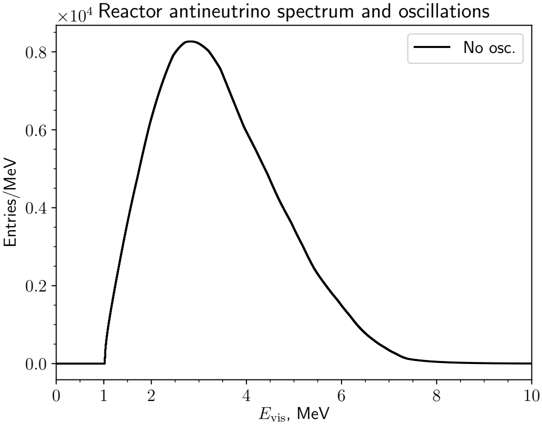
$$1 - P_{\overline{\nu}_e\to\overline{\nu}_e} = \sin^2 2\theta_{13} \left(\sin^2\theta_{12} \sin^2 \frac{\Delta m^2_{32} L}{4E} + \cos^2\theta_{12} \sin^2 \frac{\Delta m^2_{31} L}{4E} \right) + \sin^2 2\theta_{12} \cos^4\theta_{13} \sin^2 \frac{\Delta m^2_{21} L}{4E}$$

~~$\delta_{\rm CP}, \theta_{23}$~~

$E_{\rm vis} \approx E_\nu - 0.78$ MeV

Integrated with reactor $\overline{\nu}_e$ spectrum





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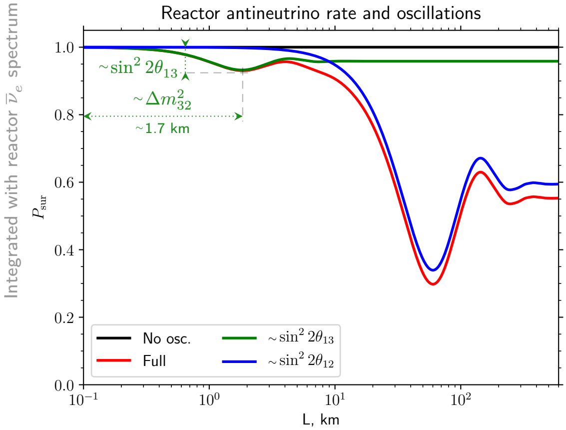
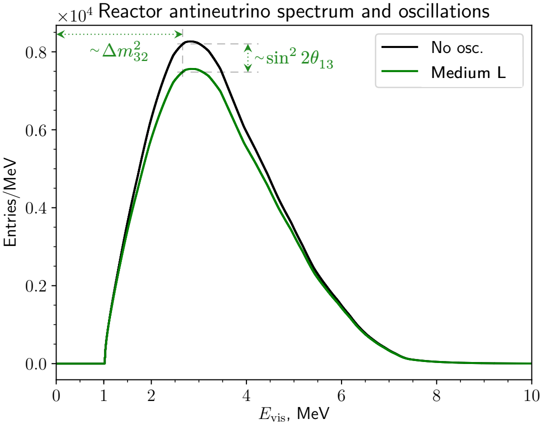
~~$\delta_{\rm CP}$, θ_{23}~~

$E_{\rm vis} \approx E_\nu - 0.78$ MeV





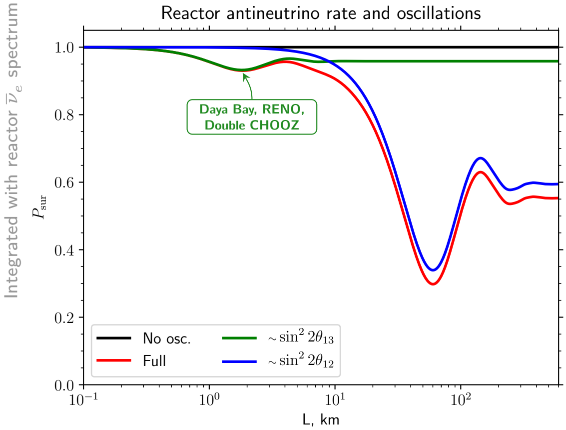
deficit value

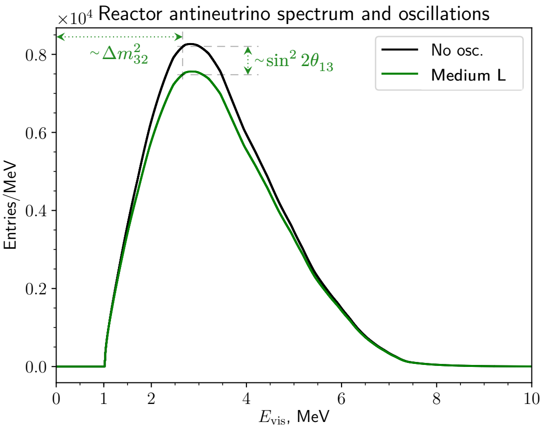
minimum location

$$1-P_{\overline{\nu}_e\to\overline{\nu}_e} = \sin^2 2\theta_{13}\underbrace{\left(\sin^2\theta_{12}\sin^2\frac{\Delta m^2_{32}L}{4E}+\cos^2\theta_{12}\sin^2\frac{\Delta m^2_{31}L}{4E}\right)}_{\stackrel{\rm def}{=}\sin^2\Delta m^2_{ee}L/(4E)}+\sin^2 2\theta_{12}\cos^4\theta_{13}\sin^2\frac{\Delta m^2_{21}L}{4E}$$

~~$\delta_{\rm CP}$, θ_{23}~~

$E_{\rm vis}\approx E_\nu - 0.78$ MeV





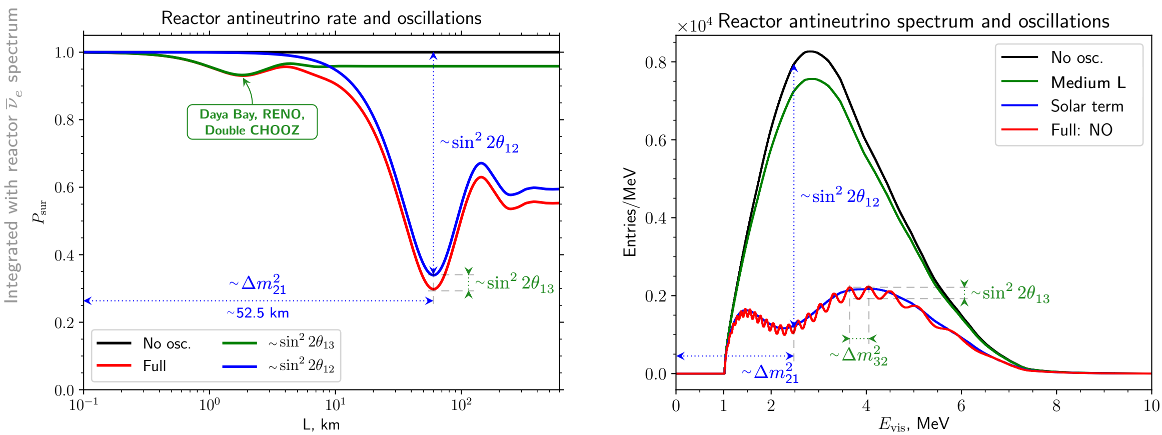
deficit value

minimum location

$$1 - P_{\overline{\nu}_e\to\overline{\nu}_e} = \sin^2 2\theta_{13} \underbrace{\left(\sin^2\theta_{12}\sin^2\frac{\Delta m^2_{32}L}{4E} + \cos^2\theta_{12}\sin^2\frac{\Delta m^2_{31}L}{4E}\right)}_{\stackrel{\text{def}}{=}\ \sin^2 \Delta m^2_{ee} L/(4E)} + \sin^2 2\theta_{12}\cos^4\theta_{13}\sin^2\frac{\Delta m^2_{21}L}{4E}$$

~~$\delta_{\text{CP}}, \theta_{23}$~~

$E_{\text{vis}} \approx E_\nu - 0.78\,\text{MeV}$



deficit value — minimum location — minimum location

$$1 - P_{\overline{\nu}_e\to\overline{\nu}_e} = \sin^2 2\theta_{13}\left(\sin^2\theta_{12}\sin^2\frac{\Delta m^2_{32}L}{4E} + \cos^2\theta_{12}\sin^2\frac{\Delta m^2_{31}L}{4E}\right) + \sin^2 2\theta_{12}\cos^4\theta_{13}\sin^2\frac{\Delta m^2_{21}L}{4E}$$

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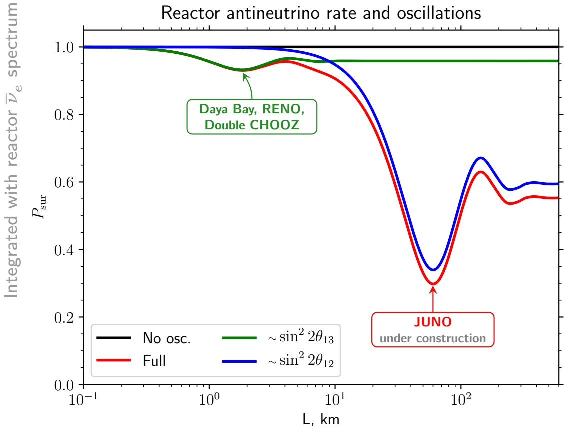

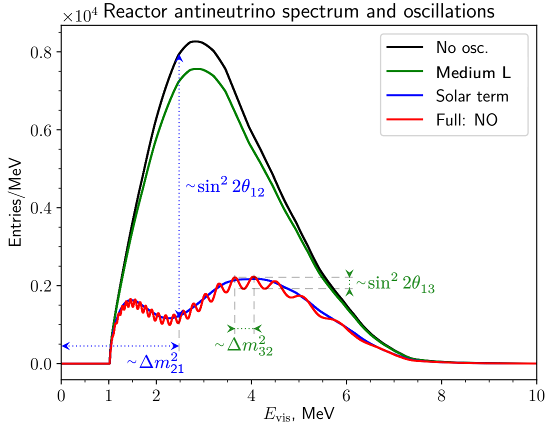

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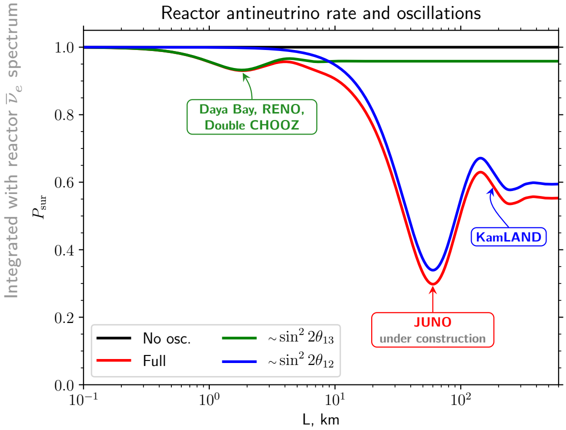

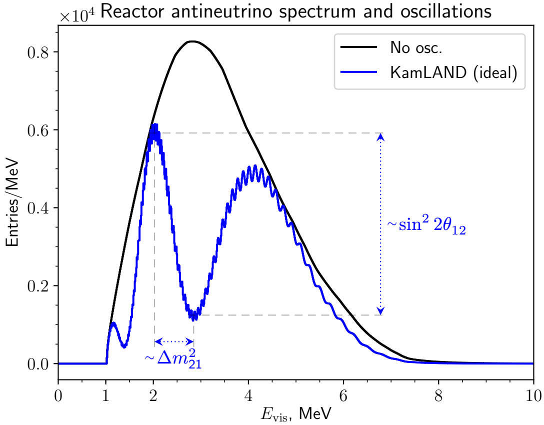

deficit value

minimum location

minimum location

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~~δ_{CP}, θ_{23}~~

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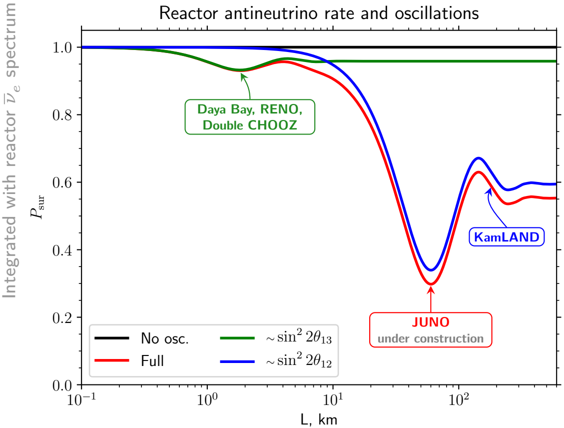

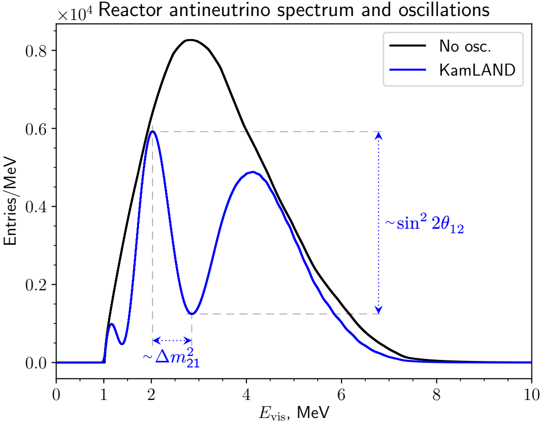

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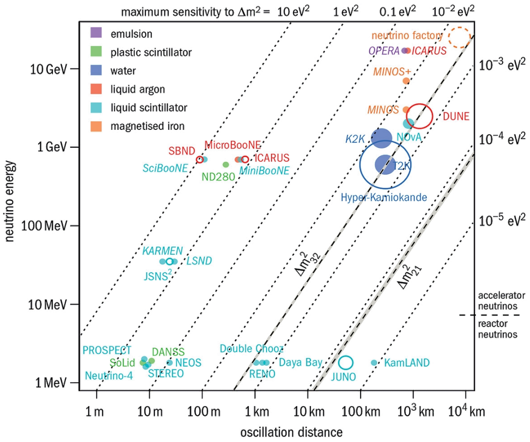
~~$\delta_{\mathrm{CP}}, \theta_{23}$~~

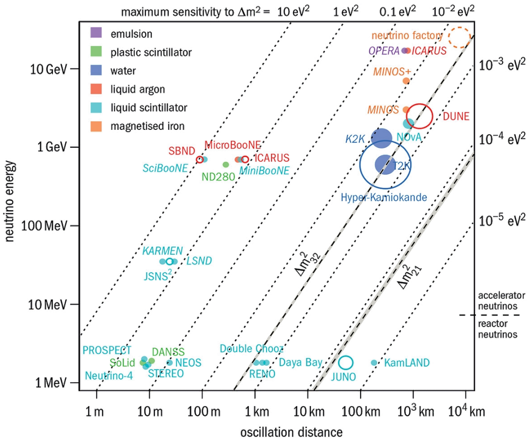
$E_{\mathrm{vis}} \approx E_\nu - 0.78\,\mathrm{MeV}$

Neutrino oscillation global picture



$$P_{\text{osc}} \propto f\left(\frac{\Delta m^2 L}{E}\right)$$

Neutrino oscillation global picture

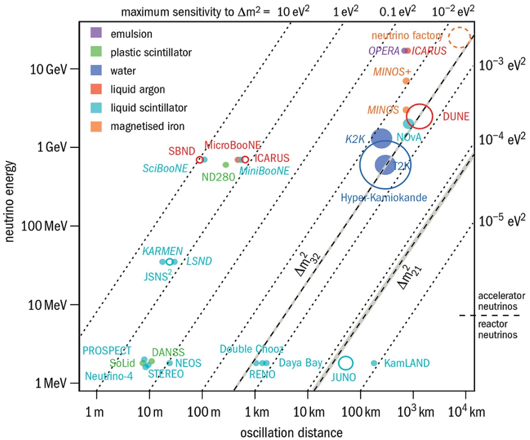


$$P_{\text{osc}} \propto f\left(\frac{\Delta m^2 L}{E}\right)$$

Reactor baselines

- SBL — small < 100 m
- MBL — medium ~ 1 km
- LBL — large $\gtrsim 50$ km

Neutrino oscillation global picture



$$P_{\text{osc}} \propto f\left(\frac{\Delta m^2 L}{E}\right)$$

Reactor baselines

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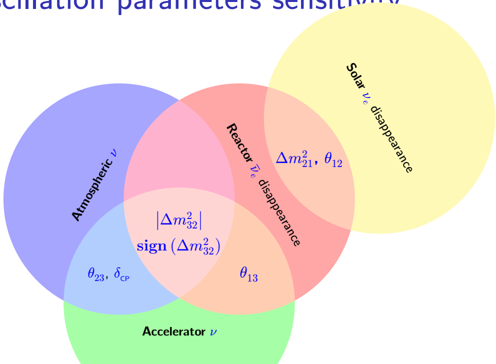
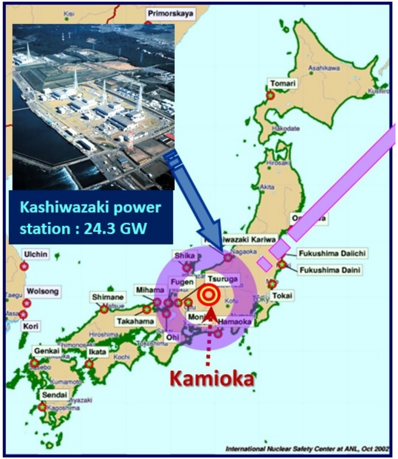
Oscillation parameters sensitivity



Kamioka Liquid Scintillator Antineutrino Detector

Goals

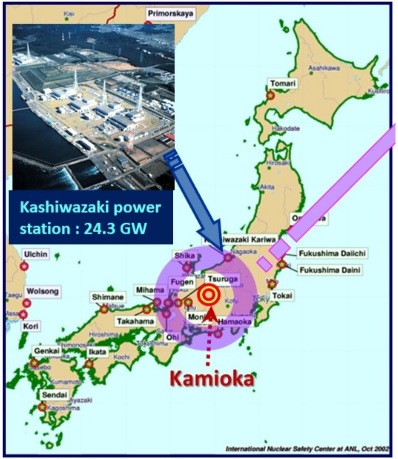
- $2002 - 2011$: Δm^2_{21} and θ_{12}



Kamioka Liquid Scintillator Antineutrino Detector

Goals

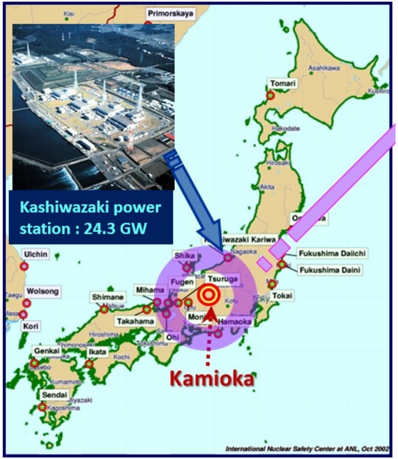
- $2002 - 2011$: Δm^2_{21} and θ_{12}
- ✗ 2012: Fukushima disaster
  ↪ NPP shutdown



KAMIOKA LIQUID SCINTILLATOR ANTINEUTRINO DETECTOR

Goals

- $2002 - 2011$: Δm^2_{21} and θ_{12}
- ✗ 2012: Fukushima disaster
  $\hookrightarrow$ NPP shutdown
- 2013—: geo-ν and 0νββ decay



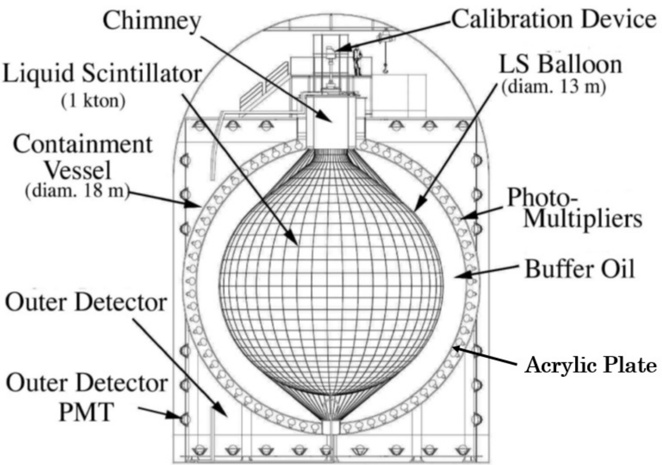
Kamioka Liquid Scintillator Antineutrino Detector

Goals

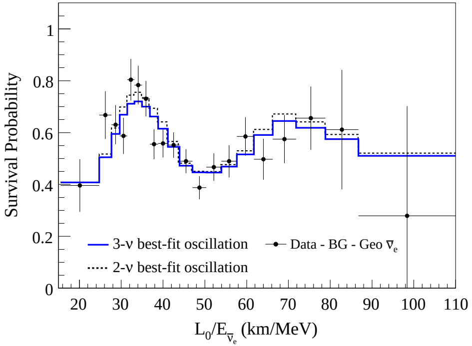
- $2002-2011$: Δm^2_{21} and θ_{12}
- ✗ 2012: Fukushima disaster
  ↪ NPP shutdown
- 2013—: geo-ν and 0νββ decay

Summary

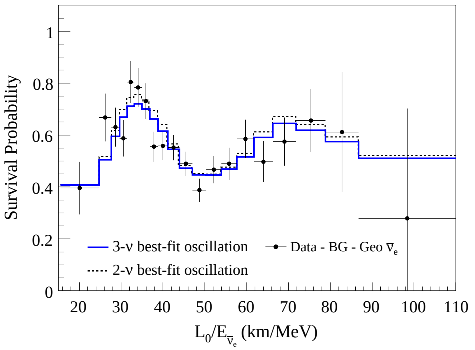
- Detector: ∅13 m balloon
- Target: 1 kt LS
- Average baseline: 180 km
- PMT: 1879 17"/20"
- Resolution: $\sigma_E = 6.4\%$ at 1 MeV

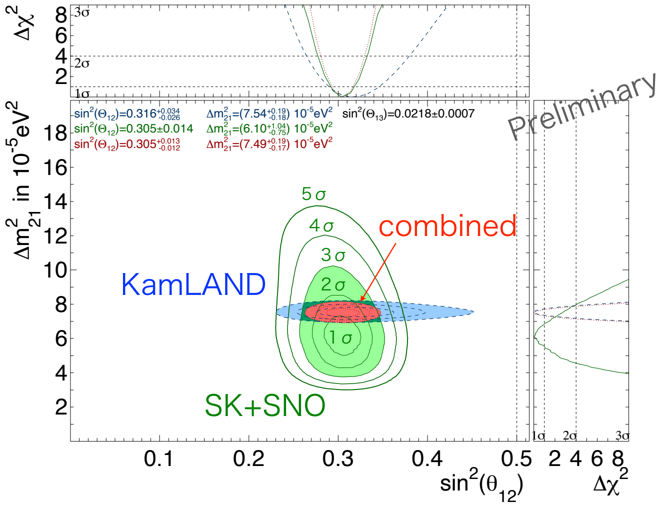


KamLAND results



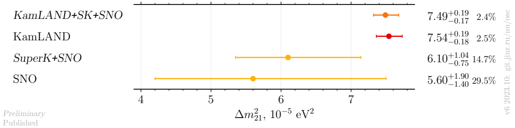
KamLAND results

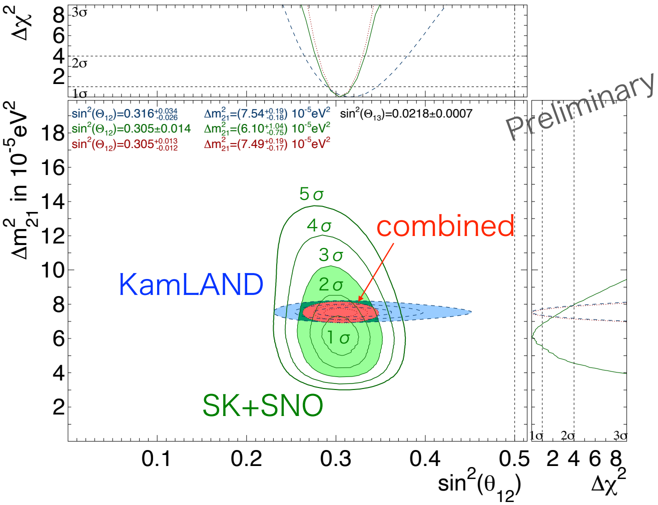




KamLAND results

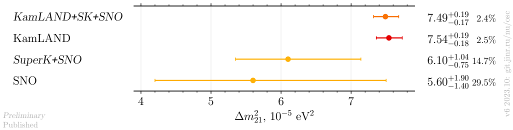
✓ Most precise Δm^2_{21} measurement

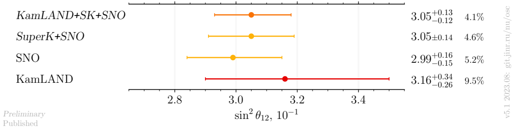


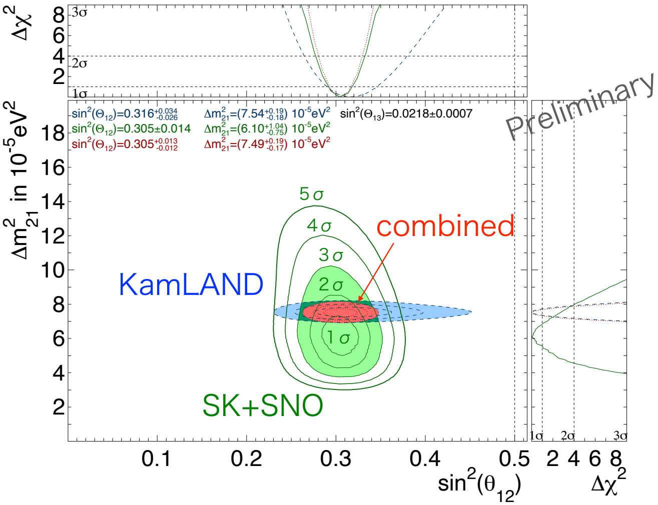


KamLAND results

- ✓ Most precise Δm^2_{21} measurement
- ✓ One of the three θ_{12} measurements

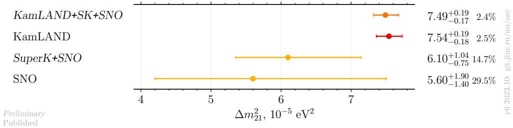


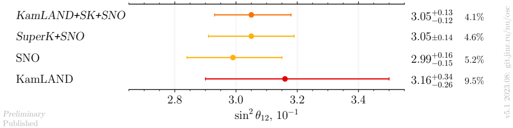


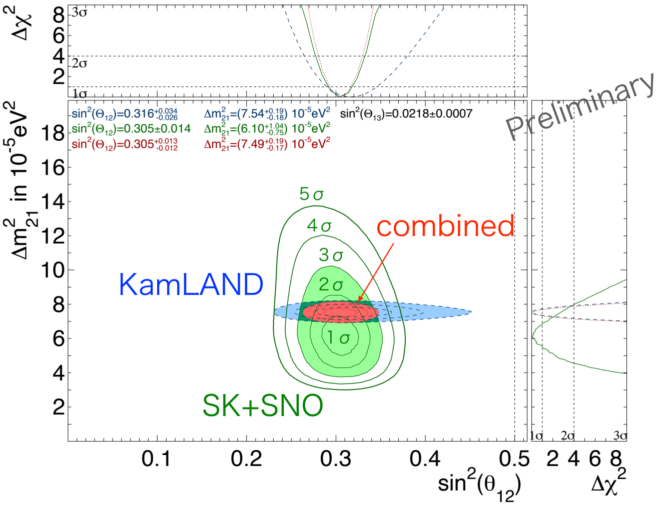


KamLAND results

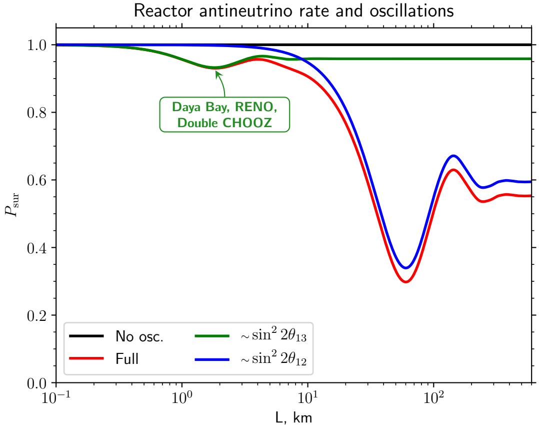
- ✓ Most precise Δm^2_{21} measurement
- ✓ One of the three θ_{12} measurements
- ✗ 1.5σ tension with SuperK
  - ↪ solar discrepancy (pretty weak)

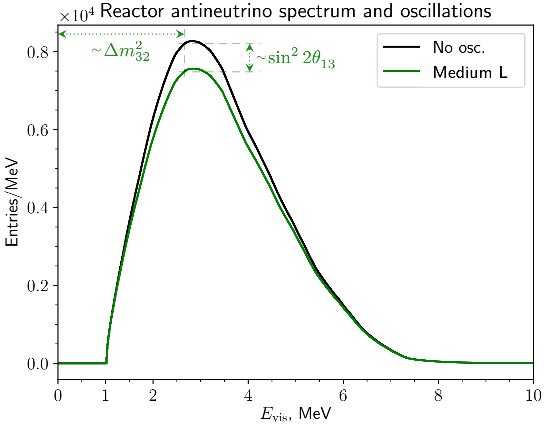






Integrated with reactor $\overline{\nu}_e$ spectrum





deficit value

minimum location

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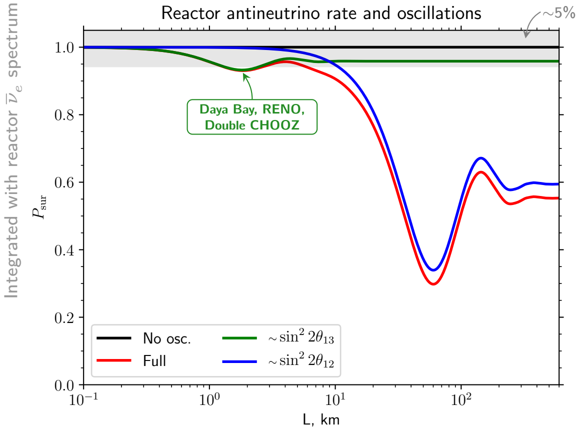
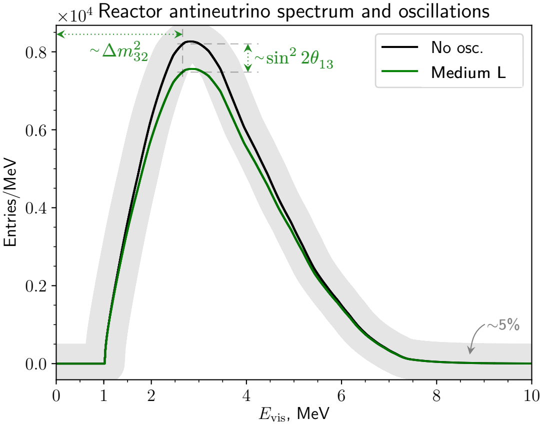
~~$\delta_{\rm CP}$, θ_{23}~~

$E_{\rm vis} \approx E_\nu - 0.78$ MeV

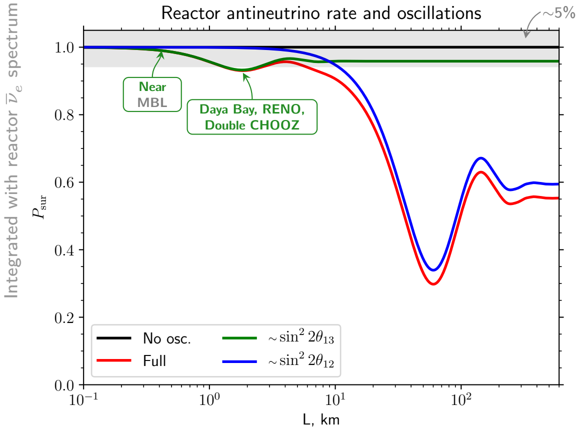


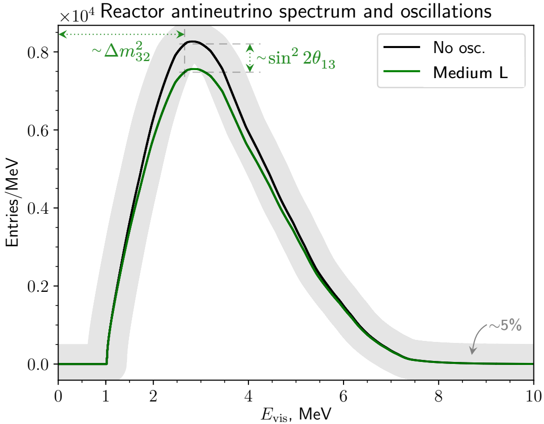


Challenges

- Unreliable antineutrino spectrum model: $\hookrightarrow$ measure reference spectrum

$E_{vis} \approx E_\nu - 0.78$ MeV





Challenges

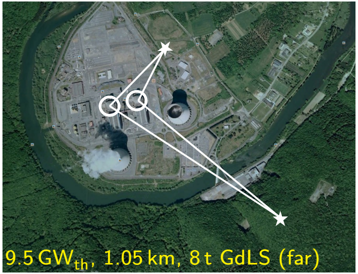
- Unreliable antineutrino spectrum model: ↪ measure reference spectrum
  - Relative detector efficiency uncertainty $< 1\%$
  - Relative energy scale uncertainty $< 1\%$

$E_{\rm vis} \approx E_\nu - 0.78\,\text{MeV}$

MBL — medium baseline

Medium baseline reactor experiments: 2011 $\rightsquigarrow$ 2020+

Double CHOOZ, France



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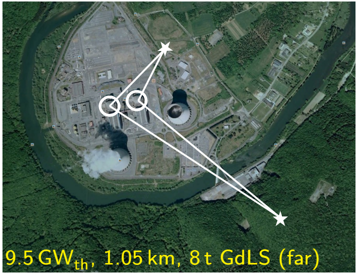

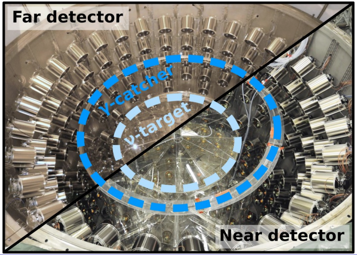

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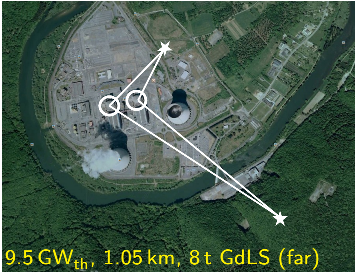
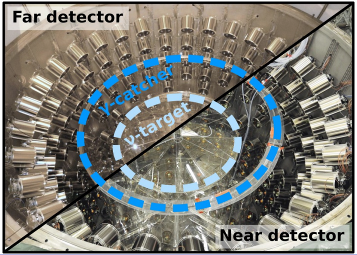
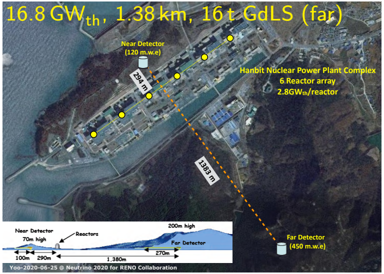




RENO, South Korea



Medium baseline reactor experiments: 2011 $\rightsquigarrow$ 2020+

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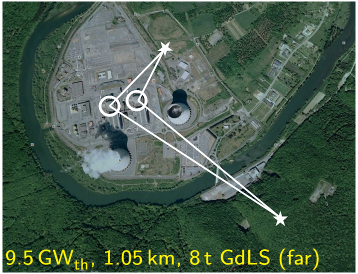

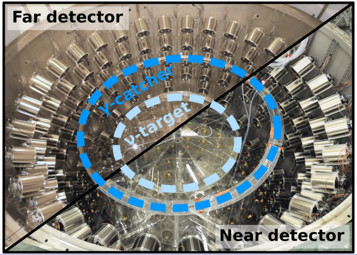

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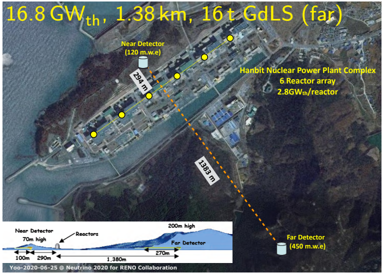

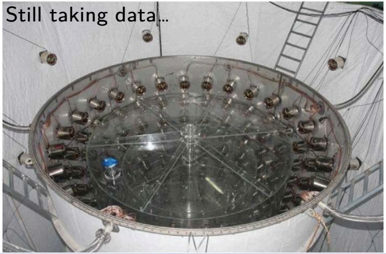

MEDIUM BASELINE REACTOR EXPERIMENTS: 2011 $\rightsquigarrow$ 2020+

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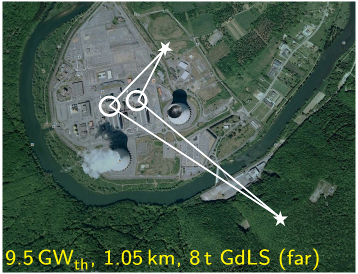

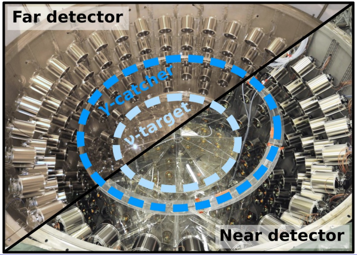

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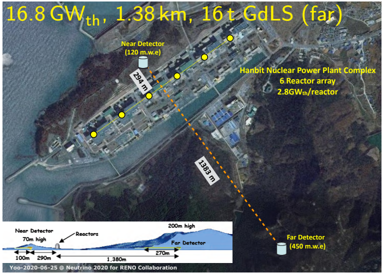
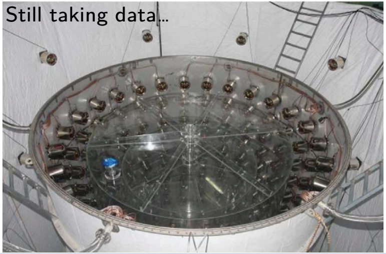
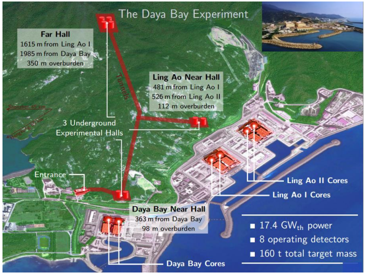




Daya Bay, China



Medium baseline reactor experiments: 2011 $\rightsquigarrow$ 2020+

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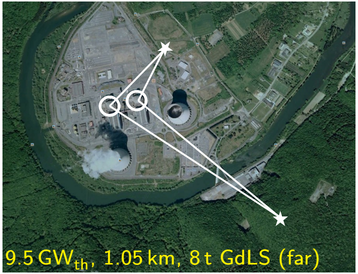

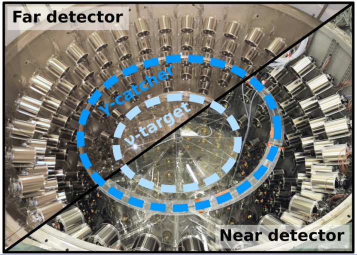

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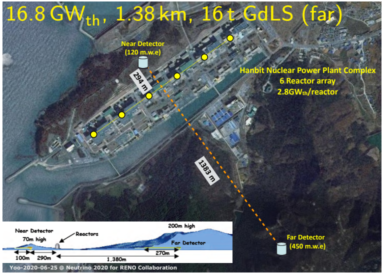

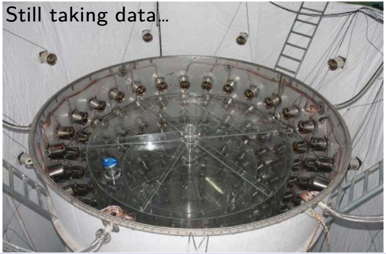

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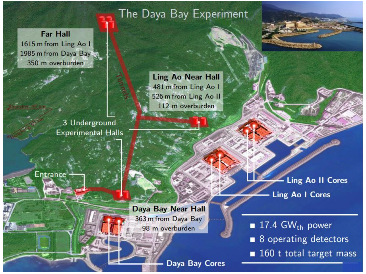
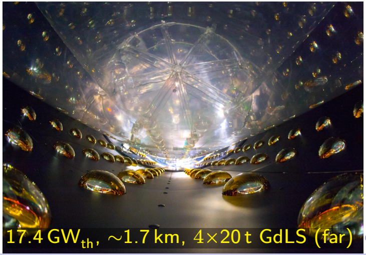
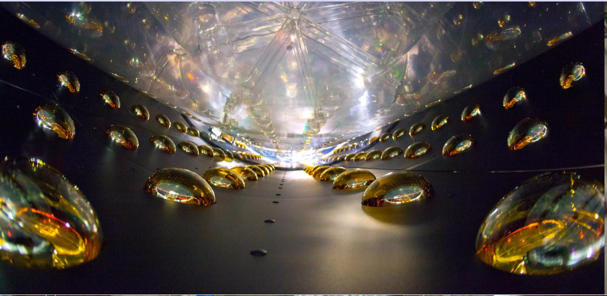
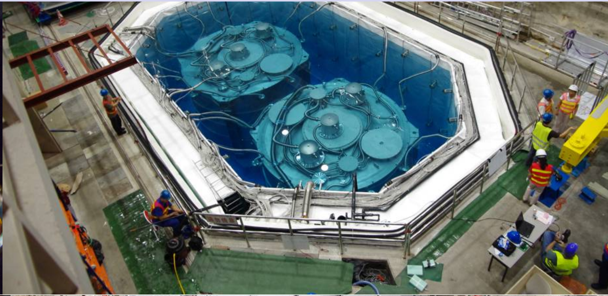
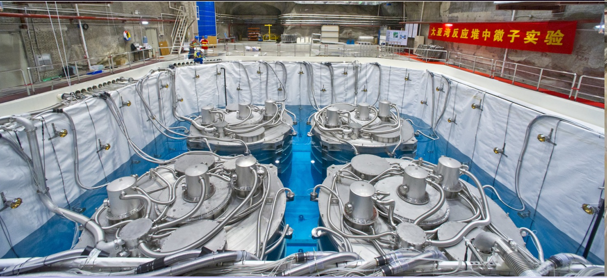
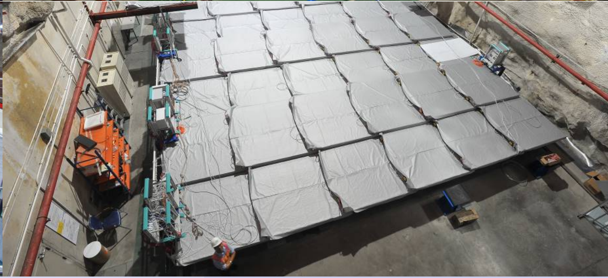


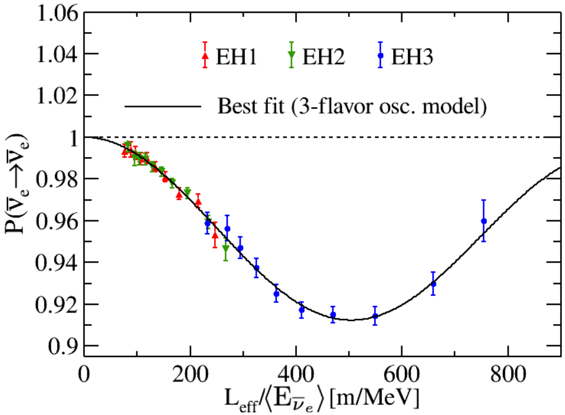


Daya Bay detectors



Daya Bay oscillation result: 750K/5.5M events



Full dataset: 3158 days, arXiv:2211.14988, PRL

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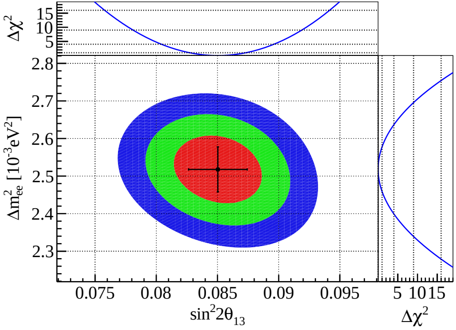

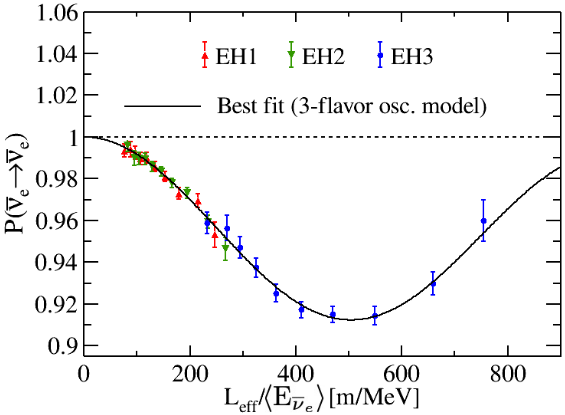

$$\sin^2 2\theta_{13} = 8.51 \pm 0.24 \quad \times 10^{-2}$$

$$|\Delta m^2_{32}| = 2.466 \pm 0.060 \quad \times 10^{-3}\ \text{eV}^2$$

✓ Consistent with 3ν oscillations

Full dataset: 3158 days, arXiv:2211.14988, PRL

ν_e appearance

$$\nu_\mu \longrightarrow \nu_e$$

T2K: Tokai to Kamioka and NOvA: NuMI Off-axis ν_e Appearance

T2K

- Location: Kamioka mine, Japan

NOvA

- Location: Ash river, Minnesota, US

T2K: Tokai to Kamioka and NOvA: NuMI Off-axis ν_e Appearance

T2K

- Location: Kamioka mine, Japan
- Beam: JPARC, 295 km, E_ν=0.6 GeV π-DIF, off-axis

NOvA

- Location: Ash river, Minnesota, US
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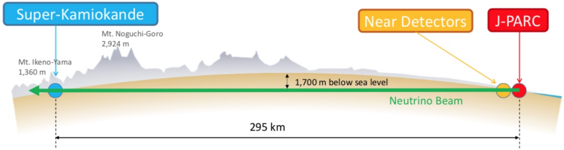

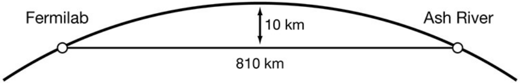

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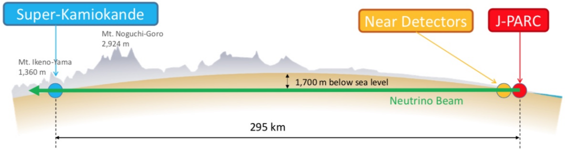

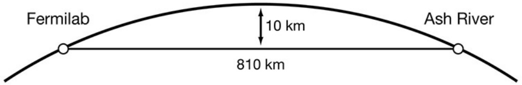

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- Operation: since 2010

NOvA

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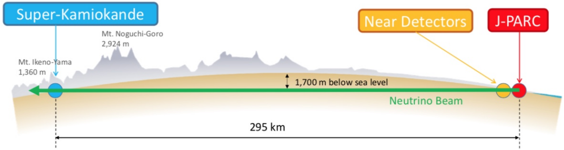
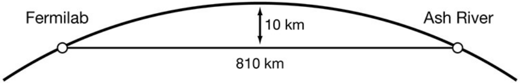
- Operation: since 2014





NOvA detector

- Target: Liquid Scintillator (LS)
- PVC "square tubes" (cells):
  - Far detector: 344 064 cells, 14 kt LS
  - Near detector: 20 192 cells, 290 t
- Light collection: looped fibers

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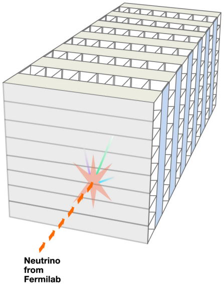

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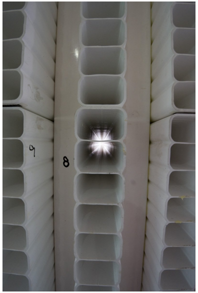
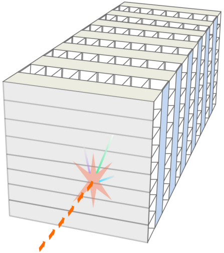
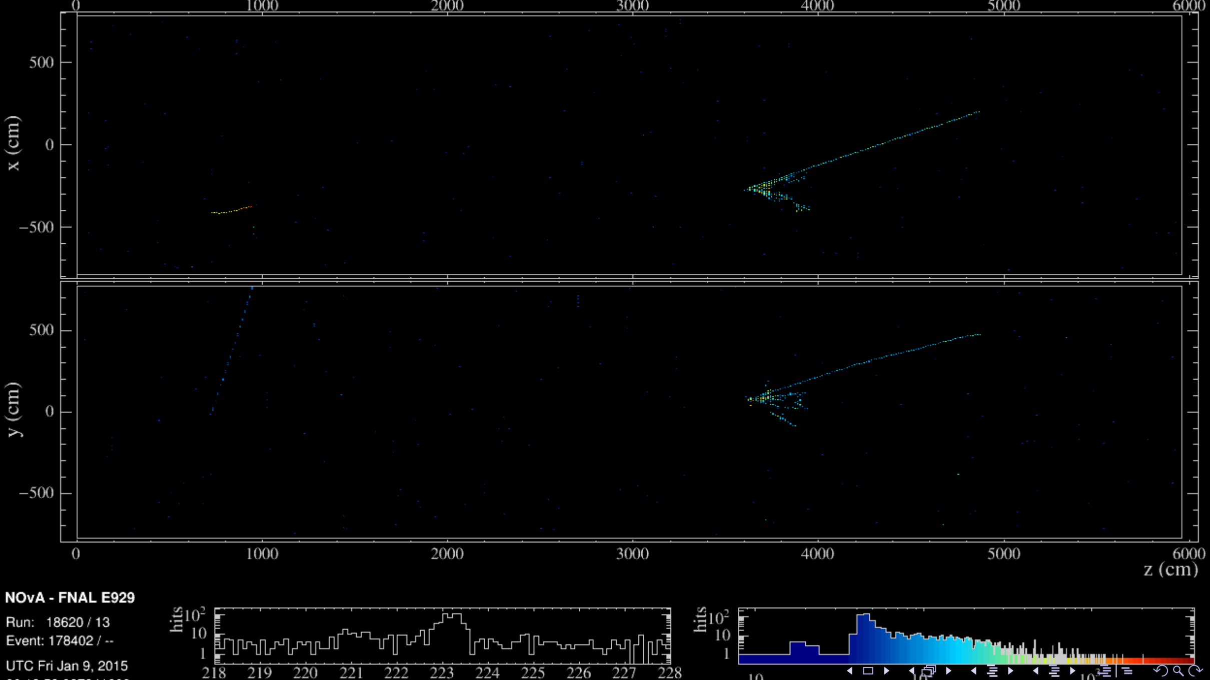
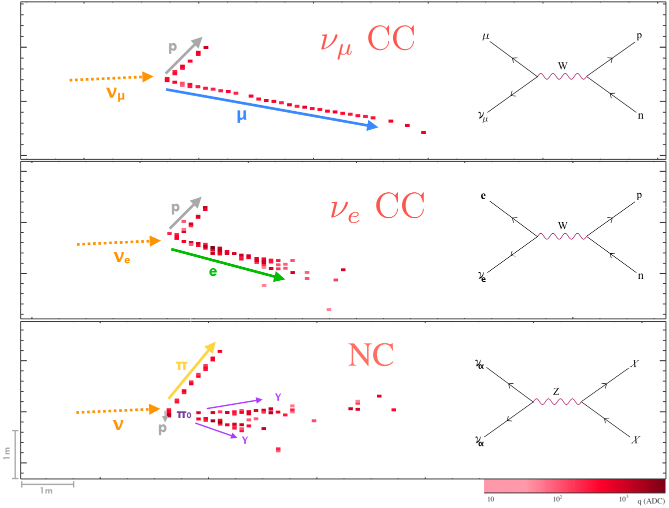




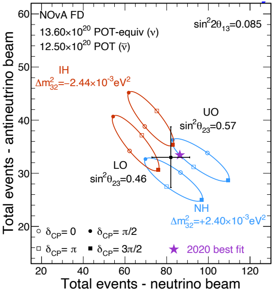

x (cm)
y (cm)
z (cm)
NOvA - FNAL E929
Run: 18620 / 13
Event: 178402 / --
UTC Fri Jan 9, 2015
hits
hits

Event types in NOvA



T2K and NOvA results

- T2K: 109 ν_e and 16 $\overline{\nu}_e$-like events
- NOvA: 80 ν_e and 33 $\overline{\nu}_e$-like events



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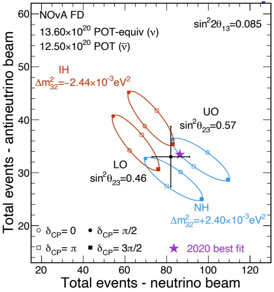

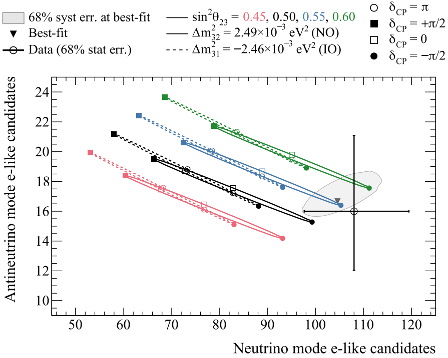

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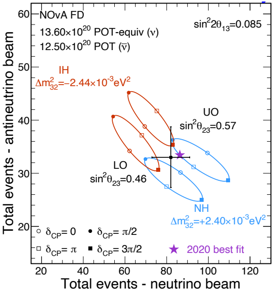

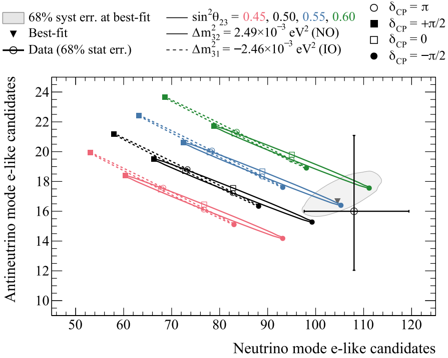

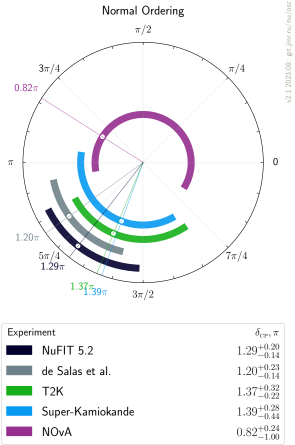

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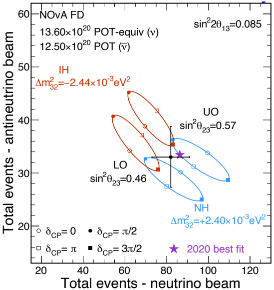

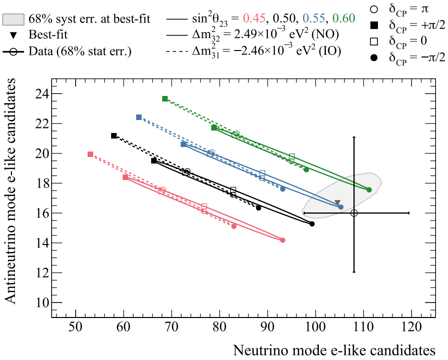

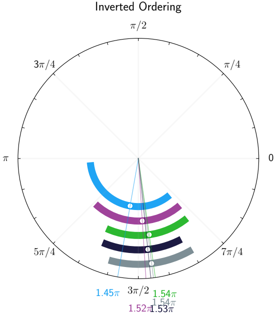

Experiment	δ_{CP}, π
de Salas et al.	$1.54^{+0.13}_{-0.13}$
NuFIT 5.2	$1.53^{+0.12}_{-0.16}$
T2K	$1.54^{+0.17}_{-0.18}$
NOvA	$1.52^{+0.21}_{-0.26}$
Super-Kamiokande	$1.45^{+0.28}_{-0.42}$

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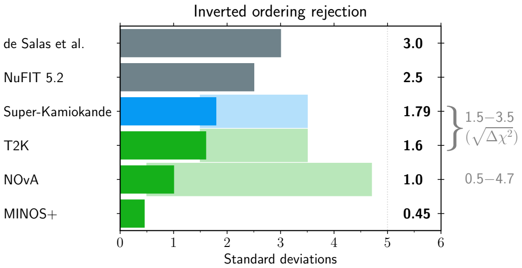

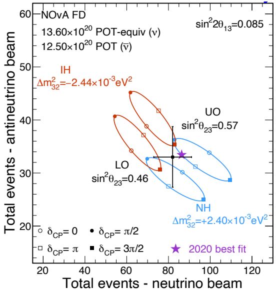

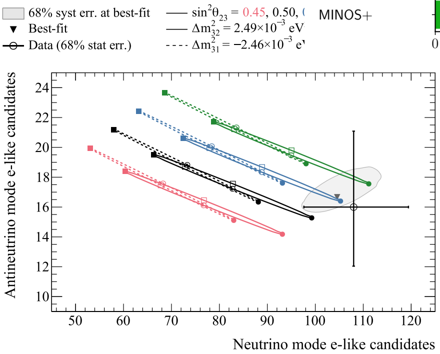

Future large scale experiments

☢ $\overline{\nu}_e \quad \longrightarrow \quad \overline{\nu}_e$

DUNE: Deep Underground Neutrino Observatory

- Location: Sanford Facility, South Dakota
- Beam: FNAL, 1300 km, $E_\nu \sim$2.5 GeV
  π-DIF, on-axis
- Expected operation: late 2020th
- Goal: δ_{CP}, mass ordering, osc. parameters

- Long baseline:
  - breaks NMO/δ_{CP} degeneracy
  - two oscillation cycles

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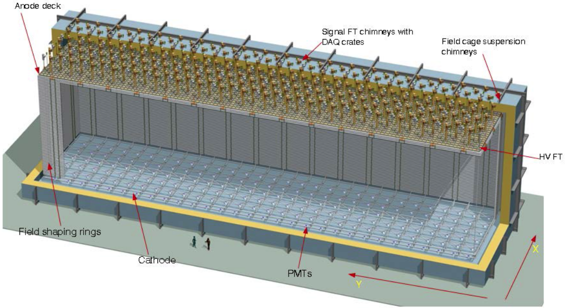

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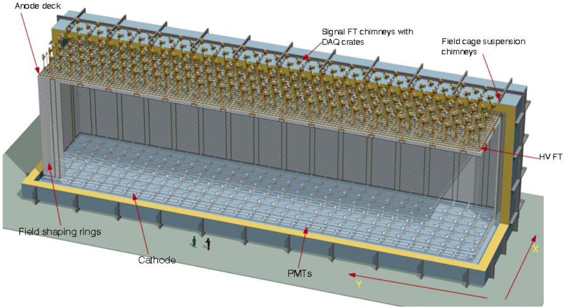
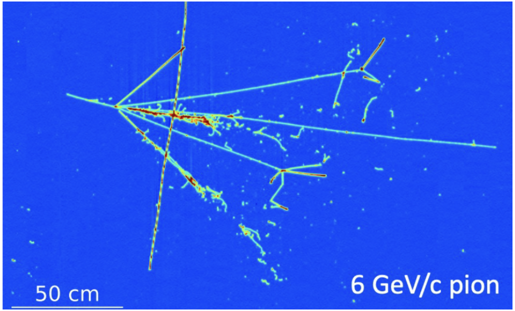


- Long baseline:
  - breaks NMO/δ_{CP} degeneracy
  - two oscillation cycles
- High precision track reconstruction



HyperKamiokande

- Location: Kamioka mine, Japan
- 3d generation: Kamiokande (3 kt), SuperK (50 kt)
- Goals: ν_e/ν_μ
  - Solar ν_e from ^{8}B
  - Atmospheric $\nu_\mu/\nu_e/\overline{\nu}_\mu/\overline{\nu}_e$
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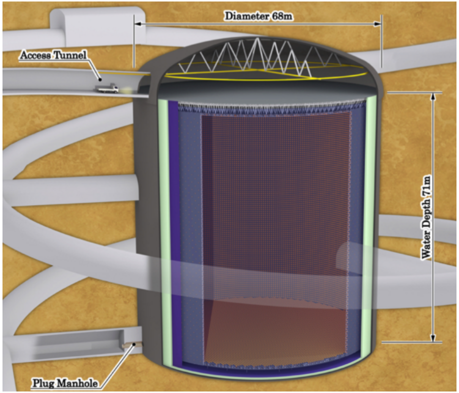

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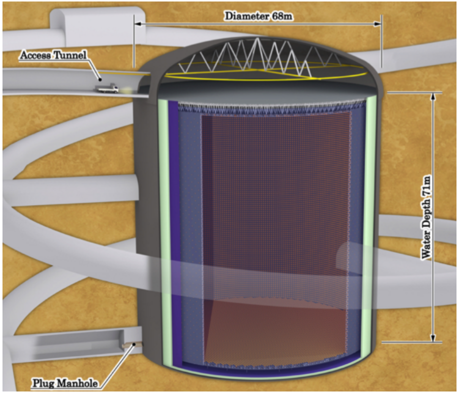
- Detector: 71 m tank
- Target: 260 kt ultra-pure H_2O
- PMT: 40 000 20"



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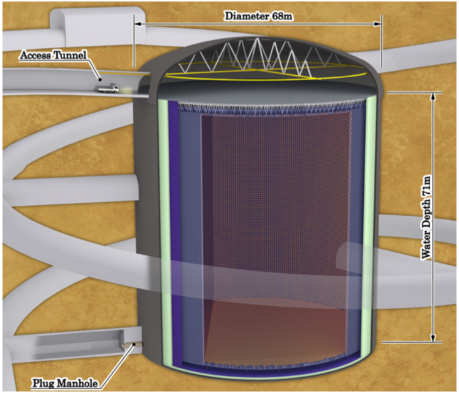

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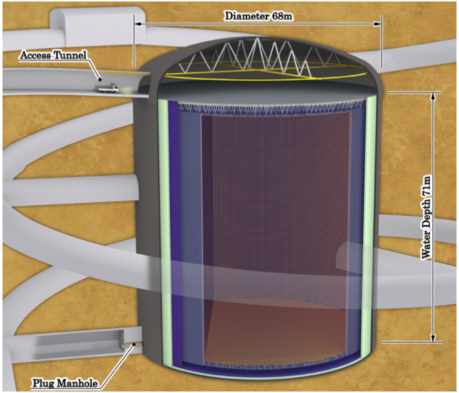
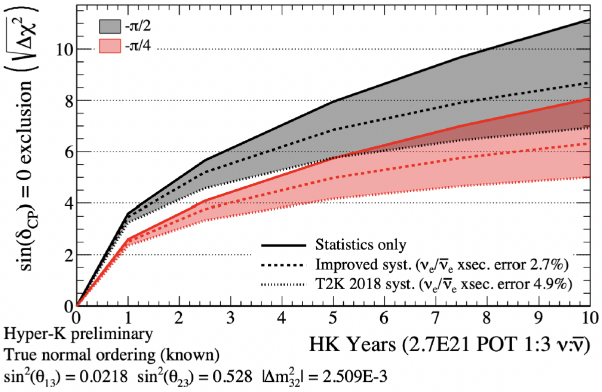
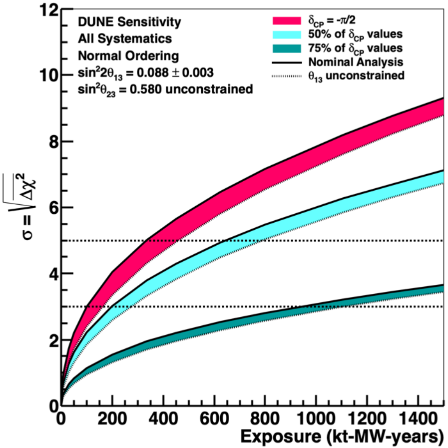
- Signal: Cherenkov "rings"
- Beam: JPARC, 295 km, E_ν=0.6 GeV
  π-DIF, off-axis, upgraded power
- Intermediate detector IWCD: 4 kt at ~2 km



DUNE and HyperK sensitivity to δ_{CP}





- The only planned experiments sensitive to δ_{CP}
- HK requires NMO as input
- DUNE will measure NMO and δ_{CP}

Future large scale experiments

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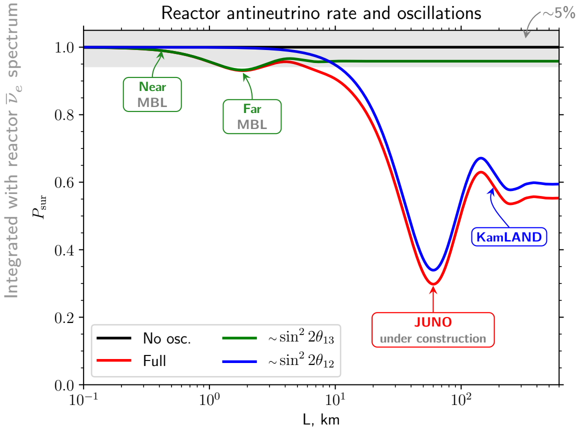
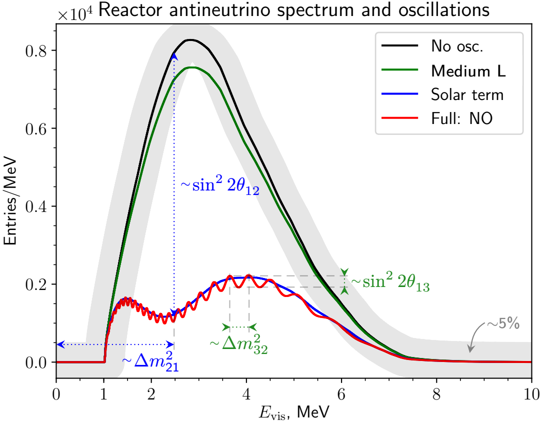


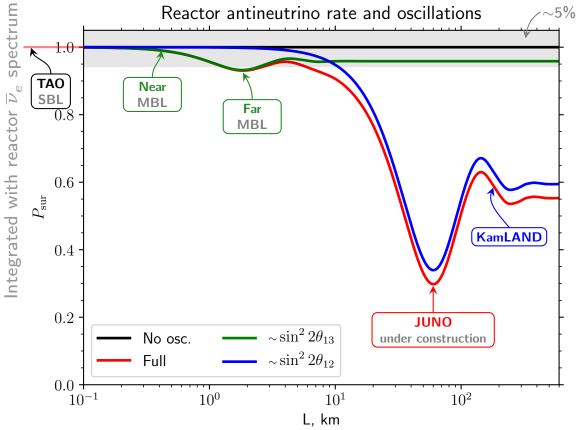


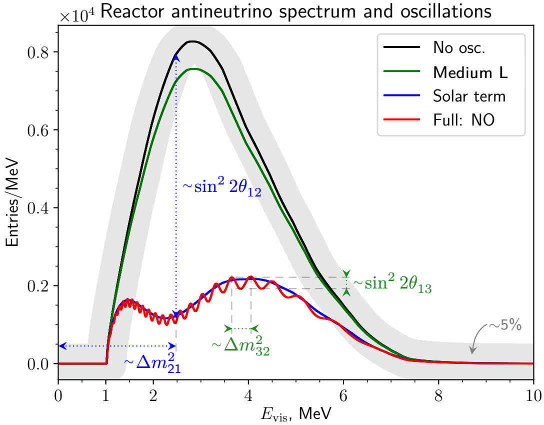
Challenges

- Unreliable antineutrino spectrum model: ↪ measure reference spectrum

$E_{vis} \approx E_\nu - 0.78$ MeV

MBL — medium baseline



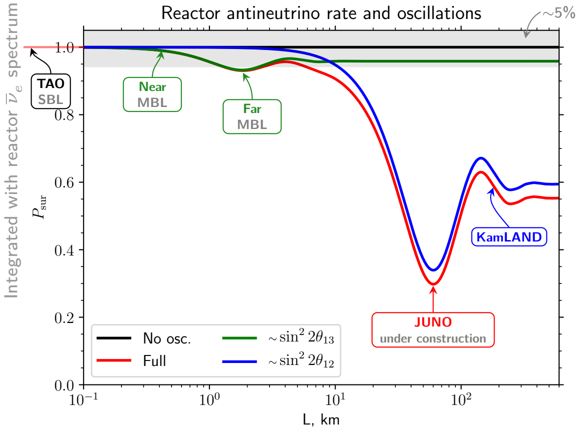


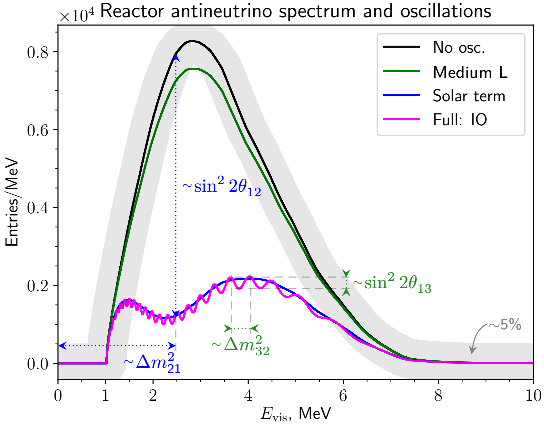
Challenges

- Unreliable antineutrino spectrum model: ↪ measure reference spectrum
- Energy resolution of the detector $\sigma < 3\%$ at 1 MeV: ↪ resolve the peaks
- Energy scale of the detector (uncertainty $< 1\%$): ↪ ensure the peak positions

$E_{\text{vis}} \approx E_\nu - 0.78\,\text{MeV}$

SBL/MBL — short/medium baseline





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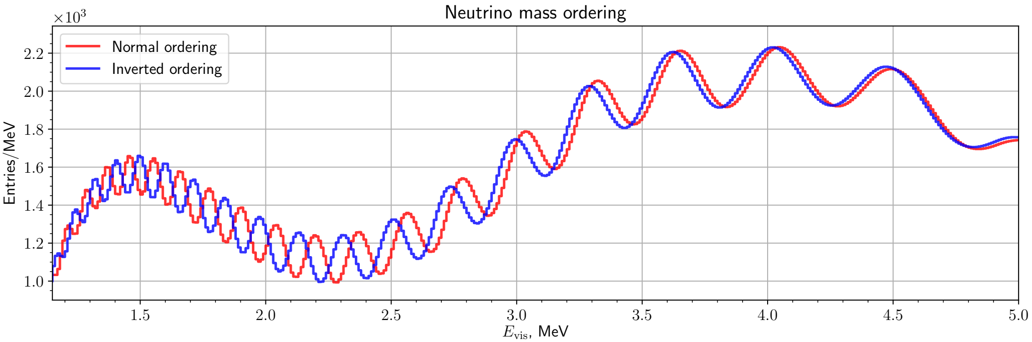

(plot: same Δm^2_{ee})

- Change of oscillation period with ordering $\ll$ energy resolution
- Cumulative effect across most of the energy range

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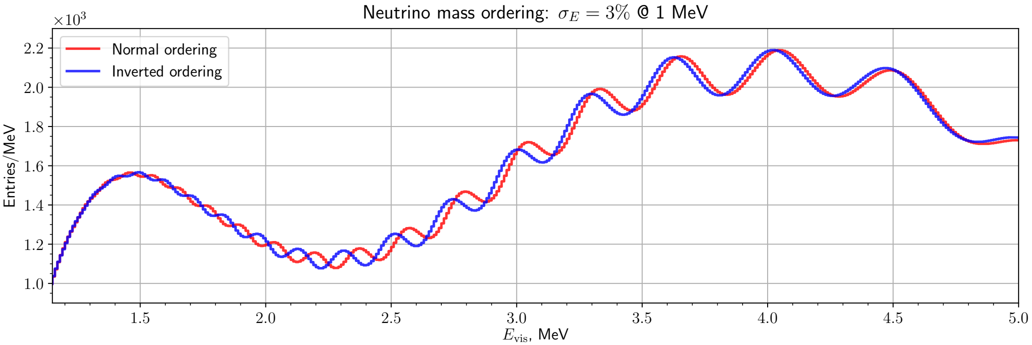

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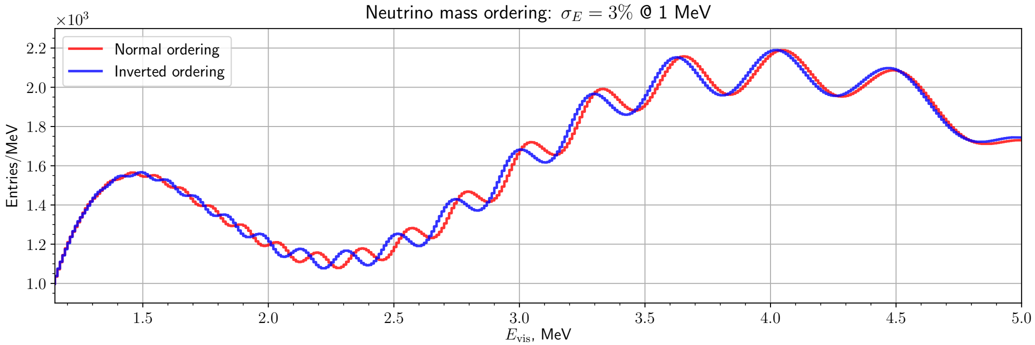
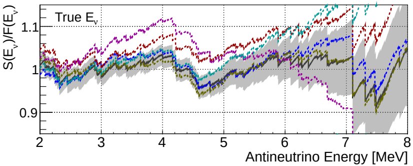


(plot: same Δm^2_{ee})

- Change of oscillation period with ordering $\ll$ energy resolution
- Cumulative effect across most of the energy range
- Possible threat: fine structure in reactor $\overline{\nu}_e$ spectrum

need a reference measurement!

$E_{\text{vis}} \approx E_\nu - 0.78$ MeV



Dwyer&Langford [1407.1281], PRL114

JUNO and TAO location

- JUNO — Jiangmen Underground Neutrino Observatory
- TAO — Taishan Antineutrino Observatory

	Yangjian (YJ)	Taishan (TS)
Thermal power, GW	2.9×6	4.6×2
Total, GW	26.6	
	signal	

JUNO and TAO location

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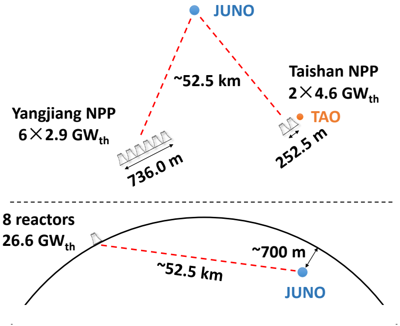

	Yangjian (YJ)	Taishan (TS)
Thermal power, GW	2.9×6	4.6×2
Total, GW	26.6	
	signal	

JUNO and TAO location

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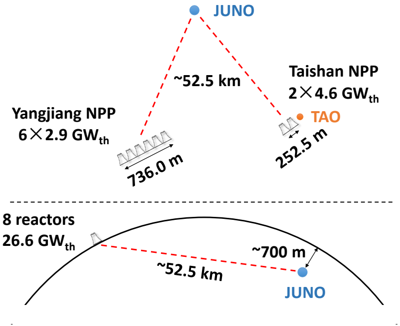
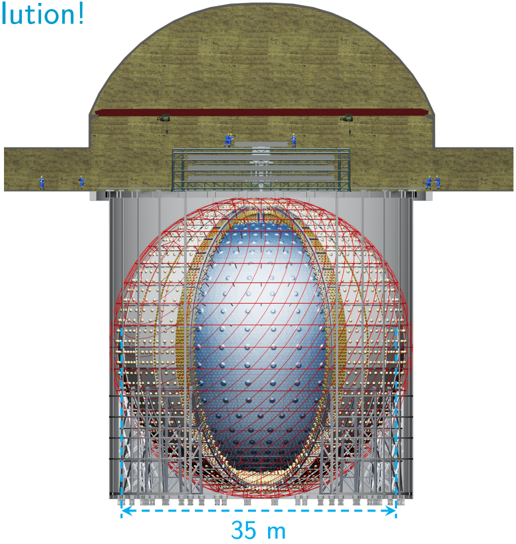


	Yangjian (YJ)	Taishan (TS)	Daya Bay/Ling Ao	World
Thermal power, GW	2.9×6	4.6×2	2.9×6	
Total, GW	26.6		17.4	...
	signal		background	

JUNO DETECTOR

More light $\longrightarrow$ better resolution!

More statistics!



JUNO DETECTOR

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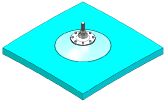
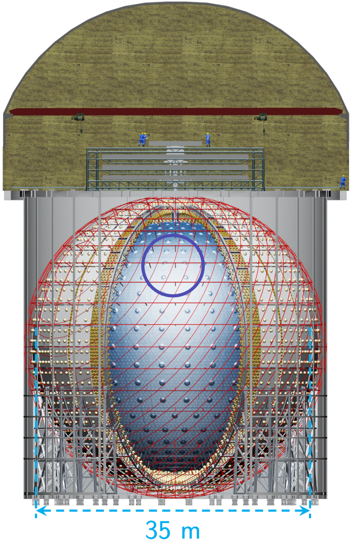
LS — Liquid Scintillator
LY — Light Yield

Target

- 20 kt LS
- Optimized LY
- Acrylic sphere





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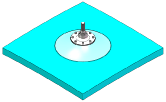

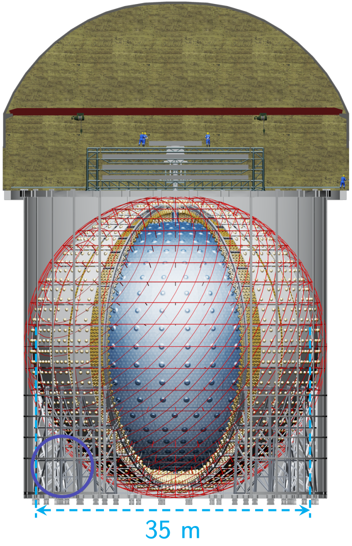

Support

- Stainless steel structure

JUNO detector

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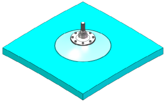

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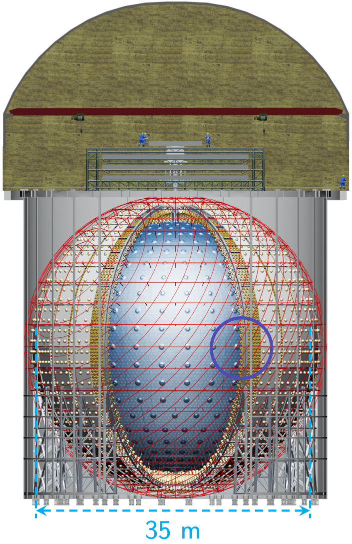

LS — Liquid Scintillator
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PMT — PhotoMultiplier Tube
QE — Quantum Efficiency
p.e. — photo-electron

Light collection

- 18k 20" PMTs
- High QE: 29.6%
- 1665 p.e./MeV
- +26k 3" PMTs

Preliminary

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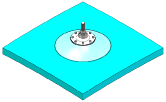
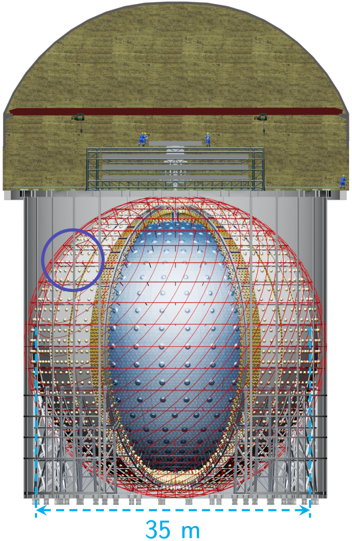


Coils

- Compensation of the Earth Magnetic Field

Support

- Stainless steel structure



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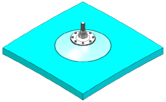

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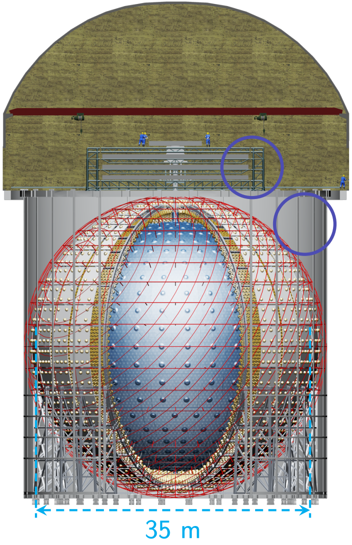

Muon veto

- Top Tracker: 3 layers PS
- Water pool

Light collection

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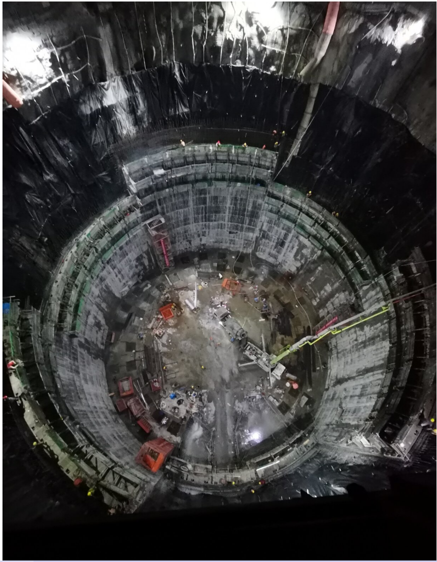
Preliminary

Civil construction

✓ Civil construction: done.

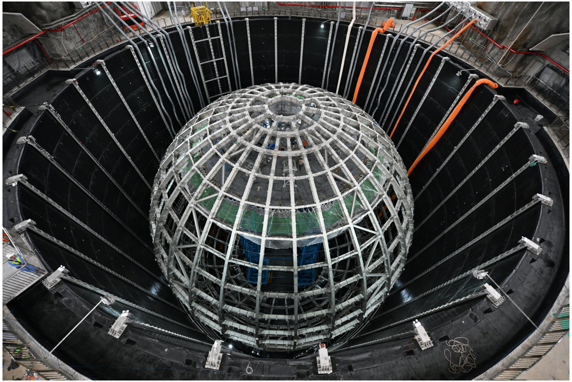
Civil construction

- ✓ Civil construction: done.
- ✓ Underground lab: done.
- ✓ Installation: ongoing.



JUNO construction status

- Stainless Steel Structure: done
- Acrylic sphere: installation in progress



JUNO construction status

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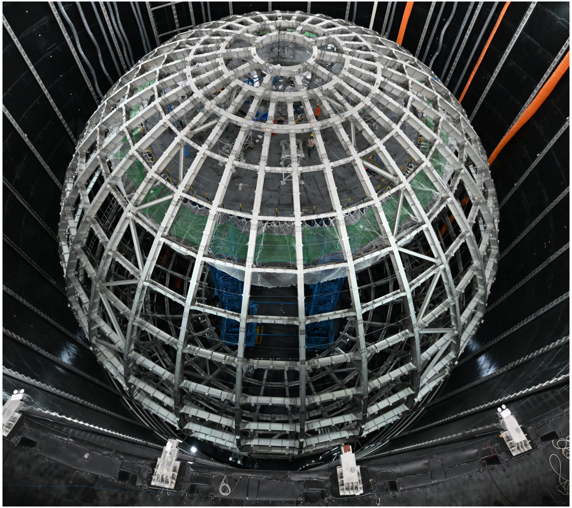
- Photomultiplier Tubes: installation in progress
- Electronics: assembly ongoing



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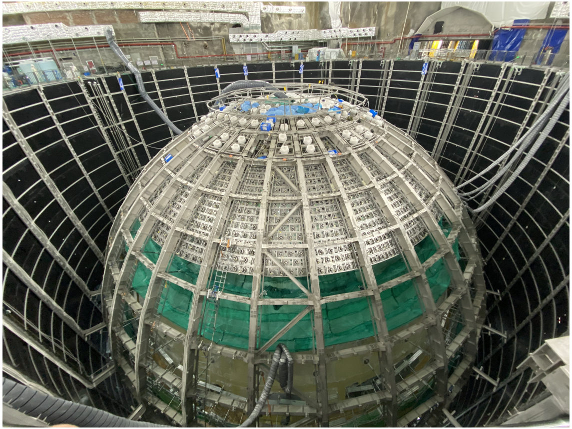

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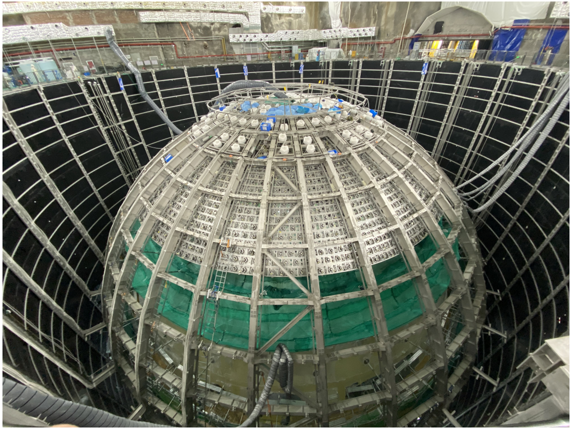
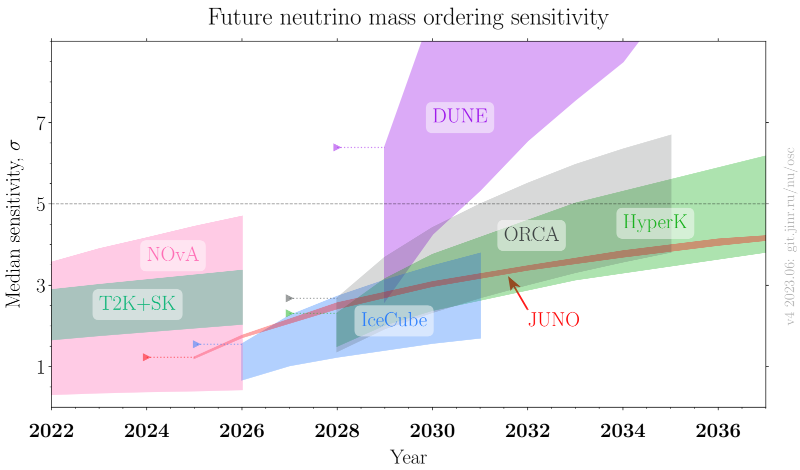


JUNO SCHEDULE

- 2014 — Complete conceptual design. International collaboration established.
- 2015 — Start civil construction, PMT production line.
- 2016 — Bidding of detector components.
- 2017 — Start PMT mass production. First electronics prototypes.
- 2018 — PMT mass production and testing.
- 2019 — Start PMT potting.
- 2020 — End of civil construction. PMT testing. Electronics mass production.

- 2021 — Underground lab preparation. Electronics mass production.
- 2022 — OSIRIS assembly. Water pool preparation. Stainless steel structure assembly.
- 2023 — We are here — Acrylic vessel assembly. PMT installation. Detector and veto construction. TAO assembly.
- 2024 — Detector completion!

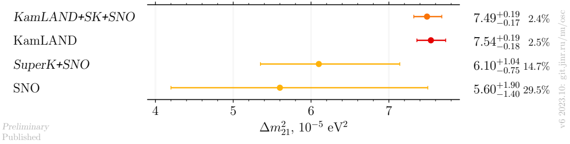
Future sensitivity to neutrino mass ordering

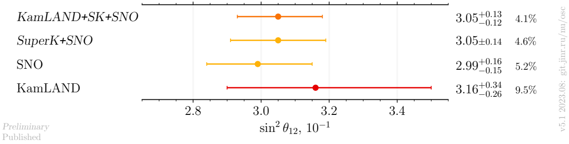


- DUNE: outstanding sensitivity
- JUNO: start data taking in 2024
- Possibility JUNO or NOvA+T2K will reach 5σ with external inputs

Competitive and complementary sensitivity to NMO.

Solar oscillation parameters status





- Dominated by KamLAND
- Dominated by SNO

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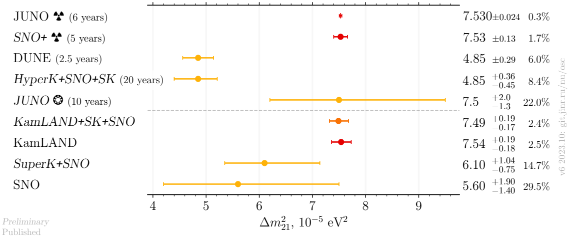

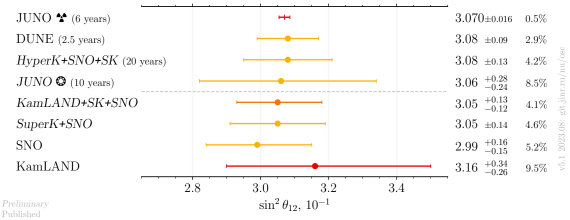

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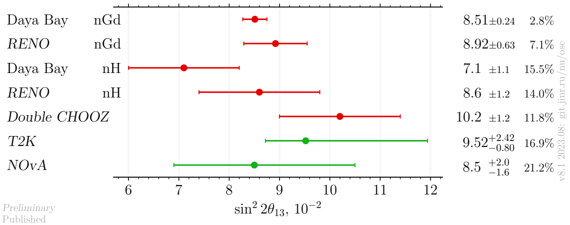

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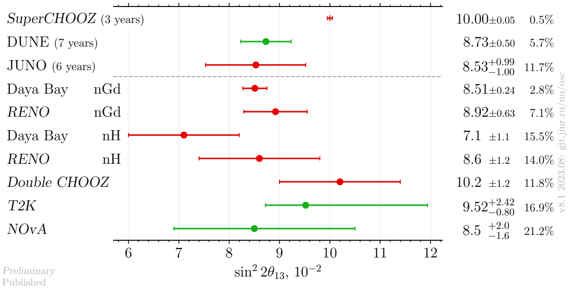

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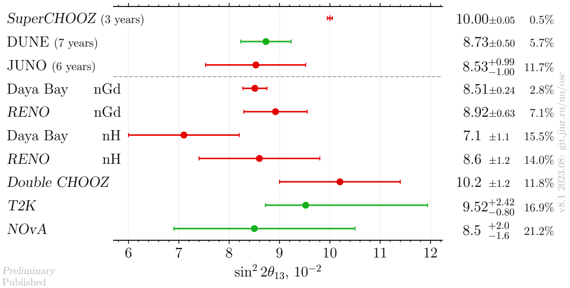

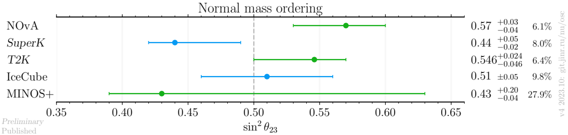

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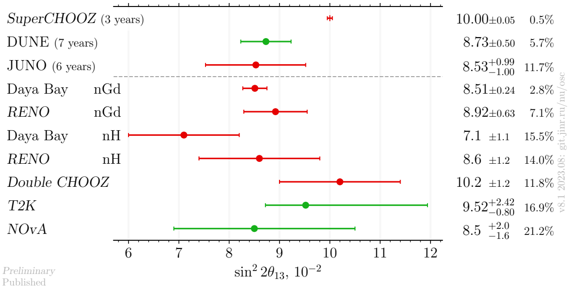

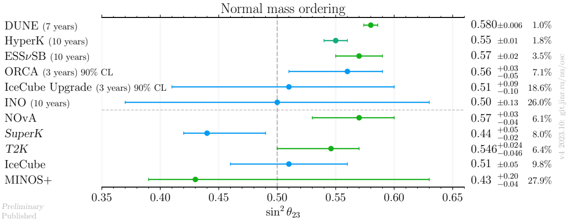

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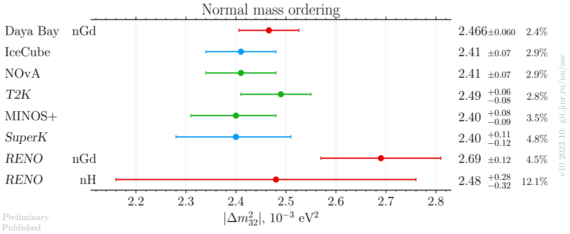
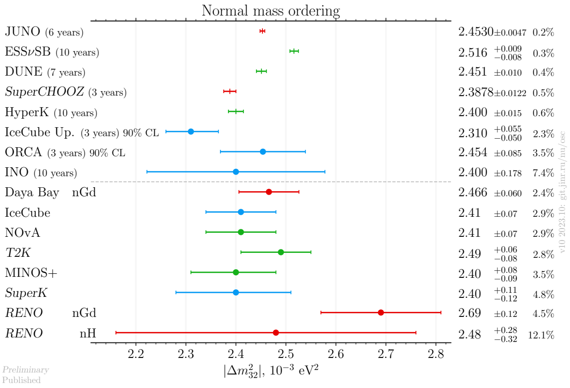
Δm^2_{32} parameters status



- Consistent picture between reactor, accelerator and atmospheric experiments

Δm^2_{32} parameters status



- Consistent picture between reactor, accelerator and atmospheric experiments
- Will be defined by accelerator experiments and JUNO to permille level

Summary

- Neutrino oscillations — unique phenomenon, enables us to observe quantum effects at large scale
- Neutrino oscillation studies are at precision stage. Next generation of experiments will provide sup-percent precision.
- Key problems: NMO and CP violation in leptonic sector to be resolved by 2040.

Thank you for your attention!
Спасибо за внимание!

Spare slides:

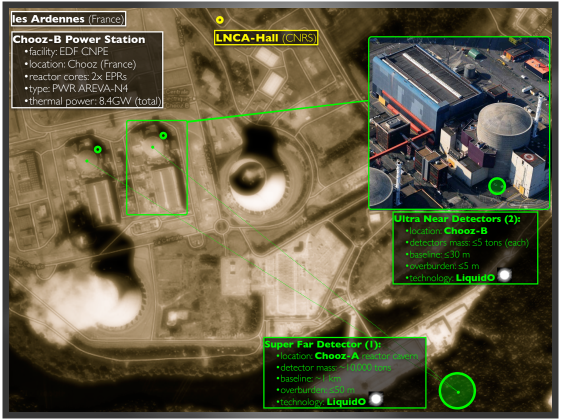
- SuperCHOOZ
- Borexino

SuperCHOOZ

Potential to significantly improve $\sin^2 2\theta_{13}$.

Goals

- $\sin^2 2\theta_{13}$ and Δm^2_{31} with 0.5% precision.
- Solar and SN neutrino physics.



(from slides by Anatael Cabrera (11.2022))

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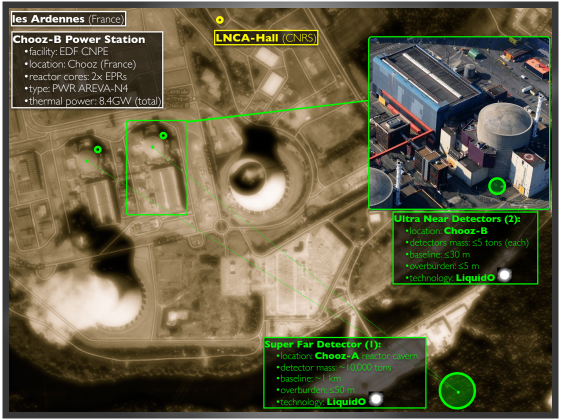
- Site: France, CHOOZ NPP
- New detection technology: opaque scintillator
- Detector: $16\ \mathrm{m} \times 16\ \mathrm{m} \times 38\ \mathrm{m}$
- Target: <5 t (near), 10 kt (far)
- Baseline: $\lesssim 30$ m, ~ 1 km
- Schedule: ...



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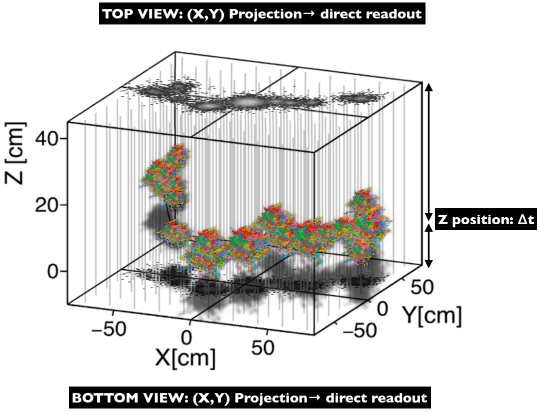

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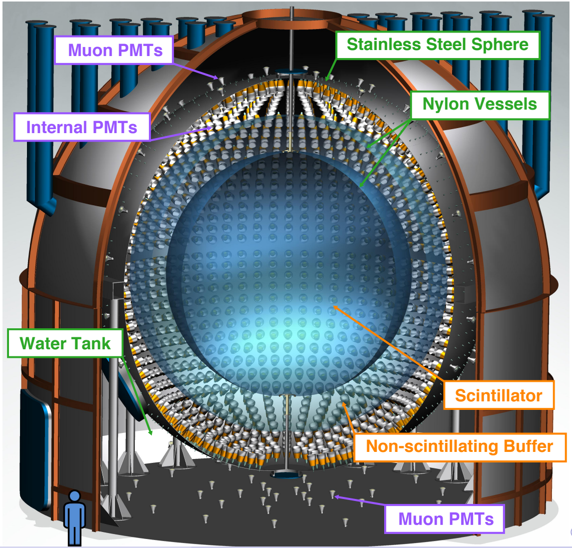
BOREXINO: Boron and Solar Neutrino Experiment

Goals

- Solar neutrino: $^{7}\mathrm{Be}$, $^{8}\mathrm{B}$, pp, pep, CNO.
- geo-ν



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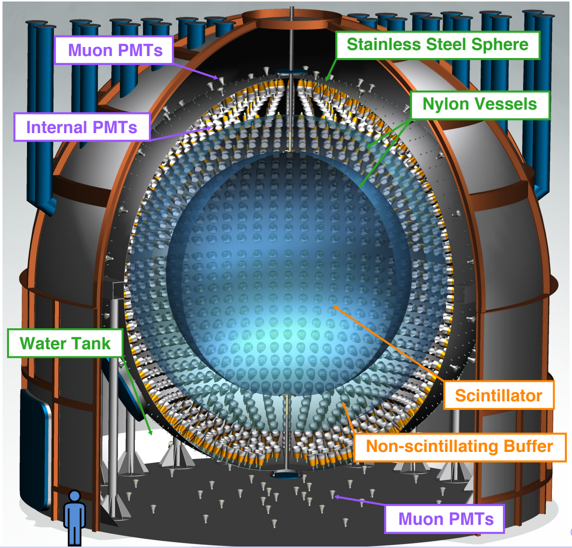
Summary

- Detector: ∅8.5 m balloon
- Target: 278 t LS
- PMT: 2212 8"
- Resolution: $\sigma_E = 5\%$ at 1 MeV



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Highlights

- Extreme radio-purity
- No nuclear power plants nearby