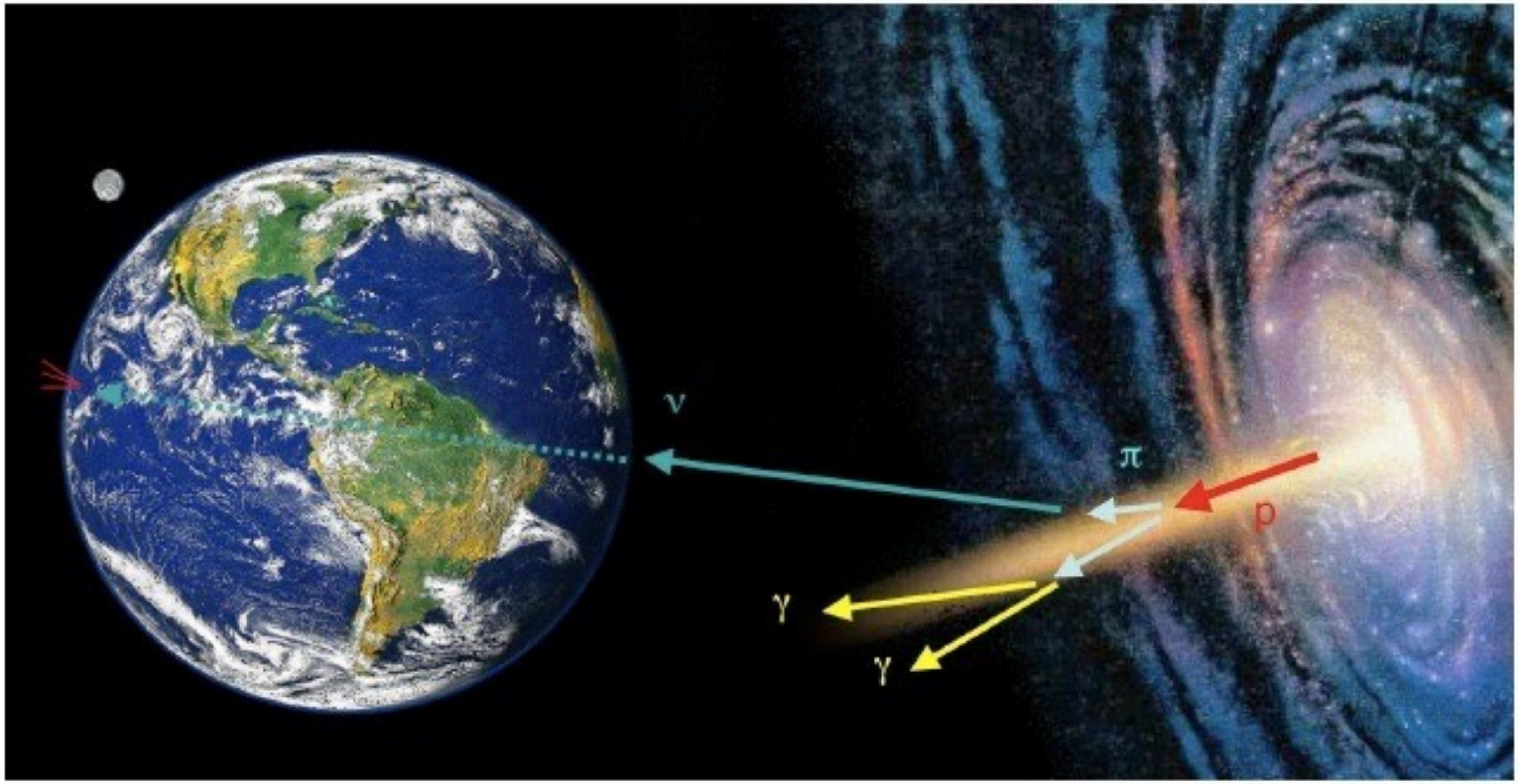
Teilchenphysik mit kosmischen und mit erdgebundenen Beschleunigern



13. Neutrinos II - Precision Oscillation Studies with Man-made Neutrinos, Cosmic Neutrinos

09.07.2018

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Where we left off last time:

Neutrino Oscillations: Overall Picture

Neutrino Oscillations - Status

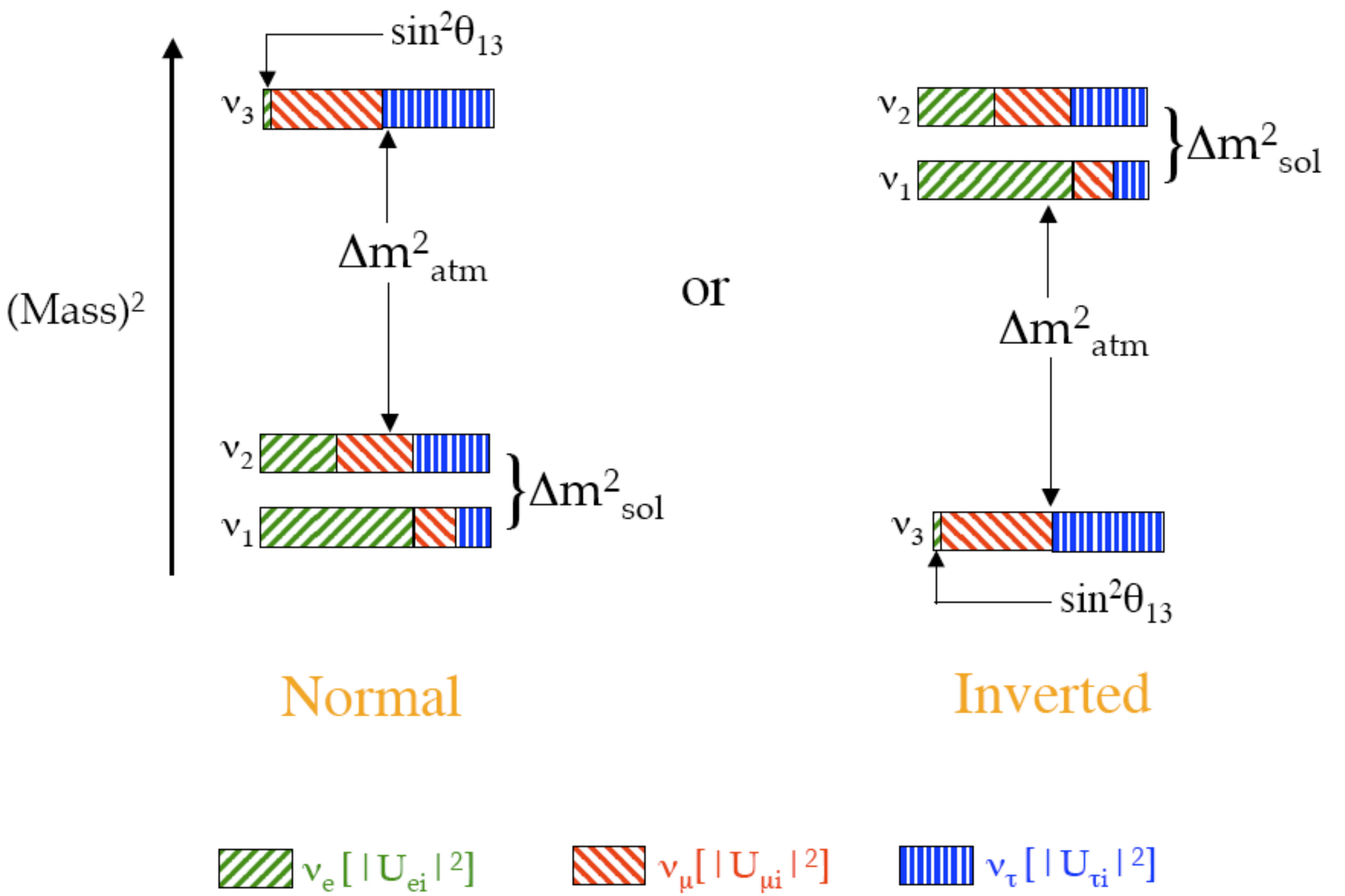
- Two distinct types of oscillations (with quite different mass splittings) have been observed:
  - Solar - disappearance of ν_e, $\Delta m^2 \sim 7.6 \times 10^{-5}$ eV^2
  - Atmospheric - disappearance of ν_μ, $\Delta m^2 \sim 2.4 \times 10^{-3}$ eV^2
- Choice of convention: small splitting between ν_1 and ν_2, big between ν_1/ν_2 and ν_3
- The data tell us: mixing between ν_1 and ν_3 is small
  - In solar oscillations, we observe $\nu_1 \rightarrow \nu_2$ oscillations, ν_1 has to have a big ν_e component
  - In atmospheric oscillations, we observe $\nu_2 \rightarrow \nu_3$, with maximal mixing: ν_3 is (almost) a 50-50 mixture of ν_τ and ν_μ

solar/ reactor

$$U_{MNS} = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix}$$

atmospheric/ accelerator

Neutrino-Oscillations: The Resulting Picture



Δm^2_{sol} ~ 7.6 x 10^{-5} eV^2

Δm^2_{atm} ~ 2.4 x 10^{-3} eV^2

One neutrino has to have a mass of at least ~ 0.05 eV!

Solar and atmospheric oscillations probe two of the three mixing angles - the 3rd (smallest) needs “laboratory” experiments

- Absolute masses and hierarchy not known yet! Two possible arrangements...

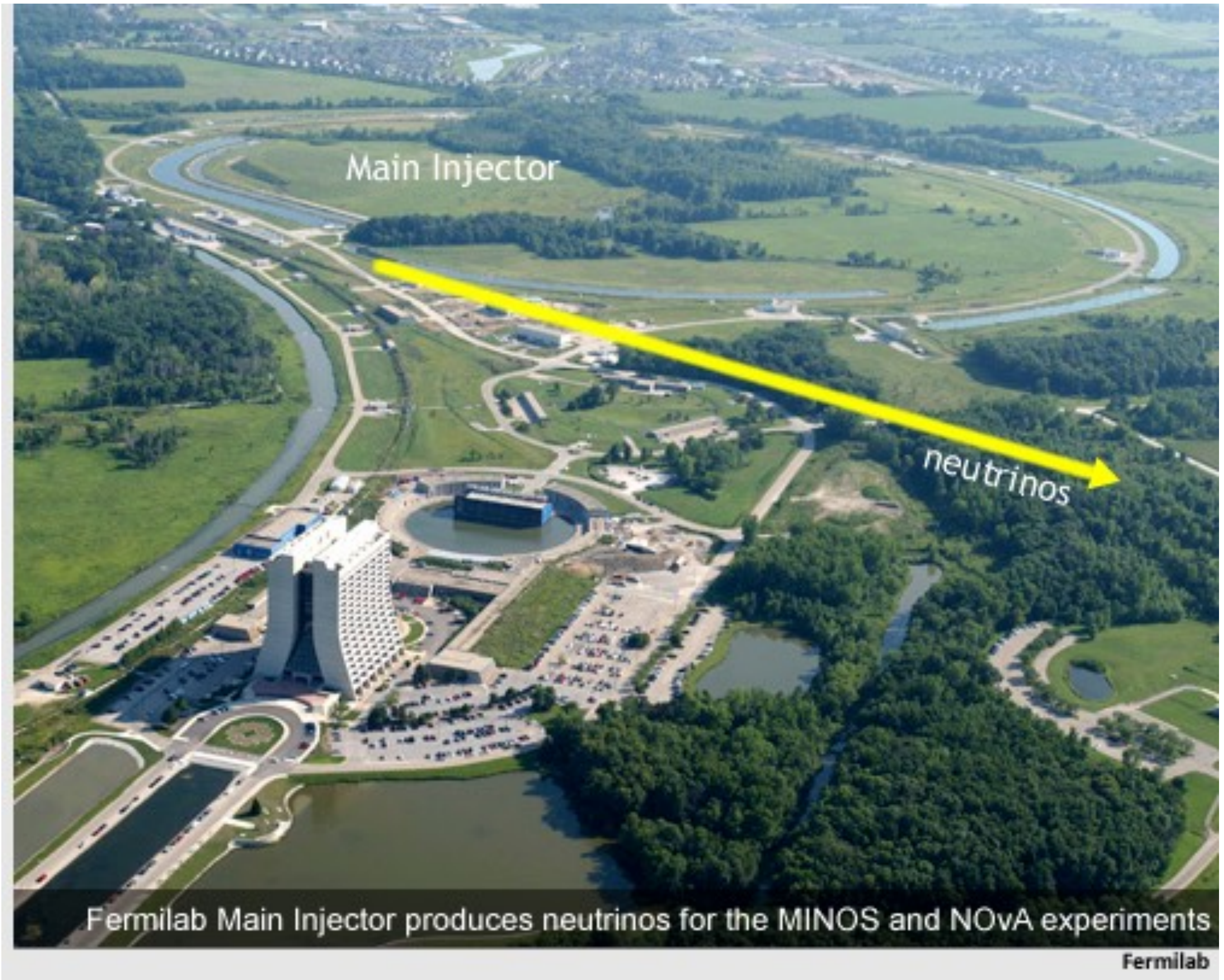
Measurements with man-made Neutrinos

Man-made Neutrino Sources

- Two main sources for neutrinos used for oscillation experiments:

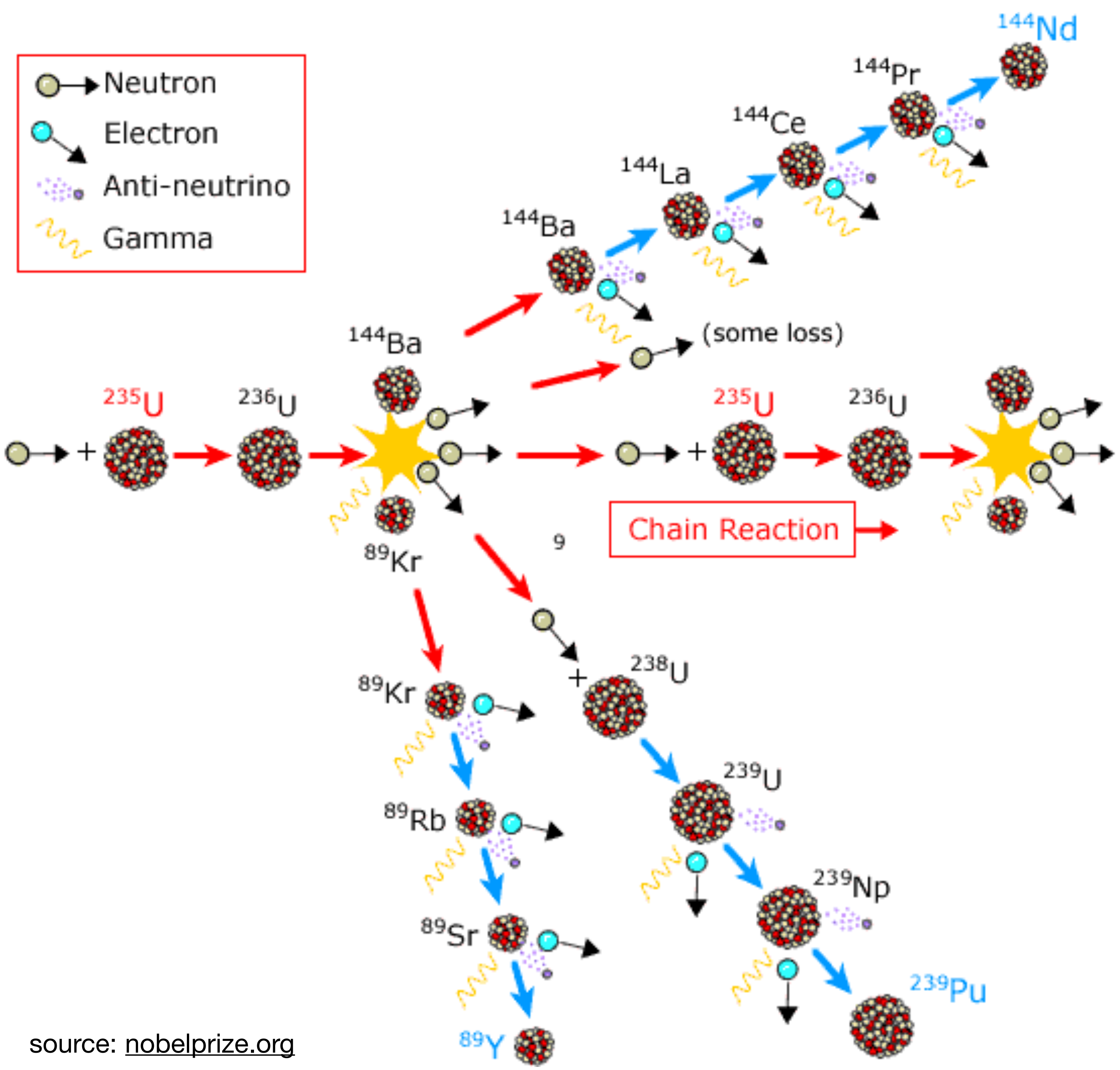
nuclear power reactors

high energy accelerators

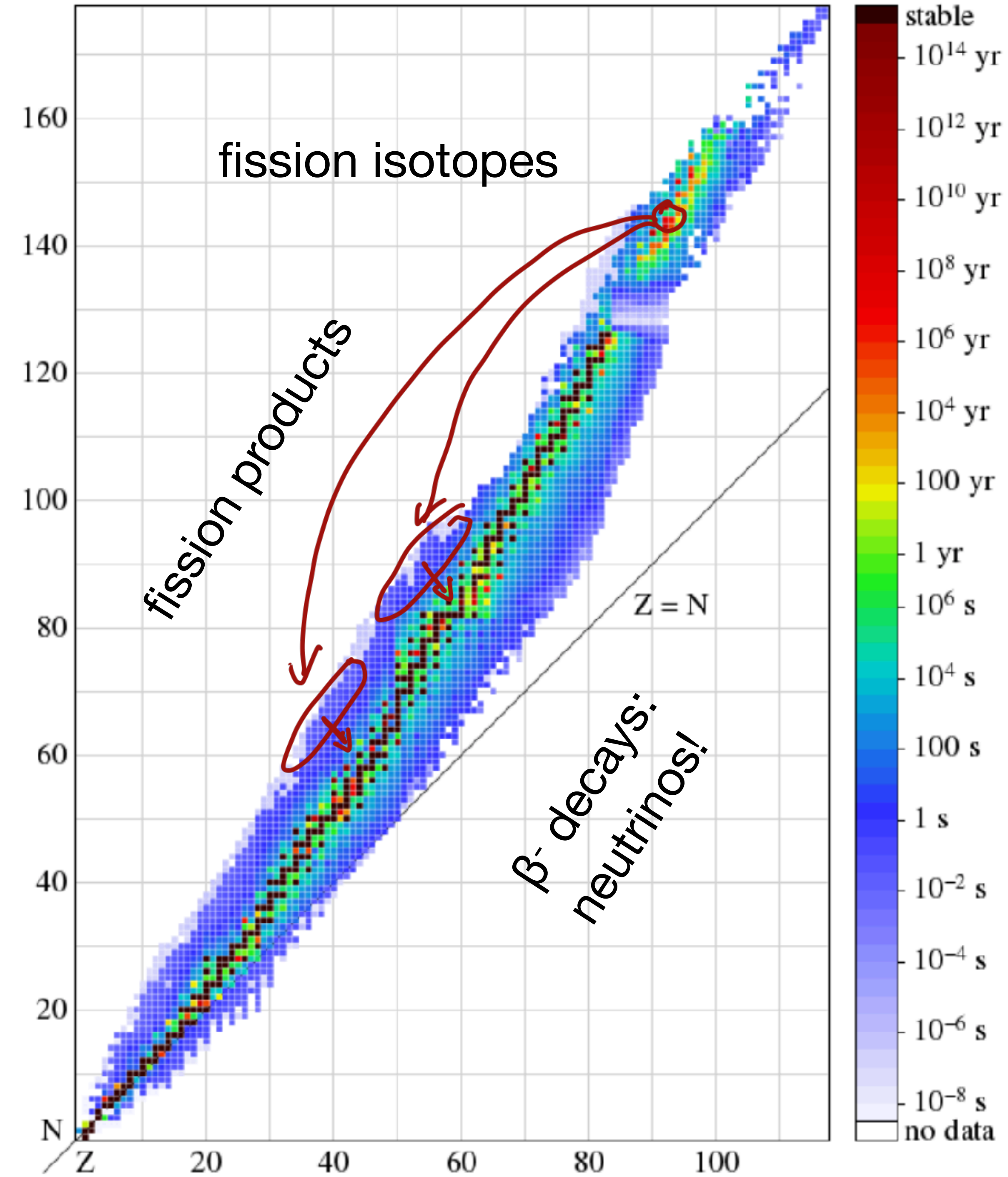


Reactor Neutrinos

- A rich spectrum of anti-electron neutrinos - Energies in the MeV range



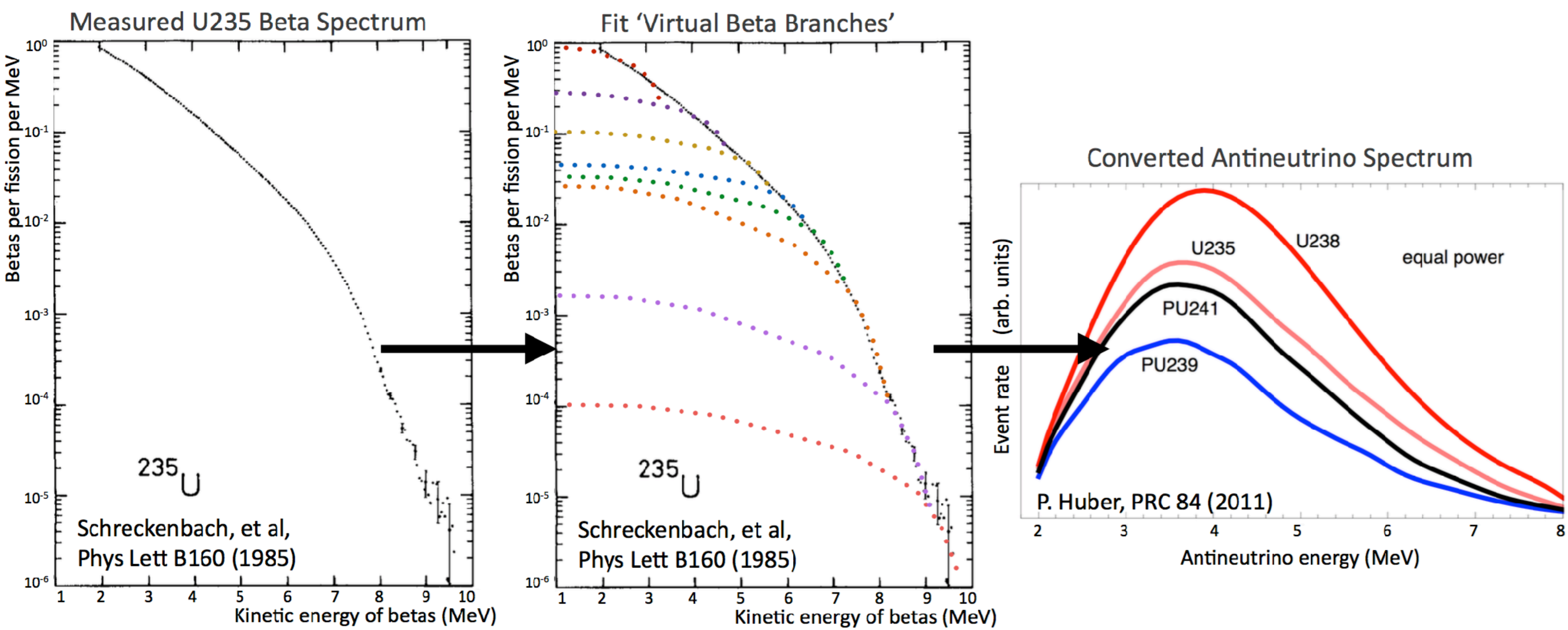
source: nobelprize.org



source: wikipedia.org

The Reactor Neutrino Spectrum

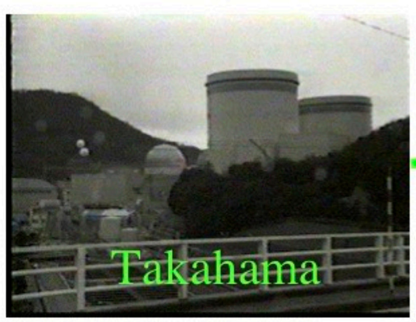
- A key component of reactor experiments: Understanding the neutrino flux and energy spectrum
  - Highly non-trivial: Many fission and complex decay chains involved

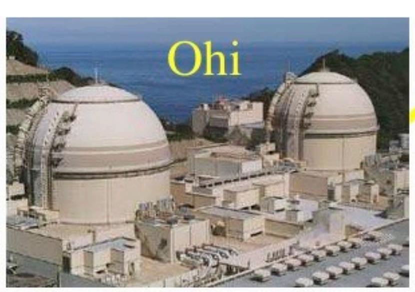


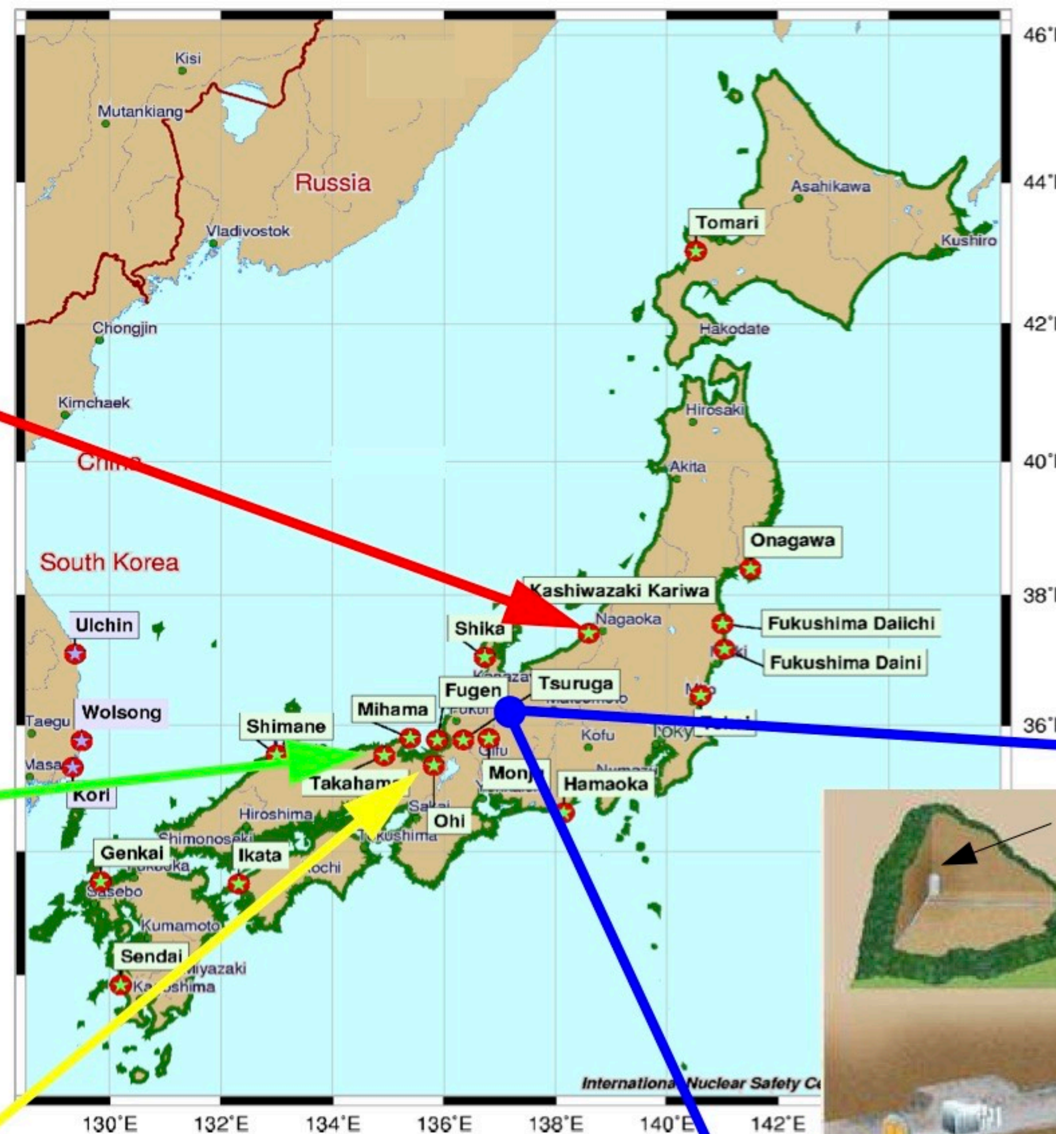
KamLAND: Using Reactors to prove Solar Oscillations

- For few MeV Neutrinos and “Large Mixing Angle” solution of solar observations: Need a baseline of ~ 100 km

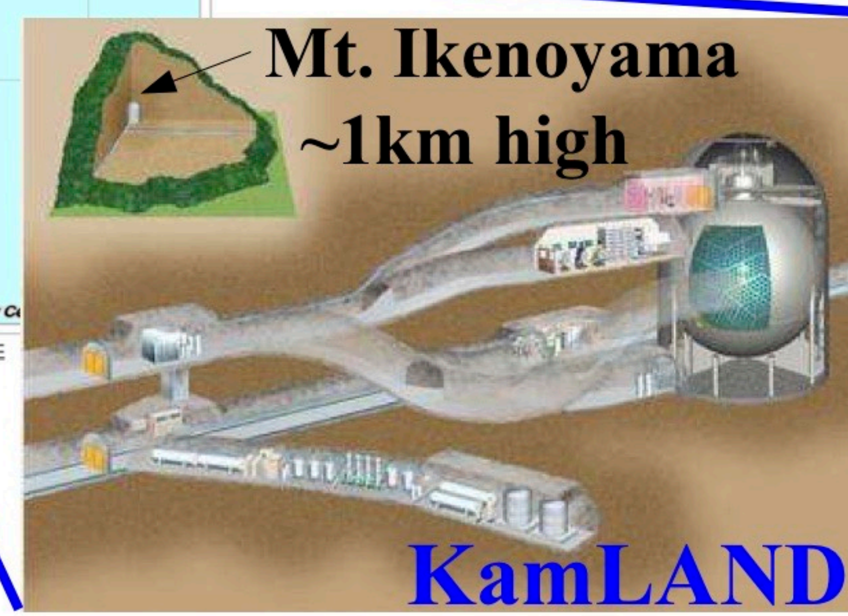
55% of total flux from:



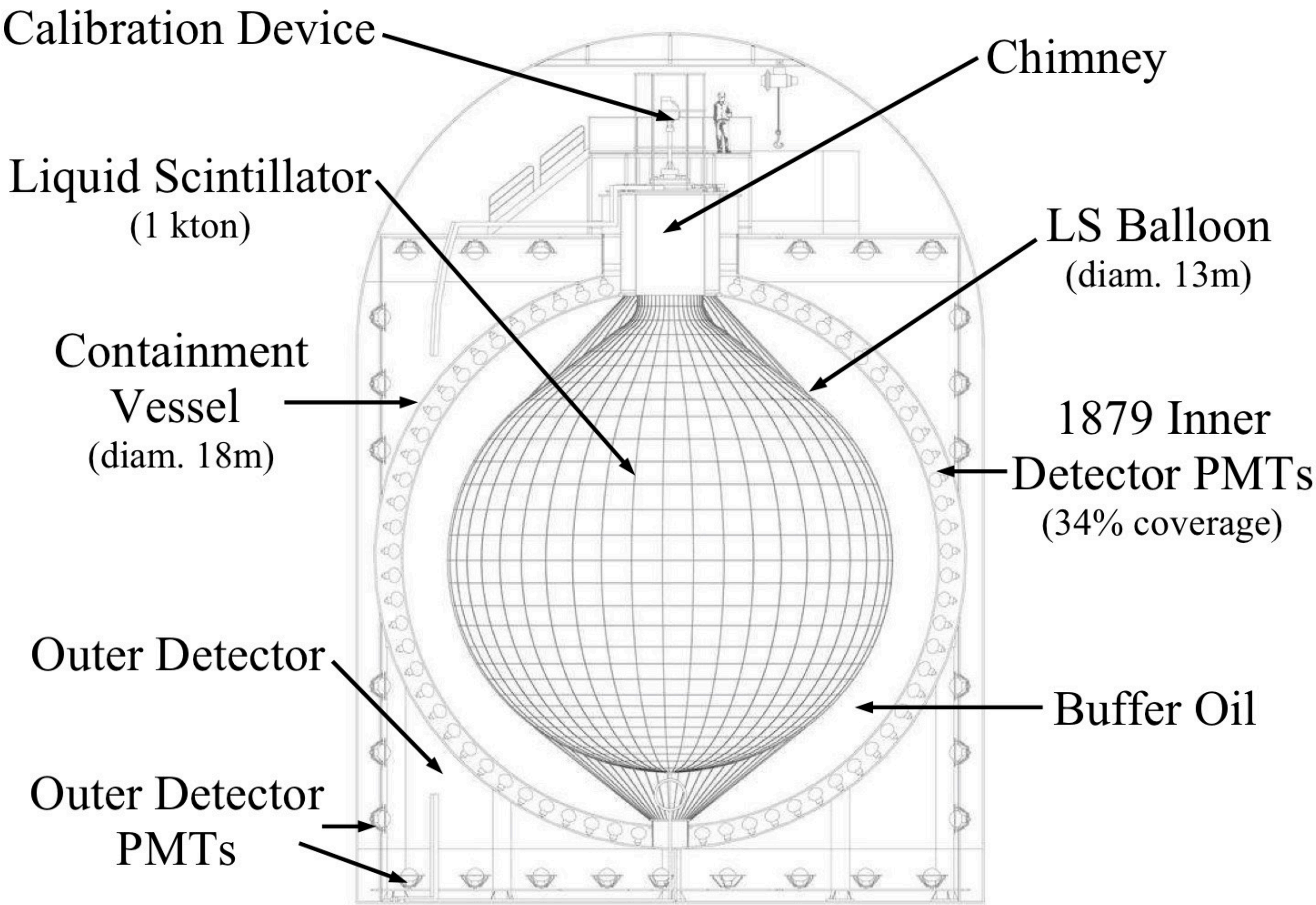




KamLAND uses the entire Japanese nuclear power industry as a 180 GW_{th} long-baseline source!



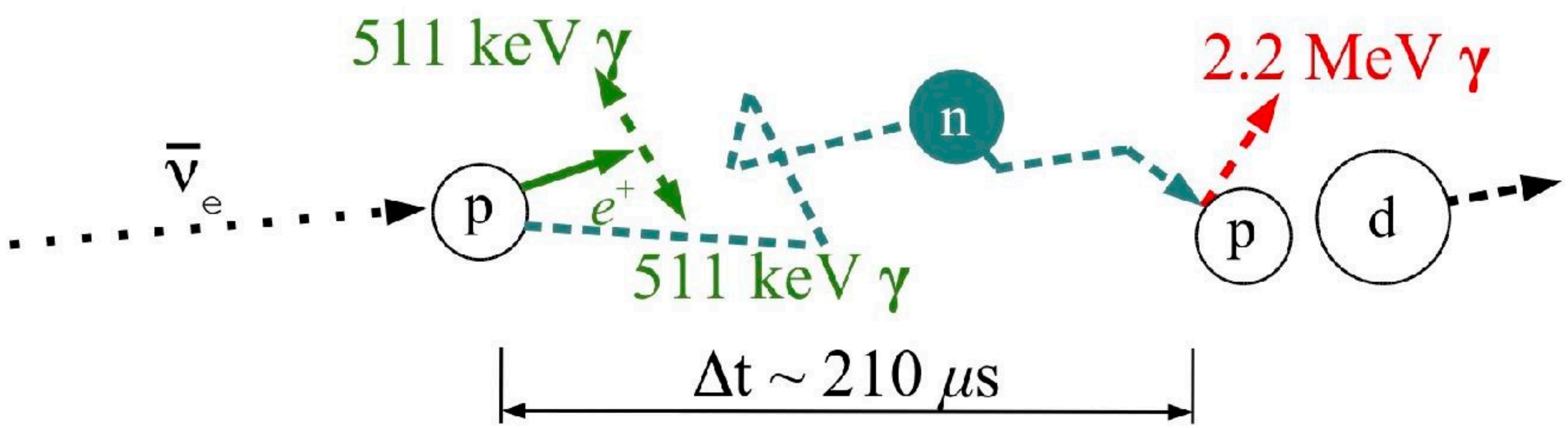
The KamLAND Experiment



The KamLAND Experiment

- Neutrino detection in KamLAND (and other reactor experiments):

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

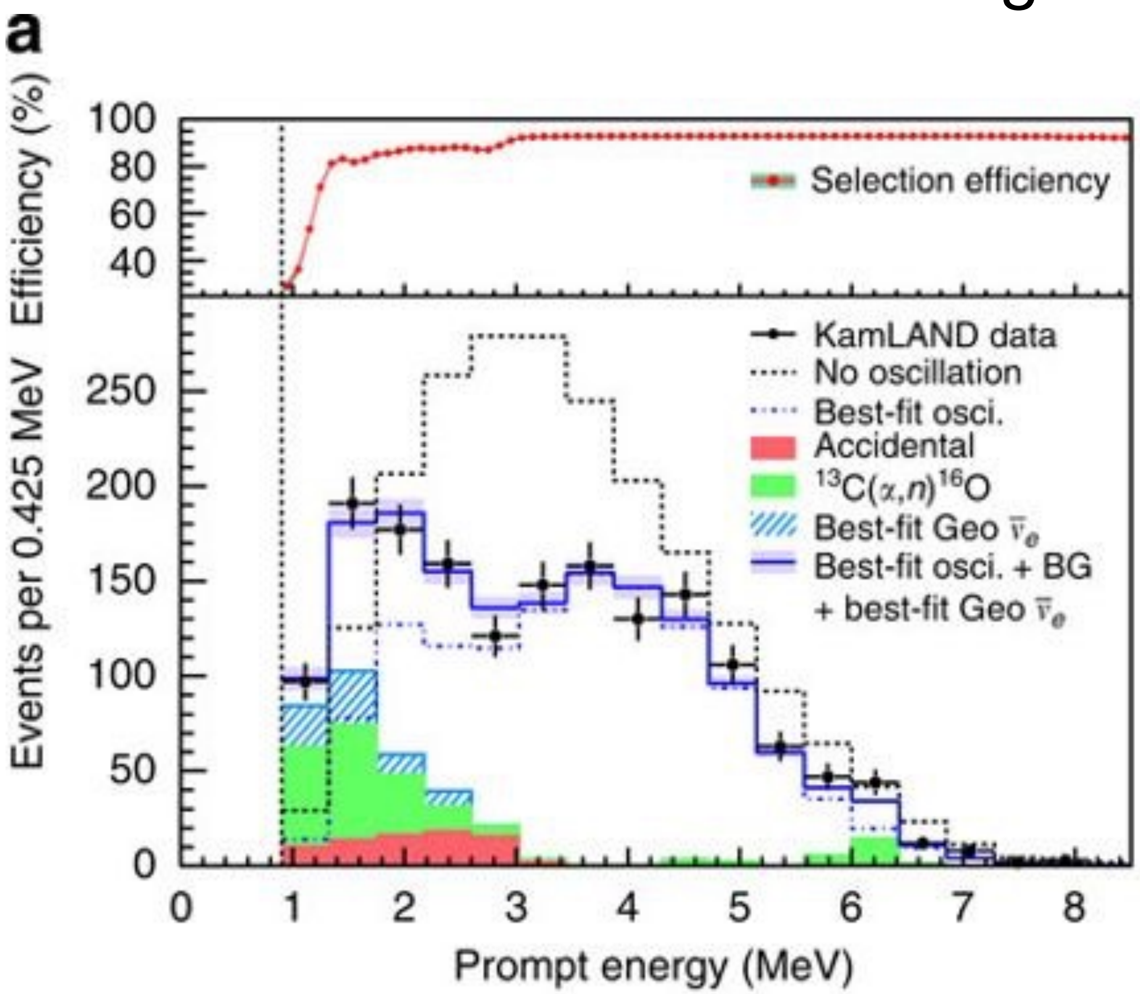


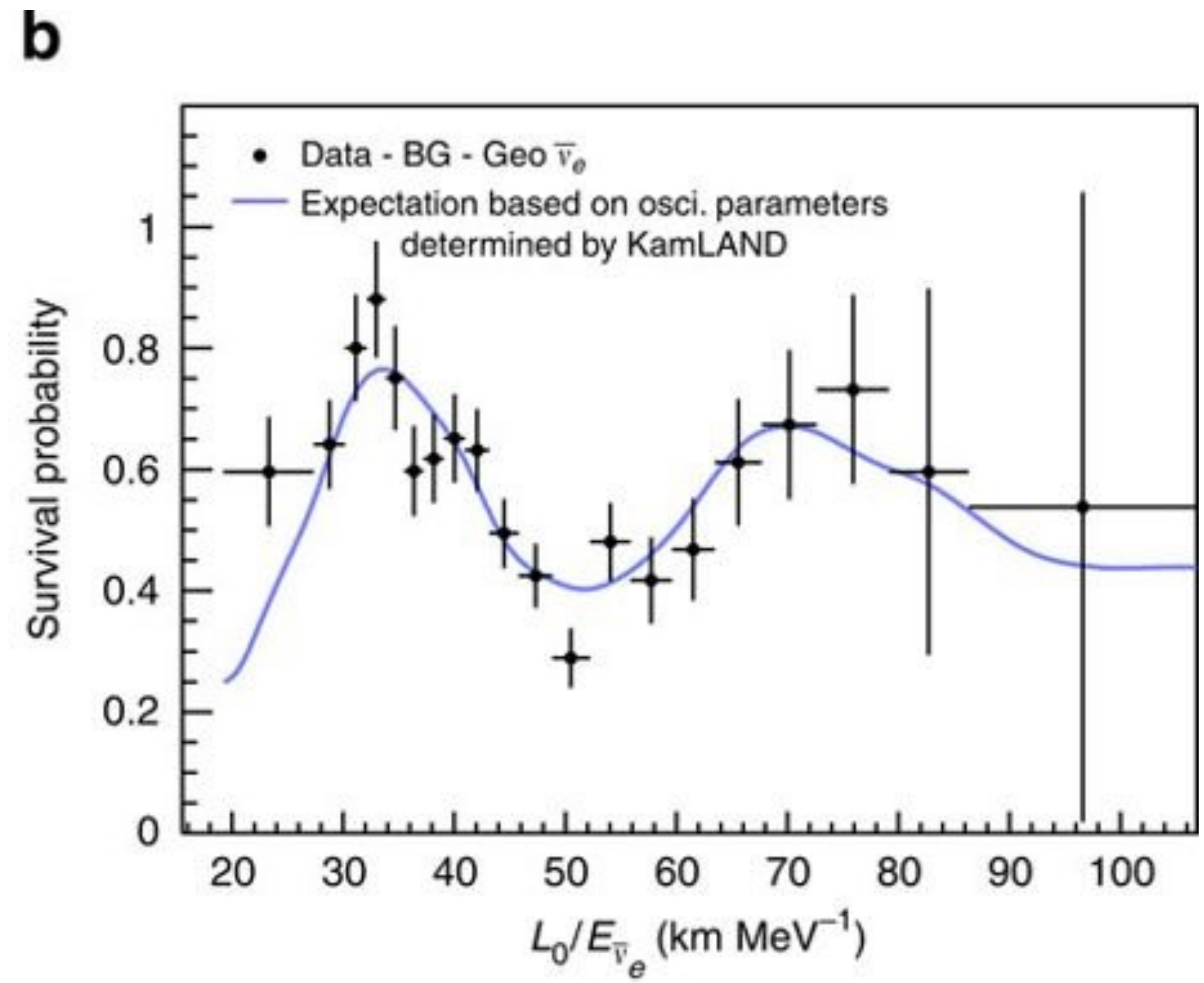
- Two-component signature:
  - Prompt signal: Ionisation energy from e^+, annihilation photons
  - Delayed signal: Photon from neutron capture

Universal feature: Only electron (anti-) neutrinos can be detected in CC reactions - Energy threshold for muon neutrinos > 105 MeV:
Reactor experiments are **disappearance experiments**

KamLAND: Proving Solar Oscillations

- Observed clear oscillation signal





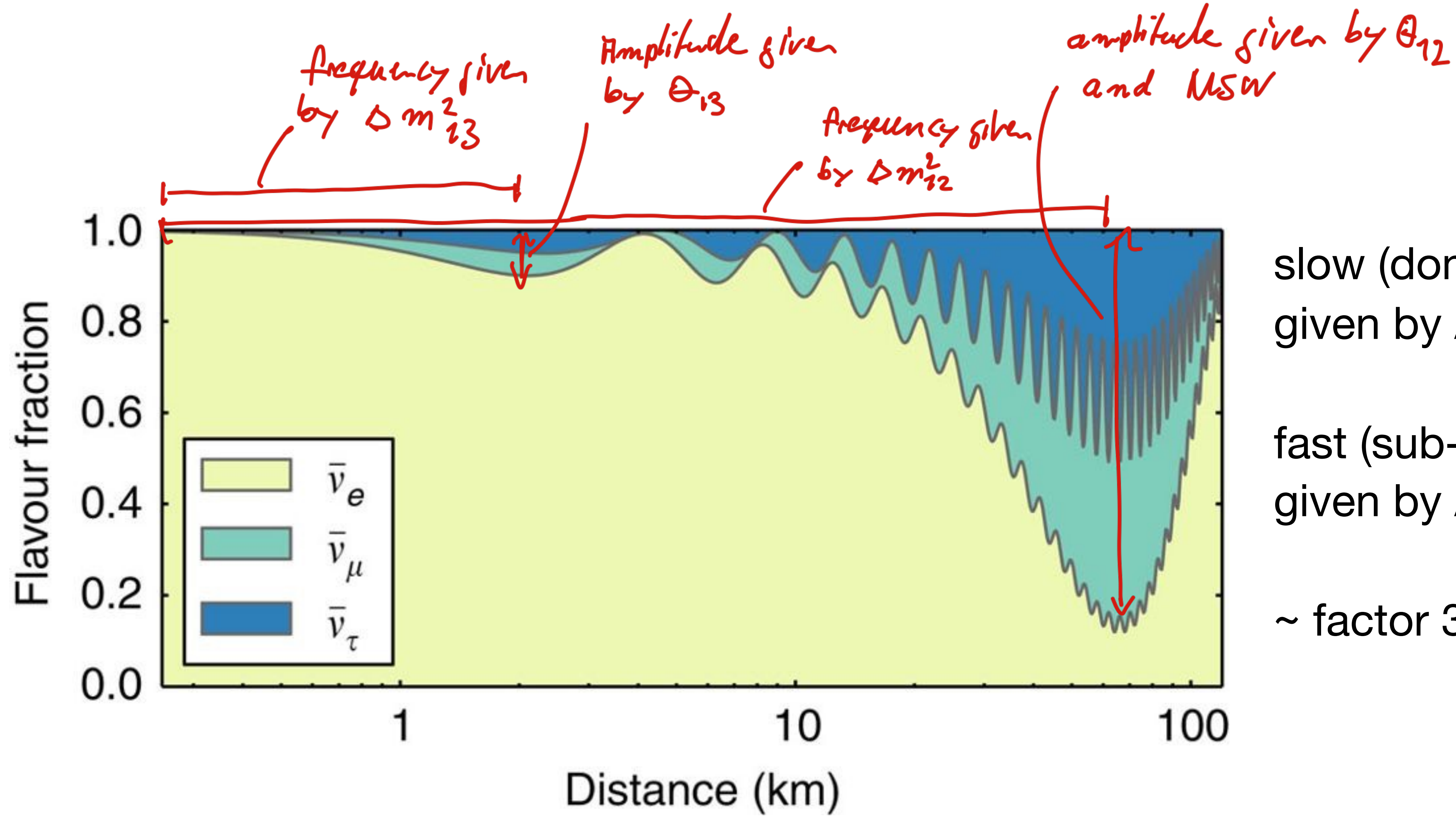
- Consistent with large mixing angle solution for solar observations

together with SNO:

$\tan^2\theta_{12} = 0.47^{+0.06}_{-0.05}$ (34.4 degrees) $\Delta m^2_{21} = 7.59^{+0.21}_{-0.21} \times 10^{-5}\,\mathrm{eV}^2$

Going beyond the leading Oscillation

- Oscillations of reactor (and solar) neutrinos are dominated by the 1->2 transition - but that is not all:



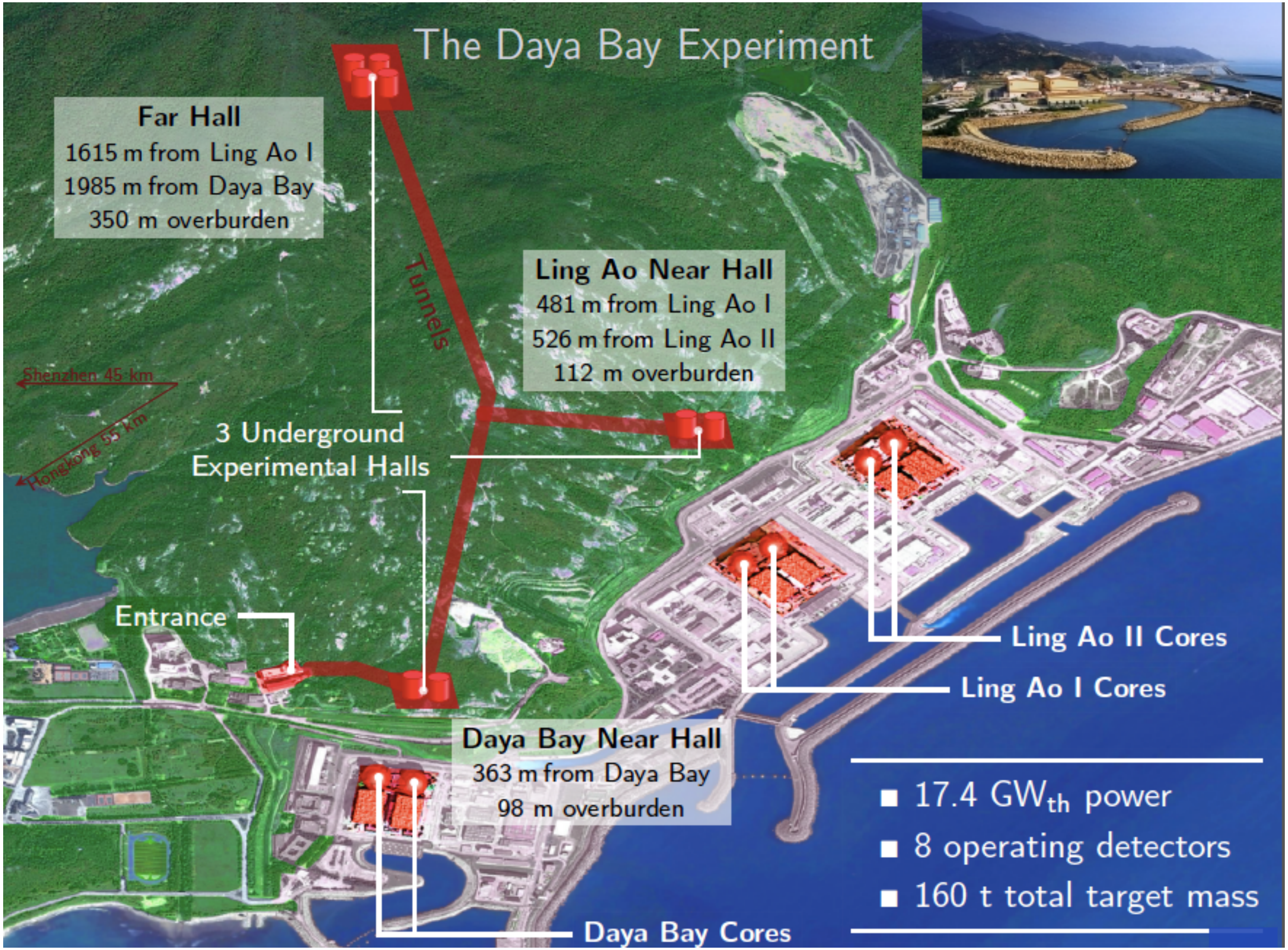
slow (dominant) oscillation: given by Δm^2_{12}

fast (sub-dominant) oscillation: given by Δm^2_{13} (~ Δm^2_{23})

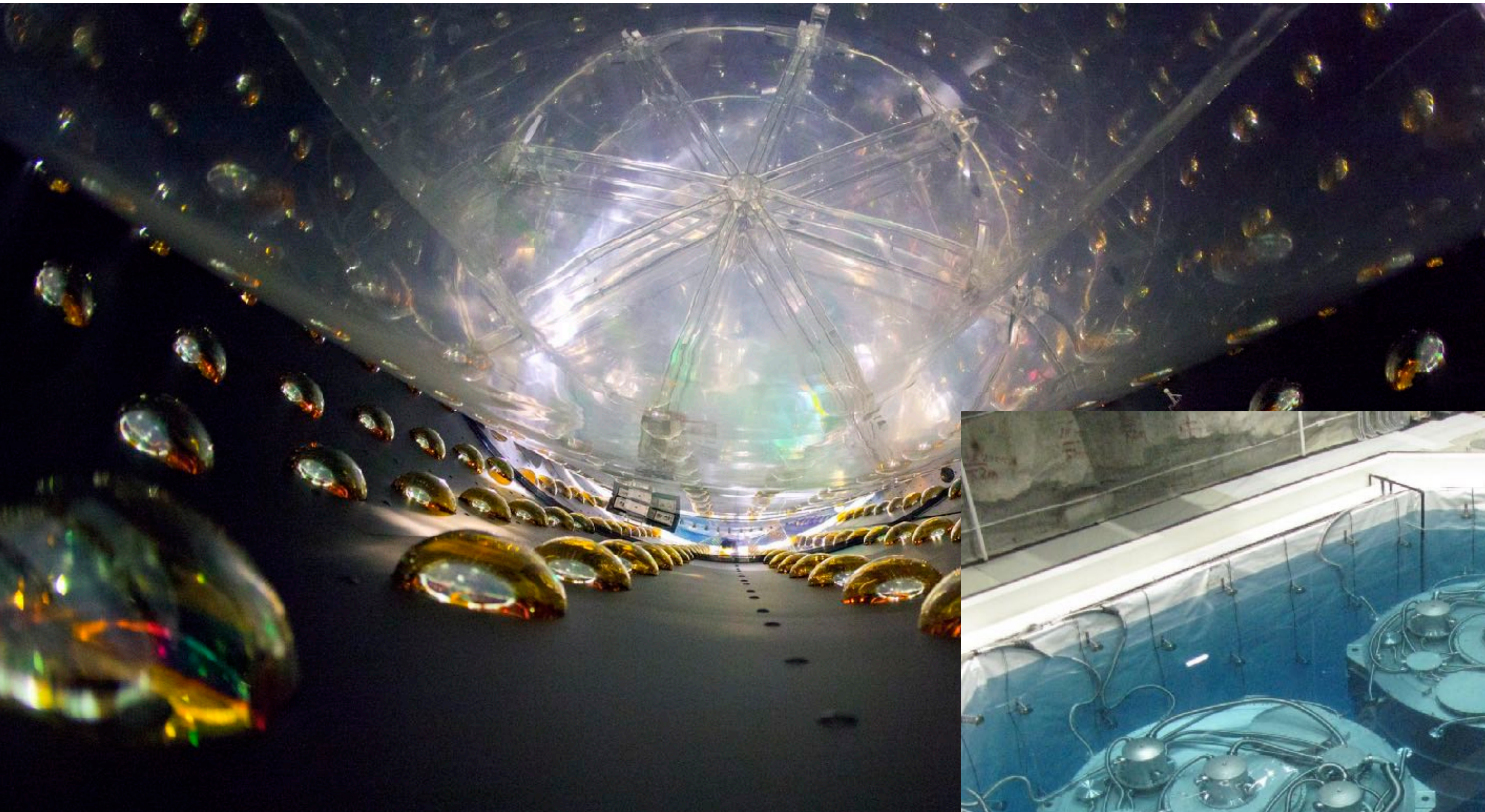
~ factor 32 in oscillation speed

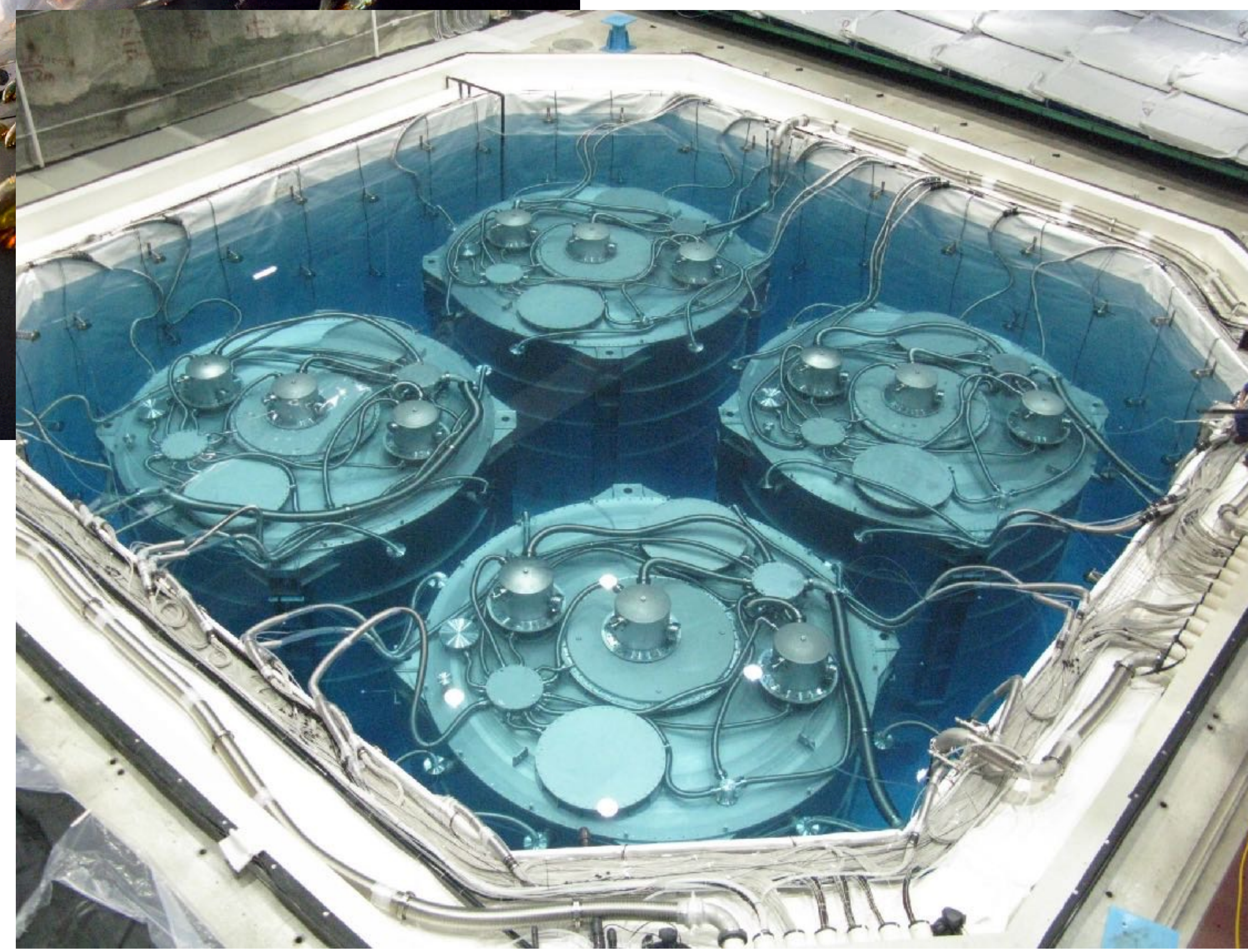
Illustrated for mono-energetic anti-electron neutrinos with E = 4 MeV

Daya Bay: Measuring Θ13



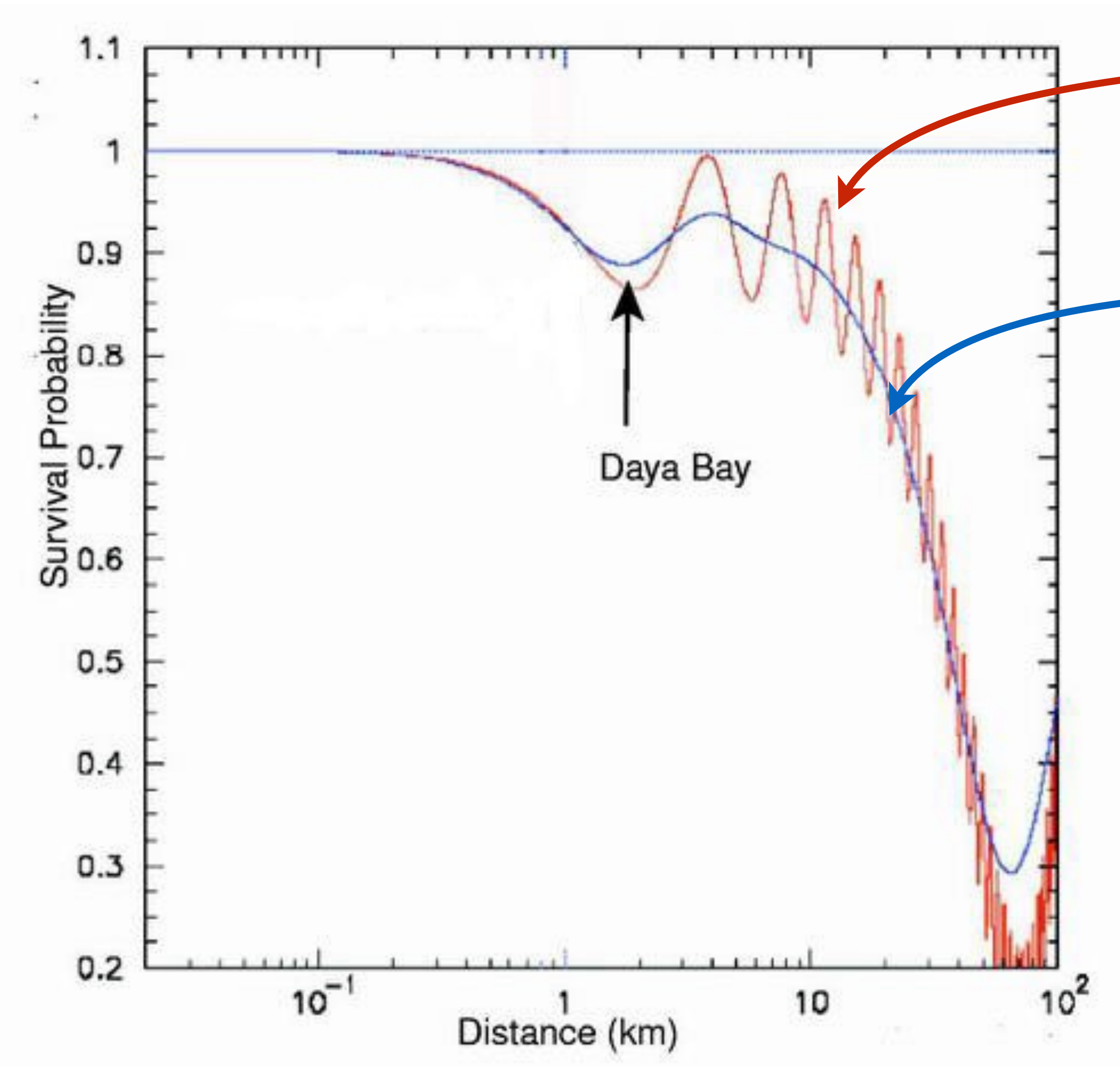
Daya Bay Detectors





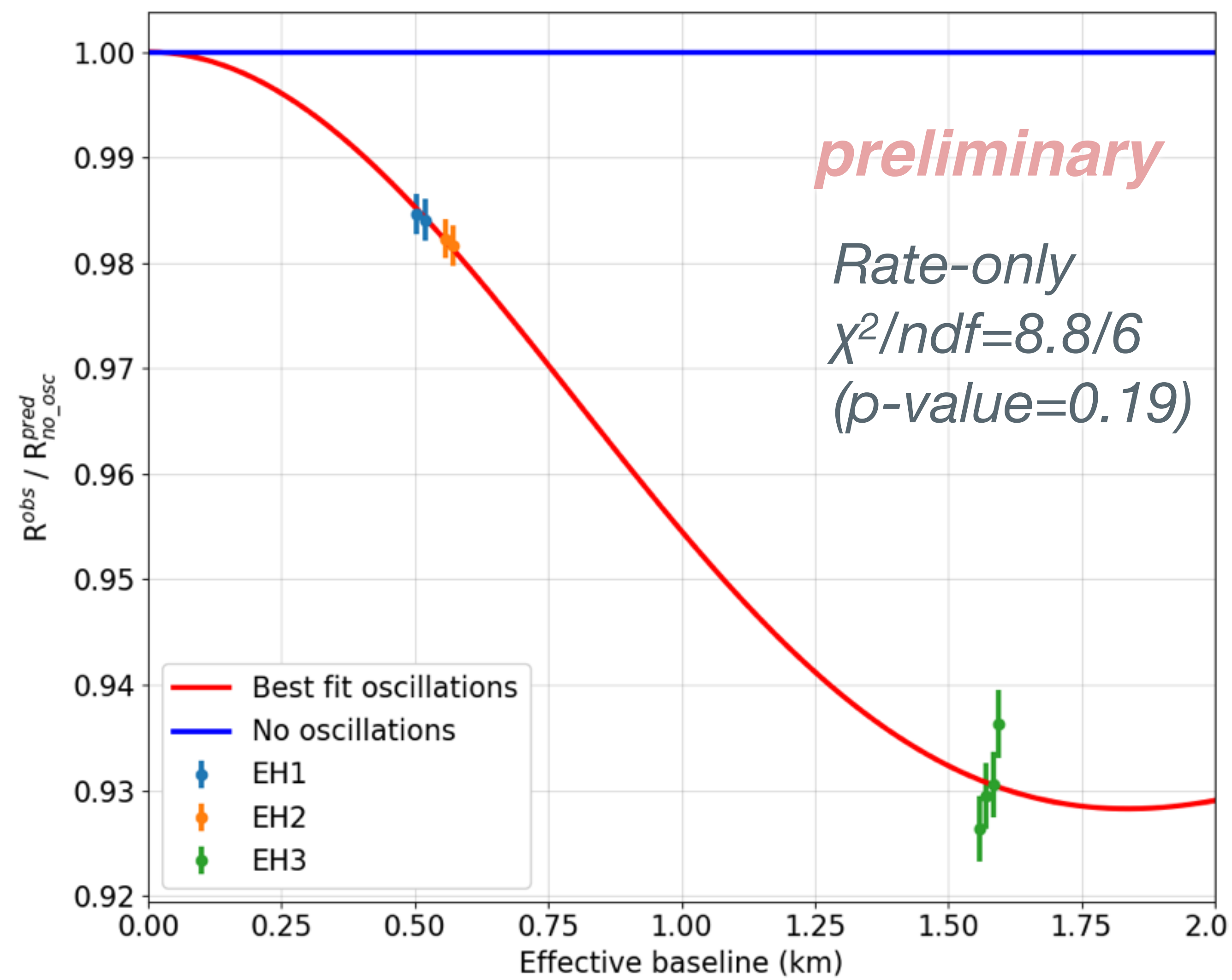
- Liquid scintillator detectors (20t)
  - Gd doped to improve neutron capture for secondary signal
- Water-based veto

Daya Bay Oscillation Signal



hypothetical signal with monoenergetic neutrinos

expected signal taking energy spectrum into account

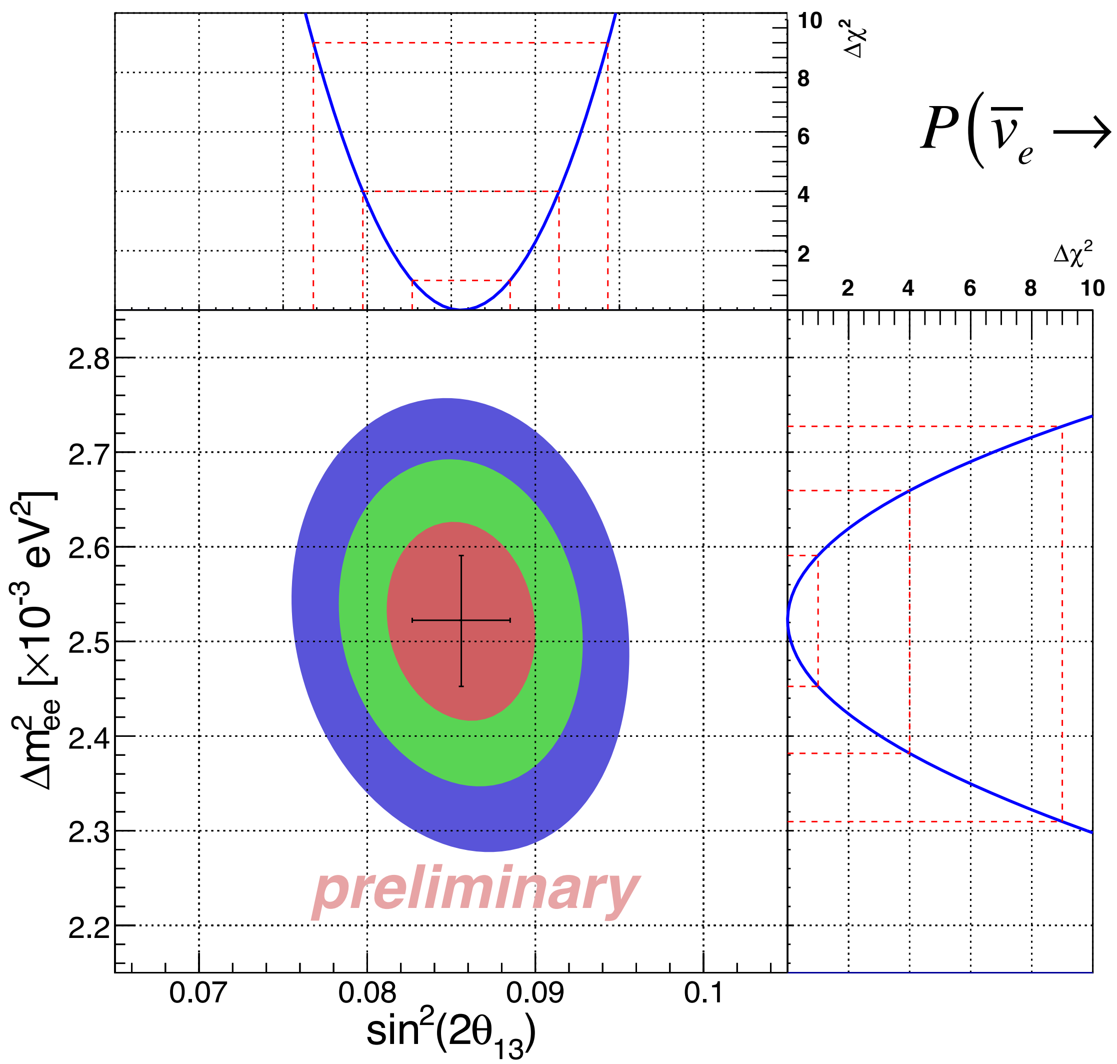


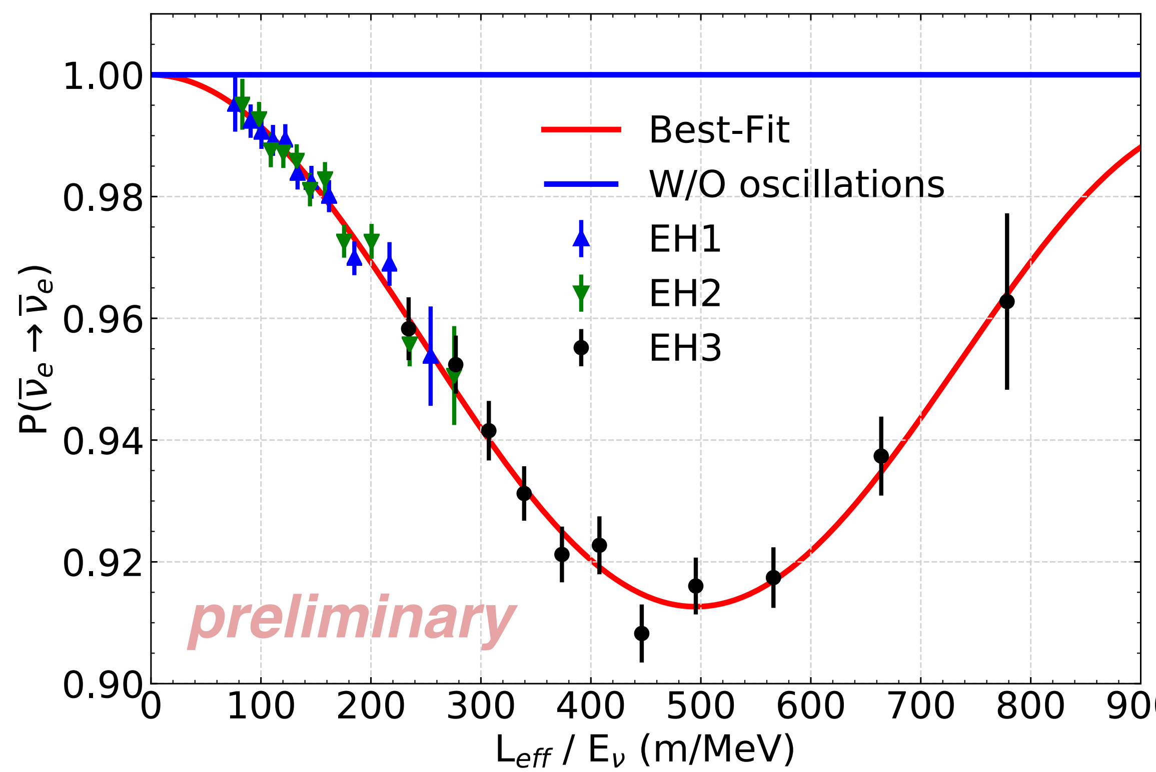
Daya Bay Result

- Measure $\sin^2 2\theta_{13}$ and $|\Delta m^2_{ee}|$ to **3.4%** and **2.8%** respectively

effective mass splitting

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2 \frac{1.267 \Delta m^2_{ee} L}{E} - \text{solar term}$$





results with 1958 days →

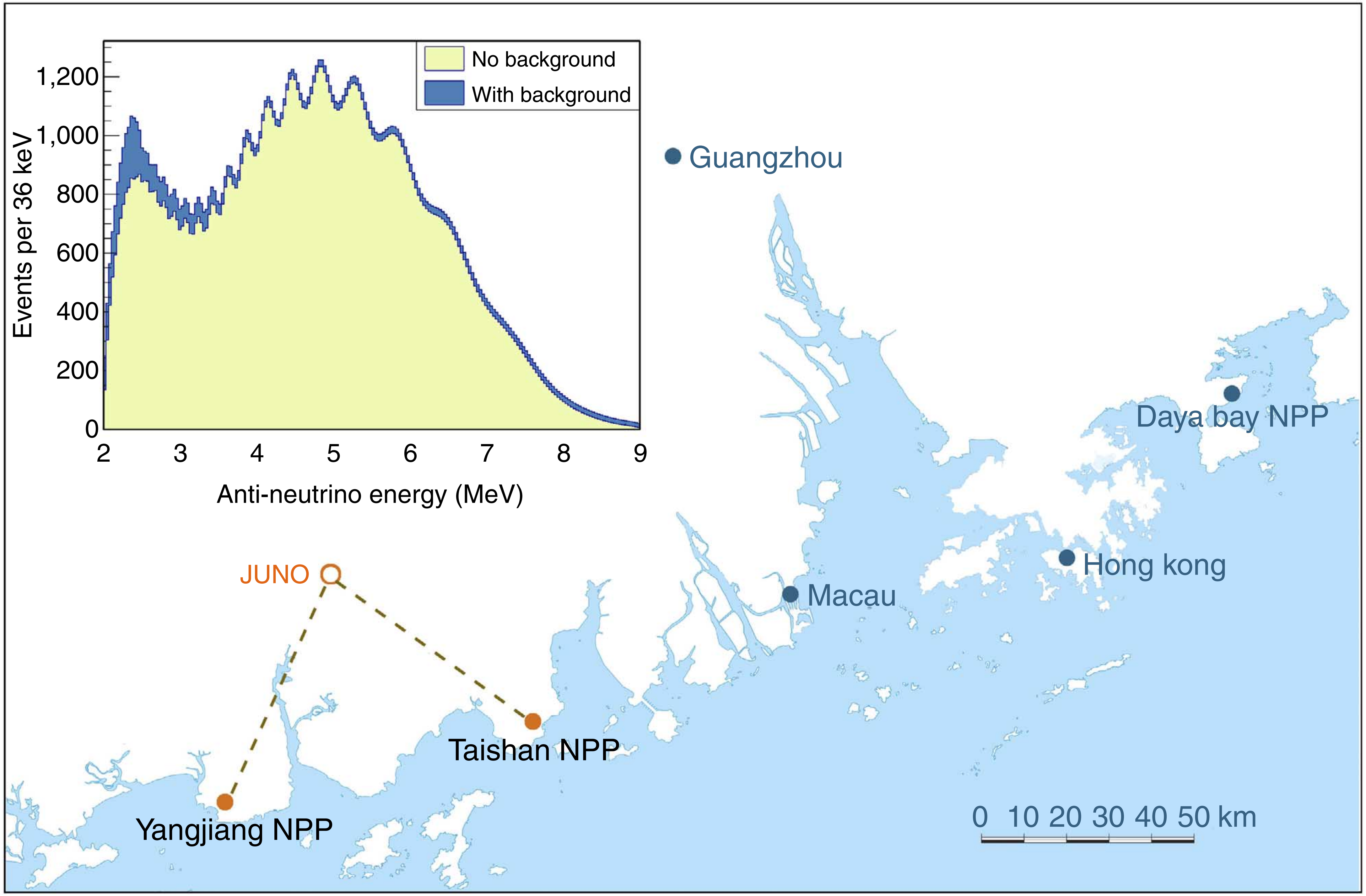
$$\sin^2 2\theta_{13} = 0.0856 \pm 0.0029$$

$$|\Delta m^2_{ee}| = (2.52 \pm 0.07) \times 10^{-3} \text{ eV}^2$$

The statistical uncertainty contributes about 60% (50%) of the total θ_{13} (Δm^2_{ee}) uncertainty.

Daya Bay is not alone: Other experiments: Double Chooz (France), RENO (Korea)

The Next Generation of Reactor Experiments



- JUNO: Measure the mass ordering of neutrinos

Neutrinos at Accelerators

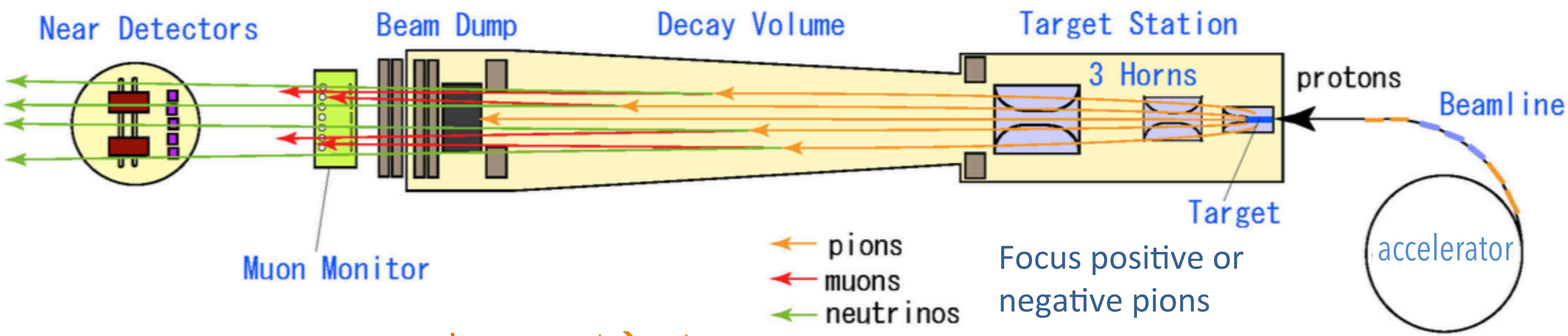
- Neutrino production:
  - Analogous to air showers: hadronic showers on impact of highly energetic protons on production target
  - Production of pions, kaons that decay in a decay tunnel:

$$\pi^-, K^- \rightarrow \mu^- + \bar{\nu}_\mu$$

  - Tunnel not long enough for substantial decay of muons: Essentially pure ν_μ beam

- There have been many different experiments with accelerator neutrinos
  - Study of the weak interaction
  - Measurement of the quark composition of nuclei
  - Discovery of the ν_τ
  - Confirmation of atmospheric measurements
  - Evidence for non-zero θ_{13}
  - First hints for CP violation

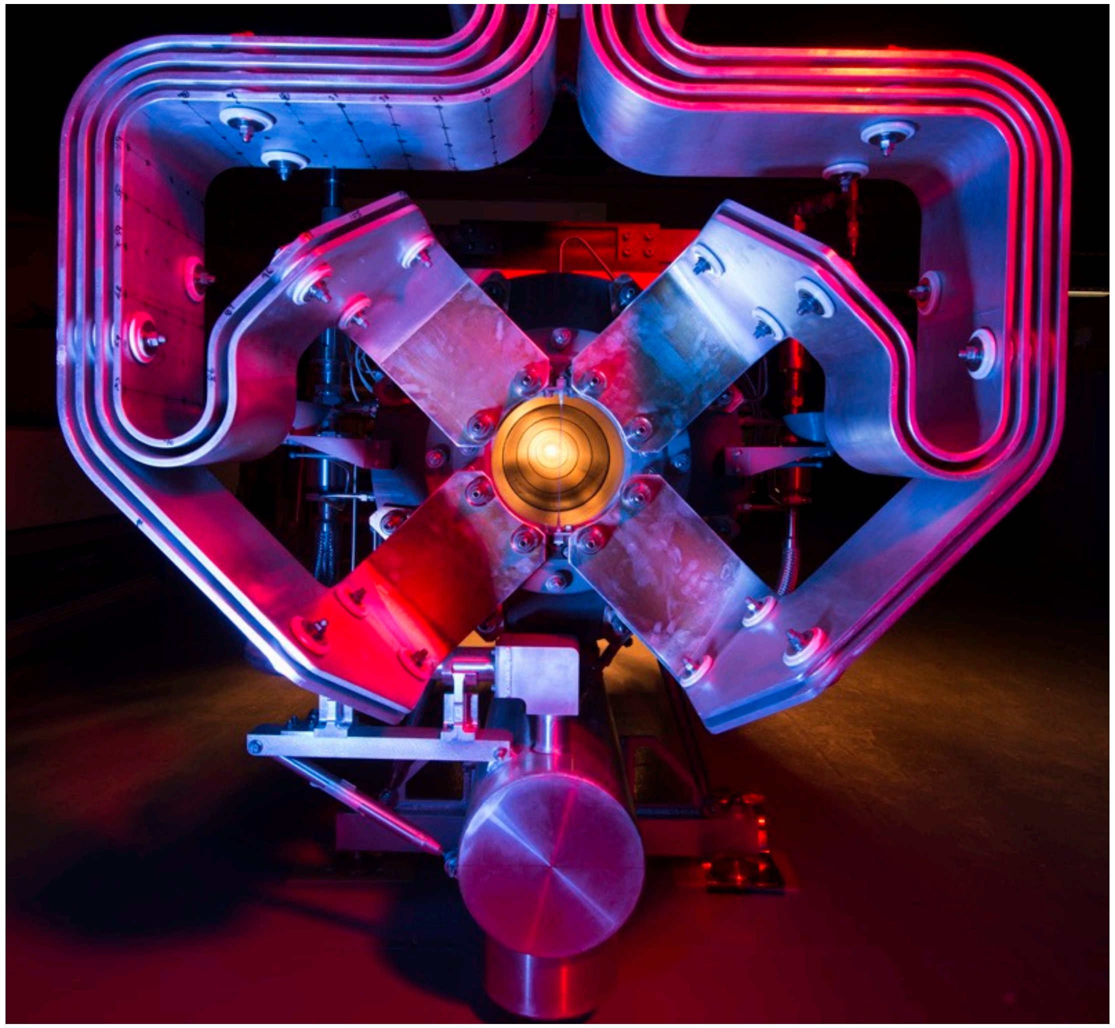
Making A Neutrino Beam



ν beam: $\pi^+ \rightarrow \mu^+ + \nu_\mu$

$\bar{\nu}$ beam: $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$

- Pions focused by specialized magnet systems:
  “Neutrino Horns”

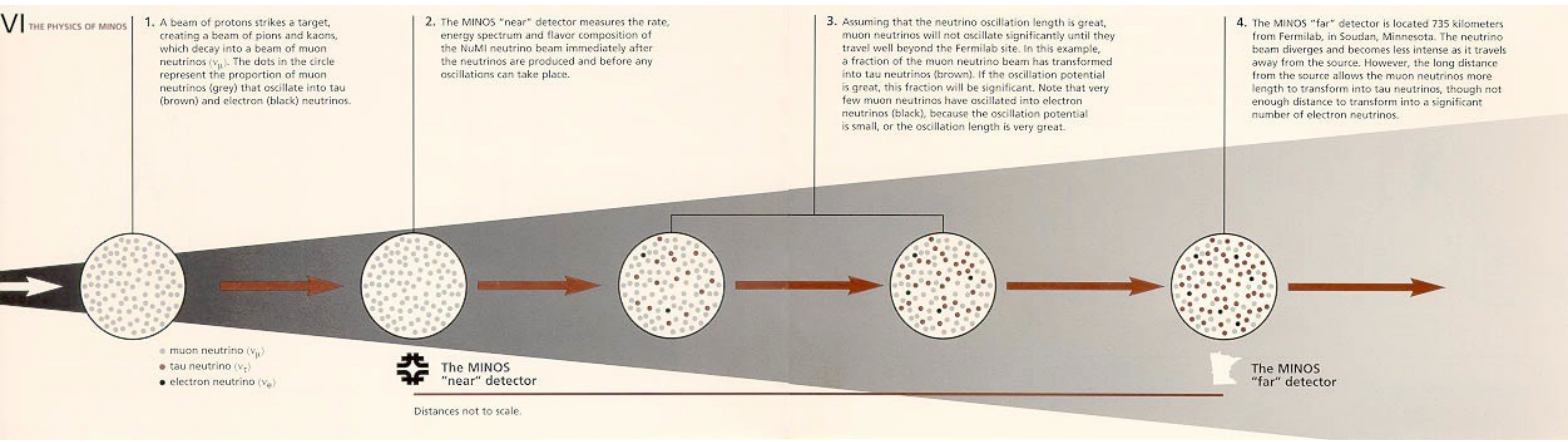


Long Baseline Experiments

- Neutrino beam produced with accelerator
- Reference measurement with a “Near Detector”
- Detection of neutrinos in a “Far Detector”

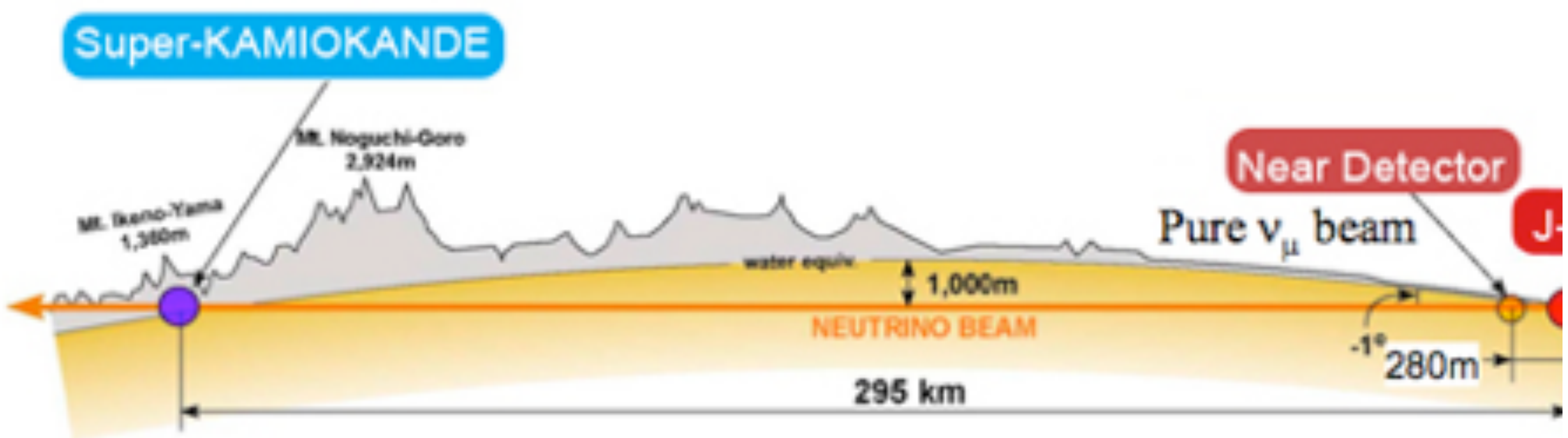
▸ Choice of distance and energy depends the region of the mixing matrix that can be probed

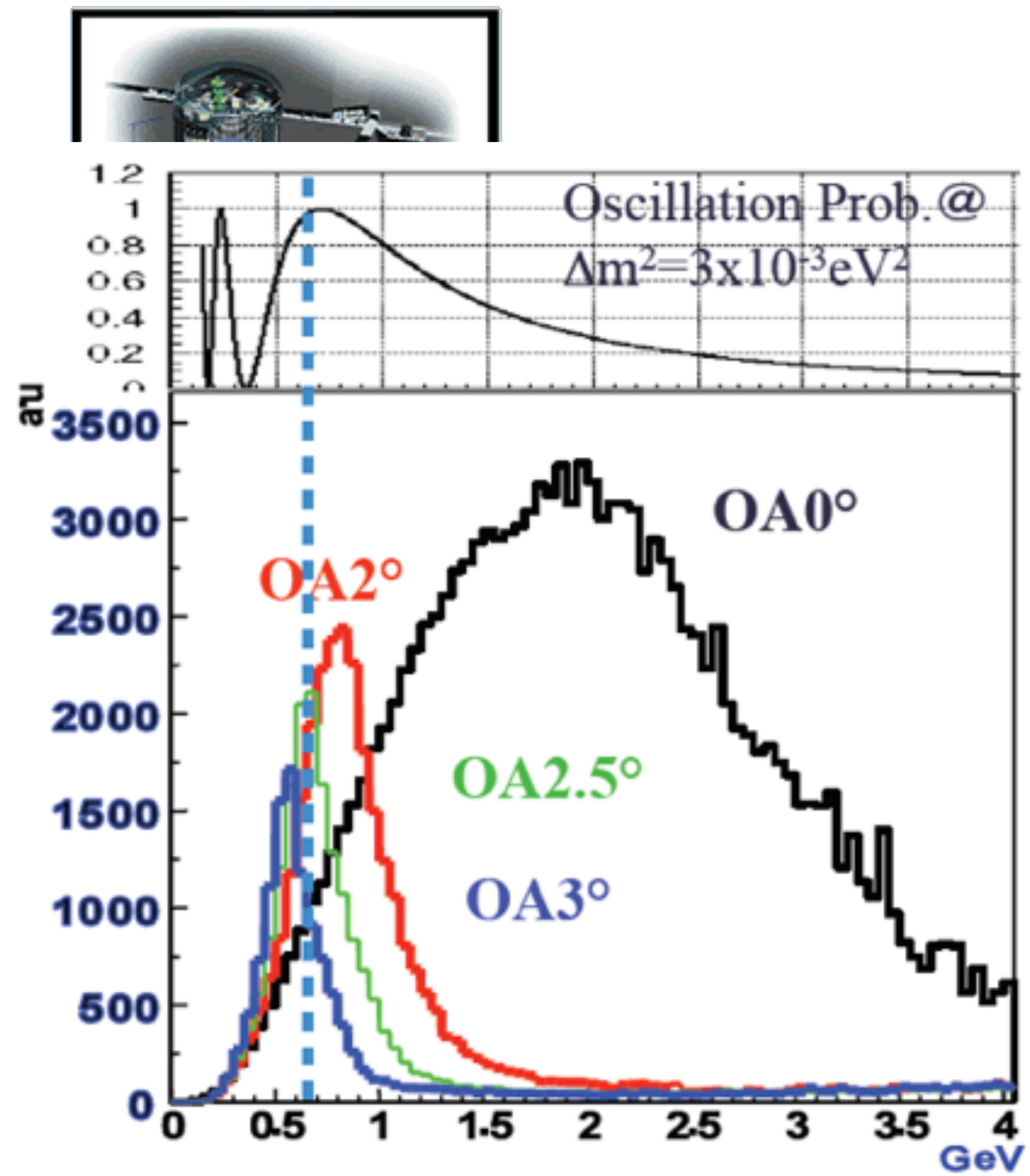
The composition of the beam changes from source to detector
From a pure ν_μ beam to a mixture of ν_μ , ν_τ and a few ν_e ($\theta_{13} \neq 0$)



T2K: Neutrino Beam to SuperK

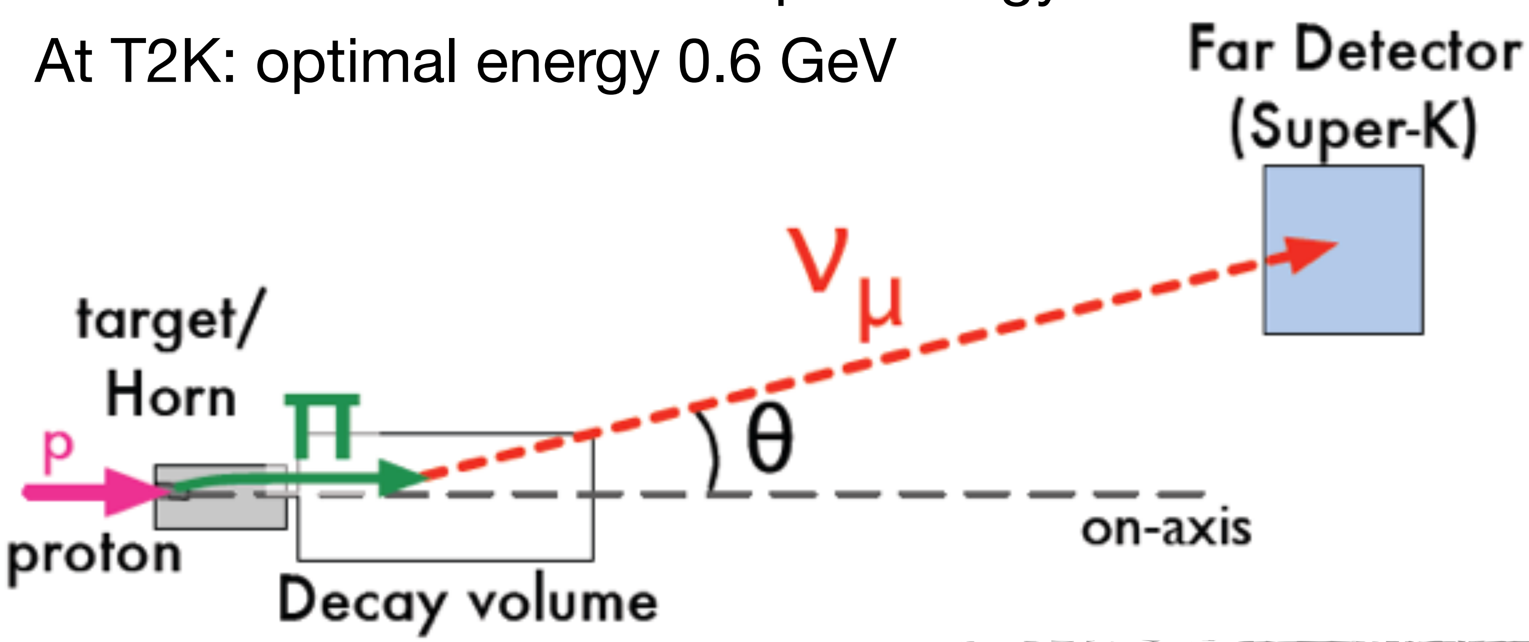
- Goal: precise measurement of atmosph. oscillation, θ_{13}, possible CP violation
- Runs since 2010 (with 1 year down time due to Tohoku Earthquake)





T2K is an “off-axis”- Beam: Aims not directly at the far detector -results in sharper energy distribution

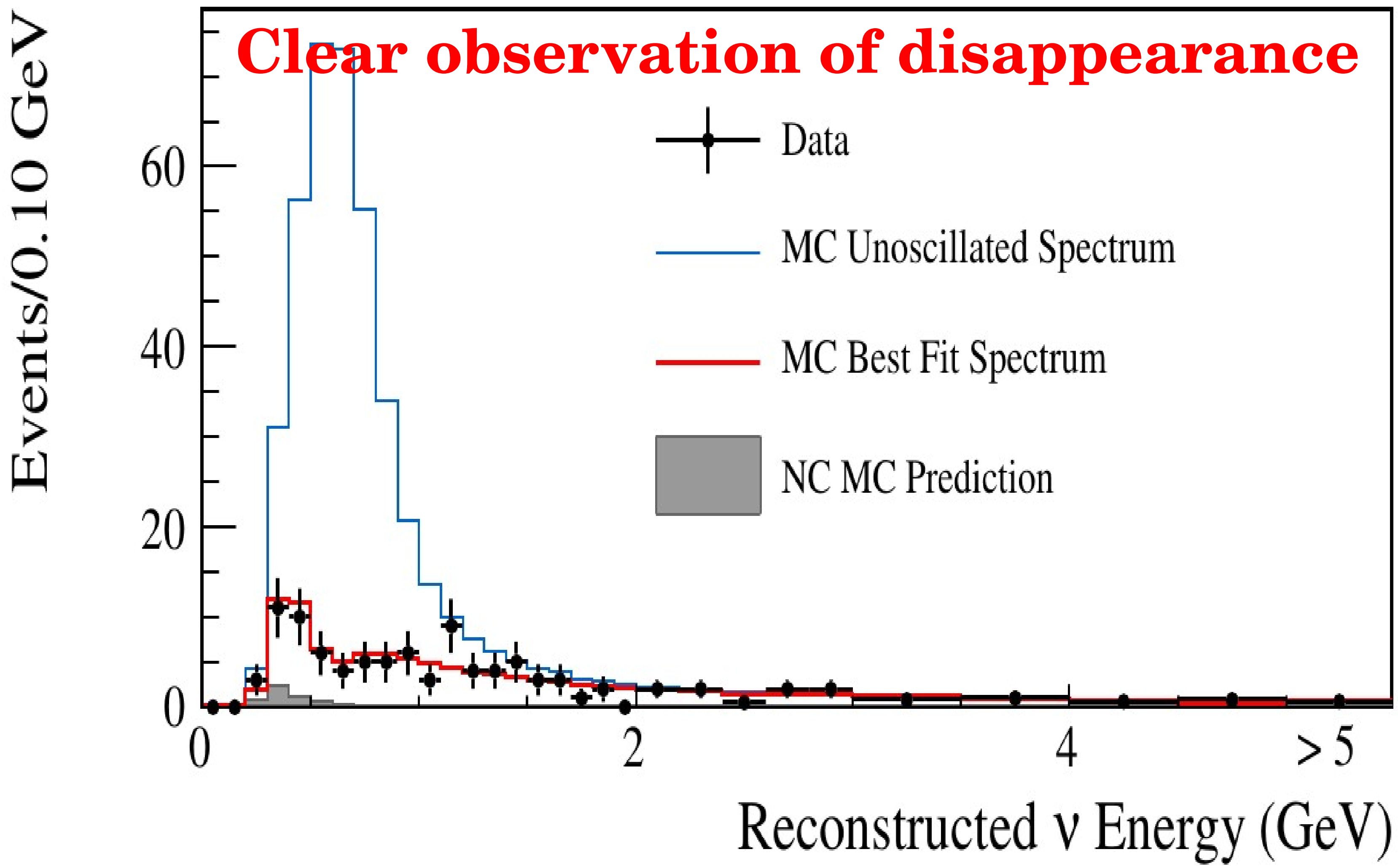
At T2K: optimal energy 0.6 GeV



Ken Sakashita, KEK Seminar

T2K - The Choice of the Right Baseline

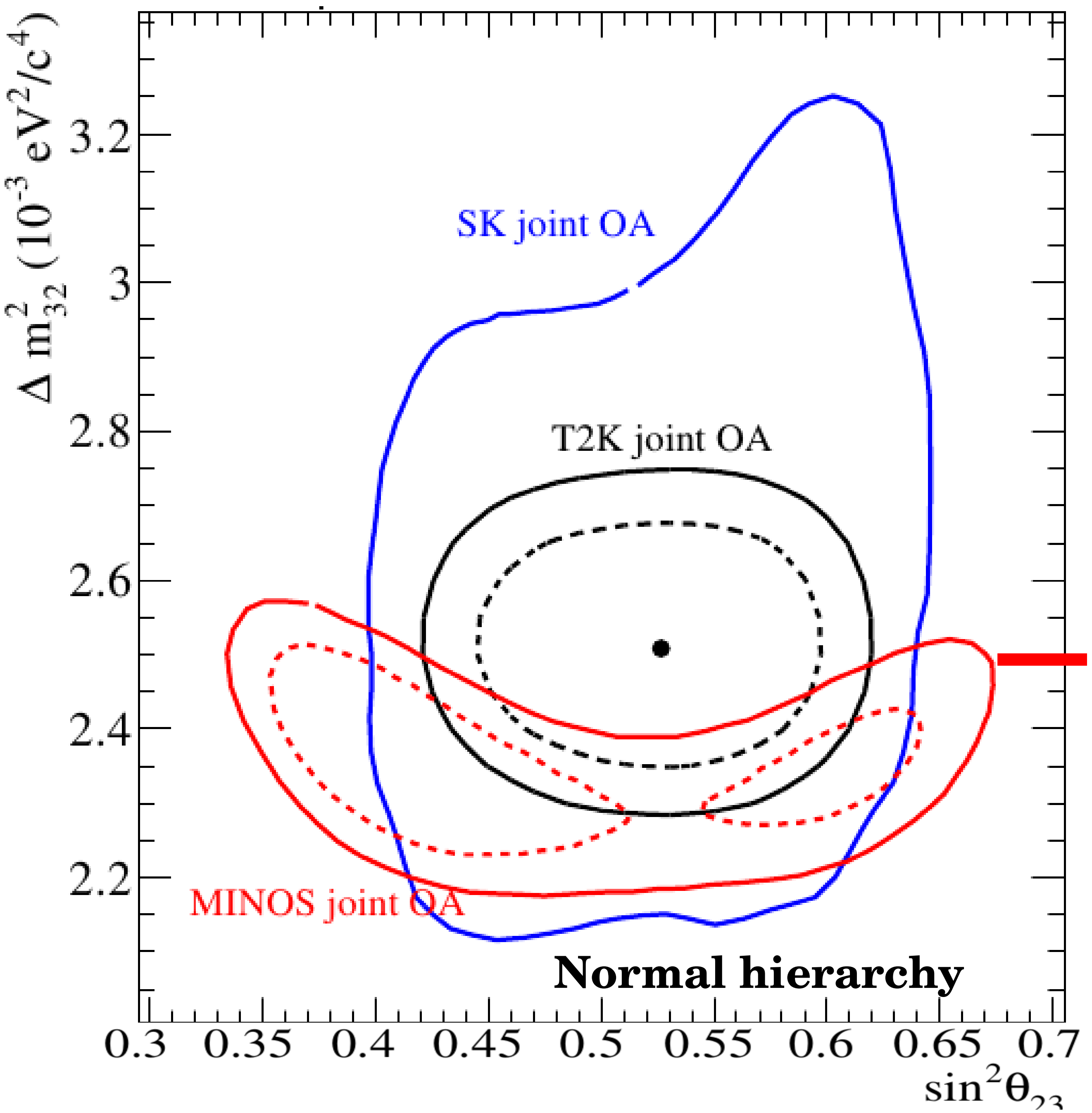
- Almost complete disappearance of ν_μ:



Also optimal for a measurement of θ_{13}!

Atmospheric & Accelerators: The Global Picture

- Super-K atmospheric compared to accelerator long baseline: all fits together, accelerators give the most precise results by now

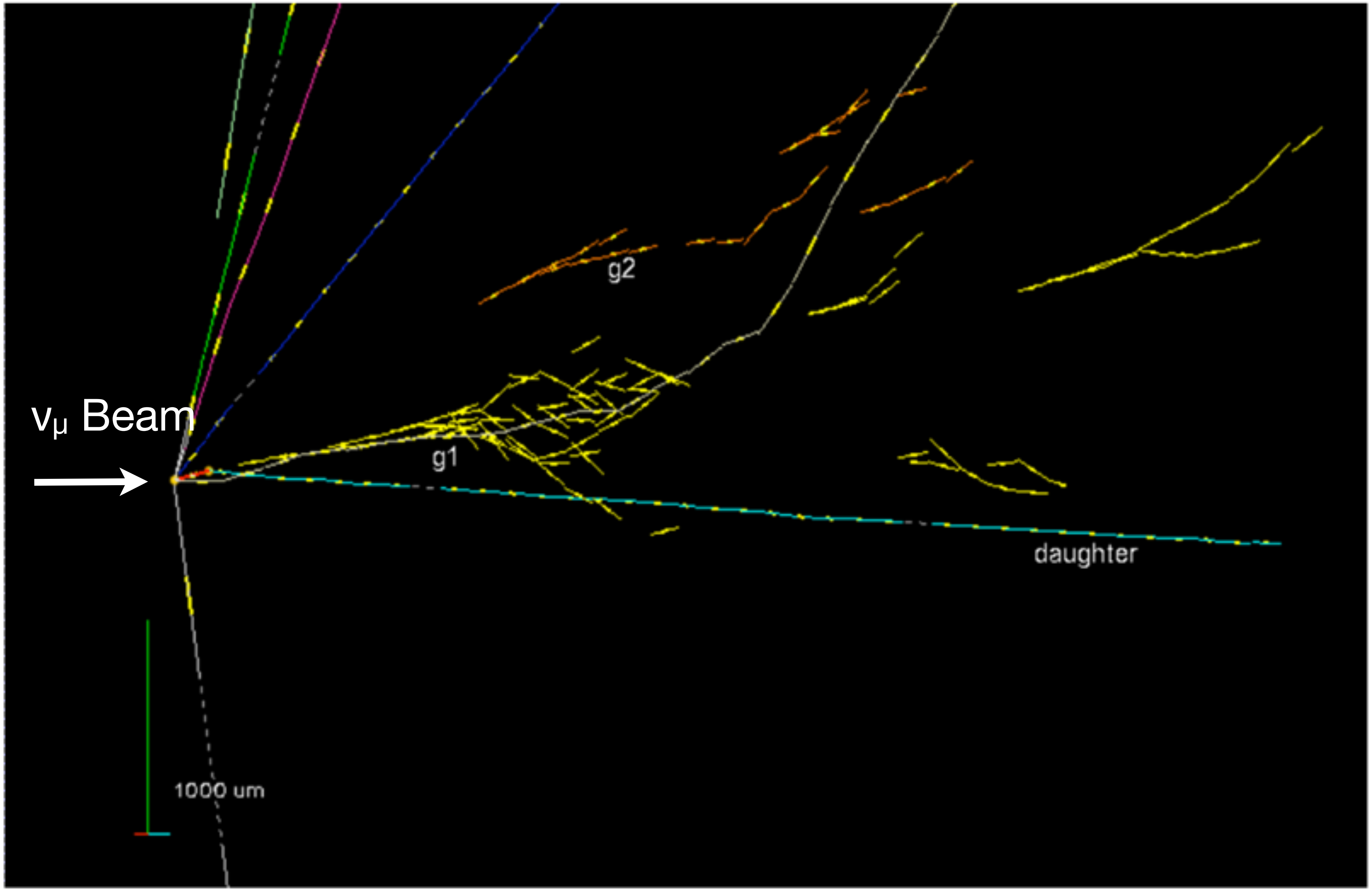


CNGS / OPERA - Confirmation

- One of the goals: Direct observation of oscillations of ν_μ to ν_τ in a ν_μ Long Baseline Beam (CERN → Gran Sasso)

- Magnetic spectrometer for track and energy reconstruction, in between blocks of photo emulsion for precise reconstruction of tracks at the interaction vertex
  - If an interesting event is observed in the spectrometer, the corresponding block is extracted and examined

OPERA: First ν_τ Candidate



In total 4 additional ν_τ have been observed - "5 -sigma discovery": matches expectations

ν_τ produces τ, fast decay into μ and vs

➯ Proof, that the atmospheric oscillation is $\nu_\mu \rightarrow \nu_\tau$

OPERA Press Release, 31.05.2010

Measuring θ_{13} at Accelerators

- θ_{13} describes $\nu_1 \rightarrow \nu_3$ oscillations: Squared mass differences (almost) as in the atmospheric case, but transitions involving ν_e (large ν_e component in ν_1!)
  - With a ν_μ beam, θ_{13} is accessible through the subdominant oscillation from ν_μ to ν_e (the dominant oscillation is ν_μ to ν_τ)

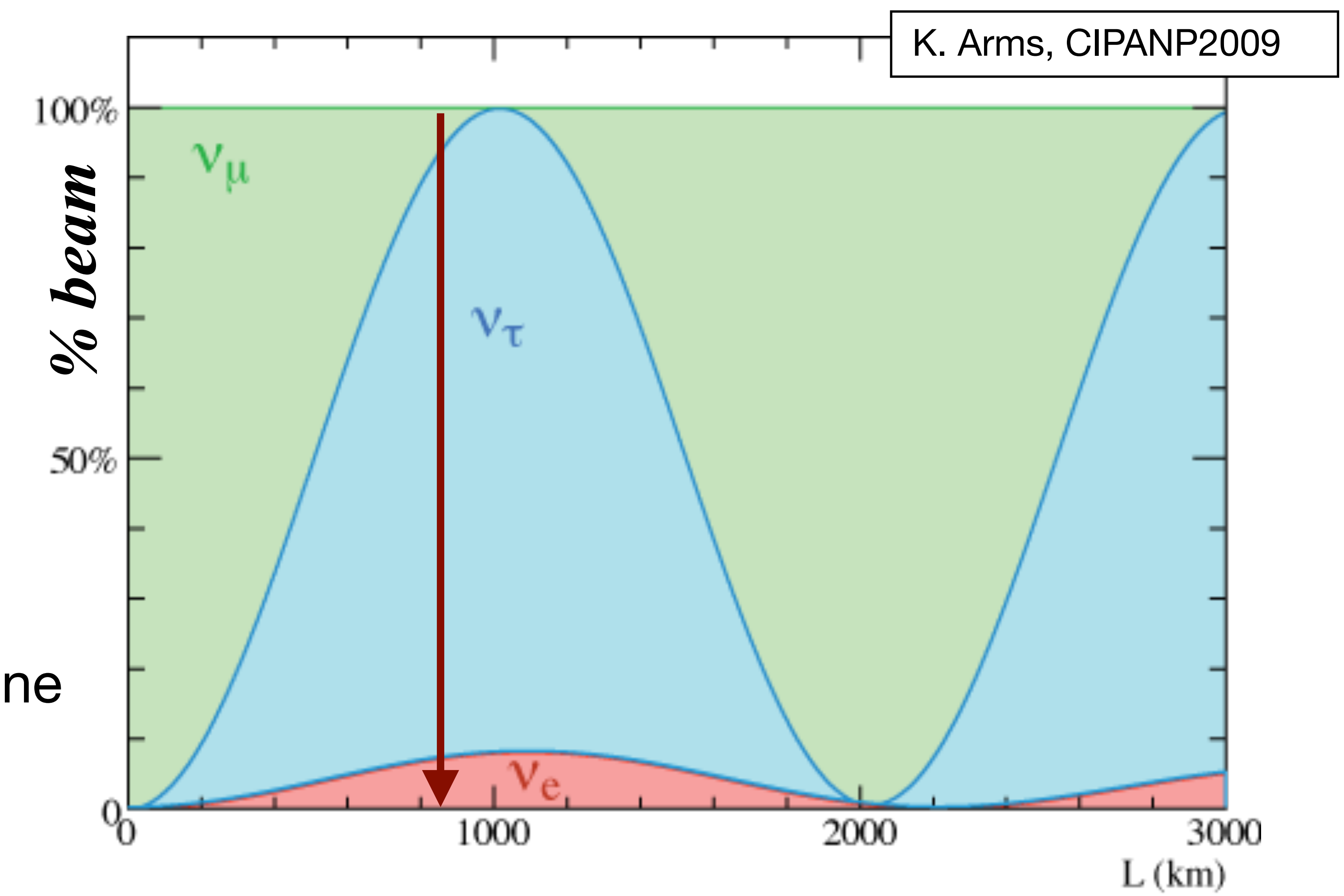
Oscillation probability: $$P(\nu_\mu \leftrightarrow \nu_e) \approx sin^2 2\theta_{13}\, sin^2\theta_{23}\, sin^2\left(\frac{\Delta m^2_{13} L}{4E}\right)$$

Strongly suppressed compared to $\nu_\mu \rightarrow \nu_\tau$ oscillations: Looking for small effects!

length scale depends on ν energy here: shown for the NOvA experiment at FNAL

Important: Energy matched to baseline

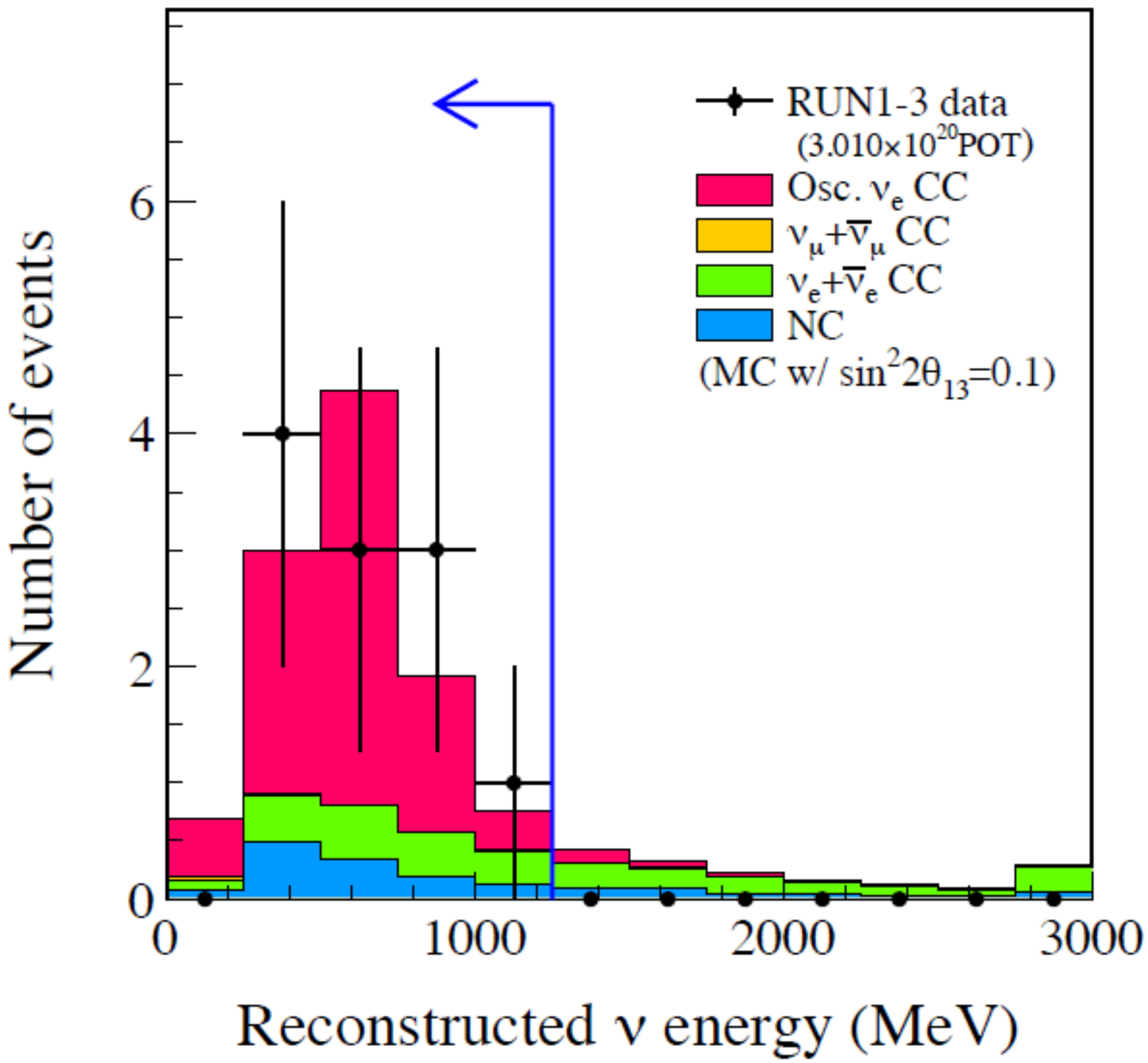
Narrow energy distribution

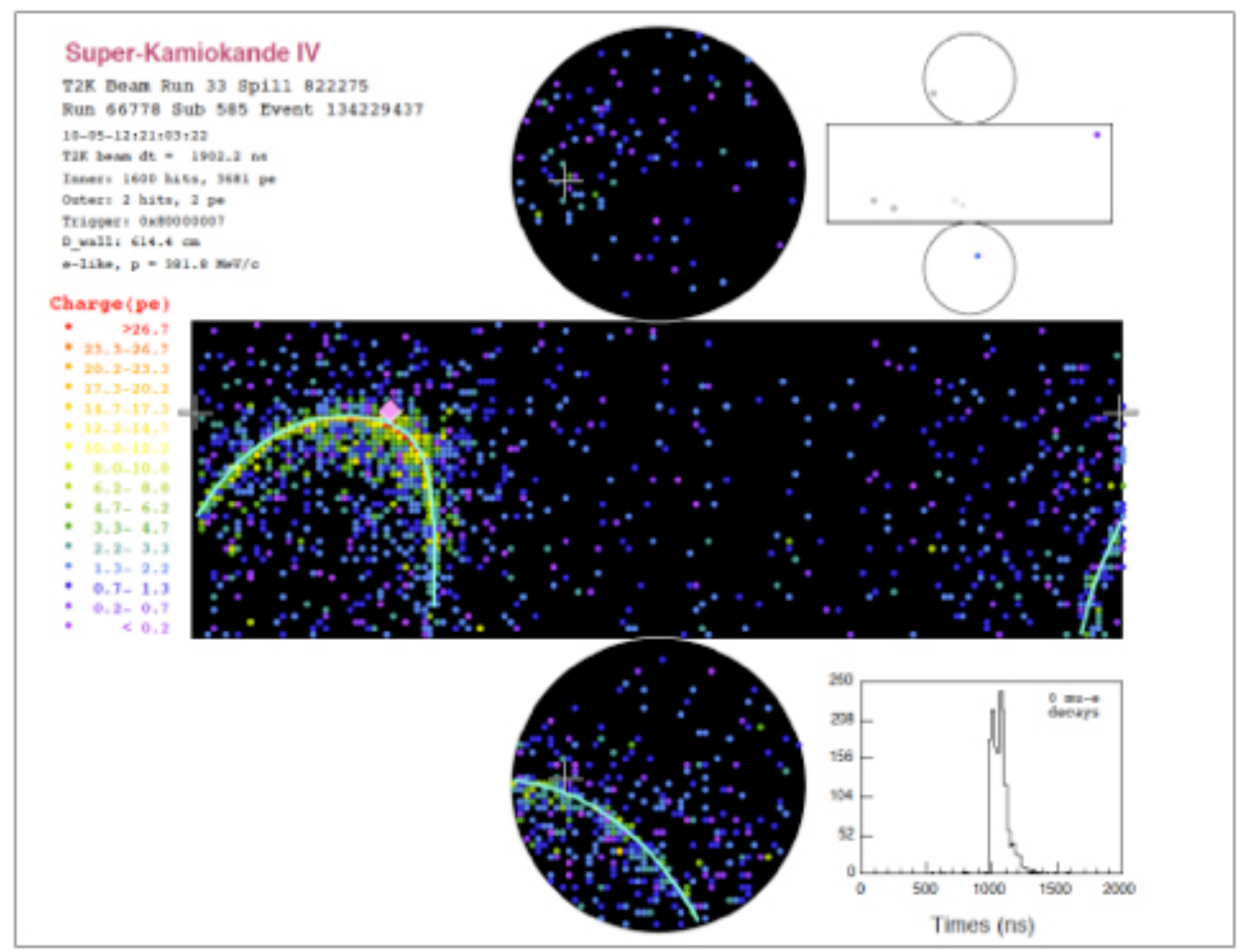


T2K - Oscillation Results

- Observation of $\nu_\mu \rightarrow \nu_e$ oscillations :

11 events (3.2 σ that θ_{13} is not 0)





T2K was first - but best results currently from Daya Bay (see above)

Searching for CP Violation in the ν - Sector

- CP Violation: A difference between matter and antimatter
- In the SM: Generated by the complex phase in the mixing matrix (Quarks, νs), if δ ≠ 0
  - Shows up in differences in oscillation behavior between neutrinos and anti-neutrinos!

$$P(\nu_\mu \to \nu_e) \simeq \sin^2 2\theta_{13} \times \sin^2 \theta_{23} \times \frac{\sin^2[(1-x)\Delta]}{(1-x)^2}$$

Phys. Rev. D64 (2001) 053003

Leading term

CP violating

$$-\alpha \sin\delta_{CP} \times \sin^2 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \times \sin\Delta \frac{\sin[x\Delta]}{x} \frac{\sin[(1-x)\Delta]}{(1-x)}$$

"+" for antineutrino

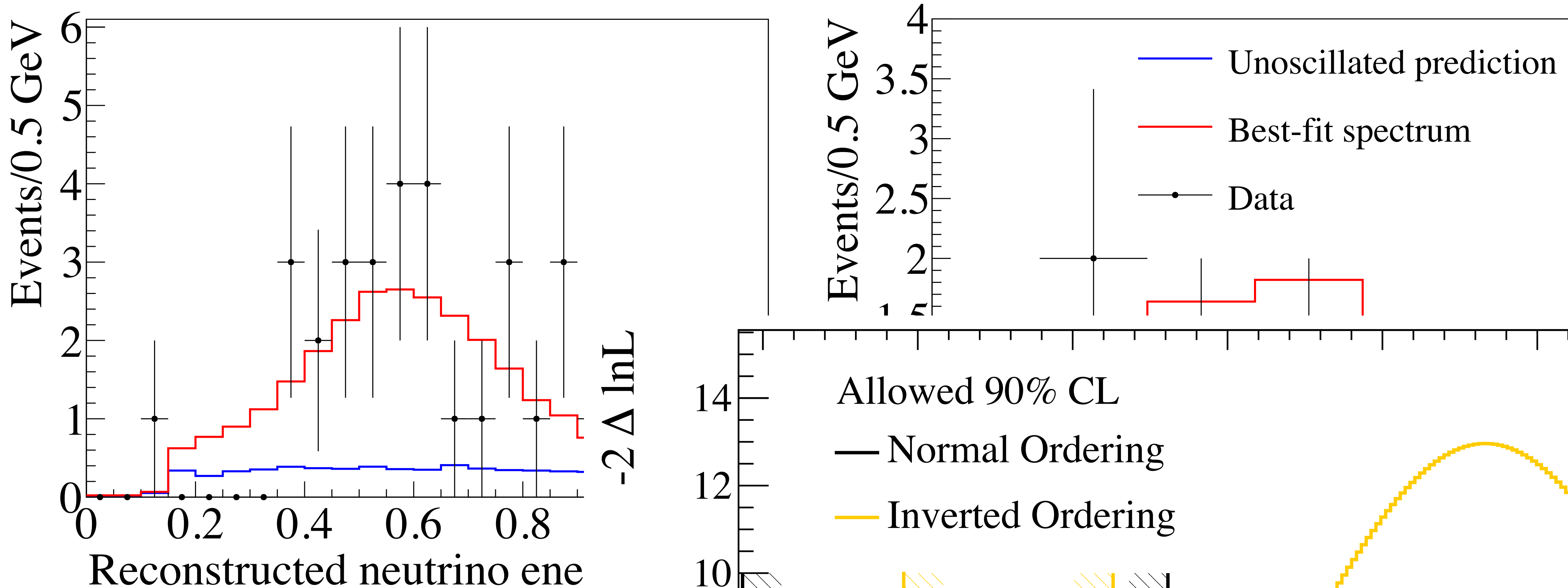
CP conserving

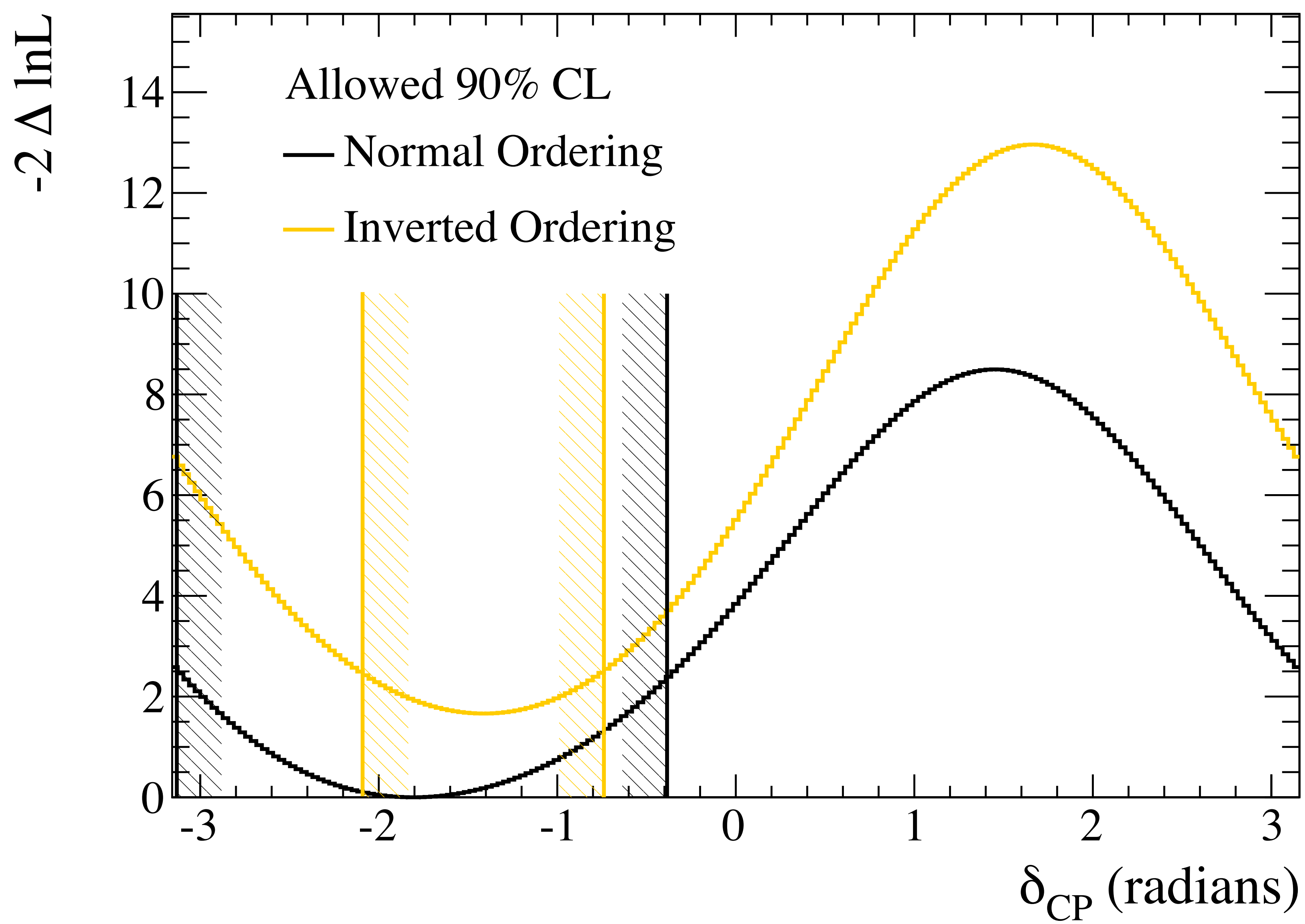
$$\alpha \cos\delta_{CP} \times \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \times \cos\Delta \frac{\sin[x\Delta]}{x} \frac{\sin[(1-x)\Delta]}{(1-x)}$$

$$+ O(\alpha^2)$$

$$x = \frac{2\sqrt{(2)}G_F N_e E}{\Delta m^2_{31}} \quad \alpha = |\frac{\Delta m^2_{21}}{\Delta m^2_{31}}| \sim \frac{1}{30} \quad \Delta = \frac{\Delta m^2_{31} L}{4E}$$

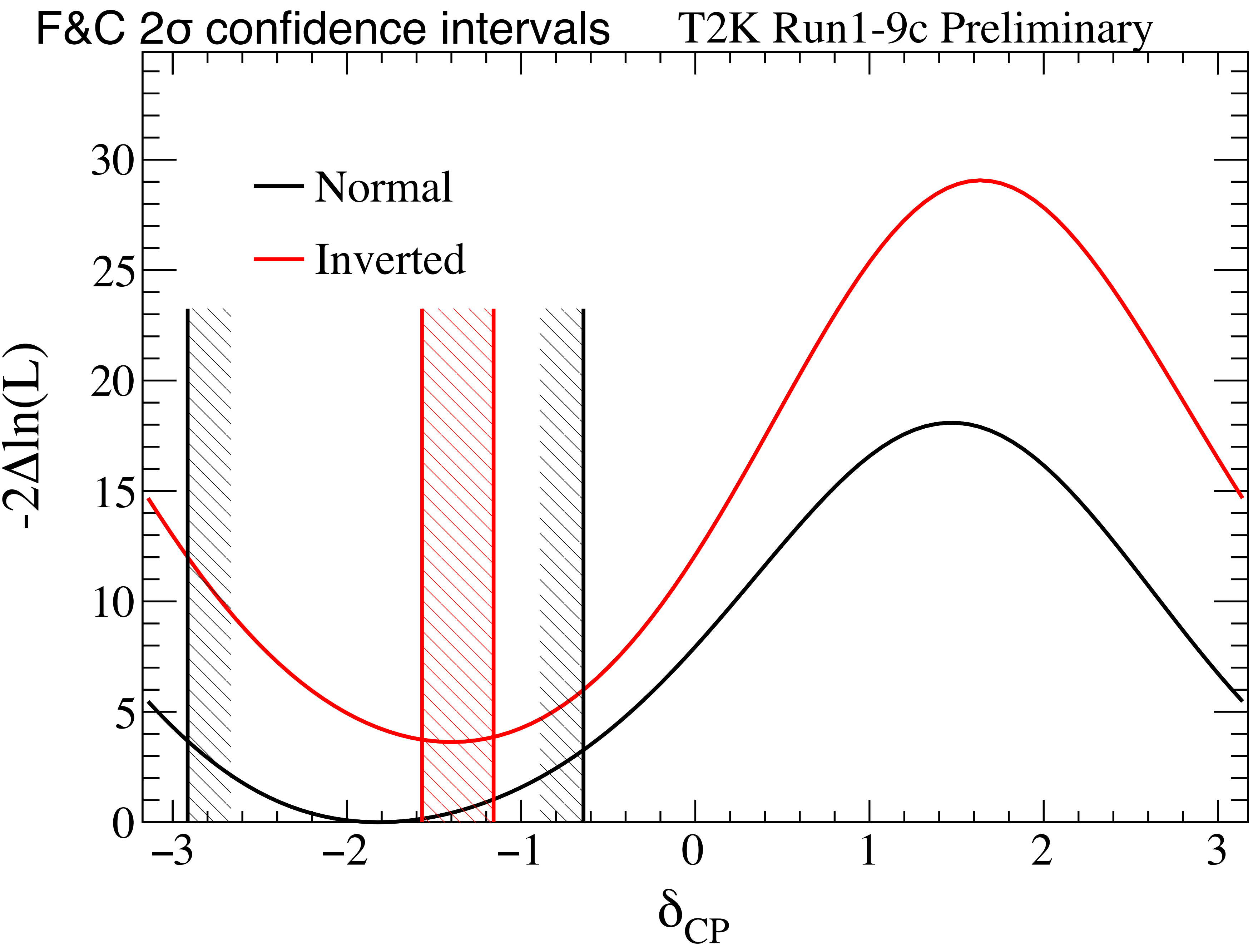
First Results from T2K - 2016





- Running both with neutrinos and anti-neutrinos: Observed less anti-ν_e than expected in any scenario: hints at maximal CP violation

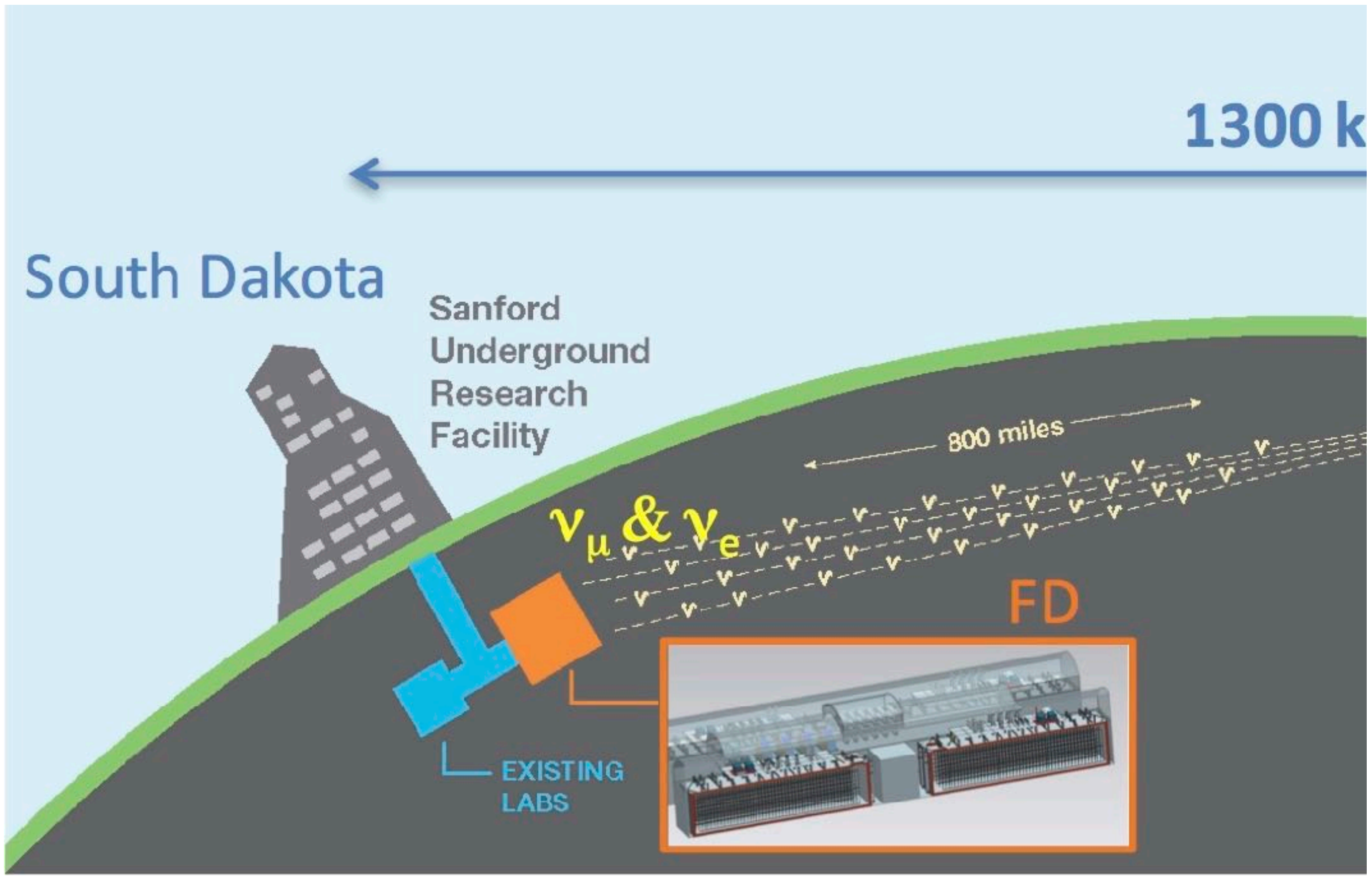
T2K - Hot off the Press Update

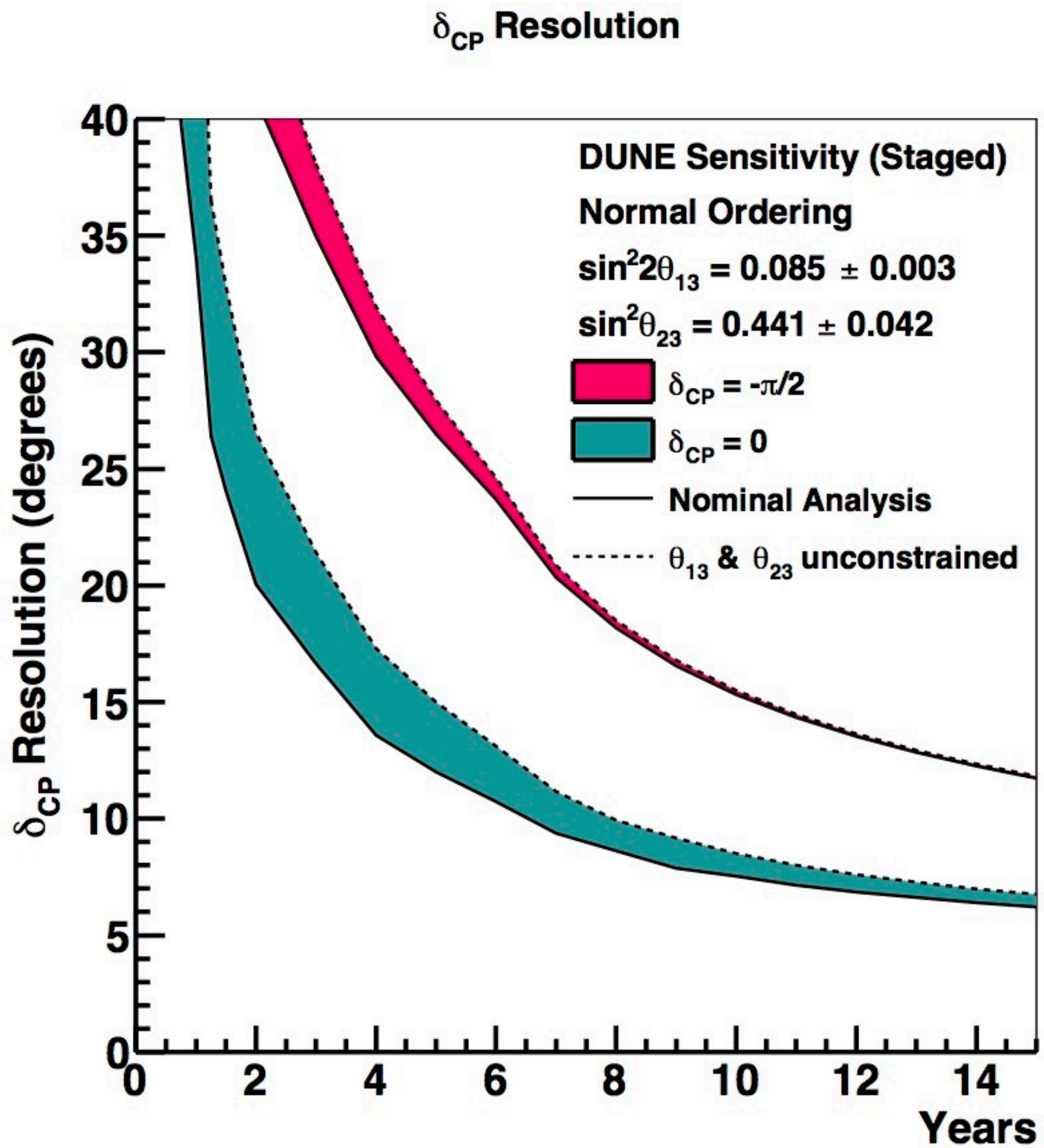


- Significance pointing towards CP violation firm up - strong dependence on mass ordering

Future Measurements of CP Violation

- The "next big thing" in neutrino physics - with future experiments to make definitive measurements



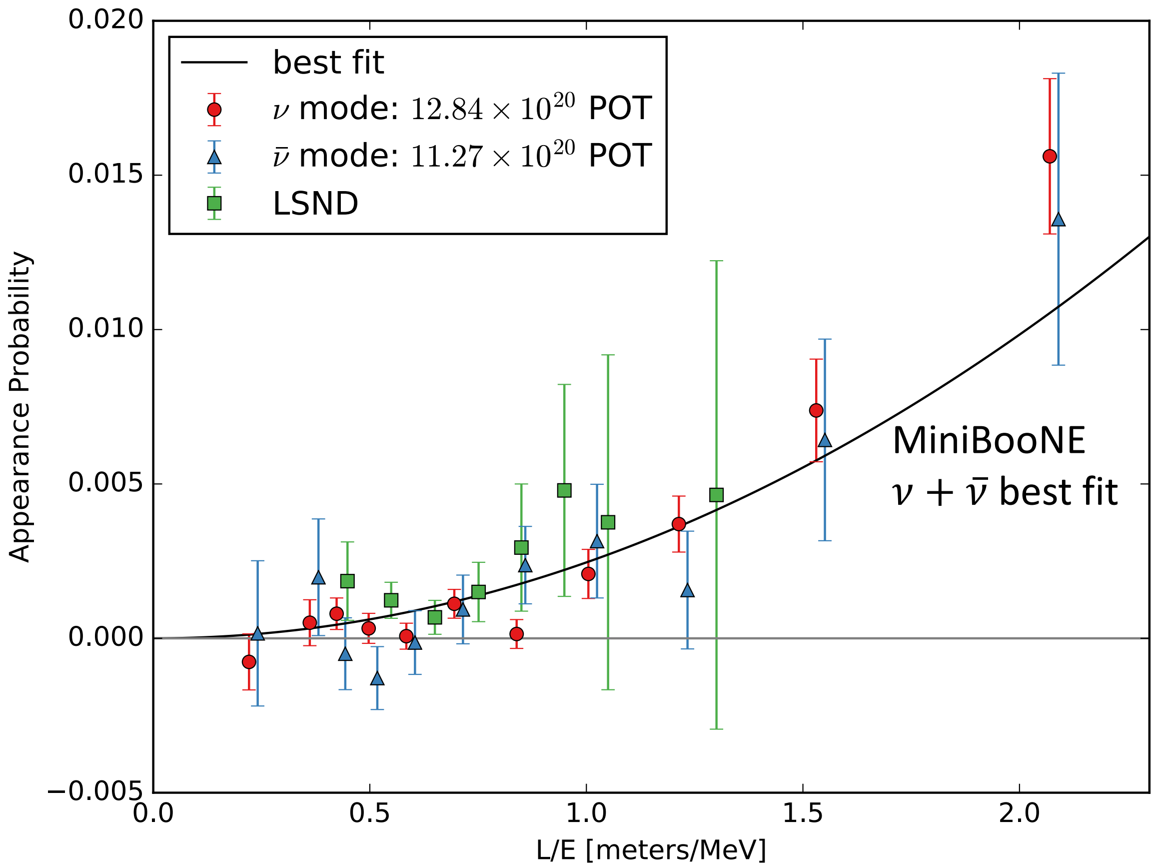


- DUNE at Fermilab - to start taking data in
  - x4 higher mean energy than T2K: longe
- Also in discussion T2HK: Much larger wat from Tokai, same baseline as T2K

Neutrinos are still mysterious

- The standard three-flavor neutrino picture is by now quite well understood
  - Missing: mass ordering, CP phase δ

- There are intriguing puzzles both in reactor and accelerator-based experiments:
  - "Reactor Anomaly": Deficit of electron anti-neutrinos already at very short baselines - Oscillations or problems in the reactor modeling?
  - Possible indications for very short baseline oscillations of muon neutrinos (LSND, MiniBooNE)

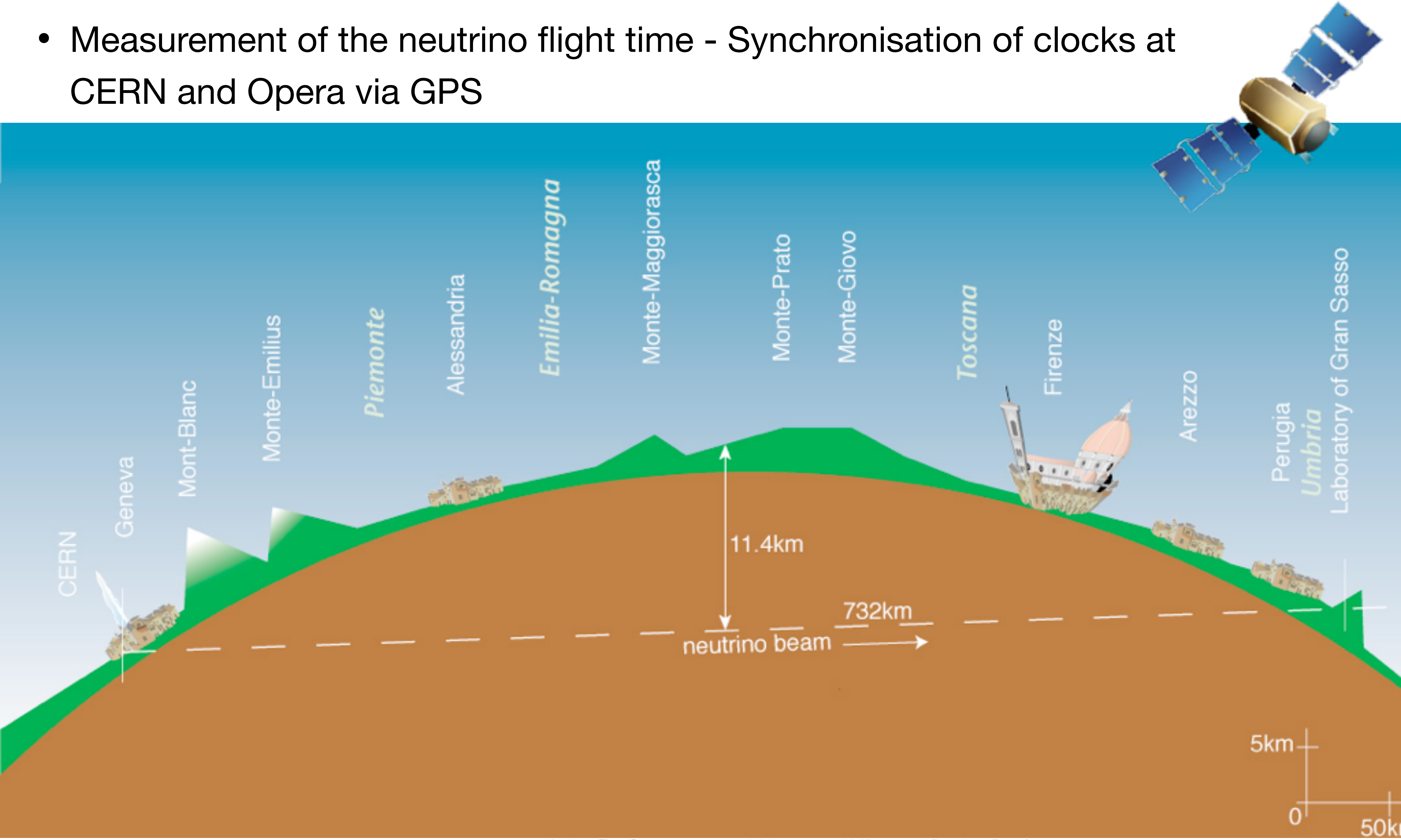


Hints for sterile neutrinos?

Future experiments will (hopefully) tell…

Now History: Neutrino Speed

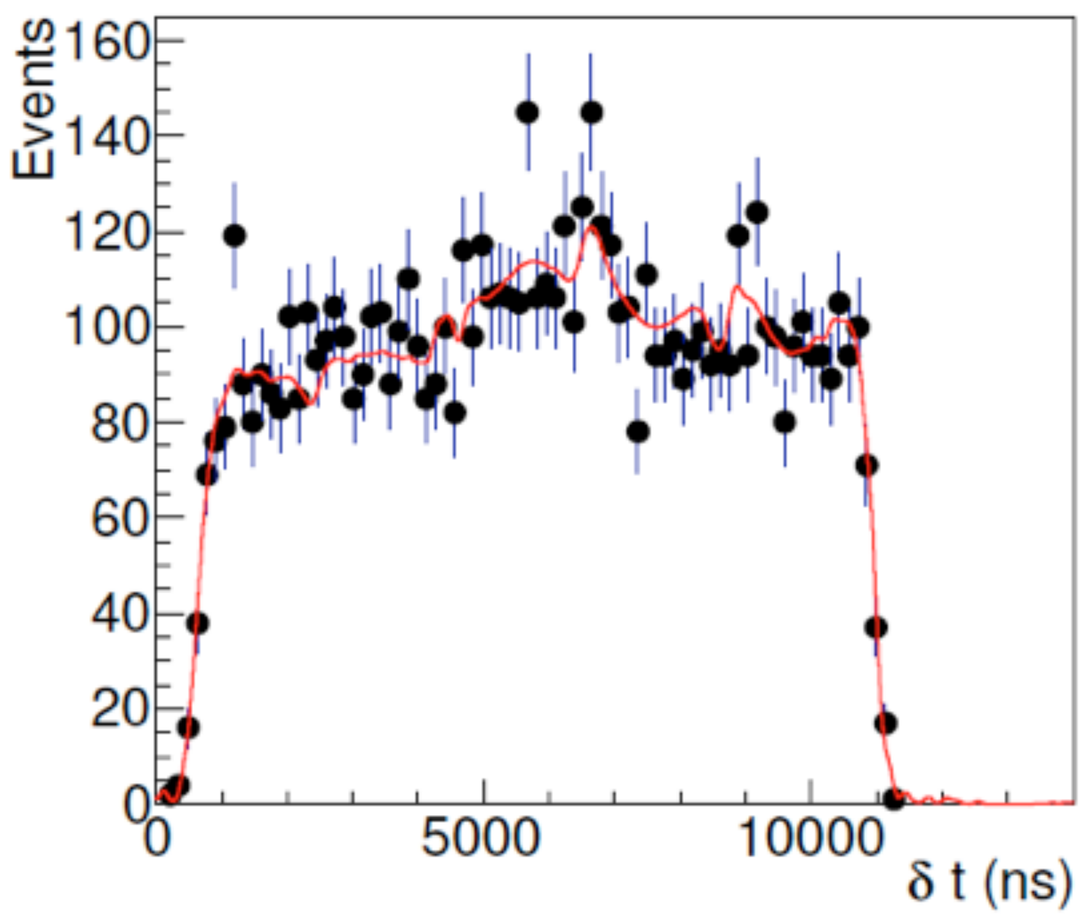
- Measurement of the neutrino flight time - Synchronisation of clocks at CERN and Opera via GPS

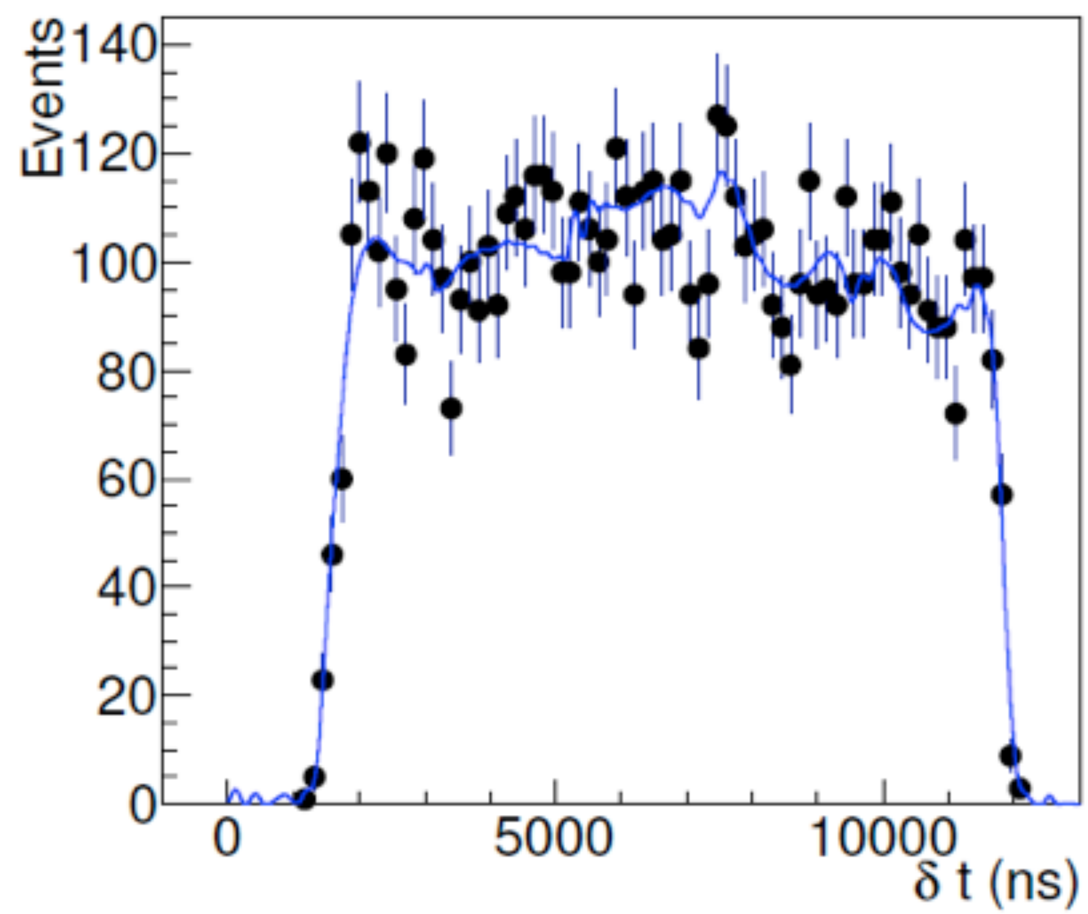


First Attempt - Spectacular Result

- September 2011: Opera observes, that the neutrinos are 60 ns too fast (with an uncertainties of 10 ns).

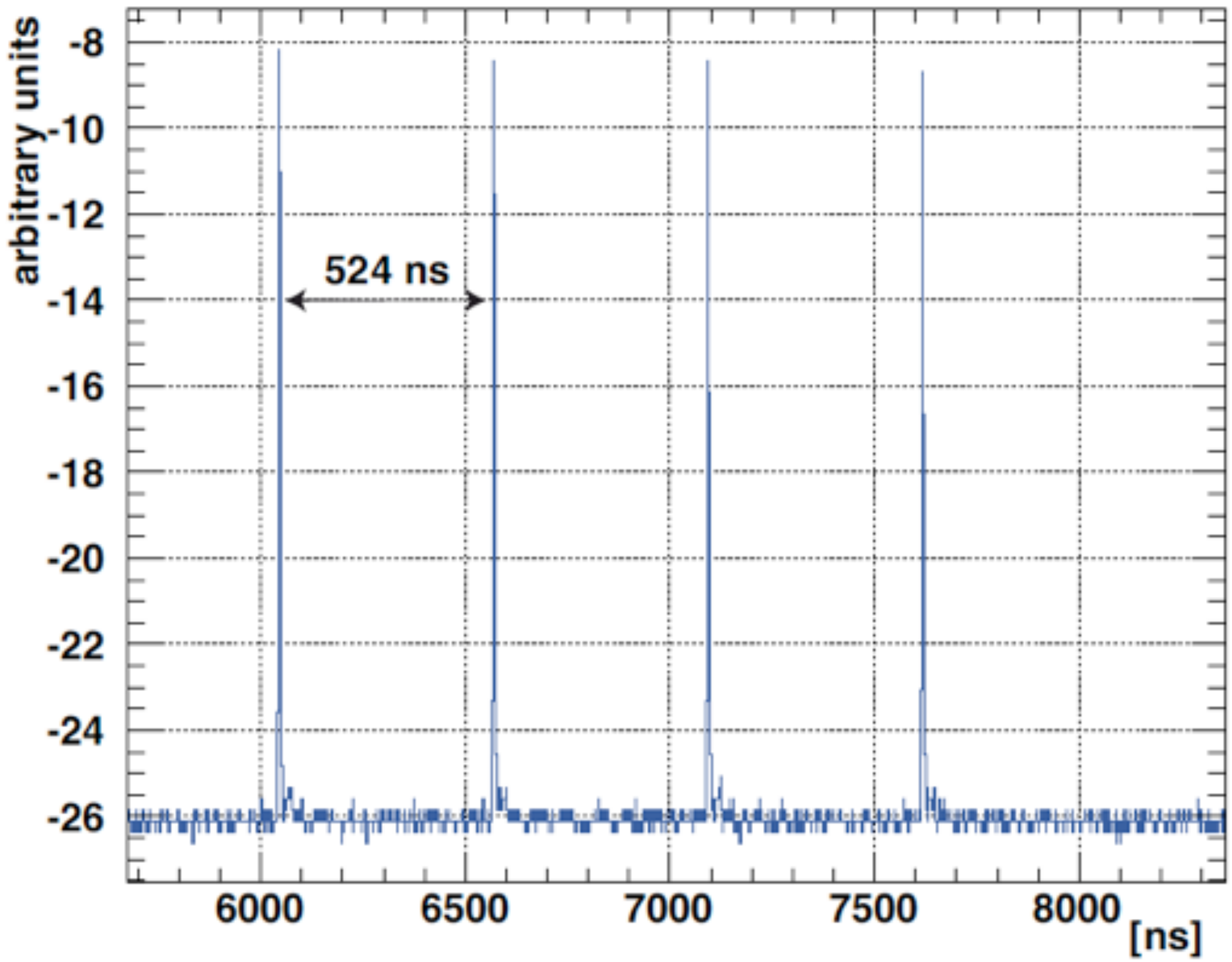
Technique: “edges” of the neutrino distribution in Opera, relative to the proton pulse -at CERN - statistical method, possible uncertainties from beam focusing (time structure of the neutrino pulse)





The Confirmation

- New measurements with pulsed beam, beam pulses 3 ns FWHM - direct measurement of flight time!



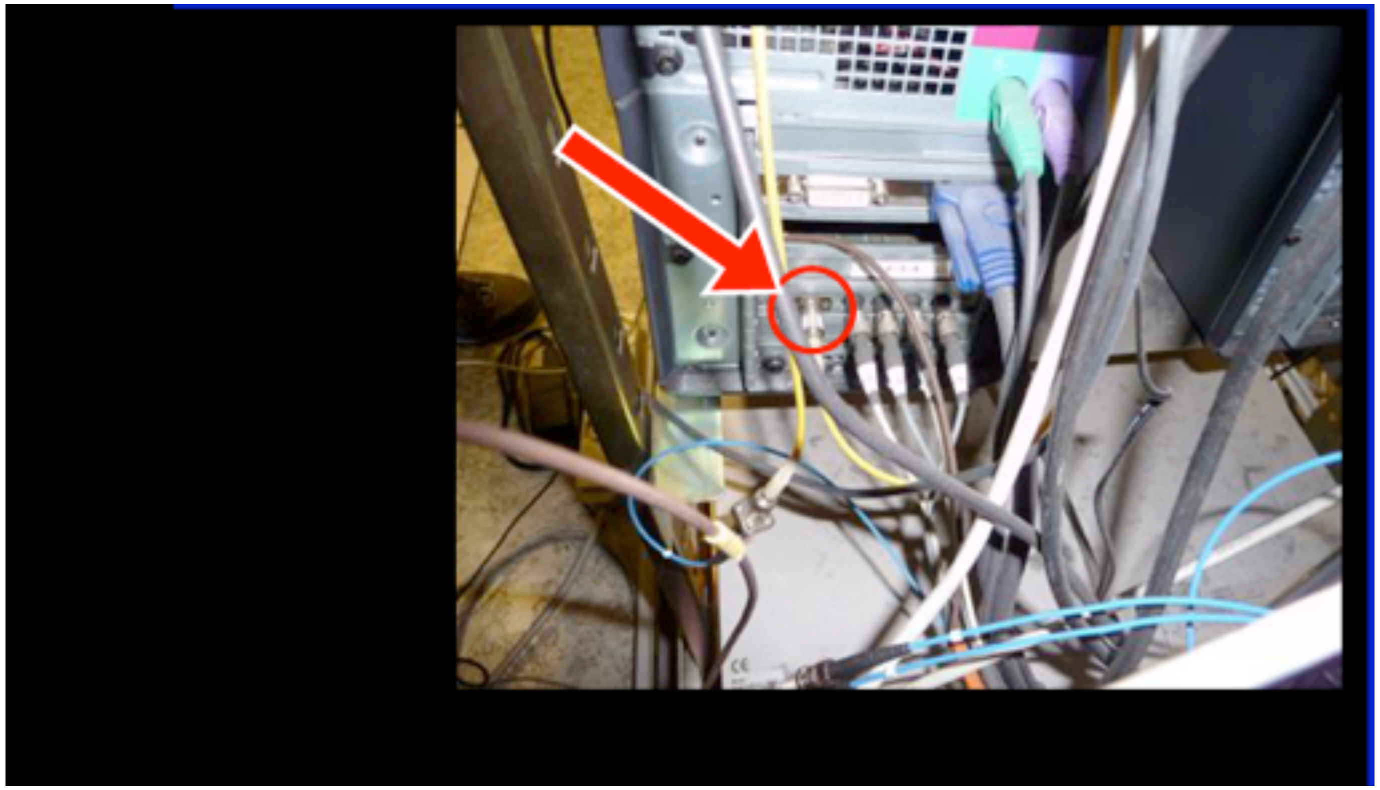
Confirms original results: beam structure as cause excluded

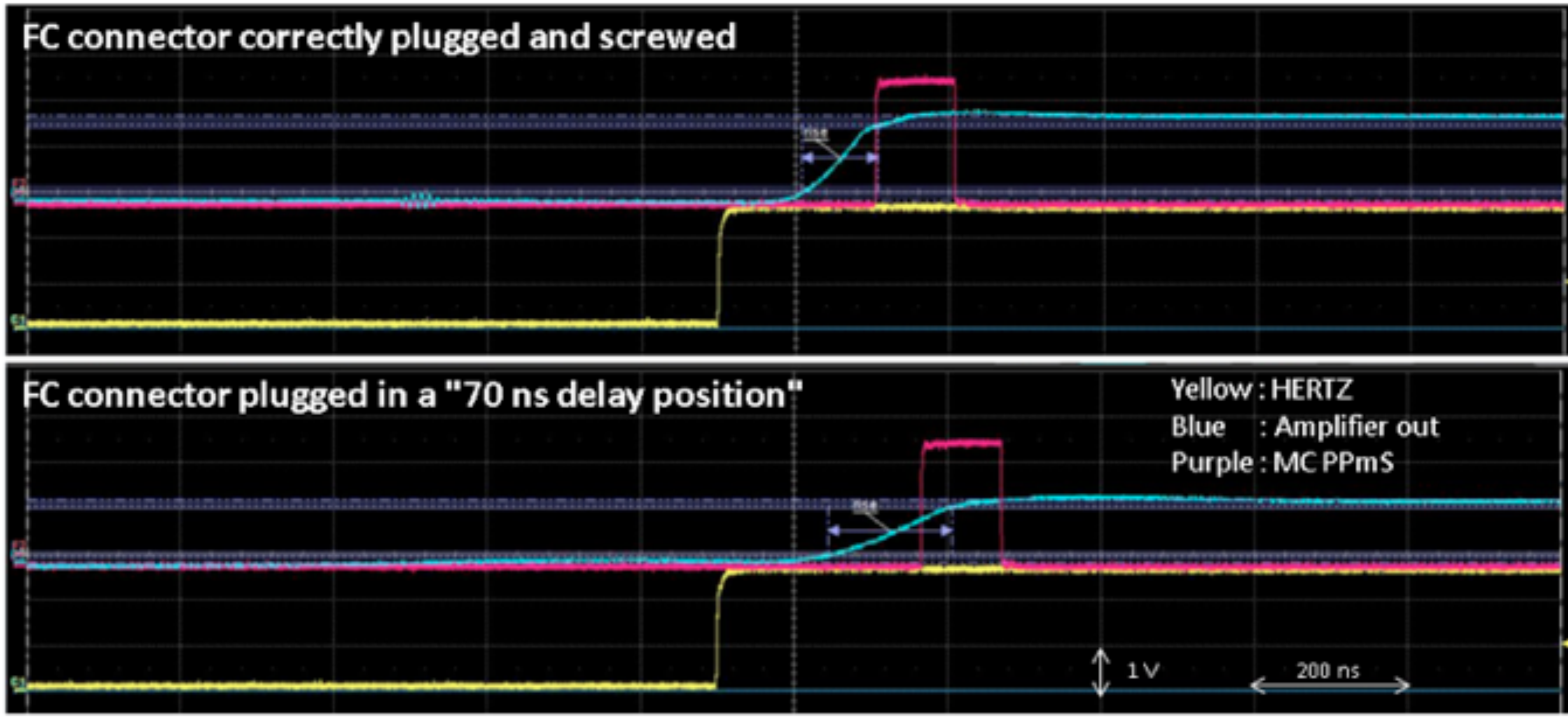
Uncertainty now only 4 ns (for a “signal” of 60 ns)

... but N.B.: There are corrections of 40 μs for signal running times in the electronics!

The Resolution

- As most had expected - It was a measurement error: An optical fiber of the timing system was not correctly plugged in - Resulted in a slower signal rise on the corresponding photo diode, the clock is a bit later due to later passing of threshold, voila...



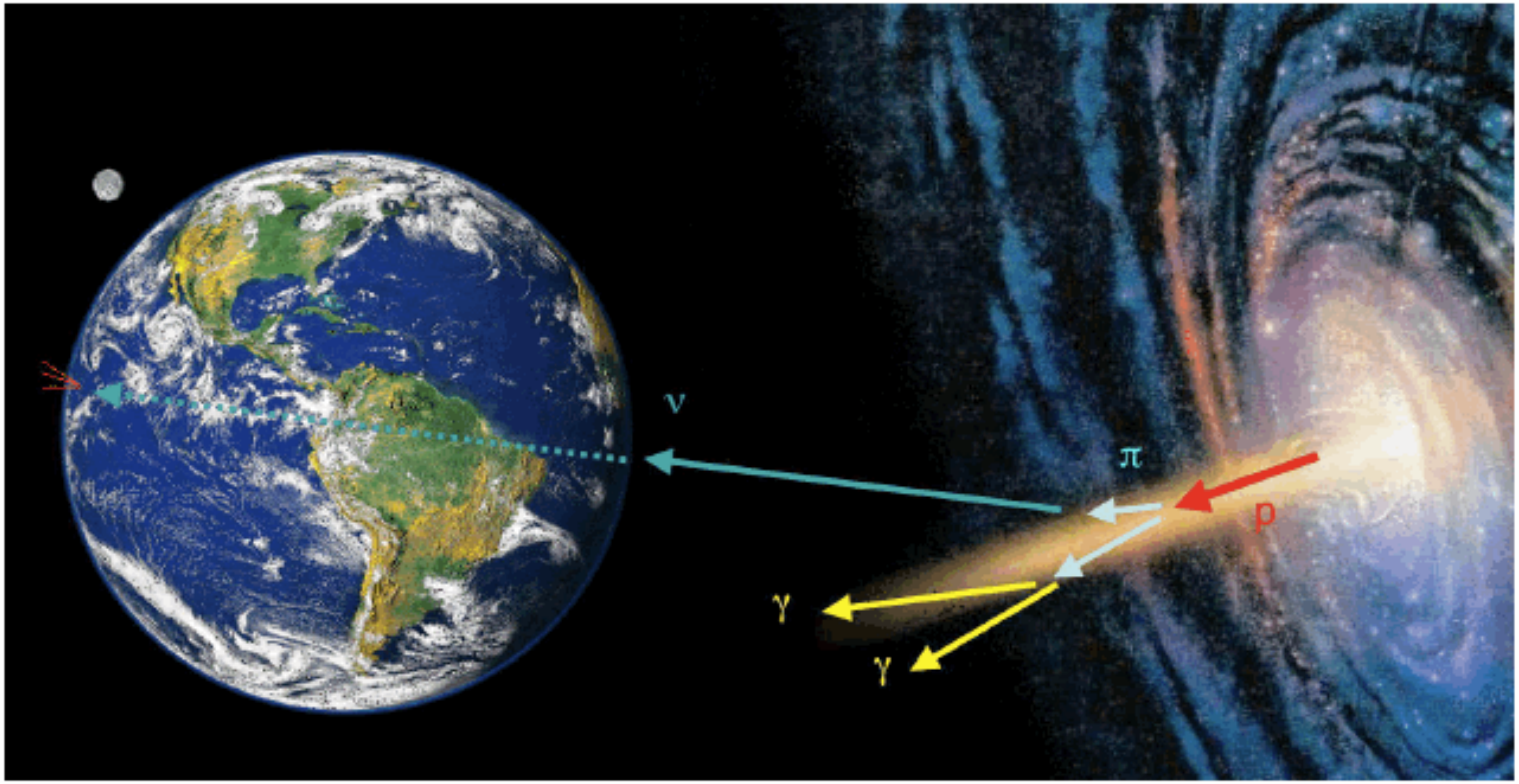


Now: The time of flight is bang on, within a few ns!

Neutrinos from Cosmic Sources

Cosmic Neutrinos

- Few events:
  - Huge detectors required
  - Very good shielding: The full earth
    - does not work for the highest energies: neutrino cross section rises with energy, above ~100 TeV neutrinos are absorbed by earth



Supernova Neutrinos

- Neutrinos from the core collapse of a star - Production of all neutrino flavors

  Formation of a neutron star:

$$A + e^- \rightarrow A' + \nu_e$$

  Thermal production of electron - positron pairs in the accretion disc, followed by neutrino production (all flavors)

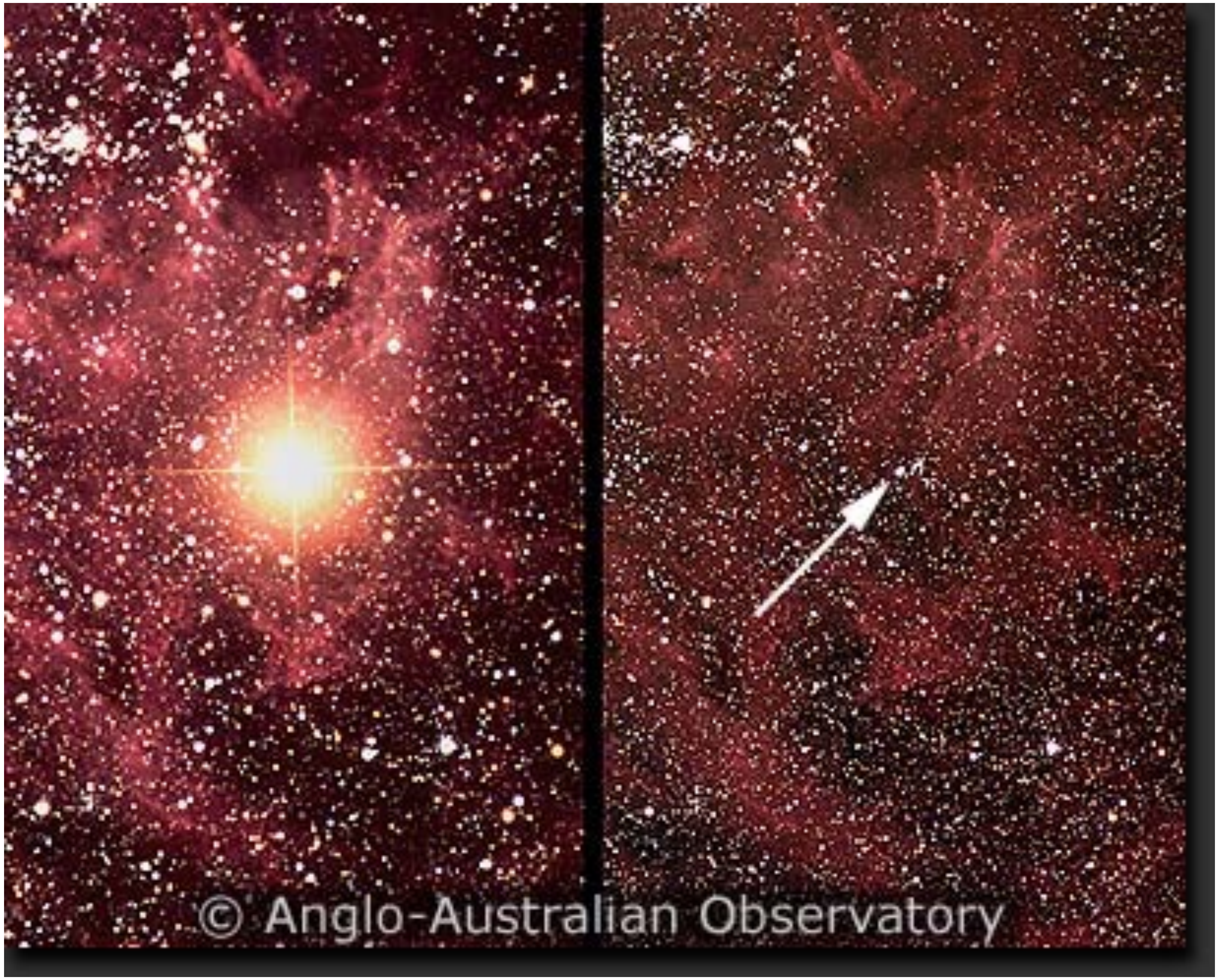
$$\gamma + \gamma \rightarrow e^+ + e^- \qquad\qquad e^+ + e^- \rightarrow \nu + \bar{\nu}$$

  Neutrinos are initially the first particles that can leave the explosion zone, all others are absorbed in the extremely dense, collapsing material: The neutrino signal reaches Earth before the optical signal!

  - A large fraction of the gravitational energy of the star is emitted in the form of neutrinos, the typical energies are in the few 10 MeV range

Supernova SN1987a

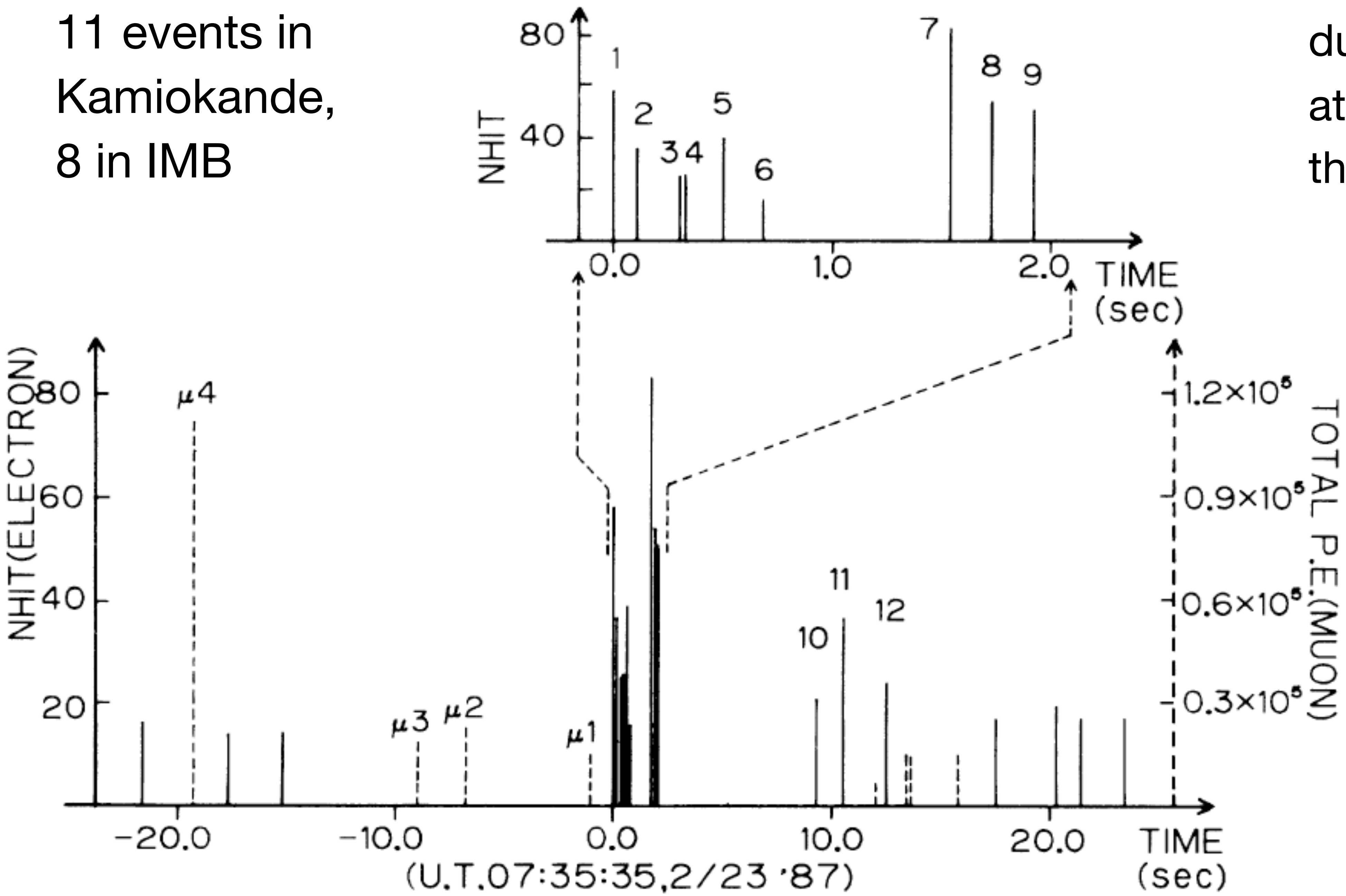
- Supernova explosion 1987 in the Large Magelanic Cloud



Kamiokande Signal

- A confirmed extraterrestrial signal

11 events in Kamiokande, 8 in IMB

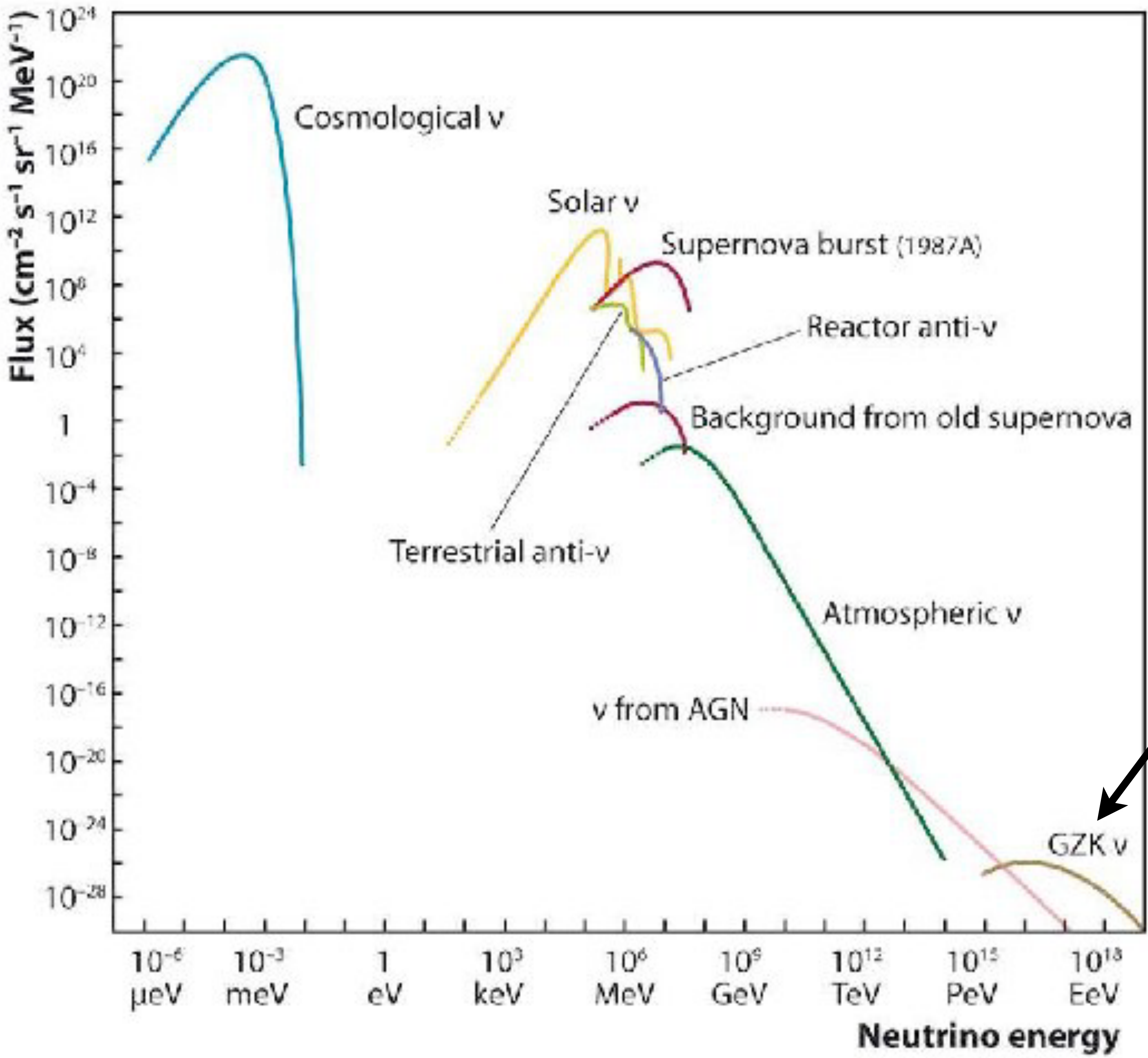


PRL 58, 1490 (1987)

A neutrino burst with a duration of ~10 s, seen at the same time also in the IMB experiment

Only $\overline{\nu_e}$: highest detection probability, lowest energy threshold

Cosmic Neutrinos: Expectations



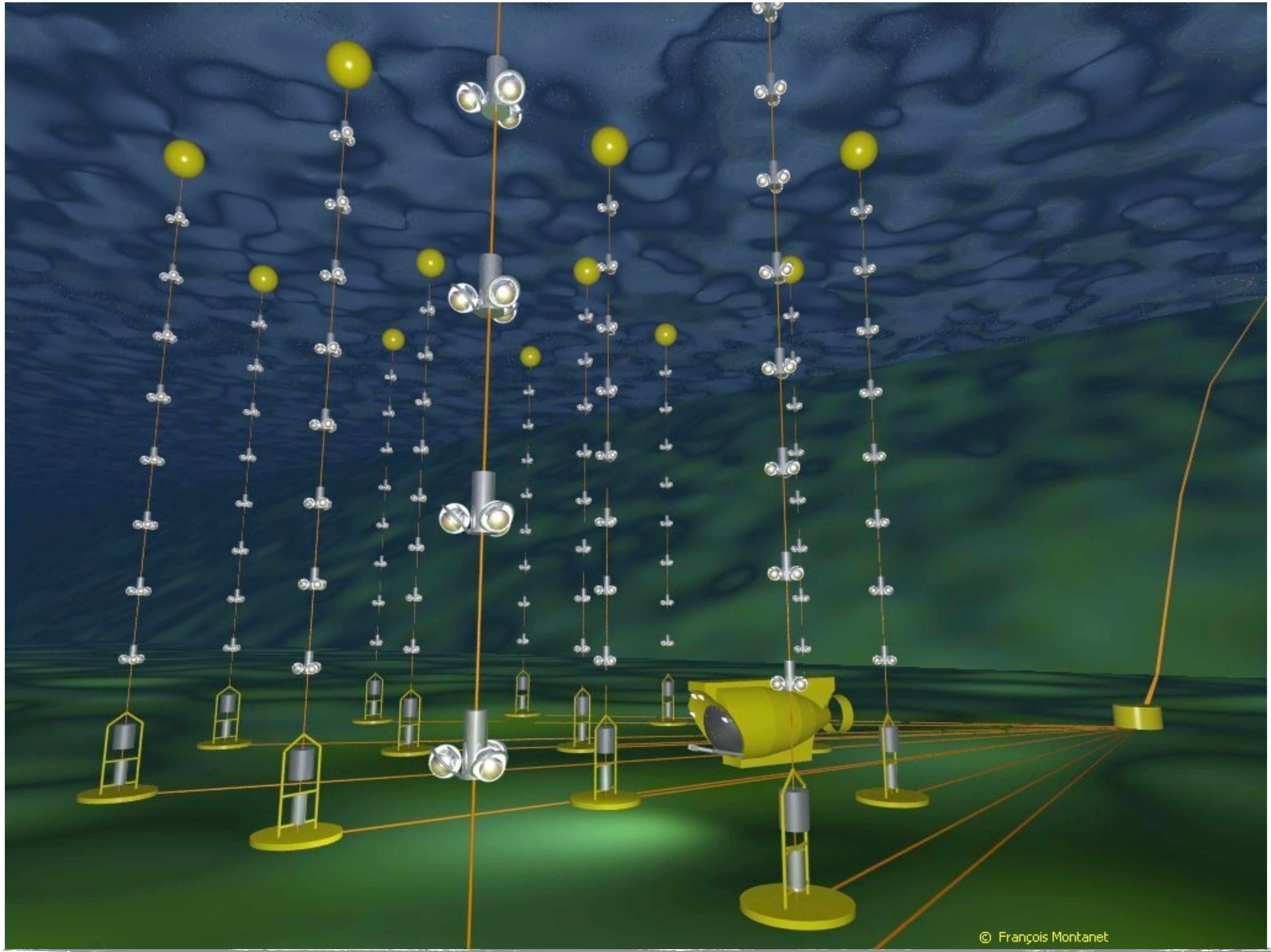
cosmogenic neutrinos: Produced in decays of pions from GZK events: Could give hints on sources and production mechanisms of highest-energy cosmic rays

in principle a "guaranteed discovery" with enough sensitivity

Detectors for Neutrino Astronomy

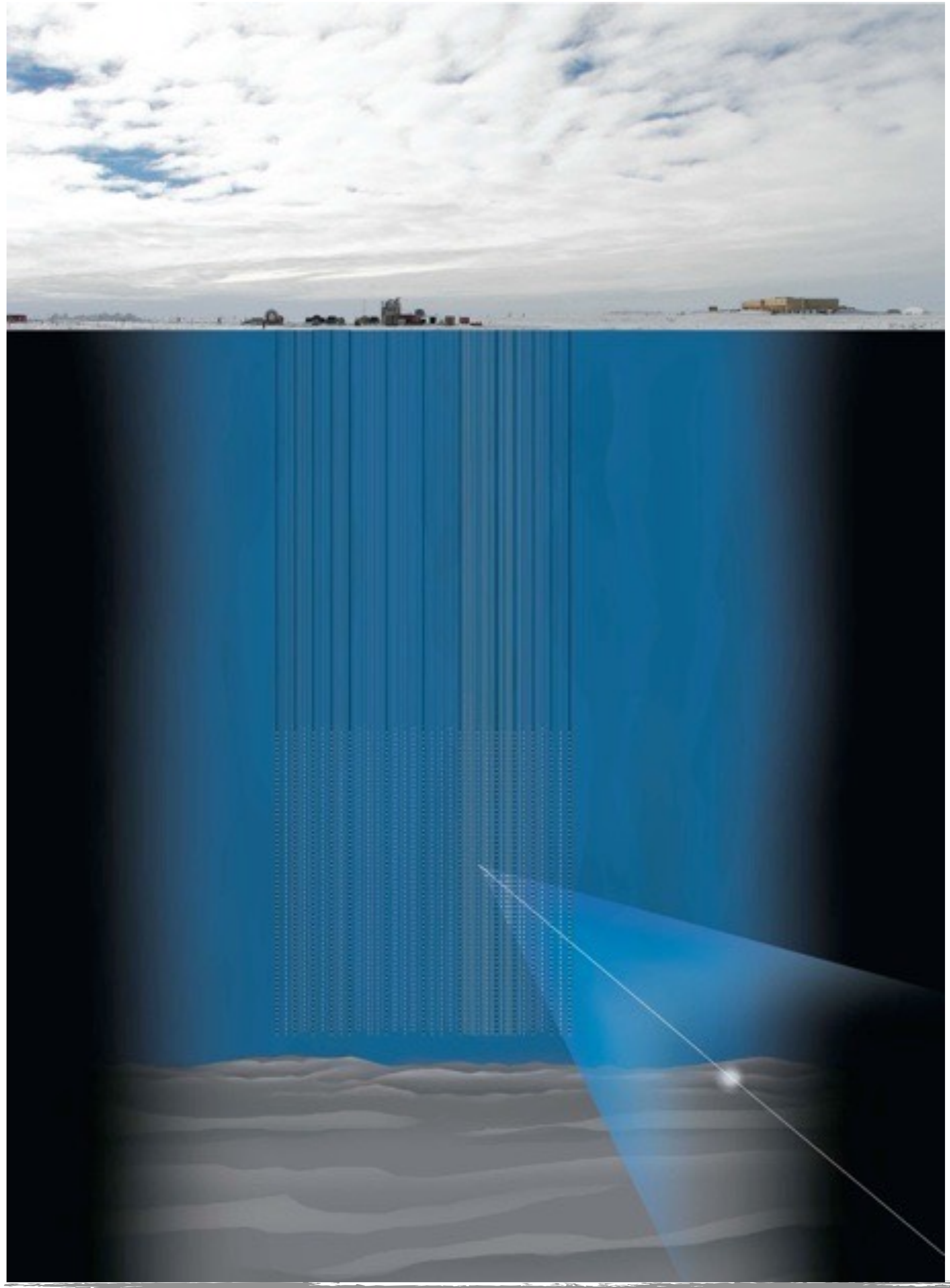
- Different detection techniques, depend on energy and sensitivity
- Energies in the TeV - PeV range:
  - Cherenkov detectors: large signal, relatively low energy threshold, requires a high sensor density due to light absorption
    - Amanda/IceCube: Antarctic ice as Cherenkov medium
    - Antares/Baikal/KM3NeT: Deep sea (or lake) - water as Cherenkov medium
- Energies above 10^{17} - 10^{19} eV:
  - Optical detection of neutrino-induced air showers: Auger, EUSO, ...
  - Acoustic detection of neutrino-induced showers in water, ice, salt:
    - Sound waves through heating of the material
  - Cherenkov radio waves from electromagnetic showers induced by ν_e
    - high range, sufficient signal for extreme energies
    - First tests with RICE in Antarctic ice, now preparing ARIANNA for higher sensitivity

Antares

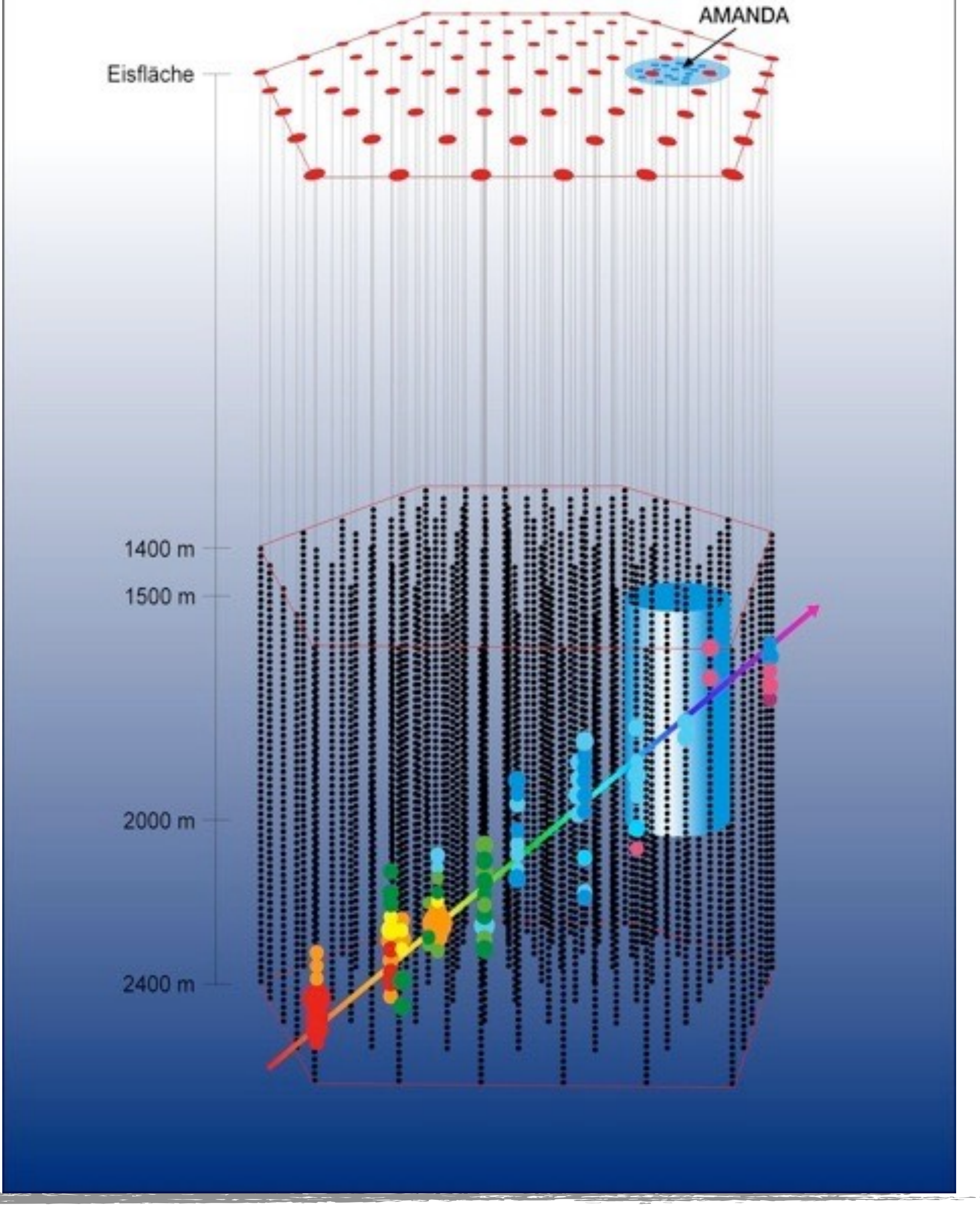


- 2.5 km deep off the southern coast of France (Toulon, between Marseille and Saint Tropez)

Amanda/IceCube

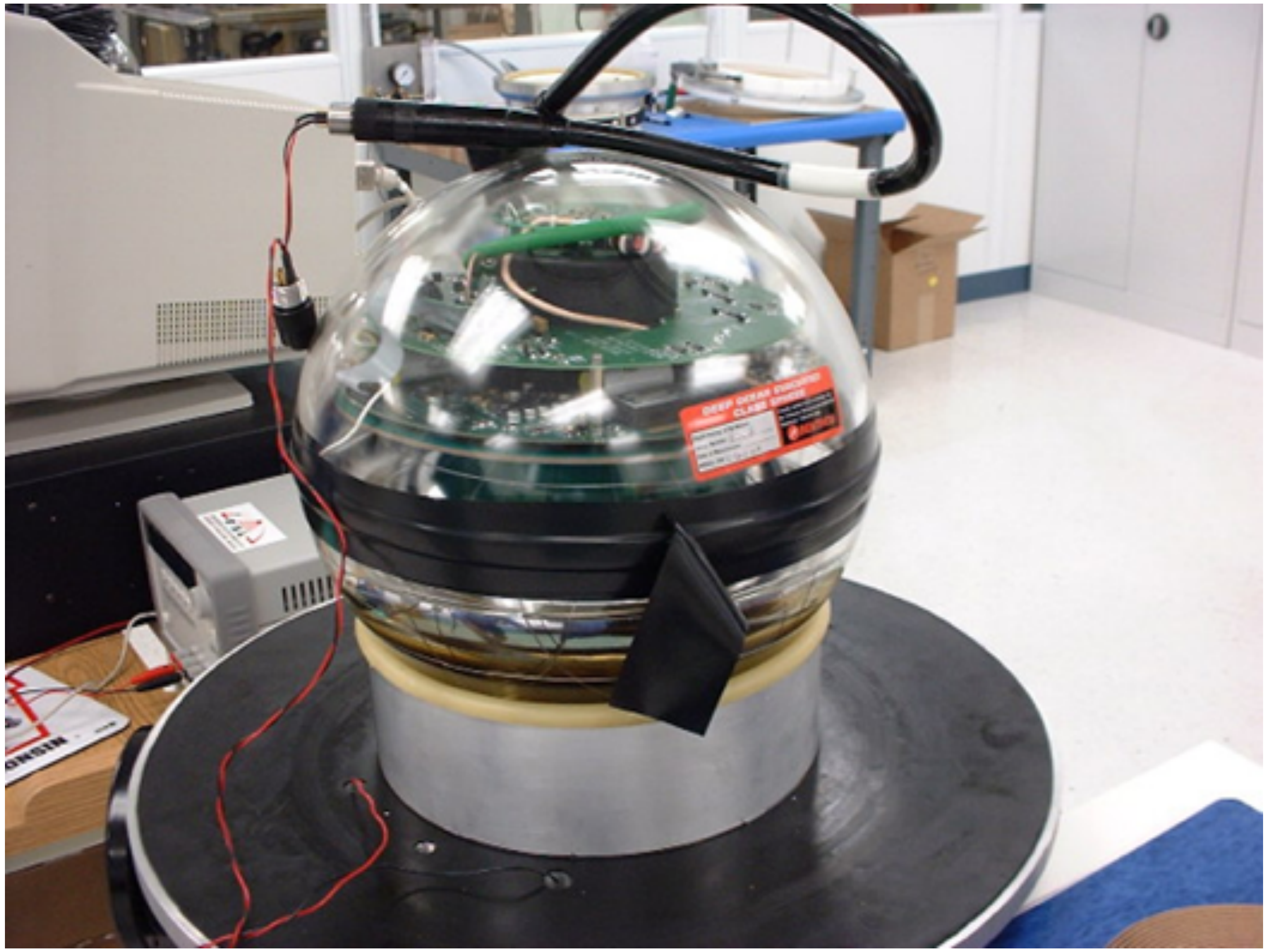


IceCube: 1 km^3 instrumented volume



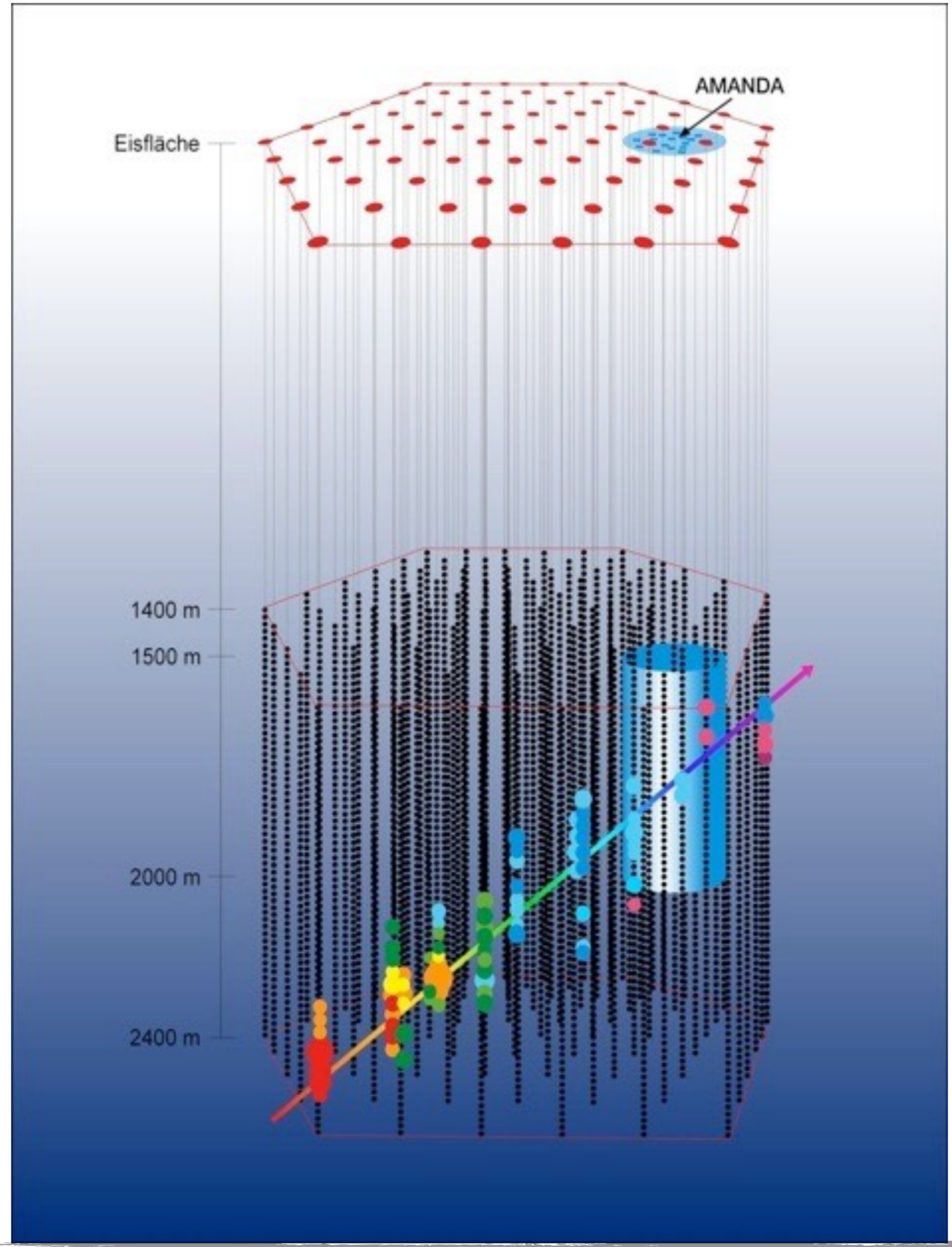
Amanda/IceCube: Neutrinos at the South Pole

Amanda/IceCube: Neutrinos at the South Pole



- Detectors for Cherenkov light:
  DOM (Digital-Optical Module)
- Total: 80 strings with 60 DOMs each

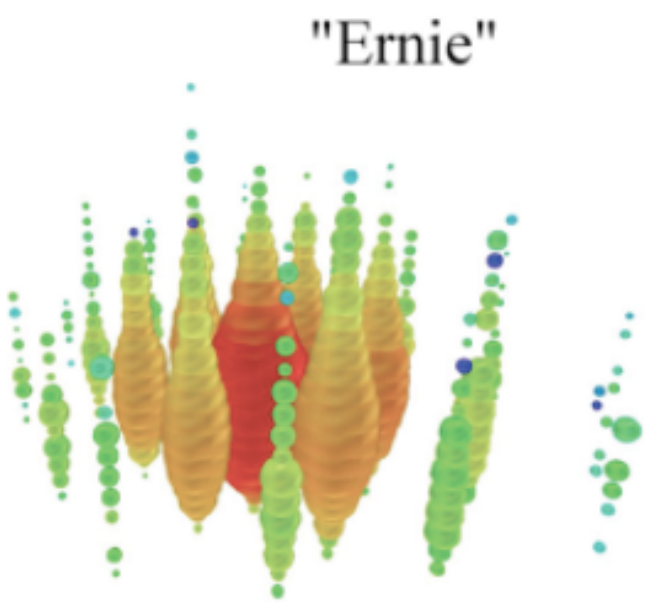
IceCube Event



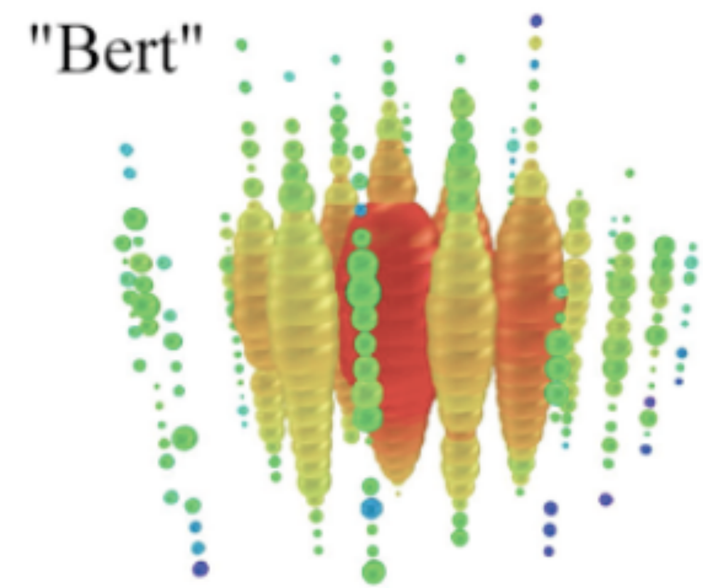
- Arrival time of light at individual detectors allows the determination of the muon direction and with that the direction of the neutrino

Highest Energies - First Observation 2012

- IceCube has observed two events:



1.14±0.17 PeV



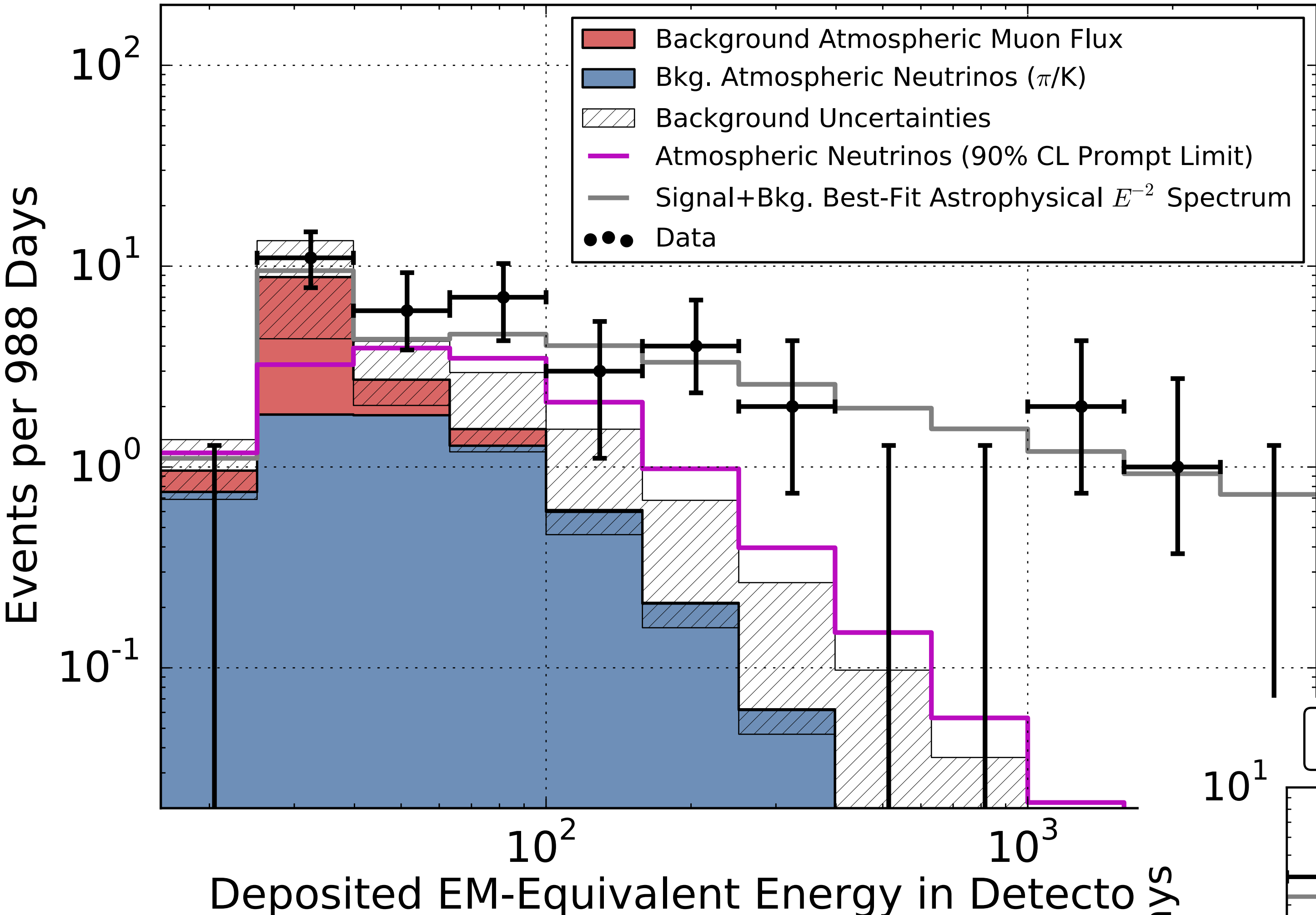
1.04±0.16 PeV

(visible energy in the detector, neutrino energy higher)

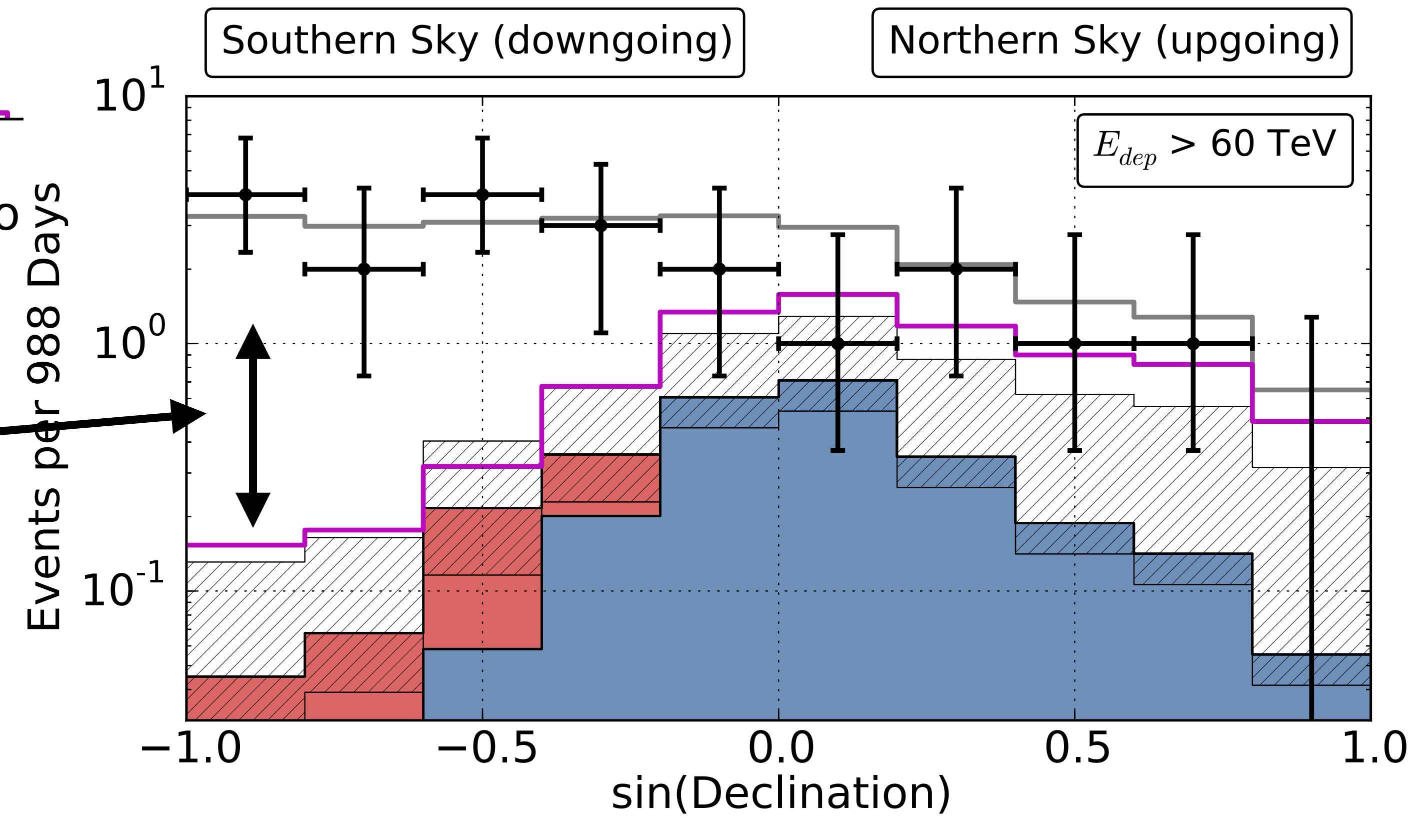
- Both events are “down-going” (as expected)
- Requires specialized event selection to exclude atmospheric neutrinos

Quite a few events observed by now (60 > 60 TeV) - highest energy 5.9 PeV

Neutrinos at Highest Energies



- Atmospheric neutrinos excluded at 5.7 σ
- Data consistent with a cosmic neutrino flux of E^{-2}



Effectivity of the exclusion of atmospheric neutrinos

Up to now no individual sources identified, no correlation with known objects - but anisotropic distribution

Summary

- Neutrino experiments using reactor and accelerator neutrinos have
    - confirmed the observations with solar and atmospheric neutrinos with high precision
    - made a precise measurement of the third mixing angle Θ_{13}
    - provided first indications for a non-zero CP violating phase
- Upcoming experiments will
    - determine the neutrino mass ordering (JUNO + DUNE)
    - discover and measure CP violation in the neutrino sector if it exists (DUNE, HyperK)

- Cosmic neutrinos have been observed
    - from the core-colapse supernova SN1987A
    - PeV neutrinos from so-far unknown (but extraterrestrial) origin
        - Watch out for an announcement by ICECUBE on Thursday - multi-messenger neutrino astronomy

Thanks for attending the lecture - and have a great Summer!

Lecture Overview

09.04.	Einführung / Introduction
16.04.	Ground-based Accelerators
23.04.	Cosmic Accelerators
30.04.	Detectors in Astroparticle Physics
07.05.	The Standard Model
14.05.	QCD and Jets at e^+e^- Colliders
21.05.	Holiday - No Lecture
28.05.	Precision Experiments with low-energy accelerators
04.06.	Dark Matter & Dark Energy
11.06.	Cosmic Rays I
18.06.	Cosmic Rays II
25.06.	Gravitational Waves, Neutrino Introduction
02.07.	Neutrinos I
09.07.	Neutrinos II