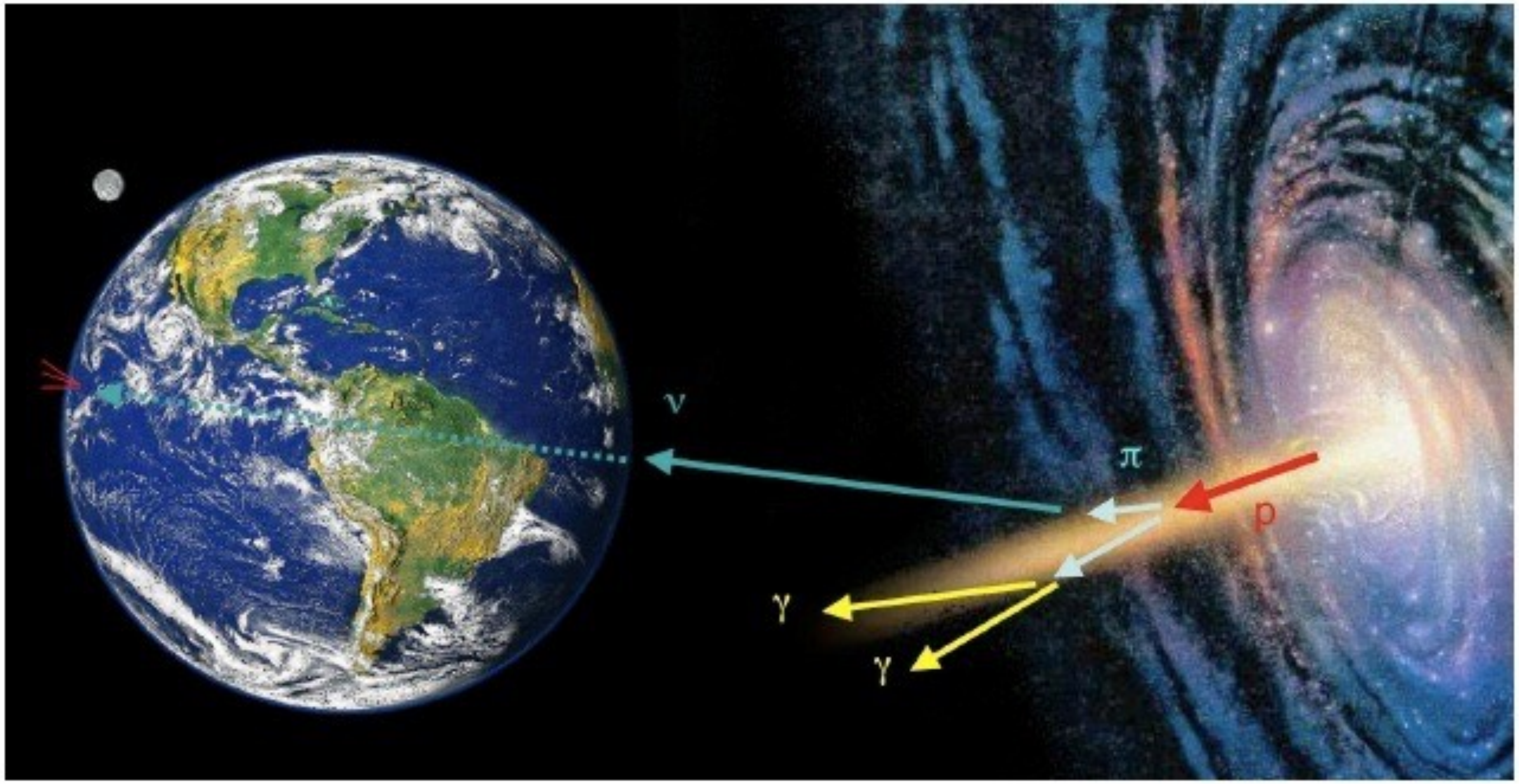
Teilchenphysik mit kosmischen und mit erdgebundenen Beschleunigern



6. Neutrinos I - Atmospheric, Accelerator and Cosmic Neutrinos

12.06.2017

Max-Planck-Institut für Physik
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Prof. Dr. Siegfried Bethke
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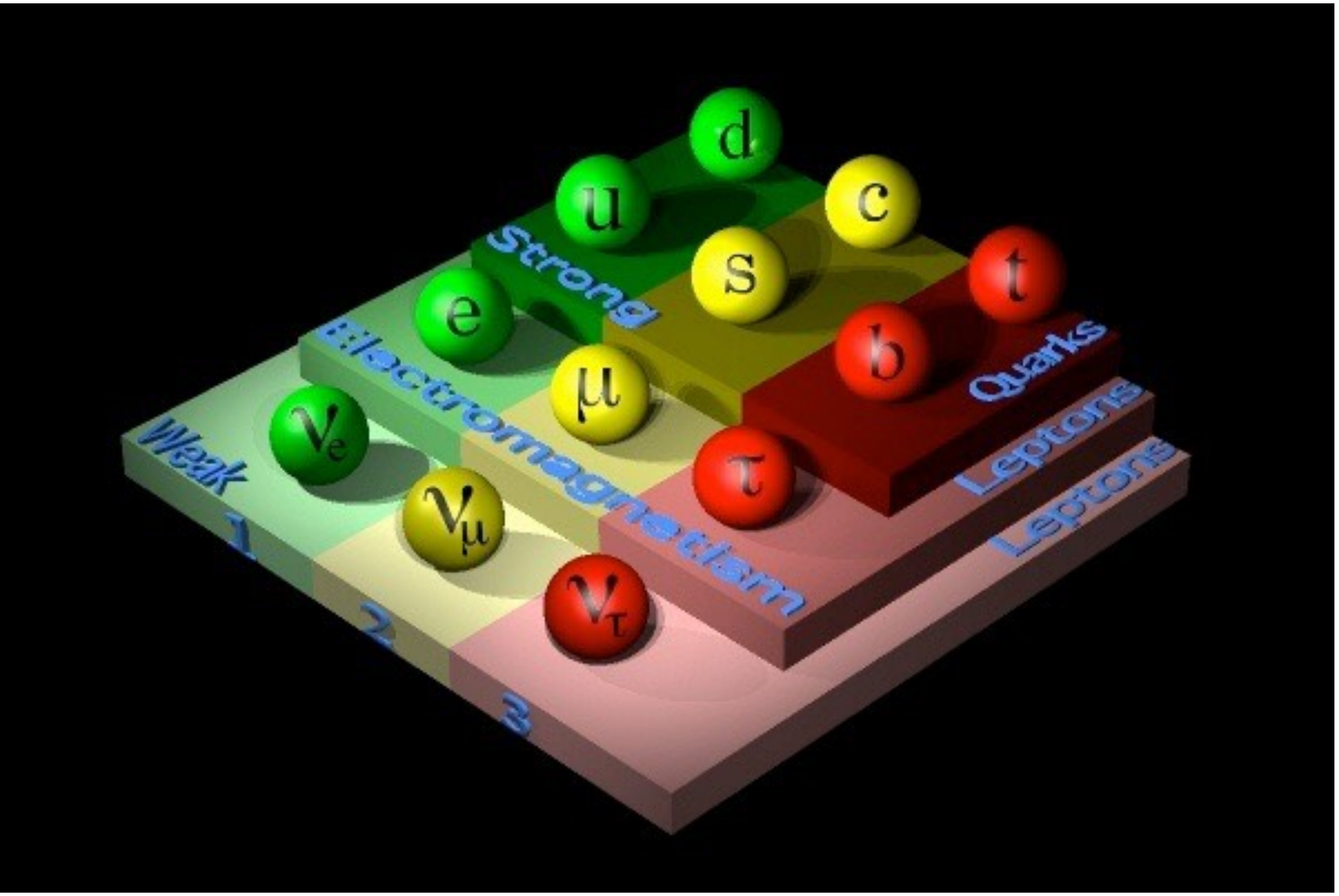
Neutrinos: Time Line I

- 1931 W. Pauli postulates the existence of the neutrino in β decay
- 1934 E. Fermi presents a theory of the π decay (incl. neutrino)
- 1959 Discovery of ν_e (Reines and Cowan; Nobel prize 1995)
- 1962 Discovery of ν_μ
- 1968 First measurement of solar neutrinos (ν_e): less than 50% of the expected intensity („Solar Neutrino Problem“)
- 1987 Kamiokande and IMB (nucleon decay experiments) detect neutrinos from SN 1987a
- 1988 Kamiokande sees only 60% of the expected atmospheric ν_μ flux
    - 2002 Nobel prize for Koshiba and Davis for solar neutrino and Kamiokande measurements
- 1990 LEP experiments prove the existence of exactly 3 generations of light neutrinos
- 1998 Super-Kamiokande shows evidence for neutrino oscillations (ν_μ), -> neutrinos have finite mass

Neutrinos: Time Line II

- 2000 explicit confirmation and observation of ν_τ
- 2001 Confirmation of solar ν_e deficit and definite proof of neutrino oscillations into other flavors by SNO
  - 2015 Nobel prize for Kajita and MacDonald for SuperK / SNO discoveries
- 2011 First evidence for non-zero Θ_{13} by T2K & MINOS
- 2012 Observation of cosmic PeV neutrinos by IceCube
- 2016 First indication for possible CP violation in the neutrino sector by T2K

Neutrinos: General Properties



- 3 known families of elementary particles:
  - 3 neutrinos as partners of the charged leptons
  - In the “simple” Standard Model neutrinos are massless
  - Experimental bounds of neutrino masses:
    $M(\nu_e) < 2$ eV
    $M(\nu_\mu) < 0.19$ MeV
    $M(\nu_\tau) < 18.2$ MeV

Neutrino Sources

- **Solar neutrinos**
  (get produced in the fusion reaction in the sun), ca 2 x 10^{38} /s,
  flux on earth ~ 7 x 10^{10} $cm^{-2}s^{-1}$
- **Cosmic neutrino background**
  freeze out ~ 1s after the Big Bang,
  temperature ~ 1.9 K, <E> ~ 5 x 10^{-4} eV, ~ 330/cm^3
- **Cosmic neutrino sources**
  supernova explosions, active galaxies, GRBs...
- **Atmospheric neutrinos**
  produced in cosmic ray air showers
- **Geo neutrinos**
  radioactive decay in earth, total power ~ 20 TW, flux ~ 10^7 $cm^{-2}s^{-1}$
- **Man made neutrinos**
  reactor neutrinos (MeV energies), accelerator neutrinos (MeV -> GeV)

Neutrinos: General Properties

- Neutrinos are special: they only interact via the weak interaction
  - Maximum parity violation of the weak interaction enforces:
    Neutrinos are always left-handed (helicity -1)
    Anti-Neutrinos are always right-handed (helicity +1)

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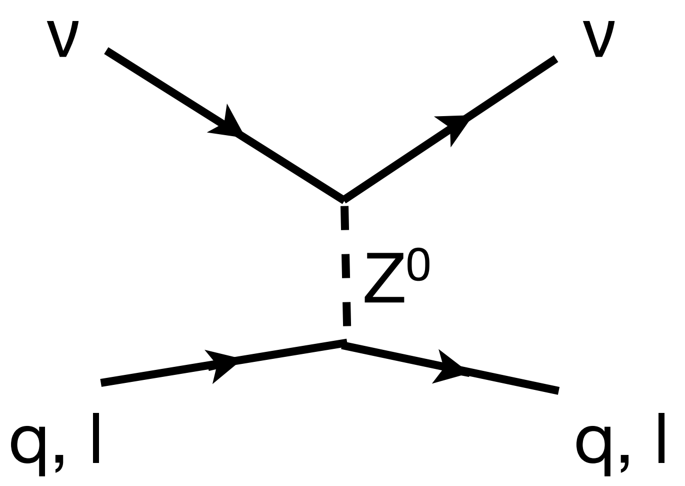
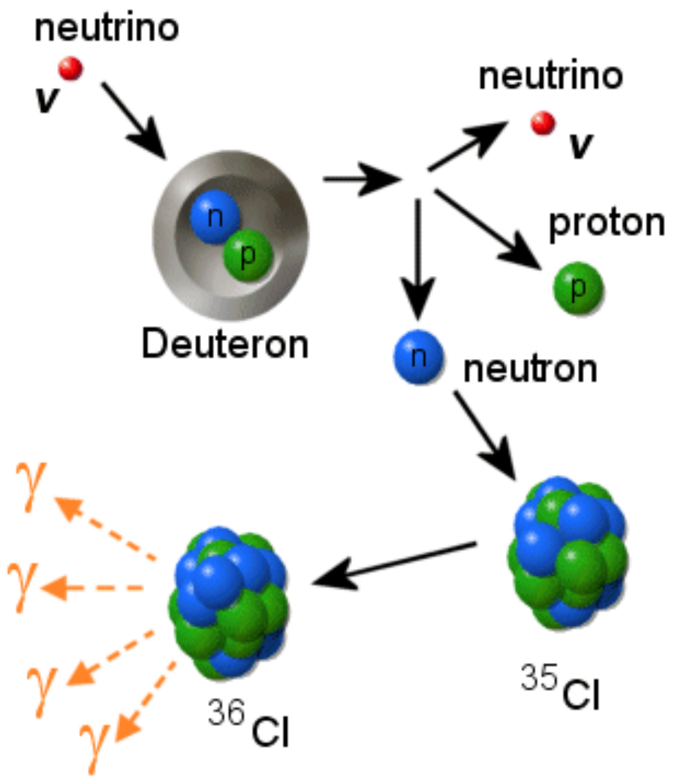
- Possible consequence:
  - Neutrinos may be their own anti-particles, so-called Majorana particles
    - A neutrino would then be a left-handed Majorana neutrino,
      an anti-neutrino a right-handed Majorana neutrino
    - ▸ The differentiation between Majorana and Dirac neutrinos is only possible for massive neutrinos

Neutrinos: Interaction with Matter

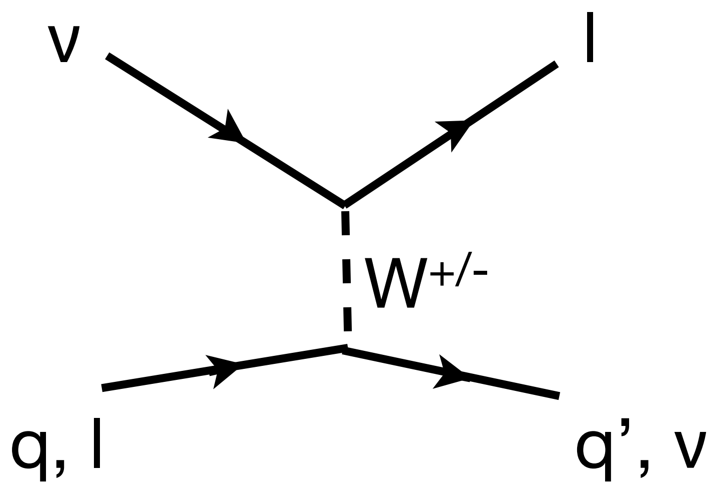
- Neutral current

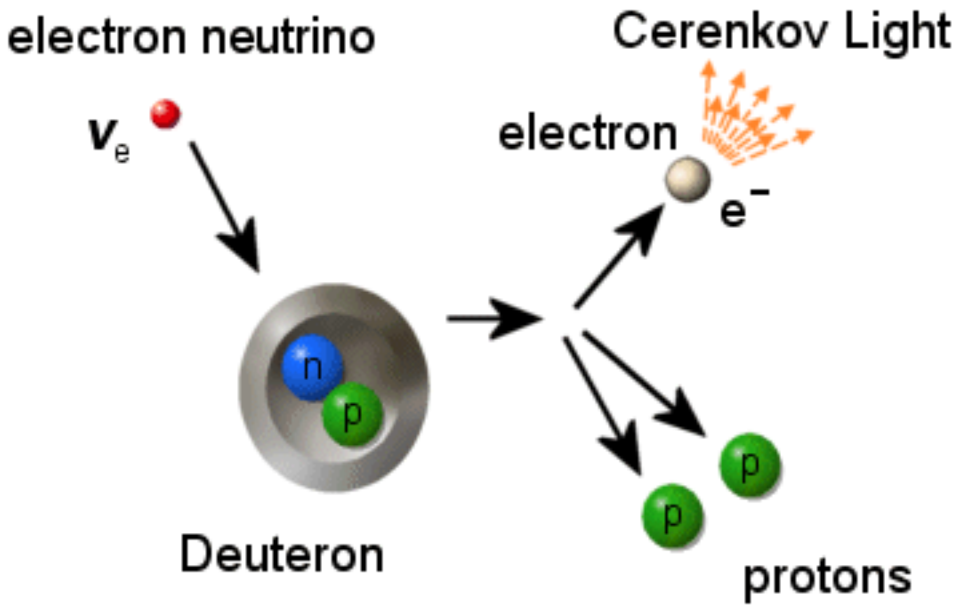




SNO

- Charged current

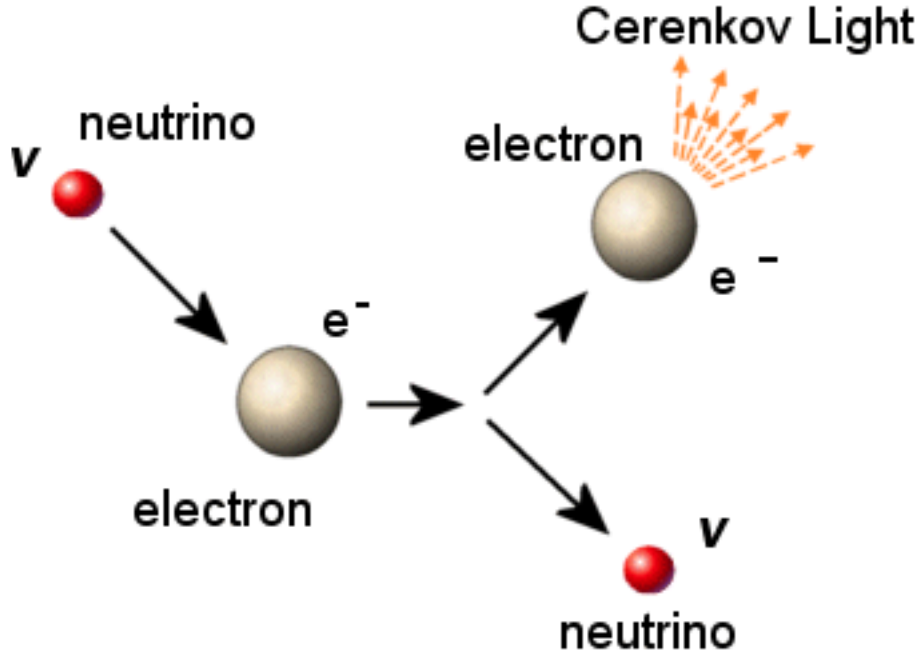




SNO

Neutrino - Elektron Scattering

- Special Case:
  - For ν_μ and ν_τ this process only works via the neutral current
  - For ν_e both neutral and charged current contributes



SNO

- Cross sections
  - $\nu_\mu e$: ~ 1.5 x 10^{-42} cm^2 E_ν/GeV
  - $\nu_e e$: ~ 10 x 10^{-42} cm^2 E_ν/GeV

‣ ~ three orders of magnitude smaller than neutrino-nucleon scattering

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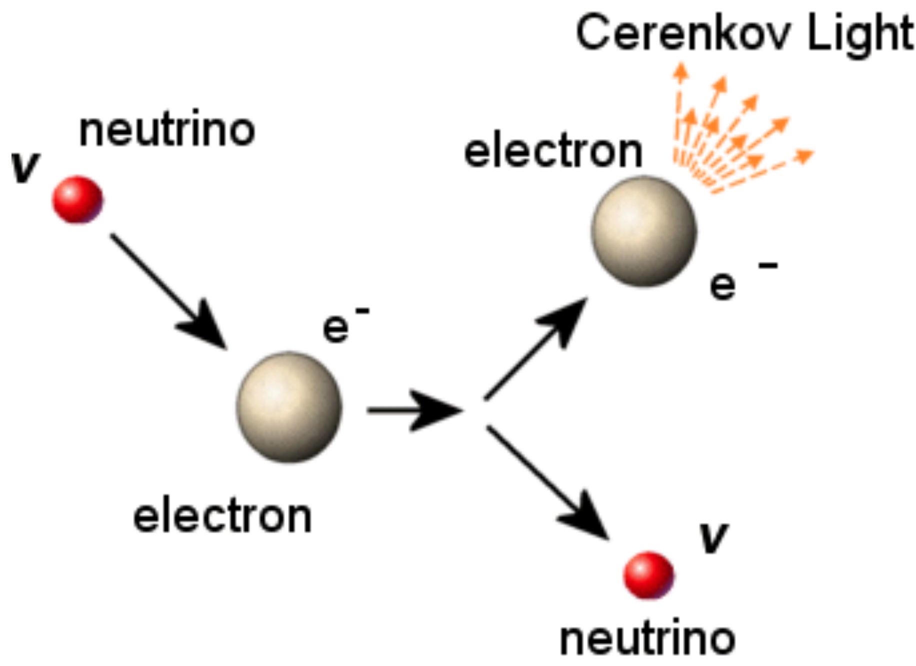

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In general: neutrino cross sections are proportional to the neutrino energy!

Neutrino Oscillations: Basic Conditions

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  - Mass eigenstates are not the same as flavor eigenstates

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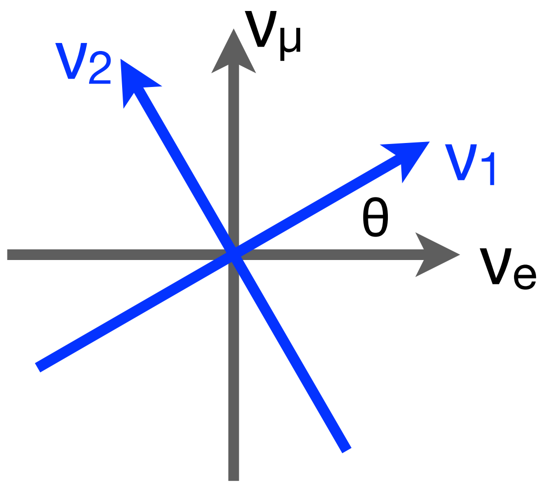
- Example: A world with two neutrino types:
  - The eigenstates of the weak interaction ν_μ und ν_e are not identical to the mass eigenstates ν_1 und ν_2



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

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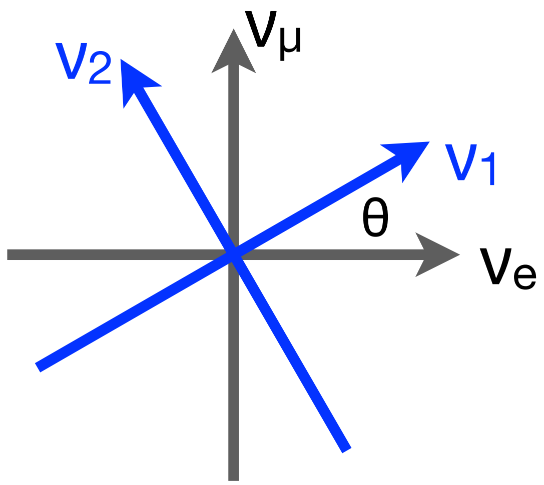

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  - The eigenstates of the weak interaction ν_μ und ν_e (which we can observe and identify) are mixes of the mass eigenstates:

$$|\nu_\mu\rangle = -sin\theta\ |\nu_1\rangle + cos\theta\ |\nu_2\rangle$$

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

Neutrino Oscillations: Two Neutrinos

- The time evolution in vacuum is given by the mass eigenstates (Schrödinger Eq):

$$|\nu_\mu(t)\rangle \;=\; -sin\theta\,(|\nu_1\rangle\; e^{-iE_1 t}) \;+\; cos\theta\,(|\nu_2\rangle\; e^{-iE_2 t})$$

$$E_i \;=\; \sqrt{p^2 + m_i^2} \;\approx\; p + \frac{m_i^2}{2p} \;\approx\; E + \frac{m_i^2}{2E}$$

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- If the two mass eigenstates have different masses the relative composition changes over time, a ν_μ can transform into a ν_e!
- The oscillation property is:

$$P(\nu_\mu \rightarrow \nu_e) \;=\; |\,\langle \nu_e|\nu_\mu(t)\rangle\,|^2$$

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- The transition probability as a function of distance and neutrino energy is:

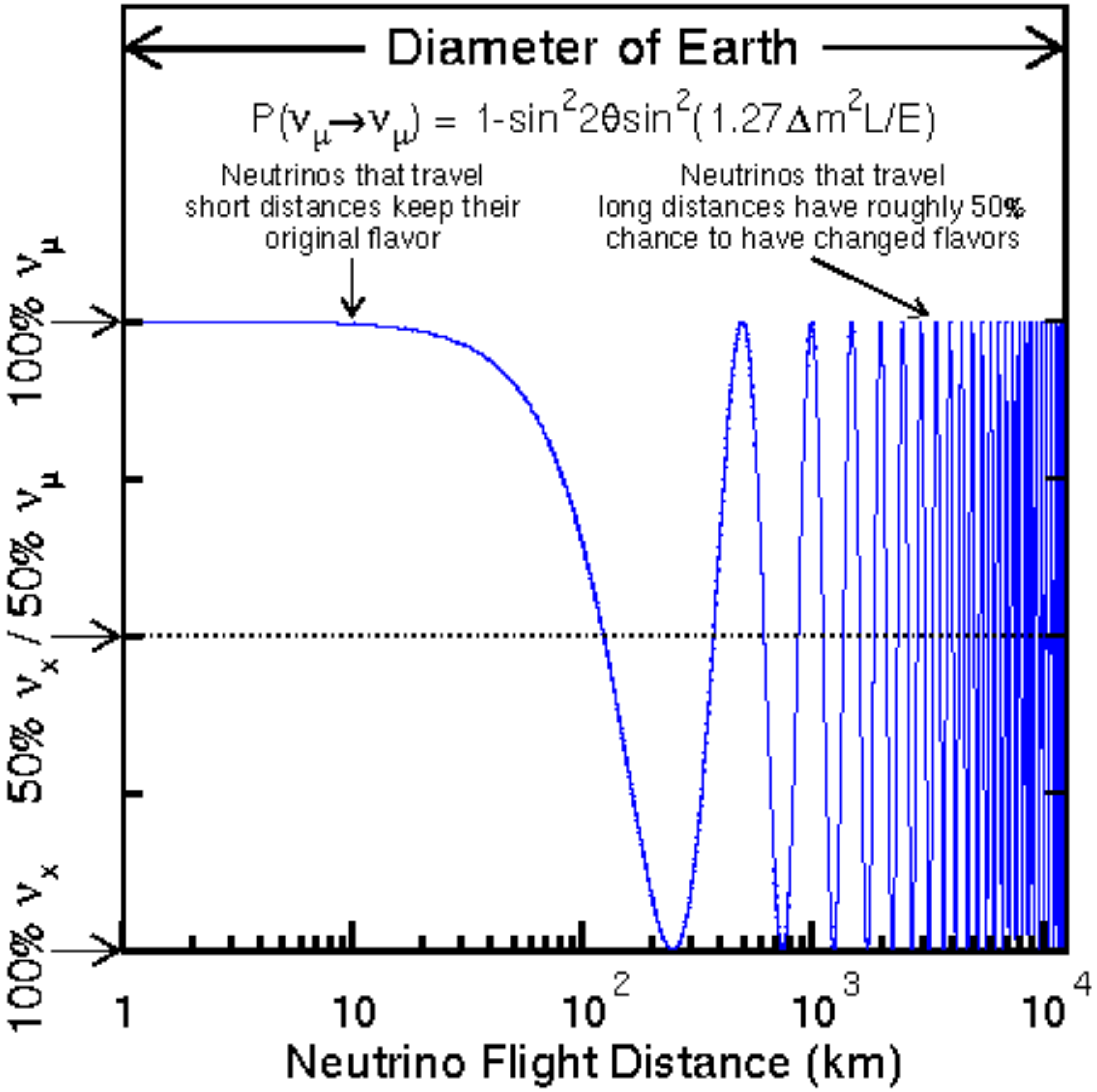
$$P(\nu_\mu \leftrightarrow \nu_e) \; = \; sin^2 2\theta \, sin^2 \left(\frac{\Delta m^2 L}{4E}\right) \; = \; sin^2 2\theta \, sin^2 \left(1.27 \, \frac{\Delta m^2}{\mathrm{eV}^2} \, \frac{L/\mathrm{m}}{E/MeV}\right)$$

$$\Delta m^2 \; = \; m_1^2 - m_2^2$$

Neutrino Oscillations

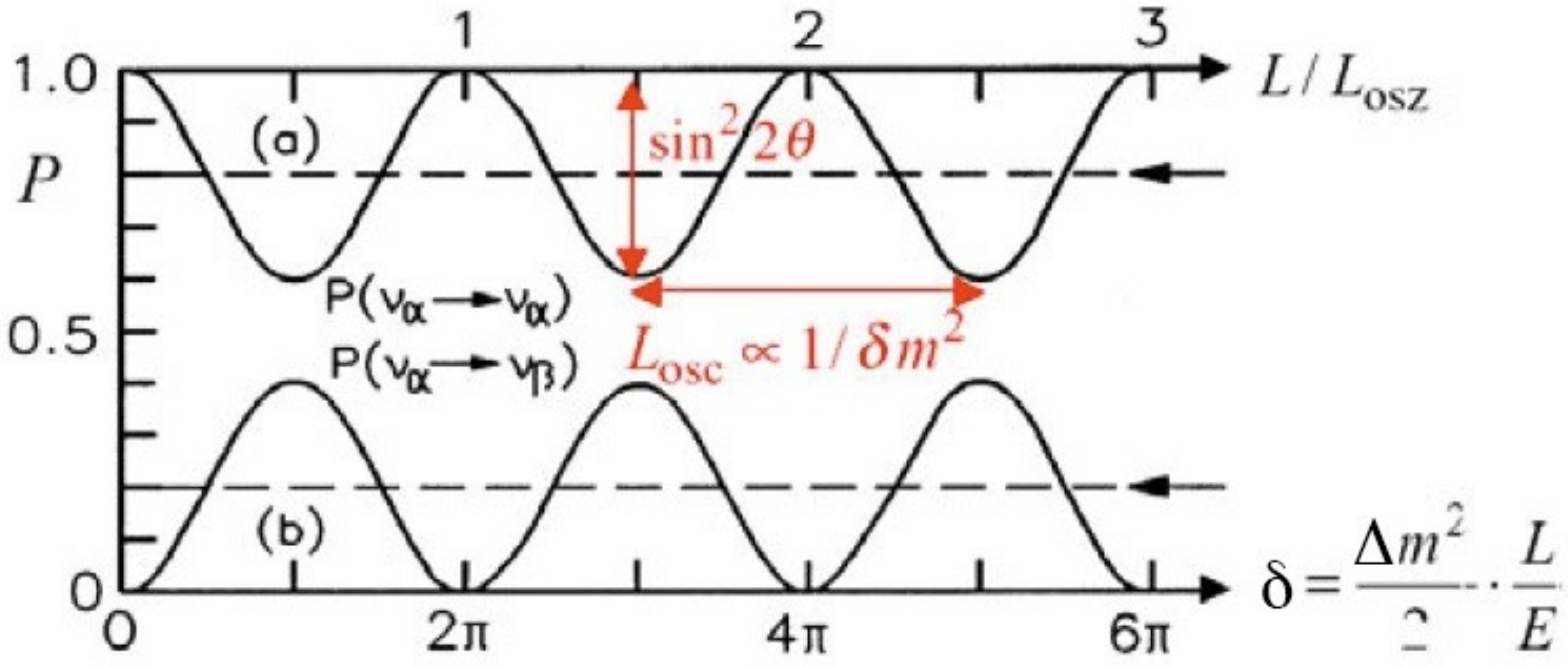
- Neutrino oscillations as a function of distance

$$\Delta m^2 = 0.005\,\mathrm{eV}^2\ ,\ sin^2 2\theta = 1\ ,\ E = 1\,\mathrm{GeV}$$



Neutrino Oscillations

- The influence of the mixing angle:



- The mixing angle determines the amplitude (the maximum level of transformation), the mass difference determines the speed of the oscillation

Neutrino Oscillations: General Case

- n flavor eigenstates $|\nu_\alpha\rangle \text{ mit } \alpha = e,\, \mu,\, \tau,\, ...$
- n mass eigenstats $|\nu_i\rangle \text{ mit } i = 1,\, 2,\, 3,\, ...$

- The states are coupled via a unitary n x n mixing matrix:

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

- $(n-1)^2$ independent parameters of the mixing matrix:
  - n(n-1)/2 mixing angles
  - (n-1)(n-2)/2 CP violating phases

- Für n = 3:
  - 3 mixing angles: $\theta_{12},\, \theta_{23},\, \theta_{13}$
  - 1 phase

General description of the 3-ν case

- Described by a 3 x 3 matrix (Pontecorvo-Maki-Nakagawa-Sakata-Matrix PMNS):
  - 3 angels and one CP violating phase
- analogous to the CKM matrix in the quark case

$$U_{MNS} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

CP violation connected to Θ13

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

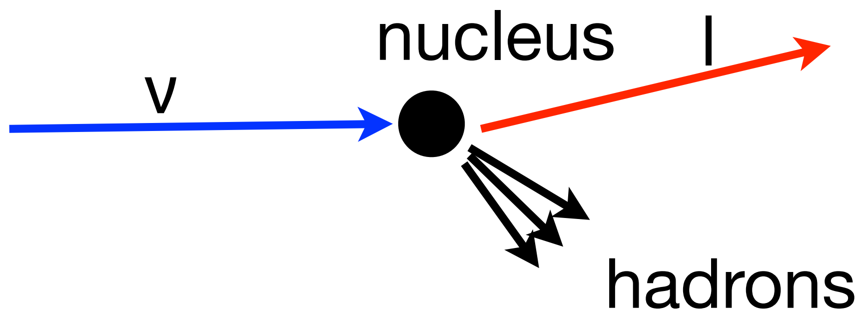
Detectors for Highly Energetic Neutrinos

- Small cross section of neutrinos: Large detector masses!
- Rare neutrino events: Good shielding from background processes:
  - Suppression of natural radioactivity: high purity
  - Shielding from cosmic muons

- Example: Kamiokande, Super-Kamiokande (Kamioka Nucleon Decay Experiment)
  - Search for proton decay with 3000 t of highly pure water (since 1983)
  - cosmic, atmospheric and solar neutrinos (since 1985)
    - 1987: 11 neutrinos from SN1987A observed
  - Upgrade to Super-K completed in 1996
    - 50 000 t highly pure water, 32 000 t active, 18 000 t as veto
    - 11 200 PMTs (50 cm diameter)

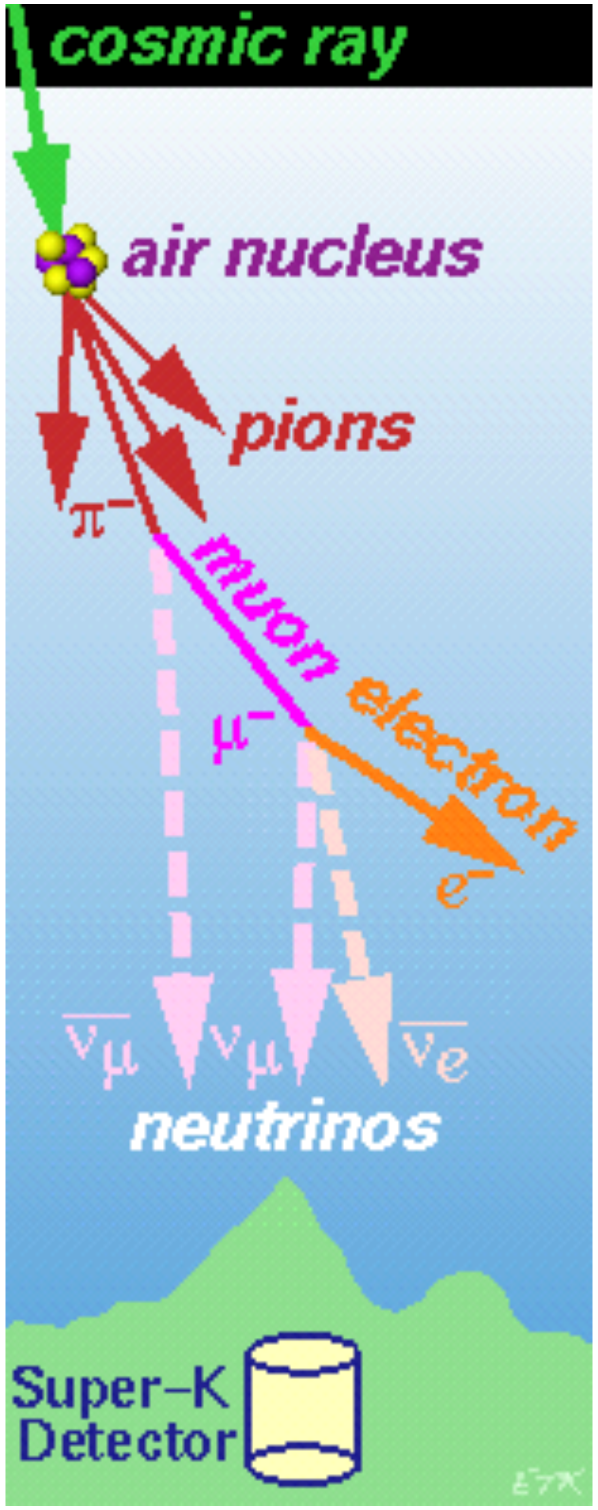
Super-Kamiokande Measurement Principle

- Neutrinos produce their corresponding leptons via charged current interaction



  - High energy threshold for τ - production due to high mass (1.777 GeV), thus only detection of electrons and muons
- Production of Cherenkov light of charged leptons in water (index of refraction 1.33)
  - Detection of Cherenkov light:
    - Light distribution enables particle identification (μ or e)
    - Amount of light enables measurement of track length, with that also energy and direction determination of the original neutrino

Atmospheric Neutrinos



- Atmospheric neutrinos are produced in air showers via pion / kaon decay and via muon decay:

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

$$\mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e$$

- Muon life time: $c\tau_\mu \approx 660\,\mathrm{m}$
- The measurement (no charge identification possible):

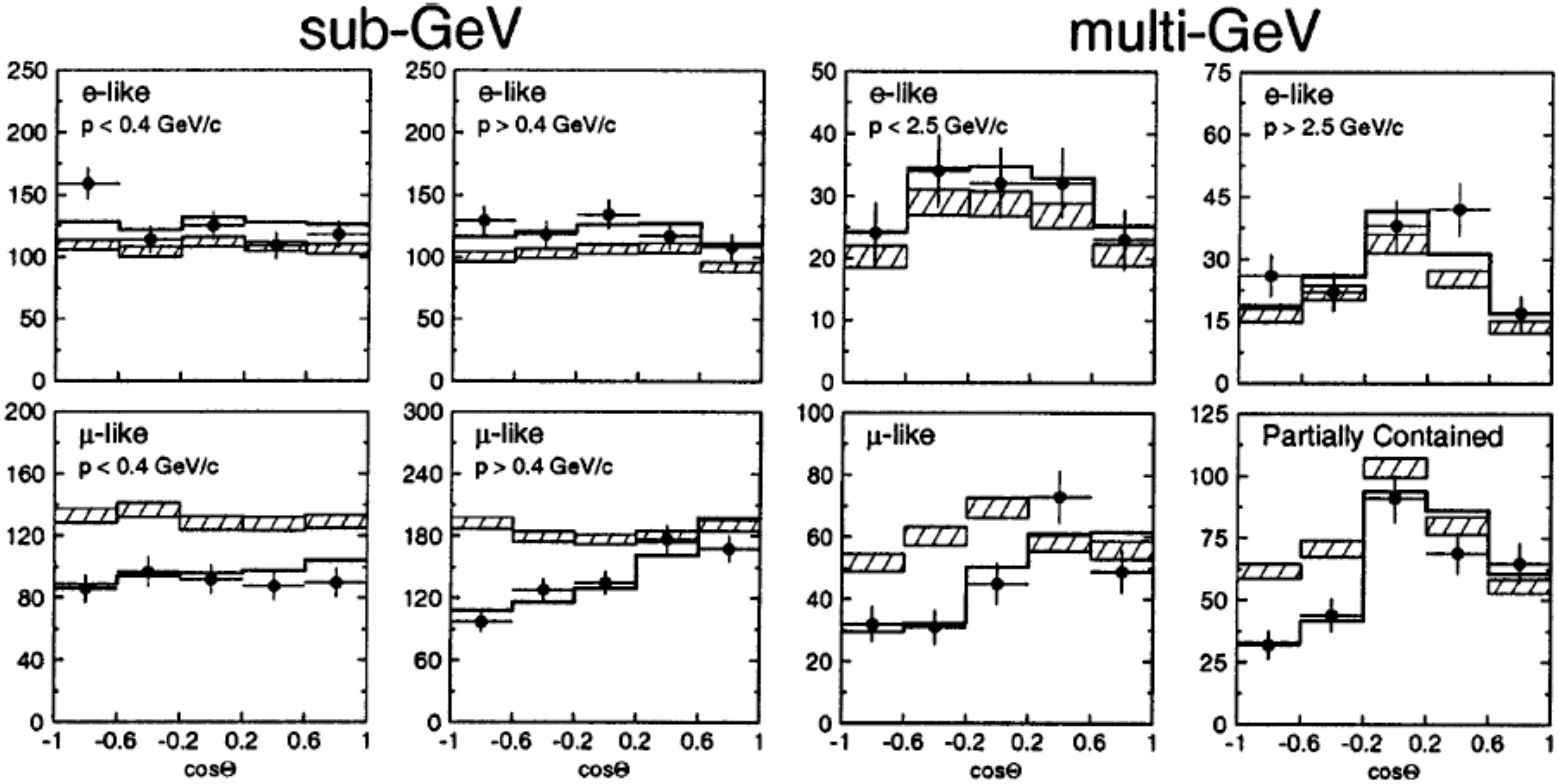
$$\frac{\mu}{e} \equiv \frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e}$$

- If all muons decay (for low energies):

$$\frac{\mu}{e} \approx 2$$

- For high energies: $\frac{\mu}{e} > 2$

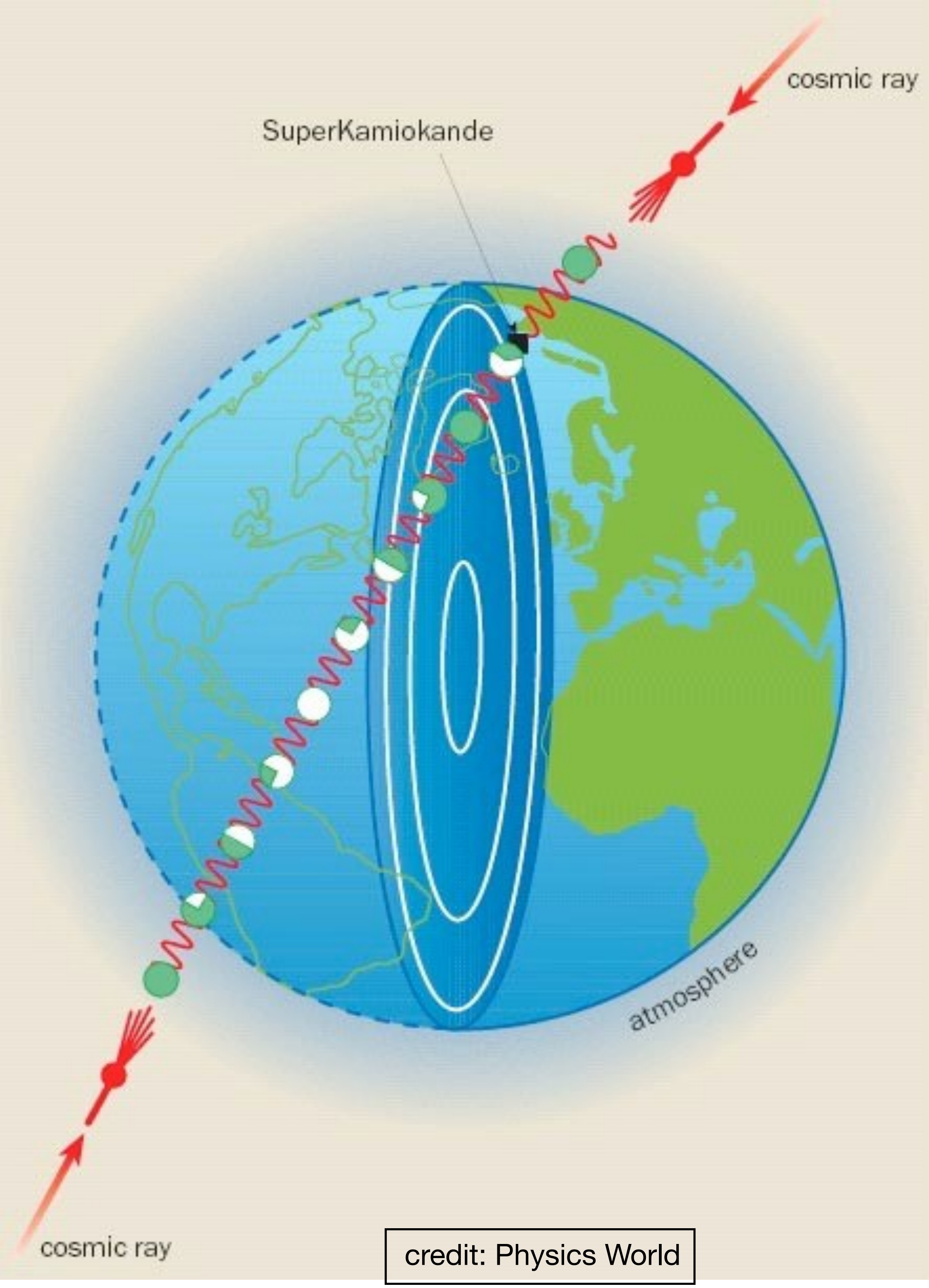
Oscillation of Atmospheric Neutrinos



Phys.Rev.Lett. 81, 1562 (1998)

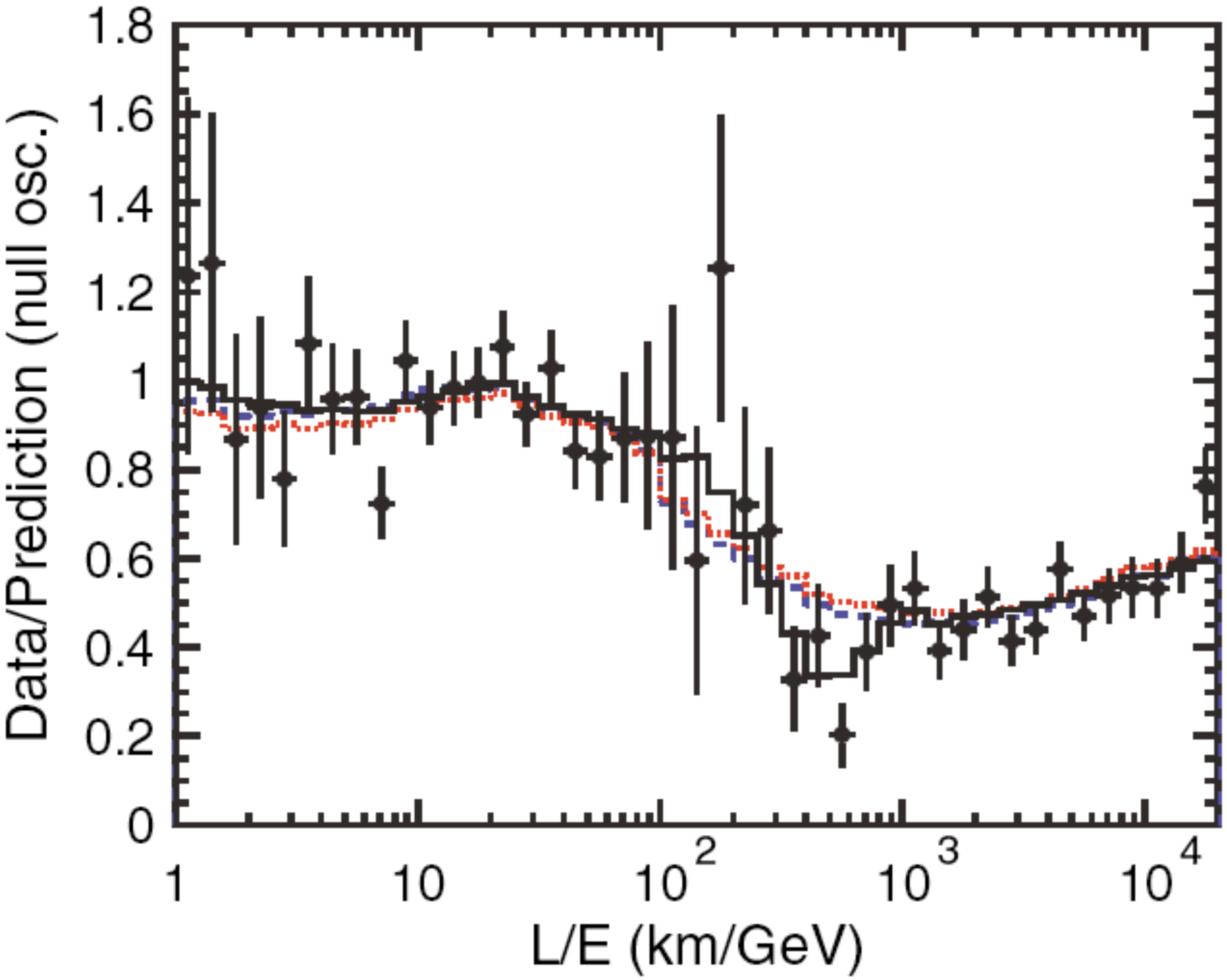
- Deficit of muon neutrinos observed, electron neutrinos match expectations
- Dependence of discrepancy with zenith angle

Oscillation of Atmospheric Neutrinos



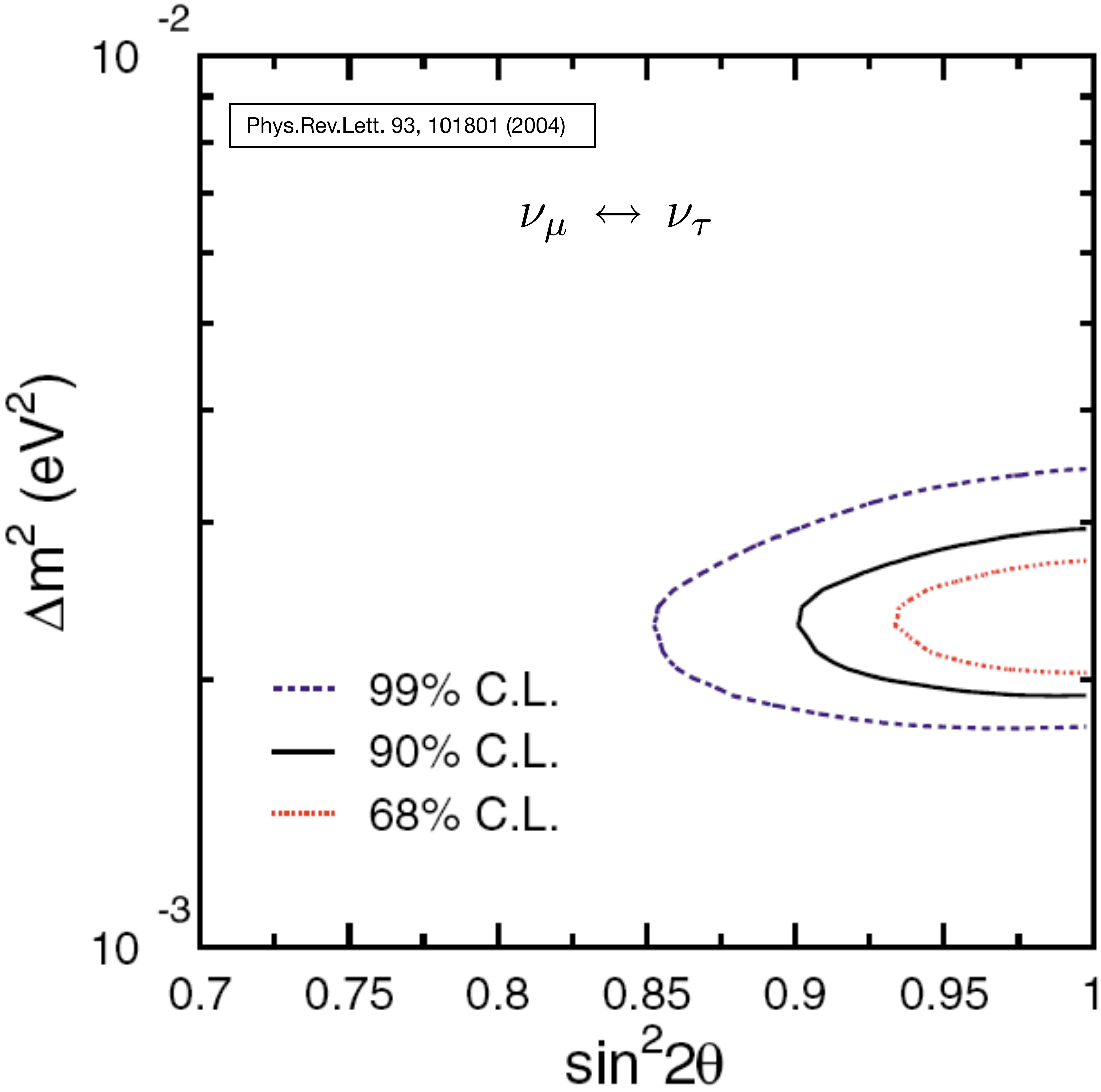
credit: Physics World

- Interpretation: On the way through earth muon neutrinos transform into tau neutrinos



Phys.Rev.Lett. 93, 101801 (2004)

Oscillation of Atmospheric Neutrinos: Result



- Best value for oscillation parameters

$$\Delta m^2 = 2.4 \times 10^{-3} \mathrm{eV}^2$$

$$sin^2 2\theta = 1.0$$

- Maximum mixing
- oscillation length ~ 1000 km E_ν/GeV

Neutrino Oscillations - Status

- Two distinct types of oscillations (with quite different mass splittings) have been observed:
    - Atmospheric - disappearance of ν_μ, $\Delta m^2 \sim 2.4 \times 10^{-3}$ eV^2
    - Solar (next week in detail) - disappearance of ν_e, $\Delta m^2 \sim 7.6 \times 10^{-5}$ 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

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solar/
reactor

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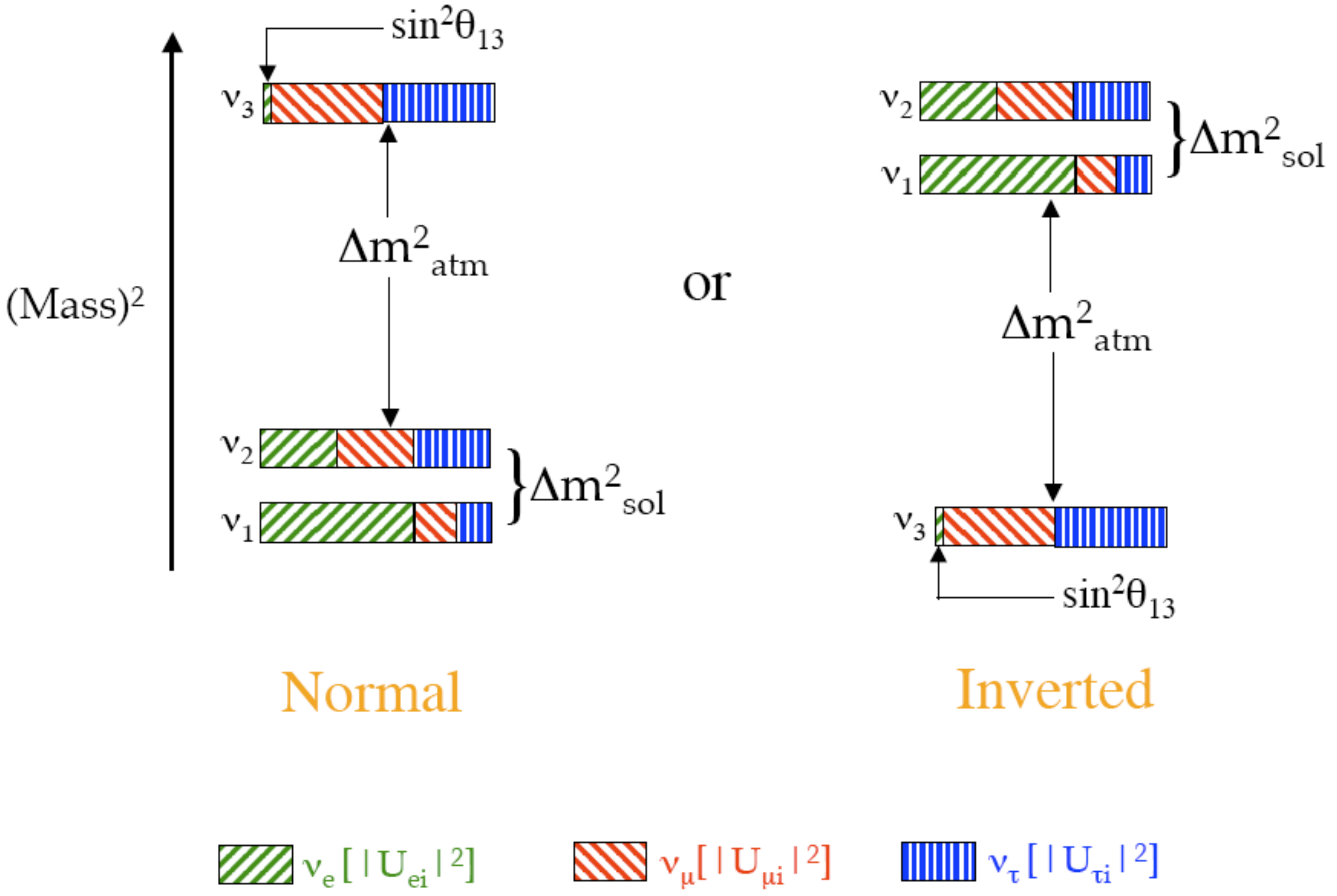
atmospheric/
accelerator

Neutrino-Oscillations: The Resulting Picture



$\Delta m^2_{sol} \sim 7.6 \times 10^{-5}\ \mathrm{eV}^2$

$\Delta m^2_{atm} \sim 2.4 \times 10^{-3}\ \mathrm{eV}^2$

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

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

Neutrinos at Accelerators

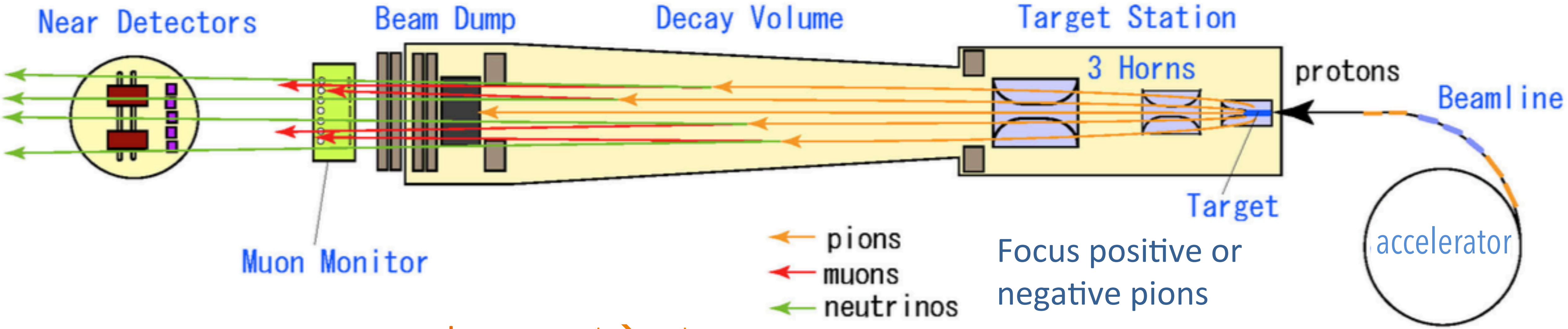
- Neutrino production:
  - Analogous to air showers: hadronic showers on impact of highly energetic protons on production target
  - Production of pions, kaons that decay in a decay tunnel:

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

  - 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

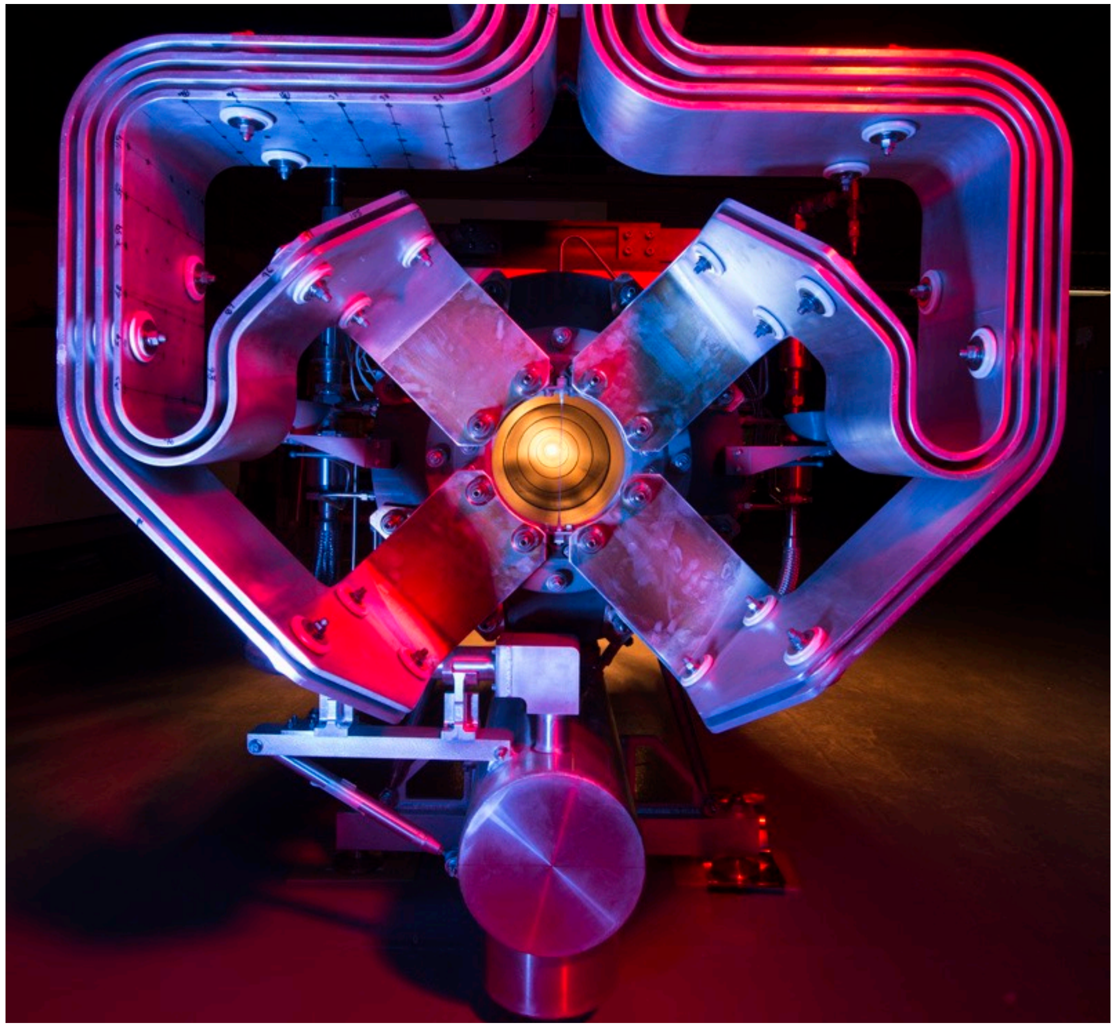


Focus positive or negative pions

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

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

- Pions focused by specialized magnet systems:
  "Neutrino Horns"

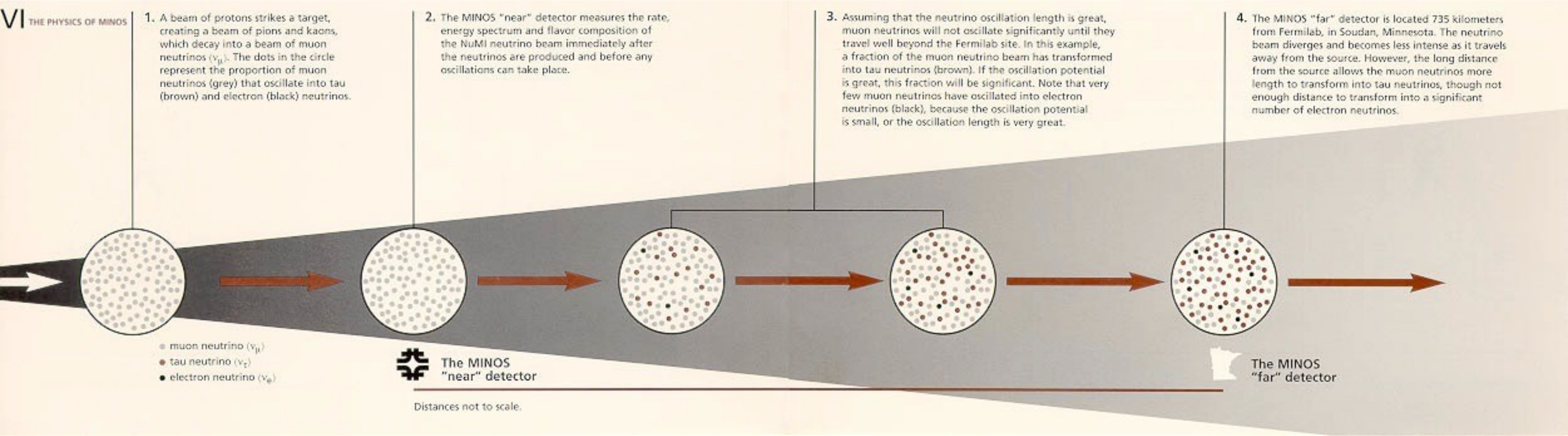


Long Baseline Experiments

- 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 ($\theta_{13} \neq 0$)



1. A beam of protons strikes a target, creating a beam of pions and kaons, which decay into a beam of muon neutrinos (ν_μ). The dots in the circle represent the proportion of muon neutrinos (grey) that oscillate into tau (brown) and electron (black) neutrinos.

2. The MINOS "near" detector measures the rate, energy spectrum and flavor composition of the NuMI neutrino beam immediately after the neutrinos are produced and before any oscillations can take place.

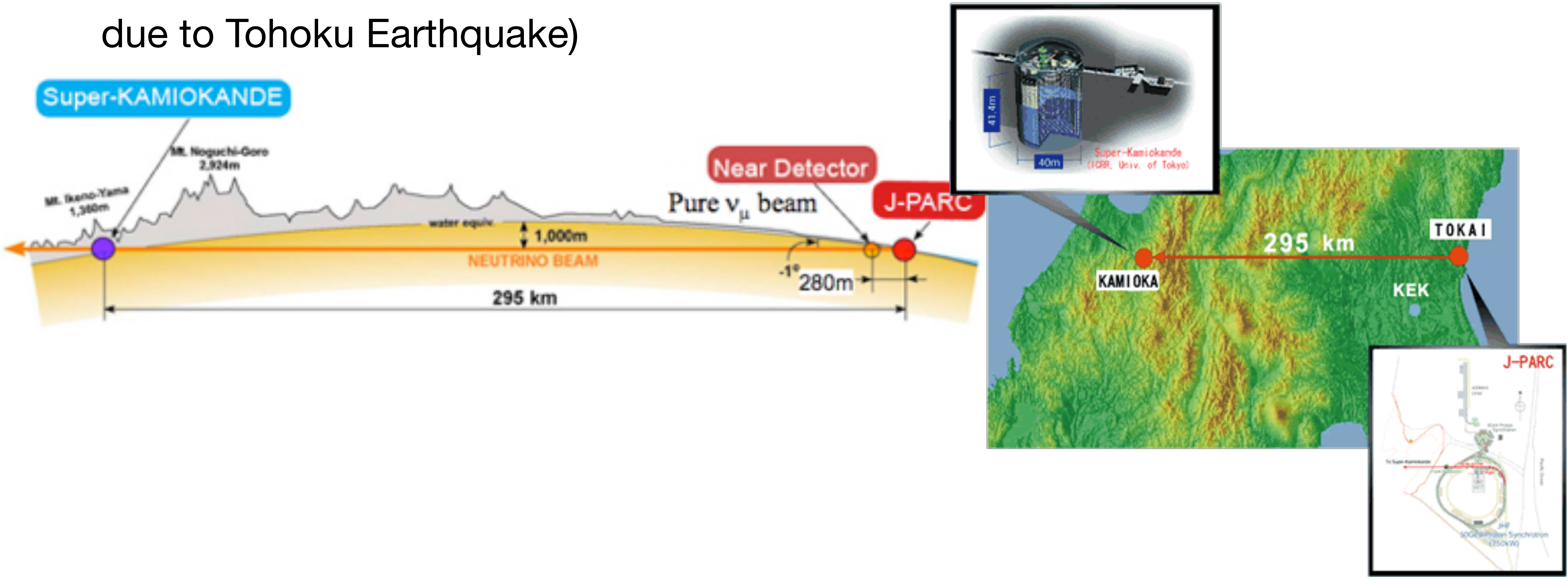
3. Assuming that the neutrino oscillation length is great, muon neutrinos will not oscillate significantly until they travel well beyond the Fermilab site. In this example, a fraction of the muon neutrino beam has transformed into tau neutrinos (brown). If the oscillation potential is great, this fraction will be significant. Note that very few muon neutrinos have oscillated into electron neutrinos (black), because the oscillation potential is small, or the oscillation length is very great.

4. The MINOS "far" detector is located 735 kilometers from Fermilab, in Soudan, Minnesota. The neutrino beam diverges and becomes less intense as it travels away from the source. However, the long distance from the source allows the muon neutrinos more length to transform into tau neutrinos, though not enough distance to transform into a significant number of electron neutrinos.

Distances not to scale.

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)



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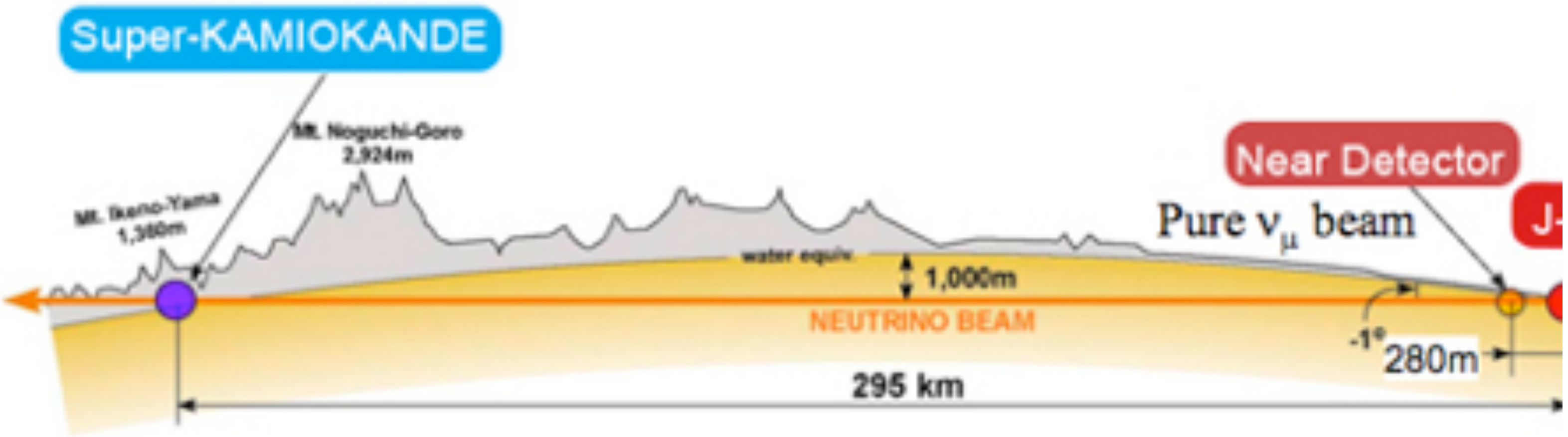
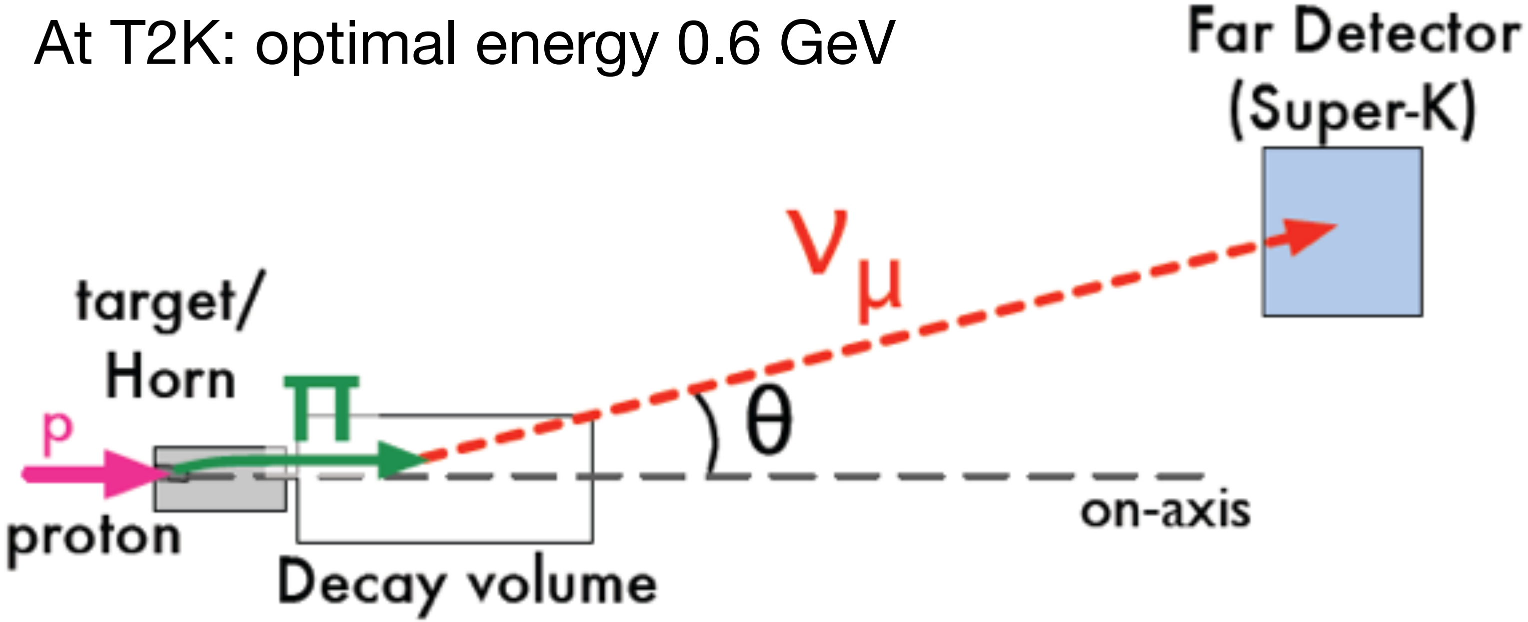
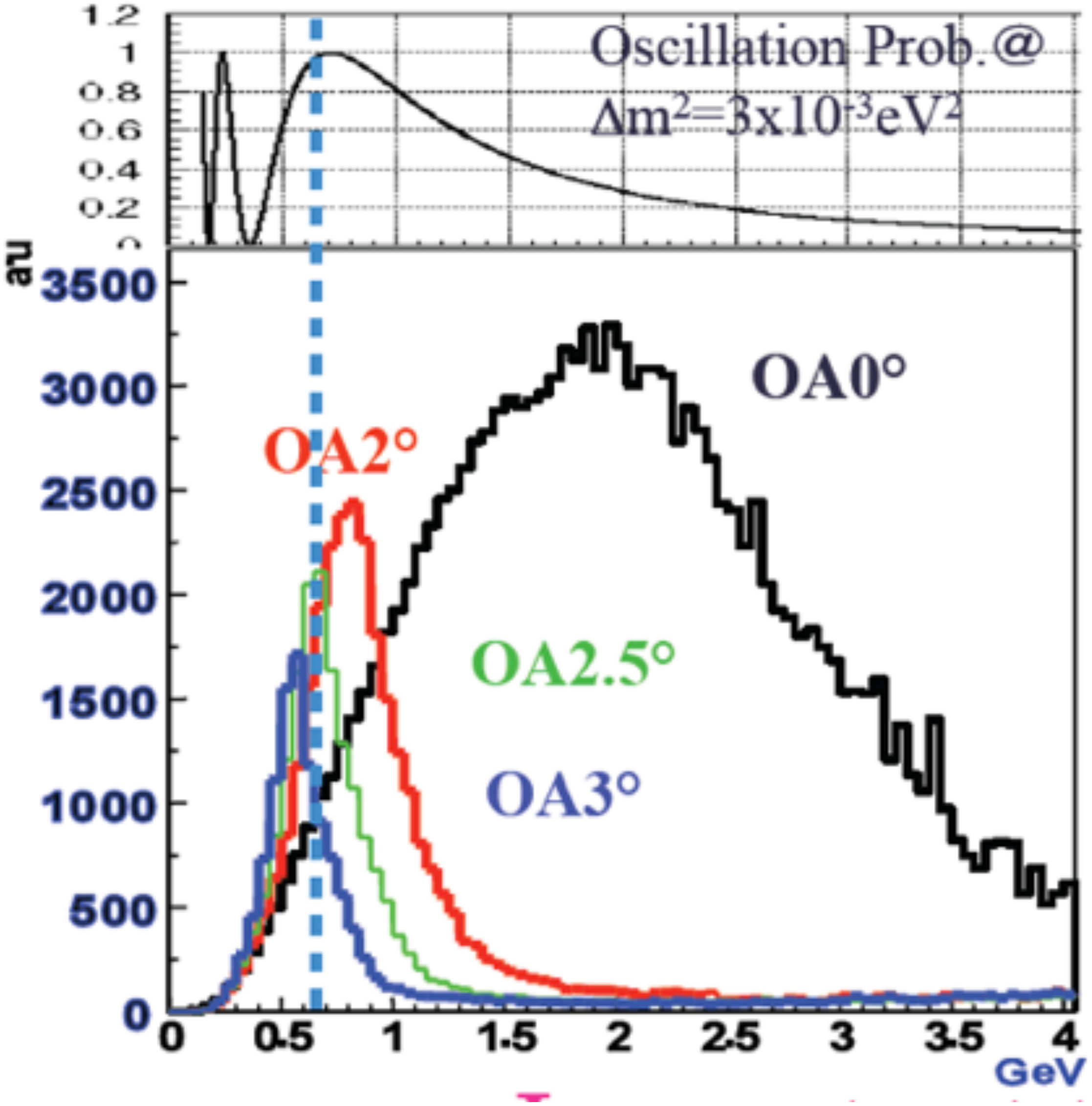


T2K is an "off-axis"- Beam: Aims not directly at the far detector -results in sharper energy distribution

At T2K: optimal energy 0.6 GeV

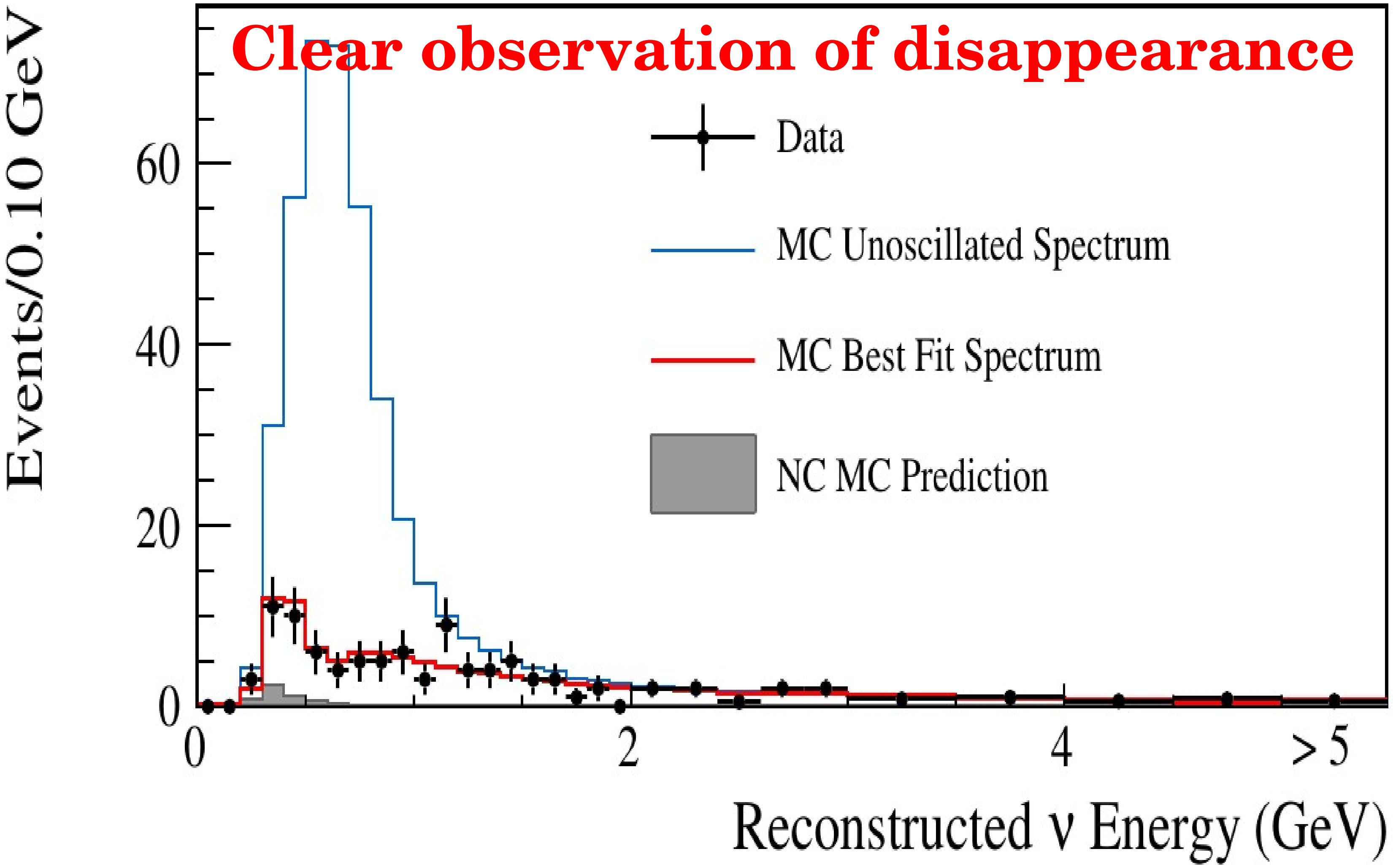




Ken Sakashita, KEK Seminar

T2K - The Choice of the Right Baseline

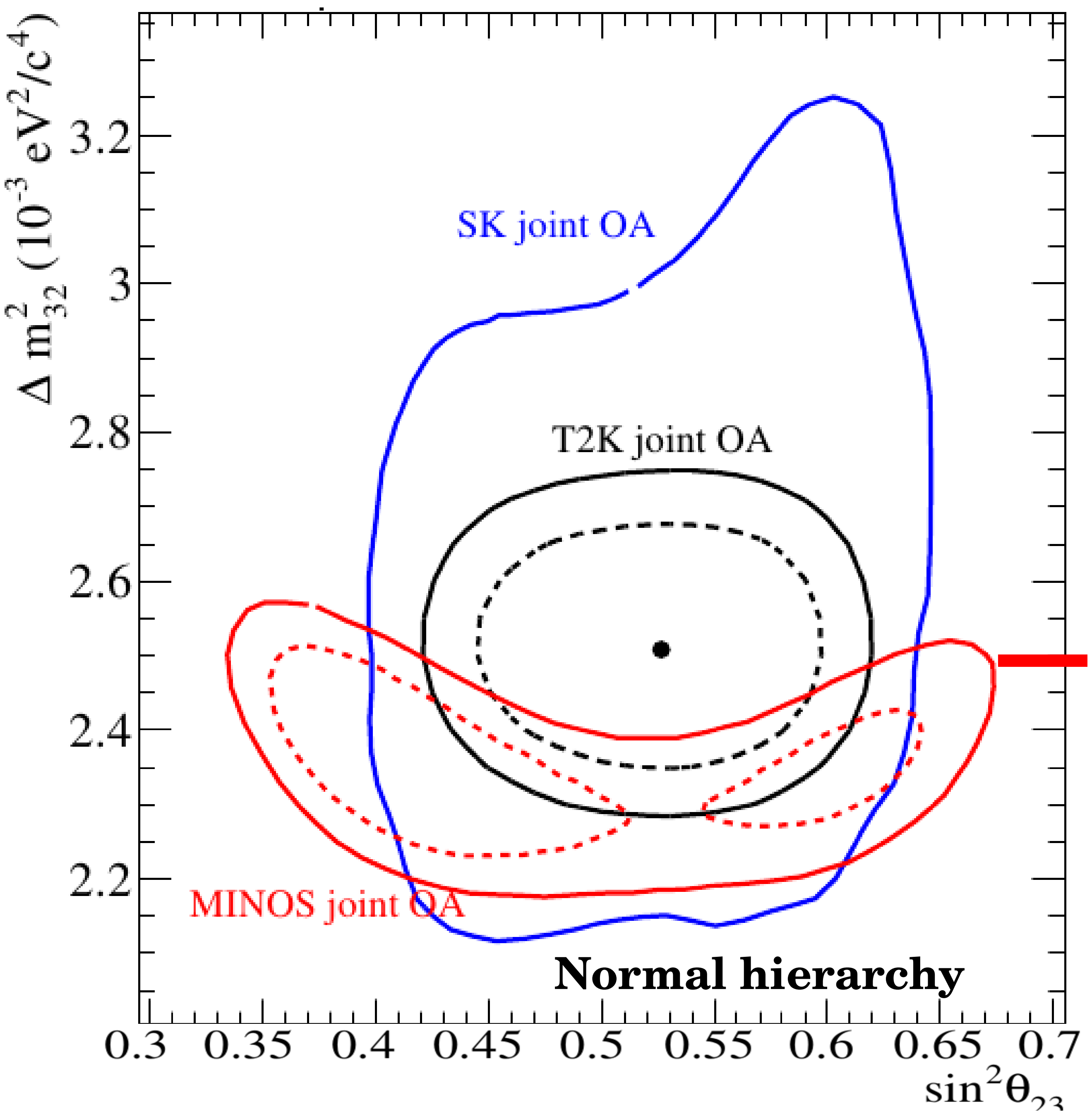
- Almost complete disappearance of ν_μ:



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

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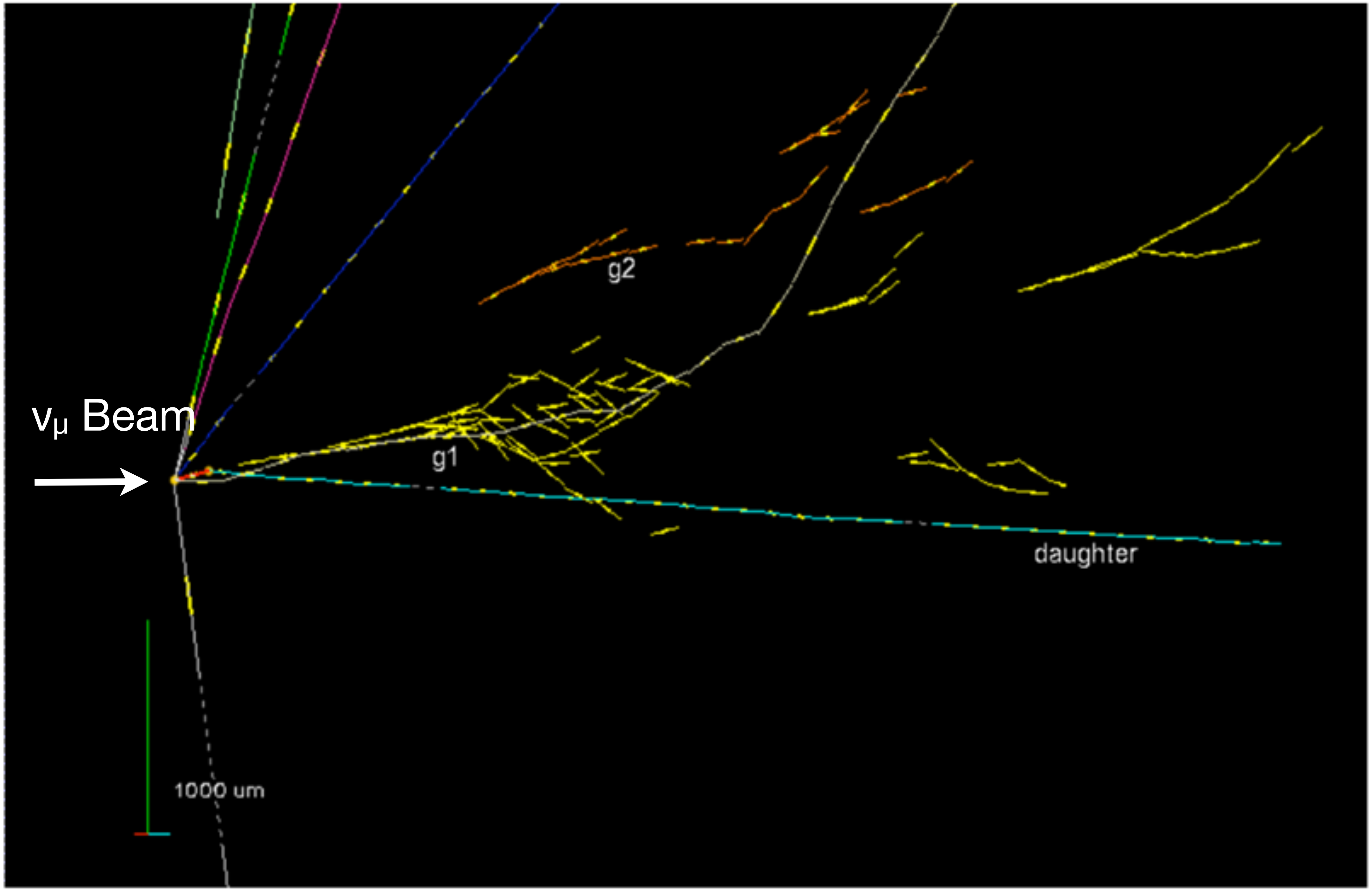
OPERA: First ν_τ Candidate

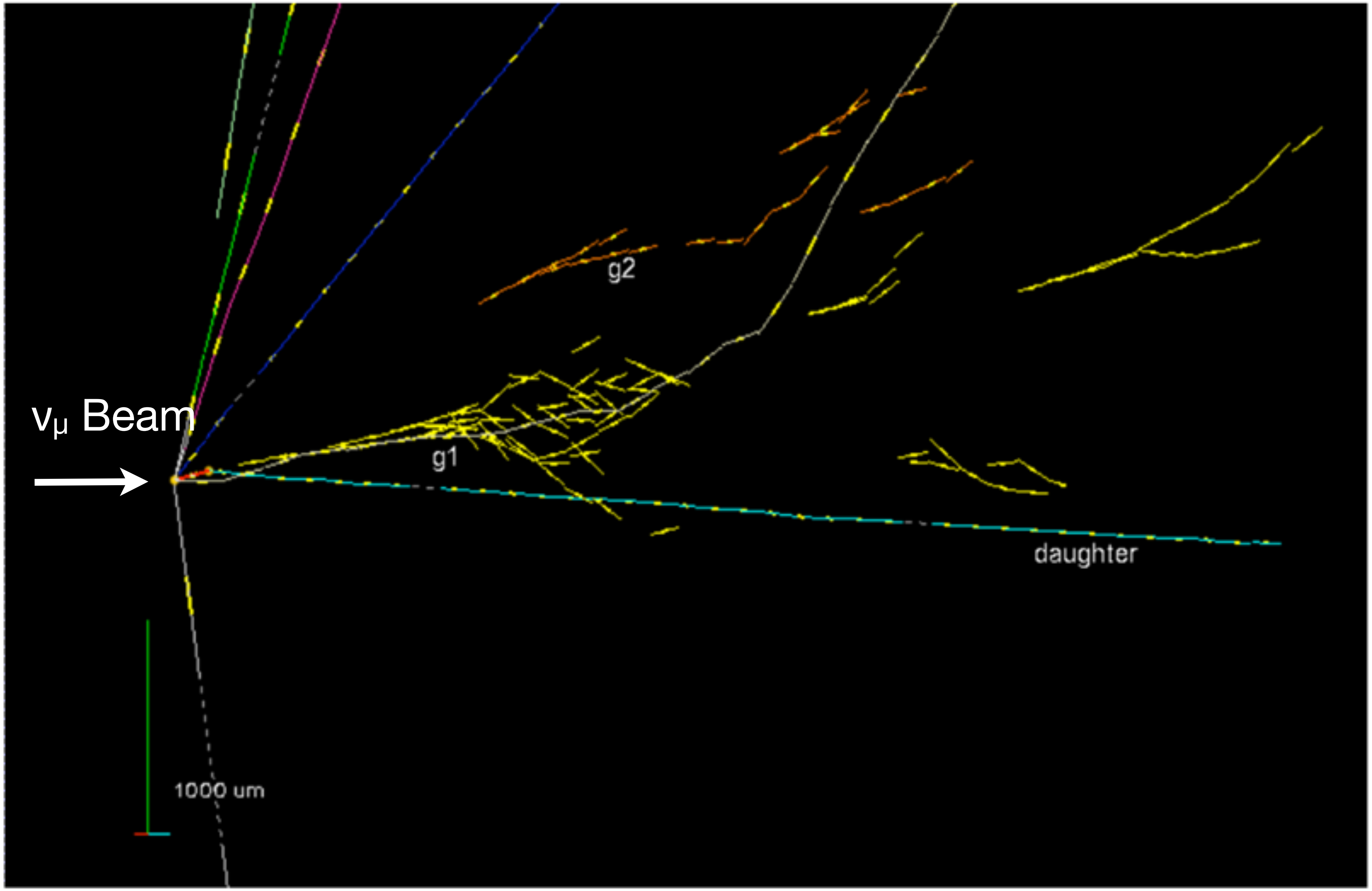


ν_τ produces τ, fast decay into μ and νs

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

OPERA Press Release, 31.05.2010

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

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OPERA Press Release, 31.05.2010

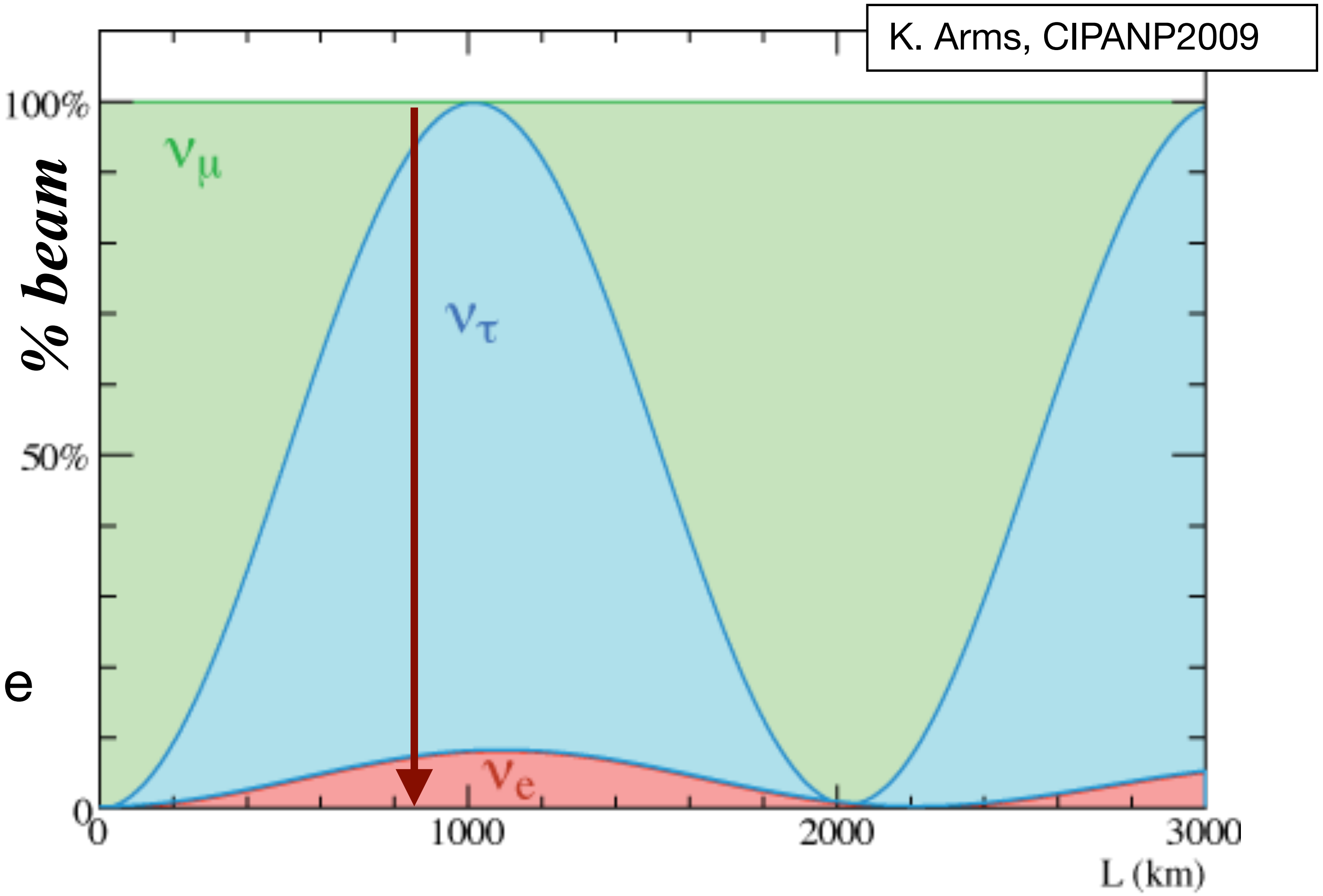
Measuring θ_{13} at Accelerators

- 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!

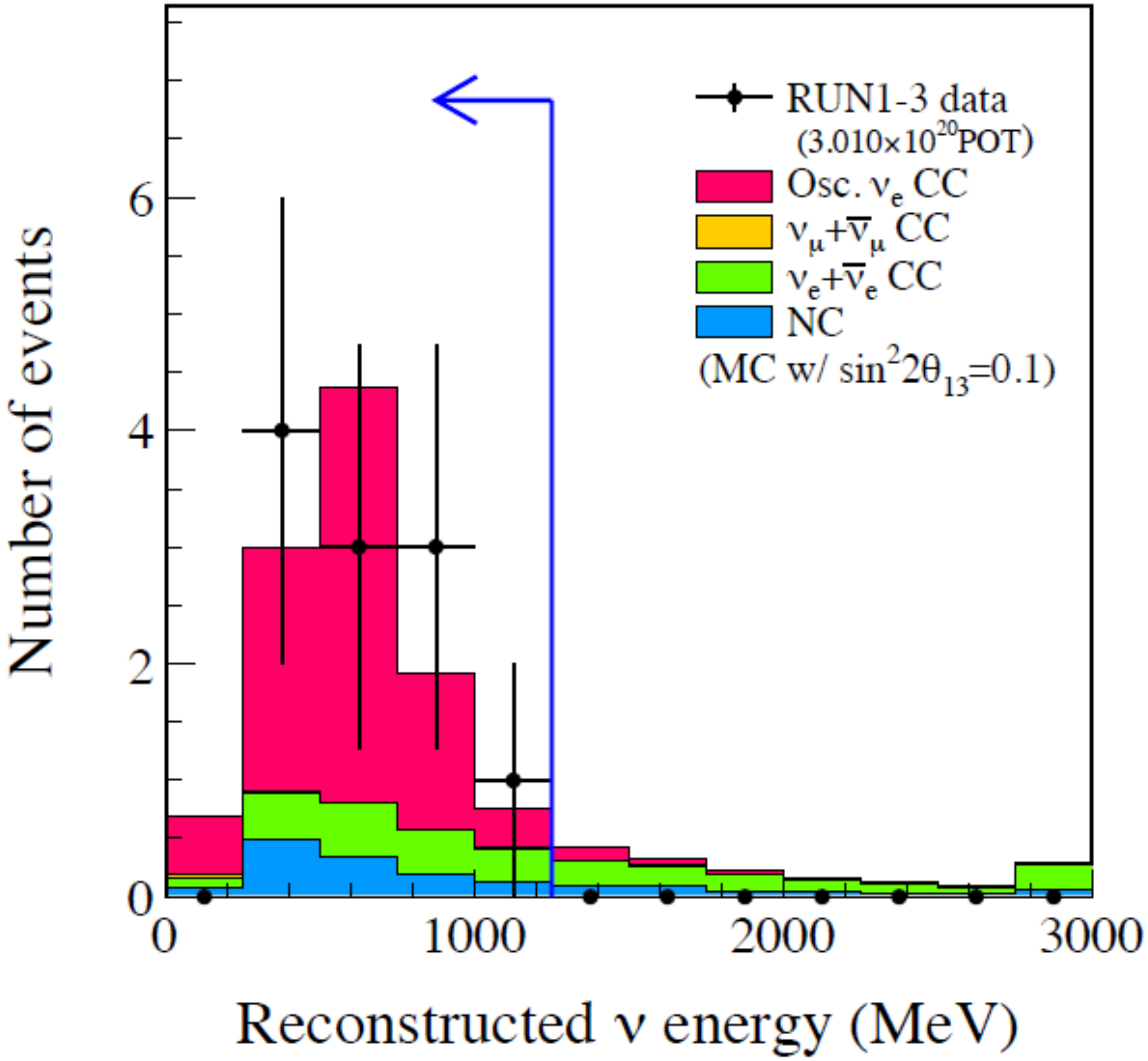
length scale depends on ν energy
here: shown for the NOvA experiment at FNAL
Important: Energy matched to baseline
Narrow energy distribution

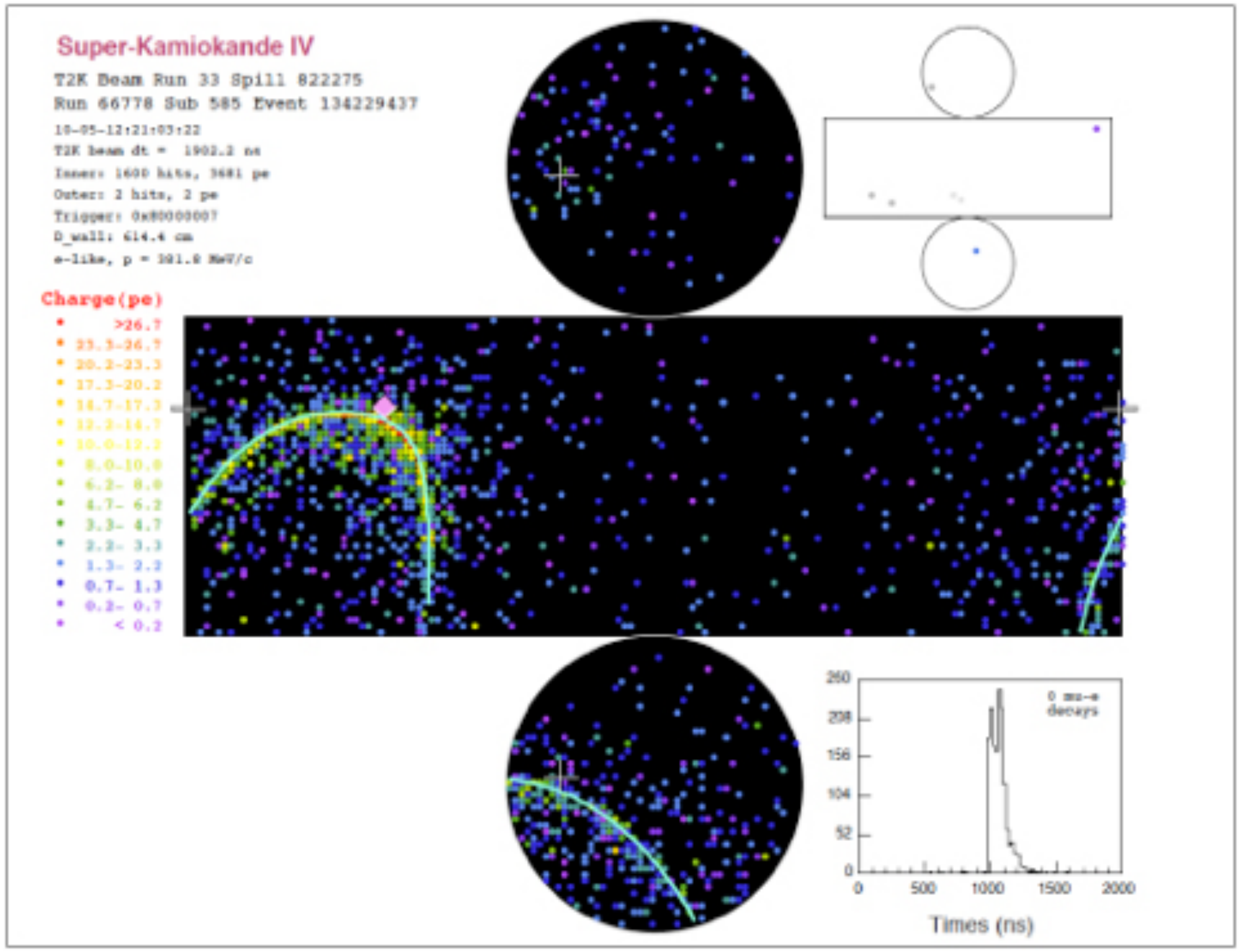


T2K - Oscillation Results

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

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





Best results currently from reactors - more next week

Searching for CP Violation in the ν - Sector

- CP Violation: A difference between matter and antimatter

Searching for CP Violation in the ν - Sector

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  - Shows up in differences in oscillation behavior between neutrinos and anti-neutrinos!

Searching for CP Violation in the ν - Sector

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

Phys. Rev. D64 (2001) 053003

Leading term

CP violating

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

“+” for antineutrino

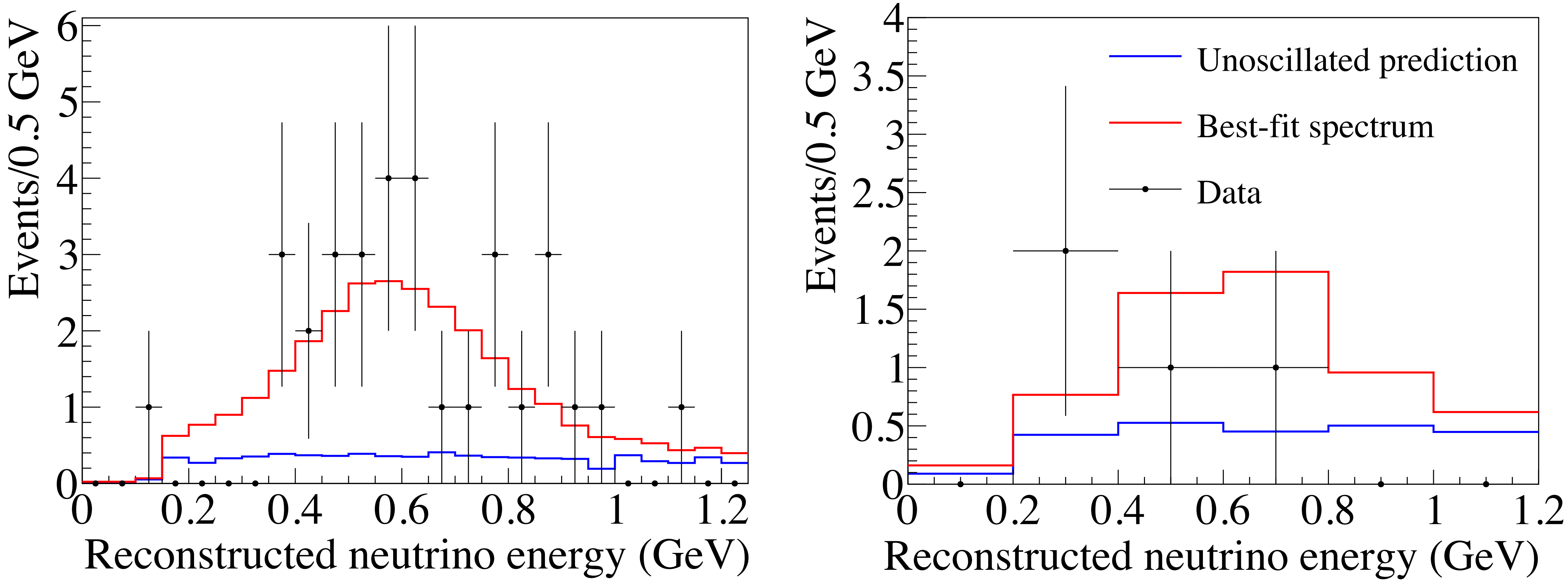
CP conserving

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

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

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

First Results from T2K



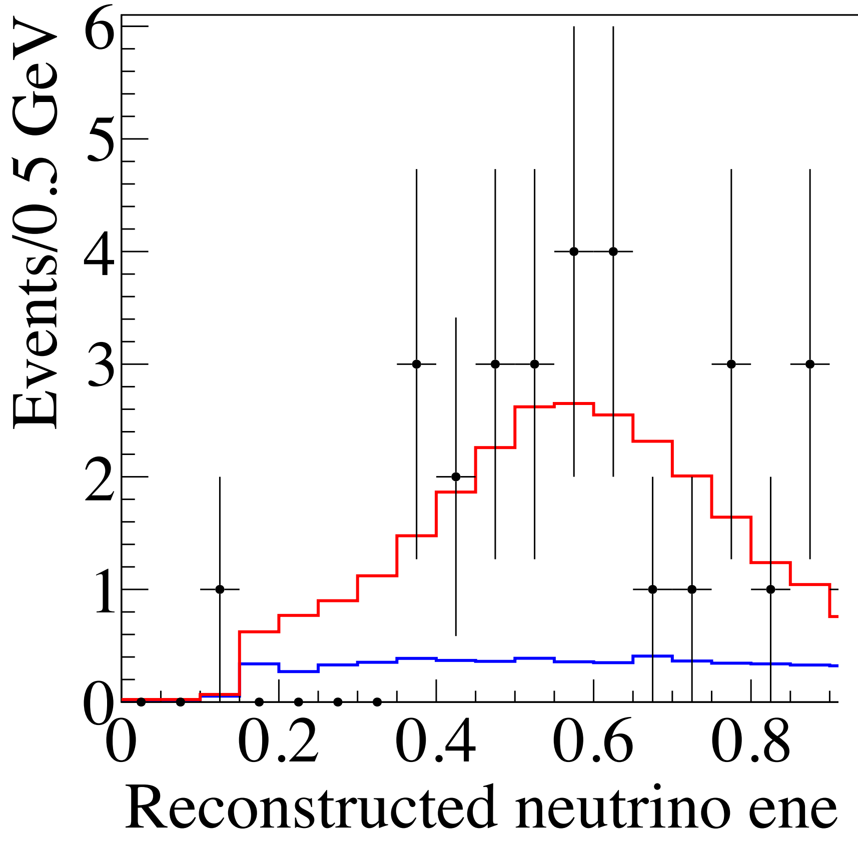
- Running both with neutrinos and anti-neutrinos: Observed less anti-ν_e than expected in any scenario: hints at maximal CP violation

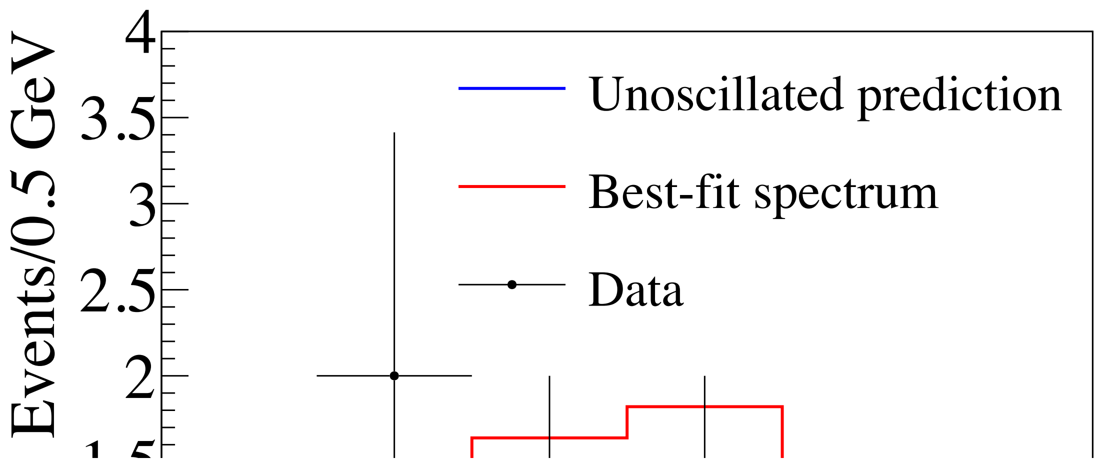
TABLE I. Number of ν_e and $\overline{\nu}_e$ events expected for various values of δ_{CP} and both mass orderings compared to the observed numbers.

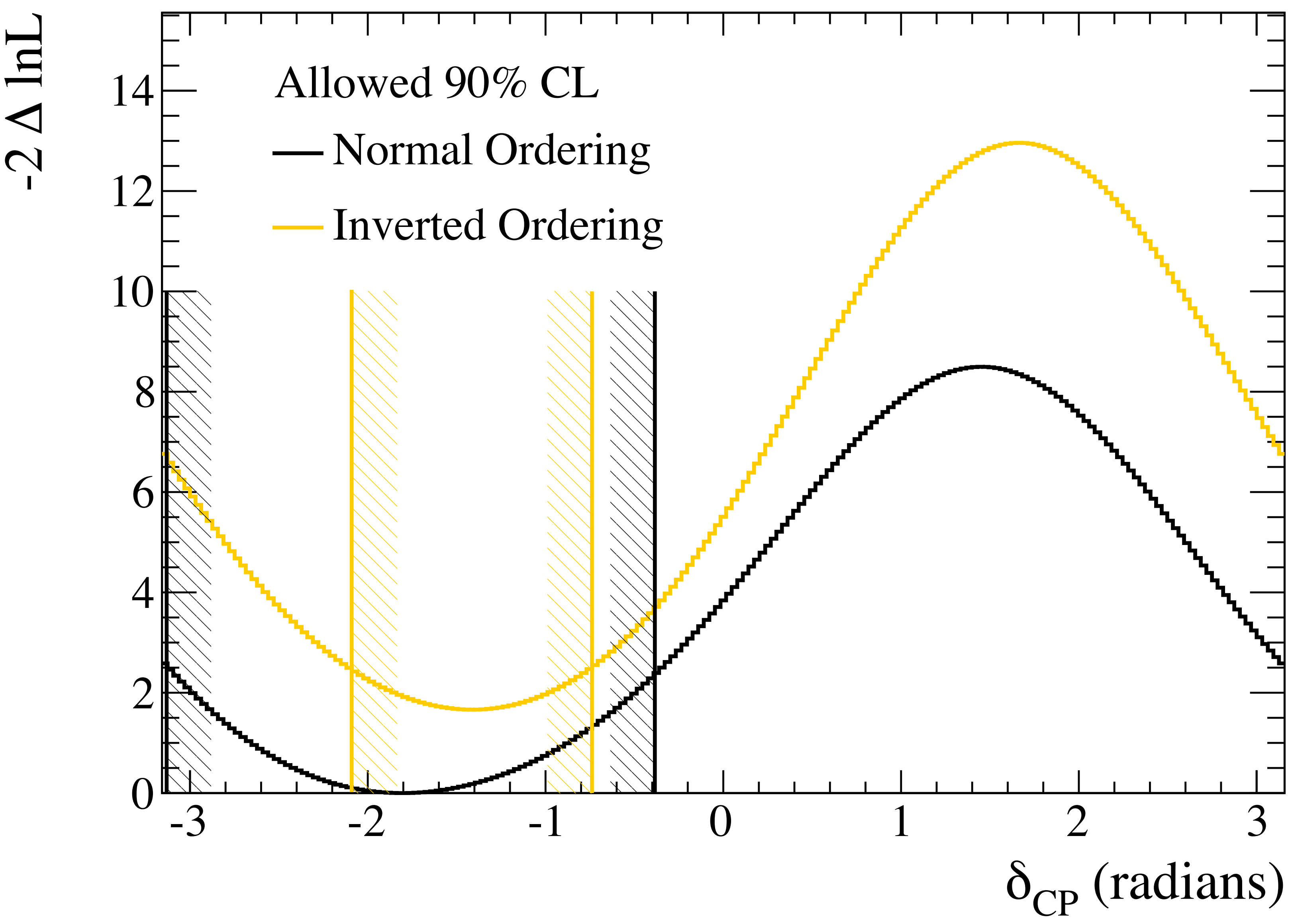
Normal	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = \pi/2$	$\delta_{CP} = \pi$	Observed
ν_e	28.7	24.2	19.6	24.1	32
$\overline{\nu}_e$	6.0	6.9	7.7	6.8	4

Inverted	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = \pi/2$	$\delta_{CP} = \pi$	Observed
ν_e	25.4	21.3	17.1	21.3	32
$\overline{\nu}_e$	6.5	7.4	8.4	7.4	4

First Results from T2K







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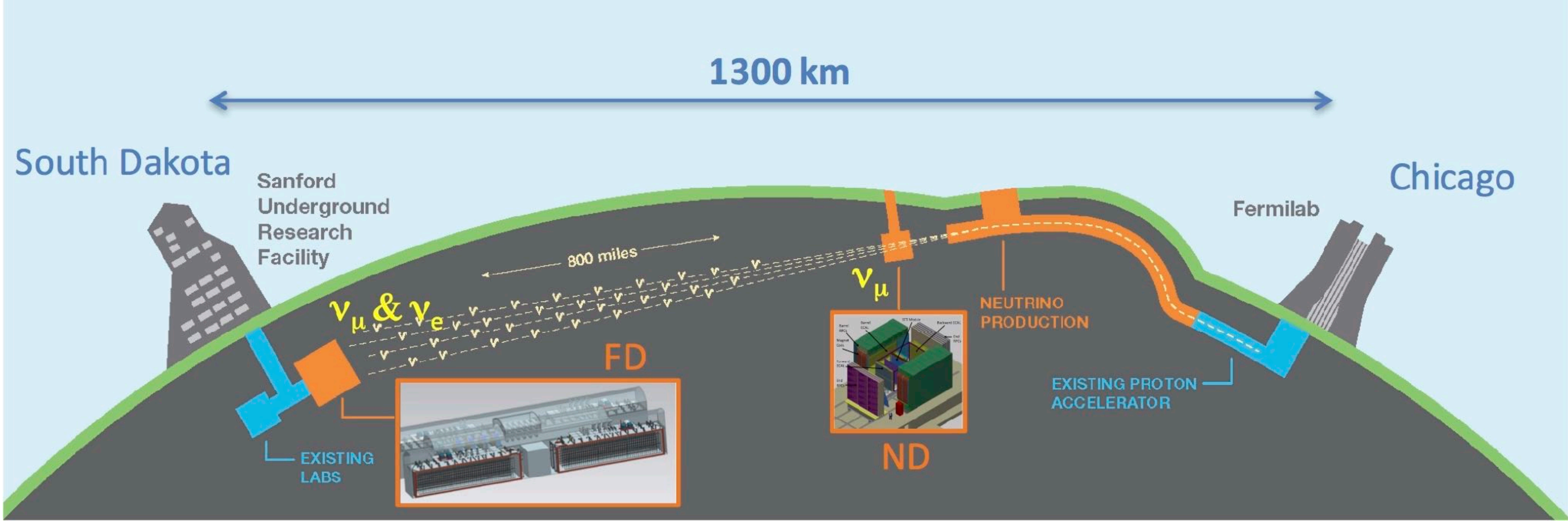
Future Measurements of CP Violation

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



- DUNE at Fermilab - to start taking data in 2026
  - x4 higher mean energy than T2K: longer baseline (good to constrain hierarchy)
- Also in discussion T2HK: Much larger water-Cherenkov detector in the beam from Tokai, same baseline as T2K

Future Measurements of CP Violation

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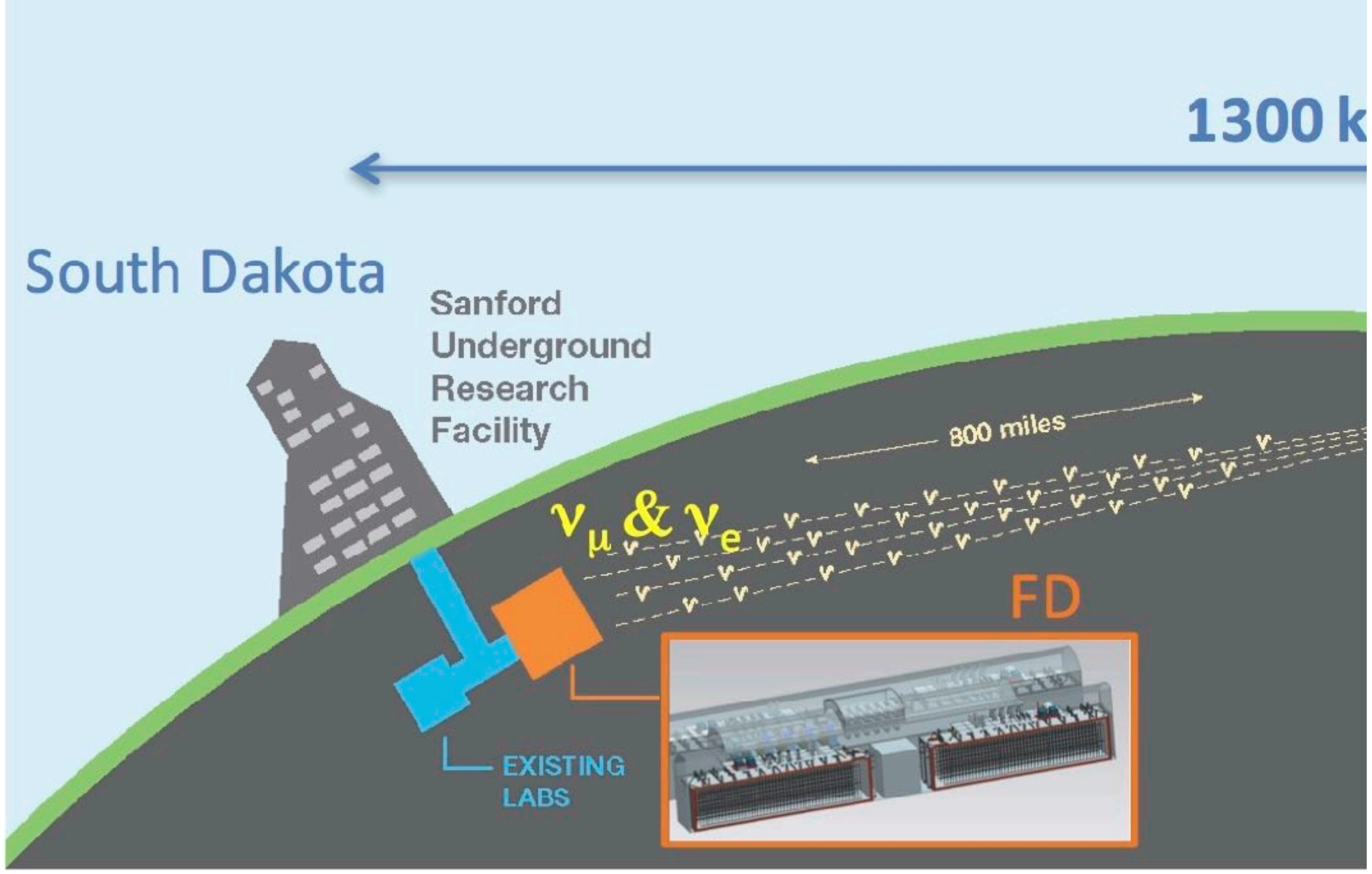
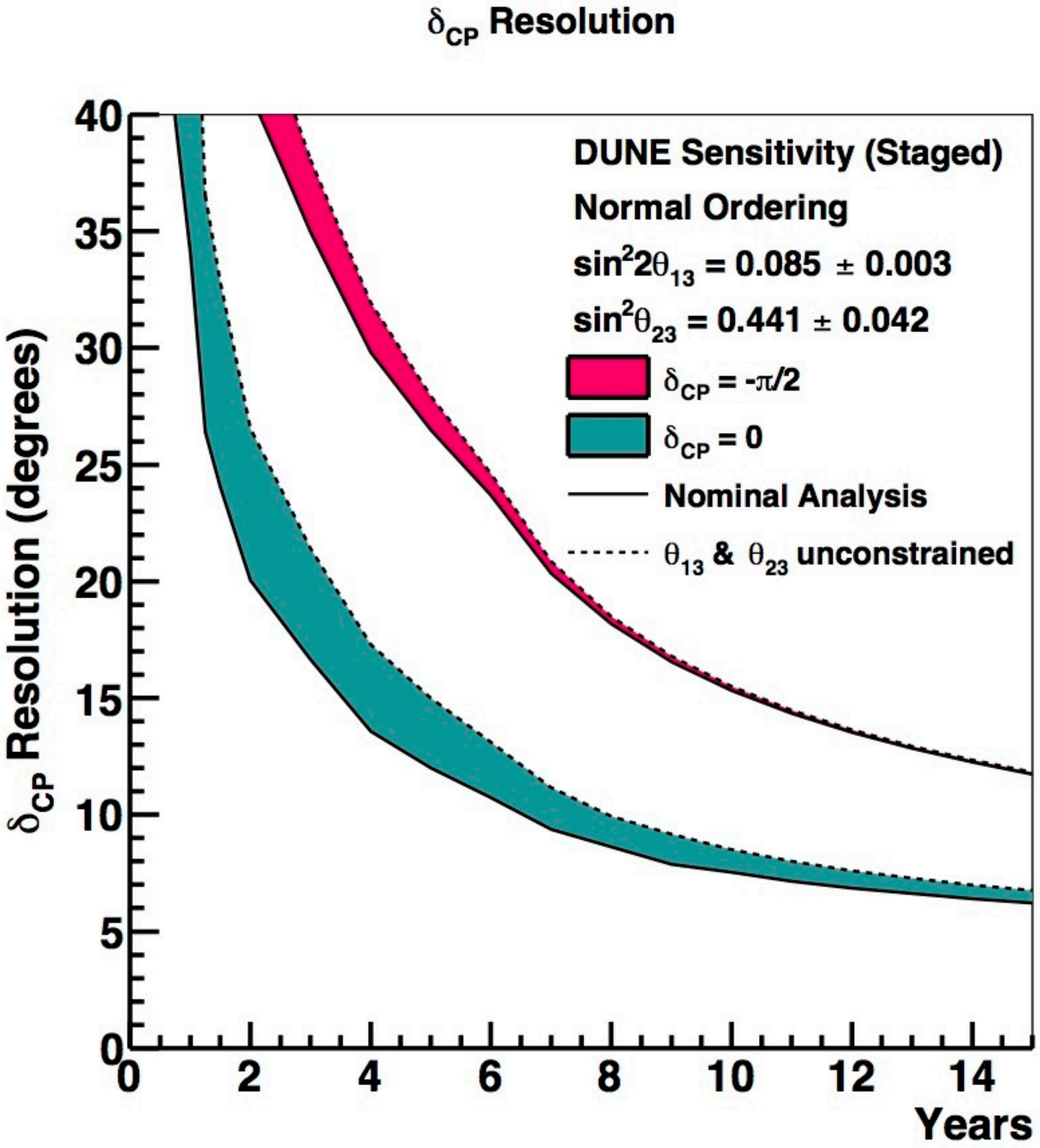
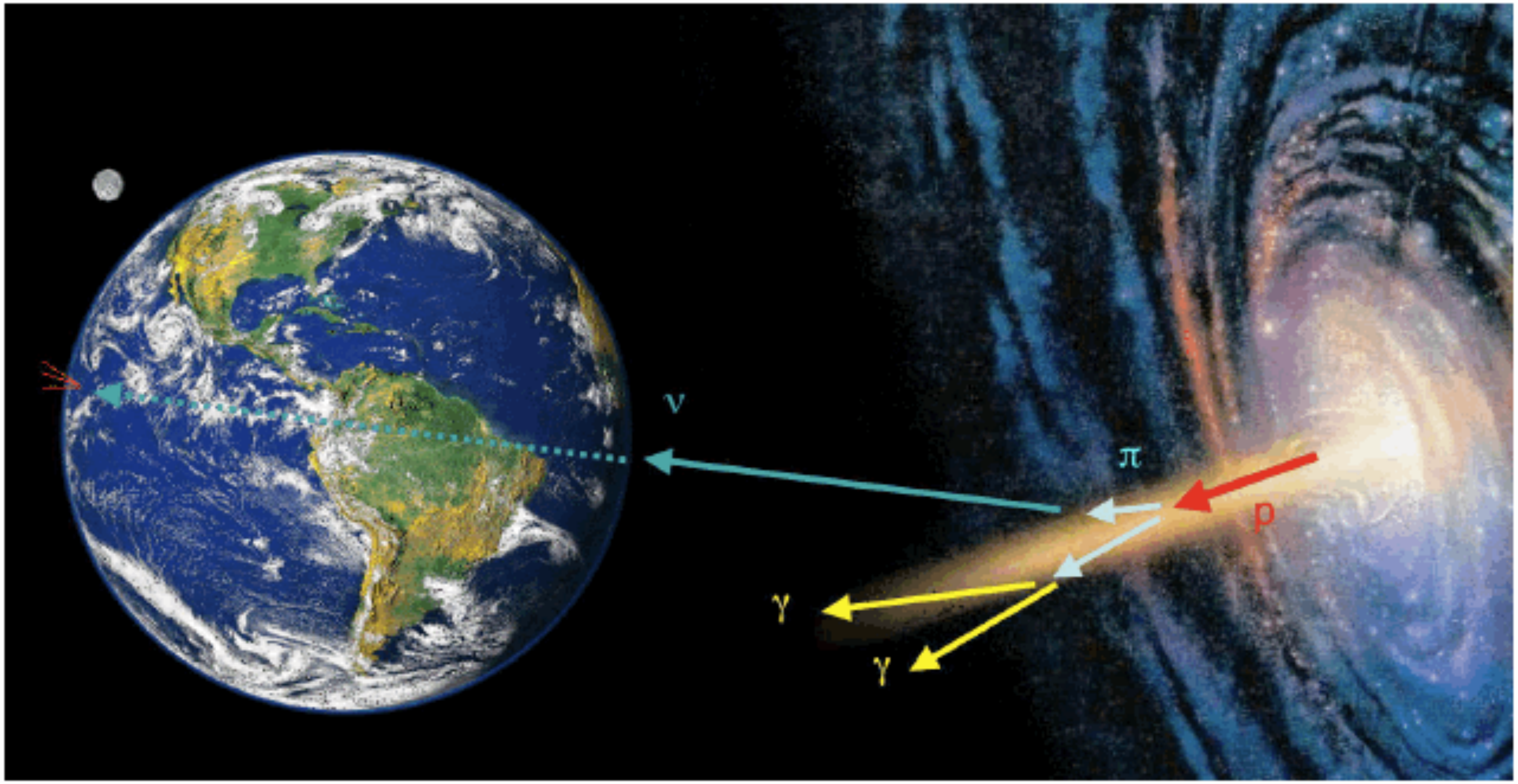




- DUNE at Fermilab - to start taking data in
  - x4 higher mean energy than T2K: longe
- Also in discussion T2HK: Much larger wat from Tokai, same baseline as T2K

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)

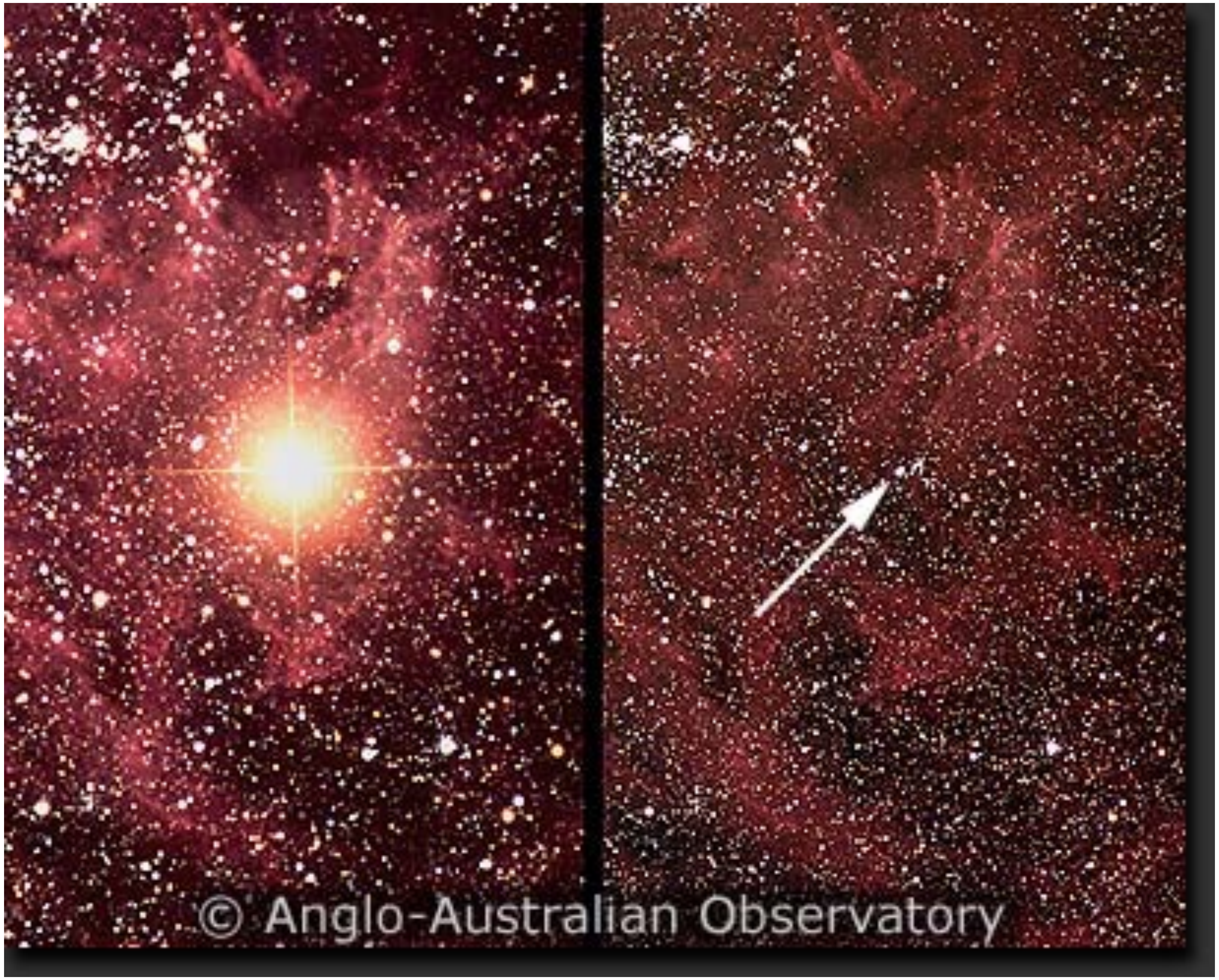
$$\gamma + \gamma \rightarrow e^+ + e^- \qquad\qquad e^+ + e^- \rightarrow \nu + \bar{\nu}$$

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

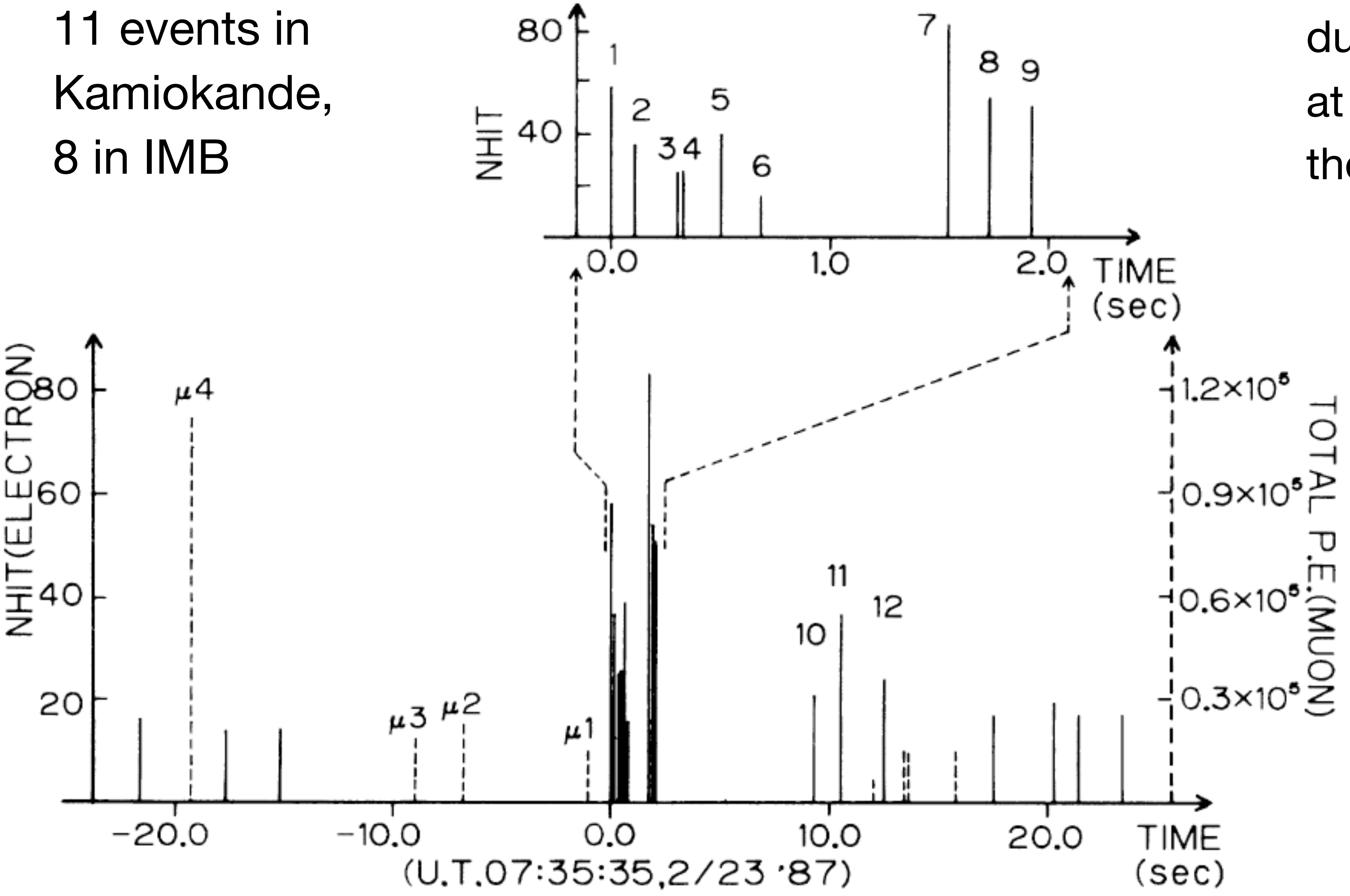

© Anglo-Australian Observatory

Kamiokande Signal

- A confirmed extraterrestrial signal

11 events in Kamiokande, 8 in IMB

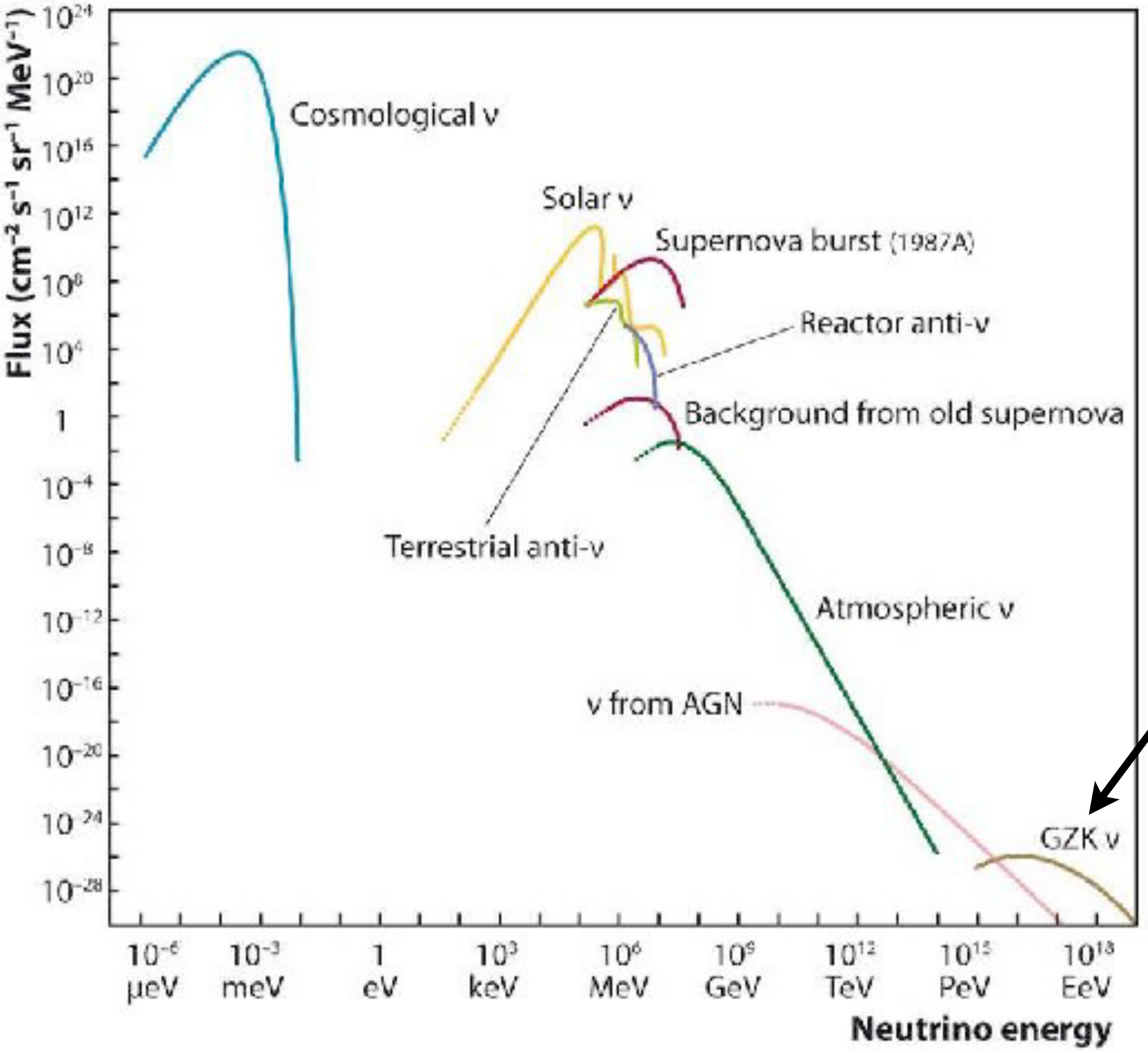
A neutrino burst with a duration of ~10 s, seen at the same time also in the IMB experiment



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

PRL 58, 1490 (1987)

Cosmic Neutrinos: Expectations



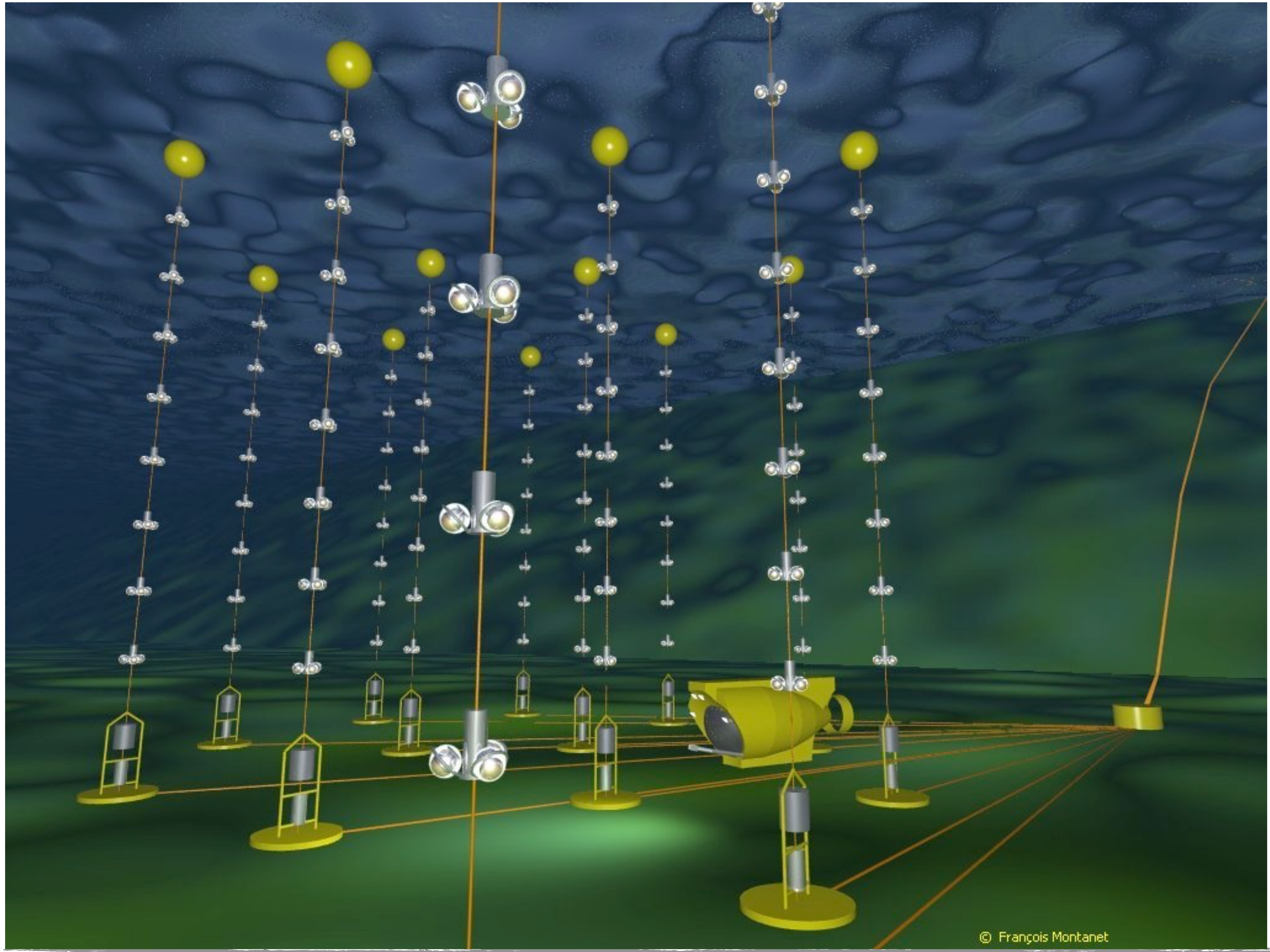
cosmogenic neutrinos: Produced in decays of pions from GZK events: Could give hints on sources and production mechanisms of highest-energy cosmic rays

in principle a “guaranteed discovery” with enough sensitivity

Detectors for Neutrino Astronomy

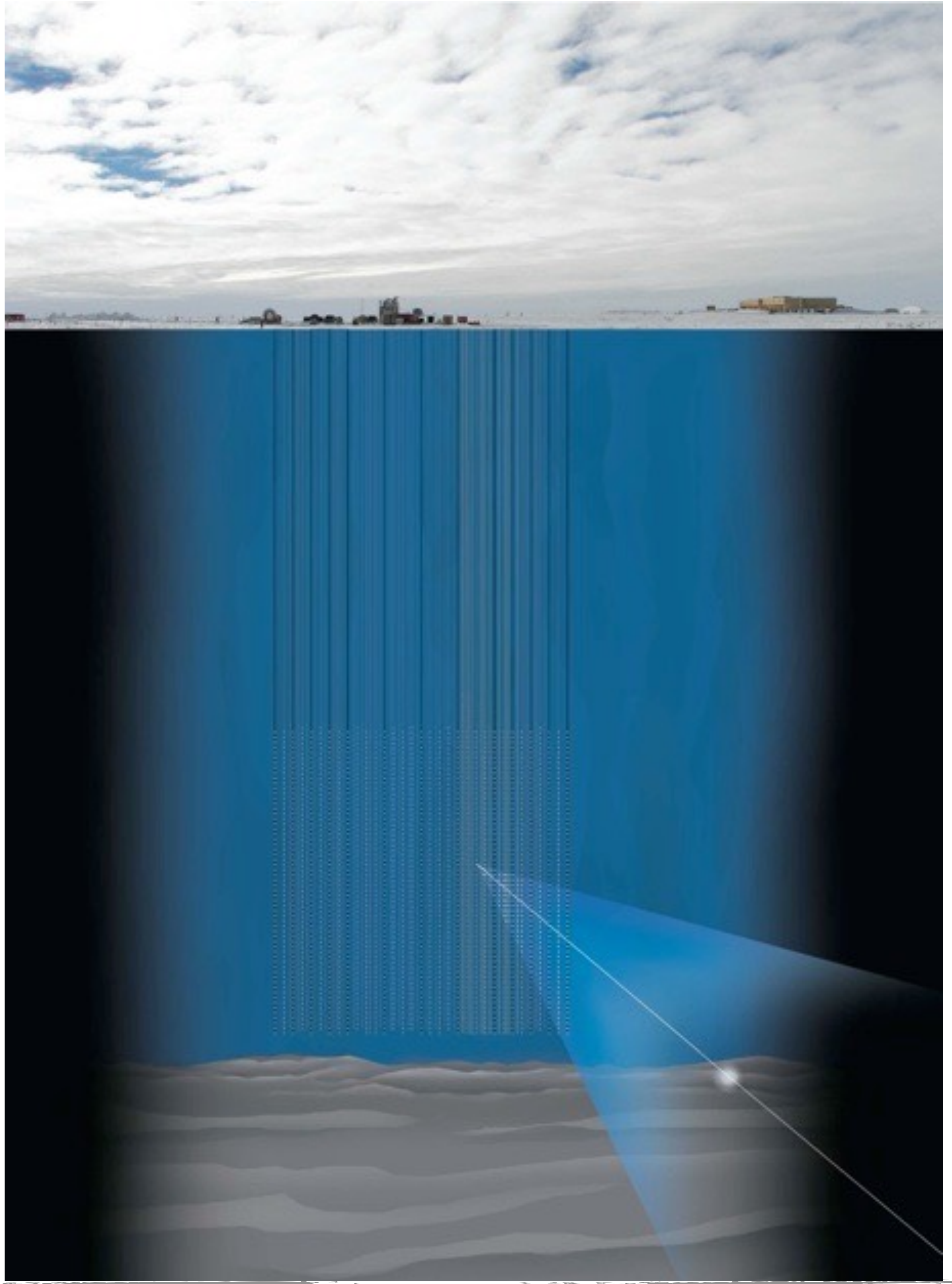
- Different detection techniques, depend on energy and sensitivity
- Energies in the TeV - PeV range:
  - Cherenkov detectors: large signal, relatively low energy threshold, requires a high sensor density due to light absorption
    - Amanda/IceCube: Antarctic ice as Cherenkov medium
    - Antares/Baikal/KM3NeT: Tiefes Meer/See - Wasser als 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

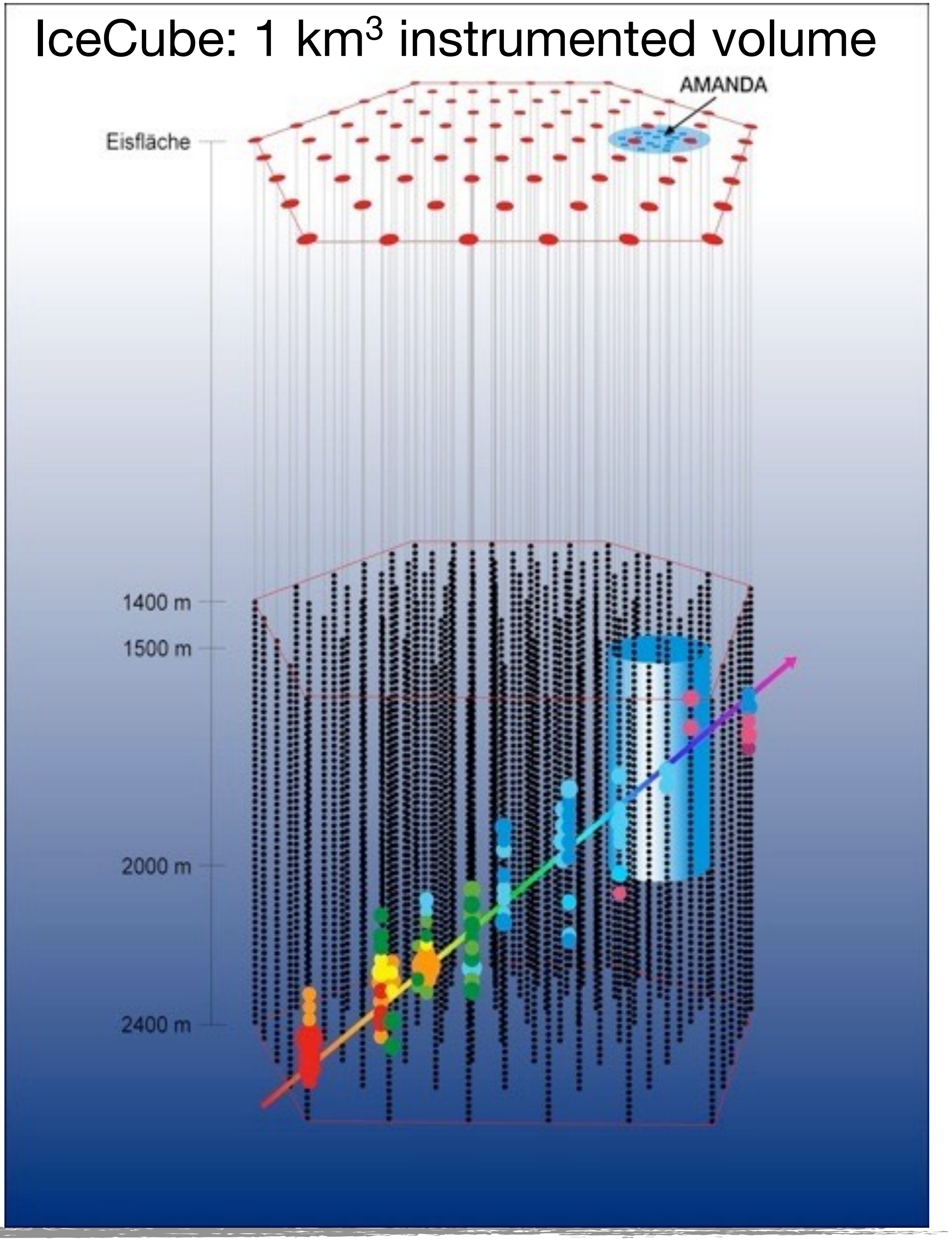
Antares


© François Montanet

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

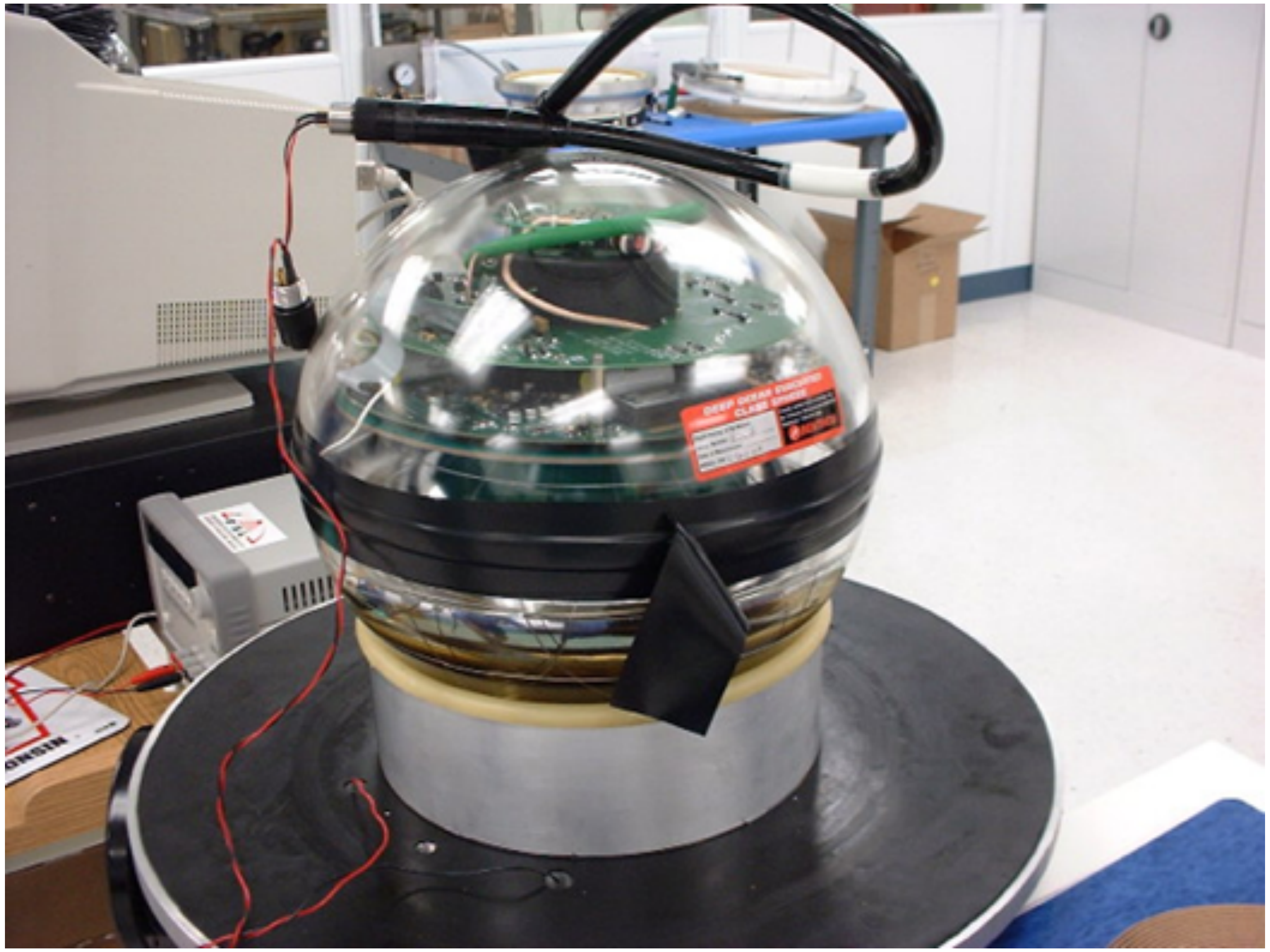
Amanda/IceCube




IceCube: 1 km^3 instrumented volume

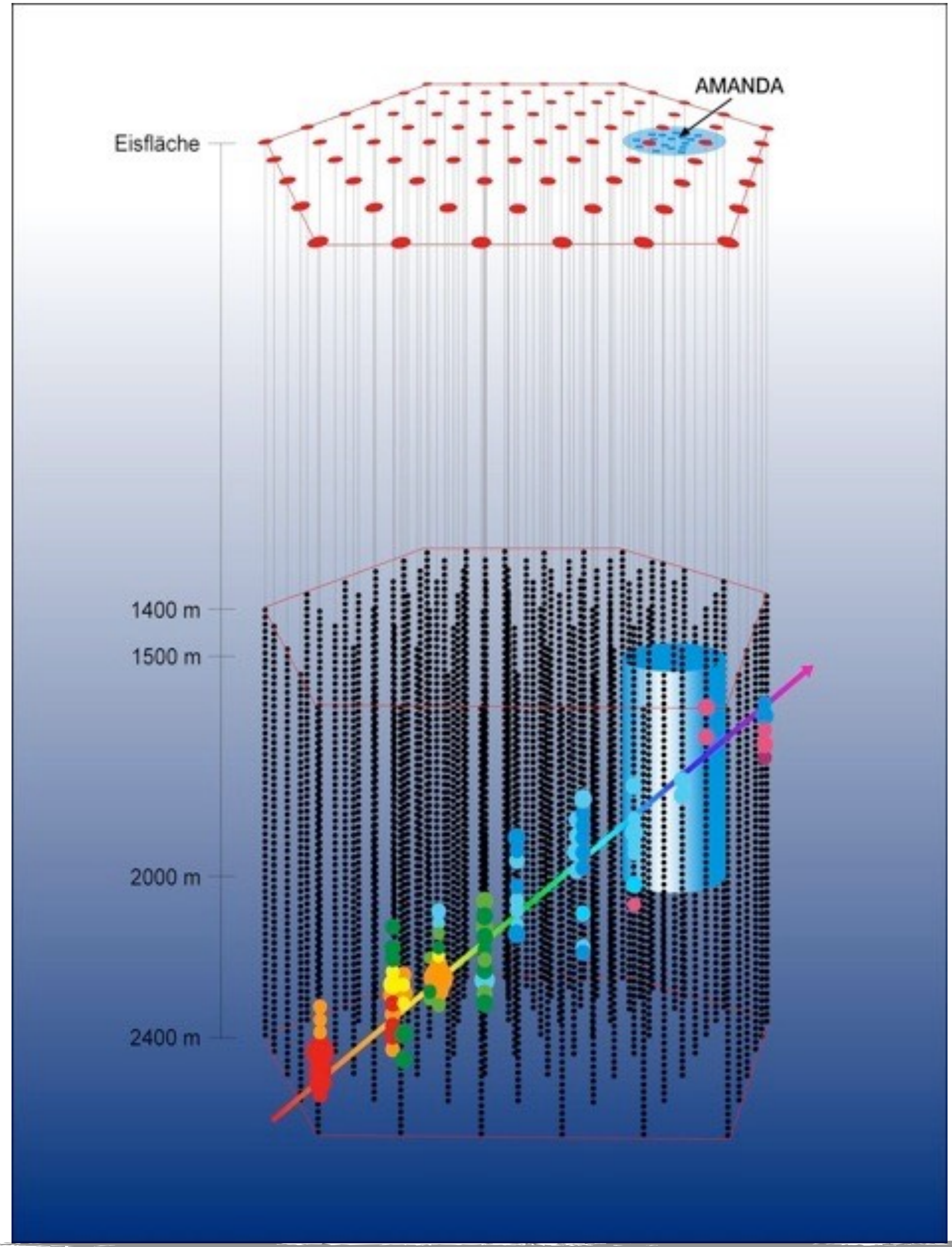
Amanda/IceCube: Neutrinos at the South Pole

Amanda/IceCube: Neutrinos at the South Pole



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

IceCube Event

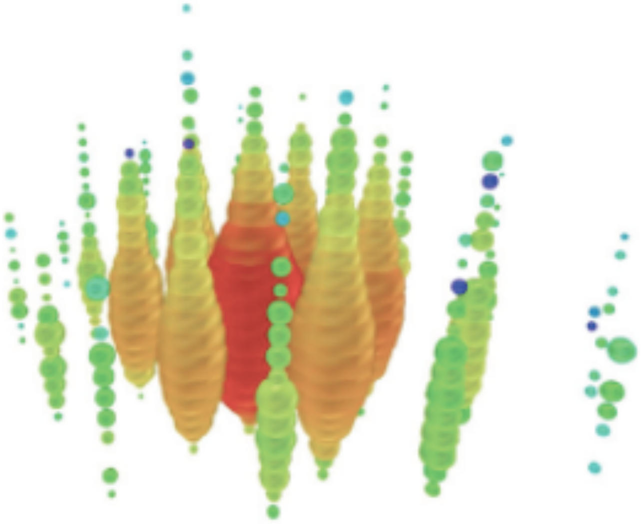


- Arrival time of light at individual detectors allows the determination of the muon direction and with that the direction of the neutrino

Highest Energies - First Observation 2012

- IceCube has observed two events:

"Ernie"



1.14±0.17 PeV

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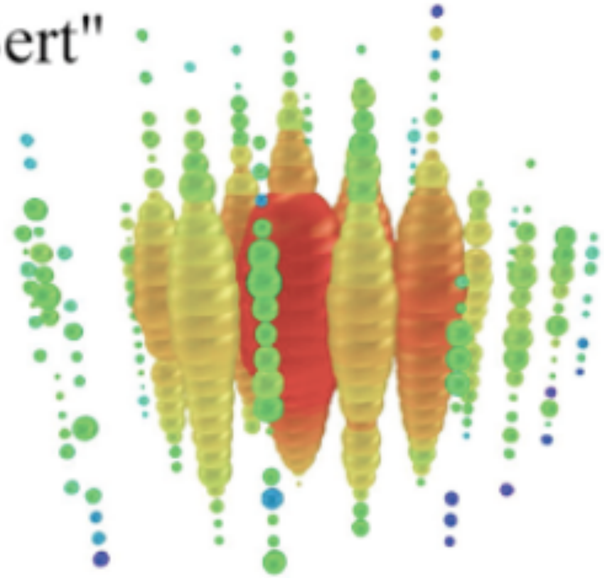
"Bert"



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

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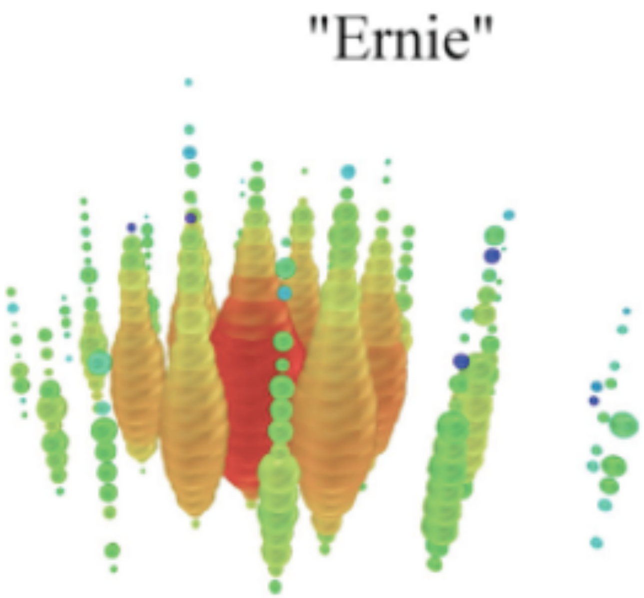

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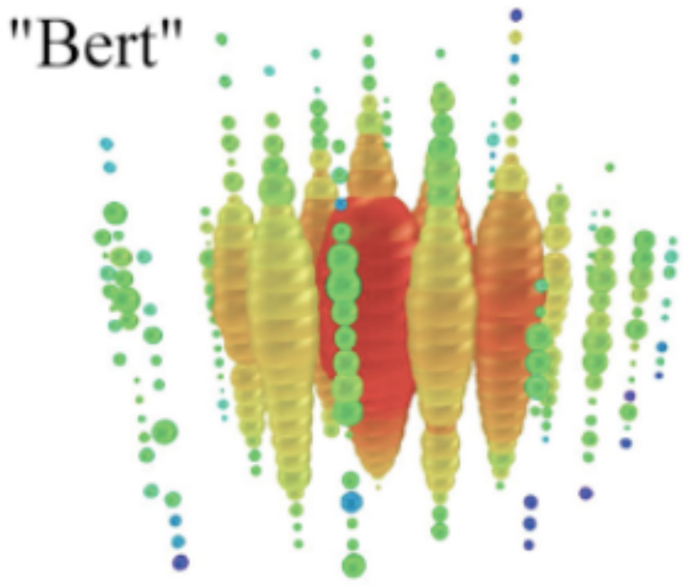

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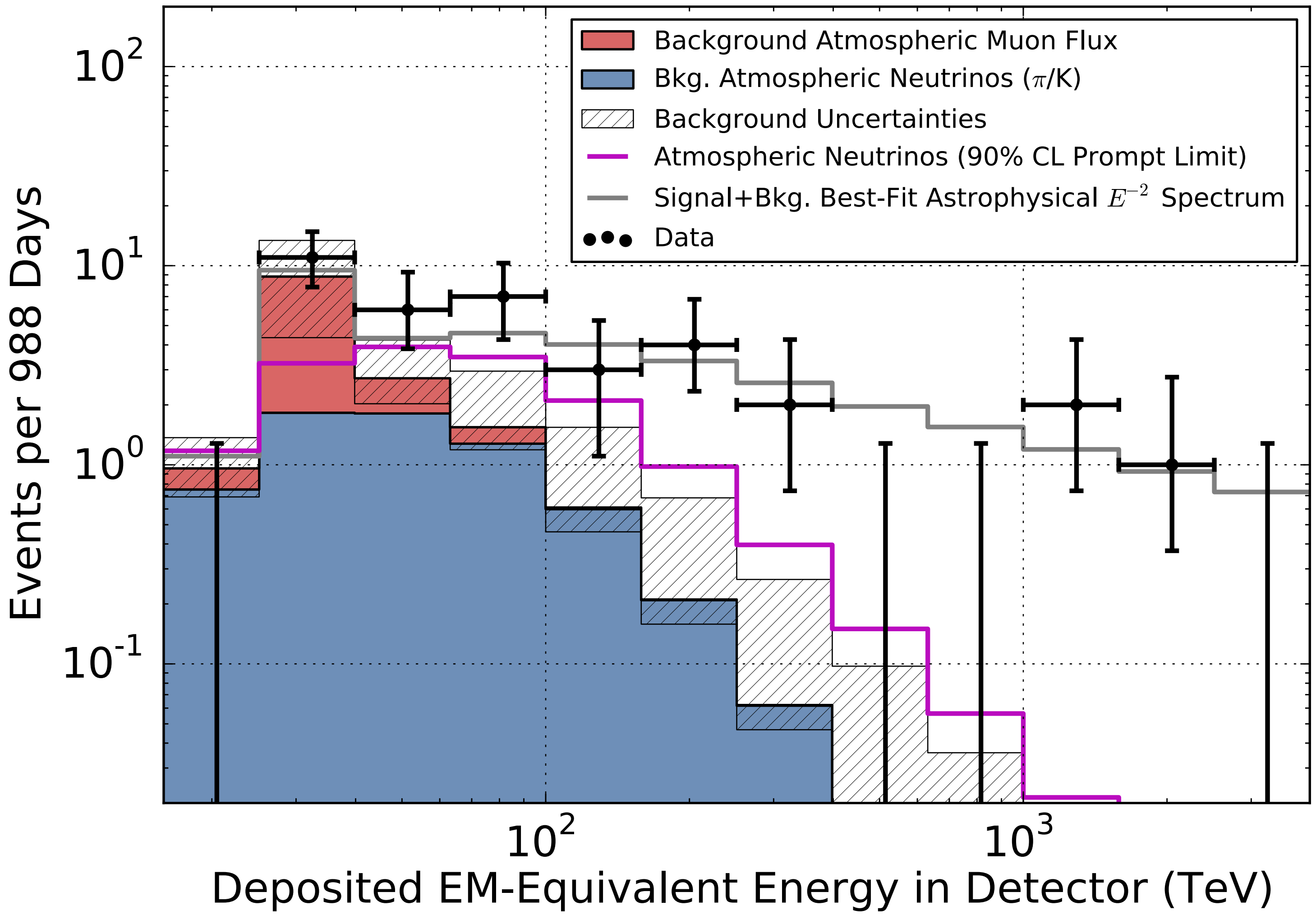
Now even an event at 2 PeV, in total 37 events > 30 TeV

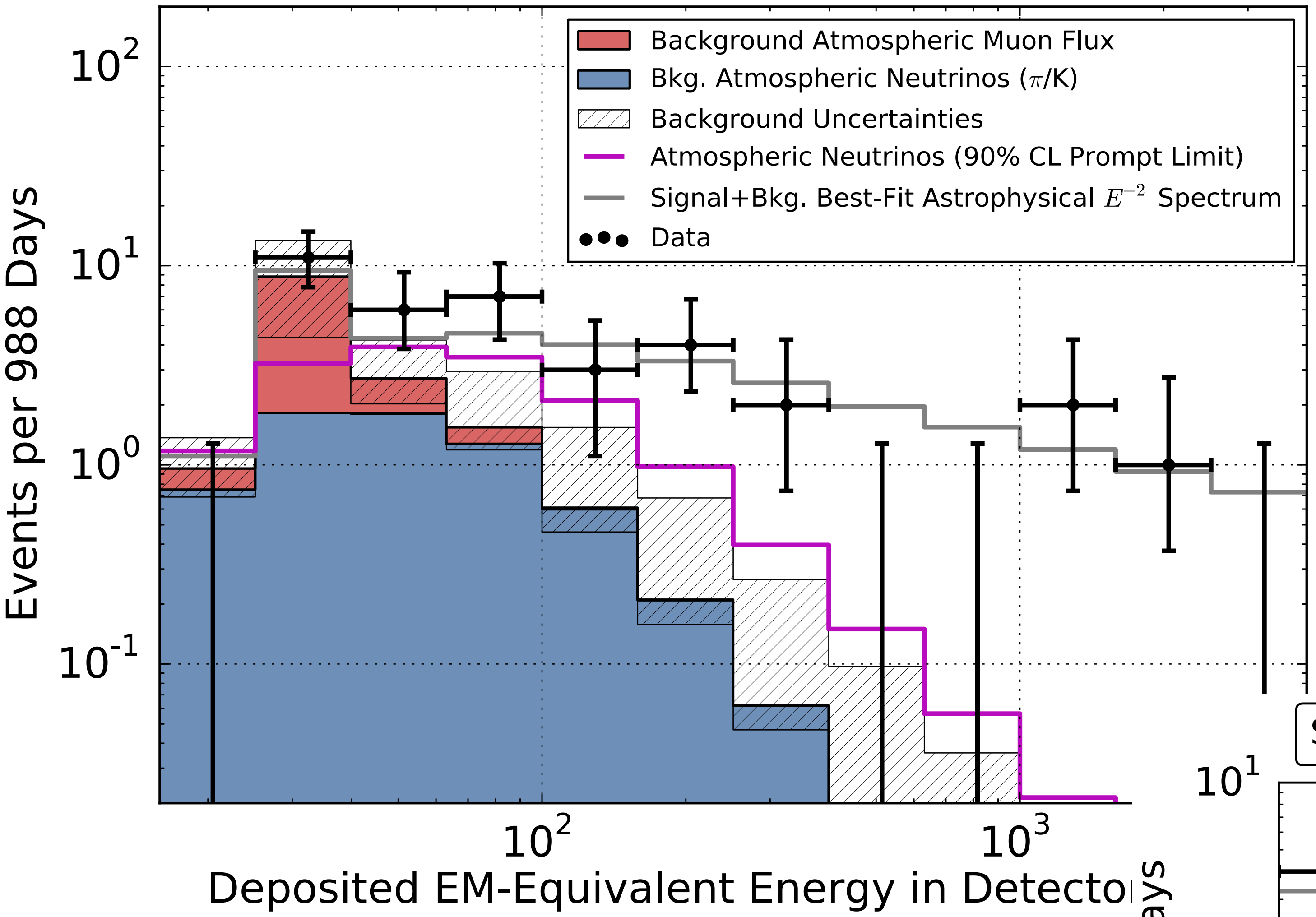
Neutrinos at Highest Energies



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

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

Neutrinos at Highest Energies



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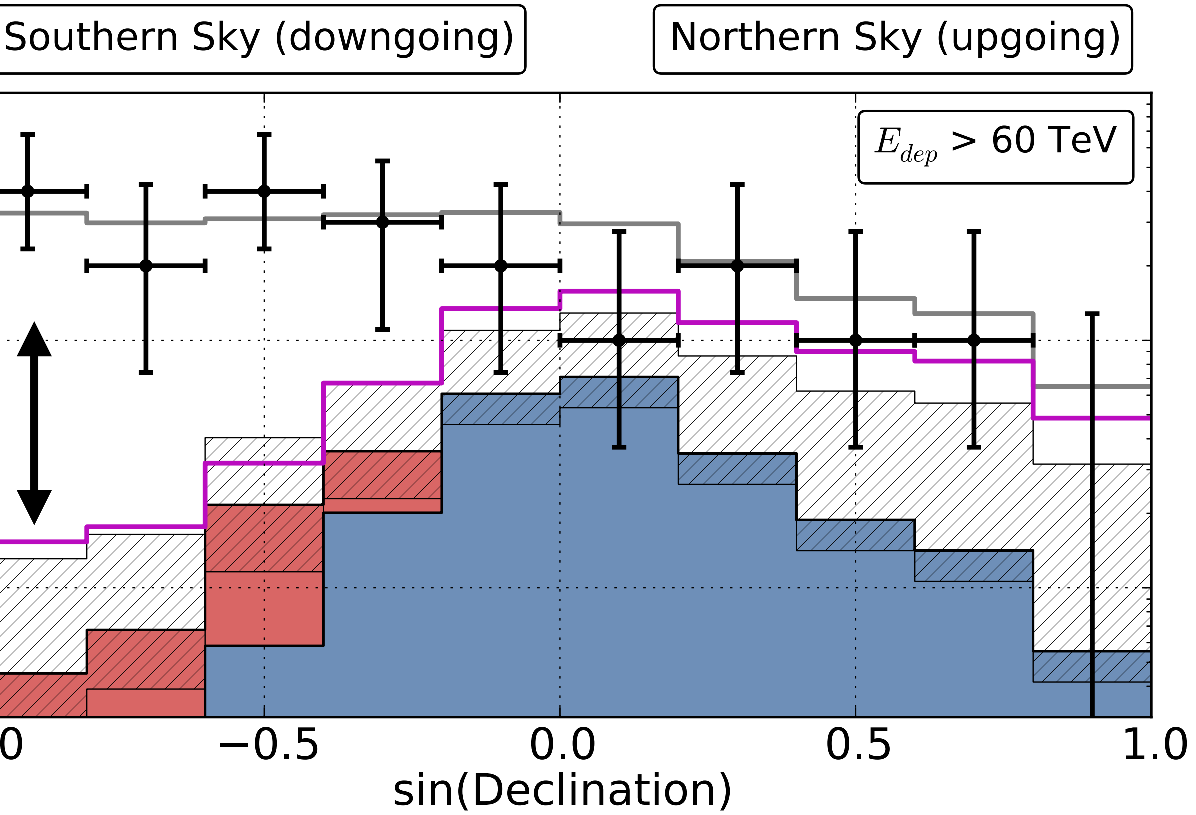
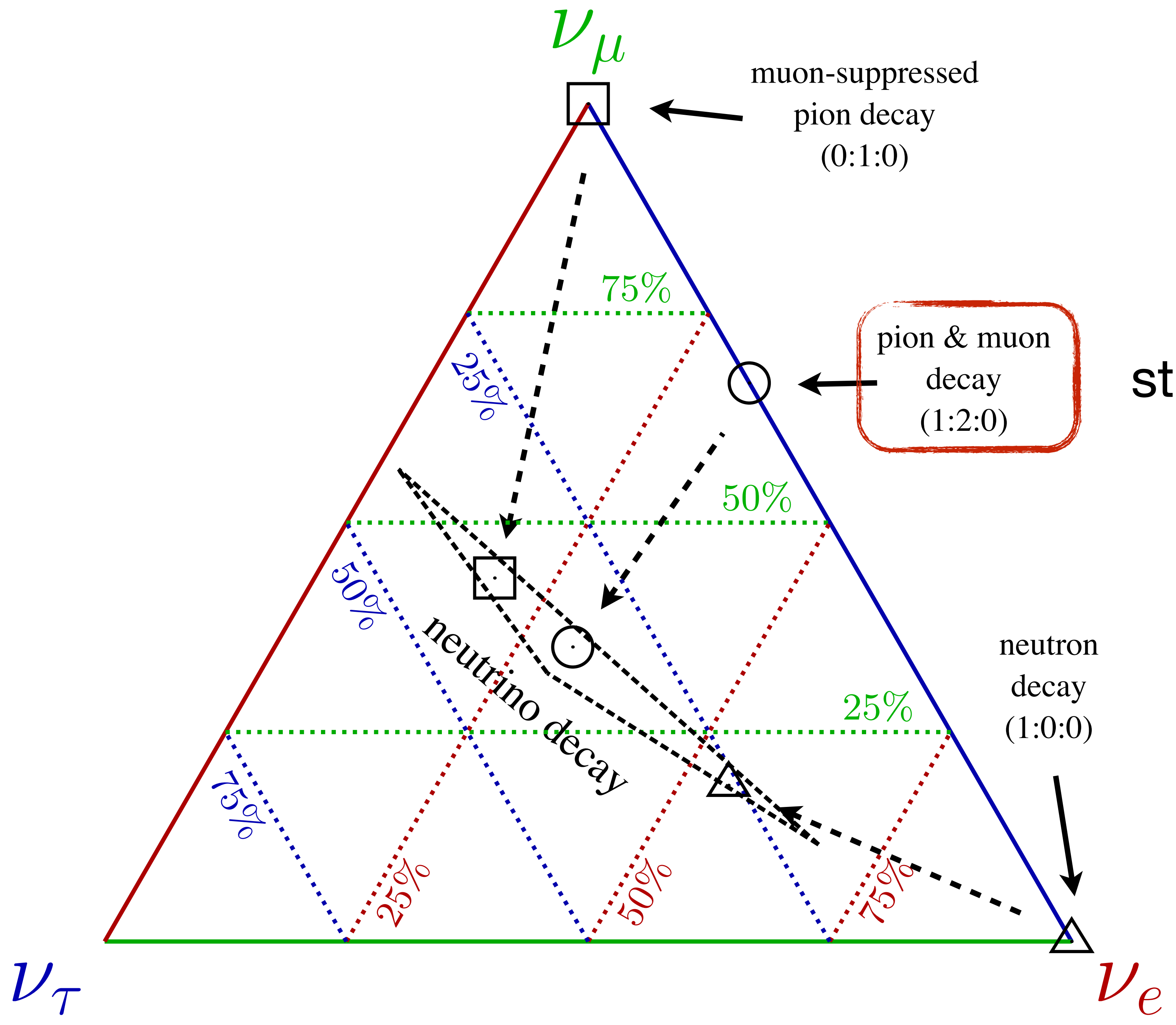


Effectivity of the exclusion of atmospheric neutrinos

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

Cosmic Neutrino Sources

- Standard scenario: pion decay (ν_μ), then muon decay ($\nu_\mu + \nu_e$):
  Source composition (1 : 2 : 1) - evolves due to neutrino oscillations



standard scenario

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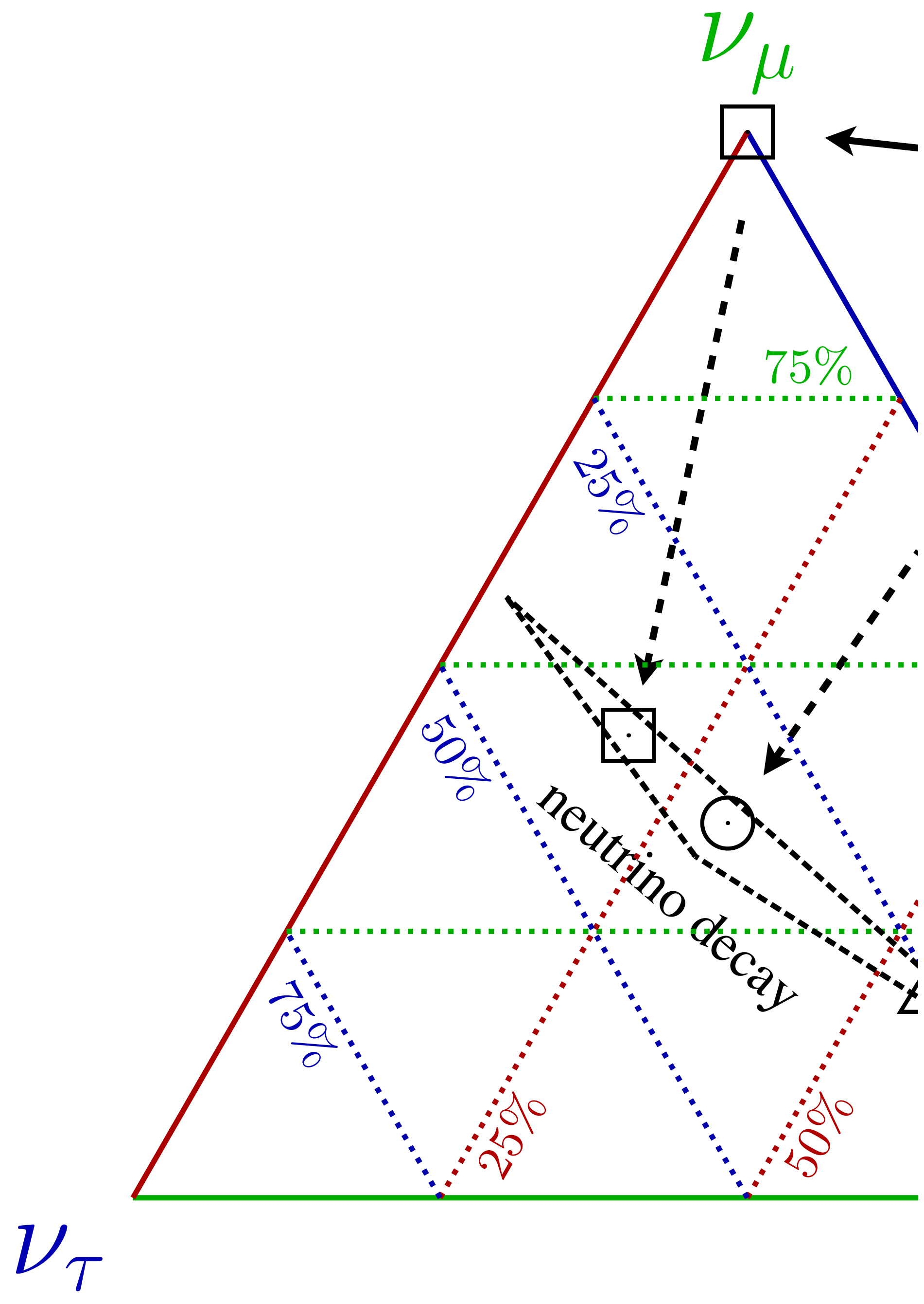

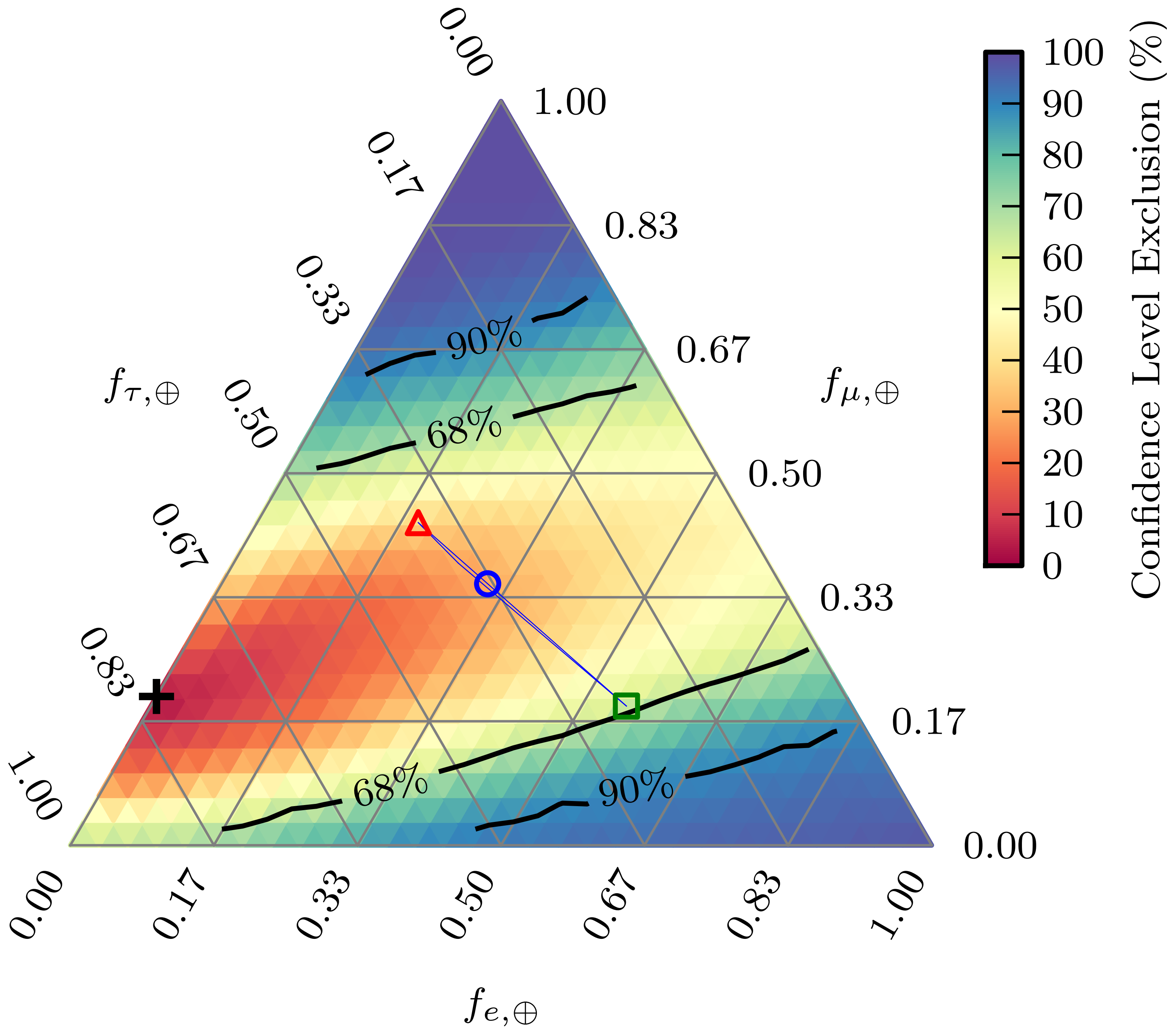

Summary

- Neutrinos are the lightest particles in the Standard Models
- Neutrinos have mass: they oscillate - There are (at least) three different mass eigenstates, that are not identical with the flavor eigenstates

- Neutrino oscillations have been observed with atmospheric and solar Neutrinos
- Accelerator experiments have confirmed the atmospheric measurements, reactor experiments have confirmed the solar measurements
- Accelerator measurements of the angle θ_{13} agree with reactor results - θ_{13} is surprisingly large: Offers the possibility to search for CP violation with new experiments
- First extraterrestrial signal: SN1987A
- Up to now no sources identified for highly energetic cosmic neutrinos, but first intriguing events have been observed

‣ Currently a very active field, improvements and new results expected!

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Next Lecture: 19.06., “Neutrinos II”, S. Bethke

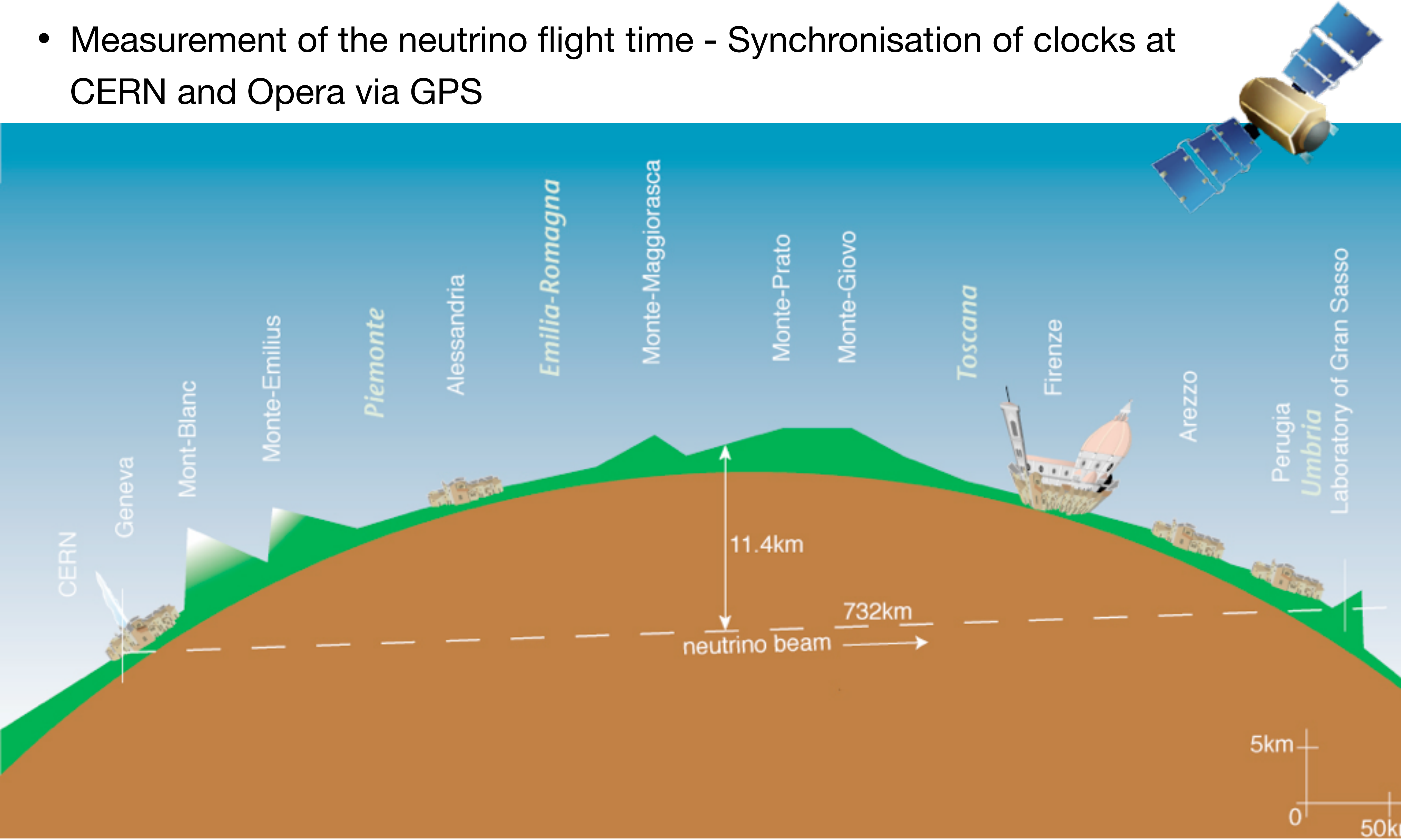
Frank Simon (fsimon@mpp.mpg.de)

Lecture Overview

24.04.	Introduction & Accelerators
01.05.	**Holiday - No Lecture**
08.05	Cosmic Accelerators
15.05.	Detectors
22.05.	The Standard Model
29.05.	QCD and Jets
05.06.	**Holiday - No Lecture**
12.06.	Neutrinos I
19.06.	Neutrinos II
26.06	**No Lecture**
03.07.	Cosmic Rays I
10.07.	Cosmic Rays II
17.07.	Precision Experiments
24.07.	Dark Matter, Dark Energy & Gravitational Waves

Now History: Neutrino Speed

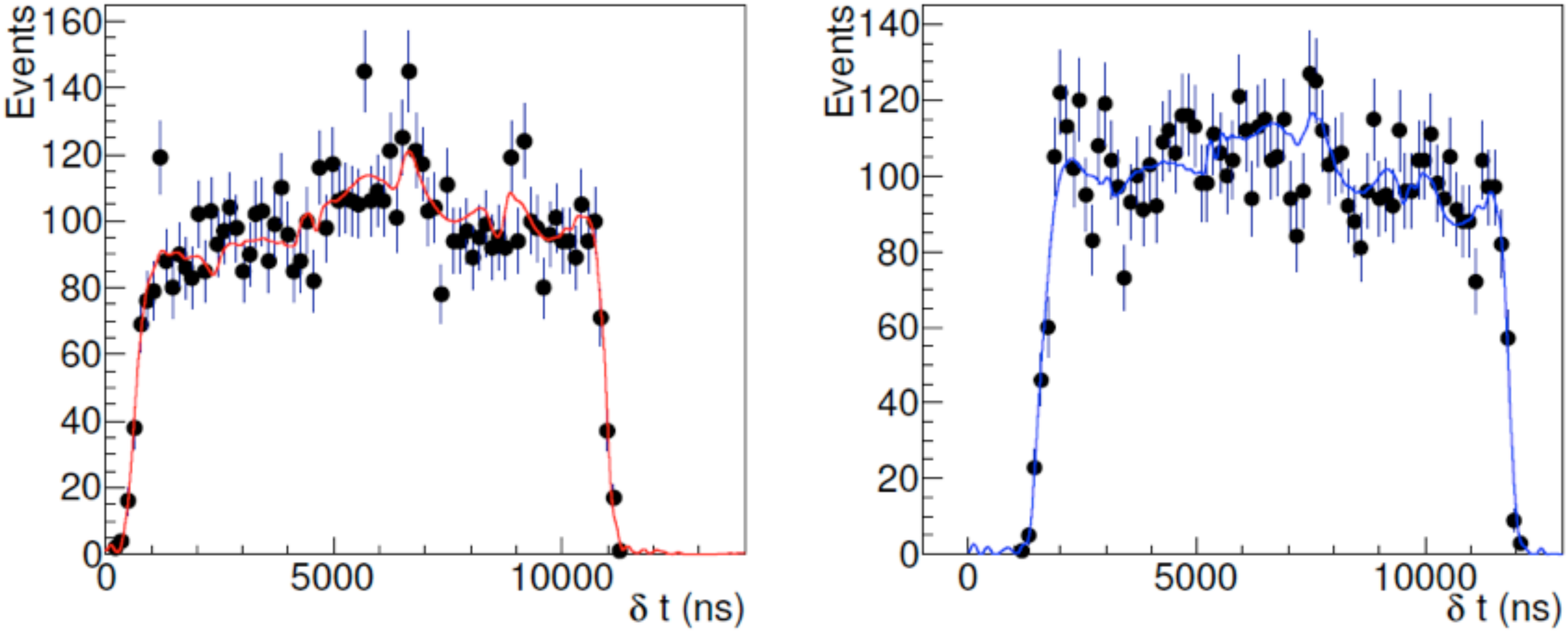
- Measurement of the neutrino flight time - Synchronisation of clocks at CERN and Opera via GPS



First Attempt - Spectacular Result

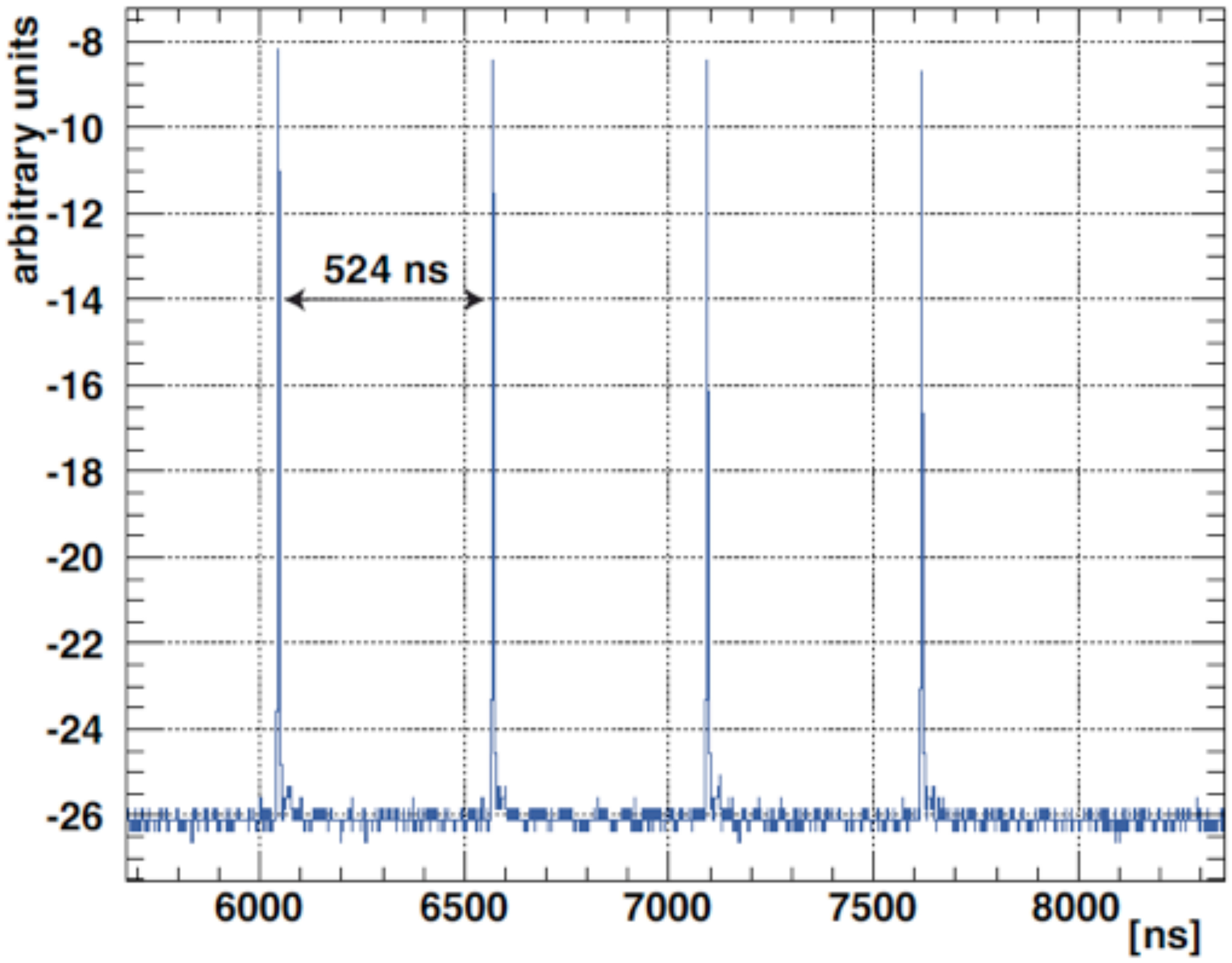
- September 2011: Opera observes, that the neutrinos are 60 ns too fast (with an uncertainties of 10 ns).

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!



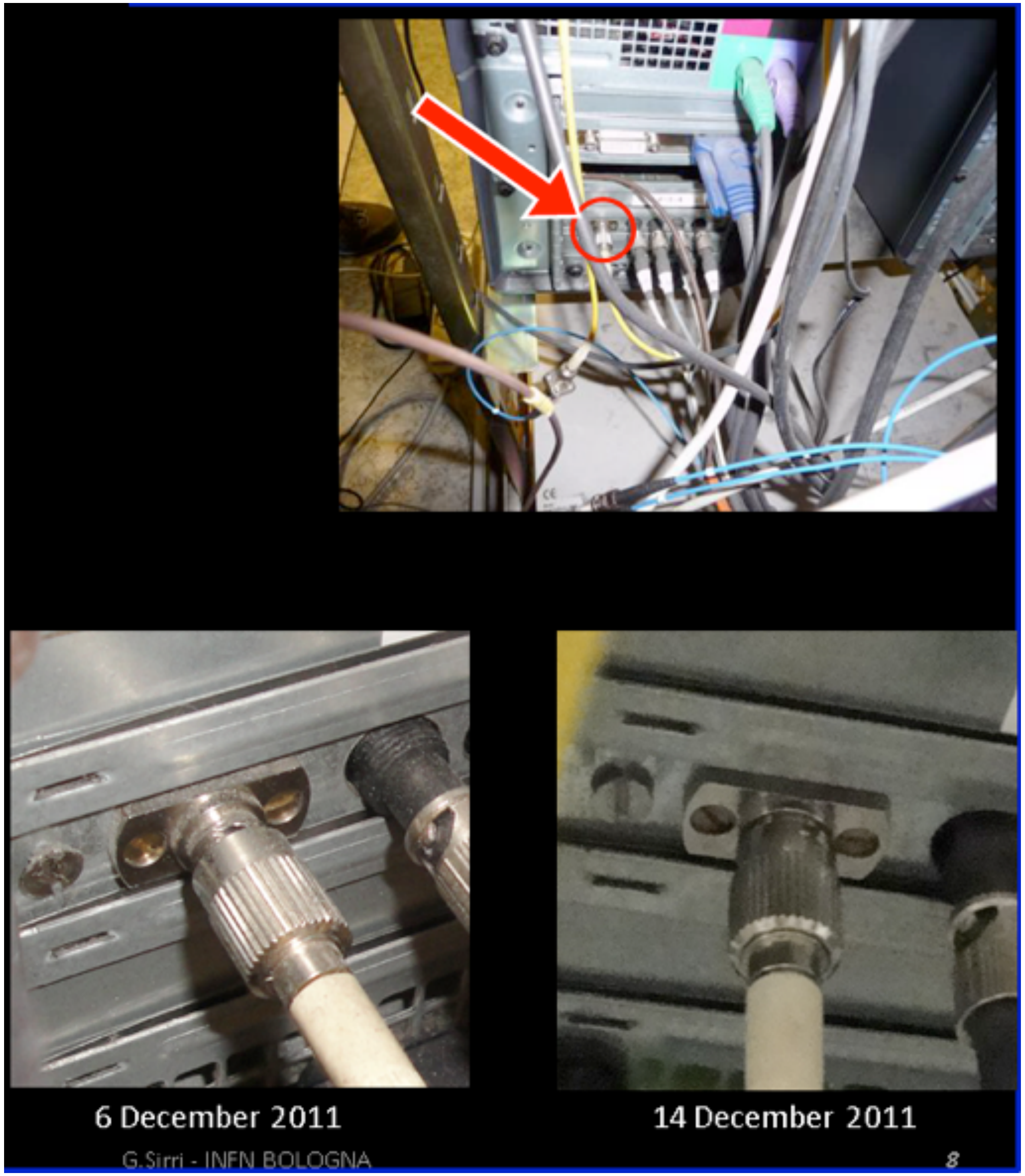
Confirms original results: beam structure as cause excluded

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...



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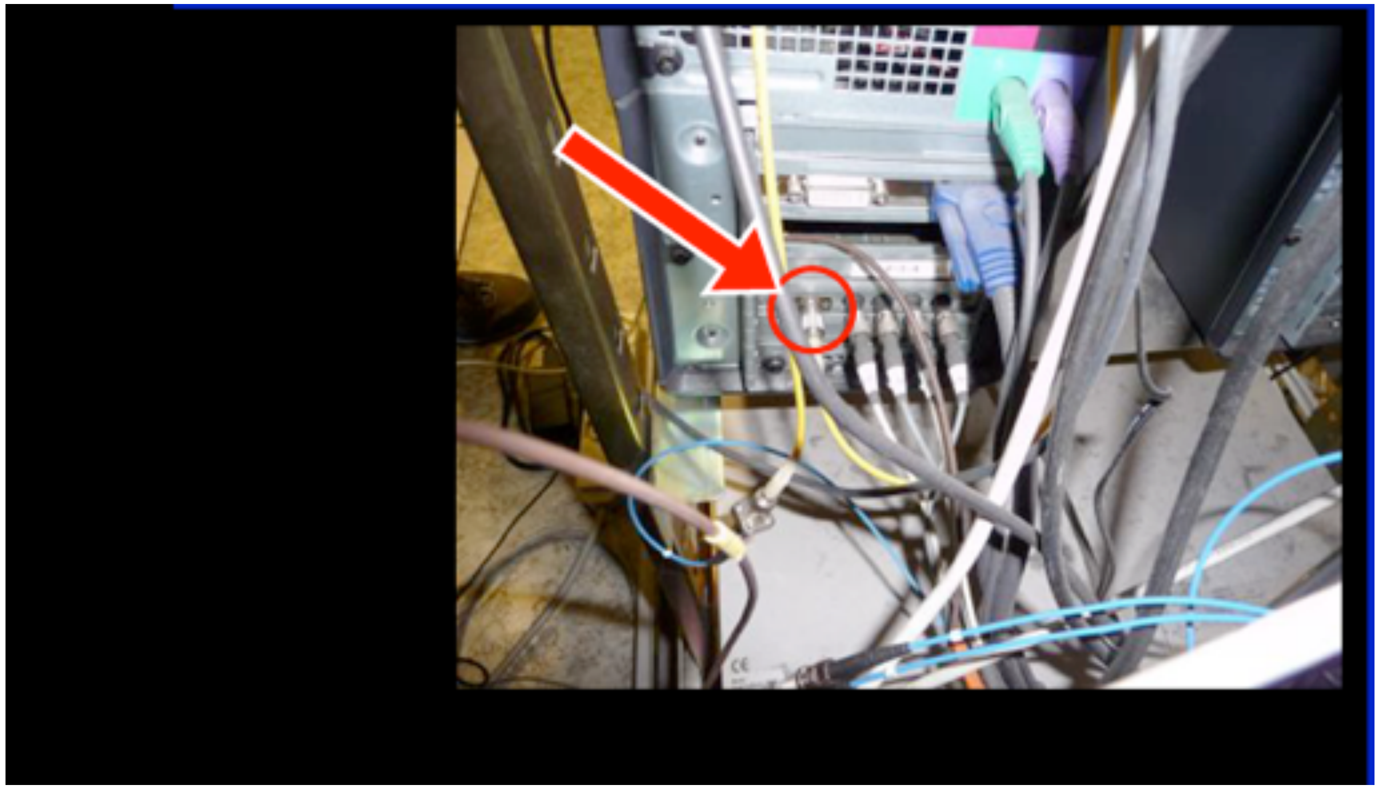

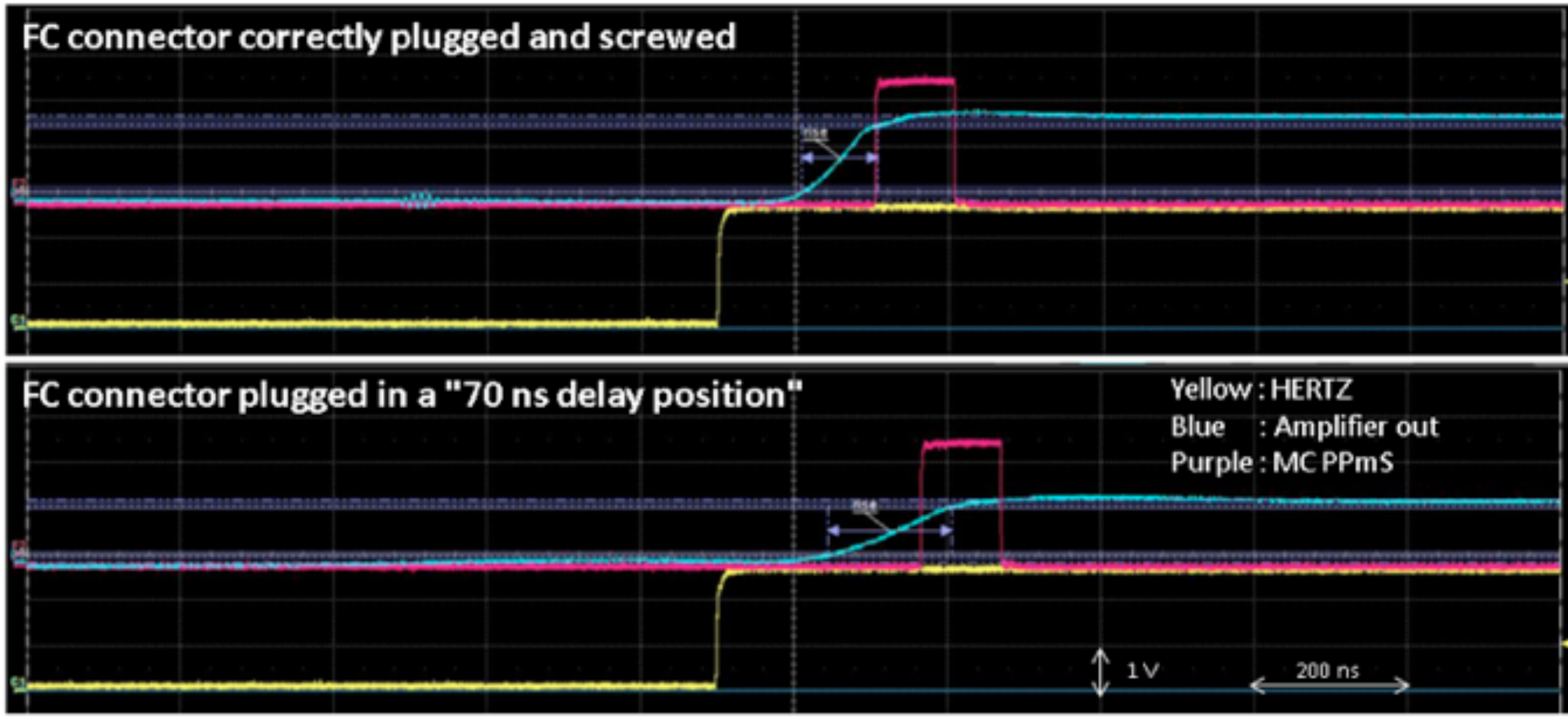

Now: The time of flight is bang on, within a few ns!