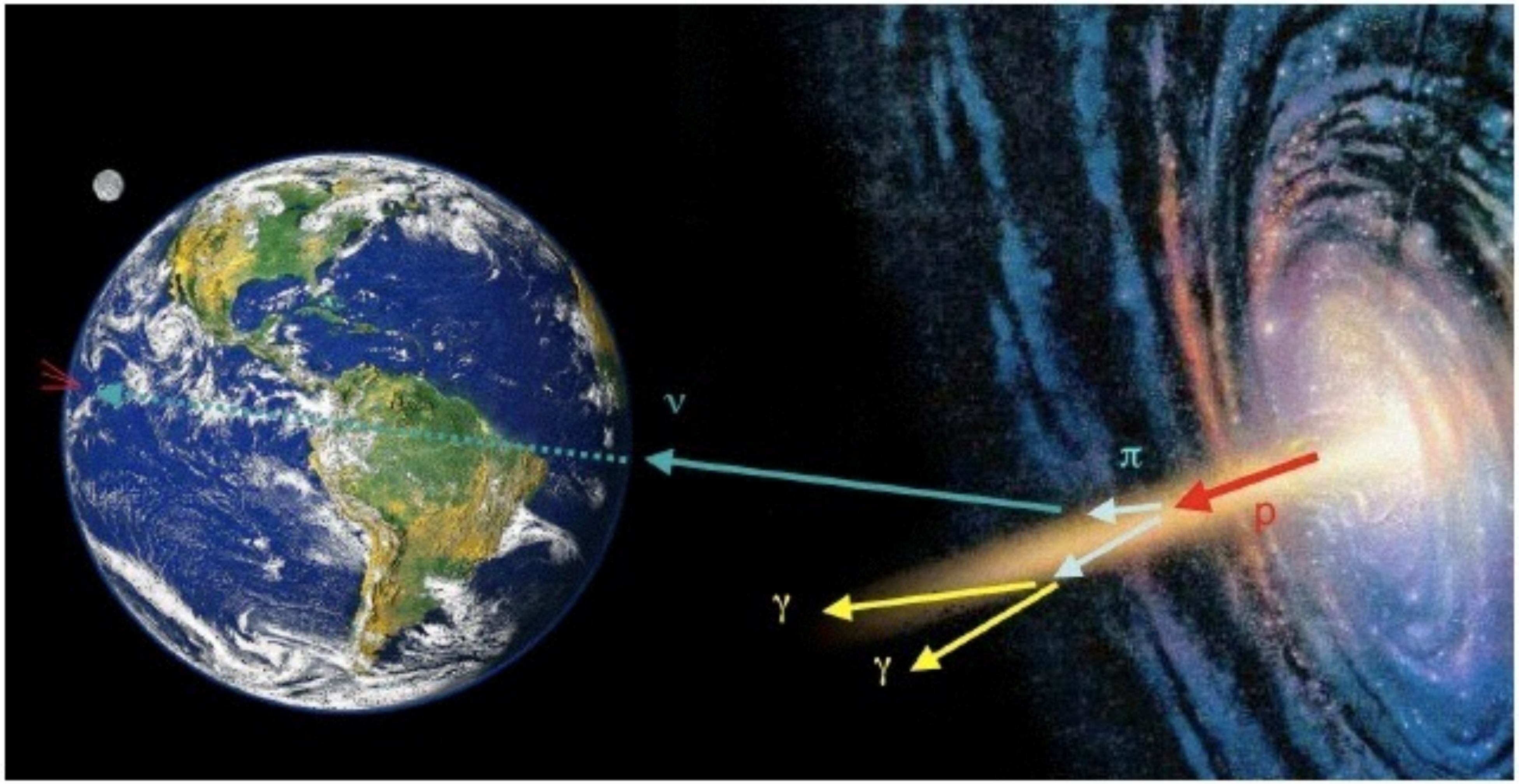
Teilchenphysik mit kosmischen und mit erdgebundenen Beschleunigern



11. Neutrinos I - Atmospheric, Accelerator and Cosmic Neutrinos

04.07.2016

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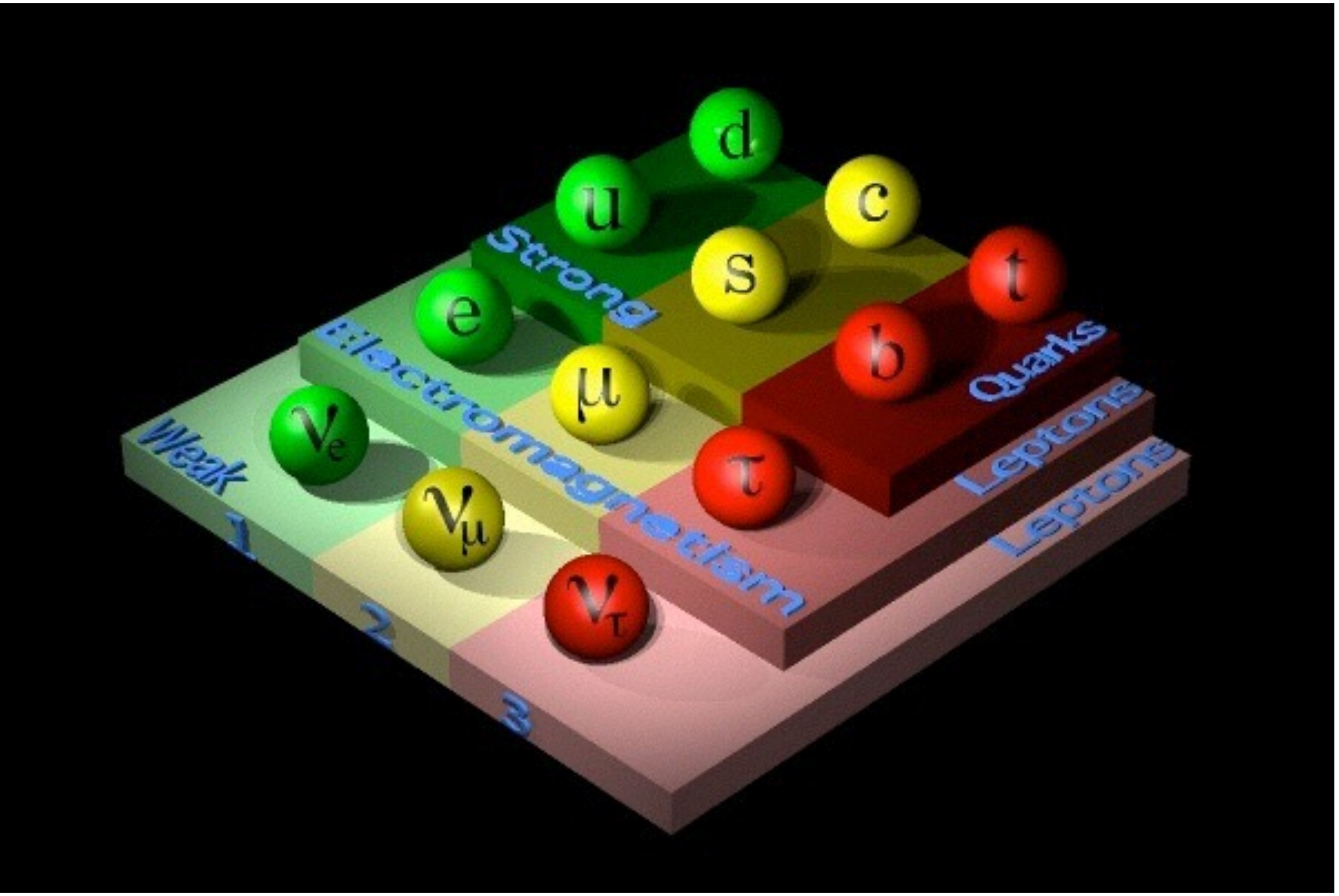
Neutrinos: Time Line I

- 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

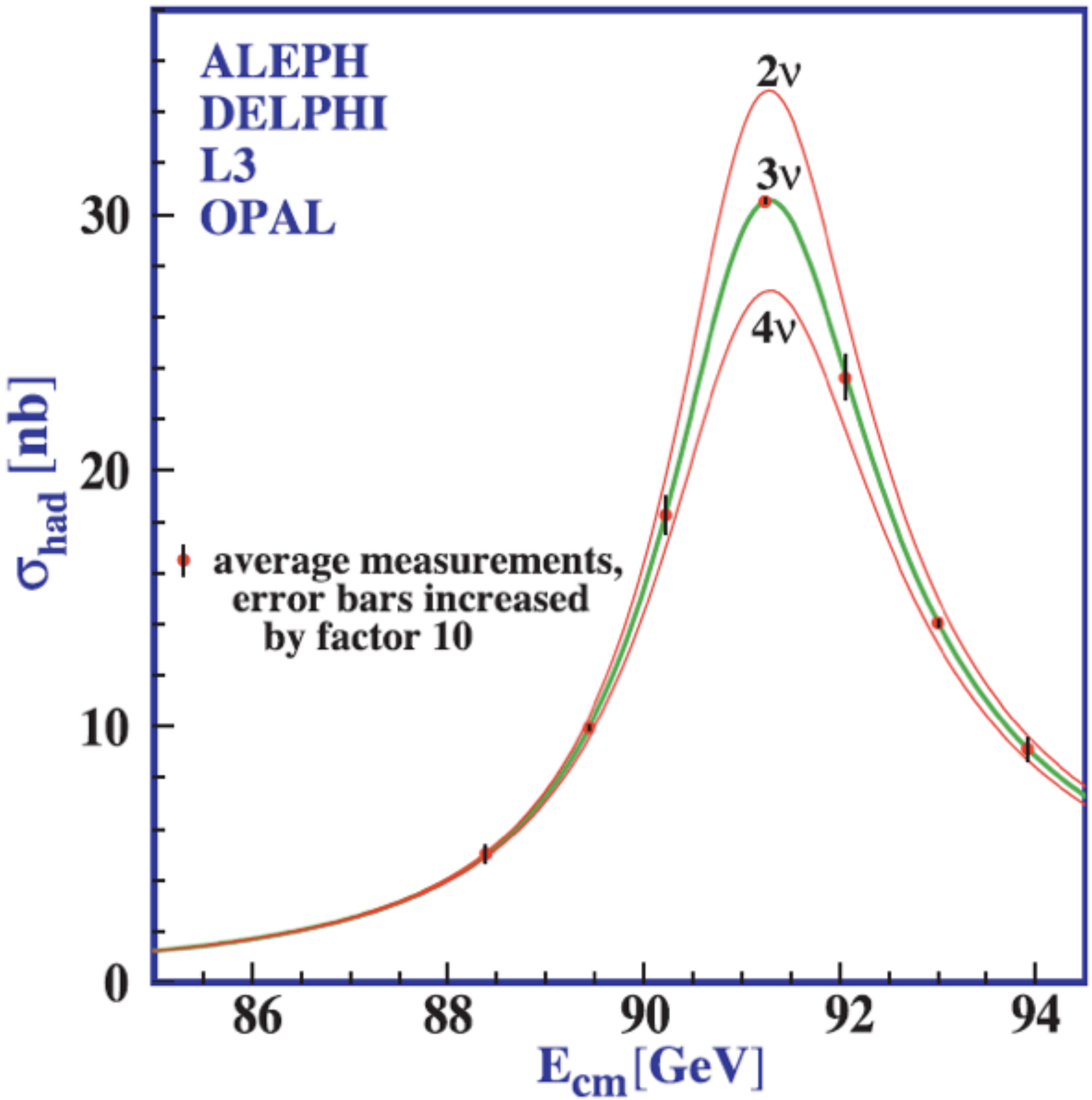
- 2000 explicit confirmation and observation of ν_τ
- 2001 Confirmation of solar ν_e deficit and definite proof of neutrino oscillations into other flavors by SNO
  - 2015 Nobel prize for Kajita and MacDonald for SuperK / SNO discoveries
- 2011 First evidence for non-zero Θ_{13} by T2K & MINOS
- 2012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

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

The Number of Neutrino Flavors



- Obtained from precision measurements of the Z^0 line shape at LEP:
- 3 light neutrinos (lighter than ~ 45 GeV), that couple to the weak interaction

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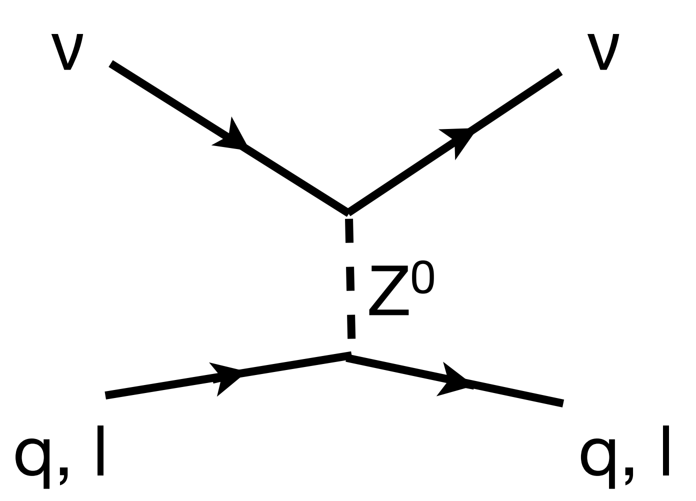
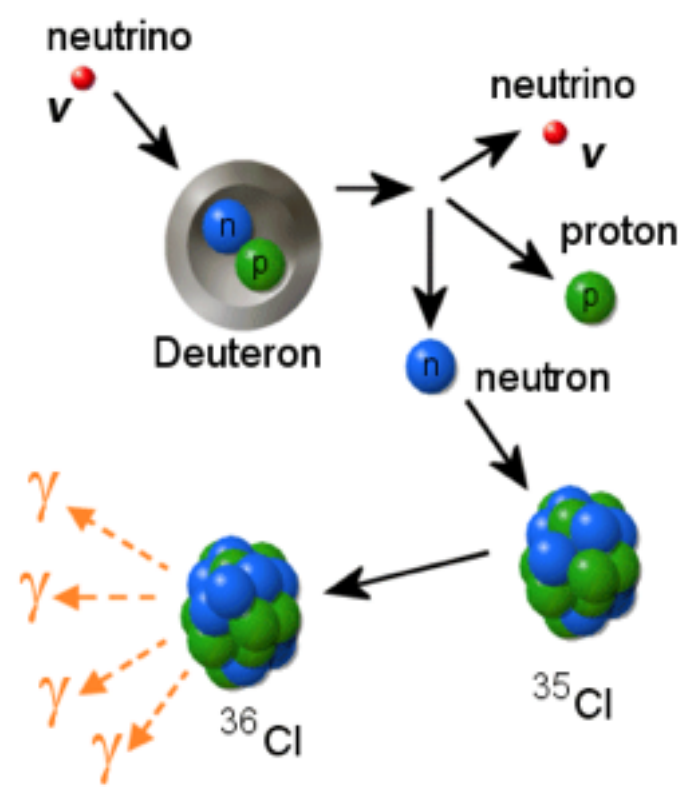
- Possible consequence:
  - Neutrinos may be their own anti-particles, so-called Majorana particles
    - A neutrino would then be a left-handed Majorana neutrino, an anti-neutrino a right-handed Majorana neutrino
    - ‣ The differentiation between Majorana and Dirac neutrinos is only possible for massive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

Neutrinos: Interaction with Matter

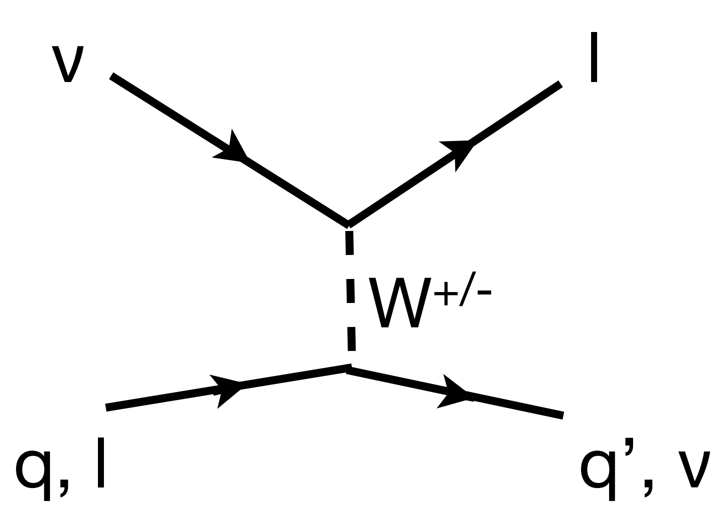
- Neutral current

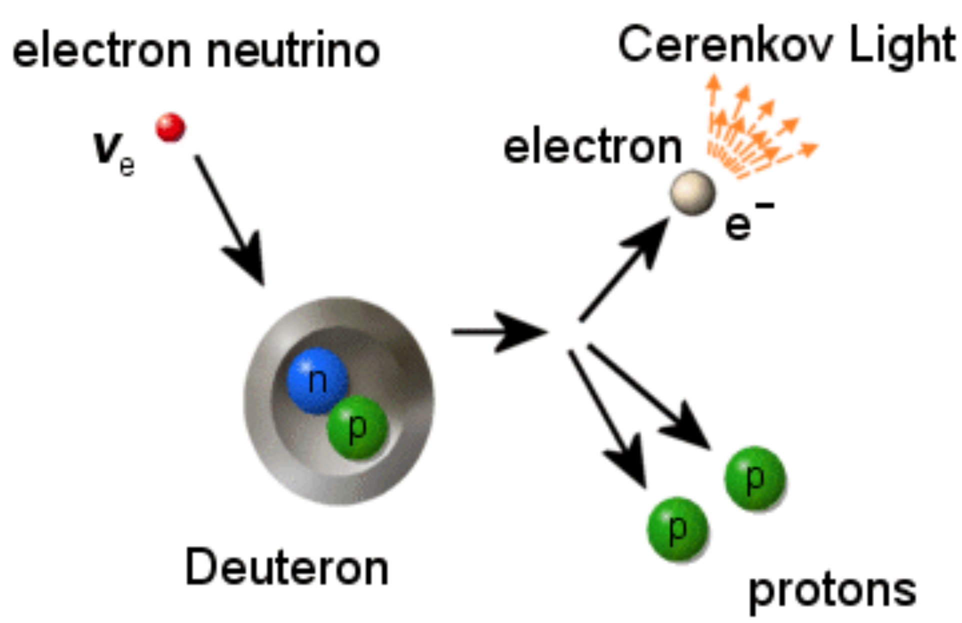




SNO

- Charged current

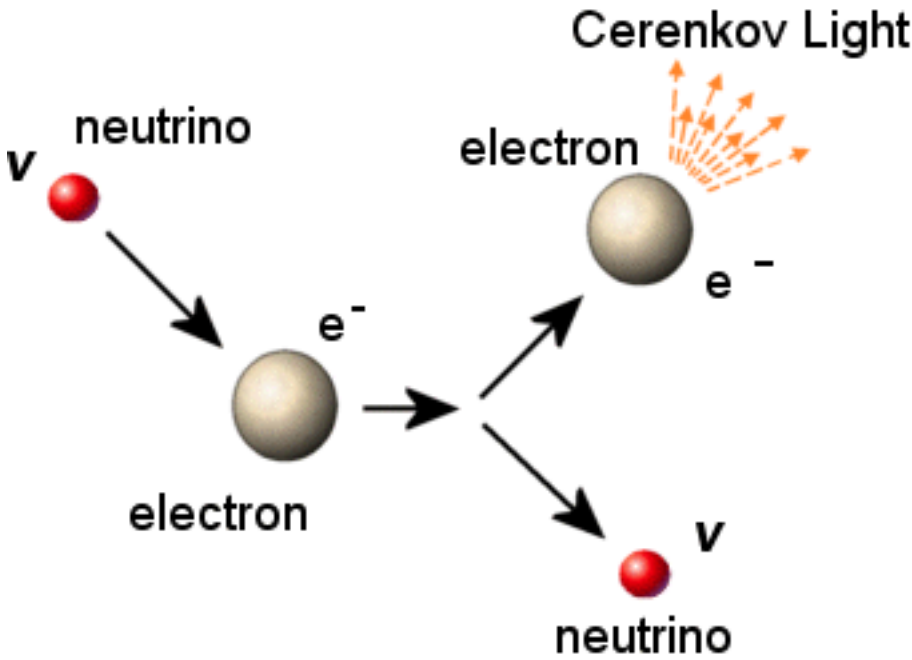




SNO

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



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- 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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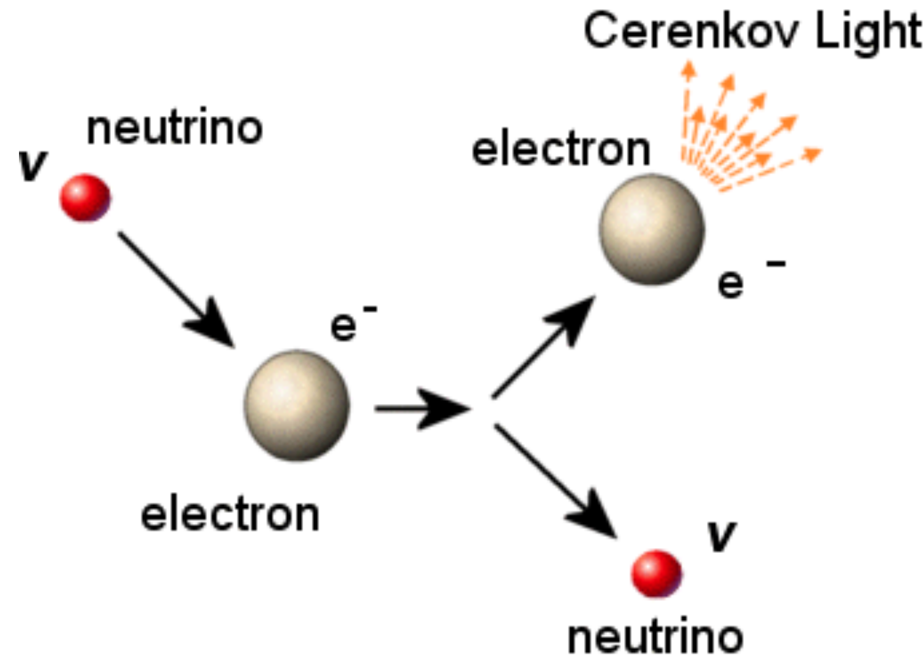

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In general: neutrino cross sections are proportional to the neutrino energy!

Neutrino Oscillations: Basic Conditions

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  - Mass eigenstates are not the same as flavor eigenstates

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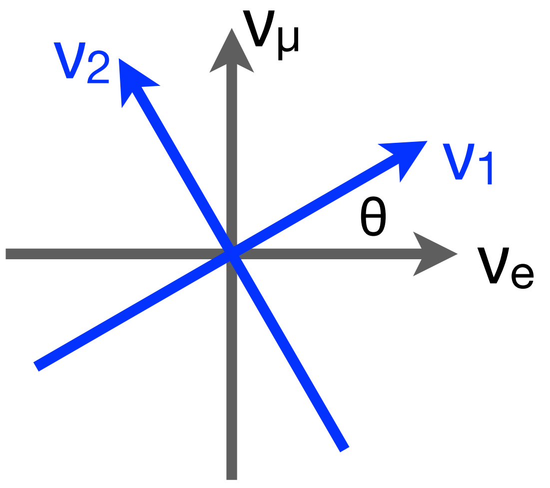
- Example: A world with two neutrino types:
  - The eigenstates of the weak interaction ν_μ und ν_e are not identical to the mass eigenstates ν_1 und ν_2



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

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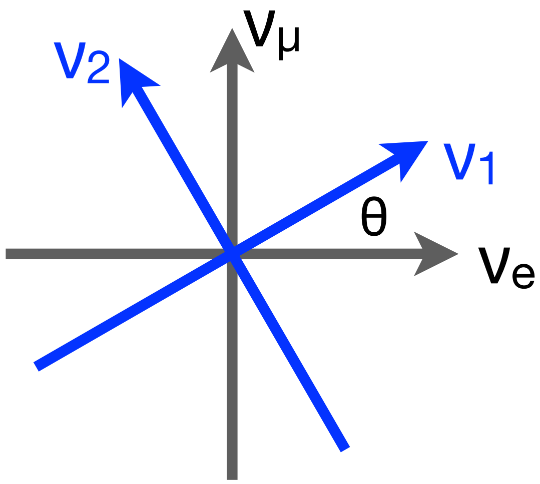

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  - The eigenstates of the weak interaction ν_μ und ν_e (which we can observe and identify) are mixes of the mass eigenstates:

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

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

Neutrino Oscillations: Two Neutrinos

- The time evolution in vacuum is given by the mass eigenstates:

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

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

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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:

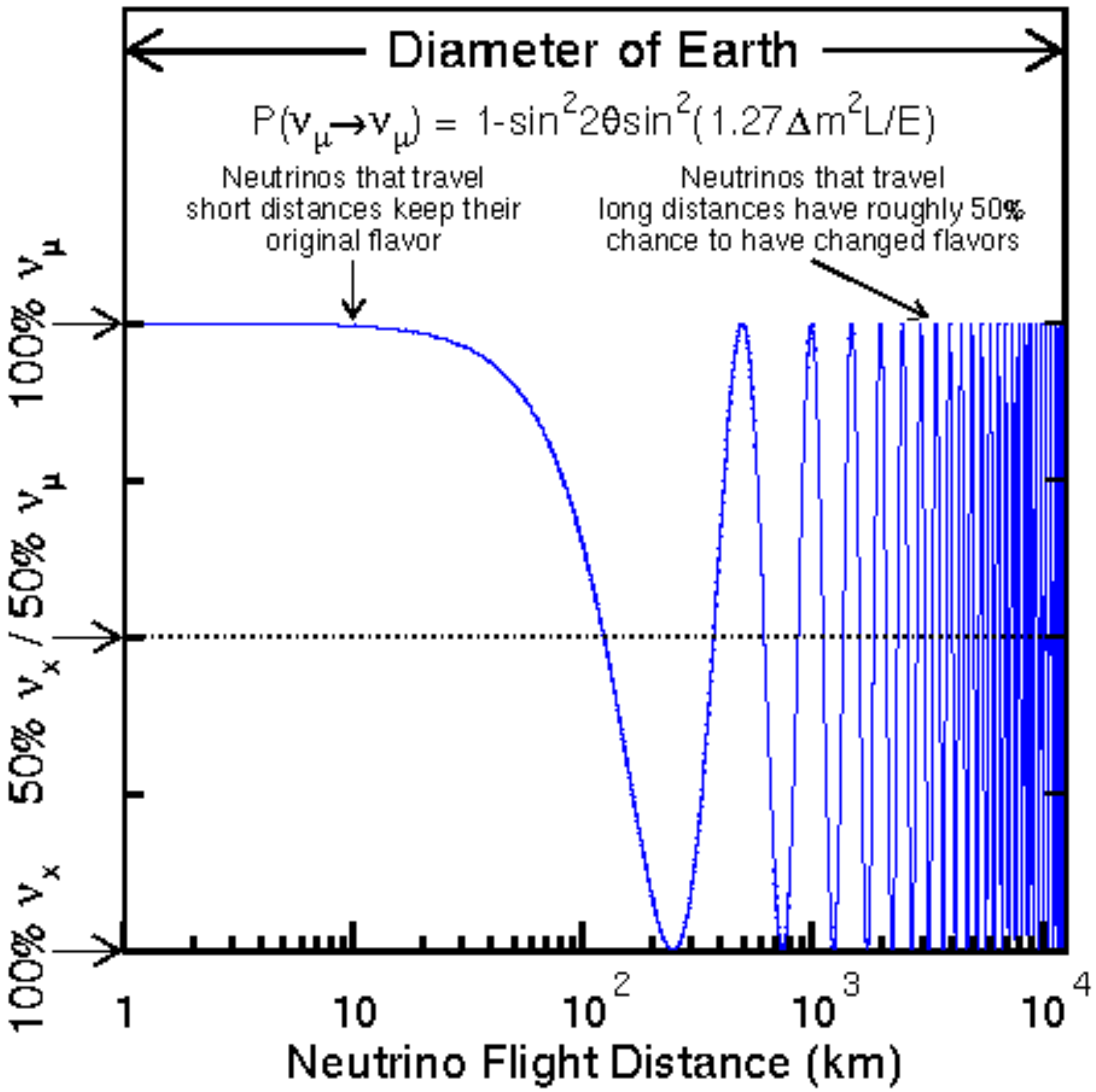
$$P(\nu_\mu \leftrightarrow \nu_e) \;=\; sin^2 2\theta\, sin^2\left(\frac{\Delta m^2 L}{4E}\right) \;=\; sin^2 2\theta\, sin^2\left(1.27\,\frac{\Delta m^2}{\mathrm{eV}^2}\,\frac{L/\mathrm{m}}{E/MeV}\right)$$

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

Neutrino Oscillations

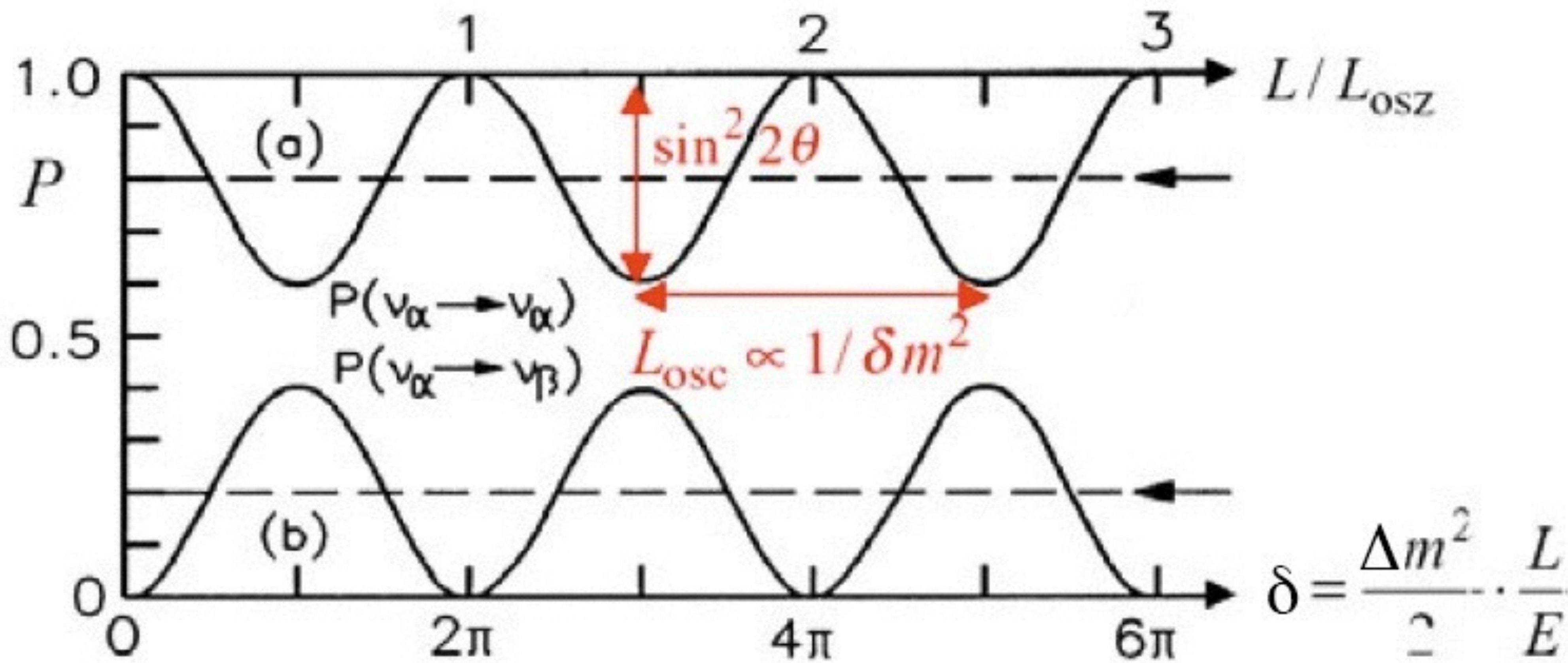
- Neutrino oscillations as a function of distance

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



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 $|\nu_\alpha\rangle$ mit $\alpha = e, \mu, \tau, ...$
- n mass eigenstats $|\nu_i\rangle$ 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 (Maki-Nakagawa-Sakata-Matrix MNS):
  - 3 angels and one CP violating phase
- analogous to the CKM matrix in the quark case

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

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

CP violation connected to Θ13

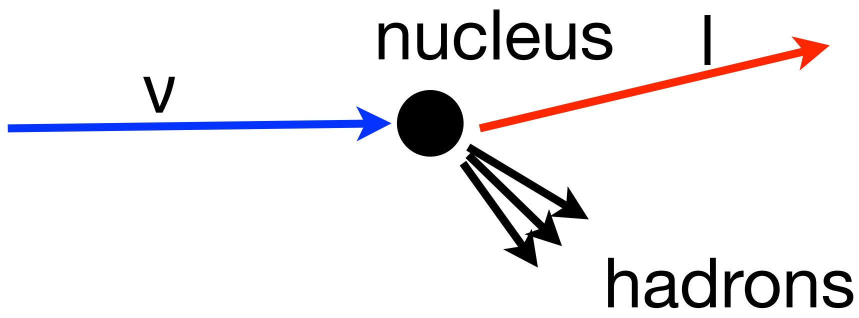
Detectors for Highly Energetic Neutrinos

- 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)

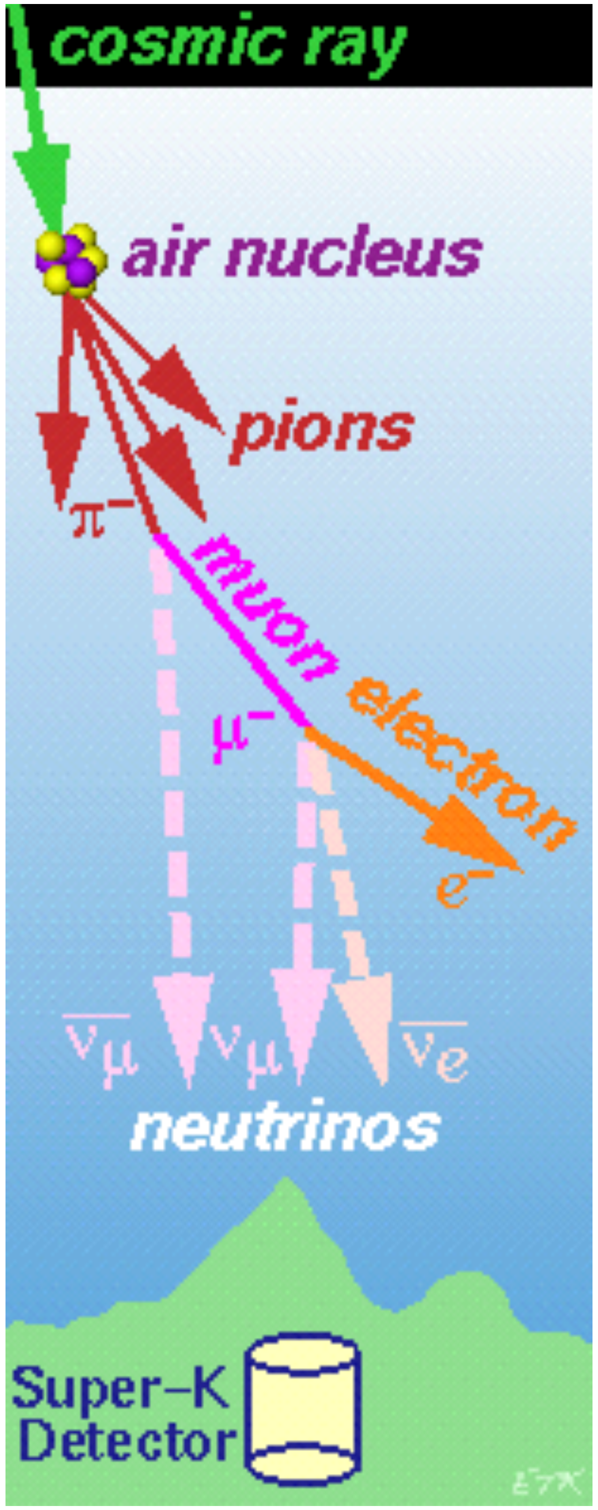
Super-Kamiokande Measurement Principle

- 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):

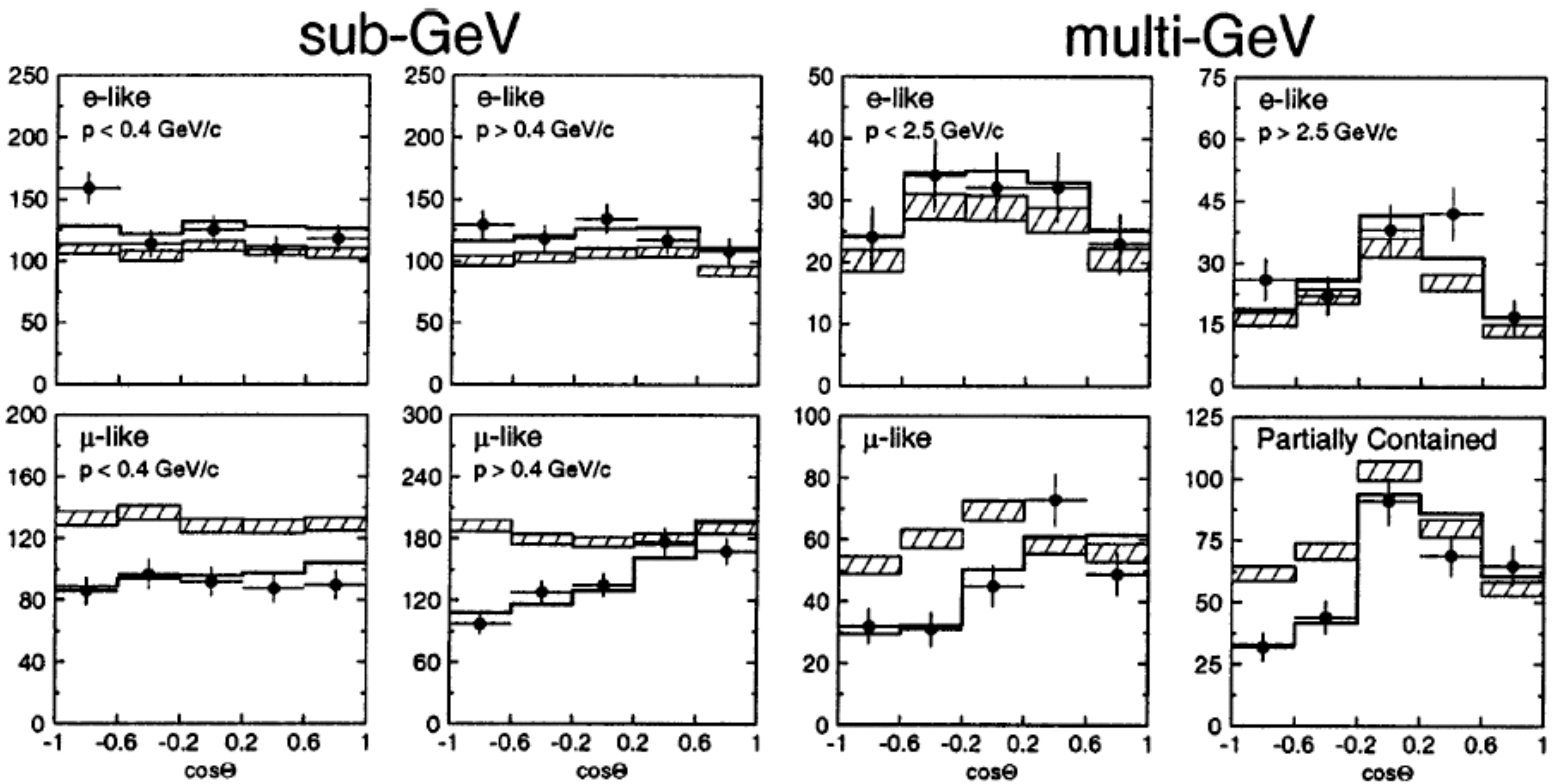
$$\frac{\mu}{e} \equiv \frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e}$$

- If all muons decay (for low energies):

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

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

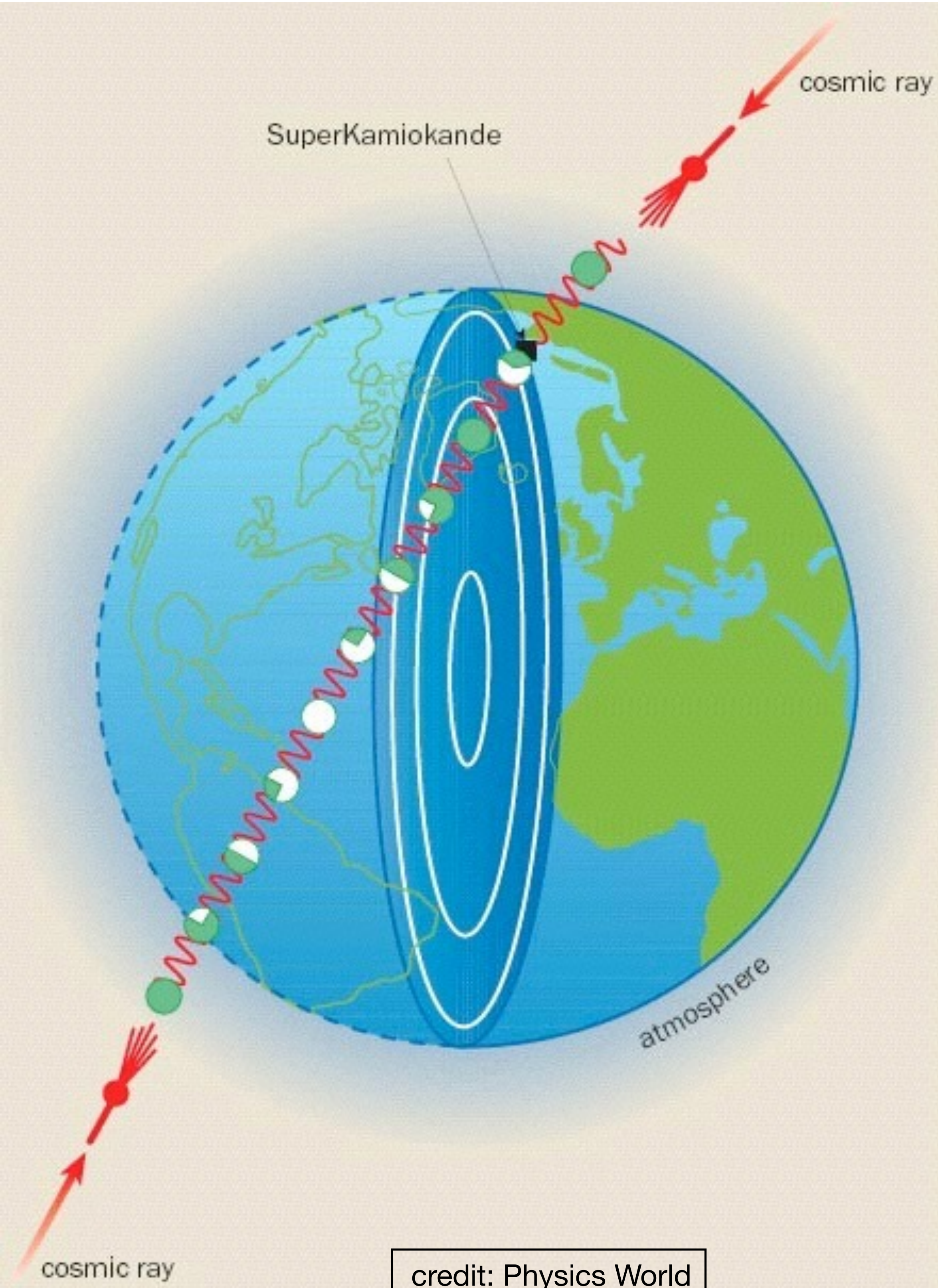
Oscillation of Atmospheric Neutrinos



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

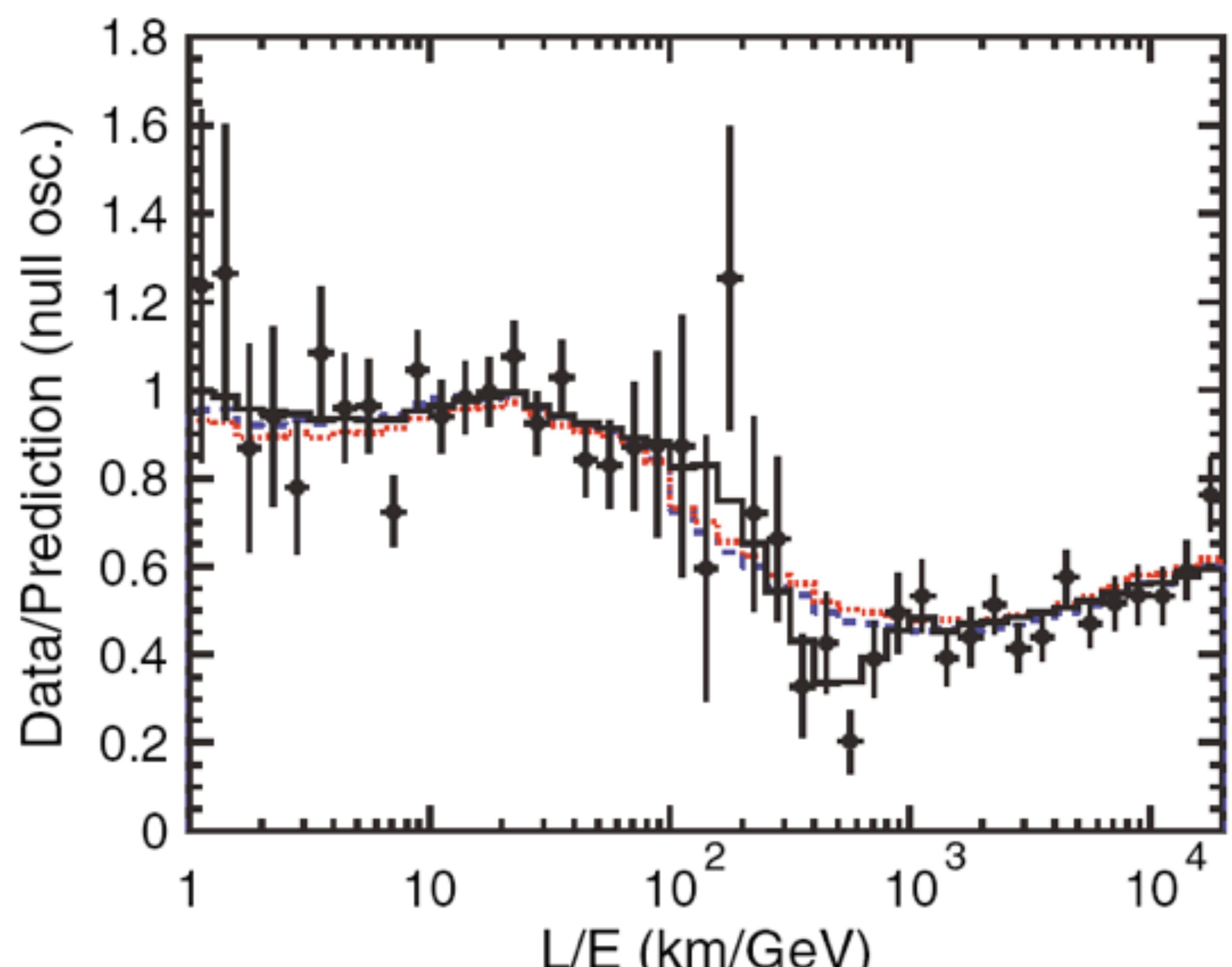
- Deficit of muon neutrinos observed, electron neutrinos match expectations
- Dependence of discrepancy with zenith angle

Oscillation of Atmospheric Neutrinos



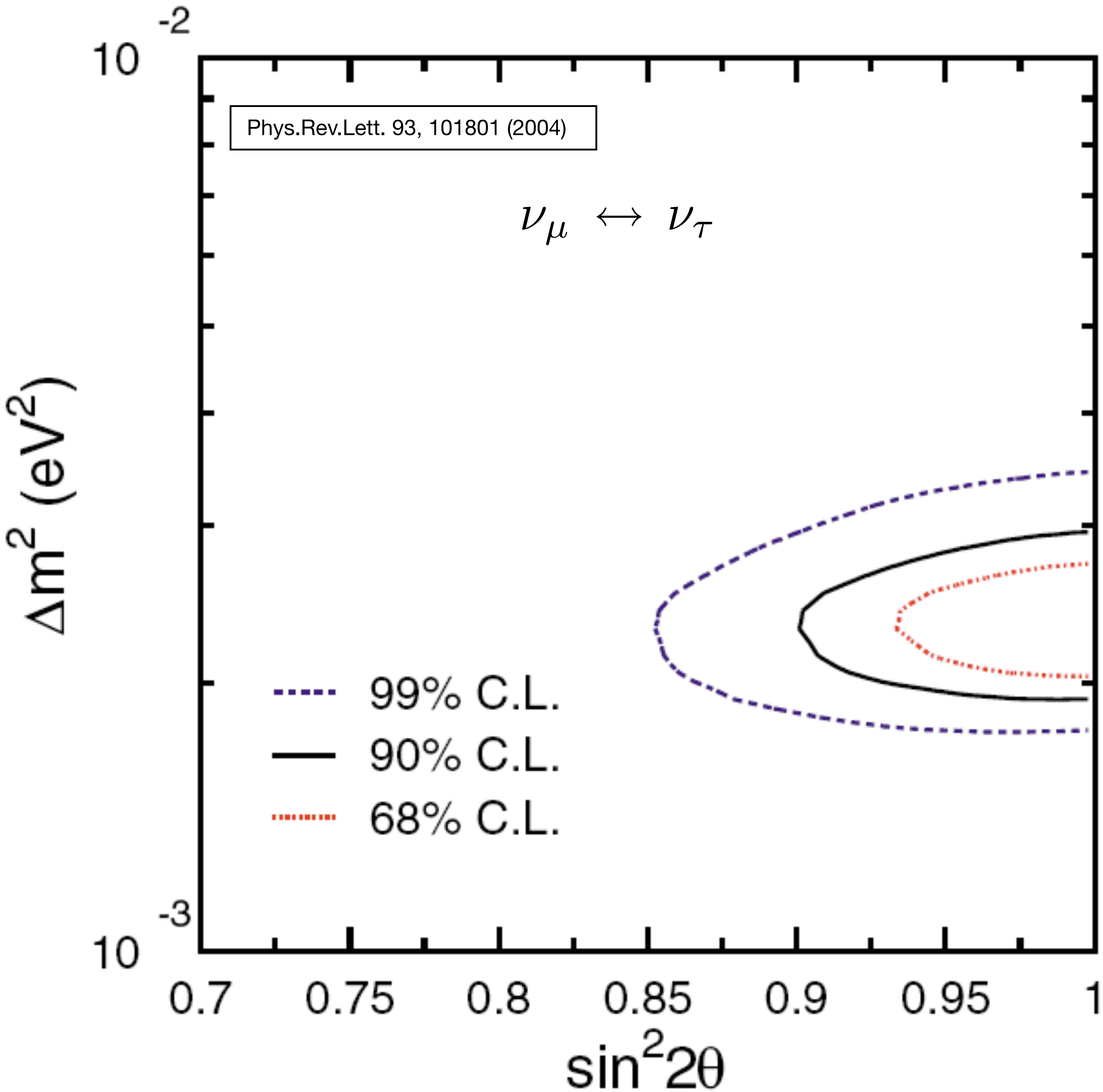
credit: Physics World

- 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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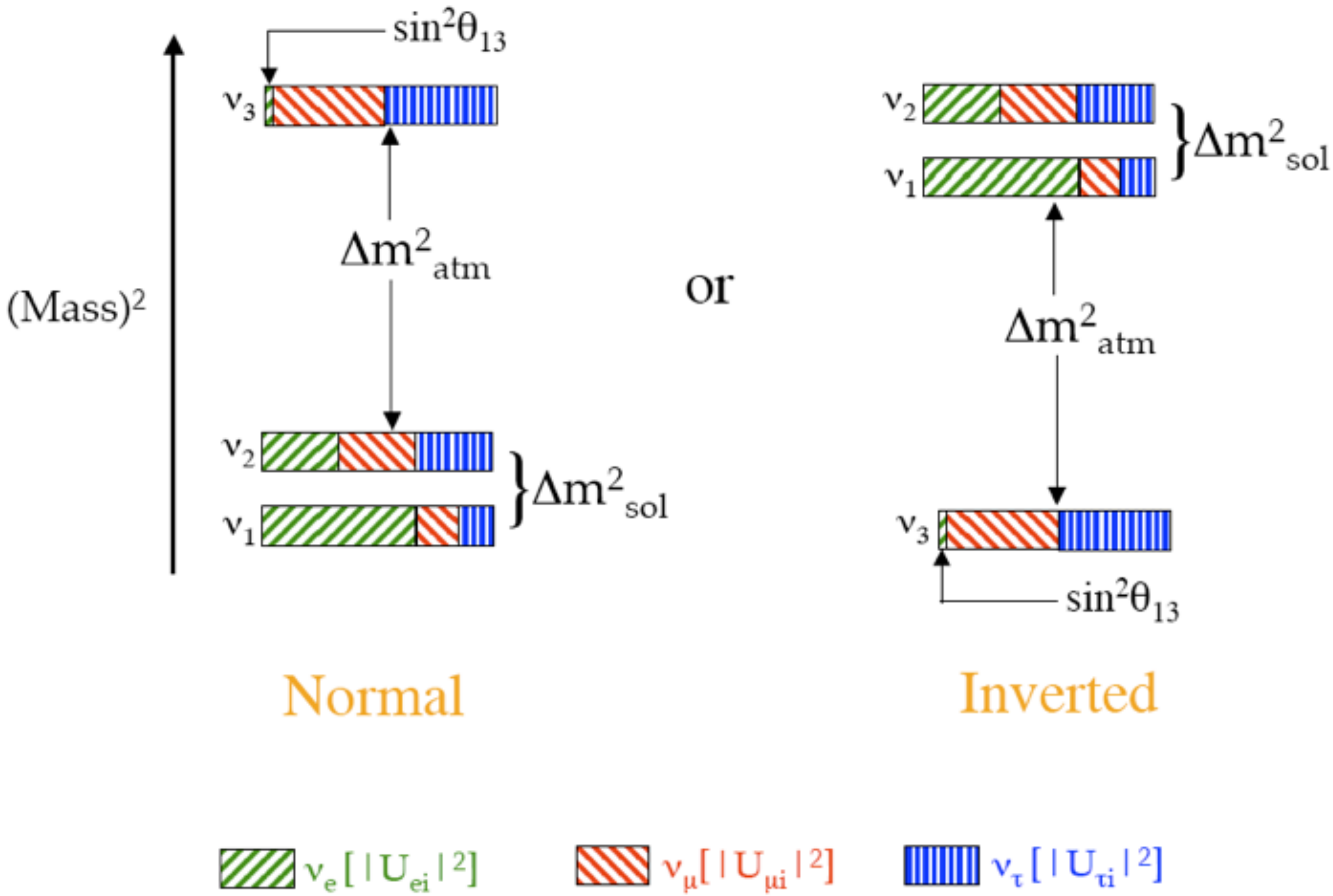
atmospheric/
accelerator

Neutrino-Oscillations: The Resulting Picture



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

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

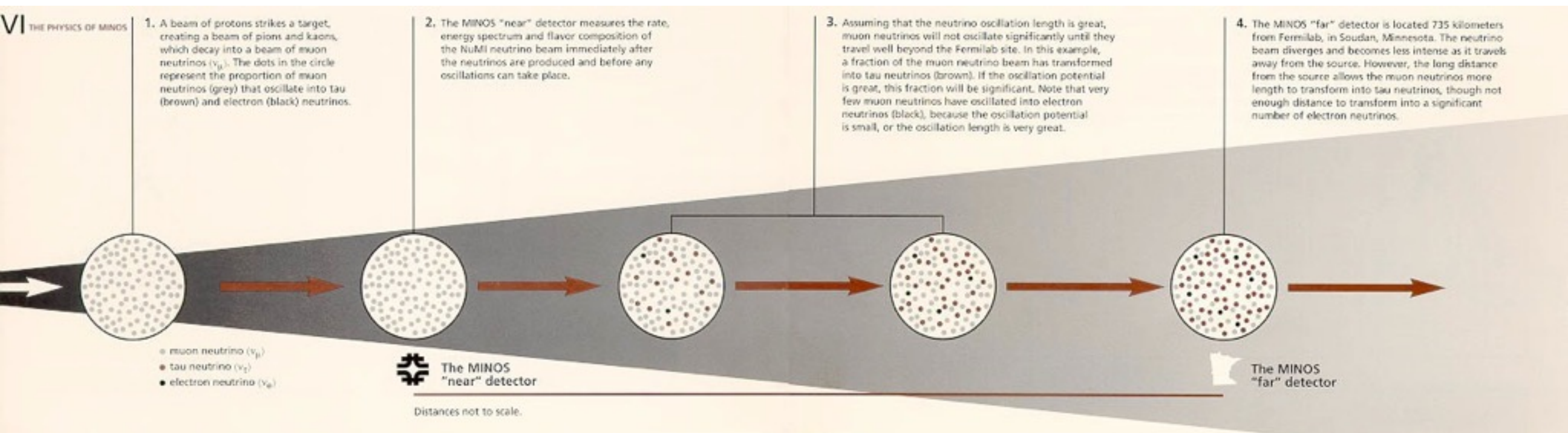
- There have been many different experiments with accelerator neutrinos
  - Study of the weak interaction
  - Measurement of the quark composition of nuclei
  - Discovery of the ν_τ
  - Confirmation of atmospheric measurements
  - Evidence for non-zero θ_{13}
  - ...

Long Baseline Experiments

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

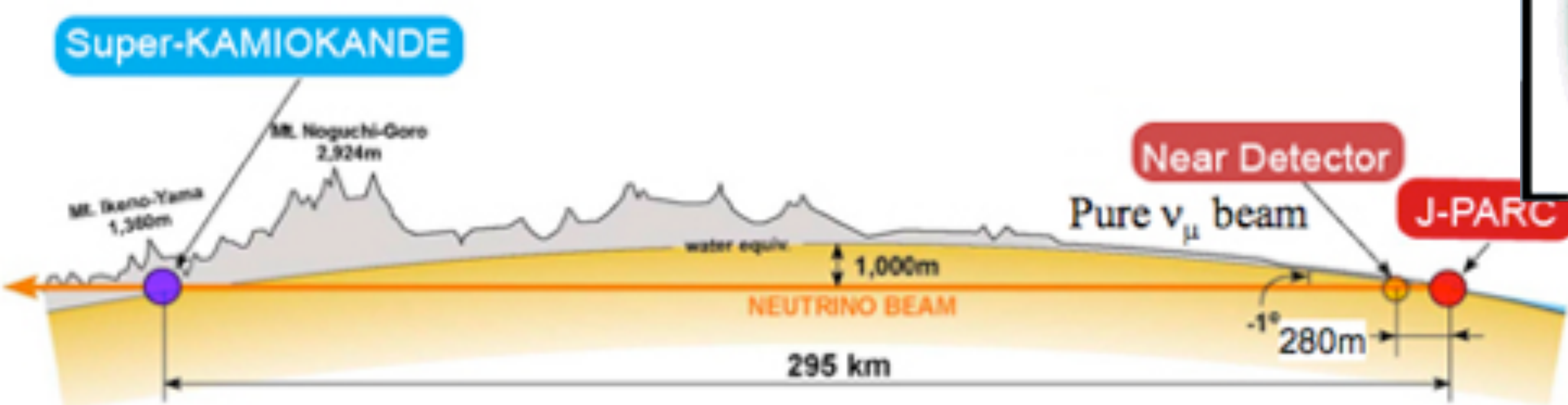
▸ Choice of distance and energy depends the region of the mixing matrix that can be probed

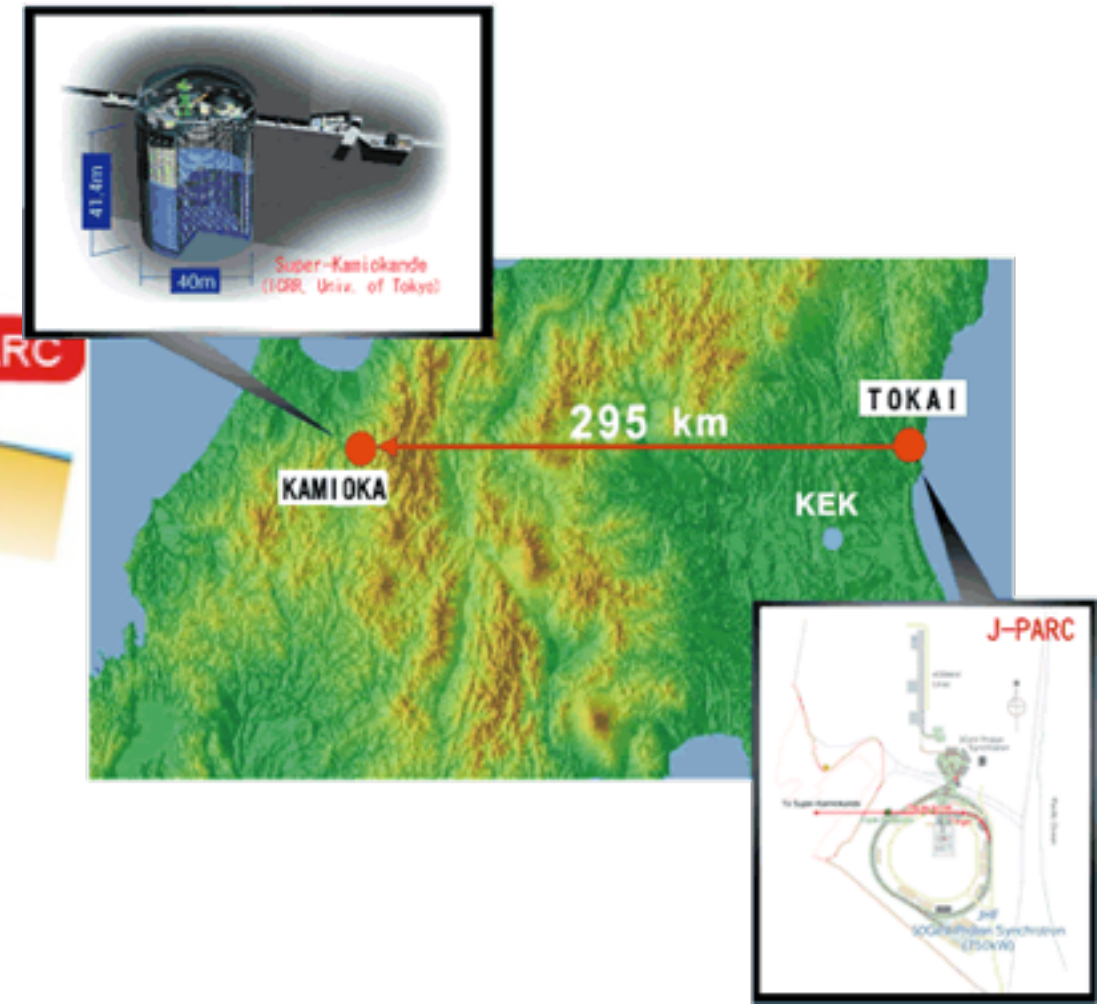
The composition of the beam changes from source to detector
From a pure ν_μ beam to a mixture of ν_μ , ν_τ and a few ν_e ($\theta_{13} \neq 0$)



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)





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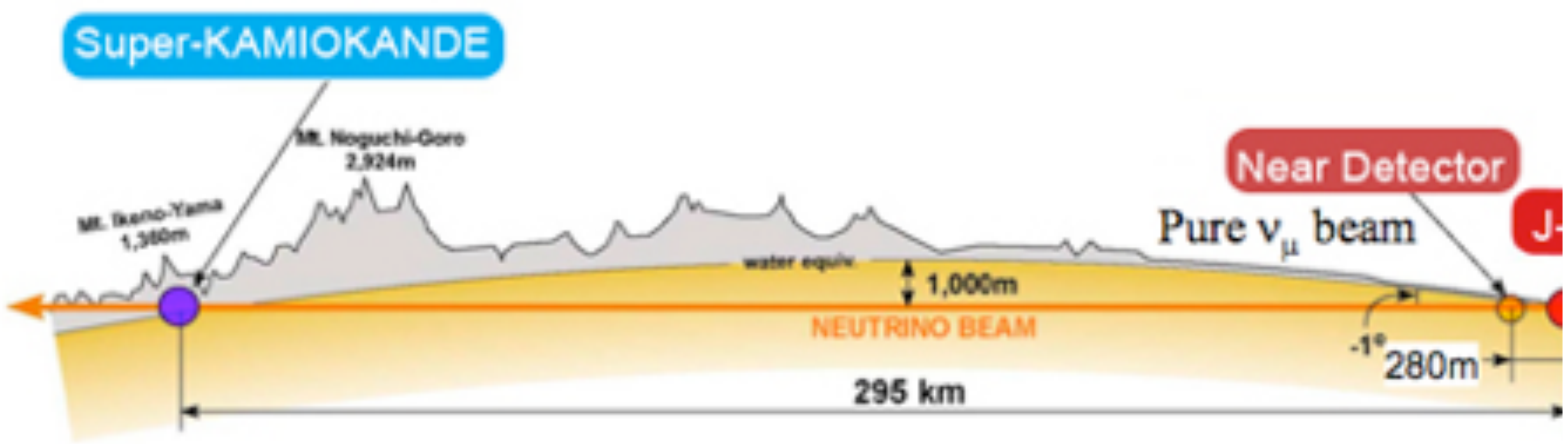
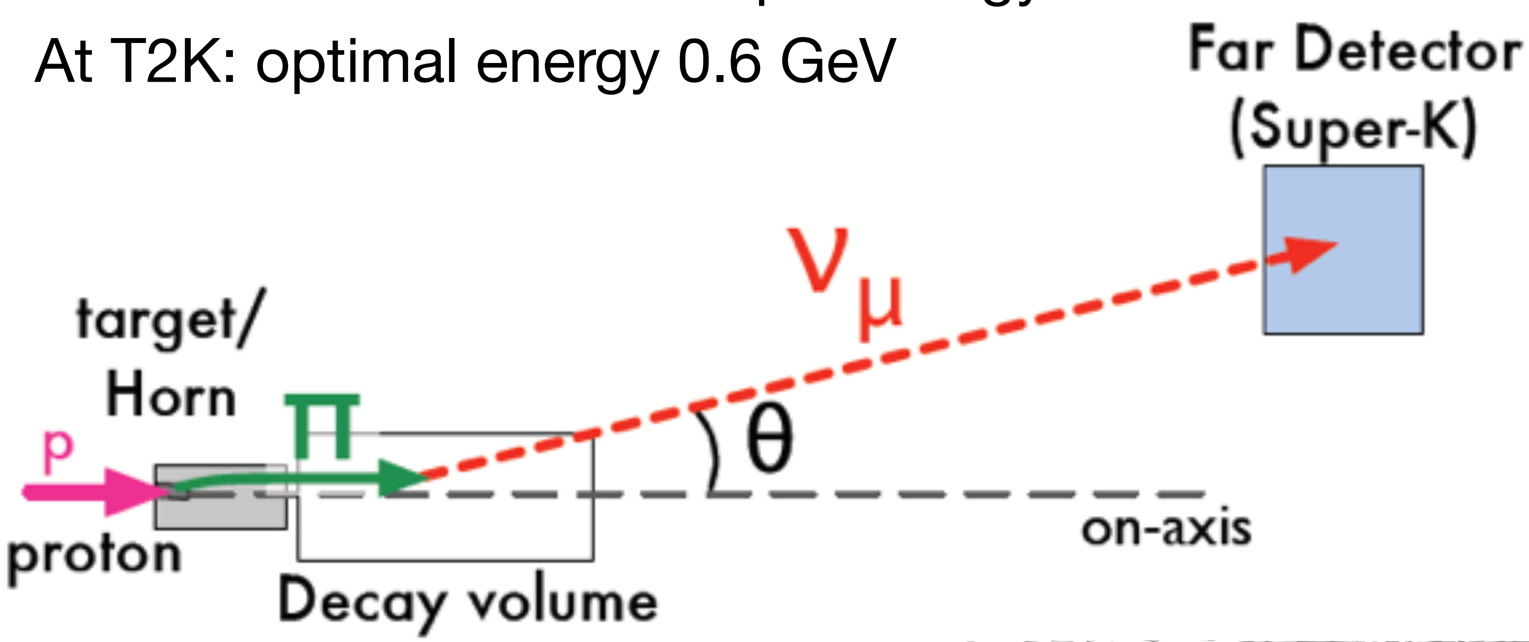
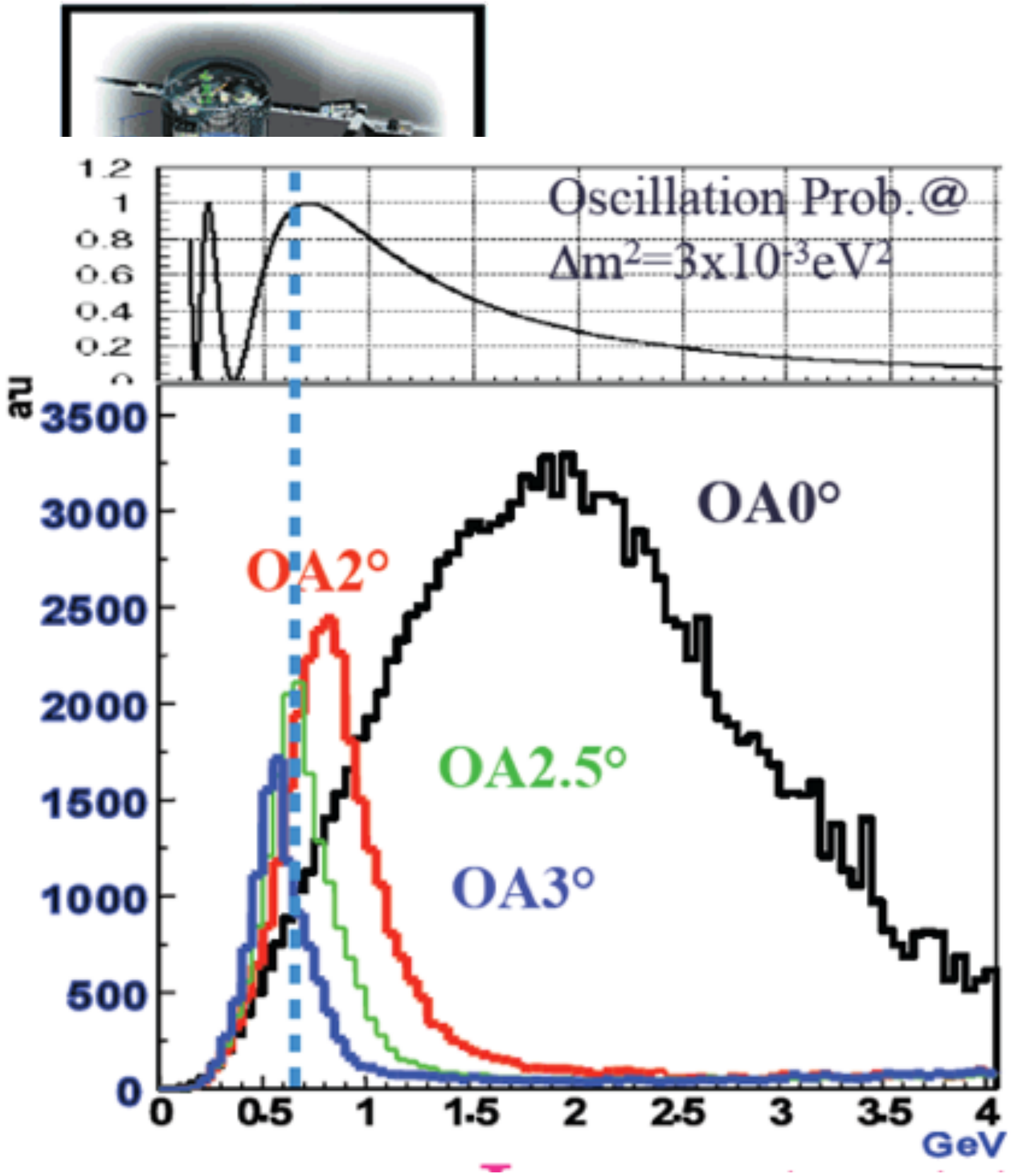


T2K is an “off-axis”- Beam: Aims not directly at the far detecor -results in sharper energy distribution

At T2K: optimal energy 0.6 GeV

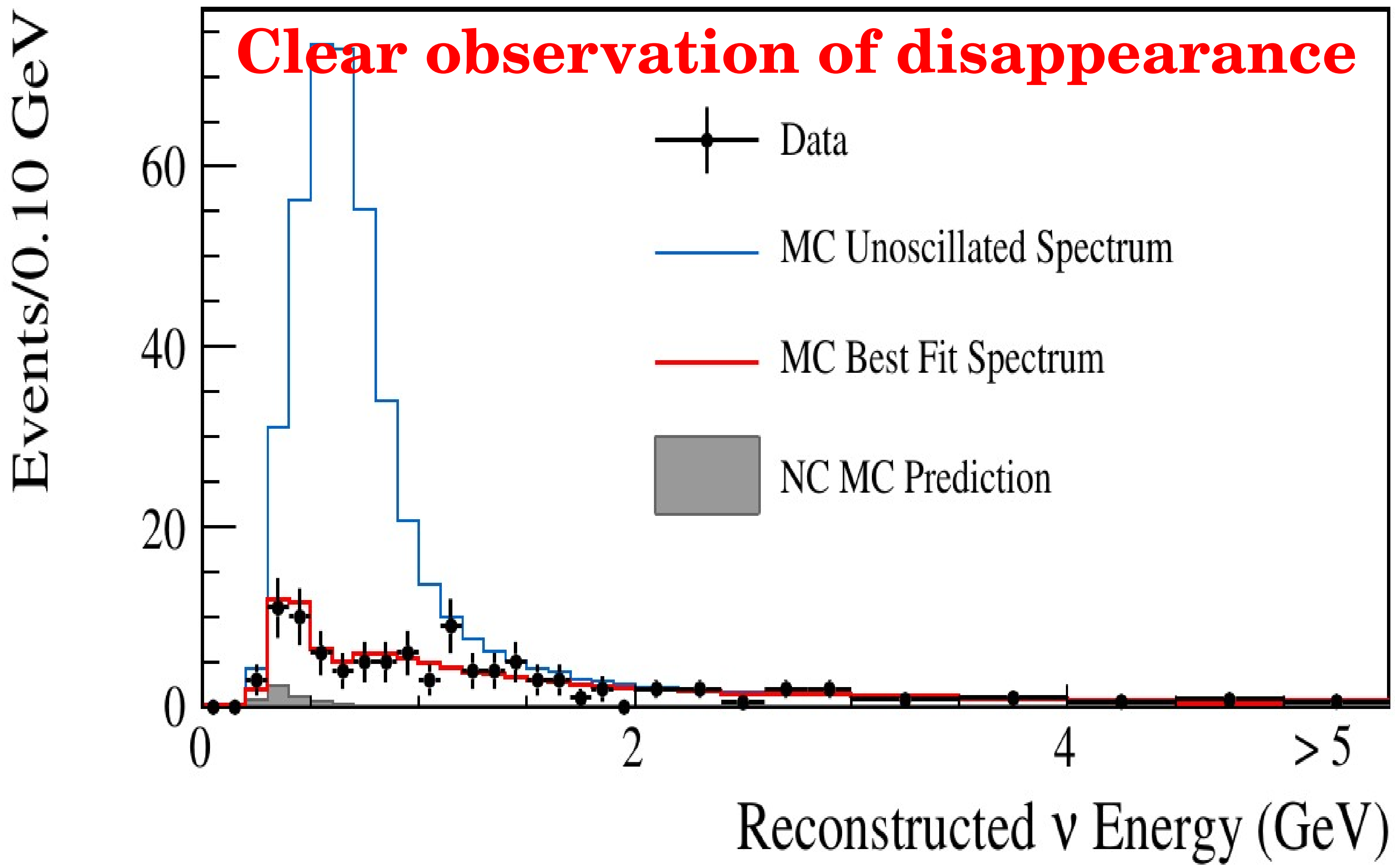




Ken Sakashita, KEK Seminar

T2K - The Choice of the Right Baseline

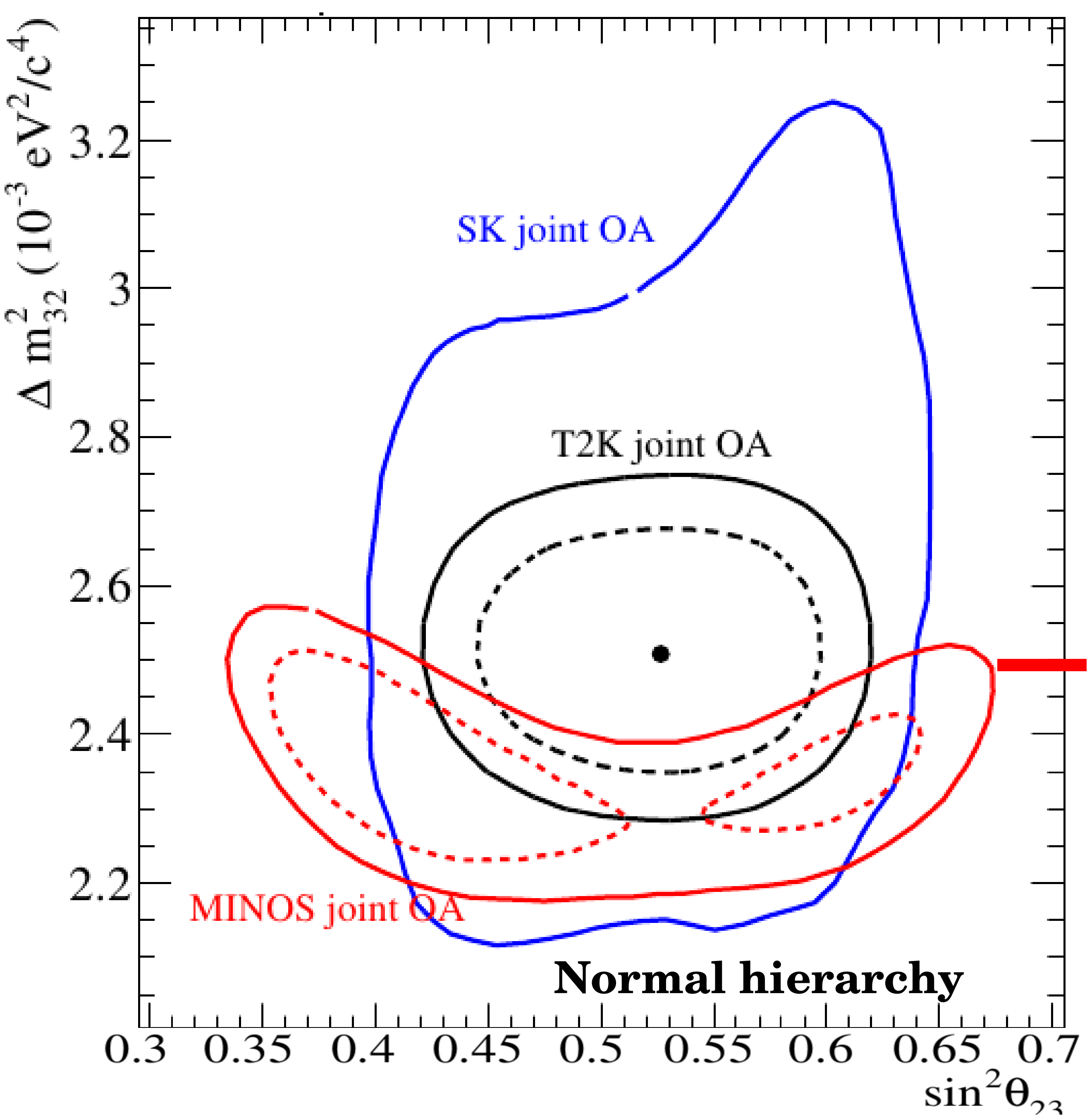
- Almost complete disappearance of ν_μ:



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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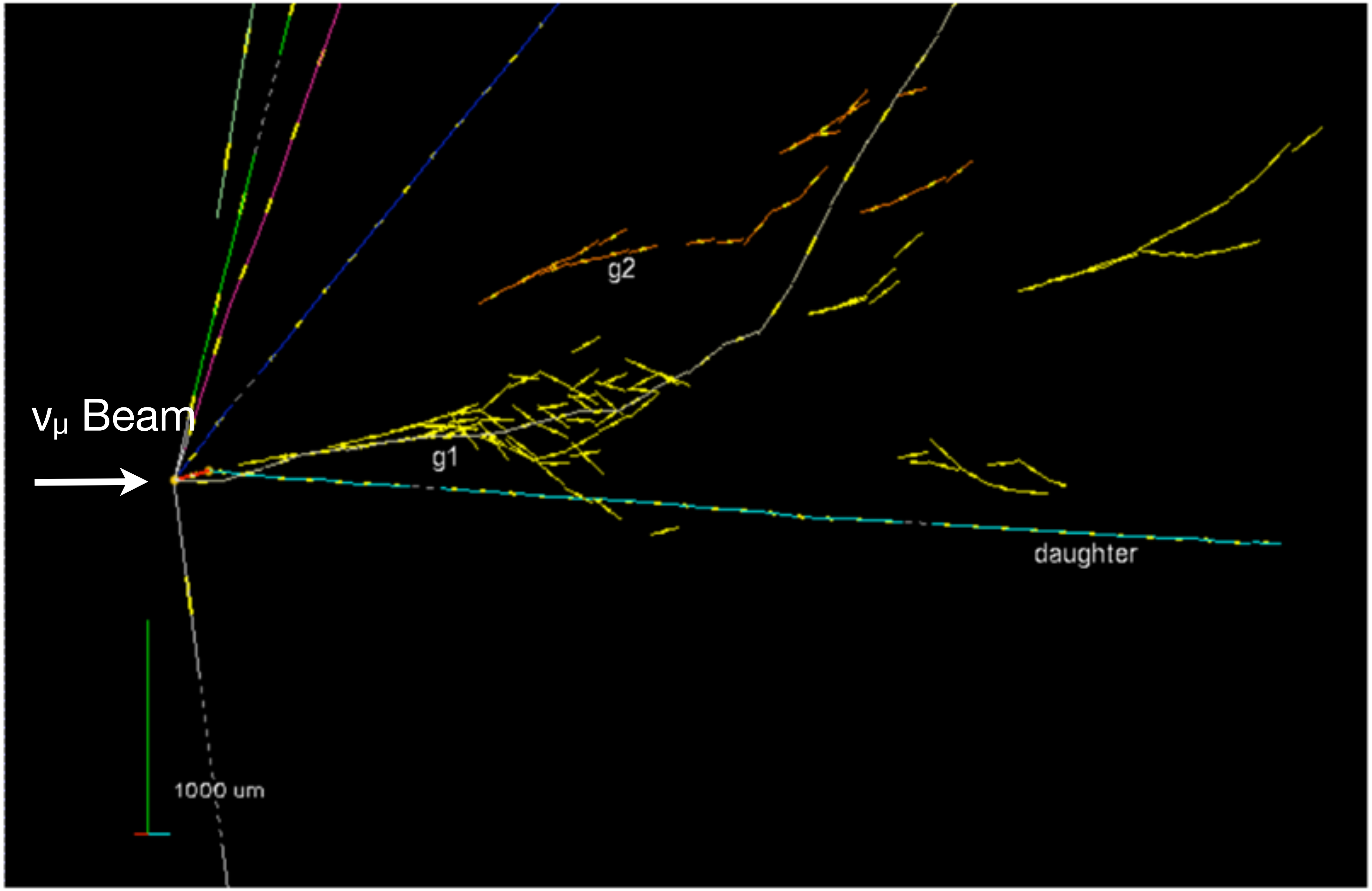
OPERA: First ν_τ Candidate

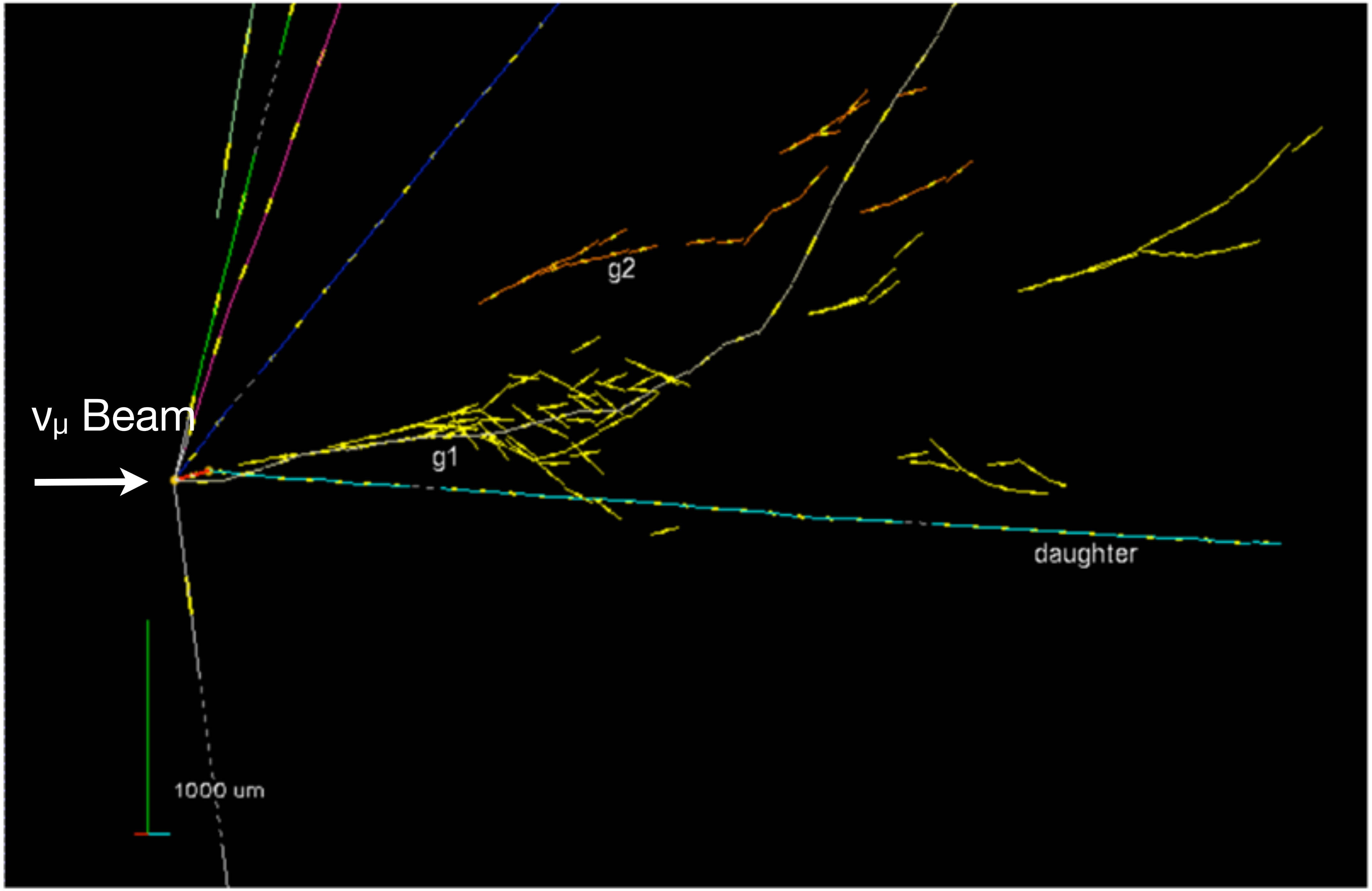


ν_τ produces τ, fast decay into μ and νs

➯ 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

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

OPERA Press Release, 31.05.2010

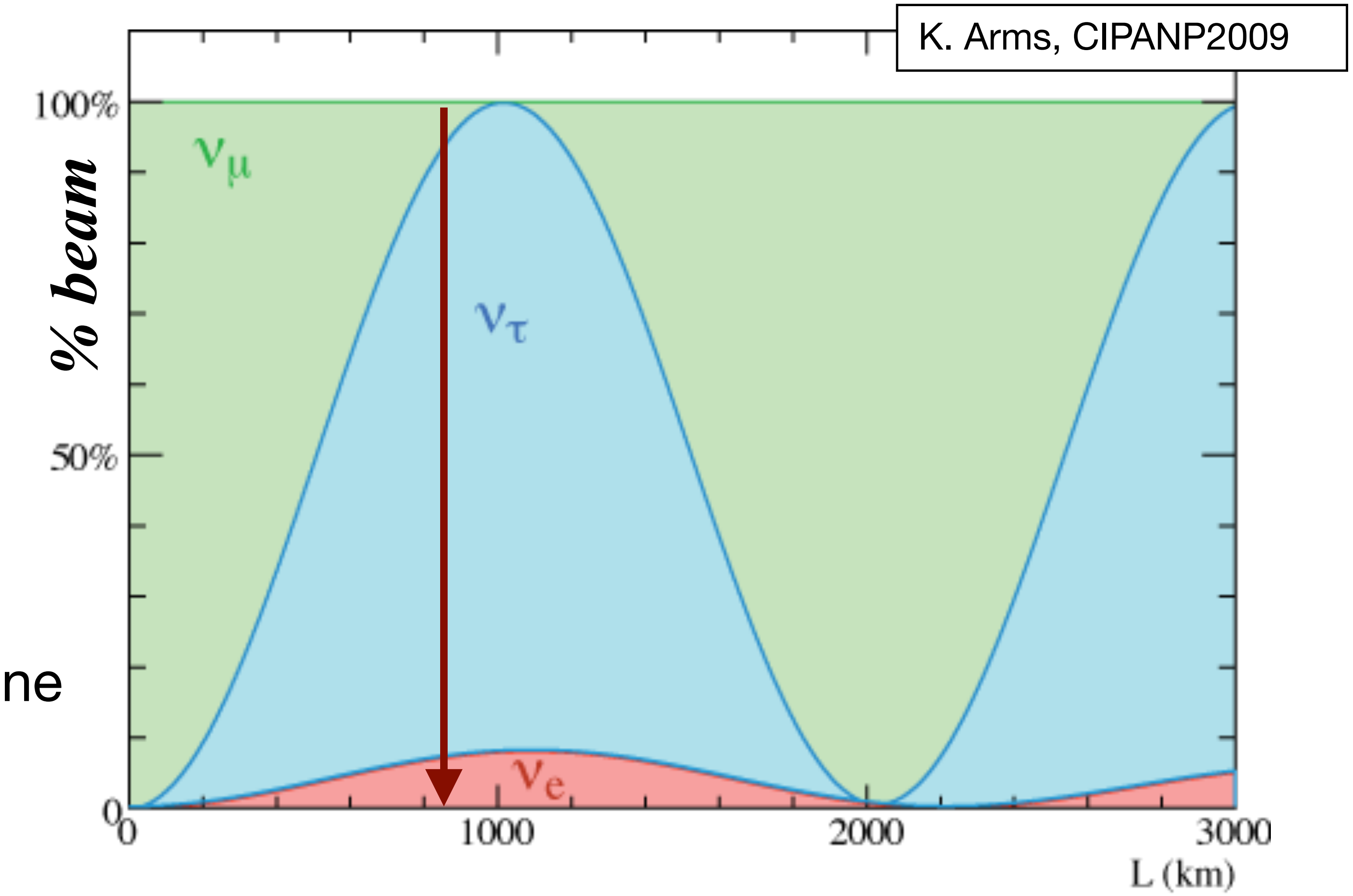
Measuring θ_{13} at Accelerators

- 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!

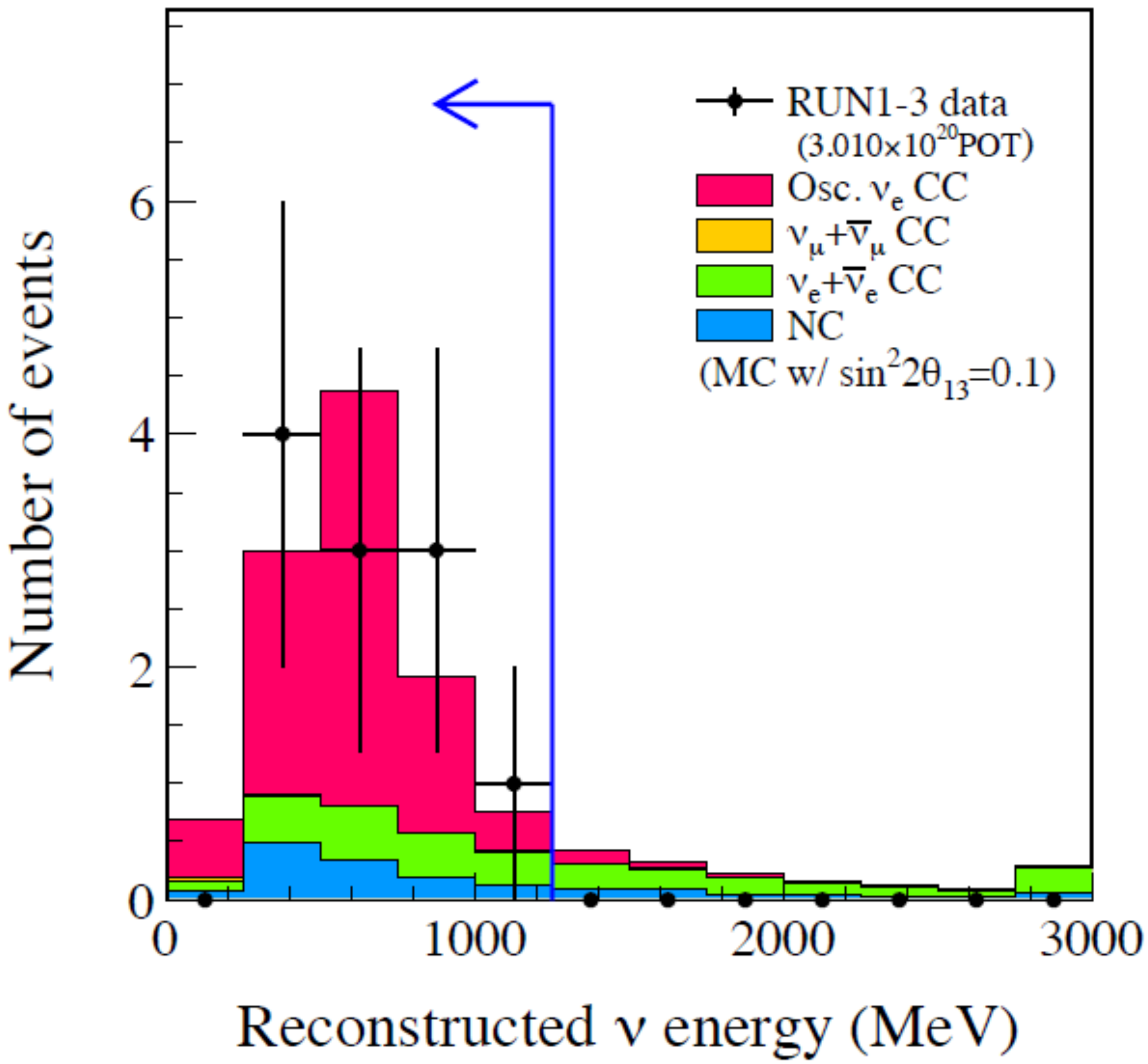
length scale depends on ν energy
here: shown for the NOvA experiment at FNAL
Important: Energy matched to baseline
Narrow energy distribution

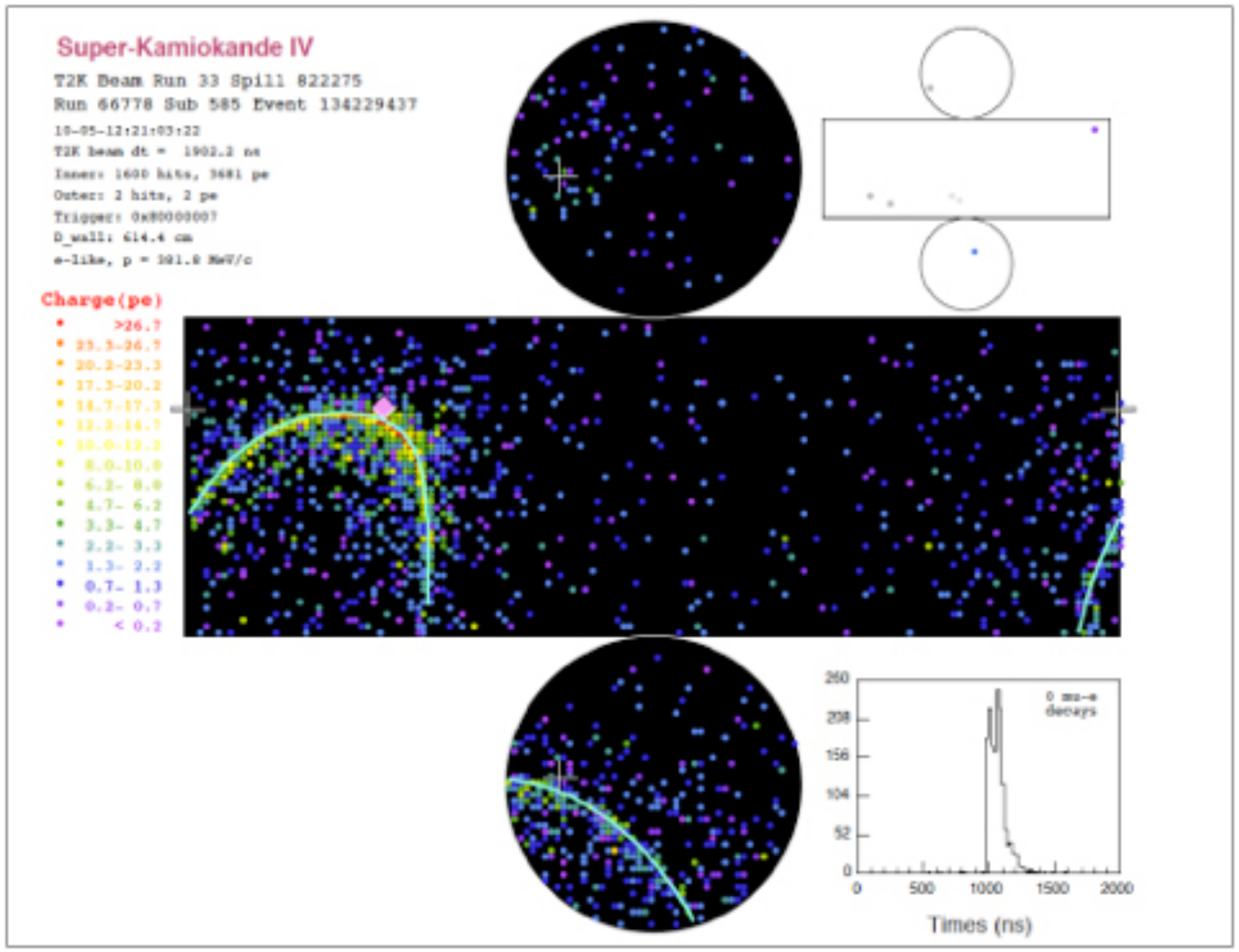


T2K - Oscillation Results

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

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

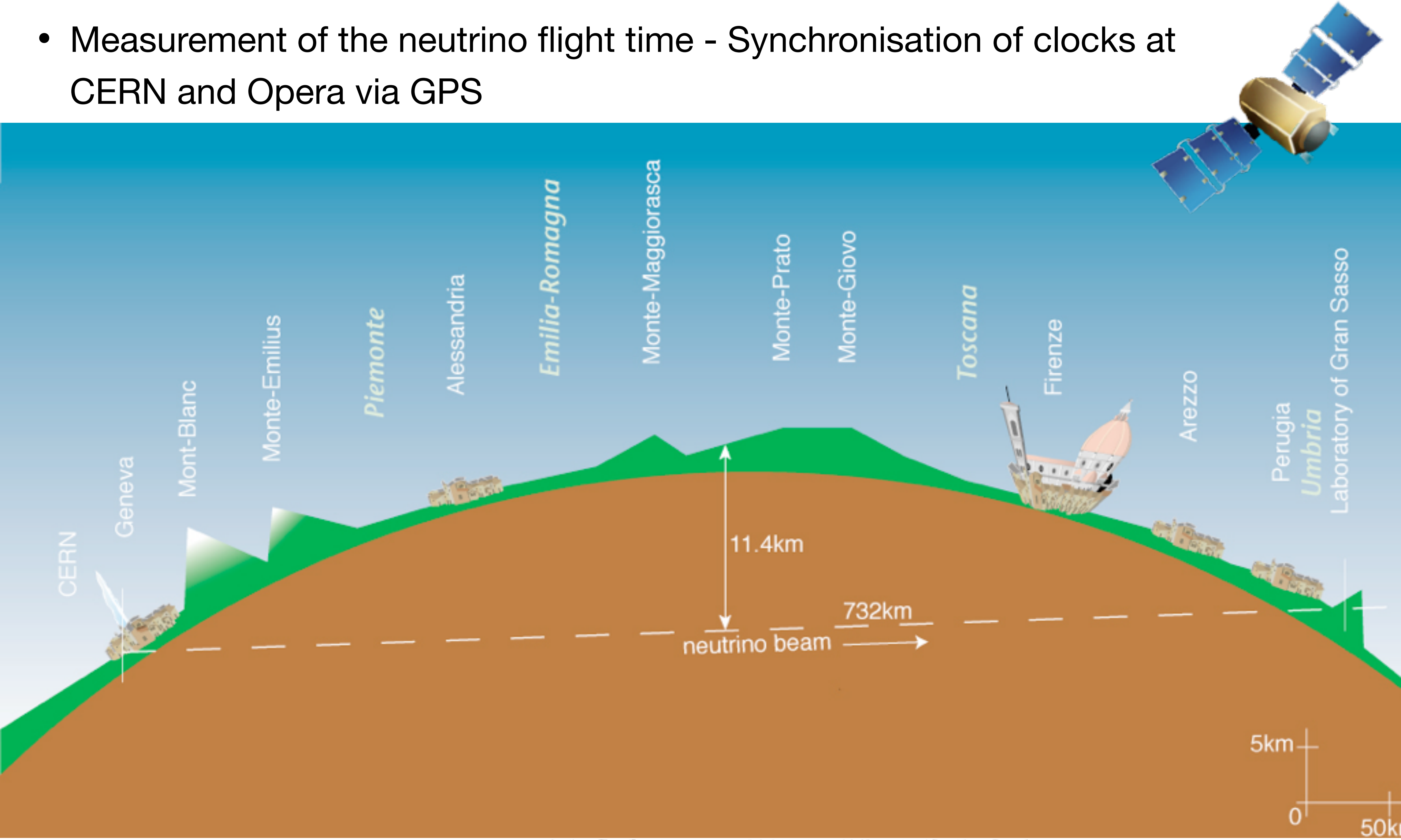




Best results currently from reactors - more next week

Neutrino Speed

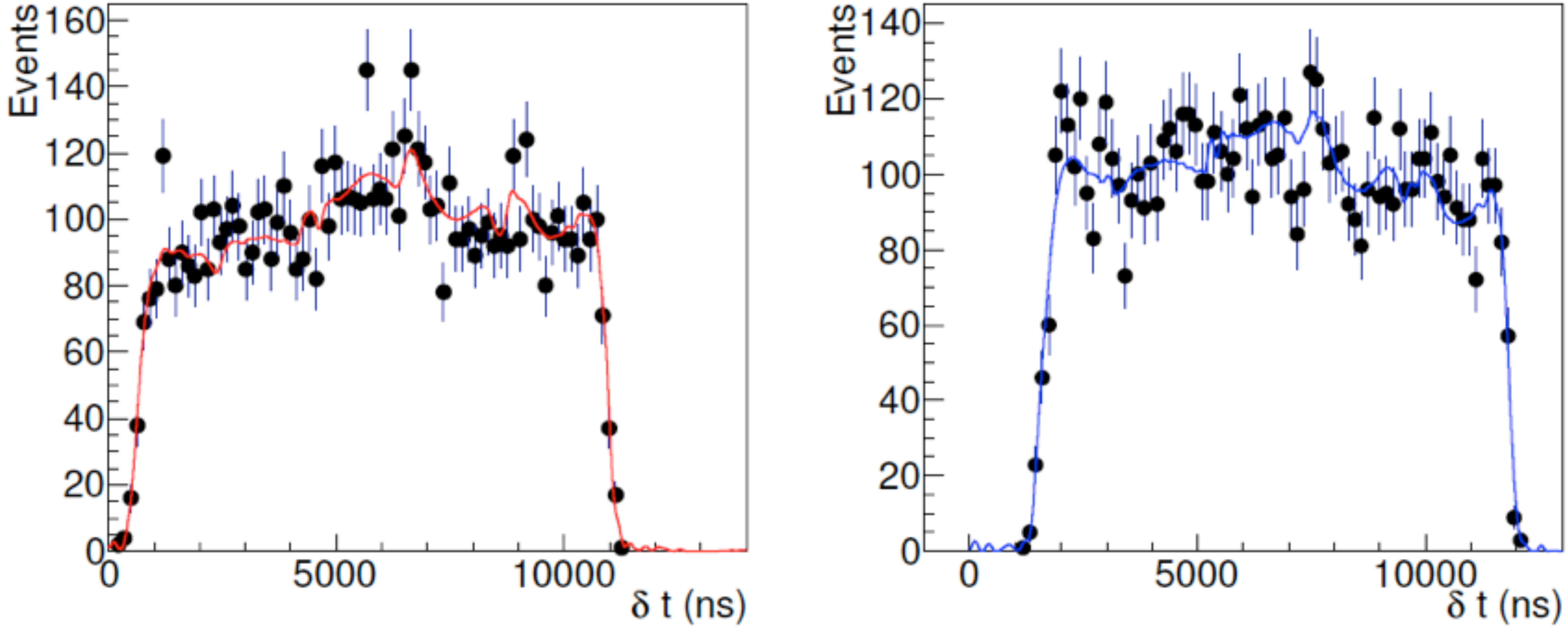
- Measurement of the neutrino flight time - Synchronisation of clocks at CERN and Opera via GPS



First Attempt - Spectacular Result

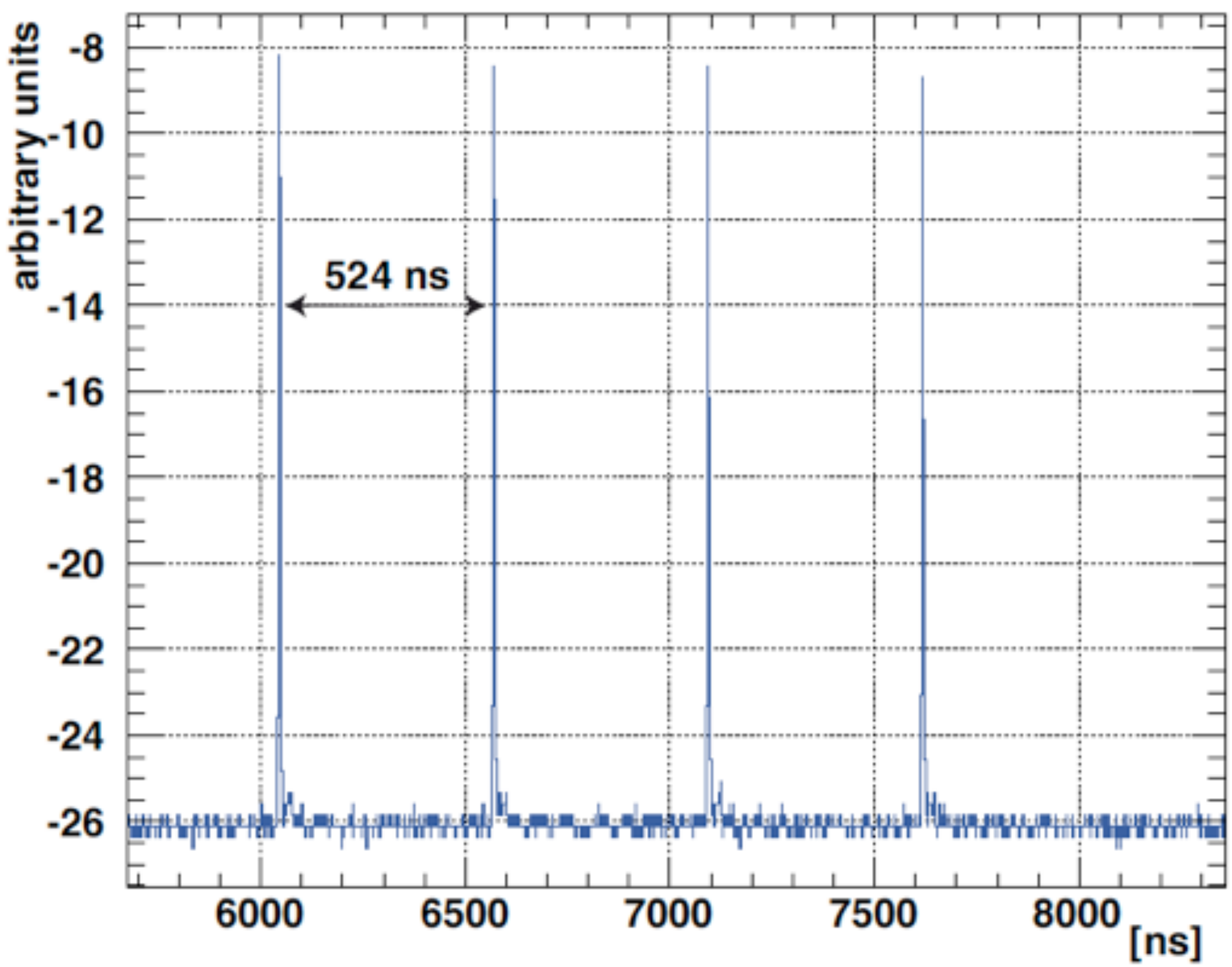
- September 2011: Opera observes, that the neutrinos are 60 ns too fast (with an uncertainties of 10 ns).

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!



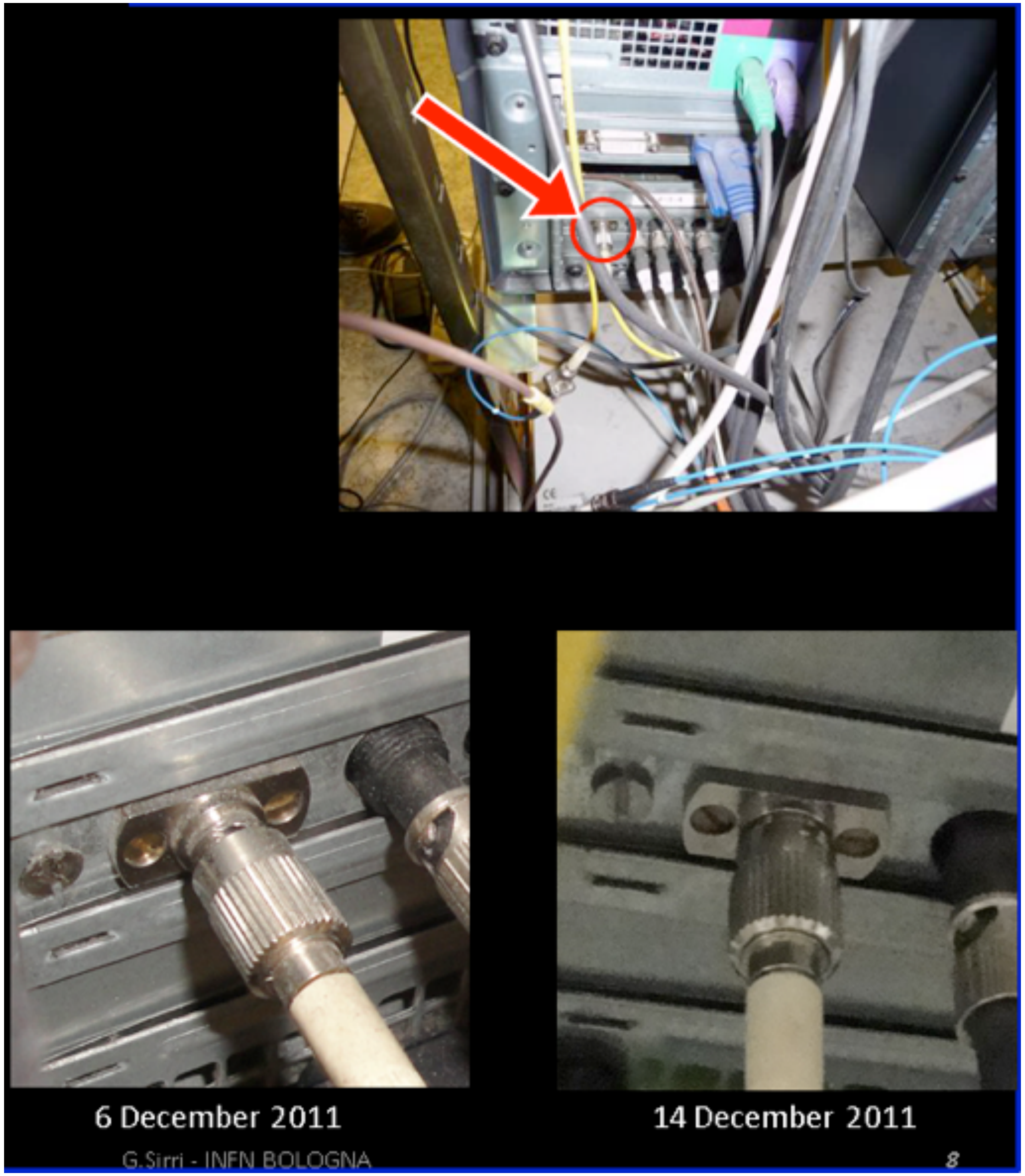
Confirms original results: beam structure as cause excluded

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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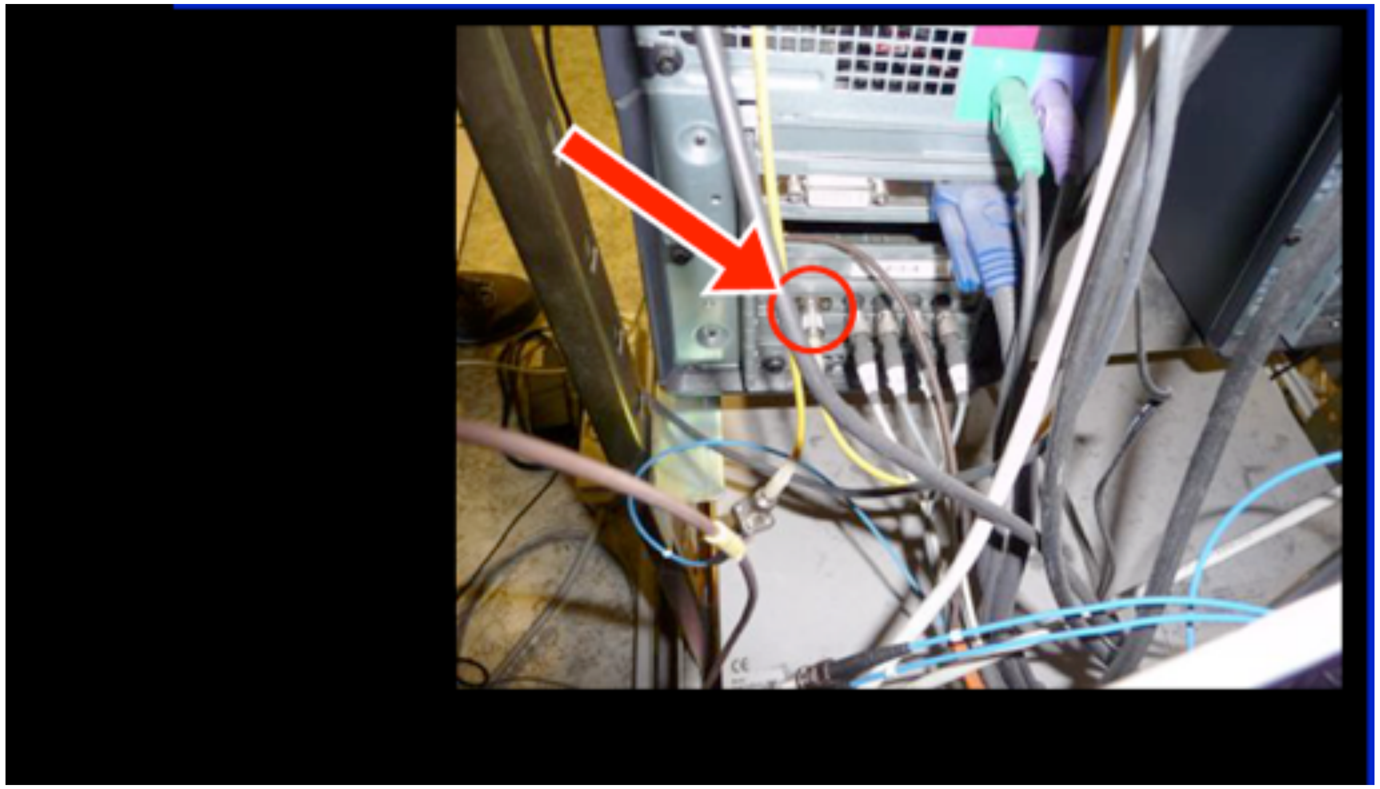
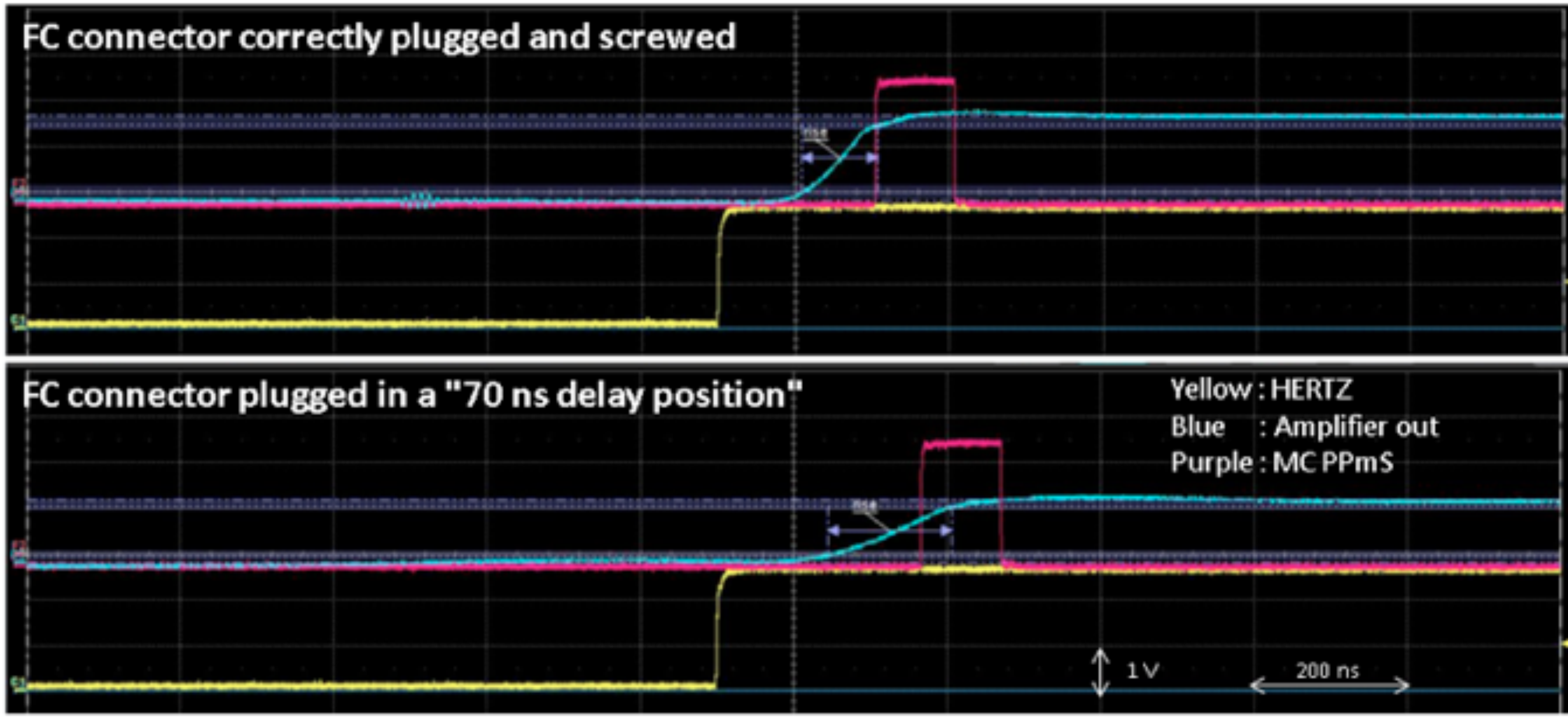
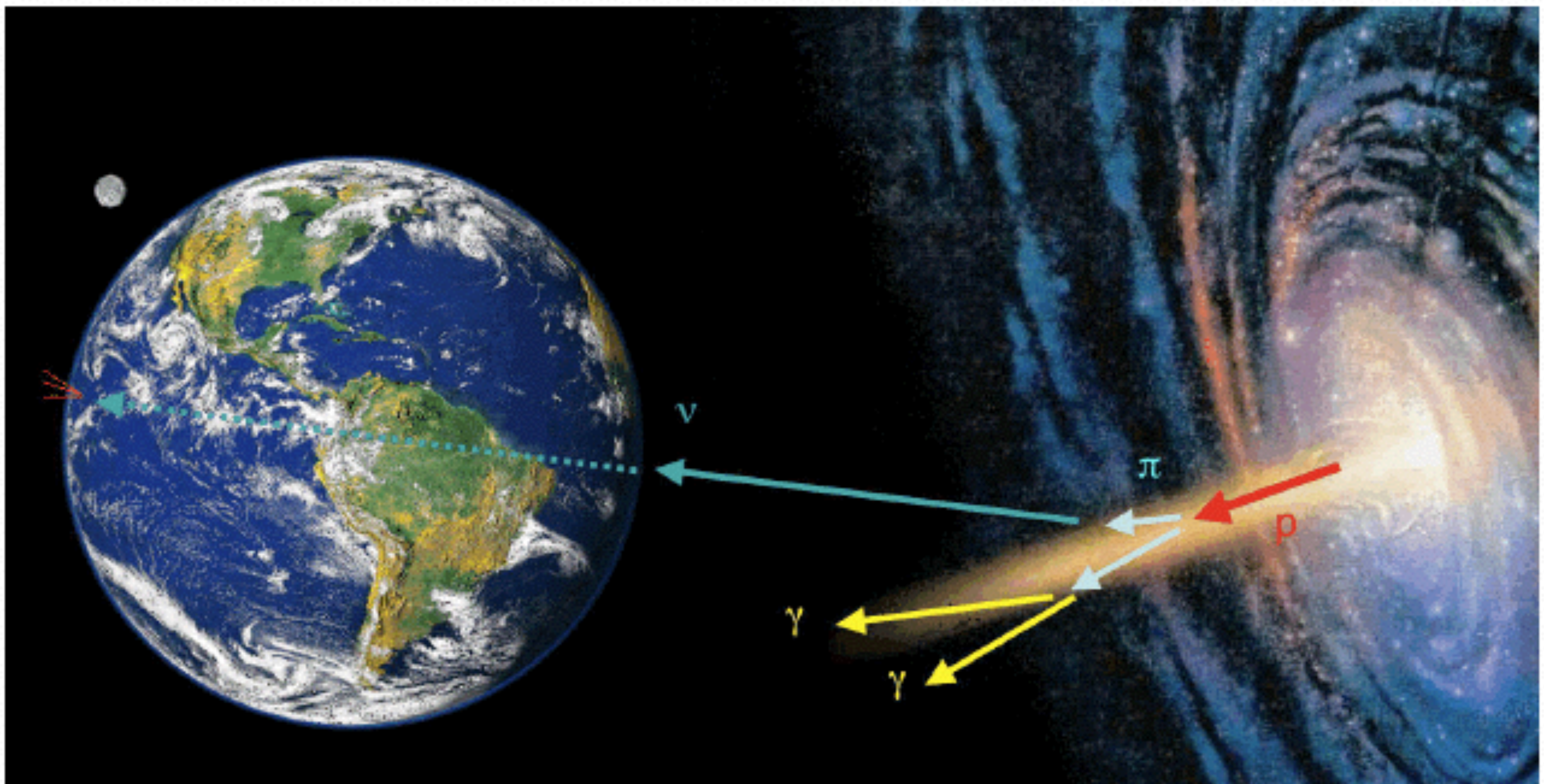




Now: The time of flight is bang on, within a few ns!

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)

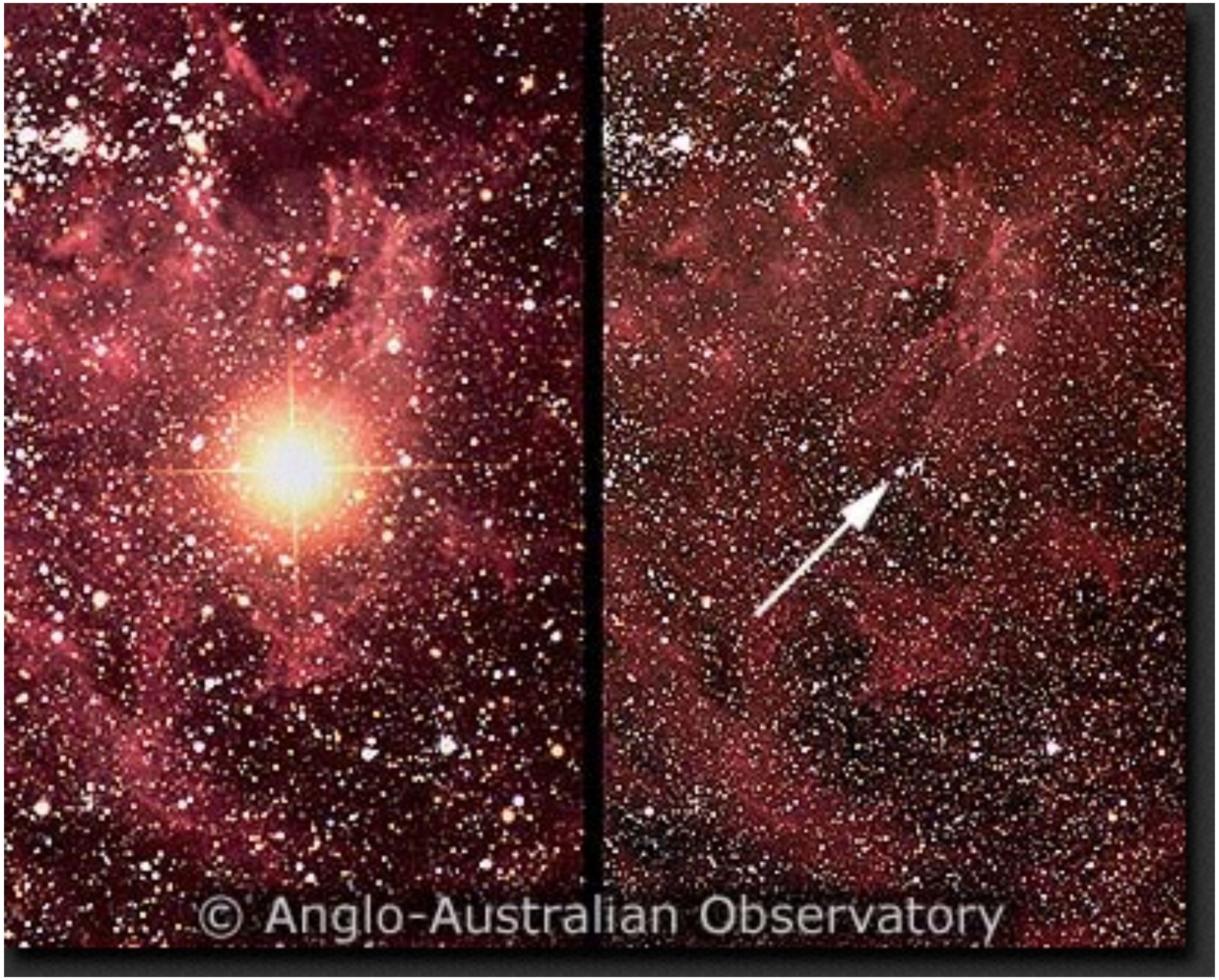
$$\gamma + \gamma \rightarrow e^+ + e^- \qquad e^+ + e^- \rightarrow \nu + \bar{\nu}$$

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

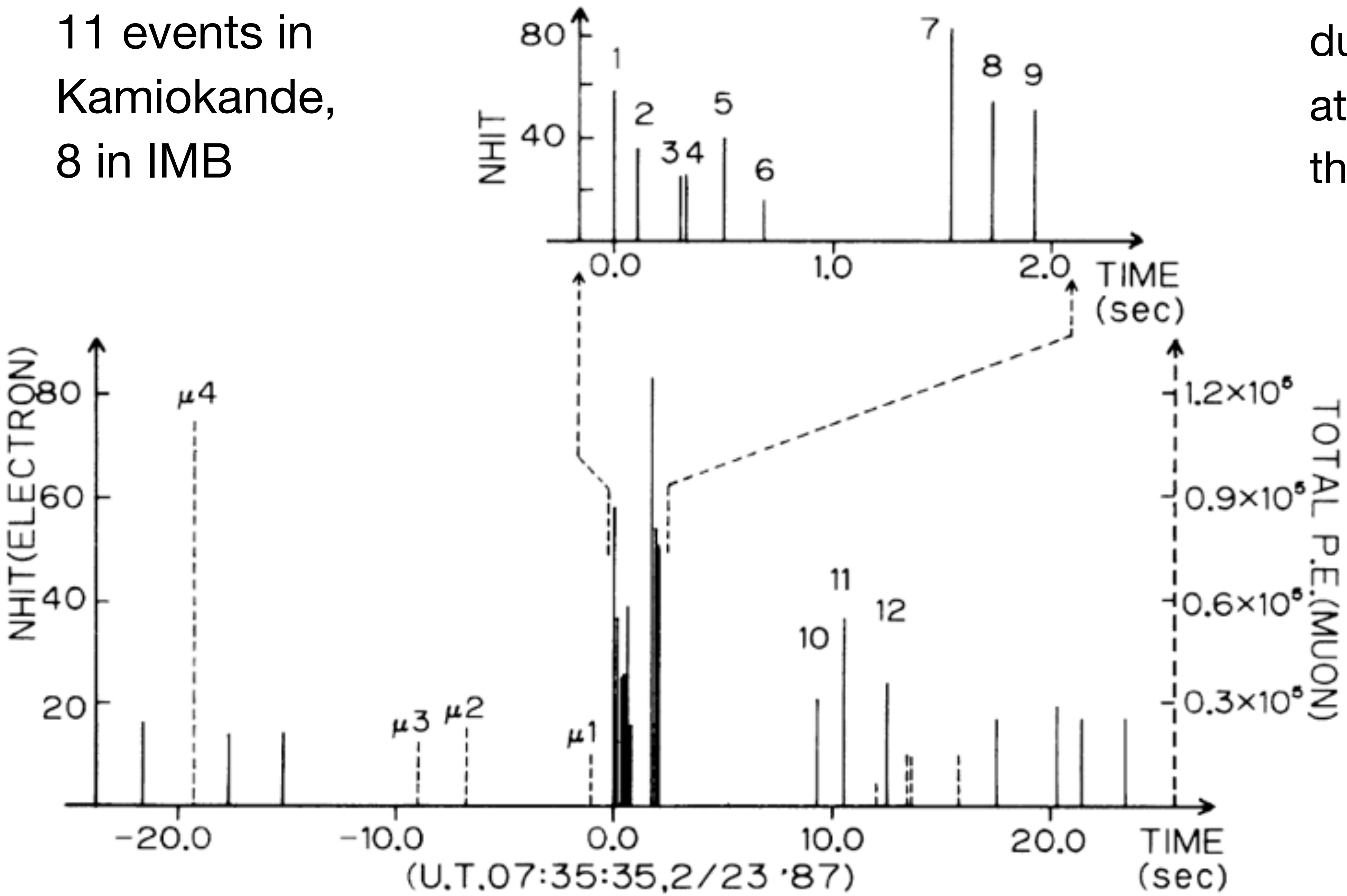
- Supernova explosion 1987 in the Large Magelanic Cloud



Kamiokande Signal

- A confirmed extraterrestrial signal

11 events in Kamiokande, 8 in IMB

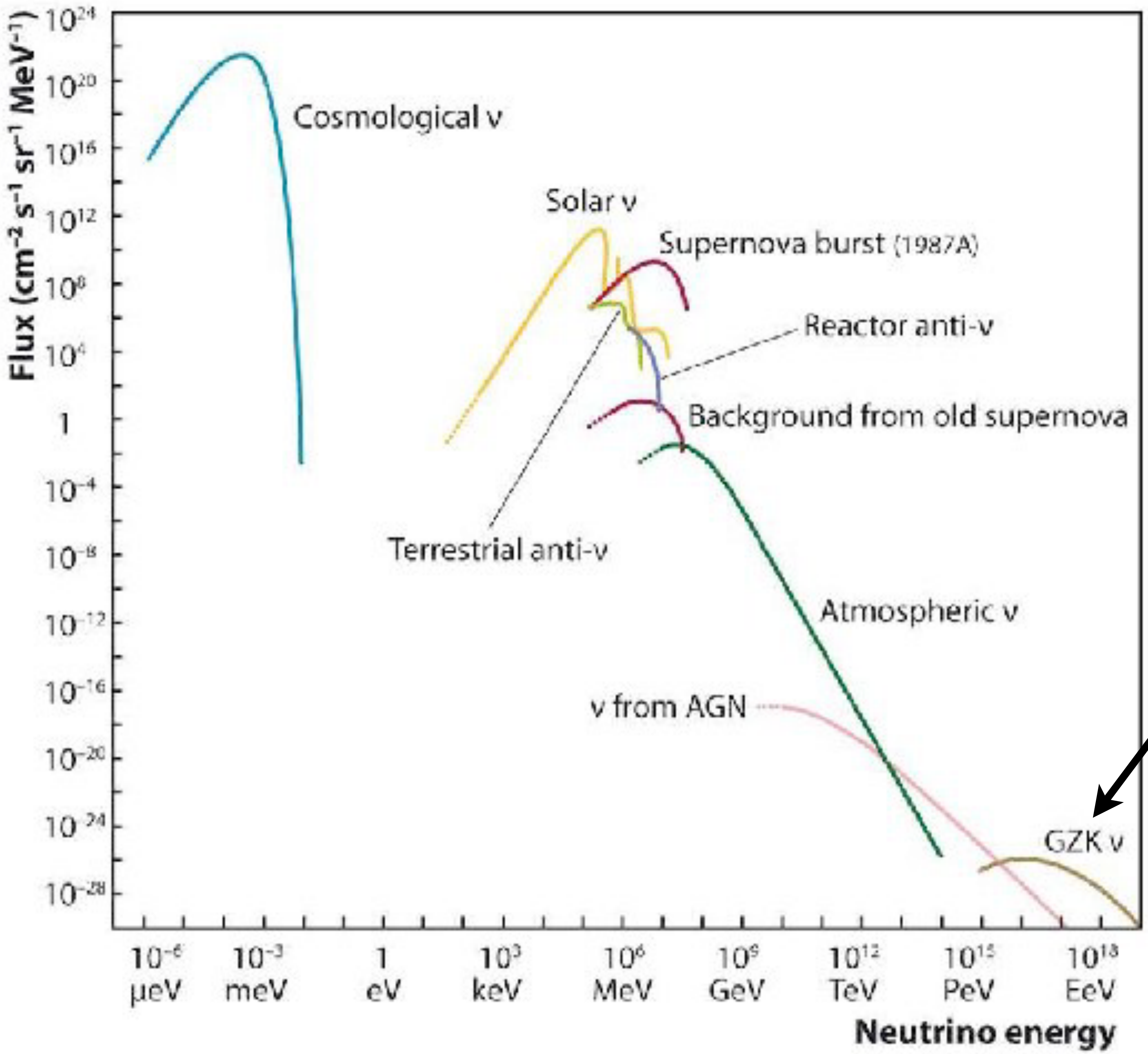


PRL 58, 1490 (1987)

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



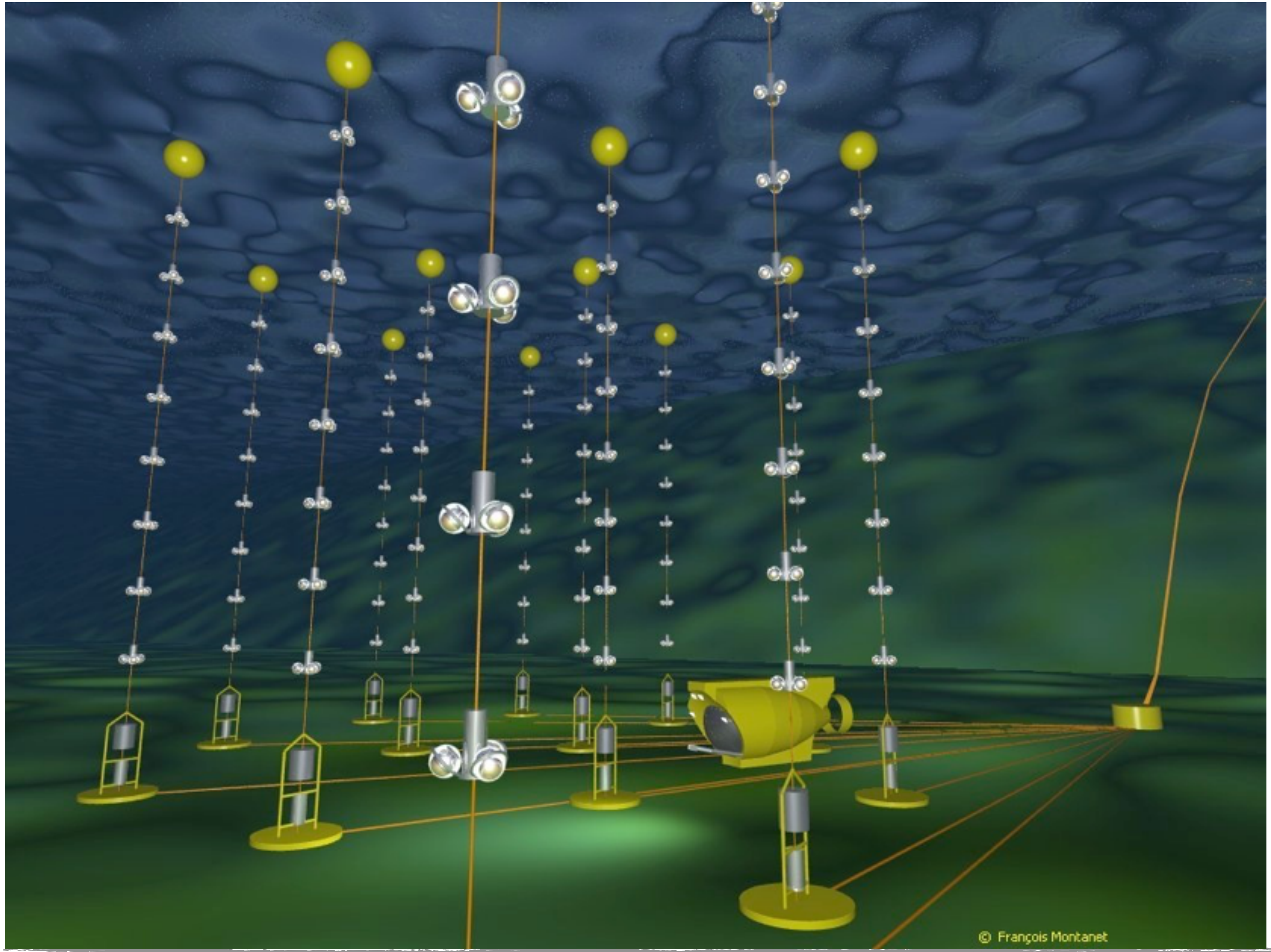
cosmogenic neutrinos: Produced in decays of pions from GZK events: Could give hints on sources and production mechanisms of highest-energy cosmic rays

in principle a "guaranteed discovery" with enough sensitivity

Detectors for Neutrino Astronomy

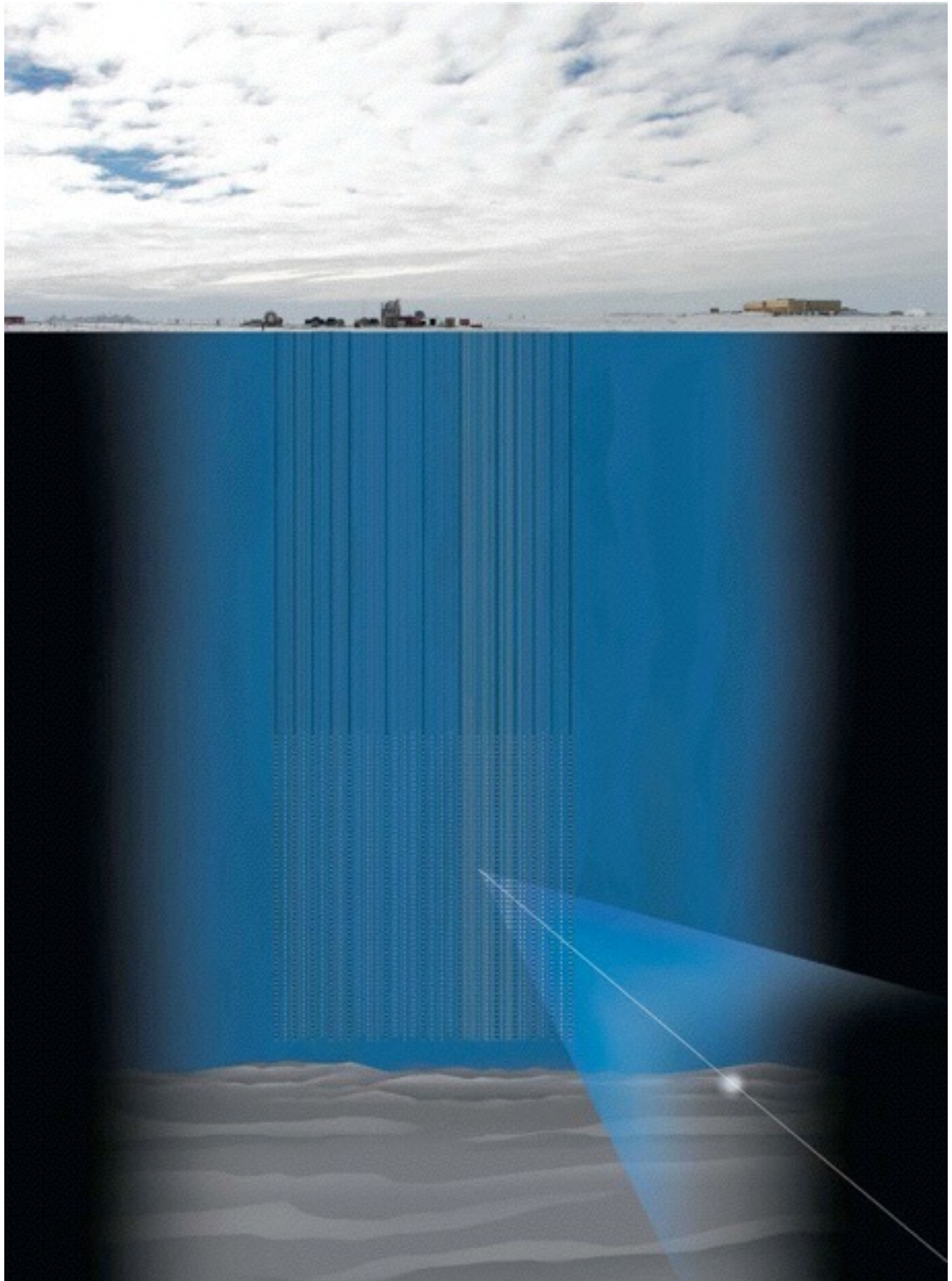
- Different detection techniques, depend on energy and sensitivity
- Energies in the TeV - PeV range:
  - Cherenkov detectors: large signal, relatively low energy threshold, requires a high sensor density due to light absorption
    - Amanda/IceCube: Antarctic ice as Cherenkov medium
    - Antares/Baikal/KM3NeT: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

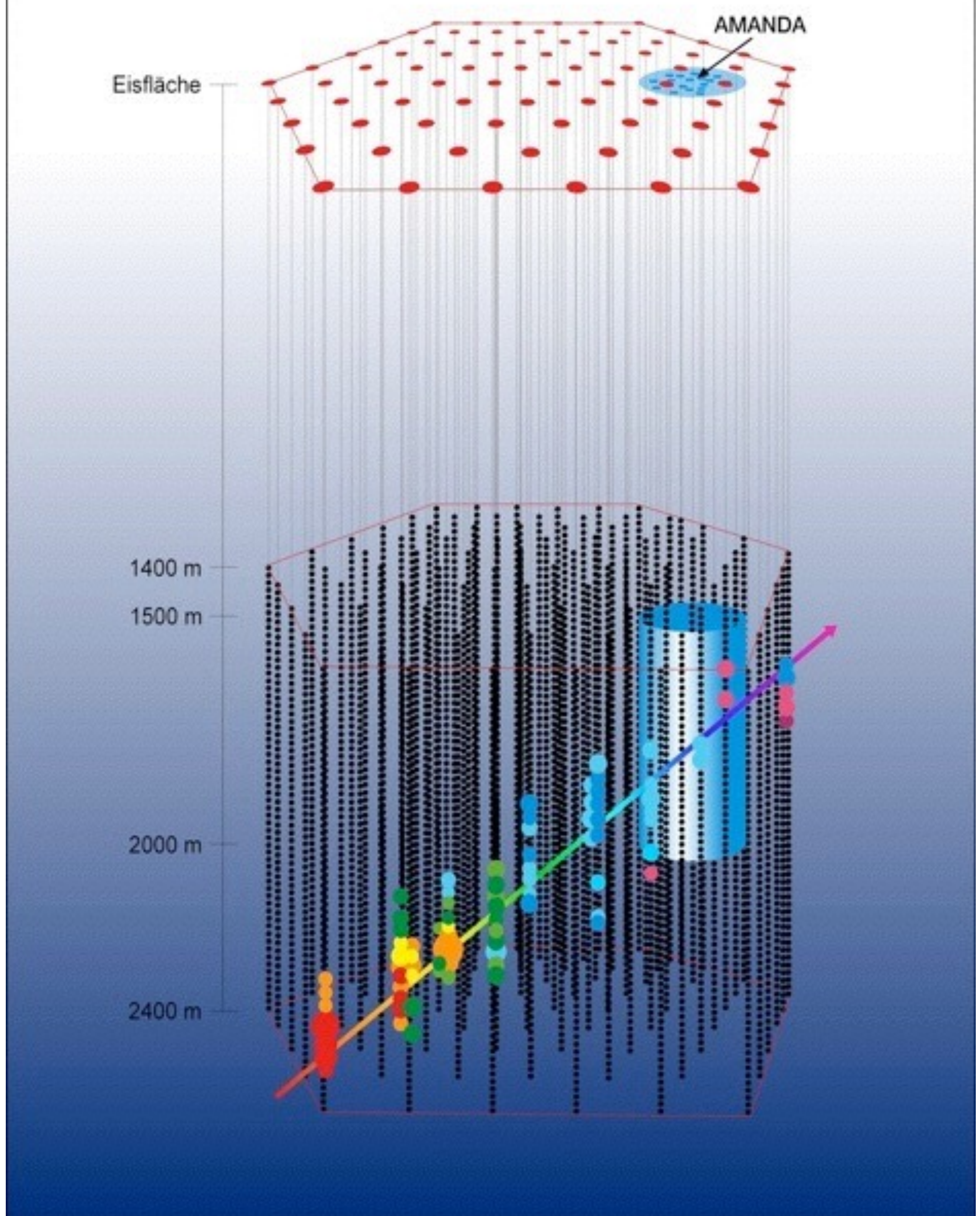


- 2.5 km deep off the southern coast of France (Toulon, between Marseille and Saint Tropez)

Amanda/IceCube

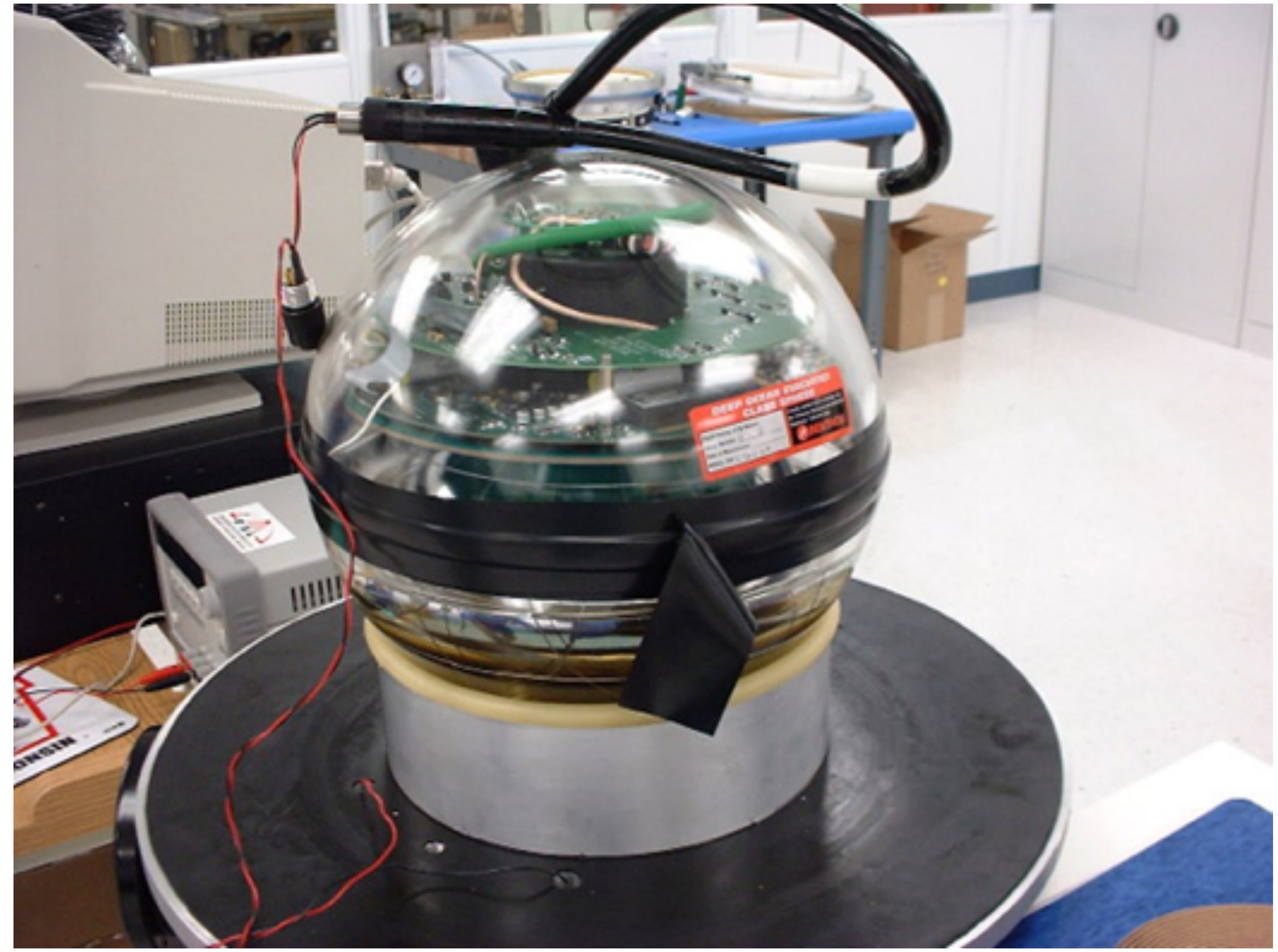


IceCube: 1 km^3 instrumented volume



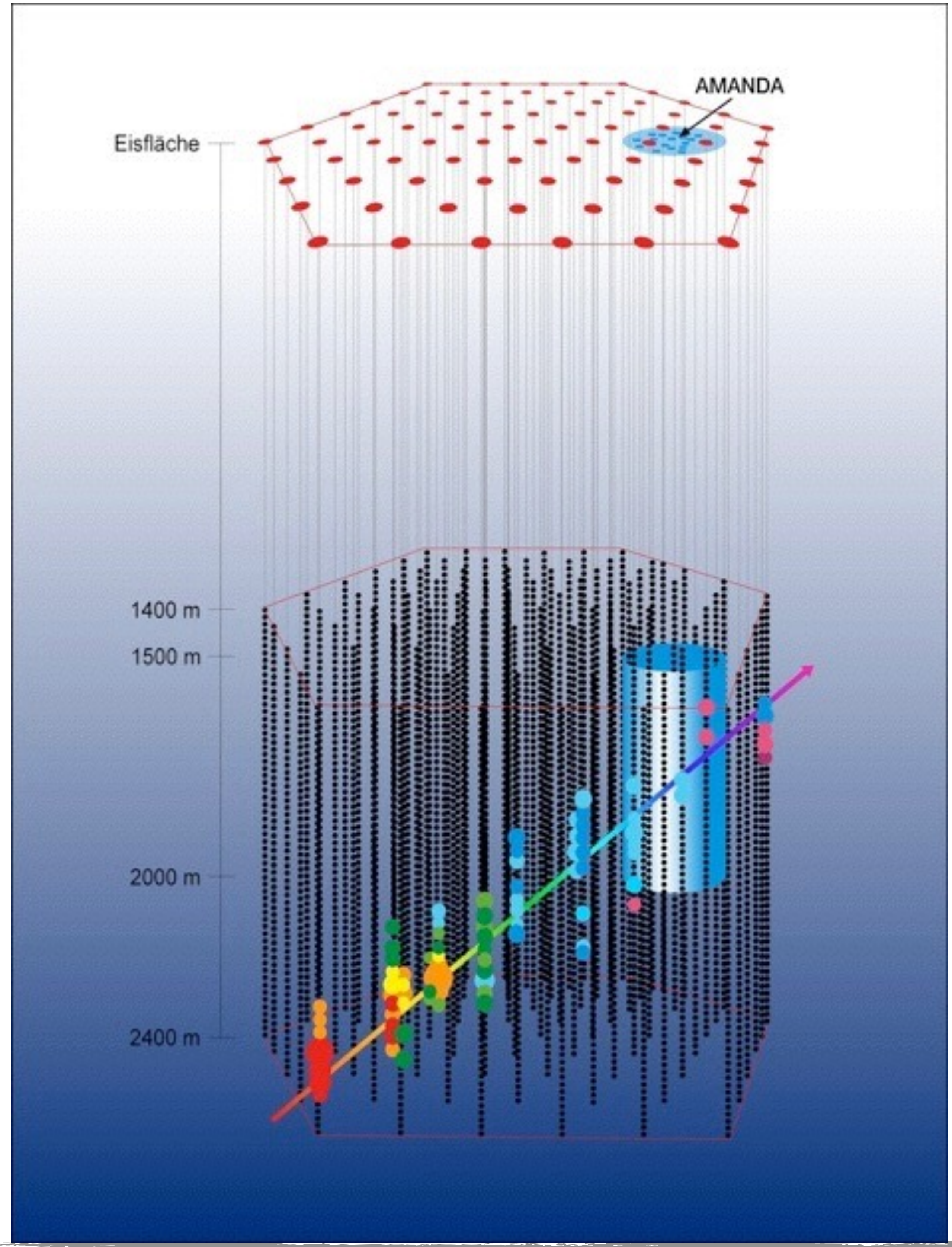
Amanda/IceCube: Neutrinos at the South Pole

Amanda/IceCube: Neutrinos at the South Pole



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

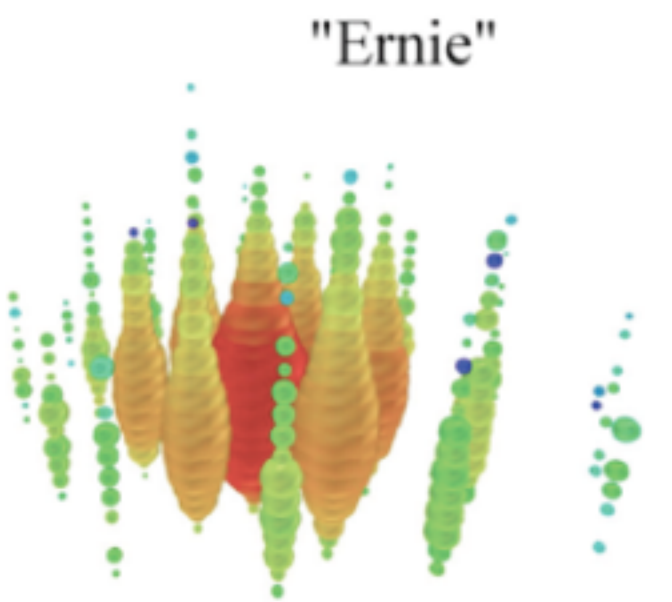
IceCube Event

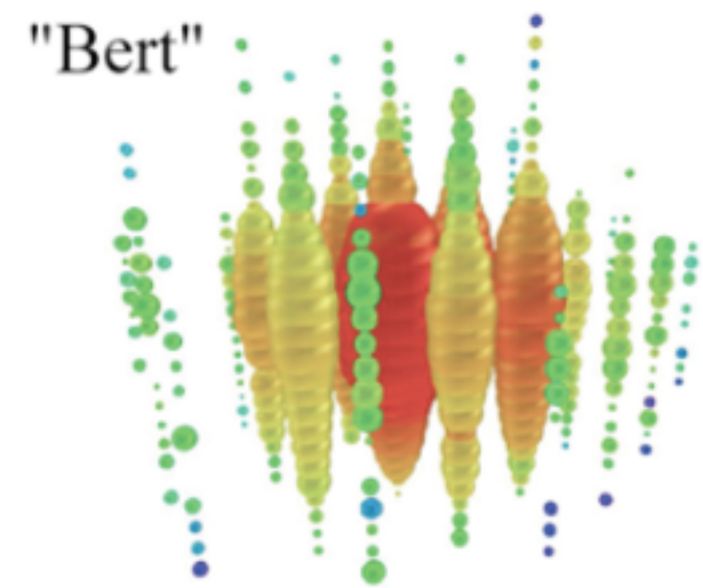


- Arrival time of light at individual detectors allows the determination of the muon direction and with that the direction of the neutrino

Highest Energies - First Observation 2012

- IceCube has observed two events:





1.14±0.17 PeV

1.04±0.16 PeV

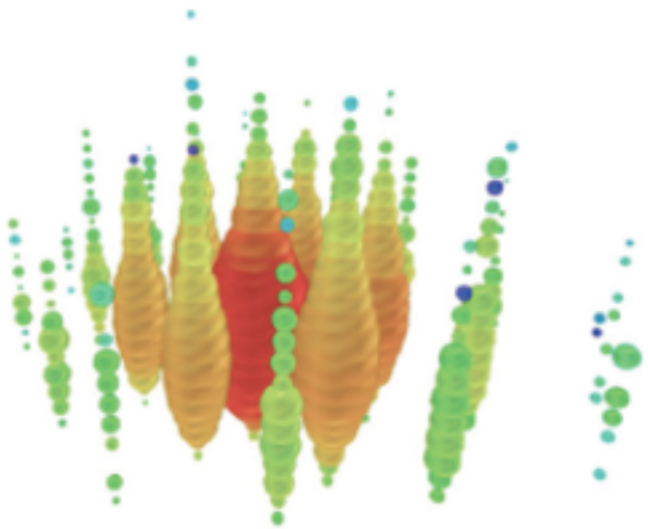
(visible energy in the detector, neutrino energy higher)

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

Highest Energies - First Observation 2012

- IceCube has observed two events:

"Ernie"



1.14±0.17 PeV

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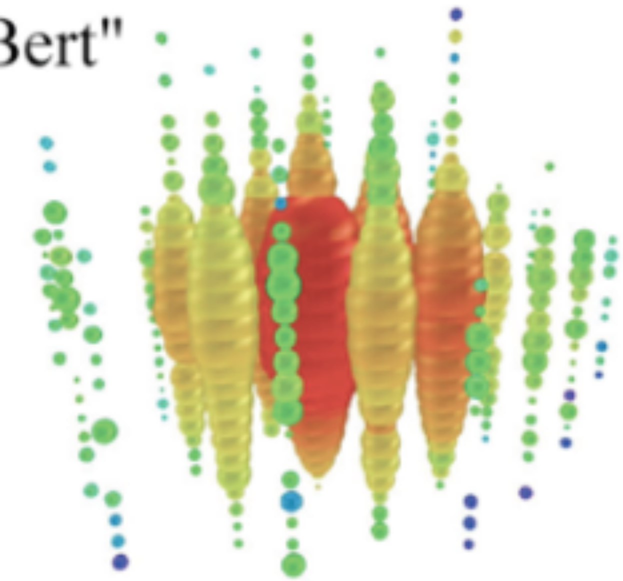
"Bert"



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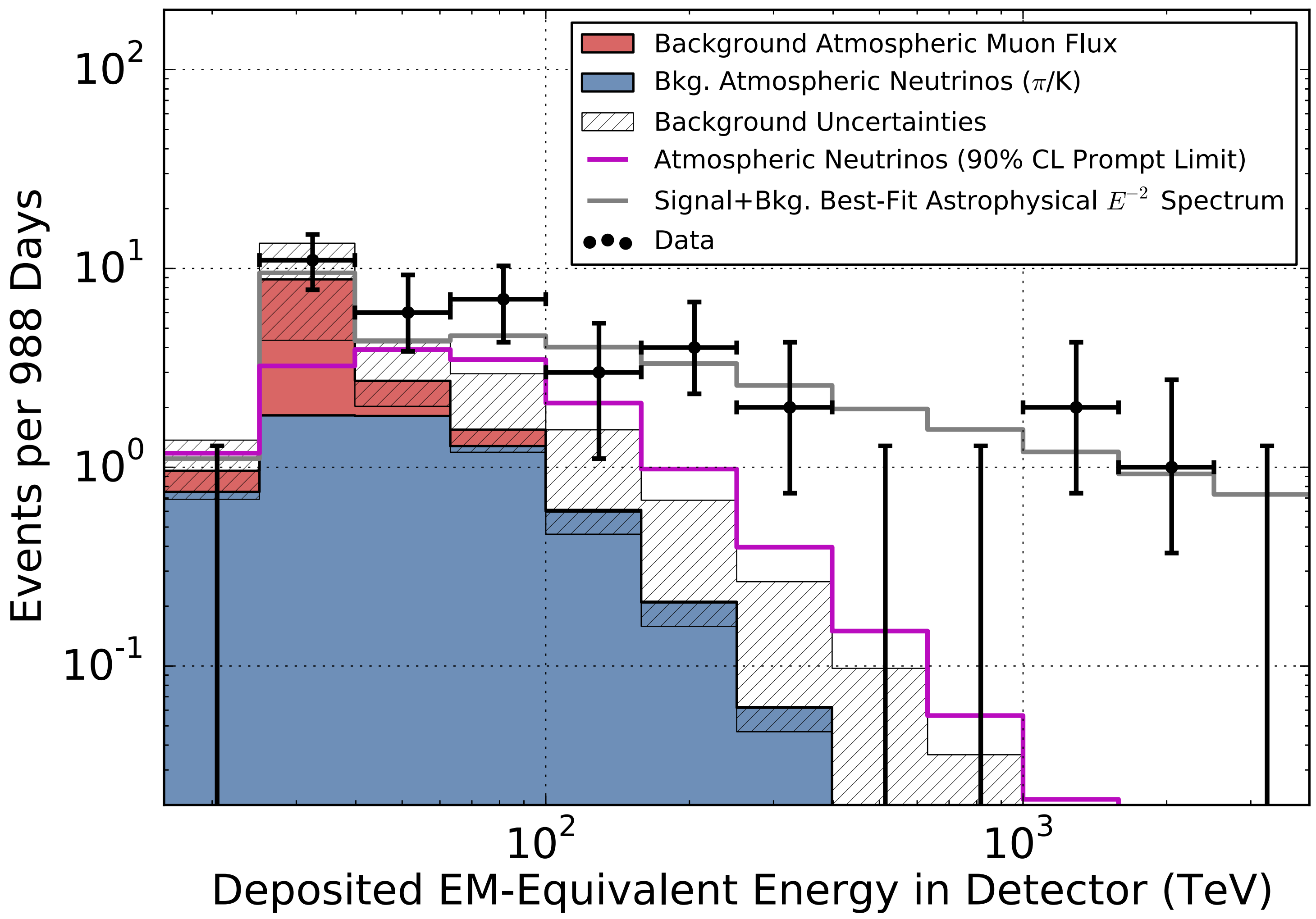
Now even an event at 2 PeV, in total 37 events > 30 TeV

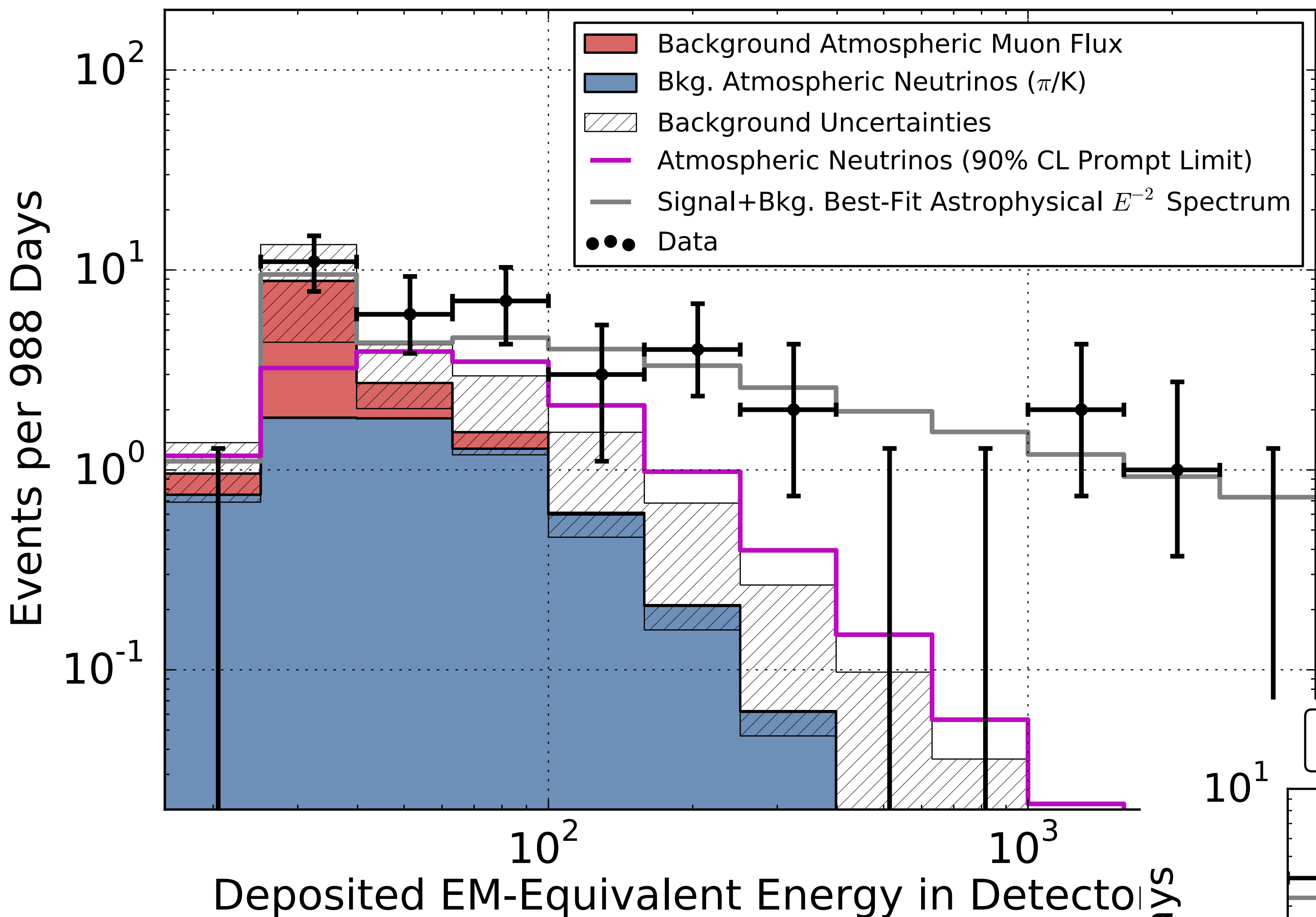
Neutrinos at Highest Energies



- 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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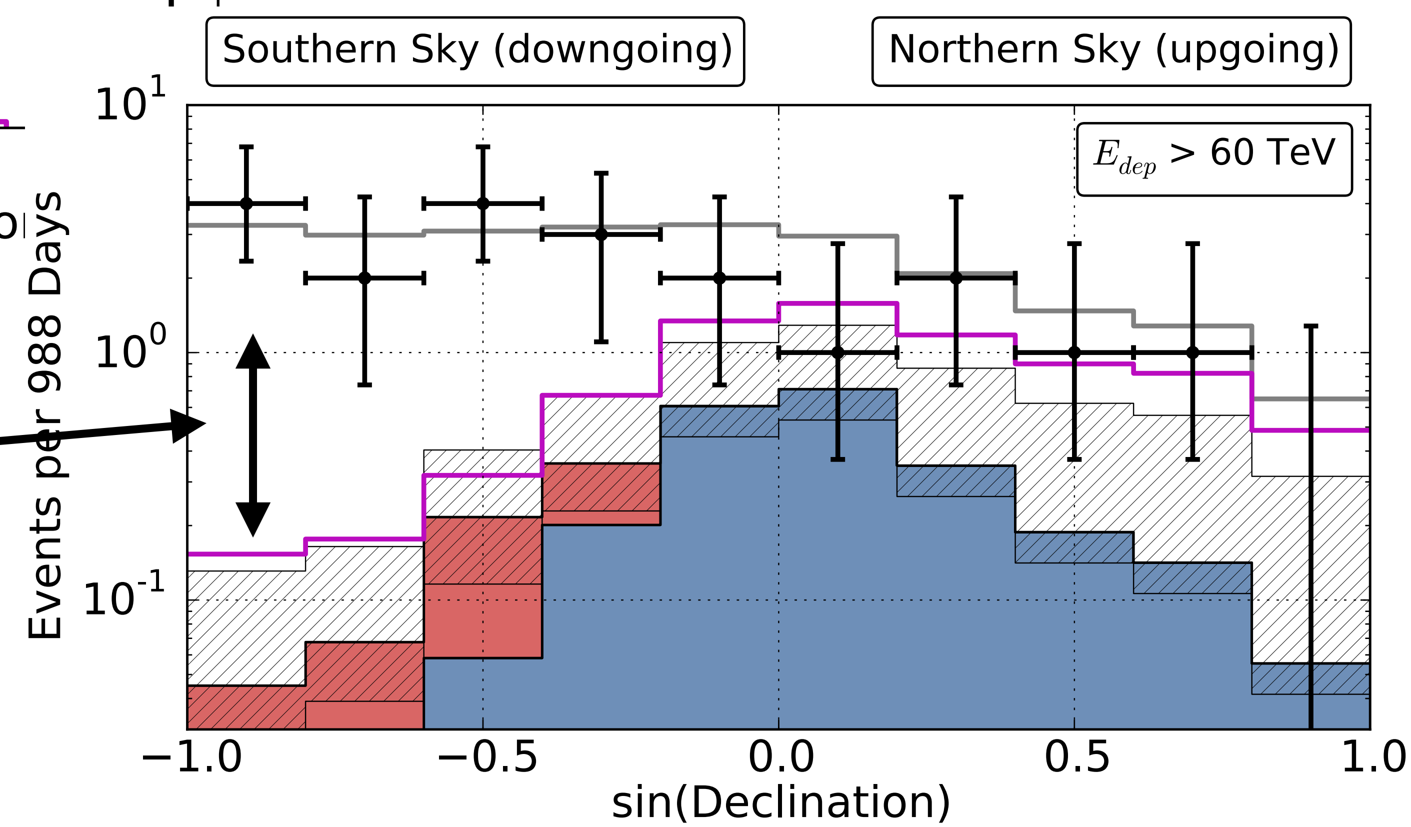
Effectivity of the exclusion of atmospheric neutrinos



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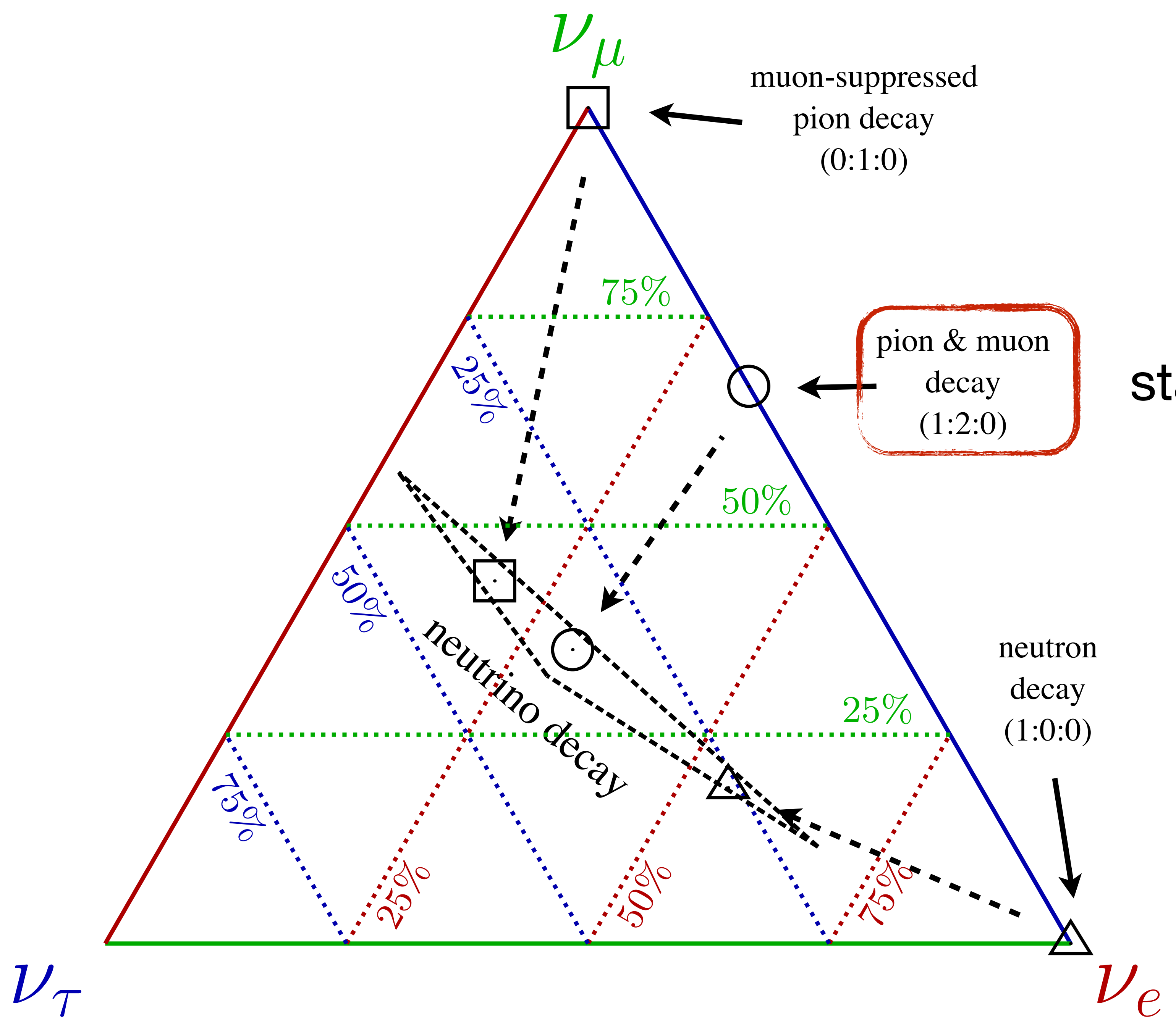
Cosmic Neutrino Sources

- 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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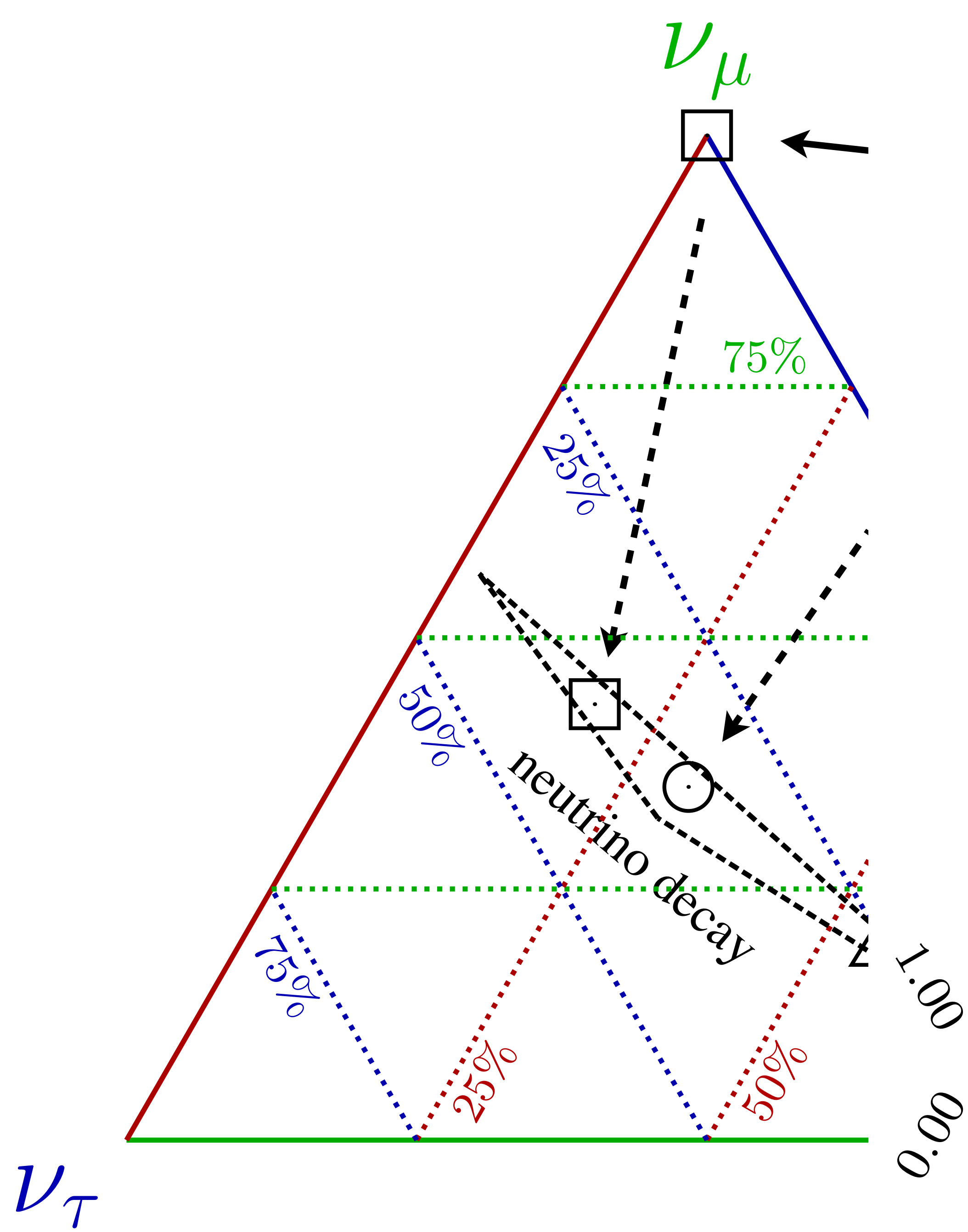

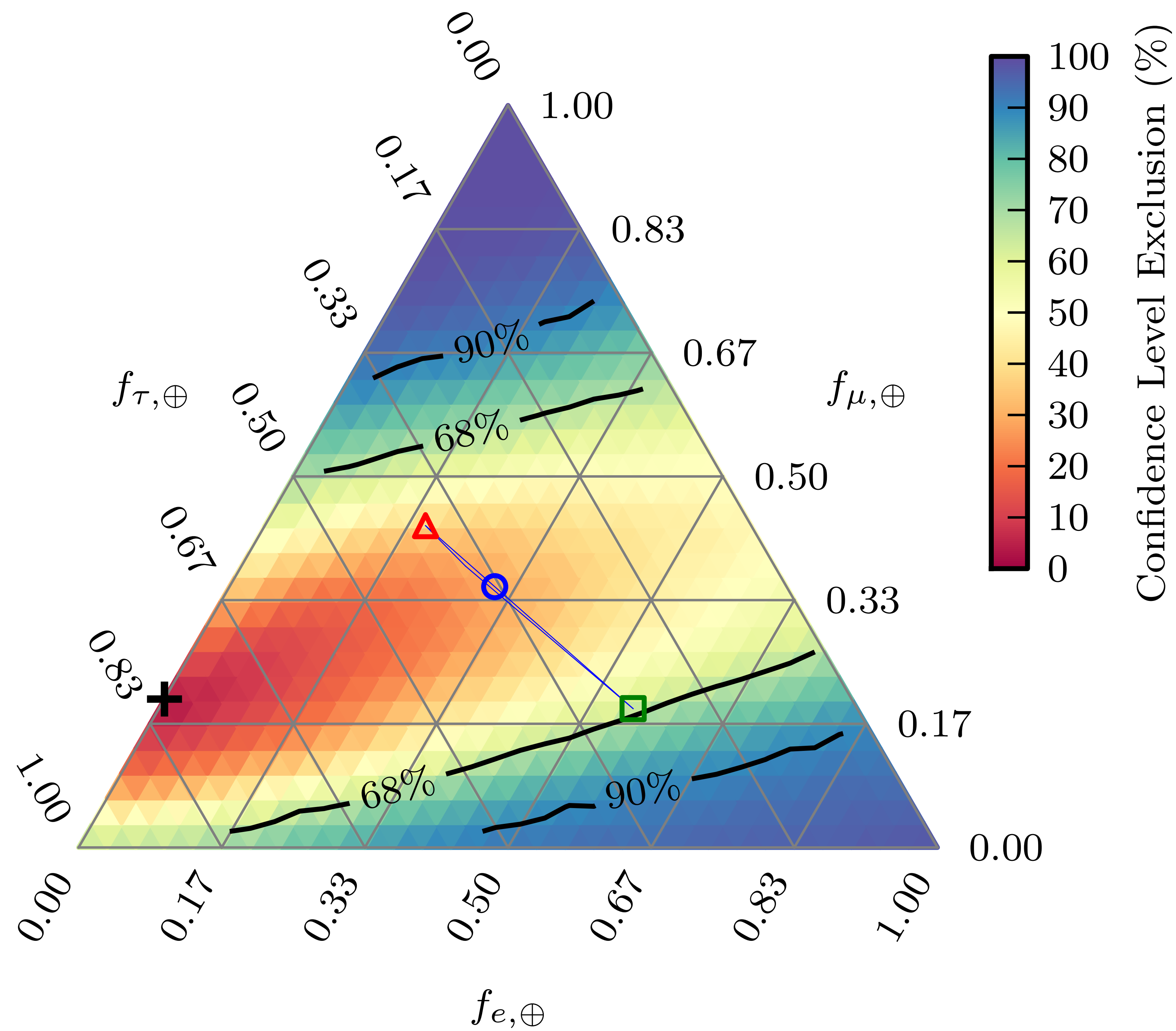

Summary

- 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 (and last) Lecture: 11.07., “Neutrinos II”, S. Bethke

Themenübersicht

11.04.	Einführung / Introduction
18.04.	Erdgebundene Beschleuniger / Accelerators
25.04.	Detektoren in der Nicht-Beschleuniger-Physik / Detectors
02.05.	Kosmische Beschleuniger / Cosmic Accelerators
09.05.	Das Standardmodell / The Standard Model
16.05.	Pfingsten - Keine Vorlesung! No Lecture
23.05.	QCD und Jet Physik an Lepton Beschleunigern / QCD and Jets
30.05.	Präzisionsexperimente (g-2) / Precision Experiments
06.06.	Gravitationswellen / Gravitational Waves
13.06.	Kosmische Strahlung I / Cosmic Rays I
20.06.	Kosmische Strahlung II / Cosmic Rays II
27.06.	Dunkle Materie & Dunkle Energie / Dark Matter & Dark Energy
04.07.	Neutrinos I
11.07.	Neutrinos II