Journées de Rencontre Jeunes Chercheurs 2013

Introduction to Neutrino physics

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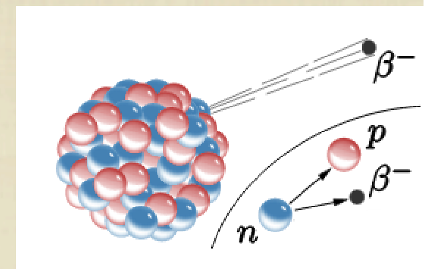
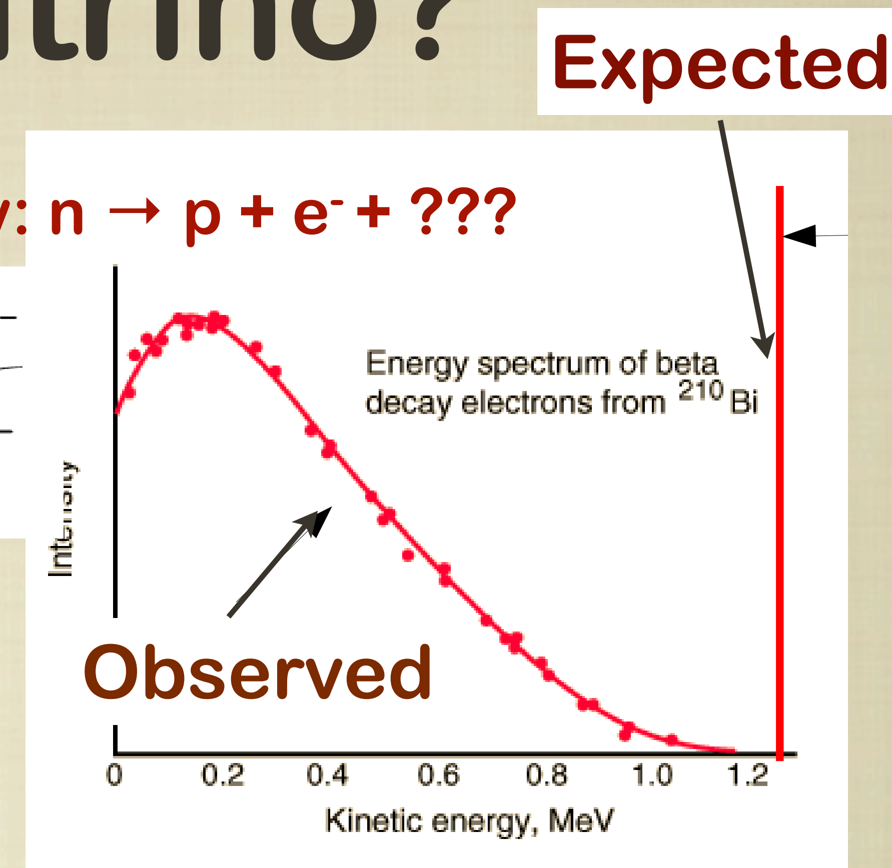
Why do we need a neutrino?

β decay: n → p + e^- + ???





- 1914 - Chadwick: continuos spectrum in the β decay
  - Energy not conserved?
- 1931 - Pauli: new particle escaping the detection that takes the energy

Dear Radioactive Ladies and Gentlemen,

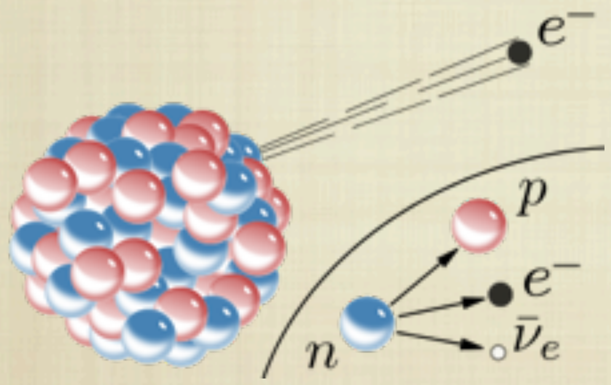
I have hit upon a desperate remedy to save the law of conservation of energy: the possibility that in the nuclei there could exist electrically neutral particles, which I will call neutrons, that have spin 1/2 and obey the exclusion principle. The mass of the neutrons should be of the same order of magnitude as the electron mass. (...) in beta decay, in addition to the electron, a neutron is emitted such that the sum of the energies of neutron and electron is constant.

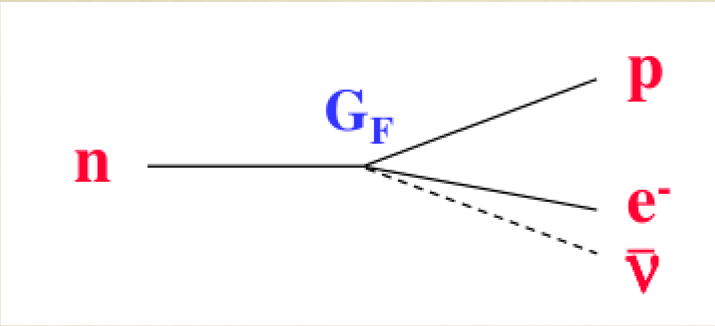
I admit that my remedy may seem almost improbable because one probably would have seen them. Thus, dear radioactive people, scrutinize and judge. -

Unfortunately, I cannot personally appear in Tübingen since I am indispensable here in Zürich because of a ball on the night from December 6 to 7.

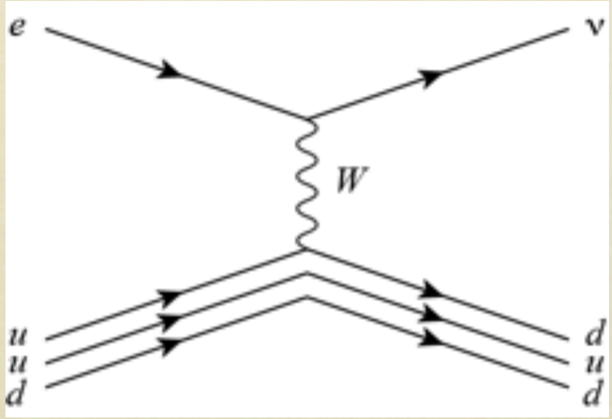
Fermi theory

- 1934 - Fermi: first theory of the weak interactions (4 fermions theory):
  - n → p + e- + ν
- ν → neutrino
- Energy is conserved in the β decay
- Introduce the Fermi constant G_F
- Paper rejected by Nature because it was “too speculative”





1964: Standard Model

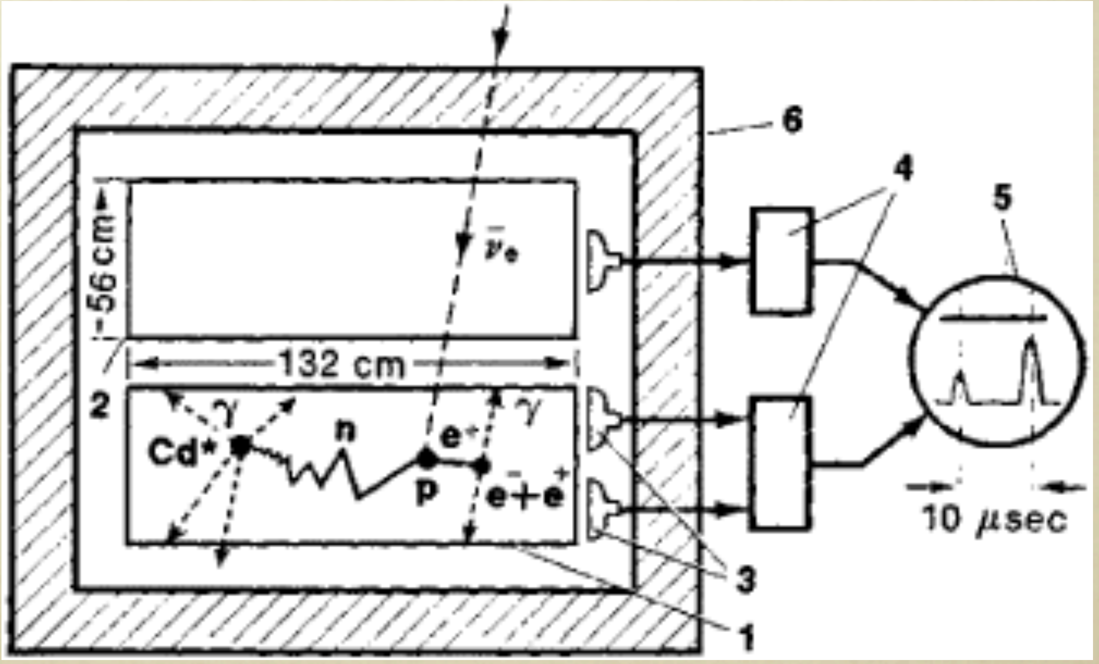


First observation of neutrinos

- If neutrinos are emitted in β-decay why we didn't observe them?
  - Small neutrino cross-section $\sigma \sim 10^{-38}$ cm^2 → Pauli: desperate remedy!
- Bruno Pontecorvo (1946):
  - use inverse β-decay → $\bar{\nu} + p \rightarrow e^+ + n$
  - Intense neutrino sources (Sun or Reactors)

- 1956: Cowan and Reines experiment
- Inverse β-decay at Savannah reactor
  - $e^+ \rightarrow 2\gamma$ of 511 keV
  - $n + {}^{108}Cd \rightarrow {}^{109}Cd^* \rightarrow {}^{109}Cd + \gamma$
- Observed difference between reactor on and reactor off → first detection of antineutrinos

25 years after Pauli remedy!
(Higgs took 50 years)



The second neutrino

- 1962: experiment of Lederman, Schwartz, Steinberger
- First man-made neutrino beam produced by pion decay: $\pi \rightarrow \mu + \nu_\mu$
- ν_μ interact into the detector producing a muon track
- $\nu_\mu \neq \nu_e \rightarrow$ at least 2 different neutrino families

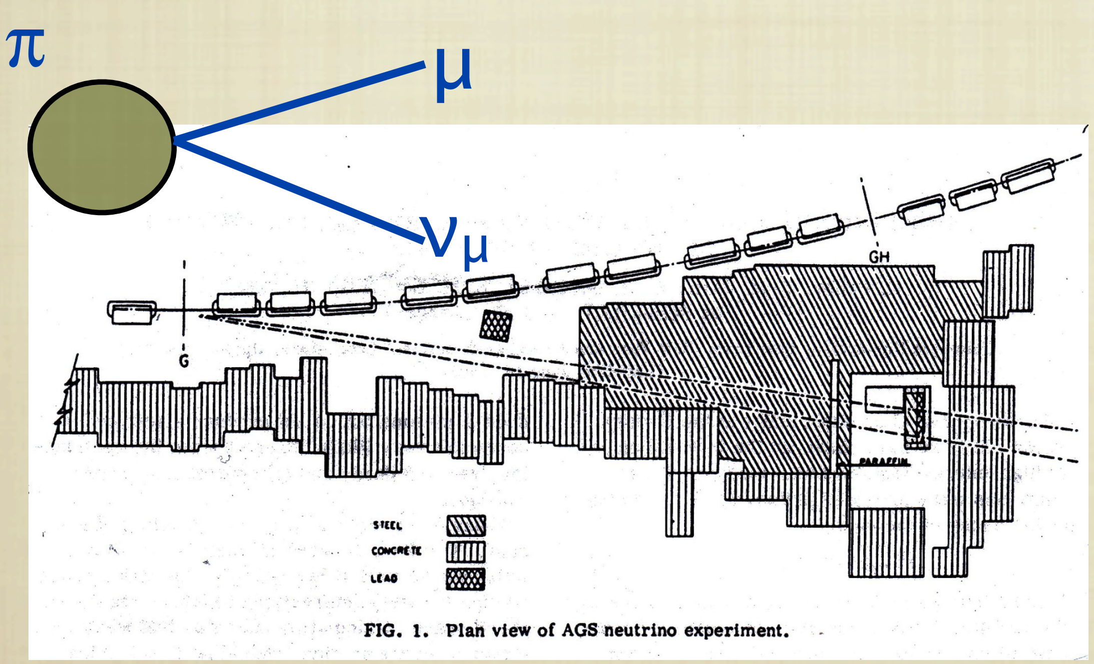
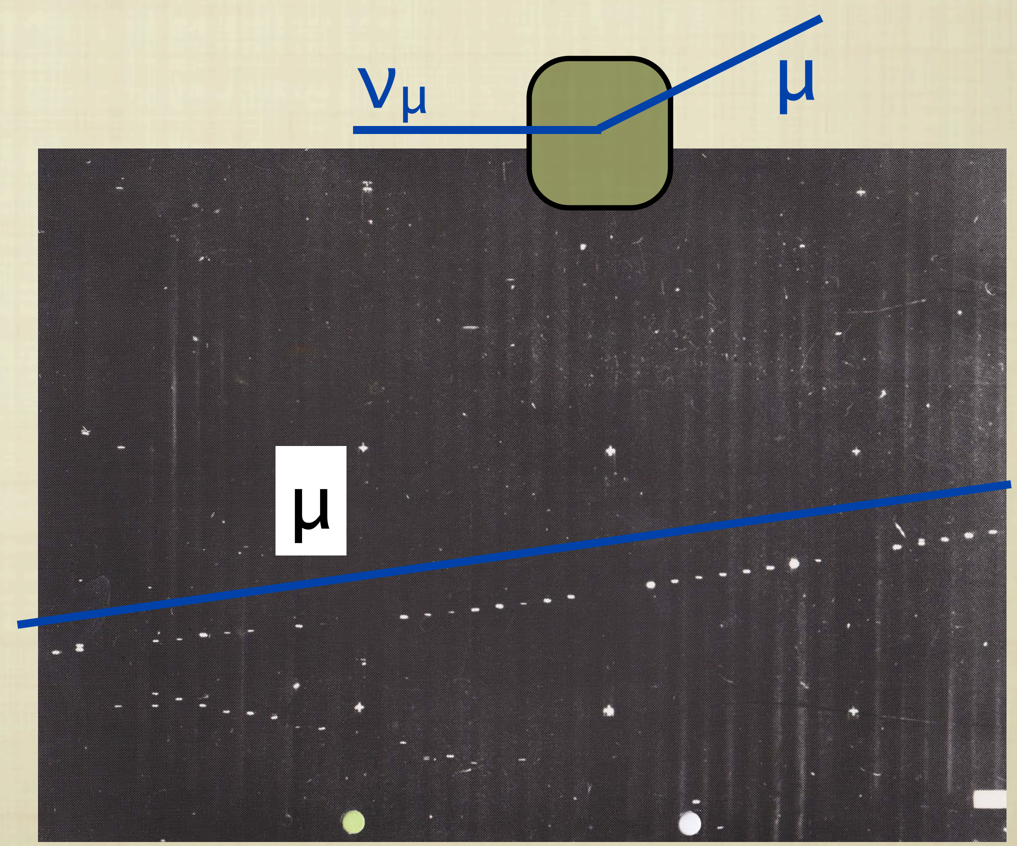
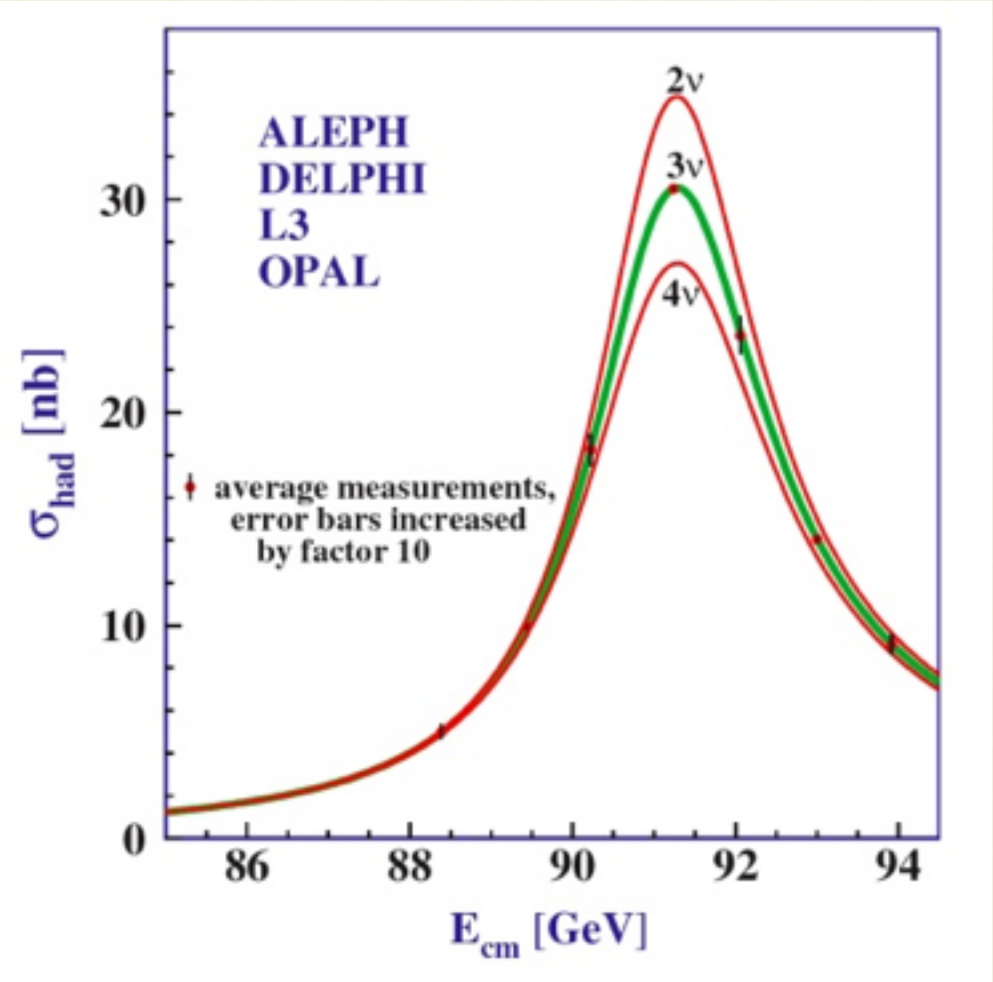


FIG. 1. Plan view of AGS neutrino experiment.



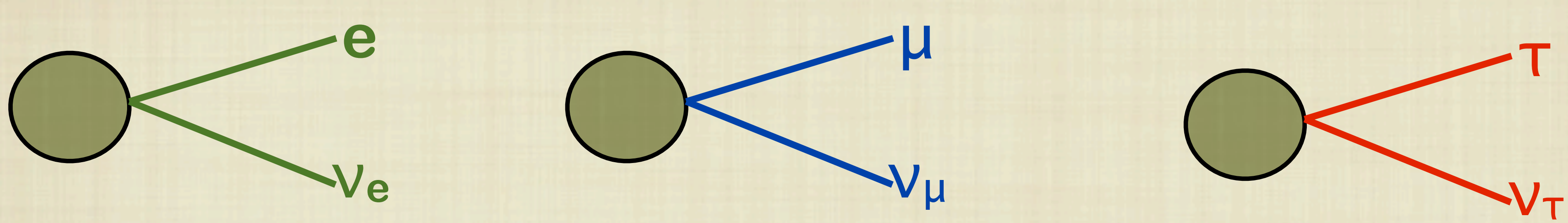
How many neutrinos?



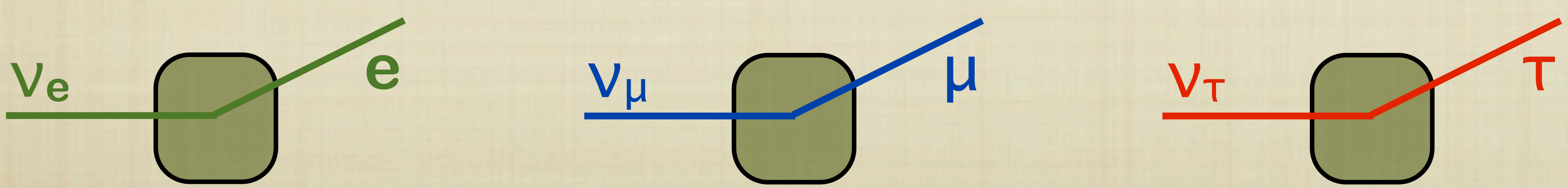
- LEP → look at the invisible Z width: Z→νν
  - The width depends on the number of neutrino families
- 3 active neutrino families
- ν_τ discovered in 2000 using photographic emulsions

Neutrinos in the SM

- In the standard model neutrino are massless
- Exist 3 different neutrino families ν_e, ν_μ, ν_τ
- Produced from a large variety of processes in association with the corresponding charged lepton (e, μ, τ)



- Detected through the weak interactions with an atom in which the neutrino produce a charged lepton with the same flavor as the interacting neutrino



That's all

- We introduced them as desperate remedy
- We calculated their cross-section
- We observed them
- 3 active families
- Perfectly fit in the SM (massless neutrinos)

Neutrino physics was over ~20 years ago…

That's all

- We introduced them as desperate remedy
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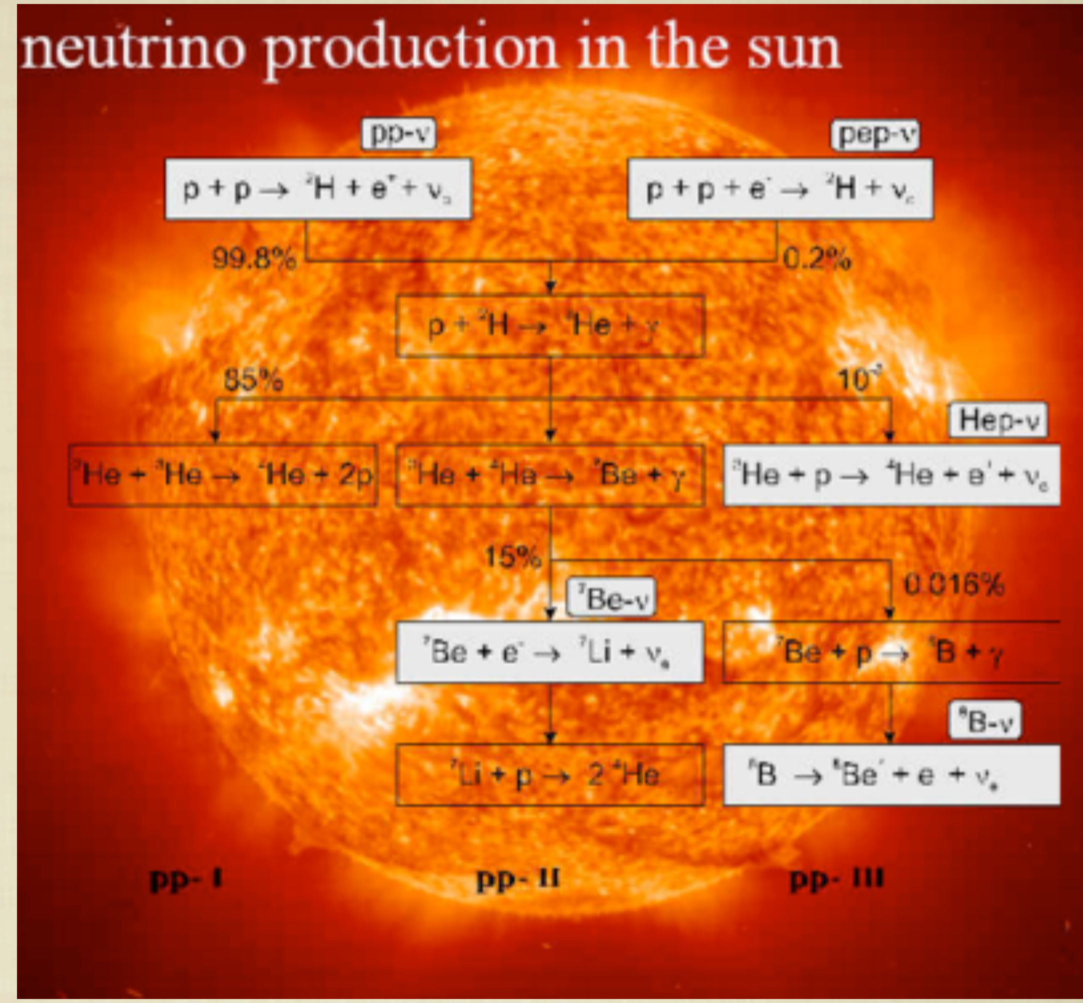
Neutrino physics was over ~20 years ago...

- I would have worked on searching Omar Sharif
- No neutrino session at the JJC2013

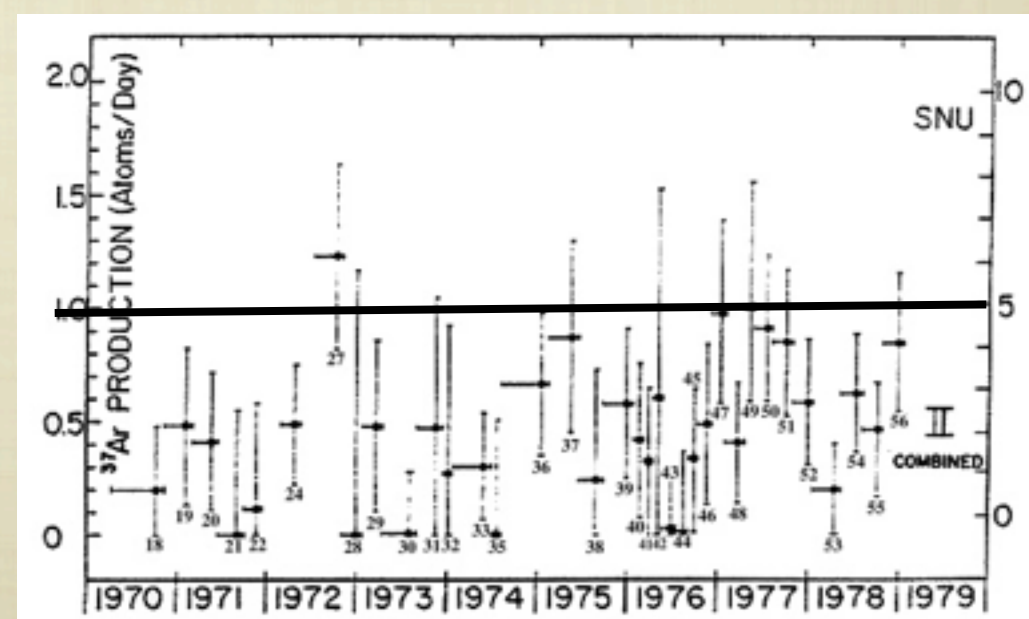
Solar neutrino problem

- ν_e produced by nuclear reactions inside the Sun
- Fluxes computed in ~1960 by Bahcall

Reaction	Label	Flux($cm^{-2}s^{-1}$)
$p+p \rightarrow {}^2H + e^+ + \nu_e$	pp	$5.95 \cdot 10^{10}$
$p+e^- + p \rightarrow {}^2H + \nu_e$	pep	$1.40 \cdot 10^8$
${}^3He + p \rightarrow {}^4He + e^+ + \nu_e$	hep	$9.3 \cdot 10^3$
${}^7Be + e^- \rightarrow {}^7Li + \nu_e$	${}^7Be$	$4.77 \cdot 10^9$
${}^8B \rightarrow {}^8Be^* + e^+ + \nu_e$	${}^8B$	$5.05 \cdot 10^6$

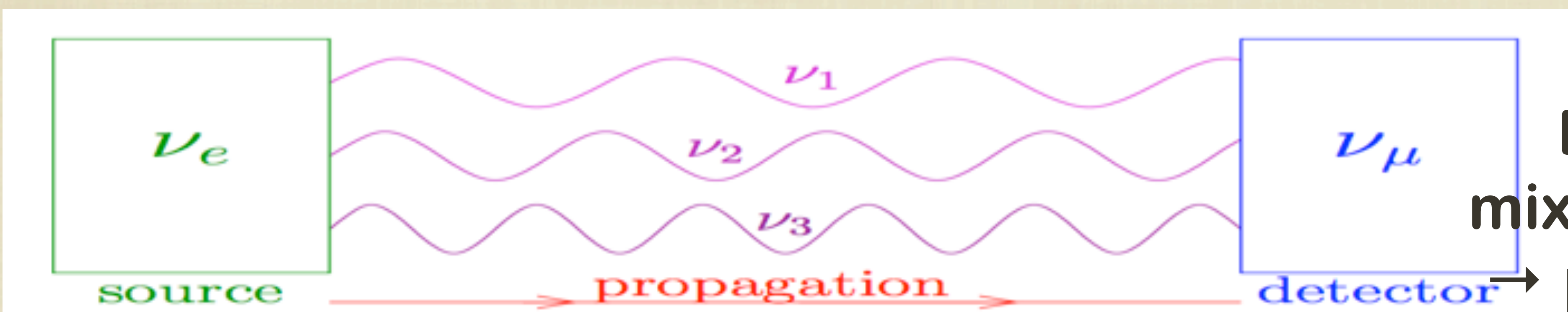


- 1968: Davies experiment (Homestake)
- First detection of Solar neutrinos
  - $\nu + {}^{38}Cl \rightarrow {}^{37}Ar + e-$
- Deficit of neutrinos of ~2/3
  - Why?



Neutrino oscillations

- First idea by Bruno Pontecorvo in 1957
- Neutrinos are produced in flavor eigenstates → ν_e, ν_μ, ν_τ
- Neutrinos propagate as mass eigenstates → ν_1, ν_2, ν_3 mixture of flavor eigenstates ν_e, ν_μ, ν_τ
- At the detection a flavor eigenstate is detected → it can be different from the one that was produced



Different mixture of $\nu_{1,2,3}$ → μ from ν_μ is detected

ν_e produced in a mixture of $\nu_{1,2,3}$

$\nu_{1,2,3}$ travel at different speed because they have different masses → interference

Neutrino oscillation implies massive neutrinos!

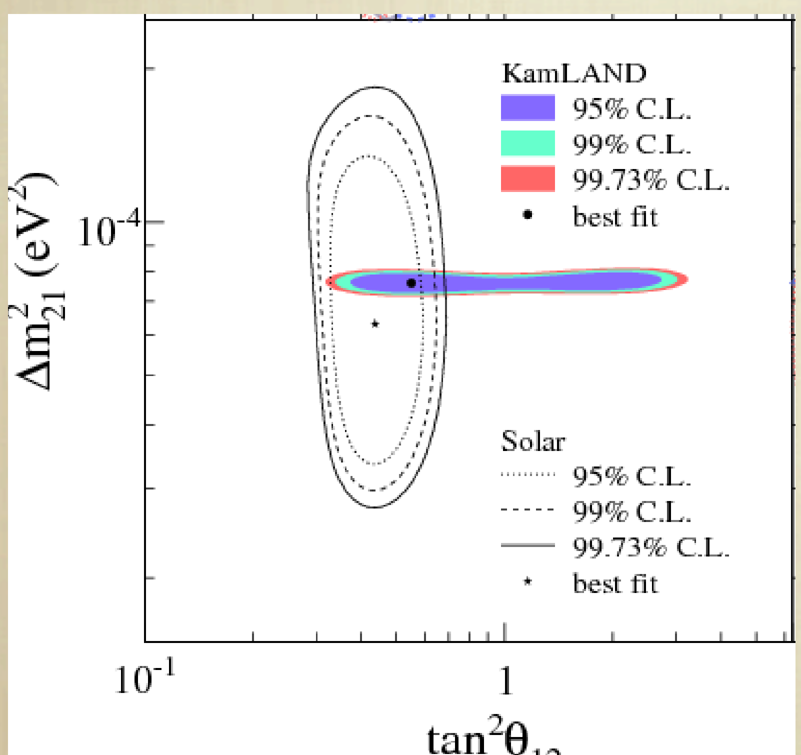
$$P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta_{ij})\sin^2\left(\frac{1.27\Delta m^2_{ij} L}{E_\nu}\right)$$

PMNS matrix

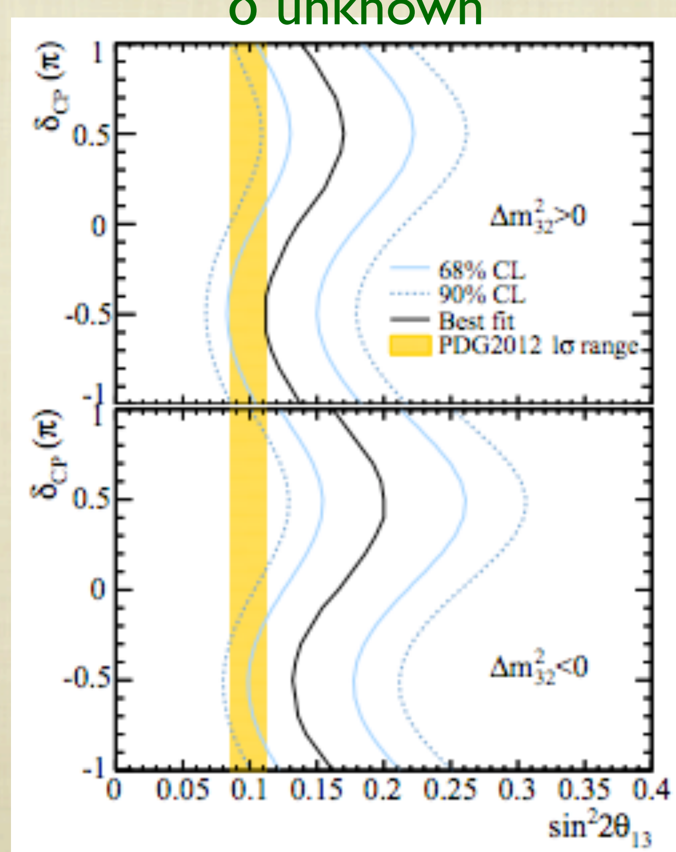
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{-i\delta} & 0 & \cos\theta_{13}\end{pmatrix}\begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

3 mixing angles (θ_{12}, θ_{23}, θ_{13}), 2 mass differences → all measured
1 CP violation phase δ → not known yet
Order of neutrino masses (hierarchy) unknown:
$m_{1,2}<m_3$ (normal hierarchy) or $m_3<m_{1,2}$ (inverted hierarchy)

Solar (SNO, KamLand)
→ θ_{12}, Δm_{12}

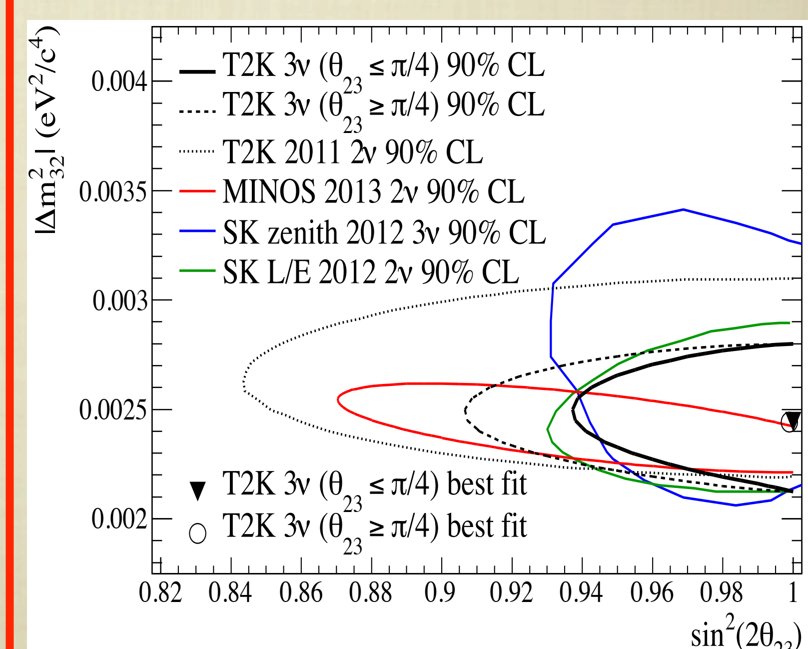


Recently measured $\sin^2(2\theta_{13})\sim0.10$
δ unknown



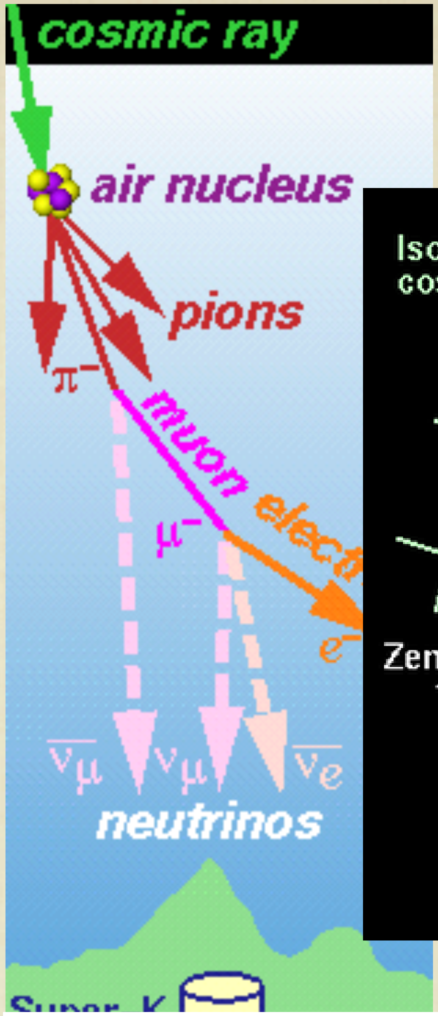
Atmospheric (K2K, SK, Minos)
→ θ_{23}, Δm_{23}

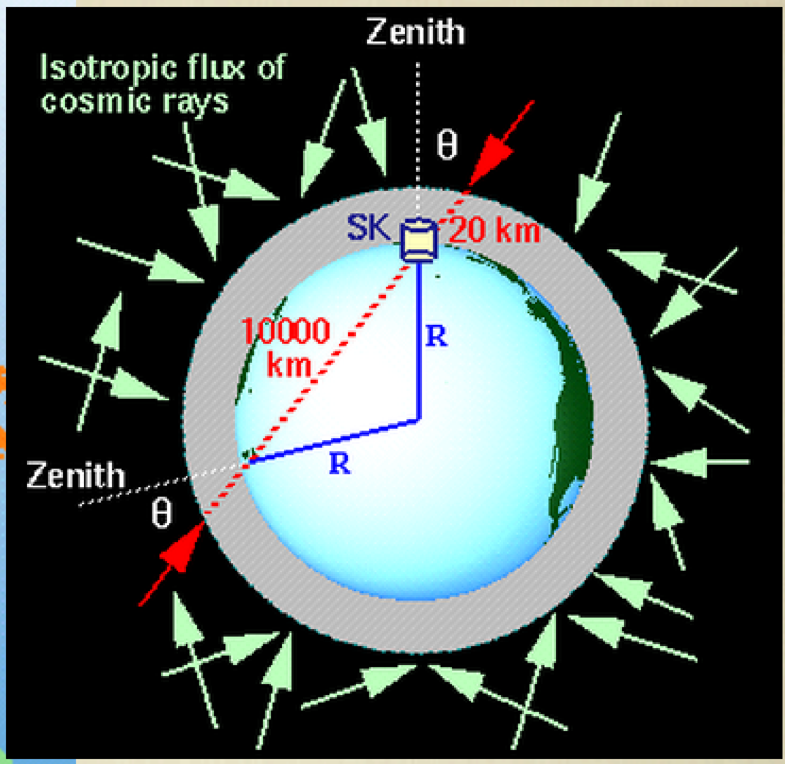
$\Delta m_{23}^2 = (2.32\pm0.10)10^{-3}$ eV^2
$\sin^2(2\theta_{23}) > 0.90$(90% C.L.)

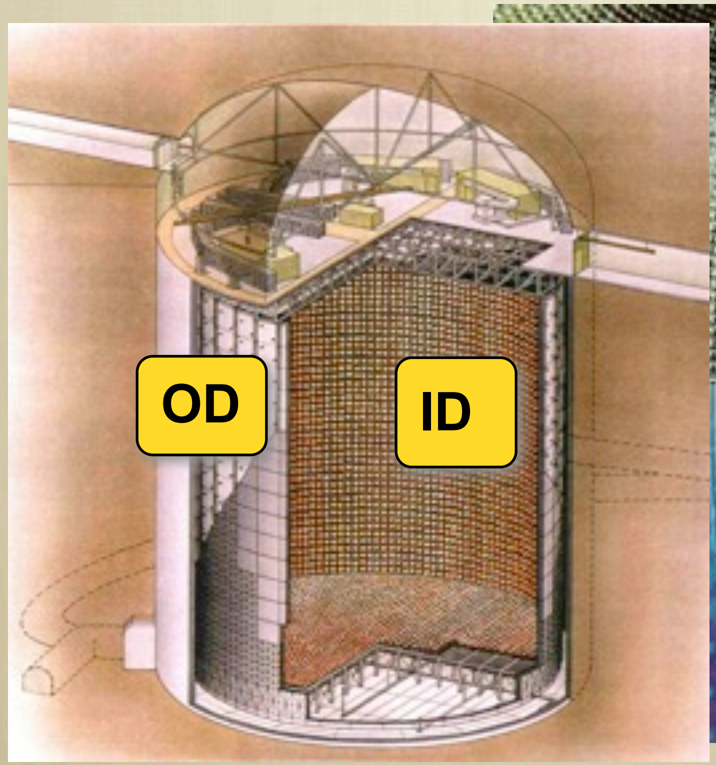


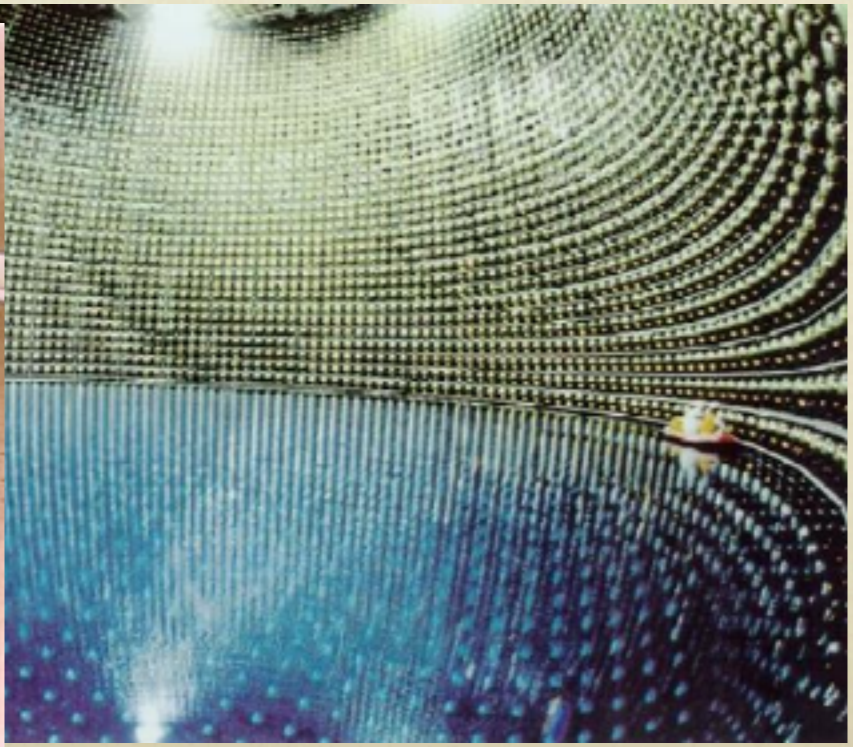
Atmospheric neutrinos (θ_{23}, Δm_{23}): SK

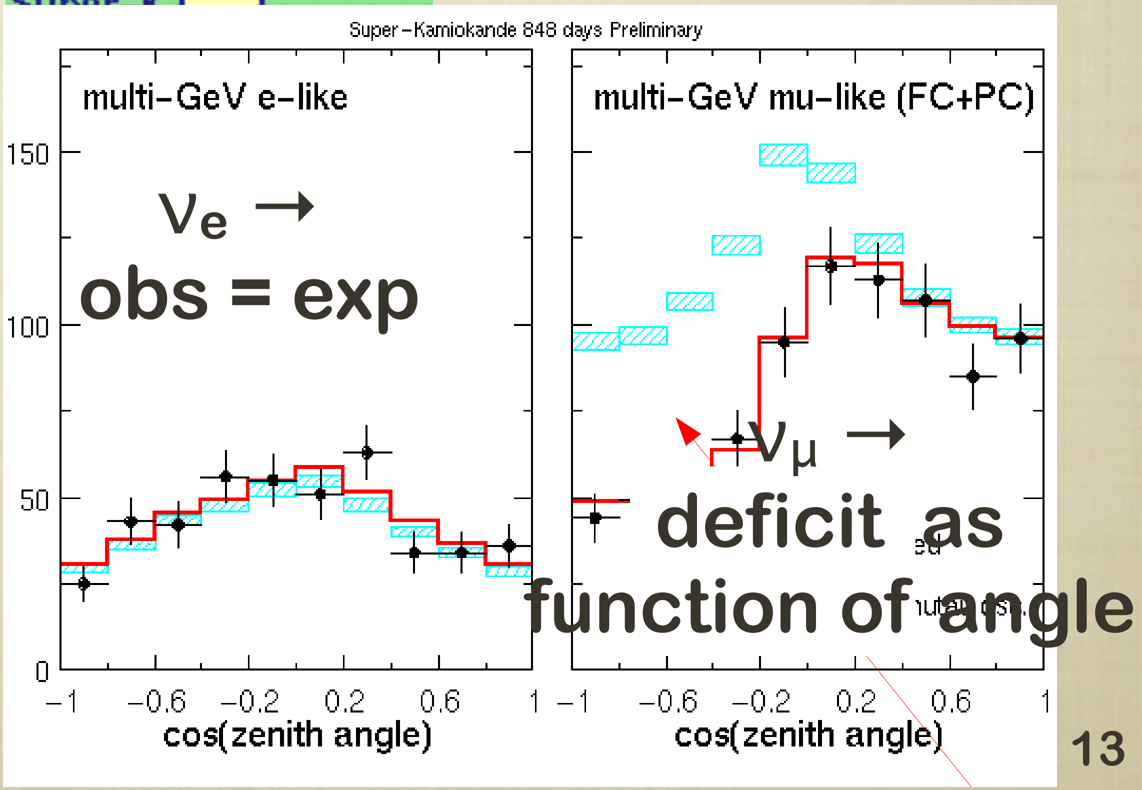
- 1998: SuperKamiokande → 50 kton Water Cherenkov detector
- Cosmic rays produce ν_μ and ν_e
- Observe ν_μ and ν_e from different zenith angles → different propagation length for ν
  - ν_e → as expected
  - ν_μ → disappearance function of angle
- ν_μ oscillates into ν_τ











Solar ν (θ_{12}, Δm_{12})→ SNO (2001)

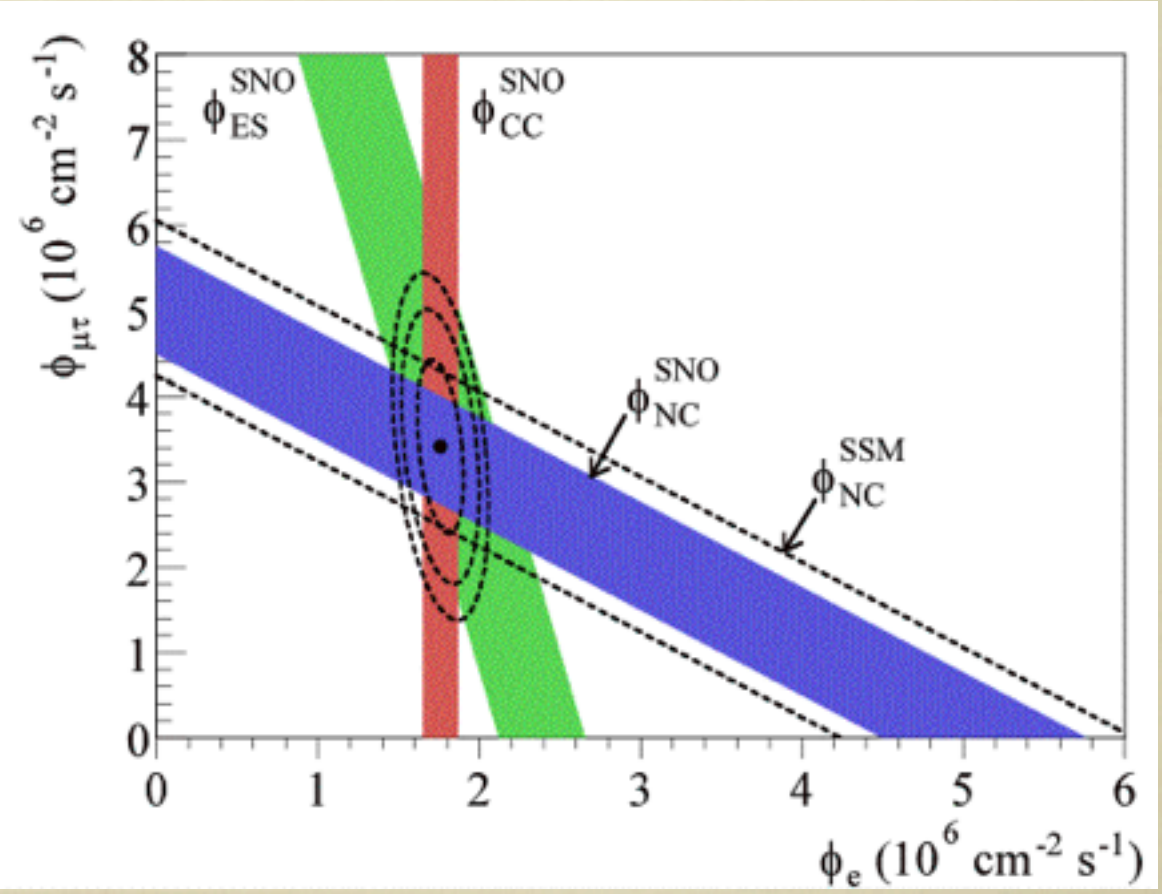
- In the Sun ν_e are produced that can oscillate traveling to the Earth
- On the Earth they arrive as a mixture of ν_e, ν_μ, ν_τ
- Solar ν have energies of ~ few MeV
- Charged current $\nu_{\mu,\tau}$ → μ,τ forbidden → ~1/3 of original ν_e flux detected

SNO is sensitive to charged current and neutral current interactions

Charged current → only ν_e → deficit of ~2/3

Neutral current → ν_e, ν_μ, ν_τ → expected flux

All the ν_e produced in the Sun reach the Earth but some of them are not ν_e



Measurement of θ_{13}

- **Most difficult angle to measure → completely unknown until 2011!**
- **2 techniques to measure θ_{13} → accelerator and reactor experiments**

<u>Reactors (DChooz, RENO, Daya Bay)</u>

✓ Disappearance of anti-νe $P(\bar{\nu}_e \rightarrow \bar{\nu}_e)$
✓ anti-ν_e produced in nuclear reactors
  ✓Neutrino energy few MeV
  ✓Distance L ~ 1 km

✓ Signature: disappearance of the anti-ν_e produced in the reactor → depends on θ_{13}

<u>Accelerators (T2K, Minos→Nova):</u>

✓ Appearance experiment: $P(\nu_\mu \rightarrow \nu_e)$
✓ ν_μ neutrino beam
  ✓ Neutrino energy ~1 GeV
  ✓ Distance L >~ 300 km

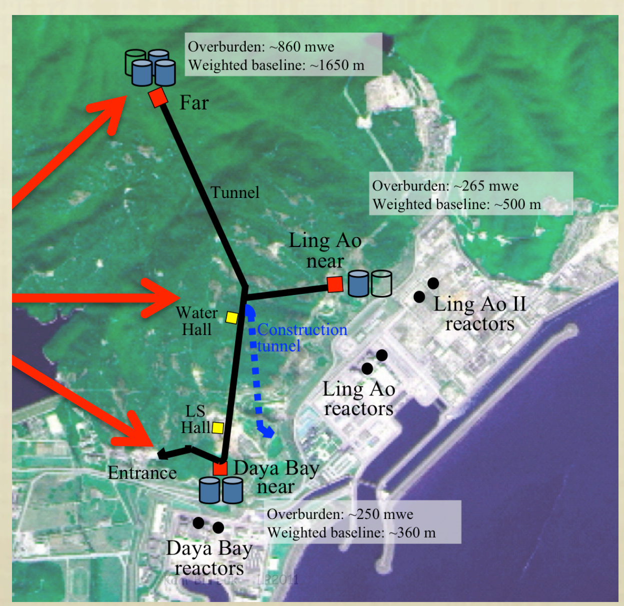
✓Signature: appearance of ν_e in the ν_μ beam
✓Degeneracy of θ_{13} with δ, sign of Δm^2

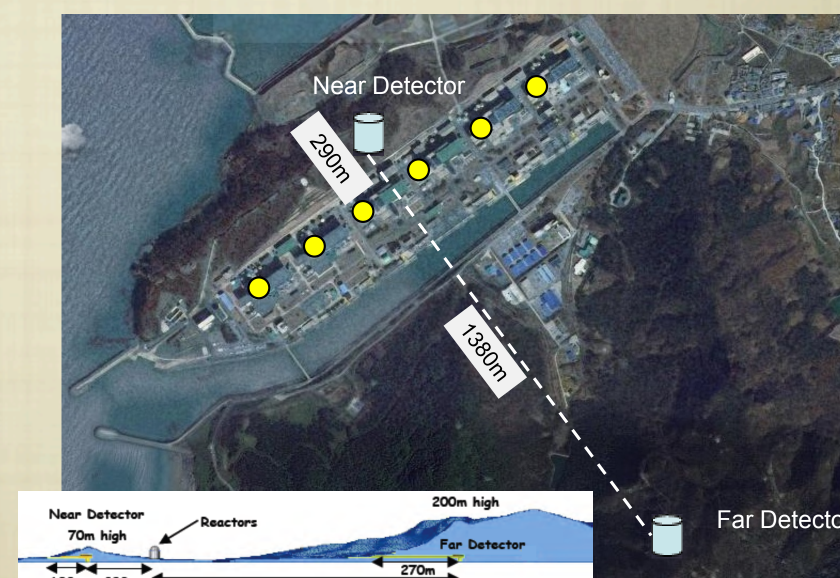
- **2011: first indication of non-zero θ_{13} from T2K**
- **2012: observation of non-zero θ_{13} from Daya Bay, confirmed by RENO and Double Chooz**
- **2013: observation of ν_e appearance from T2K**

θ_{13} at the reactors

More details in Guillaume Pronost and Alessandro Minotti talks

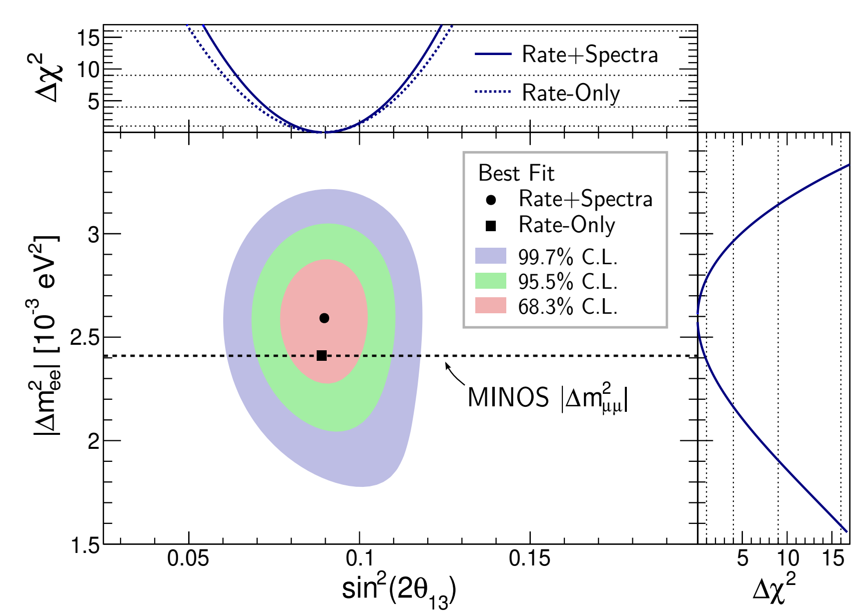
- 3 experiments searching for θ_{13} → distance from reactor core ~ 1 km
  - Double-Chooz (France), Daya Bay (China), Reno (Korea)
- Use Near detector(s) to constrain the reactor flux
- Far detector(s) to measure the ν_e disappearance due to θ_{13}
- Experimental signature: $\nu_e + p \rightarrow e^+ + n$
  - positron + annihilation γ E~1-12 MeV
  - Delayed signal (~30 μs) from neutron capture on Gd → E~8 MeV





Daya Bay results

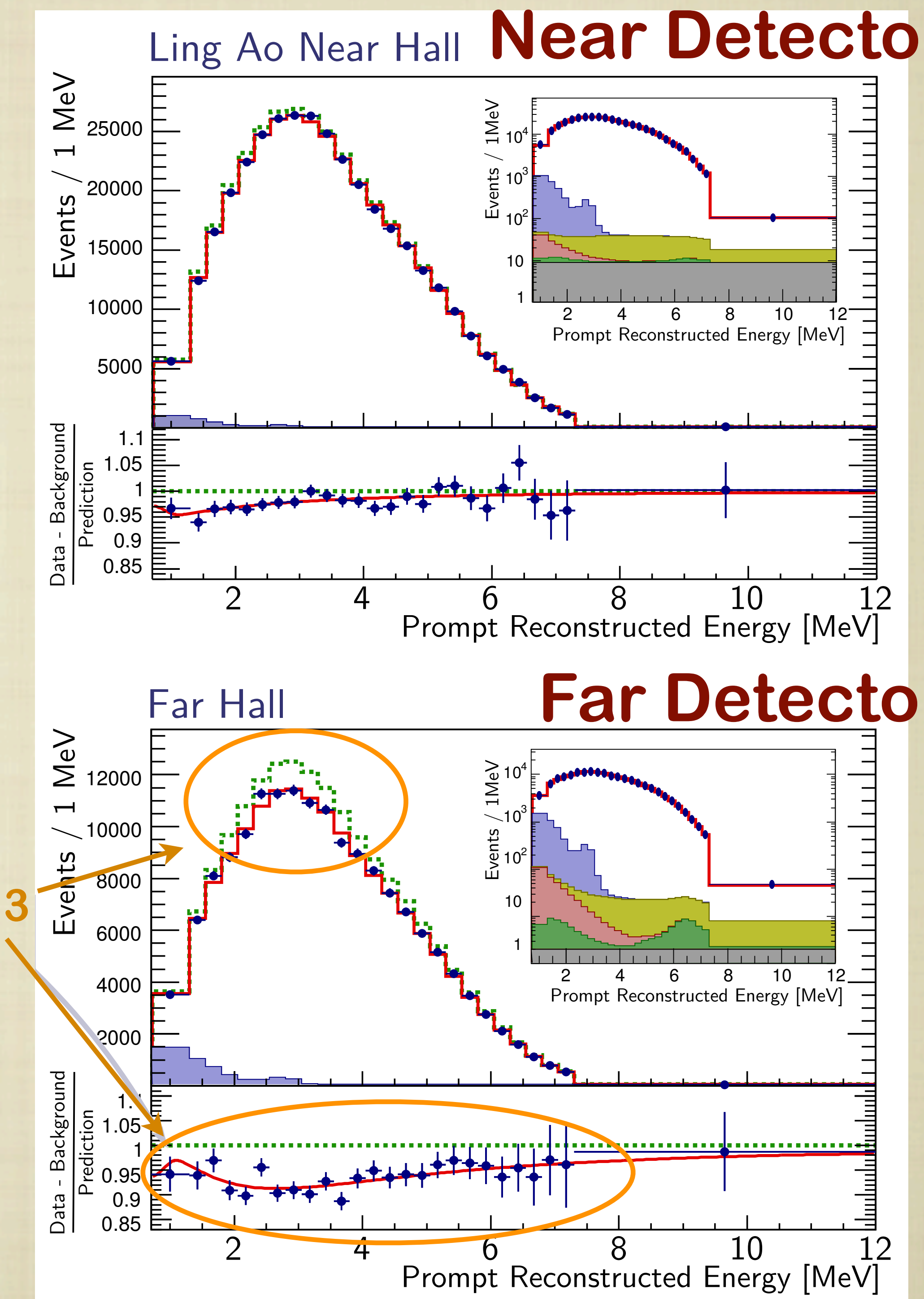
- Best measurement of the mixing angle θ13
- Combine near and far detector measurements
- Measure shape distortion



$$\sin^2 2\theta_{13} = 0.090^{+0.008}_{-0.009}$$

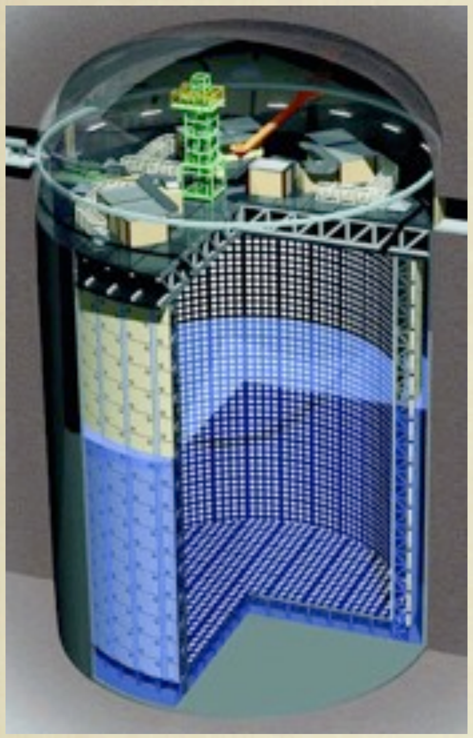
$$|\Delta m^2_{ee}| = 2.59^{+0.19}_{-0.20} \cdot 10^{-3}\mathrm{eV}^2$$

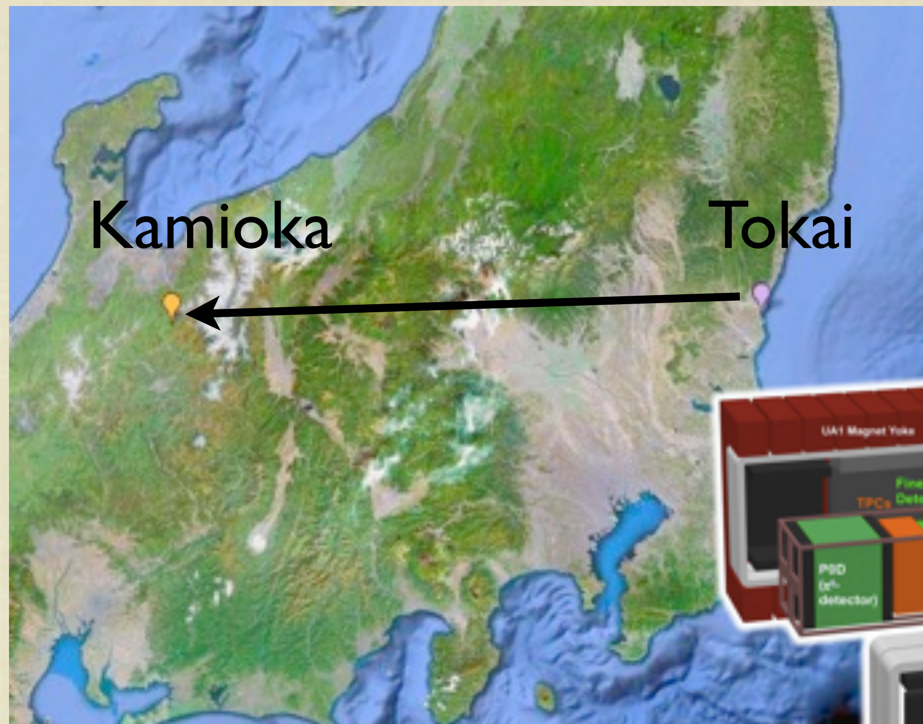
$$\chi^2/N_{\mathrm{DoF}} = 162.7/153$$



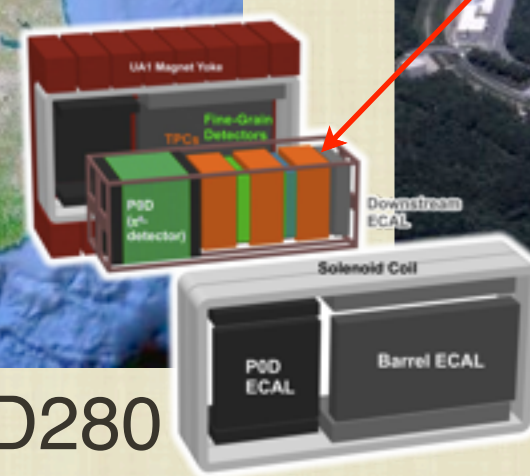
T2K experiment

Super-Kamiokande: 22.5 kt fiducial volume water Cherenkov detector





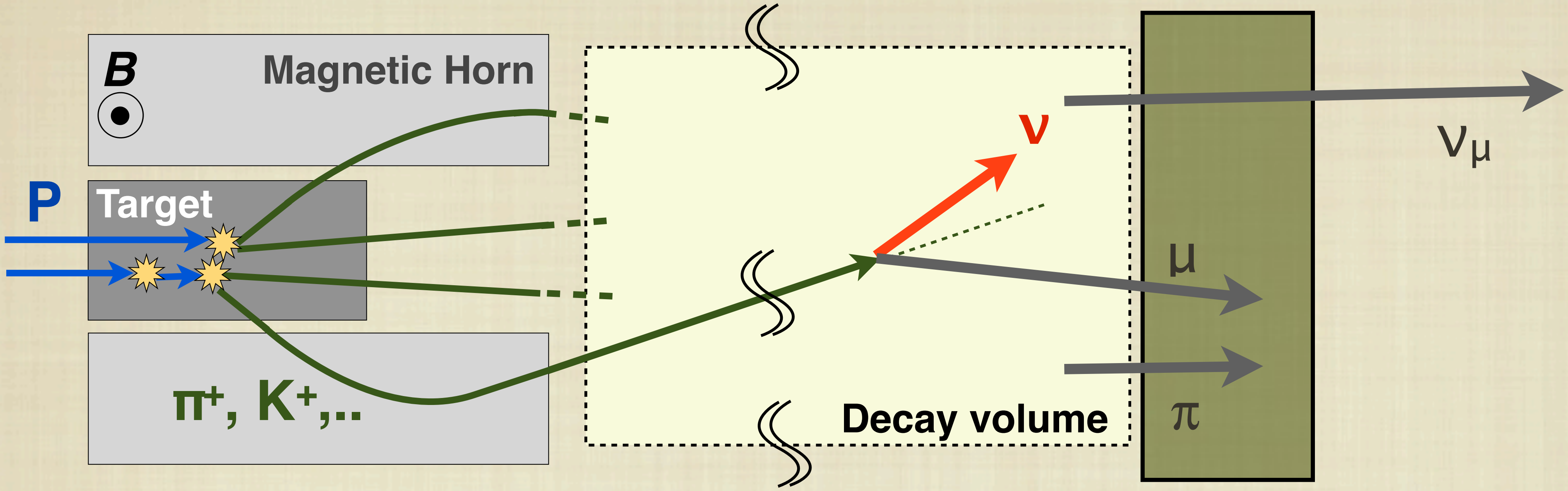
JPARC accelerator: Design power: 750 kW



ND280

- **High intensity ~700 MeV ν_μ beam produced at J-PARC (Tokai, Japan)**
- **Neutrinos detected at the Near Detector (ND280) and at the Far Detector (Super-Kamiokande) 295 km from J-PARC**
- **Observation of ν_e appearance → determine θ_{13} and δ_{CP}**
- **Precise measurement of ν_μ disappearance → θ_{23} and Δm^2_{23}**

Accelerator experiments

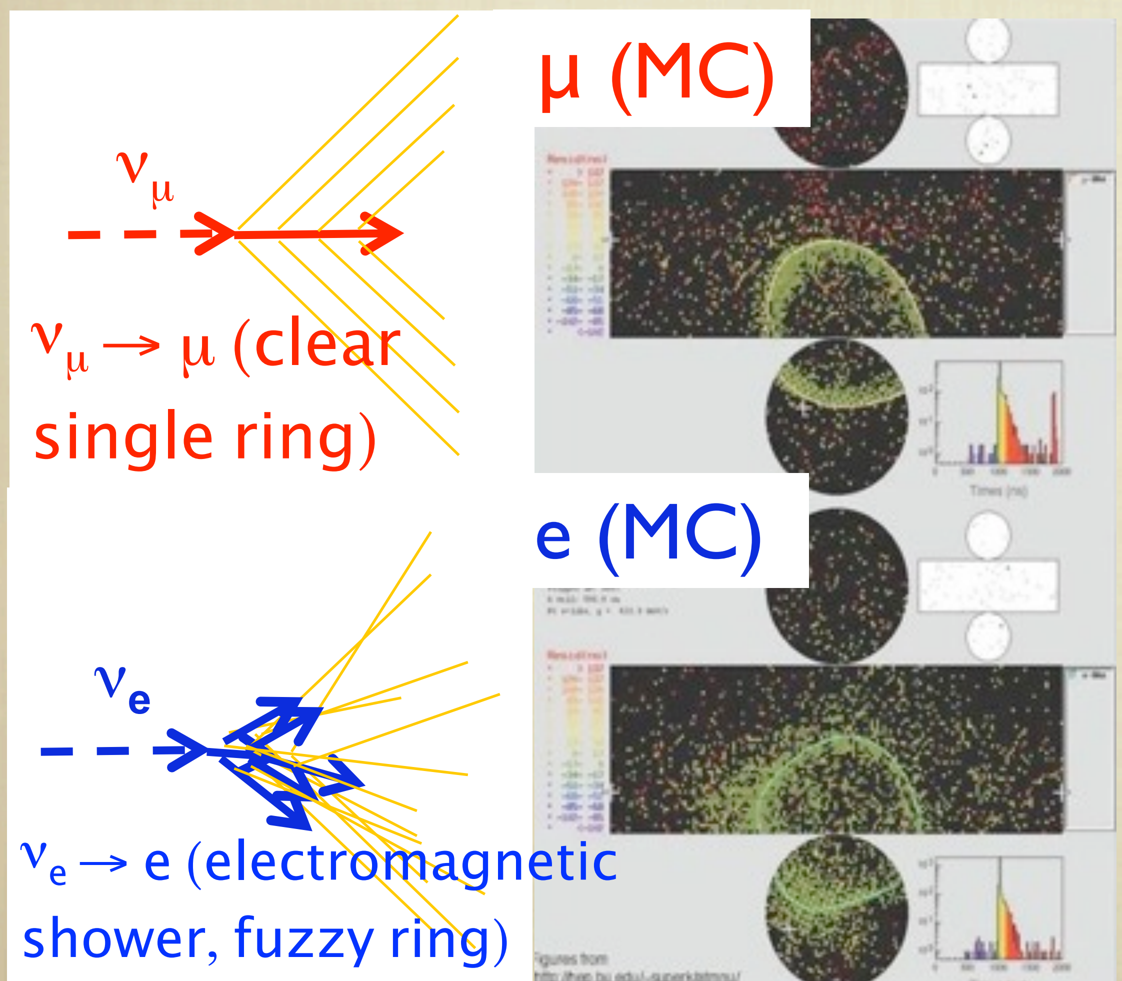


1. Proton beam hits a target producing hadrons (mainly π, few K)
2. Hadrons of a charge are focused by a system of magnetic horns
3. π enter a decay tunnel of ~100 m where they decay: $\pi \rightarrow \mu + \nu_\mu$
4. π, K, μ are stopped with a beam dump while ν_μ pass it

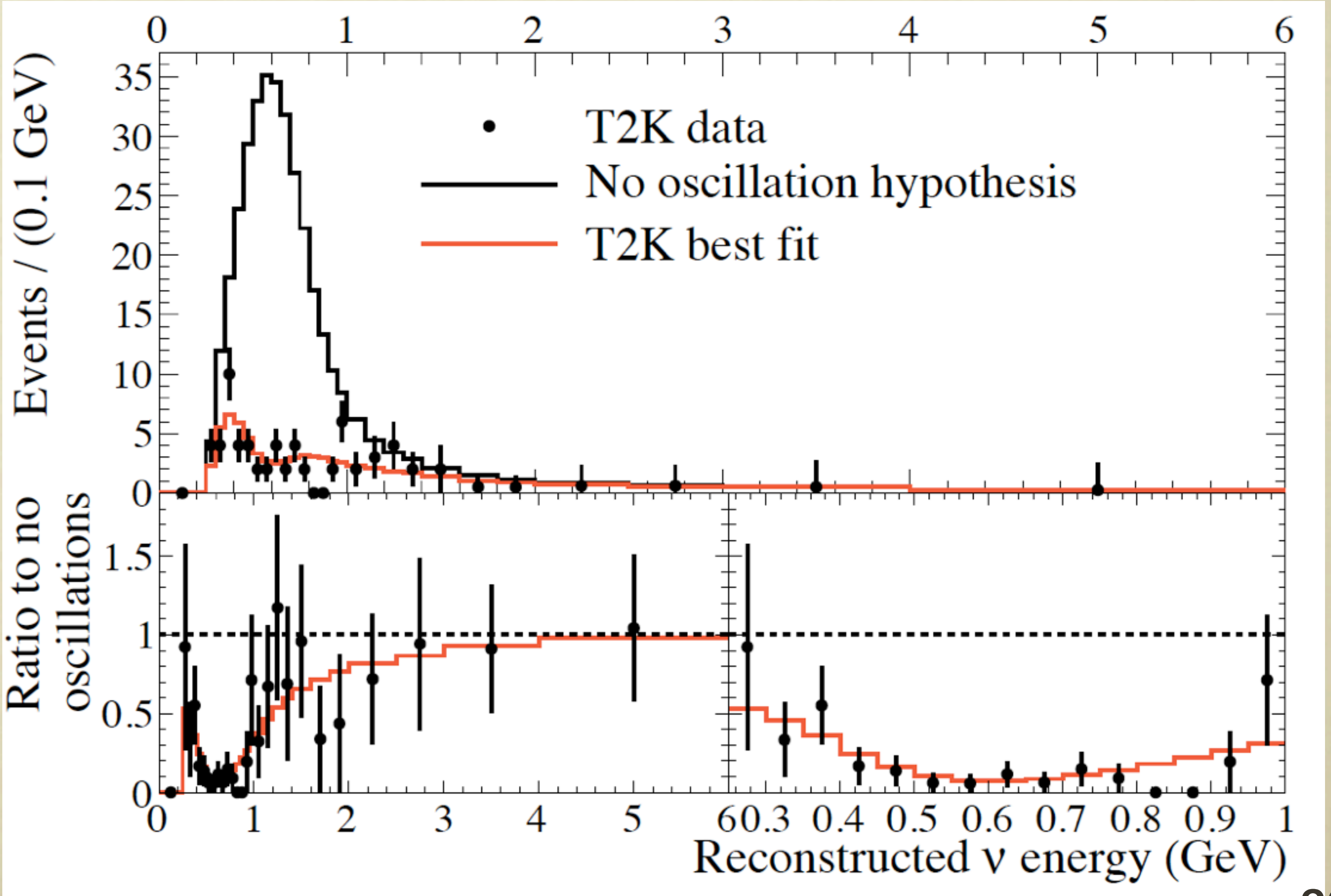
We have produced a pure (>99%) beam of ν_μ

T2K analysis

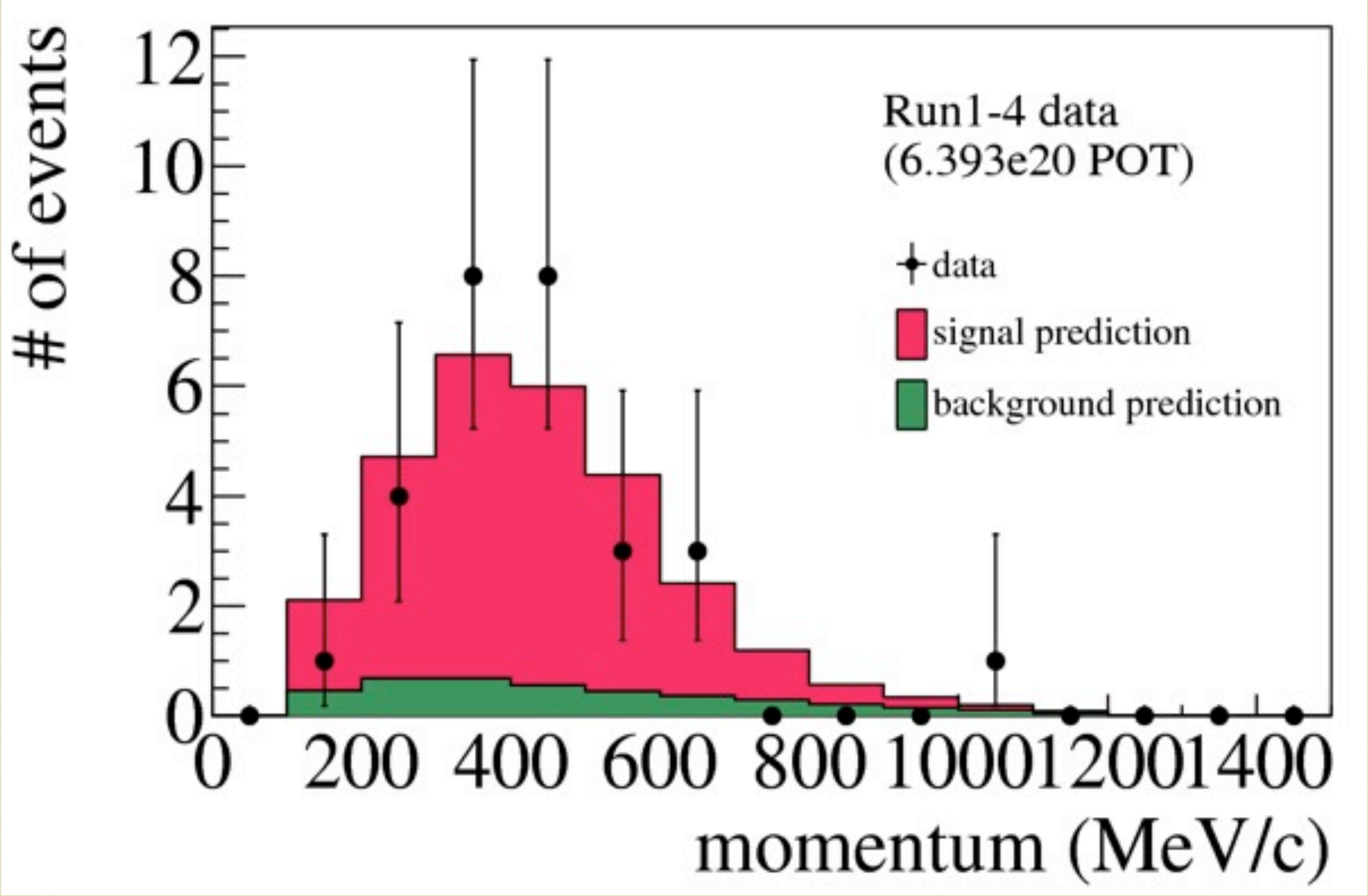
- ν_μ travels 295 km and oscillate ($\nu_\mu \rightarrow \nu_\tau$ and ν_e)
- Interact in the far detector
- Far detector distinguish between muon-like and electron-like events
- Observe:
  - ν_μ disappearance
  - ν_e appearance



ν_μ disappearance @ T2K



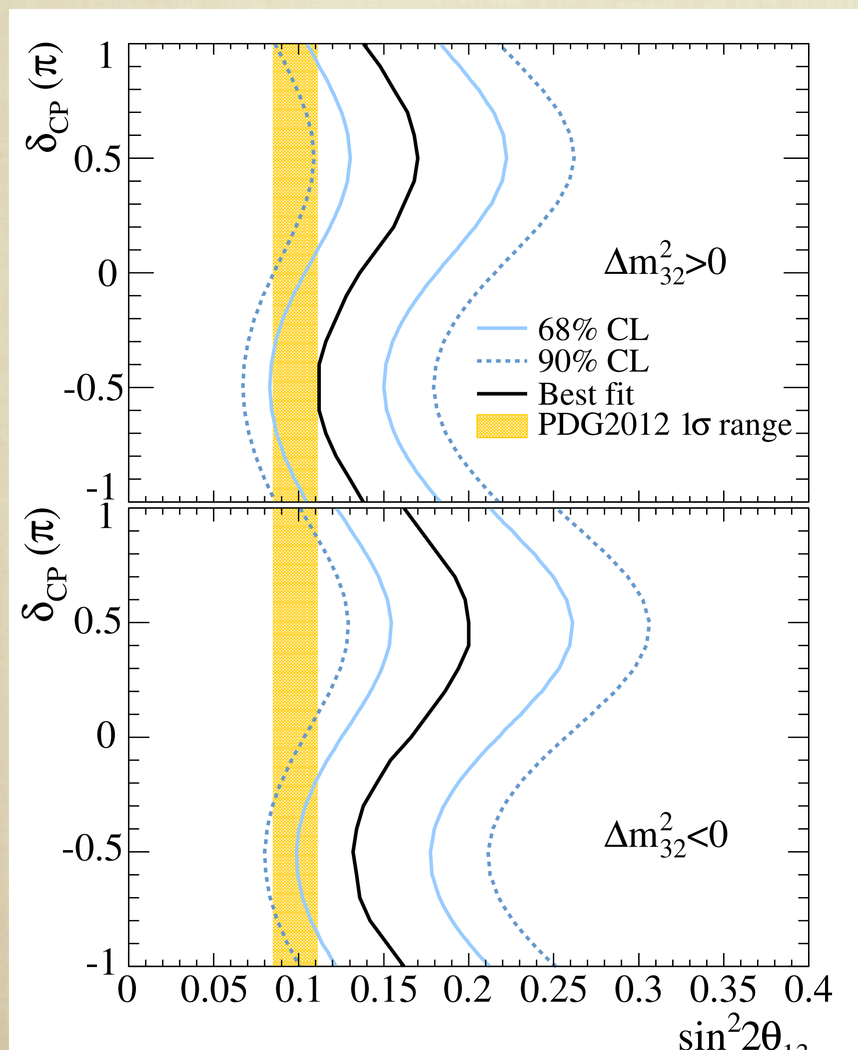
T2K ν_e appearance results



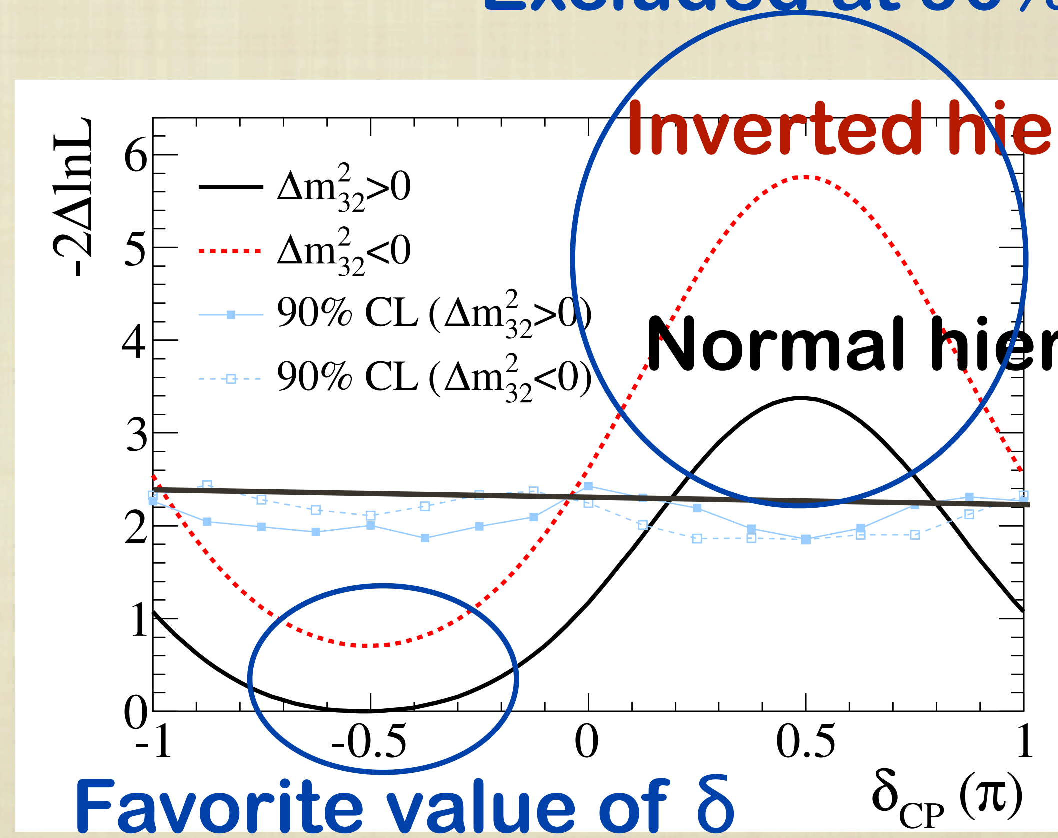
- 28 observed events, 4.4 expected from background
- 7.3 σ observation of the ν_e appearance process
  - First observation of an explicit appearance of neutrinos → up to know we always observed disappearance

Complementarity

- Look at the θ_{13} vs δ_{CP} plane
- Reactor experiments measure θ_{13} → straight line
- T2K measures a combination of θ_{13} and the CP violation phase δ
  - S-shape in the θ_{13} vs δ_{CP} plane
- Combine them to measure CP violation!



Excluded at 90% CL

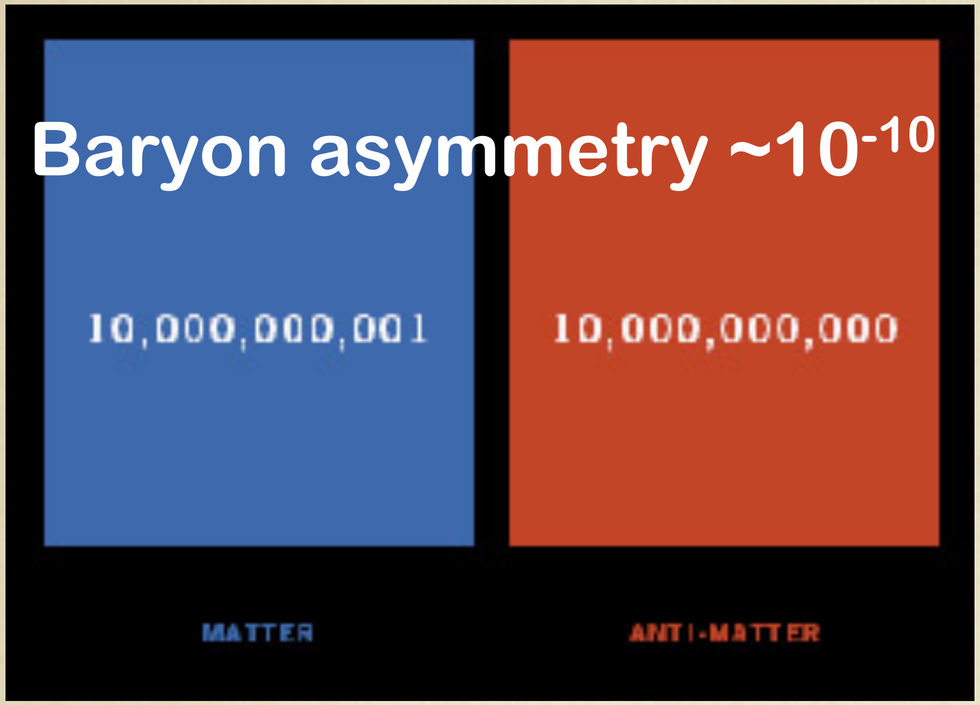


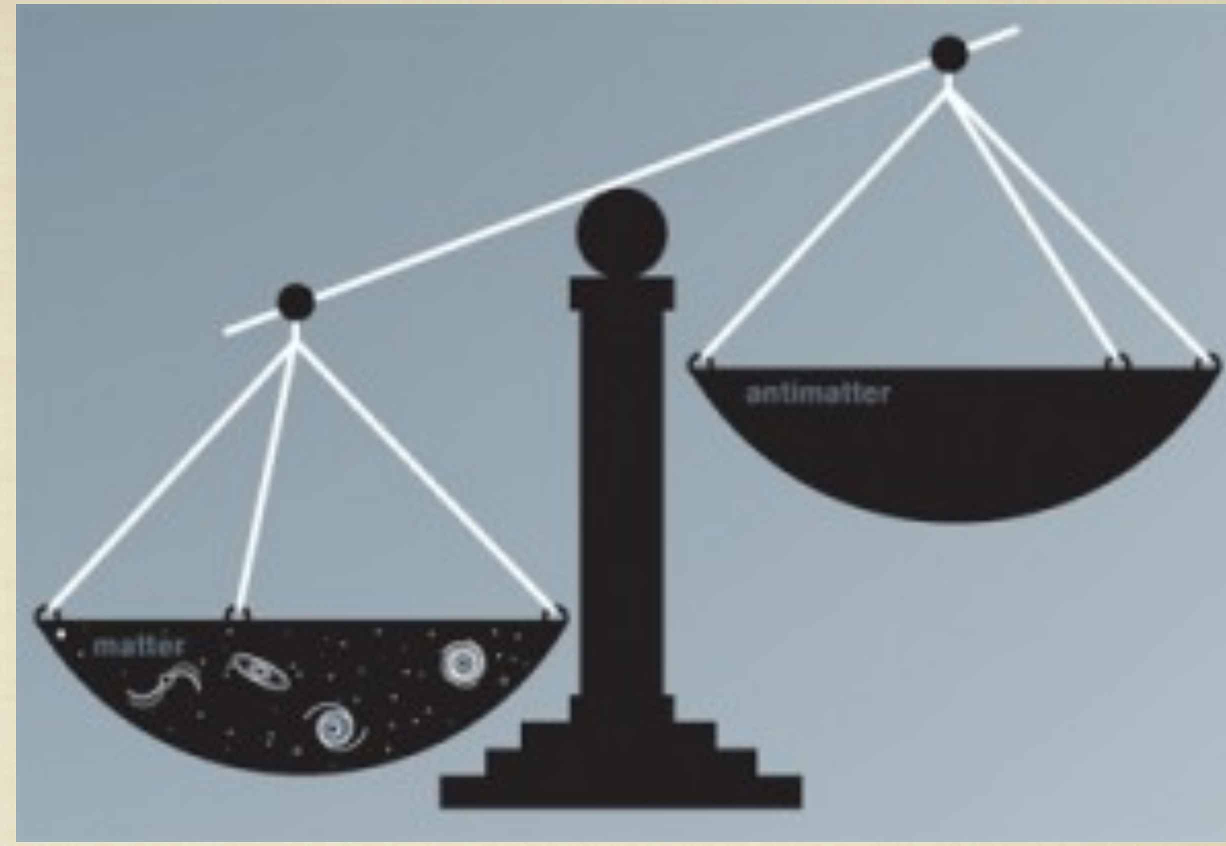
Inverted hierarchy

Normal hierarchy

Favorite value of δ
(CP violation phase)
from the combination of
T2K and reactors

CP violation



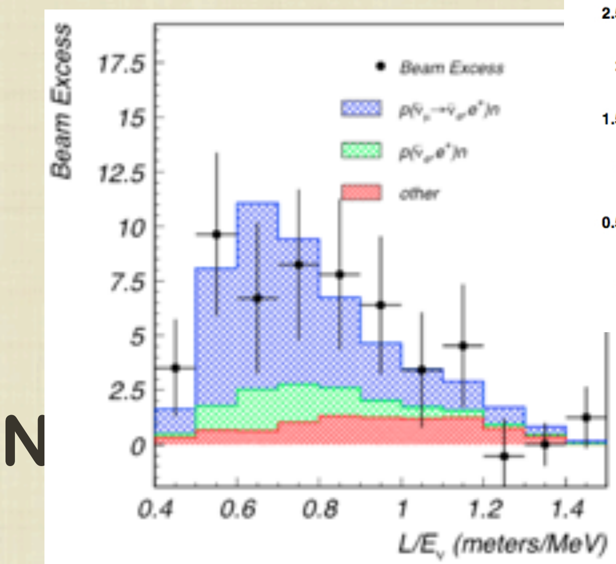


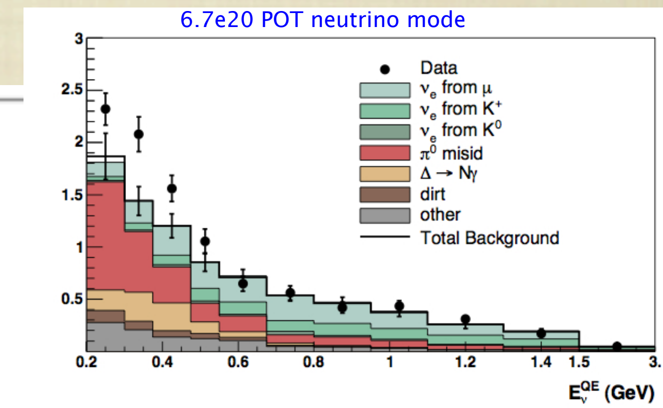
- Matter is dominant in the universe → we are here!
- Big-bang → symmetry between matter and antimatter
- How to produce the observed baryon asymmetry?
  - CP violation in baryon sector is not enough!
  - If we observe CP violation in lepton sector → it is possible to explain the asymmetry through the leptogenesis

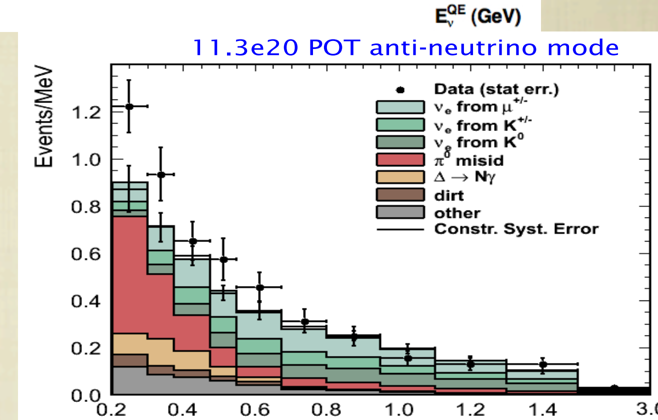
Additional sterile neutrinos?

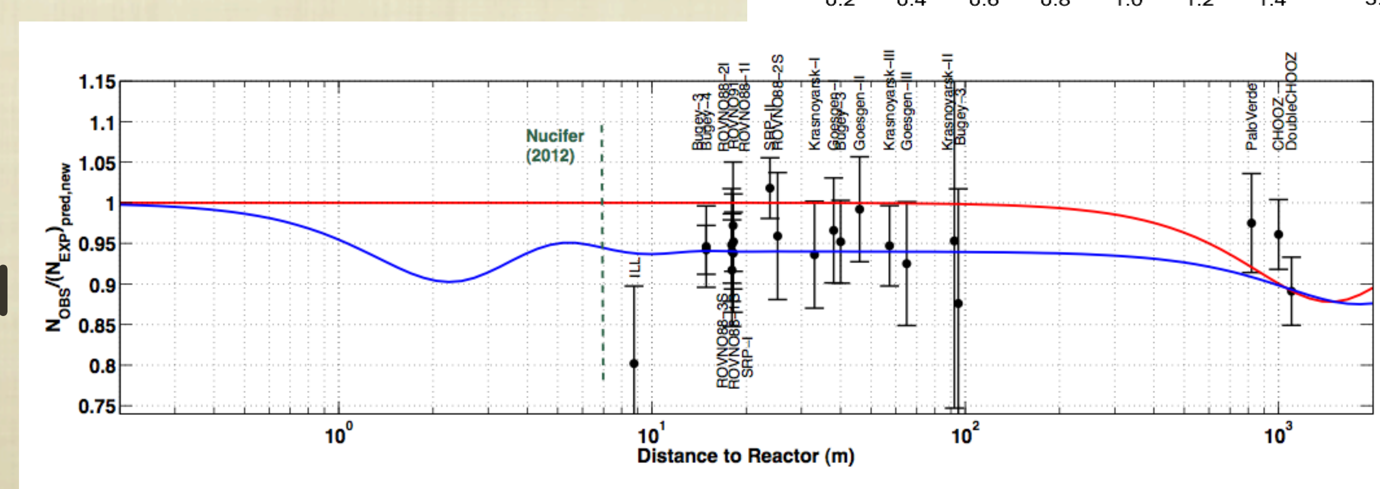
More details in Maxime Pequinot and Vincent Fischer talks

- We know that there are 3 active neutrinos (from LEP)
- (Almost) all the observed oscillations perfectly fit the PMNS framework
- Can we have additional neutrinos?
  - Sterile (not coupling with Z)
- Few hints:
  - νe appearance at high Δm^2 → LSN MiniBooNE
  - Additional νe disappearance from reactor at shorter distances → reactor neutrino anomaly
- Some constraints:
  - No νμ disappearance observed
  - Planck data

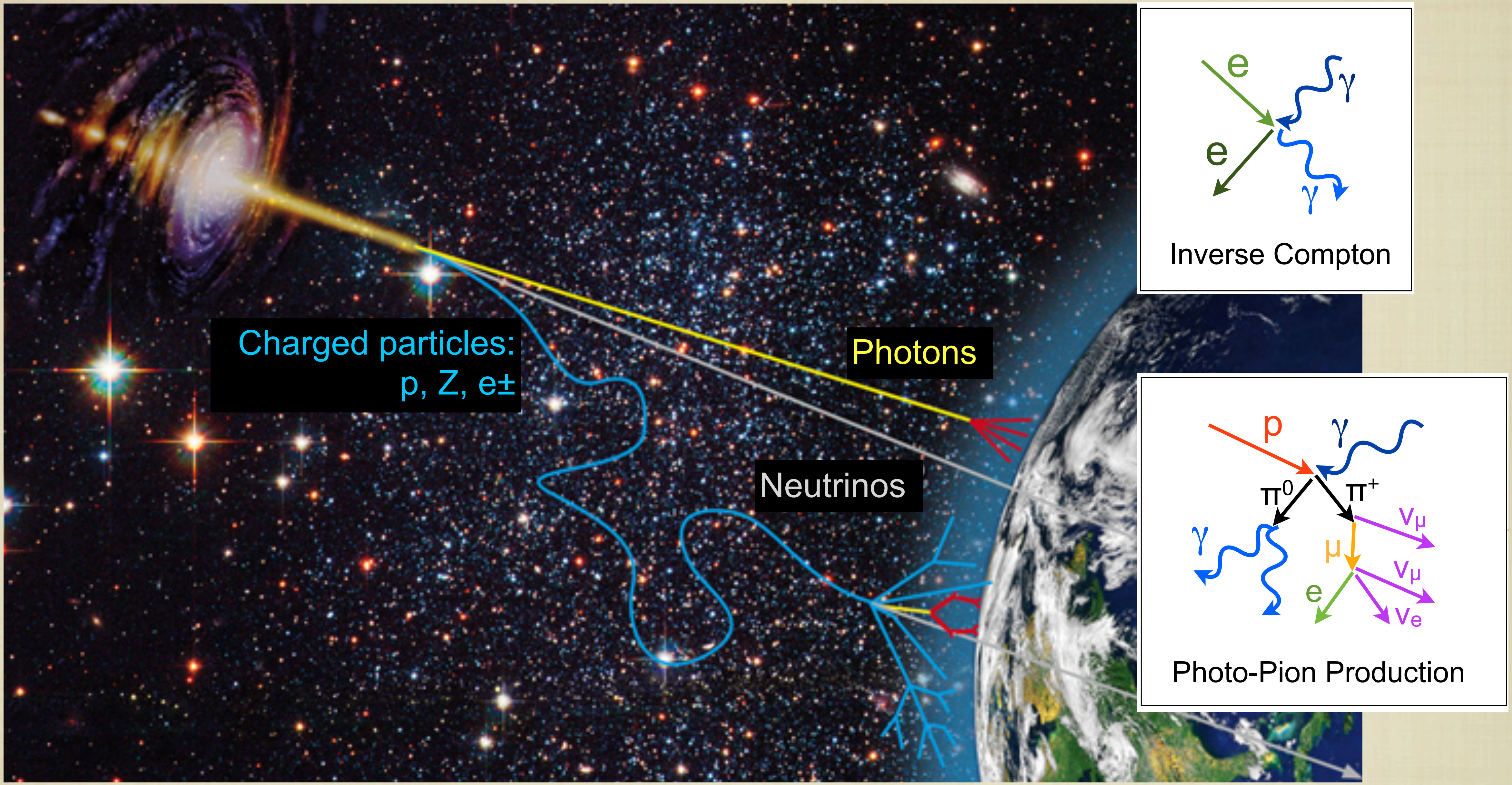








Neutrino astronomy

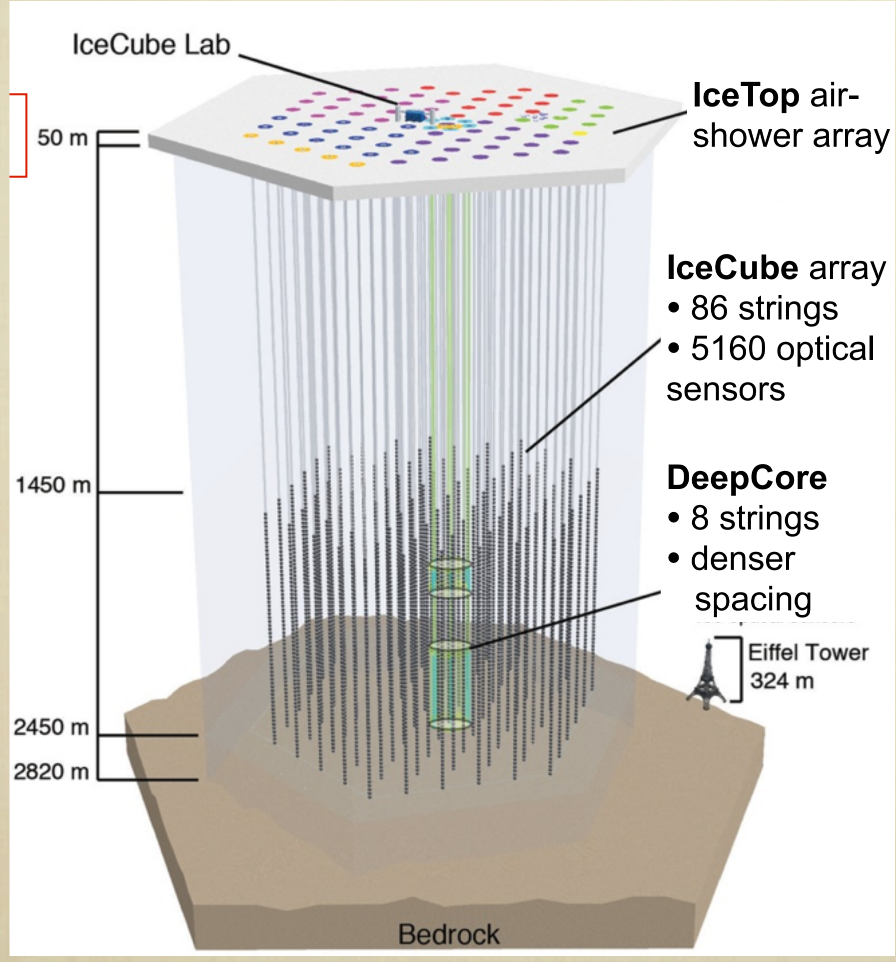


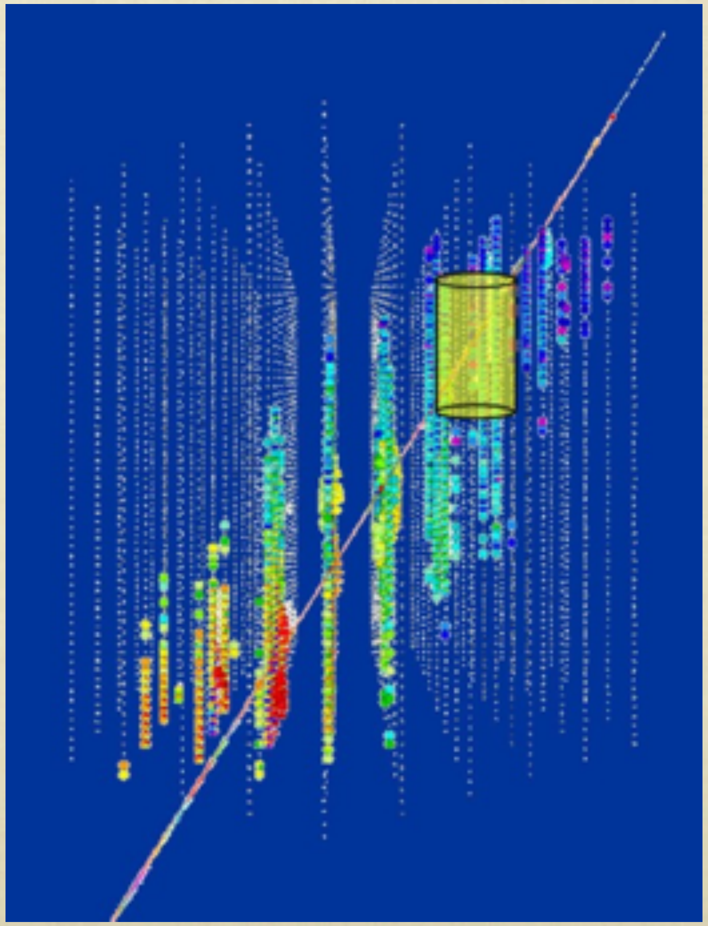
- Add information on the emission process (ν → hadronic acceleration)
- Reach higher energies and larger distances than the ones accessible with γ astronomy

ICECUBE

Similar experiment (smaller for now) in the Mediterranean sea (ANTARES)

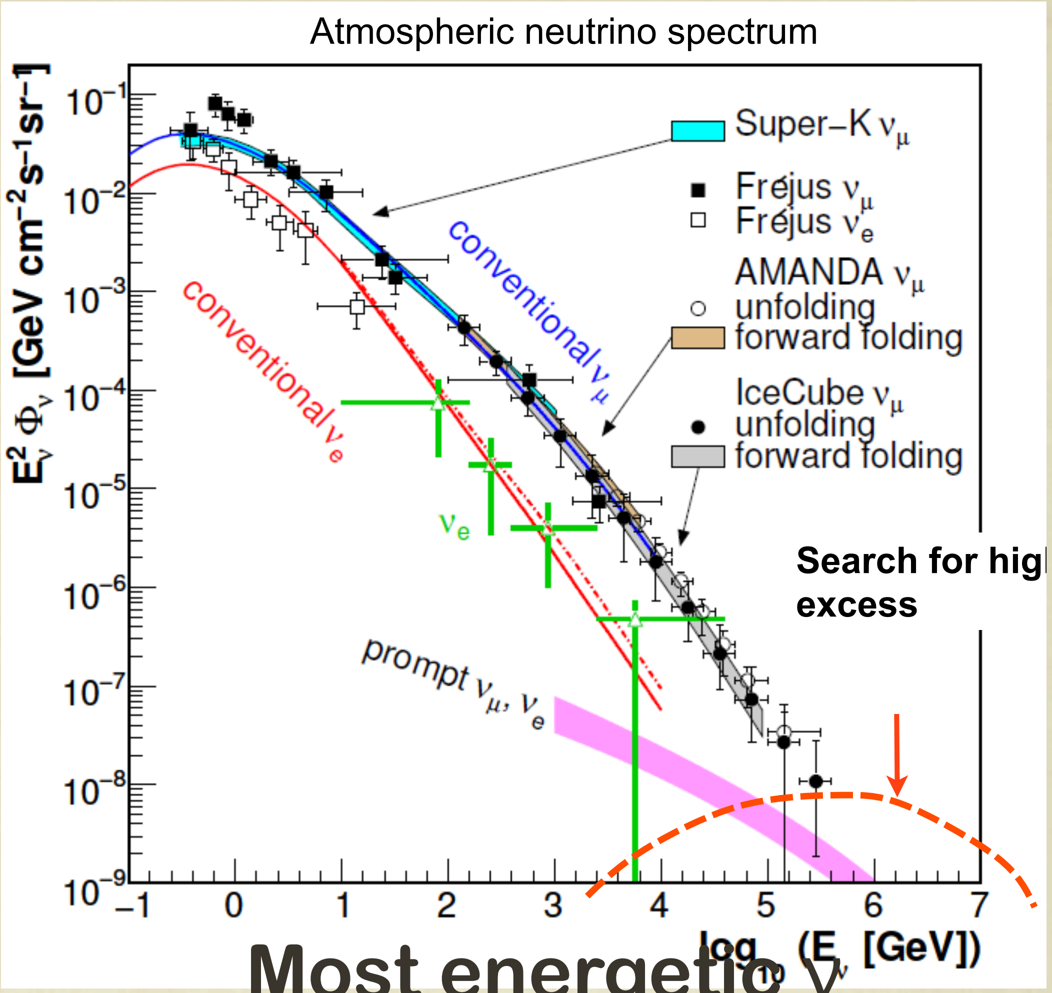
- Search for galactic and extragalactic sources of neutrinos
- Instrumented a large volume (~1 km3) of ice at the south pole
- Look for ultra-high energy neutrinos



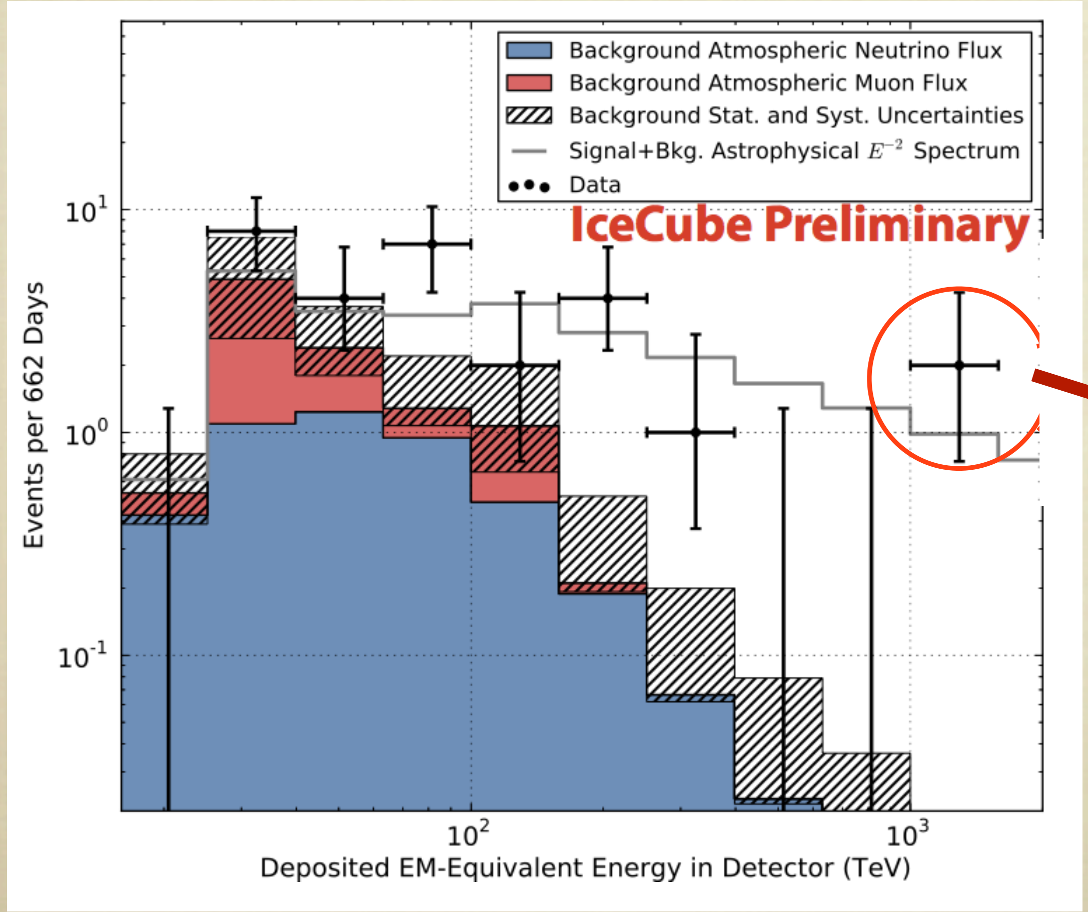


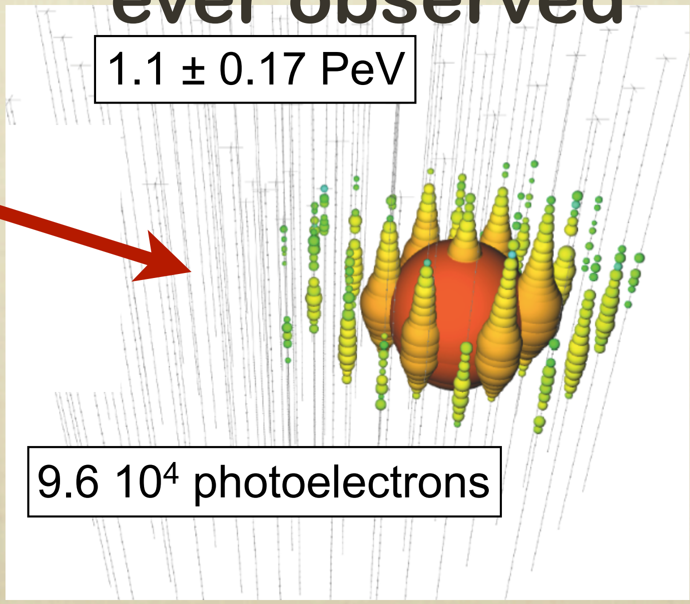
Evidence for astrophysical ν source

- Search for high energy neutrinos in the high energy region
- 28 events observed
- 4.1 σ excess with respect to expected atmospheric neutrinos



Most energetic ν ever observed





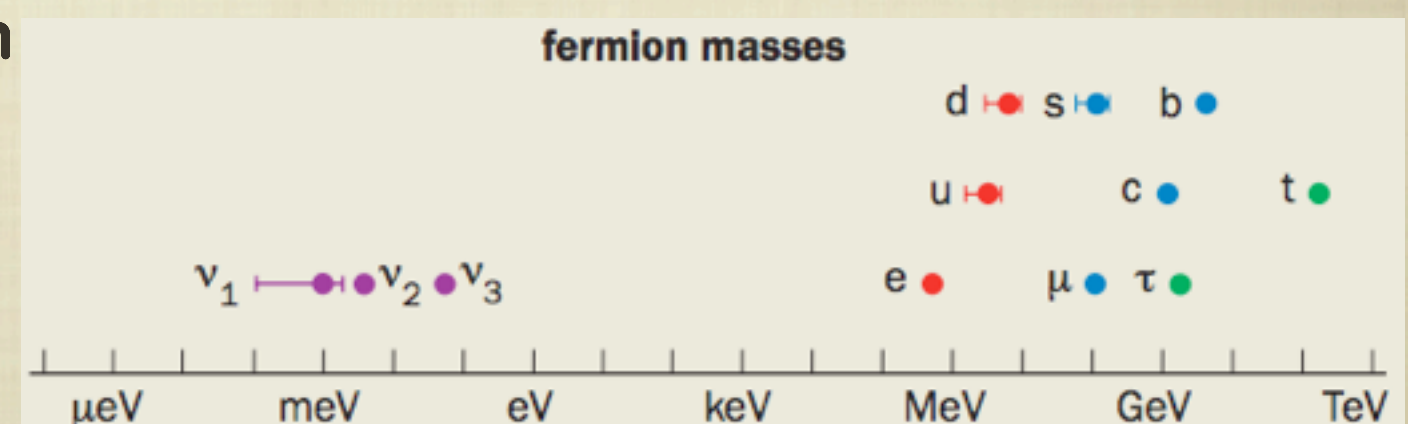
Neutrino masses

Neutrinos

vs

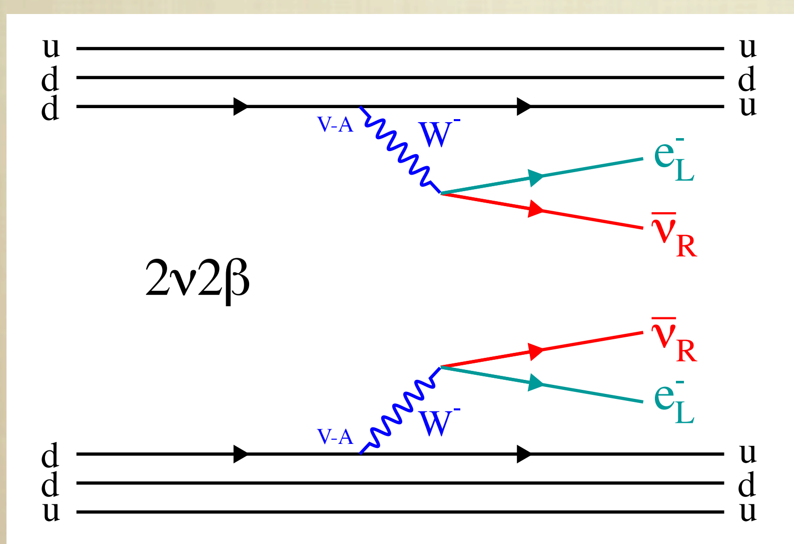
Electrons

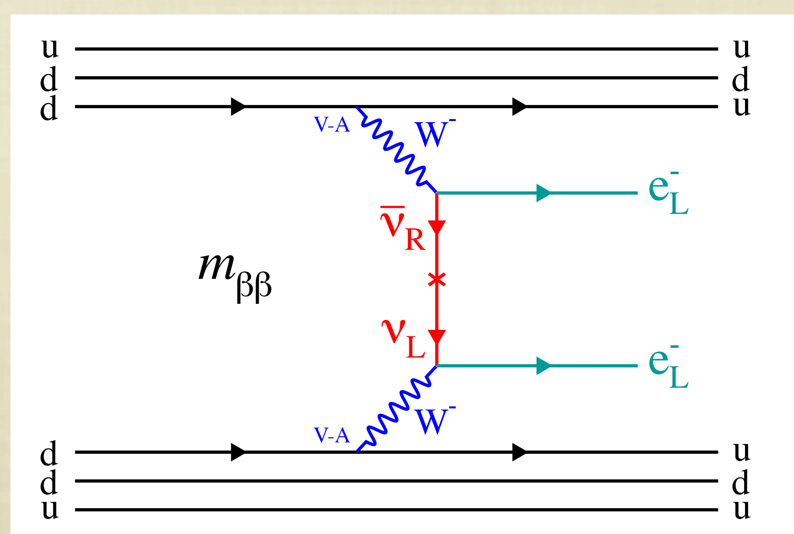
- Oscillations → difference of masses
- From β decay experiments we have upper limit on the ν mass (<~1 eV)
- The absolute value is still unknown → soon new results from KATRIN
- Why the masses are so small → easier to explain if neutrinos are Majorana particles → see-saw mechanism

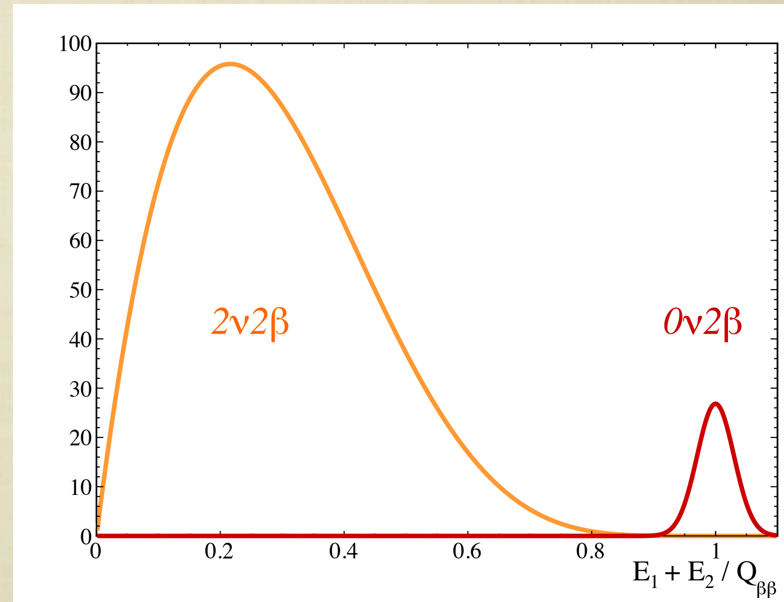


Neutrinoless double β decay

- Neutrinos is the only known fermion that can be its own antiparticle
  - Majorana particles
  - Explain small neutrino masses through the see-saw mechanism
- Search a double β decay where the two electrons take all the available energy($Q_{\beta\beta}$)
- Very difficult experiments because $Q_{\beta\beta}$ is small (few keV)
- Many different techniques but up to now only upper limits



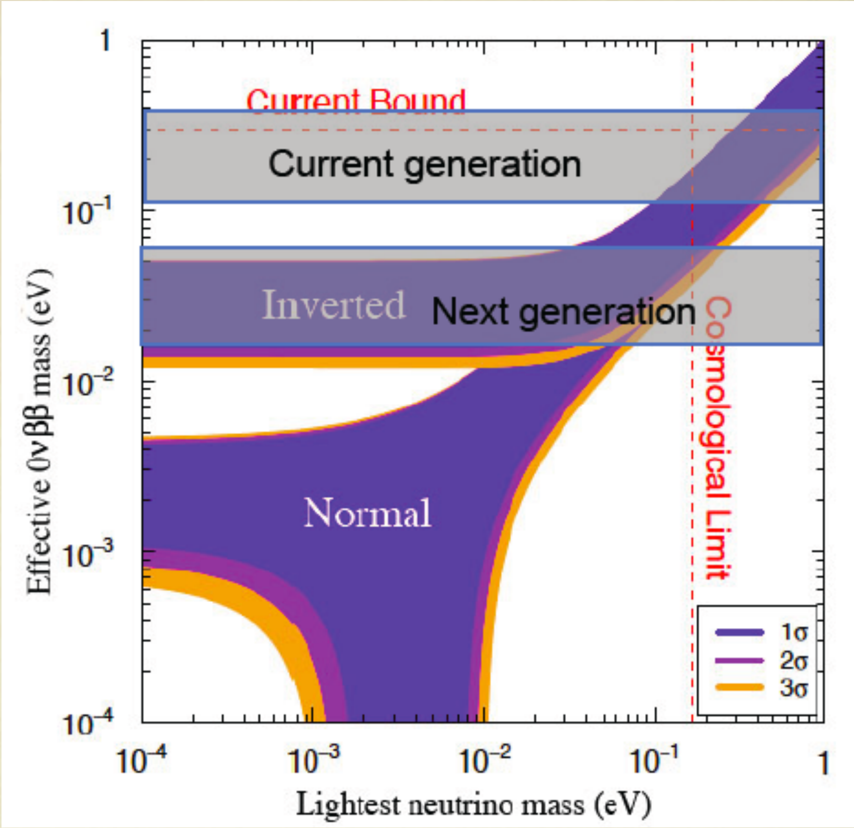


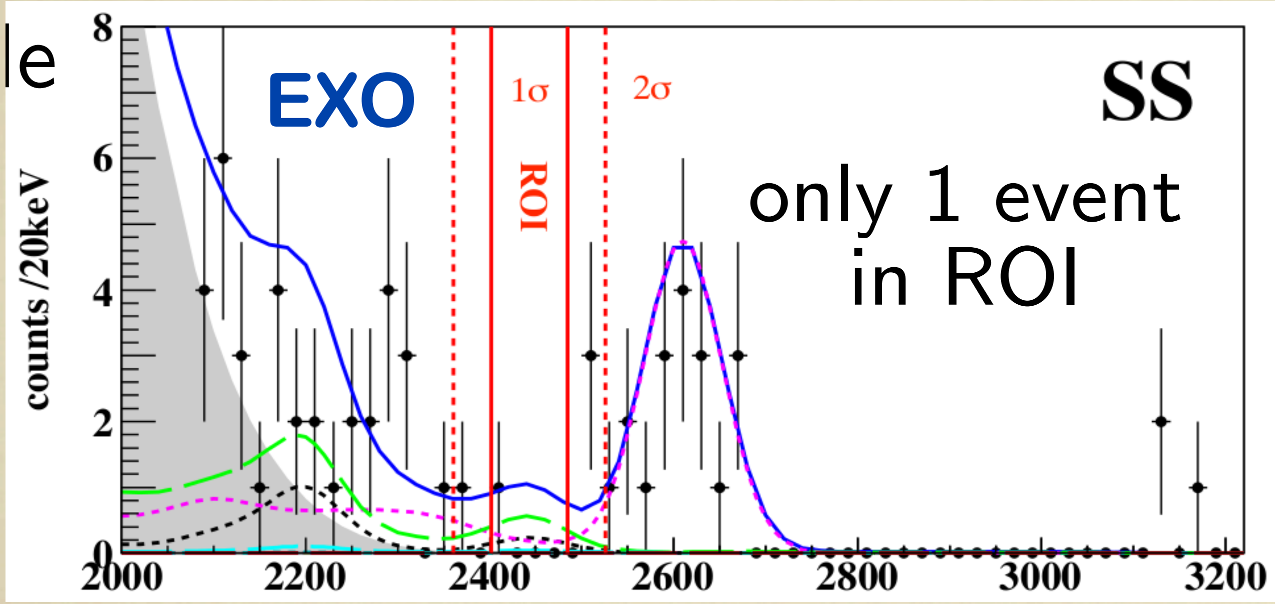


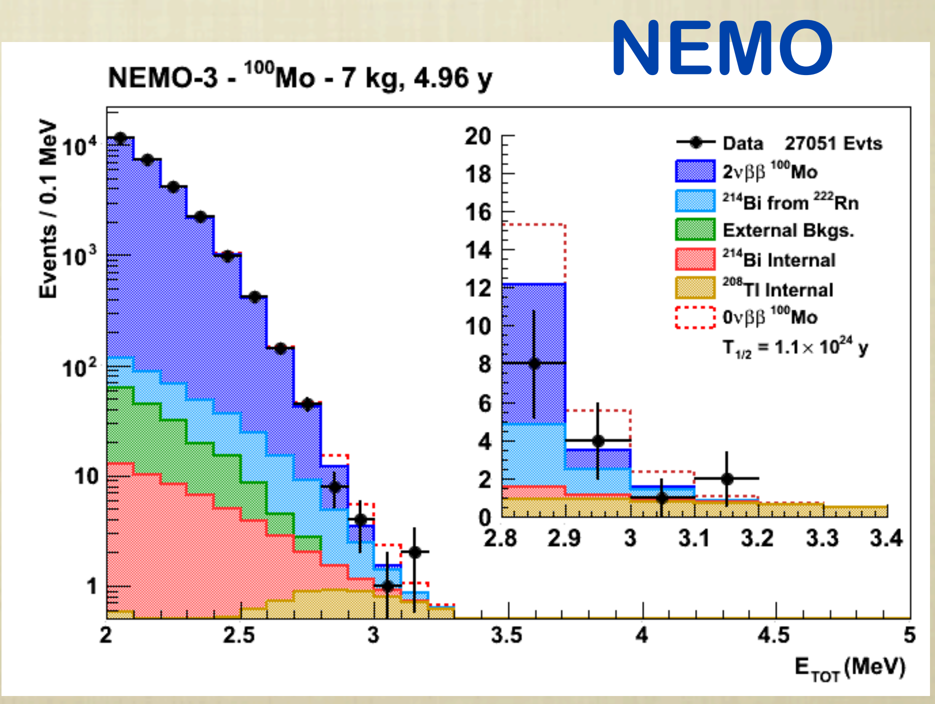
2 e^- energy equal to $Q_{\beta\beta}$

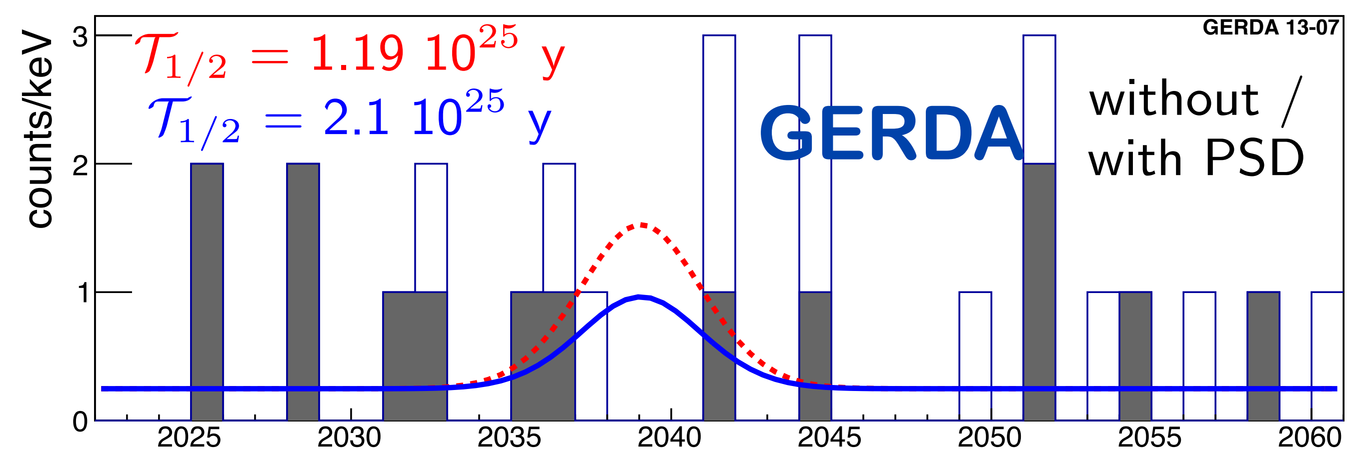
Recent results → limits, limits, limits...

- $0\nu\beta\beta$ decay don't observed yet
- New experiments will investigate new regions
- 3 orders of magnitude to exclude Majorana
  - Hopefully observe $0\nu\beta\beta$ before that!



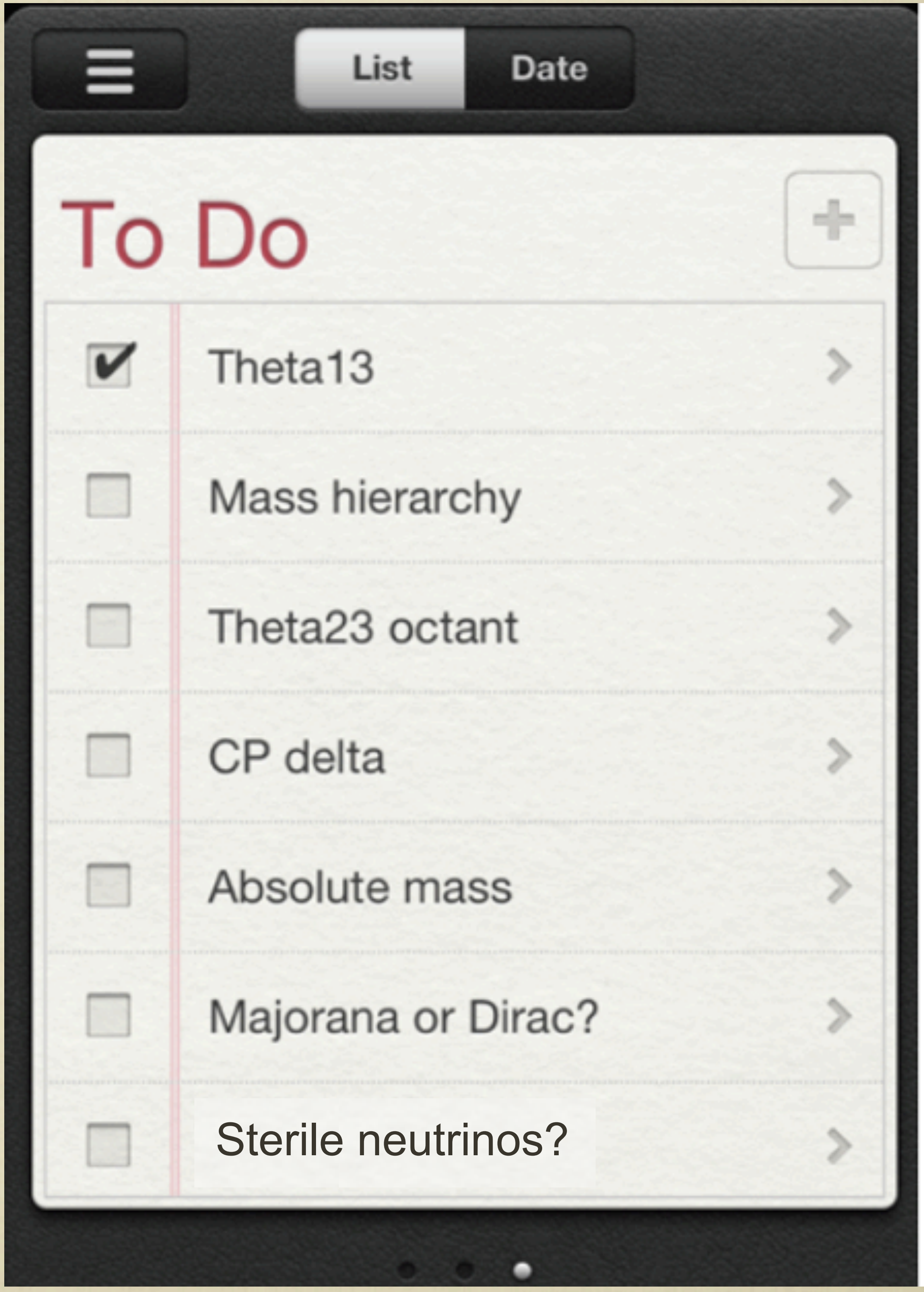






Conclusions

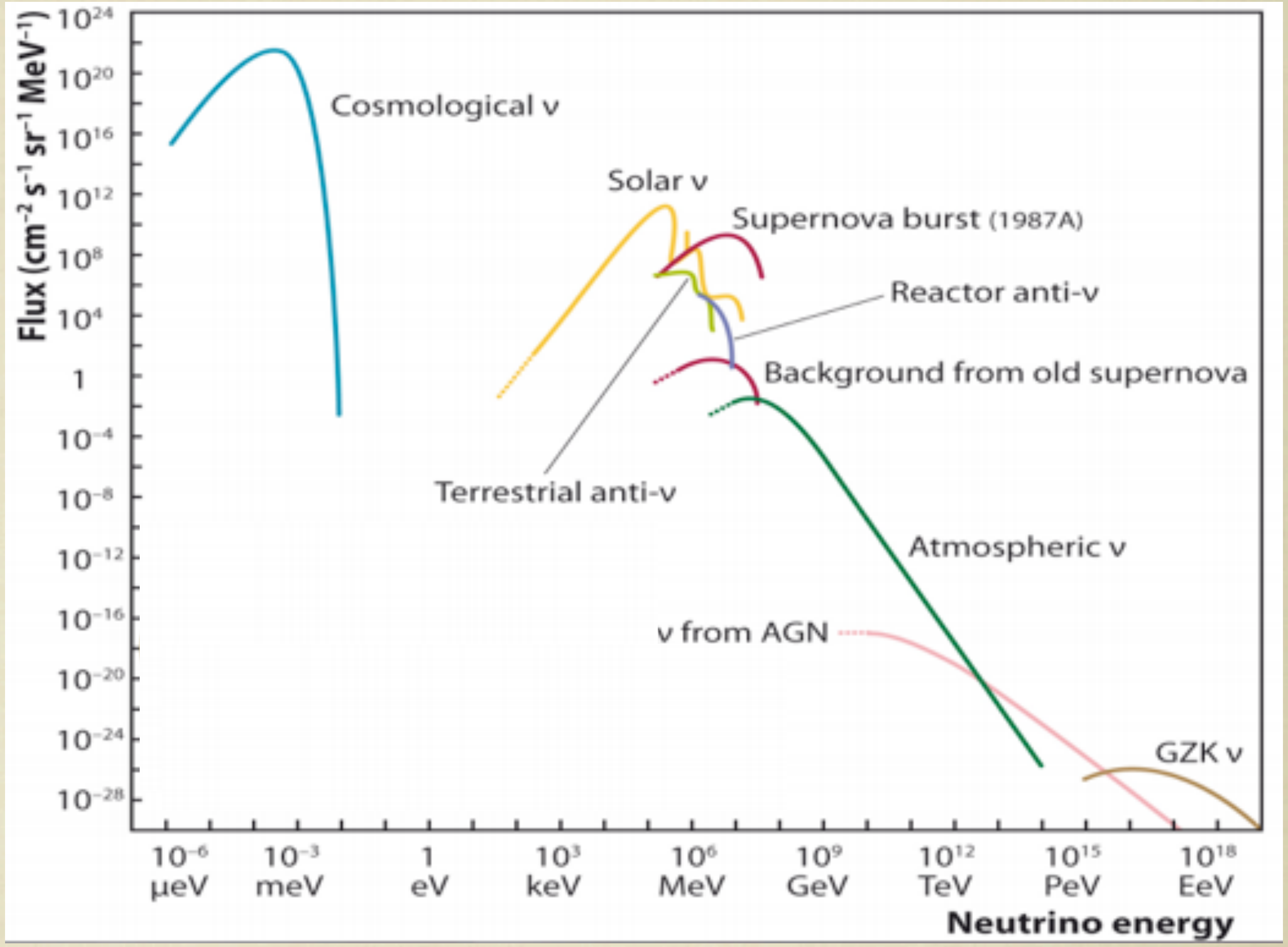
- Neutrino physics have been full of surprises in the last decades
  - Only observed physics BSM
- Still a lot to discover!
  - Many granted parameters → build good experiment and we will measure them!
- Good time to work on neutrino physics!



Back-up slides

Neutrino sources

- Big bang ν → huge flux ($3x10^6$ ν in your body now), low energy → not yet detected
- Solar ν_e → produced in nuclear reactions inside the Sun, E~MeV → detected
- SN burst (ν_e) → detected from SN1987
- Reactor anti-ν_e → first detected neutrinos
- Atmospheric ν (ν_e and ν_μ) → GeV-TeV region, detected
- Galactic and extra-galactic neutrinos sources → ICECUBE?



50 orders of magnitude in flux
25 orders of magnitude in energy

ν oscillation at reactors

- Nuclear powerplants produce 6 anti-ν of few MeV for each nuclear fission
  - $^{235}U + n \rightarrow {}^{94}Zr + {}^{140}Ce + 2n + 6e^- + 6\nu_e$
- Huge isotropic source of neutrinos
- Observe anti-νe disappearance

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{13} L}{4E_\nu}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m^2_{12} L}{4E_\nu}\right)$$

First term: sensitive to θ_{13} (small), Δm^2_{13}~2×10^{-3} → small disappearance at ~ 1 km → goal of 2012 reactor neutrino experiments

Second term: sensitive to θ_{12} (large), Δm^2_{12}~7.5×10^{-5} → large disappearance at ~ 60 km → observed by KamLAND