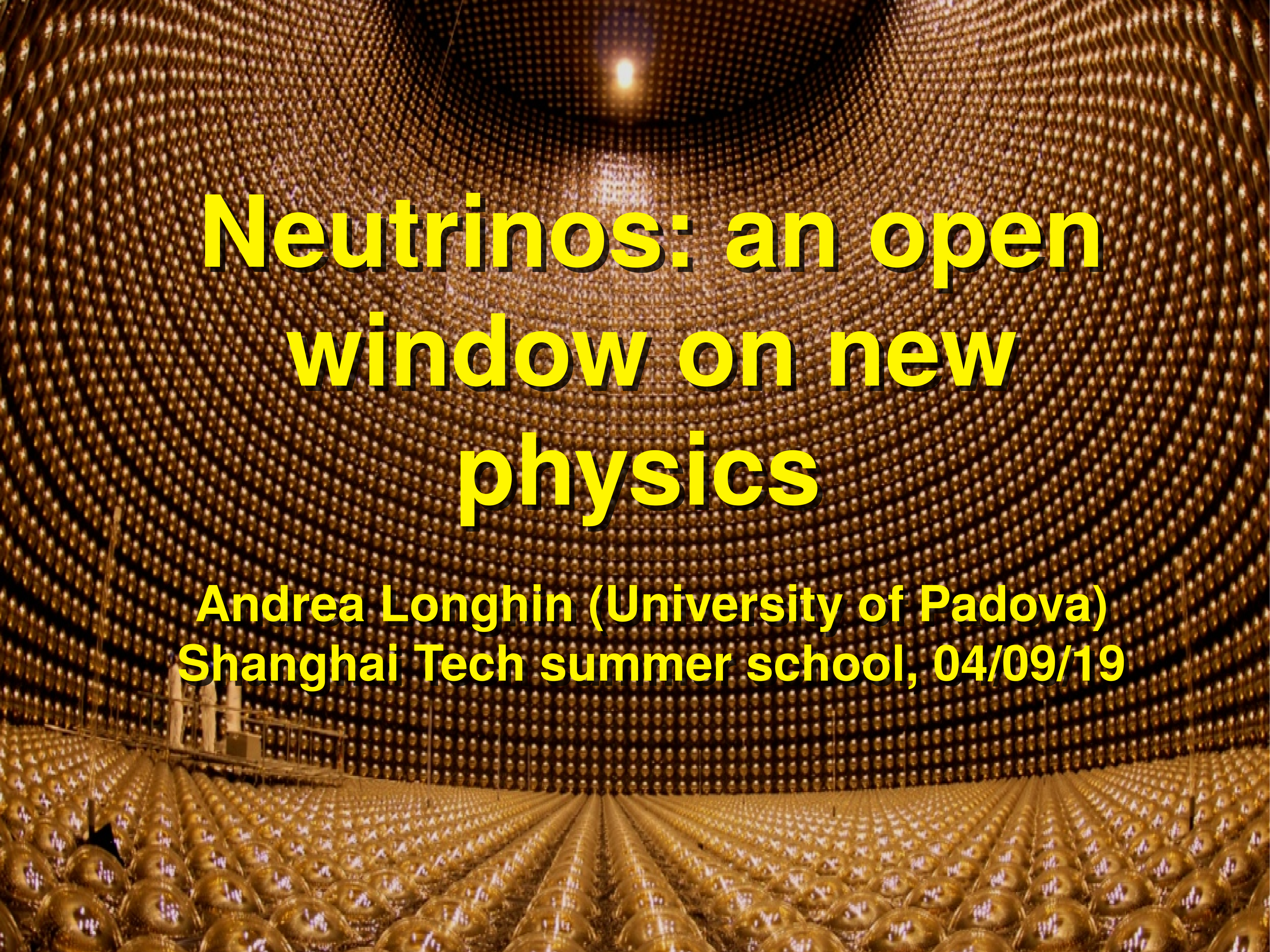
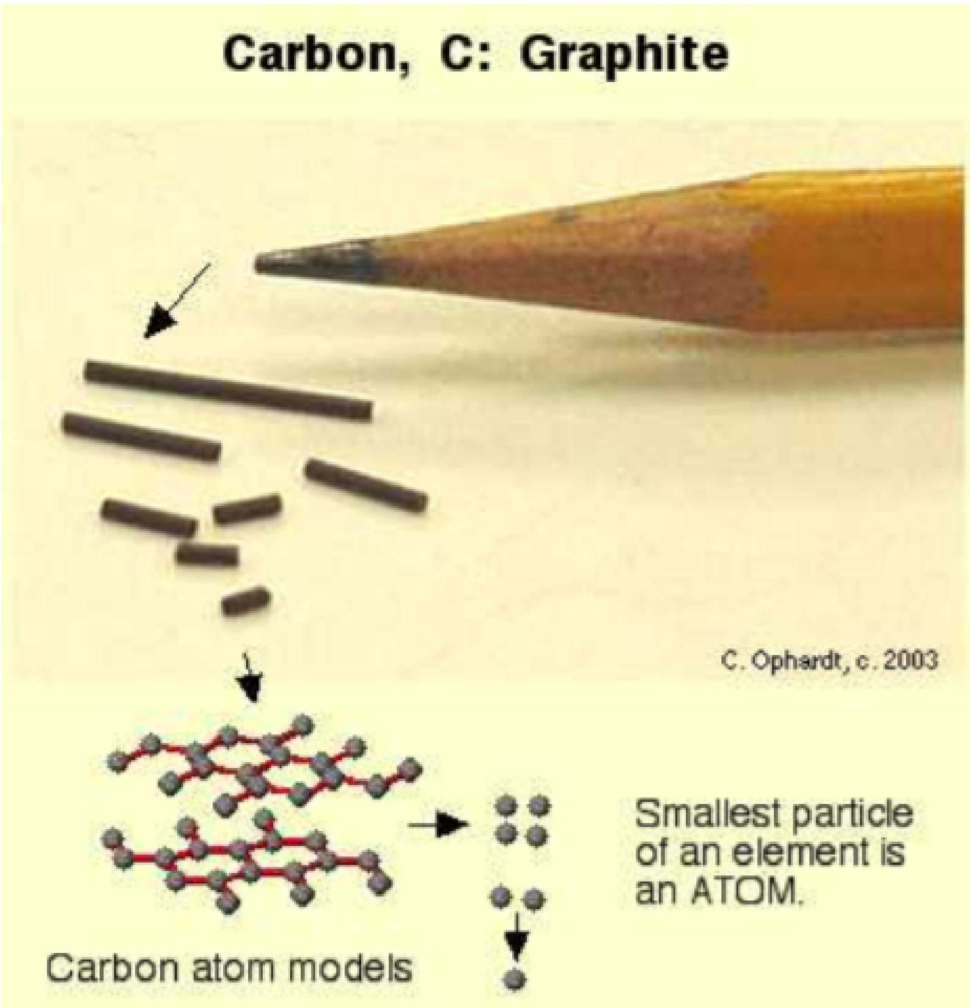


Neutrinos: an open window on new physics

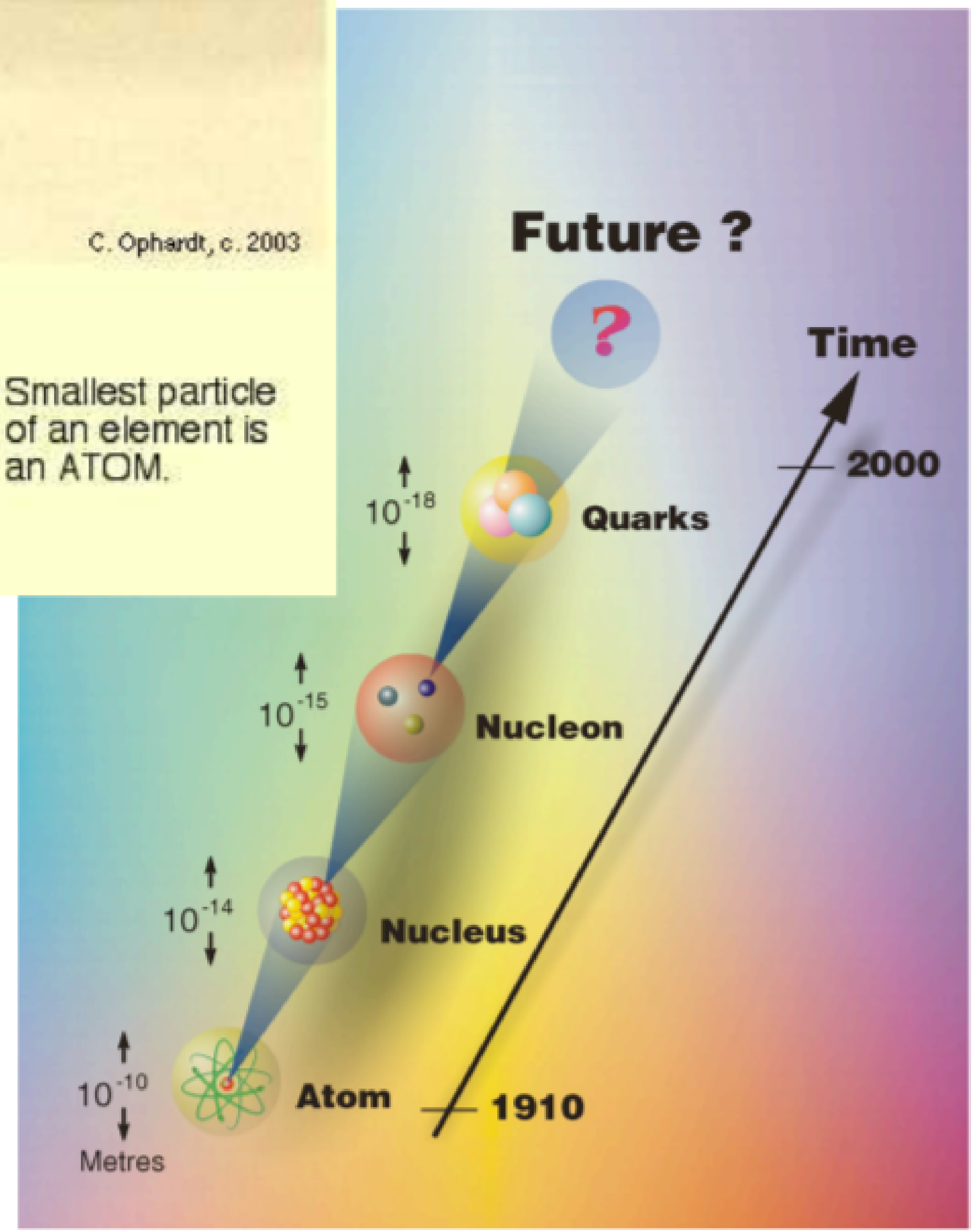
Andrea Longhin (University of Padova)

Shanghai Tech summer school, 04/09/19

Particle physics



- What are basic ingredients of matter?
- How do they interact with one another?



- What are the most fundamental laws that describe all natural phenomena (at least in principle)?

The 21st century "periodic table"

The neutrino is an **elementary particle** (as far as we know! No known "substructures")

neutral (no electric charge)
→ no electromagnetic interaction
a **lepton** (like e, μ, τ charged)
→ no strong interaction
- three **flavor** states (interaction):

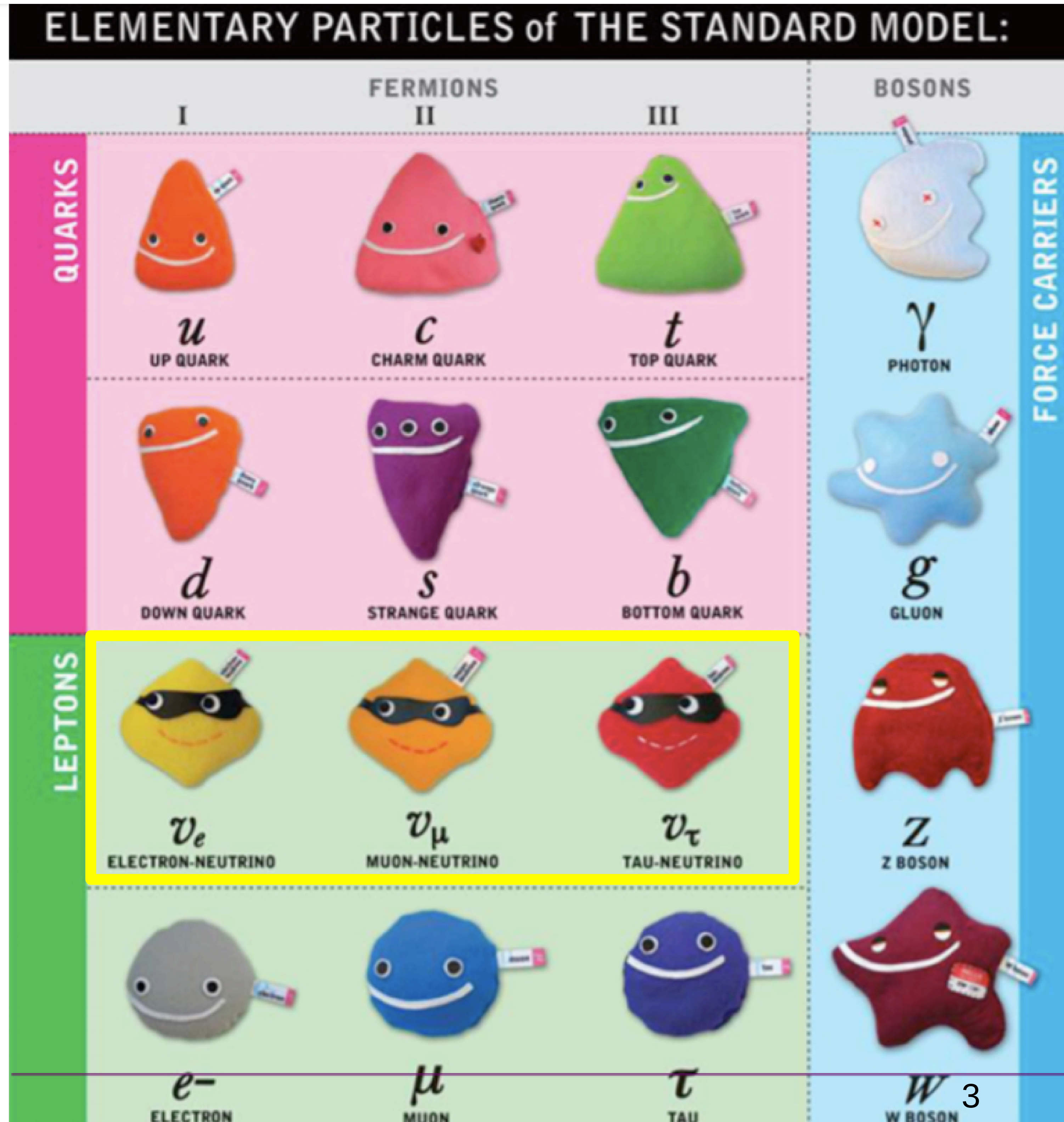
ν_e ν_μ ν_τ

It is a **fermion** (half integer spin)

It is the only elementary particle interacting only via the weak and gravitational interaction (but Its **mass is ridiculously small**!)

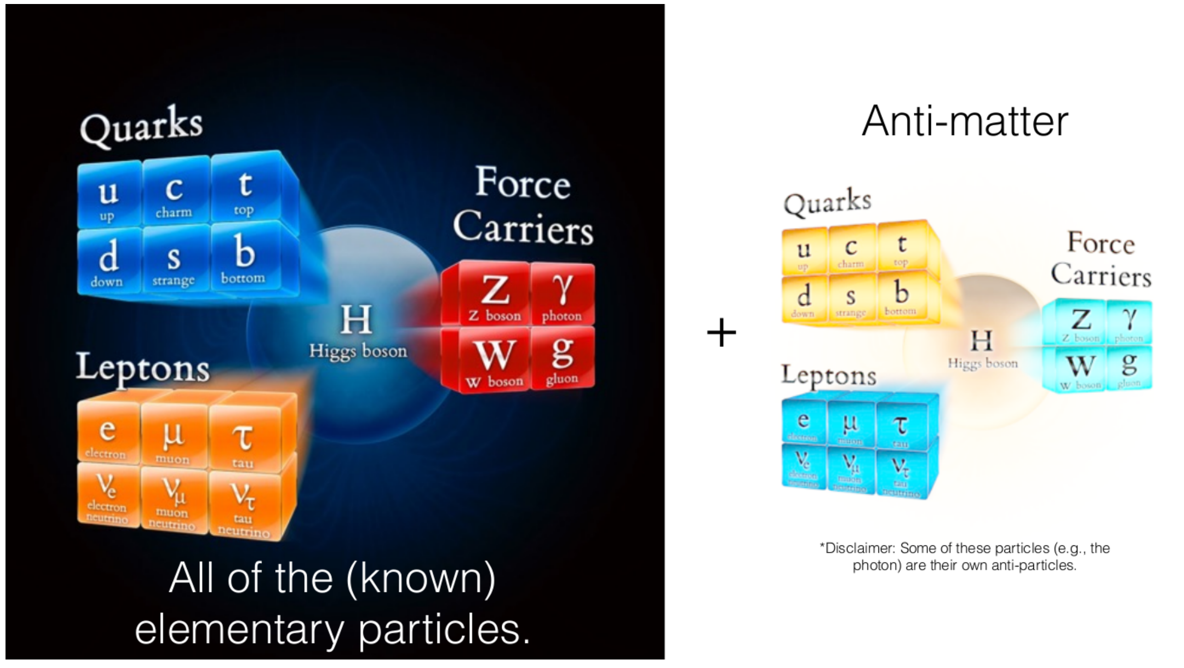
very **difficult to study** due to the very rare interactions with matter (we detect neutrinos by looking at the secondary particles that are produced when they interact with ordinary matter).

Despite being so "shy" it is the **second most abundant** particle in the universe!



Neutrinos in the standard model

The Standard Model of particle physics describes the particles which exist in Nature (fermions and bosons) and their interactions (forces). It describes the strong, electromagnetic and weak interactions of elementary particles in the framework of quantum field theory.



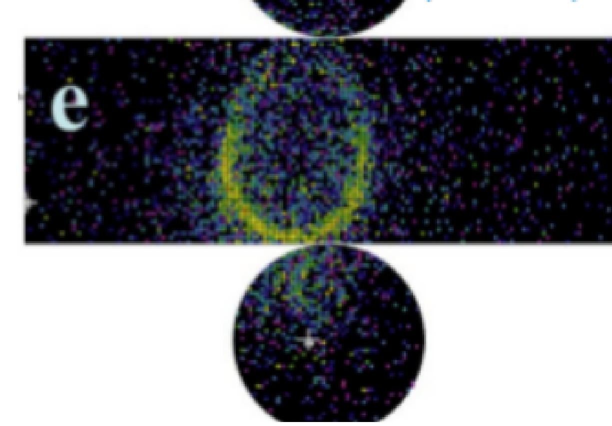
To get to this "distilled truth" was no "pleasure cruise"!
a **lengthy process** paved with **puzzles** and **surprises** (and success after all!).

But still **we do not understand a lot** of what is going on! And we are **not completely satisfied** by this theory (many parameters set "by hand")

Neutrinos continue to be a **perfect playground** for the advance of our knowledge in the field (one of the less well explored sides)

Let's see how we learned (part) of this and what is still ahead!

Outline

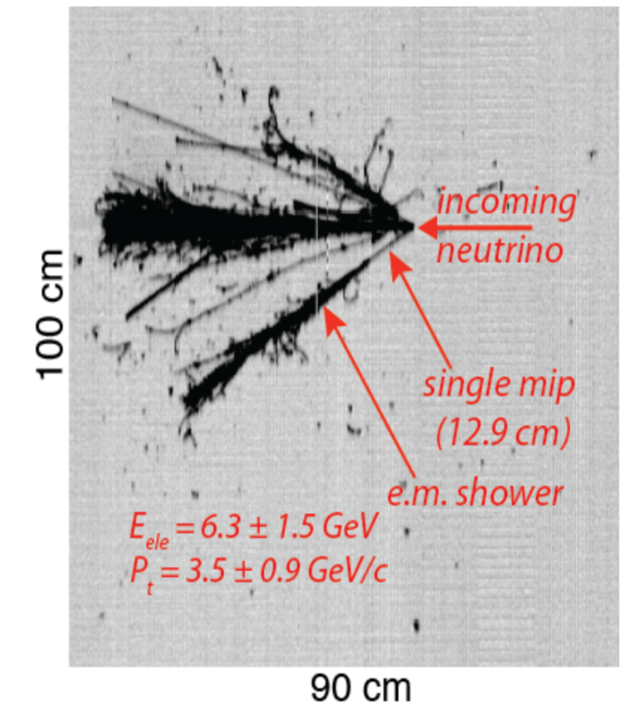


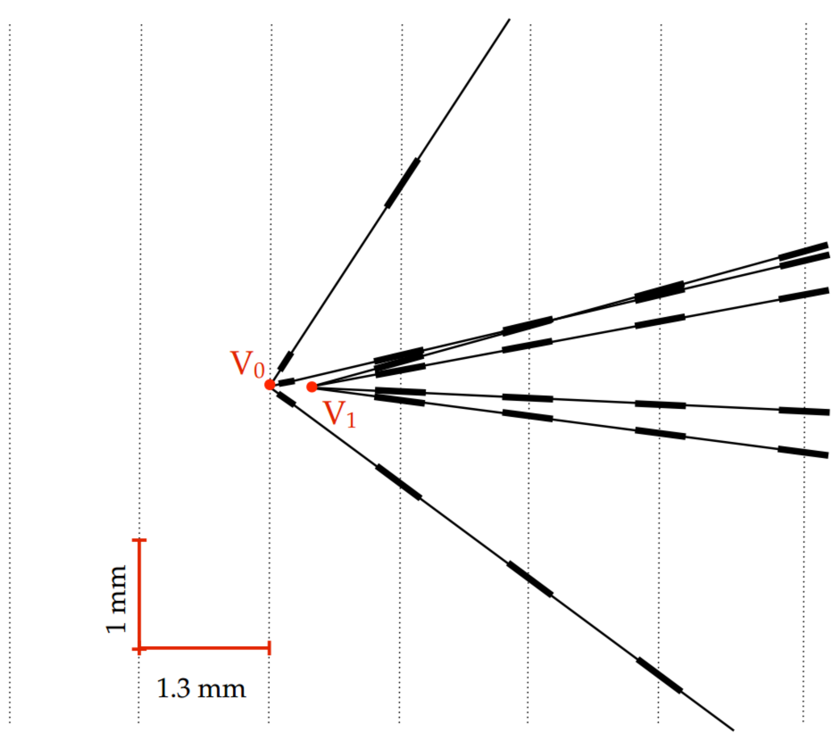
What we have discovered: an history of surprises

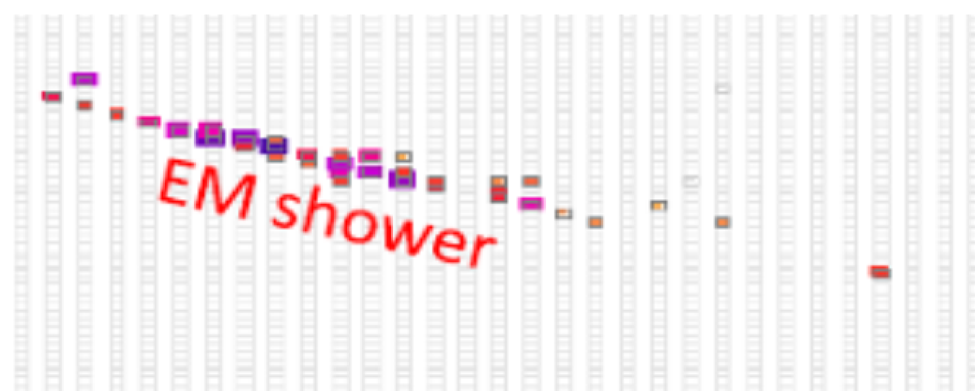
The state of the art of research

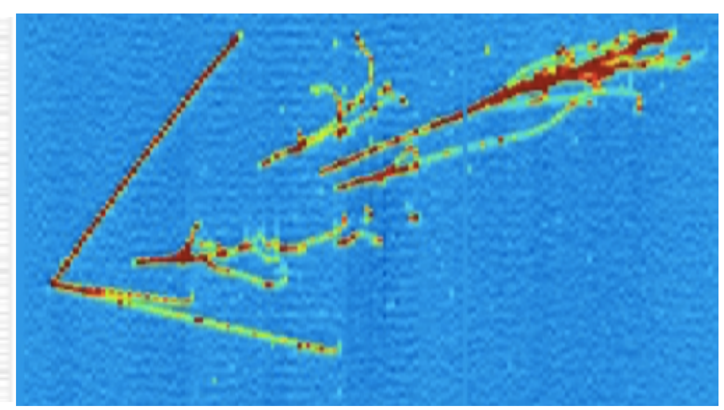
The open questions

A glimpse on new ideas growing bigger: ENUBET



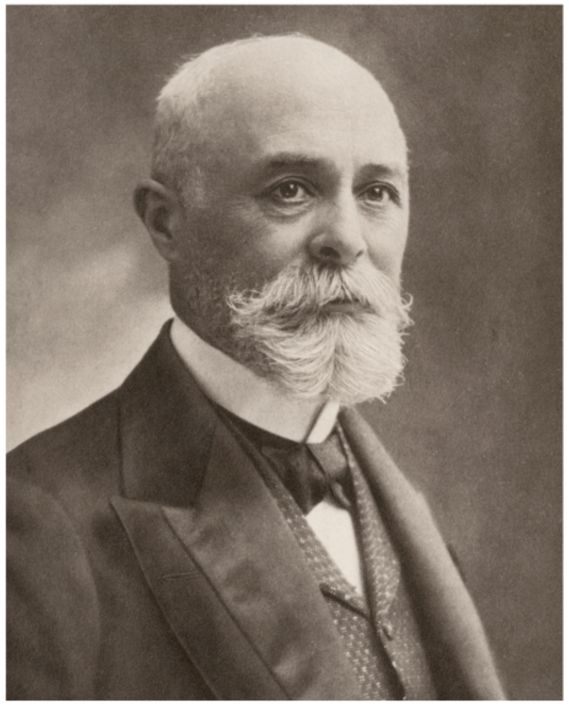


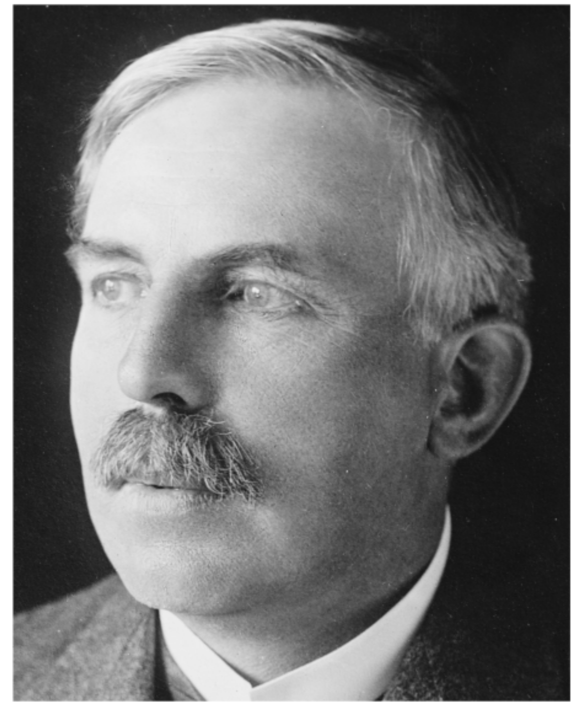


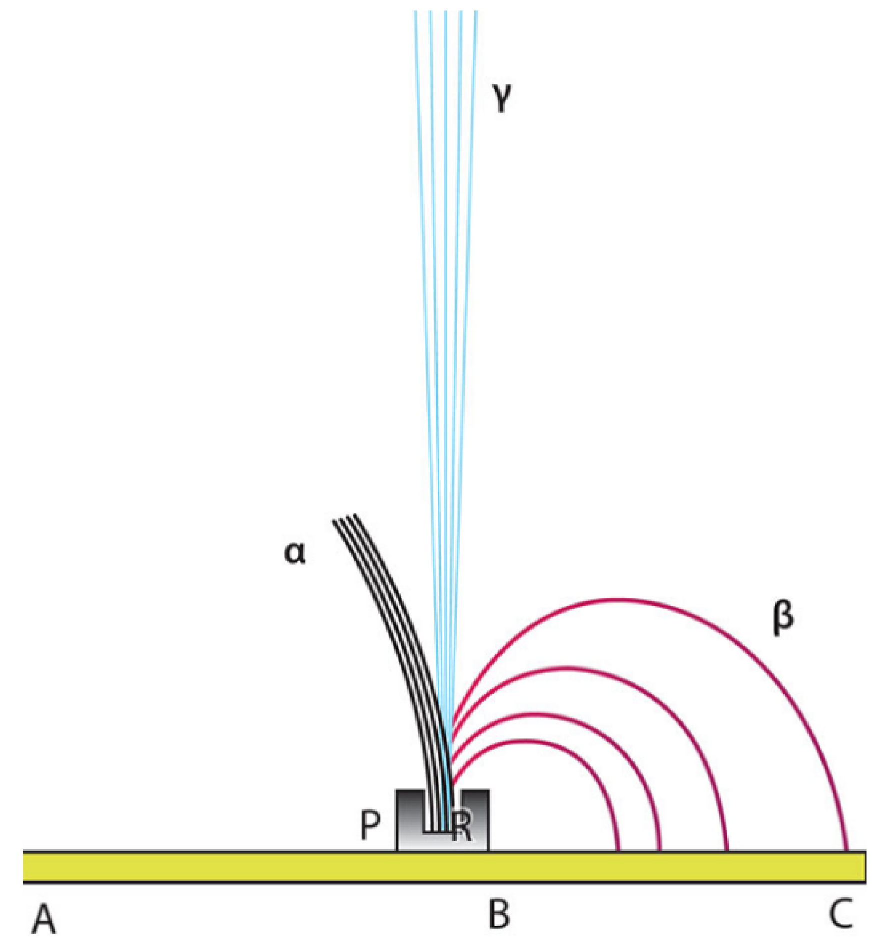


Mission impossible: I have tried to give an exhaustive overview → Q&A is an ideal way of filling the gap!

The pre-history of neutrinos: radioactivity





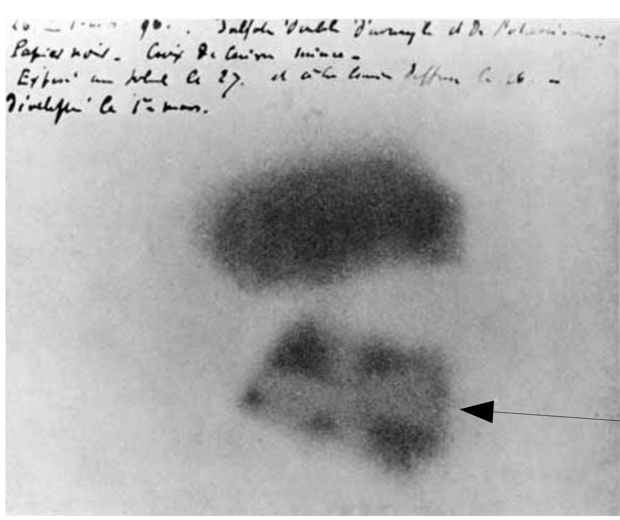


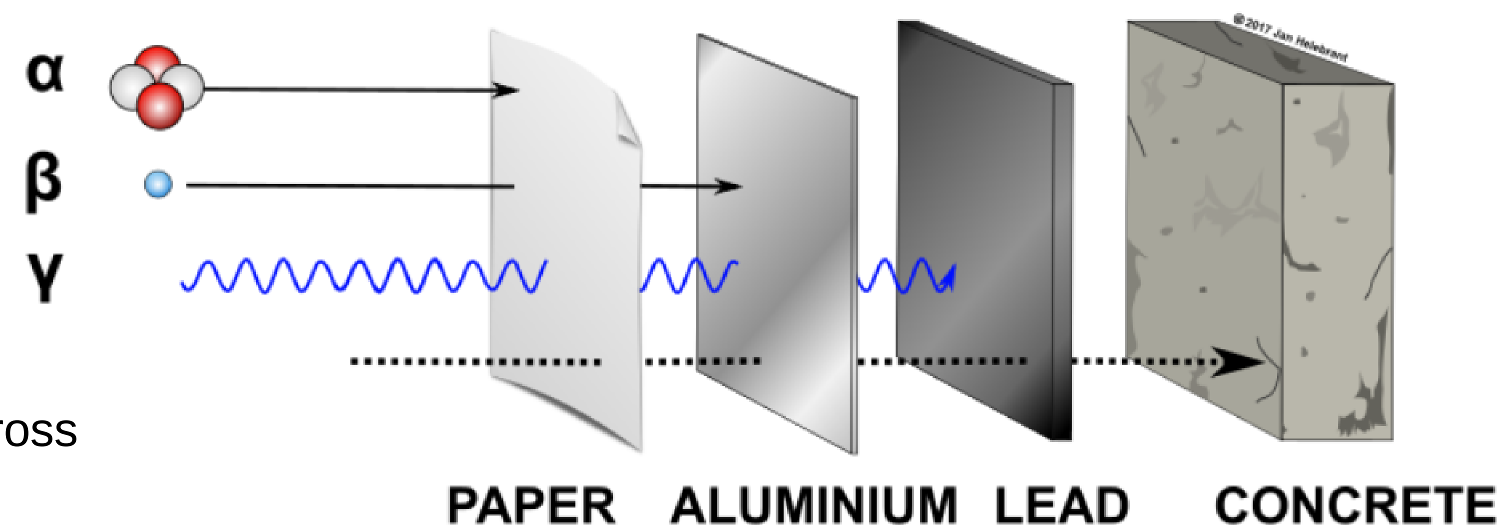
1896 : discovery of radioactivity by H. Becquerel (phosphorescence of U salt)

Nobel Prize in Physics 1903 :
"in recognition of the extraordinary services he has rendered by his discovery of spontaneous radioactivity"

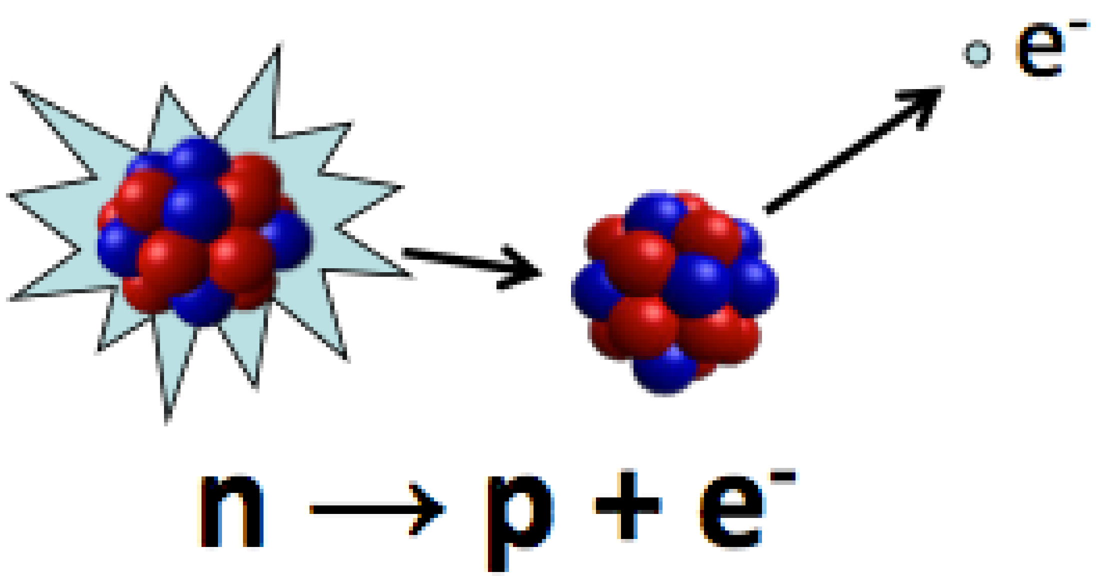
1899 : discovery of 2 different by products, α and β by E. Rutherford

Nobel Prize in Chemistry 1908 :
"for his investigations into the disintegration of the elements, and the chemistry of radioactive substances"

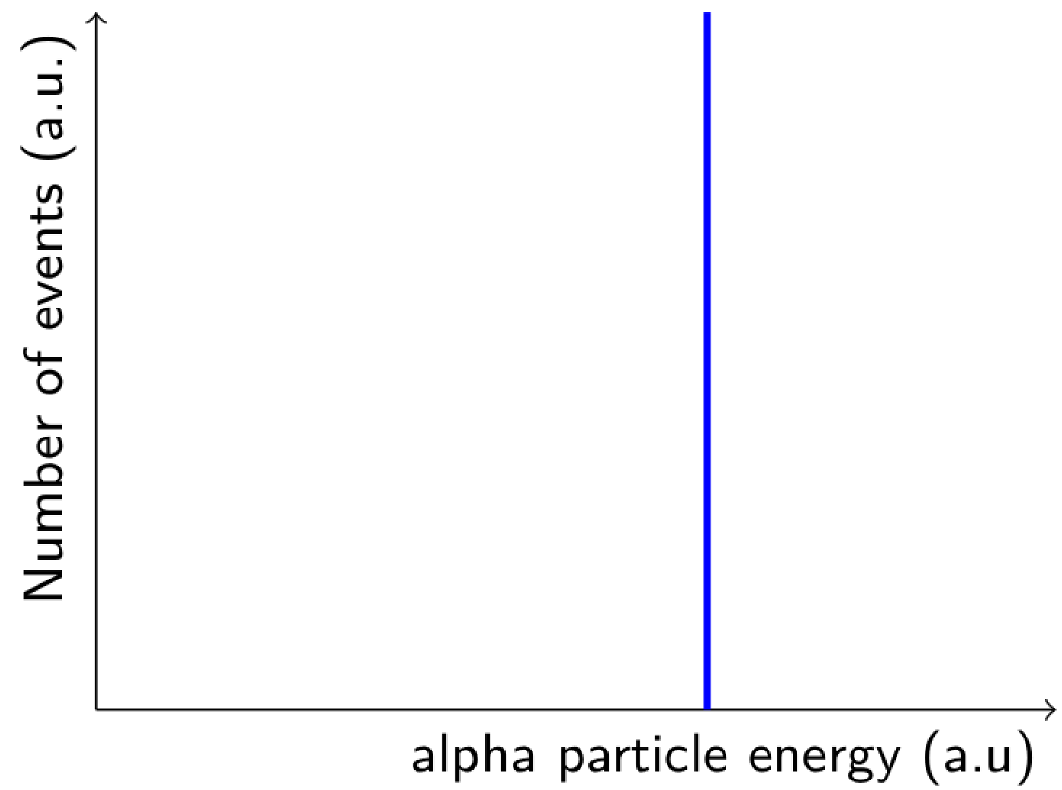




Two-body decay



$$^{A}_{Z}X \rightarrow \, ^{A-4}_{Z-2}Y + \, ^{4}_{2}He\,(\alpha)$$



Energy-momentum conservation :

$$E_1 = \sqrt{p^2 + m_1^2} = \frac{M^2 + m_1^2 - m_2^2}{2M}$$

⇒ energy of the decay products always the same

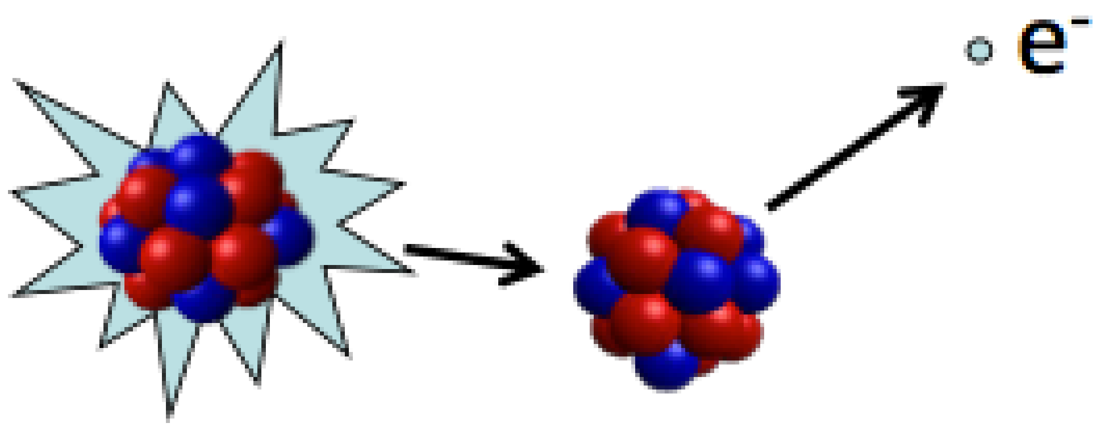
Verified in α decays but badly violated in β decays ($p \rightarrow ne^+$ or $n \rightarrow pe^-$)

1914 : J. Chadwick demonstrated that β-spectrum was continuous

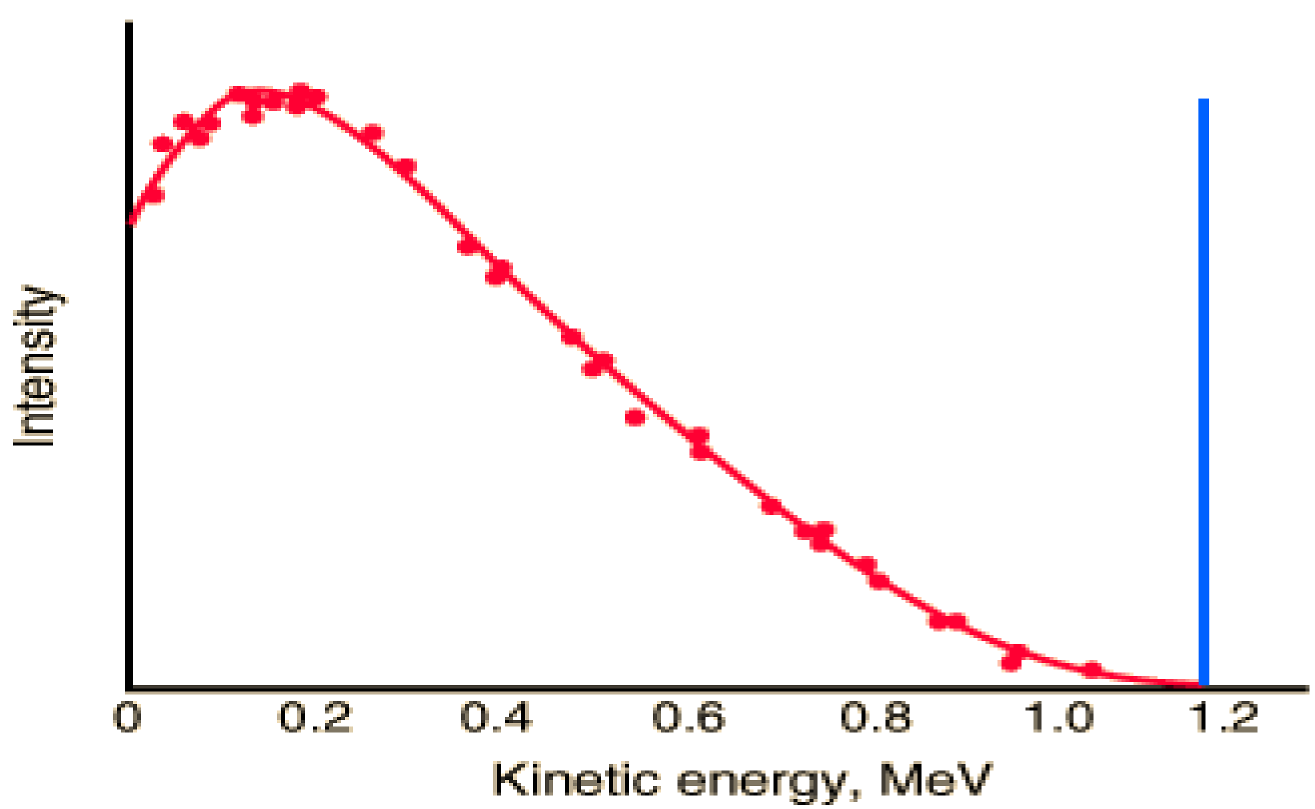
Nobel Prize in Physics 1935 : *"for the discovery of the neutron"*

The neutrino hypothesis (a "desperate remedy")

- In 1914 an unexpected feature of β^- decay was observed
- The electron energy spectrum was continuous



$$n \rightarrow p + e^-$$



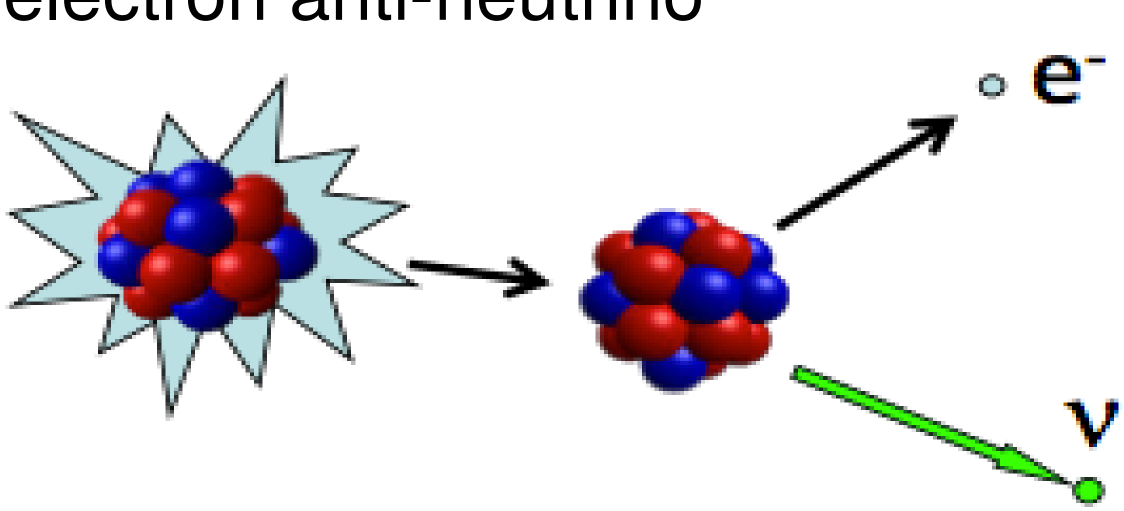
Energy IS NOT conserved!?

?

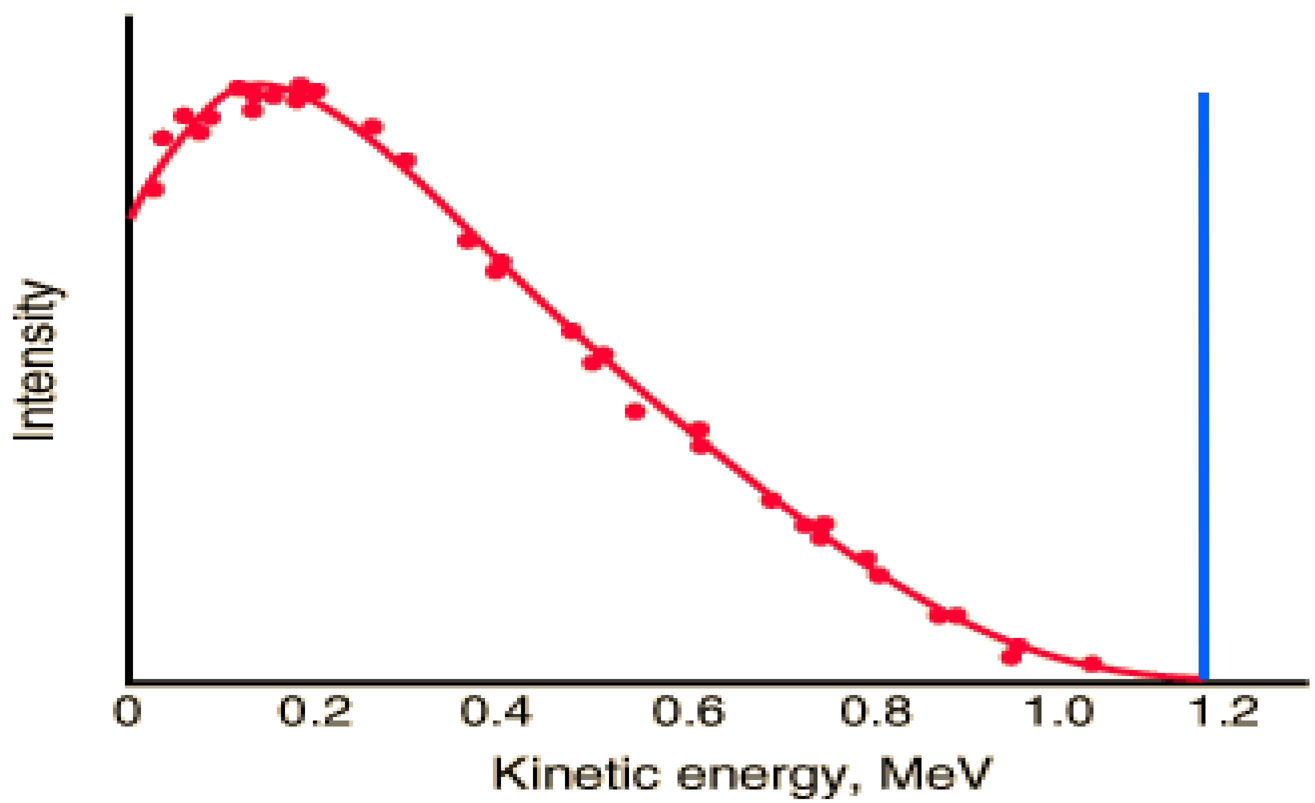
Prof. Wolfgang Pauli

The neutrino hypothesis (a “desperate remedy”)

- In 1914 an unexpected feature of β^- decay was observed
- The electron energy spectrum was continuos
- A new neutral particle that travels through matter must exists: the **neutrino**!
- It is an electron anti-neutrino



$$n \longrightarrow p + e^- + \nu$$



Energy IS conserved!

Prof. Wolfgang Pauli

The neutrino hypothesis (a “desperate remedy”)

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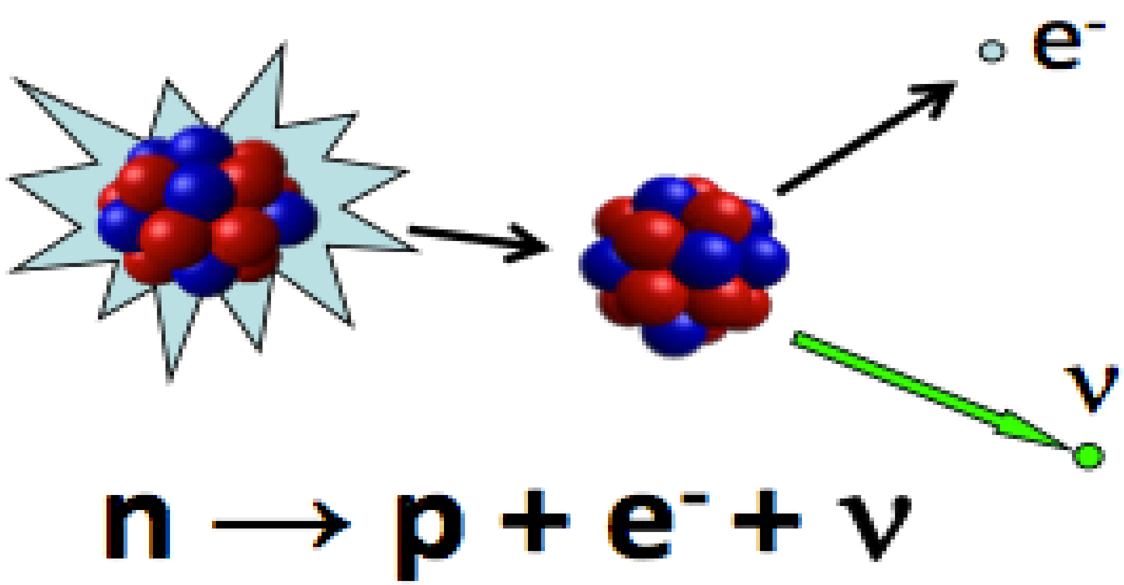


Energy IS conserved!

But a fraction of the energy (the missing part) is carried away by an “invisible host”. This is why the energy of the beta ray (e^+ or e^-) is less than the available one. Neutrino took his share!

Prof. Wolfgang Pauli

Original - Photocopie of PLC 0393

Abschrift/15.12.56 FM

Offener Brief an die
Gauvereins-Tagung zu

Dear radioactive Ladies and Gentlemen,

Sounds spooky today

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grossenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

Dear radioactive ladies and sirs...

I do not consider advisable, for the moment, to publish something about these ideas and first I apply to with confidence, dear Radioactives, with the question: what do you think about the possibility of providing the experimental proof of such a neutron, if it would possess a penetrating power equal or ten times greater of that of gamma rays?

Pauli launches a challenge to colleagues doing experiments. He had the intuition that this new particle had to be extremely weakly interacting. It was soon understood that "a penetrating equal or ten times greater gamma rays" was grossly too optimistic!

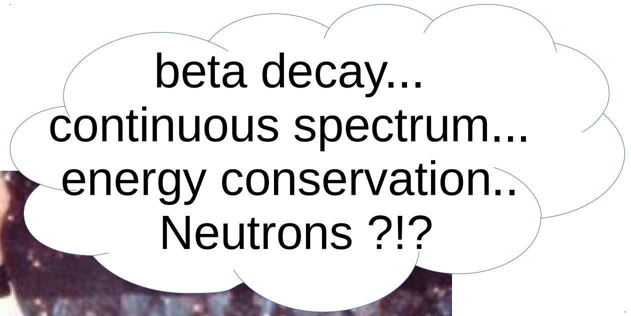
W. Pauli : "I have done something very bad today by proposing a particle that cannot be detected; it is something no theorist should ever do."

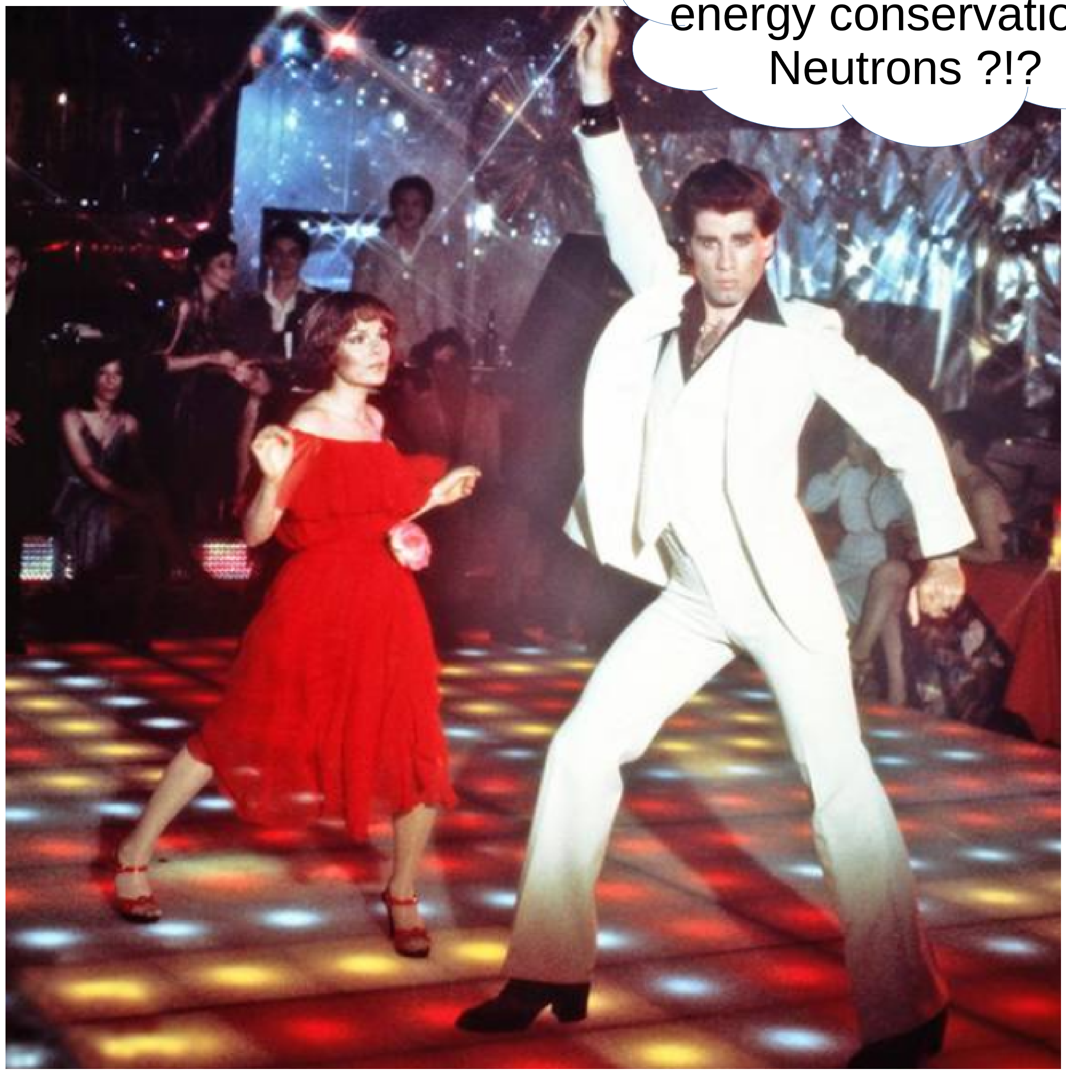
Nobel Prize in Physics 1945 :
"for the discovery of the Exclusion Principle, also called the Pauli Principle"

Don't worry Wolfgang, experimentalists are hungry for difficult measurements and theoreticians nowadays can do much worse!

Dear radioactive ladies and sirs...

should consider seriously any way towards safety. Thus, dear Radioactives, consider and judge. Unfortunately I cannot come personally to Tubingen, because I am necessary here for a ball that will take place in Zurich the night from 6 to 7 December. With many greetings to you as well as to Mr. Black. Your devoted servant, W. Pauli





My conclusions about the ballet:

1) Even if you are desperate, if you are brilliant enough you can safely skip conferences and go to dance (but not summer schools!)

2) since the 30's not all physicists are nerds !

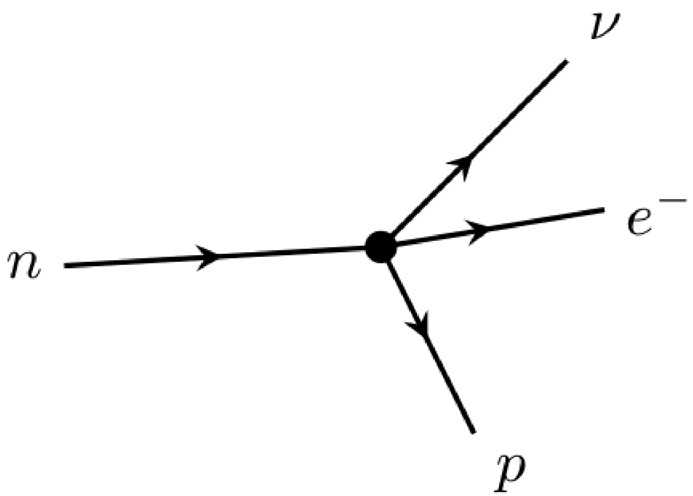
Fermi: a first theory of weak interactions

Given the energy of the beta ray (electron) the neutrino had to be extremely light and neutral (charge balance)

- In 1934, E. Fermi formulated a theory of β-decay, in analogy with quantum electrodynamics (QED) involving the neutrino

Nobel Prize in Physics 1938 : *"for his demonstrations of the existence of new radioactive elements produced by neutron irradiation, and for his related discovery of nuclear reactions brought about by slow neutrons"*

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



Fermi constant : $G_F = 1.6637 \times 10^{-5}\ \text{GeV}^2 \ll \alpha_e$

A **new extremely weak force** had to be involved much weaker then electromagnetic interactions.
→ Neutrino had to interact with matter extremely weakly.

The interaction is weak because **very heavy particles are "exchanged"** → vector bosons (W/Z^0)
discovered at CERN, 1983 Nobel prize, Rubbia,Van Der Meer in 1983

The name

1914 : J. Chadwick demonstrated that β-spectrum was continuous

Nobel Prize in Physics 1935 :
"for the discovery of the neutron"

Pauli had called his hypothetical particle a "neutron"
In the meantime in 1932 Chadwick had discovered what we today call "neutron", another neutral particle involved in nuclear decays (a "neutral proton") →

Fermi: Neutron → neutr**ino** (small neutron in italian)

The name

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In the meantime in 1932 Chadwick had discovered what we today call "neutron", another neutral particle involved in nuclear decays (a "neutral proton") →

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Fermi: Neutron → neutr**ino** (small neutron in italian)

gatt**o**

gatt**ino**

gatt**one**

gattino & gattone ~ 1-2 orders of magnitude in mass.
neutrino & neutrone: at least 9! "almost massless"
(see later)

Beyond an hypothesis: detection strategies

- 1934, H. Bethe : if one observes

$$n \rightarrow p + e^{-} + \nu$$

then what about an inverse β-decay (IBD)

$$\nu + p \rightarrow n + e^{+} \, ?$$

Nobel Prize in Physics 1967 :
"for his contributions to the theory of nuclear reactions, especially his discoveries concerning the energy production in stars"

- H. Bethe and R. Peierls calculated their cross section $\sim 10^{-44}$ cm^2
<u>remember</u>: probability of a reaction = cross section $\times$ number of target/area

- In order to detect neutrinos, one needs huge targets ($\sim 10^{21}$ cm of water) or a lot of neutrinos...

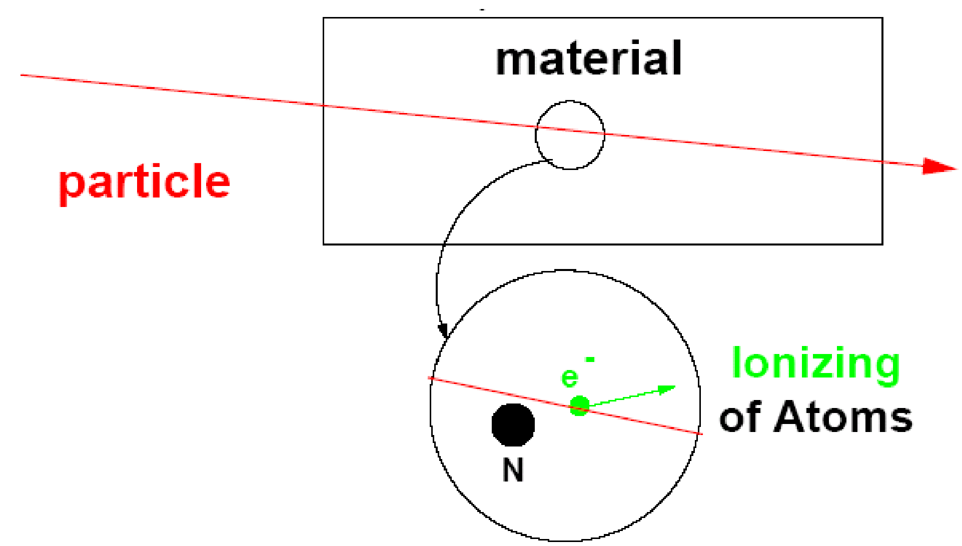
→ True… but along with times a very powerful source of electron anti-neutrinos became indeed available… ("a lot of neutrinos")→

H. Bethe and R. Peierls : *"one can conclude that <u>there is no possible way of observing neutrinos</u>"* in Nature 133 (1934) 532

How to hunt for a neutrino?

How do we "see" a particle?
➔ Electromagnetic interactions kick e^- away from atoms

But neutrinos don't have electric charge…



➔ They only interact weakly.
➔ See only by-products of their weak interactions (eg. leptons or the debris of the struck nucleus).

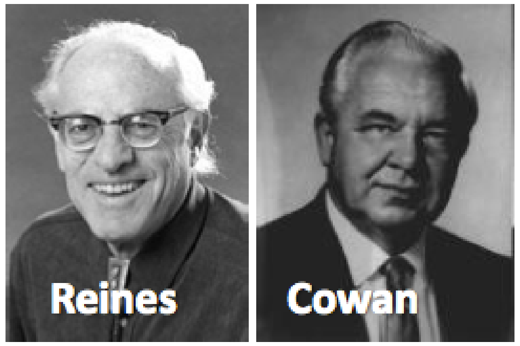
How weak is weak?

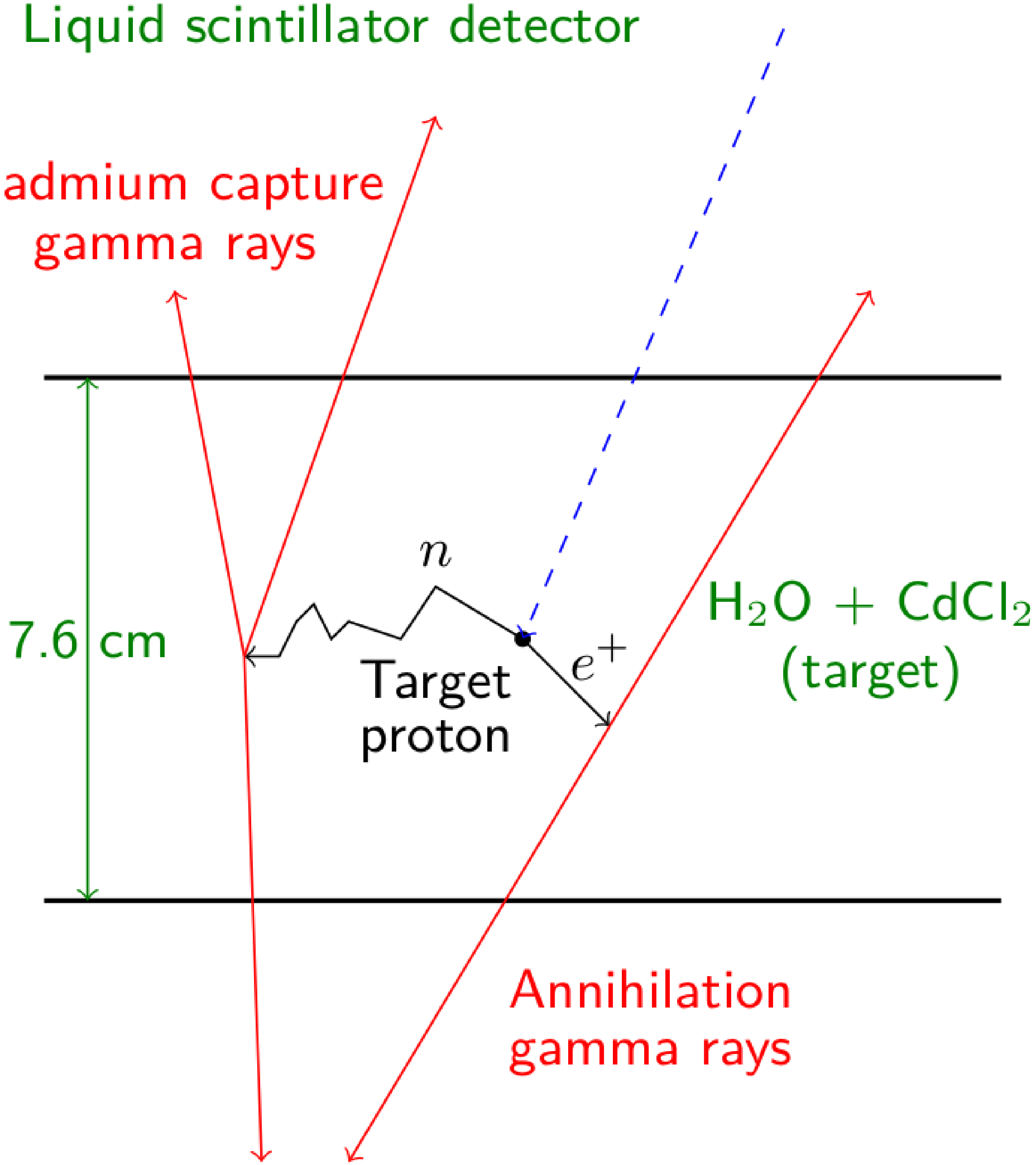
➔ A 3 MeV neutrino (i.e. from the Sun) travels **53 light years** through water, on average, before interacting.
A 3 MeV positron ("anti-electron") produced in the same fusion process will travel **3 cm**, on average.

* The interaction probability rises with energy so at larger energies the situation improves a bit

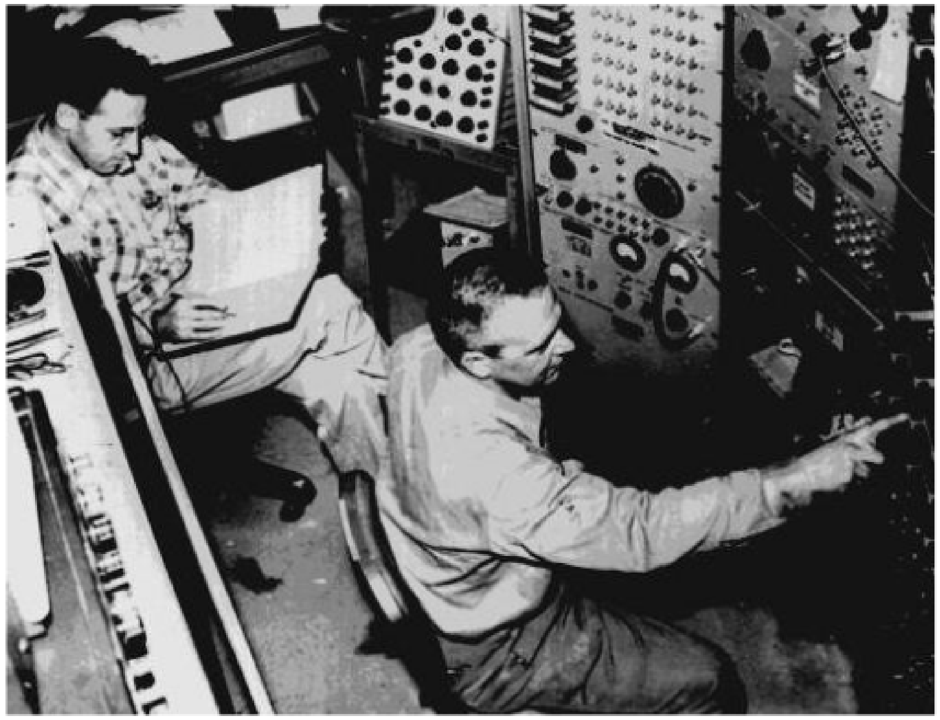
Moral: you need lots of neutrinos and large detectors!

The discovery at a nuclear reactor





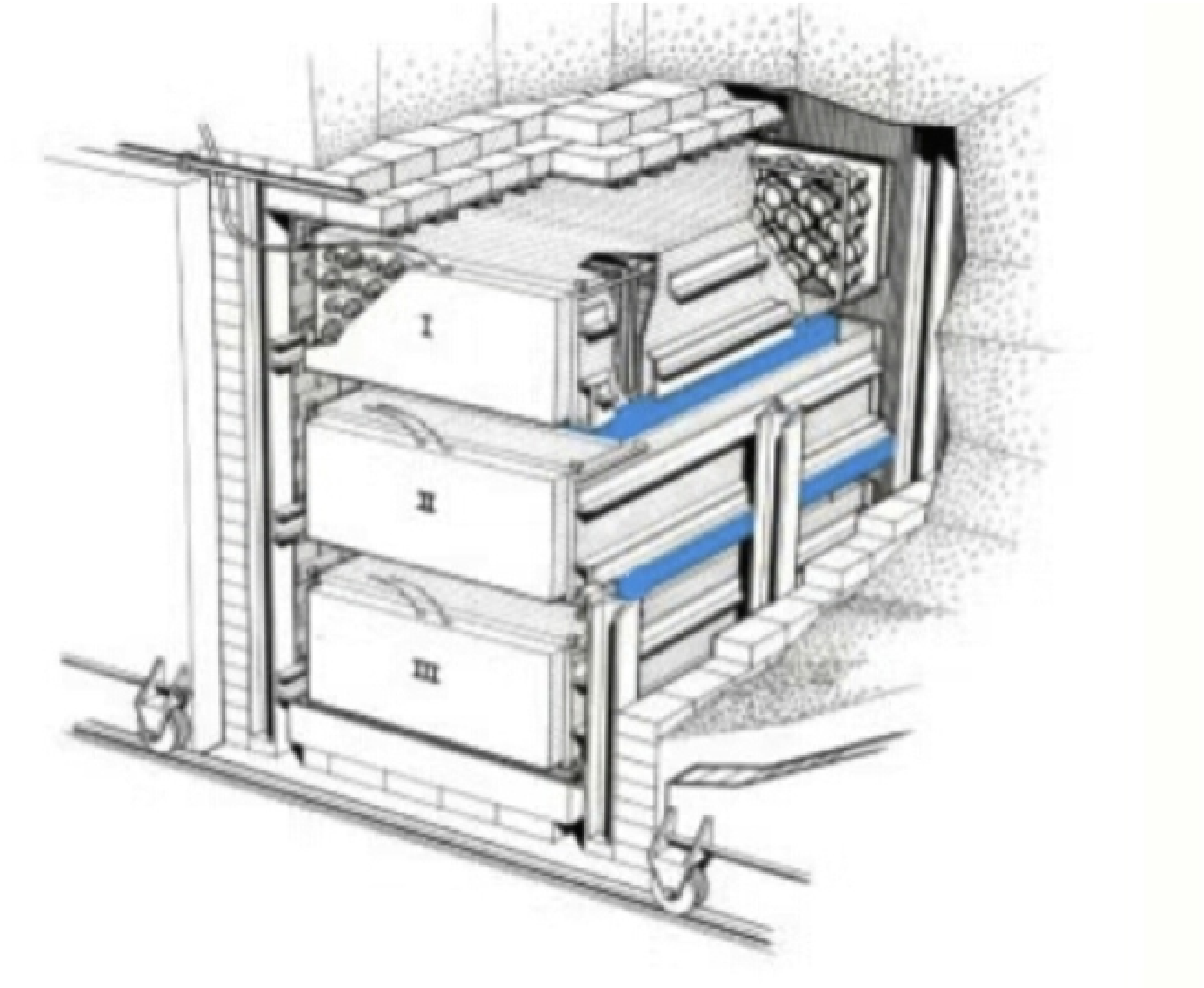
- In the Early 50's, F. Reines and C. Cowan search for a way to measure inverse β-decay

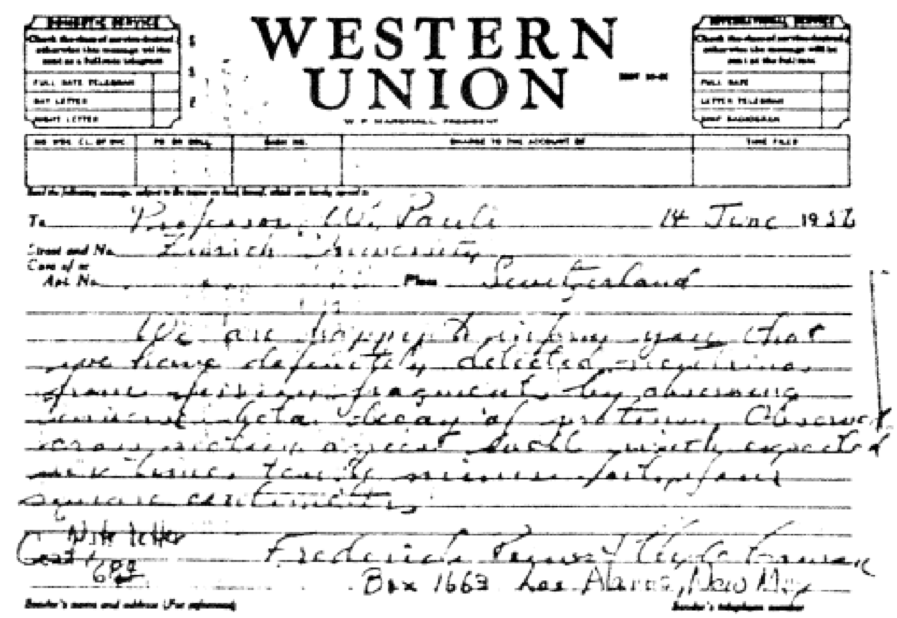


- After considering several methods, including a nuclear explosion, they settled using the large flux from a nuclear reactor ($\sim 10^{21}\ \bar{\nu}/\mathrm{GW}/s$)
  $\Rightarrow$ first reactor-neutrino experiment

The discovery at a nuclear reactor

Detector @ Savannah River power plant





The text reads: *"We are happy to inform you that we have definitely detected neutrinos from fission fragments by observing inverse beta decay of protons. Observed cross section agrees with expected six times ten to minus forty-four square centimeters."*

Nobel Prize in Physics 1995 :
for the detection of the neutrino
to Reines (Cowan passed away)

1934 $\rightarrow$ 1956 : 26 years between postulate and discovery!

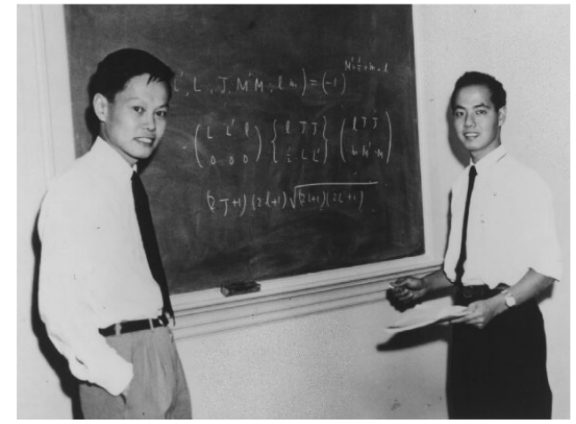
A path of knowledge

1950-60: a fruitful **interplay of theoretical ideas and brilliant experiments** allowed to pin down the theory of **weak interactions** using neutrinos

Further reading:

https://en.wikipedia.org/wiki/Chien-Shiung_Wu

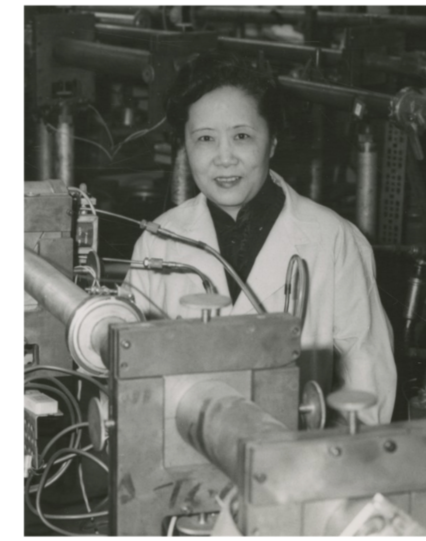
Parity violation in weak interactions



1956: T. D. Lee and C. N. Yang no evidence for parity conservation in weak interactions

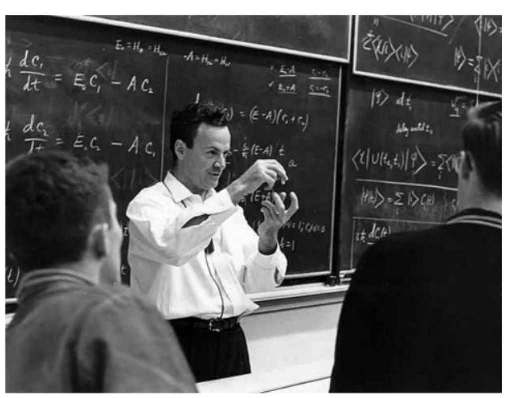
Nobel prize in 1957 : *"for their penetrating investigation of the so-called parity laws which has led to important discoveries regarding the elementary particles"*

1957: Madame Wu *et al.* observation of maximal parity violation in the β-decay of polarized ^{60}Co



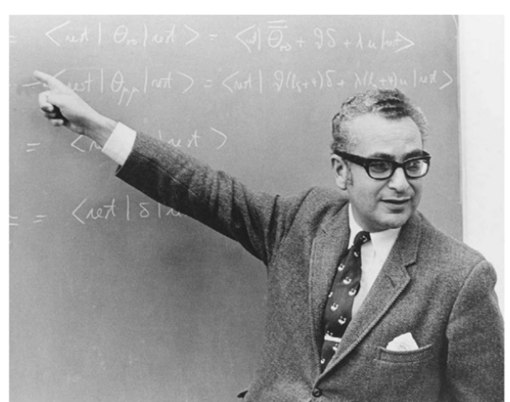
The V-A theory of weak interaction

R. P. Feynman



Nobel Prize in Physics 1965 *"for their fundamental work in quantum electrodynamics, with deep-ploughing consequences for the physics of elementary particles"* with S. Tomonaga & J. Schwinger

M. Gell-Mann

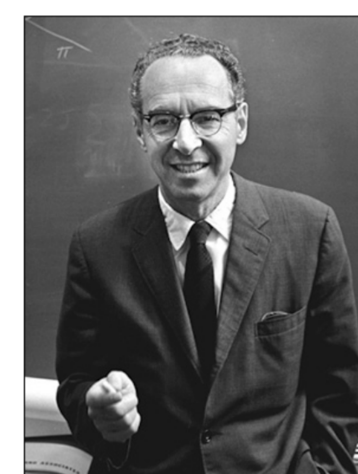


Nobel Prize in Physics 1969 *"for his contributions and discoveries concerning the classification of elementary particles and their interactions"*

Helicity of Neutrinos*

M. Goldhaber, L. Grodzins, and A. W. Sunyar
Brookhaven National Laboratory, Upton, New York
(Received December 11, 1957)

A COMBINED analysis of circular polarization and resonant scattering of γ rays following orbital electron capture measures the helicity of the neutrino. We have carried out such a measurement with Eu^{152m}, which decays by orbital electron capture. If we assume the most plausible spin-parity assignment for this isomer compatible with its decay scheme,[1] 0−, we find that the neutrino is "left-handed," i.e., $\sigma_\nu \cdot \hat{p}_\nu = -1$ (negative helicity).



One neutrino or two ?

A sort of "heavy electron"

- 1937 : discovery of the muon in cosmic rays

$$\mu \longrightarrow e + \ldots$$

the associated e spectrum corrsponds to a 3-body decay (continuous)

Who ordered that ?

- Lepton number conservation allows

$$\mu \longrightarrow e + \gamma$$

but experimental limits were many orders of magnitude smaller than predicted

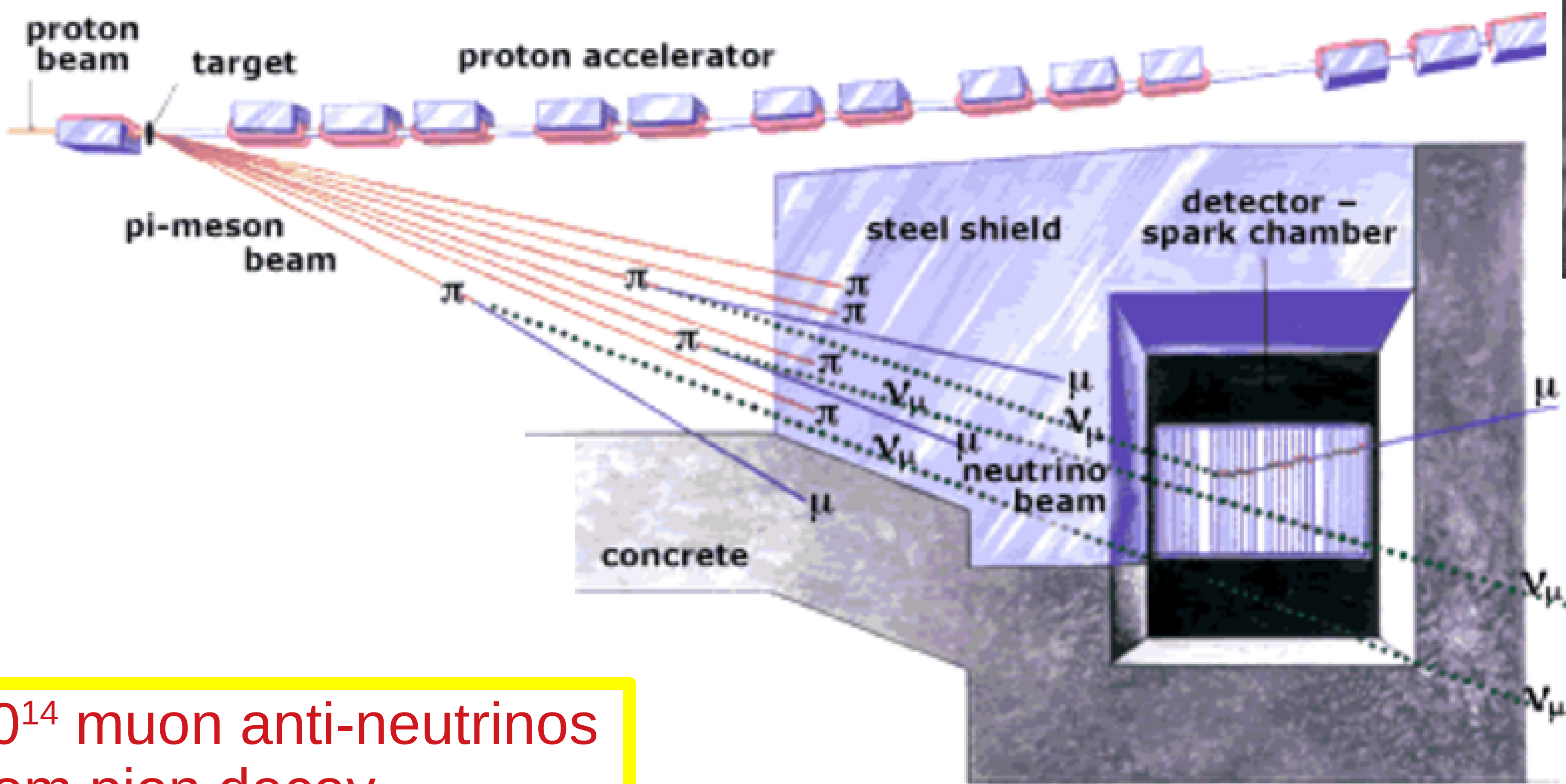
- New conservation law which assign different lepton numbers to each lepton family
- Pontecorvo : if it is shown that the neutrino produced in

$$\pi^+ \to \mu^+ + \nu_{(\mu)}$$ "Pion decay"

cannot induce e^-, then $\nu_{(\mu)}$ and $\nu_{(e)}$ are indeed different particle

Discovery of the muon-neutrino

- L. M. Lederman, M. Schwartz, J. Steinberger *et al.* succeeded in 1962 at Brookhaven National Laboratory (BNL) in establishing the existence of a second neutrino ν_μ



10^{14} muon anti-neutrinos from pion decay

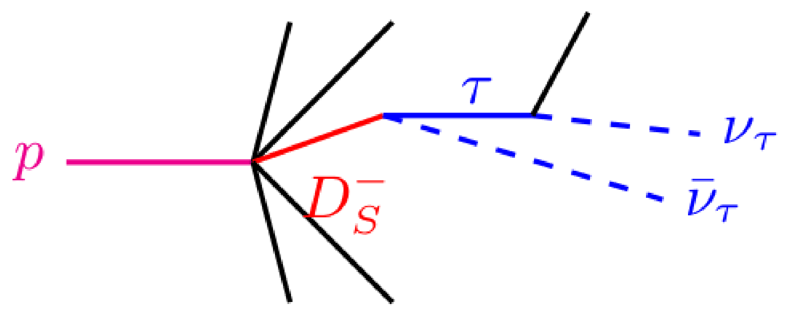
L. M. Lederman M. Schwartz J. Steinberger

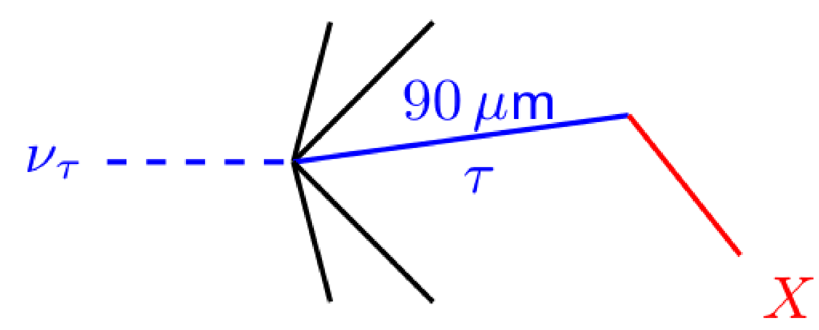
Nobel Prize in Physics 1988

- First serious accelerator neutrino experiment
- 29 μ^+ recorded, 0 e^- recorded : the neutrinos accompanying μ from π decays produced in the detector are ν_μ and not ν_e. They are different from the neutrinos discovered by Reines & Cowan

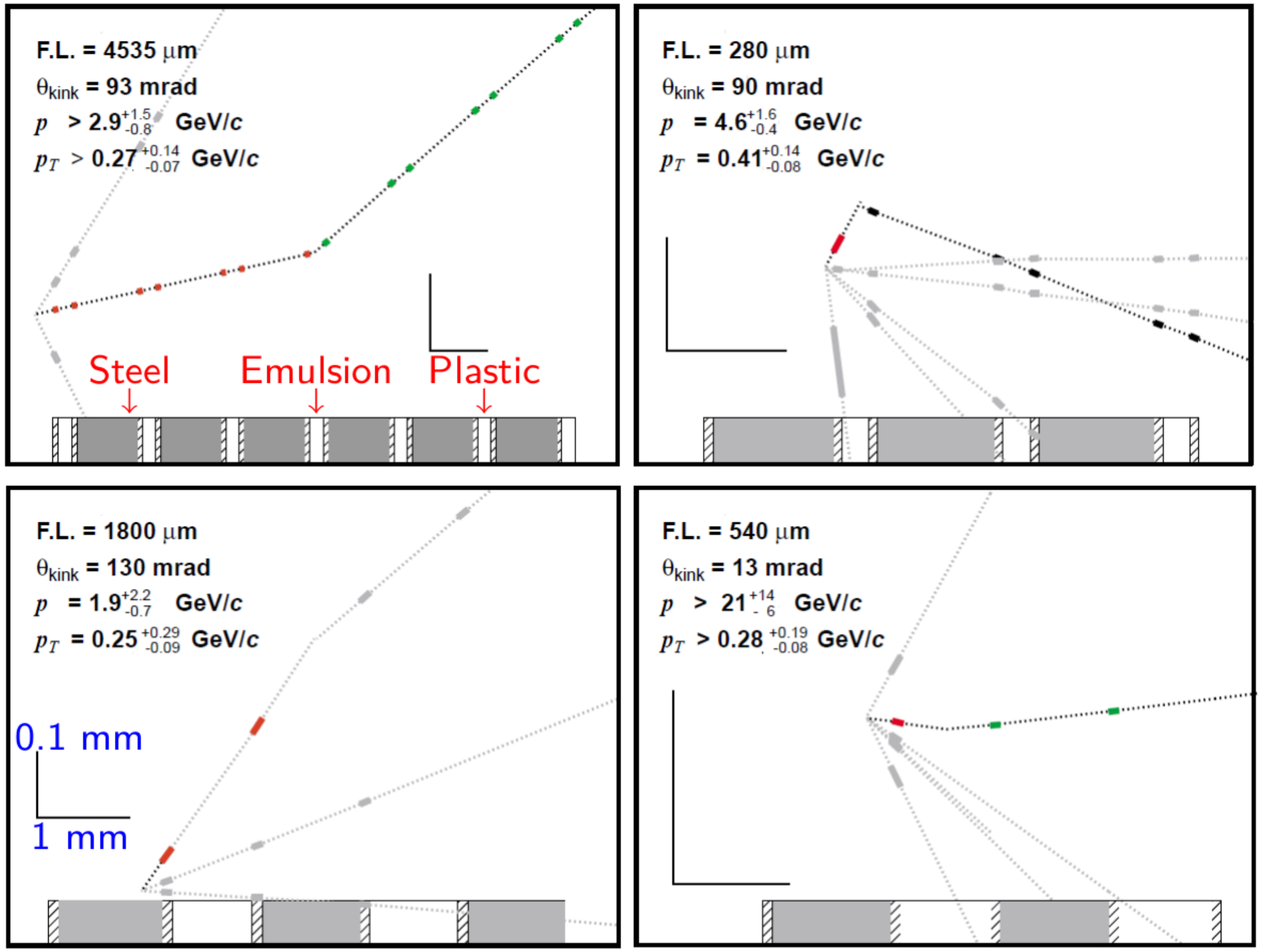
The third neutrino: ν_τ

Indirect evidence at e^+e^- colliders where τ lepton was discovered → "missing energy"
Direct evidence through interactions in a photographic emulsion experiment in 2000

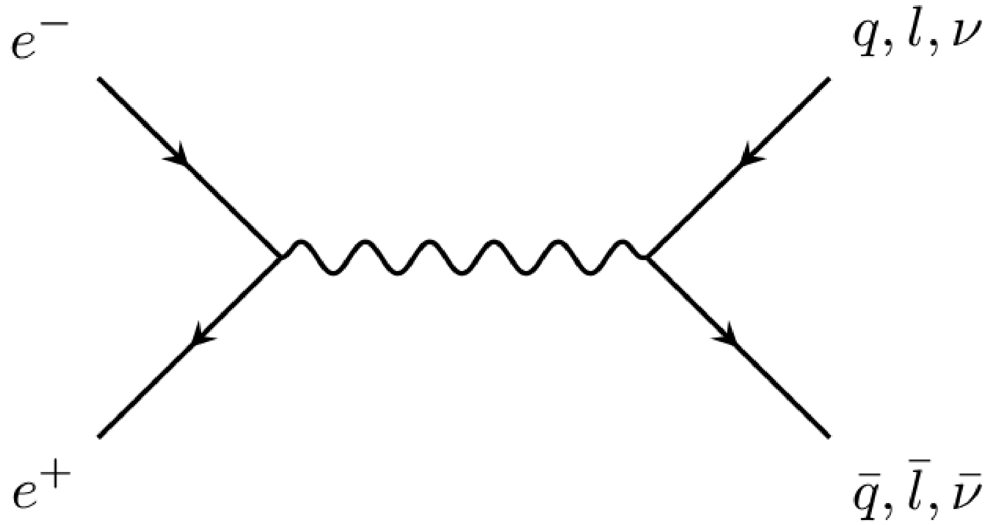


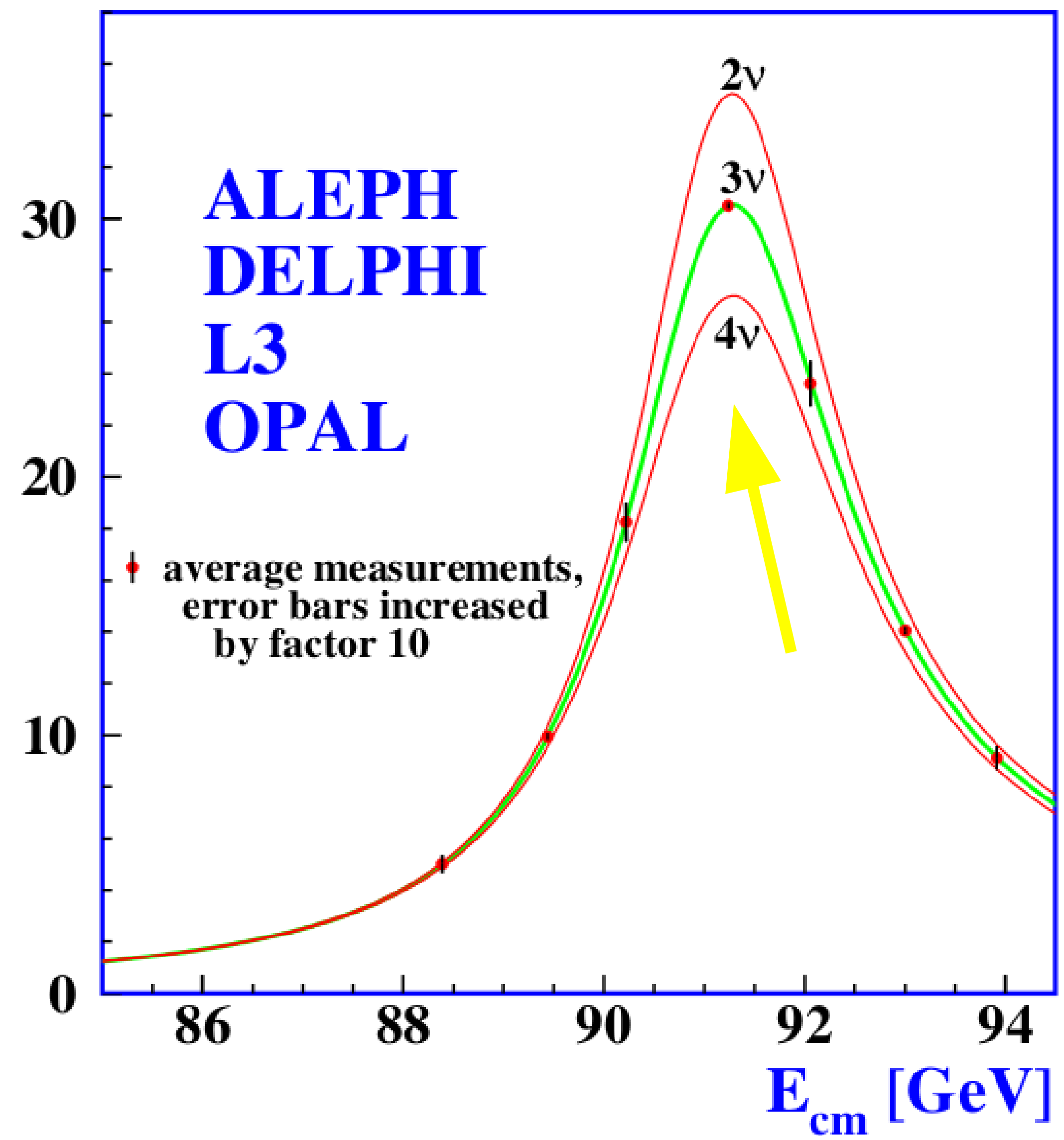


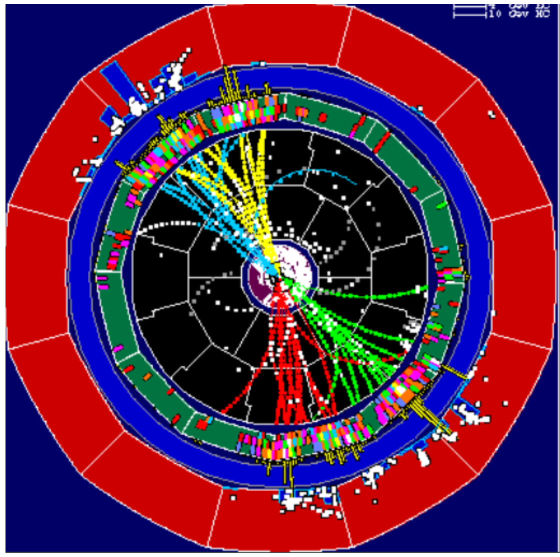
Tau neutrino interactions in the DONUT emulsion detector

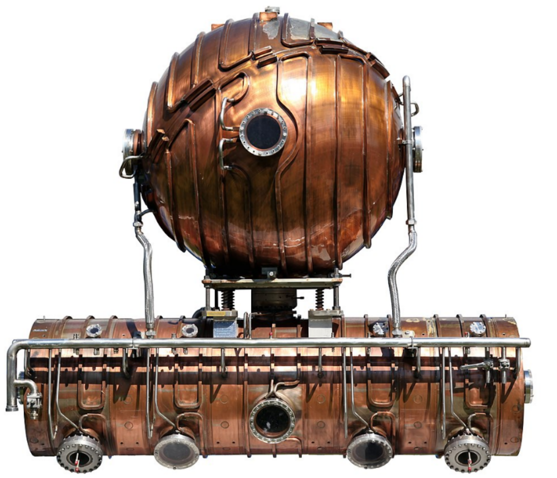


How many ?









1989: LEP experiments measure precisely how a Z boson, produced in an e+e- collision, decays →

Allows **counting the number of neutrino flavours**!

$$\Gamma_Z = \Gamma_{had} + 3\Gamma_l + N_\nu \Gamma_\nu \Rightarrow N_\nu = 2.99 \pm 0.02$$

$\Gamma_Z, \Gamma_l, \Gamma_{had}$ - measured
Γ_ν - calculated

The answer is three! (not 42!). Ironically ... nobody really knows why!

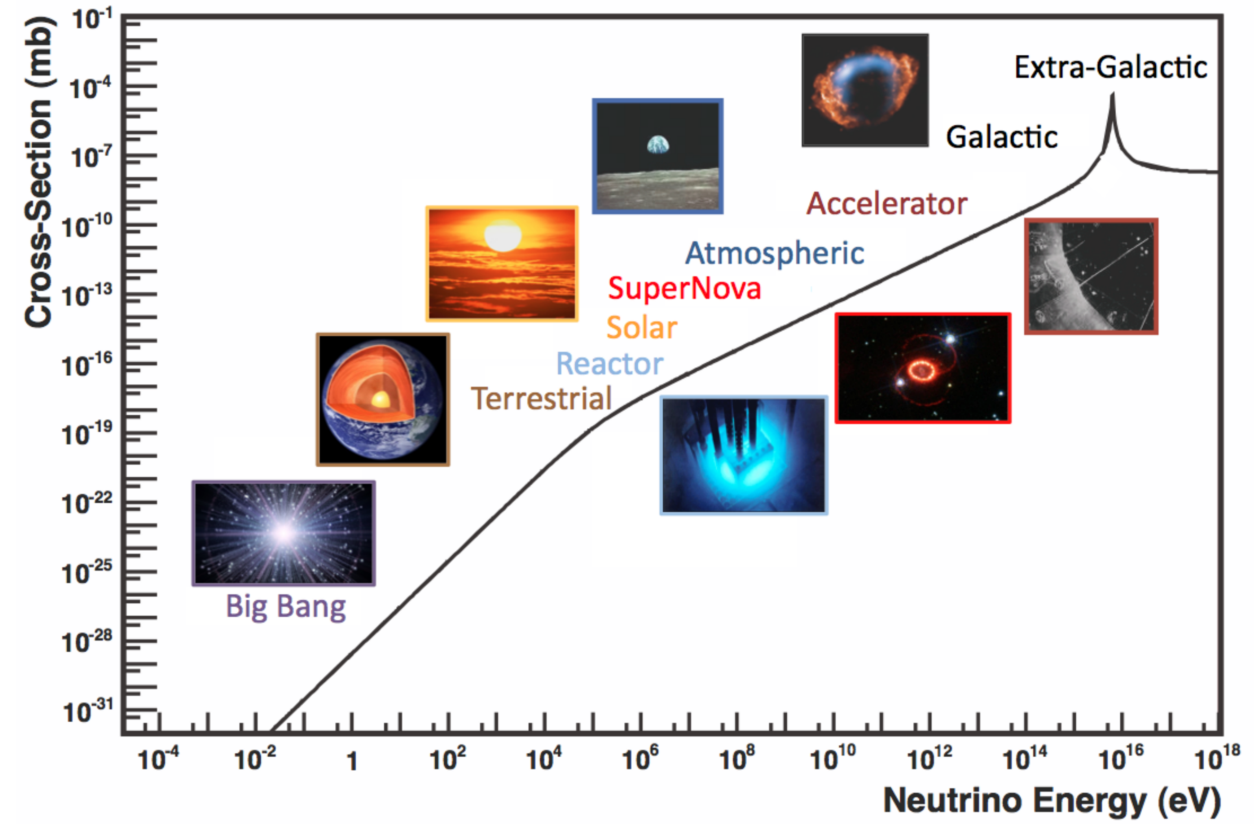
Very strong conclusion: **no additional light neutrinos** (< 45 GeV) coupling to the Z boson ("active") besides the 3 that we found.

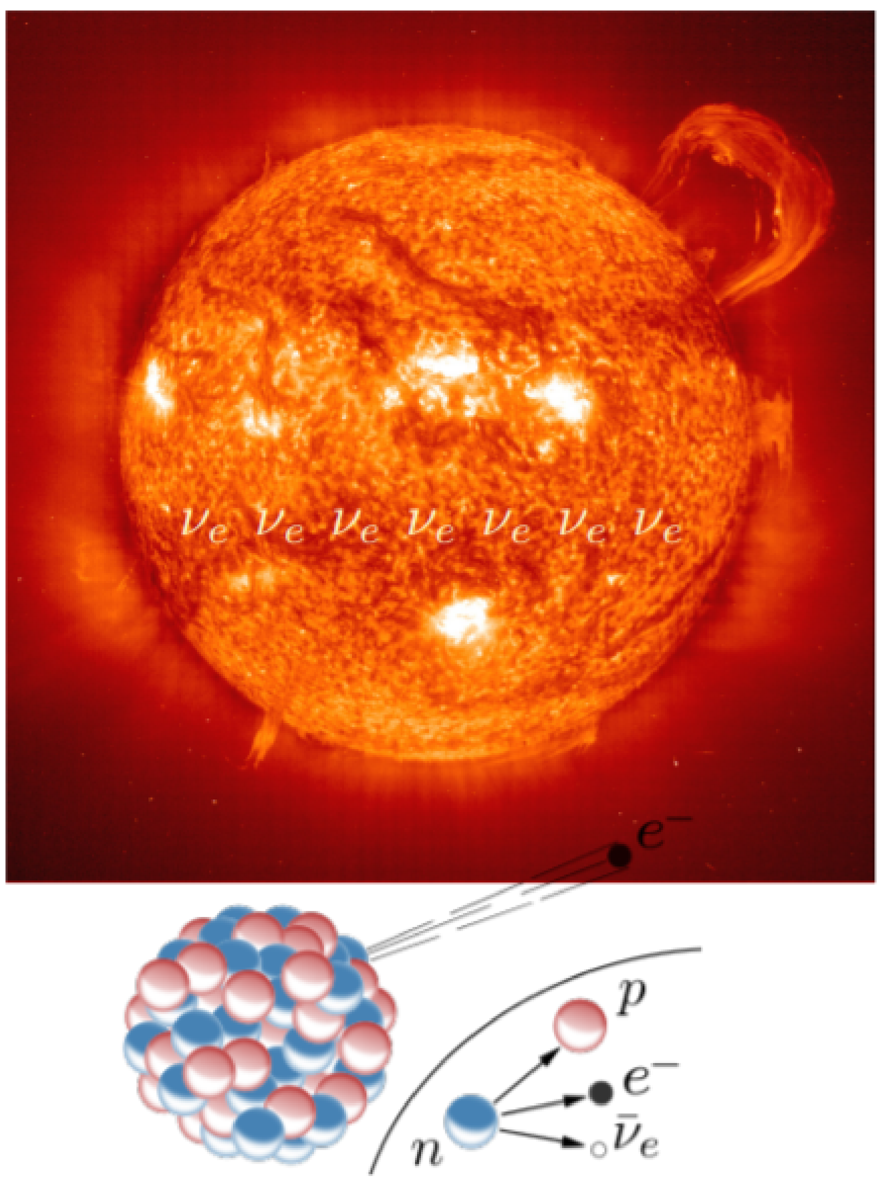
Still there could be neutrinos that do not "talk" with the Z boson. They are called "**sterile neutrinos**" and its search is a full chapter of present research!

Neutrino sources

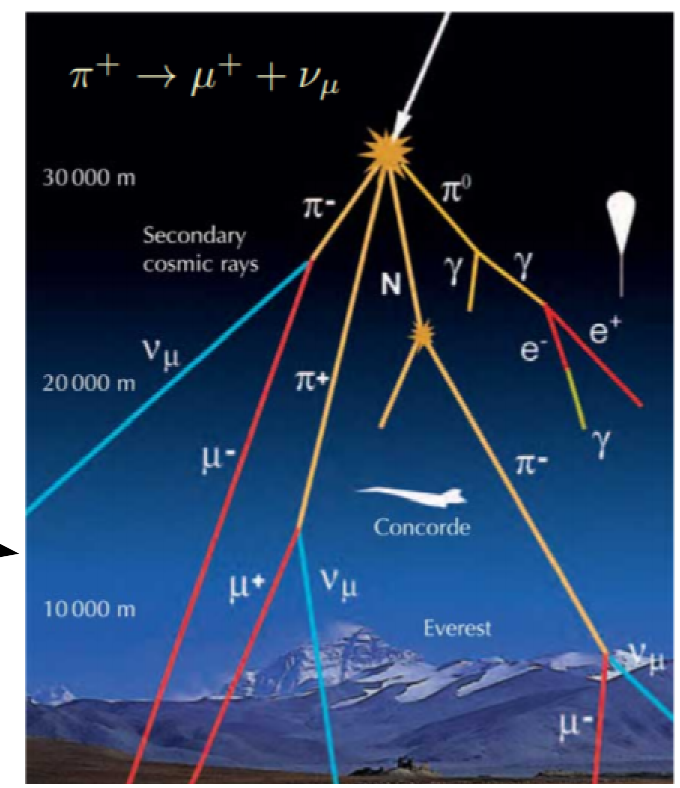
Natural:
the Sun, the atmosphere, SuperNovae, blazars (recent !!), relic neutrinos from the Big Bang (not seen yet!)

Artificial: nuclear power plants, accelerator neutrino beams



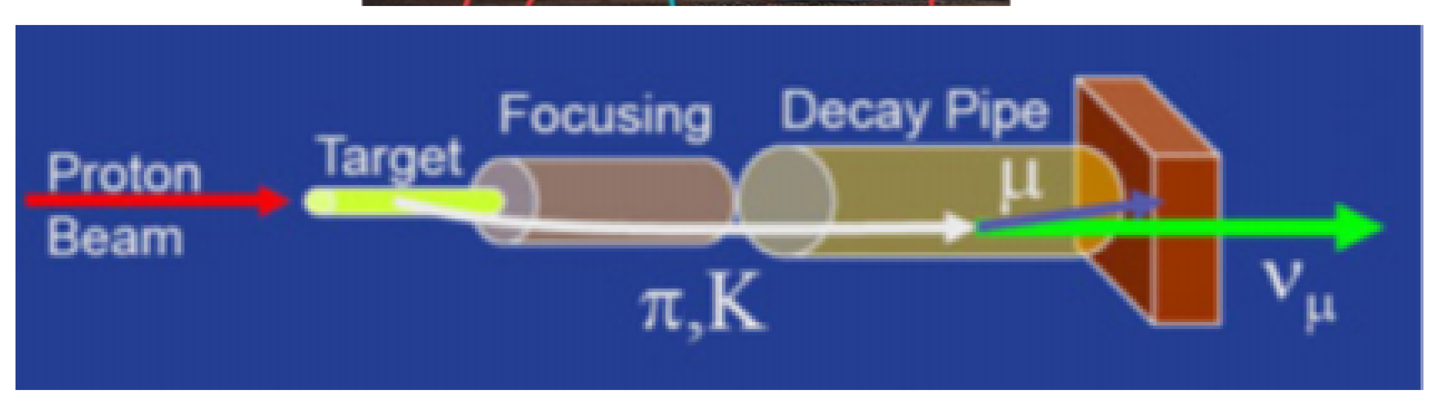


MeV energies



GeV energies

MeV (supernovae)
PeV (blazars)



The solar neutrino puzzle

$$\nu_e + {}^{37}\mathrm{Cl} \longrightarrow {}^{37}\mathrm{Ar} + e^-$$

Inverse beta decay again

On average one ^{37}Ar atom every two days!

380.000 l tank of **perchloroethylene** 1.5 km underground in the **Homestake Gold Mine** in South Dakota.

developed techniques for quantitatively extracting a **few atoms** (!) of Argon from the tank (using their radioactivity)

The chlorine target was located deep underground to protect it from cosmic rays.

The target had to be big because the probability of chlorine's capturing a neutrino was much smaller than its capturing a neutron (i.e. originated from cosmic rays).

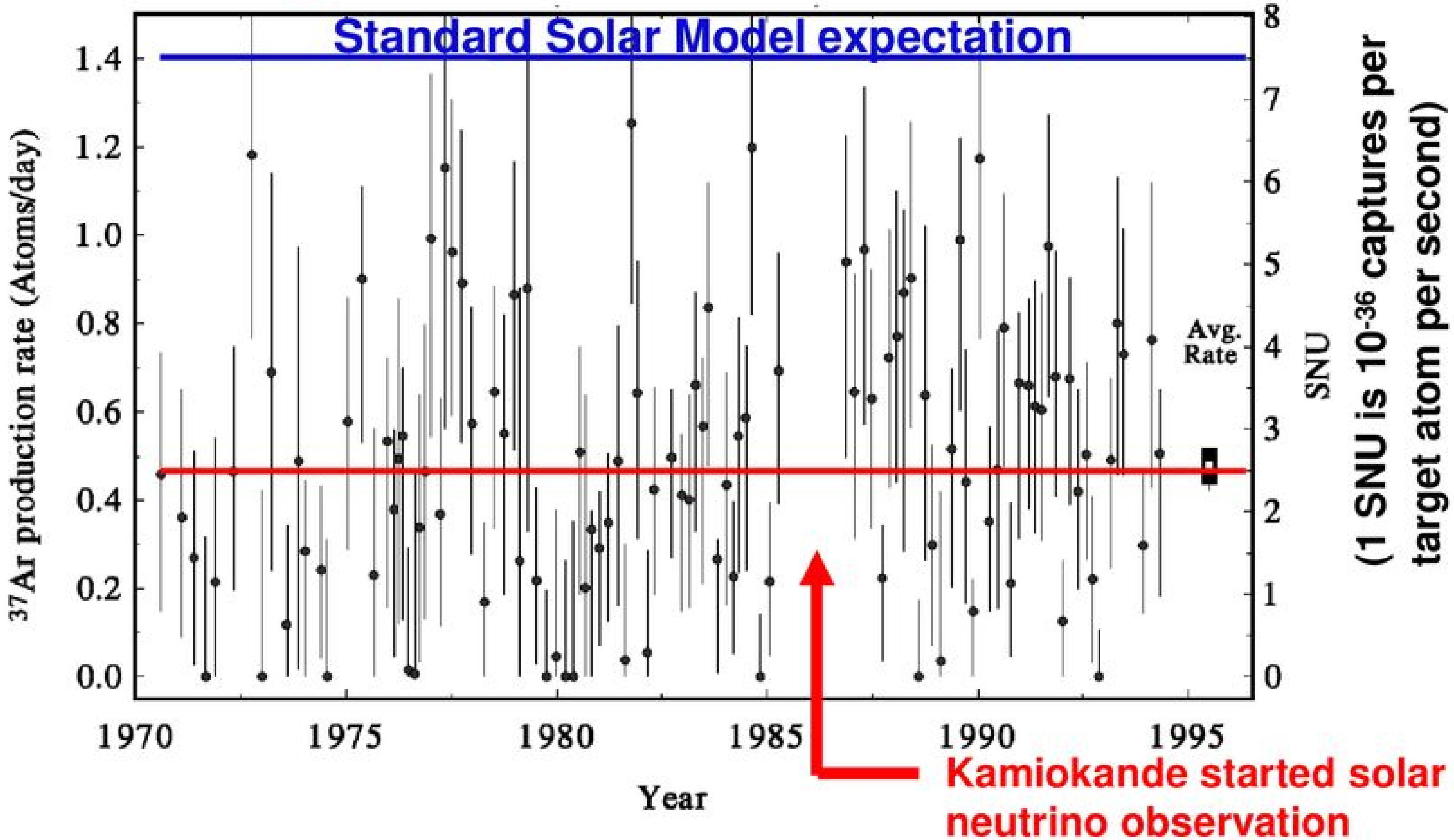
Physicists typically need to be quite “stubborn” and self confident ...

The solar neutrino puzzle

- The number of solar neutrino events measured by Homestake experiment is about 1/3 of the Standard Solar Model prediction. The first result was published in 1968. R. Davis et al., Phys. Rev. Lett. 20, 1205(1968)

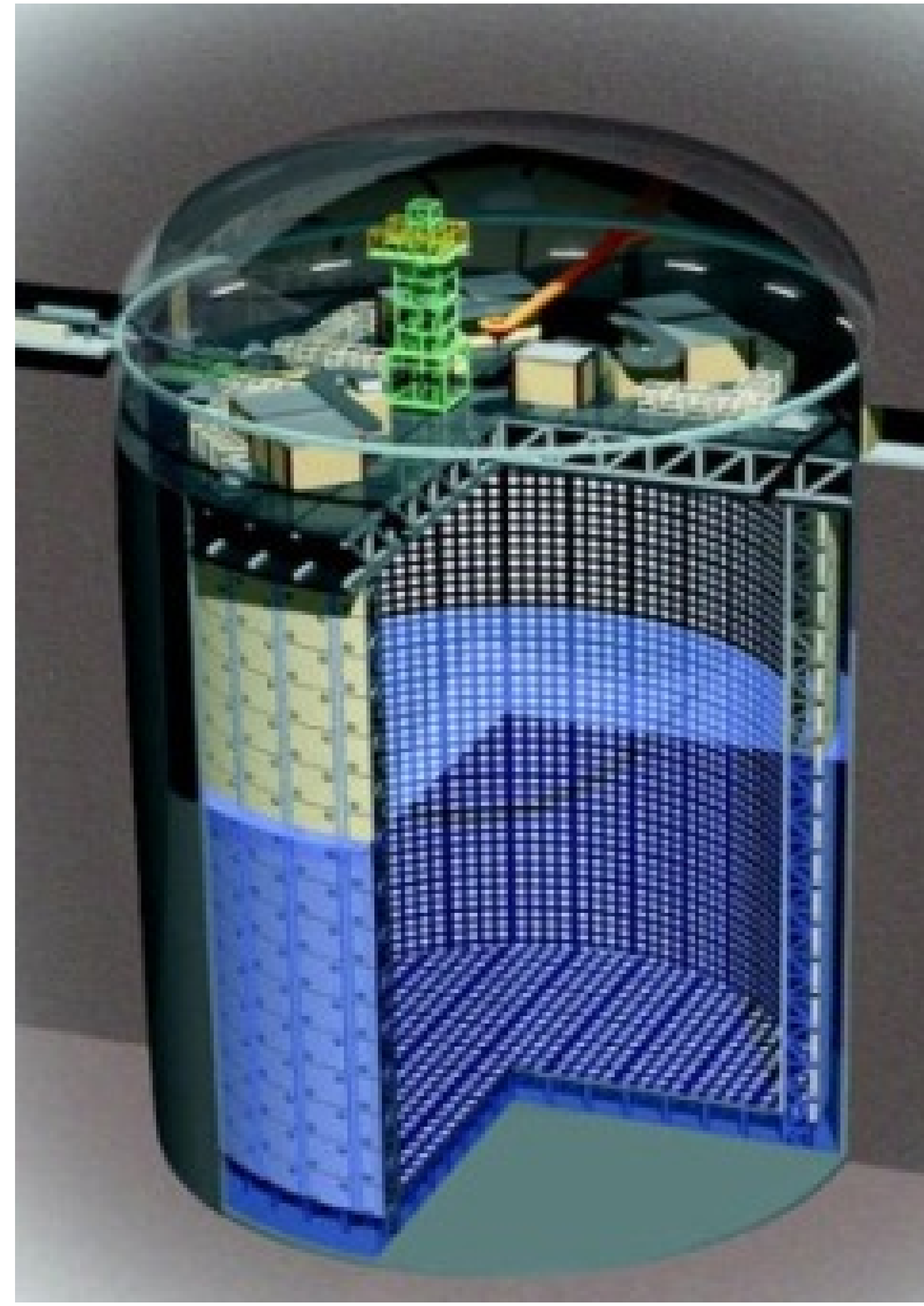
- It was an evidence of neutrino oscillation, but it was not widely believed.

~25 years of data
2200 solar neutrinos



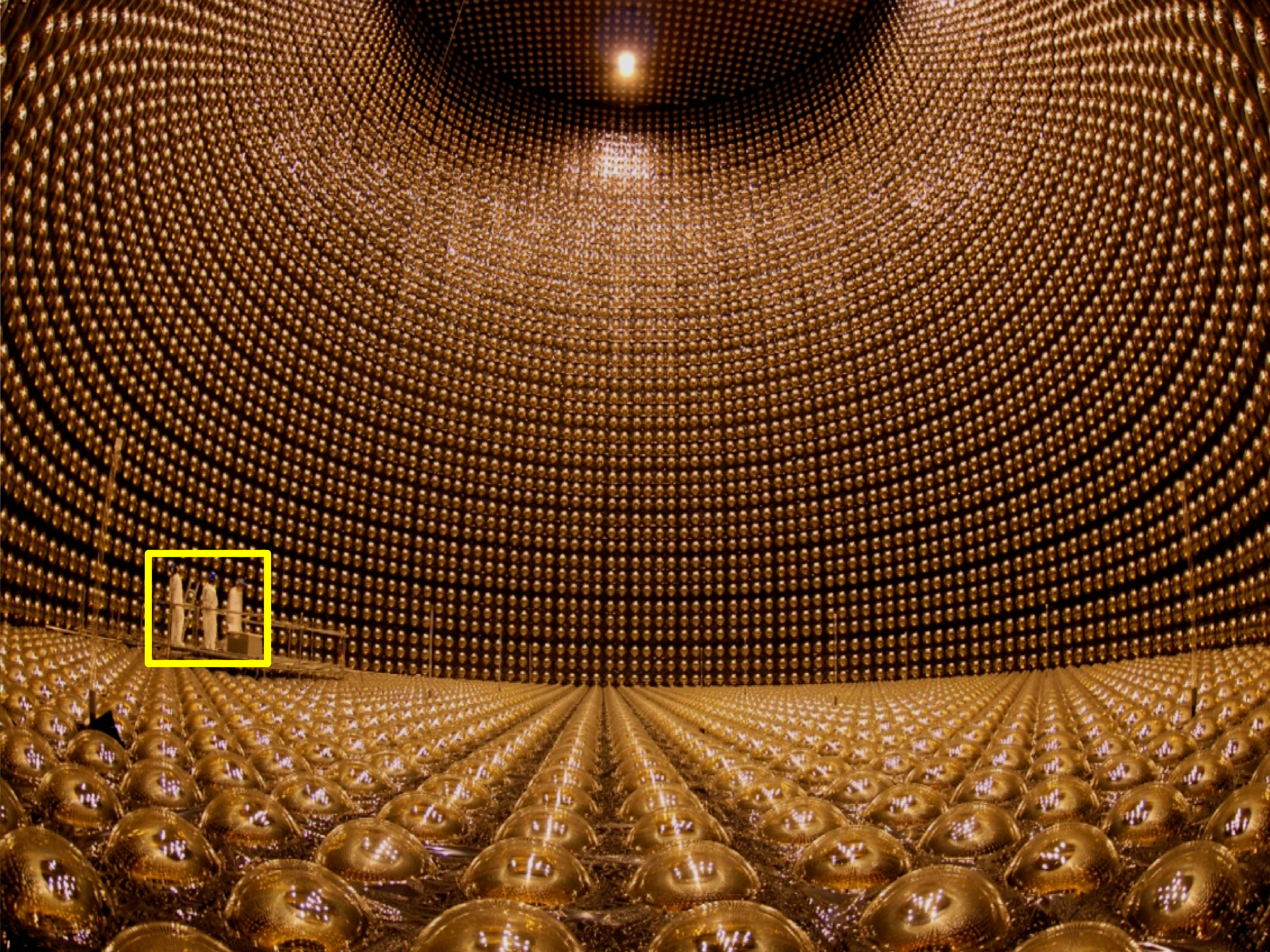
SuperKamiokande in Japan

- Water Cherenkov detector (22.5 kton)
- The largest in the world (still for a few years…)
- Ultra-pure water
- Underground (screen cosmic rays)
- ~13000 PhotoMultipliers (PMTs)
- With its predecessor (Kamiokande) built to discover “proton decay”



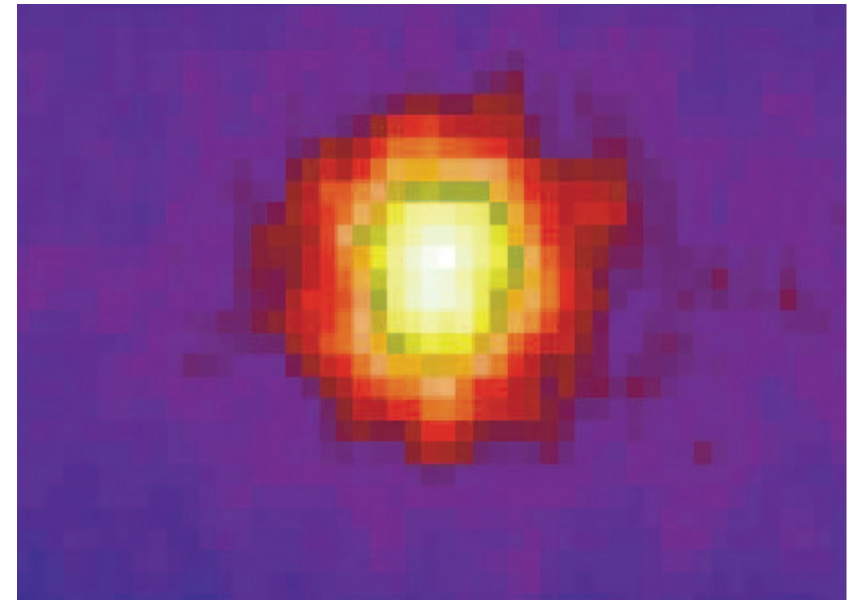
41.4m

39.3m

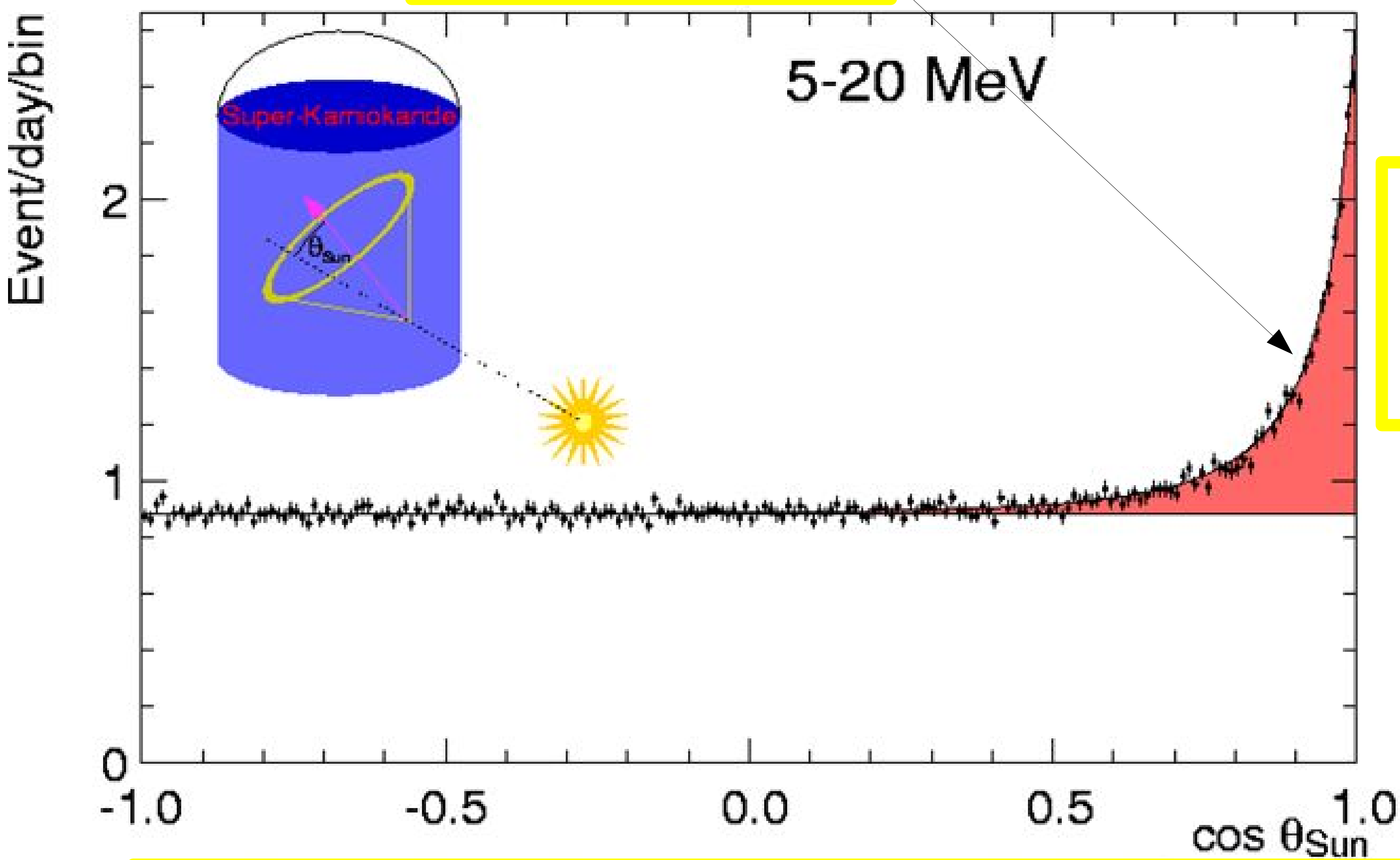


The solar neutrino puzzle

The sun “neutrino shine” →



- Proof that neutrinos come from sun: angular correlation
- Neutrino flux is 46.5% that expected from the solar model



Confirmation Solar Neutrino Puzzle!

$$0.465 \pm 0.005(\text{stat.})^{+0.016}_{-0.015}(\text{sys.}) \times \text{SSM}$$

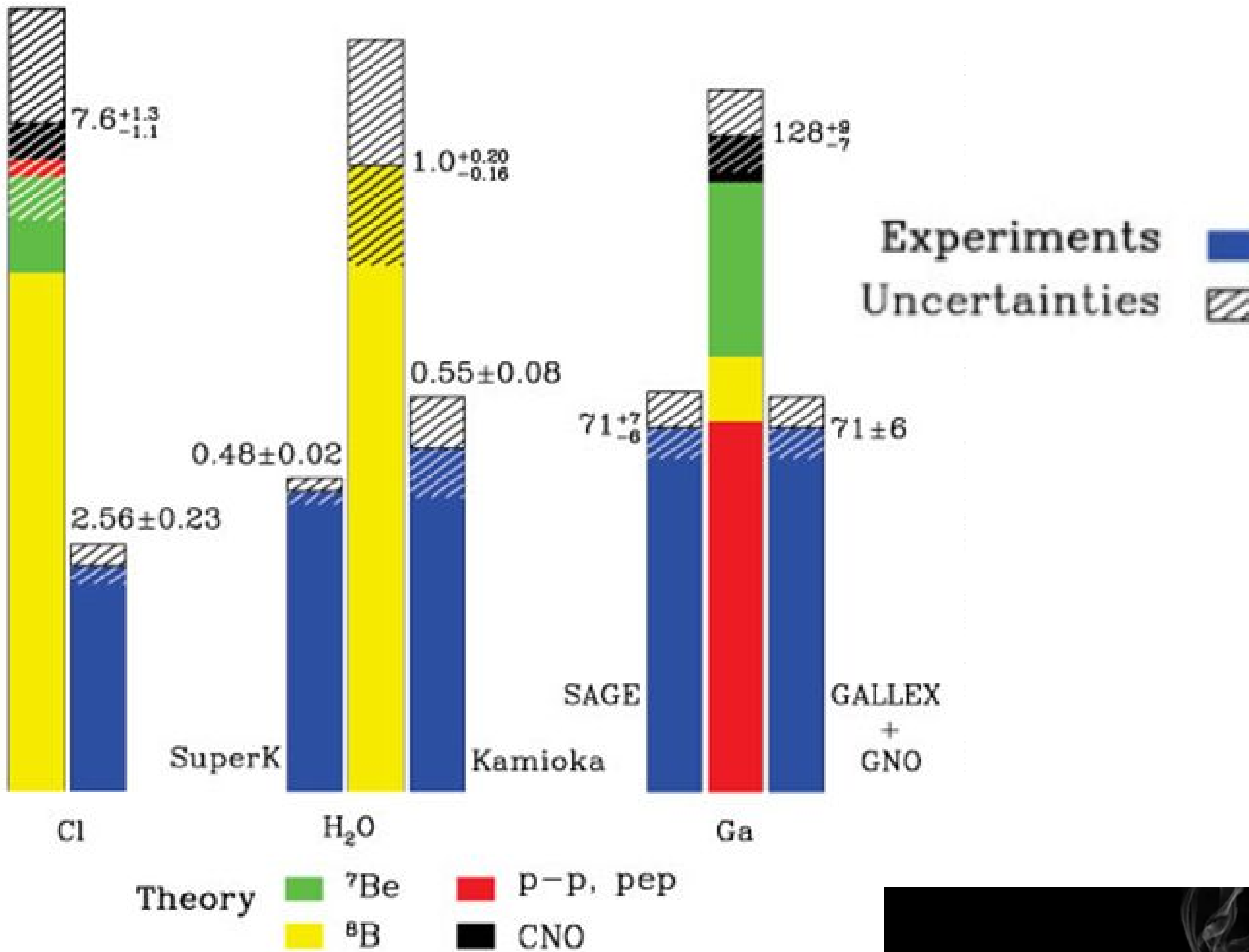
The solar neutrino puzzle

Completely different experiments (Cl, H_2O, Ga) confirmed the solar neutrino deficit with a certain dependance of the deficit on the average probed neutrino energy.

Kamiokande (JP)
SAGE (USSR)
GALLEX+GNO (Italy)
SuperKamiokande (JP)

Uncertainties on the solar neutrino fluxes (J. Bahcall) were too small to fill the gap. **A real tension!** Still people were missing a “**smoking gun**” showing that there was not an error on the predicted fluxes.

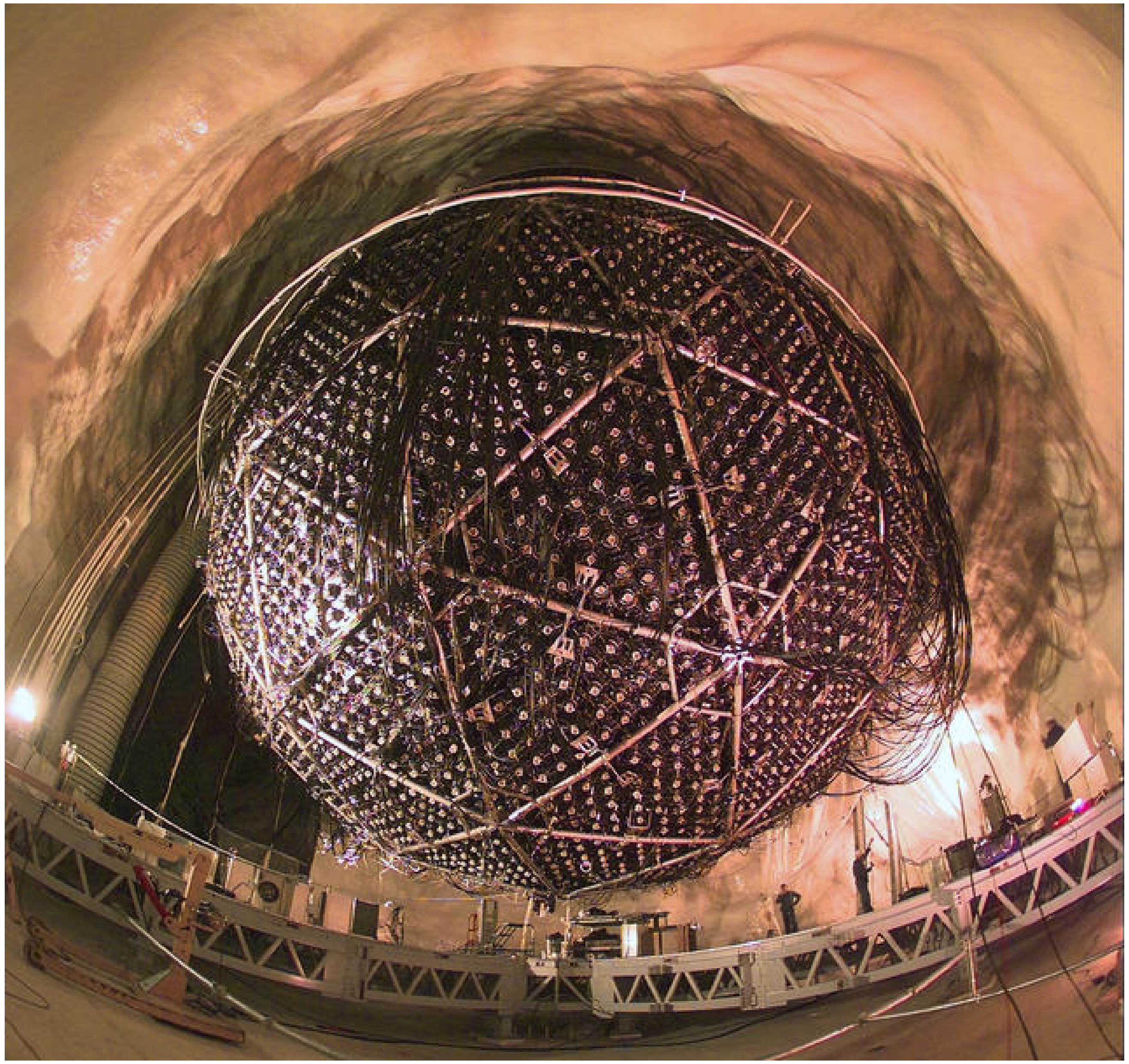
“Extraordinary claims require extraordinary evidence”

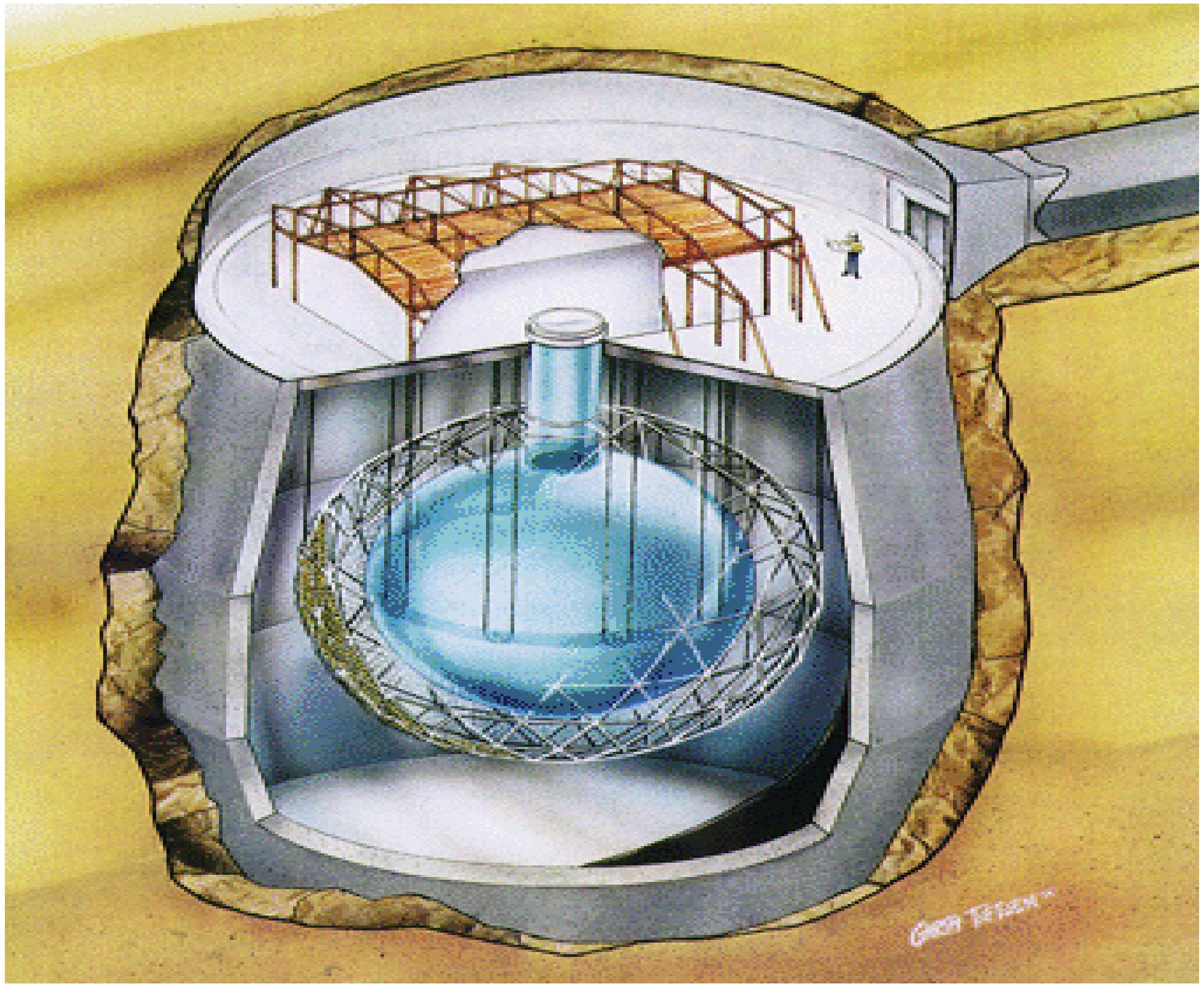


2001-2002, **SNO, the Sudbury Neutrino Observatory** in Ontario. Strong evidence that the neutrinos **oscillate**, or change form, among its three known types →

SNO: the smoking gun

- **Subdury Neutrino Observation (SNO)** in Canada was built to probe the Solar anomaly was due to neutrino oscillations
- Underground Cherenkov detector with 1 kt of heavy water (D_2O)
- 9600 PMTs to detect the Cherenkov light
- Sensitive to some of the electron Anti-Neutrinos from the Sun (~6 MeV)





2100 m underground

SNO: the smoking gun

By using heavy water (p substituded by deuterium – np). SNO was **sensitive to all the types of neutrinos** from the Sun and not only to electron neutrinos as in previous experiments.

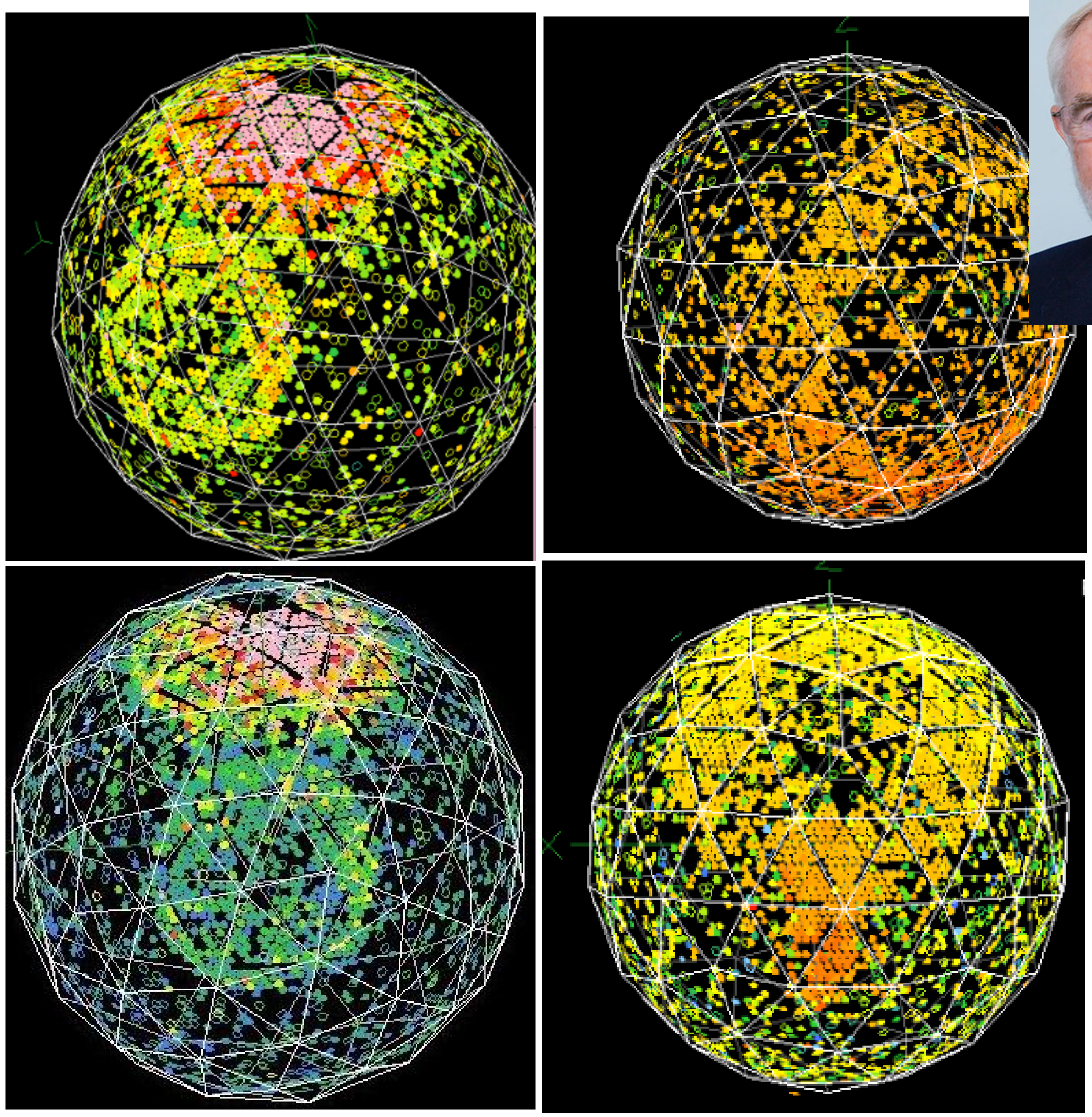
$$\text{CC: } \nu_e + d \rightarrow p + p + \mathbf{e}^-$$

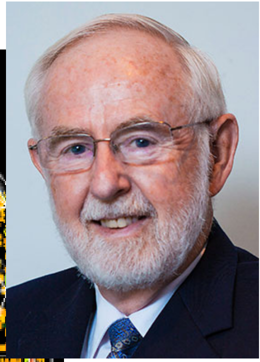
$$\text{NC: } \nu_\alpha + d \rightarrow p + \mathbf{n} + \nu_\alpha$$

NC reaction measures $\nu_e + \nu_\mu + \nu_\tau$

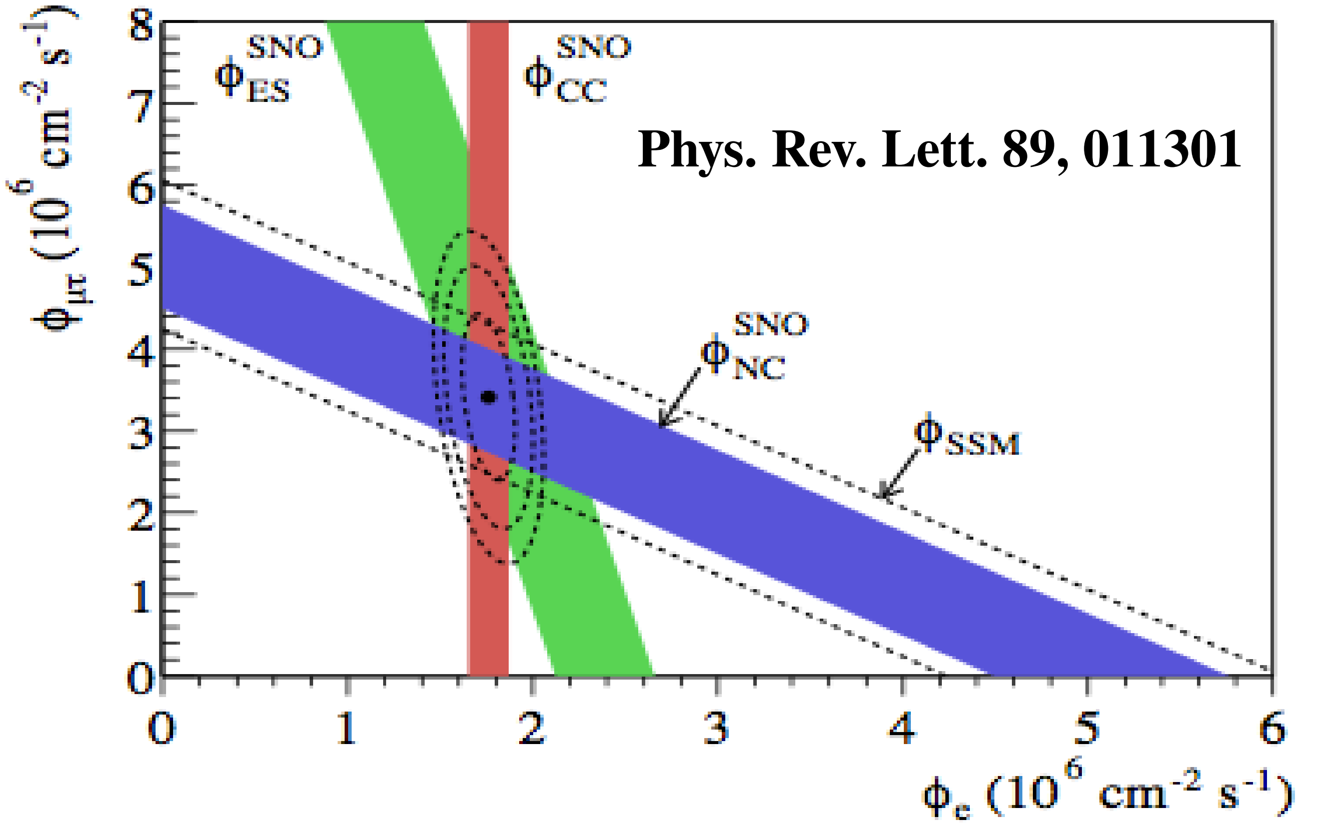
CC measures ν_e

If you count **all neutrinos their number is compatible with the prediciton** while the **electron neutrinos are less** because **they have oscillated to muon and tau neutrinos during their propagation (Sun emits only ν_e) !**





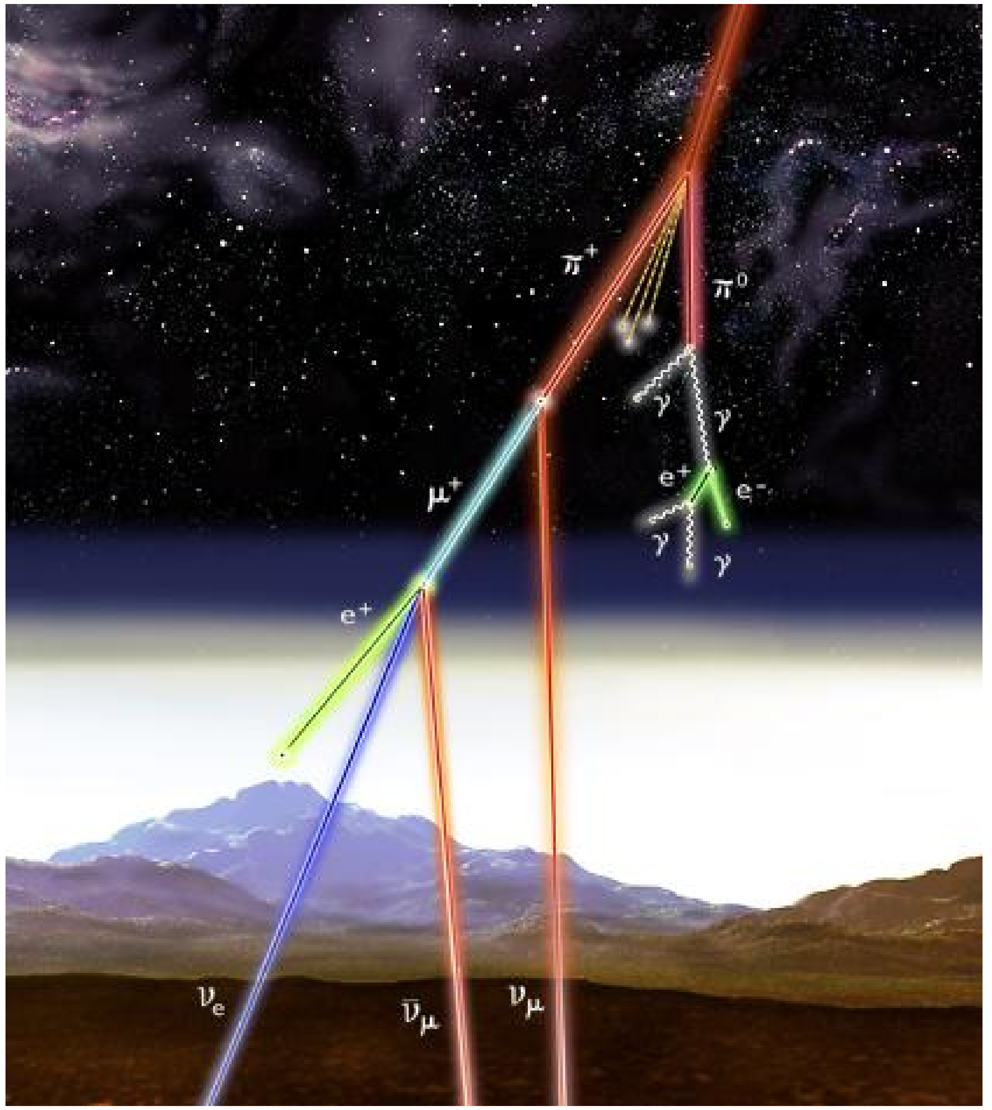
Mc Donald



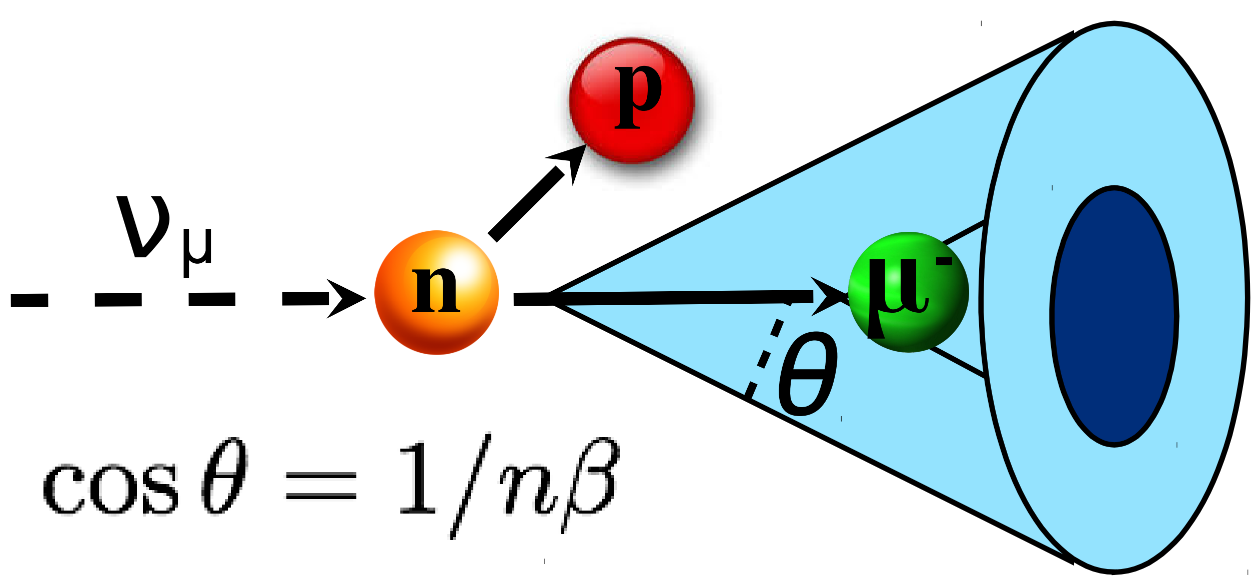
Atmospheric neutrinos

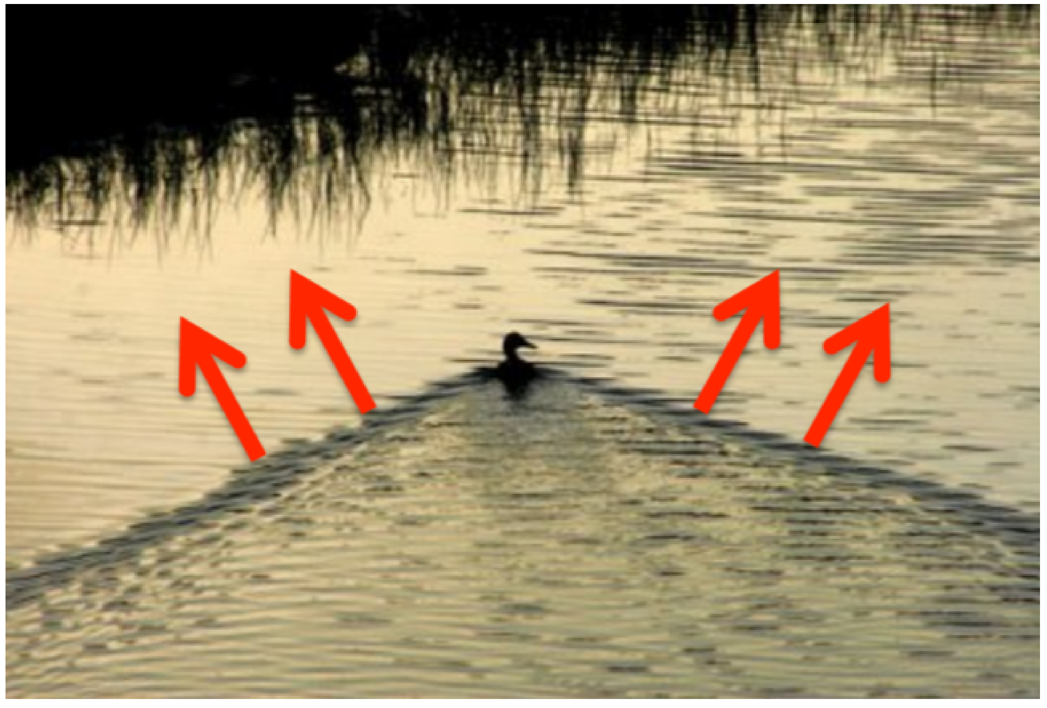
- Cosmic rays interact in the atmosphere and produce muon and electron neutrinos in a proportion of ~ 2:1 →

$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu})$$
$$\rightarrow e^{\pm} + \nu_e(\bar{\nu}_e) + \bar{\nu}_{\mu}(\nu_{\mu})$$



- Cherenkov light detection: particle that travels in matter faster than the speed of light emits a cone of light

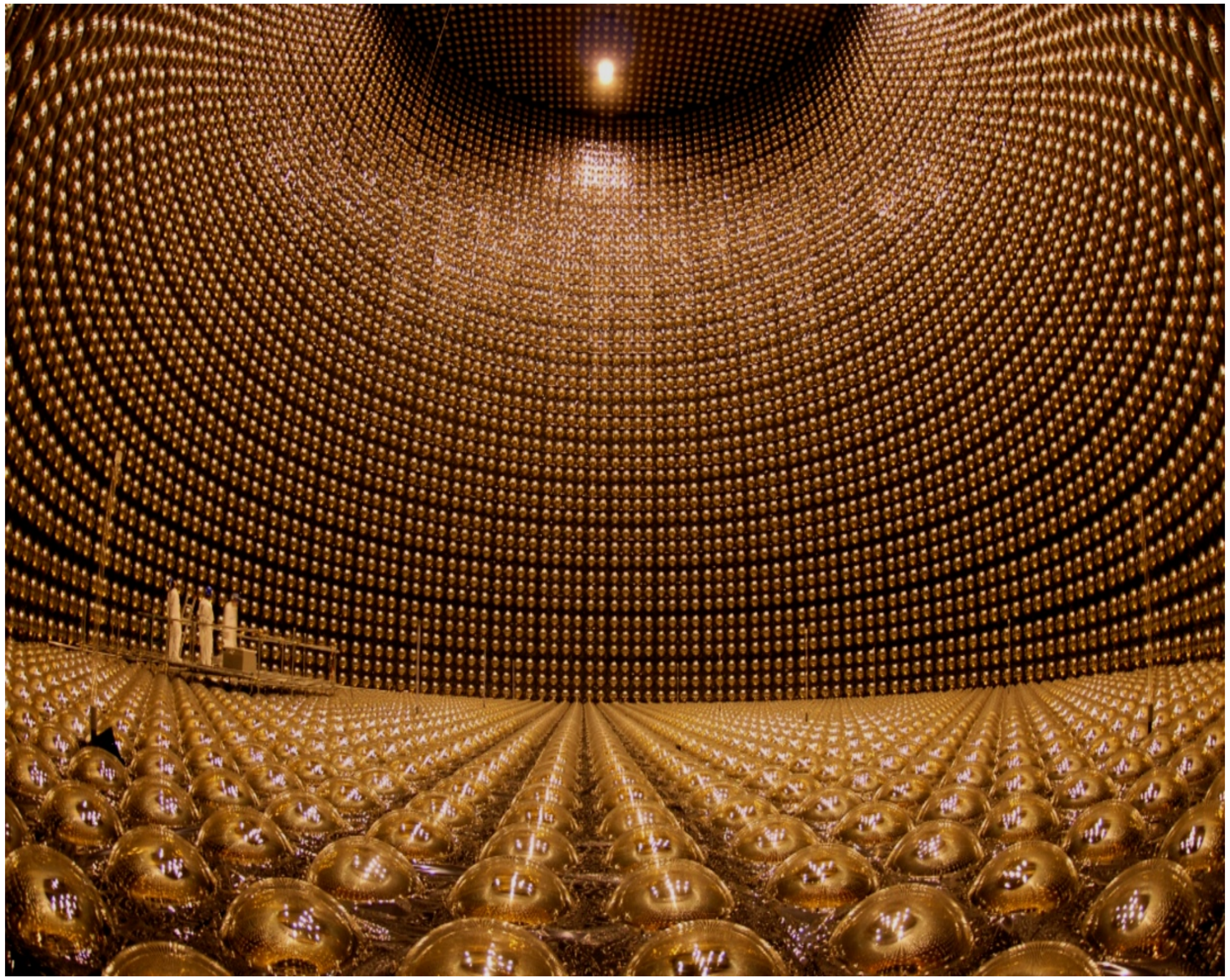


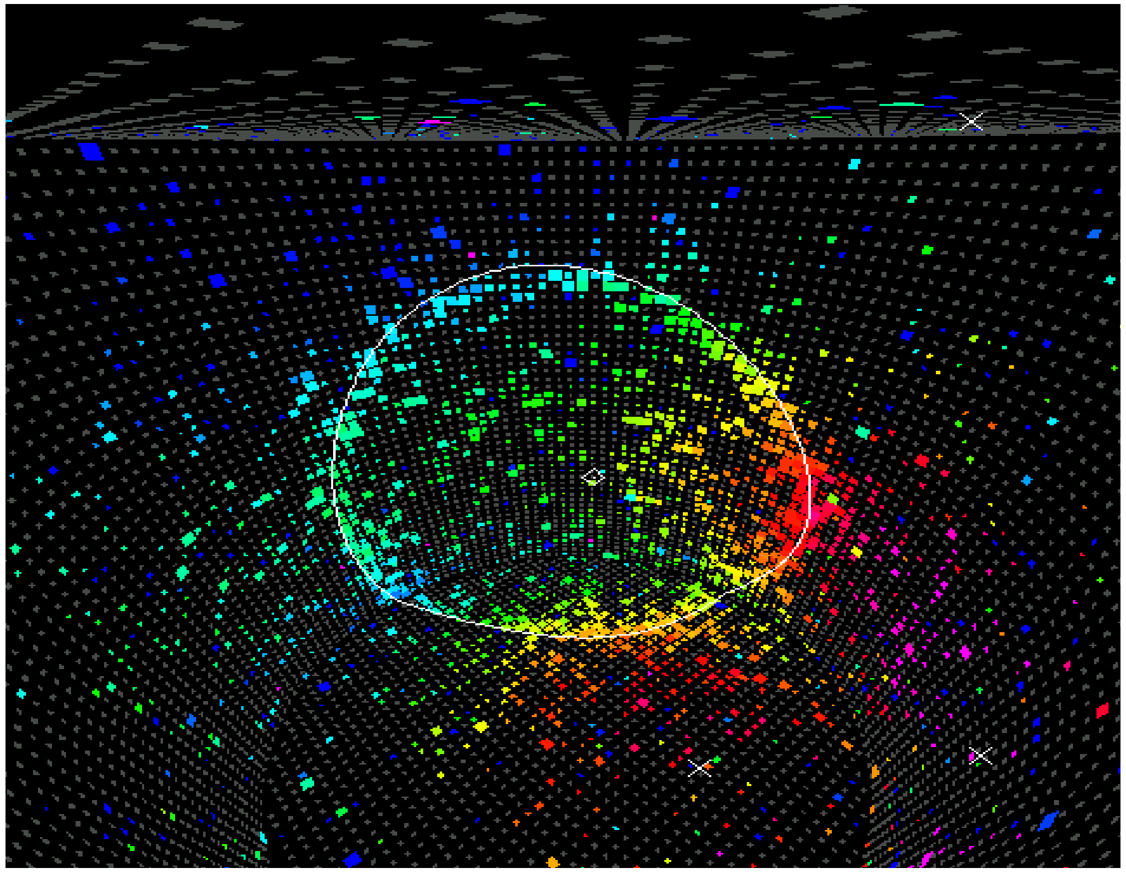


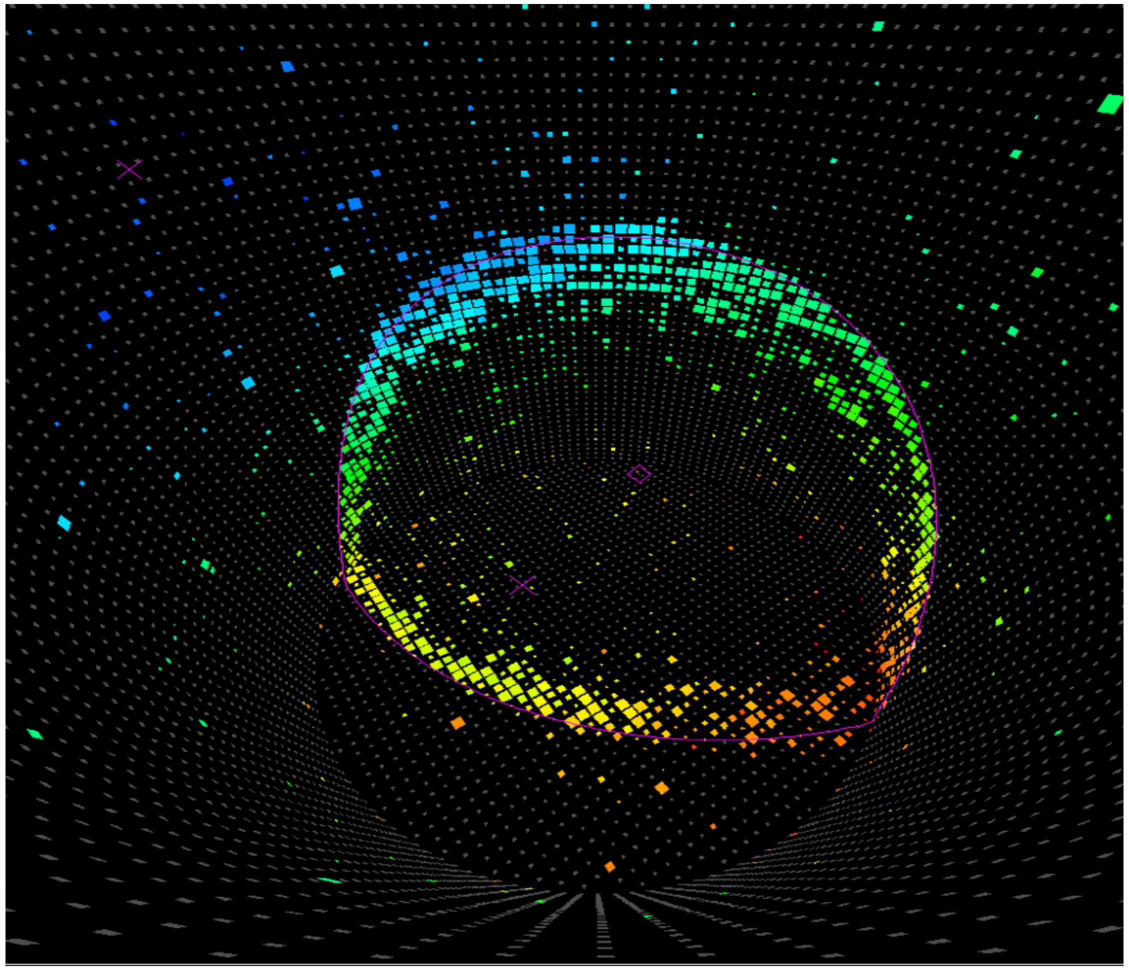
Atmospheric neutrinos

SuperKamiokande

Rings from muons are "sharper" (they go "straight") while the lighter electrons scatters and produce "fuzzy" rings → **possible to separate electron and muon neutrinos and reconstruct their direction!**

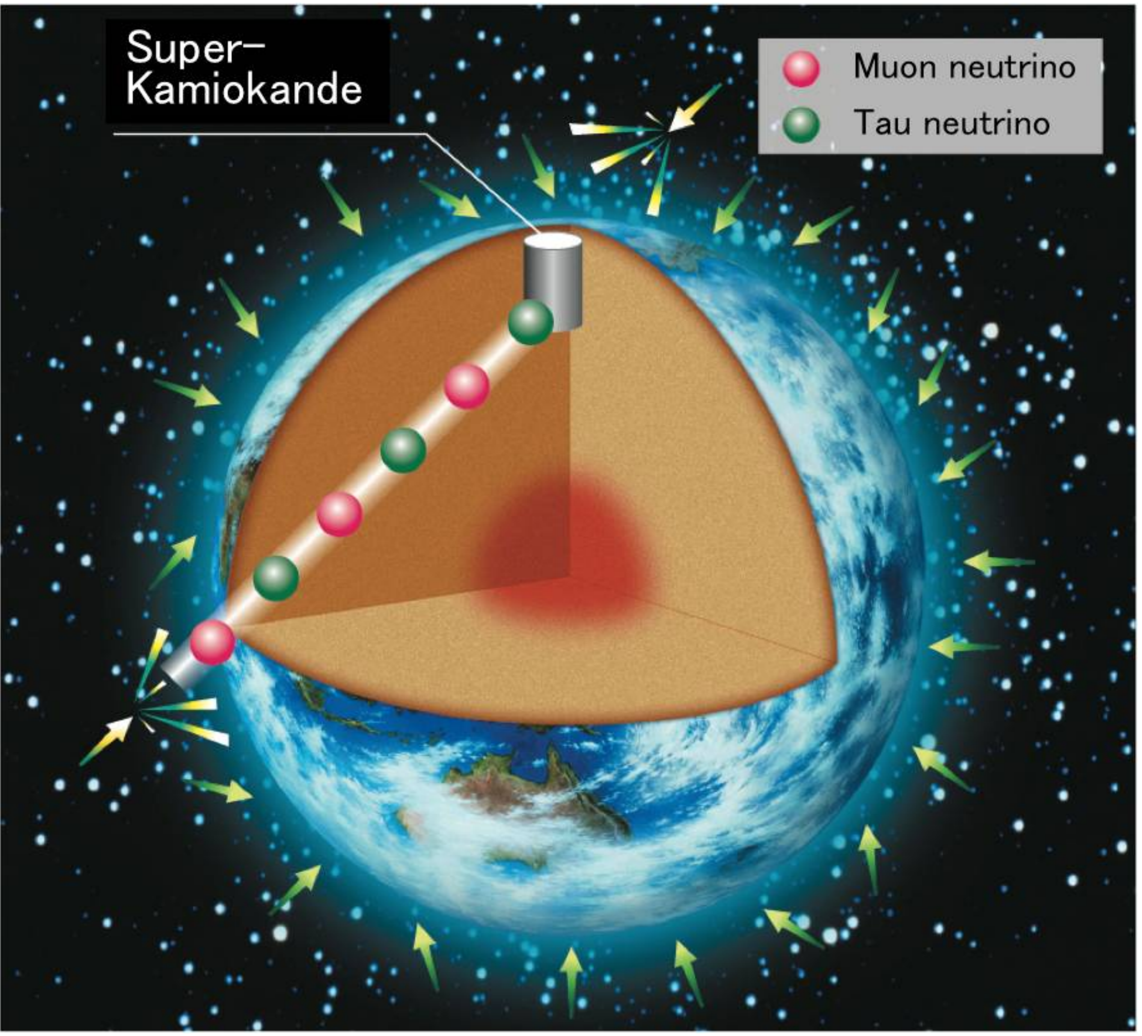




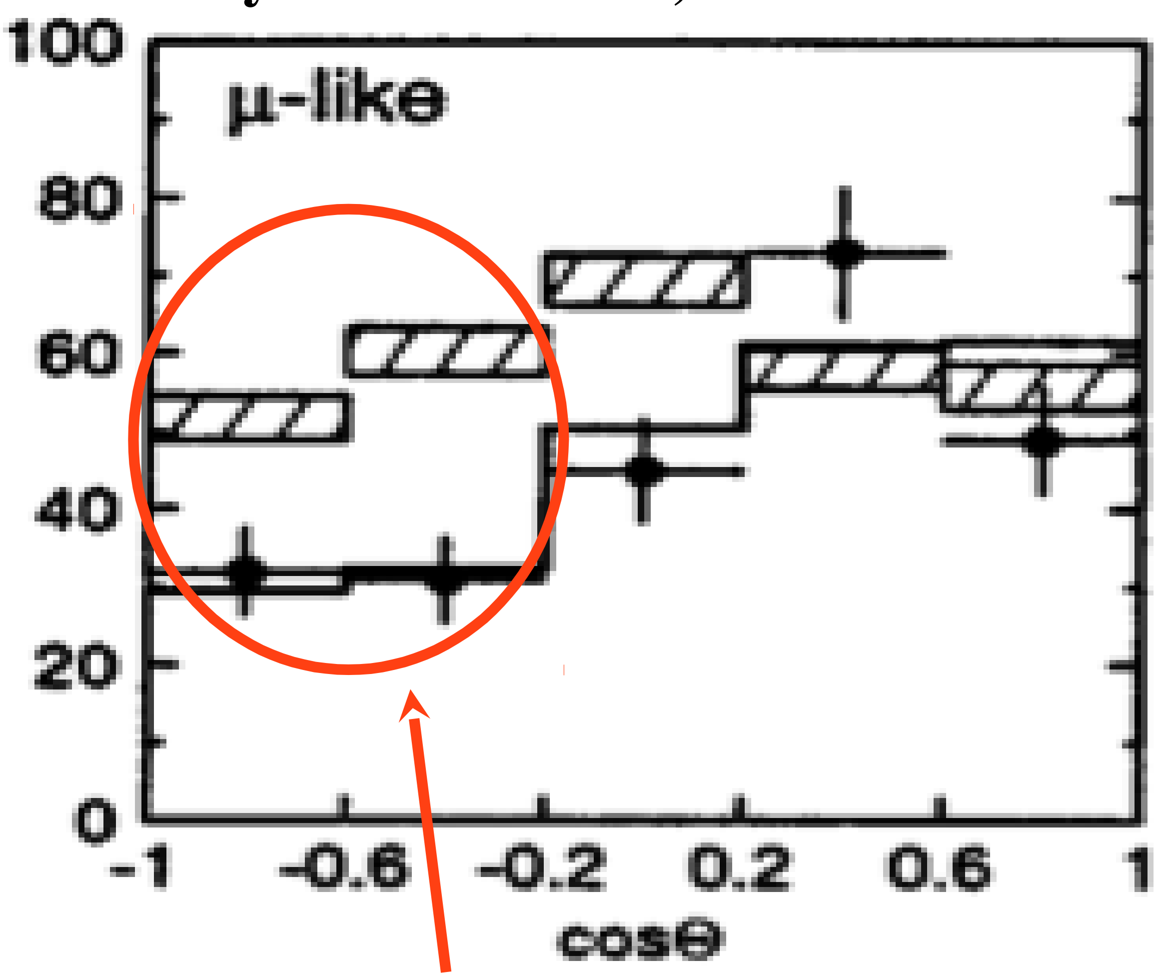


Oscillation of atmospheric neutrinos

- Upward-going: neutrinos travel ~10000 km
- Downward-going: neutrinos travel ~10-100 km
- **Super-Kamiokande clearly observed a big deficit of muon neutrinos from below since 1998 (but not of electrons)**
- **The muon neutrinos coming from below had ~10000 km to oscillate into tau neutrinos while the ones from above stayed mostly as muon neutrinos**



Phys. Rev. Lett. 81, 1562

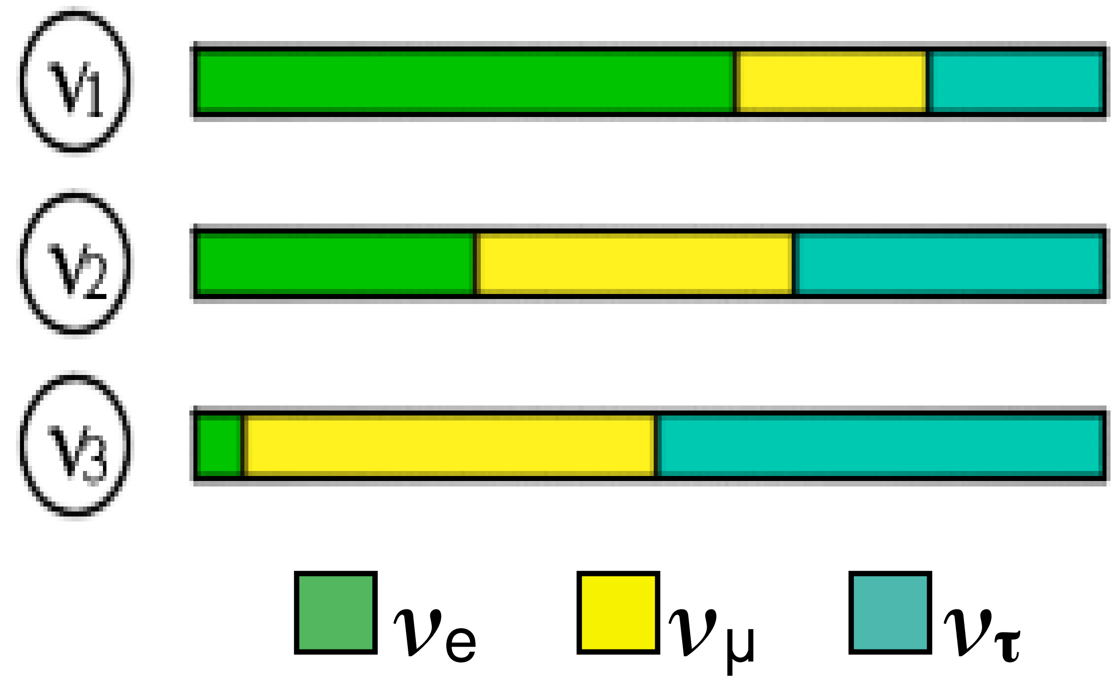


- Up-going: cosΘ = -1
- Down-going: cosΘ = +1

Deficit of up-going muon neutrino candidates

Neutrino oscillations theory

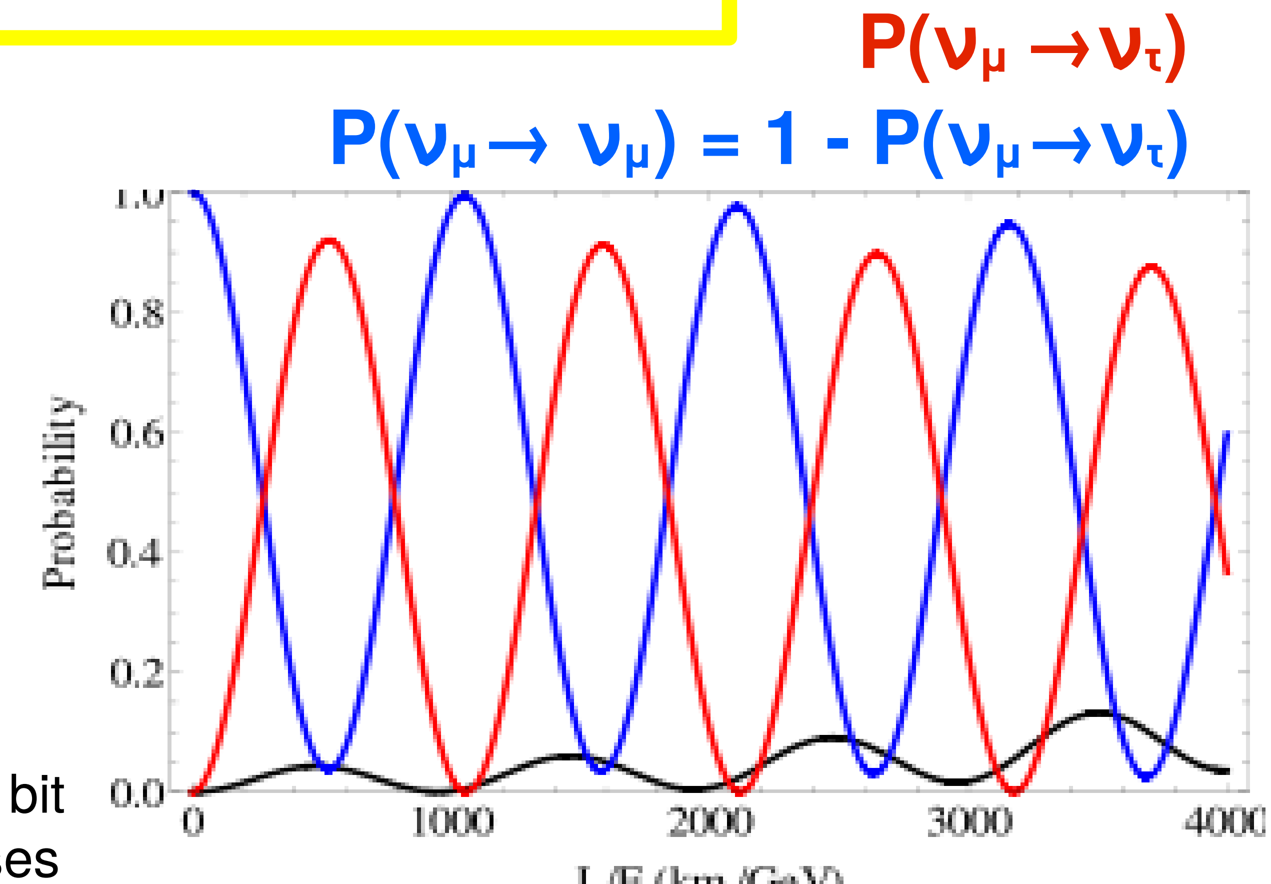
- In 1967 Bruno Pontecorvo proposed that neutrinos can change flavor (oscillate)
- Interact as flavor states: ν_e, ν_μ, ν_τ
- Propagate as mass states: ν_1, ν_2, ν_3
- Mass state is a quantum mechanical superposition of flavor states defined by the phase $\Delta m^2 = m^2_i - m^2_j$ (i,j=1,2,3) and a "mixing matrix" **U**



- **Oscillations occur only if at least 2 neutrinos have mass!!**

Probability to detect a ν_τ with energy (E) after a distance (L) in a beam of ν_μ

$$P(\nu_\mu \to \nu_\tau) = \sin^2 2\theta \cdot \sin\left(\frac{1.27\Delta m^2 L}{E}\right)$$



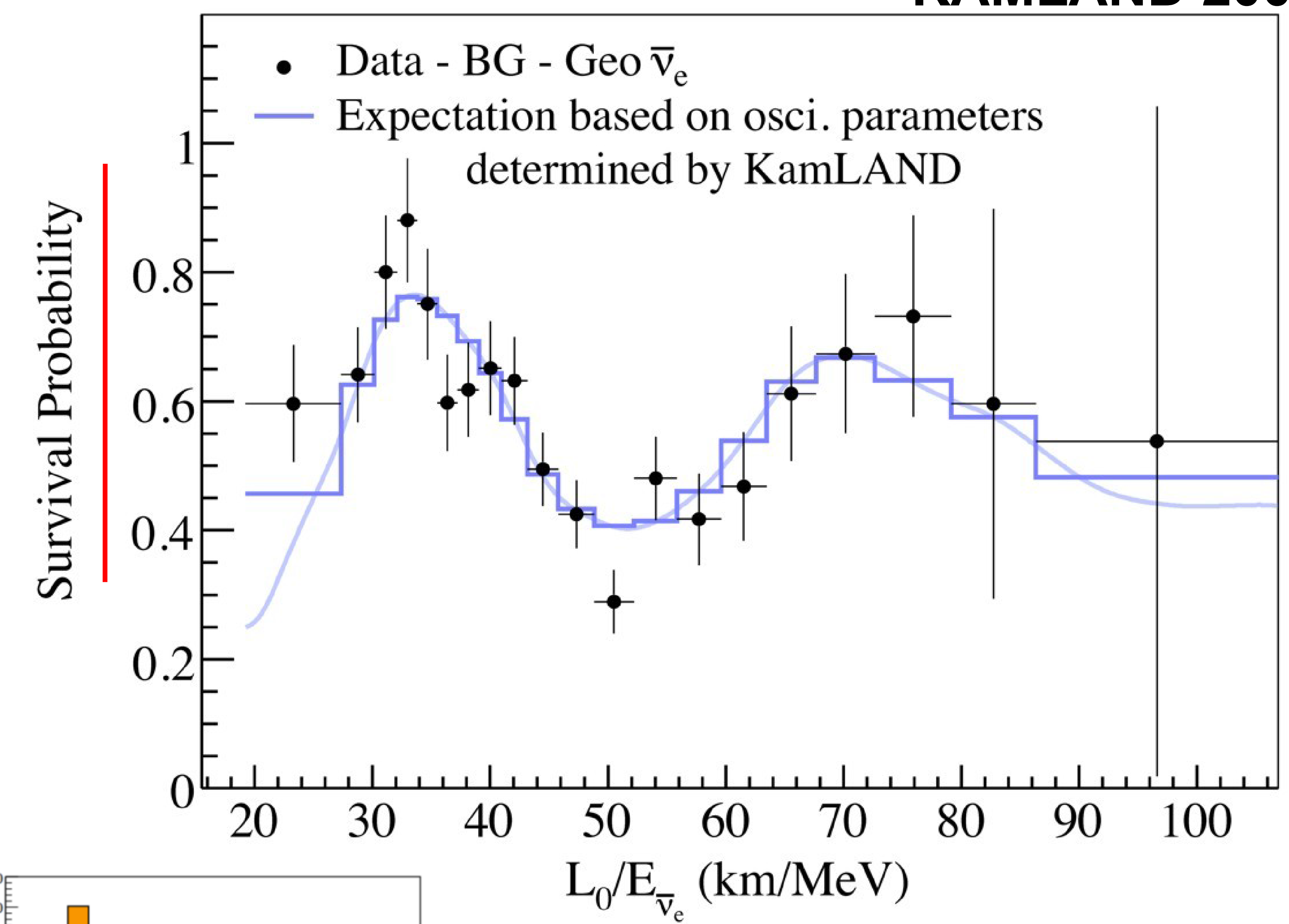
- Simplified formula: 2 flavors. Exact formula (3 flavours) a bit more complicated but a good approximation in several cases

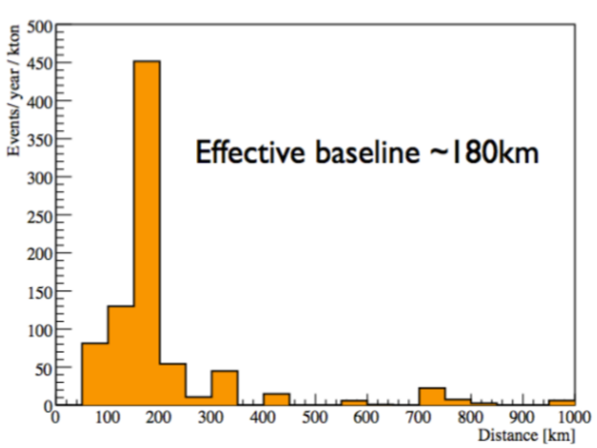
The oscillatory pattern with reactor neutrinos

Oscillation pattern for anti-electron neutrinos from Japanese/Korean power reactors as a function of L/E

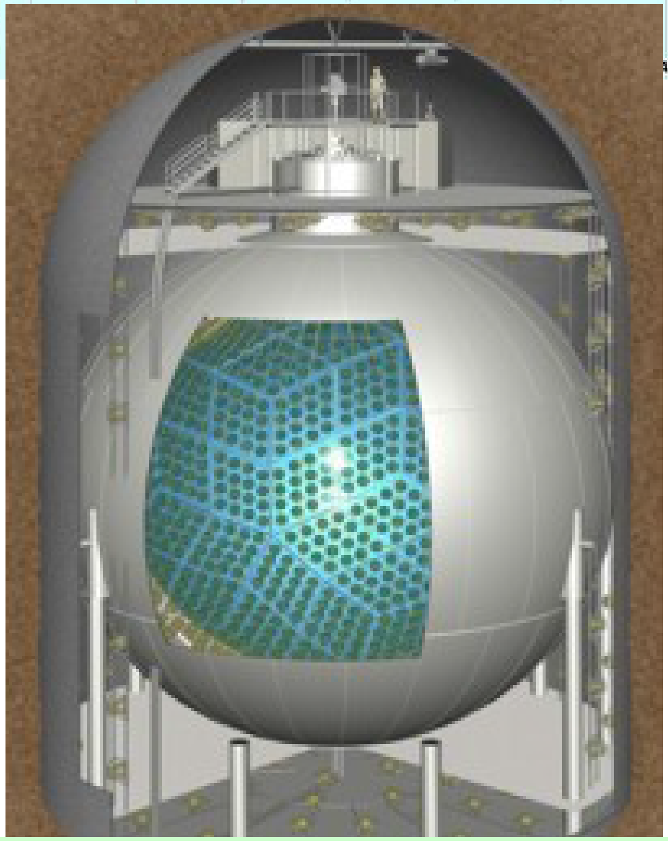
“Solar” $\Delta m^2 \sim 7.6 \times 10^{-5}\ eV^2$

KAMLAND 2002





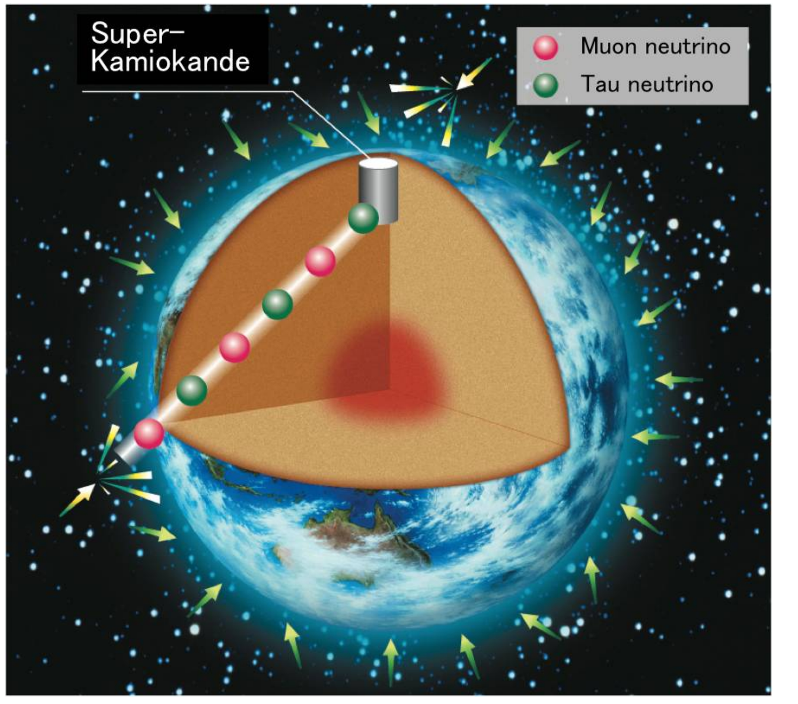
Reactors at 180 km (effective baseline)



KamLAND Liquid Scintillator detector (1000 t)

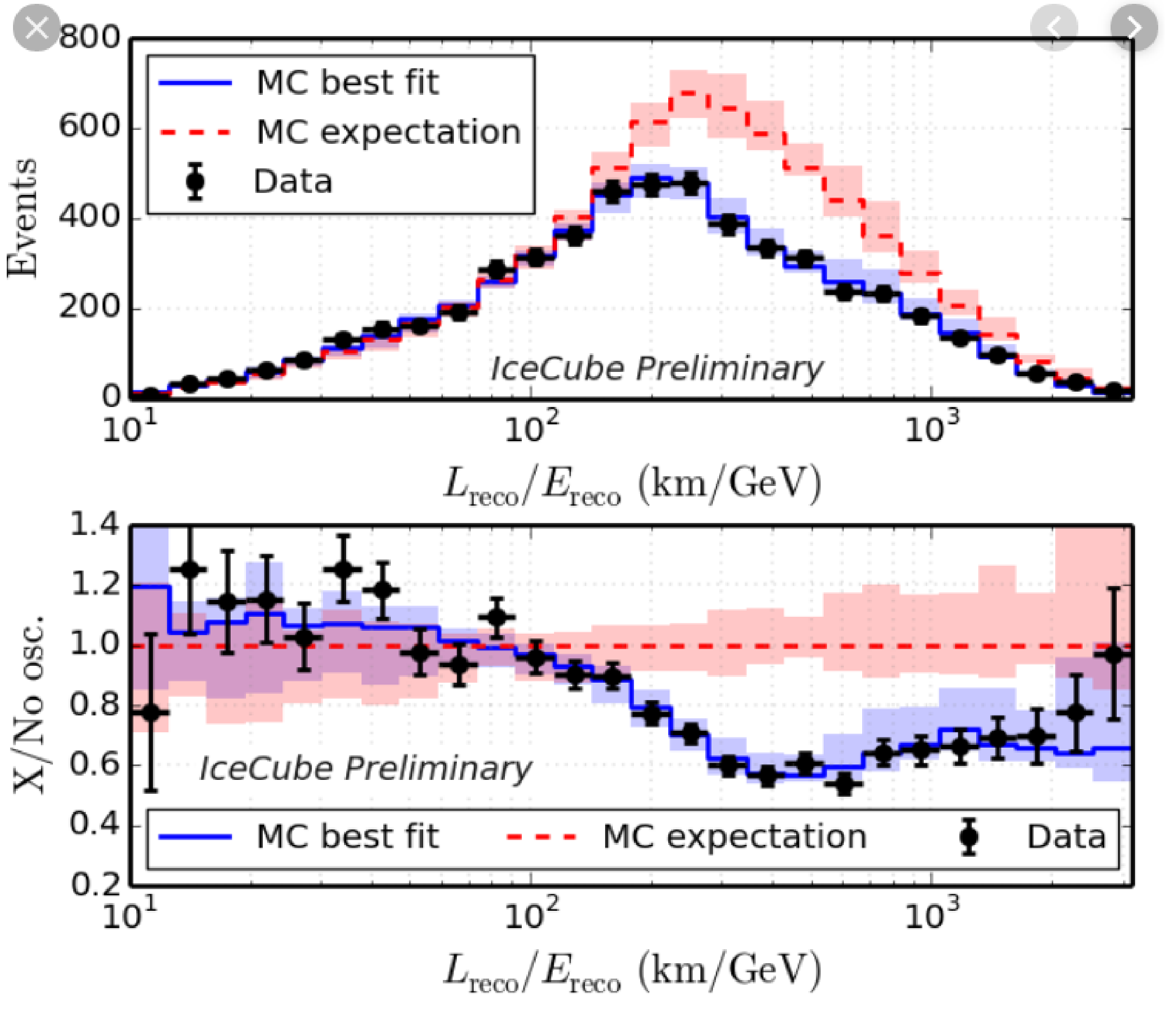
The oscillatory pattern with atmospheric neutrinos

$$P(\nu_\mu \rightarrow \nu_\tau) = \sin^2 2\theta \cdot \sin\left(\frac{1.27\Delta m^2 L}{E}\right)$$

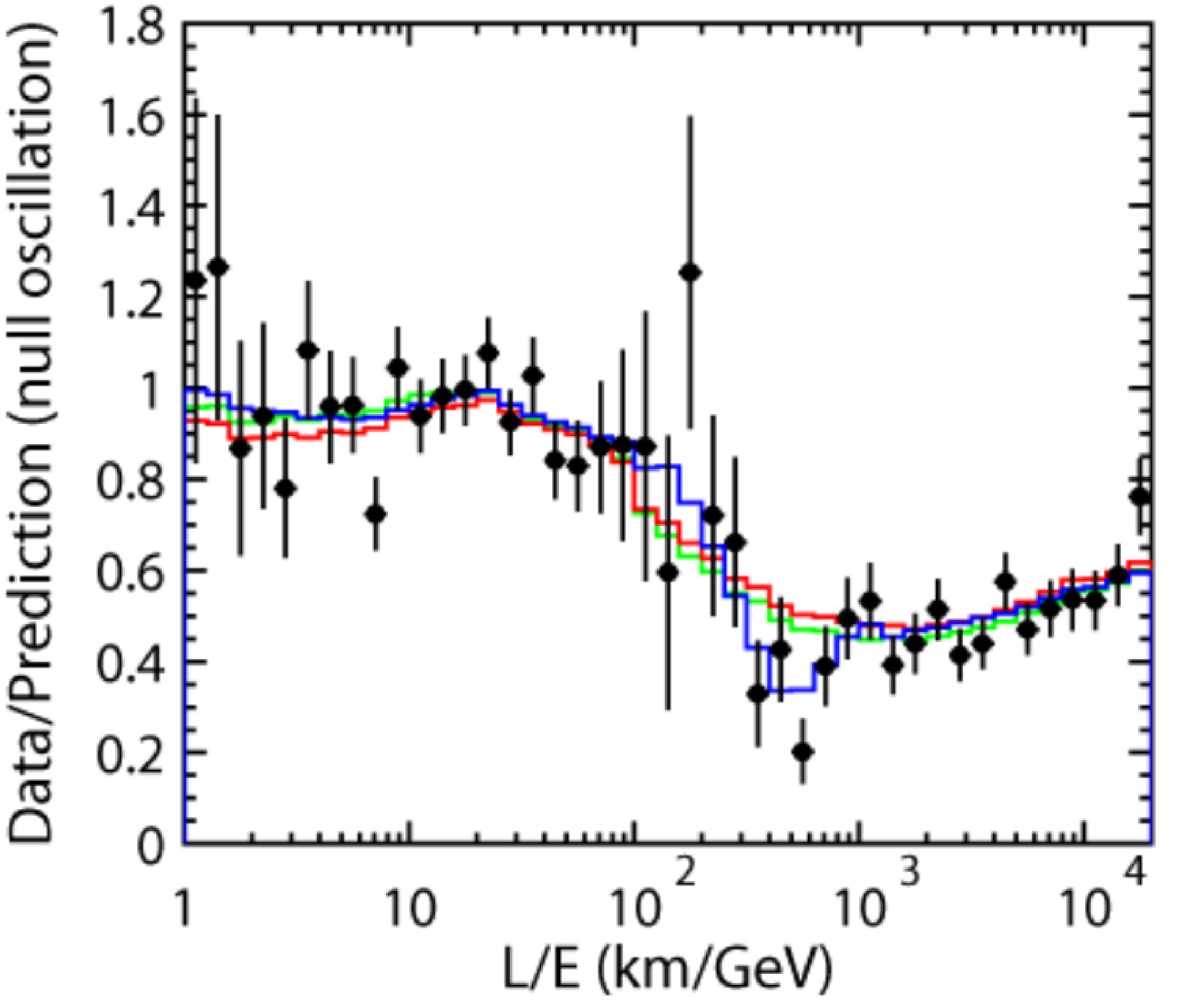


"Atmospheric" $\Delta m^2 \sim 2.5 \times 10^{-3}$ eV^2

IceCube



SuperKamiokande

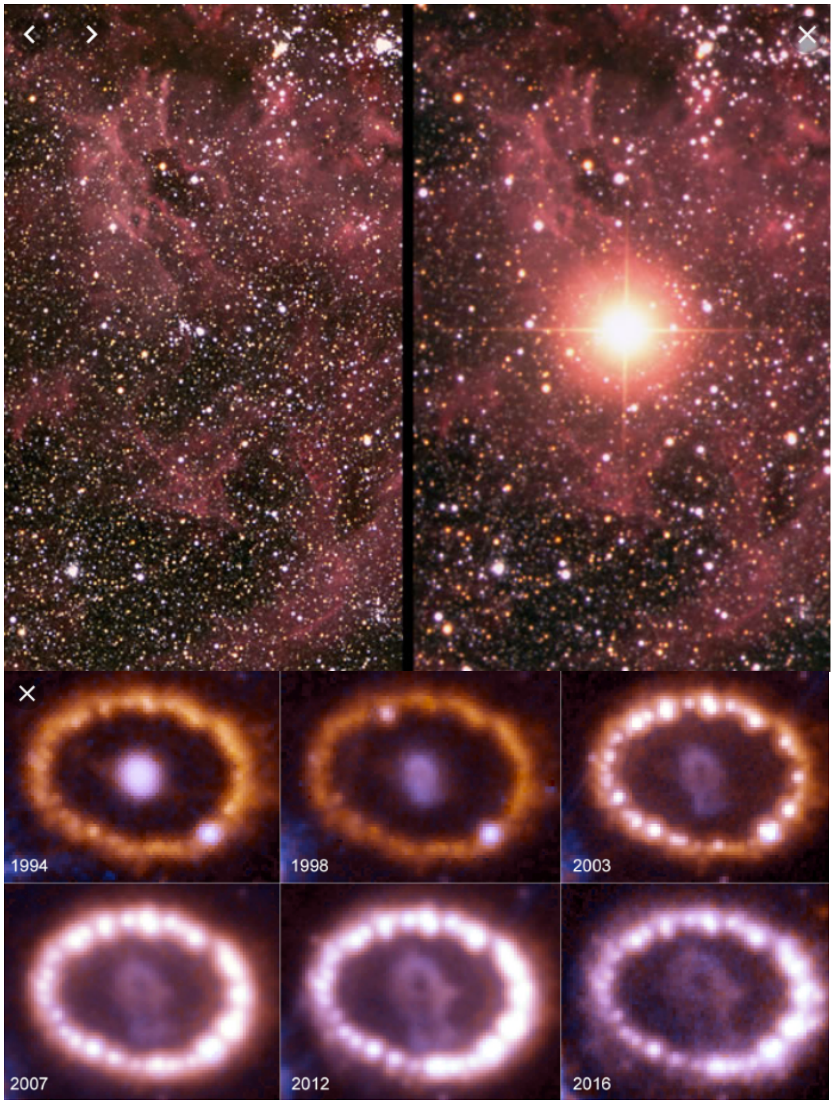


NB. Log scale

Supernova neutrinos

168000 light years away (Large Magellanic Cloud). SN1987A. Core collapse

Koshiba



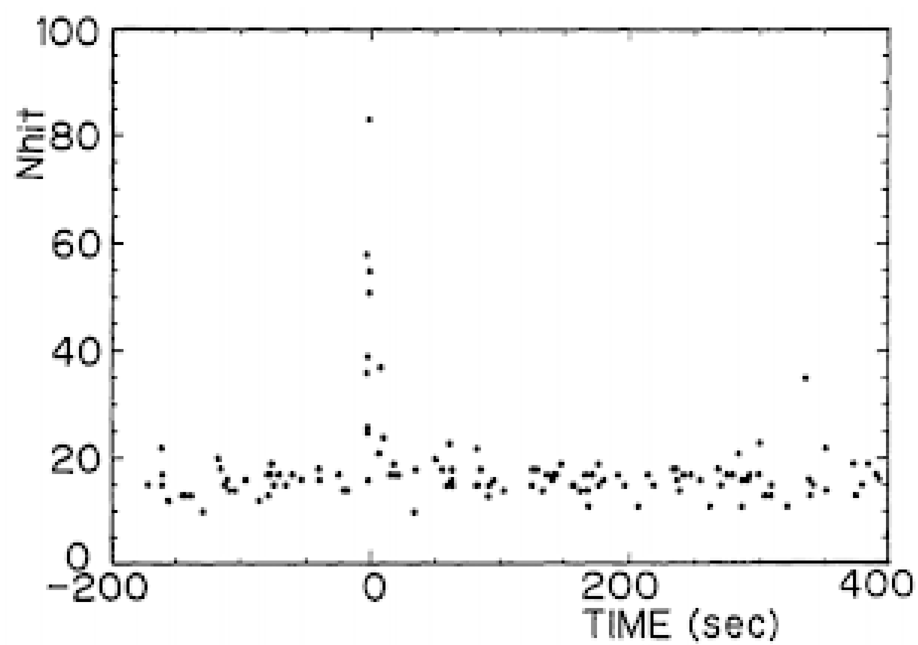
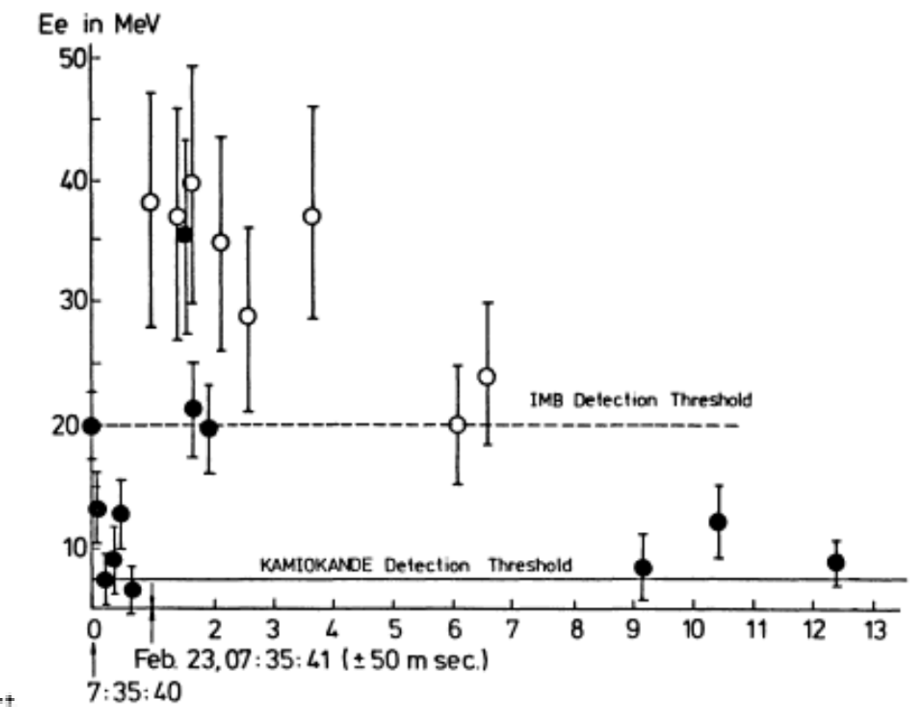


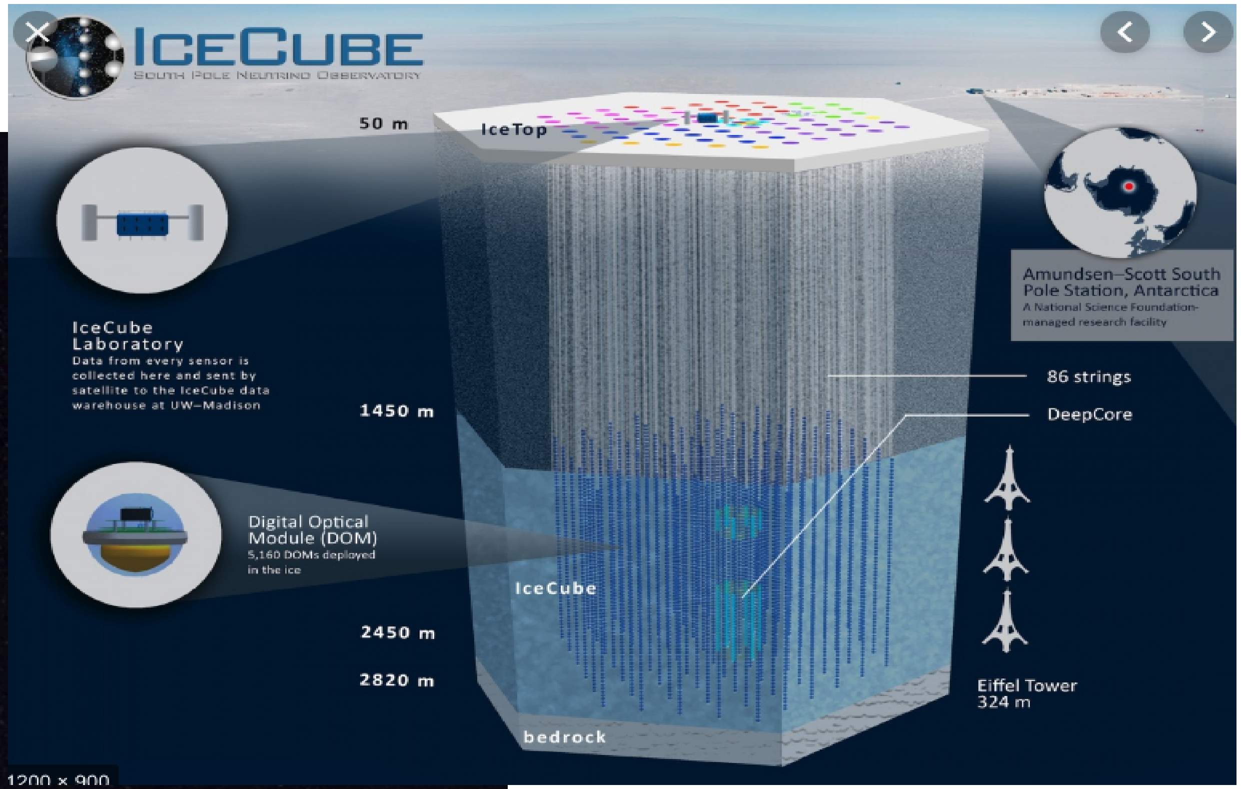
Fig. 2a : The supernova signal of the KAMIOKANDE-II experiment. It is a part of the laser printer output of the low energy raw data. Nhit is the number of hit photomultipliers.



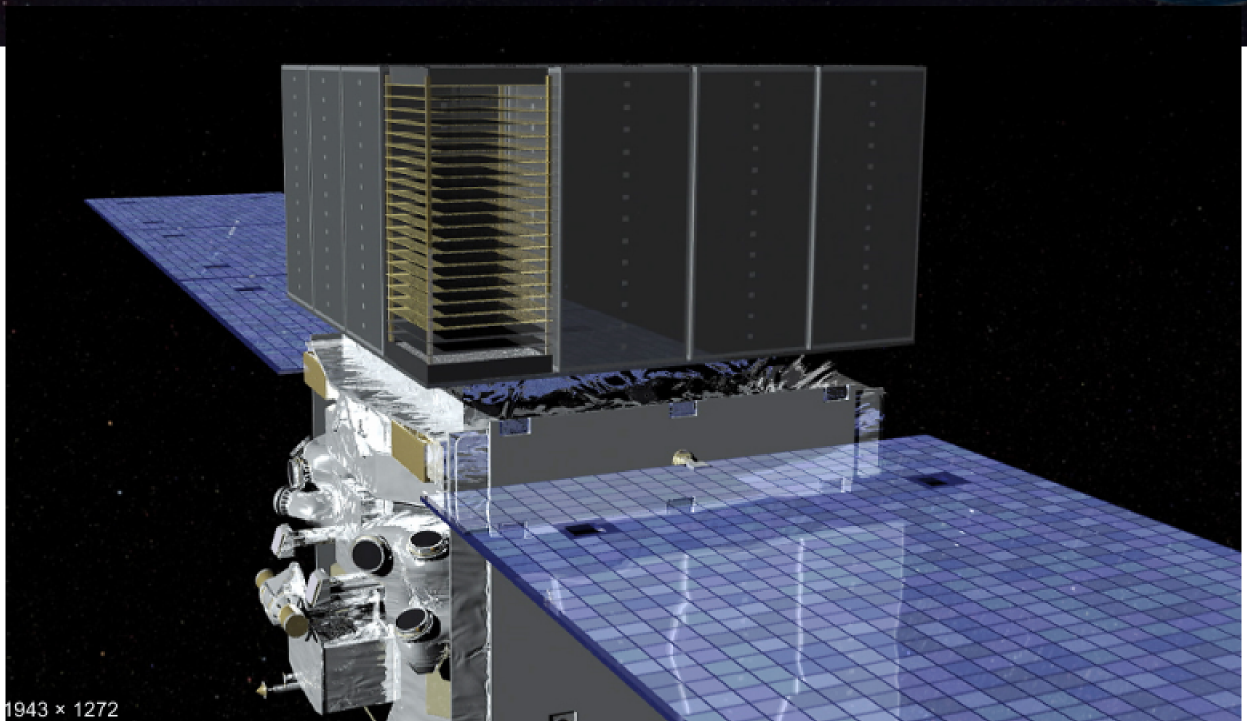
Energy release: 10^{44} J (!!!!) 99% carried away by neutrinos!
That is why despite the extreme distance and the extremely low interaction probability a bunch of interactions have been observed in a detector of ~ 1 kton at **168000 light years away**!

Nowadays a certain number of **larger detectors** are eagerly awaiting for a new galactic supernova to gather lots of events. Interesting for both **stellar astrophysics and fundamental neutrino properties**.

Neutrino astronomy



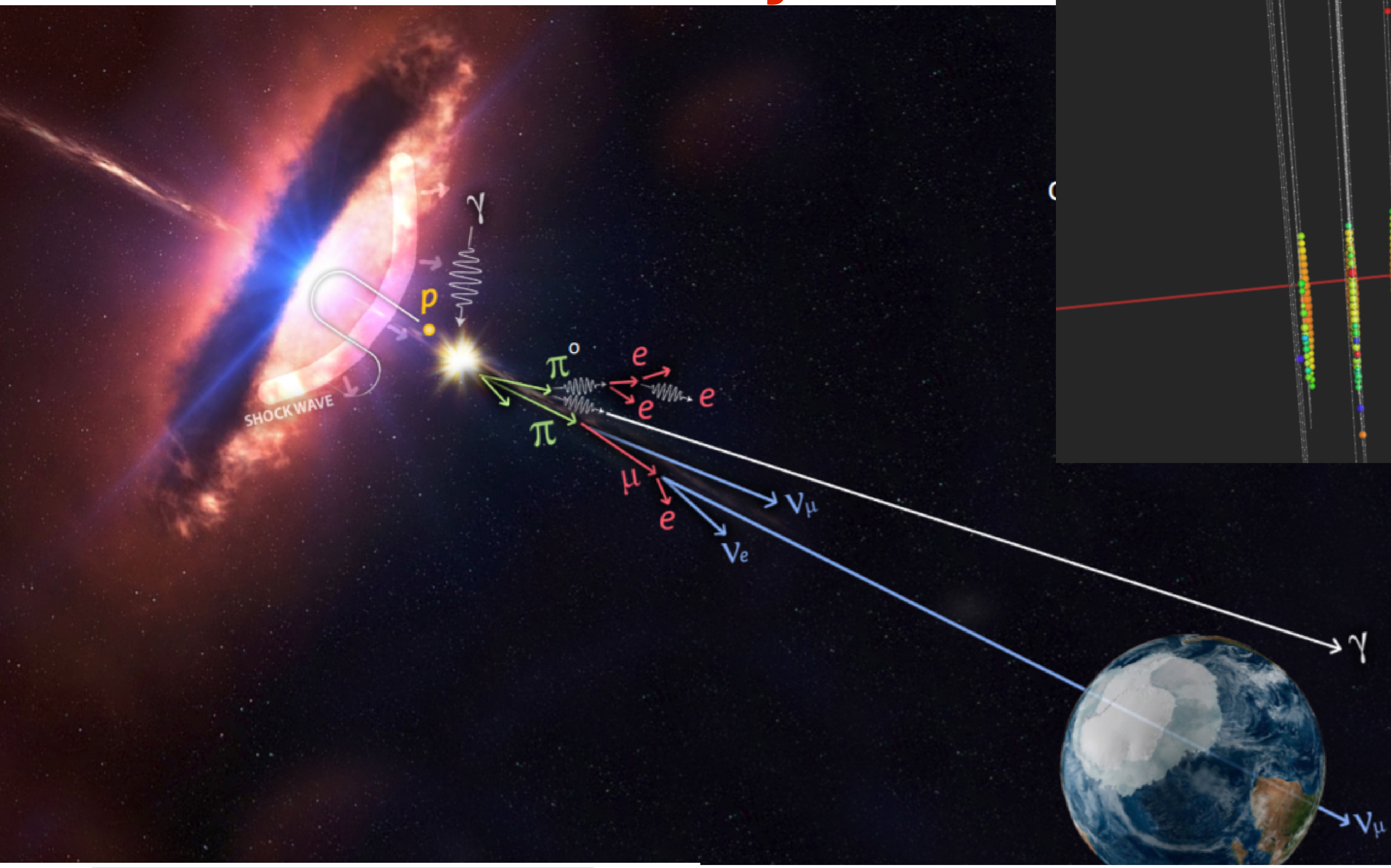
ICECUBE neutrino telescope (South Pole)

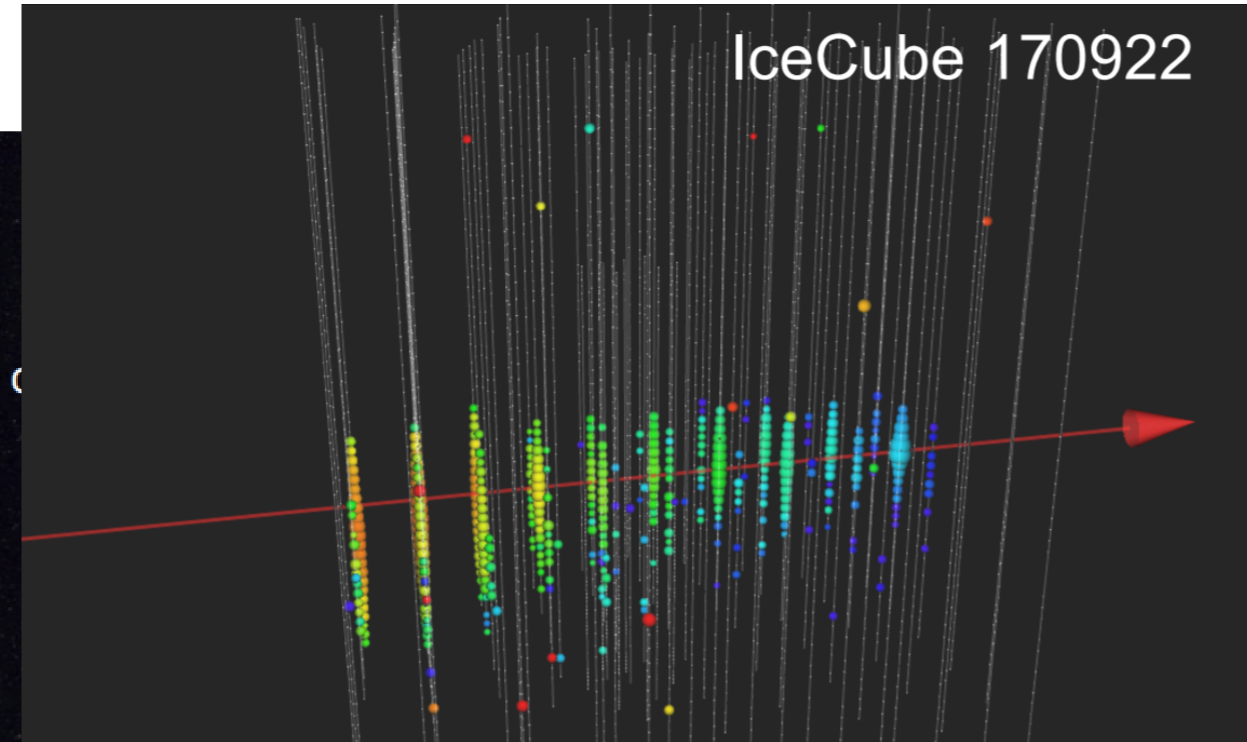


FERMI Gamma ray satellite (in orbit)

MAGIC Cherenkov gamma ray telescope (Canary islands)

Neutrino astronomy



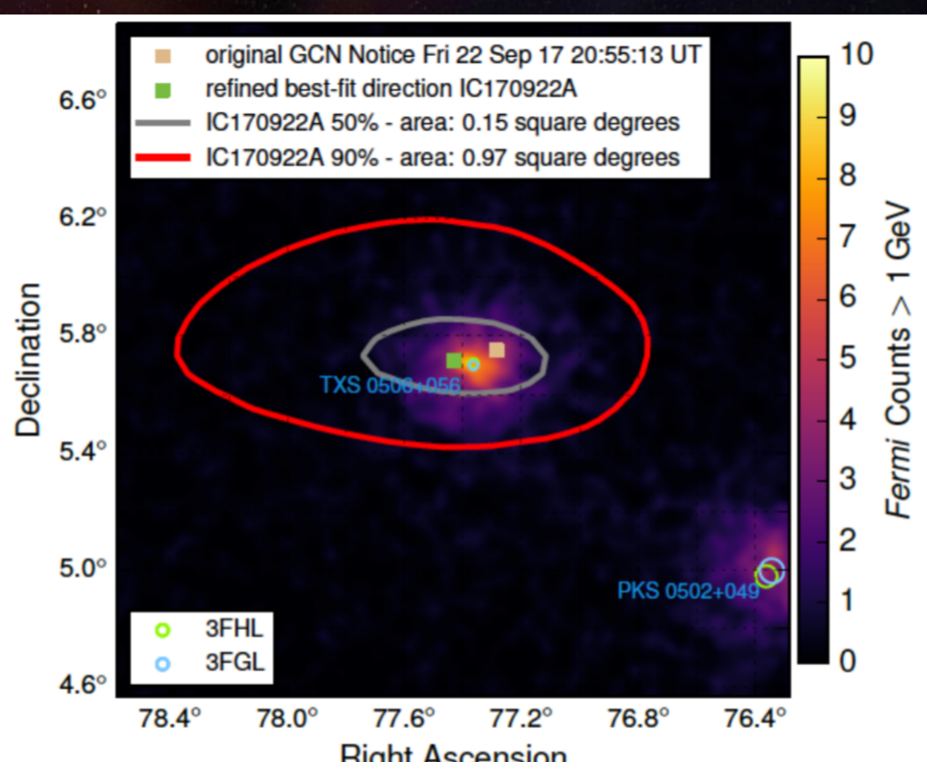


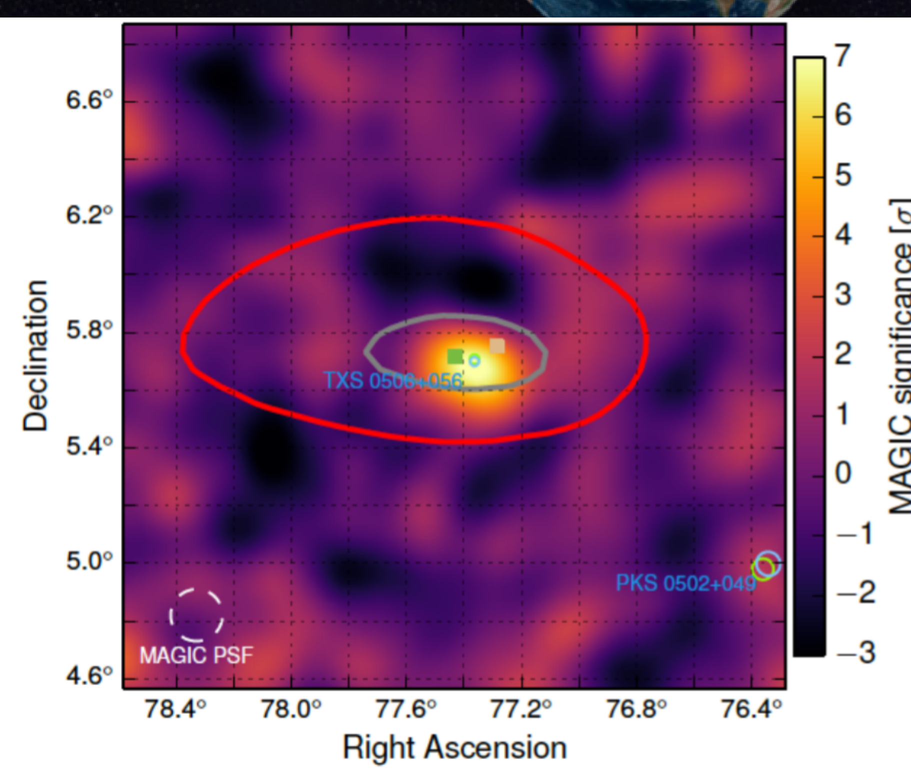
On. **Sep. 22, 2017** these three instruments see a simultaneous signal from the same direction (within 0.1°)

The source is **a flaring blazar from 4 billion light years away!**

The beginning of multi-messenger astronomy

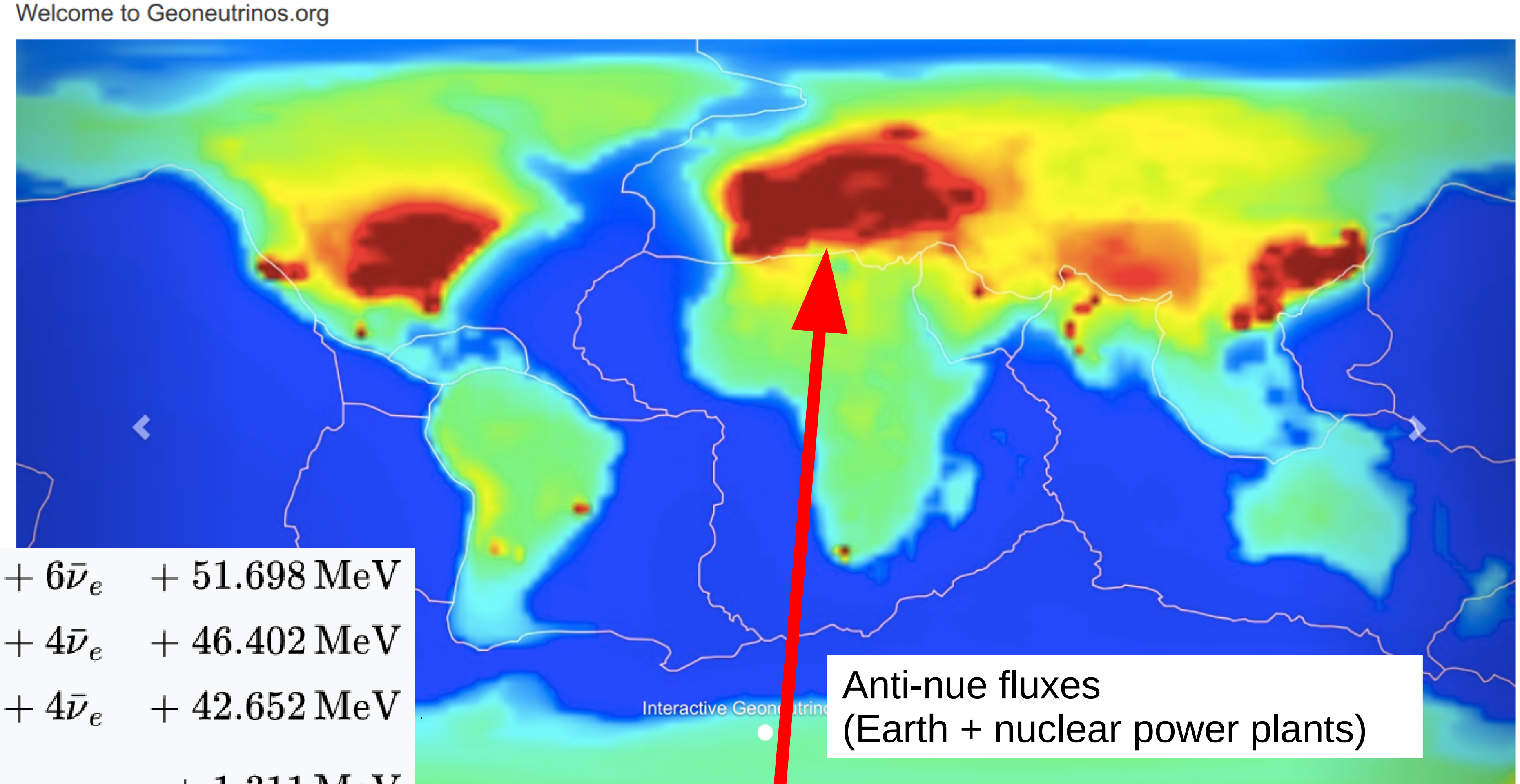
Neutrinos have a very big advantage: they are not absorbed and they travel straight (not affected by magnetic fields) → **pointing probes**





Geo-neutrinos

Radioactive decays of **Uranium, Thorium, Potassium** produce **electron antineutrinos** which have been measured (except K). A unique way **to monitor the heat budget** of the deep interior of the Earth.



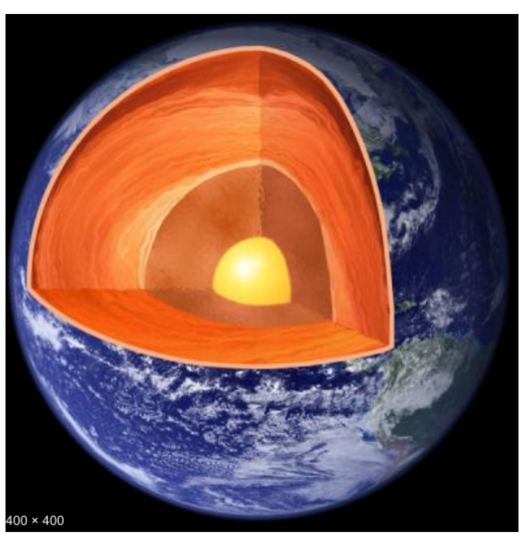
$$^{238}_{92}\mathrm{U} \longrightarrow {}^{206}_{82}\mathrm{Pb} + 8\alpha + 6e^- + 6\bar{\nu}_e \quad + 51.698\,\mathrm{MeV}$$

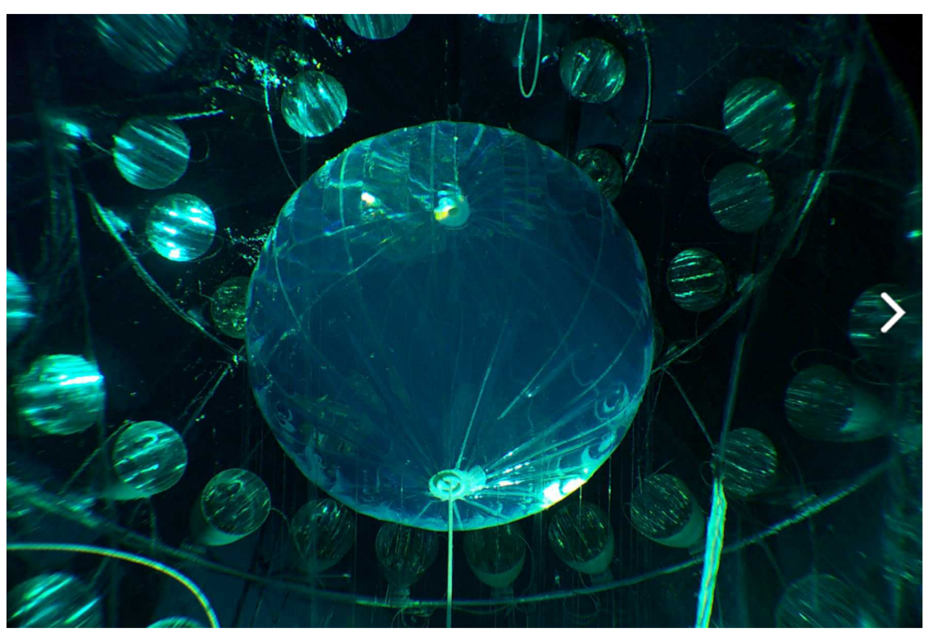
$$^{235}_{92}\mathrm{U} \longrightarrow {}^{207}_{82}\mathrm{Pb} + 7\alpha + 4e^- + 4\bar{\nu}_e \quad + 46.402\,\mathrm{MeV}$$

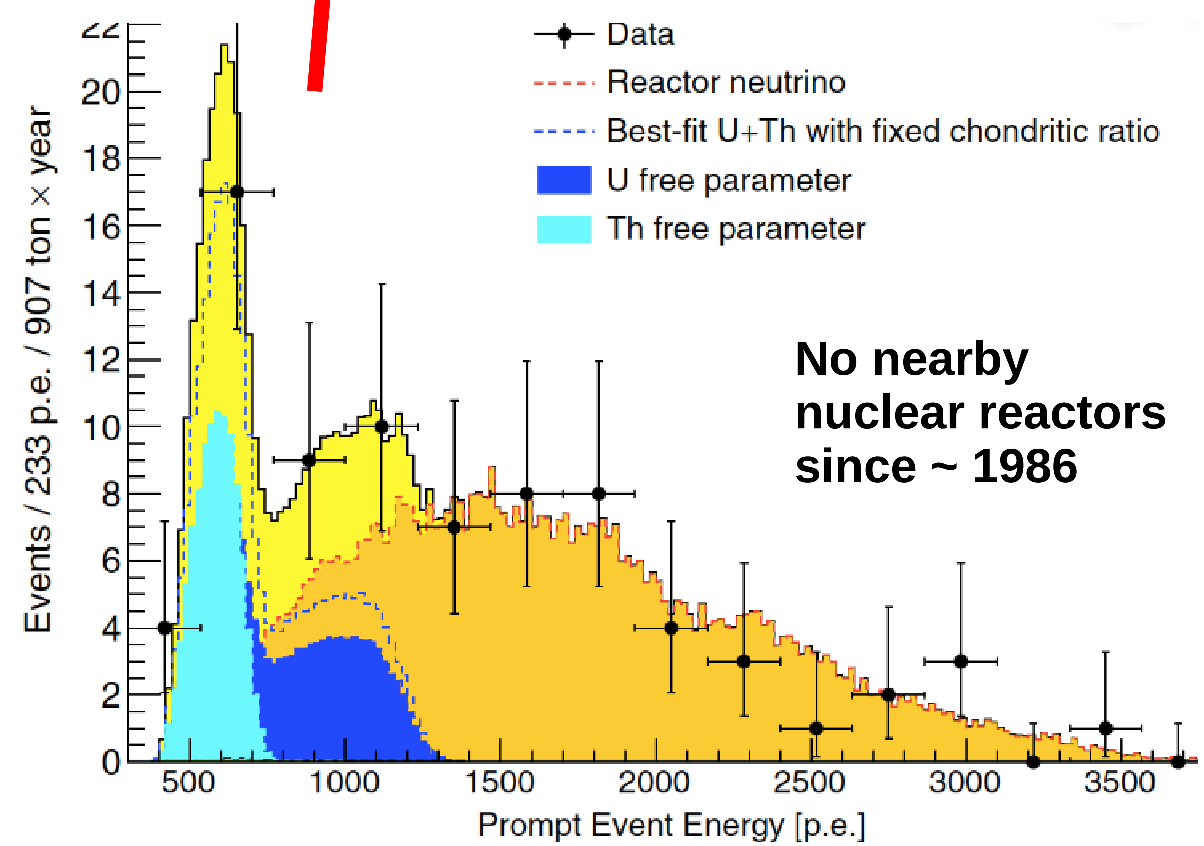
$$^{232}_{90}\mathrm{Th} \longrightarrow {}^{208}_{82}\mathrm{Pb} + 6\alpha + 4e^- + 4\bar{\nu}_e \quad + 42.652\,\mathrm{MeV}$$

$$^{40}_{19}\mathrm{K} \xrightarrow{89.3\,\%} {}^{40}_{20}\mathrm{Ca} + e^- + \bar{\nu}_e \quad + 1.311\,\mathrm{MeV}$$

$$^{40}_{19}\mathrm{K} + e^- \xrightarrow{10.7\,\%} {}^{40}_{18}\mathrm{Ar} + \nu_e \quad + 1.505\,\mathrm{MeV}$$





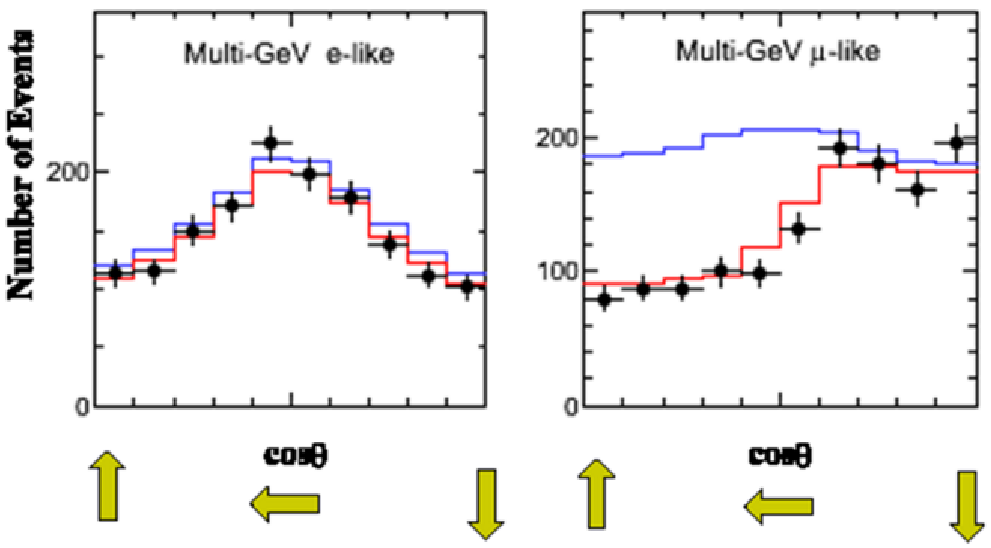


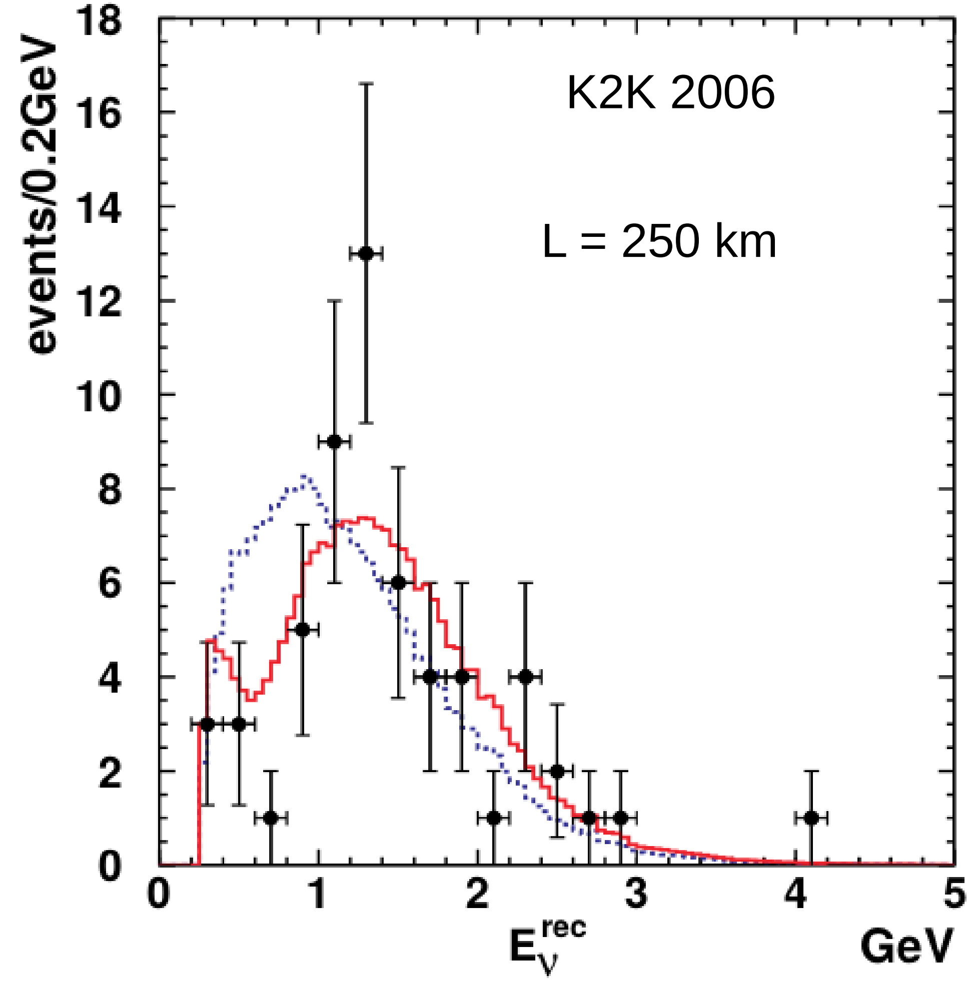
Borexino detector at LNGS (IT)
(Laboratori Nazionali del Gran Sasso INFN)

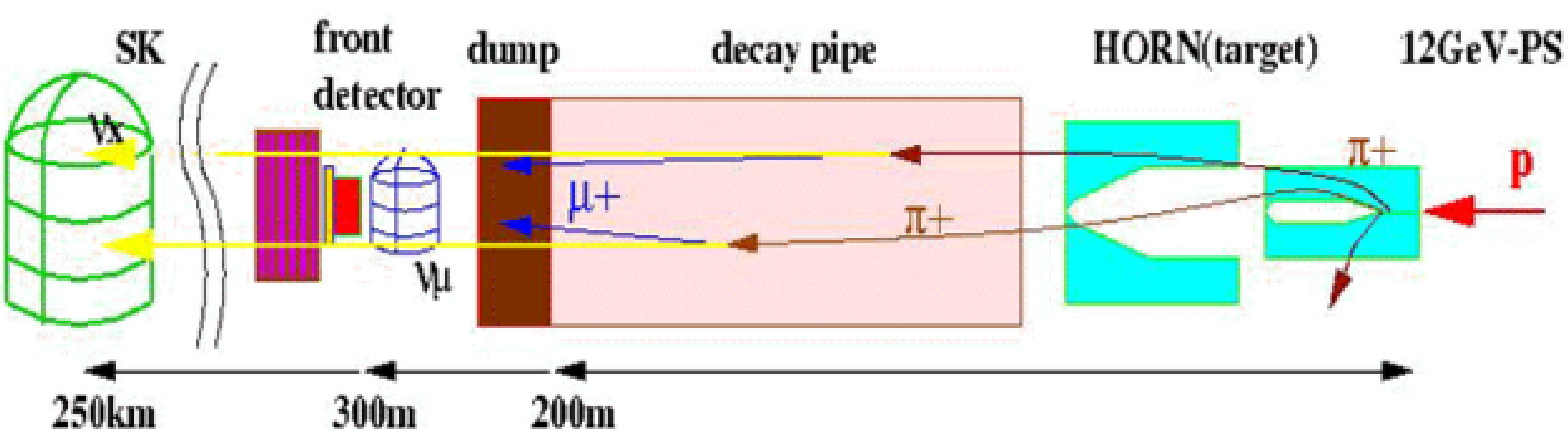
Accelerator based artificial neutrino beams

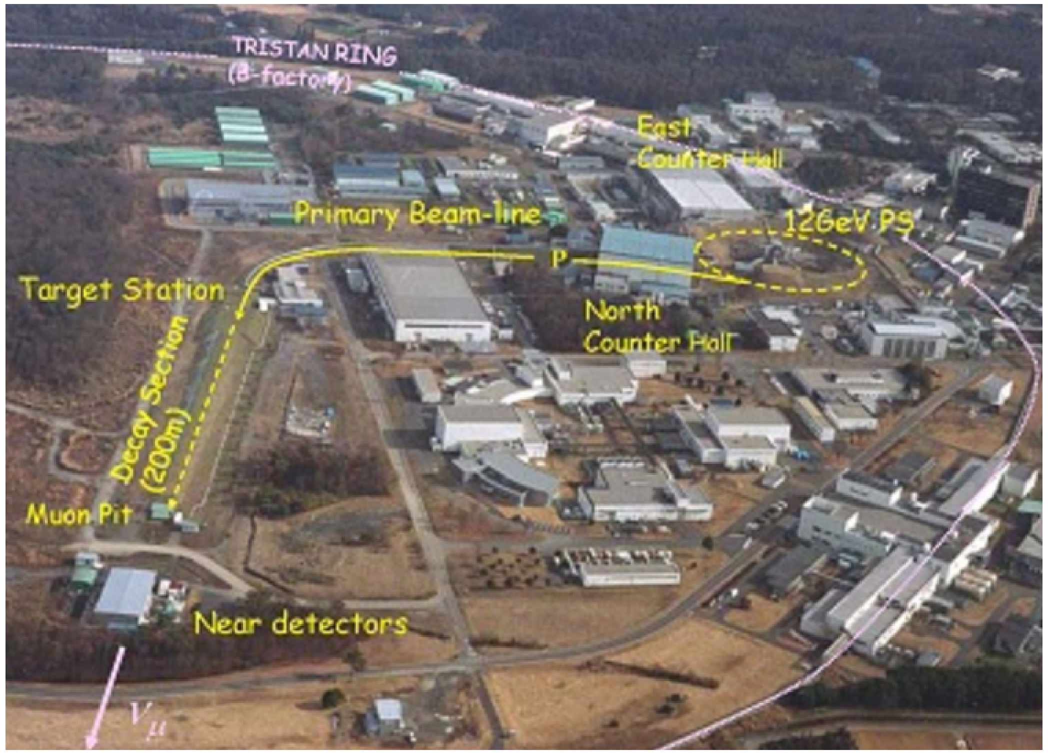
K2K confirms atmospheric oscillation by Super-Kamiokande with an artificial neutrino beam at long baseline

Super-K atmospheric ν



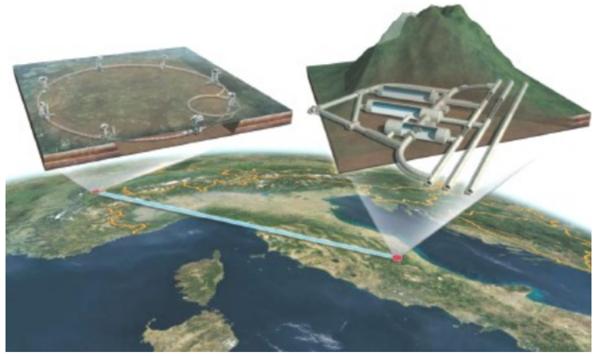






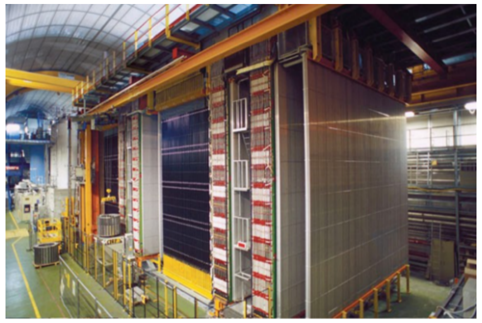
ν-beams (recent past and present)

CERN-SPS (400 GeV)
<E> = 17 GeV (2006-2012)

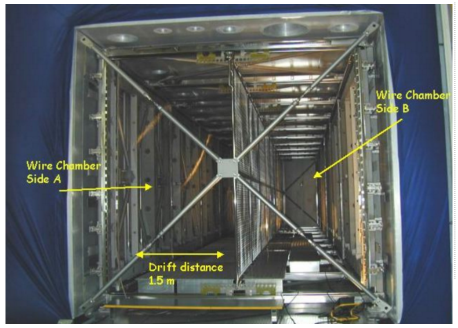


732 km
on-axis

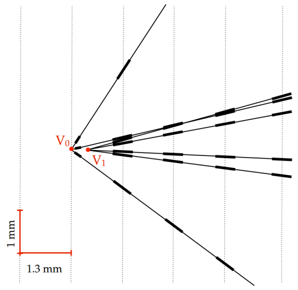
OPERA 1.2 kt



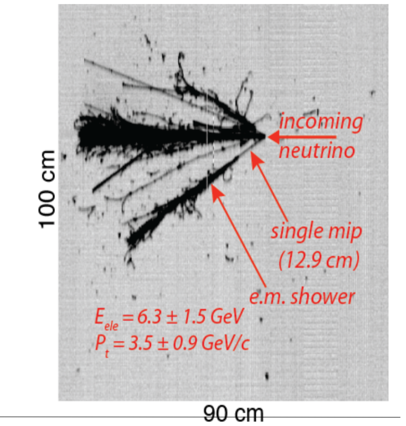
ICARUS 0.6 kt



Emulsions

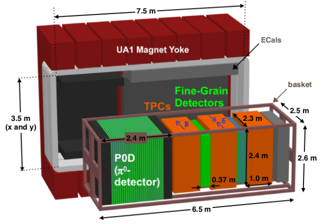


LAr TPC



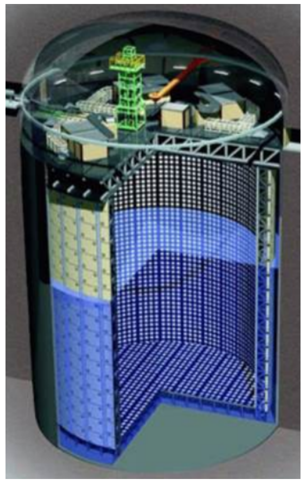
J-PARC Main Ring (30 GeV)
<E> = 0.6 GeV (2009)

ND280

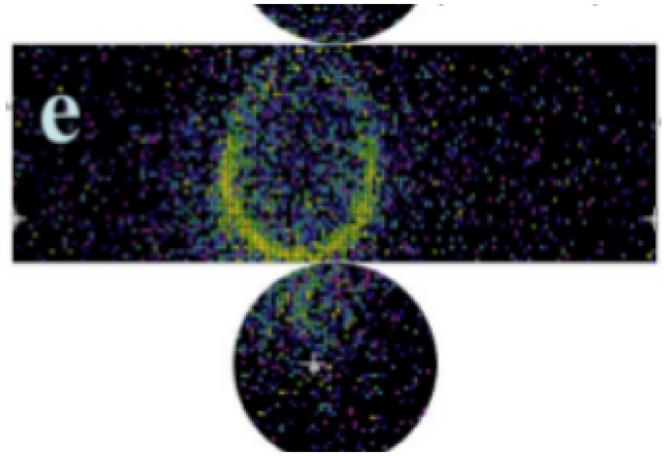


295 km
2.5° off-axis

Super-K 22.5 kt

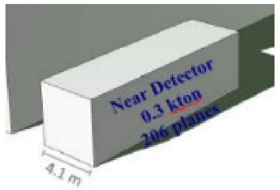


Water Cherenkov

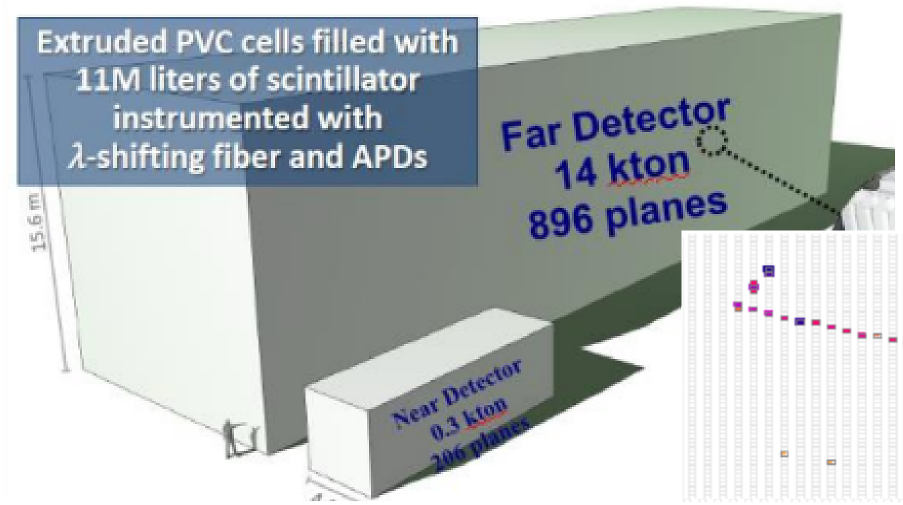


FNAL Main Injector (120 GeV)
<E> = 2 GeV (2013)

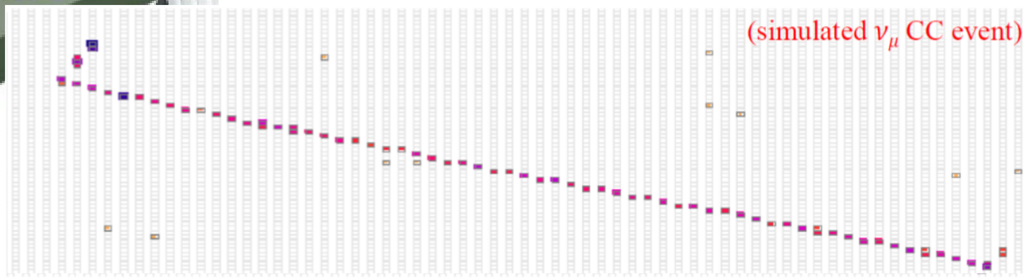
810 km
0.84° off-axis



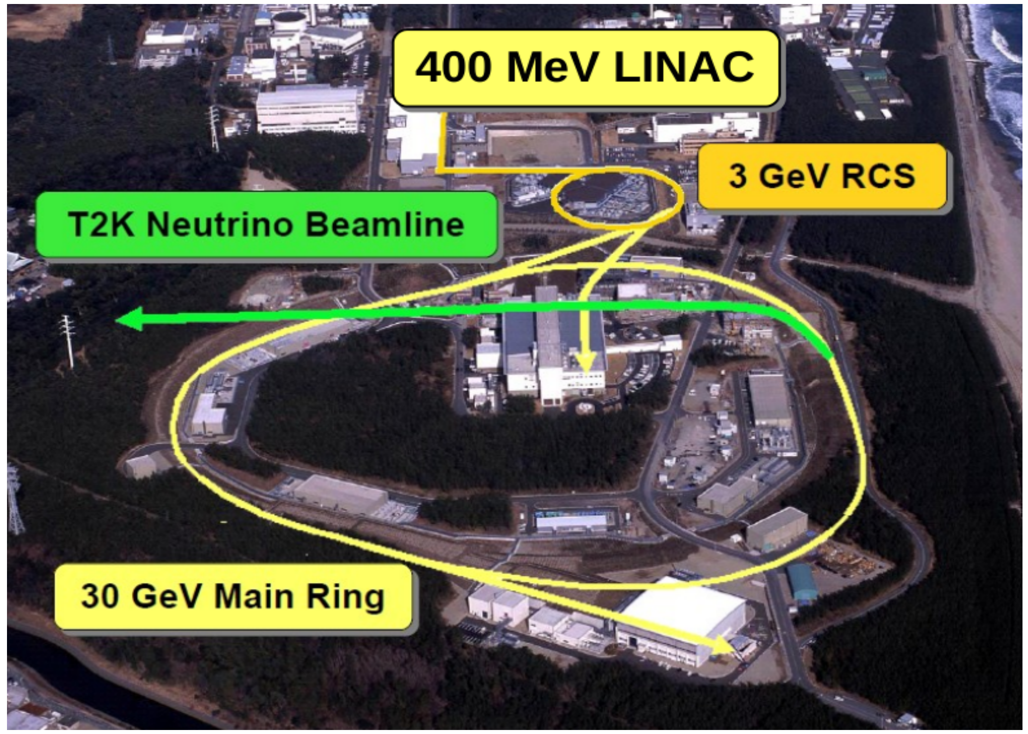
NOνA 14 kt



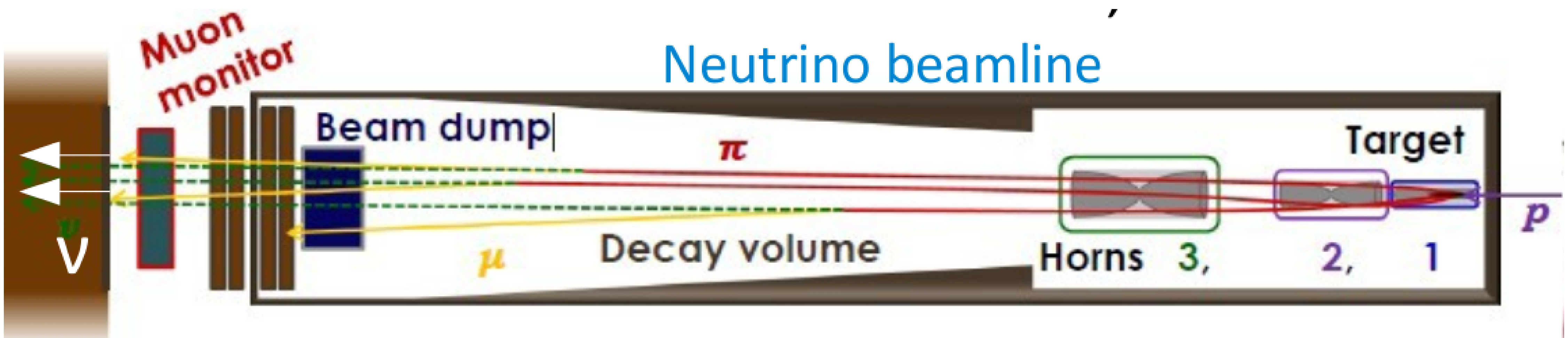
Liquid scintillator



The T2K experiment



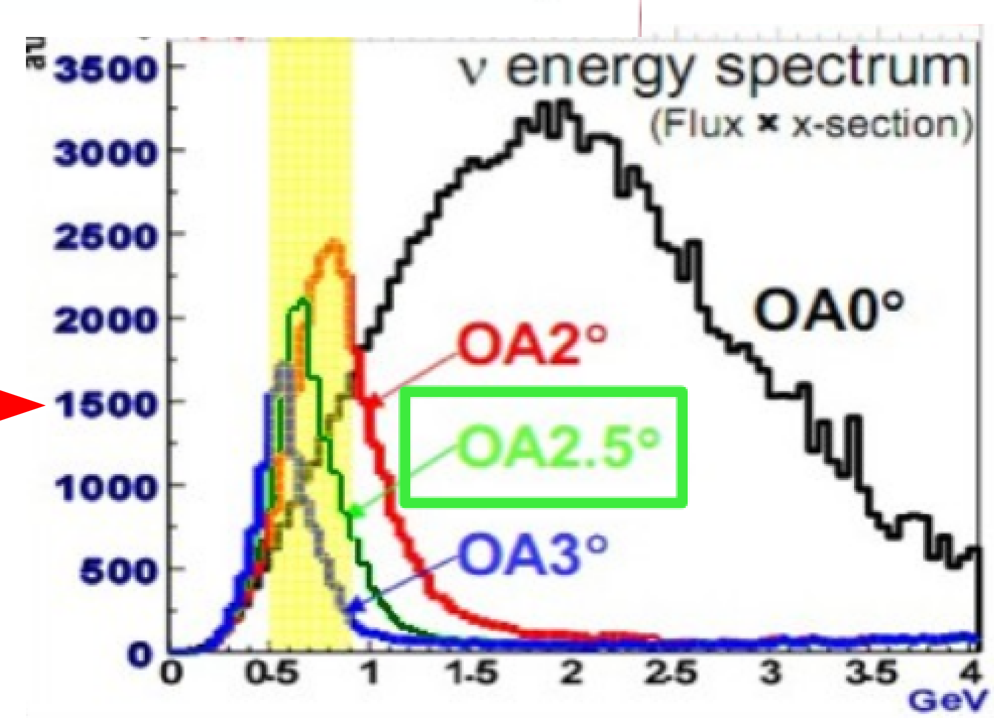
500 members
59 istitutes
11 countries



← 30 GeV

First "off-axis" beam

- 2.5^{o} → peak at ~ 0.6 GeV
- Enriched in Quasi-elastic interactions (good measurement of E_{ν})
- Reduced instrinsic ν_e background
- Reduced NC π^0 ~backg. from D.I.S.
- Double detector: **280 m and 295 km**



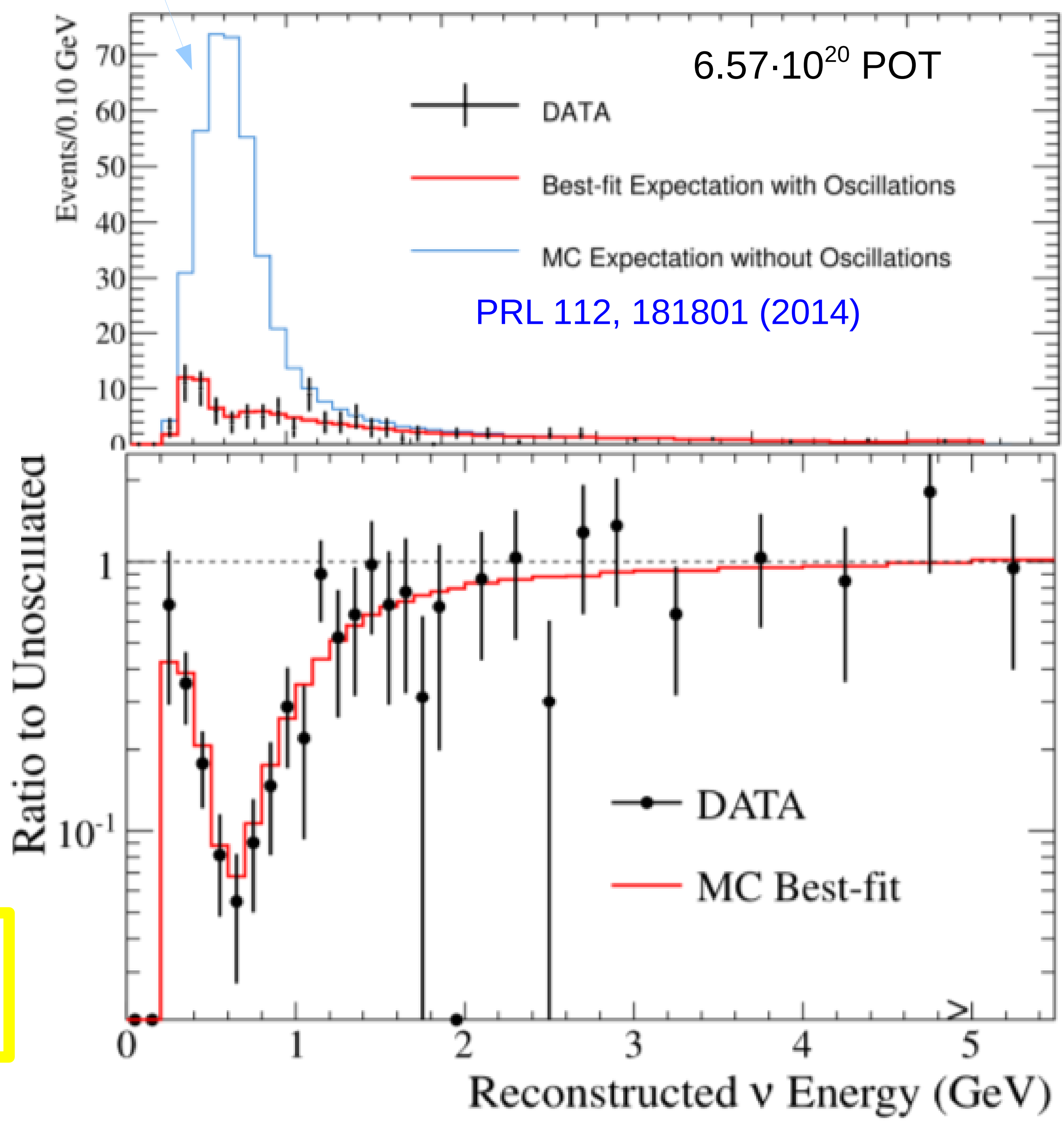
ν_μ ``disappearance'' with T2K

Approximate value of Δm_{23}^2 known at design phase.

Maximal suppression exactly at peak – not the case f.e. in the earlier long baseline experiment (MINOS in the US)

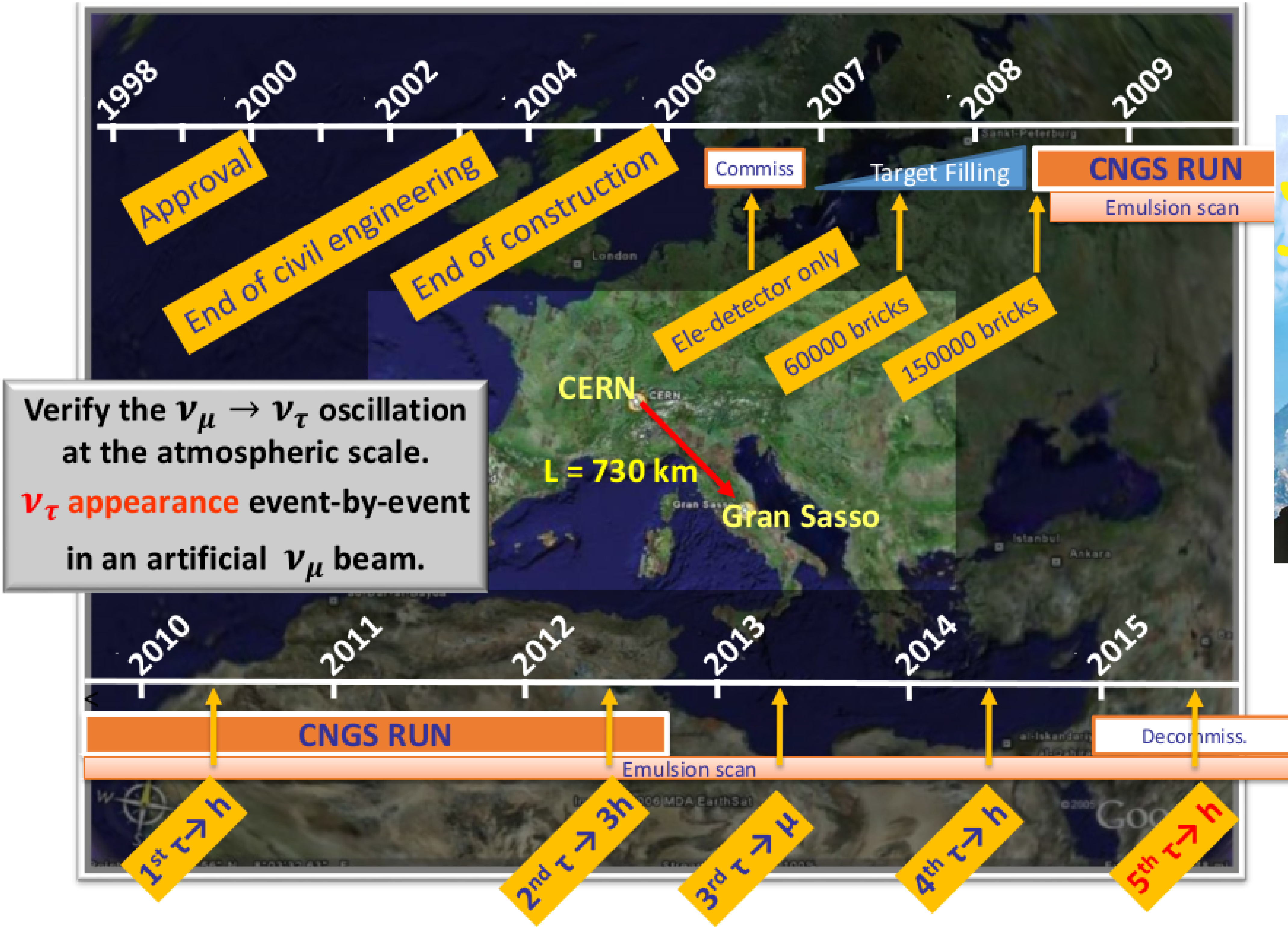
$$P(\nu_\mu \rightarrow \nu_\tau) = \sin^2 2\theta \cdot \sin\left(\frac{1.27\Delta m^2 L}{E}\right)$$

446 ± 23 exp. (no osc.) **120 obs.**



ν_τ ``appearance'' with the OPERA experiment

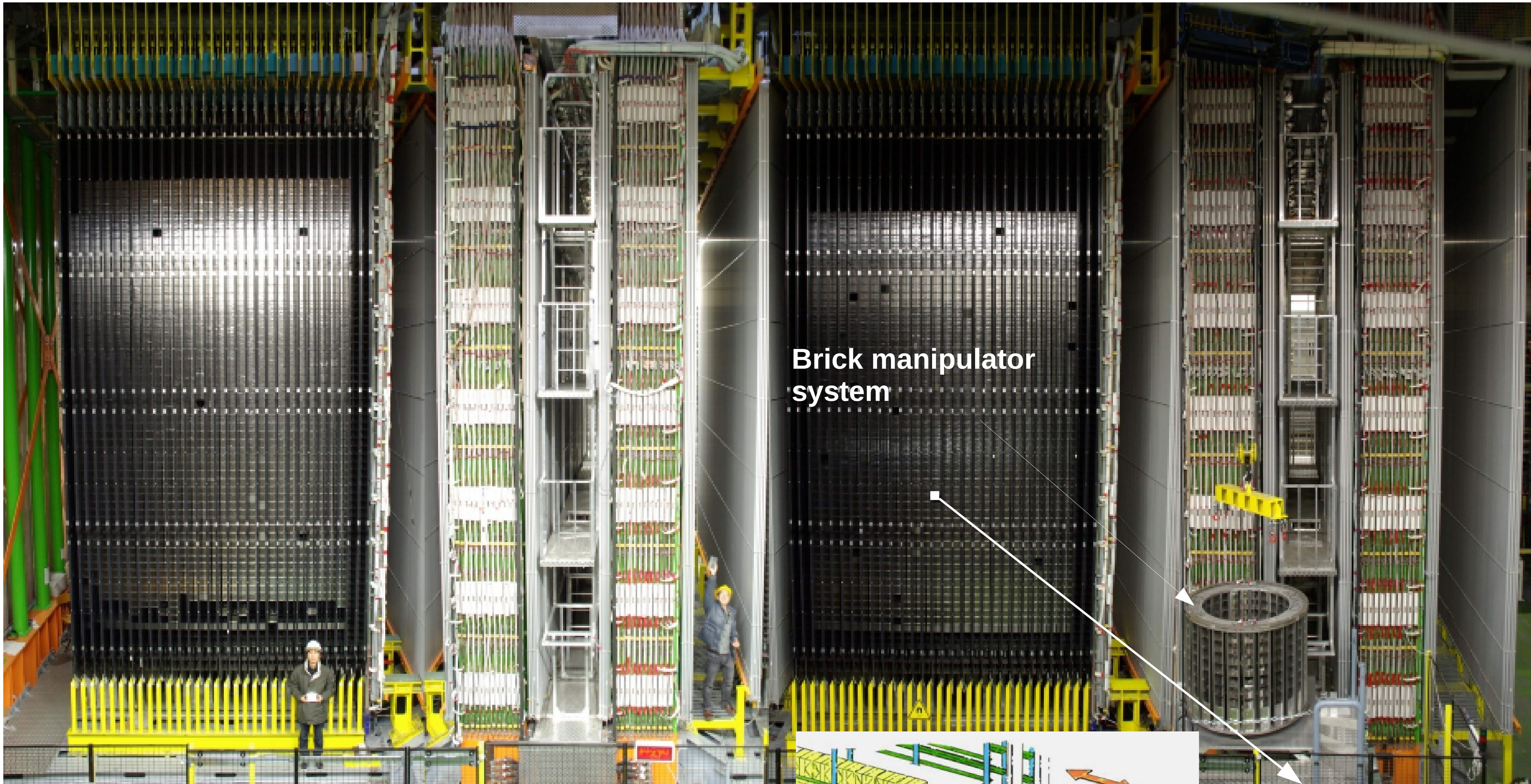
An experimental and technological challenge. 732 km baseline. Beam O(10) more energetic (17 GeV) than any other LBL (m_τ). A "fine-grained" detector ~ 100 x more massive (1.25 kt) than the precursors.



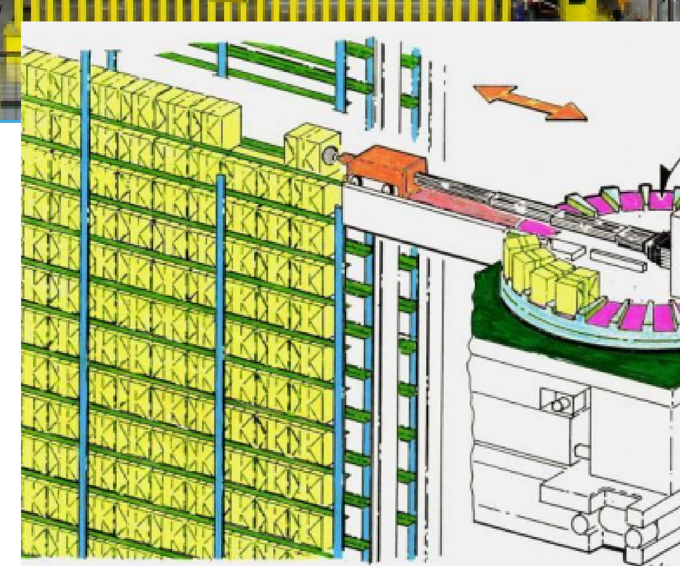
The OPERA “hybrid” detector

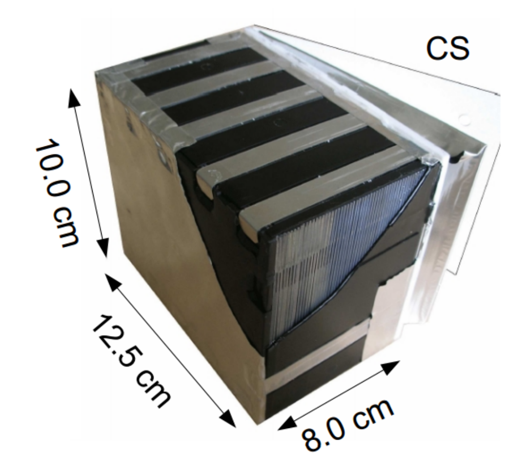
the needle in the haystack!

Super Module 1 | **Super Module 2**



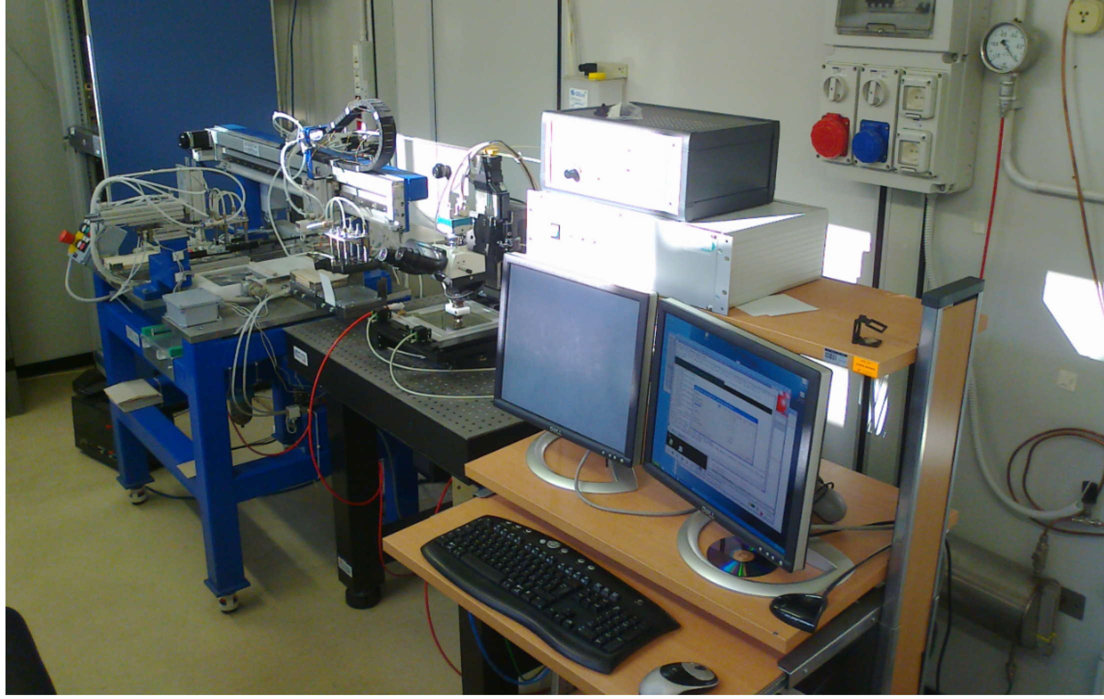
Target area | **μ spectrometer**





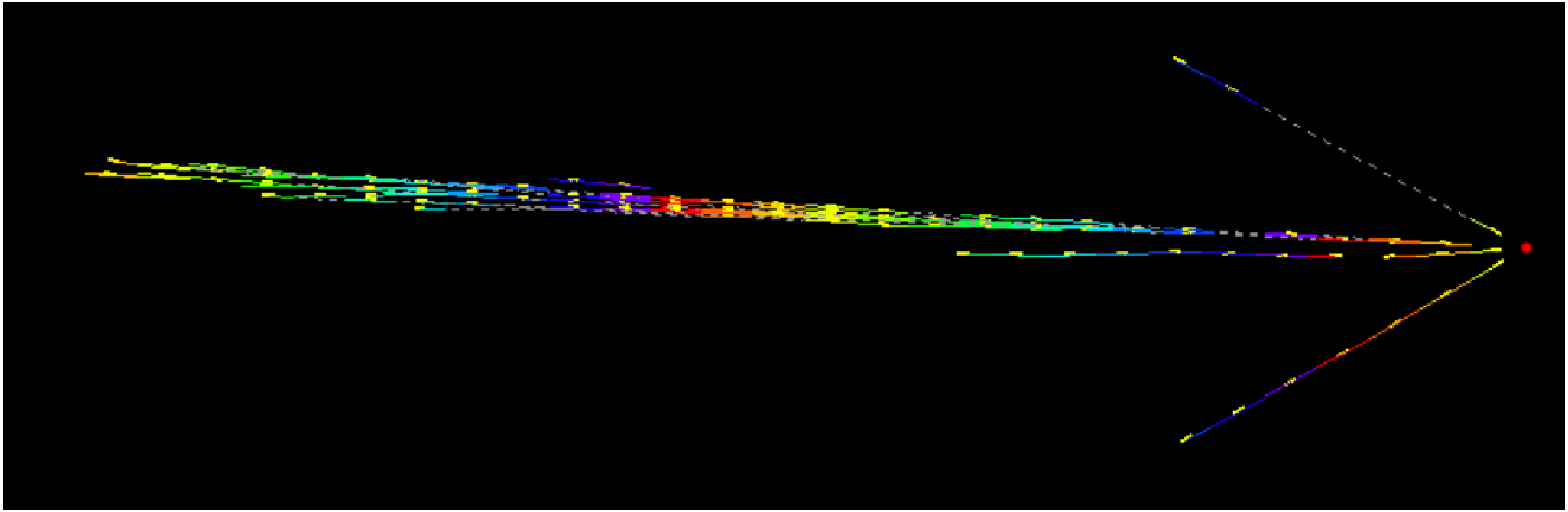
~ 150.000 bricks in total. 1.25 kt mass
A τ travels a fraction of a mm before decay. 5 of them were clearly identified.

The OPERA “hybrid” detector

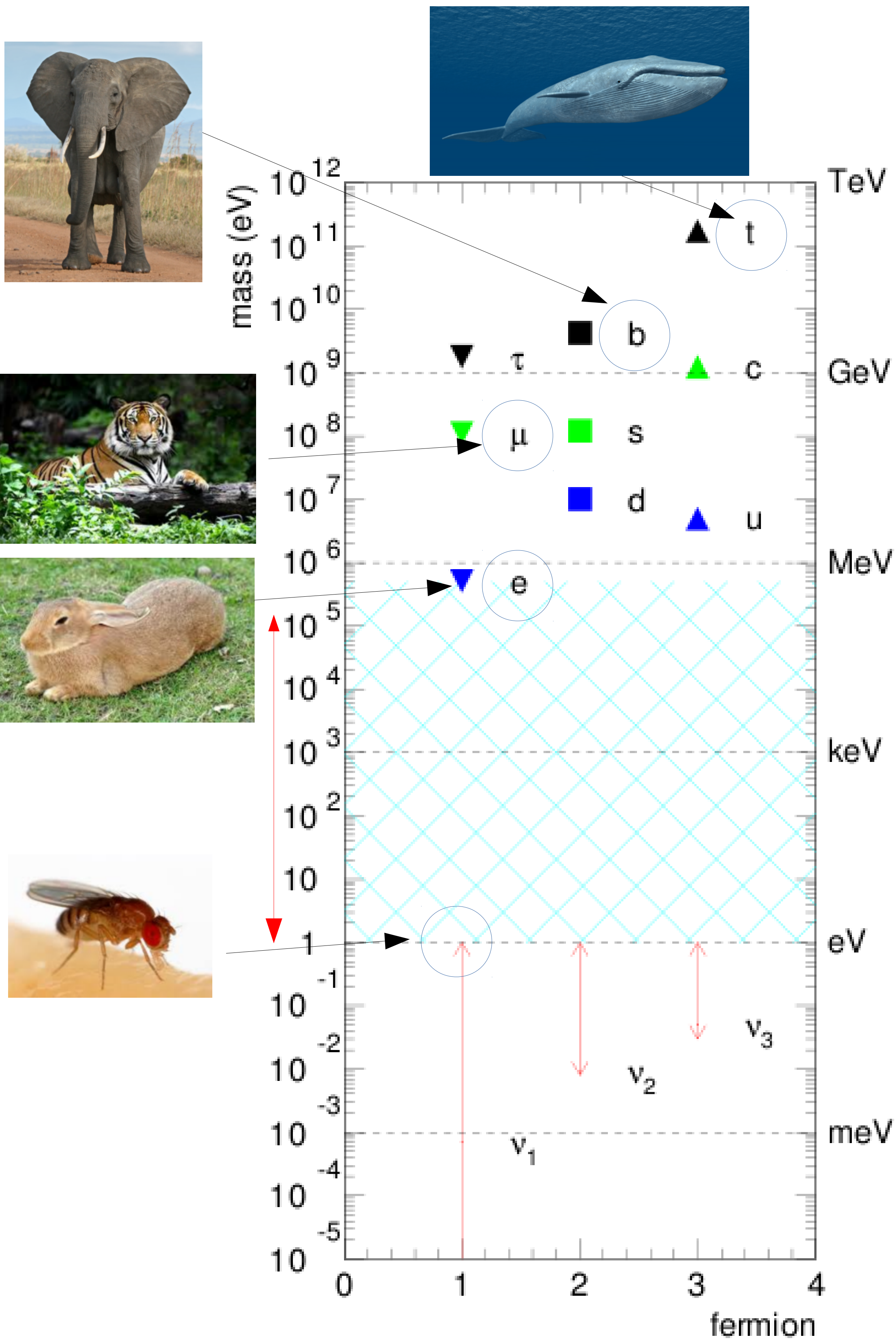


A very nice neutrino interaction (proudly) found by myself using one of the OPERA “bricks” with an optical scanning microscope at INFN-Frascati.

Animated view:
https://www.lnf.infn.it/esperimenti/opera/scanning/figs/animation_54105.gif



Open questions



Why such tiny masses?

Heaviest neutrino **at least 6 orders of magnitude lighter than the lightest lepton**

Even the masses of quarks and leptons are not understood (free parameters) but … this gap looks even more "**unnatural**"

Theoreticians speculate that this might be the result of the **existence of very heavy particles with masses of ~ 10^{16} protons**.

The interplay with the mass of the Higgs boson simply generates very low masses for neutrinos

see-saw mechanism

meV ~ $(10^2 \text{ GeV})^2 / 10^{16}$ GeV

The **only way to probe** these particles!
they are way **too heavy to be produced at accelerators**.

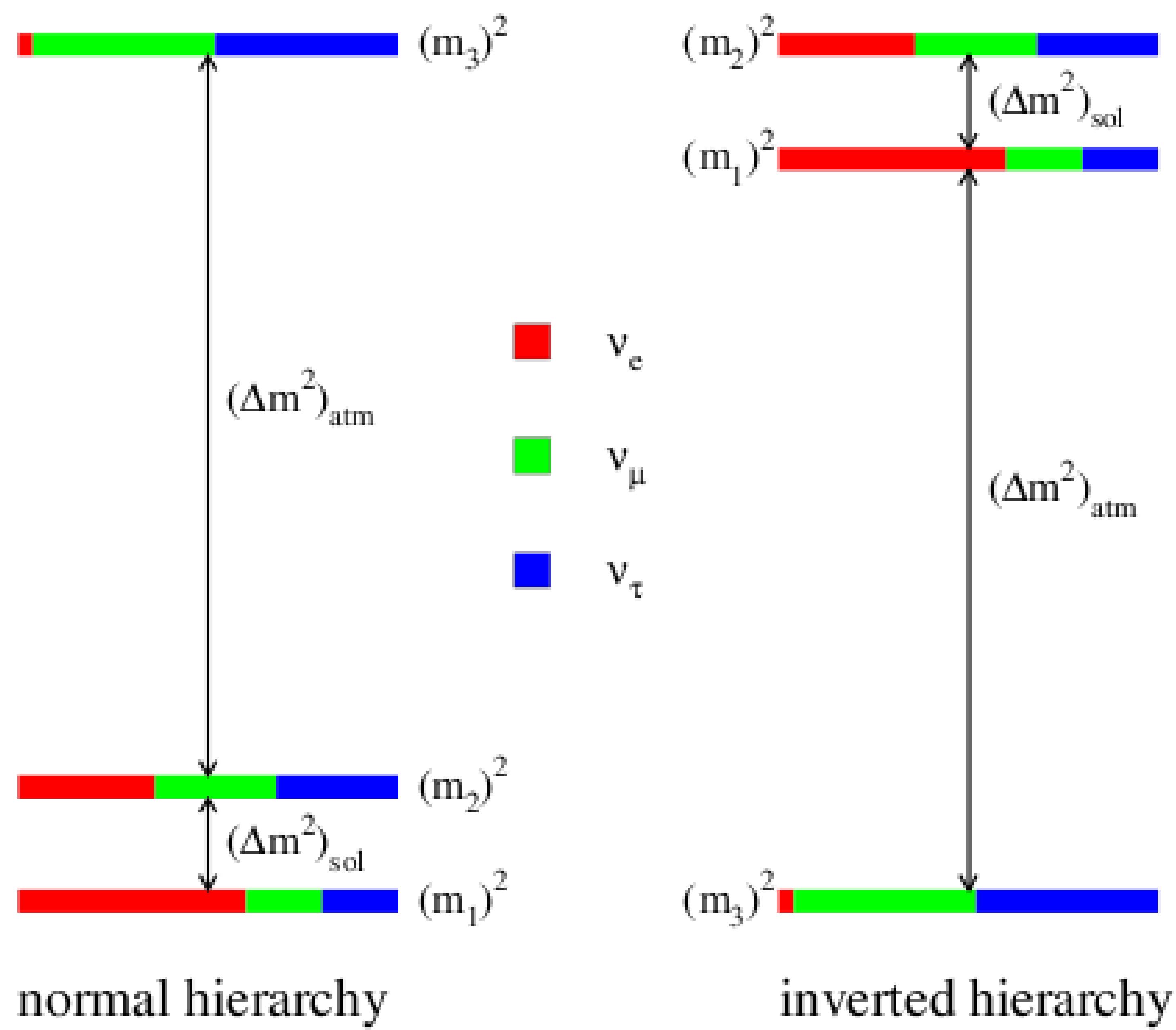
Open questions

Which mass hierarchy ?

Oscillations give information on squared mass differences not their absolute values !

$$P(\nu_\mu \to \nu_\tau) = \sin^2 2\theta \cdot \sin\left(\frac{1.27\Delta m^2 L}{E}\right)$$

We only know that two neutrinos pairs are "close" (8 meV, solar oscillations) and two are "far" (30 meV, atmospheric oscillation)



Present data slightly favor the "normal hierarchy" hypothesis

Several present and future experiments (NOvA, SK, PINGU, ORCA...) but let's talk about JUNO! →

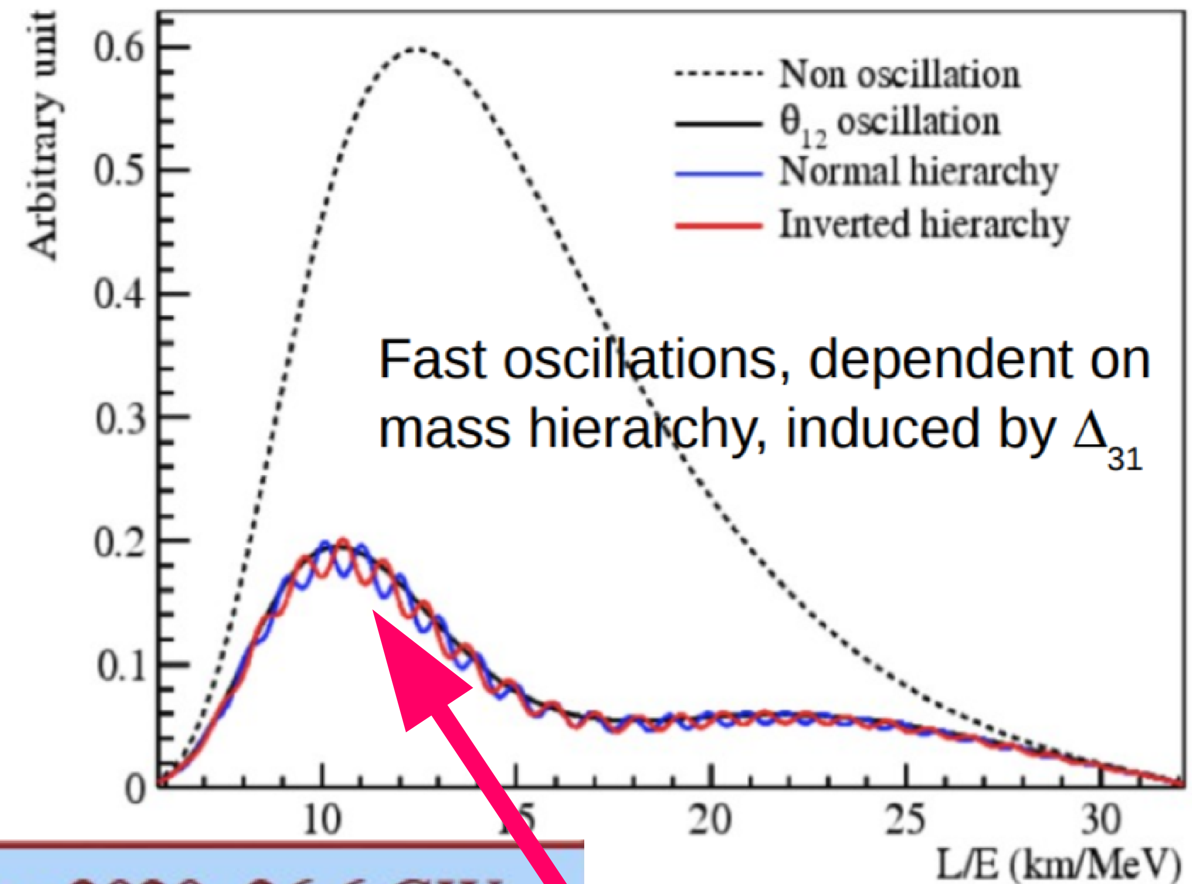
JUNO **Which mass hierarchy ?**

JUNO (**Jiangmen Underground Neutrino Observatory**) is a multipurpose anti-ν_e detector near Kaiping (South China).

Baseline (53 km) from Yangjian and Taishan reactors (10 cores) optimized in the region of maximum Δm^2_{21} - driven oscillations.

Expected to start data taking in **2021**.

Antineutrino flux for L=53 km, maximum for solar parameters driven oscillations



Cores	YJ-C1	YJ-C2	YJ-C3	YJ-C4	YJ-C5	YJ-C6
Power (GW)	2.9	2.9	2.9	2.9	2.9	2.9
Baseline (km)	52.75	52.84	52.42	52.51	52.12	52.21
Cores	TS-C1	TS-C2	TS-C3	TS-C4	DYB	HZ
Power (GW)	4.6	4.6	4.6	4.6	17.4	17.4
Baseline (km)	52.76	52.63	52.32	52.20	215	265

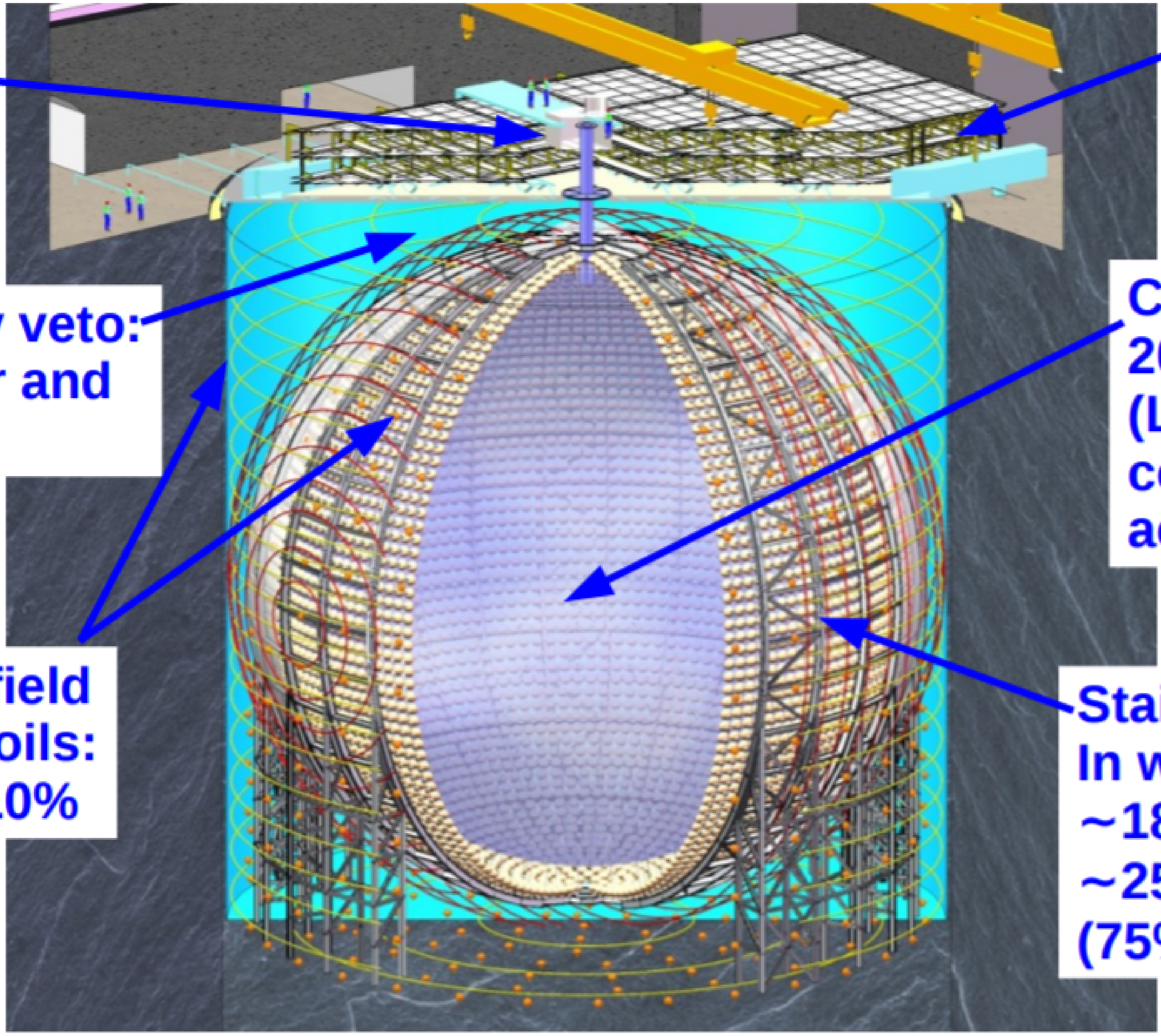
Needs unprecedented **mass and energy resolution** to pin down if the measured energy spectrum will follow the **red** or the **blue** curve!

JUNO

Which mass hierarchy ?

10^5 events in 6 years of data taking: 20 ktons of **liquid scintillator**. Sphere ~ **35 m diameter**.
JUNO will be the **largest scintillator detector ever built.**
Padova is involved in the **readout electronics** of photomultipliers (INFN and University staff).

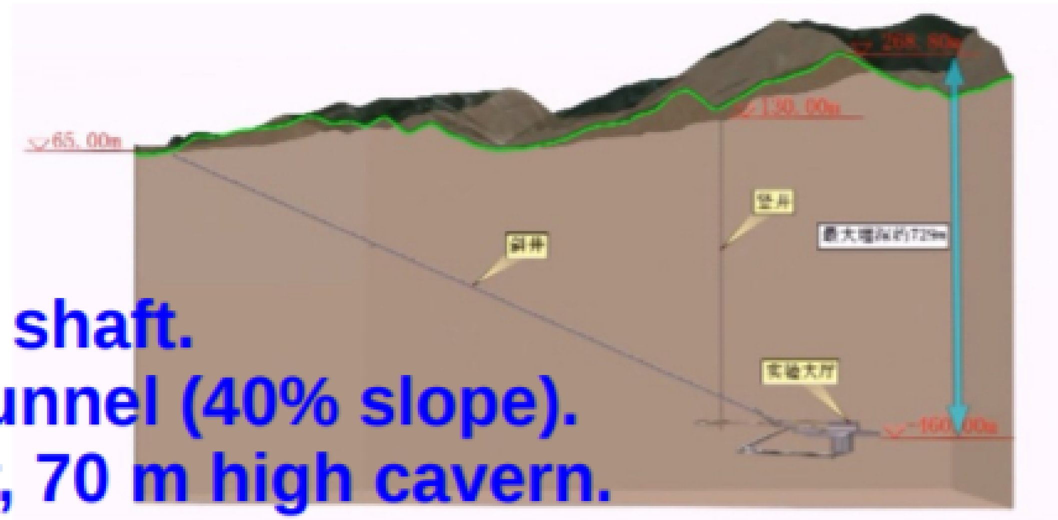
700 m overburden.



JUNO

Which mass hierarchy ?

Civil engineering



- 564 m vertical shaft.
- 1266 m long tunnel (40% slope).
- 50 m diameter, 70 m high cavern.

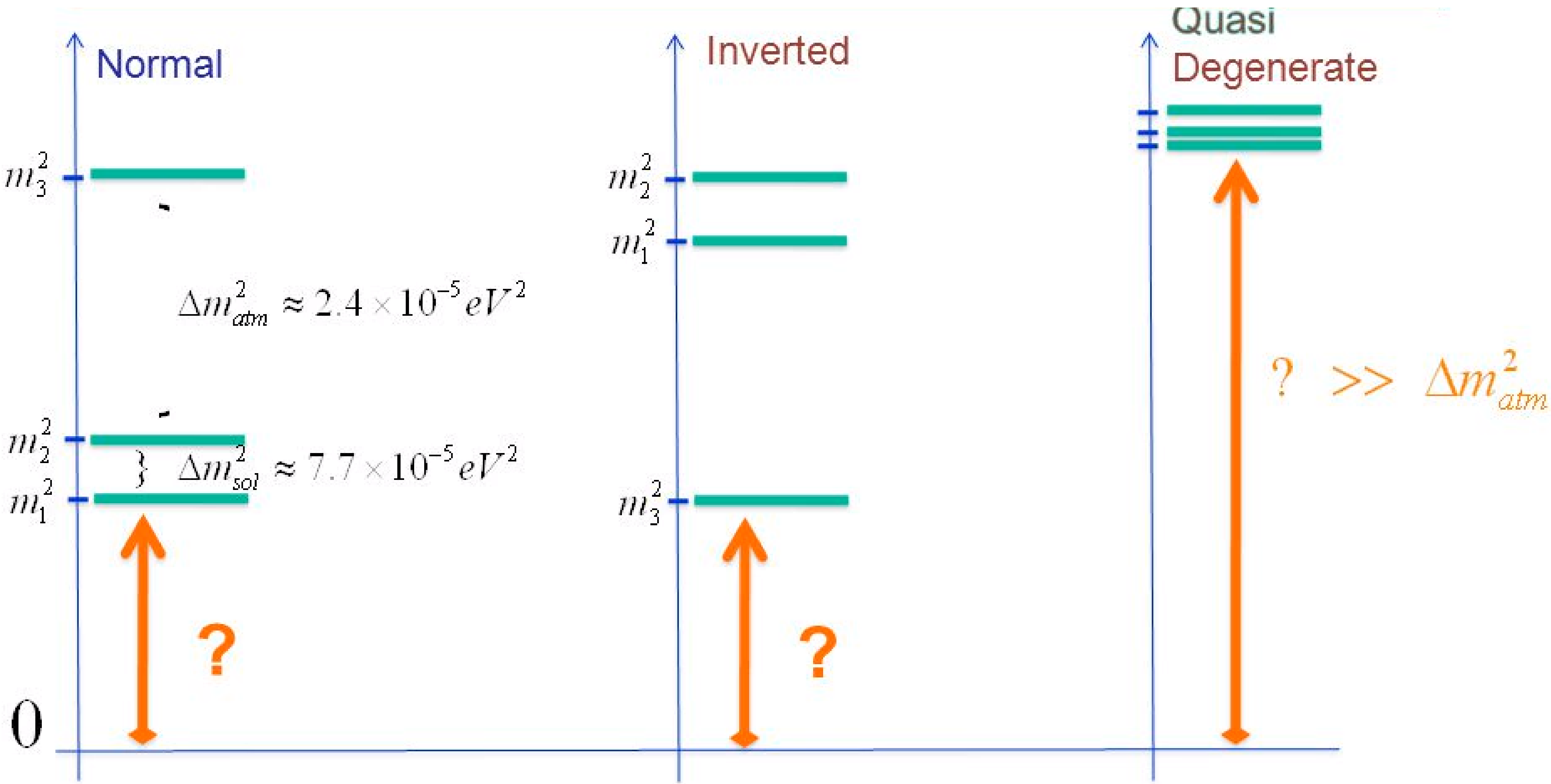
Open questions

What is the mass of the lightest neutrino ?

From **oscillations we only know the squared mass differences** but … **how light is the lightest neutrino** ? It could be zero in principle!

The 2nd lightest neutrino must be at least $\sqrt{\Delta m^2_{sol}}$ (8 meV), the heaviest ~ $\sqrt{\Delta m^2_{atm}}$ (50 meV).

They could also have rather similar masses (quasi-degenerate) if the lightest neutrino is much more massive than $\sqrt{\Delta m^2_{atm}}$ (i.e. ~ 1 eV).



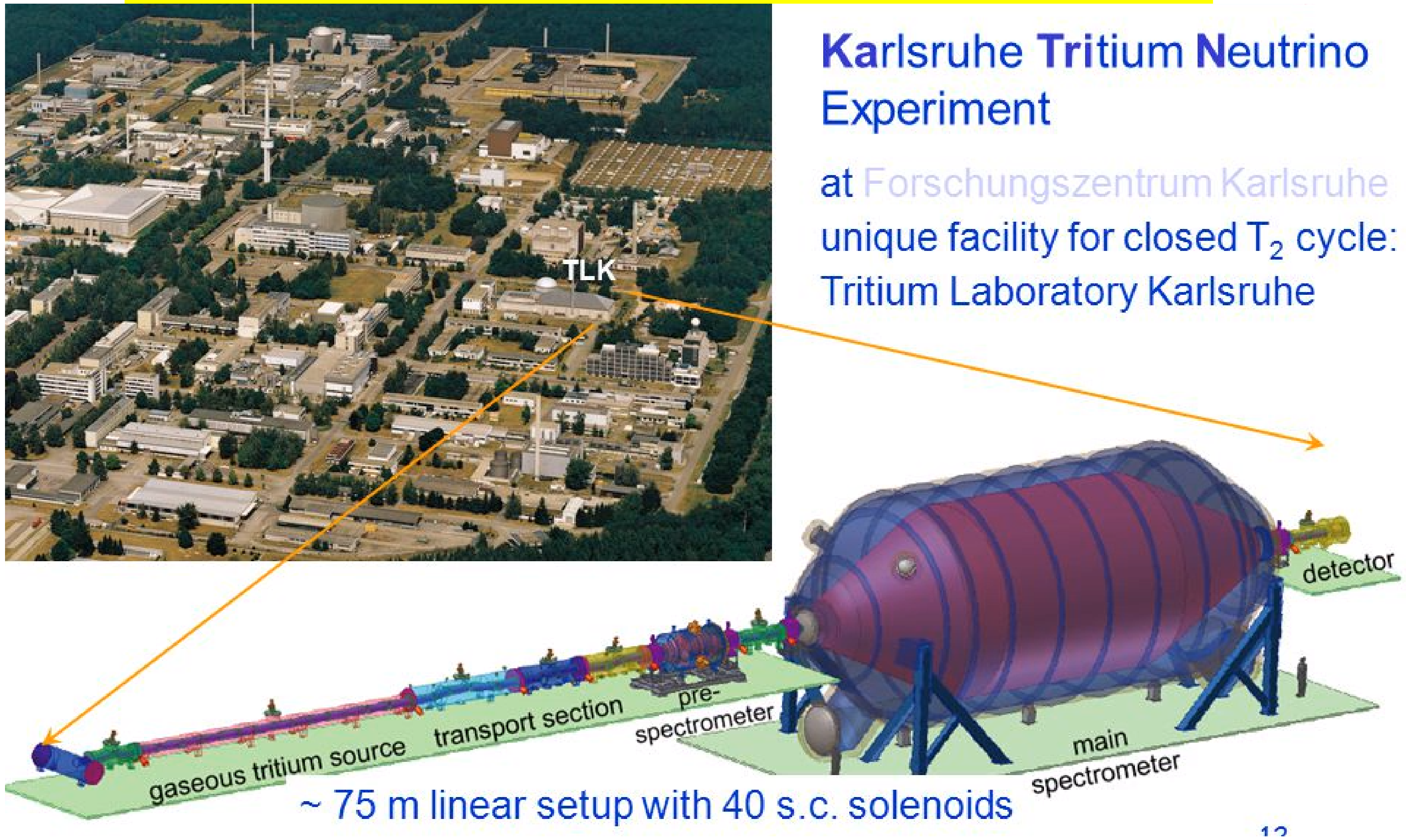
Open questions

As we saw Pauli had already understood that the neutrino had to be light from the energy of the electrons in beta decays → the same old/solid idea is used nowadays by pushing it to an extreme level of precision to set stringent constraints on the absolute neutrino mass.

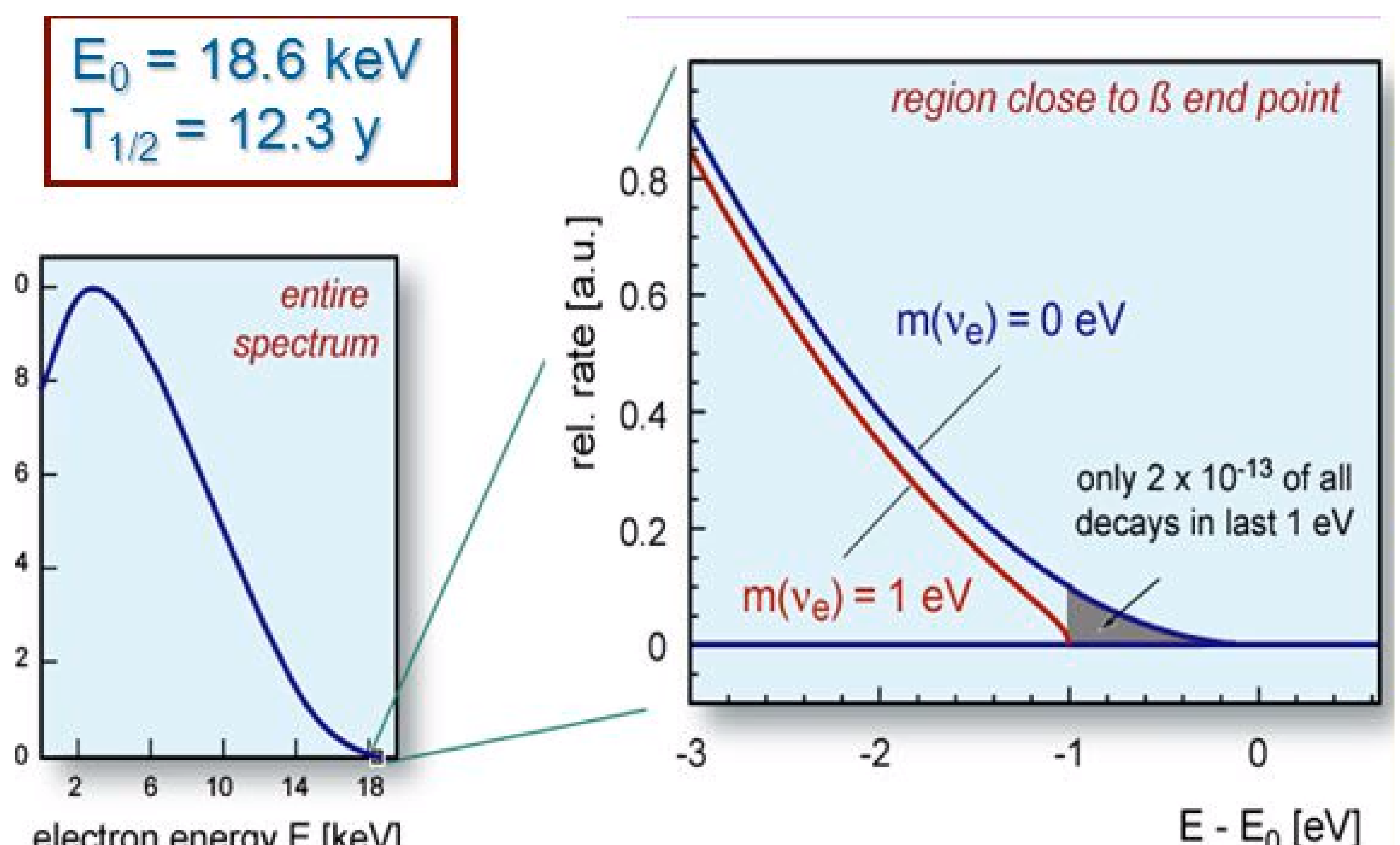
The **KATRIN experiment**

$$^{3}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + e^{-} + \bar{\nu}_e$$

What is the mass of the lightest neutrino ?



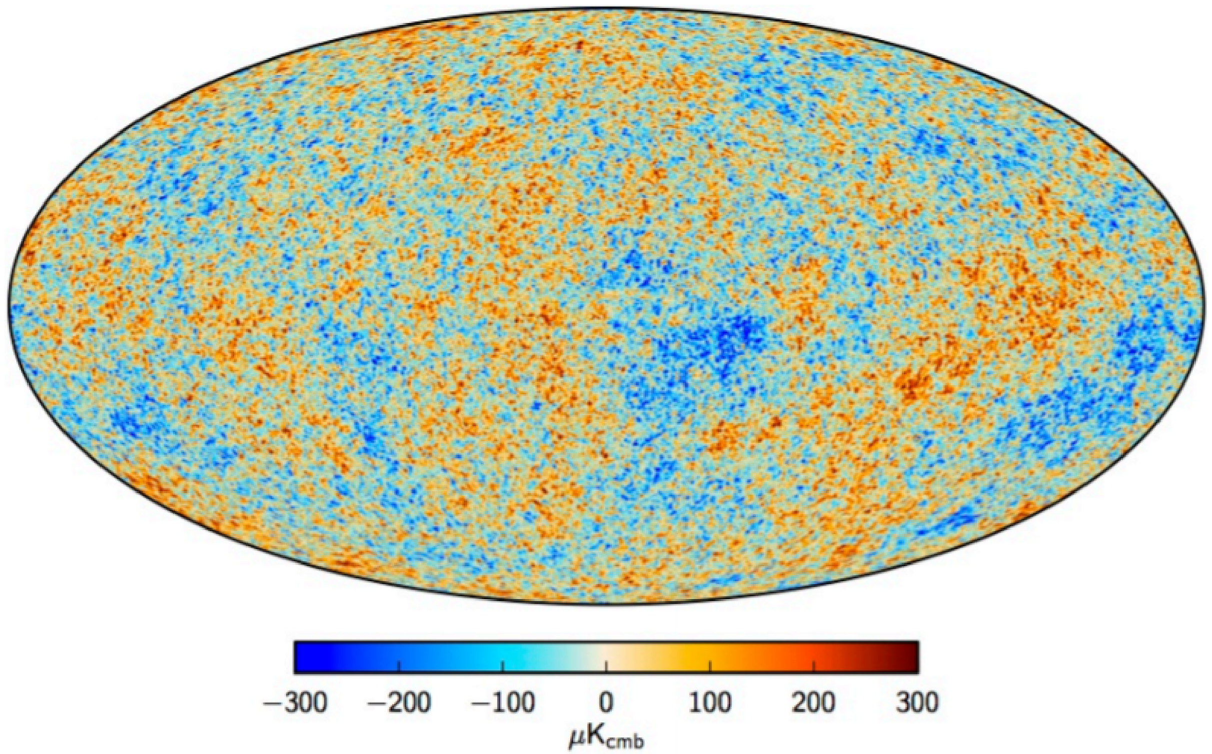
E_0 = 18.6 keV
$T_{1/2}$ = 12.3 y



Open questions

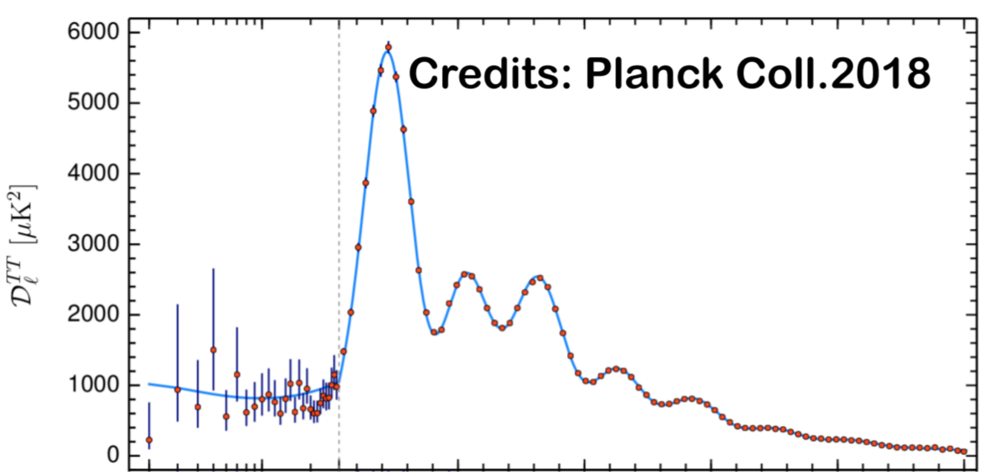
What is the mass of the lightest neutrino ?

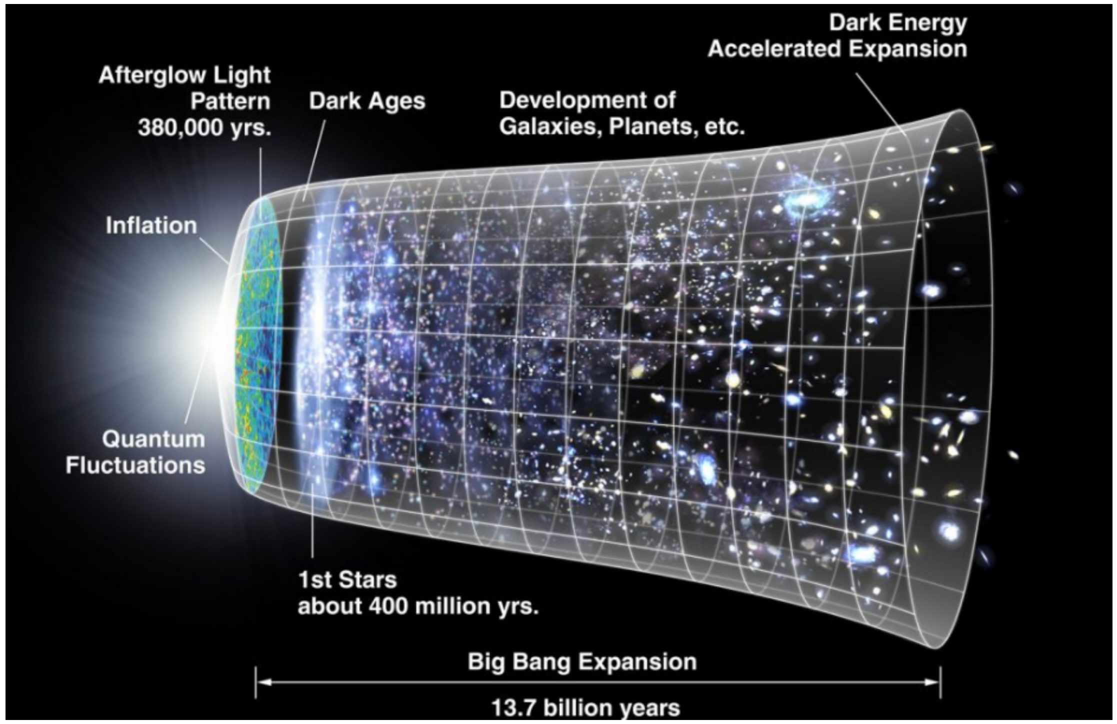
The Cosmic Microwave Background



The CMB is a blackbody radiation with T=2.7 K extremely uniform across the whole sky; it is the relic radiation emitted at the time the nuclei and electrons recombined to form neutral hydrogen, when the Universe was ~ 400,000 years old (the so-called last scattering surface, LSS).

Its tiny (~ 10^{-5}) temperature and polarization anisotropies encode a wealth of cosmological information.





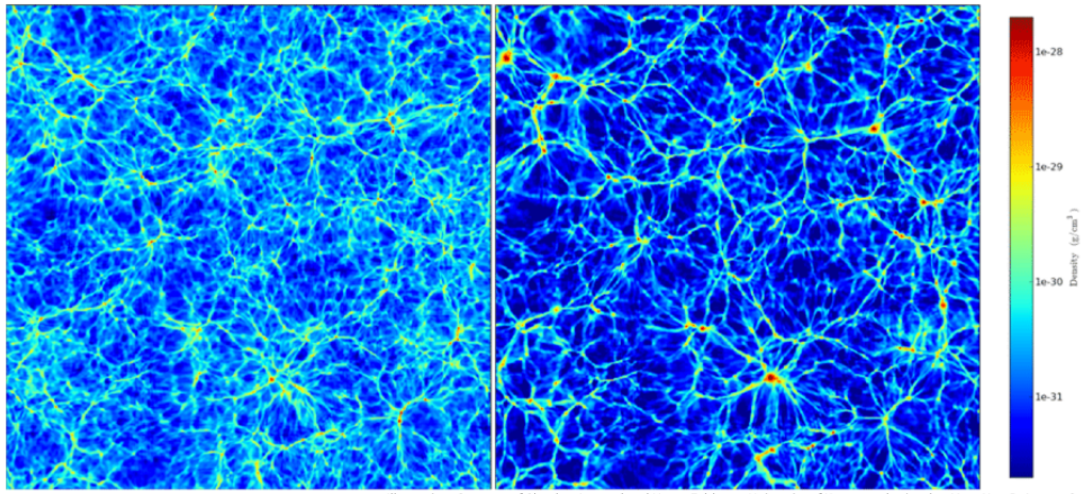


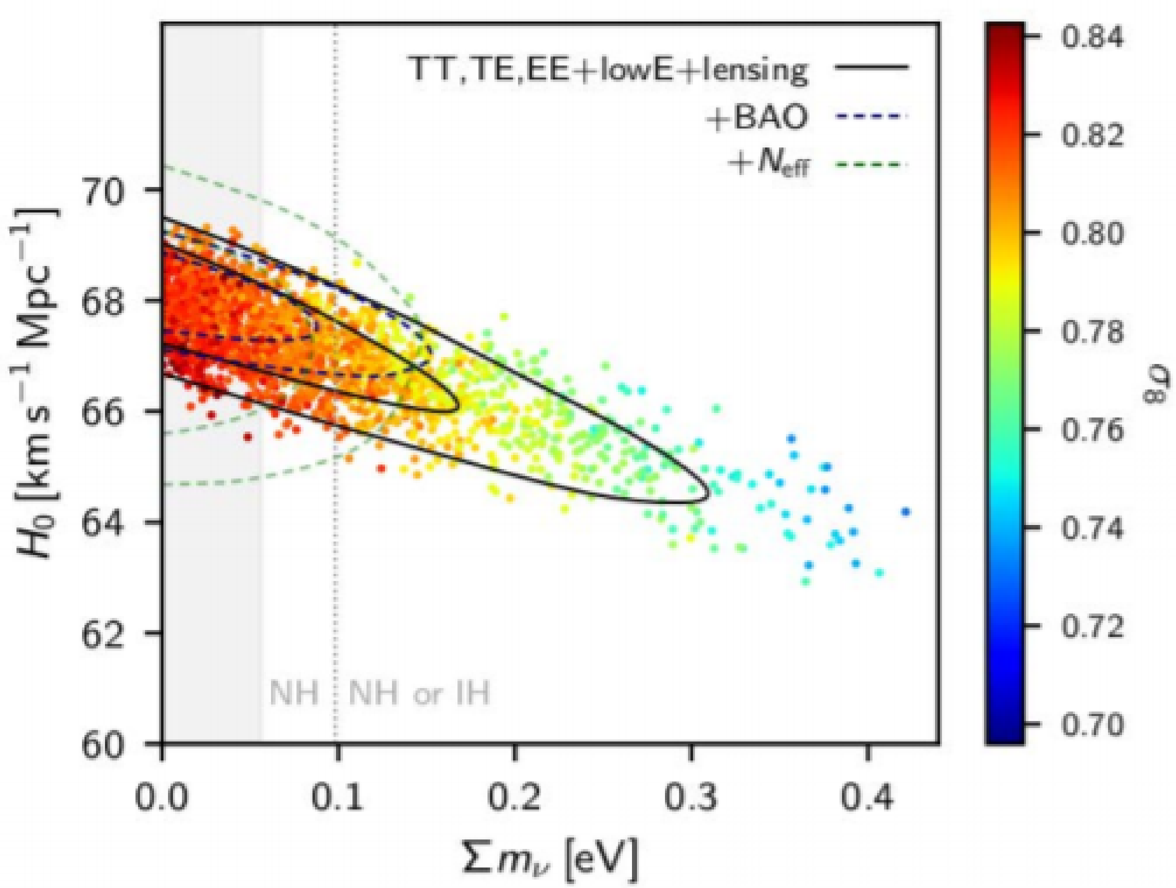
Illustration: Courtesy of Shankar Agarwal and Hume Feldman, University of Kansas; submitted to Mon. Not. R. Astron. Soc.

Figure 1: Comparison of density distribution in the Universe with (left) and without (right) massive neutrinos. The maps are based on numerical simulations [8]. The colors account for the density of ordinary (baryonic) matter in one slice of the simulation box [9]. The two simulations started from the same initial conditions, with either $M_\nu = 0$ (right) or $M_\nu = 1.9$ eV (left). In the massive neutrino case, matter is spread over a larger number of structures and there is less density contrast. (The unrealistically large neutrino mass of 1.9 eV was chosen so as to make the comparison clear.)

Open questions

What is the mass of the lightest neutrino ?

Neutrino legacy of Planck: Σm_ν



- Tightest constraint from a single experiment
- First constraint exploiting the information encoded in the CMB weak lensing
- One order of magnitude better than present kinematic constraints, already at the same level than future expectations for KATRIN
- The combined limits from Planck and large scale structure probes are starting to corner the inverted hierarchy scenario

$m_\nu < 0.44$ eV (95%CL, TT + lowE + lensing)

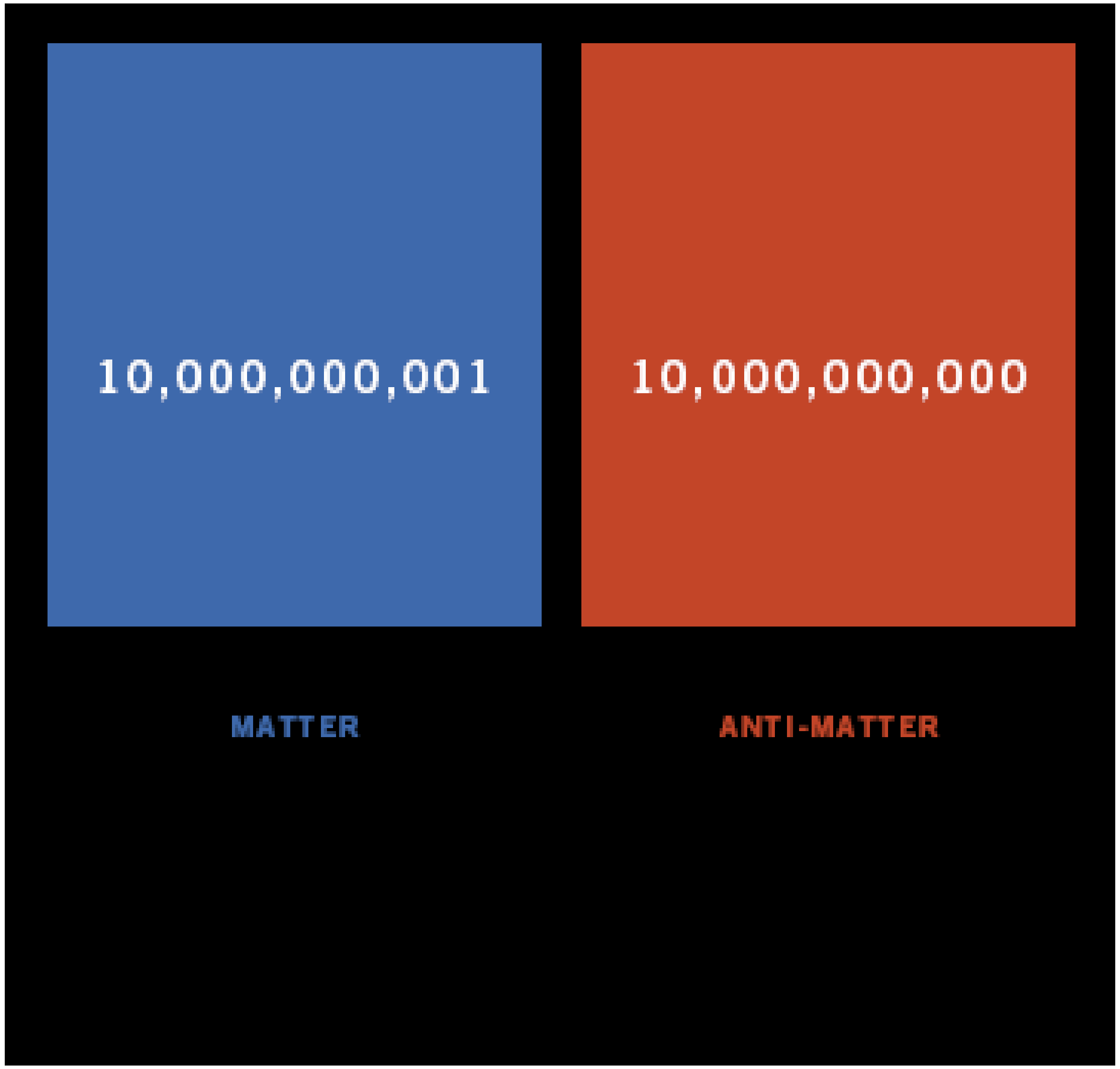
$m_\nu < 0.13$ eV (95% CL, TT+lowE+lensing+BAO)

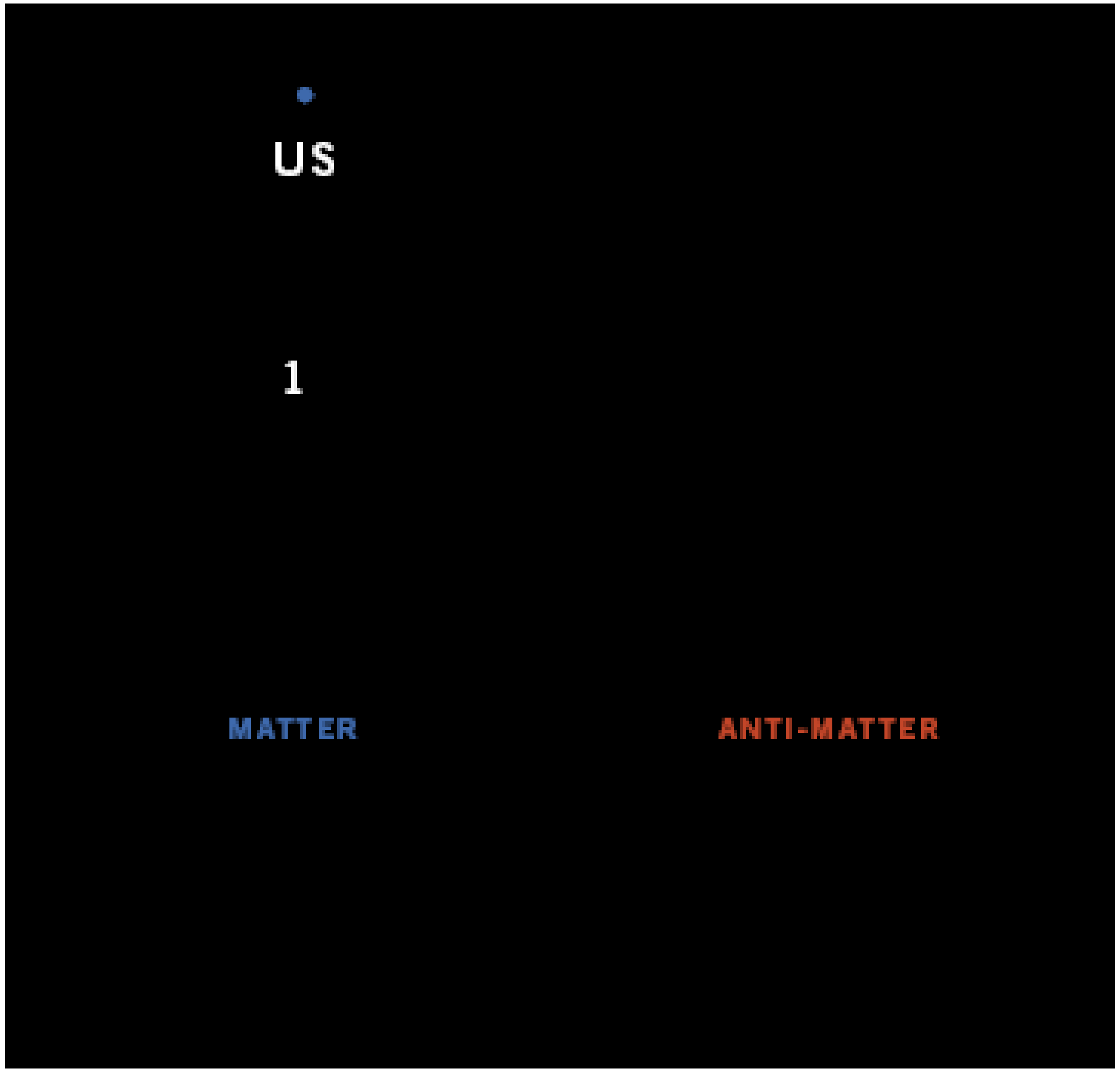
Open questions

Could the origin of the matter-antimatter asymmetry in the universe be related to neutrinos?

Open questions

Could the origin of the matter-antimatter asymmetry in the universe be related to neutrinos?





Open questions

Could the origin of the matter-antimatter asymmetry in the universe be related to neutrinos?

There is room for much larger **"CP violating"** effects than for quarks (already well studied and not sufficient).

How ? → **Study very precisely how muon neutrinos transform into electron neutrinos during the propagation over hundreds of km**.

$$\mathcal{A}_{CP} = \frac{\mathcal{P}_{\nu_\mu \to \nu_e} - \mathcal{P}_{\bar{\nu}_\mu \to \bar{\nu}_e}}{\mathcal{P}_{\nu_\mu \to \nu_e} + \mathcal{P}_{\bar{\nu}_\mu \to \bar{\nu}_e}}$$

Some hints already at present experiments (T2K, NOvA).Future large experiments HyperKamiokande and DUNE will mainly measure this

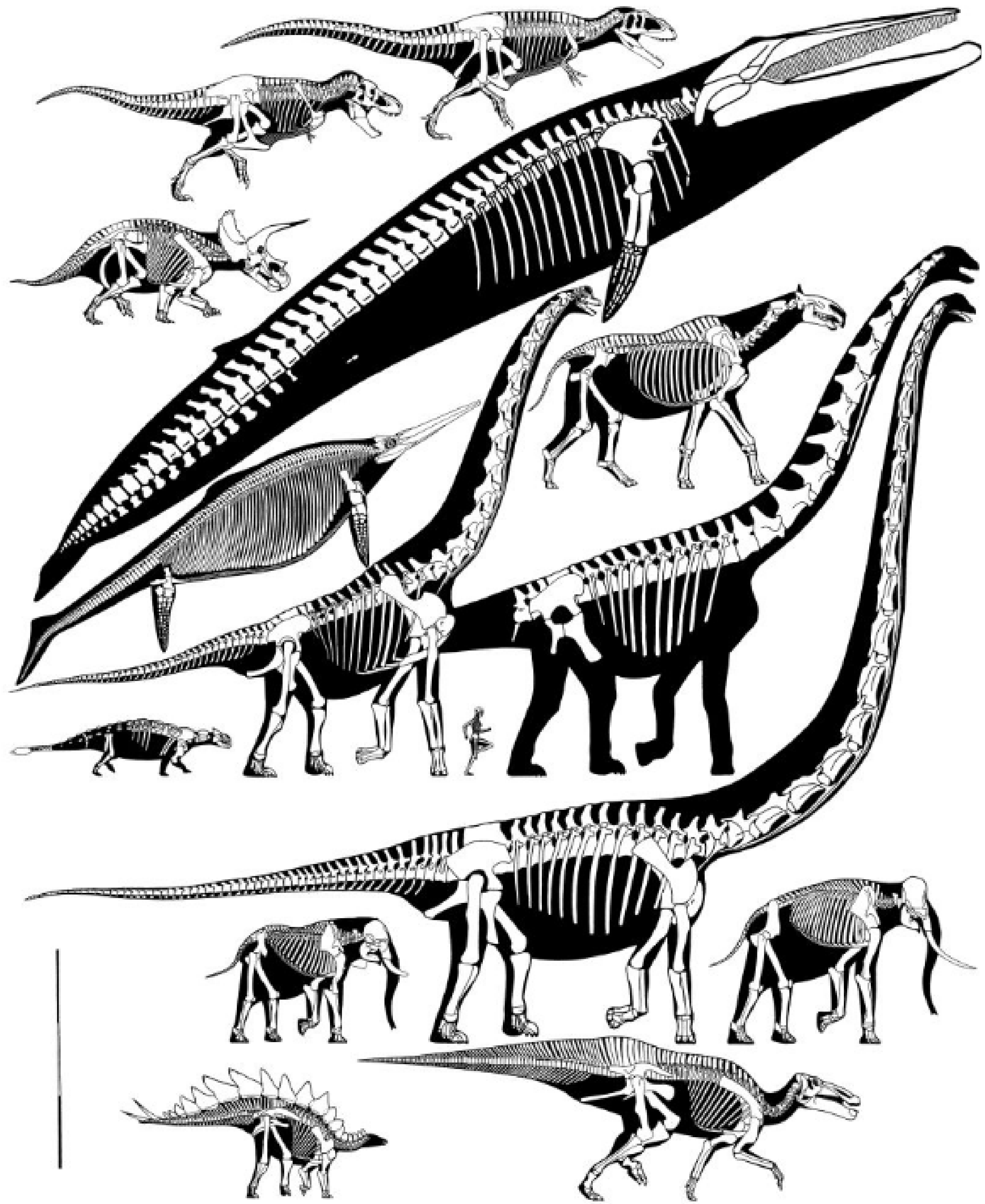
The "leptogenesis theory" explains how this asymmetry could be reflected into the asymmetry of baryons (~quarks) that we observe today (lepton→ baryon asymmetry)

This program received a tremendous boost in 2012 when the parameter $\theta_{13} \neq 0$ was measured to be quite large. It seems nature is being quite generous towards the curiosity of neutrino physicists :)

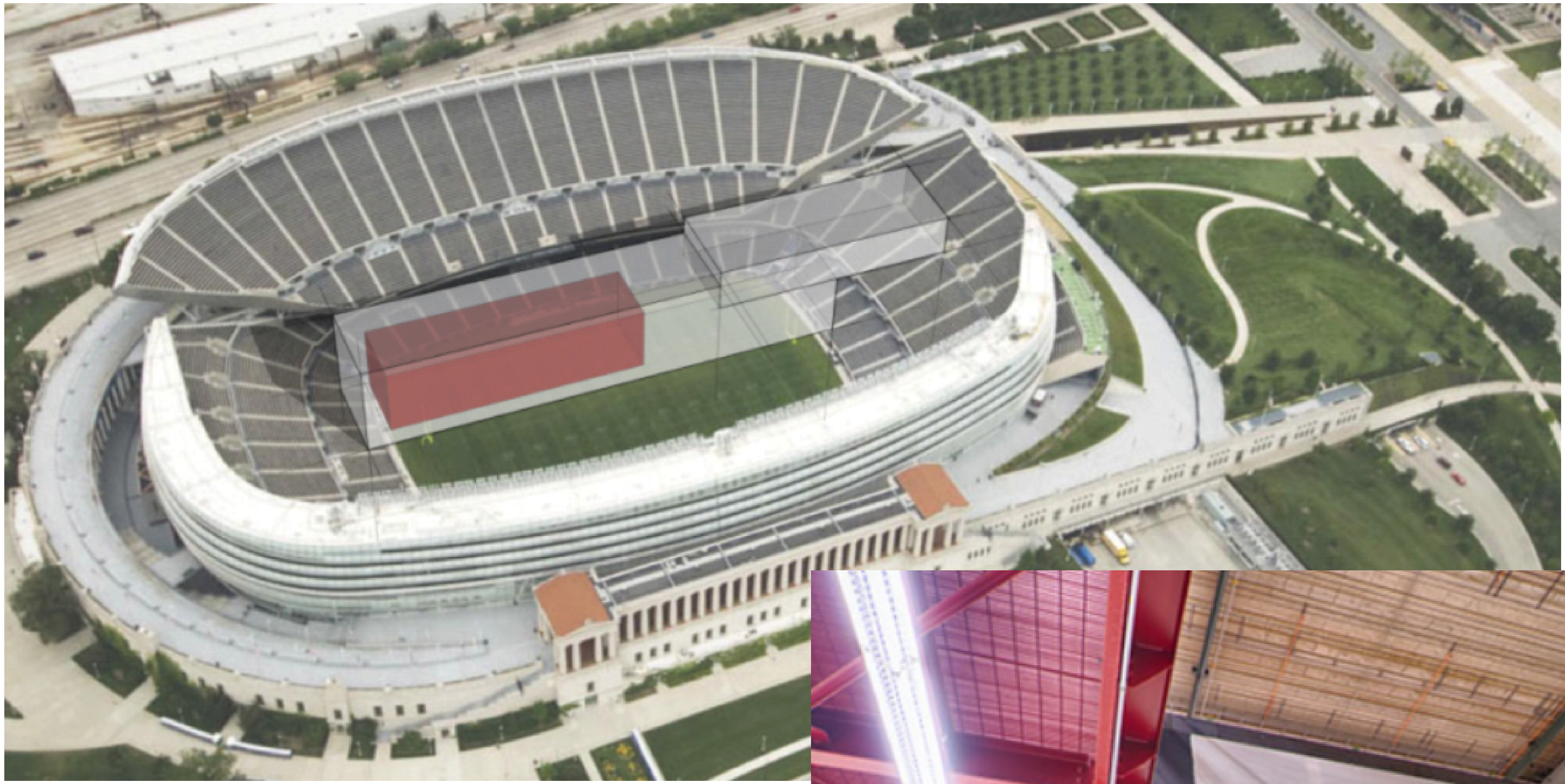
The age of neutrino gigantism

Large mass (**~100 kt**) +
Long baseline (**100-1000 km**)
MW power neutrino beams

Neutrino experiments have never been “table-top” (maybe just at beta decay times)... but this tendency is ramping up! →



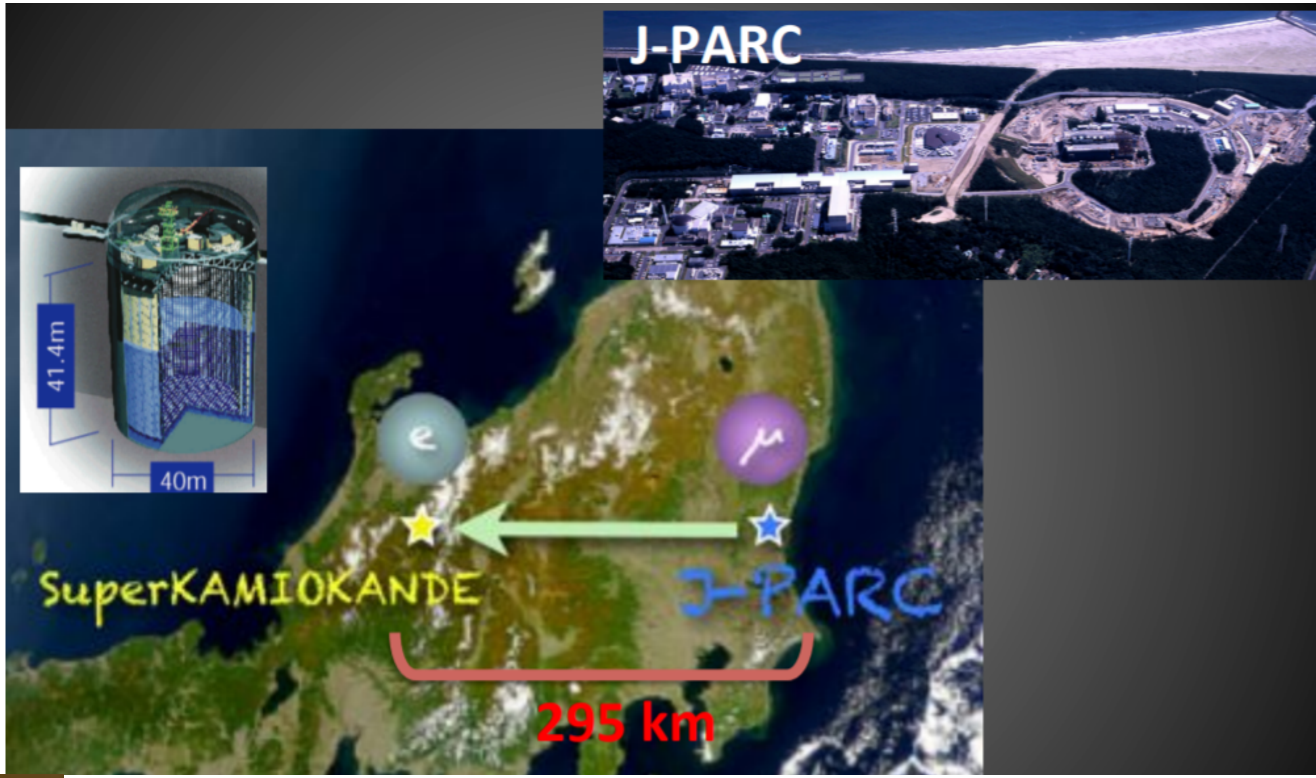
The NOvA experiment

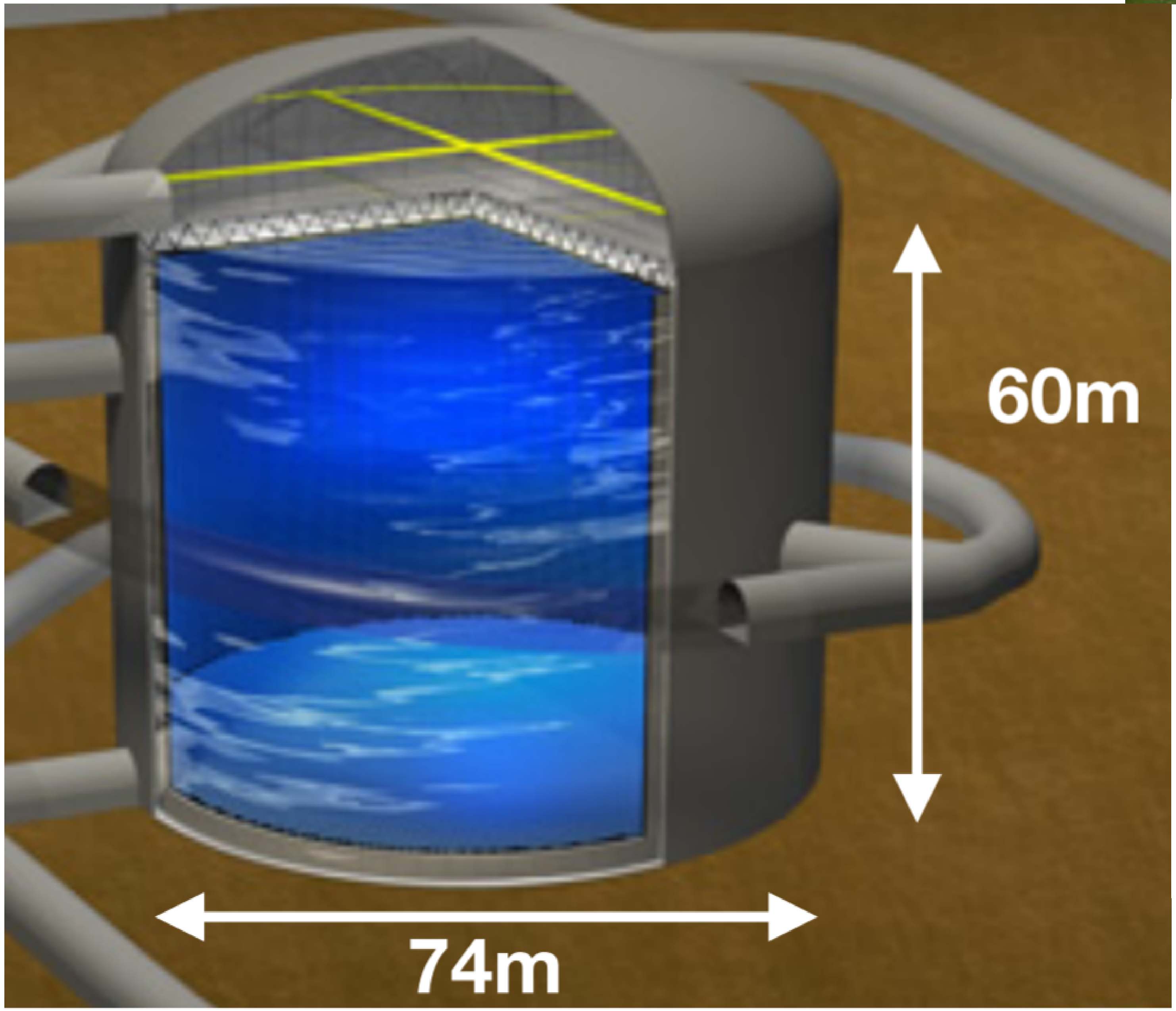


14000 ton of scintillator bars at 810 km from the source

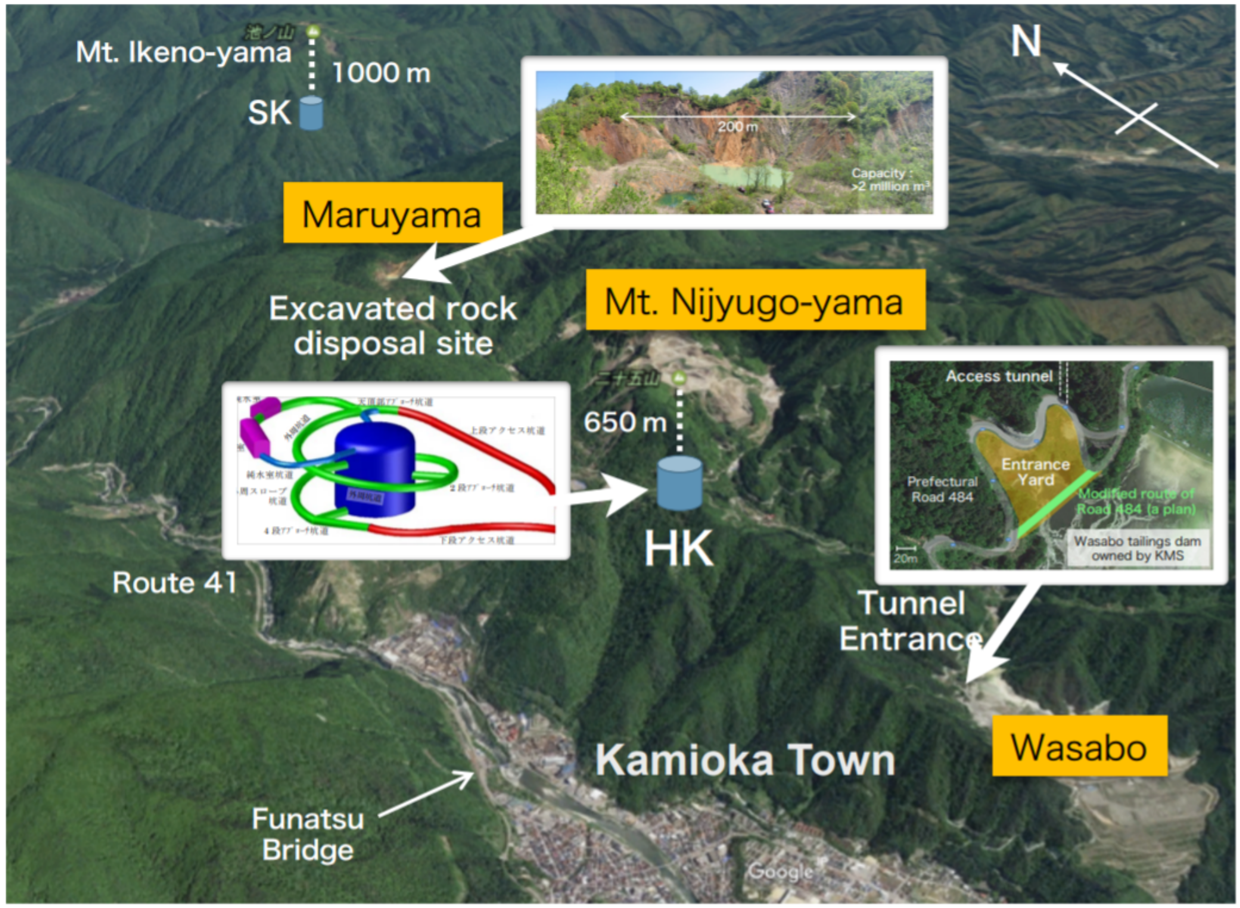
The Hyper-Kamiokande project

190 kton mass (~8 x SuperKamiokande)
1.3 MW neutrino beam from the pacific coast
295 km baseline

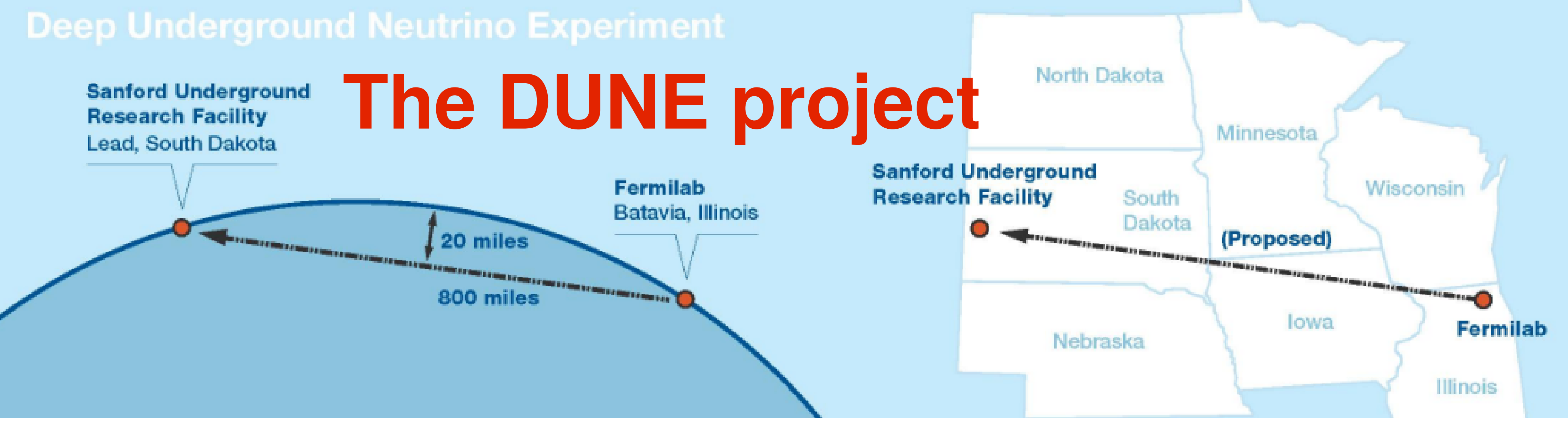




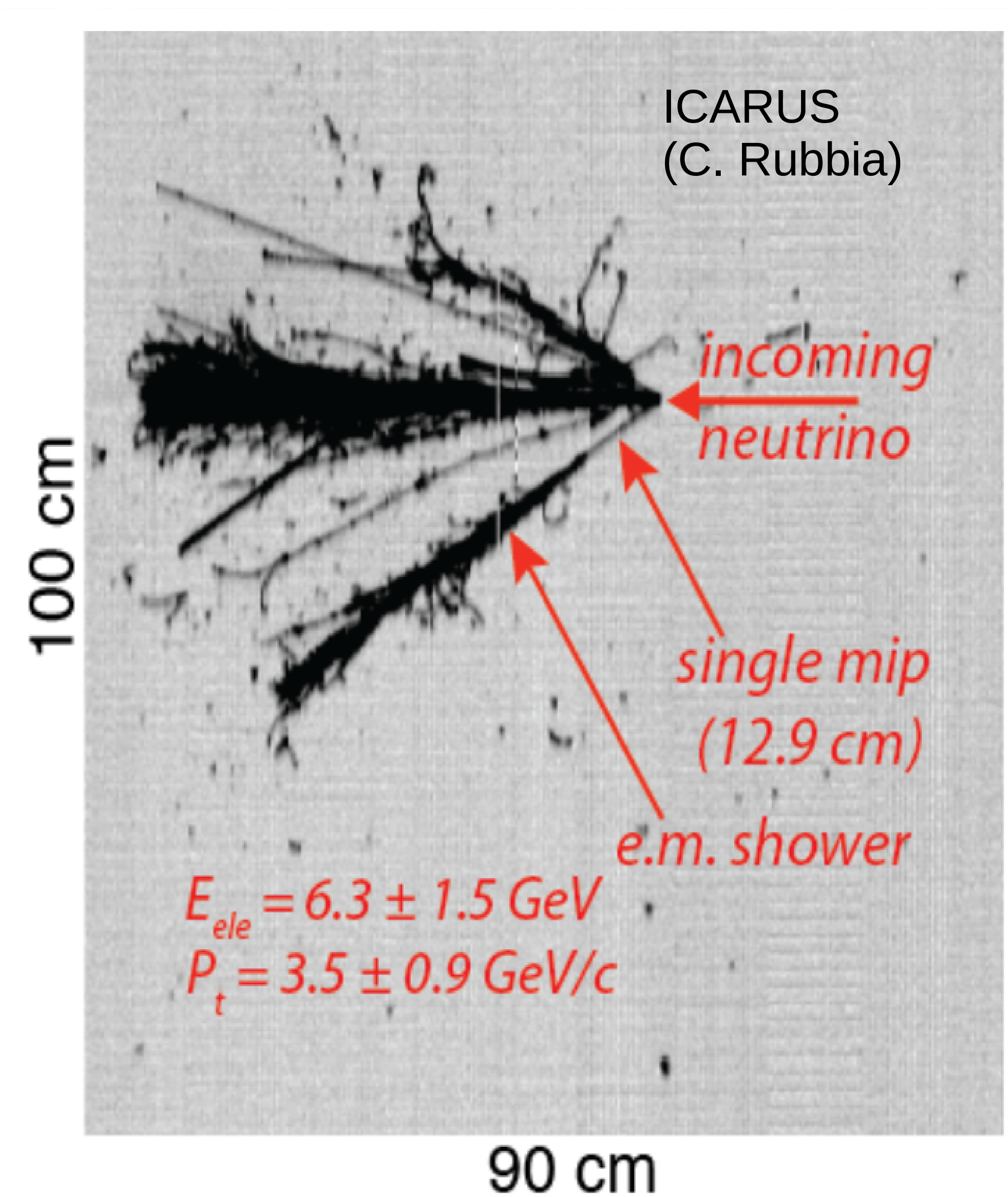
8 km south of Super-K
650 m rock overburden

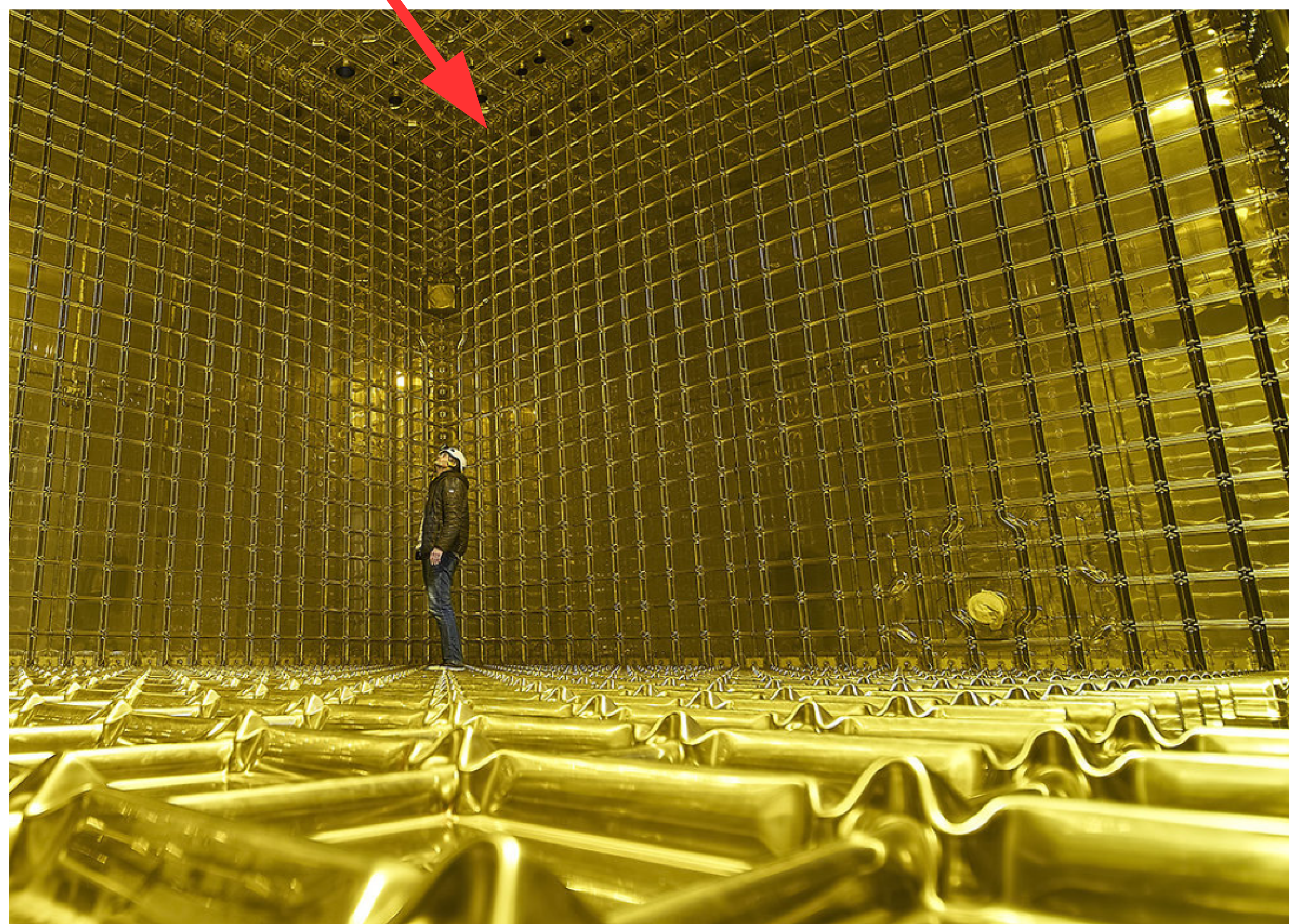


The DUNE project



Based on the **Liquid Argon Time Projection Chamber** detector technique. Can get large mass and **terrific views of neutrino interactions**! This is a prototype built at CERN (**protoDUNE SP cryostat**)



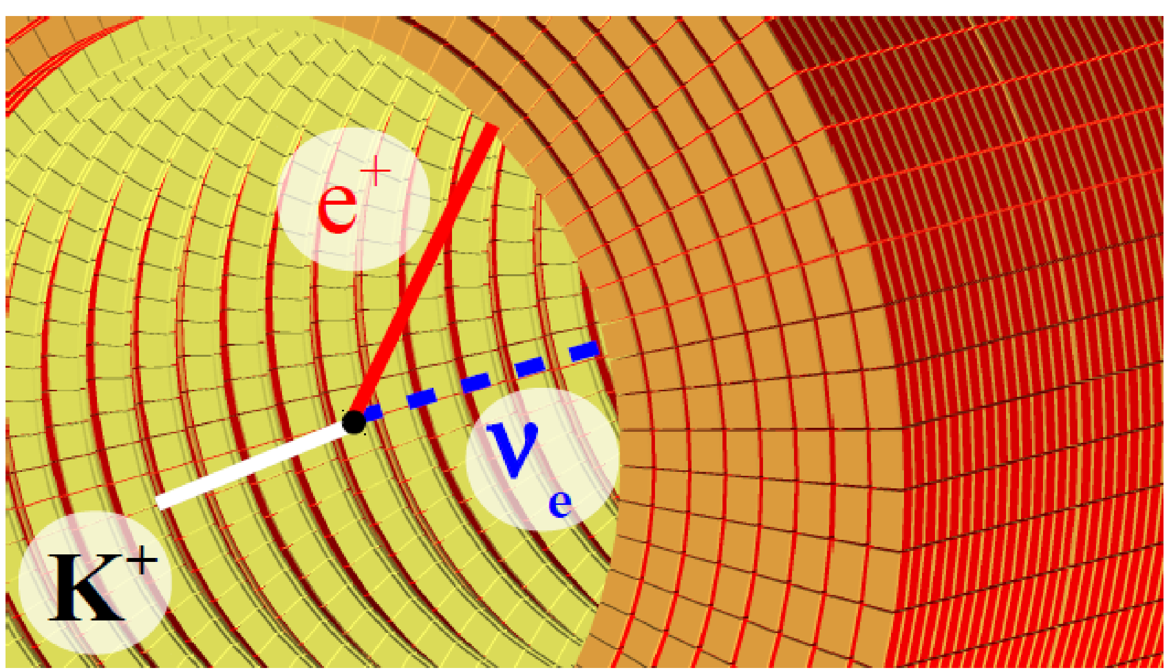


A day in the life ... of a neutrino physicist

Behind the scenes of the ENUBET ERC project …
a glimpse on what I am (we are) actually DOING!

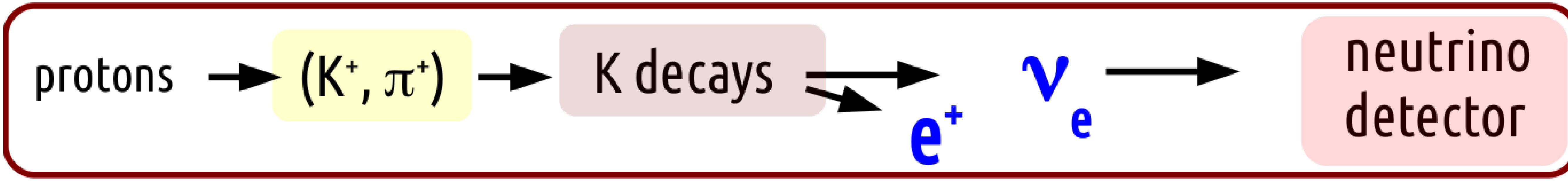
Enhanced NeUtrino
BEams from kaon Tagging

ERC-CoG-2015, G.A. 681647 (2016-21)
PI A. Longhin, **Padova University, INFN**



The idea: monitored beams!

Based on **conventional technologies**, aiming for a **1% precision on the ν_e flux**



- Monitor (~ inclusively) the **decays** in which ν are produced **event-by-event**
- "By-pass" **hadro-production**, **PoT**, **beam-line efficiency** uncertainties

- **Fully instrumented decay region**

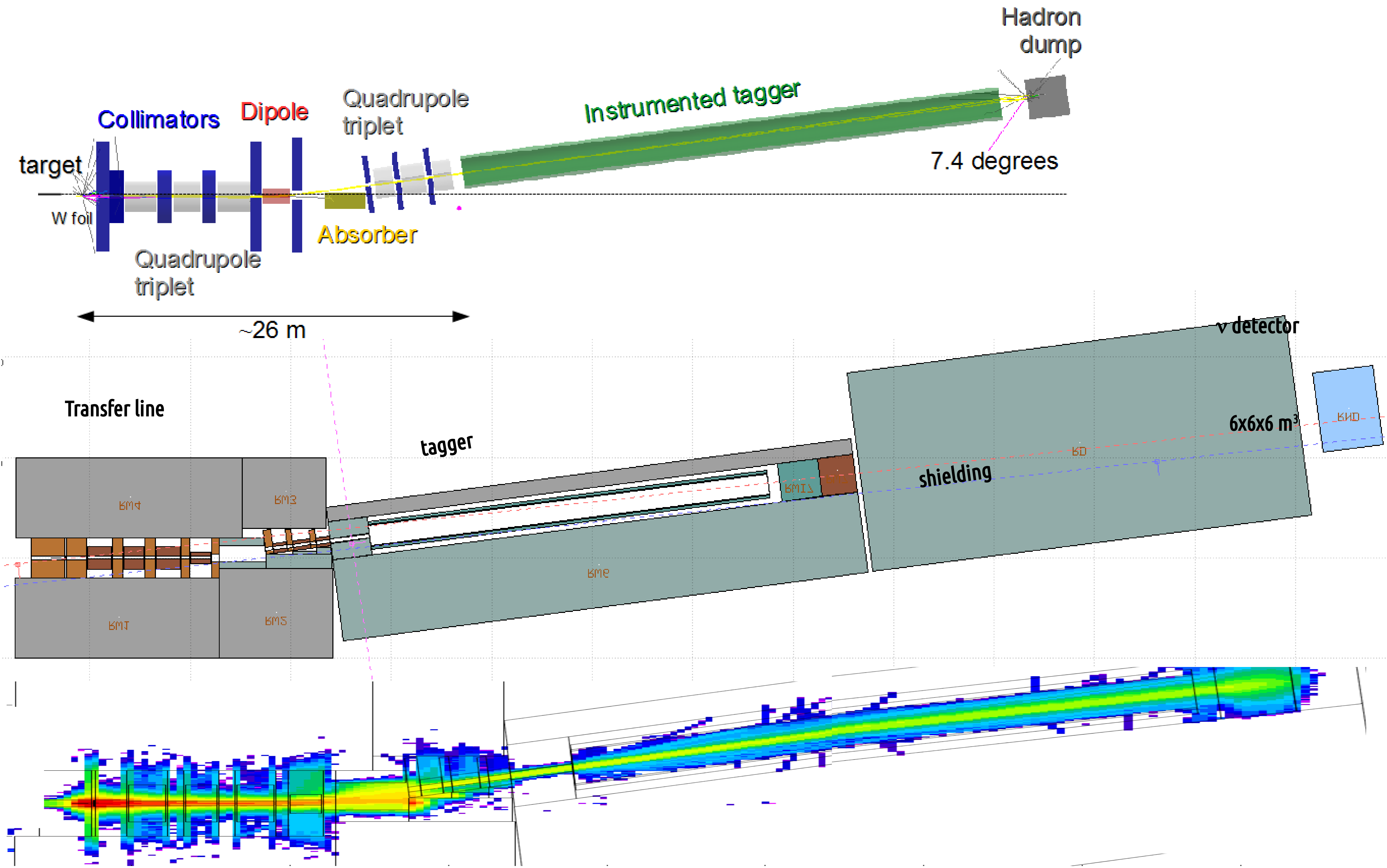
  $K^+ \rightarrow e^+ \nu_e \pi^0 \rightarrow$ large angle e^+

- ν_e **flux prediction = e^+ counting**

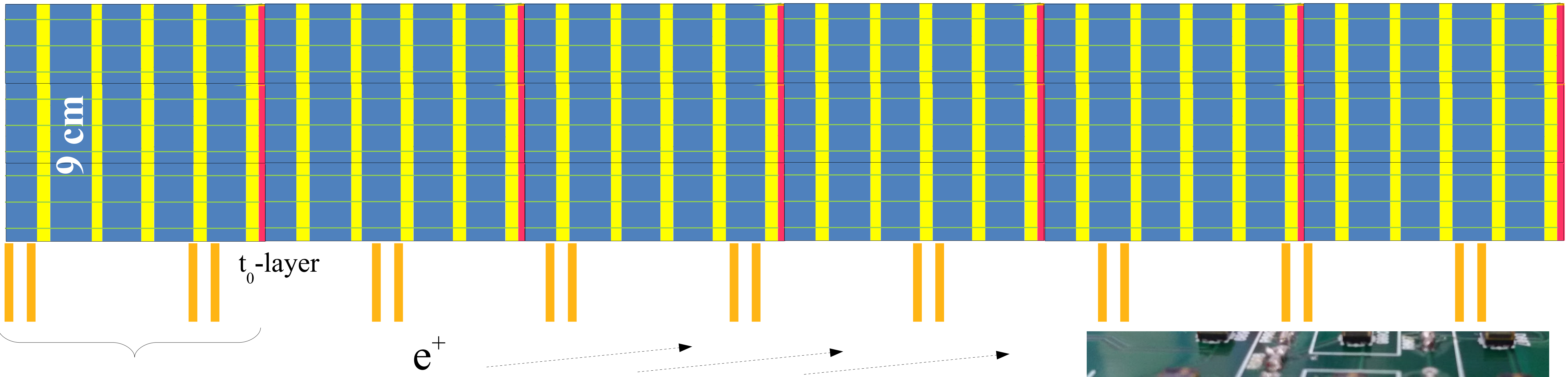
Removes the **leading source of uncertainty in ν cross section measurements**

To get the correct spectra and avoid swamping the instrumentation → needs a **collimated momentum selected hadron beam** → **only decay products in the tagger**
→ Correlations with interaction radius allows an **a priori knowledge of the ν spectra**

Simulation and design of particle beams

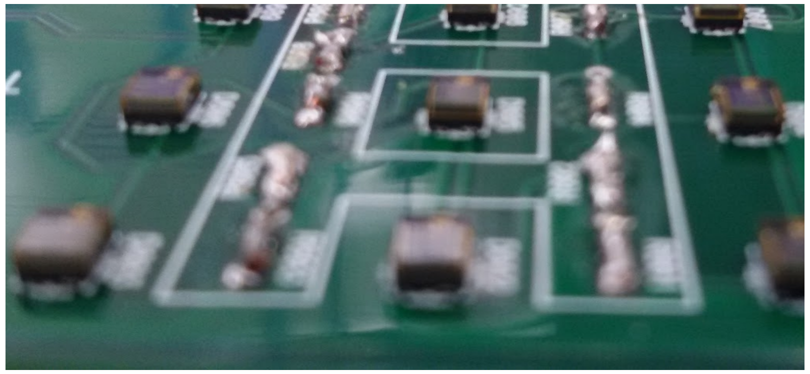


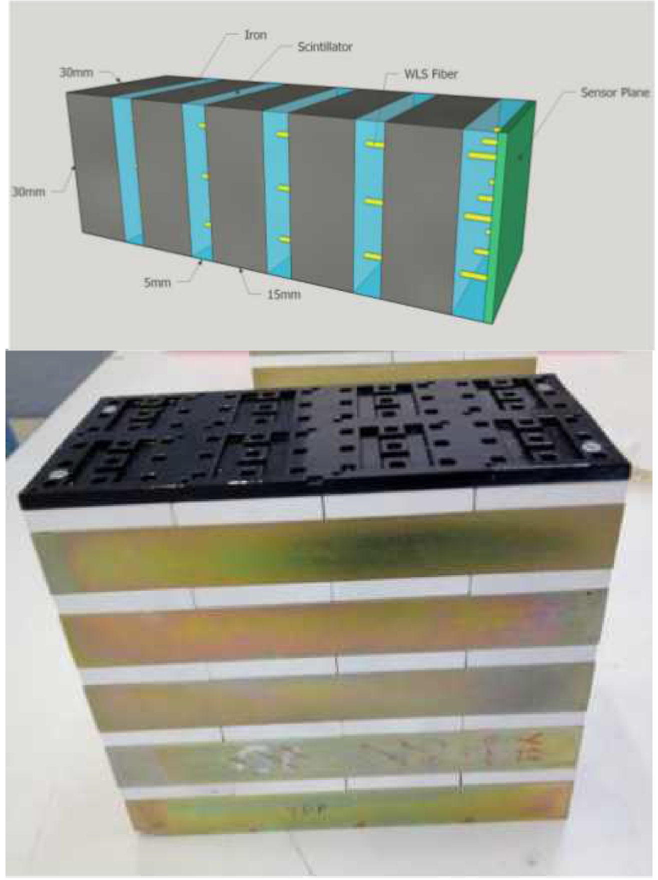
Construction and tests of particle detectors



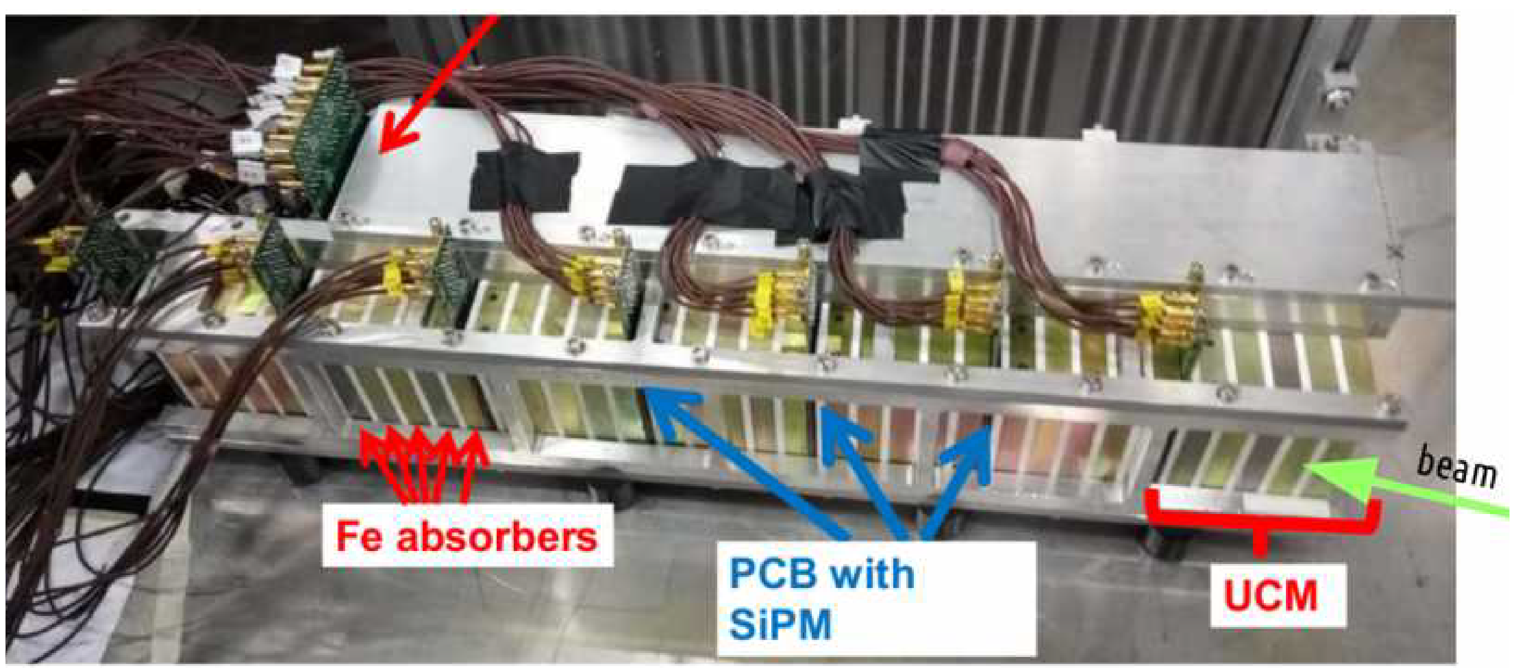
$10\ cm = 5\ X_0$

UCM: ultra compact module.
SiPM and electronics embedded in the shashlik calorimeter

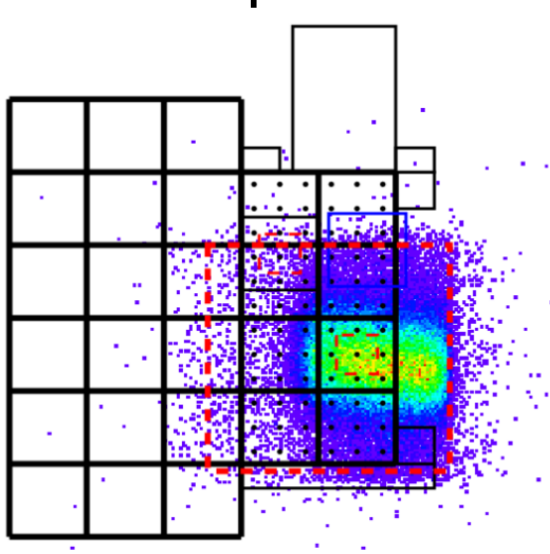




CERN PS test beam Nov 2016

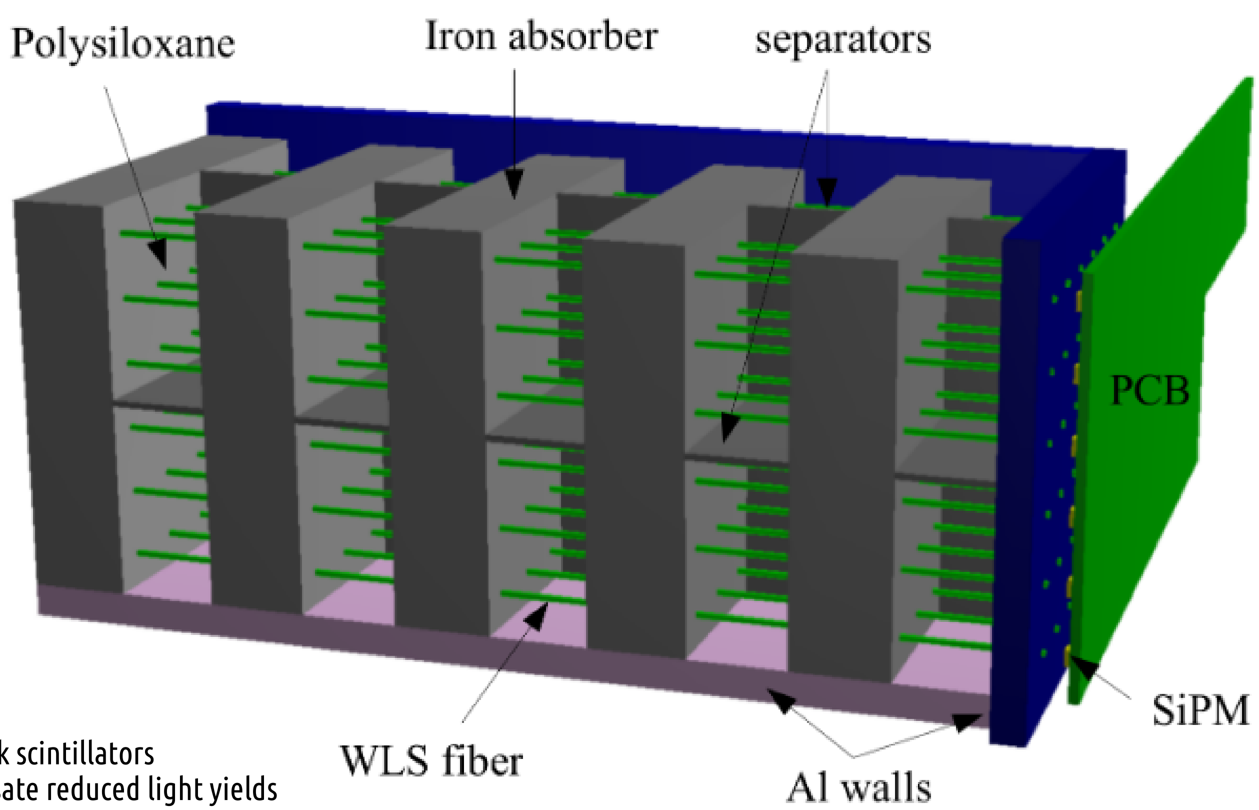


Beam spot

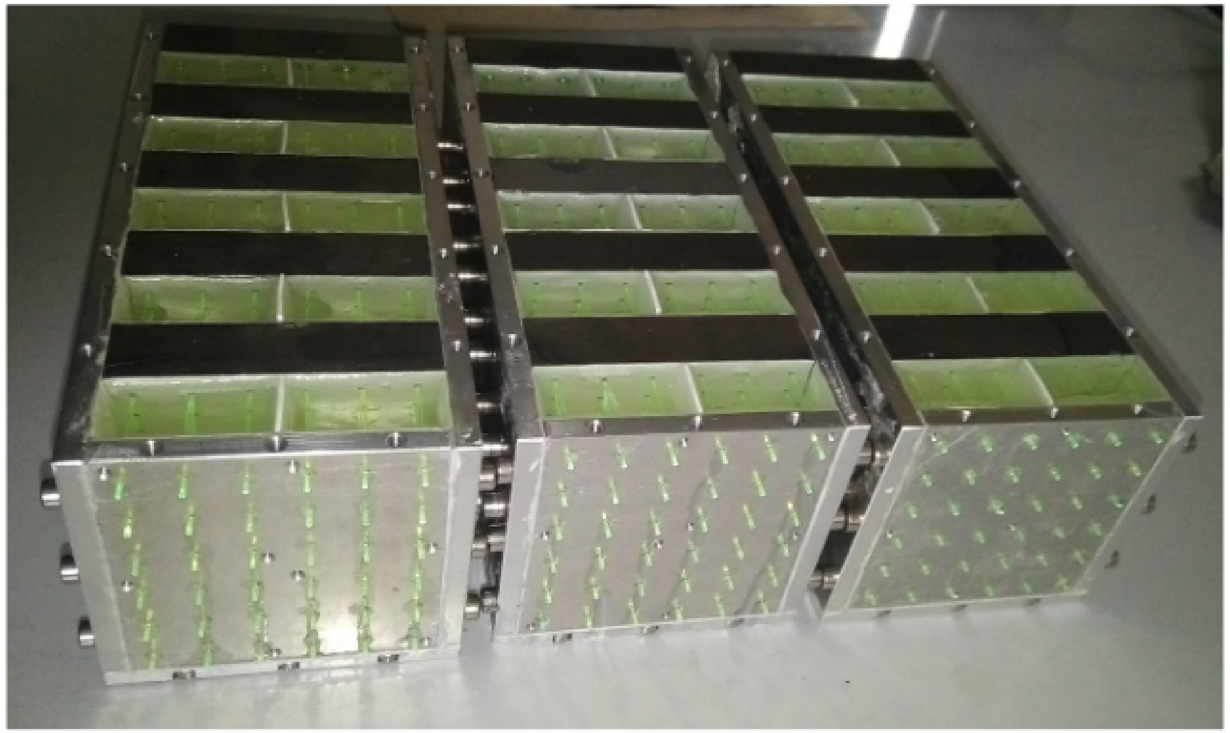


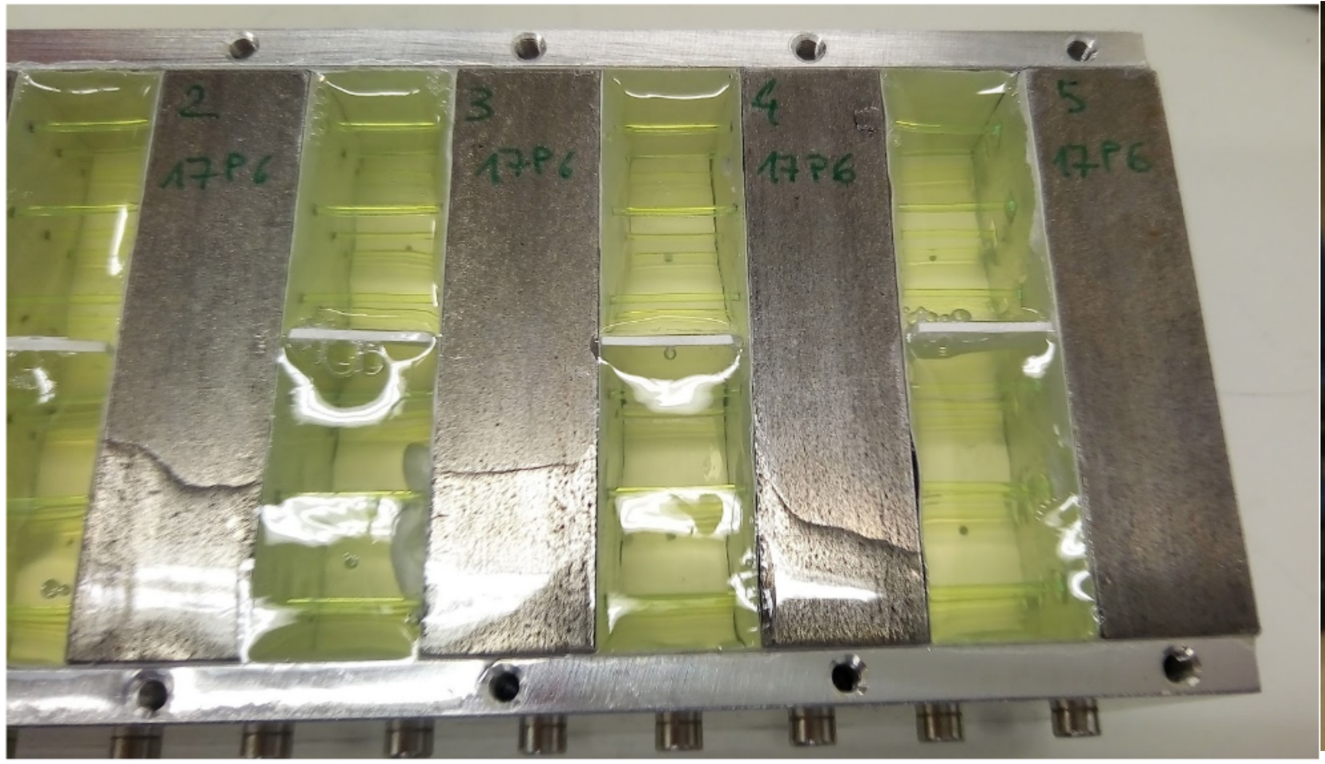
Construction and tests of particle detectors

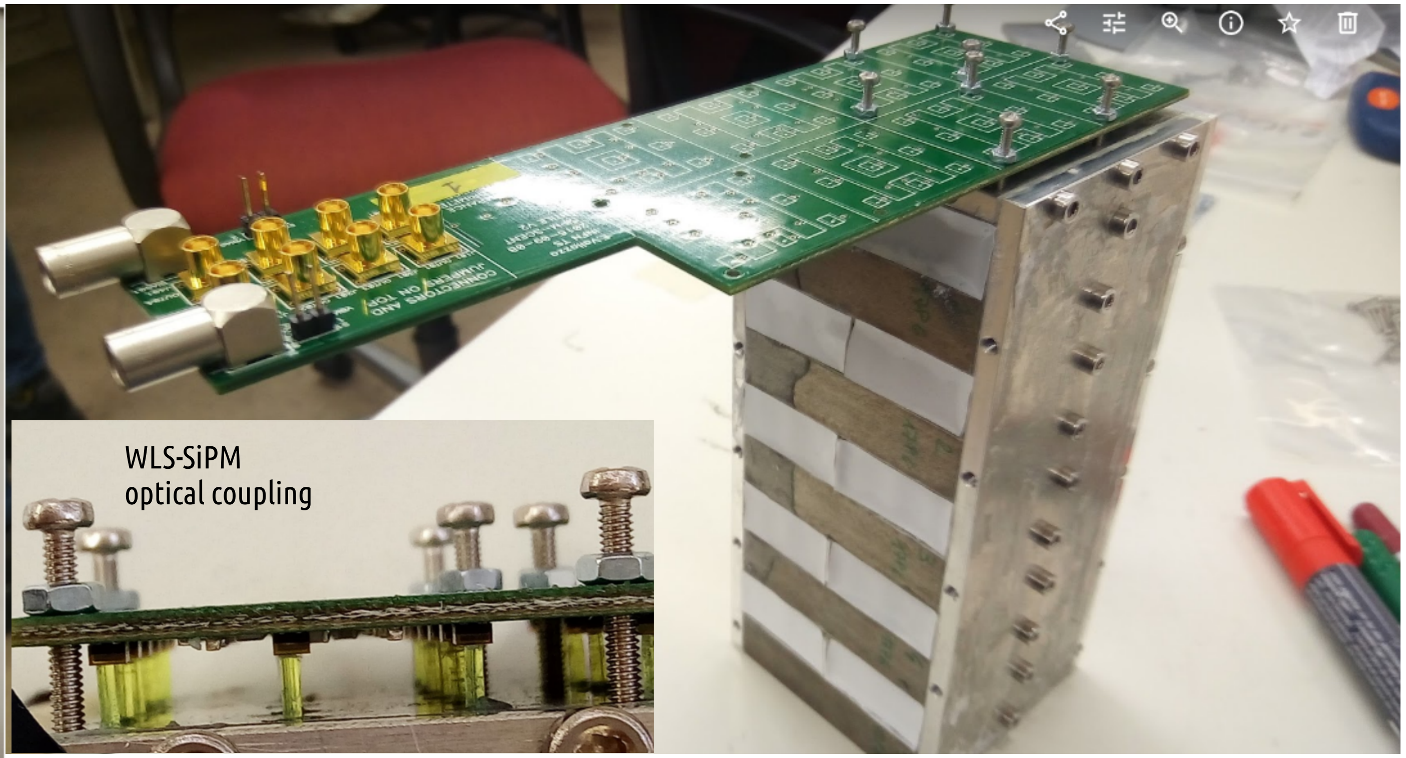
Pros : **increased resistance to irradiation** (no yellowing), **simpler** (just pouring + reticulation)
A **$13X_0$ shashlik prototype** tested in May 2018 and October 2017 (**first application** in HEP)



15 mm thick scintillators
to compensate reduced light yields



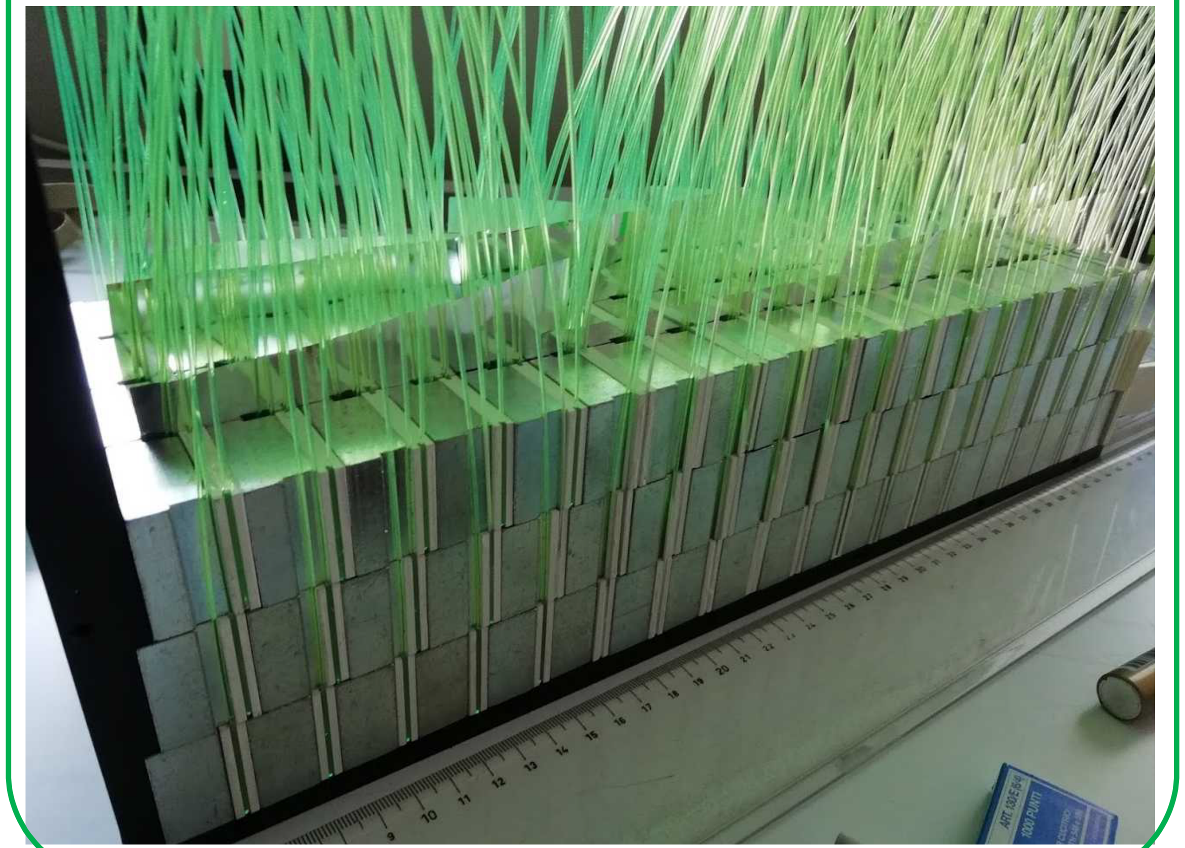




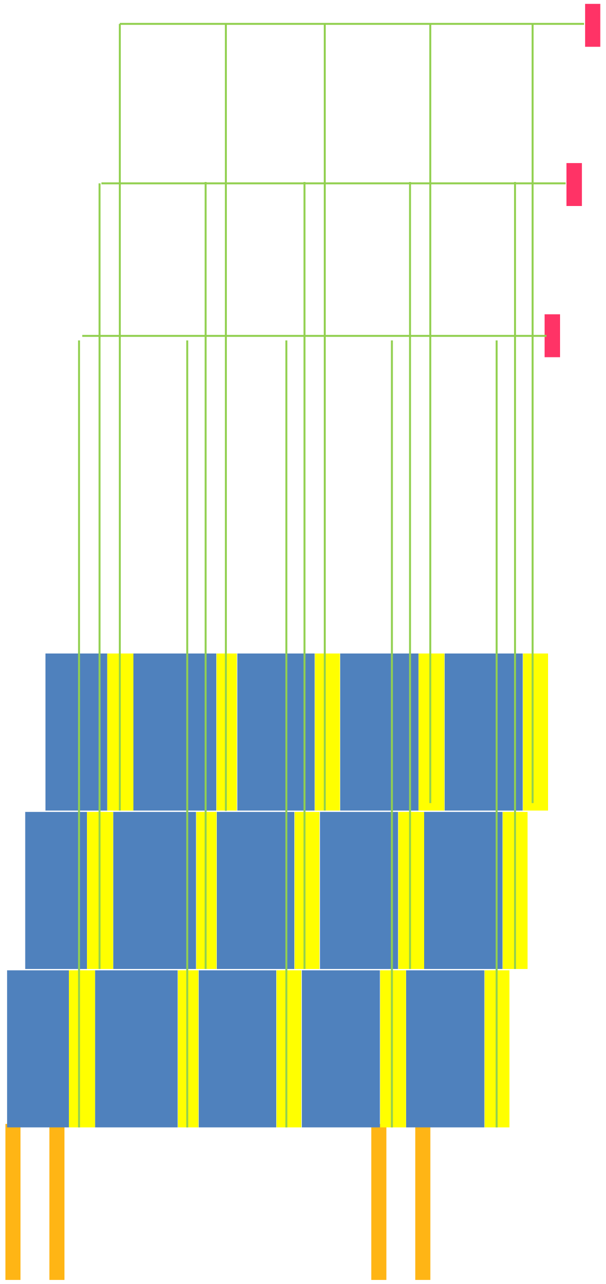
Construction and tests of particle detectors

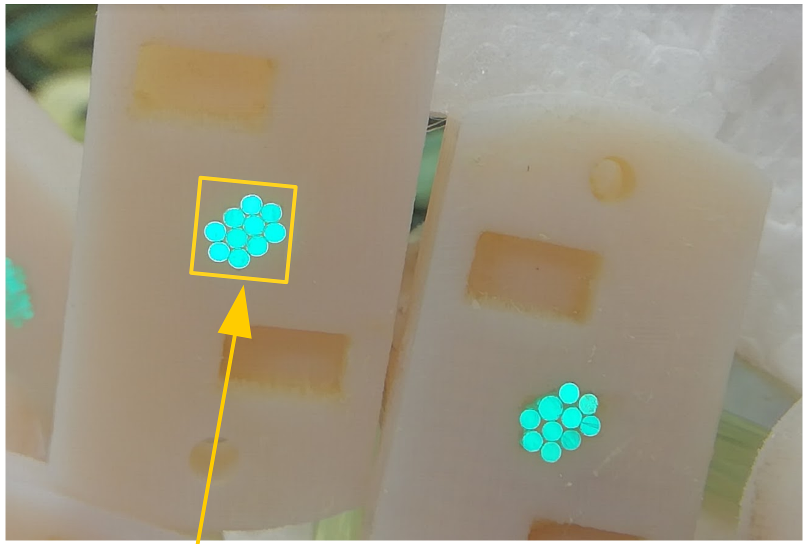
Tests at CERN or INFN Legnaro

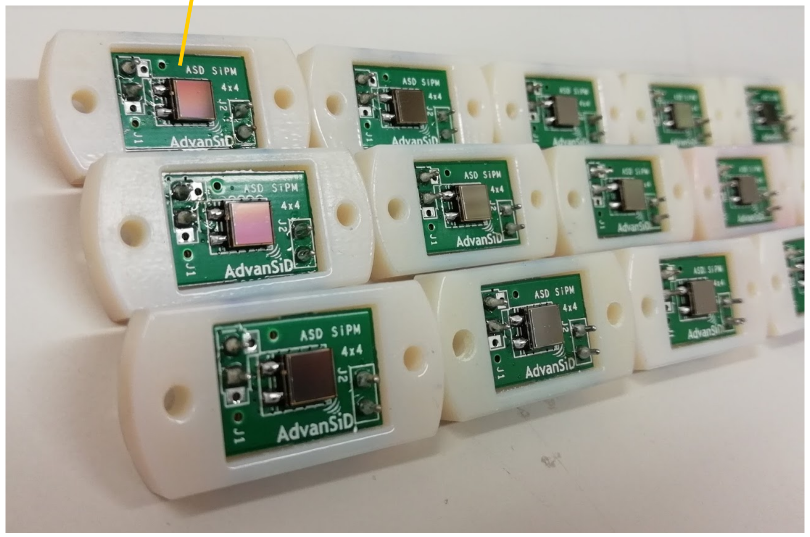
Sampling calorimeter with
lateral WLS light collection



May 2018, CERN-PS test beam





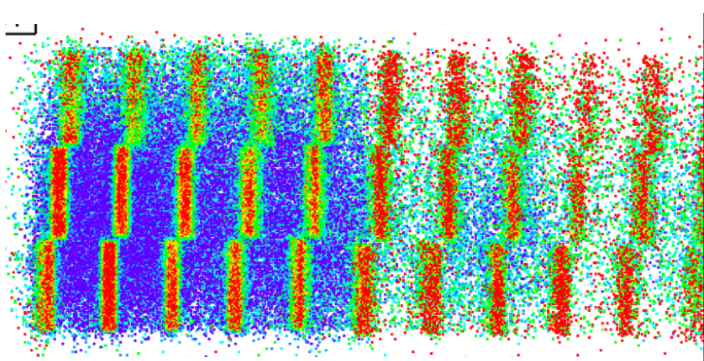


Large SiPM for 10 WLS
4x4 mm^2

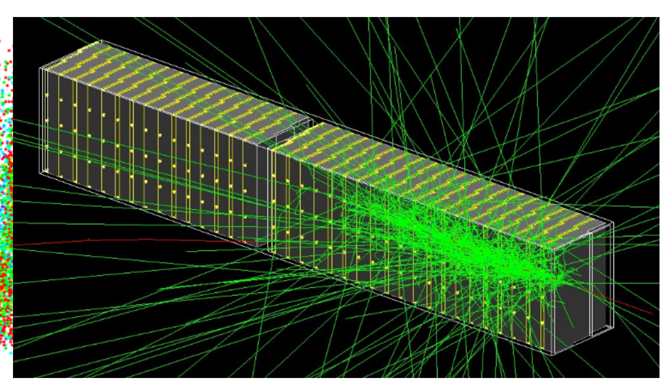
Construction and tests of particle detectors

September 2018 CERN-PS: a module with hadronic cal. for pion containment and **integrated t_0-layer**

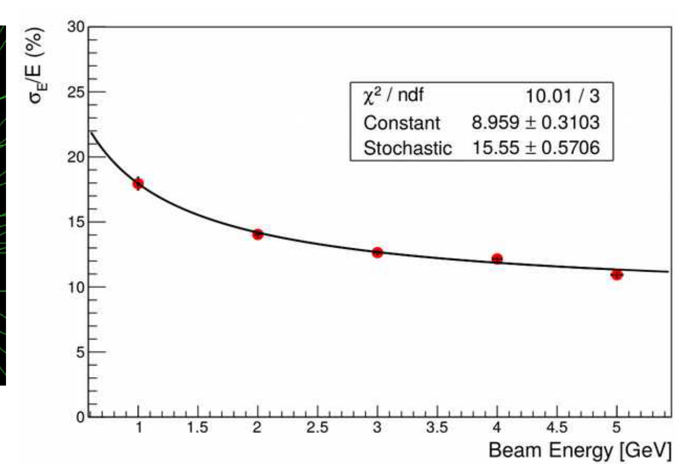
Efficiency maps



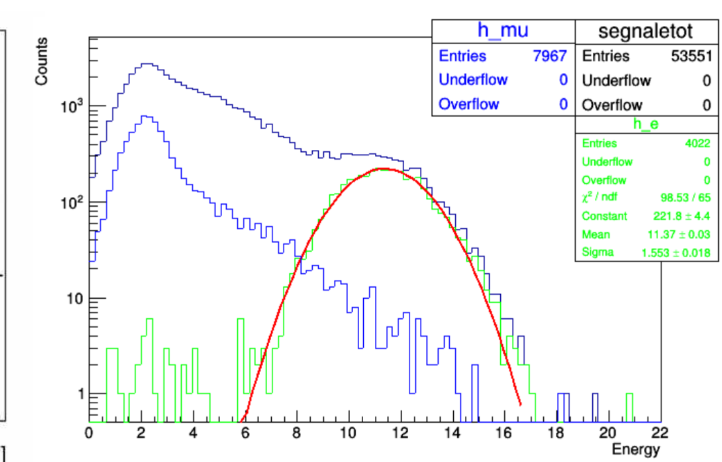
Simulation



Resolution

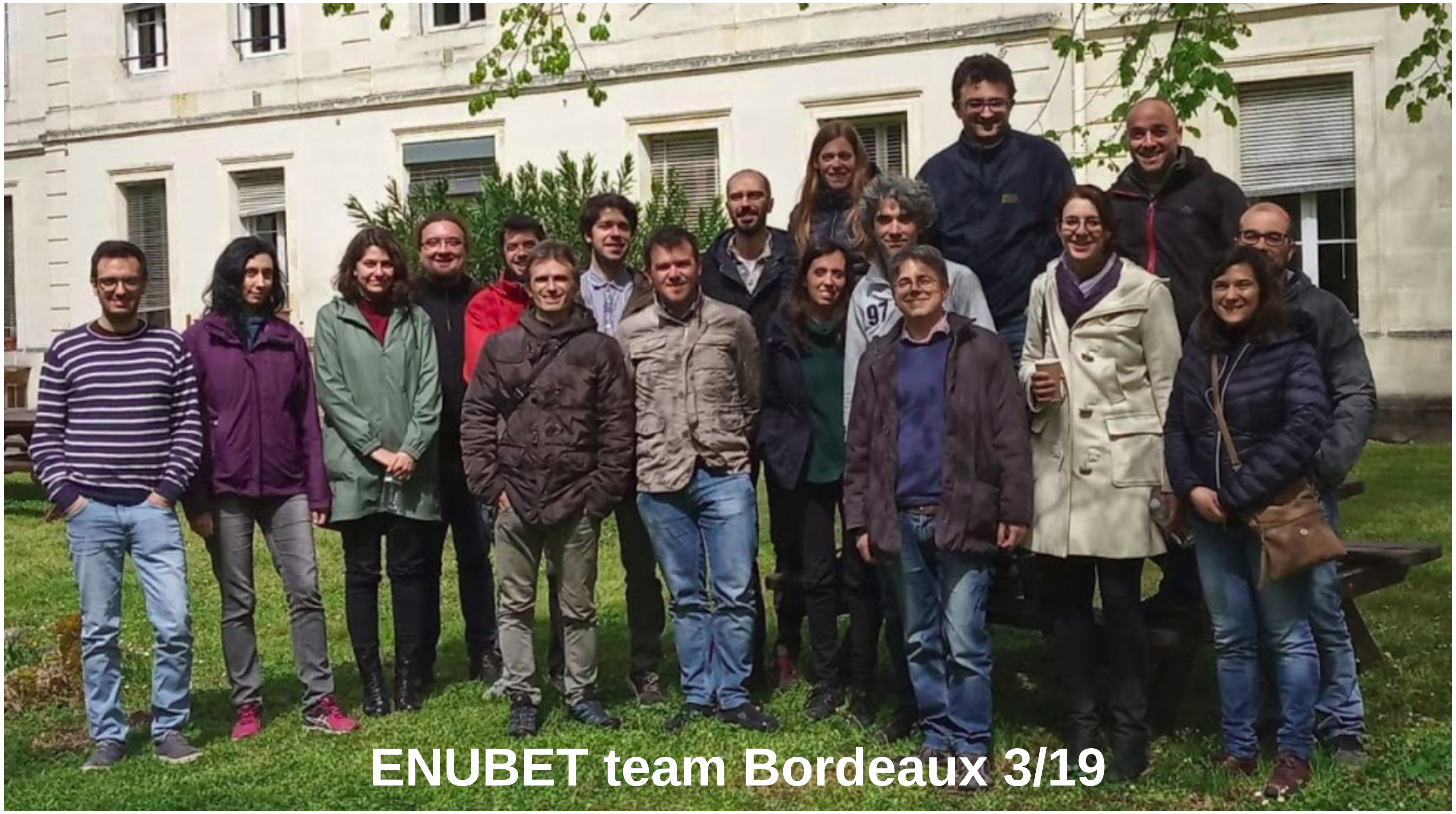


PID



Conclusions ?

I hope to have stimulated your curiosity on this lively field and to get a lot of questions!



Bonus slides

Open questions

Why do quarks and neutrinos "mix" so differently ?

quarks — neutrinos

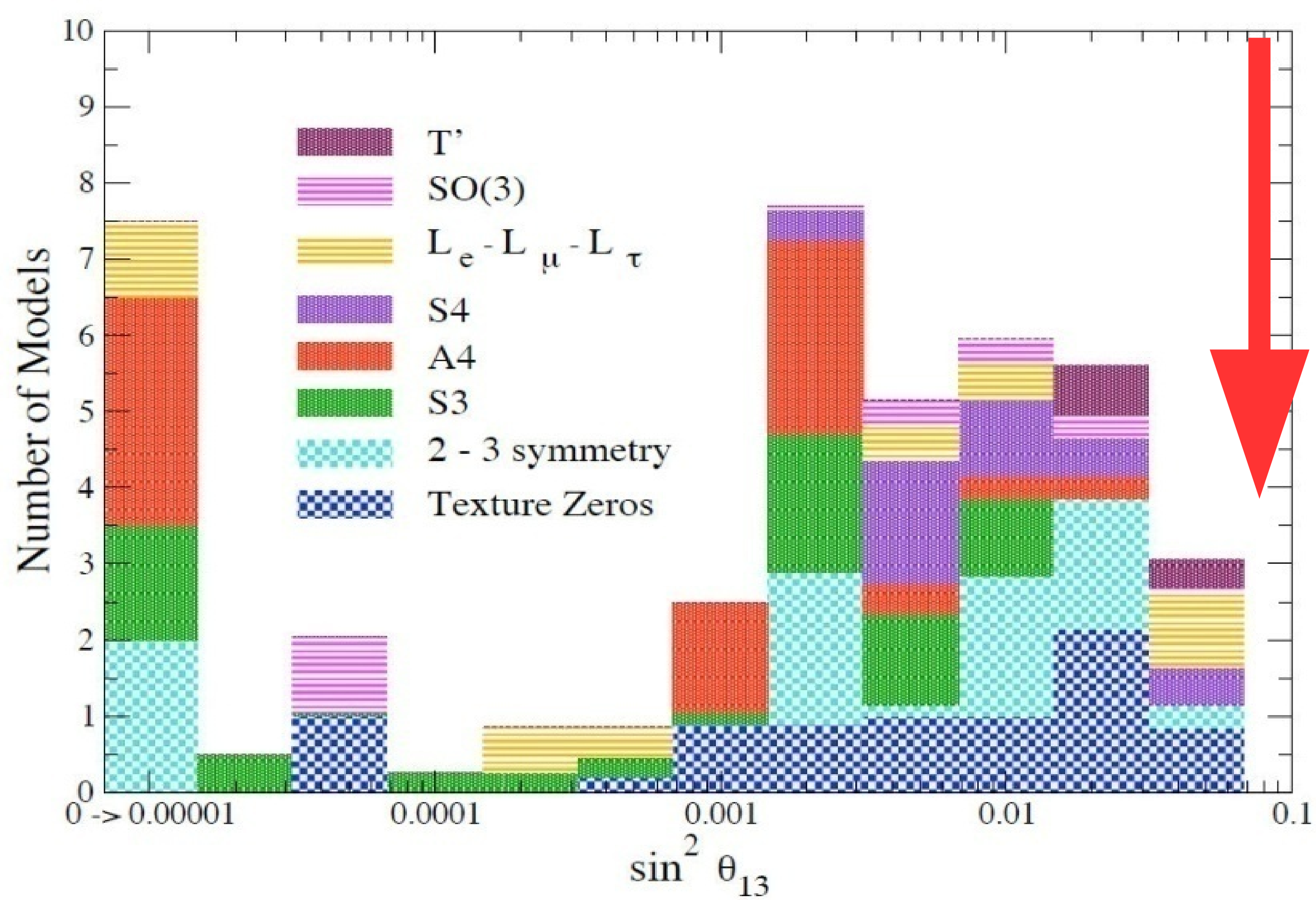
$$V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{pmatrix} \longleftrightarrow V_{MNS} \sim \begin{pmatrix} 0.8 & 0.5 & 0.2 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

No strong theoretical guidance! Measurements could lead to totally unexpected results
As already happened.

Crisis = opportunity!

→ an example : the θ_{13} angle

Distribution of $\sin^2 2\theta_{13}$ "predictions"!



Measured here in 2012! large!

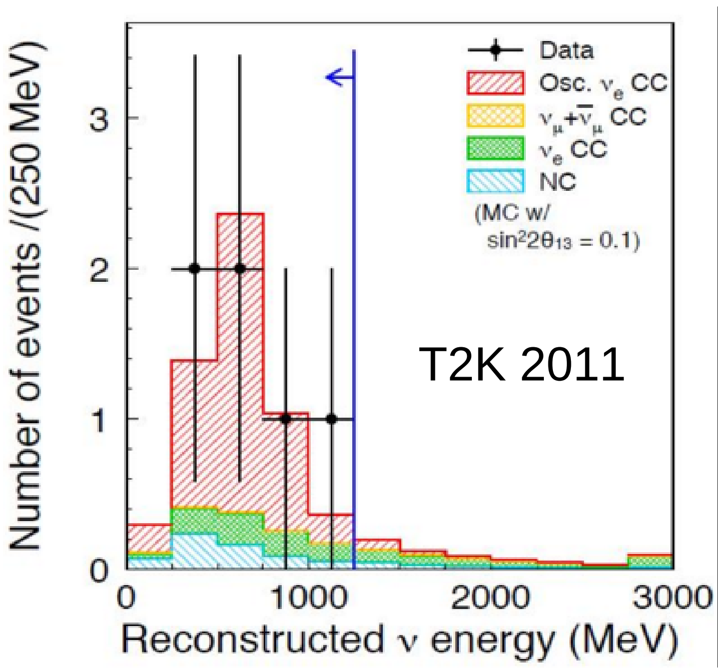
Open questions

Why do quarks and neutrinos "mix" so differently ?

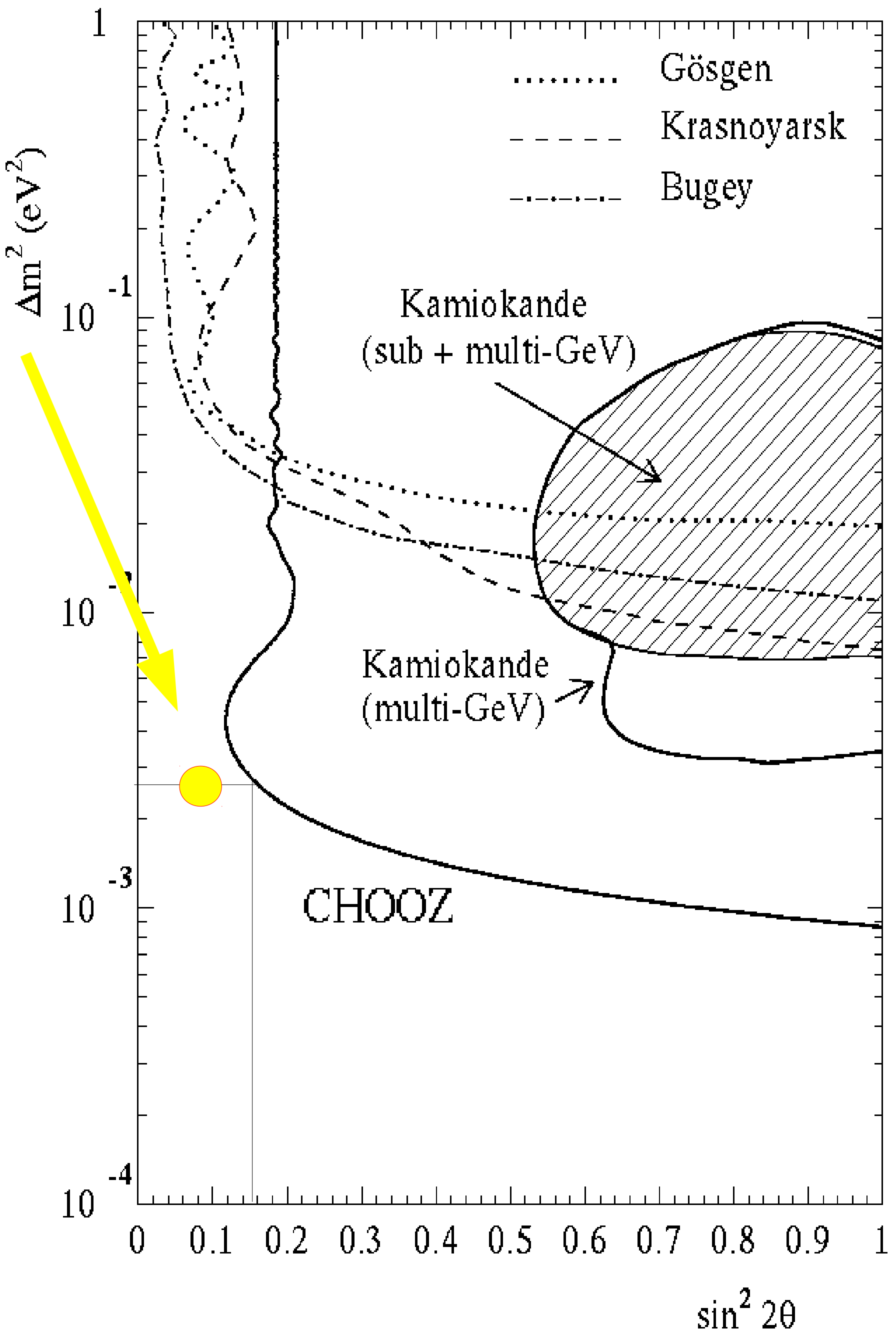
2012: new scenarios θ_{13} is large!

$\sin^2 2\theta_{13}$: 14 y "behind the corner"

- >1998: < 0.15 @ 90% C.L. CHOOZ limit
- 2010: hints. Solar+reactor global fits, Fogli et al.
- 2011: 0.11 (0.14), T2K best fit of 2011 (2.5 σ)
- 2012: 0.092 ± 0.017, Daya Bay, (5.2 σ)
- 2013: T2K, 7.5 σ
- 2015: NOvA, 5.5 σ

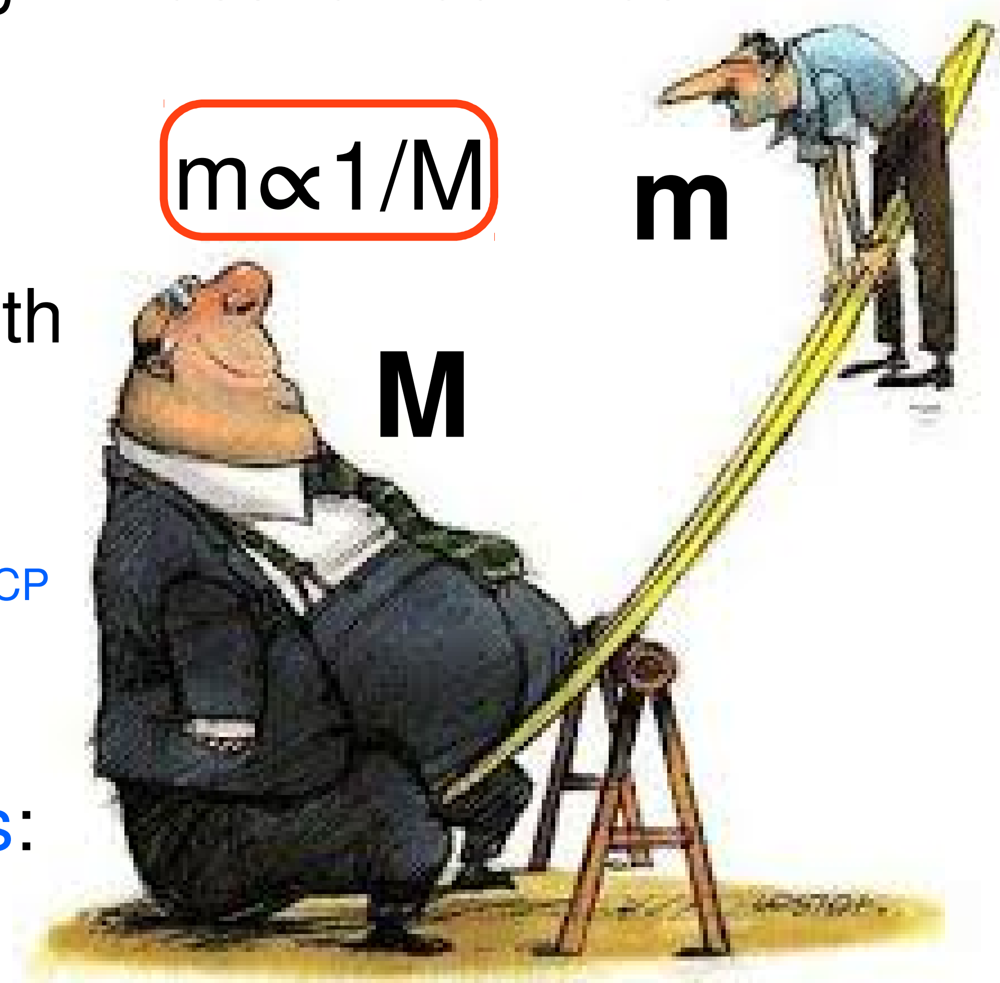


A necessary condition to move forward →



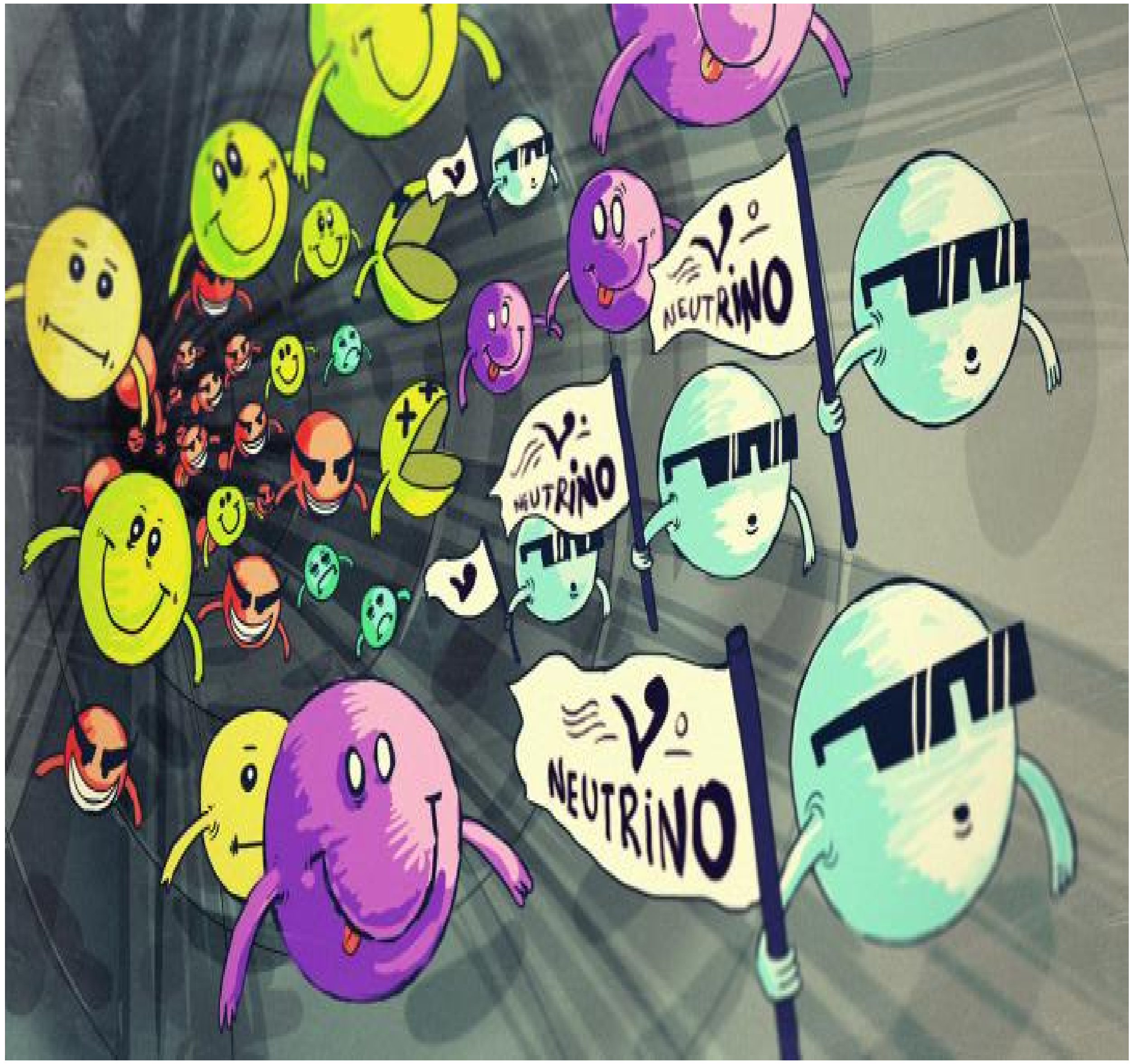
What is next?

- Neutrinos (at least two) have mass and must be very light ($m \lesssim 2$eV from cosmology and direct measurements)
- We don't know why: NOT predicted by the Standard Model
- Most promising theory (most elegant) is the "See-Saw" mechanisms: Neutrino and Anti-Neutrino are the same particle (Majorana-like)!
- New heavy neutrinos ($M \sim 10^{10}$-10^{15} GeV) give a light mass to neutrinos!
- They would be "sterile": no interaction with matter
- Asymmetry matter-antimatter can be explained with the "leptogenesis" model
- Requires Majorana-like neutrinos, CP violation ($\delta_{CP} = -\pi/2$ would be better)
- Also possible hints of lower mass sterile neutrinos: detectable with short base-line oscillations



Conclusions

- In the past 20 years many discoveries have been made
- We know that neutrinos have a light mass but we don't know why
- But we still don't know if Neutrino and Anti-Neutrino oscillate in the same way
- But still many open questions



- Why our world is done of matter and not anti-matter?
- Are Neutrinos and Anti-Neutrinos the same particle?
- Are there other particles we don't know?
- Many experiments are running now trying to answer these questions and...
- Many new experiments are planned for the future
- We believe there are still many things to discover about neutrinos

Current knowledge of neutrino oscillations

- Neutrinos (at least two) have mass
- Not predicted by the Standard Model: we need new physics to explain it!

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad \begin{matrix} c_{ij} = \cos\theta_{ij} \\ s_{ij} = \sin\theta_{ij} \end{matrix}$$

$$\Delta m^2_{21} = 7.58^{+0.22}_{-0.26} \times 10^{-5}\mathrm{eV}^2/\mathrm{c}^4$$

$$|\Delta m^2_{32}| = 2.35^{+0.12}_{-0.09} \times 10^{-3}\mathrm{eV}^2/\mathrm{c}^4$$

$\sin^2(2\theta_{23}) > 0.95$ (90%CL) $\sin^2(2\theta_{13}) = 0.098 \pm 0.013$ $\sin^2(2\theta_{12}) = 0.857 \pm 0.024$

Atmospheric / accelerator: SK, MINOS, K2K, T2K

Reactor / accelerator: T2K, MINOS, Daya Bay, RENO, Double Chooz

Solar / reactor: KamLAND, SNO, SK

- **The only parameter not measured yet is δ_{CP}**
- If $\delta_{CP} \neq 0 \rightarrow$ CP violation in leptonic sector: physics law are not exactly the same for Neutrinos and Anti-Neutrinos. Oscillate in different way
- We need to know the other oscillation parameters with high precision

Systematics on the ν_e flux

Golden sample $\varepsilon \sim O(10^{-2})$

$\phi(\nu_e) = \alpha\, N(K_{e3}) + \varepsilon\ N(\mu)$ →

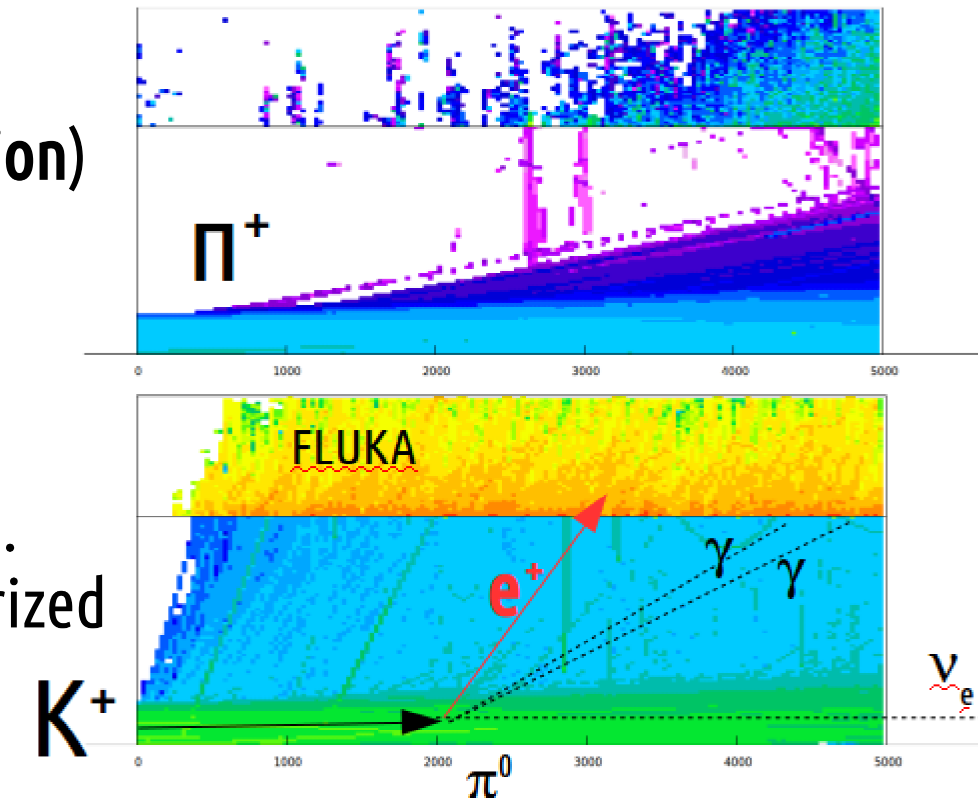
Uncertainties from K yields, efficiency and stability of the transfer line are by-passed by the **e^+ tagging**

α encodes the residual geometrical (decay lengths, beam spread) and kinematic factors from K decays → "**easy" corrections**.

The **background** in the positron sample has to be controlled
→ simple robust detector validated at test beams (**e/$\pi^{\pm 0}$/μ separation**)

Silver sample $\phi'(\nu_e) = \alpha\, N(K) \times BR(K_{e3})$

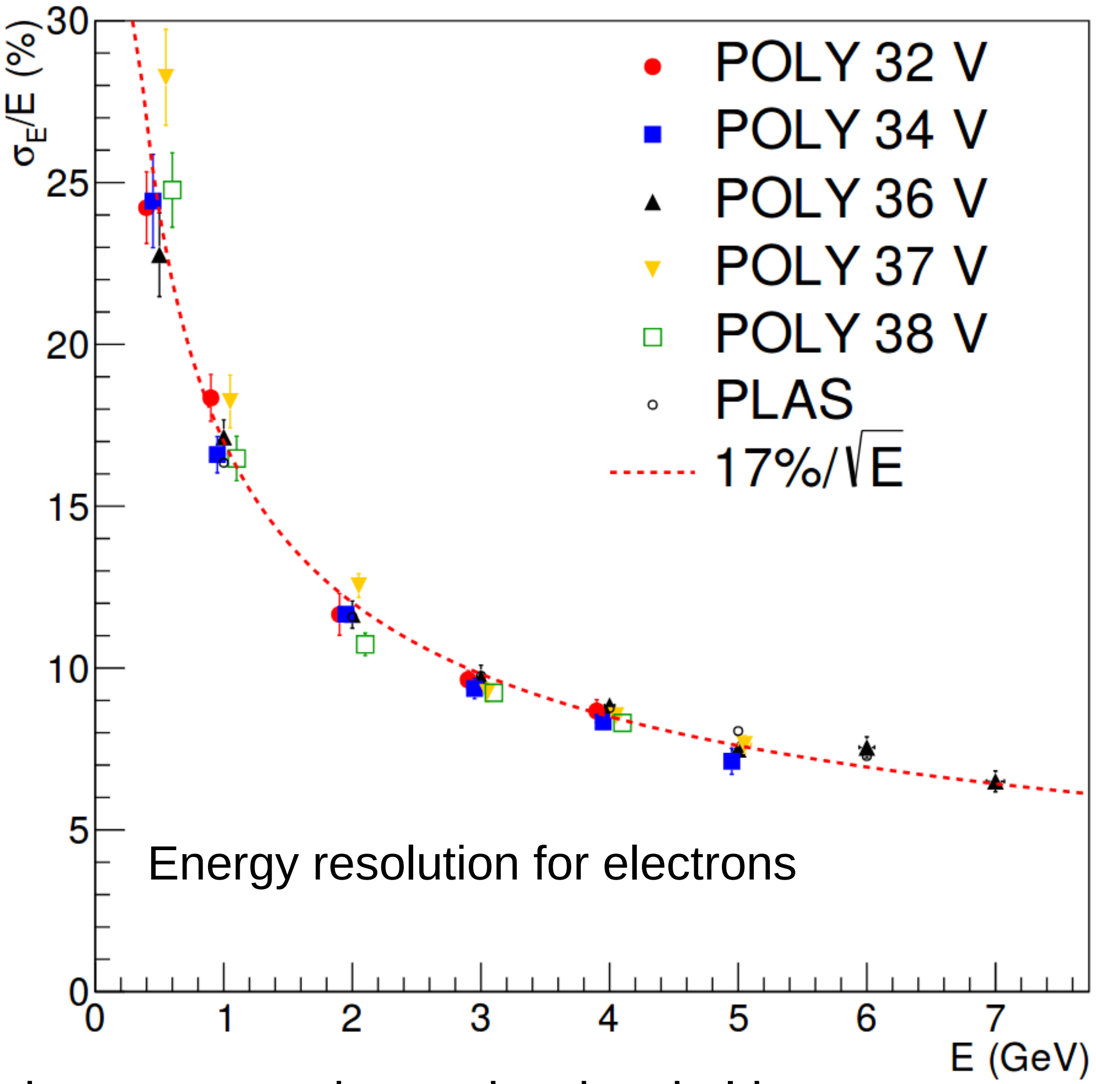
Measuring the **inclusive rate of K decays** is also very powerful. Branching ratios known to < 0.1% (additional uncertainty is small). Residual background is **stray pions from beam tails** (well characterized in terms of azimuth and longitudinal position)

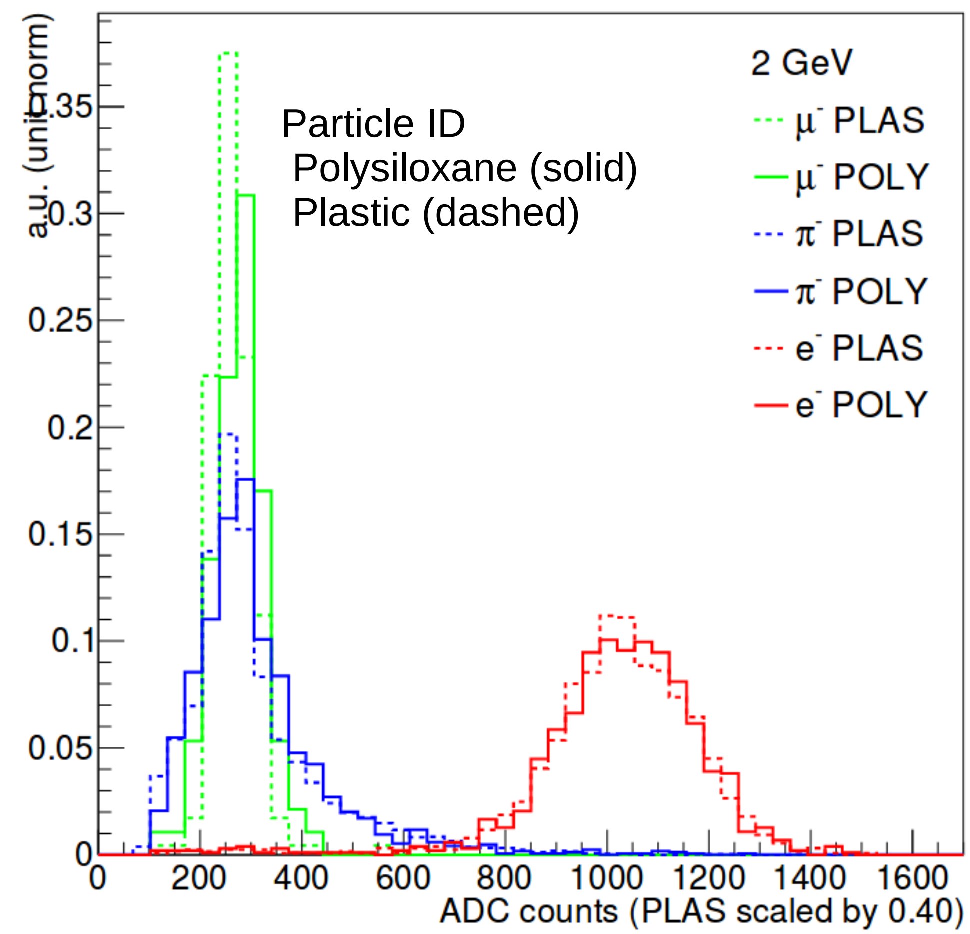


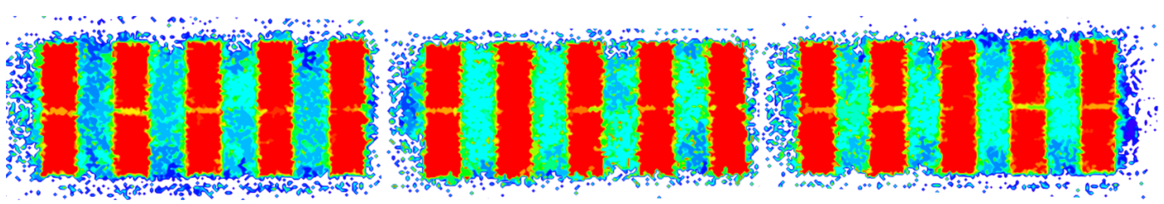
- **can we get to 1% ?** assessment in progress: **toy Monte Carlos** + **full simulation**
- Address the effect of each uncertainty and the degree of **cancellations allowed by the large correlations between e^+ rate and ν_e flux**.

Polysiloxane shashlik prototypes

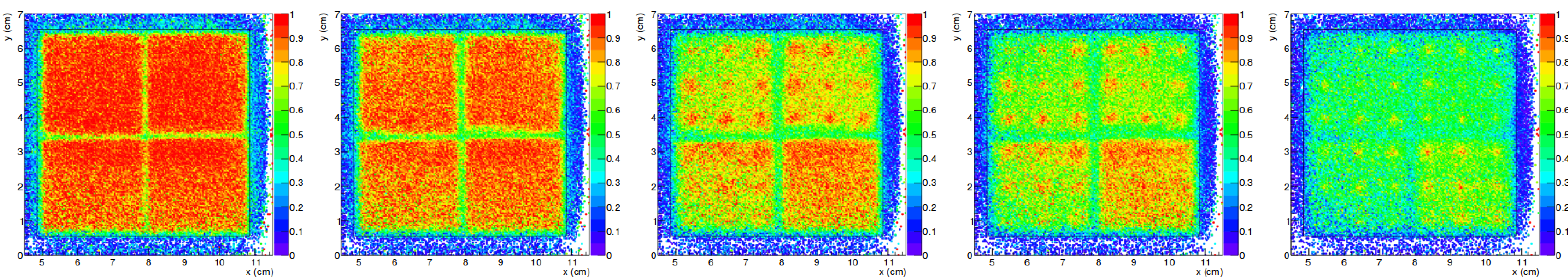
Light yield (normalized to thickness) is ~ 1/3 of plastic scintillator
→ tests light transmission on WLS fibers in absence of air gap
Energy resolution, particle-ID and uniformity in line with the one achieved with plastic scintillator







Efficiency maps at increasing thresholds →



Padova June 2016

CERN Nov 2016

CERN Aug 2017

CERN Oct 2017

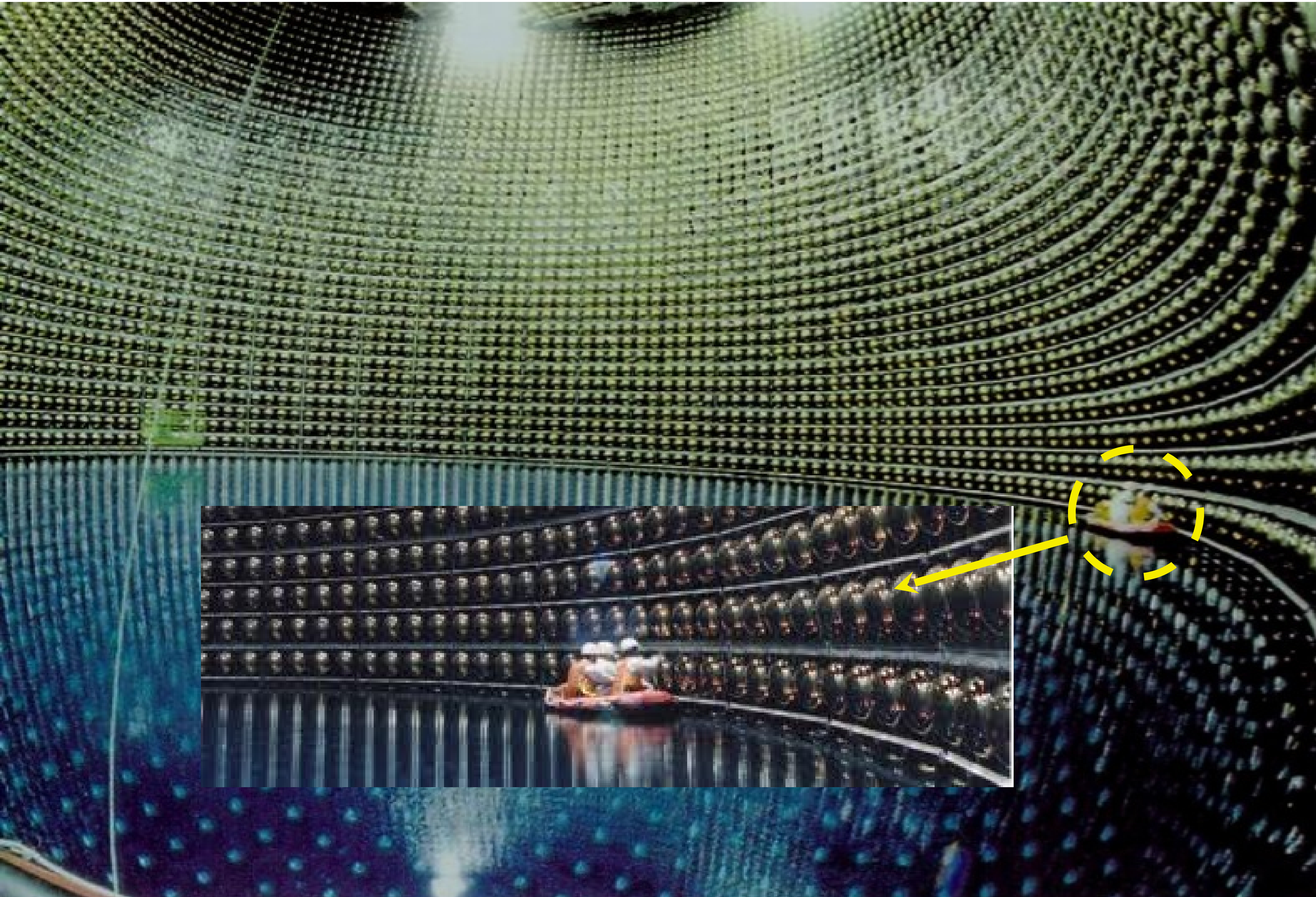
INFN-LNL Jun 2017

CERN May 2018

CERN Sep 2018

Milan Oct 2017

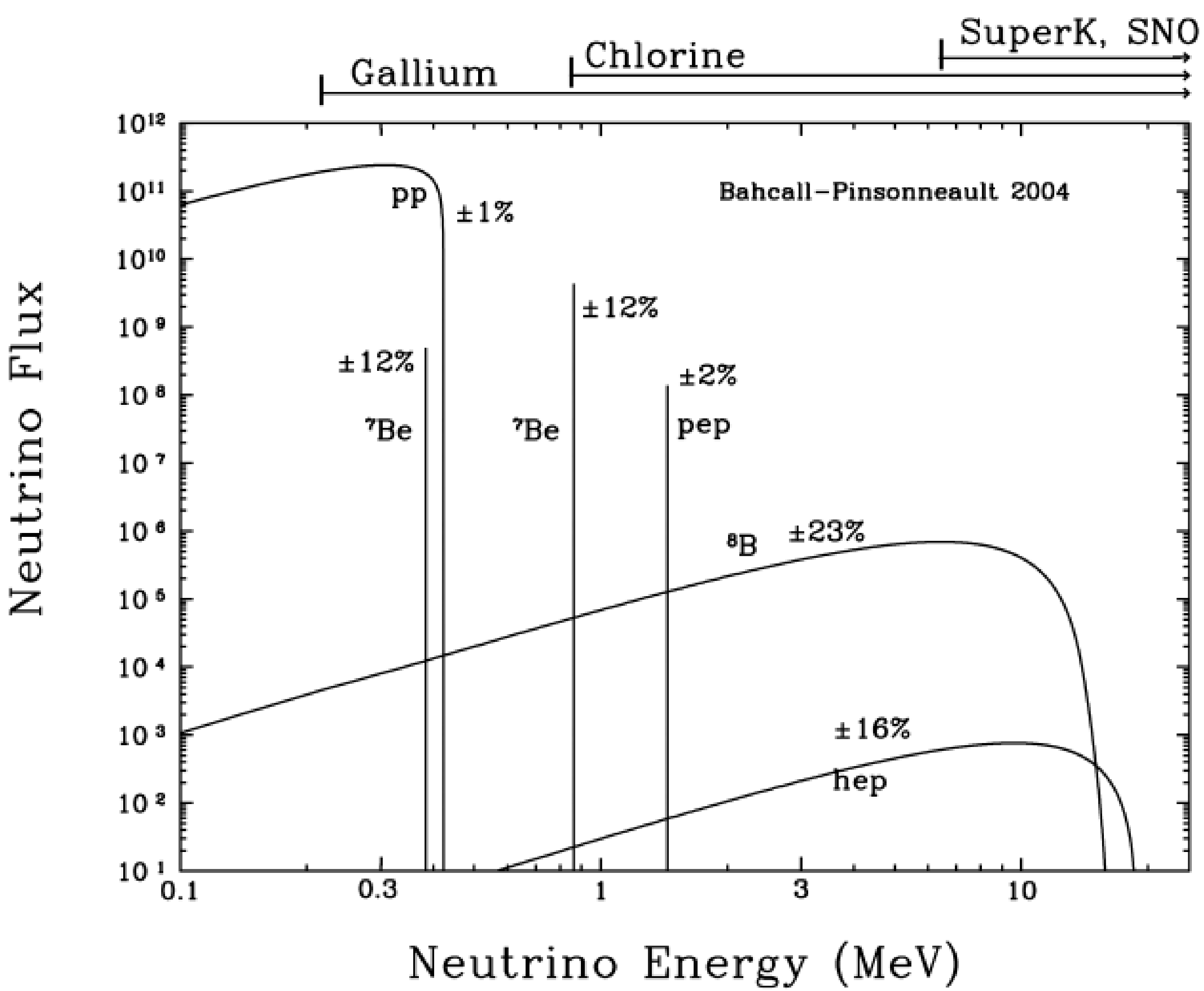
Oscillation of atmospheric neutrinos



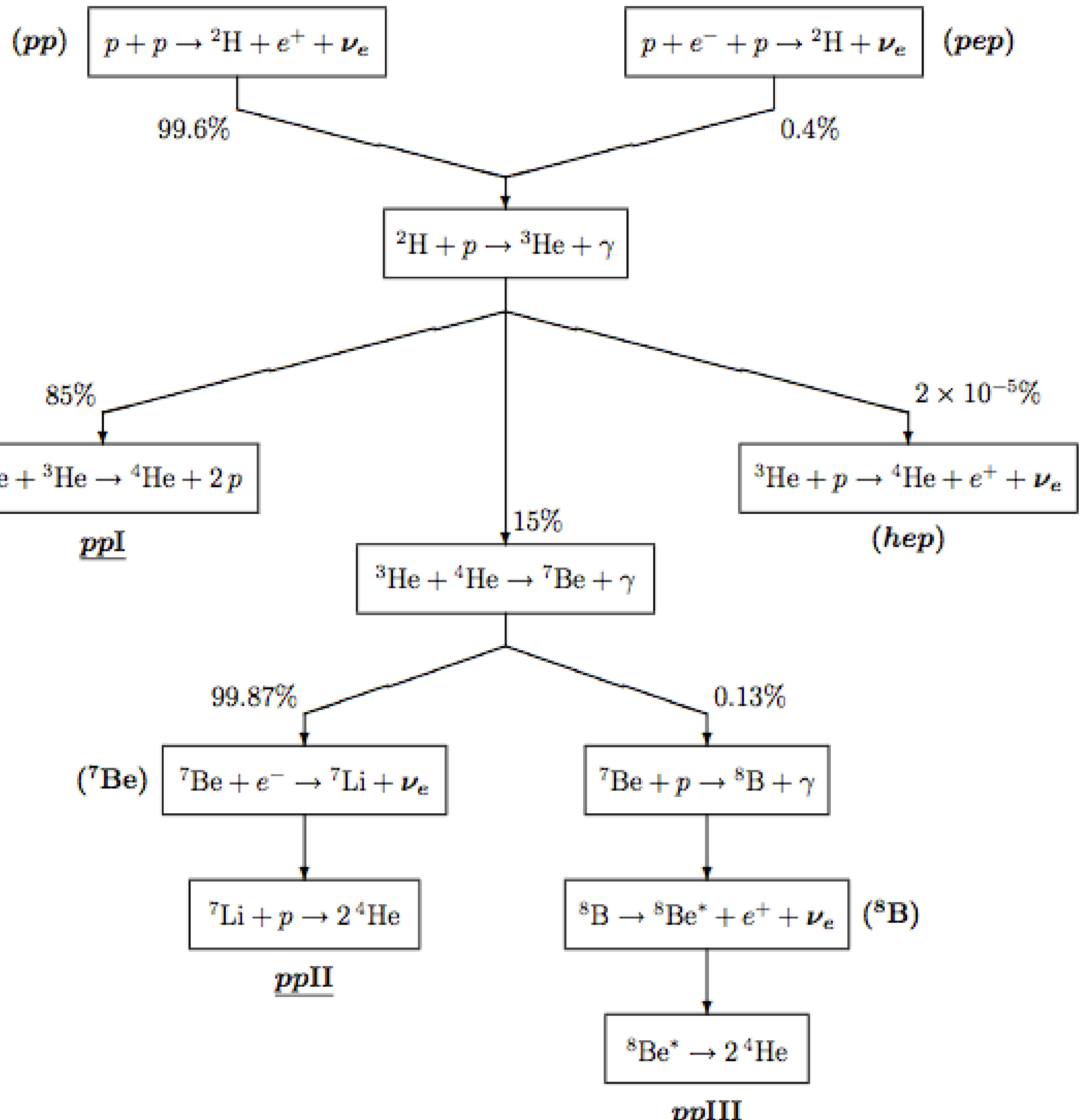
Oscillation of solar neutrinos

- Electron neutrinos are produced in the Sun as a product of nuclear fusion
- 86% of electron neutrinos come from $p + p \to d + e^+ + \nu_e \ (\sim 0.3 \text{ MeV})$
- Detected by SK and SNO: ${}^8B \to {}^8 Be^* + e^+ + \nu_e(\sim 6 \text{ MeV})$
- In the late 1960s the solar neutrino problem was observed: ~1/3-1/2 less neutrinos from the Sun than predicted from Standard Solar Model
- Underground Cherenkov detector with heavy water (D_2O), 1kton
- NC are detected through

$$n + d \to {}^3 \text{H} + \gamma$$

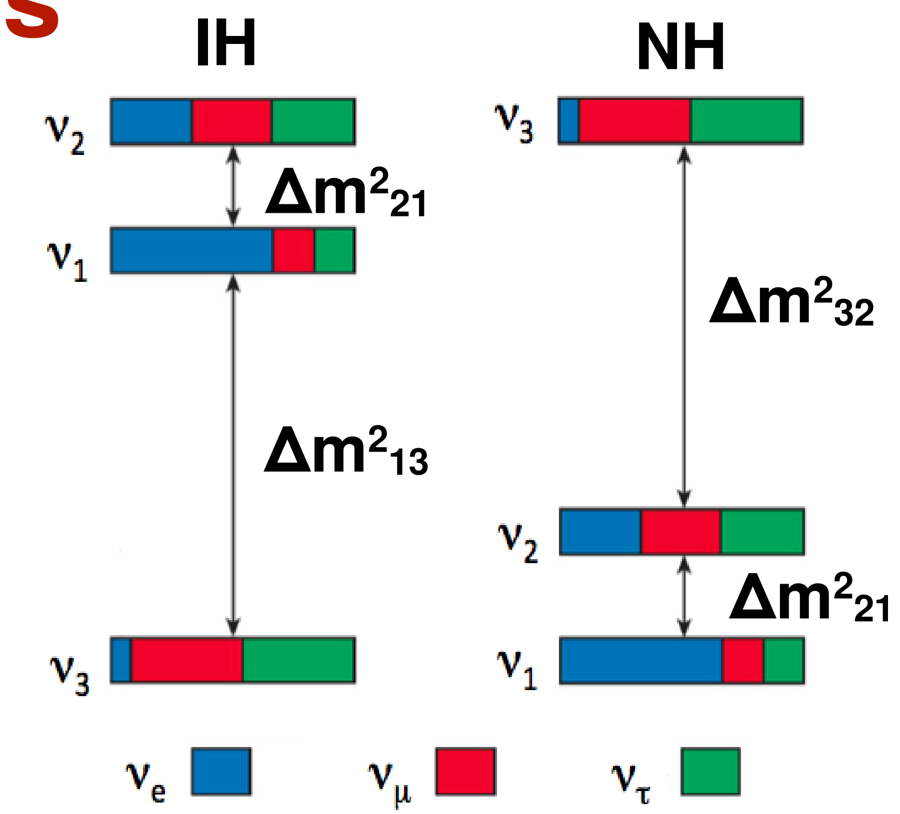


SOLAR NEUTRINOS



Neutrino oscillations

$$P(\overset{(-)}{\nu_\alpha} \rightarrow \overset{(-)}{\nu_\beta}) = \delta_{\alpha\beta} - 4\sum_{i>j} \Re(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}) \sin^2(\Delta m^2_{ij}\frac{L}{4E})$$
$$\overset{+}{\underset{(-)}{}} 2\sum_{i>j} \Im(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}) \sin(\Delta m^2_{ij}\frac{L}{2E})$$



L: neutrino flight path

E: neutrino energy

$$c_{ij} = \cos\theta_{ij}$$
$$s_{ij} = \sin\theta_{ij}$$

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \times \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \times \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

atmospheric/ accelerator — $\sin^2(2\theta_{23}) > 0.95$ (90%CL) — **SK, MINOS, K2K, T2K**

Majorana phases (no effects)

reactor/ accelerator — $\sin^2(2\theta_{13}) > 0.098 \pm 0.013$ — **T2K, MINOS, DB, RENO, DC**

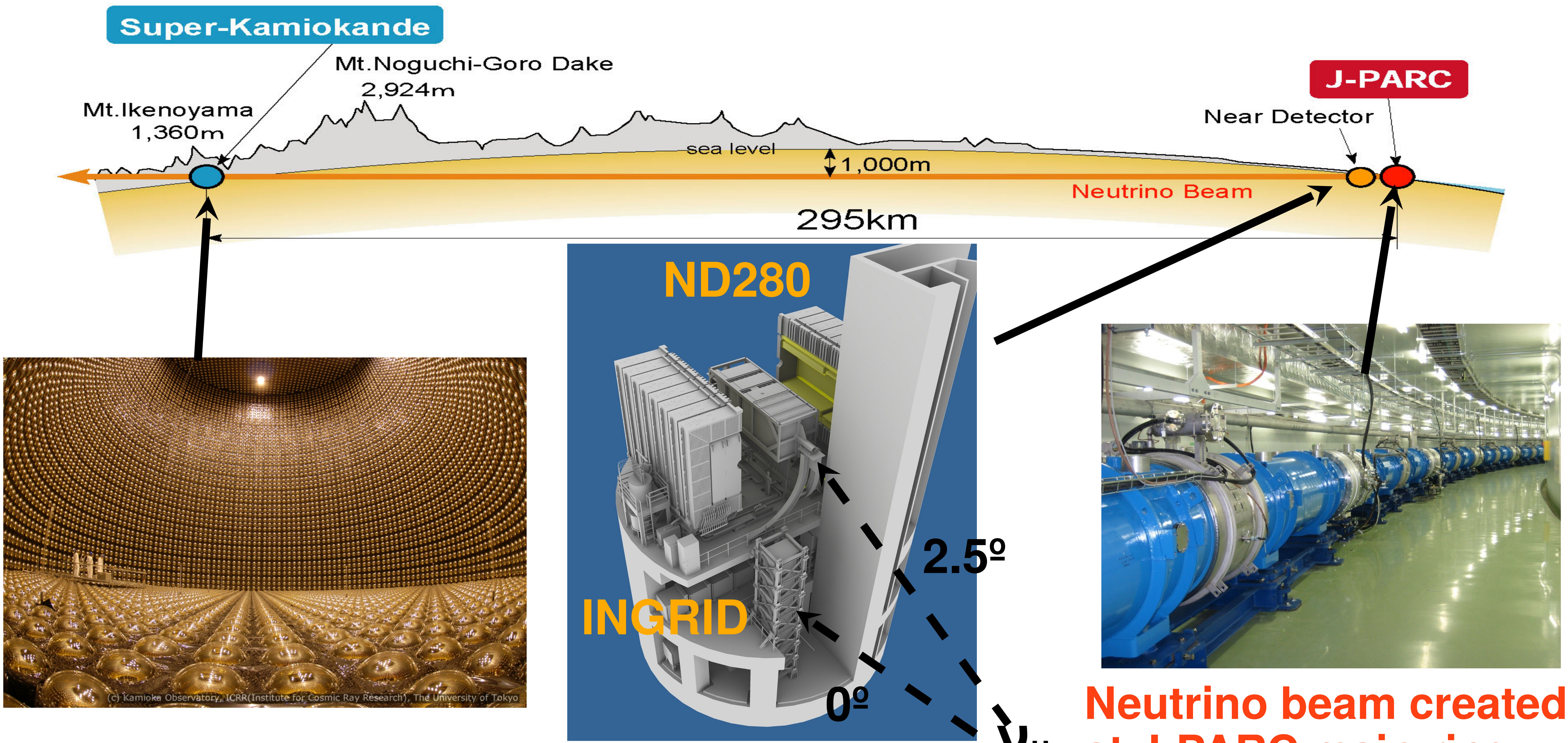
Solar/ reactor — $\sin^2(2\theta_{12}) > 0.857 \pm 0.024$ — **KamLAND, SNO, SK**

$$\Delta m^2_{21} = 7.58^{+0.22}_{-0.26} \times 10^{-5} \mathrm{eV}^2/\mathrm{c}^4$$

$$|\Delta m^2_{32}| = 2.35^{+0.12}_{-0.09} \times 10^{-3} \mathrm{eV}^2/\mathrm{c}^4$$

An accelerator experiment: T2K

- Interactions of protons on a carbon target produce particles (parent) that decay to neutrinos
- ν_μ travel through the earth and oscillate after travelling 295 km
- Detect ν_μ and ν_e at the near (280 m) and far detectors (295 km)
- Oscillation probability is measured by comparing the number of neutrinos at the near and far detector



Super-Kamiokande

INGRID (on-axis) and ND280 (off-axis)

Neutrino beam created at J-PARC main ring

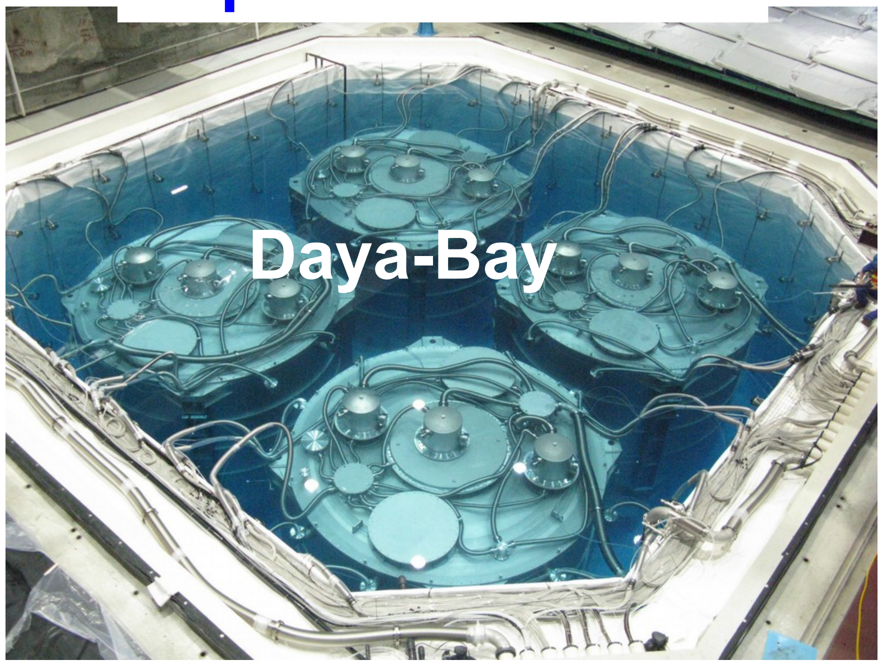
Modern neutrino detectors

We are mainly interested in the **final state charged particles** as these can emit light and/or leave tracks in segmented detectors (magnetization→ charged reconstruction)

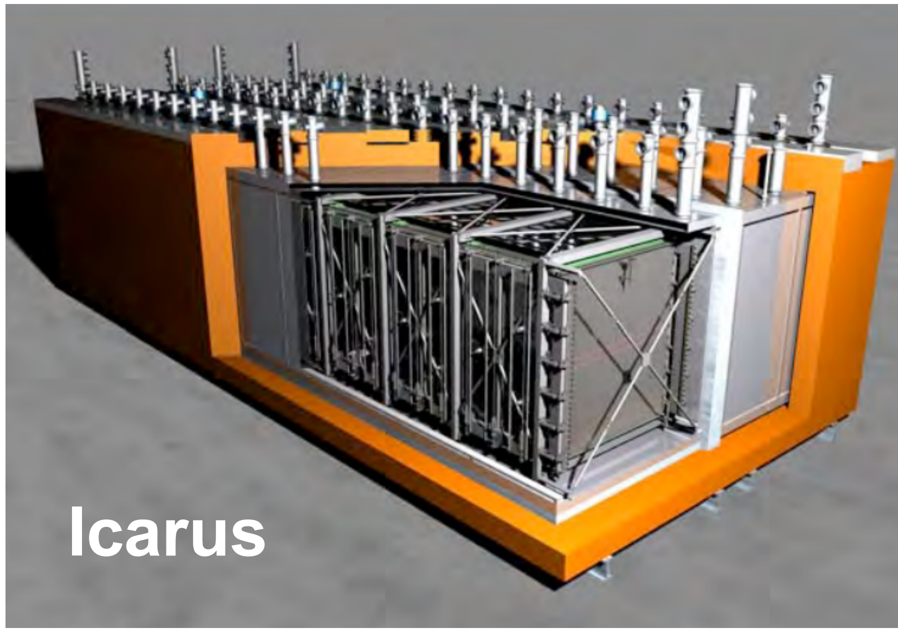
Water Cherenkov

3dnews.ru->novostey.com

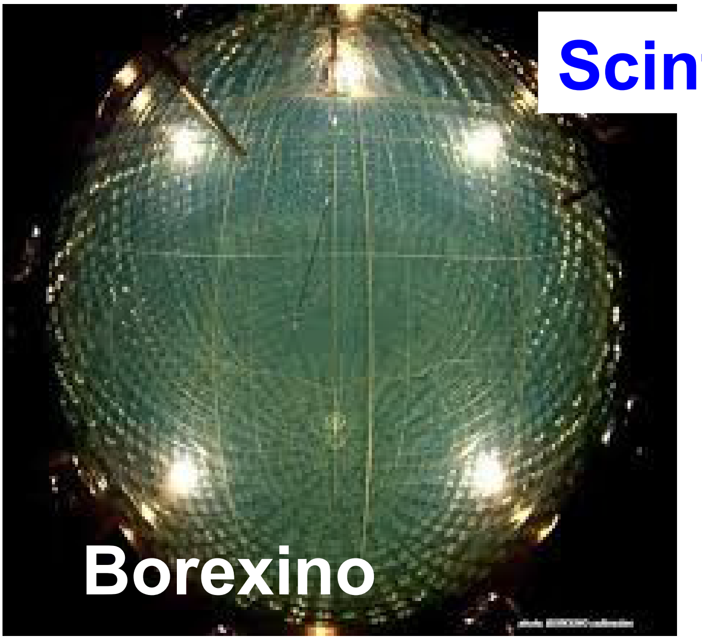
Liquid Scintillators

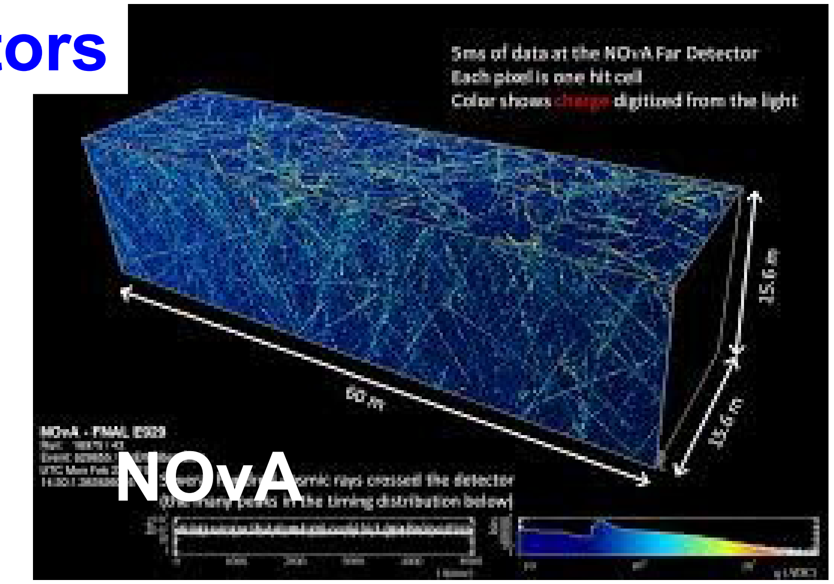


Liquid Argon



Scintillators





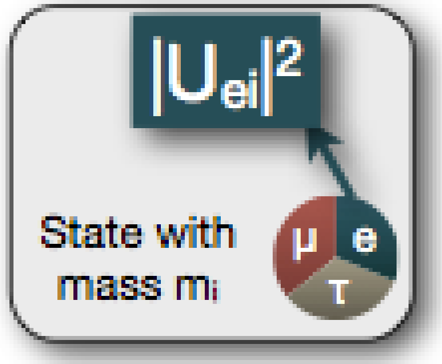
Photographic films and Magnetized iron

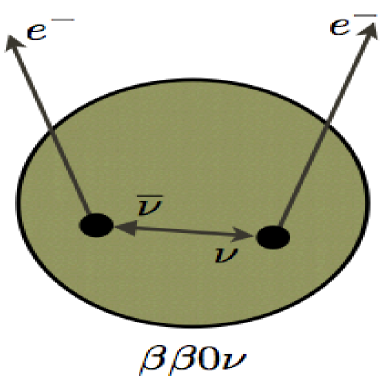
Neutrino-less double beta decay experiments

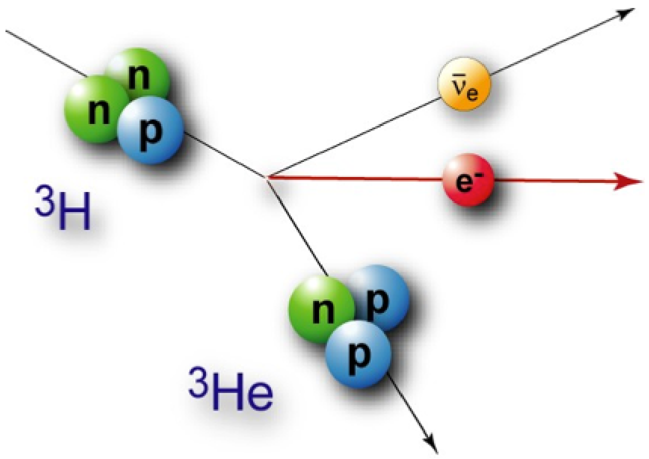
- Lepton number violation
- Neutrinos are Majorana
- Measures $m_{\beta\beta}$
- Result depends on mass hierarchy
- Uncertainties due to nuclear models
- A discovery determines the mass hierarchy, the scale of neutrino mass and the nature of neutrino

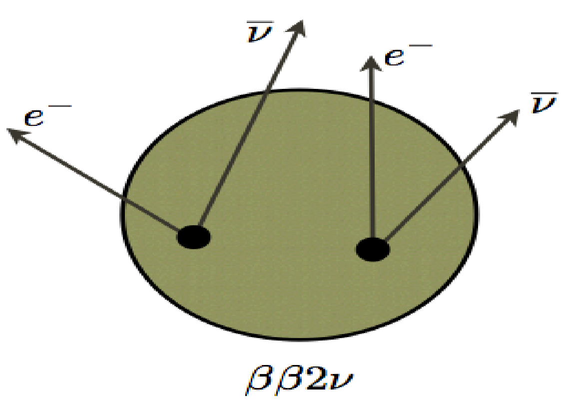
$(\text{Rate})_{\beta\beta0\nu} \propto m_{\beta\beta}^2$

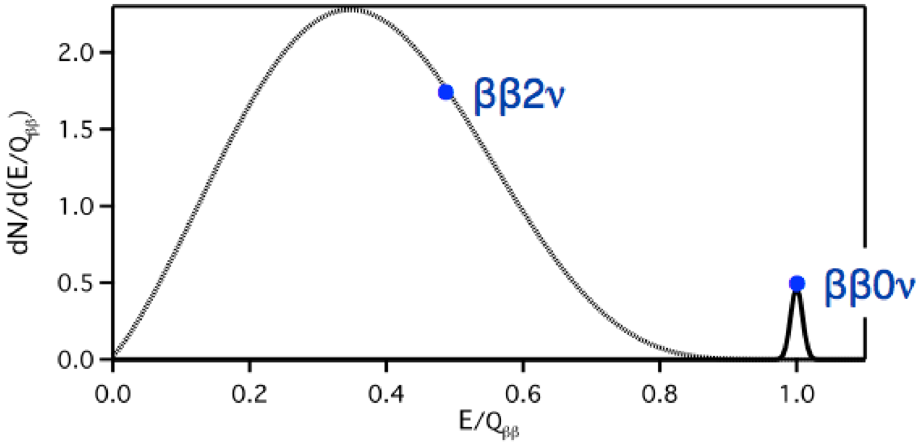
Majorana ν mass:
$m_{\beta\beta} \equiv \left| \sum_i m_i U_{ei}^2 \right|$

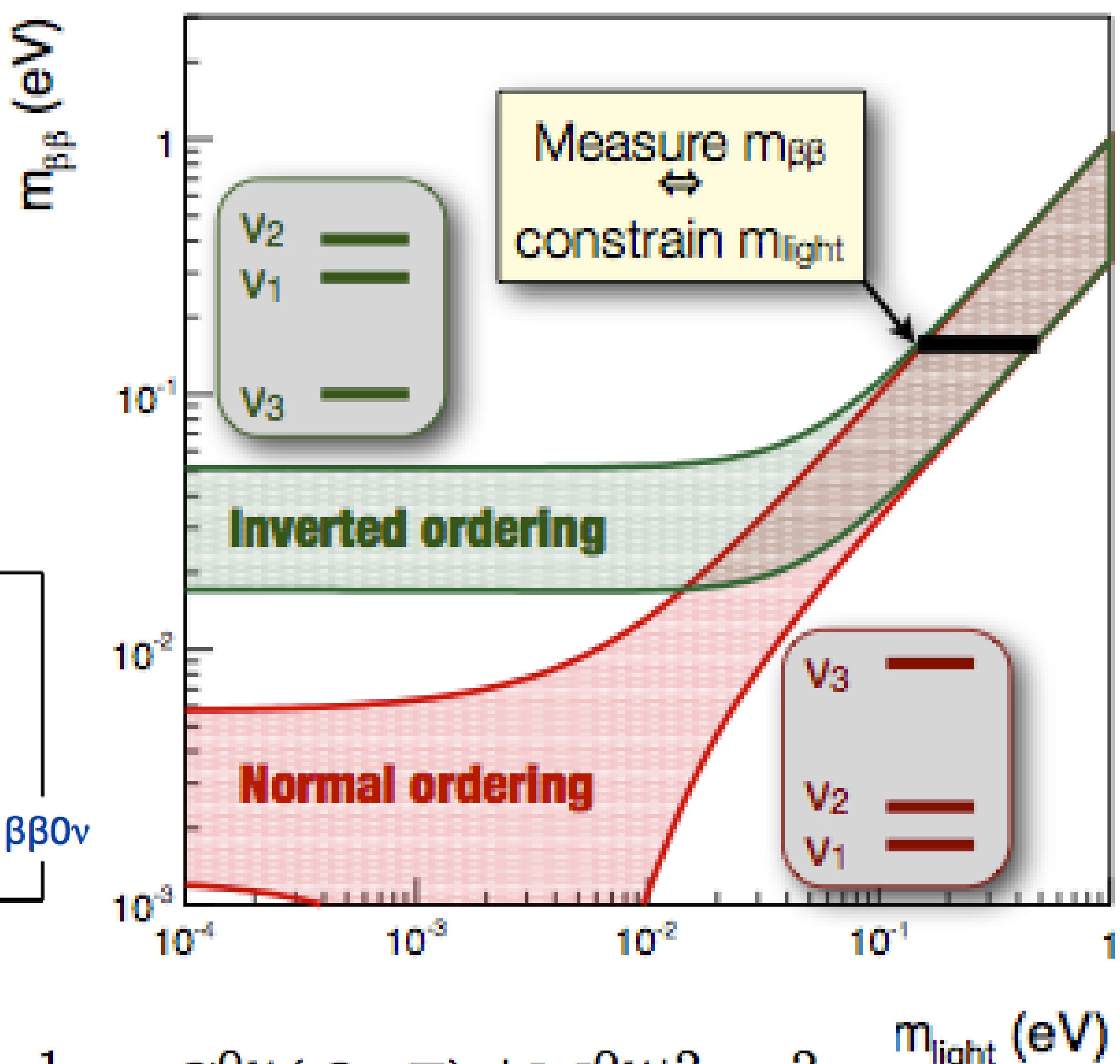












GERDA, CUORE, SuperNEMO, EXO, Majorana, NEXT

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q,Z)\,|M^{0\nu}|^2\, m^2_{\beta\beta}$$