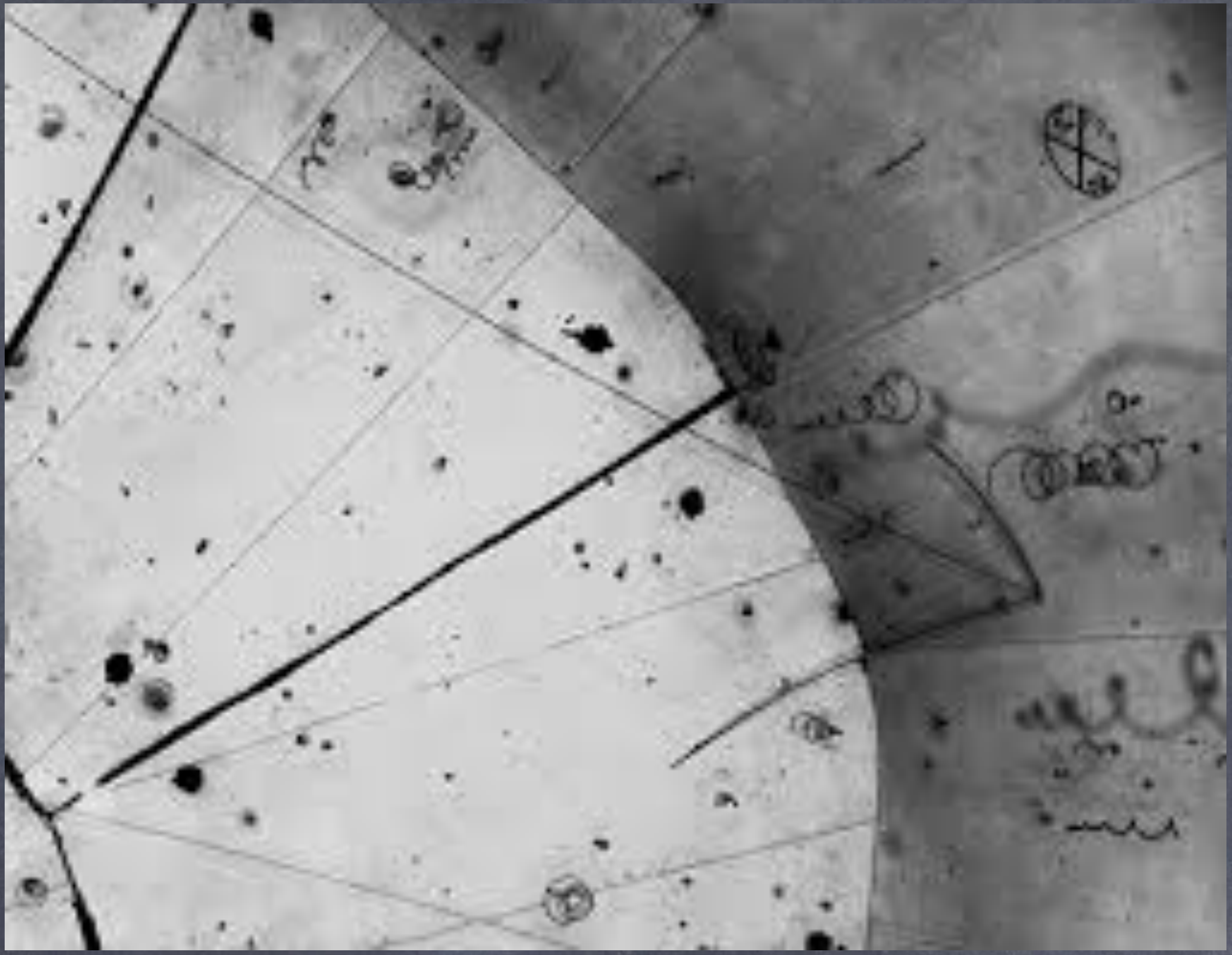


Neutrinos : ghostly particles

Stefania Bordoni - CERN

what we are going to see

- what are neutrinos?
- where we can find them?
- How can we see them?
- Neutrinos: chameleons of the Universe
- What can we learn from neutrinos?

+ short introduction about the visit

What are Neutrinos?

A neutrino (denoted by the Greek letter ν) is a fermion (an elementary particle with half-integer spin) that interacts only via the weak subatomic force and gravity. The mass of the neutrino is much smaller than that of the other known elementary particles

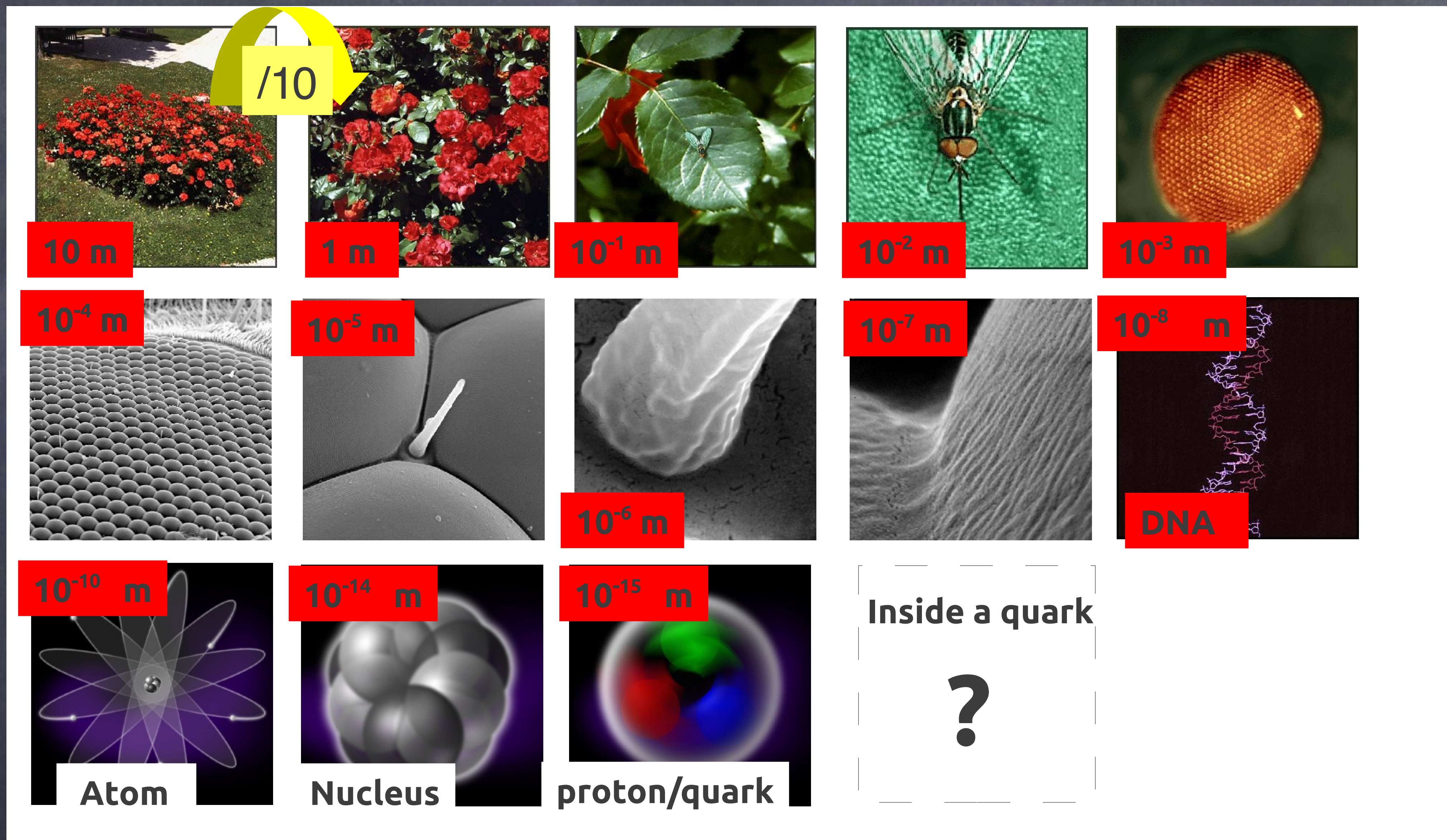
What are Neutrinos?

A neutrino (denoted by the Greek letter ν) is a fermion (an elementary particle with half-integer spin) that interacts only via the weak subatomic force and gravity. The mass of the neutrino is much smaller than that of the other known elementary particles

a lot of informations!

- What the matter is made of?
- how neutrinos have been discovered?

Order of magnitude



Scientific notation

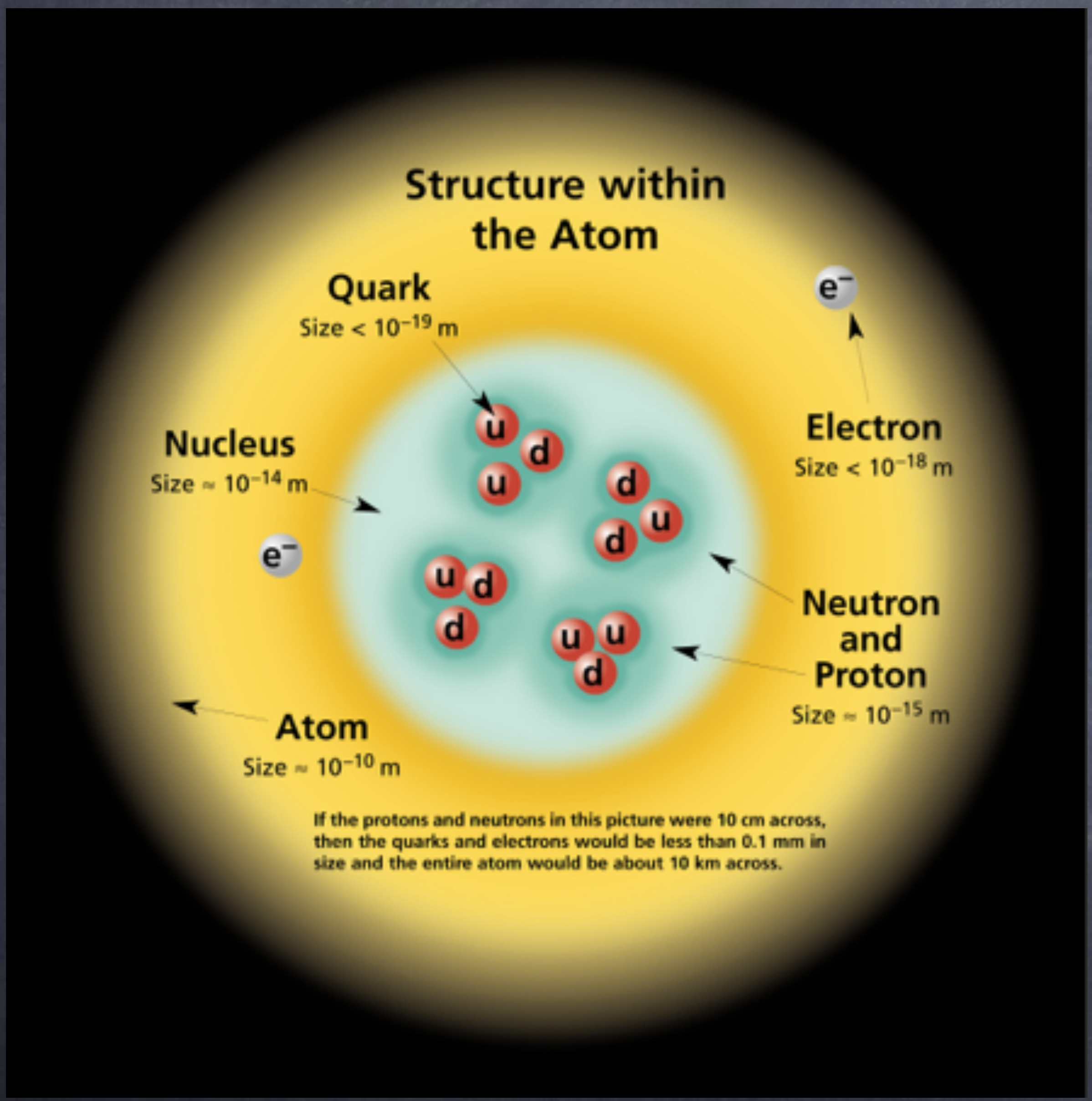
$$1 = 10^{0}$$

$$/10 = 0{,}1 = 10^{-1}$$

$$/10 = 0{,}01 = 10^{-2}$$

$$/10 = 0{,}001 = 10^{-3}$$

The structure within the atom



- Proton
- neutron
- electron
- .. and quarks

All are <u>sub-atomic particles</u>

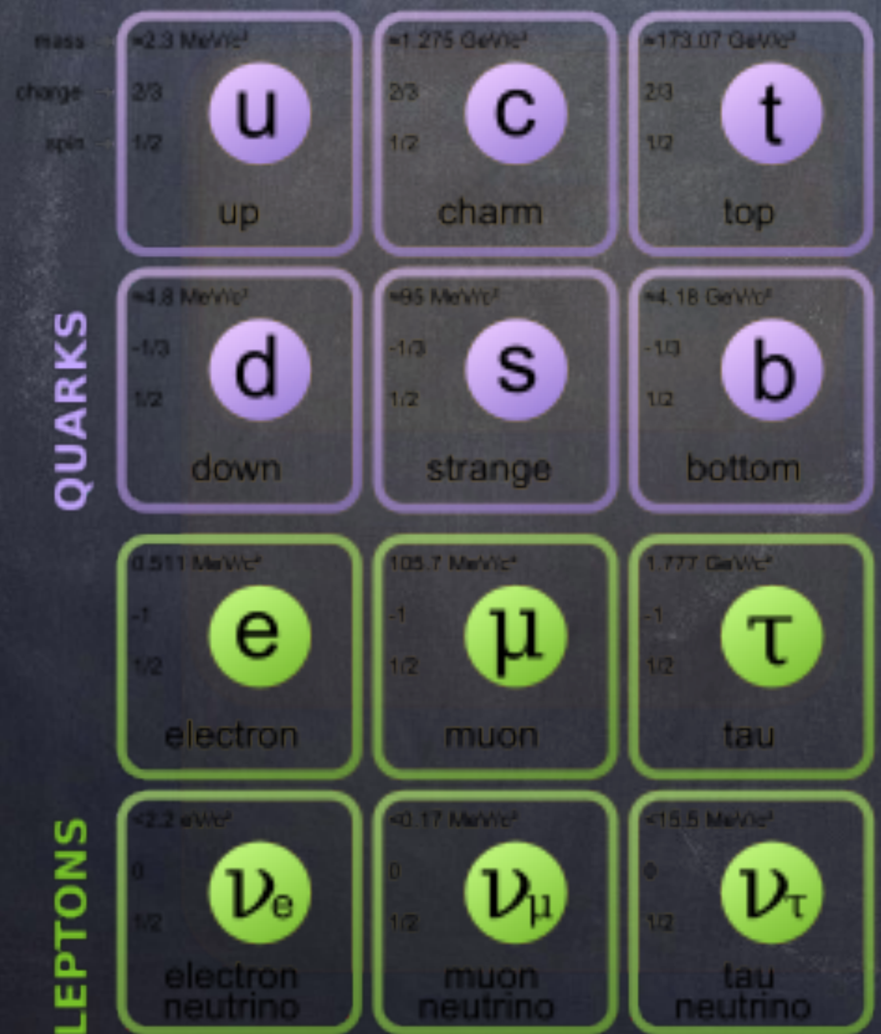
Are they all fundamental particles?

The Standard model

fermions

particles of matter

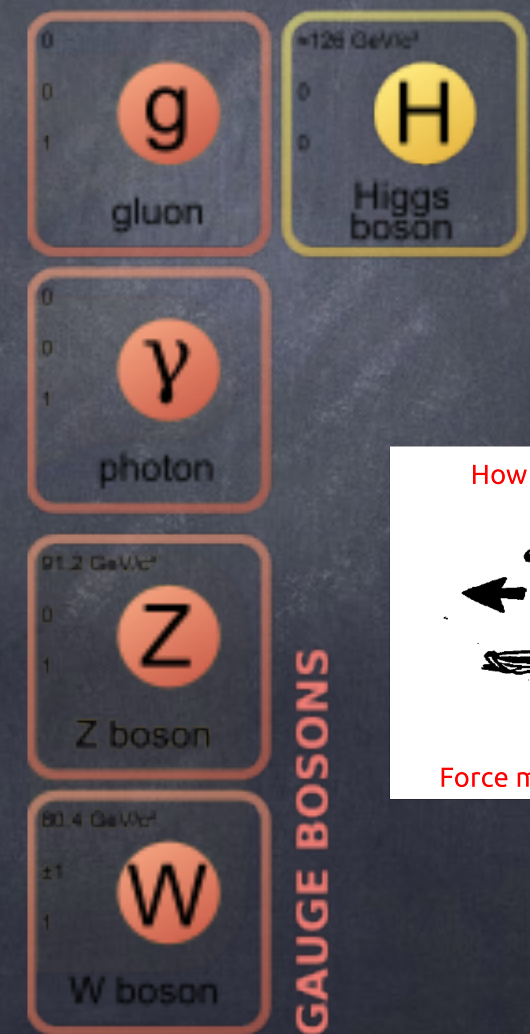
s = 1/2 * x

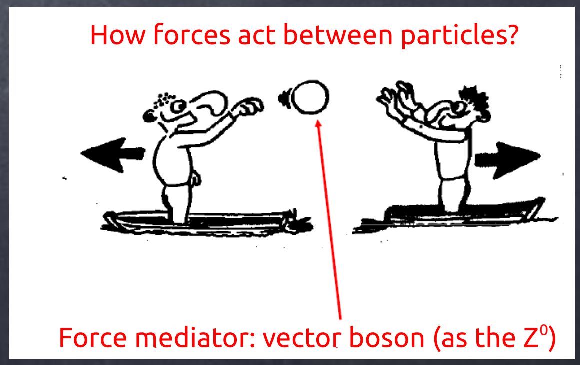


bosons

forces mediators

s = 0, 1, 2..



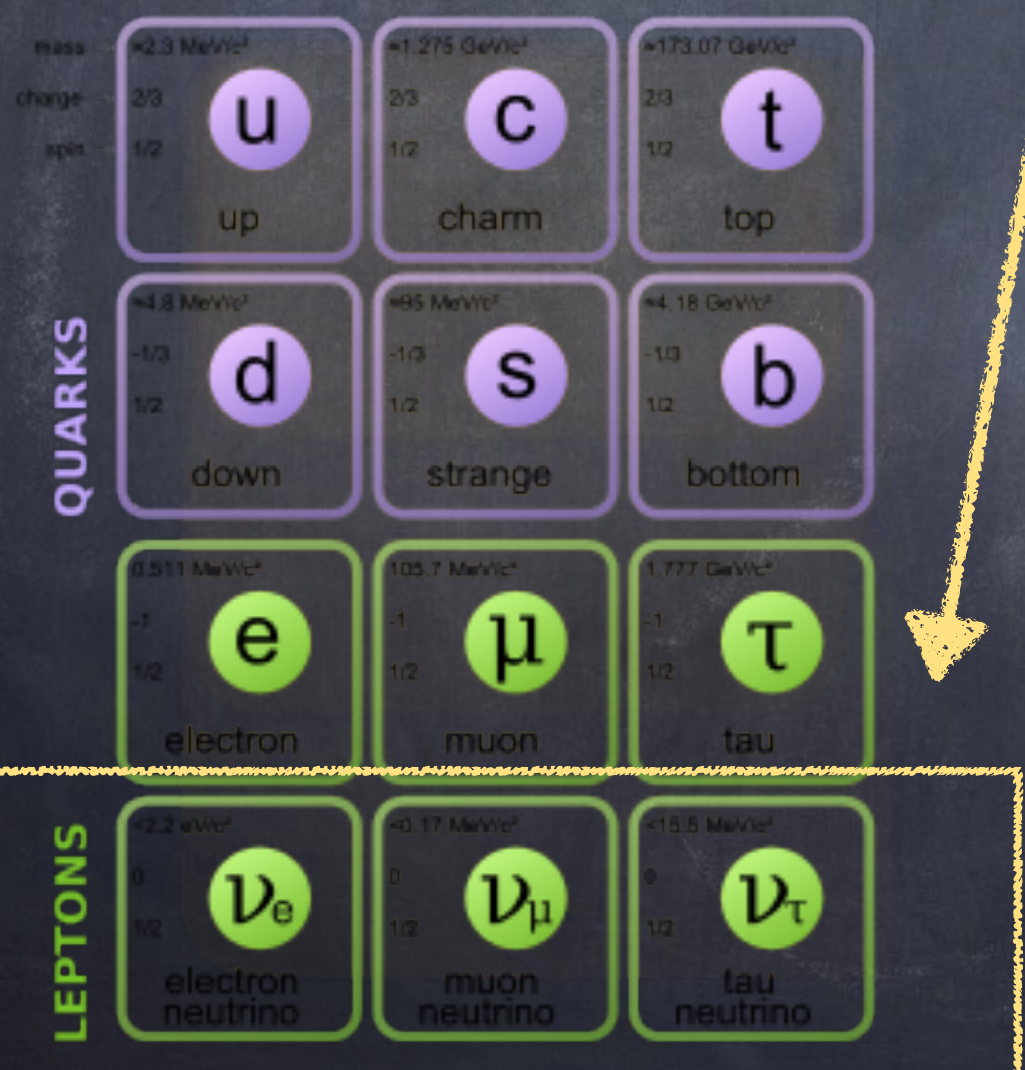


The Standard model

fermions

$s = 1/2 * x$

particles of matter



neutrinos are :

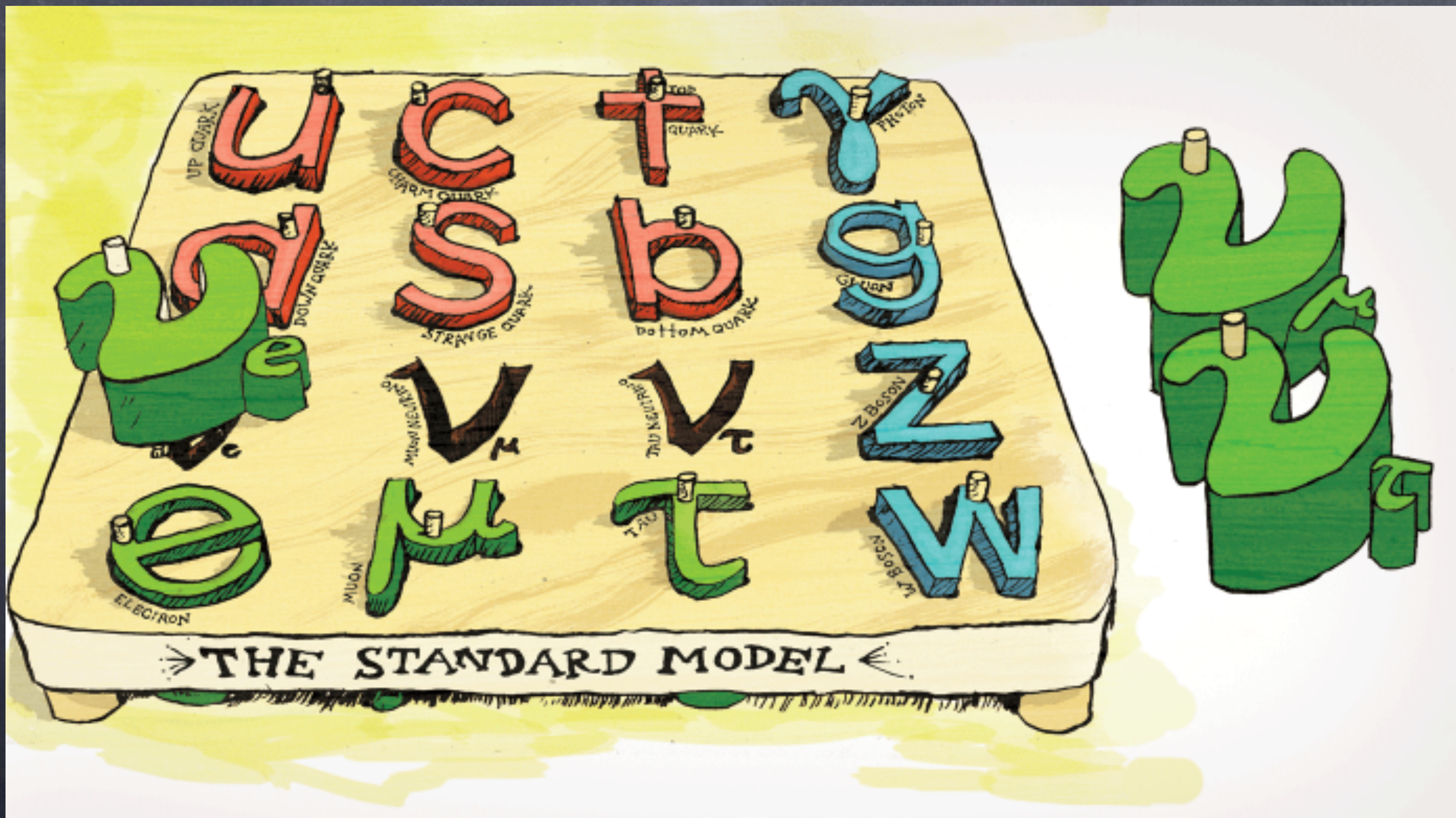
leptons 

neutral particles 

they only feel the weak and gravitational force

> 1 000 000 lighter than electrons!
So far, any experiment could measure their mass

The Standard Model



A bit of history..

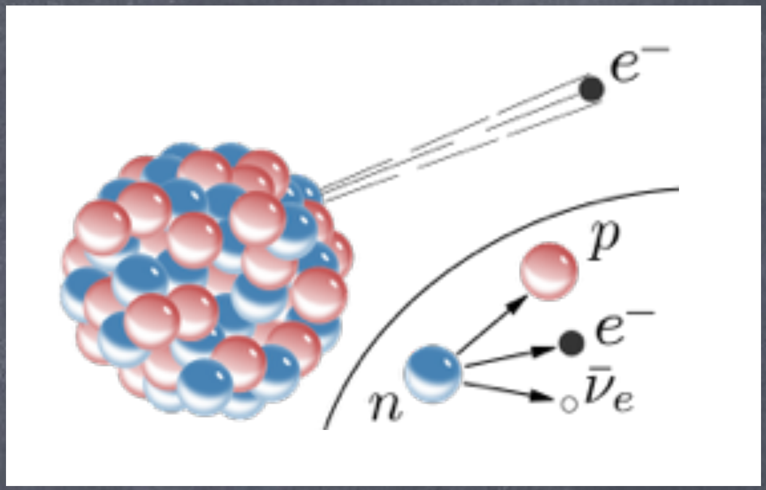
The radioactivity

1900- 1930 "radioactive years"

- 1896 Becquerel : accidental discovery of the radioactivity in the Uranium while studying fluorescence (Nobel 1903)
- Pierre and Marie Curie : studies (Nobel 1903)
- 1899 Rutherford : classification of the radioactivity "alpha" and "beta"

The beta decay

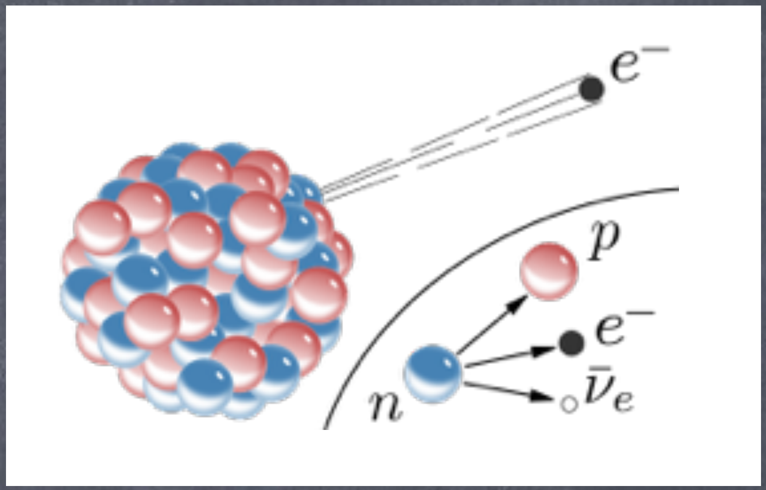
Observed for the first time by M. Curie



$$^{A}_{Z}X \rightarrow ^{A}_{Z+1}Y + e^-$$

The beta decay

Observed for the first time by M. Curie



$${}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + e^-$$

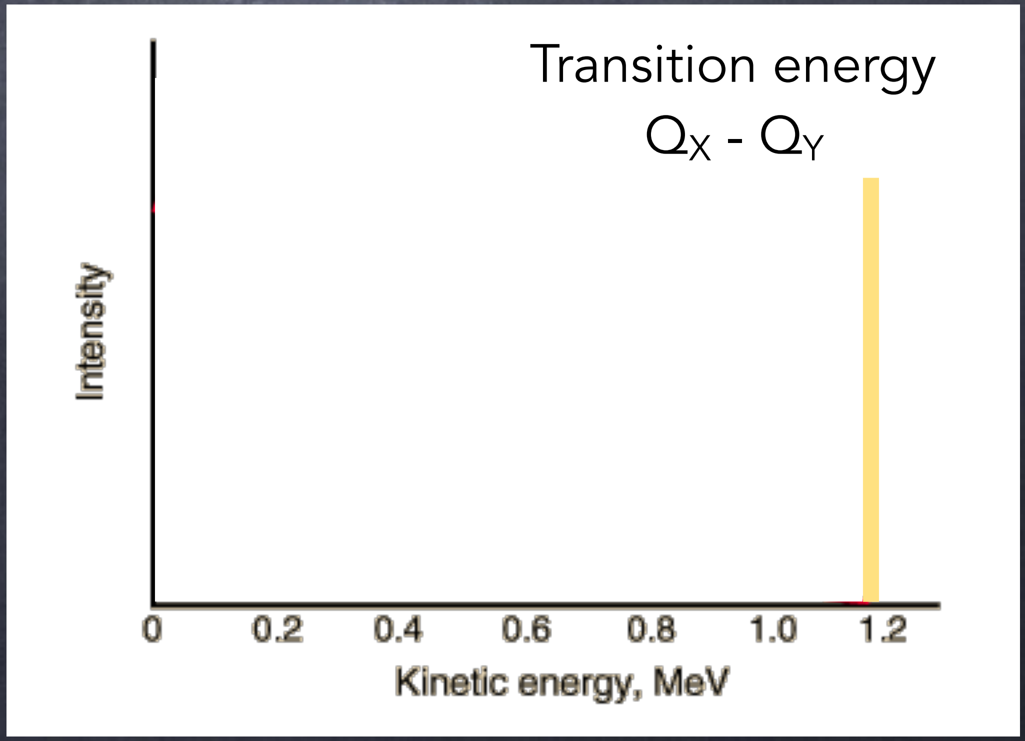
Energy conservation :

$$Q_X - Q_Y = E_e$$

Q_X: energy of the initial nucleus

Q_Y: energy of the final nucleus

E_e: energy of the emitted electron



The beta decay

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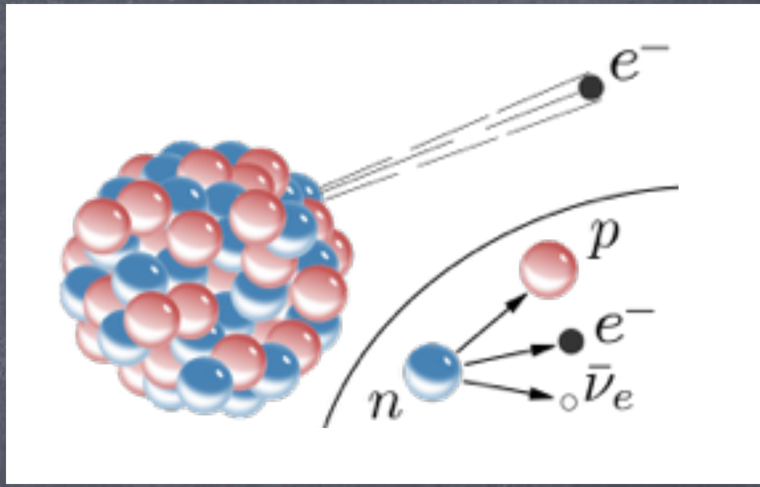
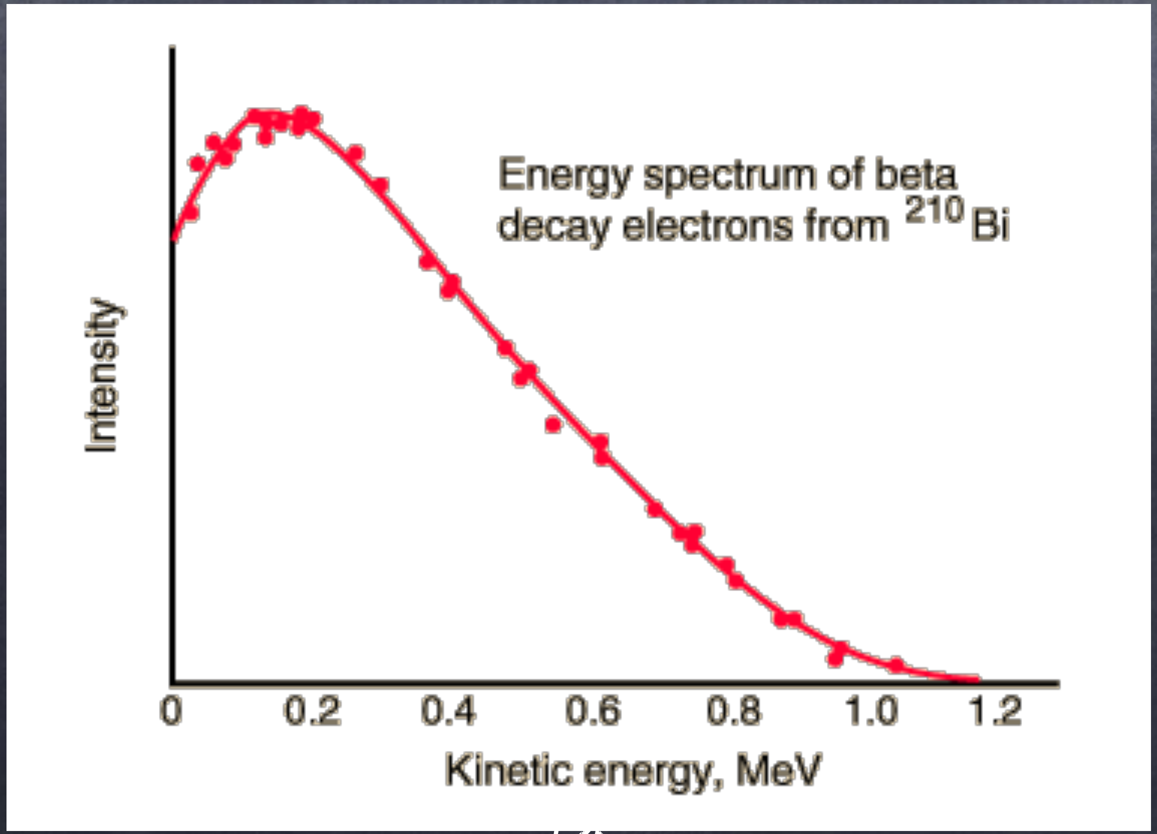


1914: Chadwick observed a continuum spectrum



The beta decay

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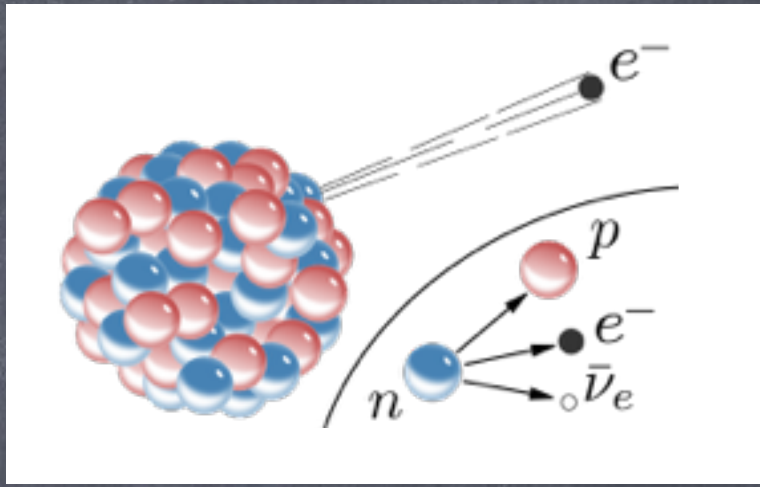


$$ {}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + e^- $$

Energy conservation :

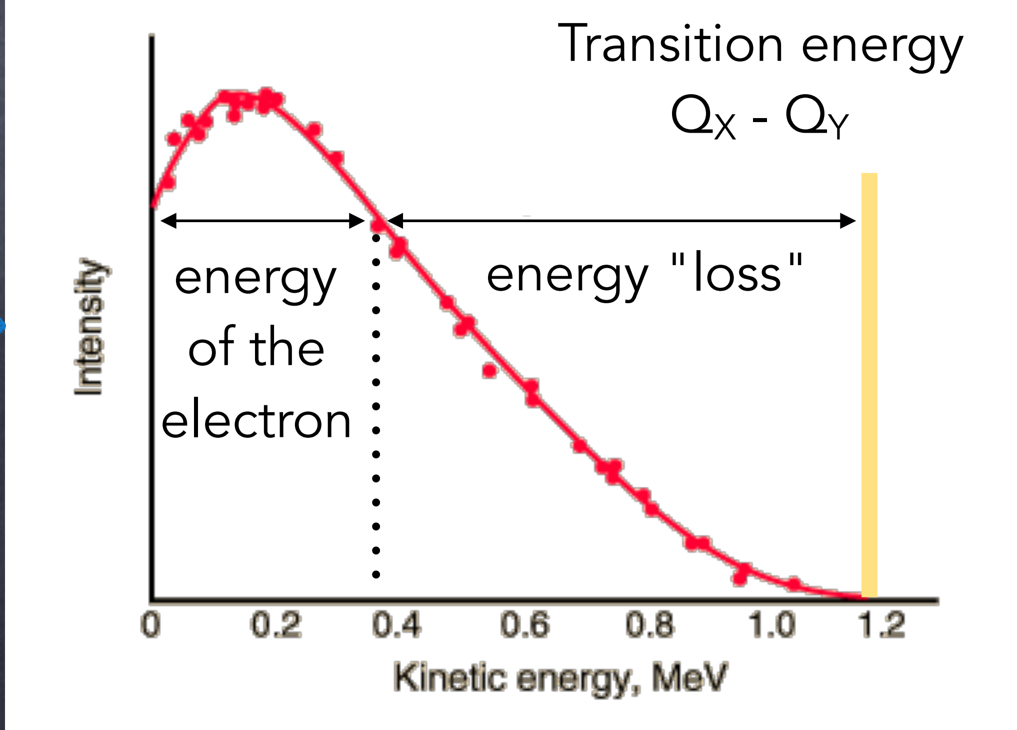
$$ Q_X - Q_Y = E_e + ? $$

energy of the initial nucleus

energy of the final nucleus

energy of the emitted electron

Is there something else?



Neutrinos : a bit of history

N. Bohr: energy is not conserved in the beta decay

W. Pauli: desperate remedy: there's a neutral particle we cannot see and that's taking the energy we do not measure

- 1931 : Pauli postulate the existence of neutrinos

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

Neutrinos : a bit of history

N. Bohr: energy is not conserved in the beta decay

W. Pauli: desperate remedy: there's a neutral particle we cannot see and that's taking the energy we do not measure

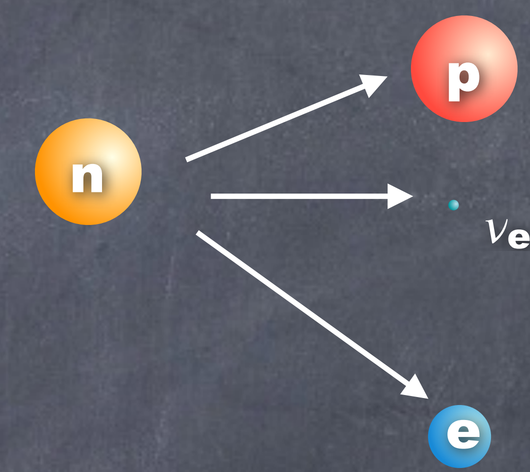
- 1931 : Pauli postulate the existence of neutrinos
- 1934: Fermi propose a theory to explain the existence of neutrinos (weak interaction)

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

Neutrinos : a bit of history

- neutrinos are produced by beta decay

$$n \to p + e + \bar{\nu}$$

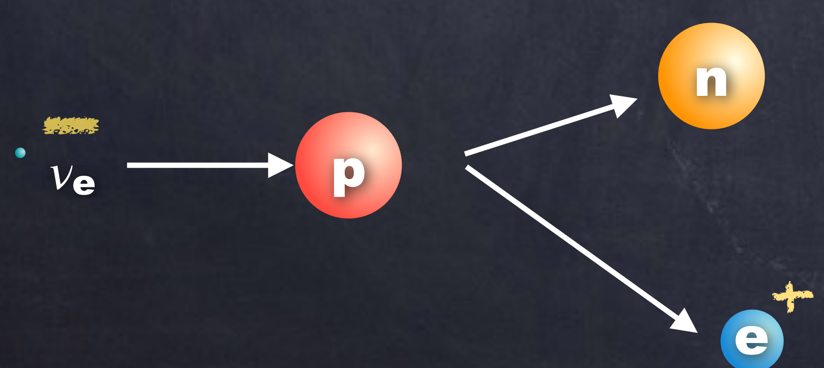


atomic bomb : $\sim 10^{40}\ \nu$ / s x cm^2

nuclear reactors : $5 \times 10^{13}\ \nu$ / s x cm^2

- 1934 Bethe: if the beta decay exists, than also the opposite should exist too!

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



Neutrino discovery

- 1956 - Cowan and Reines: Let's use a nuclear bomb...

Neutrino discovery

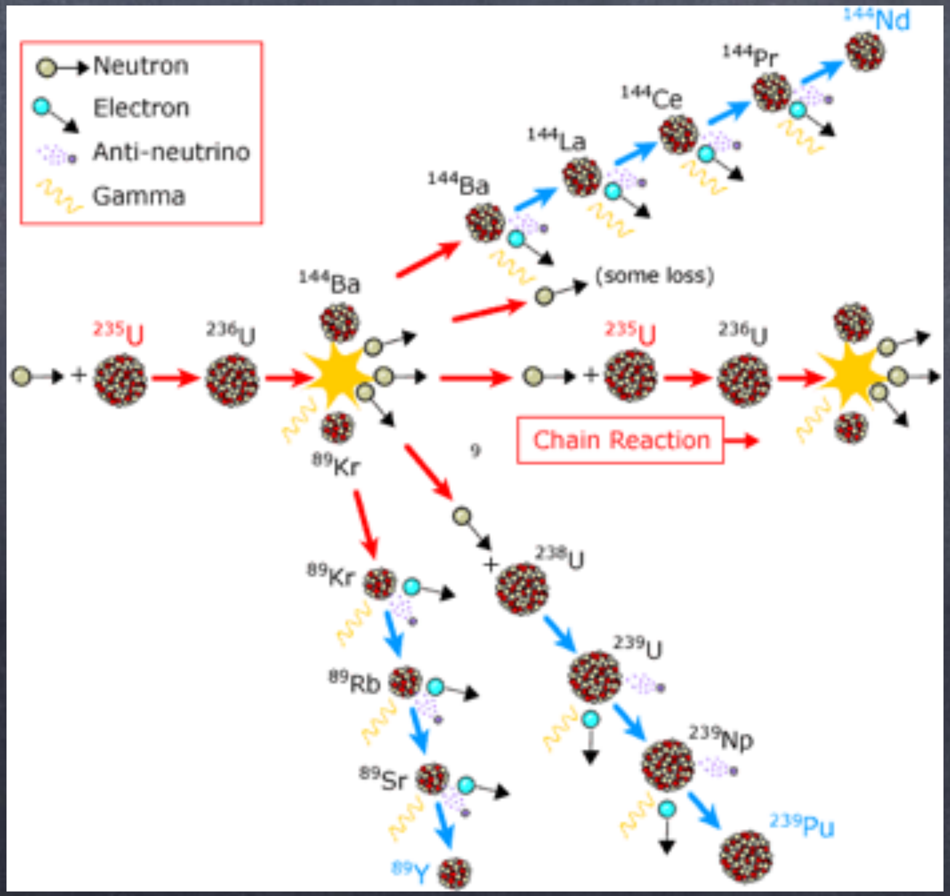
- 1956 - Cowan and Reines: Let's use a nuclear bomb… …

Neutrino discovery

- 1956 - Cowan and Reines: Let's use a nuclear bomb... ... ...

The Neutrino discovery

- 1956 – Cowan and Reines: ok, well, .. let's use a nuclear reactor

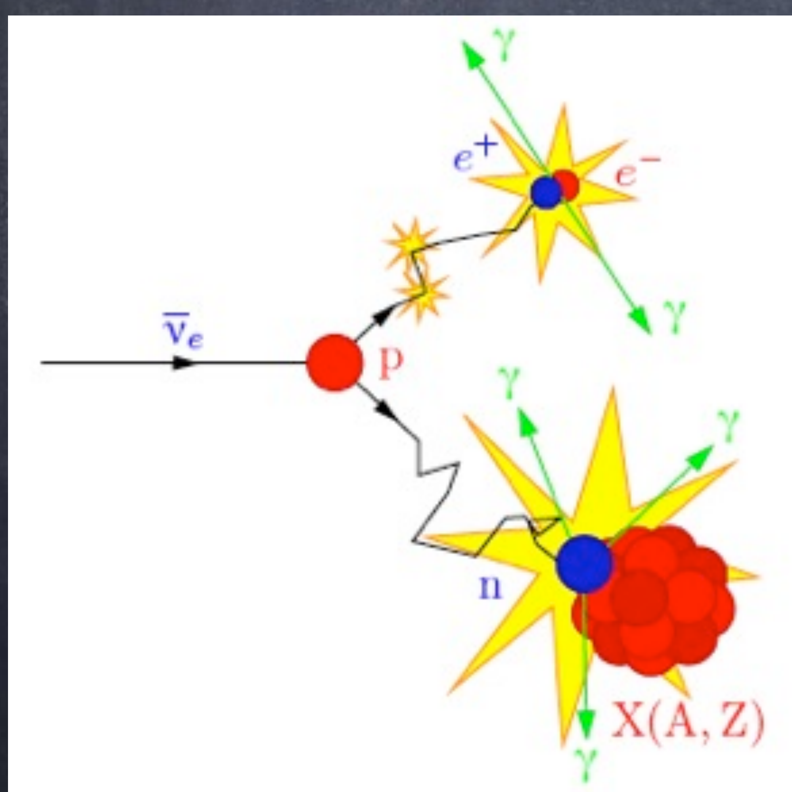


The Neutrino discovery

- 1956 - Cowan and Reines: Let's use a nuclear reactor

Nobel Prize 1995

  - two photons from the positron annihilation
  - a photon from the neutron capture (5μs later)



- Where we can find neutrinos?
- why ghostly particles ?

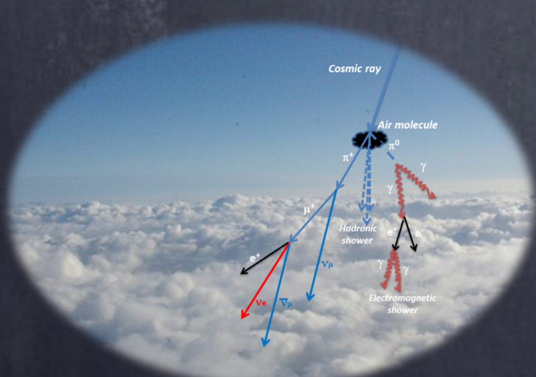
Where we can find neutrinos ?

some natural sources

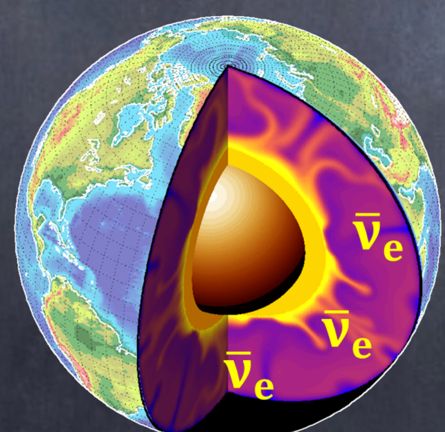
330 ν/cm^3 with E_ν ~4 μeV

~10^{58} ν in a few sec
with E_ν ~10-15 MeV

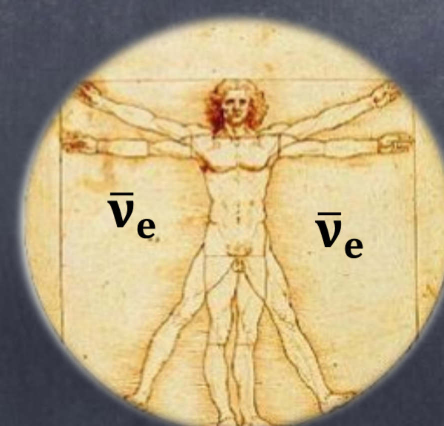
~6.5 10^{15} ν/m^2/sec earth surface
with E_ν ~0.3-3 MeV



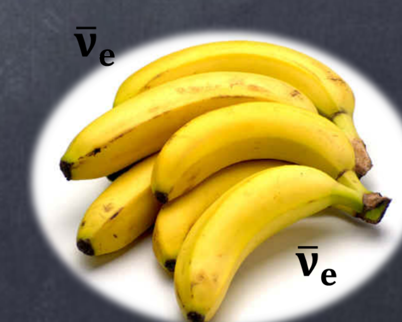
Earth Atmosphere



U, Th and K in the earth crust
~5 10^{10} ν/m^2/sec



~20 mg ^{40}K, ~340 millions ν/day

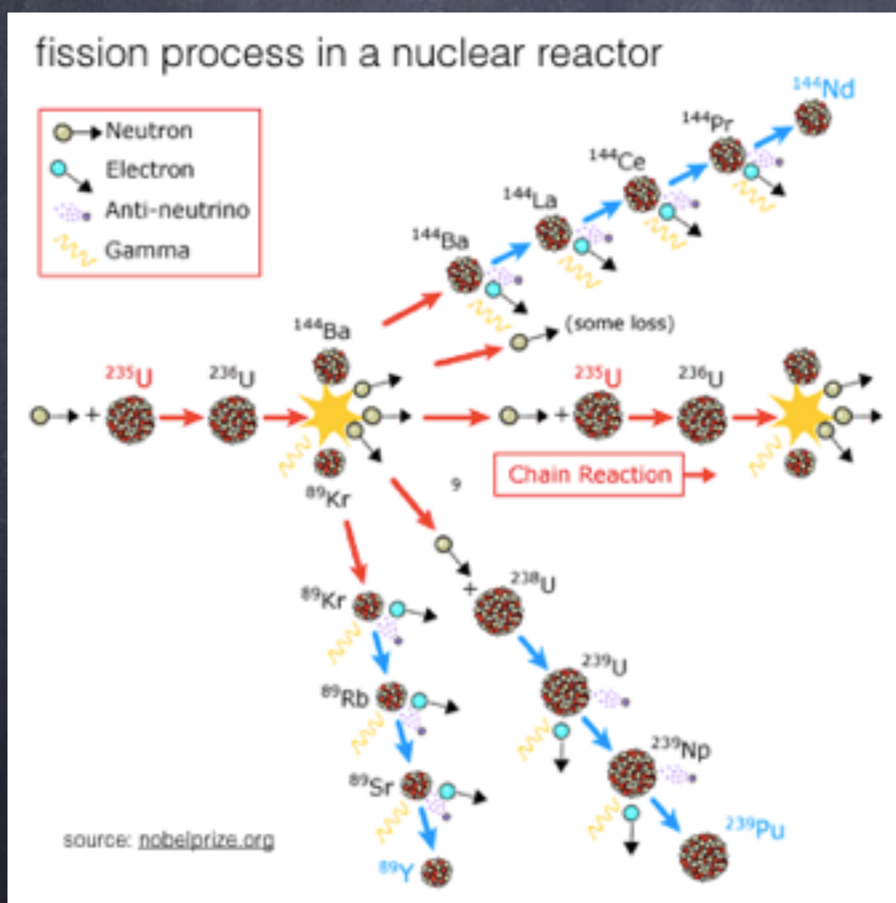


^{40}K in Banana ~5 millions ν/day

Where we can find neutrinos ?

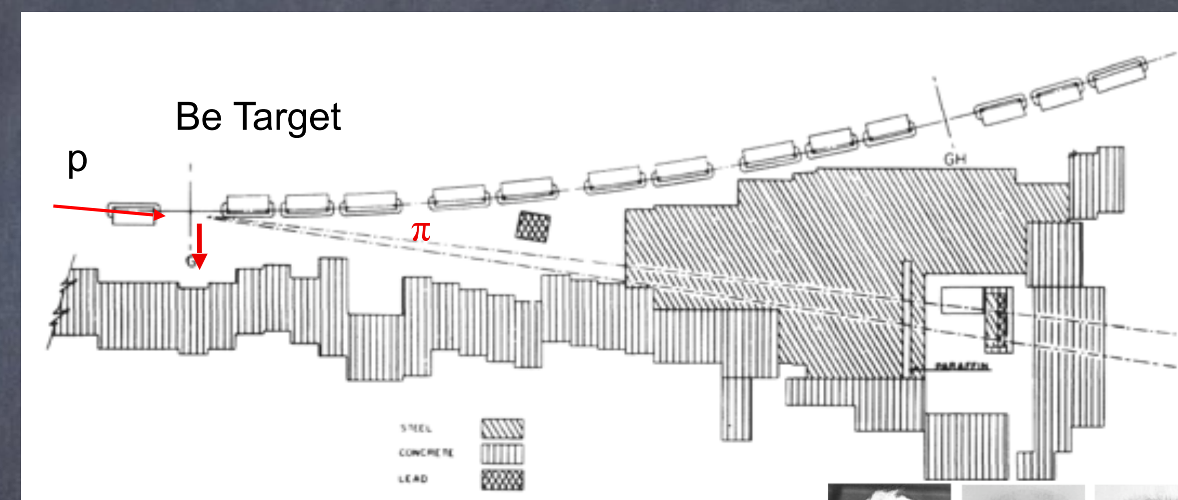
.. or "hand-made"

nuclear reactors



almost a billion of billion (10^{20}) de ν / cm²/s

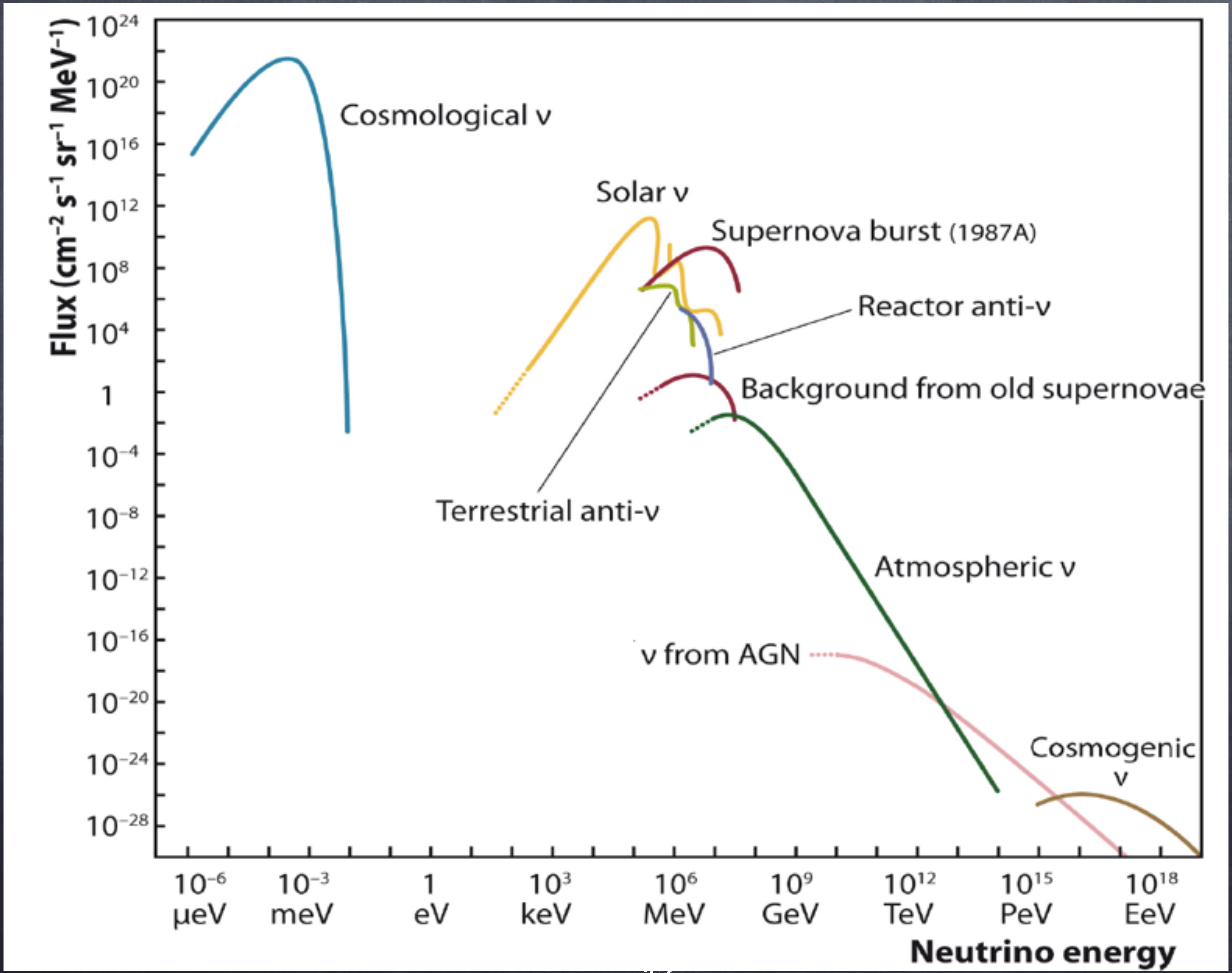
Particle accelerator



Phys.Rev.Lett. 9, 36 (1962)

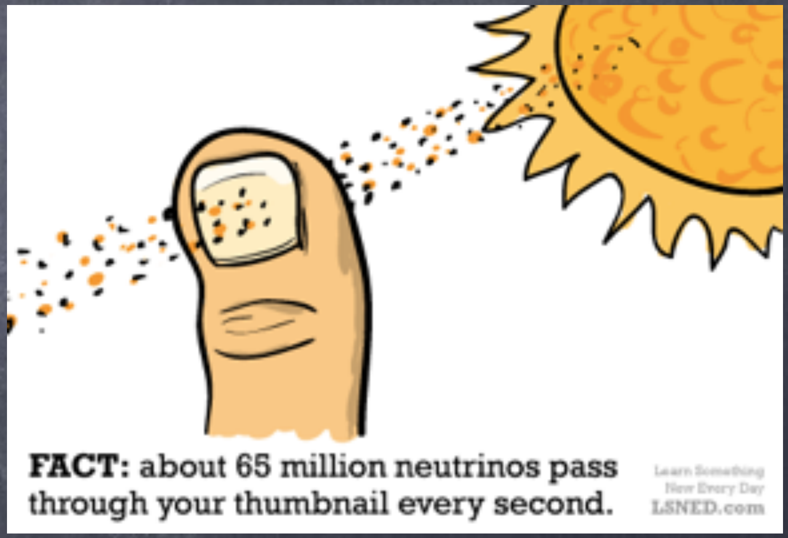
Lederman, Schwartz, Steinberger

The wide neutrino energy spectrum



Ghostly particles

- 100 trillions of neutrinos pass through our body every second
- approximately in all our life, only one neutrino interacts in our body



Ghostly particles :

- electrically neutral
- most abundant particle of the Universe
- they react very very rarely

Why it's so difficult to see them?

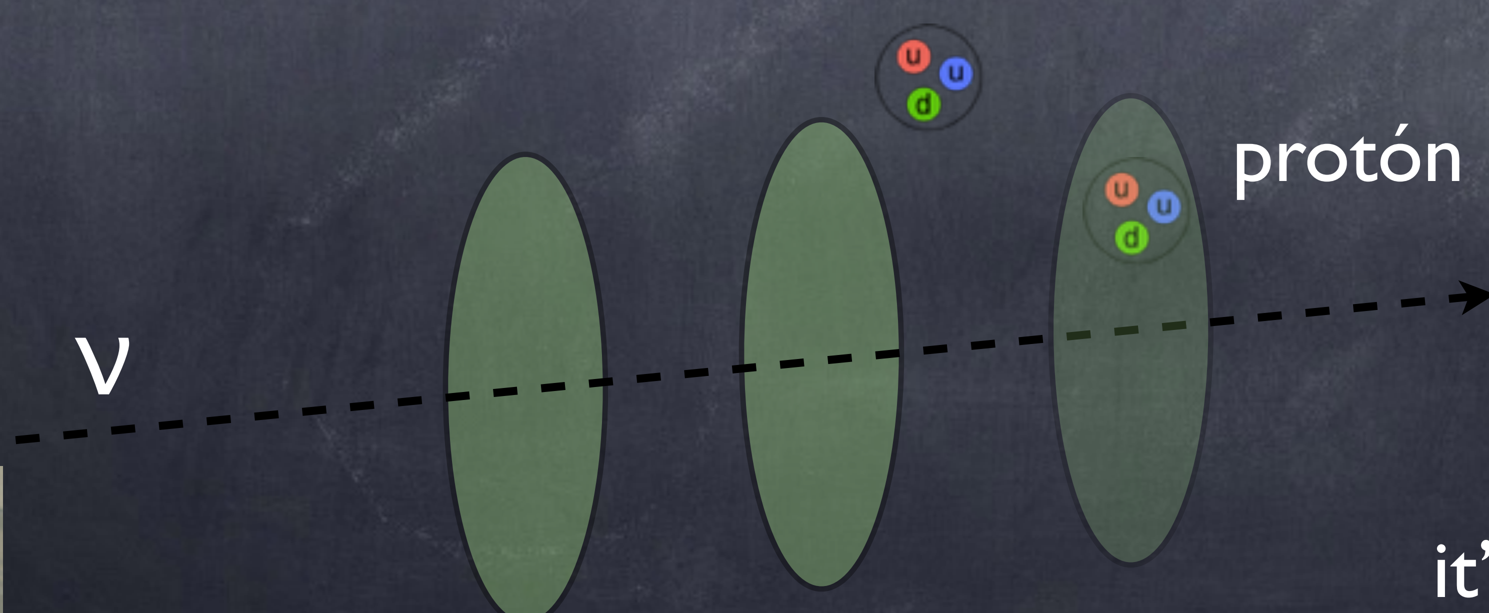
- In quantum physics, each process has a given probability P to happen
- If we want to observe some process, we need to try it N times as that: $N \times P \sim 1$

$P = 1/2 \rightarrow N = 2$

Why it's so difficult to see them?

In particle physics this probablity is called <u>cross section</u>: effective surface of the incident particle

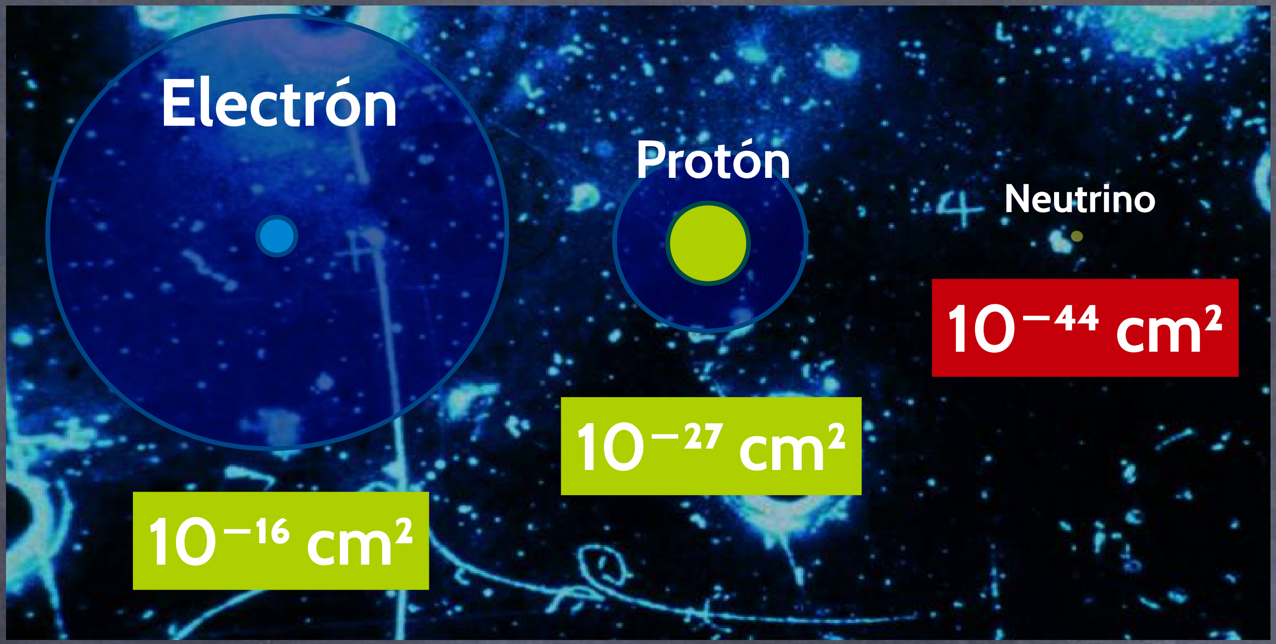
What is the probability that the incident particle see (interact) the particle target??



it's measured in cm^2

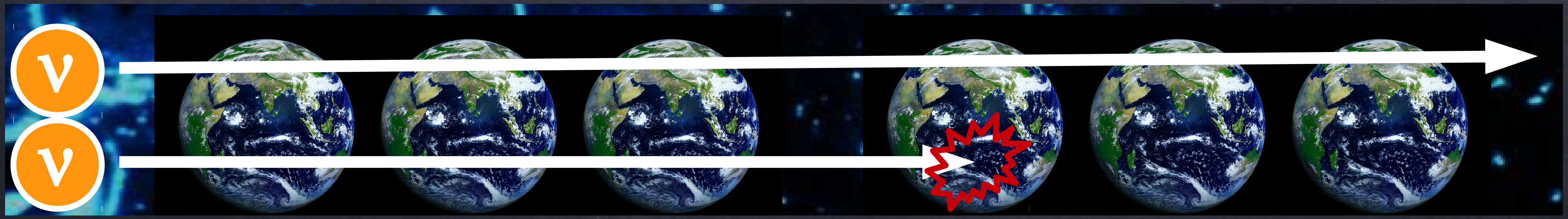
Why it's so difficult to see them?

Neutrinos cross section : 10^{-44} cm^2 !!



It's similar to :

even crossing 1 trillion (10^{12}) of trillion of Earths only half of the neutrinos would interact



How do we detect them?

- As neutrinos interact very very rarely, to have a probability of success ~ 1 :

Number of neutrino interactions	=	cross section	x	N thrown particles	x	N target particles

How do we detect them?

- As neutrinos interact very very rarely, to have a probability of success ~ 1 :

Number of neutrino interactions = cross section × N thrown particles × N target particles

- cross section → ~ 10^{-44} cm^2
- N thrown particles → As LARGE as possible ~10^{21}
- N target particles → usually very very large
  10^{23} N atoms in 1 gram of matter

How do we detect them?

- As neutrinos interact very very rarely, to have a probability of success ~ 1 :

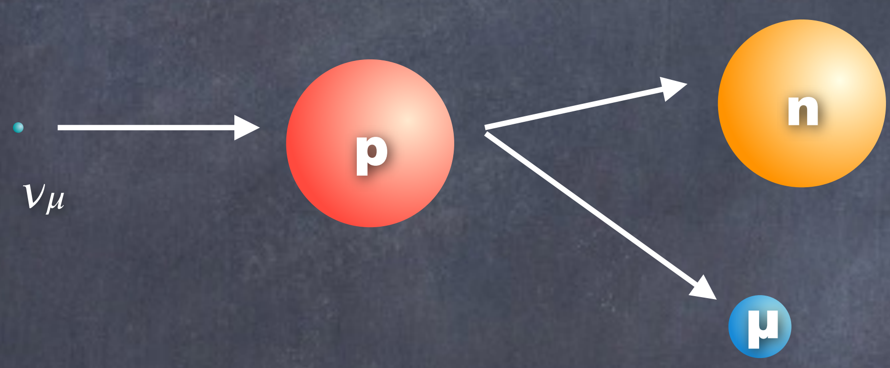
Number of neutrino interactions	=	cross section	x	N thrown particles	x	N target particles
		~ 10^{-44} cm^2		As LARGE as possible ~10^{21}		usually very large 10^{23} N atoms in 1 gram of matter

To detect neutrinos, we need:

- a very intense beam
- very large detectors
- time (a lot of patience!)

How do we detect them?

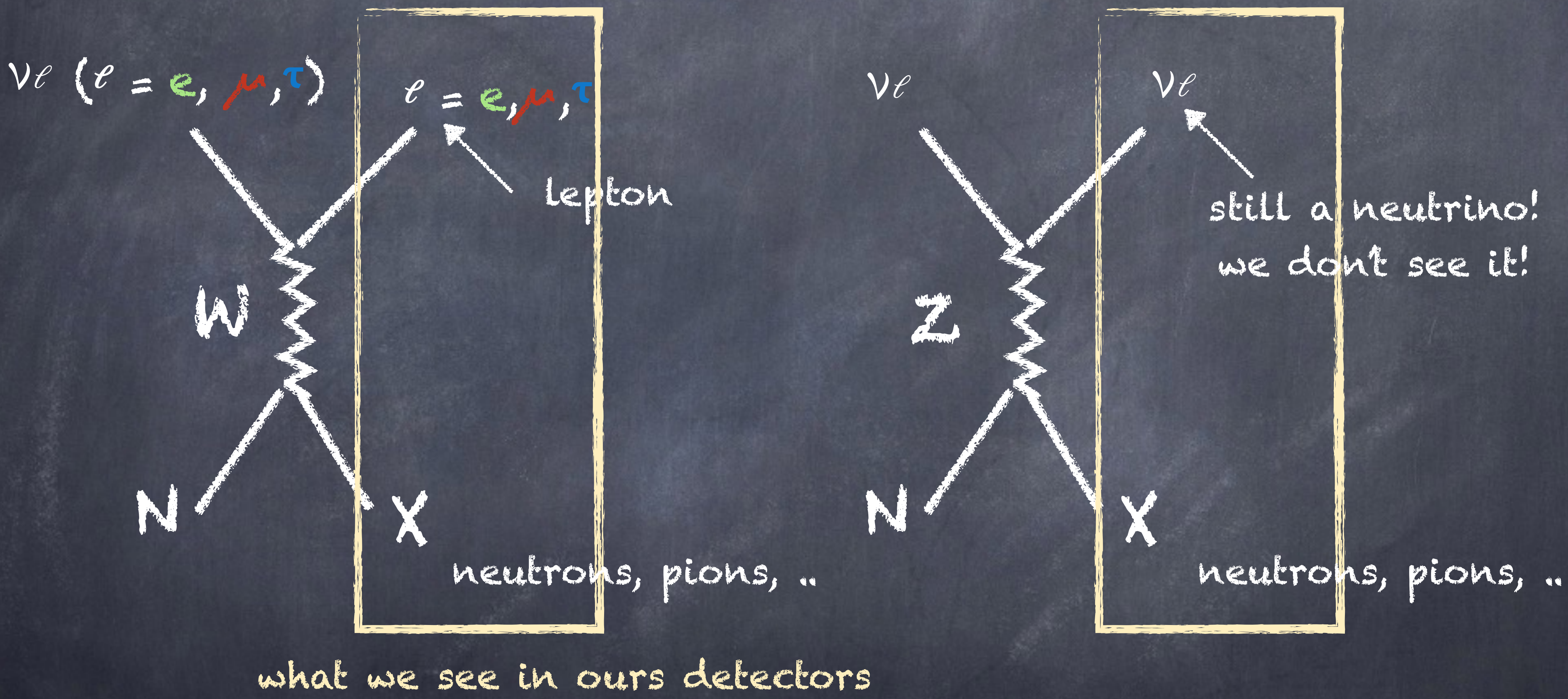
- We always detect the product of the interaction
- if the interaction produce a lepton, from its flavour we can deduce the flavour of the neutrino



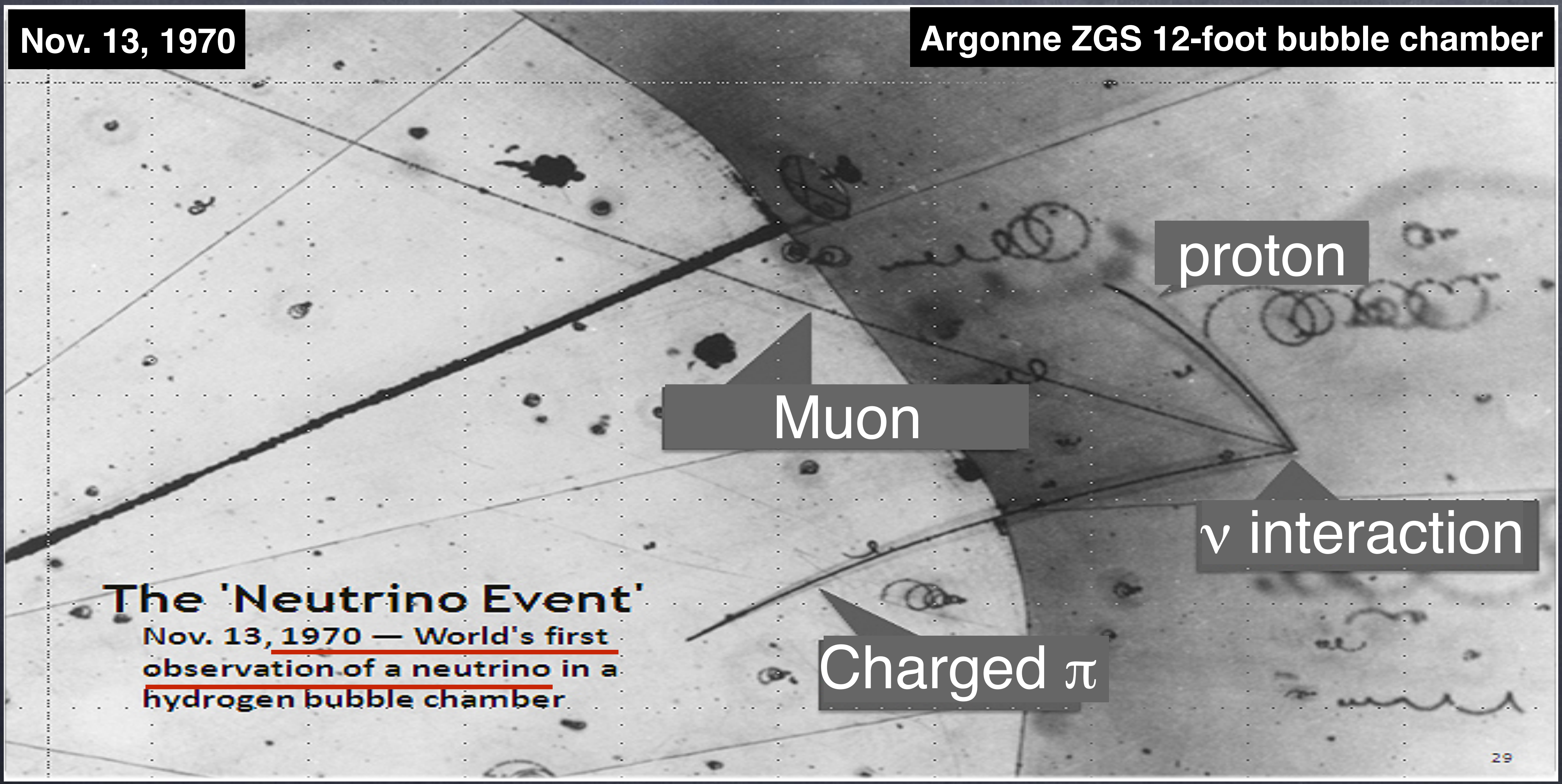
- $E = mc^2$
- Energy conservation (and mass)

If the energy (of the neutrino) is not enough, the heaviest leptons cannot be produced

Neutrino interactions



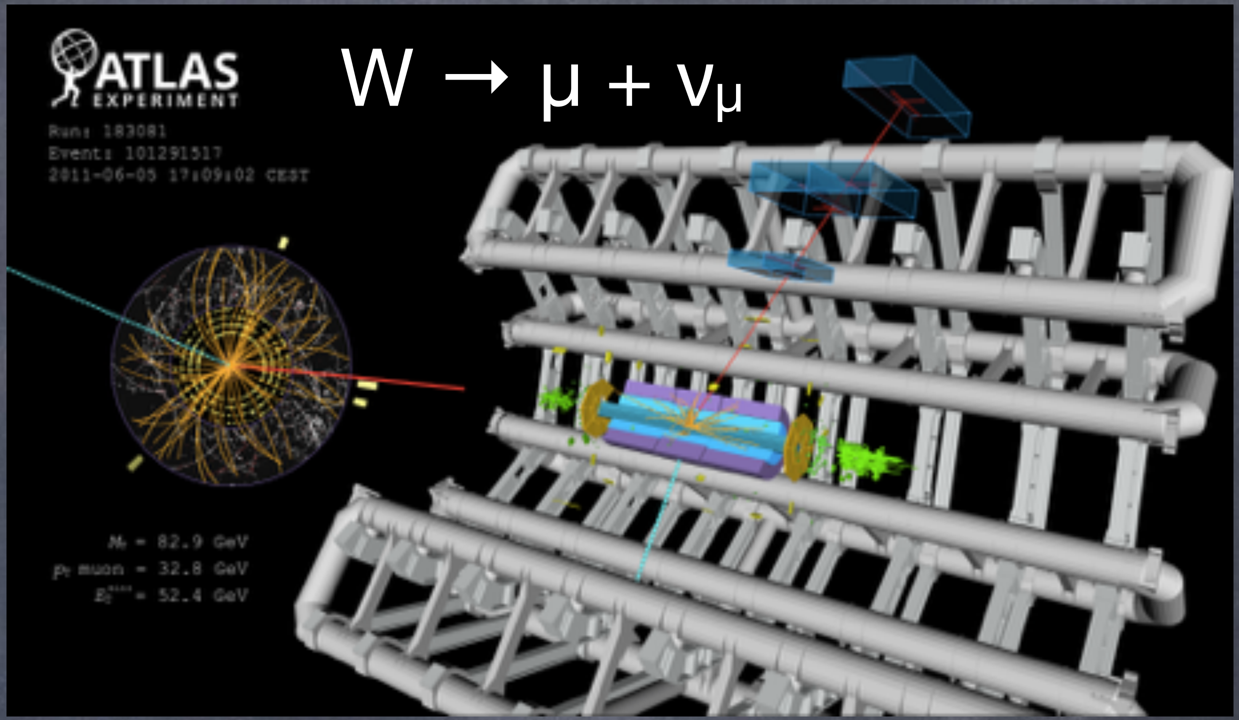
How do we see them?

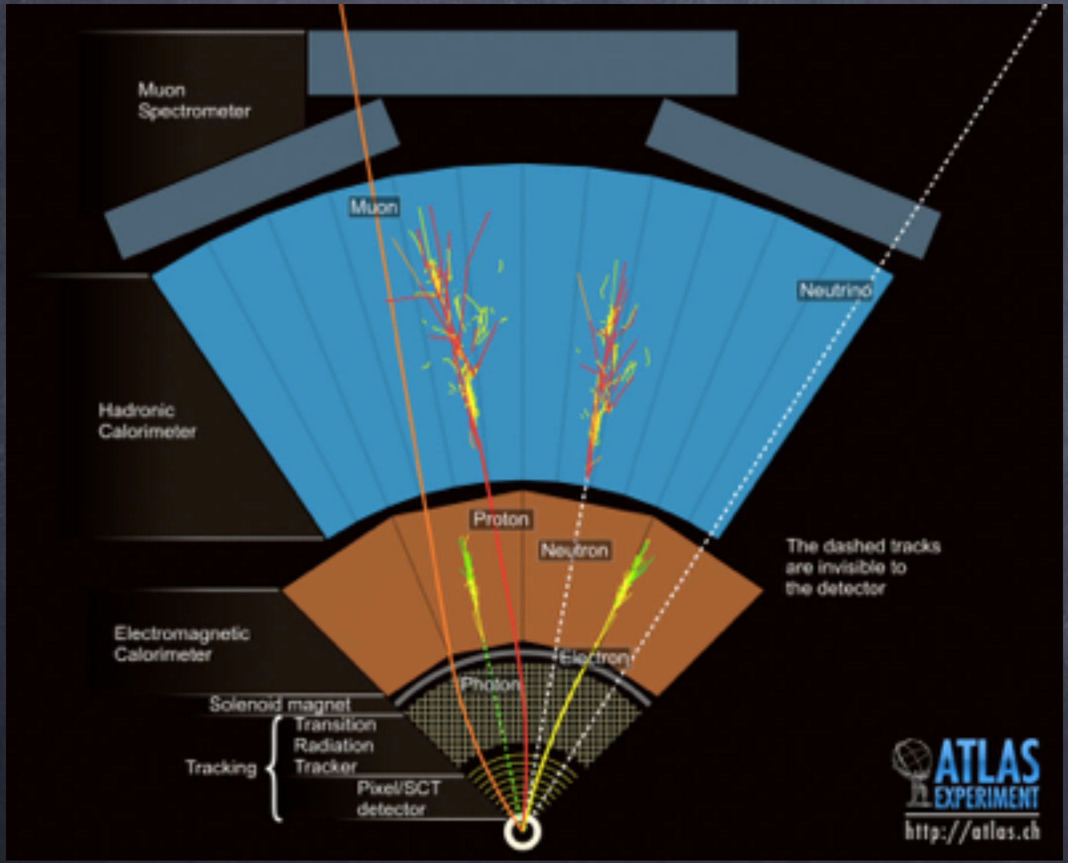


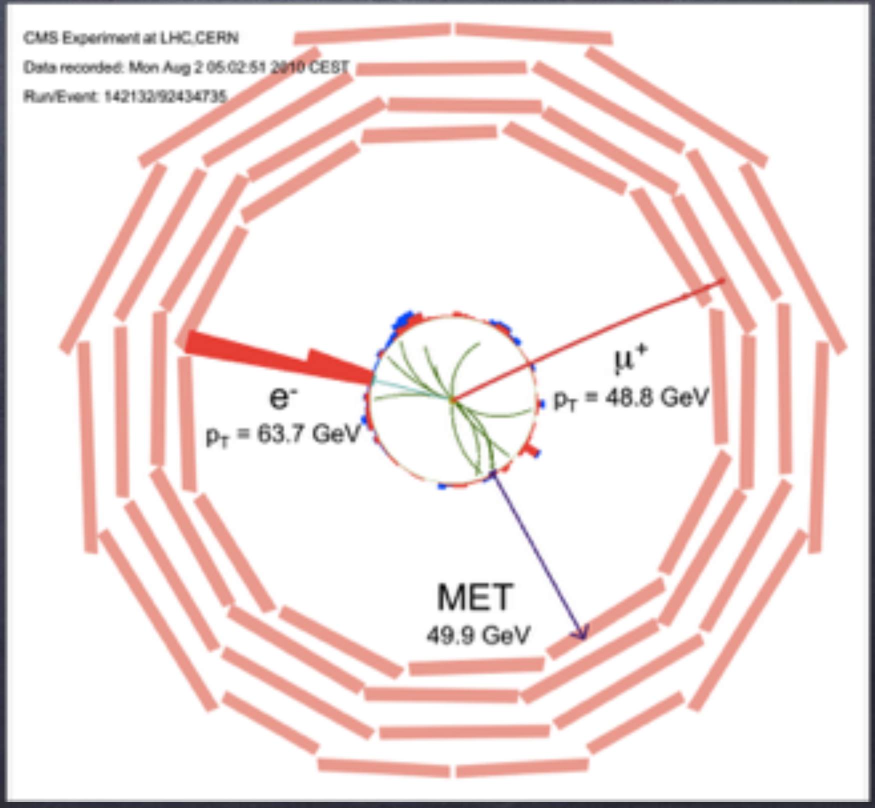
How do we see them?

At ATLAS and CMS neutrinos are invisible :

"missing energy" (MET)





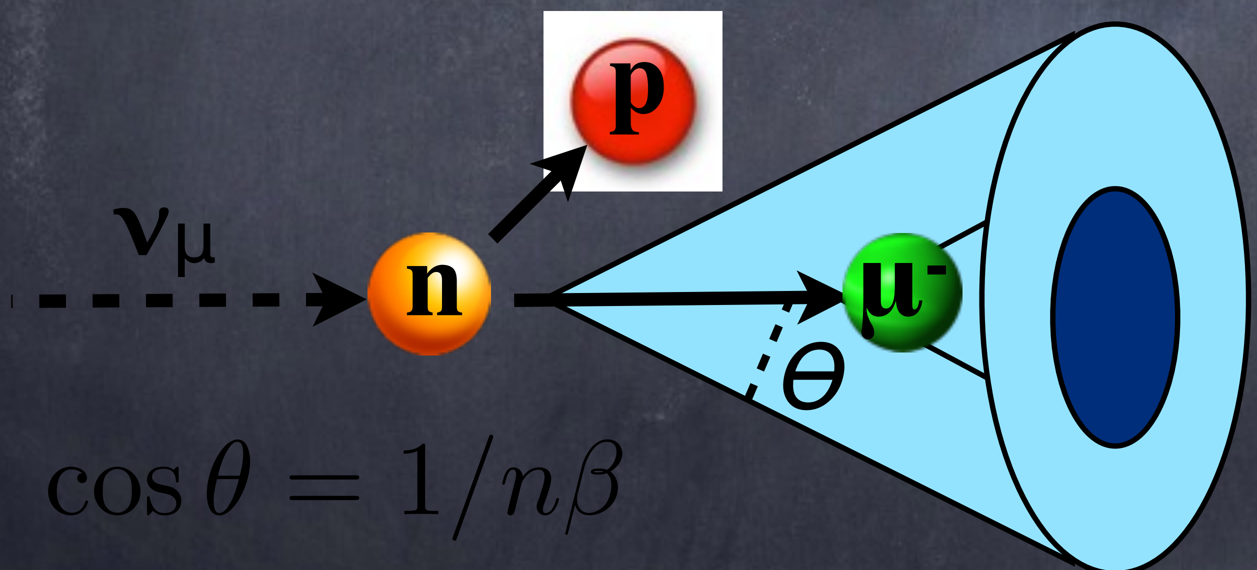


$H \rightarrow W^+ W^- \rightarrow \mu + \nu_\mu + e + \nu_e$

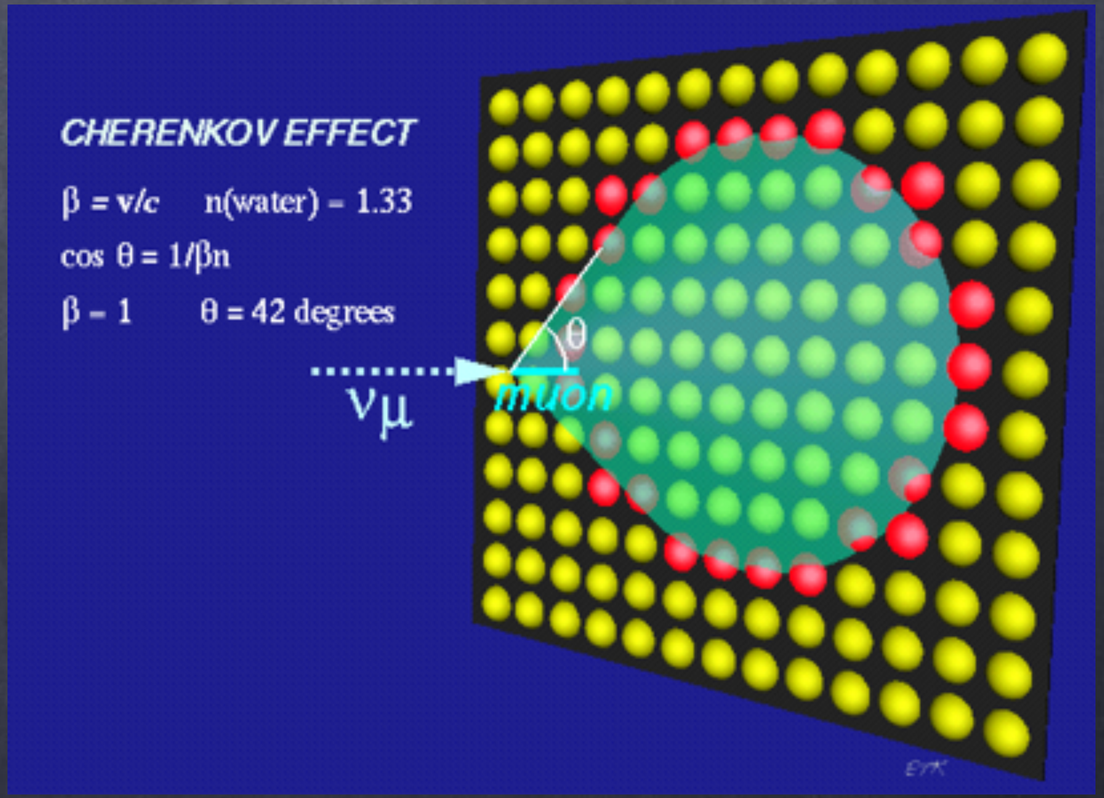
How can we see them?

exemple: <u>Cherenkov radiation</u>

particles who travel in a medium faster then the light in that medium emit a cone of light



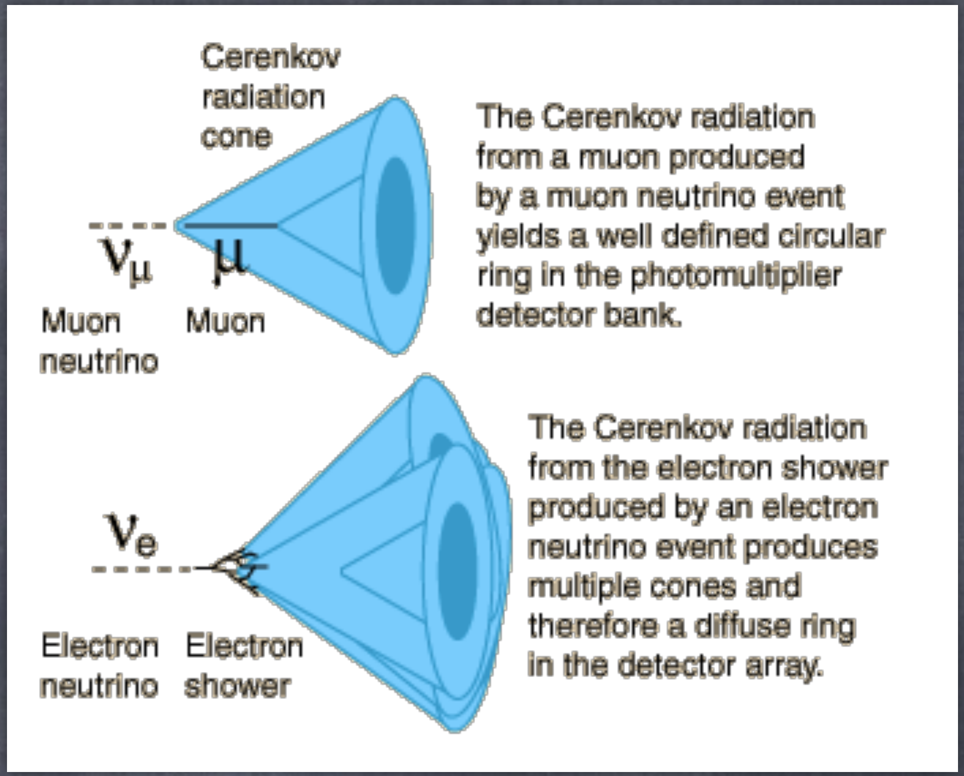
$$\cos\theta = 1/n\beta$$



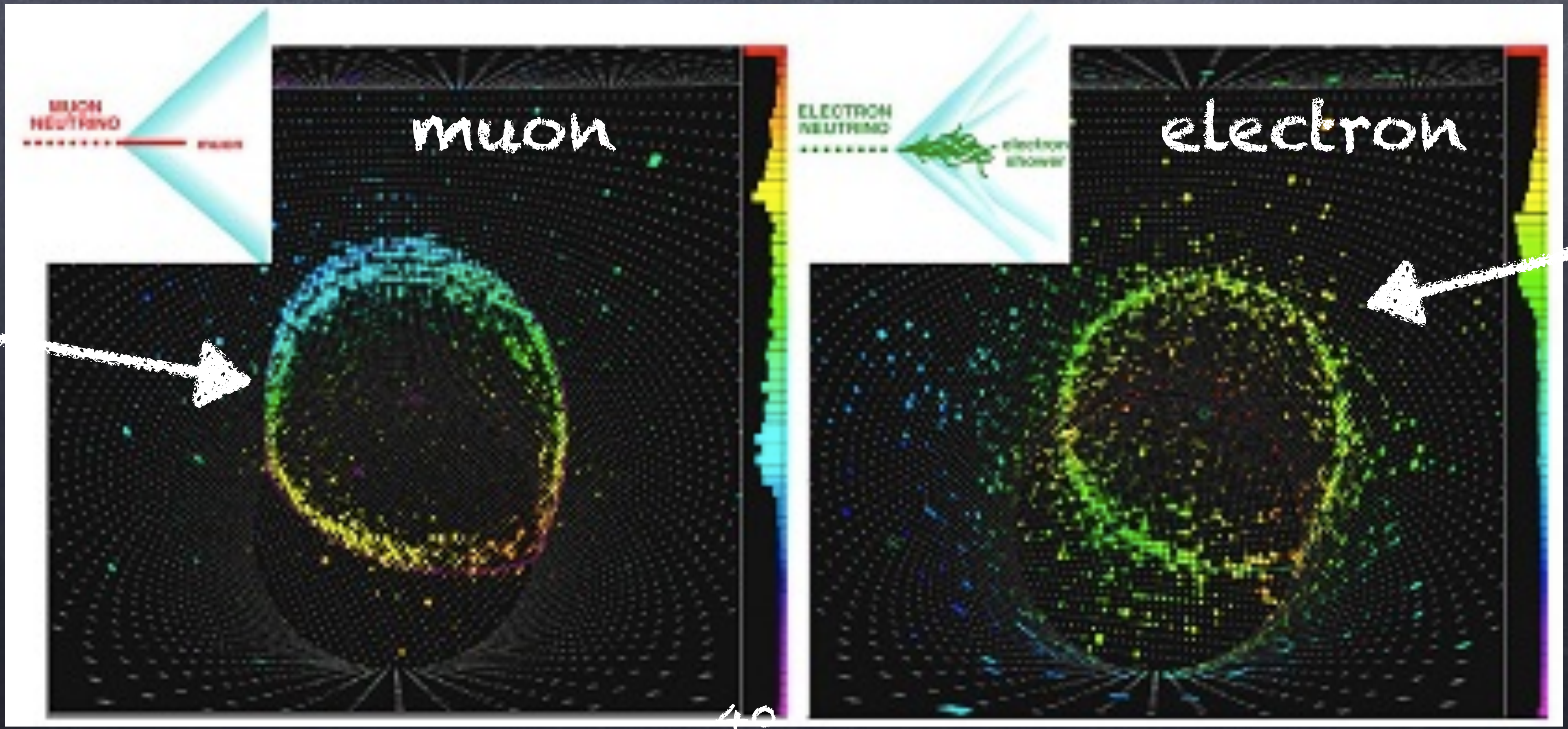
How do we see them?

example: Cherenkov radiation

from the shape of the ring we can disentangle electrons and muons



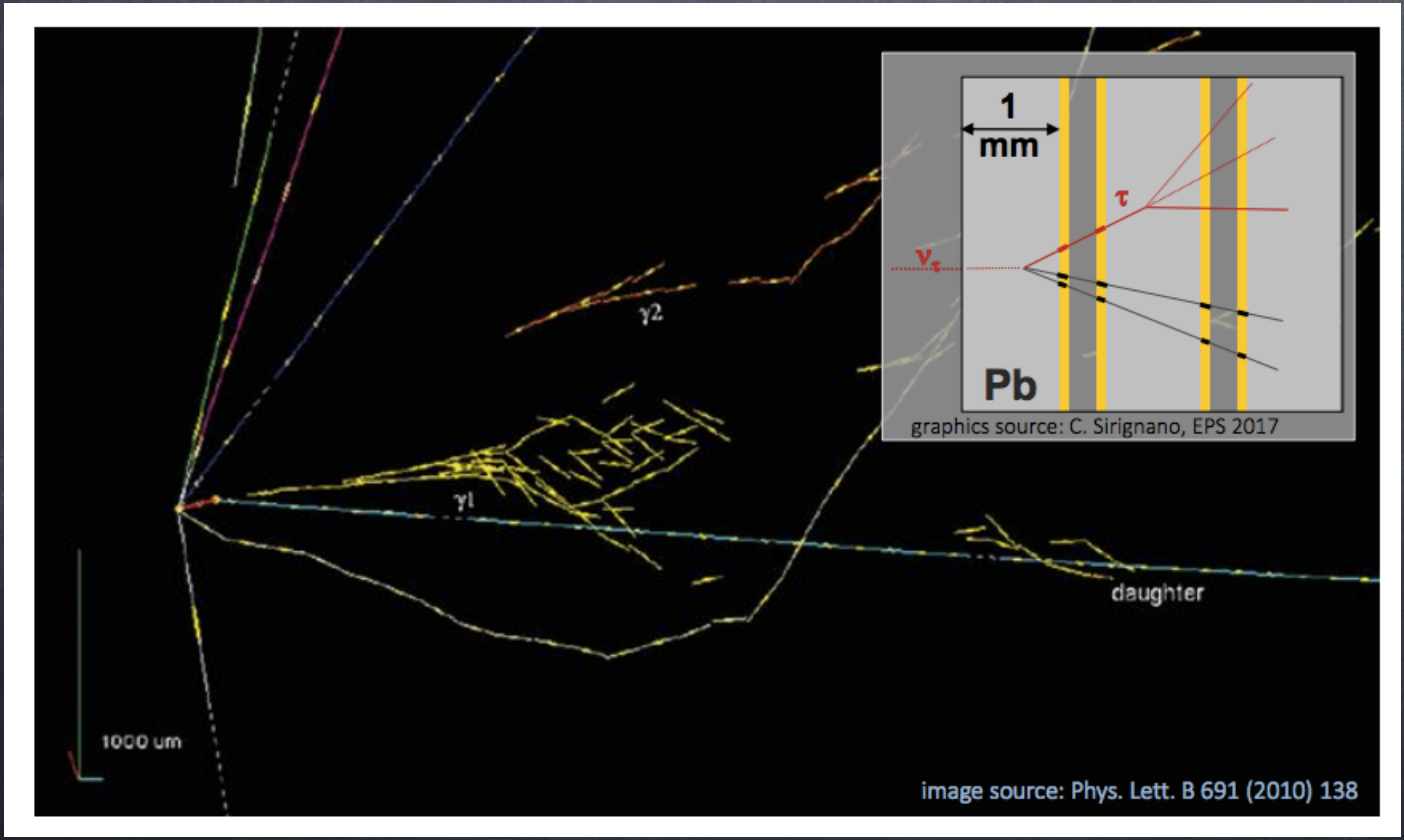
sharp edges



fuzzy edges

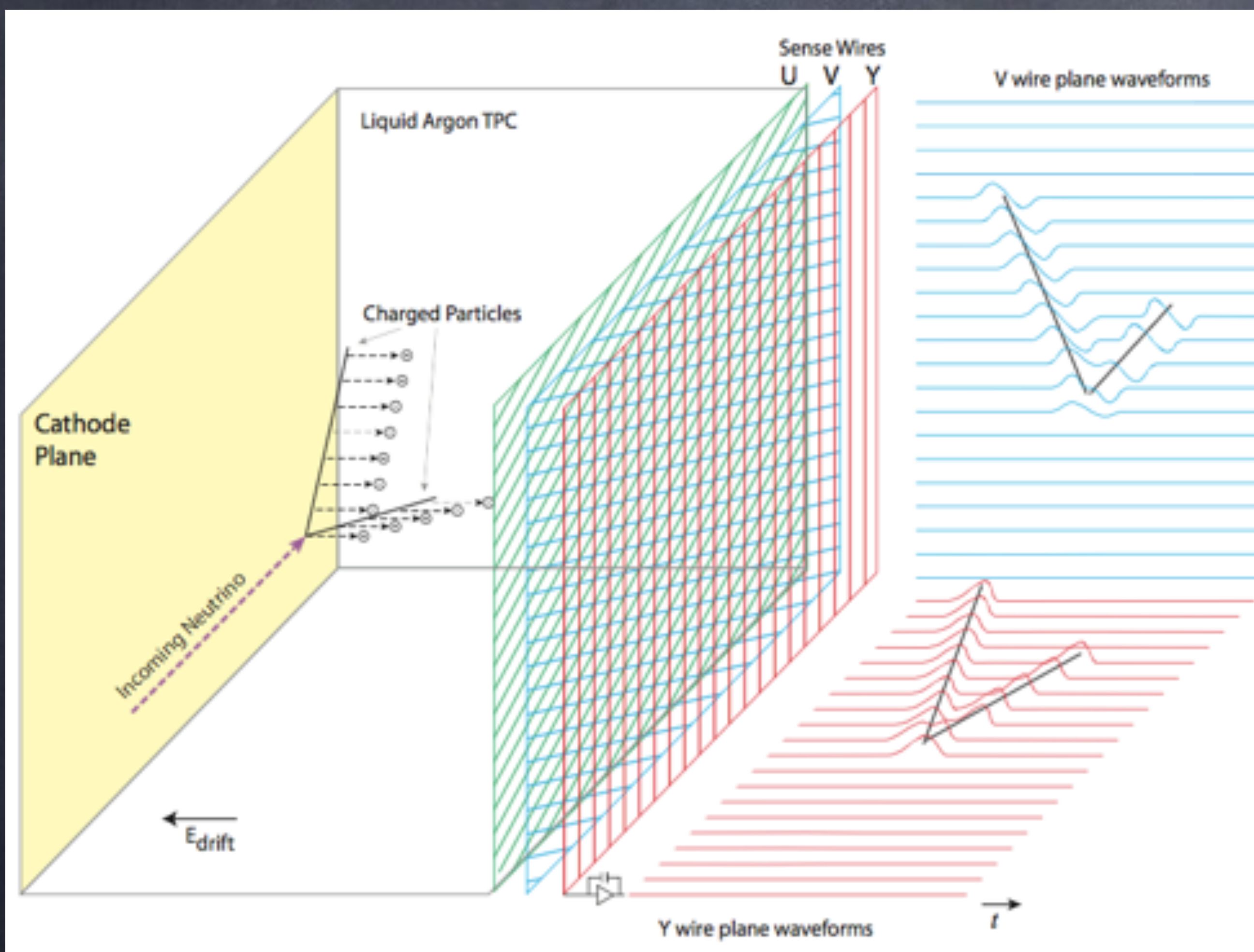
How can we see them?

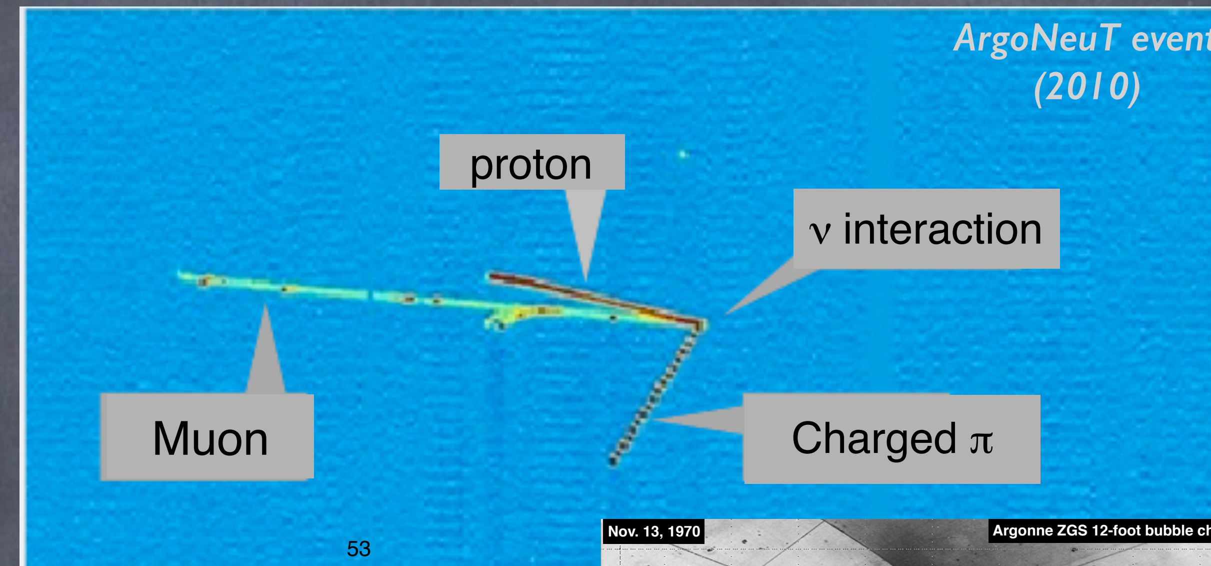
OPERA

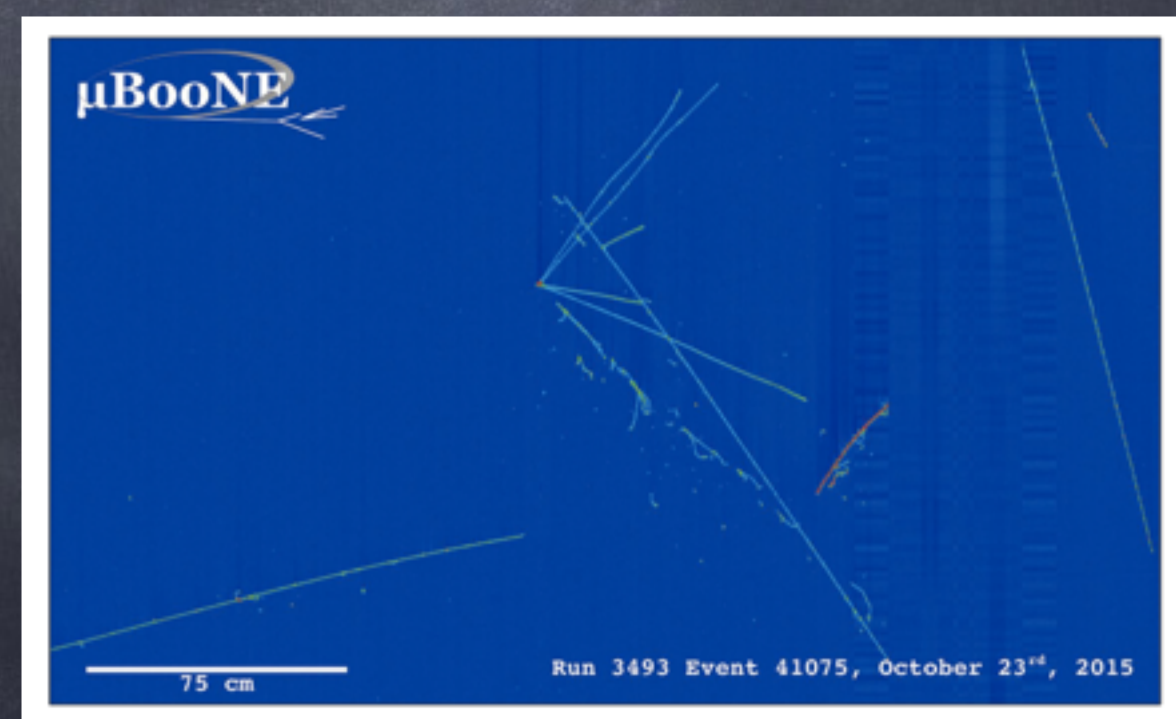


How do we see them?

another example: TPC (Liquid, Gas, ...)







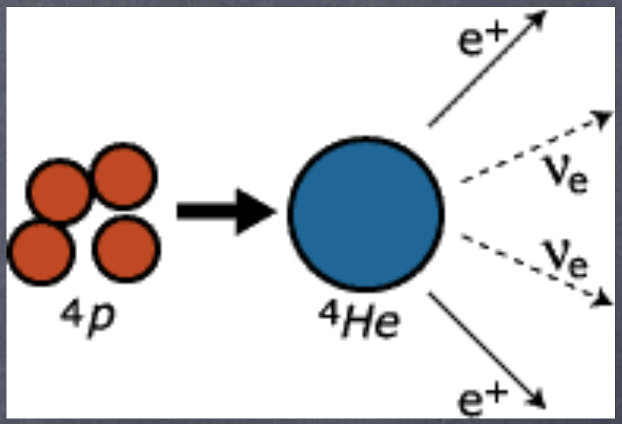
TPC: Time Projection Chamber

Chameleons of the universe

The solar neutrino mystery

- the sun is like a giant nuclear reactor

  $4\ H \rightarrow {}^4He + 2e^+ + 2\nu_e$



- 1968 - R. Davies: verify the solar model with neutrinos

The solar neutrino mystery

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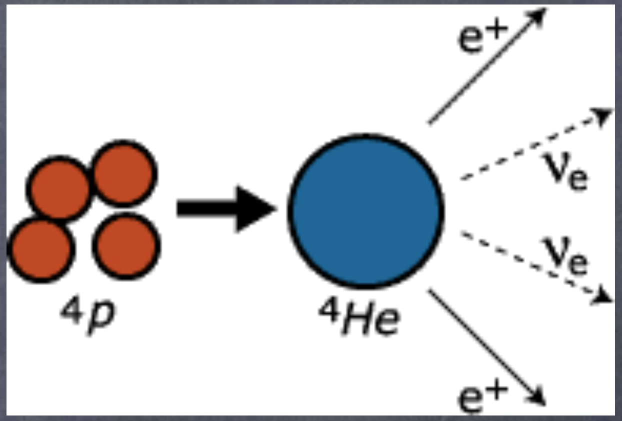
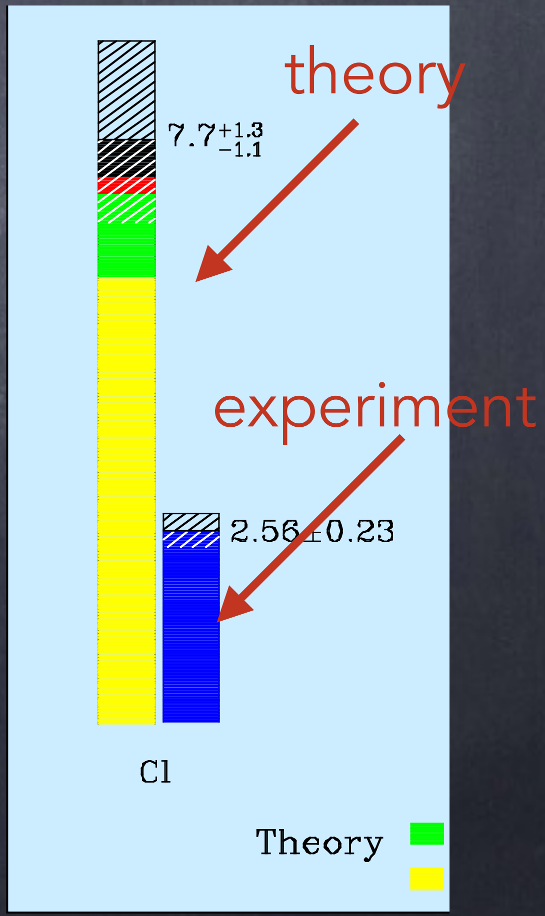


- 1968 – R. Davies: verify the solar model with neutrinos

Experimentally we can see it as the transformation of a nucleus in another nucleus by the interaction of solar neutrinos.

$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^{-}$ o $\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^{-}$

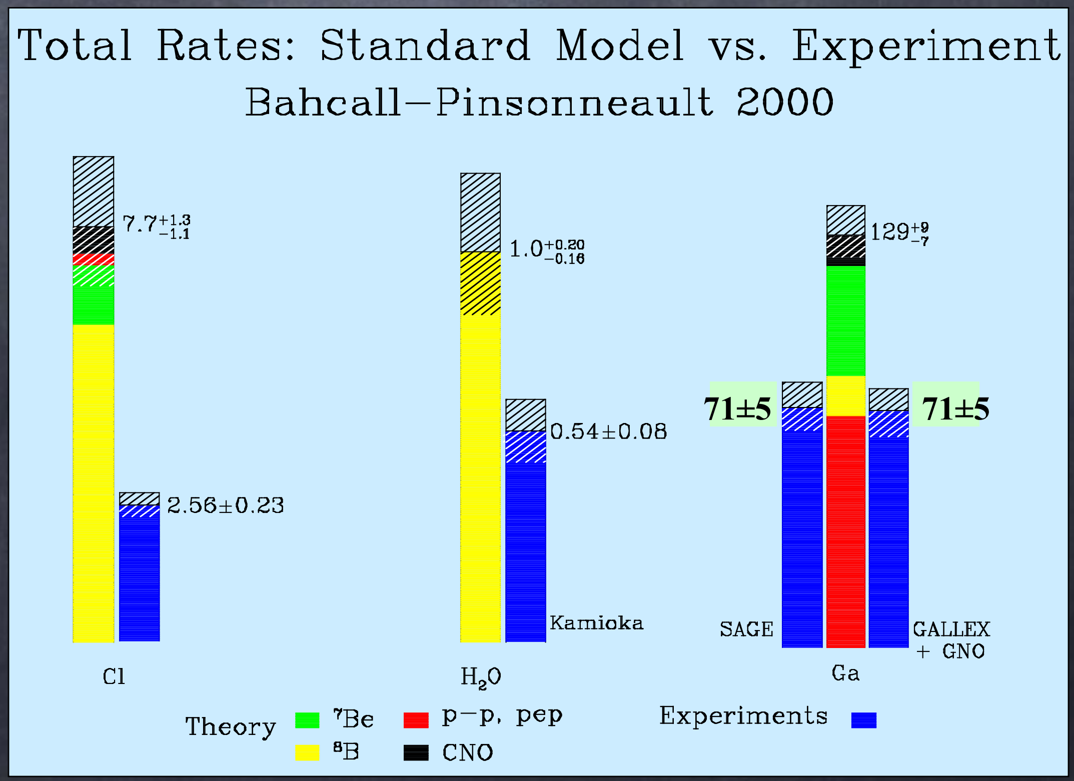


2/3 of neutrinos are missing!

The solar neutrino mystery

- Is the prediction wrong?
- Are the measurements not correct ?
- Do we miss something in our understanding?

In years 1980 - 2000 other experiments measured the flux of solar neutrinos



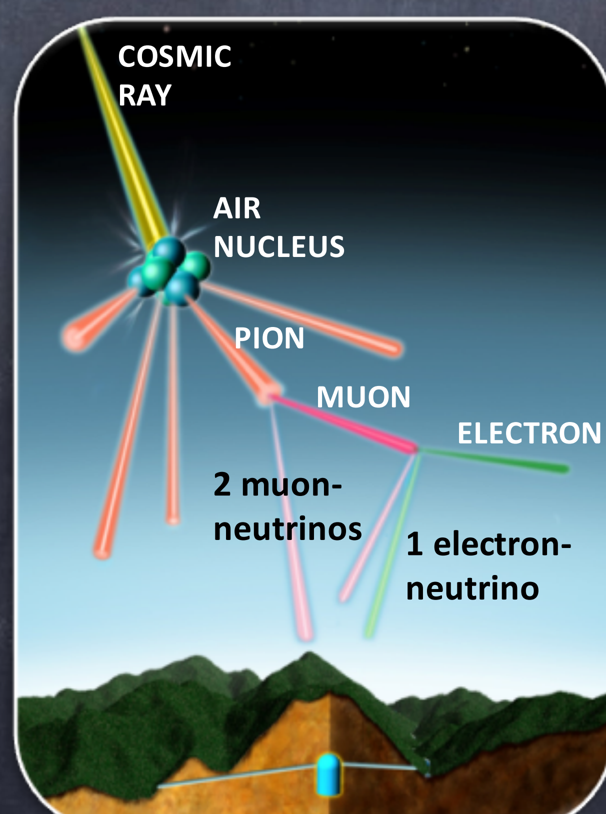
Always something missing!

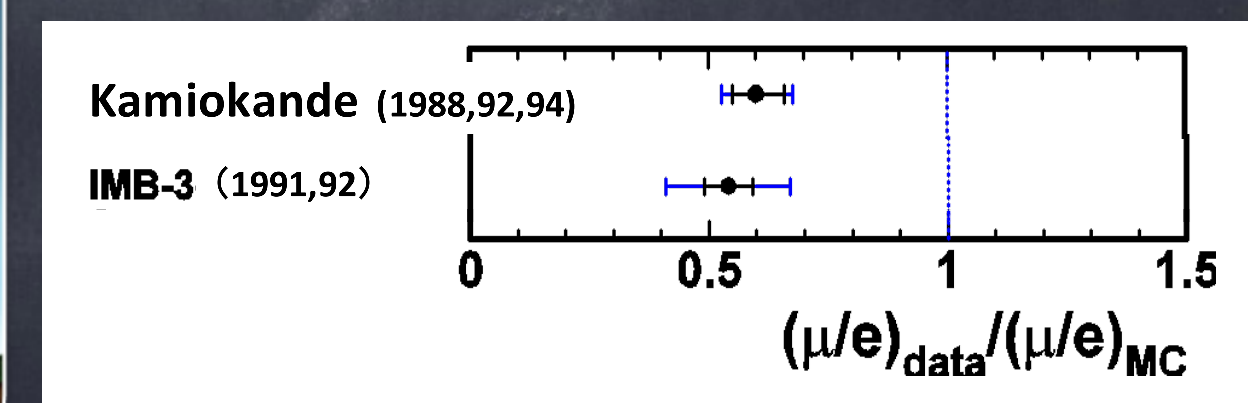
The atmospheric neutrino anomaly

- Atmospheric neutrinos come from the interaction of primary cosmic rays with the atmosphere
- Neutrino comes from pion and muon decay
- ratio well known and expected to be 2:1 but observed ~1

1/2 of ν_μ missing !

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\downarrow$$
$$e^+ + \nu_e + \bar{\nu}_\mu$$



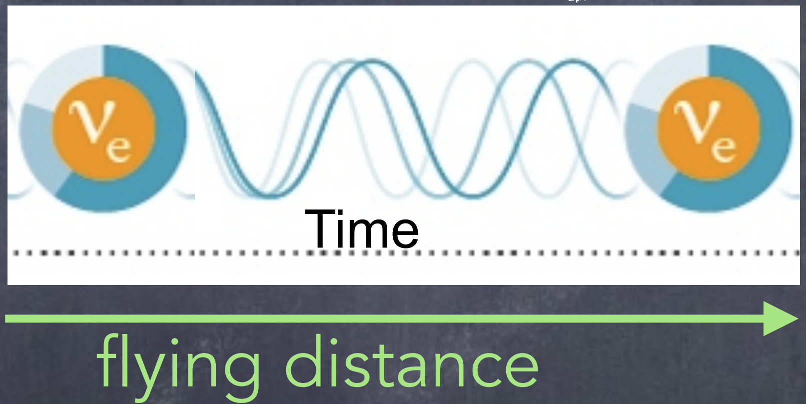


from T. Kajita (Neutrino 2016)

The solution: neutrino oscillations

In quantum physics particles are as well waves: they can mix, superpose, cancel, ...

If neutrinos were massless they would fly all at the speed (speed of light)

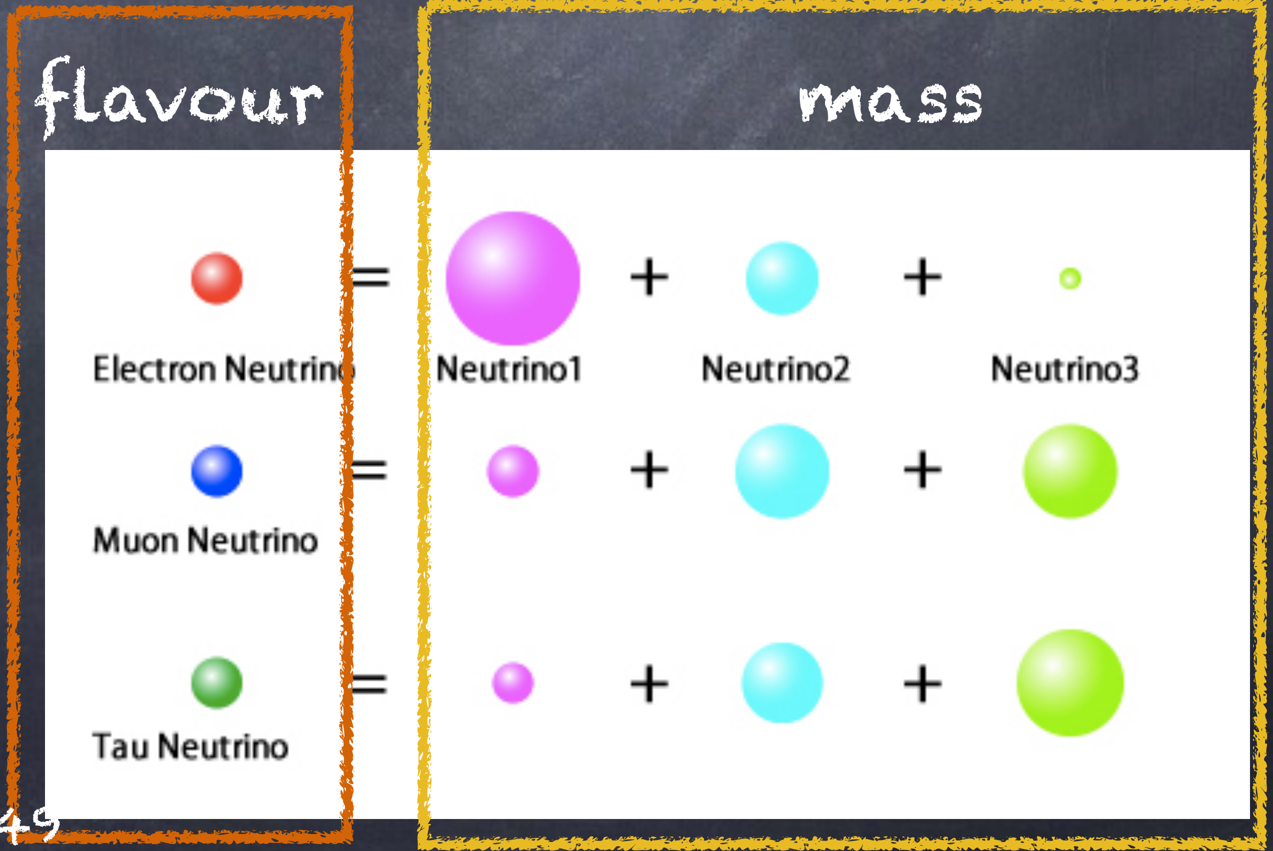


The solution: neutrino oscillations

In quantum physics particles are as well waves: they can mix, superpose, cancel, ...

If neutrinos instead have different masses (m1, m2, m3) they would fly with different speed and they could have different phases!

In quantum physics neutrinos 1, 2 and 3 do not identify with e, μ and τ



The solution: neutrino oscillations

In quantum physics particles are as well waves: they can mix, superpose, cancel, …

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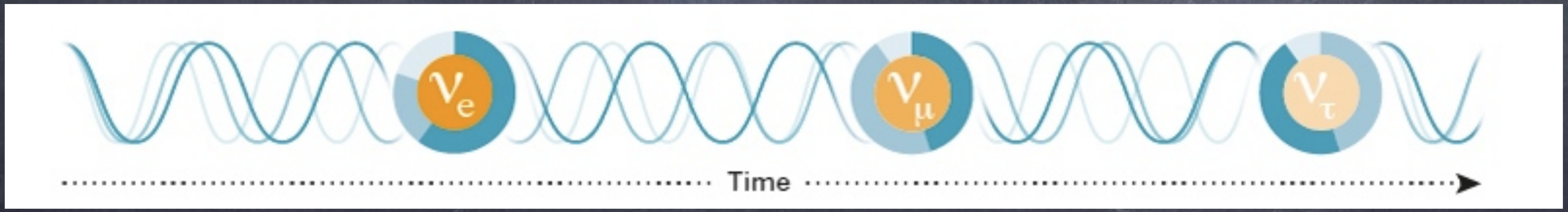
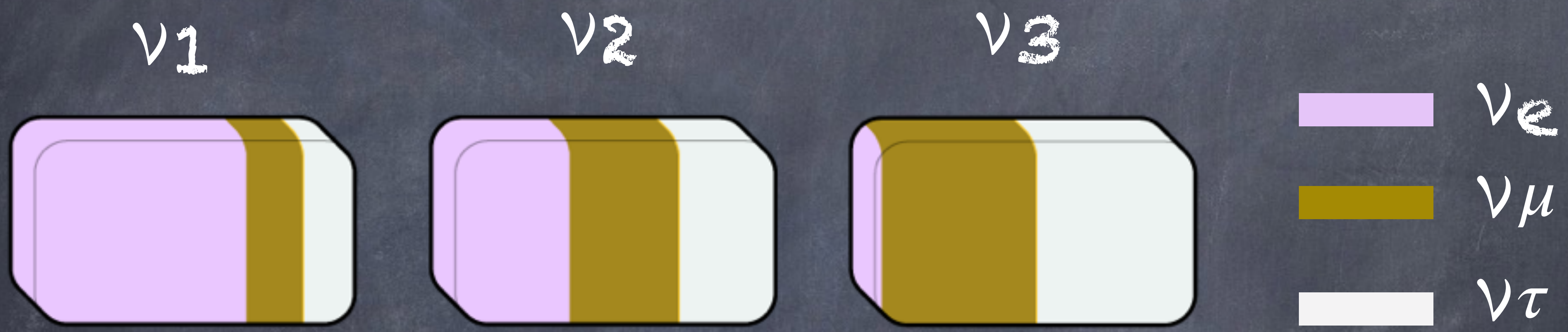


flying distance

they mix !

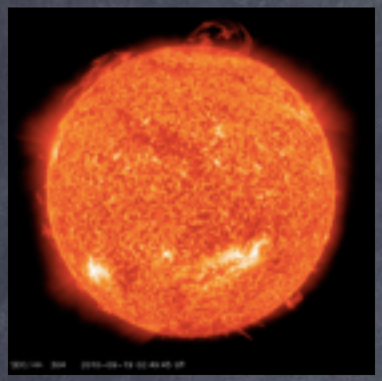
The solution: neutrino oscillations

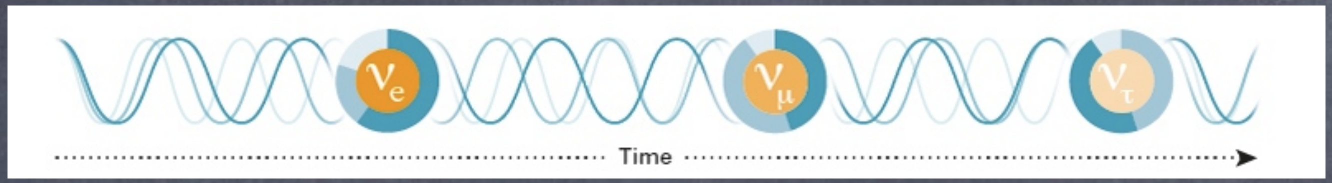
Each neutrino mass state (ν_1, ν_2, ν_3) is a linear superposition di neutrino mass flavour



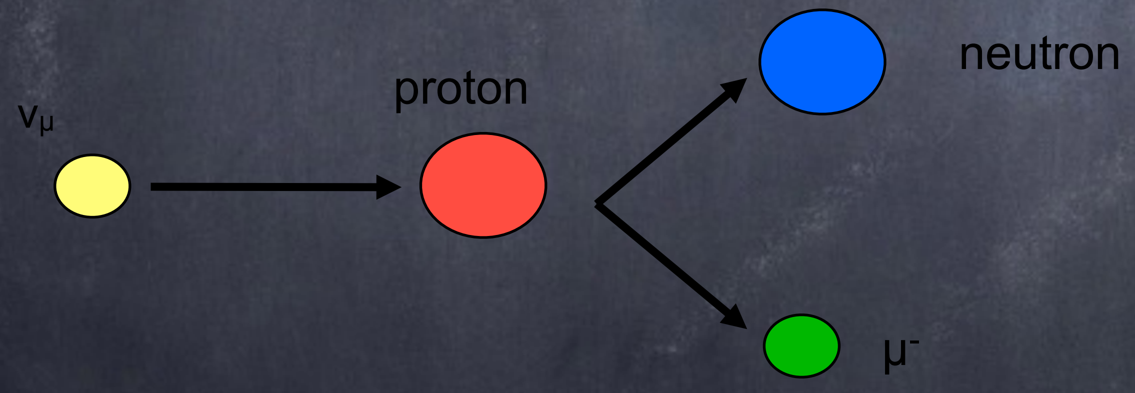
Neutrinos when detected are in flavour states, while when they travel are in mass states

The solar neutrino mystery





$$N^{sun}_{\nu e} = N_{\nu e} + (N_{\nu\mu} + N_{\nu\tau})$$



If :

$$E(\nu_\mu) + M_{protón} < M_{neutrón} + M_\mu$$

FORBIDDEN

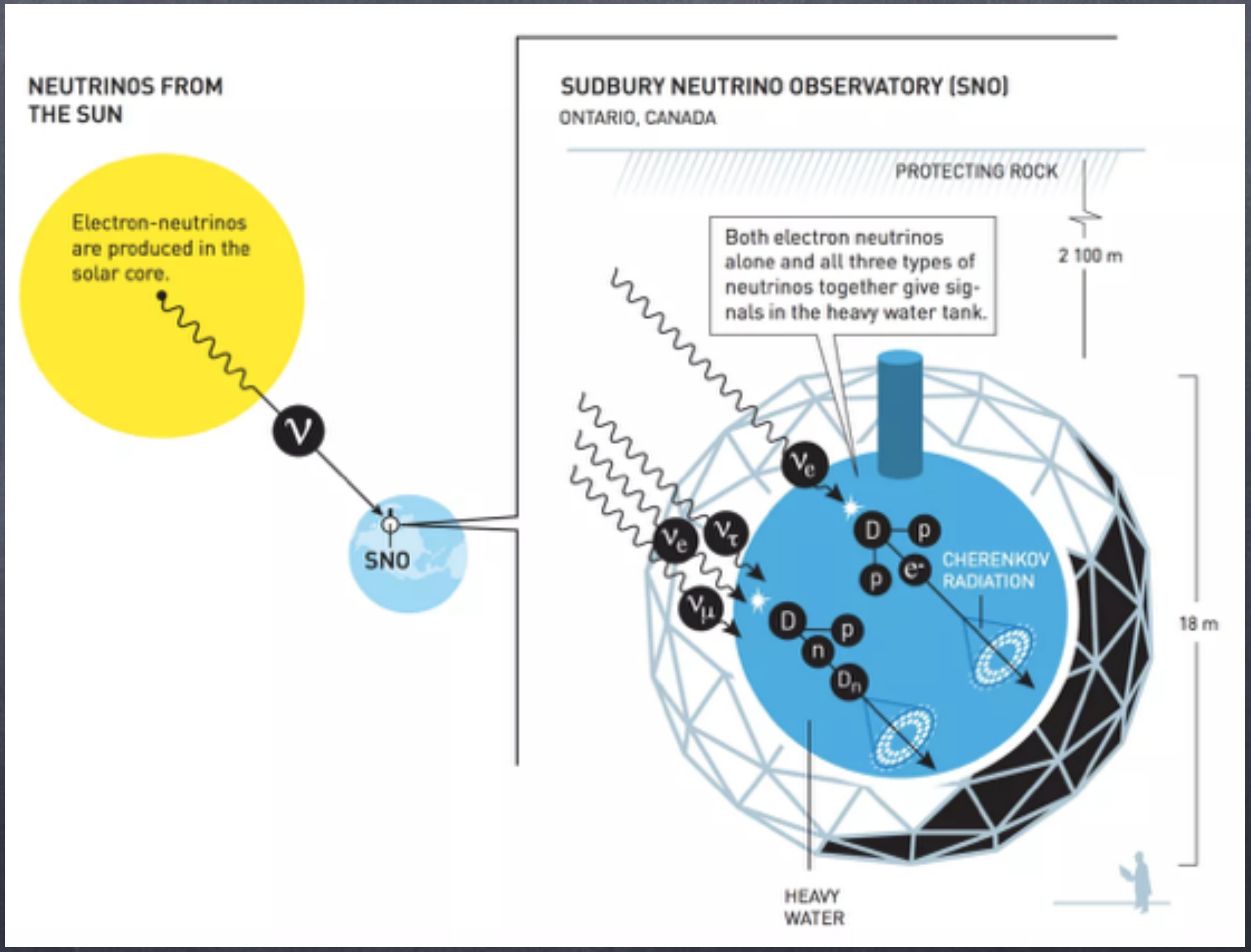
If the energy of the incoming neutrinos it is not enough to produce a muon or a tau, we will not be able do detect ν_μ or ν_τ!

Neutrino Oscillations experiments

Sudbury Neutrino Observatory (USA)

- sphere (12m diameter)
- full of water (1000 ton)
- 2km underground

neutrino from the sun are of all three flavours: e, μ , τ !



source nobelprize.org

Neutrino Oscillations experiments

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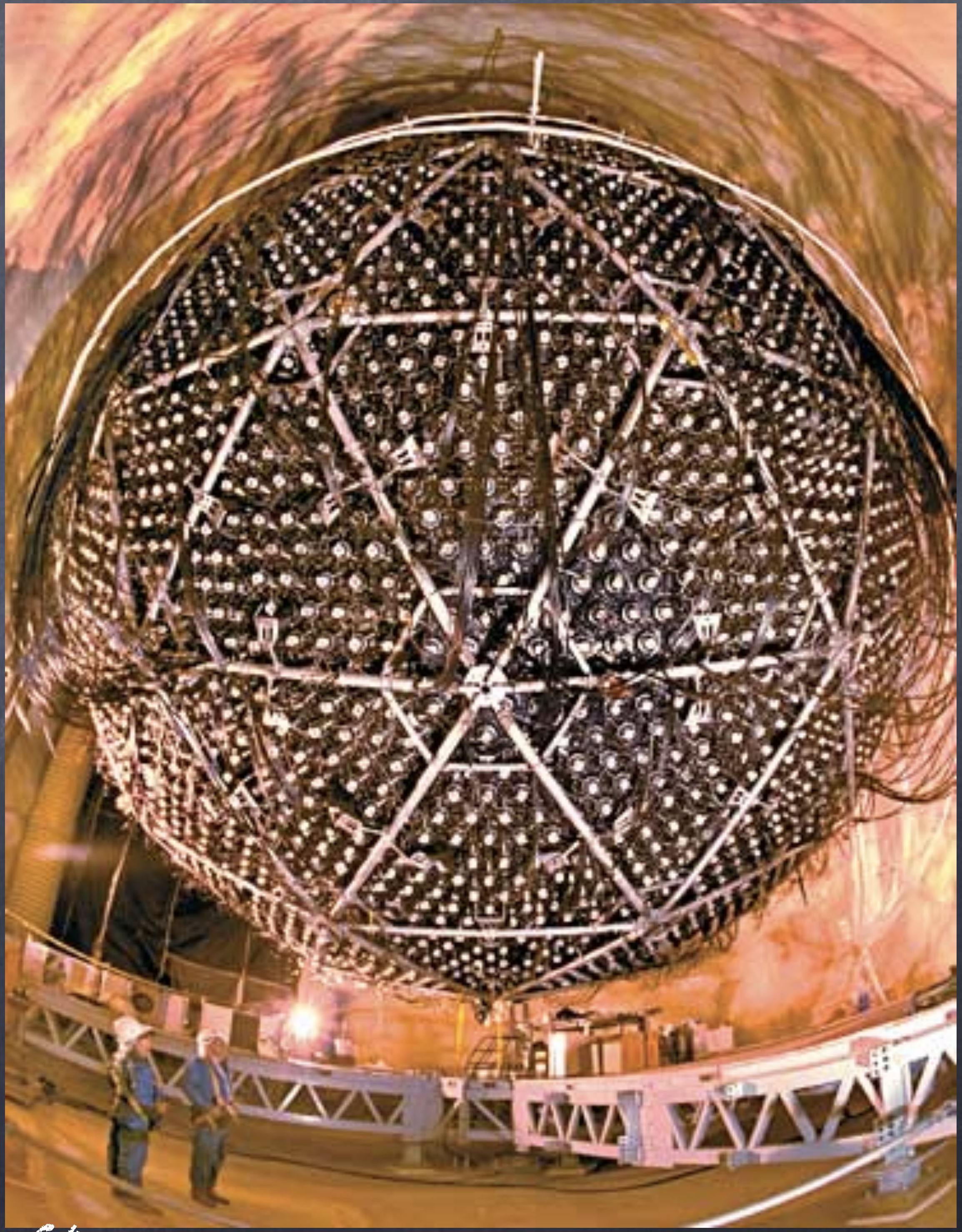
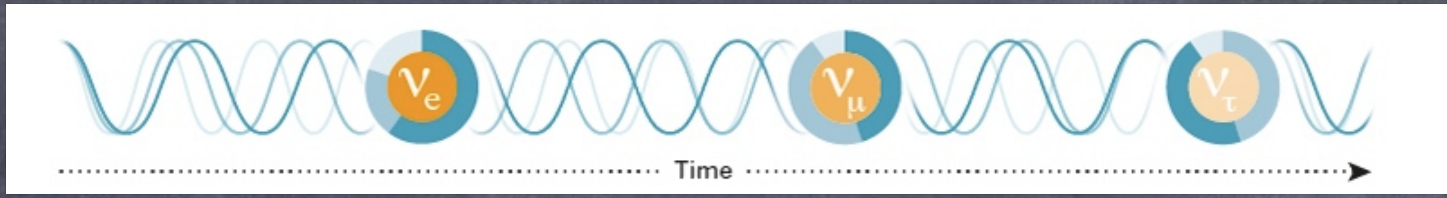
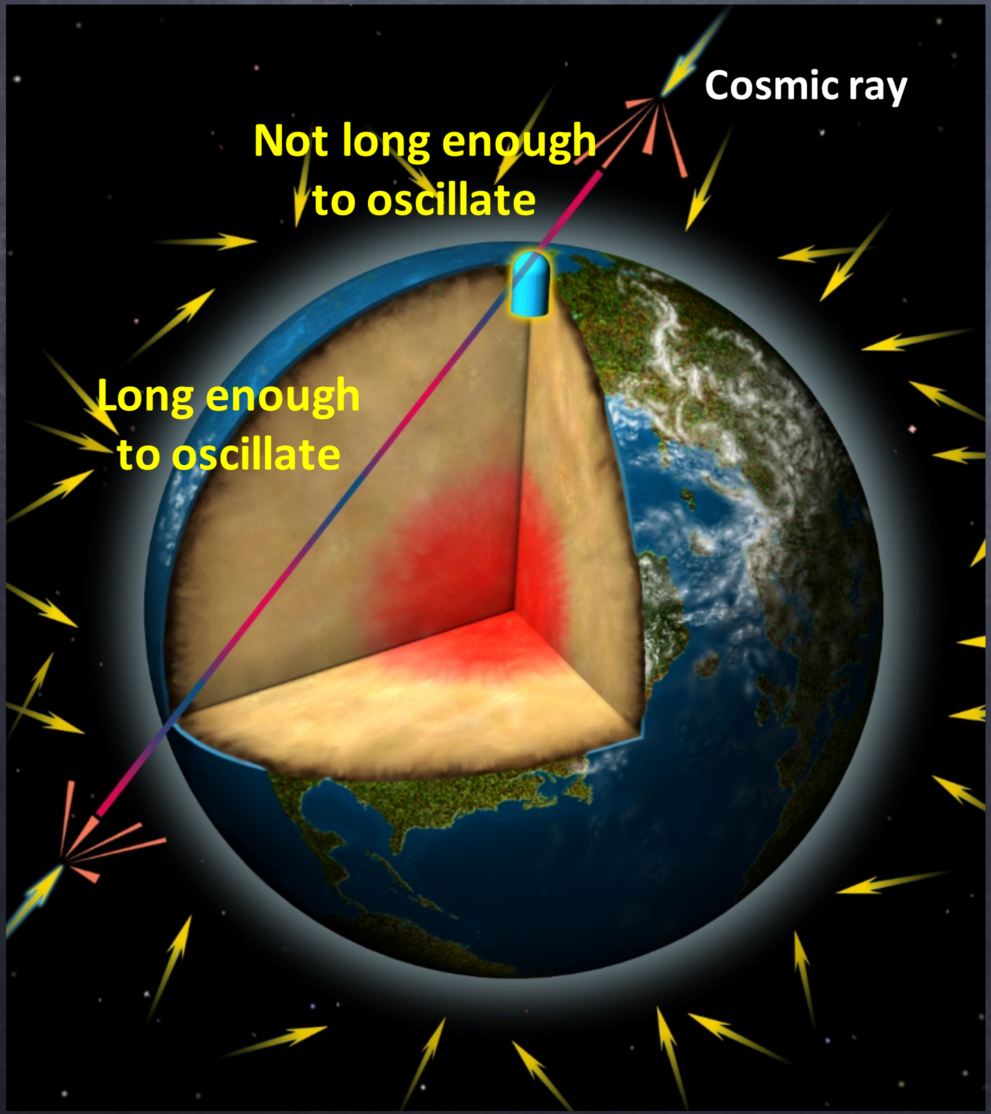


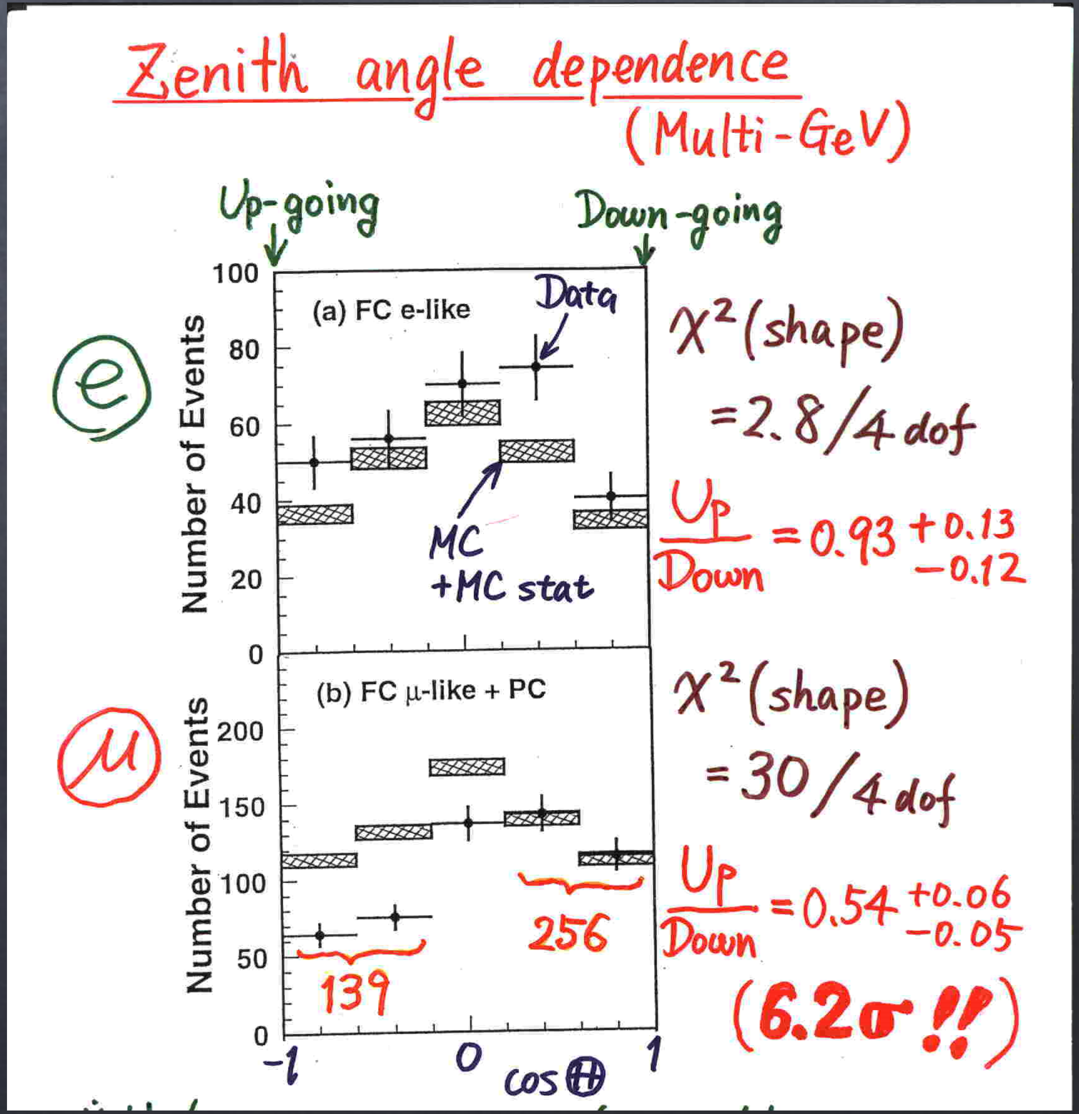
The atmospheric anomaly

Neutrino oscillations



Presented at Neutrino Conference in 1998



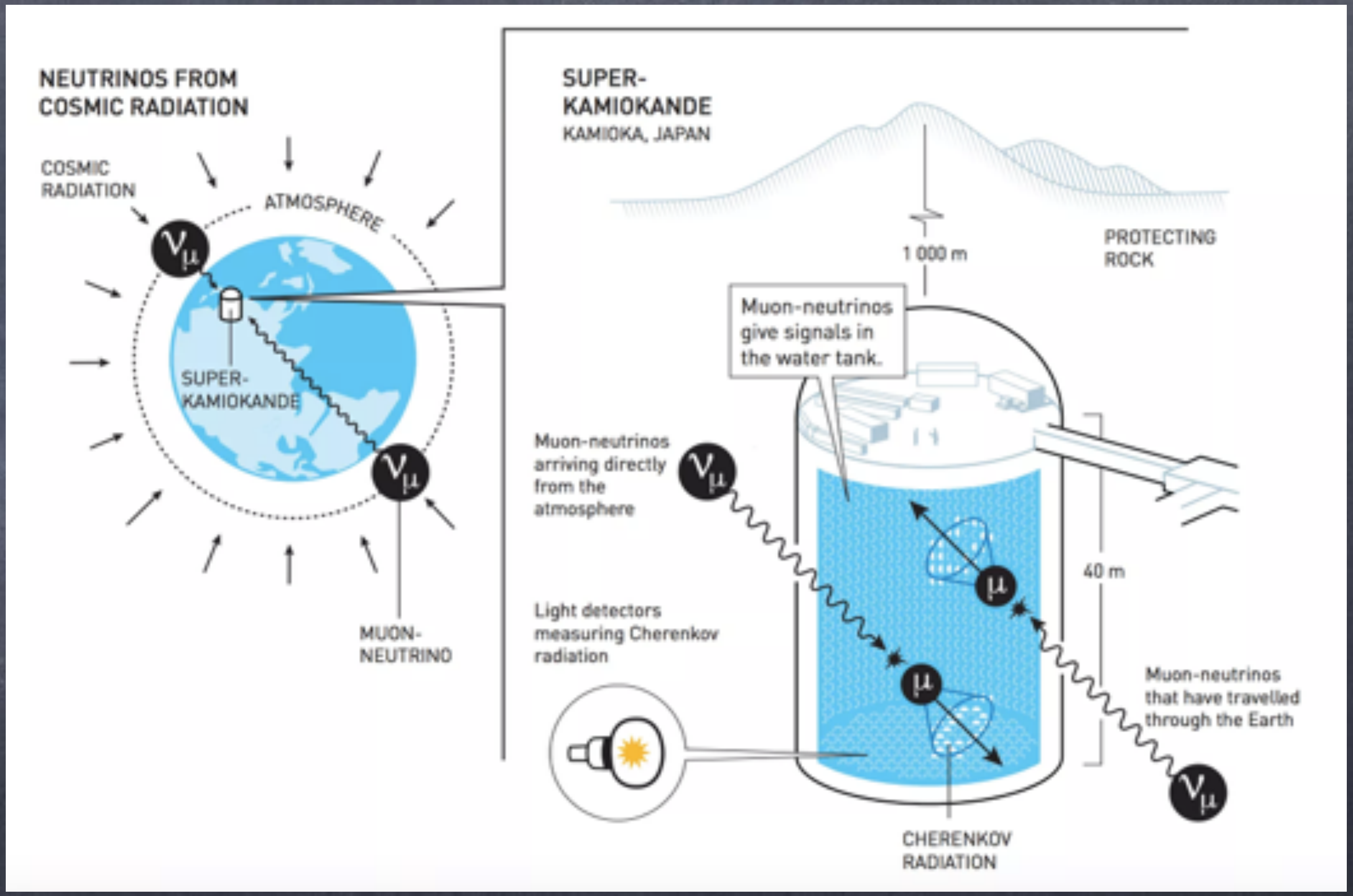


Neutrino Oscillations experiments

Super-Kamiokande (Japan)

- Cylinder (39mØ ,42m alto)
- full of water 50 000 ton
- 1km underground

atmospheric neutrinos

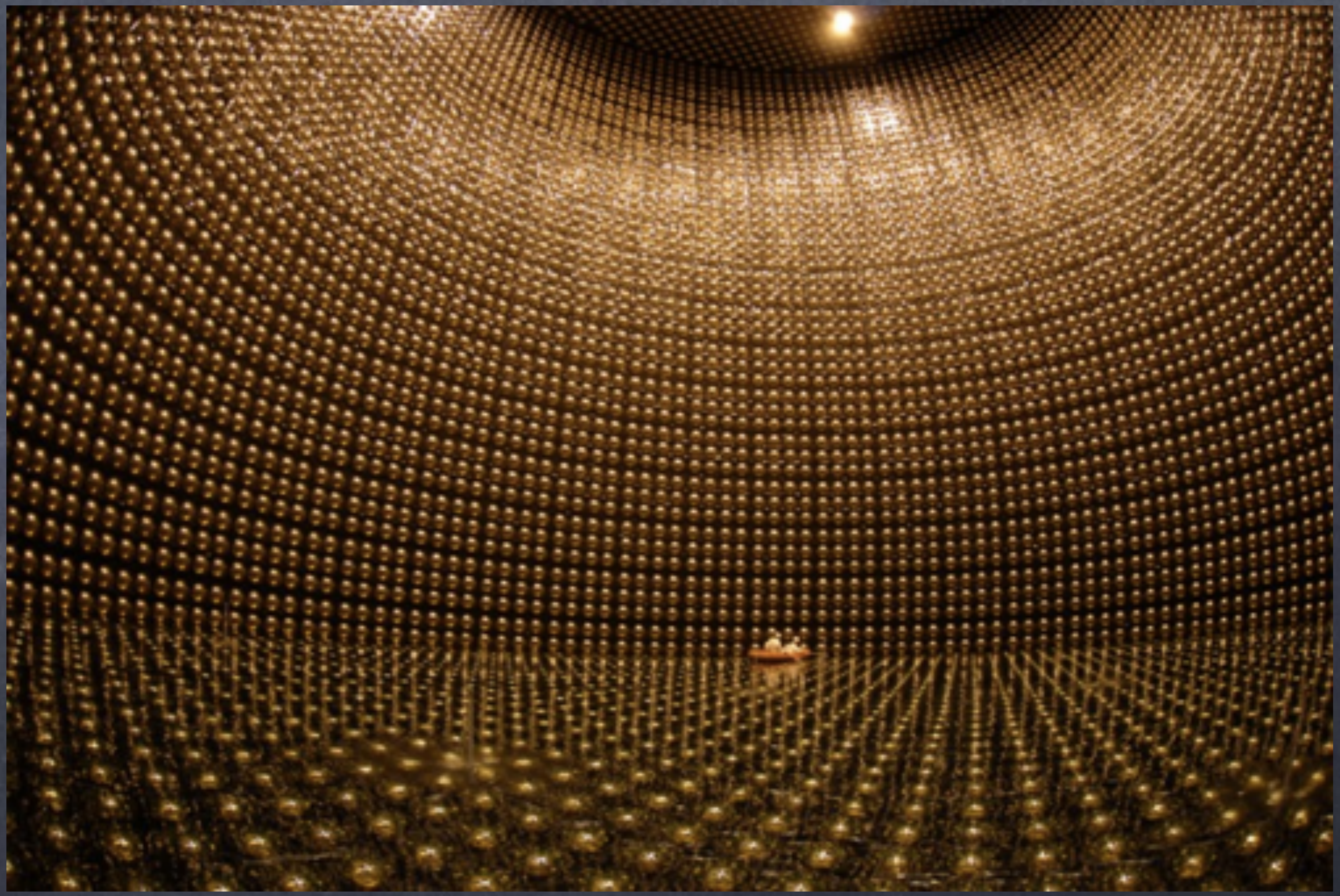


source nobelprize.org

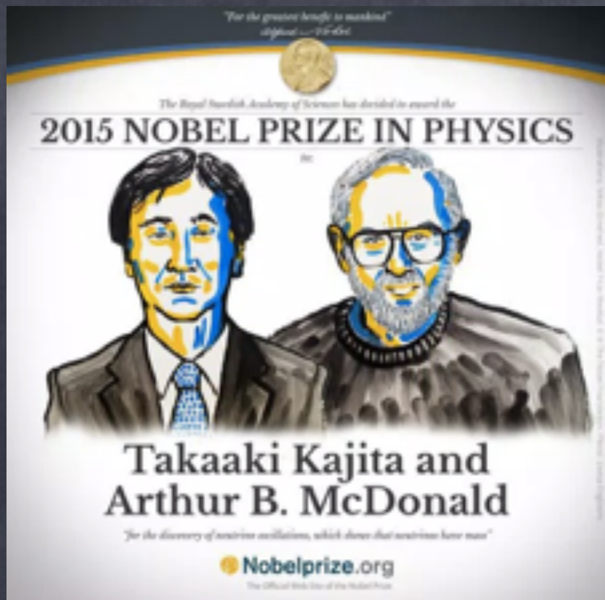
Las oscilaciones: experimentalmente

Super-Kamiokande (Japan)

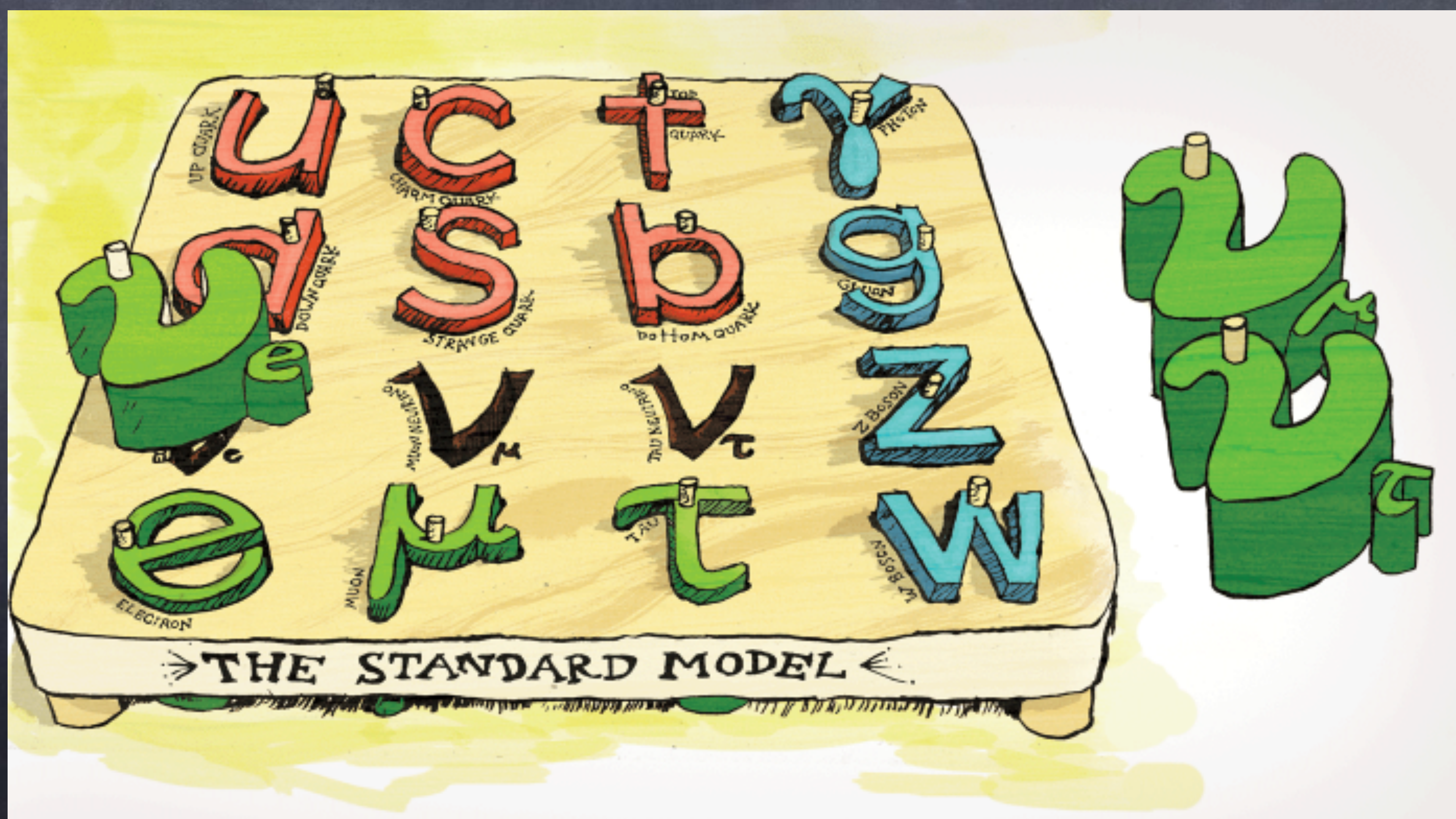
- Cylinder (39mØ ,42m alto)
- full of water 50 000 ton
- 1km underground



atmospheric neutrinos



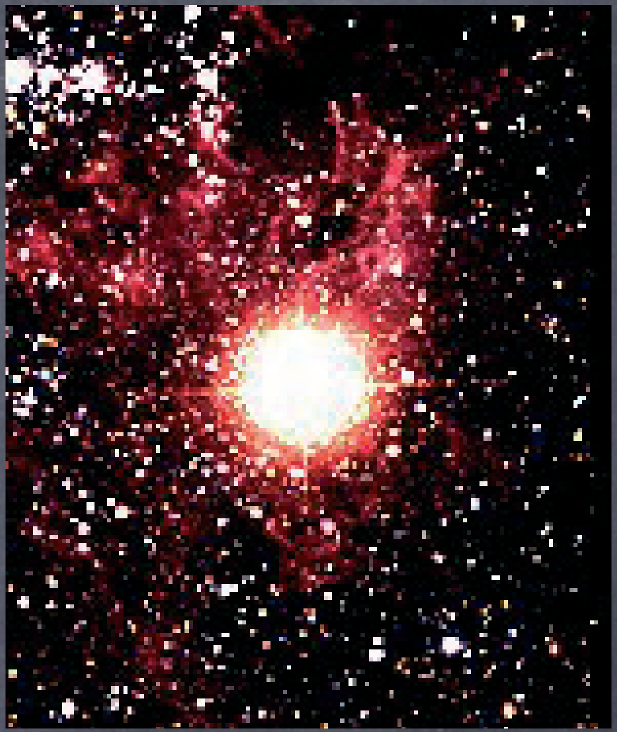
- Neutrinos oscillate!
- Neutrino have masses!
- Neutrinos are the first hint of physics beyond the Standard Model



What else we can learn from neutrinos?

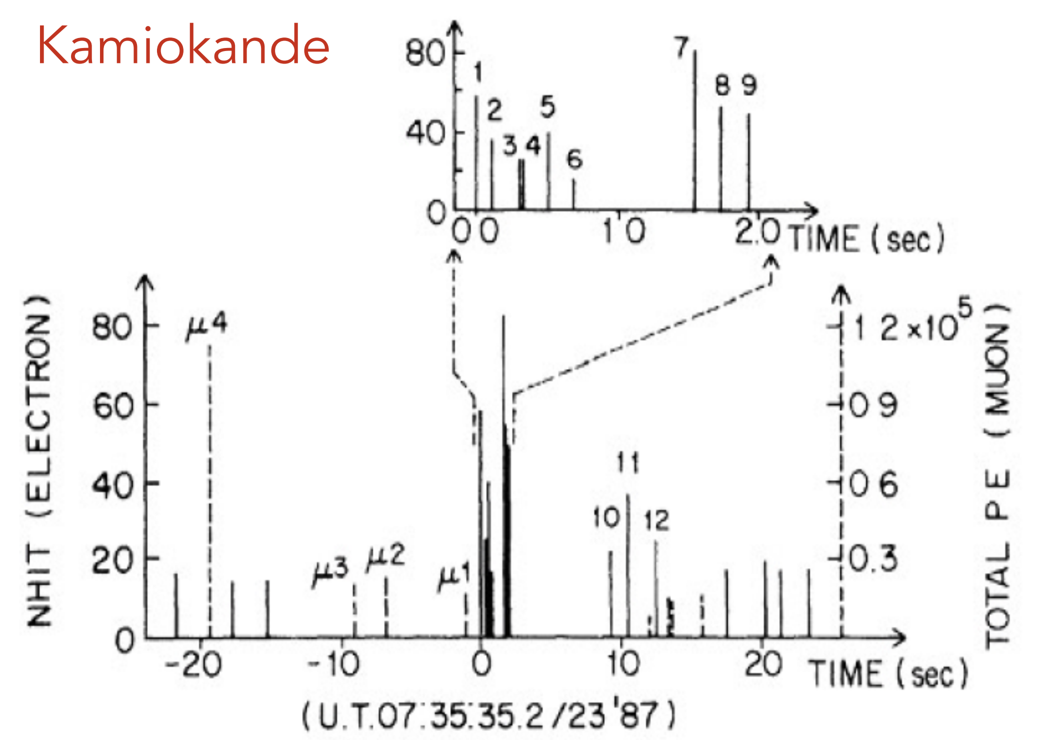
Supernovae neutrinos

- stars with a $m > 10 M_{sun}$ when dying they have an explosion which end with a neutron star or a black hole
- explosion : huge neutrino emission via $e^- + p \to n + \nu_e$



SN1987A

11 events in 10 sec !

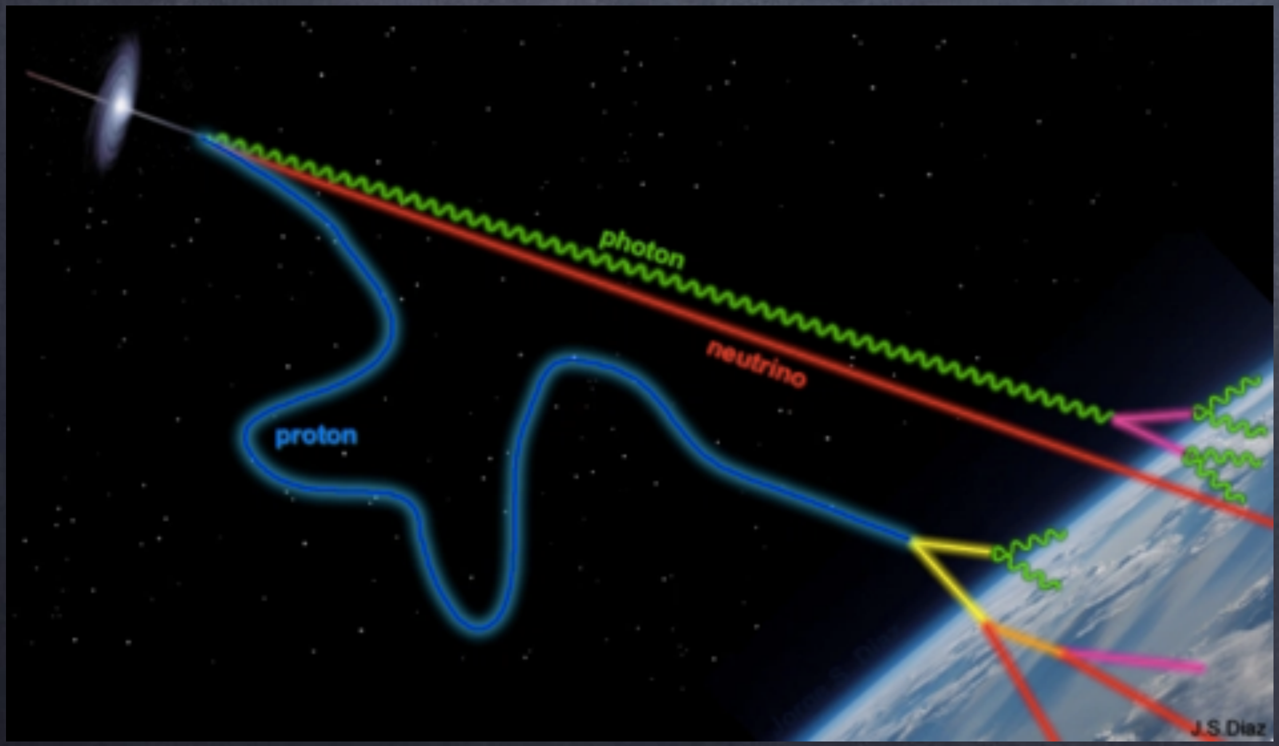


Neutrino astrophysics: neutrinos can give us information about the supernovae formation process

Neutrinos as messengers from the past

Neutrinos are neutral particles interacting very rarely

-> they can fly straight for millions (billions) years bringing us informations about the site where they have been produced



If we achieve to detect them, neutrinos can tell us about the Universe just 1 second after the Big-Bang

(13 800 000 000 years ago) !!

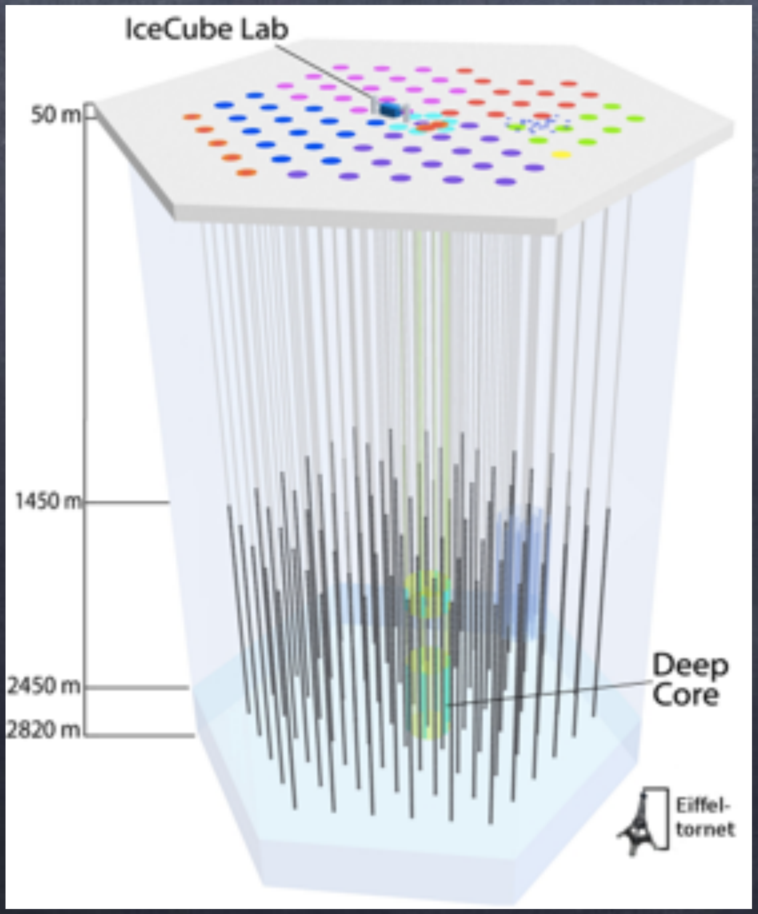
Cosmogenic neutrinos

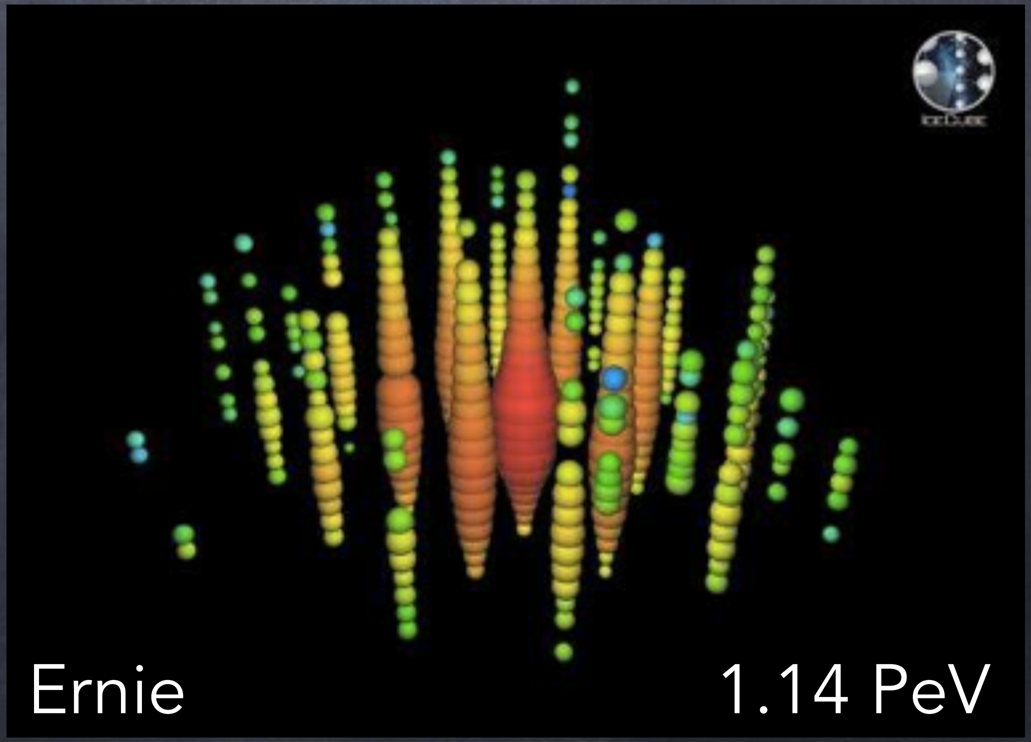
Neutrinos can bring informations about the big cosmic events as explosion of gamma-rays, black holes, start formation..

Those are neutrinos at very high energy but very rare!

IceCube

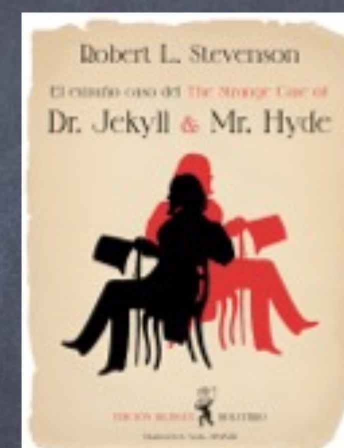
1 km^3 in the Antarctic ice



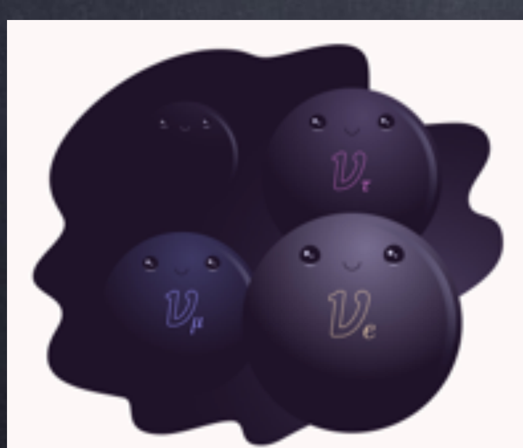


neutrinos have masses but which is the heaviest?

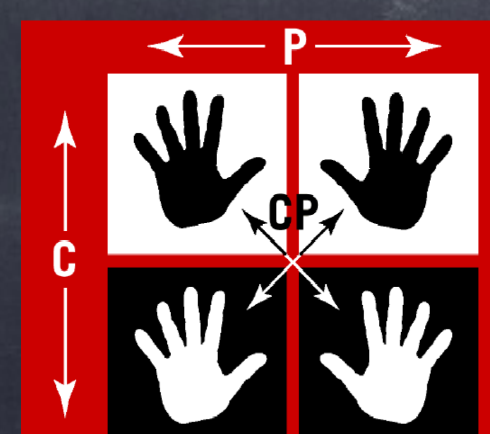
m1, m2 or m3?



Are neutrinos at the same time also anti-neutrinos?



how many they are?



can neutrinos tell us about anti-matter?

Neutrino oscillations with an accelerator beam and the CERN Neutrino Platform

How do we do a neutrino beam ?

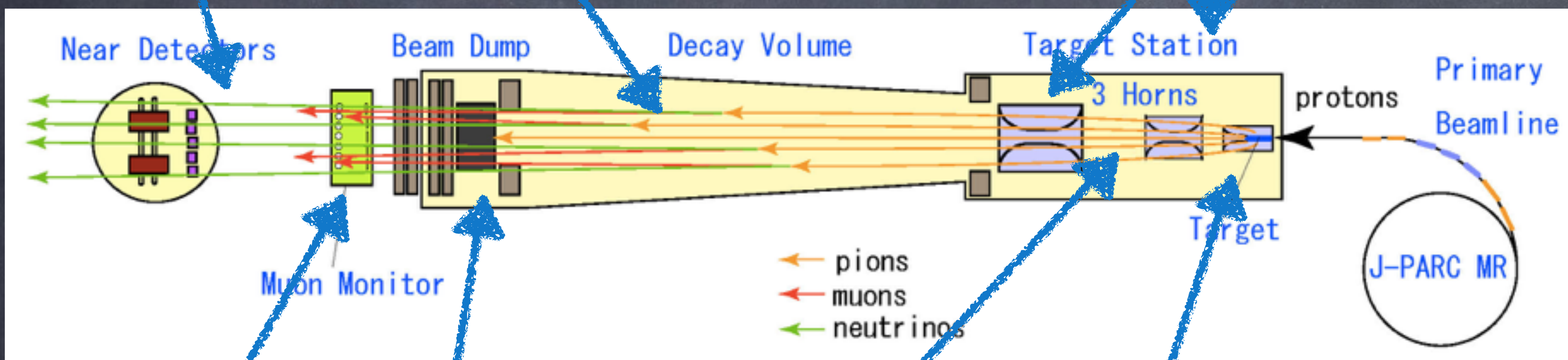
8. neutrino beam!

5. let the hadrons decay

$\pi^{+/-} \rightarrow \mu^{+/-} + \nu_\mu$

$K^{+/-} \rightarrow \mu^{+/-} + \nu_\mu$

3. focus and select in charge the produced hadrons



7. from the remaining muon get infos about the ν beam

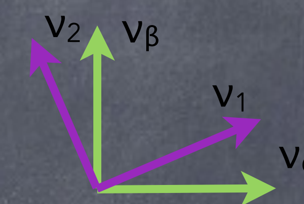
6. stop all remaining particles (muons will survive!)

4. from the interactions in the target hadrons (pions, kaons) are produced

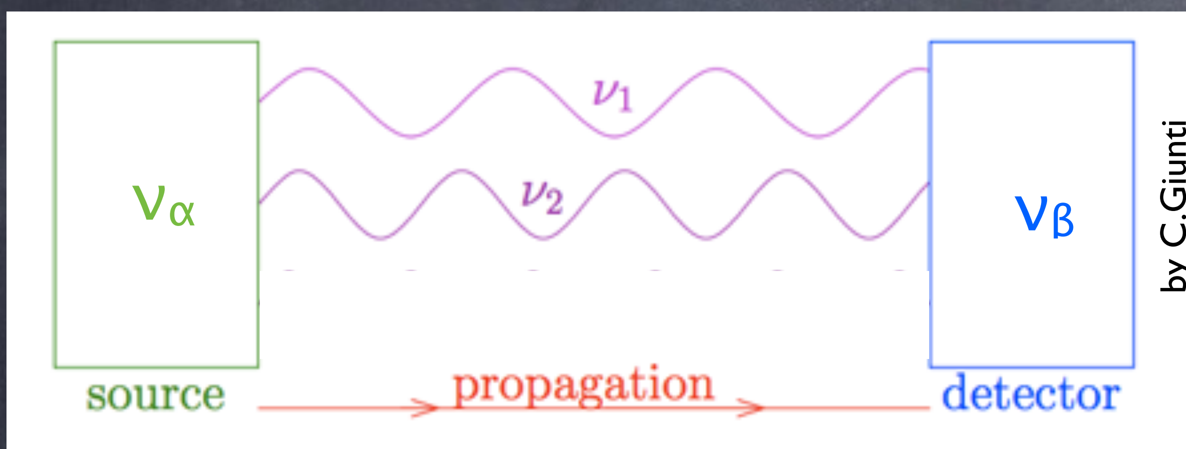
2. smash them on a target (graphite)

1. accelerate protons

The oscillation mechanism



2 neutrino scenario



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

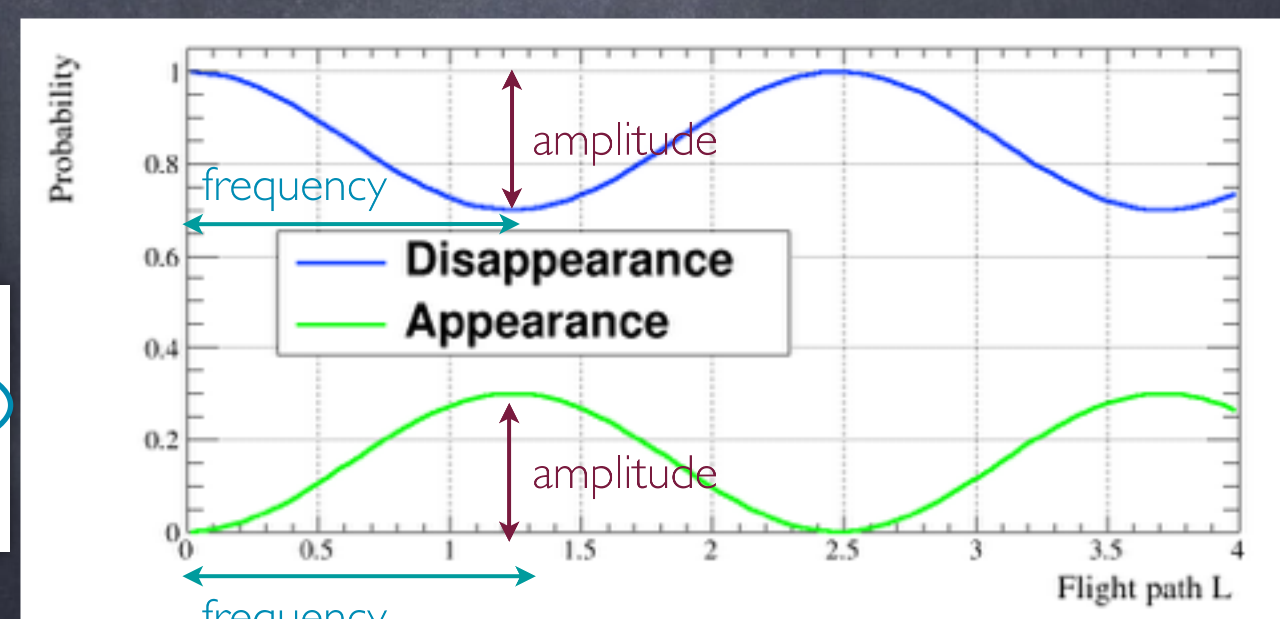
flavor states　　mixing matrix　　mass states

$$P_{\nu_\alpha \to \nu_\beta} = \sin^2 2\theta \sin^2(1.27 \frac{\Delta m^2 [eV^2]}{E[GeV]} L[Km])$$

amplitude　　frequency

$$P_{\nu_\alpha \to \nu_\alpha} = 1 - \sin^2 2\theta \sin^2(1.27 \frac{\Delta m^2 [eV^2]}{E[GeV]} L[Km])$$

amplitude　　frequency



L = distance travelled by ν
E = ν energy

The oscillation mechanism

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

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

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

atmospheric, accelerator — accelerator, reactor — solar, reactor

3 Flavour states

3 Mass states

3 mixing angles, 2 squared mass difference, 1 complex phase (δ_{CP})

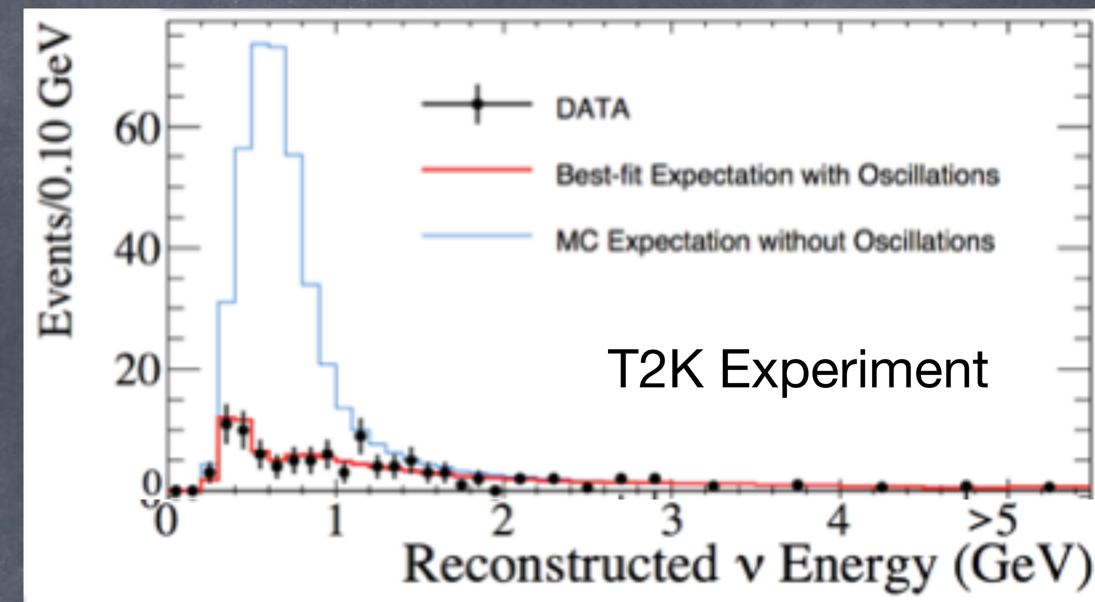
More than 15 years of experimental efforts

Parameters		Experiment	signal
$\lvert\Delta m_{21}\rvert^2 = \lvert m^2_2 - m^2_1\rvert$	ϑ_{12}	solar and reactor	$P(\nu_e \to \nu_{\mu,\tau})$
$\lvert\Delta m_{32}\rvert^2 = \lvert m^2_3 - m^2_2\rvert$	ϑ_{23}	atmospheric and accelerator	$P(\nu_\mu \to \nu_\mu)$ & $P(\nu_\mu \to \nu_\tau)$
	ϑ_{13}	reactor and accelerator	$P(\nu_\mu \to \nu_e)$ & $P(\bar{\nu}_e \to \bar{\nu}_e)$
	δ_{CP}	accelerator	$P(\nu_\mu \to \nu_e)$

Neutrino oscillation experiments: how does they work

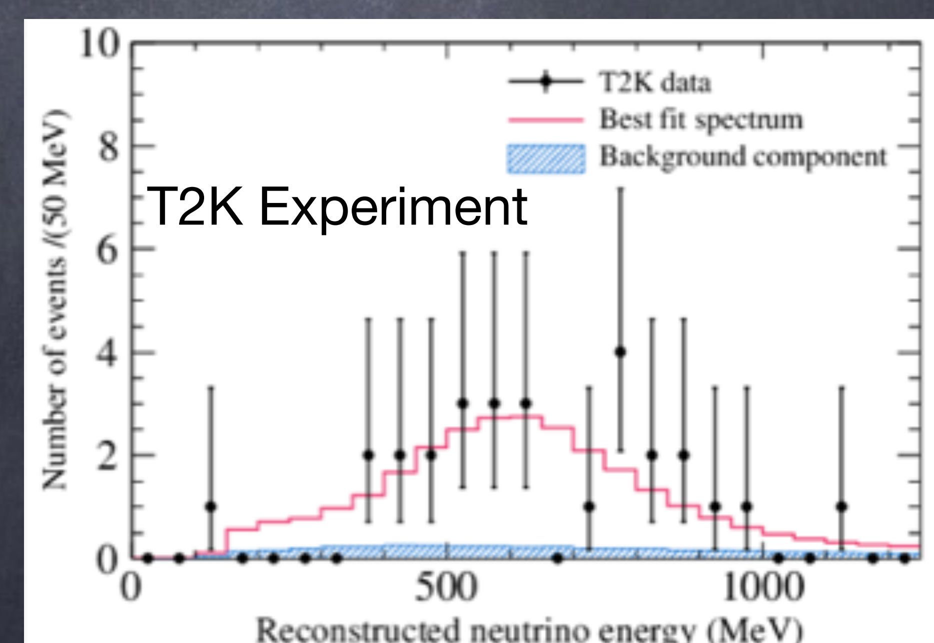
ν_μ ν_τ

- if we cannot see ν_τ we will observe a disappearance of neutrinos



ν_μ ν_e

- if $\nu_\mu \rightarrow \nu_e$ we will see "appearance" of neutrinos



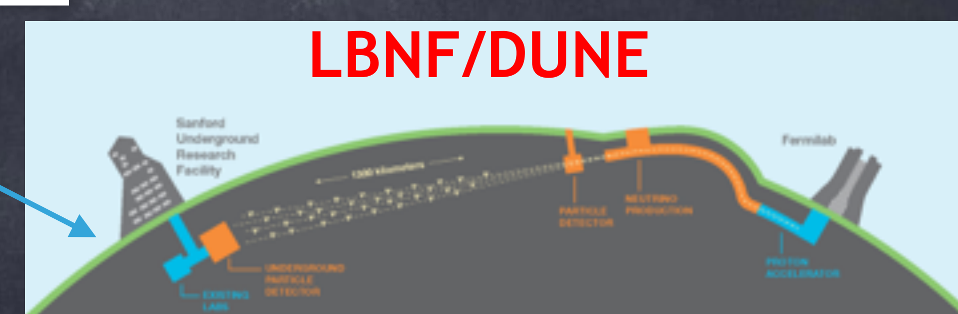
The CERN neutrino platform

- CERN support European activities towards future LBN experiments in US and Japan
- Neutrino Platform started in 2015 following the recommendation of the 2013 European strategy of Particle Physics

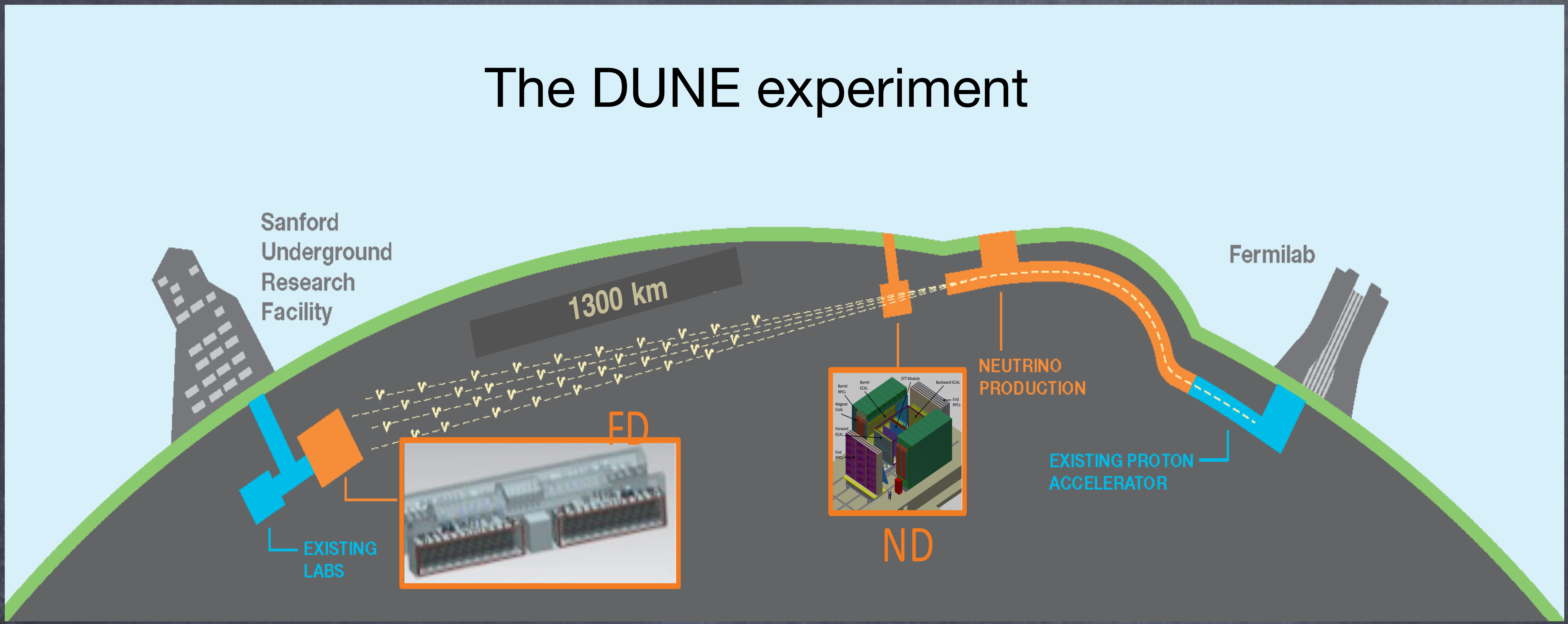
SBN (short baseline)

Neutrino PLATFORM

http://cenf.web.cern.ch/

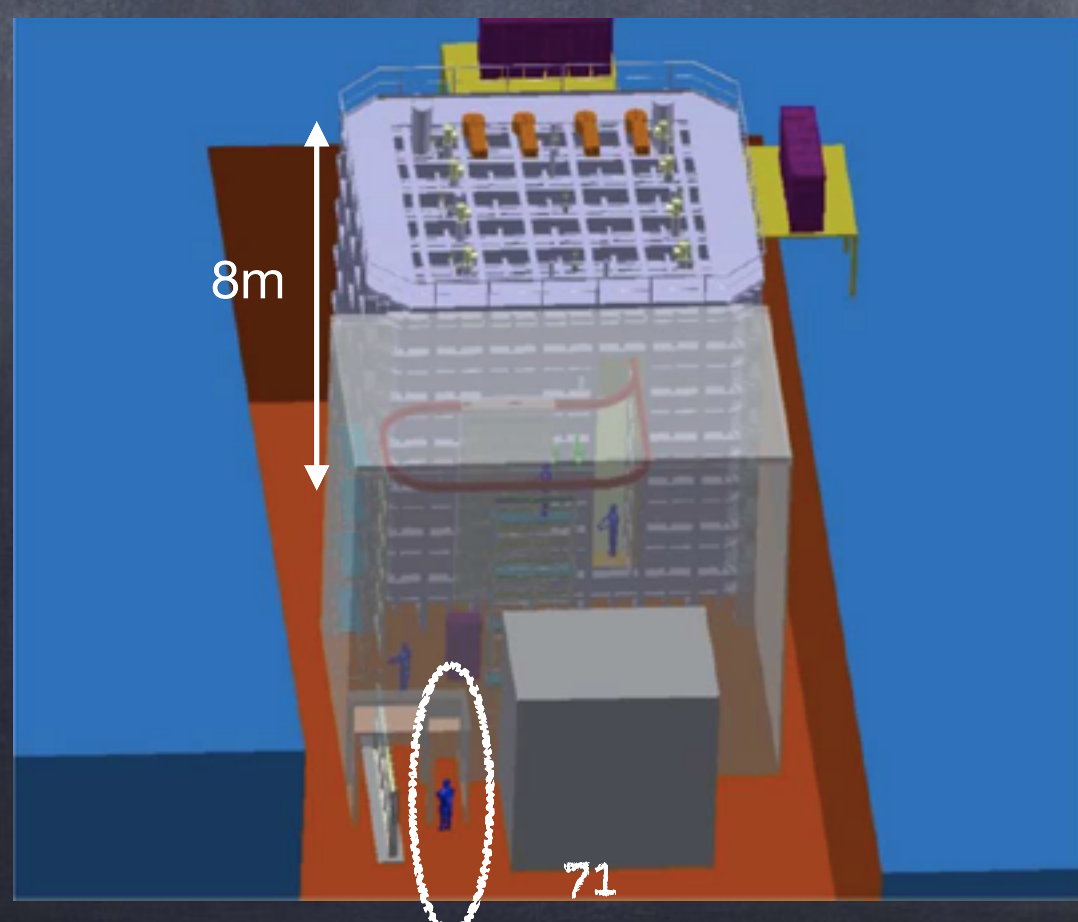


The DUNE experiment



What are we going to see

- CERN is deeply involved in the DUNE experiment and host 2 prototypes for the Far Detector
- prototypes are 2 TPC with LAr
- not usual dimension for prototypes: 8mx8mx8m! and ~800 tons of LAr each!

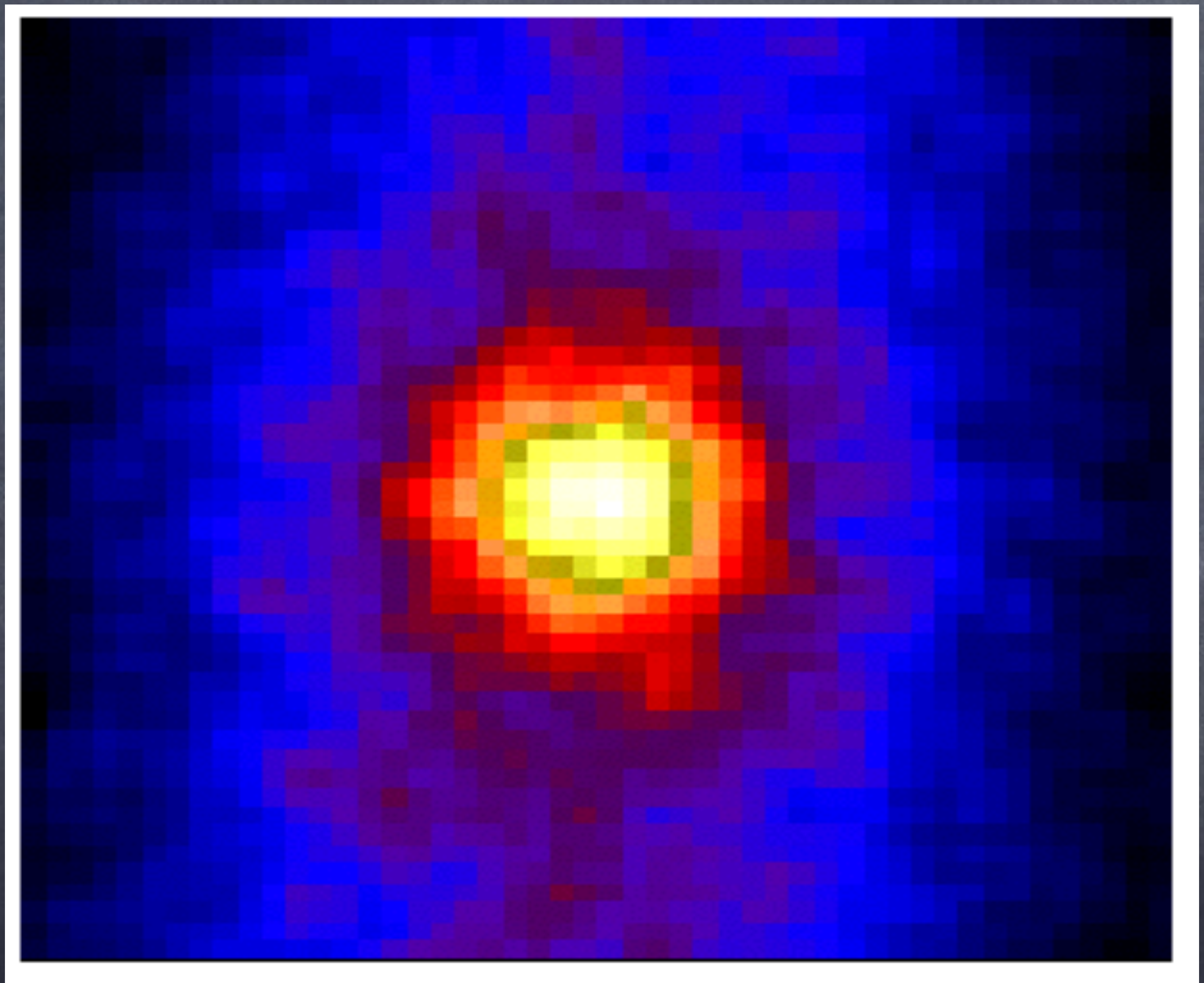


Some recommendation for the visit

- We are going to an experimental hall with installation works on going
  - to enter you should wear flat and close shoes.
  - wear the helmet all the time (will be given to you at the entrance
- The area where we will stay is clean from material but still: DO NOT touch to anything, DO NOT take risks
- Please stay in the area foreseen for the visit !

Thanks !

The sun seen with neutrinos



Super K collaboration

neutrinos : 8 minutes
light : 10^6 years

"It is ironic that the best place to observe the sun is two miles underground..." A. McDonald

supplementary