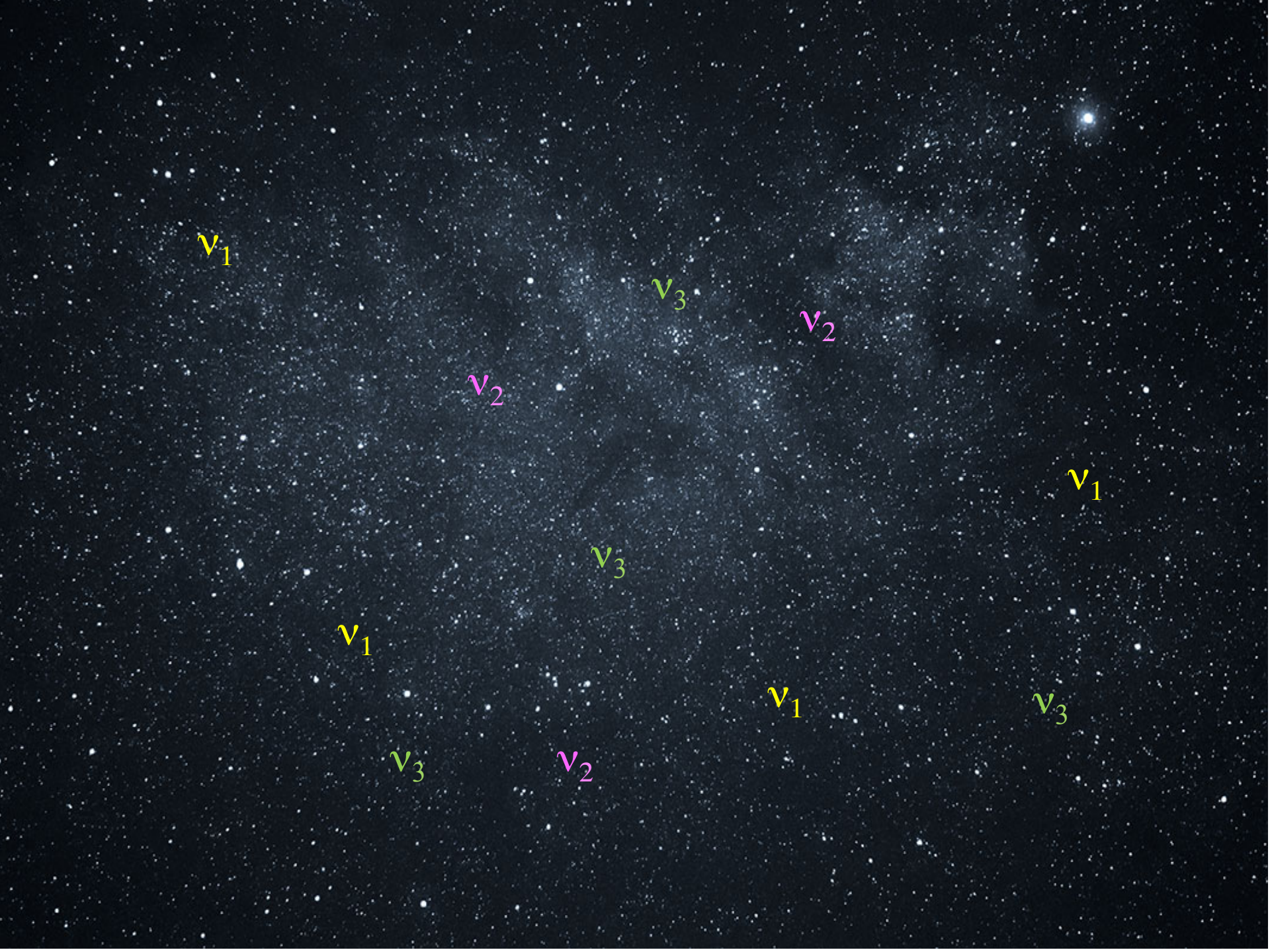
NEUTRINOS:
The messengers of the invisible world

Loin d'être un appauvrissement, l'adjonction à la chose visible de la chose invisible fait plus que de l'enrichir, elle lui donne un sens, elle la complète.

Far from being an impoverishment, the addition to the visible thing of the invisible thing does more than enrich it, it gives it a meaning, it completes it.

Paul Claudel (*Positions et propositions)*


ν_1
ν_3
ν_2
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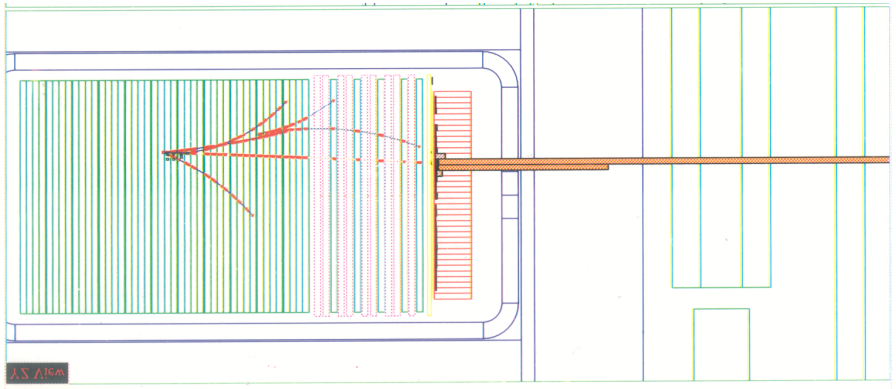
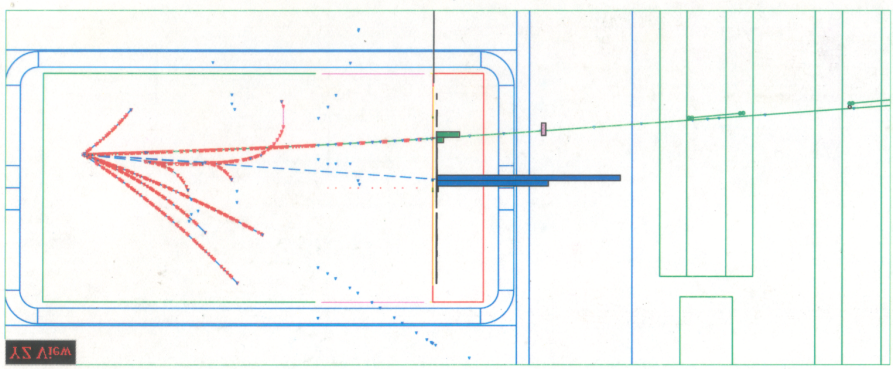
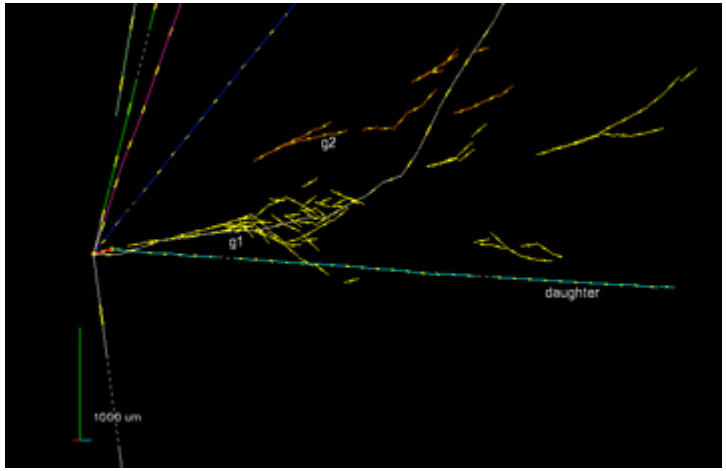
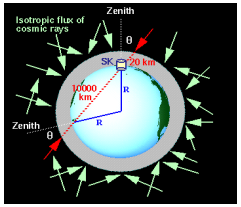
The three types of neutrinos

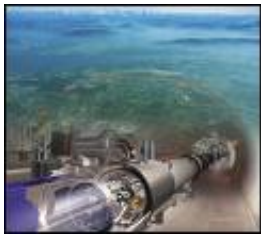


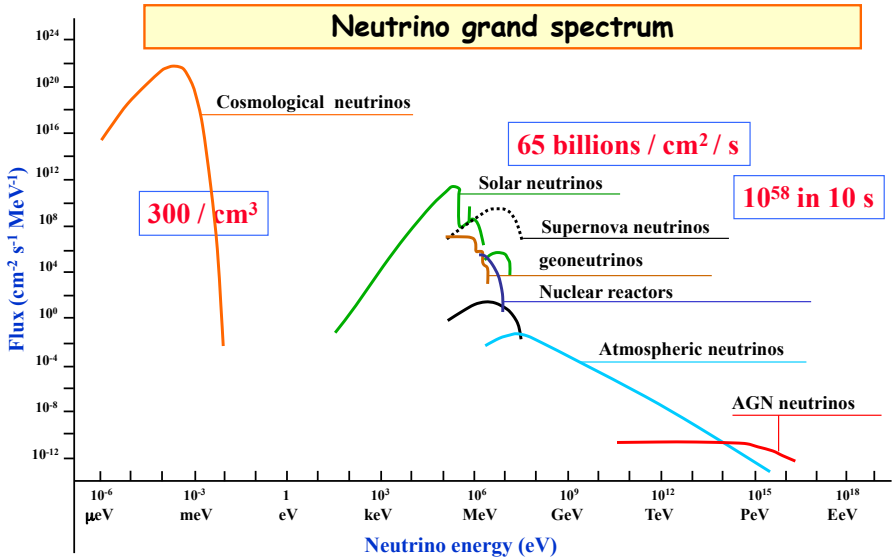




Sources of neutrinos







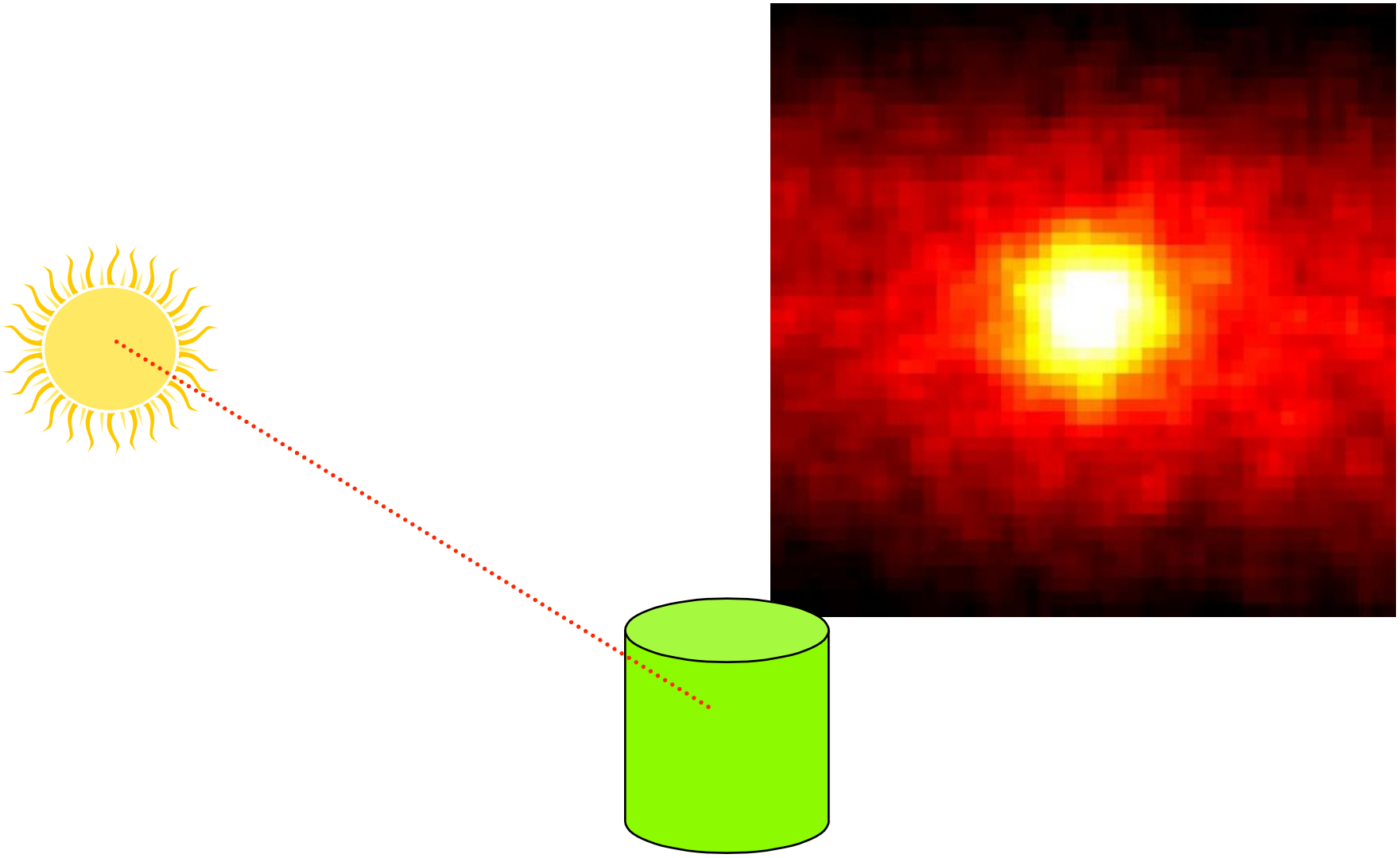
SuperKamiokande

Constructed under a moutain in Japan, SuperK is an immense reservoir full of 50 kilotonnes of purified water, spied by 11000 giant photomultipliers tubes.

•In water charged particles emit Cerenkov light. Energy-threshold for electrons is 5 MeV.

•*SuperK has studied solar as well as atmospheric neutrinos.*

Neutrinography in real time

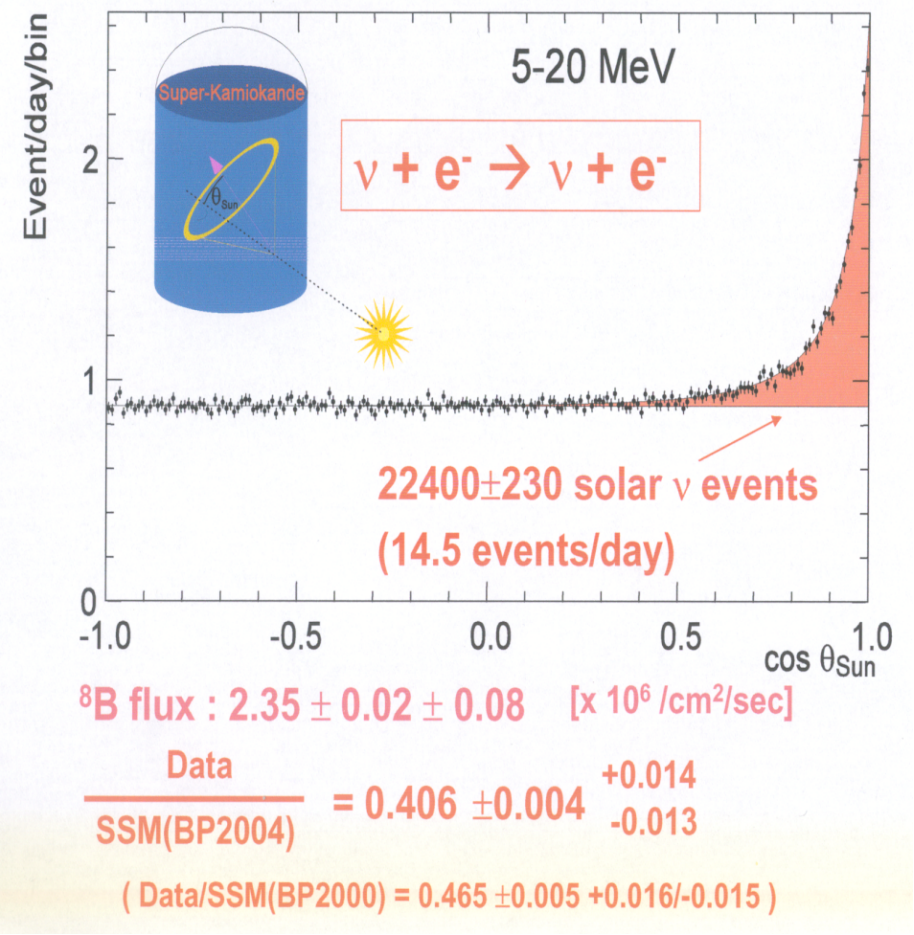


Result of SuperK

•In 1500 days, SuperK detected 22000 events when 48000 were predicted.

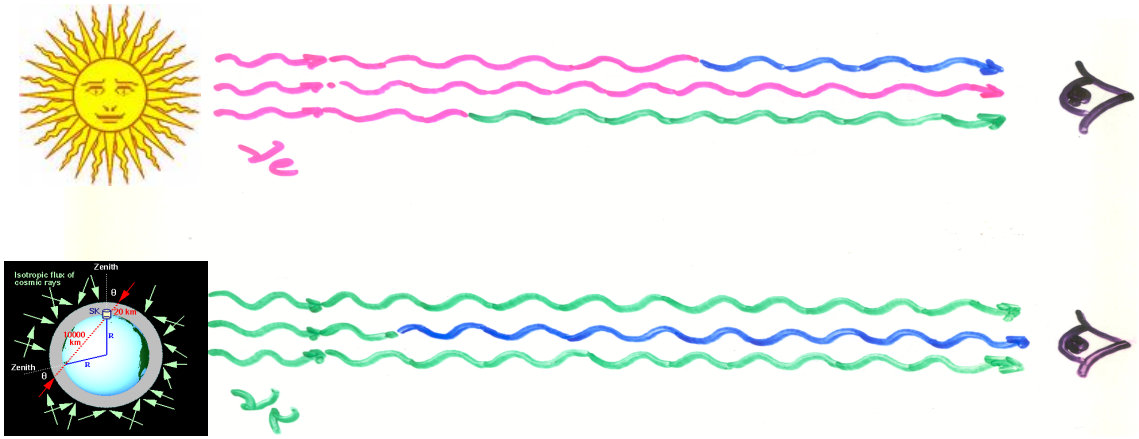
•Problem of the solar *deficit*
First seen by Homestake then confirmed by Gallex.

SuperK also detected a deficit of atmospheric neutrinos



OSCILLATIONS ?

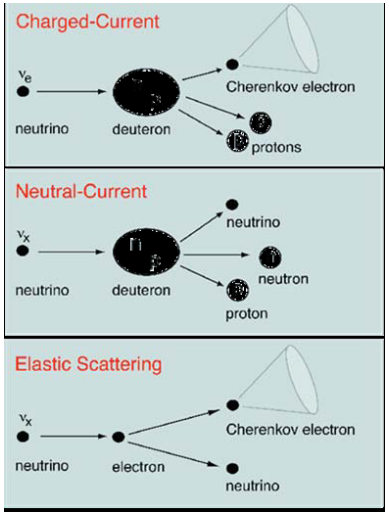
•The *deficit* of neutrinos can be explained by a spontaneous change of the neutrino type during its propagation (the SK detector counts only solar ν_e).

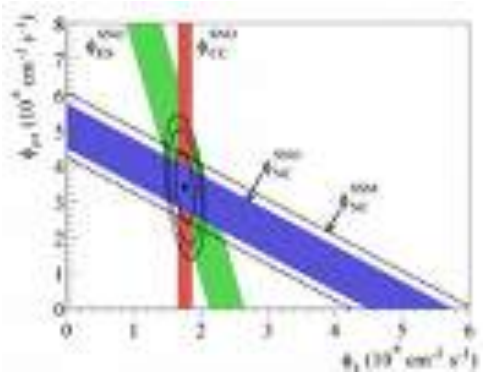


God plays dice with neutrinos!

The SNO experiment

- The target consists in1000 tonnes of heavy water D_2O.
- SNO messures separately the flux of ν_e, but also the other types.





- Agreement between total flux and predictions, ν_e represent ~1/3 of the total.

Phenomenology of oscillations

Interaction states ν_e ν_μ ν_τ differ from mass states (propagation) ν_1 ν_2 ν_3

Unitary mixing matrix (with 2 neutrinos):

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

Probability of oscillation:

$$\mathcal{P} = \sin^2 2\theta \, \sin^2(\pi L/\Lambda)$$

With an oscillation length $\Lambda = 2{,}5 \; E(\mathrm{GeV})/\Delta m^2(\mathrm{eV}^2)$

Masses of the neutrinos

In the simplest scenario one obtains:

$m(\nu_3) \sim 50$ meV/c^2

$m(\nu_2) \sim 9$ meV/c^2

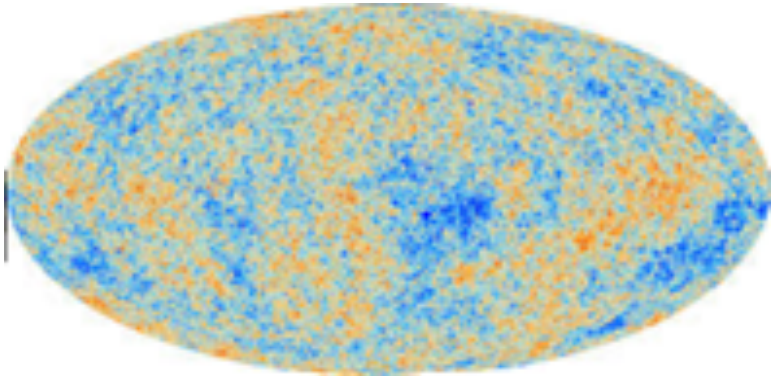
$m(\nu_1)$ smaller

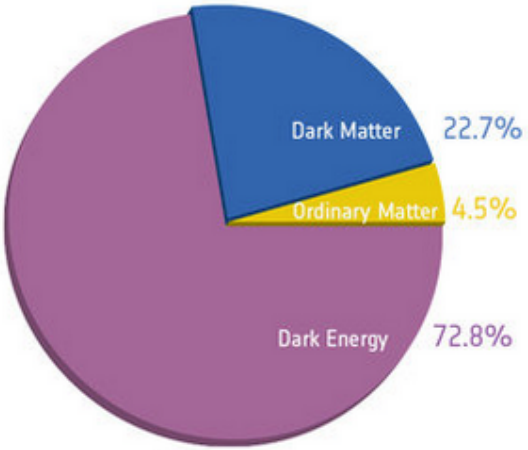
The heaviest neutrino has a mass 20 billion times smaller than that of the proton. The Big Bang model predicts 2 billion times more neutrinos than protons.

Admirable conclusion : neutrinos weigh as much as all the stars of all the galaxies !

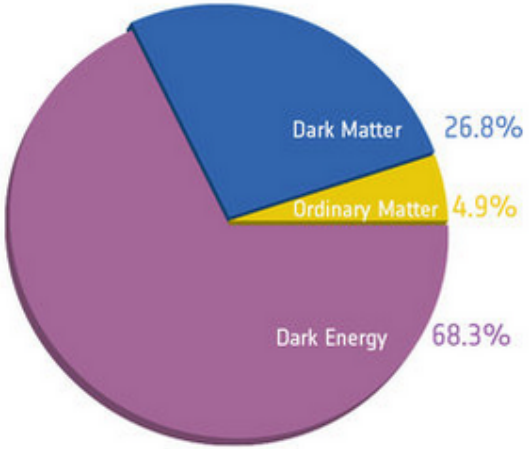
But there is much more in the Universe!!

Analysis of the CMB





Before Planck



After Planck

$\Sigma m_\nu < 0.23$ eV

The large kyrielle of questions

Why 3 active neutrinos ?

Mass hierarchy normal or inverted ?

Violation of CP ?

Nature of the neutrinos, Dirac or Majorana?

Electromagnetic interactions?

Sterile neutrinos?

Neutrinos of astrophysics ?

Neutrinos of the Big Bang?

Conclusions

Very recent progresses: neutrinos are massive.

$m(\nu_3) = 50$ meV, $m(\nu_2) = 9$ meV, $m(\nu_1) = ?$

They represent ≈ 0,5% of the mass-energy of the Universe.

Responsible for antimatter disappearance?

Solution to the problem of Dark Matter?

Solution to the puzzle of Dark Energy?

Cosmic Gall

Neutrinos, they are very small
They have no charge and have no mass
And do not interact at all.
The earth is just a silly ball
To them, through which they simply pass,
Like dustmaids down a drafty hall
Or photons through a sheet of glass.
They snub the most exquisite gas,
Ignore the most substantial wall,
Cold-shoulder steel and sounding brass,
Insult the stallion in his stall,
And, scoring barriers of class,
Infiltrate you and me. Like tall
And painless guillotines, they fall
Down through our heads into the grass.
At night, they enter at Nepal
And pierce the lover and his lass
From underneath the bed-you call
It wonderful: I call it crass.

John Updike 1960