NEUTRINOS:
Messengers of the invisible world

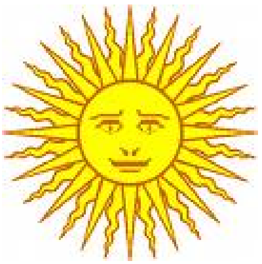
Loin d'être un appauvrissement, l'adjonction à la chose visible de la chose invisible fait plus que de l'enrichir, elle lui donne un sens, elle la complète.

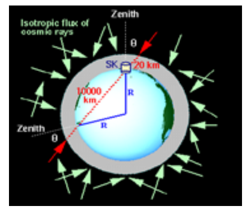
Far from being an impoverishment, the addition to the visible thing of the invisible thing does more than enrich it, it gives it a meaning, it completes it.

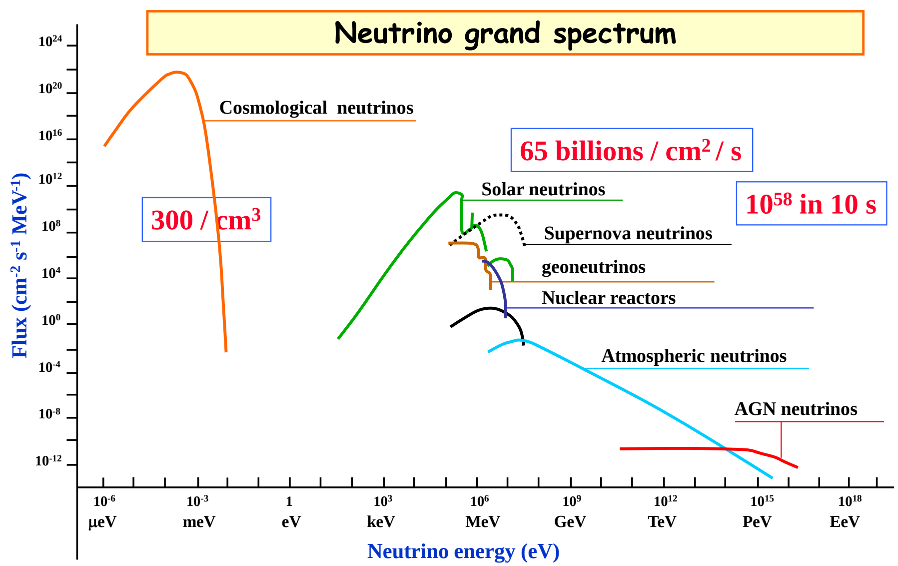
Paul Claudel

Positions et propositions

Sources of neutrinos







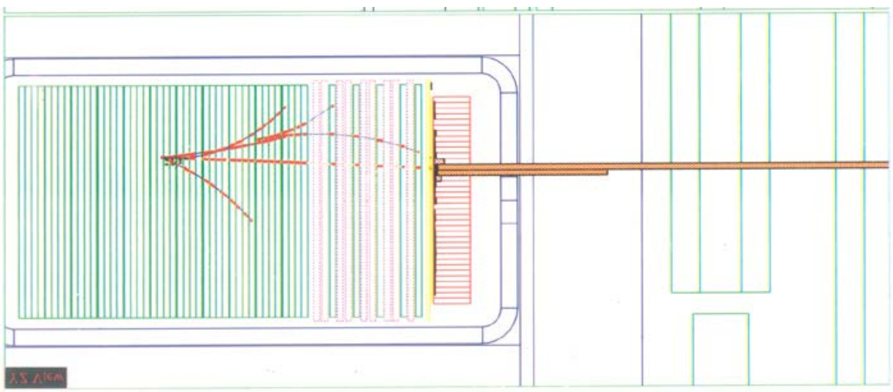
Neutrino: topics of interest

Neutrino interactions
Neutrino sources
Neutrino oscillations
Neutrino masses
Neutrinoless double beta decays
Electromagnetic interactions: magnetic moment, radiative decay
Neutrino coherent interactions
Sterile neutrinos
Neutrino astronomy
Neutrino in cosmology

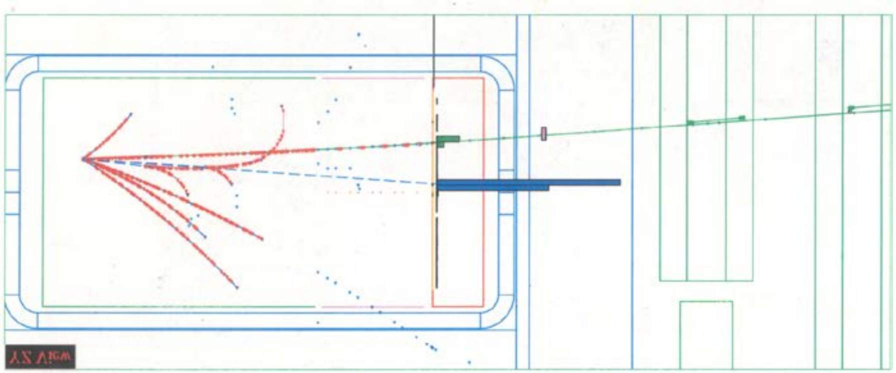
Neutrino oscillations

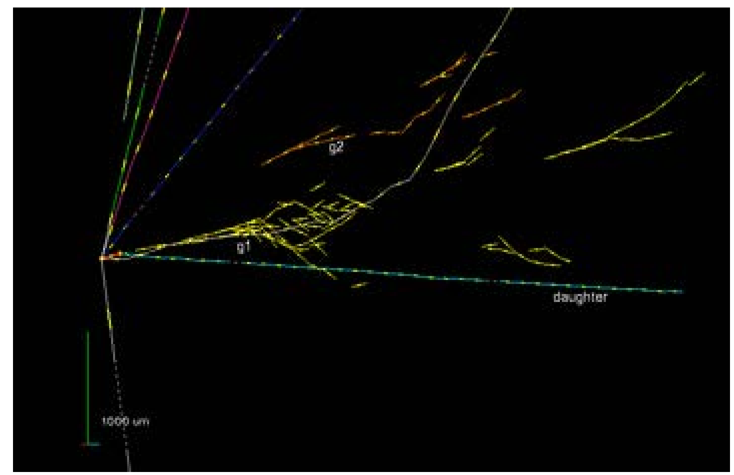
The three known neutrino types

ν_e



ν_μ





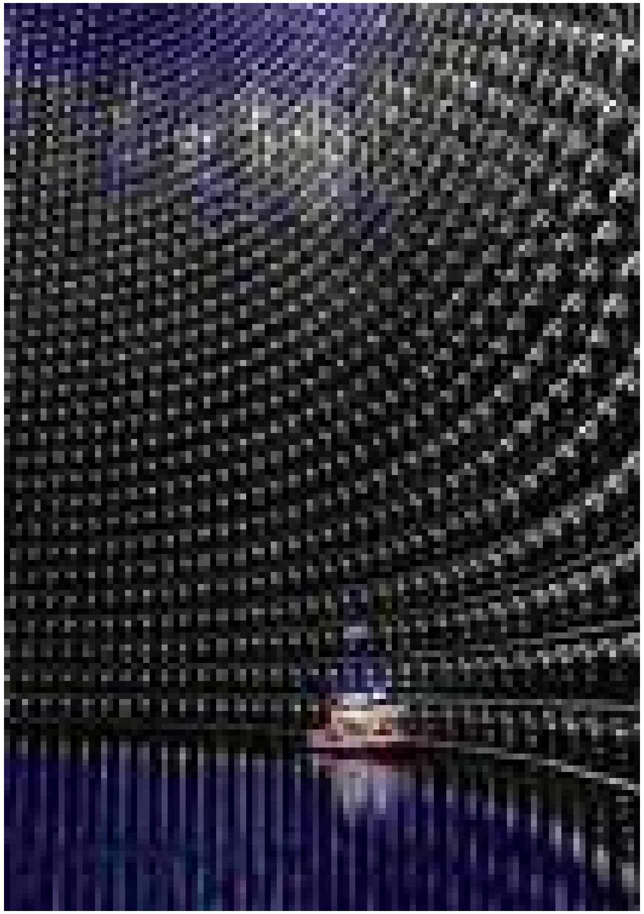
ν_τ

The SuperKamiokande detector

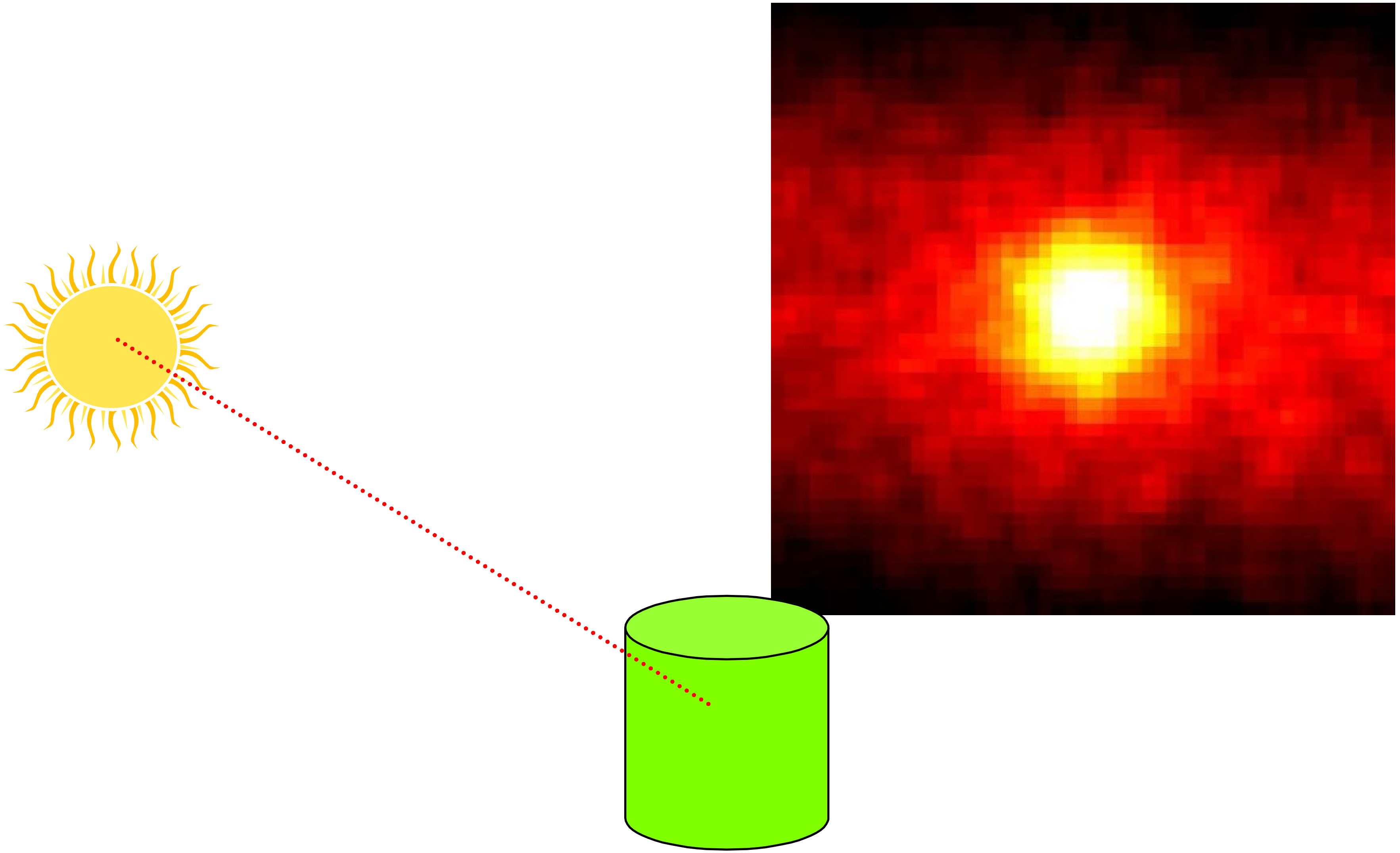
Constructed under a Japanese mountain, SuperK is an immense reservoir full of 50 kilotons of purified water, spied by 11000 very large PM's.

•In water charged particles emit Cerenkov light. For electrons the threshold is at ≈ 5 MeV.

•*SuperK studied solar neutrinos and also atmospheric ones.*



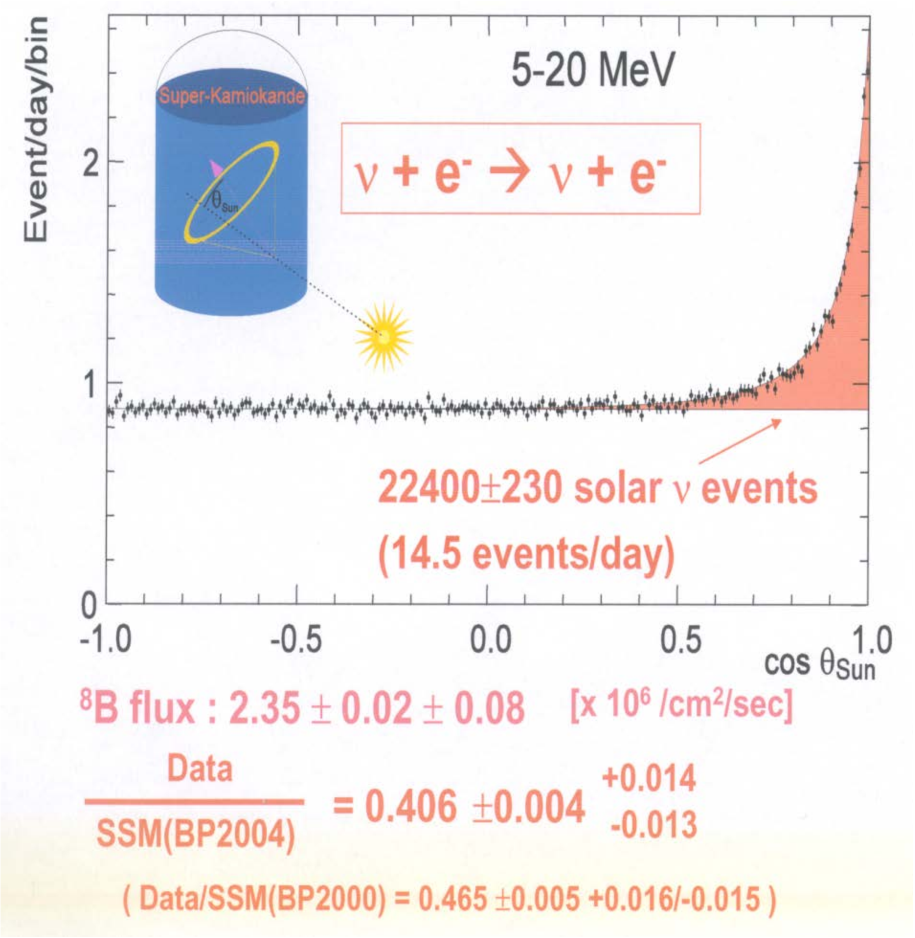
Neutrinography in real time



Result of SuperK

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

•Problem of the *deficit* of solar neutrinos, first observed by Homestake then confirmed by Gallex.

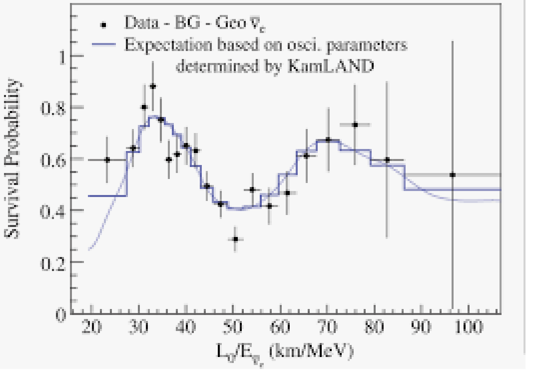


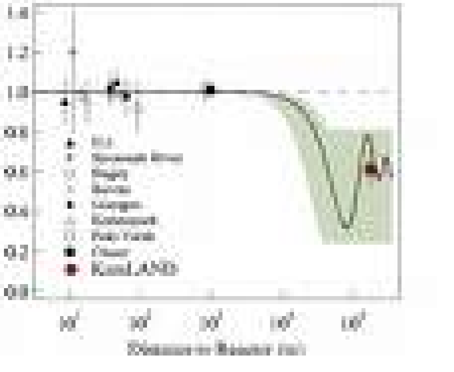
Confirmation by Kamland

Neutrinos from Japanese reactors (and Korean)

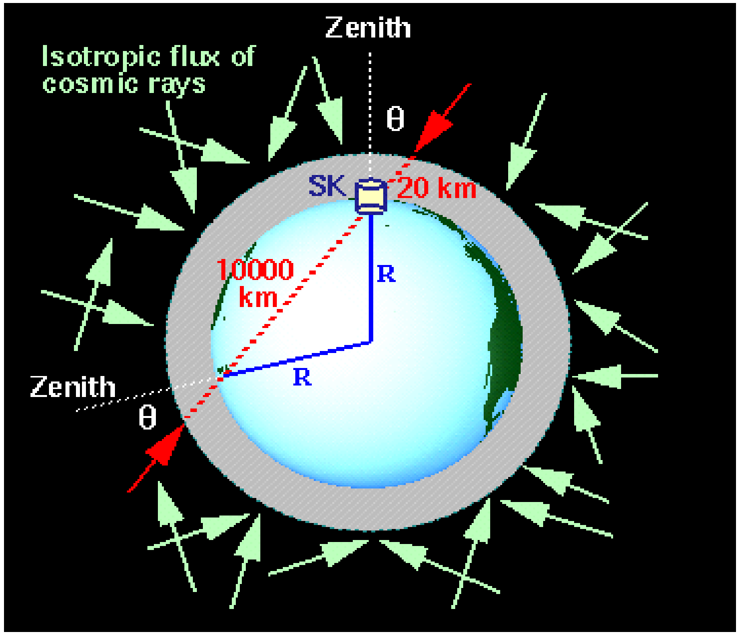
Average distance 180 km

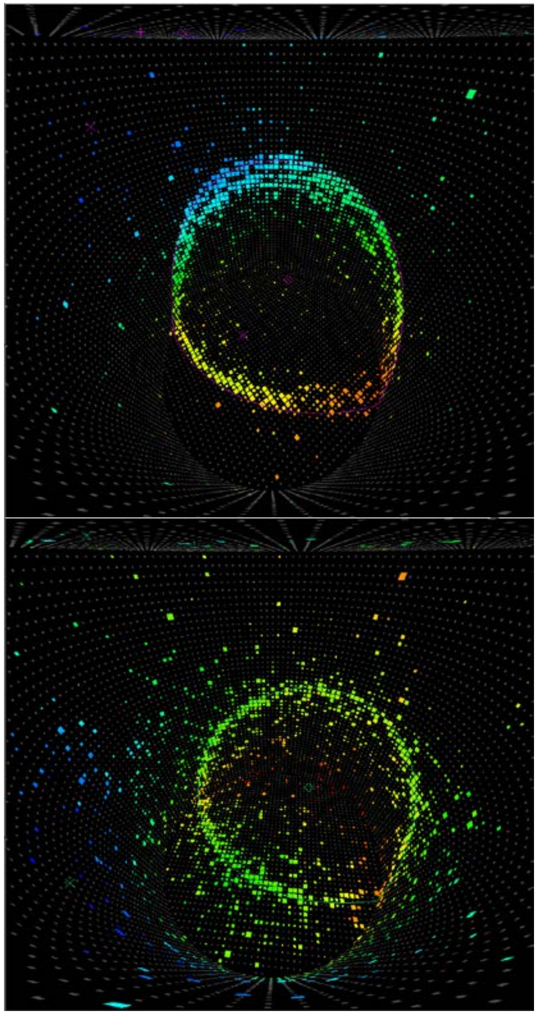
Artificial neutrinos also diseappear in flight

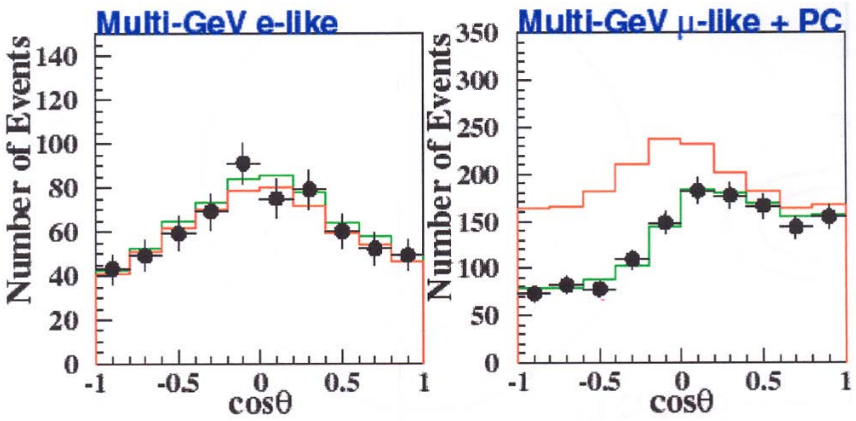




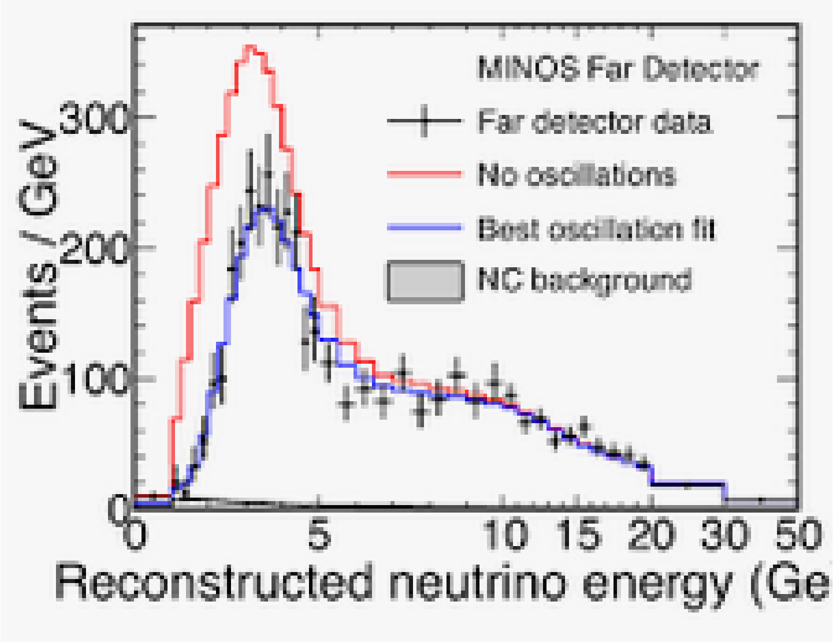
Atmospheric neutrinos







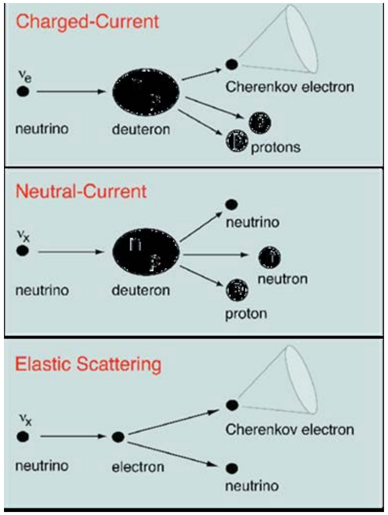
Confirmation by MINOS

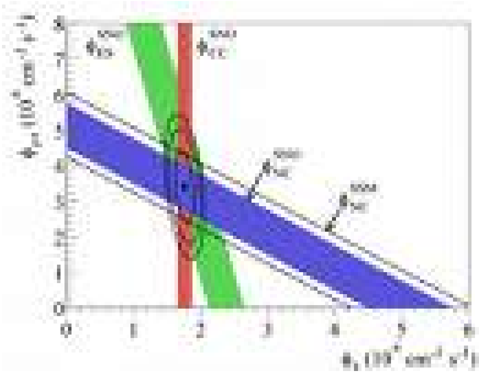


Final word with SNO

•The target consisted in 1kiloton of heavy water D_2O.

•SNO measured the flux of solar ν_e, but also the sum total of all solar neutrinos.

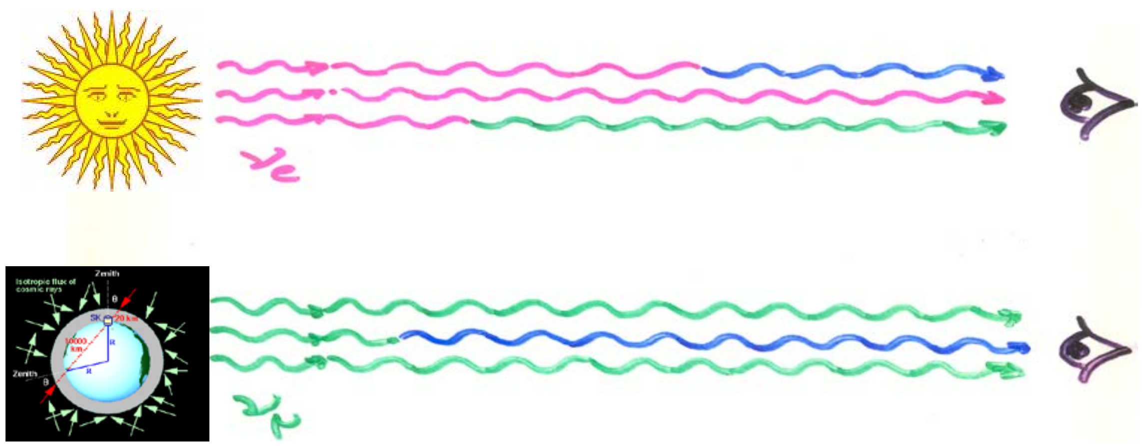




•The total flux agrees with solar predictions, but ν_e represent ~1/3 of the sum.

OSCILLATIONS ?

•These *deficits* can be explained by a spontaneous change of ν_e (from the Sun) or ν_μ (from the atmosphere) during their propagation giving neutrinos of another type.



Neutrino, what is your « being in oneself » ?

Phenomenology of oscillations

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

Unitary mixing matrix (case of 2 neutrinos):

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

Oscillation probability :

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

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

With three neutrinos

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

Δm^2_{31} Δm^2_{21}

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & e^{-i\delta} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta} s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

atmospheric+LBL Chooz solar+KamLAND

Sun + Kamland $\sin^2(2\theta_{12}) = 0.304 \pm 0.019$

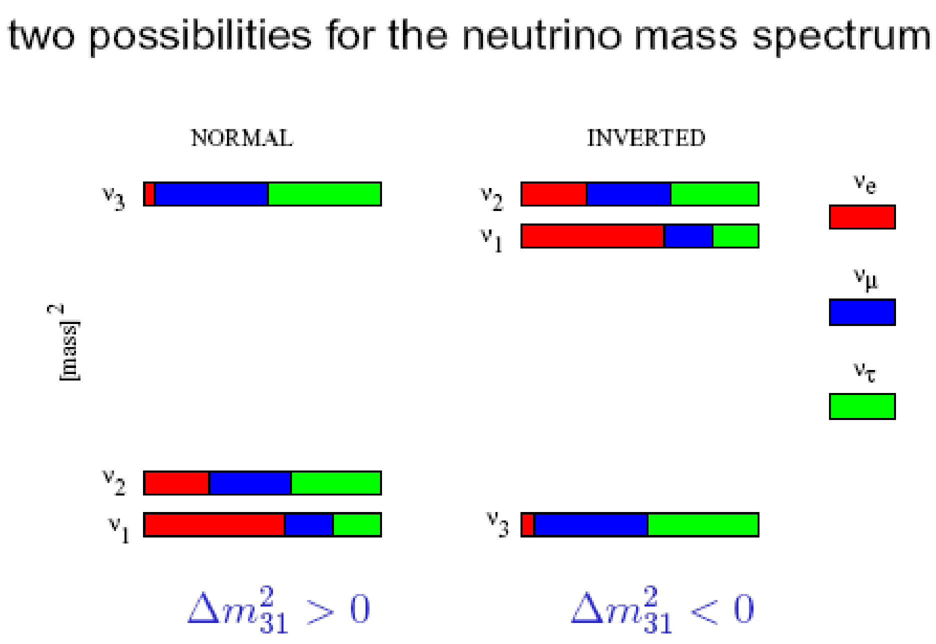
Atmosphere + Minos $\sin^2(2\theta_{23}) = 0.500 \pm 0.070$

Reactors + T2K $\sin^2(2\theta_{13}) = 0.096 \pm 0.013$

$\Delta m^2_{21} = 7.65\ 10^{-5}\ eV^2$

$\Delta m^2_{31} = 2.40\ 10^{-3}\ eV^2$

Mass hierarchy (ordering)



Neutrino masses

In the simplest scenario (normal hierarchy, no degeneracy), one obtains:

$m(\nu_\tau) \sim 50\ \text{meV}/c^2$

$m(\nu_\mu) \sim 9\ \text{meV}/c^2$

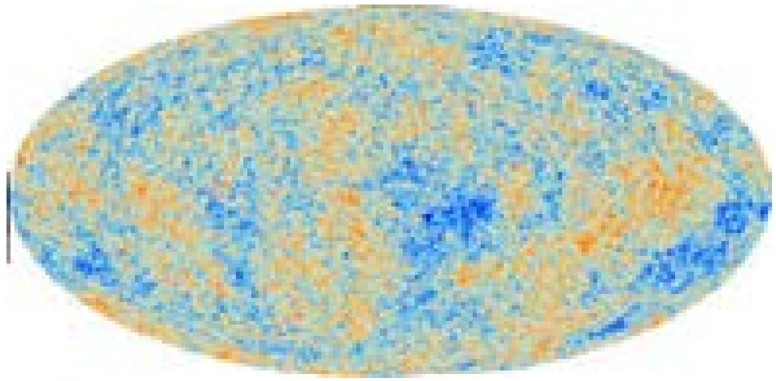
with $m(\nu_e)$ smaller

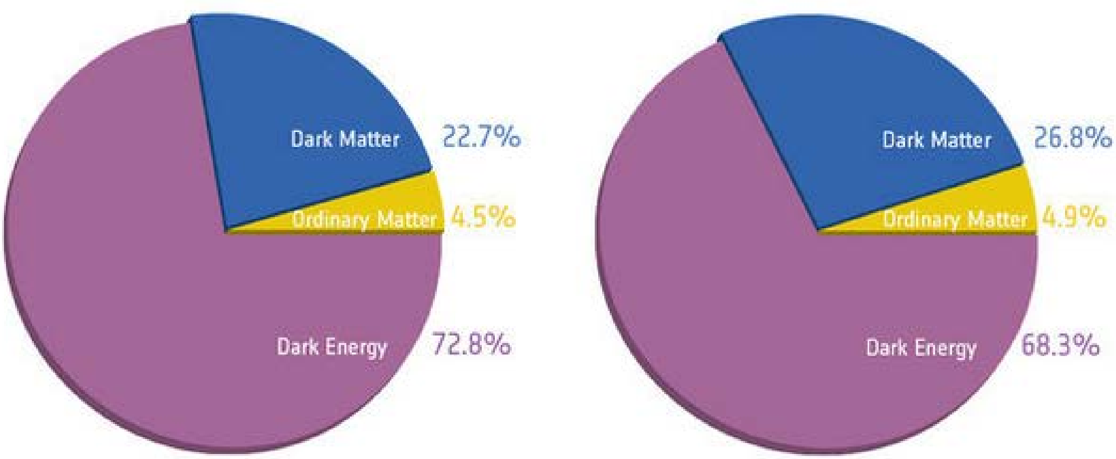
The heaviest neutrino has a mass ≈ 20 billion times smaller than that of the proton. The Big Bang model predicts 2 billion times more neutrinos than protons.

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

But there is much more in the Universe!!

CMB analysis





Before Planck

After Planck

$\Sigma m_\nu < 0.23$ eV

… and KATRIN

$m(\nu_1) < 0.8$ eV

Now, what about antineutrinos?

$$\begin{bmatrix} \overline{\nu_e} \\ \overline{\nu_\mu} \\ \overline{\nu_\tau} \end{bmatrix} = \begin{bmatrix} \overline{U}_{e1} & \overline{U}_{e2} & \overline{U}_{e3} \\ \overline{U}_{\mu 1} & \overline{U}_{\mu 2} & \overline{U}_{\mu 3} \\ \overline{U}_{\tau 1} & \overline{U}_{\tau 2} & \overline{U}_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

ν_e ν_μ ν_τ masses are not defined

ν_1 ν_2 ν_3 leptonic charges are not defined (superposition)

Problem: after ≈ 20 oscillations, waves do not interfere anymore

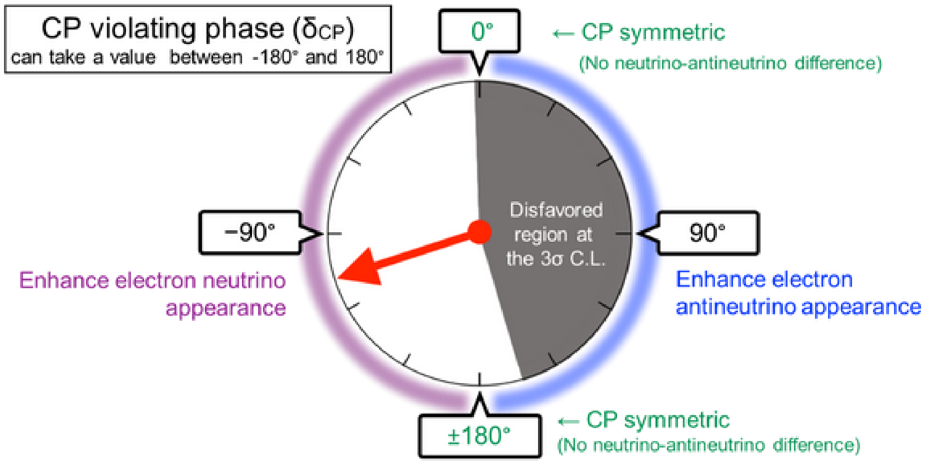
ν_1 ν_2 ν_3 remain.

How will they interact? Helicity will decide

Cosmological neutrinos are ν_1 ν_2 ν_3 !

Near future

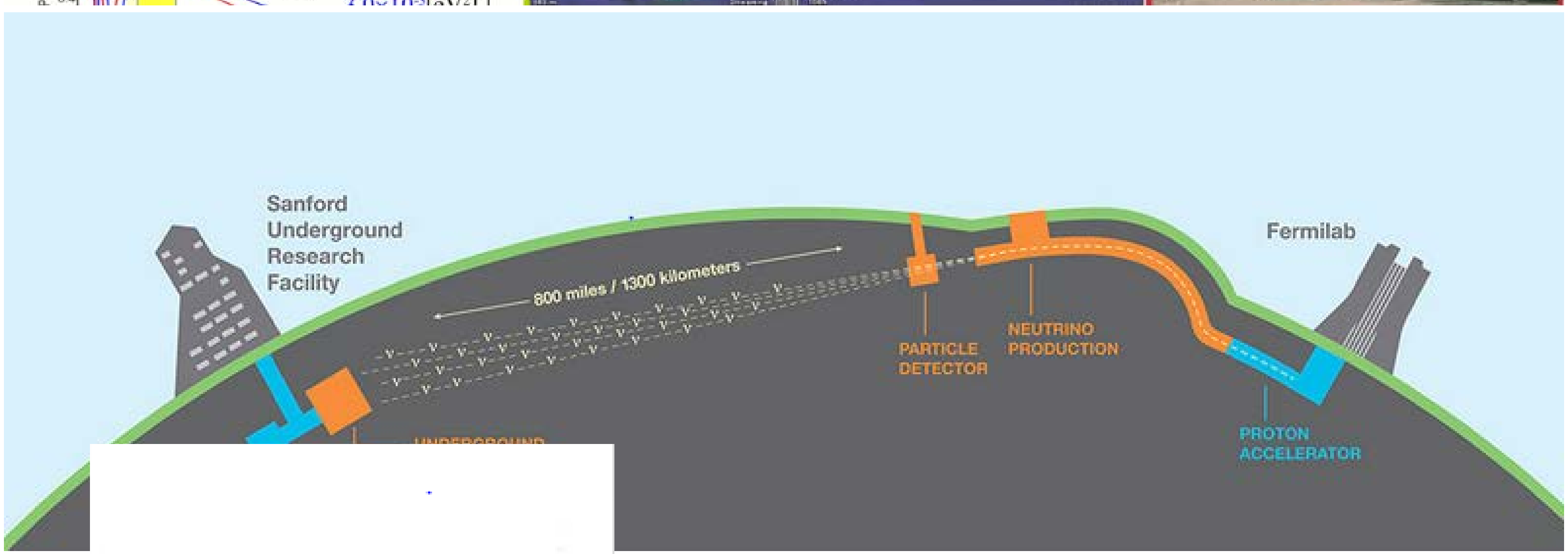
Measuring the CP violation angle δ



Very encouraging!

HyperK/DUNE

2027

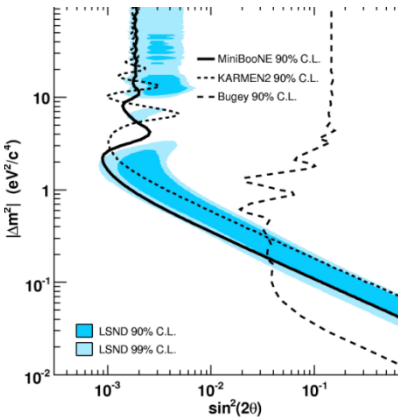


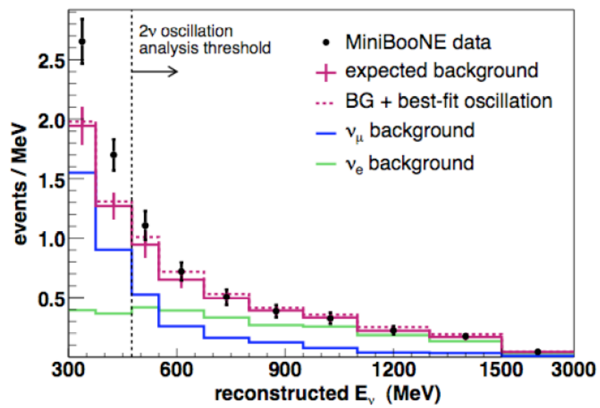
2029

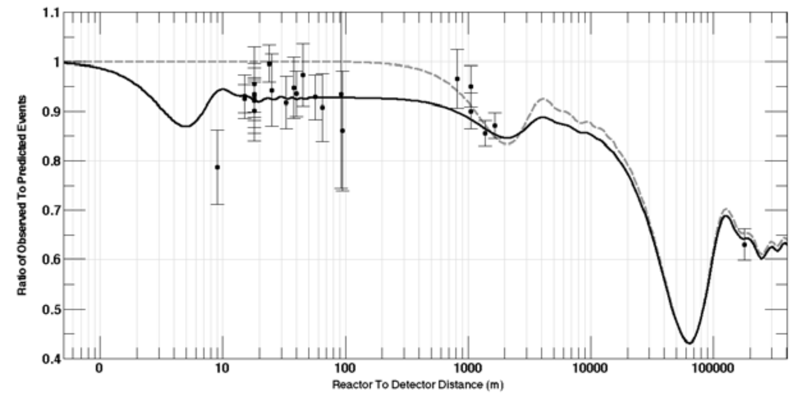
Sterile neutrinos

Why sterile neutrinos?

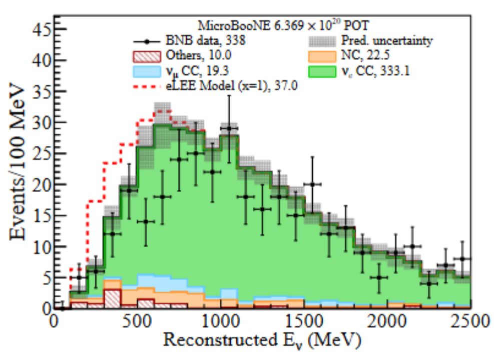
Bad reasons: *anomalies*

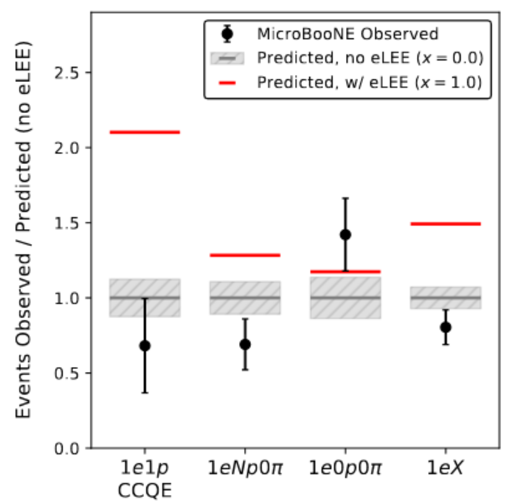






MicroBOONE





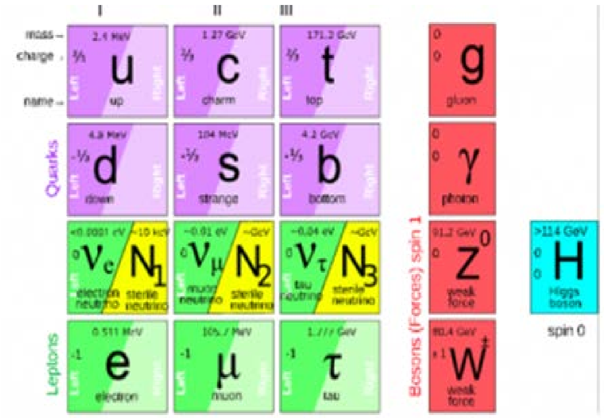
Alleluia !

The very good reason

To understand the smallness of the active neutrino masses ν_1 ν_2 ν_3

See-saw model

$$m_\nu \approx m_D^2/M_M$$

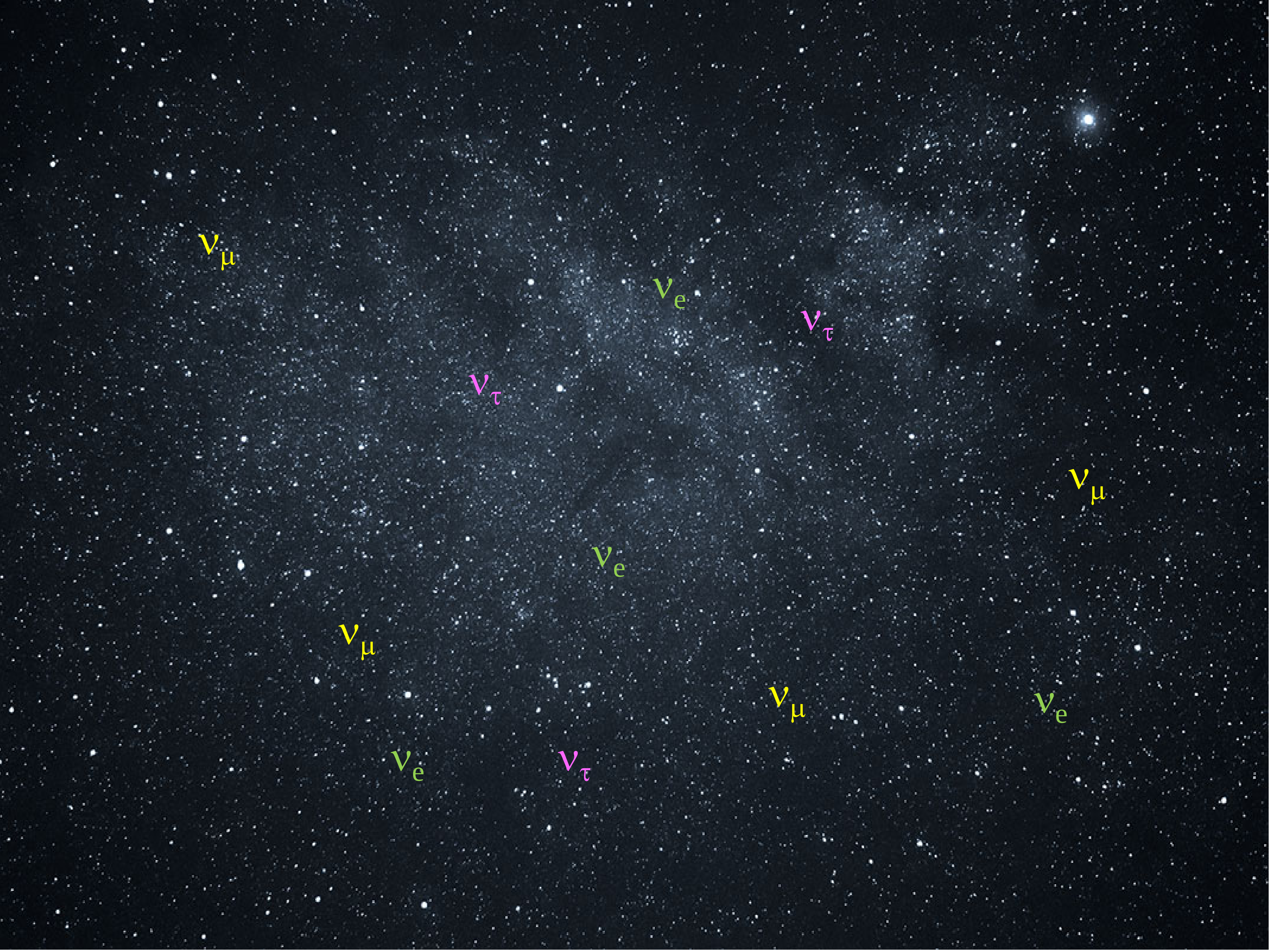


The νMSM

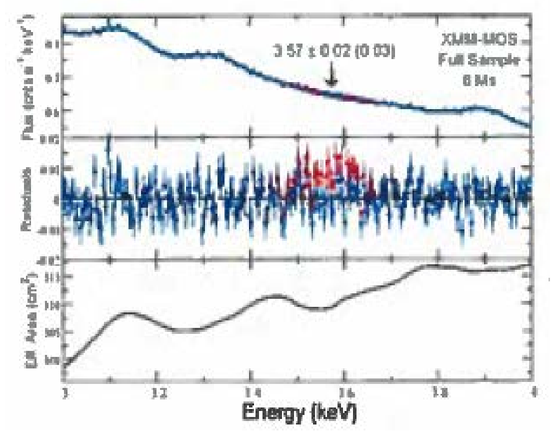
$$\nu_e = U_{e1}\,\nu_1 + U_{e2}\,\nu_2 + U_{e3}\,\nu_3$$

Now: $$\nu_e = U_{e1}\,\nu_1 + U_{e2}\,\nu_2 + U_{e3}\,\nu_3 + U_{e4}\,\nu_4$$


LE NEU-TRINO !
C'EST LA MATIÈRE NOIRE !


ν_μ
ν_e
ν_τ
ν_τ
ν_μ
ν_e
ν_μ
ν_μ
ν_e
ν_e
ν_τ

Hint?



Photons from a cluster of galaxies: decay of a heavy neutrinos ?

$m(\nu_H) \sim 7$ keV $\quad U^2 \sim 10^{-10}$

Lifetime: $\tau_0 = 4\ 10^{34}$ *s*

Simple calculation between the two infinites

Dark matter constitutes 26% of the Universe content, while ordinary matter (stars + gases) amounts to 5%.

Primordial nucleosynthesis fixes the fraction between matter and photons :

$$baryon/photon = 6\ x10^{-10}$$

A dark matter candidate having the mass of a baryon would be present at the level :

$$\nu_H/\gamma = 6\ x10^{-10}\ x\ 26/5$$

With a mass of 7 keV, the density of ν_H *is increased by 1 GeV/7 keV. Then :*

$$\nu_H/\gamma = 5\ x10^{-4}$$

Within the whole Universe, cosmological photons amount to 400/cm^3*, and calculations give a density of 110/cm*^{3} *for each flavor of cosmological neutrinos.*

As a consequence : $\nu_H/\nu_e = 2\ x10^{-3}$

If these new objects are sterile neutrinos produced at the Big Bang epoch, they mix with ν_e

Thus : $U_{He}{}^2 = 2\ x10^{-3}$

Interesting constraint… but 7 orders of magnitude off from the present hint!

$$\tau = 7\ 10^{43}\ (1eV/m)^5\ 1/\ U_{He}{}^2$$

$$\tau = 2\ 10^{27}\ s$$

The kyrielle of remaining questions

Hierarchy normal or inverted ?

Violation of CP ?

Nature of neutrinos, Dirac or Majorana?

Electromagnetic interactions?

Why 3 active neutrinos ?

New sterile neutrinos?

Neutrinos from astrophysics ?

Neutrinos from the Big Bang?

Conclusion

Great progresses with recent results : neutrinos are massive.

$m(\nu_\tau) = 50$ meV, $m(\nu_\mu) = 9$ meV, $m(\nu_e) = ?$

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

Responsible for the disappearance of antimatter?

Solution to the problem of the dark mass?

Solution to the problem of dark energy?