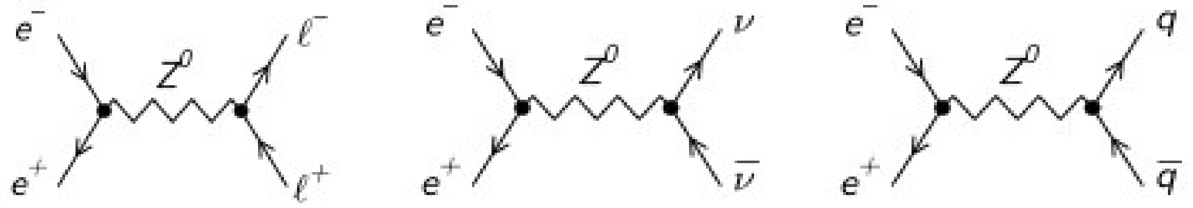
Sterile neutrino searches

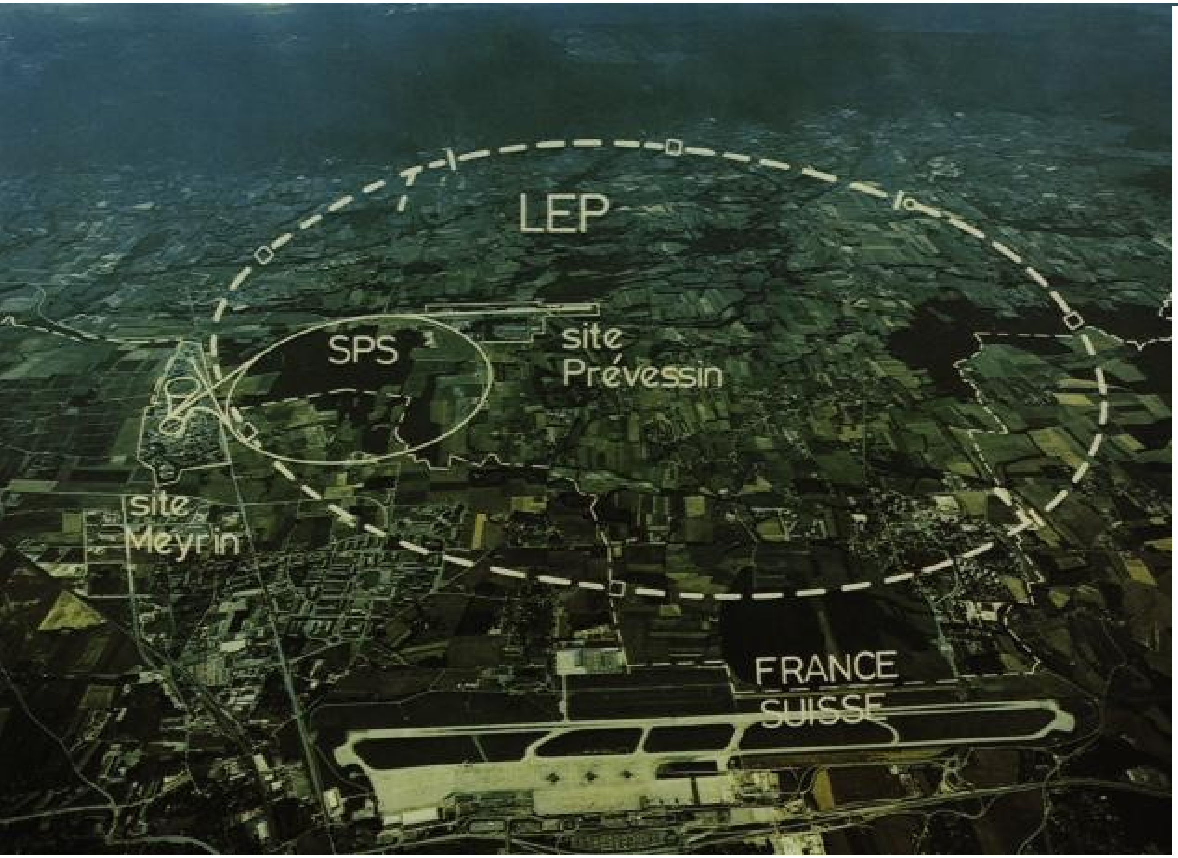
A. Paoloni (INFN-LNF)

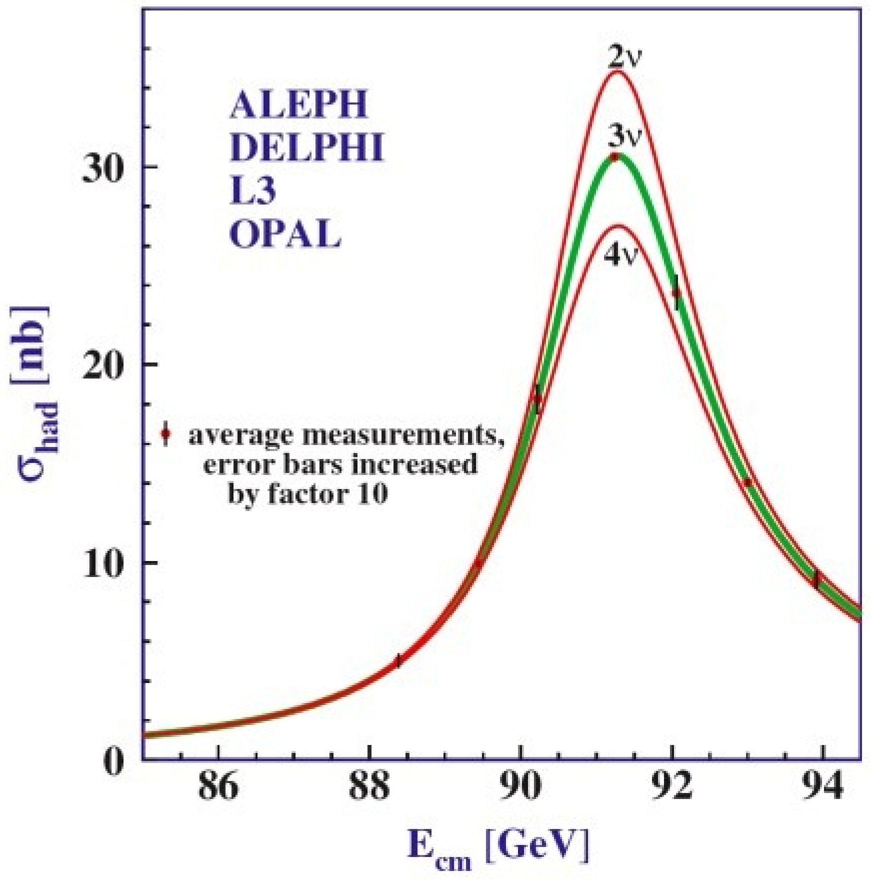
1st synergy LNF-OAR workshop

Number of neutrinos

Precise number of neutrino types at CERN with LEP I, from coupling with Z0.





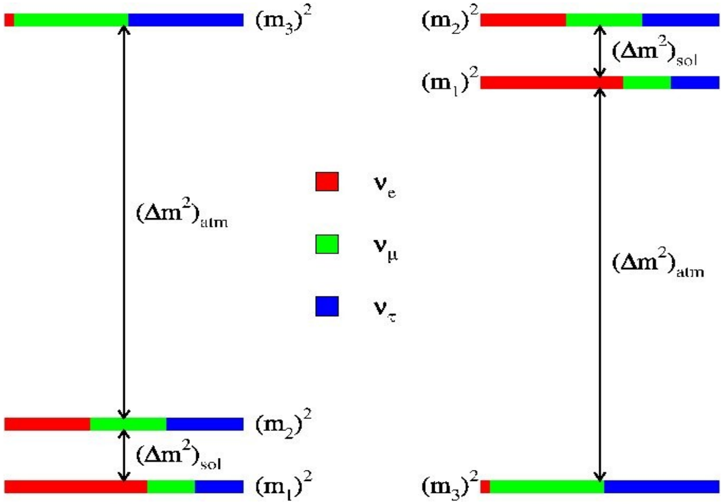


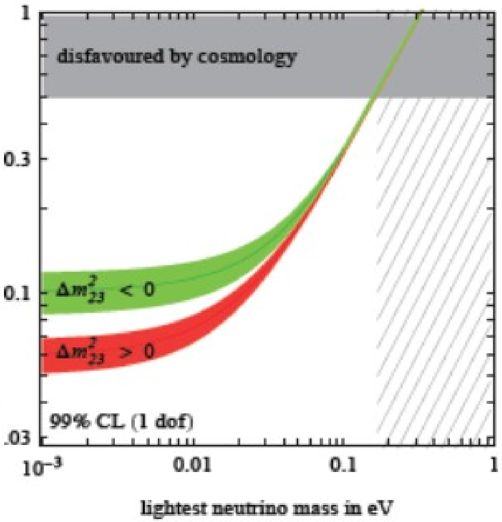
Neutrino masses

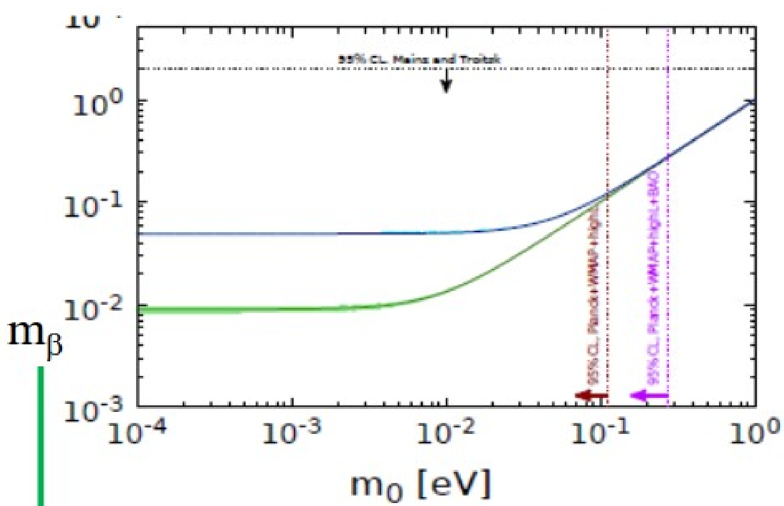
From INFN "What next" meeting

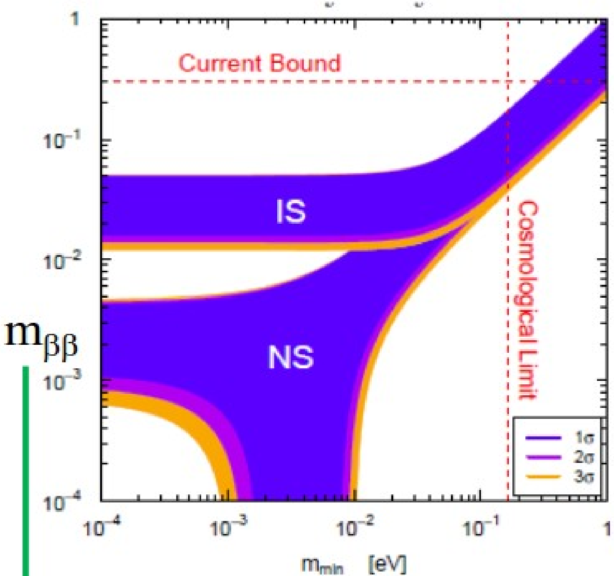
Parameter	best-fit ($\pm1\sigma$)
Δm^2_{21} [10^{-5} eV ^{2}]	$7.54^{+0.26}_{-0.22}$
$\lvert\Delta m^2\rvert$ [10^{-3} eV ^{2}]	$2.43^{+0.06}_{-0.10}$ $(2.42^{+0.07}_{-0.11})$
$\sin^2\theta_{12}$	$0.307^{+0.018}_{-0.016}$
$\sin^2\theta_{23}$	$0.386^{+0.024}_{-0.021}$ $(0.392^{+0.039}_{-0.022})$
$\sin^2\theta_{13}$ [173]	0.0241 ± 0.0025 $(0.0244^{+0.0023}_{-0.0025})$

2 Δm^2 (solar and atmospheric) means 3 neutrinos.
But we don't know the absolute mass scale, nor their hierarchy.









$$m_\beta = \left[c^2_{13}c^2_{12}m^2_1 + c^2_{13}s^2_{12}m^2_2 + s^2_{13}m^2_3\right]^{\frac{1}{2}}$$

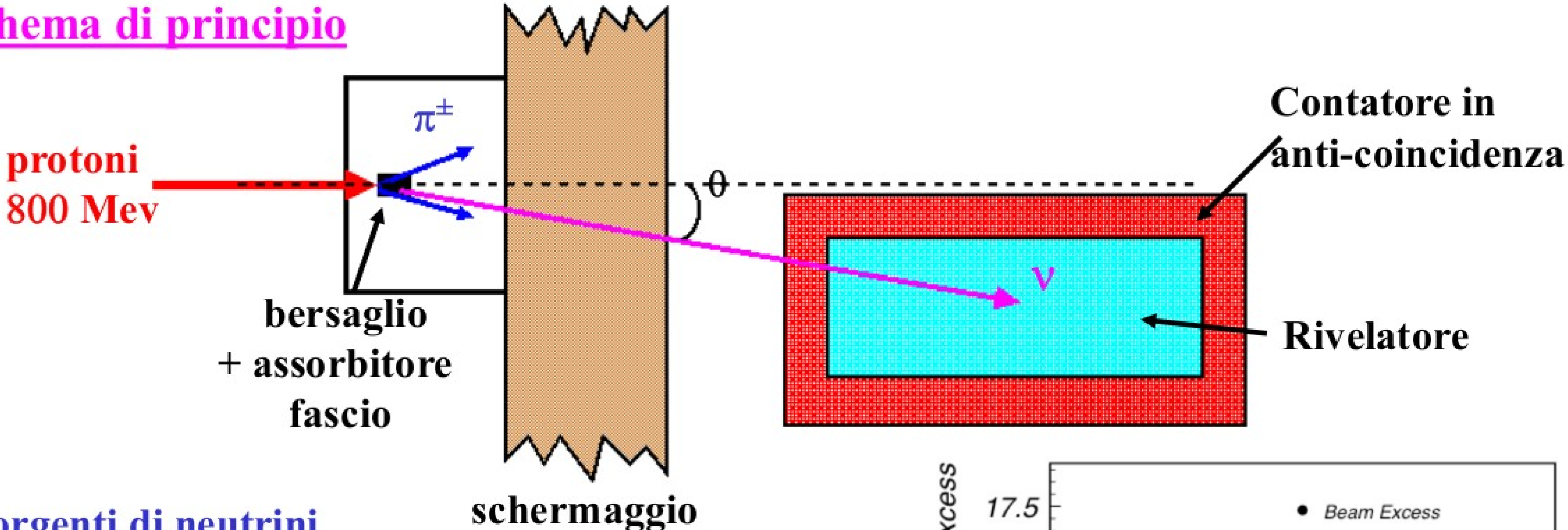
$$\Sigma = m_1 + m_2 + m_3$$

$$m_{\beta\beta} = \left|c^2_{13}c^2_{12}m_1 + c^2_{13}s^2_{12}m_2e^{i\phi_2} + s^2_{13}m_3e^{i\phi_3}\right|$$

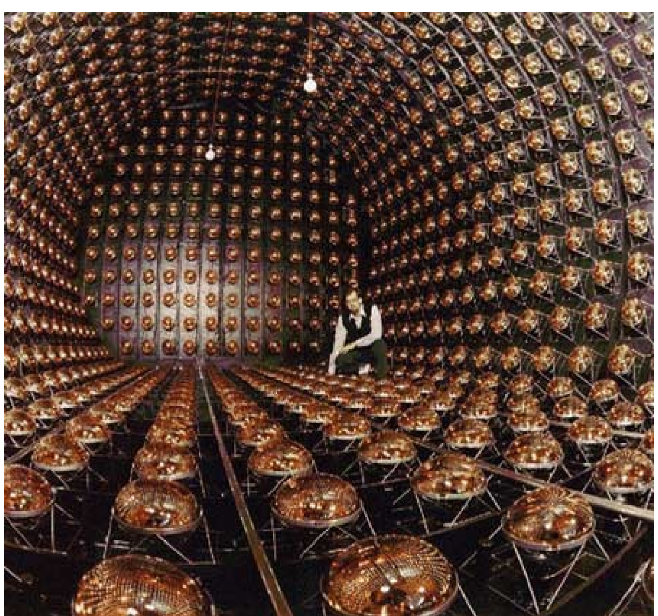
Other neutrinos ?

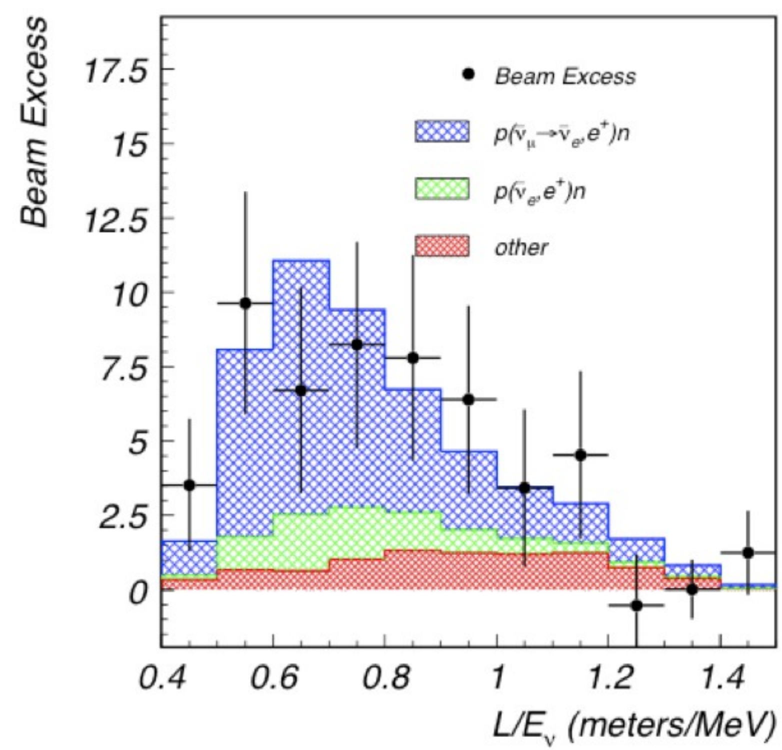
Esperimenti LSND e KARMEN : ricerca di oscillazioni $\bar{\nu}_\mu - \bar{\nu}_e$

Schema di principio



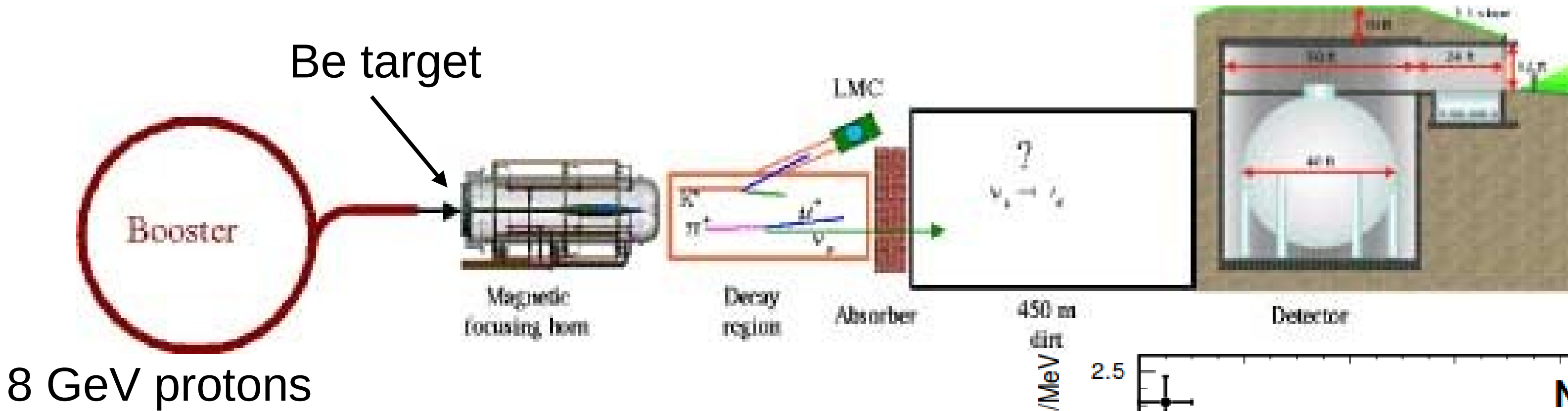
Sorgenti di neutrini

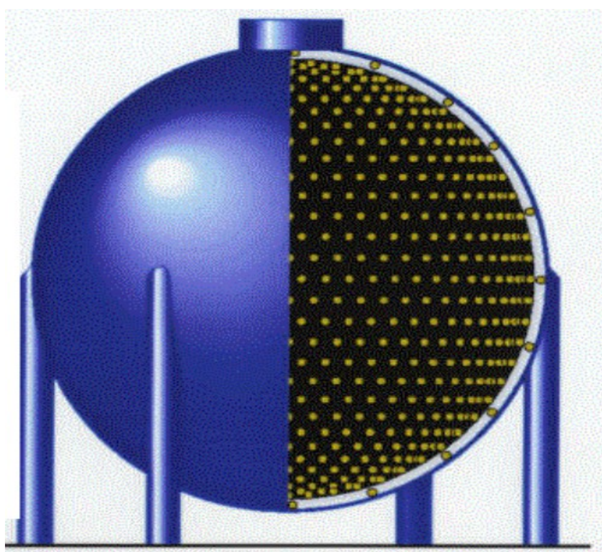




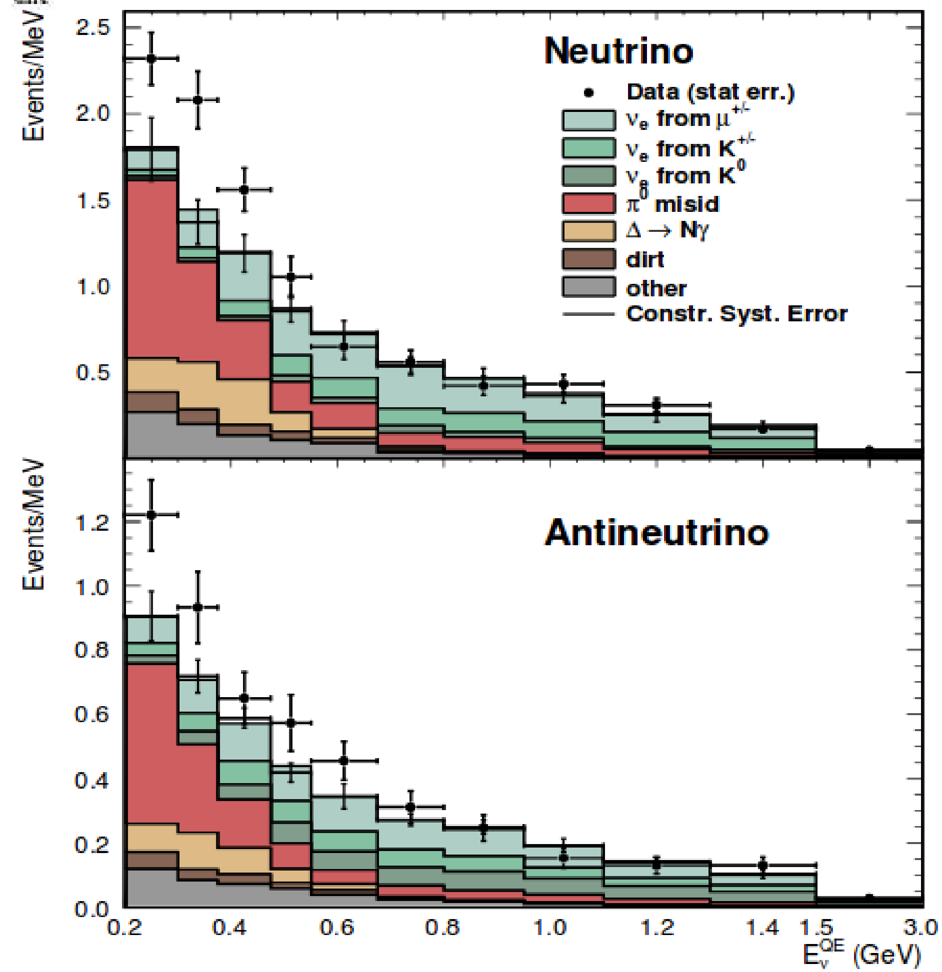
Other neutrinos ?

MiniBoone experiment



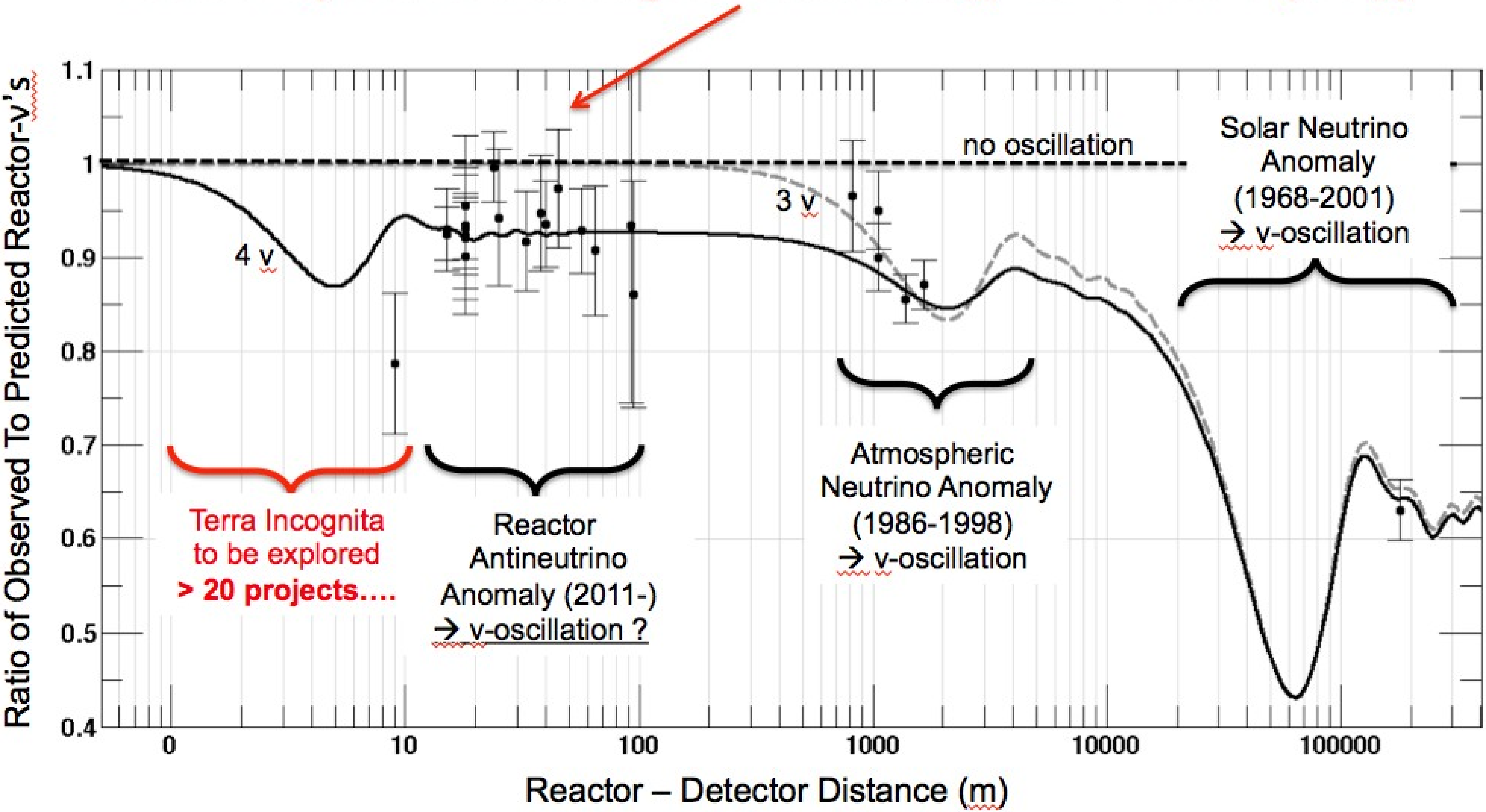


Spherical detector (d=12 m)
Filled with mineral oil (800 tonnes)
Fiducial volume: 445 tonnes.
1280 PMTs (20 cm) in the internal region, detecting Cerenkov (directional) and scintillation light.



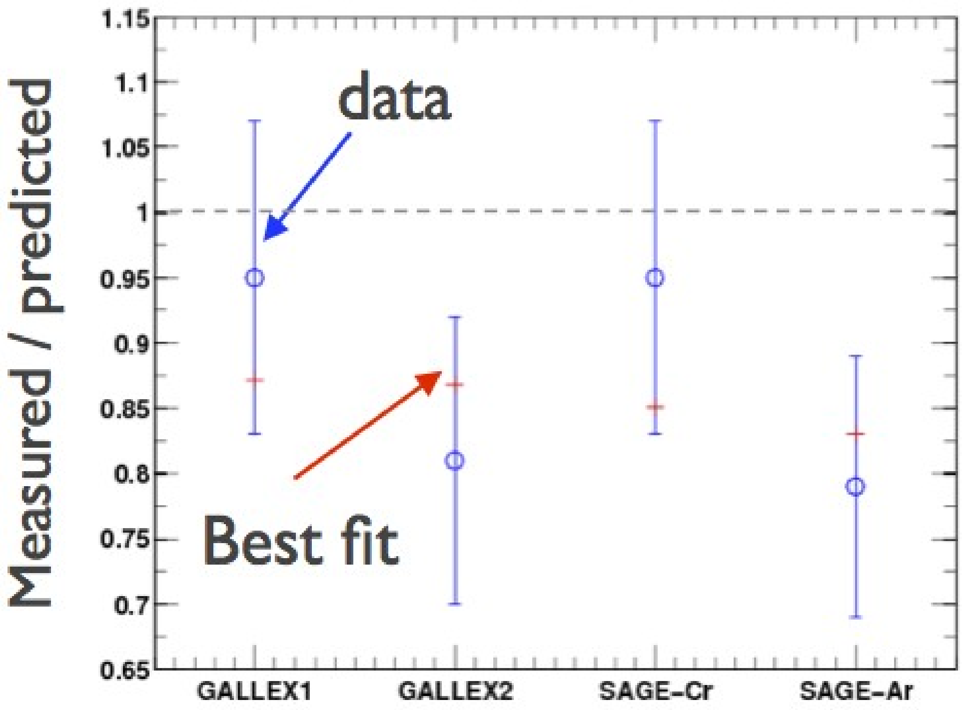
The Reactor Antineutrino Anomaly

- Observed/predicted averaged event ratio: R=0.927±0.023 (3.0 σ)



Th. Lasserre – TPC-Paris 2012

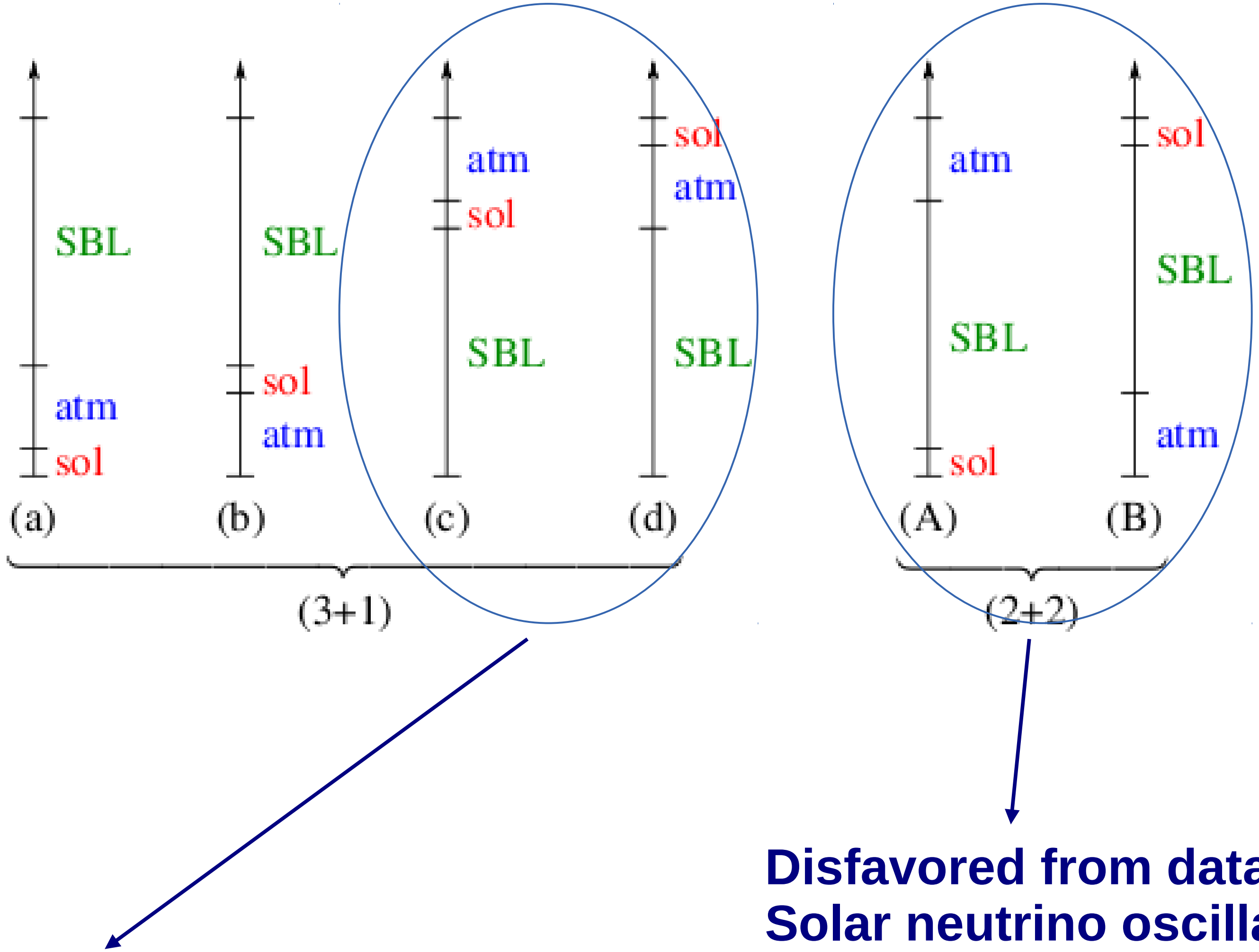
Other neutrinos ?



Gallium anomaly:
calibration of Gallium solar neutrino experiments with Cr source.

Several hints for a fourth neutrino (a third $\Delta m^2 \sim$ eV^2), no one very strong.
Only three neutrinos coupled to Z0, therefore it is called sterile.

Mass hierarchy with one sterile neutrino



Disfavored from cosmologic results on the sum of neutrino masses

Disfavored from data:
Solar neutrino oscillations and Atmospheric neutrino oscillations happen between standard neutrinos

3+1 model mixing matrix

3 standard neutrinos : 3 angles + 1 CP violating phase
3 + 1 sterile neutrino: 6 angles + 3 CP violating phases
(Majorana phases not considered, since not visible in oscillations)

$|\nu_l\rangle = U^+_{lj}\, |\nu_j\rangle$ (l=flavor state, j=mass state)

No definite convention for matrix definition.

$$U = R_{34}(\theta_{34})R_{24}(\theta_{24},\delta_2)R_{14}(\theta_{14})R_{23}(\theta_{23})R_{13}(\theta_{13},\delta_1)R_{12}(\theta_{12},\delta_3)$$

$$U = \begin{bmatrix} U_{e1} & U_{e2} & c_{14}s_{13}e^{-i\delta_1} & s_{14} \\ U_{\mu1} & U_{\mu2} & -s_{14}s_{13}e^{-i\delta_1}s_{24}e^{-i\delta_2} + c_{13}s_{23}c_{24} & c_{14}s_{24}e^{-i\delta_2} \\ U_{\tau1} & U_{\tau2} & -s_{14}c_{24}s_{34}s_{13}e^{-i\delta_1} - c_{13}s_{23}s_{34}s_{24}e^{i\delta_2} + c_{13}c_{23}c_{34} & c_{14}c_{24}s_{34} \\ U_{s1} & U_{s2} & -s_{14}c_{24}c_{34}s_{13}e^{-i\delta_1} - c_{13}s_{23}c_{34}s_{24}e^{i\delta_2} - c_{13}c_{23}s_{34} & c_{14}c_{24}c_{34} \end{bmatrix}$$

3+1 model oscillation probabilities

In general are complicate functions of $\sin^2(\Delta m^2_{ij} L/4E)$, $\sin(\Delta m^2_{ij} L/2E)$ and of the mixing matrix elements.
There are also specific codes for data analysis (Globes).

Suitable approximations for

Short Baseline experiments (SBL): Δm^2_{21} L/E~0, Δm^2_{31} L/E~0, Δm^2_{41} L/E≠0

Long Baseline experiments (LBL): Δm^2_{21} L/E~0, Δm^2_{31} L/E≠0, Δm^2_{41} L/E→∞

SBL

appearance

$$P_{\mu e} = \sin^2 2\theta_{\mu e} \sin^2 \frac{\Delta m^2_{41} L}{4E} \qquad \sin^2 2\theta_{\mu e} = 4|U_{e4}|^2|U_{\mu 4}|^2$$

disappearance $(\alpha = e, \mu)$

$$P_{\alpha\alpha} = 1 - \sin^2 2\theta_{\alpha\alpha} \sin^2 \frac{\Delta m^2_{41} L}{4E} \qquad \sin^2 2\theta_{\alpha\alpha} = 4|U_{\alpha 4}|^2(1 - |U_{\alpha 4}|^2)$$

Fitting all together?

there are three classes of data:

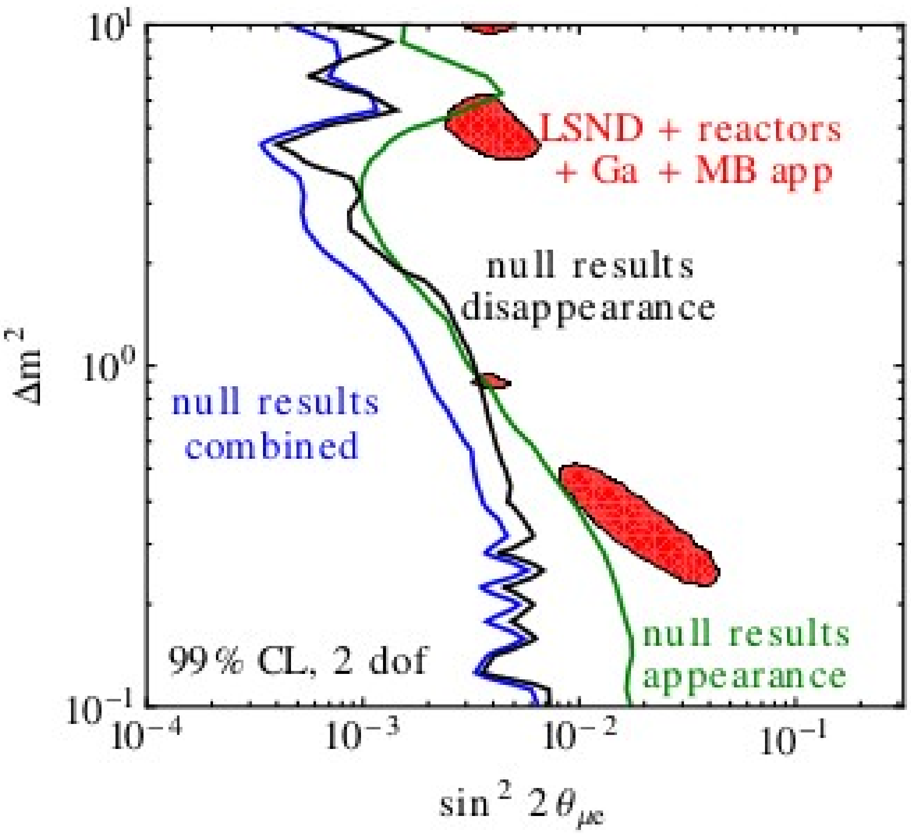
$\nu_e \rightarrow \nu_e$ disappearance $\sin^2 2\theta_{ee}$

$\nu_\mu \rightarrow \nu_\mu$ disappearance $\sin^2 2\theta_{\mu\mu}$

$\nu_\mu \rightarrow \nu_e$ appearance $\sin^2 2\theta_{\mu e}$

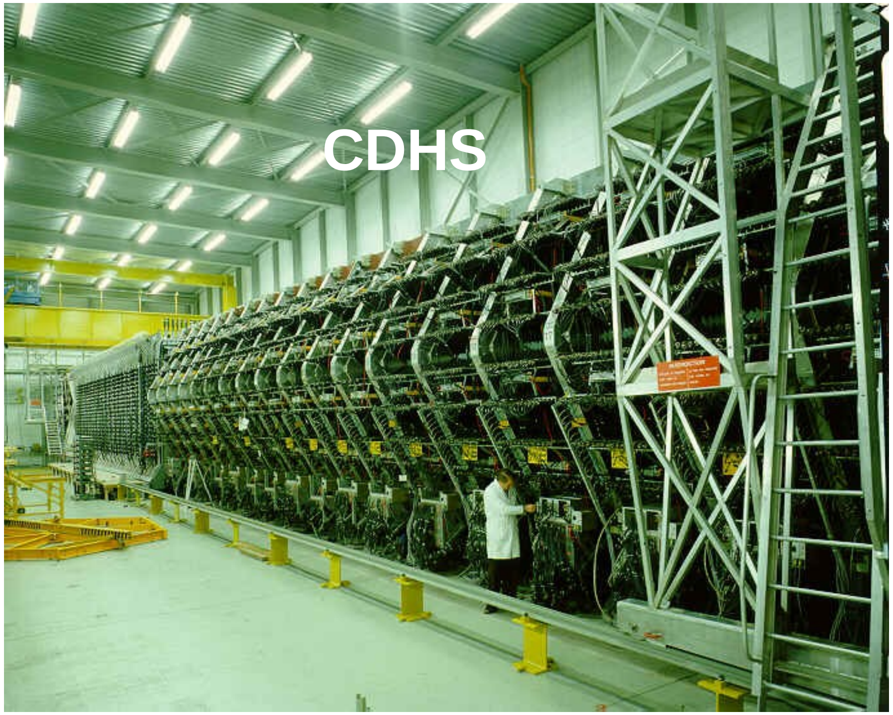
$$\sin^2 2\theta_{\mu e} \approx \frac{1}{4}\sin^2 2\theta_{ee} \sin^2 2\theta_{\mu\mu}$$

$\nu_\mu \rightarrow \nu_e$ appearance **requires** ν_μ and ν_e disappearance!!!



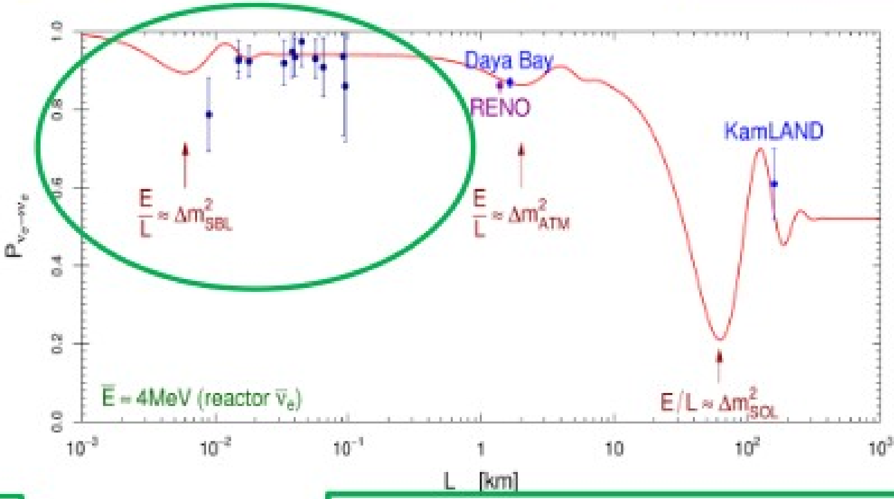
(arXiv 1303.3011v3)

Tensions with results on ν_μ disappearance



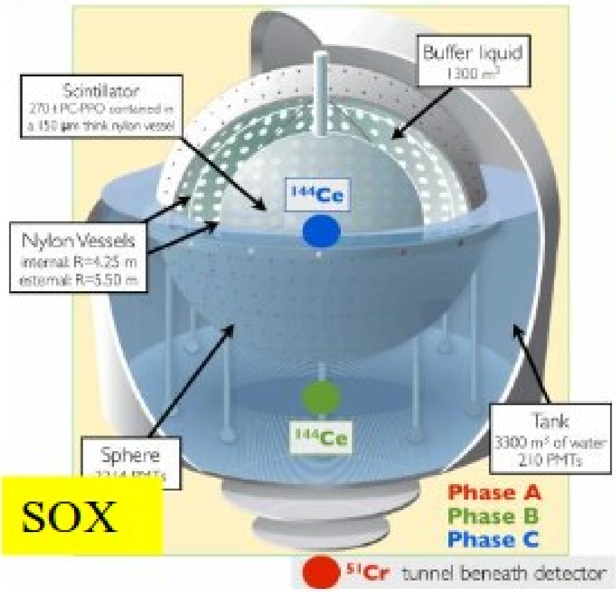
Tensioni nei paradigmi standard

La combinazione di informazioni così eterogenee è garantita dalla consistenza dello SM (WG SM), del paradigma ΛCDM della cosmologia (WG new directions) e del paradigma a 3 famiglie dei neutrini

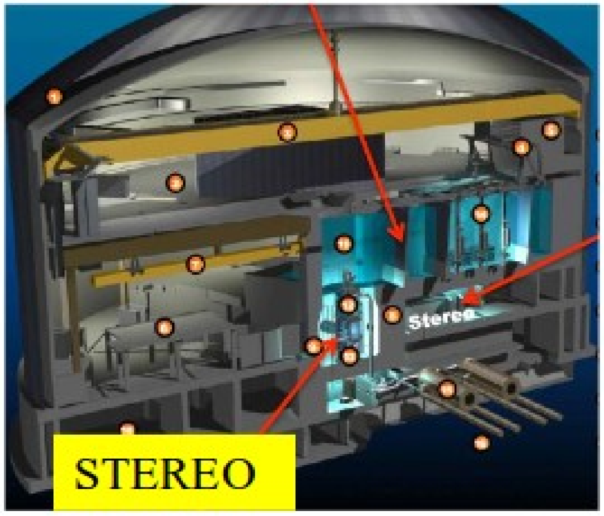


Neutrini sterili all' eV
La più importante anomalia sperimentale del nostro settore

Sorgenti radiattive

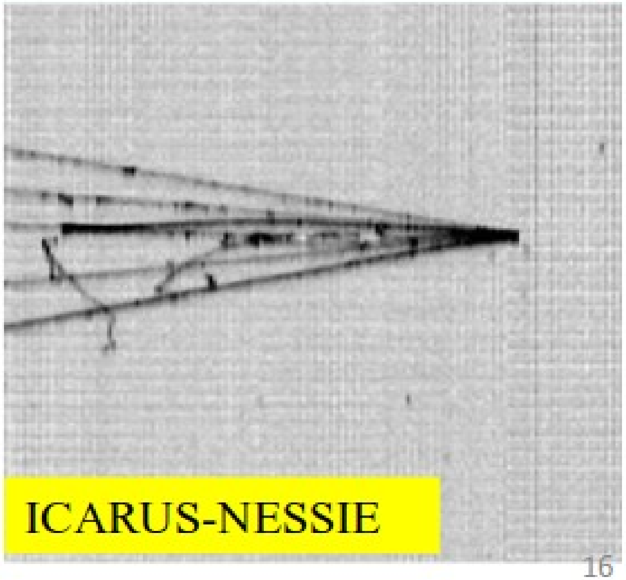


Reattori



Ma anche **Teseo**, DANSS...

Short baseline (Fermilab/CERN)



From INFN "What next" meeting

Proposal for NESSiE at FNAL-Booster

Neutrino Experiment with SpectrometerS in Europe

or

Neutrino Experiment with SpectrometerS in FERMILAB ?

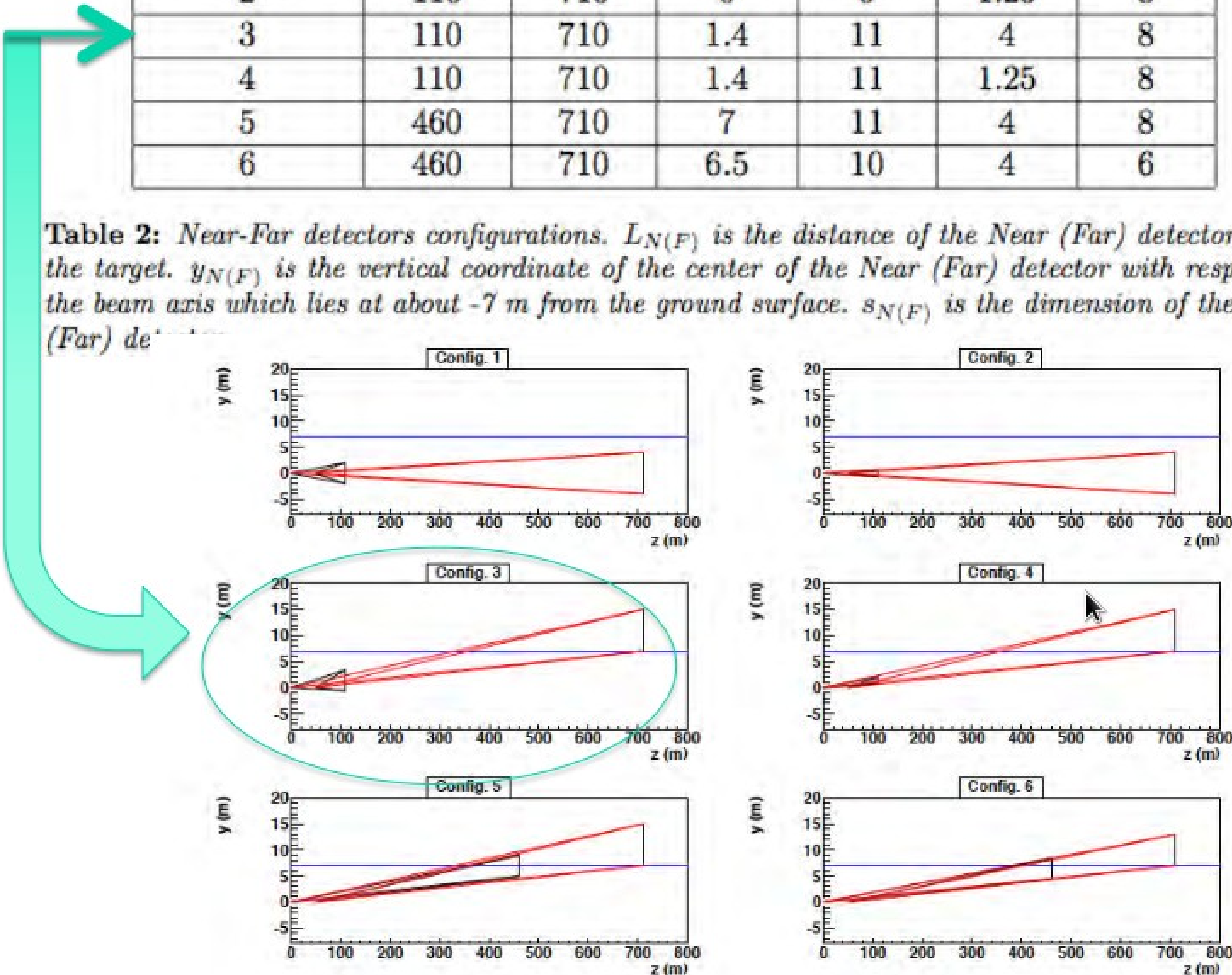
Prospects for the measurement of ν_μ disappearance at the FNAL-Booster

The NESSiE Collaboration

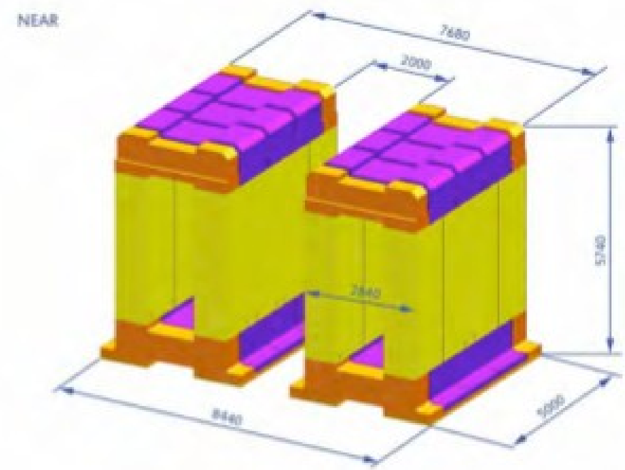
arXiv:1404.2521

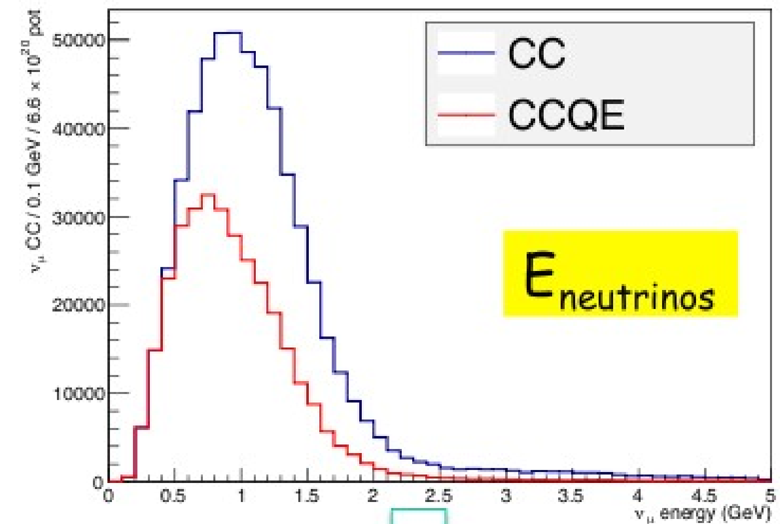
configuration	L_N (m)	L_F (m)	y_N (m)	y_F (m)	s_N (m)	s_F (m)
1	110	710	0	0	4	8
2	110	710	0	0	1.25	8
3	110	710	1.4	11	4	8
4	110	710	1.4	11	1.25	8
5	460	710	7	11	4	8
6	460	710	6.5	10	4	6

Table 2: *Near-Far detectors configurations. $L_{N(F)}$ is the distance of the Near (Far) detector from the target. $y_{N(F)}$ is the vertical coordinate of the center of the Near (Far) detector with respect to the beam axis which lies at about -7 m from the ground surface. $s_{N(F)}$ is the dimension of the Near (Far) de...*

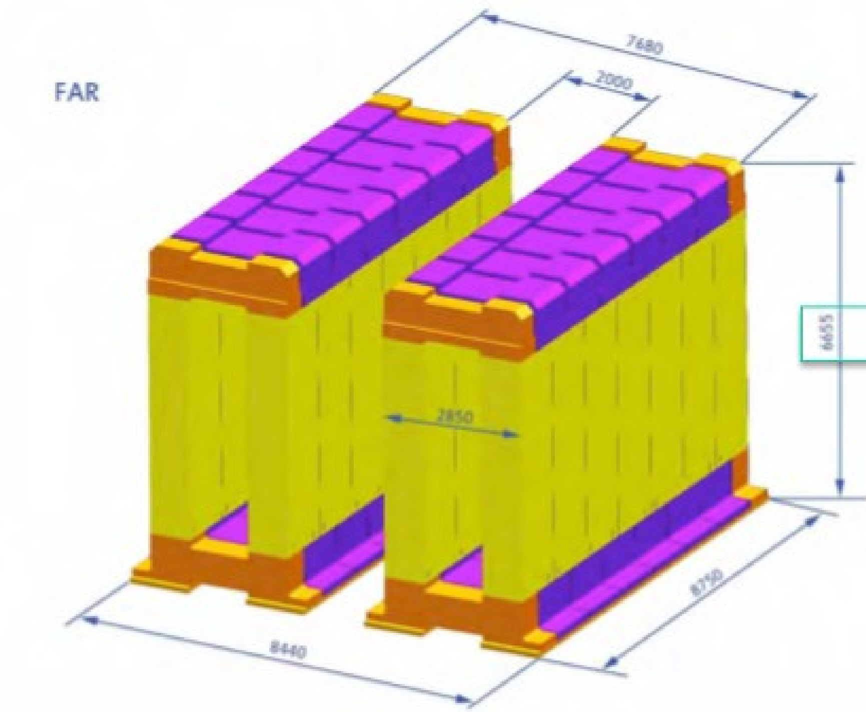


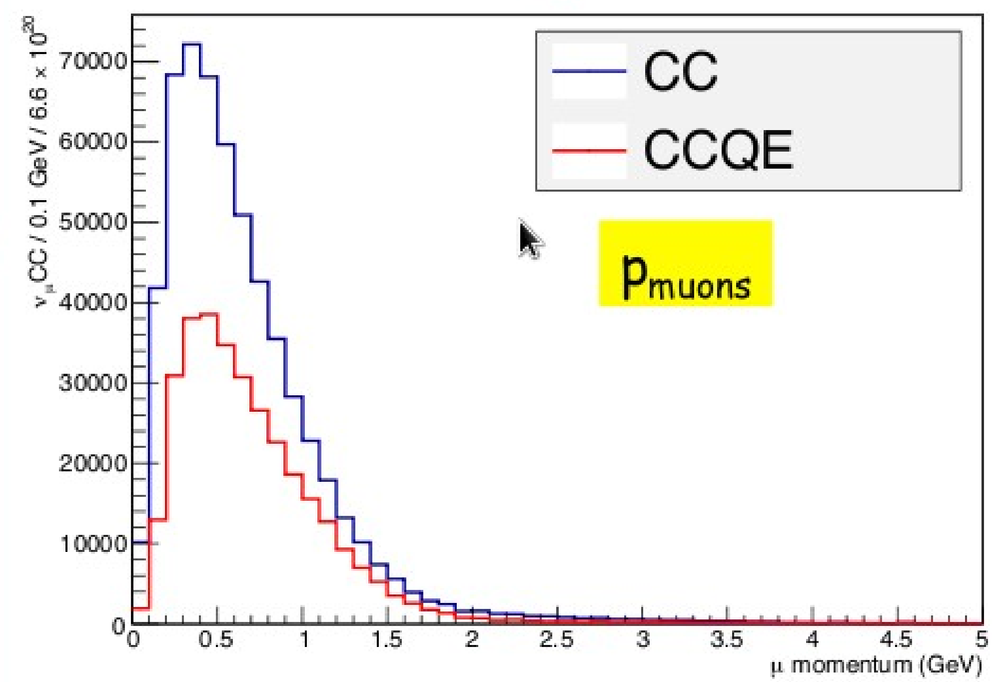
Near site





Far site

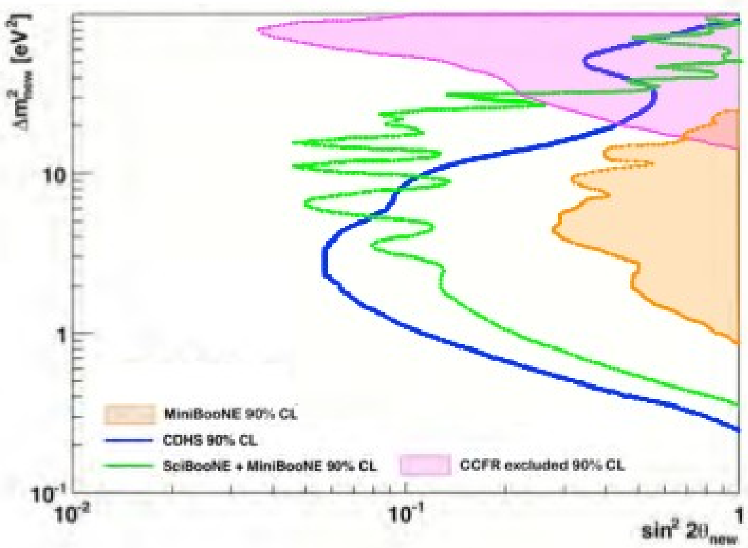




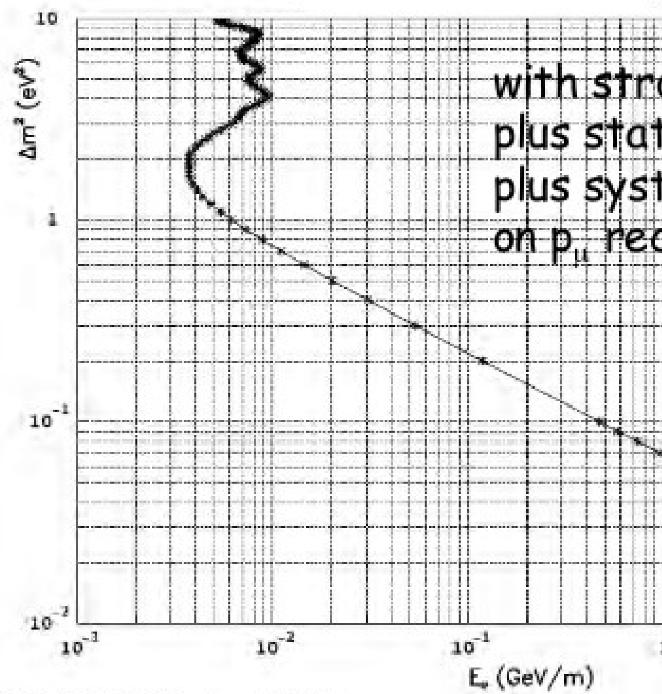
ABSOLUTE nb. interactions in fiducial volume Far, 3 years data taking

Sensitivity

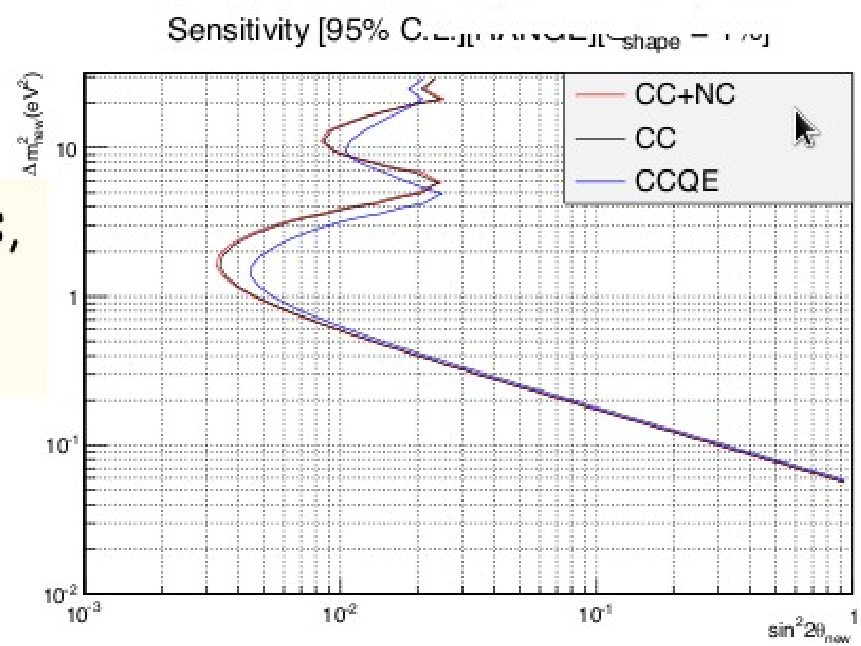
From here (now)



to here (from NESSiE)



with strong cuts
plus statistical error
plus systematics only
on p_μ reconstruction

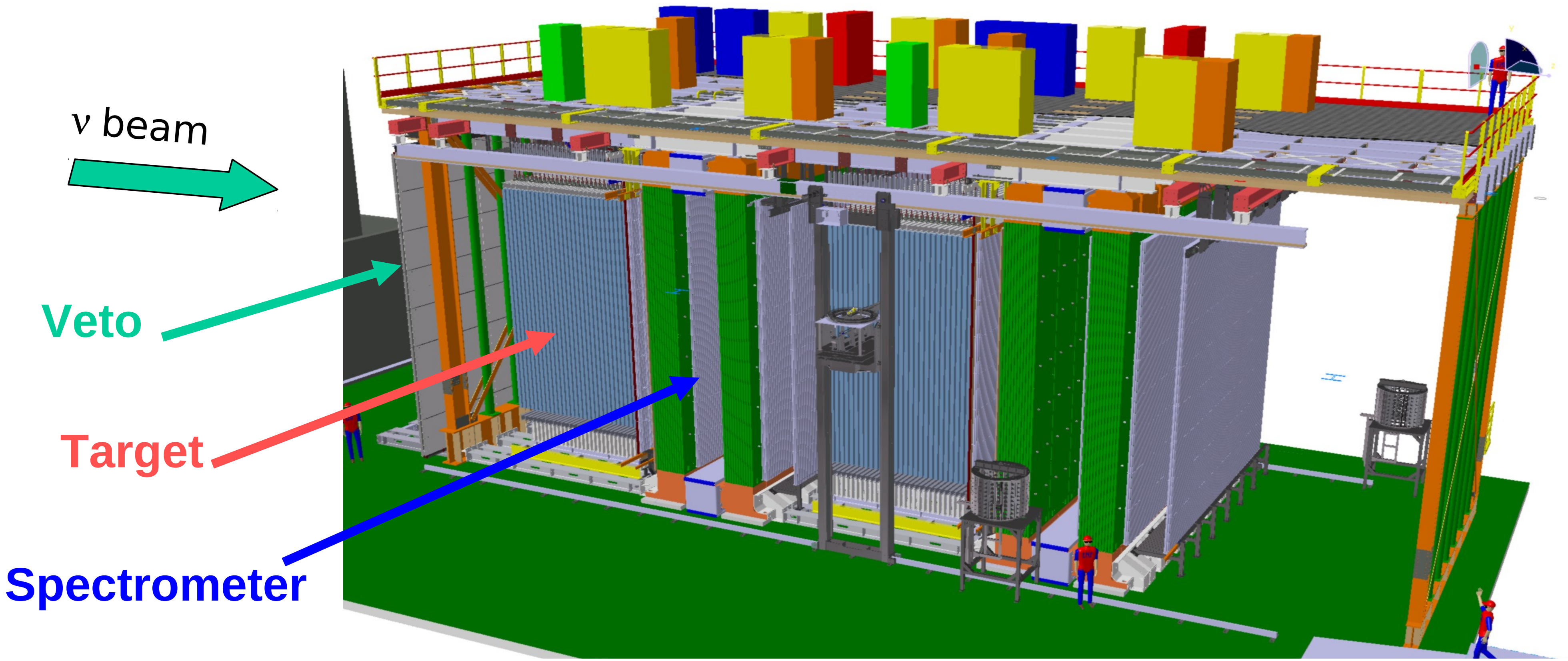


Three independent analysis, with different statistical approaches

Above conditions plus
a full simulation
and a careful treatment
of 1% systematics error

OPERA (Oscillation Project with Emulsion tRacking Apparatus)

Experiment for the detection of $\nu_\mu \rightarrow \nu_\tau$ oscillations on CNGS beam (L=732 km)



- 2 Supermodules (1 Supermodule = 1 target section + 1 spectrometer)
- 2 Target sections with 150000 bricks arranged into walls
- 1 Brick= 56 lead sheets (target) alternated to 57 nuclear emulsions (vertex reconstruction)
- Target sect.=31 Target Walls/Target Tracker (TT, xy crossed scintillator strips)
- Total target mass (1.25 ktons)
- Spectrometer: 1 kton dipolar magnet equipped with drift tubes and RPCs
- Veto system to tag external neutrino interactions (glass RPCs)

3+1 model $\nu_\mu \to \nu_\tau$ oscillation probability in LBL approximation

2-neutrino formula for atmospheric term

2-neutrino formula for "exotic" term

Δm^2_{21} **L/E~0**

$$
\begin{aligned}
P \;=\;& 4|U_{\mu 3}|^2|U_{\tau 3}|^2 sin^2(\Delta m^2_{31} L/(4E)) \; + 4|U_{\mu 4}|^2|U_{\tau 4}|^2 sin^2(\Delta m^2_{41} L/(4E)) \; + \\
+ \;& 2Re(U^*_{\mu 3} U_{\tau 3} U_{\mu 4} U^*_{\tau 4}) sin(\Delta m^2_{31} L/(2E)) sin(\Delta m^2_{41} L/(2E)) \; + \\
+ \;& 4Im(U^*_{\mu 3} U_{\tau 3} U_{\mu 4} U^*_{\tau 4}) sin^2(\Delta m^2_{31} L/(4E)) sin(\Delta m^2_{41} L/(2E)) \; + \\
+ \;& 8Re(U^*_{\mu 3} U_{\tau 3} U_{\mu 4} U^*_{\tau 4}) sin^2(\Delta m^2_{31} L/(4E)) sin^2(\Delta m^2_{41} L/(4E)) \; + \\
- \;& 4Im(U^*_{\mu 3} U_{\tau 3} U_{\mu 4} U^*_{\tau 4}) sin(\Delta m^2_{31} L/(2E)) sin^2(\Delta m^2_{41} L/(4E))
\end{aligned}
$$

interference terms

Δm^2_{41} **L/E → ∞**

$$
\begin{aligned}
P \;=\;& 4|U_{\mu 3}|^2|U_{\tau 3}|^2 sin^2(\Delta m^2_{31} L/(4E)) \; + 2|U_{\mu 4}|^2|U_{\tau 4}|^2 \; + \\
+ \;& 4Re(U^*_{\mu 3} U_{\tau 3} U_{\mu 4} U^*_{\tau 4}) sin^2(\Delta m^2_{31} L/(4E)) \; + \\
- \;& 2Im(U^*_{\mu 3} U_{\tau 3} U_{\mu 4} U^*_{\tau 4}) sin(\Delta m^2_{31} L/(2E))
\end{aligned}
$$

Last term CP-violating and sensible to mass hierarchy, direct ($\Delta m^2_{31}>0$) or inverted ($\Delta m^2_{31}<0$).

OPERA $\nu_\mu \rightarrow \nu_\tau$ oscillation results

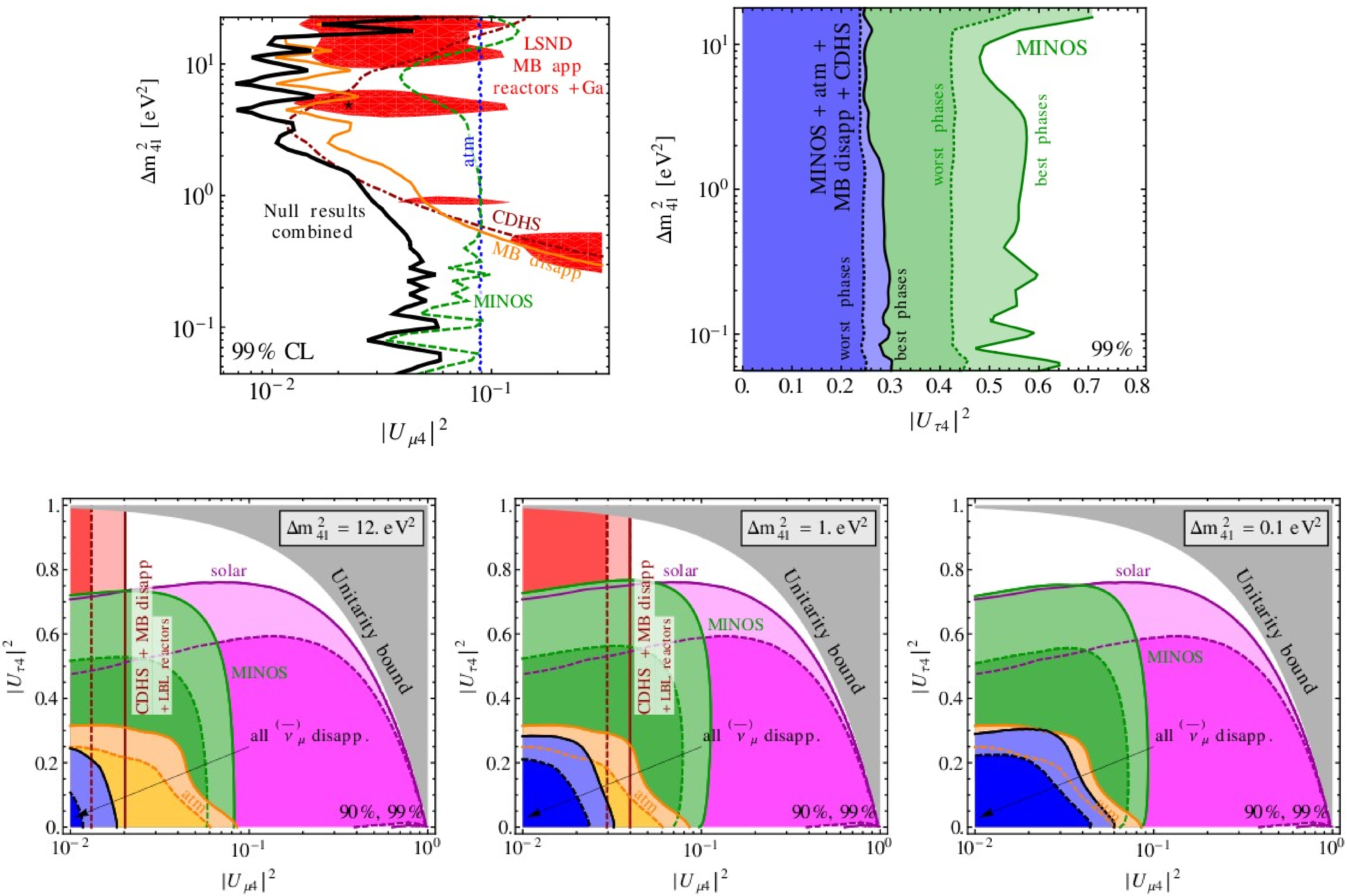
OPERA collected $18*10^{19}$ pot from 2008 to 2012, and about 20000 ν interactions in the target (1.25 kt).
The collaboration has observed 3 ν_τ , with 1.7 expected events and a background estimation of 0.18 events (3.4 σ significance).

Summary of observed candidates

Decay channel	Signal Candidates	Background Events
$\tau \to h$	1	0.027 ± 0.005
$\tau \to 3h$	1	0.12 ± 0.02
$\tau \to \mu$	1	0.021 ± 0.010
$\tau \to e$	0	0.020 ± 0.004
Overall	3	0.184 ± 0.025

OPERA results consistent with the standard three neutrino framework.
They can be used to derive limits on 3+1 matrix elements.

3+1 global analysis (arXiv 1303.3011v3) on data of other experiments



Conclusions
(My personal point of view....)

On particle physics side:

Many possible hints about the existence of sterile neutrinos,

No one really convincing.

It's worth to have a look.

Super Heavy Dark Matter, meteors and JEM-EUSO

* Super Heavy Dark Matter outside standard paradigms but is a possibility, see for example: Rafelski, Labun, and Birrell Phys. Rev. Lett. 110, 111102 (2013)– Compact Ultradense Matter Impactors

* Super Heavy Dark Matter should have a flux much lower than the current limits in the laboratory dedicated small size DM experiments

Differences in
Light profiles and
speeds
between meteors and
Super Heavy DM

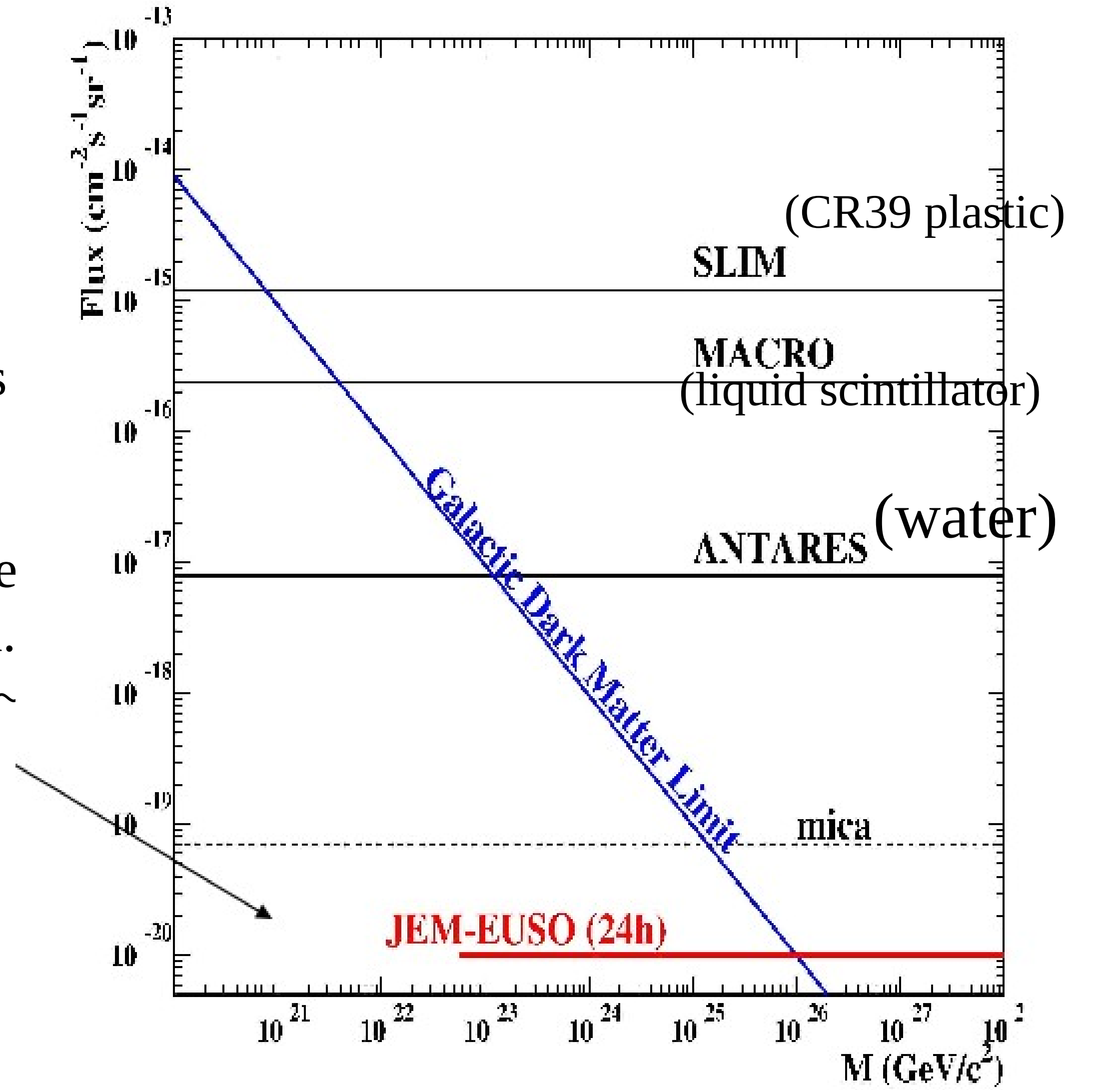
Example :Differences between meteors and neutral strange quark matter (nuclearites)

From M Bertaina A Cellino and F Ronga *JEM-EUSO: Meteor and nuclearite observations* Experimental Astronomy (April 2004)
http://link.springer.com/article/10.1007/s10686-014-9375-4

* speed : meteor up to 70 km/sec, DM nuclearites ~ 300km/sec

* light profile : in meteors the light starts immediately and then decreases due to the mass ablation, most of the meteors doesn't reach earth.On the contrary nuclearites are very compact objects, the energy loss is similar to the one of an elementary particle. No mass ablation. The light emission is ~ constant starting from h~ 30 Km

*Earth is transparent for mass >0.1 gr nuclearites. Upward going nuclearites



Nuclearites in Gravitational Wave bar detector (NAUTILUS - LNF)

See: P Astone et al “Quark nuggets search using 2350 Kg gravitational waves aluminum bar detectors” astro-ph arXiv:1306.5164

* The geometrical acceptance of the bar detectors is 19.5 m^2 sr much smaller than that of other detectors

* However, the detection mechanism is completely different and is more straightforward than in other detectors (Nautilus is like a bolometer).

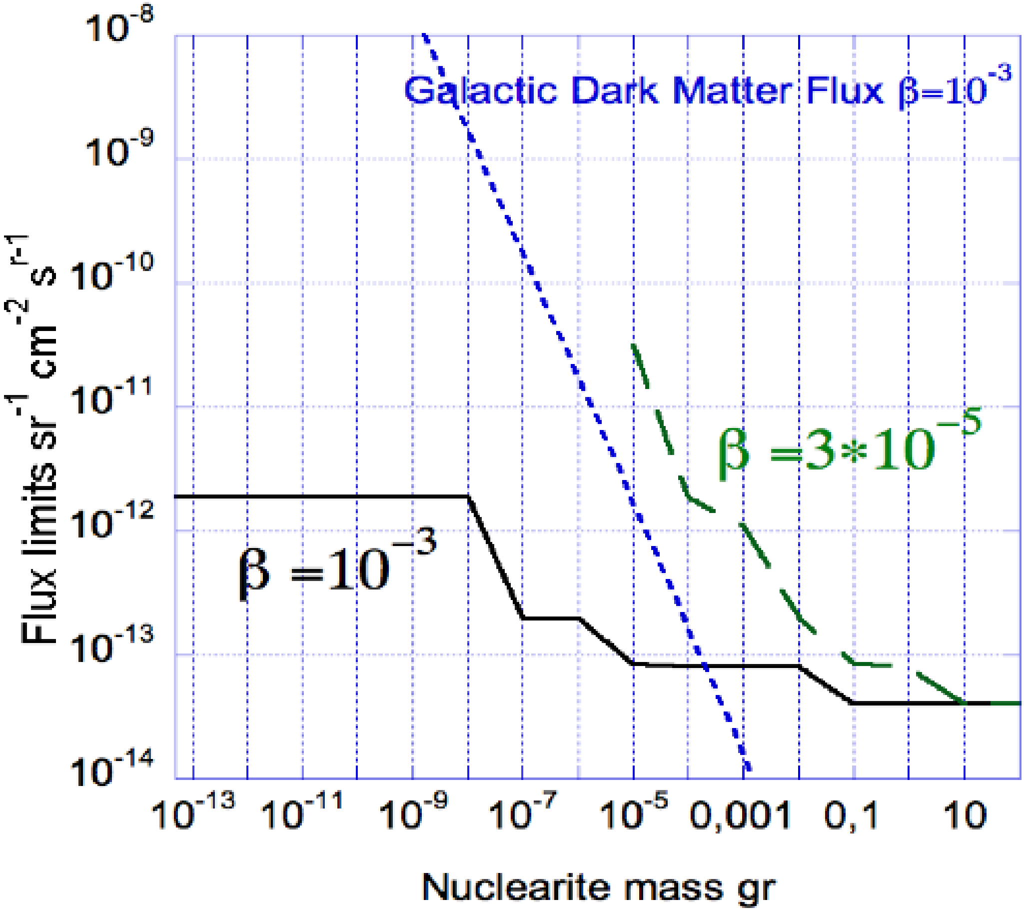


Fig. 5: Flux upper limits for $\beta = 10^{-3}$ and $\beta = 3 \cdot 10^{-5}$ (Earth escape velocity) vs mass.