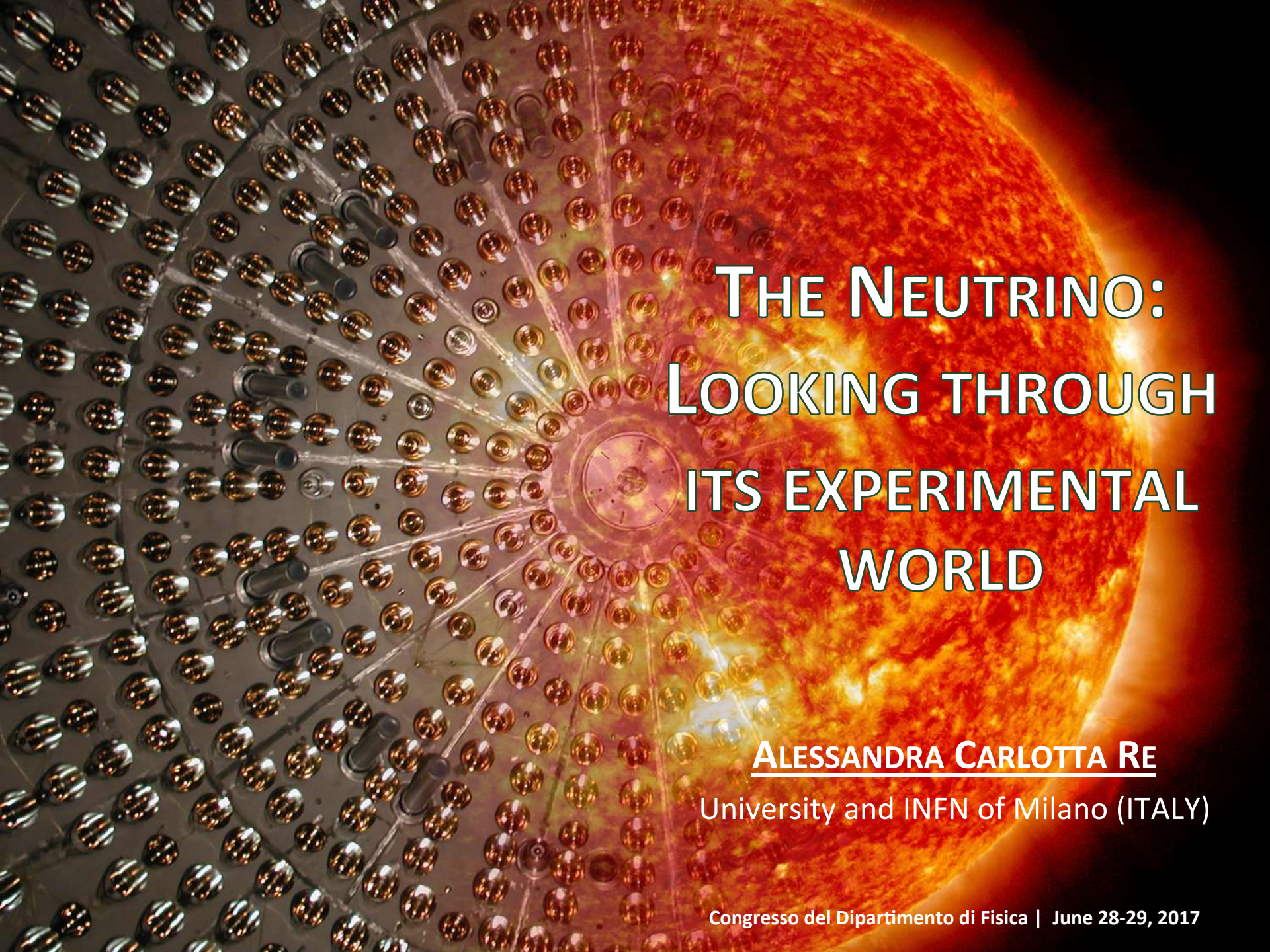


The Neutrino: Looking through its experimental world

Alessandra Carlotta Re

University and INFN of Milano (ITALY)

Congresso del Dipartimento di Fisica | June 28-29, 2017

OUTLINE

- **Neutrinos:**
  - What are they?
  - Where do they come from?
  - Why do we (still) study them?

- **The Neutrino experimental world:**

  … here at the Dipartimento di Fisica of Milano
  - The BOREXINO experiment
  - The SOX experiment
  - The JUNO experiment

NEUTRINOS IN THE STANDARD MODEL

Neutrinos are…

- Elementary particles: three bricks of the Standard Model (SM) wall;
- Fermions;
- Electrically neutral leptons
  → Weak interactions;
- Arranged in three familes according to their flavour;

and moreover… Neutrinos OSCILLATE!!

NEUTRINO OSCILLATIONS

As soon as the first solar neutrino experiments started taking data, the so-called Solar Neutrino Problem arose: the measured event rate was significantly lower than expected.

However, these experimental results could be easily explained assuming neutrino flavor oscillations which, as pointed out by Pontecorvo in 1968, can occur only if neutrinos are massive and mixed….

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} \mathrm{U}_{\alpha i} |\nu_i\rangle, \qquad \alpha = \mathrm{e}, \mu, \tau$$

where U is the Pontecorvo-Maki-Nagakawa-Sakata mixing matrix:

$$\mathrm{U} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}\, e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}\, e^{-i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}, \qquad \begin{aligned} c_{ij} &= \cos\theta_{ij}\,, \\ s_{ij} &= \sin\theta_{ij}\,. \end{aligned}$$

NEUTRINO OSCILLATIONS

As soon as the first solar neutrino experiments started taking data, the so-called Solar Neutrino Problem arose: the measured event rate was significantly lower than expected.

However, these experimental results could be easily explained assuming neutrino flavor oscillations which, as pointed out by Pontecorvo in 1968, can occur only if neutrinos are massive and mixed….

KEY PARAMETER: ⟹ NEUTRINO SURVIVAL PROBABILITY

If we assume the normal hierarchy ($\Delta m^2_{31} \gg \Delta m^2_{21}$), a reasonable expression of the survival probability of an electron neutrino can be written as:

$$P_{ee} = \cos^4\theta_{13}\left[1 - \sin^2 2\theta_{12}\sin^2\left(\frac{\Delta m^2_{21}}{4E}L\right)\right] + \sin^4\theta_{13}$$

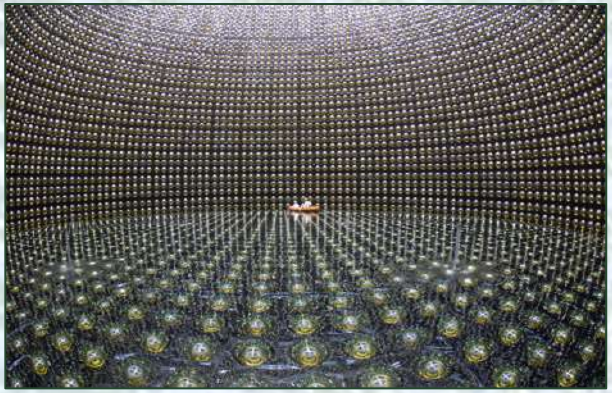
NEUTRINO OPEN QUESTIONS

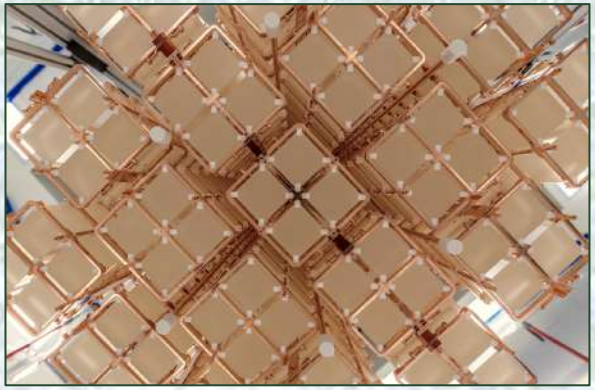
- **Particles Physics:**
  - Number of neutrino species.
    Any Sterile neutrino?
  - Non-Standard interactions?
  - Dirac or Majorana neutrino?
  - Hierarchy:
    Normal or Inverted?
  - δ_{CP} value?

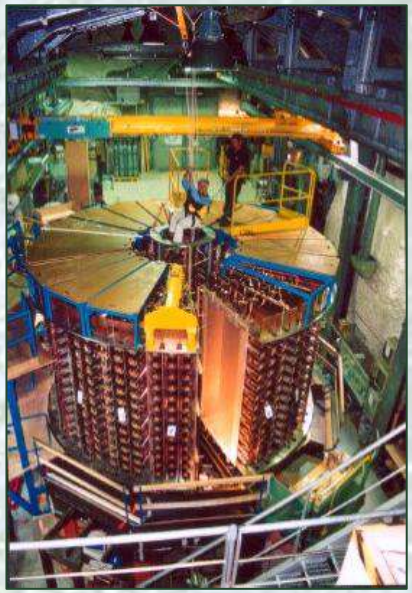
- **AstroPhysics:**
  - Low/High metallicity: What is the correct hypothesis?
  - How a star works/burns? We only have infos from starlight spectroscopy.

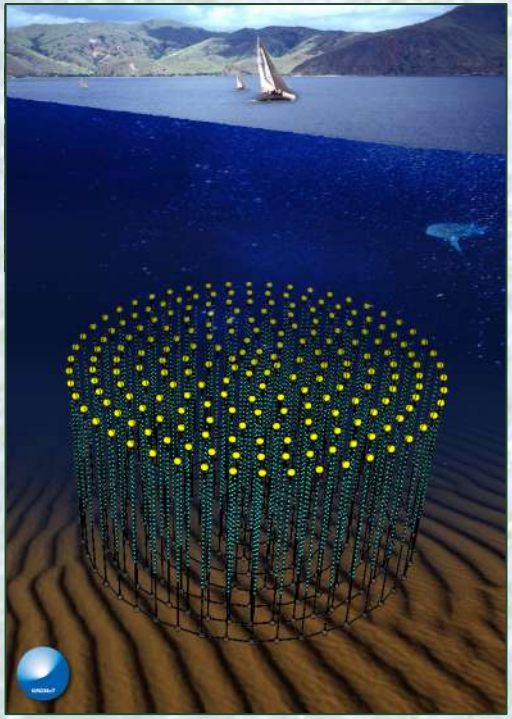
- **Earth Physics:**
  - Geoneutrinos: a unique direct probe of our planet's interior!

NEUTRINOS EXPERIMENTS







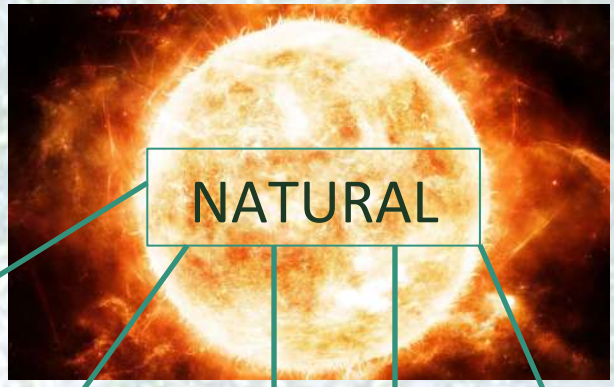


ANNIE, ANTARES, ARIANNA,
BDUNT, BOREXINO, CLEAN, COBRA,
CUORE, DAYA BAY, DOUBLE CHOOZ, EXO,
GALLEX, GERDA.....

Starting from 1970's more than 50 experiments about neutrinos… and still counting!

Different tecniques, different approach according to different neutrino origins and to the peculiar object of investigation.

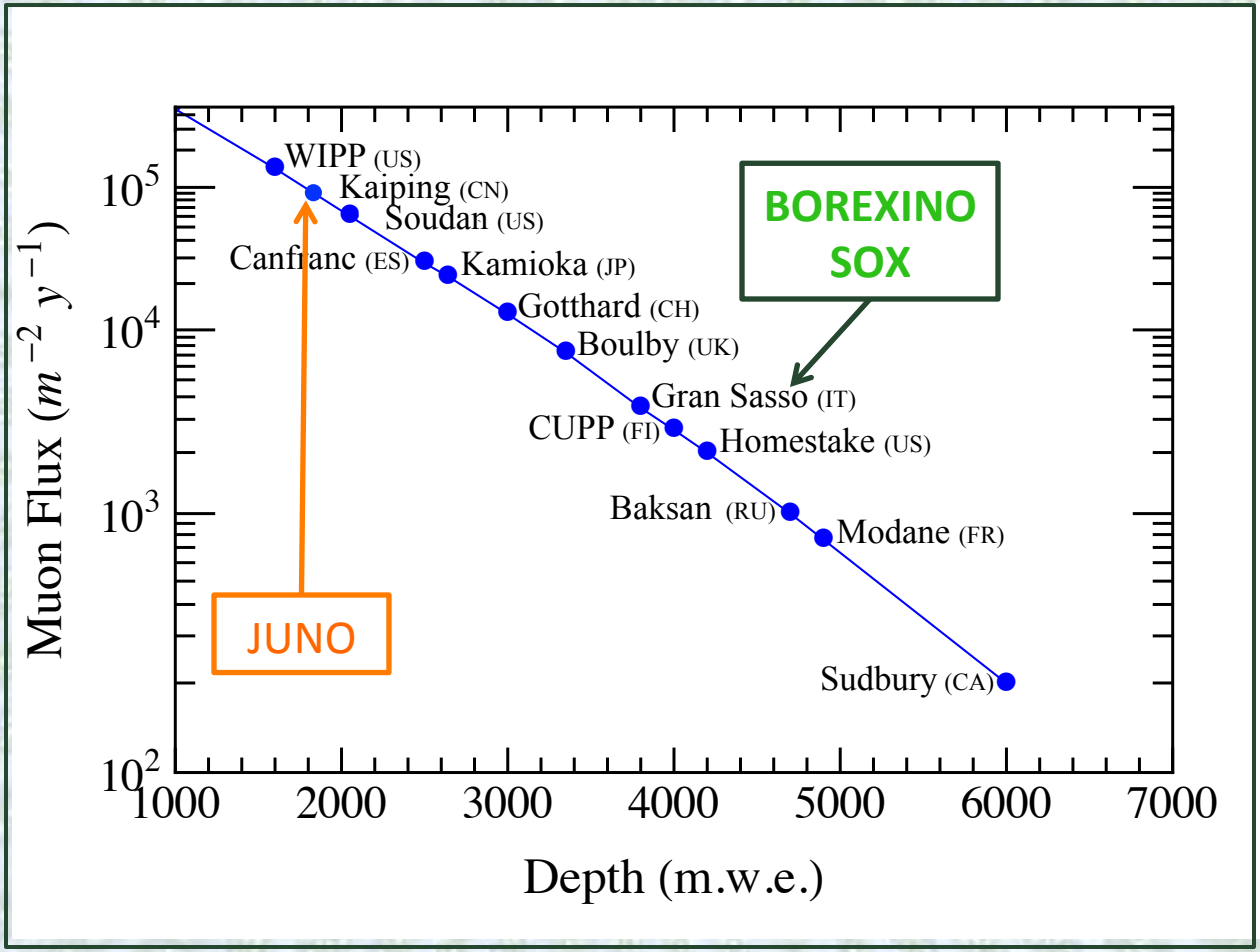
NEUTRINOS SOURCES



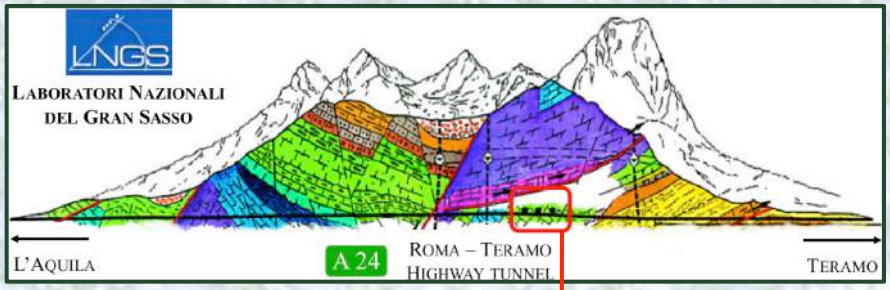
NEUTRINO EXPERIMENTS: WHERE?

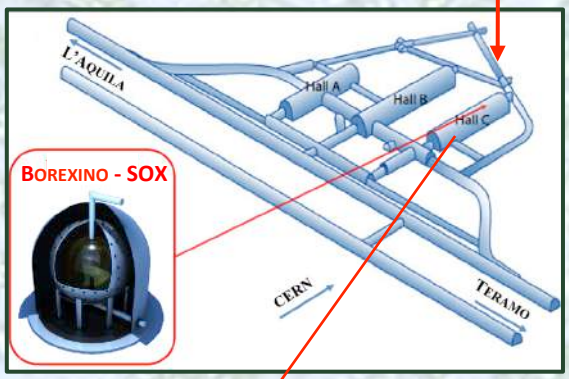
Due to the very small neutrino interaction rates, the shielding against cosmic rays and the experiment extreme radiopurity are mandatory.

→ Neutrinos experiments can be carried out in underground laboratories only.



LABORATORI NAZIONALI GRAN SASSO (ITALY)





INFN
Istituto Nazionale di Fisica Nucleare

The **LNGS** altitude is 963 m and the average rock cover is about 1,400 m.

The shielding capacity against cosmic rays is about 3,800 meter water equivalent (m.w.e.): the muon flux is reduced of a factor 10^6 respect to the surface.

$$\Phi(\mu) \sim 1\,\mu/\mathrm{m}^2/\mathrm{h}$$

THE BOREXINO EXPERIMENT

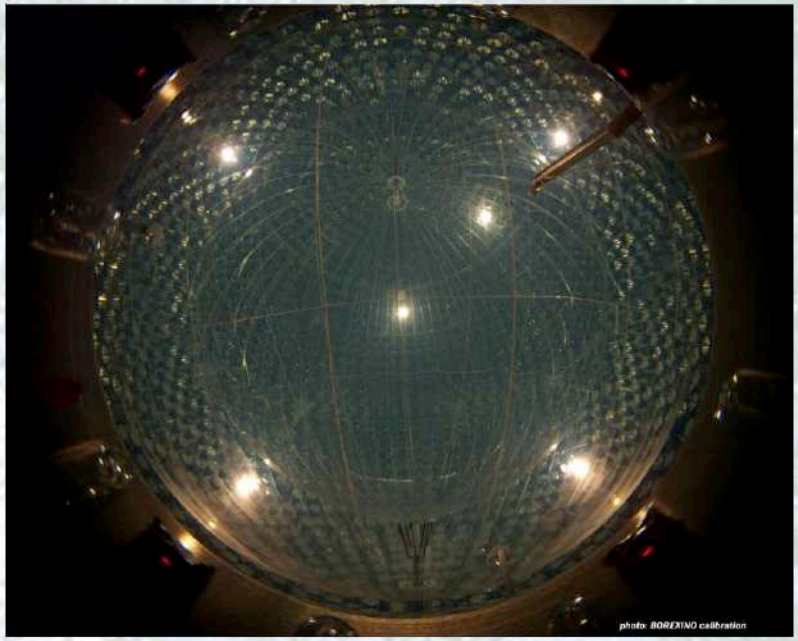
- **Main goal**: the detection of low energies solar neutrinos, in particular ^{7}Be neutrinos.

- **Detection method**: elastic scattering of neutrinos on electrons.

$$\nu_x + e \rightarrow \nu_x + e \quad x = e, \mu, \tau$$

- **Detection medium**: large mass of organic liquid scintillator.
  - Advantages: large light-yield;
  - Disadvantages: no directional information.

Signal is indistinguishable from background: high radiopurity is a MUST!



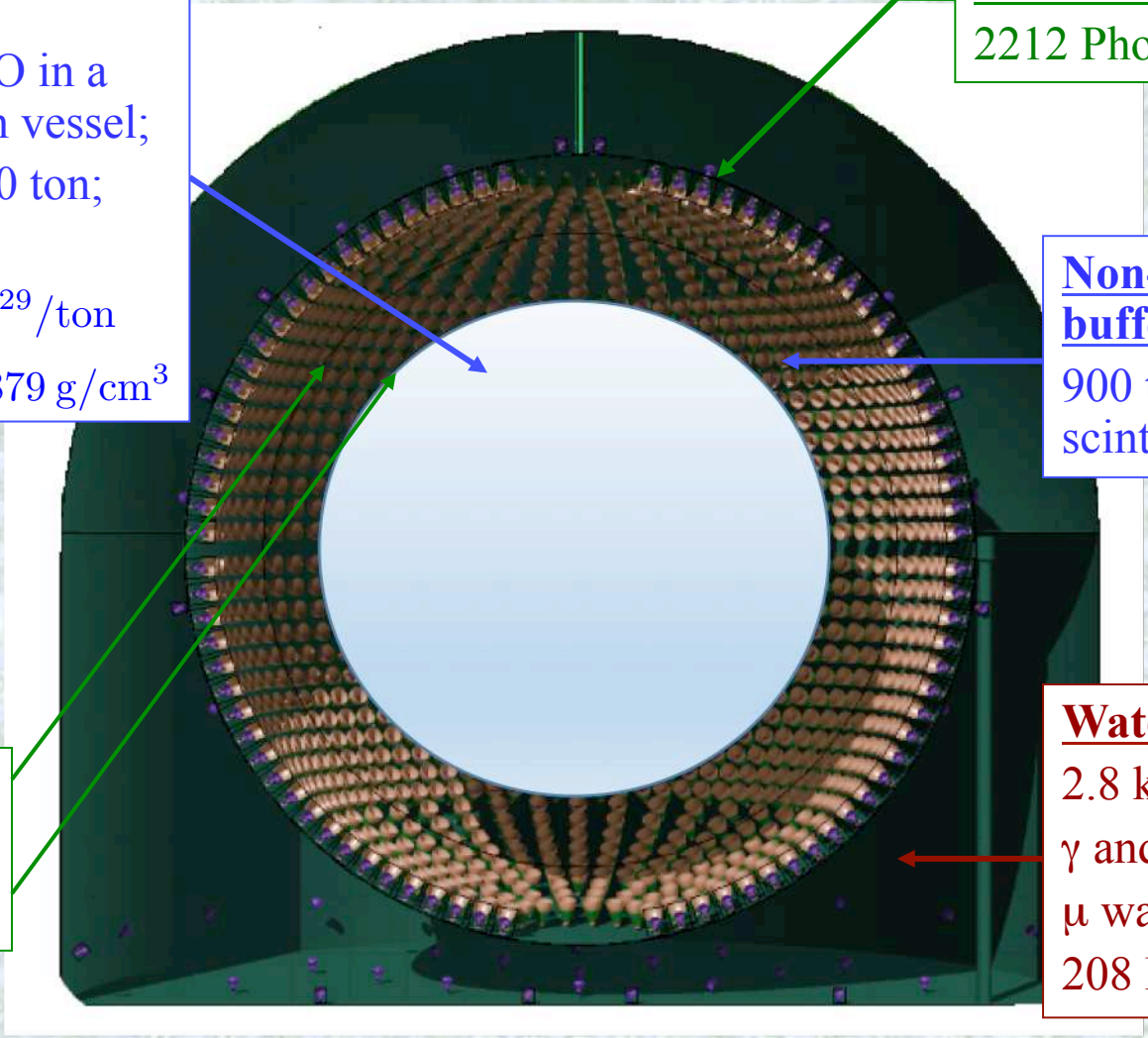
The expected rate of ^{7}Be solar neutrinos in 100 ton of BX scintillator is about 50 counts/day which corresponds to 10^{-9} Bq/Kg.

Just for comparison, natural water is about 10 Bq/Kg in ^{238}U, ^{232}Th and ^{40}K.

THE BOREXINO EXPERIMENT(2)

Scintillator:
280 ton of PC+PPO in a 125 μm thick nylon vessel;
Fiducial mass ~ 100 ton;
Electron density:
$(3.307 \pm 0.003) \times 10^{29}$/ton
Mass density: $\simeq 0.879$ g/cm^3

Stainless Steel Sphere:
2212 PhotoMultipliers

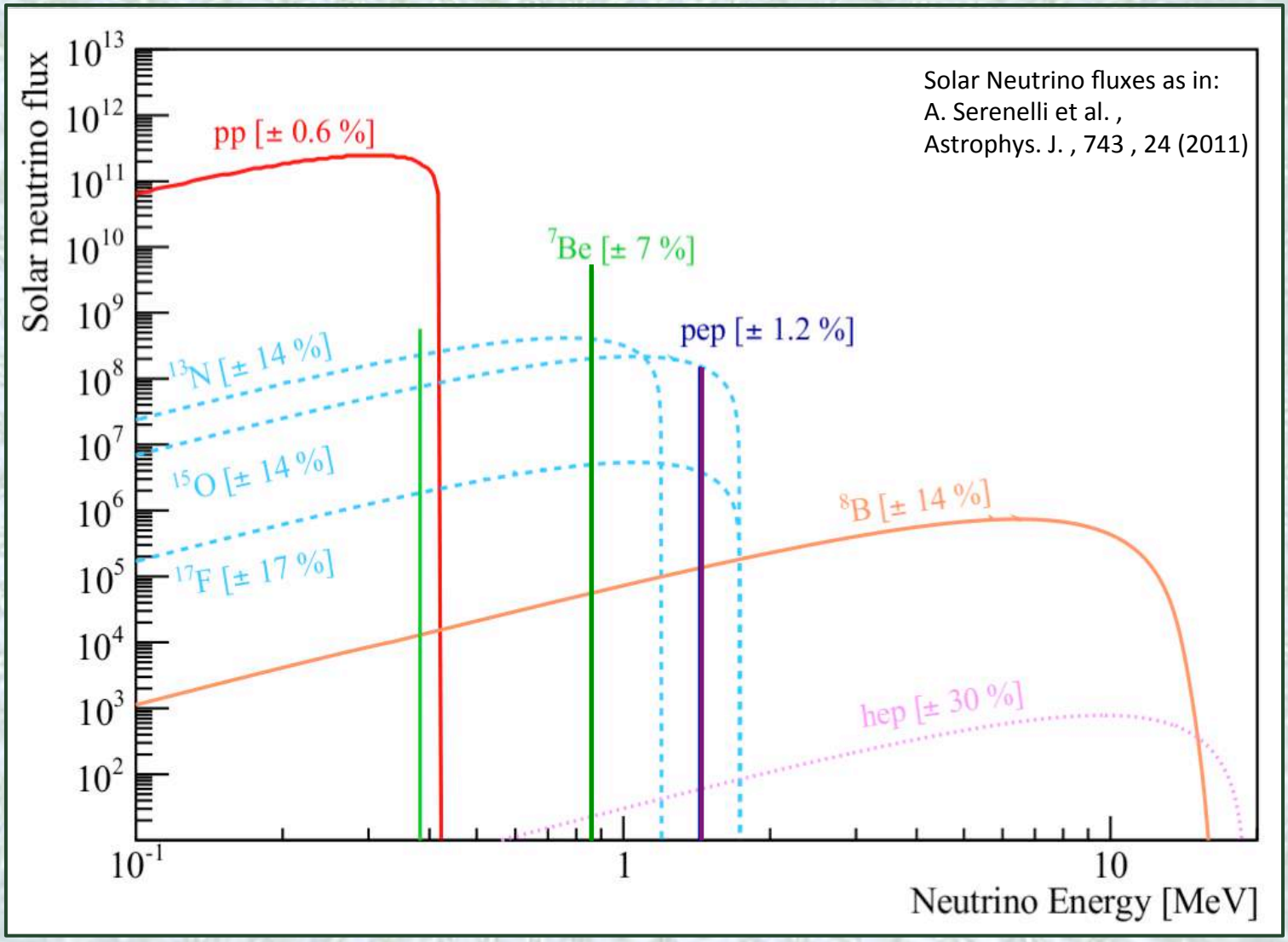


Non-scintillating buffer:
900 ton of quenched scintillator

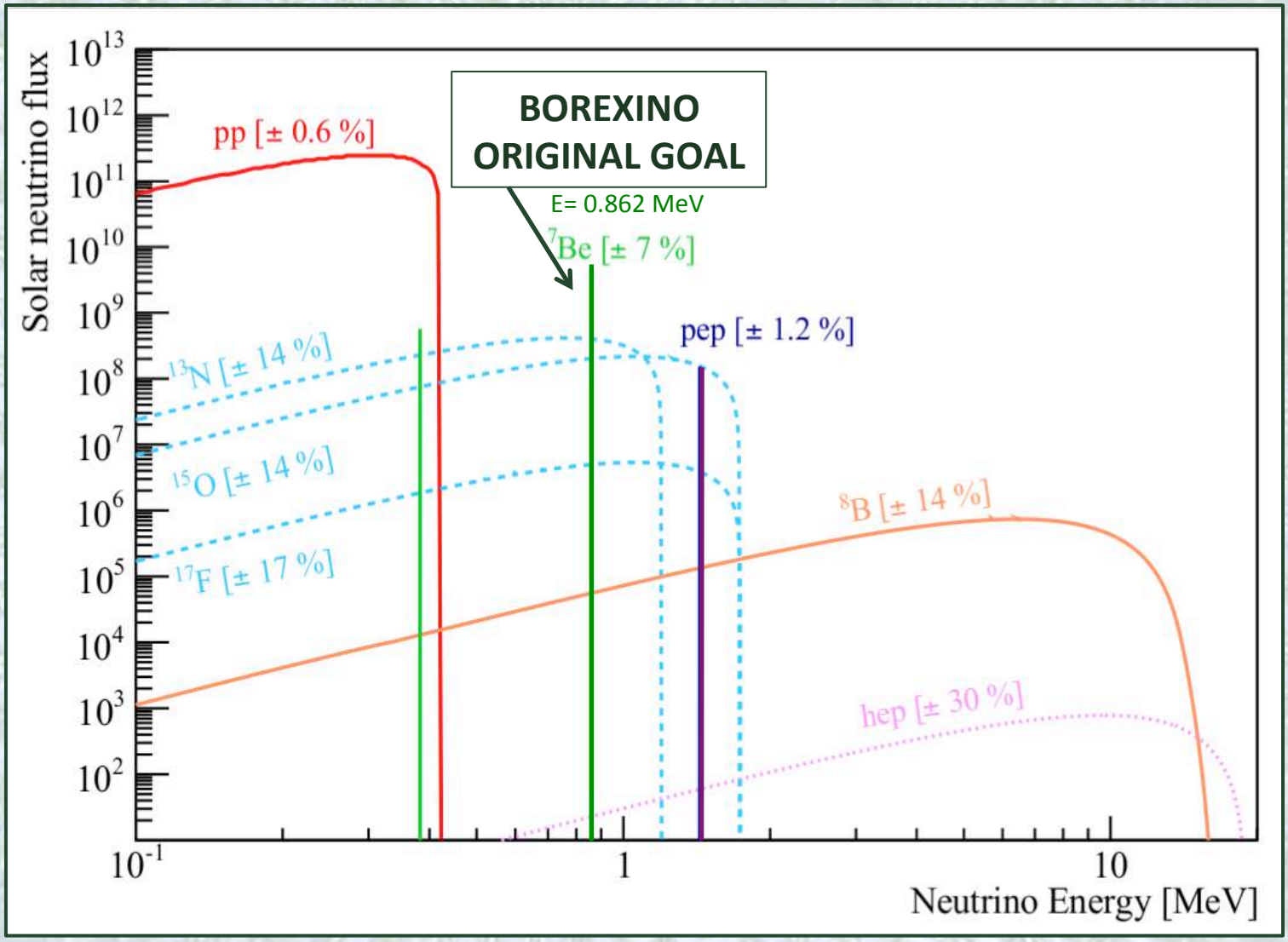
Nylon vessels:
Outer: 5.50 m
Inner: 4.25 m

Water Tank:
2.8 kton of pure H_2O
γ and n shield
μ water Č detector
208 PMTs in water

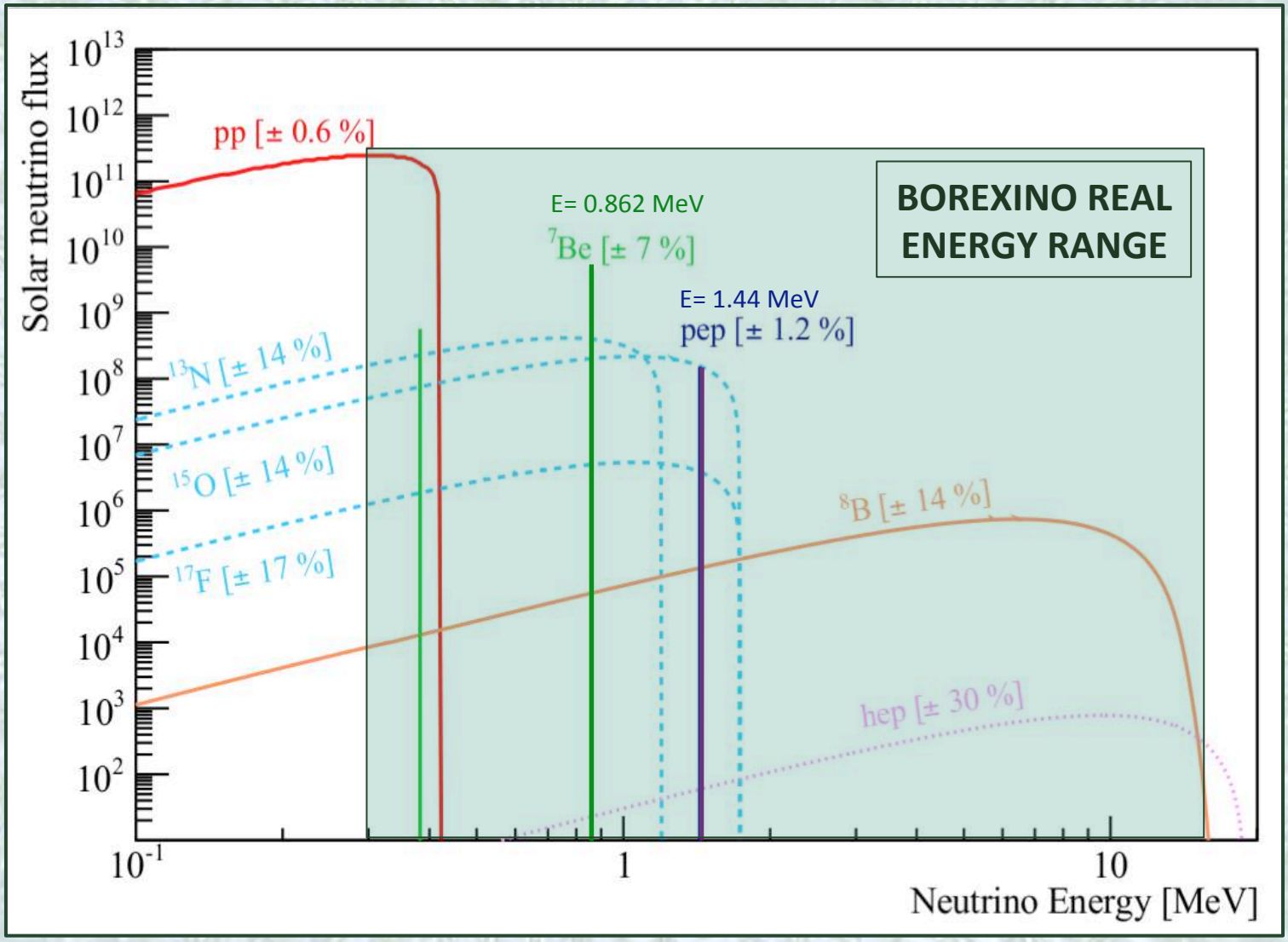
THE SOLAR NEUTRINO SPECTRUM



THE SOLAR NEUTRINO SPECTRUM



THE SOLAR NEUTRINO SPECTRUM



THE BOREXINO RESULTS… SO FAR

Purification I

Phase I (2007-2010)

Purification II

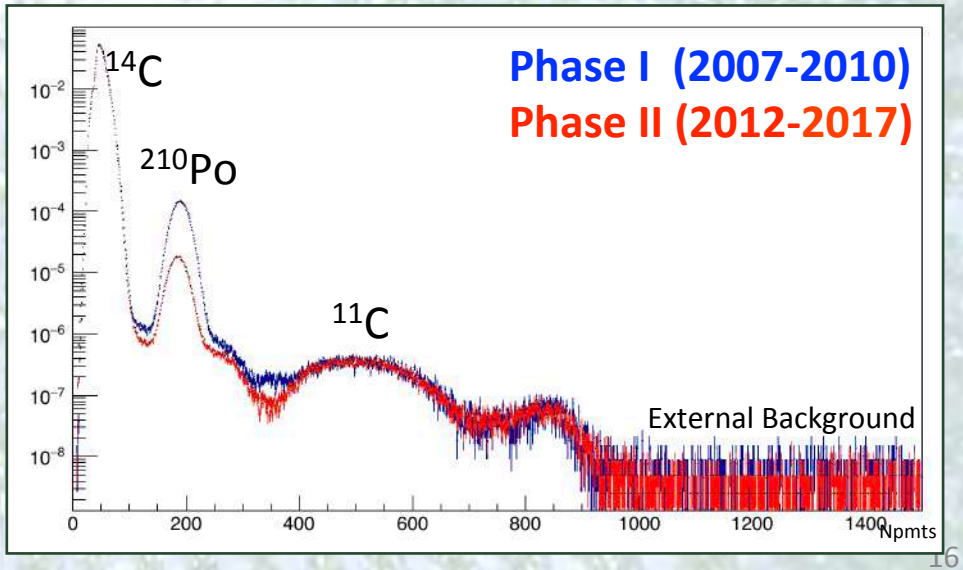
Phase II (2012-2017)

2007 2010 2012 2017

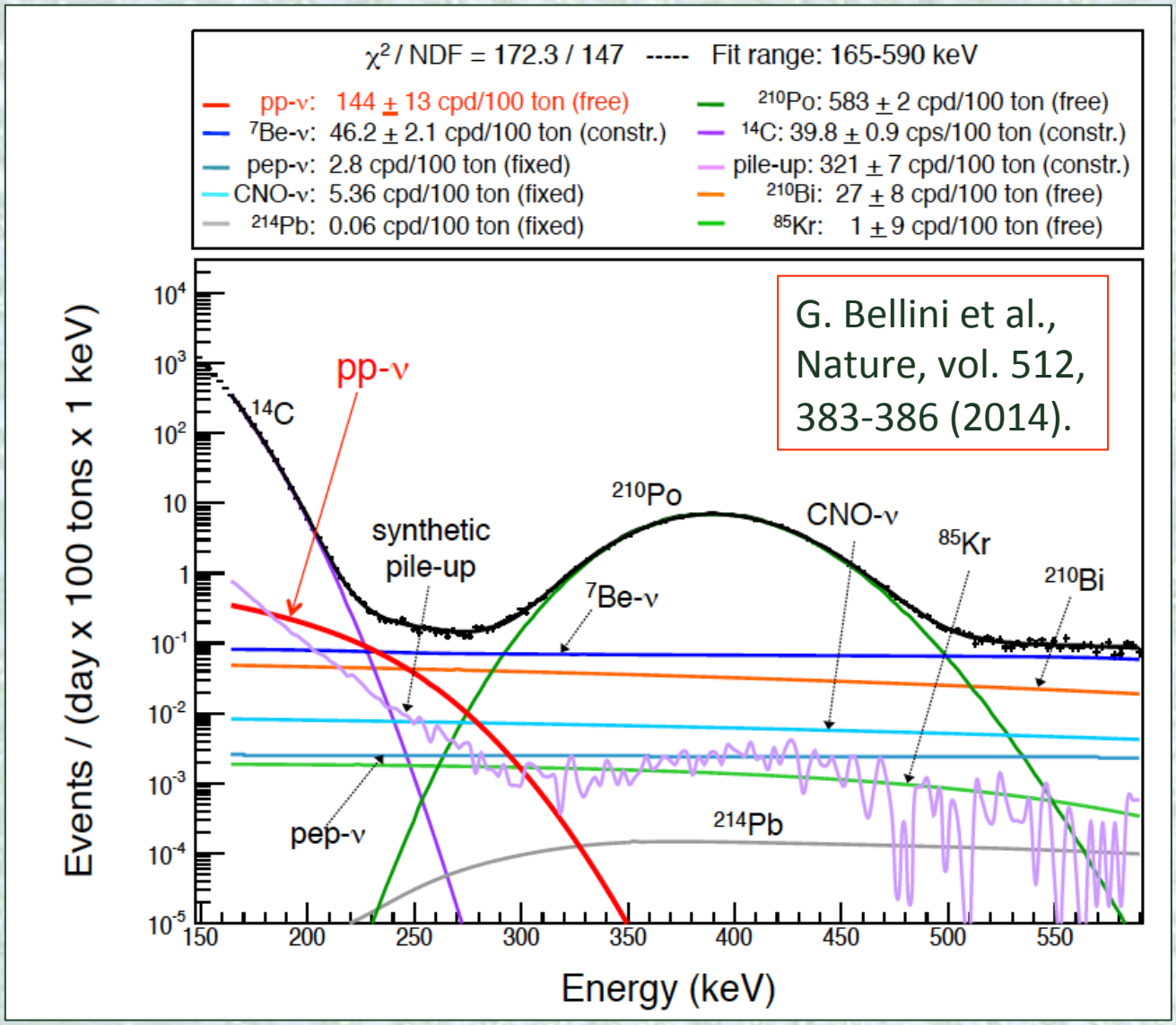
Direct measurements of:
- ^{7}Be flux;
- Absence of day/night asymmetry for ^{7}Be signal => MSW-LMA singled out
- ^{8}B flux;
- pep flux;
- CNO upper limit (best to date)

Further radiopurity improvement

- pp flux direct measurement
- Geoneutrinos (> 5σ);
- e^{-} charge conservation;
- ^{7}Be flux seasonal modulation;
- Gamma-ray burst correlation.



SOLAR NEUTRINOS: THE BOREXINO PP RESULT

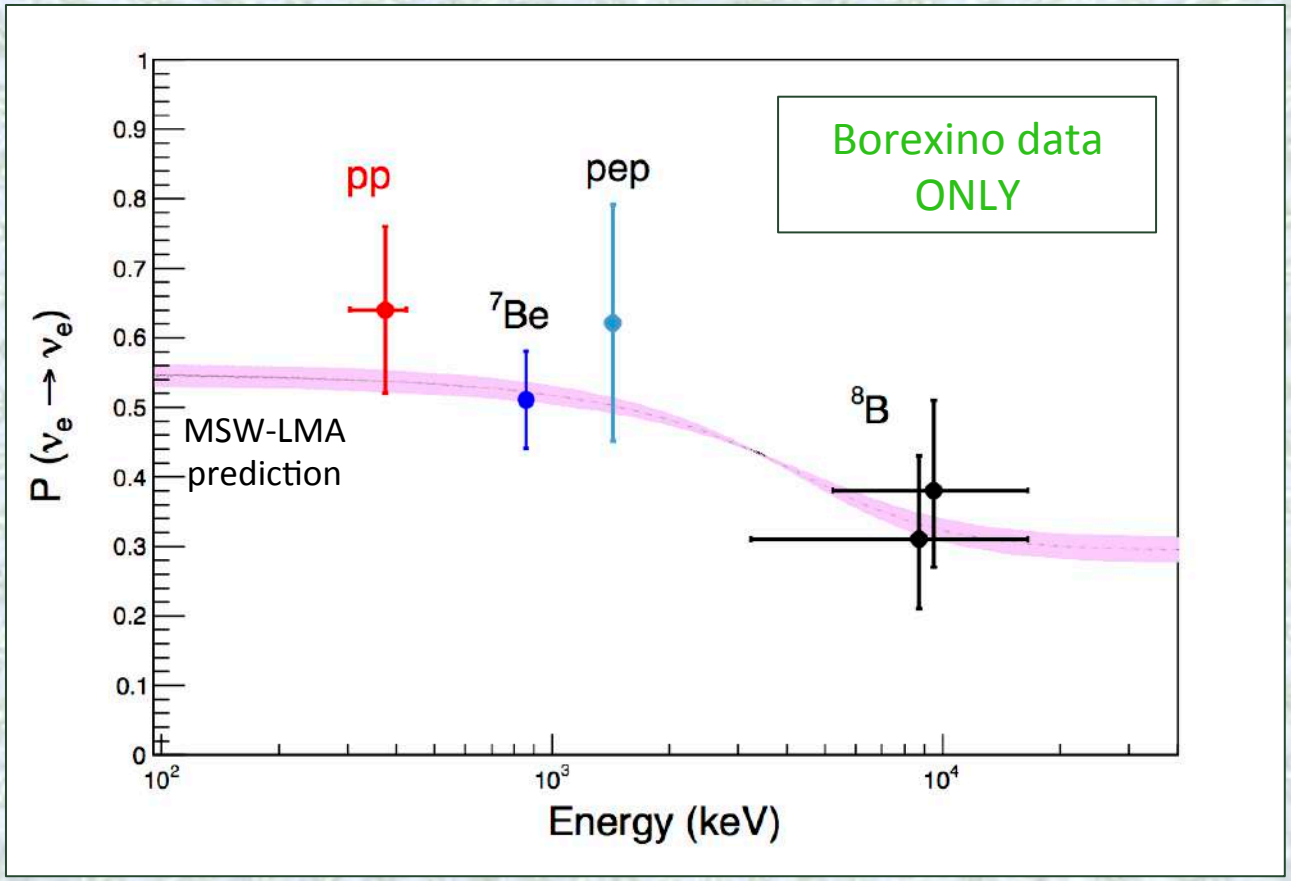


First pp flux DIRECT measurement:

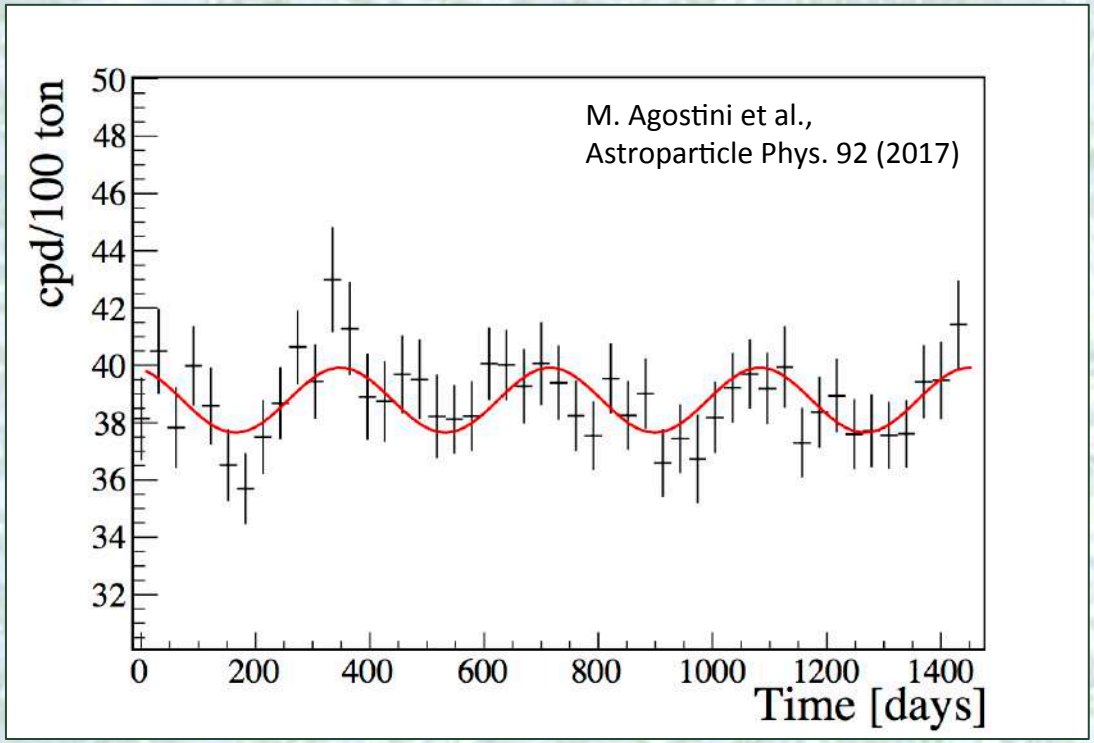
A direct glimpse at the keystone fusion process that keeps the Sun shining and strongly reinforces our theories on the origin of almost the entirety of the Sun's energy.

By analyzing pp neutrino emission, Borexino has shown that the energy produced today in the Sun's core is equal to that produced 100.000 years ago.

STUDYING THE SUN WITH NEUTRINOS…
…STUDYING NEUTRINOS WITH THE SUN



SOLAR NEUTRINOS: THE BOREXINO ^{7}BE SIGNAL SEASONAL MODULATION



Astronomical observations:

- T = 365.256 d
- ε = 0.0167

Borexino result:

- T = 367±10 d
- **ε** = 0.0174±0.0045

3 different Data Analysis Method:

- Analytic Fit
- Lomb-Scargle (Fourier)
- Empirical Mode Decomposition

All approaches show consistency with the solar origin of ^{7}Be neutrinos.

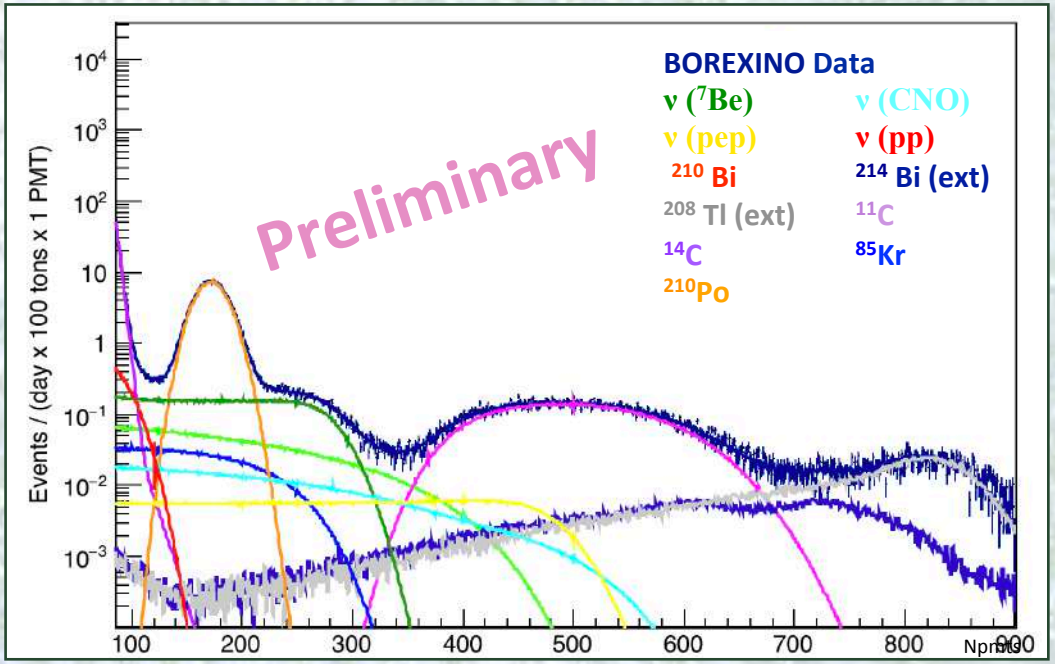
The absence of seasonal modulation is ruled out at 99.99% C.L. (3.9σ).

SOLAR NEUTRINOS: BOREXINO SUMMARY

Now that the background levels are much lower than Phase I…. All challenges at once! For the first time, we are performing a fit on the whole energy region!

Goals of the Borexino Phase II solar analysis:

- ✧ Improvement of ^{7}Be flux (3%)
- ✧ Improvement of pep flux (> 3σ)
- ✧ Improvement of pp flux
- ✧ Improvement of ^{8}B flux
- ✧ Update CNO limit
- ✧ Constraints on neutrino NSI



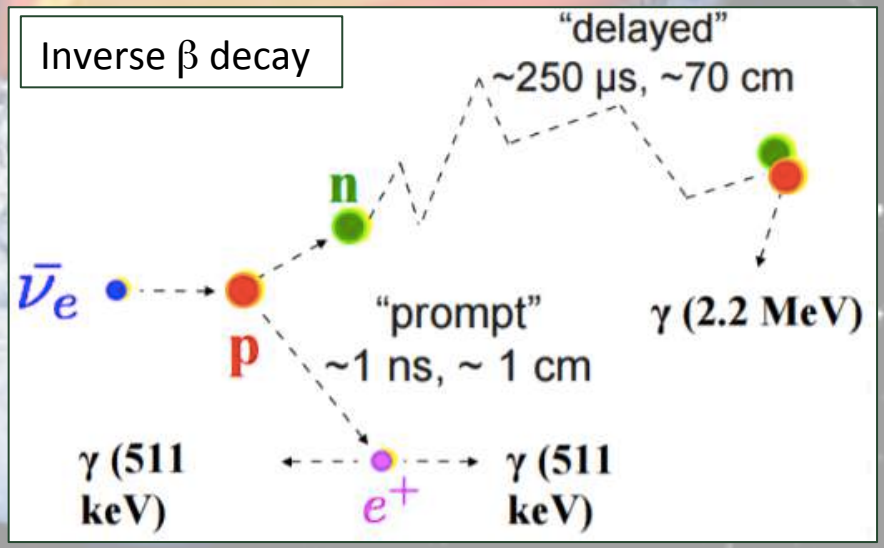
GEO-NEUTRINOS WITH BOREXINO

Geo-neutrinos are the anti-neutrinos produced in the decays of the progenies of Uranium, of Thorium and Potassium. Geo-neutrinos bring to the surface information from the interior of the planet.

We could find answers to the questions:

- What is the radiogenic contribution to the terrestrial heat?
- What is the distribution of the radiogenic elements within the Earth?

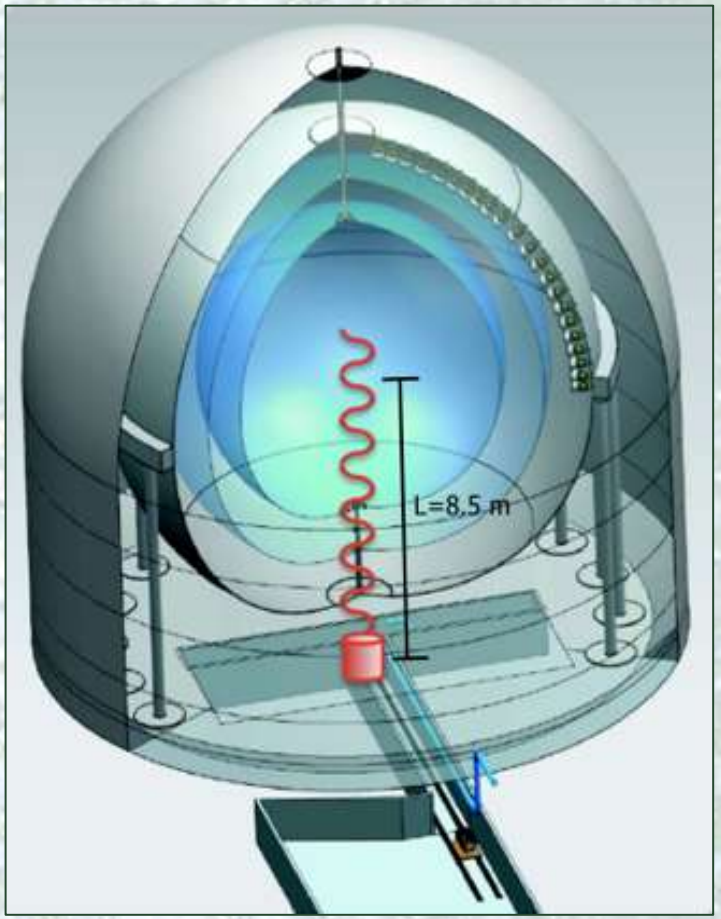
Borexino offers a unique opportunity for a sensitive search for anti-ν in the MeV range due to its unprecedented low intrinsic radioactivity and to a very favourable Geo-ν / reactor anti-ν ratio.



THE SOX EXPERIMENT

- **Main goal**:
  The SOX (Short distance neutrino Oscillation with BoreXino) experiment aims at the complete confirmation or at a clear disproof of the so called neutrino anomalies that is it aims at the discovery of sterile neutrinos.

- **How:**
  A powerful (nominal 100-150 kCi) artificial anti-neutrino source made of ^{144}Ce-^{144}Pr (1.8 MeV ≤ E ≤ 3 MeV, $T_{1/2}$= 285d, 17min) will be located inside a special pit below the Borexino detector so that L = 8.5m is the source/detector distance.



$$P_{\bar{\nu}_e \to \bar{\nu}_s} \propto \sin^2\left(\frac{\pi}{2.48}\frac{L}{E}\Delta m^2_{41}\right)$$

$$L \sim m,\ E \sim MeV \ \rightarrow\ \Delta m^2 \sim \frac{E}{L} \sim (0.1-10)\ eV^2$$

→ SOX is the perfect experiment to test the sterile-ν hypothesis

THE SOX EXPERIMENT: MOTIVATION

Experimental hints:

- ν_e/ν_e - disappearance:

reactor anomaly (≈2.5 σ) and GALLEX/SAGE anomaly (≈3 σ)

- ν_e/ν_e - appearance:

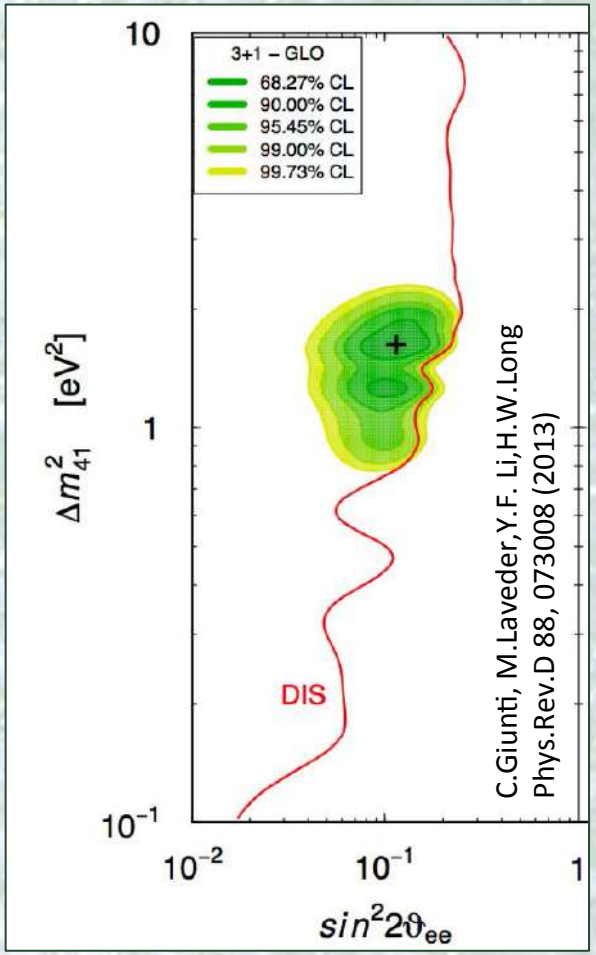
miniBooNE and LSND accelerator anomalies (3.8 σ)

possible solution: sterile neutrino in eV mass range.

Global anomalies data fit by C. Giunti et al.:

$$0.82 < \Delta m_{41}^2 < 2.14 \text{ eV}^2 \ (3\sigma)$$

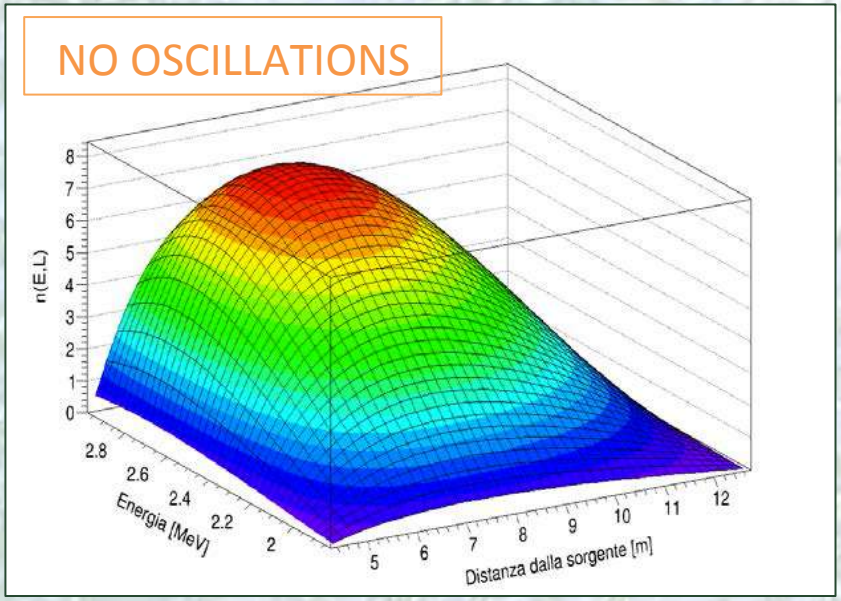
More experimental data are needed: short-baseline experiments… like SOX!

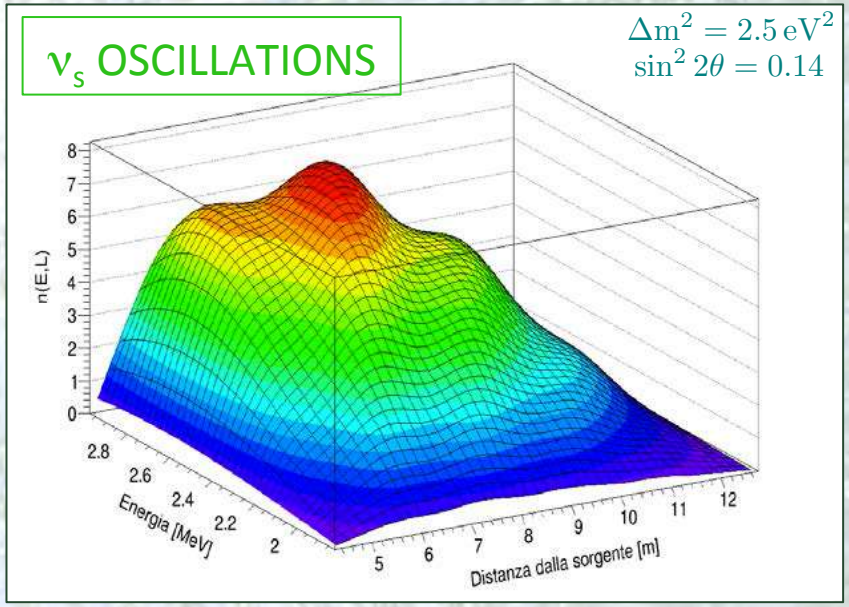


THE SOX EXPERIMENT: SENSITIVITY

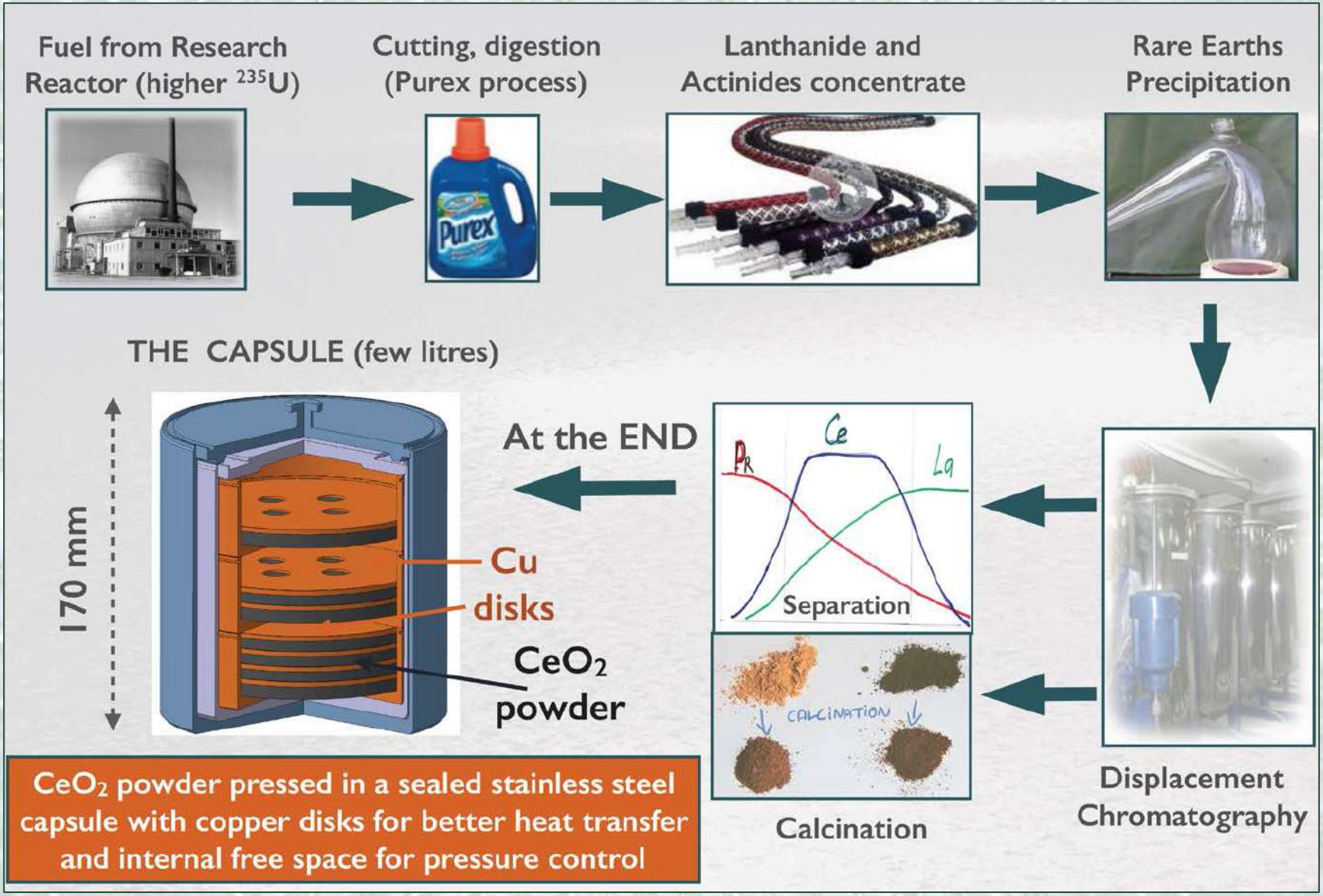
Two types of analysis will be performed and combined:

- **RATE ANALYSIS**: look for a deficit in the total anti-neutrino number (the activity of the source must be known very precisely!)
- **SHAPE ANALYSIS**: look for anomaly in the distribution of events as a function of E and L (distance from the source)

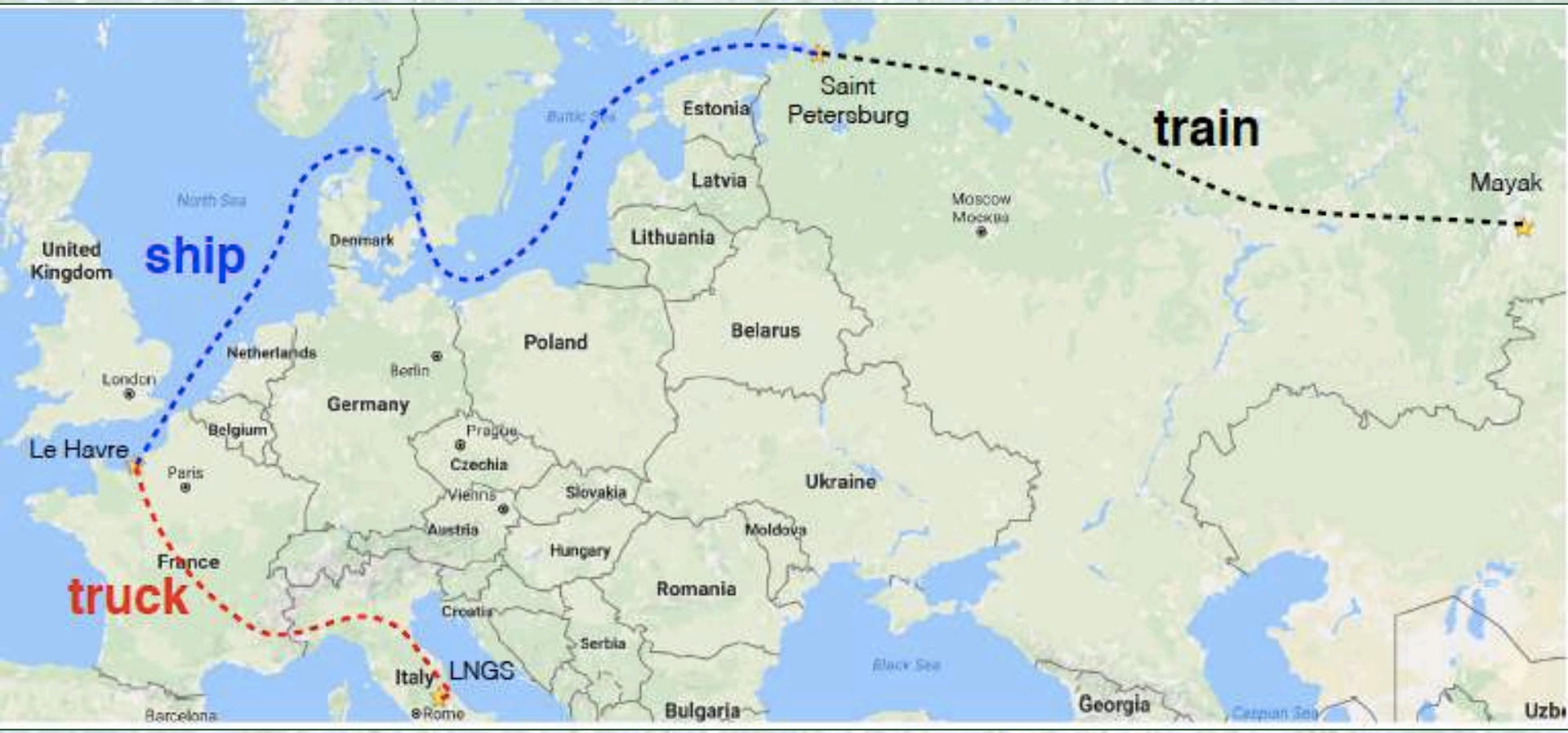




THE SOX SOURCE: HOW IS IT MADE?

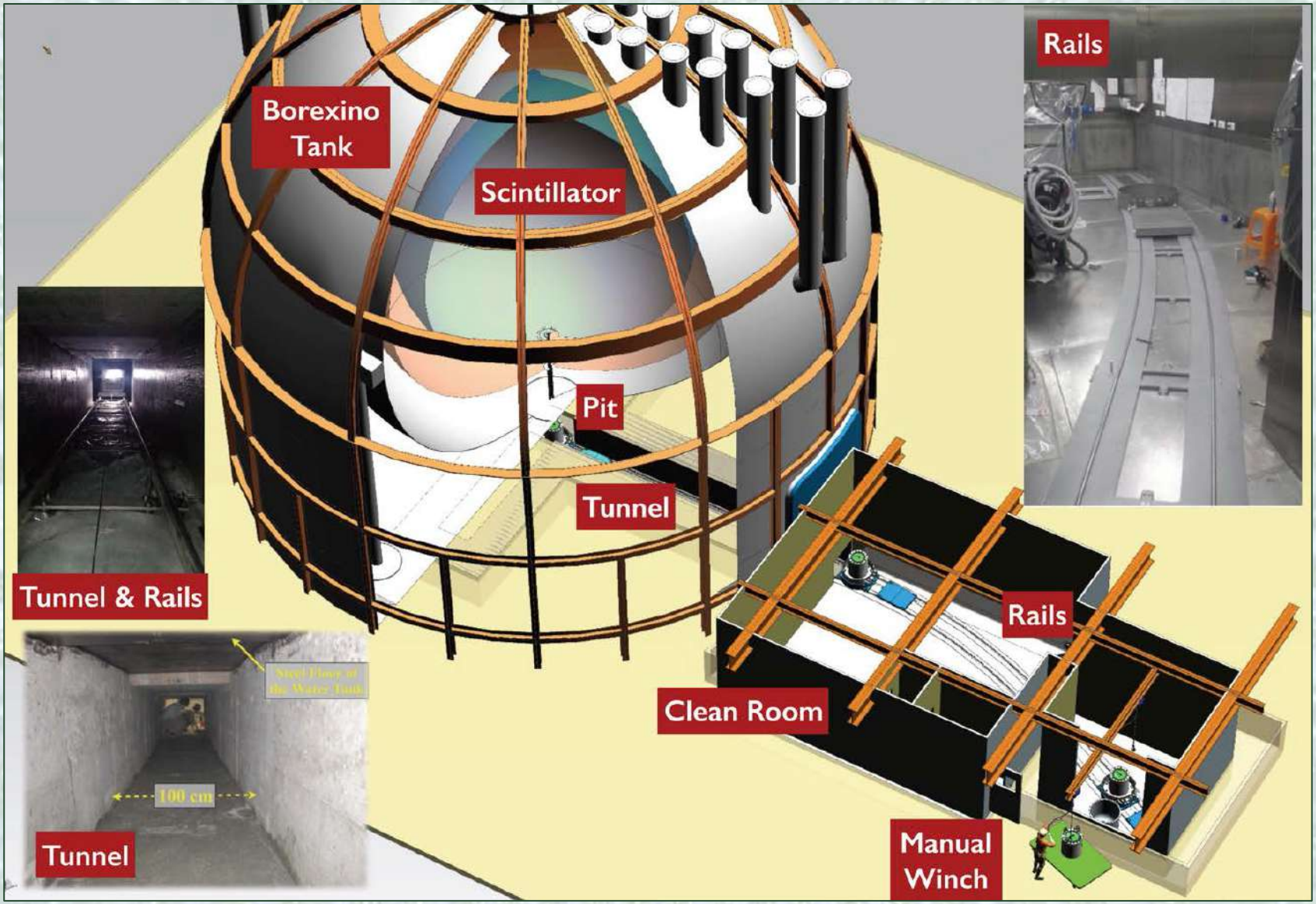


THE SOX SOURCE: TRANSPORTATION



- transit time: 5days (train) + 3 days (ship) + 2 days (truck) = 10 days
- overall transport time: ≈ 3 weeks
- arrival at LNGS (Gran Sasso) at latest by April 2018 with activity loss of ≈ 5%

THE SOX SOURCE: PLACEMENT



THE SOX PROJECT: SUMMARY

SOX is REAL! And is getting ready to start data-taking

- The contract with the Mayak Nuclear Plant for the source production has been signed: the source is on production.
- The site is ready (Borexino detector, Clean Rooms, rail, pit…);
- The tungsten shield has been produced and delivered to Gran Sasso to perform some preliminary tests;
- The two calorimeters are under commissioning;
- A complete test of the procedures for the installation of the source underneath the detector is planned for this summer (with a mockup source).

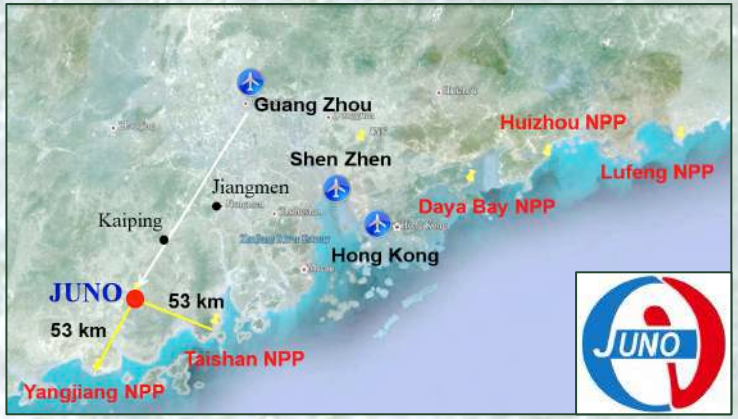
SOX will start taking data in 2018 and will be able of covering most of the currently allowed region in the oscillation parameter space!

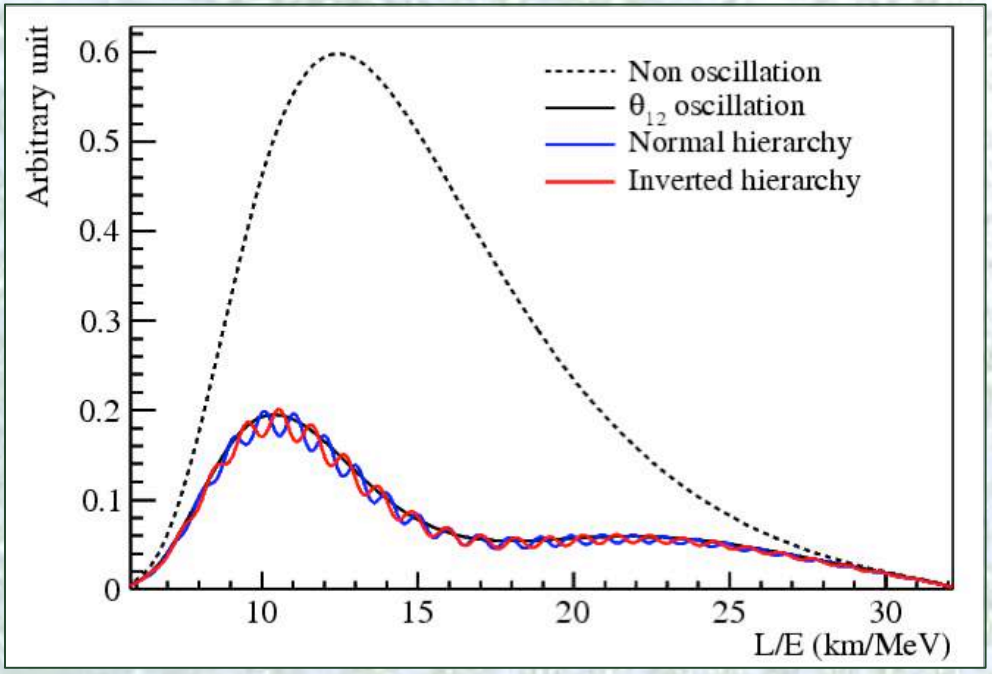
THE JUNO EXPERIMENT

The Jiangmen Underground Neutrino observatory will be located in Kaiping, China.

It will be approximatively 50 km far from 2 (4) Nuclear Power Plant (Power ≈ 17.5 GW)

Reactors -> Source of electronic antineutrinos!





Impressive list of physics goals:

- Neutrino mass hierarchy
- Neutrino oscillation parameters
- Supernova neutrinos
- Solar neutrinos
- Atmospheric neutrinos
- Geoneutrinos
- Sterile neutrinos
- Nucleon decays
- Neutrinos from DM
- Exotic searches with neutrinos

THE JUNO EXPERIMENT(2)

JUNO will be a large multipurpose detector:

- 20 kt LAB-based liquid scintillator;
- 18000 PMT (20”) + 25000 PMT (3”) --> 77% geometric coverage;
- High Quantum Efficiency PMTS 35%
- Expected Energy resolution 3%/√E

The Schedule	
2013	Funding approved
2014	Collaboration officially formed
2014-2018	Civil construction
2016-2019	Detector component and PMT production
2018-2019	Detector assembly & installation
2020	Liquid scintillator filling
2020	Start of data taking

The Milano NEUTRINO GROUP

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Dott. Laura Collica
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Dott. Andrey Formozov
Dott. Davide D'Angelo
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