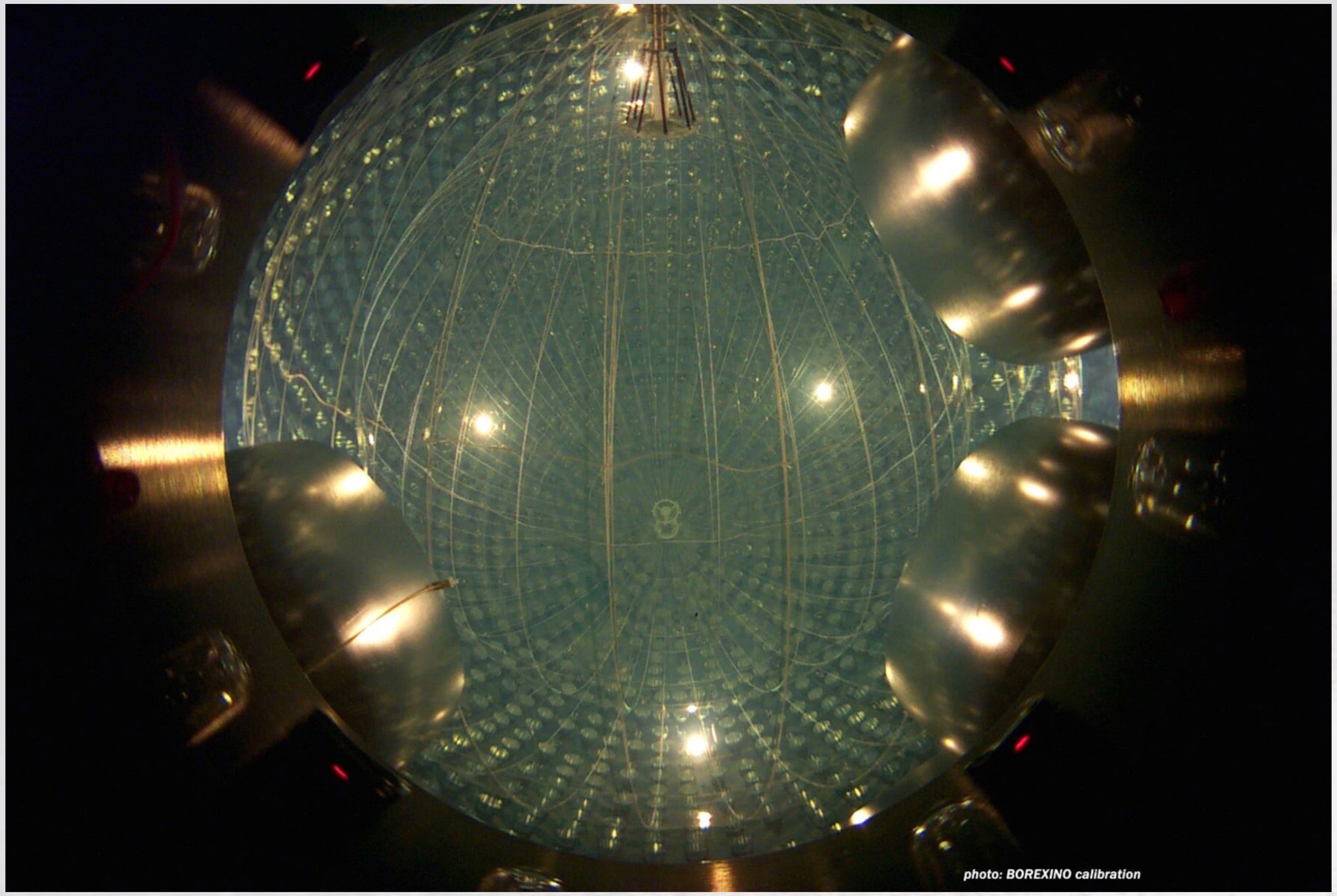


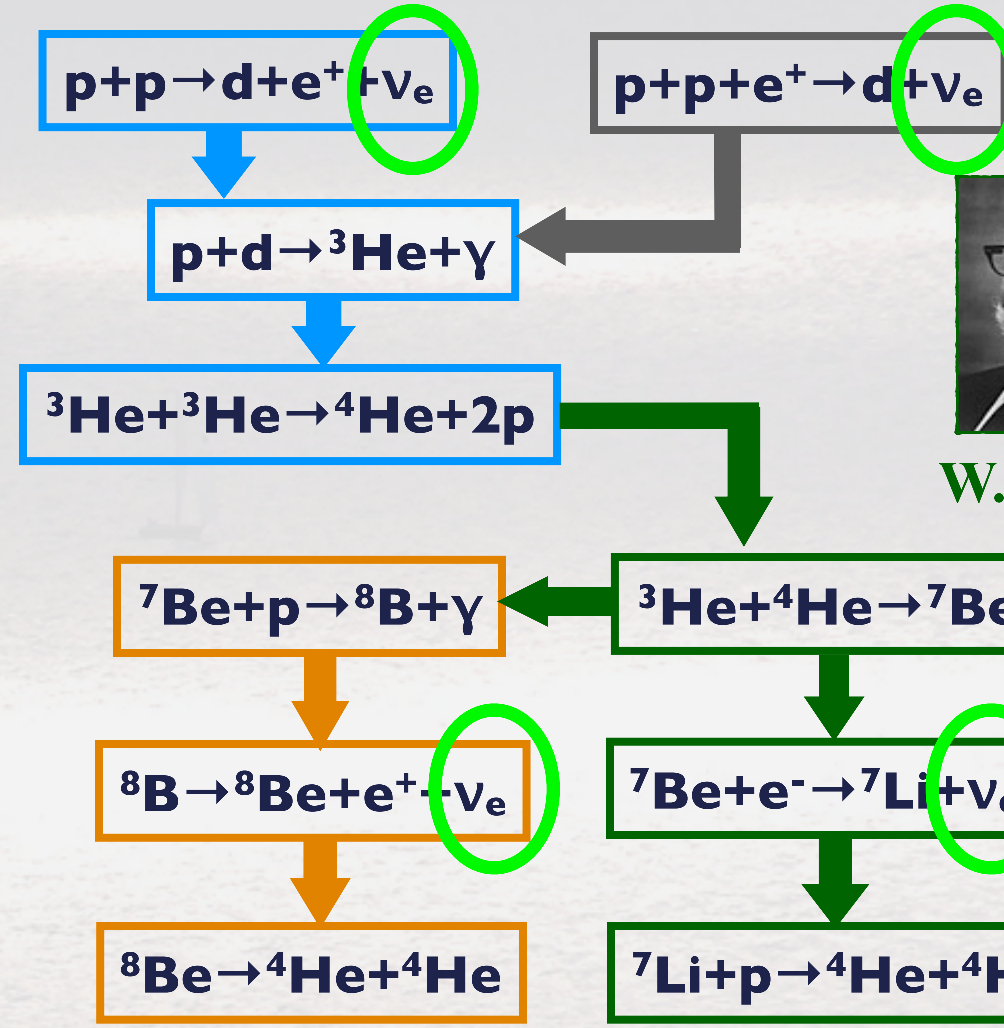
The Borexino experiment: Past, Present and Future of an Underground Neutrino Detector

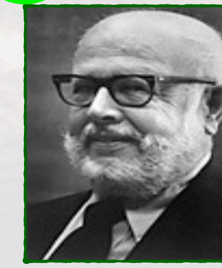
5th Int. Workshop for the Design of the ANDES Underground Laboratory

UNSAM - Buenos Aires, June 29th, 2017

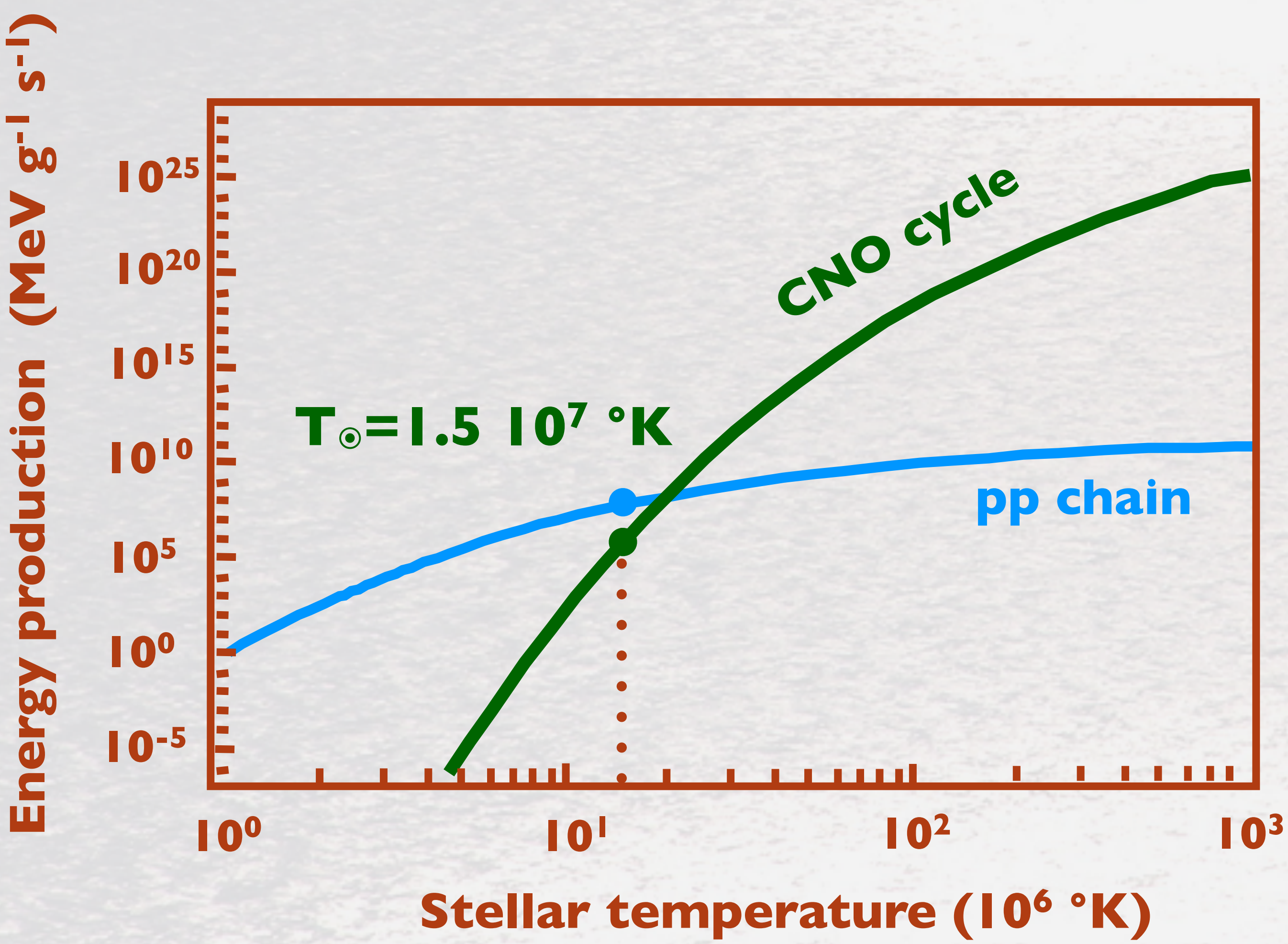
Marco Pallavicini
Dipartimento di Fisica - Università di Genova
e Istituto Nazionale di Fisica Nucleare (INFN)

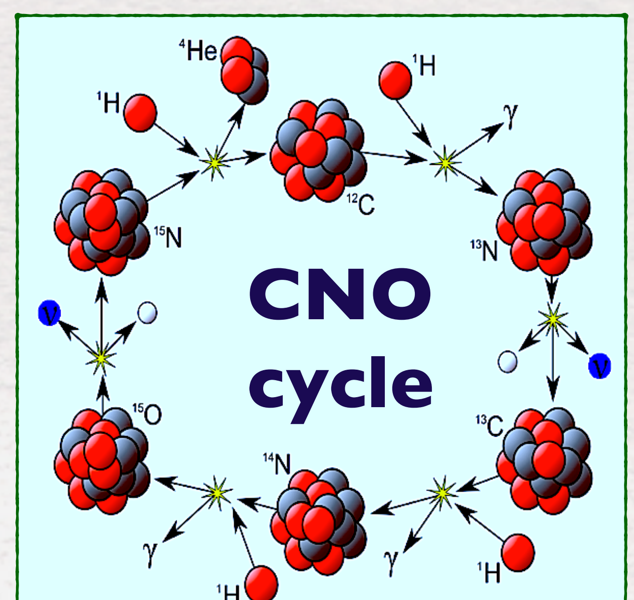
- **Nuclear fusion feeds stars**
  - **pp chain:** dominant in Sun-like main sequence stars
  - **CNO cycle:** dominant in more massive stars
    - The role of CNO in the Sun is still uncertain (**metallicity problem**)

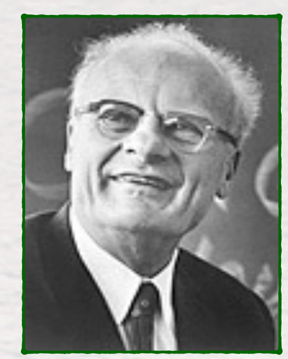




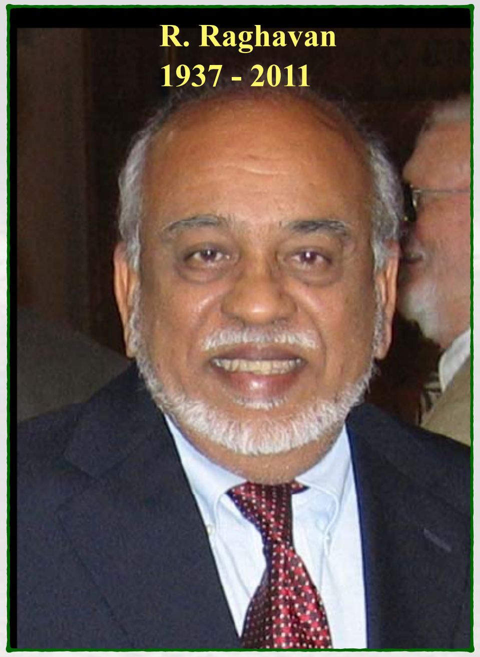
W. Fowler





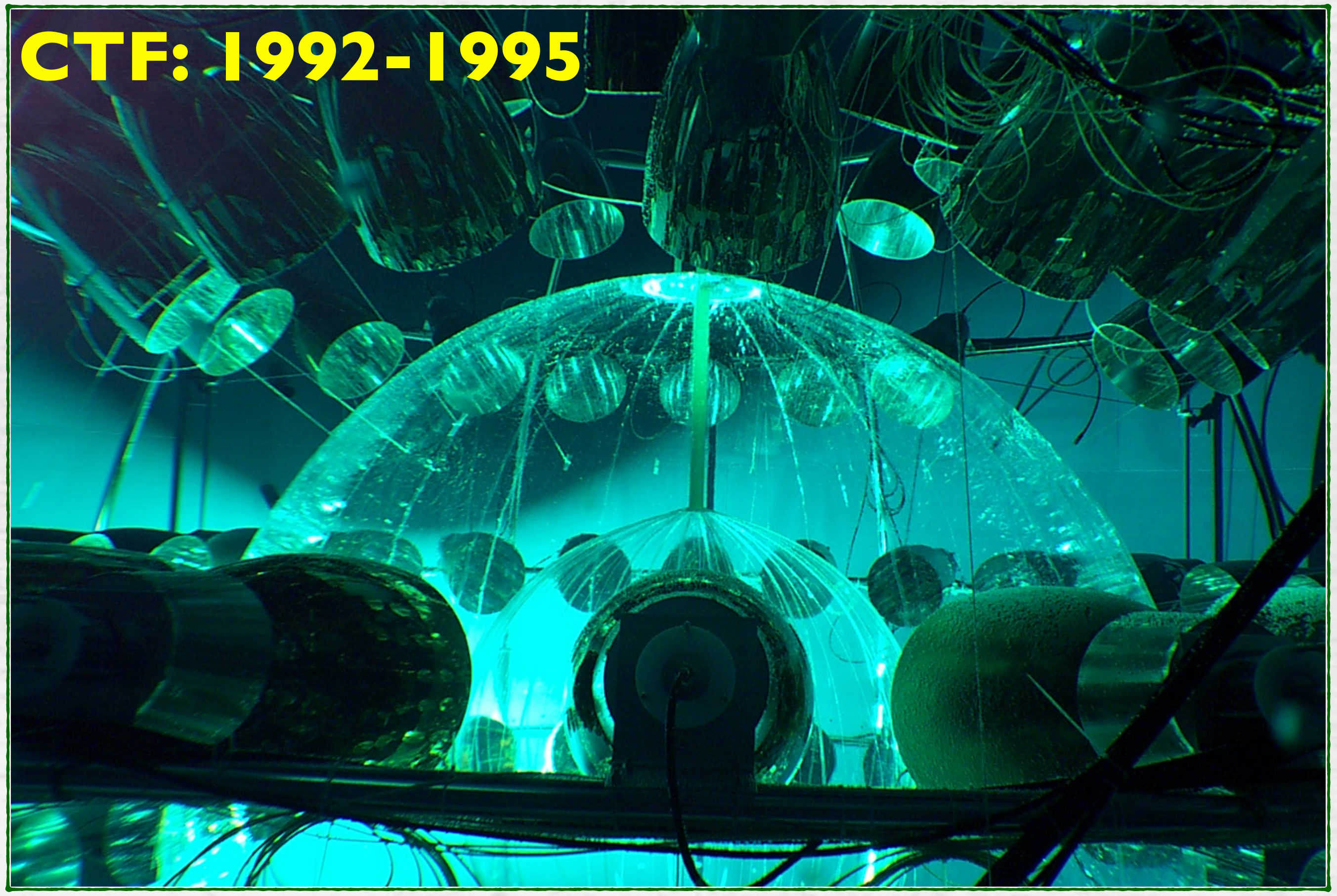


H. Bethe



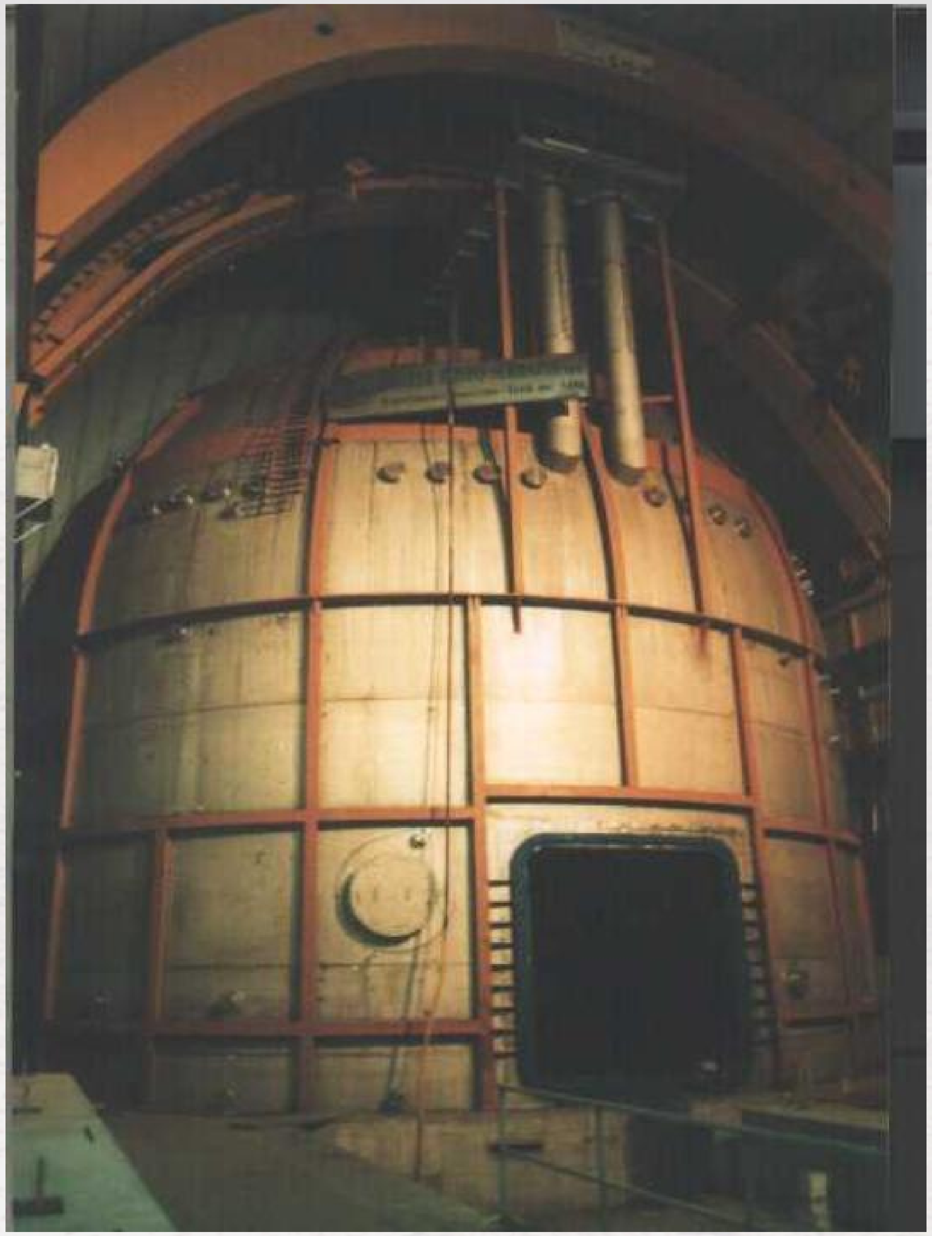
- In the late **80s**, thanks to **R. Raghavan,** a project was started:
  - **Detection of sub-MeV solar ν** to solve the **"solar ν problem"**
    - First attempt: search for inverse beta decay on B ⇒ "BOREX"
      - Proved not to be feasible in the space available at Gran Sasso
    - A smaller detector searching for elastic scattering on e^- was proposed ⇒ **BOREXino**
  - **Scintillator: low energy threshold, good energy resolution, no direction**

- **The key problem:**
  - The scintillator must be (by far) **the most radio-pure thing ever built!**
    - 15 years of R&D to solve it
    - At that time the goals were unprecedented:
      - **10^{-16} g/g in ^{238}U and ^{232}Th**
      - **10^{-18} g/g in ^{14}C**
      - **10^{-14} g/g in K_{nat}**



- **1989-1995:** R&D and construction of **"Counting Test Facility"** (CTF)
- **1995:** first CTF results. the feasibility of the project is proved.
  - Actually, it was proved that the project was not impossible….

Phys. Lett. B422 (1998)
Astrop. Phys. 8 (1998)
Astrop. Phys. 18 (2002)



- **1996-1998:** funding agencies in Italy, Germany and USA approve Borexino
  - 1997: construction of the Water Tank
- **2002-2005:** the project is stopped because of a small accident and a big fight triggered by it
- **2006-2007:** activities resume and data taking begins on **May 15, 2007**
- **2007-2017:** **physics!**

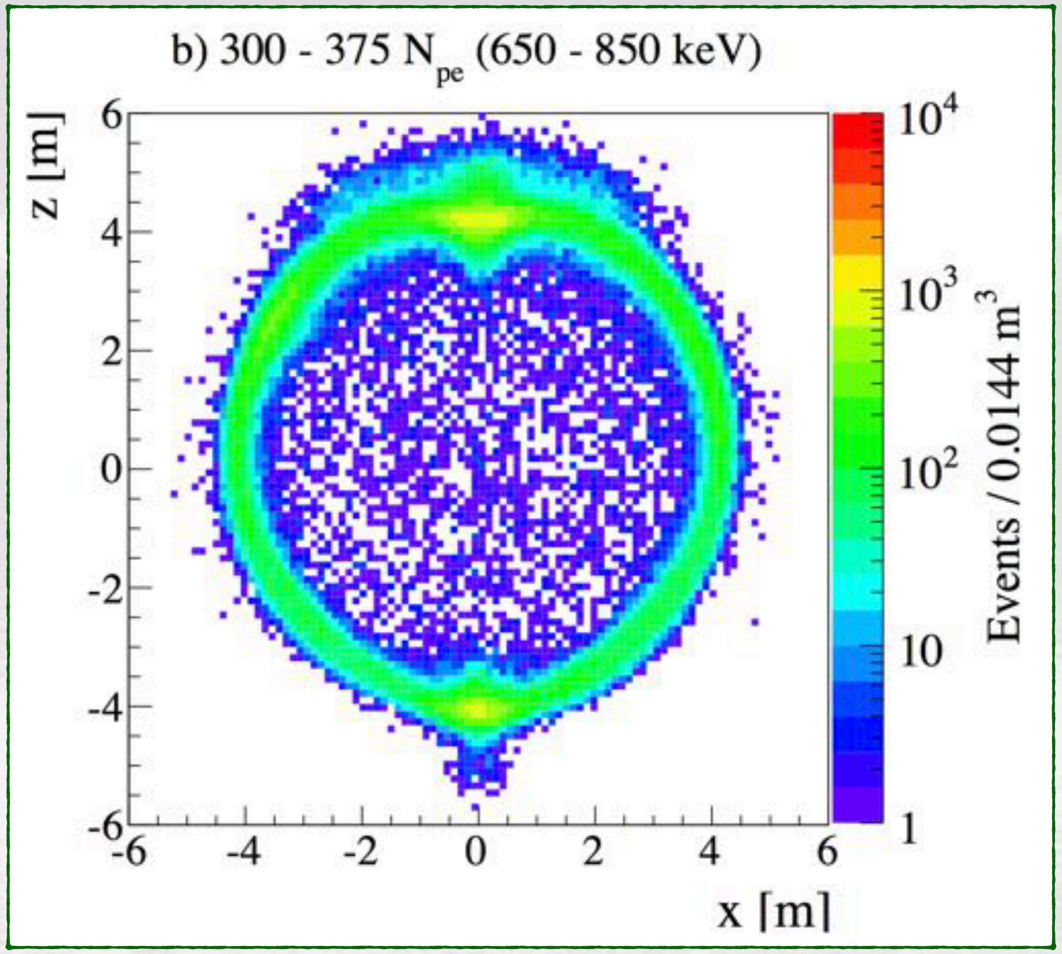
WHY SO LONG ?

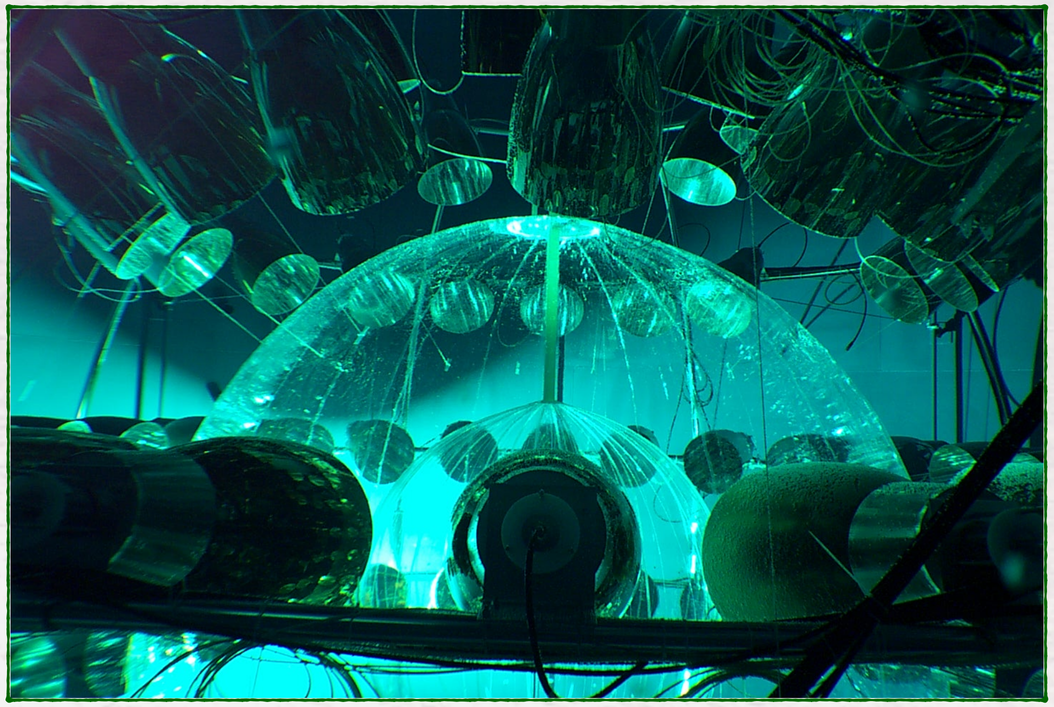
- A few numbers:
  - With 100 t of target mass, you expect about **50 ev/day** from ^{7}Be solar ν
    - 50 / 86400 / 100 t ~ **6 10^{-9} Bq/kg**
  - **ν-e scattering** is **intrinsically not distinguishable** from a **β radioactivity** event or from Compton scattering from **γ radioactivity**

- **BUT:**
  - Good mineral water: ~10 Bq/kg ^{40}K, ^{238}U, ^{232}Th
  - Air: ~10 Bq/m^{3} ^{222}Rn, ^{39}Ar, ^{85}Kr
  - Typical rock ~100-1000 Bq/kg ^{40}K, ^{238}U, ^{232}Th, + many others

- If you want to detect solar neutrinos with liquid scintillator, you must be **9-10 orders of magnitude more pure than anything on earth**
  - **Not easy, but possible !**

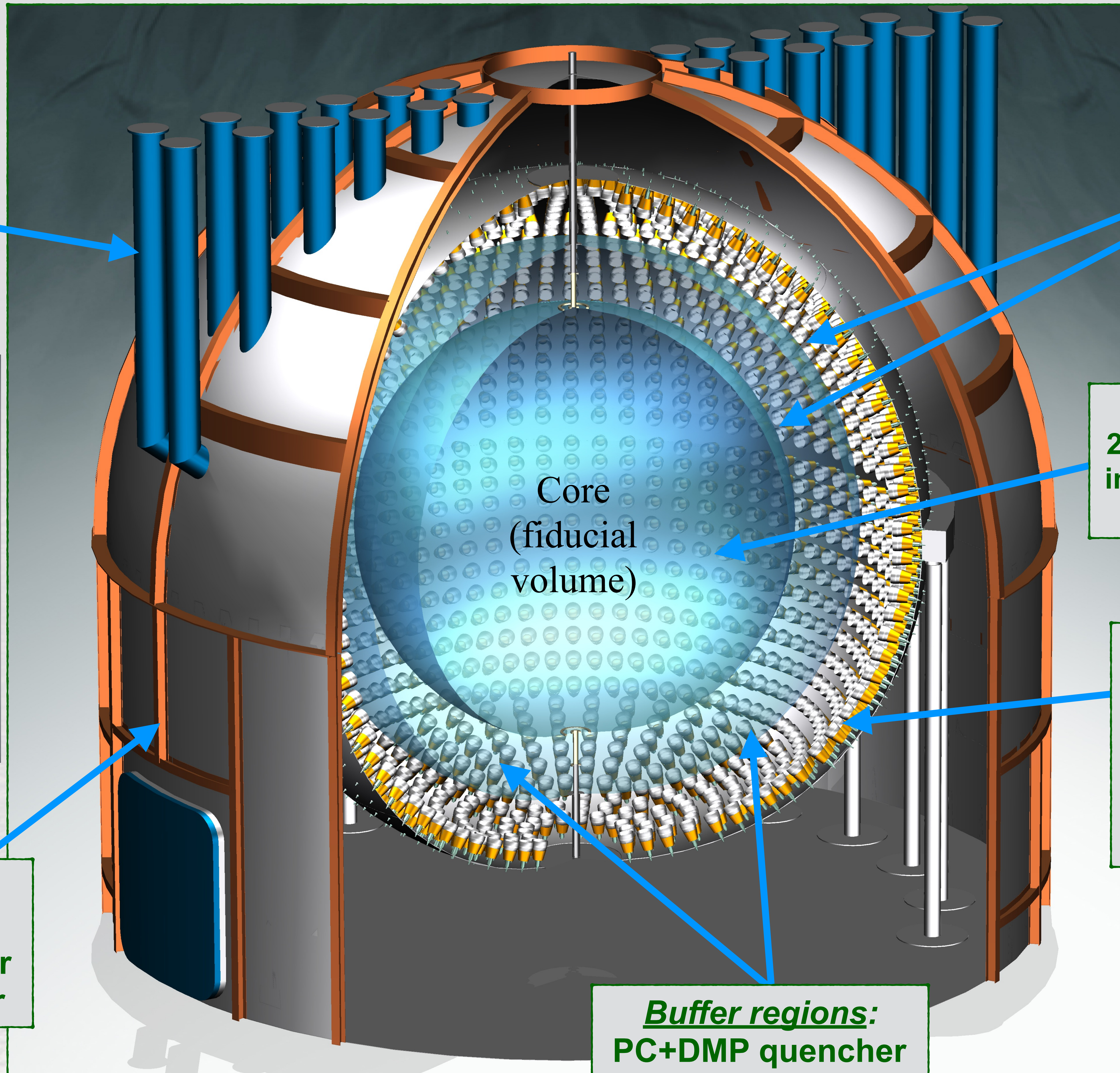
- **Go deep underground**
  - Reduce muons (10^6 @ LNGS) and even more important reduce cosmogenic production of radioactive contaminants
- Introduce the concept of **"graded shielding"**
  - "Onion-like" detector with purer and purer materials going deep inside
- Very carefully **select all materials**
- **Ask chemistry to help you,** i.e. select a target in which solubility of radioactive ions is low
  - **Organic liquid scintillator** MUCH better than water
- Develop **purification techniques** and, even more important, **measurement technique** to achieve desired purity





THE CONCEPT OF GRADED SHIELDING

CABLE PIPES



NYLON VESSELS
(container & Rn barriers)

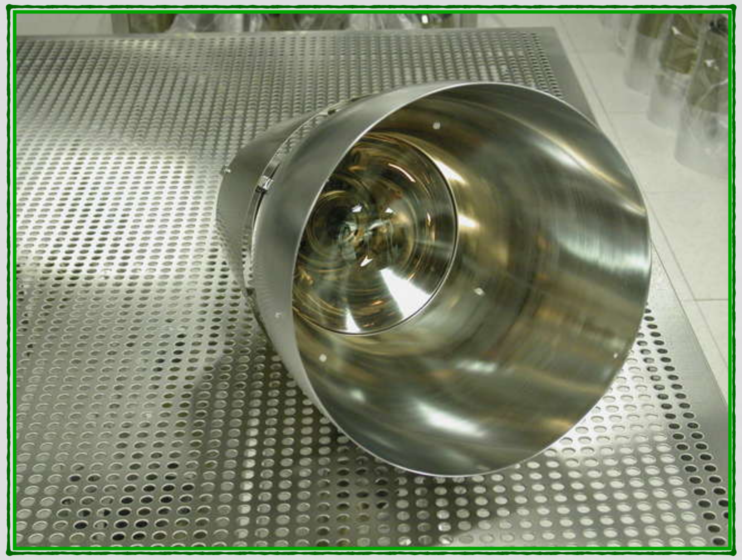
Scintillator:
270 t PC+PPO (1.5 g/l) in 150 μm thick nylon vessel (R = 4.25 m)

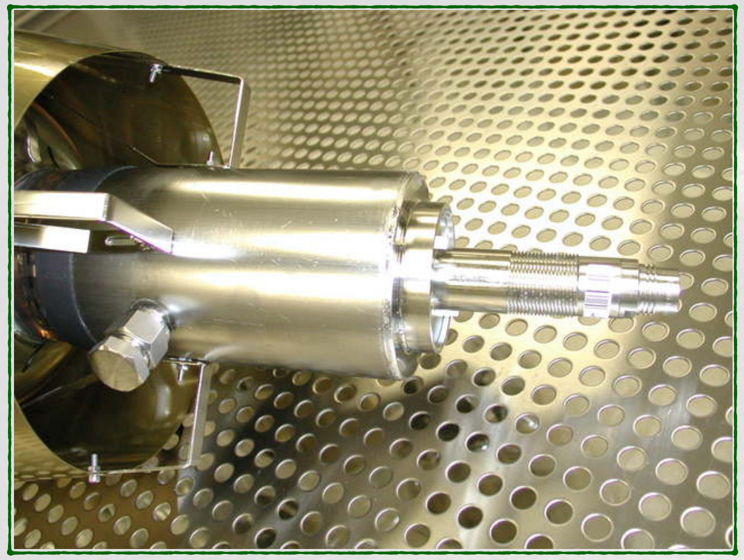
Stainless Steel Sphere:
R = 6.75 m
2212 PMTs
(container & support)

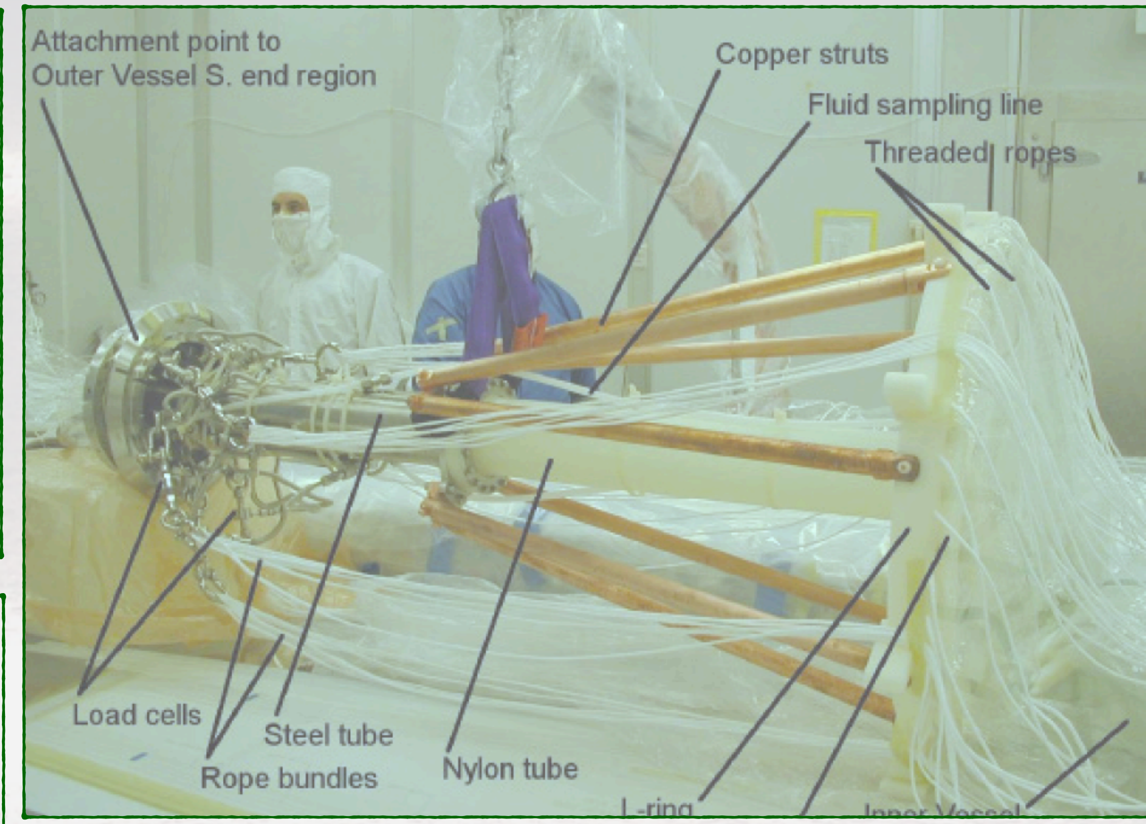
Water Tank:
γ and n shield
μ water Č detector
208 PMTs in water

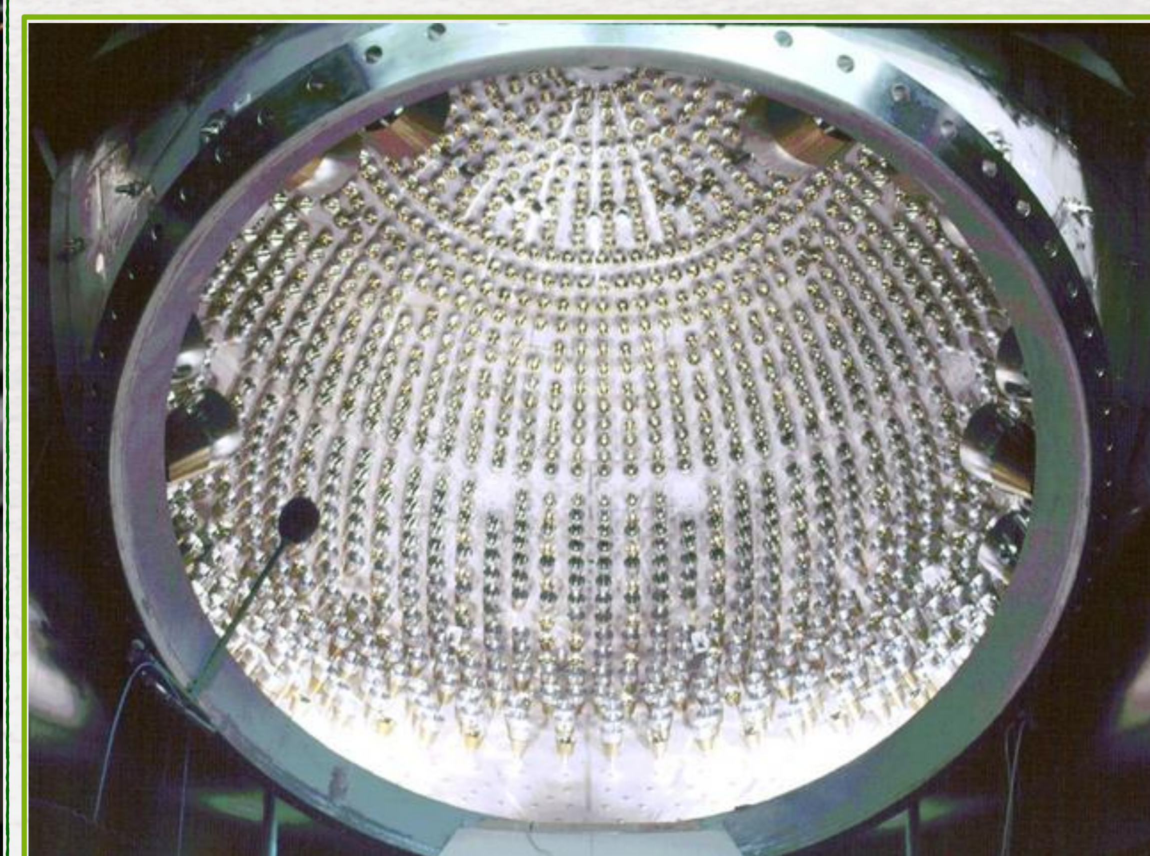
Buffer regions:
PC+DMP quencher
4.25 m < R < 6.75 m

MATERIAL SELECTION AND CLEANLINESS





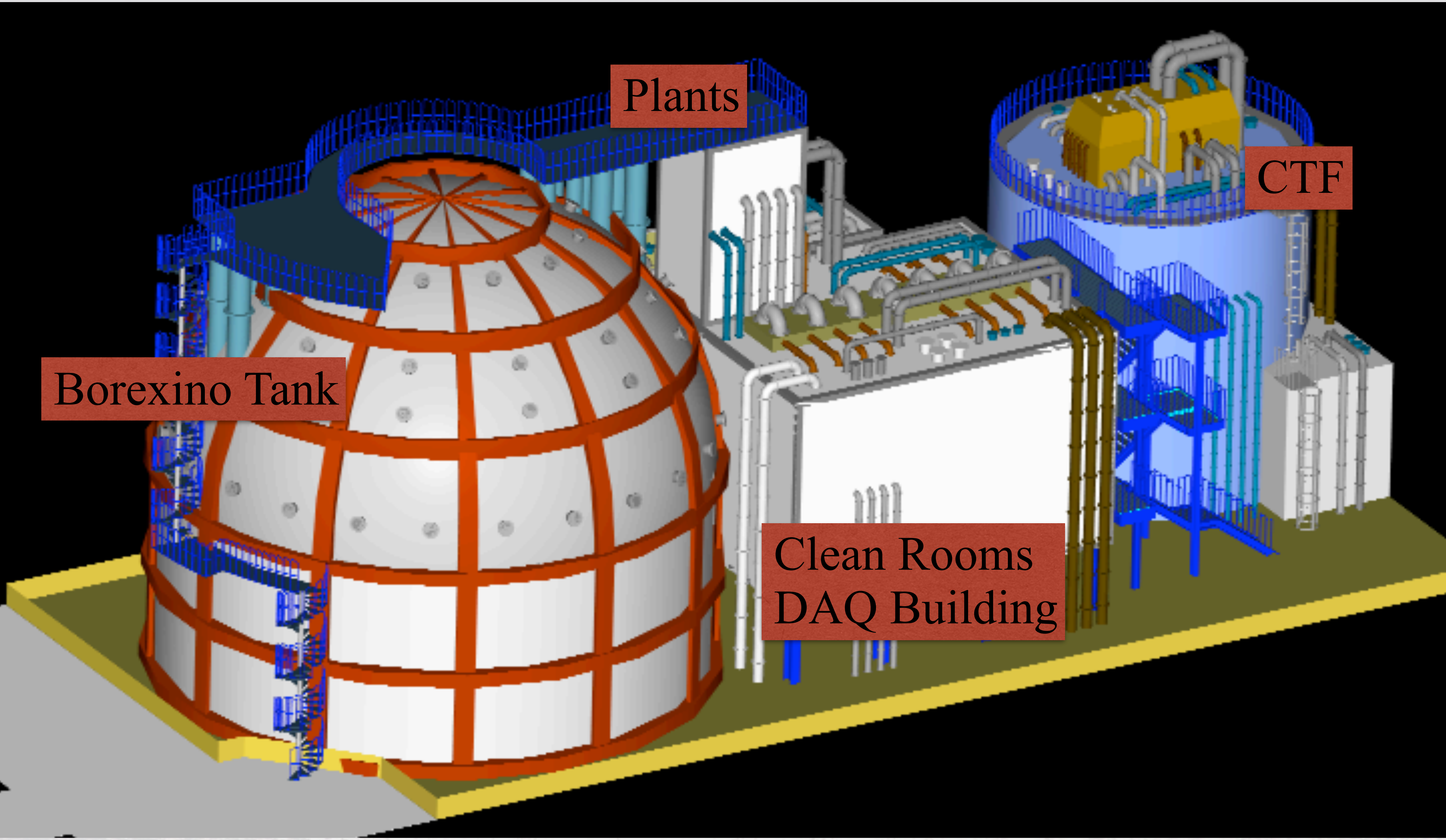


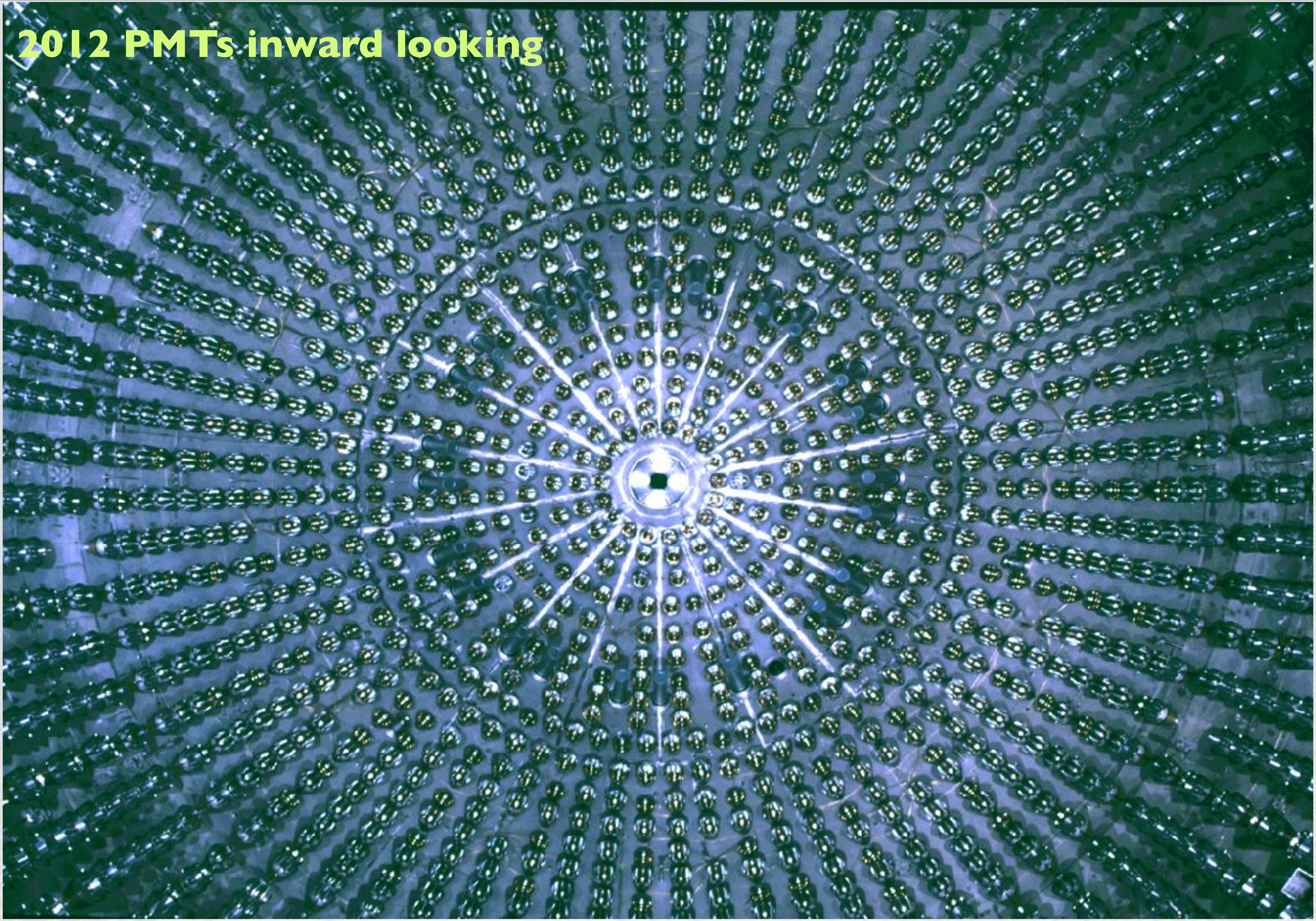


15 YEARS OF WORK IN 1 SLIDE

Radio-Isotope		Concentration or Flux		Strategy for Reduction		Final
Name	**Source**	**Typical**	**Required**	**Hardware**	**Software**	**Achieved**
μ	cosmic	~ 200 s^{-1} m^{-2} @ sea level	**<$10^{-10}$$s^{-1}$ m^{-2}**	underground water detector	Cerenkov PS analysis	**< 10^{-10} eff. > 0.9992**
γ	rock			water	fid. vol.	negligible
γ	PMTs, SSS			buffer	fid. vol.	negligible
^{14}C	intrinsic PC	~10^{-12} g/g	~10^{-18} g/g	selection	threshold	~ 2 10^{-18} g/g
^{238}U ^{232}Th	dust, metallic	10^{-5}-10^{-6} g/g	**<10^{-16} g/g**	distillation, W.E., filtration, mat. selection, cleanliness	tagging, α/β	**1.6±0.1 10^{-17} g/g 5.1±1 10^{-18} g/g**
^{7}Be	cosmogenic	~3 10^{-2} Bq/t	<10^{-6} Bq/t	distillation	--	not seen
^{40}K	dust, PPO	~2. 10^{-6} g/g (dust)	<10^{-18} g/g	distillation,W.E.	--	not seen
^{210}Po	surface cont. from ^{222}Rn		**<1 c/d/t**	distillation, W.E., filtration, cleanliness	fit	**May '07: 70 c/d/t Jan '10: ~1 c/d/t**
^{222}Rn	emanation from materials, rock	10 Bq/l air, water 100-1000 Bq rock	<10 cpd 100 t	N_2 stripping cleanliness	tagging, α/β	<1 cpd 100 t
^{39}Ar	air, cosmogenic	17 mBq/m^3 (air)	< 1 cpd 100 t	N_2 stripping	fit	<< ^{85}Kr
^{85}Kr	air, nuclear weapons	~ 1 Bq/m^3 (air)	**< 1 cpd 100 t**	N_2 stripping	fit	**May 07: 30 ± 5 cpd/100 t NOW: < 3 cpd/100 t**

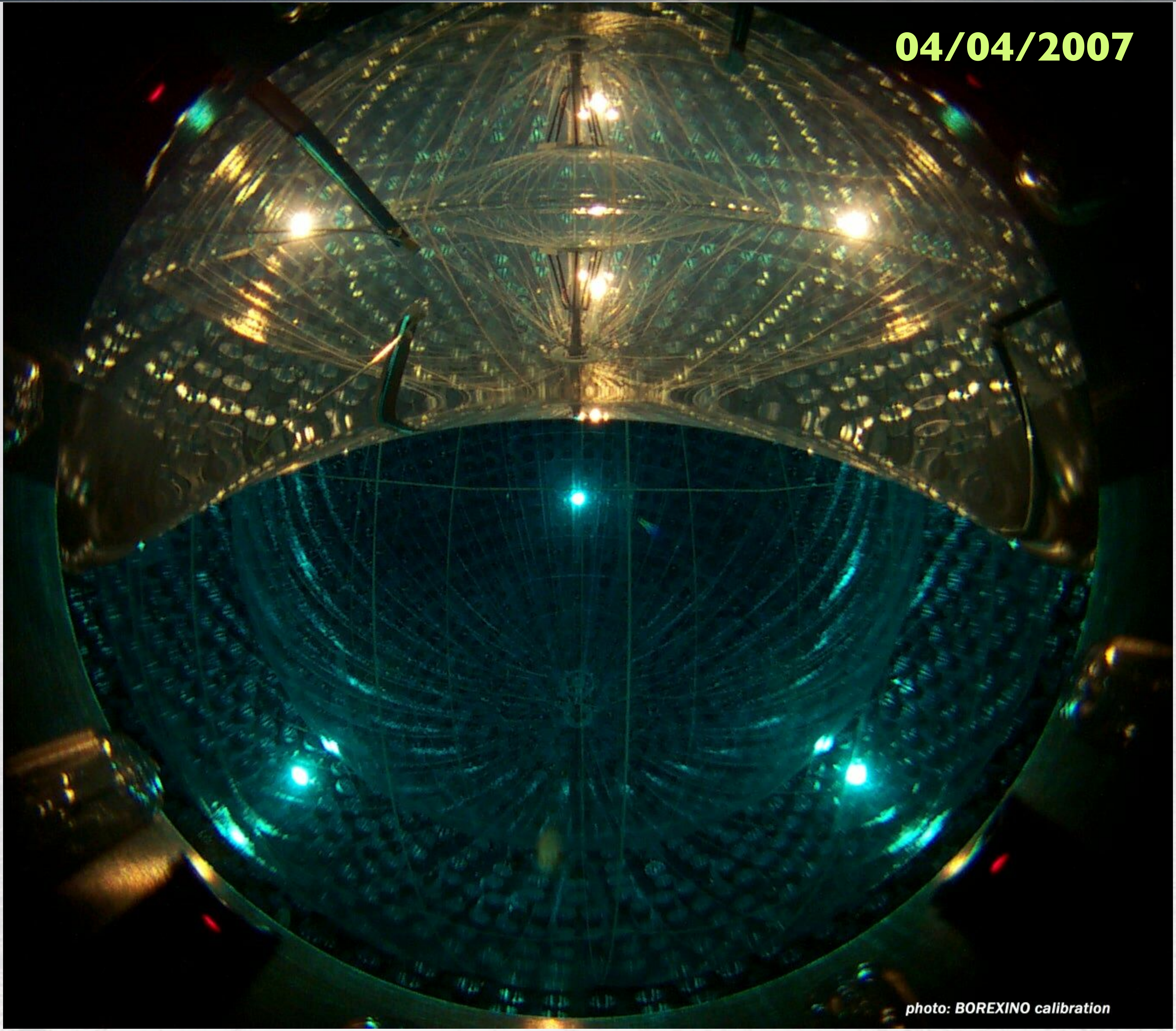
BOREXINO LAYOUT




2012 PMTs inward looking

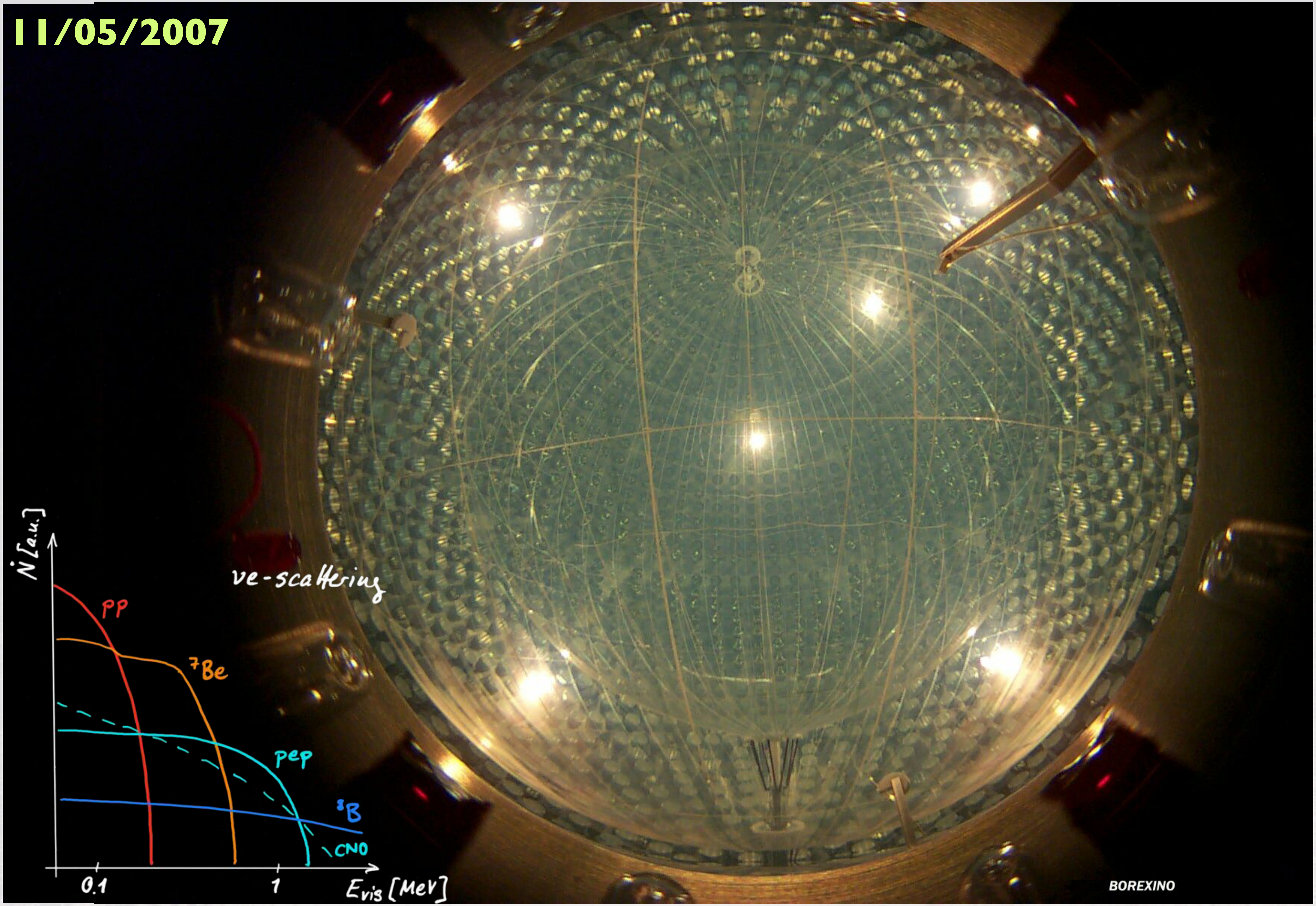
DURING WATER FILLING - 2006

PC AND WATER

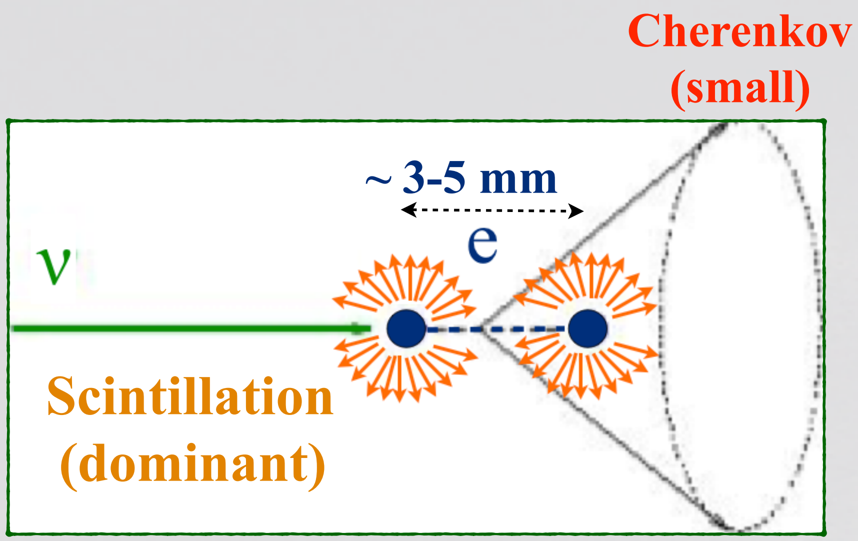


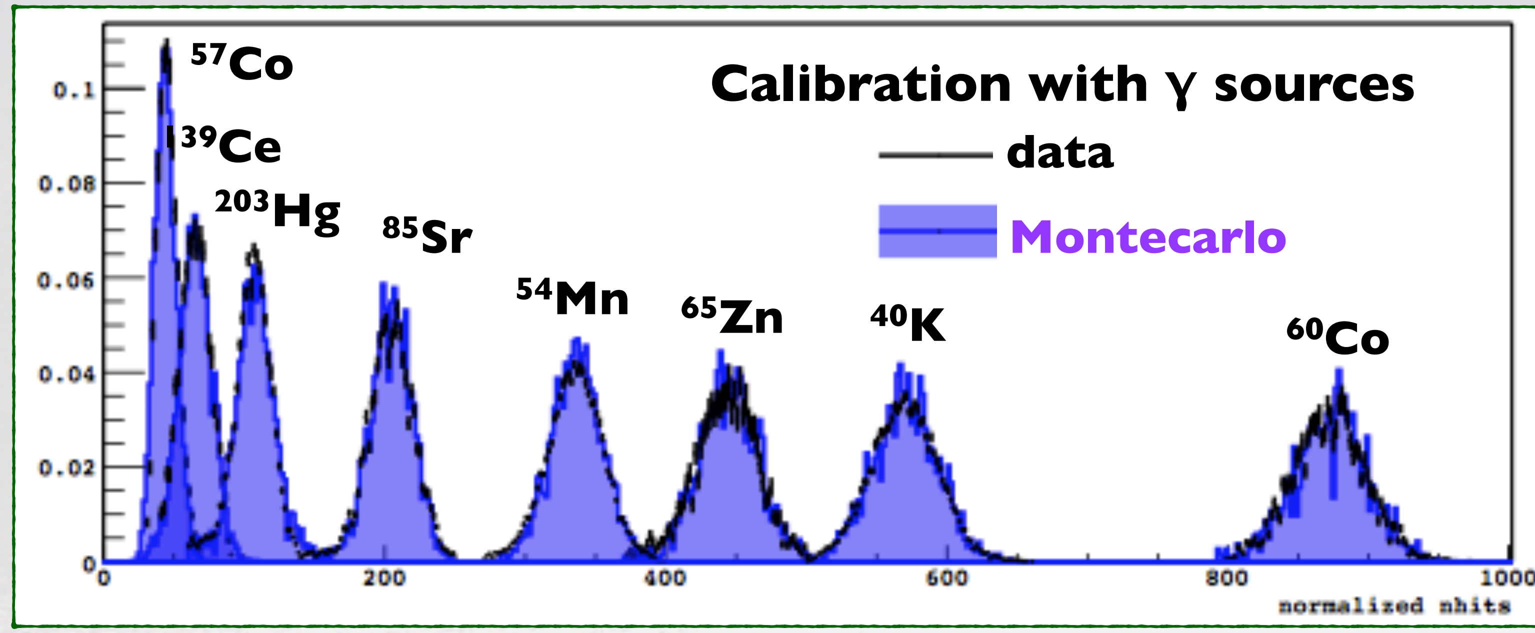
DETECTOR READY FOR DATA

11/05/2007

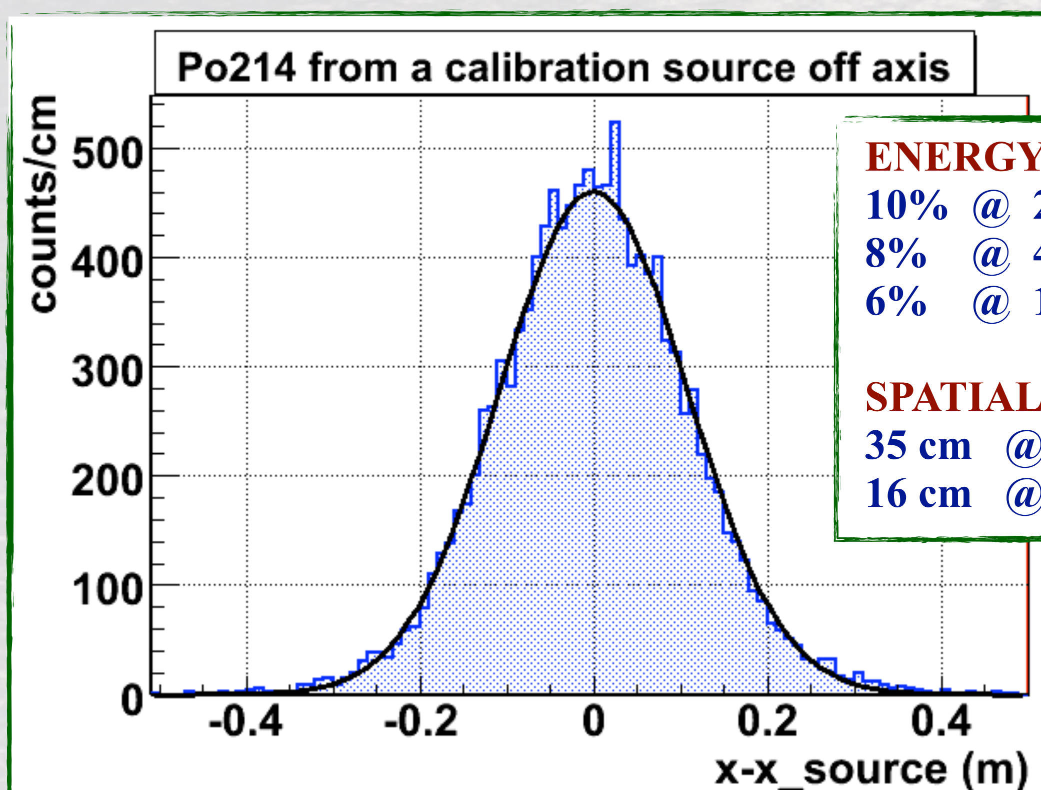


LIQUID SCINTILLATOR FEATURES



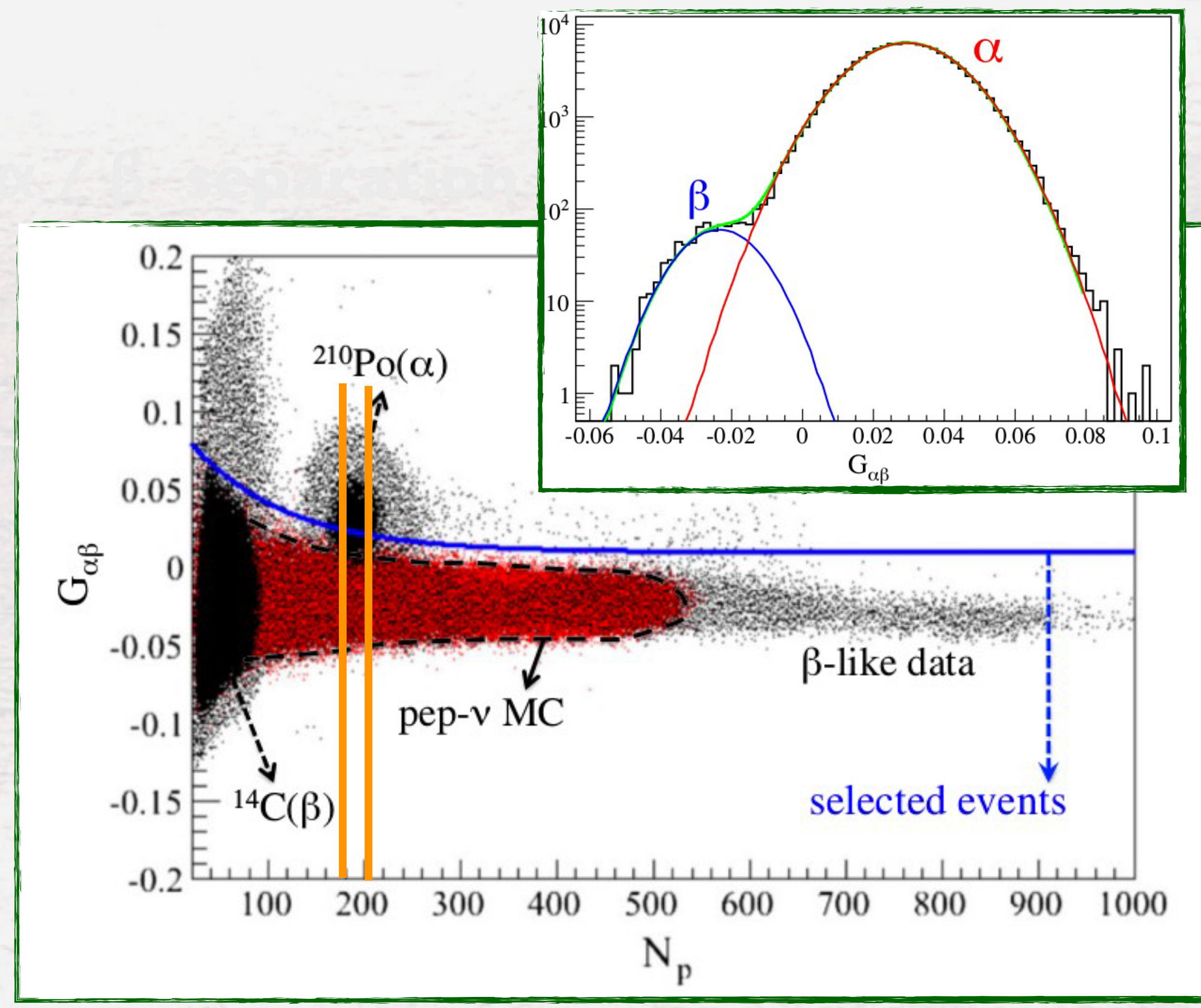


- Scintillation light
  - # of photons → **energy**
  - time of flight → **position**
  - pulse shape → **α/β β^+/β^-**



ENERGY RESOLUTION
10% @ 200 keV
8% @ 400 keV
6% @ 1 MeV

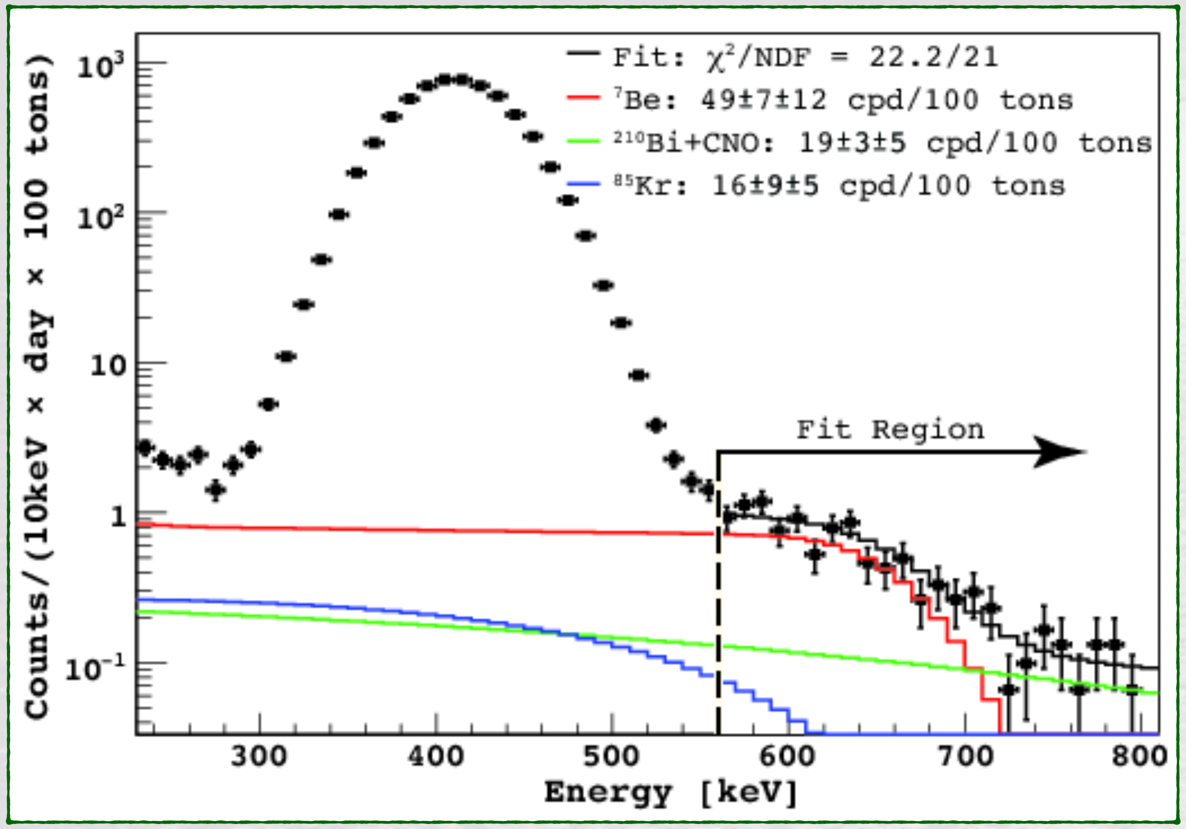
SPATIAL RESOLUTION
35 cm @ 200 keV
16 cm @ 500 keV

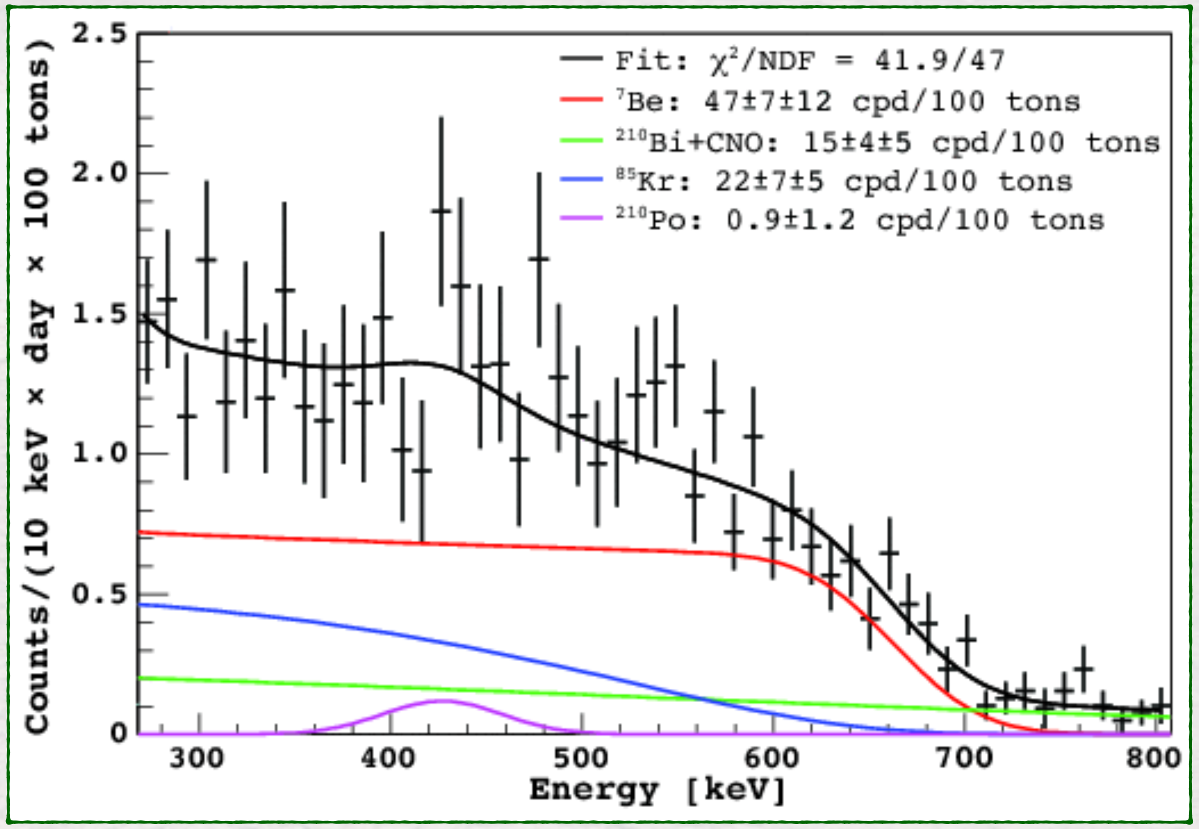


- The large effort made in 1990-2007 paid off

2007

  - Detector purity was immediately understood to be better than design goals
  - The first detection of ^{7}Be neutrinos could be done in ~ 1 month



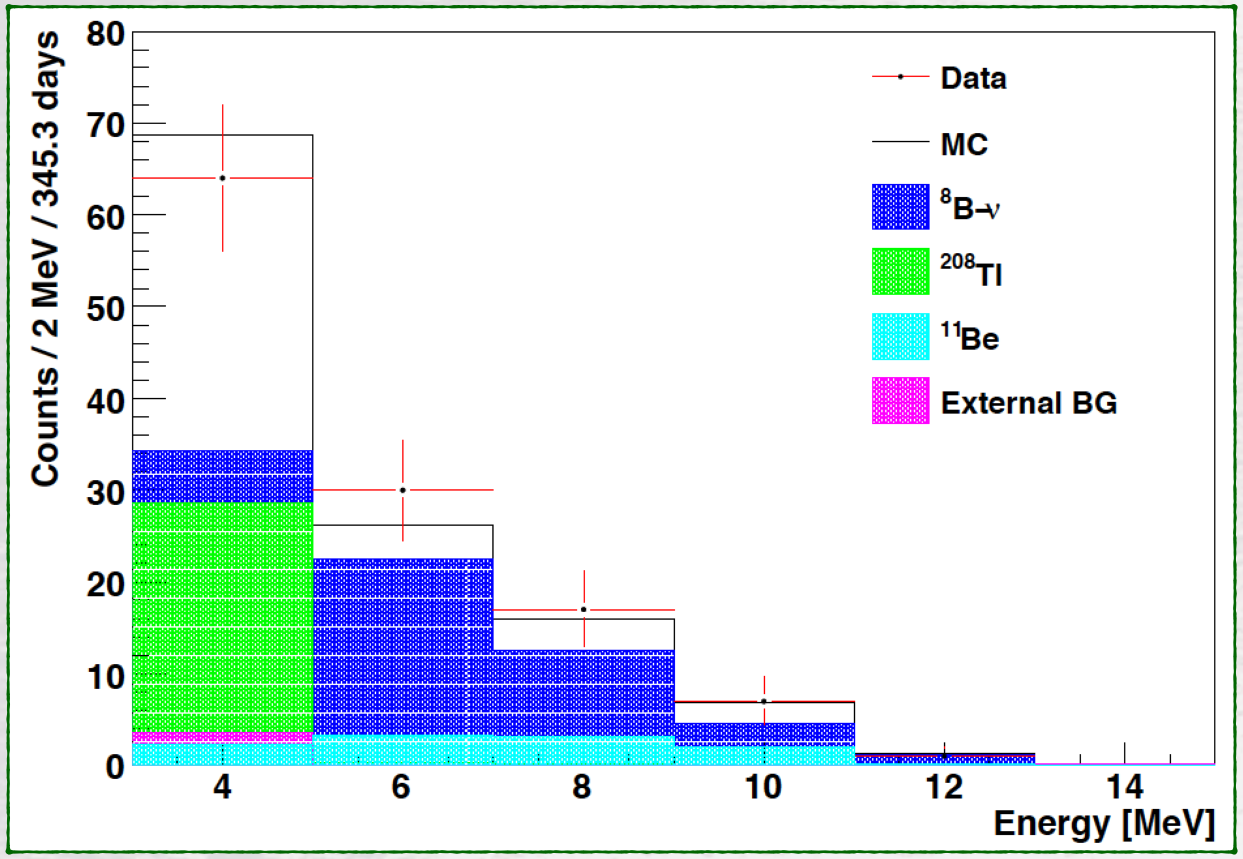


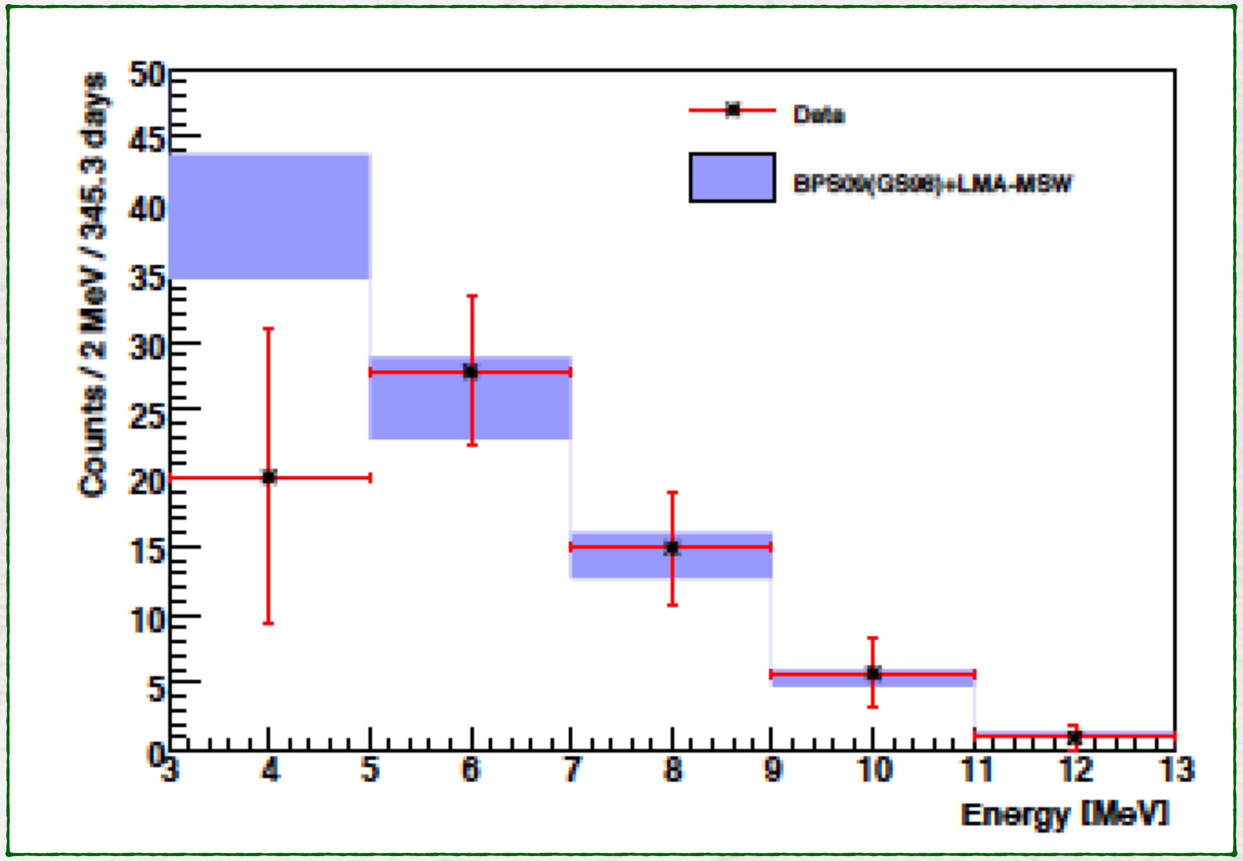
FIRST DETECTION OF ^{8}B BELOW 4 MeV

- The very clean scintillator and the low threshold allows a measurement of ^{8}B neutrinos with a threshold of 3 MeV
  - Much lower statistics that Water Cherenkov detectors

2009

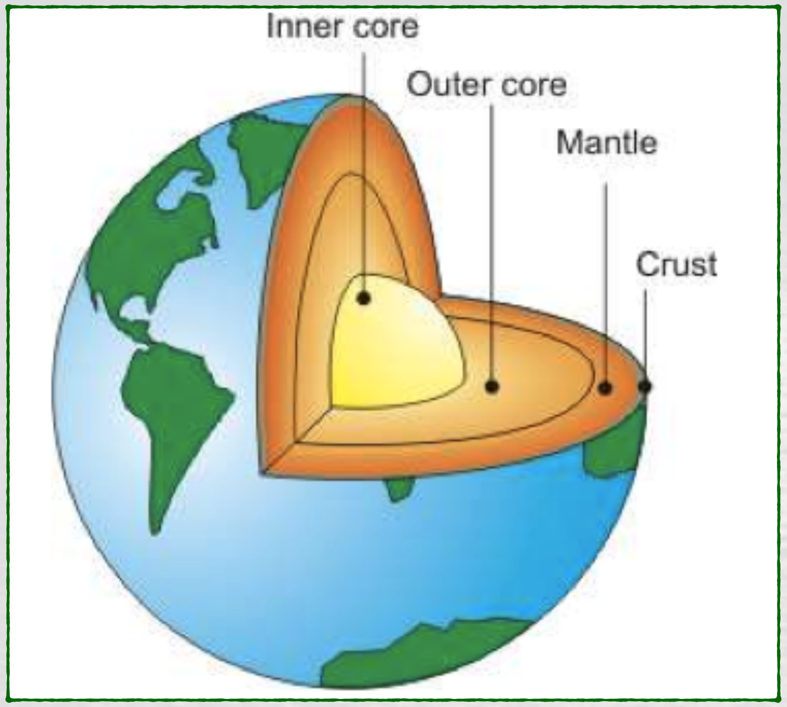
	3.0–16.3 MeV	5.0–16.3 MeV
Rate [c/d/100 t]	0.22±0.04±0.01	0.13±0.02±0.01
Φ^{ES}_{exp} [10^6 cm^{-2}s^{-1}]	2.4±0.4±0.1	2.7±0.4±0.2
$\Phi^{ES}_{exp}/\Phi^{ES}_{th}$	0.88±0.19	1.08±0.23

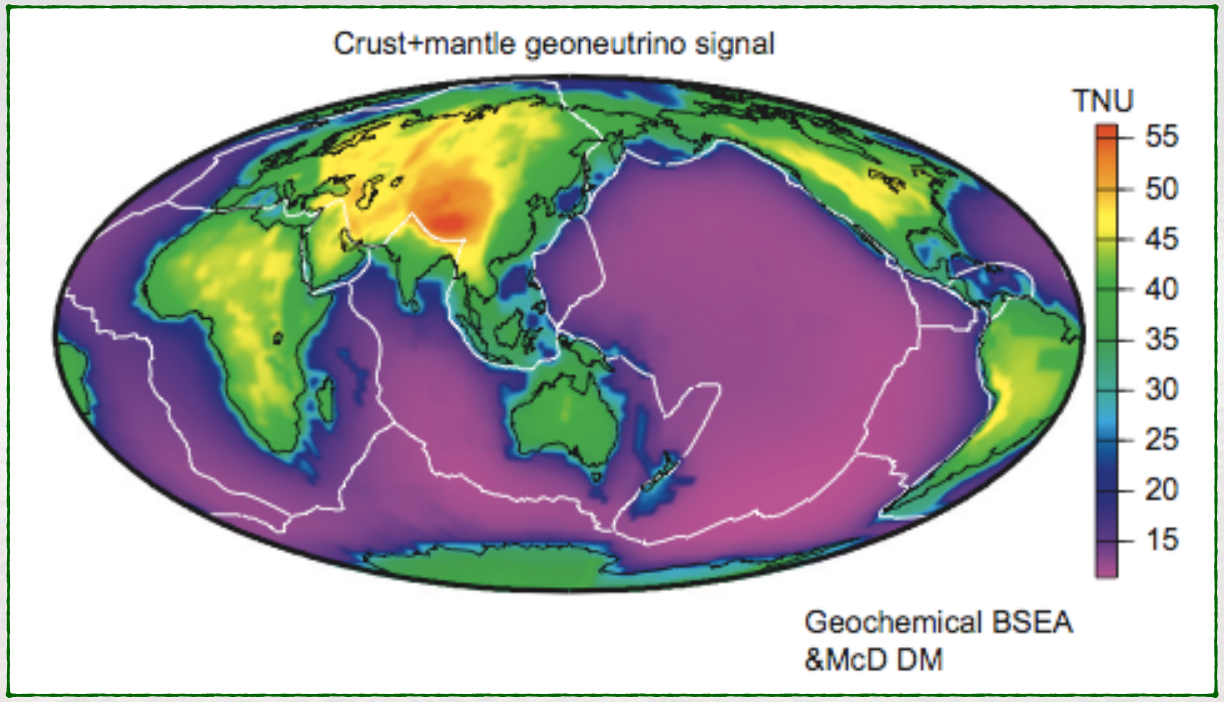




INTERMEZZO - GEO-NEUTRINOS

- The very high purity and the lack of nuclear reactors in Italy make Borexino an idea location for geo-neutrino detection
  - Main purpose: help understanding radiogenic heat





The Earth shines in anti-ν ($\Phi_\nu \sim 10^6\ cm^{-2}\ s^{-1}$)

$^{232}Th \rightarrow {}^{208}Pb + 6\,\alpha + 4\,e^- + \mathbf{4}\,\bar{\nu}_e + 42.8$ MeV

$^{238}U \rightarrow {}^{206}Pb + 8\,\alpha + 8\,e^- + \mathbf{6}\,\bar{\nu}_e + 51.7$ MeV

$^{235}U \rightarrow {}^{207}Pb + 7\,\alpha + 4\,e^- + \mathbf{4}\,\bar{\nu}_e + 46.4$ MeV

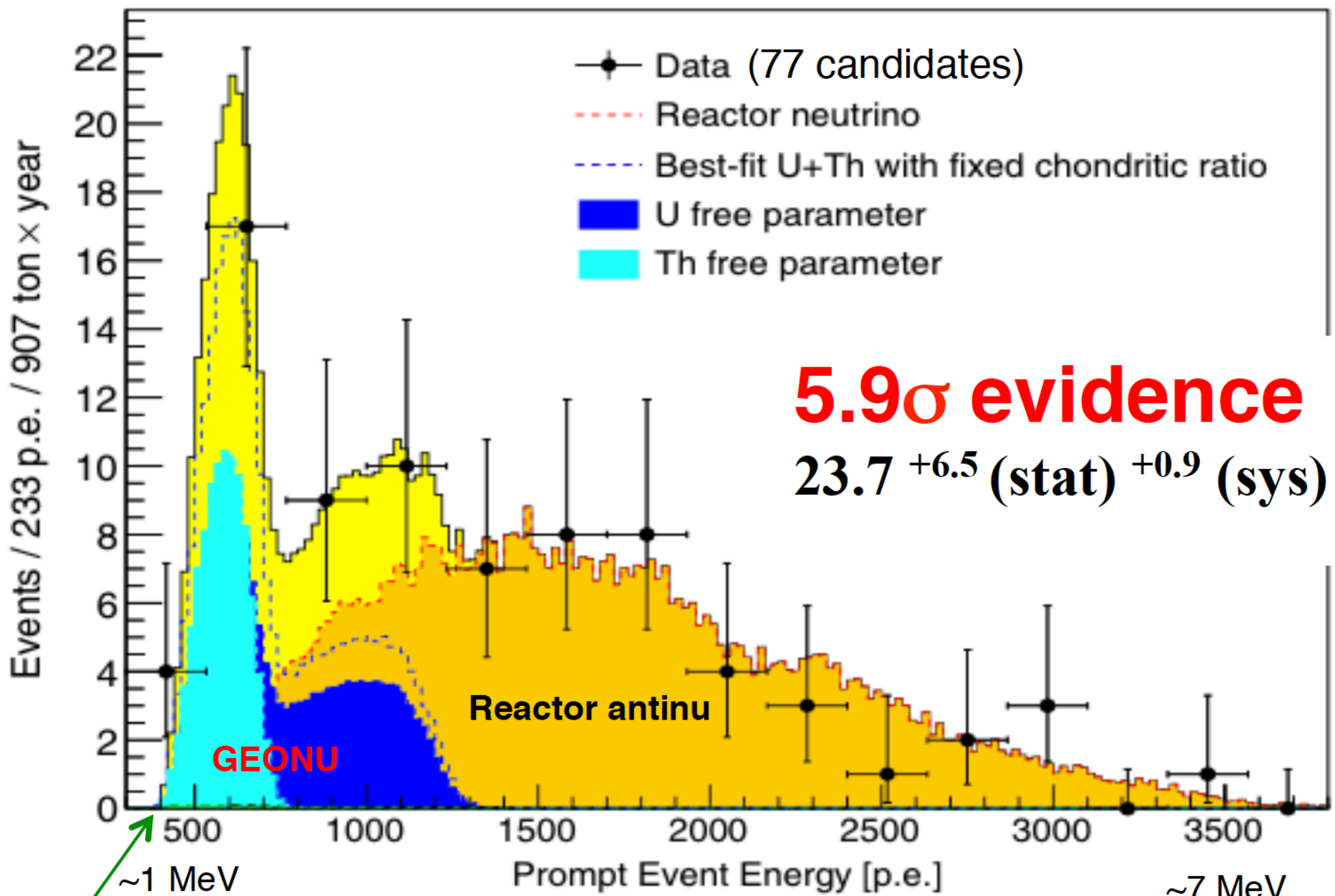
$^{40}K \rightarrow {}^{40}Ca + e^- + \mathbf{1}\,\bar{\nu}_e + 1.32$ MeV (89.3%)

$^{40}K + e \rightarrow {}^{40}Ar + e^+ + \mathbf{1}\,\nu_e + 1.505$ MeV (10.7%)

Heat Producing Elements
HPE's

✓ **Released heat and anti-neutrinos flux in a well fixed ratio!**

Geo-ν fluxes => HPE's abundances => Earth energetics



2010
2015

5.9σ evidence

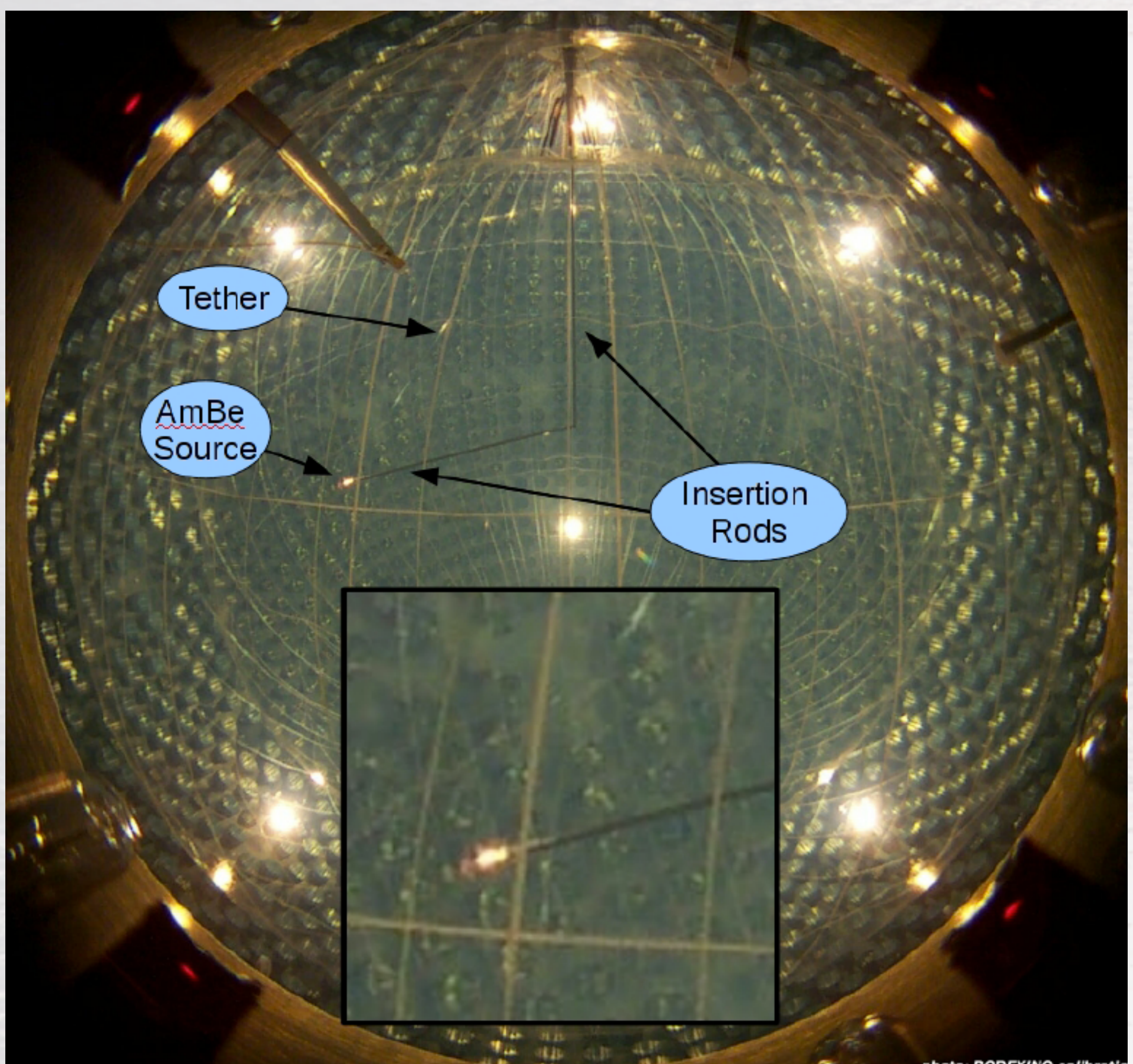
23.7 $^{+6.5}$ (stat) $^{+0.9}$ (sys) geonu's

Non antineutrino background is almost invisible!

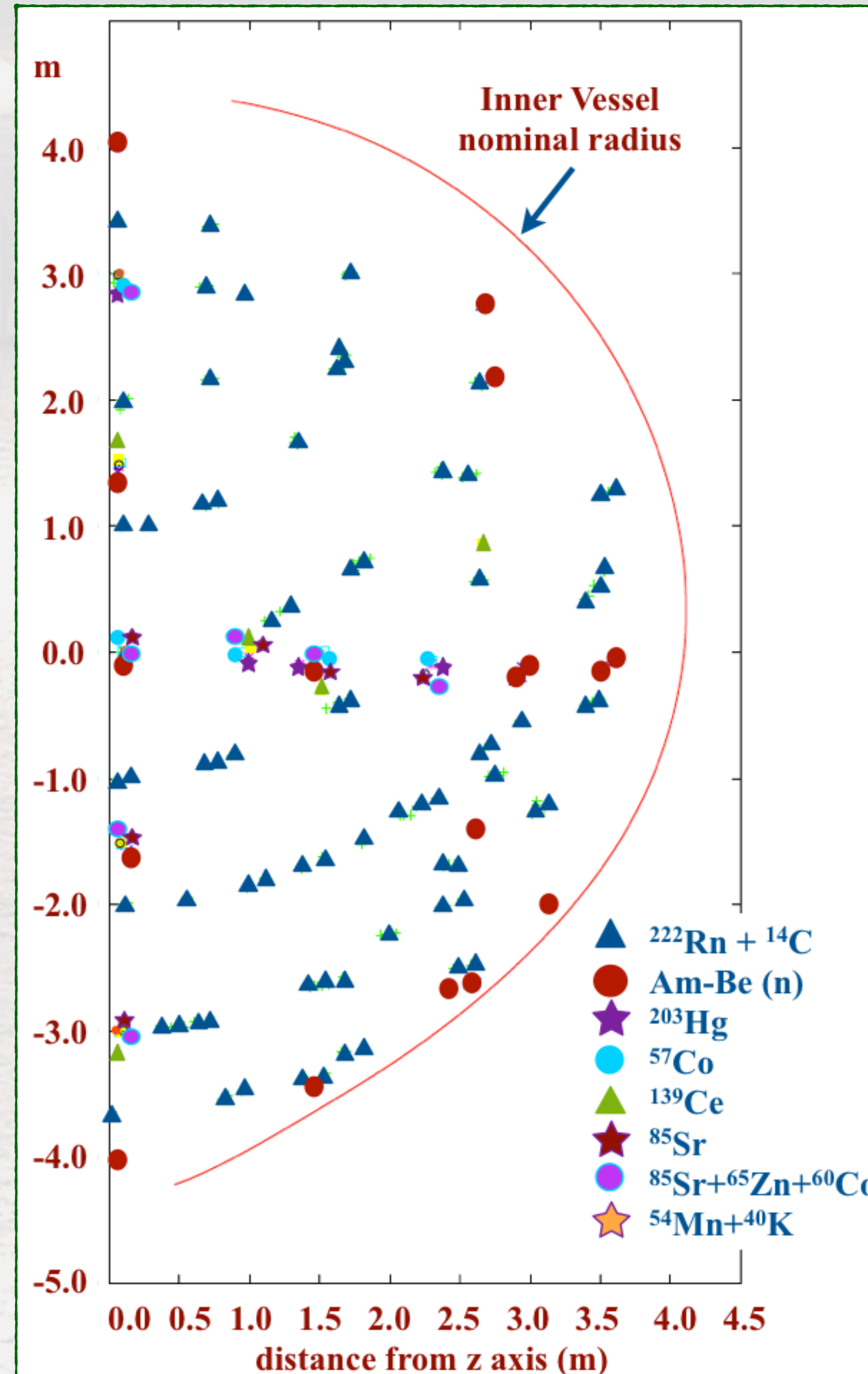
Phys. Lett. B687:299-304 (2010)
Phys. Rev. D 92, 031101 (2015)

- Calibrations done in 2010
  - Key points
    - Precise energy calibration
    - Precise determination of the fiducial volume
    - Strong effort on Monte Carlo simulation

A source inside Borexino



Location of calibration points

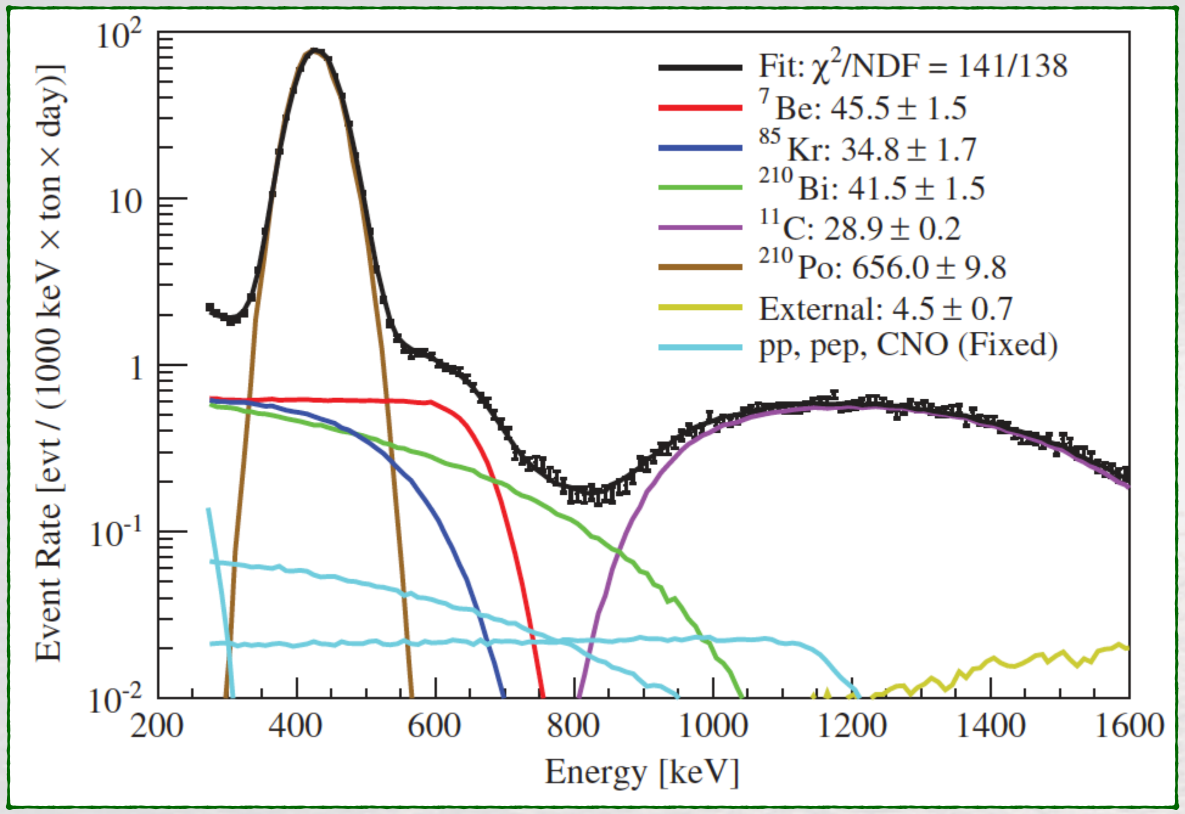


^{7}Be RATE AT HIGH PRECISION - 2011

- Two approaches to control systematic errors due to analysis procedure:

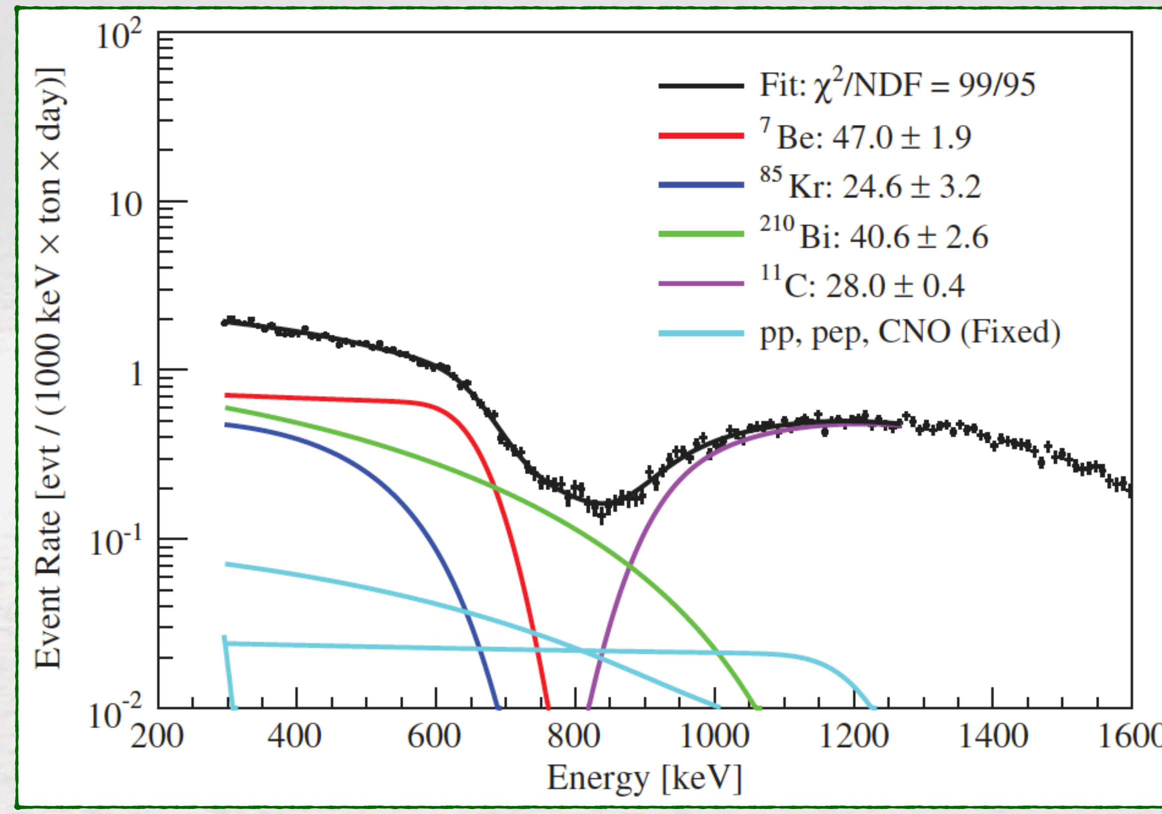
2011

Monte Carlo fit to the spectrum, no α/β ^{210}Po peak subtraction



Phys. Rev. Lett. 107, 141302, 2011

Analytical fit to the spectrum, after α/β ^{210}Po peak subtraction



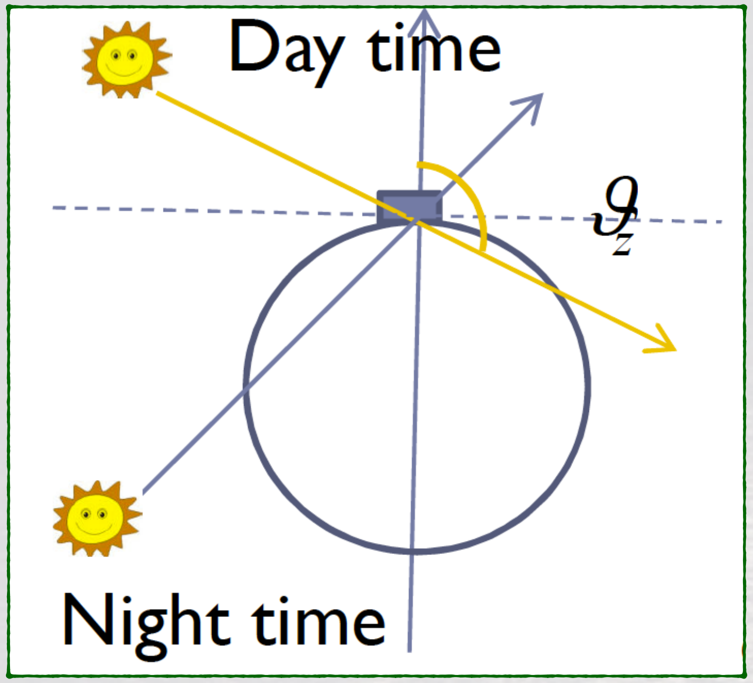
- Very Consistent results, small difference included in sys. uncertainty
- Rate for 100 t target:
  - **46.0 ± 1.5 (stat) ± 1.5 (sys) c d^{-1}**

Source	%
Trigger efficiency and stability	< 0.1
Live time	0,04
Scintillator density	0,05
Fiducial volume	+0.5 -1.3
Fit methods	2
Energy response	2,7
Sacrifice of cuts	0,1
Total	**+3.4 -3.6**

^{7}Be DAY-NIGHT ASYMMETRY

- Lack of day-night asymmetry selects MSW-LMA

2012



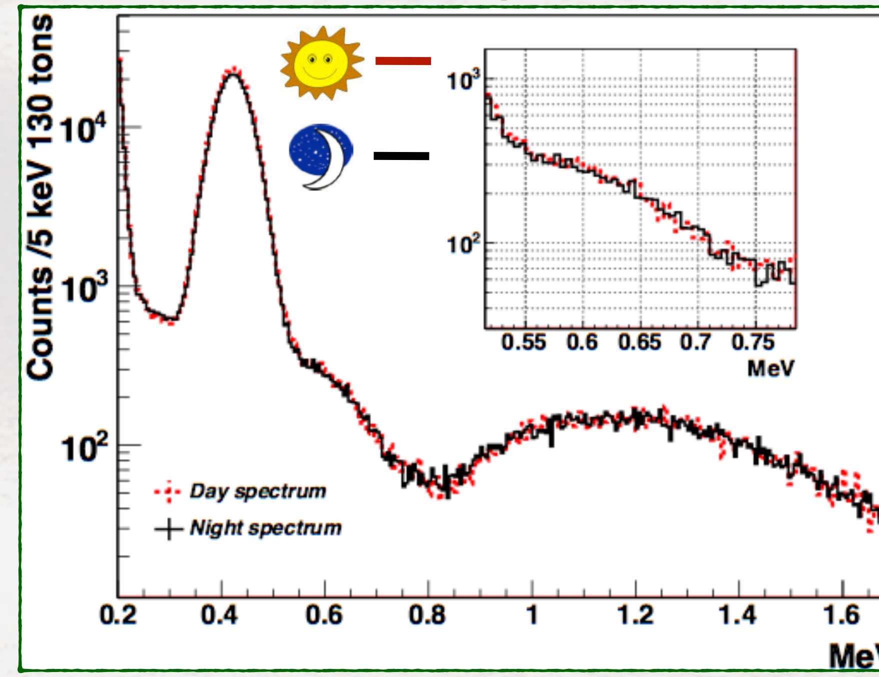
Phys. Lett. B707:22–26, 2012

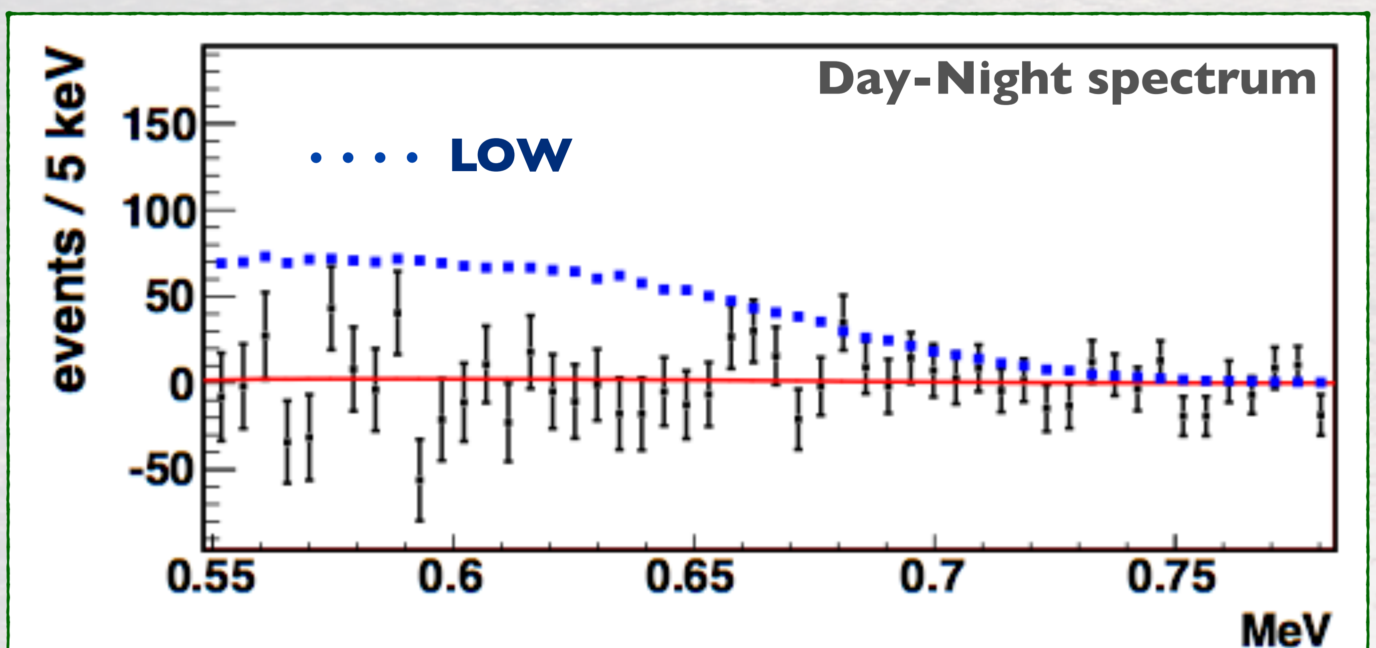
$$A_{dn} = 2\frac{R_N - R_D}{R_N + R_D} =$$

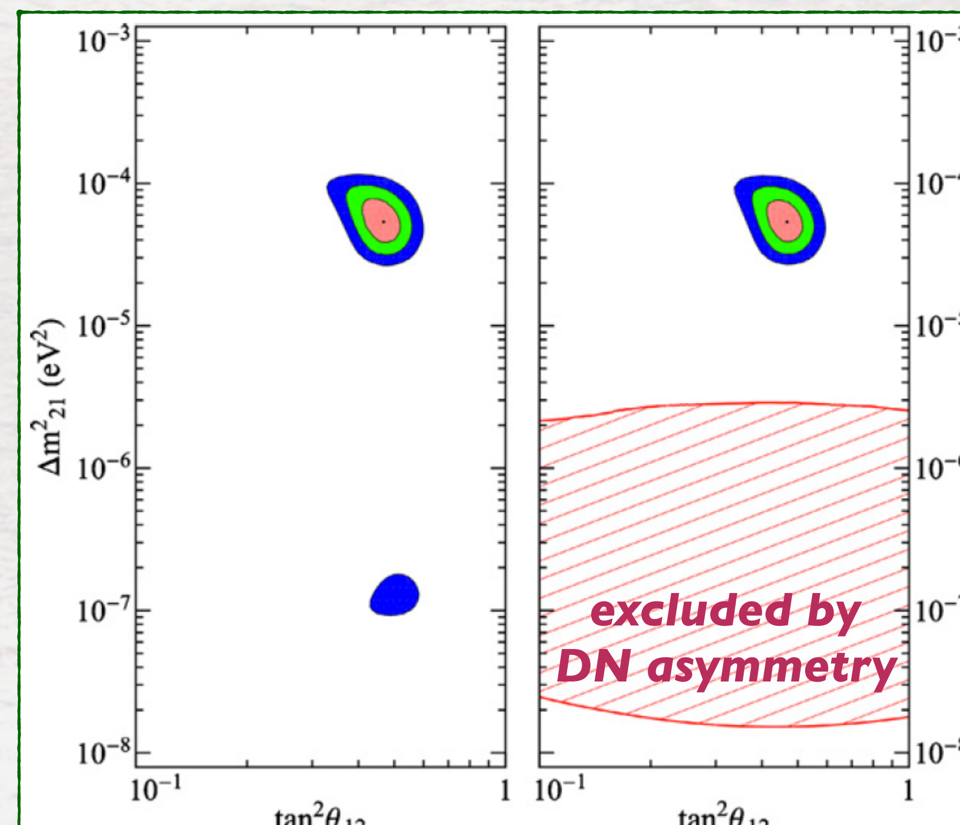
$$= 0.001 \pm 0.012 \pm 0.007$$

No asymmetry

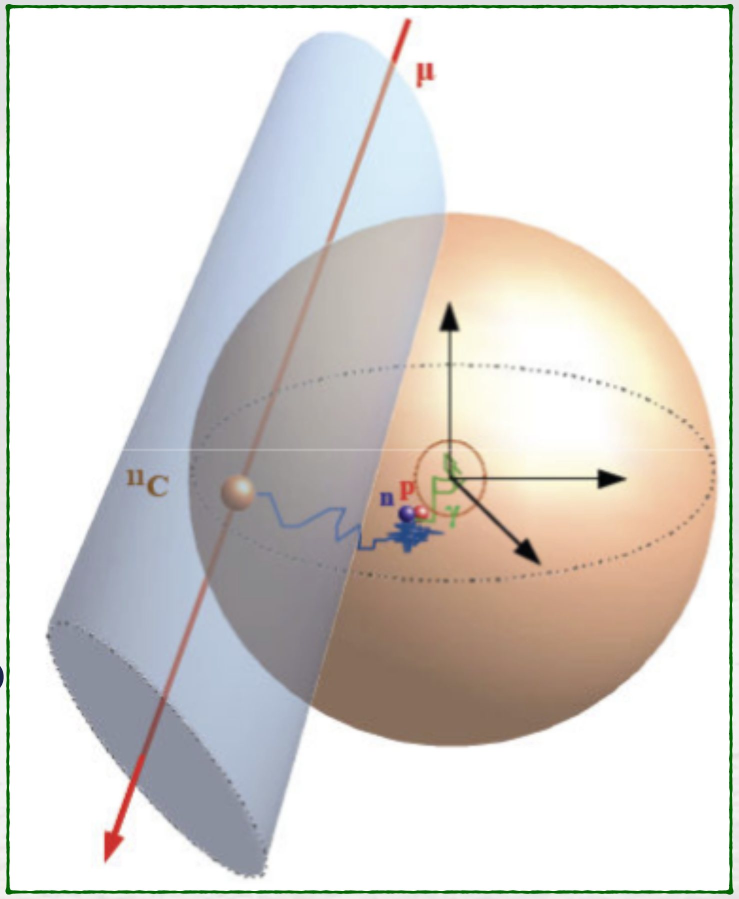
Day and Night spectra







- We obtained first evidence of **pep neutrinos**
  - Thanks to the very low background and analysis tools developed for **^{11}C rejection**
    - **Three fold coincidence** tagging of ^{11}C events
    - **β+ - β** separation exploiting **positronium** induced pulse shape distortion
    - Multivariate maximum likelihood test using all availab information



- **Three-fold coincidence**

$\mu + {}^{12}C \rightarrow n + {}^{11}C + \mu$

236 μs

No convection
¹¹C doesn't move

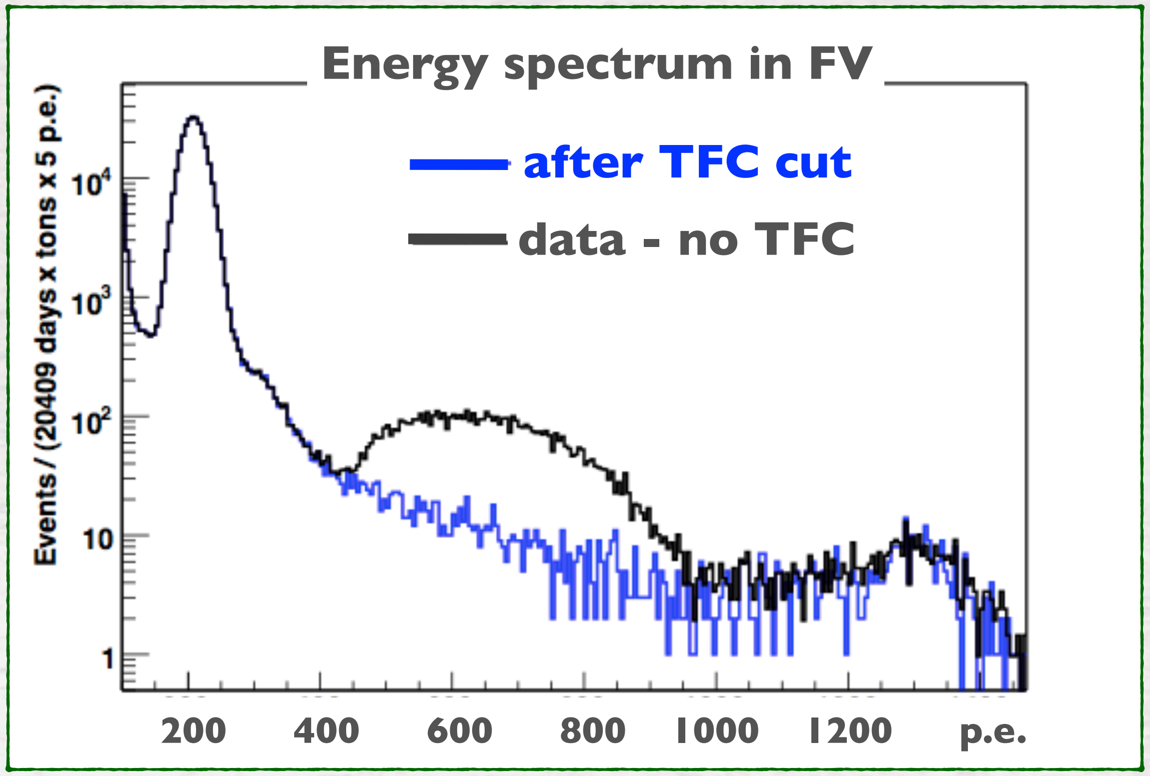
29.4 min

$^{11}C \rightarrow {}^{11}B + e^+ + \nu_e$

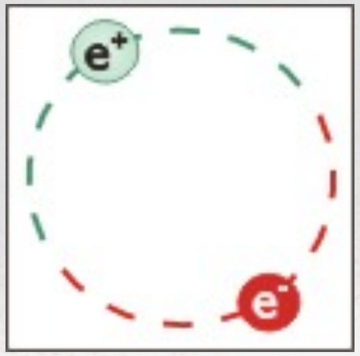
Quick neutron thermalisation and capture yields clear tag

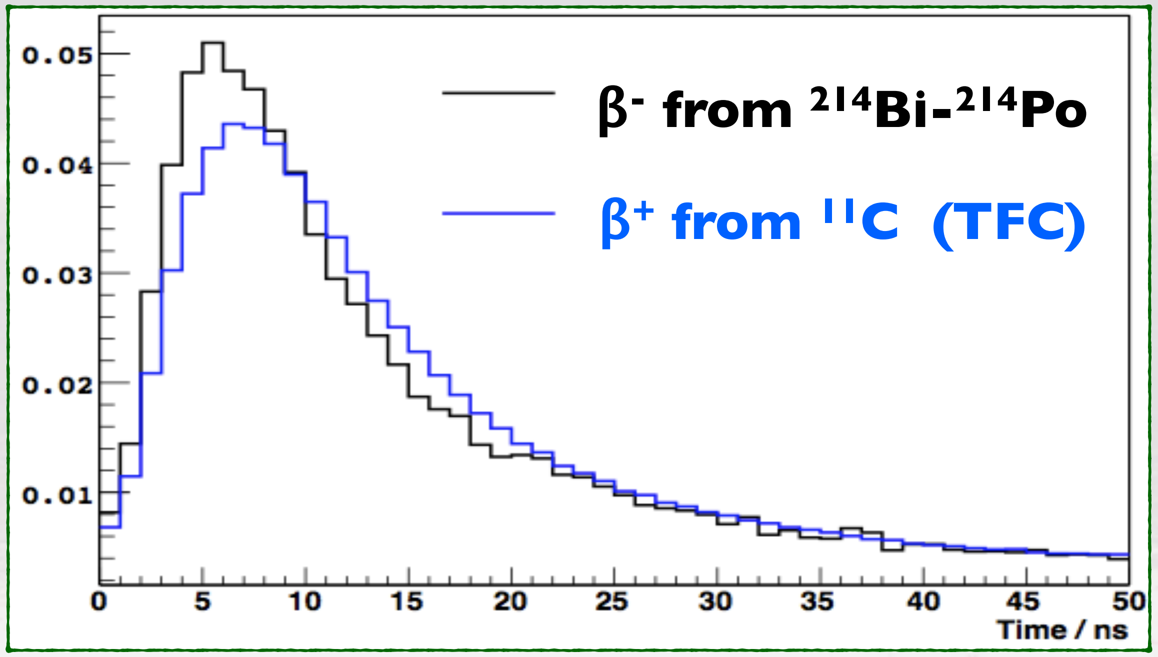
$n + p \rightarrow D + \gamma$ (2.2 MeV)

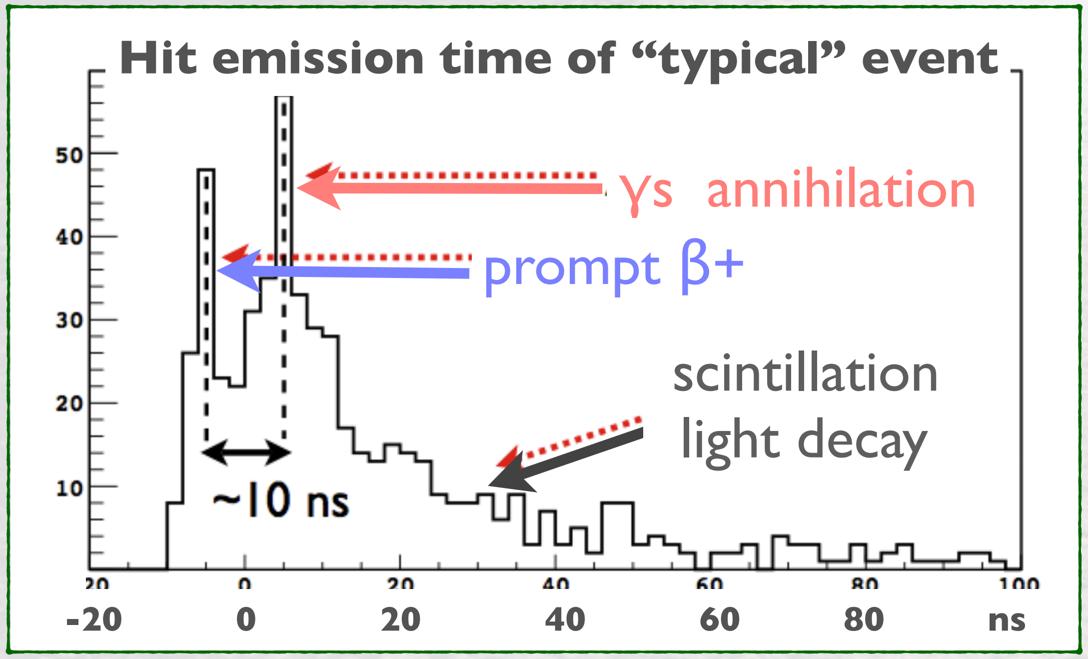
PHYSICAL REVIEW C 74, 045805 (2006)

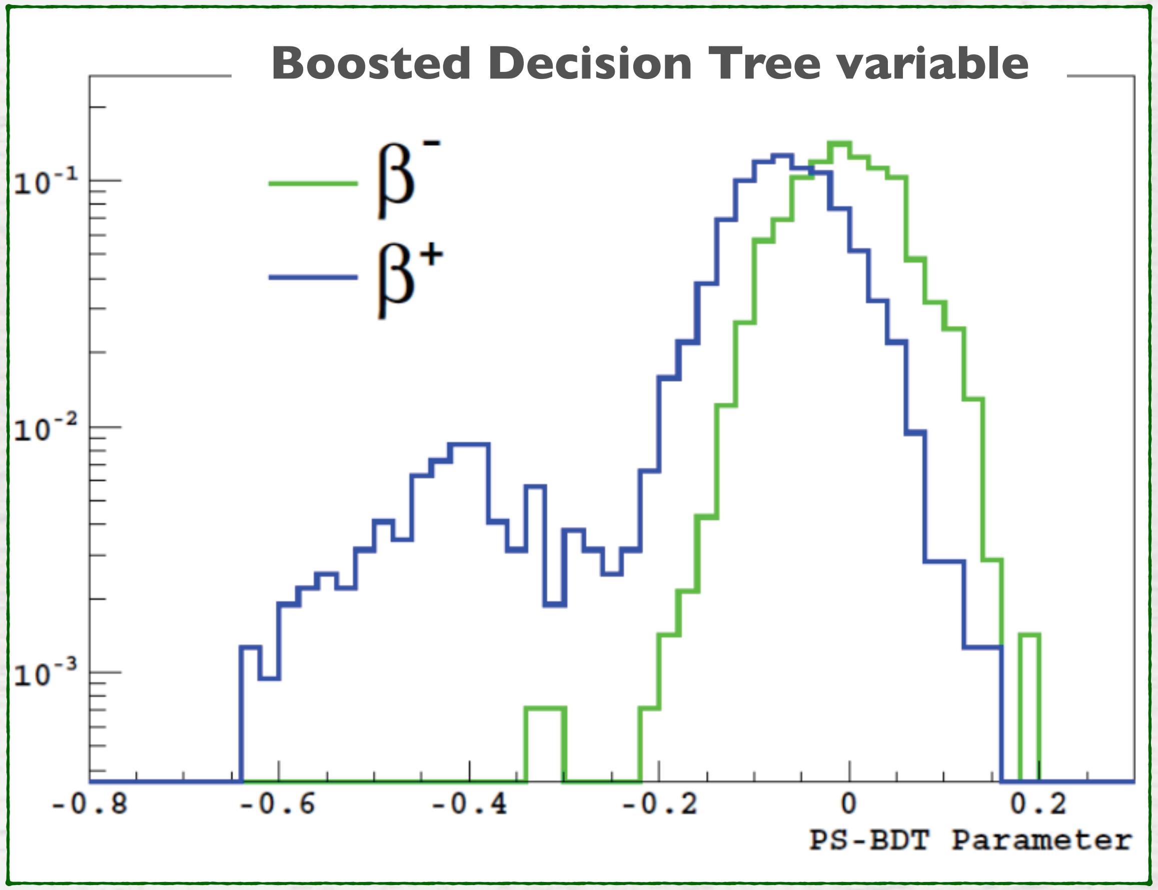


- Positrons form **ortho-positronium** in ~ 50% of cases (in PC)
  - Scintillation signal **delayed** by **~ 3 ns**
  - **Pulse shape is different**
  - Parameters measured in dedicated experiment







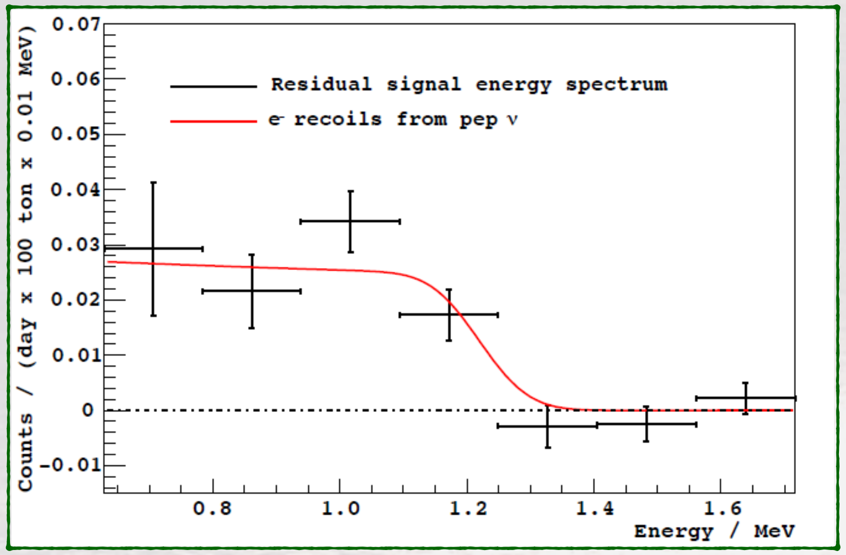


- A Pulse Shape discriminating variable was developed, based on a **Boosted Decision Tree (BDT)**

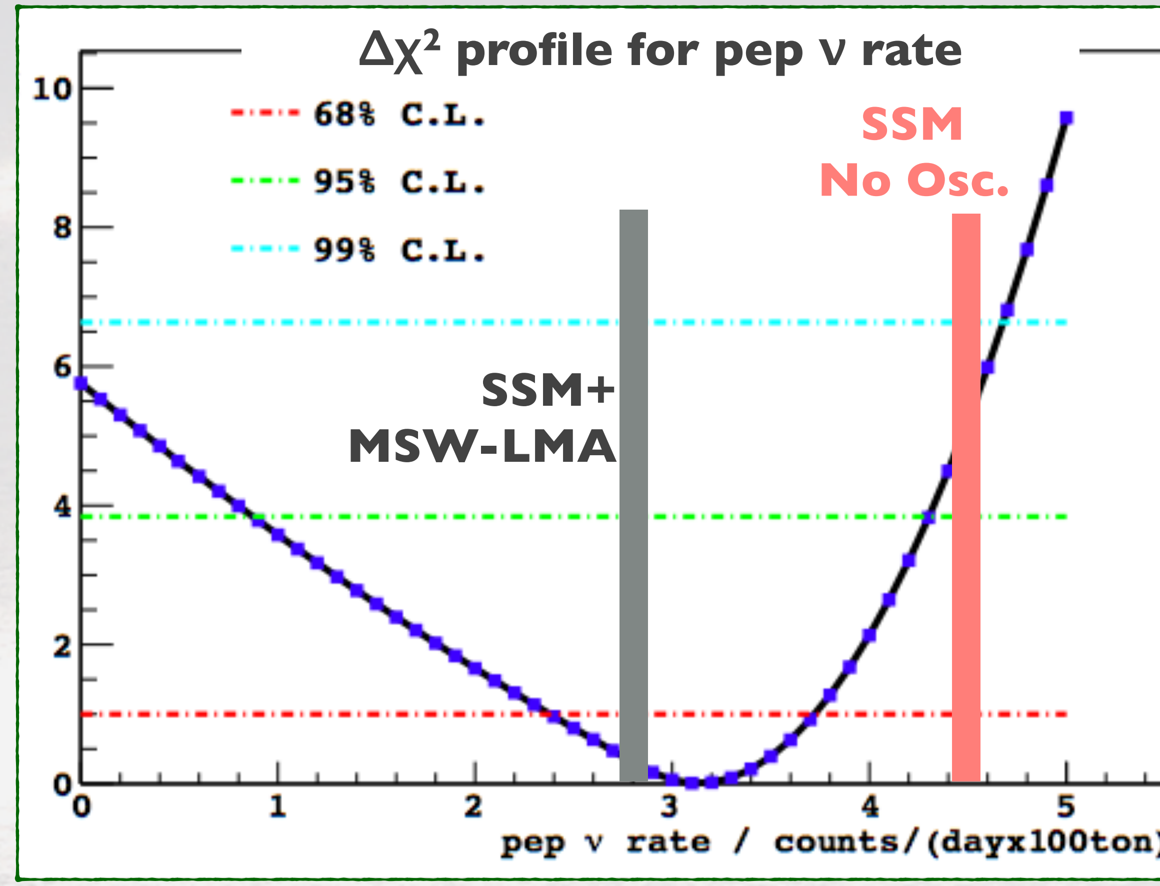
FIRST DETECTION OF PEP NEUTRINOS (II)

- Rate: **3.1 ± 0.6$_{(stat)}$ ± 0.3$_{(sys)}$ cpd/100 t**

PRL 108, 051302 (2012)



- No oscillations excluded at **97% c.l.**
- Absence of pep solar ν excluded at 98%

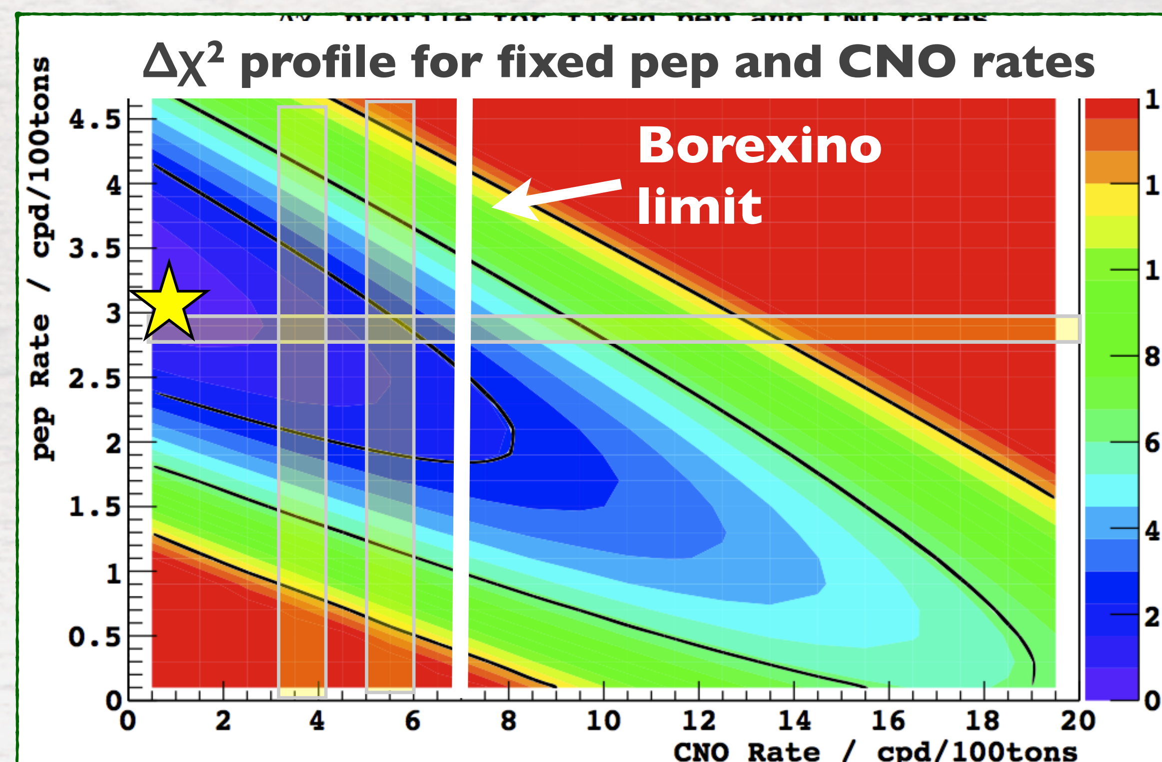


- Assuming MSW-LMA:
  - Φ_{pep} = **1.6 ± 0.3 10^8 cm^{-2} s^{-1}**

- CNO limit obtained assuming pep @ SSM

  - **CNO rate < 7.1 cpd/100 t (95% c.l.)**

2012



BACKGROUND IN PHASE 2 (2012-2014)

- Extensive **purification** by means of **water extraction** in loop in 2011

- **^{238}U**
  - Searching for ^{222}Rn events (^{214}Bi-^{214}Po), **^{238}U < 1.2 10^{-19} g/g**
  - At least a factor 20 better than in Phase 1

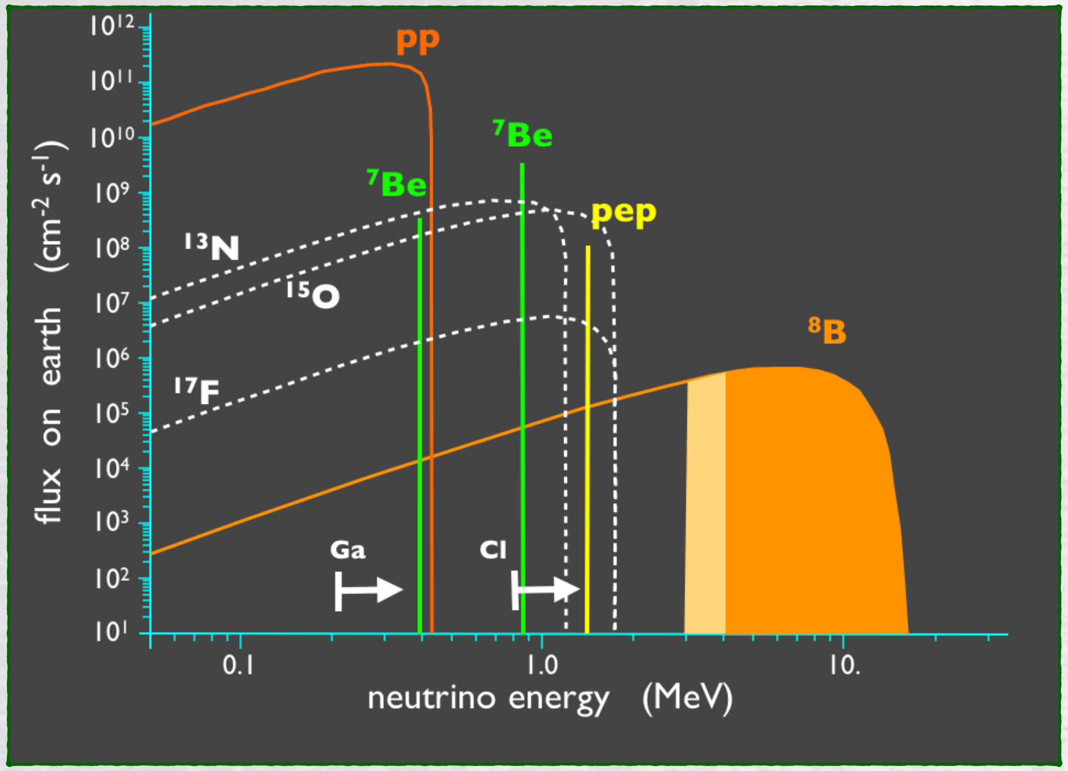
- **^{232}Th**
  - Searching for ^{220}Rn events (^{212}Bi-^{212}Po), **^{232}Th < 1.2 10^{-18} g/g**
  - At least a factor 10 better than in Phase 1

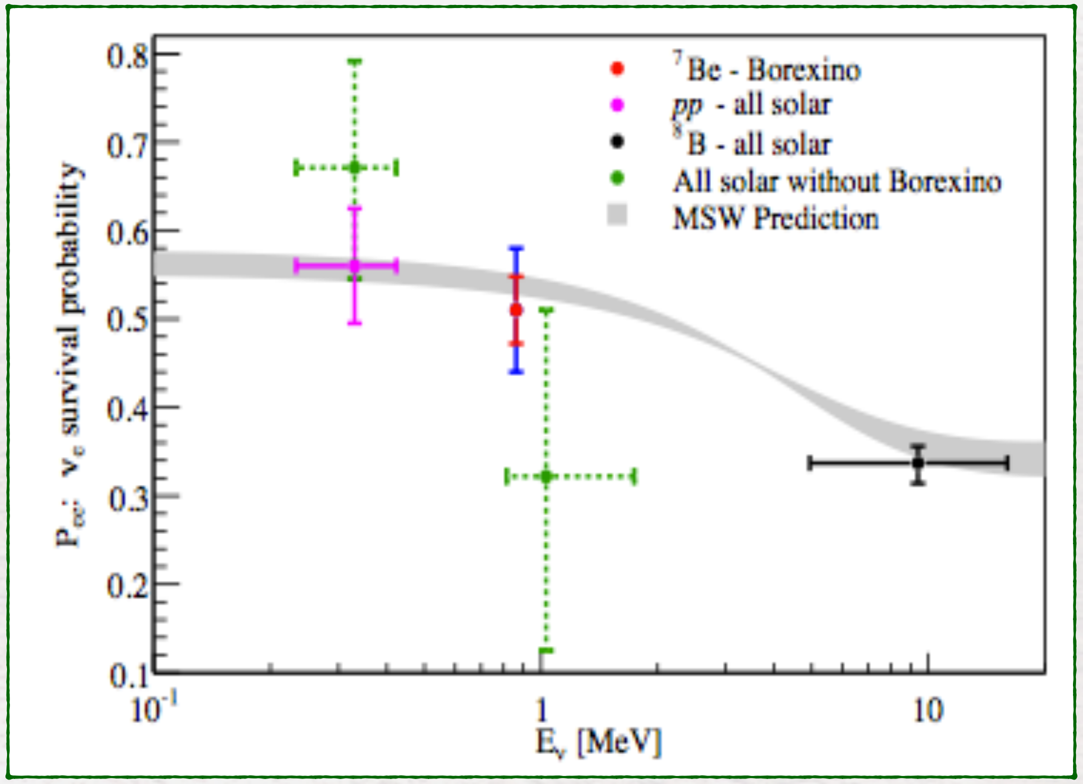
- **^{85}Kr**
  - Currently **compatible with zero.** It was 35 cpd/100 t

- **^{210}Bi**
  - Reduced down to ~ 25 cpd/100 t. It was ~ 60 cpd/100 t

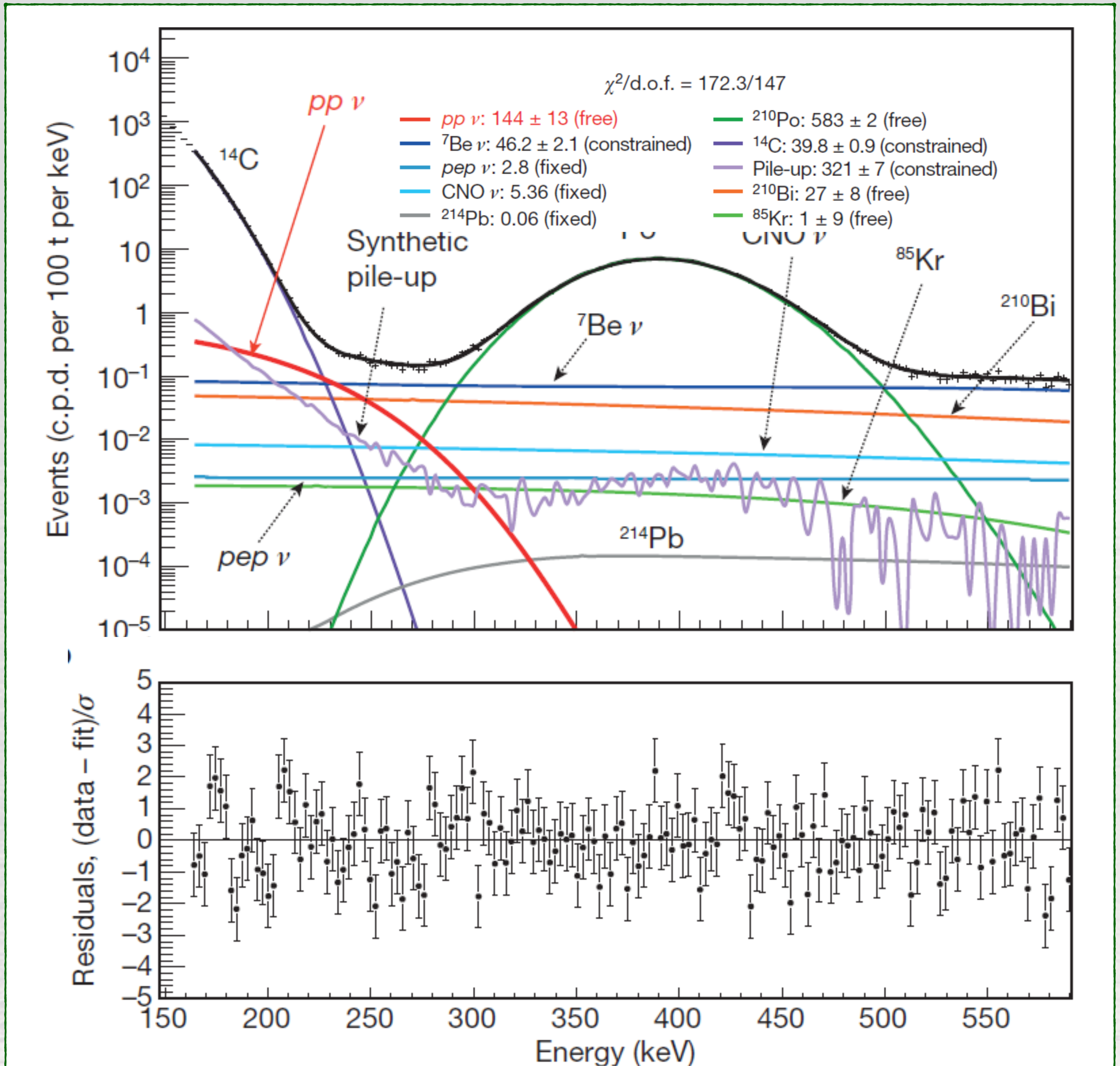
WHY SEARCH FOR PP NEUTRINOS ?

- They are the most important component, though lowest in energy
- They give directly the Sun's power in real time, allowing a comparison between neutrino luminosity and photon luminosity
  - Stability
  - Other particles i.e. axions or sterile
- They probe neutrino oscillations in vacuum (no MSW)





PP FIT RESULTS



FINAL RESULT : 2014

- **pp detection rate:**
  - **144 ± 13 (stat) ± 10 (syst) cpd/100 t**
- **expected: (HM-SSM+LMA-MSW):**
  - **131 ± 2 cpd/100 t**
- main consequence:
  - real time check of Sun's power
    - 8 min for neutrinos, 100-300 ky for photons
  - some interest related to long term climatology and archeo-climatology

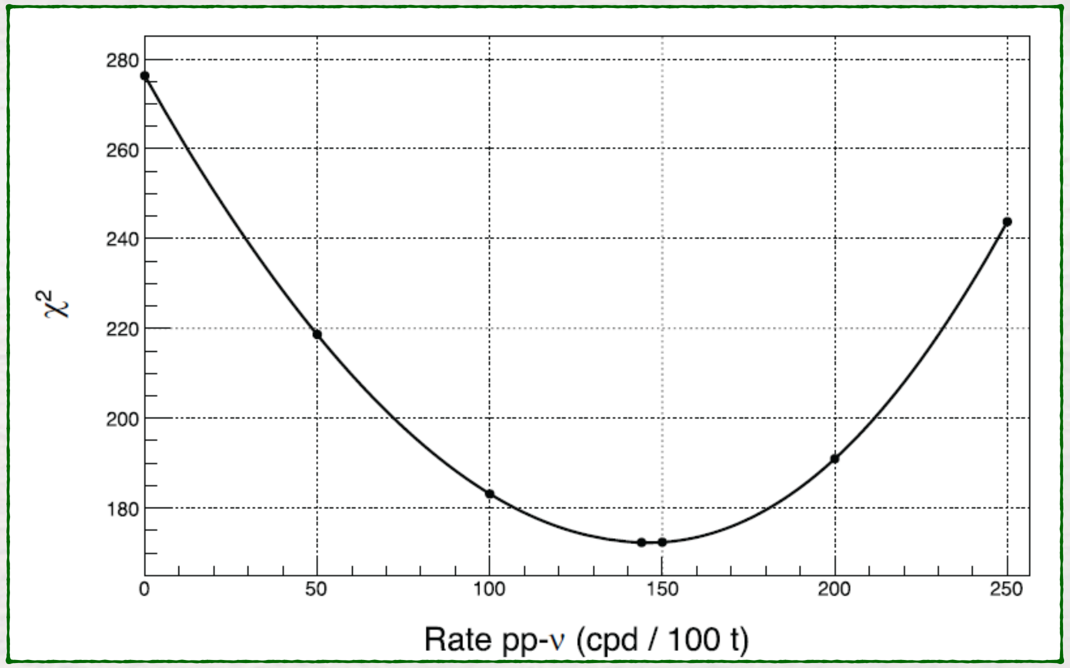
ARTICLE

doi:10.1038/nature13702

Neutrinos from the primary proton–proton fusion process in the Sun

Borexino Collaboration*

In the core of the Sun, energy is released through sequences of nuclear reactions that convert hydrogen into helium. The primary reaction is thought to be the fusion of two protons with the emission of a low-energy neutrino. These so-called *pp* neutrinos constitute nearly the entirety of the solar neutrino flux, vastly outnumbering those emitted in the reactions that follow. Although solar neutrinos from secondary processes have been observed, proving the nuclear origin of the Sun's energy and contributing to the discovery of neutrino oscillations, those from proton–proton fusion have hitherto eluded direct detection. Here we report spectral observations of *pp* neutrinos, demonstrating that about 99 per cent of the power of the Sun, 3.84×10^{33} ergs per second, is generated by the proton–proton fusion process.



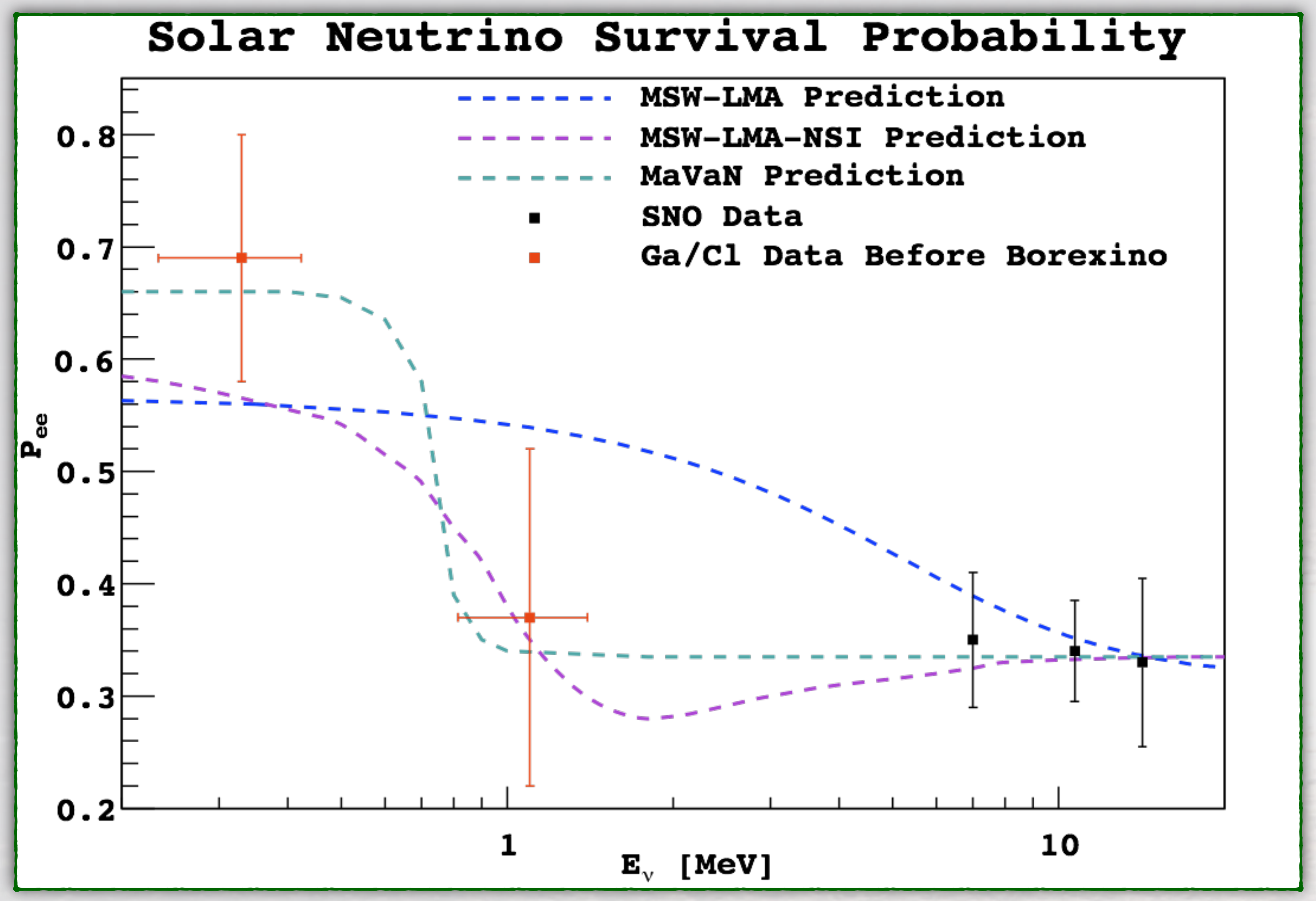
SCIENCE IDEAS

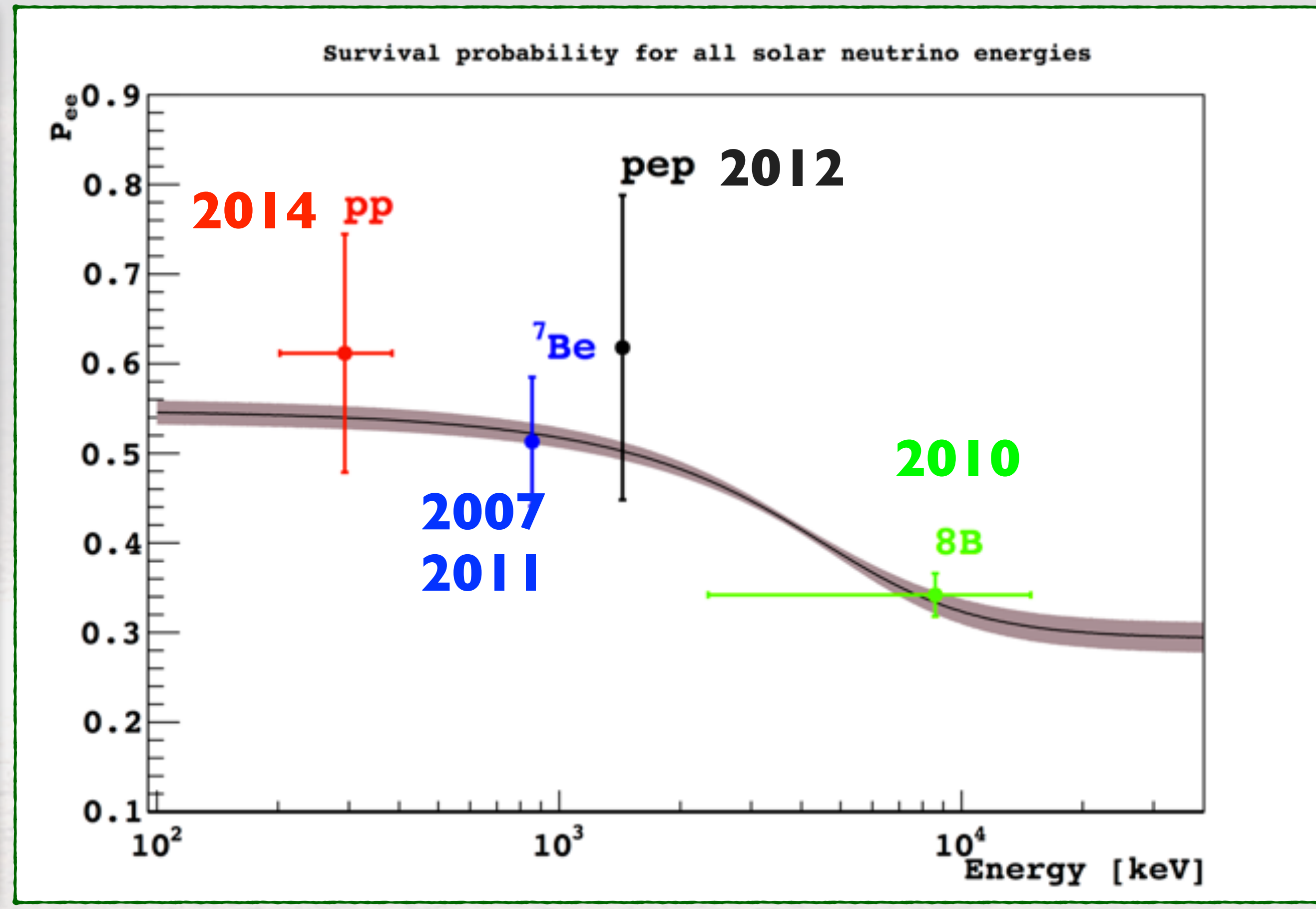
Solar Variability

Glacial Epochs, and Solar Neutrinos

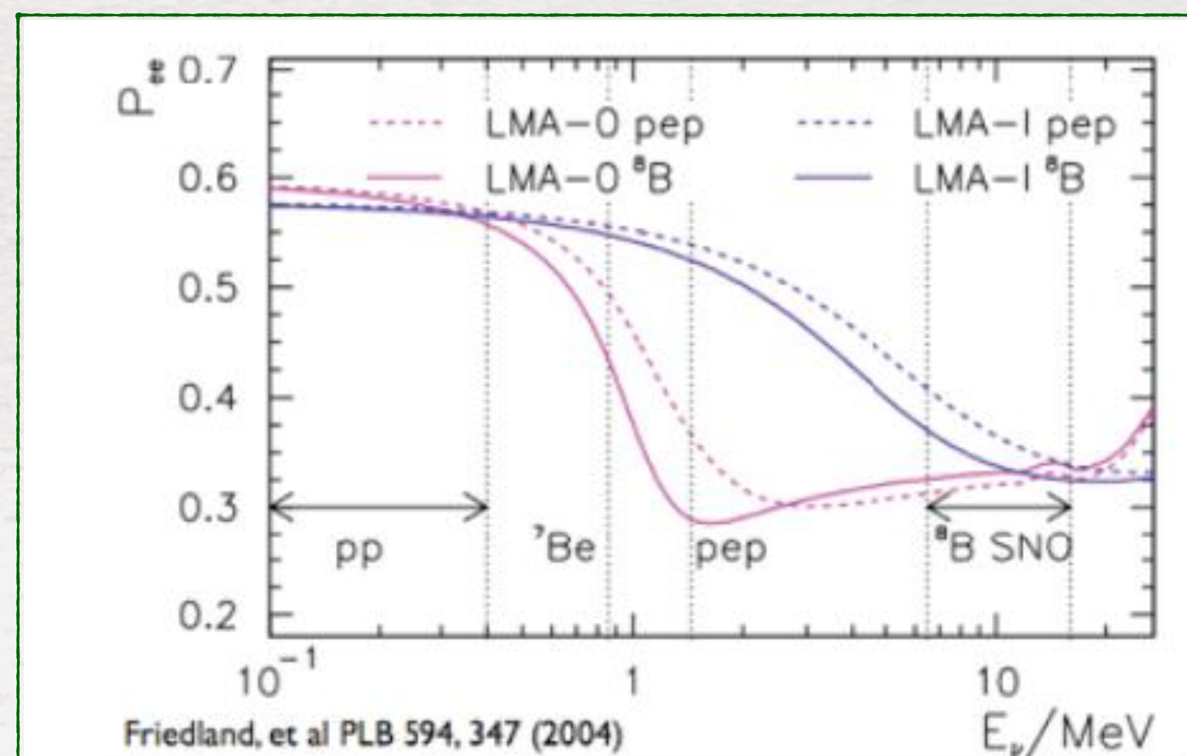
by George A. Cowan and Wick C. Haxton

9 YEARS OF BOREXINO





$$P_{ee}^{vac} = \begin{cases} 0.612 \pm 0.133 & \text{measured} \\ 0.543 \pm 0.013 & \text{expected} \end{cases}$$



Example of non-standard interactions [Friedland et al. PLB 594 (2004) 347]

FUTURE PROSPECTIVES FOR SOLAR ν

- What can we still learn from solar neutrinos ?
  - **CNO** depends on high-Z catalysers, directly linked to **metallicity**
    - The most direct way to solve the problem and measure core temperature
    - We try hard, but it is very difficult

- ^{7}Be, ^{8}B, pep, pp: high precision era ?
  - Precise ^{7}Be and ^{8}B fluxes may help solve metallicity problem
    - Unlikely for Borexino even with 2017 final release. Theoretical problems as well.
  - ^{7}Be shape puts constraints on new physics. We will see how far we can go.
  - Lack or deformation of ^{8}B upturn may bring new physics. Difficult for Borexino.
  - With higher precision, pp may check Sun's stability and probe the existence of new particles through luminosity constraints. Borexino will not reach this.

- Solar neutrino detectors are key tools for fundamental ν physics
  - **Sterile neutrinos search,** neutrino-less double beta decay

coming soon !

SOLAR FLUXES: METALLICITY

Source	High metallicity Flux [$cm^{-2}s^{-1}$] SSM-GS98	Low metallicity Flux [$cm^{-2}s^{-1}$] SSM-AGSS09	Old calculations Flux [$cm^{-2}s^{-1}$] SSM-GS98-2004
pp	$5.98(1\pm0.006)\times10^{10}$	$6.03(1\pm0.006)\times10^{10}$	$5.94(1\pm0.01)\times10^{10}$
pep	$1.44(1\pm0.012)\times10^{8}$	$1.47(1\pm0.012)\times10^{8}$	$1.40(1\pm0.02)\times10^{8}$
^{7}Be	$5.00(1\pm0.07)\times10^{9}$	$4.56(1\pm0.07)\times10^{9}$	$4.86(1\pm0.12)\times10^{9}$
^{8}B	$5.58(1\pm0.13)\times10^{6}$	$4.59(1\pm0.13)\times10^{6}$	$5.79(1\pm0.23)\times10^{6}$
^{13}N	$2.96(1\pm0.15)\times10^{8}$	$2.17(1\pm0.15)\times10^{8}$	$5.71(1\pm0.36)\times10^{8}$
^{15}O	$2.23(1\pm0.16)\times10^{8}$	$1.56(1\pm0.16)\times10^{8}$	$5.03(1\pm0.41)\times10^{8}$
^{17}F	$5.52(1\pm0.18)\times10^{6}$	$3.40(1\pm0.16)\times10^{6}$	$5.91(1\pm0.44)\times10^{6}$
Total CNO:	5.24×10^{8}	3.76×10^{8}	10.8×10^{8}

Aldo M. Serenelli et al. 2011 ApJ 743 24

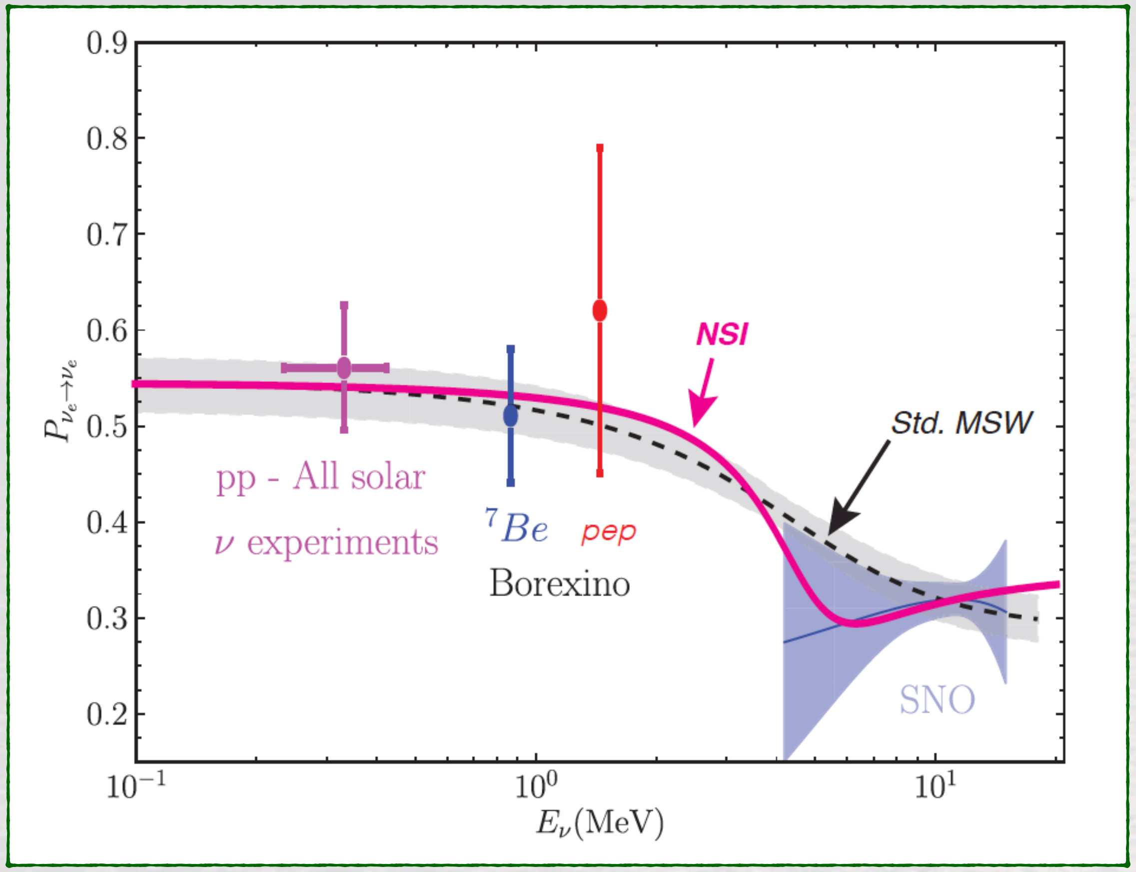
Relative difference due to metallicity

ν	% diff
pp	0,8
pep	2,1
^{7}Be	8,8
^{8}B	17,7
^{13}N	26,7
^{15}O	30
^{17}F	38,4

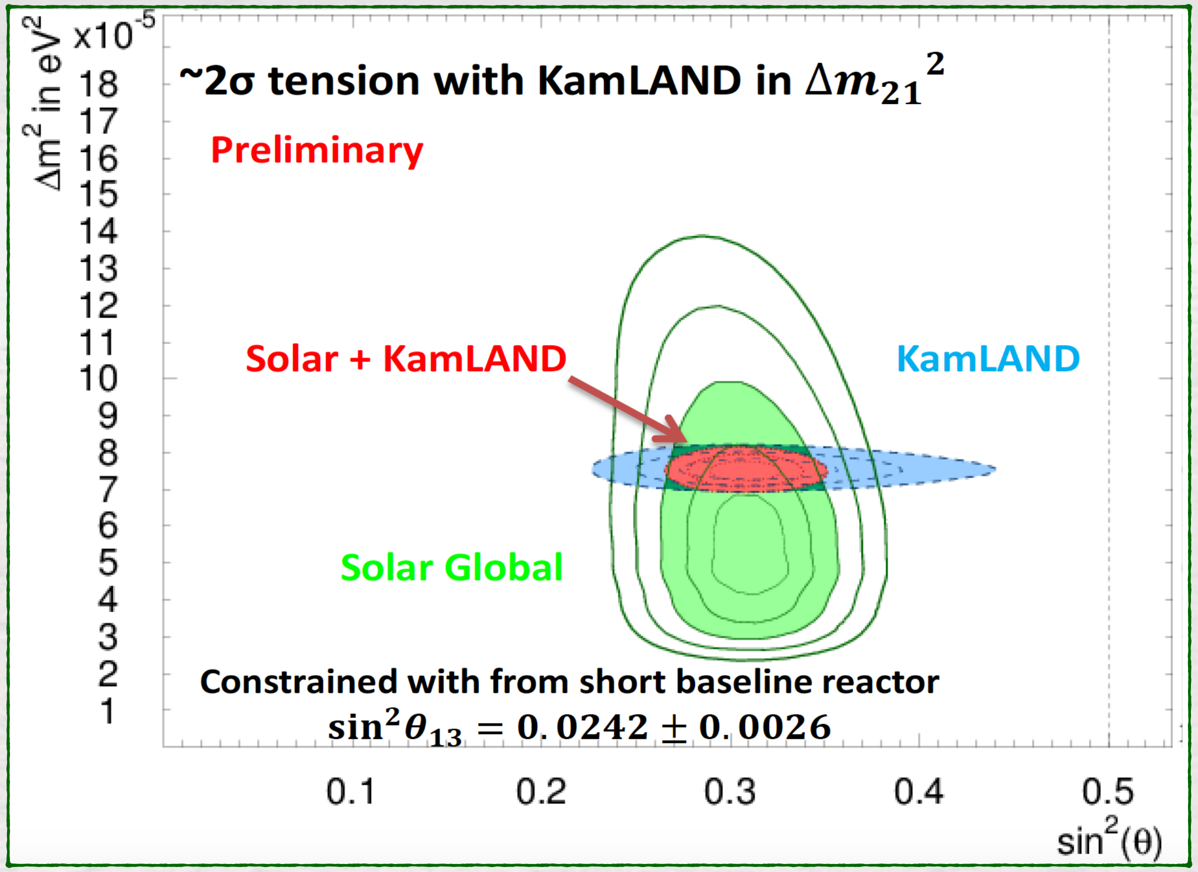
- Significant progress in last 10 years:
  - CNO flux reduced by new cross section measurement of 14N(p,γ)15O
  - Better accuracy for the 3He(4He,γ)7Be cross section
  - New opacity calculations
  - New abundance based on 3D models

- **MSW-LMA** effect is observed, still with relatively large errors
  - **Probe of P_{ee} requires higher precision**
  - No evidence yet of upturn in ^{8}B neutrinos

Precision probe of P_{ee}

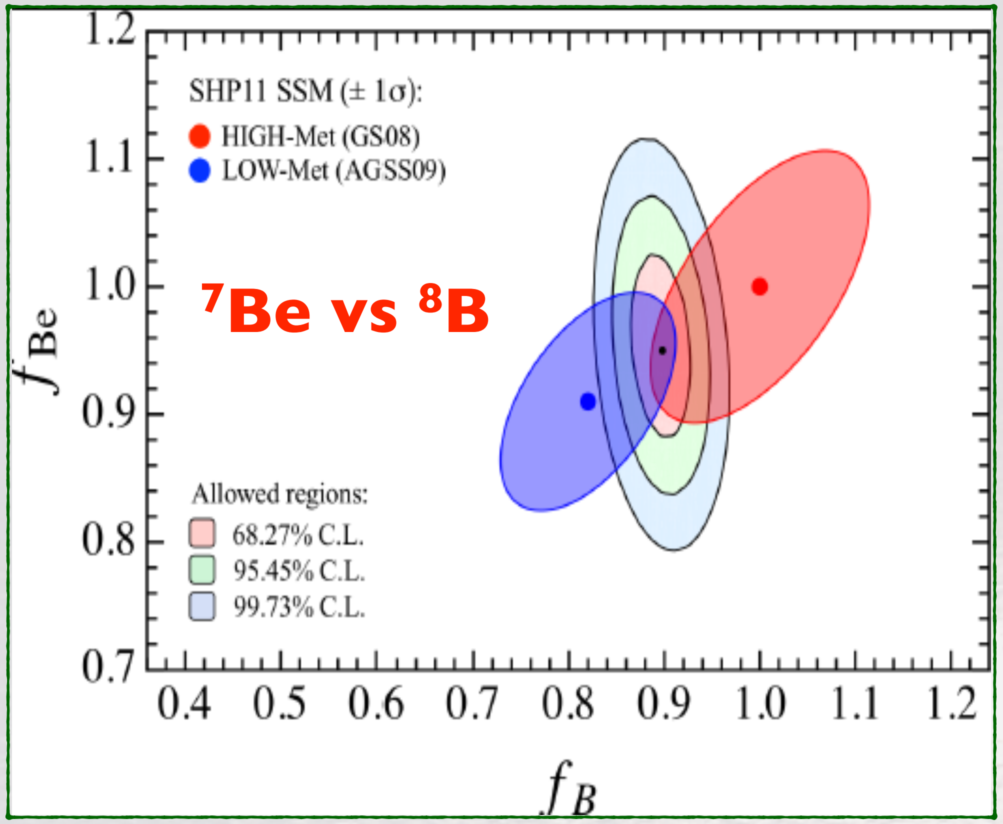


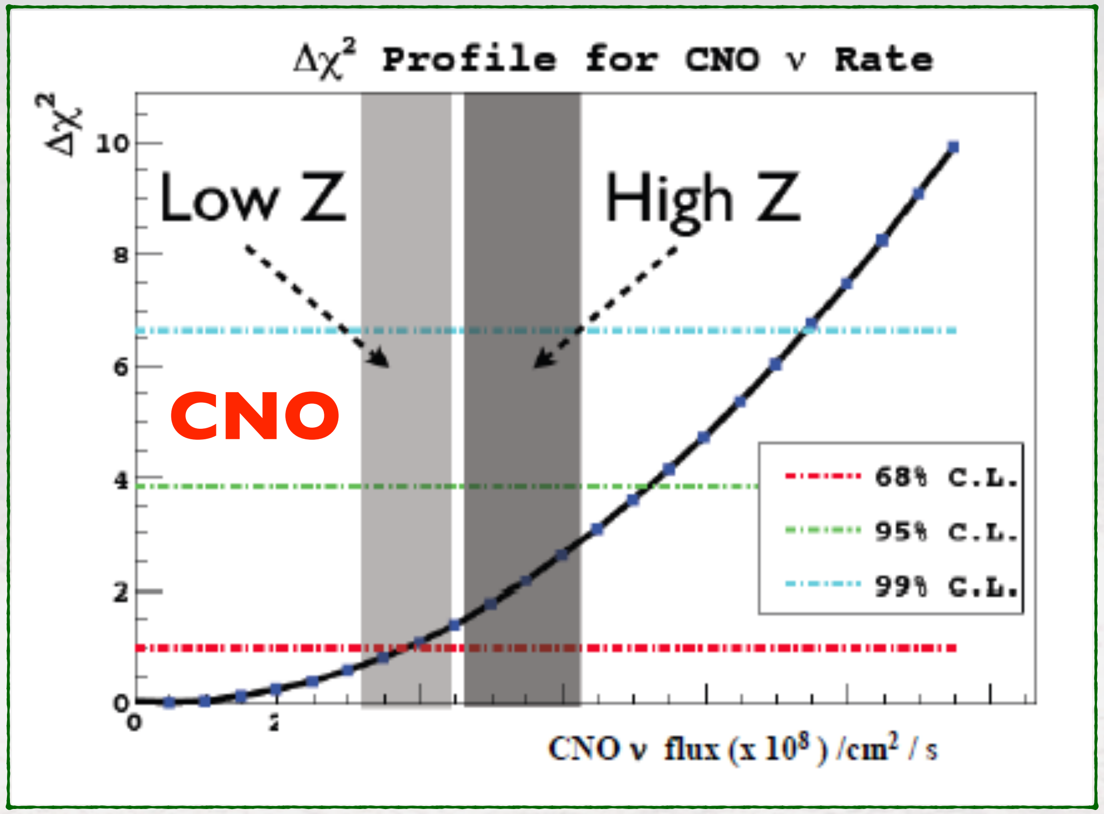
Tension between solar and reactor ?



ϑ_{12} dominated by solar data
Δm_{12} dominated by KamLAND

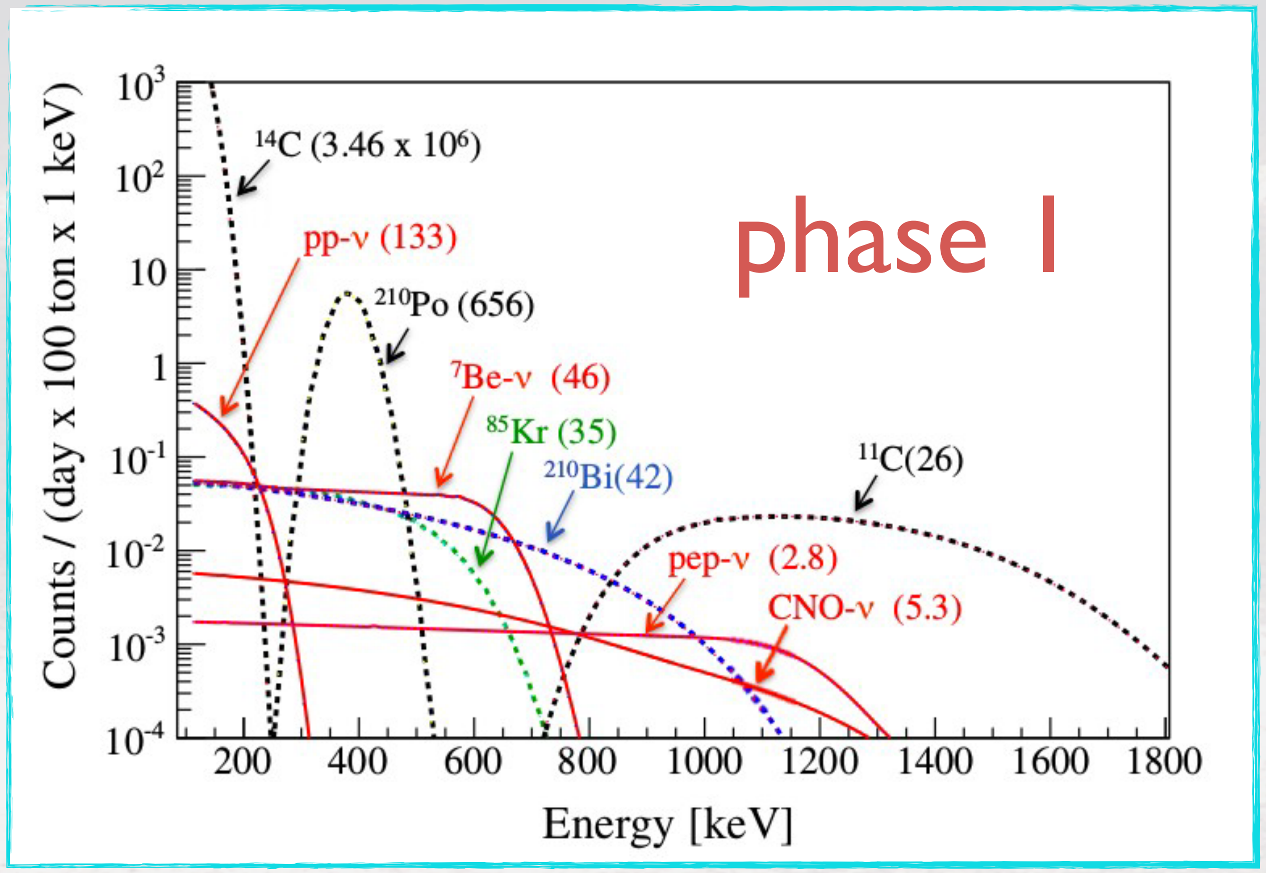
CAN WE ESTABLISH METALLICITY ?





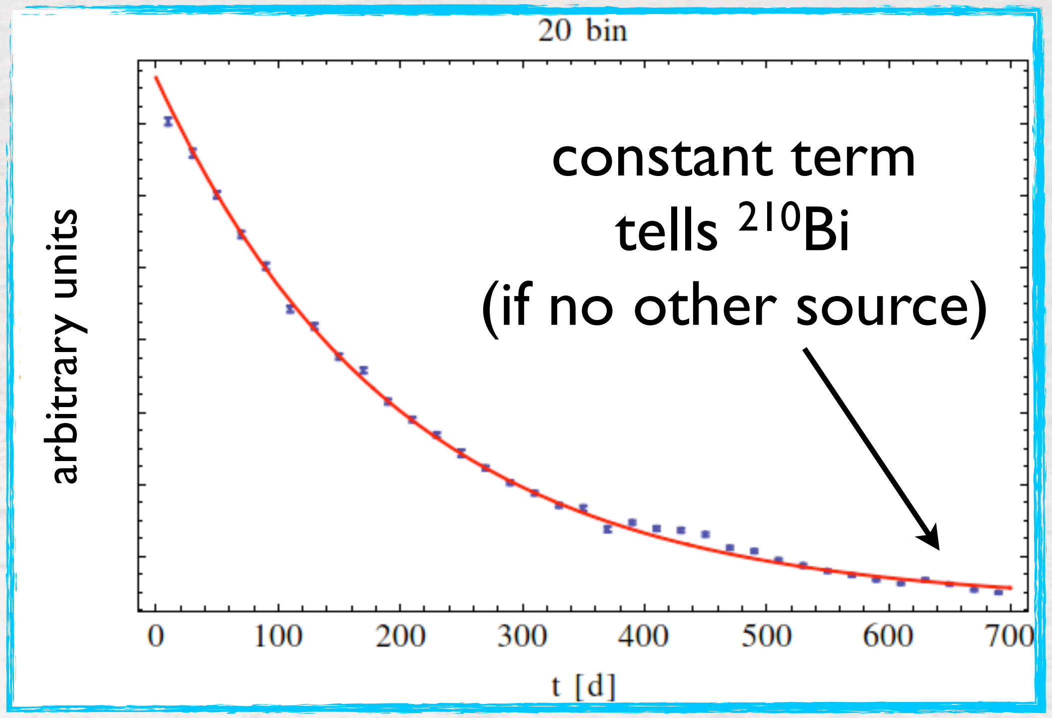
- **Not yet**
  - ^{7}Be and ^{8}B central values is right in the middle.....
    - Smaller error is possible in Phase 2 (maybe, 3%) but this is not enough to give more than a hint unless the central value moves a lot
  - CNO measurement would work, but it is difficult
    - Disfavouring High Metallicity is possible in Phase 2, if Nature chose Low..
    - For a measurement, see next slides

- **What are the problems ?**
  - ^{11}C: only partially solved
    - SNO+ can do better
  - **^{210}Bi: the worst background**
    - Spectrally very similar. Regardless of its value you must know it by other means to extract CNO
    - An idea: use ^{210}Pb decay chain
    - You ***must*** have a **very stable detector**



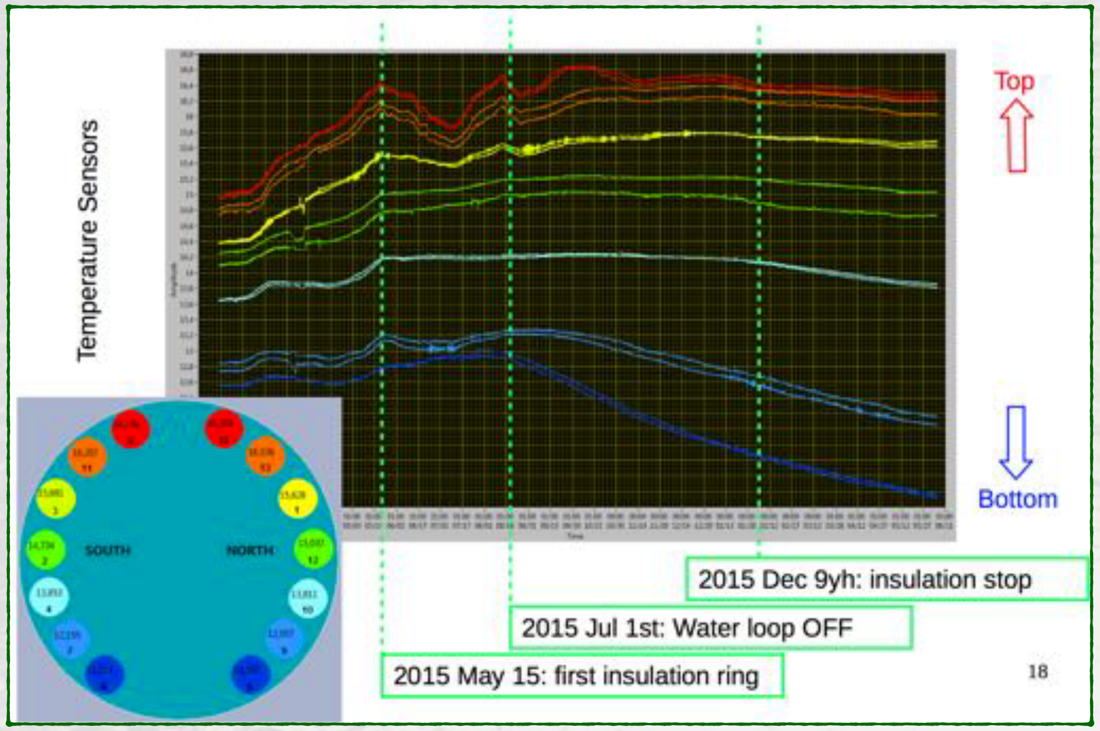
^{210}Pb 21.4 y
↓ β
^{210}Bi 5 d
↓ β
^{210}Po 138 d

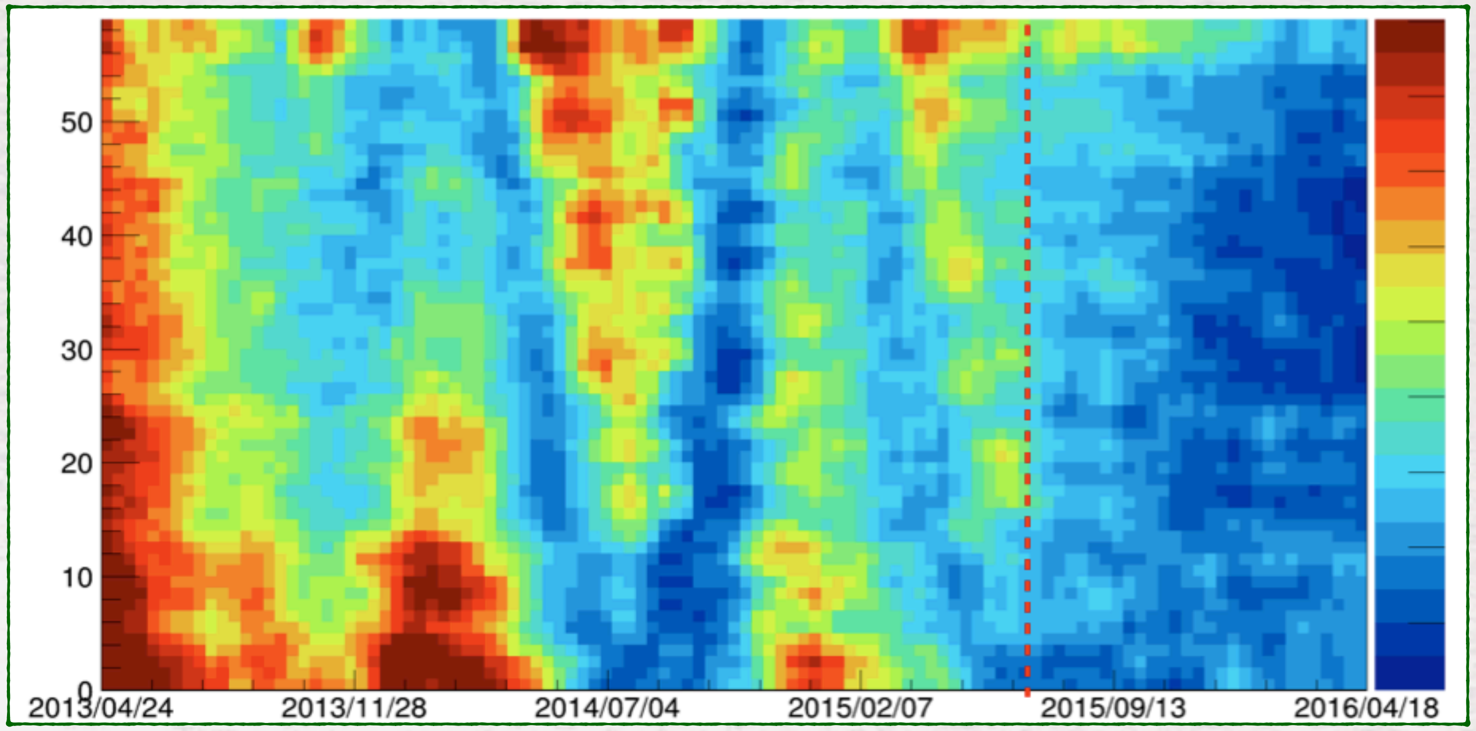
$$\frac{dN_{Po}}{dt} = -\frac{N_{Po}}{\tau_{Po}} + \frac{N_{Bi}}{\tau_{Bi}} + S_{Po}(t)$$



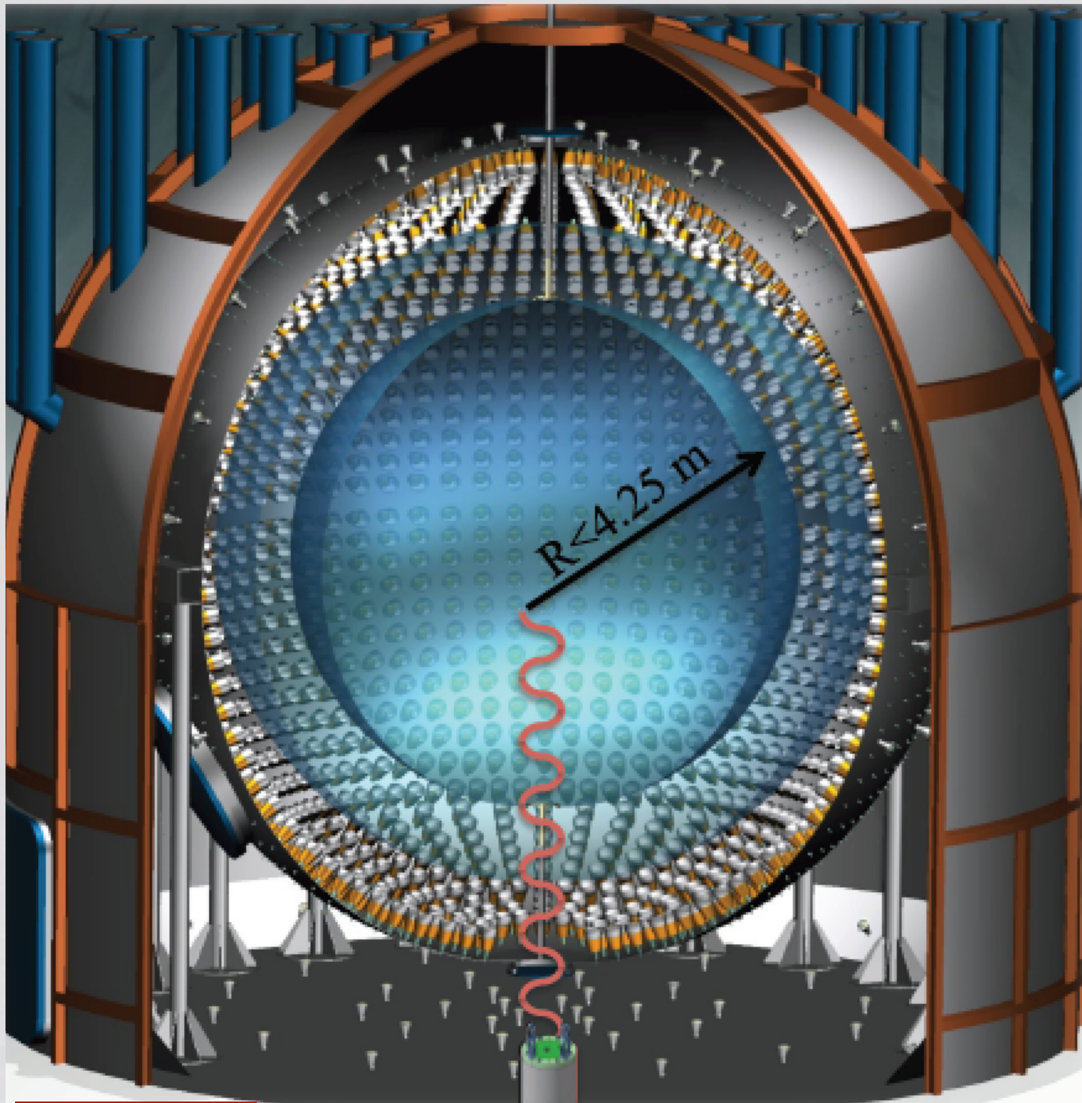
CAN BOREXINO MEASURE CNO ?

- To achieve **temperature stability** we have covered the tank with heat insulating material and with T sensors
  - Temperature are more stable
  - ^{210}**Po** is moving less
  - It is not clear whether we will achieve sufficient stability

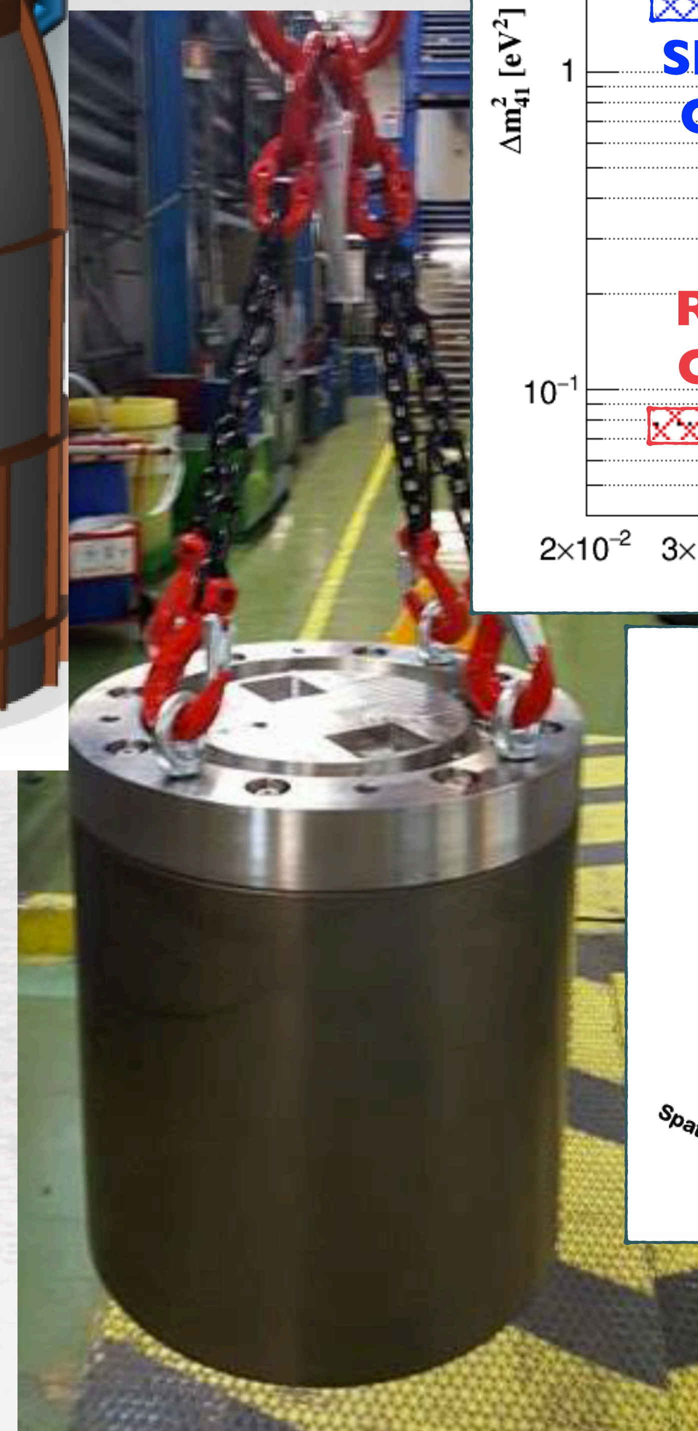


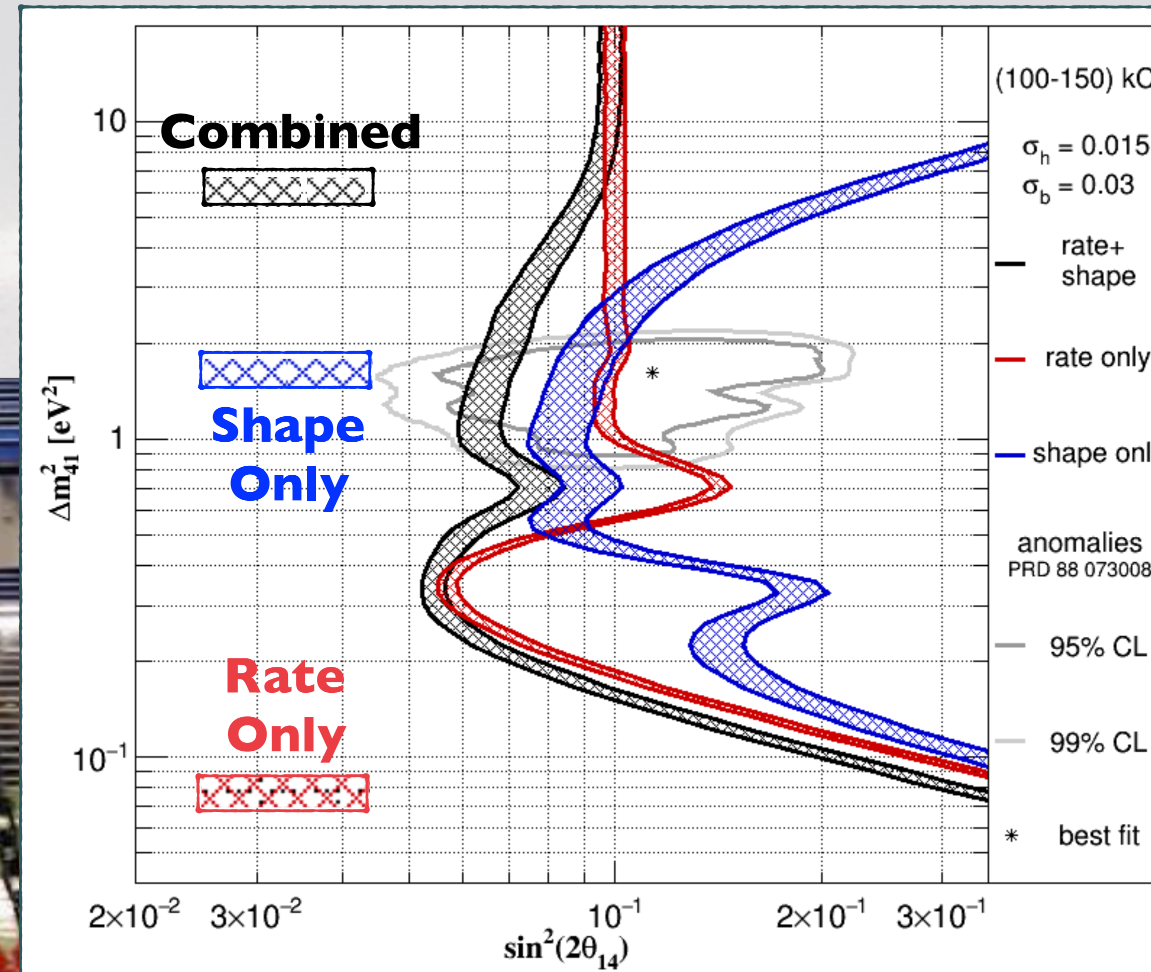


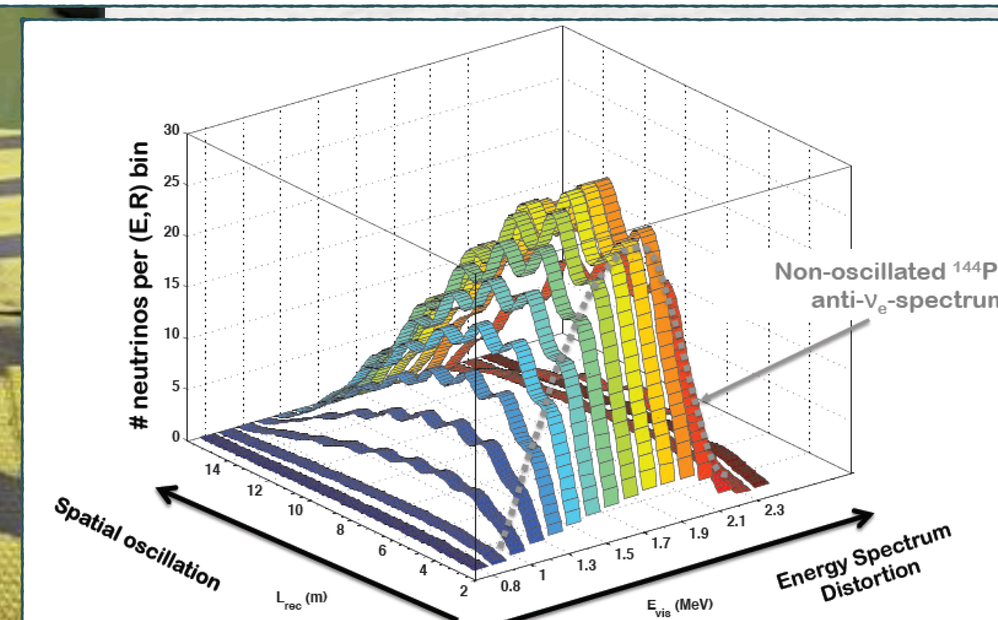
THE NEAR FUTURE: SOX



Tunnel







CONCLUSIONS

- Solar neutrinos have been pivotal to the discovery of ν oscillations
  - Still, a very active field of research

  - Next goals: **precision** low energy neutrino physics and stellar physics
    - Search for **new physics** in solar neutrino interactions by means of **high precision measurements**
    - Detection of **CNO neutrinos**
  - Solar ν detectors are ideal sterile ν hunters

- Solar neutrino detectors important for other science as well
  - **Geo-neutrinos**, **Dark matter search**, **0νββ**

- For CNO neutrinos, future very large mass noble liquid detectors might be interesting

Gracias