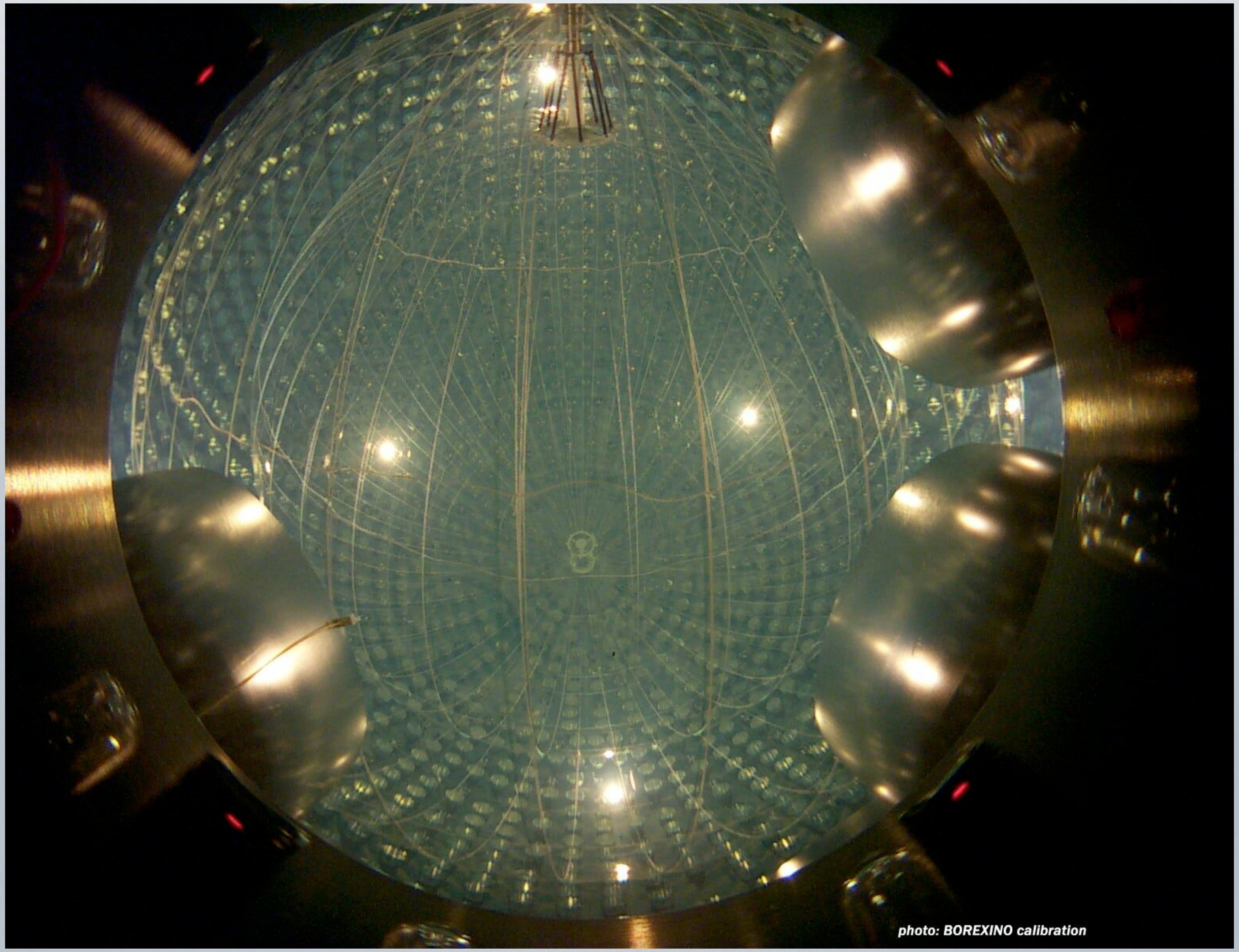


photo: BOREXINO calibration

SHORT AND MEDIUM TERM PROGRAM FOR BOREXINO

What Next Workshop
Dec. 2, 2014 - Padova

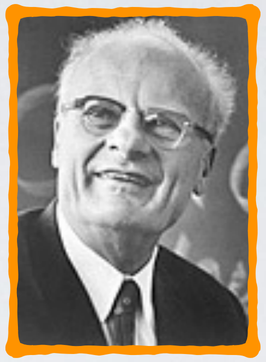
Marco Pallavicini
Università di Genova and INFN

TALK OUTLINE

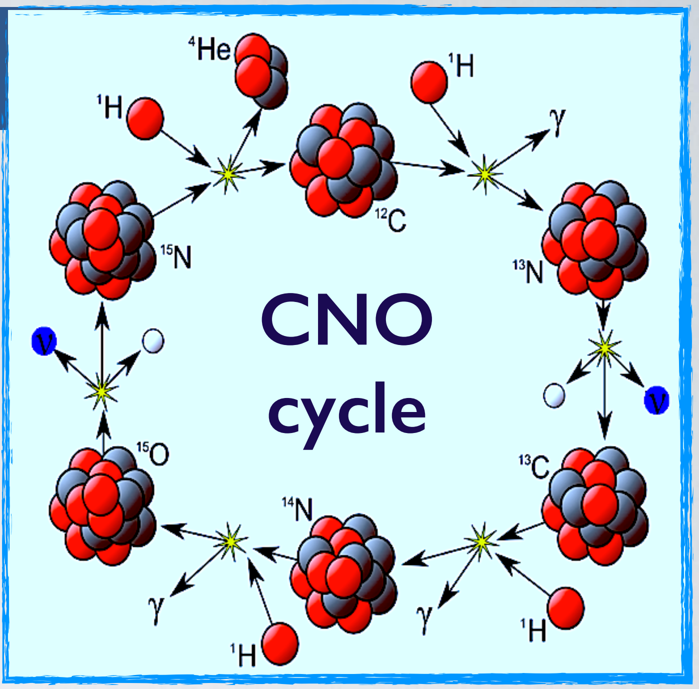
- Status of solar physics AD 2014
- Results achieved so far by Borexino
- **What Next**
  - Search for CNO neutrinos
  - Search for sterile neutrinos

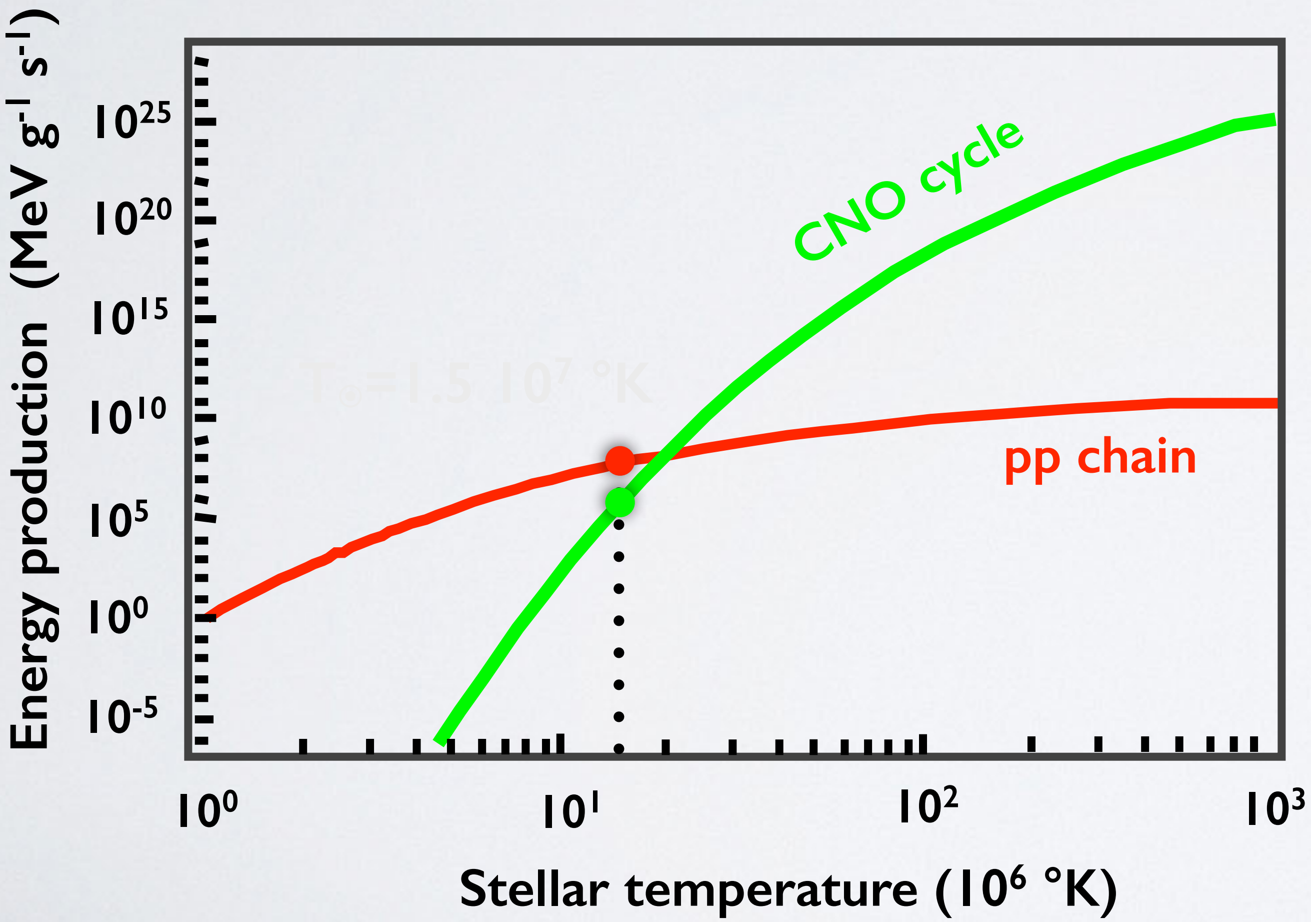
SOLAR NEUTRINOS

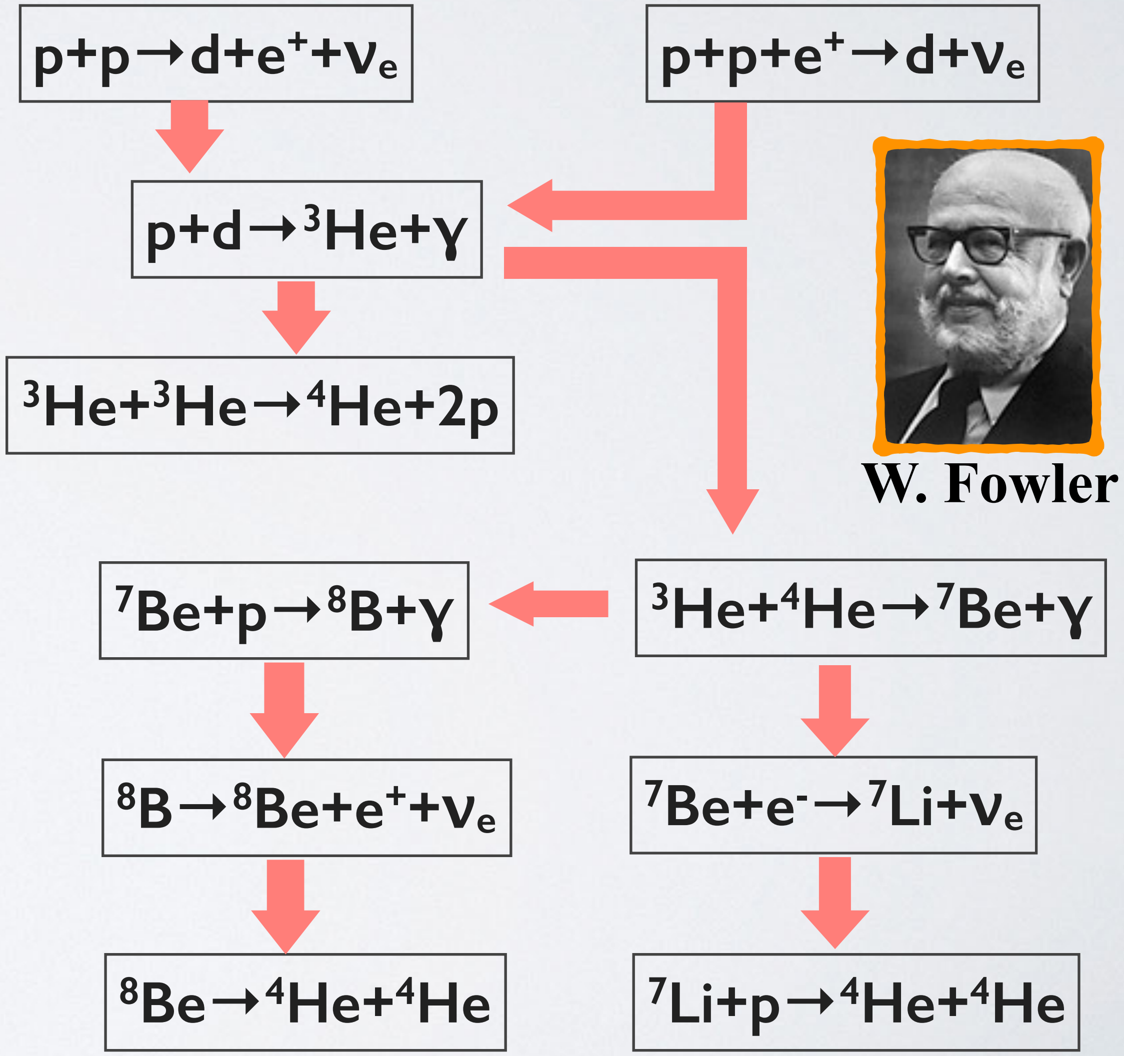
- Nuclear fusion feeds stars
  - pp chain: dominant in Sun-like MS stars
  - CNO cycle: dominant in massive stars
    - The role of CNO in the Sun is still uncertain **(metallicity problem)**



H. Bethe







$p+p \rightarrow d+e^{+}+\nu_e$

$p+p+e^{+} \rightarrow d+\nu_e$

$p+d \rightarrow {}^{3}He+\gamma$

${}^{3}He+{}^{3}He \rightarrow {}^{4}He+2p$

${}^{3}He+{}^{4}He \rightarrow {}^{7}Be+\gamma$

${}^{7}Be+p \rightarrow {}^{8}B+\gamma$

${}^{8}B \rightarrow {}^{8}Be+e^{+}+\nu_e$

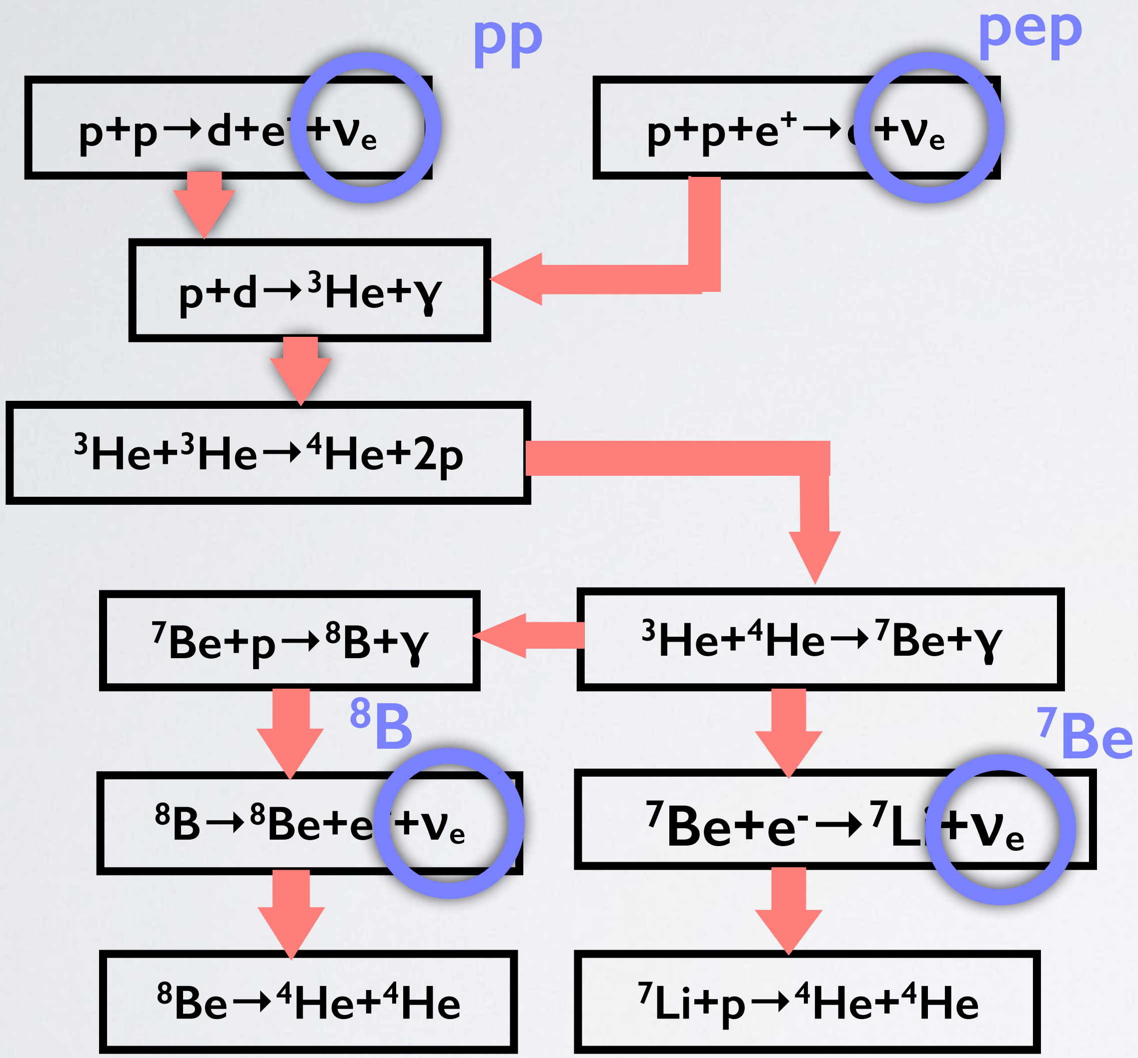
${}^{8}Be \rightarrow {}^{4}He+{}^{4}He$

${}^{7}Be+e^{-} \rightarrow {}^{7}Li+\nu_e$

${}^{7}Li+p \rightarrow {}^{4}He+{}^{4}He$

W. Fowler

SOLAR NEUTRINOS (2)



pp

pep

$p+p\to d+e\ +\nu_e$

$p+p+e^+\to\ +\nu_e$

$p+d\to {}^3He+\gamma$

${}^3He+{}^3He\to {}^4He+2p$

${}^7Be+p\to {}^8B+\gamma$

${}^3He+{}^4He\to {}^7Be+\gamma$

${}^8B$

${}^7Be$

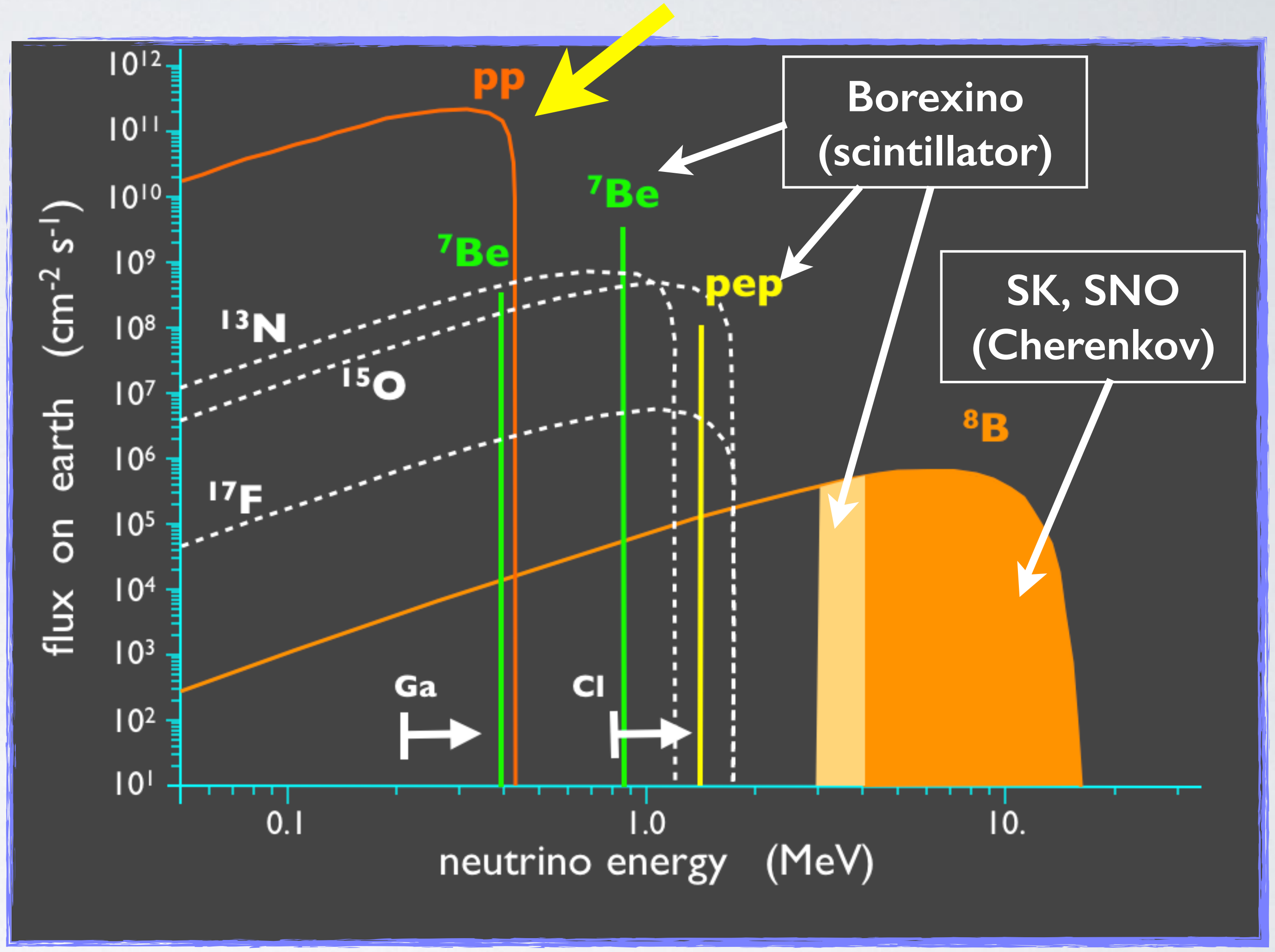
${}^8B\to {}^8Be+e\ +\nu_e$

${}^7Be+e^-\to {}^7L\ +\nu_e$

${}^8Be\to {}^4He+{}^4He$

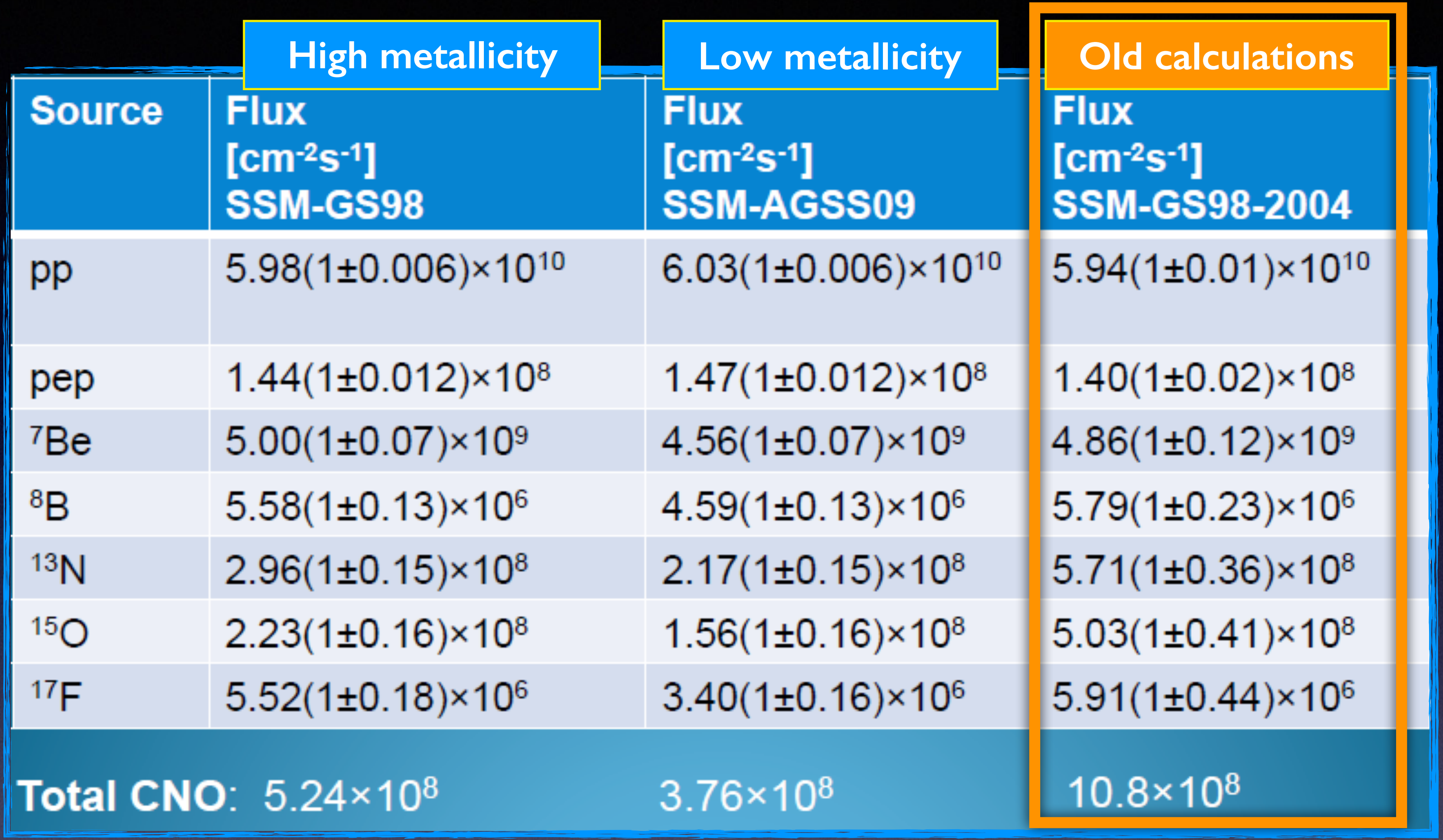
${}^7Li+p\to {}^4He+{}^4He$

new



PRL 94 081801 (2005)

Solar ν 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}	8,8
^{8}	17,7
^{13}	26,7
^{15}	30
^{17}	38,4

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

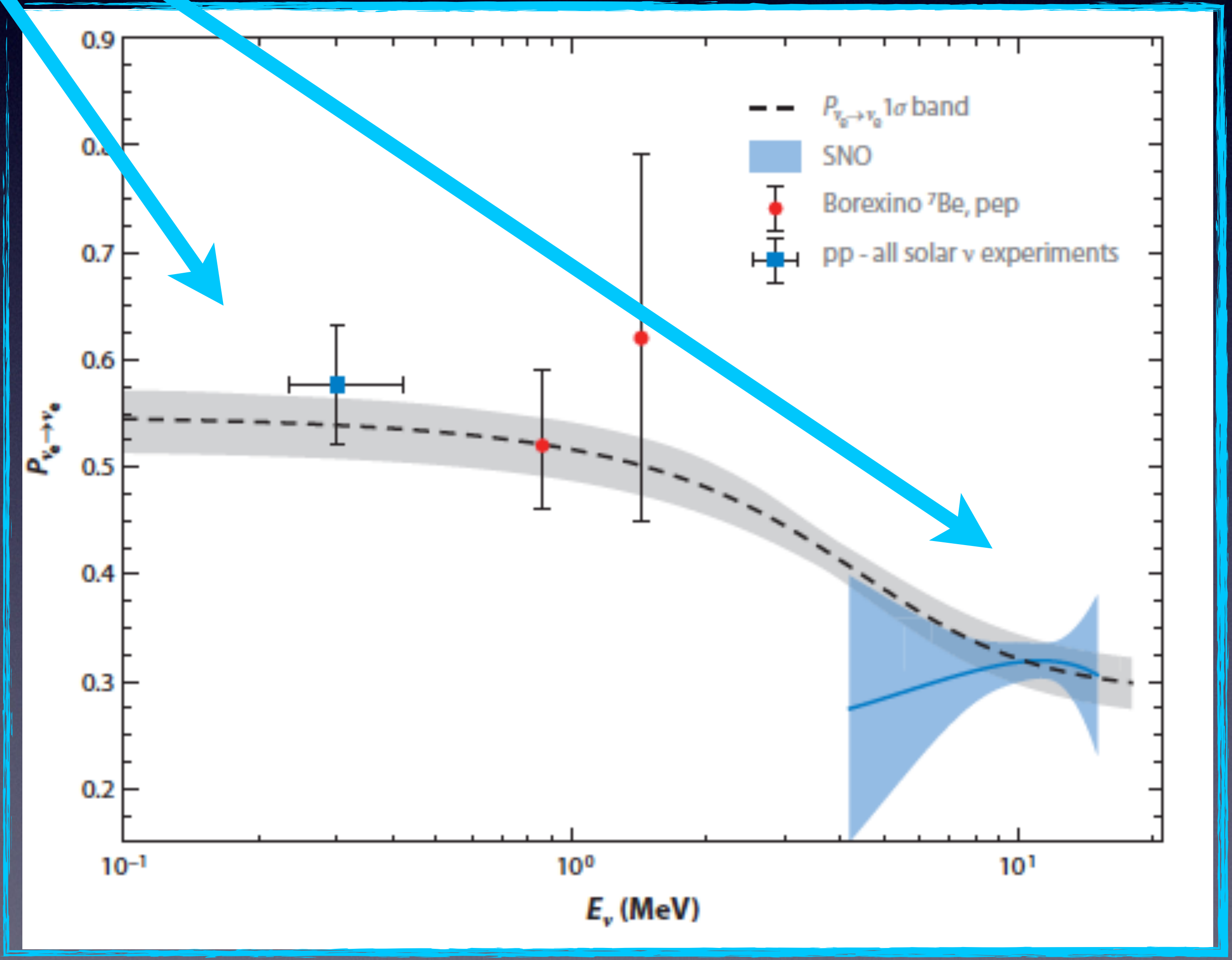
What may we still learn from solar ν ?

- **CNO cycle** is the most important on most stars
        - It depends on high Z catalysts, so is directly linked to metallicity
    - **Metallicity:** ^{7}Be, CNO and Luna-MeV may solve the issue
        - If low, eliosismology has severe problems
        - If high, standard solar formation model is wrong

- The **high precision** era of solar ν physics is coming!
    - Comparison of % precision ν fluxes with photon flux may teach us a lot about solar physics
        - Are there other emitted particles (axions, sterile neutrinos, ?)
        - Is the Sun in steady state ?
            - Big science gain if we discover it is not !

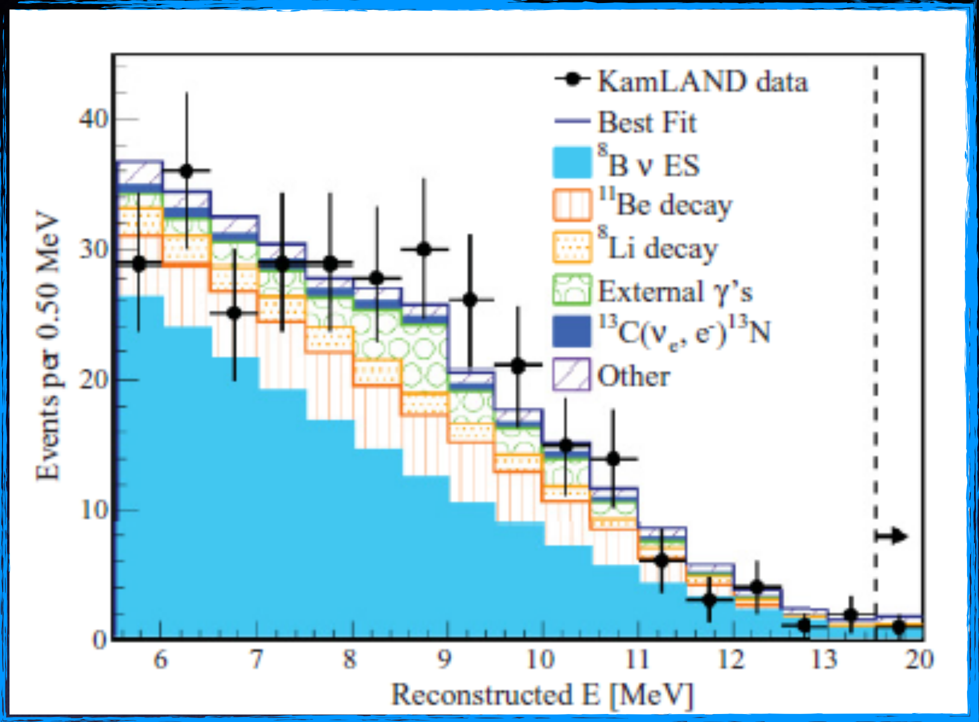
What may we still learn from solar ν ?

- 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 (see later)
  - Precision measurements will probe P$_{ee}$ and constrain non-standard neutrino and solar physics

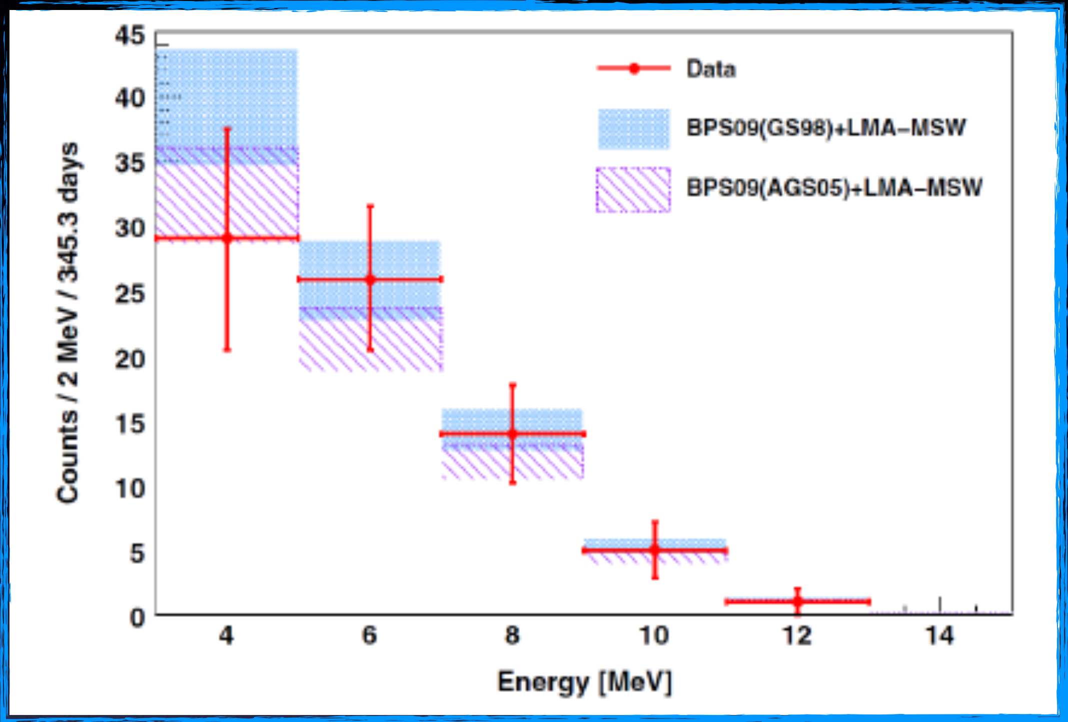


^{8}B results

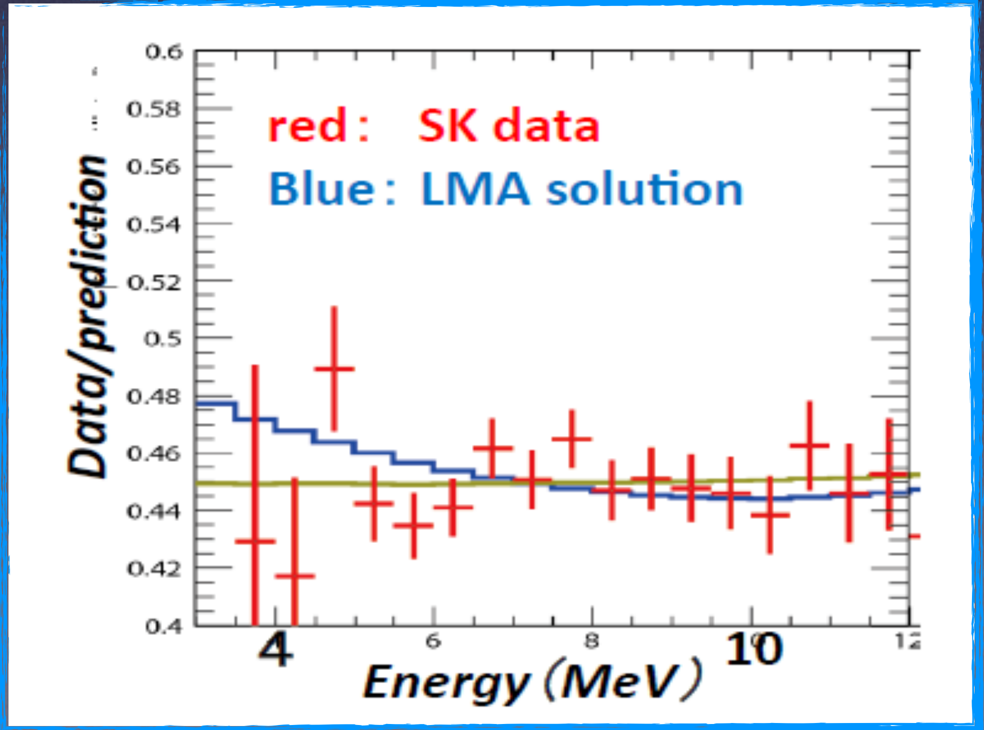
Kamland PRC 84, 035804 (2011)



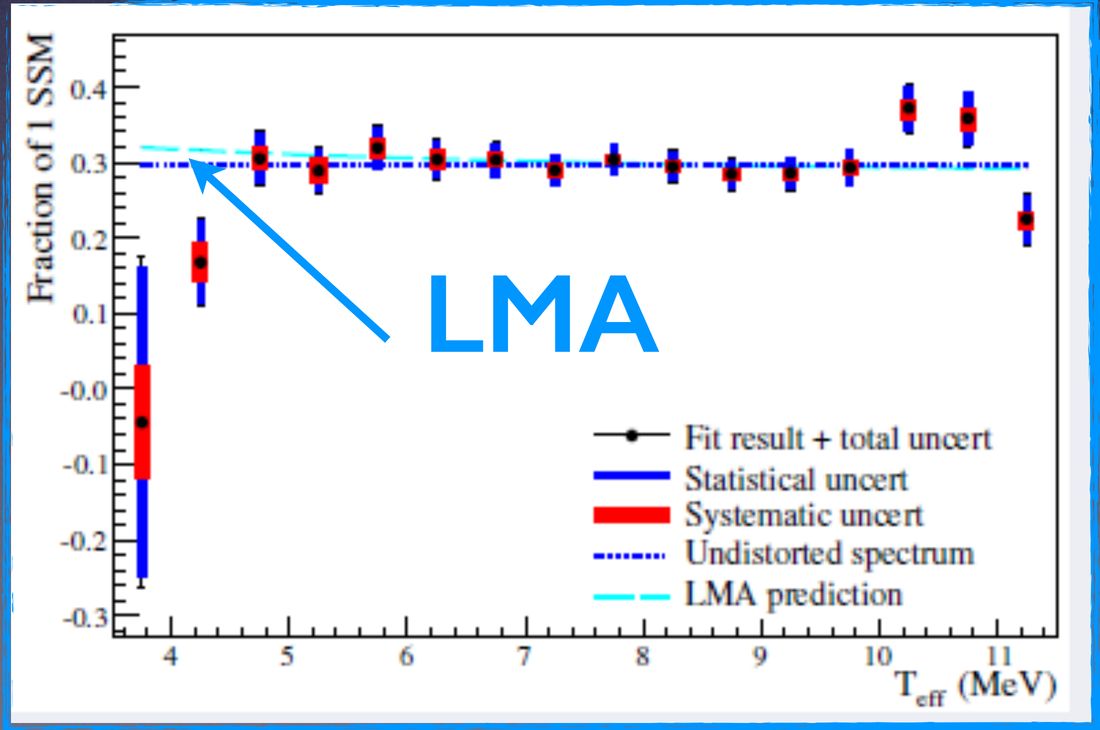
Borexino PRD 82 033006 (2010)



SK Suzuki@Neutrino Telescopes Venice 2013



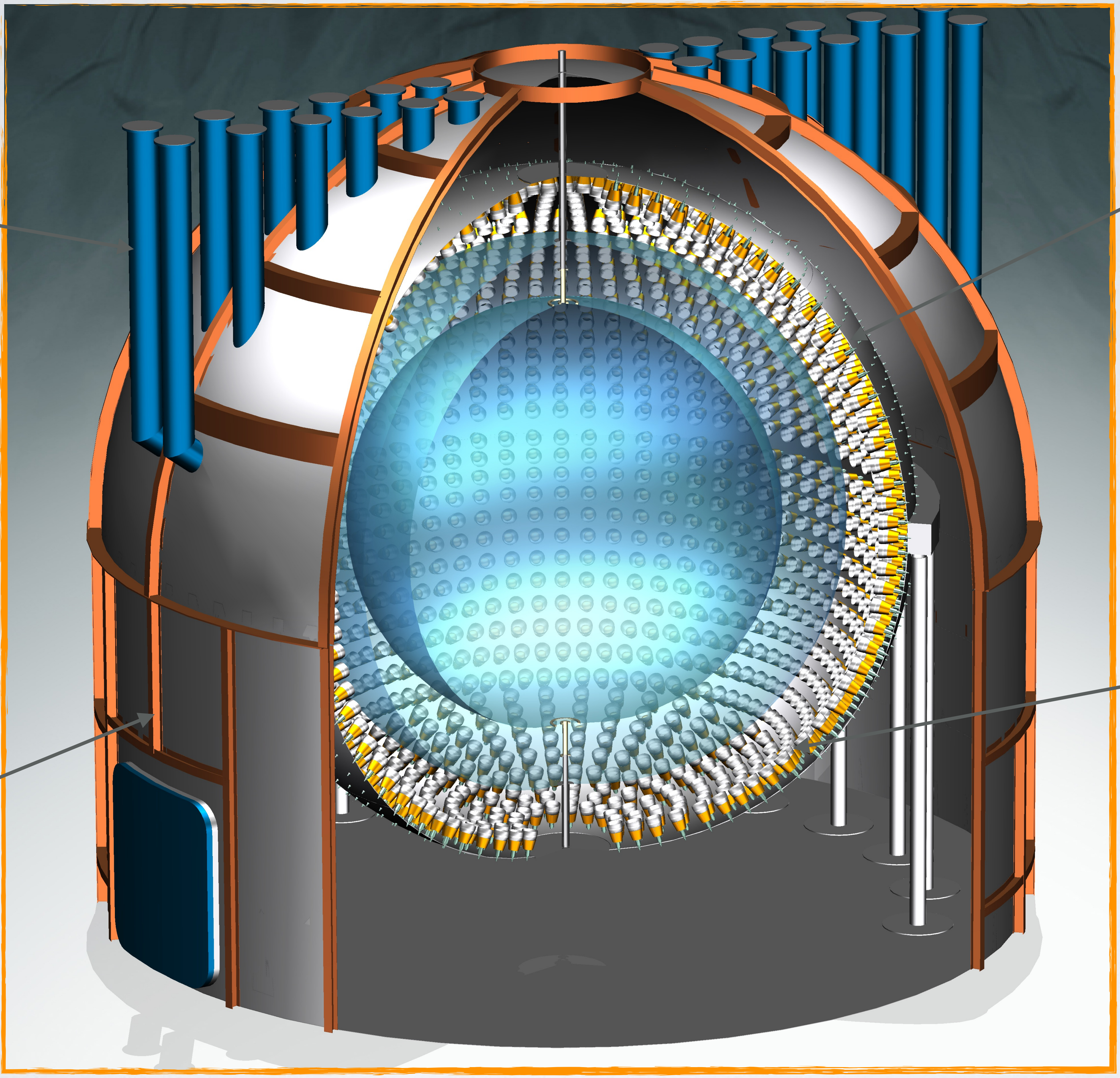
SNO LETA 3.5 MeV threshold arxiv 1109.0763



BOREXINO DETECTOR

CABLE
PIPES

WATER TANK
(shielding &
active veto)



NYLON
(container &
Rn barriers)

SPHERE
(container &
pmt support)

RESULTS 2007-2014

- First detection (2007) and precision measurement of ^{7}Be neutrinos
- Detection at low energy of ^{8}B neutrinos
- First detection of pep neutrinos
- First real time detection of pp neutrinos
- Best upper limit on CNO

Phys. Lett. B658:101-108, 2008
Phys. Rev. Lett. 101, 091302, 2008
Nucl. Instr. & Meth A600:568-593, 2009
Nucl. Instr. & Meth A609:58-78, 2009
Phys. Lett. B687:299-304, 2010
Phys. Rev. D82, 033006, 2010
Phys. Rev. C81, 034317, 2010
Phys. Rev. Lett. 107, 141302, 2011
JINST 6 P05005, 2011
Phys. Lett. B707:22–26, 2012
Phys. Rev. Lett. 108, 051302, 2012
Phys. Rev. D85, 092003, 2012

Final results of Borexino Phase-I on low energy solar neutrino spectroscopy

Phys. Rev. D 89, 112007 (2014)

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

Nature 512, 383 (2014)

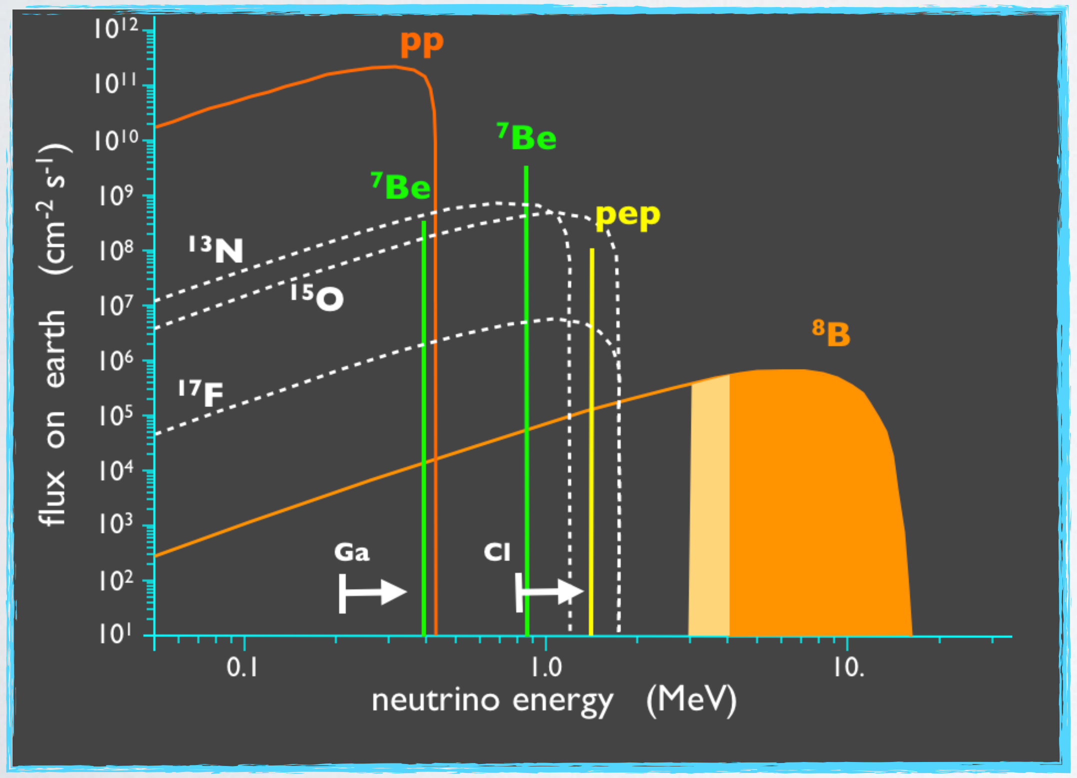
BACKGROUND IN PHASE 2 (2012-2014)

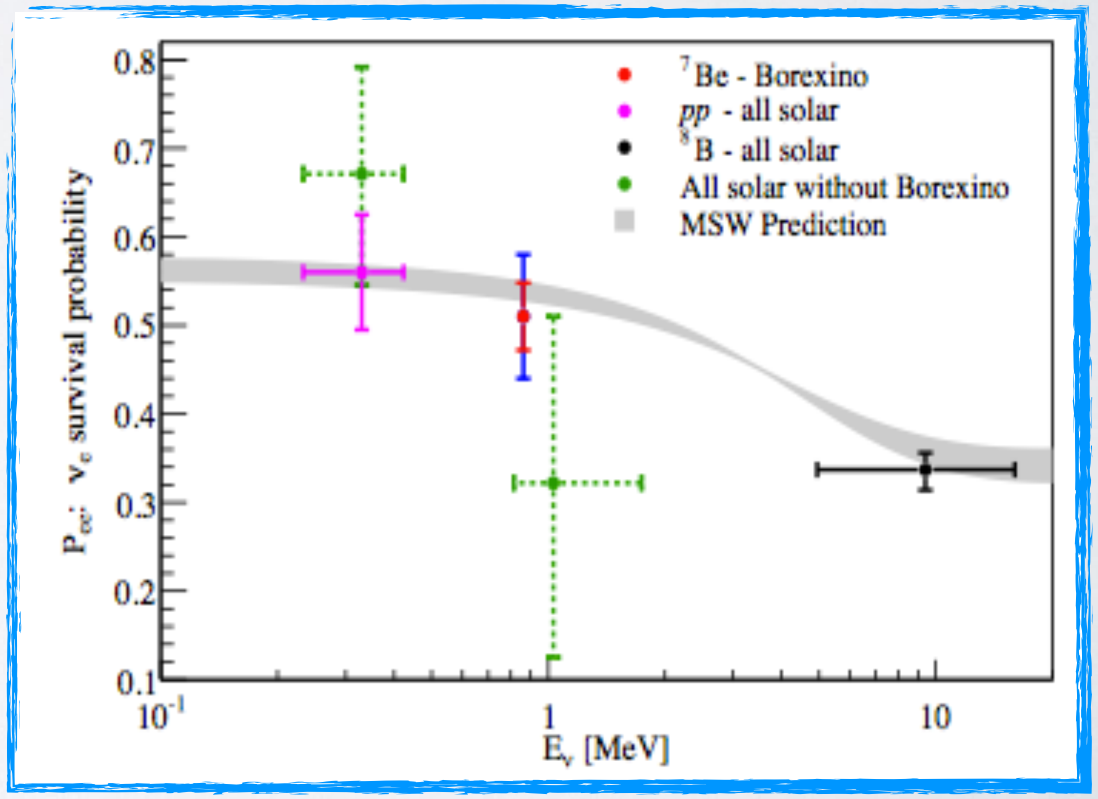
- We made an extensive purification by means of water extraction in loop in 2011

- ^{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
  - Reduce down to ~ 20 cpd/100 t. It was ~ 60 cpd/100 t

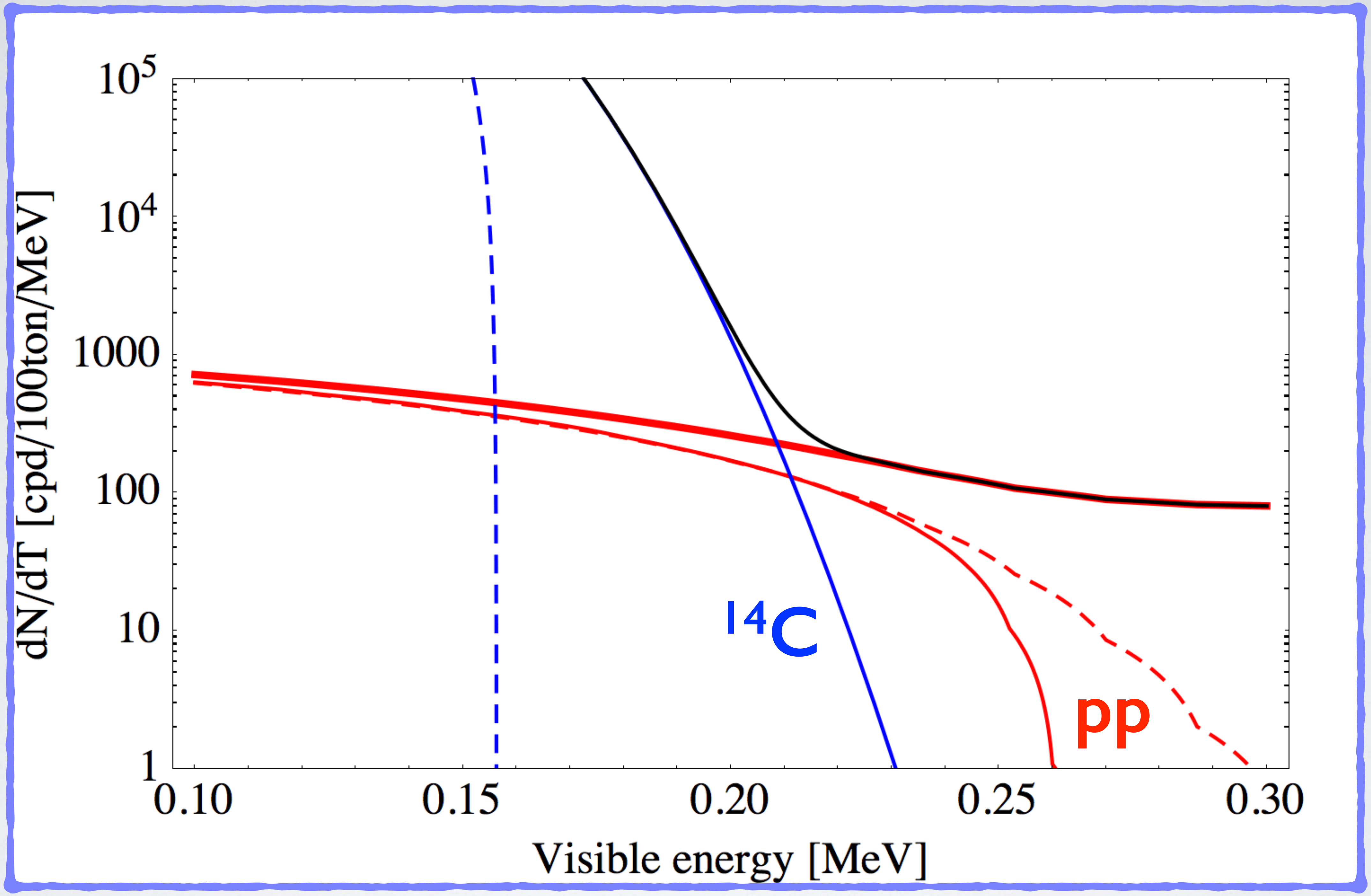
WHY SEARCH FOR PP NEUTRINOS ?

- They are the most important component, though lowest in energy
  - They set the time scale
  - They provide 99% of the energy
    - Comparison between neutrino luminosity and photon luminosity
    - Stability
    - Other particles i.e. axions or sterile
  - They probe neutrino oscillations in vacuum (no MSW)





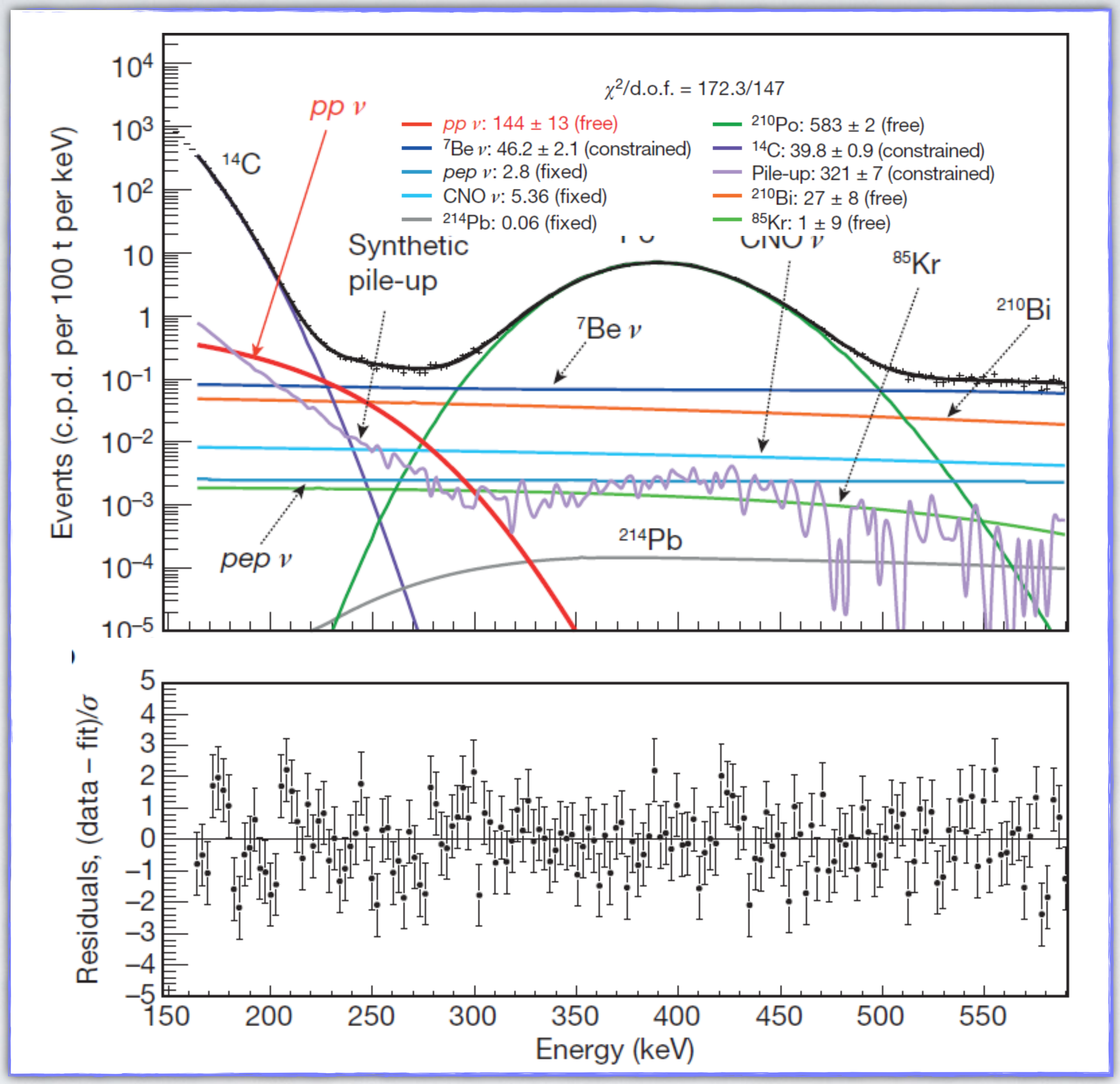
PP NEUTRINOS: EXPECTED SIGNAL



PP NEUTRINOS: A LARGE EFFORT

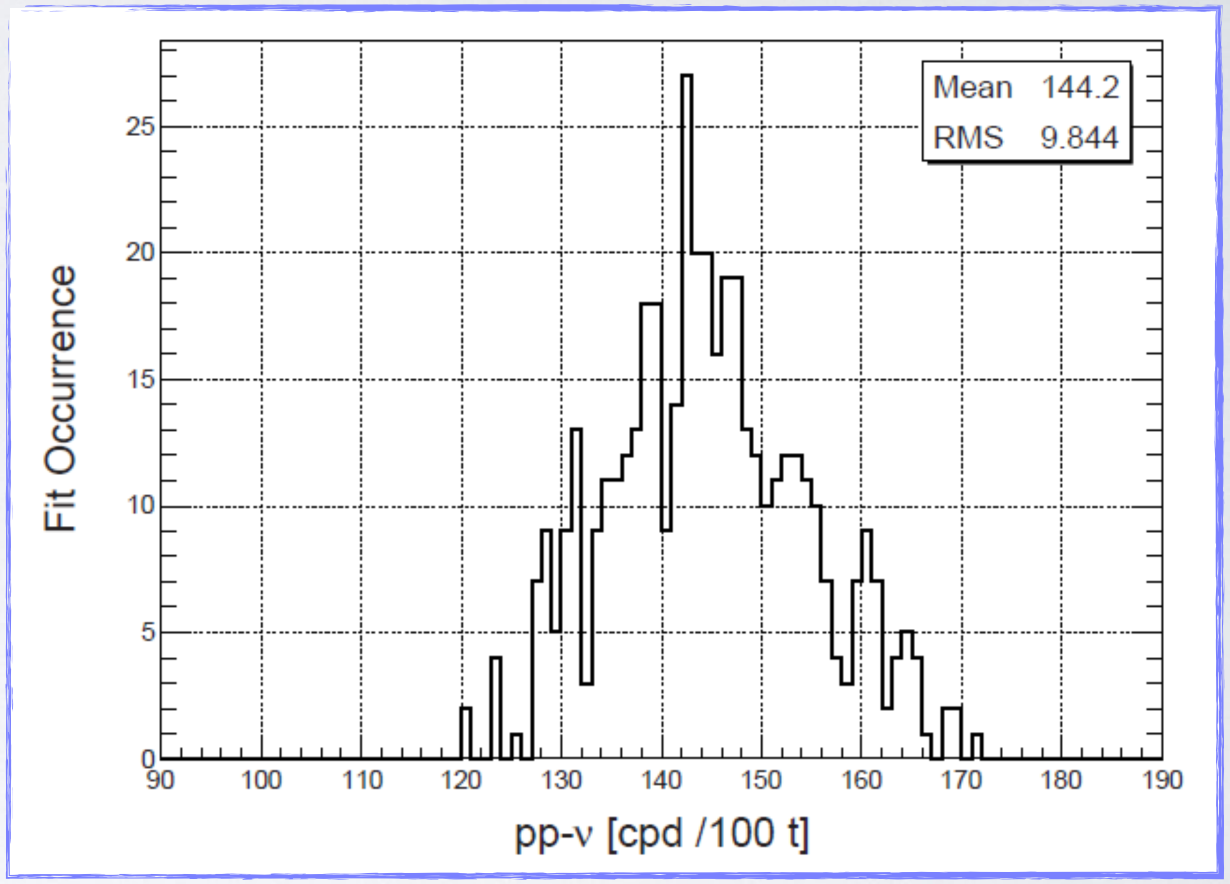
- A substantial effort was made to:
  - Understand the **energy response** of the detector at low energy
  - Understand the exact **shape of ^{14}C** background, including pile-up
  - Understand and correct for electronic noise and random hits, which are important at such low energies and huge event statistics
  - Skipping many details, we got…

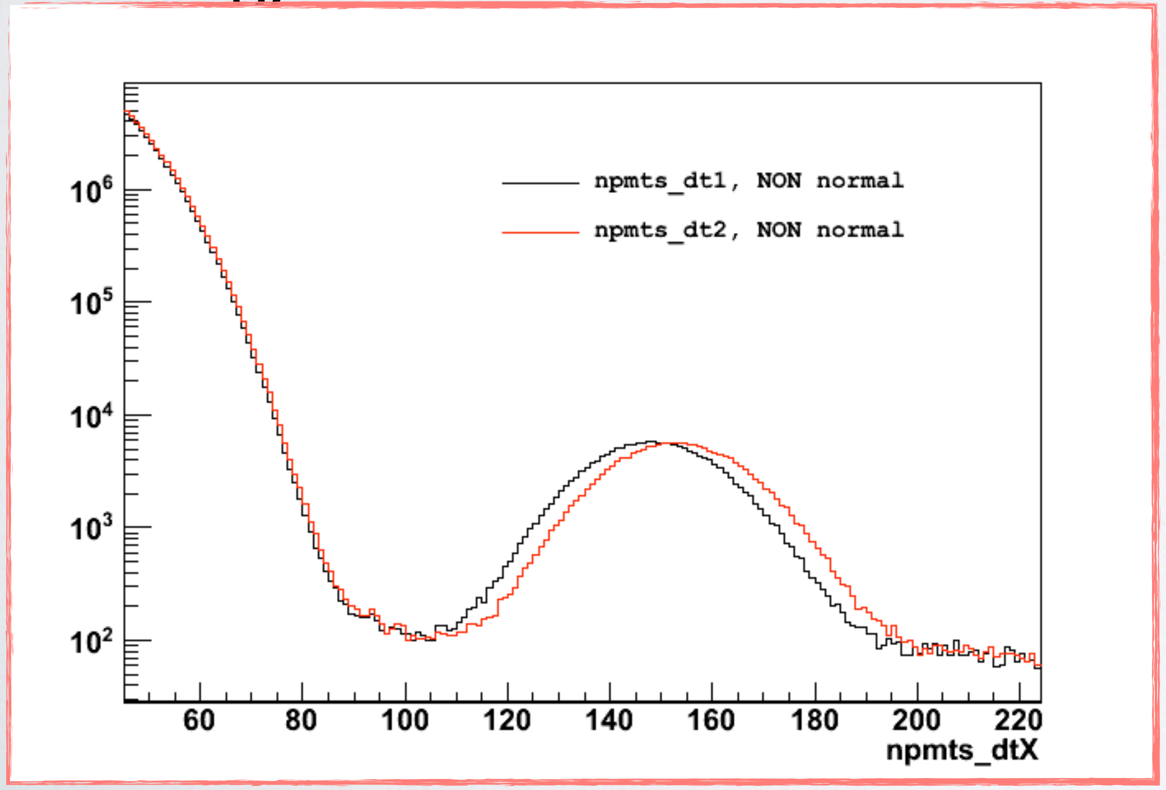
PP FIT RESULTS



SYSTEMATICS

- **Systematic error** is studied by varying fit conditions on all reasonable parameters within their known or data-constrained values
  - Distribution is peaked at ≈ 144 cpd / 100 t
- Main sources:
  - Pile-up : synthetic vs convolution
  - 7% ^{85}Kr rate
  - 8% Fiducial vol.: signal / background
  - 8% Energy estimator





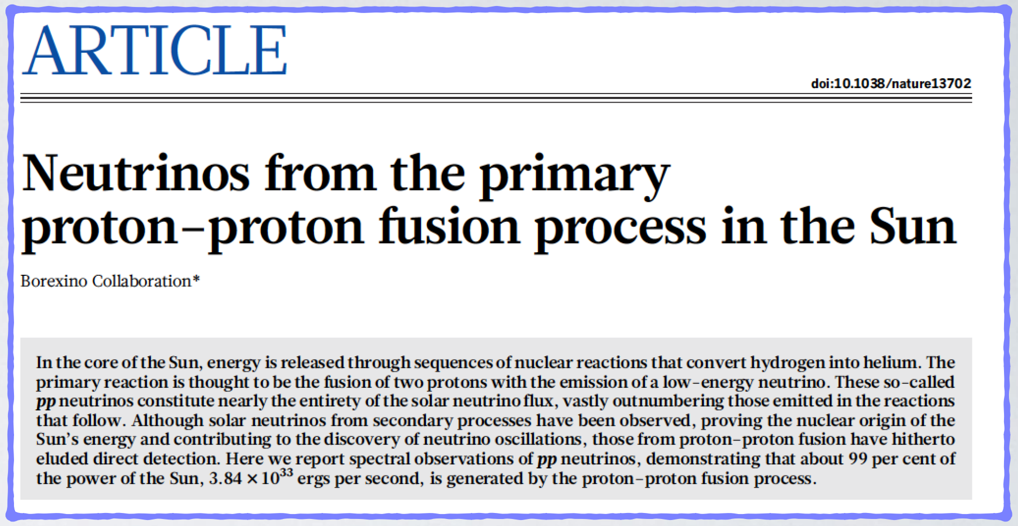
FINAL RESULT : 2014

***pp* detection rate:**

144 ± 13 *(stat)* ± 10 *(syst)* cpd/100 t

expected: (HM-SSM+LMA-MSW):

131 ± 2 cpd/100 t



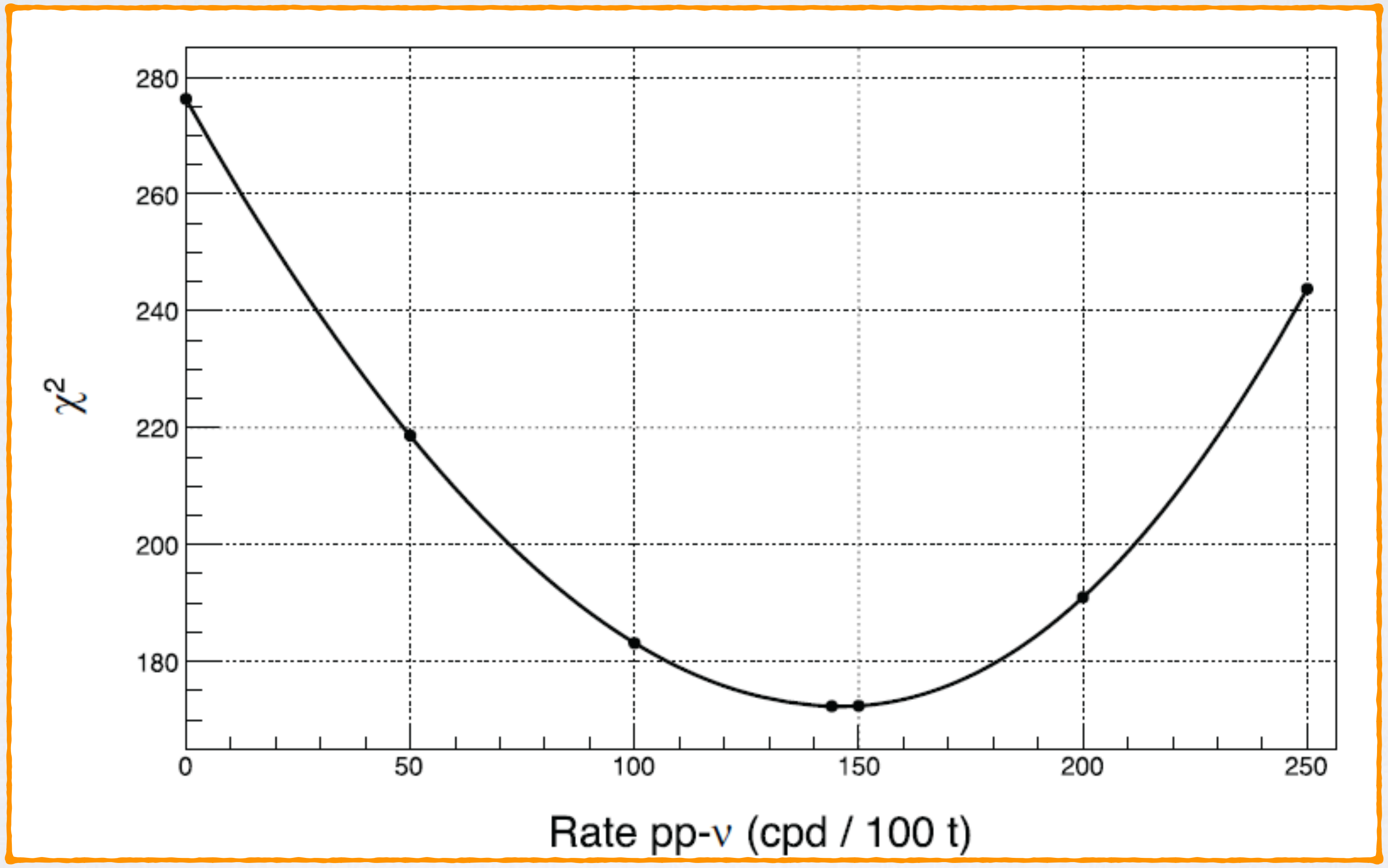
ARTICLE

doi:10.1038/nature13702

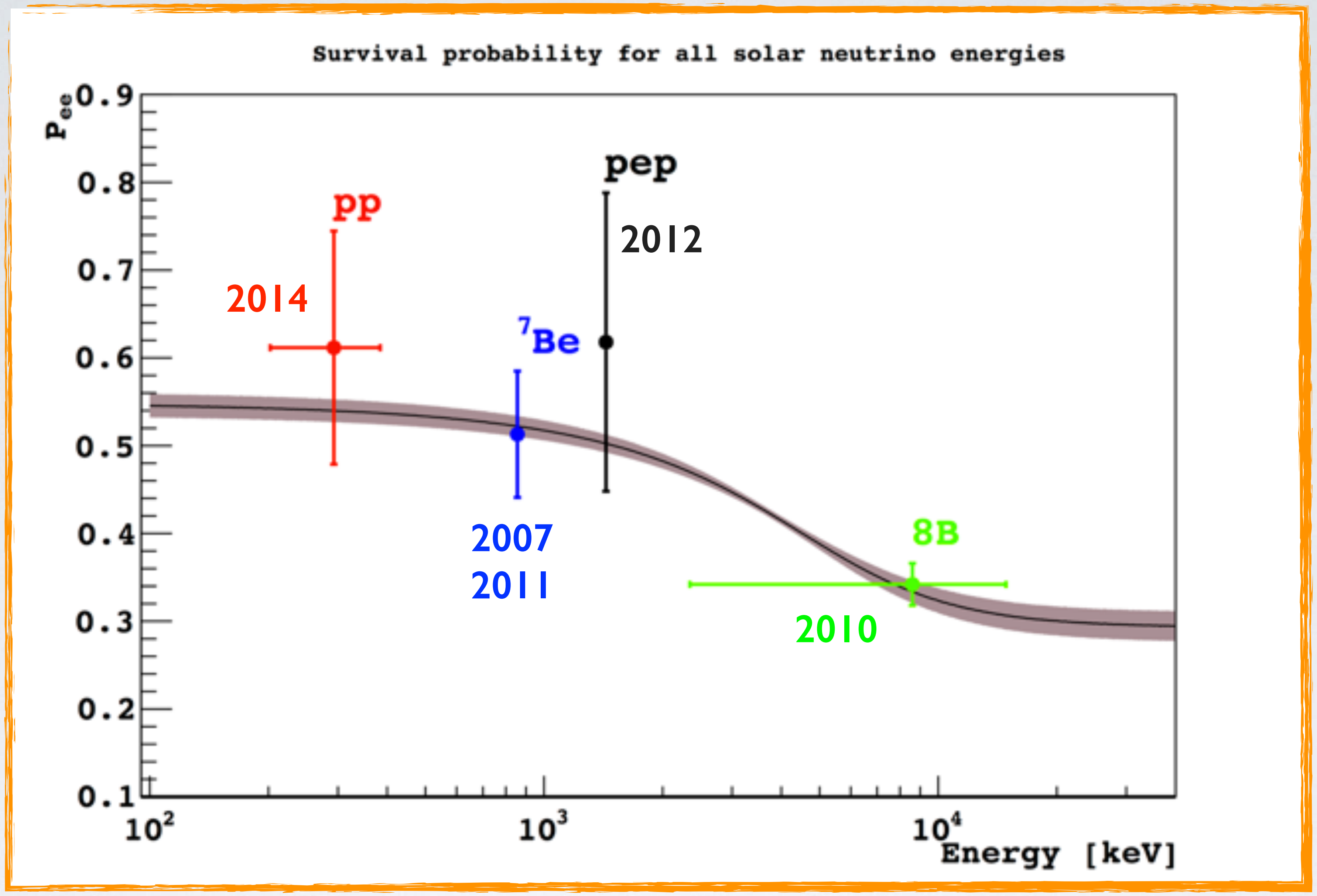
Neutrinos from the primary proton–proton fusion process in the Sun

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.



7 YEARS OF BOREXINO



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

BOREXINO FUTURE

- Borexino has done most of what it can possibly do

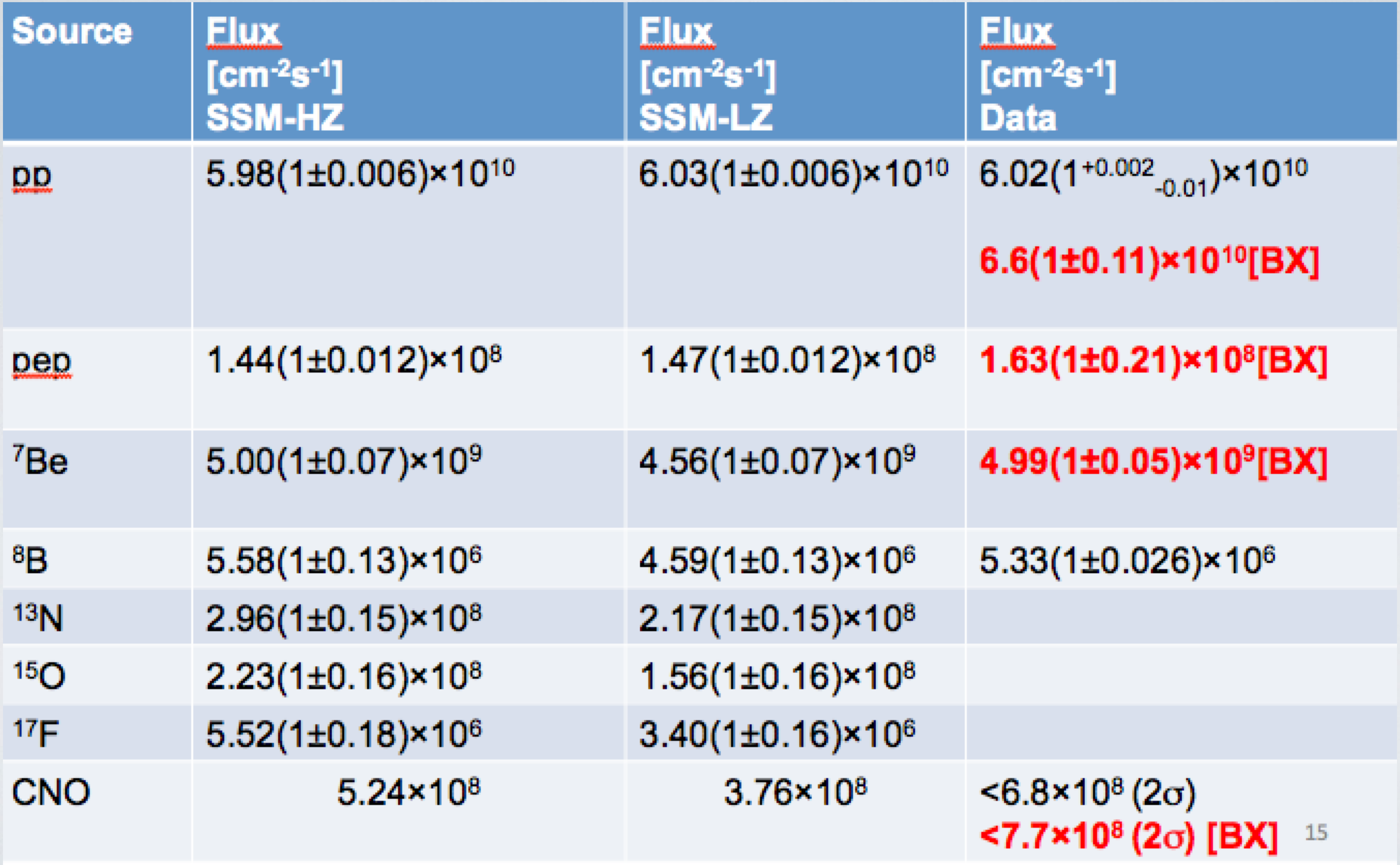
- A few very difficult problems are still on the table

  - Can we detect the ^{8}B upturn ?
    - Probably not. Despite low energy threshold, the detector is too small to gain sufficient statistics on ^{8}B neutrinos

  - Can we detect CNO neutrinos ?
    - Maybe, but it is hard

  - Can we improve other measurement to get higher precision ?
    - A little bit, not much

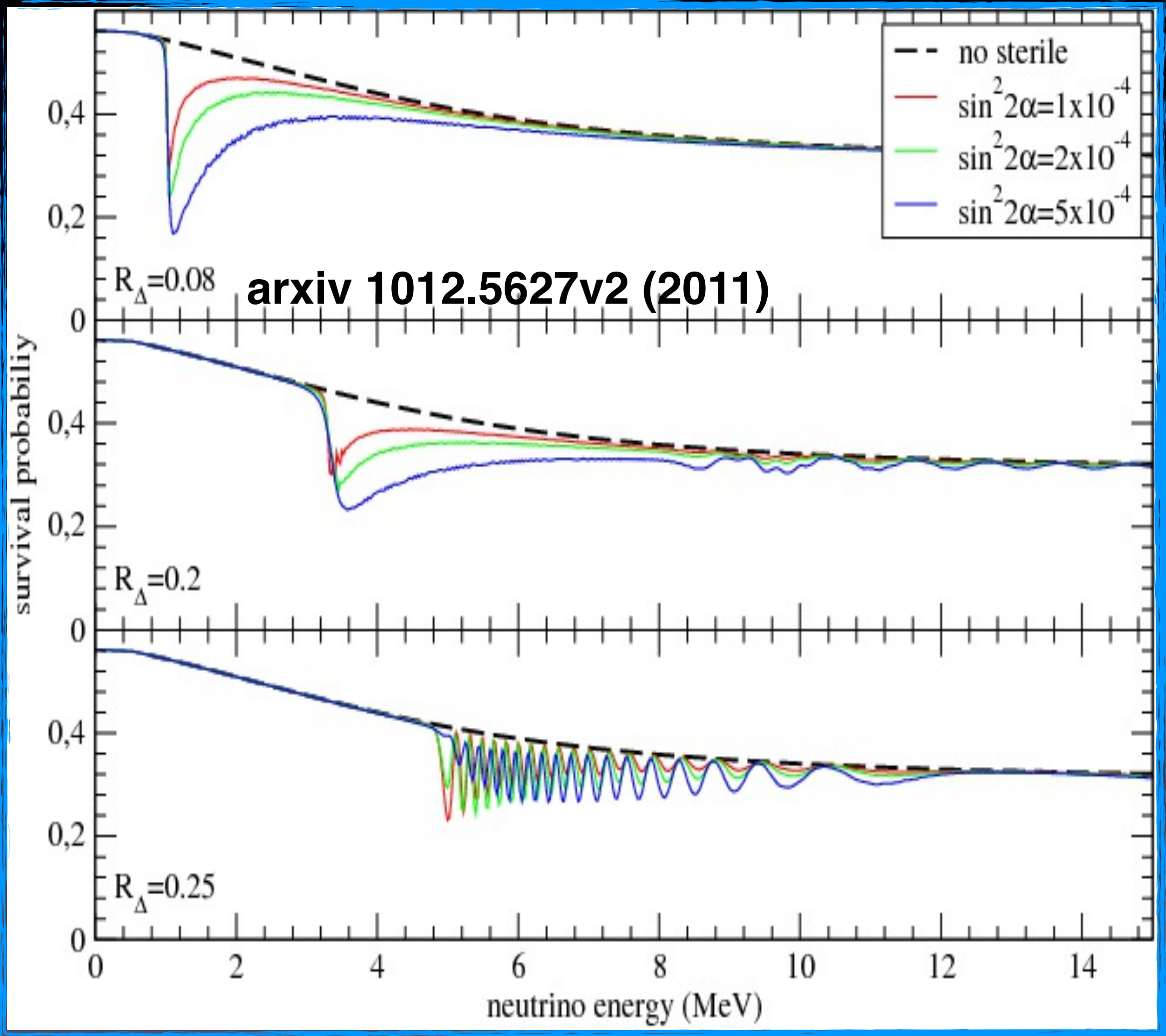
WHERE WE ARE NOW ?



Source	Flux [cm^{-2}s^{-1}] SSM-HZ	Flux [cm^{-2}s^{-1}] SSM-LZ	Flux [cm^{-2}s^{-1}] Data
pp	$5.98(1\pm0.006)\times10^{10}$	$6.03(1\pm0.006)\times10^{10}$	$6.02(1^{+0.002}_{-0.01})\times10^{10}$ **$6.6(1\pm0.11)\times10^{10}$[BX]**
pep	$1.44(1\pm0.012)\times10^{8}$	$1.47(1\pm0.012)\times10^{8}$	**$1.63(1\pm0.21)\times10^{8}$[BX]**
^{7}Be	$5.00(1\pm0.07)\times10^{9}$	$4.56(1\pm0.07)\times10^{9}$	**$4.99(1\pm0.05)\times10^{9}$[BX]**
^{8}B	$5.58(1\pm0.13)\times10^{6}$	$4.59(1\pm0.13)\times10^{6}$	$5.33(1\pm0.026)\times10^{6}$
^{13}N	$2.96(1\pm0.15)\times10^{8}$	$2.17(1\pm0.15)\times10^{8}$	
^{15}O	$2.23(1\pm0.16)\times10^{8}$	$1.56(1\pm0.16)\times10^{8}$	
^{17}F	$5.52(1\pm0.18)\times10^{6}$	$3.40(1\pm0.16)\times10^{6}$	
CNO	5.24×10^{8}	3.76×10^{8}	$<6.8\times10^{8}$ (2σ) **$<7.7\times10^{8}$ (2σ) [BX]** 15

Upturn or not upturn ?

- LMA-MSW predicts P_{ee} increase below 6 MeV (upturn)
  - **No evidence so far**
    - All experiments see a flat distributions or even a decrease, but *statistics is still insufficient*
    - **Intriguing, however**
    - Sterile ν or non-standard interactions may play a role

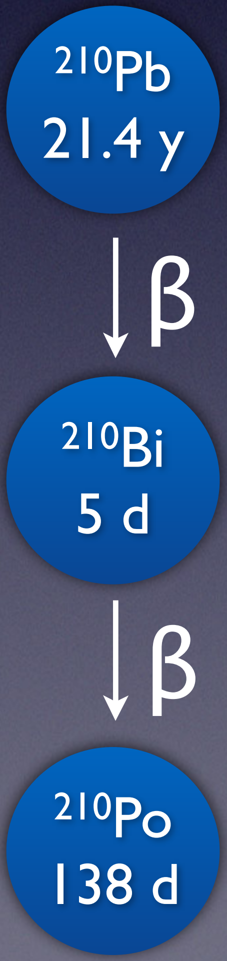


arxiv 1012.5627v2 (2011)

  - **SK** might be able to say something clear
    - HK certainly, if threshold low enough
  - **Borexino** probably too small, despite lower energy threshold
    - Of course, we work hard! We have now x3 statistics w.r.t. 2010 paper

Can we measure CNO ?

- **What are the experimental problems ?**
  - Cosmogenic ^{11}C: solved with tagging and subtraction (see pep)
    - Deeper detectors (e.g. SNO+) might be in better shape
  - **^{210}Bi: the worst background**
    - Spectrally very similar. Regardless of its value (of course, the smaller the better) you must know it by other means to extract CNO
    - A possibility: measure a constant value in ^{210}Po decay
    - You must have a very stable detector with no other ^{210}Bi sources than ^{210}Pb in equilibrium in the scintillator

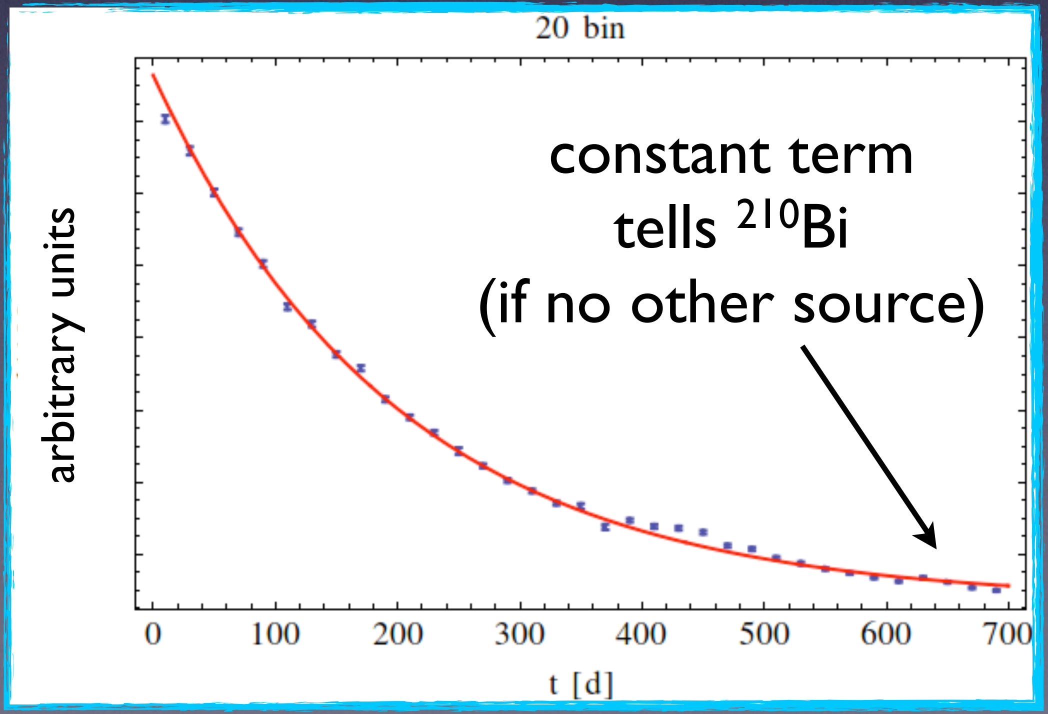


$$\frac{dN_{Po}}{dt} = -\frac{N_{Po}}{\tau_{Po}} + \frac{N_{Bi}}{\tau_{Bi}} + S_{Po}(t)$$

arXiv:1104.1335v1

CNO High Metallicity: ~ 5 cpd/100 t

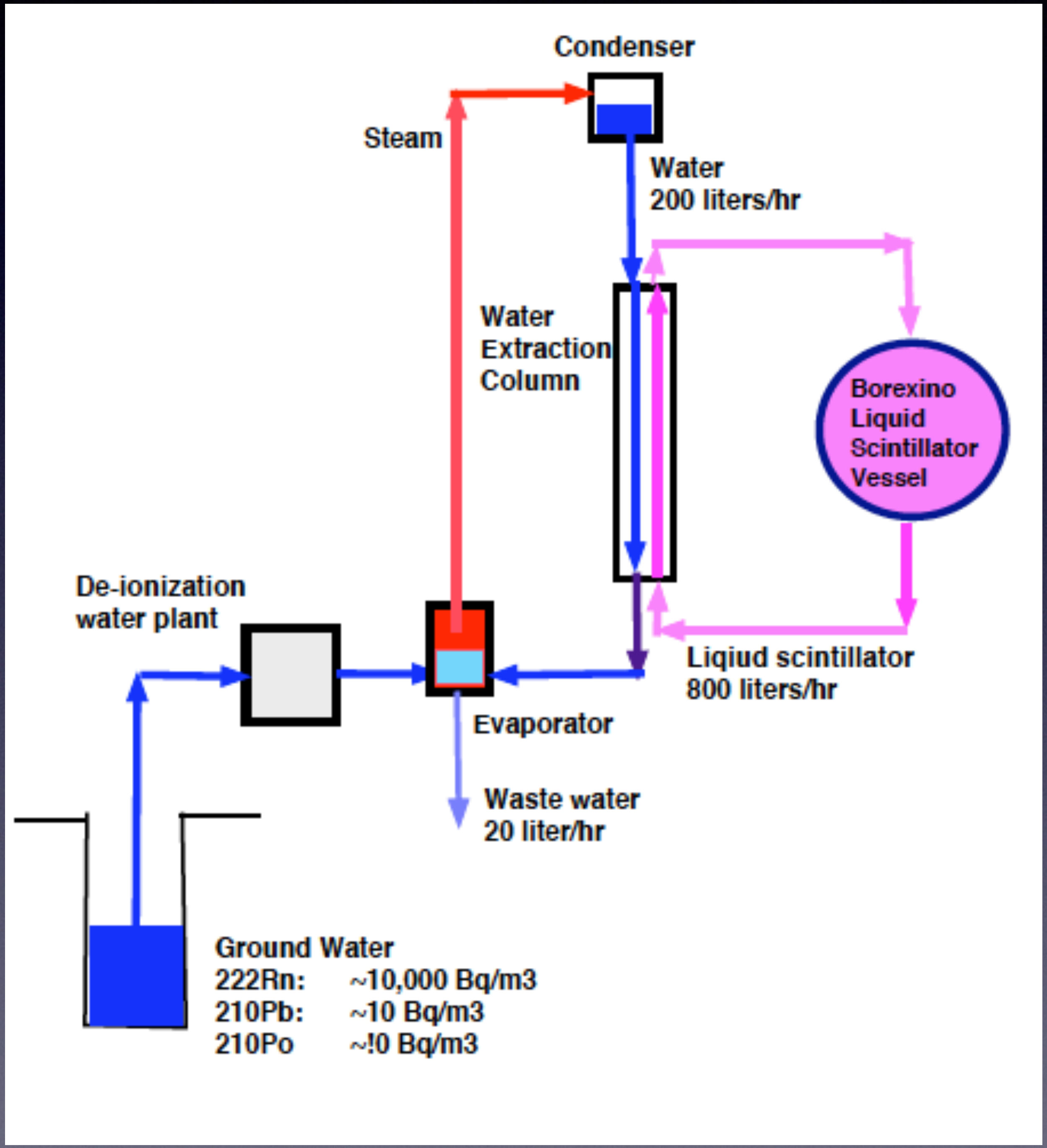
^{210}Bi (now) : ~ 20 cpd/100 t

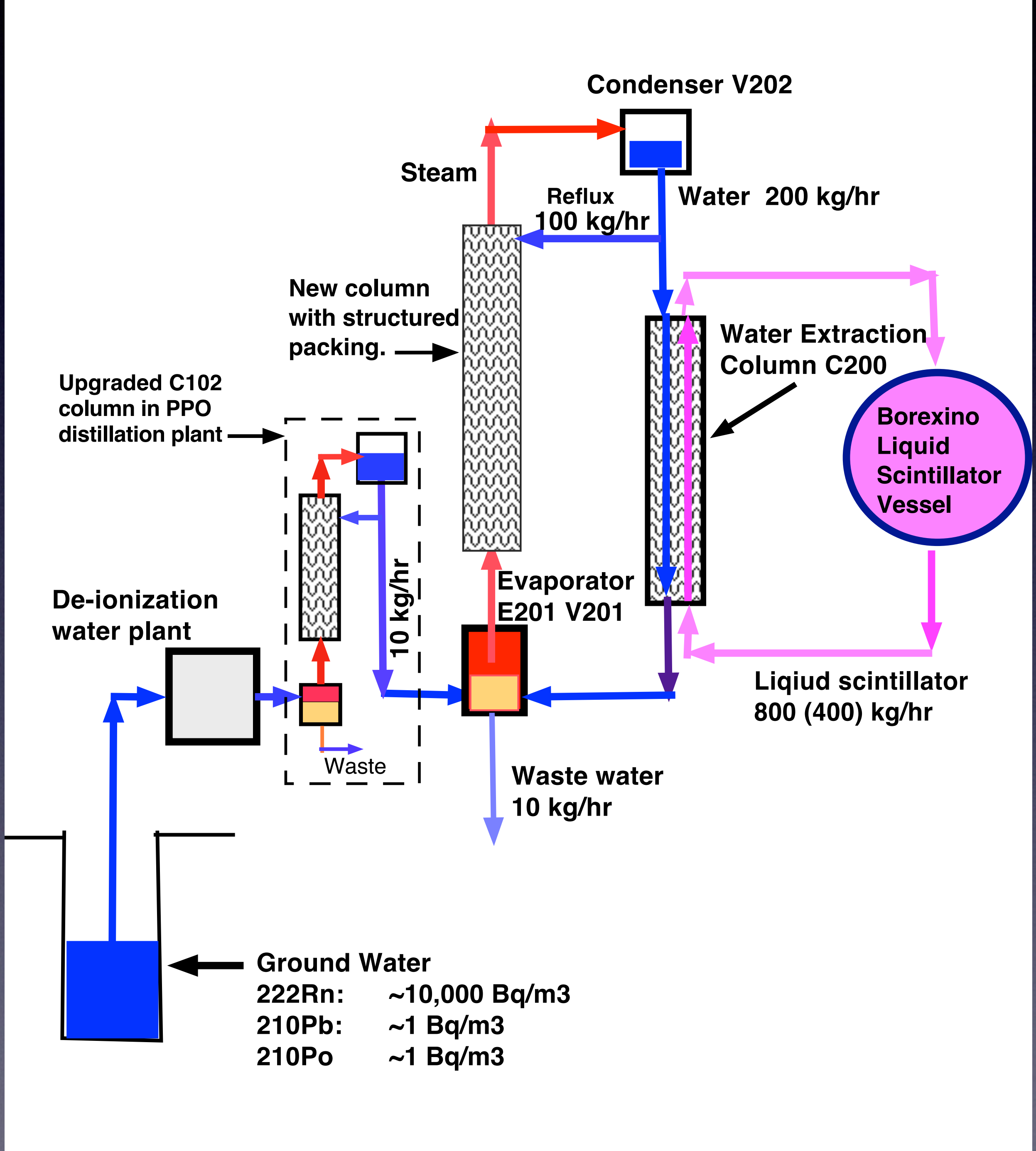


Can we measure CNO ?

- Yes, maybe, if:
  - We succeed to keep the **detector stable** for a reasonable time
    - **Temperature instabilities** are the main problem
    - Mixing of liquid (convective currents) increases background in non-uniform and time-dependent way in the fiducial volume
  - **Further purification** will be attempted too. It might help if:
    - We succeed to remove ^{210}Po. Some measurements suggest that it comes from water, but we need to prove this hypothesis
    - We succeed to remove ^{210}Bi further
    - We meet the previous stability condition
  - Purification tests in 2015
    - If successful, campaign in 2015/2016, possibly during SOX Ce run

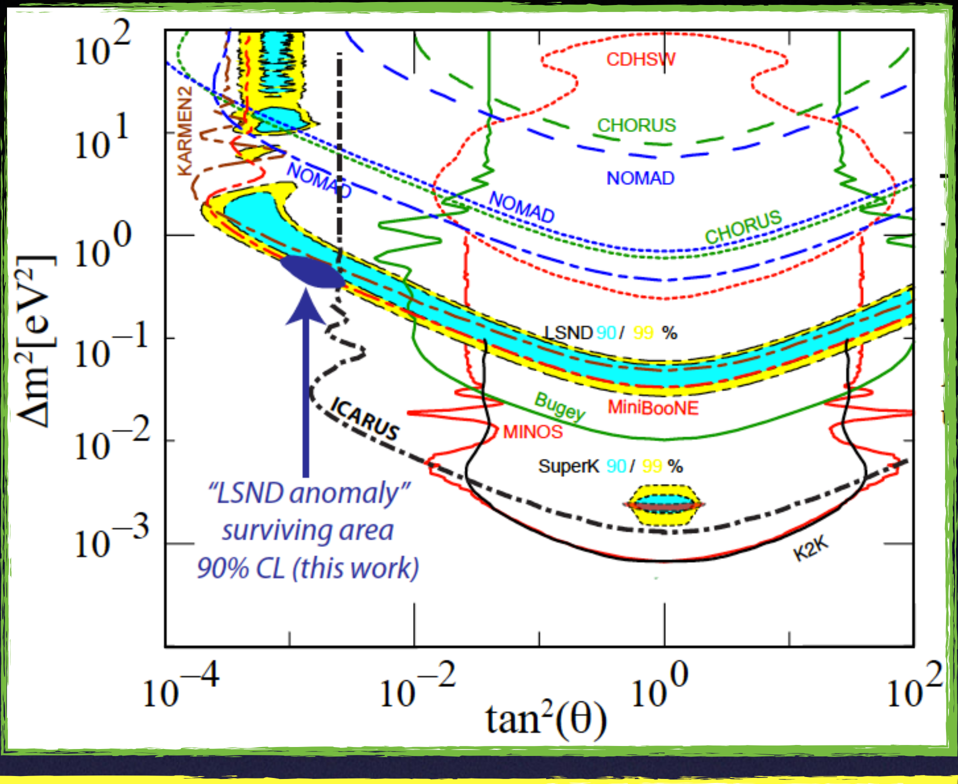
Plant upgrade for water purity

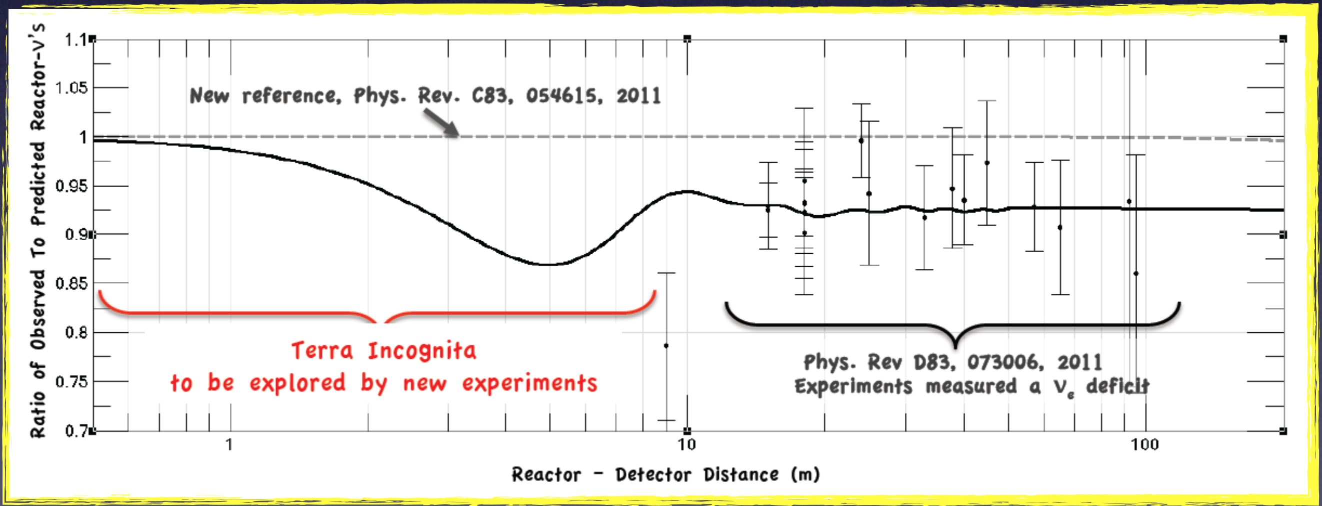




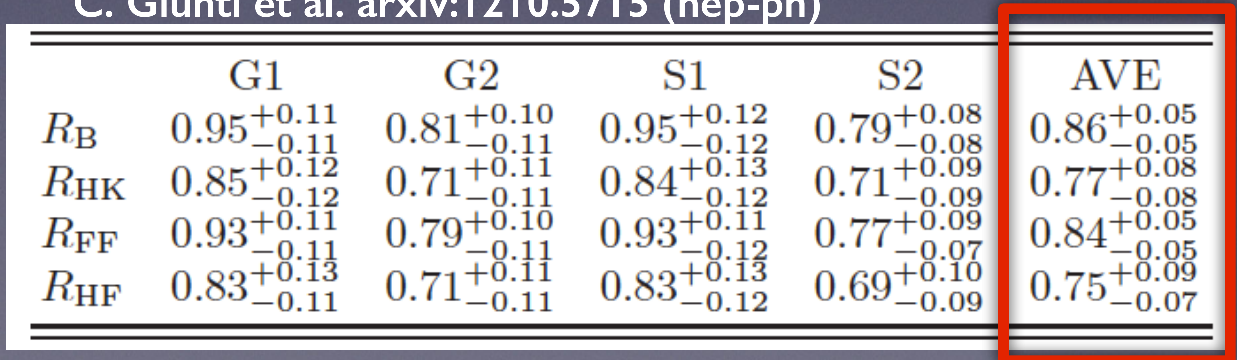
Sterile: the science case

- "anomalies": a few experiments deviate from the standard 3-flavor mixing at L/E ~ 1 m/MeV
  - LSND 2001 (see T. Katori talk yesterday)
    - Clear excess: **87.9 ± 22.4 ± 6.0 (3.8 σ)**
    - Only partially confirmed by MiniBoone
    - Allowed region restricted by ICARUS to $\Delta m^2 \sim 1$ eV^2 (arxiv: 1209.0122v4)
  - Gallium and Reactor anomalies:
    - deficit at short distances
    - $\nu_e + {}^{71}\mathrm{Ga} \rightarrow {}^{71}\mathrm{Ge} + e^-$
  - Cosmology
    - Weaker evidence after Planck
    - More than 3 not excluded (model dependent)





C. Giunti et al. arxiv:1210.5715 (hep-ph)



	G1	G2	S1	S2	AVE
R_{B}	$0.95^{+0.11}_{-0.11}$	$0.81^{+0.10}_{-0.11}$	$0.95^{+0.12}_{-0.12}$	$0.79^{+0.08}_{-0.08}$	$0.86^{+0.05}_{-0.05}$
R_{HK}	$0.85^{+0.12}_{-0.12}$	$0.71^{+0.11}_{-0.11}$	$0.84^{+0.13}_{-0.12}$	$0.71^{+0.09}_{-0.09}$	$0.77^{+0.08}_{-0.08}$
R_{FF}	$0.93^{+0.11}_{-0.11}$	$0.79^{+0.10}_{-0.11}$	$0.93^{+0.11}_{-0.12}$	$0.77^{+0.09}_{-0.07}$	$0.84^{+0.05}_{-0.05}$
R_{HF}	$0.83^{+0.13}_{-0.11}$	$0.71^{+0.11}_{-0.11}$	$0.83^{+0.13}_{-0.12}$	$0.69^{+0.10}_{-0.09}$	$0.75^{+0.09}_{-0.07}$

- **Key point: an experimental issue can be solved only by better experiments**

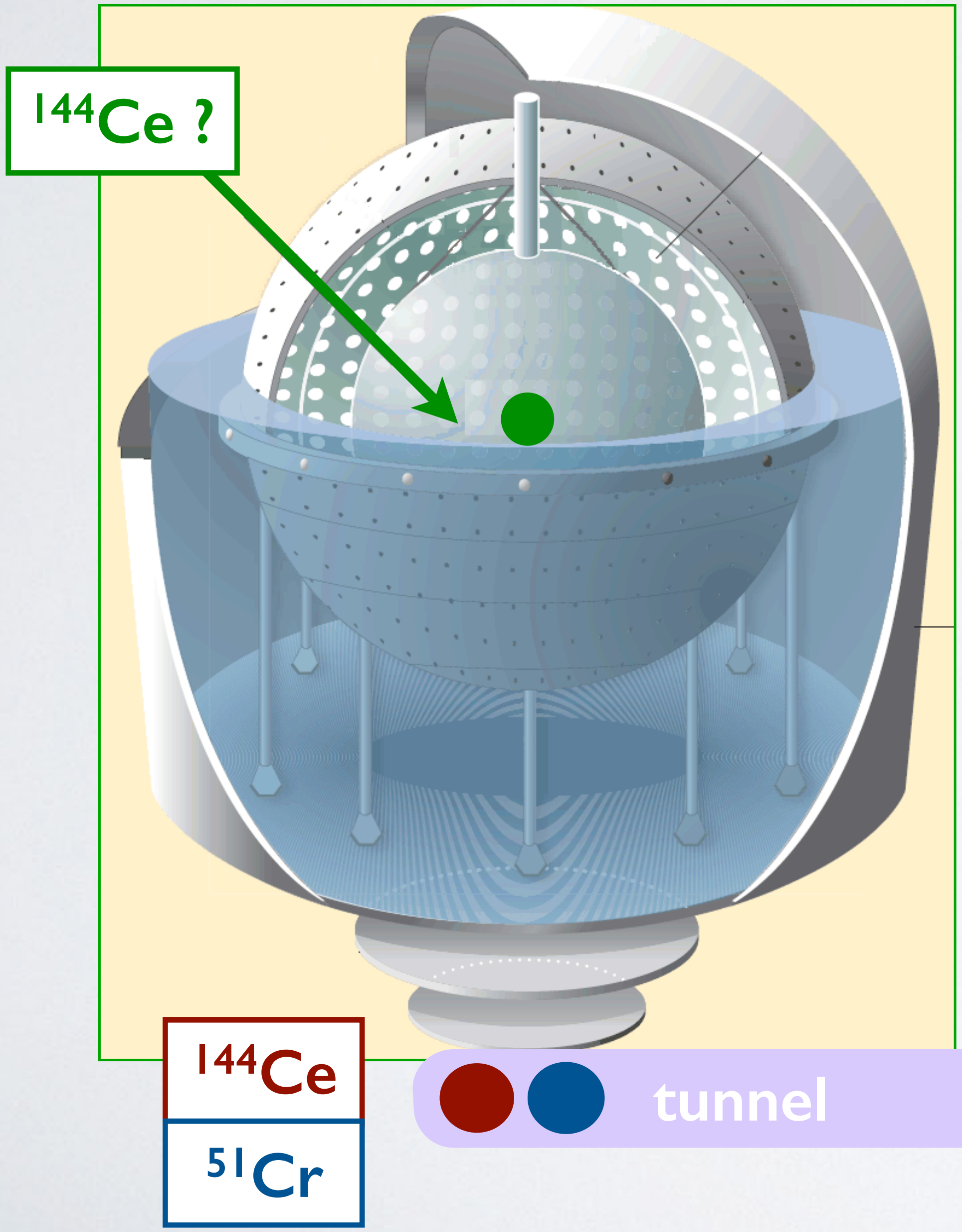
Solar ν detectors hunting for sterile ν

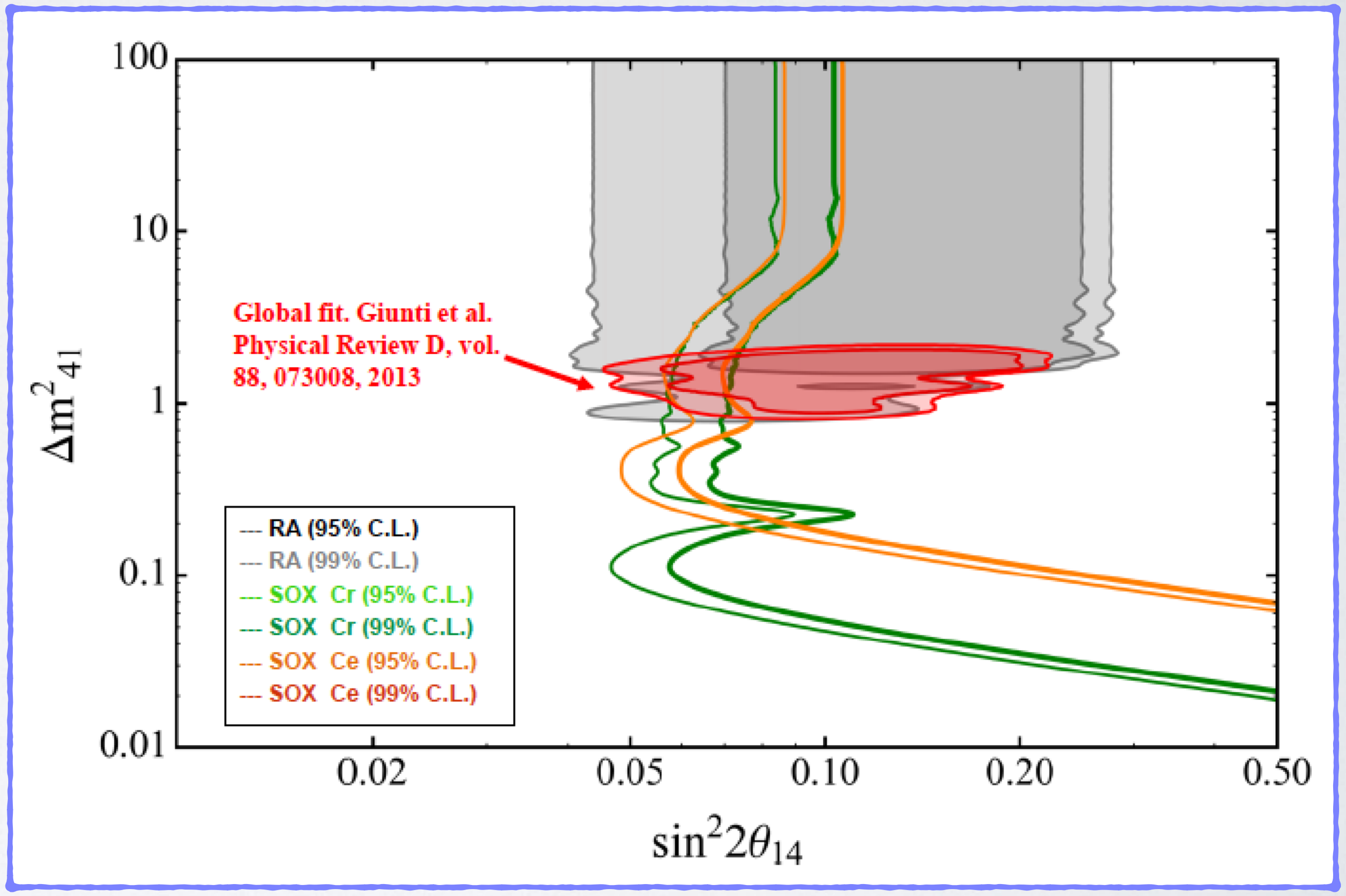
- Solar neutrino detectors are particularly suitable for sterile neutrino search **in disappearance experiments**
  - Low background and low energy detection threshold: neutrino from artificial sources can easily be detected
  - **They are big:** sterile ν of mass **~ 1 eV** and energy **~ 1 MeV** have oscillation lengths of **~ 1 m**, easily detectable with kton detectors
    - **Oscillometry: direct detection of oscillation waves**
  - Two proposals in particular have been suppored by ERC
    - **CeLAND:** **^{144}Ce anti-neutrino source** in **KamLAND** (P.I. T. Lasserre, Saclay, ERC starting grant)
    - **SOX:** **^{51}Cr neutrino source** in **Borexino** (P.I. M.P., ERC Advanced grant)

NOW a single project: SOX-Ce

STERILE NEUTRINOS

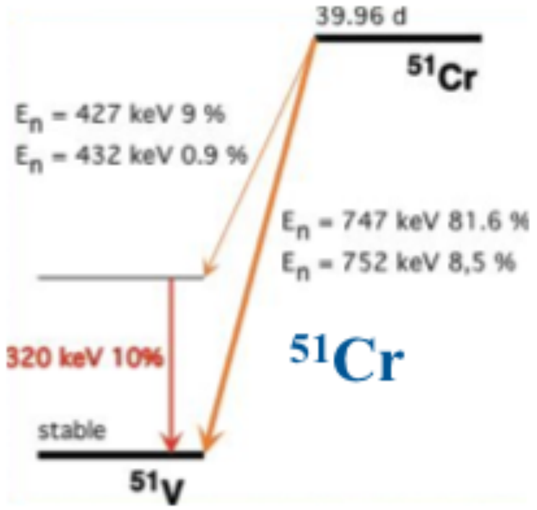
- **SOX**: Short **D**istance **O**scillations with Bore**X**ino
  - Search for sterile neutrinos or other proximity effect in neutrino oscillations by means of powerful anti-neutrino and possibly neutrino sources
  - Collaboration between Borexino and CEA - France

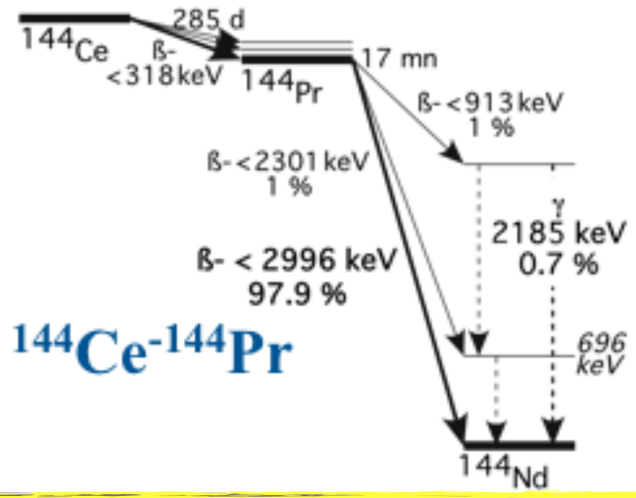


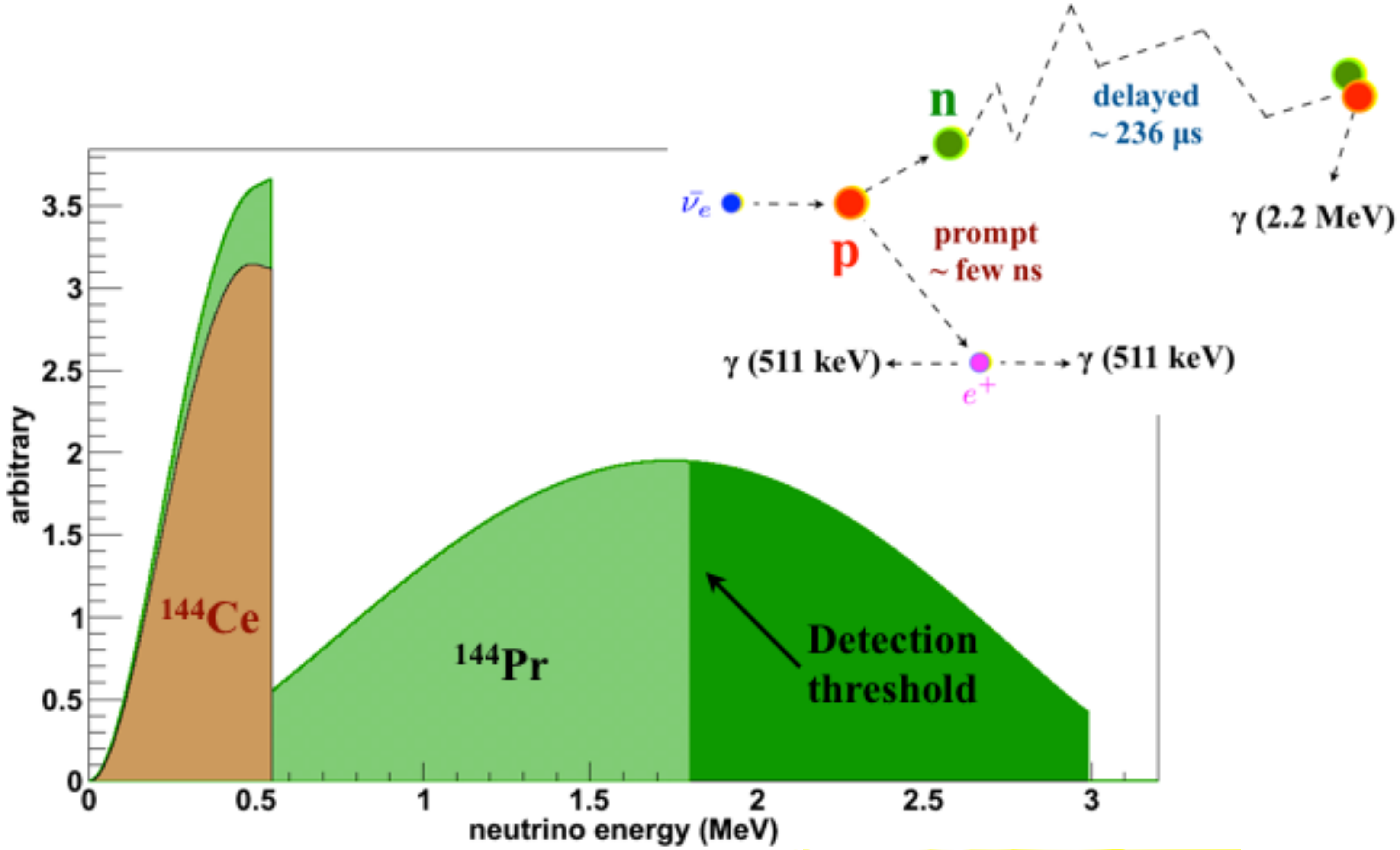


Neutrino generators

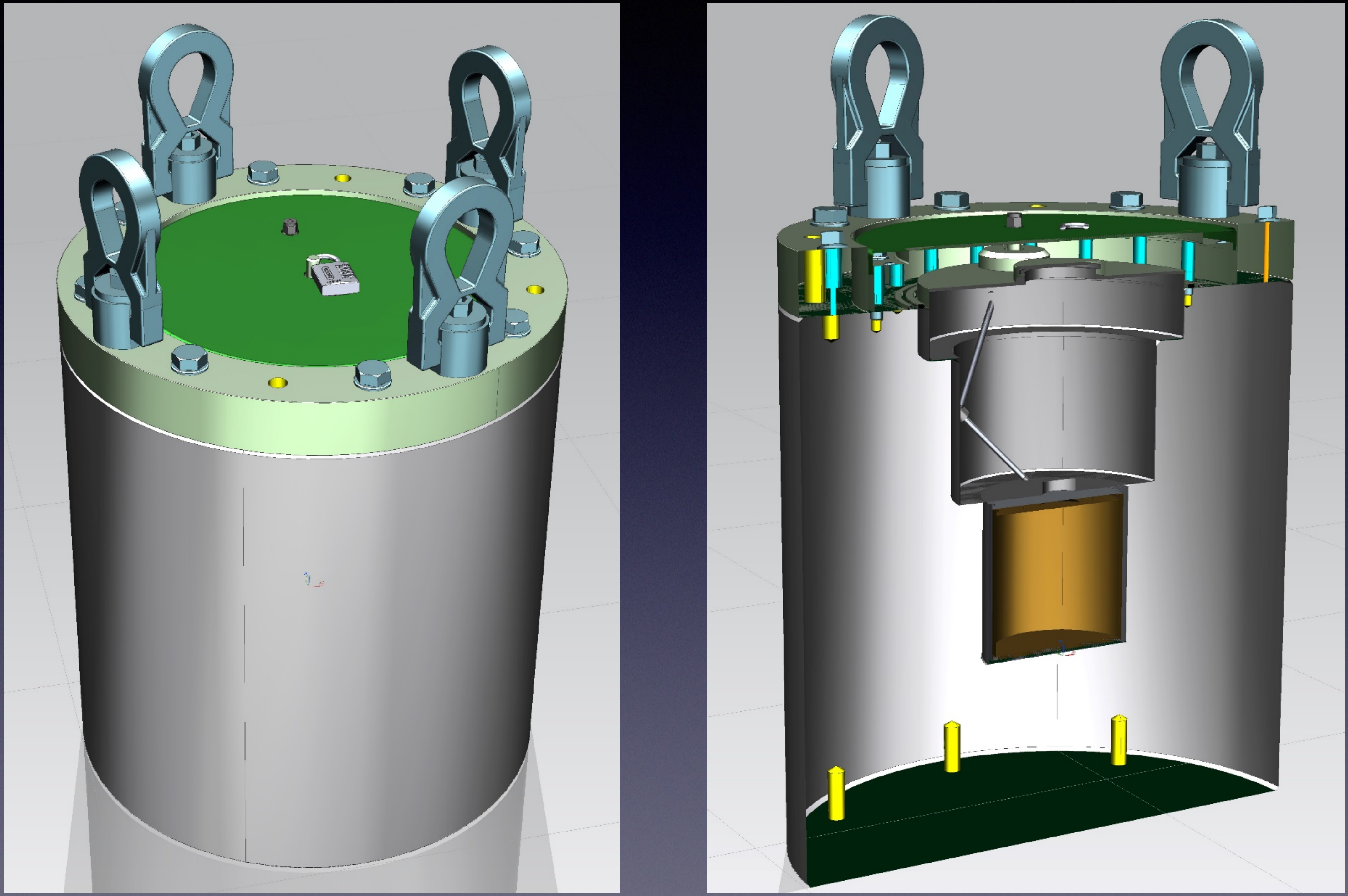
Source	Production	T (days)	Decay mode	Energy [MeV]	Mass [kg/MCi]	Heat [W/kCi]
^{51}Cr ν_e	Neutron irradiation of ^{50}Cr in reactor $\Phi_n \gtrsim 5.\ 10^{14}\ cm^{-2}\ s^{-1}$	40	EC γ 320 keV (10%)	0.746	0.011	0.19
^{144}Ce-^{144}Pr $\bar{\nu}_e$	Chemical extraction from spent nuclear fuel	411	β-	<2.9975	0.314	7.6



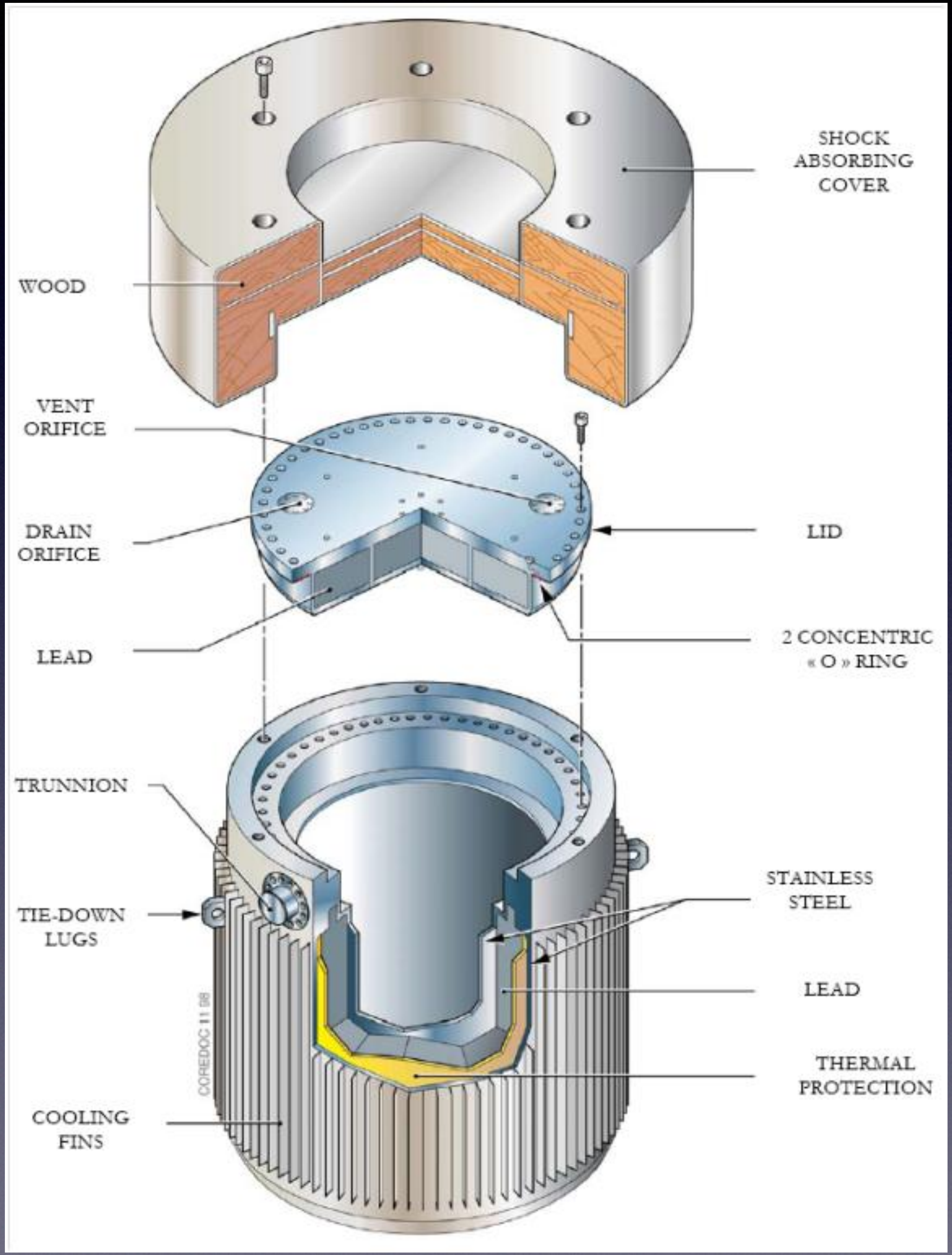




Ce Source Design

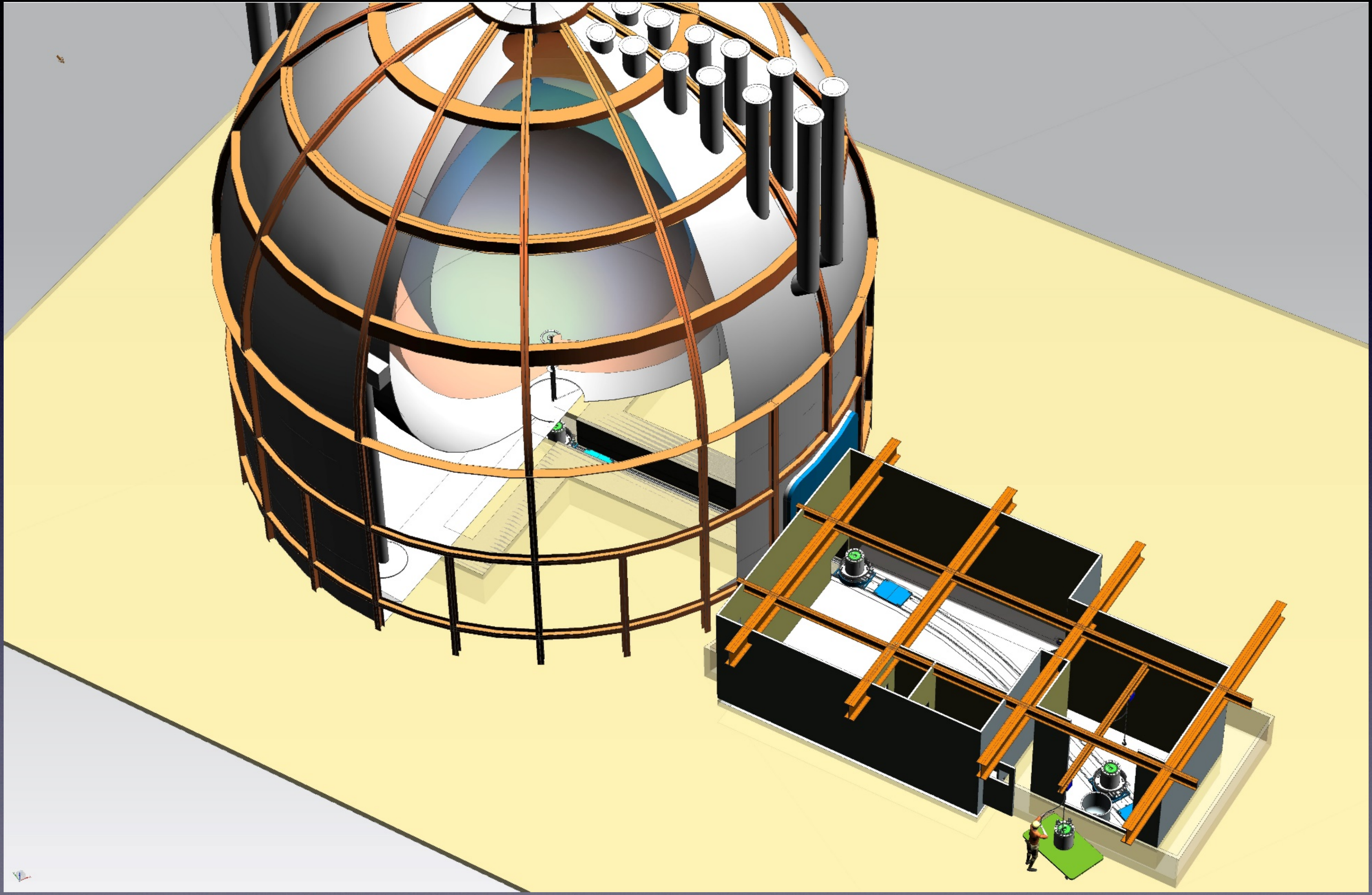


Transportation container

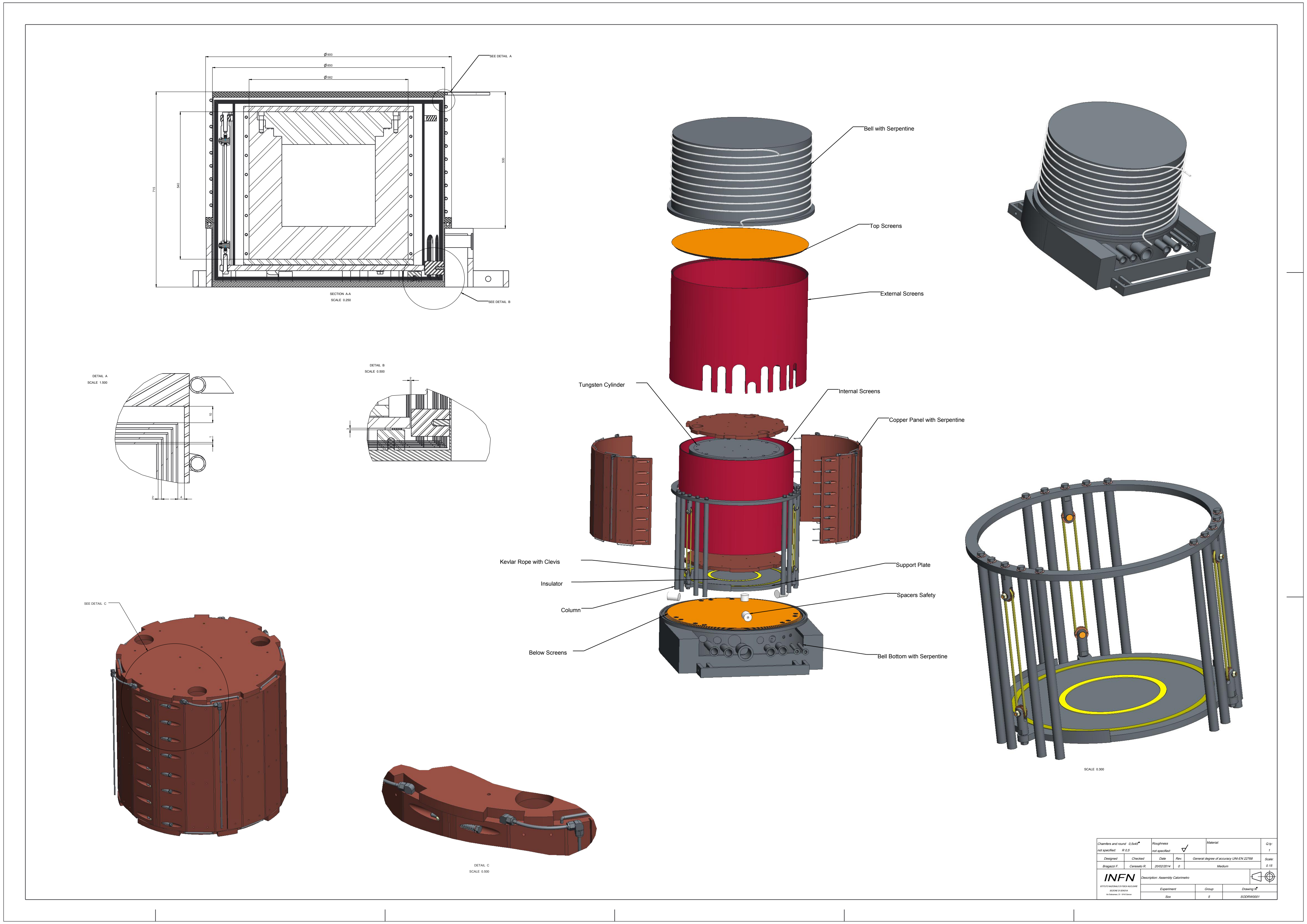


Custom AREVA spreader

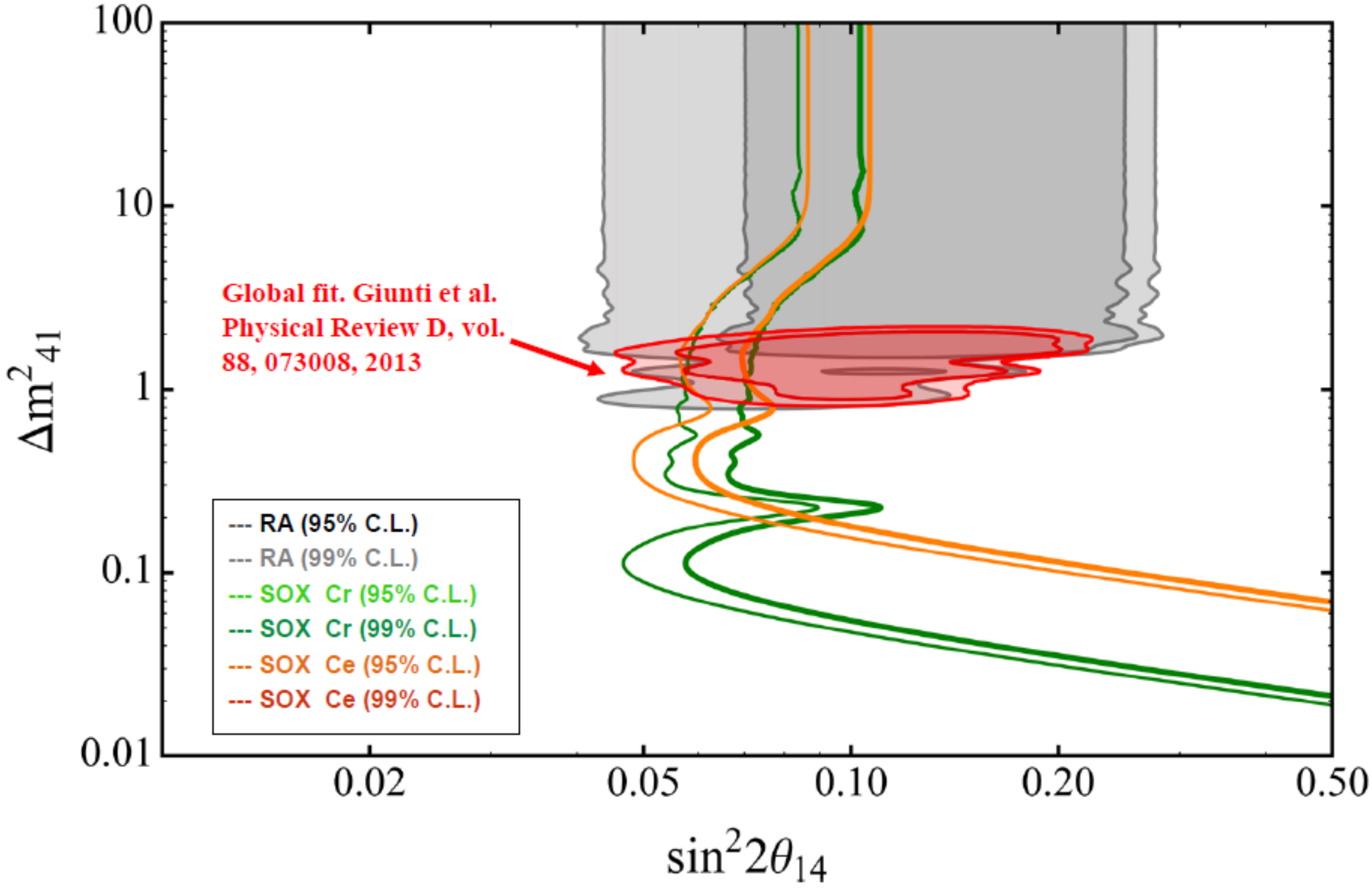
Logistic inside Hall C



High precision calorimetry



SOX: sensitivity to sterile neutrino



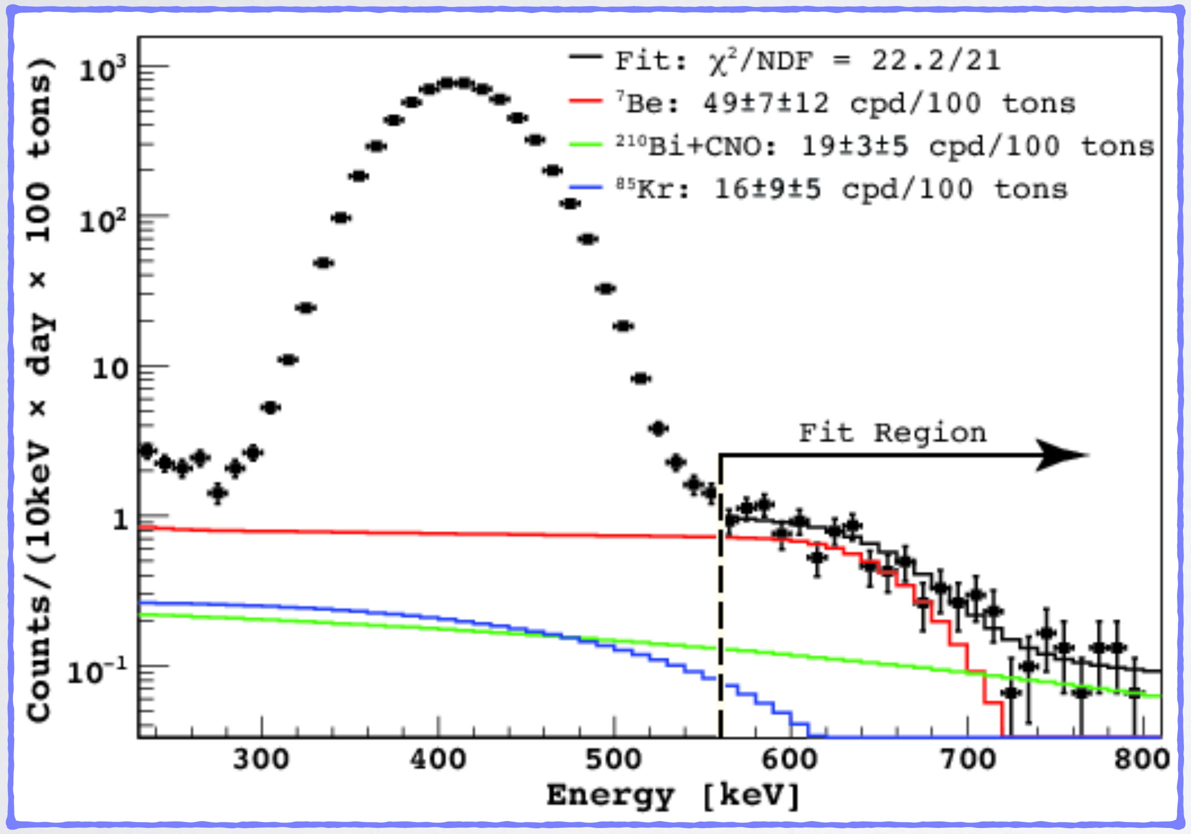
CONCLUSIONS

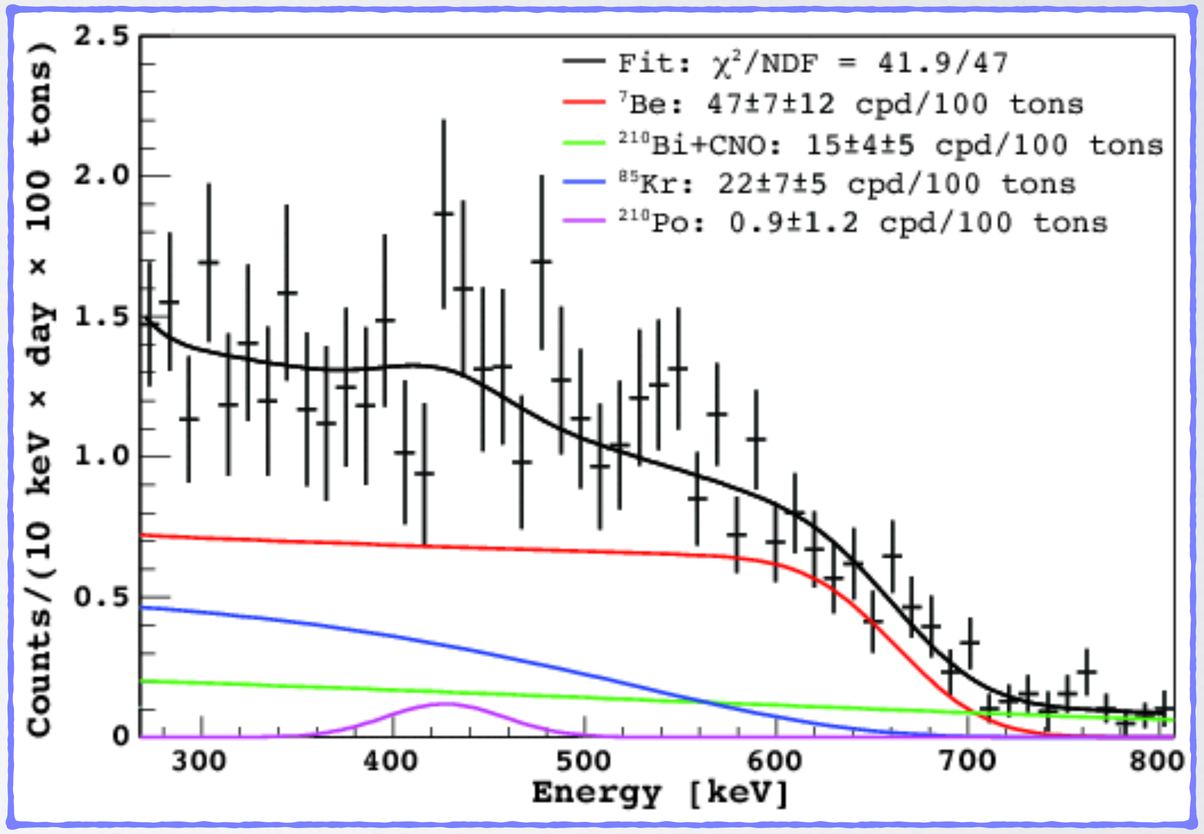
- The Phase I of the Borexino experiment was very successful
  - First detection and 5% measurement of ^{7}**Be** line
  - ^{8}**B** at low energy, ^{7}Be day-night, **geo-neutrinos** at 99.997% c.l.
  - First detection of **pep** solar neutrinos
  - New limits on Pauli Principle Violation and Solar Axions
- Purification was successful, and phase 2 has started in 2012
  - A rich program on solar neutrino physics to be completed
    - **Measure pp neutrinos. DONE!**
    - Probe MSW through ^{8}B at low energy, pep and more precise ^{7}Be
    - Attempt to detect pp in real time and possible interesting upper limit on CNO
- Medium / Long term plans include:
  - Possible additional purification campaign
  - SOX: Sterile Neutrino Search with neutrino and/or anti-neutrino sources
    - Anti-neutrino source in Nov. 2015

BACKUP

FIRST DETECTION OF ^{7}Be ν - 2007

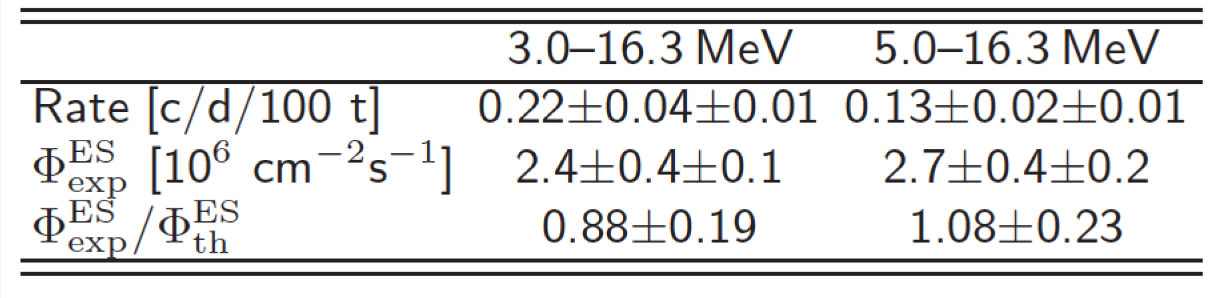
- The large effort made in 1990-2007 paid off
  - Detector purity was immediately understood to be better than design goals
  - The first detection of ^{7}Be neutrinos could be done in ~ 1 month



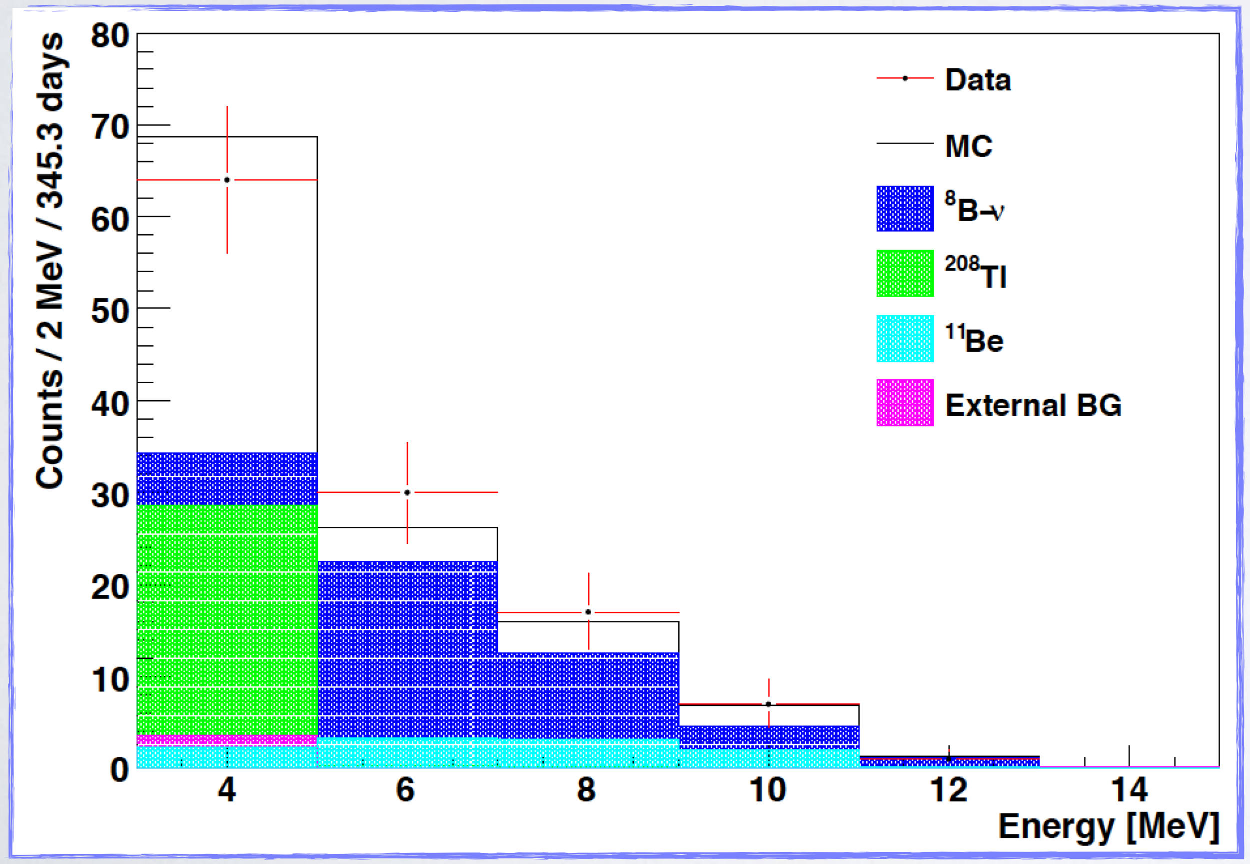


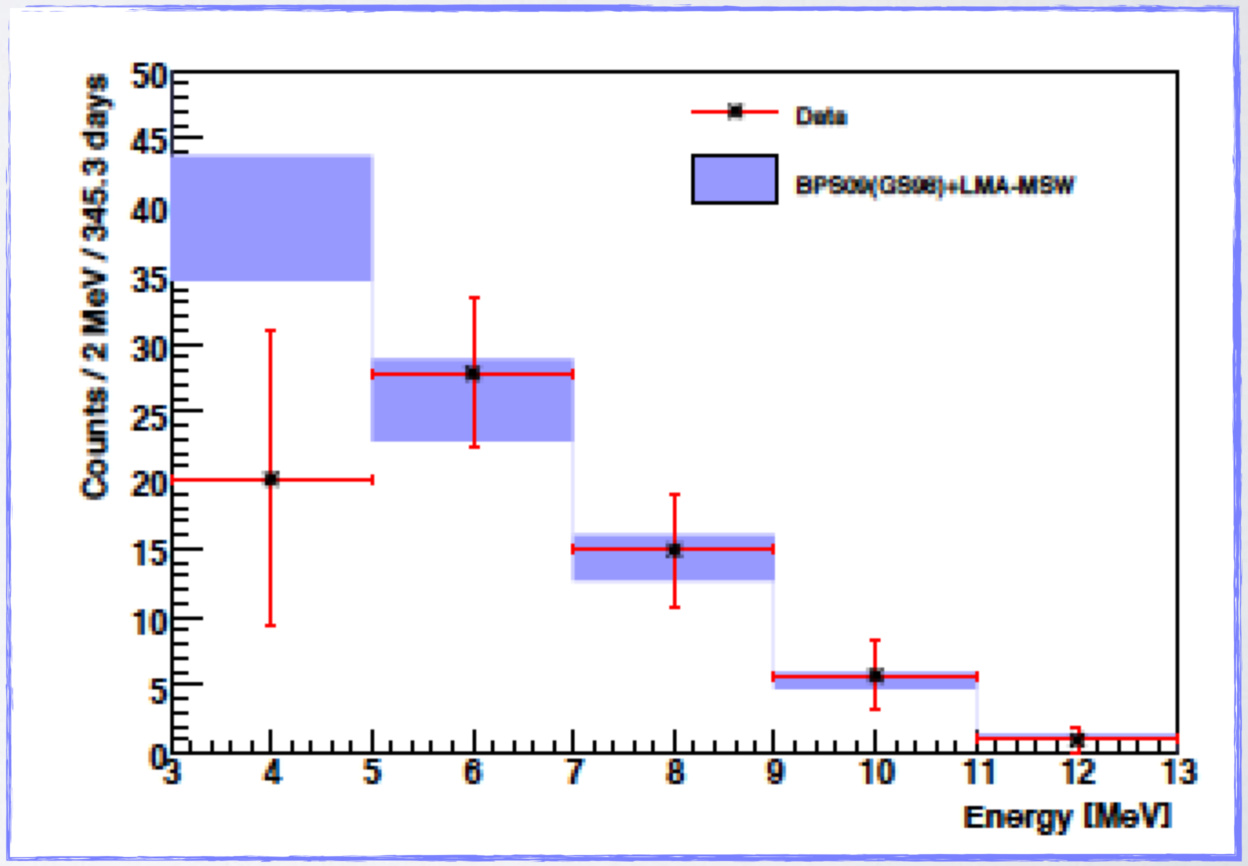
FIRST DETECTION OF ^{8}B BELOW 4 MeV

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



	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
$\Phi^{\mathrm{ES}}_{\mathrm{exp}}$ [10^6 cm^{-2}s^{-1}]	2.4±0.4±0.1	2.7±0.4±0.2
$\Phi^{\mathrm{ES}}_{\mathrm{exp}}/\Phi^{\mathrm{ES}}_{\mathrm{th}}$	0.88±0.19	1.08±0.23

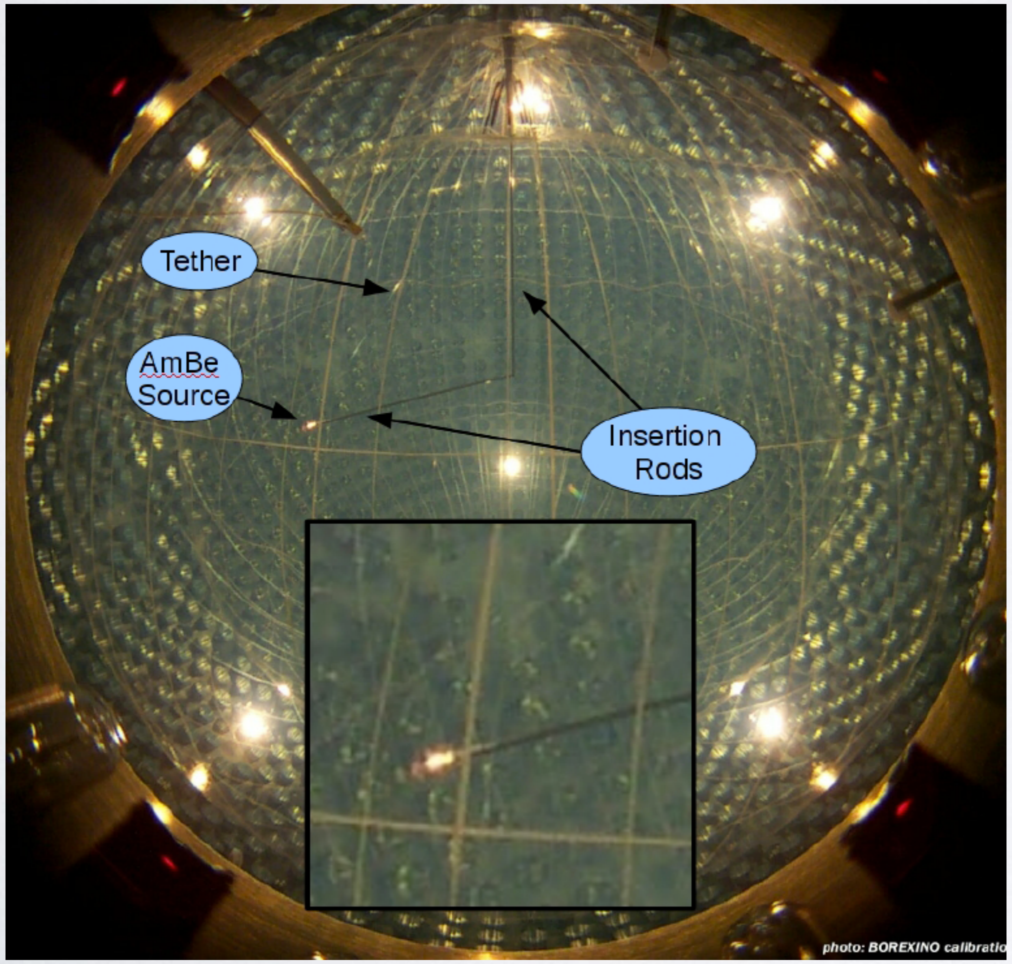




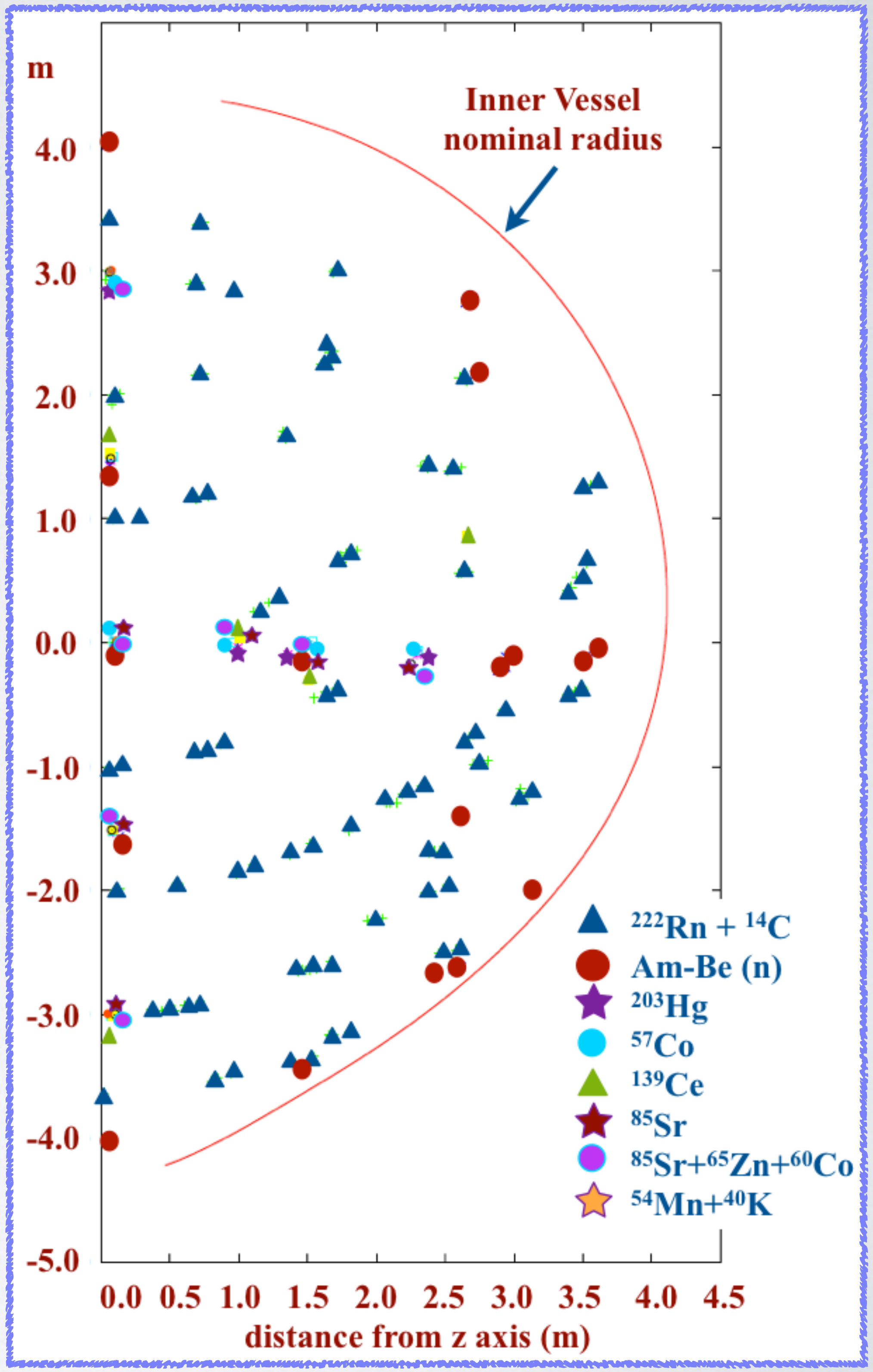
^{7}Be RATE AT HIGH PRECISION (I)

- Main goal: measurement of the ^{7}Be **solar ν interaction rate**
  - key points for high precision paper:
    - Precise energy calibration
    - Precise determination of the fiducial volume
    - Strong effort on Monte Carlo simulation

A source inside Borexino



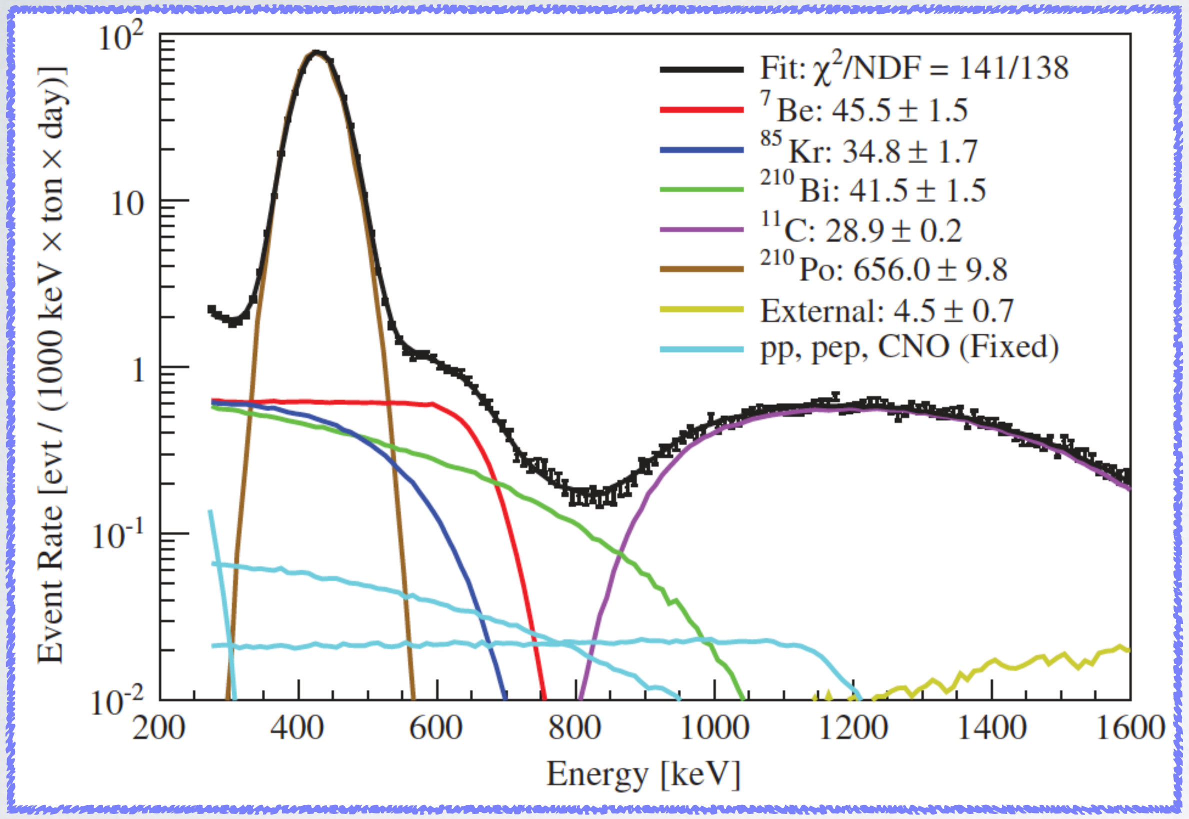
Location of calibration points



^{7}Be RATE AT HIGH PRECISION (II)

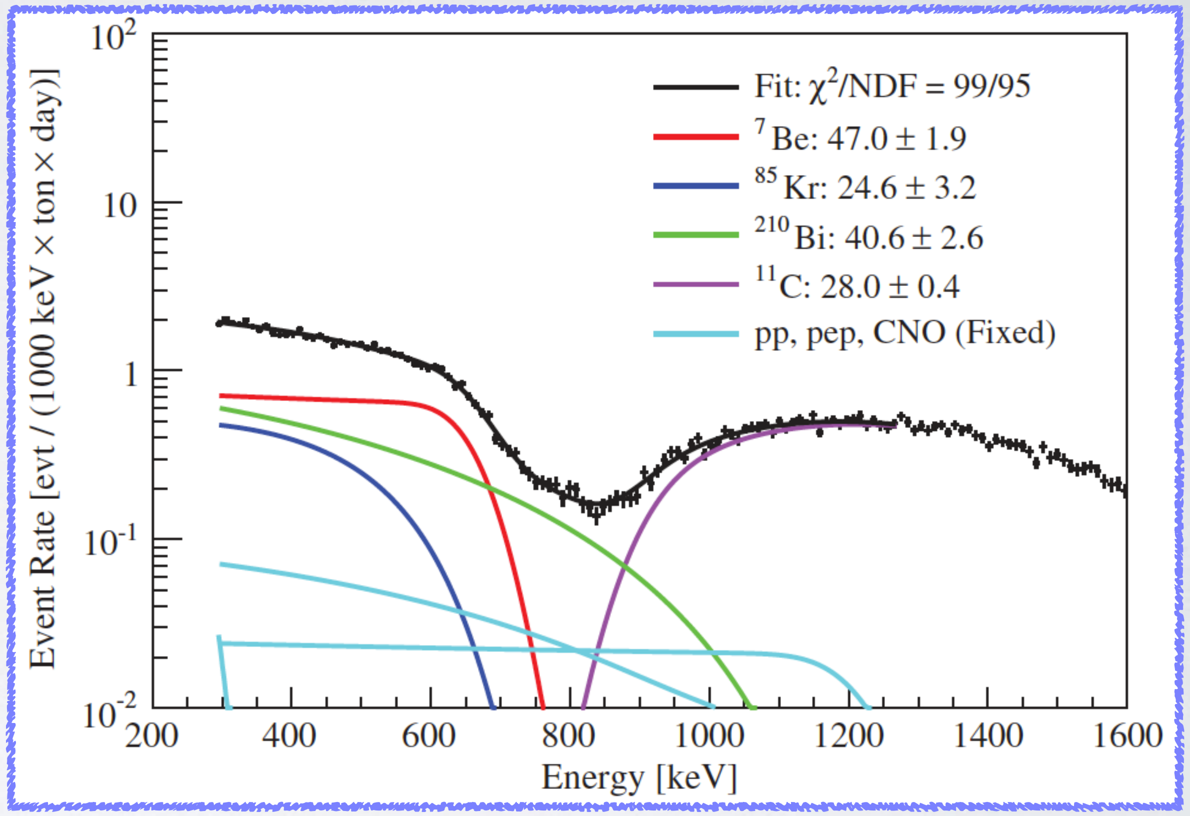
- Two approaches to control systematic errors due to analysis procedure:

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

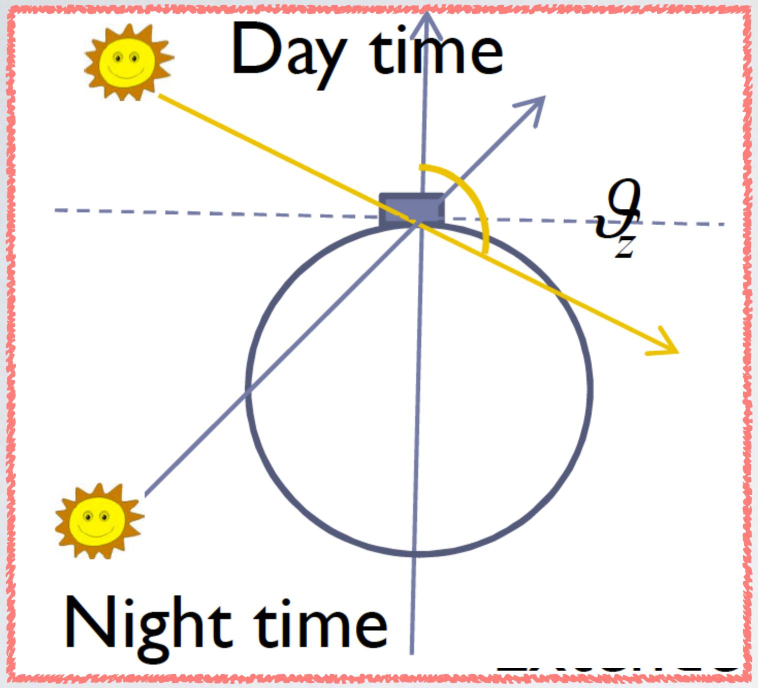


- Very Consistent results, small difference included in sys. uncertainty
- Rate for 100 t target:

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



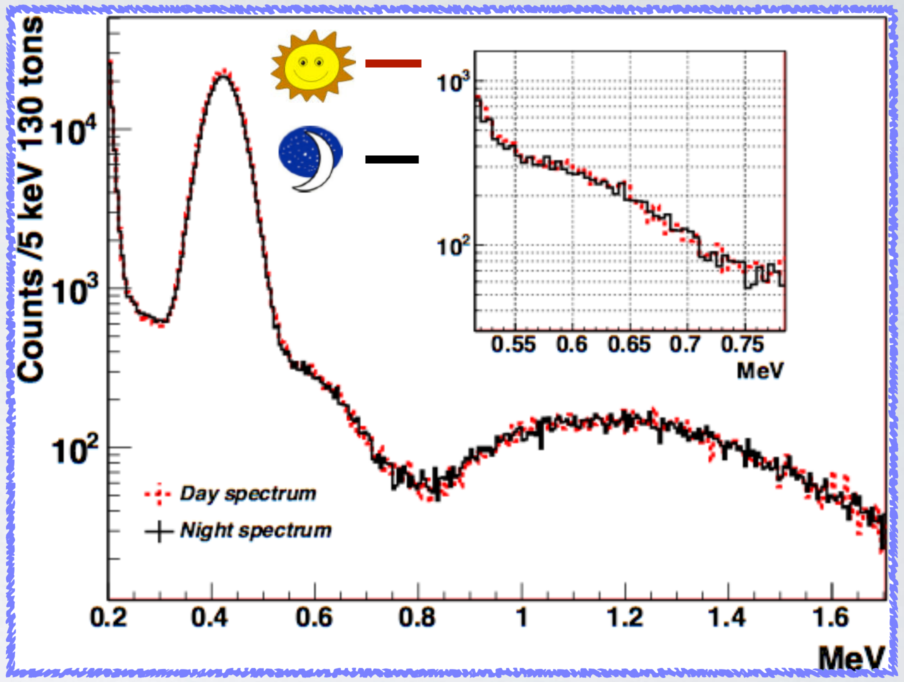
Phys. Lett. B707:22–26, 2012

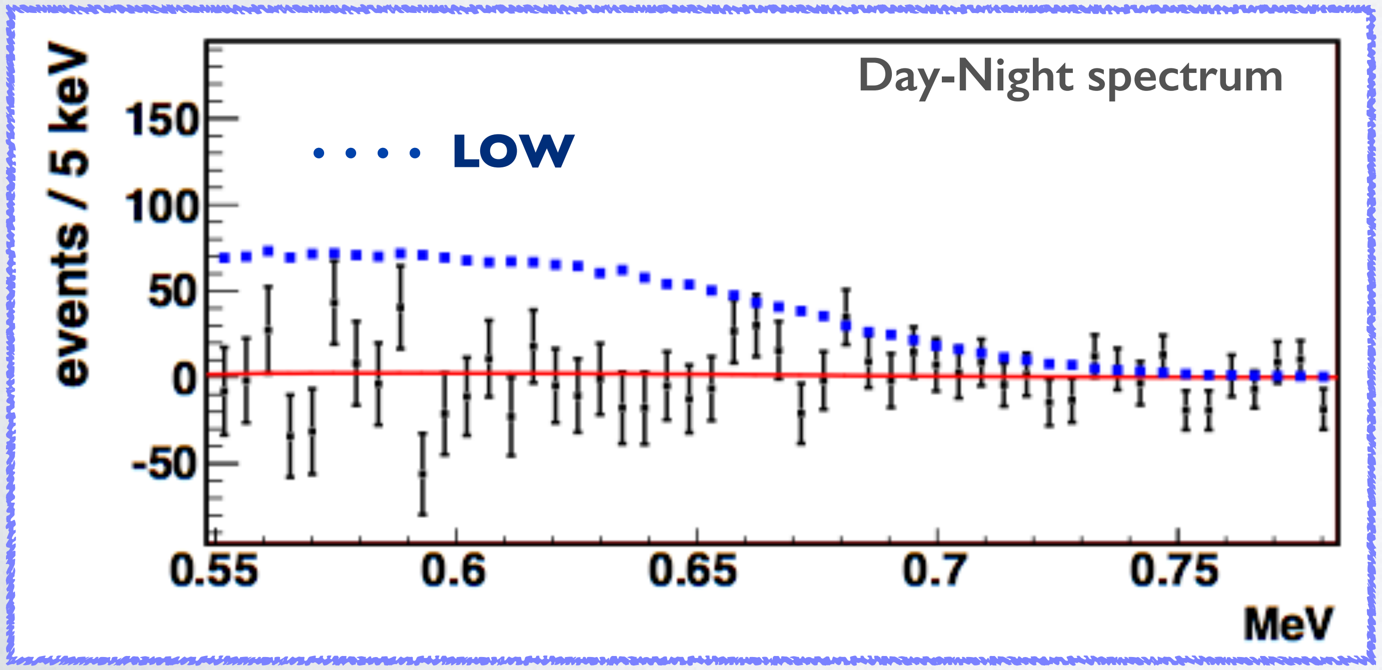
$$A_{dn} = 2\frac{R_N - R_D}{R_N + R_D} =$$

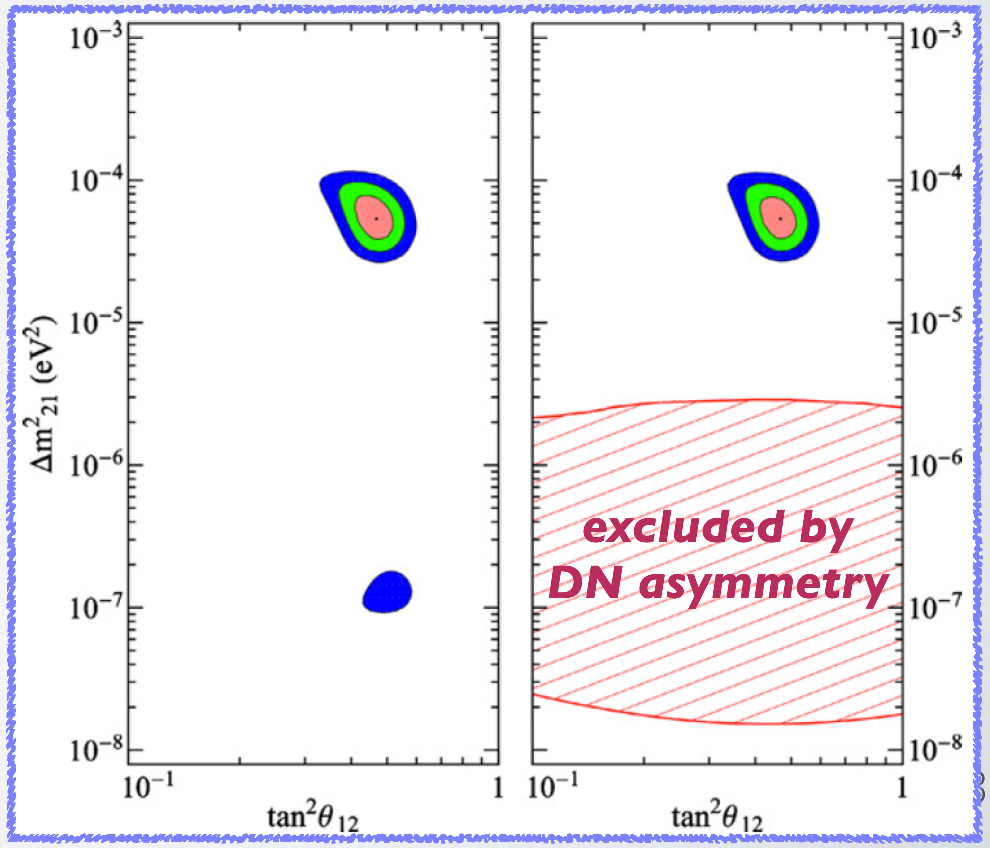
$$= 0.001 \pm 0.012 \pm 0.007$$

No asymmetry

Day and Night spectra

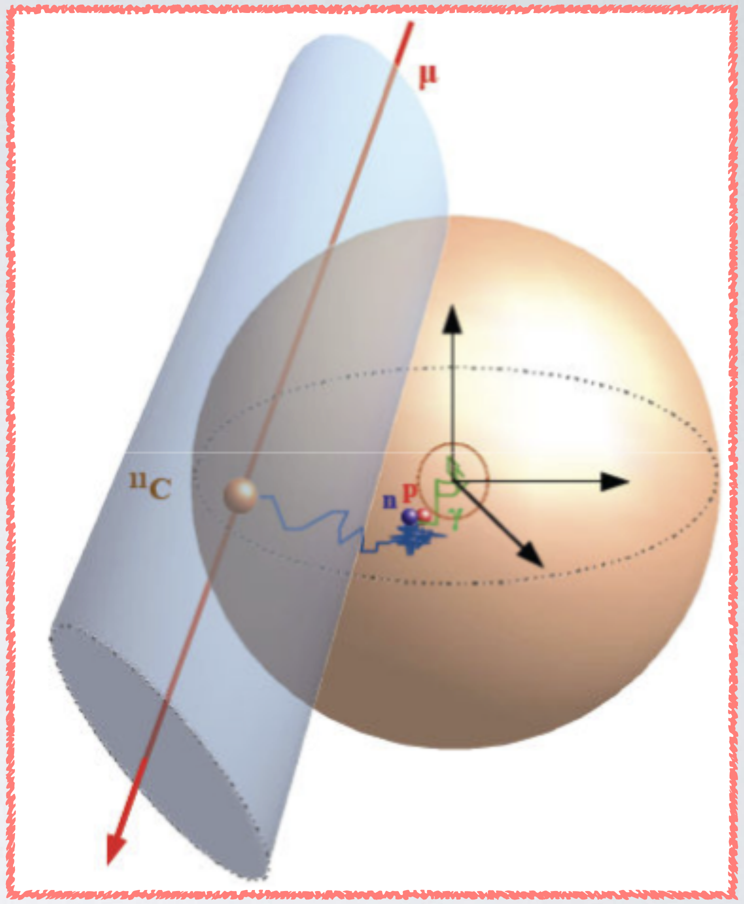




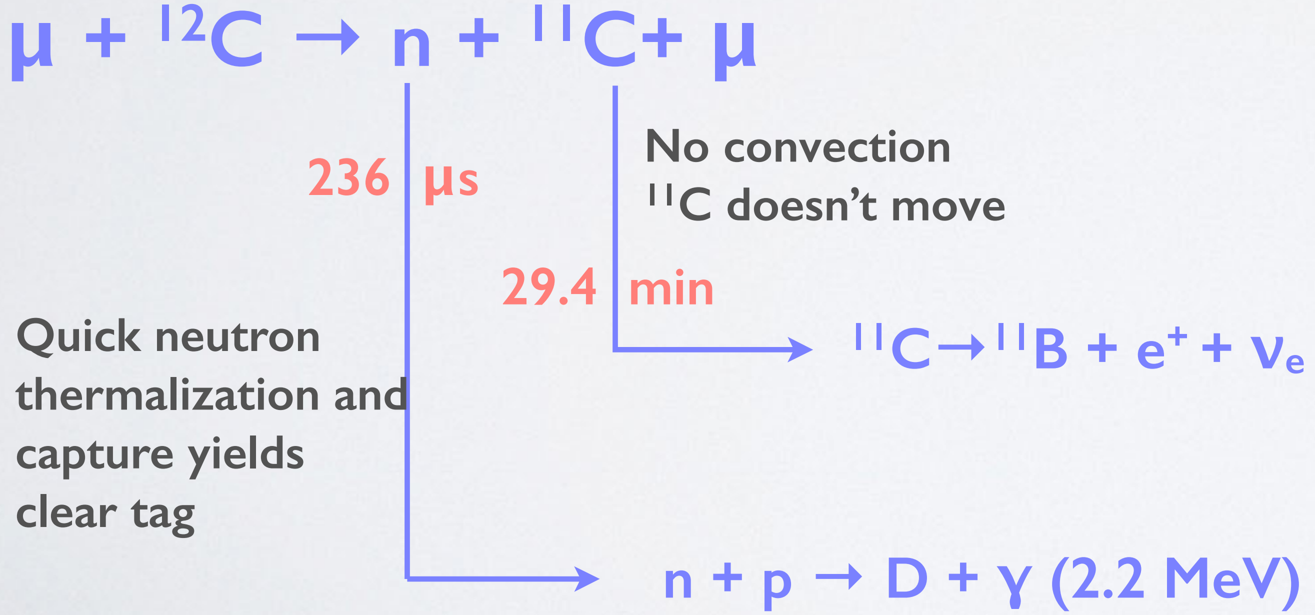


FIRST DETECTION OF PEP NEUTRINOS (I)

- 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 available information



- **Three-fold coincidence**



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

236 μs

No convection
^{11}C doesn't move

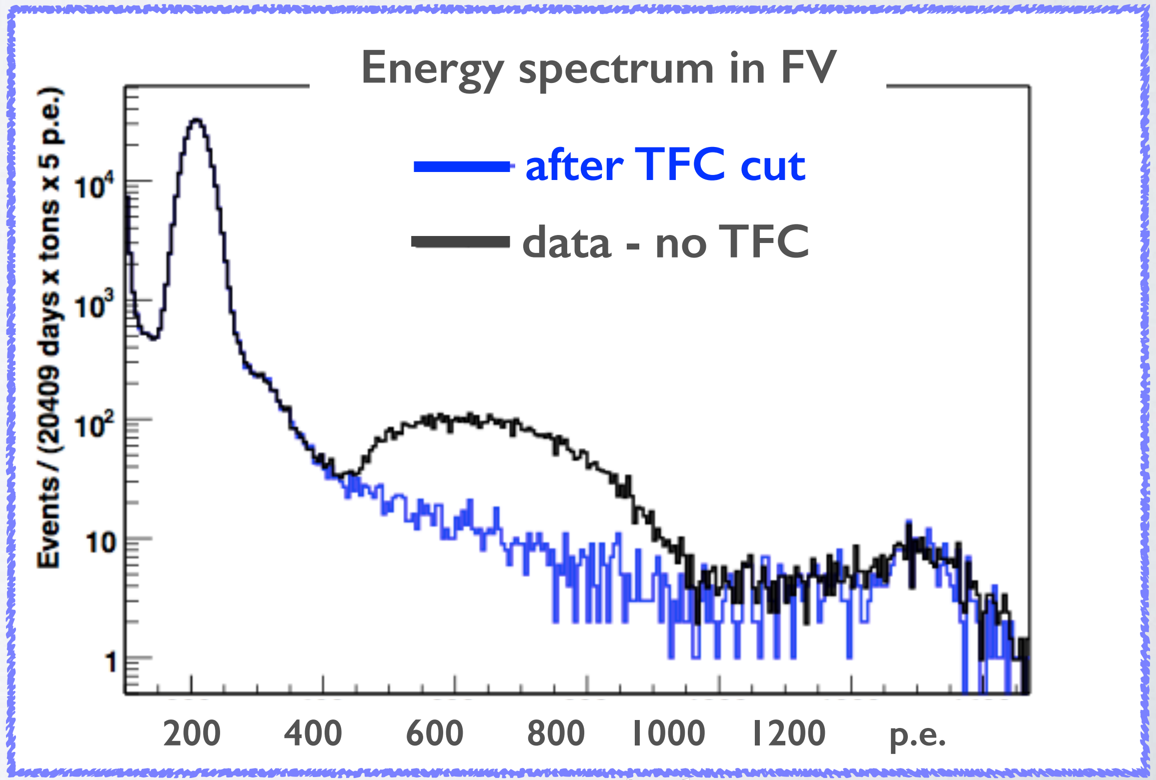
29.4 min

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

Quick neutron thermalization and capture yields clear tag

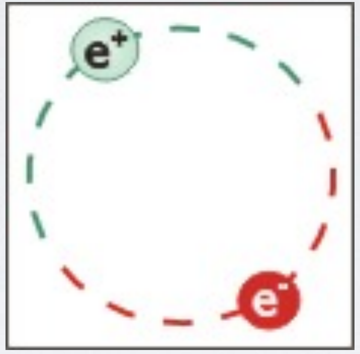
$n + p \rightarrow D + \gamma$ (2.2 MeV)

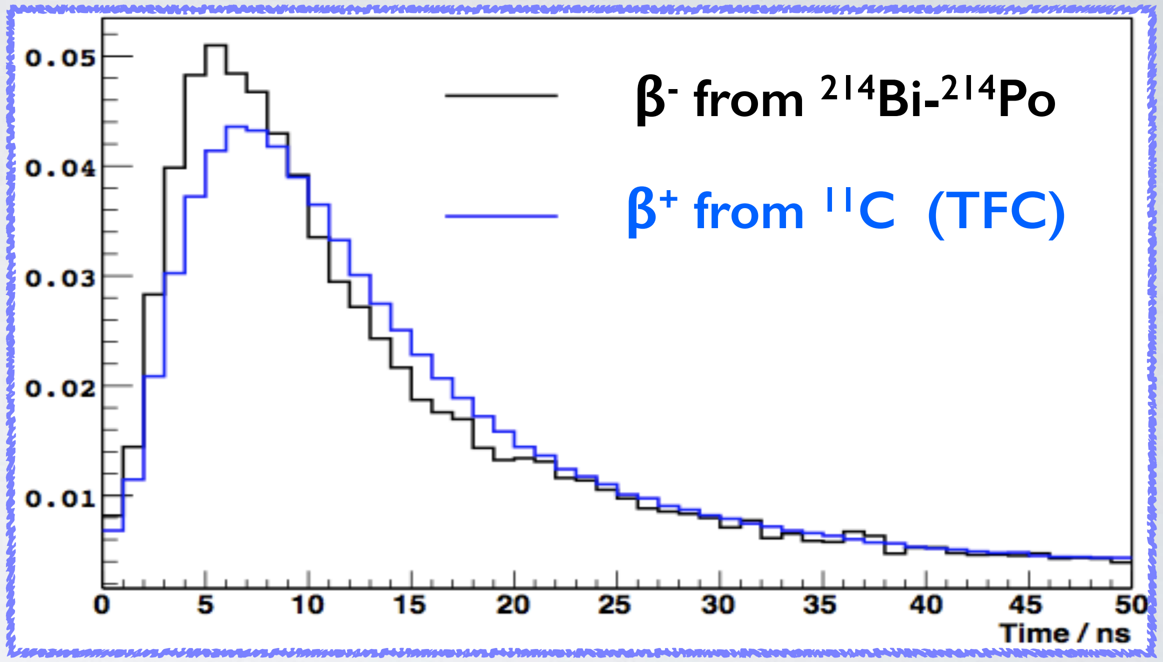
PHYSICAL REVIEW C 74, 045805 (2006)

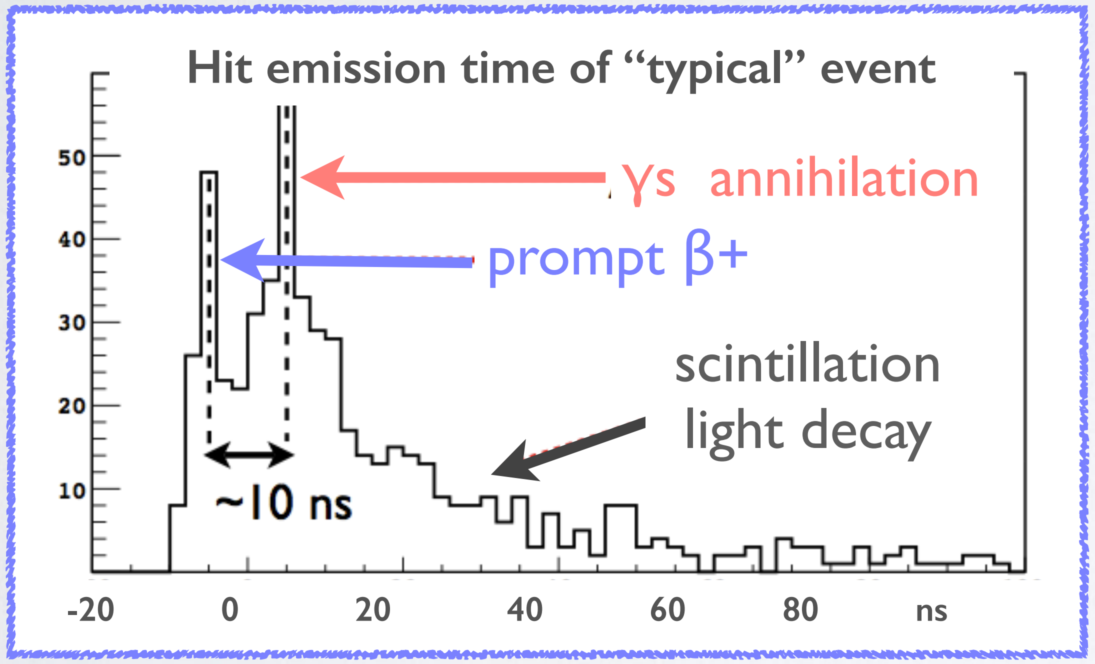


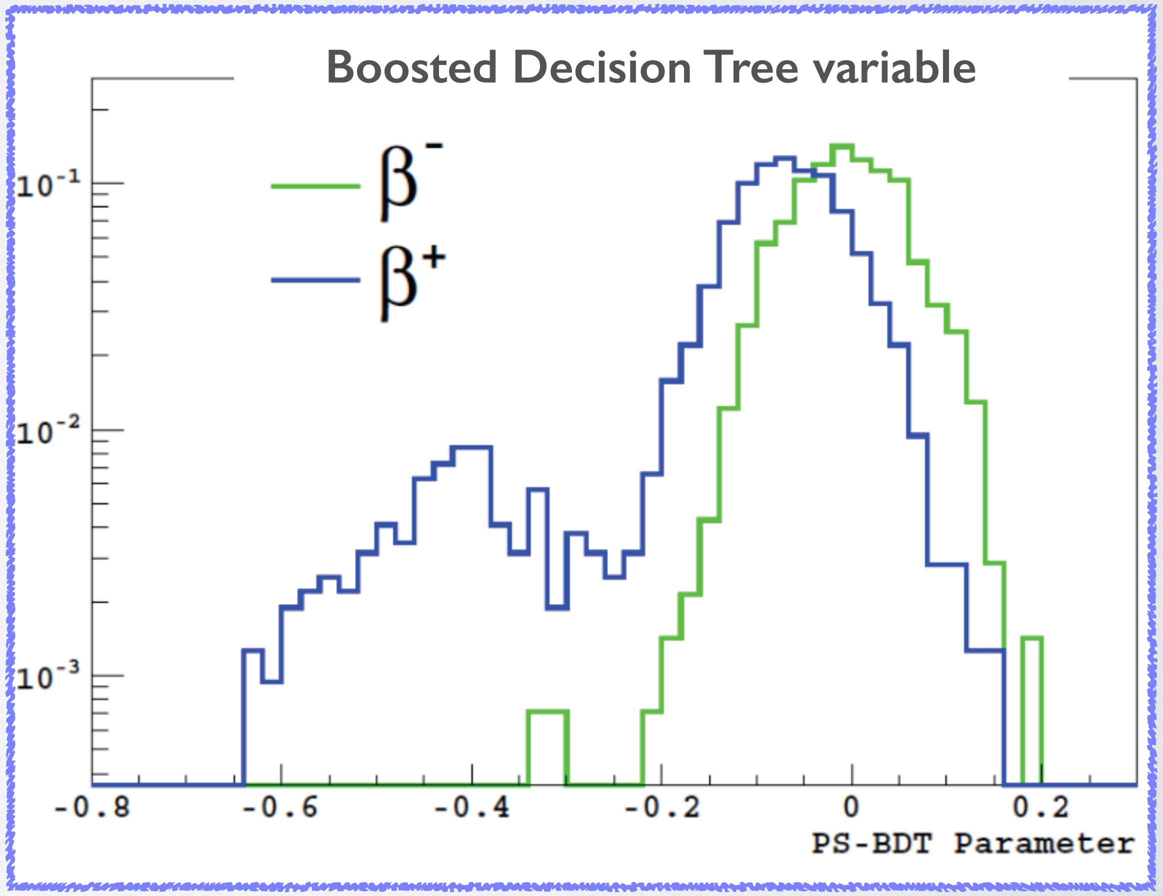
β+ - β- DISCRIMINATION

- 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






Hit emission time of "typical" event

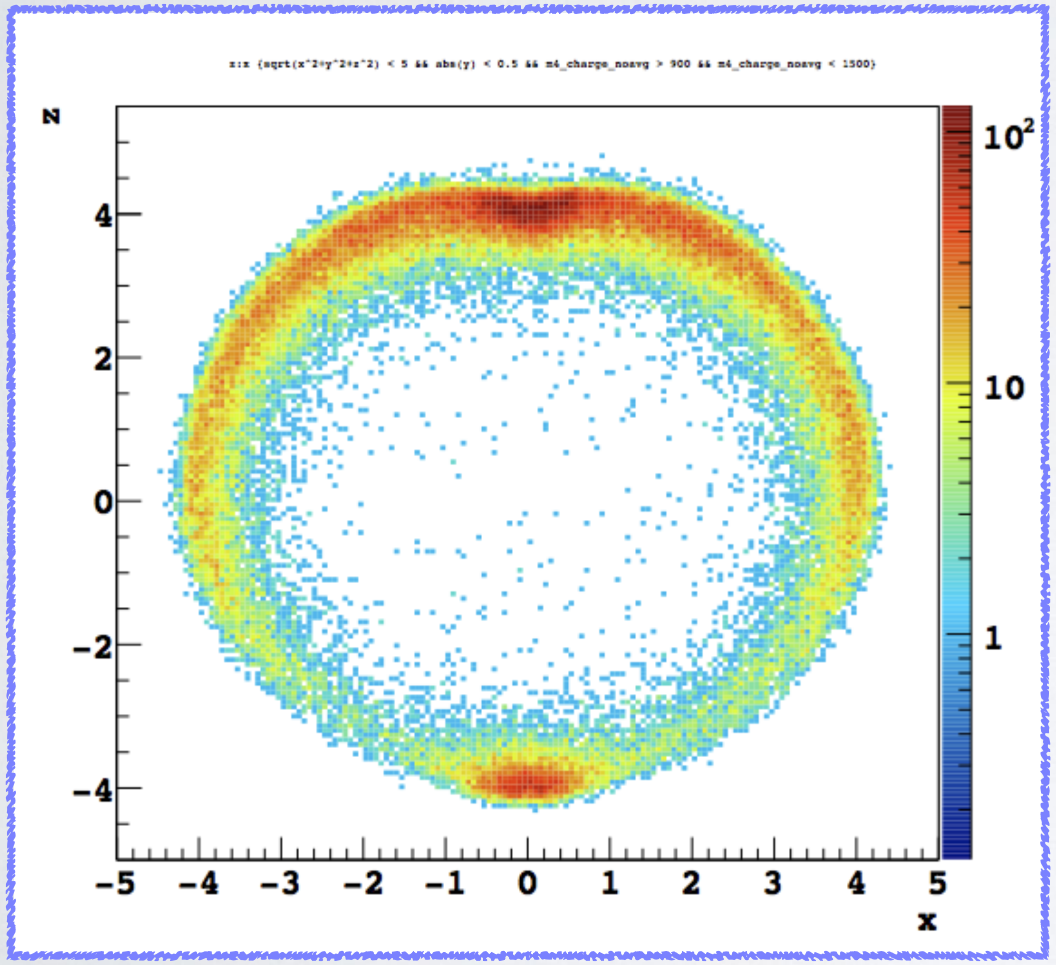

Boosted Decision Tree variable

- A Pulse Shape discriminating variable was developed, based on a **Boosted**

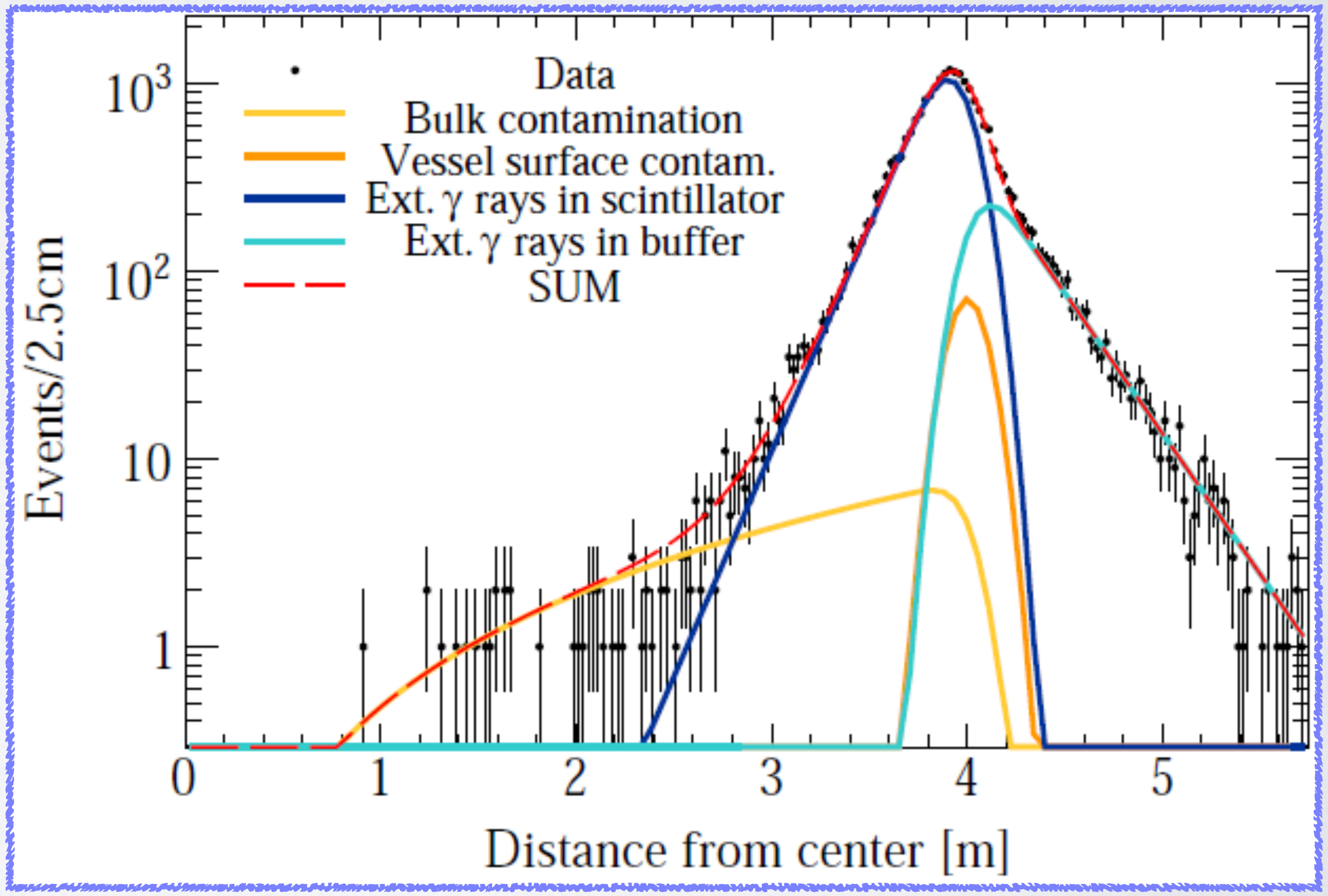
FIRST DETECTION OF PEP NEUTRINOS (III)

- Final fit done with multivariate likelihood fit
  - External background identified by means of its spatial distribution
  - ^{11}C by means of BDT variable
  - Energy used to disentangle other β backgrounds (^{210}Bi in particular)

Radial distribution of events



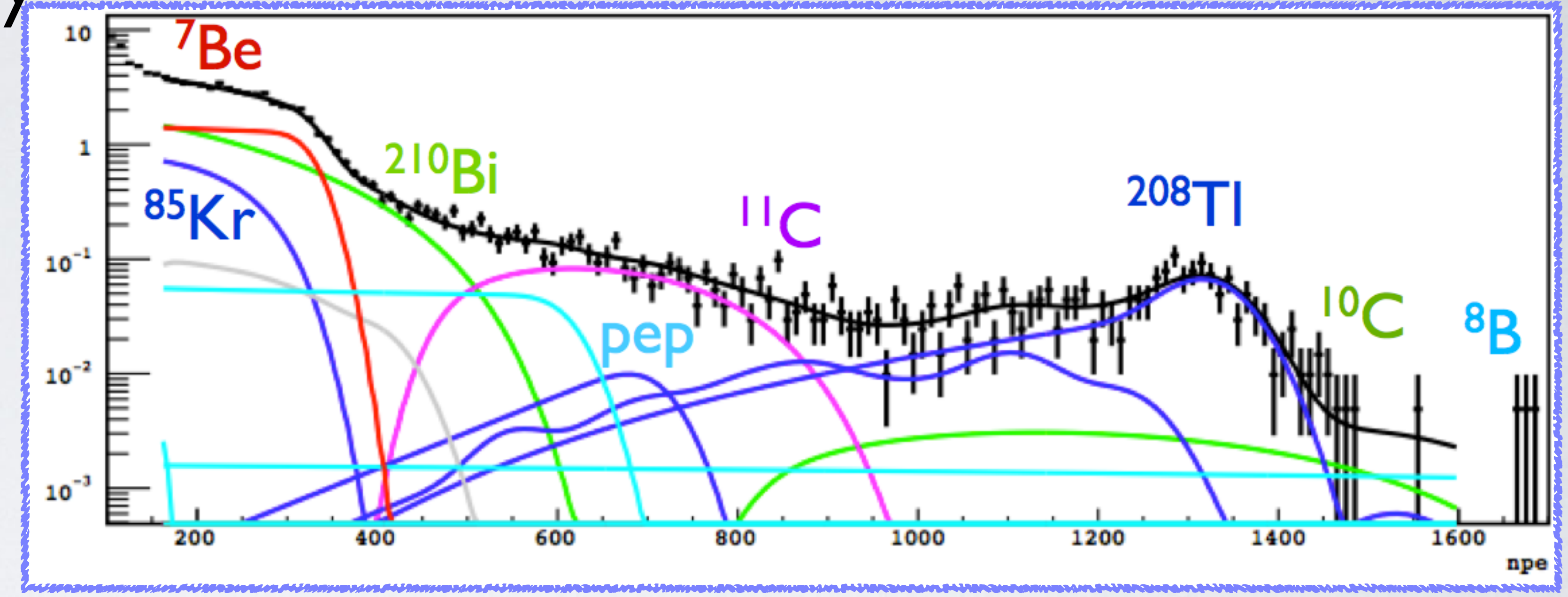
Fit to data collected with ^{228}Th external source



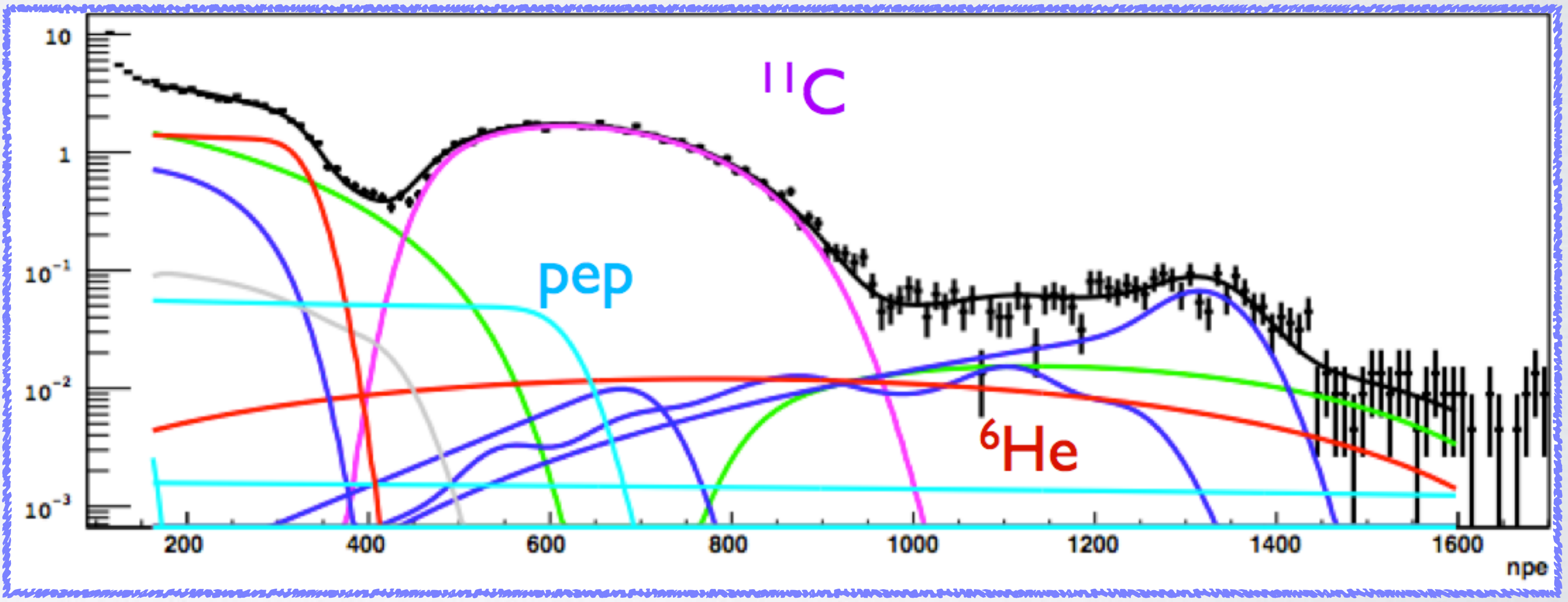
FIRST DETECTION OF PEP NEUTRINOS (IV)

- Multidimensional fit strategy
  - Binned likelihood which includes
    - energy spectrum
    - **BDT parameter**
    - radial shape
  - Simultaneous fit to events surviving TFC veto and to rejected events, constrainin non-cosmogenic species to be the same
  - Hundreds of MC experiments done to

Spectrum after TFC veto



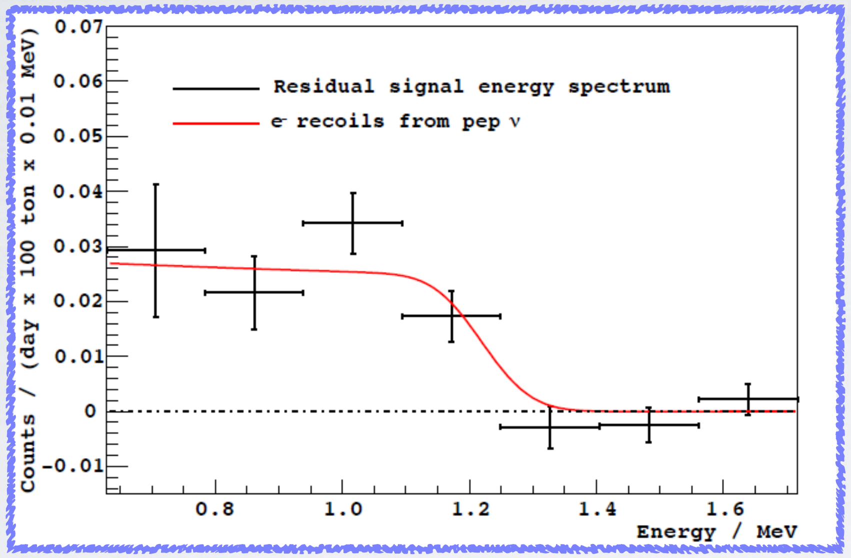
Spectrum of vetoed events



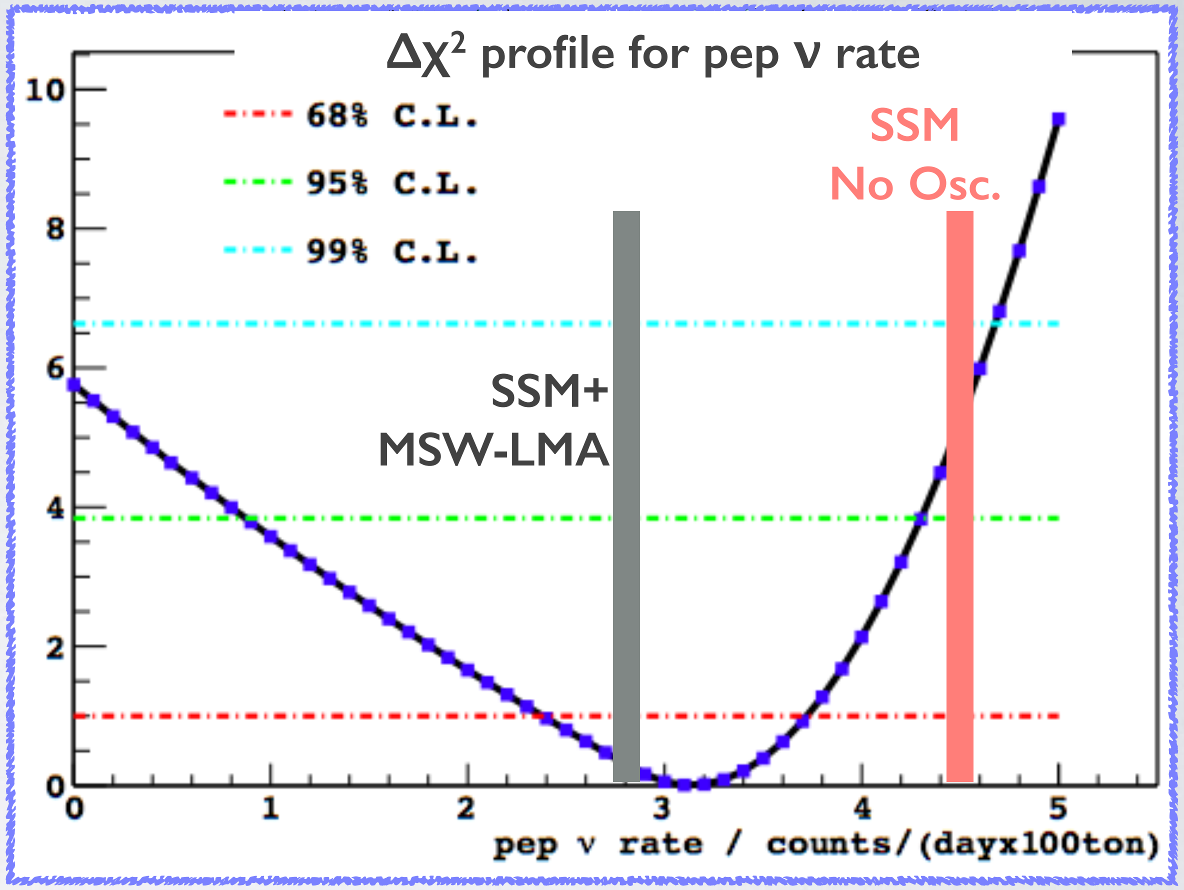
FIRST DETECTION OF PEP NEUTRINOS (V)

- Rate: 3.1 ± 0.6$_{\text{(stat)}}$ ± 0.3$_{\text{(sys)}}$ 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:
  - $\Phi_{pep} = 1.6 \pm 0.3\ 10^8\ \text{cm}^{-2}\ \text{s}^{-1}$
- CNO limit obtained assuming pep @ SSM
  - **CNO rate < 7.1 cpd/100 t (95% c.l.)**