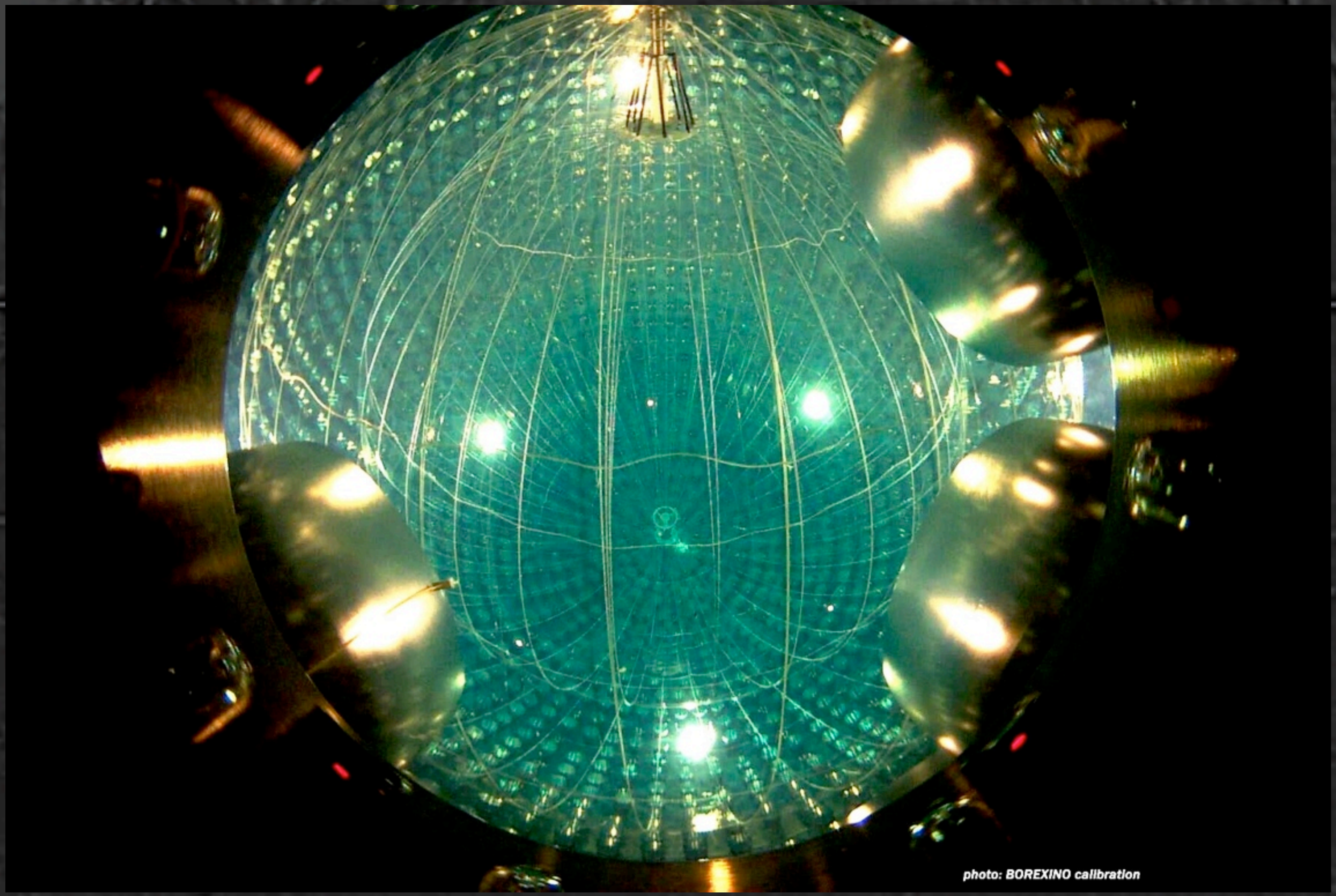


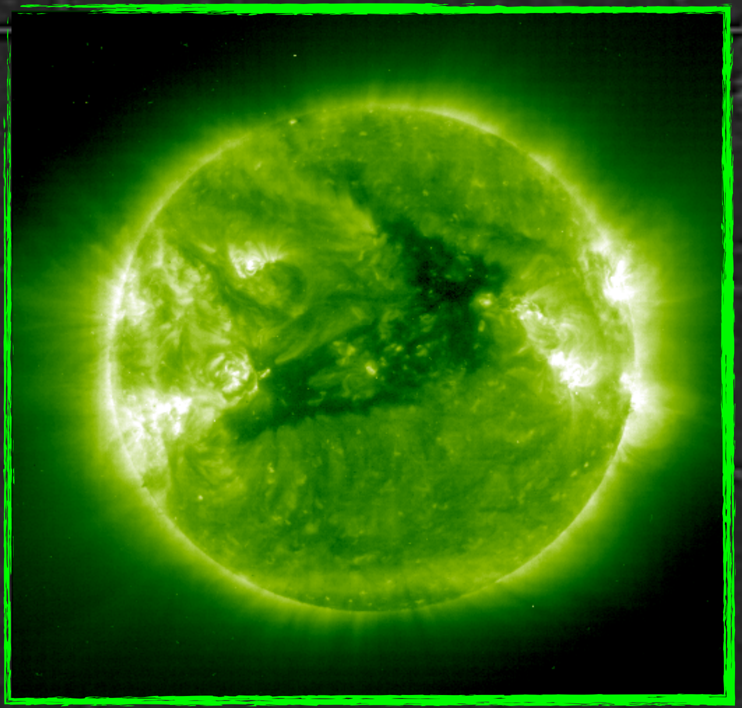
Neutrinos from the Sun and the Earth: what we understood in the last ten years

Marco Pallavicini

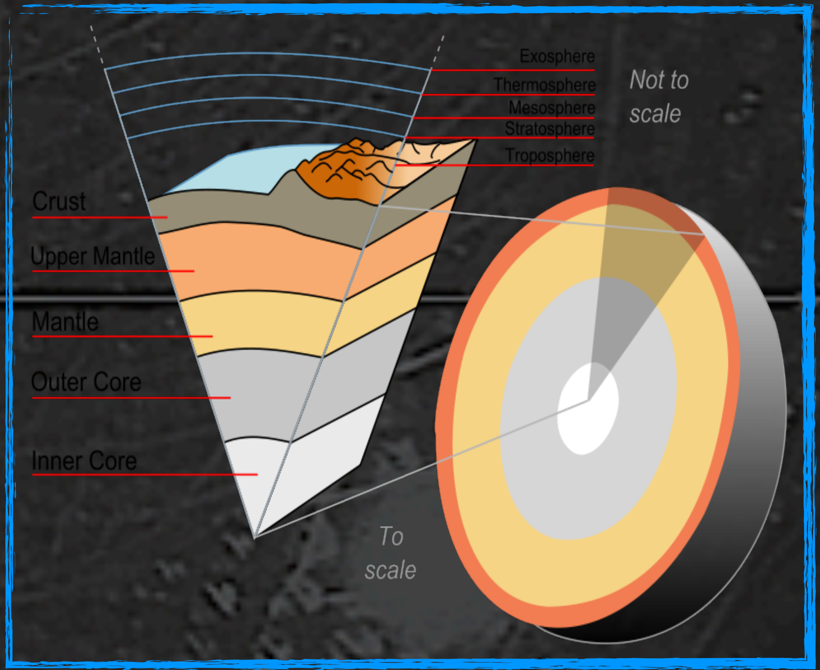
Università di Genova and INFN Genova

Talk outline

- **Solar neutrinos**
  - Introduction
  - Scientific motivations
  - Running experiments
  - Recent results
  - Future developments



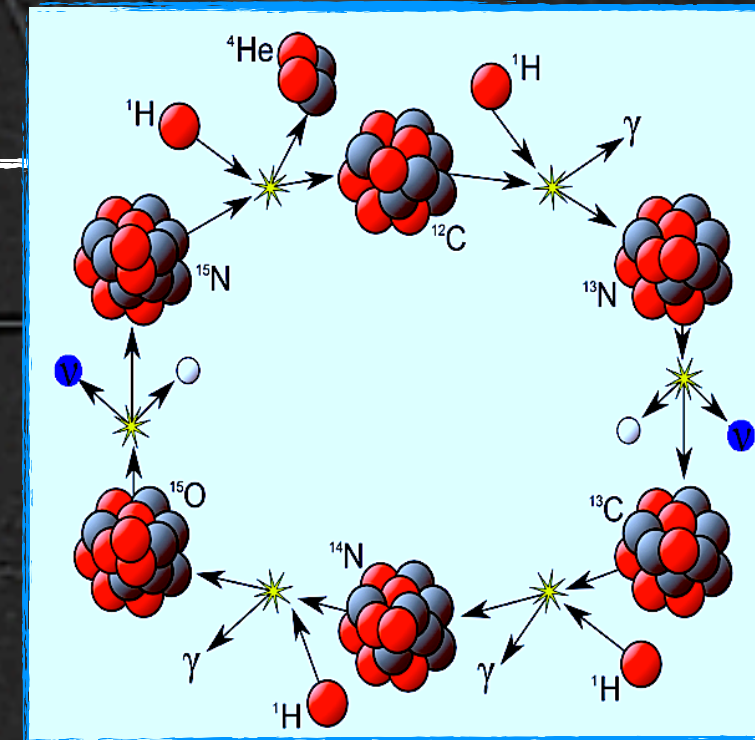
- **Geo-neutrinos** [see S. Zavatarelli's talk]
  - Discovery and status



- **Conclusions**

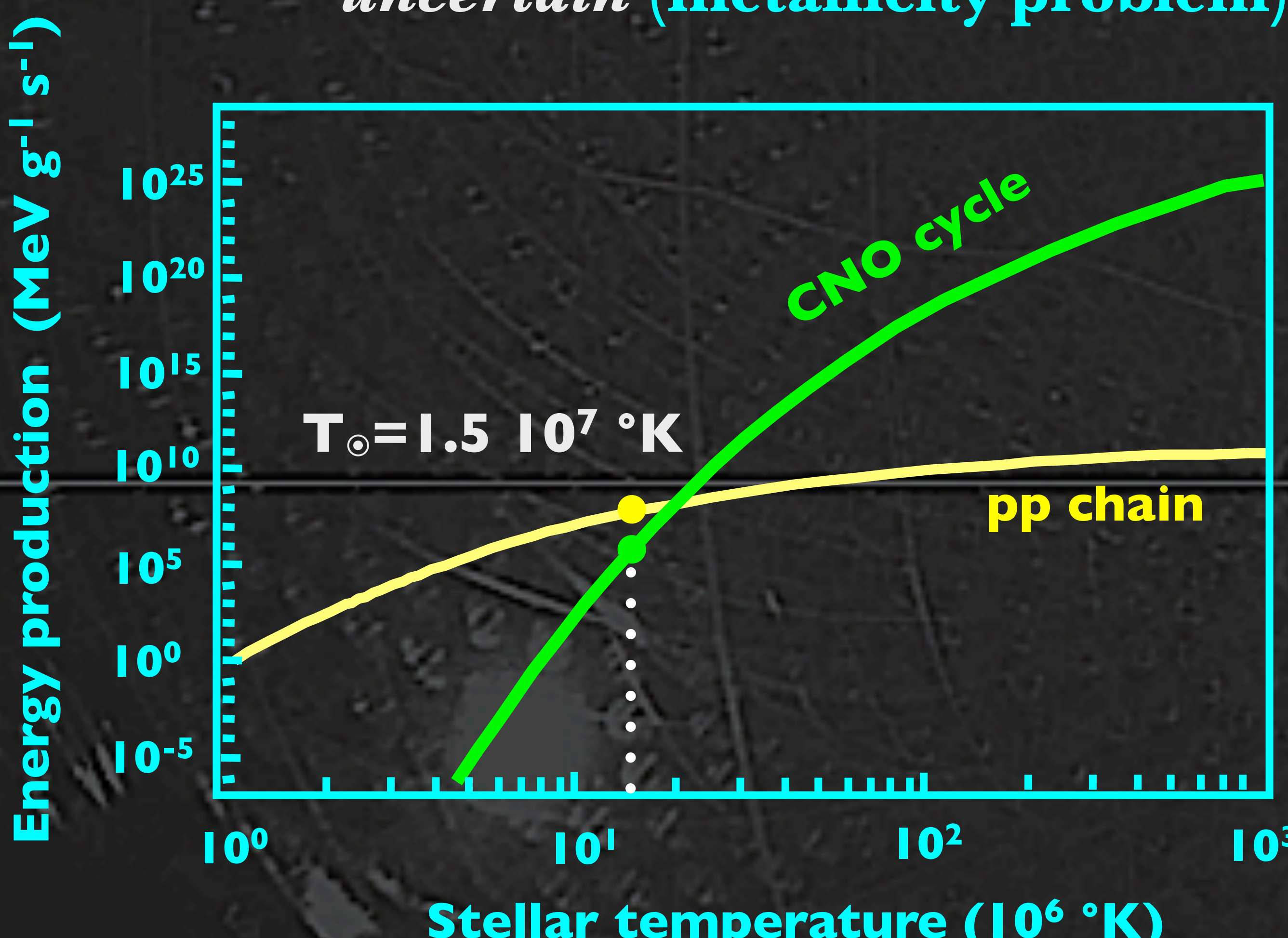
SOLAR NEUTRINOS

CNO cycle



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

H. Bethe



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

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

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

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

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

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

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

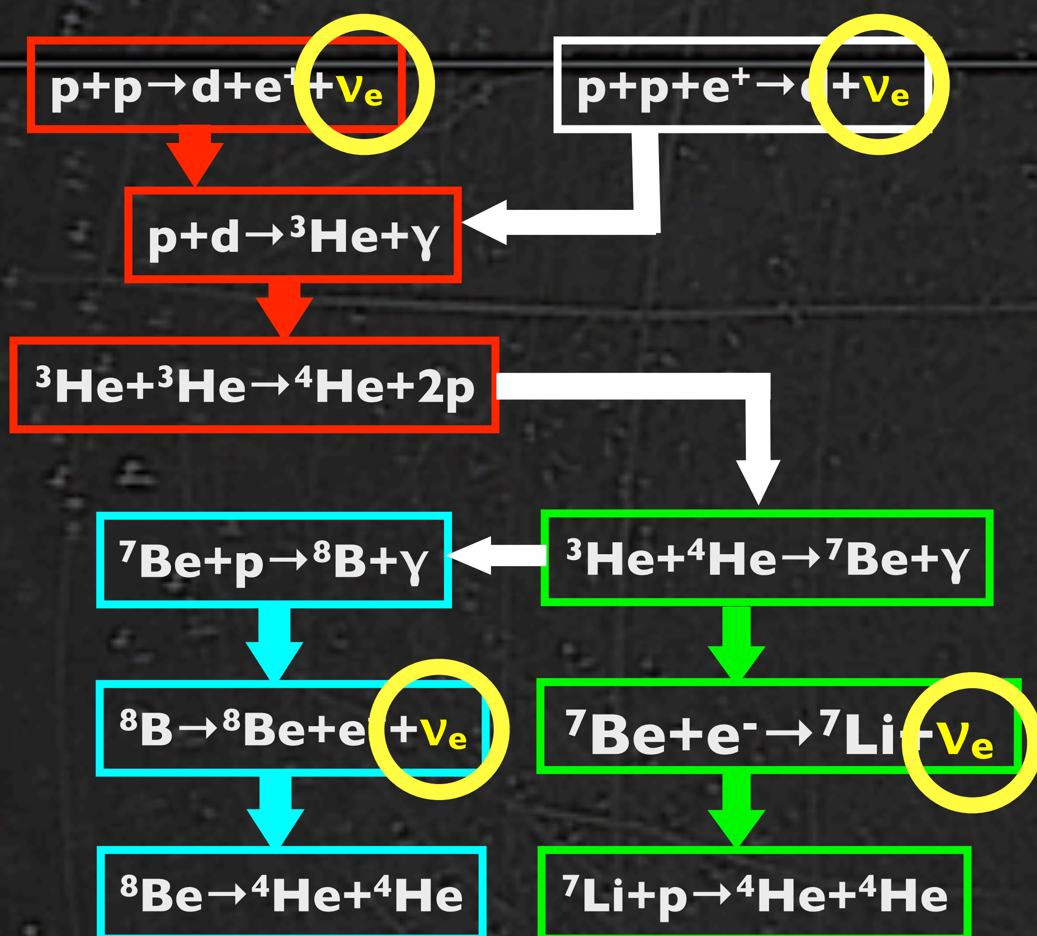
${}^{7}Be+e^{-} \rightarrow {}^{7}Li+\nu_e$

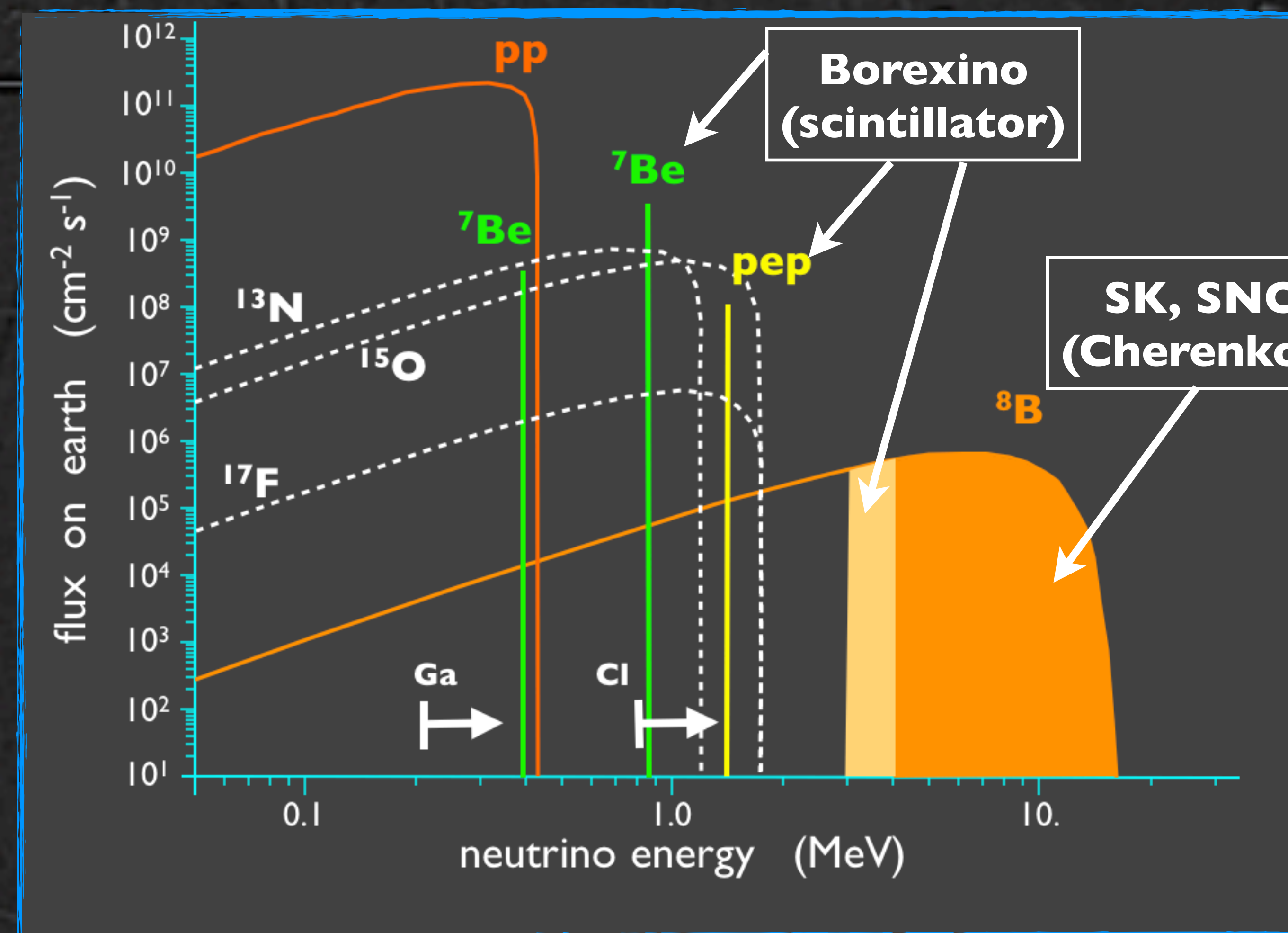
${}^{8}Be \rightarrow {}^{4}He+{}^{4}He$

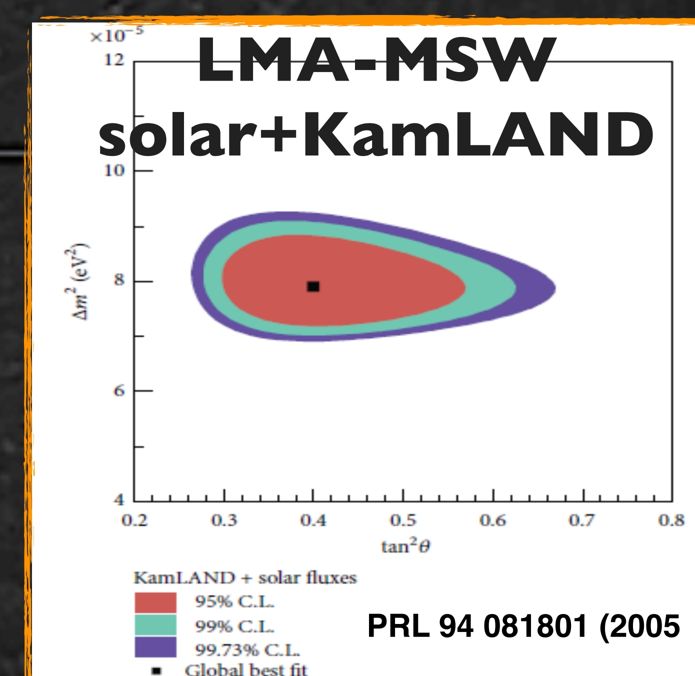
${}^{7}Li+p \rightarrow {}^{4}He+{}^{4}He$

W. Fowler

SOLAR NEUTRINOS (2)







- **BUT**
  - Neutrinos oscillate from Sun to Earth (SNO, 2000)
  - MSW-LMA solution (solar data + KamLAND)
  - Energy dependent P_{ee}

SOLAR NEUTRINO FLUXES: METALLICTY PROBLEM

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	30.0
^{17}F	38.4

- Since 2004:
  - CNO 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

DETECTION OF SOLAR NEUTRINOS

- Radiochemical (Homestake [Cl], Gallex, SAGE [Ga])
  - Only integral count rate above threshold
  - Historically crucial, now less appealing
- Water (or $D_2$0) Cherenkov detector (SK, SNO)
  - Directionality, neutral-charge currents separation with $D_2$0
  - Very large mass cost effective (SK)
  - ^{8}B neutrinos only (E>4 MeV)
- Liquid scintillator (Borexino, KamLAND, SNO+)
  - Low energy threshold (200 keV, limited by ^{14}C, not by signal)
  - No directionality, superbe purity required to reject radioactivity
- Possibly, future detectors with noble liquids (XMASS, Clean)

^{8}B measurements

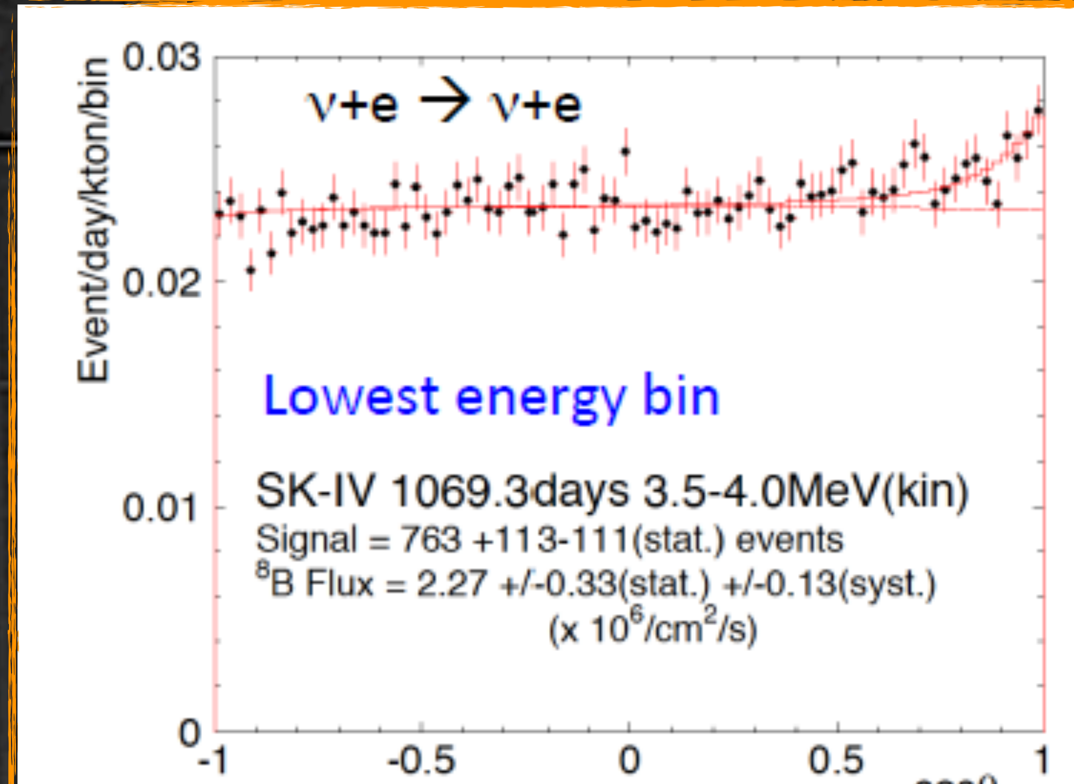
- Kamiokande and SK original measurement
  - E > 6 MeV (90's)
  - Now down to 4.5 MeV
- SNO: charged and neutral currents, total flux confirmed (2000-2002)
  - *Discovery of neutrino oscillations*
  - SNO Leta and SK low energy analysis down to 3.5 MeV
- KamLAND > 5 MeV
- Borexino E>3 MeV
  - Lowest threshold, but smaller statistics w.r.t. SK and SNO

SUPER-KAMIOKANDE

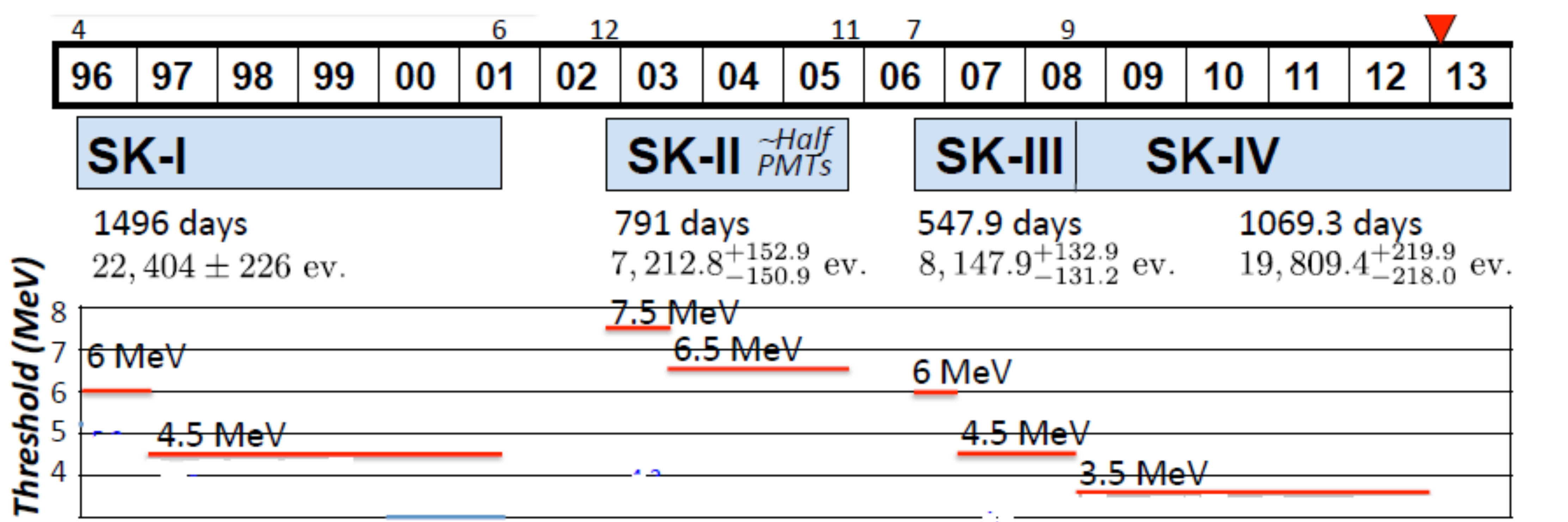
- Succesfull effort to reduce threshold
  - Better water purity
  - Better electronics and triggering

Fiducial mass

22.5 kt (E > 5 MeV)
13.3 kt (4.5 < E < 5. MeV)
8.8 kt (3.5 < E < 4.5 MeV)



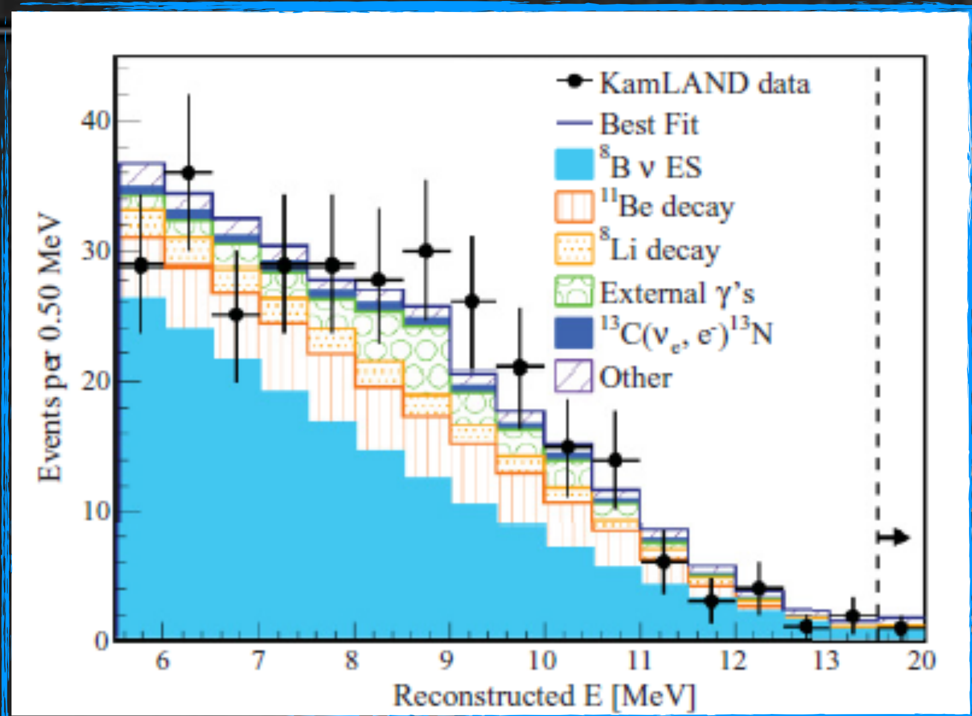
Y. Suzuki Neutrino telescopes March 2013



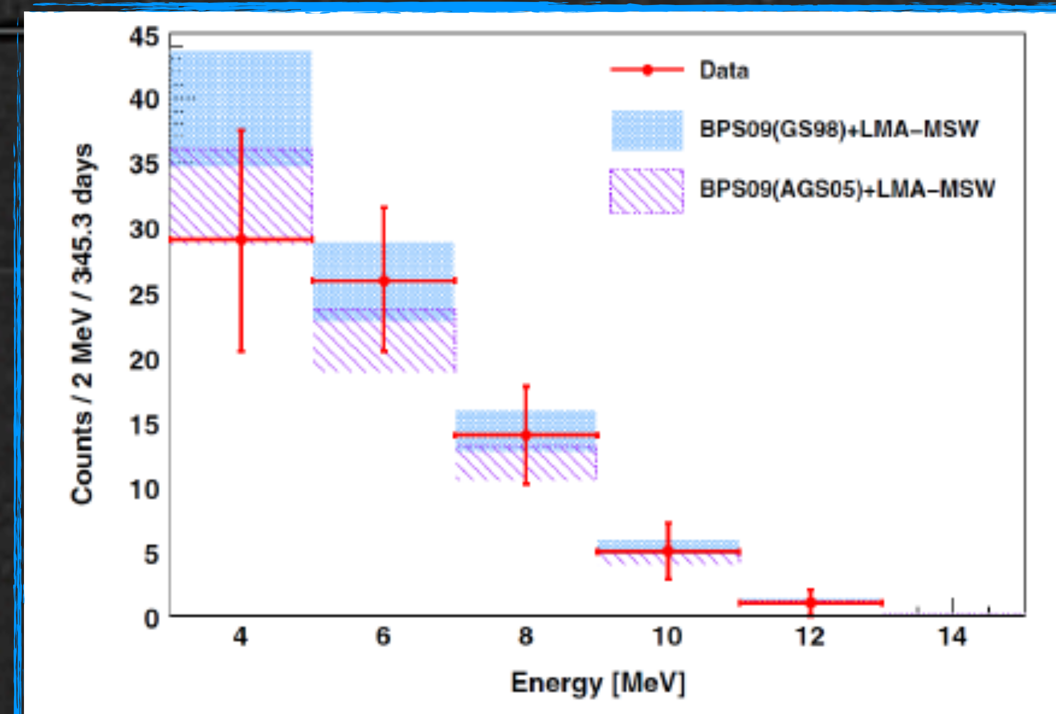
Y. Suzuki Neutrino telescopes March 2013

^{8}B RESULTS

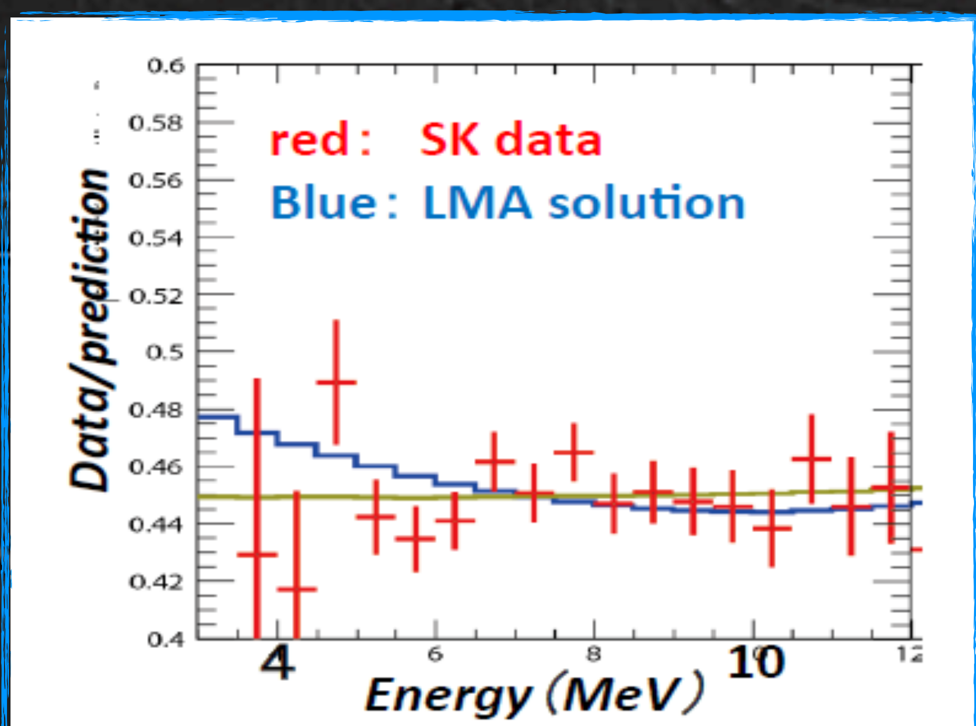
Kamland PRC 84, 035804 (2011)



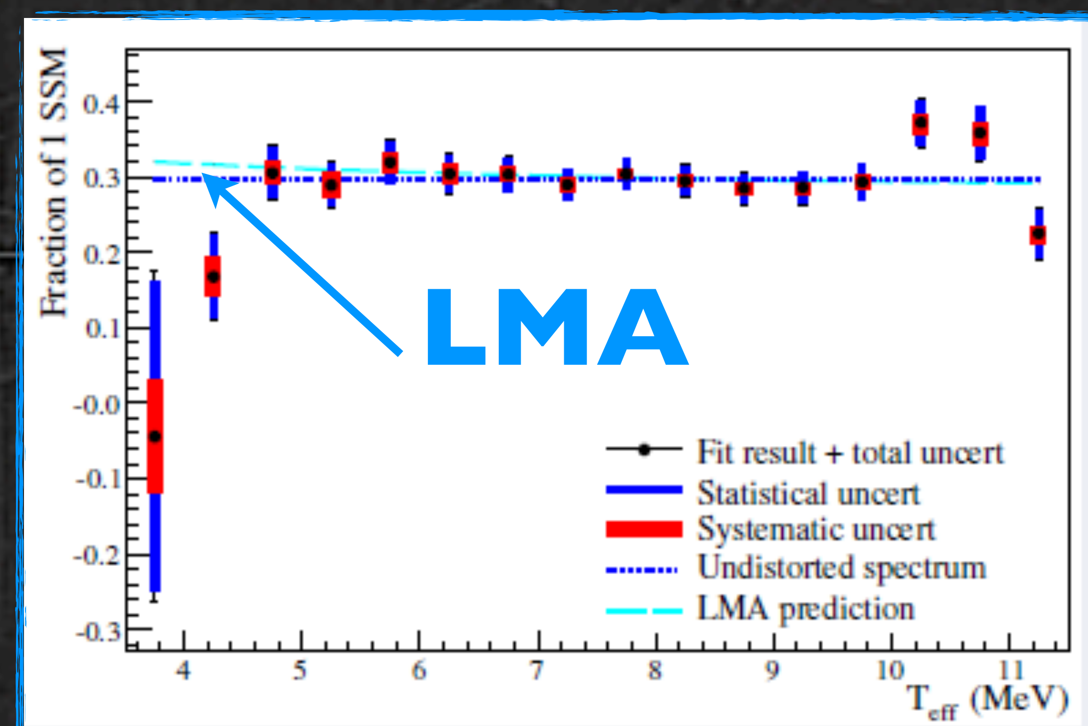
Borexino PRD 82 033006 (2010)



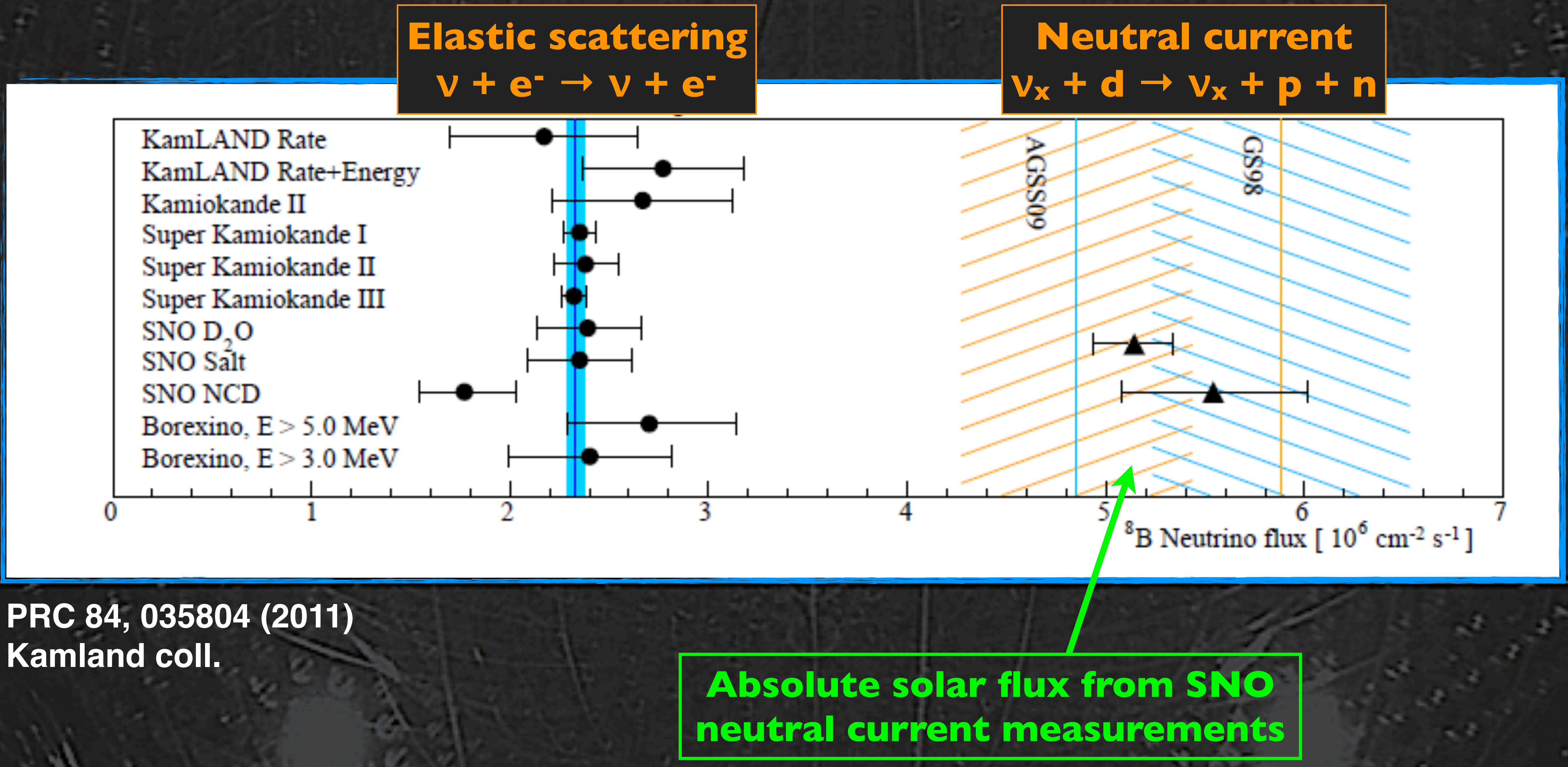
SK Suzuki@Neutrino Telescopes Venice 2013



SNO LETA 3.5 MeV threshold arxiv 1109.0763



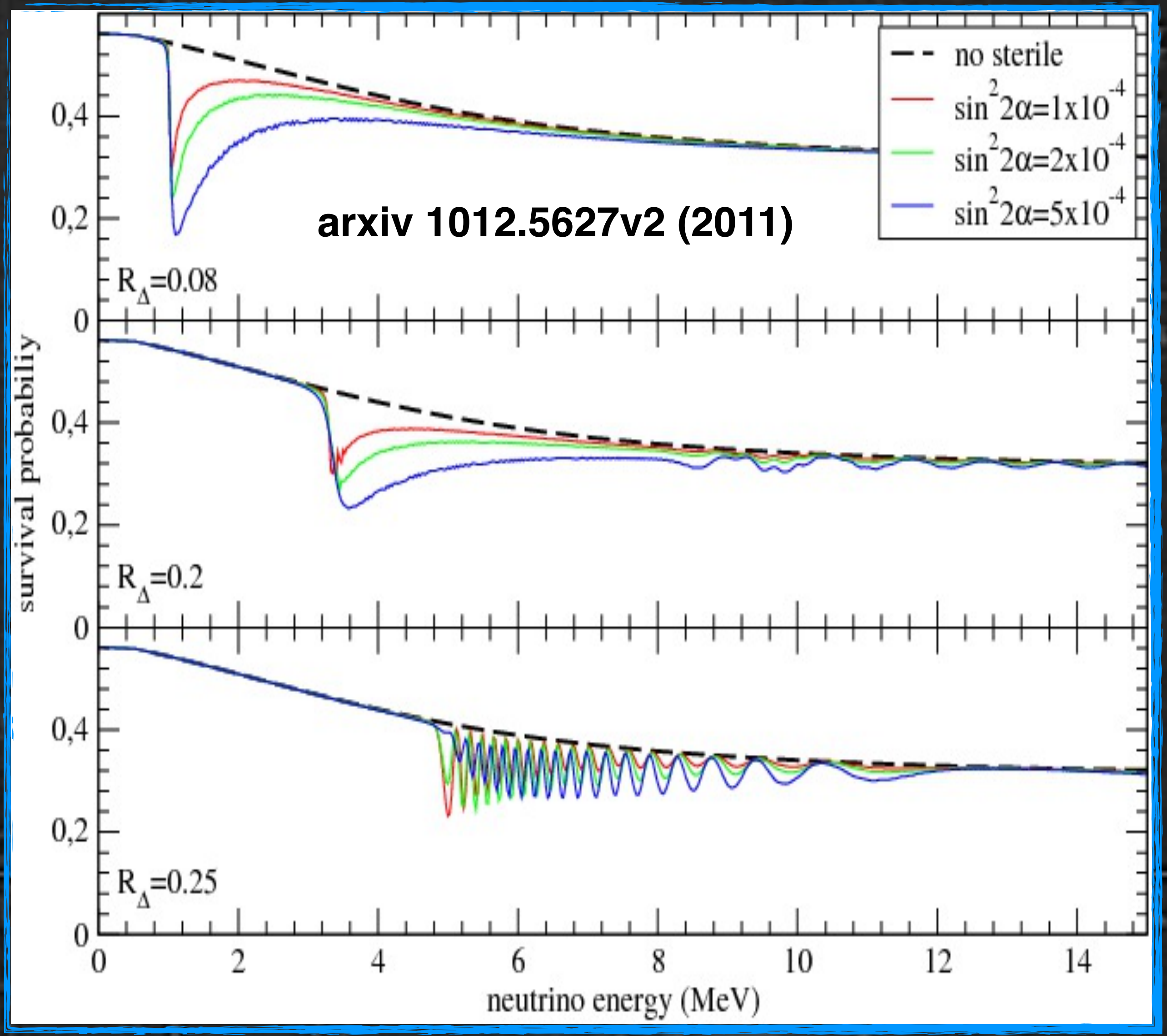
SUMMARY OF ^{8}B RESULTS



PRC 84, 035804 (2011)
Kamland coll.

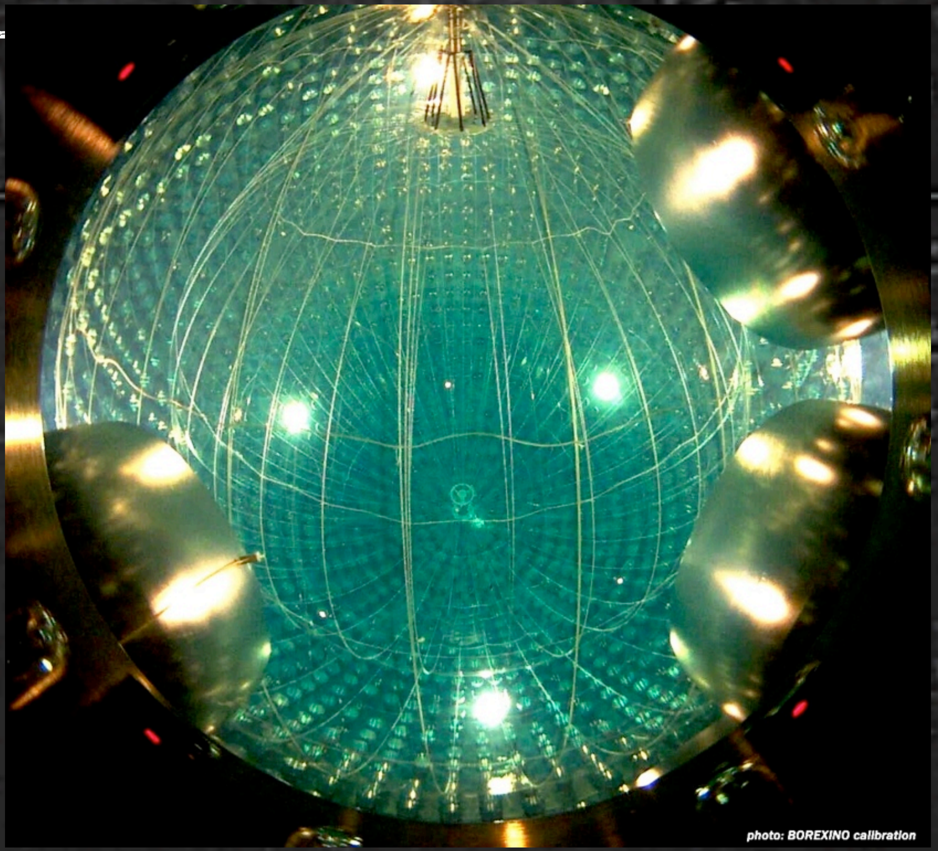
UPTURN OR NOT UPTURN ?

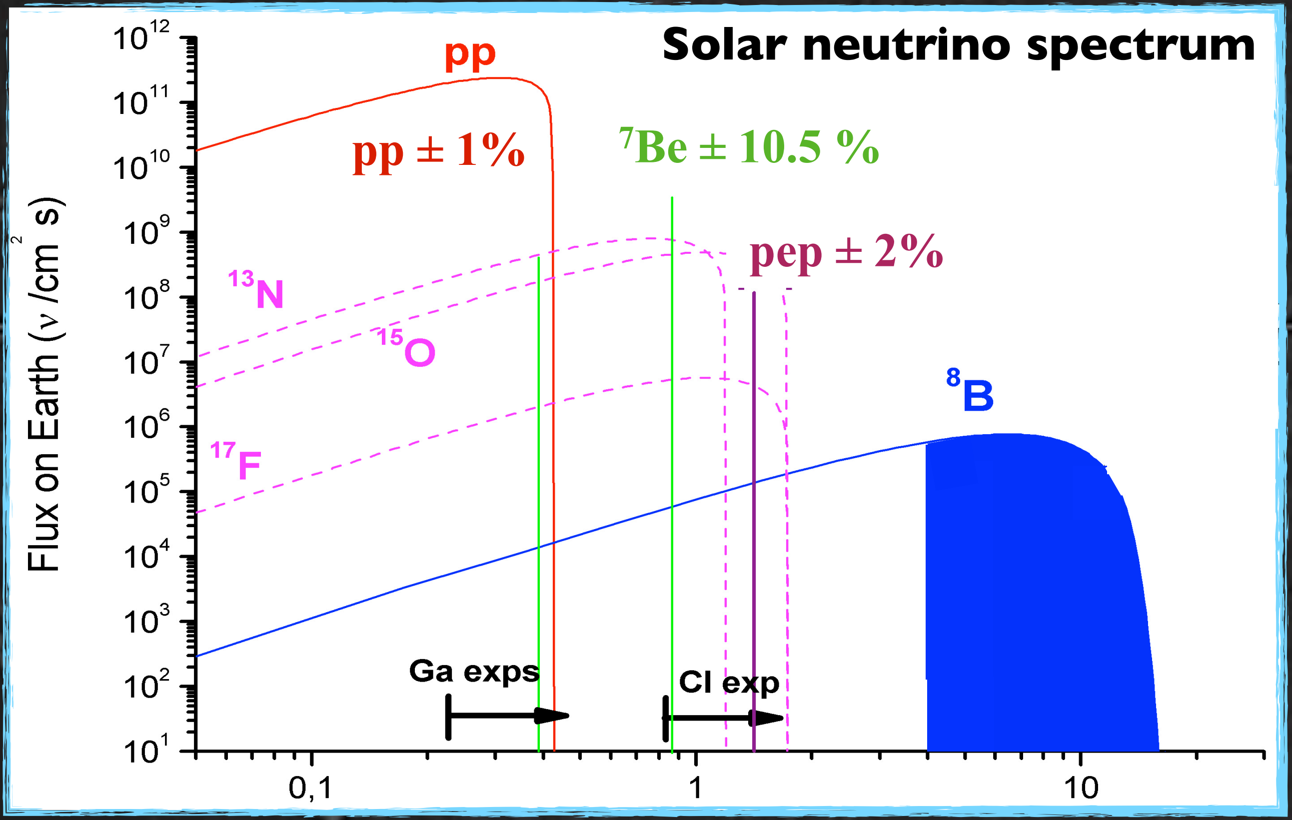
- **LMA-MSW predicts P_{ee} increase below 6 MeV (upturn)**
  - ***No evidence so far***
    - **All experiments see flat distributions or even a decrease, but *statistics is still insufficient***
    - ***Intriguing, however***
    - **Sterile ν or non-standard interactions may play a role**
  - **SK might be able to say something clear**
  - **Borexino probably too small, despite lower energy threshold**

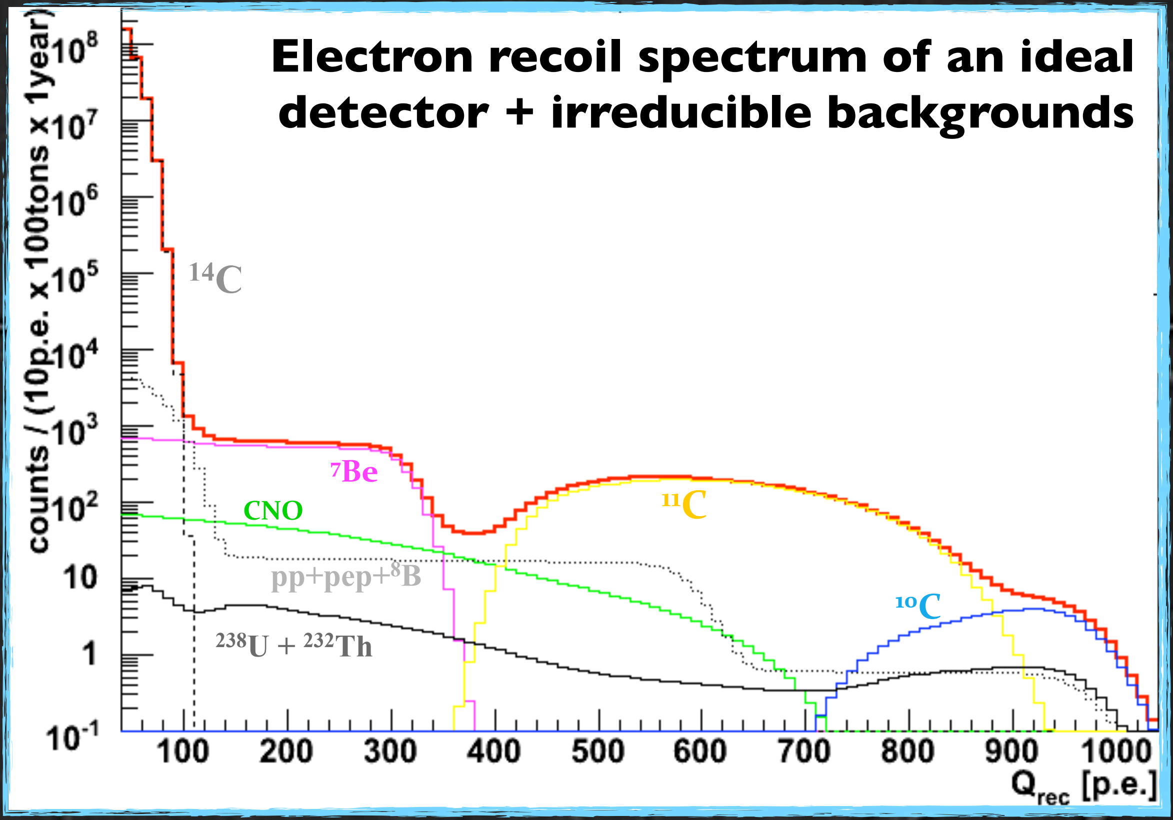


BOREXINO EXPERIMENT

- Mainly, a solar ν experiment:
  - ν + e⁻ → ν + e⁻ in liquid scintillator
    - Ultra-low radioactive background obtained via selection, shielding, and purifications
    - Low energy threshold, good resolution, spatial reconstruction, and pulse shape ID
  - But also:
    - Geo-neutrinos, search for rare events







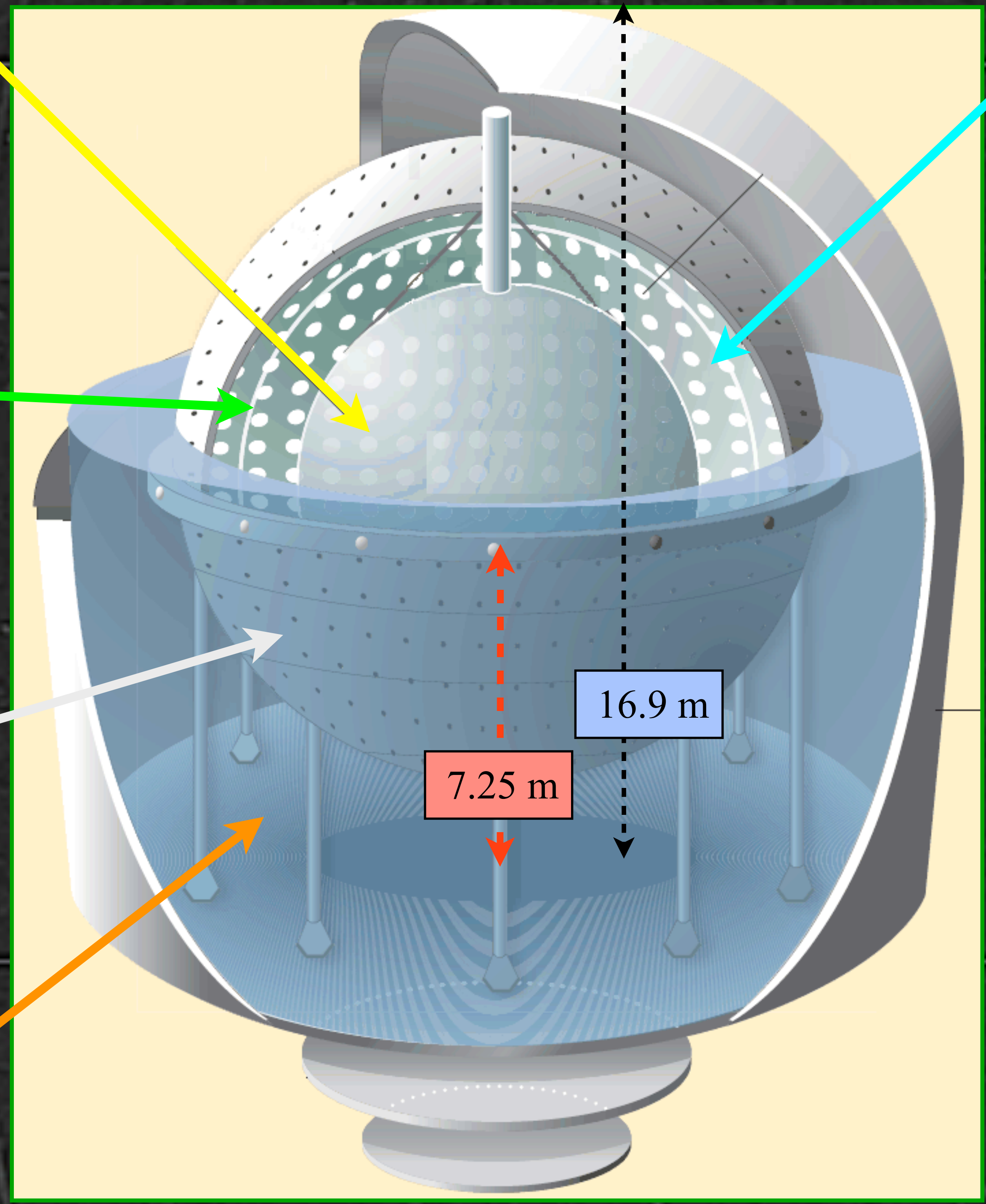
BOREXINO DETECTOR

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

Outer nylon vessel:
R = 5.50 m
(^{222}Rn barrier)

Stainless Steel Sphere:
R = 6.75 m
2212 PMTs

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

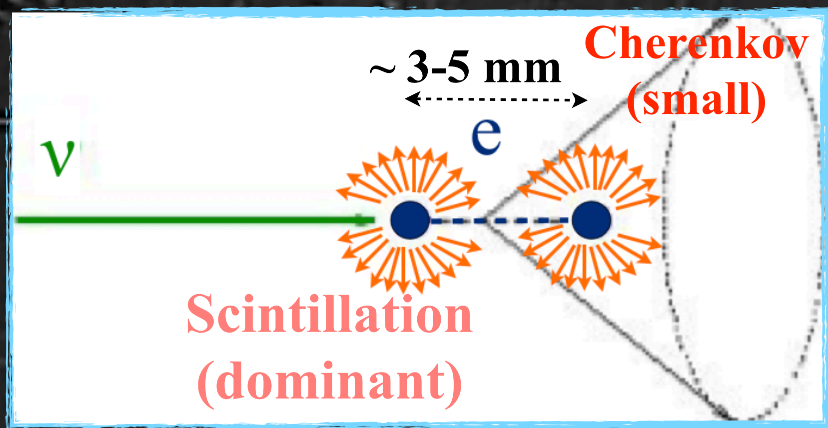


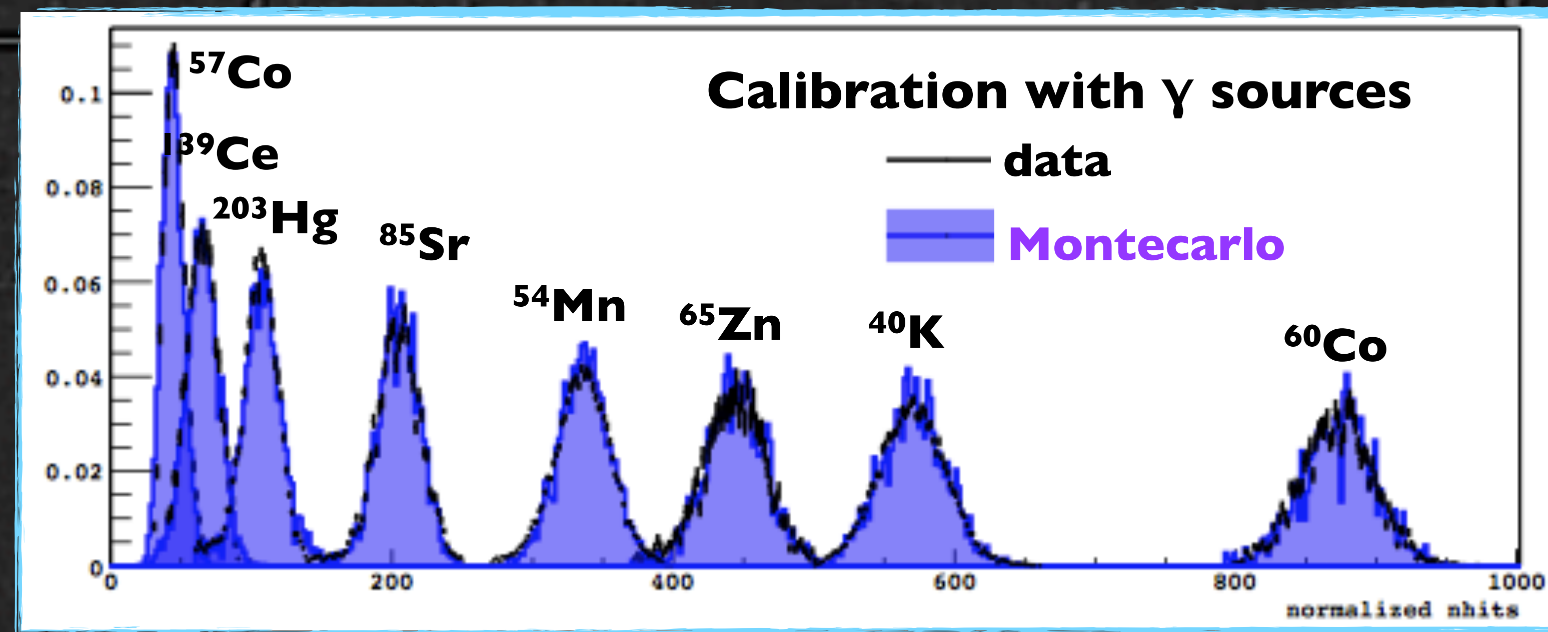
Buffer region:
PC+DMP quencher
4.25 m < R < 6.75 m

The principle of graded shielding: materials more and more pure moving toward center.

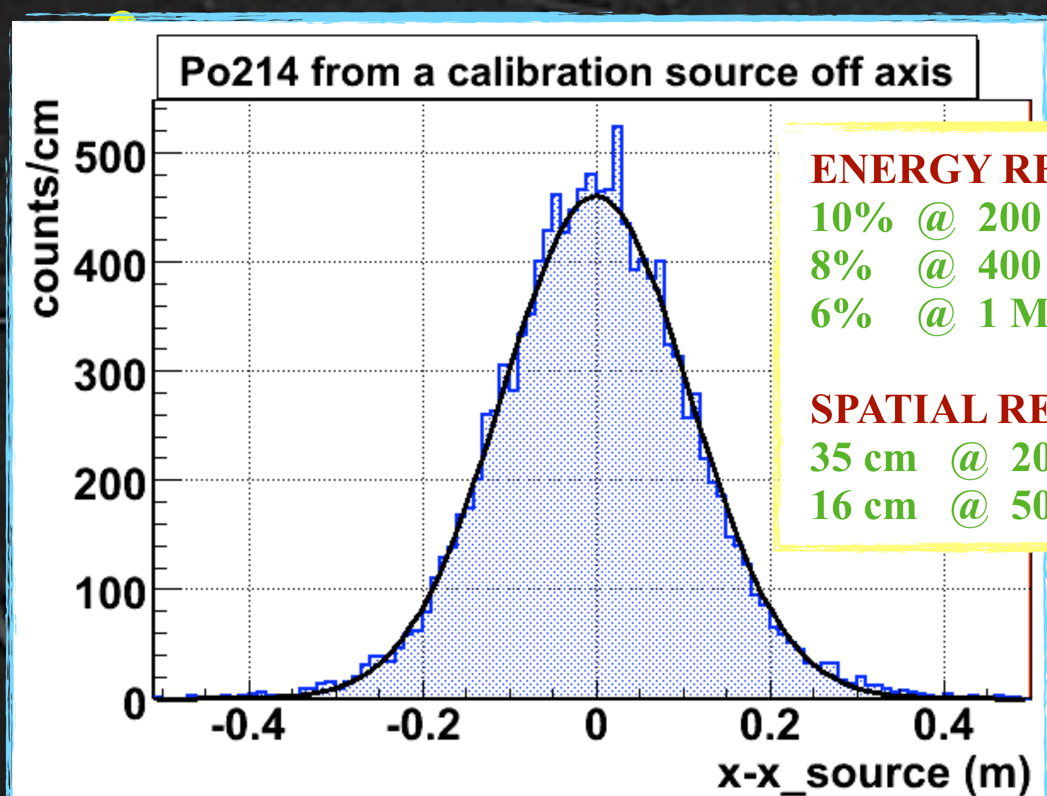
Borexino core is the **less radioactive place on Earth:** **9-10** orders of magnitude less than good mineral water

ν DETECTION IN BOREXINO





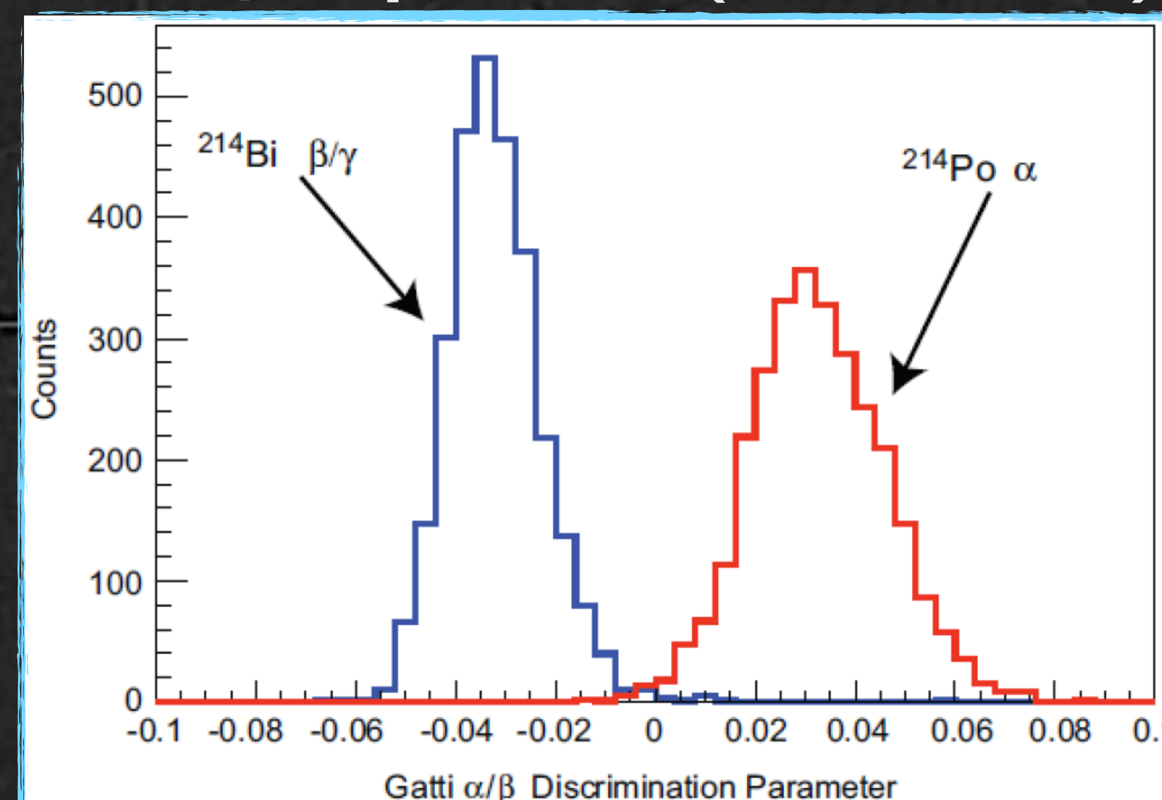
- Scintillation light
  - # of photons → energy
  - time of flight → position
  - pulse shape → α/β β^+/β^-



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

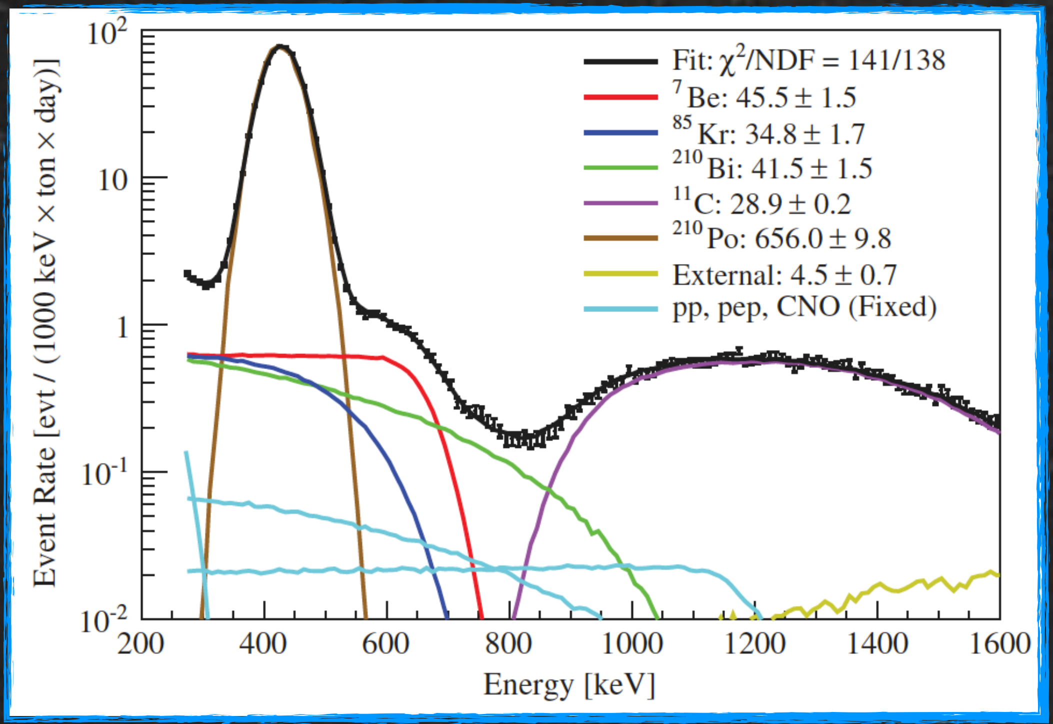
SPATIAL RESOLUTION
35 cm @ 200 keV
16 cm @ 500 keV

α / β separation (^{214}Bi - ^{214}Po)



Measurement of ^{7}Be rate

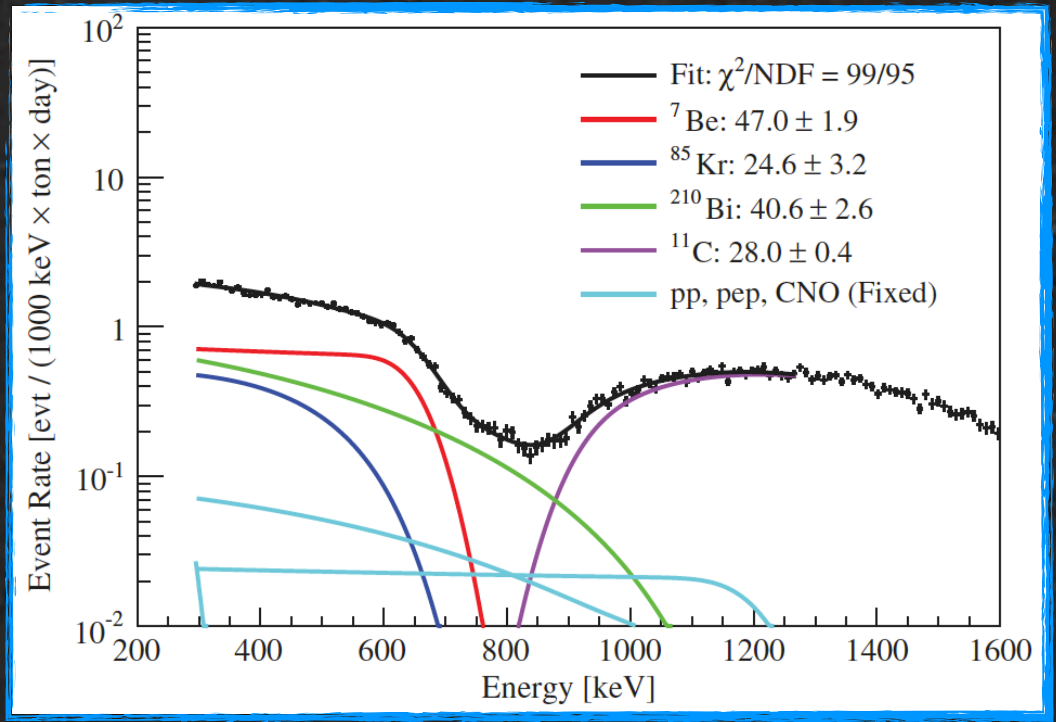
Monte Carlo fit to the spectrum, without α/β subtraction of the ^{210}Po peak



Phys. Lett. B658:101-108, 2008
Phys. Rev. Lett. 101, 091302, 2008
Phys. Rev. Lett. 107, 141302, 2011

- Two methods:
  - Consistent results. Small difference included in systematic error.
  - Final rate (100 t target):
    - **46.0 ± 1.5 (stat) ± 1.5 (sys) c d^{-1}**

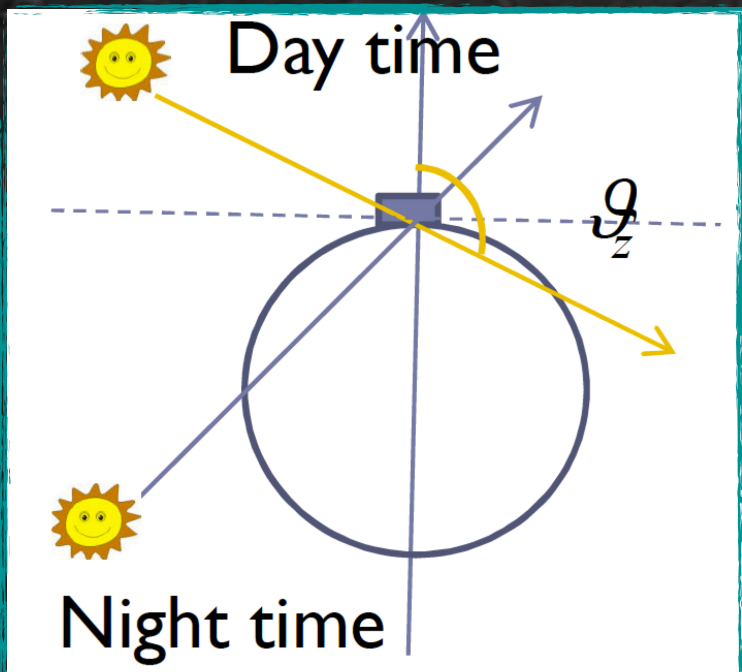
Analytical fit of the spectrum after α/β subtraction of ^{210}Po peak



Source	%
Trigger (eff. and stability)	< 0.1
Live time	0.04
Scintillator density	0.05
Fiducial volume	+0.5 -1.3
Fit method	2
Energy response	2.7
Cuts efficiency	0.1
Total	+3.4 -3.6

DAY-NIGHT MODULATION OF ^{7}BE RATE

- **Lack of modulation selects MSW-LMA**



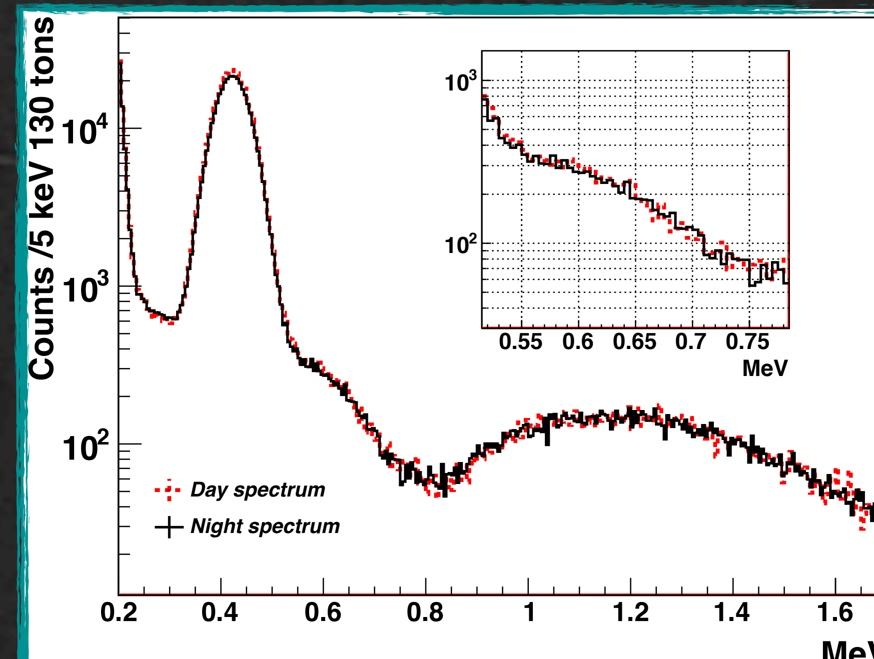
Phys. Lett. B707:22–26, 2012

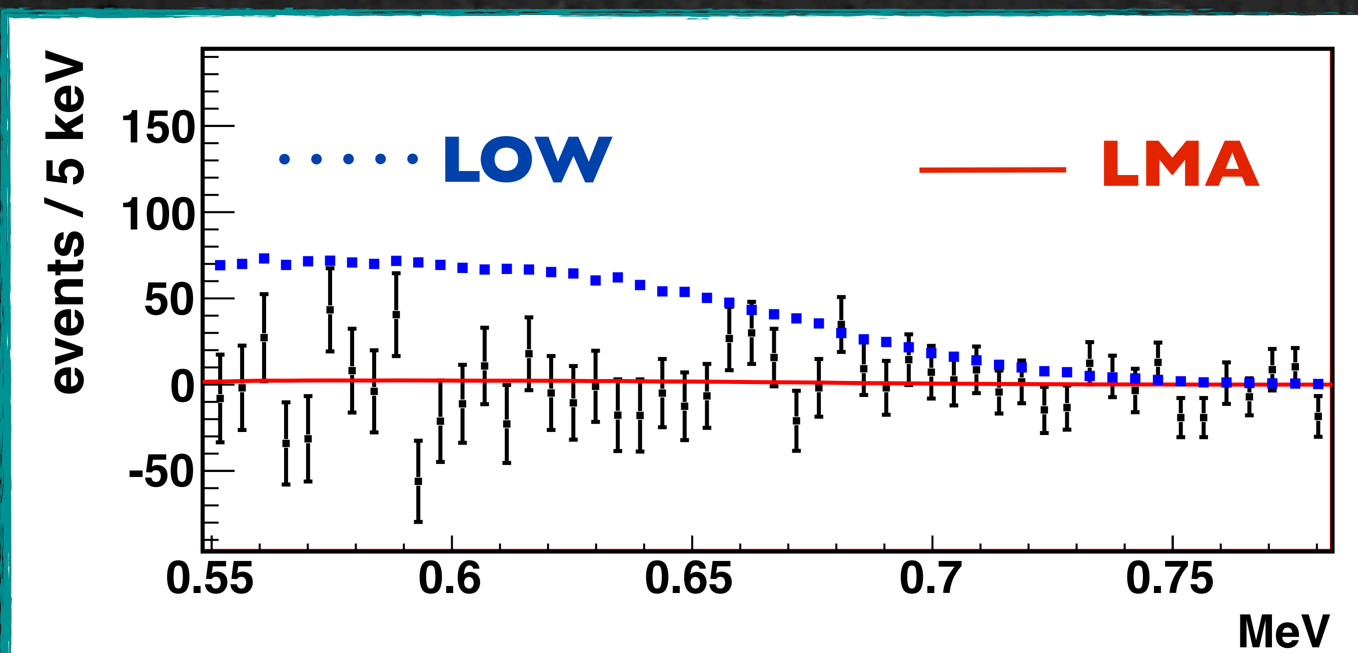
$$A_{dn} = 2\frac{R_n - R_d}{R_n + R_d}$$

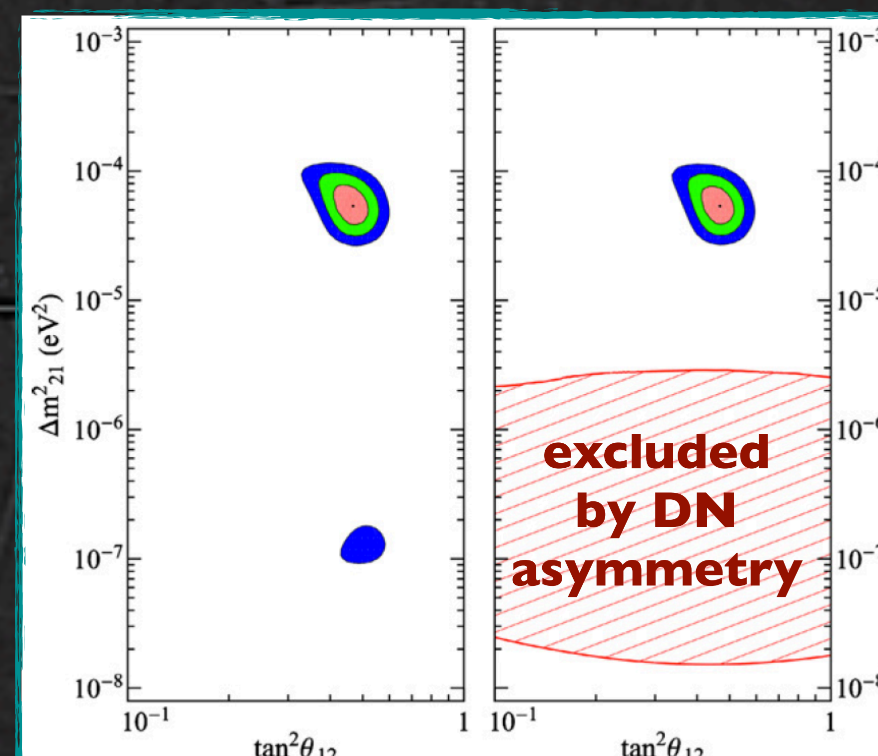
$$= 0.001 \pm 0.012 \pm 0.007$$

No modulation observed

Day--night spectra



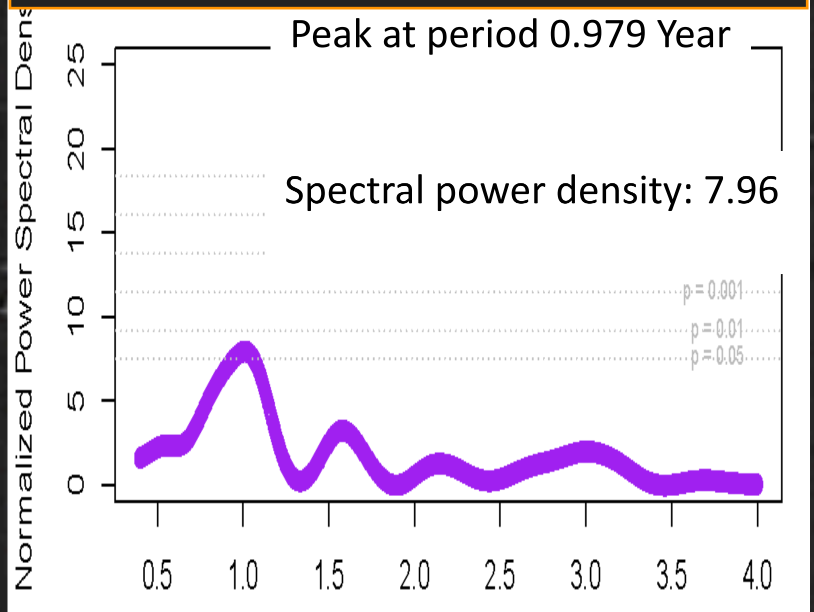




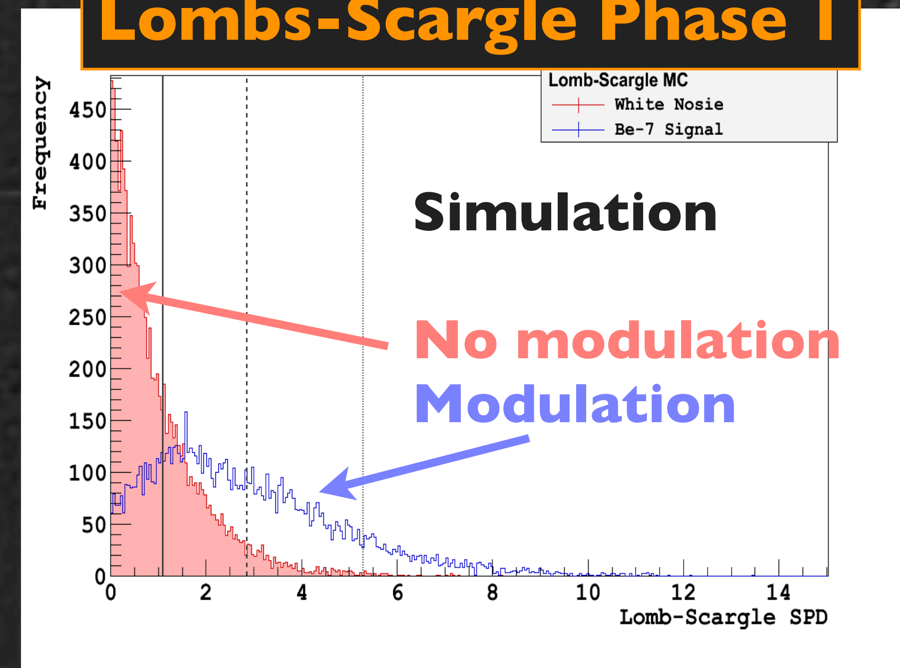
^{7}Be annual modulation

- Two methods: count rate and Lombs-Scargle periodogram

Lombs-Scargle Phase I



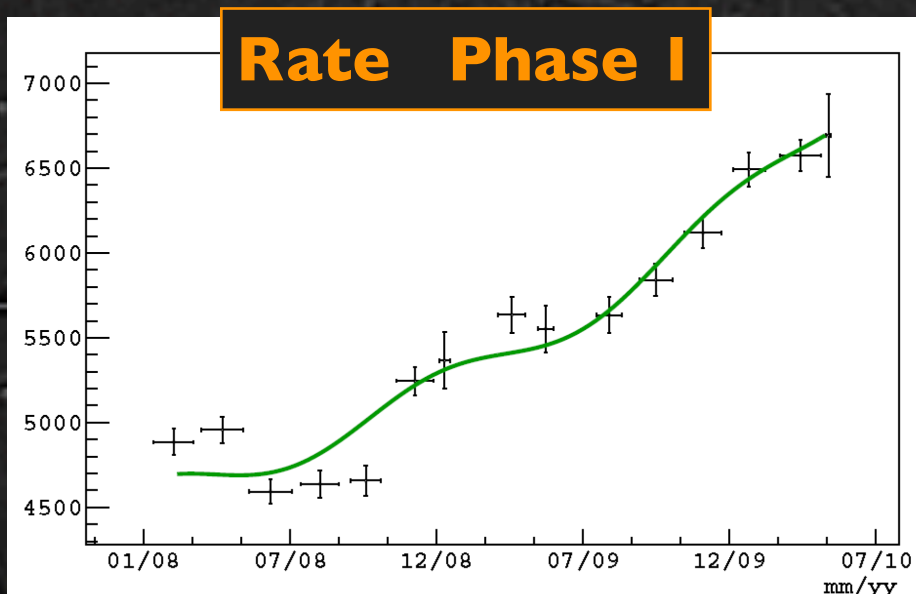
Lombs-Scargle Phase I



arxiv 1308.0443

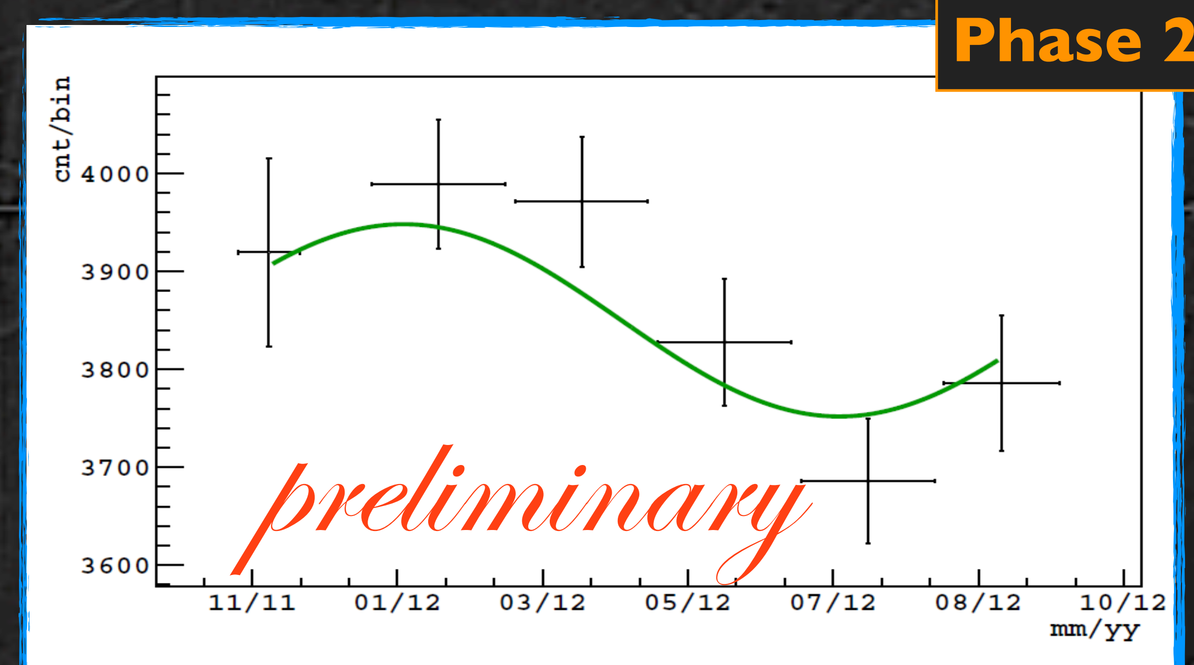
submitted to PRD

Rate Phase I



No oscillations excluded at > 3 σ

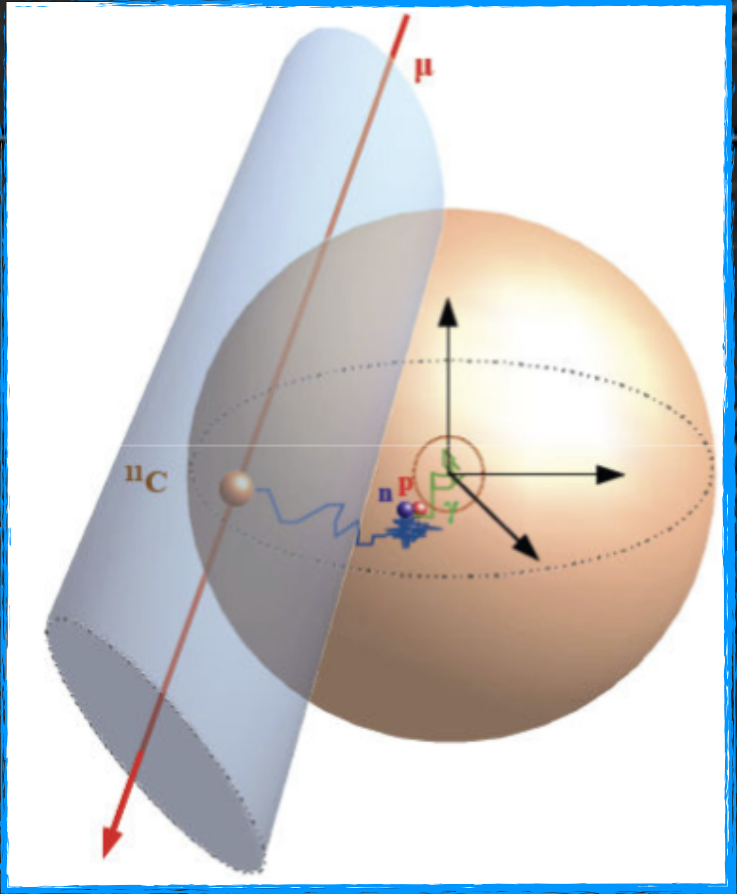
Phase 2



$$R = R_0 + e^{\Lambda_{Bi210}} + \bar{R}\left[1 + 2\epsilon\cos\left(\frac{2\pi}{T} - \varphi\right)\right]$$

First pep detection and CNO limit

- **Borexino got first direct evidence of pep ν and set a strong upper limit on CNO**
  - **Thanks to low background and ^{11}C rejection techniques**
    - **Tagging of ^{11}C with triple coincidence (TFC)**
    - **β^+ - β separation exploiting positronium formation**
    - **Global multivariate analysis**

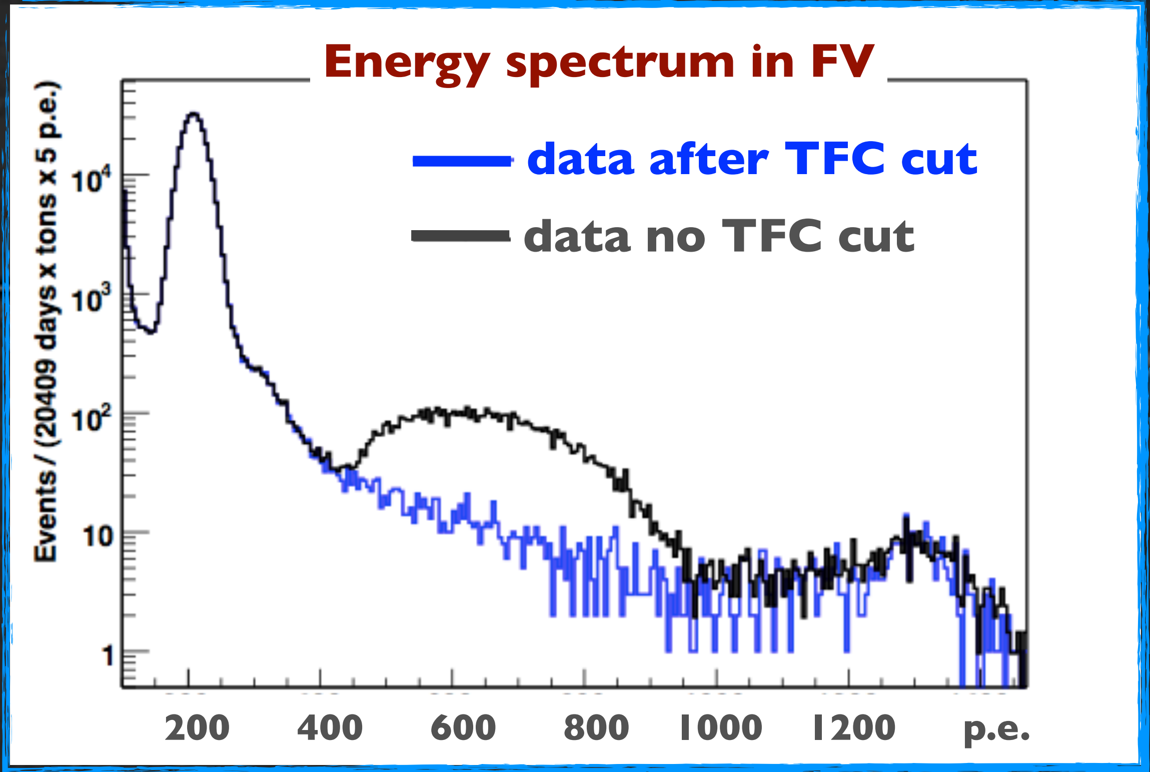


$\mu + {}^{12}C \rightarrow n + {}^{11}C + \mu$

236 μs — Fast neutron thermalization and capture: $n + p \rightarrow D + \gamma$ (2.2 MeV)

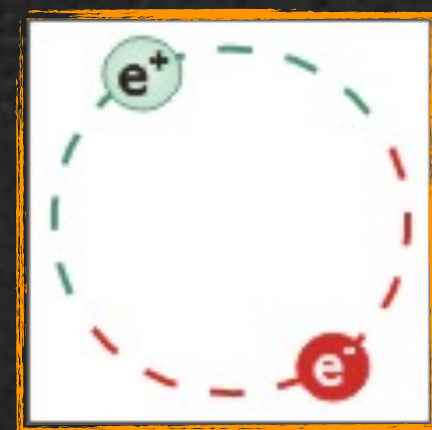
29.4 min — No convection, ^{11}C does not move: $^{11}C \rightarrow {}^{11}B + e^+ + \nu_e$

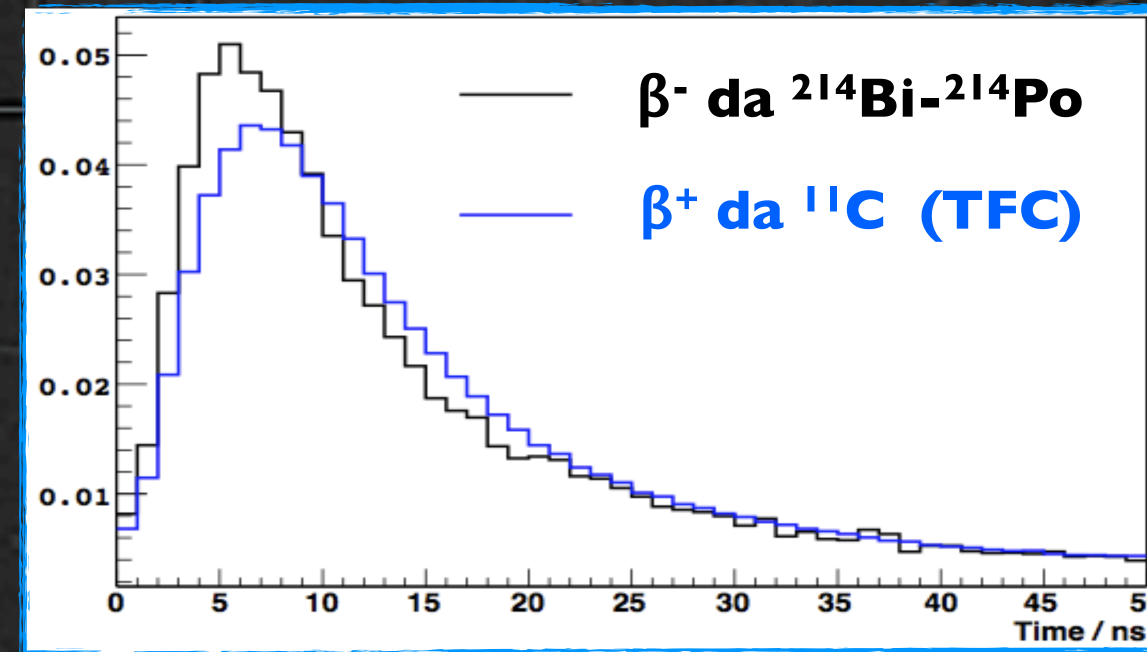
PHYSICAL REVIEW C 74, 045805 (2006)

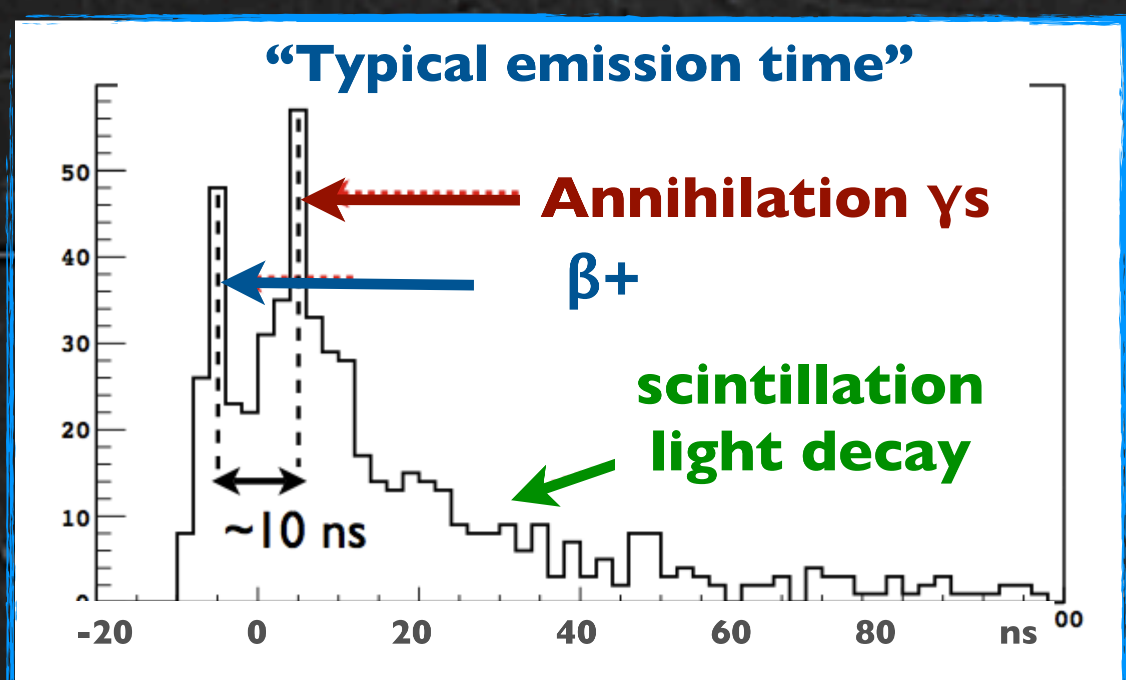


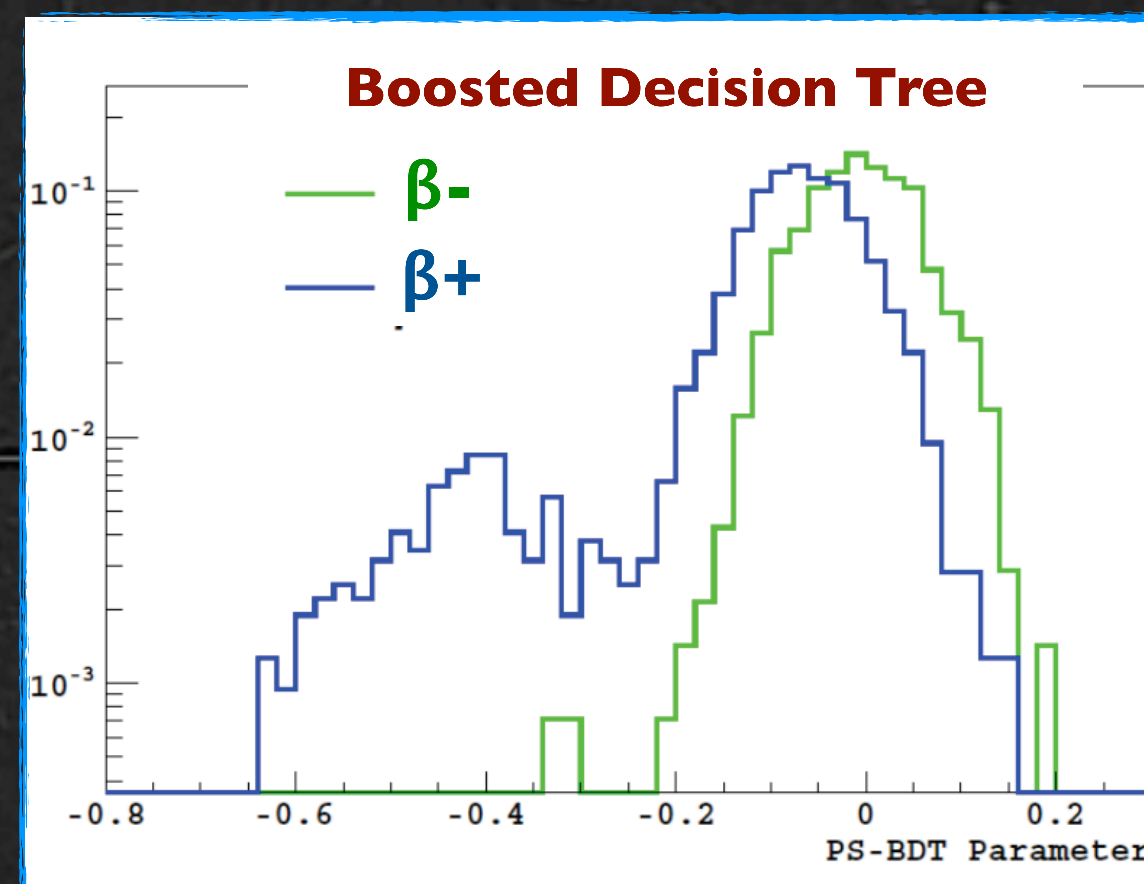
PEP: B^+ TAGGING WITH POSITRONIUM

- **Orto-positronium ~ 50% (in PC)**
  - **Signal is delayed by ~ 3 ns**
    - **Different pulse shape!**
    - **Parameters measured in a dedicated setup**



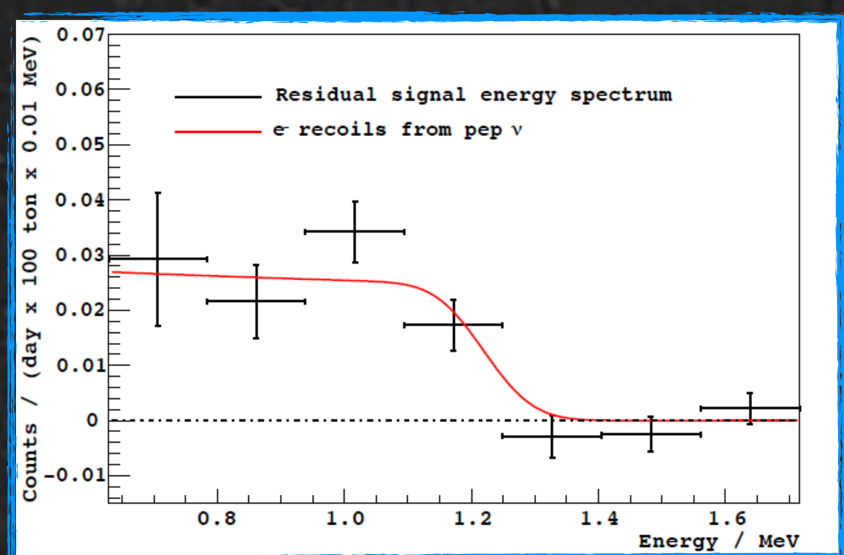




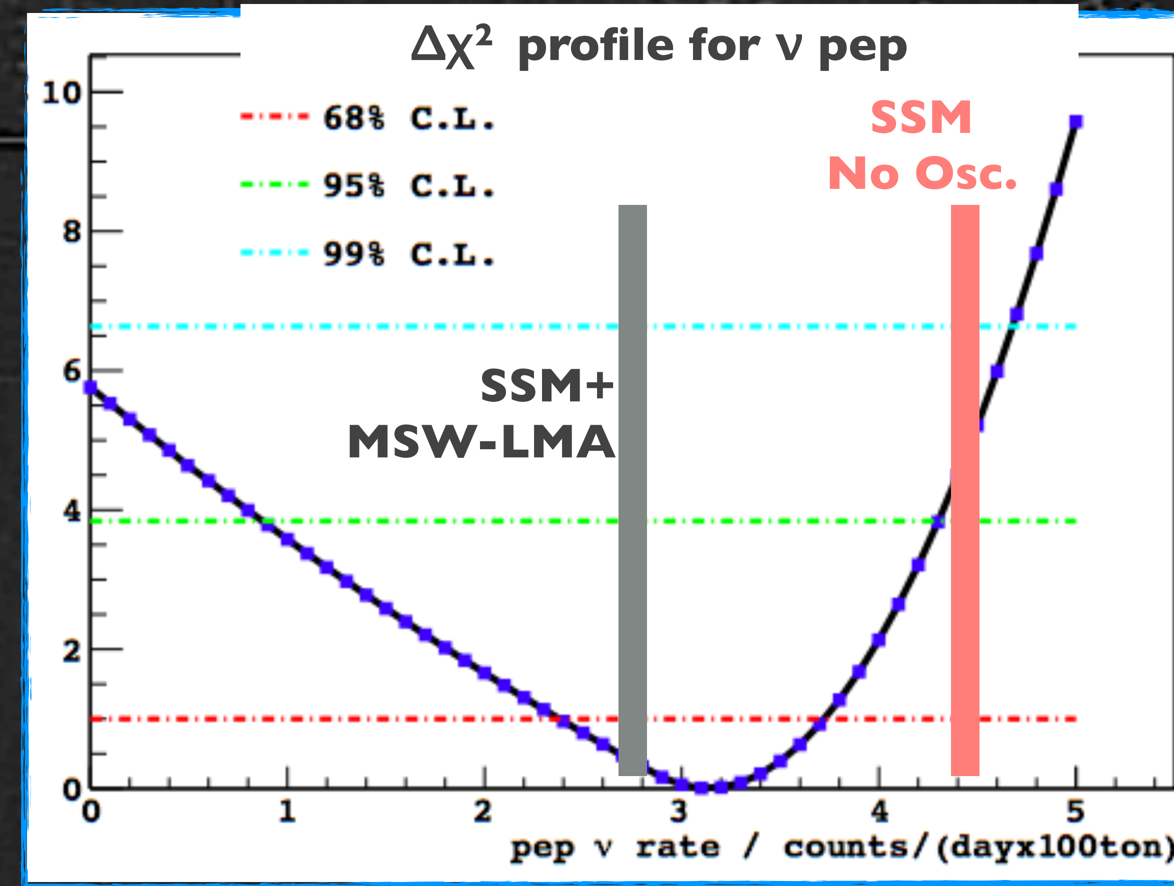


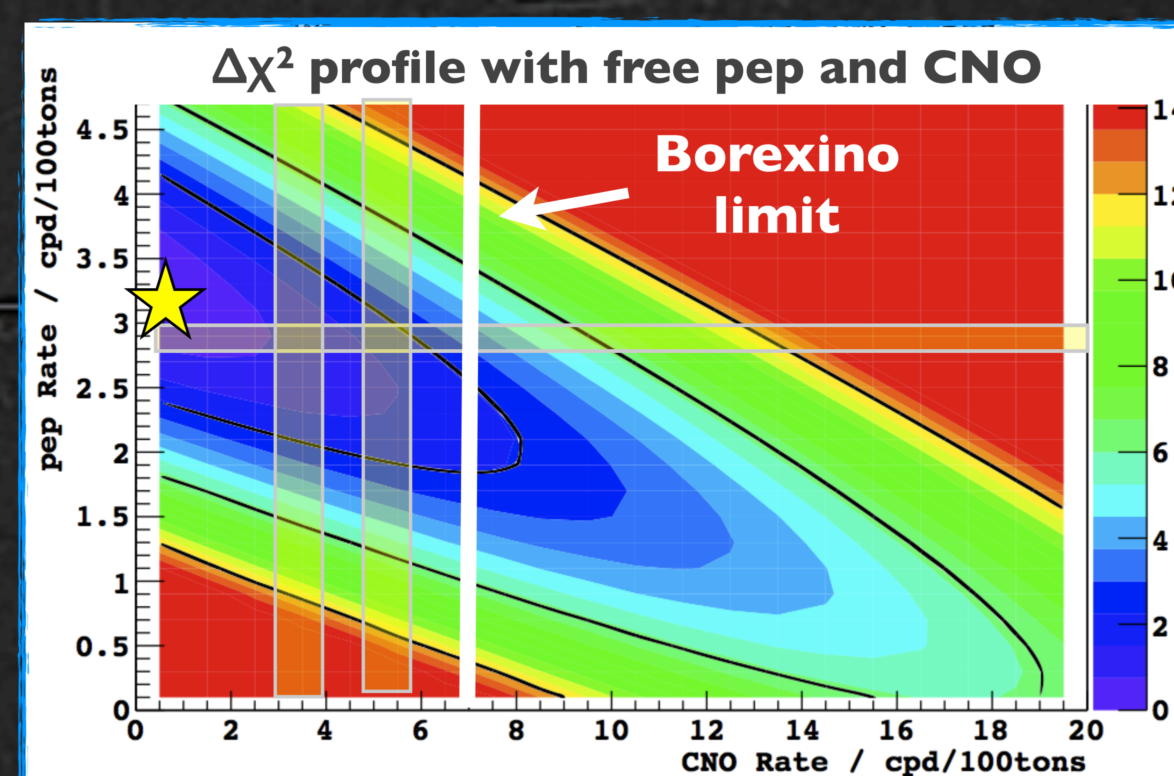
PEP-CNO: FINAL RESULT

- pep rate:
  $3.1 \pm 0.6(\text{stat}) \pm 0.3(\text{sys})$ cpd/100 t
  - No oscillations excluded at 97% c.l.
  - No ν pep excluded at 98%



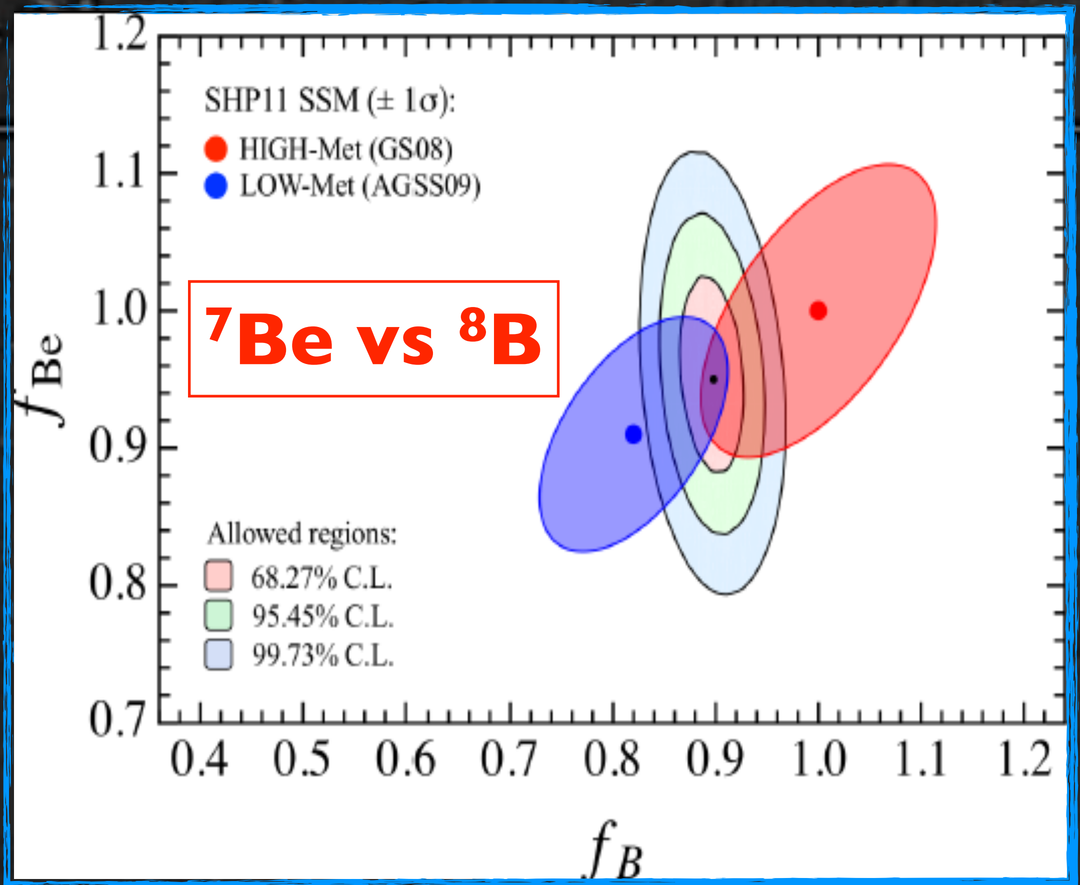
PRL 108, 051302 (2012)

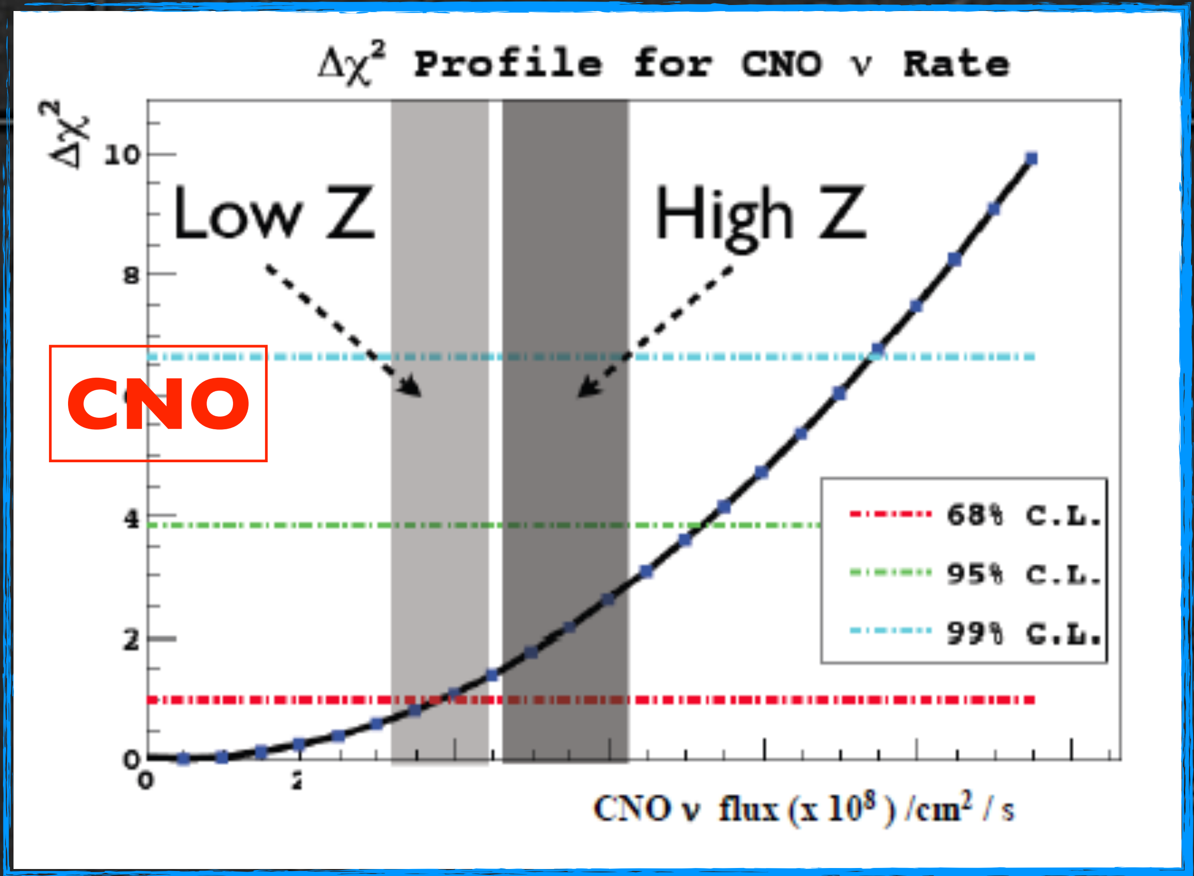




- Assuming MSW-LMA:
  - $\Phi_{pep} = 1.6 \pm 0.3\ 10^{8}\ cm^{-2}\ s^{-1}$
- CNO limit assuming pep @ SSM
  - CNO rate < 7.1 cpd/100 t (95% c.l.)

CAN WE ESTABLISH METALLICITY ?

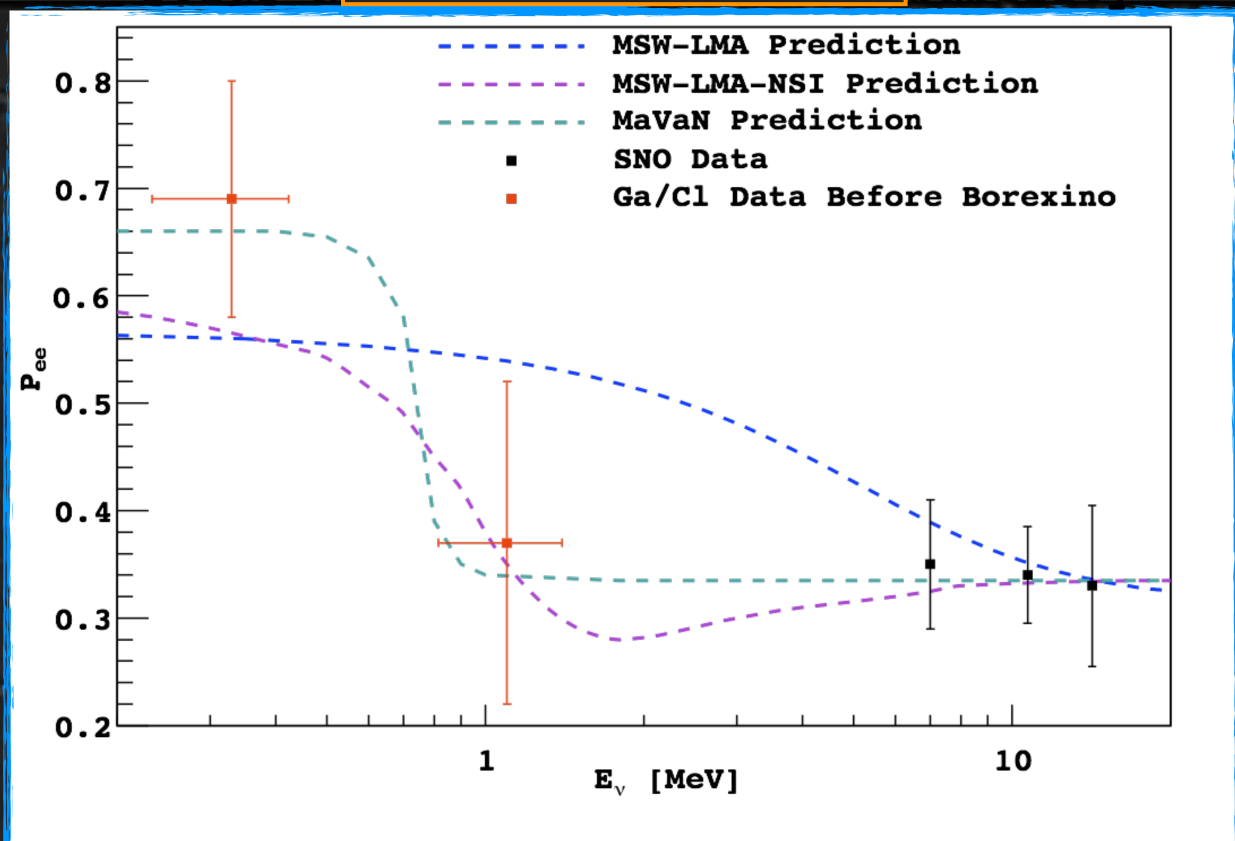




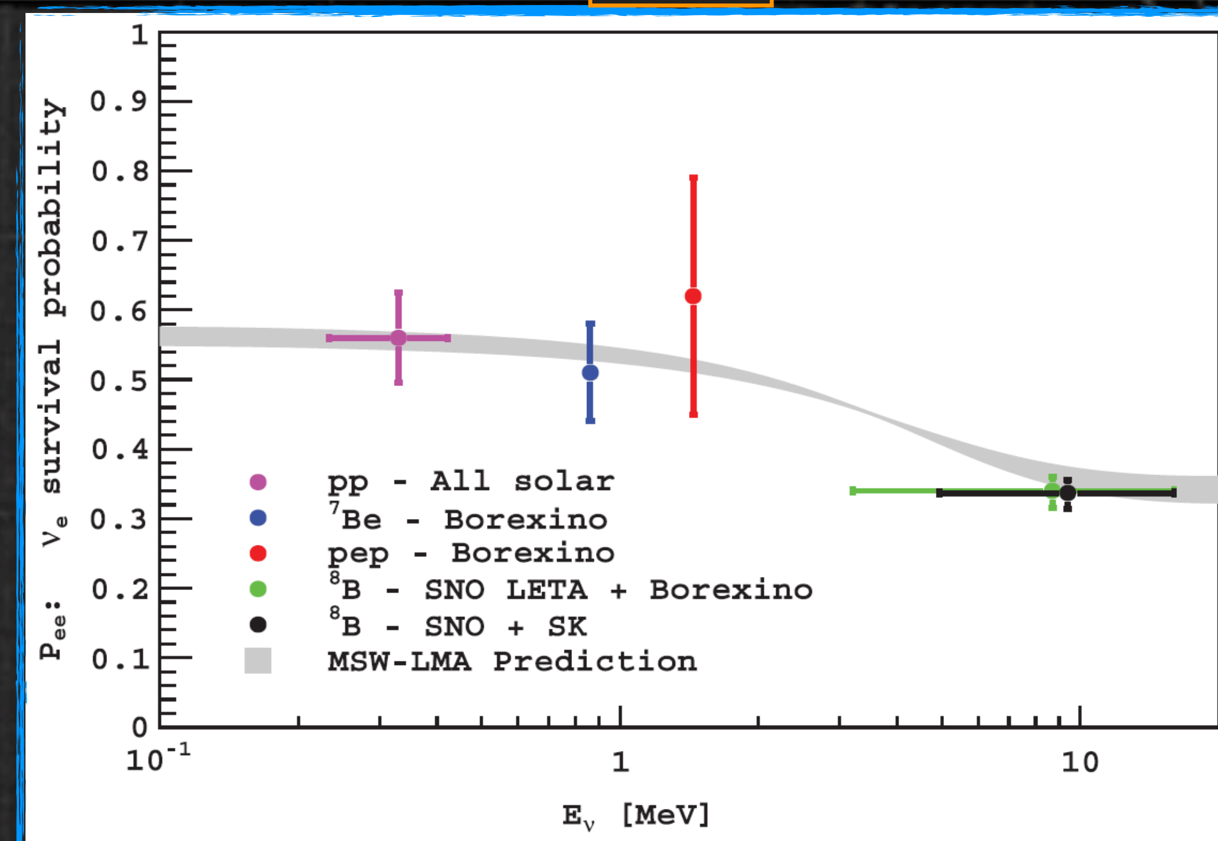
- Not yet
  - ^{7}Be central value is right in the middle.....
    - Smaller error is possible in Phase 2 (maybe, 3%) but this is not enough to give more than a hint
  - CNO measurement would work, but it is very difficult
    - An upper limit disfavoring High Metallicity is maybe possible in Phase 2, if Nature chose Low.....

CURRENT STATUS OF P_{ee} PROBE

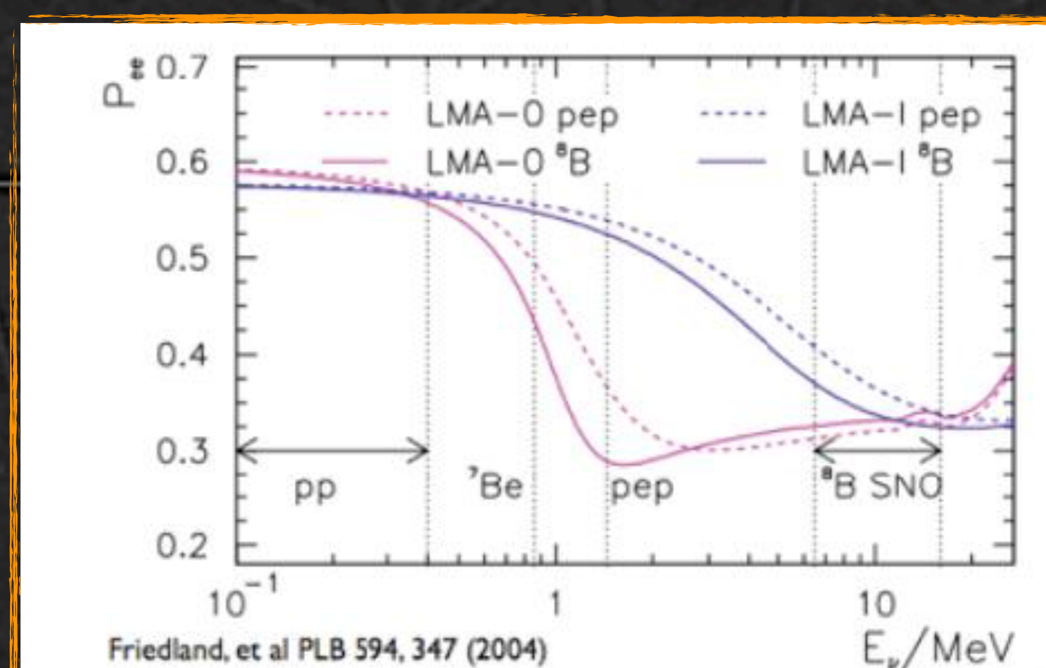
Before Borexino



2013



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

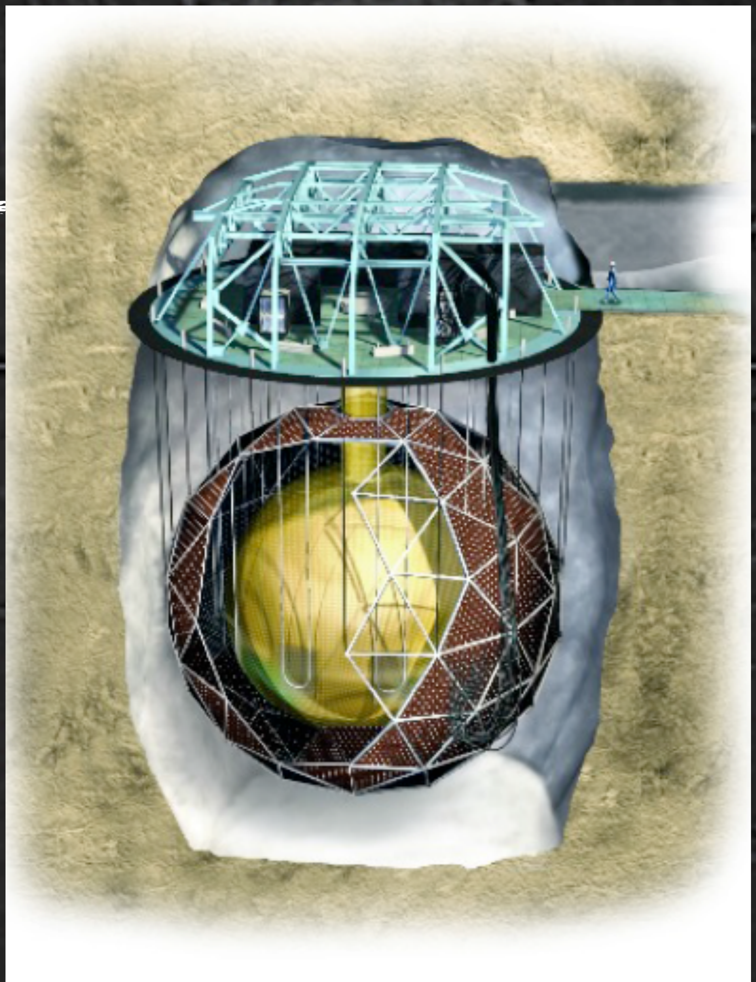


WHAT NEXT ON SOLAR NEUTRINOS ?

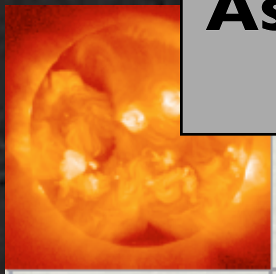
- **Hot items:** ***Borex Phase 2 goal***
  - **Direct measurement of pp νs: test Sun luminosity** — **yes**
  - **High precision pep: Non Standard Interactions (NSI), precision test of P_{ee}** — **yes, not easy to improve much**
  - **Measure CNO : solar and stellar models** — **good upper limit possible measurement very difficult**
  - **^{8}B up-turn: reduce the threshold (NSI, sterile νs…)** — **gain a factor 3 in statistics**
  - **Improve ^{7}Be measurement (usefull if model and calculation improve as well)** — **down to 3% maybe**

WHAT NEXT: SNO+

- SNO detector with liquid scintillator
  - 780 tonnes LAB+PPO
  - 9000 PMTS
  - Water shield by Ultra Pure Water
  - Wide physics program
- Reduced ^{11}C background due to the depth
  - 10^4 μ/day@Borexino
  - 70 μ/day@SNO+
    - Worse background is 210Bi
- Begin scintillator filling: early 2014
  - Check background
  - Priority is ββ decay (with ^{130}Te in scintillator)

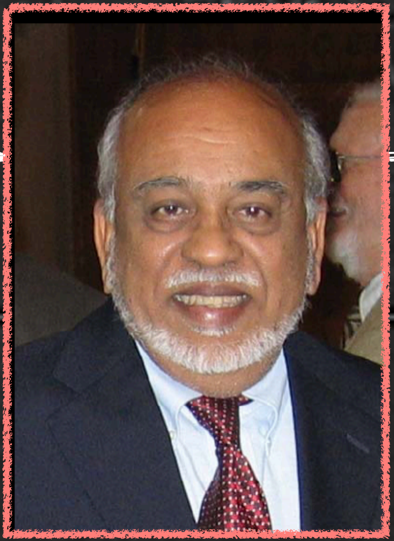


Assuming Borexino Background



	1 year	2 yrs
pep	9.1%	6.5%
^8B	7.5%	5.4%
^7Be	4%	2.8%
pp	a few %?	
CNO	15%?	

WHAT NEXT: LENS

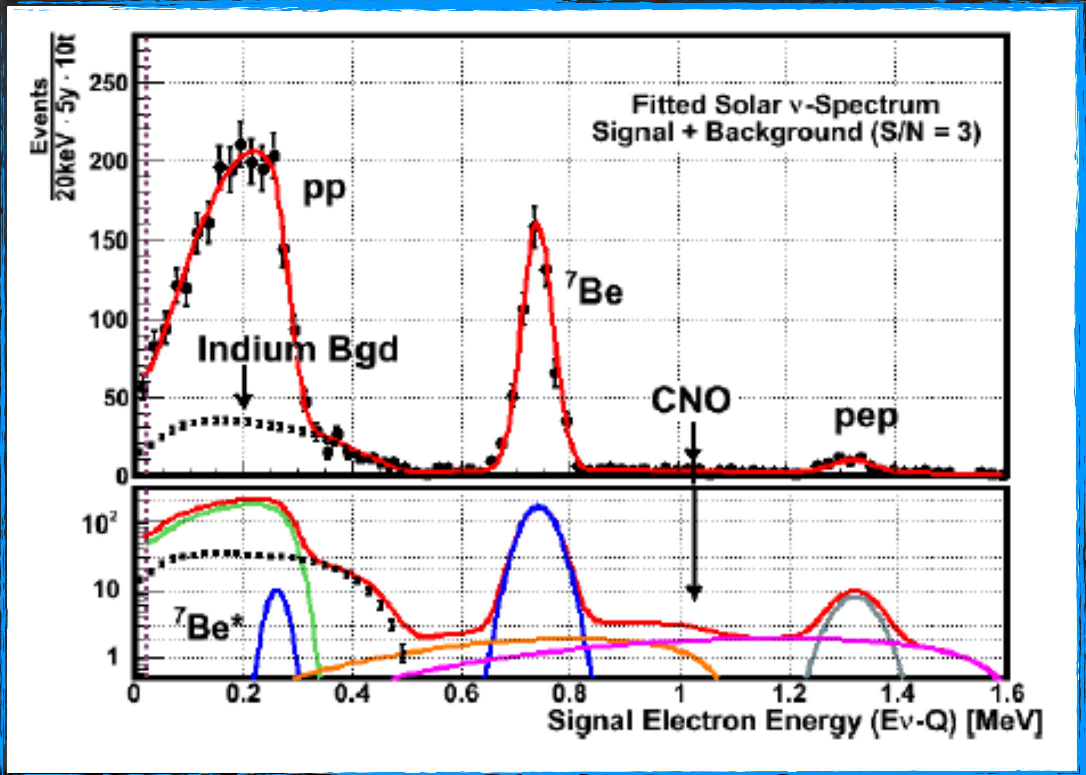


- ^{115}In provides a nice neutrino tagging

$$\nu_e +^{115} In \rightarrow e^- +^{155} Sn^*$$

$$^{155}Sn^* \rightarrow^{155} Sn + \gamma + \gamma$$

  - Q= 114 keV
    - sensitivity to pp , ^{7}Be, pep, CNO, ^{8}B
    - Neat coincidence
  - Main background from ^{115}In β decay
    - Relevant for pp only



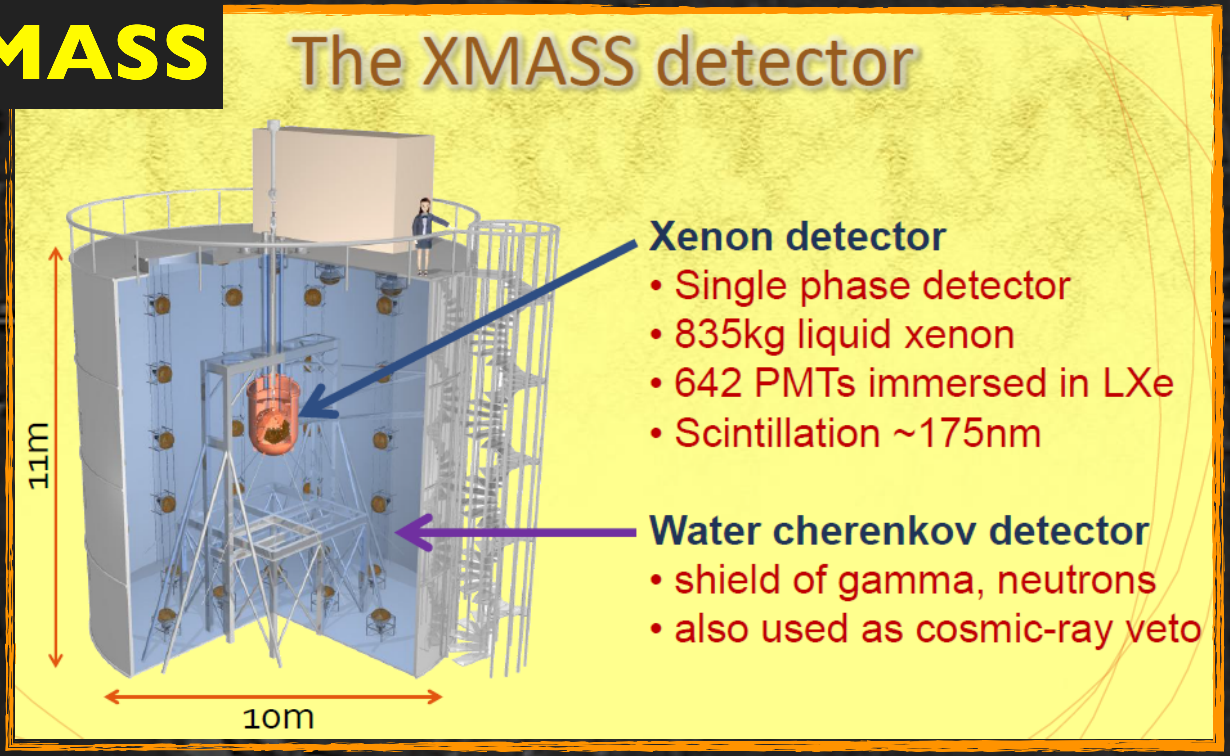
- μLENS at Kimbalton (VA, USA)
- LENS not approved yet

Cell Size mm	Cube size m	Pe yield /MeV	Det Eff %	pp-ν /t In/y	Bgd /t In/y	S/N	M (In)* ton	M (InLS) ton	PMT
75	4	1000	64%	40	13	3	10	125	13300 (3")
125	5	950	40%	26	9	2.9	15.3	190	6250 (5")

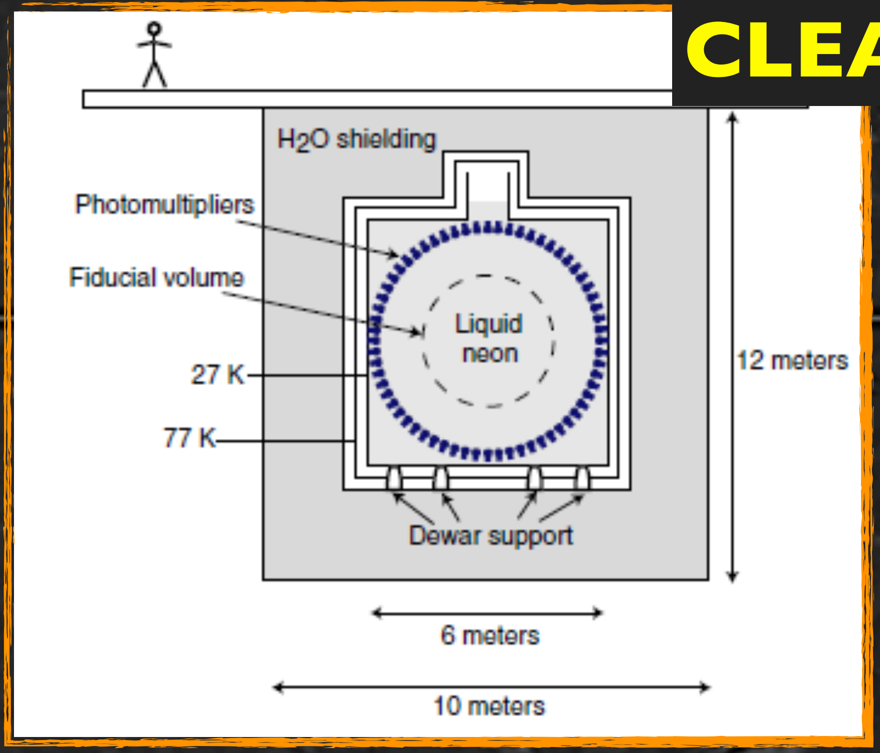
WHAT NEXT: XMASS, CLEAN

- **Liquid noble gas as scintillators**
  - **XMASS: liquid xenon for dark matter and solar neutrinos**
    - **First run done, upgrade in progress, resume data taking soon**
    - **Current focus: dark matter**
  - **CLEAN: liquid neon**
    - **Small prototype running at SNOlab**
    - **100t detector under design**

XMASS

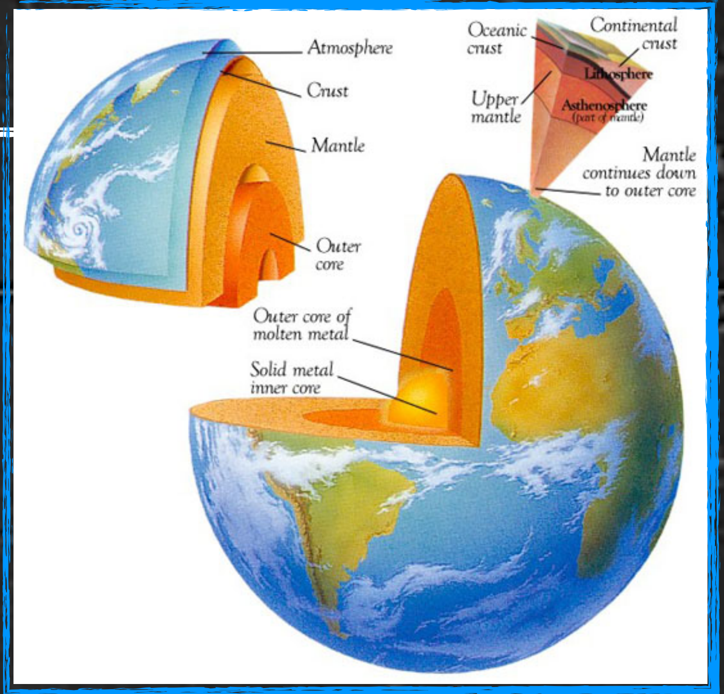


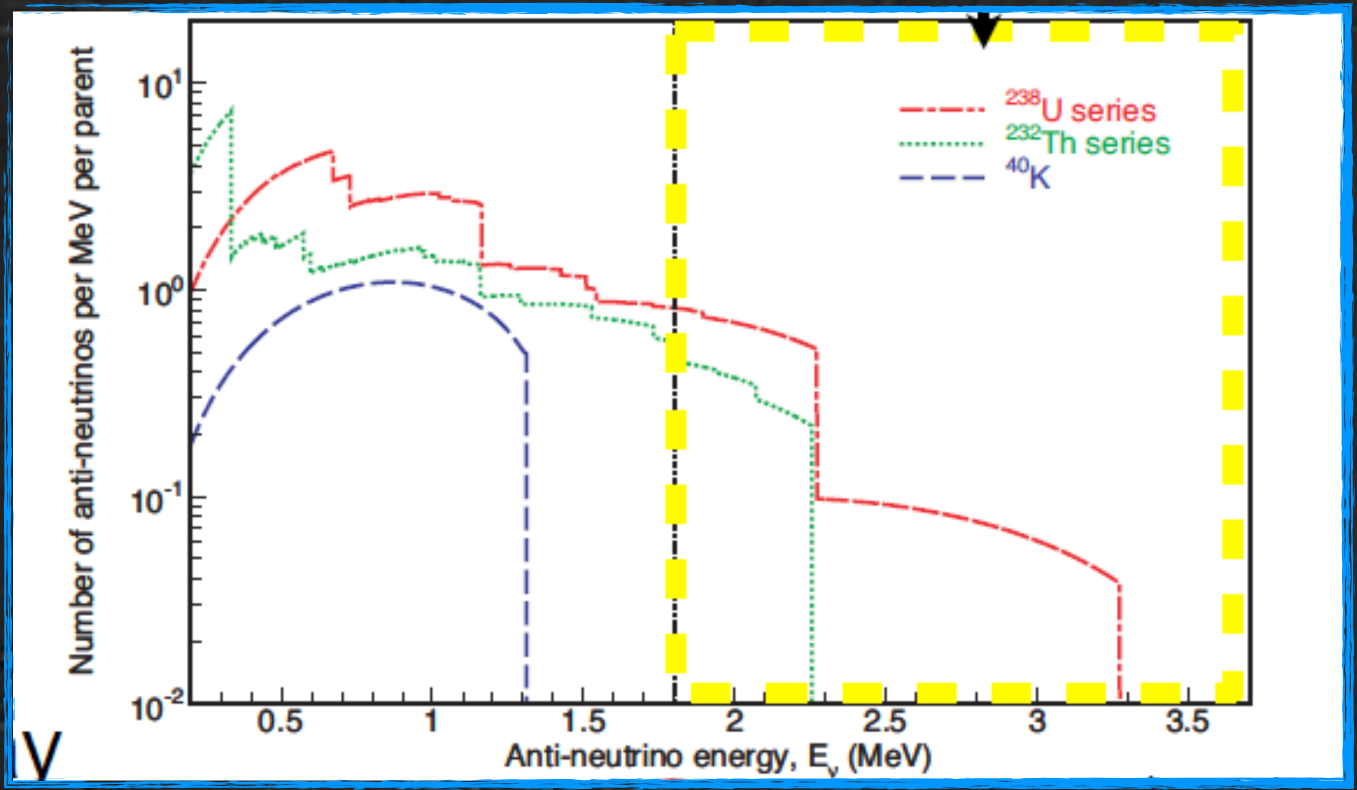
CLEAN

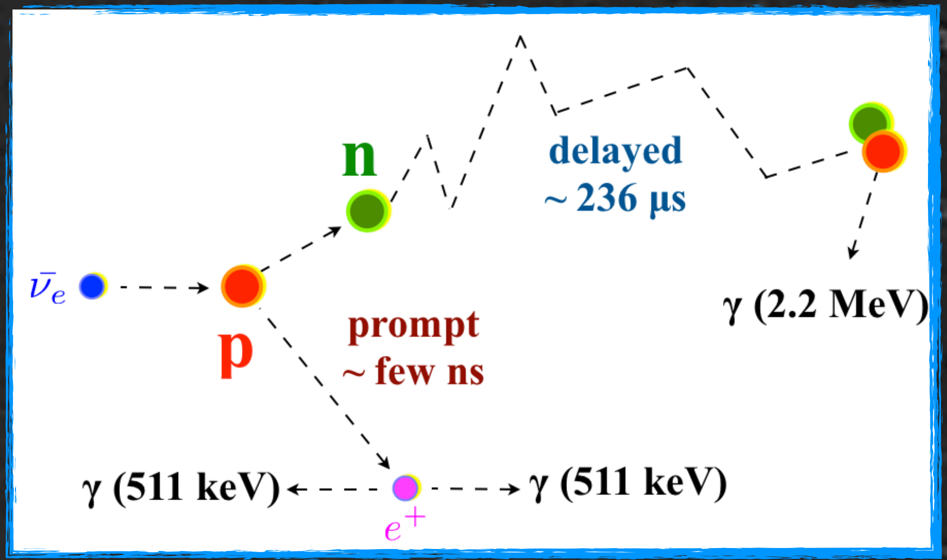


GEO-NEUTRINOS

- Anti-neutrinos emitted by Earth radioactivity
  - First detected by KamLAND and Borexino





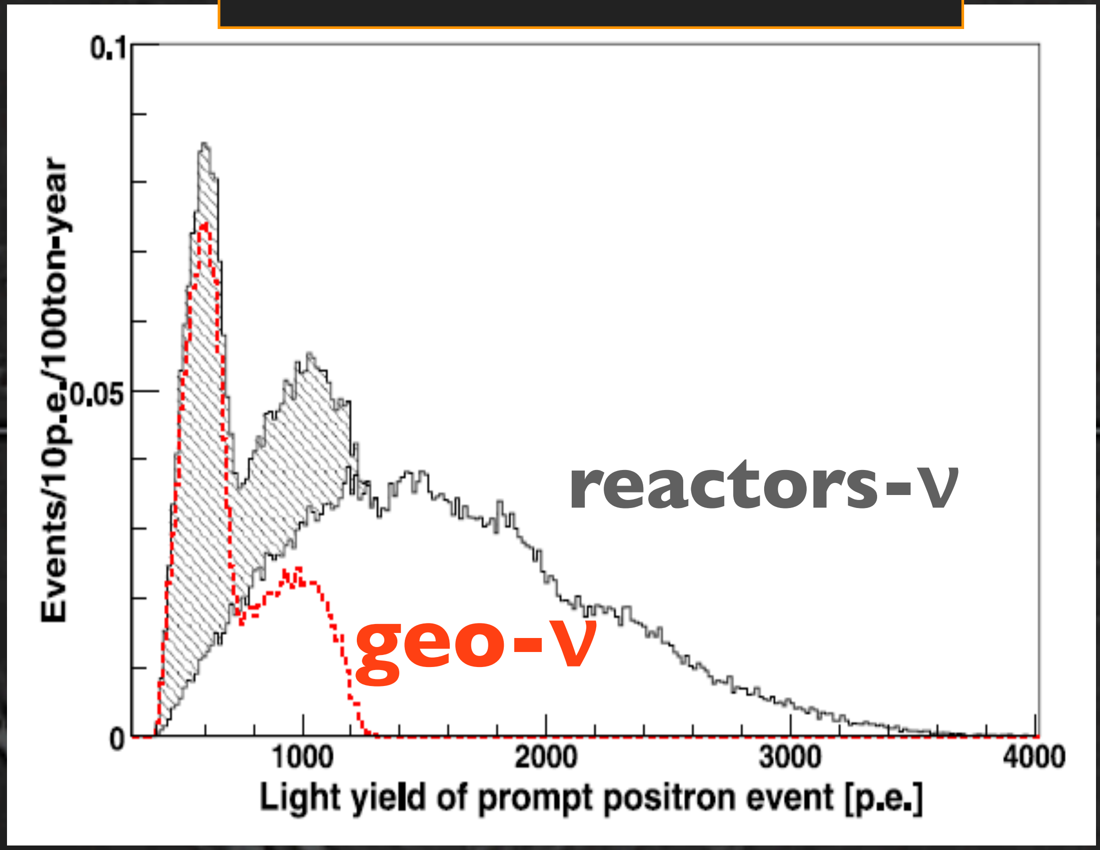


- Very low flux (3 orders less than solar neutrinos)
  - Clean anti-neutrino signature
  - Only background: reactors (much bigger at KamLAND site)

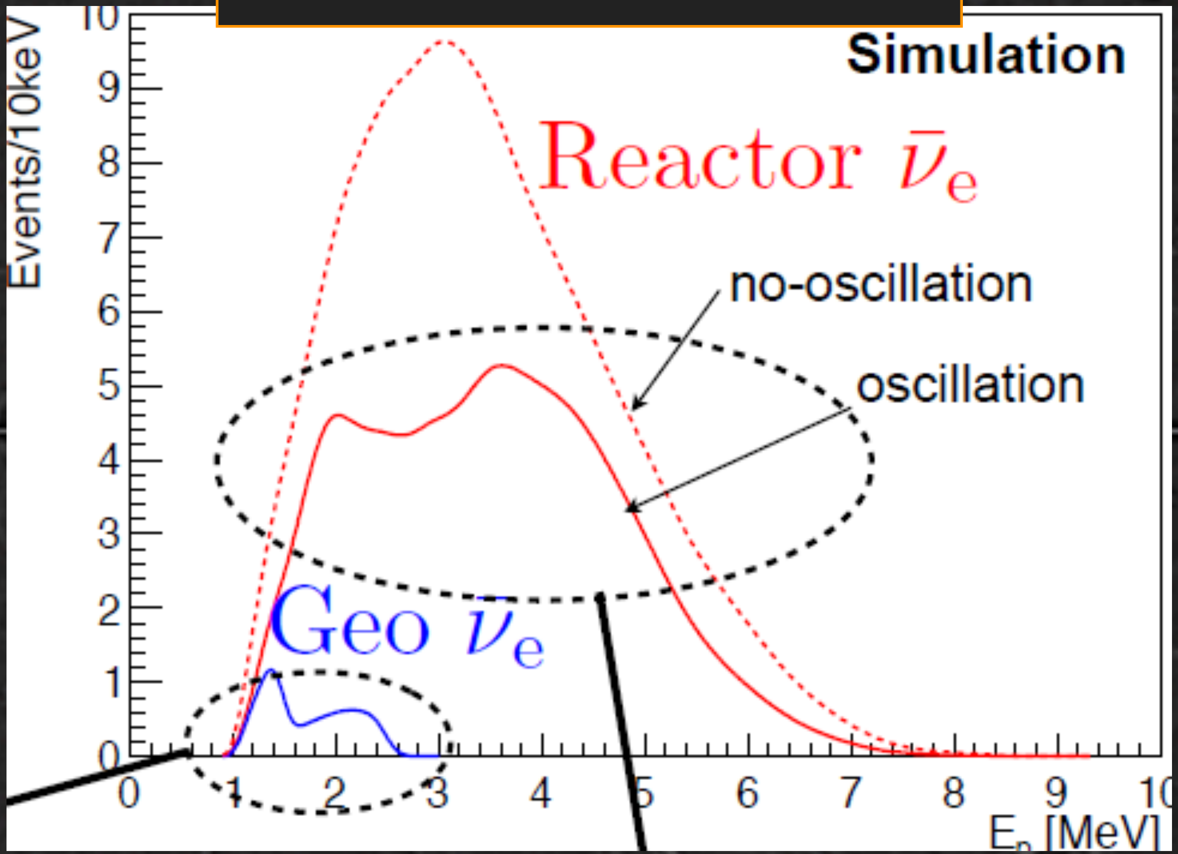
GEO-NEUTRINOS

- Expected signal differ between KamLAND and Borexino
  - Reactor background very different
    - No reactors in Italy, several in Japan around KamLAND site
  - Continental crust for Borexino, partially oceanic in Japan

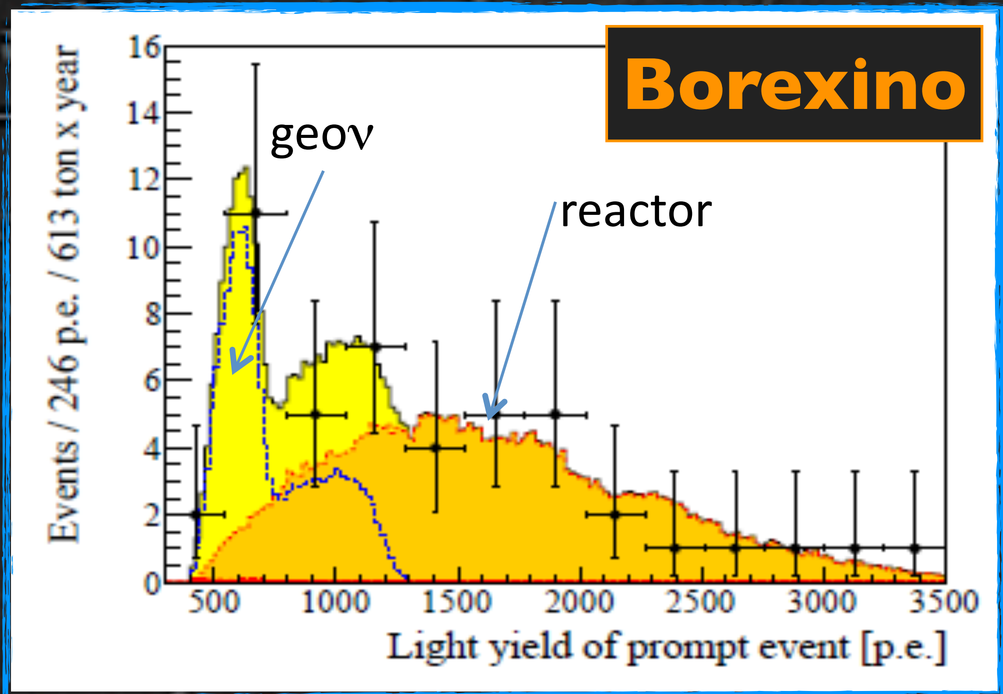
Borexino simulation



KamLAND simulation



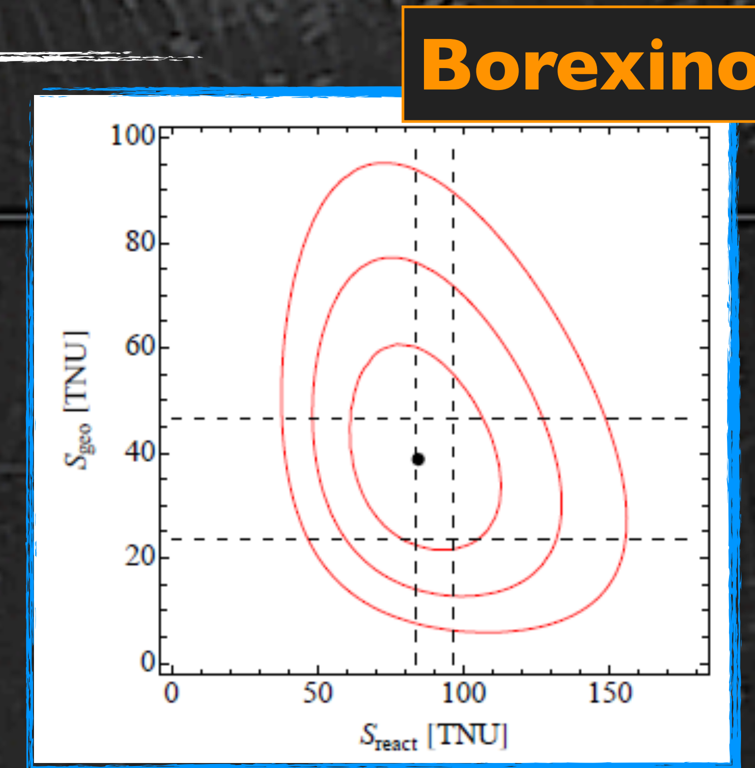
BOREXINO AND KAMLAND RESULTS

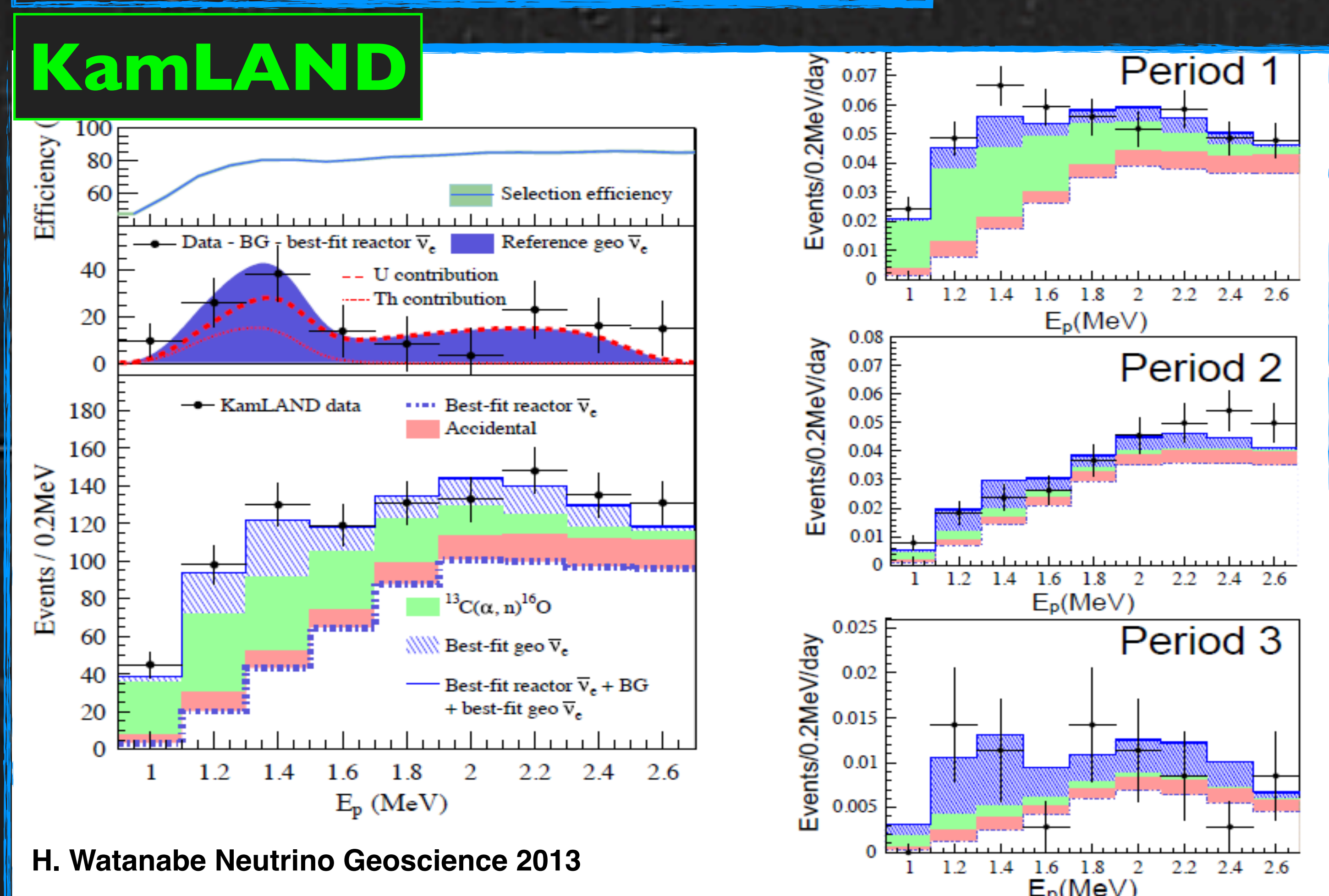


No geoν signal: rejected at 4.5 σ C.L.

N_{geo} = 14.4 ± 4.4 events = = 38.8 ± 12.0 TNU

Reactor events consistent with neutrino oscillations





KamLAND

N_{geo} = 31.1 ± 7.3 TNU

Low background period gave consistent results

CONCLUSIONS

- **Solar neutrinos have been pivotal to the discovery of neutrino oscillations**
  - **A very active field of research yet**
  - **Next goals: precision low energy neutrino physics and stellar physics**
    - **Search for new physics in solar neutrino interactions**
    - **Several projects under way**
- **Solar neutrino detectors important for other science as well**
  - **Geo-neutrinos (KamLAND, Borexino)**
  - **Dark matter search (XMass, Clean)**
  - **Neutrinoless double beta decay (KamLAND, SNO+, Borexino in the future)**
  - **Sterile neutrino search (Borexino-SOX, KamLAND-Celand)**
    - **See T. Lasserre and I. Machulin talks**

Thanks