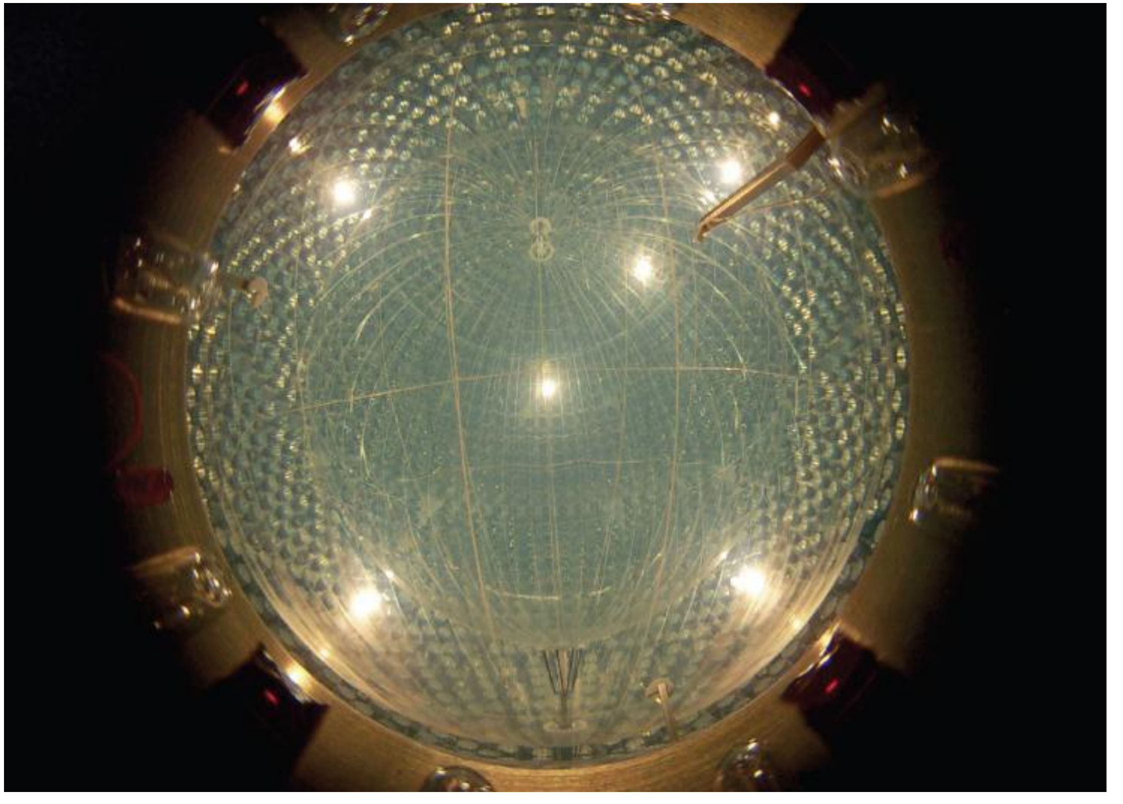
The recent results of solar neutrino measurement in Borexino



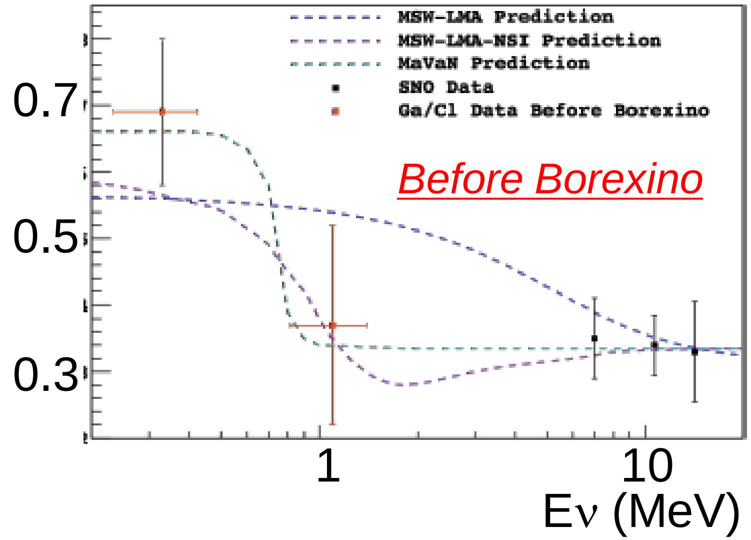
Yusuke Koshio
On behalf of Borexino collaboration

Why solar neutrinos?

- Neutrino physics
  - MSW-LMA scenario is our current understandings

    Precise determination of the neutrino oscillation parameters
  - Any other possibility?
    - ✓ Day/Night asymmetry
    - ✓ Survival probability in ν_e

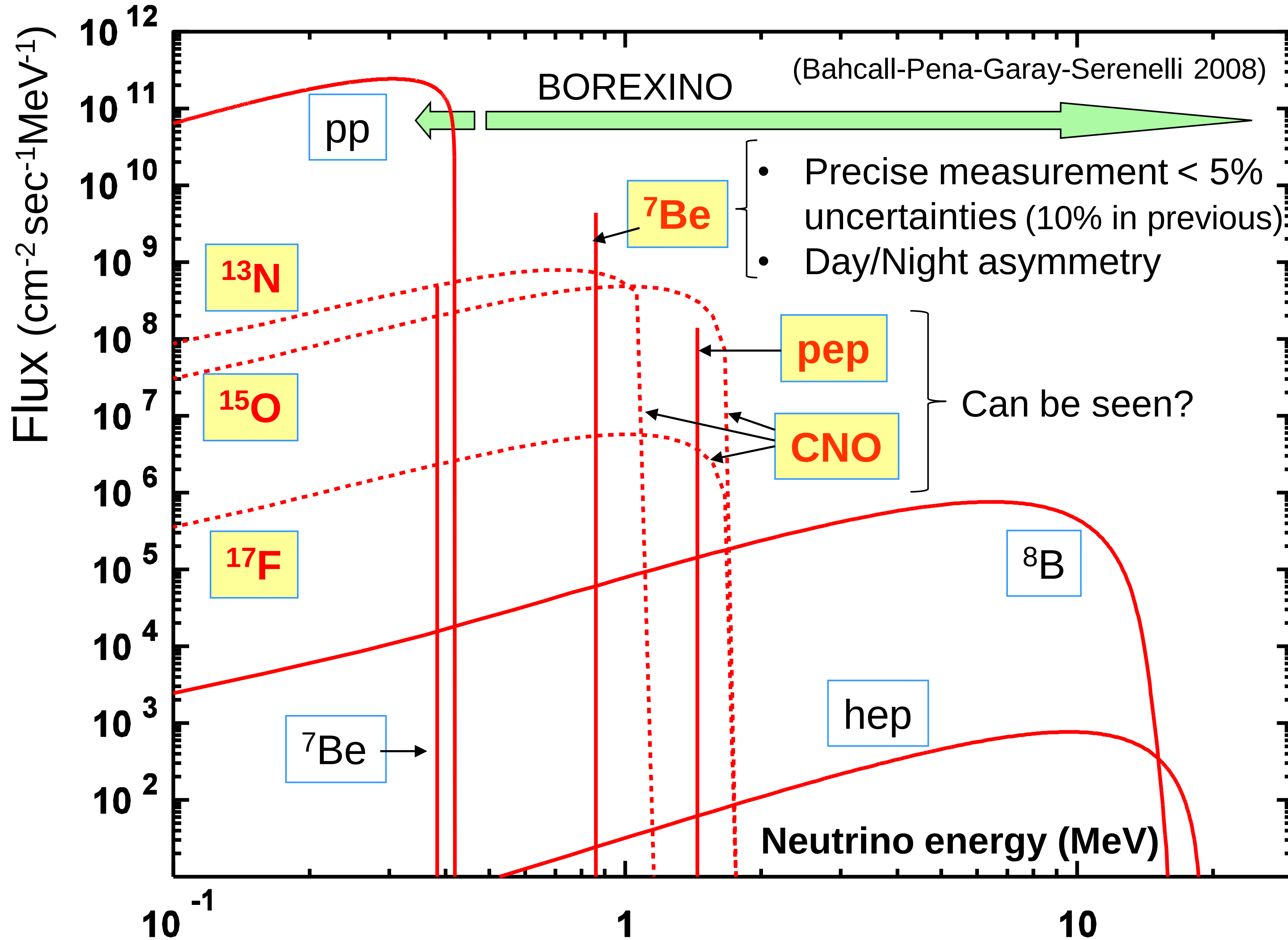
ν_e survival Probability (Pee)



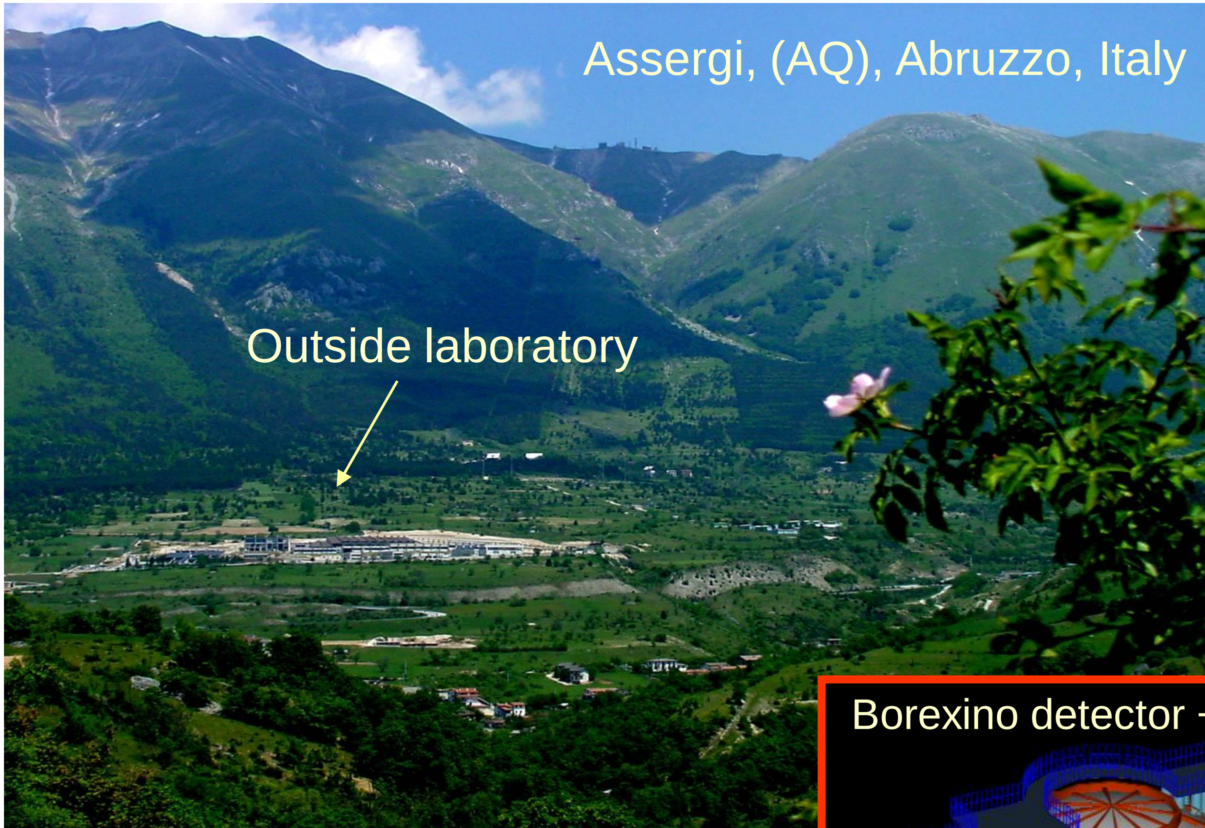
- Solar astrophysics
  - Verify the Standard Solar Model (SSM)

    Direct measurements for sub-MeV solar neutrino flux
    - ✓ Does CNO cycle really happen in the sun?
    - ✓ pep (1.1%) and pp (0.6%) are predicted with higher precision.
  - Study the metallicity (High or Low) controversy
    - ✓ Differences are ~10% in ^{7}Be, ~20% in ^{8}B, ~30% in CNO

Solar neutrino spectrum

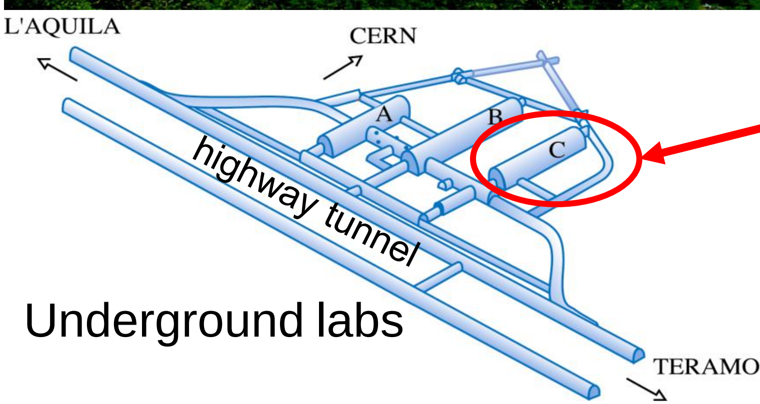


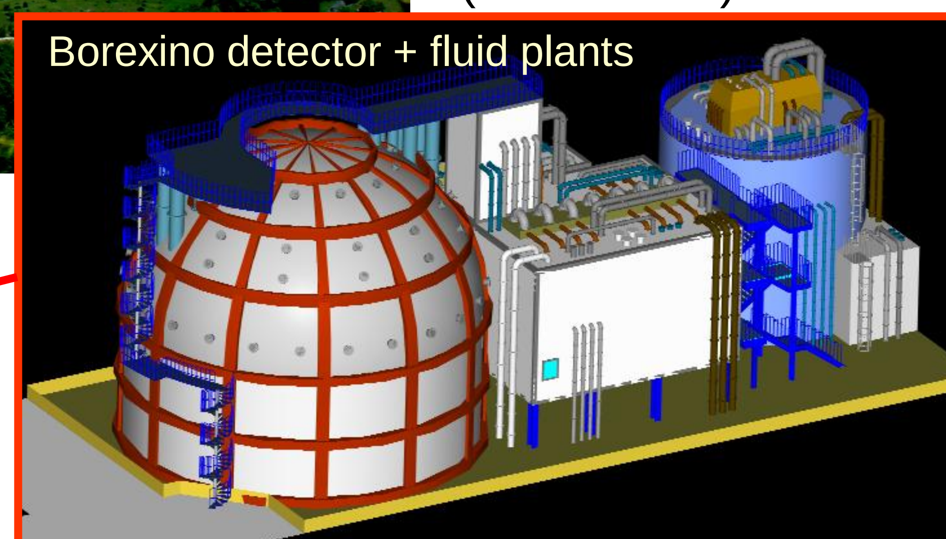
Laboratori Nazionali del Gran Sasso



120km from Roma

1300m underground
(3500m w.e.)





BOREXINO

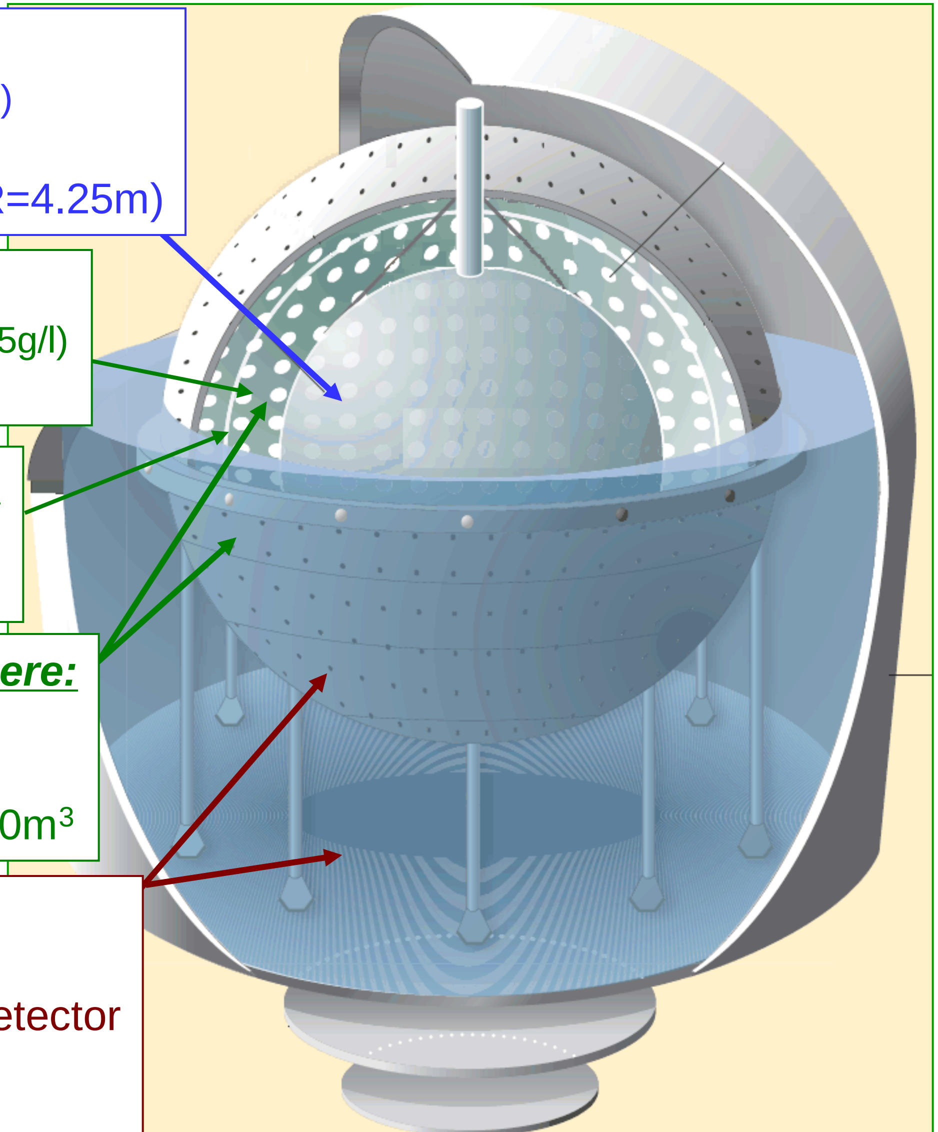
Liquid scintillator:
270 t PC+PPO (1.5g/l)
in a 150μm thick
Inner nylon vessel (R=4.25m)

Buffer region:
PC+DMP quencher (5g/l)
4.25m<R<6.75m

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

Stainless Steel Sphere:
R=6.75m
2212 8” PMTs with
light guide cone. 1350m^3

Water tank:
γ and n shield
μ water cherenkov detector
208 PMTs in water
2100m^3



Data taking started in 2007

Experimental target :

- Solar Neutrinos

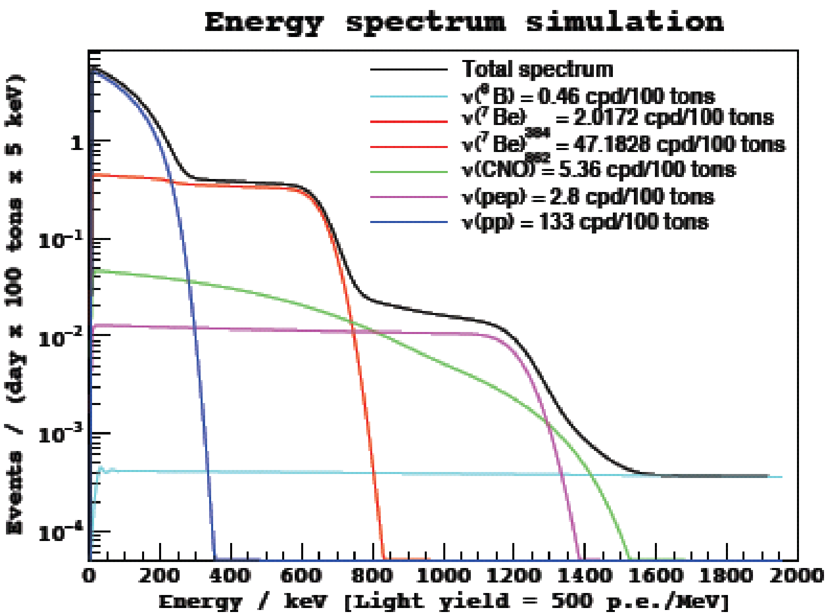
The wide energy range in real time are measurable.

- Geo Neutrinos
- SuperNova neutrinos
- Long/Short base line neutrinos
- etc…

Detection principle

Solar neutrinos are detected through elastic scattering on electrons

$\nu_{solar} + e \rightarrow \nu + e$



Scintillation lights are emitted

- ✓ High light yield (~500 p.e. /MeV)
- ✓ Good timing response
- ✓ Pulse shape discrimination

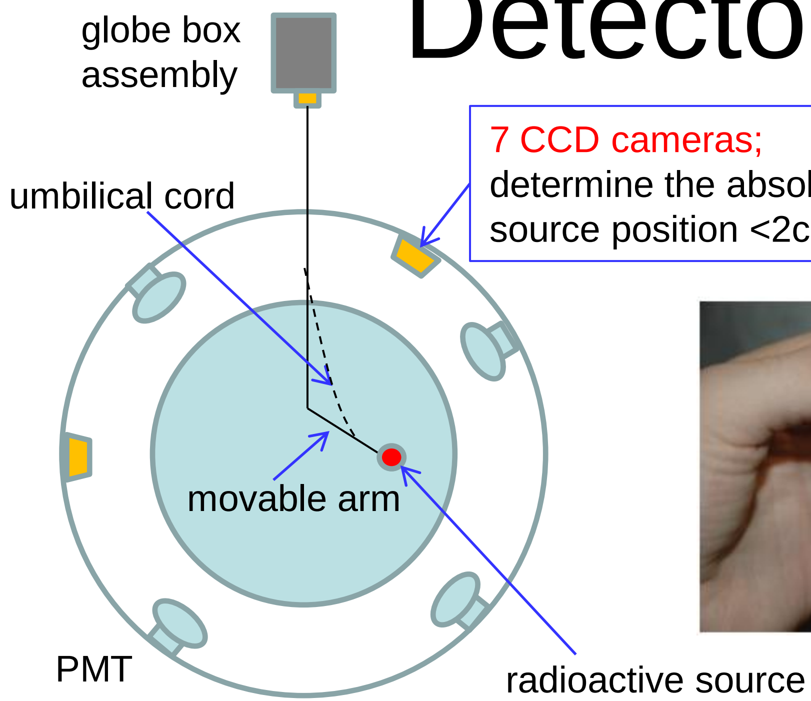
but…

- ✓ No neutrino direction
- ✓ No way to distinguish between neutrinos and β/γ backgrounds

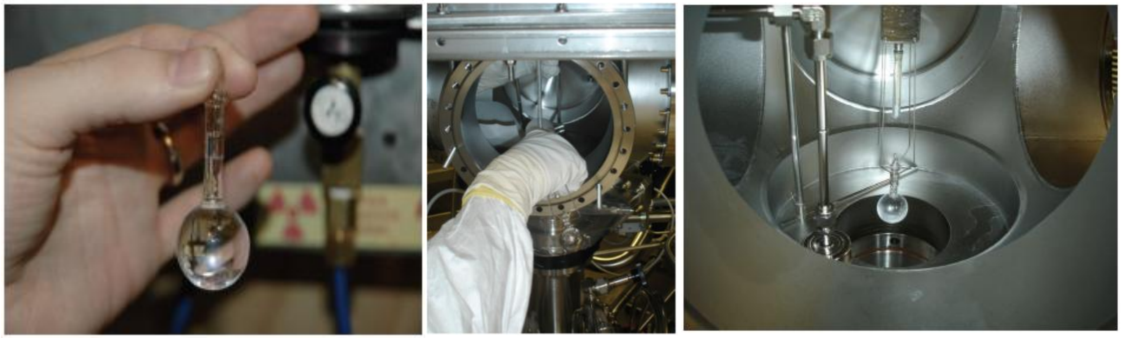
→ ***Extreme radiopurity is required***

(NIM A, 609, 1 (2009) 58)

Detector calibration



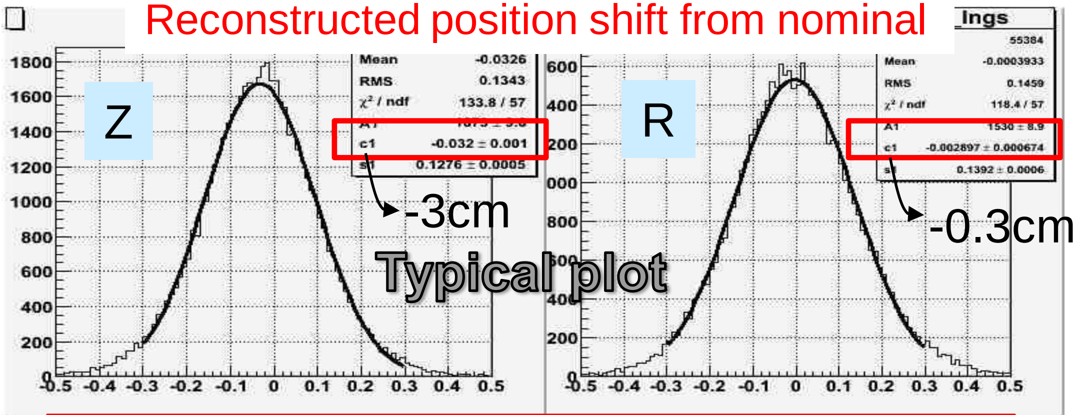
Source insertion



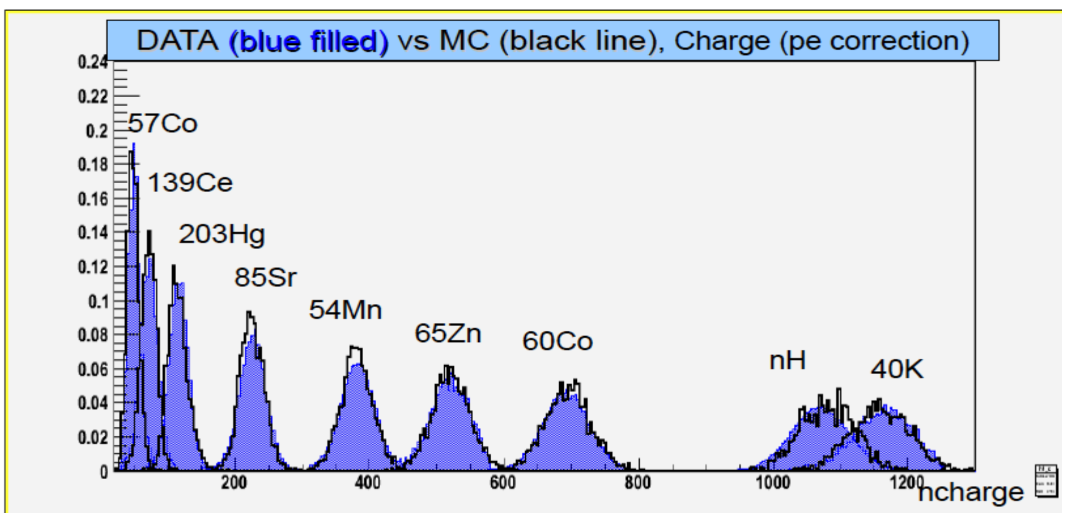
	γ								β		α	n		
	dopant dissolved in small water vial								^{222}Rn loaded liq. scint. vial			Am-Be		
	^{57}Co	^{139}Ce	^{203}Hg	^{85}Sr	^{54}Mn	^{65}Zn	^{60}Co	^{40}K	^{14}C	^{214}Bi	^{214}Po	n-p	n +^{12}C	n+Fe
Energy (MeV)	0.122	0.165	0.279	0.514	0,834	1.1	1.1 1.3	1.4	0.15	3.2	(7.6)	2.2	4.94	~7.5

clear tag from Bi-Po
fast coincidence

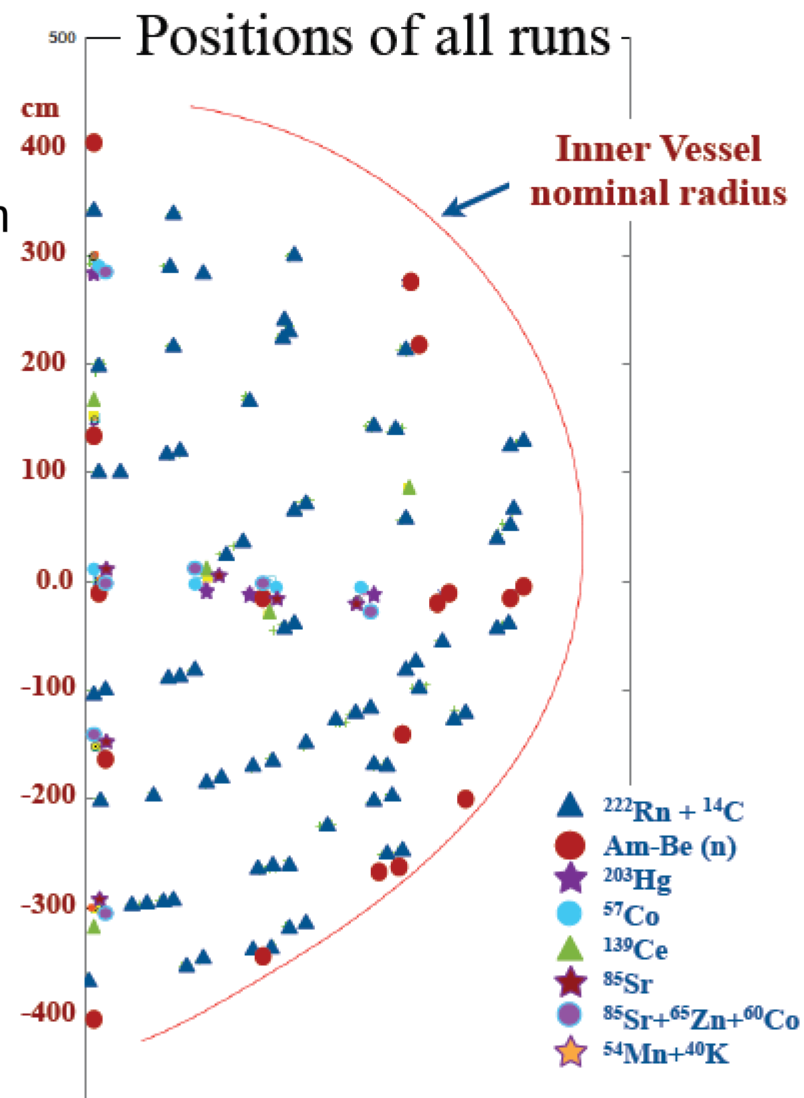
Position and Energy calibration



Using the 184 points of Rn calibration data, the fiducial volume uncertainty is 1.3%

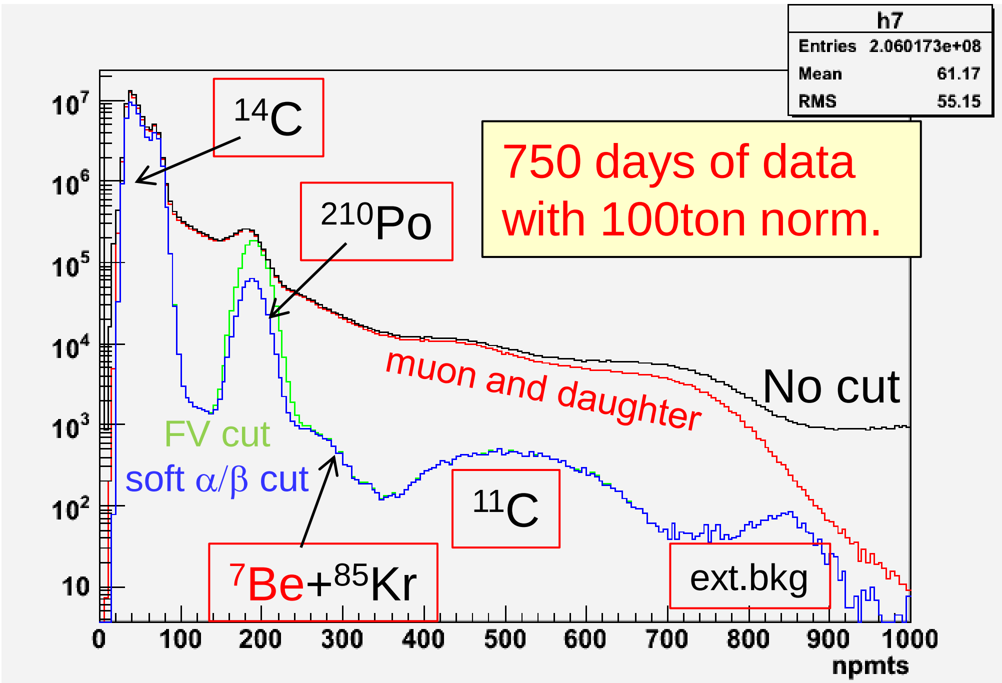


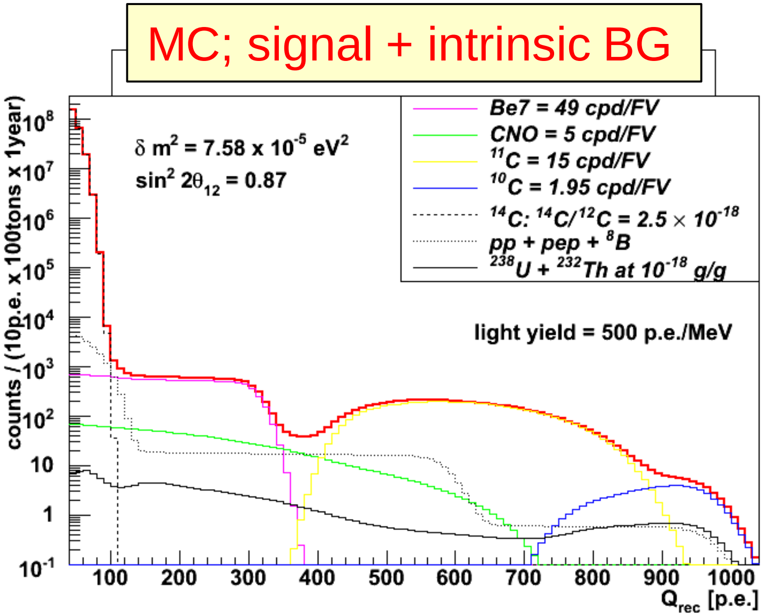
The energy scale uncertainty is 1.5%



Results in ^{7}Be neutrino

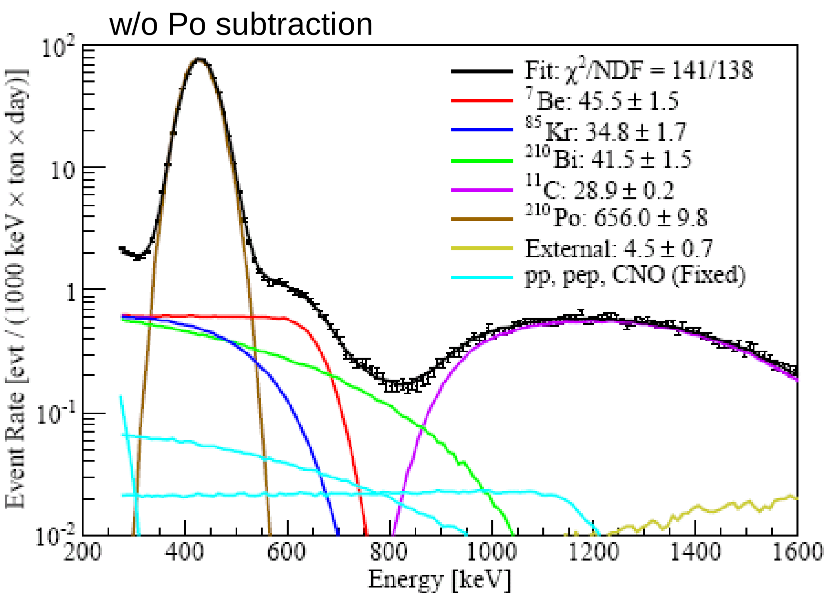
Reduction and signal extraction

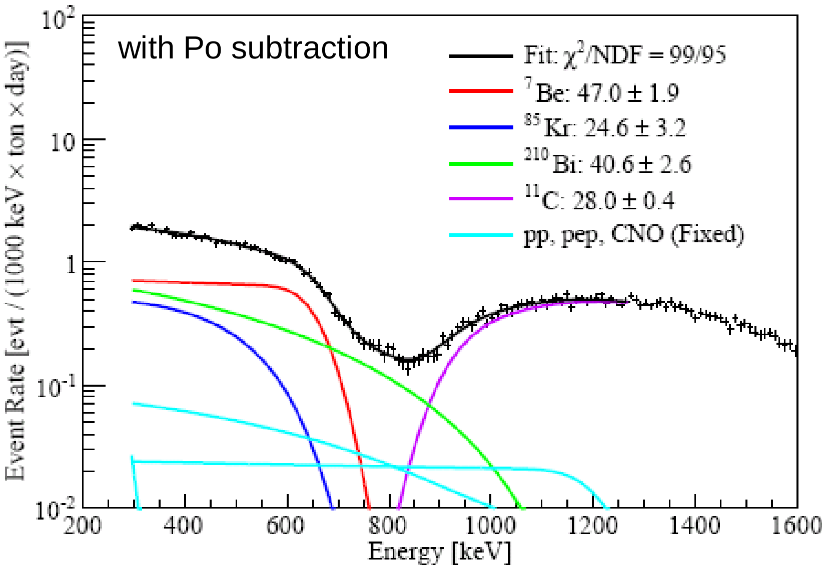




A spectral fit was applied by solar neutrino signals and all the intrinsic backgrounds

Result of ^{7}Be solar neutrino rate





^{7}Be rate (E=862 keV line)
in 750 days of data

46.0 ± 1.5 (stat) $^{+1.5}_{-1.6}$ (sys)

counts/(day x 100t)
(total uncertainty is 4.7%)

Source of systematic error	
Trigger eff. And stability	<0.1 %
Live time	0.04%
Scintillator density	0.05 %
Sacrifice of cuts	0.10 %
Fiducial volume	+0.5 –1.3%
Fit methods	2.0 %
Energy response	2.7 %
Total syst. error	**+3.4 –3.6%**

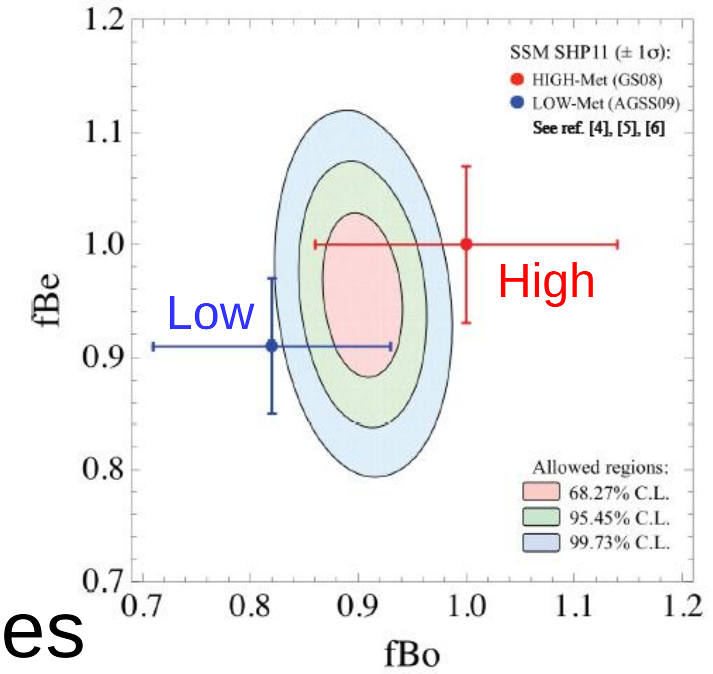
previous
Fiducial volume ← 6%
Energy response ← 6%
Total syst. error ← 8.5%

Implication on solar physics

- Metallicity controversy

  Fit to the available all solar neutrino data leaving free f_{Be} and f_{BO} ($f = \Phi/\Phi(SSM)$)

  Hard to discriminate



- Other solar neutrino sources

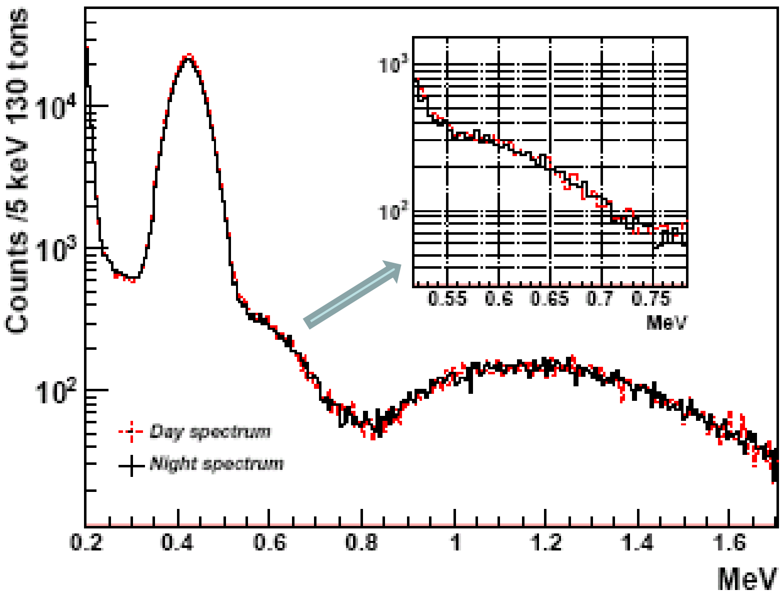
  Each solar neutrino flux can be calculated with solar luminosity constraint.

M.C.Gonzalez-Garcia, M.Martoni, J.Salvado
JHEP 05(2010)072 / 0910.4584

$\Phi_{pp} = (6.06^{+0.02}_{-0.06})\times 10^{10} cm^{-2}s^{-1}$ ($f_{pp} = 1.013$)
$\Phi_{CNO} < 1.3\times 10^{9} cm^{-2}s^{-1}$ ($f_{CNO} < 2.5$) at 95%C.L.

Day/Night asymmetry in ^{7}Be rate

- In the MSW scenario, the flux rate in Night should be higher than Day because of the regeneration effect.
- In the ^{7}Be energy region, no effect expected in MSW-LMA region, but large in MSW-LOW region (~20%).



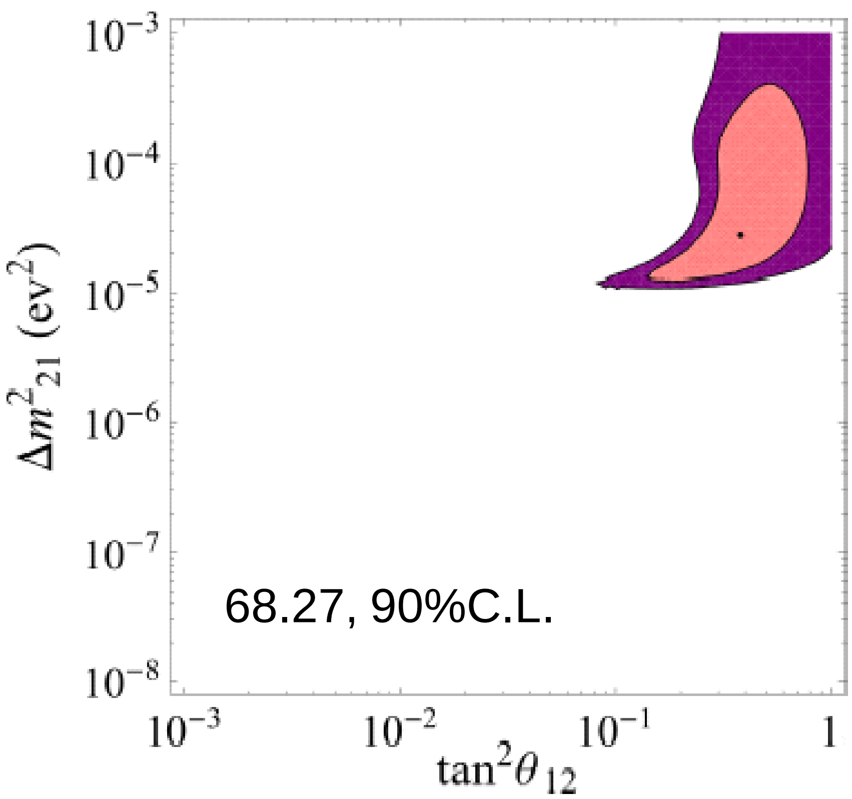
Day (positive Sun altitude) 360.25 days
Night (negative Sun altitude) 380.63 days

No significant effect was found

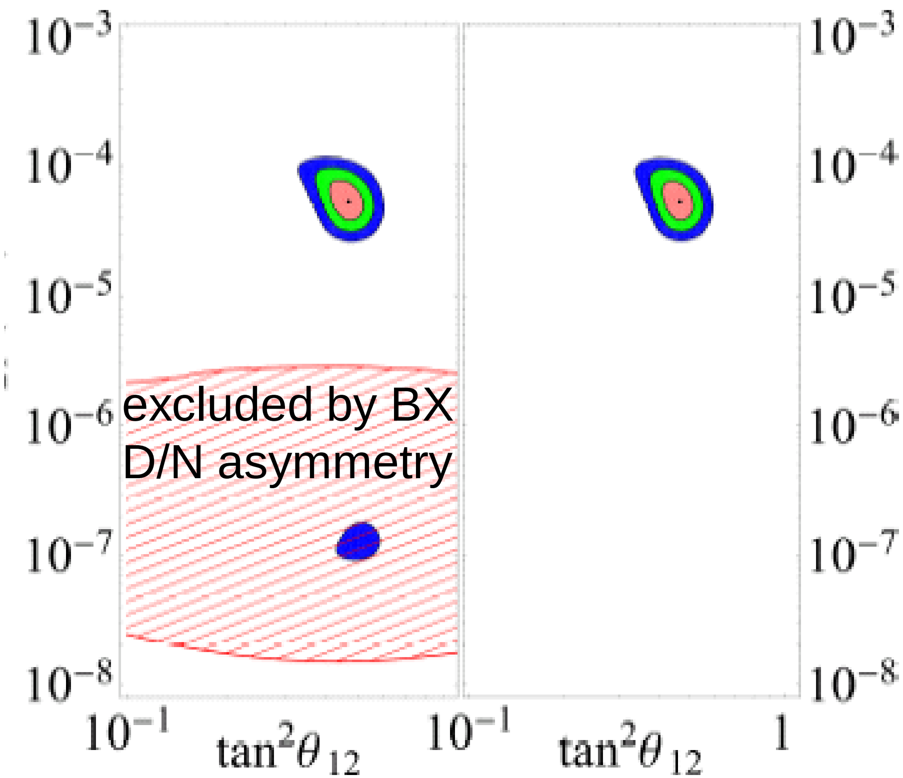
$$Adn = \frac{N - D}{(N + D)/2}$$
$$= 0.001 \pm 0.012\,(stat.) \pm 0.007(sys.)$$

Neutrino oscillation analysis

Only Borexino



All solar w/o BX All solar with BX



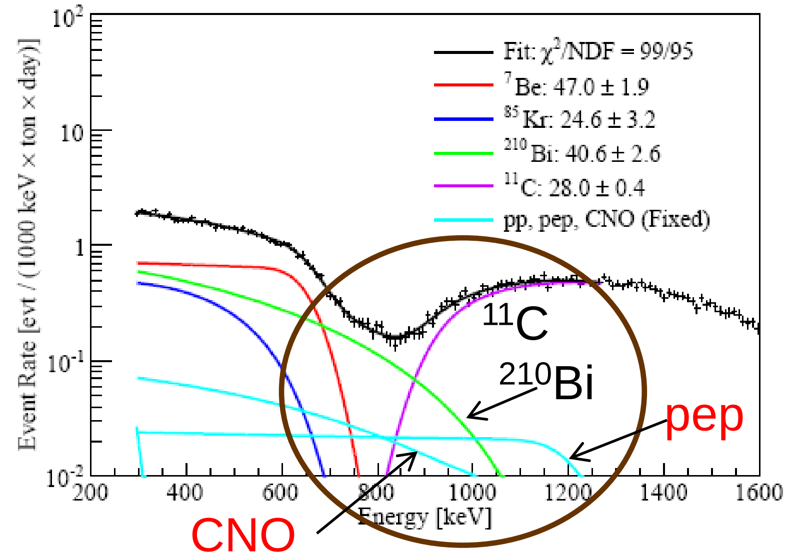
Confirm LMA scenario by BX data alone

LOW solution excluded at >8σ by BX data

Results in pep and CNO

A challenging task

- Low signal rates with large backgrounds
  - A few cpd/100ton for signal, while ^{11}C as a dominant BG for pep is ~28 cpd/100ton.
  - External BG of ^{208}Tl, ^{214}Bi from PMTs, stainless steel sphere…
- How to separate?
  - Three Fold Coincidence
  - e+/e- pulse shape discrimination
  - Position distribution
  - Spectrum



Cosmogenic ^{11}C

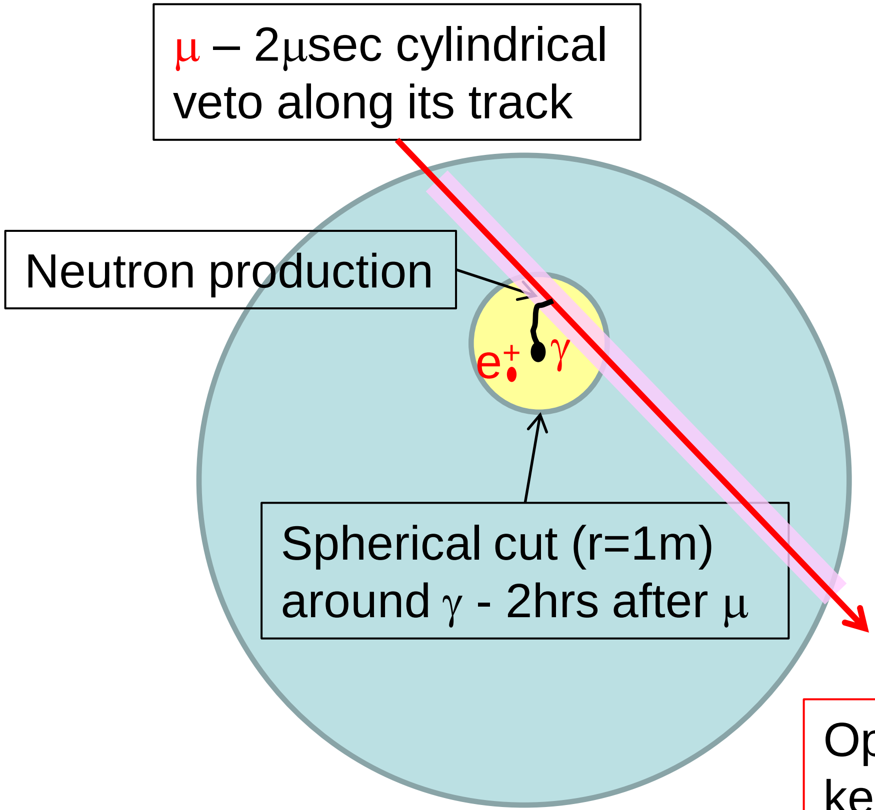
$\mu + {}^{12}C \rightarrow {}^{11}C + n + \mu$

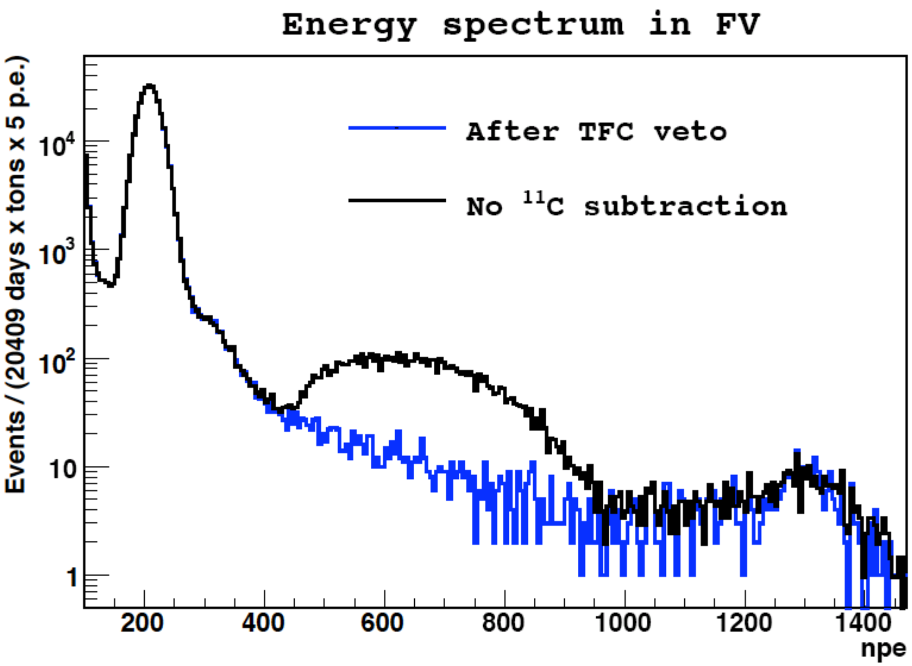
n: captured by proton (2.2MeV γ)

^{11}C: $\rightarrow {}^{11}B + e^{+} + \nu_e$ (τ~30min)

Three Fold Coincidence

- Veto using space-time correlation



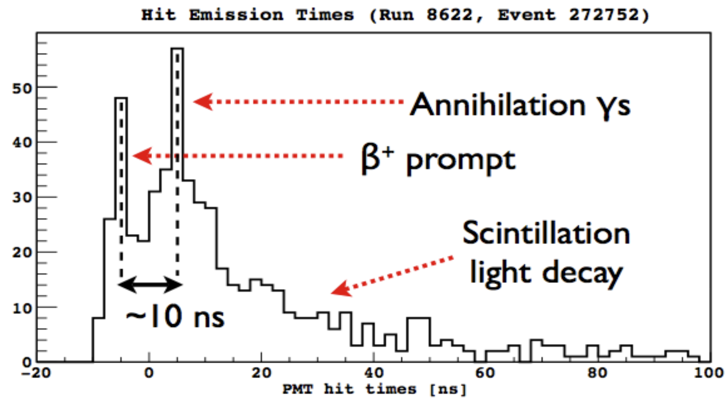


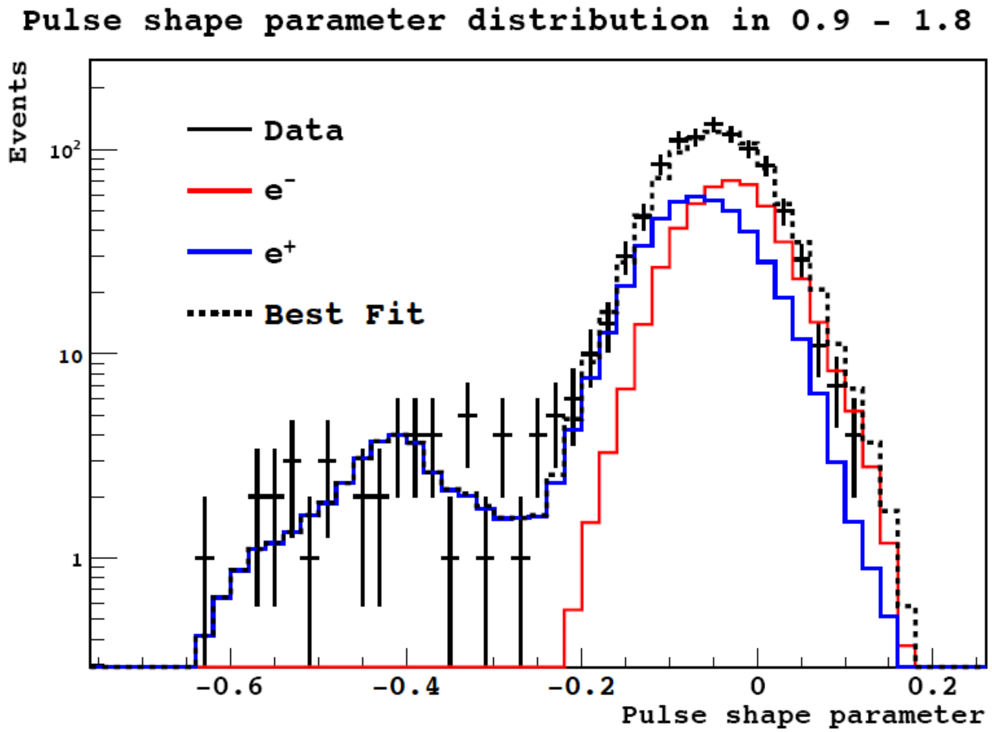
Optimal compromise: 91% rejection of ^{11}C keeping 48.5% residual exposure

e+/e- pulse shape discrimination

Positrons have different time profile and event topology with electrons.

- Form positoronium (51.2%, 3.12ns) (Phys.Rev.C 83(2010)015504)
- Annihilation γs

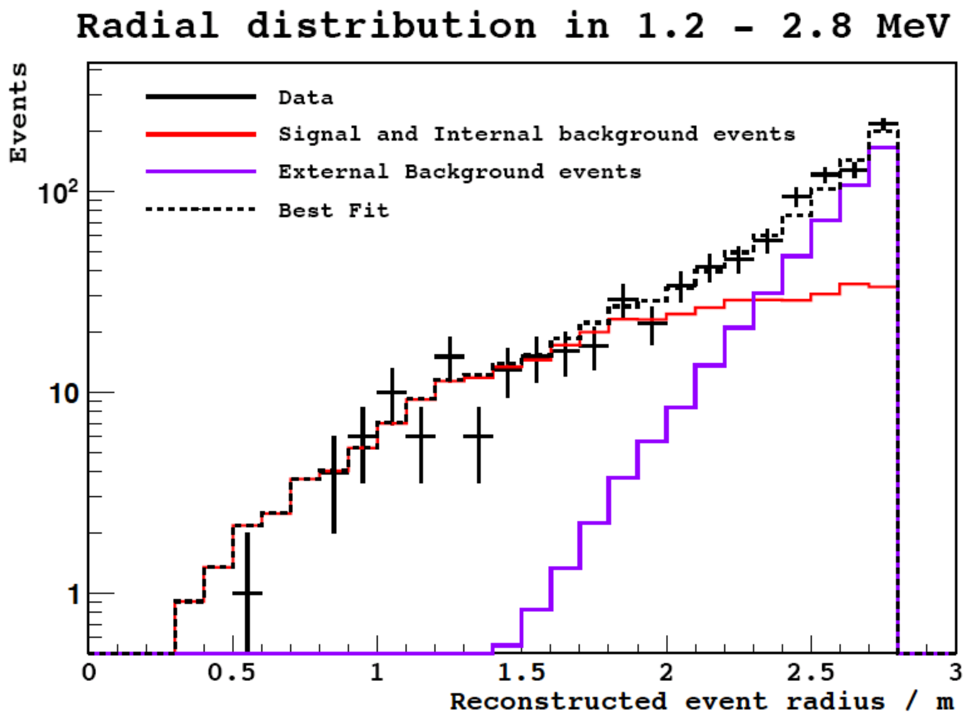




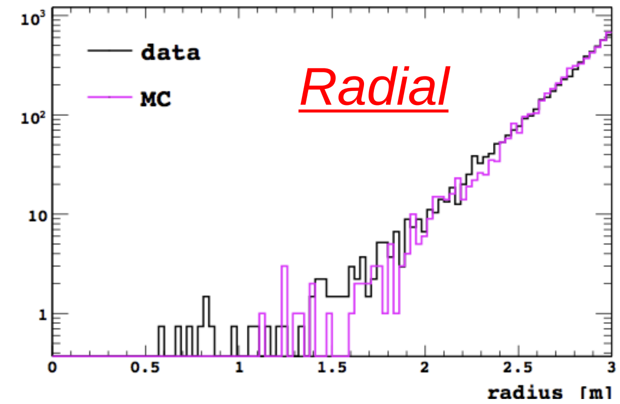
External background

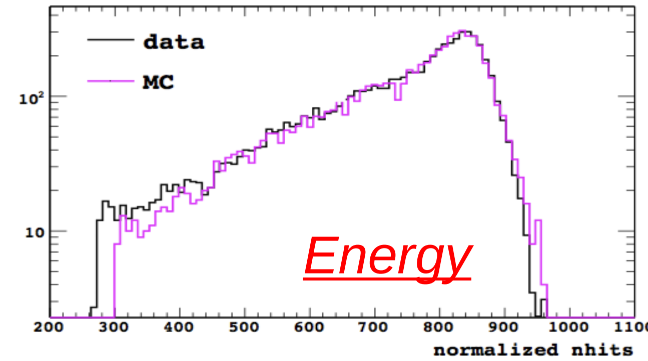
- Recognized by position and energy distribution by MC simulation
- Simulation validated with calibration data of high activity external ^{228}Th source

(arXiv 1110.1217)



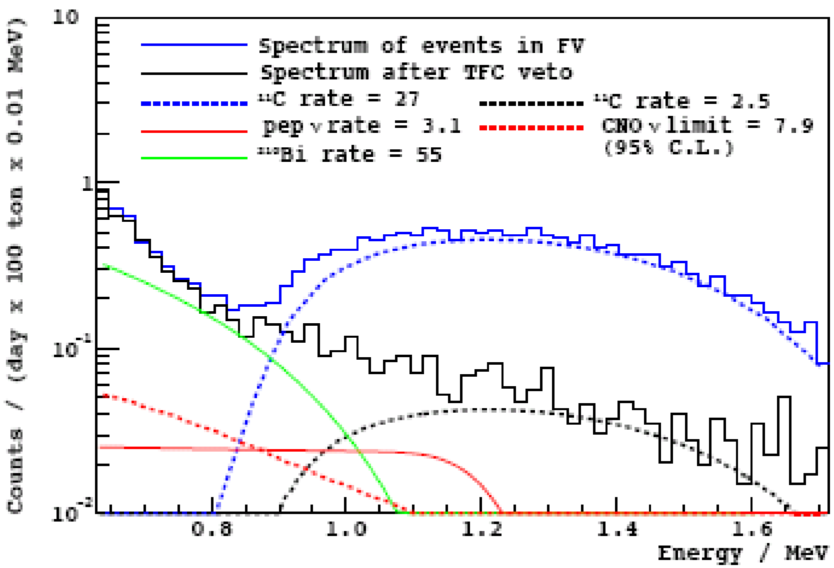
Calibration data vs MC

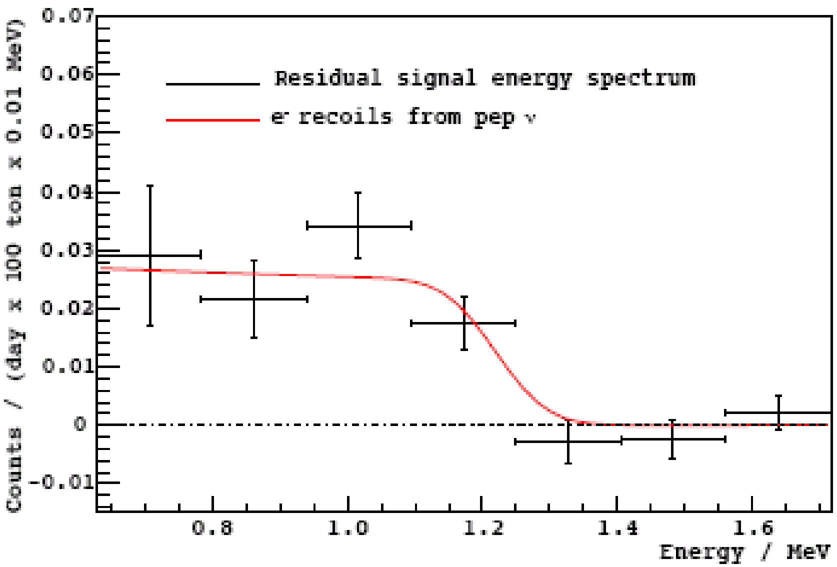




Good agreement

Results of the spectrum fitting





pep rate:

3.1±0.6(stat.)±0.3(sys.)

count/day/100ton

→ (1.6±0.3) x 10^8 cm^{-2} s^{-1}

Main systematics:

fit configuration / energy scale

First direct observation. (98%C.L.)

CNO rate:

< 7.9 count/day/100ton

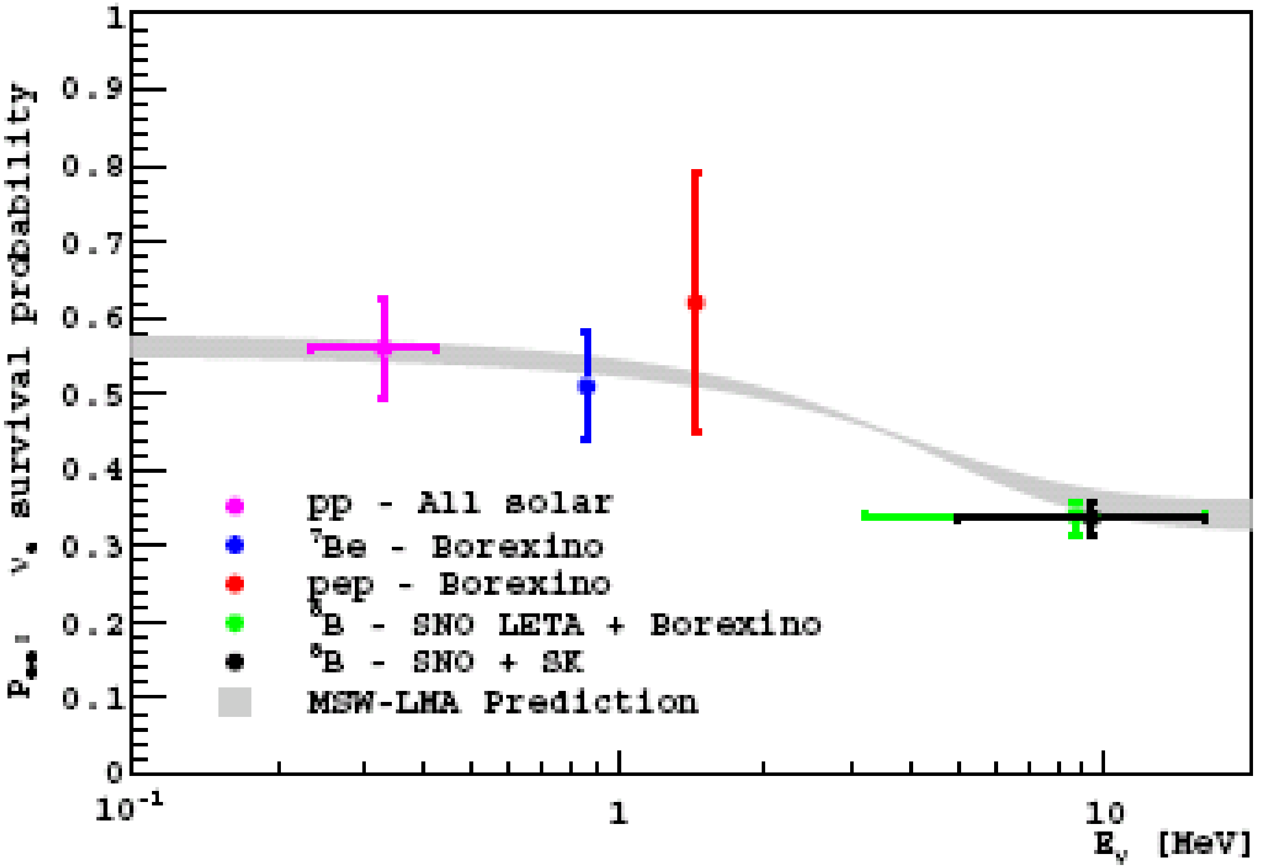
→ < 7.7x 10^8 cm^{-2} s^{-1}

(95%C.L. upper limit)

Strongest constraint

(f_{CNO} < 1.4)

ν_e survival Probability (Pee)

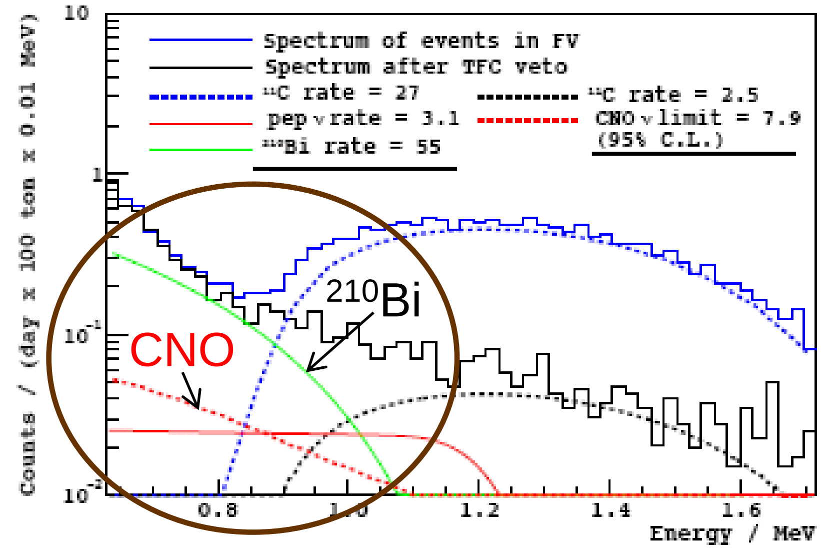


Consistent with MSW-LMA scenario

CNO measurement in future

- Similar spectra as ^{210}Bi
  difficult to separate…

Reduce as much as possible



- Borexino phase II
  - We have undertaken a series of purification campaigns (mainly water extraction and nitrogen stripping) to decrease radioactive backgrounds since July 2010.
  - Significant removal of ^{210}Bi was found.
  - Operation is now on-going.

Summary

- Precise measurement (<5% uncertainty) of the ^{7}Be solar neutrino has achieved thanks to the internal source calibration.
- The analysis techniques have been able to suppress backgrounds.
- First direct measurement of pep neutrinos, and strongest constraint to CNO flux.
- Purification efforts are now on-going, which should improve the pep flux measurement and directly observe the CNO neutrinos.

Thank you for your attention

Milano

Genova

Borexino Collaboration

LNGS Laboratori Nazionali del Gran Sasso

Istituto Nazionale di Fisica Nucleare INFN

INFN

Virginia Tech. University
(USA)

UMass Amherst
(USA)

Kurchatov
Institute
(Russia)

Jagiellonian U.
Cracow
(Poland)

Heidelberg
(Germany)

Dubna JINR
(Russia)

APC Paris

Munich
(Germany)

Perugia

Princeton University
(USA)

Backup

CNGS ν velocity

- Activity is in progress to check the OPERA result about the CNGS neutrino velocity
- Need some hardware upgrade
- Ready for the 2012 beam
- Check the data already collected.
  - Time resolution was not accurate enough…
  - Independent way from OPERA all the steps of the measurement
- Also available to collaborate with OPERA

Metallicity controversy inside the sun

- "Improved" calculation of the solar composition changes the fluxes.
  - Z/X=0.0229(GS98)→0.0165(AGS05)

    (X:hydrogen, Y:helium, Z:others)
  - But, disagree with helioseismology ??
- Observed ^{8}B flux

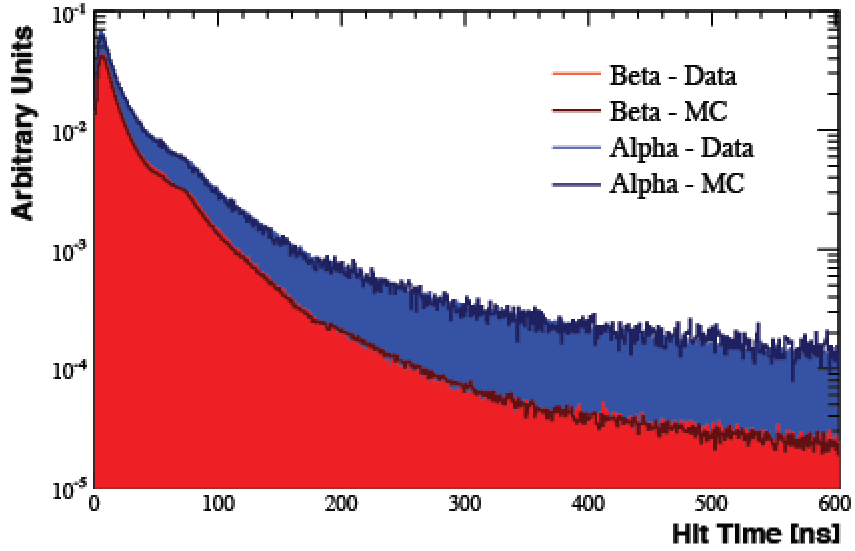
$$\phi_{^8B} = 5.3^{+0.1}_{-0.2} \times 10^6 cm^{-2} s^{-1}$$

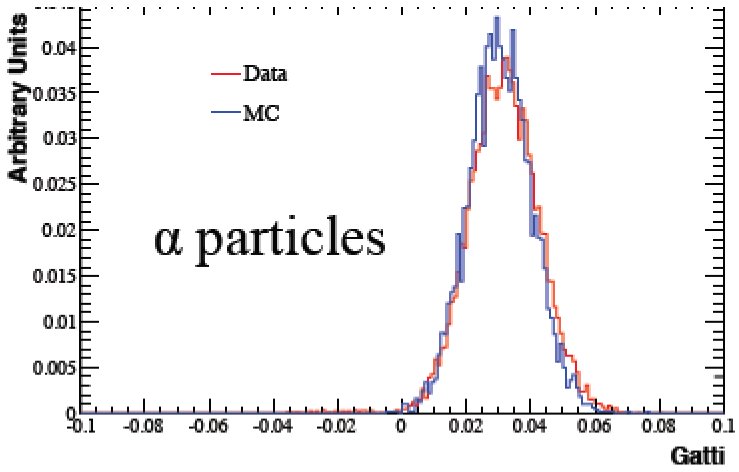
- Precise ^{7}Be flux may useful information.
- CNO ν observation may solve the problem.
  - Study in progress in Borexino
  - One of goal for SNO+

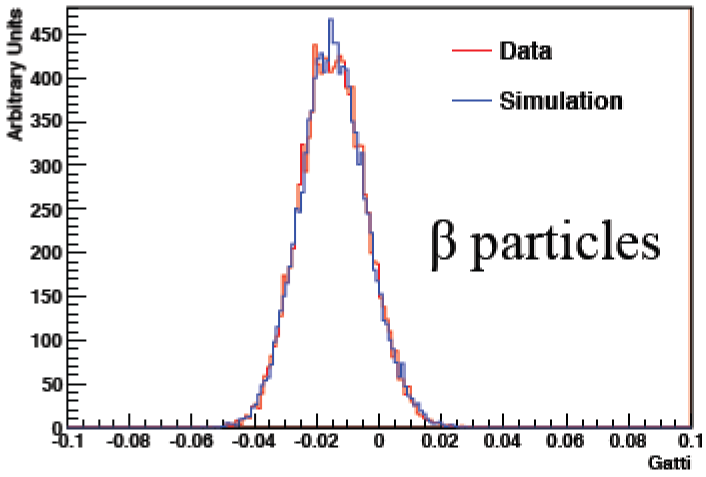
		GS98	AGS05
	pp	5.97×10^{10}	6.04×10^{10}
	pep	1.41×10^{8}	1.45×10^{8}
	hep	7.90×10^{3}	8.22×10^{3}
~10%	^{7}Be	5.07×10^{9}	4.55×10^{9}
	^{8}B	5.94×10^{6}	4.72×10^{6}
~30%	^{13}N	2.88×10^{8}	1.89×10^{8}
	^{15}O	2.15×10^{8}	1.34×10^{8}
	^{17}F	5.84×10^{6}	3.25×10^{6}

α/β discrimination

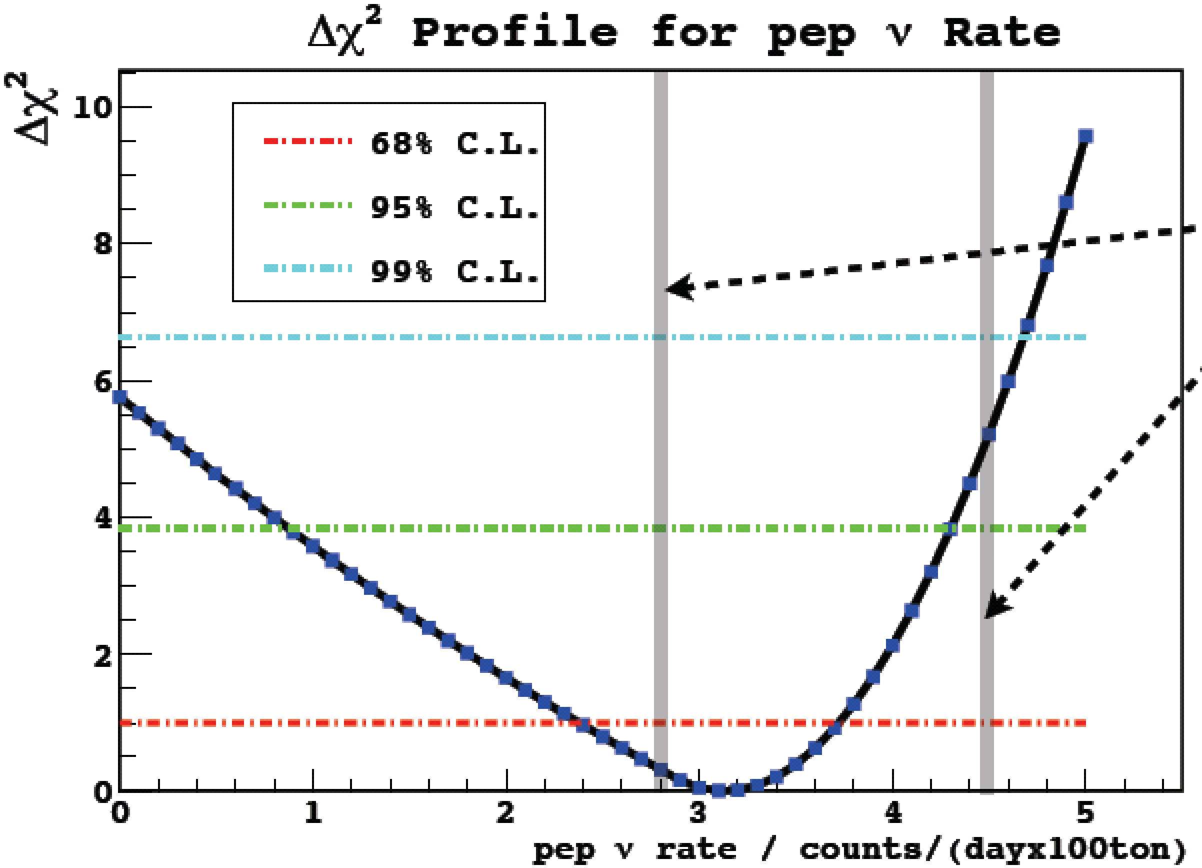
PMT hit timing distribution







Significance of result (pep)



SSM Prediction:

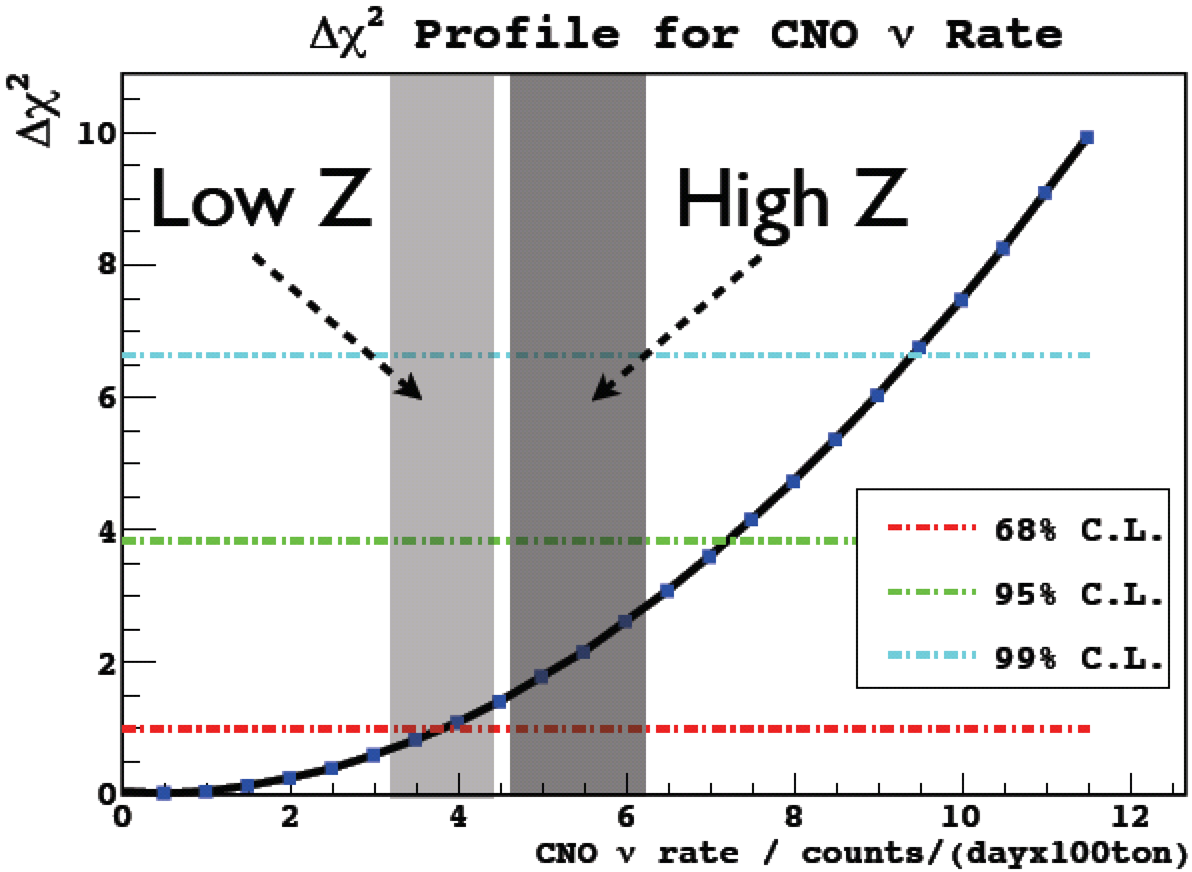
MSW-LMA

No Oscillation

Absence of signal disfavored at 97% C.L.

$3.13 \pm 0.55_{stat}$ counts/day/100ton

Significance of result (CNO)

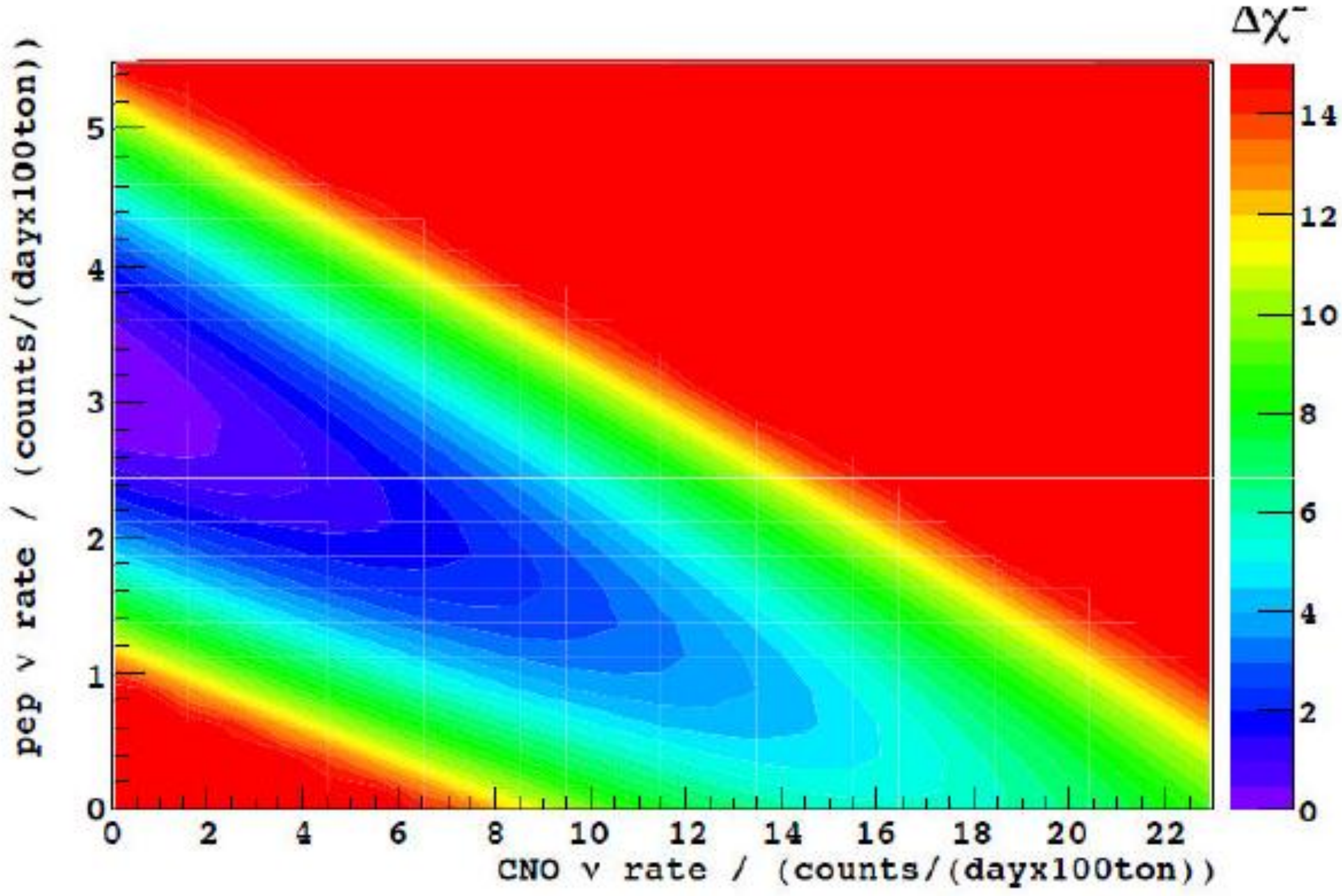


Upper limit (95% C.L.) <7.6 counts/day/100ton

pep fixed at SSM predicted value: 2.8 counts/day/100ton

Assuming MSW-LMA

Significance of result
in pep and CNO analysis



Background suppression

- γs from rocks, PMT, tank, nylon vessel
  - Detector design: concentric shells to shield the inner scintillator
  - Material selection and surface treatment
  - Clean construction and handling

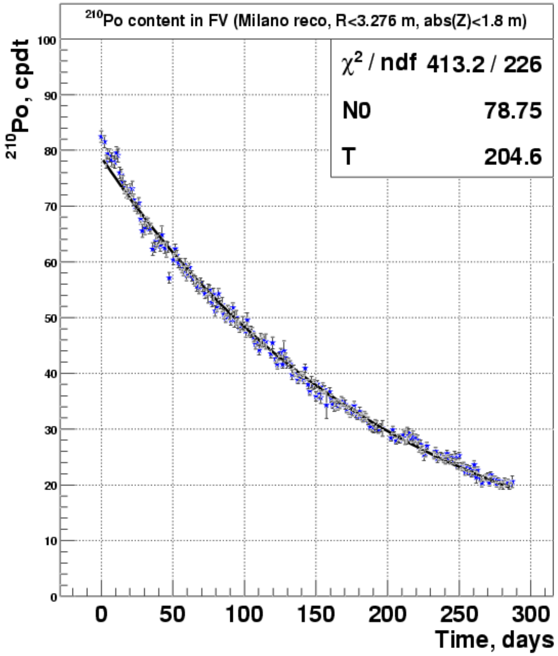
- Internal background (^{238}U, ^{232}Th, ^{40}K, ^{39}Ar, ^{85}Kr, ^{222}Rn)
  - **Scintillator purification**:
    - Distillation (6 stages distillation, 80 mbar, 90 ° C)
    - Vacuum Stripping by LAK N_2 (^{222}Rn: 8 μBq/m^3, Ar: 0.01 ppm, Kr: 0.03 ppt)
    - Humidified with water vapor 30%
  - **Master solution (PPO) purification**:
    - **Water extraction** (5 cycles)
    - Filtration
    - **Single step distillation**
    - N_2 stripping with LAKN
  - **Leak requirements** for all systems and plants < 10^{-8} atm/cc/s
    - Critical regions (pumps, valves, big flanges, small failures) were protected with additional nitrogen blanketing

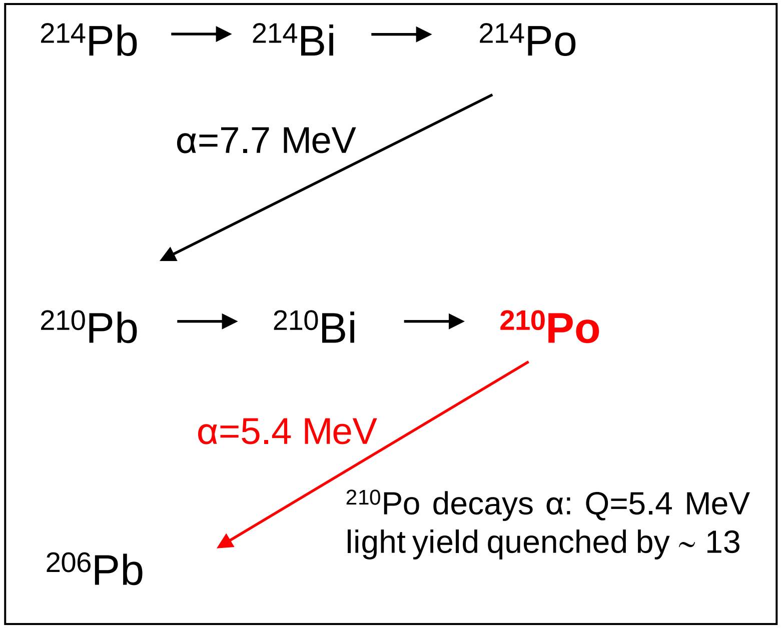
Primary sources of radio impurities

	source	Typical Concentrations	Borexino level	Removal strategy
^{14}C	Cosmic ray activation of ^{14}N	$^{14}C/\ ^{12}C \sim 10^{-12}$	$^{14}C/\ ^{12}C < 10^{-17}$	Old carbon (solvent from oil)
^{7}Be	Cosmic ray Activation of ^{12}C	~3 cpd/ton	< 0.01 cpd/ton	Distillation, underground storage
^{238}U, ^{232}Th	Suspended dust, organometallics	~ 1ppm in dust ~ 1ppb stainless steel ~ 1ppt IV nylon	$\sim 10^{-16}$g/g(PC)	Distillation, filtration
K_{nat}	Suspended dust, Contaminant found in fluor	~ 1ppm in dust	$<10^{-13}$g/g(PC)	Distillation, water extraction , filtration
^{222}Rn	Air and emanation from materials	~ 10Bq / m^3 in air	~ 70 μBq / m^3 in PC (0.3ev/day/100tons)	Nitrogen stripping
^{210}Bi, ^{210}Po	^{210}Pb decay	2 x 10^4 cpd/ton from exposing a surface to 10Bq/m^3 of ^{222}Rn	<0.01 cpd/ton	Surface cleaning
^{85}Kr, (^{39}Ar)	air	1.1Bq/m^3 (13mBq/m^3) in air	0.16μBq/m^3 (0.5 μ Bq/m^3) in N_2 0.01 events/day/ton	Nitrogen stripping

Background : ^{210}Po

- In the start, ~6000 cpd/100ton
- The origin of the contamination is not known
- It is NOT in equilibrium with ^{238}U nor ^{210}Pb
- It decays away as expected, (life time 200days)
- Can be rejected by pulse shape discrimination.
- The statistical subtraction is also used for spectrum fit.
- As for the ^{210}Bi, since no direct evidence, taken as a free parameter for spectrum fit.





Background : ^{85}Kr

- Probably because of a few litter air leak happened during filling.
- Since the spectrum of the β decay by ^{85}Kr is similar to the ^{7}Be recoil electron spectrum, an estimation of the amount is important.
- The contamination can be measured directly by means of a relatively rare but easy-to-measure decay to excited 85Rb*.

^{85}Kr $\xrightarrow{\beta\ (687\ \text{keV})}$ ^{85}Rb

τ = 10.76 y - BR: 99.56%

^{85}Kr $\xrightarrow{\beta\ (173\ \text{keV})}$ ^{85m}Rb $\xrightarrow{\gamma\ (514\ \text{keV})}$ ^{85}Rb

τ= 1.46 μs - BR: 0.43%

- Measured with 751days of data
- 32 candidate events in final data sample
  - Calculate ^{85}Kr contamination is

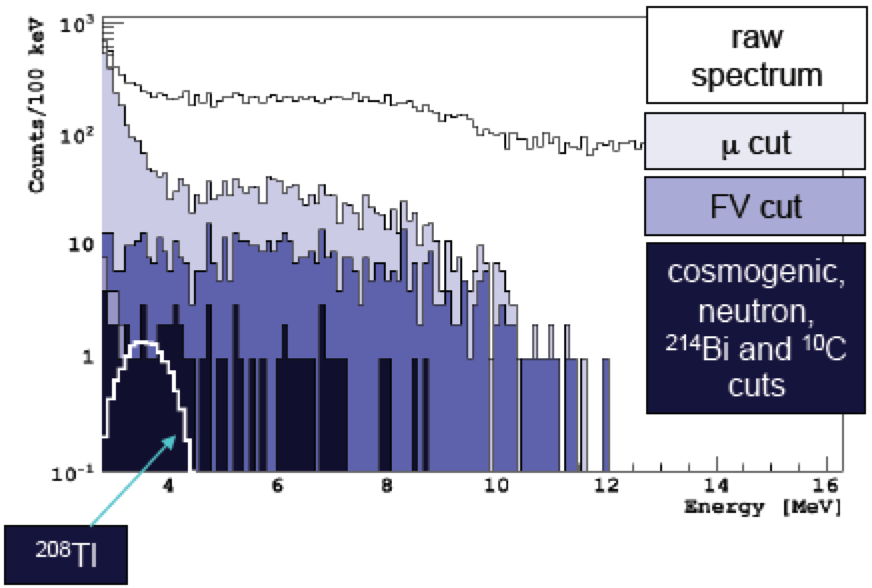
30 ± 5 cpd / 100ton

→ Taken as free parameter in the spectrum fit.

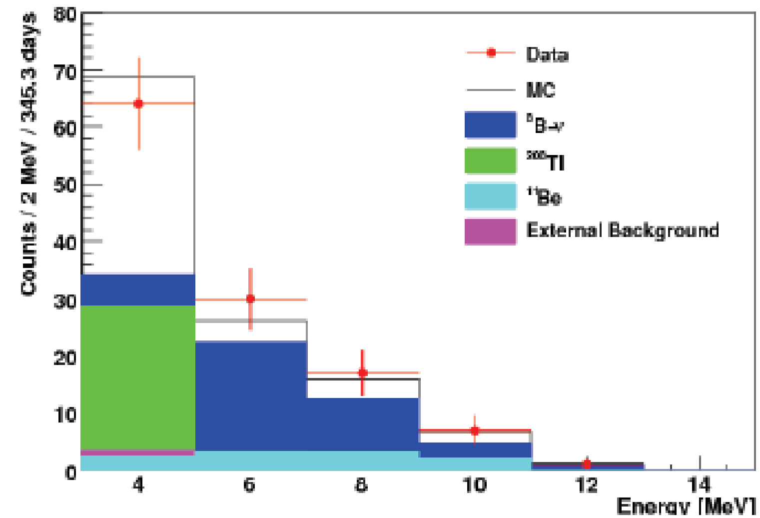
^{8}B neutrino measurement in Borexino

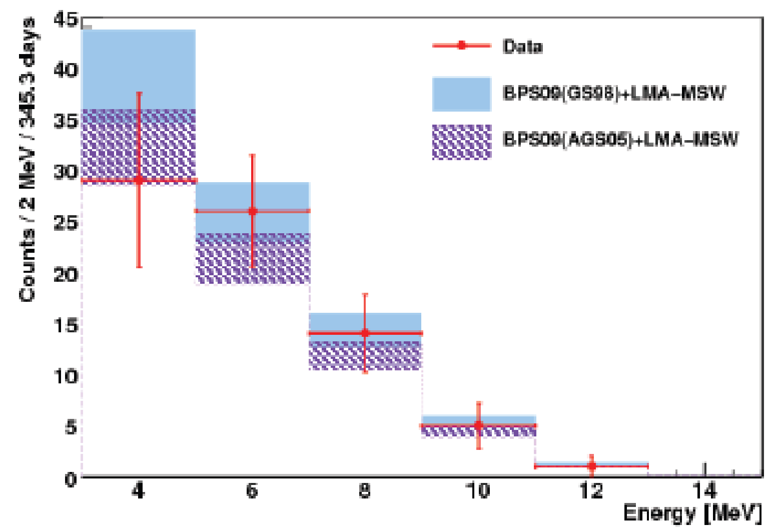
PRD 82 (2010) 0033006

Final spectrum above 3MeV



Comparison with the expectation



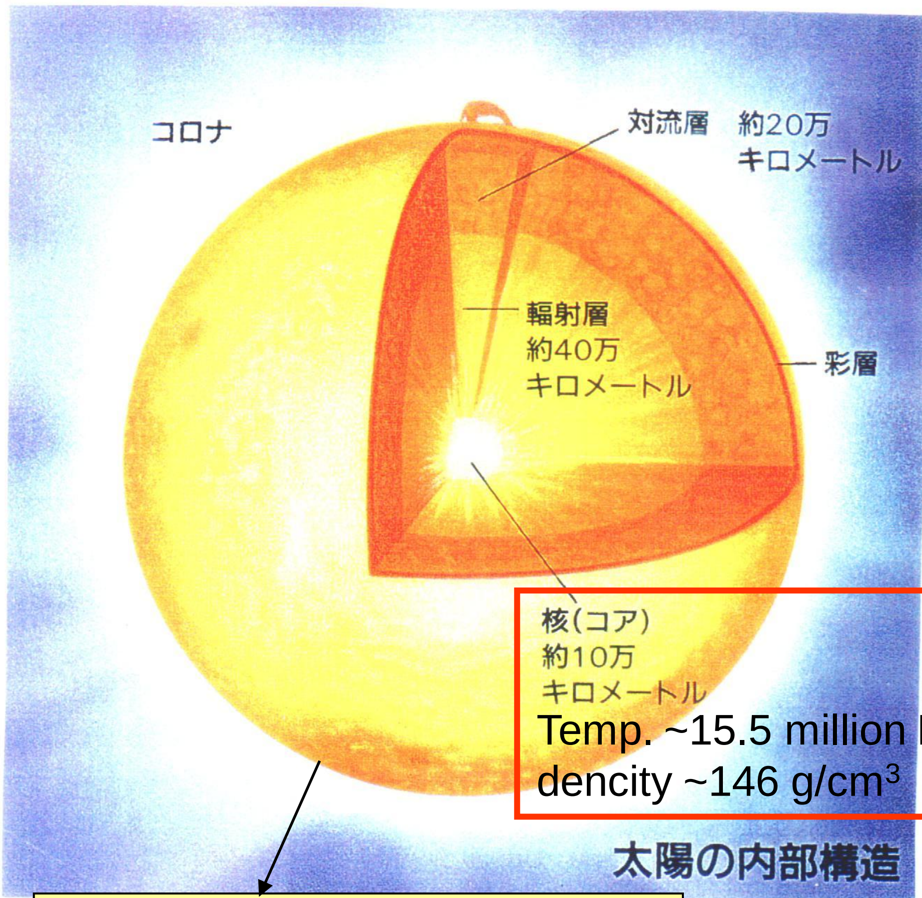


^{8}B solar neutrino rate in Borexino

	3.0–16.3 MeV	5.0–16.3 MeV
Rate [cpd/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

What's solar neutrino?

How does the sun shine?

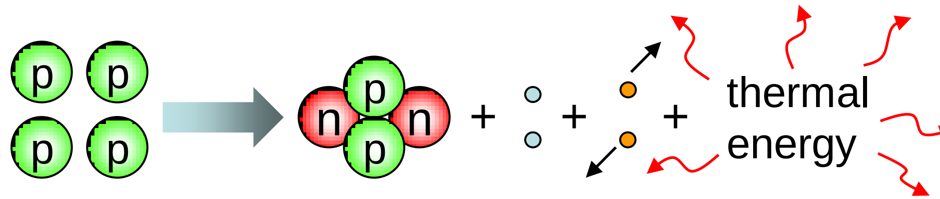


Temp. ~15.5 million K
dencity ~146 g/cm^3

Photon-measured luminosity

→ ~10^{7}years radiated from the center to the surface.

Nuclear fusion reactions can occur deep inside the sun



$$4p \rightarrow {}^4He + 2\,e^+ + 2\,\nu_e + \underline{26.7MeV}$$

- Flux : ~66 billon neutrinos /sec/cm^2
- Go through the sun immediately (~2sec), since neutrinos only interact with matter via weak force. After ~8min, arrival at the earth → Measurements of solar neutrinos can see the current status in the center of the sun.

Neutrino-measured luminosity

Actually, this reaction is realized via pp-chain and CNO cycle.