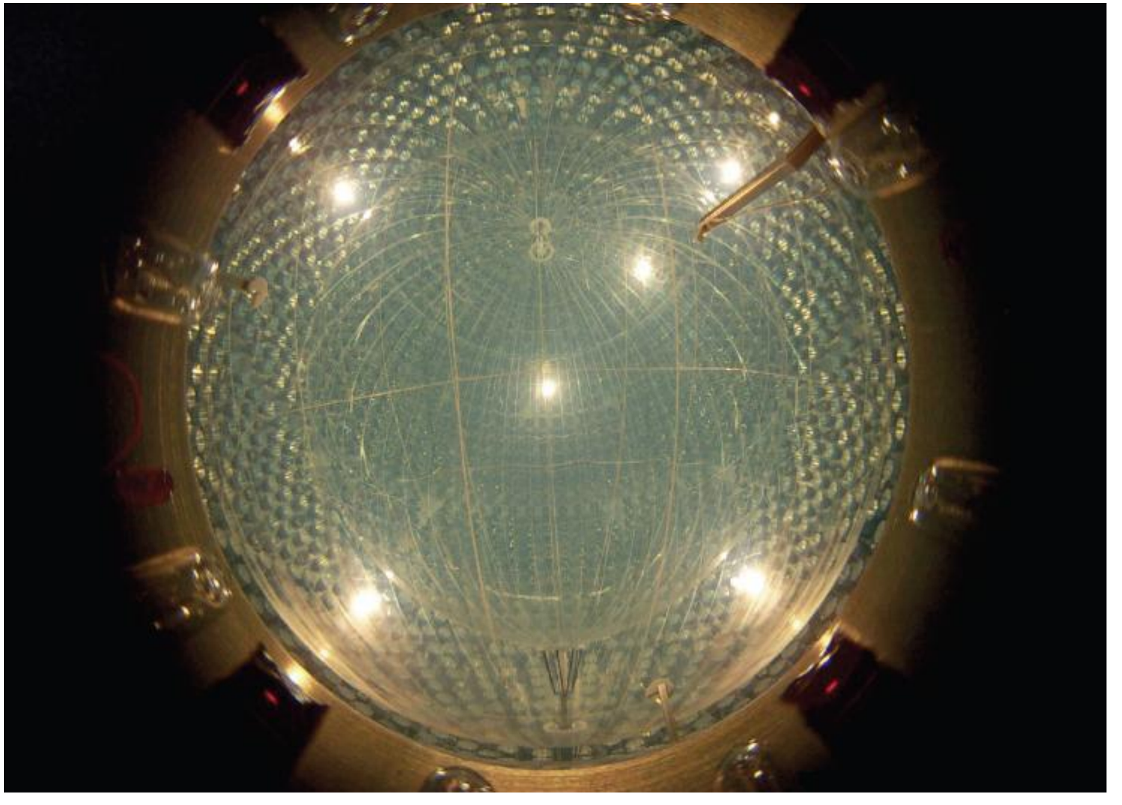
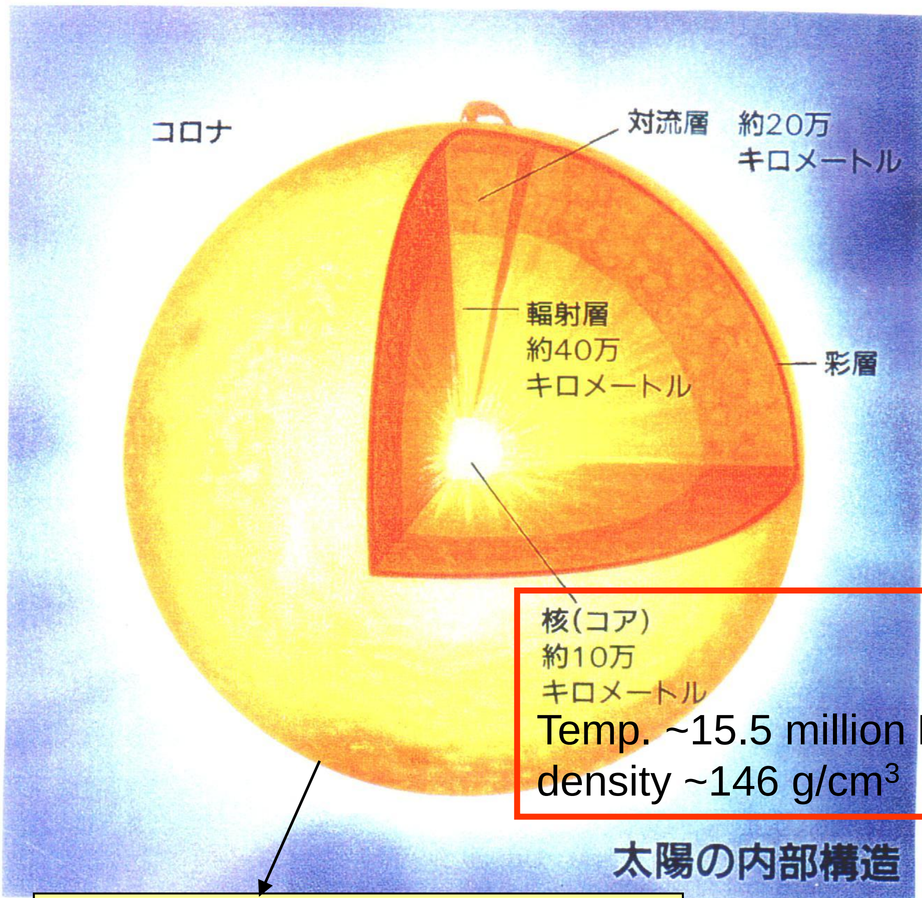
The recent results of solar neutrino measurement in Borexino



Yusuke Koshio
LNGS, INFN, Italy
On behalf of Borexino collaboration

What's solar neutrino?

How does the sun shine?

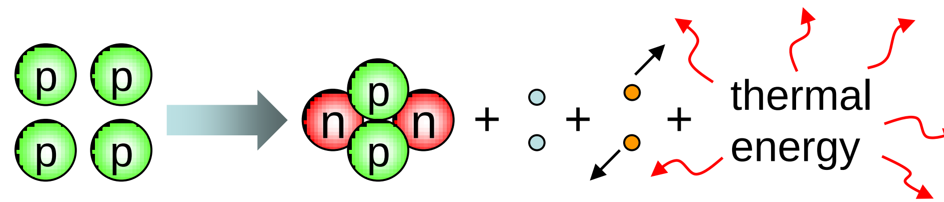


Temp. ~15.5 million K
density ~146 g/cm^3

Photon-measured luminosity

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

Nuclear fusion reactions can occur deep inside the sun



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

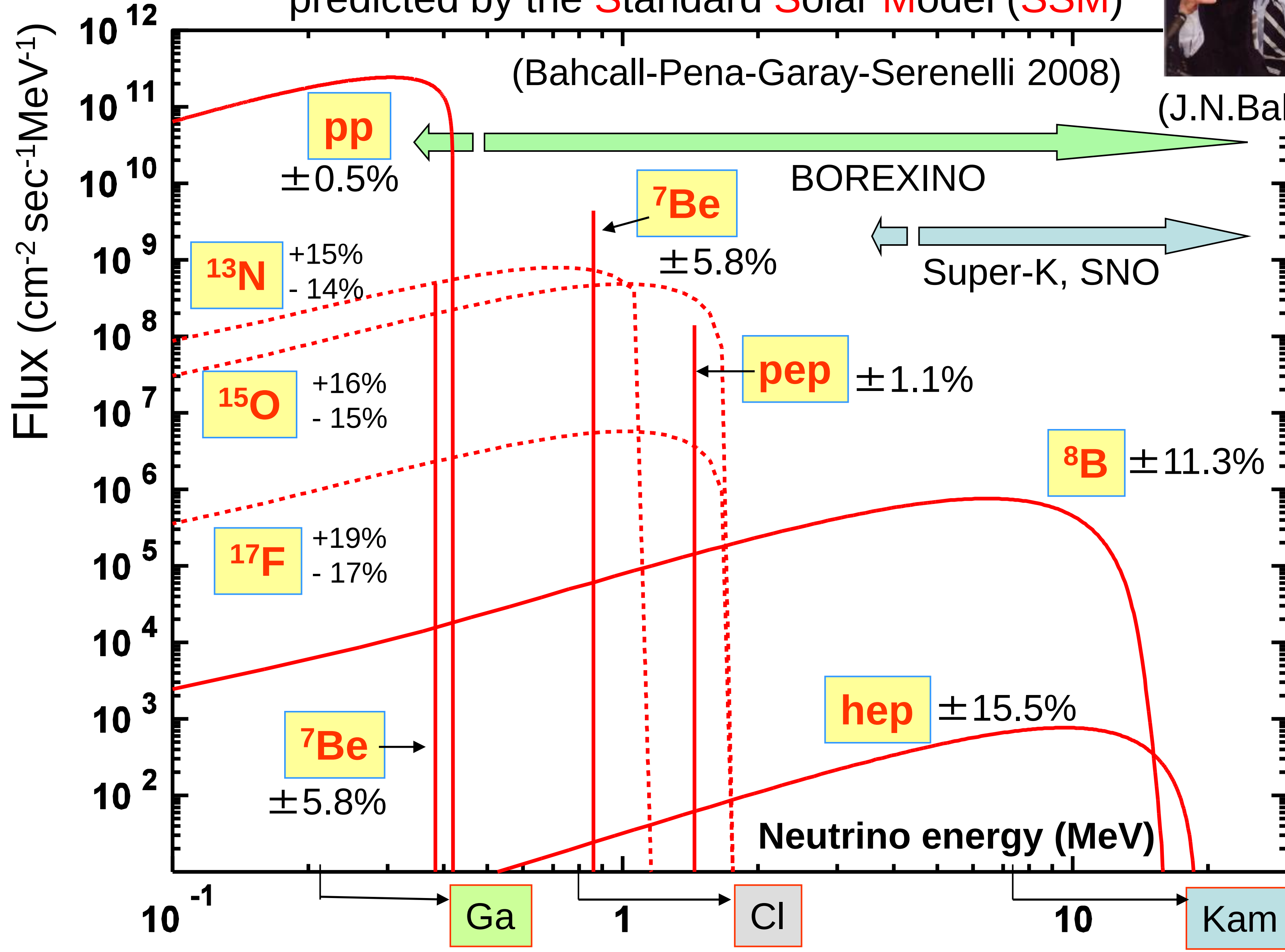
- Flux : ~66 billion neutrinos /sec/cm^2
- Go through the sun immediately (~2sec), since neutrinos only interact with matter via weak force. After ~8min, arrival at the earth → Measurements of solar neutrinos can see the current status in the center of the sun.

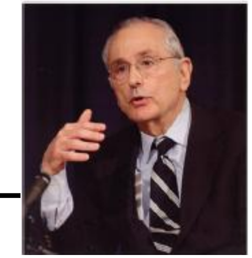
Neutrino-measured luminosity

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

Solar neutrino spectrum

predicted by the Standard Solar Model (SSM)

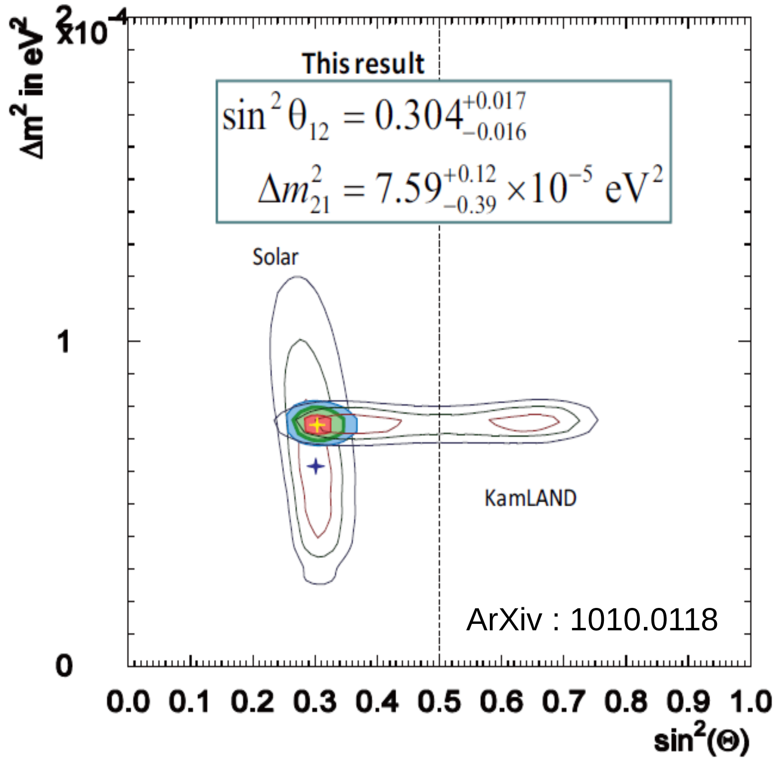




(J.N.Bahcall)

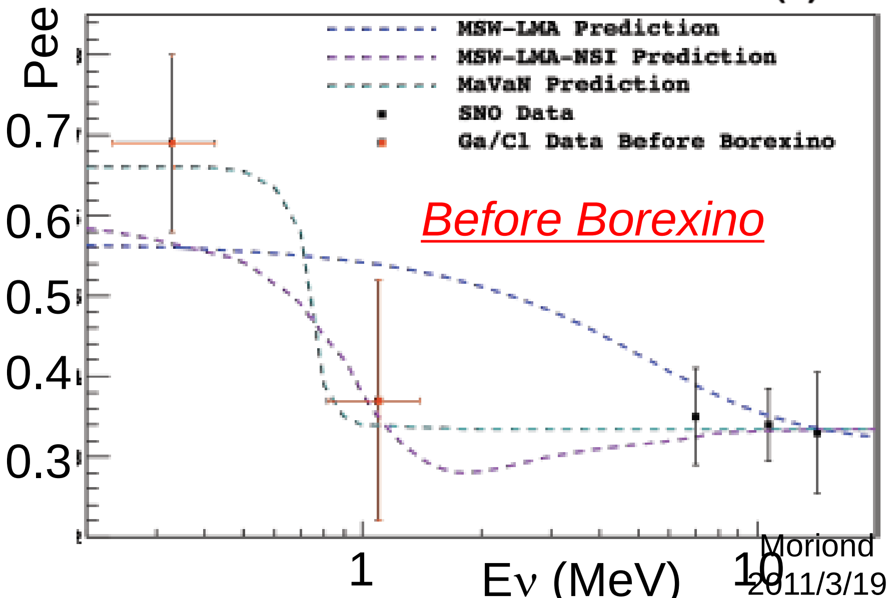
Physics motivation

- Neutrino physics
  - MSW-LMA scenario is our current understanding
    - Results of ^{8}B neutrinos, radio-chemical experiments and reactor experiment
  - The survival probability in ν_e (Pee) was very poor constraint before Borexino.
- Solar Physics
  - Sub-MeV Solar neutrino flux, (^{7}Be, CNO, pep, pp…)
  - Metallicity (high/low) controversy

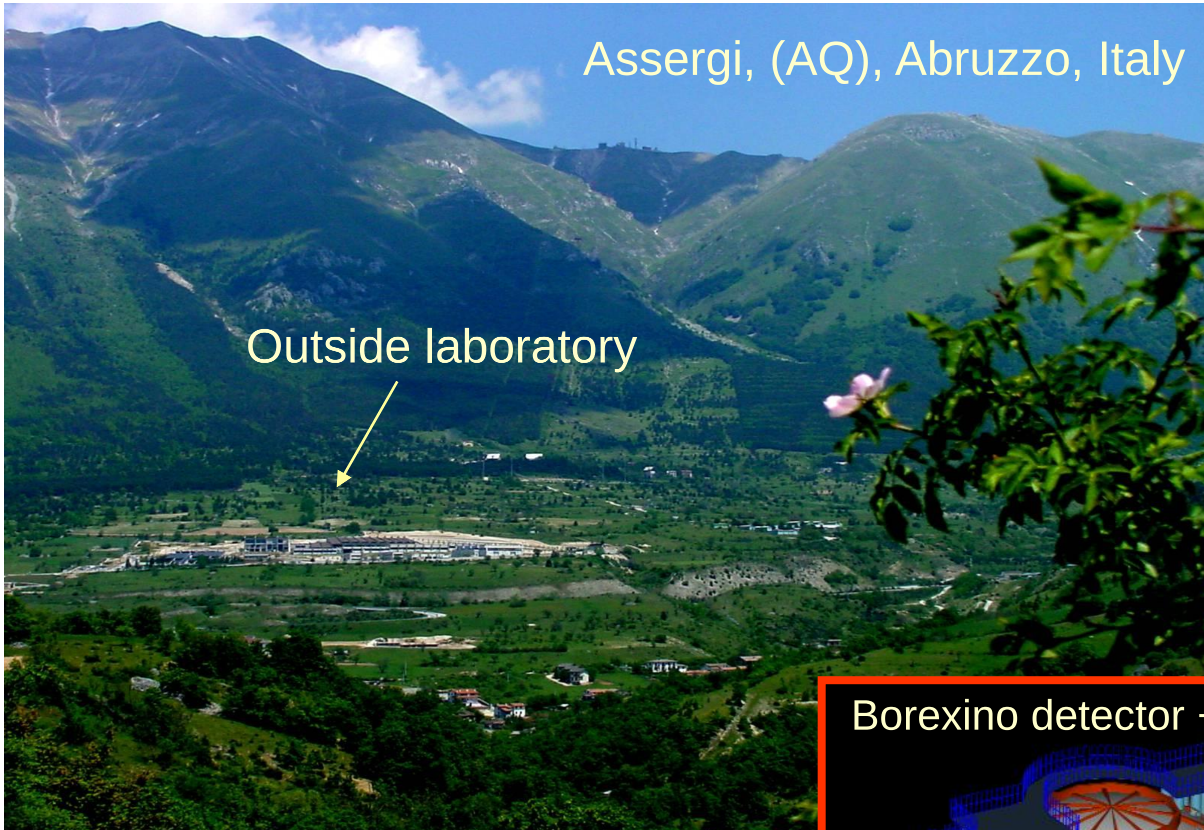


Goal of Borexino measurement

- ✓ ^{7}Be neutrino rate with a total error < 5% (10% in previous)
- ✓ Also ^{8}B neutrino rate
- ✓ Day/Night flux asymmetry, which is sensitive MSW-LOW region. (in progress)

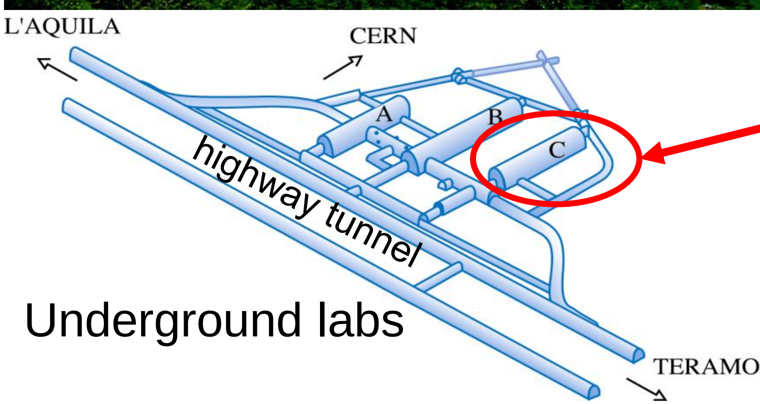


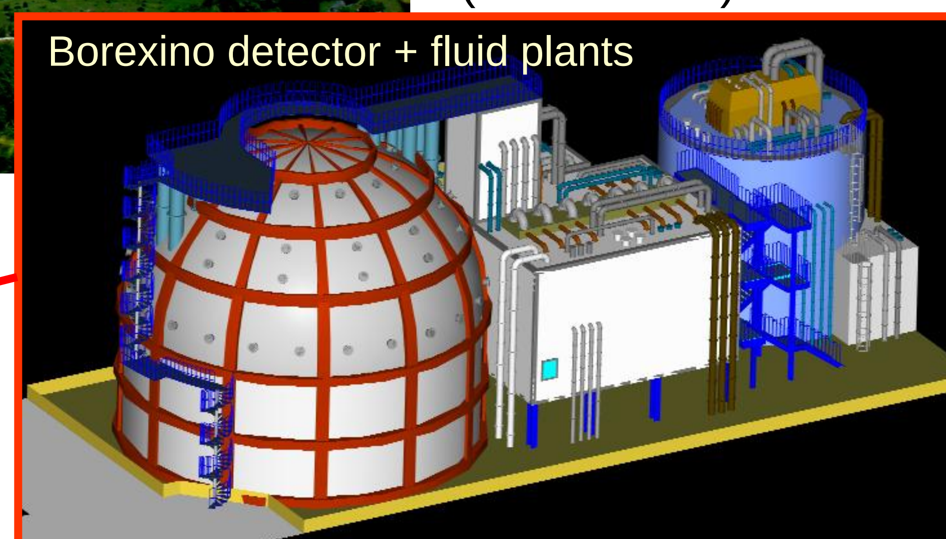
Laboratori Nazionali del Gran Sasso



120km from Roma

1300m underground
(3800m w.e.)





BOREXINO

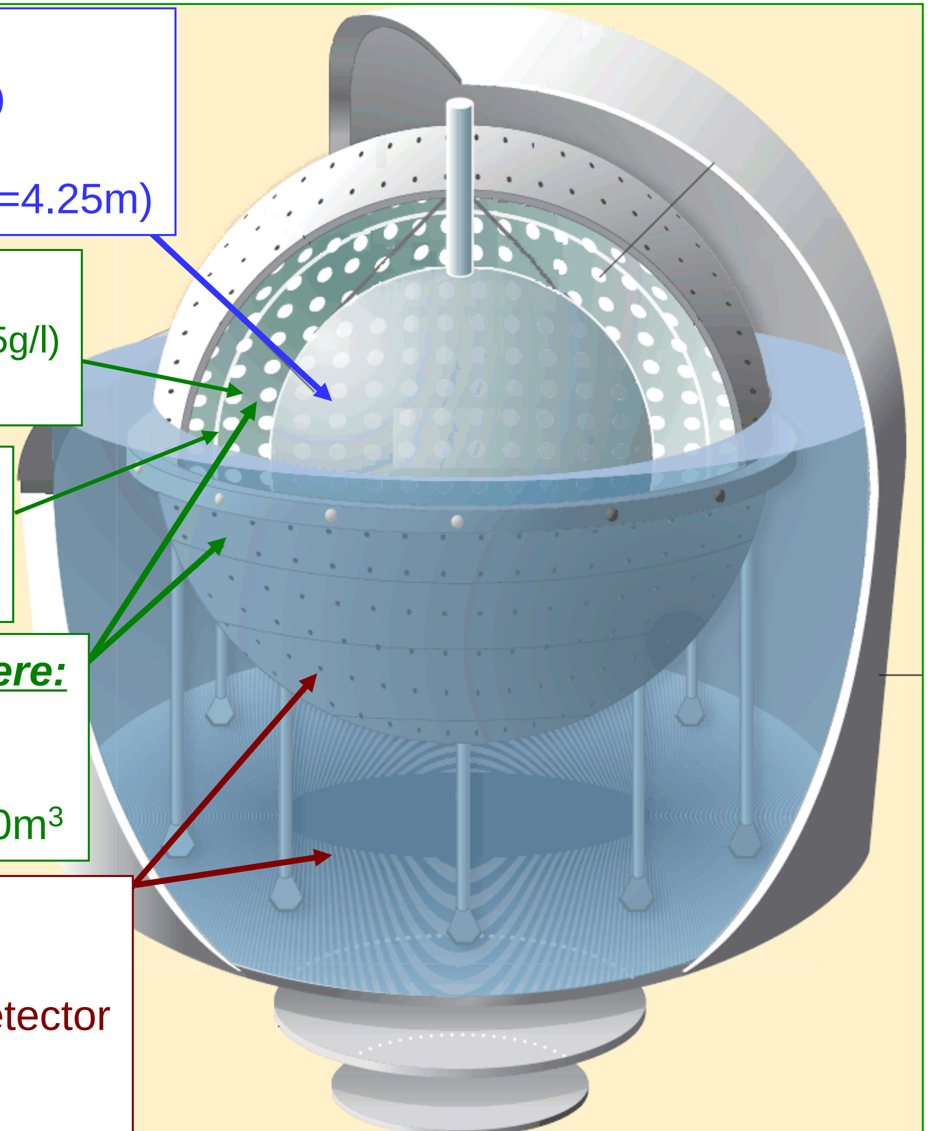
Scintillator:
270 t PC+PPO (1.5g/l)
in a 150μm thick
Inner nylon vessel (R=4.25m)

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

Physics target :

- Solar Neutrinos

$\nu_{solar} + e \rightarrow \nu + e$ (ES)

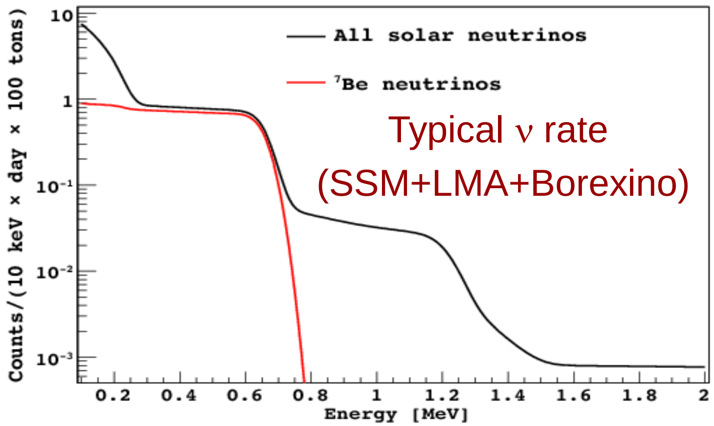
The wide energy range in real time are measurable, especially;
^{7}Be (mono-energetic 0.862MeV)
^{8}B (upto 16MeV)
Also CNO, pep, and possibly pp in future

- Geo Neutrinos
- Supernova neutrinos
- etc

Detection principle

- Solar neutrino scatter on electron in liquid scintillator
  - Scintillation light
    - High light yield (~500 p.e./MeV)
      - Low energy threshold
      - Good energy resolution
    - Pulse shape discrimination
  - but…
    - No ν direction
    - No way to distinguish ν and radioactivity

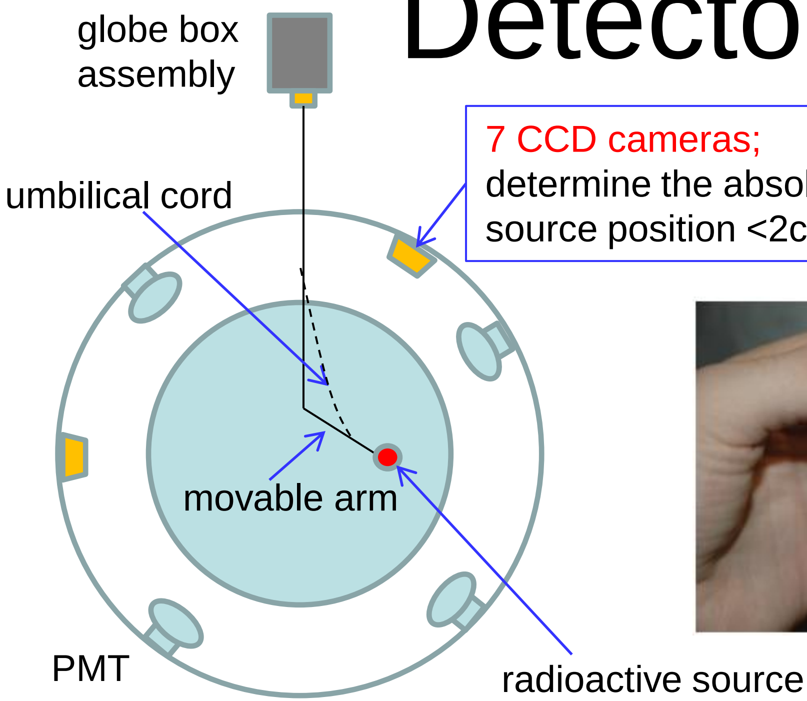
    → *<u>Extreme radiopurity is required</u>*



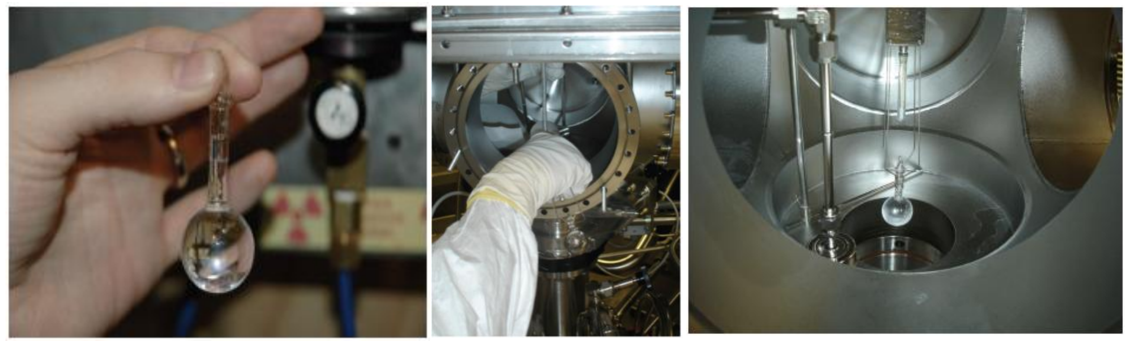
→ NIM A, 609, 1 (2009) 58

- Detector calibration
  - Background events in normal data were used until previous
  - Internal source calibrations were done in 2009.
    - Position response (~6% systematic error in previous)
      - Reduce the fiducial volume uncertainty
      - Modify the position reconstruction algorithm.
    - Energy response (~6% systematic error in previous)
      - Reduce the energy scale uncertainty.
      - Tuning the MC simulation
    - Particle identification (alpha-beta discrimination)
      - Modify the algorithm, and tuning the MC simulation.

Detector calibration



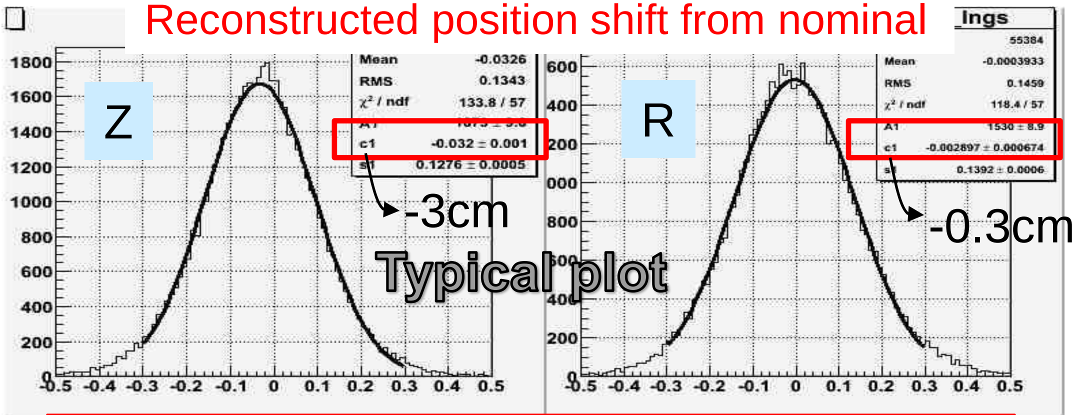
Source insertion



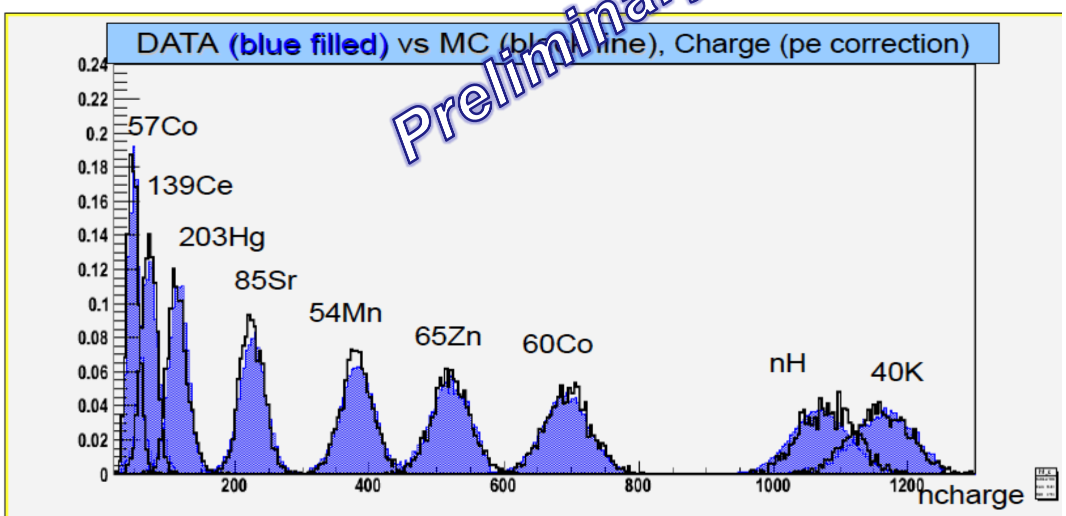
	γ								β		α	n		
	dopant dissolved in small water vial								^{222}Rn loaded liq. scint. vial			Am-Be		
	^{57}Co	^{139}Ce	^{203}Hg	^{85}Sr	^{54}Mn	^{65}Zn	^{60}Co	^{40}K	^{14}C	^{214}Bi	^{214}Po	n-p	n +^{12}C	n+Fe
Energy (MeV)	0.122	0.165	0.279	0.514	0,834	1.1	1.1 1.3	1.4	0.15	3.2	(7.6)	2.2	4.94	~7.5

clear tag from Bi-Po
fast coincidence

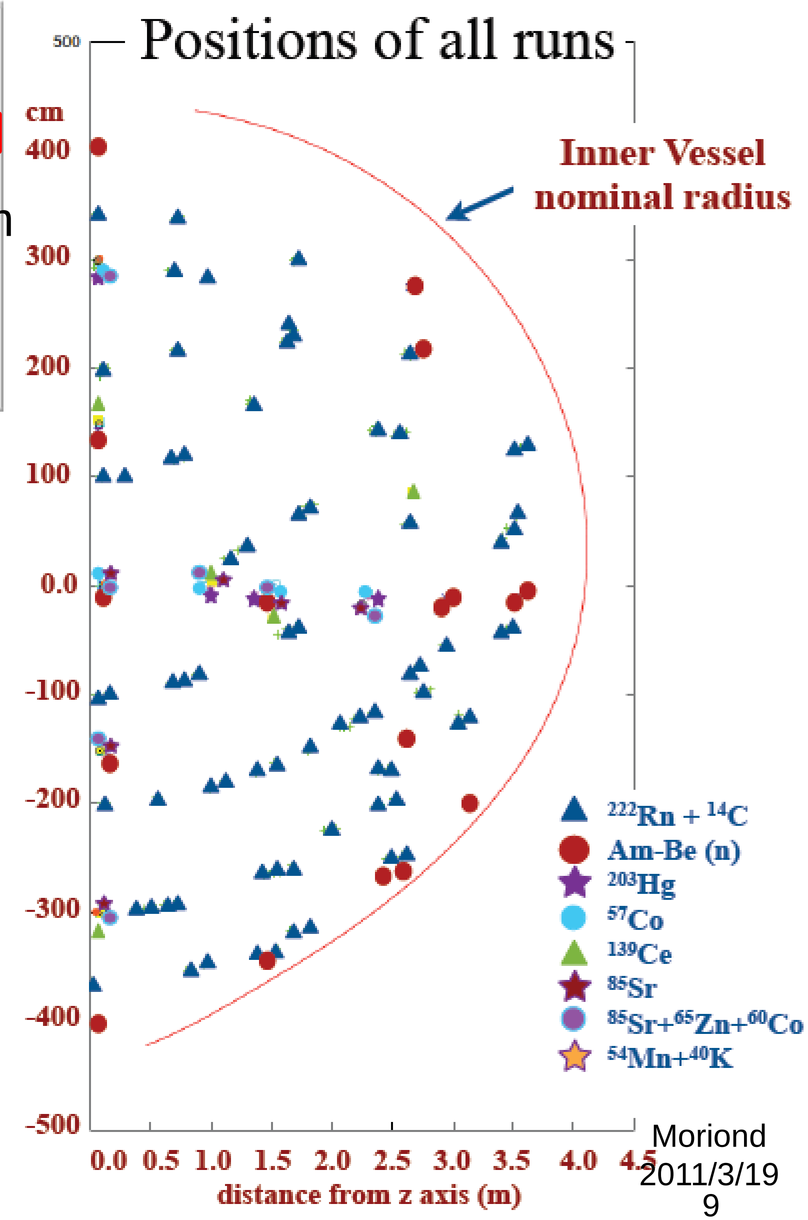
Position and Energy calibration



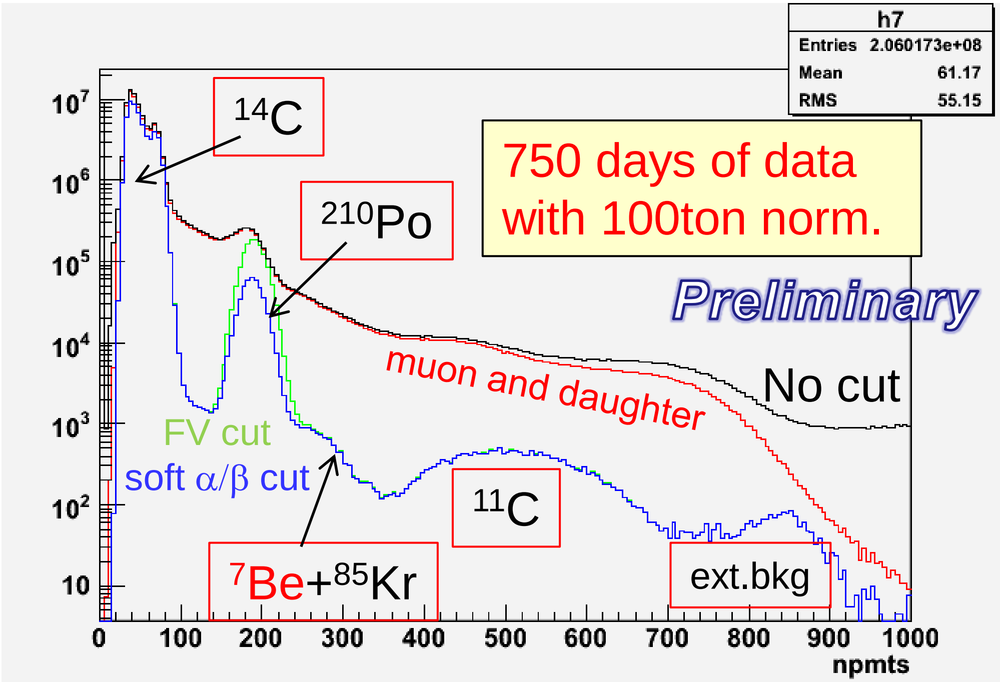
Using the 184 points of Rn calibration data, the fiducial volume uncertainty is 1.3%

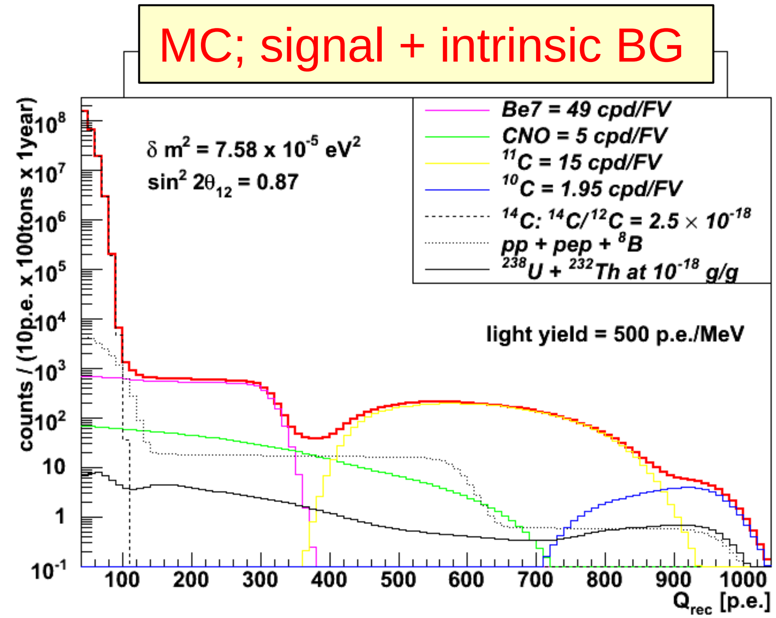


The energy scale uncertainty is less than 1.5% between 0~2MeV



Reduction and signal extraction

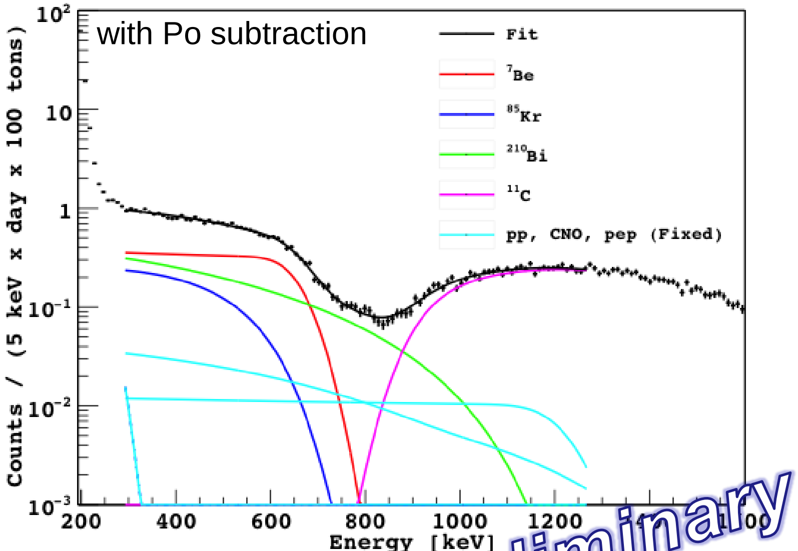


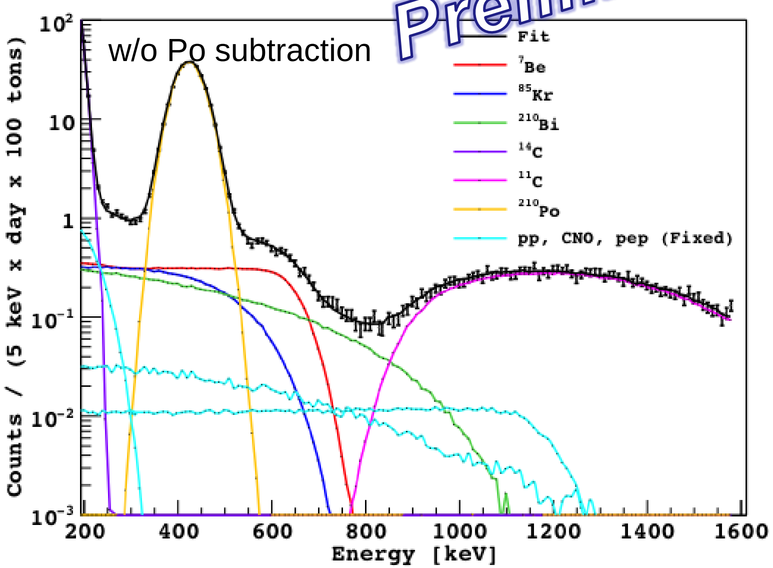


- A spectral fit is applied including the following signal + all intrinsic back ground components.
  - ^{7}Be, ^{85}Kr, ^{14}C, ^{11}C
  - ^{210}Bi (very similar to CNO in this limited energy region)
  - pp, pep, ^{8}B, and CNO neutrinos fixed at SSM-LMA value
- Fit with and without statistical subtraction of ^{210}Po events, based on α/β pulse shape discrimination.
- Two independent way (MC based and analytical) were applied.

Result of ^{7}Be rate

Preliminary





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

46.0 ± 1.5 (stat) ± 1.3 (sys)

counts/(day x 100t)
(total uncertainty is 4.3%)

Source of systematic error	
Tot. Scint. mass	±0.3 %
Live time	±0.1 %
Fraction of good events removed by cuts	±0.6 %
Energy scale	±1.3 %
Fiducial mass	±1.3 %
Fit method (a/b subtraction)	±1.0 %
Fit assumption	±1.7 %
Total syst. error	**±2.73 %**

Compare to the expected ^{7}Be rate

Measured rate: *Preliminary*

46.0 ± 1.5 (stat) ± 1.3 (sys) cpd/100ton

Hypothesis	Expected rate
No oscillation +High Metallicity	74±4
No oscillation + Low Metallicity	67±4
Oscillation MSW + High Metallicity	48±4
Oscillation MSW + Low Metallicity	44±4

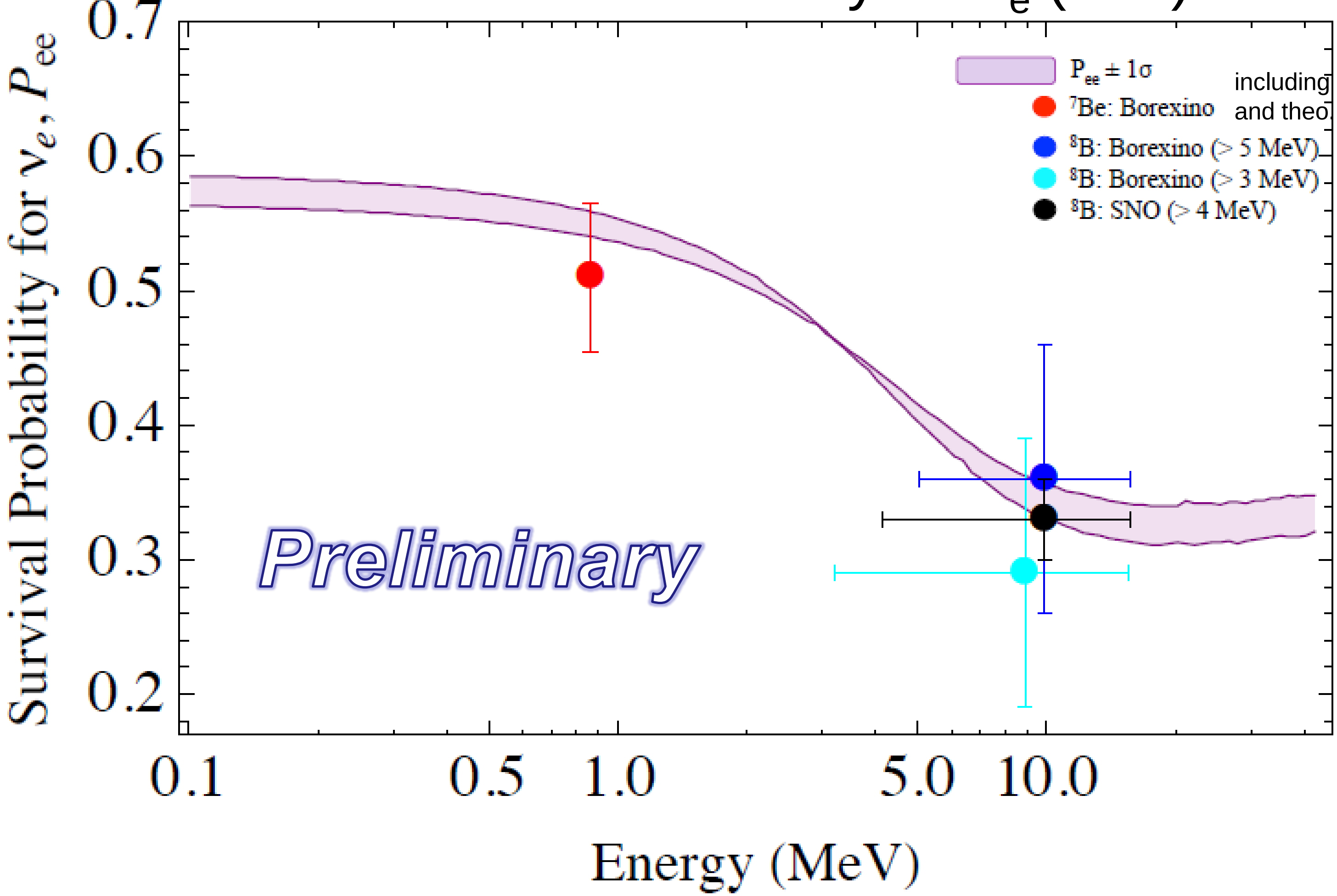
Discussion

- Measurement in Borexino confirms MSW-LMA scenario. (n)
- Detailed neutrino oscillation analysis is now on going, present soon.
- Hard to discriminate between High and Low metallicity model yet.

  → CNO solar neutrino measurement in future is crucial.

Probe MSW-LMA scenario directly

Survival Probability for ν_e (Pee)



including both exp. and theo. error

Compare to the expected ^{7}Be rate

Measured rate: *Preliminary*

46.0 ± 1.5 (stat) ± 1.3 (sys) cpd/100ton

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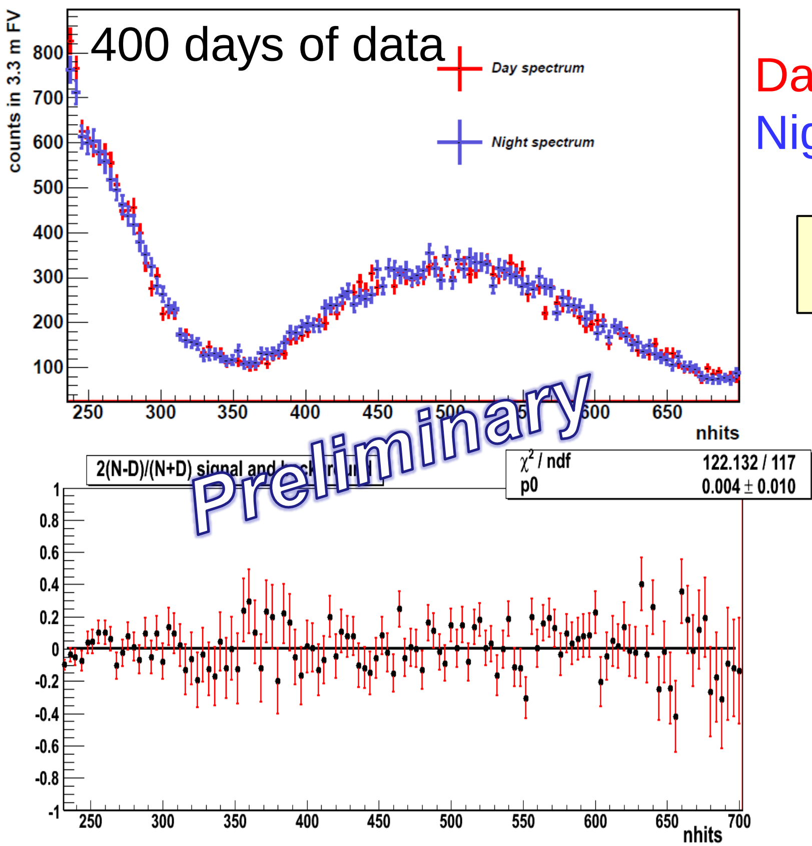
Day/Night asymmetry in ^{7}Be rate

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



Day (positive Sun altitude) 387.46 days

Night (negative Sun altitude) 401.57 days

No significant effect was found

$$Adn = \frac{N-D}{(N+D)/2} = 0.007 + -0.073\,(stat)$$

Preliminary

More refined analysis is in progress aiming to reduce the error

Conclusion

- Borexino has been running well since May 2007.
- Internal source calibration had been done in 2009.

  It is successful to reduce the systematic error.
- Total ^{7}Be neutrino rate is

  46.0 ± 1.5(stat.)± 1.3(sys.) cpd/100ton (preliminary)
- Detailed neutrino oscillation analysis is now on going,

  but the MSW-LMA scenario is confirmed in Borexino data.
- New results of ^{7}Be rate and day/night asymmetry with reduced uncertainties will be published soon.
- Future;
  - Search for pep and CNO solar neutrinos is now in progress.
  - Purification with water extraction is in progress to reduce the internal background.
  - Search for pp neutrinos is also one of important theme in future for complete understanding the solar interior.

Thank you for your attention

UMass Amherst (USA)

Milano

Genova

Borexino Collaboration

INFN

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Dubna JINR
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APC Paris

Munich
(Germany)

Perugia

Princeton University
(USA)

Backup

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

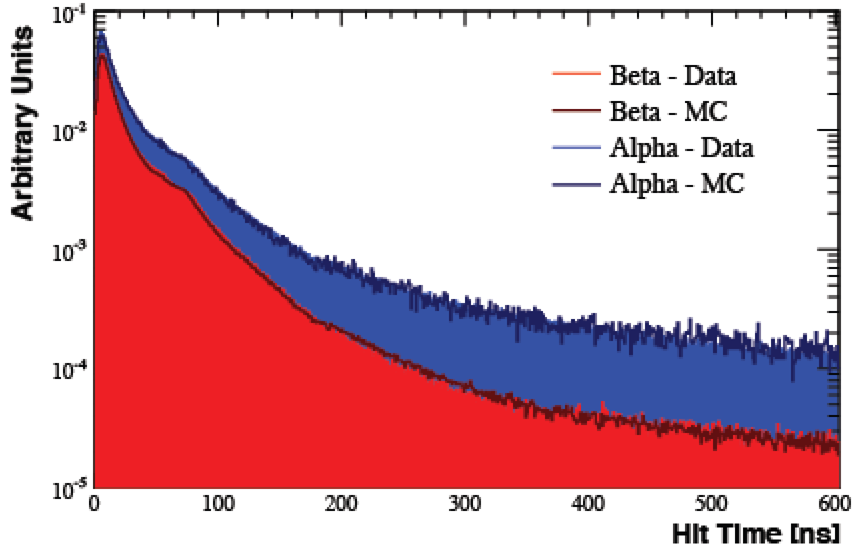
$$\phi_{^8B} = 5.3^{+0.1}_{-0.2} \times 10^6 cm^{-2} s^{-1}$$

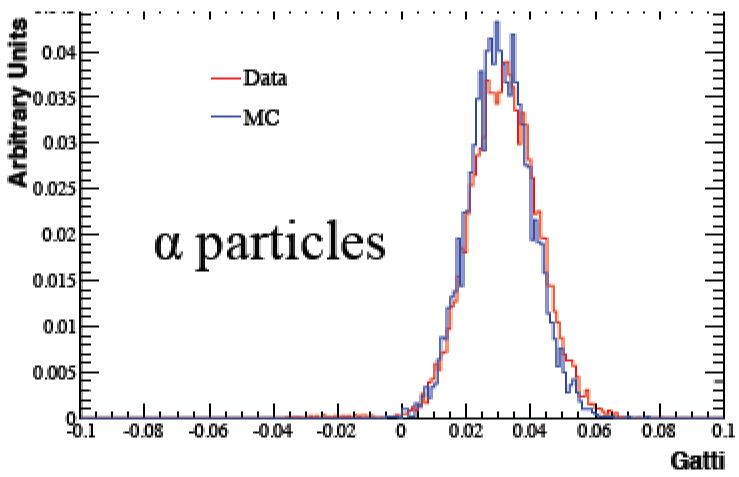
- Precise ^{7}Be flux may useful information.
- CNO ν observation may solve the problem.
  - Study in progress in Borexino
  - One of goal for SNO+

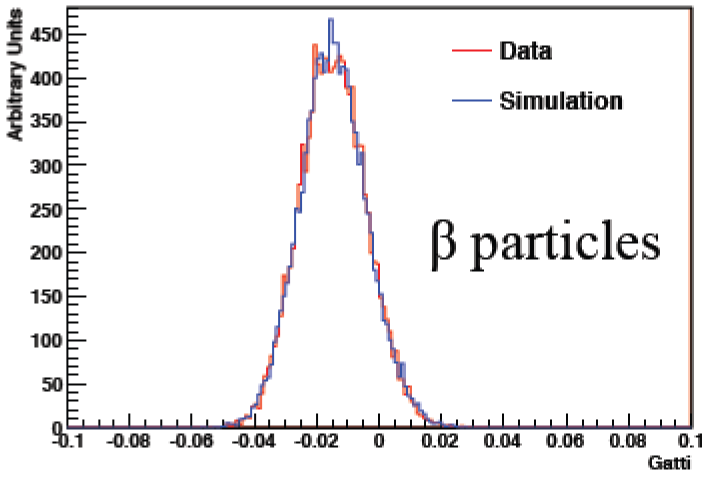
		GS98	AGS05
	pp	5.97×10^{10}	6.04×10^{10}
	pep	1.41×10^8	1.45×10^8
	hep	7.90×10^3	8.22×10^3
~10%	^{7}Be	5.07×10^9	4.55×10^9
	^{8}B	5.94×10^6	4.72×10^6
~30%	^{13}N	2.88×10^8	1.89×10^8
	^{15}O	2.15×10^8	1.34×10^8
	^{17}F	5.84×10^6	3.25×10^6

α/β discrimination

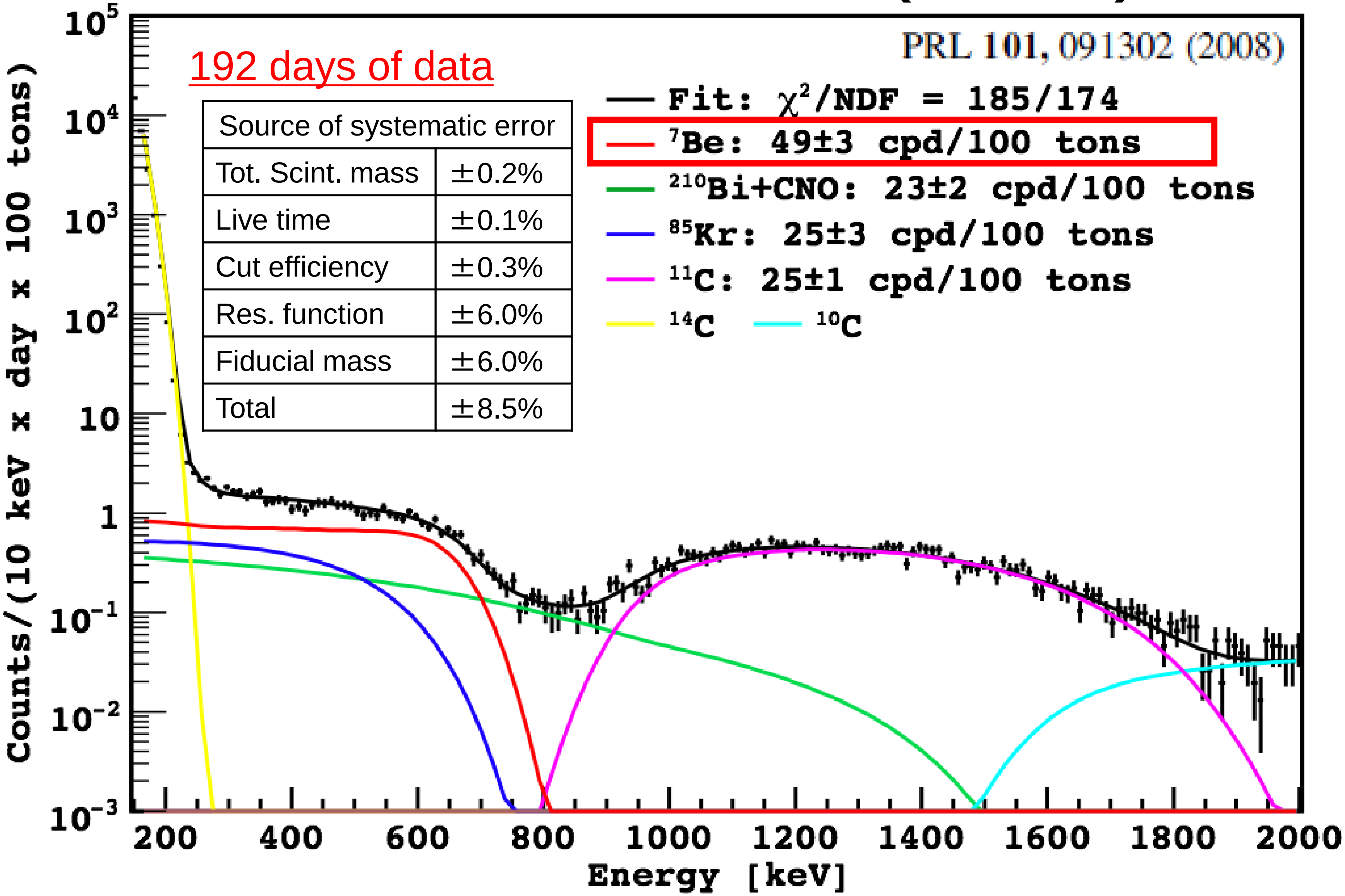
PMT hit timing distribution







Previous results (2008)



Source of systematic error	
Tot. Scint. mass	±0.2%
Live time	±0.1%
Cut efficiency	±0.3%
Res. function	±6.0%
Fiducial mass	±6.0%
Total	±8.5%

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

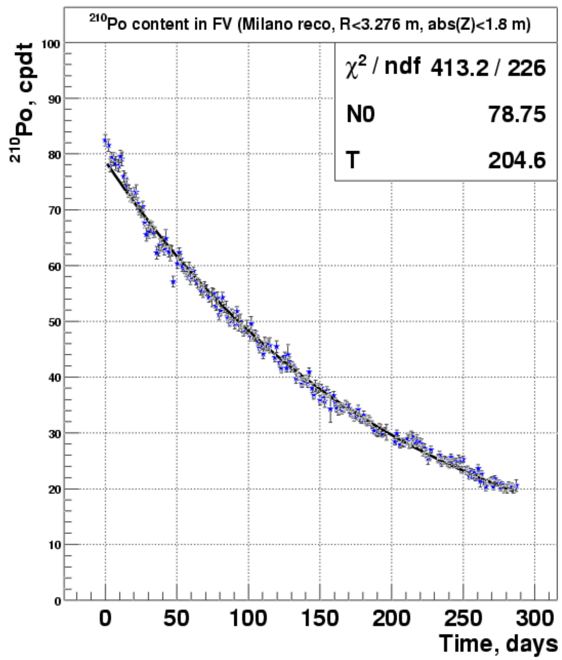
- Internal background (^{238}U, ^{232}Th, ^{40}K, ^{39}Ar, ^{85}Kr, ^{222}Rn)
  - **Scintillator purification**:
    - Distillation (6 stages distillation, 80 mbar, 90 ° C)
    - Vacuum Stripping by LAK N_2 (^{222}Rn: 8 μBq/m^3, Ar: 0.01 ppm, Kr: 0.03 ppt)
    - Humidified with water vapor 30%
  - **Master 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

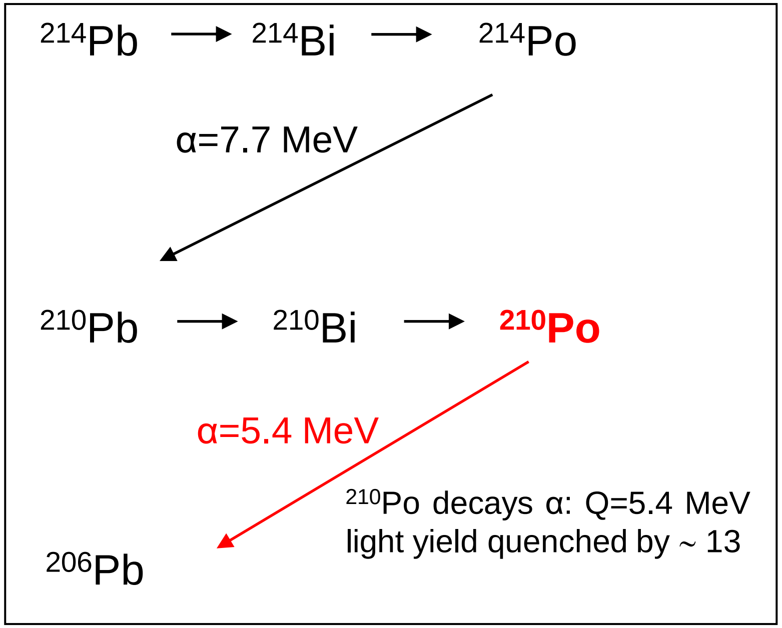
Primary sources of radio impurities

	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*.

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

τ = 10.76 y - BR: 99.56%

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

τ= 1.46 μs - BR: 0.43%

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

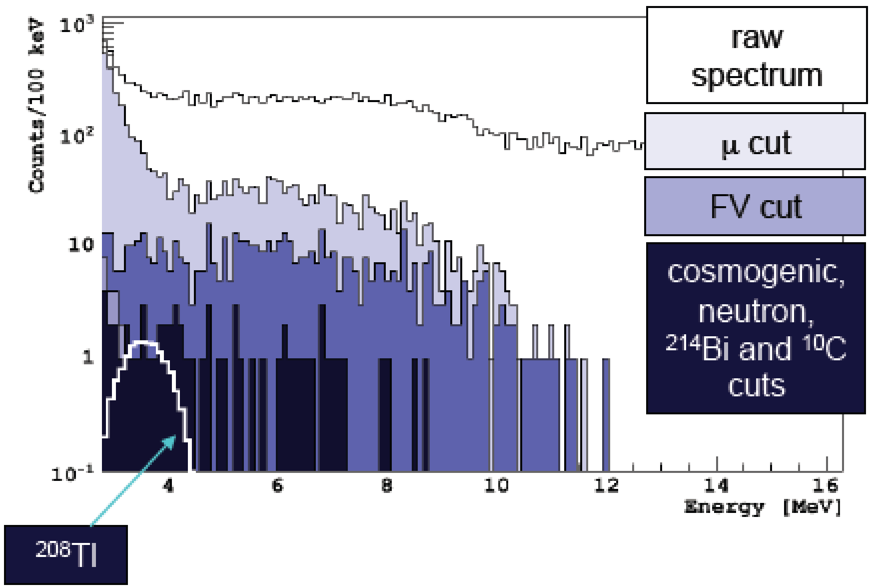
30 ± 5 cpd / 100ton

→ Taken as free parameter in the spectrum fit.

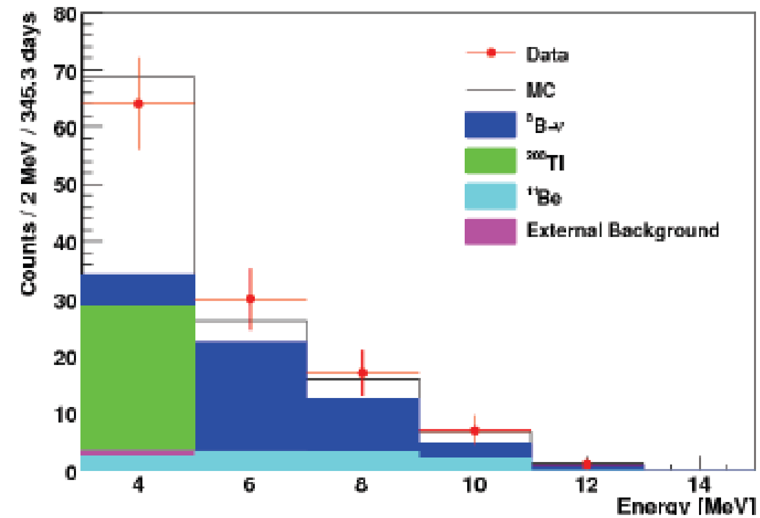
^{8}B neutrino measurement in Borexino

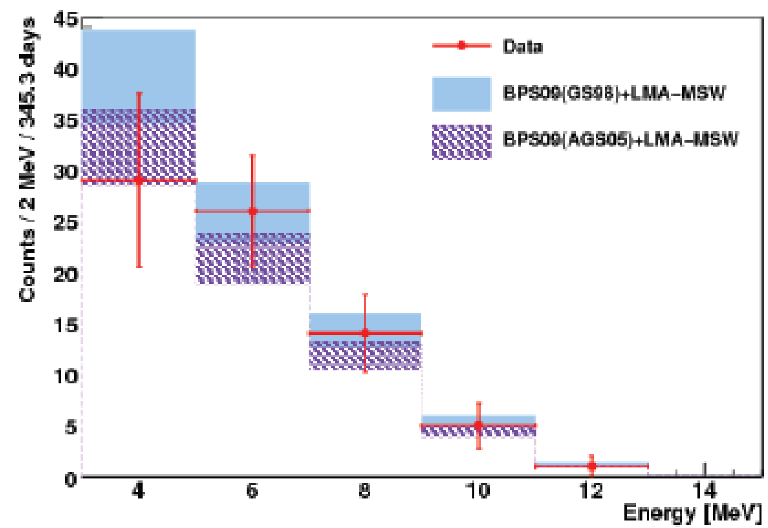
PRD 82 (2010) 0033006

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