Recent (and future) results from Borexino

LAPP
July4, 2011 – Annecy

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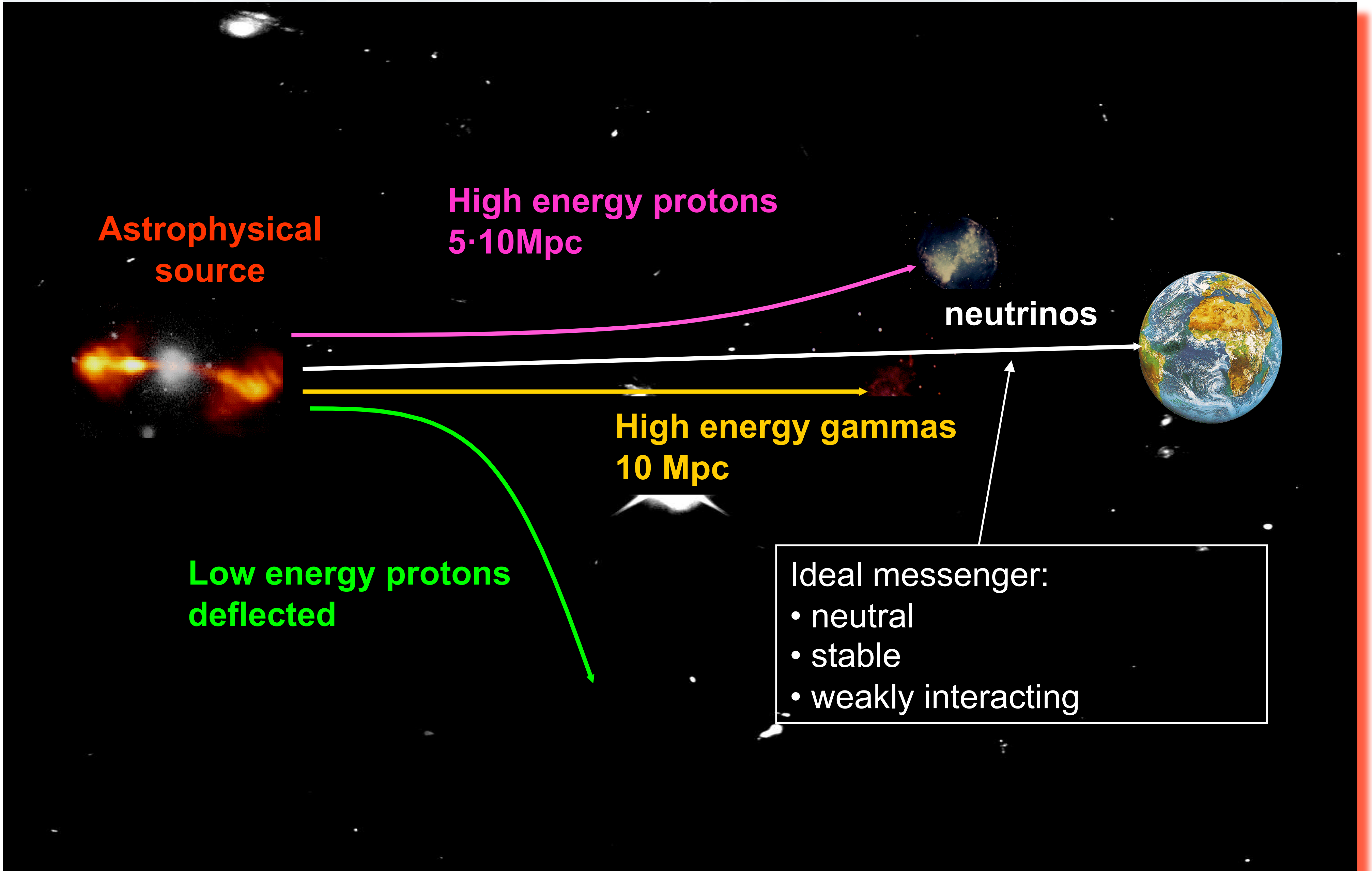
Outline

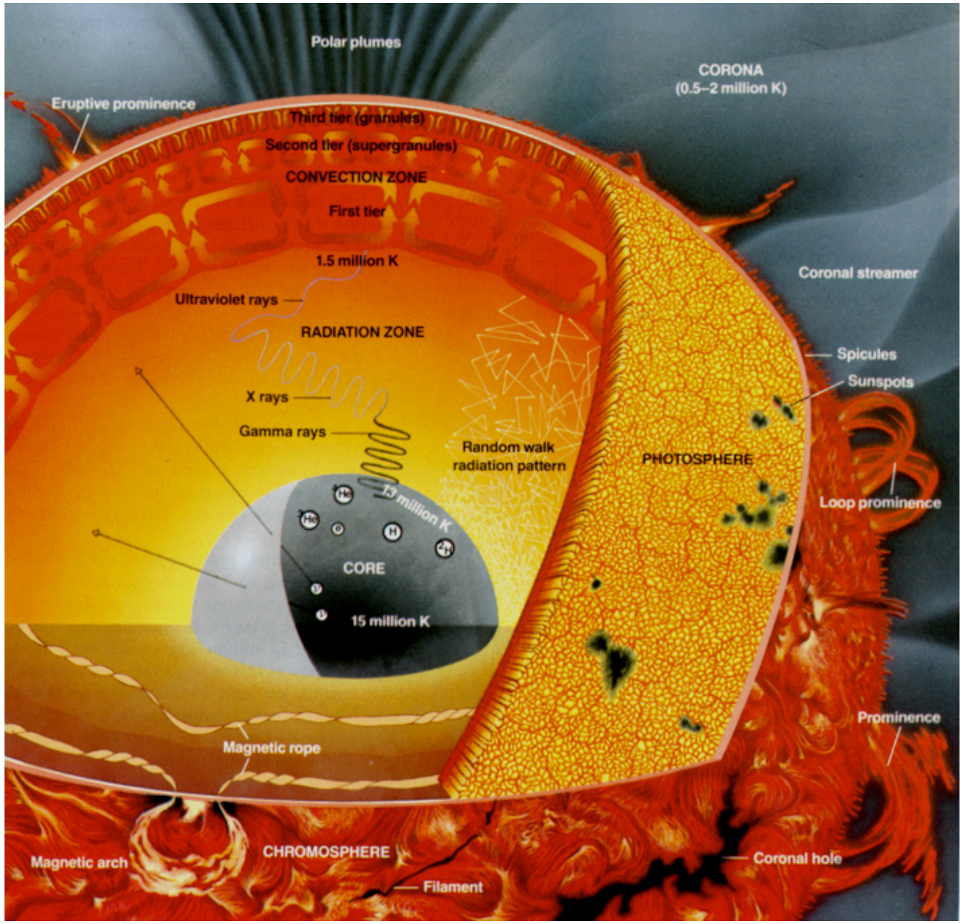
- ✓ Neutrinos from the Sun
- ✓ The physics of Borexino
- ✓ The Borexino detector
- ✓ The "radio-purity" challenge
- ✓ The reached goals (^{7}Be, ^{8}B and geo-ν, day/night,...)
- ✓ Near and far future goals
- ✓ Sterile neutrinos (?)

Neutrinos: cosmic messengers



Messengers from the Sun's core

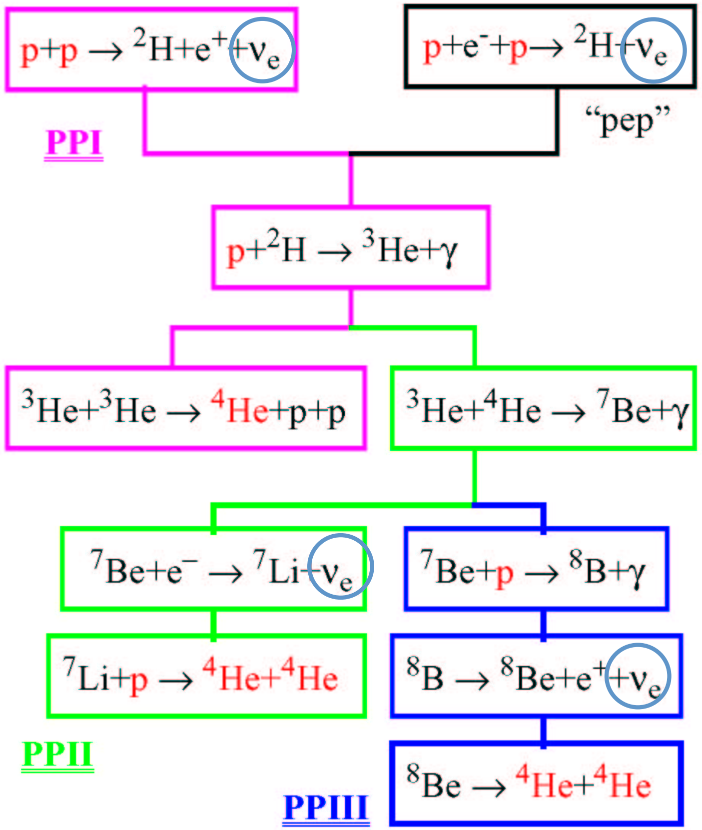
- ✓ **Core (0-0.25 R_s)**
  - ✓ Nuclear reactions: T~1.5 10^7 °K
  - ✓ energy chains pp e CNO (neutrino production)
- ✓ **Radiative region (0.25-0.75 Rs)**
  - ✓ Photons carry energy in ~ 10^5 y
- ✓ **Convective region (0.75-1 Rs)**
  - ✓ Strong convection and turbulence
  - ✓ Complex surface phenomena
- ✓ **Corona (> 1 Rs)**
  - ✓ Complex magneto-hydrodynamic phenomena
  - ✓ Gas at T~ 10^6 °K



Neutrino Production In The Sun

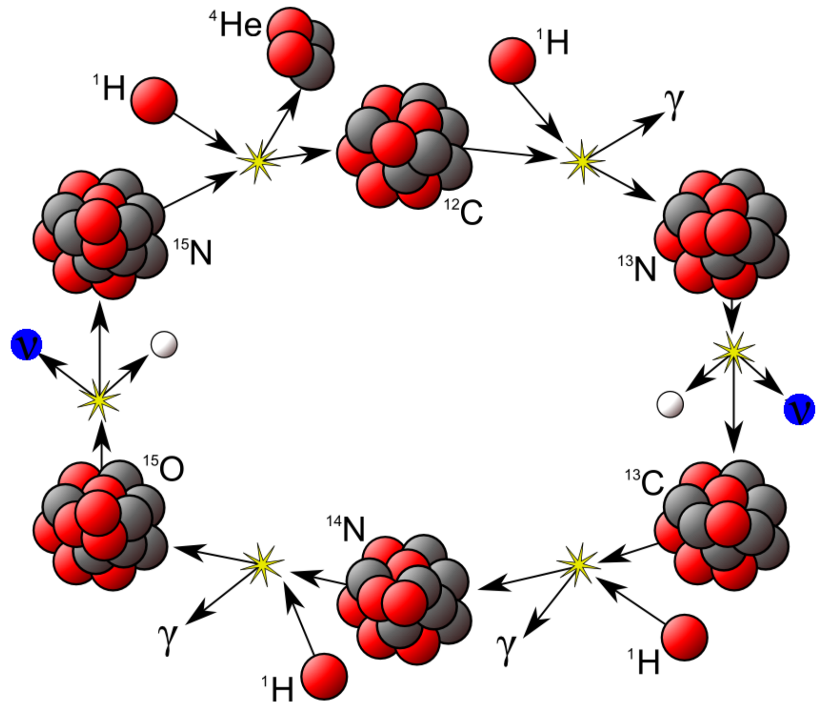
pp chain:

pp, *pep*, ^{7}Be, *hep* ,and ^{8}B ν

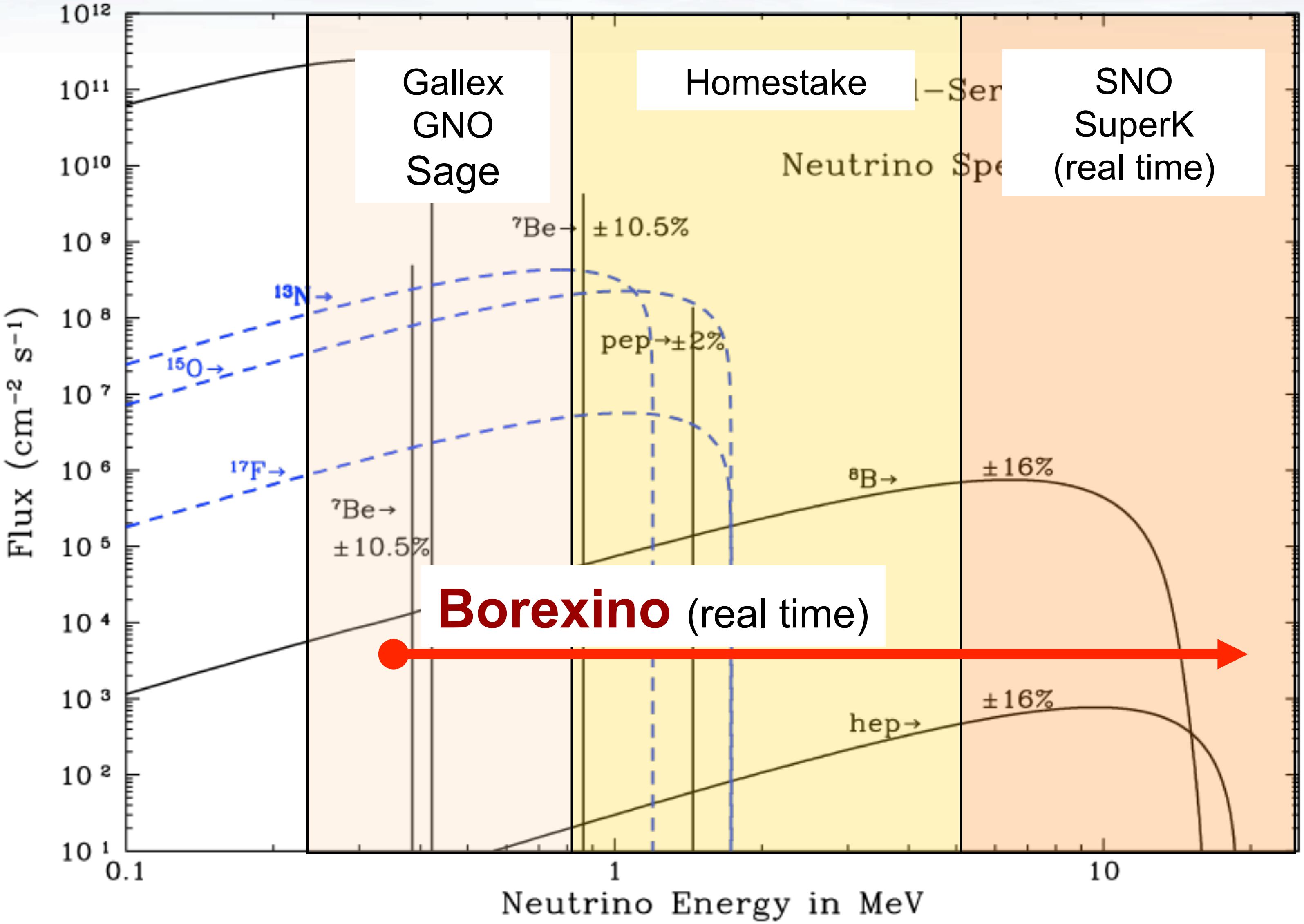


CNO cycle:

^{13}N, ^{15}O, and ^{17}F ν



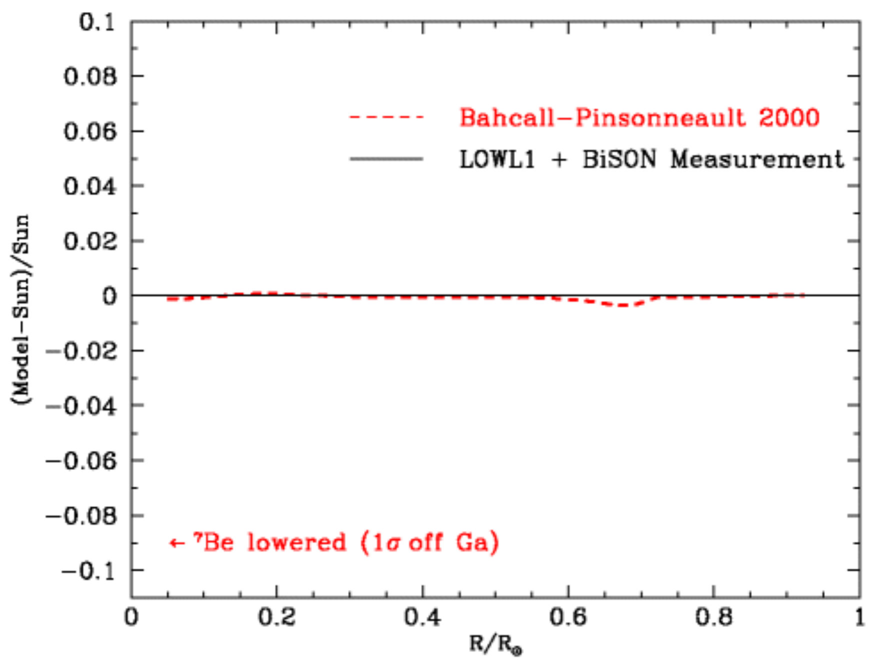
Solar Neutrino Spectra



The Standard Solar Model before 2004

One fundamental input of the Standard Solar Model is the **metallicity** of the Sun - abundance of all elements above Helium:

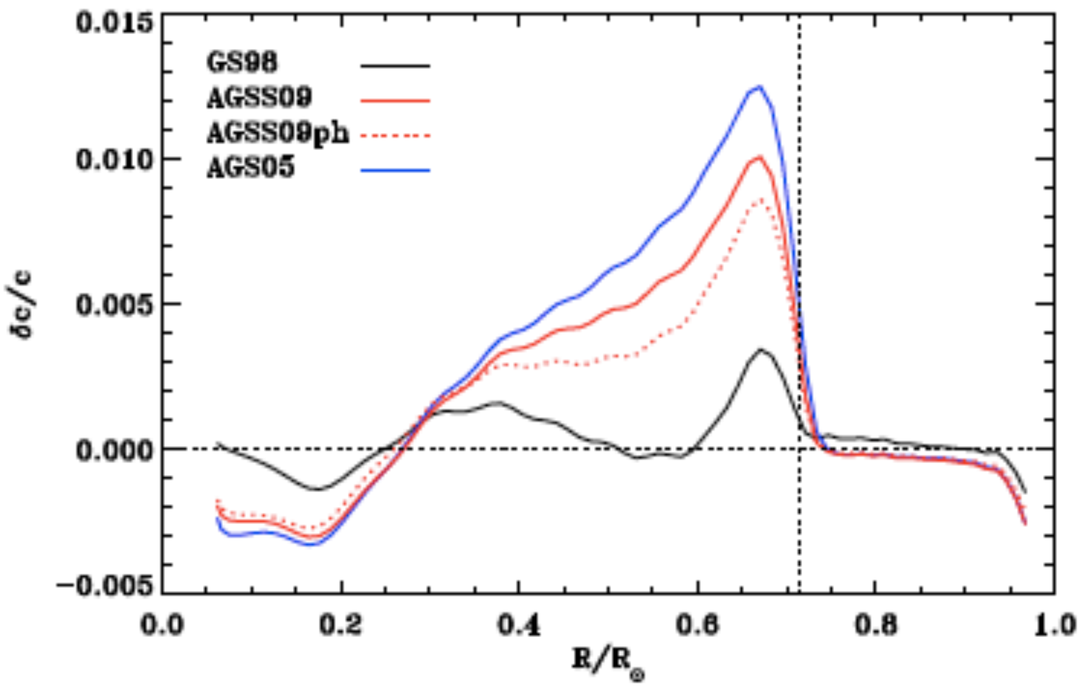
The Standard Solar Model, based on the old metallicity derived by Grevesse and Sauval (Space Sci. Rev. **85**, 161 (1998)), was in **agreement within 0.5 in %** with the solar sound speed measured by helioseismology.



The Standard Solar Model after 2004

Latest work by Asplund, Grevesse and Sauval (Nucl. Phys. A **777**, 1 (2006)) indicates a **lower** metallicity **by a factor ~2**. This result destroys the agreement with helioseismology.

Revised model in 2009 by Serenelli, Basu, Ferguson, Asplund (Astrophys.J. 705:L123-L127,2009) slightly reduced the discrepancy.



What about neutrinos?

$[cm^{-2}\ s^{-1}]$	pp (10^{10})	pep (10^{10})	hep (10^{3})	^{7}Be (10^{9})	^{8}B (10^{6})	^{13}N (10^{8})	^{15}O (10^{8})	^{17}F (10^{6})
GS 98	5.97	1.41	7.91	5.08	5.88	2.82	2.09	5.65
AGS 09	6.03	1.44	8.18	4.64	4.85	2.07	1.47	3.48
Δ	-1%	-2%	-3%	-9%	-18%	-27%	-30%	-38%

Solar neutrino measurements can solve the problem!

Borexino goals: solar physics

✓ First ever observations of **sub-MeV neutrinos** in real time

✓ Check the balance between photon **luminosity** and neutrino luminosity of the Sun

✓ **CNO** neutrinos (direct indication of metallicity in the Sun's core)

✓ ***pep*** neutrinos (indirect constraint on *pp* neutrino flux)

✓ Low energy (**3-5 MeV**) ^{8}B neutrinos

✓ Tail end of ***pp* neutrino spectrum**?

Borexino goals: neutrino physics

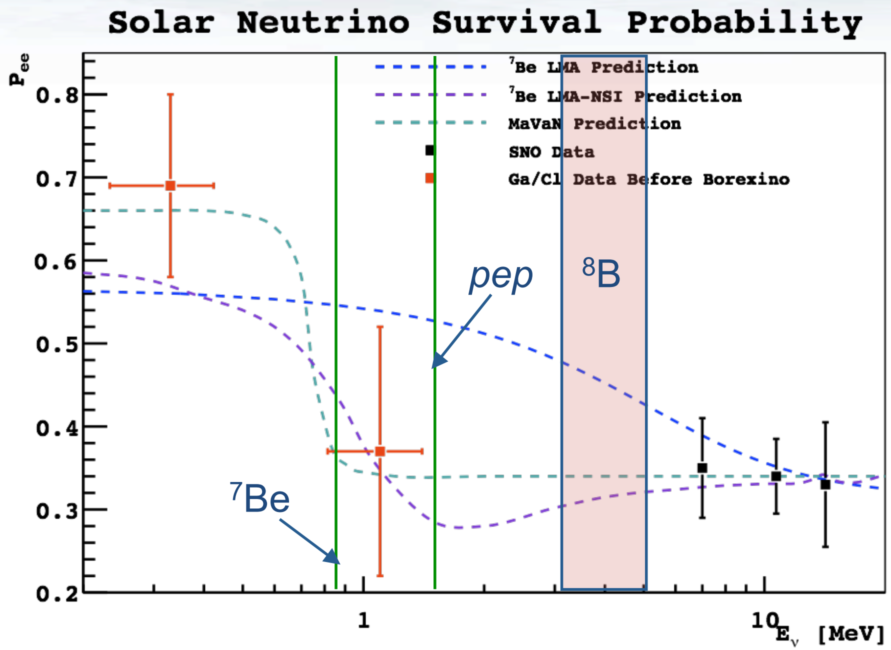
✓ Test of the **matter-vacuum oscillation transition** with ^{7}Be, *pep,* and low energy ^{8}B neutrinos

✓ Limit on the **neutrino magnetic moment** by analyzing the ^{7}Be energy spectrum and with Cr source

✓ SNEWS network for **supernovae**

✓ First evidence (>3σ) of **geoneutrinos**

✓ **Sterile neutrinos ??**



Map of reactors in Europe

Borexino Collaboration

Genova

Milano

Perugia

APC Paris

Princeton University

Virginia Tech. University

Dubna JINR (Russia)

Kurchatov Institute (Russia)

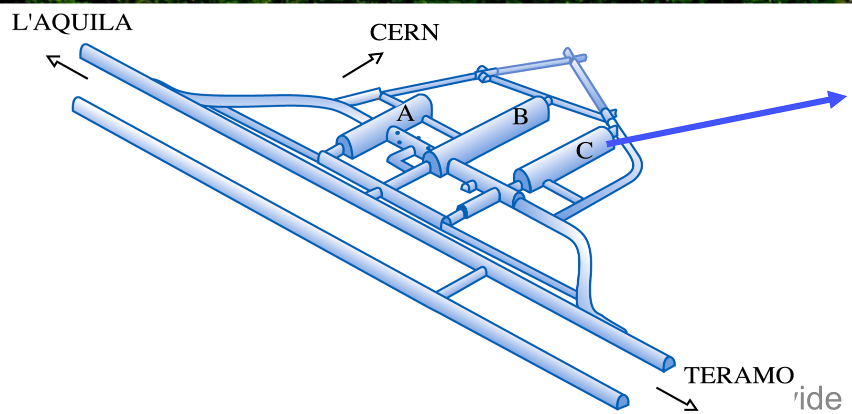
Jagiellonian U. Cracow (Poland)

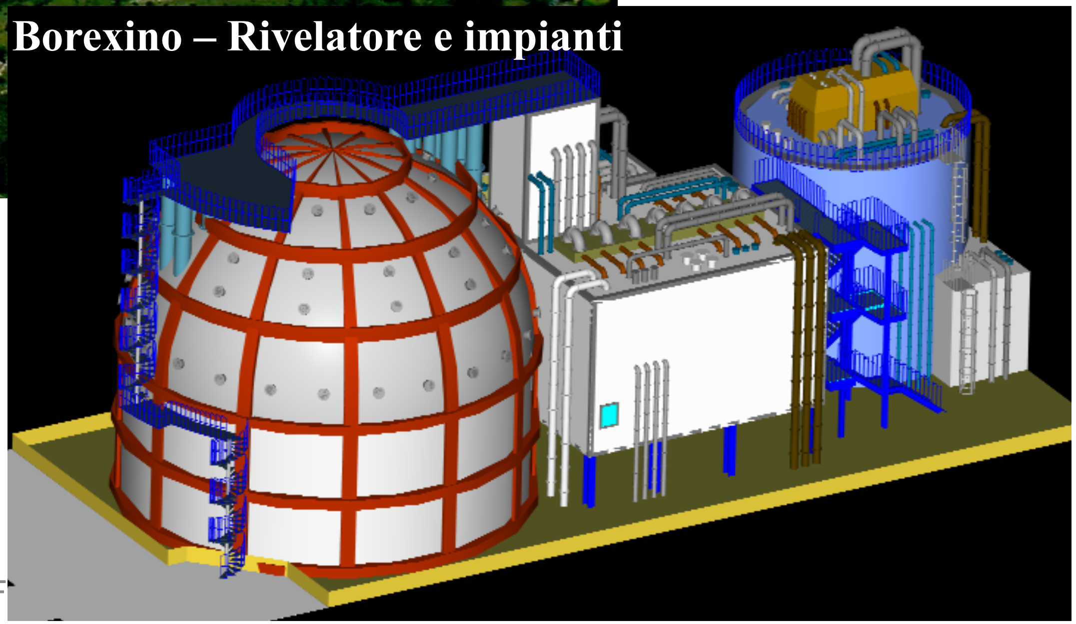
Heidelberg (Germany)

Munich (Germany)

Laboratori Nazionali del Gran Sasso

Assergi (AQ)
Italy
~3500 m.w.e



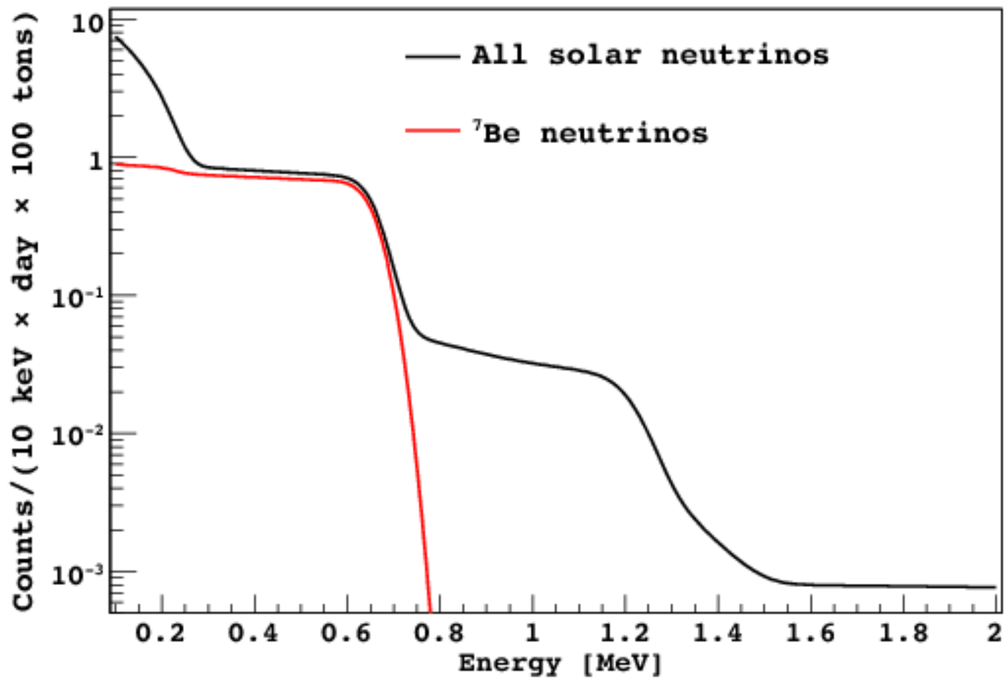


Detection principles and ν signature

- ✓ Borexino detects solar ν via their **elastic scattering off electrons** in a volume of **highly purified liquid scintillator**
  - ✓ Mono-energetic **0.862 MeV ^{7}Be ν** are the main target, and the only considered so far
  - ✓ Mono-energetic pep ν , CNO ν and possibly pp ν will be studied in the future

- ✓ Detection via scintillation light:
  - ✓ Very low energy threshold
  - ✓ Good position reconstruction
  - ✓ Good energy resolution

  BUT…
  - ✓ No direction measurement
  - ✓ The ν induced events can't be distinguished from other β events due to natural radioactivity



✓ **Extreme radiopurity of the scintillator is a must!**

Borexino Background

Expected solar neutrino rate in 100 tons of scintillator ~ 50 counts/day (**~ 5 10^{-9} Bq/kg**)

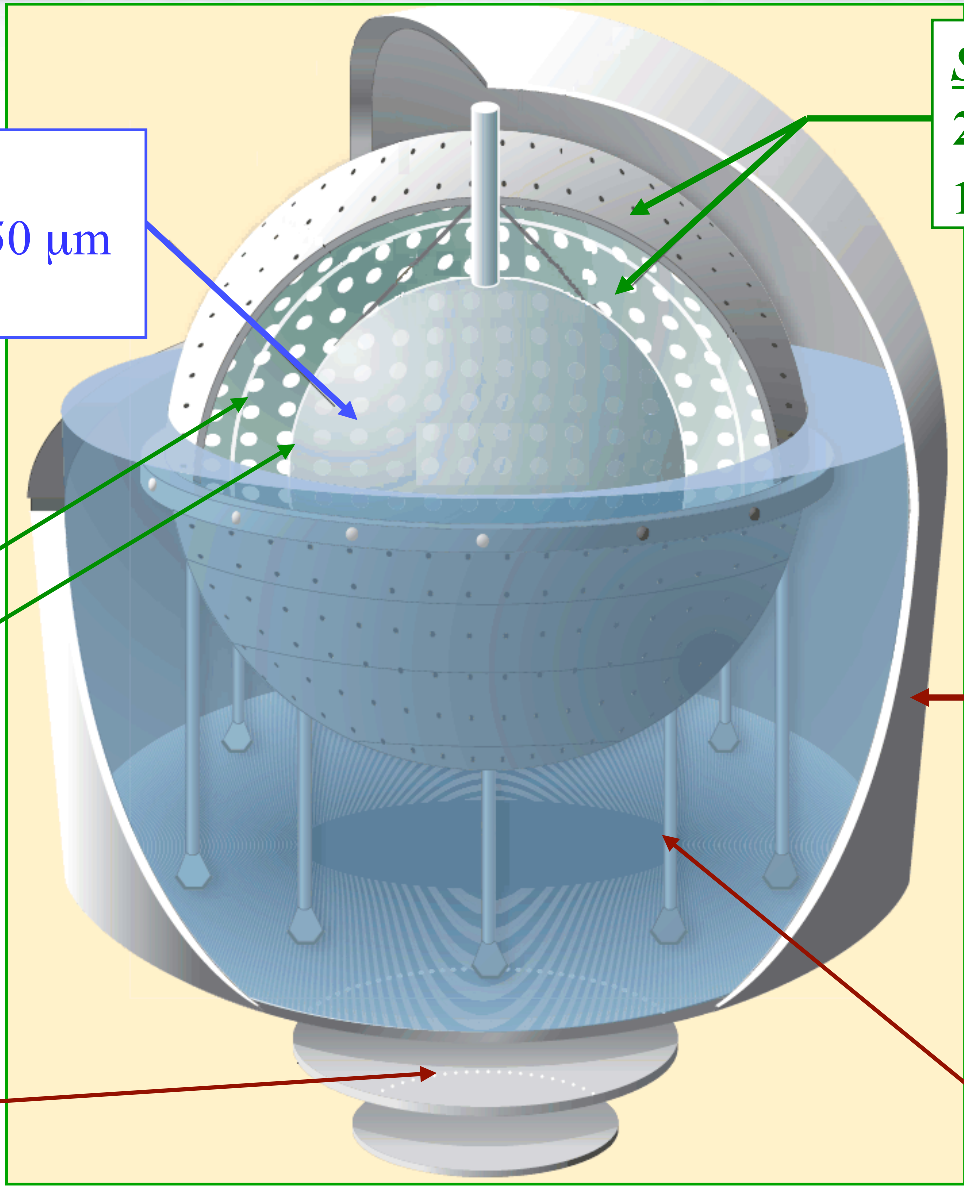
Just for comparison:

Natural water	~ 10 Bq/kg in ^{238}U, ^{232}Th and ^{40}K
Air	~ 10 Bq/m^3 in ^{39}Ar, ^{85}Kr and ^{222}Rn
Typical rock	~ 100-1000 Bq/kg in ^{238}U, ^{232}Th and ^{40}K

BX scintillator must be **9/10 order of magnitude less** radioactive than anything on earth!

- **Low background nylon vessel** fabricated in hermetically sealed low radon clean room (~1 yr)
- **Rapid transport** of scintillator solvent (PC) from production plant to underground lab to avoid cosmogenic production of radioactivity (^7Be)
- Underground **purification plant** to distill scintillator components.
- **Gas stripping** of scintlllator with special nitrogen free of radioactive ^{85}Kr and ^{39}Ar from air
- All materials **electropolished SS or teflon**, precision cleaned with a dedicated cleaning module

Detector layout and main features



Scintillator:
270 t PC+PPO in a 150 μm thick nylon vessel

Stainless Steel Sphere:
2212 PMTs
1350 m^3

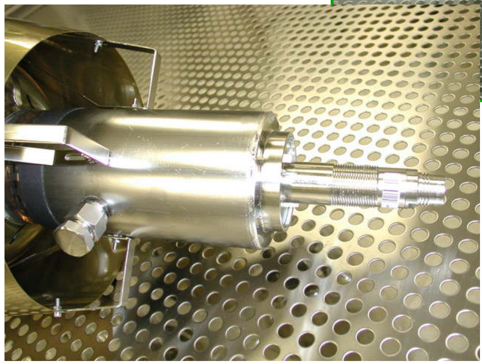
Nylon vessels:
Inner: 4.25 m
Outer: 5.50 m

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

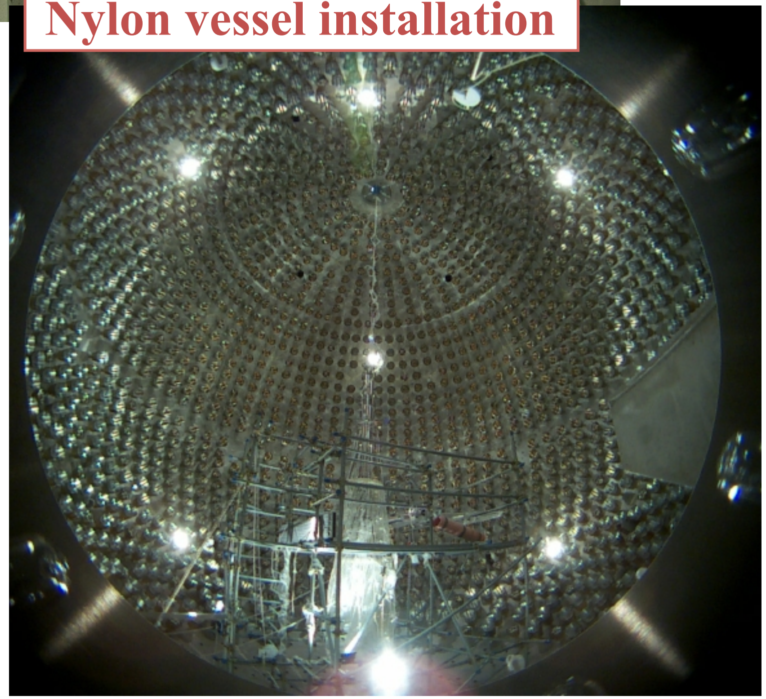
Carbon steel plates

20 legs

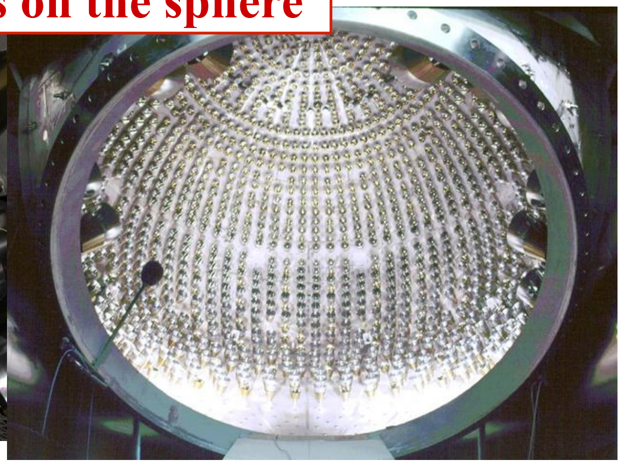
PMTs: PC & Water proof



Nylon vessel installation



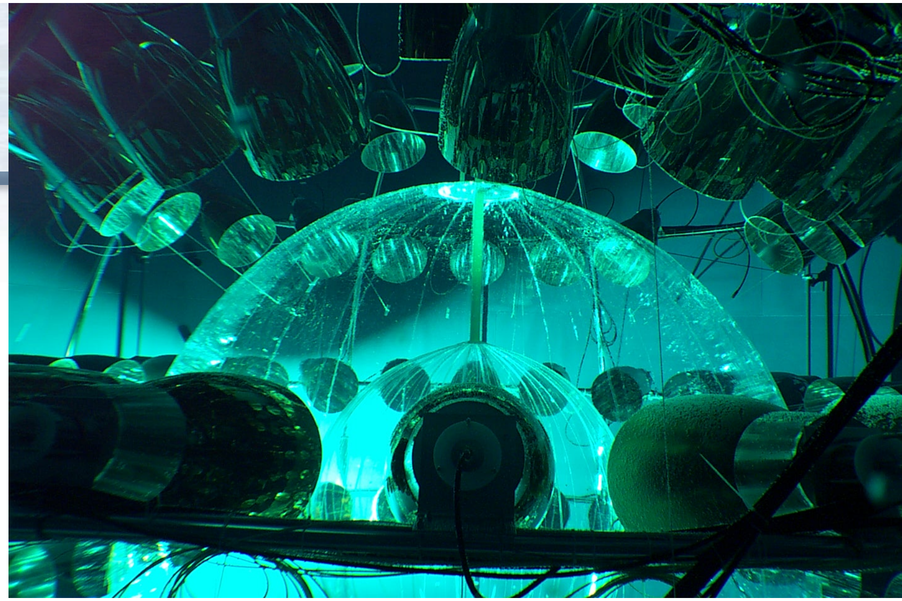
Installation of PMTs on the sphere



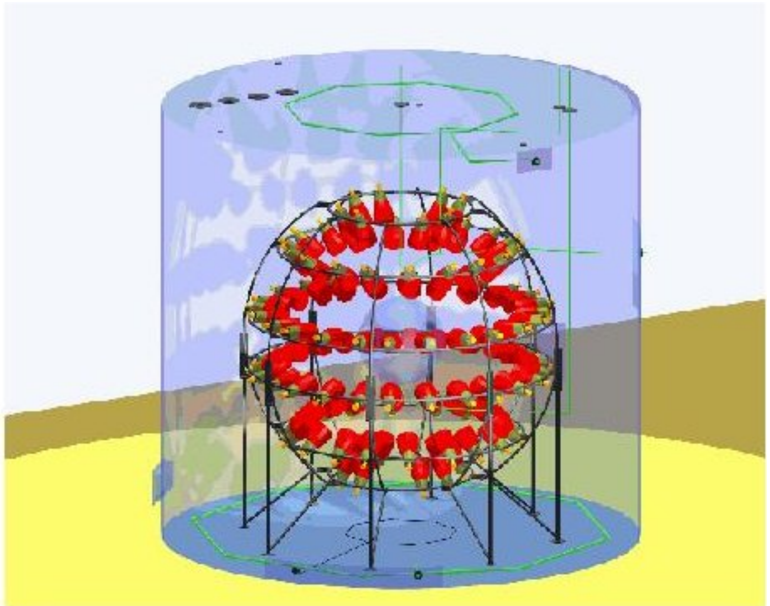
Water Plant

Storage area and Plants

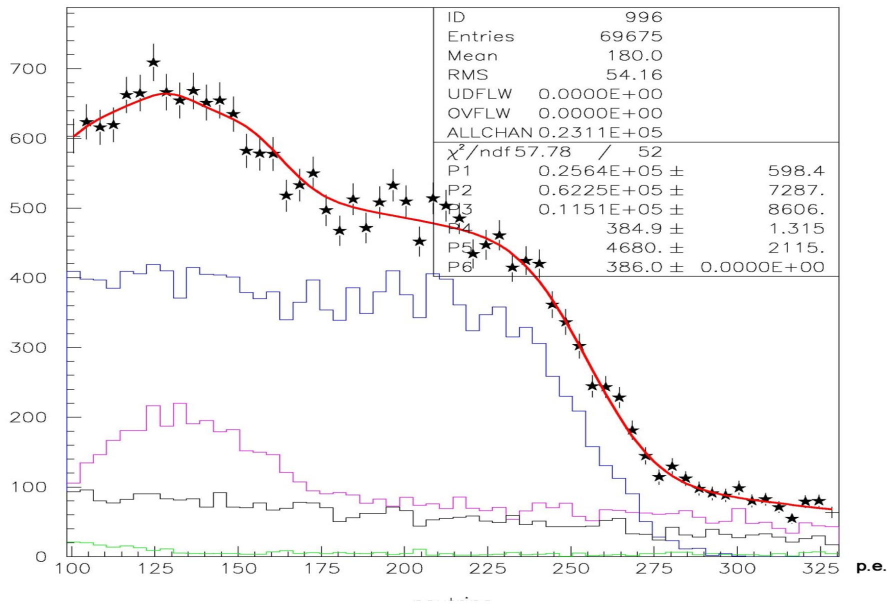
Counting Test Facility

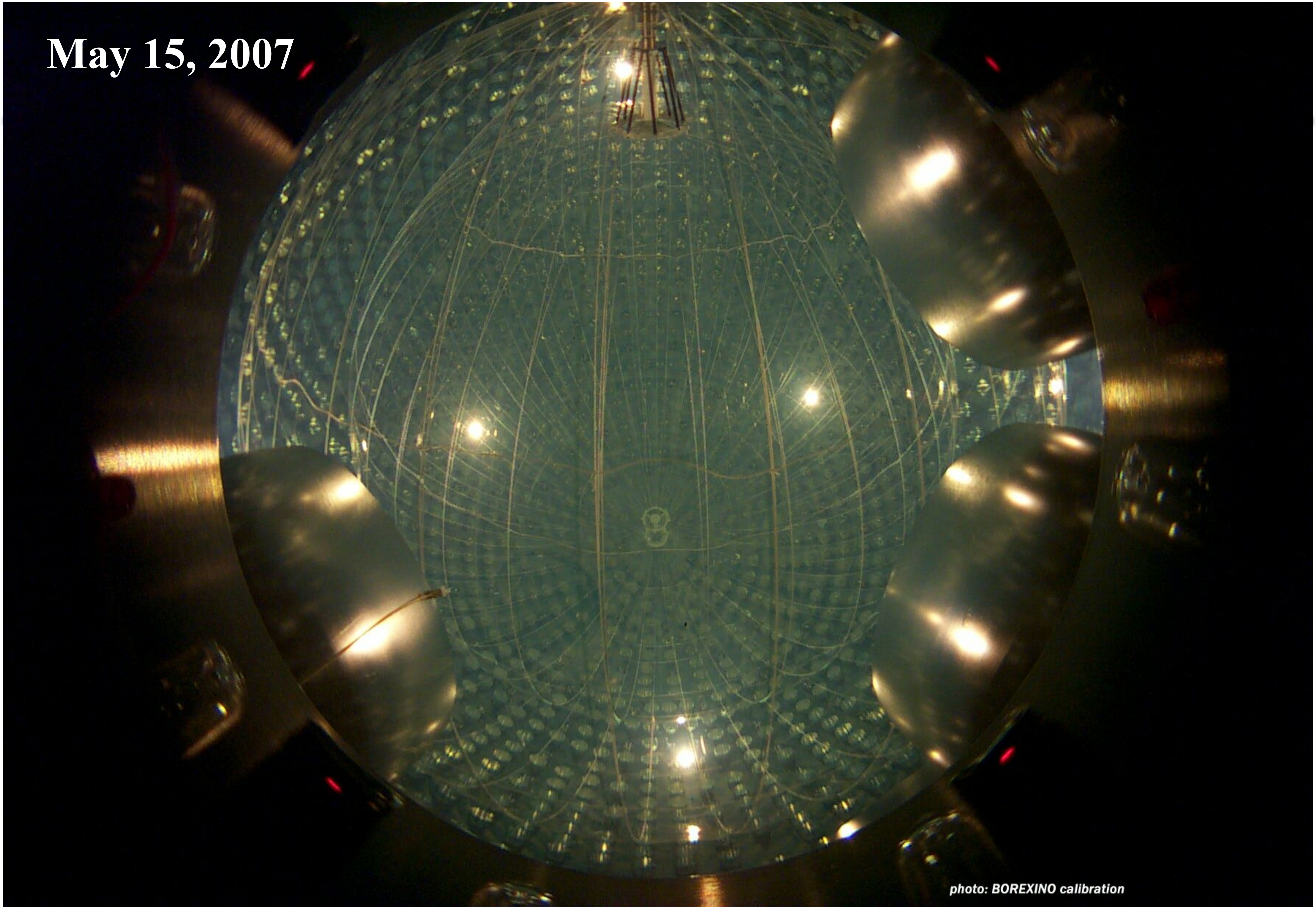


✓CTF is a small scale prototype of Borexino:
- ✓ ~ 4 tons of scintillator
- ✓ 100 PMTs
- ✓ Buffer of water
- ✓ Muon veto
- ✓ Vessel radius: 1 m



CTF demonstrates the Borexino feasibility

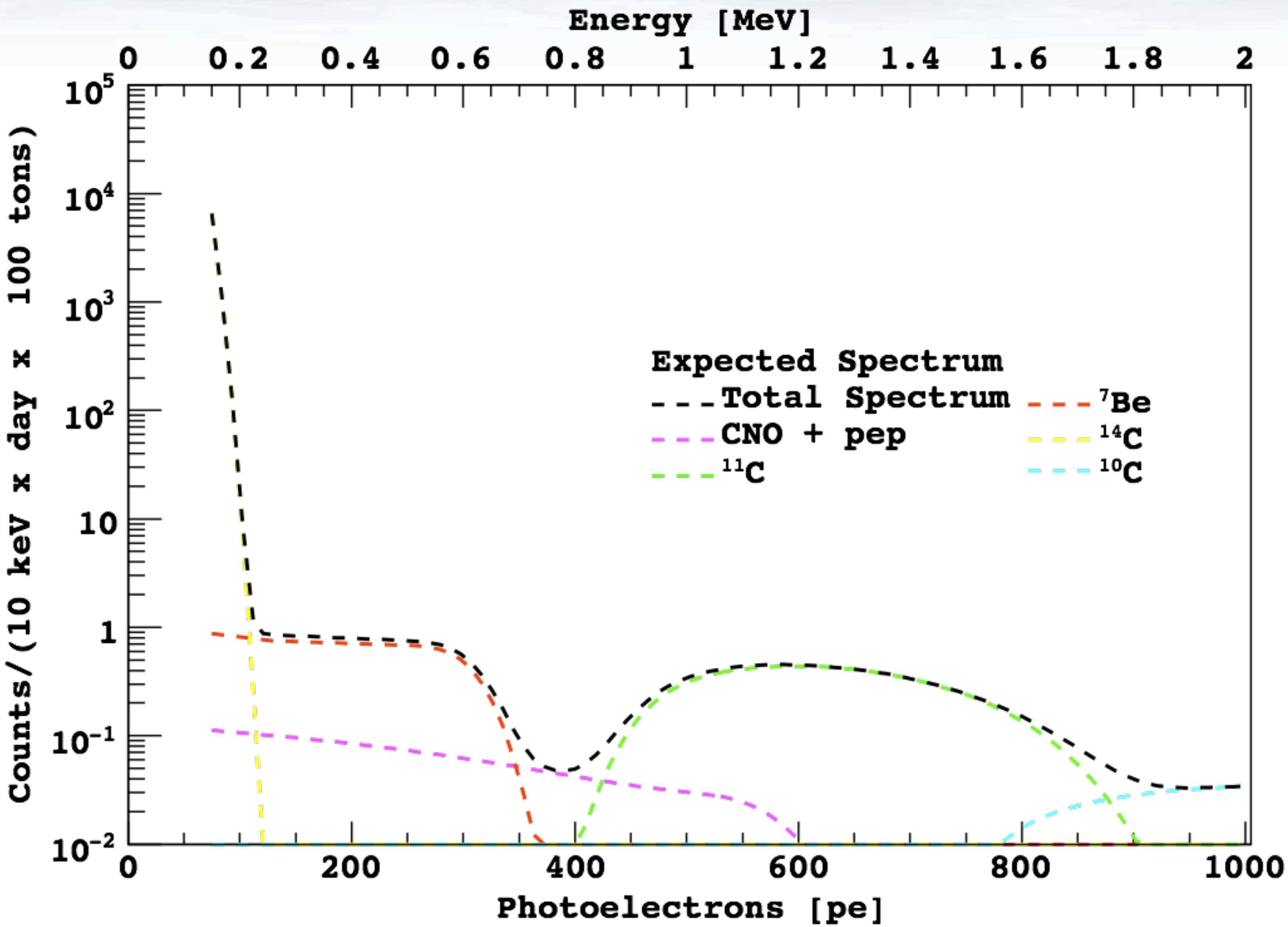



May 15, 2007
photo: BOREXINO calibration

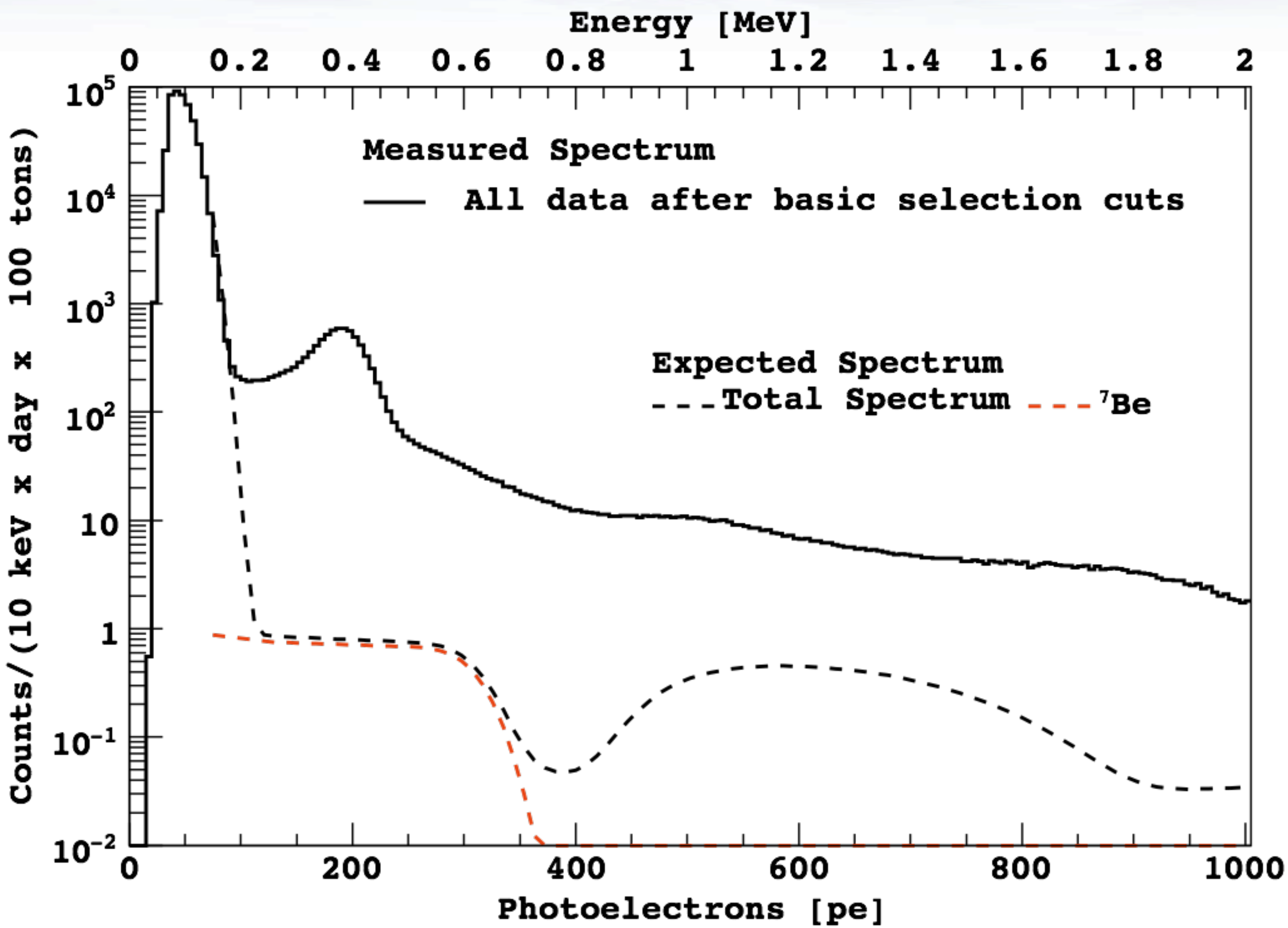
Borexino background

RadioIsotope		Concentration or Flux		Strategy for Reduction		
Name	Source	Typical	Required	Hardware	Software	Achieved
μ	cosmic	~200 s^{-1} m^{-2} at sea level	~ 10^{-10}	Underground Cherenkov detector	Cherenkov signal PS analysis	<10^{-10} (overall)
Ext. γ	rock			Water Tank shielding	Fiducial Volume	negligible
Int. γ	PMTs, SSS Water, Vessels			Material Selection Clean constr. and handling	Fiducial Volume	negligible
^{14}C	Intrinsic PC/PPO	~ 10^{-12}	~ 10^{-18}	Old Oil, check in CTF	Threshold cut	~ 10^{-18}
^{238}U ^{232}Th	Dust Organometallic (?)	~ 10^{-5}-10^{-6} g/g (dust)	< 10^{-16} g/g (in scintillator)	Distillation, Water Extraction Filtration, cleanliness		~ 2 10^{-17} ~ 7 10^{-18}
^{7}Be	Cosmogenic (^{12}C)	~ 3 10^{-2} Bq/t	< 10^{-6} Bq/ton	Fast procurement, distillation	Not yet measurable	?
^{40}K	Dust, PPO	~ 2 10^{-6} g/g (dust)	< 10^{-14} g/g scin. < 10^{-11} g/g PPO	Water Extraction Distillation	Not yet measurable	?
^{210}Pb	Surface contam. from ^{222}Rn decay			Cleanliness, distillation	Not yet measurable (NOT in eq. with ^{210}Po)	?
^{210}Po	Surface contam. from ^{222}Rn decay			Cleanliness, distillation	Spectral analysis α/β stat. subtraction	~ 14 ~ 0.01 c/d/t
^{222}Rn	air, emanation from materials, vessels	~ 10 Bq/l (air) ~100 Bq/l (water)	< 1 c/d/100 t (scintillator)	Water and PC N_2 stripping, cleanliness, material selection	Delayed coincidence	< 0.02 c/d/t
^{39}Ar	Air (nitrogen)	~17 mBq/m^3 (air)	< 1 c/d/100 t	Select vendor, leak tightness	Not yet measurable	?
^{85}Kr	Air (nitrogen)	~ 1 Bq/m^3 in air	< 1 c/d/100 t	Select vendor, leak tightness (learn how to measure it)	Spectral fit fast coincidence	= 25±3 = 29±14

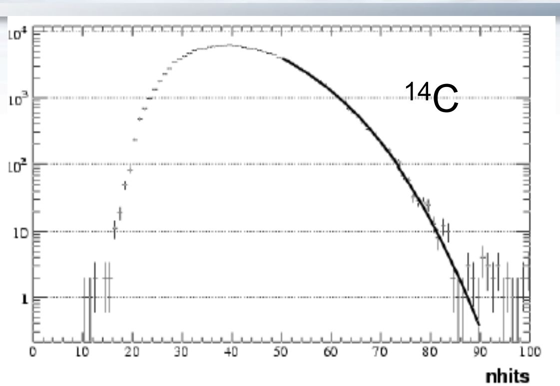
Expected Spectrum

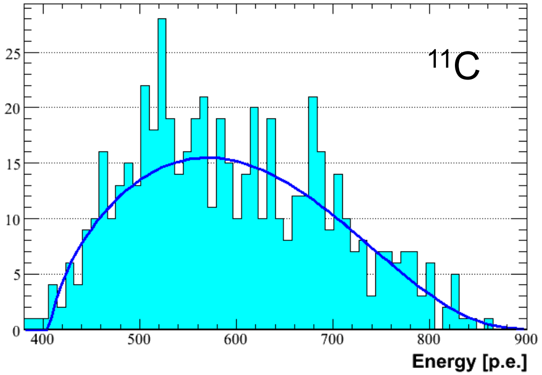


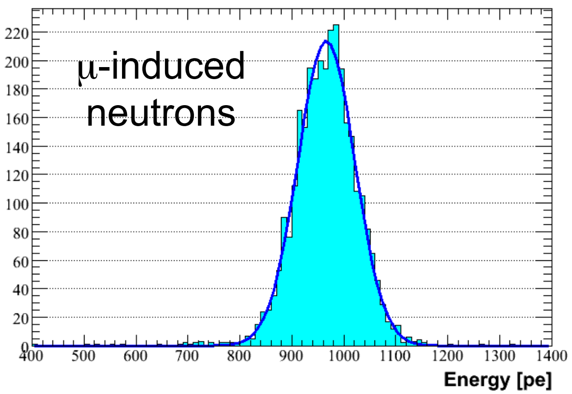
The starting point: no cut spectrum



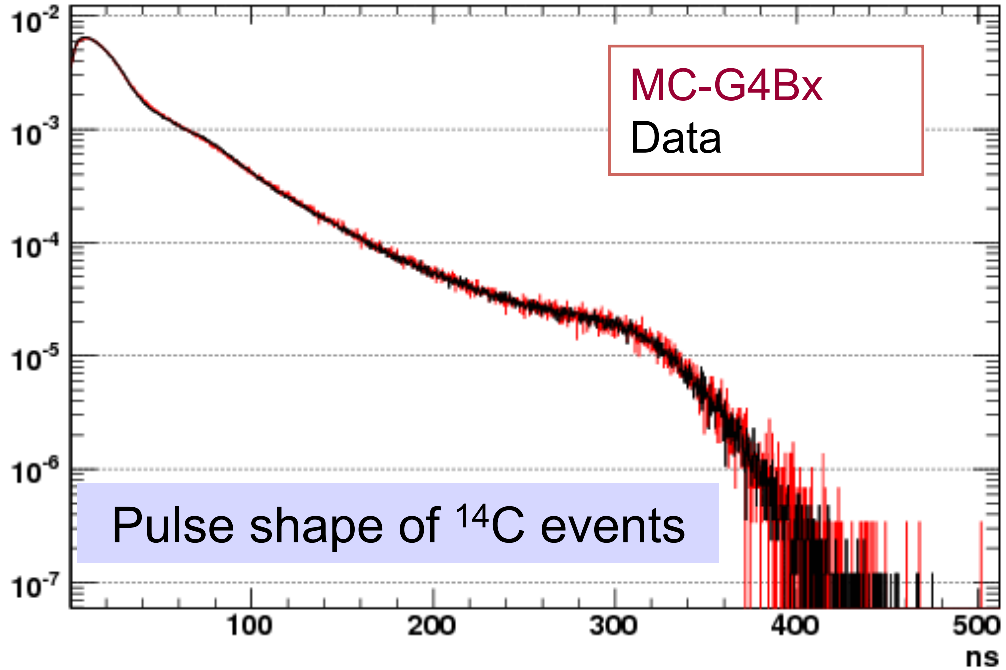
Energy scale







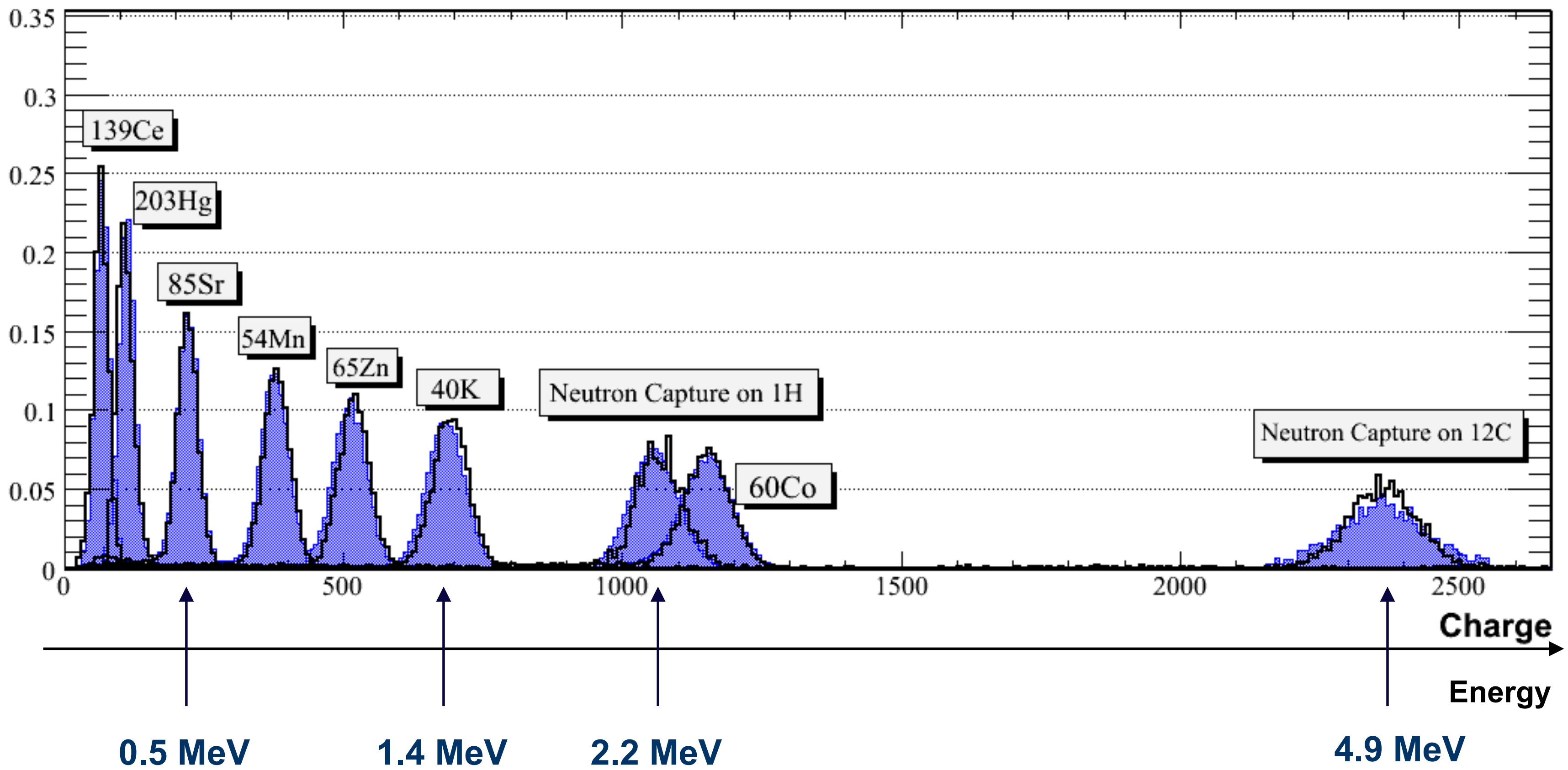
MC vs data comparison of photoelectron time distributions from ^{14}C



LY = 510 (1%) p.e./MeV
kB = 0.0197 (15%) cm/MeV
Ph.Y. ~ 12000 photons/MeV

Calibrations: Monte Carlo vs Data

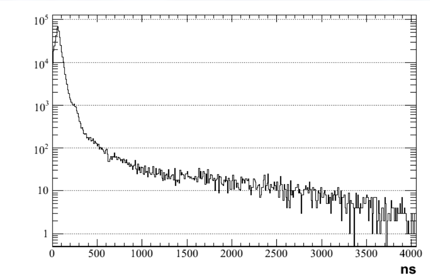
Gamma sources in the detector center



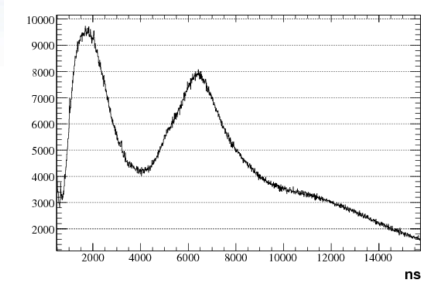
Detecting (and rejecting) cosmic muons

- μ are identified by ID and OD
  - OD eff: ~ 99%
  - ID based on pulse shape analysis
  - Rejection factor
    - > 10^3 (conservative)

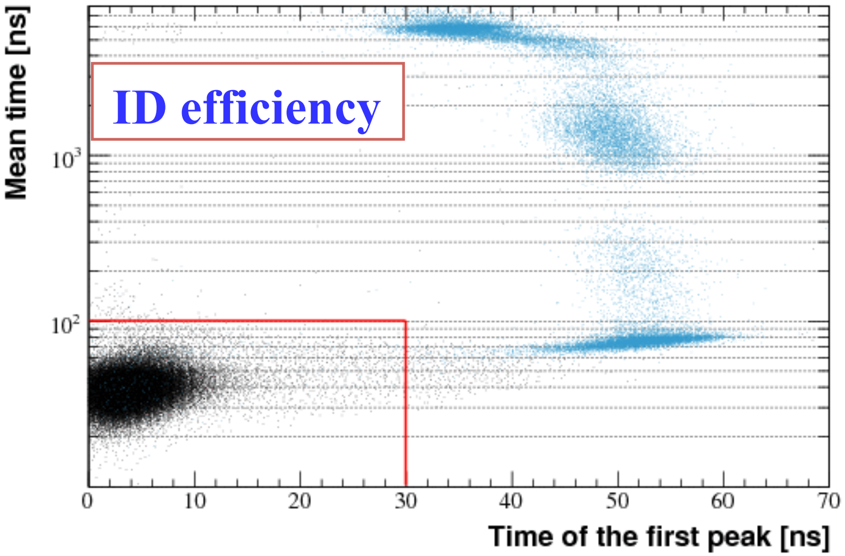
μ pulses

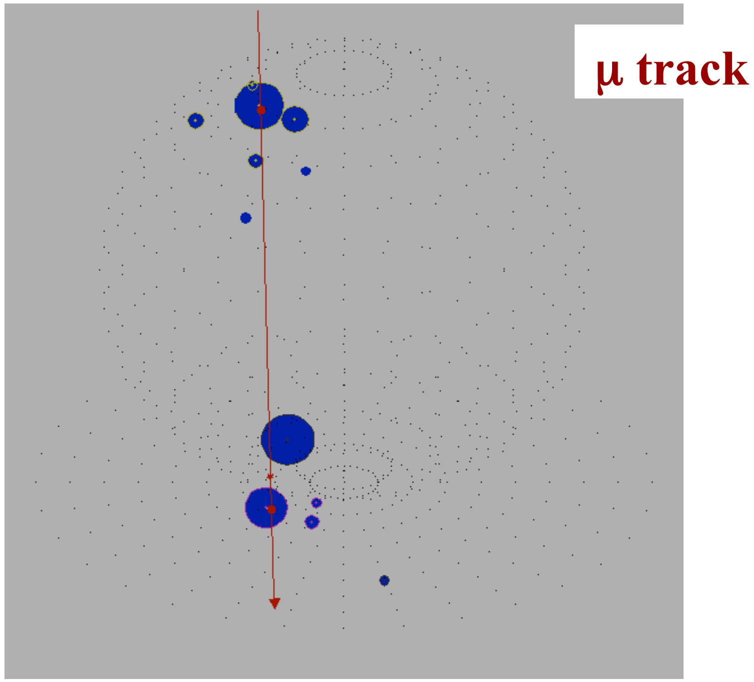


μ crossing the buffer only



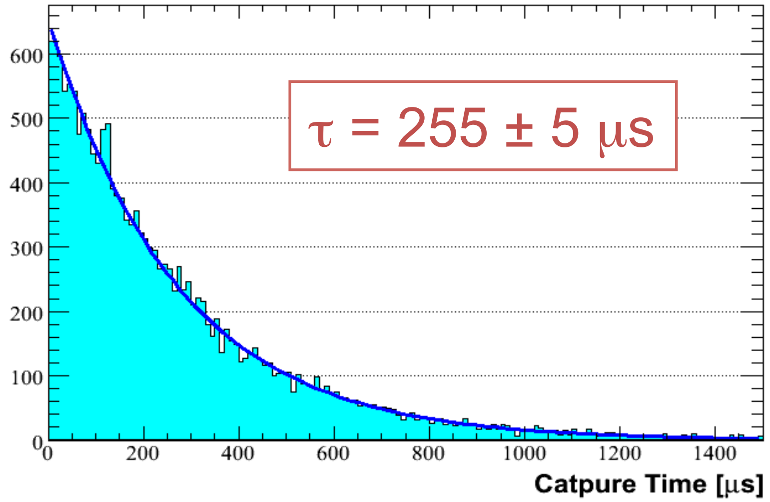
μ crossing the scintillator



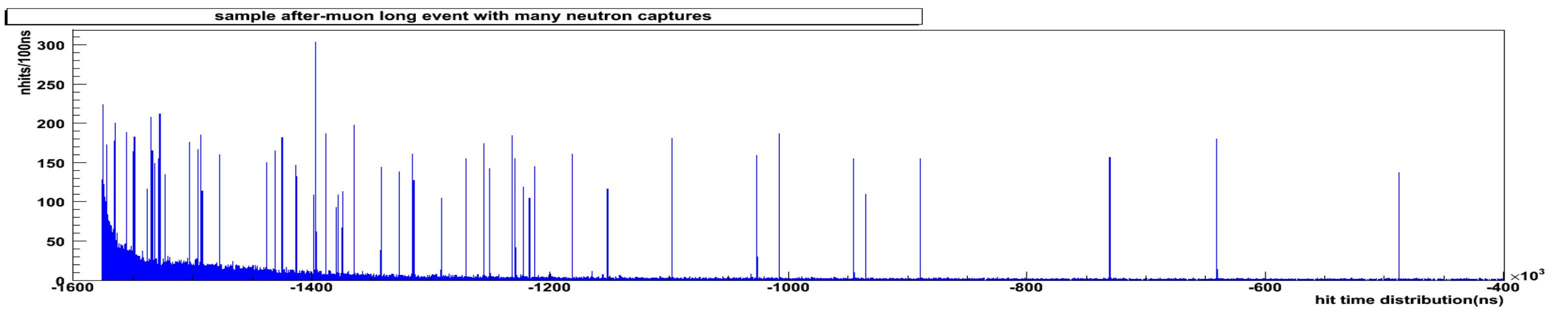


Detecting (and rejecting) cosmogenic neutrons

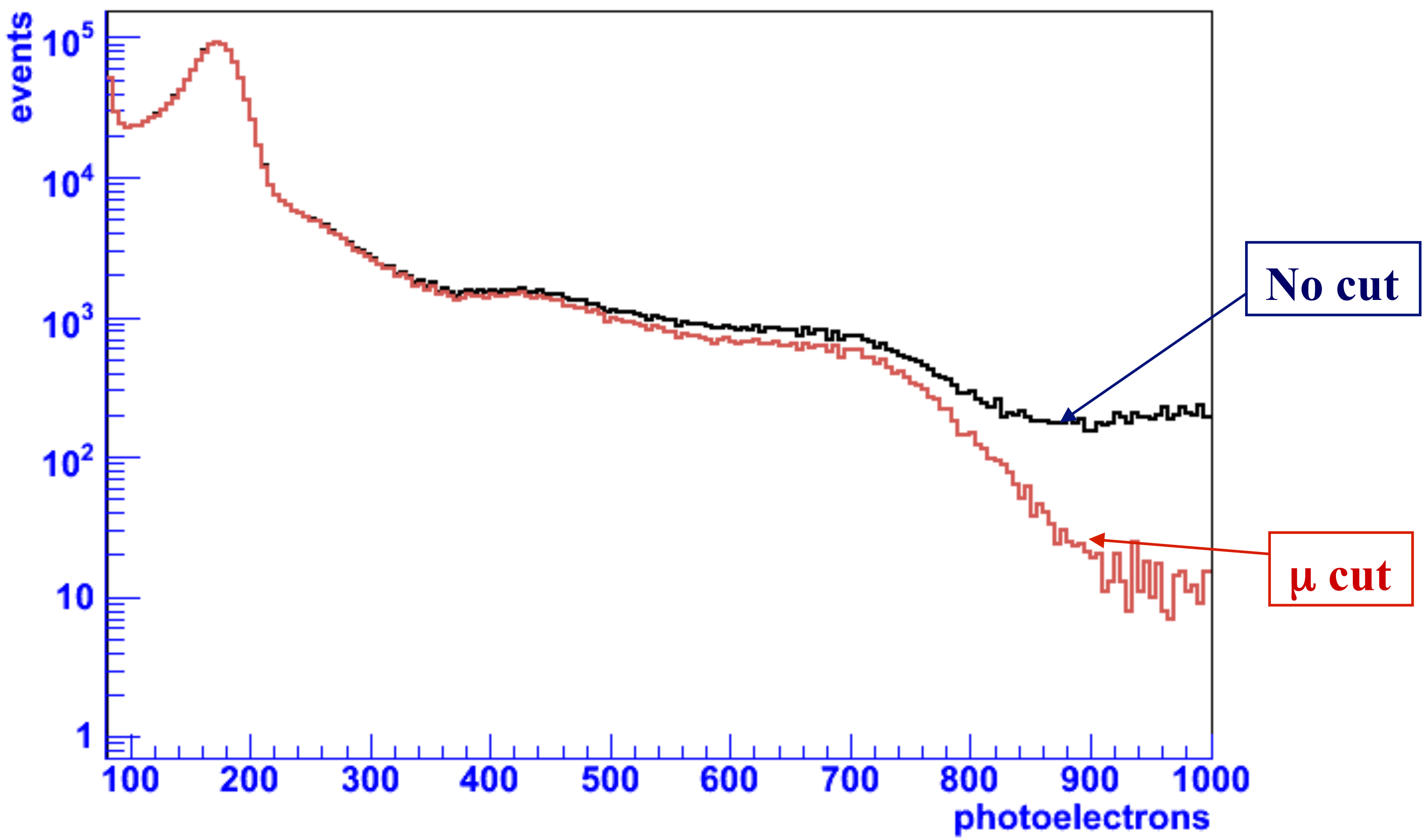
$$n + p \xrightarrow{\tau \sim 250\ \mu s} d + \gamma$$



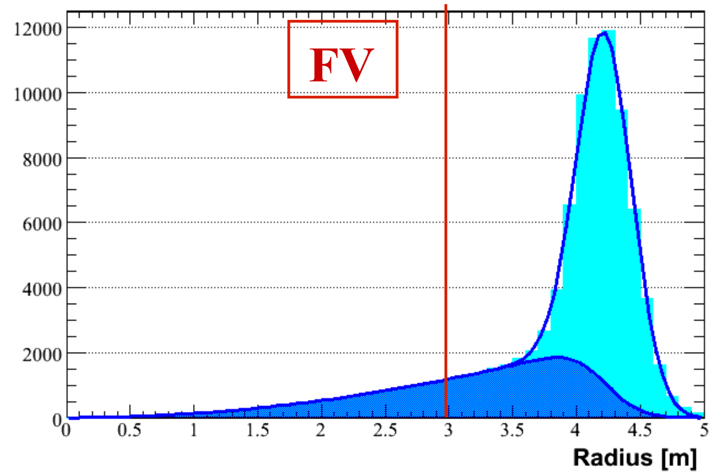
A dedicated trigger starts after each muon opening a gate for 1.6 ms.
An offline clustering algorithm identifies neutron in high multiplicity events



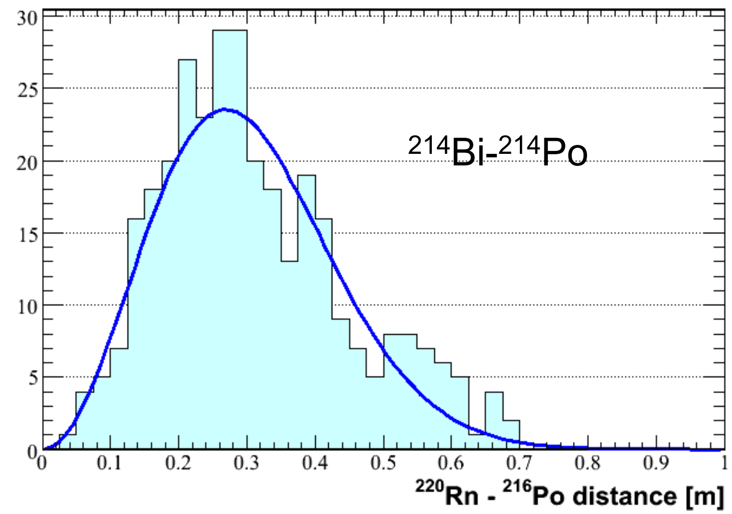
Muon and neutron cuts

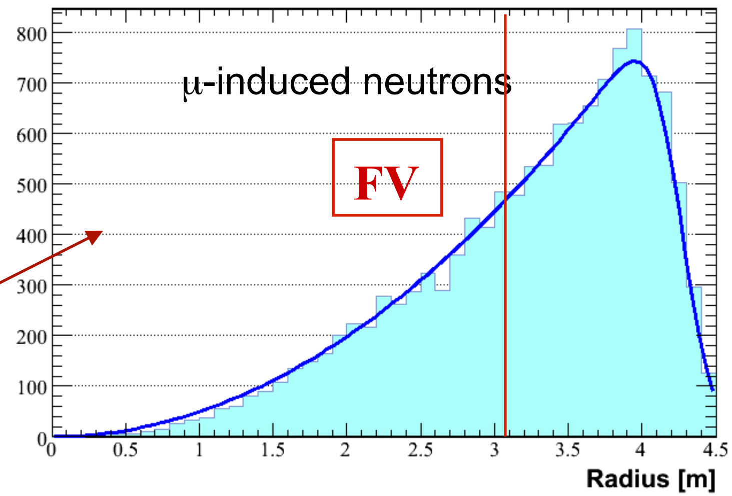


Spatial distributions and resolutions



^{7}Be energy region (mainly ^{210}Po)





11 cm @ ~2200 keV

^{214}Bi-^{214}Po (~800 KeV)

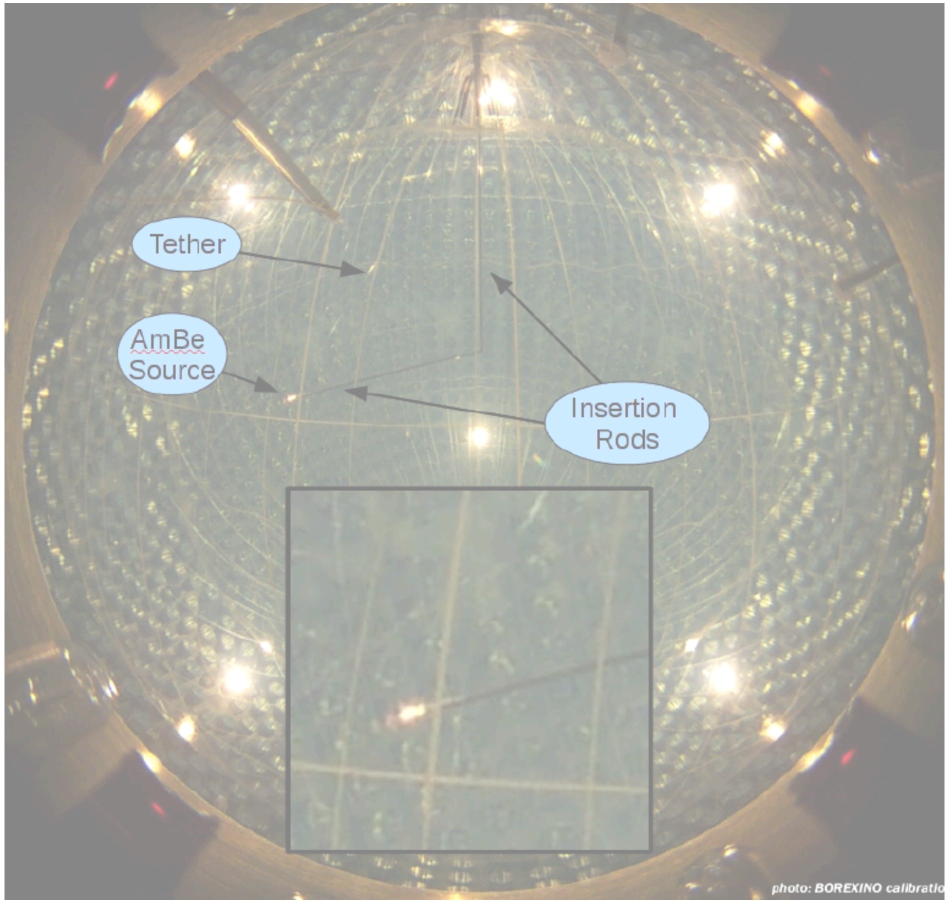
14±2 cm

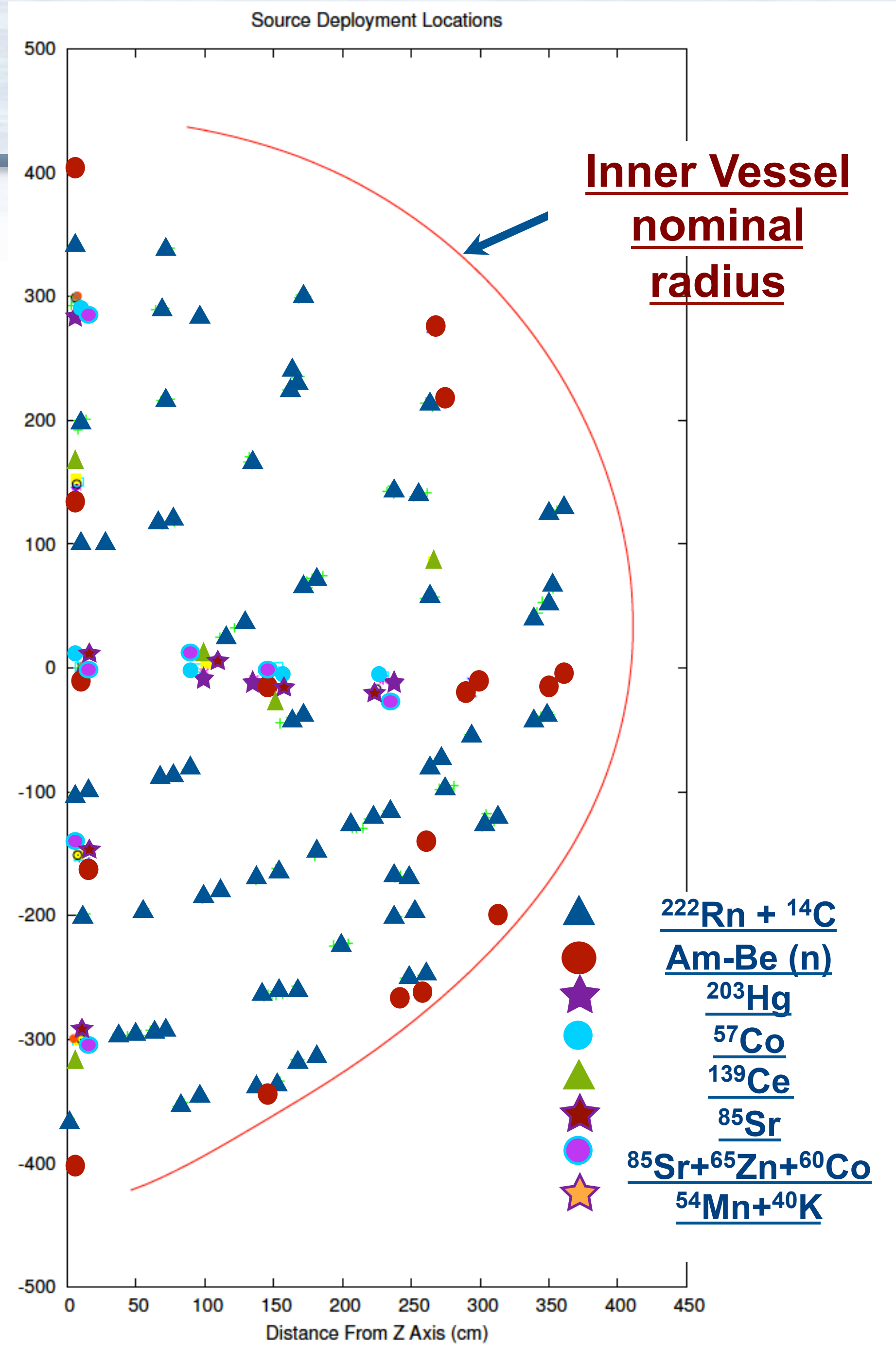
^{14}C (~100 KeV):

41±4 cm

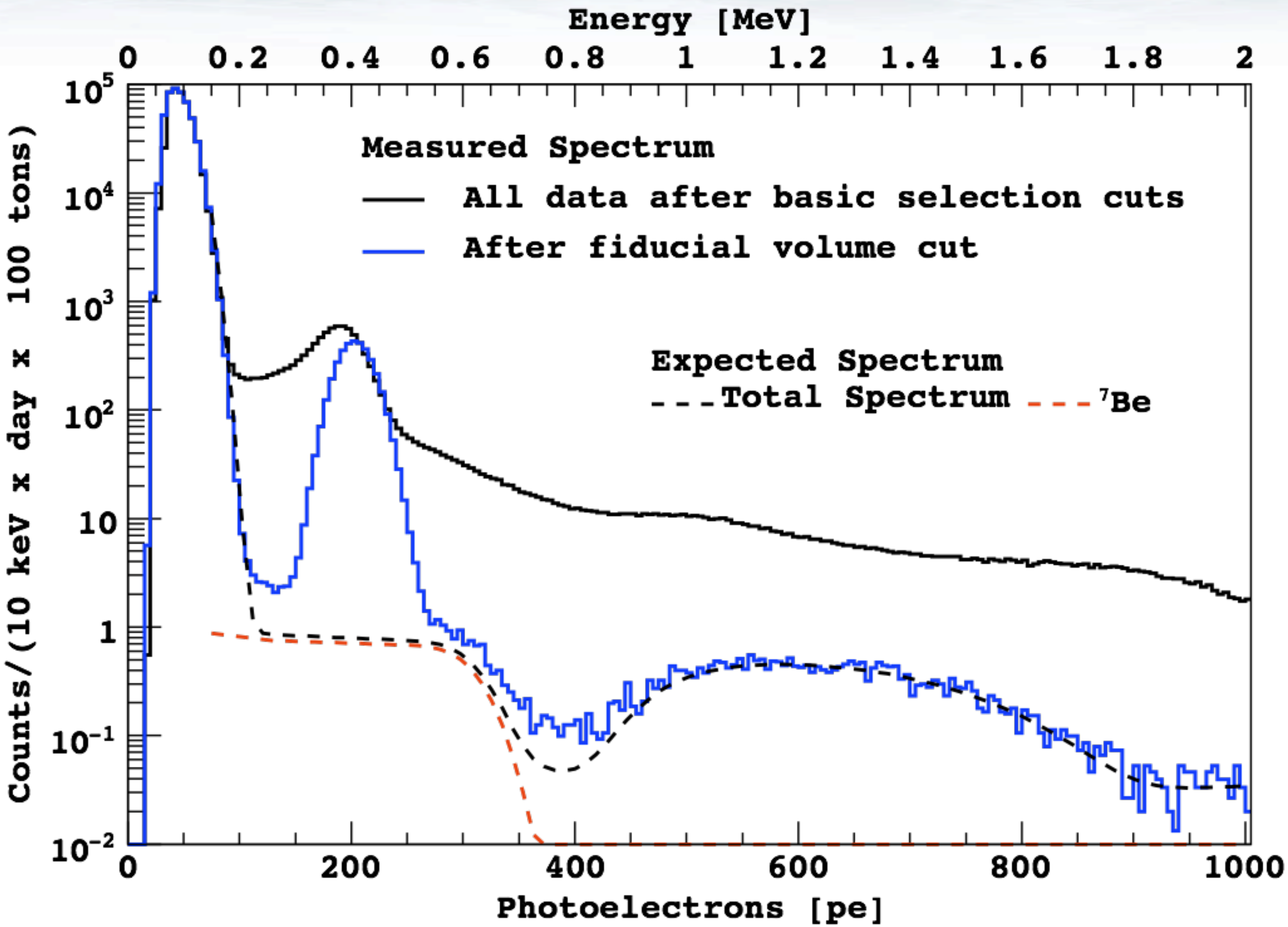
Fiducial volume

Careful study as a function of the position of the source in the whole Inner Vessel

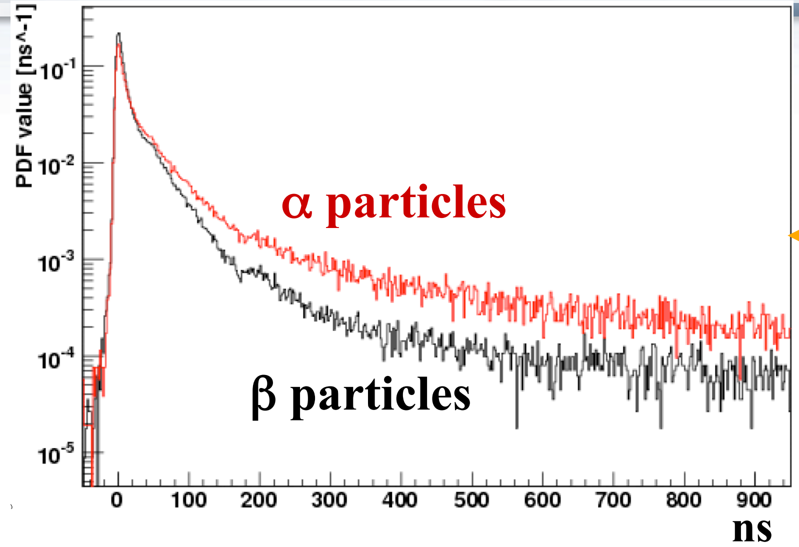




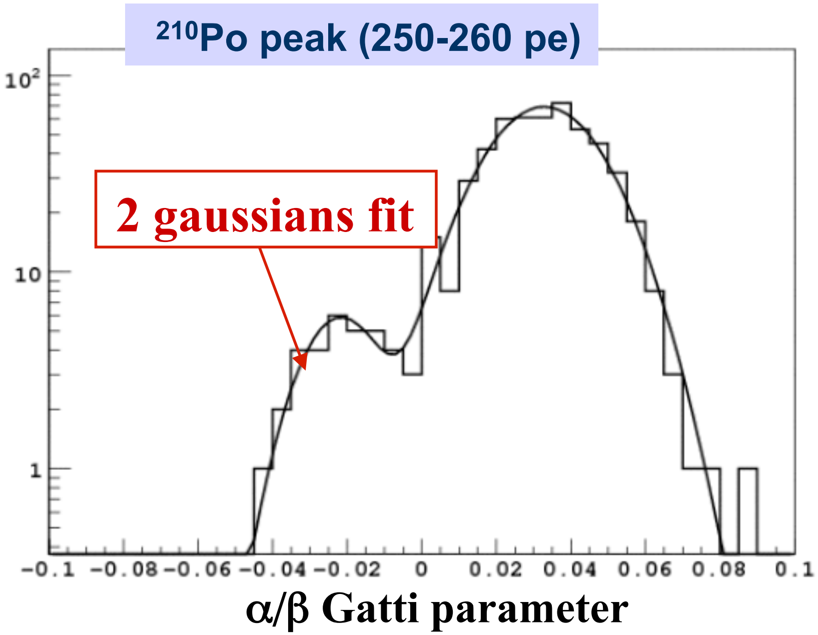
Spectrum after FV cut (100 tons)

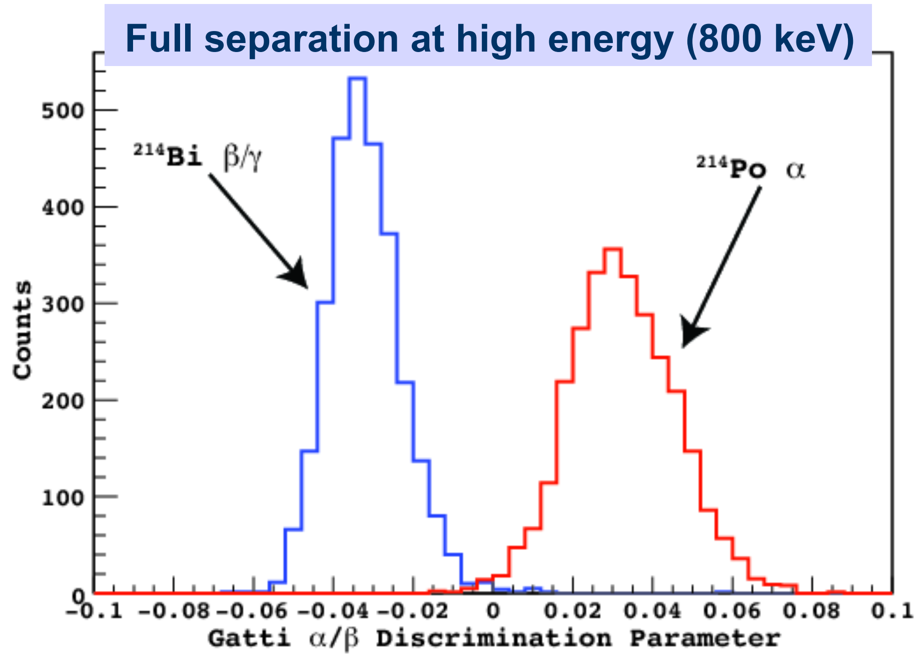


α/β discrimination



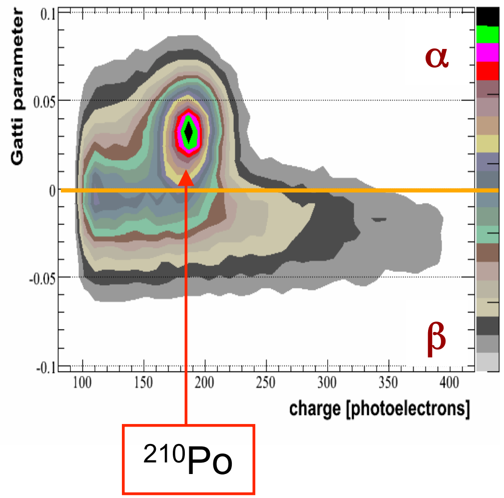
Average **time profiles of the scintillation pulses** emitted by a PC+PPO (1.5 g/l) mixture under alpha and beta irradiation



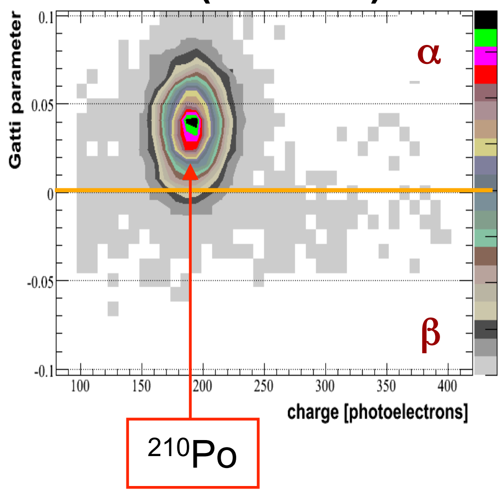


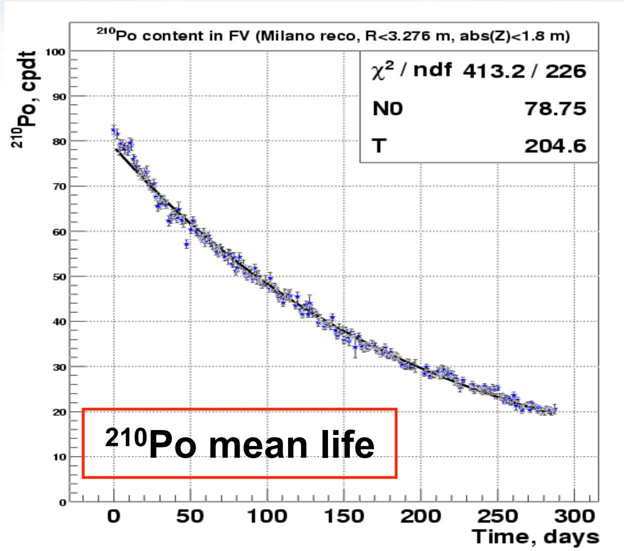
^{210}Po contamination

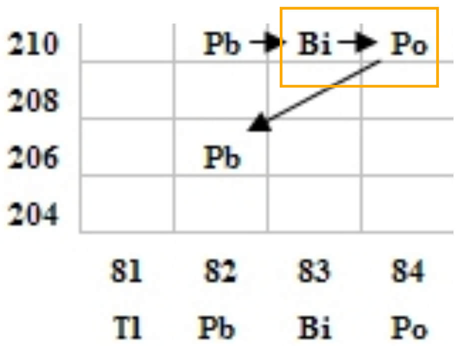
No radial cut



FV (R < 3 m)

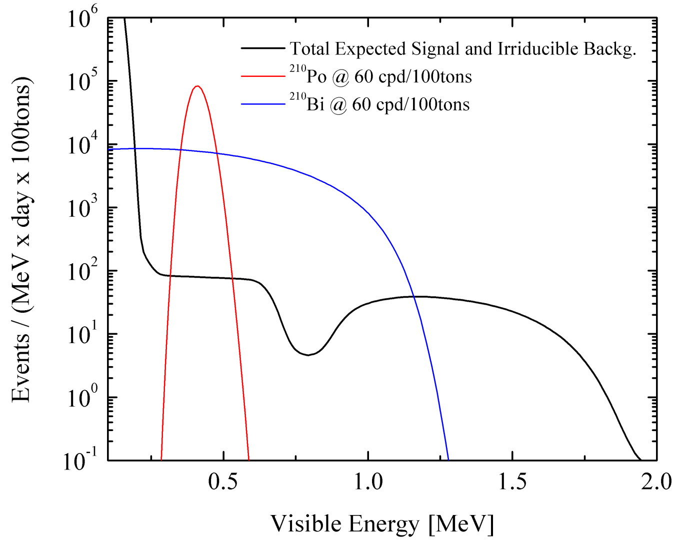




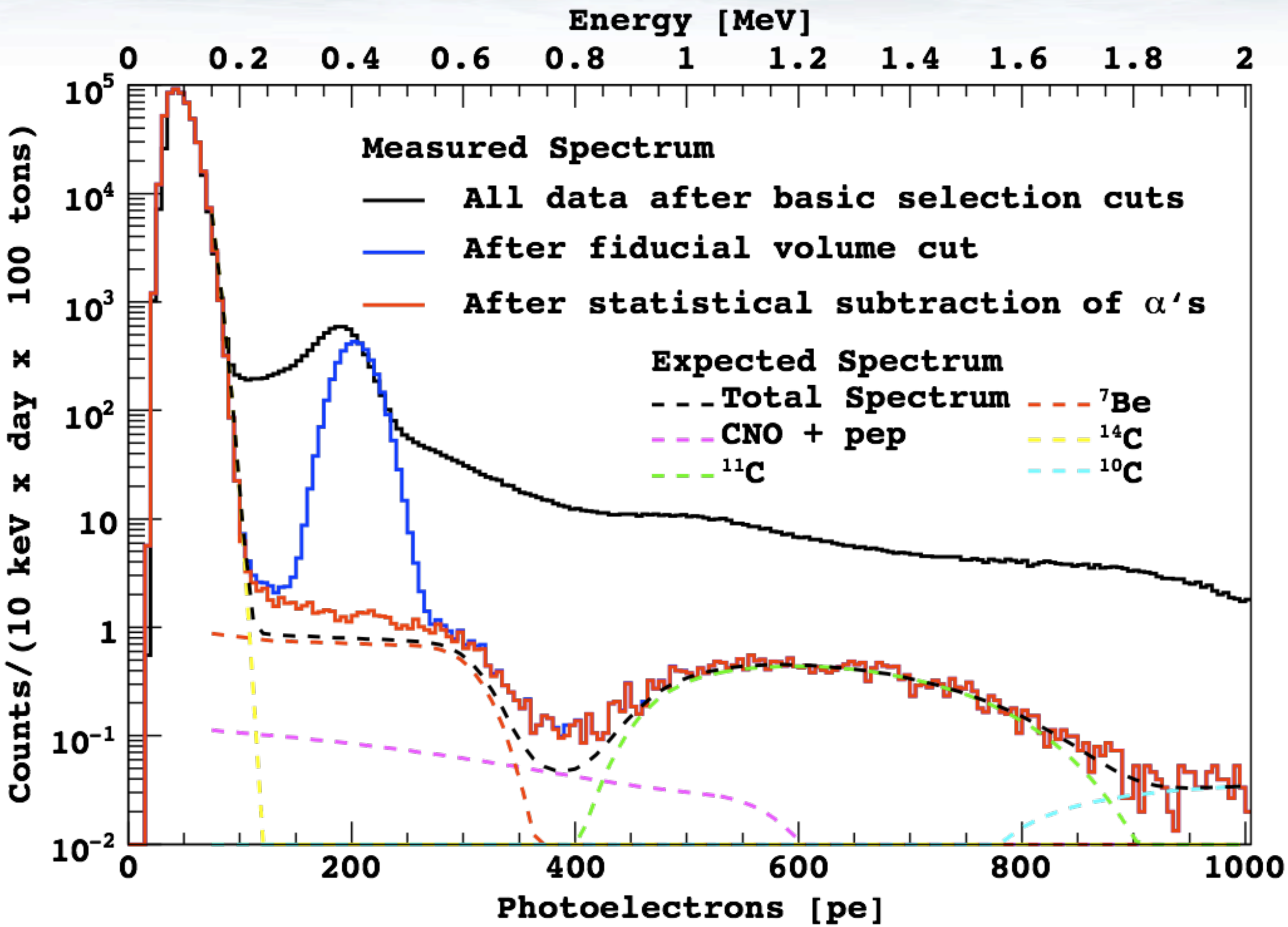


Not from ^{210}Pb

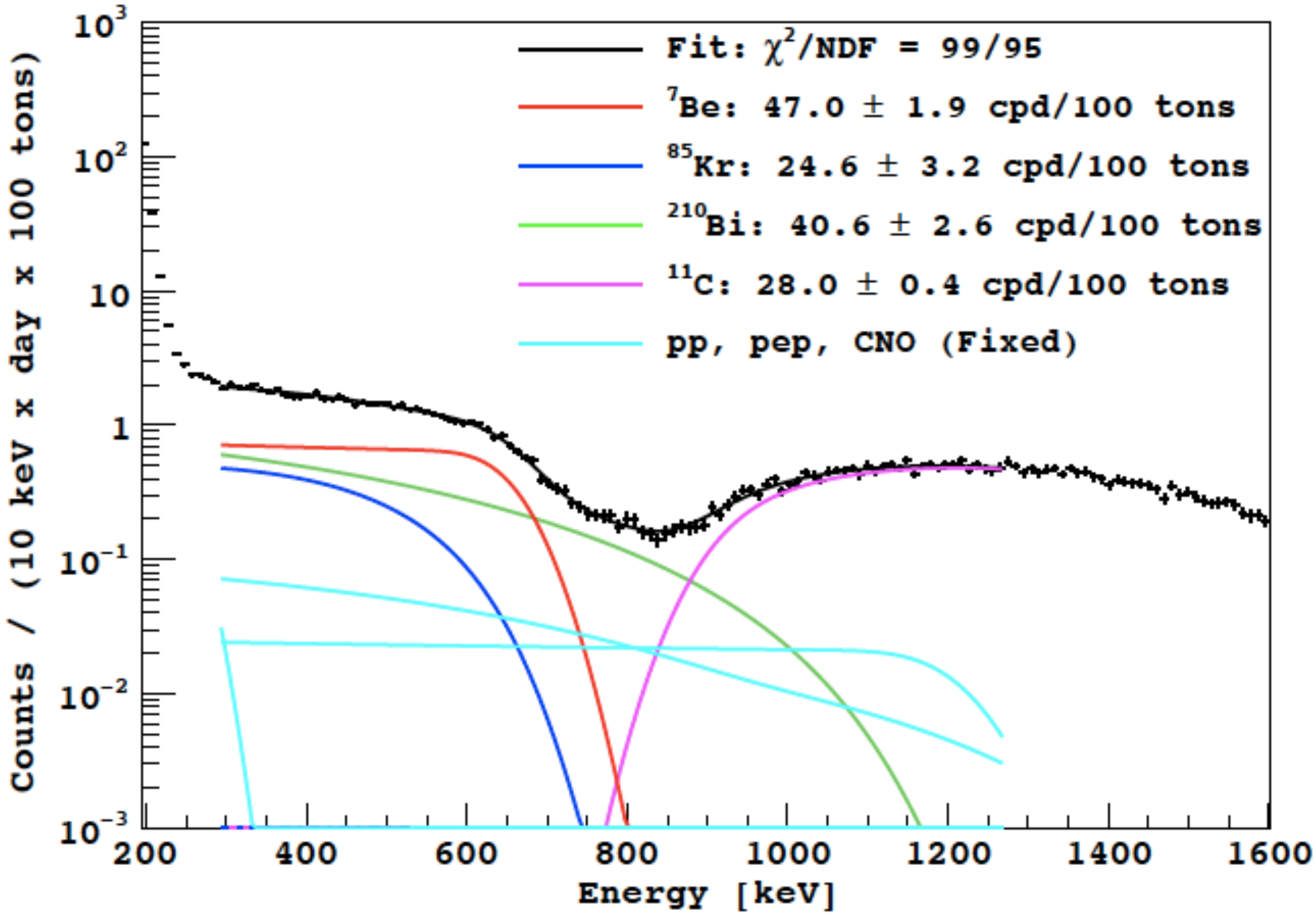
^{210}Po vs ^{210}Bi



α/β statistical subtraction



New results with 740 days of statistics



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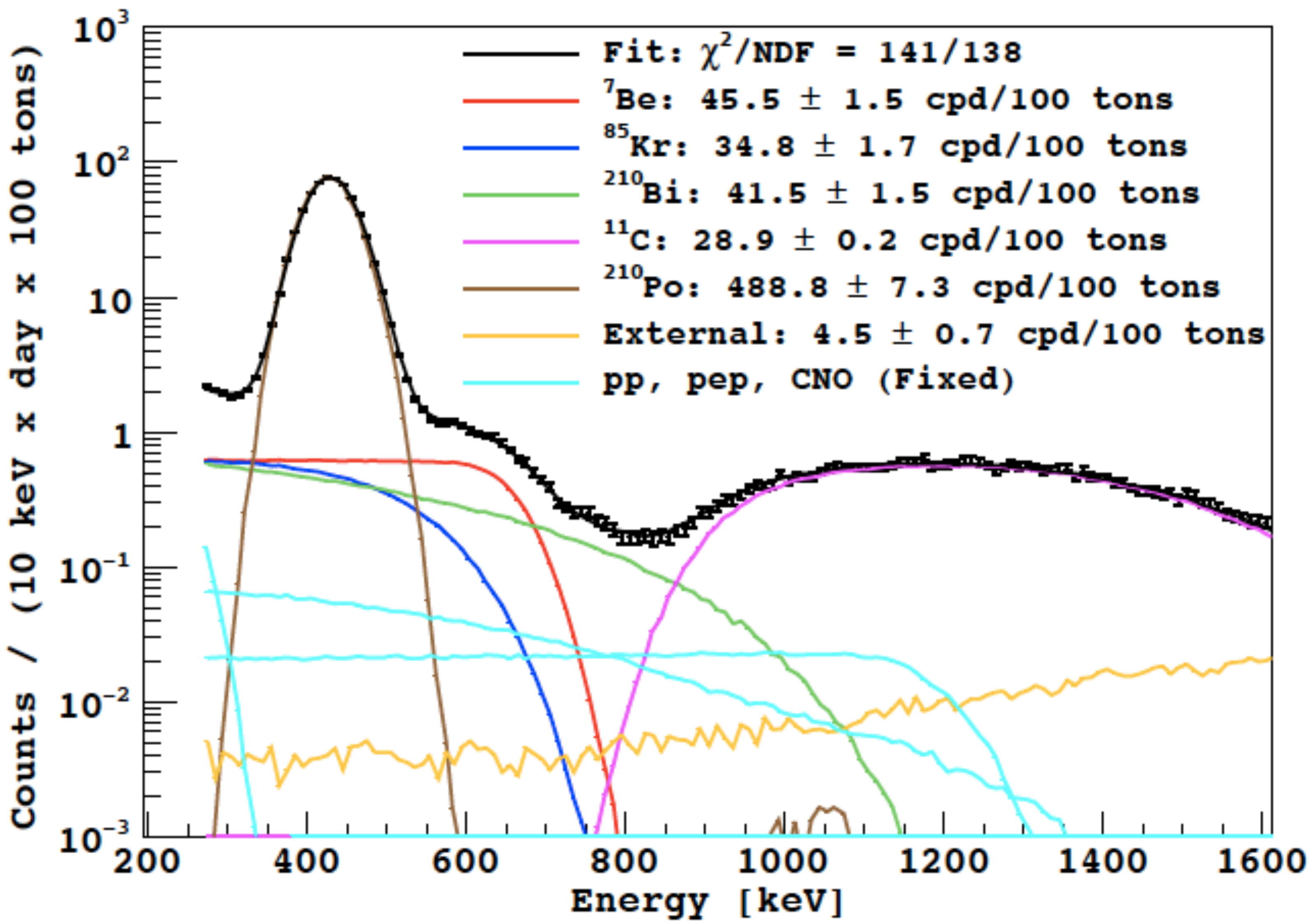


Systematic and Final Result

Estimated 1σ Systematic Uncertainties* [%]

Source	[%]
Trigger efficiency and stability	<0.1
Live time	0.04
Scintillator density	0.05
Sacrifice of cuts	0.1
Position reconstruction	$^{+1.3}_{-0.5}$
Energy scale	2.7
Fit consistency	1.7
Fit methods	1.0
Total Systematic Error	$^{+3.6}_{-3.4}$

Expected interaction rate in absence of oscillations:
74±5 cpd/100 tons

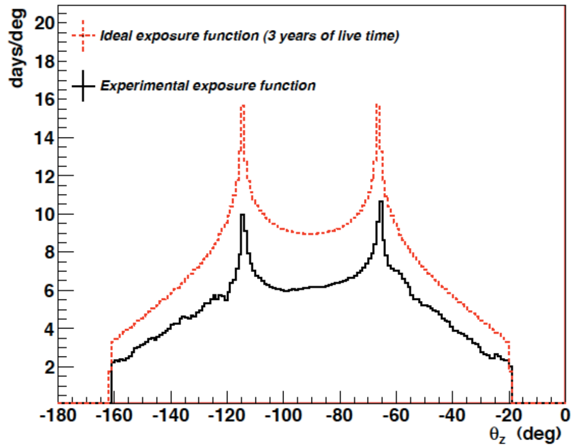
for LMA-MSW oscillations:
48±4 cpd/100 tons:

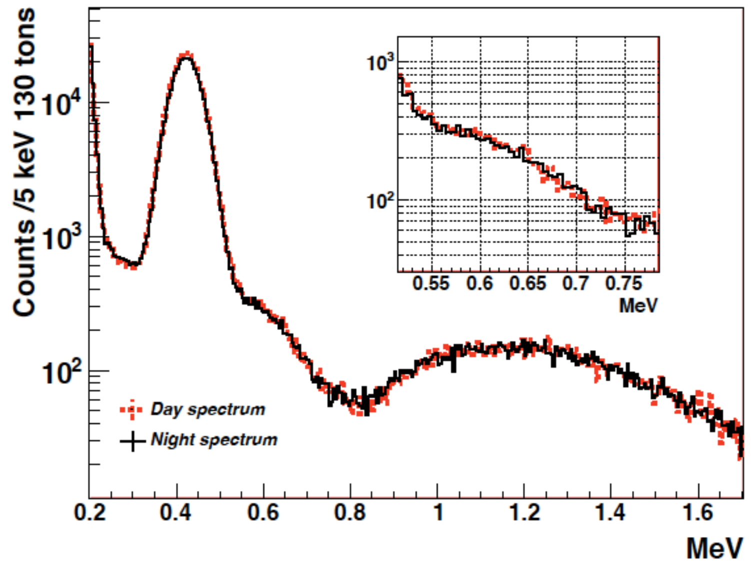
^{7}Be Rate: $46.0 \pm 1.5_{stat}\,{}^{+1.6}_{-1.5\,syst}$ cpd/100 tons , which means:

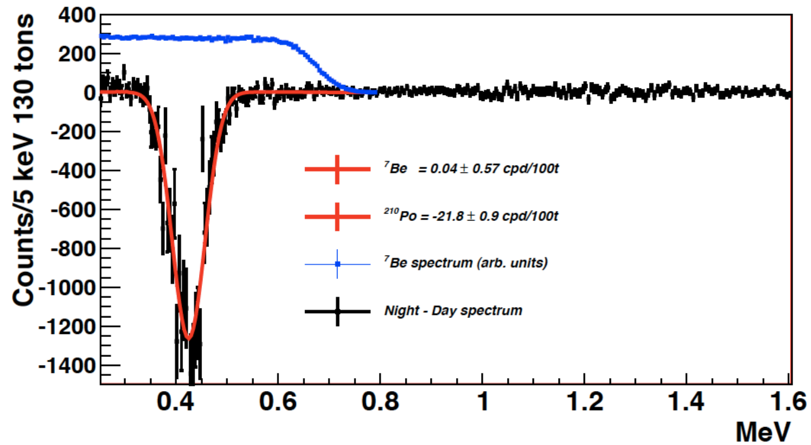
$f_{Be} = 0.97 \pm 0.05$ and $P_{ee} = 0.52^{+0.07}_{-0.06}$

Day Night Effect

Exposure: 760 days



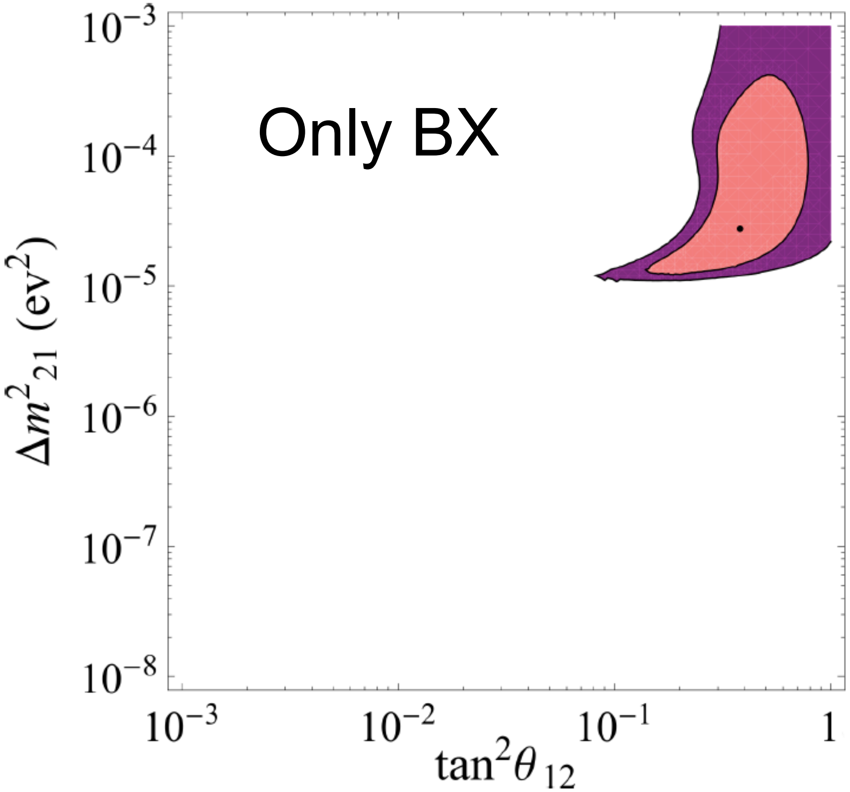


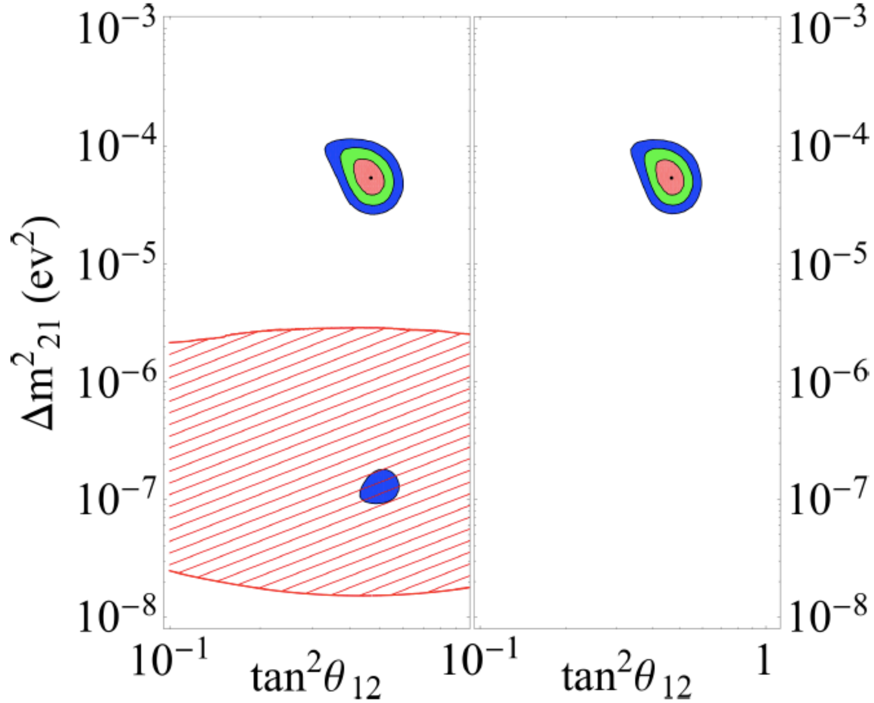


$$A_{dn} = 2\,\frac{R_N - R_D}{R_N + R_D}$$

A_{dn} = 0.001 +-0.012 (stat) +- 0.007 (syst)

Day Night Effect





All solar without Bx

All solar with Bx

Neutrino Magnetic Moment

Neutrino-electron scattering is the most sensitive test for μ_ν search

$$\left(\frac{d\sigma}{dT}\right)_W = \frac{2G_F^2 m_e}{\pi}\left[g_L^2 + g_R^2\left(1-\frac{T}{E_\nu}\right)^2 - g_L g_R \frac{m_e T}{E_\nu^2}\right]$$

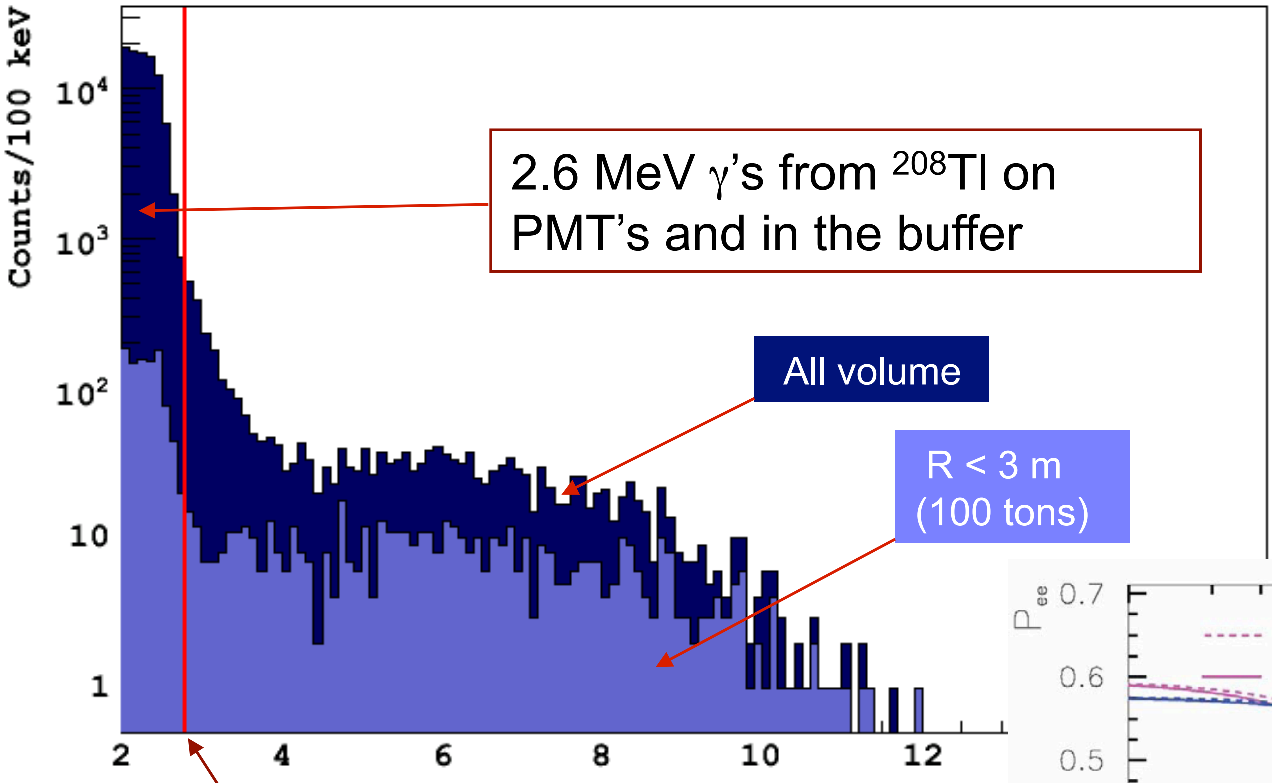
EM current affects cross section: spectral shape sensitive to μ_ν sensitivity enhanced at low energies (c.s.≈ 1/T)

$$\left(\frac{d\sigma}{dT}\right)_{EM} = \mu_\nu^2 \frac{\pi\alpha_{em}^2}{m_e^2}\left(\frac{1}{T}-\frac{1}{E_\nu}\right)$$

A fit is performed to the energy spectrum including contributions from ^{14}C, leaving μ_ν as free parameter of the fit

Estimate	Method	10^{-11} μ_B
SuperK	^8B	<11
Montanino et al.	^7Be	<8.4
GEMMA	Reactor	<5.8
Borexino	^7Be	<5.4

^8B neutrinos with the lowest threshold: 3 MeV

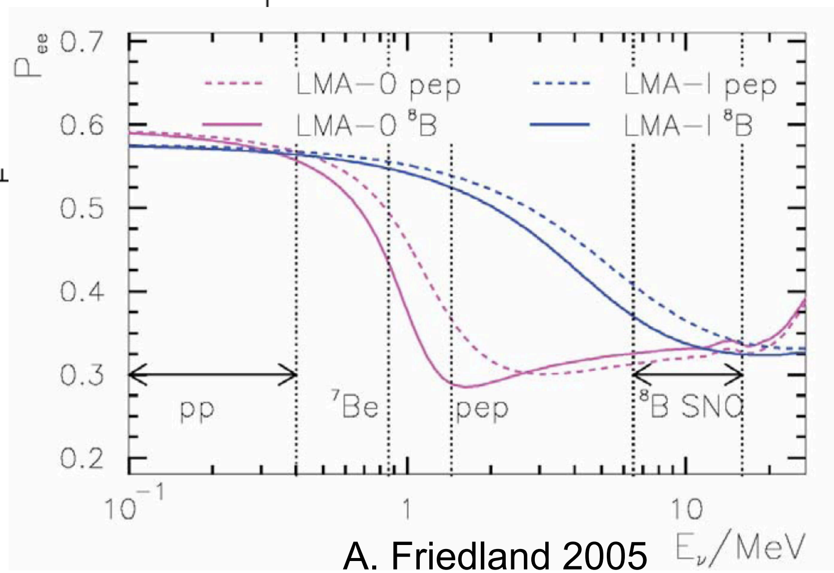


Energy spectrum in Borexino (after μ subtraction)

> 5σ distant from the 2.6 MeV γ peak

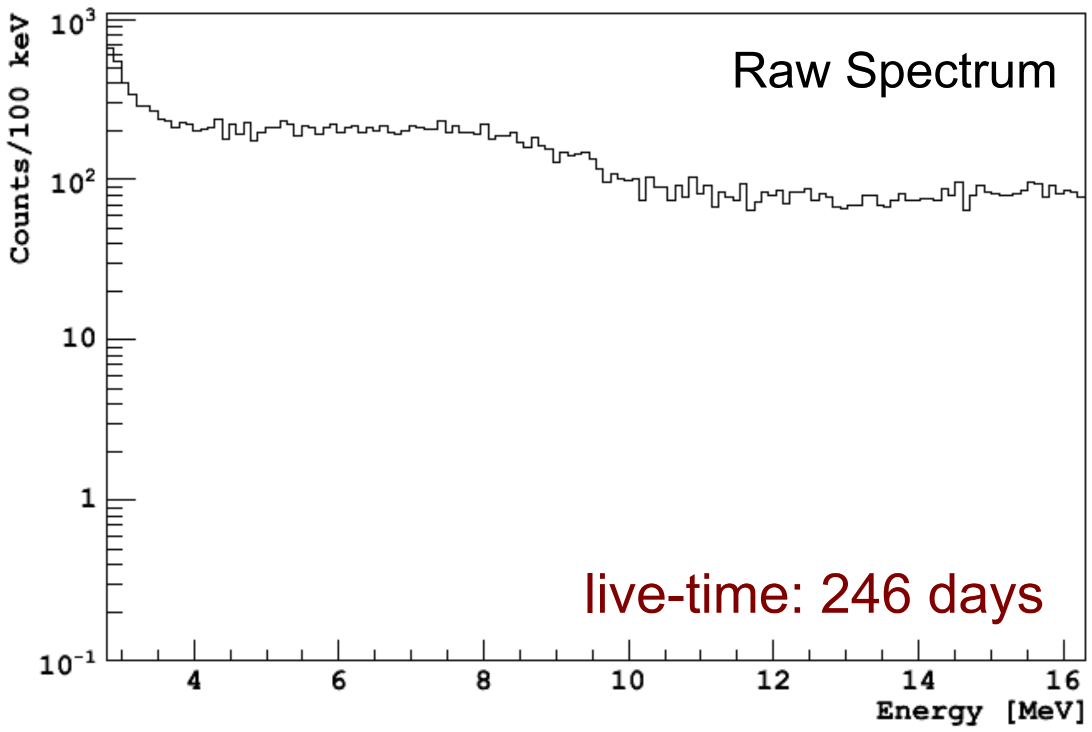
Expected ^8B ν rate in 100 tons of liquid scintillator above 3.0 MeV:

0.26±0.03 c/d/ 100 tons



A. Friedland 2005

Background in the 3-16.3 MeV range



- ✓ Cosmic Muons
- ✓ External background
- ✓ High energy gamma's from neutron captures
- ✓ ^{208}Tl and ^{214}Bi from radon emanation from nylon vessel
- ✓ Cosmogenic isotopes
- ✓ ^{214}Bi and ^{208}Tl from ^{238}U and ^{232}Th bulk contamination

Count-rate: 1500 c/d/100 ton

S/B ratio < 1/6000!!!

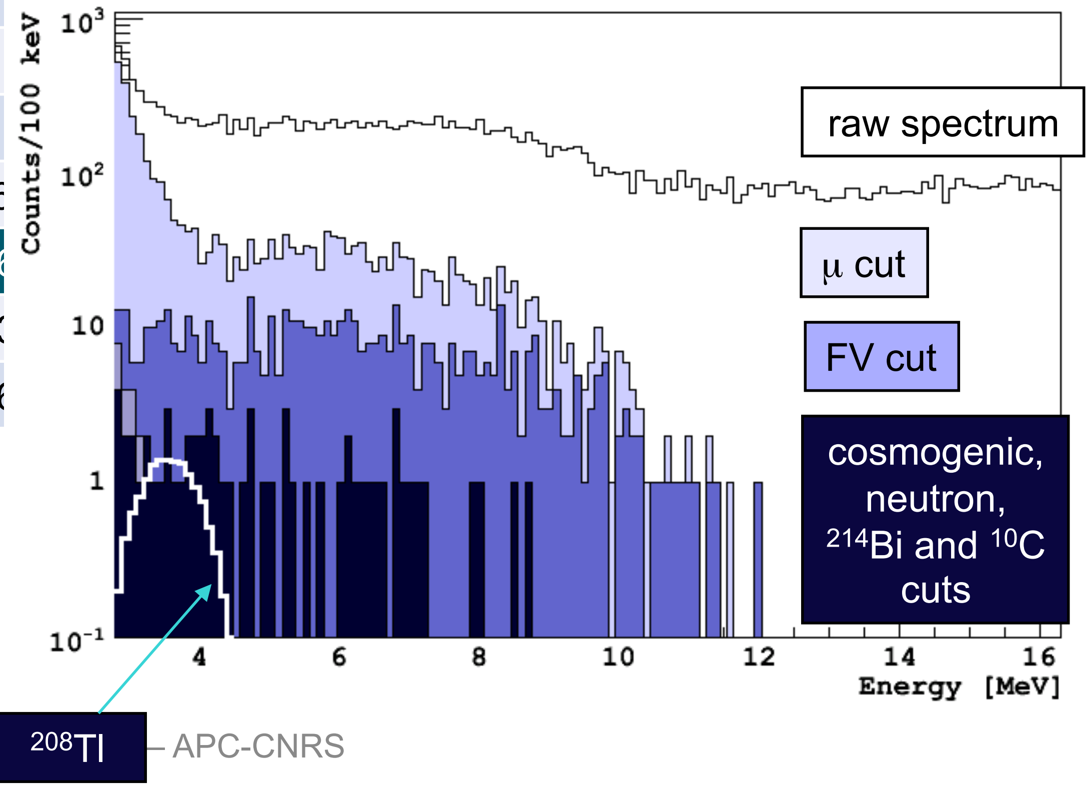
Summary of the Cuts and Systematic

Cut	Counts 3.0-16.3 MeV	Counts 5.0-16.3 MeV
None	1932181	1824858
Muon cut	6552	2679
FV cut	1329	970
Cosmogenic cut	131	
^{10}C removal	128	
^{214}Bi removal	119	
^{208}Tl and ^{11}Be sub.	75 ± 13	46
Measured ^{8}B-ν	75 ± 13	46
BPS09(GS98) ^{8}B-ν	86 ± 10	43
BPS09(AGS05) ^{8}B-ν	73 ± 7	36

✓Systematic errors:

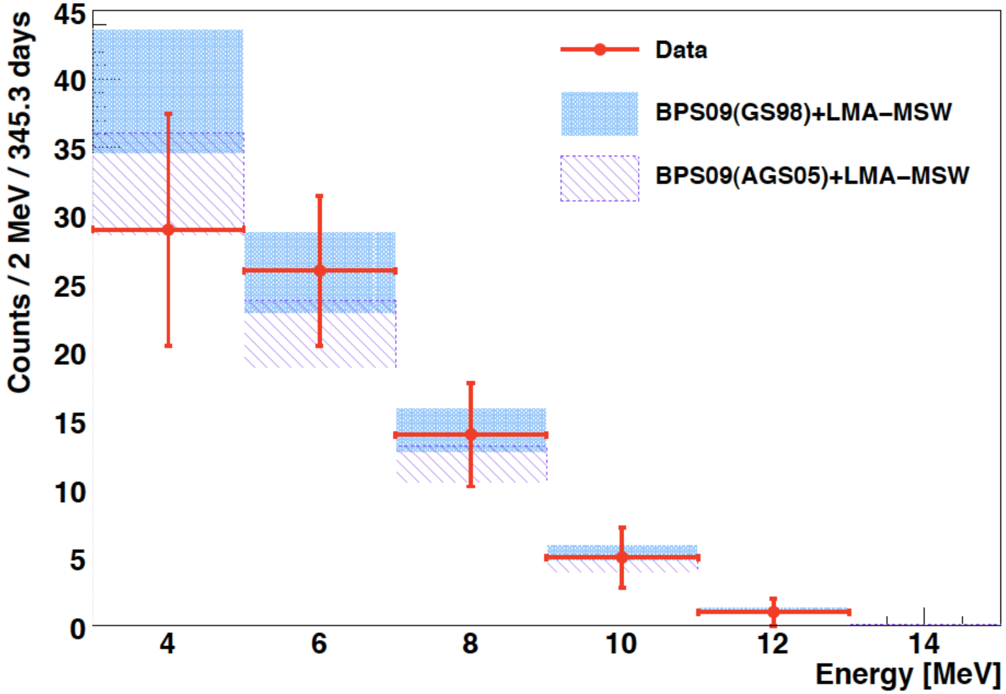
✓ 3.8% from the determination of the fiducial mass

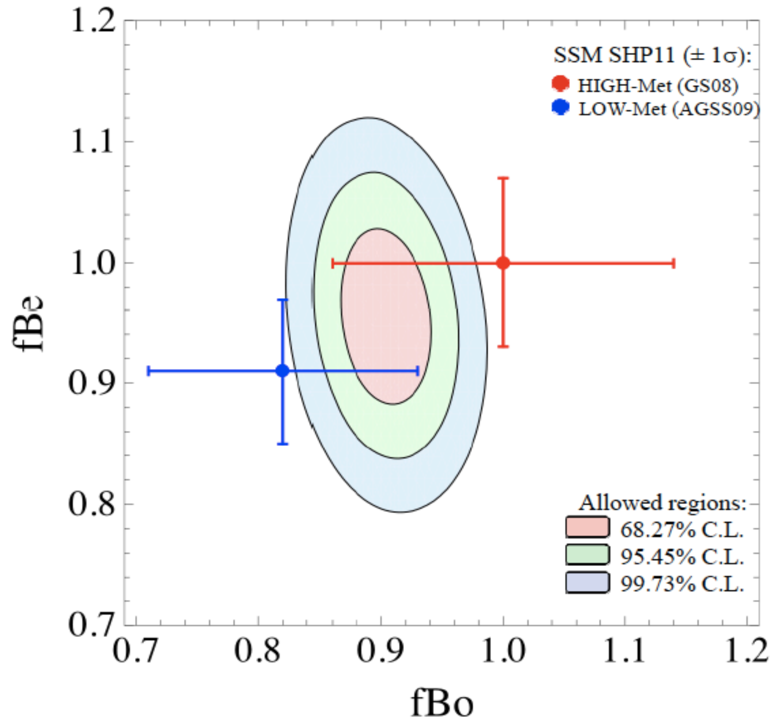
✓ 3.5% (5.5%) uncertainty in the ^{8}B rate above 3.0 MeV (5.0 MeV) from the determination of the light yield (1%)



*MSW-LMA: $\Delta m^2=7.69\times10^{-5}$ eV^2, $\tan^2\theta=0.45$

The ^8B ν spectrum





Neutrino oscillation is confirmed **at 4.2 σ**, including the theoretical uncertainty (10%) on the ^8B flux from the Standard Solar Model

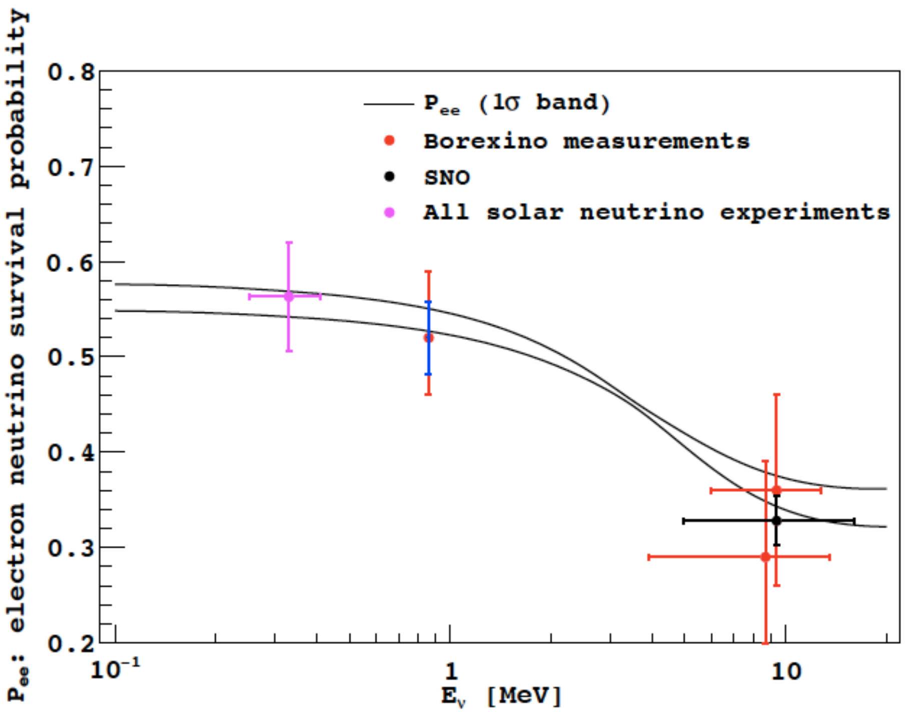
Electron Neutrino Survival Probability

$\overline{P}_{ee}$ is **defined** such that:

R: measured rate
E_ν and T_e: neutrino and recoiled electron energies
T_0 = 2.8 MeV: energy threshold

E_0 = 3.0 MeV: minimum neutrino energy at T_0
N_e: number of target electrons
σ_x ($x=e,\mu-\tau$): elastic cross sections

$$R = \int_{T_e>T_0} dT_e \int_{E_\nu>E_0} dE_\nu \left(\overline{P}_{ee} \cdot \frac{d\sigma_e}{dT_e}(E_\nu,T_e) + (1-\overline{P}_{ee}) \cdot \frac{d\sigma_{\mu\text{-}\tau}}{dT_e}(E_\nu,T_e)\right) N_e \cdot \frac{d\Phi_e}{dE_\nu}(E_\nu)$$

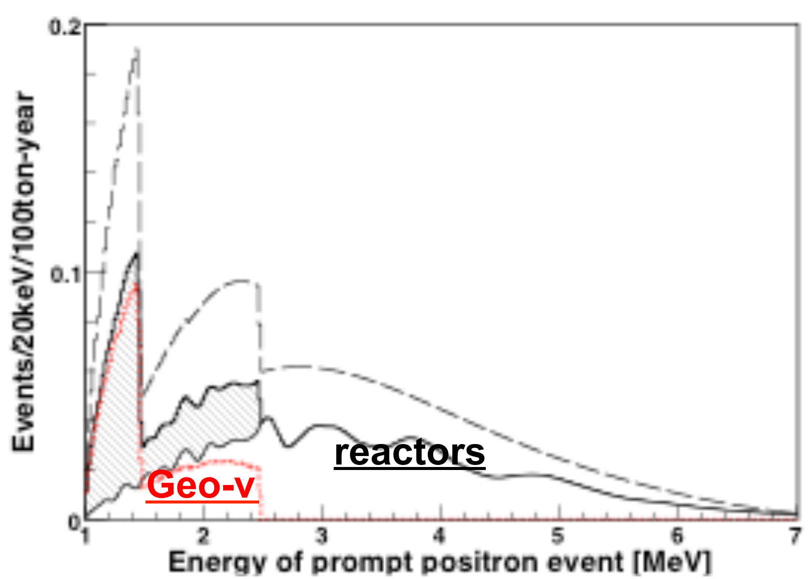


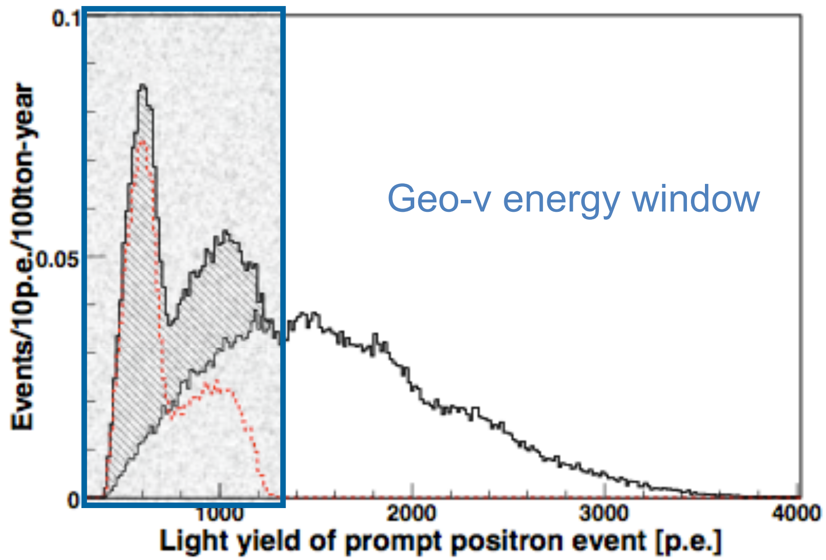
$\overline{P}_{ee}(^8B)$ = 0.29 ± 0.10 (8.6 MeV)

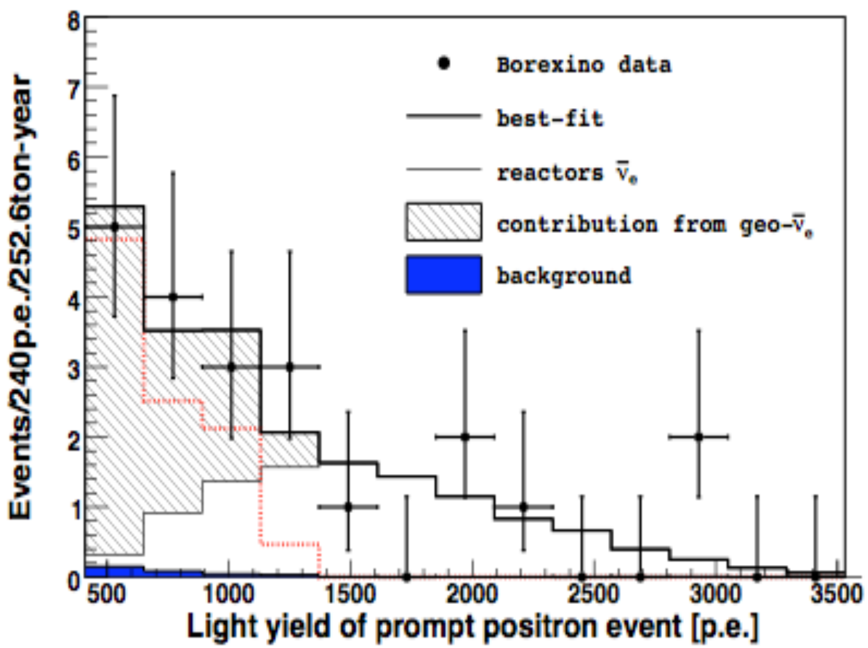
$P_{ee}(^7Be)$ = 0.52 +0.07 -0.06 (0.862 MeV)

For the first time, we confirm at 1.9 σ, using data from a single detector, the presence of a transition between the low energy vacuum-driven and the high-energy matter-enhanced solar neutrino oscillations, in agreement with the prediction of the MSW-LMA solution for solar neutrinos

Geoneutrinos







USED IN THE UNBINNED MAXIMUM LIKELIHOOD FIT OF THE DATA

68.3 % 99.7%

$$N_{geo} = 9.9^{+4.1\ +14.6}_{-3.4\ \ -8.2}$$

Null hypothesis rejected at 4.2σ

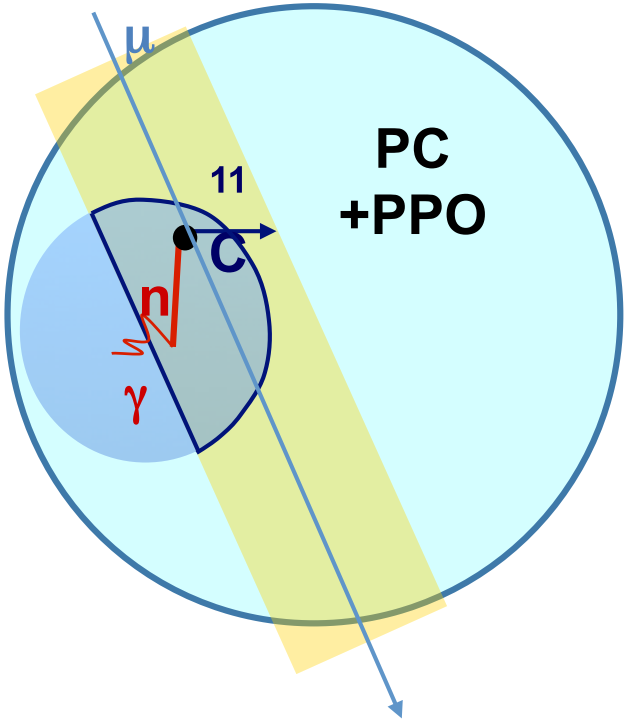
What next?

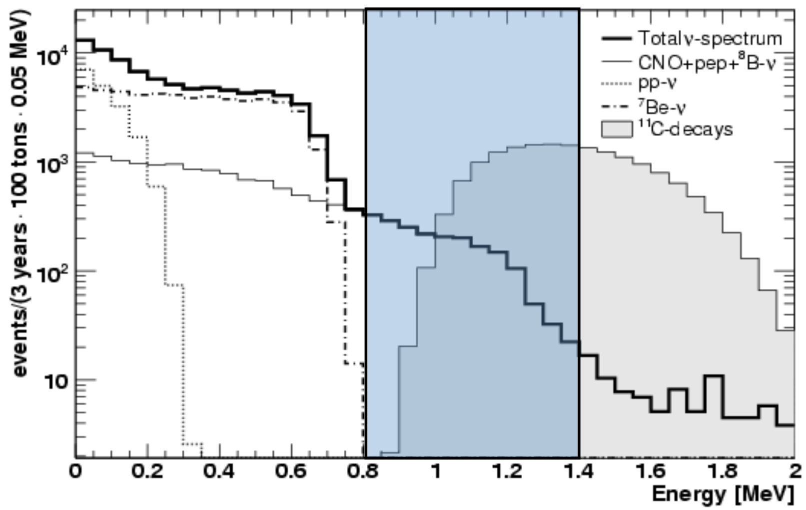
pep and CNO neutrinos

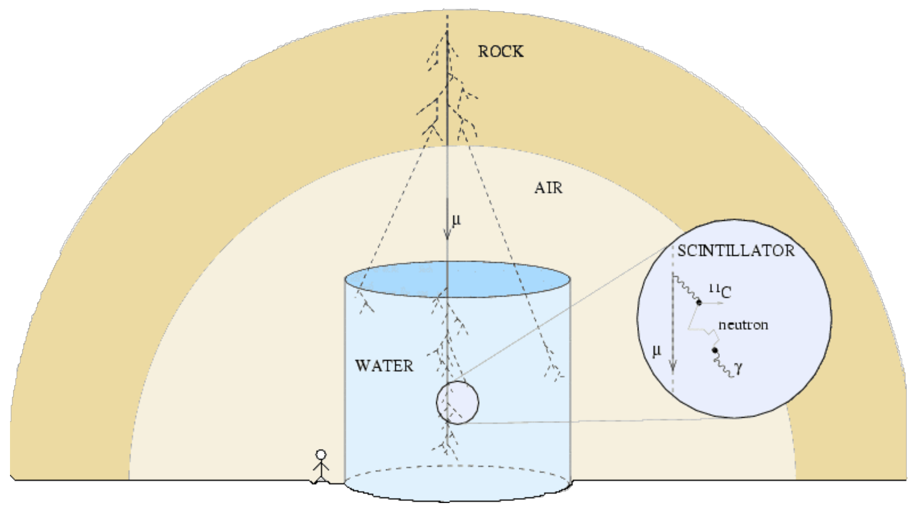
μ (+ secondaries) + $^{12}C \rightarrow \mu$ (+ secondaries) + ^{11}C + n

$n + p \rightarrow d + \gamma$

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

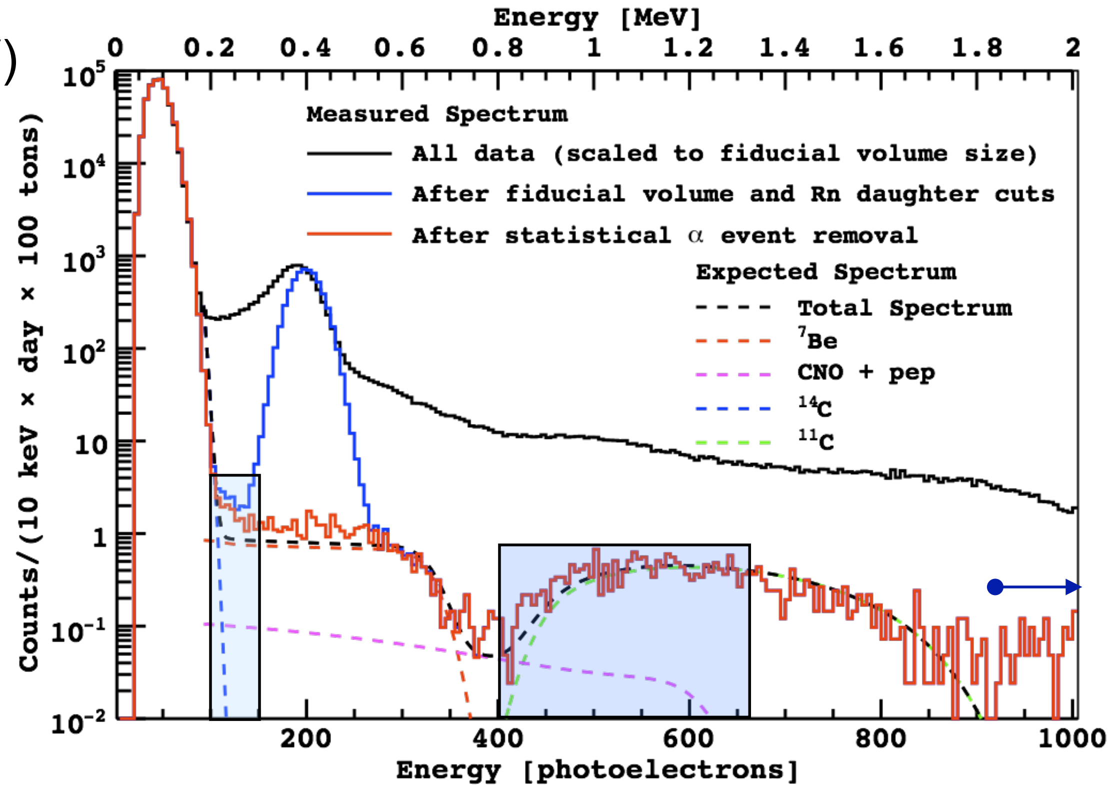




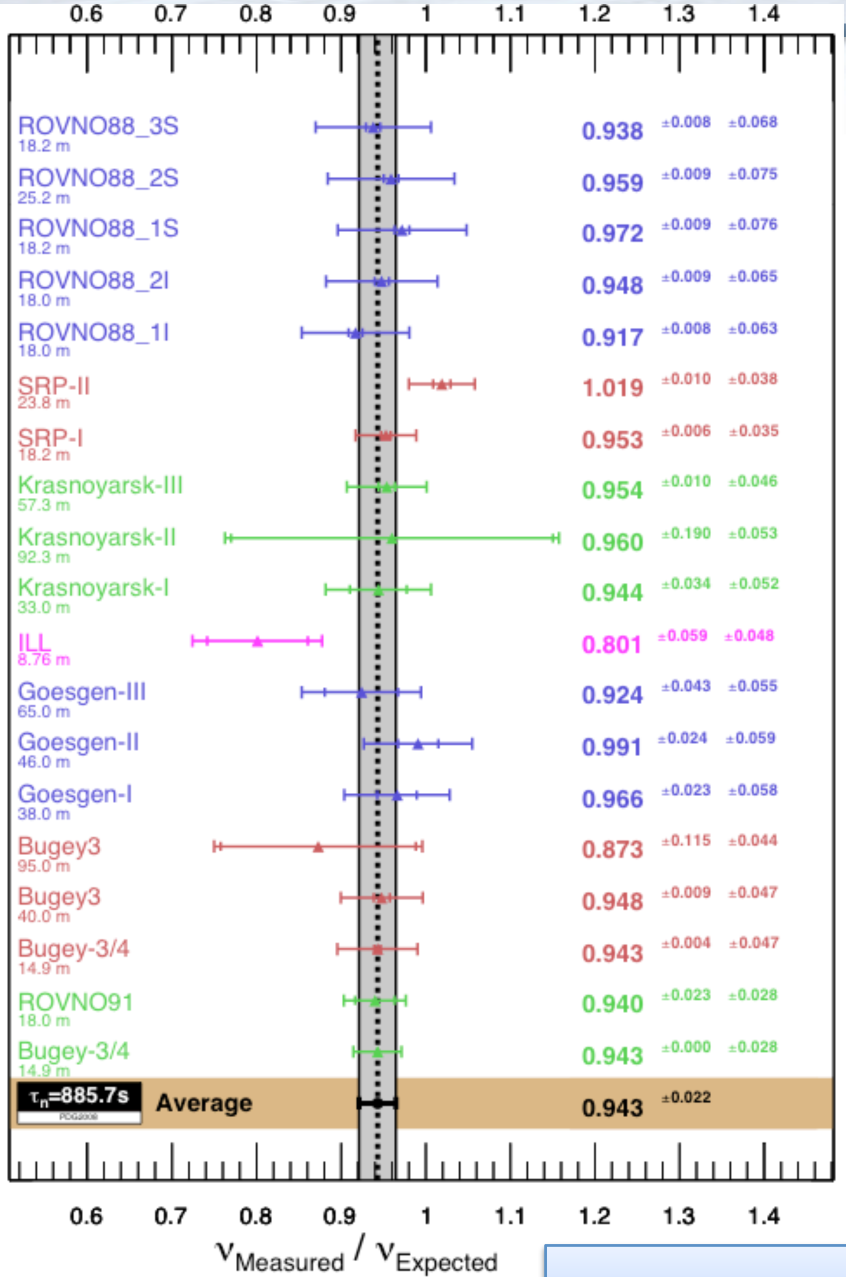


Summary of the present and future goals

- ✓ ***pep*** and **CNO** ν fluxes
  - ✓ software algorithm based on a three-fold coincidence analysis to subtract efficiently cosmogenic ^{11}C background
  - ✓ Muon track reconstruction
- ✓ ^{8}**B** at low energy region (3-5 MeV)
- ✓ **pp** neutrinos
  - ✓ seasonal variations
  - ✓ ^{14}C subtraction
- ✓ **geoneutrinos**
- ✓ ^{7}**Be** with errors < 5%
  - ✓ Systematic reduction
  - ✓ Calibrations



The reactor anti-neutrino anomaly



The synthesis of published experiments at reactor-detector distances ≤ 100 m leads to a ratio R of observed event rate to predicted rate of

0.979 ± 0.029.

With our **new flux** evaluation, this ratio shifts to

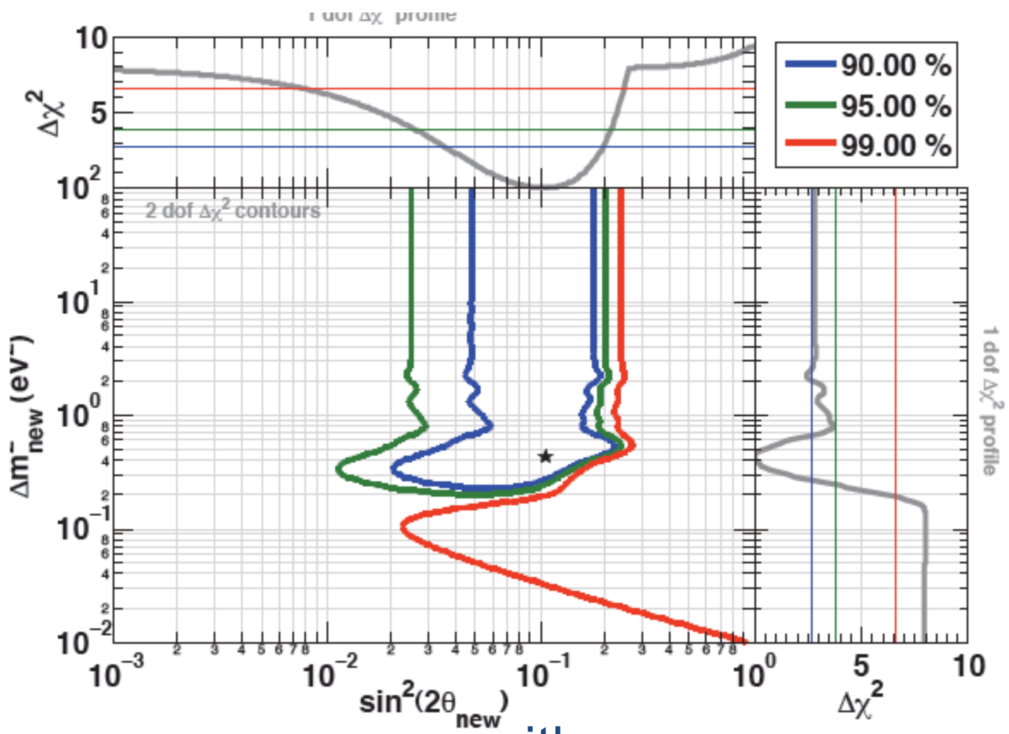
0.943 ± 0.023,

leading to a deviation from unity at 98.4% C.L.

From G. Mention presentation at SPP

Beyond Solar Neutrino: sterile neutrinos?

Fit from the Reactor Neutrino Anomaly paper

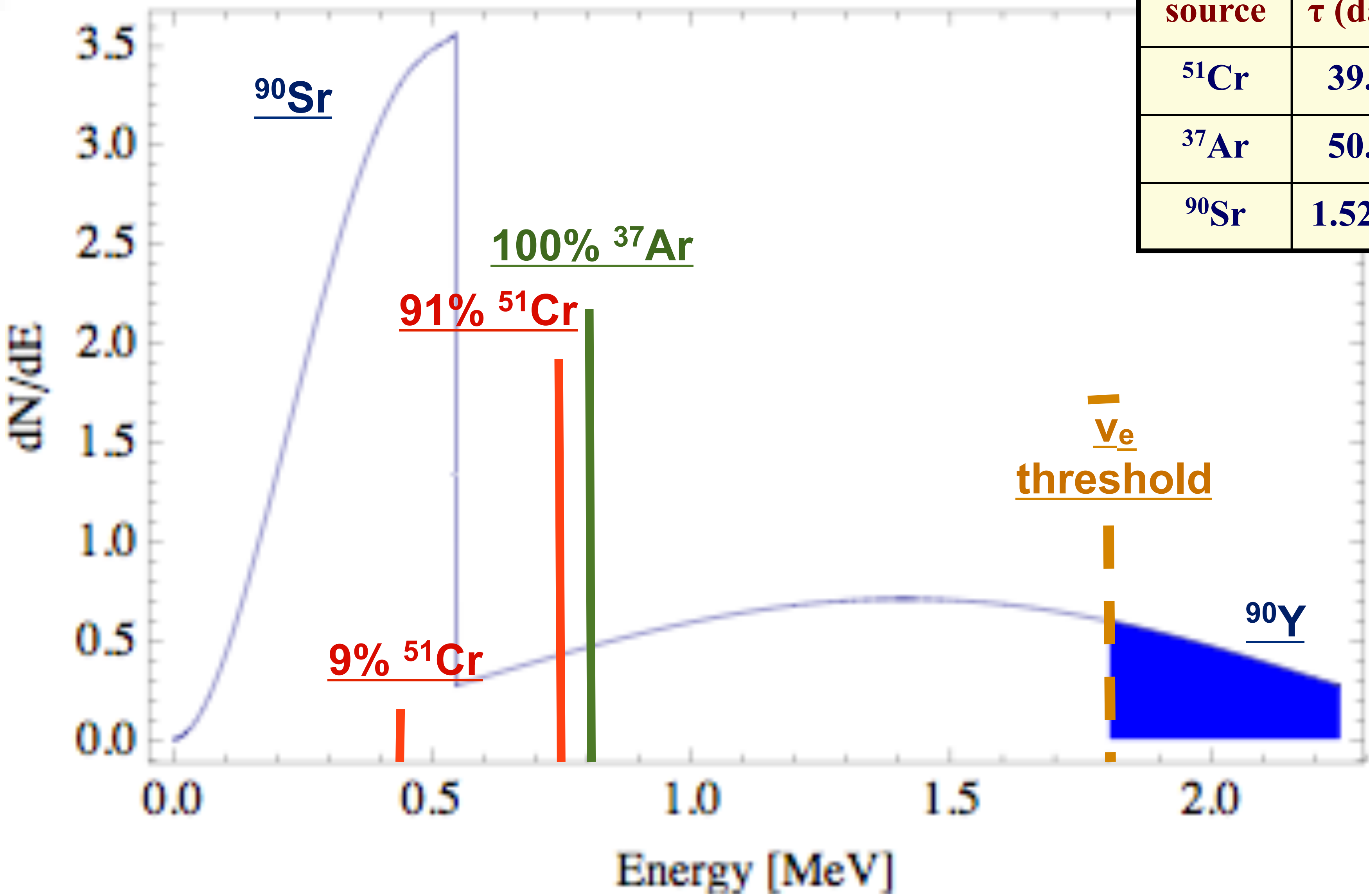


with

$\Delta m^2 \approx 1\ eV^2$ $\sin^2(2\vartheta_s) \approx 0.1$

oscillation lengths at MeV of the order of **1 m**

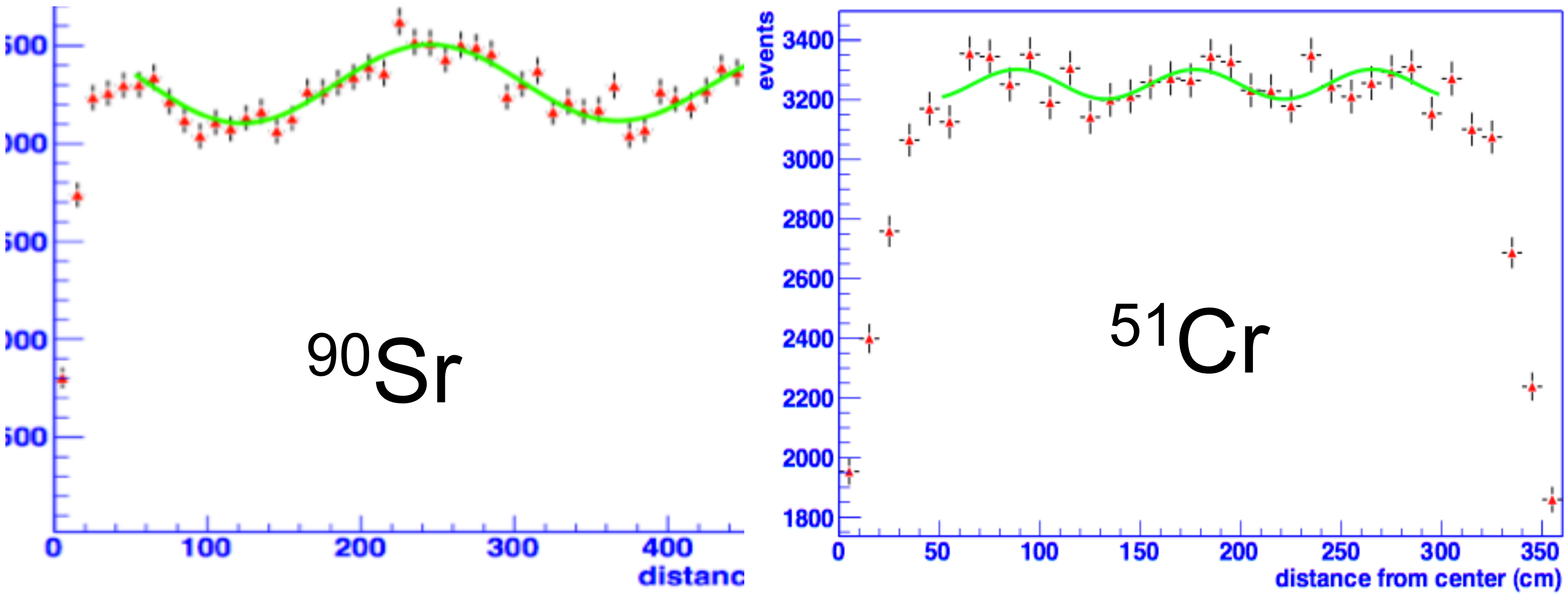
Neutrino source candidates



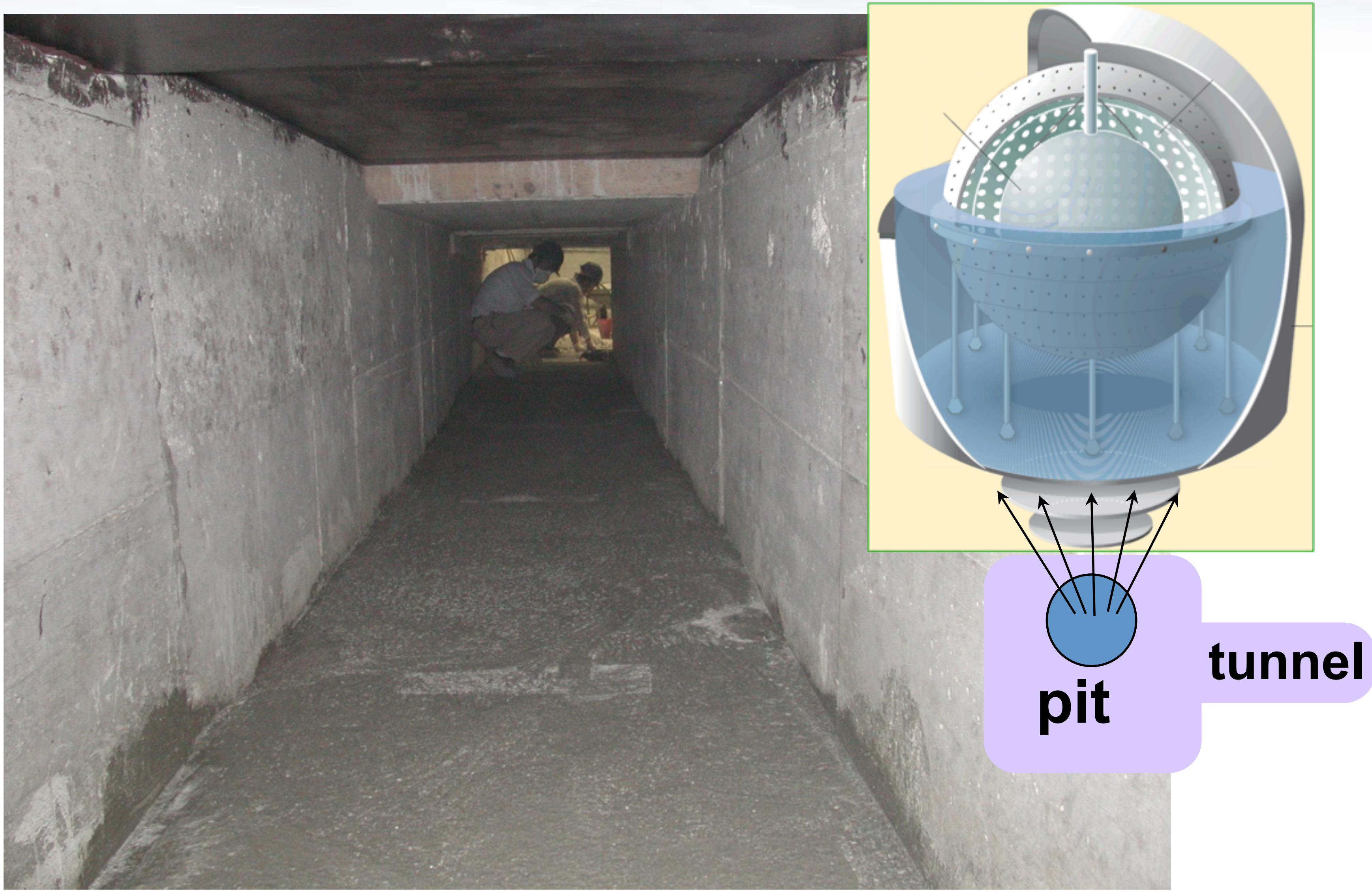
source	τ (days)
^{51}Cr	39.96
^{37}Ar	50.55
^{90}Sr	1.52 E4

Examples: ^{90}Sr and ^{51}Cr in the center

- **5 MCi 51Cr** and **1 MCi 90Sr** sources in the **center** of Borexino
- 3.3 m F.V. radius **$\Delta m^2 = 2\ eV^2$** **$\sin^2(2\vartheta_s) = 0.10$**



The Icarus pit



A few numbers

Source	Location		
	Icarus Pit	Water Tank	Center
^{51}Cr 5 MCi R=3.3 m	7131	10047	129255
^{51}Cr 10 MCi R=3.3 m	14262	20094	258410
^{37}Ar 2.5 MCi R=3.3 m	6275	8850	113780
^{37}Ar 5 MCi R=3.3 m	12550	17700	227560
^{90}Sr 1 MCi 1y R=4.25 m	17596	25095	187626
^{90}Sr 1 MCi 1y R=6m	56002	79868	265000
^{90}Sr 1 MCi 1y R=6m	162006	238804	795000

Conclusion

- ✓ Borexino opened the study of the solar neutrinos in real time below the barrier of natural radioactivity (5 MeV)
  - ✓ Two measurements reported for **^{7}Be** neutrinos
  - ✓ Best limits for ***pp*** and **CNO** neutrinos, combining information from SNO and radiochemical experiments
  - ✓ Opportunities to tackle ***pep*** and **CNO** neutrinos in direct measurement
  - ✓ First observation of **^{8}B** neutrino spectrum below 5 MeV
- ✓ First observation of **geoneutrino**
- ✓ Borexino is a powerful observatory for neutrinos from **Supernovae** explosions within few tens of kpc
- ✓ Best limit on neutrino **magnetic moment**. Improve by dedicated measurement with ^{51}Cr neutrino source
- ✓ Potential in **sterile neutrinos**

- ✓ …and do not forget the technological success of the **high-radiopurity** scintillator!