Solar neutrino spectroscopy and oscillation with Borexino

LPNHE
November 17, 2011 – Paris

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APC-CNRS

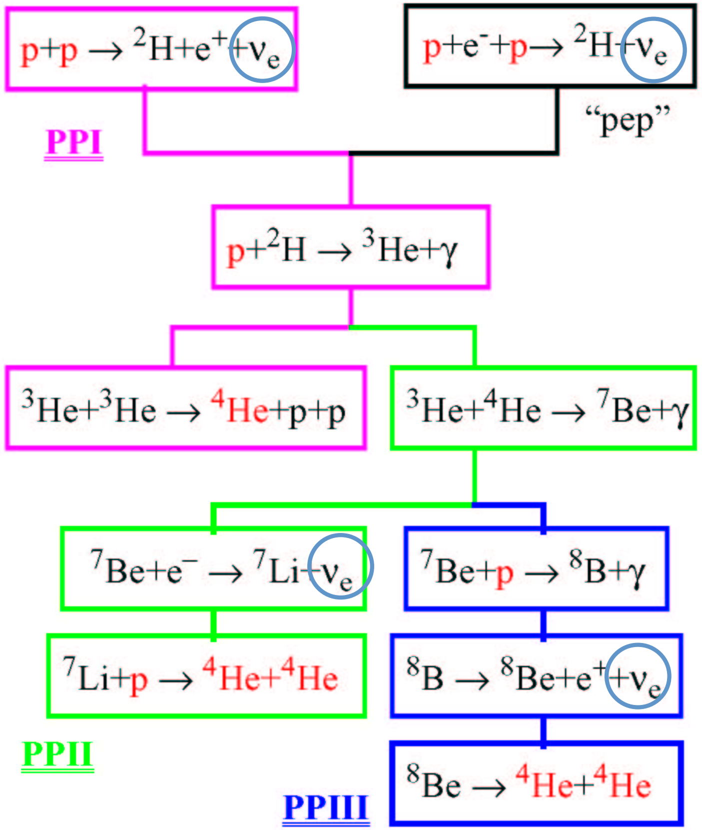
Outline

- ✓ The Solar neutrino physics
- ✓ The physics of Borexino
- ✓ The detector
- ✓ **The "radio-purity" challenge**
- ✓ **The reached goals (^{7}Be, ^{8}B, pep and geo-ν, day/night, ...)**
- ✓ Future goals in the Solar sector
- ✓ Sterile neutrinos, superluminal (?)

Neutrino Production In The Sun

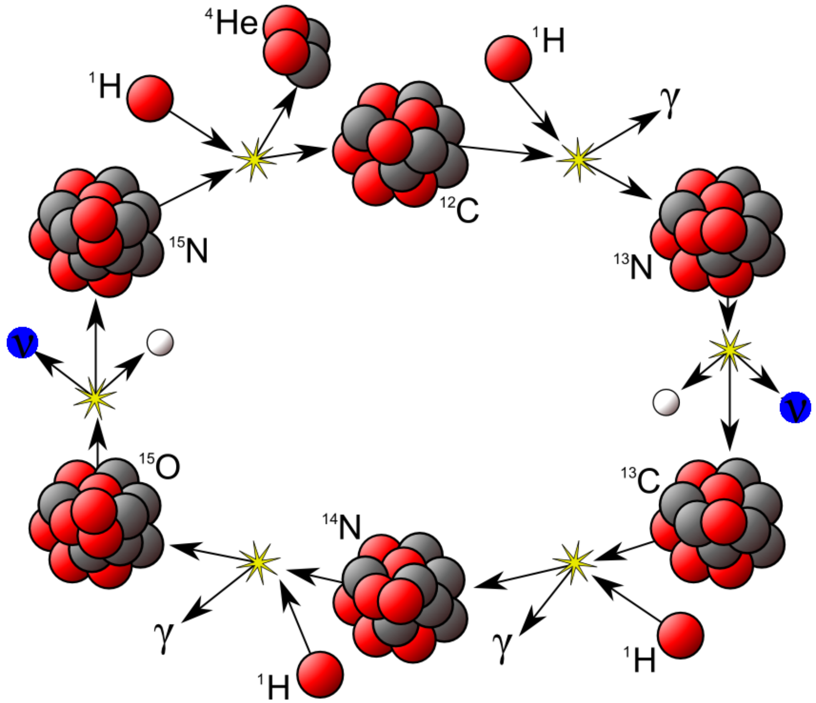
pp chain:

pp, *pep*, ^{7}Be, *hep* ,and ^{8}B ν

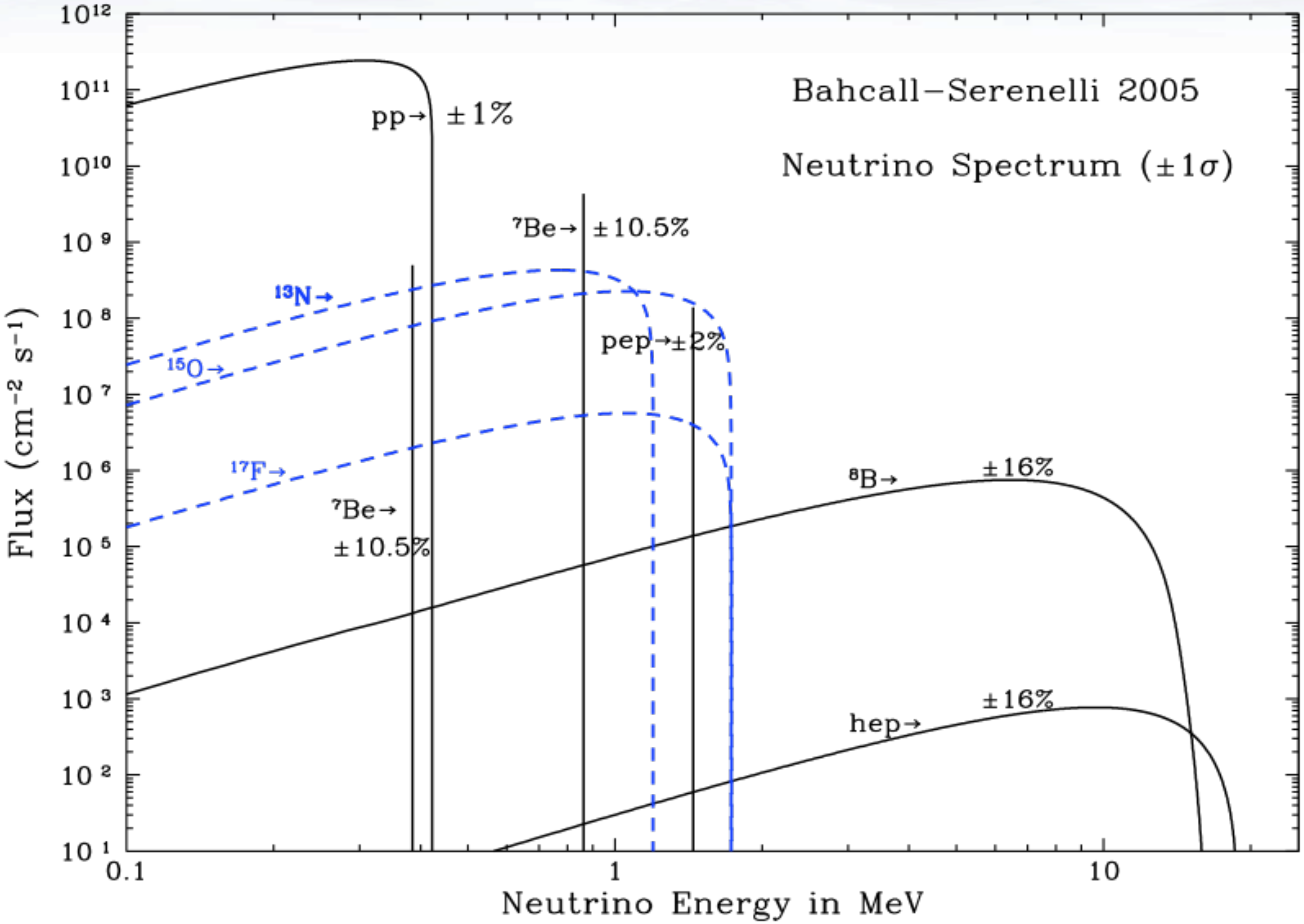


CNO cycle:

^{13}N, ^{15}O, and ^{17}F ν



Solar Neutrino Spectra



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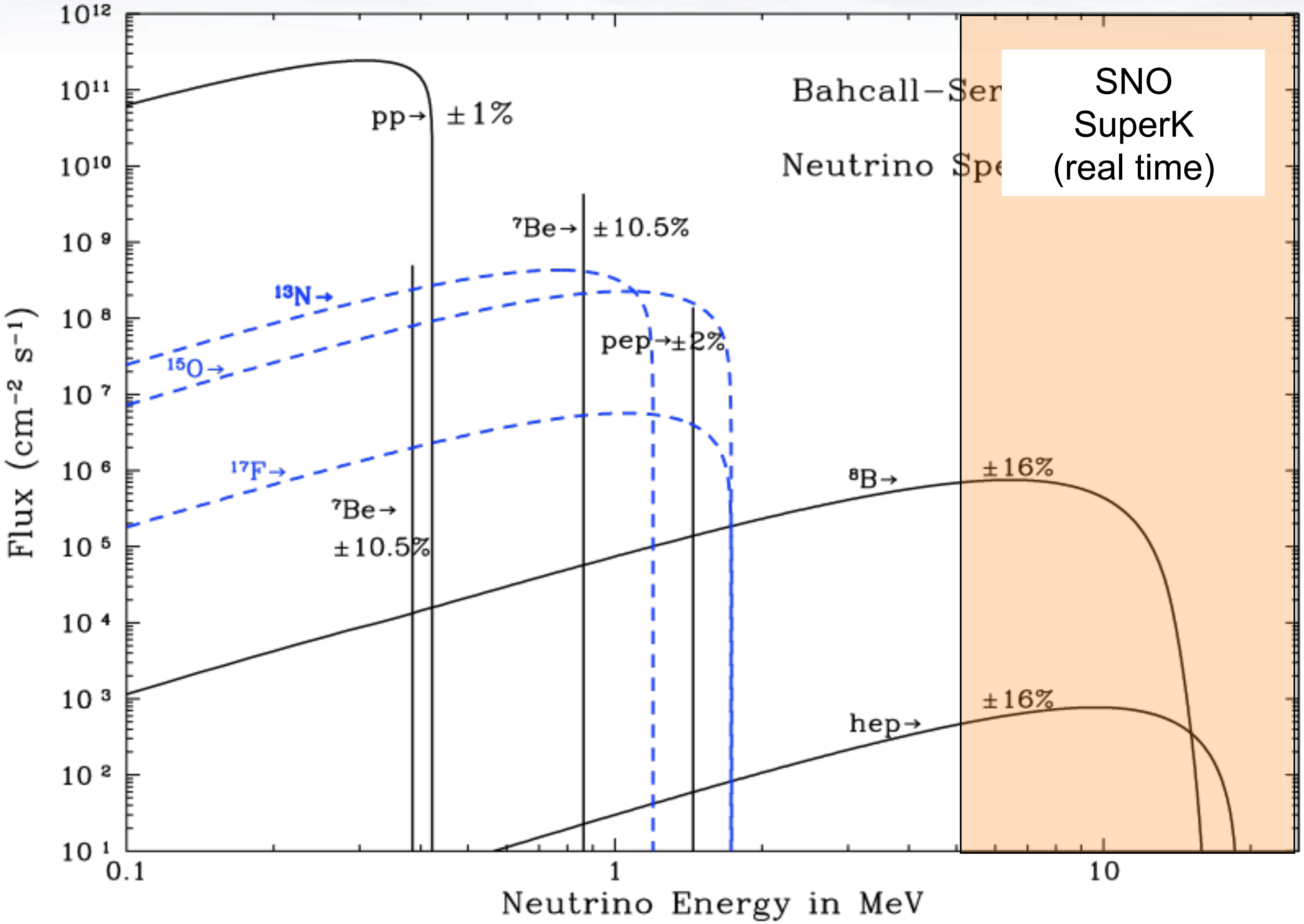

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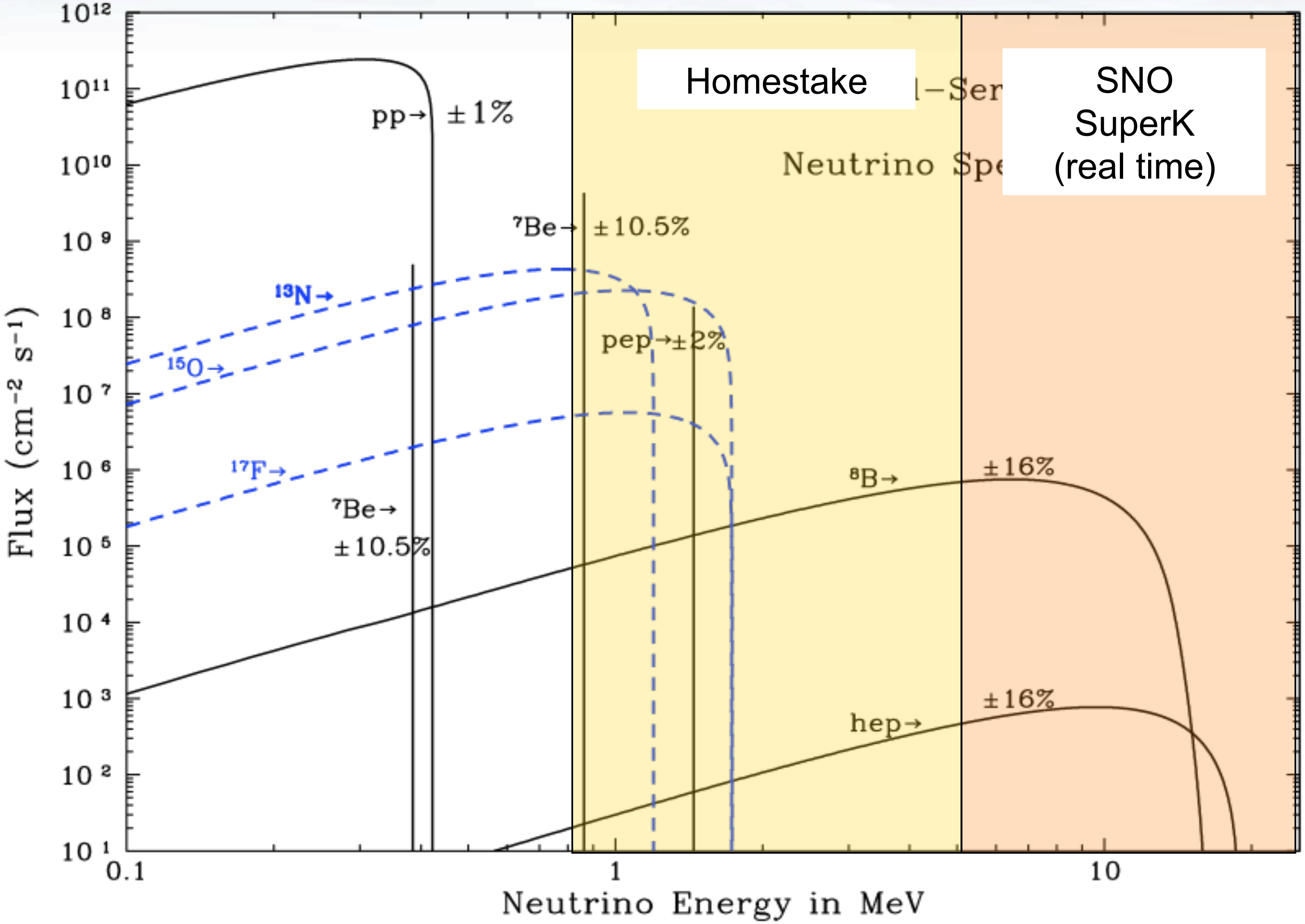

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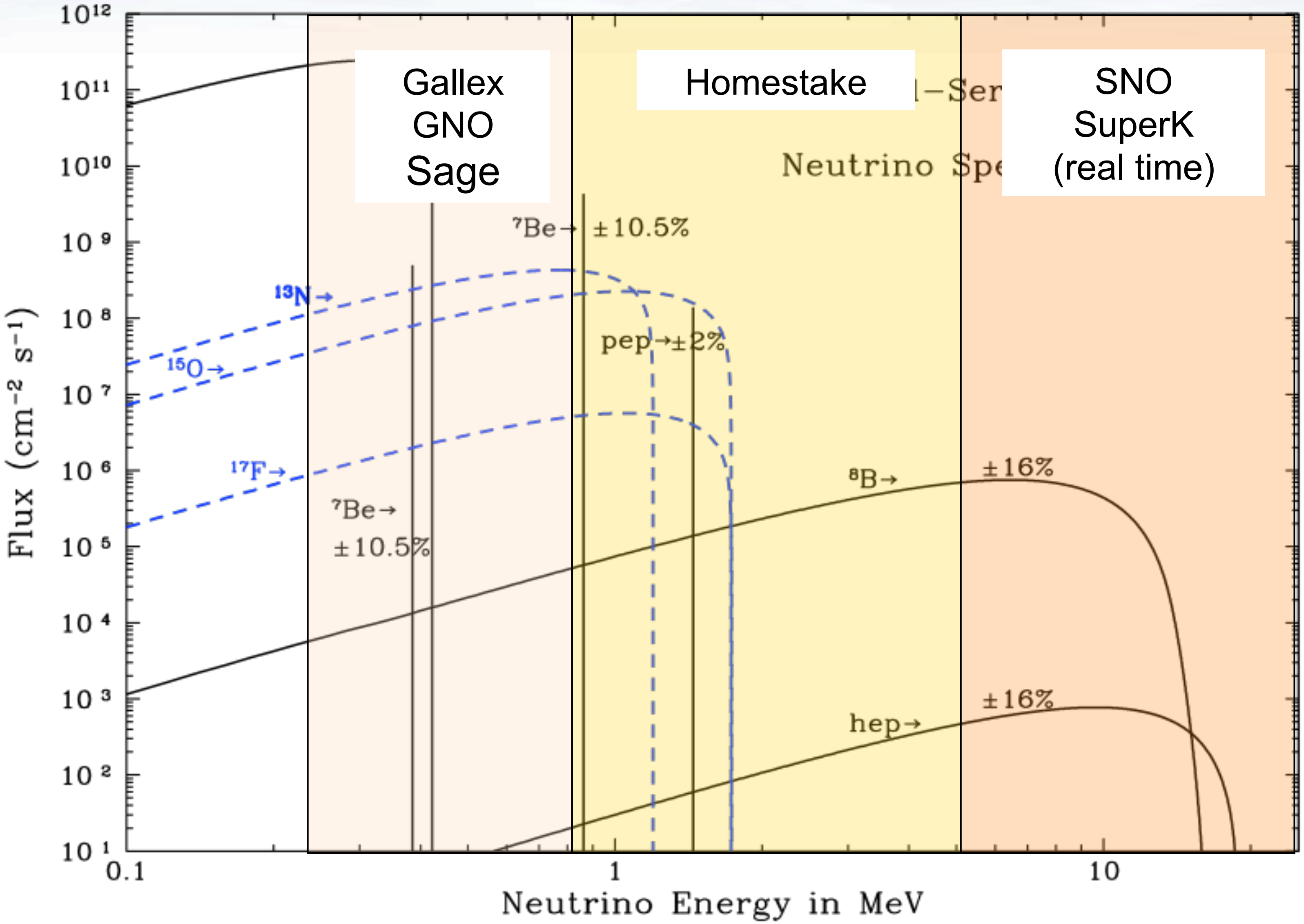

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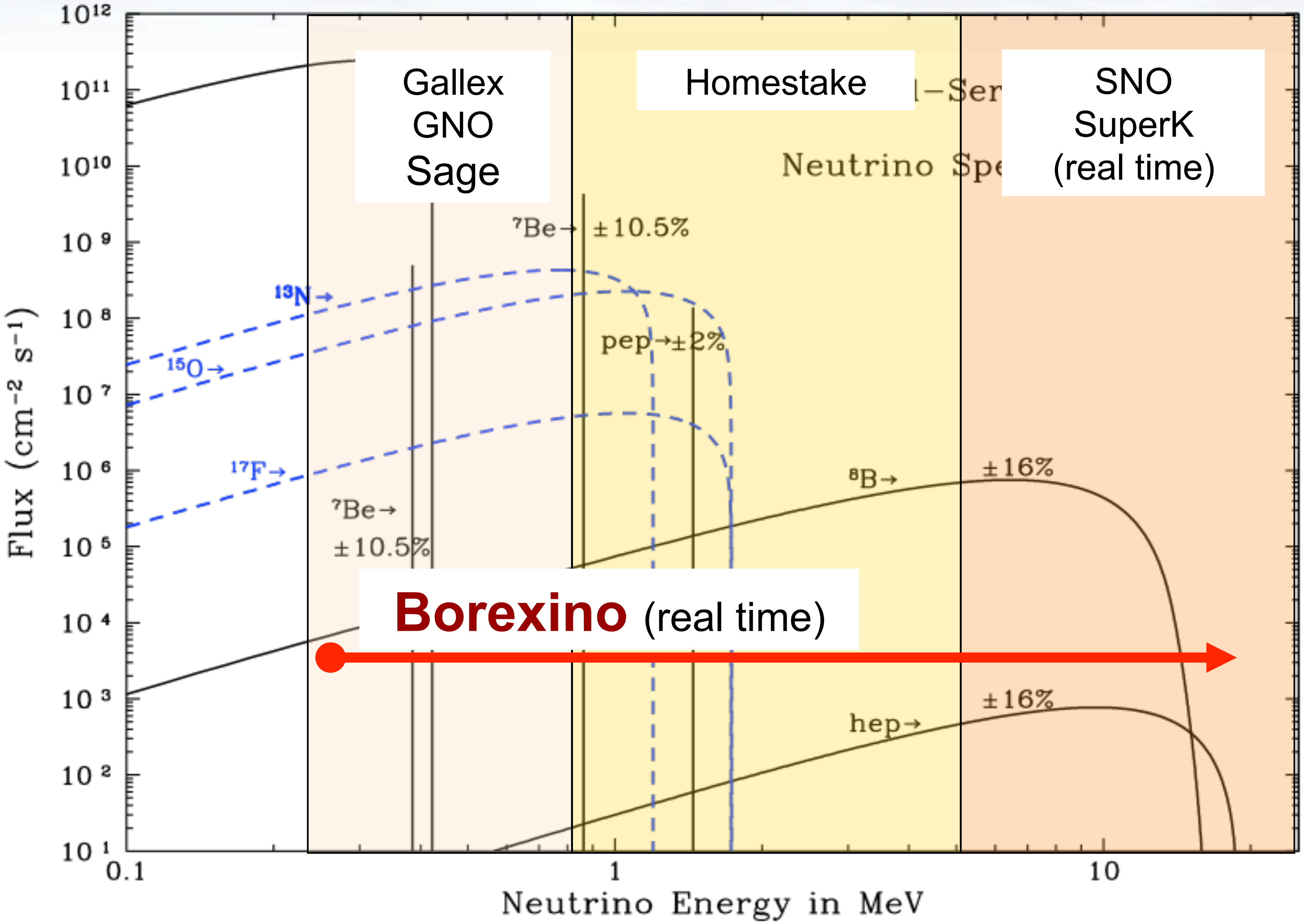
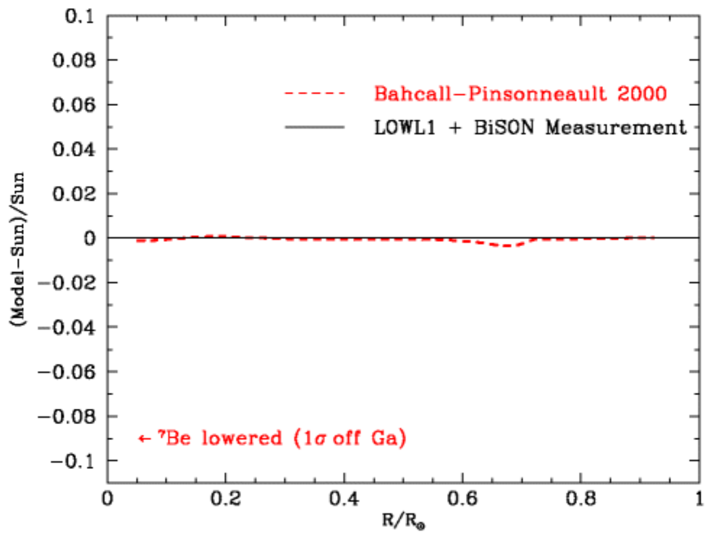


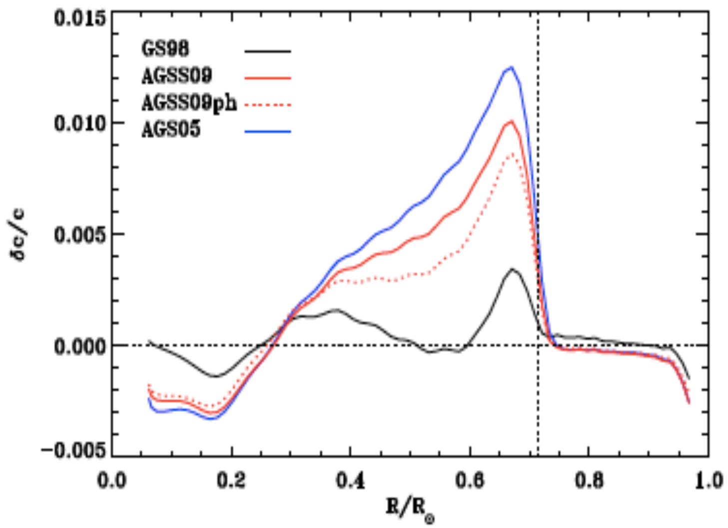
The Standard Solar Model before/after 2004

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.

< 2004



> 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

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 physics goals

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

✓ Balance between photon **luminosity** and neutrino luminosity of the Sun

X **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

X Tail end of ***pp* neutrino spectrum**

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

✓ **Day/night** effect

✓ Limit on the **neutrino magnetic moment**

✓ SNEWS network for **supernovae**

✓ Evidence (>3σ) of **geoneutrinos**

X **Sterile** neutrinos

X **Superluminal** neutrinos

✓ done
X in progress

Borexino Collaboration

Genova

Perugia

Milano

APC Paris

Princeton University

Virginia Tech. University

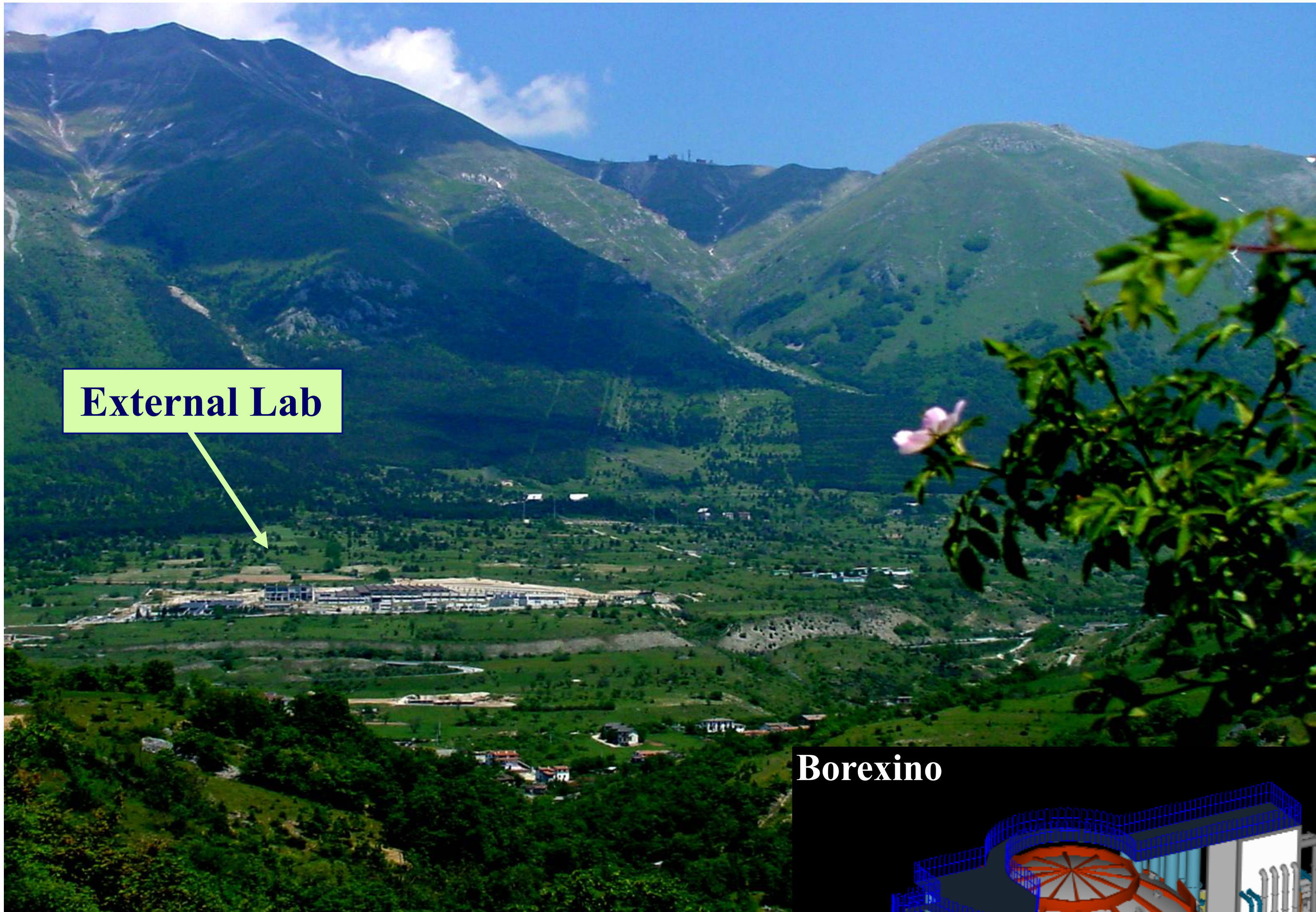
Dubna JINR
(Russia)

Kurchatov
Institute
(Russia)

Jagiellonian U.
Cracow
(Poland)

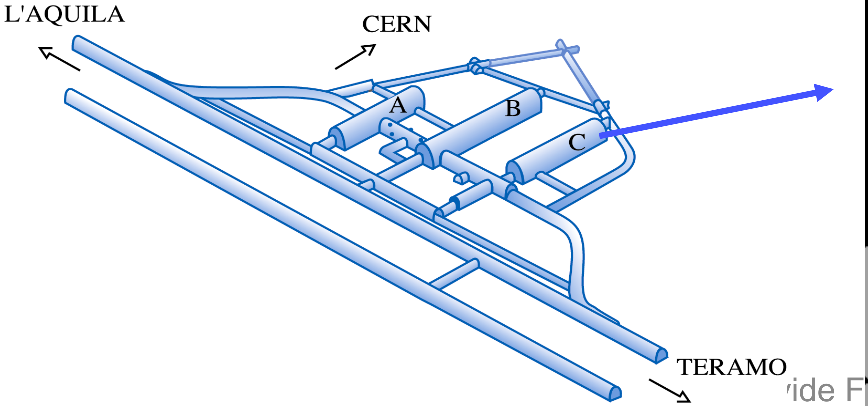
Heidelberg
(Germany)

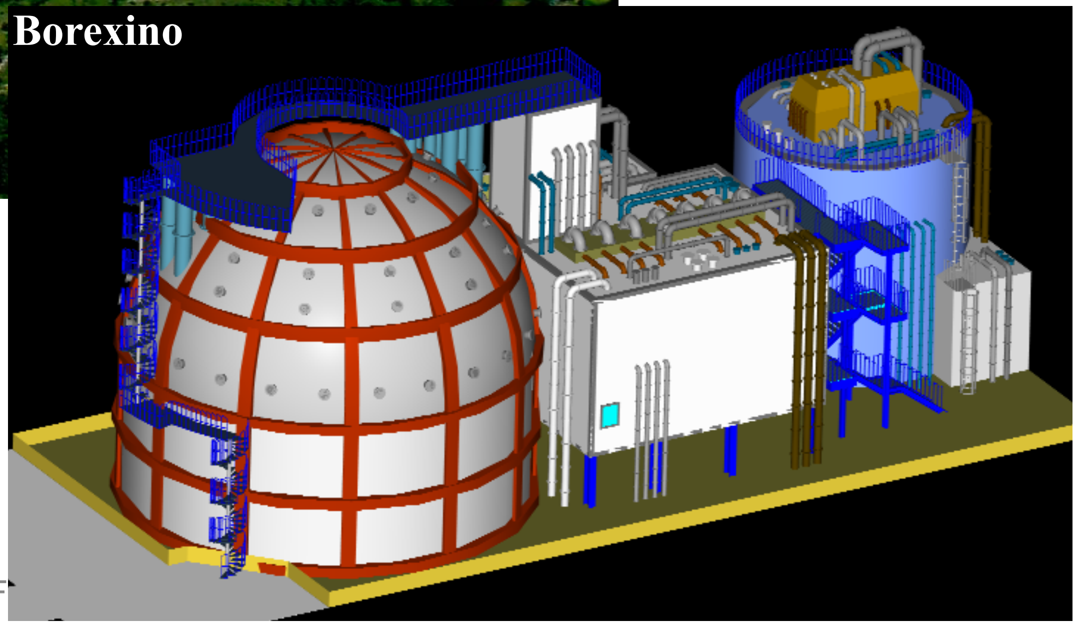
Munich
(Germany)



Laboratori Nazionali del Gran Sasso

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



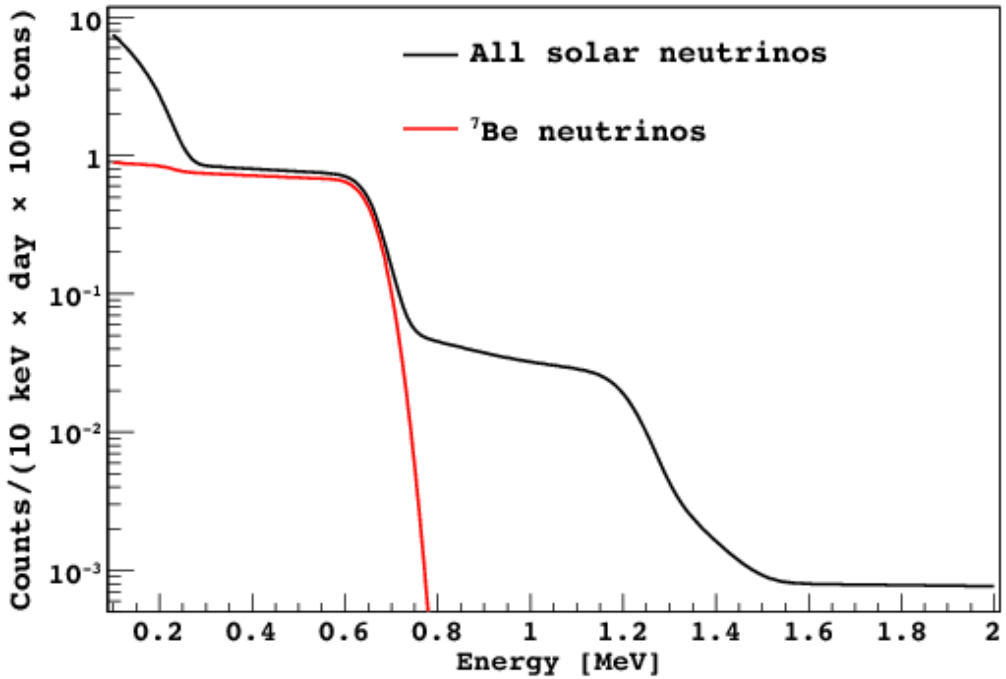


Detection principles and ν signature

- ✓ 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!

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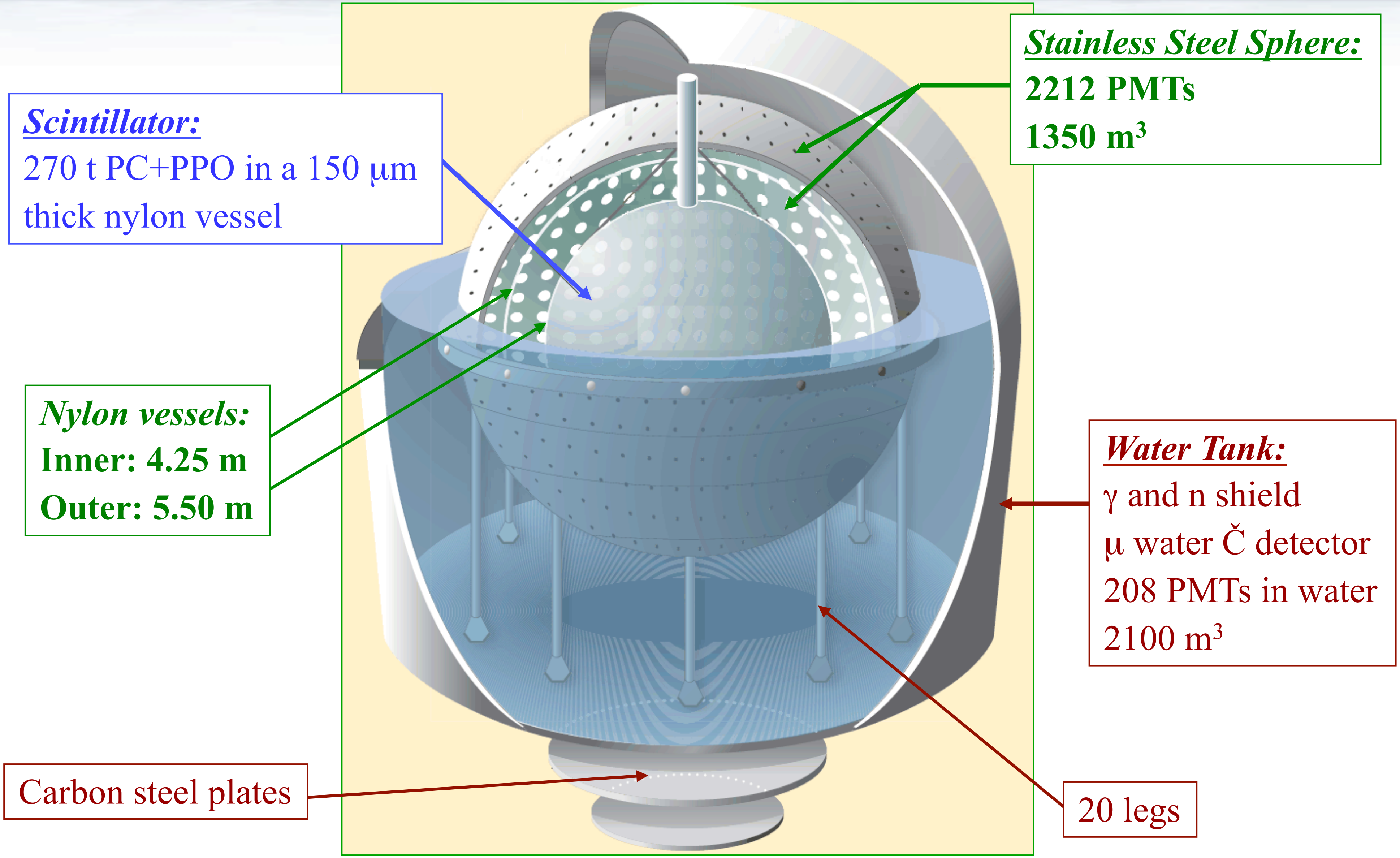
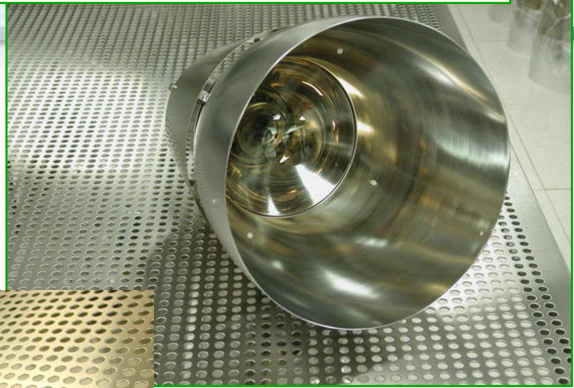
BX scintillator must be **9/10 order of magnitude less** radioactive than anything on earth!

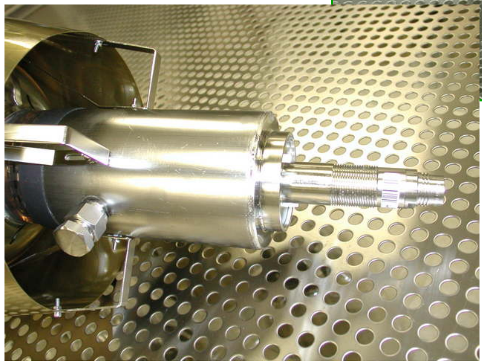
- **Low background nylon vessel** fabricated in hermetically sealed low radon clean room (~1 yr)
- **Rapid transport** of scintillator solvent (PC) from production plant to underground lab to avoid cosmogenic production of radioactivity (^{7}Be)
- Underground **purification plant** to distill scintillator 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

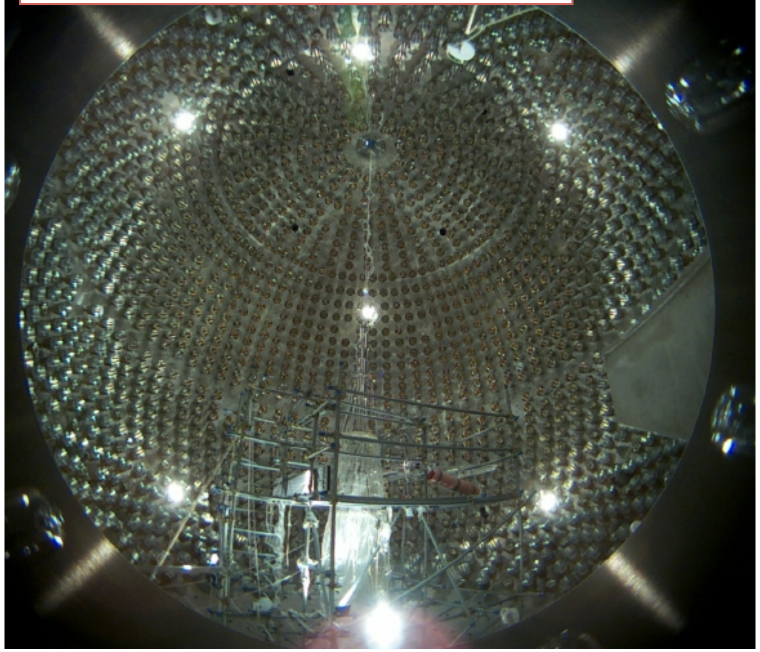


PMTs: PC & Water proof

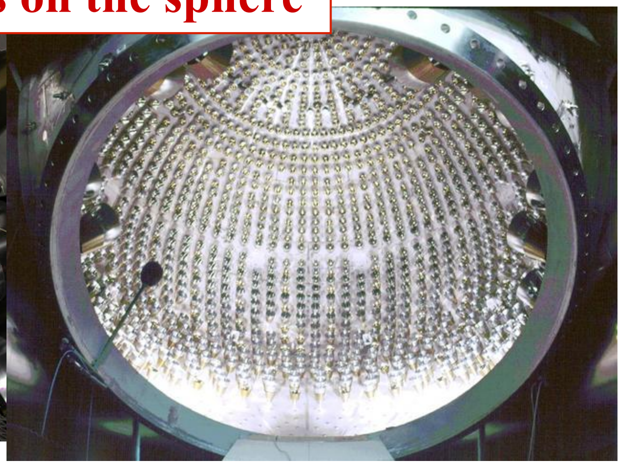




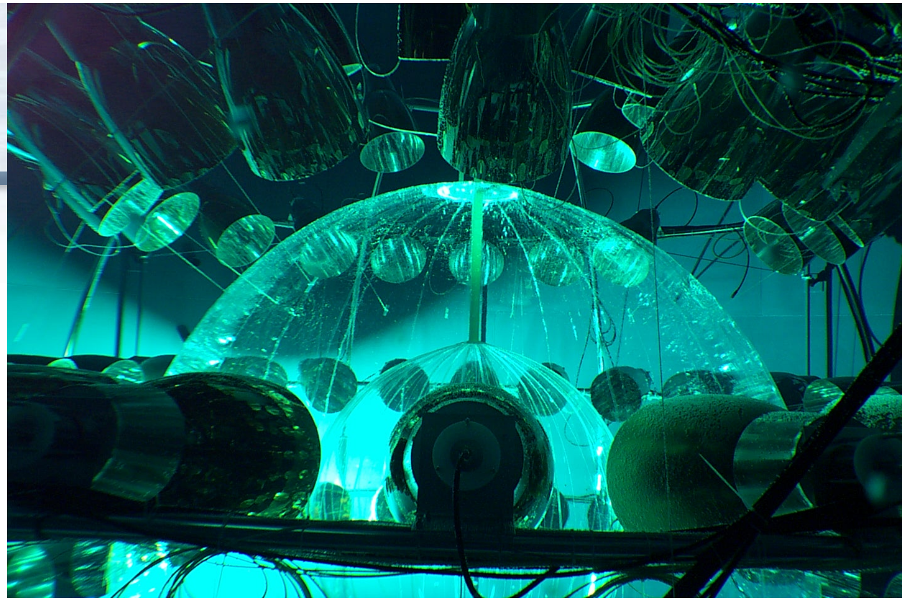
Nylon vessel installation



Installation of PMTs on the sphere

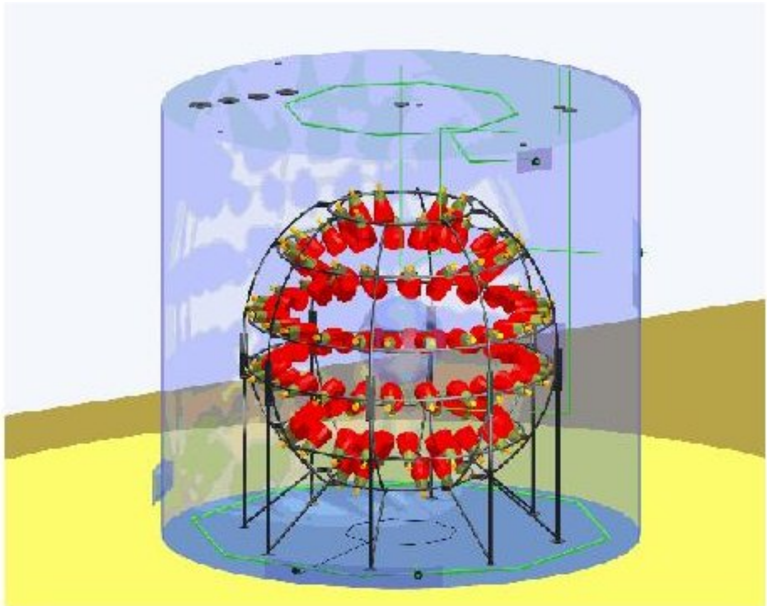


Counting Test Facility

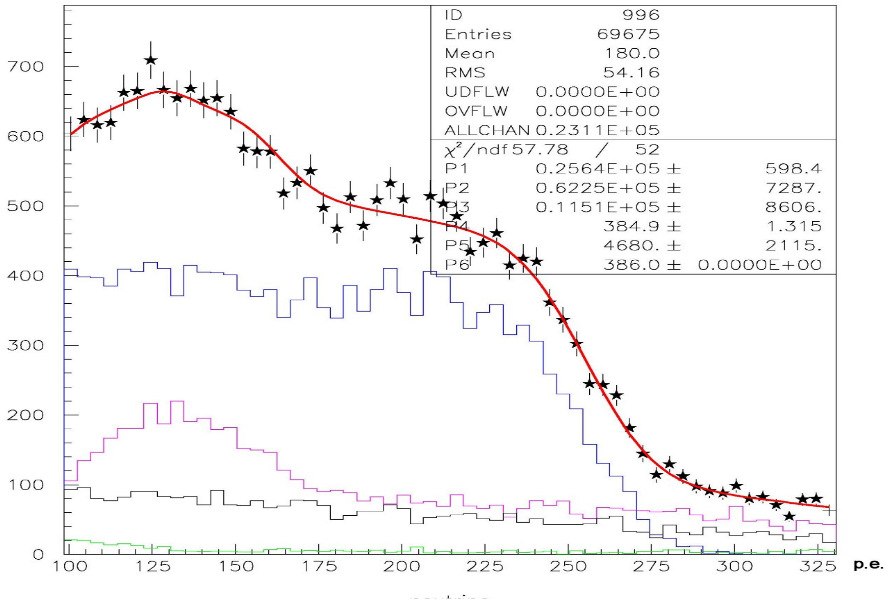


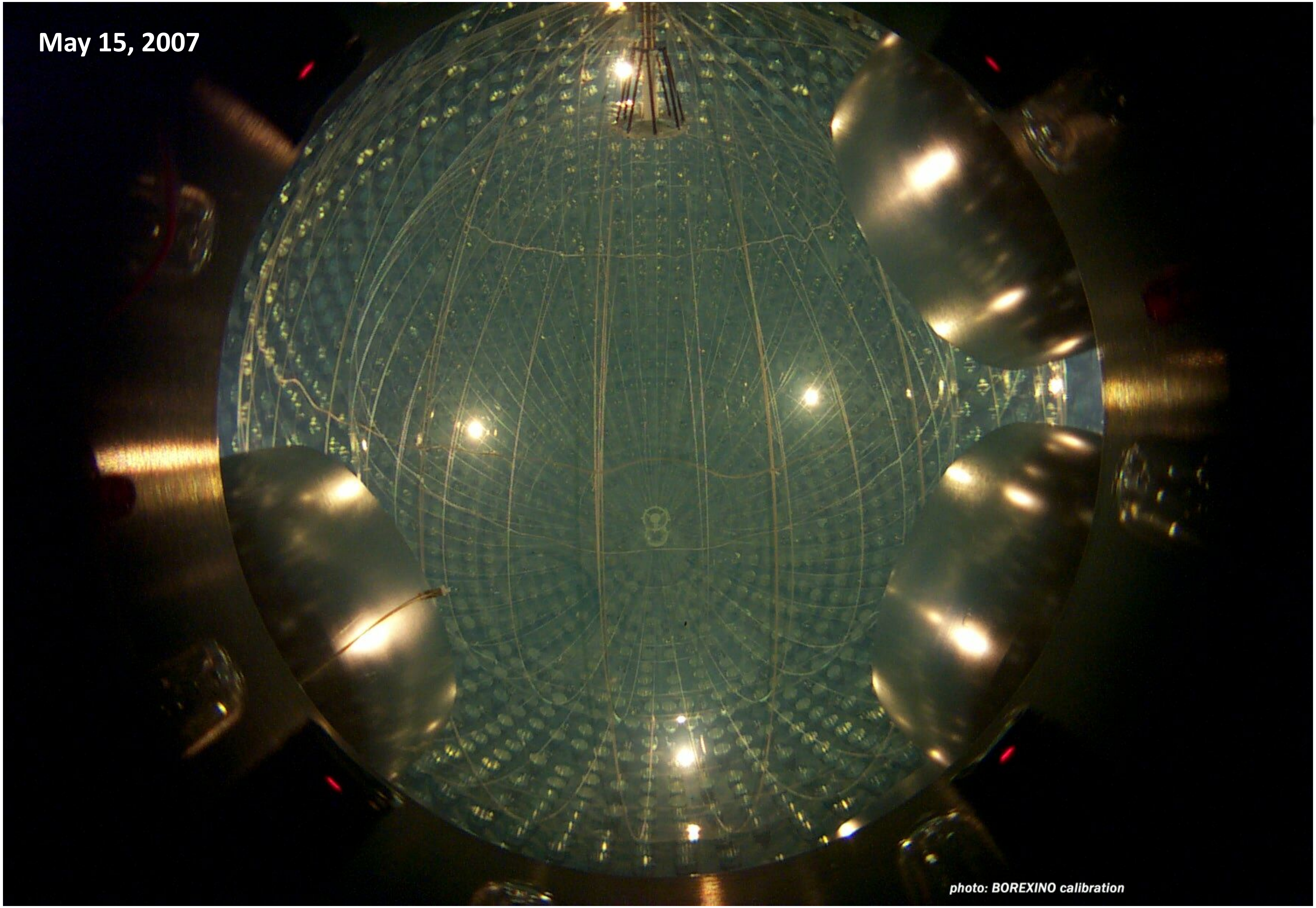
✓CTF is a small scale prototype of Borexino:

- ✓ ~ 4 tons of scintillator
- ✓ 100 PMTs
- ✓ Buffer of water
- ✓ Muon veto
- ✓ Vessel radius: 1 m



CTF demonstrates the Borexino feasibility

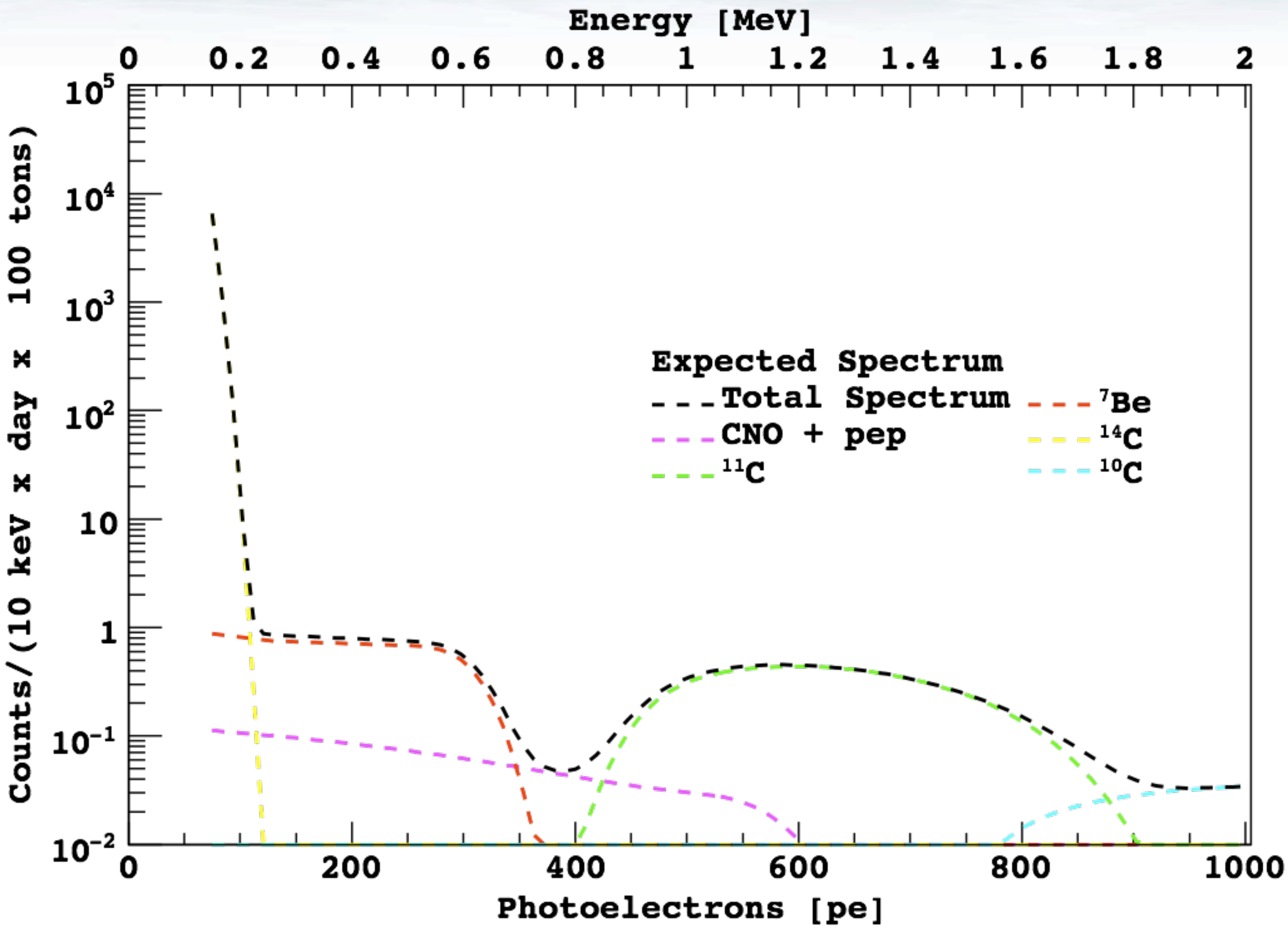



May 15, 2007
photo: BOREXINO calibration

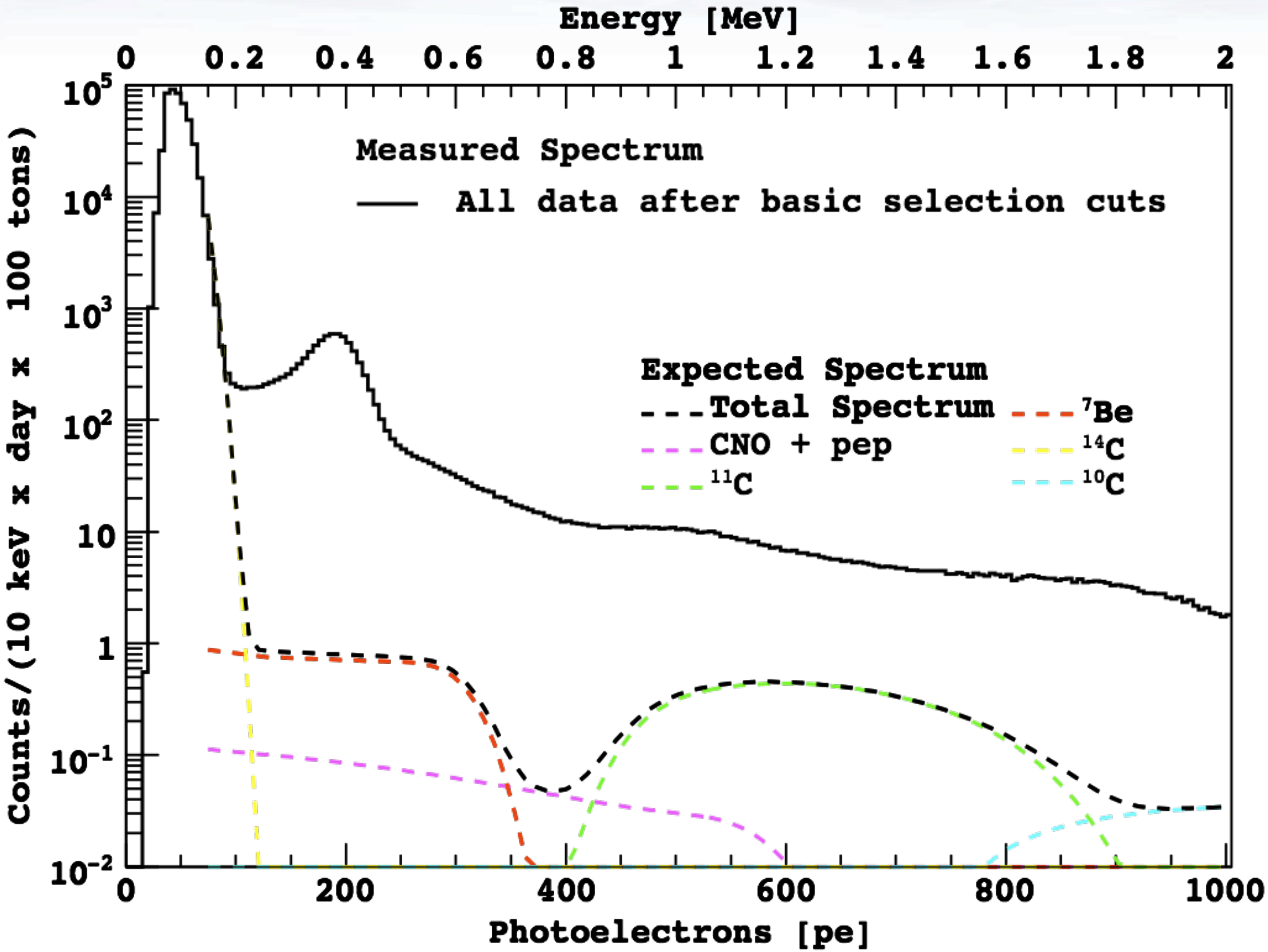
Borexino background

Radiolsotope		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

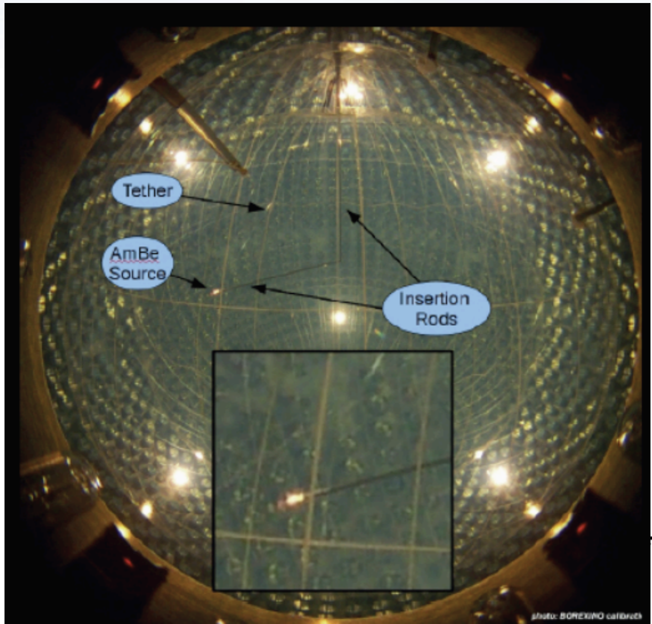


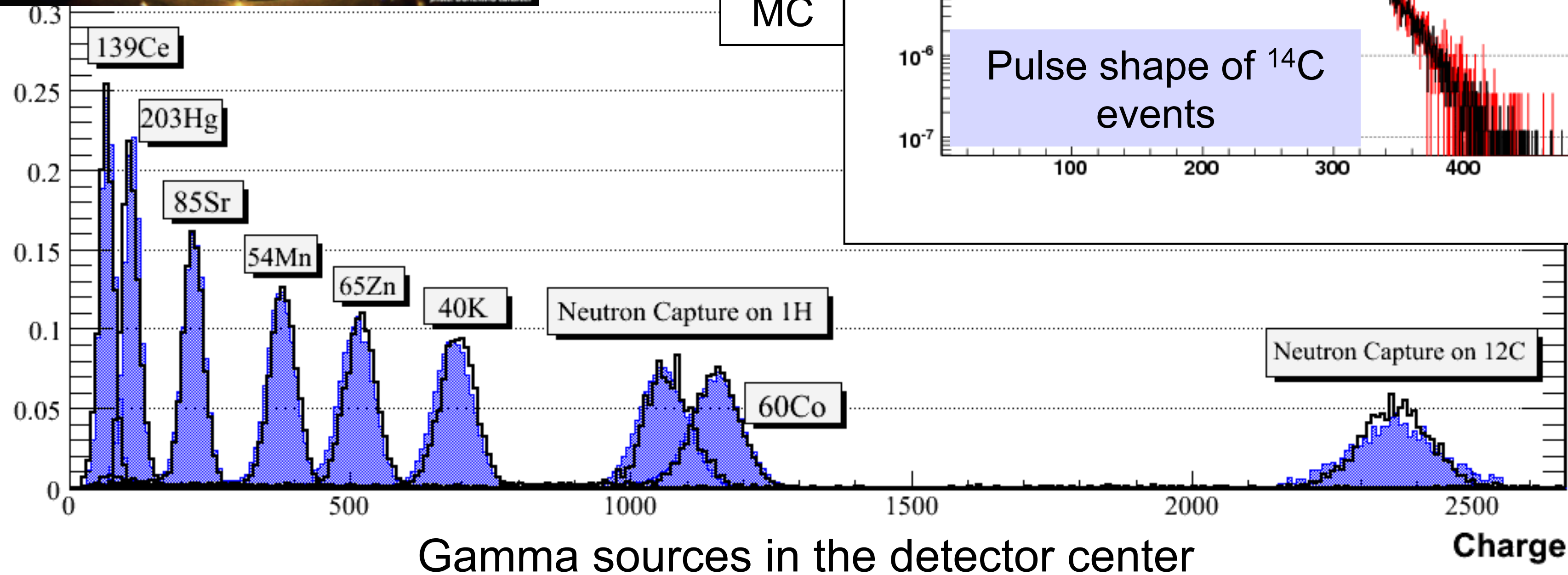
The starting point: no cut spectrum

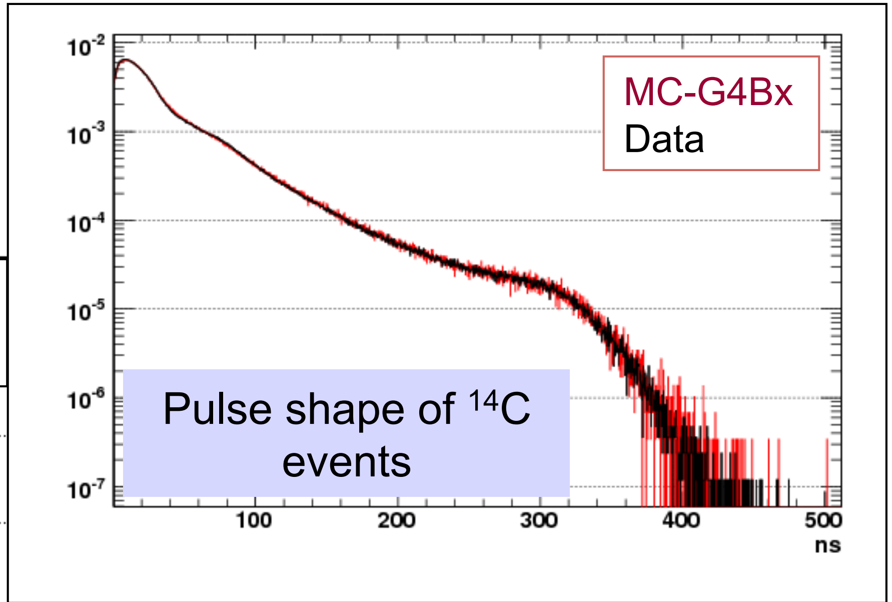


Calibrations: Monte Carlo vs Data

Uncertainties on:
energy scale ~ 1.5%
fiducial volume: +0.6% - 1.3%



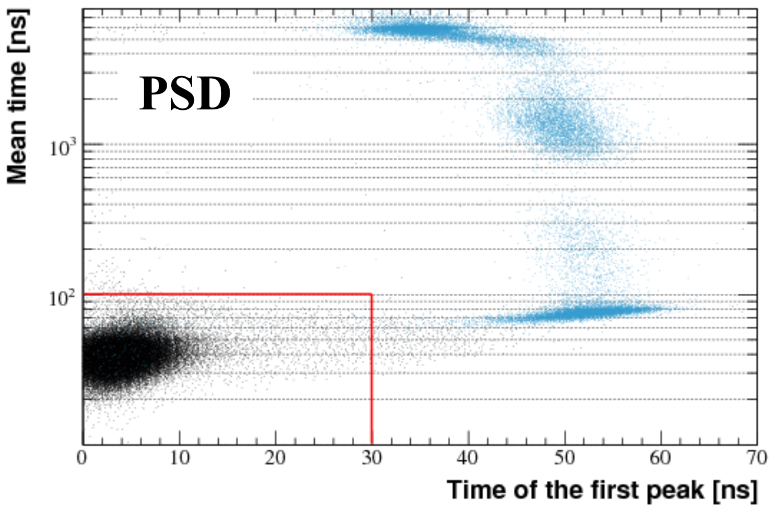


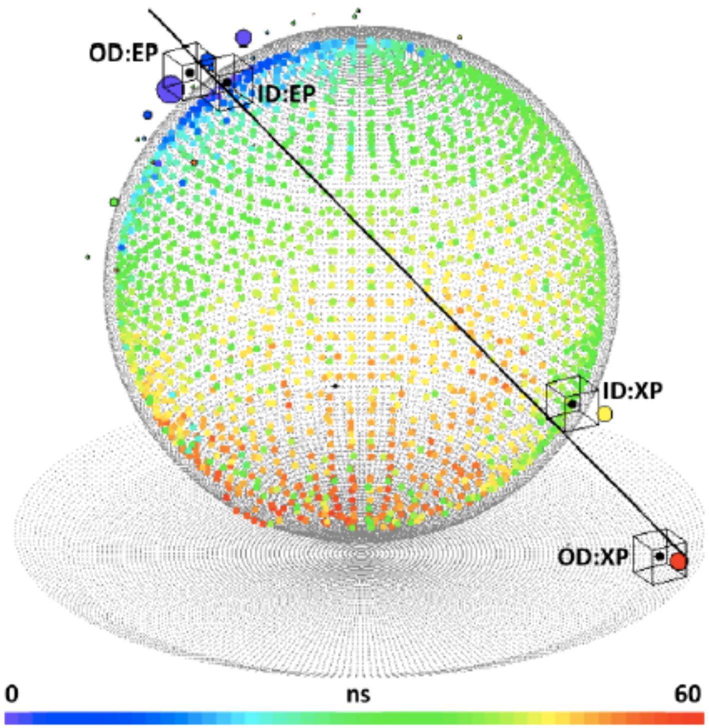


Gamma sources in the detector center

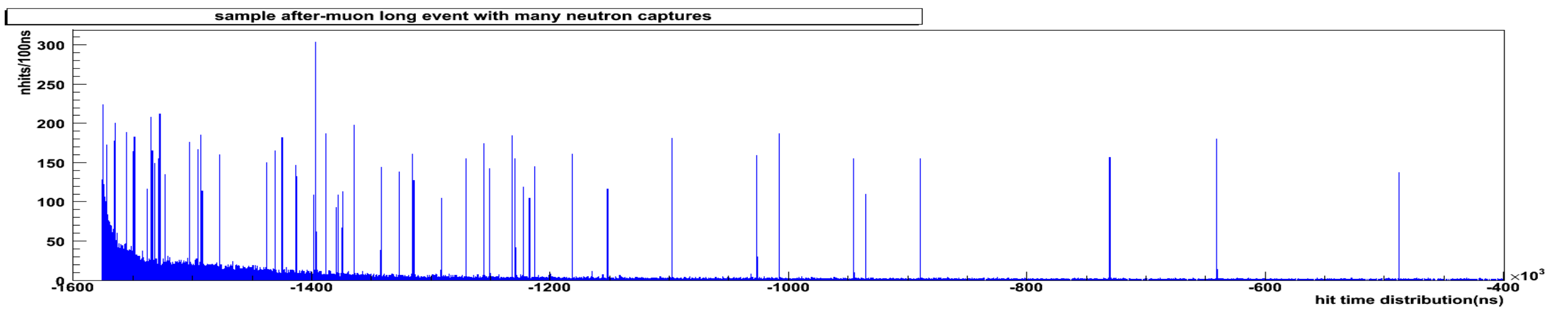
Cosmic muons and induced neutrons

muons are identified by the outer veto and the pulse shape identification. Rejection factor > 10^3 (conservative)



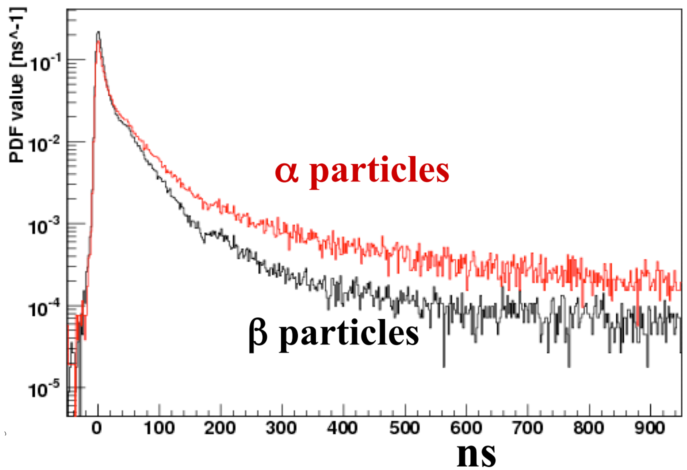


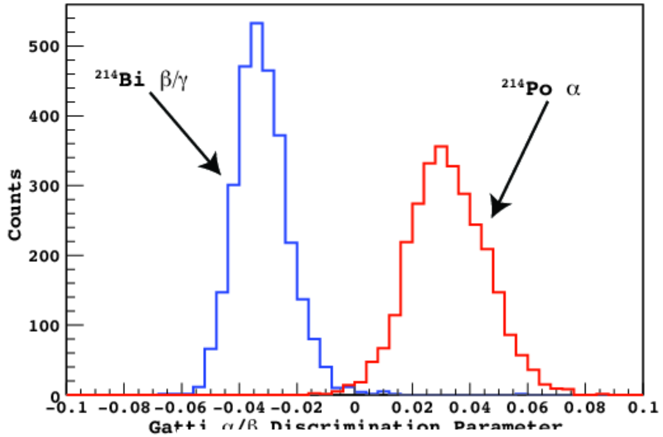
A second electronic chain records all **neutrons** following a muon

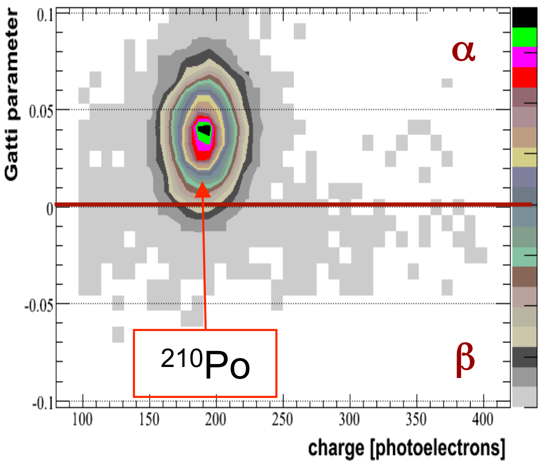


The α/β discrimination and the ^{210}Po puzzle

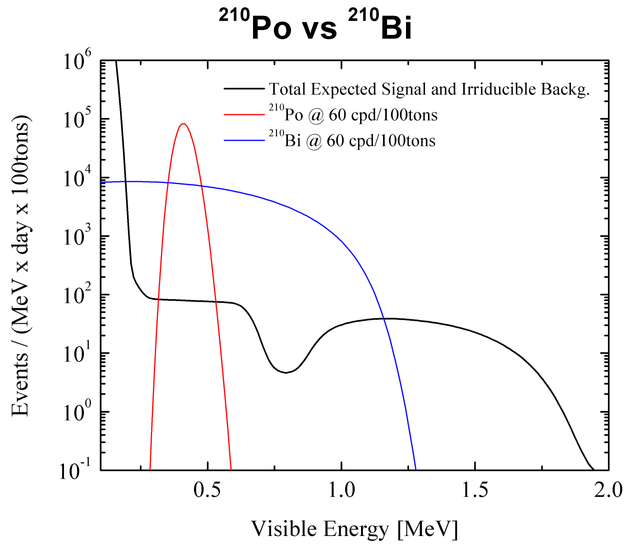
Different response in the scintillation emission time depending on the particle nature



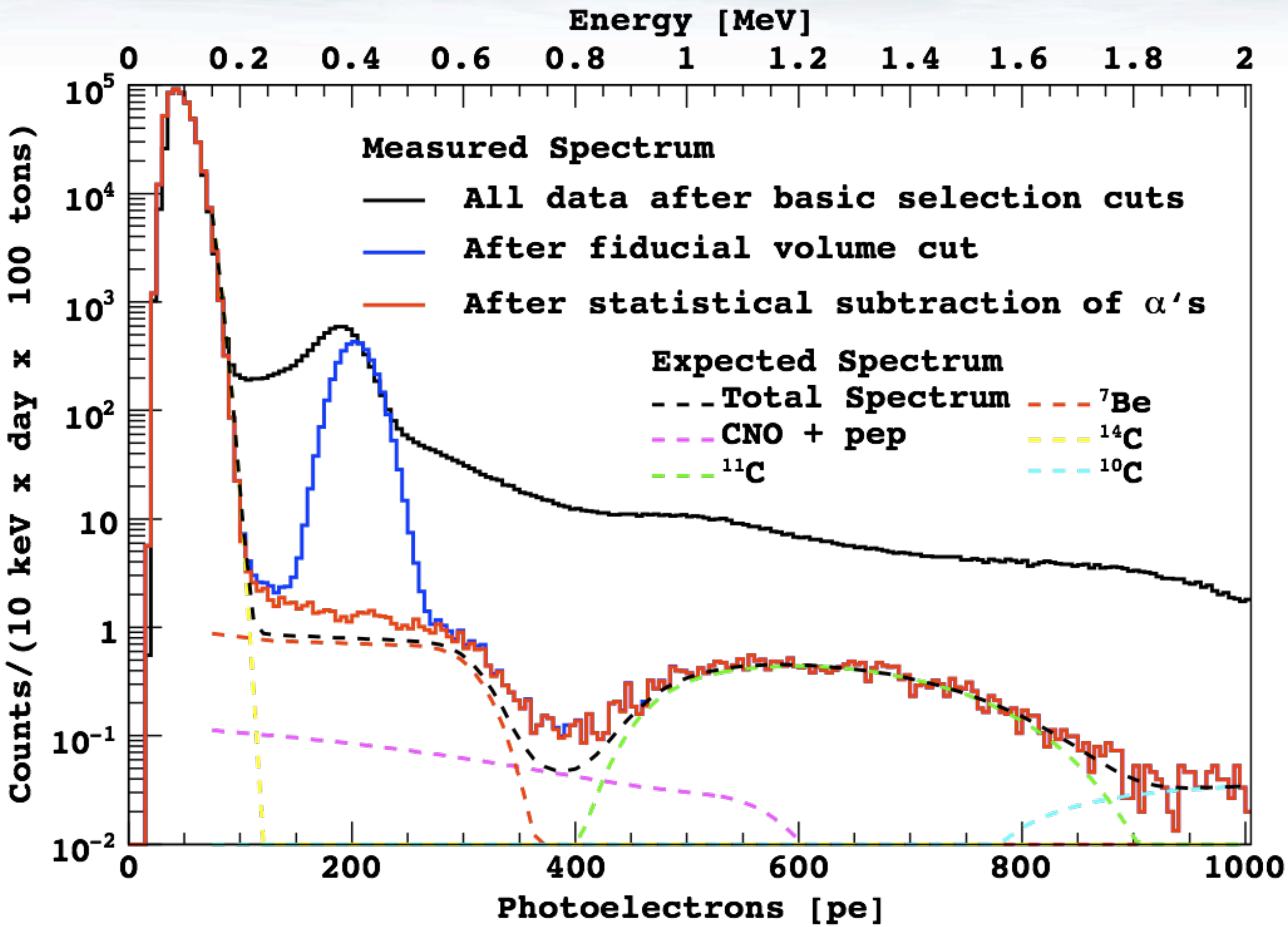




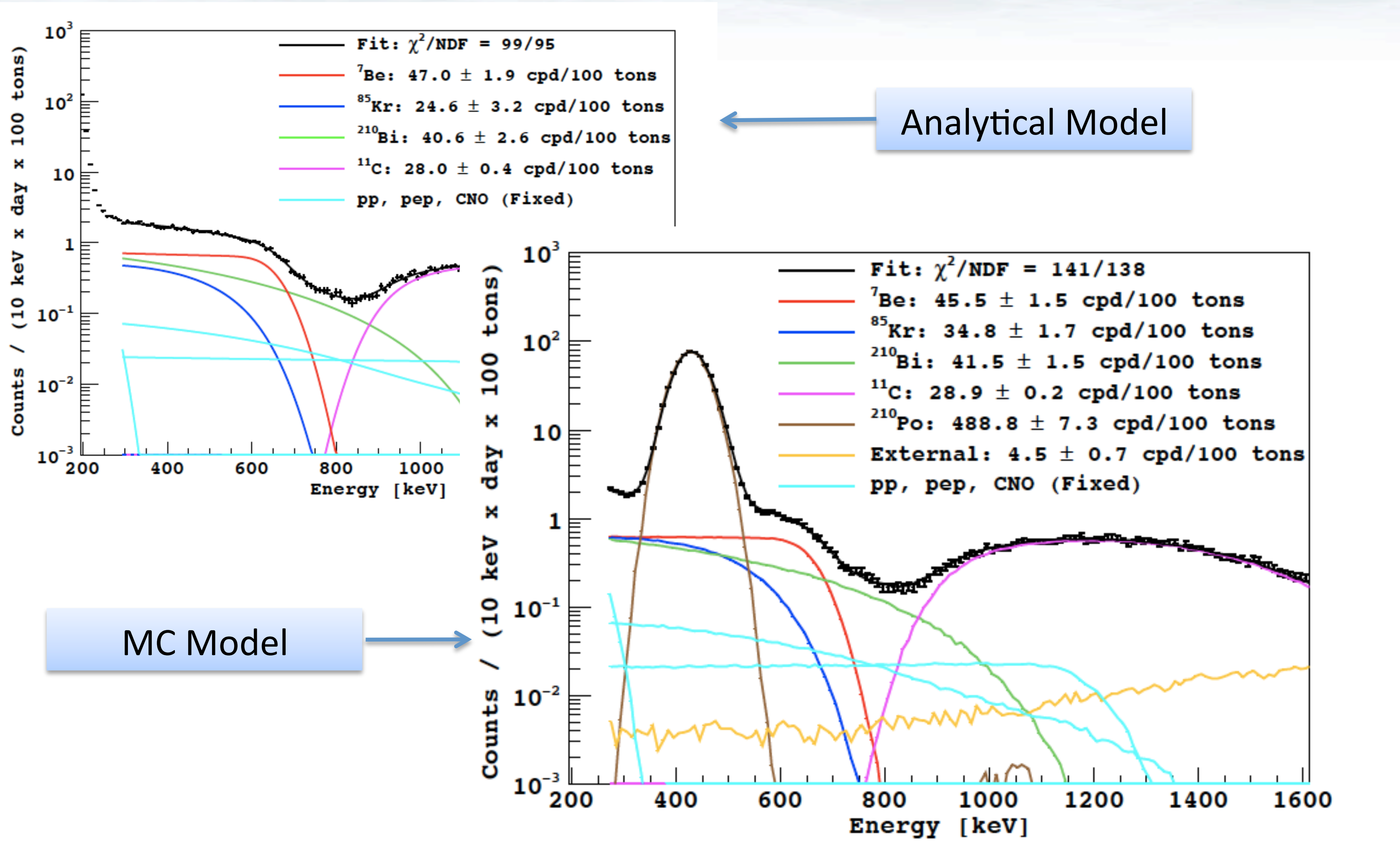
The **puzzle**: high 210Po contamination not in equilibrium with its "father": 210Bi



After the selection cuts



Final fit: 740 days of statistics



^{7}Be-ν result

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	$^{+3.6}_{-3.4}$

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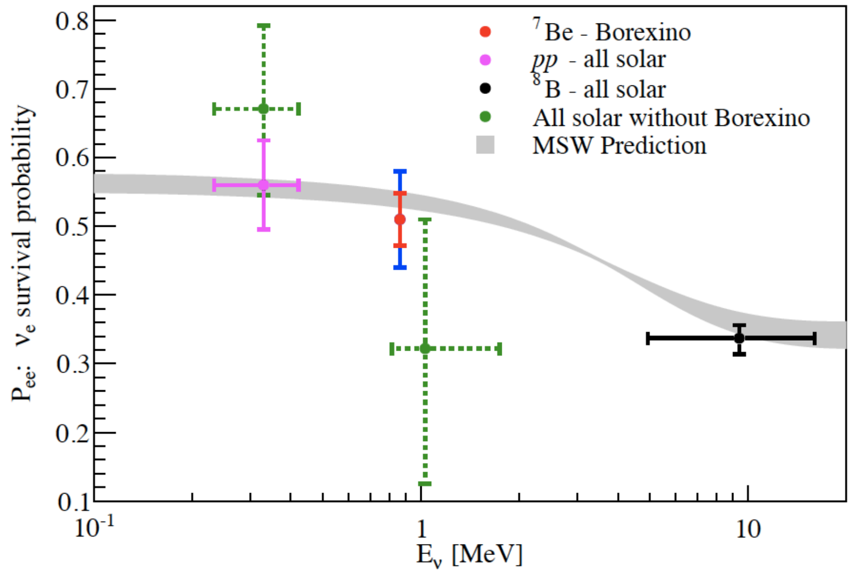


R: $46.0 \pm 1.5_{stat}{}^{+1.6}_{-1.5\ syst}$ cpd/100 t

$f_{Be} = 0.97 \pm 0.05$

$P_{ee} = 0.52^{+0.07}_{-0.06}$

Under the luminosity constraint:

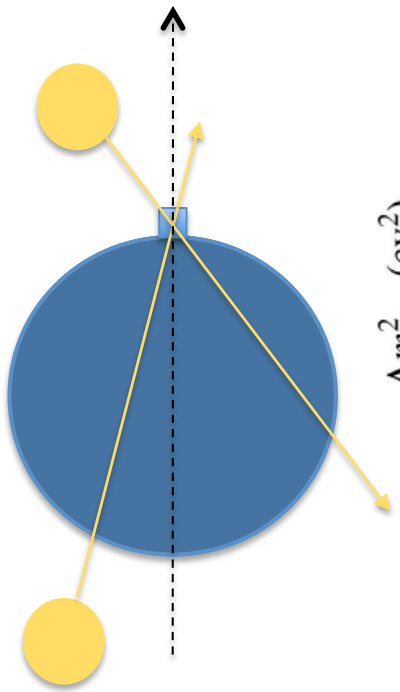
$\Phi pp = (6.06^{+0.02}_{-0.06}) \times 10^{10}$ cm^{-2}s^{-1}

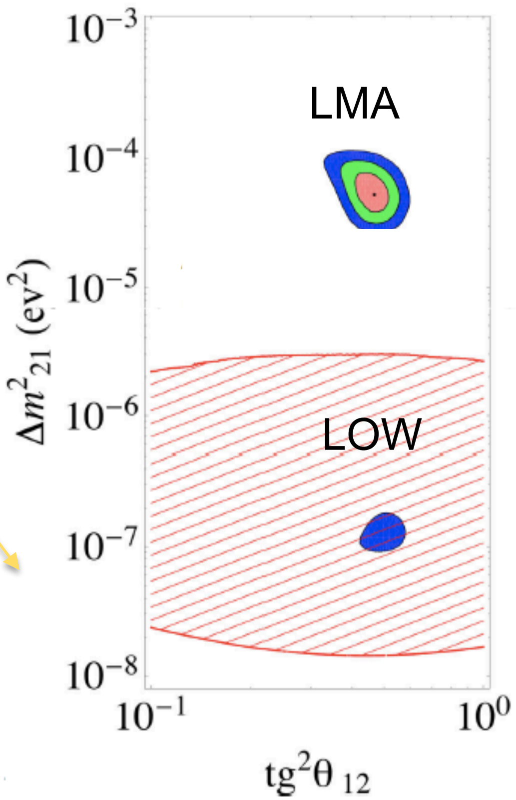
CNO <1.7% (95% C.L.)

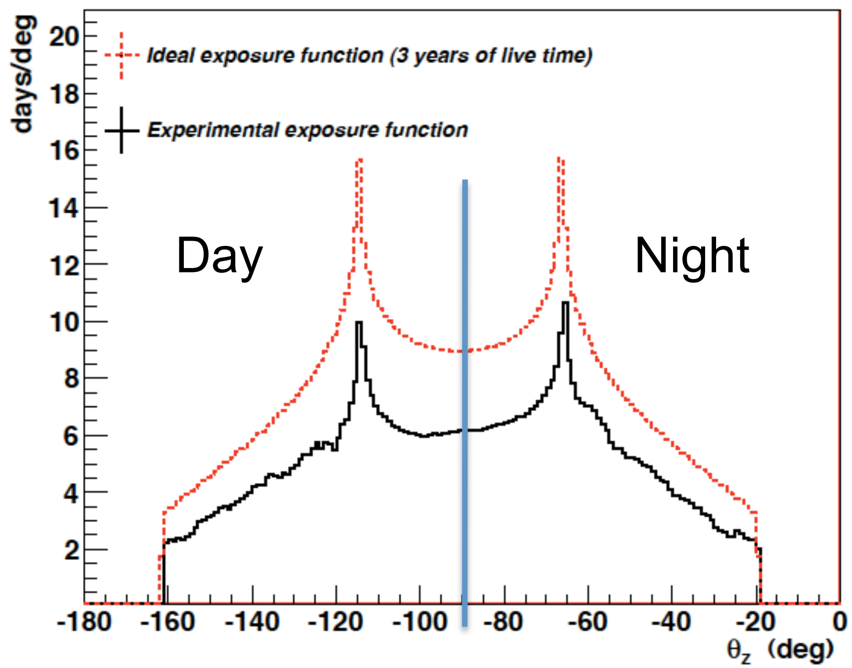
The Day-Night regeneration

A neutrino "regeneration" is expected only in the LOW solution

Exposure

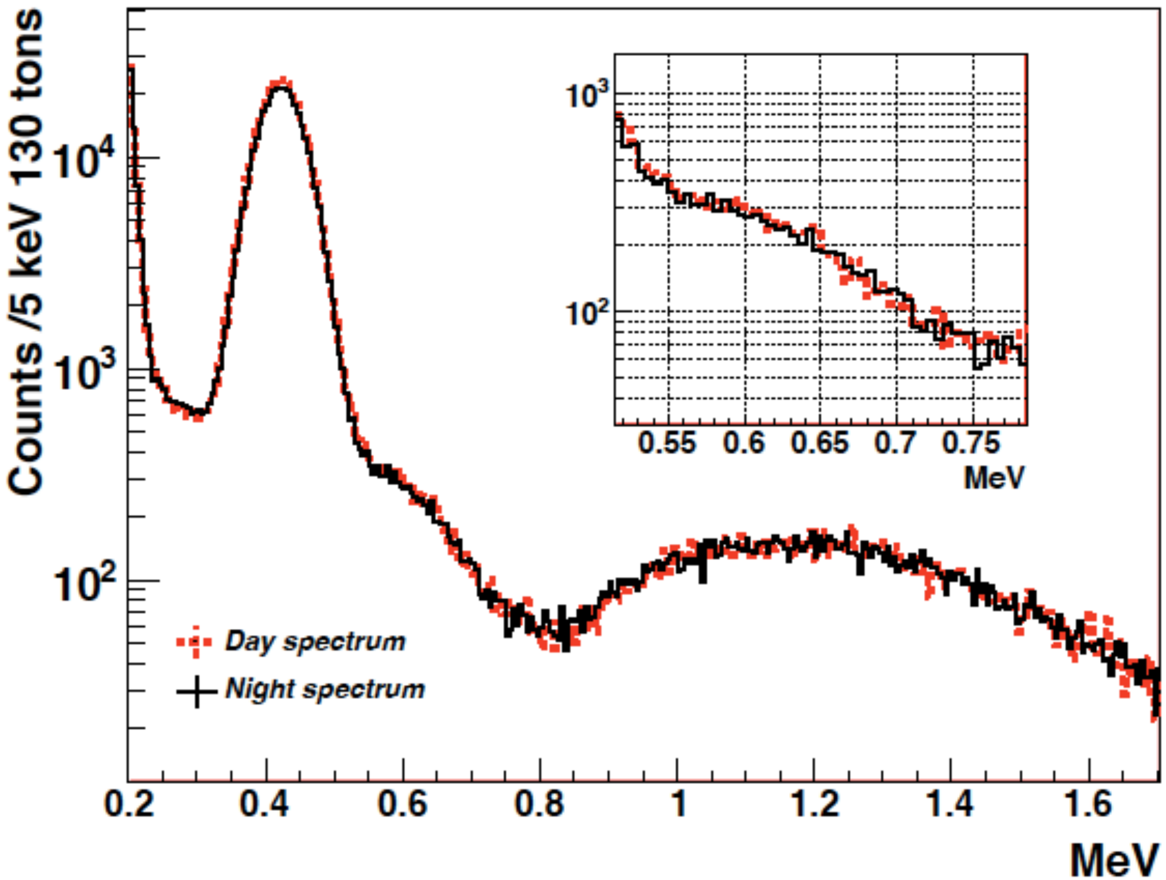




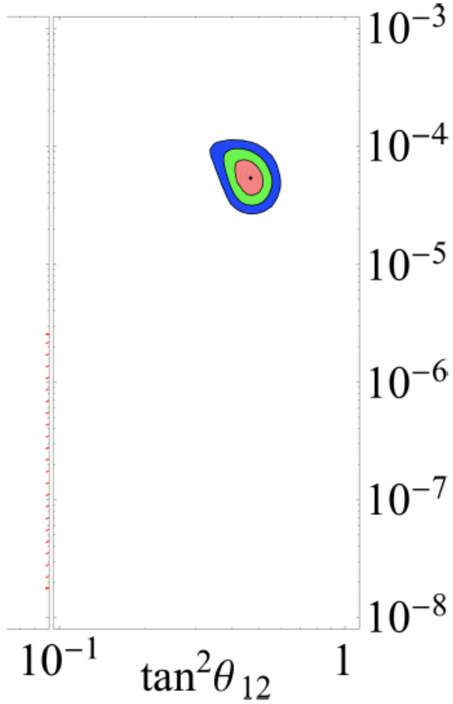


The Day-Night Asymmetry

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



LOW ruled out at 8.5 σ



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

Neutrino Magnetic Moment

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

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

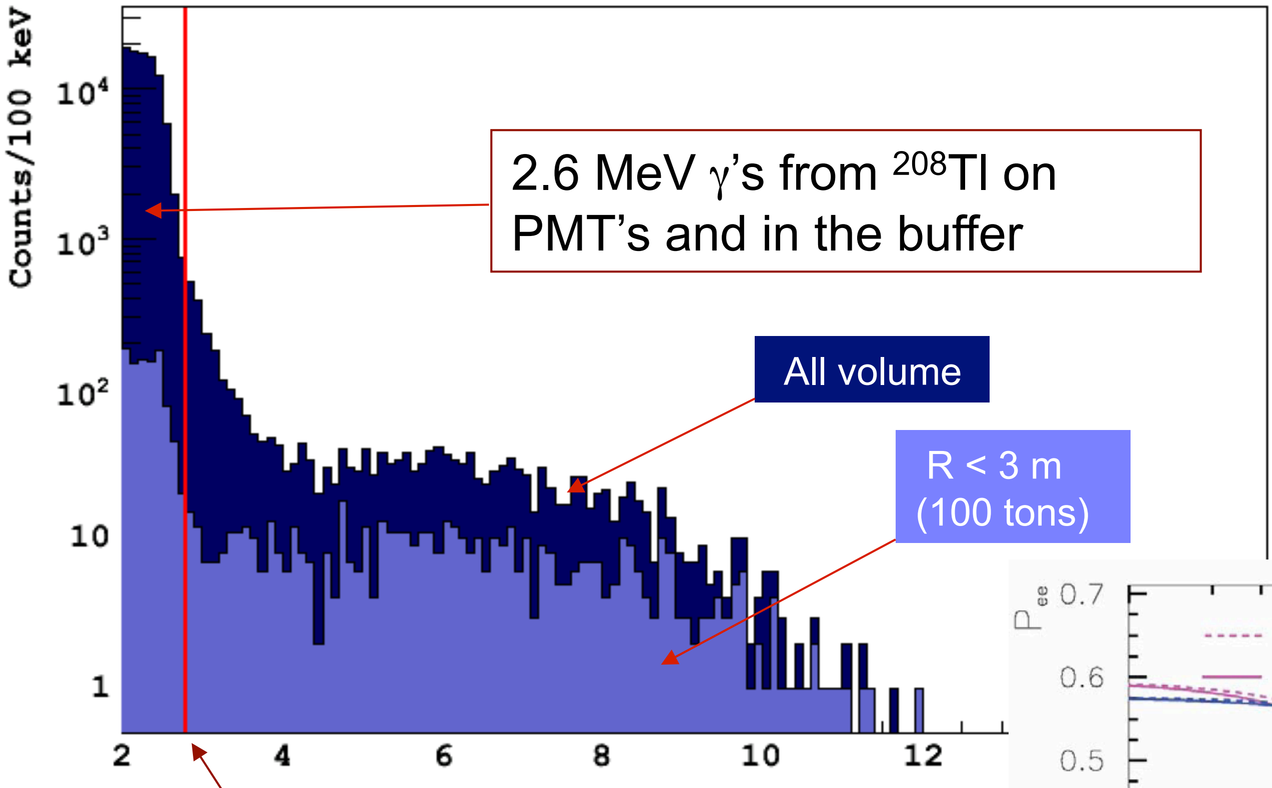
EM current affects cross section: spectral shape sensitive to μ_ν sensitivity enhanced at low energies (c.s.≈ 1/T)

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

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

^{8}B neutrinos with the lowest threshold: 3 MeV

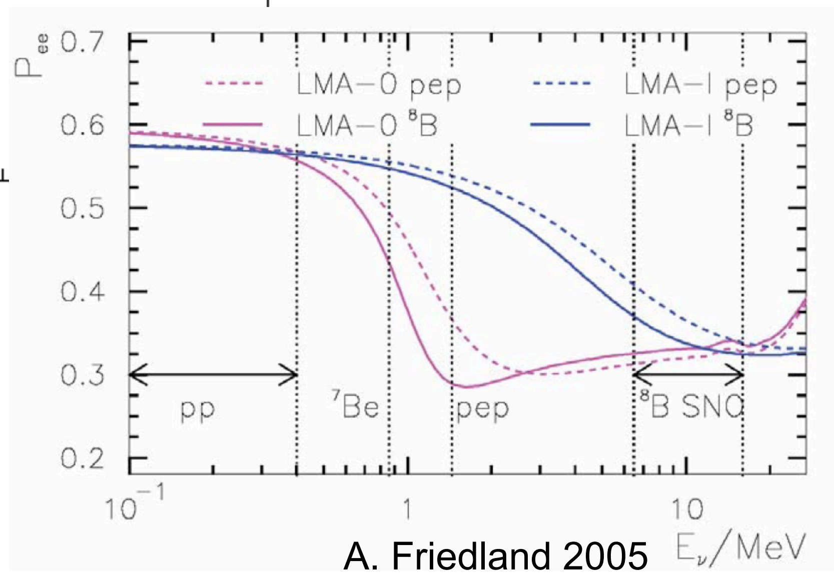


Energy spectrum in Borexino (after μ subtraction)

> 5σ distant from the 2.6 MeV γ peak

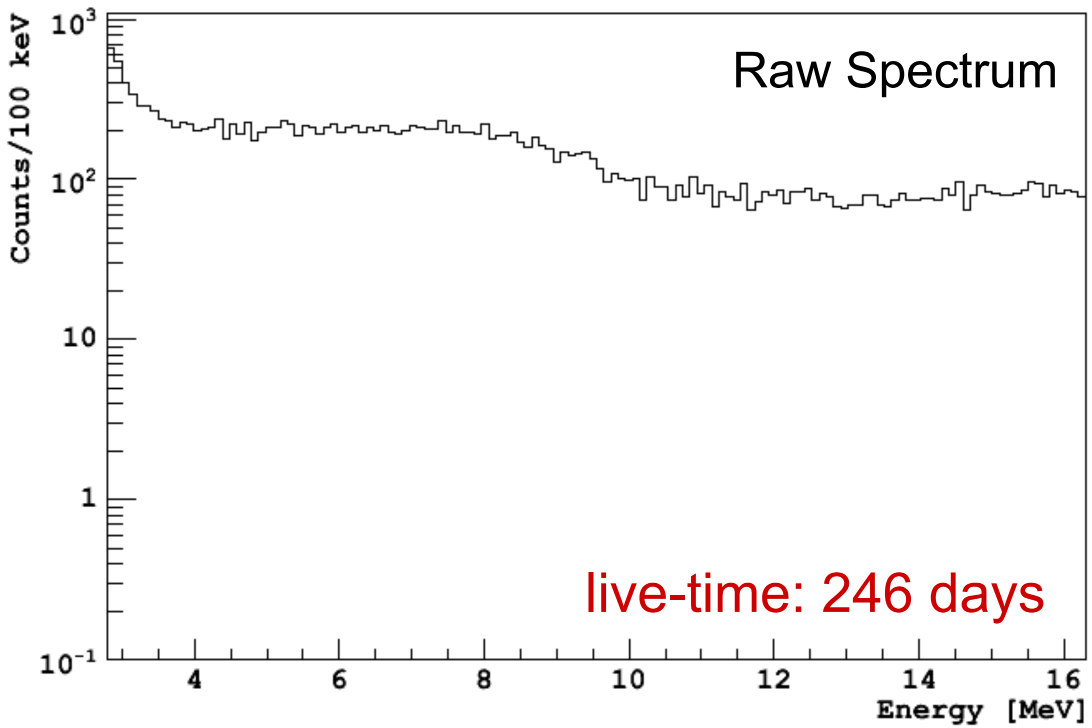
Expected ^{8}B ν rate in 100 tons of liquid scintillator above 3.0 MeV:

0.26±0.03 c/d/100 t



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!

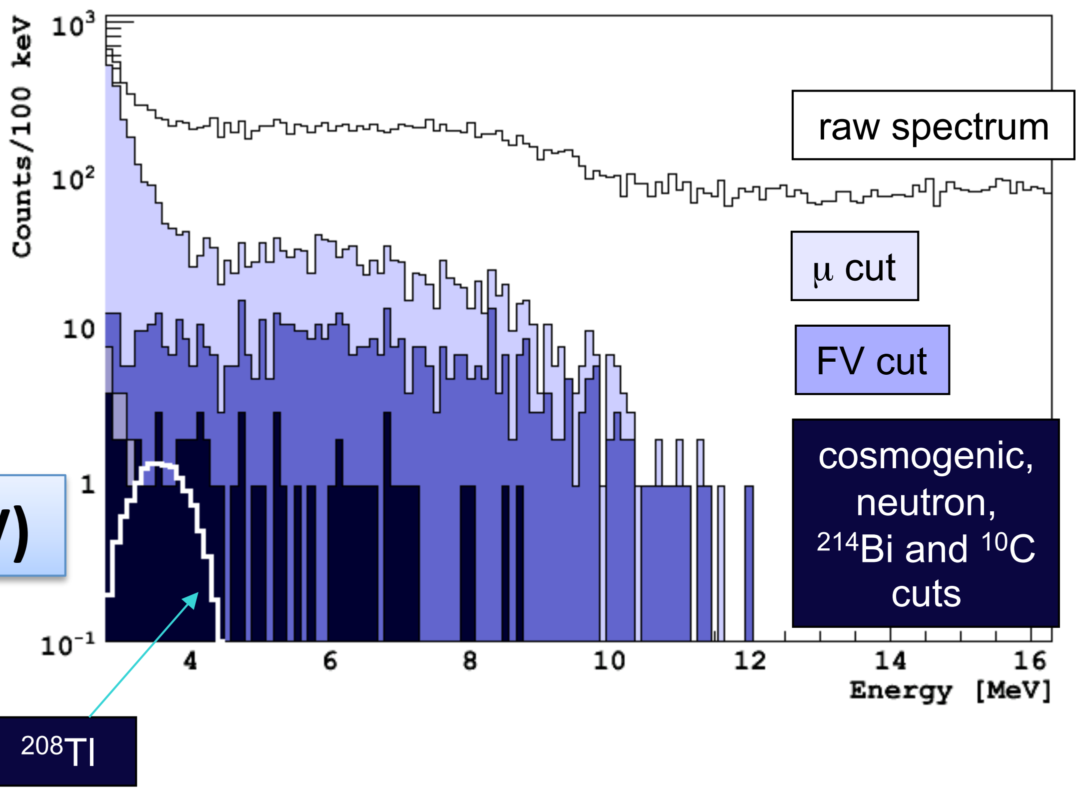
Summary of the Cuts and Systematic

Cut	Counts >3 MeV	Counts > 5 MeV
None	1932181	1824858
Muon cut	6552	2679
FV cut	1329	970
Cosmogenic cut	131	55
^{10}C removal	128	55
^{214}Bi removal	119	55
^{208}Tl and ^{11}Be sub.	75 ± 13	46 ± 8
Measured ^{8}B-ν	75 ± 13	46 ± 8
BPS09(GS98) ^{8}B-ν	86 ± 10	43 ± 6
BPS09(AGS05) ^{8}B-ν	73 ± 7	36 ± 4

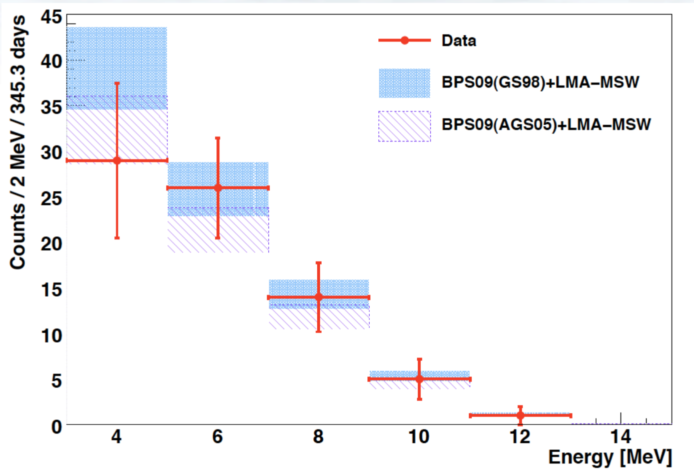
*MSW-LMA: $\Delta m^2=7.69\times10^{-5}$ eV^2, $\tan^2\theta=0.45$

$P_{ee}(^{8}B)$ = **0.29 ± 0.10 (8.6 MeV)**

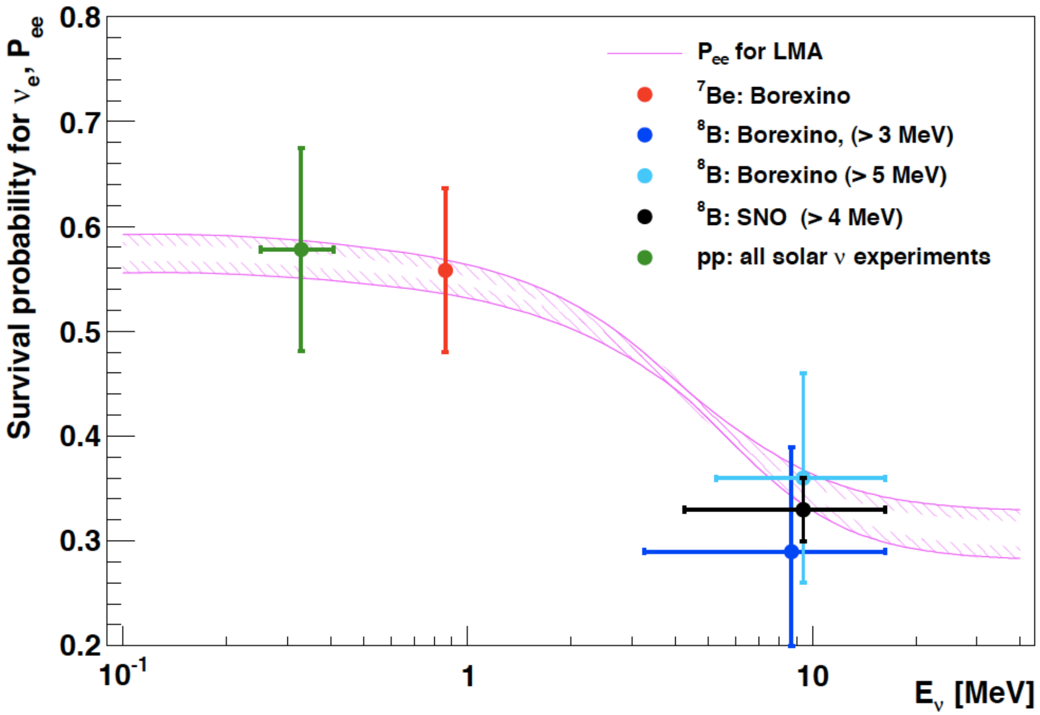
✓Systematic errors:
✓ 3.8% from the determination of the fiducial mass
✓ 3.5% (5.5%) uncertainty in the ^{8}B rate above 3.0 MeV (5.0 MeV) from the determination of the light yield (1%)

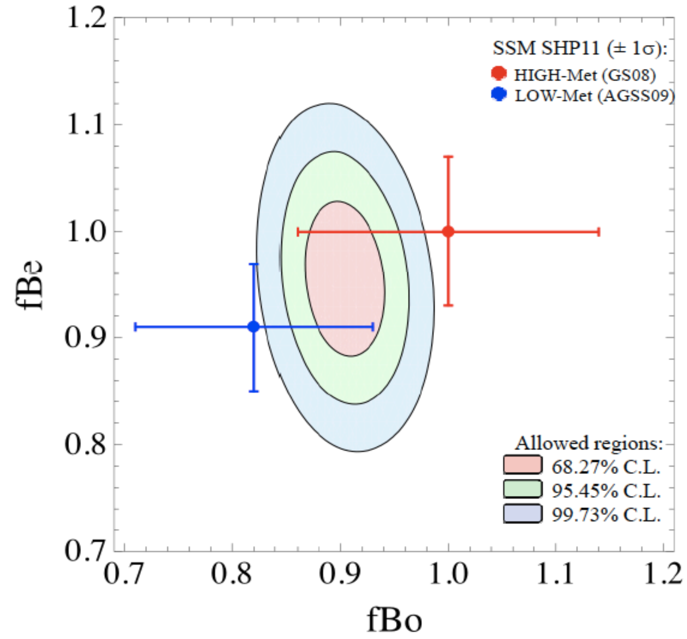


The ^{8}B ν spectrum



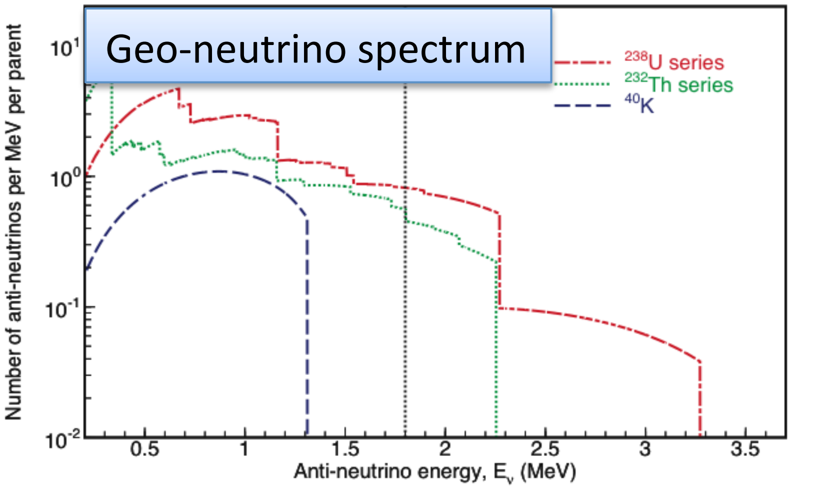
- Borexino data (^{7}Be and ^{8}B) confirm neutrino oscillation **at 4.2 σ**,
- No discrimination between log and high **metallicity** SSM's

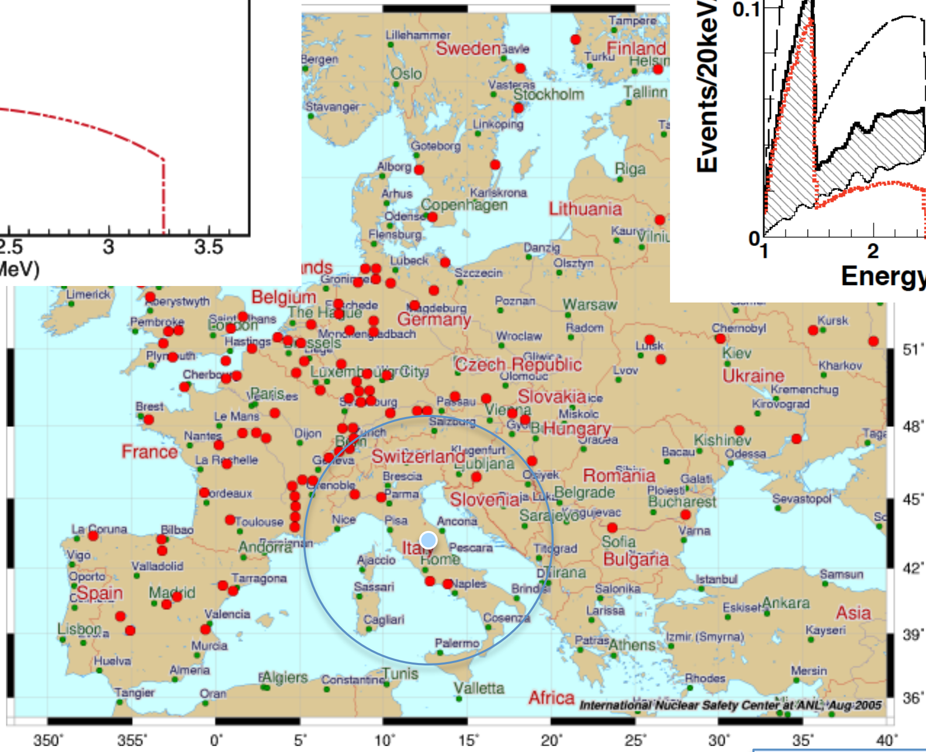




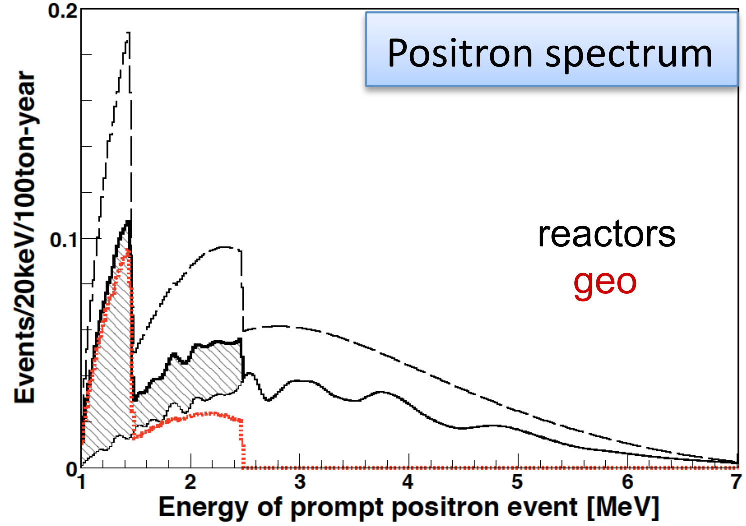
Geo-neutrinos

Geo-neutrino spectrum





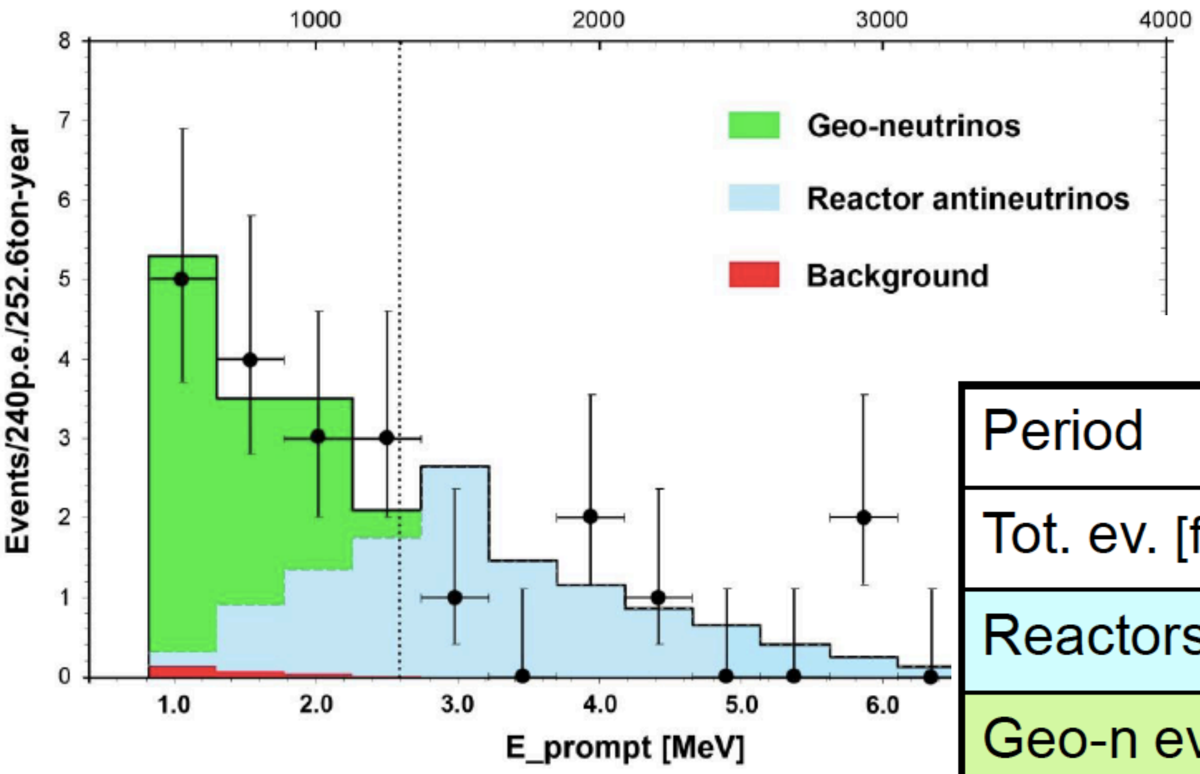
Positron spectrum



S/B ratio ~ 1
(entire energy spectrum)

Expectations
geo-ν: 6.3 cpy / 300 t
reactor-ν: 5.7 cpy / 300 t

Geo-neutrinos: results



Period	Dec. 07 – Dec. 09
Tot. ev. [full sp.]	21
Reactors ev.	$10.7_{-3.4}^{+4.3}$
Geo-n ev.	$9.9_{-3.4}^{+4.1}$
Background ev.	$0.4_{-0.05}^{+0.05}$

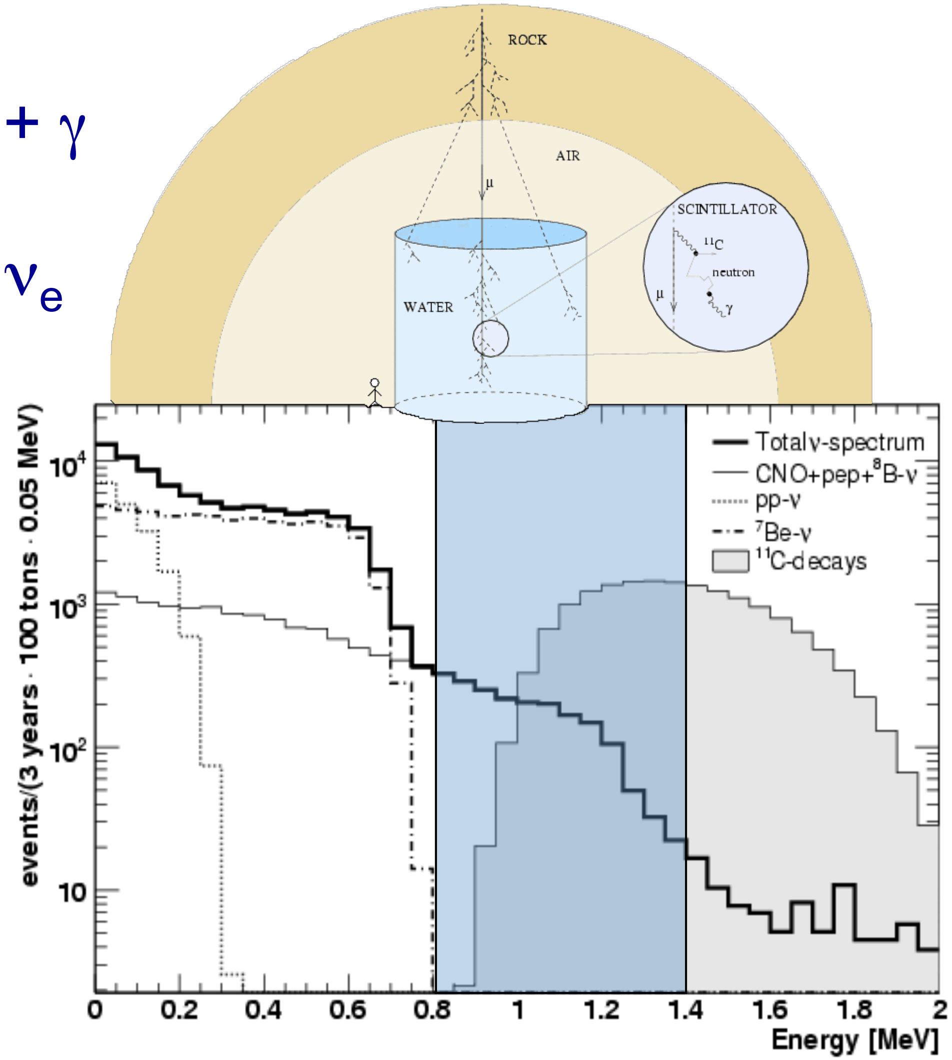
Null hypothesis rejected at 4.2σ

pep neutrinos: the ^{11}C background

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

$\quad \hookrightarrow + p \rightarrow d + \gamma$

$\quad \hookrightarrow {}^{11}B + e^{+} + \nu_e$



Expectations in [0.8-1.4] MeV
pep-ν ~ 0.01 cpd / t
^{11}C ~ 0.15 cpd / t

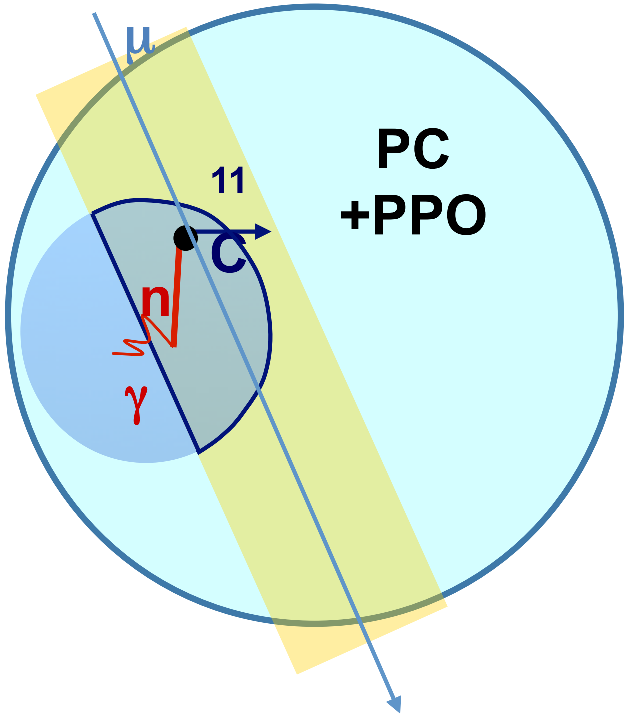
Required ^{11}C rejection factor
> 15

^{11}C rejection: the three-fold coincidence technique

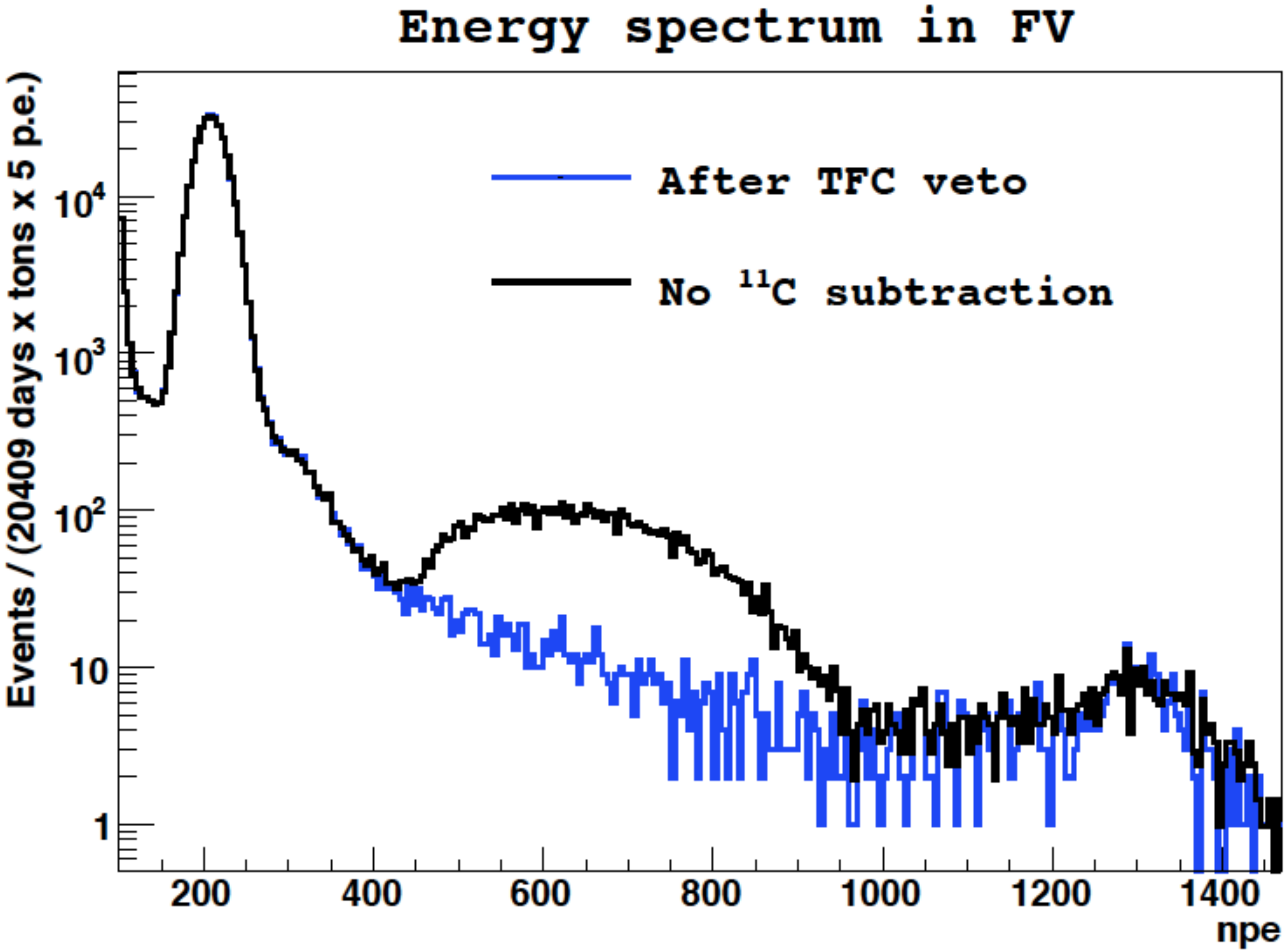
Coincidence among the muon father, the neutron capture and the ^{11}C decay

- problem 1: ^{11}C meanlife ~ 30 min
- problem 2: ~5% of 11C production without neutron emission

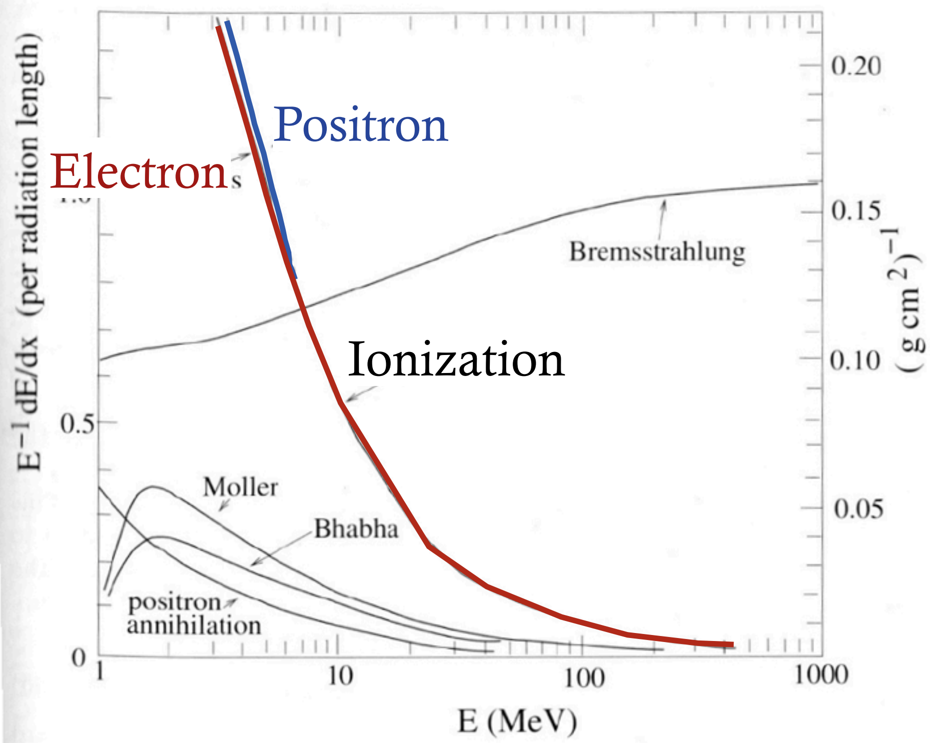
E_μ [GeV]	100	190	285	320	350
Process	Rate $[10^{-4}/\mu/m]$				
$^{12}C(p,p+n)^{11}C$	1.8	3.2	4.9	5.5	5.6
$^{12}C(p,d)^{11}C$	0.2	0.4	0.5	0.6	0.6
$^{12}C(\gamma,n)^{11}C$	19.3	26.3	33.3	35.6	37.4
$^{12}C(n,2n)^{11}C$	2.6	4.7	7.0	8.0	8.2
$^{12}C(\pi^+,\pi+N)^{11}C$	1.0	1.8	2.8	3.2	3.3
$^{12}C(\pi^-,\pi^-+n)^{11}C$	1.3	2.3	3.6	4.1	4.2
$^{12}C(e,e+n)^{11}C$	0.2	0.3	0.4	0.4	0.4
$^{12}C(\mu,\mu+n)^{11}C$	2.0	2.3	2.4	2.4	2.4
Invisible channels	0.9	1.6	2.4	2.7	2.8
Total	28.3	41.3	54.8	59.9	62.2
1σ systematic	1.9	3.1	4.4	5.0	5.2
Measured	22.9	36.0			
1σ experimental	1.8	2.3			
Extrapolated			47.8	51.8	55.1



pep neutrinos after the TFC



^{11}C rejection: a new PSD



Pulse Shape Discrimination (**PSD**) for **e^+/ e^-** may meet a general interest in the neutrino community

However scintillators have almost **equal response to e^+/e^-** in the energy region of interest (<10 MeV)

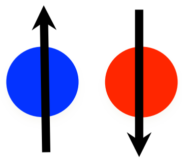
standard PSD can not be applied!!

No way (**up to now!!**) to disentangle electron (positron) induced signal and positron (electron) background in scintillator

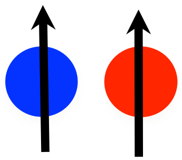
Exploiting positronium formation…

In matter **positrons** may either directly **annihilate** or form a **positronium** state

Positronium has two ground states:



para-positronium (p-Ps) mean life in vacuum of ~ 120 ps
singlet - 2 gamma decay



ortho-positronium (o-Ps) mean life in vacuum of ~ 140 ns
triplet - 3 gamma decay

In matter o-Ps has a **shorter mean life**, mainly because of:

spin-flip: conversion to p-Ps due to a magnetic field

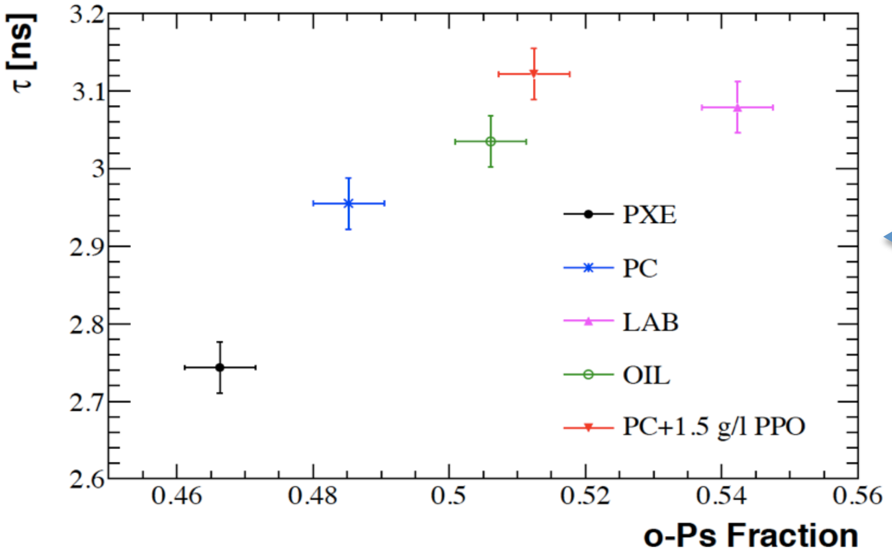
pick off: annihilation on collision with an anti-parallel spin electron

Note!! the 3 body decay channel is negligible in matter

Even a **short delay** (**few ns**) in energy depositions **between positron** (via ionization) **and** annihilation **gammas** (via Compton scattering) can provide a **signature for tagging (a subset of) positrons**

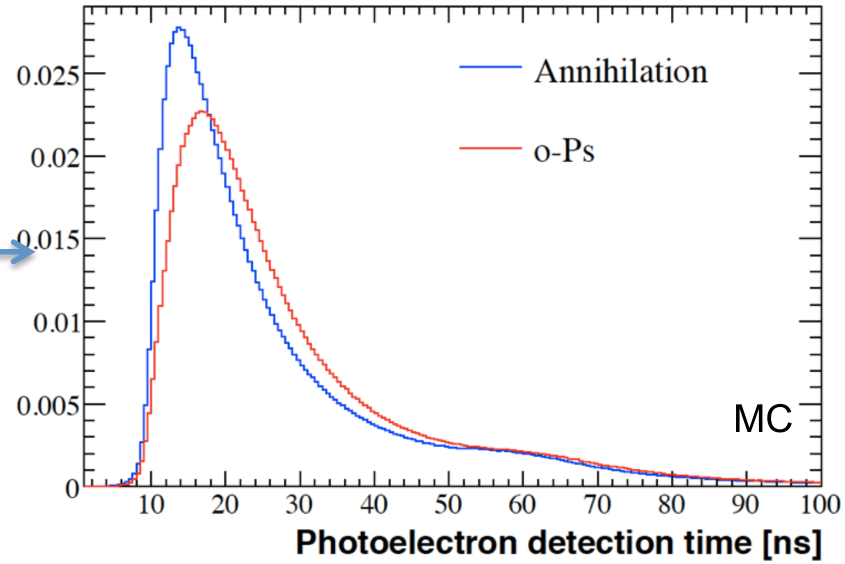
o-Ps in scintillators

D. Franco, G. Consolati, D. Trezzi, Phys. Rev. C83 (2011) 015504

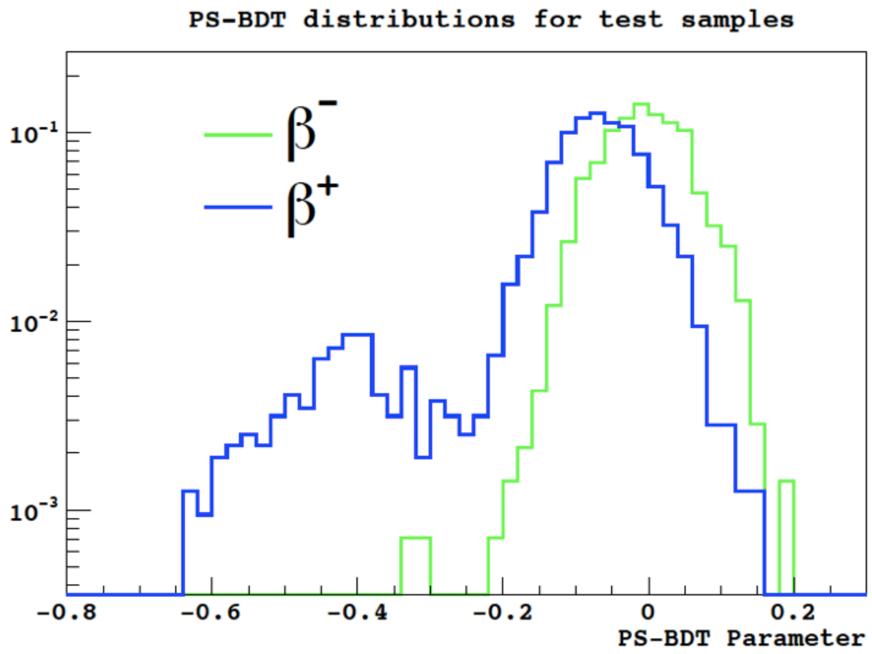


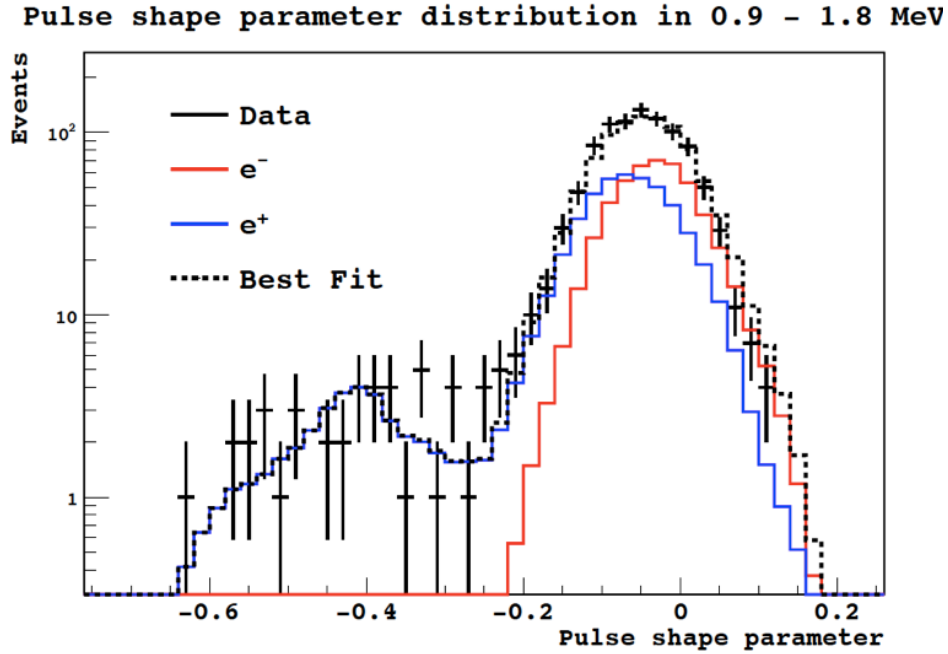
Measurements of the o-Ps meanlife and formation probability in scintillators with the PALS technique

Pulse shape induced distortion

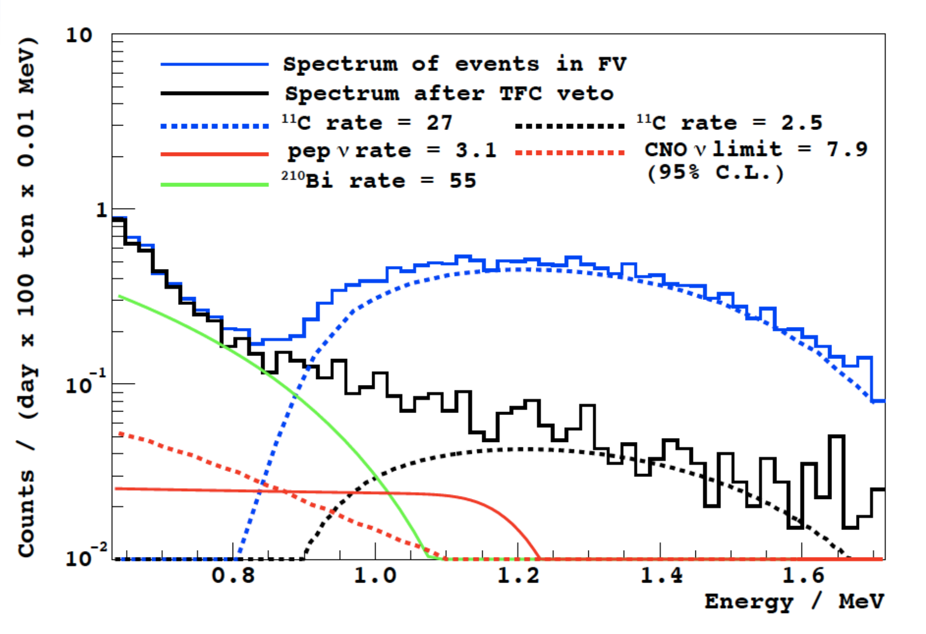


The o-Ps technique in Borexino



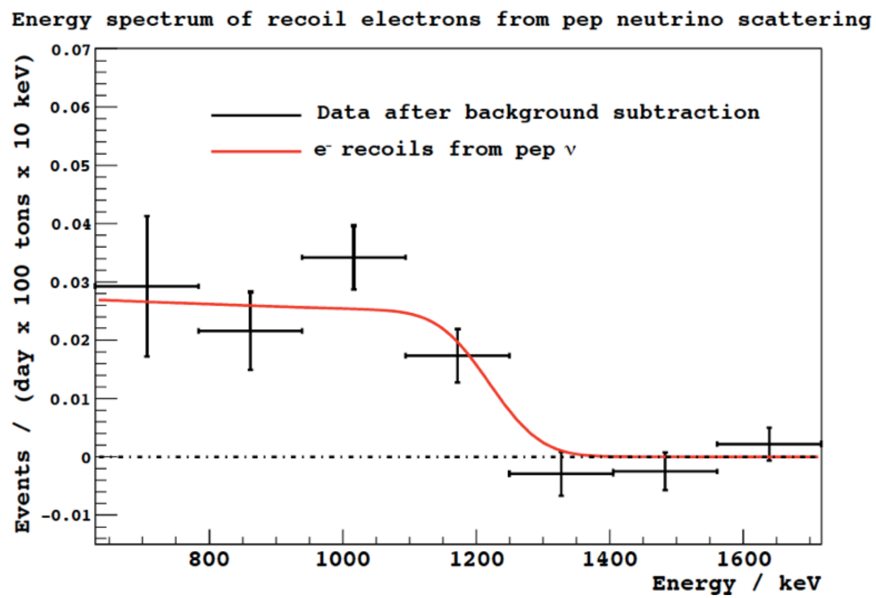


pep neutrinos: results



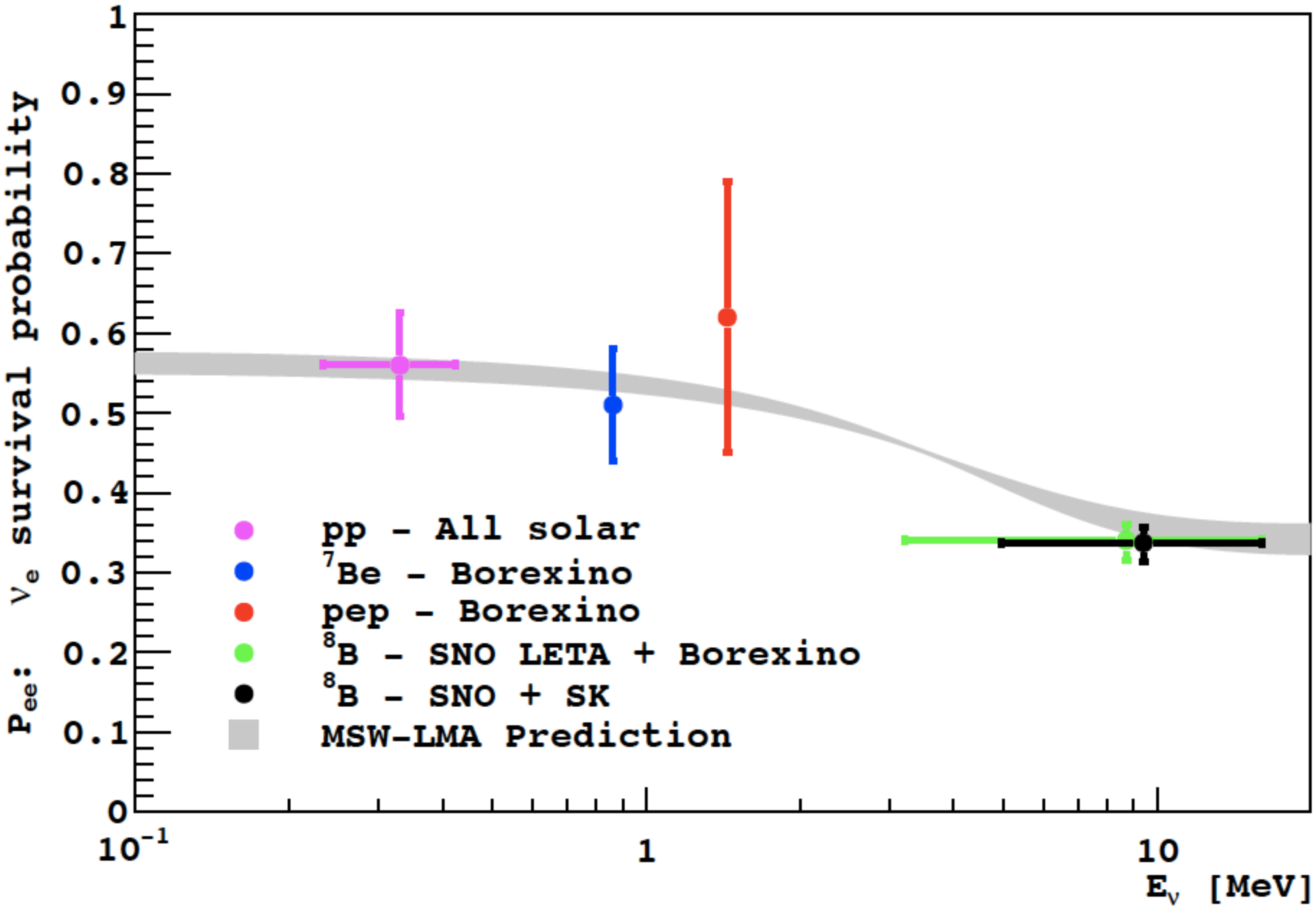
the fit

the subtraction

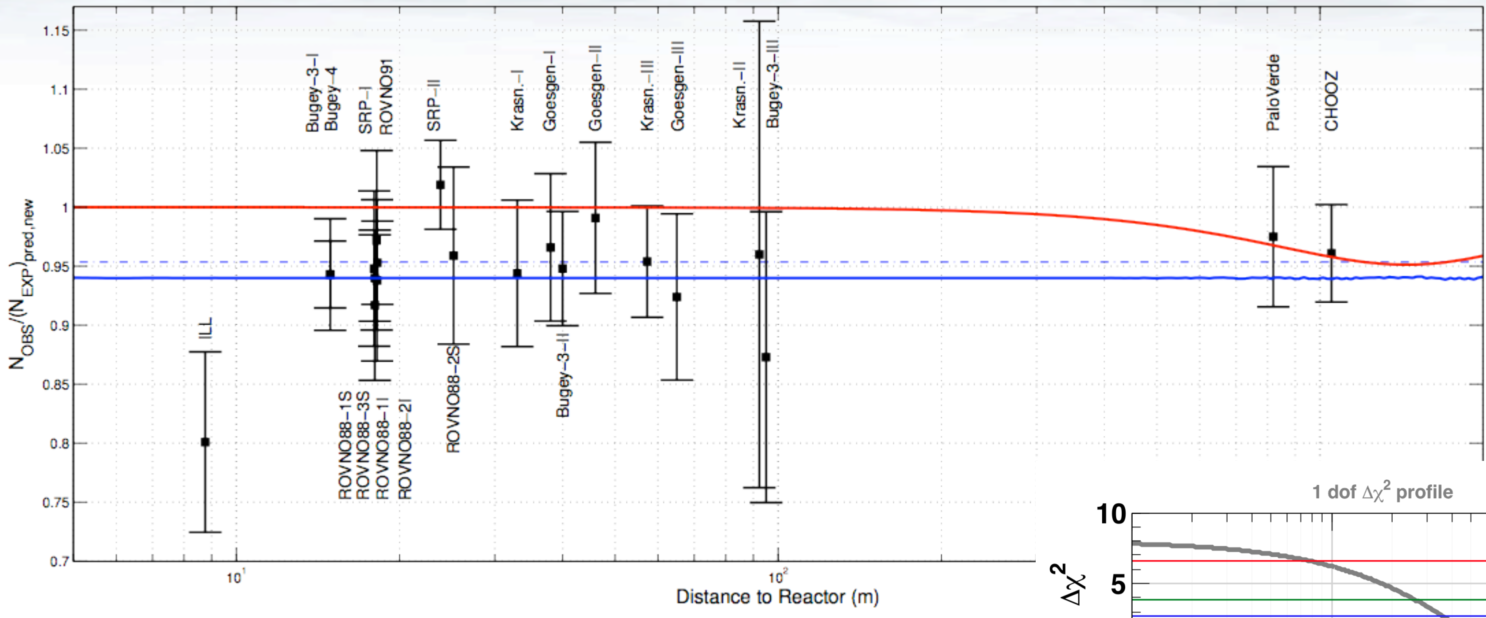


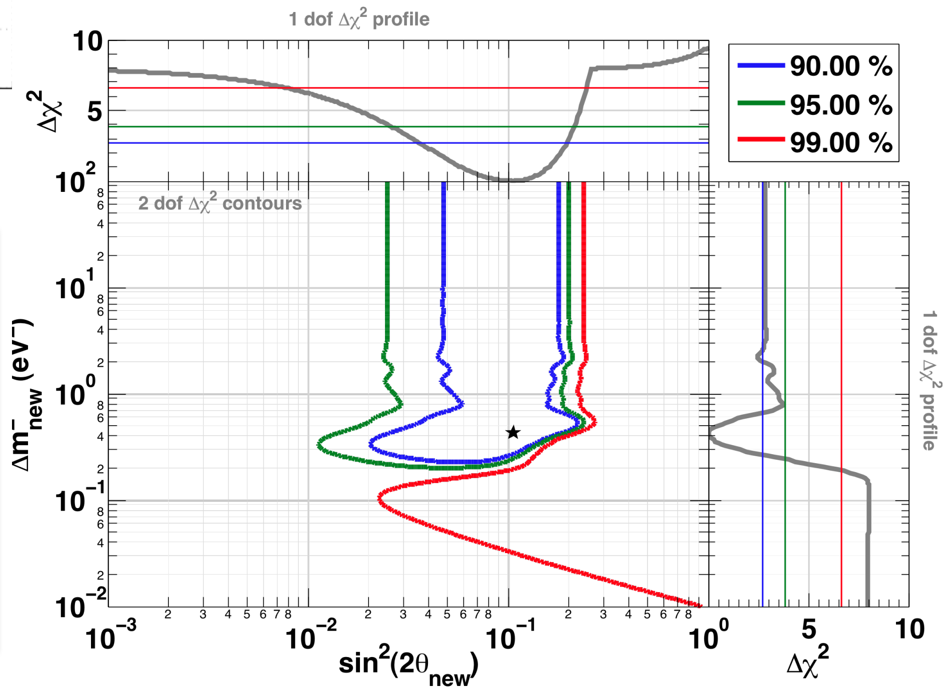
pep-n flux = $(1.6 \pm 0.3)\times 10^{8}$ cm^{-2} s^{-1}
CNO-n flux < 7.4×10^{8} cm^{-2} s^{-1}

The Borexino Solar neutrino spectroscopy



Next future: sterile neutrinos?





Several anomalies/hints for $\Delta m^2 \sim 1$ eV^2:

reactor anomaly

gallium anomaly

LSND

MiniBooNE

cosmological constraints

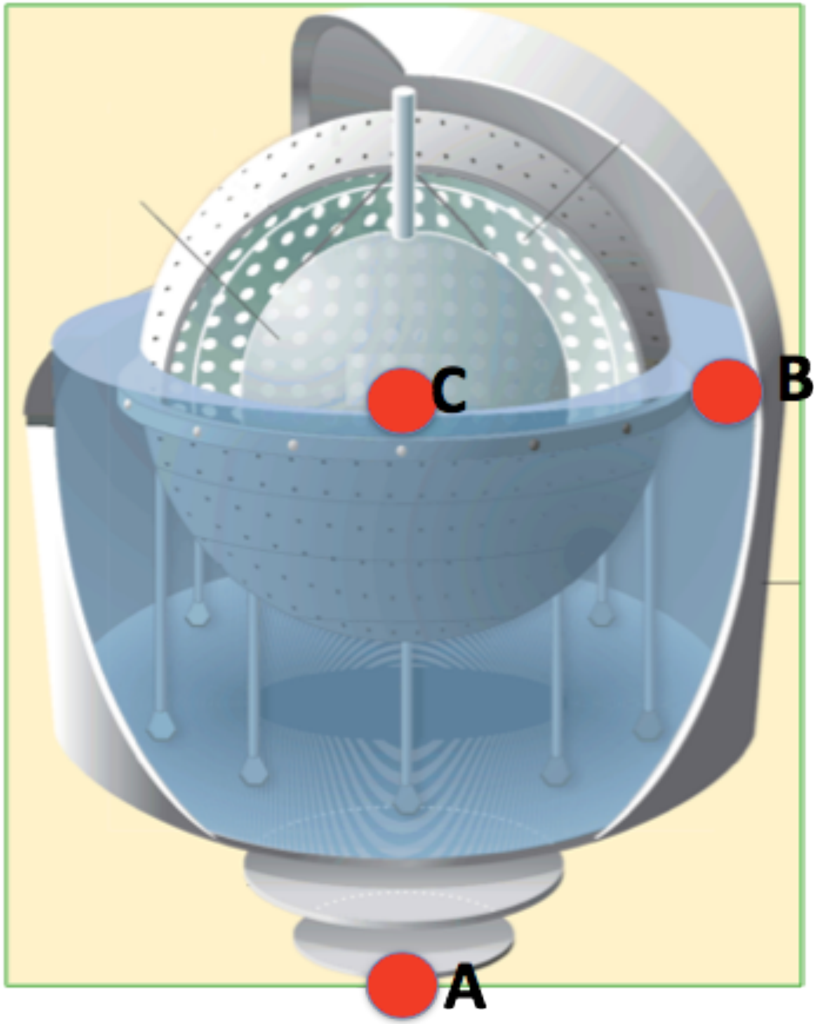
A neutrino/anti-neutrino source in Borexino

The physics

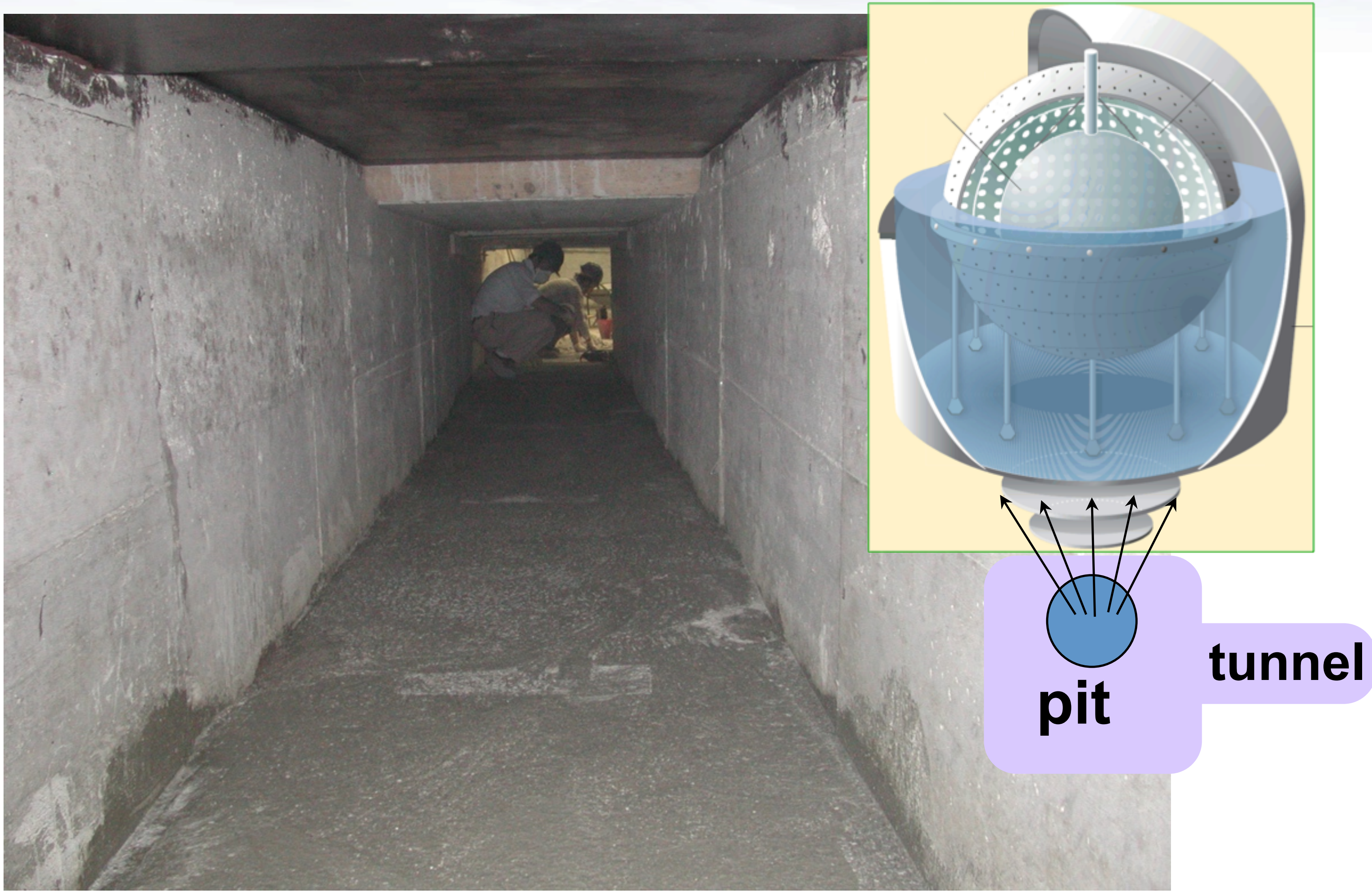
- Neutrino magnetic moment
- Neutrino-electron non standard interactions
- ν_e- e weak couplings at 1 MeV scale
- Sterile neutrinos at 1 eV scale
- Neutrino vs anti-neutrino oscillations on 10 m scale

The location

- A: underneath - D = 825 cm - No change to present configuration
- B: inside - D = 700 cm - Need to remove shielding water
- C: center - Major change - Remove inner vessels



The Icarus pit



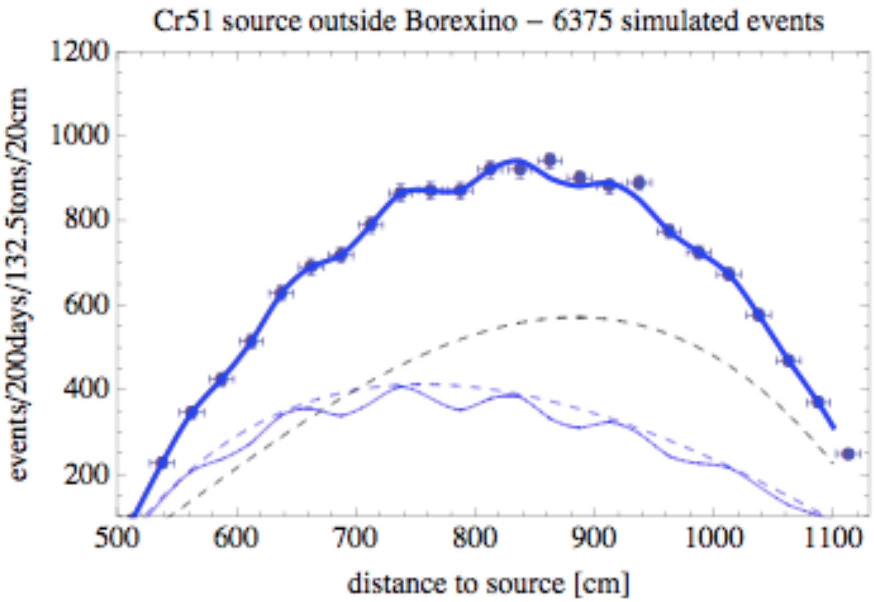
The source candidates

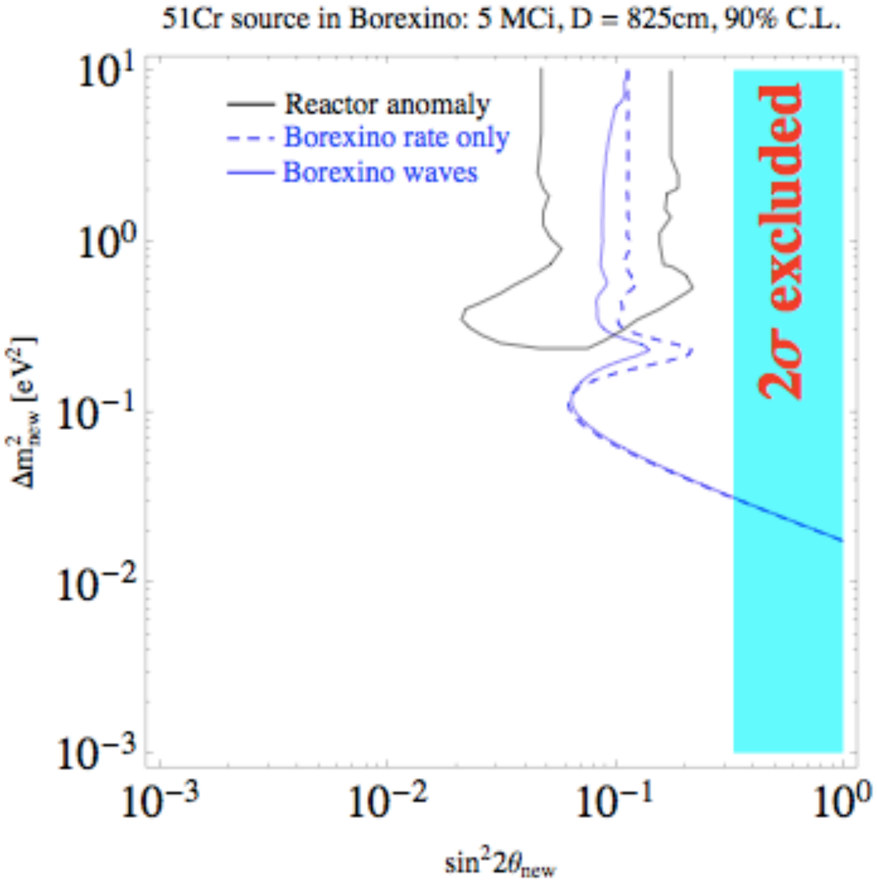
Sources in the Icarus Pit

Source	<E> [MeV]	R_{FV} [m]	Interaction channel	L_{osc}[m] Δm^2=0.1 eV^2	L_{osc}[m] Δm^2=1.5 eV^2	N_{ev}/MCi	$N_{background}$
51Cr	0.71	3.3	ES	17.5	1.2	~1426 200 days	~9700 200 days
37Ar	0.81	3.3	ES	20	1.3	~1875 200 days	~7520 200 days
90Sr-90Y	0.86	3.3	ES	21	1.4	~31419 1year	~14100 1year
90Y	2.0	4.25	IBD	49	3.3	~17596 1year	~12 1 year
106Rh	2.5	4.25	IBD	61.8	4.1	~156689 1year	~12 1 year

An example: 5 MCi ^{51}Cr in the Icarus Pit

$(\Delta m^2, \sin^2 2\theta_{SBL}) = (2eV^2, 0.15)$





Conclusion

- ✓ Borexino opened the study of the solar neutrinos in real time below the barrier of natural radioactivity (5 MeV)
  - ✓ Three measurements reported for **^{7}Be** neutrinos
  - ✓ Best limits for ***pp*** and **CNO** neutrinos, combining information from SNO and radiochemical experiments
  - ✓ First real time measurement of ***pep***
  - ✓ First observation of **^{8}B** neutrino spectrum below 5 MeV
- ✓ First observation of **geoneutrinos**
- ✓ Best limit on neutrino **magnetic moment**
- ✓ Potential in **sterile neutrinos**
- ✓ **Superluminal neutrinos**

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