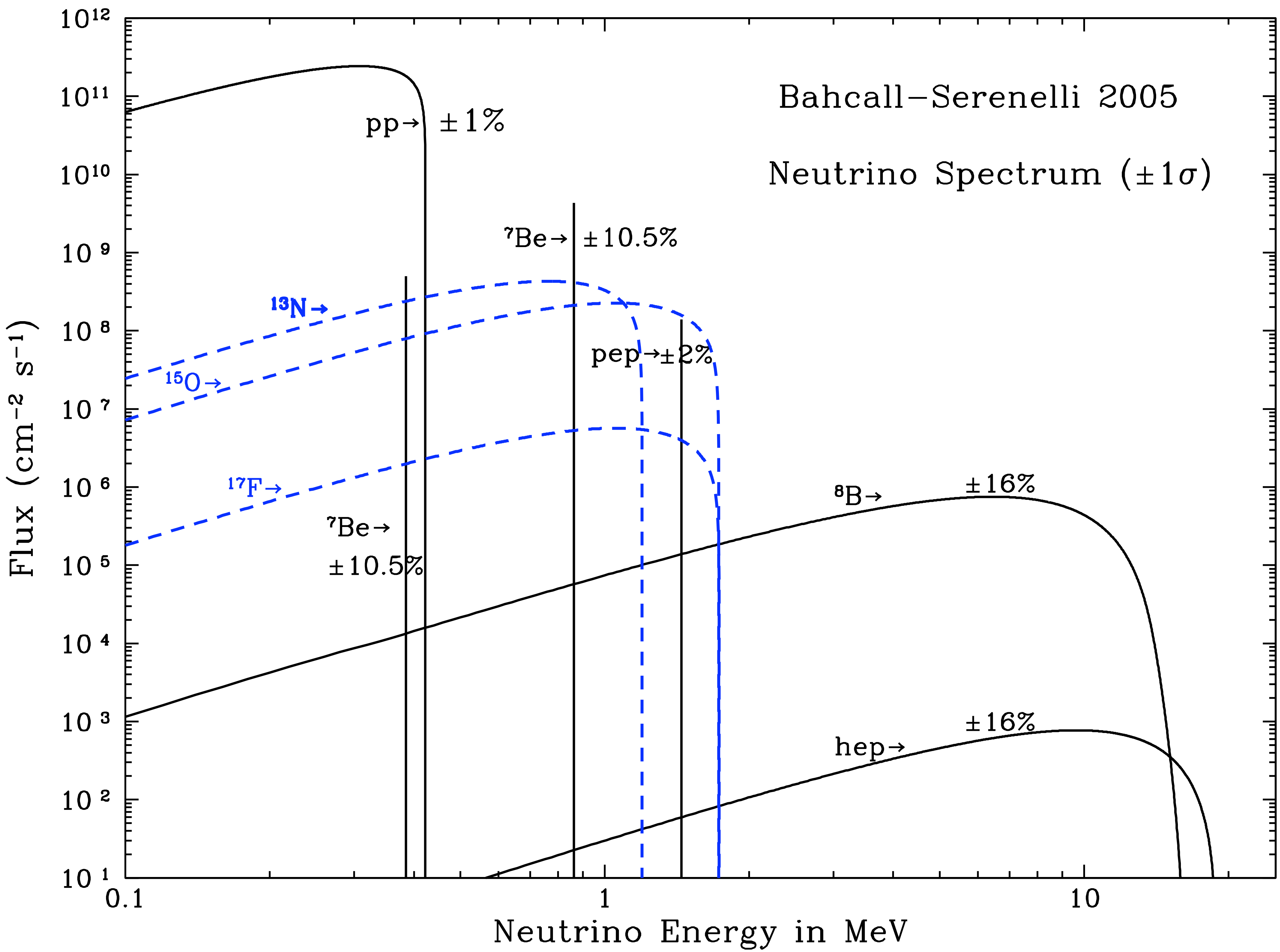
Borexino

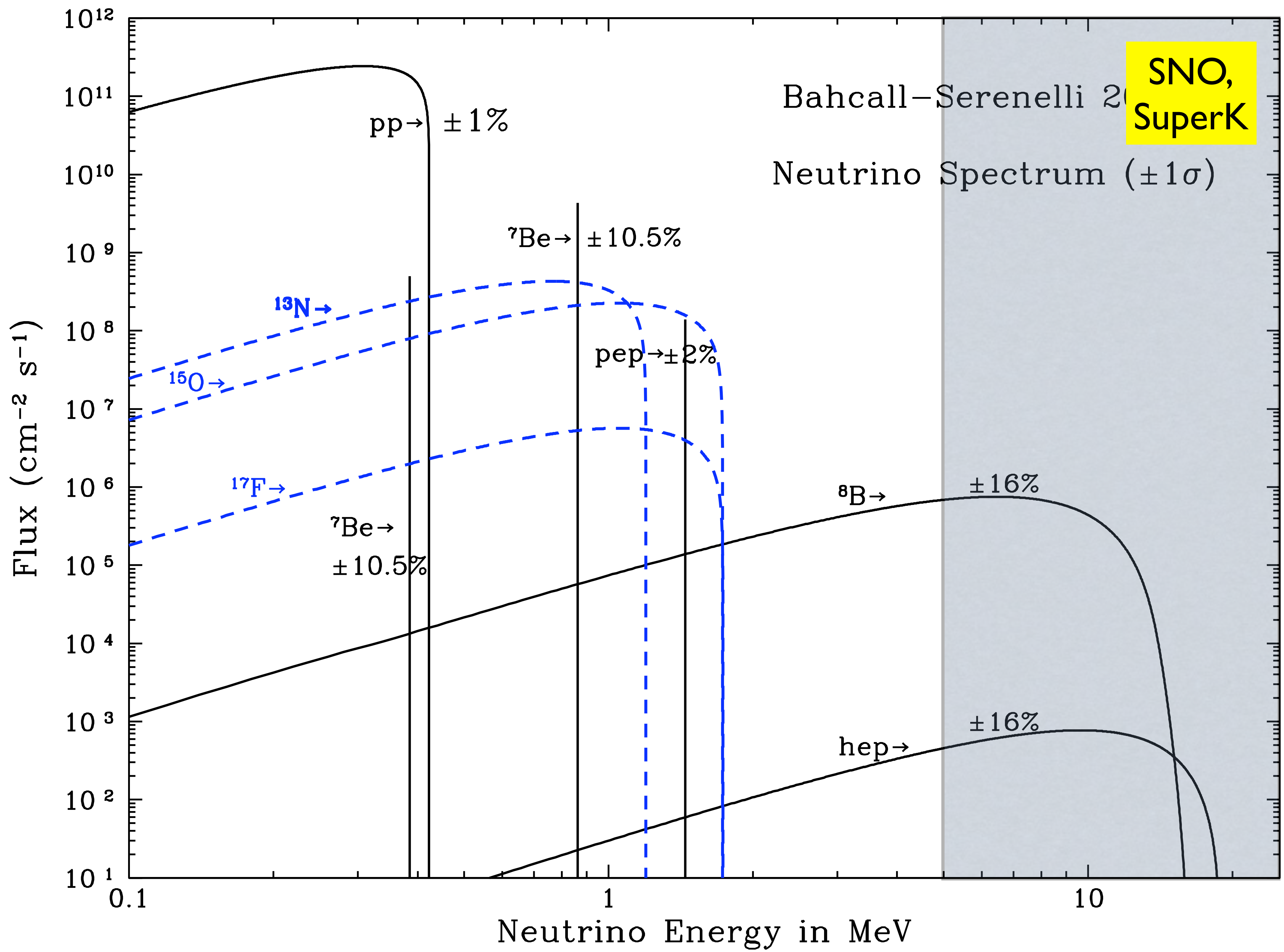
XVI Neutrino Telescopes
Venezia
March 3, 2015

Cristiano Galbiati
Princeton University
on behalf of
Borexino Collaboration

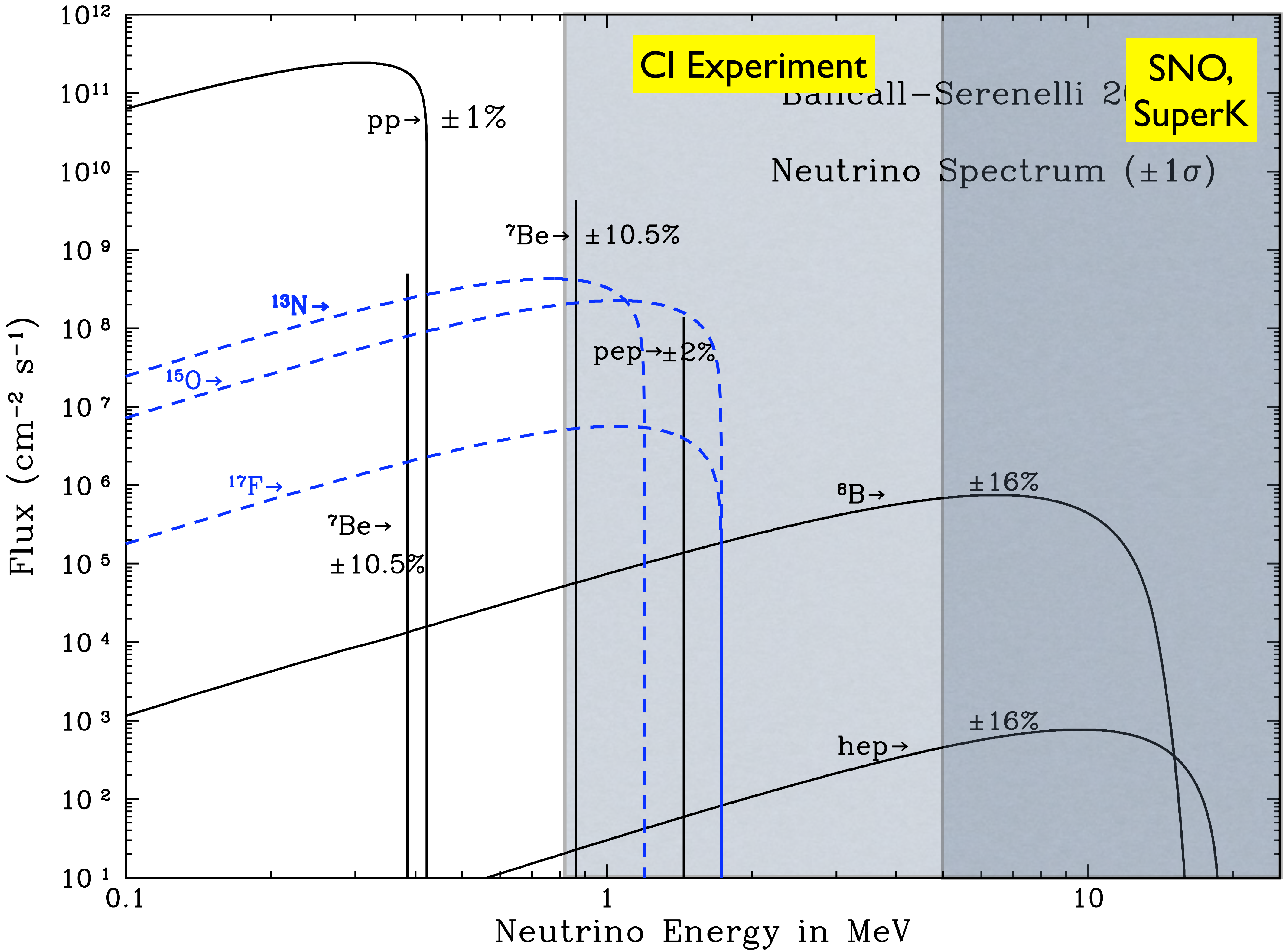
Solar Neutrinos Spectrum



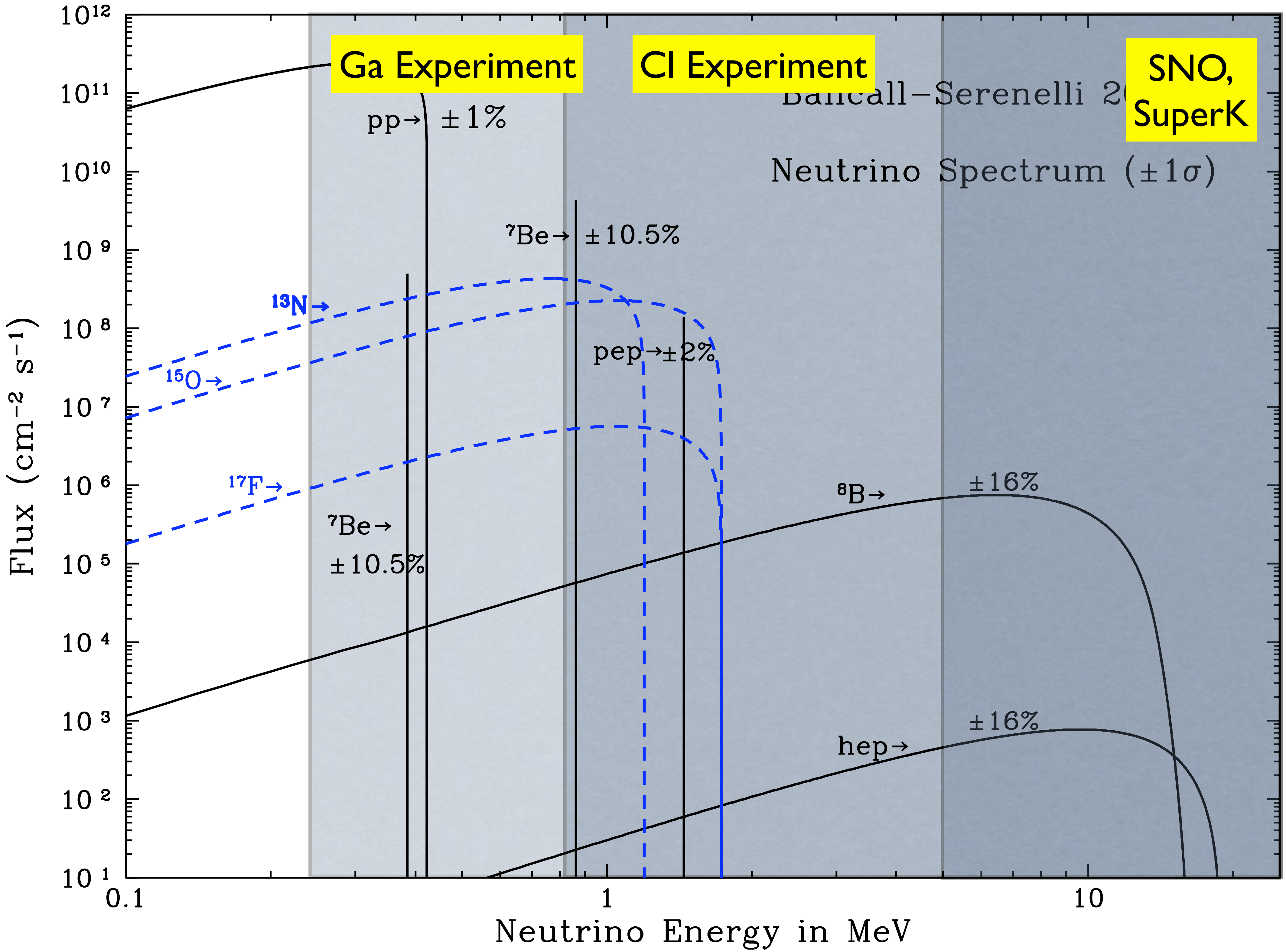
Solar Neutrinos Spectrum



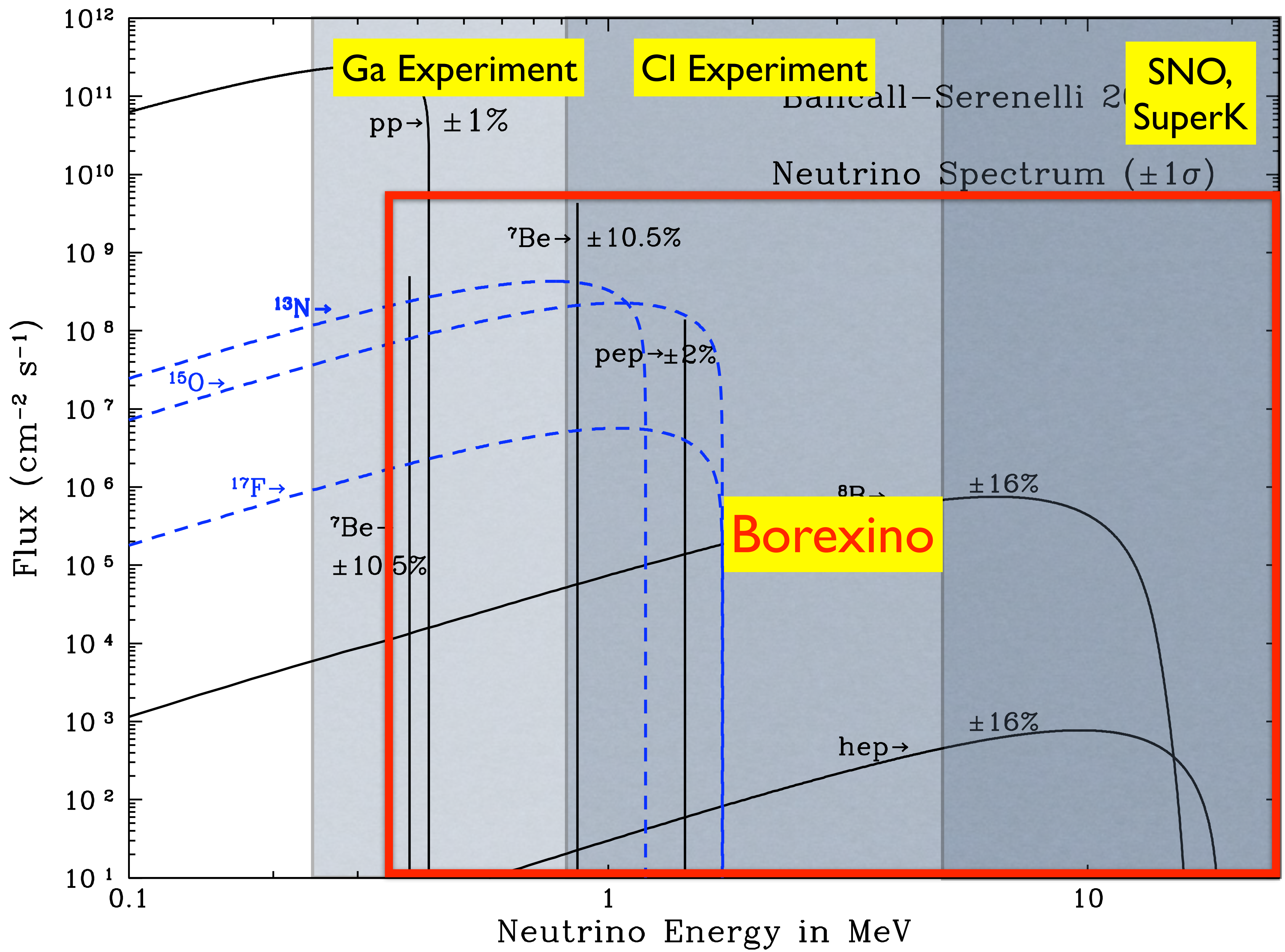
Solar Neutrinos Spectrum



Solar Neutrinos Spectrum



Solar Neutrinos Spectrum



Resonant Oscillations in Matter: the MSW effect

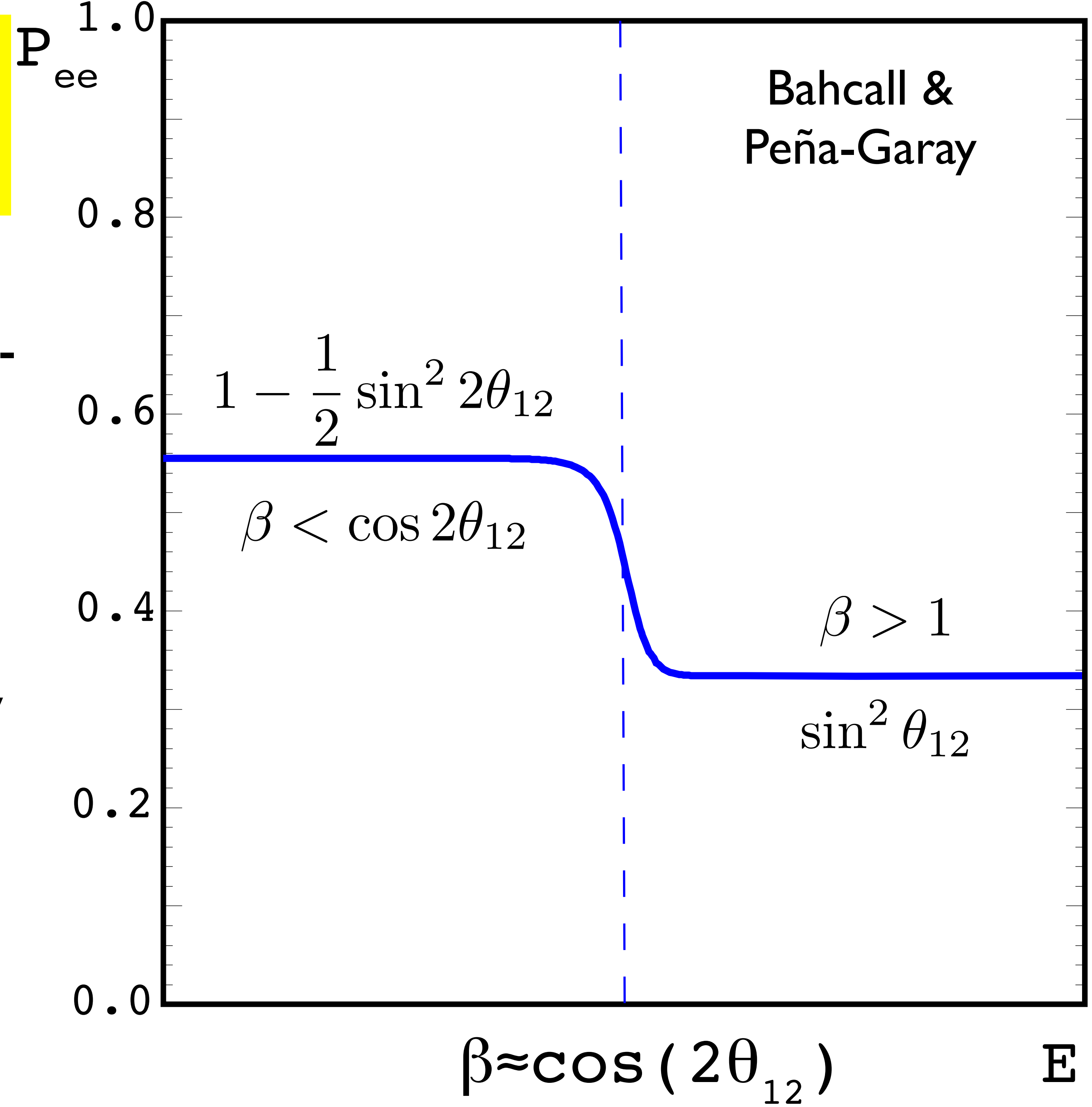
For high energy ^{8}B neutrinos - object of observation by SNO and SuperKamiokaNDE - matter dominated oscillations in the high density of electrons N_e in sun's core

For low energy neutrinos, flavor change dominated by vacuum oscillations.

Regime transition expected between 1-2 MeV

Fundamental prediction of MSW-LMA theory
Exploring the vacuum-matter transition:
- untested feature of MSW-LMA solution
- possibly sensitive to new physics

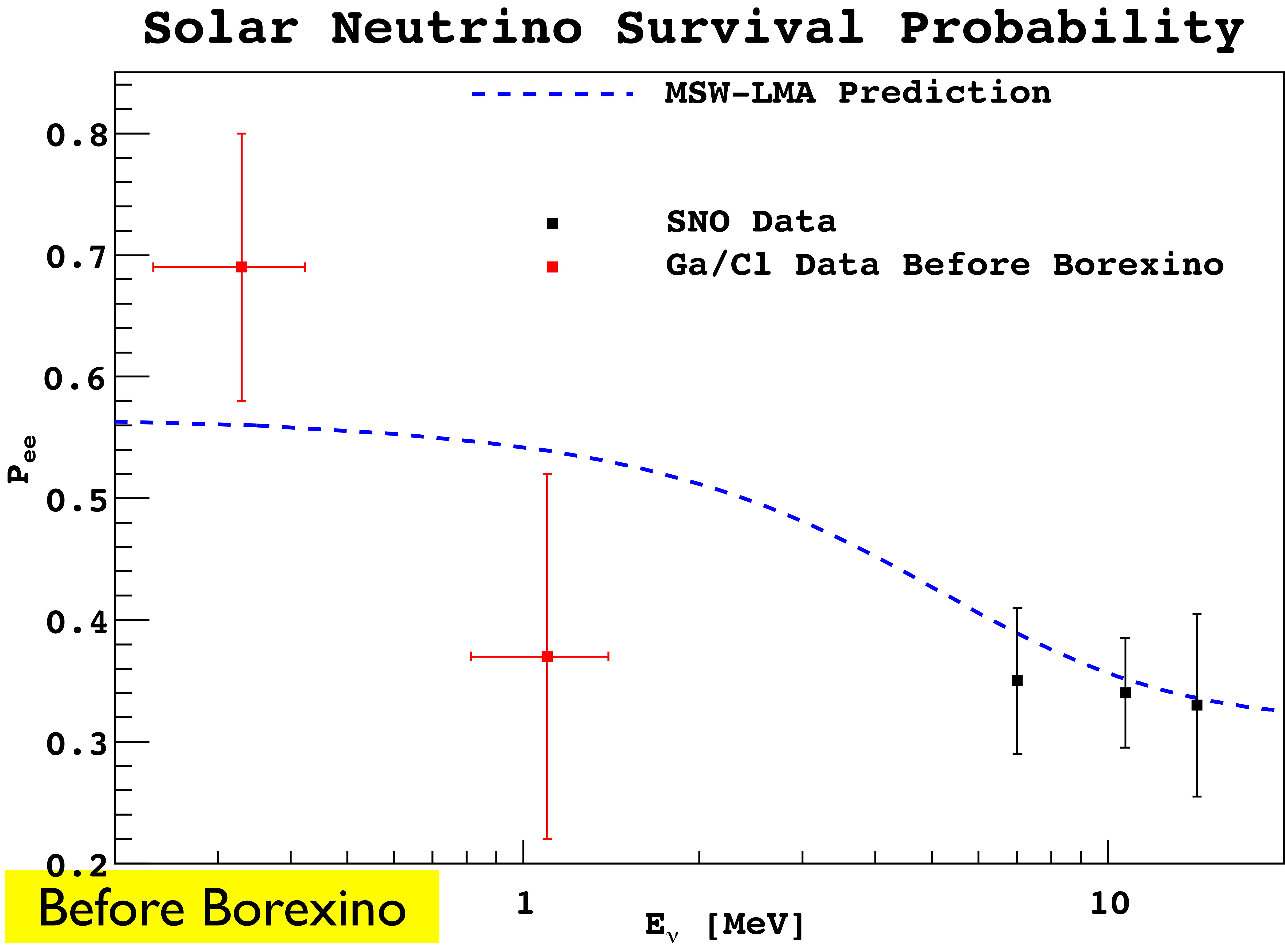
pep and ^{7}Be neutrinos good sources to study the transition!



$$\begin{pmatrix} -\frac{\Delta m^2_{12}}{4E}\cos 2\theta_{12} + \sqrt{2}G_F N_e & \frac{\Delta m^2_{12}}{4E}\sin 2\theta_{12} \\ \frac{\Delta m^2_{12}}{4E}\sin 2\theta_{12} & \frac{\Delta m^2_{12}}{4E}\cos 2\theta_{12} \end{pmatrix}$$

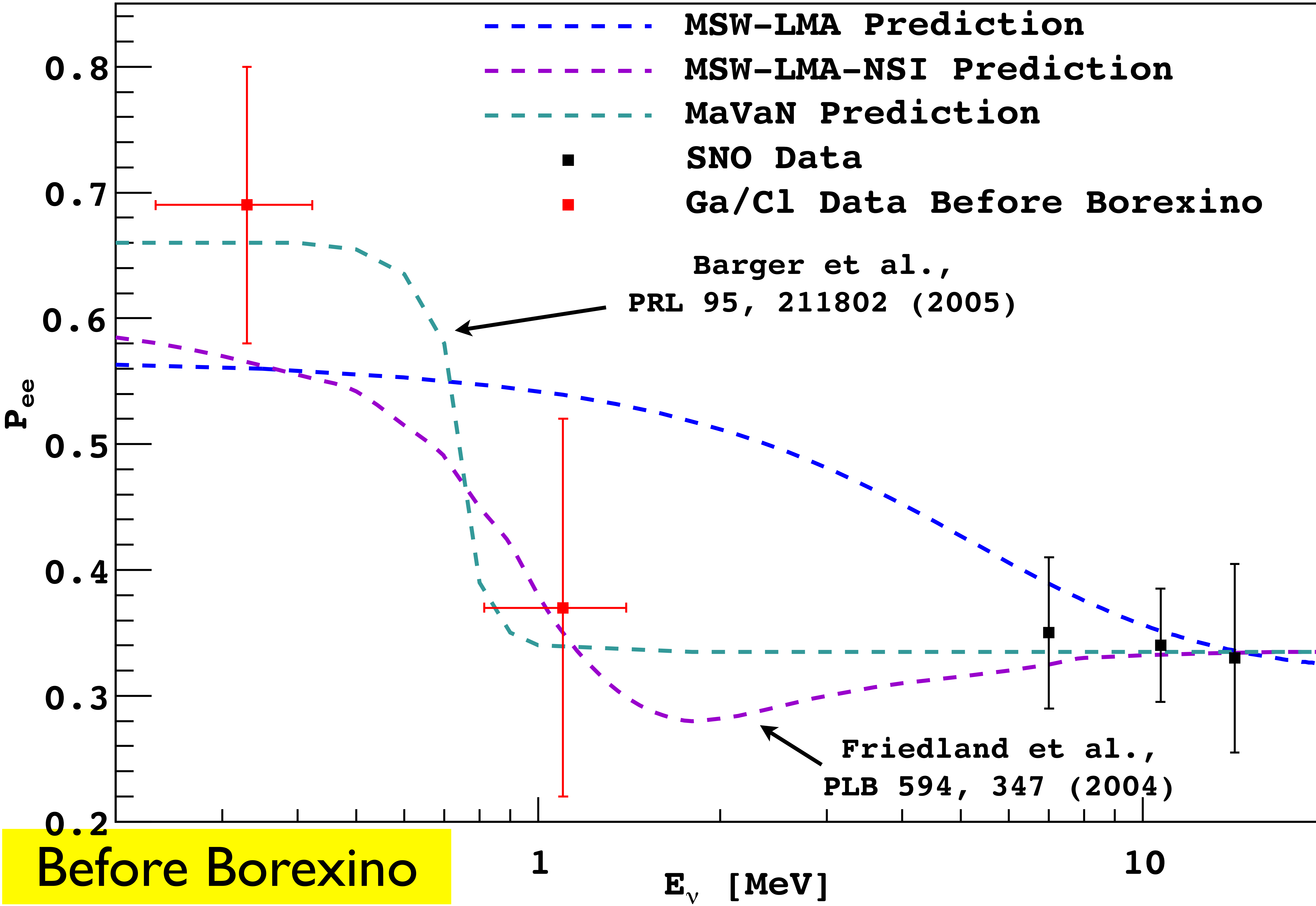
$$\beta = \frac{2^{3/2}G_F N_e E}{\Delta m^2} = 0.22\left[\frac{E}{1\ \mathrm{MeV}}\right]\left[\frac{\rho\cdot Z/A}{100\ \mathrm{g\ cm^{-3}}}\right]\left[\frac{7\times 10^{-5}\ \mathrm{ev}^2}{\Delta m^2}\right]$$

$$E[\mathrm{MeV}] = 6.8\times 10^6\,\frac{\cos(2\theta_{12})\Delta \mathrm{m}^2_{12}[\mathrm{eV}^2]}{\rho[\mathrm{g/cm}^3]\mathrm{Z/A}} \simeq 1\text{–}2\ \mathrm{MeV}$$



Solar Neutrino Survival Probability
MSW-LMA Prediction
SNO Data
Ga/Cl Data Before Borexino
P_{ee}
0.8
0.7
0.6
0.5
0.4
0.3
0.2
1
10
E_ν [MeV]
Before Borexino

Solar Neutrino Survival Probability



Borexino: the Science Goals

- To make the first ever observations of sub-MeV neutrinos in real time, especially for ^{7}Be neutrinos, testing the Standard Solar Model and the MSW-LMA solution of the Solar Neutrino Problem
- To provide a strong constraint on the ^{7}Be rate, at or below 5%, such as to provide an essential input to check the balance between photon luminosity and neutrino luminosity of the Sun

J.N. Bahcall and C. Pena-Garay, JHEP 11, 004 (2003)

$$\frac{\mathcal{L}_\odot(\mathrm{neutrino-inferred})}{\mathcal{L}_\odot(\mathrm{photon})} = 1.4^{+0.2}_{-0.3}\left({}^{+0.7}_{-0.6}\right)$$

balance check at 1% level ideal. Requires ^{7}Be flux measured at 5% and *pp* flux measured at 1% level

- To confirm the solar origin of ^{7}Be neutrinos, by checking the expected 7% seasonal variation of the signal due to the Earth's orbital eccentricity
- To explore possible traces of non-standard neutrino-matter interactions or presence of mass varying neutrinos.

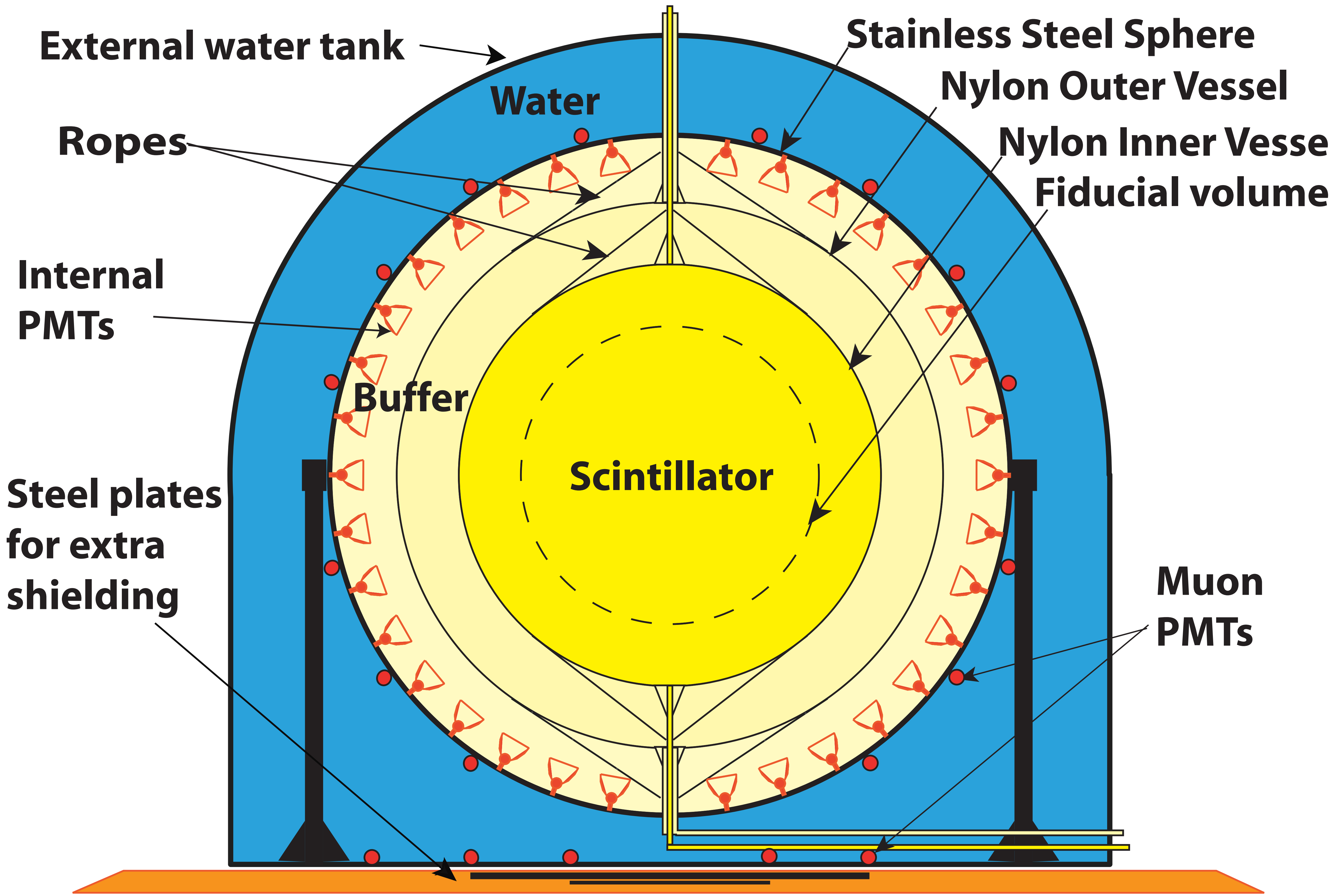
Detection Principles

- Detection via scintillation light
- Features:
  - Very low energy threshold
  - Good position recostruction by time of flight
  - Good energy resolution
- Drawbacks:
  - No direction measurements
  - ν induced events can't be distinguished from other β/γ due to natural radioactivity
- Experiment requires extreme purity from all radioactive contaminants

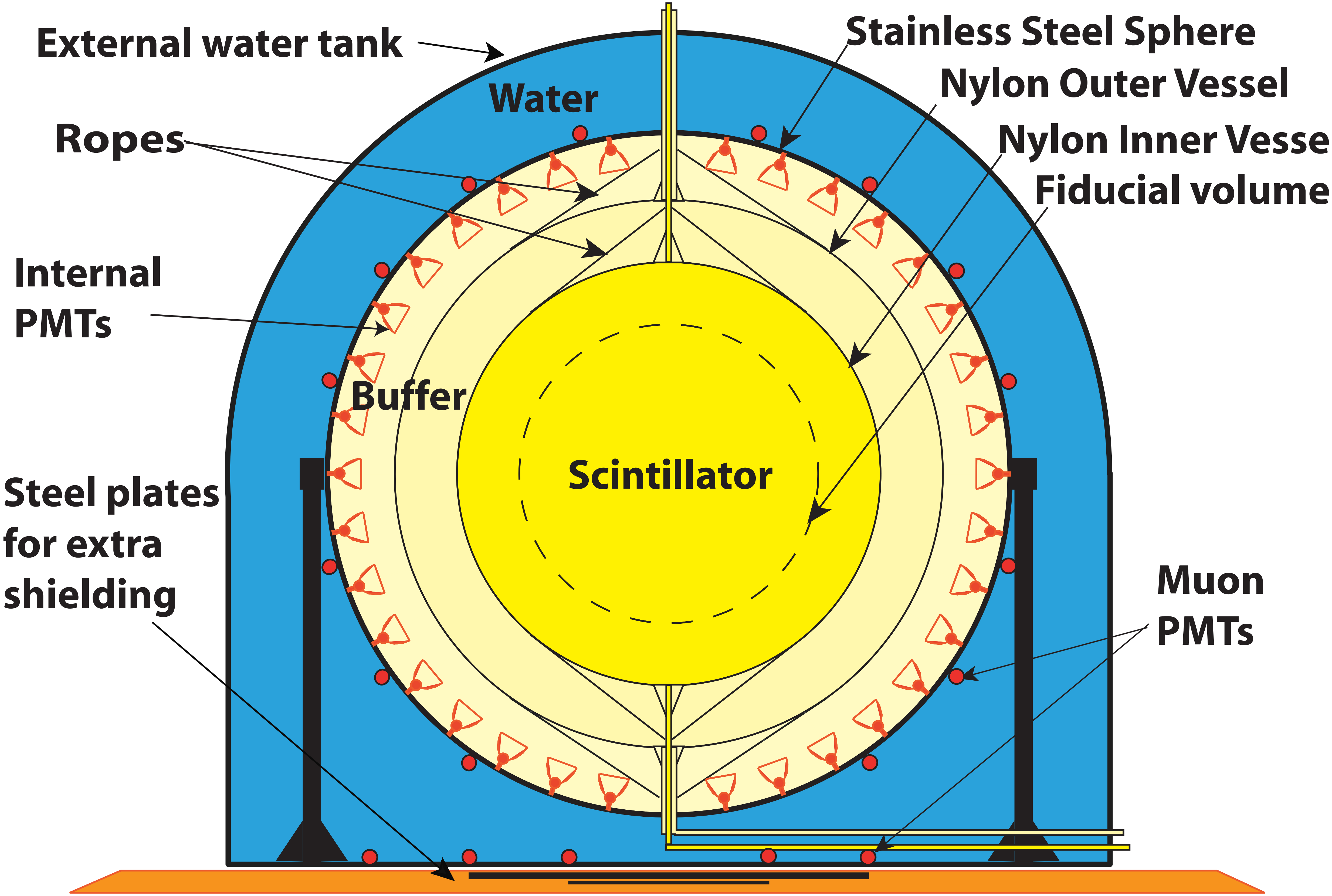
Collaboration

Astroparticle and Cosmology Laboratory – Paris, France
INFN Laboratori Nazionali del Gran Sasso – Assergi, Italy
INFN e Dipartimento di Fisica dell'Università – Genova, Italy
INFN e Dipartimento di Fisica dell'Università– Milano, Italy
INFN e Dipartimento di Chimica dell'Università – Perugia, Italy
Institute for Nuclear Research – Gatchina, Russia
Institute of Physics, Jagellonian University – Cracow, Poland
Join Institute for Nuclear Research – Dubna, Russia
Kurchatov Institute – Moscow, Russia
Max-Planck Institute fuer Kernphysik – Heidelberg, Germany
Princeton University – Princeton, NJ, USA
Technische Universität – Muenchen, Germany
University of Massachusetts at Amherst, MA, USA
University of Moscow – Moscow, Russia
Virginia Tech – Blacksburg, VA, USA

Borexino Detector

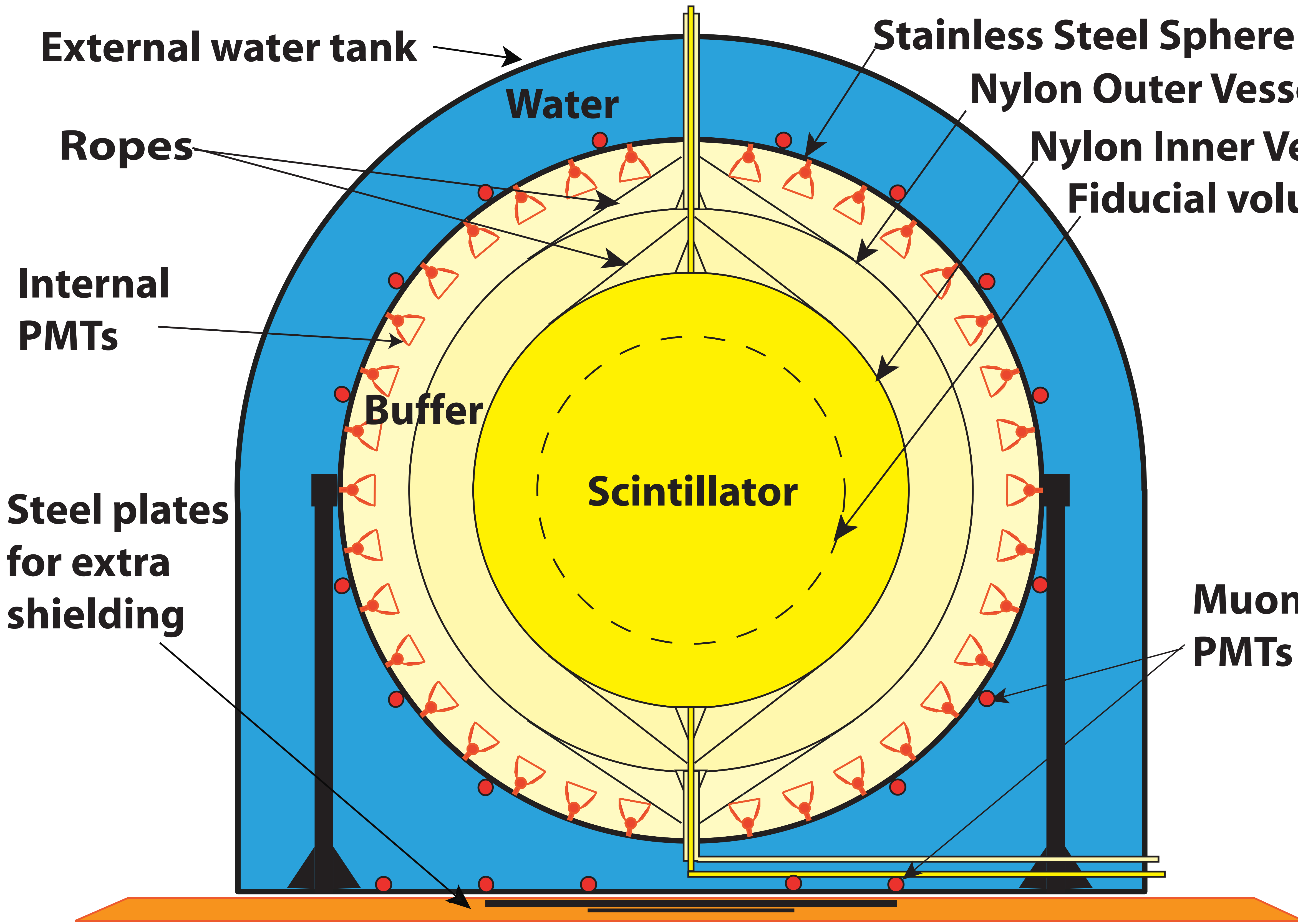


Borexino Detector



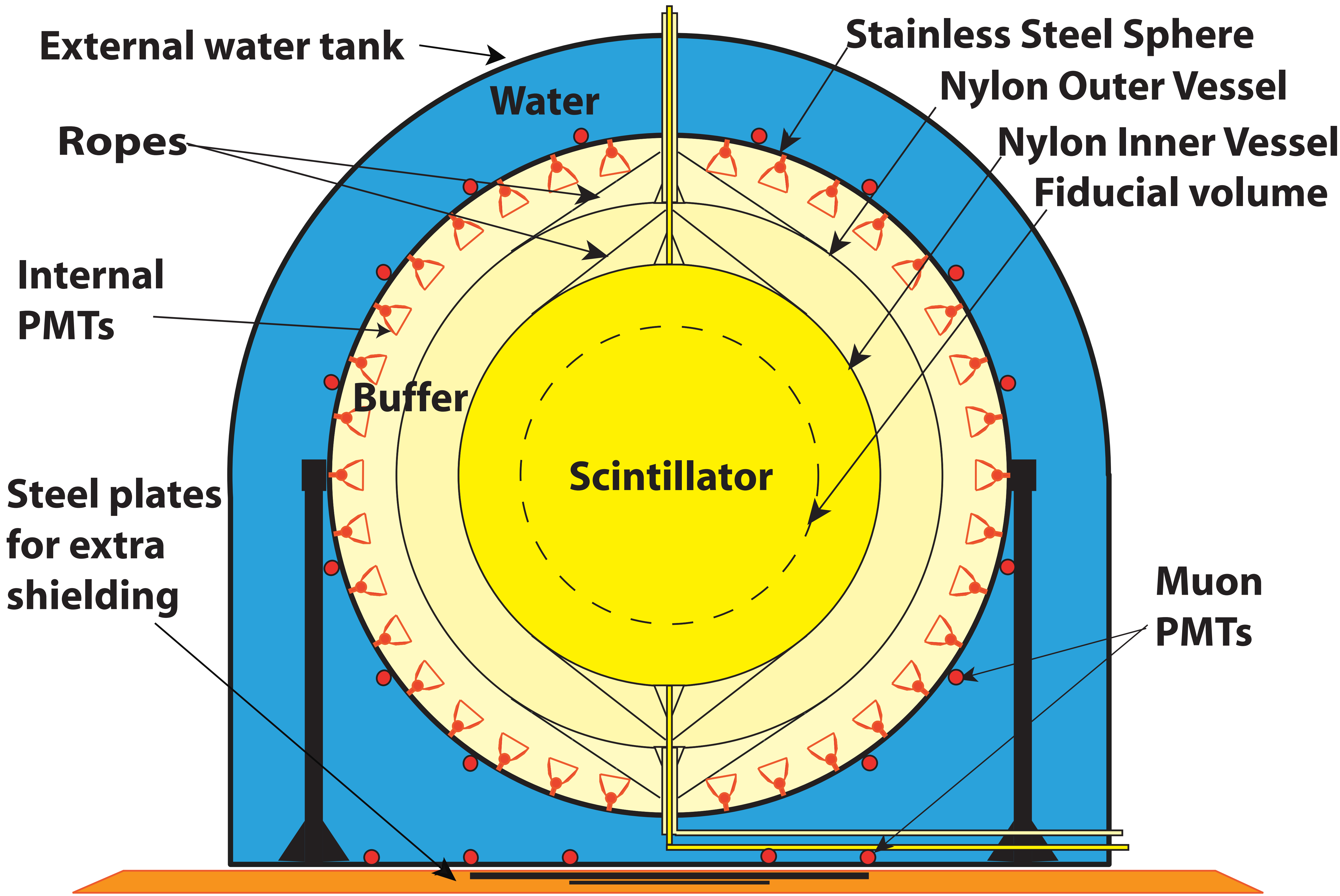
Located in LNGS - 3800 m.w.e. against cosmic rays

Borexino Detector



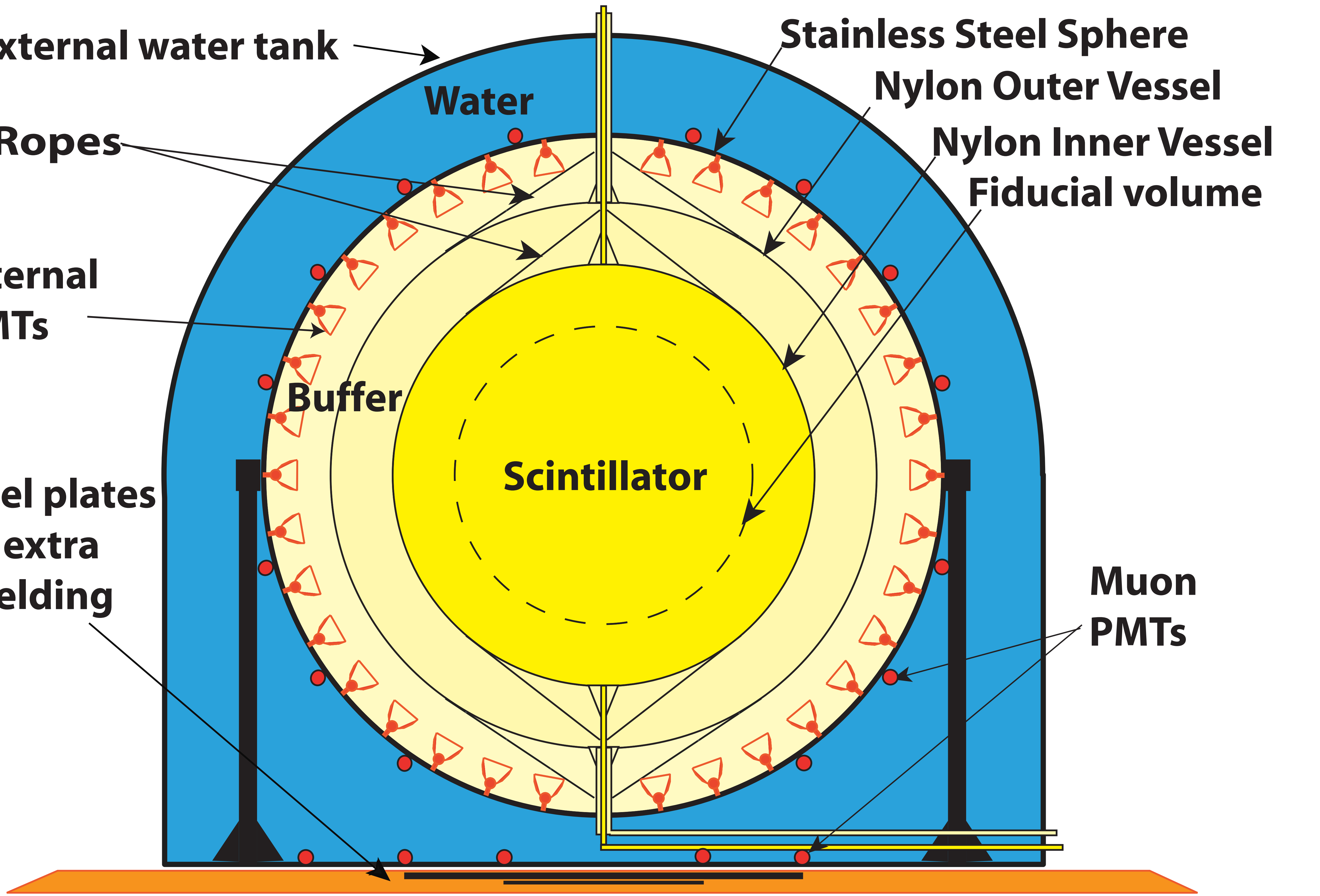
Active Target: 278 Tons of Liquid Scintillator
in Nylon Vessel of 4.25 m radius

Borexino Detector



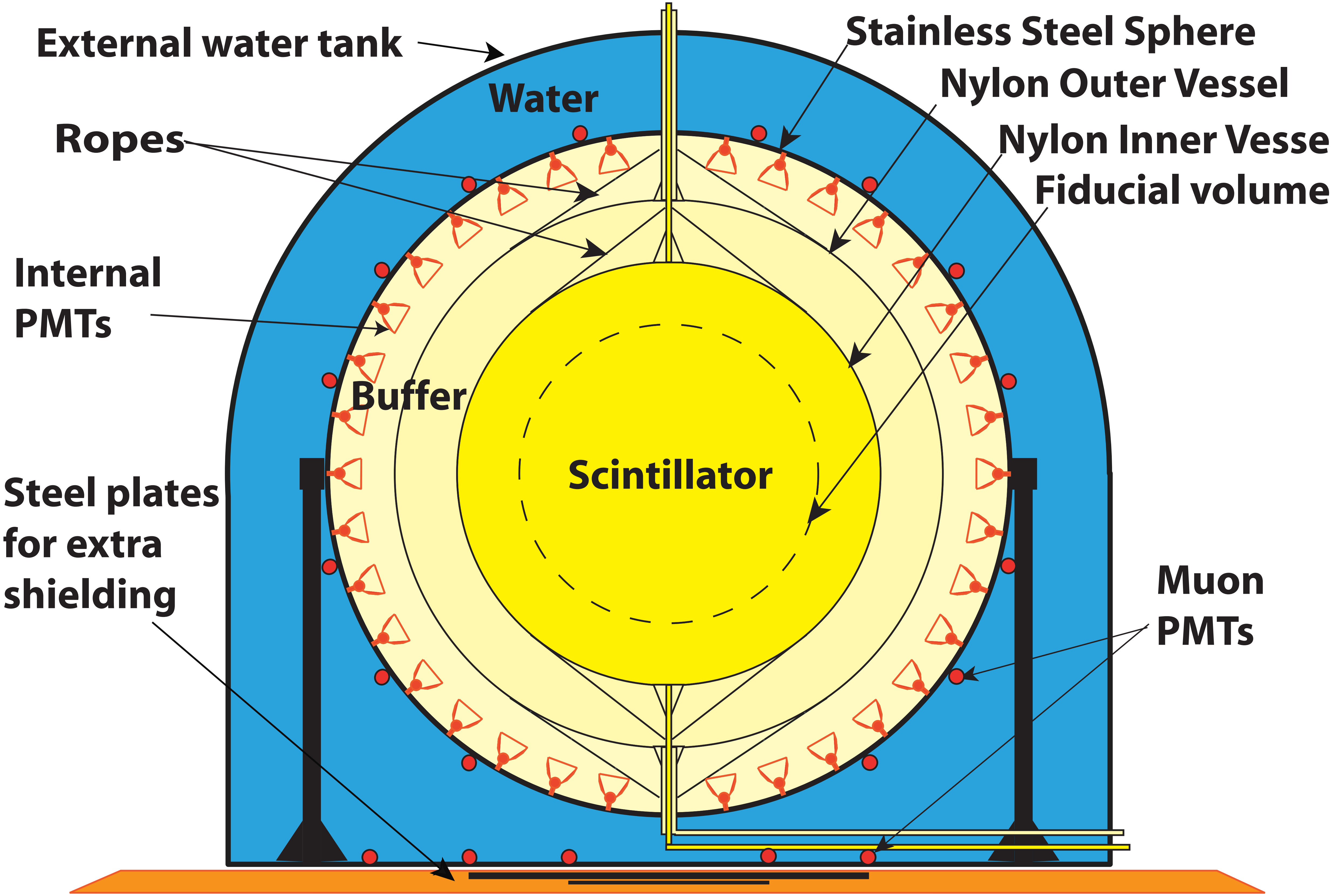
1[st] shield: 890 tons of ultra-pure buffer liquid
in a stainless steel sphere of 6.75 m radius

Borexino Detector



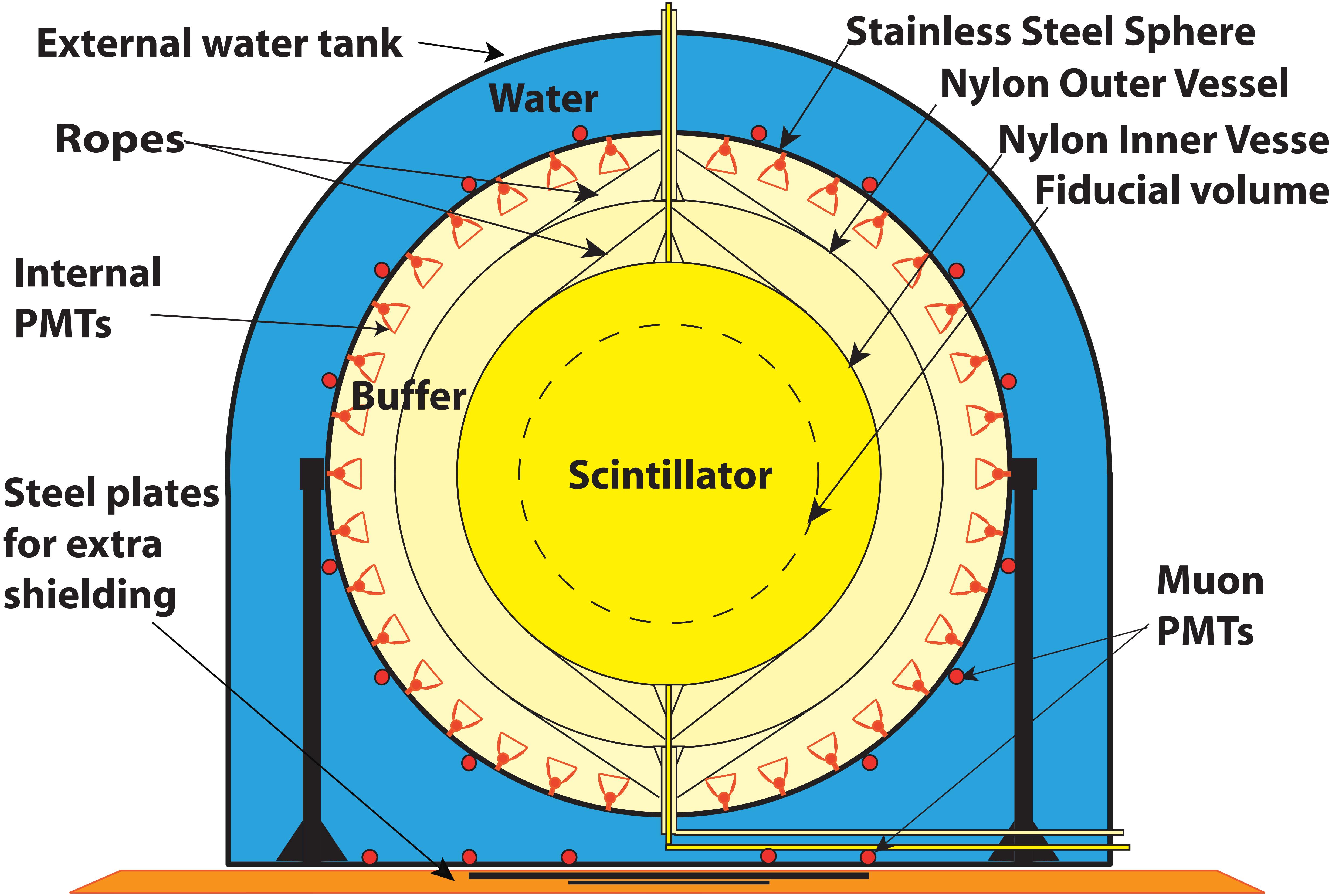
External nylon vessel - A barrier against Rn emitted by PMTs and Stainless Steel

Borexino Detector



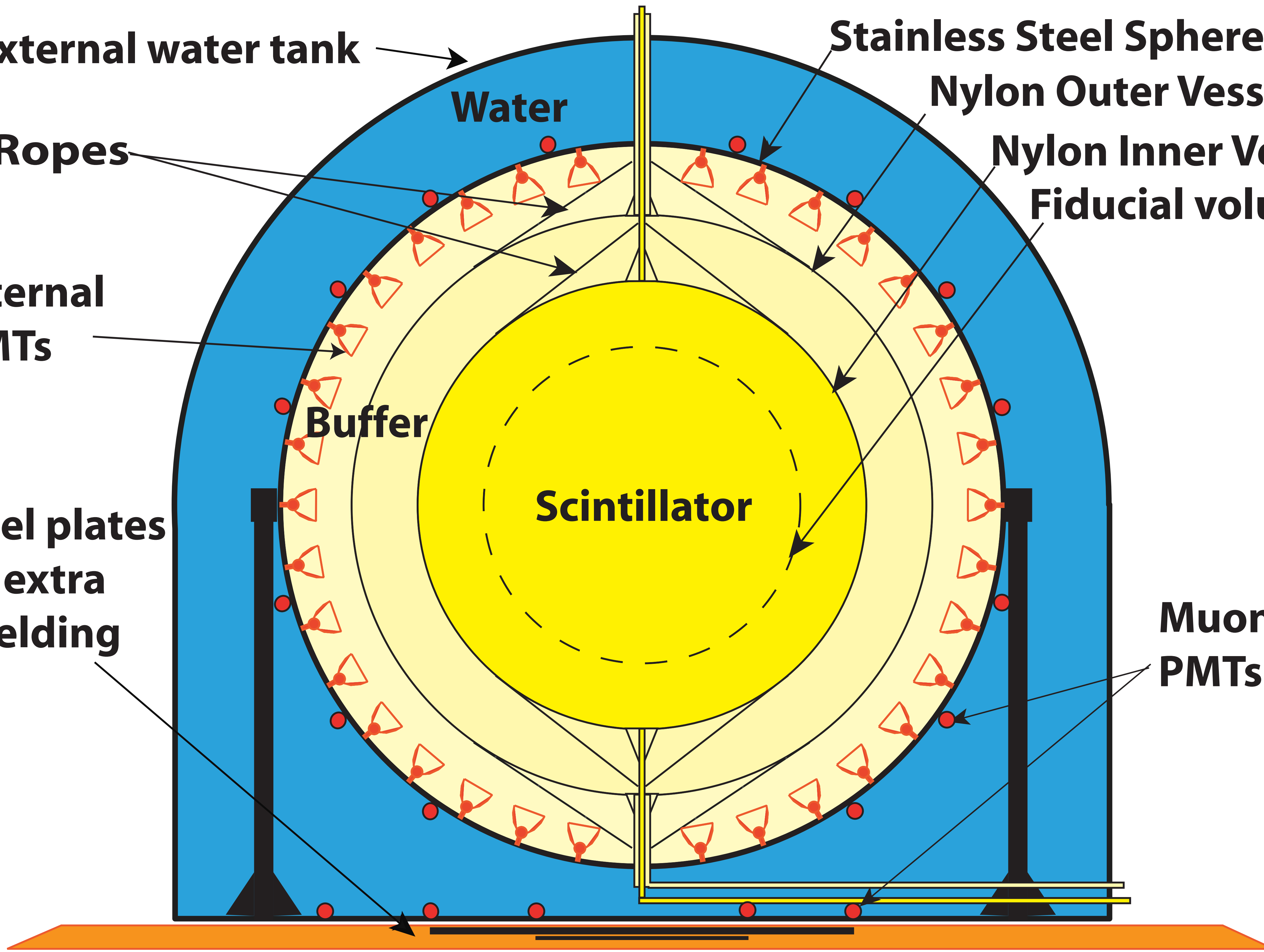
2214 PMTs detect light emitted by the scintillator
1843 with optical concentrators, the rest without for muons

Borexino Detector



2nd shield: 2100 tons of ultra-pure water in a cylindrical dome

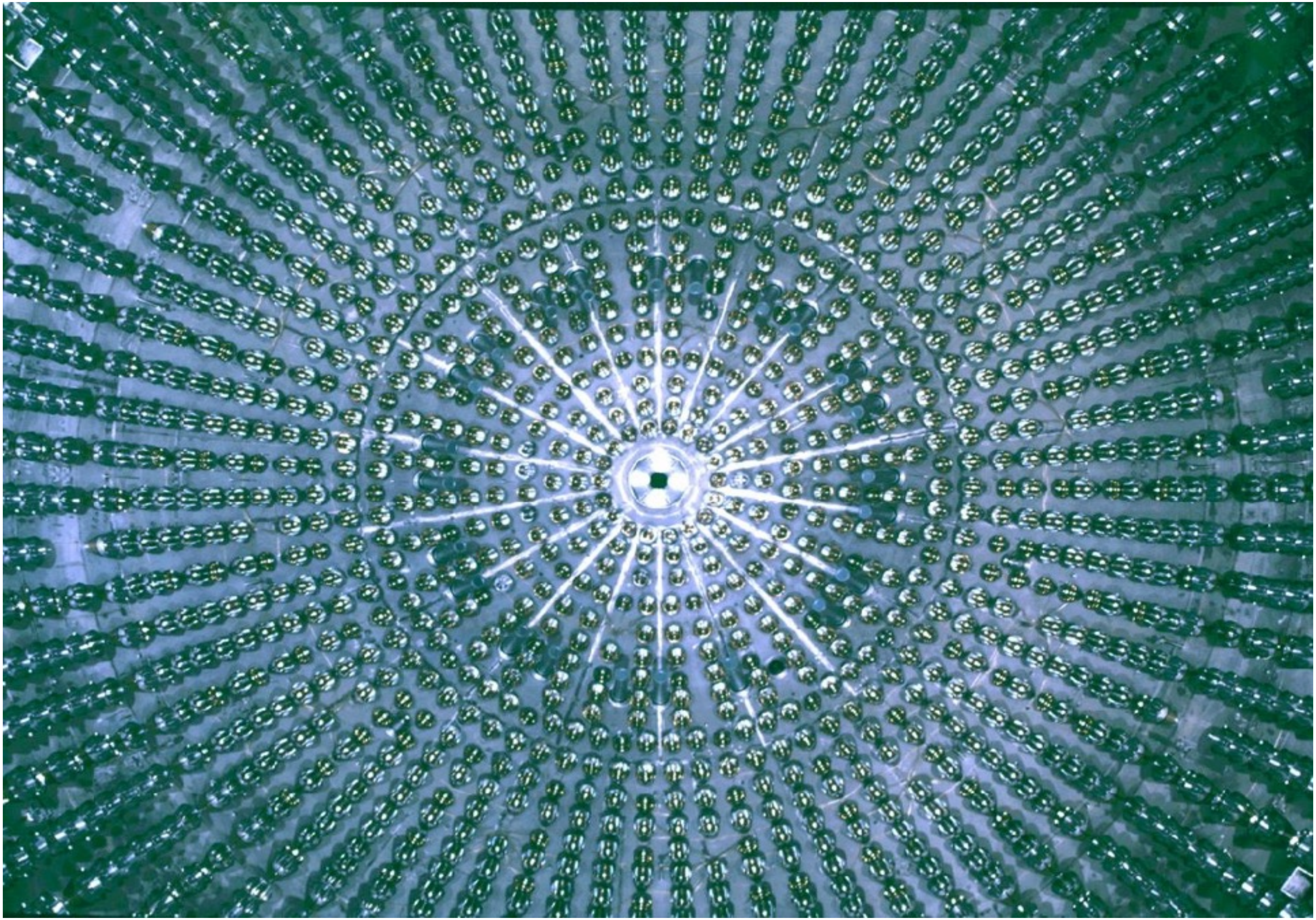
Borexino Detector

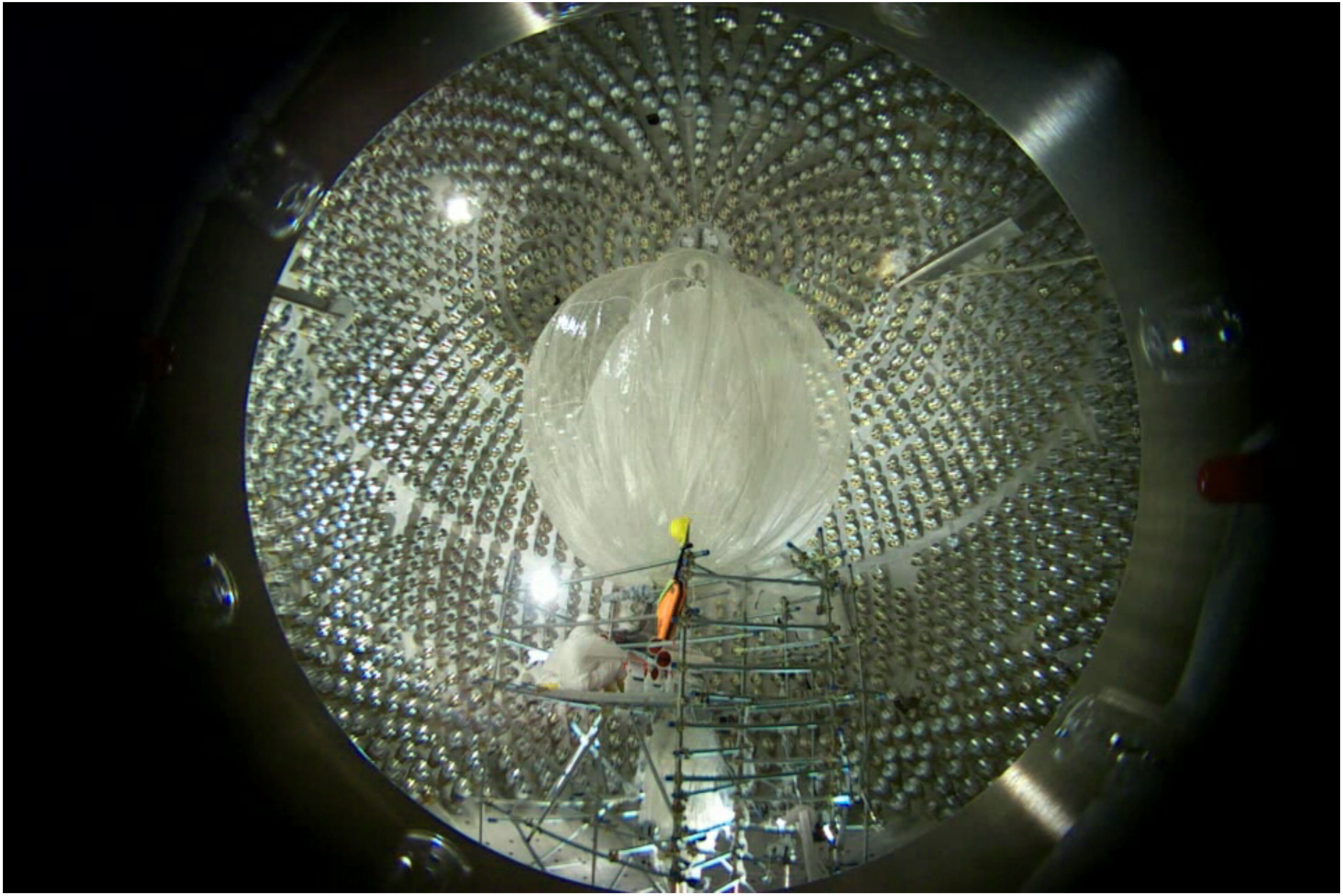


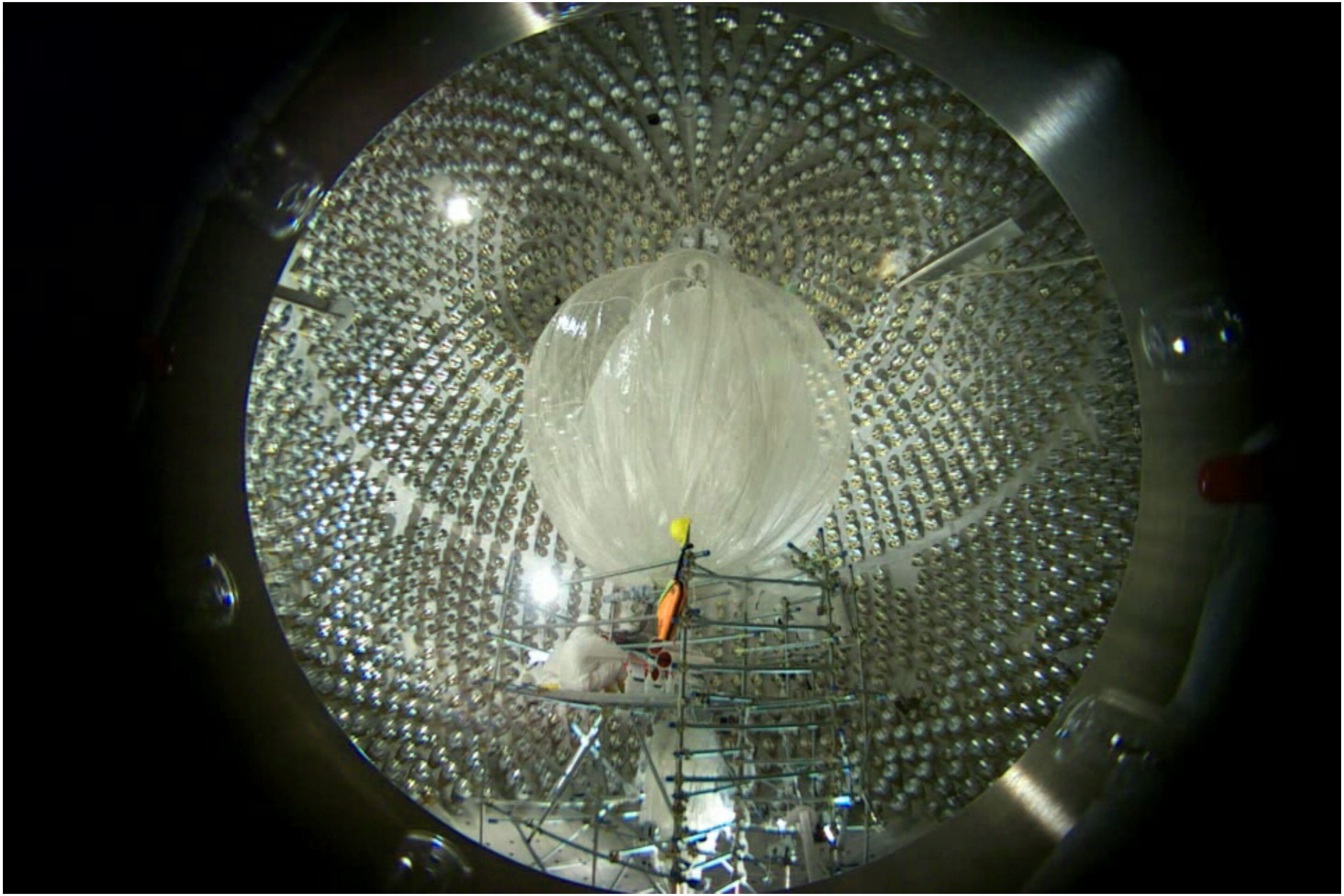
200 PMTs mounted on the SSS detect
Cherenkov light emitted in the water by muons

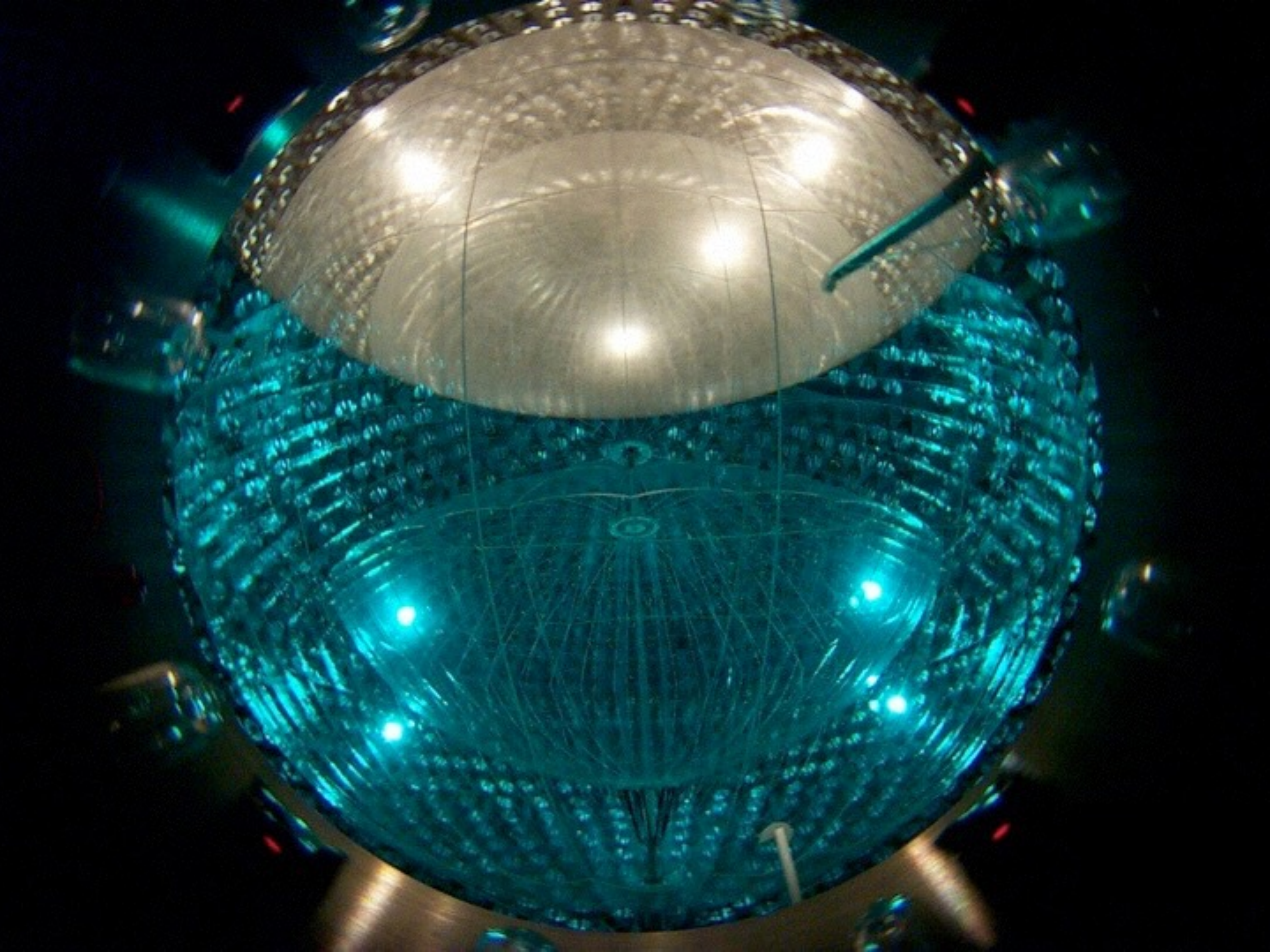
Special Methods Developed

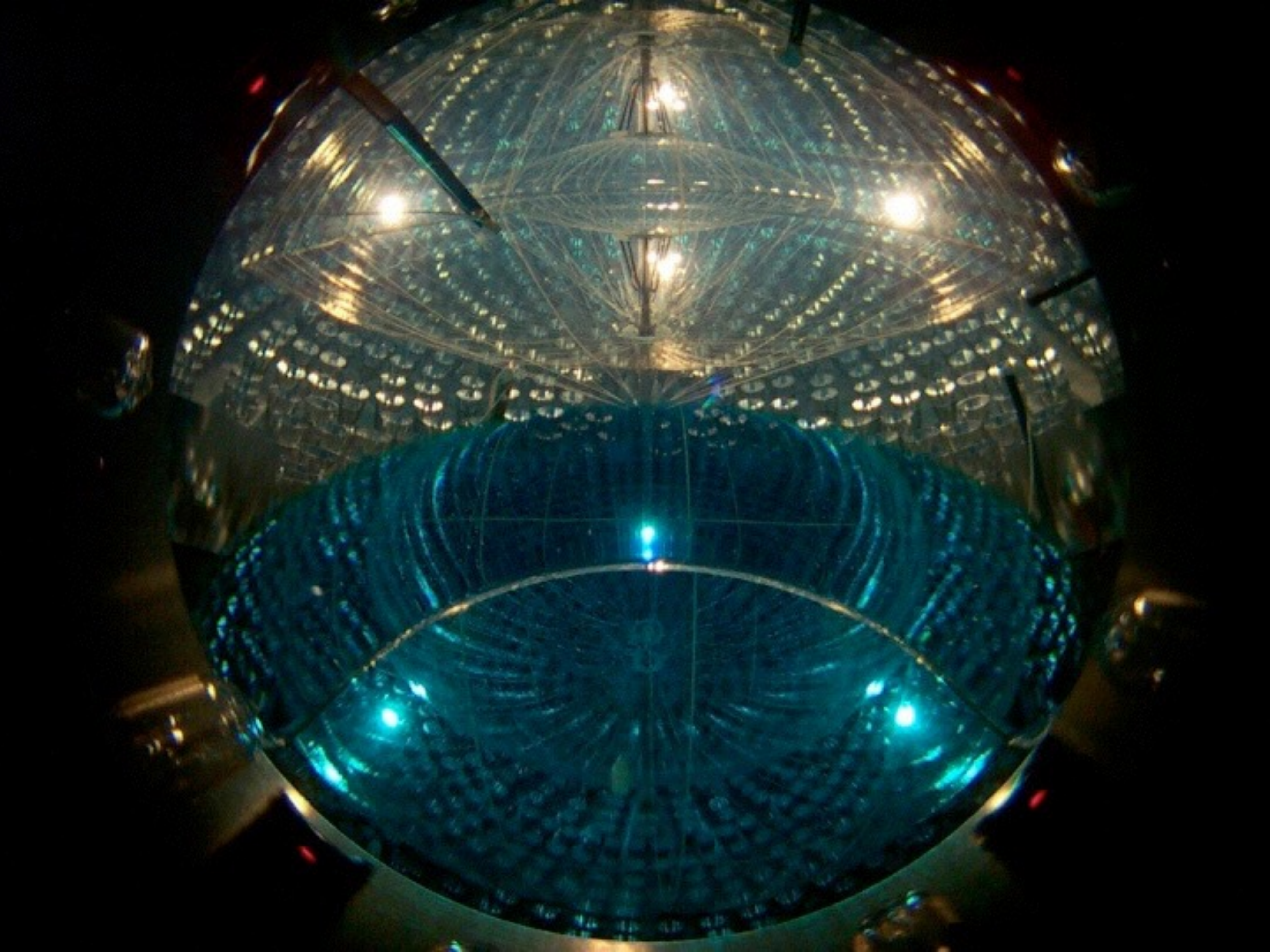
- Low background nylon vessel fabricated in hermetically sealed low radon clean room (~1 yr)
- Rapid transport of scintillator solvent (PC) from production plant to underground lab to avoid cosmogenic production of radioactivity (^{7}Be)
- Underground purification plant to distill scintillator components.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

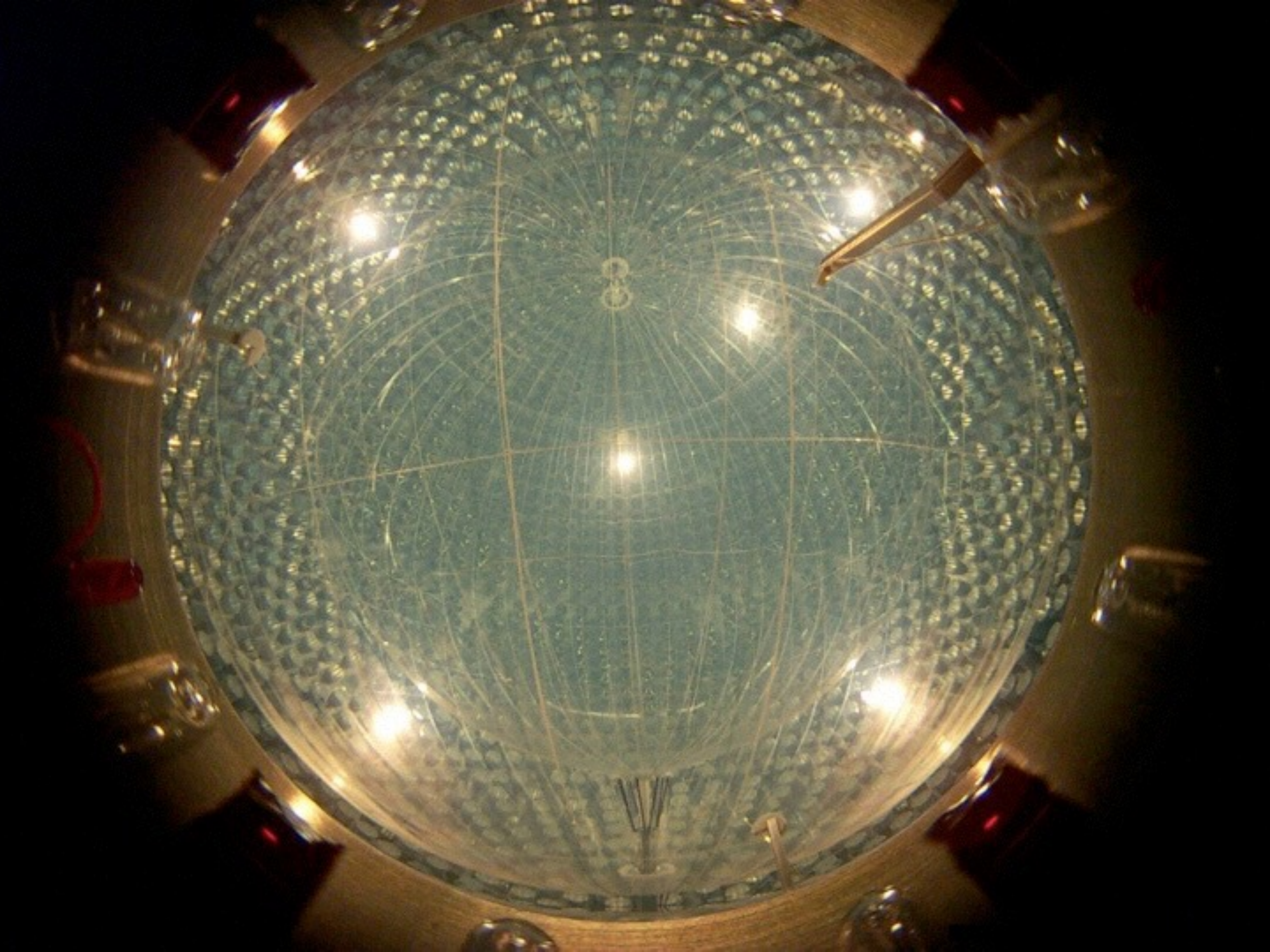




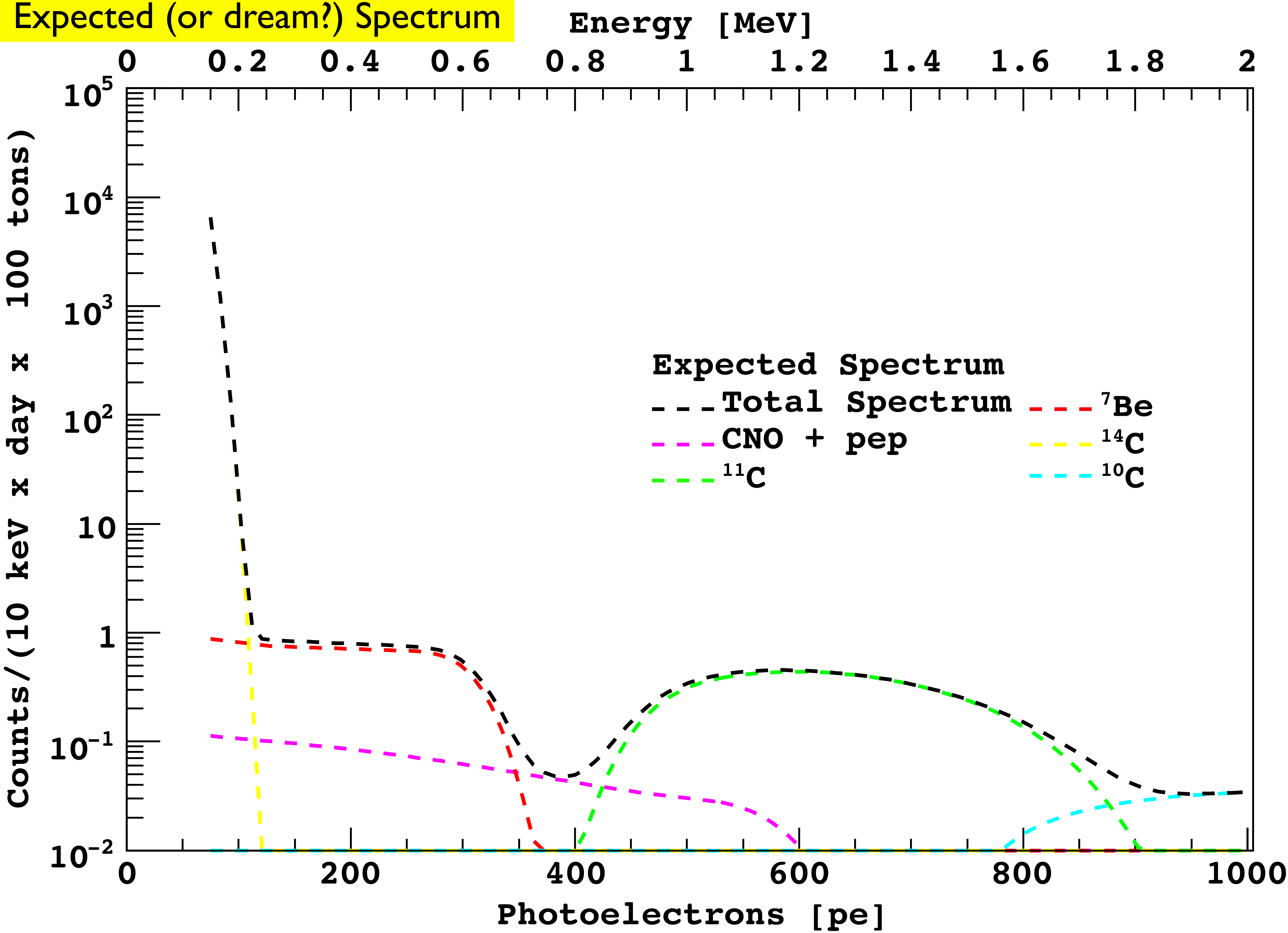




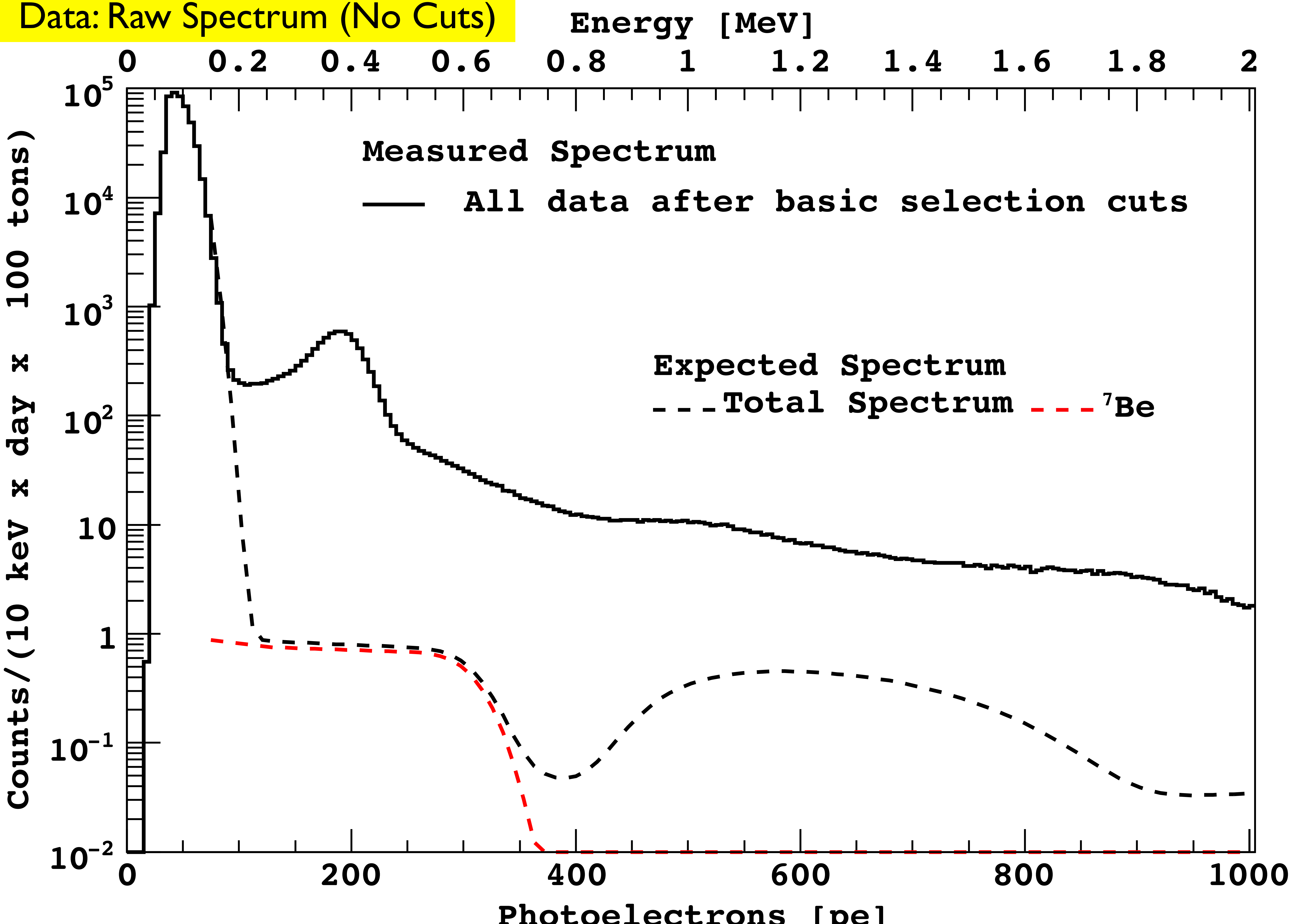




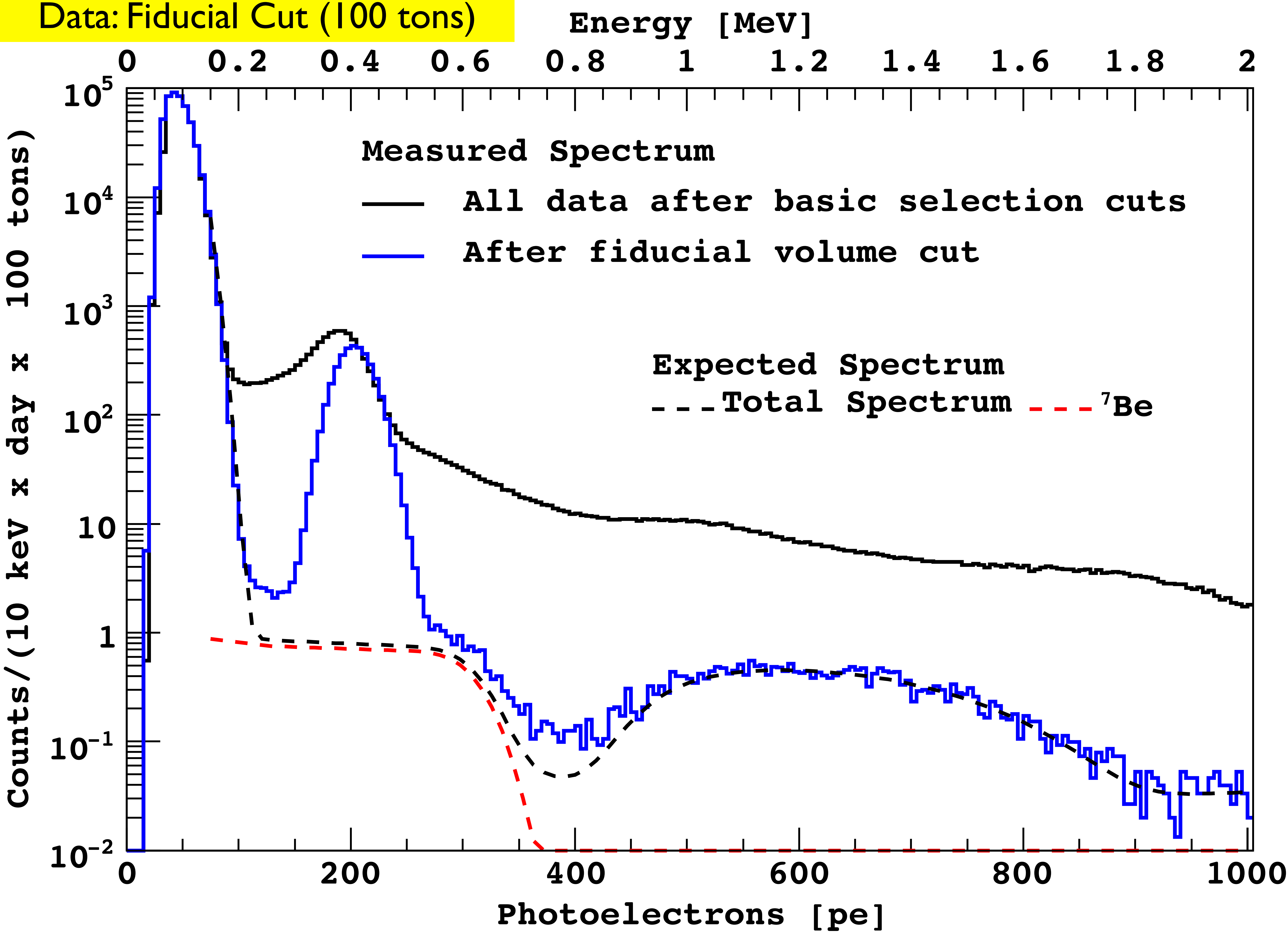
Expected (or dream?) Spectrum



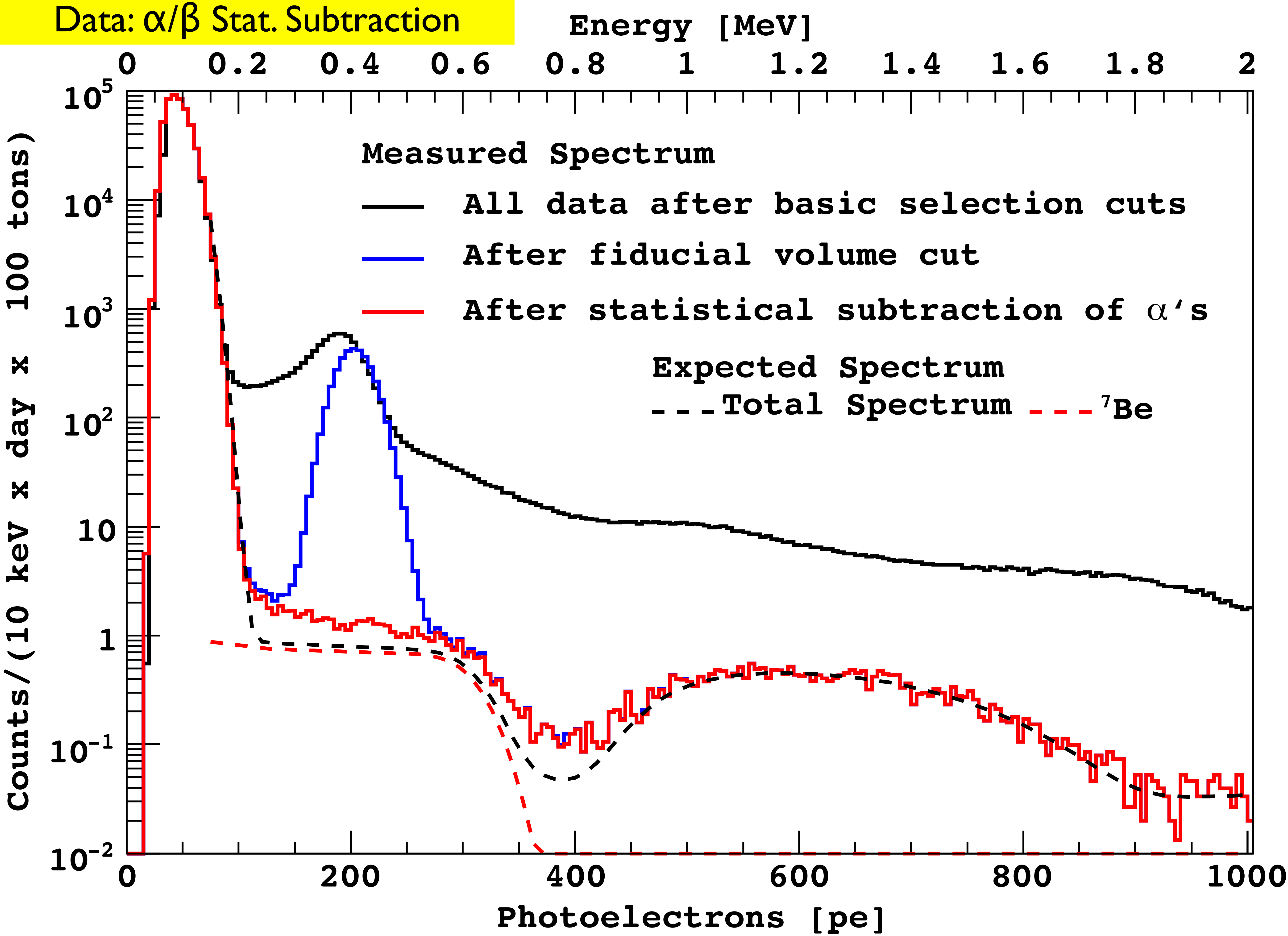
Data: Raw Spectrum (No Cuts)



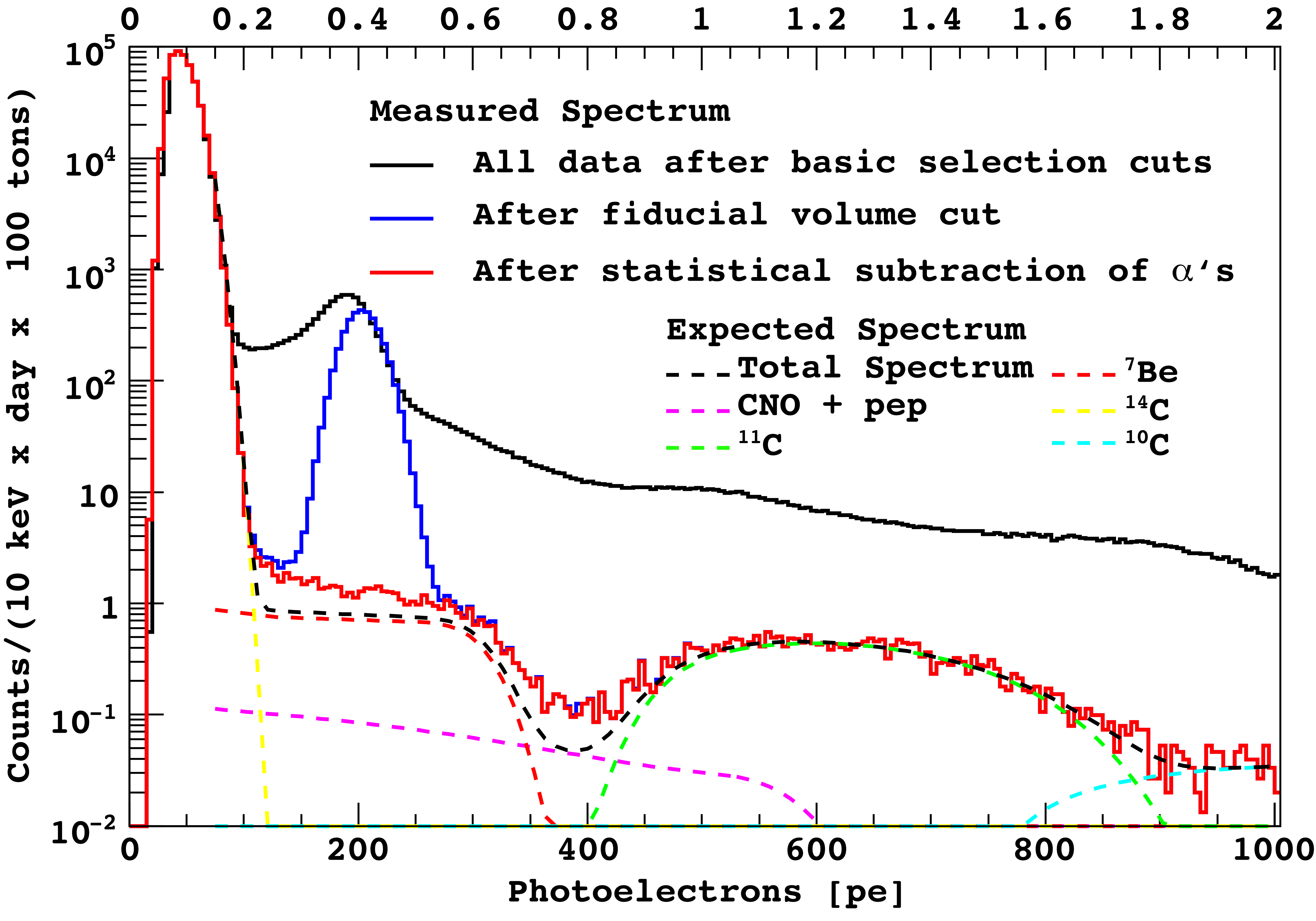
Data: Fiducial Cut (100 tons)



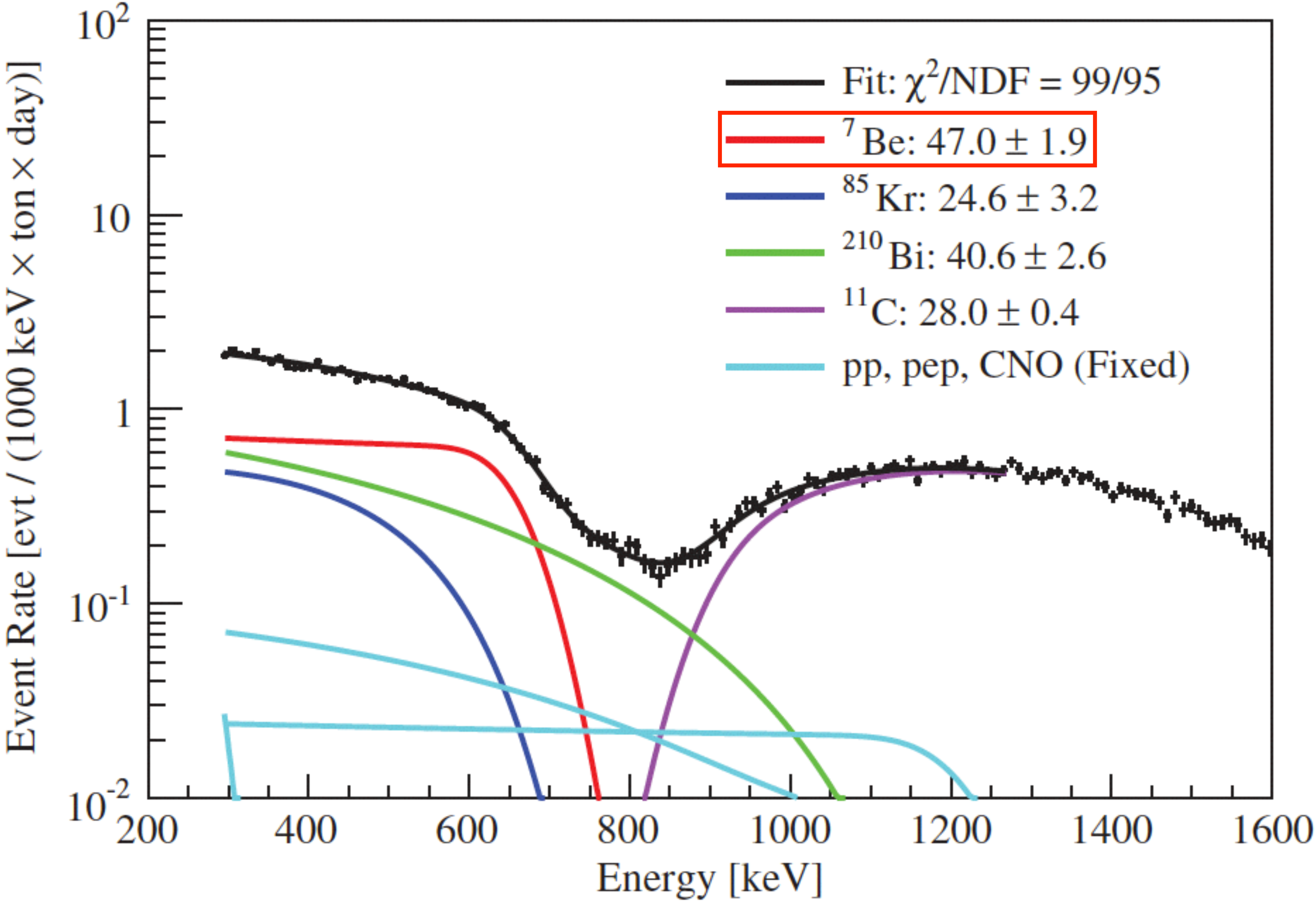
Data: α/β Stat. Subtraction



Data: Final Comparison



^{7}Be Results

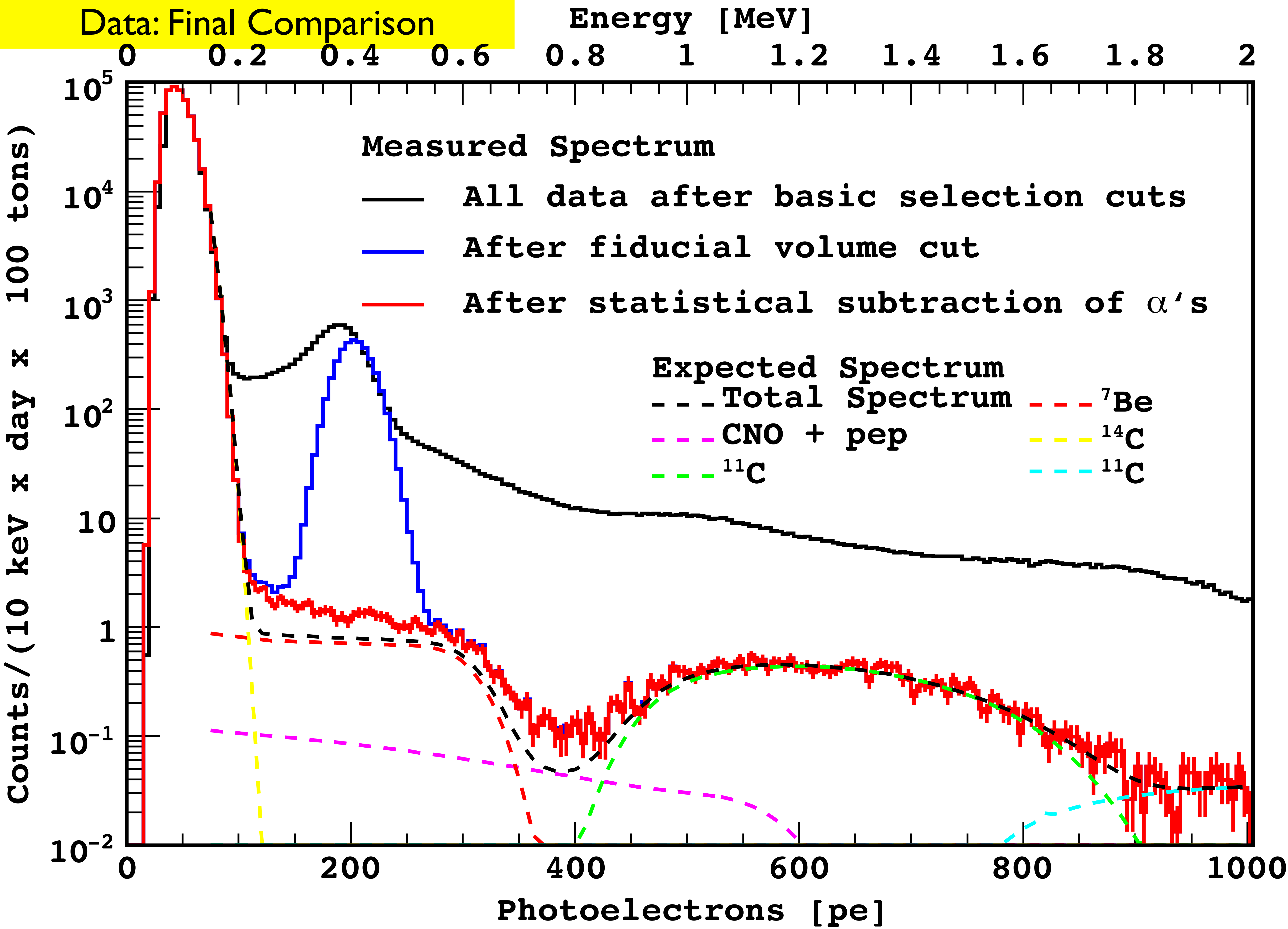


Fit: χ²/NDF = 99/95
⁷Be: 47.0 ± 1.9
⁸⁵Kr: 24.6 ± 3.2
²¹⁰Bi: 40.6 ± 2.6
¹¹C: 28.0 ± 0.4
pp, pep, CNO (Fixed)
Event Rate [evt / (1000 keV × ton × day)]
Energy [keV]
10²
10
1
10⁻¹
10⁻²
200
400
600
800
1000
1200
1400
1600

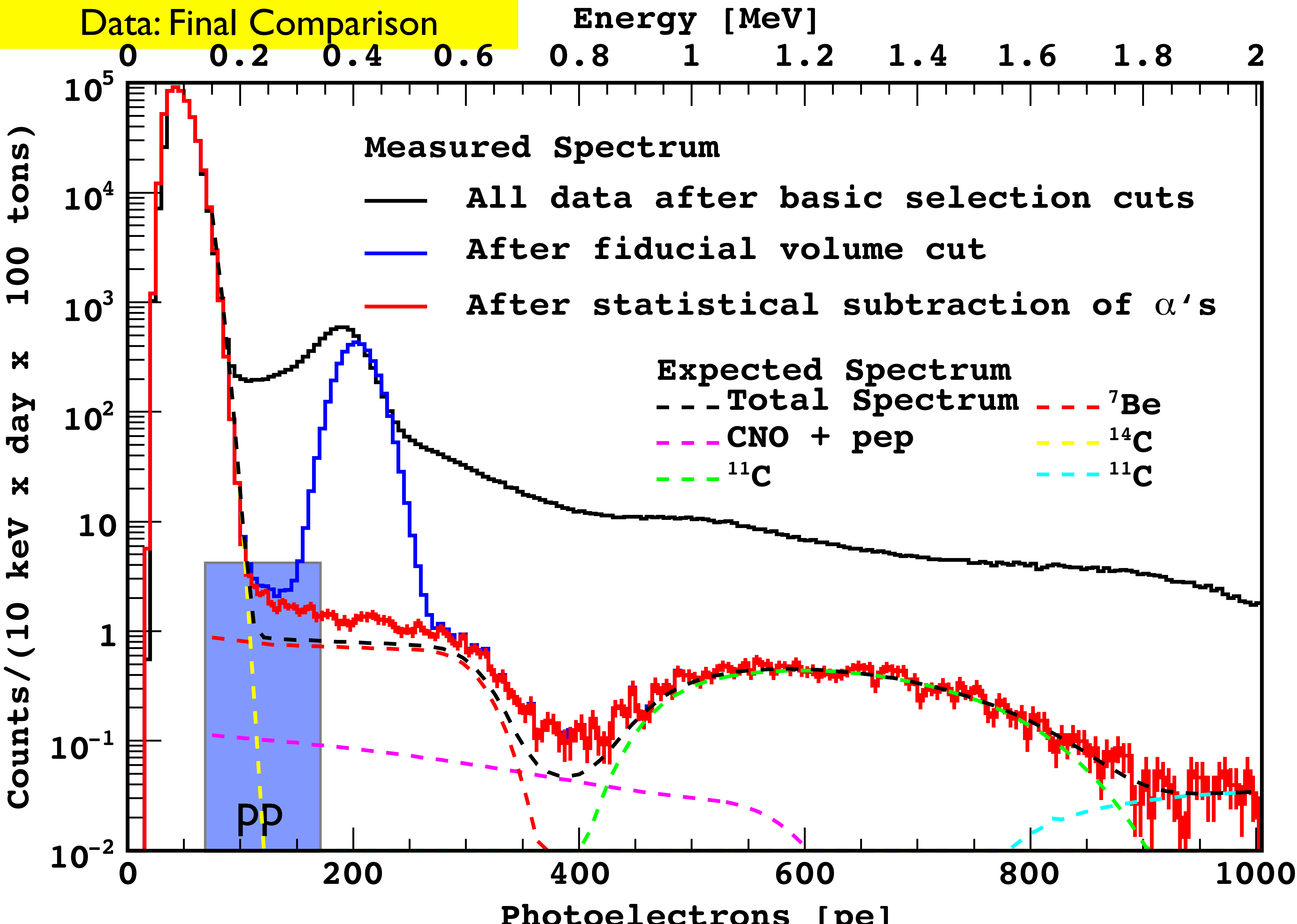
Borexino: Additional Possibilities for First Time Measurements

- *pep* neutrinos (indirect constraint on pp neutrino flux)
- Low energy (2-5 MeV) ^{8}B neutrinos
- Tail end of *pp* neutrinos spectrum
- CNO neutrinos (direct indication of metallicity in the Sun's core)

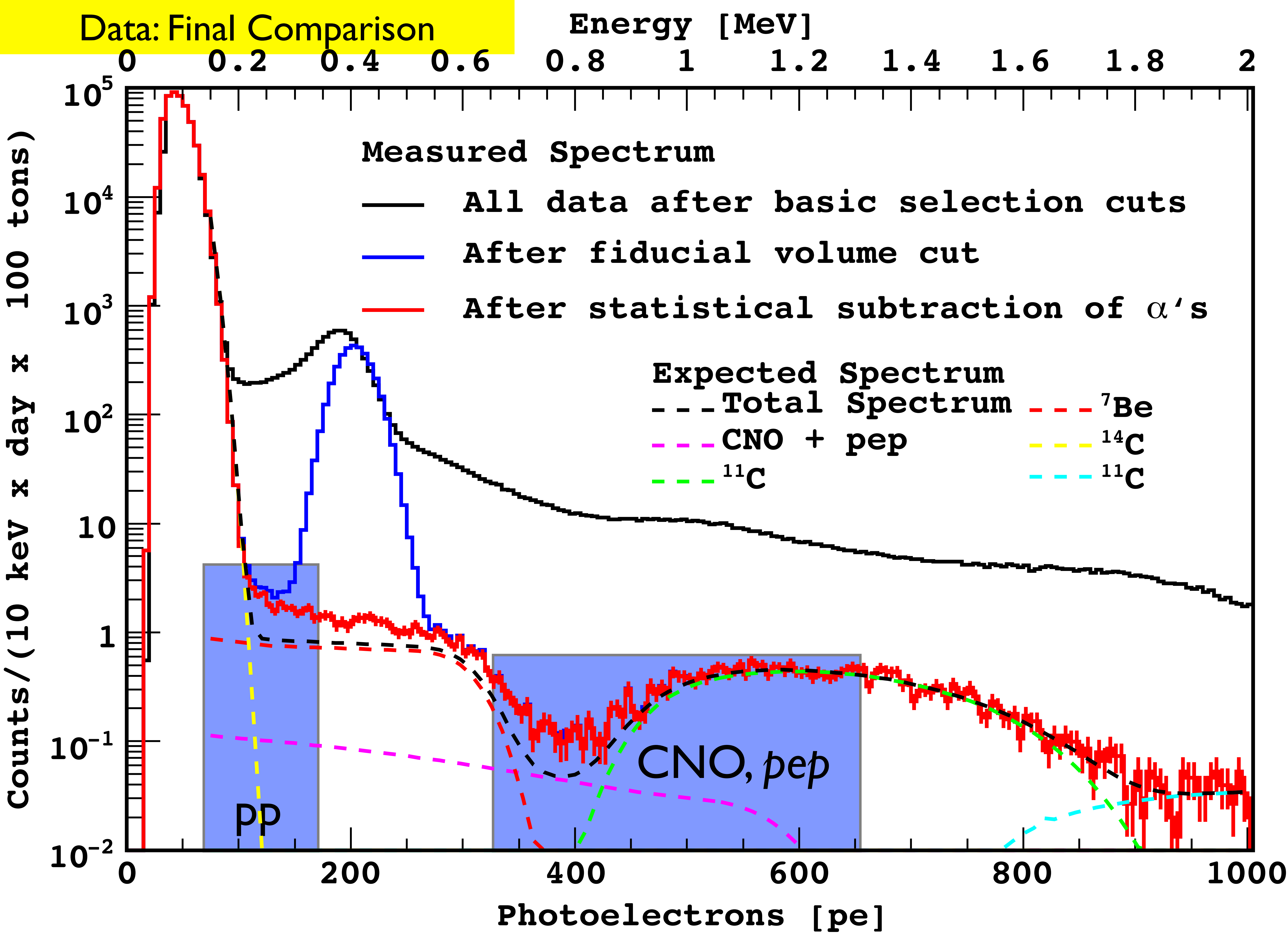
Data: Final Comparison



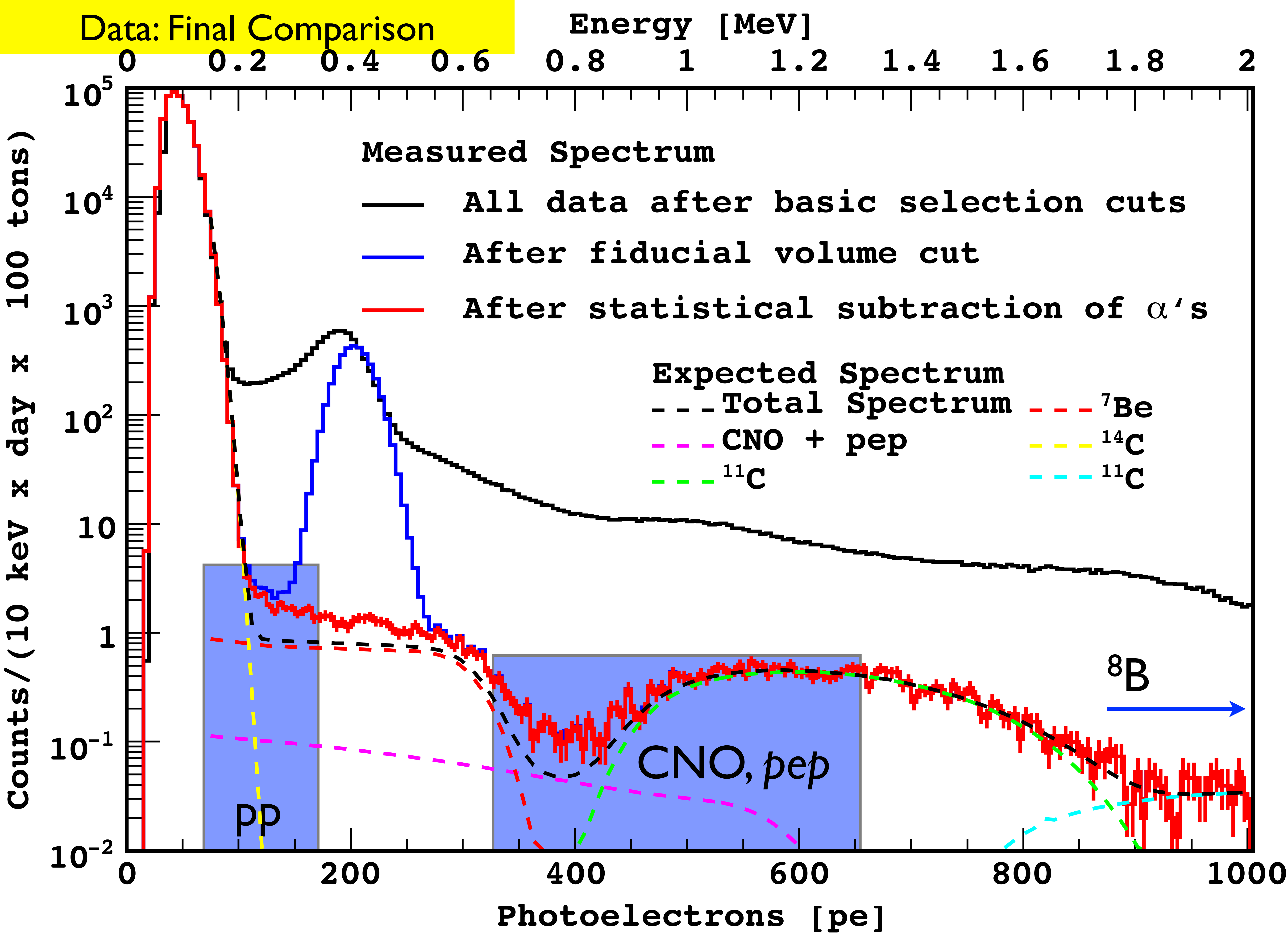
Data: Final Comparison



Data: Final Comparison

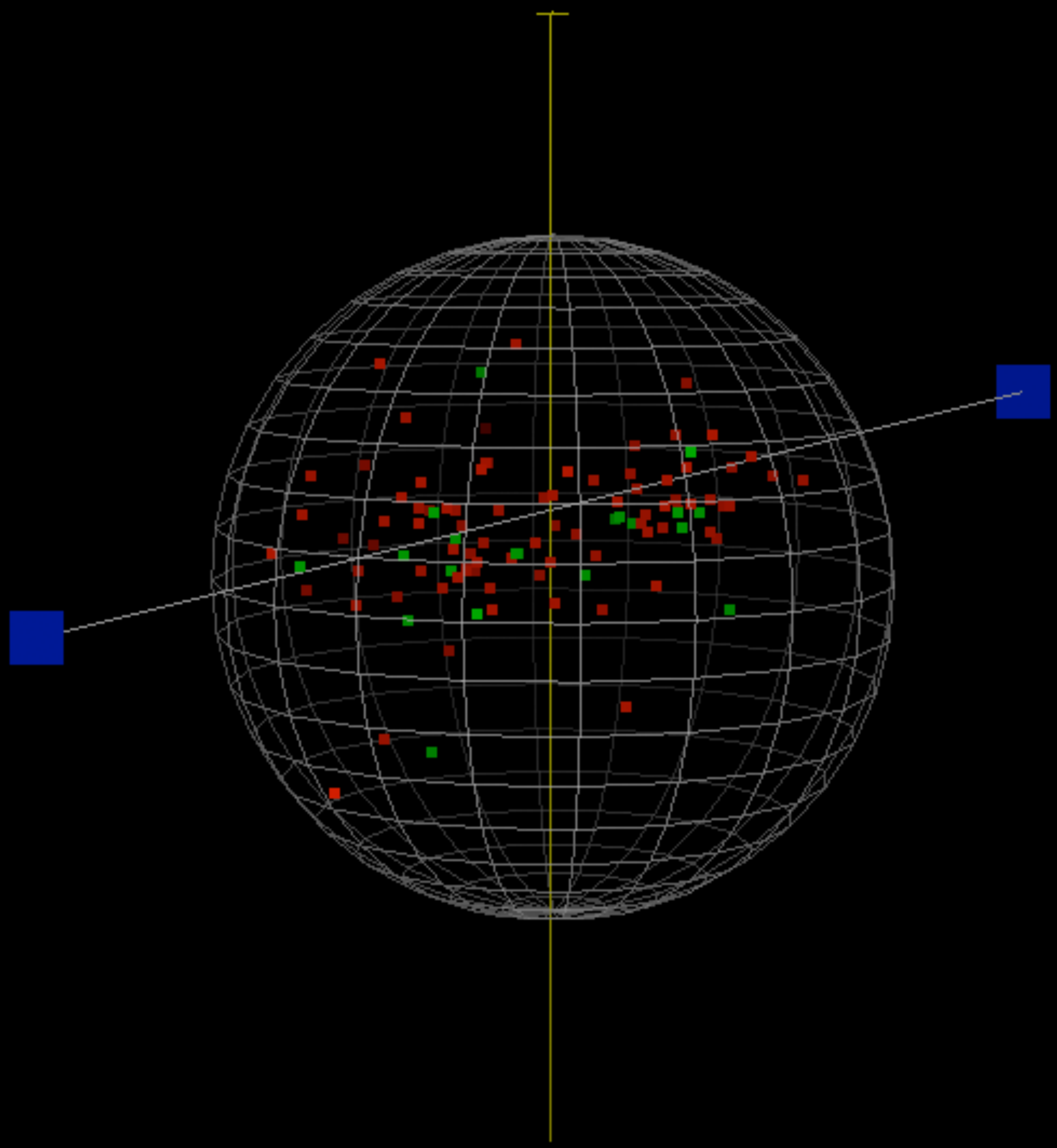


Data: Final Comparison



pep and CNO neutrinos

- Tests of MSW-LMA with ^{7}Be limited due to uncertainty in solar flux.
- *pep* flux predicted with higher precision, 1.2% uncertainty. Allows for more stringent tests of oscillation models. Also mono-energetic.
- CNO fluxes directly related to Solar Metallicity. It could allow to discern between High Z and Low Z models.
- Small fluxes: ~5 interactions per day per 100 tons of target. End points 1-2 MeV.
- ^{11}C is the dominant background in Borexino.



Reconstructed μ entry/exit points

Reconstructed position of neutron

Reconstructed position of ^{11}C

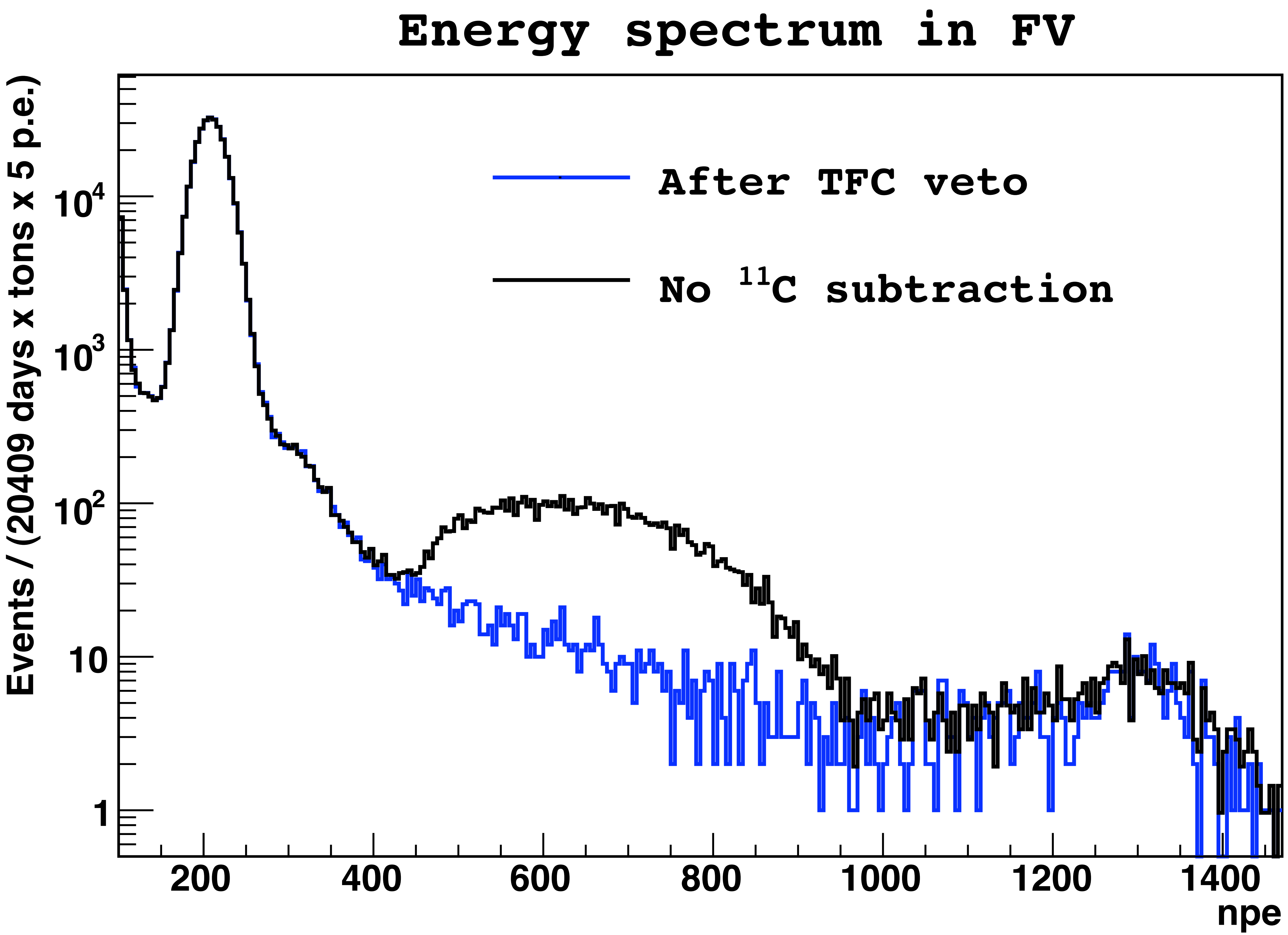
Cosmogenic ^{11}C

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

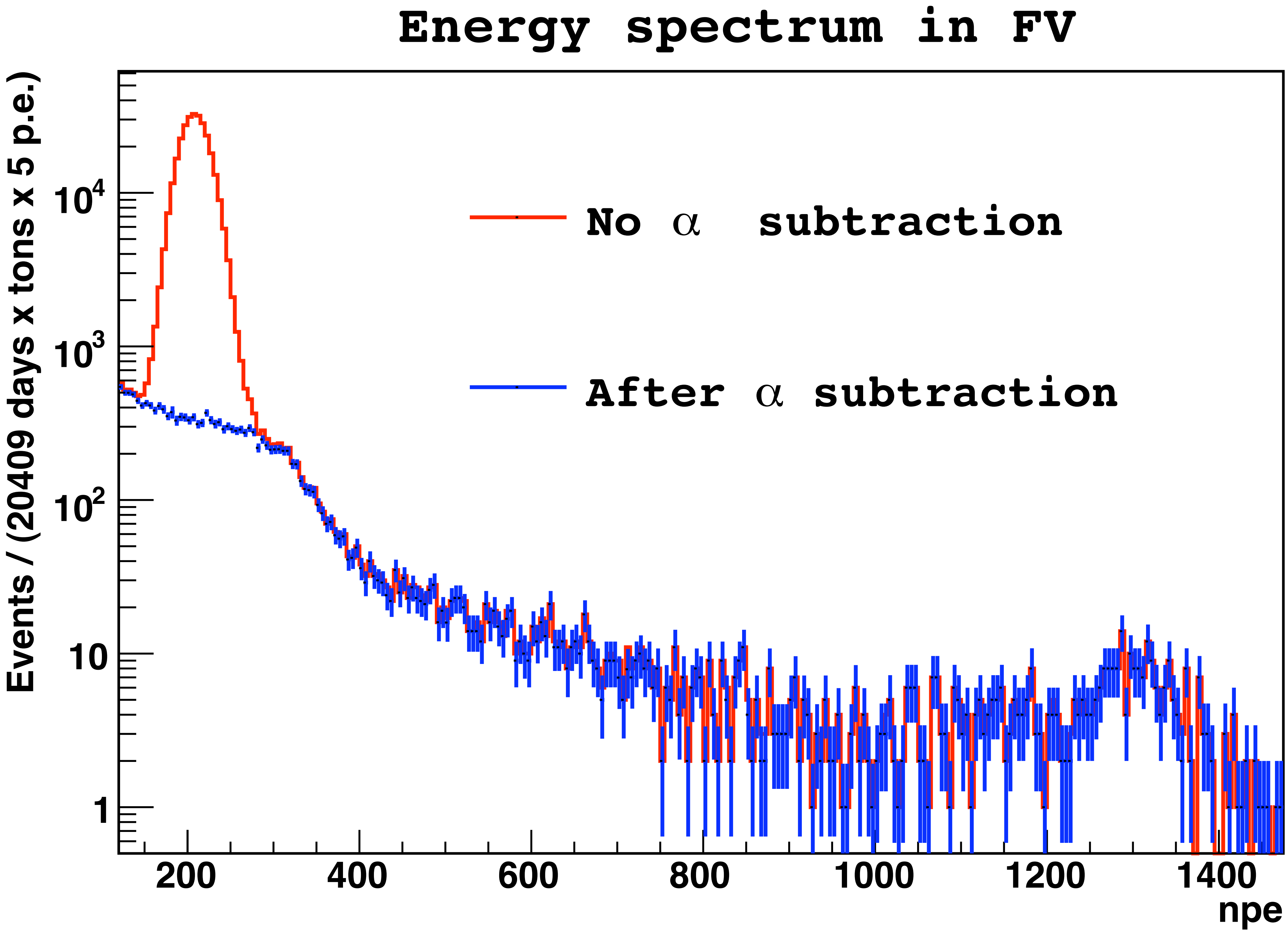
Track of the parent μ.
Neutrons within 1.6 ms after μ.
^{11}C candidates within 2 h after μ.

Can use space + time correlation with μ + n to veto regions of the detector with higher ^{11}C background: Three-fold coincidence (TFC) technique

TFC decreases ^{11}C rate to ~10% of its original value with ~50% loss of exposure.
Limiting background internal ^{210}Bi.

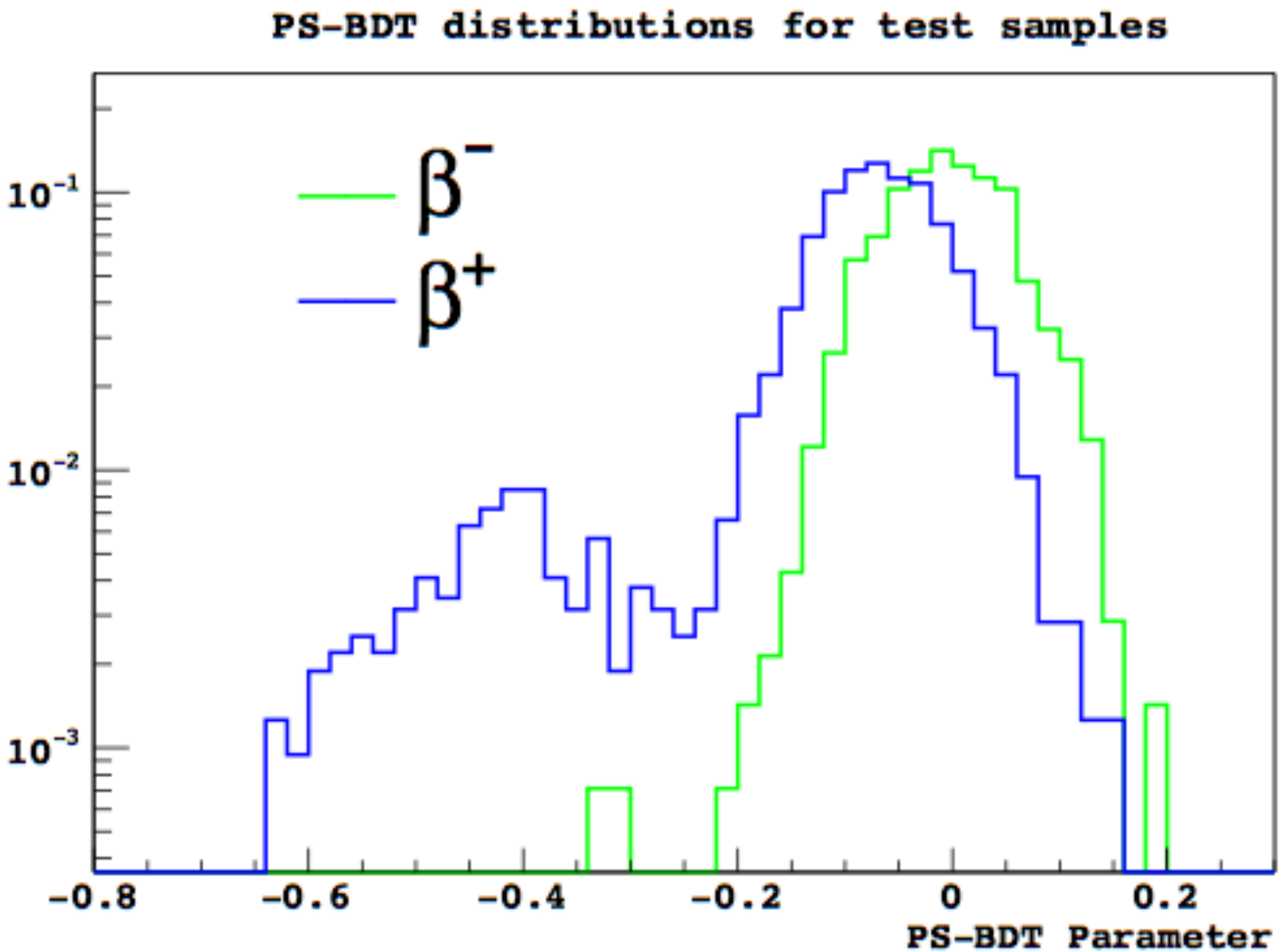


Additional pulse shape rejection of α particles andof 11C by BDT exploitation of β^+/β^- pulse shape differences (next slides)



β-/β+ Pulse Shape Discrimination (BDT)

Formation of positronium and multiple energy deposits from annihilation γ's lead to different reconstructed emission time profiles.



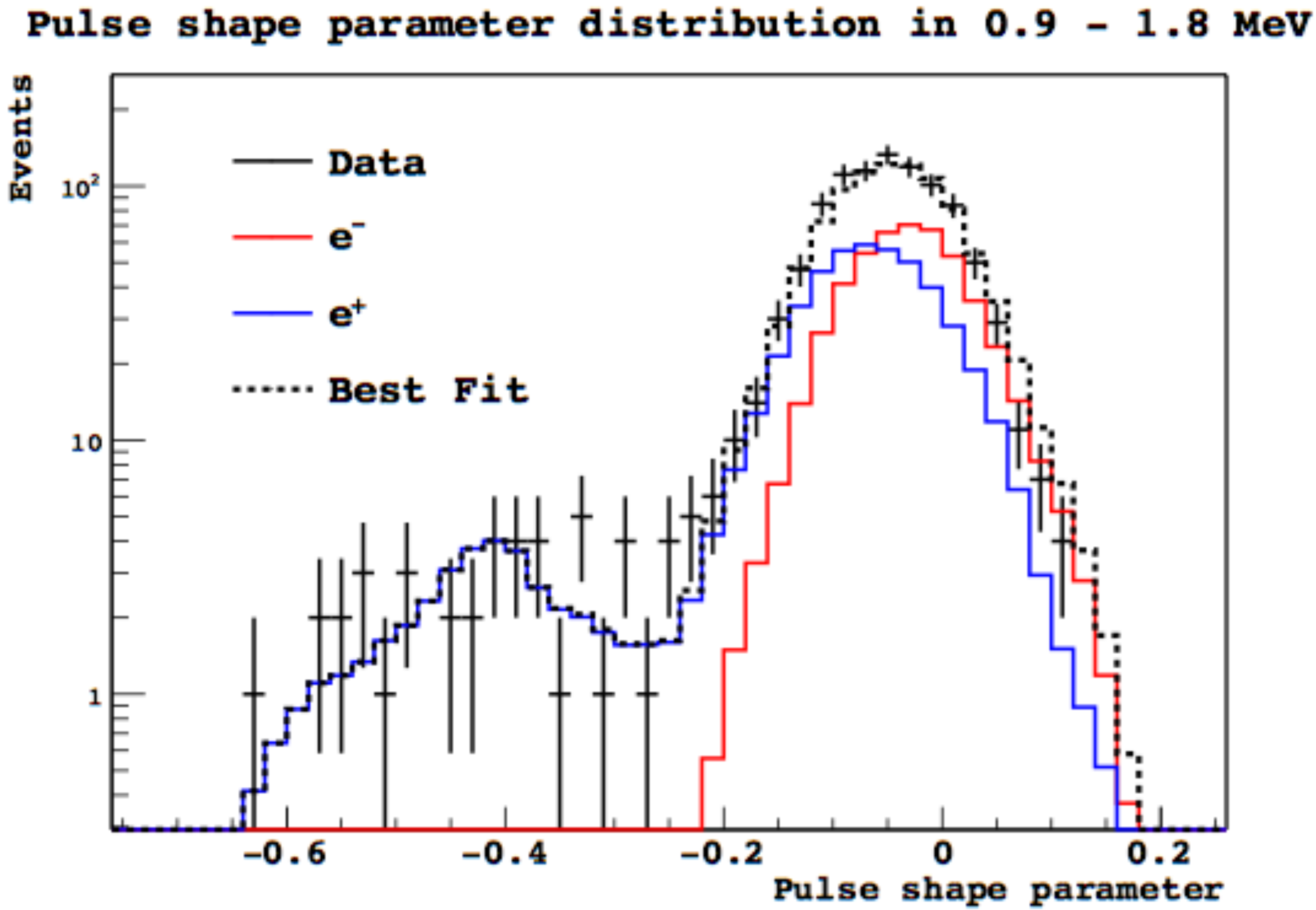
Multivariate Analysis

- Symultaneous fit:

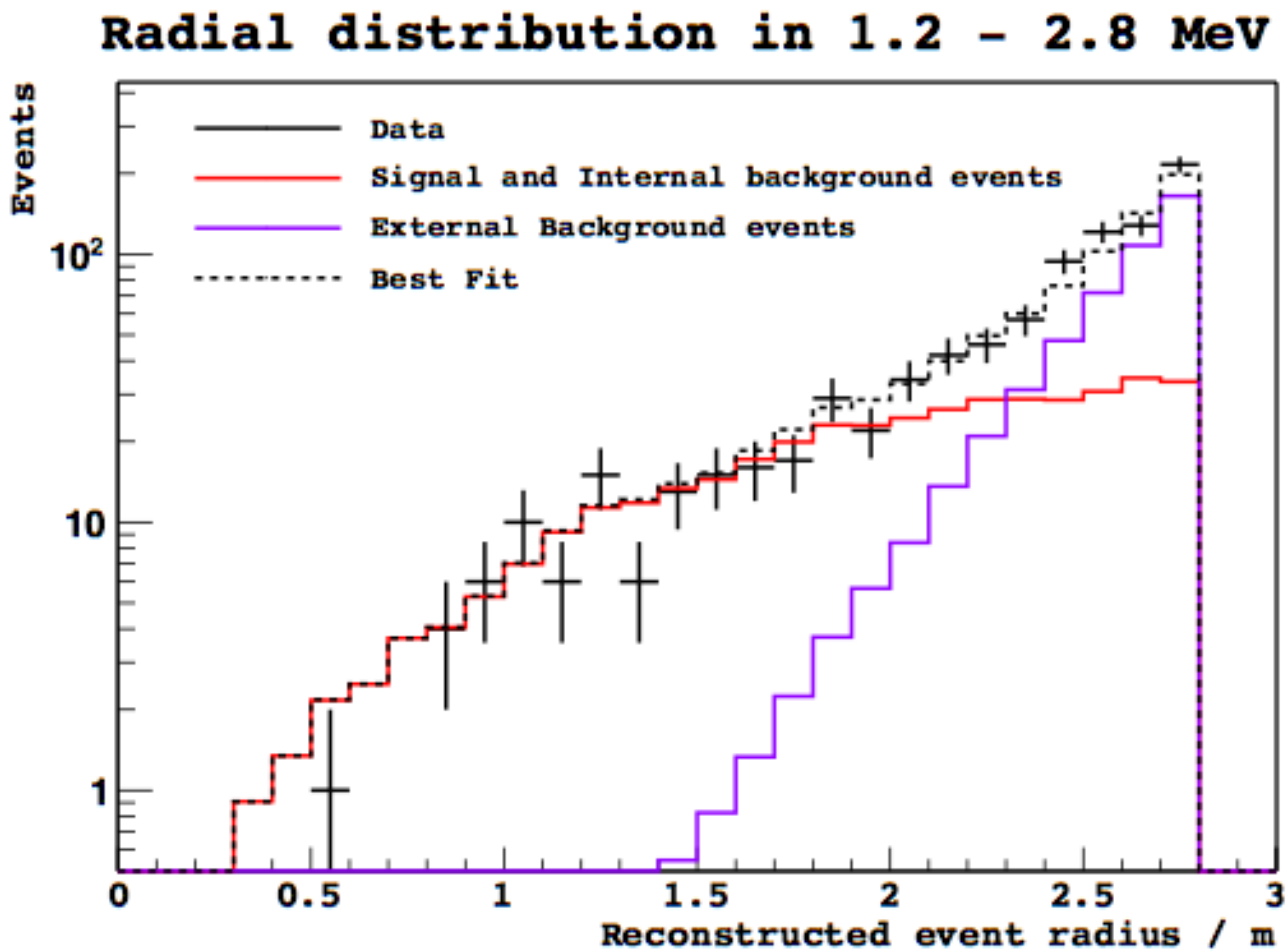
1. Pulse shape distribution with β+ (11C,10C) and β- (other)
2. Radial distribution with external background and signal + internal backgrounds
3. Energy distribution with spectral shapes

Simultaneously fit three parameter spaces

1. Pulse shape distribution with β^+ (^{11}C, ^{10}C) and β^- (other)

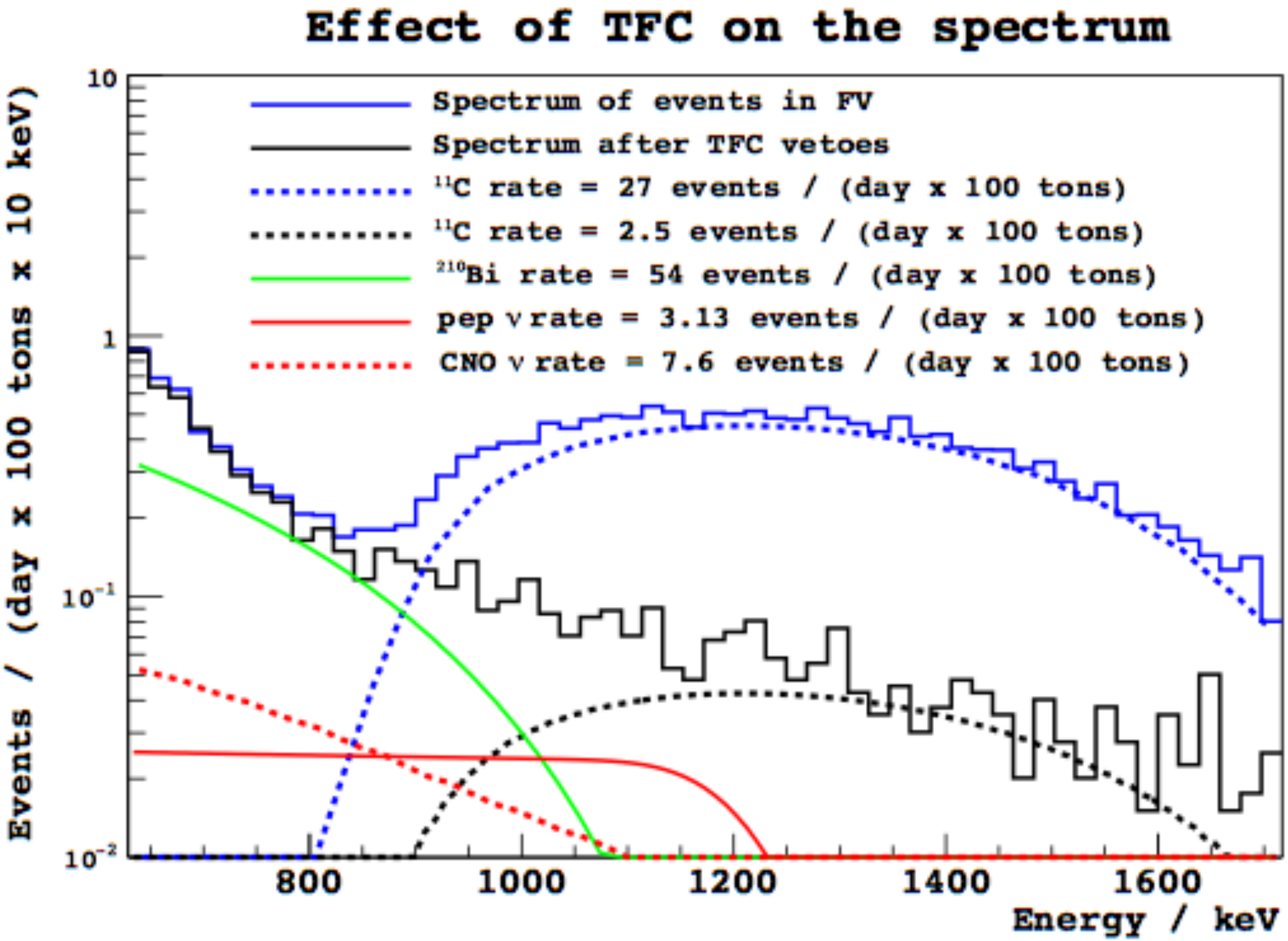


Simultaneously fit three parameter spaces
2. Radial distribution with external background and signal + internal backgrounds

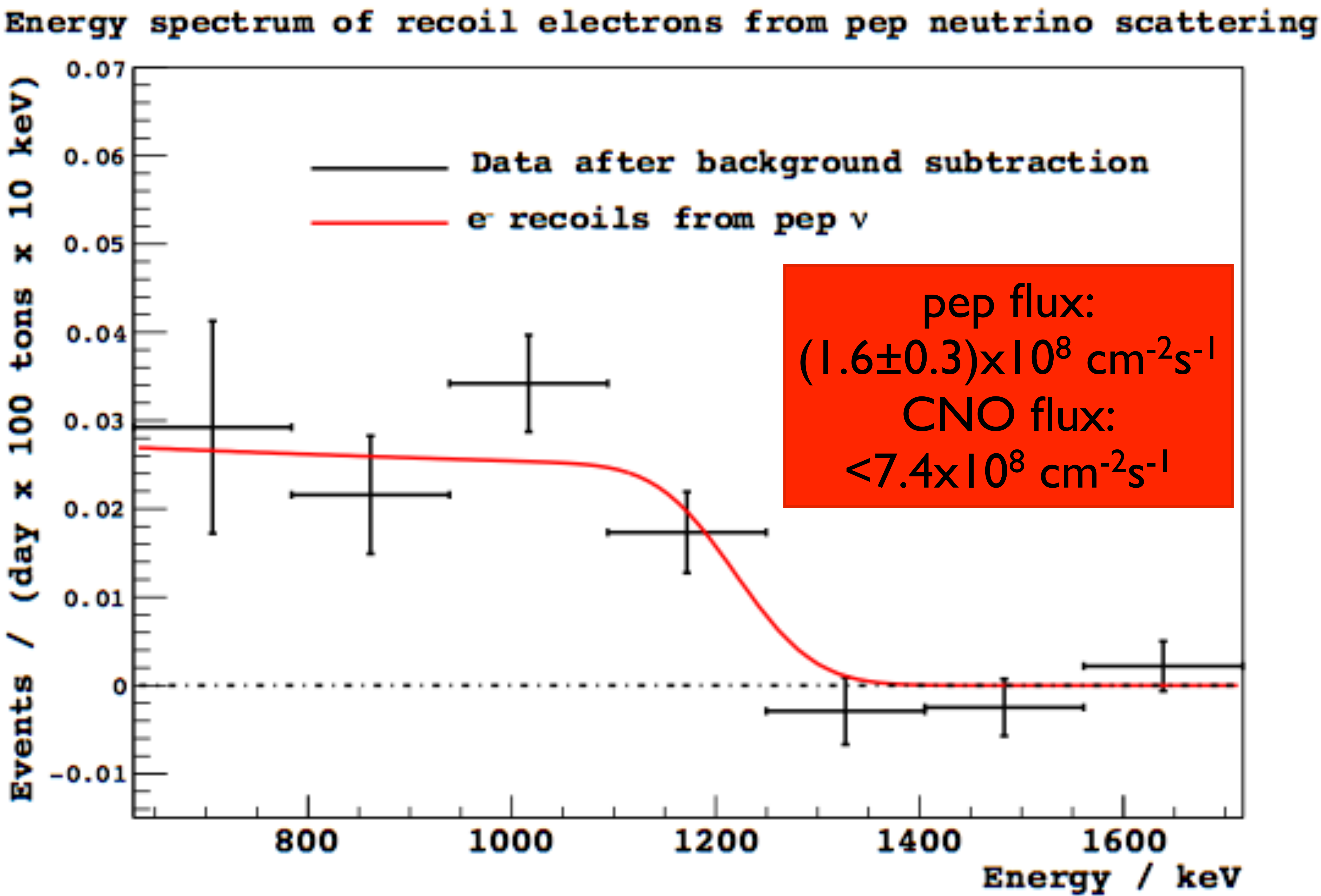


Simultaneously fit three parameter spaces

3. Energy distribution with spectral shapes



Energy Fit Residuals



pep flux:
$(1.6\pm0.3)\times10^{8}\ cm^{-2}s^{-1}$
CNO flux:
$<7.4\times10^{8}\ cm^{-2}s^{-1}$

Implications

pep:
Fit uncertainty: 18%
Syst uncertainty: 10%
Statistical significance of pep measurement 97% C.L.

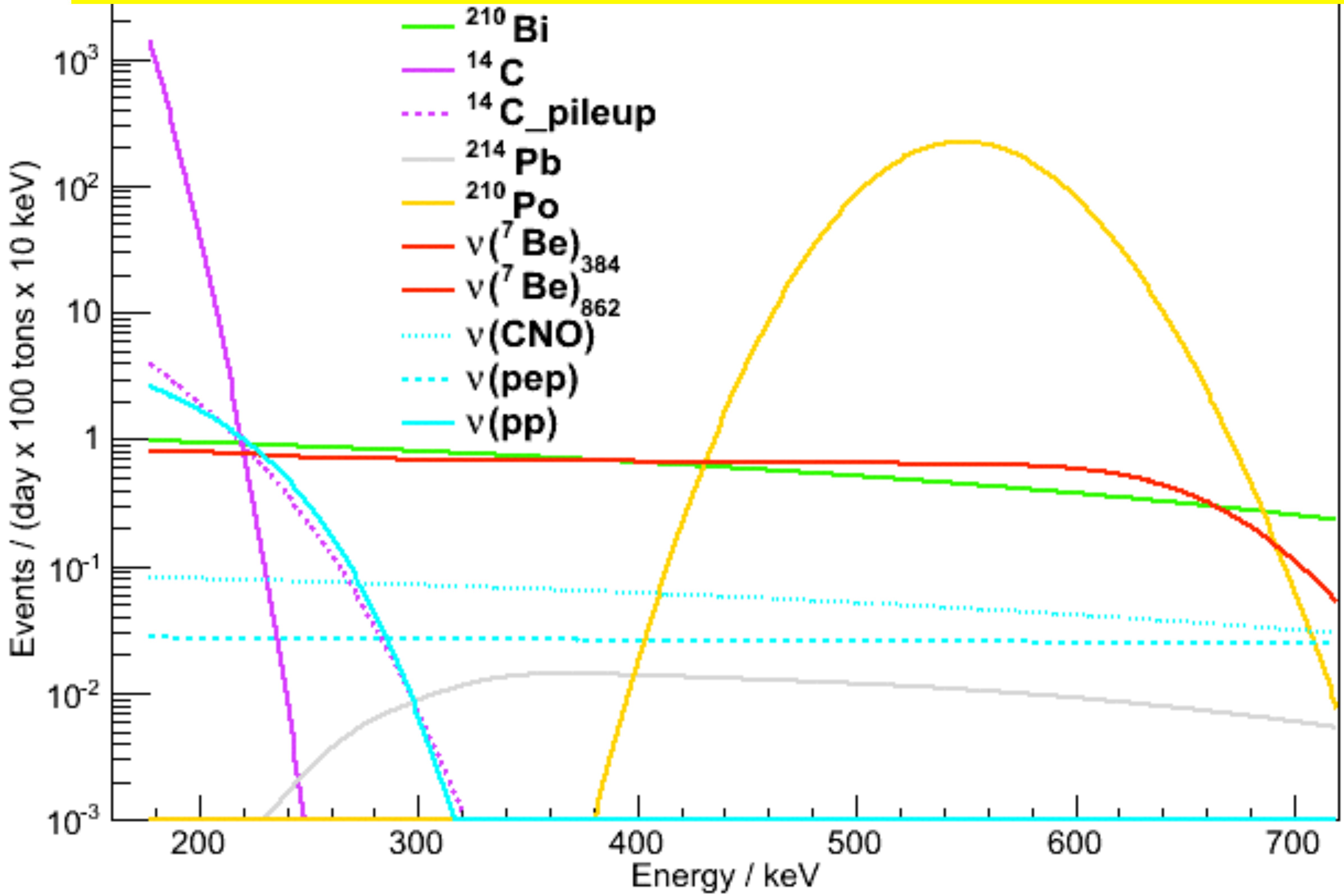
CNO:
Correlation between ^{210}Bi and CNO spectral shapes lead to only a limit on CNO

Total fluxes from direct measurement:

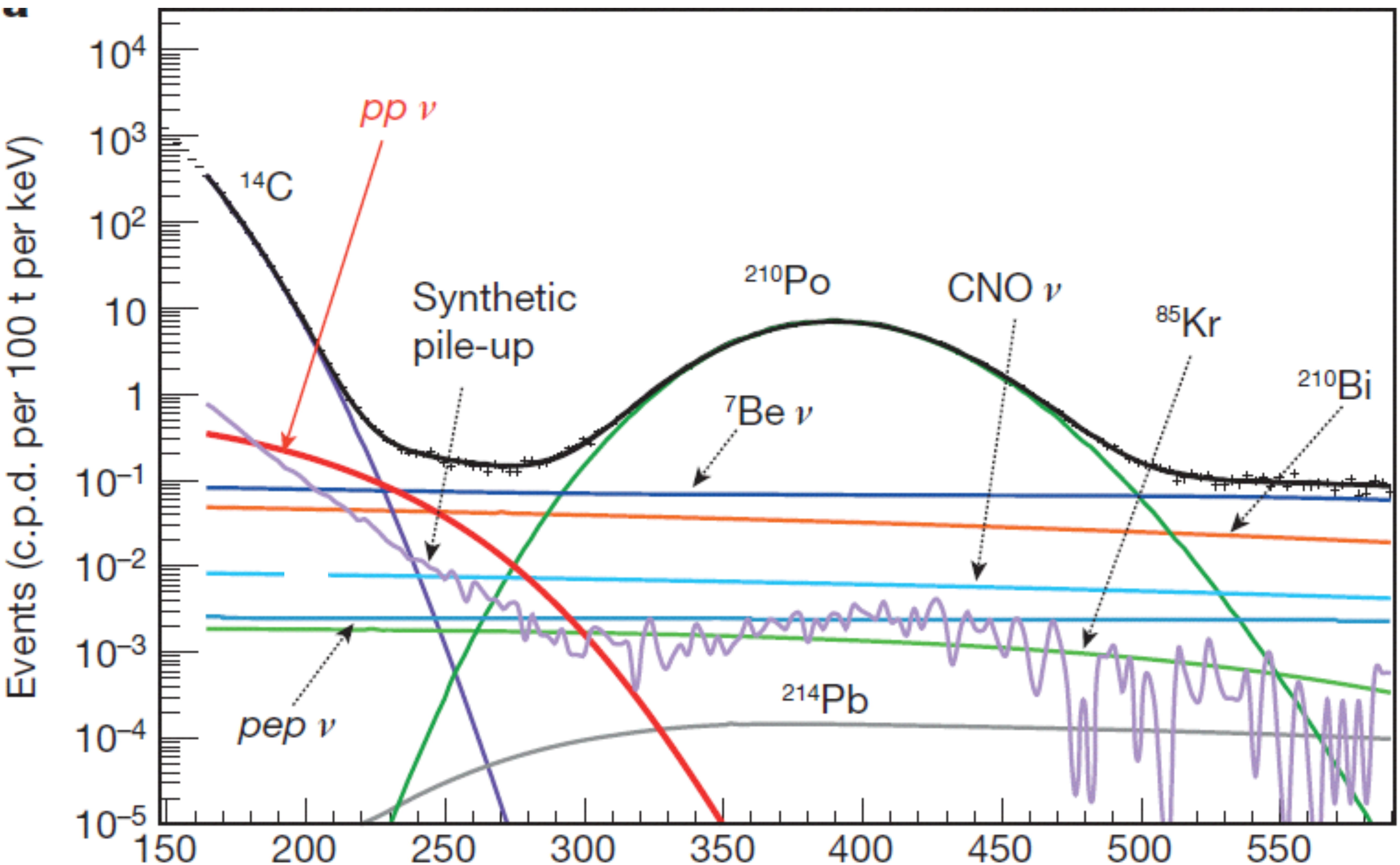
pep flux:
$(1.6\pm0.3)\times10^{8}$ cm^{-2}s^{-1}
CNO flux:
$<7.4\times10^{8}$ cm^{-2}s^{-1}

No oscillation hypothesis disfavored at 96% C.L.
CNO rate limit 1.4 times High Z prediction
Results consistent with MSW-LMA and SSM

pp neutrinos and backgrounds expected spectral contributions



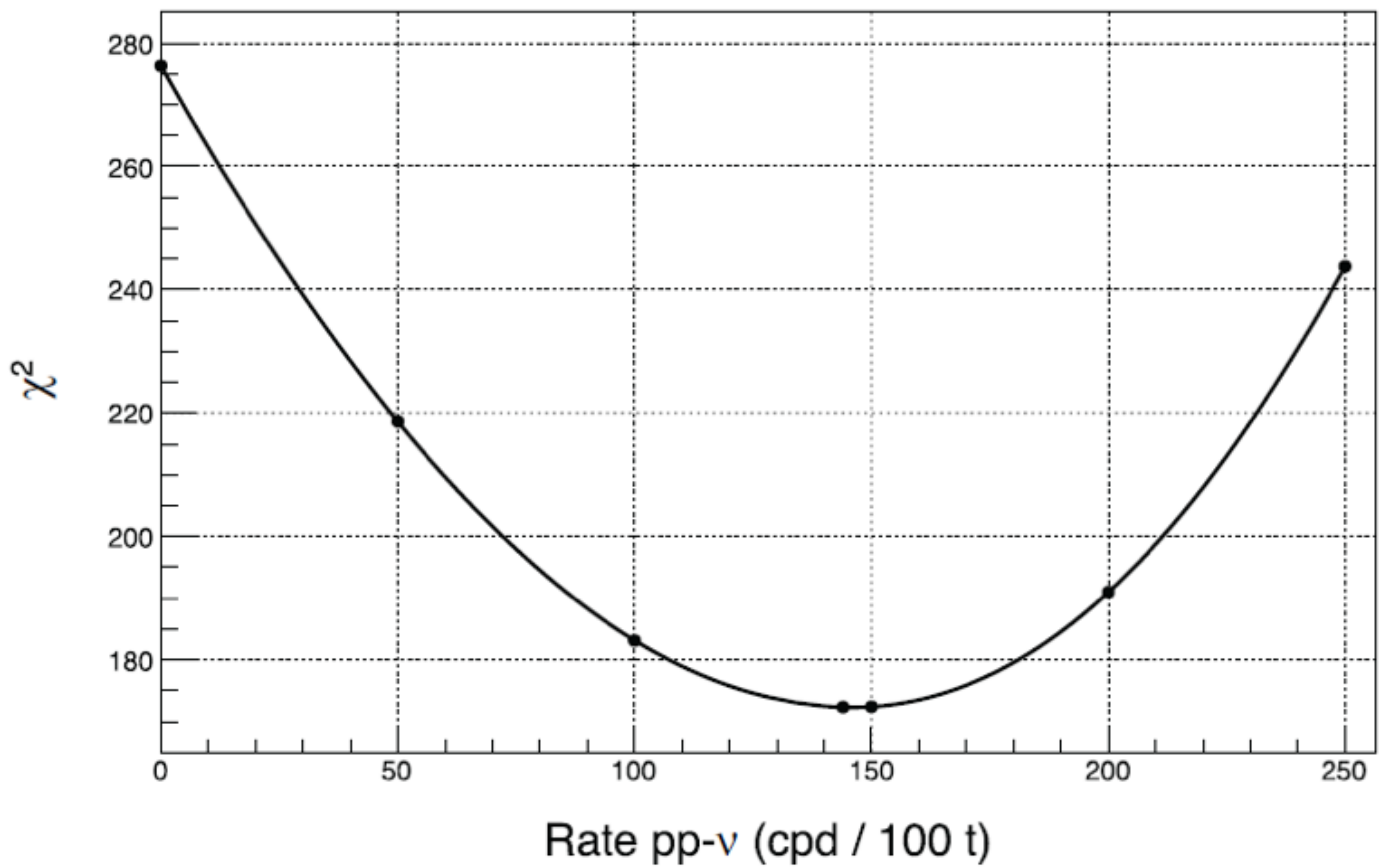
pp Neutrinos



$pp = 144 \pm 13$ *(stat)* cpd/100 t

Nature **512**, 383-386 (28 August 2014)

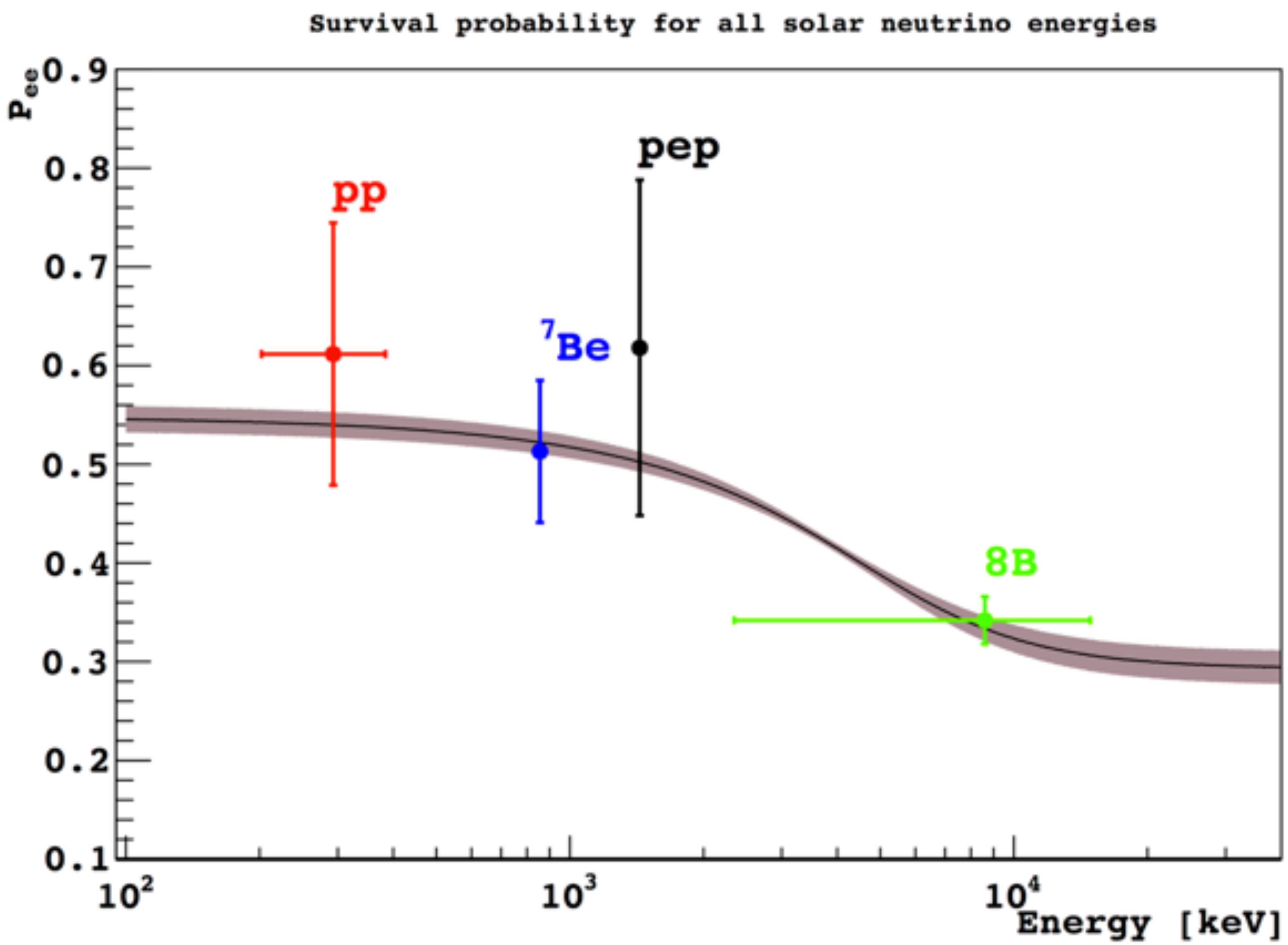
Final result



pp detection rate: 144 ± 13 *(stat)* ± 10 *(syst)* cpd/100 t

HM-SSM + LMA-MSW: 131 ± 2 cpd/100 t

Interpretation:
Survival probability measurement



$$P_{ee} = \begin{cases} 0.612 \pm 0.133 & \text{measured} \\ 0.543 \pm 0.013 & \text{expected} \end{cases}$$

Interpretation:
Solar (in)variability

Check the time stability of the Sun (time scale 10^5 years), which is a crucial assumption in the Standard Solar Model

SCIENCE IDEAS

Solar Variability

Glacial Epochs, and Solar Neutrinos

by George A. Cowan and Wick C. Haxton

[Los Alamos Science, 1982]

What Next?

Neutrinos and Solar Metallicity

- A direct measurement of the CNO neutrinos rate could help solve the latest controversy surrounding the Standard Solar Model
- 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)), is in agreement within 0.5% with the solar sound speed measured by helioseismology.
- Latest work by Asplund, Grevesse and Sauval (Nucl. Phys. A **777**, 1 (2006)) indicates a metallicity lower by a factor ~2. This result destroys the agreement with helioseismology
  maybe it was fortuitous agreement before with high metallicity?
- use solar neutrino measurements to help resolve!
  ^{7}Be (12% difference) and CNO (50-60% difference)

Solar Model Chemical Controversy

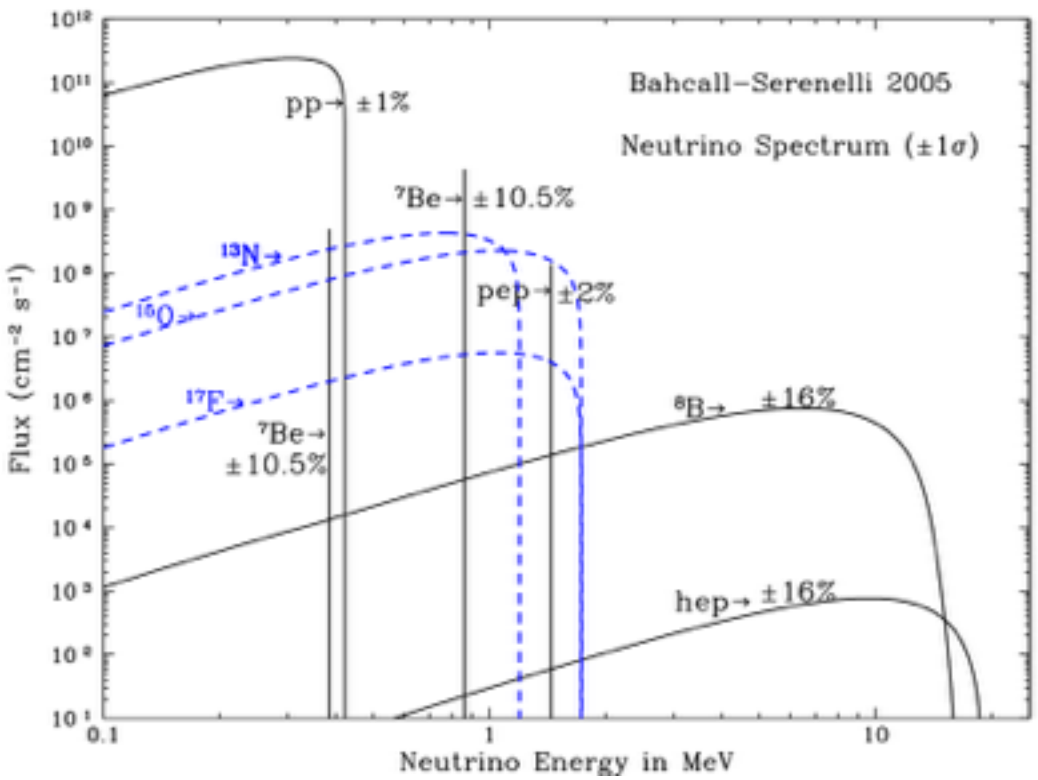
Bahcall, Serenelli and Basu, AstropJ 621, L85(2005)

Φ ($cm^{-2}s^{-1}$)	*pp* ($\times 10^{10}$)	^{7}Be ($\times 10^{9}$)	^{8}B ($\times 10^{6}$)	^{13}N ($\times 10^{8}$)	^{15}O ($\times 10^{8}$)	^{17}F ($\times 10^{6}$)
BS05 GS 98	5.99	4.84	5.69	3.07	2.33	5.84
BS05 AGS 05	6.05	4.34	4.51	2.01	1.45	3.25
Δ	+1%	-10%	-21%	-35%	-38%	-44%
σ SSM	±1%	±5%	±16%	±15%	±15%	±15%

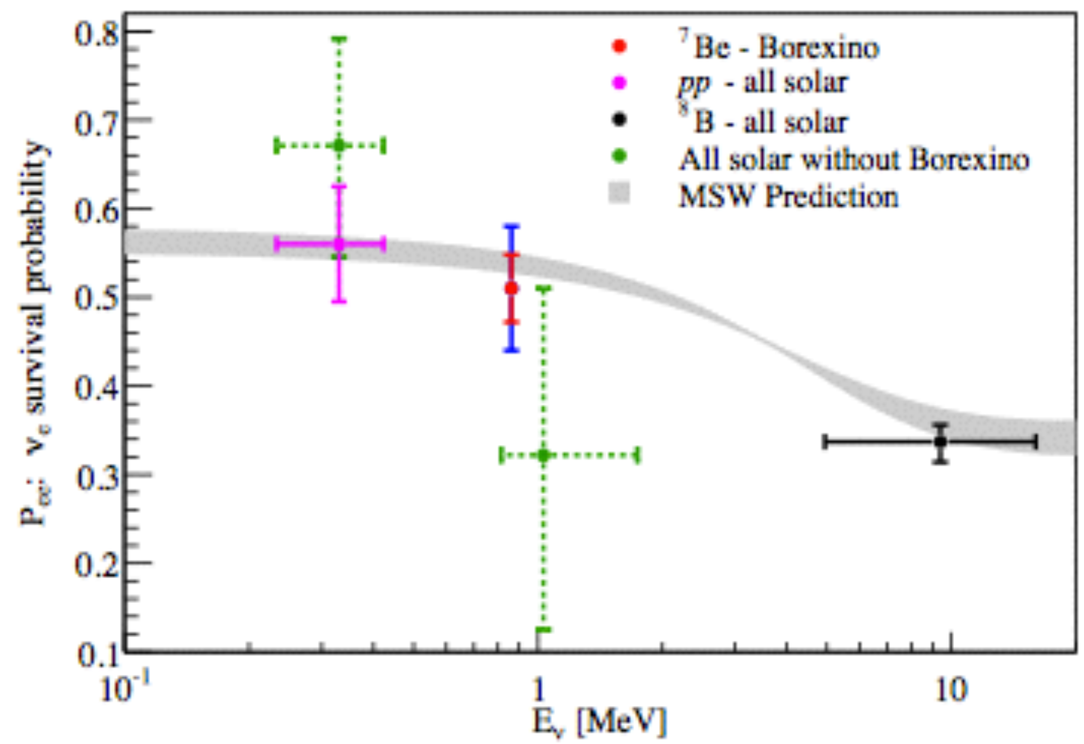
Helioseismology incompatible with low metallicity solar models. Could be resolved by measuring CNO neutrinos

The End

Interpretation 2:
pp neutrino flux measurement



←



$$\phi = \begin{cases} (6.42 \pm 0.85) \times 10^{10}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1} & \text{measured} \\ (5.98 \pm 0.04) \times 10^{10}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1} & \text{expected (high}-Z) \\ (6.03 \pm 0.04) \times 10^{10}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1} & \text{expected (low}-Z) \end{cases}$$