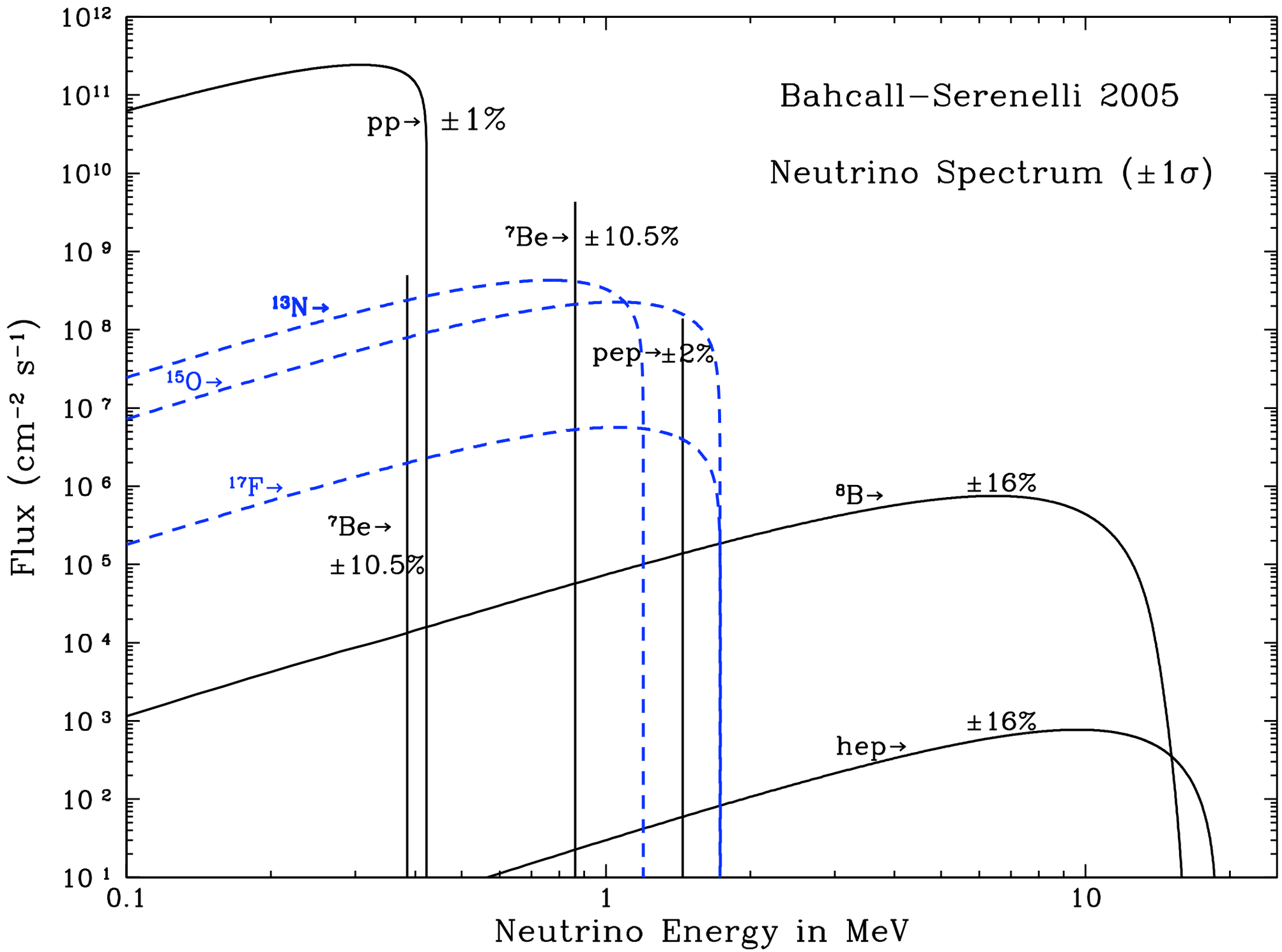
192 days of Borexino

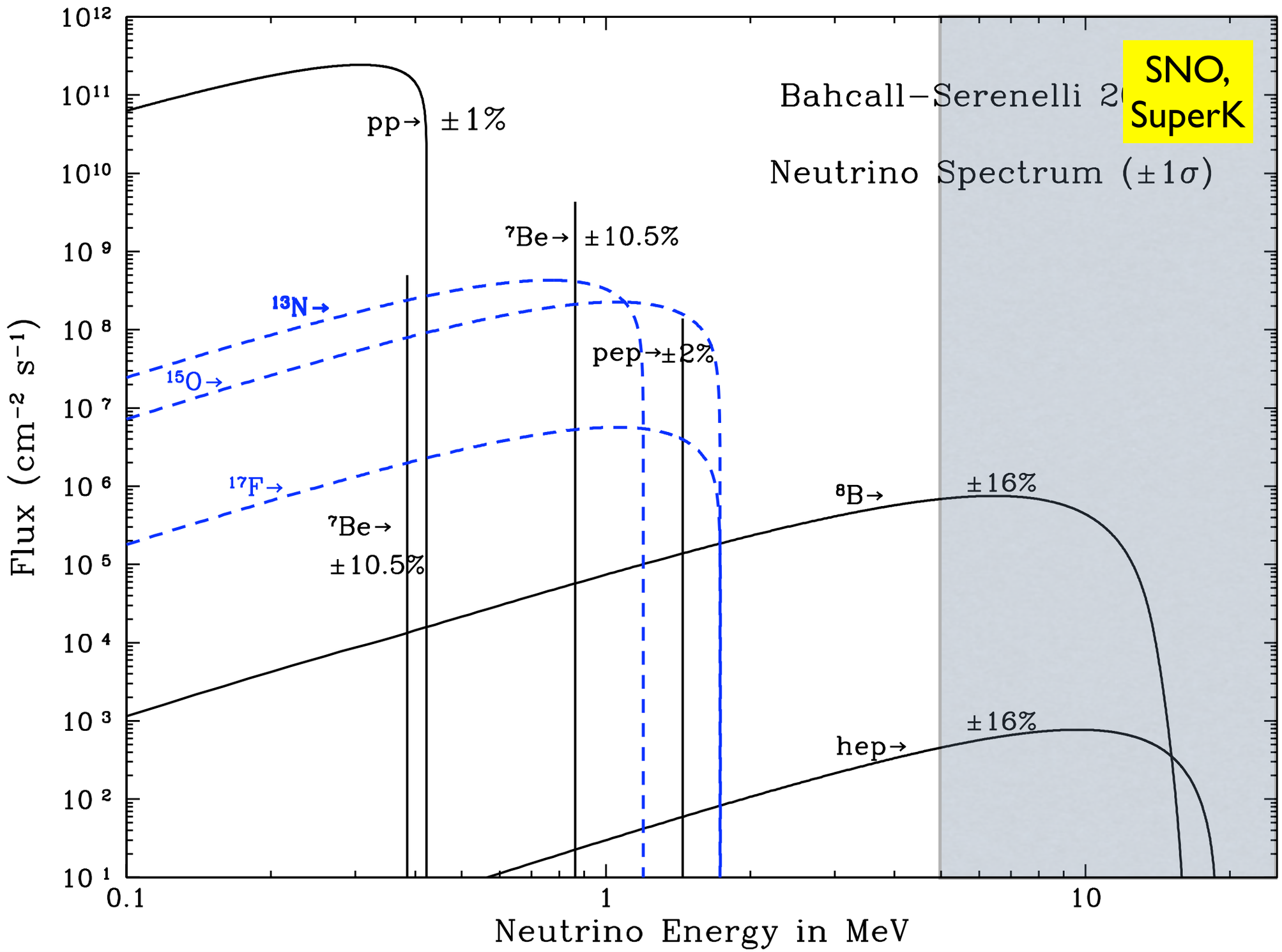
Neutrino 2008
Christchurch, New Zeland
May 26, 2008

Cristiano Galbiati
on behalf of
Borexino Collaboration

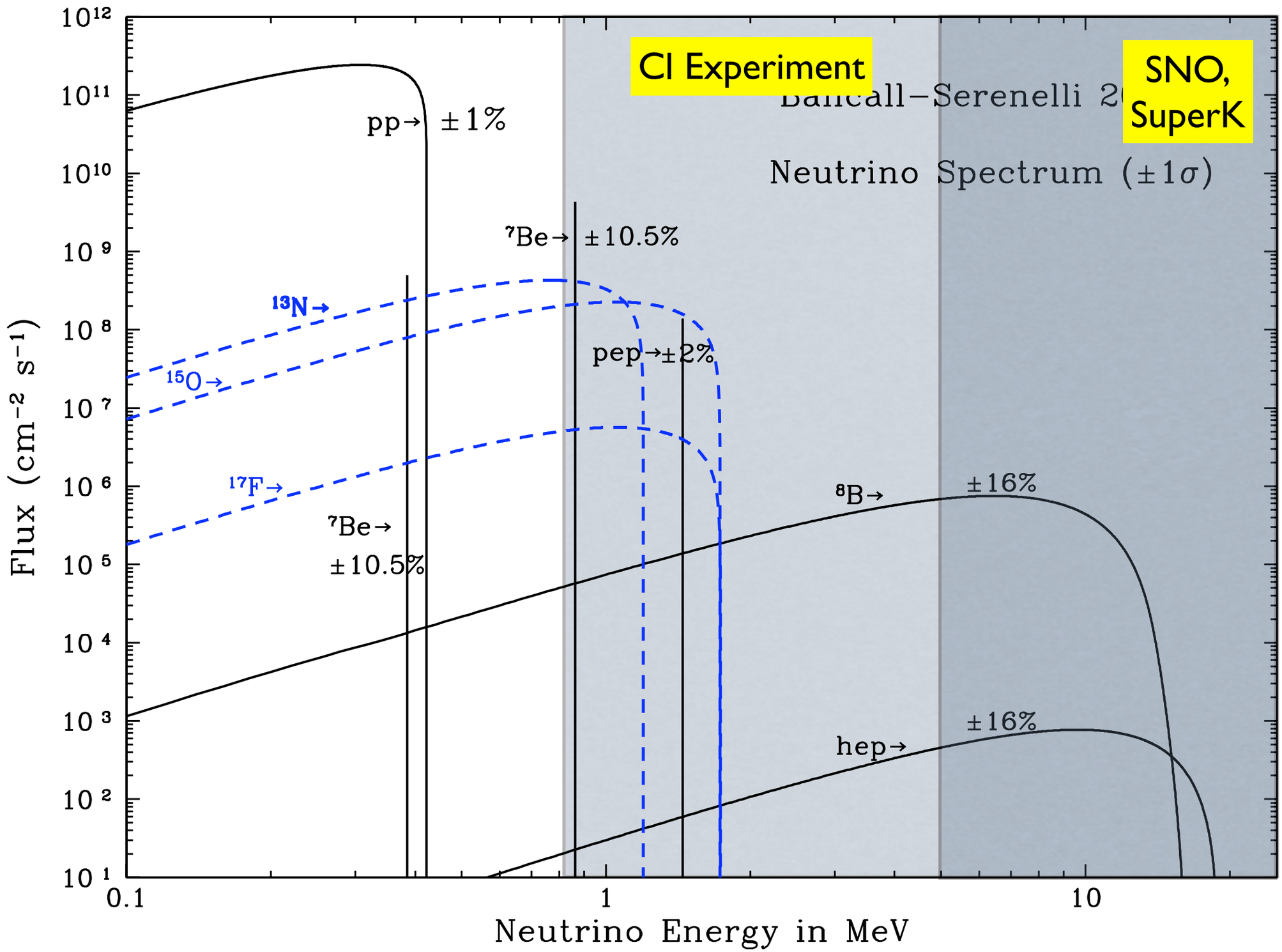
Solar Neutrinos Spectrum



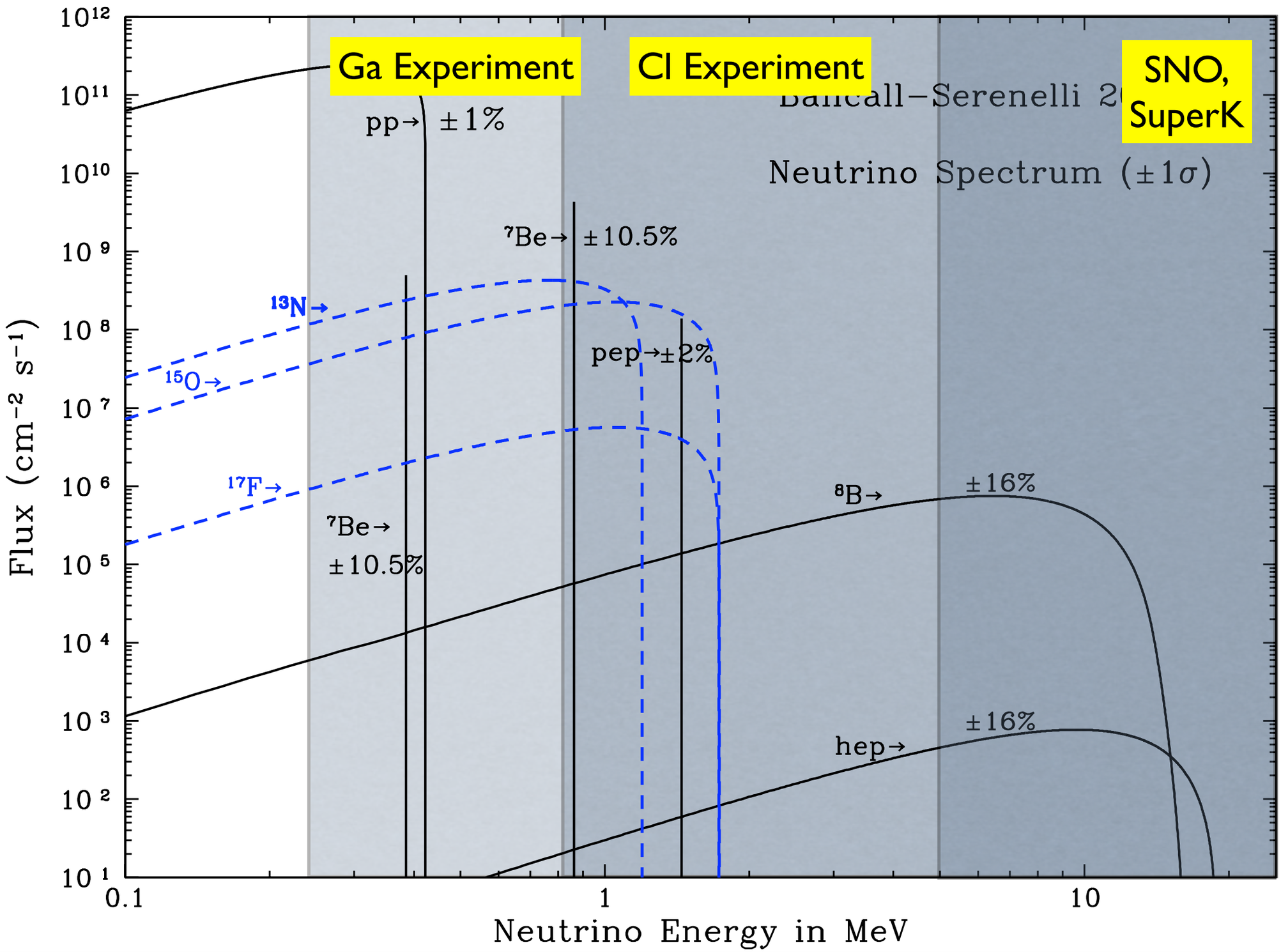
Solar Neutrinos Spectrum



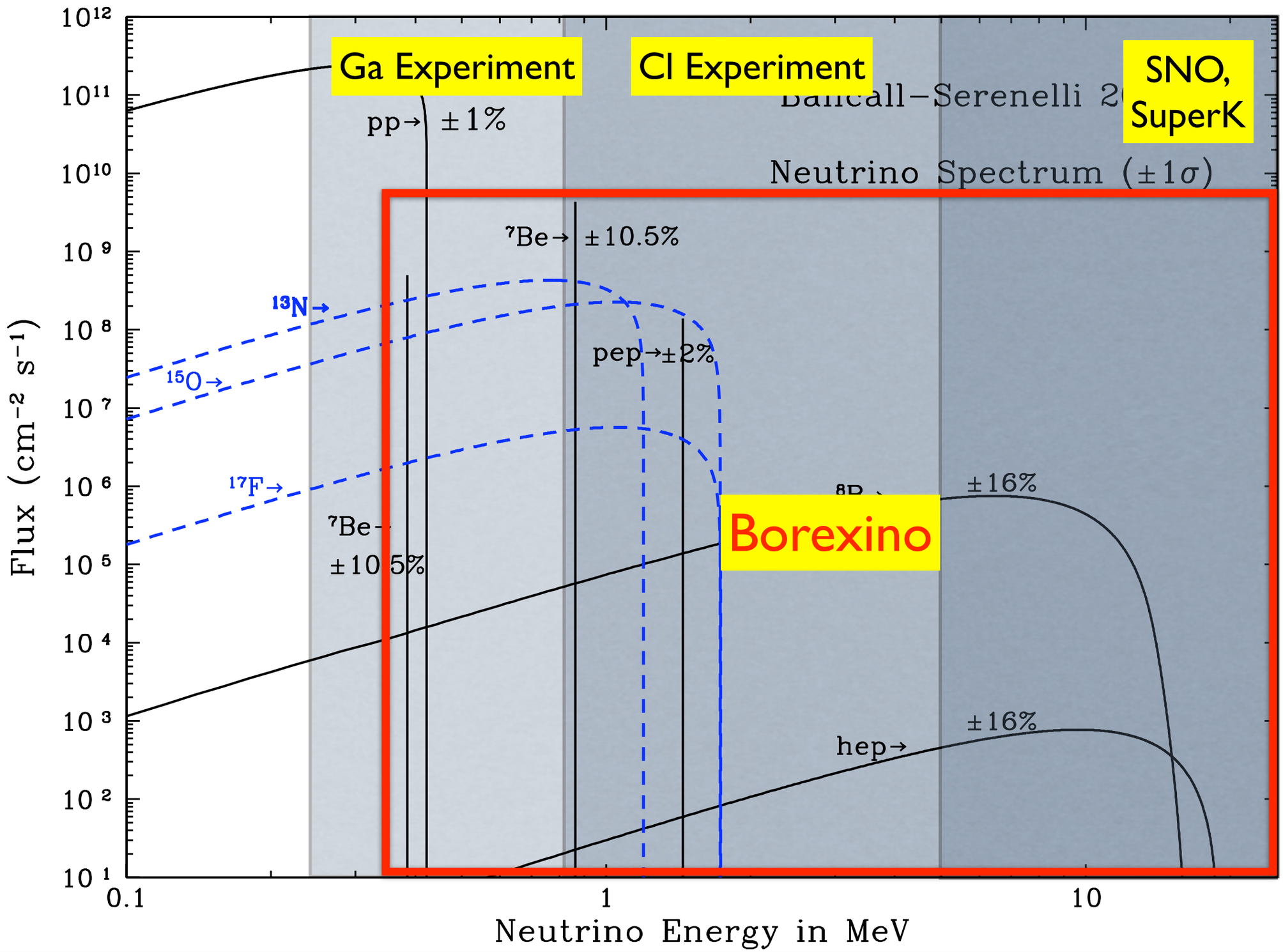
Solar Neutrinos Spectrum



Solar Neutrinos Spectrum



Solar Neutrinos Spectrum



Resonant Oscillations in Matter: the MSW effect

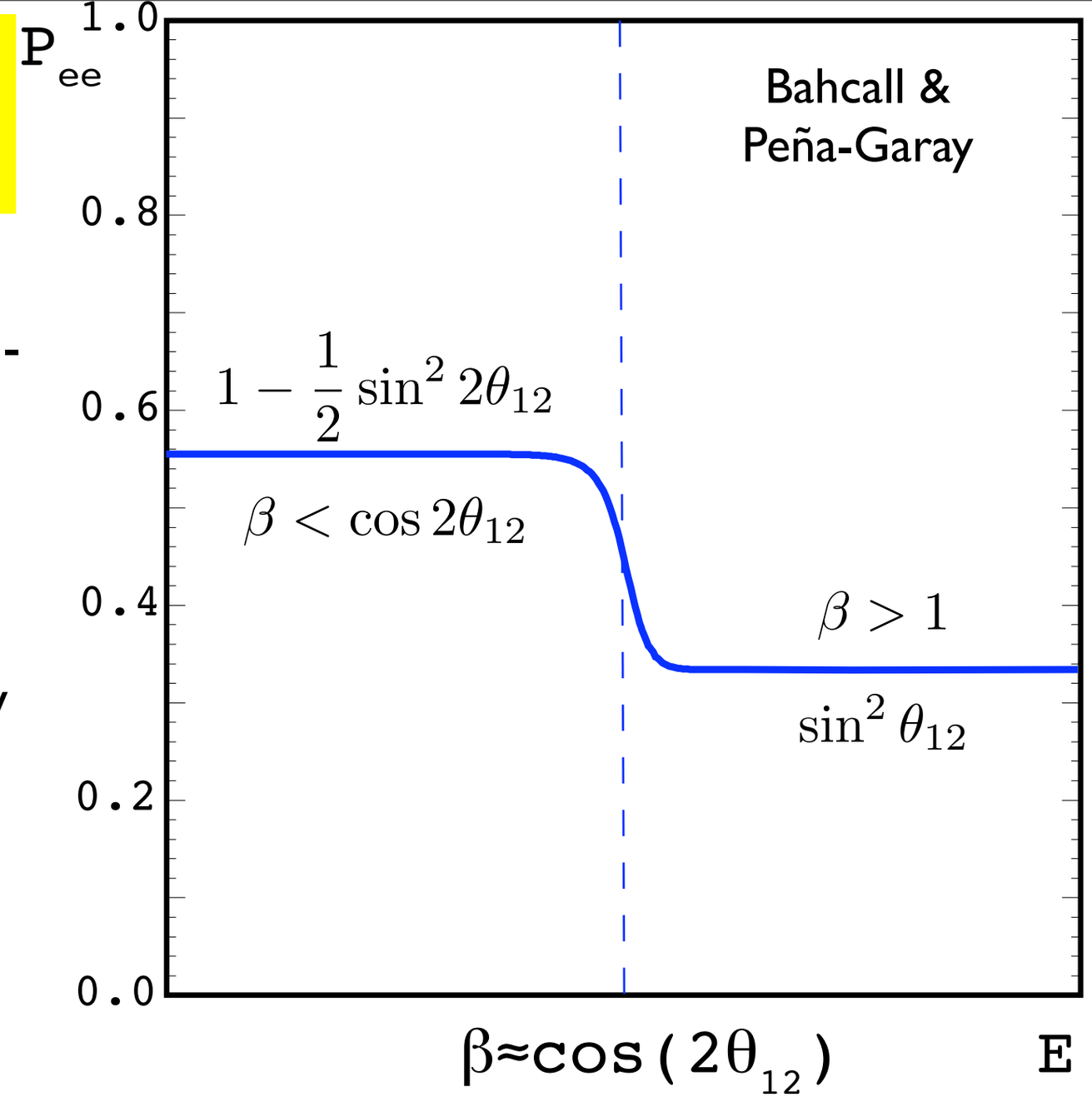
For high energy ^{8}B neutrinos - object of observation by SNO and SuperKamiokaNDE - matter dominated oscillations in the high density of electrons N_e in sun's core

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!

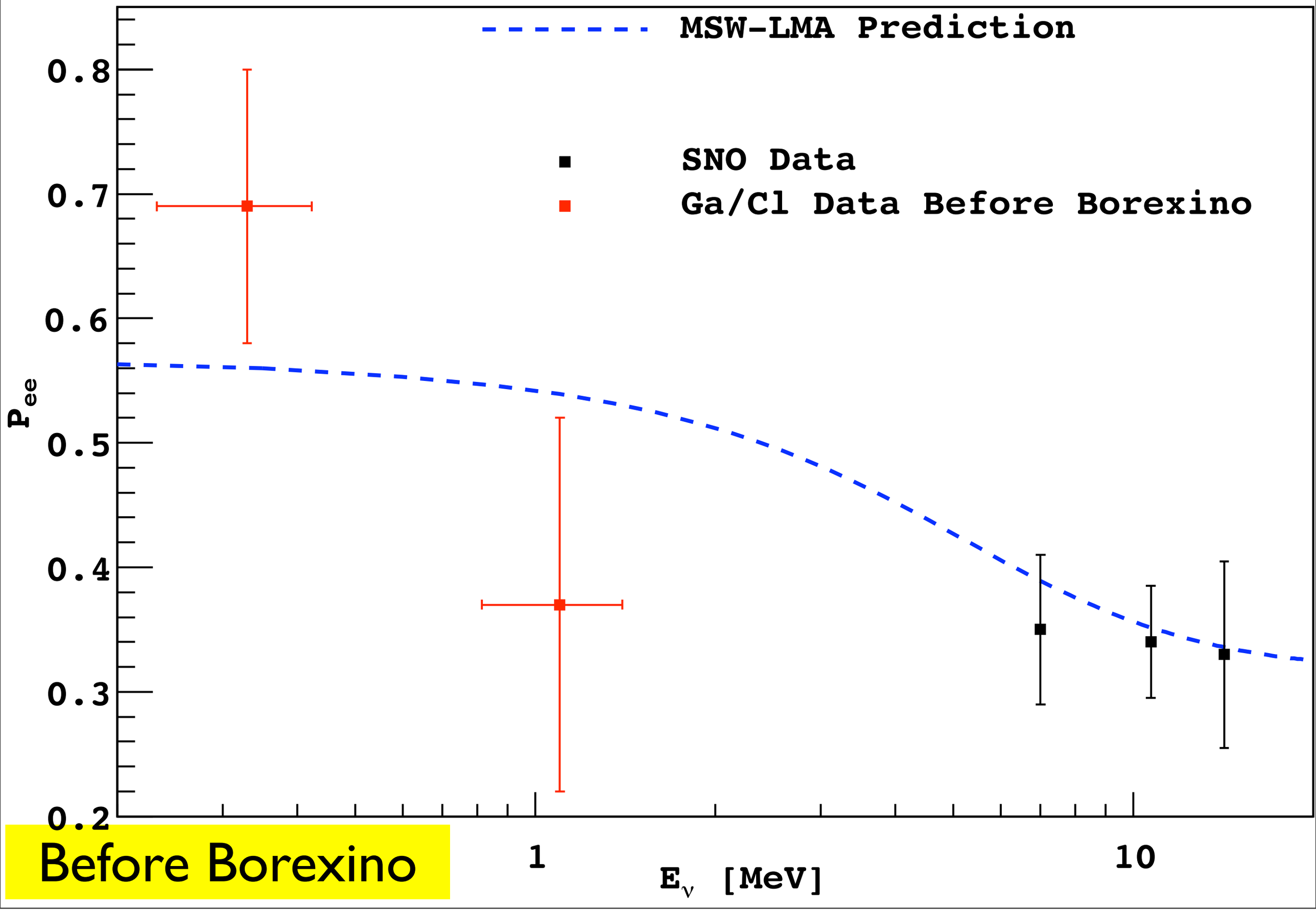


$$\begin{pmatrix} -\frac{\Delta m^2_{12}}{4E}\cos 2\theta_{12} + \boxed{\sqrt{2}G_F N_e} & \frac{\Delta m^2_{12}}{4E}\sin 2\theta_{12} \\ \frac{\Delta m^2_{12}}{4E}\sin 2\theta_{12} & \frac{\Delta m^2_{12}}{4E}\cos 2\theta_{12} \end{pmatrix}$$

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

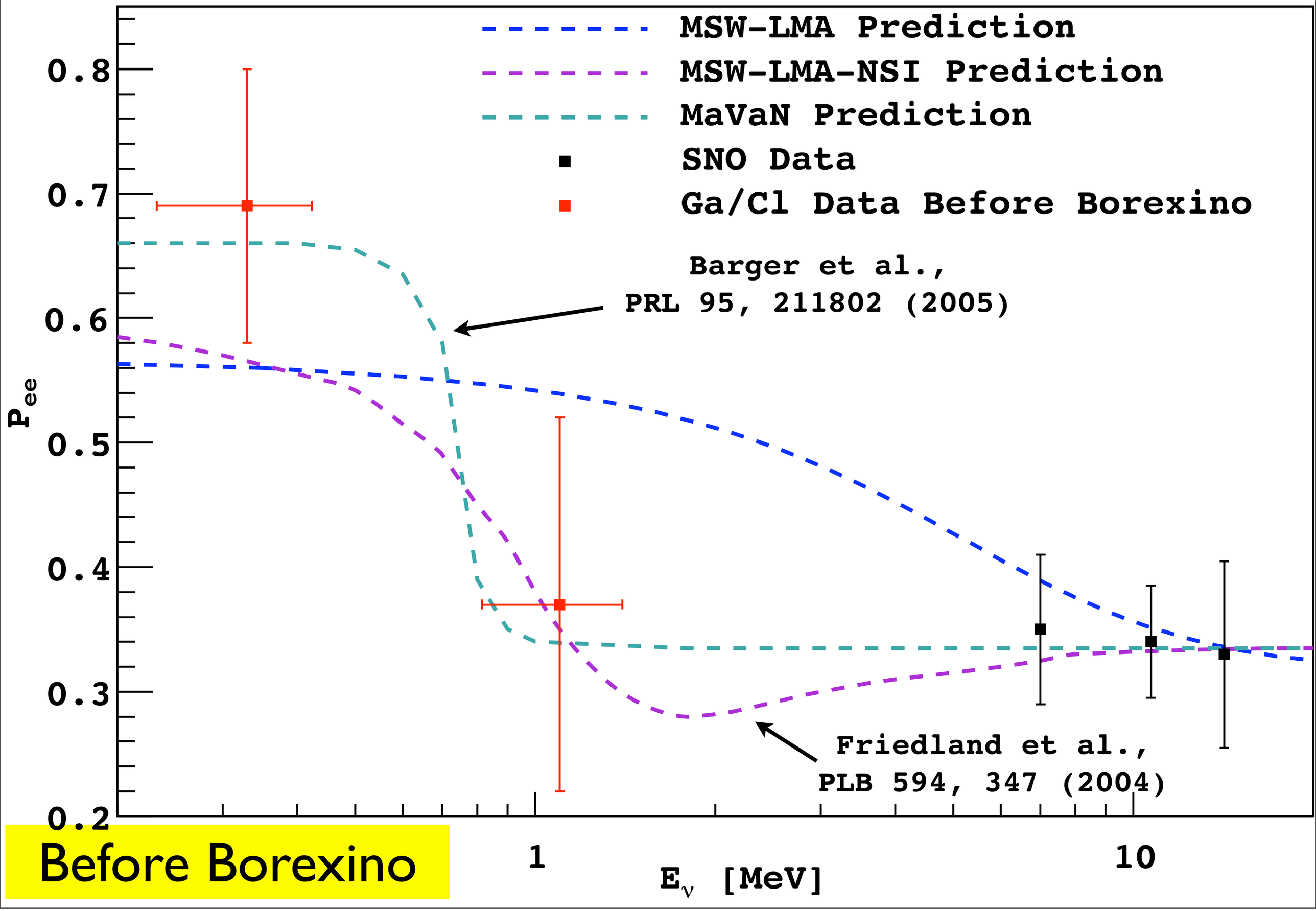
$$E[\mathrm{MeV}] = 6.8\times 10^6 \frac{\cos(2\theta_{12})\Delta \mathrm{m}^2_{12}[\mathrm{eV}^2]}{\rho[\mathrm{g/cm^3}]\mathrm{Z/A}} \simeq 1\text{–}2\ \mathrm{MeV}$$

Solar Neutrino Survival Probability



Before Borexino

Solar Neutrino Survival Probability



Before Borexino

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

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)

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

  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.

Borexino: Additional Possibilities for First Time Measurements

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

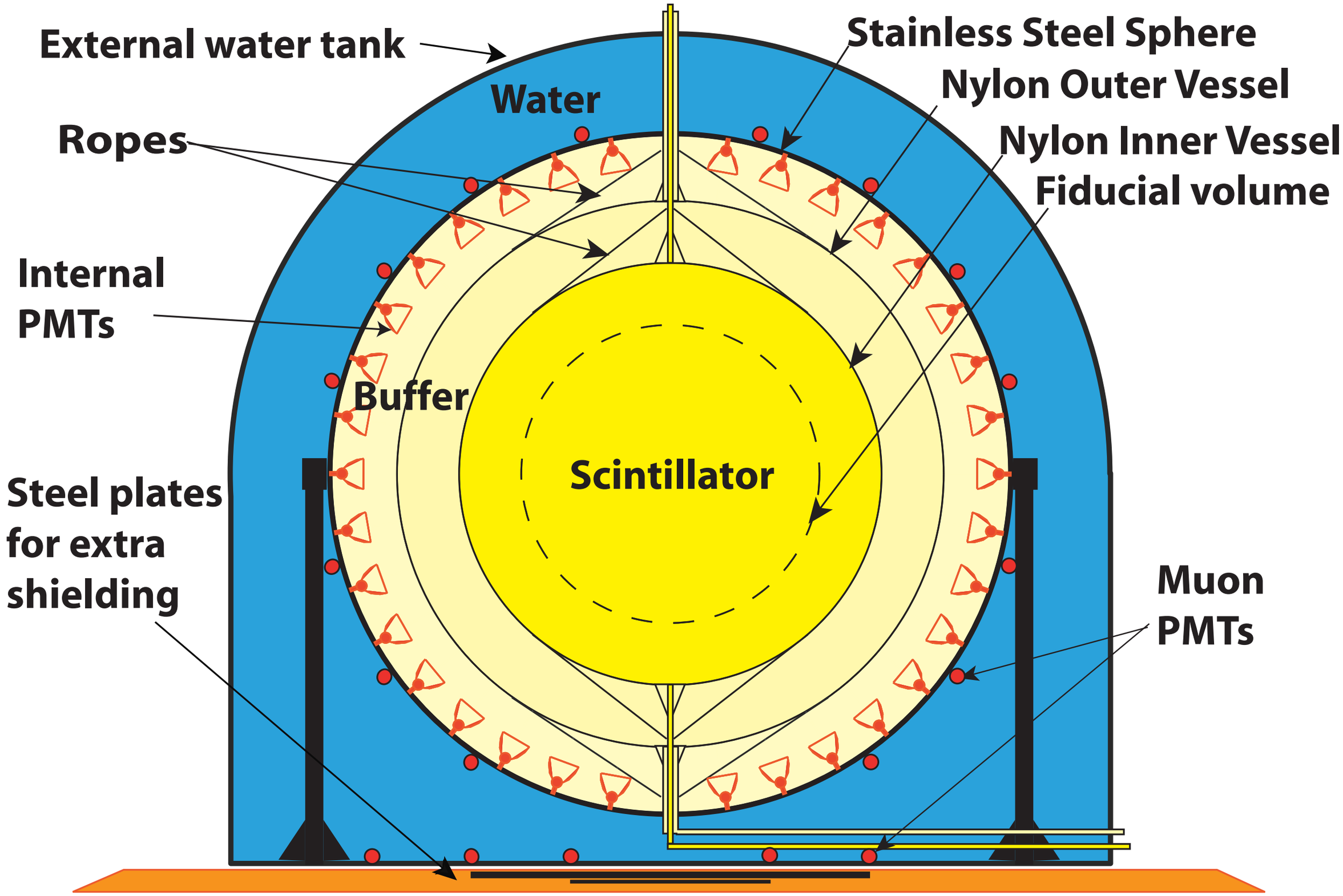
Detection Principles

- 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

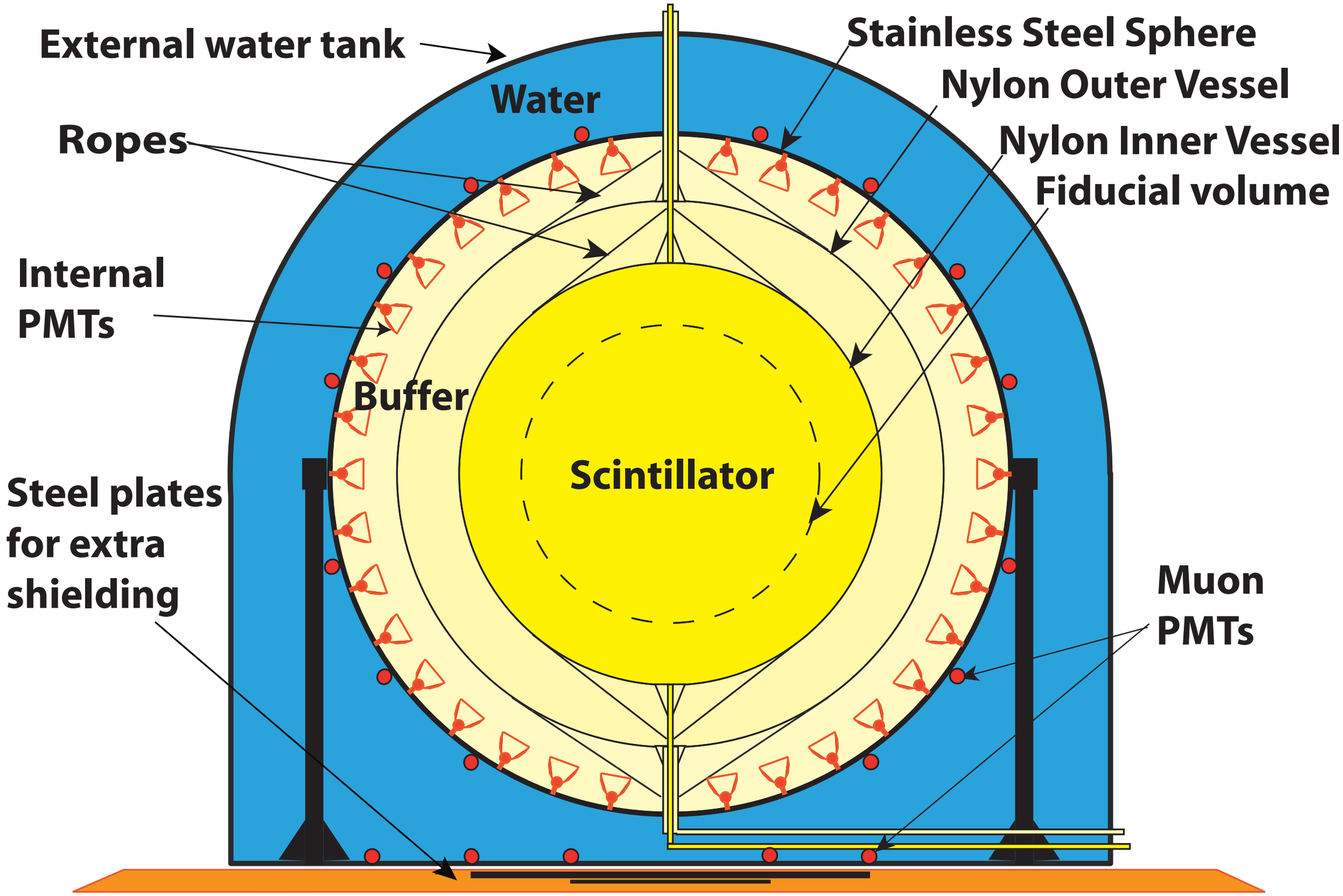
Collaboration

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

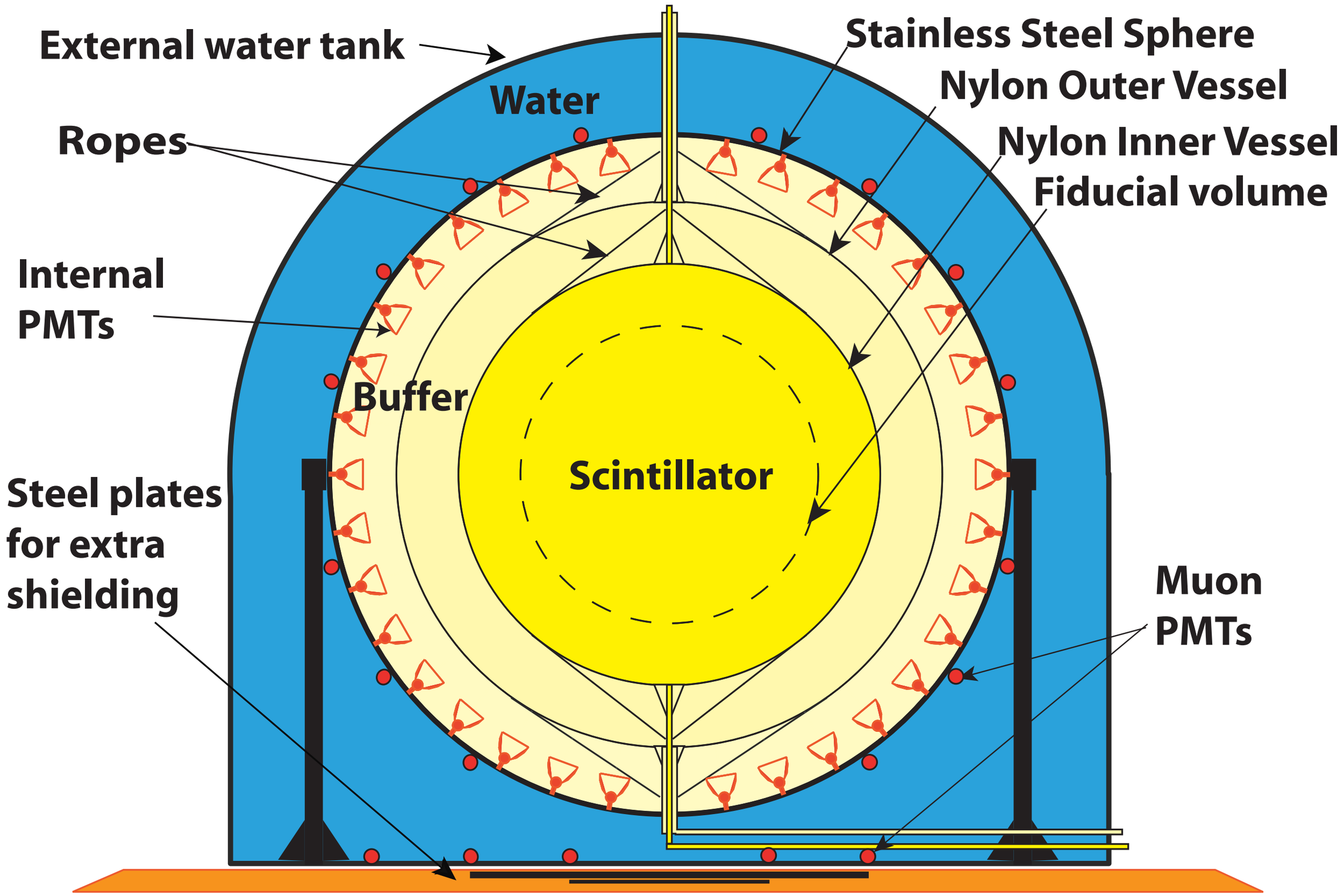


Borexino Detector



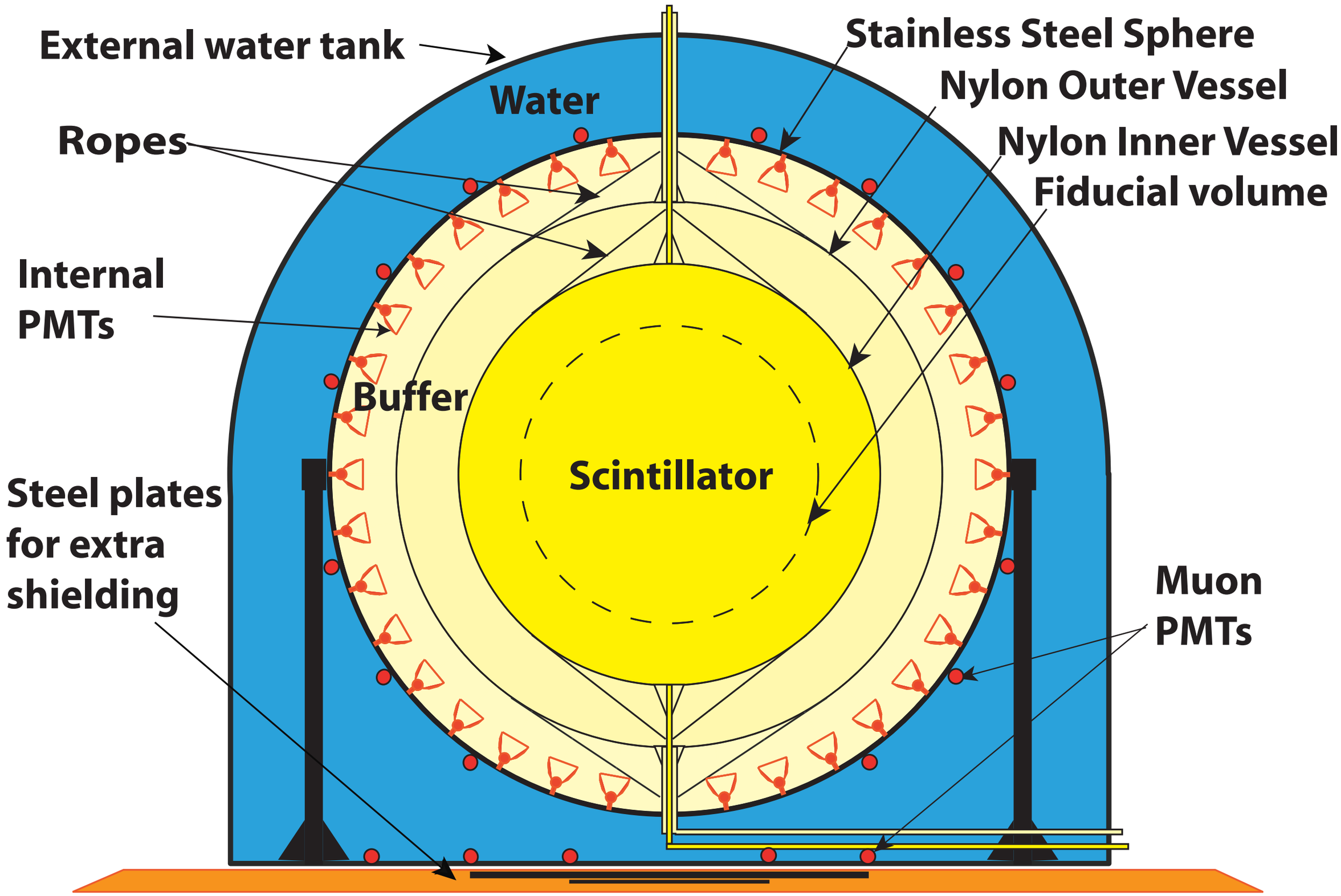
Located in LNGS - 3800 m.w.e. against cosmic rays

Borexino Detector



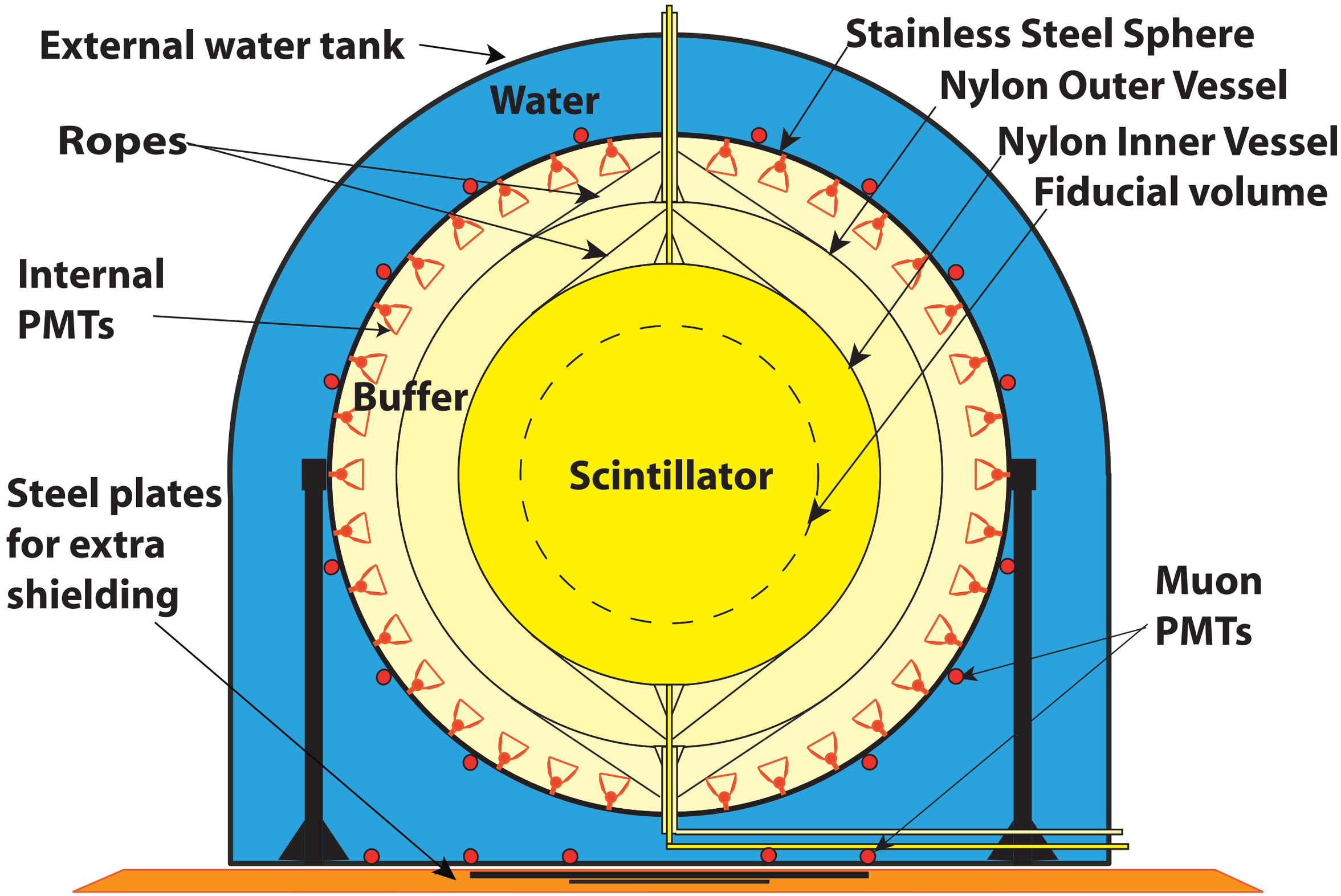
Active Target: 278 Tons of Liquid Scintillator in Nylon Vessel of 4.25 m radius

Borexino Detector



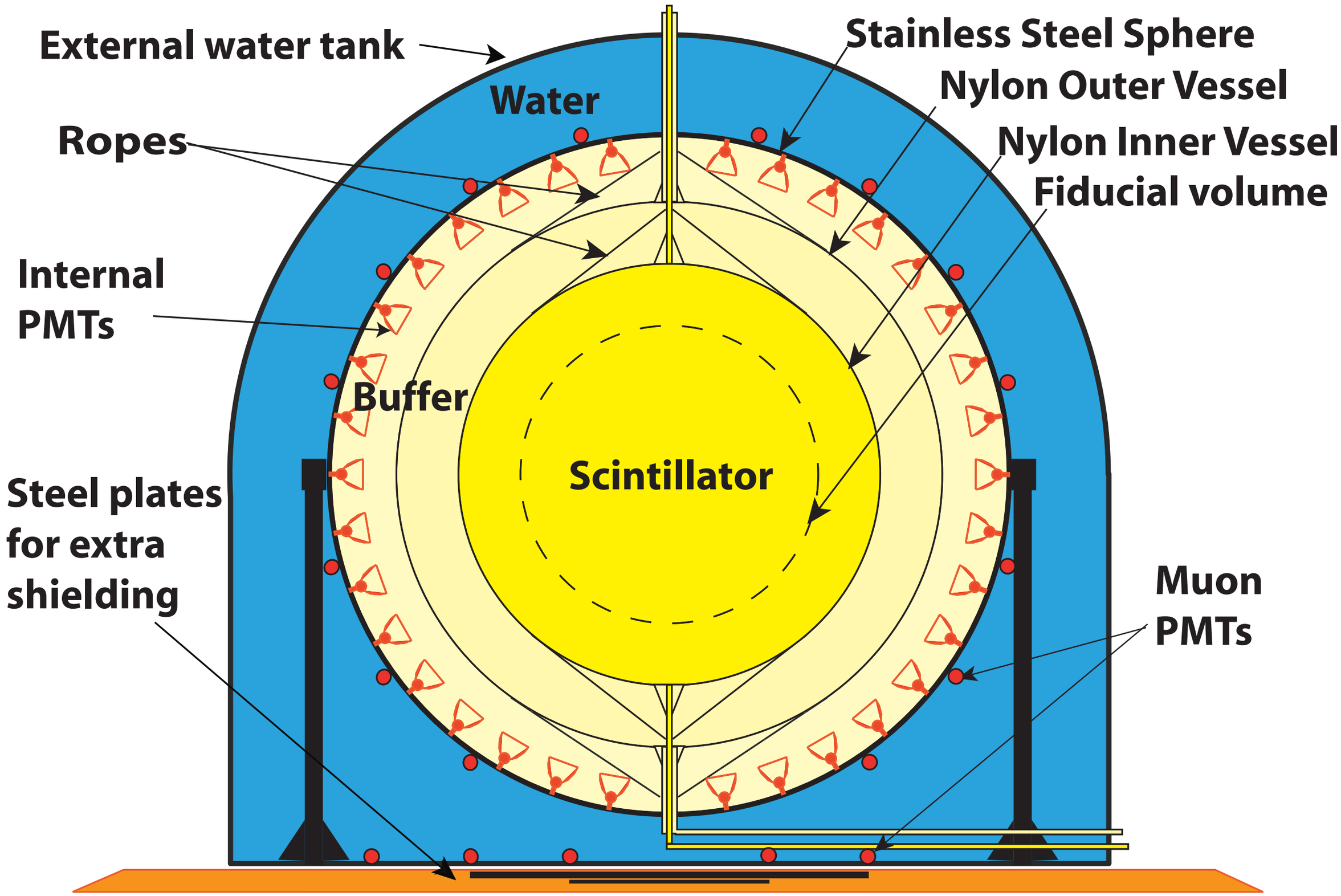
1st shield: 890 tons of ultra-pure buffer liquid in a stainless steel sphere of 6.75 m radius

Borexino Detector



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

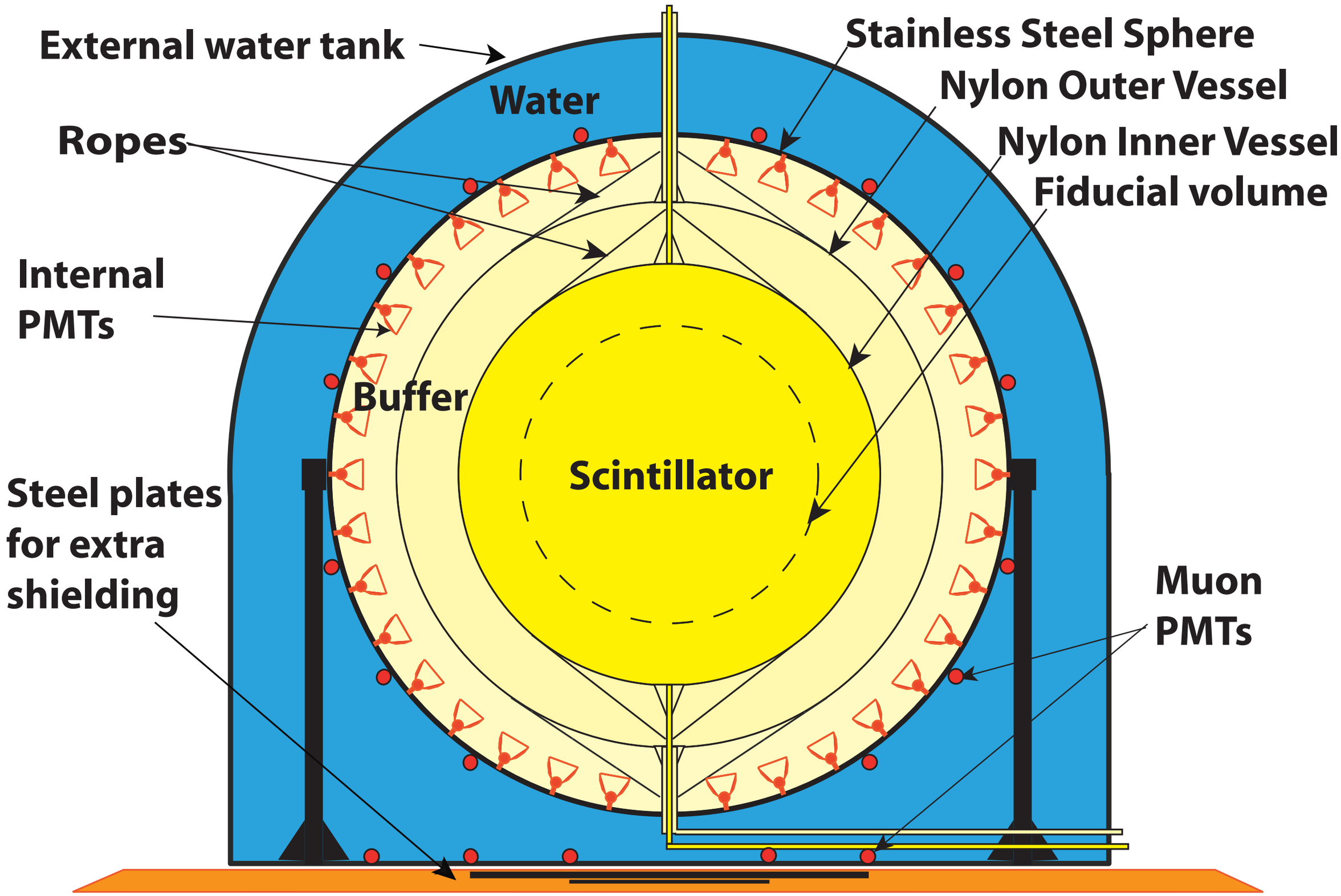
Borexino Detector



2214 PMTs detect light emitted by the scintillator

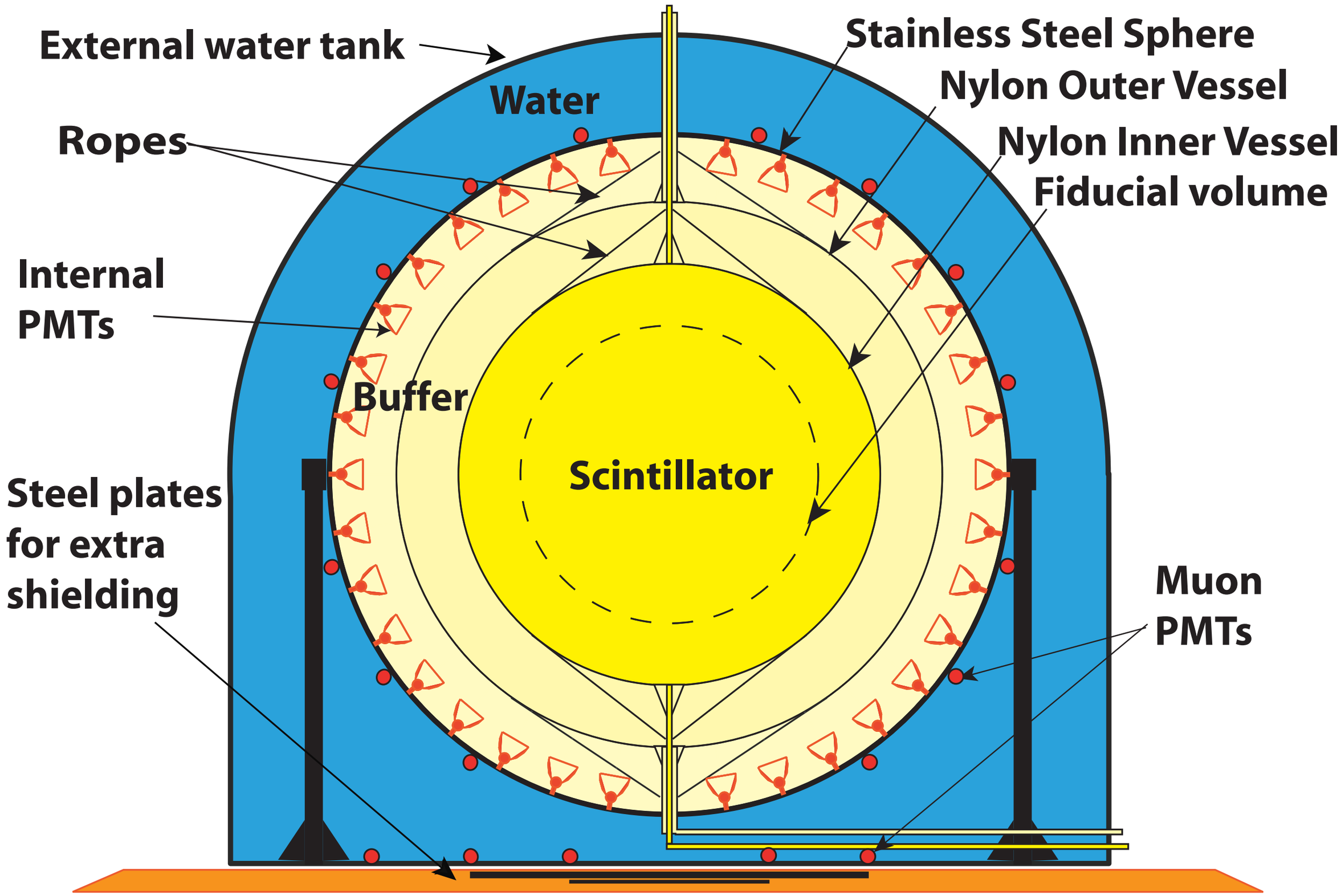
1843 with optical concentrators, the rest without for muons

Borexino Detector



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

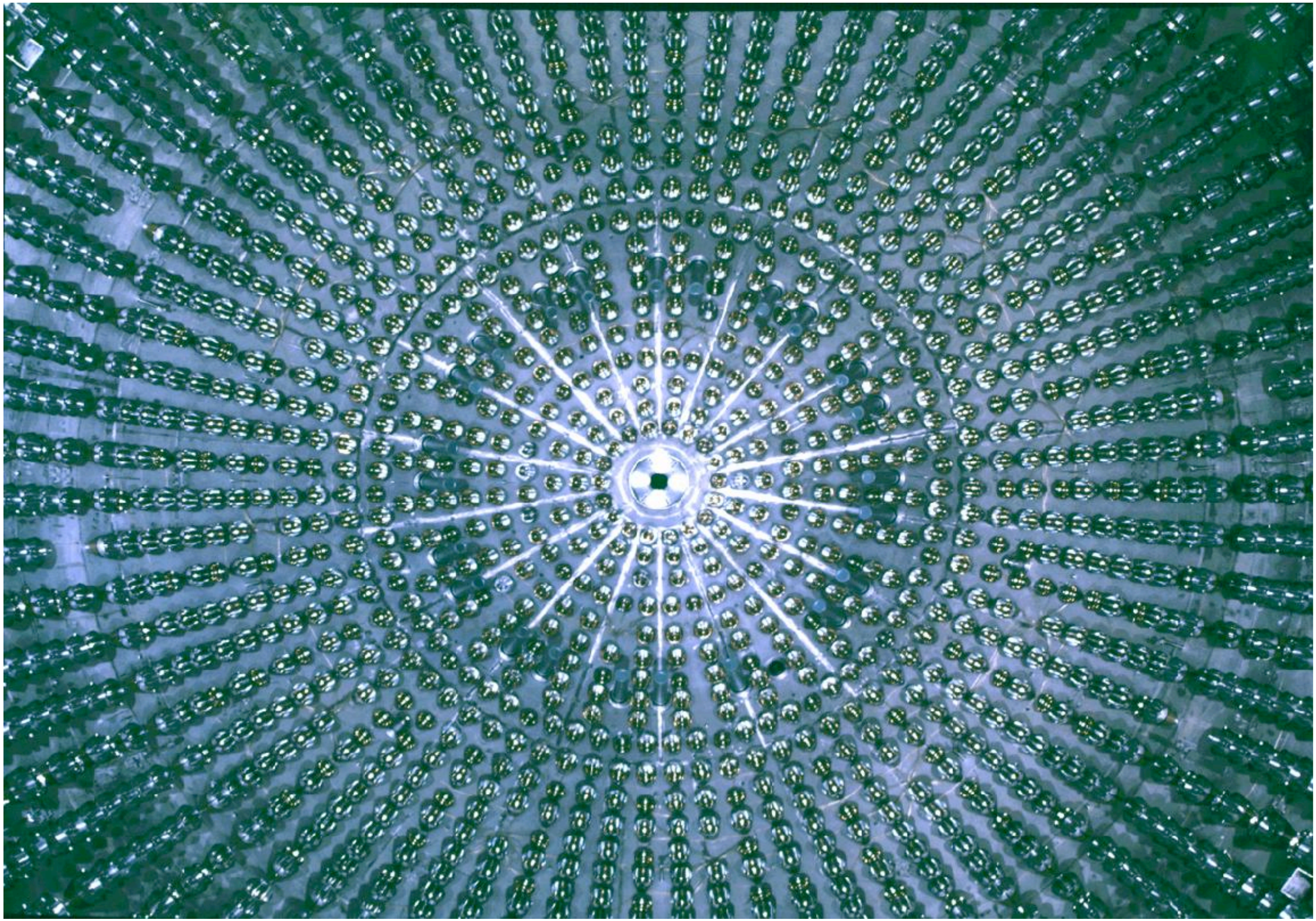
Borexino Detector

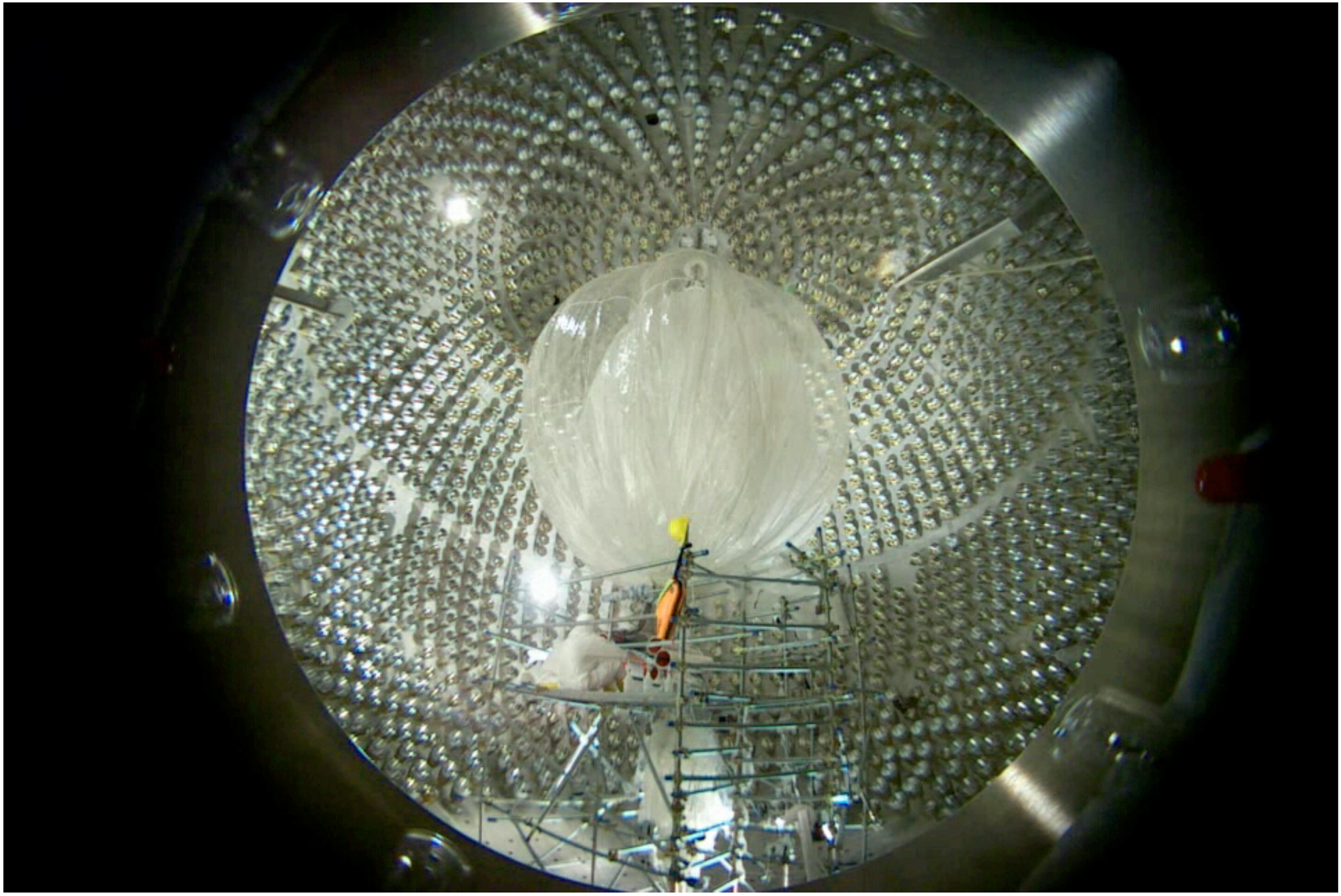


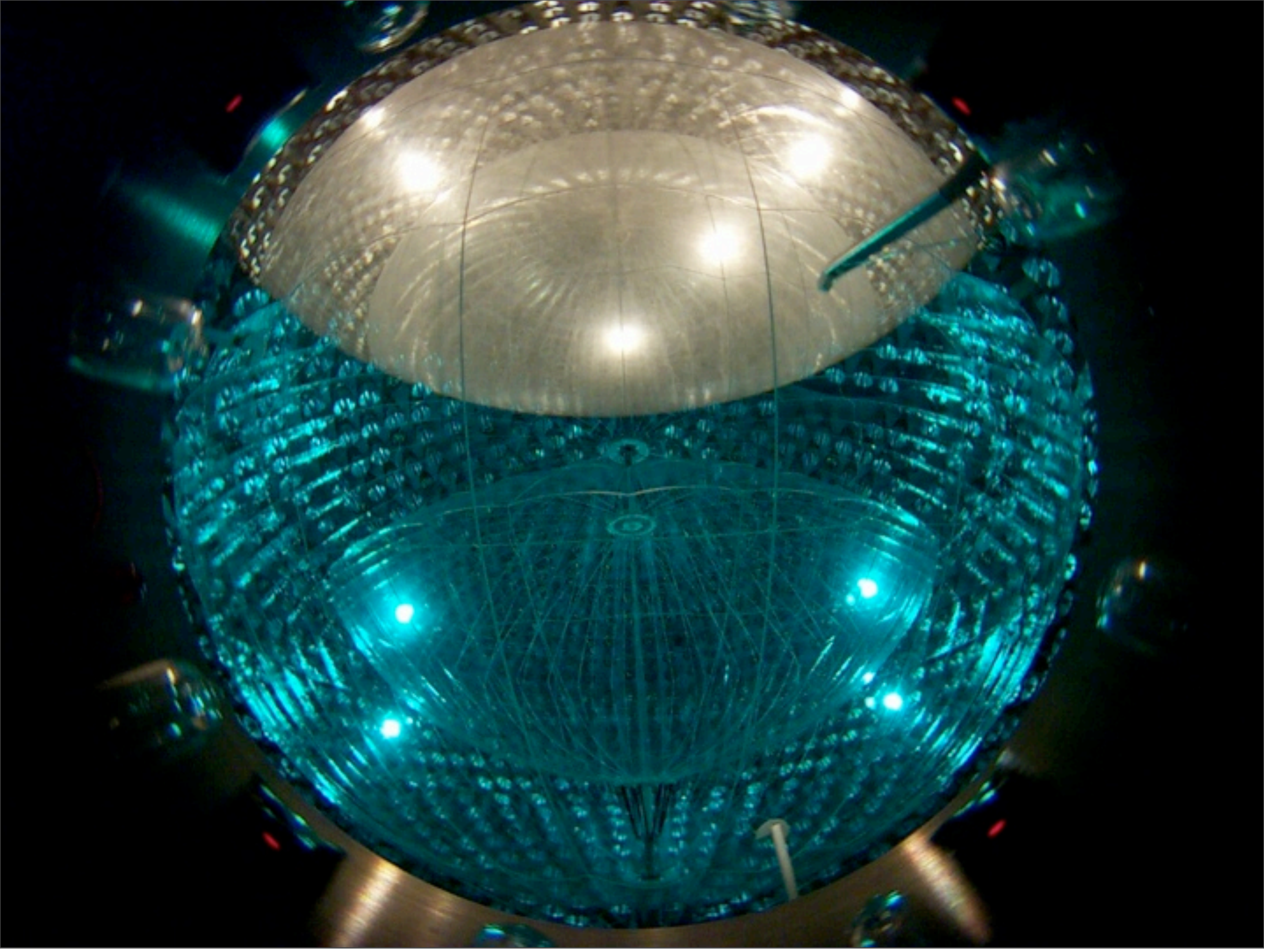
200 PMTs mounted on the SSS detect Cherenkov light emitted in the water by muons

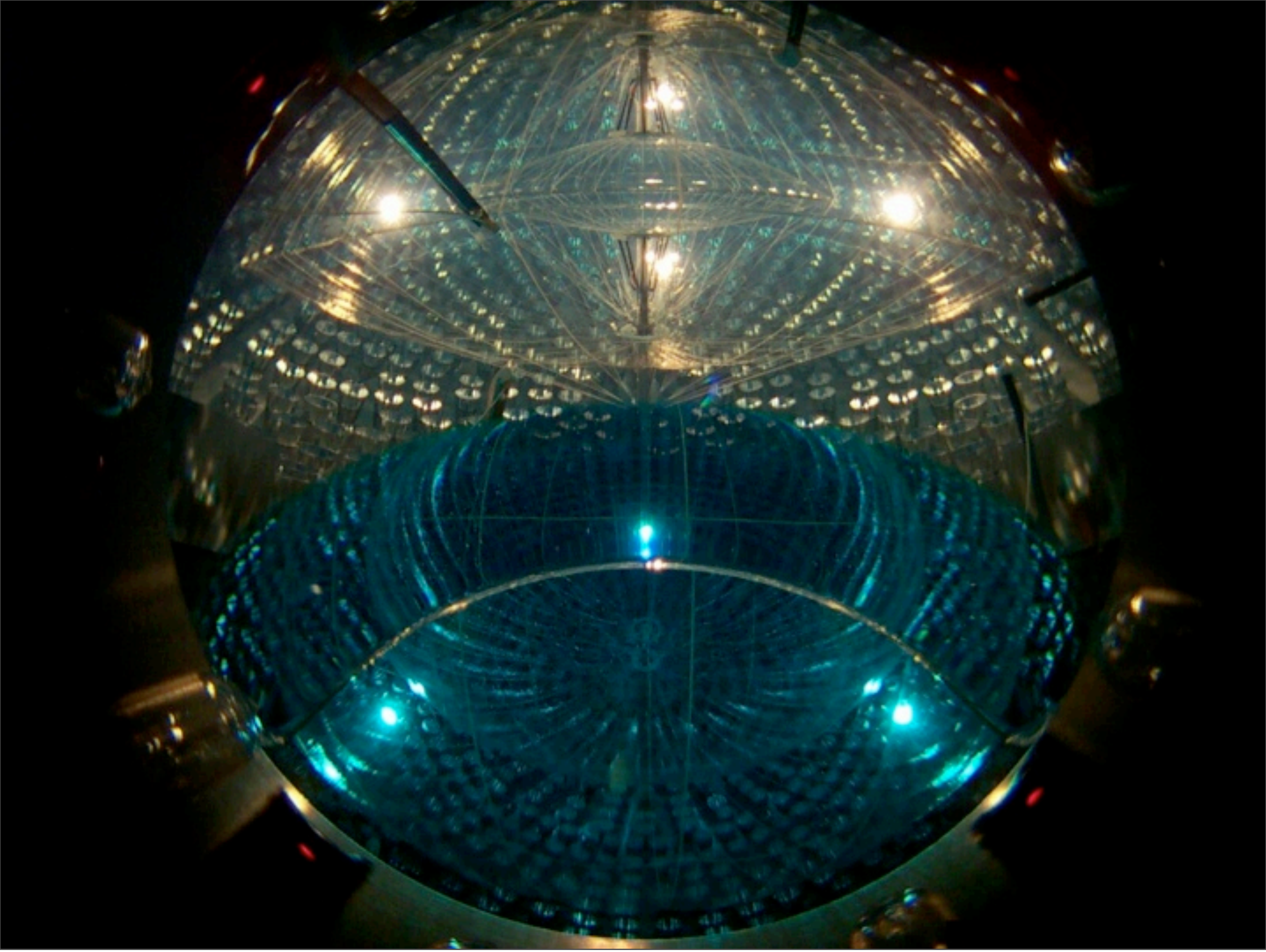
Special Methods Developed

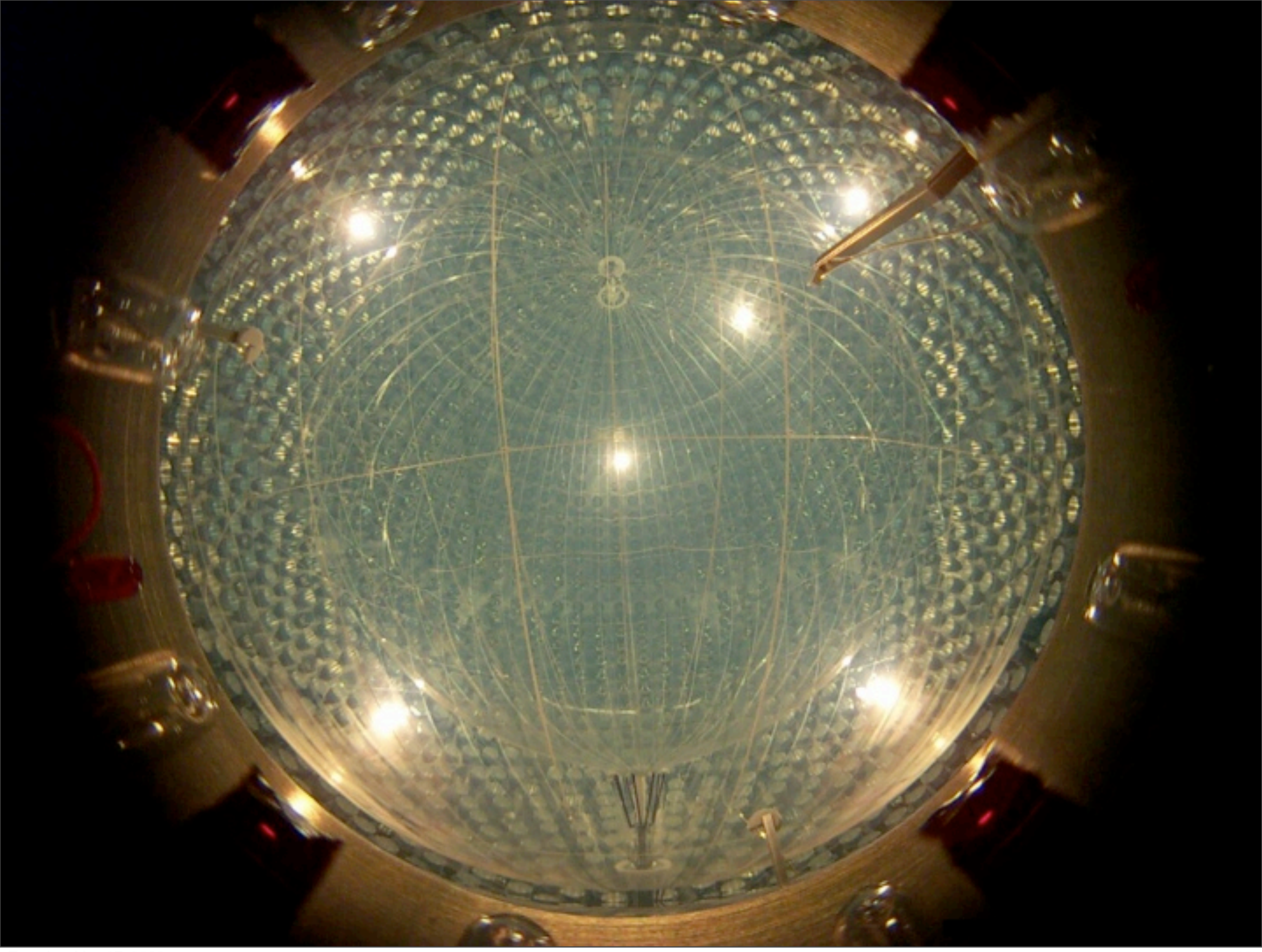
- Low background nylon vessel fabricated in hermetically sealed low radon clean room (~1 yr)
- Rapid transport of scintillator solvent (PC) from production plant to underground lab to avoid cosmogenic production of radioactivity (^{7}Be)
- Underground purification plant to distill scintillator components.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



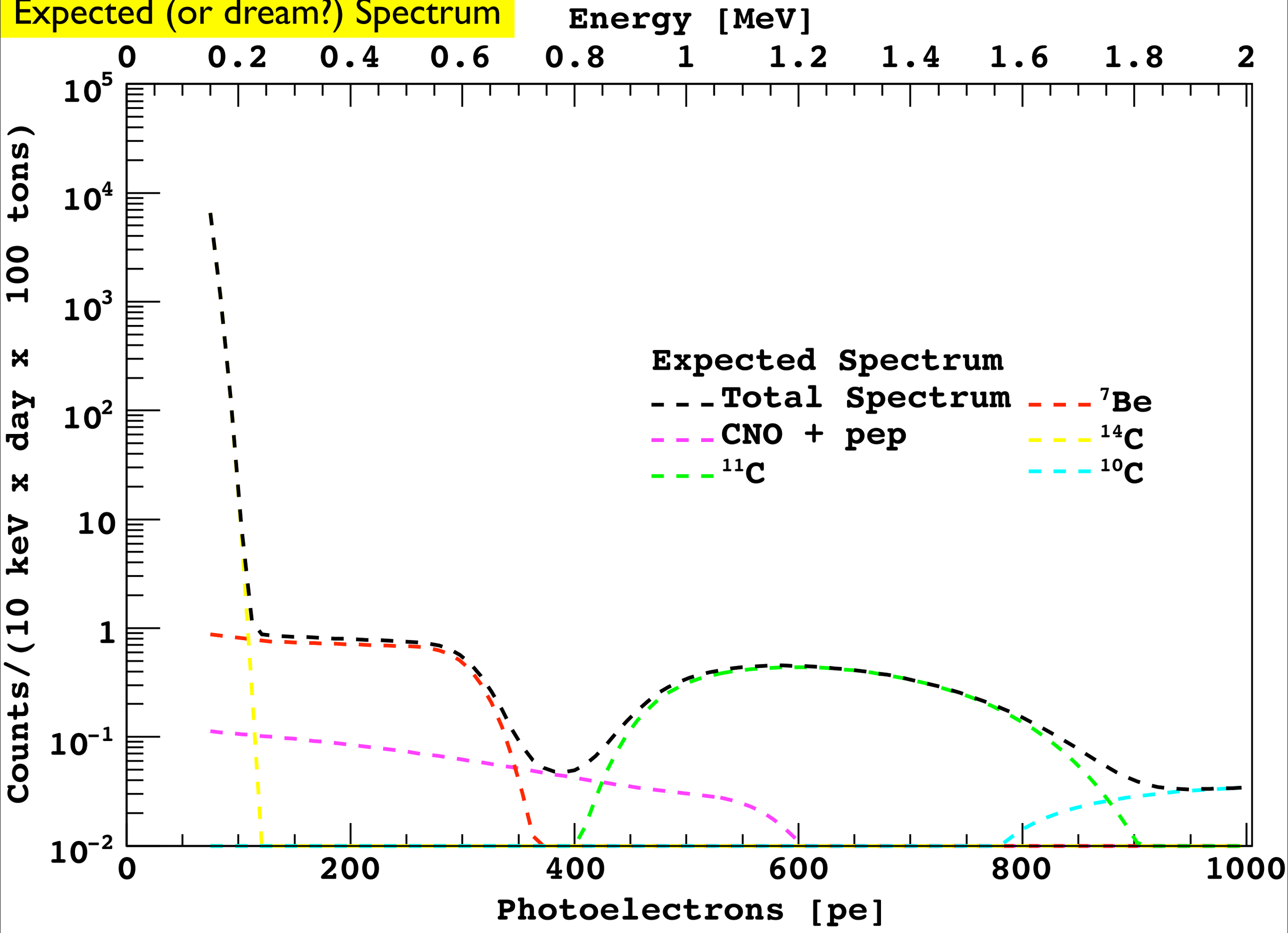




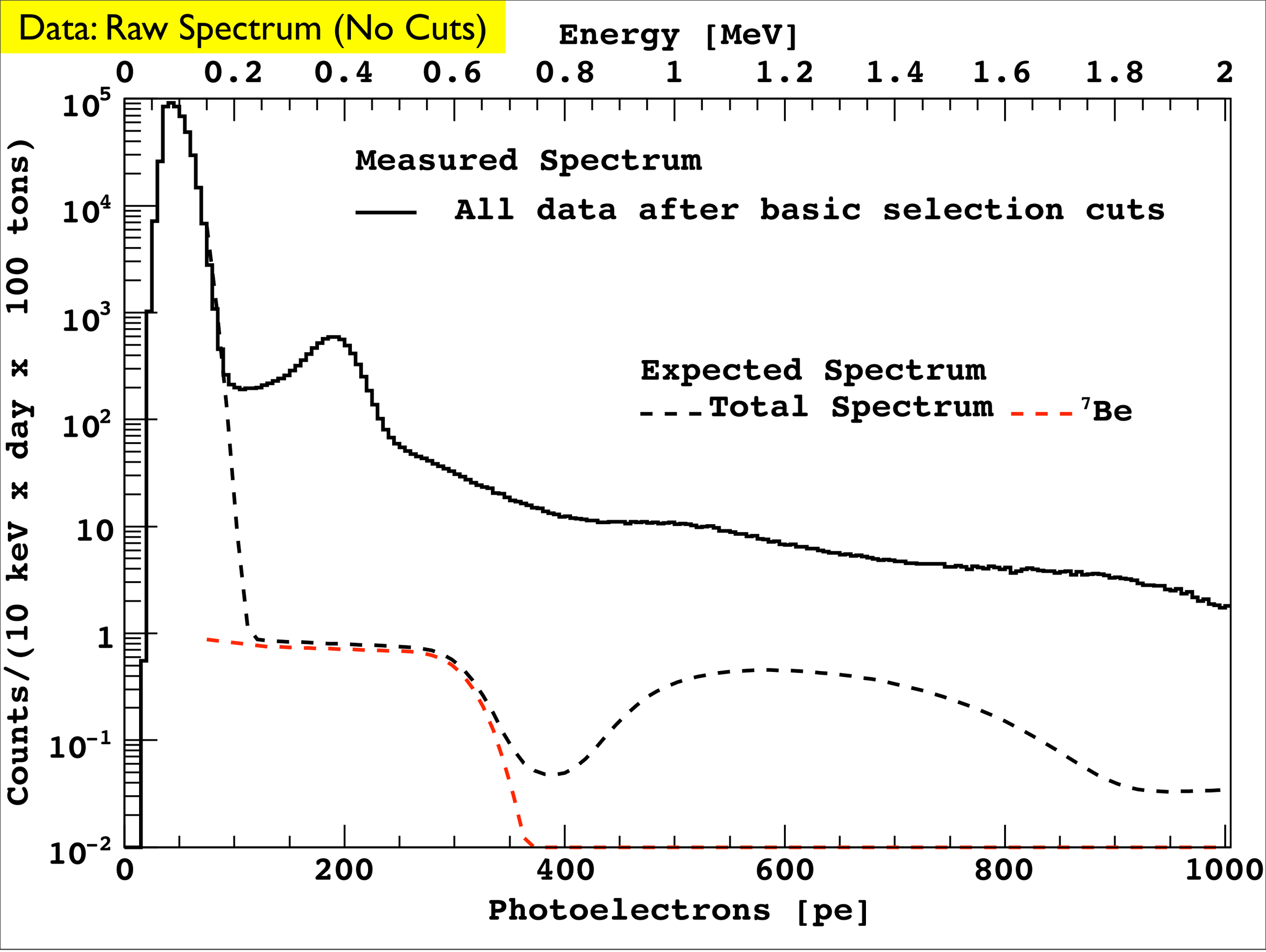




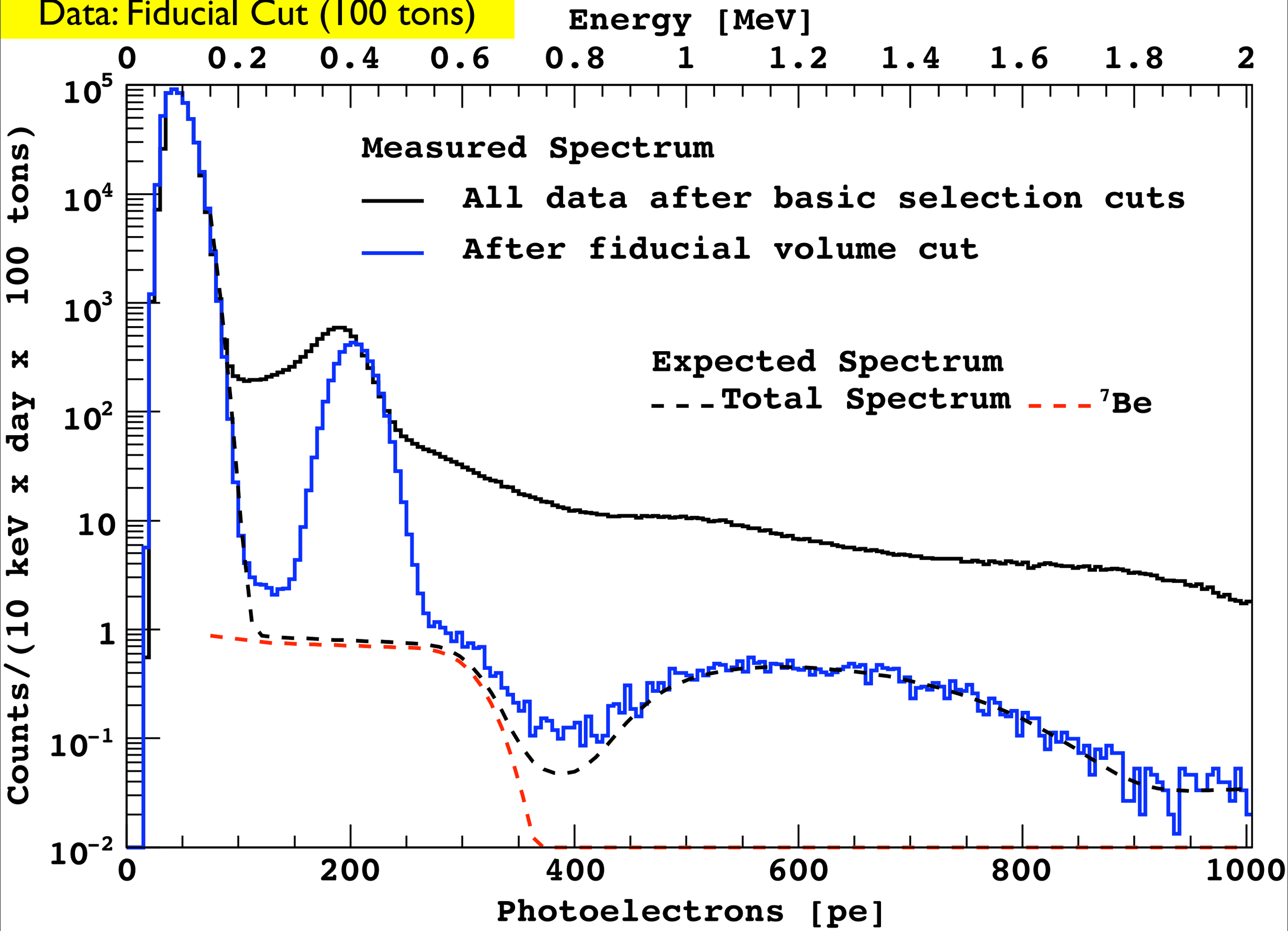
Expected (or dream?) Spectrum



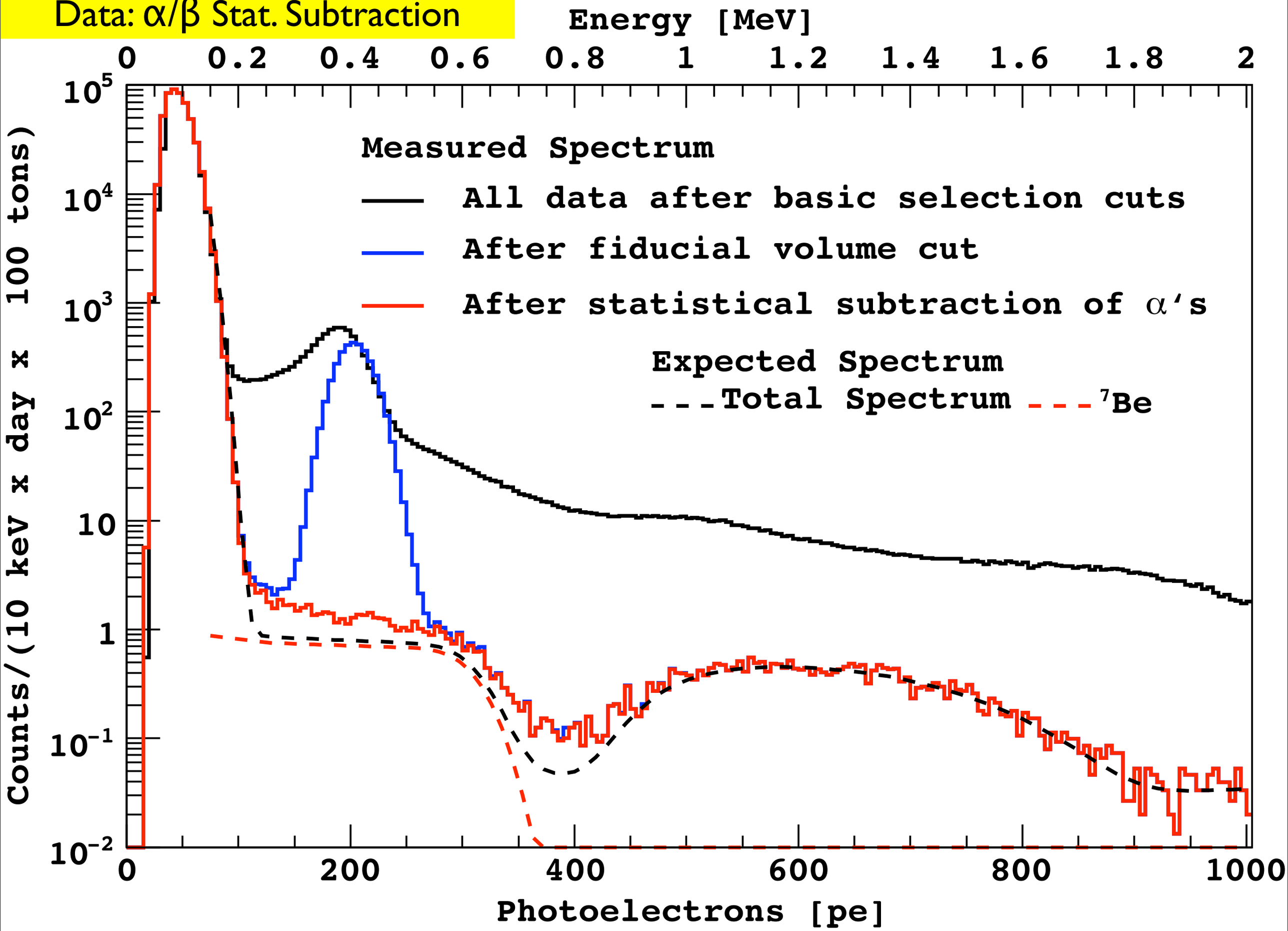
Data: Raw Spectrum (No Cuts)



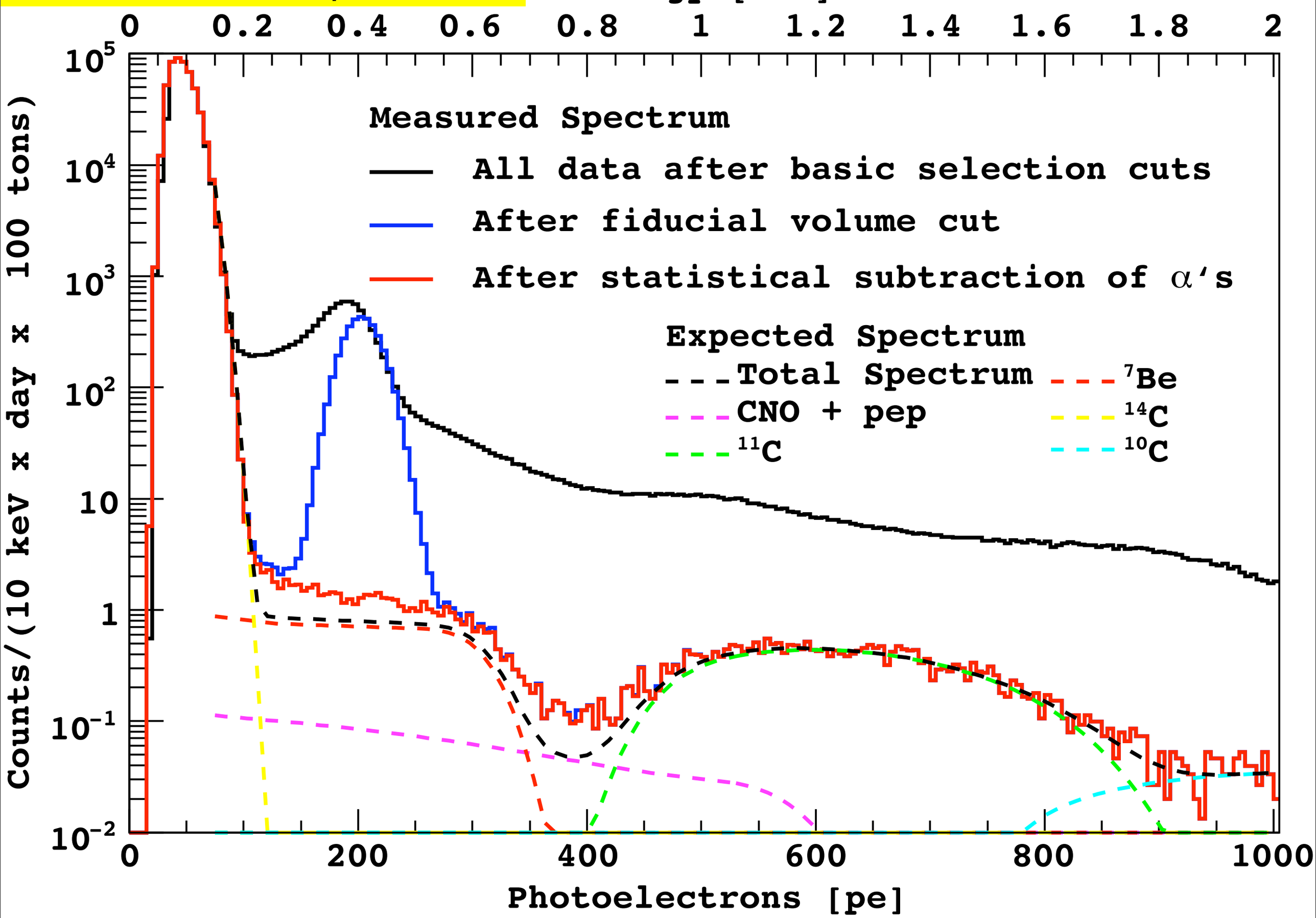
Data: Fiducial Cut (100 tons)



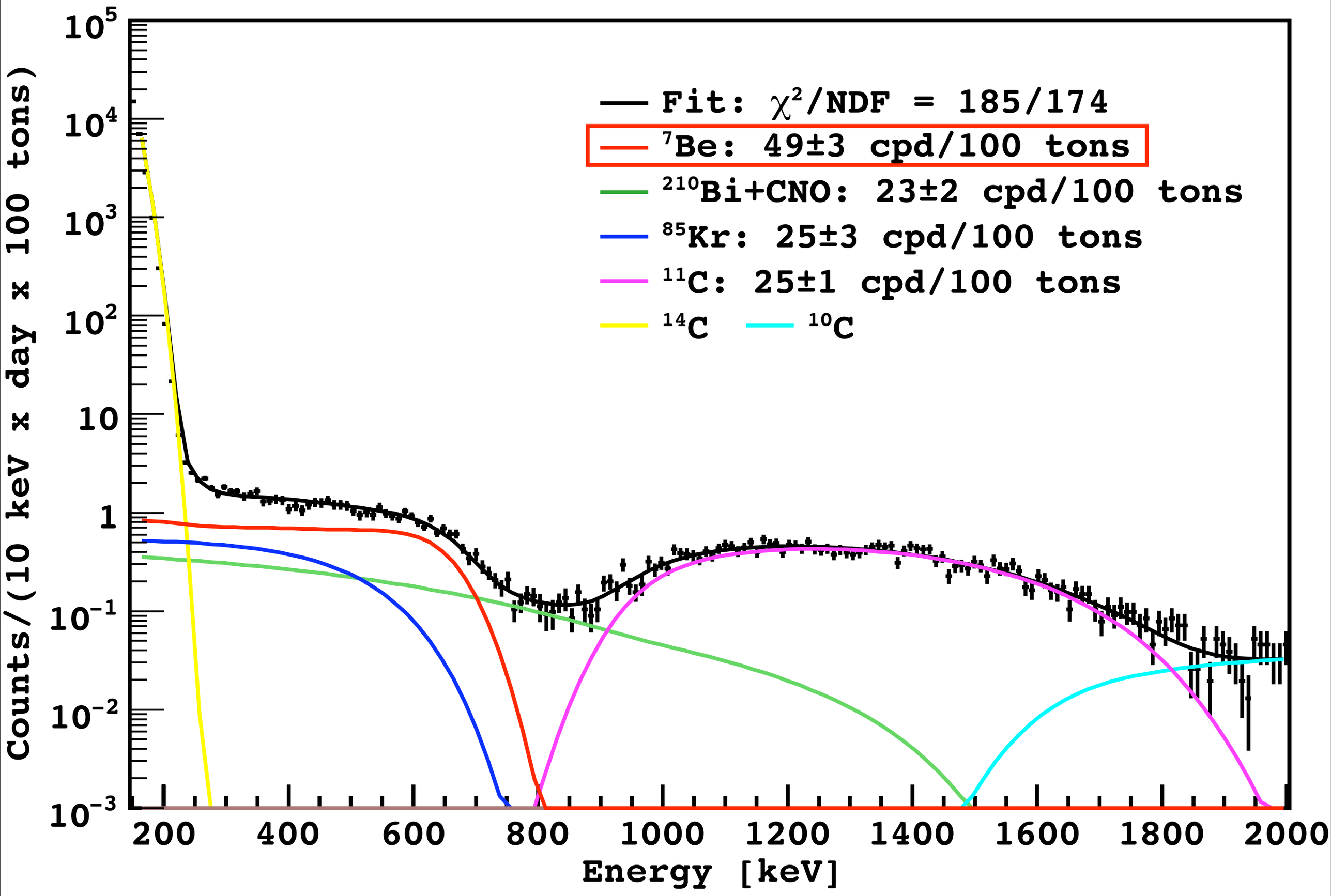
Data: α/β Stat. Subtraction



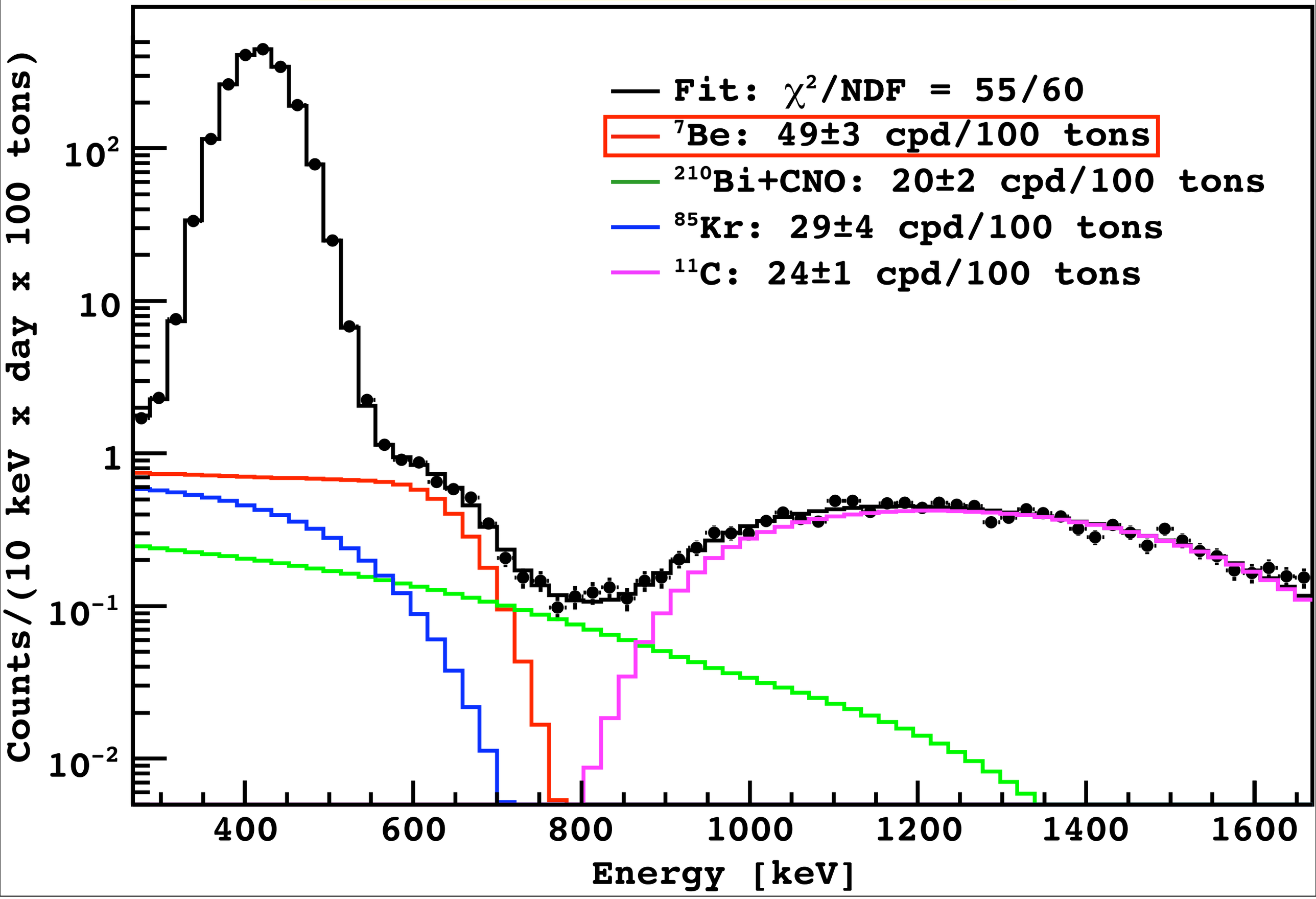
Data: Final Comparison



New Results:192 Days



New Results:192 Days



Systematic & Measurement

Expected interaction rate in absence of oscillations:

75±4 cpd/100 tons

for LMA-MSW oscillations:

48±4 cpd/100 tons

Estimated 1σ Systematic Uncertainties* [%]

Total Scintillator Mass	0.2
Fiducial Mass Ratio	6.0
Live Time	0.1
Detector Resp. Function	6.0
Cuts Efficiency	0.3
Total	8.5

*Prior to Calibration

^{7}Be Rate:

$49 \pm 3_{stat} \pm 4_{syst}$ cpd/100 tons

Neutrino Magnetic Moment

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

EM current affects cross section σ

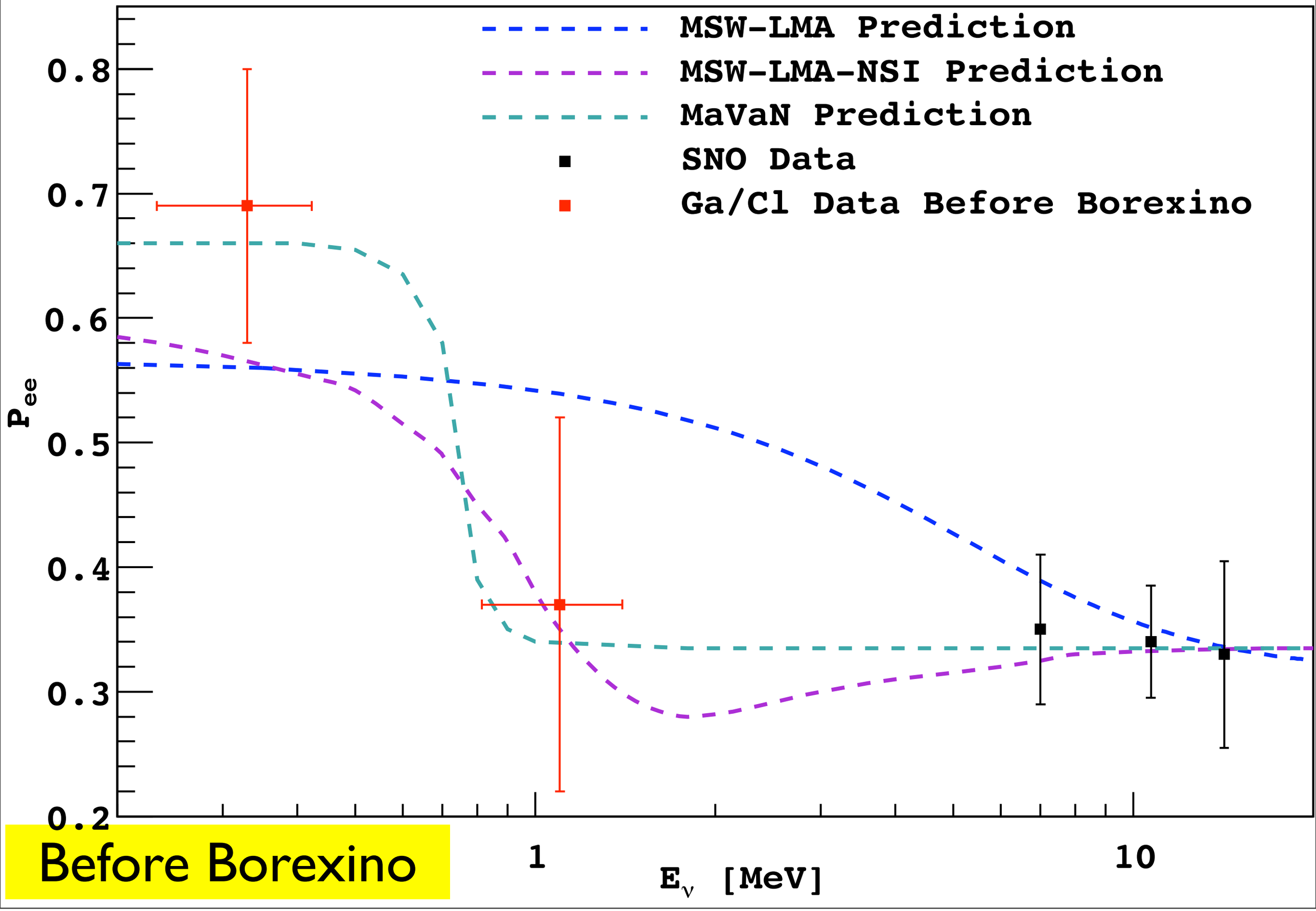
Spectral shape sensitive to μ_ν

Sensitivity enhanced at low energies ($\sigma \approx 1/T$)

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

Estimate	Method	90% C.L. 10^{-11} μ_B
SuperK	^{8}B	<11
Montanino et al.	^{7}Be	<8.4
GEMMA	Reactor	<5.8
Borexino	^{7}Be	<5.4

Solar Neutrino Survival Probability



Before Borexino

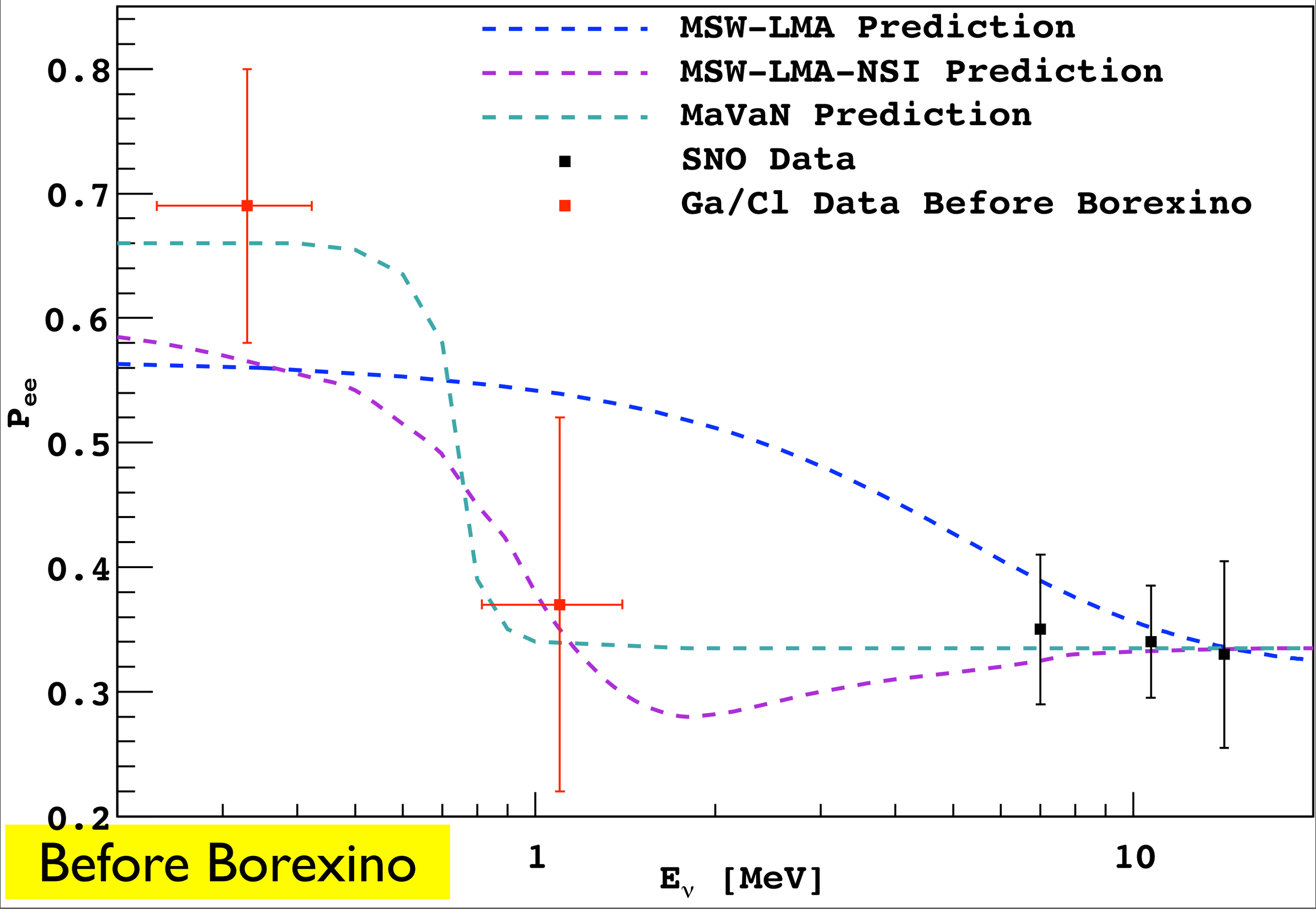
ν_e Survival Probability Global Analysis

- We determine the survival probability for ^{7}Be electron neutrinos ν_e under the assumption of the high-Z SSM (Bahcall-Pena Garay-Serenelli 2007, BPS07)
  - $\Phi\left(^7\mathrm{Be}\right) = (5.08 \pm 0.25) \times 10^9\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
  - $P_{ee}\left(^7\mathrm{Be}\right) = 0.56 \pm 0.10$
- Consistent with expectation from MSW-LMA (S. Abe et al., arXiv:0801.4589v2)
  - $P_{ee}\left(^7\mathrm{Be}\right) = 0.541 \pm 0.017$
  - No oscillations hypothesis (P_{ee}=1) excluded at 4σ C.L.

ν_e Survival Probability Global Analysis

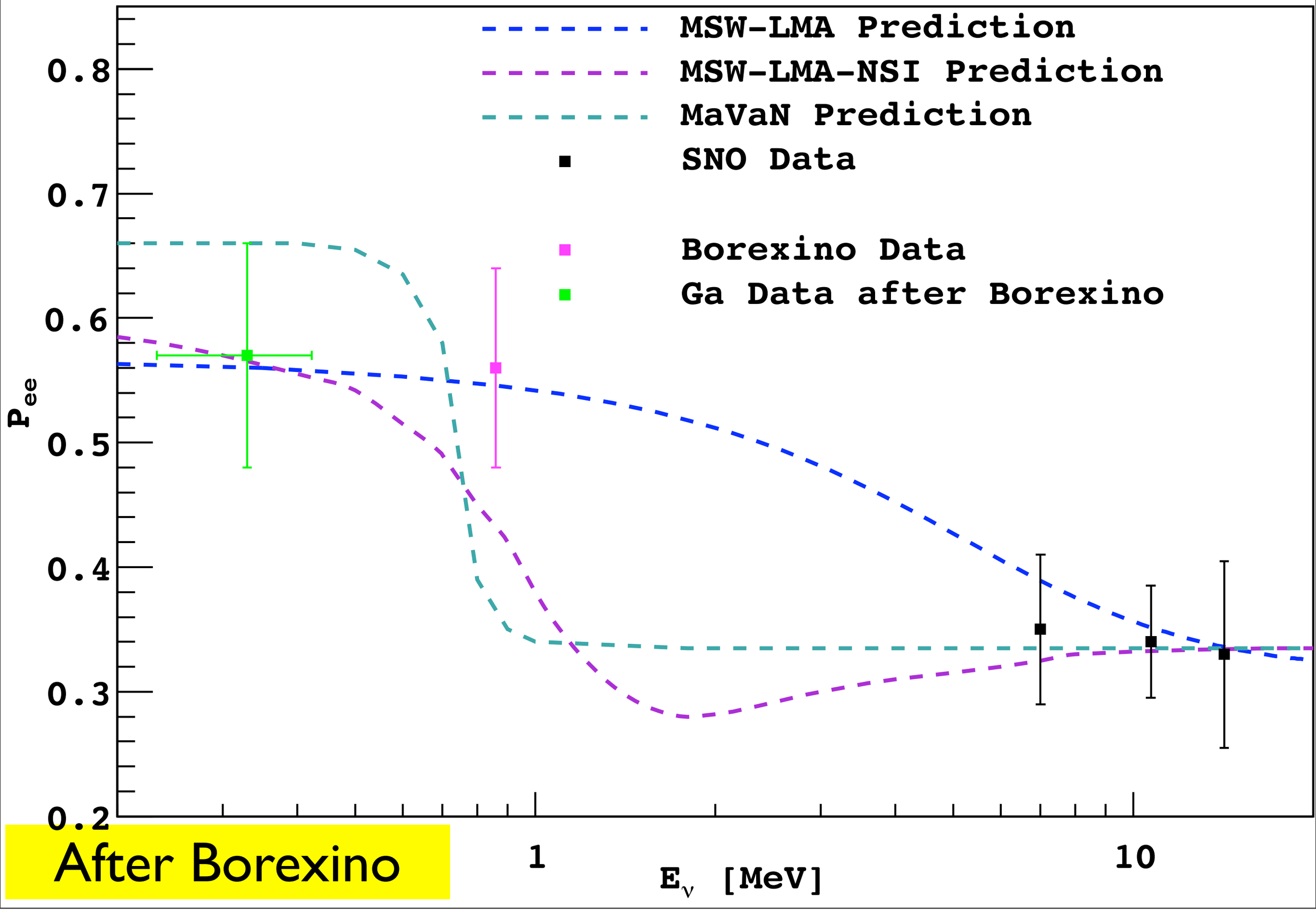
- We determine the survival probability for ^{7}Be and *pp* electron neutrinos ν_e under the assumption of the high-Z BPS07 SSM and using input from all solar experiments (cfr. Barger et al., PRL 88, 011302 (2002))
  - $P_{ee}\left(^7\mathrm{Be}\right) = 0.56 \pm 0.08$
  - $P_{ee}\left(pp\right) = 0.57 \pm 0.09$

Solar Neutrino Survival Probability



Before Borexino

Solar Neutrino Survival Probability



After Borexino

^{7}Be Neutrinos Flux

- Note: $f_i = \frac{\Phi_i}{\Phi_i^{\rm SSM}}$
- Best estimate prior to Borexino, as determined with global fit to all solar and reactor data, with the assumption of the constraint on solar luminosity (M.C. Gonzalez-Garcia and Maltoni, Phys. Rep 460, 1 (2008)
  - $f_{\rm Be} = 1.03^{+0.24}_{-1.03}$
- Assuming the high-Z BPS07 SSM and the constraint on solar luminosity, we obtain:
  - $f_{\rm Be} = 1.02 \pm 0.10$

    $\Phi\left(^7{\rm Be}\right) = (5.18 \pm 0.52) \times 10^9 \ {\rm cm}^{-2}{\rm s}^{-1}$

pp and CNO Neutrinos Fluxes

$$R_l \ [\mathrm{SNU}] = \sum_i R_{l,i} f_i P_{ee}^{l,i}$$

$l = \{\mathrm{Ga}, \mathrm{Cl}\}$

$i = \{pp, pep, \mathrm{CNO}, {}^7\mathrm{Be}, {}^8\mathrm{B}\}$

f_i Ratio between measured and predicted flux

$P_{ee}^{l,i}$ Survival Probability Averaged over Threshold

$$R_{\mathrm{Ga}}^{\mathrm{th}} \ [\mathrm{SNU}] = 38.56 f_{\mathrm{pp}} + 2.34 f_{\mathrm{CNO}} + 19.44 f_{\mathrm{Be}} + 5.43 f_{\mathrm{B}}$$

$$R_{\mathrm{Cl}}^{\mathrm{th}} \ [\mathrm{SNU}] = 0.12 f_{\mathrm{pep}} + 0.11 f_{\mathrm{CNO}} + 0.59 f_{\mathrm{Be}} + 2.58 f_{\mathrm{B}}$$

$R_{\mathrm{Ga}} = 68.10 \pm 3.75 \ \mathrm{SNU}$

$R_{\mathrm{Cl}} = 2.56 \pm 0.23 \ \mathrm{SNU}$

$f_{\mathrm{B}} = 0.87 \pm 0.08$ SNO

$f_{\mathrm{Be}} = 1.02 \pm 0.10$ Borexino

pp and CNO Neutrinos Fluxes

Without Luminosity Constraint:

$$f_{pp} = 1.04^{+0.13}_{-0.20}$$

$$\mathcal{L}_{\rm CNO}/\mathcal{L}_{\odot} < 13.8\%\ 3\sigma$$

$$f_{pp} = 1.04^{+0.18}_{-0.25}$$

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

With Luminosity Constraint:

$$f_{pp} = 1.004^{+0.008}_{-0.020}$$

$$\mathcal{L}_{\rm CNO}/\mathcal{L}_{\odot} < 6.2\%\ 3\sigma$$

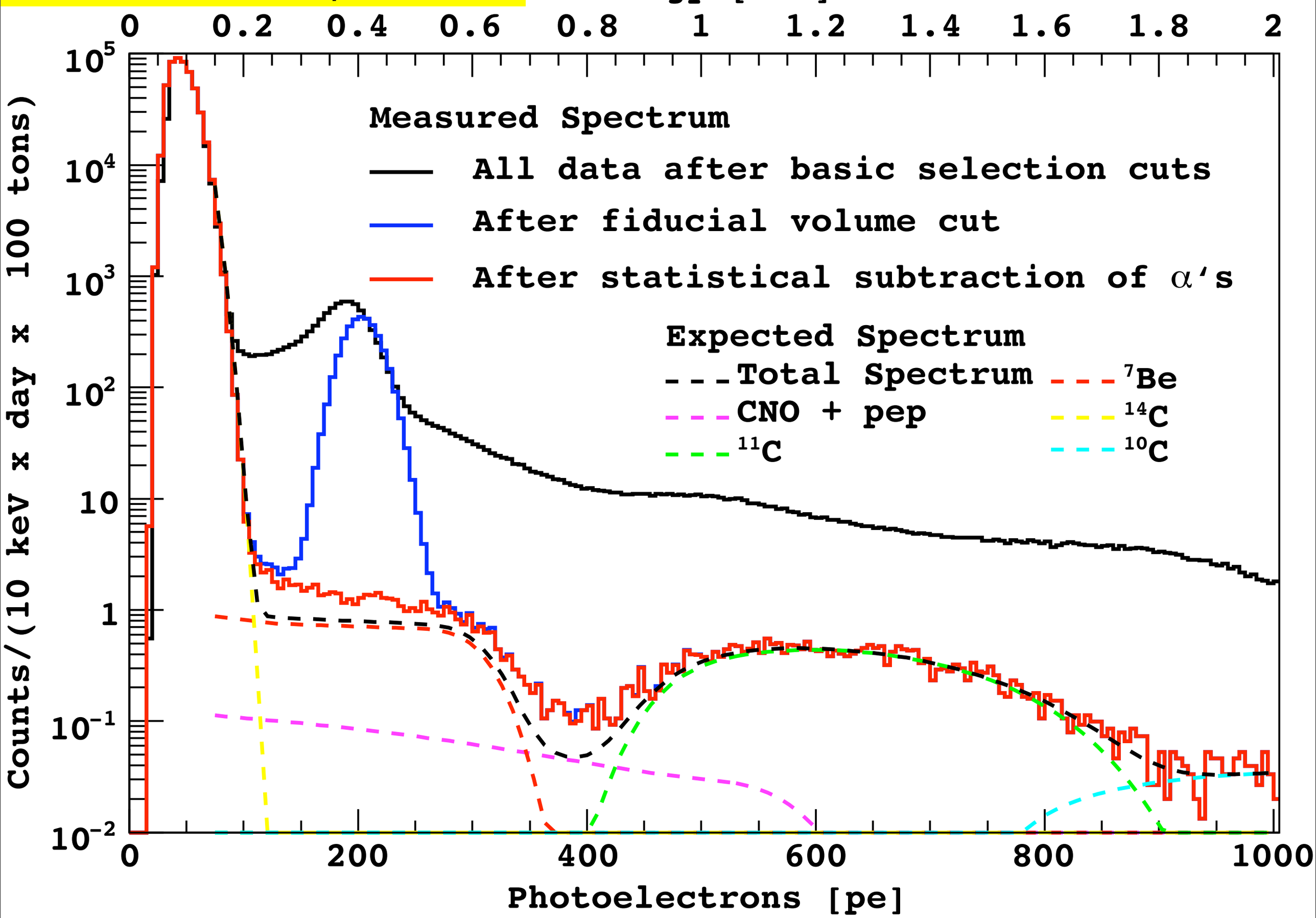
J.N. Bahcall and C. Pena-Garay,
JHEP 11, 004 (2003)

$$f_{pp} = 1.02 \pm 0.02$$

$$\mathcal{L}_{\rm CNO}/\mathcal{L}_{\odot} < 6.5\%\ 3\sigma$$

M. Altmann et all. (GNO Coll.),
PLB **616**, 574 (2005)

Data: Final Comparison



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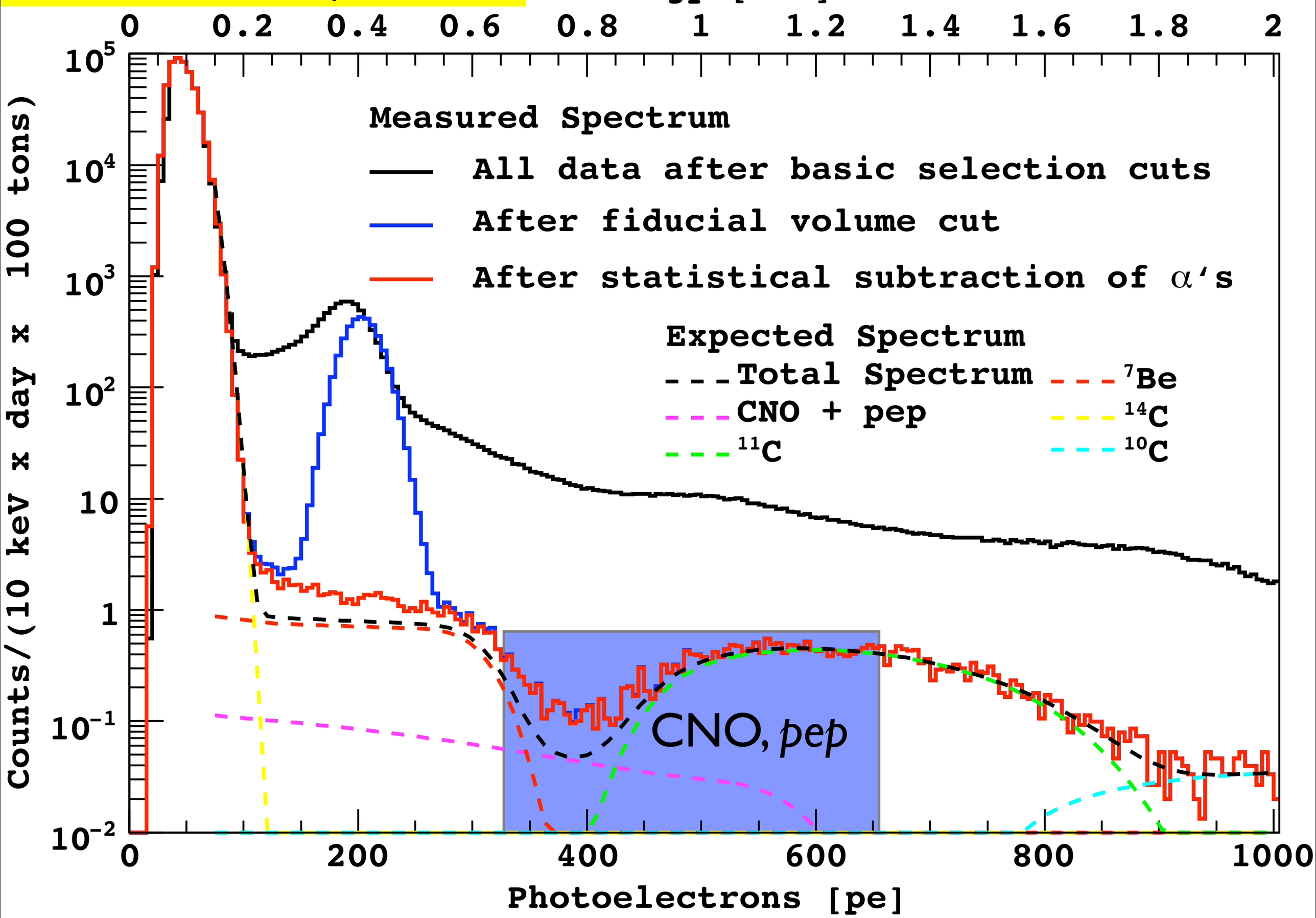


Removal of ^{11}C Background

Measuring 25 cpd/100 tons of ^{11}C
- Major background for CNO and *pep*
- CNO: 5 cpd/100 tons
- *pep*: 2 cpd/100 tons

Long-lived isotope (30 min mean life)
- Simple coincidence with muon impractical (dead time kills!)

Deutsch 1995:
- Neutron must be emitted with ^{11}C formation
- Tag in coincidence with muon and neutron capture (300 μs, 2.2 MeV γ-ray)

@Princeton 2005:
- First detailed calculation of cosmogenic production rate!
- 95% of ^{11}C produced in conjuction with a neutron!
- ^{11}C background can be reduced very significantly in Borexino and KamLAND!
- Opens opportunity for measurement of CNO and *pep* neutrinos in Borexino and KamLAND!

PHYSICAL REVIEW C **71**, 055805 (2005)

Cosmogenic ^{11}C production and sensitivity of organic scintillator detectors to *pep* and CNO neutrinos

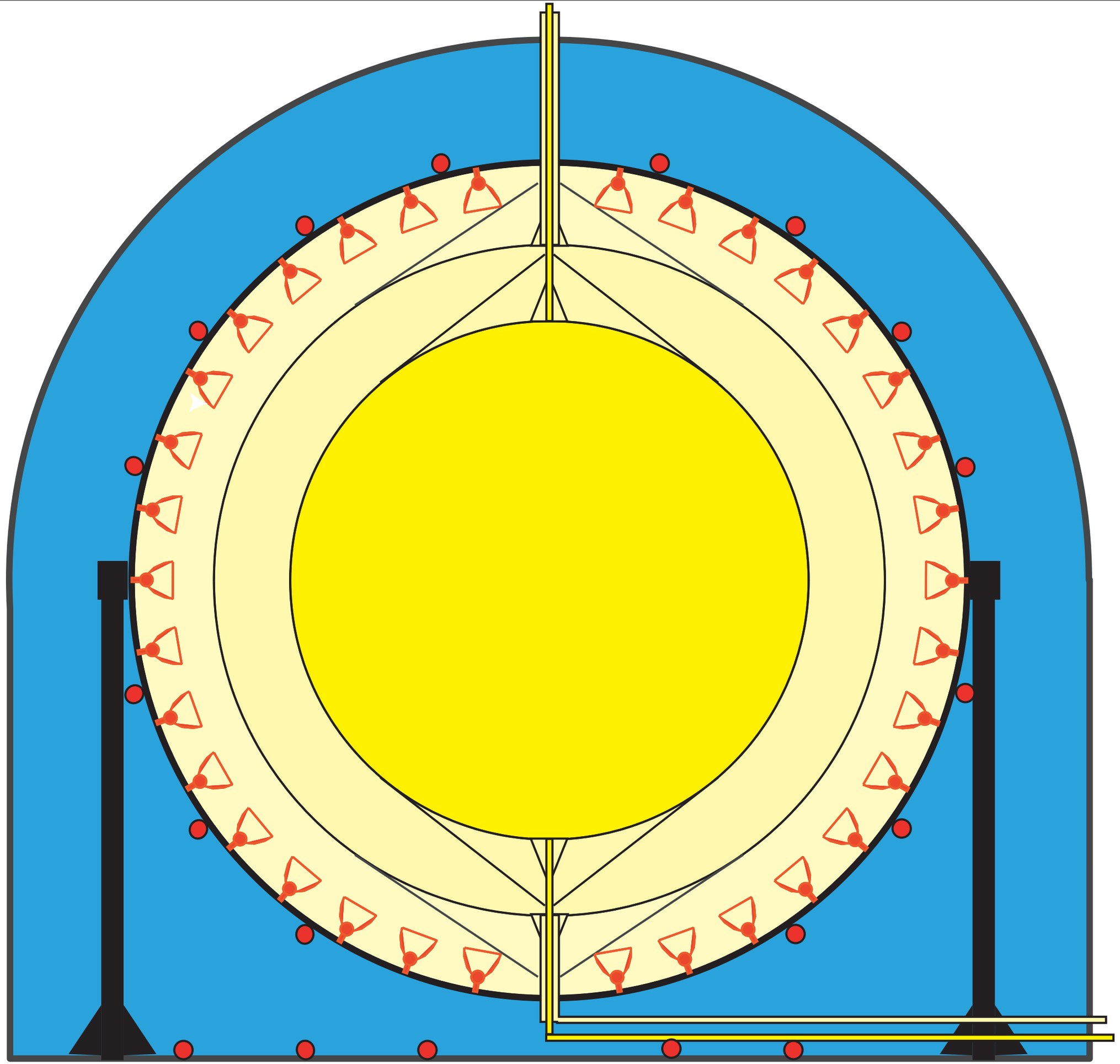
Cristiano Galbiati* and Andrea Pocar†
Physics Department, Princeton University, Princeton, New Jersey 08544

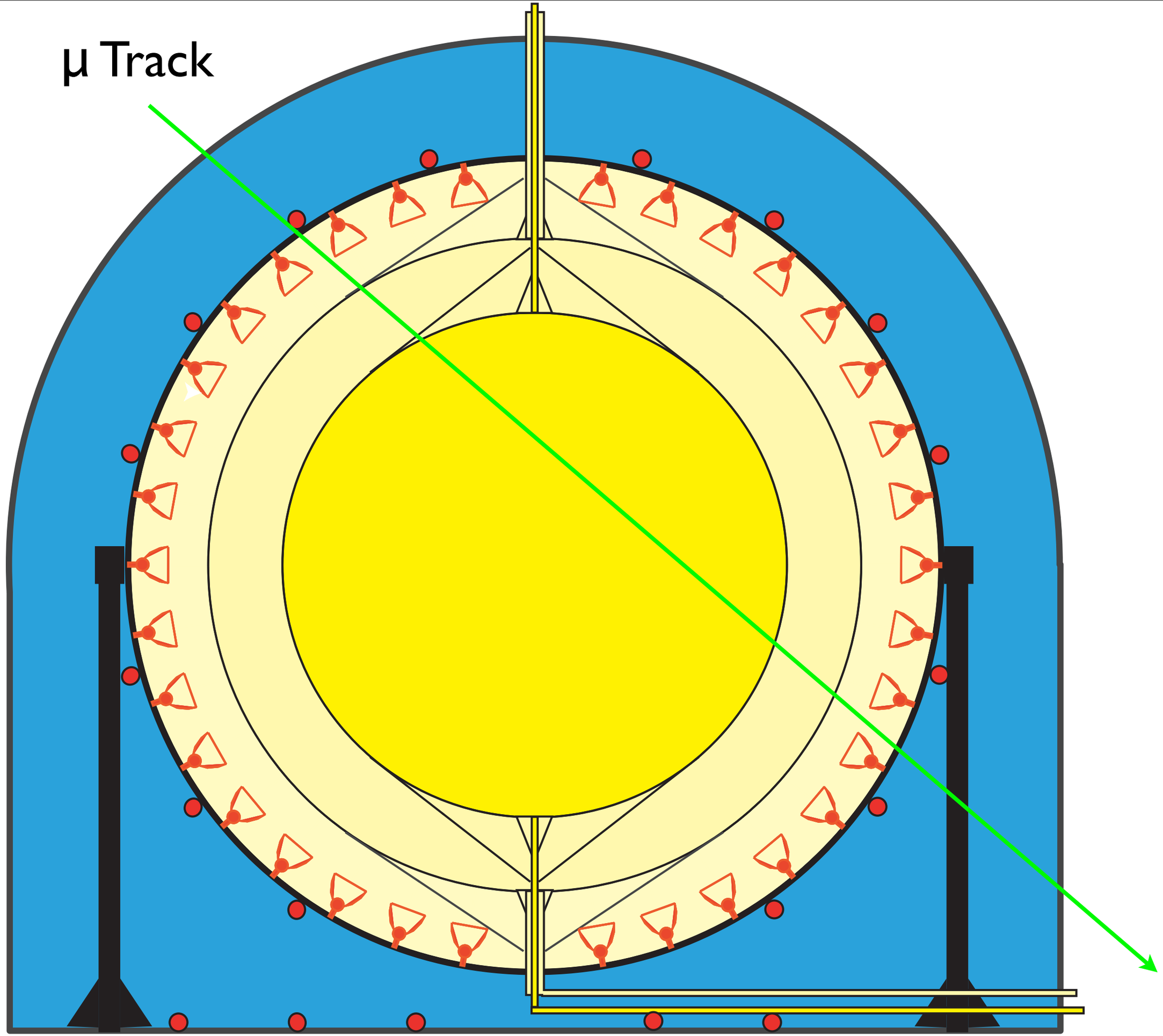
Davide Franco‡
Dipartimento di Fisica, Università degli Studi di Milano, I-20133 Milano, Italy

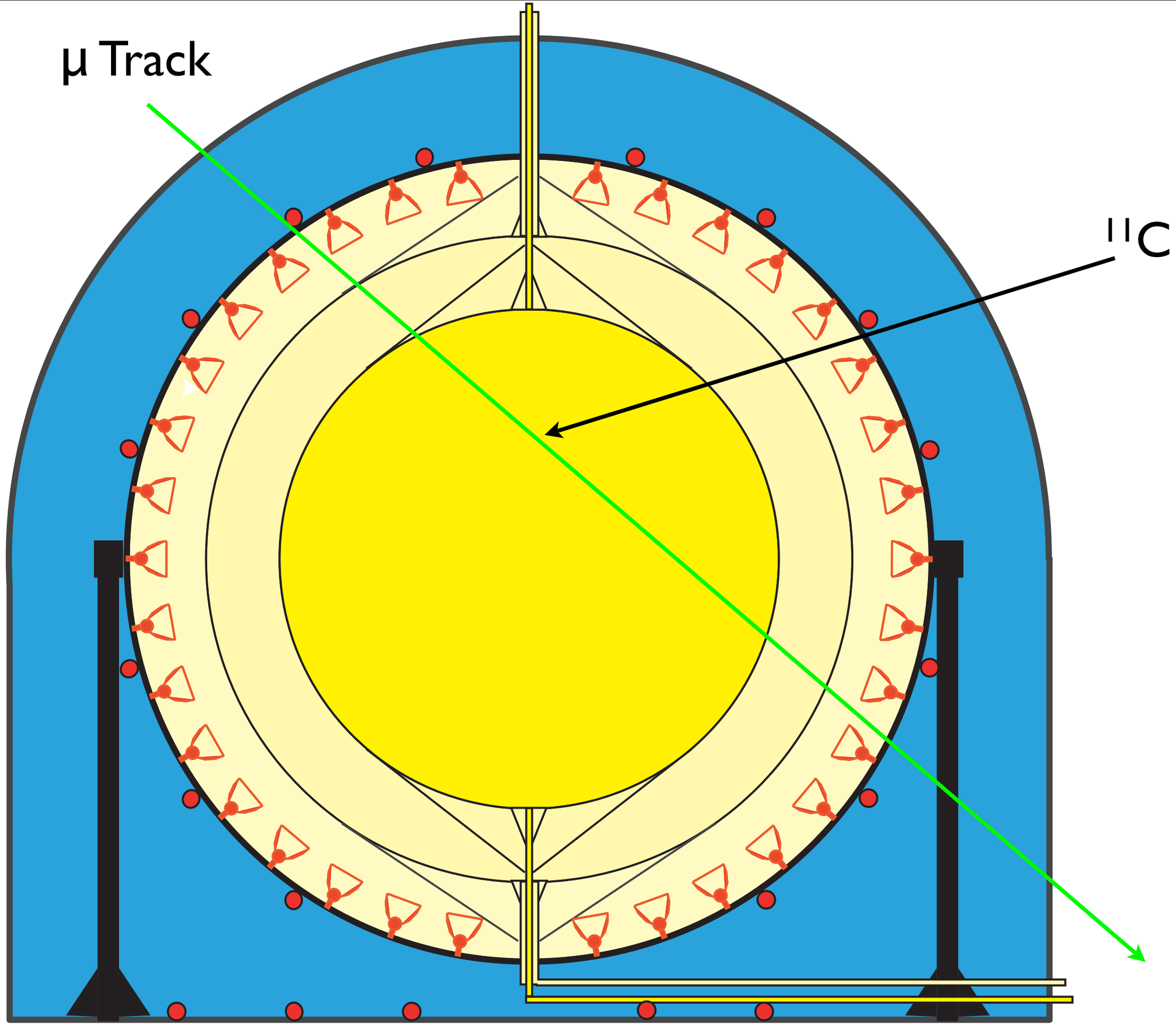
Aldo Ianni
Laboratori Nazionali del Gran Sasso, I-67010 Assergi, Italy

Laura Cadonati
Physics Department, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

E_μ [GeV]	100	190	285	320	350
Process	Rate $[10^{-4}/\mu/\mathrm{m}]$				
$^{12}C(p,p+n)^{11}C$	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




μ Track


μ Track
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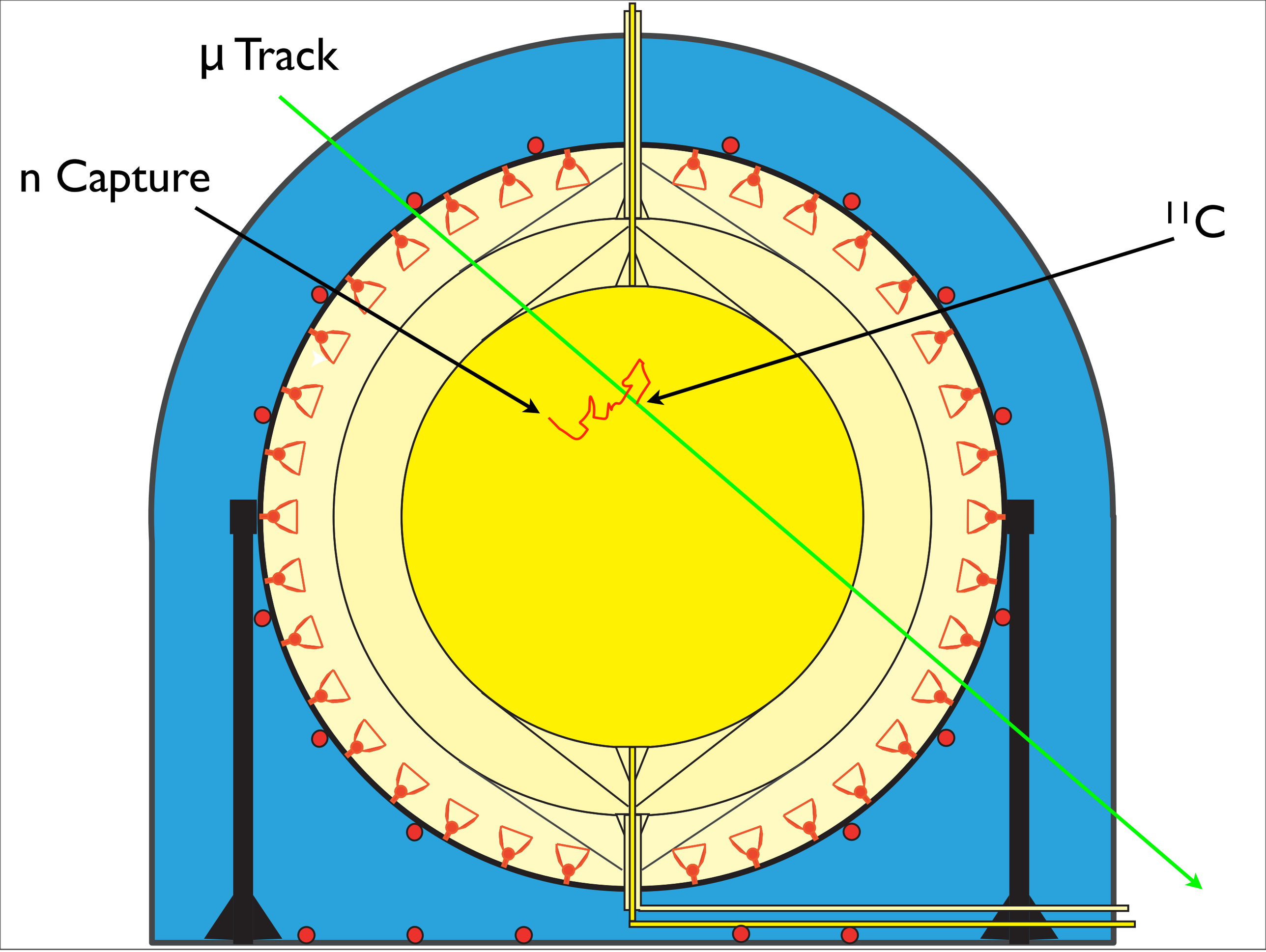
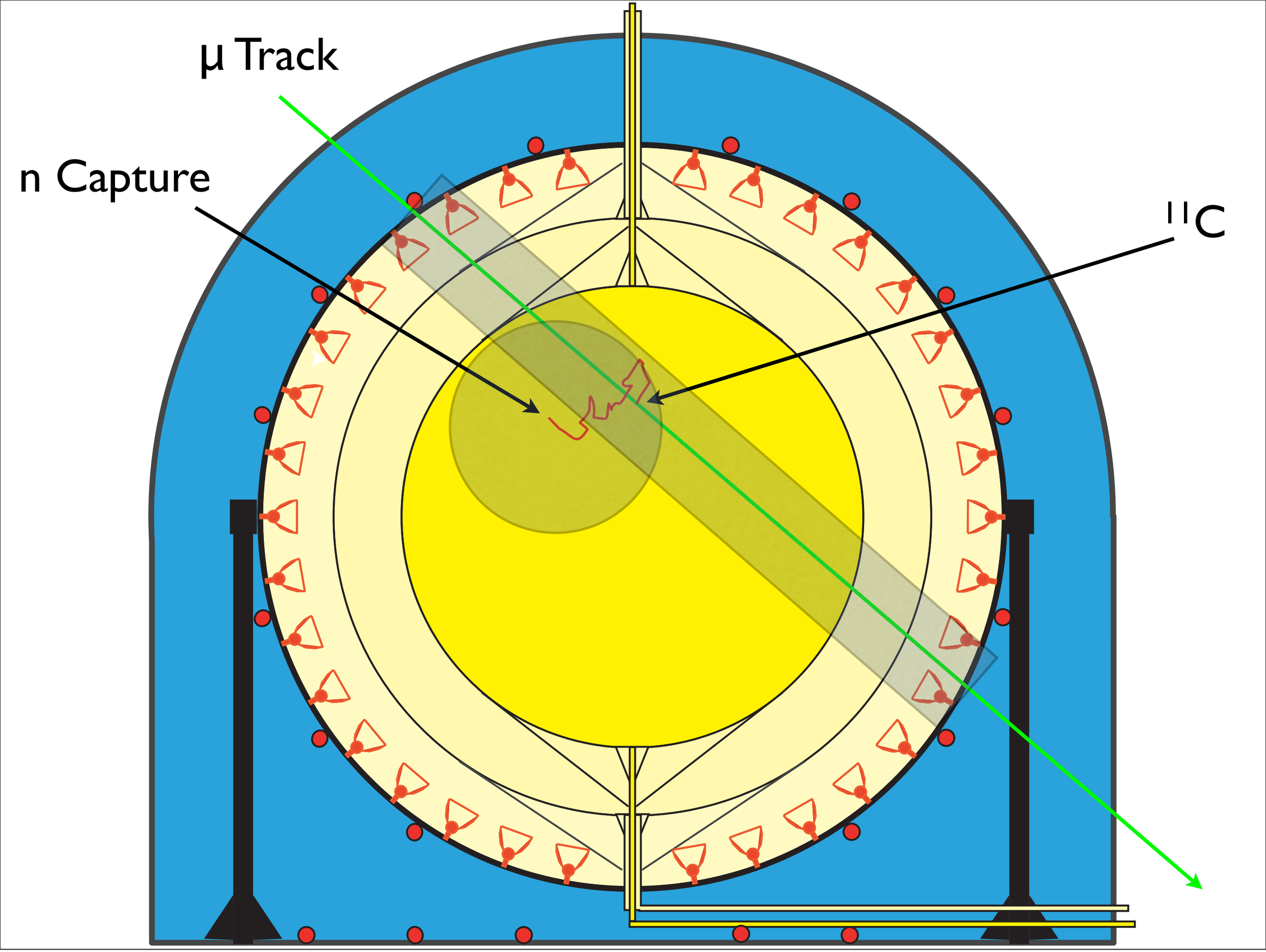

μ Track
n Capture
^{11}C


μ Track
n Capture
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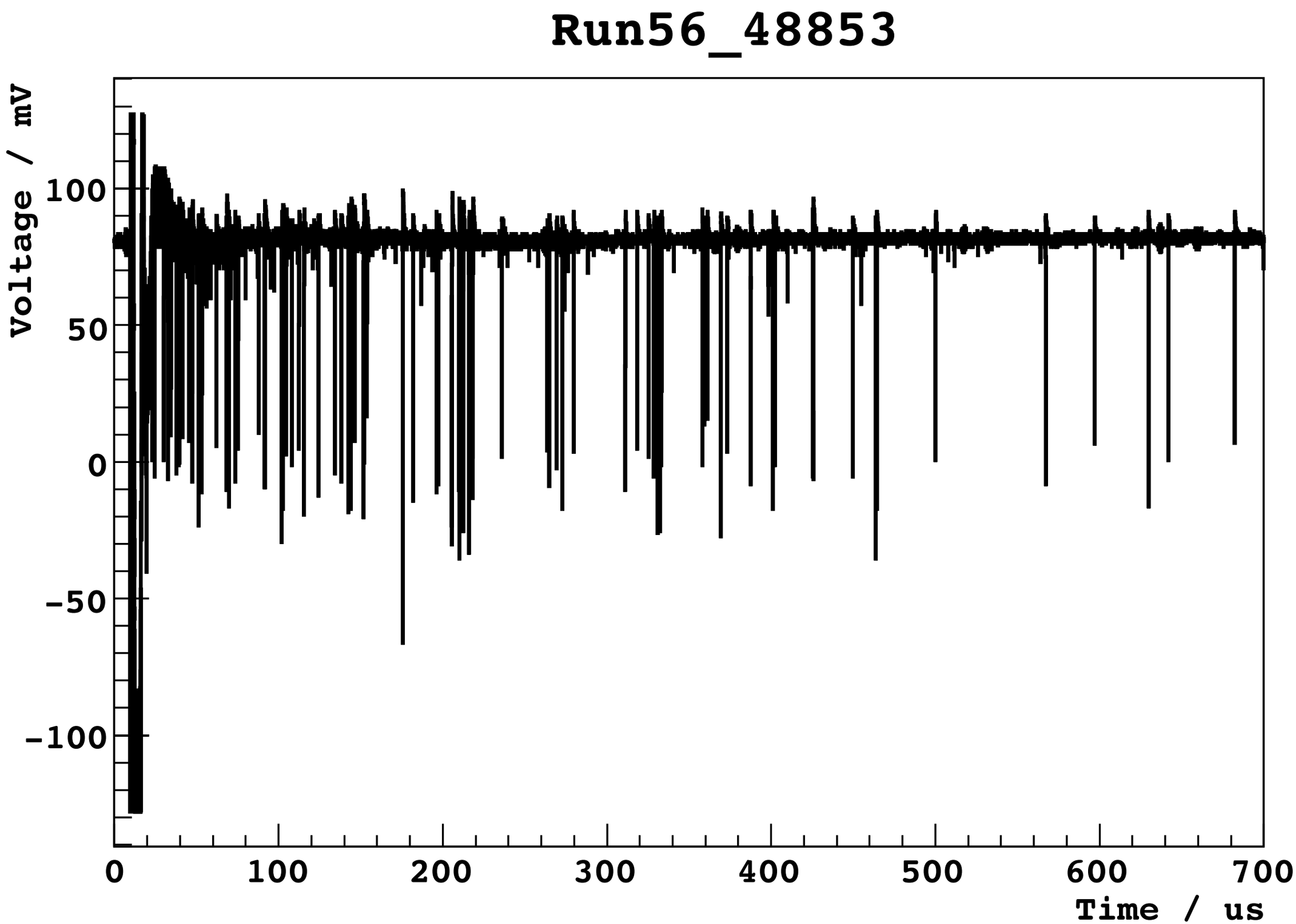
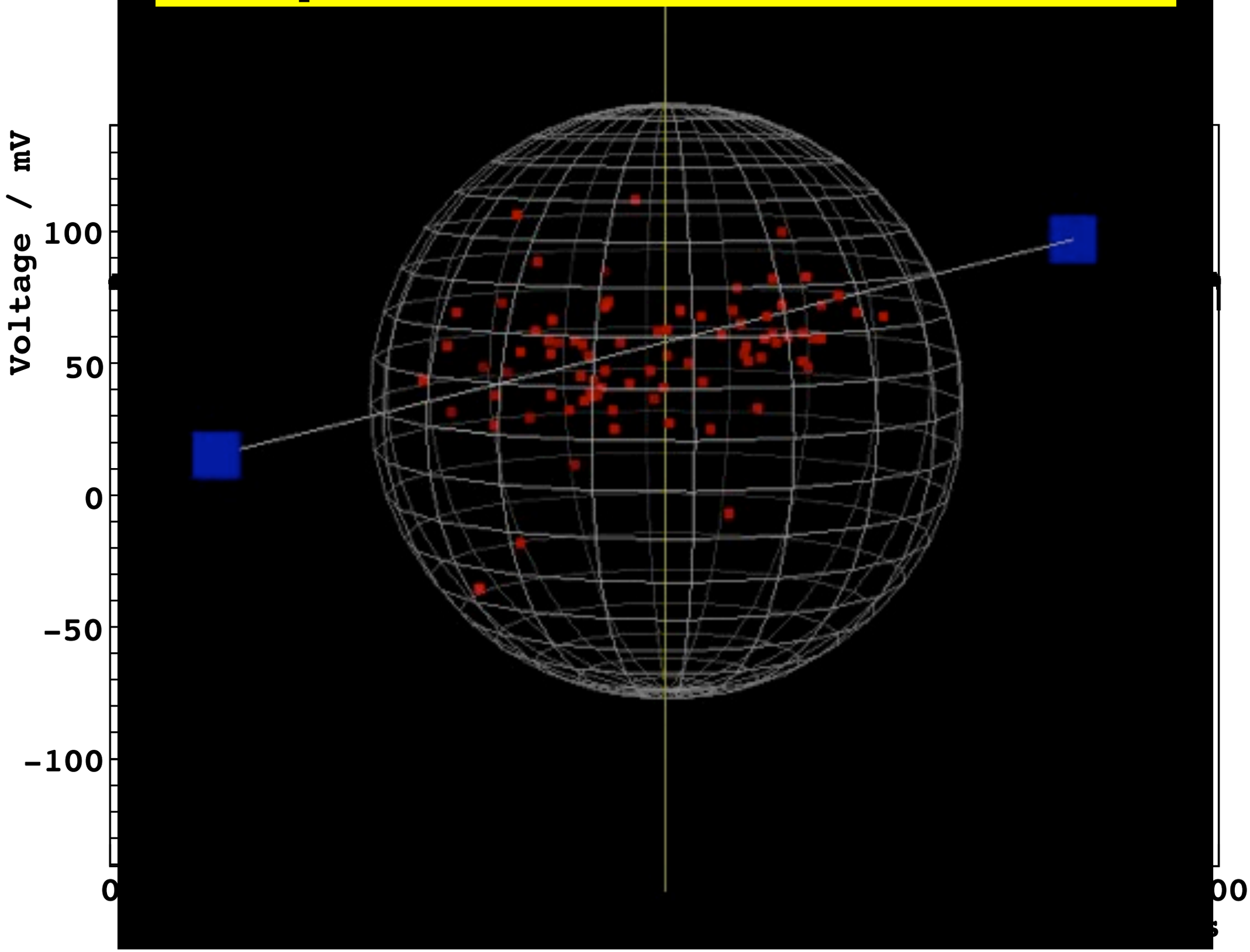
Improved Electronics



Improved Electronics



Conclusions

- Borexino opened the study of the solar neutrinos in real time below the barrier of natural radioactivity (4 MeV)
  - Two measurements reported for ^{7}Be neutrinos, favor MSW-LMA solution
  - Best limits for *pp* and CNO neutrinos, combining information from all solar and reactor experiments
  - Opportunities to tackle *pep* and CNO neutrinos in direct measurement
- Borexino will run comprehensive program for study of antineutrinos (from Earth, Sun, and Reactors)
- May prove solar origin of ^{7}Be signal by study of seasonal oscillations
- Borexino a powerful observatory for neutrinos from Supernovae explosions within few tens of kpc

1989-92:
Conception, start
of CTF program

1995-96: Low
background
achieved in CTF

1997-98:
Borexino Funded

August 16 2002:
Borexino Mishap

2005: Restarts of
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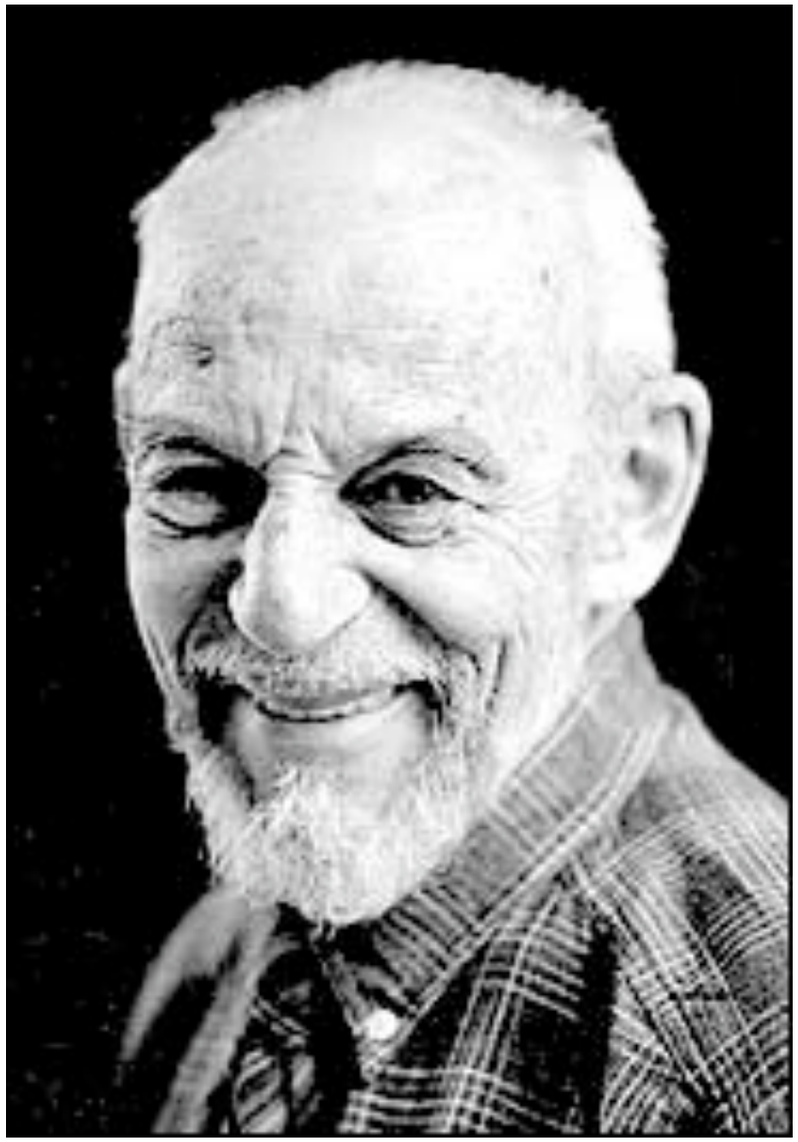
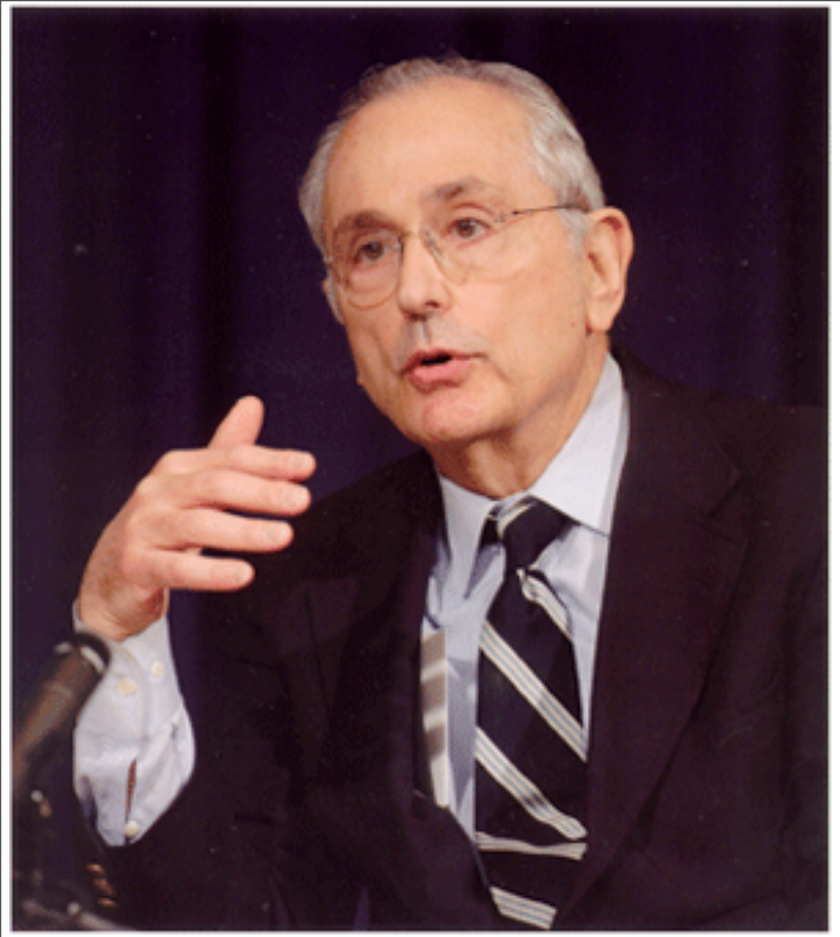


Martin Deutsch
January 29, 1917
August 16, 2002



John Bahcall
December 30, 1934
August 17, 2005

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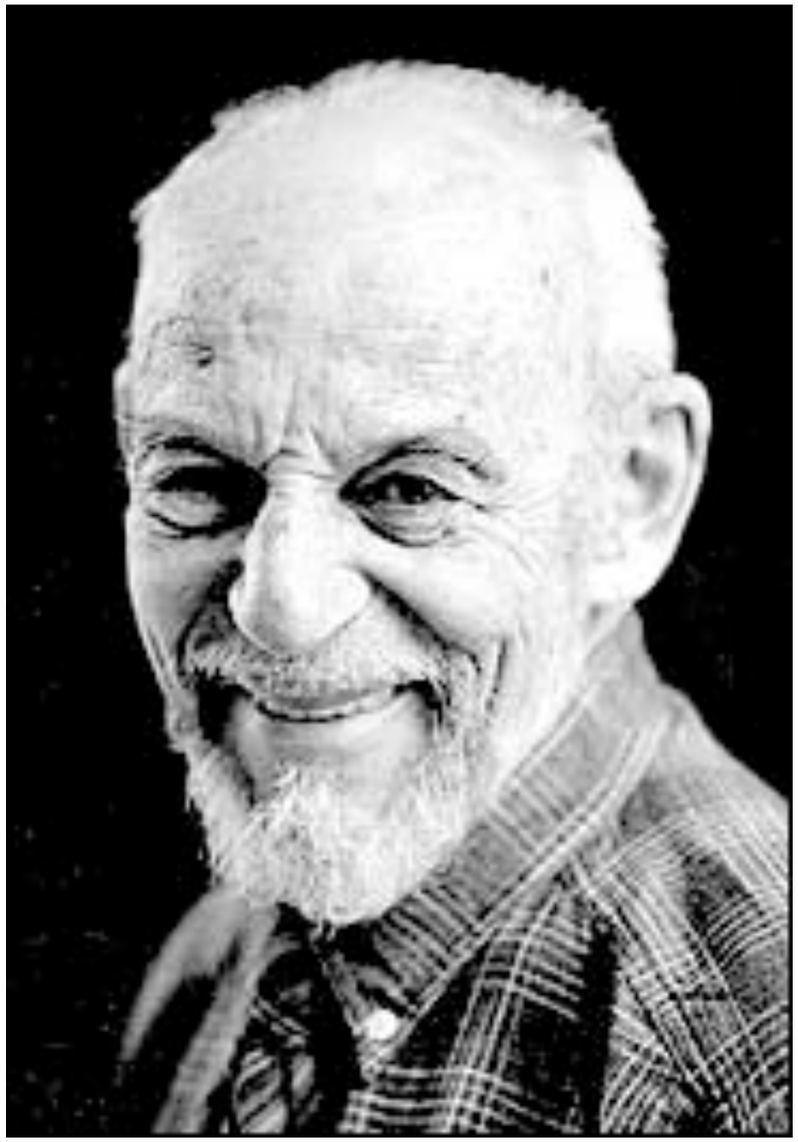

Martin Deutsch
January 29, 1917
August 16, 2002

More Info

- Letter submitted to online pre-print server
  - arXiv:0805.3843
- See also mini-talks and posters by:
- D. d'Angelo:
  - "The Borexino detector: very low background levels in the scintillator"
- D. Franco:
  - "Performances of the Borexino Deetector"
- S. Hardy:
  - "Source Insertion and Location Systems for the Borexino Solar Neutrino Detector"
- P. Lombardi:
  - "The Borexino detector: photomultipliers system"
- R. Saldanha:
  - "Cosmogenic ^{11}C tagging in organic liquid scintillators"

The End