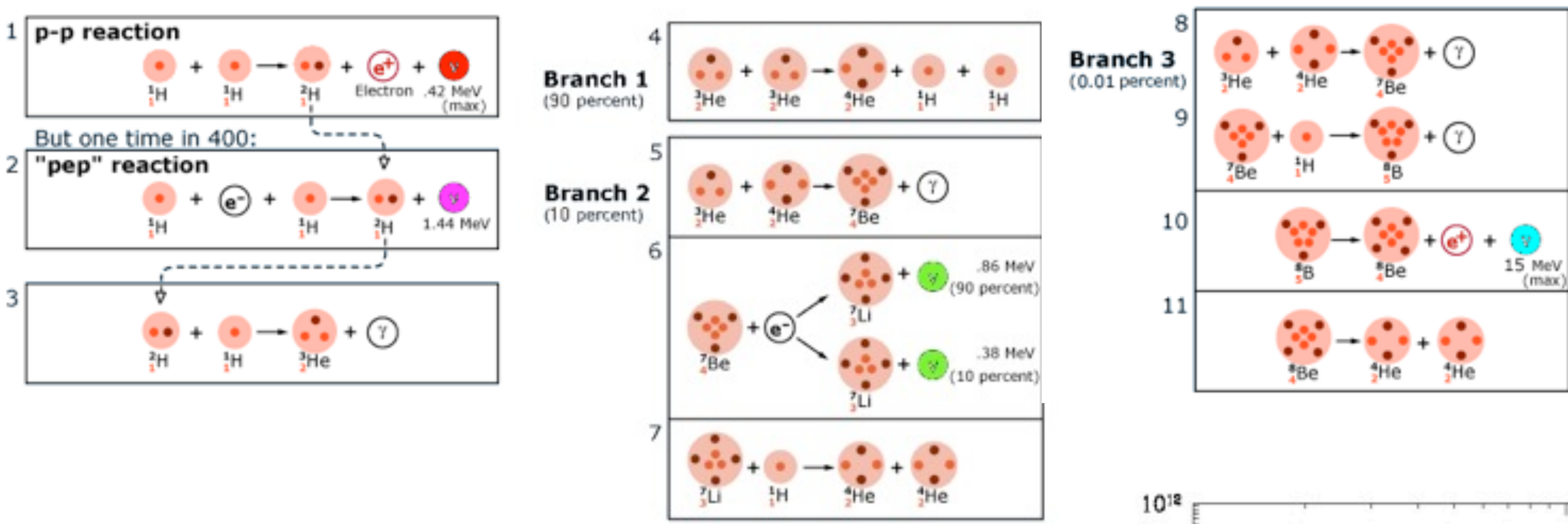
Solar Neutrinos

Aspen Winter 2009
Workshop on Physics at the LHC era
Aspen, CO
February 13, 2009

Cristiano Galbiati
Princeton University

Solar Neutrinos Production



pp chain:

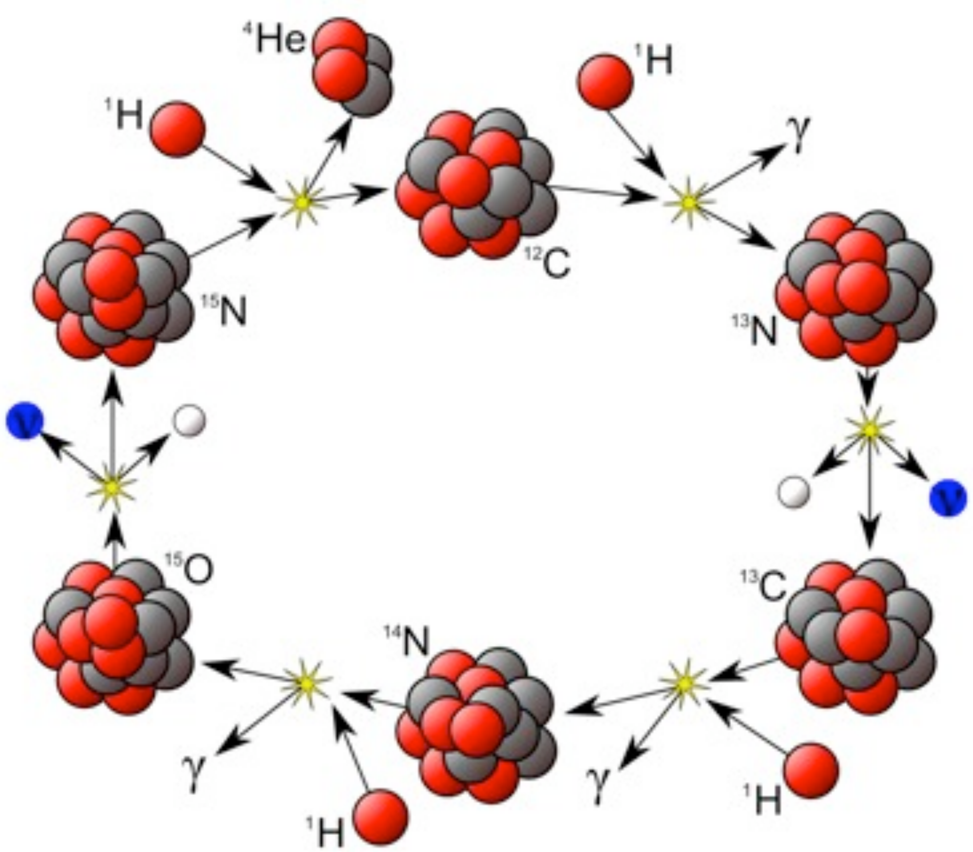
pp, *pep*,

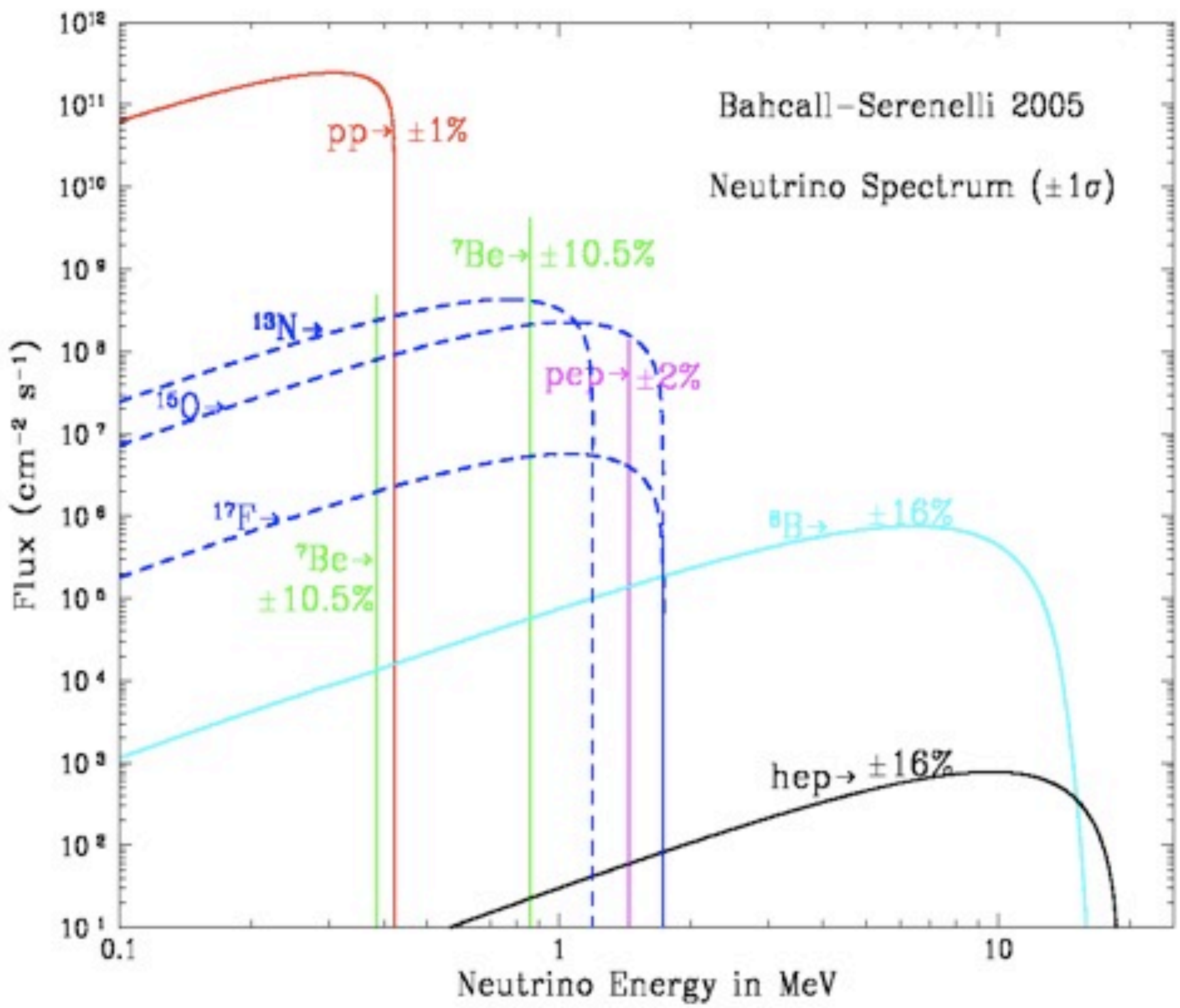
^{7}Be, and ^{8}B

neutrinos

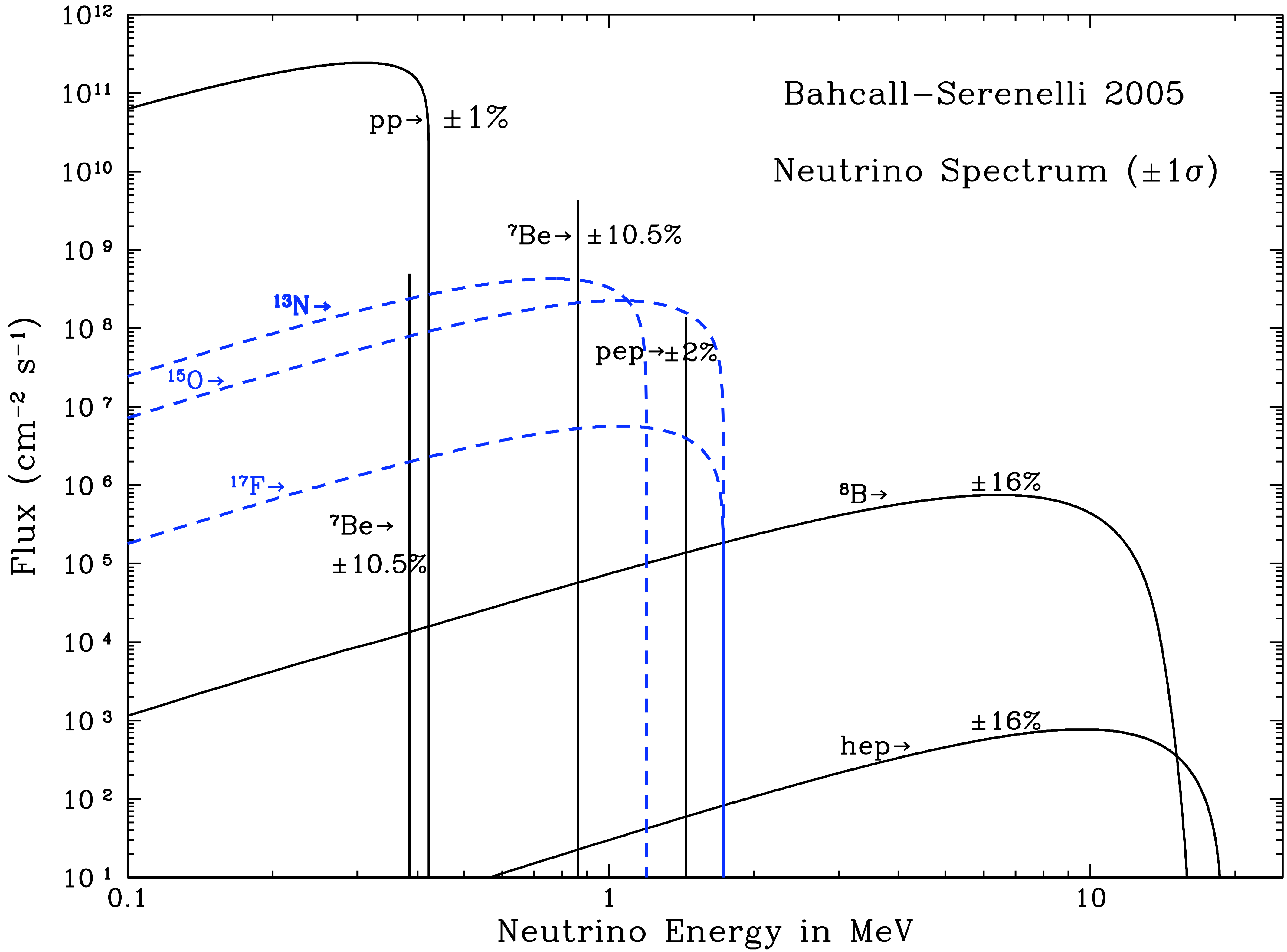
CNO chain:

^{13}N, ^{15}O, and ^{17}F neutrinos

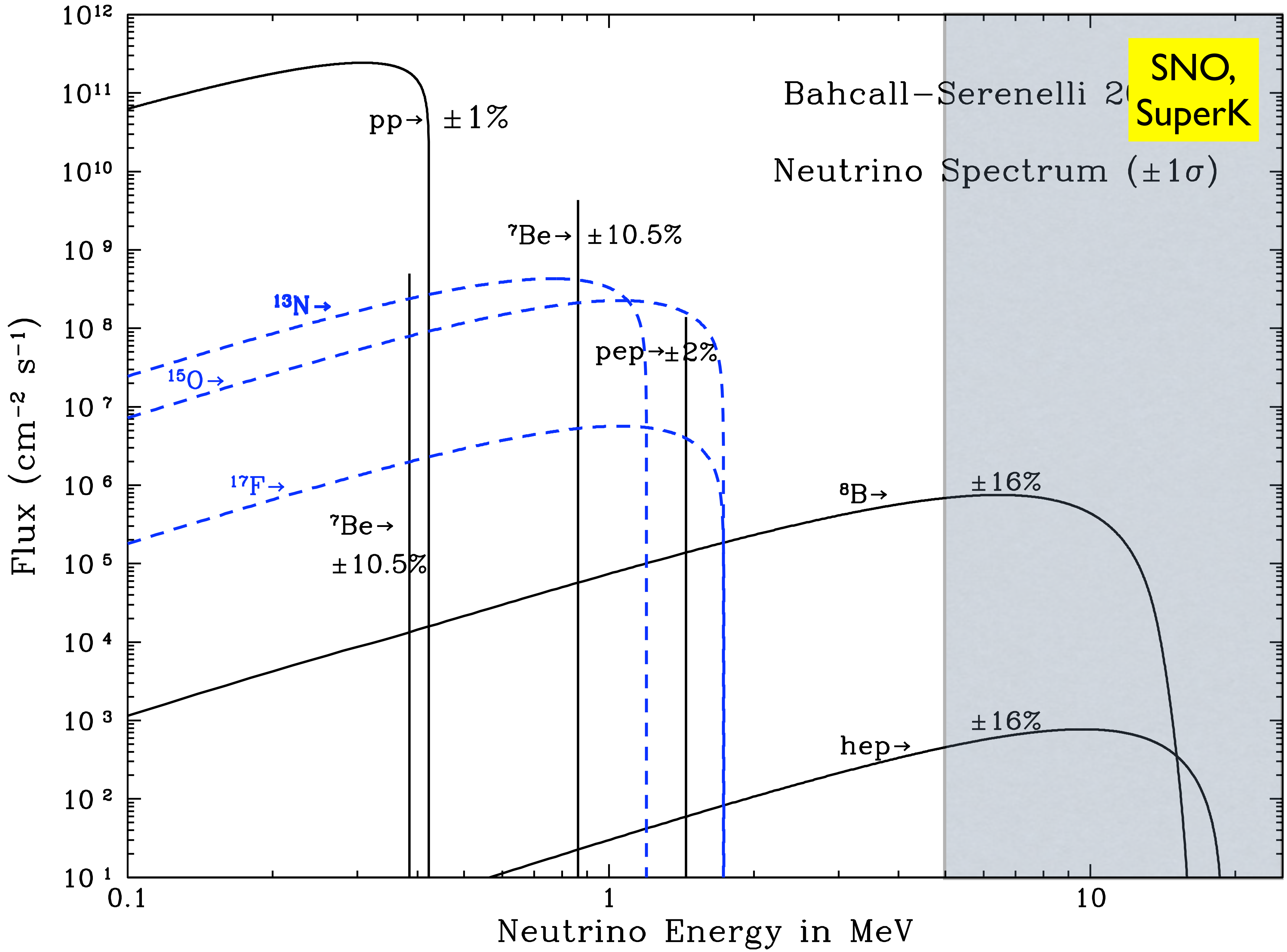




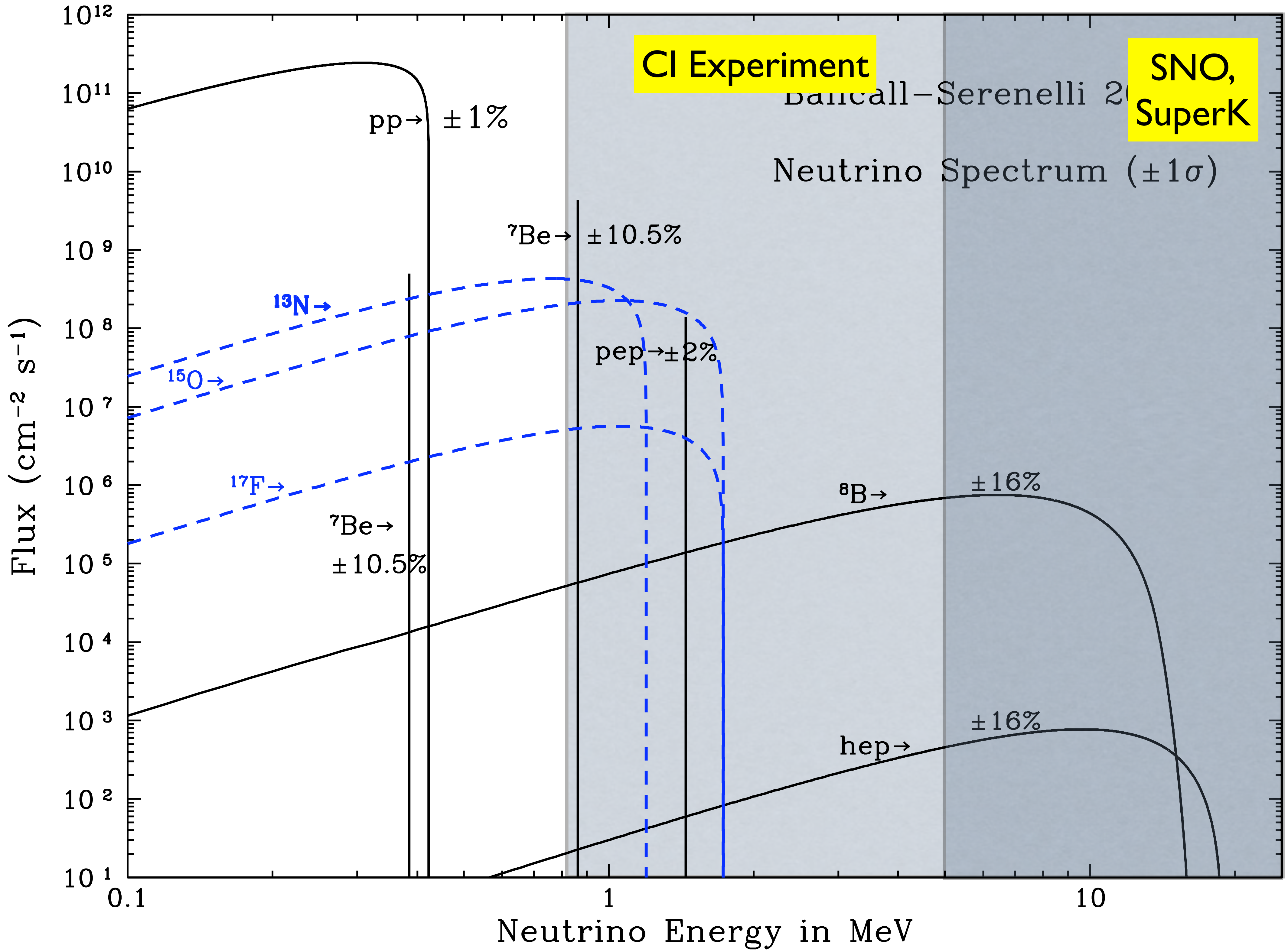
Solar Neutrinos Spectrum



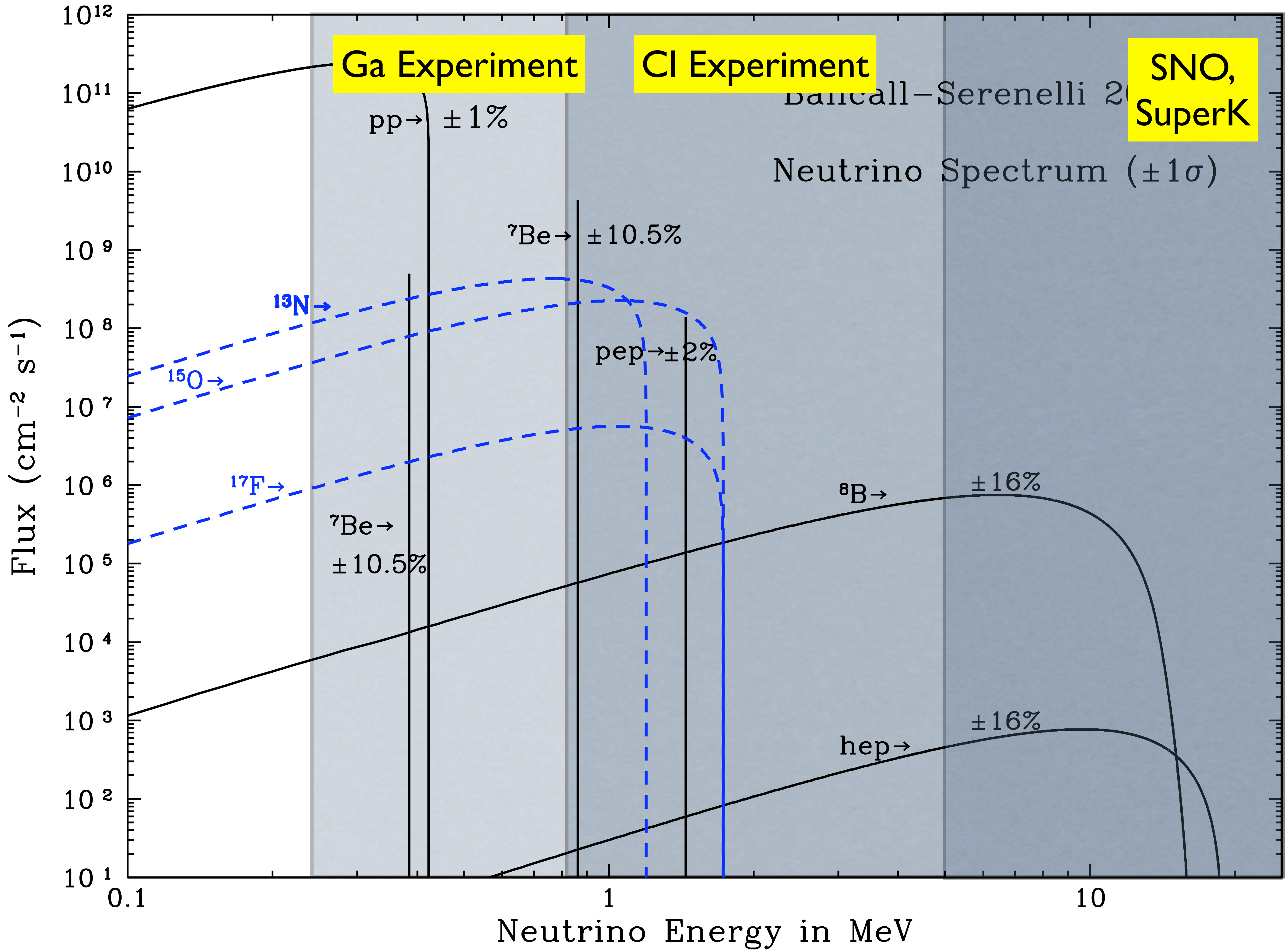
Solar Neutrinos Spectrum



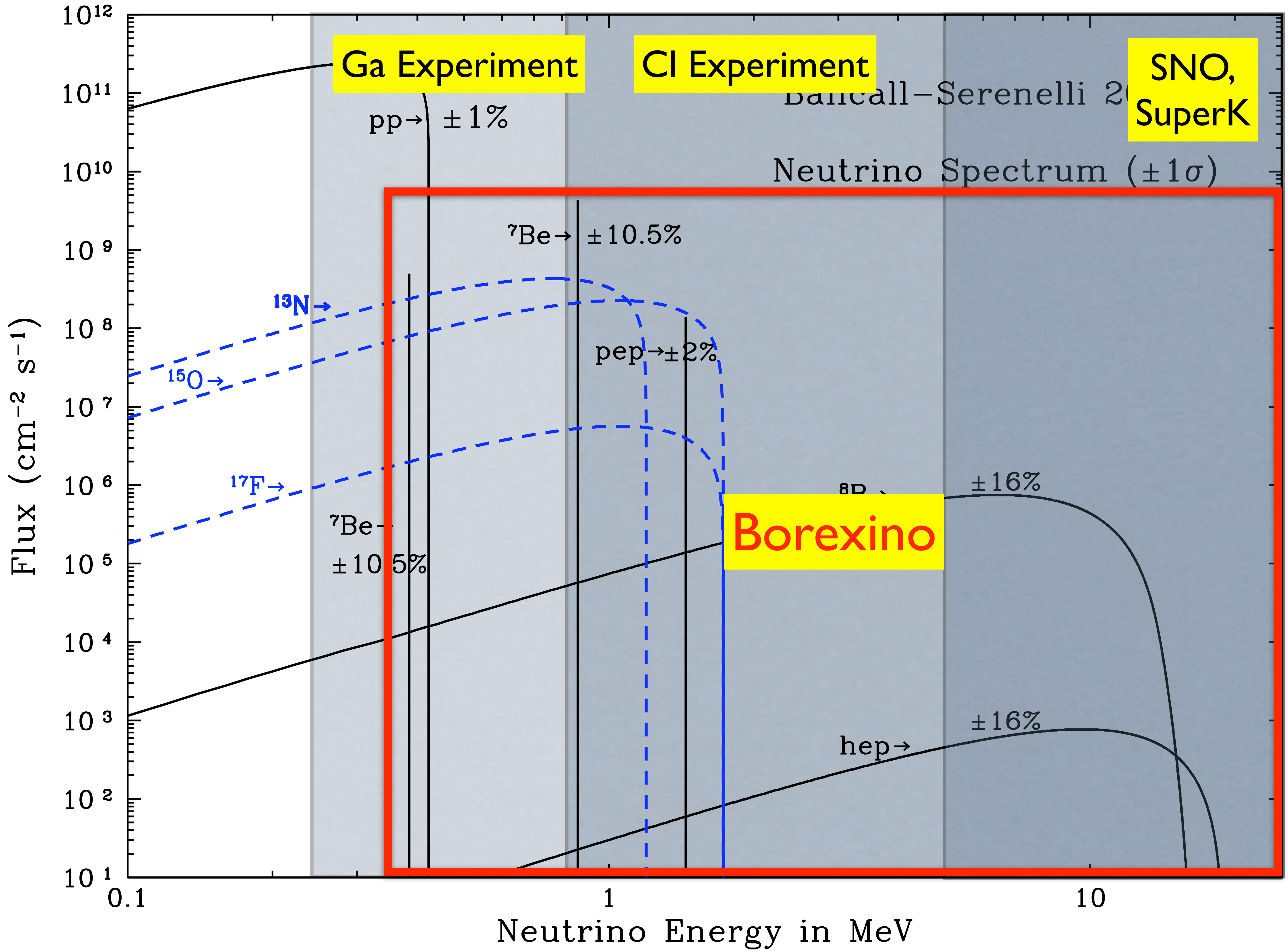
Solar Neutrinos Spectrum



Solar Neutrinos Spectrum

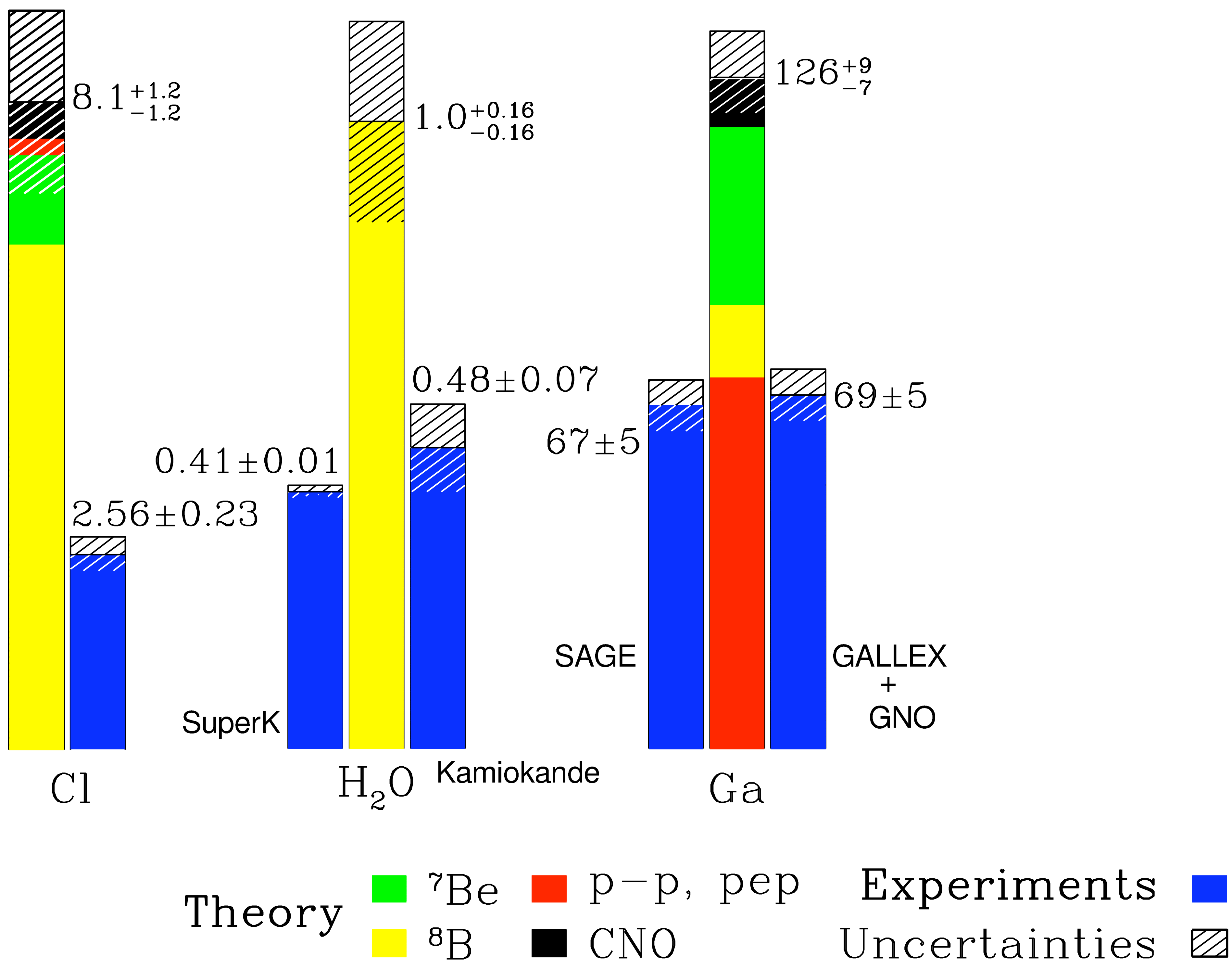


Solar Neutrinos Spectrum



Total Rates: Standard Model vs. Experiment

Bahcall–Serenelli 2005 [BS05(OP)]



Total Rates: Standard Model vs. Experiment
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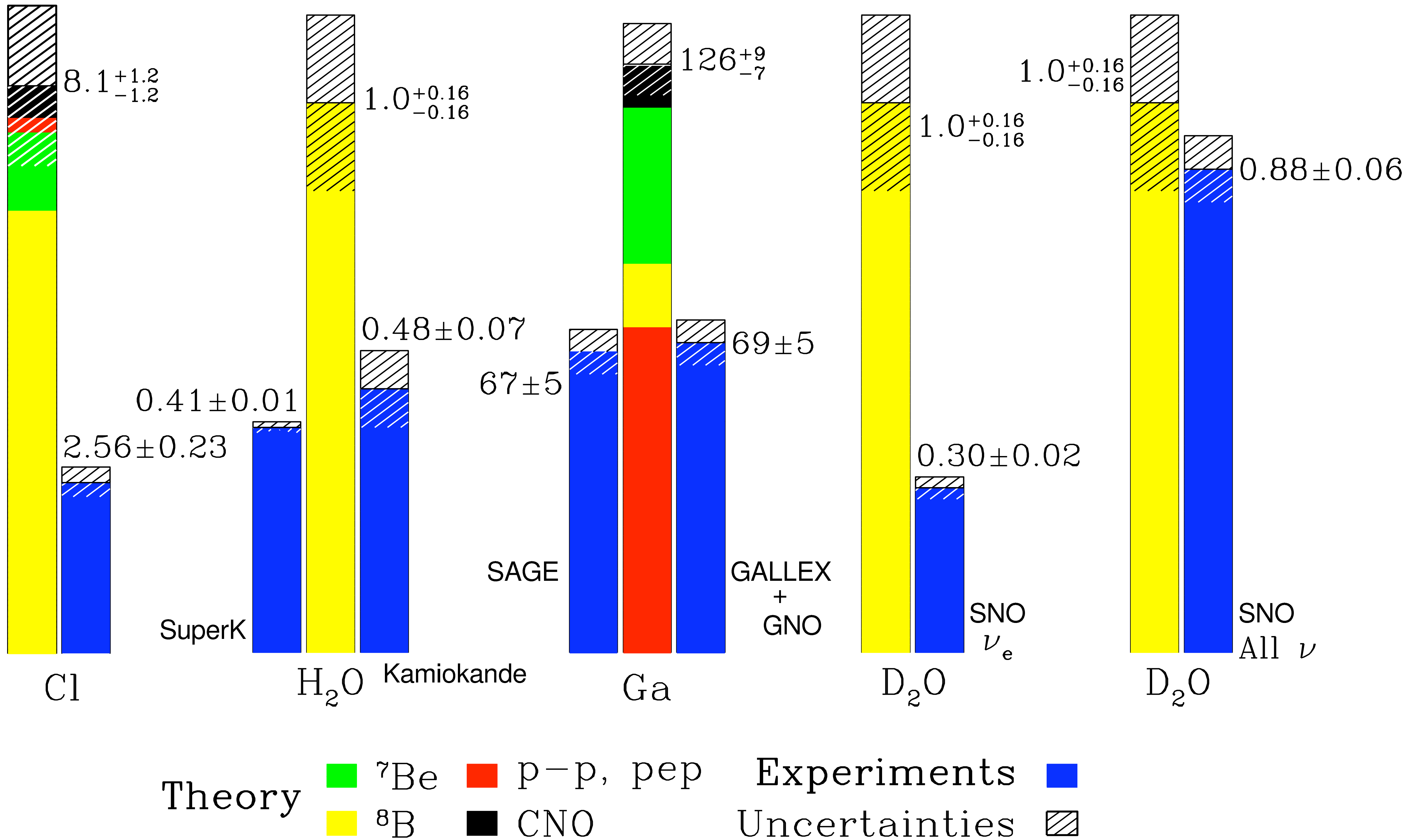
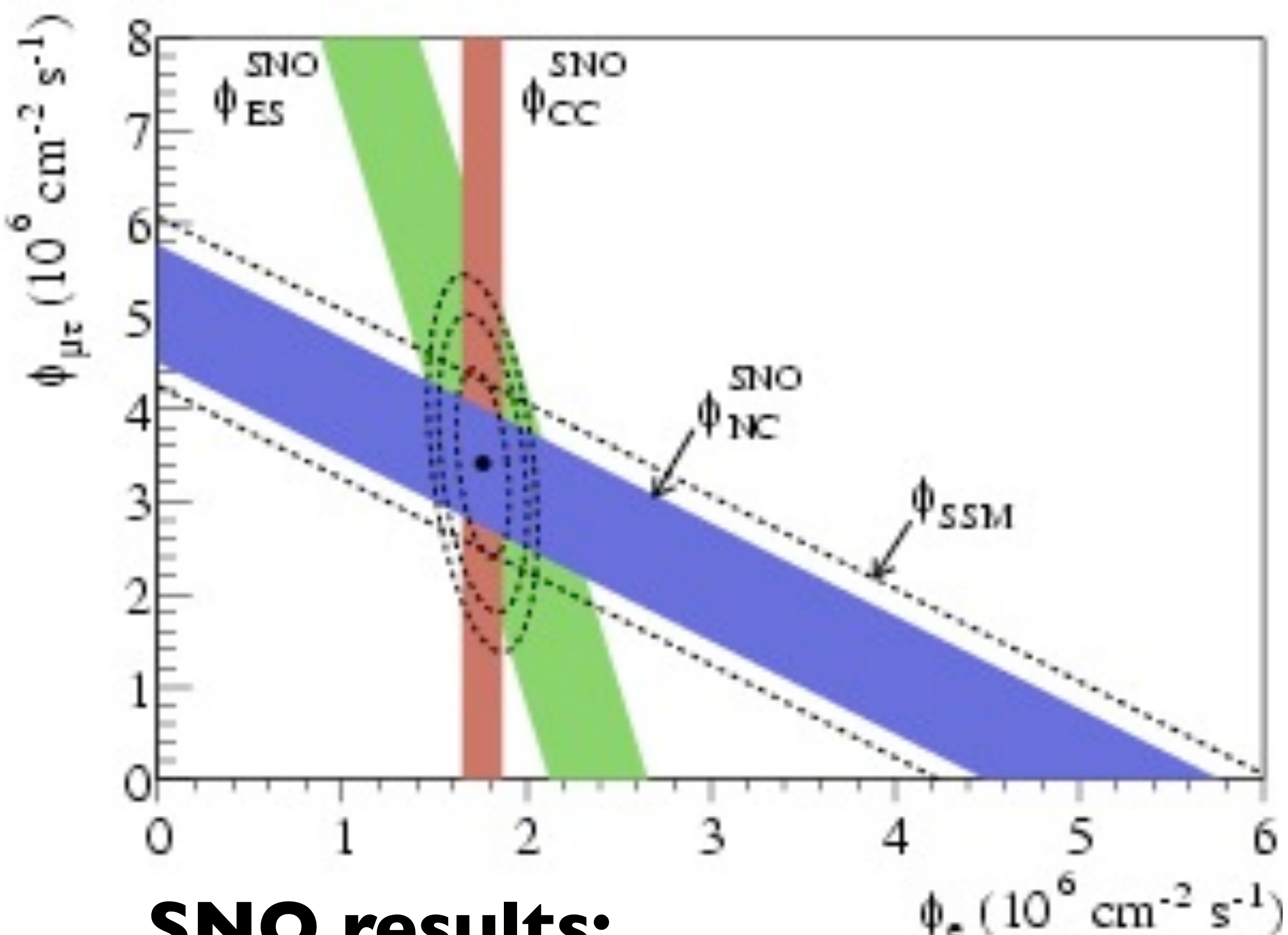
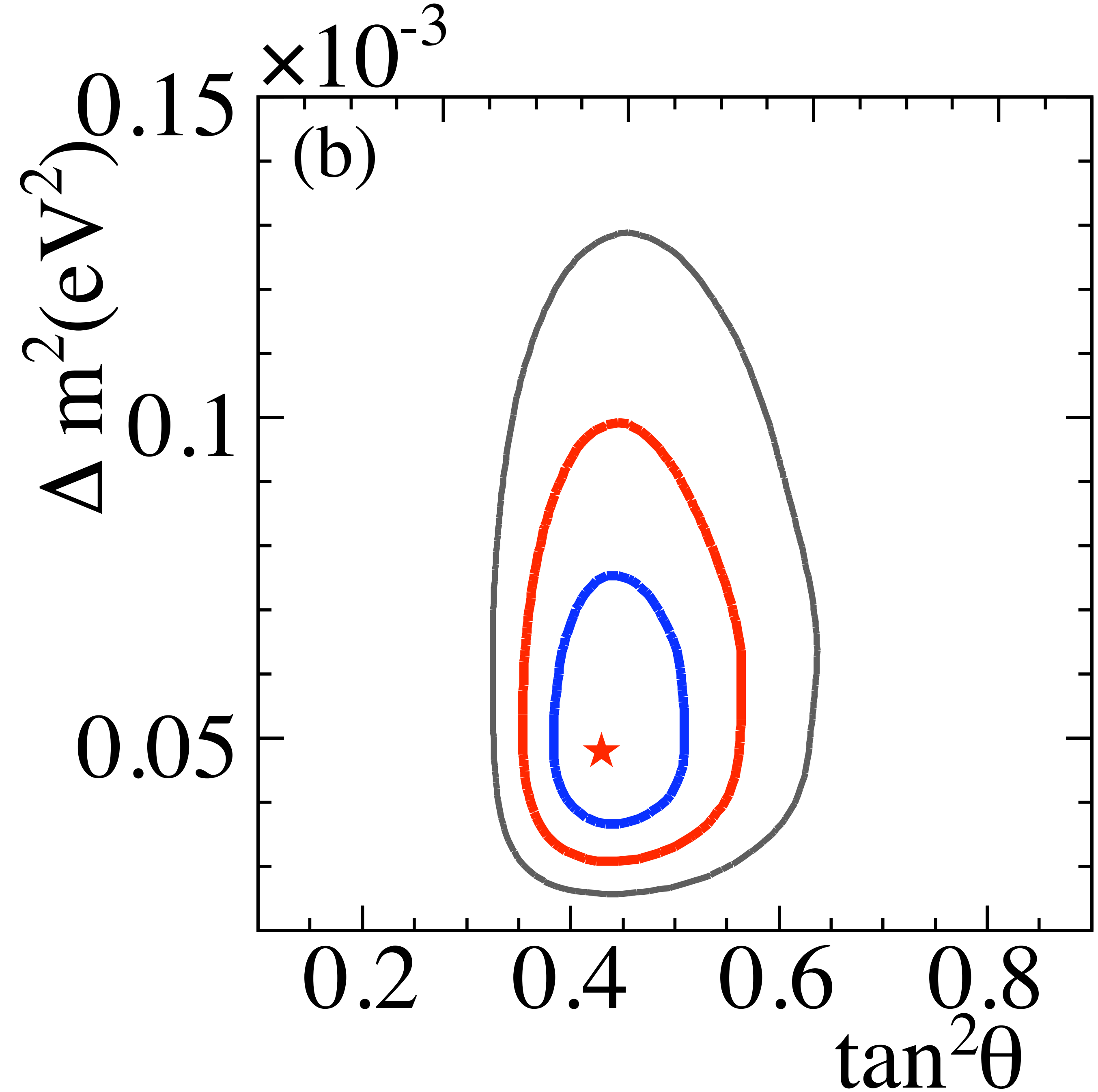


Neutrino Oscillations



SNO results:

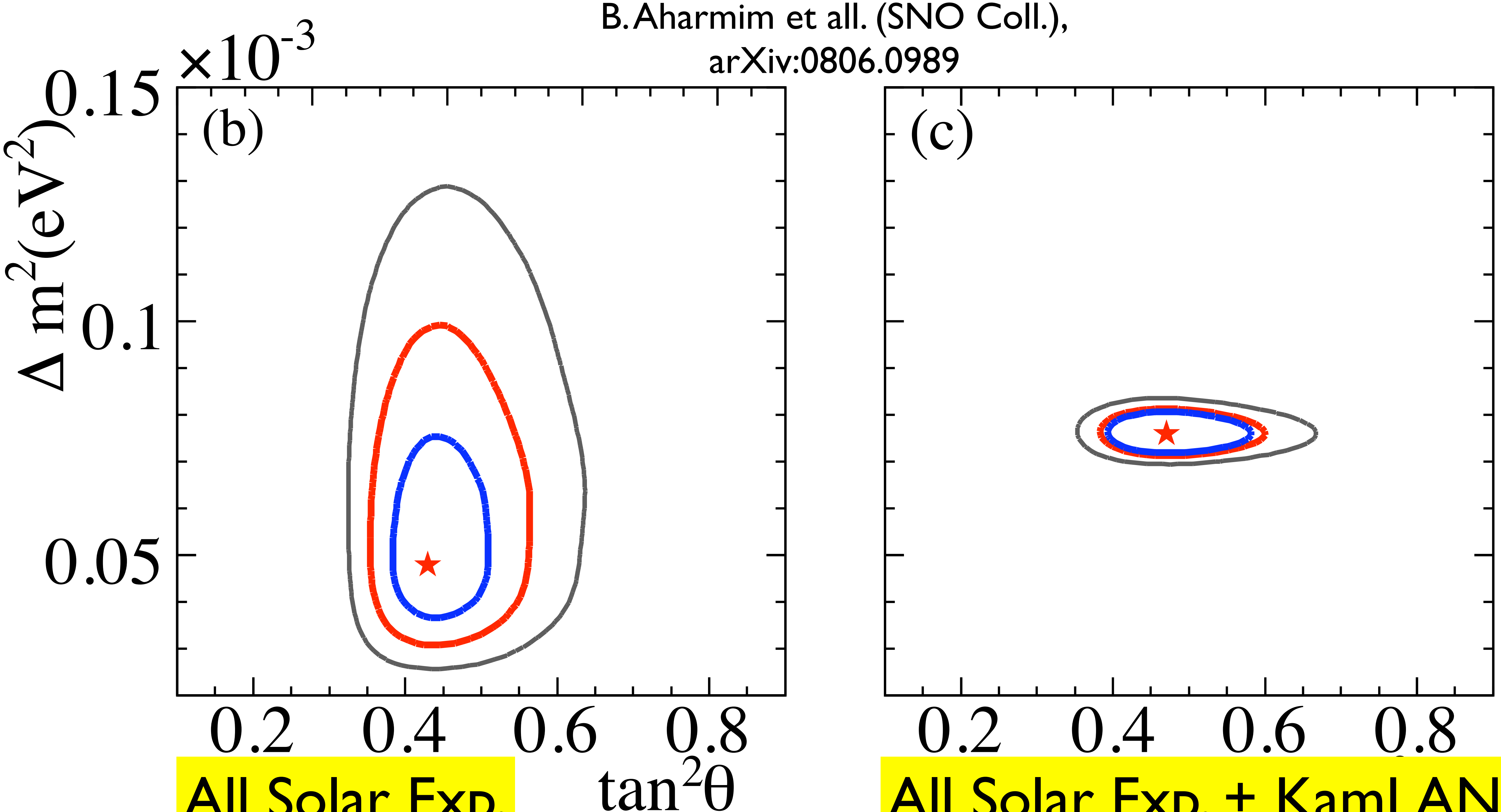
Neutral current interactions
(sensitive to all neutrinos equally)
Elastic scattering interactions
(sensitive to all neutrinos, enhanced sensitivity for electron neutrinos)
Charged current interactions
(sensitive only to electron neutrinos)



Includes all solar ν data until 2005

Solar Neutrinos and Reactor Anti-Neutrinos

B. Aharmim et all. (SNO Coll.), arXiv:0806.0989



All Solar Exp.

All Solar Exp. + KamLAND

Current Status of Exploration

- Very clear signal of neutrino mixing from solar experiments
- Confirmation of validity of Standard Solar Model
- Restriction of parameters to MSW-LMA
- Confirmation of neutrino mixing and MSW-LMA parameters from study of reactor antineutrinos (KamLAND)
- Confirmed solar origin of neutrinos by correlation of electron scattering with direction towards Sun in KamiokaNDE, SuperKamiokaNDE, and SNO

J. Klein
Neutrino '08

Open Questions: Neutrino Physics

- Demonstrate two unobserved specific signatures of MSW-LMA
  - Transition from vacuum-driven to matter-enhanced oscillations
  - Day-night asymmetry (regeneration of neutrinos crossing Earth)
- Probe possible new physics in the very sensitive region of the transition between vacuum-driven and matter-enhanced oscillations

Open Questions: The Sun

- The metallicity problem: is the Standard Solar Model in trouble?

- Check the balance between photon luminosity and neutrino luminosity of the Sun. Requires ^{7}Be flux measured at 5% and *pp* flux measured at 1% level

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

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

- To confirm the solar origin of neutrinos, by checking the expected 7% seasonal variation of the signal due to the Earth's orbital eccentricity

Resonant Oscillations in Matter: the MSW effect

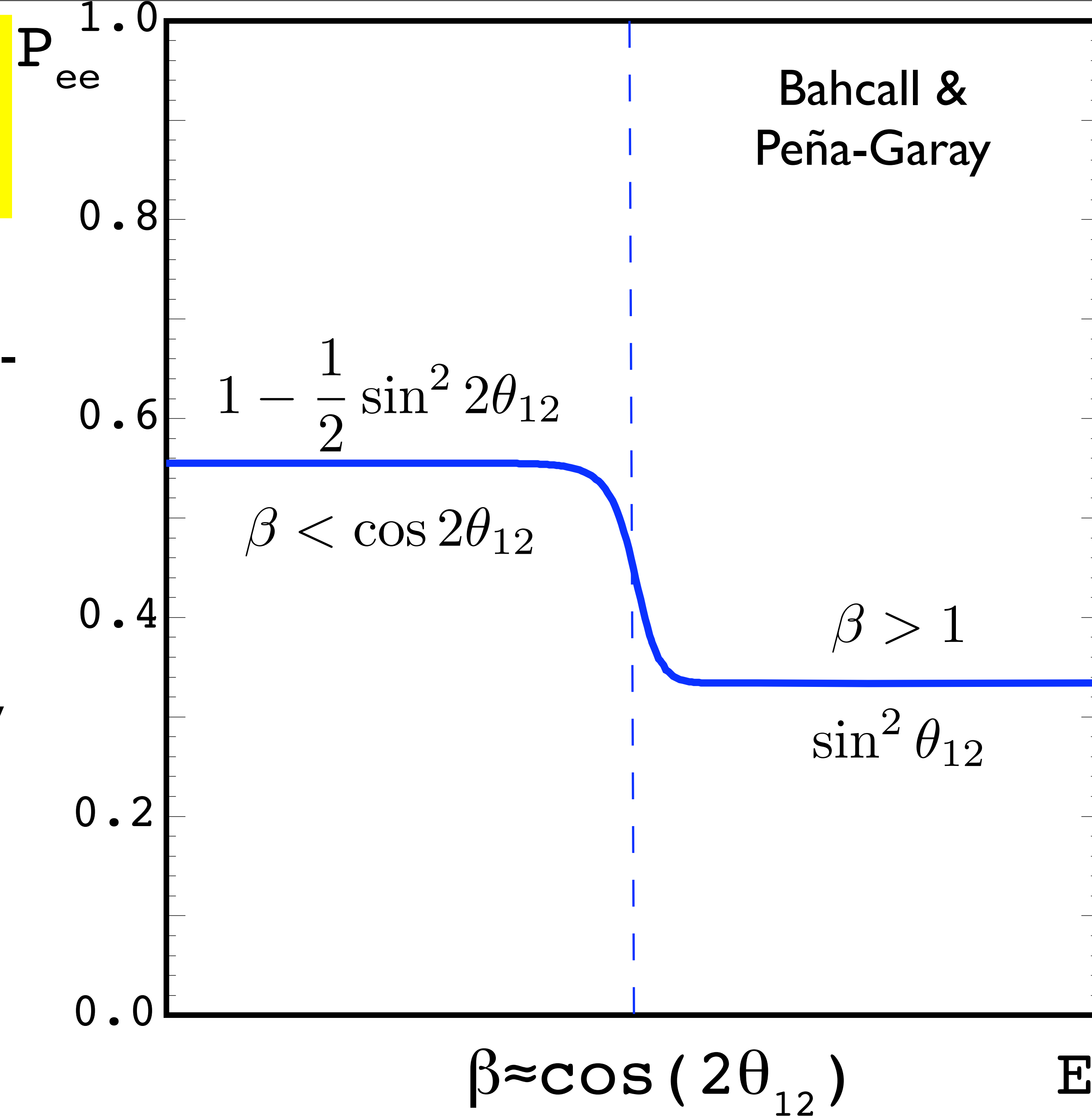
For high energy ^{8}B neutrinos - object of observation by SNO and SuperKamiokaNDE - matter dominated oscillations in the high density of electrons N_e in sun's core

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!

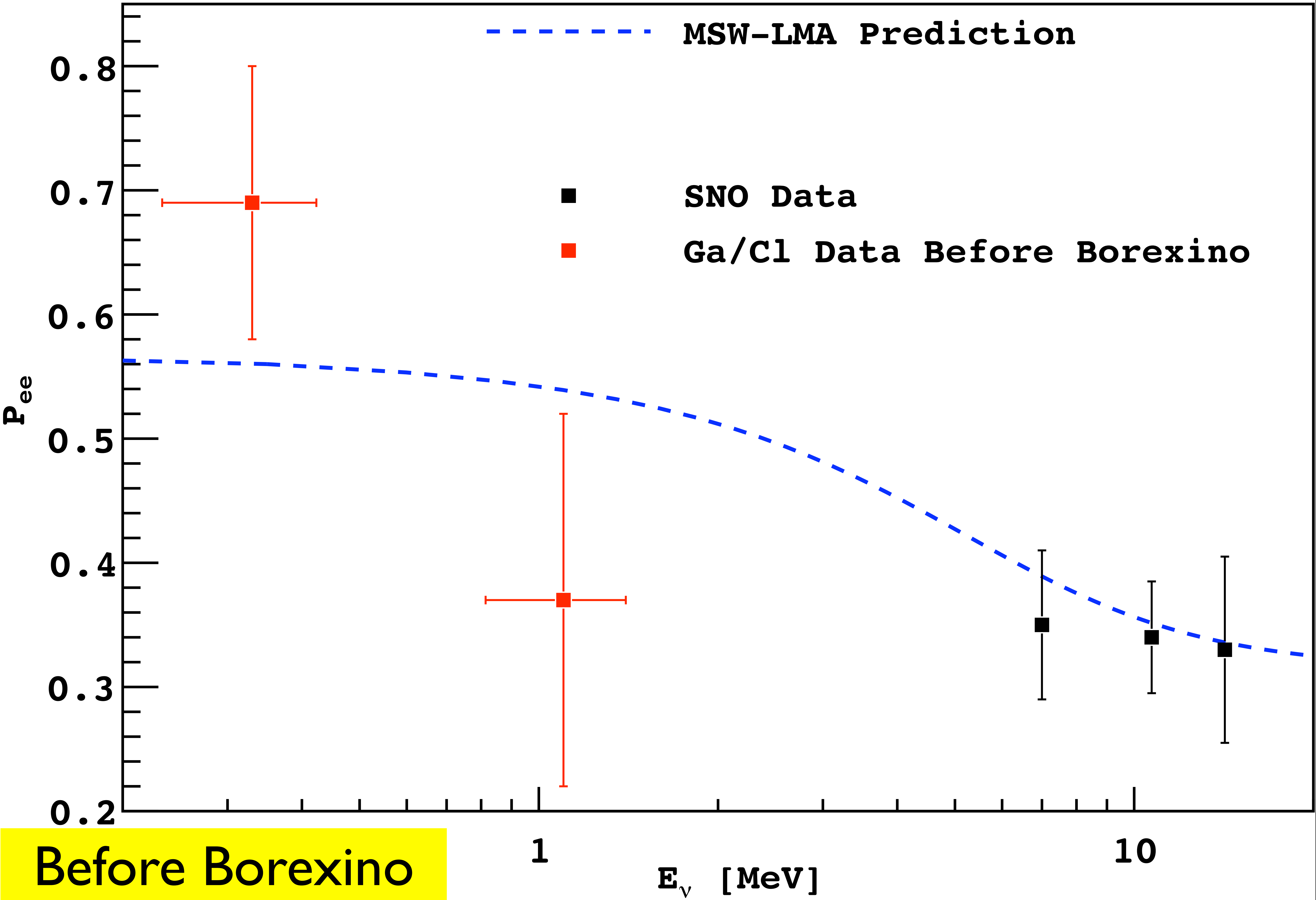


$$\begin{pmatrix} -\frac{\Delta m^2_{12}}{4E}\cos 2\theta_{12} + \sqrt{2}G_F N_e & \frac{\Delta m^2_{12}}{4E}\sin 2\theta_{12} \\ \frac{\Delta m^2_{12}}{4E}\sin 2\theta_{12} & \frac{\Delta m^2_{12}}{4E}\cos 2\theta_{12} \end{pmatrix}$$

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

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

Solar Neutrino Survival Probability



Before Borexino

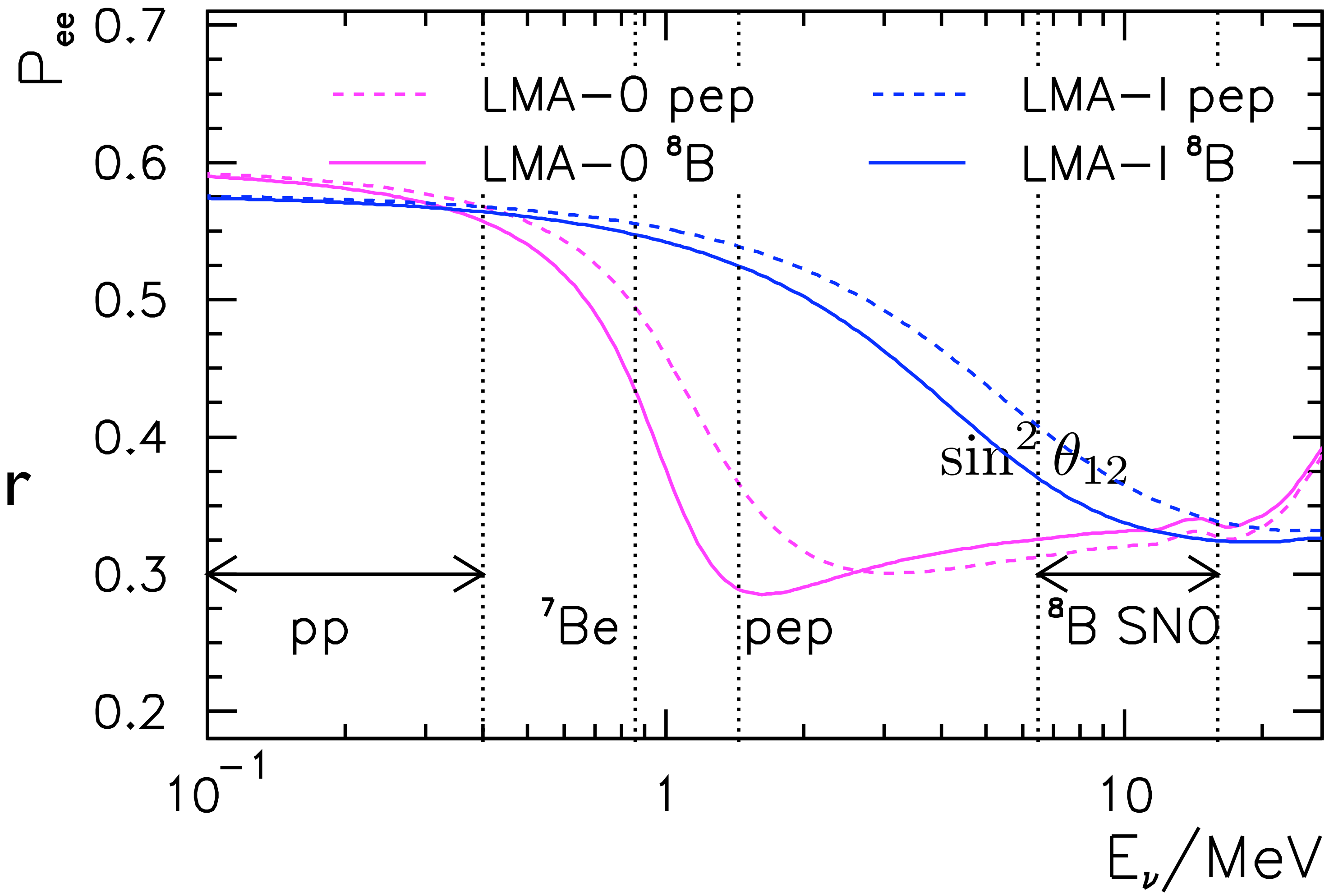
Non-Standard Neutrino-Matter Interactions

Exploring the vacuum-matter transition is sensitive to new physics

New neutrino-matter couplings (either flavor-changing or lepton flavor violating) can be parametrized by a new MSW-equivalent term ε

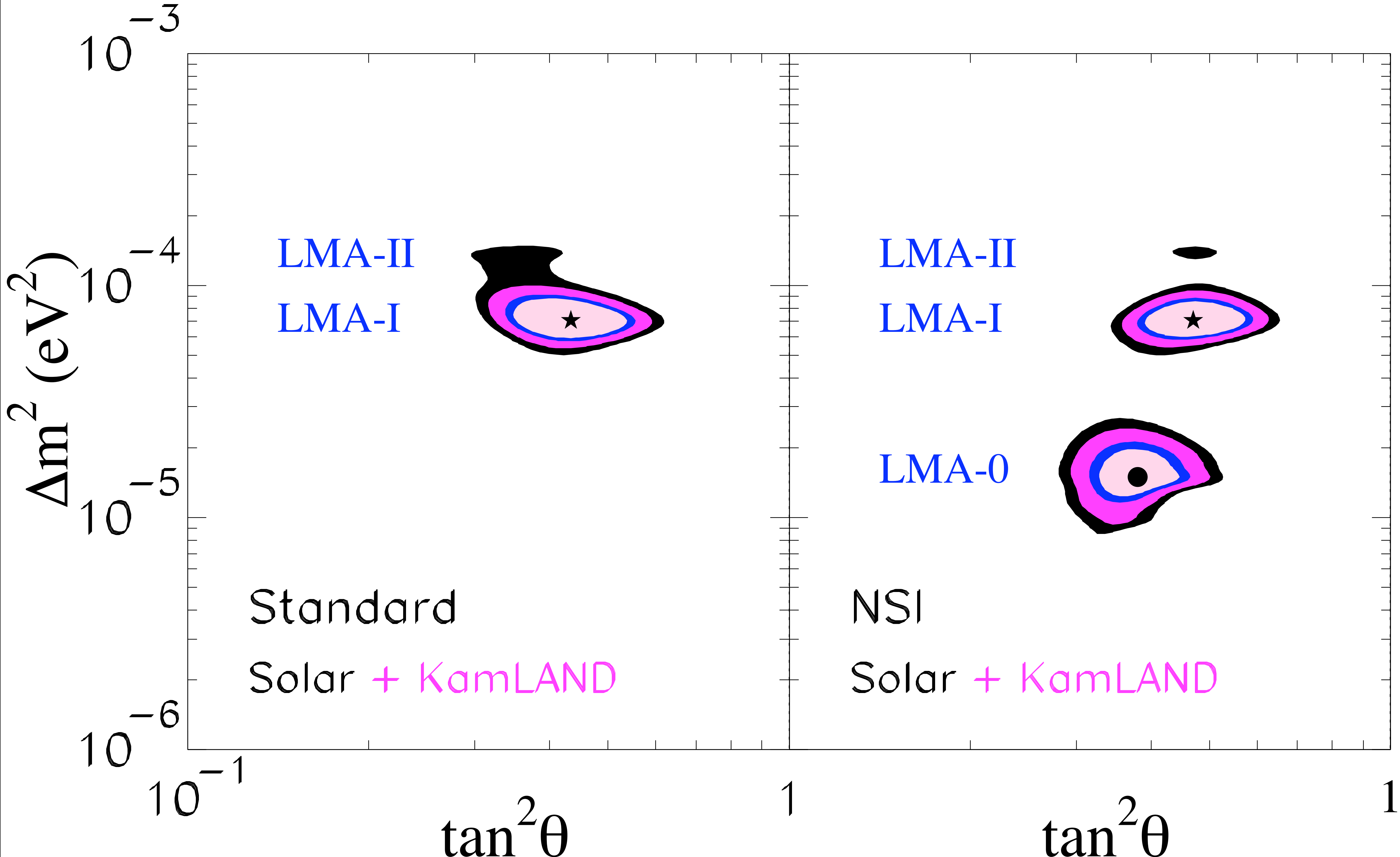
Where is the relative effect of new physics the largest? At resonance!

Friedland, Lundardini & Peña-Garay



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

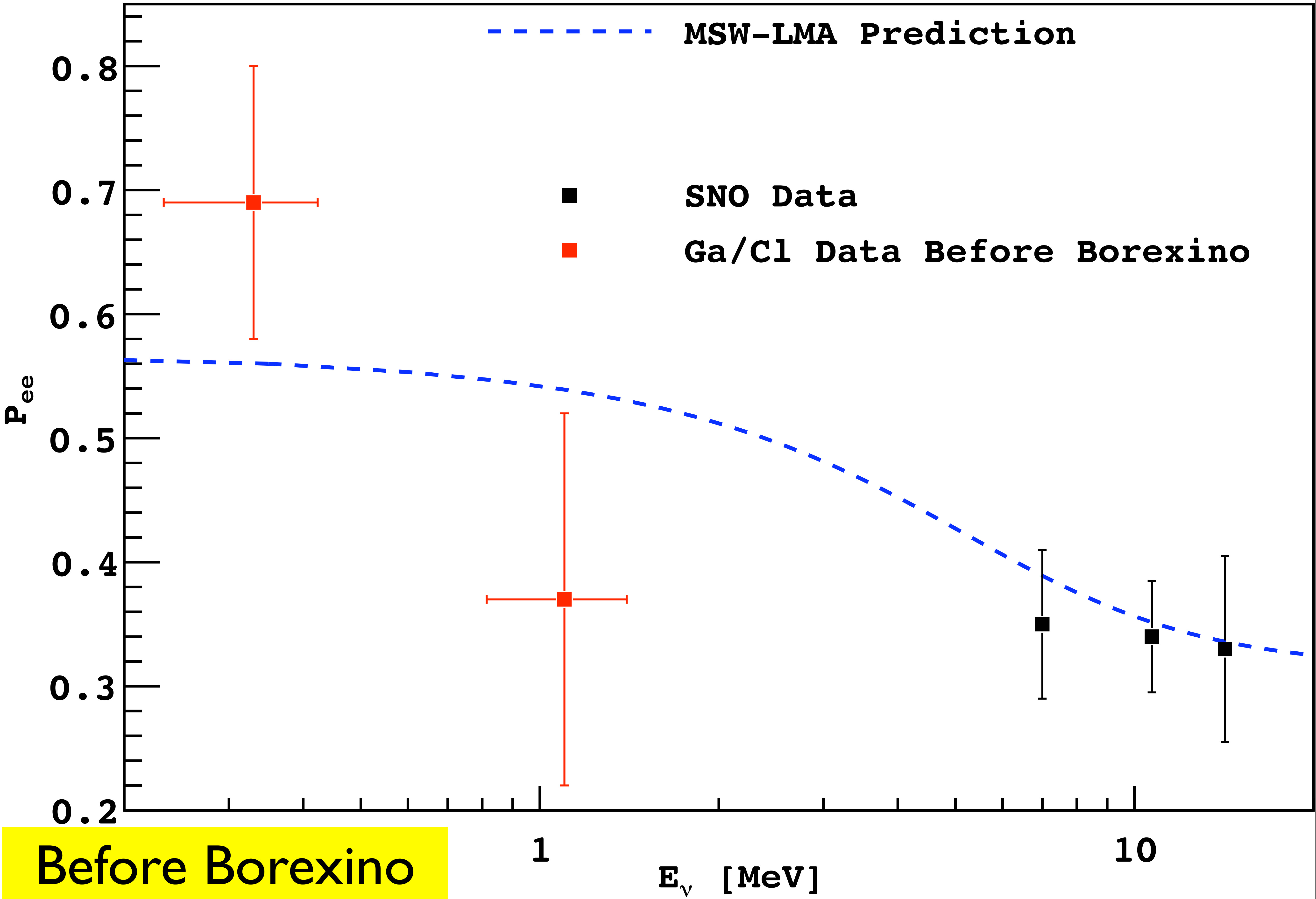
$$\begin{pmatrix} -\frac{\Delta m^2_{12}}{4E}\cos 2\theta_{12} + \sqrt{2}G_F N_e & \frac{\Delta m^2_{12}}{4E}\sin 2\theta_{12} + \epsilon^* \\ \frac{\Delta m^2_{12}}{4E}\sin 2\theta_{12} + \epsilon & \frac{\Delta m^2_{12}}{4E}\cos 2\theta_{12} + \epsilon' \end{pmatrix}$$



Regions allowed in case of null Non-Standard Interactions

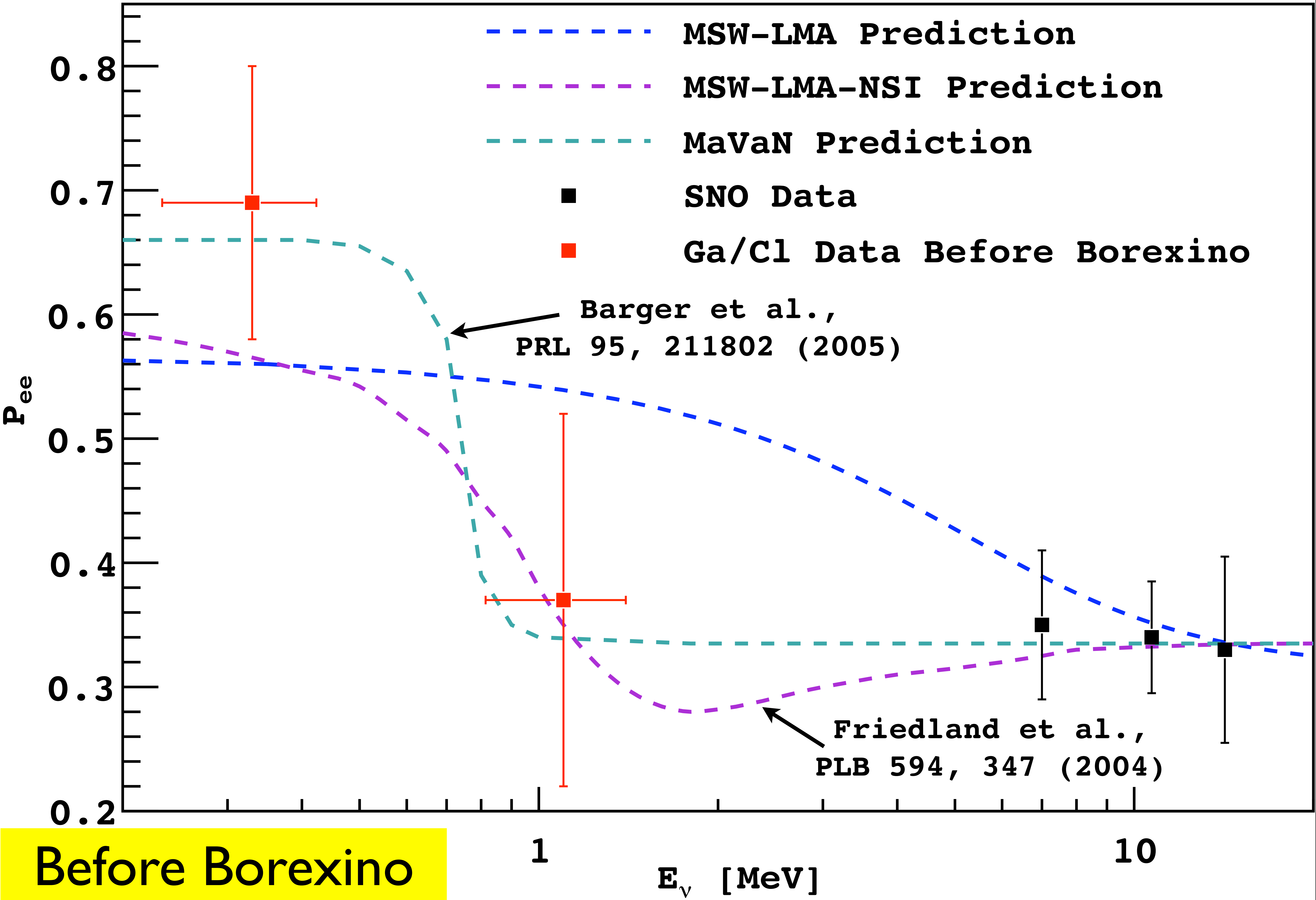
Regions allowed within present experimental boundaries to Non-Standard Interactions

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 ~1.7/1.2=1.4. 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)

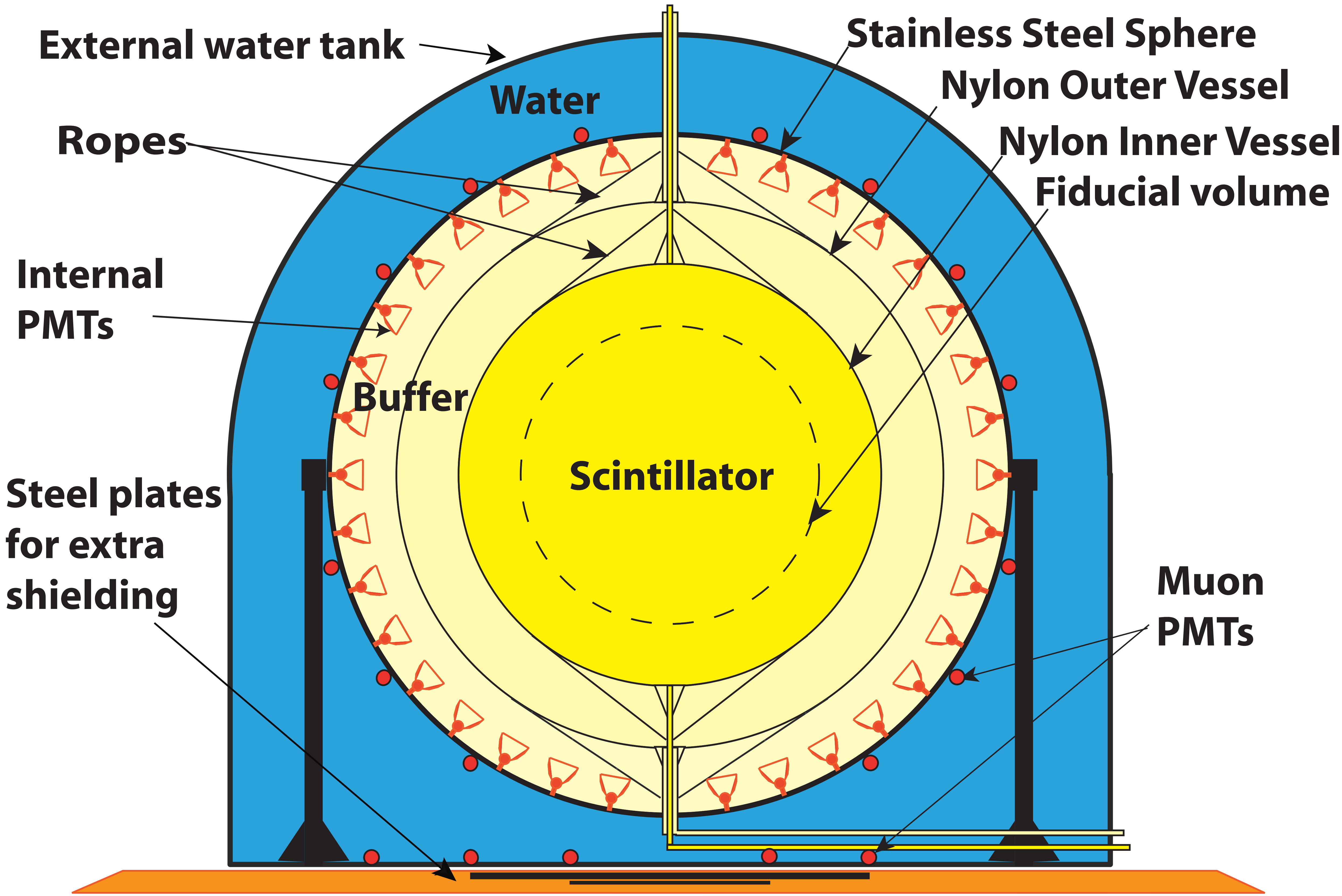
ϕ ($cm^{-2}s^{-1}$)	*pp* ($\times 10^{10}$)	^{7}Be ($\times 10^{9}$)	^{8}B ($\times 10^{6}$)	^{13}N ($\times 10^{8}$)	^{15}O ($\times 10^{8}$)	^{17}F ($\times 10^{6}$)
BS05 GS 98	5.99	4.84	5.69	3.07	2.33	5.84
BS05 AGS 05	6.05	4.34	4.51	2.01	1.45	3.25
Δ	+1%	-10%	-21%	-35%	-38%	-44%
σ SSM	±1%	±5%	±16%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

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

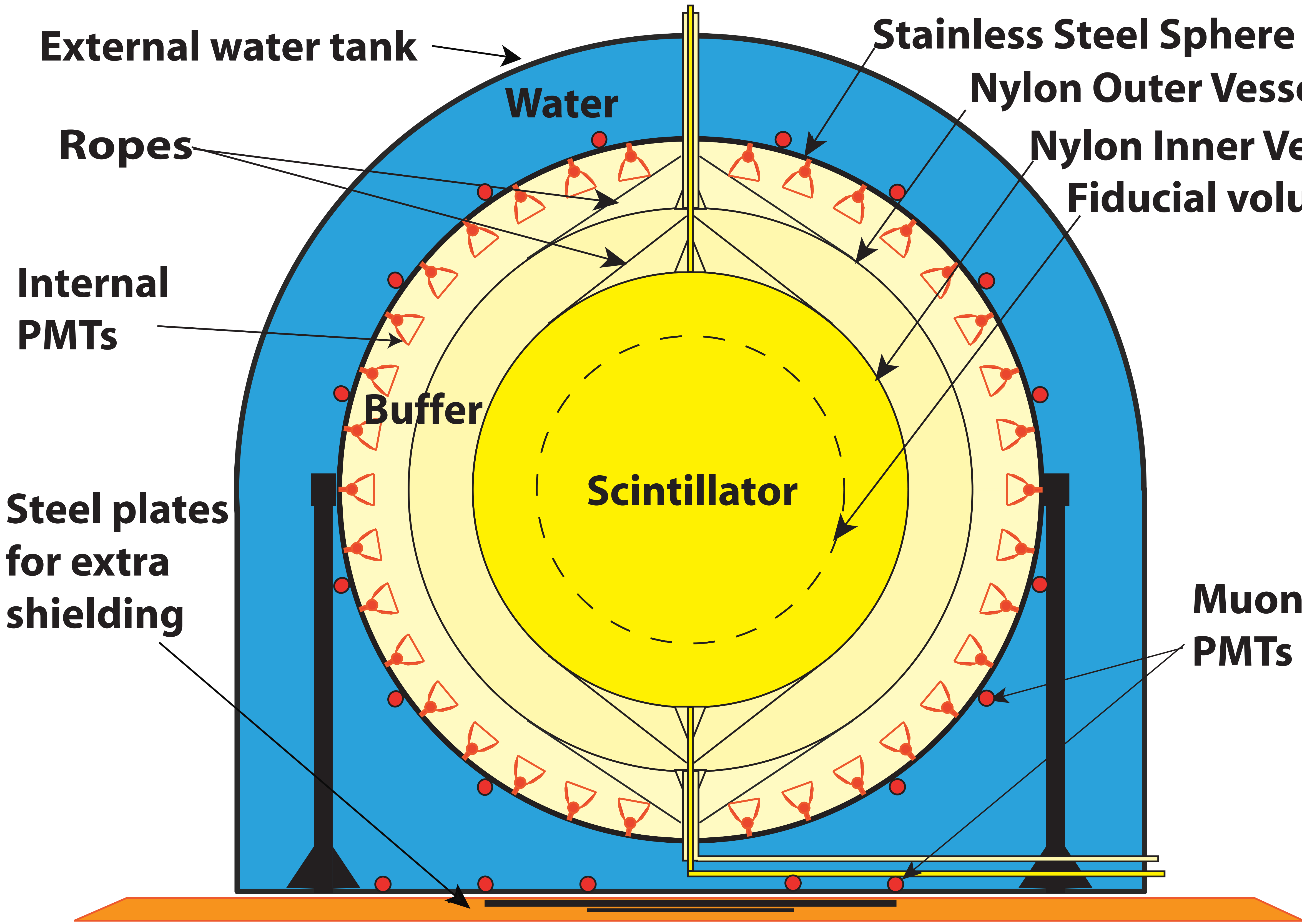
Collaboration

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

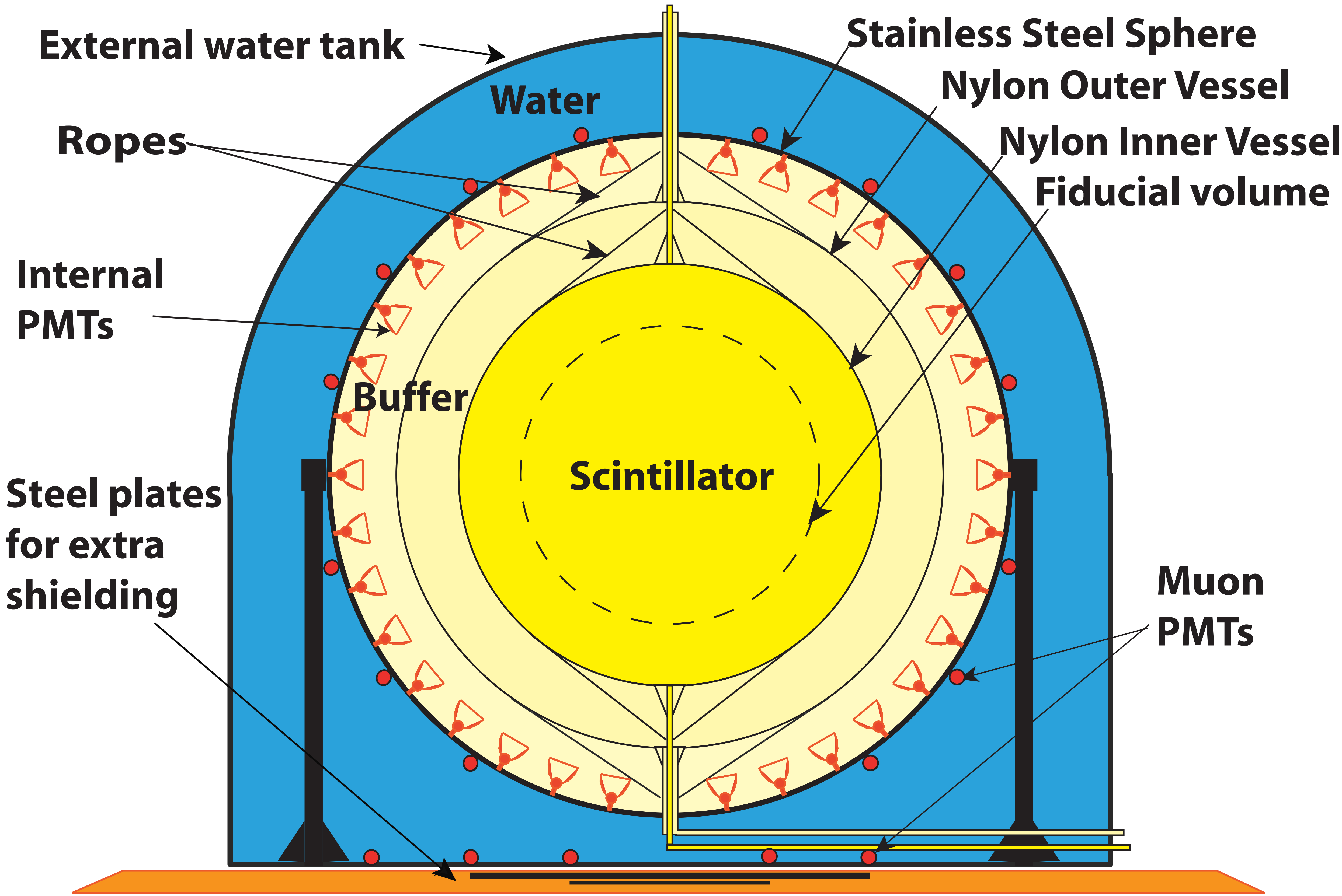


Borexino Detector



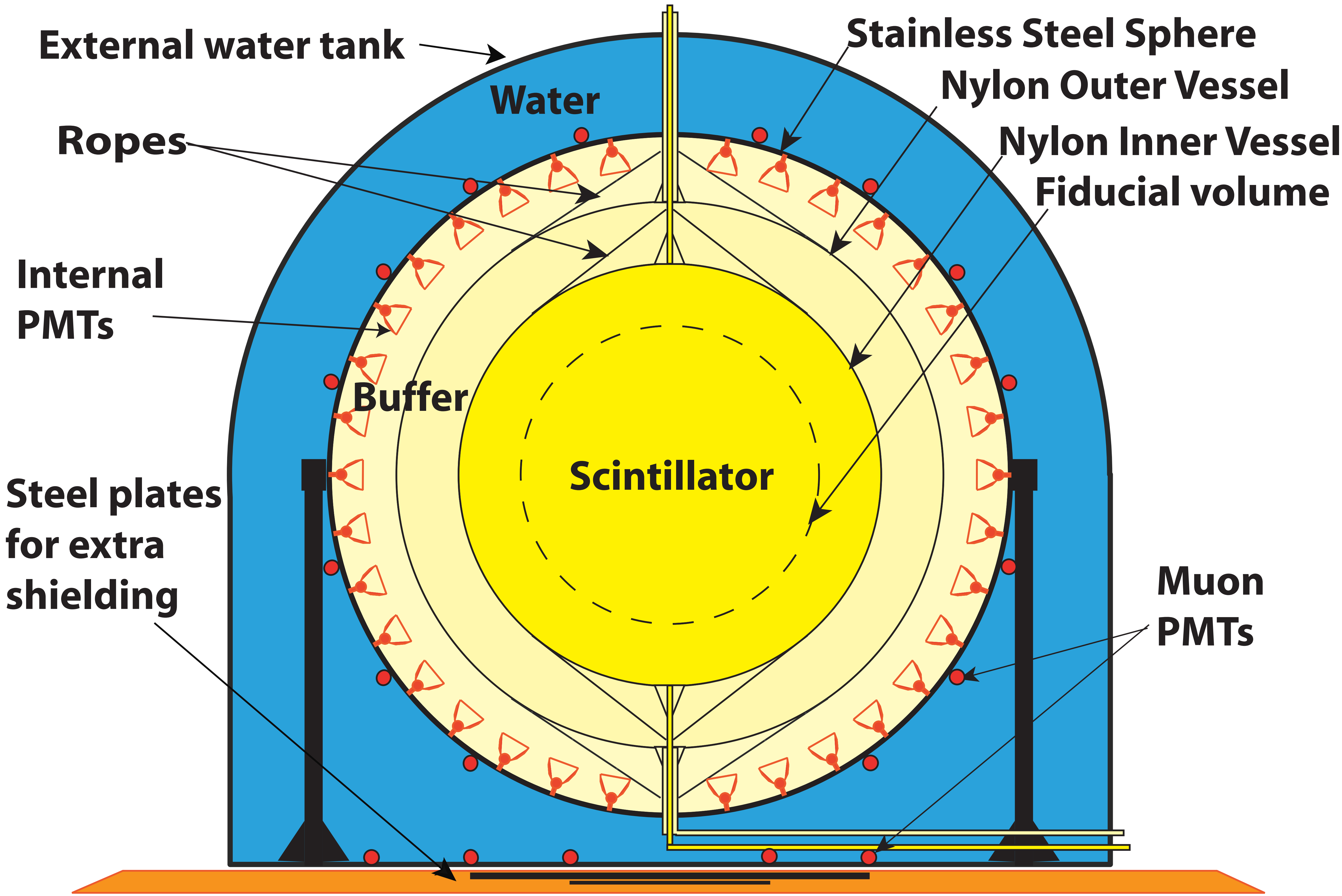
Located in LNGS - 3800 m.w.e. against cosmic rays

Borexino Detector



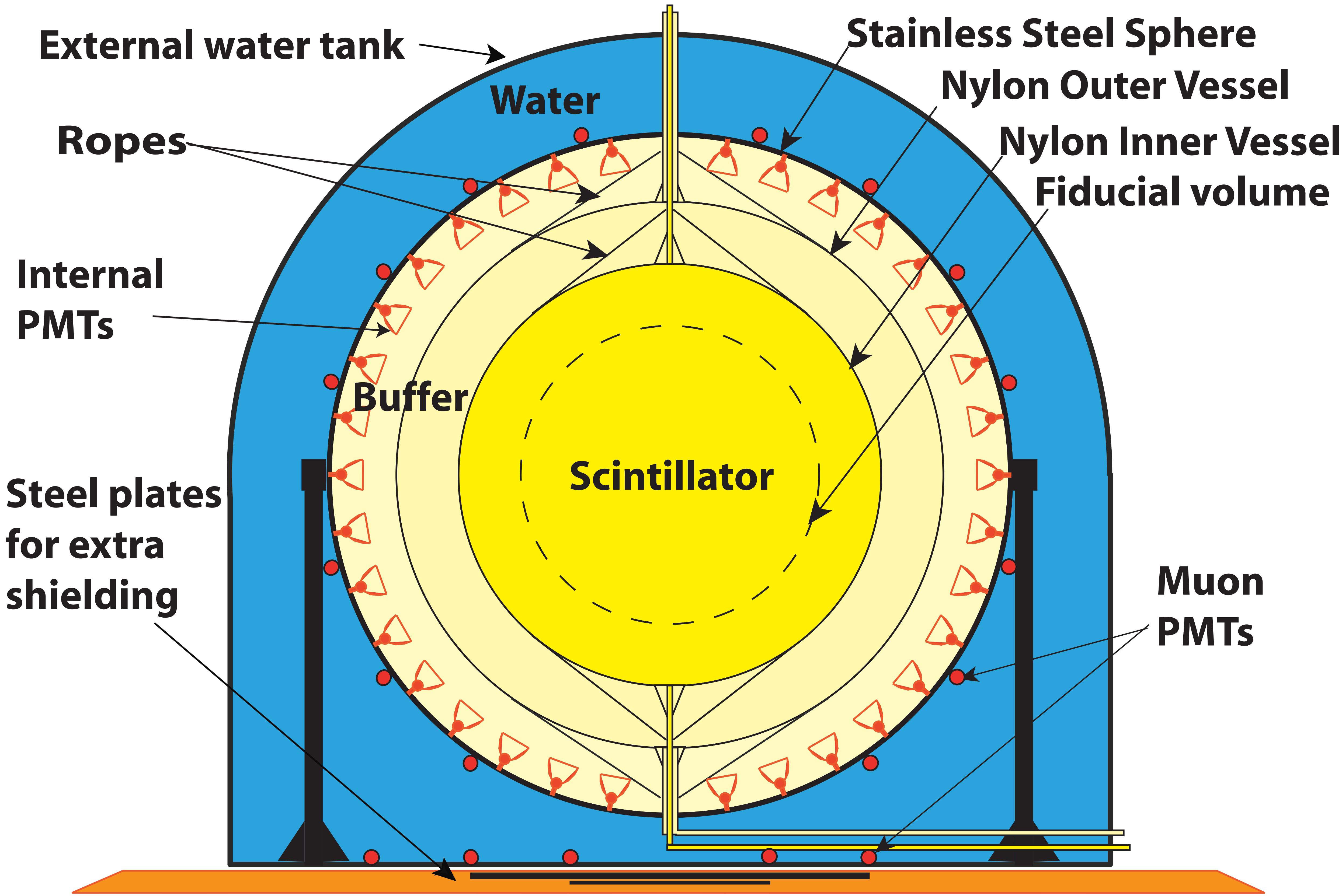
Active Target: 278 Tons of Liquid Scintillator
in Nylon Vessel of 4.25 m radius

Borexino Detector



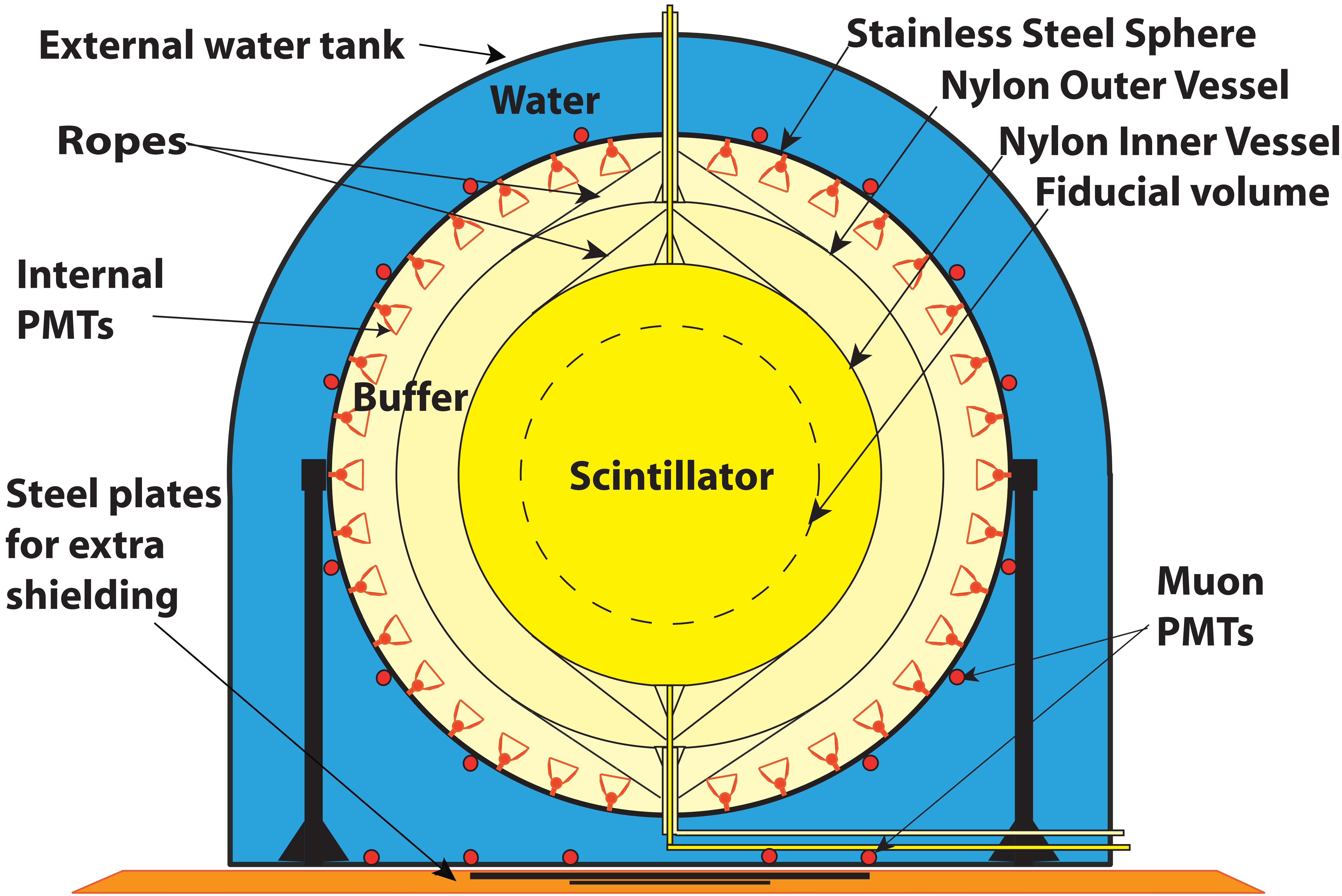
1st shield: 890 tons of ultra-pure buffer liquid in a stainless steel sphere of 6.75 m radius

Borexino Detector



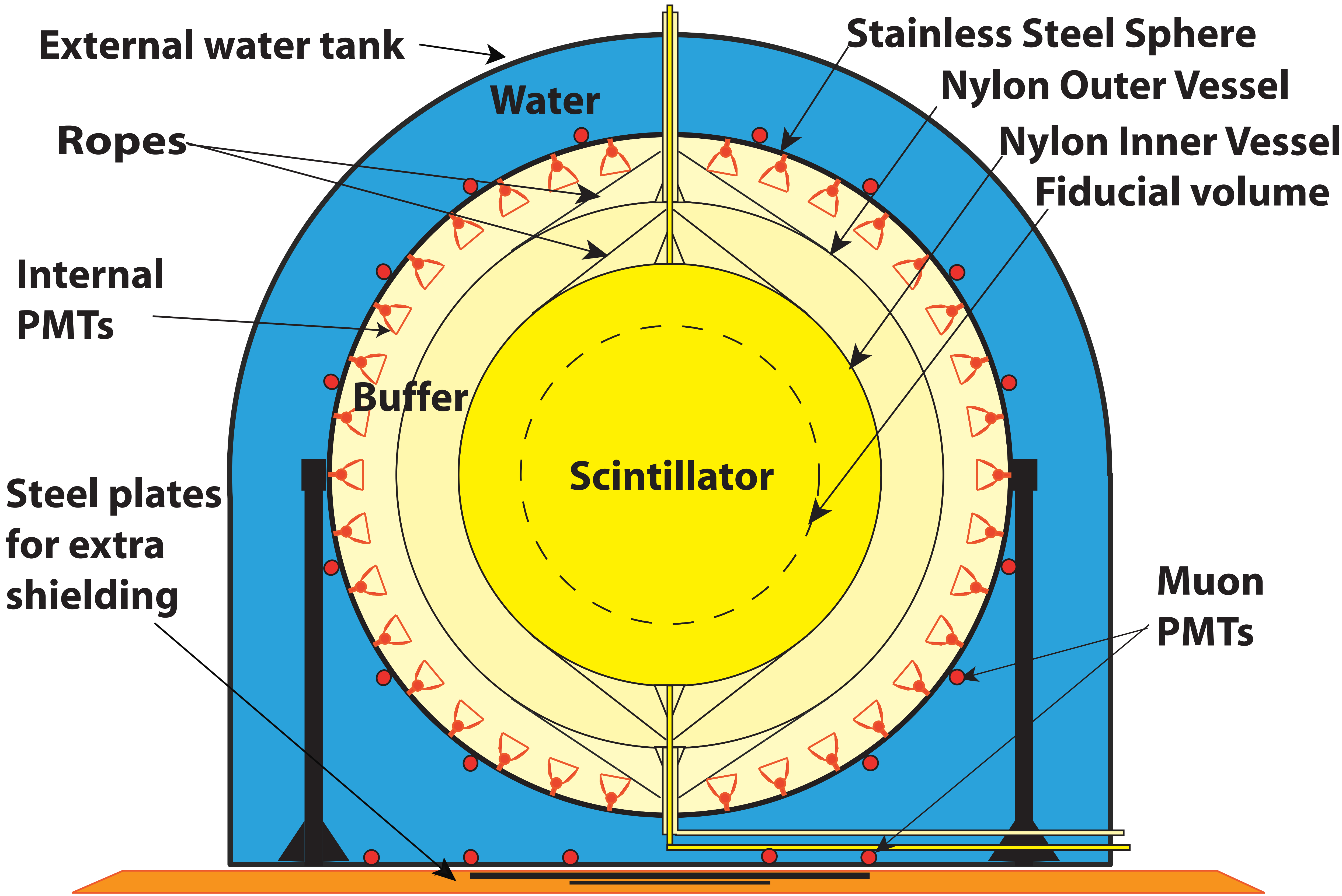
External nylon vessel - A barrier against Rn
emitted by PMTs and Stainless Steel

Borexino Detector



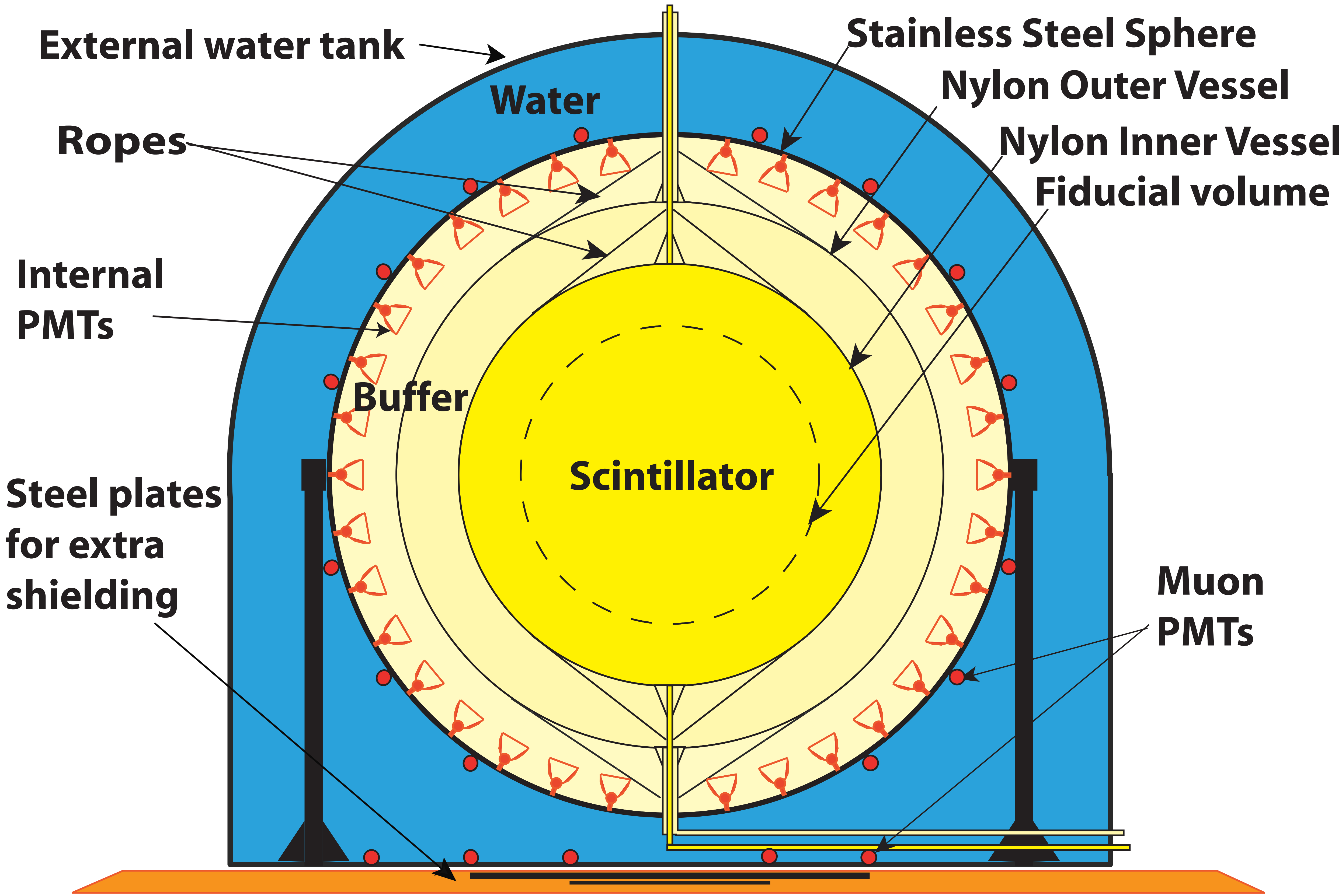
2214 PMTs detect light emitted by the scintillator
1843 with optical concentrators, the rest without for muons

Borexino Detector



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

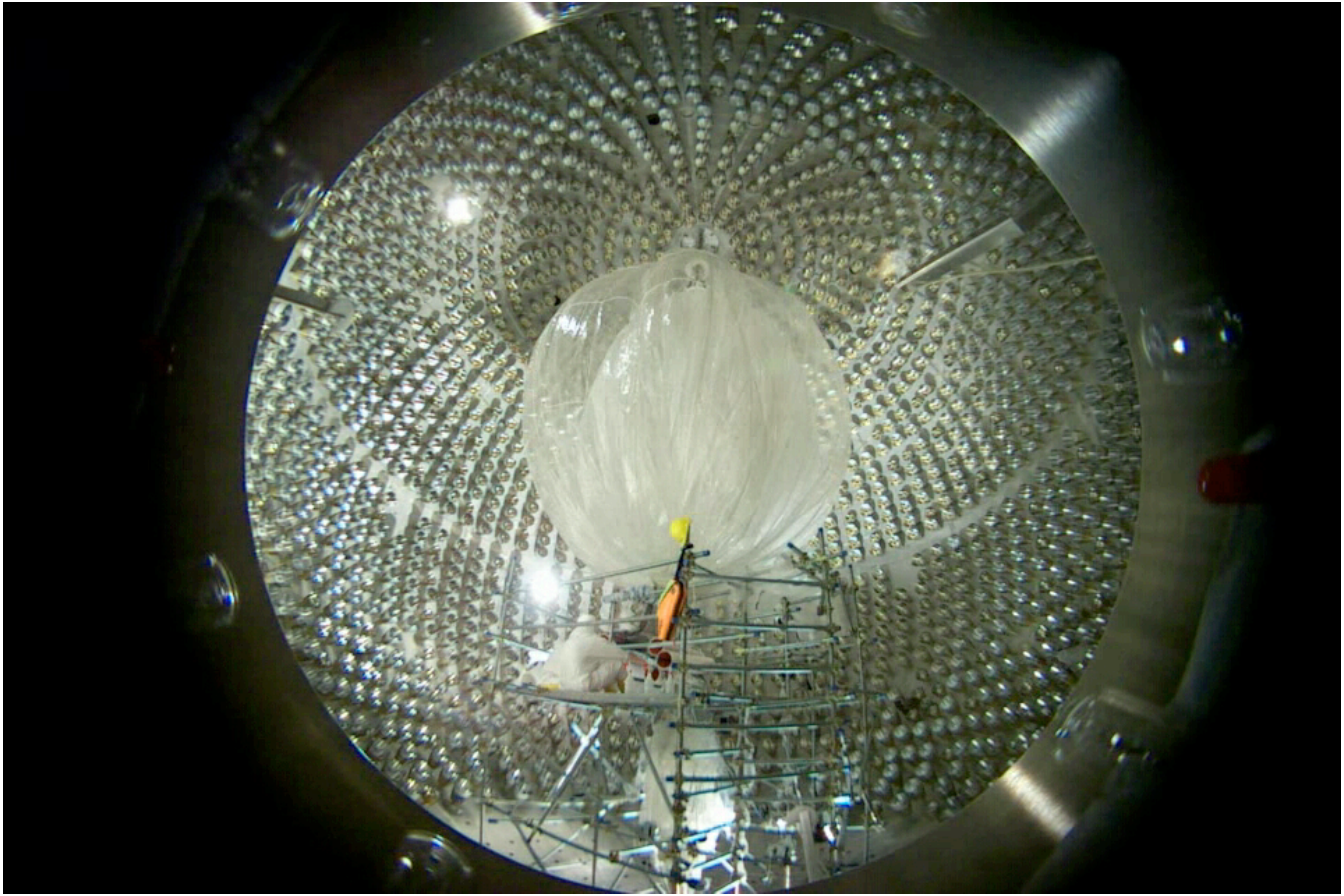
Borexino Detector

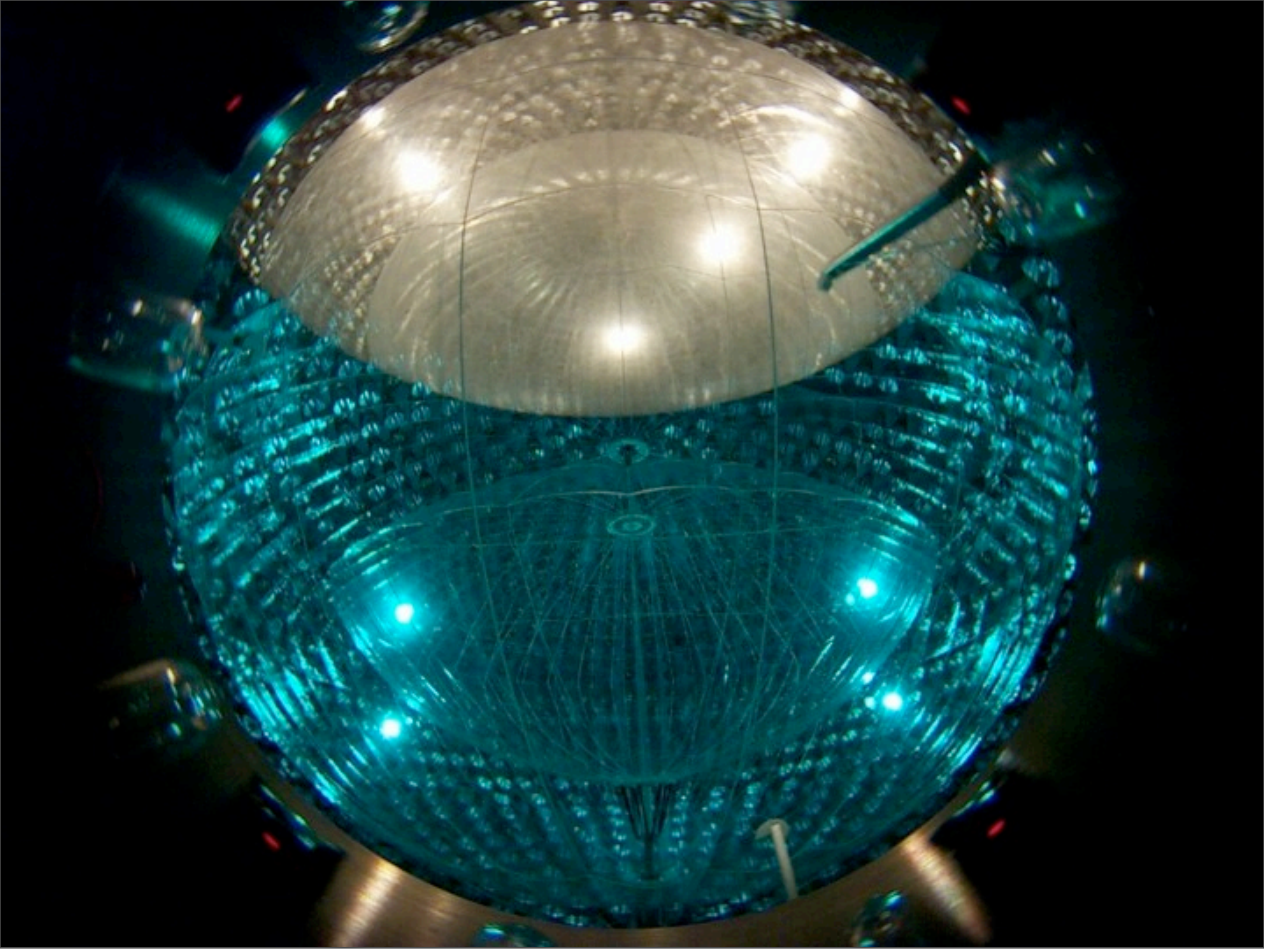


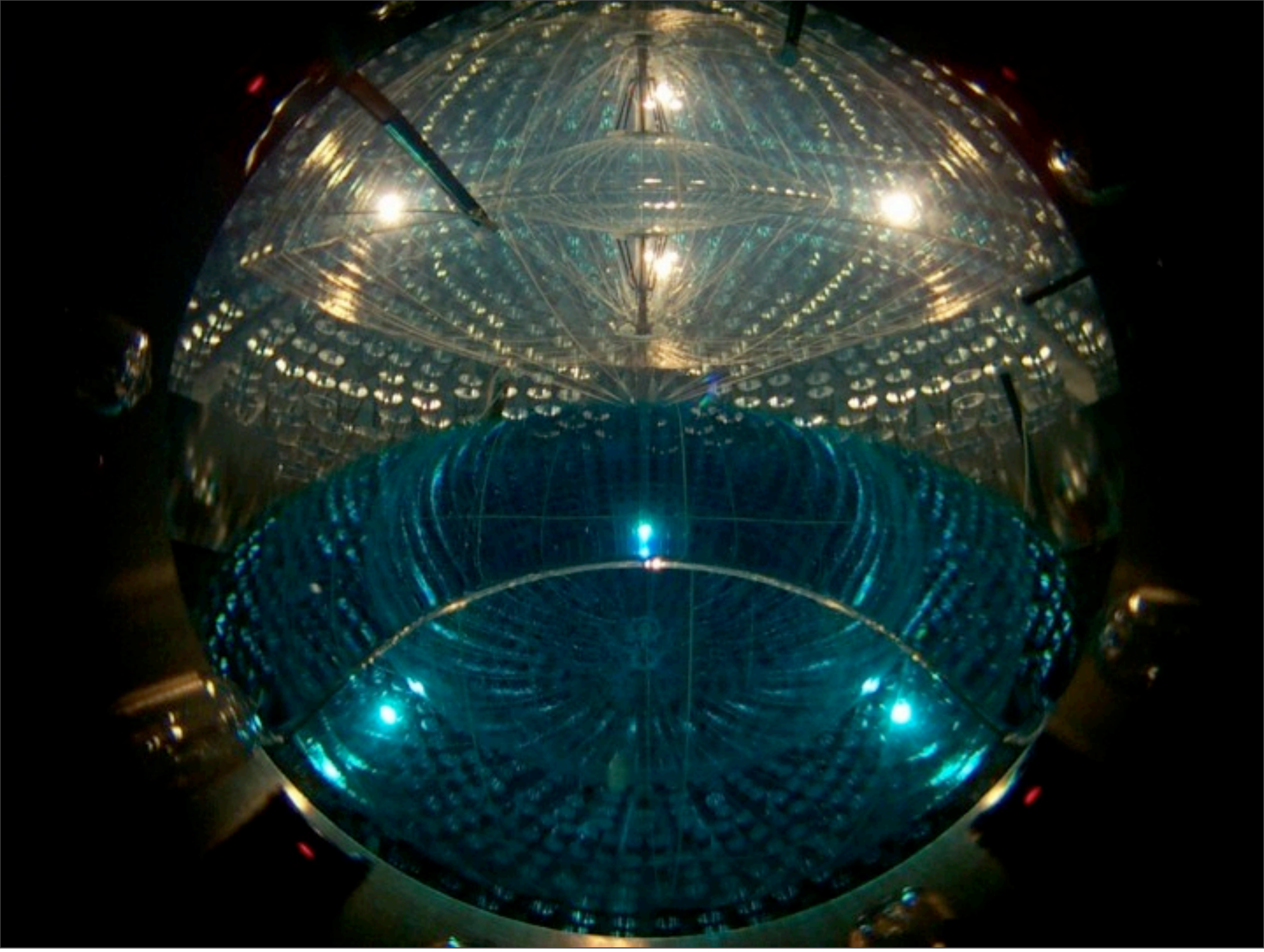
200 PMTs mounted on the SSS detect
Cherenkov light emitted in the water by muons

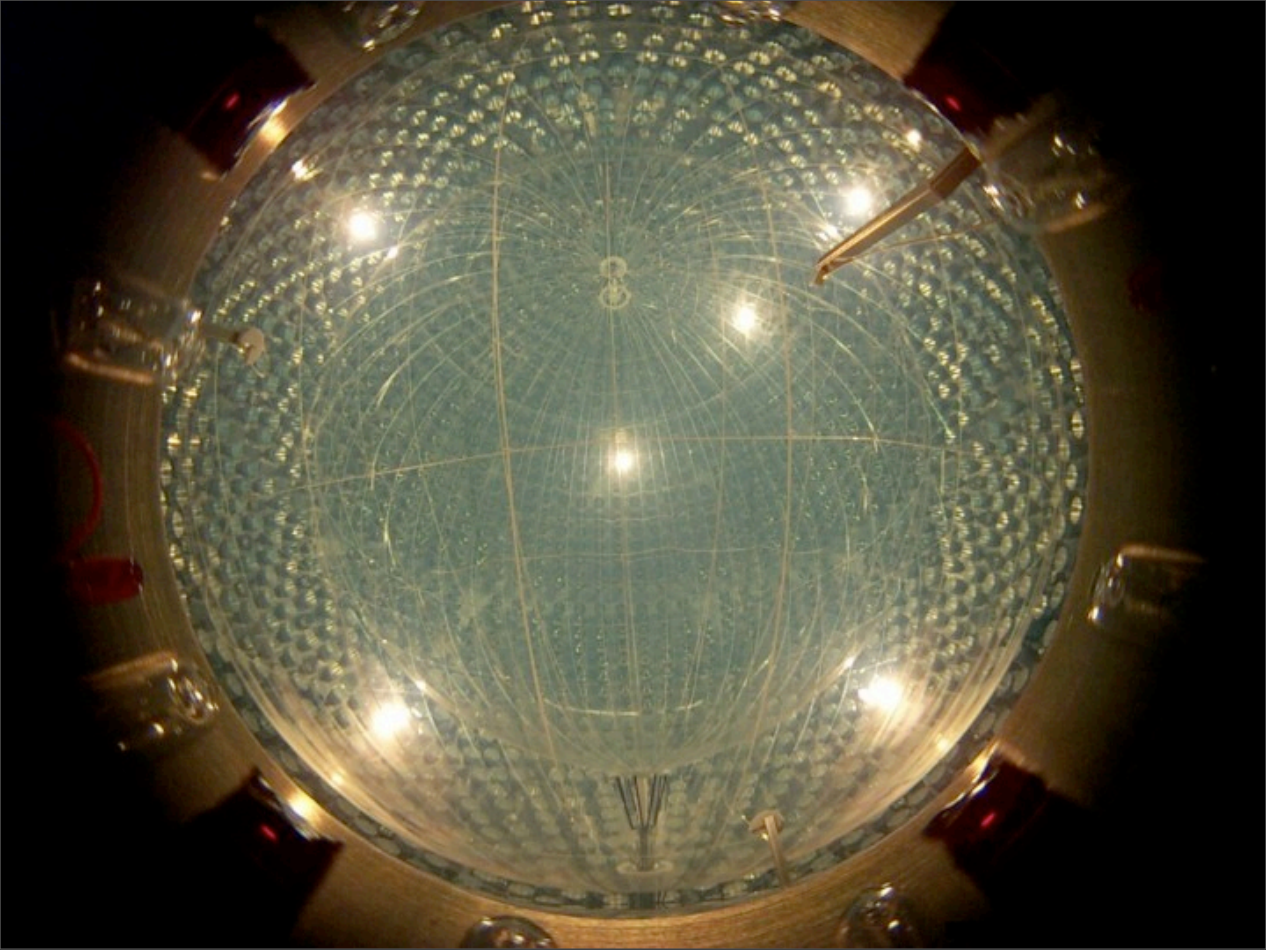
Detection Principles

- 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

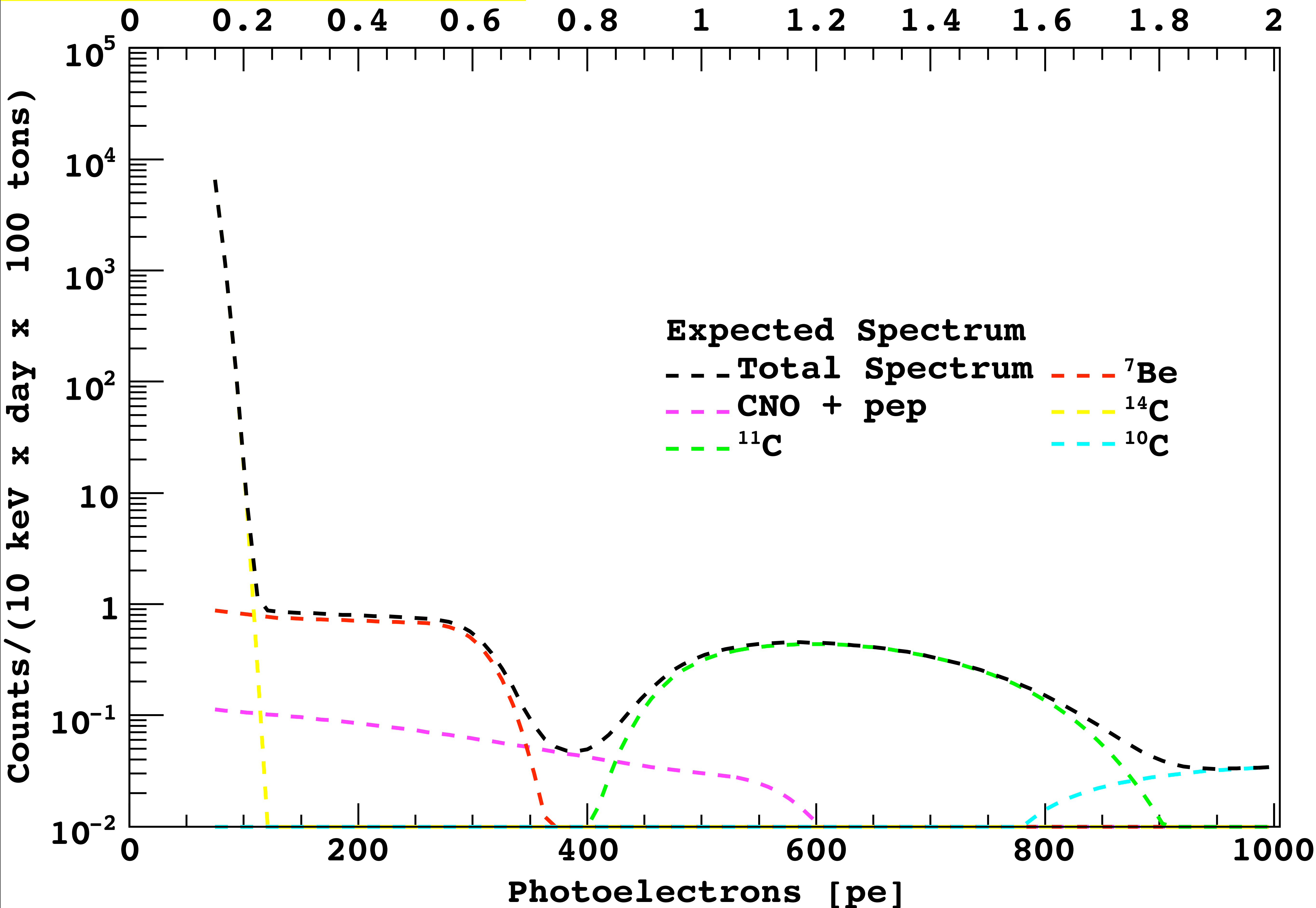




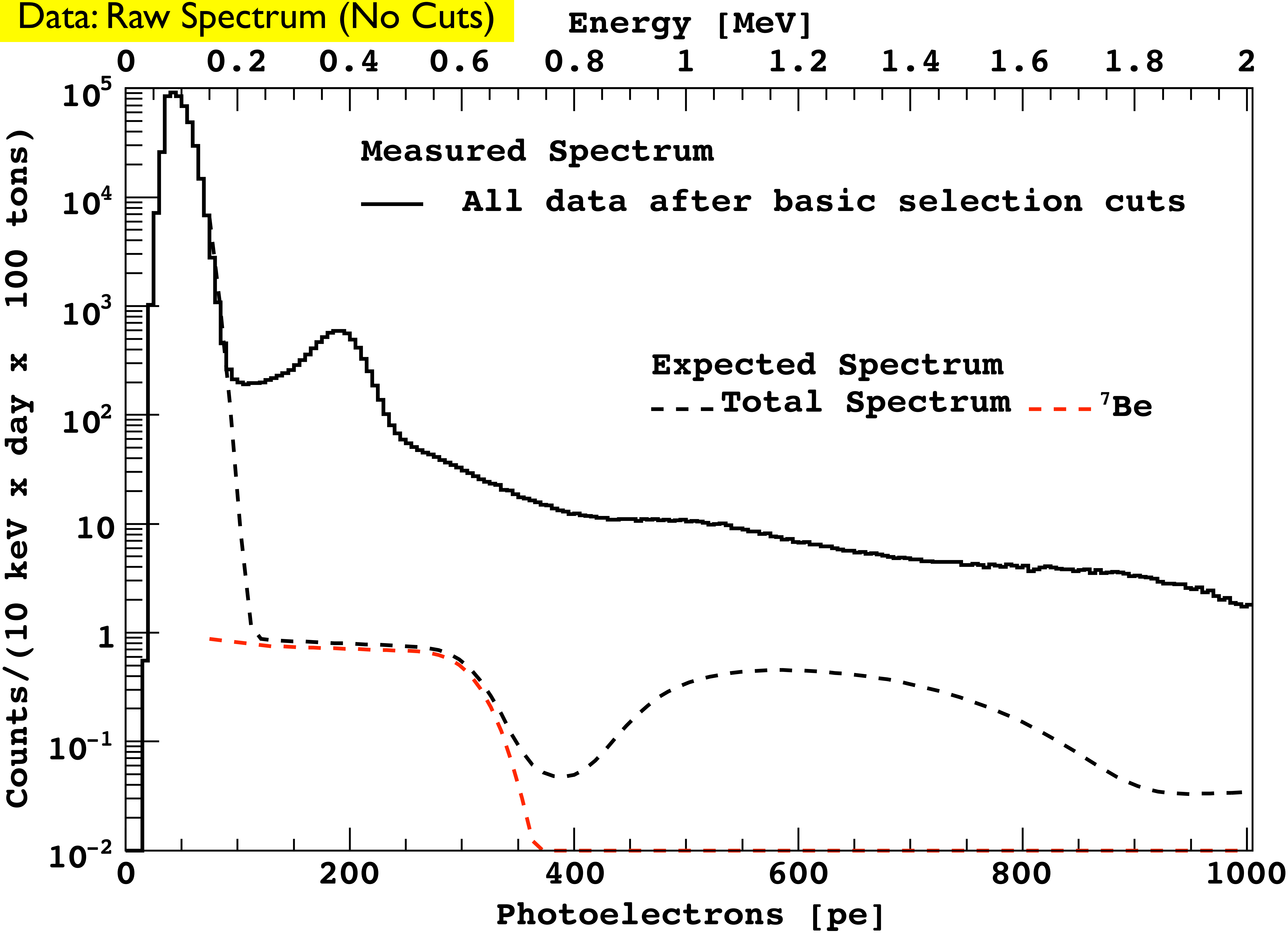




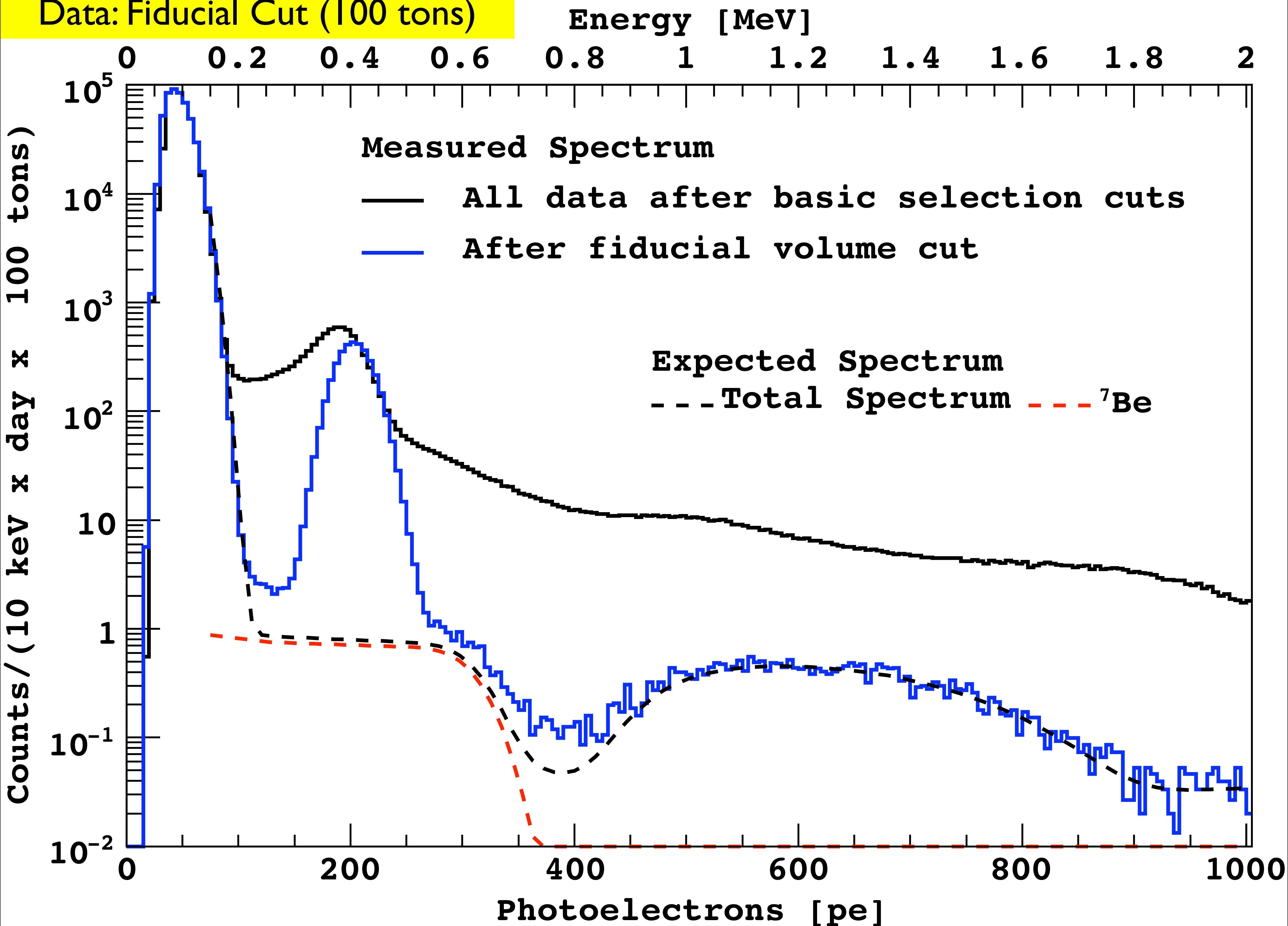
Expected (or dream?) Spectrum



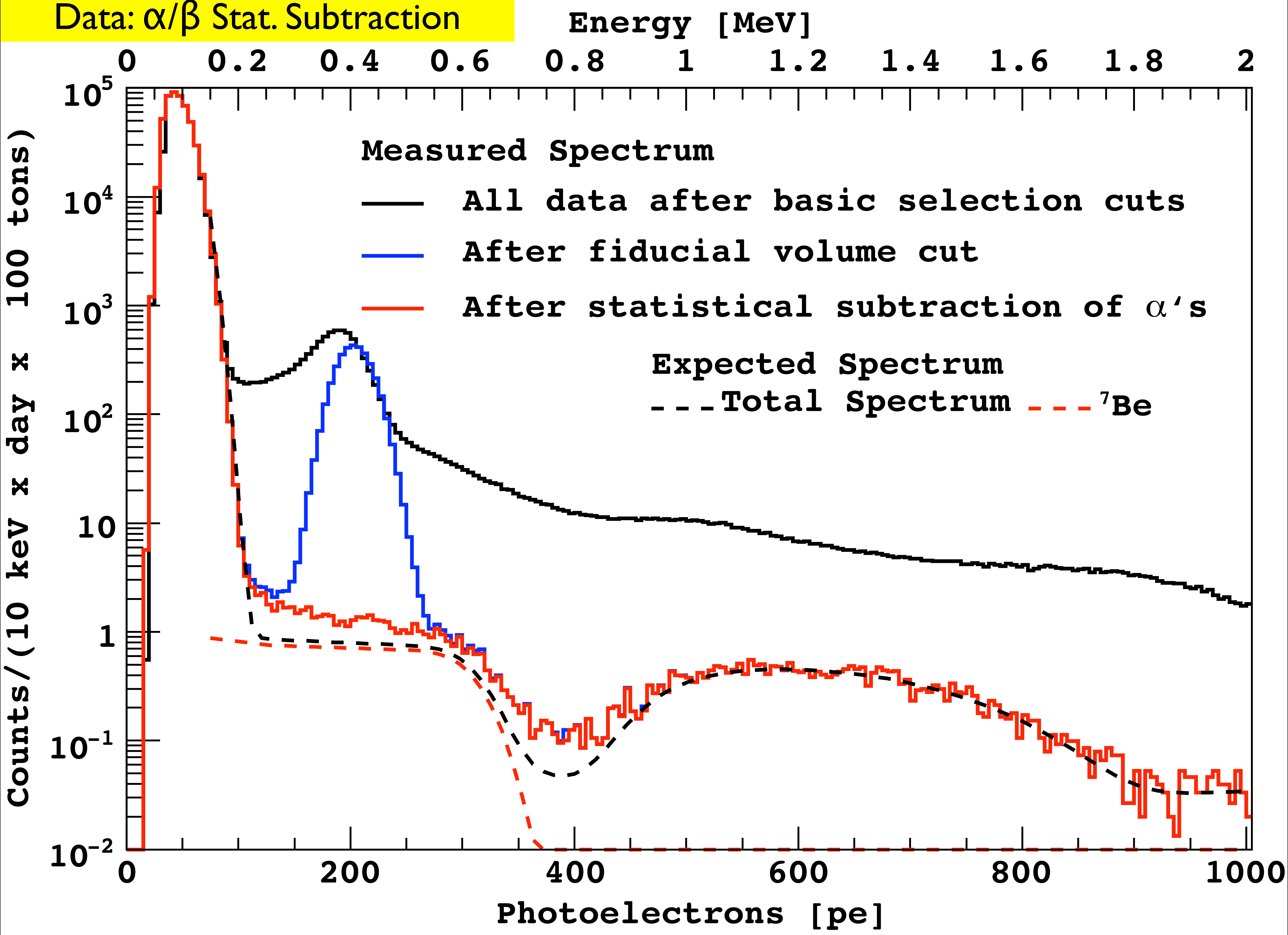
Data: Raw Spectrum (No Cuts)



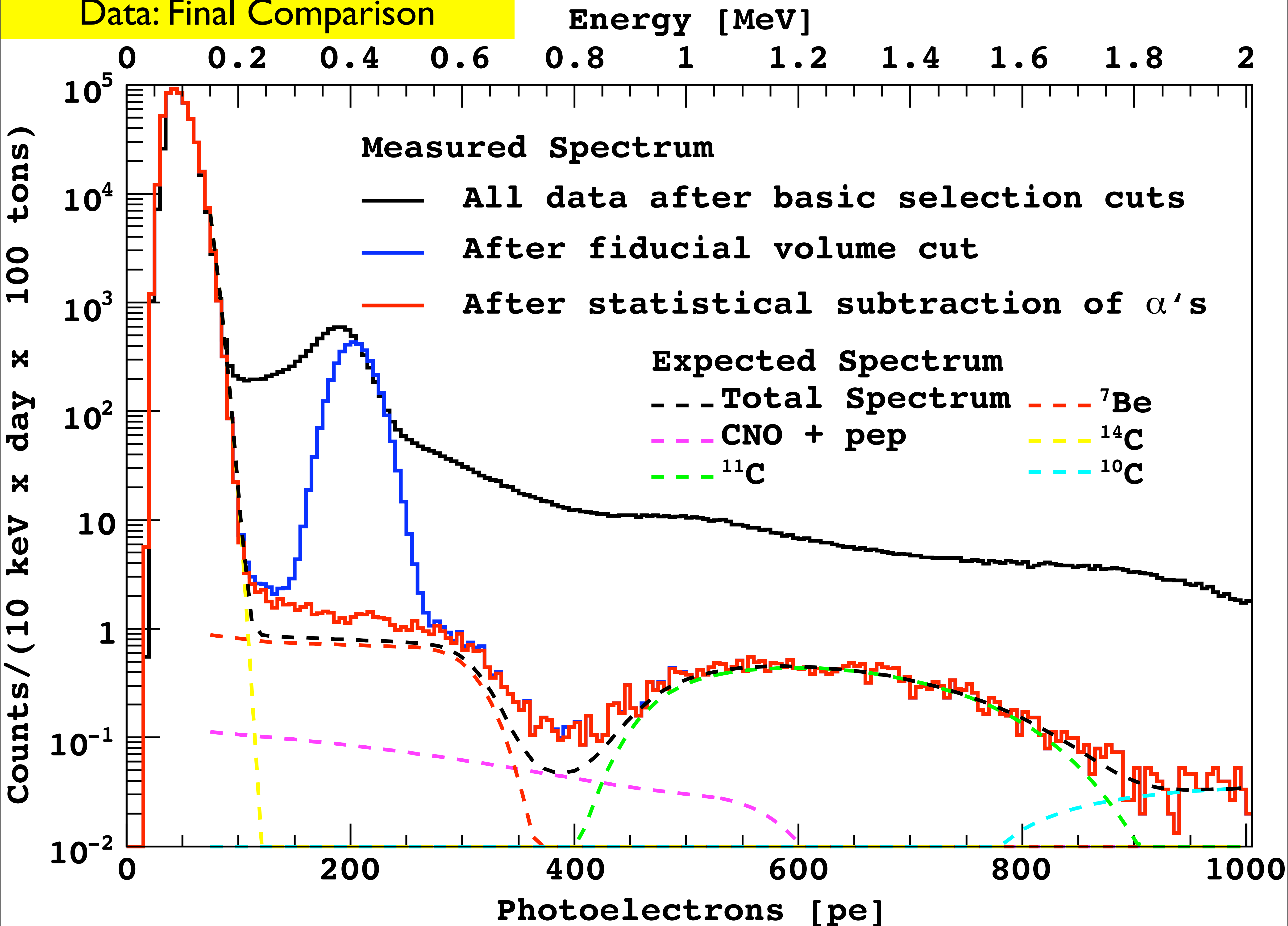
Data: Fiducial Cut (100 tons)



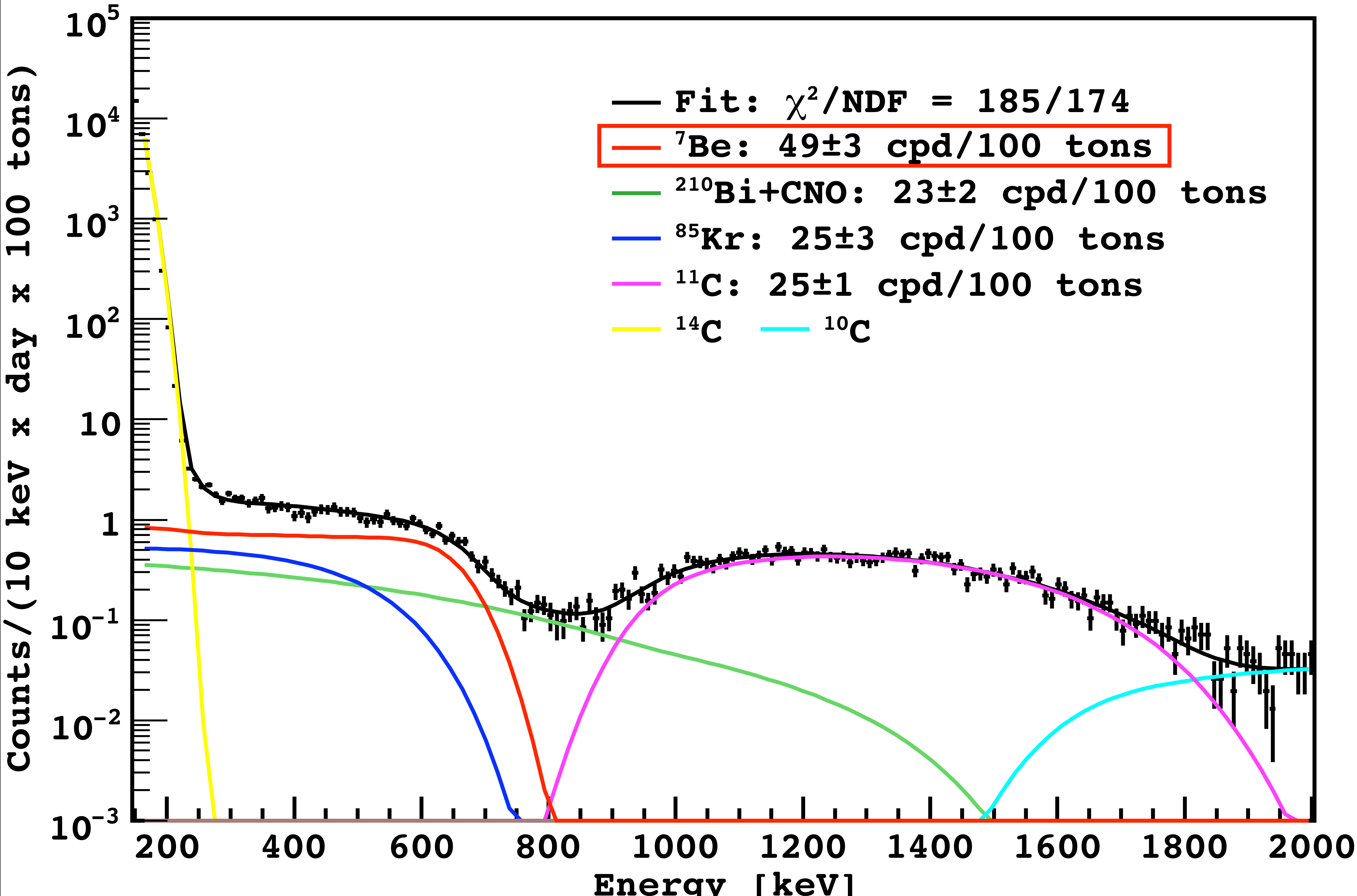
Data: α/β Stat. Subtraction



Data: Final Comparison



New Results: 192 Days



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 ($\sigma \approx 1/T$)

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

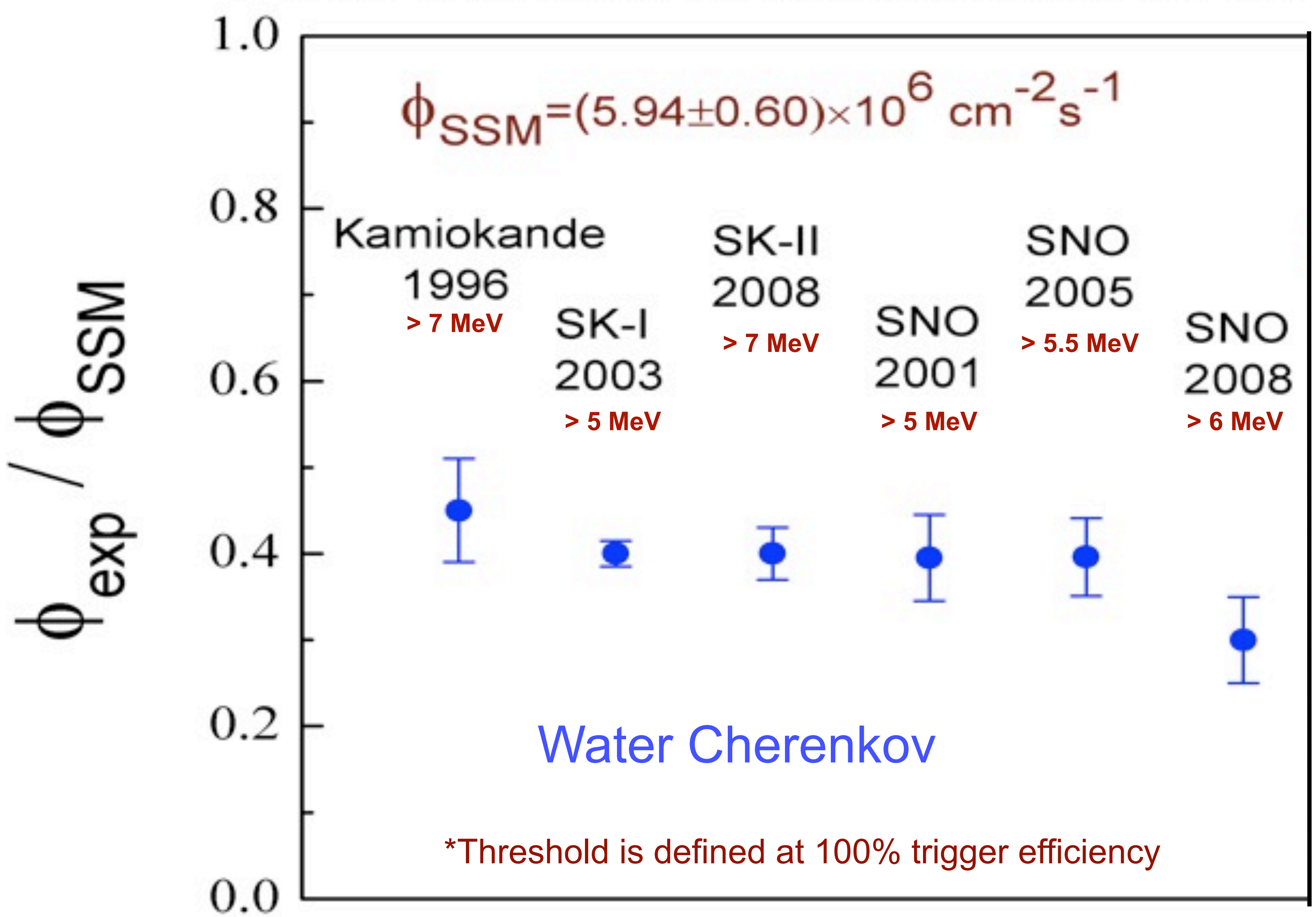
Estimate	Method	90% C.L. $10^{-11}\ \mu_B$
SuperK	^{8}B	<11
Montanino et al.	^{7}Be	<8.4
GEMMA	Reactor	<5.8
Borexino	^{7}Be	<5.4

^{8}B Measurement by ES

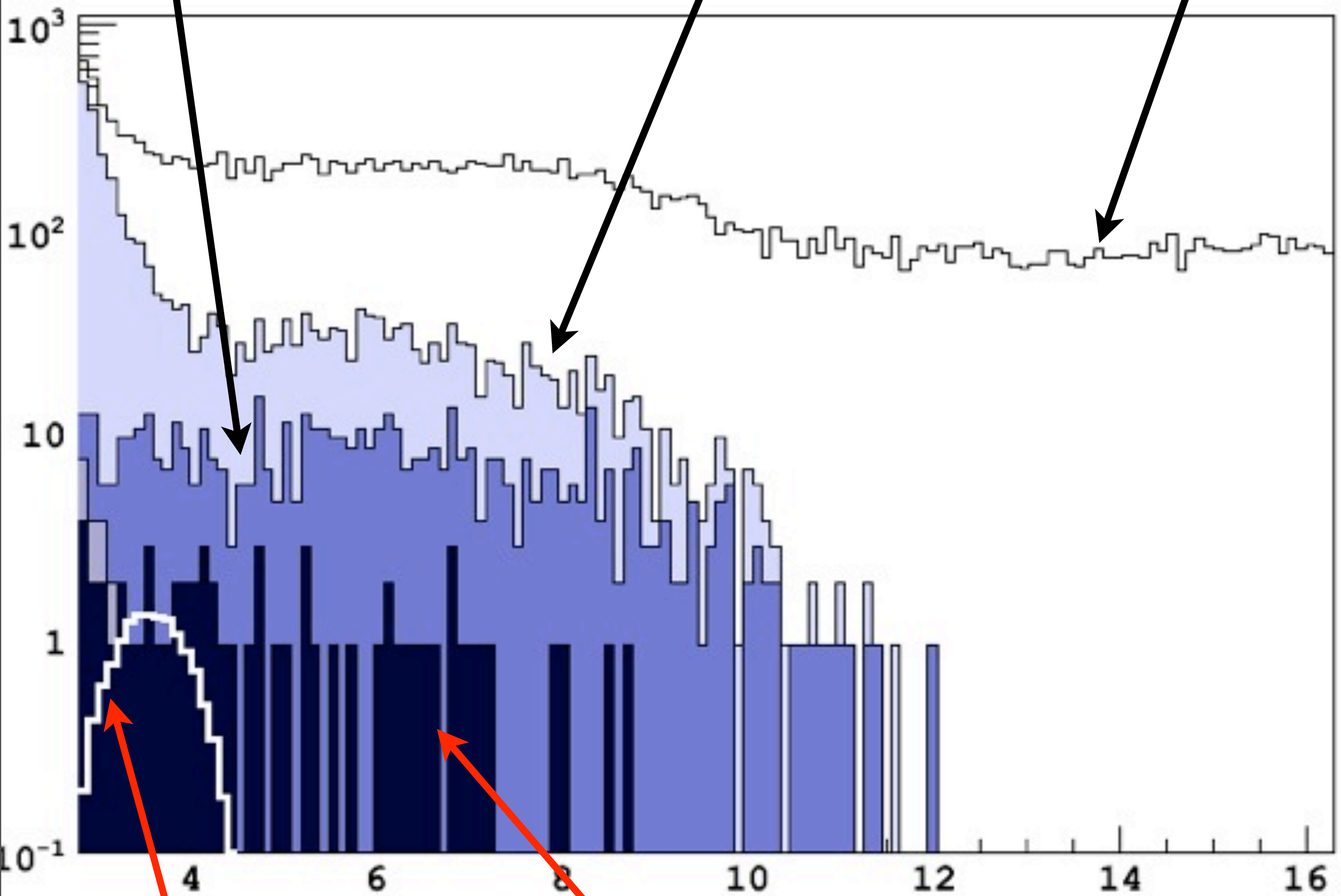
MSW-LMA (arXiv: 0806.2649):
$\Delta m^2 = 7.69\times10{-}5\ eV^2$
$\tan 2\theta = 0.45$

Borexino expected rate:
0.49±0.05 c/d/100 tons

Borexino expected rate above 5 MeV threshold:
0.14±0.01 c/d/100 tons



^{8}B Region in Borexino



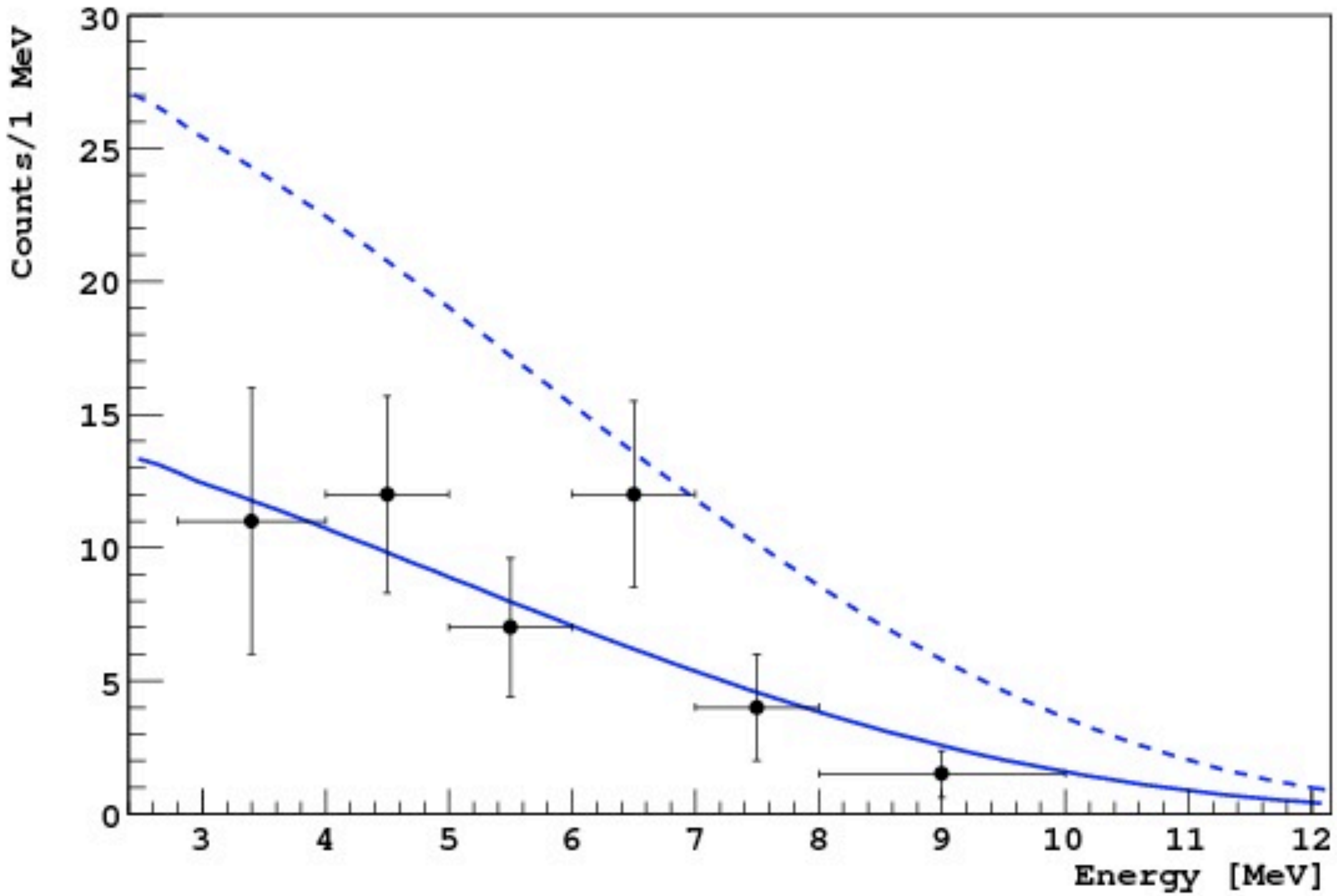
Systematic errors:

6% from the determination of the fiducial mass

3% (2%) uncertainty in the ^{8}B rate above 2.8 MeV (5.0 MeV) from the uncertainty threshold

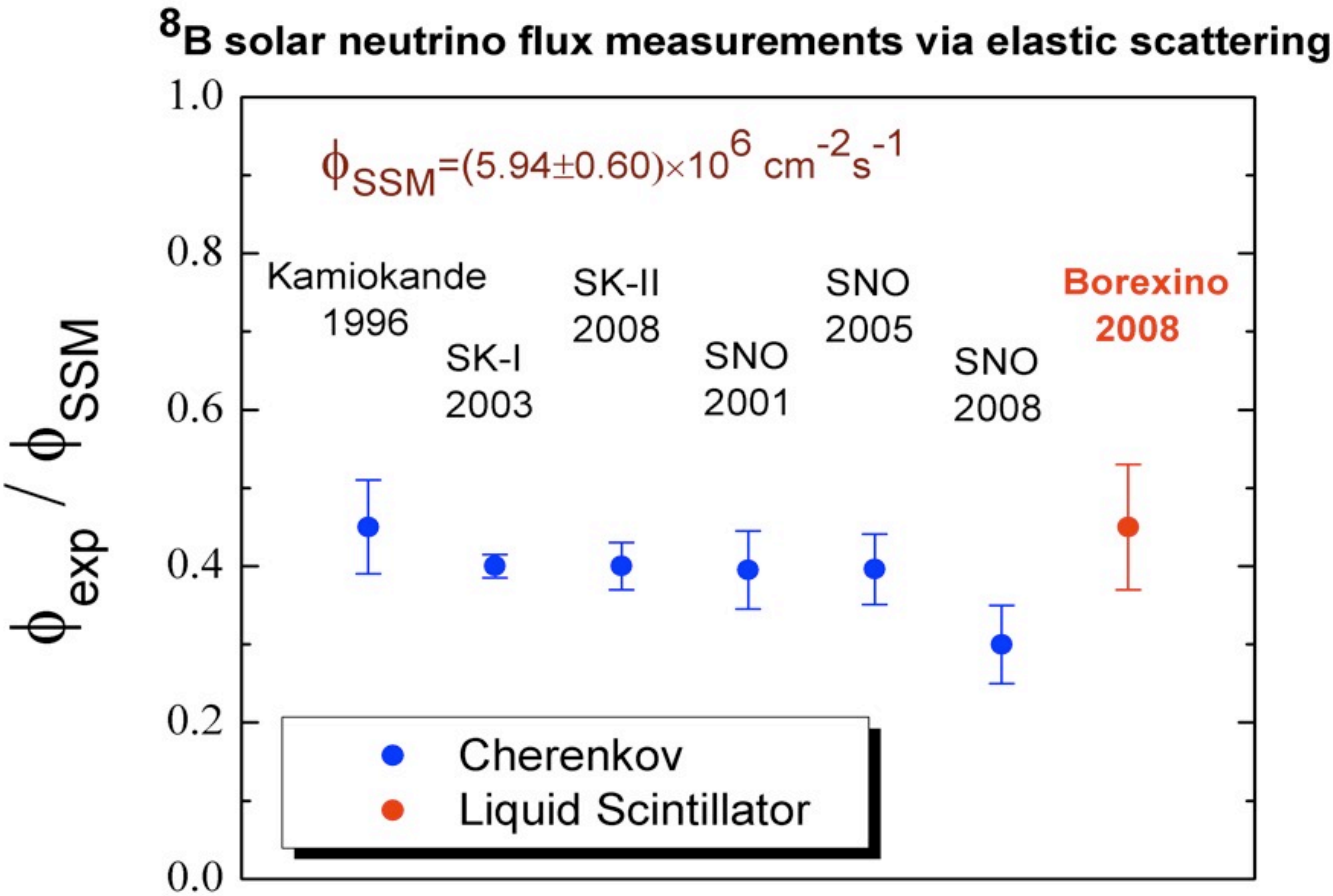
	Counts in 18.8 kton×day	
Threshold	2.8 MeV	5.0 MeV
All Data	20449	14304
After Muon Cut	3363	1135
After Neutron Cut	3280	1114
After FV Cut	567	372
After Cosm. Cut	71	26
After ^{10}C Removal	65	26
After ^{214}Bi Removal	62	26
^{208}Tl Contamination	14 ± 3	0
Measured ^{8}B ν	48 ± 8	26 ± 5
BS07(GS98) ^{8}B ν	50 ± 5	25 ± 3
BS07(AGS05) ^{8}B ν	40 ± 4	20 ± 2

^{8}B Borexino ES Spectrum

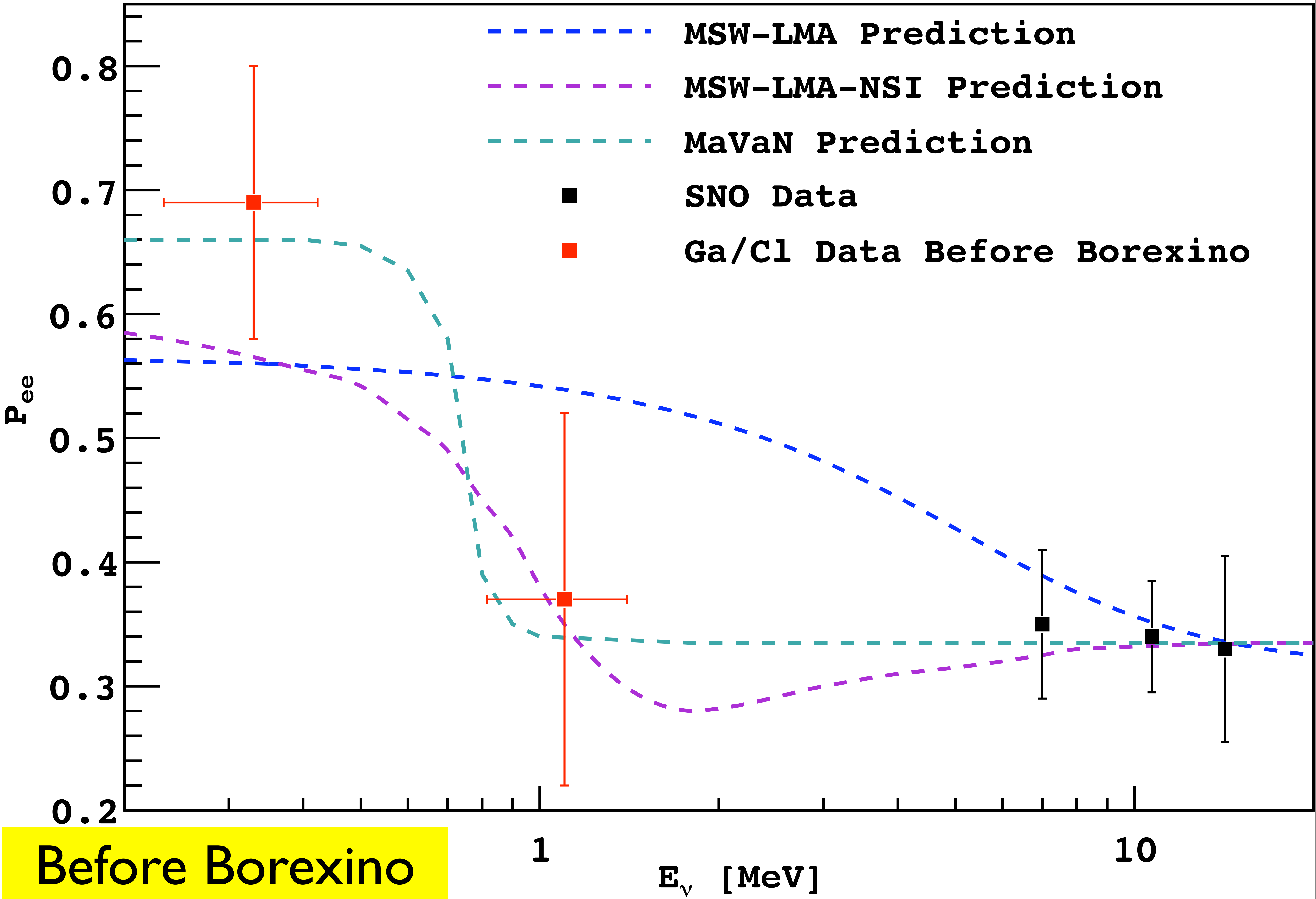


Neutrino oscillation confirmed at 4.2 σ, including the theoretical uncertainty (10%) on the ^{8}B flux from the Standard Solar Model

All ^{8}B ES Measurements



Solar Neutrino Survival Probability



Before Borexino

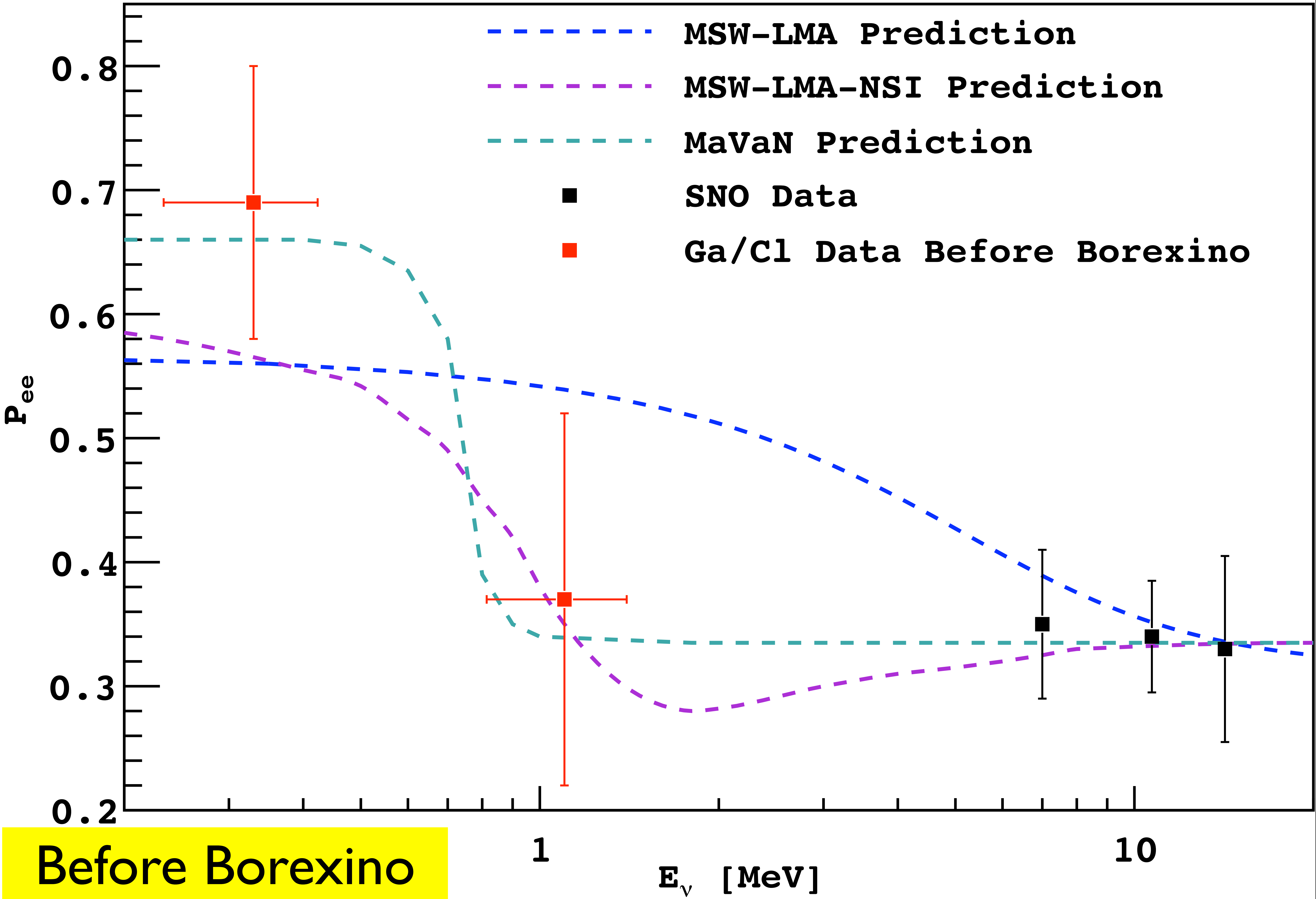
ν_e Survival Probability Global Analysis

- 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

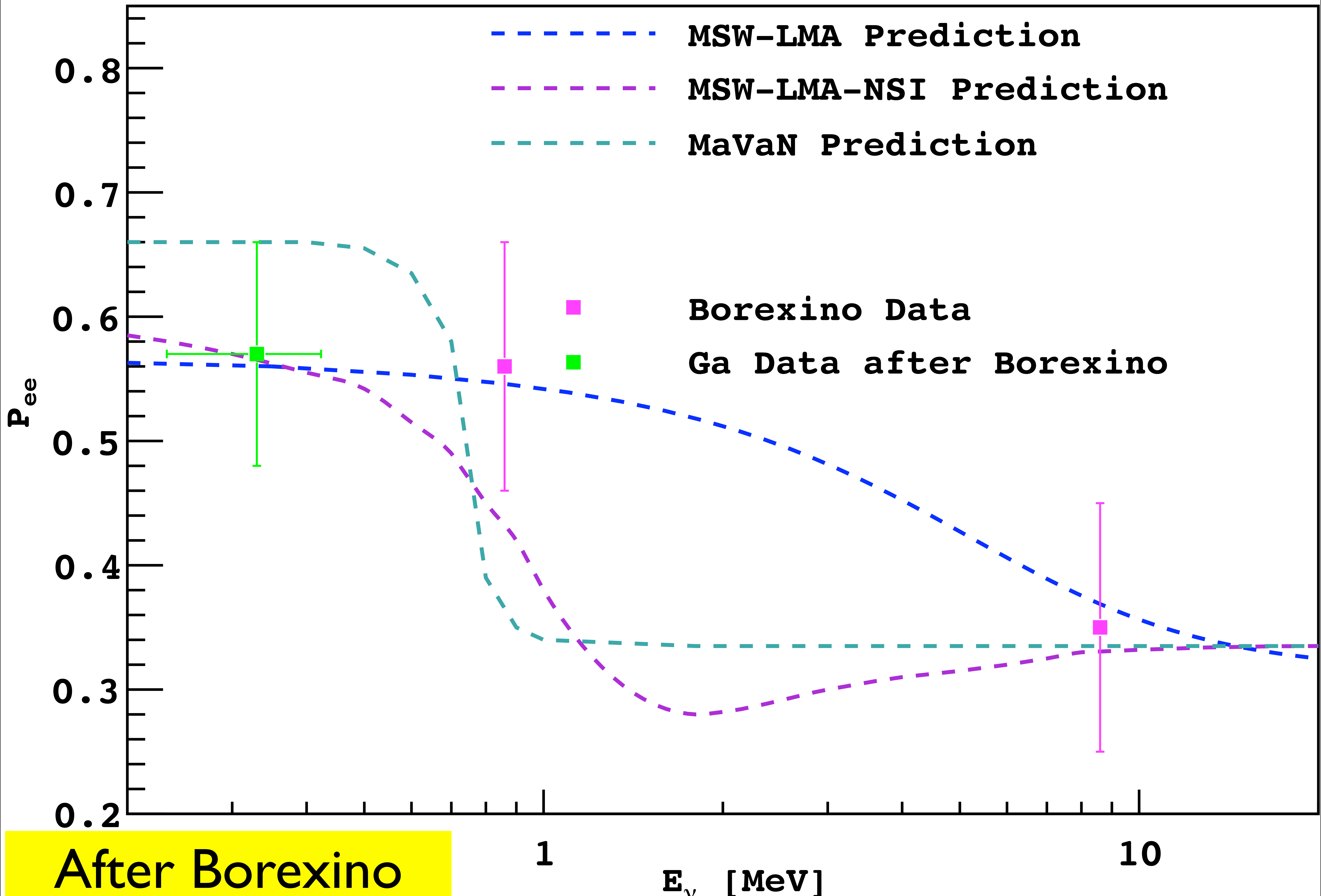
- We determine the survival probability for ^{7}Be and *pp* electron neutrinos ν_e under the assumption of the high-Z BPS07 SSM and using input from all solar experiments (cfr. Barger et al., PRL 88, 011302 (2002))
  - $P_{ee}\left({}^7\mathrm{Be}\right) = 0.56 \pm 0.08$
  - $P_{ee}\left(pp\right) =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

Solar Neutrino Survival Probability



Before Borexino

Solar Neutrino Survival Probability



After Borexino

LMA-MSW Transition

- $P_{ee}\left({}^{7}\mathrm{Be}\right) = 0.56 \pm 0.10$
- $P_{ee}\left({}^{8}\mathrm{B}\right) = 0.35 \pm 0.10$
- Eliminating the common sources of systematic errors:
- $P_{ee}\left({}^{7}\mathrm{Be}\right) / P_{ee}\left({}^{8}\mathrm{B}\right) = 1.60 \pm 0.33$ 1.8σ from 1!
- For the first time we confirm, 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.

^{7}Be Neutrinos Flux

- Note: $f_i = \frac{\Phi_i}{\Phi_i^{\mathrm{SSM}}}$
- 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)
  - $f_{\mathrm{Be}} = 1.03^{+0.24}_{-1.03}$
- Assuming the high-Z BPS07 SSM and the constraint on solar luminosity, we obtain:
  - $f_{\mathrm{Be}} = 1.02 \pm 0.10$

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

pp and CNO Neutrinos Fluxes

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

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

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

f_i Ratio between measured and predicted flux

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

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

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

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

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

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

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

pp and CNO Neutrinos Fluxes

Without Luminosity Constraint:

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

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

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

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

With Luminosity Constraint:

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

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

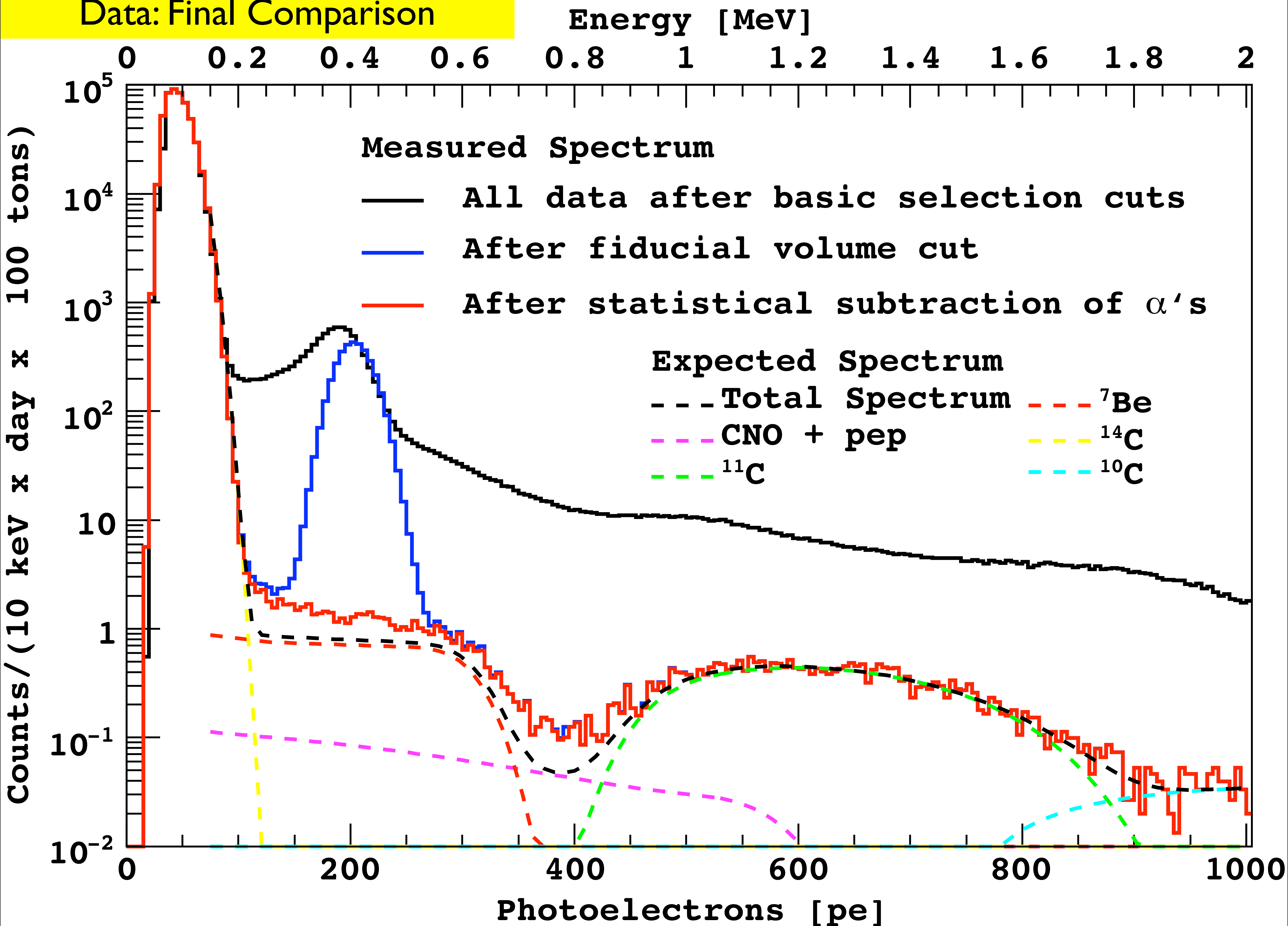
J.N. Bahcall and C. Pena-Garay, JHEP 11, 004 (2003)

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

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

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

Data: Final Comparison



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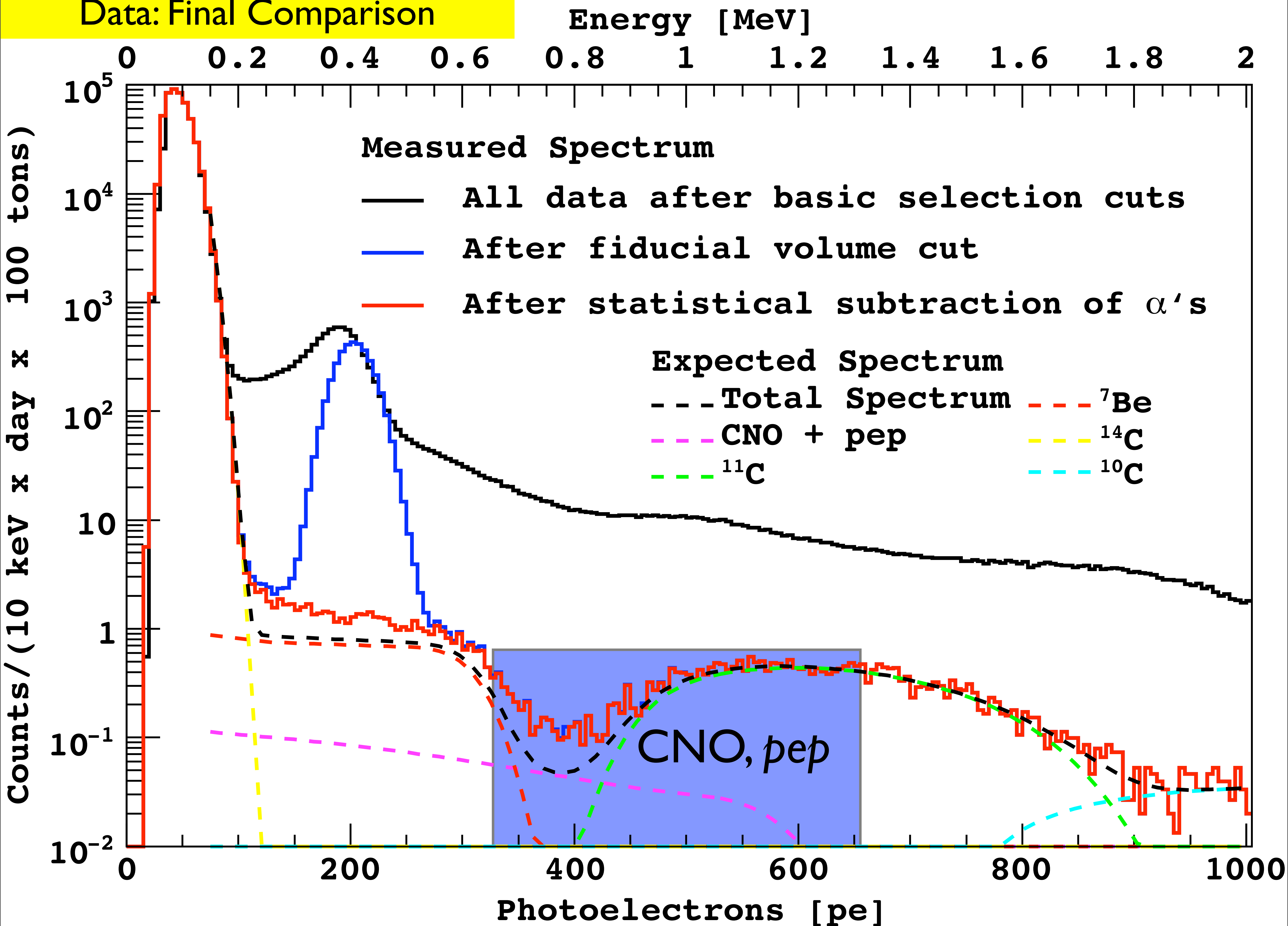

Removal of ^{11}C Background

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

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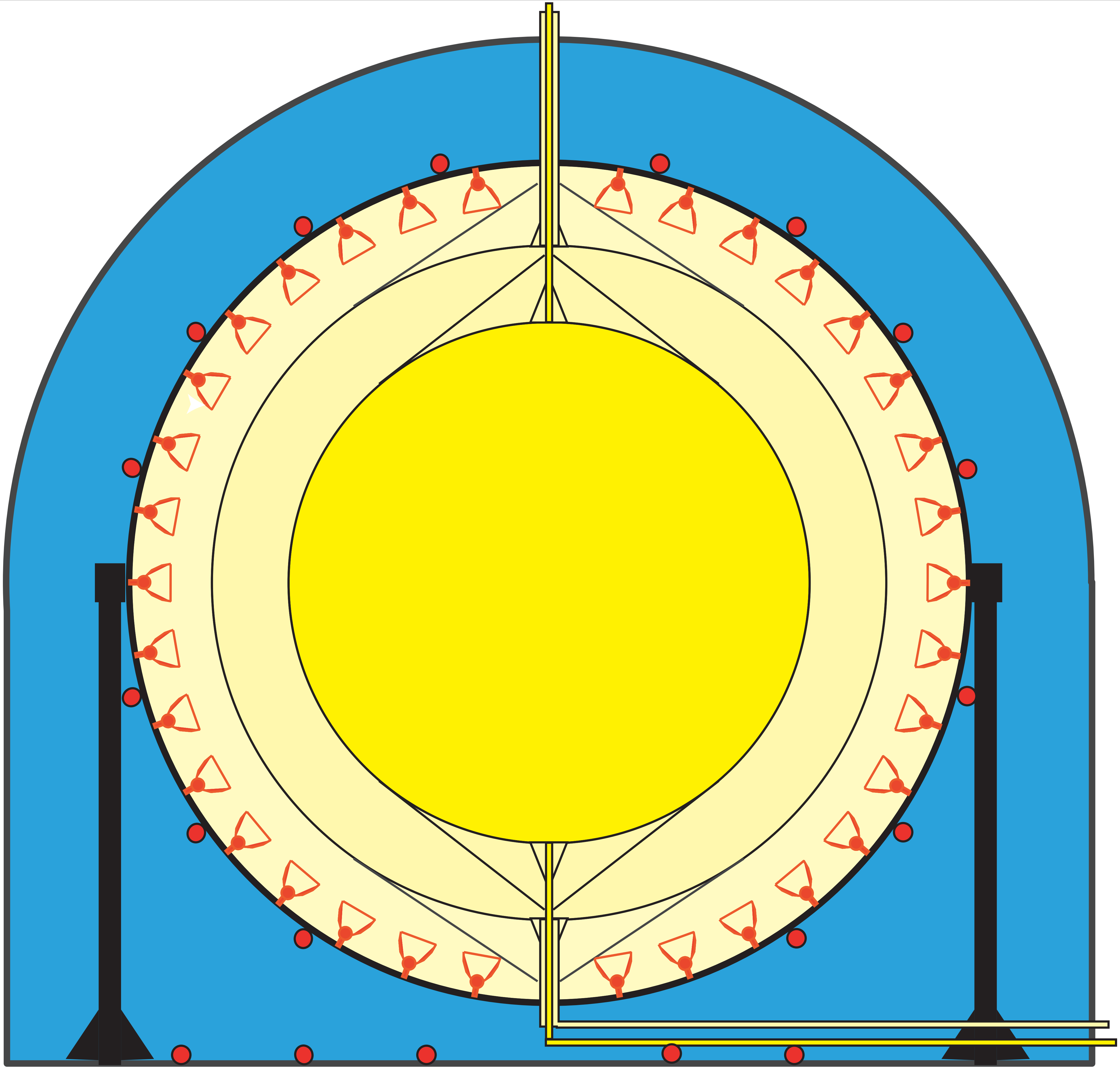
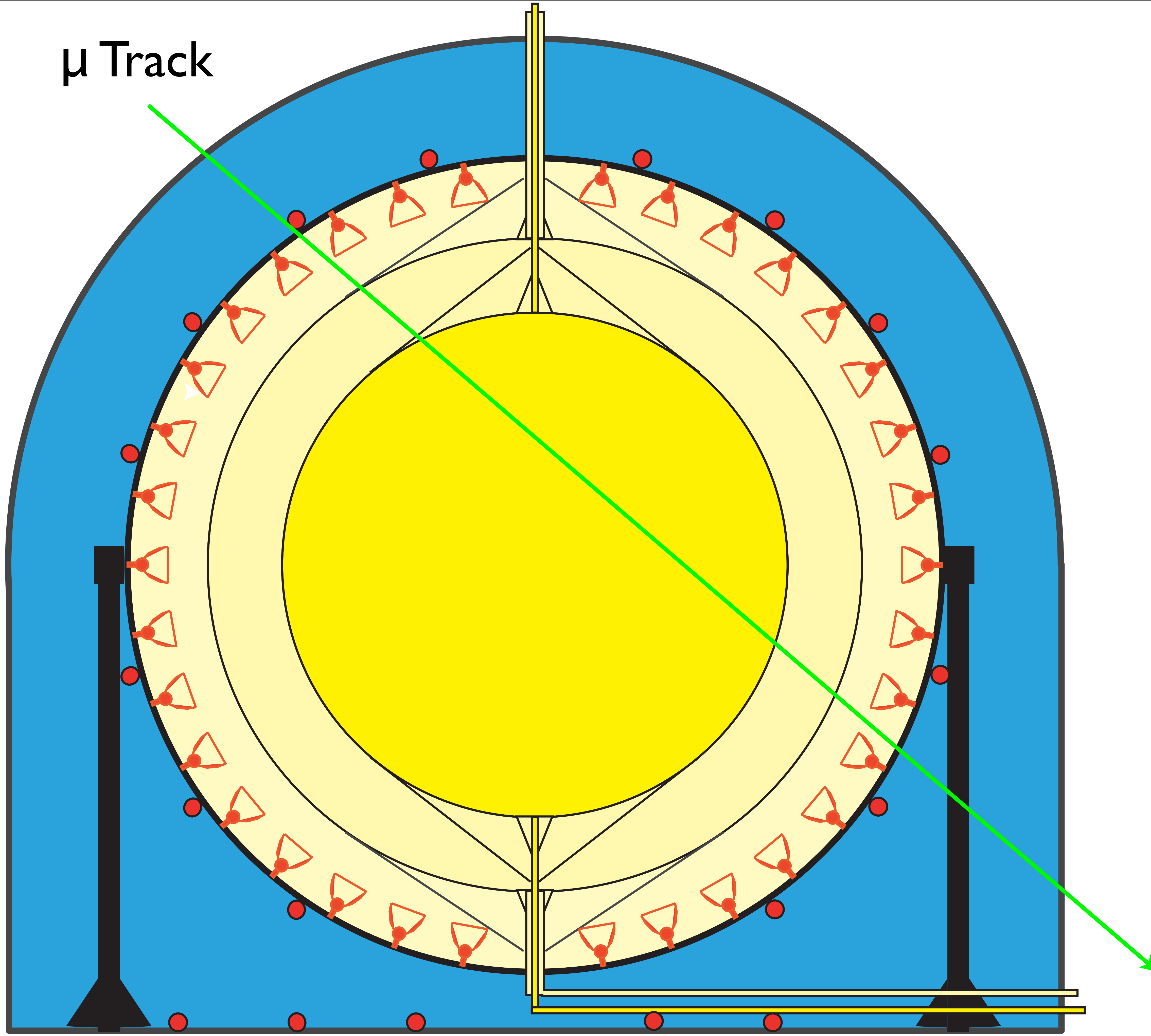
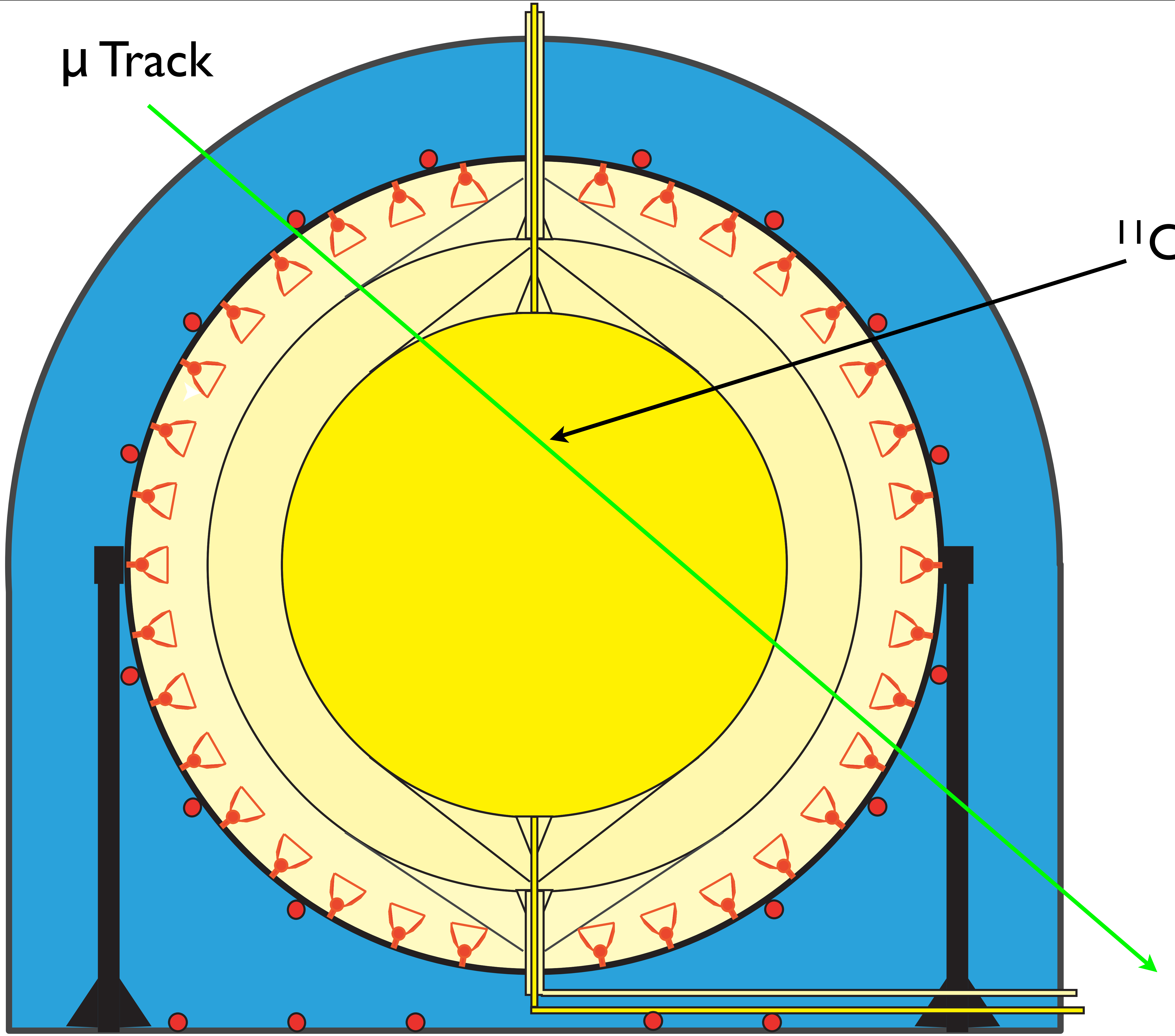
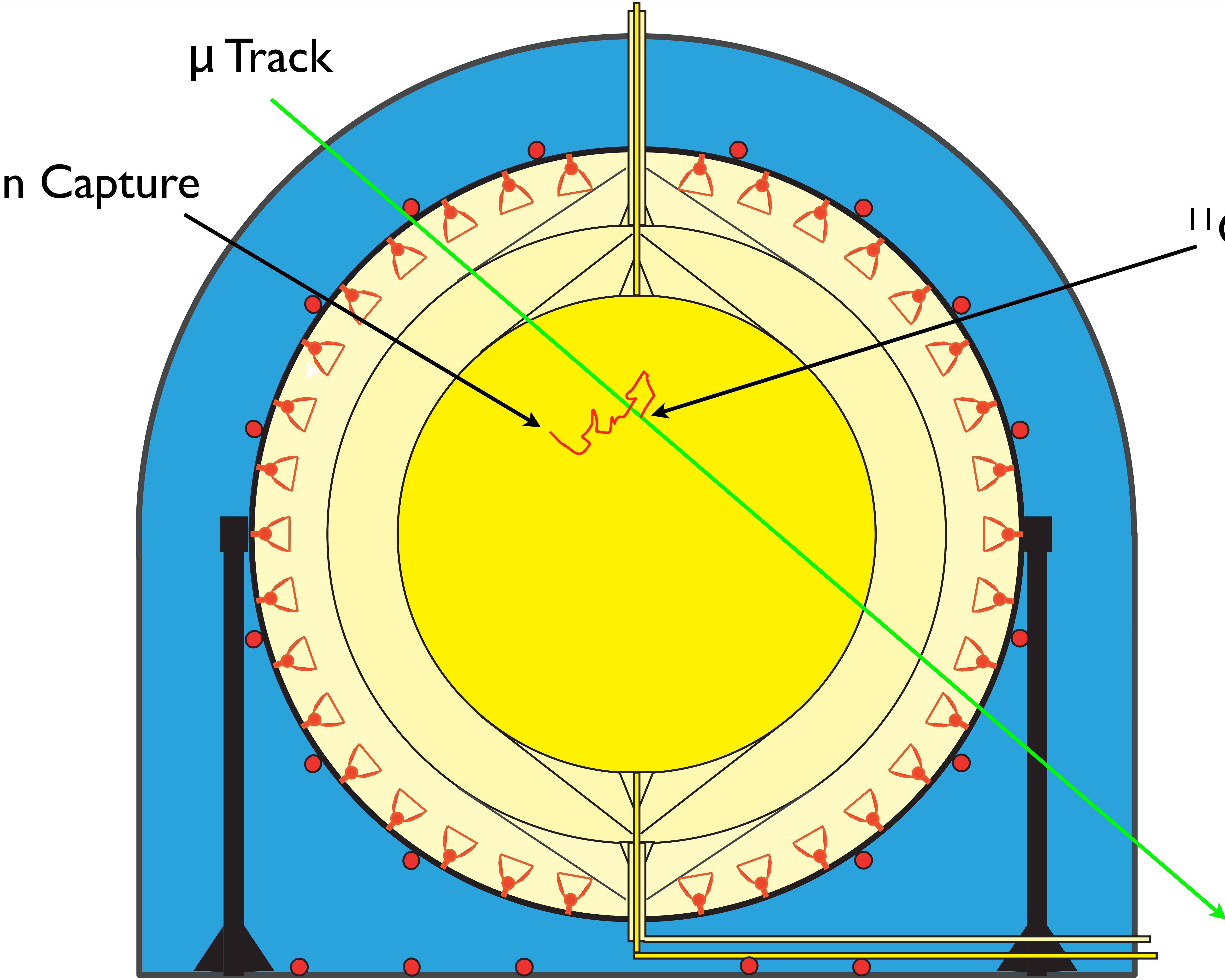
Laura Cadonati
Physics Department, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

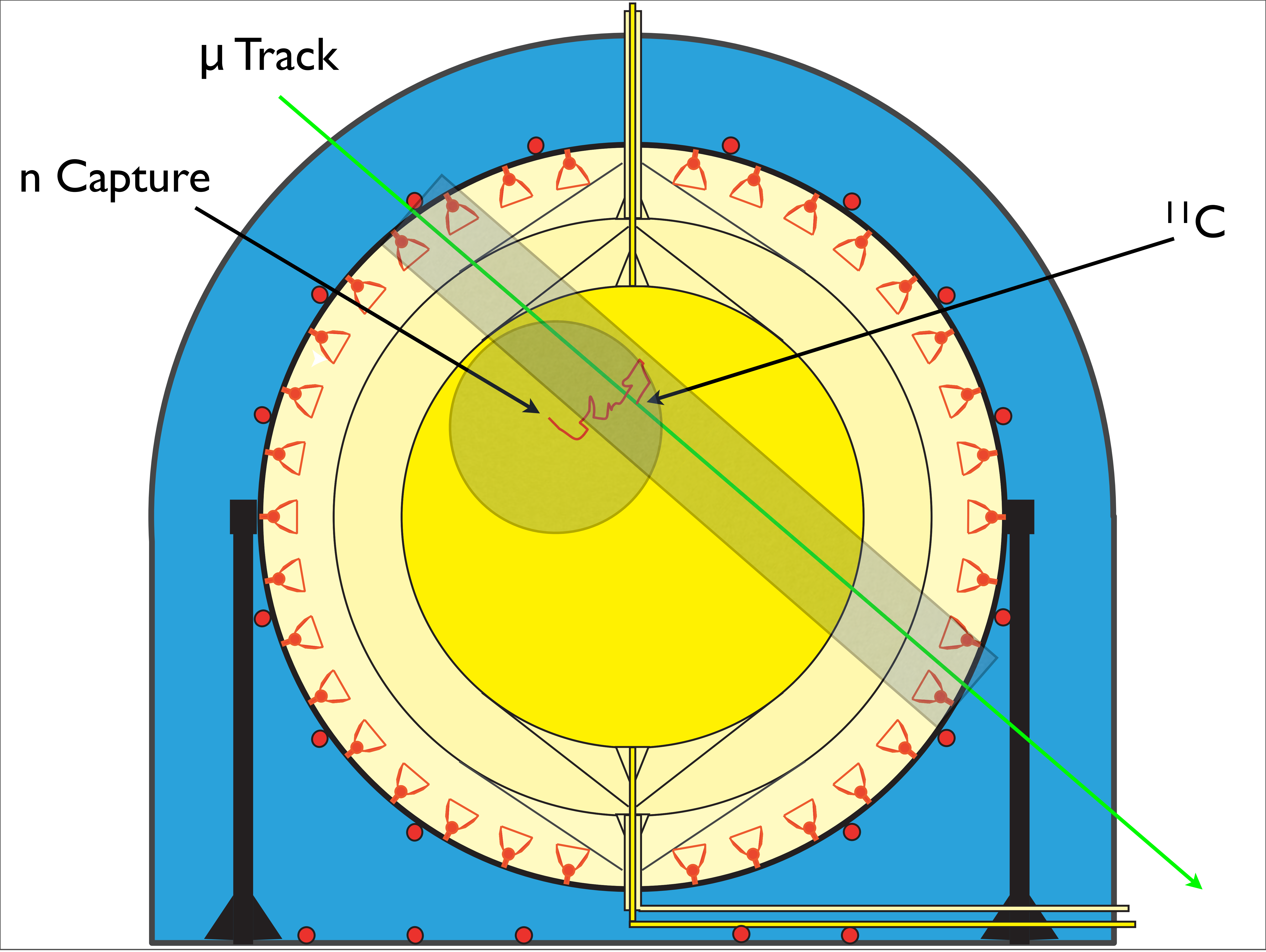
E_μ [GeV]	100	190	285	320	350
Process	Rate $[10^{-4}/\mu/m]$				
$^{12}C(p,p+n)^{11}C$	1.8	3.2	4.9	5.5	5.6
$^{12}C(p,d)^{11}C$	0.2	0.4	0.5	0.6	0.6
$^{12}C(\gamma,n)^{11}C$	19.3	26.3	33.3	35.6	37.4
$^{12}C(n,2n)^{11}C$	2.6	4.7	7.0	8.0	8.2
$^{12}C(\pi^+,\pi+N)^{11}C$	1.0	1.8	2.8	3.2	3.3
$^{12}C(\pi^-,\pi^-+n)^{11}C$	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




μ Track

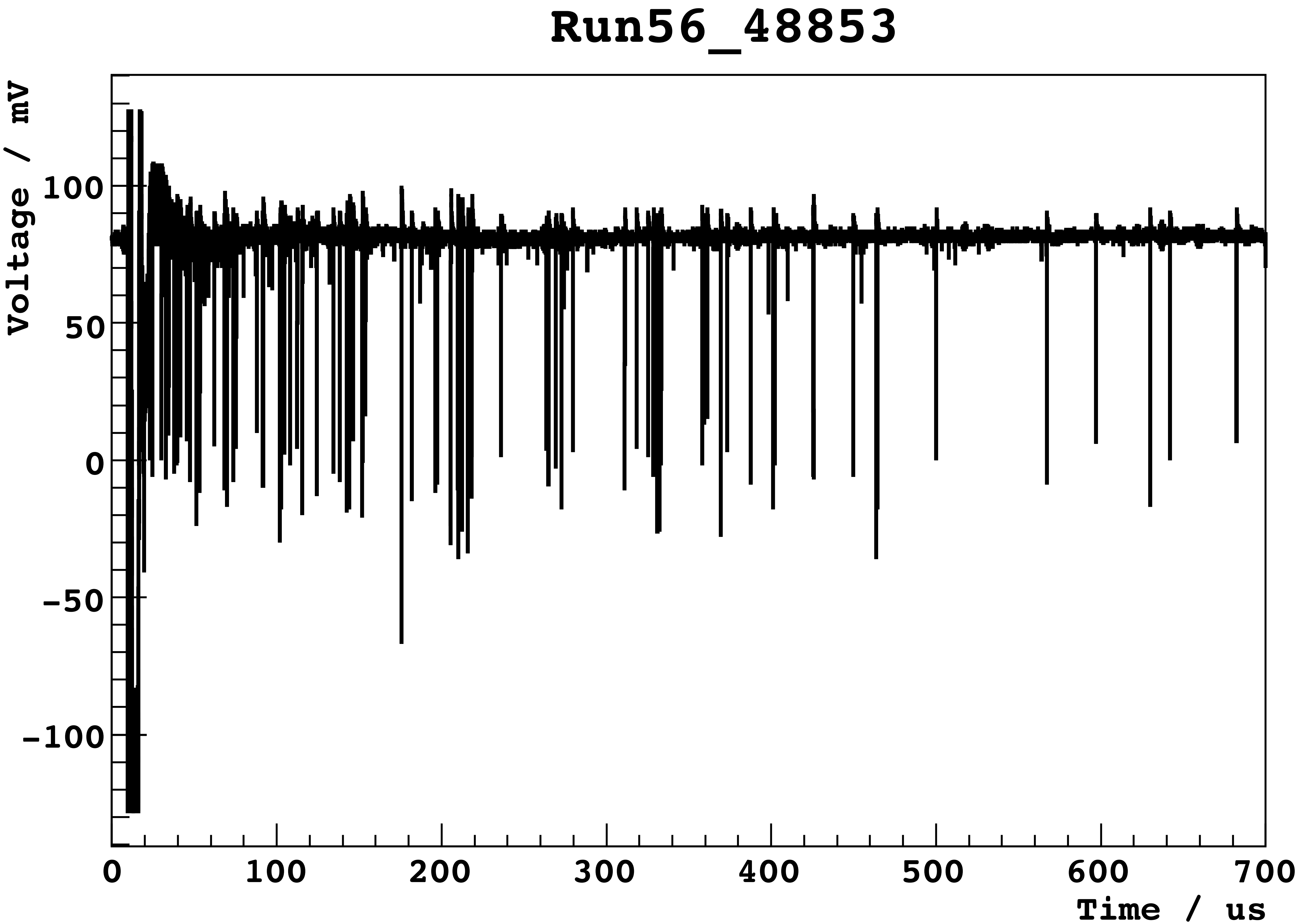

μ Track
^{11}C


μ Track
n Capture
^{11}C



μ Track
n Capture
^{11}C

Improved Electronics



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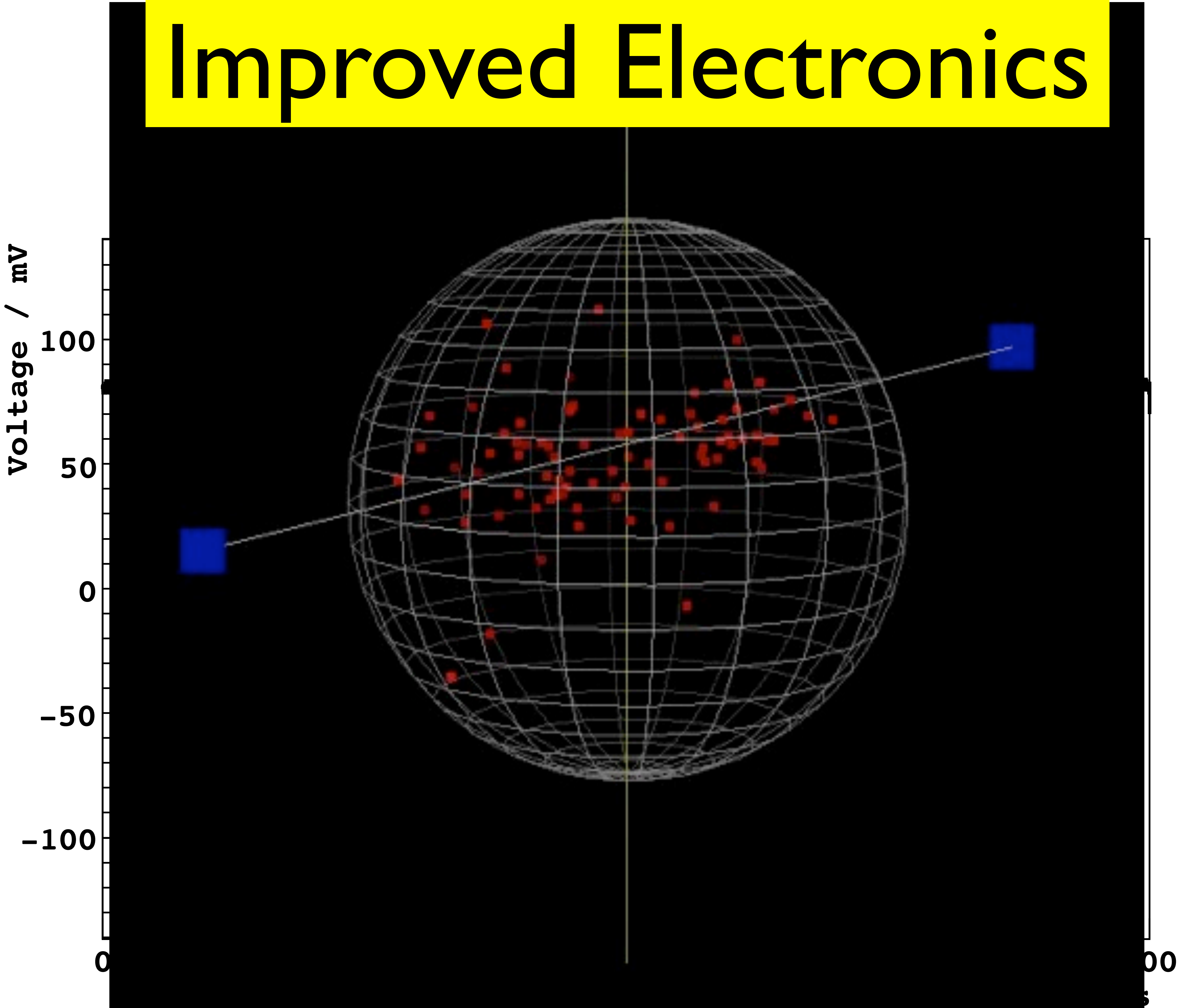
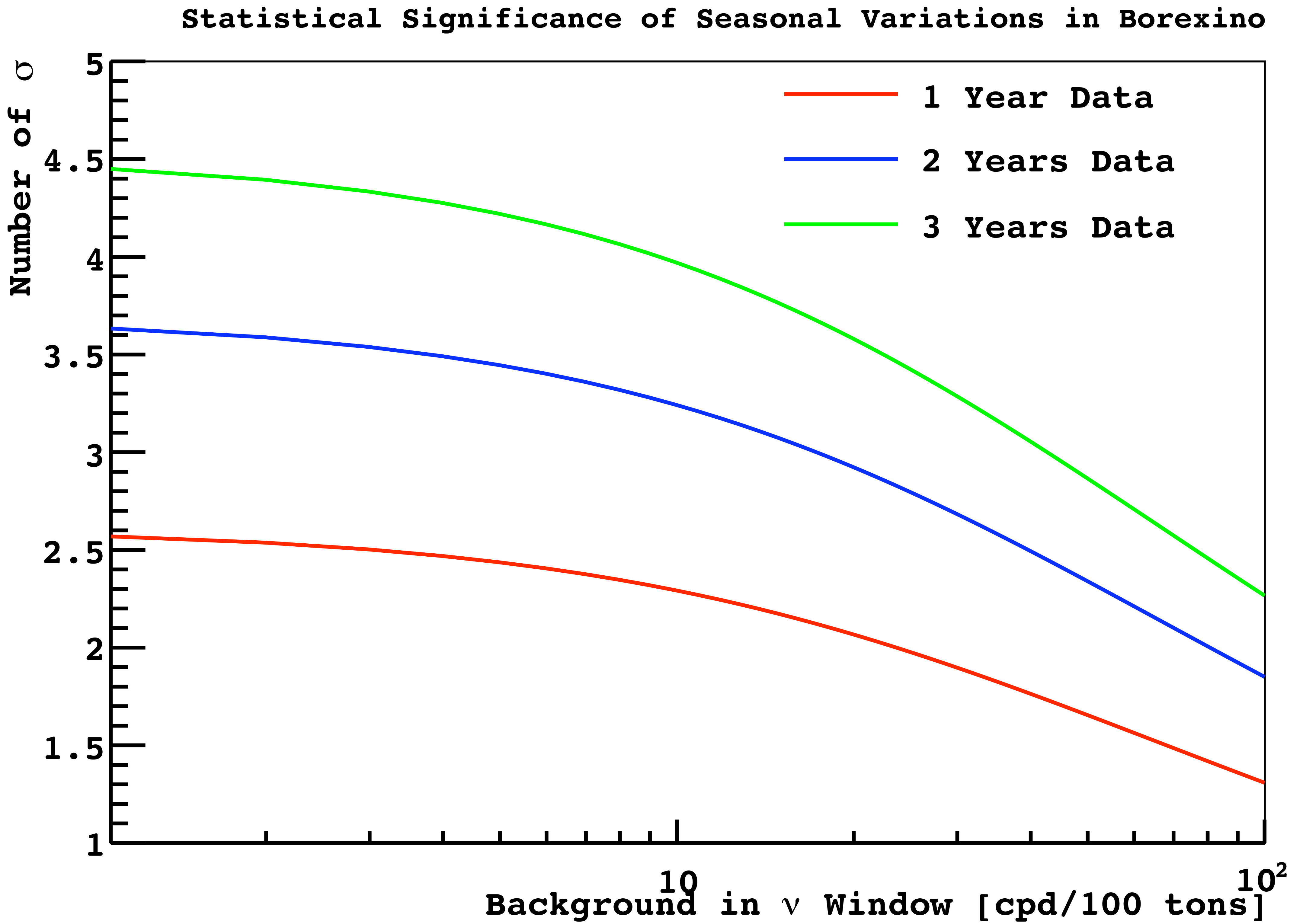


Confirm Solar Origin of ^{7}Be ν: Seasonal Oscillations

Expect 7% difference in flux between aphelion and perihelion, due to eccentricity of Earth's orbit



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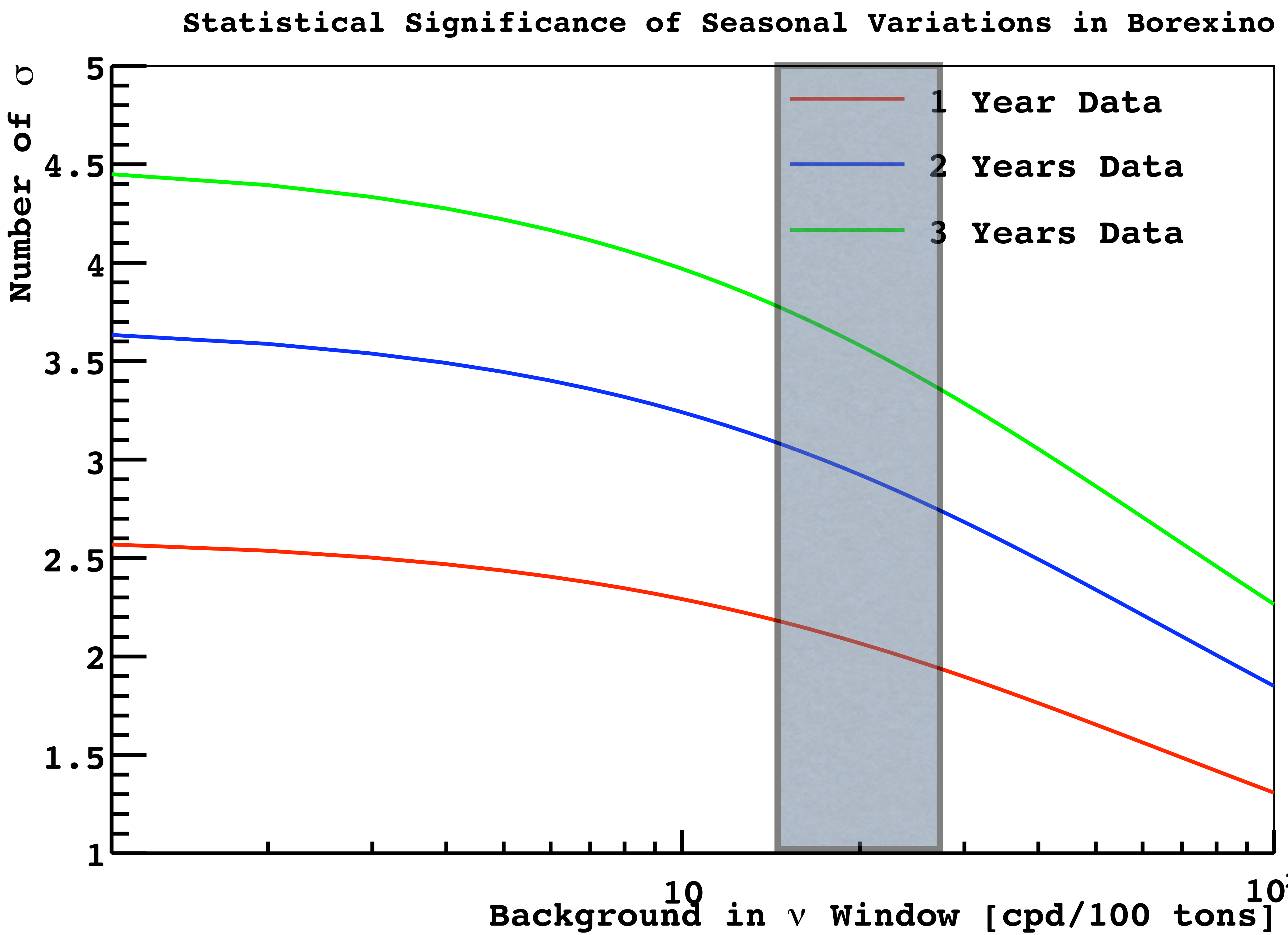

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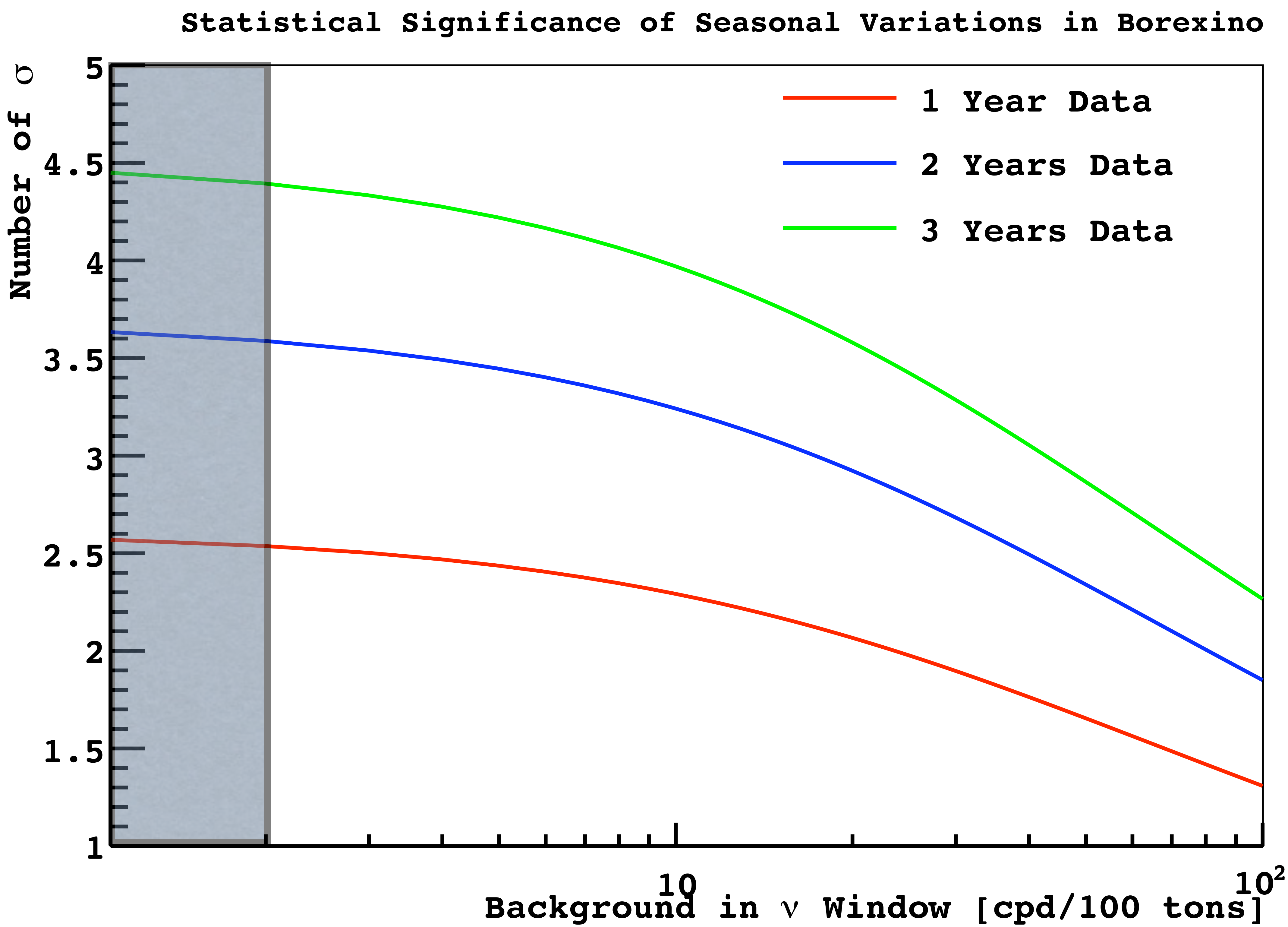


AntiNeutrinos

Excellent Coincidence Tagging!

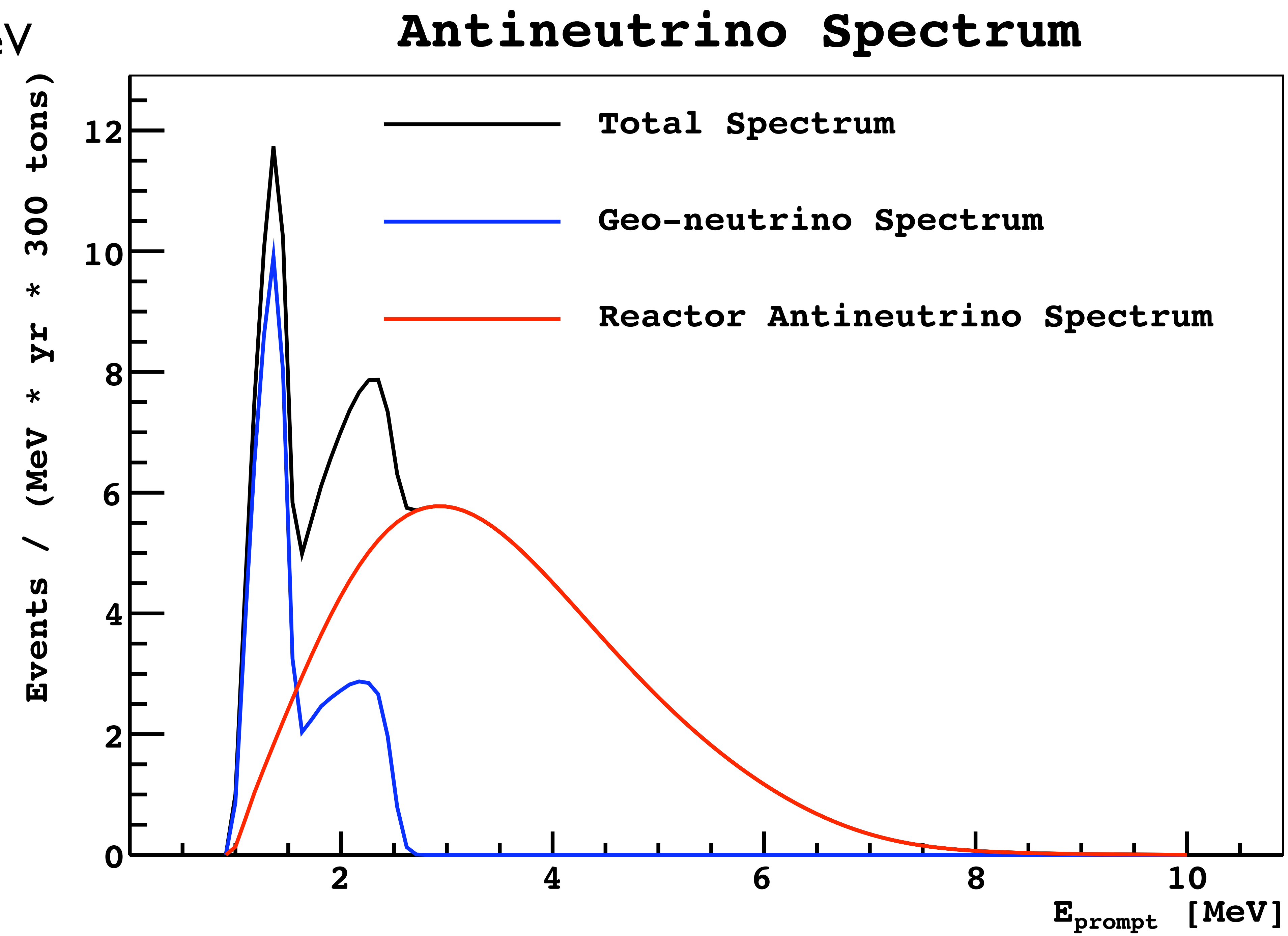
$\bar{\nu} + p \rightarrow n + e^+$

- Prompt e^+ signal >1 MeV
- Delayed (300 μs) n capture signal 2.2 MeV

Possibility to study antineutrinos from U and Th decay in Earth's crust!

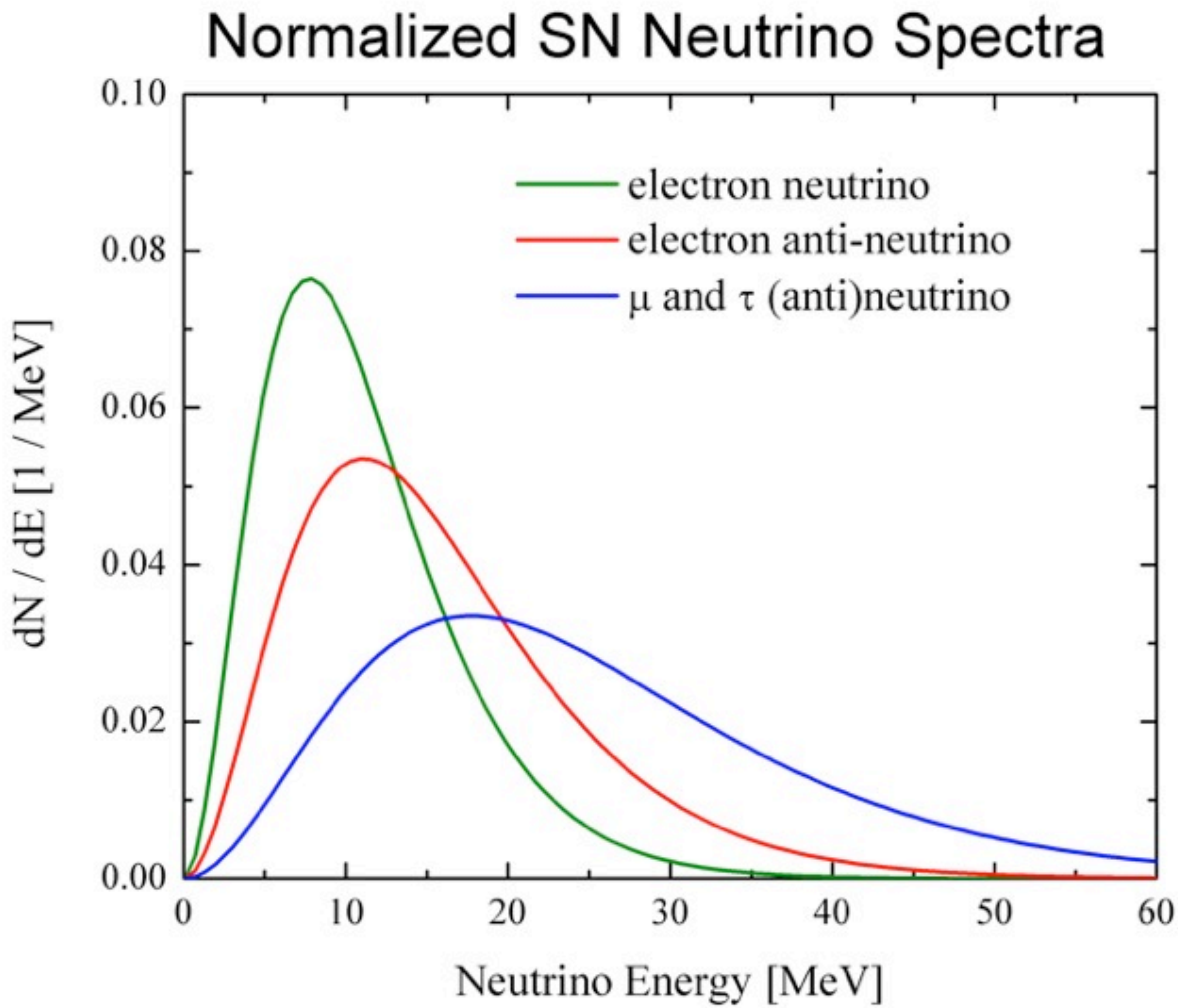
7 counts per year

Reactor Background 20 counts per year



Supernovae Neutrinos

Detection Channel	Expected Events [SN @10 kpc]
Inverse Beta Decay (E_ν>1.8 MeV)	79
ν-p Elastic Scattering (E_ν>0.25 MeV)	55
$^{12}C(\nu,\nu)^{12}C^*$ (E_γ=15.1 MeV)	17



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
  - One measurement just reported for ^{8}B high-energy neutrinos
  - Best limits for *pp* and CNO neutrinos, combining information from all solar and reactor experiments
  - Opportunities to tackle *pep* and CNO neutrinos
- Observation of vacuum-matter transition in a single experiment! Region sensitive to possible new physics, to be probed with very high sensitivity in the years to come
- Borexino will run comprehensive program for study of antineutrinos (from Earth, Sun, and Reactors) and will serve as powerful observatory for neutrinos from Supernovae explosions

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 Fluid Operations

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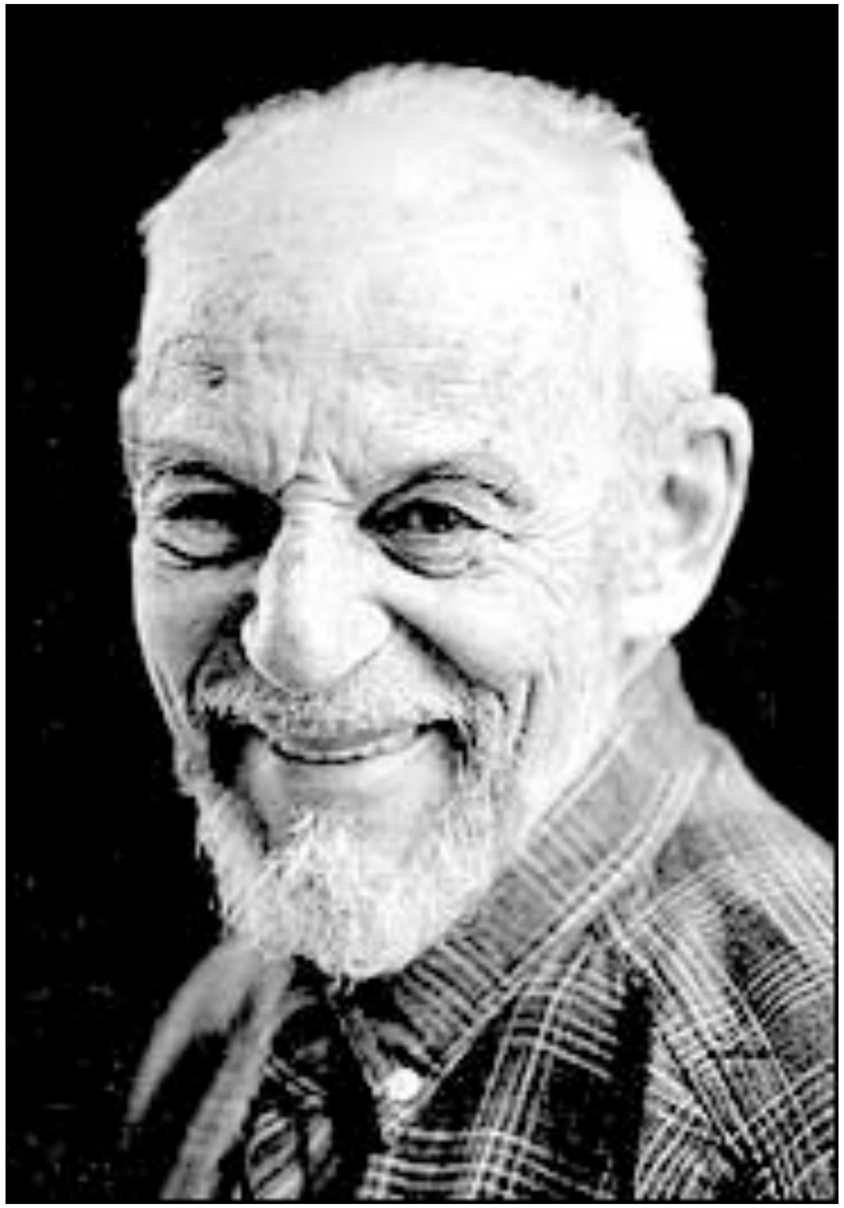
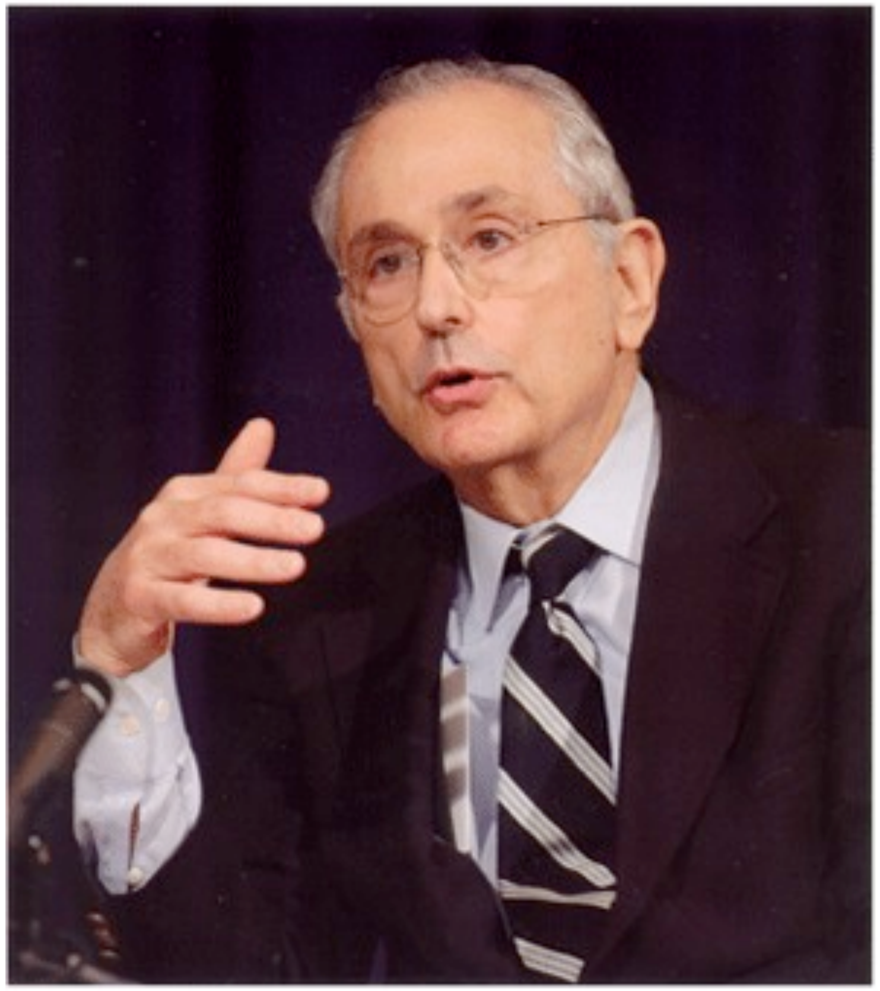


Martin Deutsch
January 29, 1917
August 16, 2002



John Bahcall
December 30, 1934
August 17, 2005

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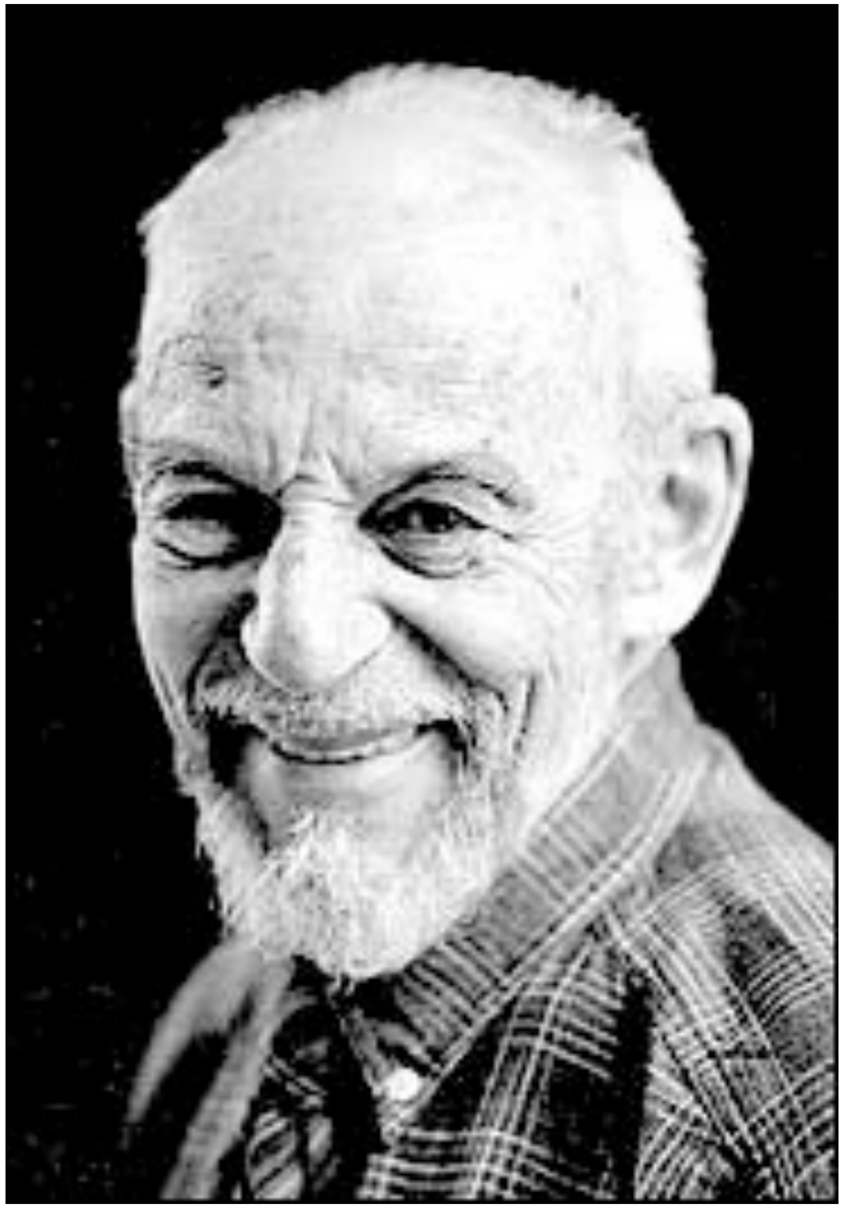

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The End