Recent results from Borexino

Barbara Caccianiga-INFN Milano
on behalf of the Borexino collaboration

50th Rencontres de Moriond- La Thuile, March 14th 21st 2015

pp-neutrino observation in Borexino

ARTICLE

doi:10.1038/nature13702

Neutrinos from the primary proton–proton fusion process in the Sun

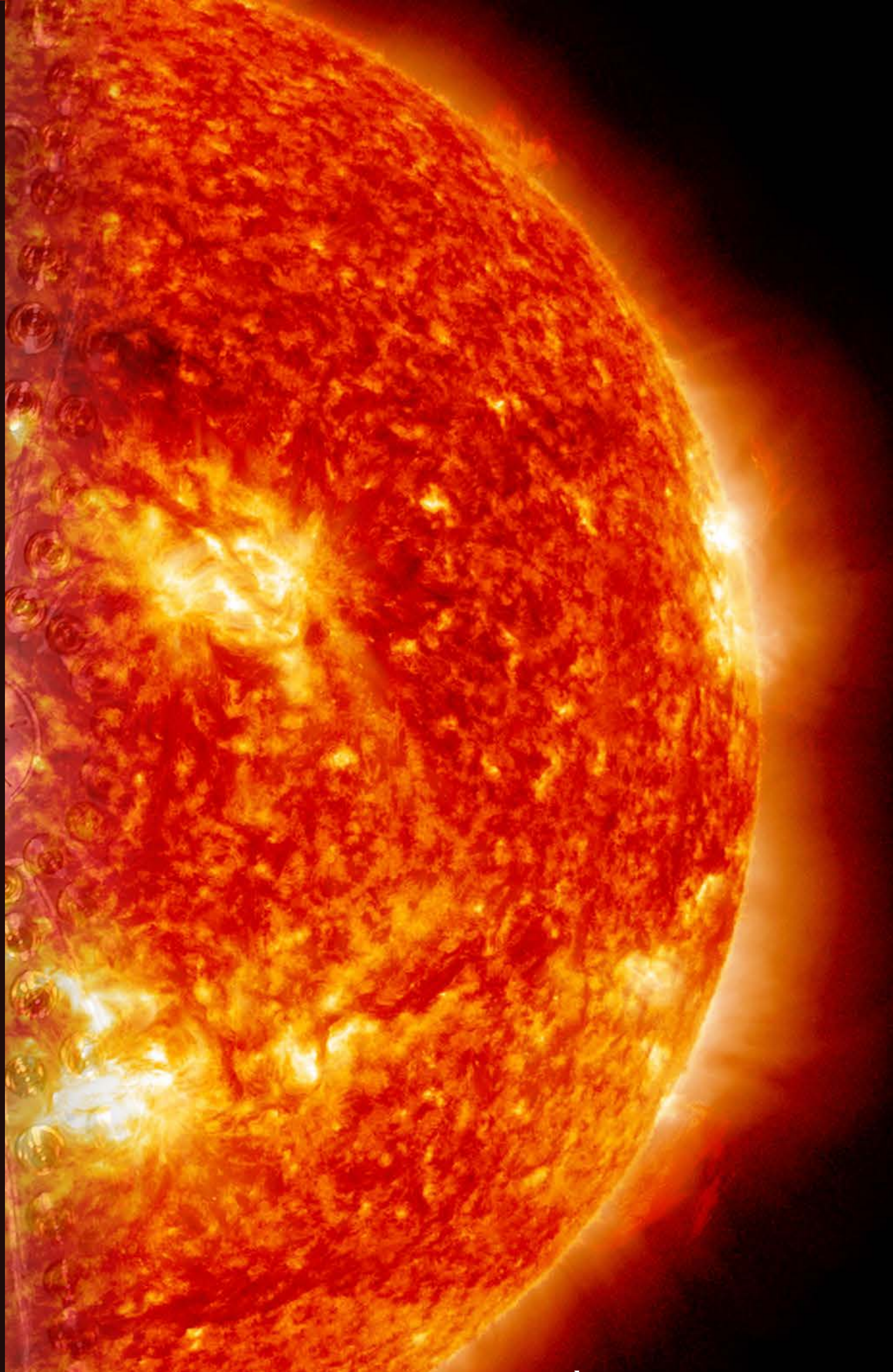
Borexino Collaboration*

In the core of the Sun, energy is released through sequences of nuclear reactions that convert hydrogen into helium. The primary reaction is thought to be the fusion of two protons with the emission of a low-energy neutrino. These so-called *pp* neutrinos constitute nearly the entirety of the solar neutrino flux, vastly outnumbering those emitted in the reactions that follow. Although solar neutrinos from secondary processes have been observed, proving the n
Sun's energy and contributing to the discovery of neutrino oscillations, those from proton–proton f
eluded direct detection. Here we report spectral observations of *pp* neutrinos, demonstrating that a
the power of the Sun, 3.84×10^{33} ergs per second, is generated by the proton–proton fusion proces

physicsworld TOP 10 BREAKTHROUGH 2014

Published on Nature 512, 383-386 (2014)

Our Sun



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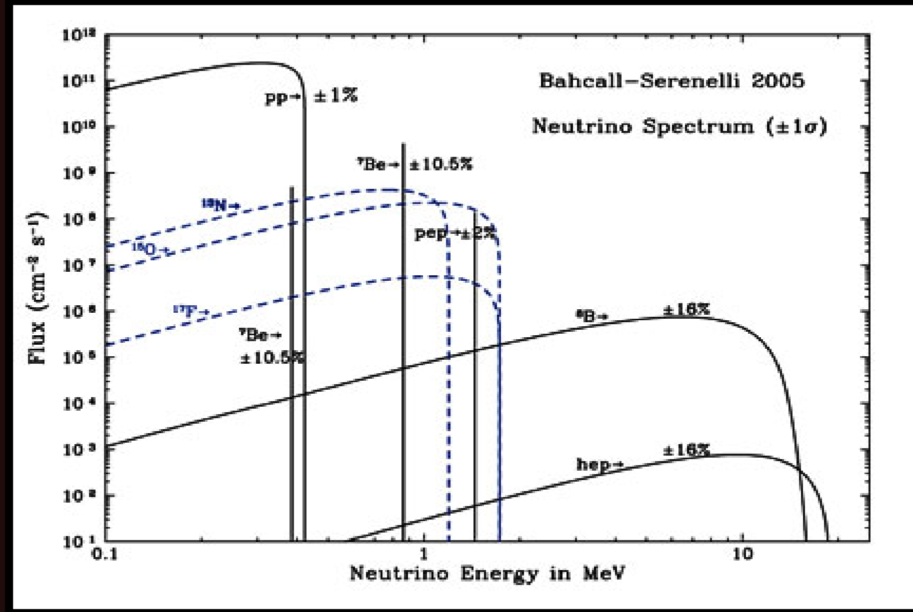
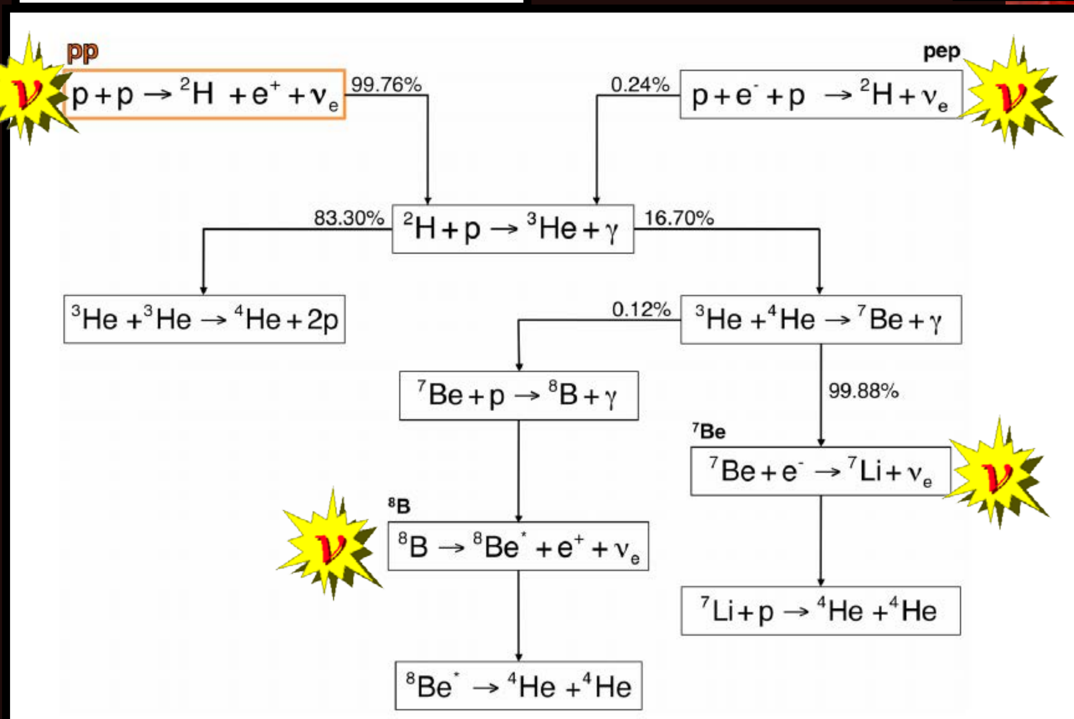
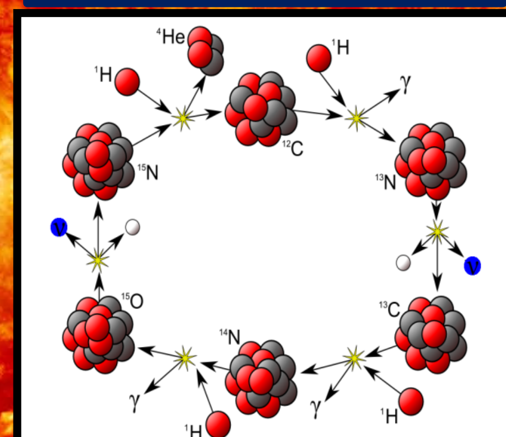


pp CYCLE: ~99% of the sun energy



CNO CYCLE: <1% of the sun energy



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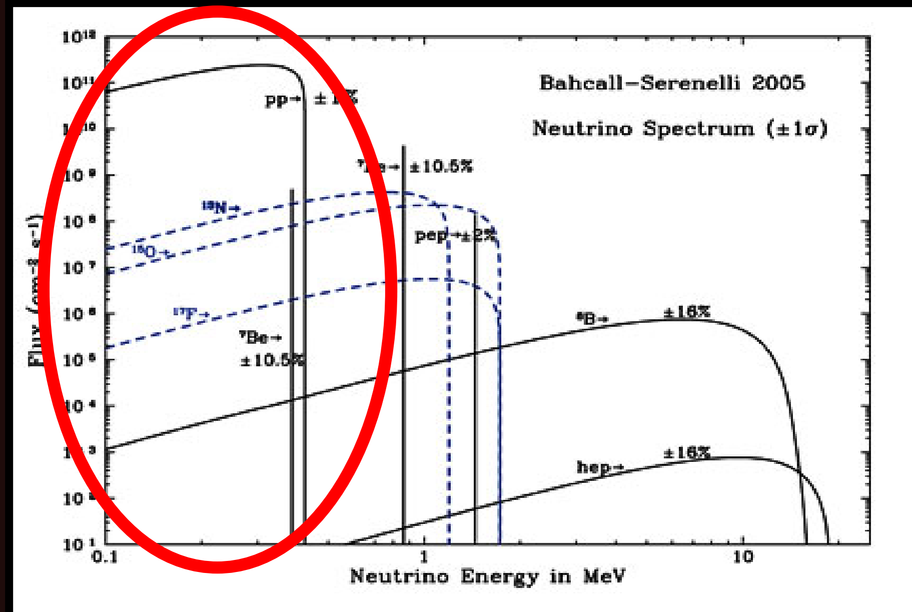

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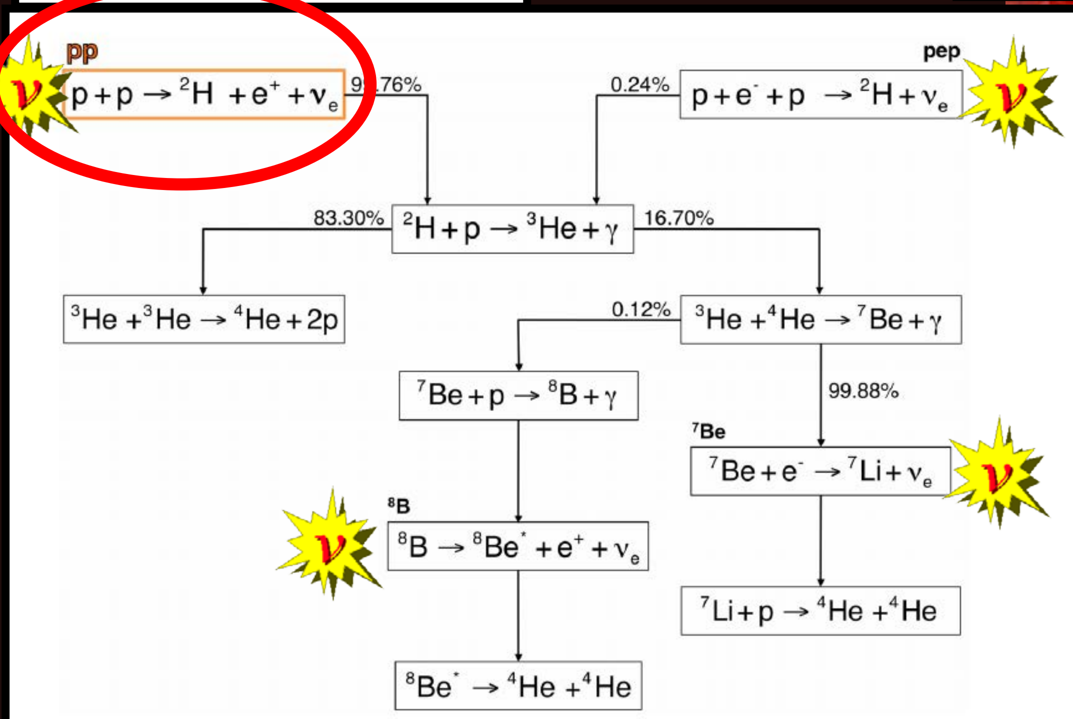

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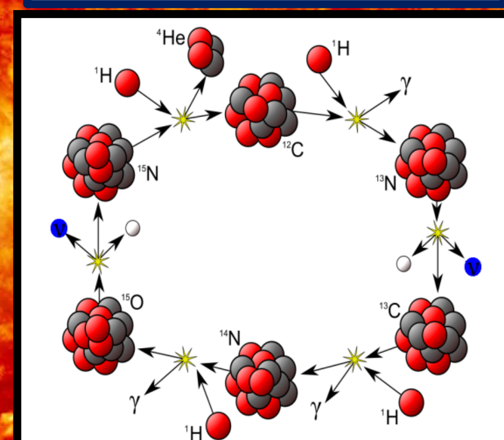

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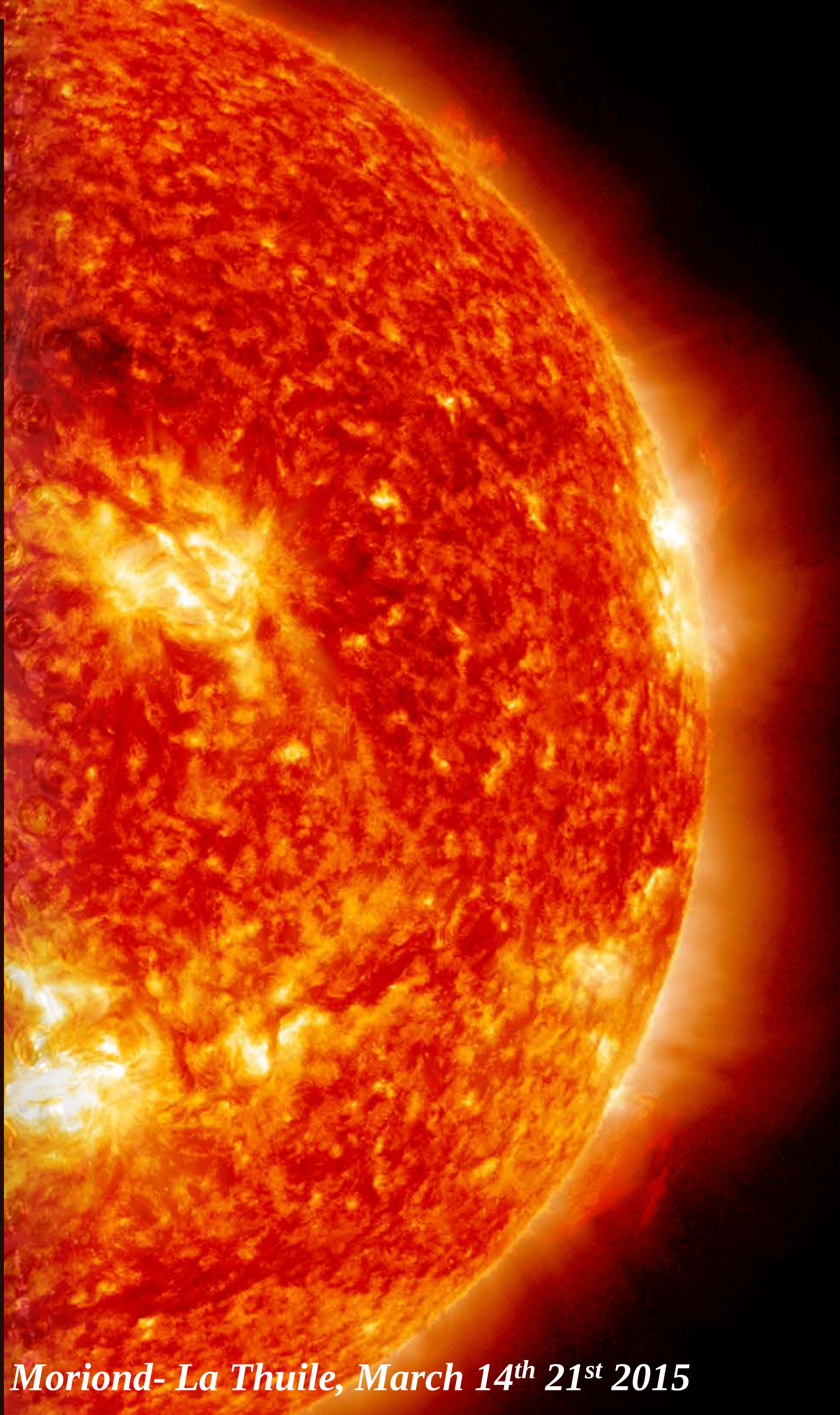

Why studying solar neutrinos?

•The standard Solar Model predicts the neutrino fluxes and their spectrum;

•Studying solar neutrinos is interesting both for ASTROPHYSICS (comparison with predictions of the SSM) and for PARTICLE PHYSICS (neutrinos oscillations);

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ASTROPHYSICS

Sources	$\Phi(\nu\ \mathrm{sec}^{-1}\ \mathrm{cm}^{2})$ *high-metallicity*	$\Phi(\nu\ \mathrm{sec}^{-1}\ \mathrm{cm}^{2})$ *low-metallicity*	Difference %
pp	$5.98(1\pm0.006)\times10^{10}$	$6.03(1\pm0.006)\times10^{10}$	0.8
pep	$1.44(1\pm0.012)\times10^{8}$	$1.47(1\pm0.012)\times10^{8}$	2.1
hep	$8.04(1\pm0.300)\times10^{3}$	$8.31(1\pm0.300)\times10^{3}$	3.3
^{7}Be	$5.00(1\pm0.070)\times10^{9}$	$4.56(1\pm0.070)\times10^{9}$	8.8
^{8}B	$5.58(1\pm0.140)\times10^{6}$	$4.59(1\pm0.140)\times10^{6}$	17.7
^{13}N	$2.96(1\pm0.140)\times10^{8}$	$2.17(1\pm0.140)\times10^{8}$	26.7
^{15}O	$2.23(1\pm0.150)\times10^{8}$	$1.56(1\pm0.150)\times10^{8}$	30.0
^{17}F	$5.52(1\pm0.170)\times10^{6}$	$3.40(1\pm0.160)\times10^{6}$	38.4

•**Solar Model:** Serenelli, Haxton and Pena-Garay arXiV:1104.1639
•**High metallicity GS98** = Grevesse et al.*S. Sci. Rev. 85,161 ('98);*
•***Low metallicity AGS09*** = *Asplund, et al,* A.R.A.&A. 47(2009)481

Open Issues: solar metallicity

•Metallicity is input in the Standard Solar Model;

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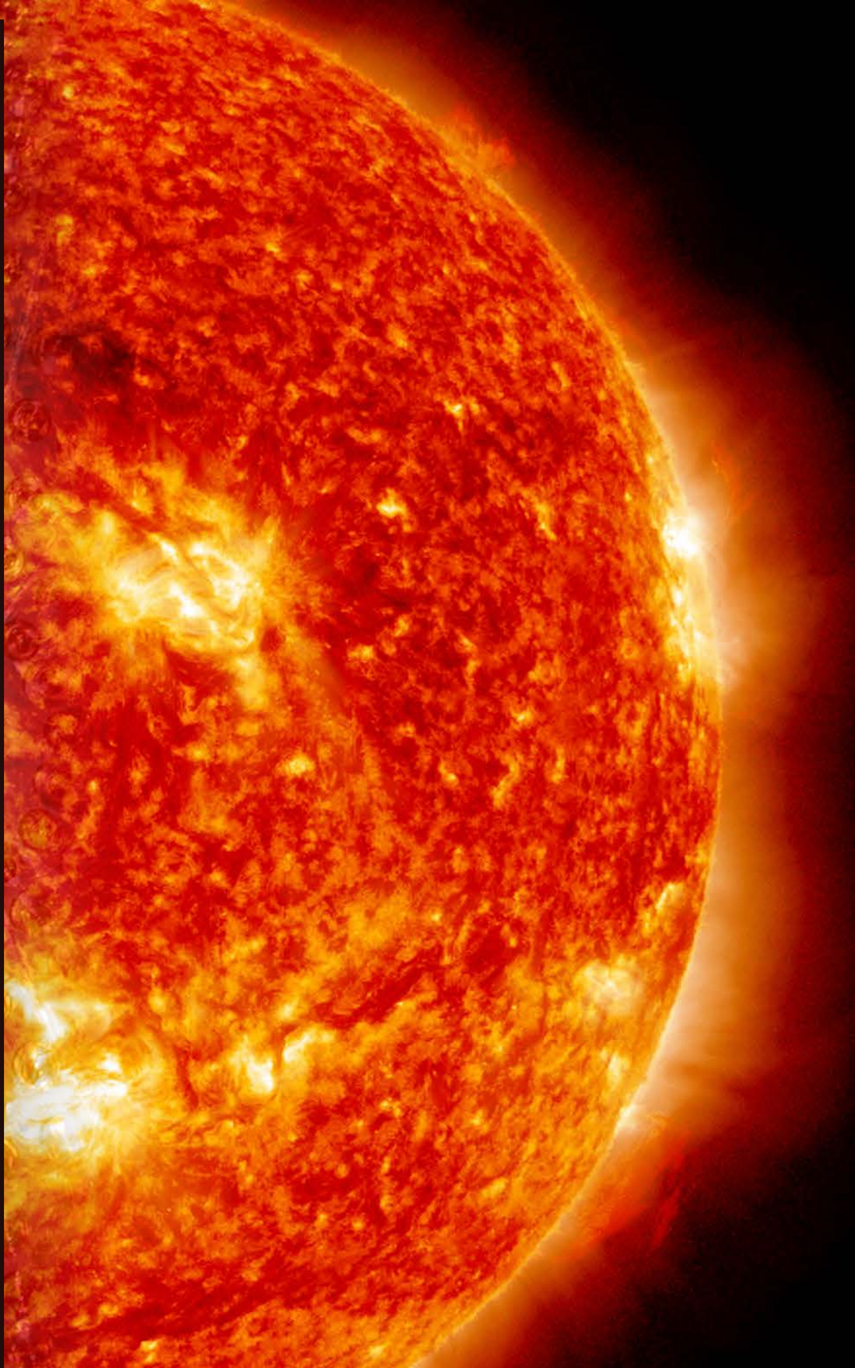

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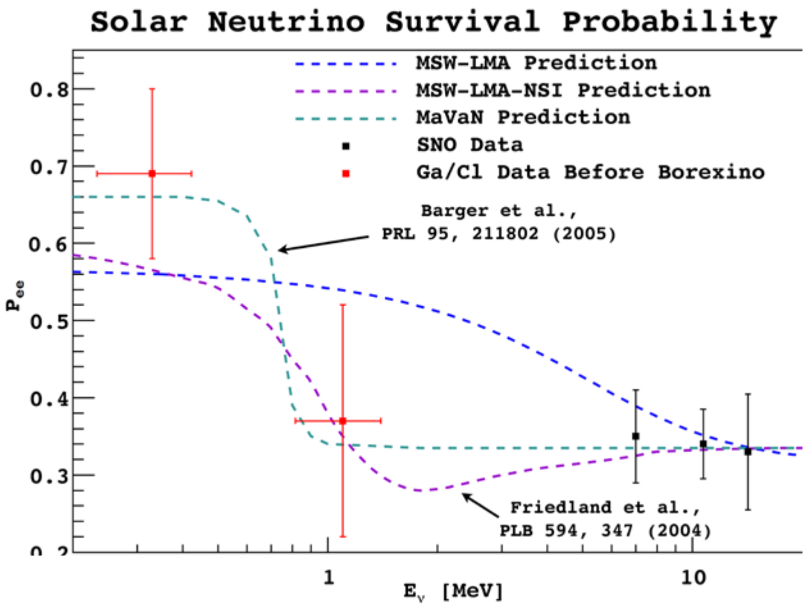
The "solar neutrino problem" has provided one of the first hints towards neutrino oscillations;

•Now we know that solar neutrinos oscillate:

"LMA solution": $\Delta m^2 = 7.6\times10^{-5}$ eV^2; $tg^2\theta = 0.468$

Open issues: probe P_{ee} in the vacuum to matter transition region

- sensitive to new physics;



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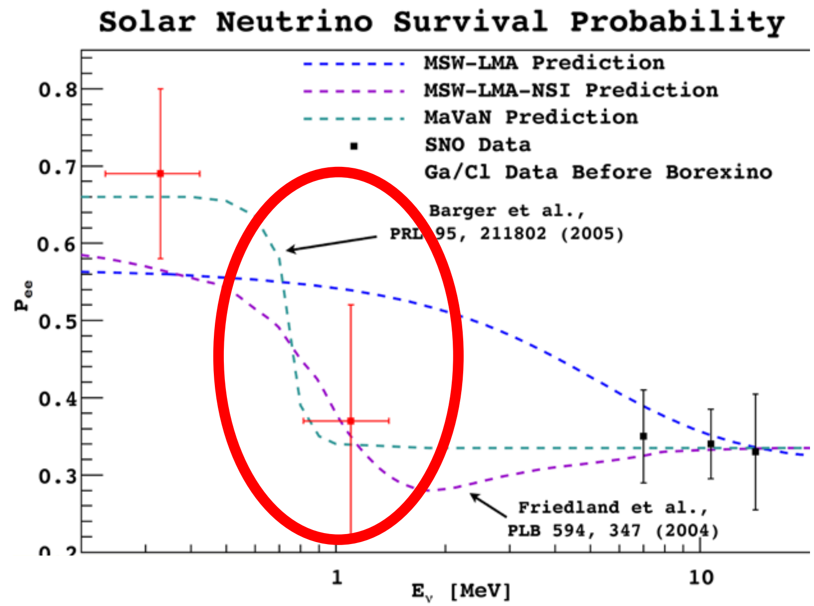

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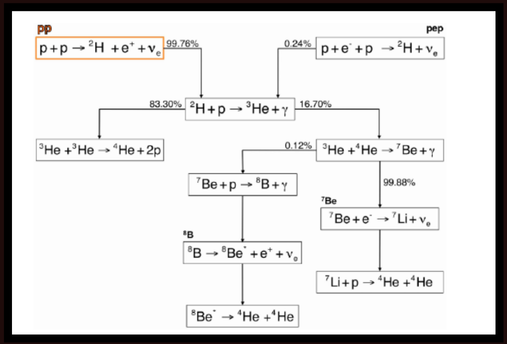
- pp neutrinos provide a direct glimpse into the main fusion process that keeps the Sun shining;
- in fact, pp neutrinos are produced in the primary nuclear reaction of the pp-cycle;



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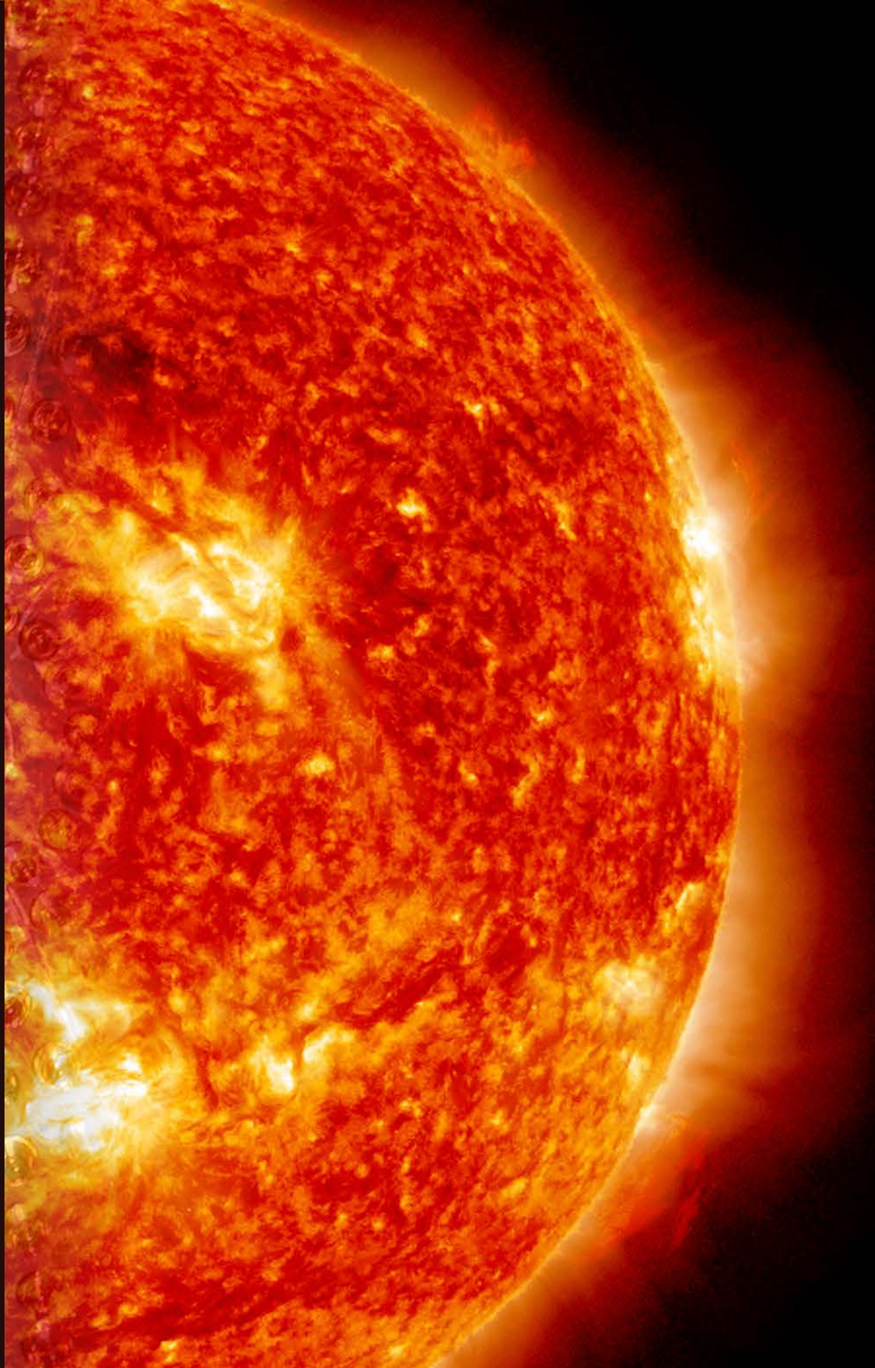

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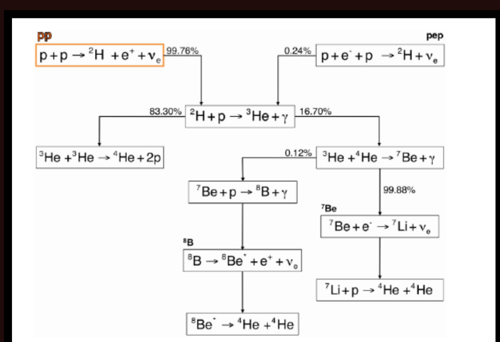

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DIFFICULT TO DETECT

- pp neutrinos have low energy → they are difficult to detect;
- GALLEX and SAGE have performed an integrated measurement of the low energy solar neutrino flux (E>233 keV);
- Only real-time detectors can single-out different components of solar neutrino spectrum;
- **pp neutrinos never observed in real time befor Borexino!**

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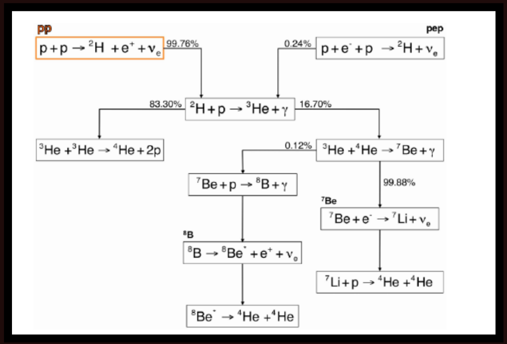

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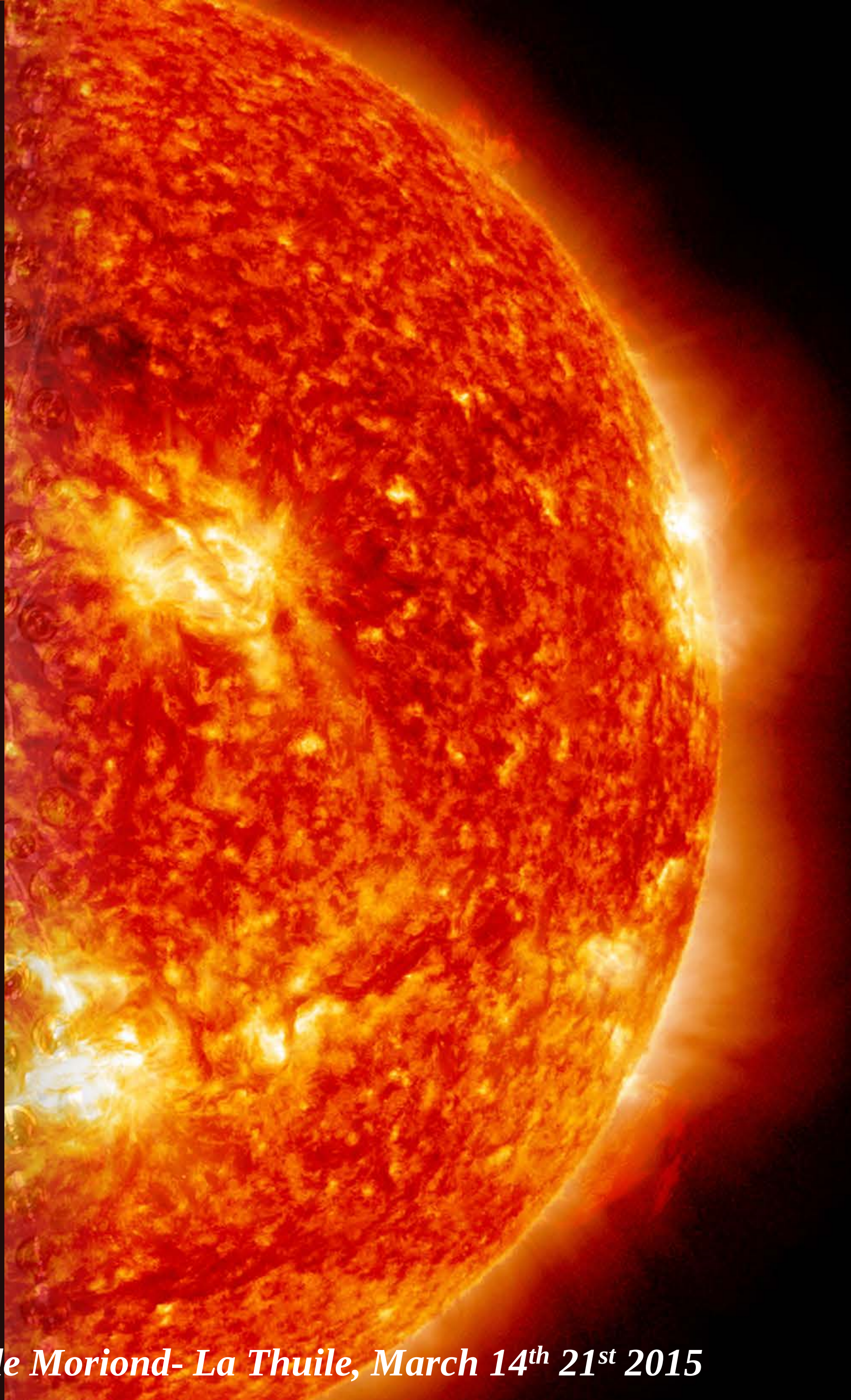

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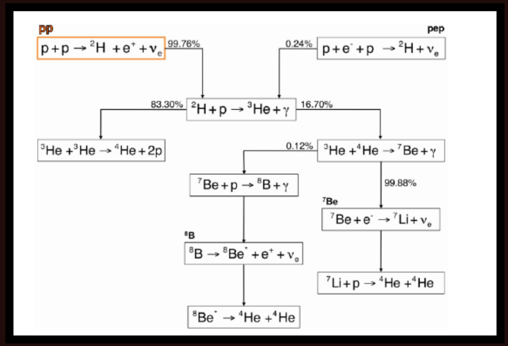

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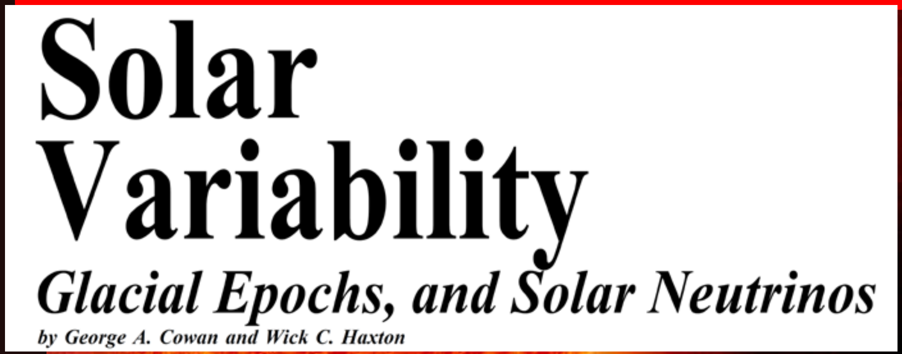
SOLAR (IN)VARIABILITY

•pp neutrinos are "instant messangers" from the center of the Sun;

•neutrinos take only few seconds to travel from the center of the Sun to the surface (and then 8 minutes to reach Earth);

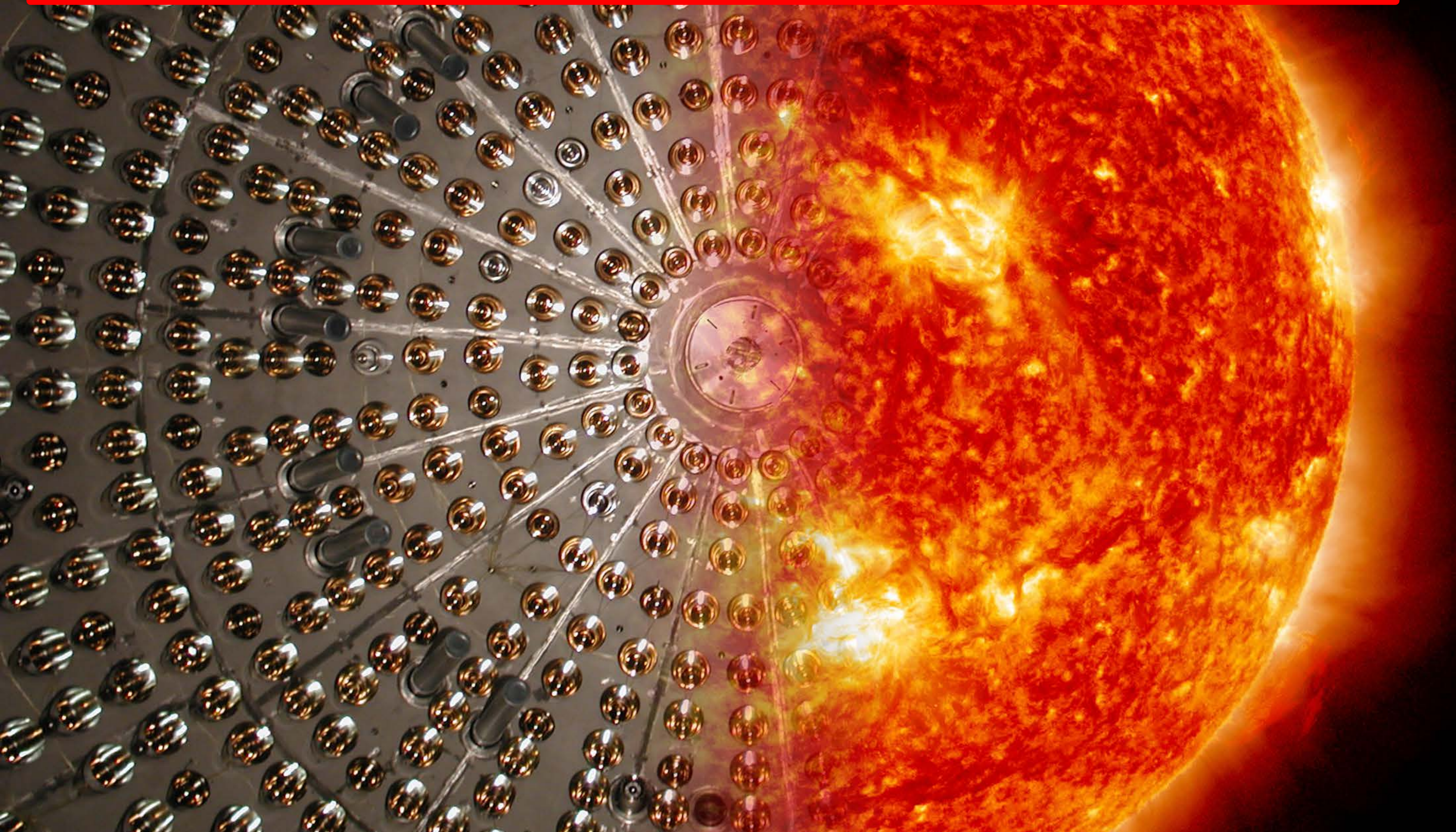
•photons take over ~10^5 years;

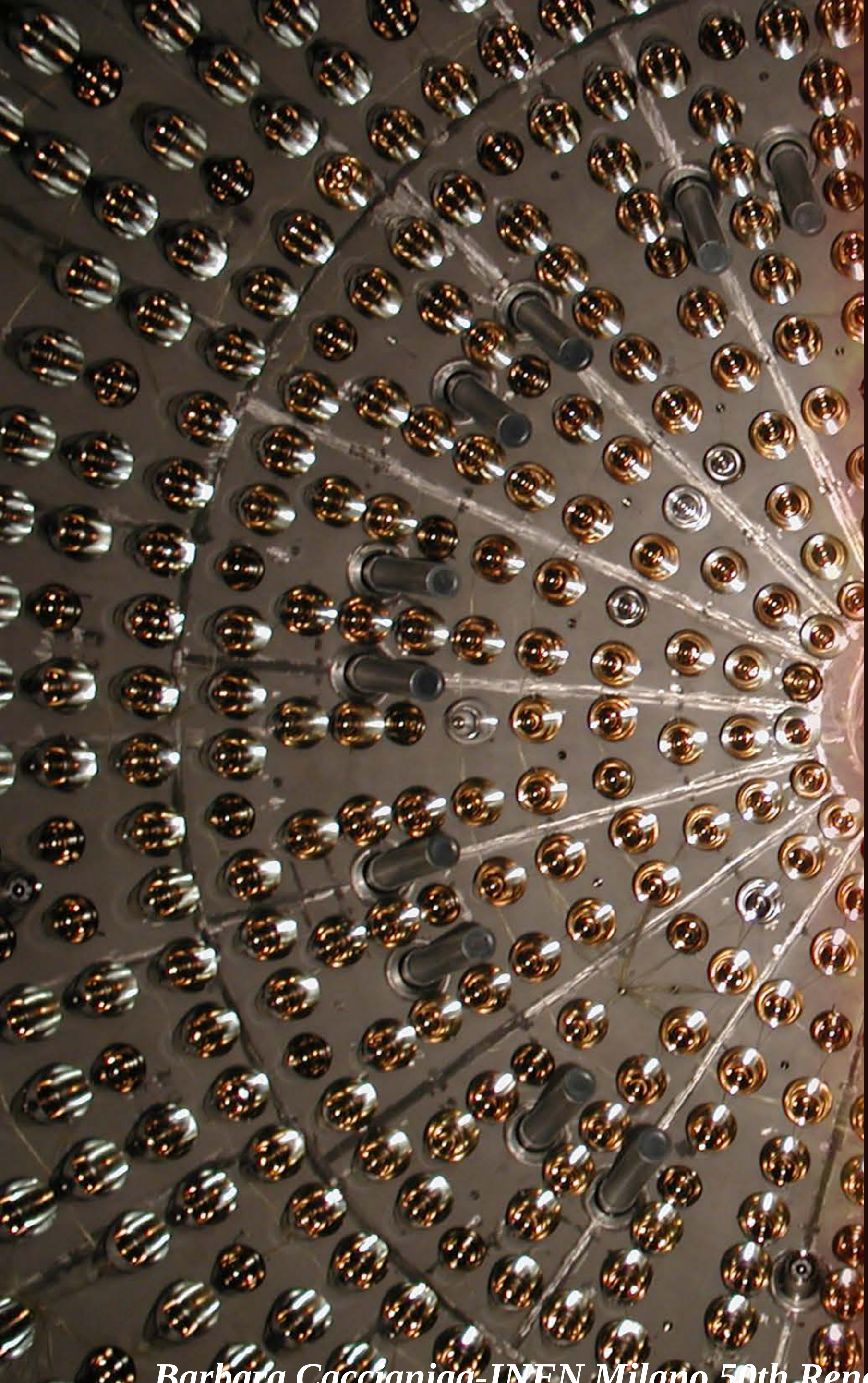
•Verifying that the solar luminosity in neutrinos is the same as the one in photons demonstrate the stability of the Sun on the 10^5 years time scale;


Solar Variability
Glacial Epochs, and Solar Neutrinos
by George A. Cowan and Wick C. Haxton

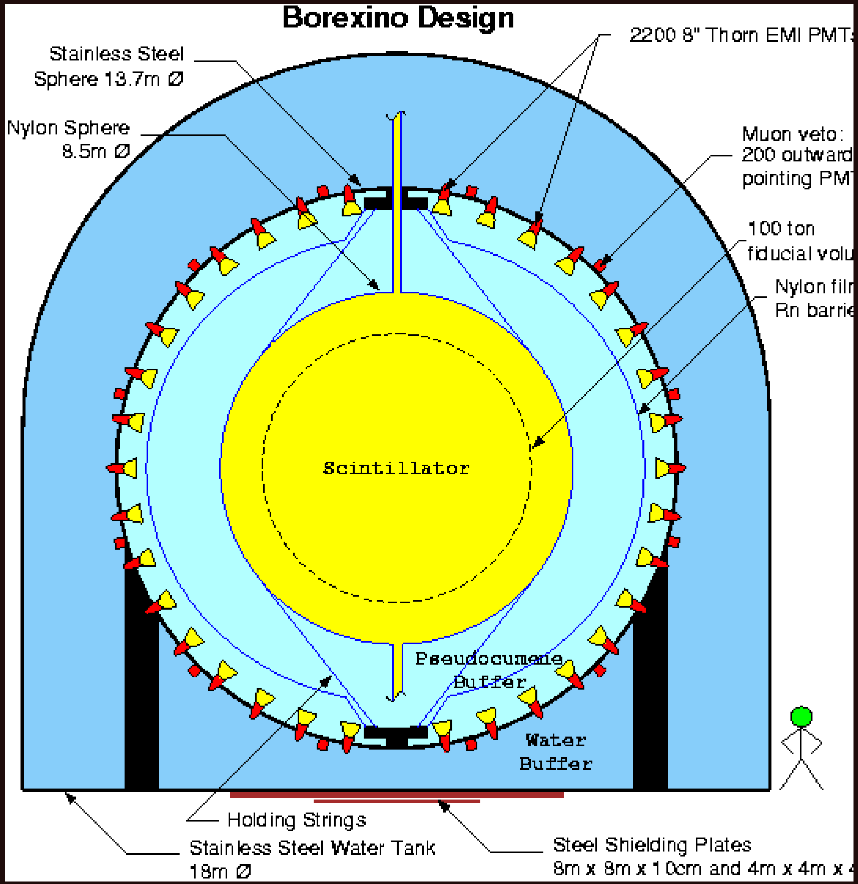
Los Alamos Science 3 (2) (1982) 46

How can we study neutrinos from the Sun?

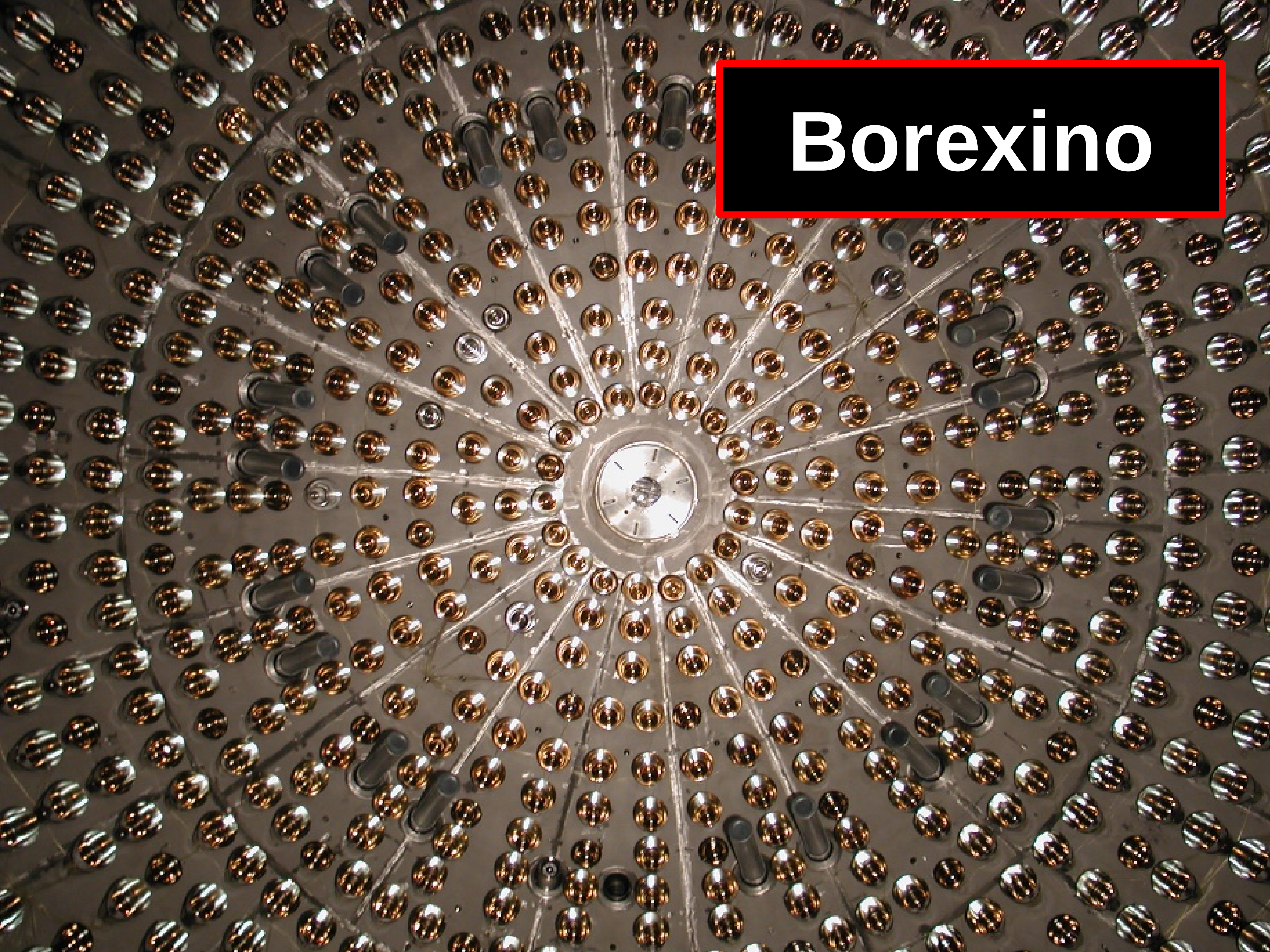




Borexino



Borexino Design
Stainless Steel Sphere 13.7m Ø
2200 8" Thorn EMI PMTs
Nylon Sphere 8.5m Ø
Muon veto: 200 outward pointing PMT
100 ton fiducial volu
Nylon film Rn barrie
Scintillator
Pseudocumene Buffer
Water Buffer
Holding Strings
Stainless Steel Water Tank 18m Ø
Steel Shielding Plates 8m x 8m x 10cm and 4m x 4m x 4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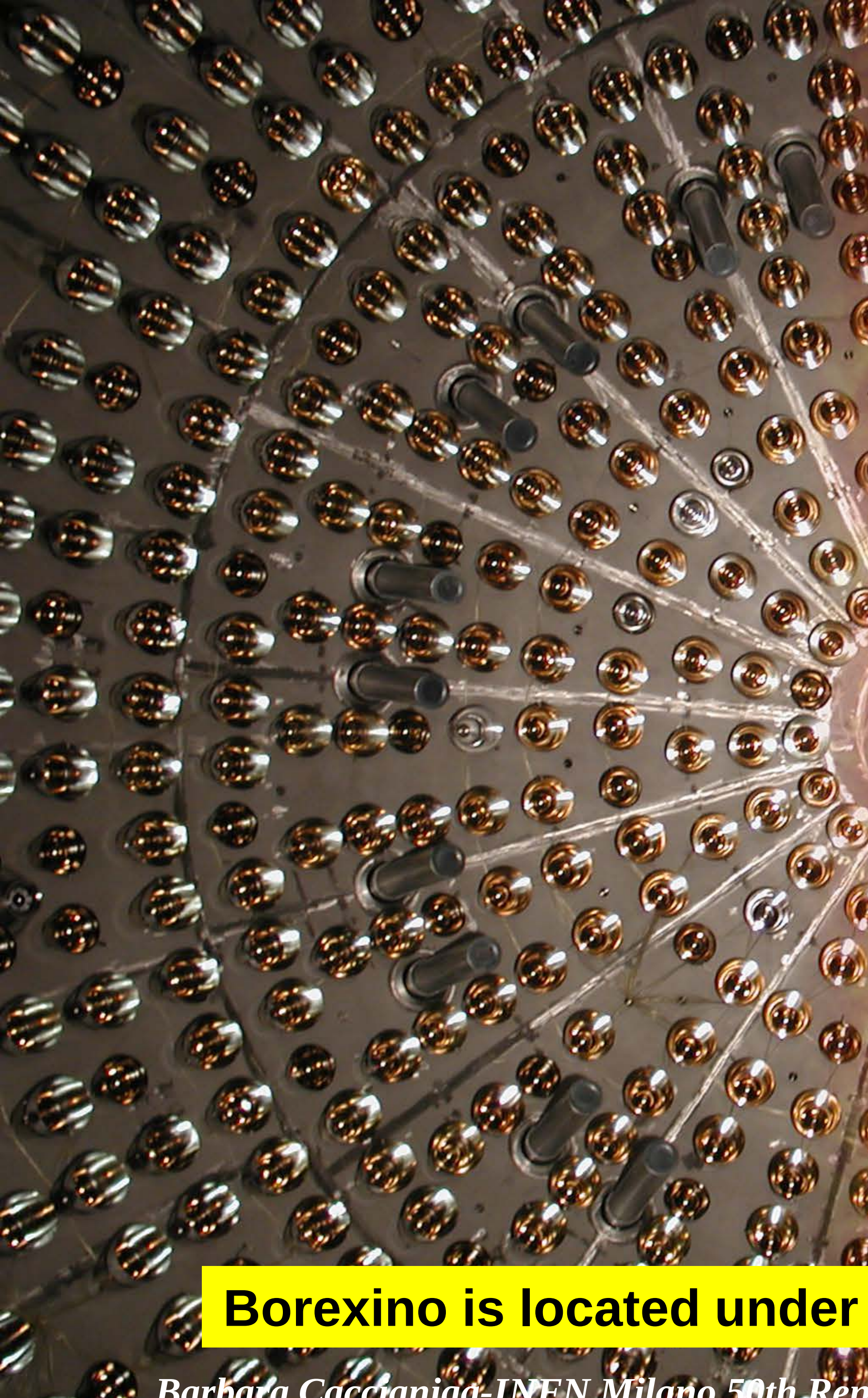
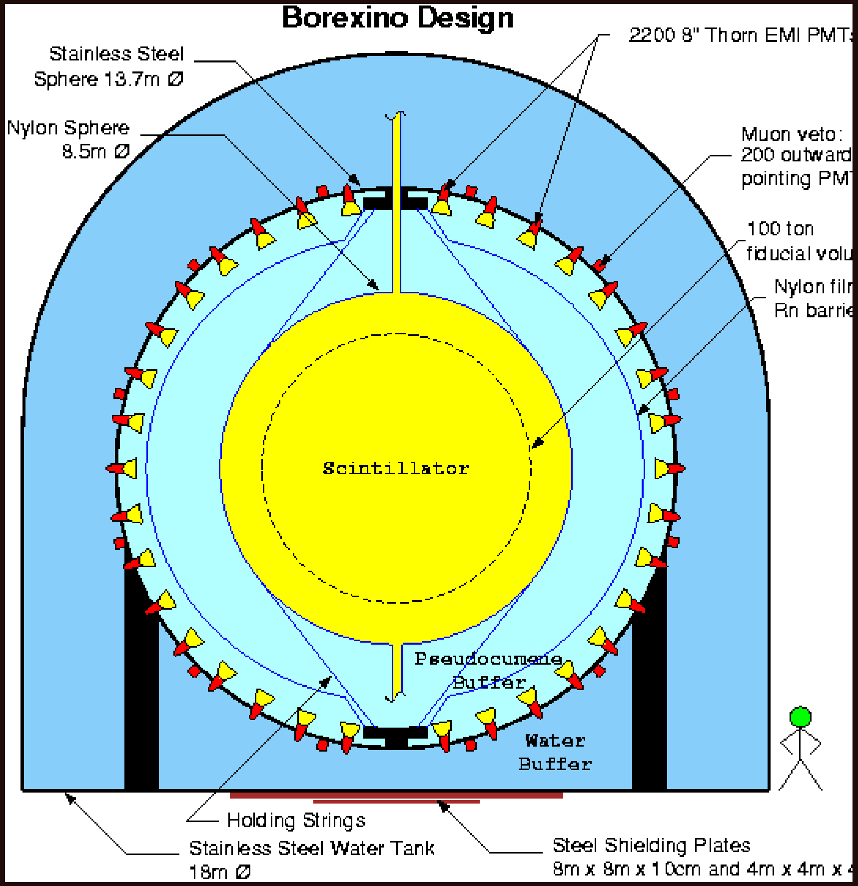
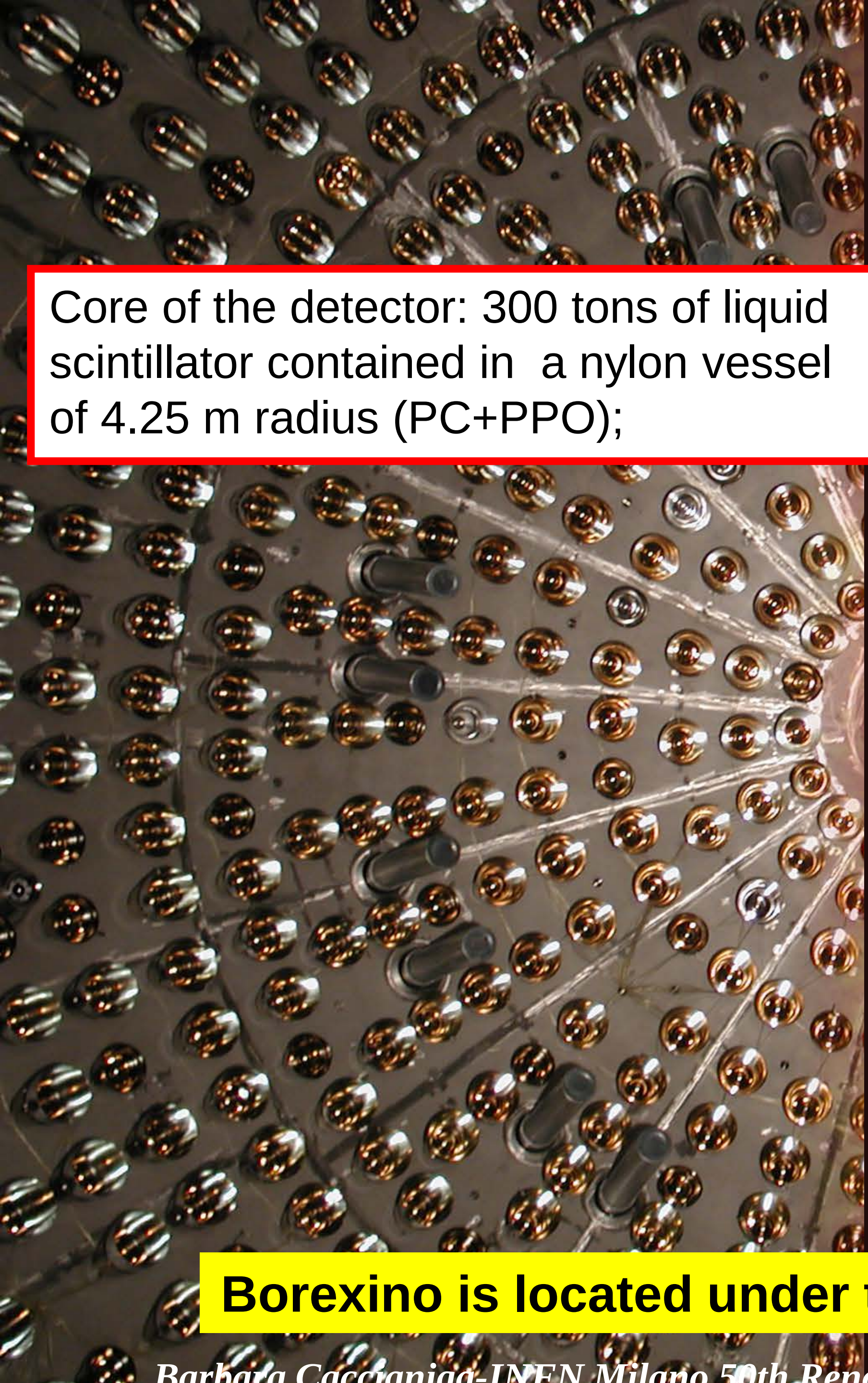


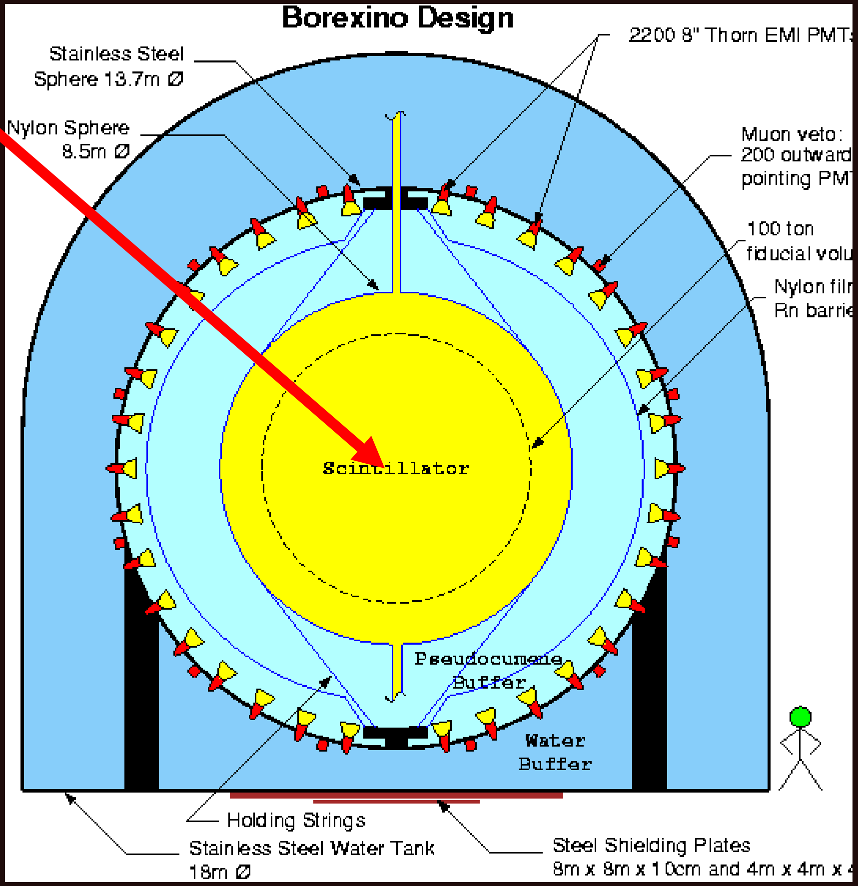


Borexino is located under the Gran Sasso mountain in Italy

Borexino

Core of the detector: 300 tons of liquid scintillator contained in a nylon vessel of 4.25 m radius (PC+PPO);





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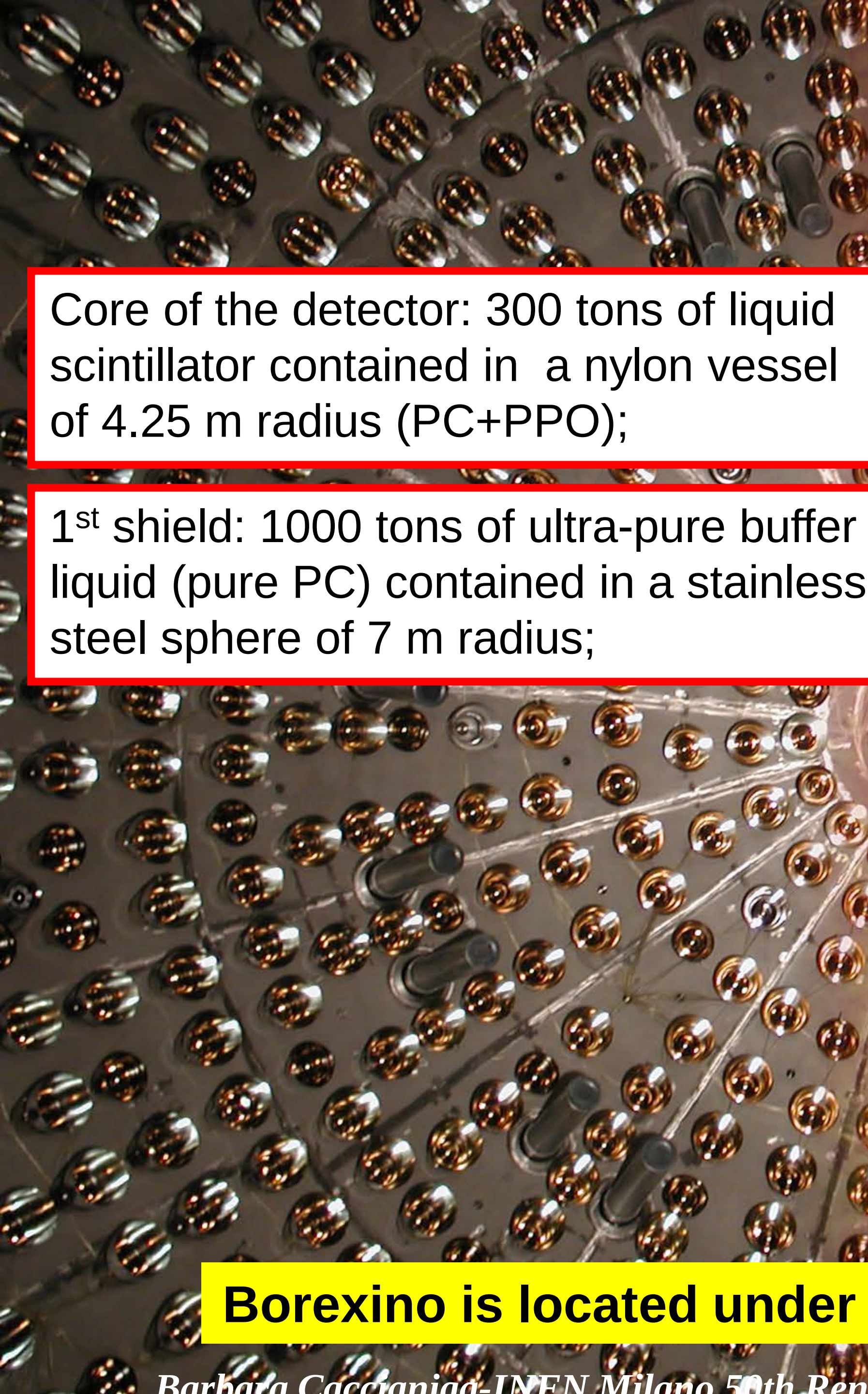

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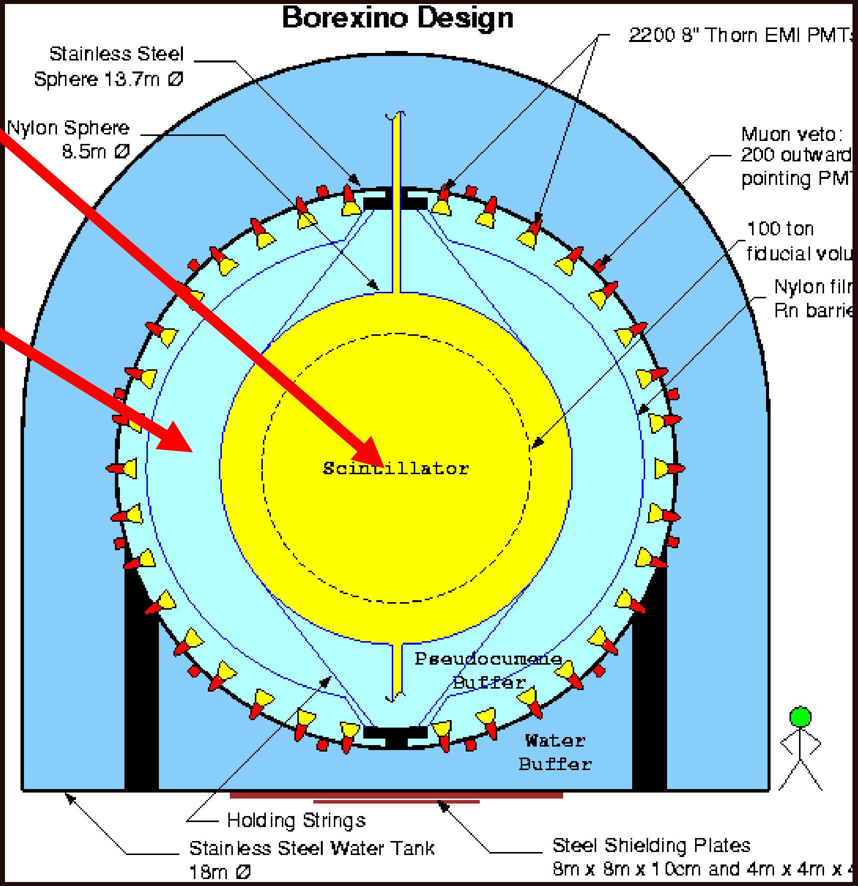

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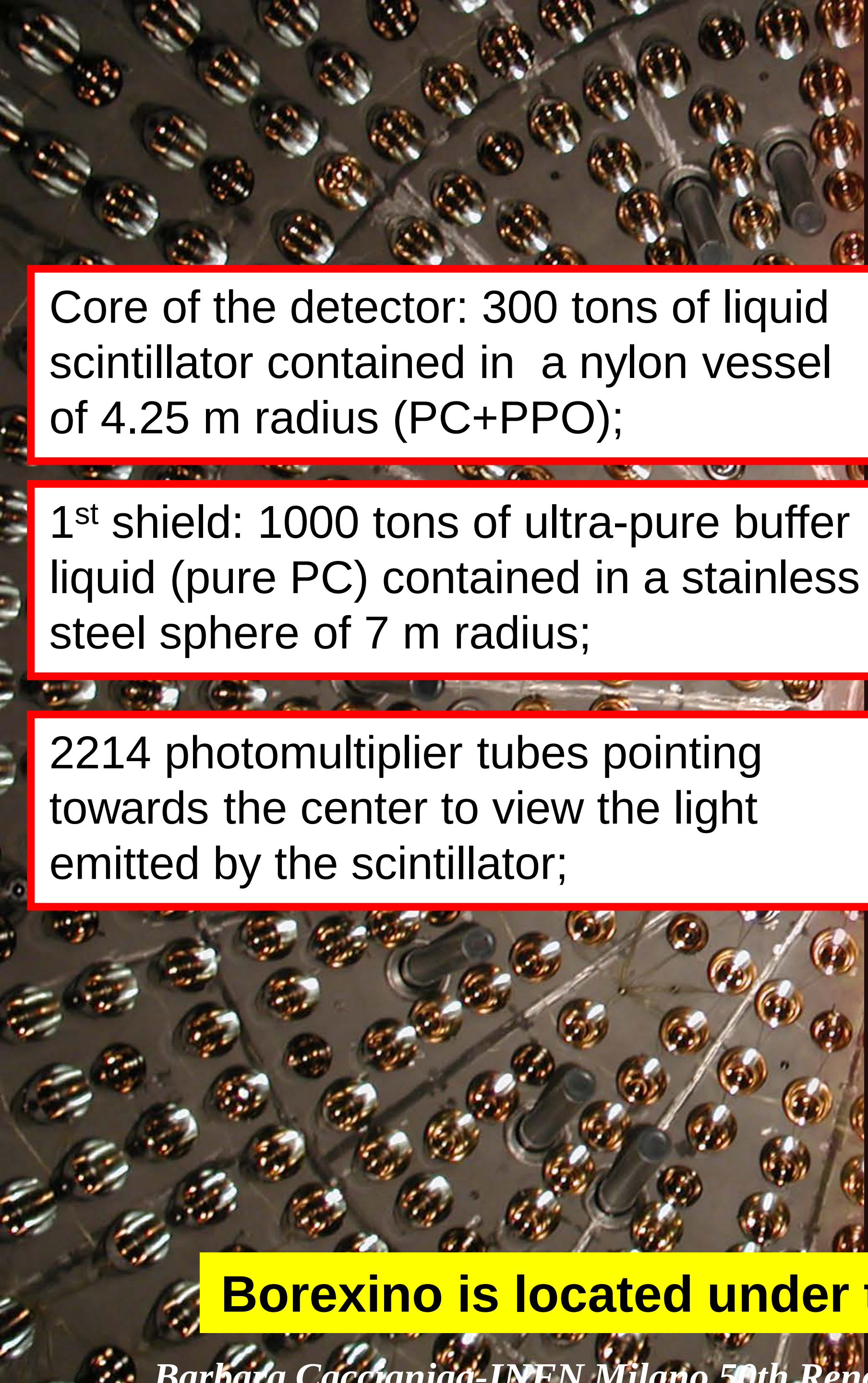

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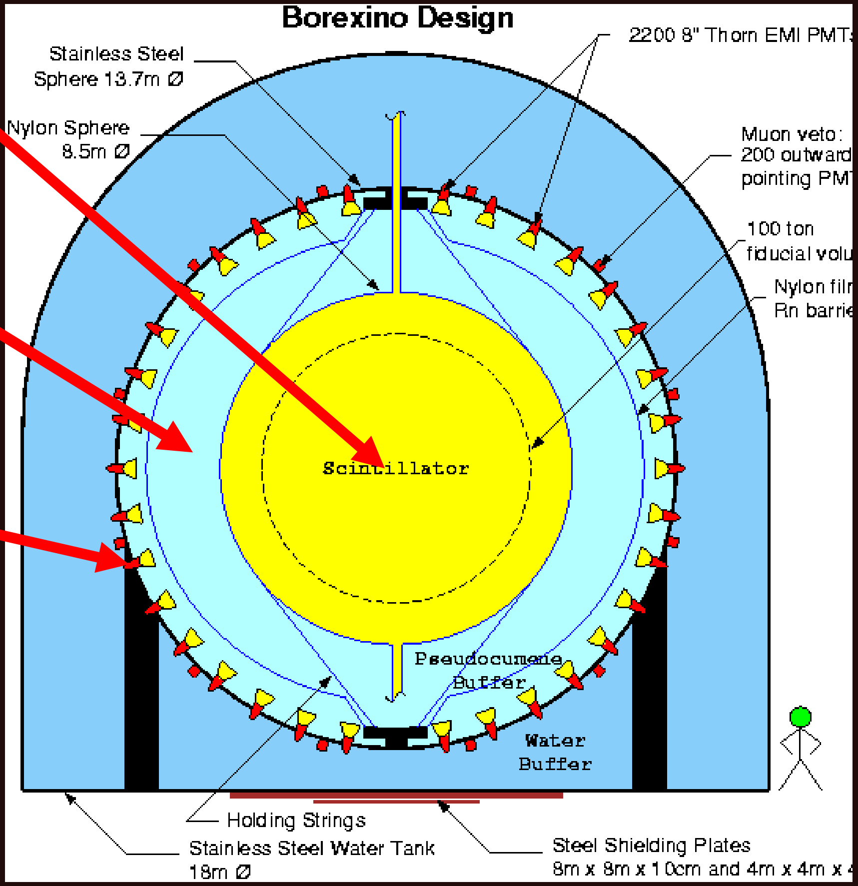

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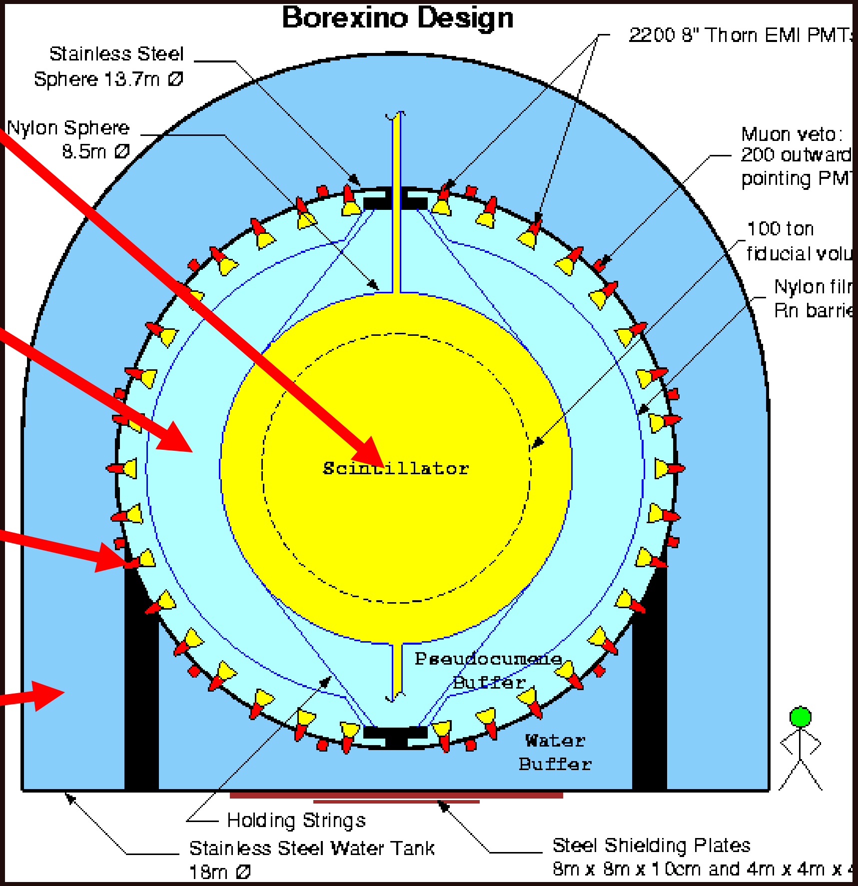
2nd shield: 2000 tons of ultra-pure water contained in a cylindrical dome;



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- **Main goal**: detecting low energies solar neutrinos, in particular ^7Be neutrinos;
- **Detection principle:** scattering of neutrinos on electrons $\nu_x + e^- \rightarrow \nu_x + e^-$
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- Just for comparison:
  - Natural water is ~ 10 Bq/Kg in ^{238}U, ^{232}Th and ^{40}K
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BX scintillator must be 9/10 order of magnitude less radioactive than anything on earth!

Background suppression: 15 years of work

- **Internal background: contamination of the scintillator itself (^{238}U, ^{232}Th, ^{40}K, ^{39}Ar, ^{85}Kr, ^{222}Rn)**
  - Solvent purification (pseudocumene): distillation, vacuum stripping with low Argon/Kripton N2 (LAKN);
  - Fluor purification (PPO): water extraction, filtration, distillation,N_2 stripping with LAKN;
  - Leak requirements for all systems and plants < 10^{-8} mbar· liter/sec;
- **External background: γ and neutrons from surrounding materials**
  - Detector design: concentric shells to shield the inner scintillator;
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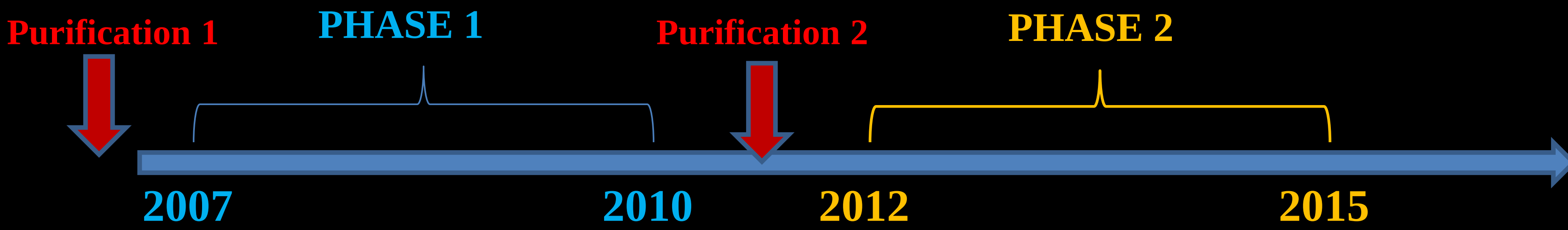
Background suppression: achievements

•Contamination from ^{238}U and ^{232}Th chain are found to be in the range of ~10^{-17} g/g and ~5x×10^{-18} g/g respectively;

•**More than one order of magnitude better than specifications!**

•Three backgrounds out of specifications: ^{210}Po, ^{210}Bi and ^{85}Kr.

History of Borexino



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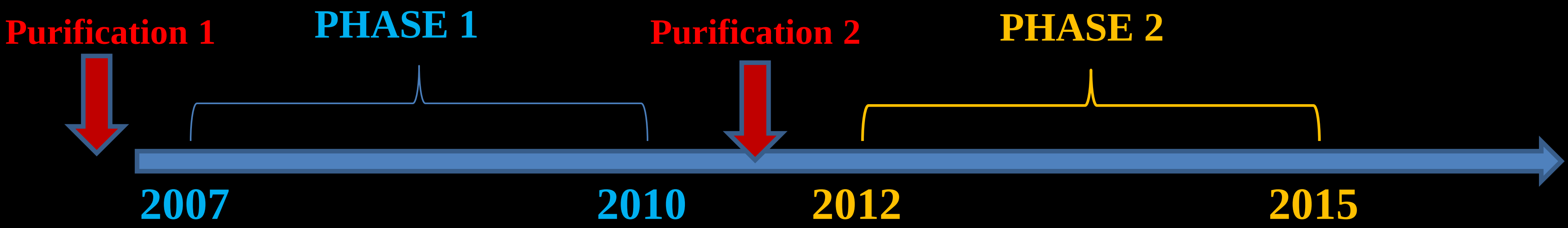

PHASE 1 (2007-2010)

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- Day/Night asymmetry; √
- pep ν: 1st observation; √
- ^{8}B ν; √
- CNO n: best limit √

Geo-neutrinos

- Evidence > 4.5σ √

- Limit on rare processes √
- Study on cosmogenics √

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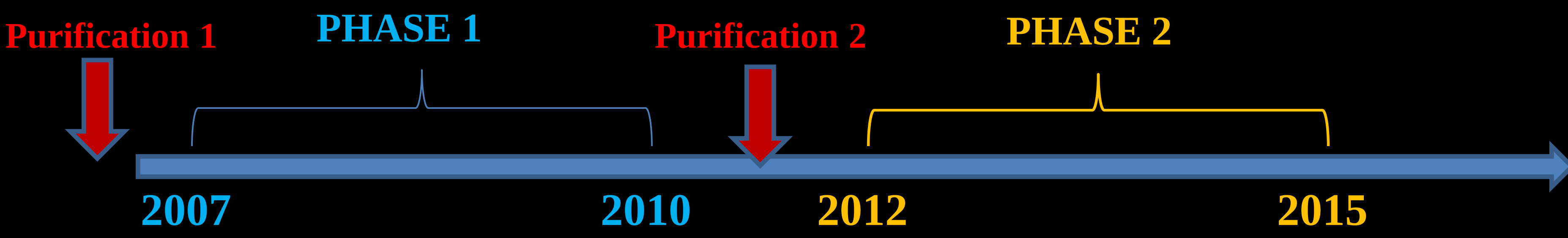

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- Evidence > 4.5σ √

- Limit on rare processes √
- Study on cosmogenics √

PHASE 2 (2012-2015)

Improved radiopurity

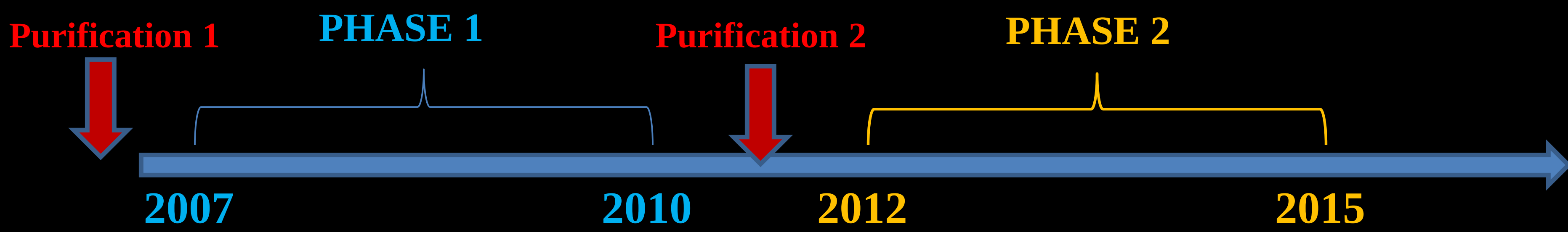
- ^{85}Kr rate compatible with 0
- ^{210}Bi reduced by a factor ~3;
- ^{232}Th and ^{238}U negligible;

<u>pp neutrinos</u>

"*Neutrinos from the primary proton-proton fusion process in the Sun*" Nature **512** 383-386 (2014)

More to come!

History of Borexino



PHASE 1 (2007-2010)

<u>Solar neutrinos</u>

- ^{7}Be ν : 1st observation+ precise measurement (5%); √
- Day/Night asymmetry; √
- pep ν: 1st observation; √
- ^{8}B ν; √
- CNO n: best limit √

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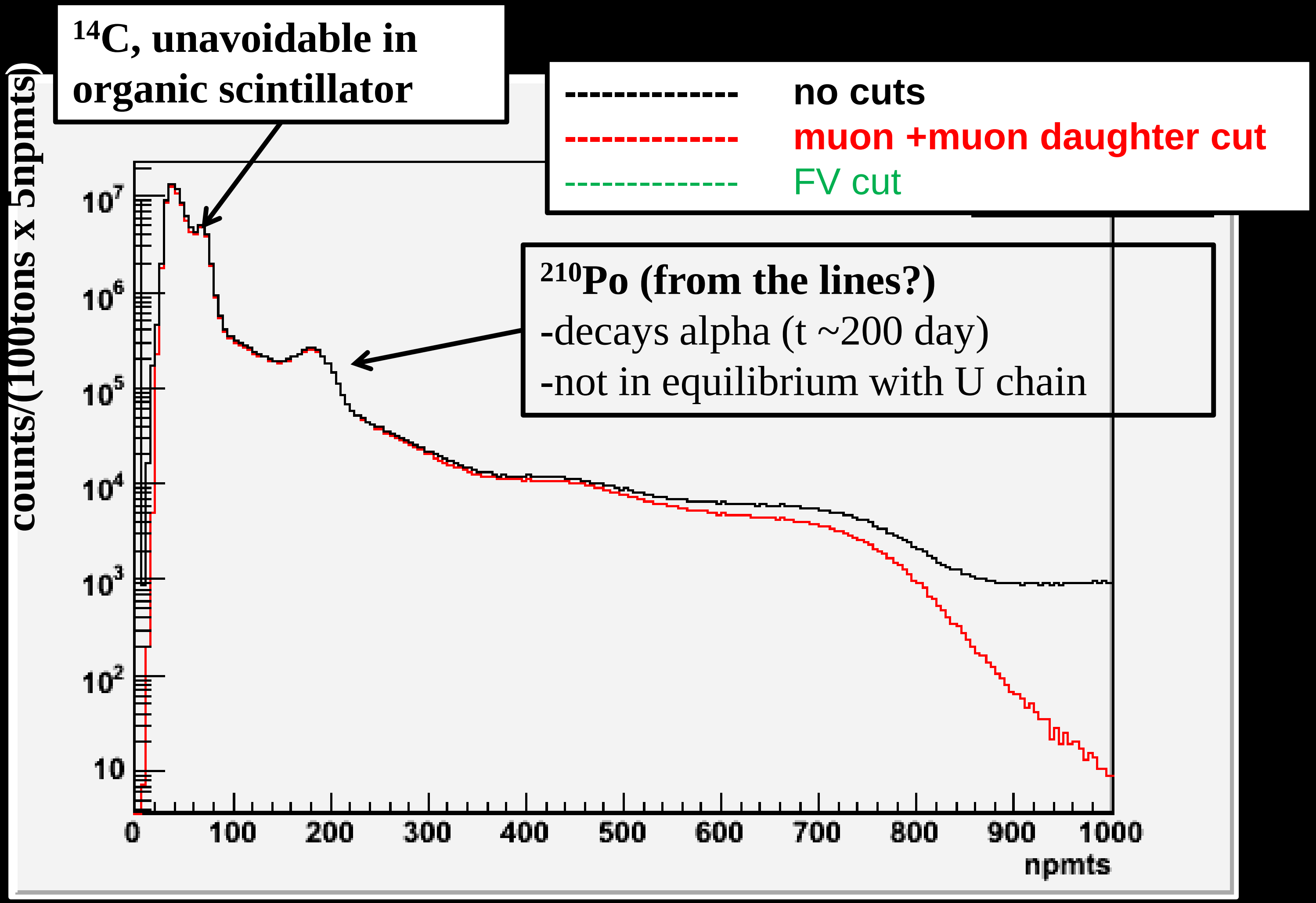
Borexino Phase 1 (2007-2010) results

Data after 750 days (normalized to 100tons)



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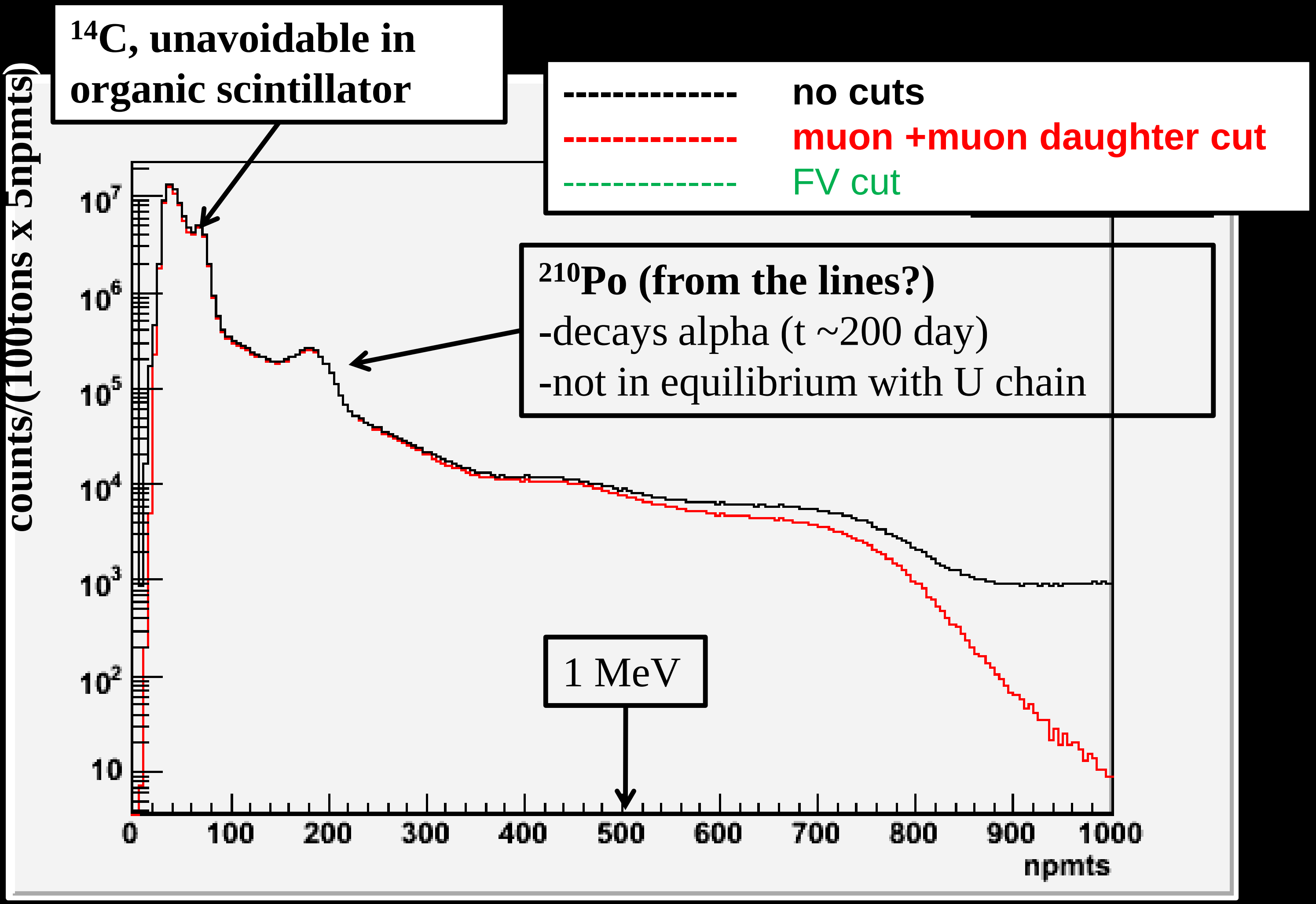

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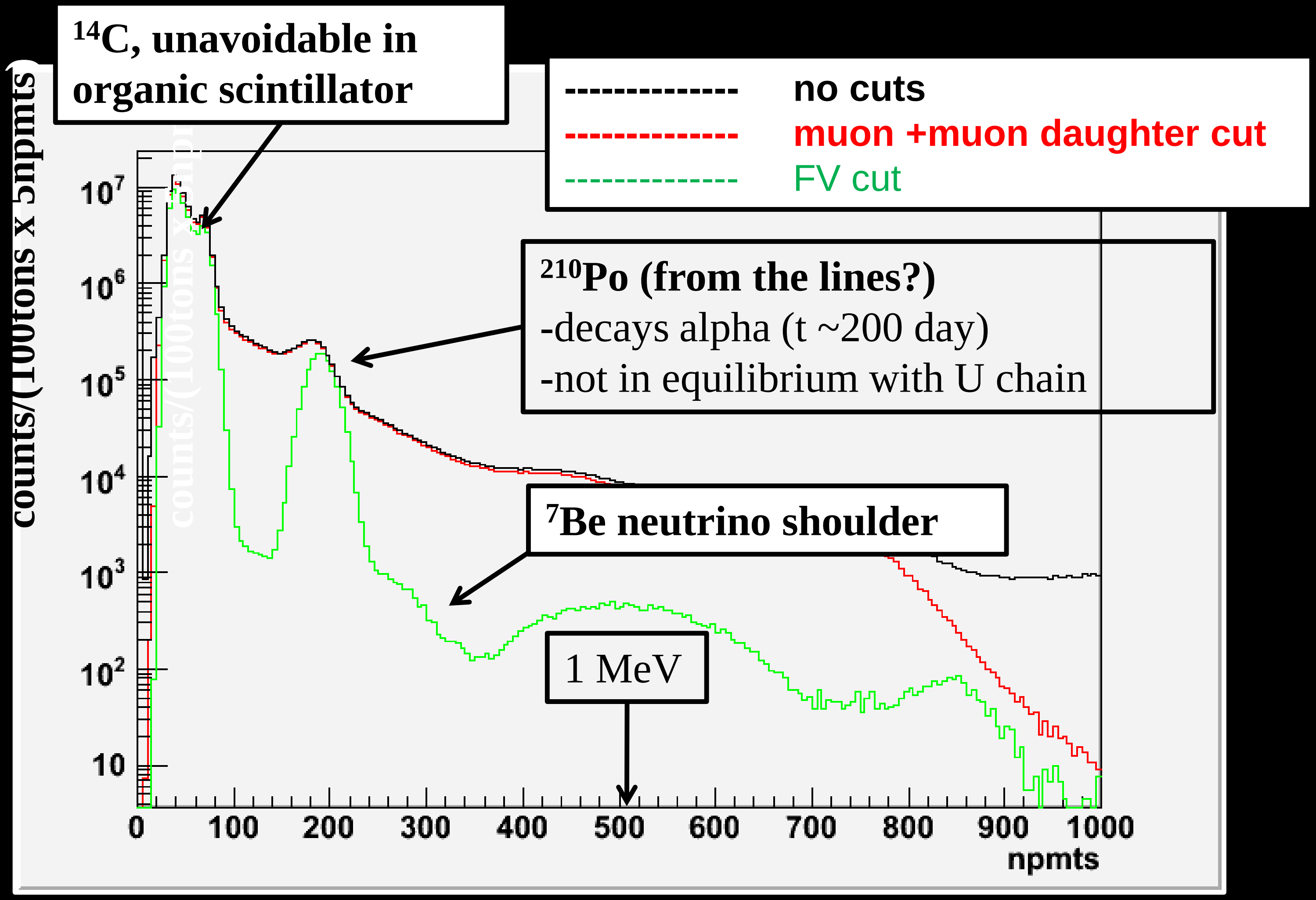

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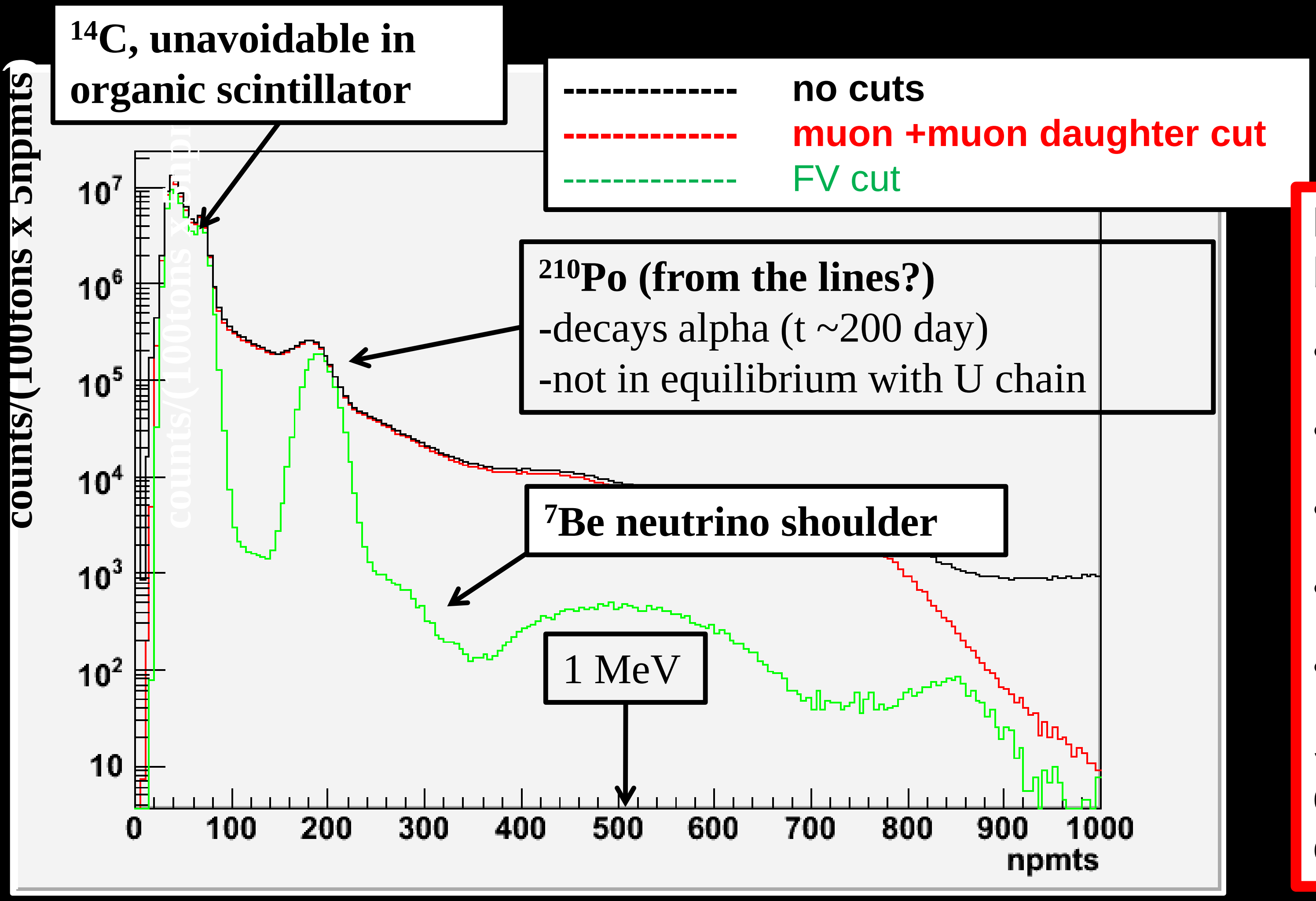

Residual backgrounds

- ^{14}C
- ^{14}C pile-up
- ^{85}Kr
- ^{210}Bi
- ^{210}Po

Spectral fit to disentangle contributions

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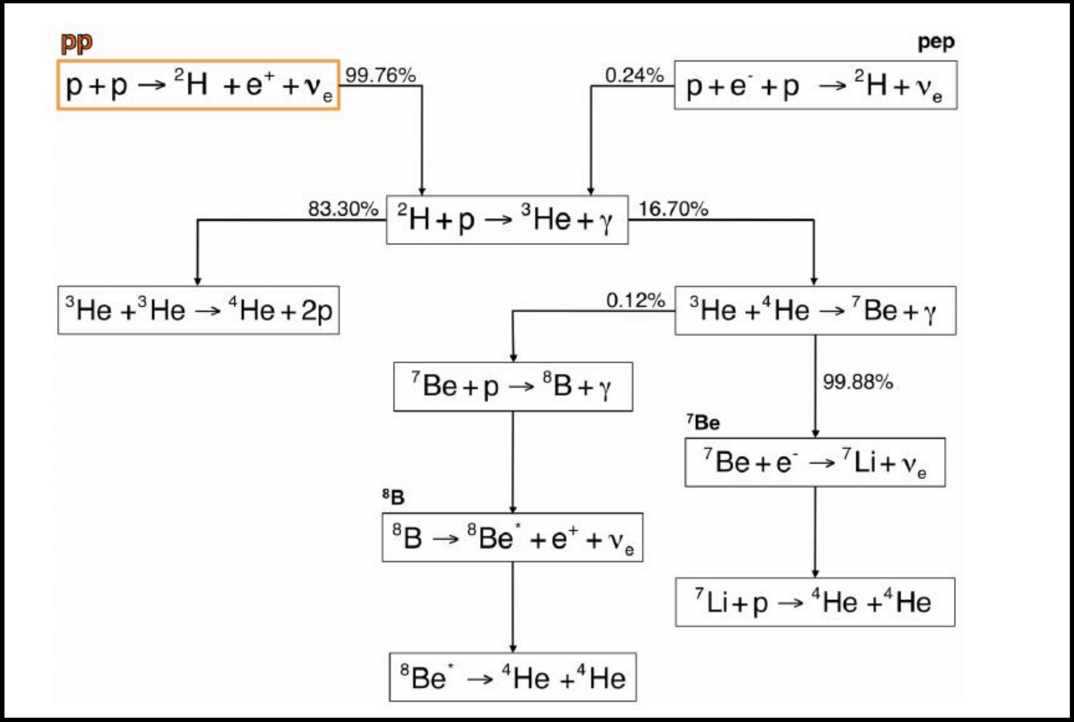

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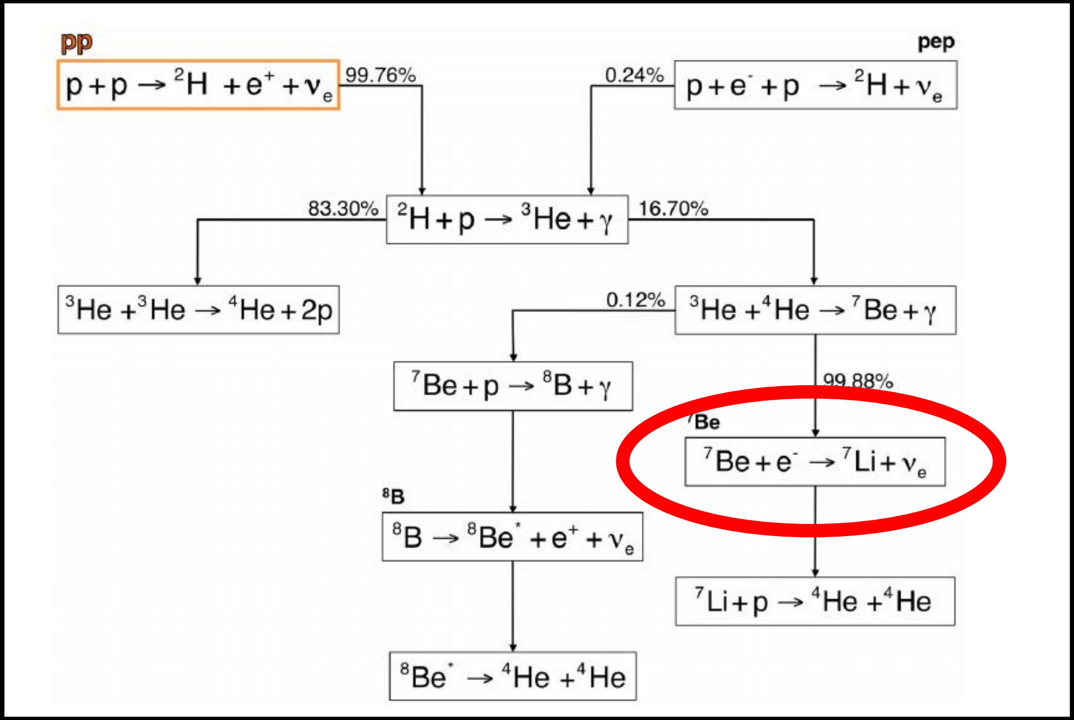

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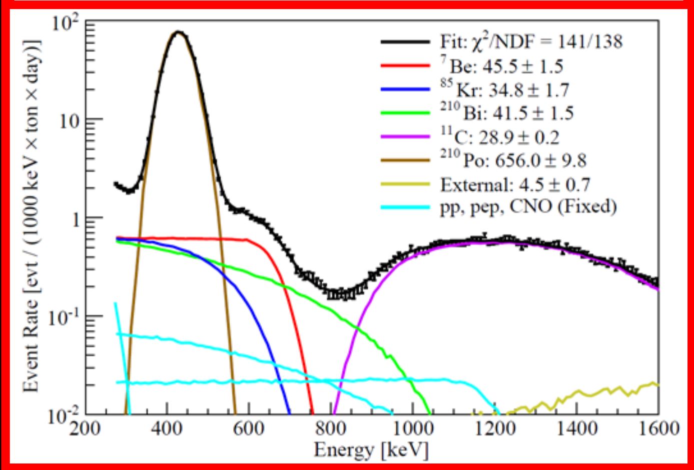
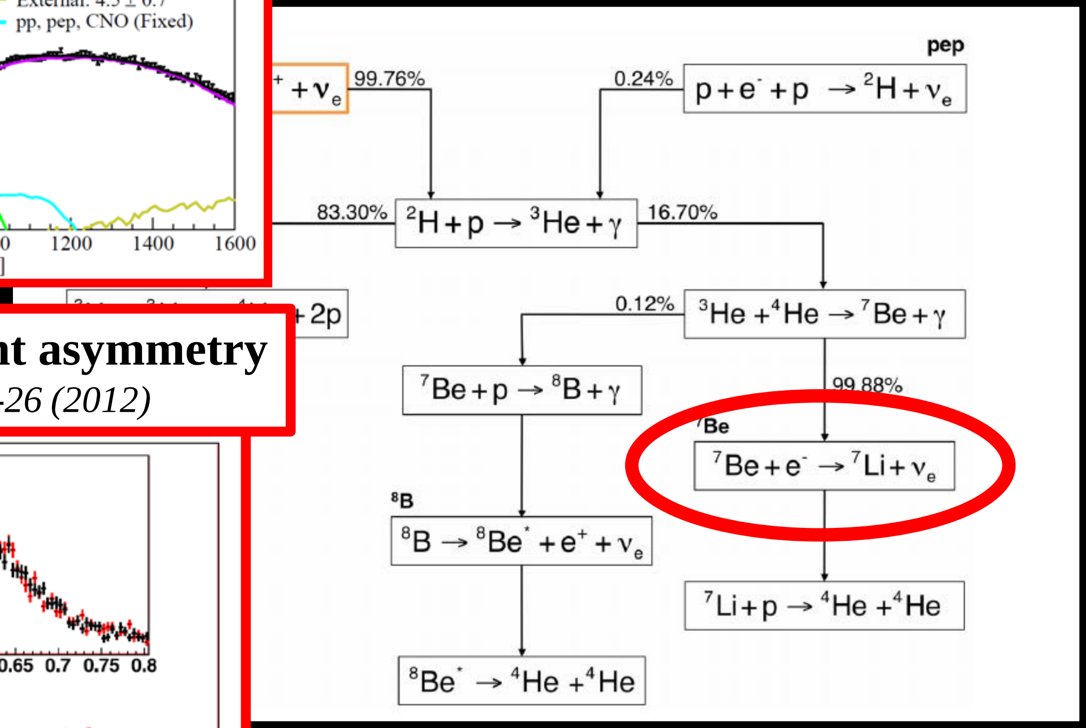
^{7}Be ν with 5% error

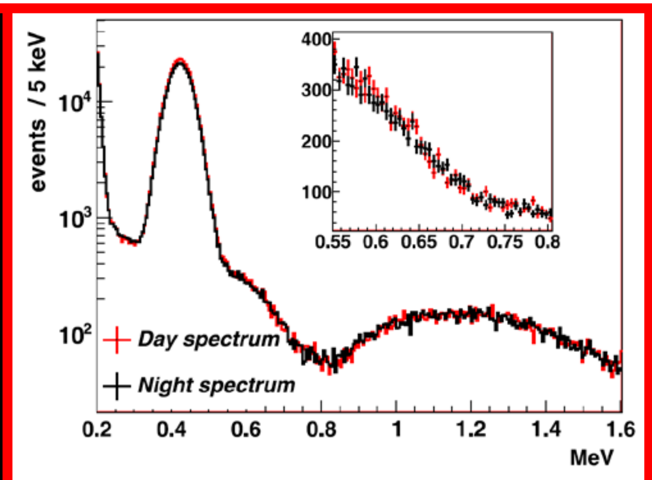
PRL ***107****, 1411302 (2011)*





Absence of Day/Night asymmetry

Phys.Lett.B ***707****, 22-26 (2012)*



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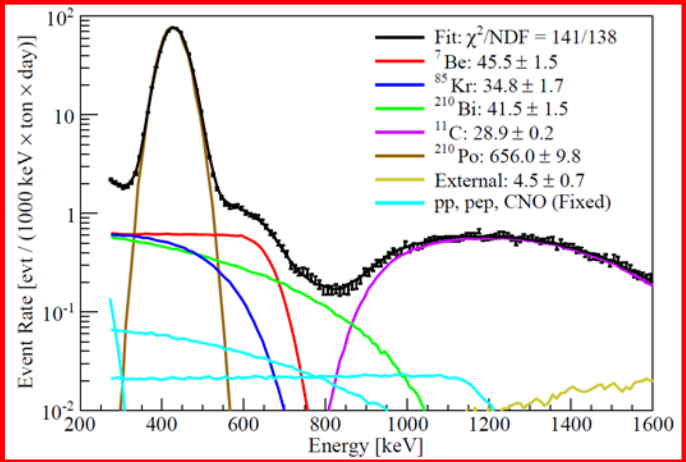

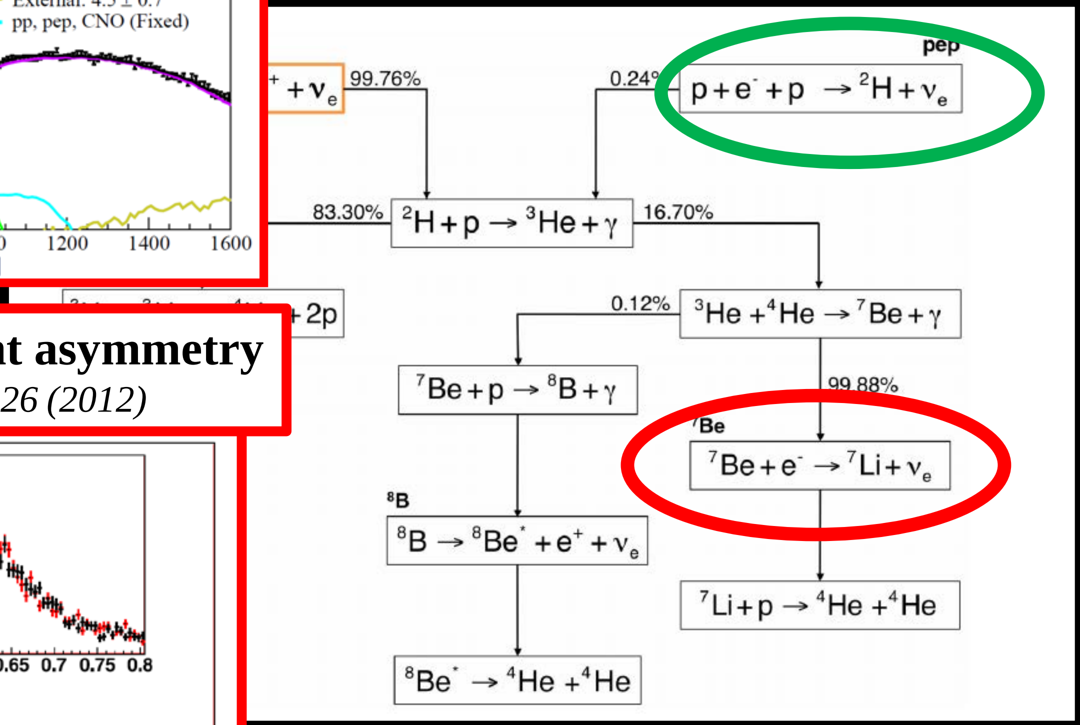

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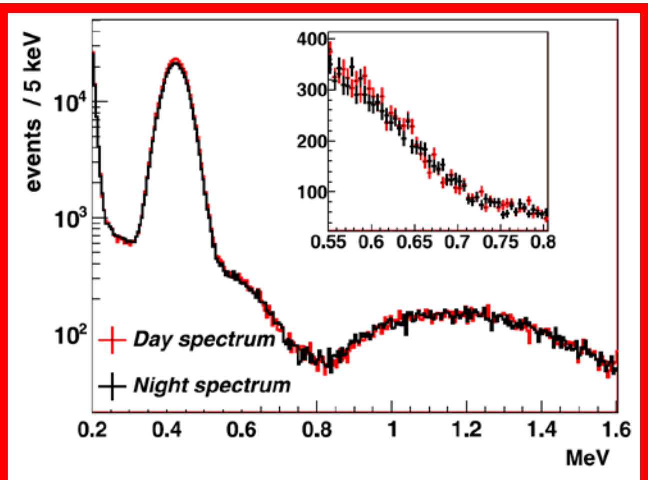

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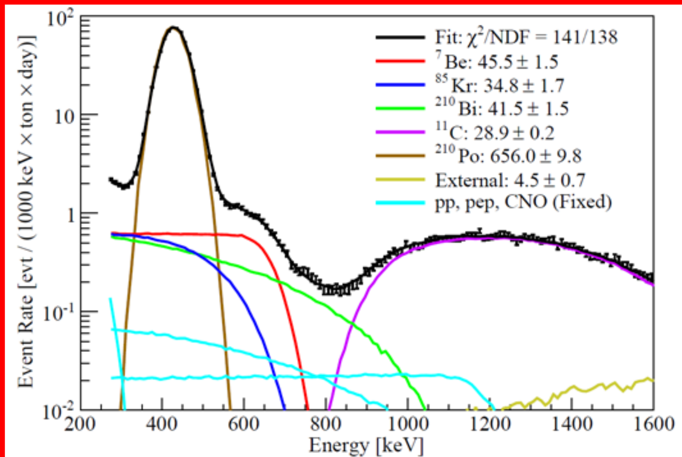

pep ν and limit on CNO ν

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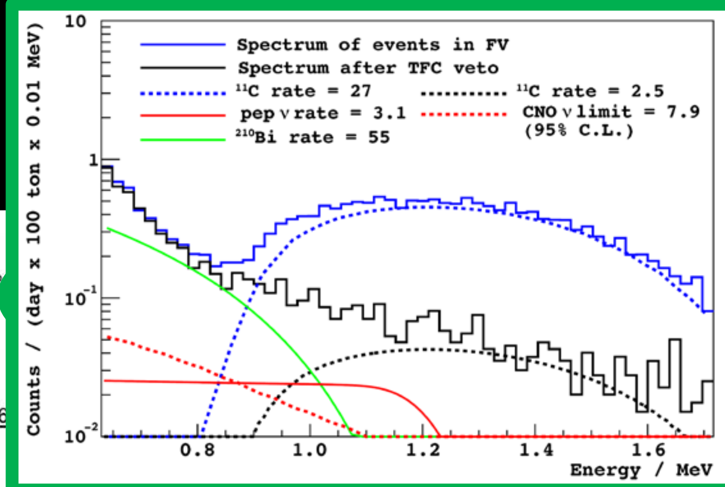

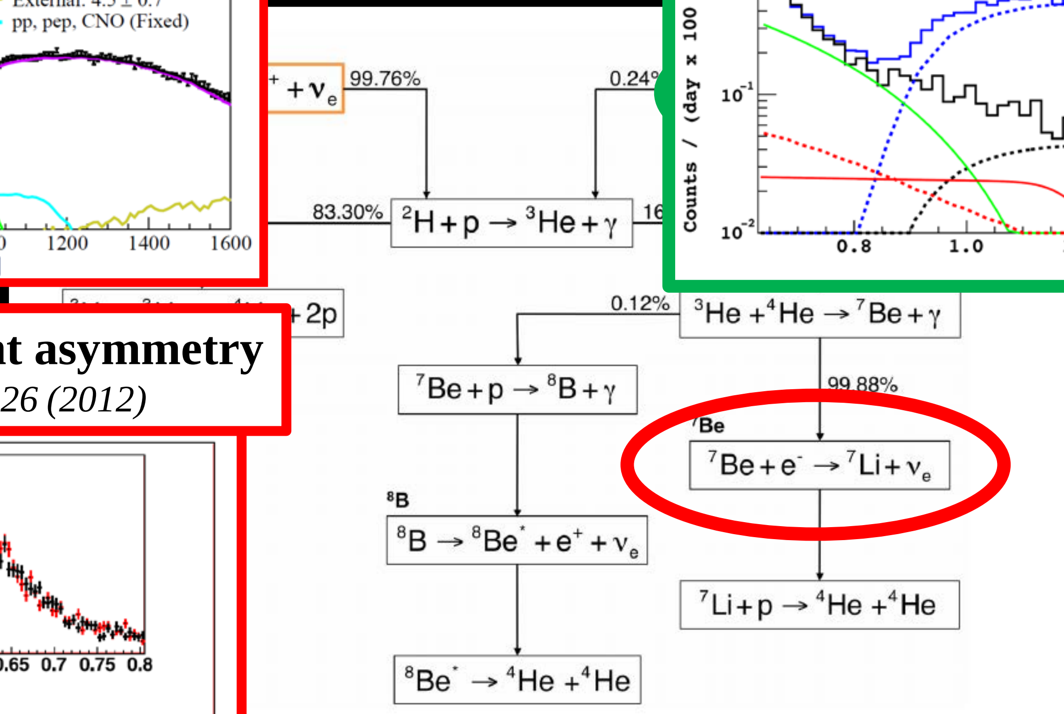

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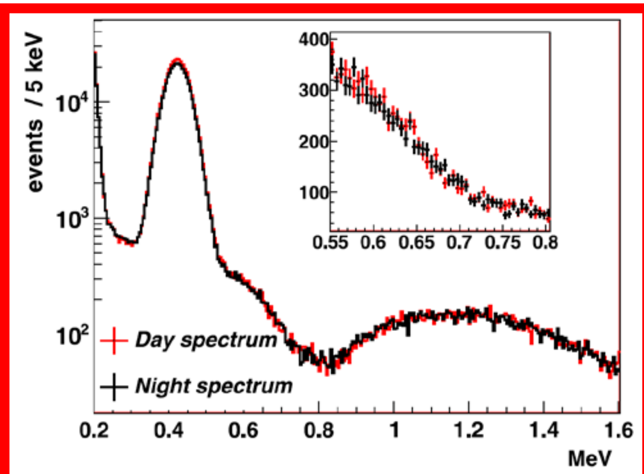

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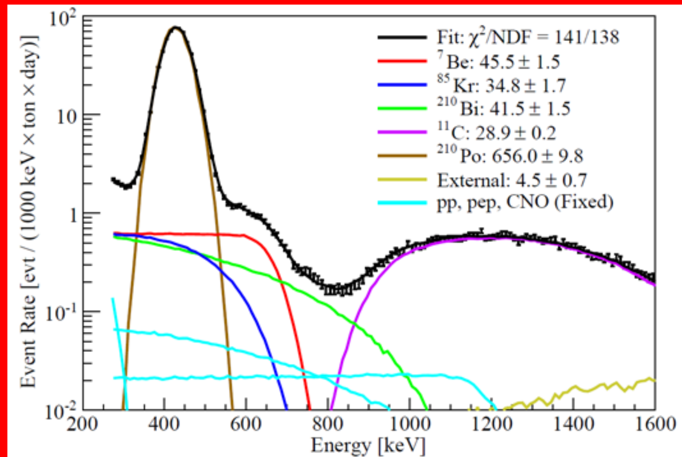

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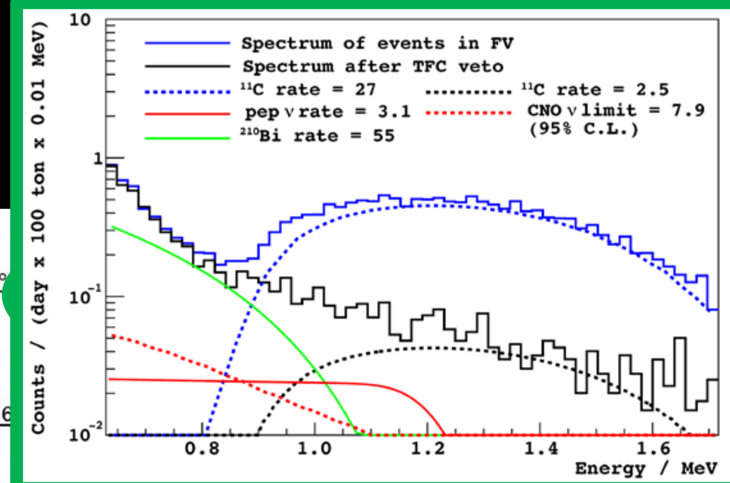

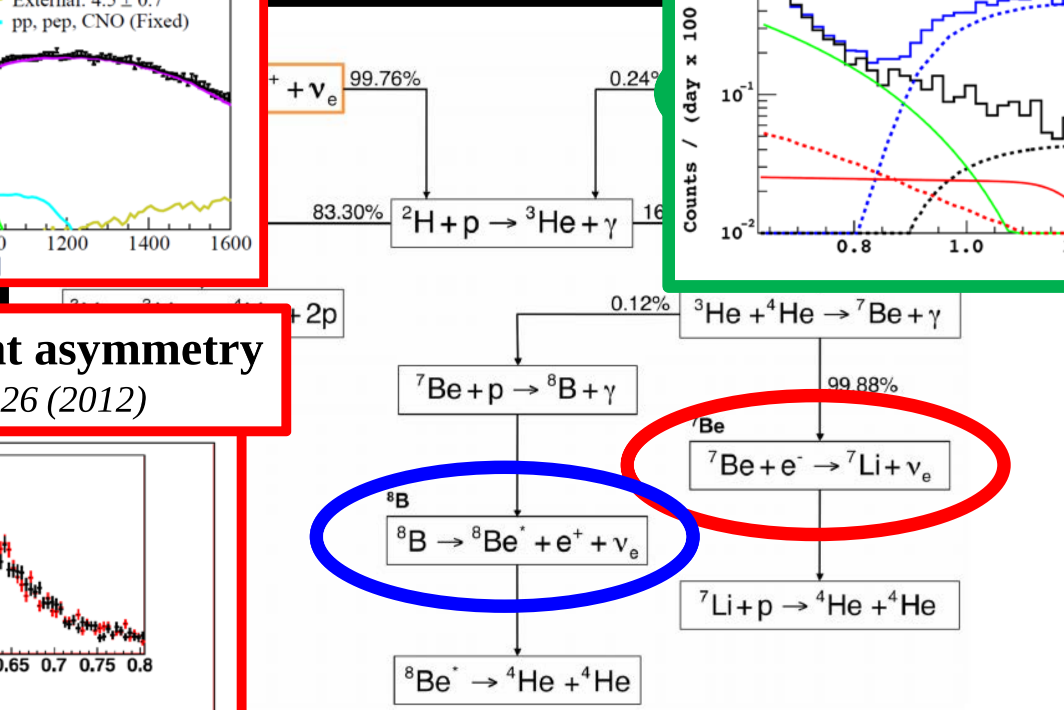

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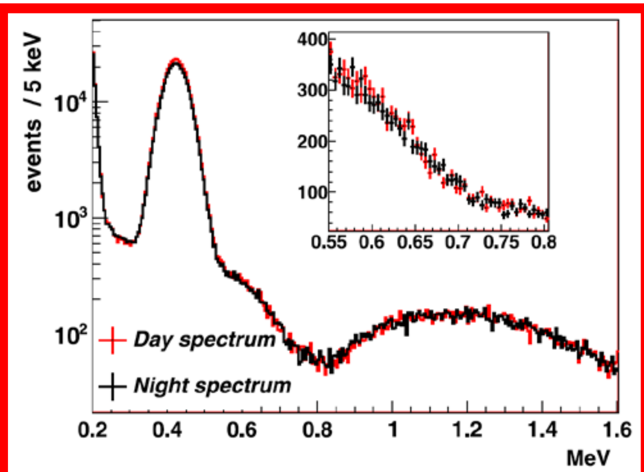

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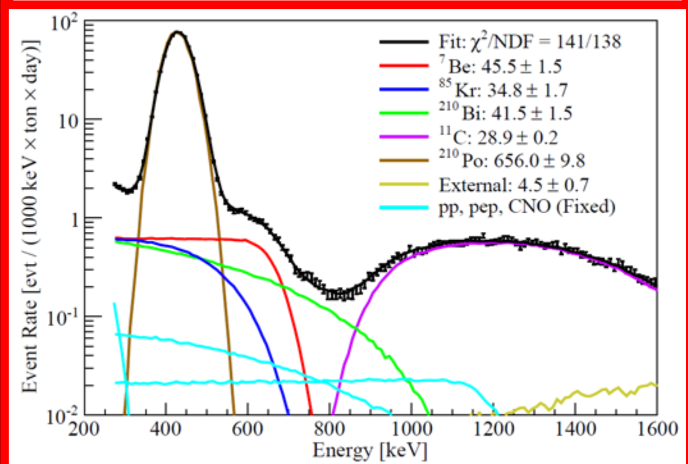

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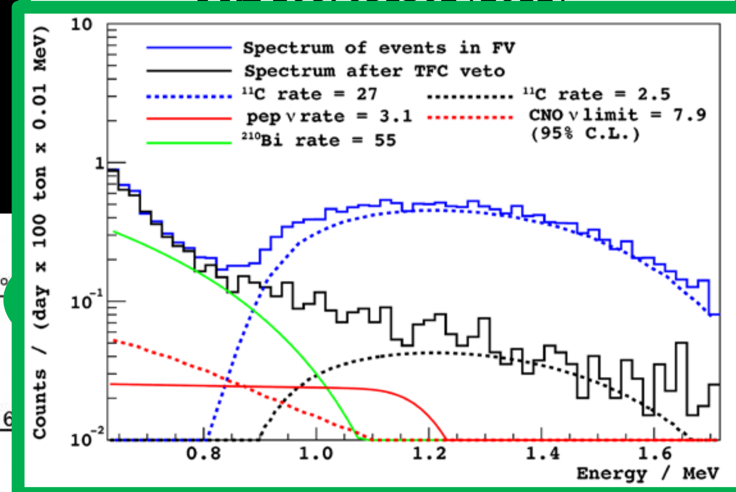

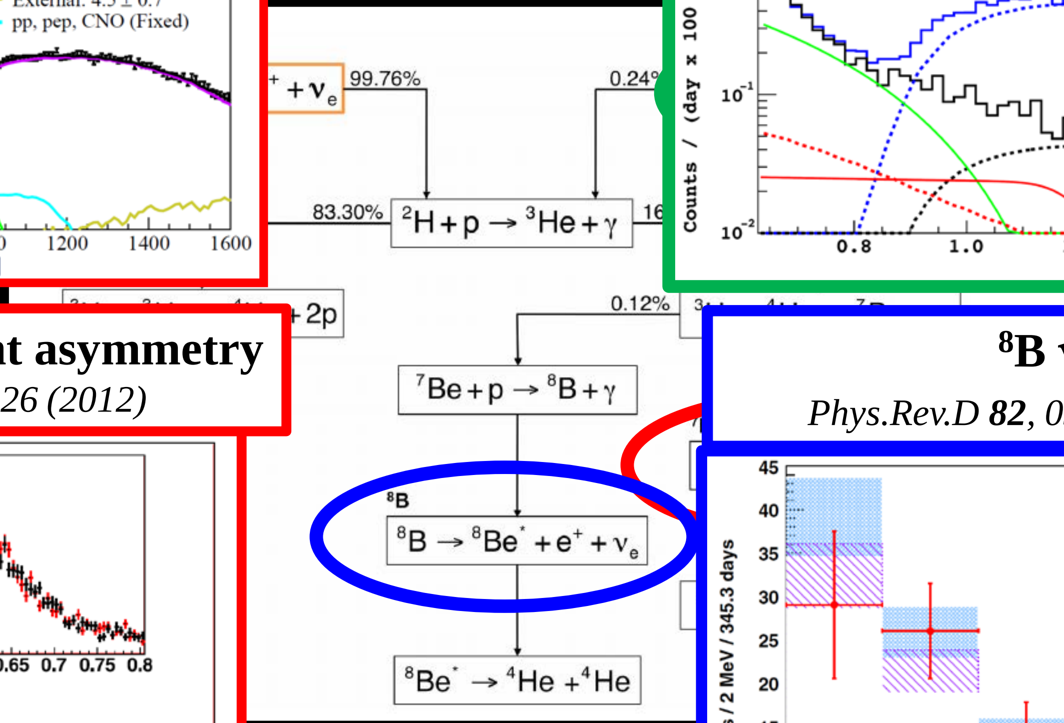

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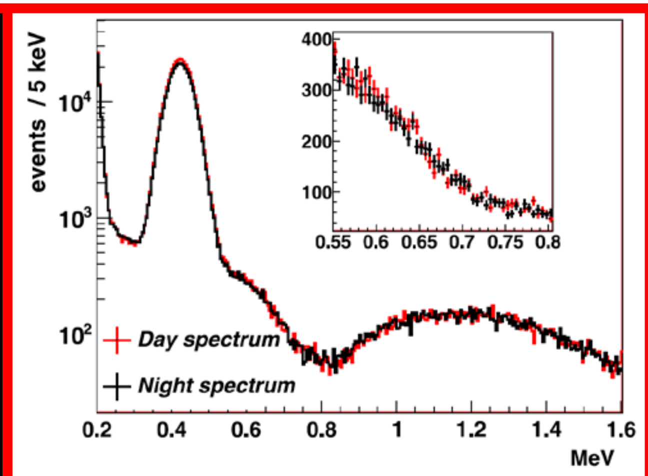

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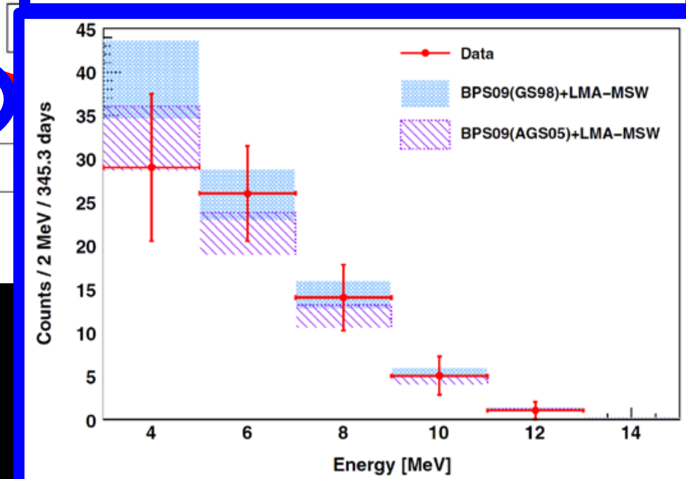
*Phys.Rev.D **82**, 0330066 (2010)*



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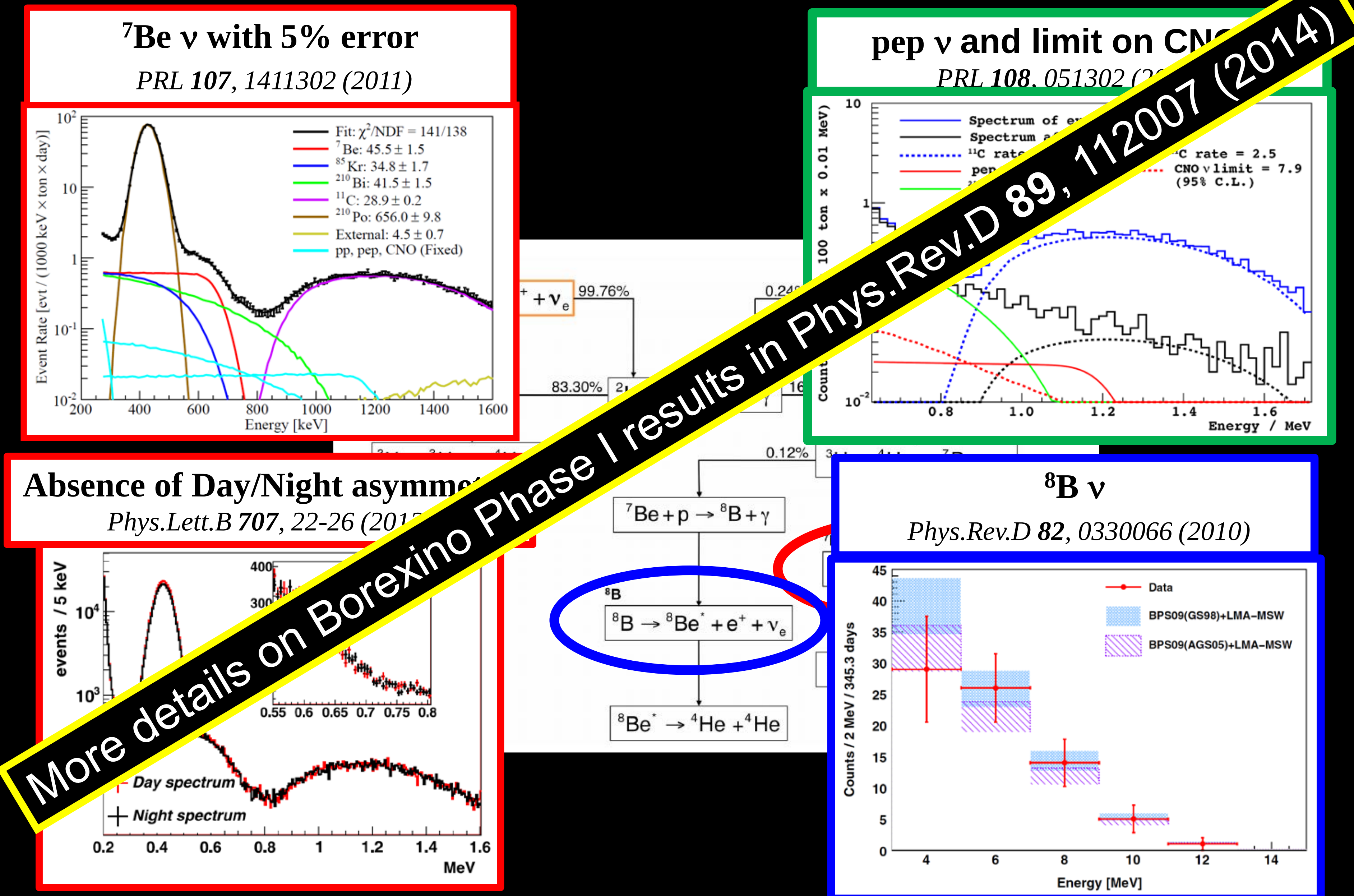
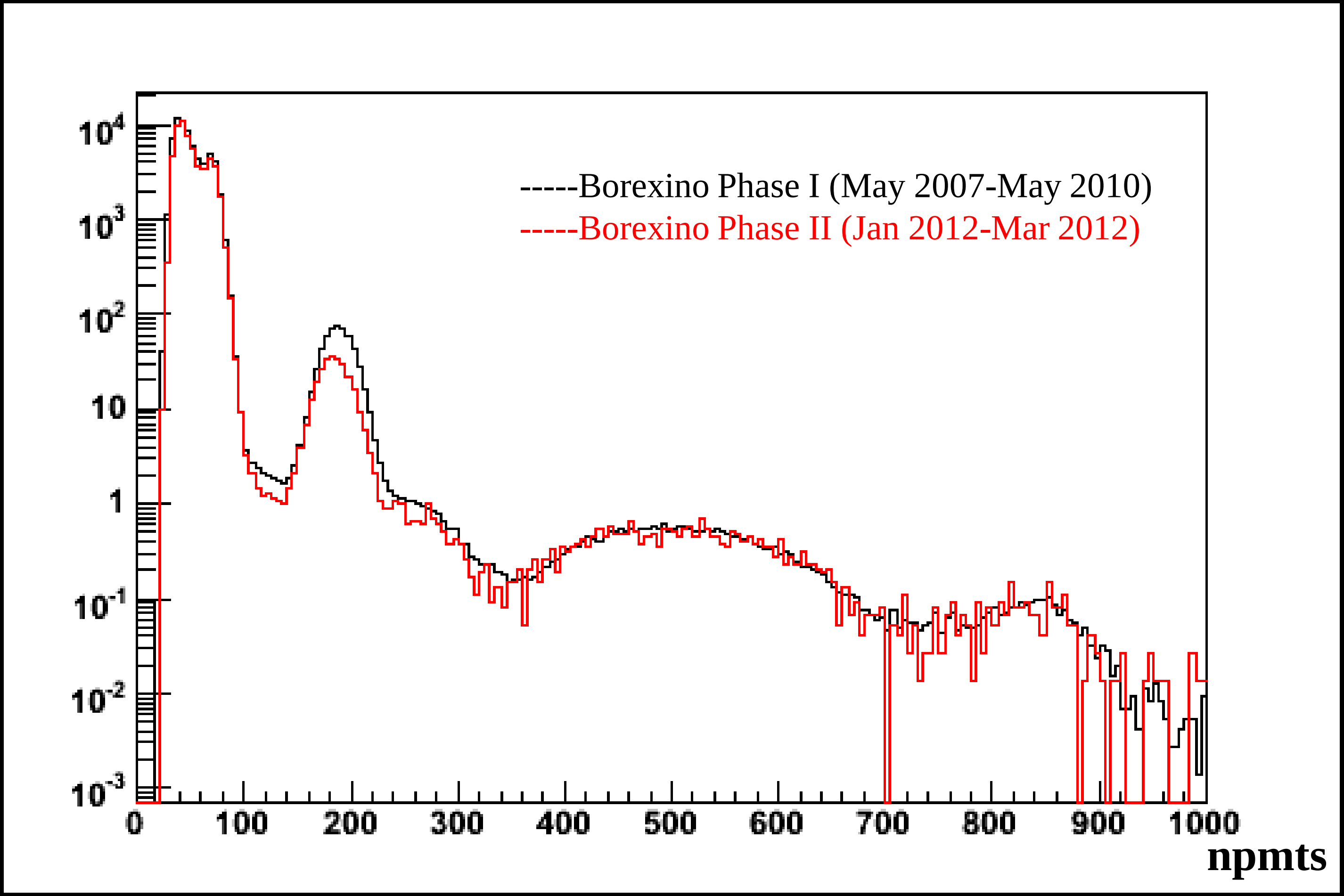


Borexino Phase 2: new challenges

Comparison between Phase 1 and Phase 2 data



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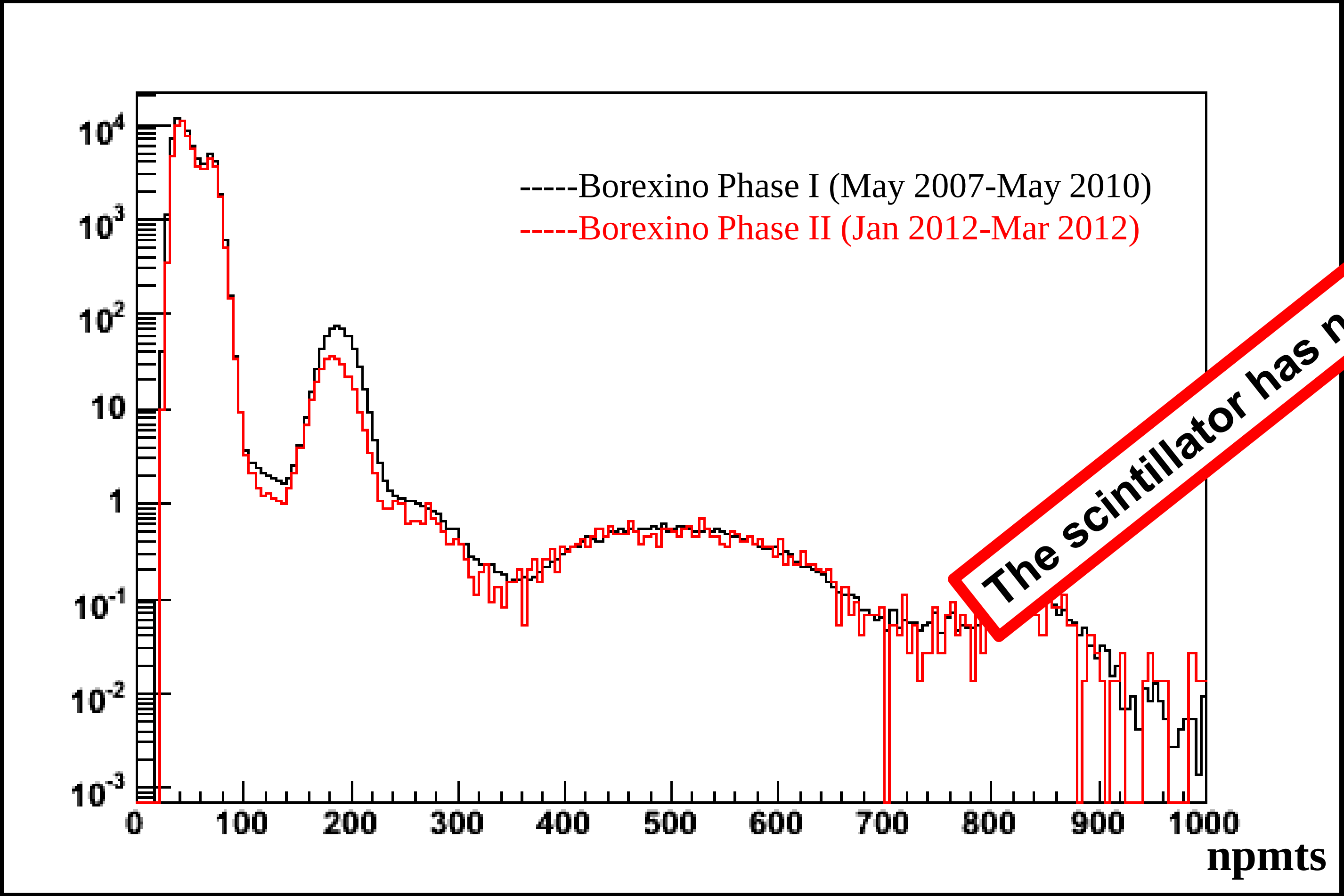

The scintillator has never been so clean!

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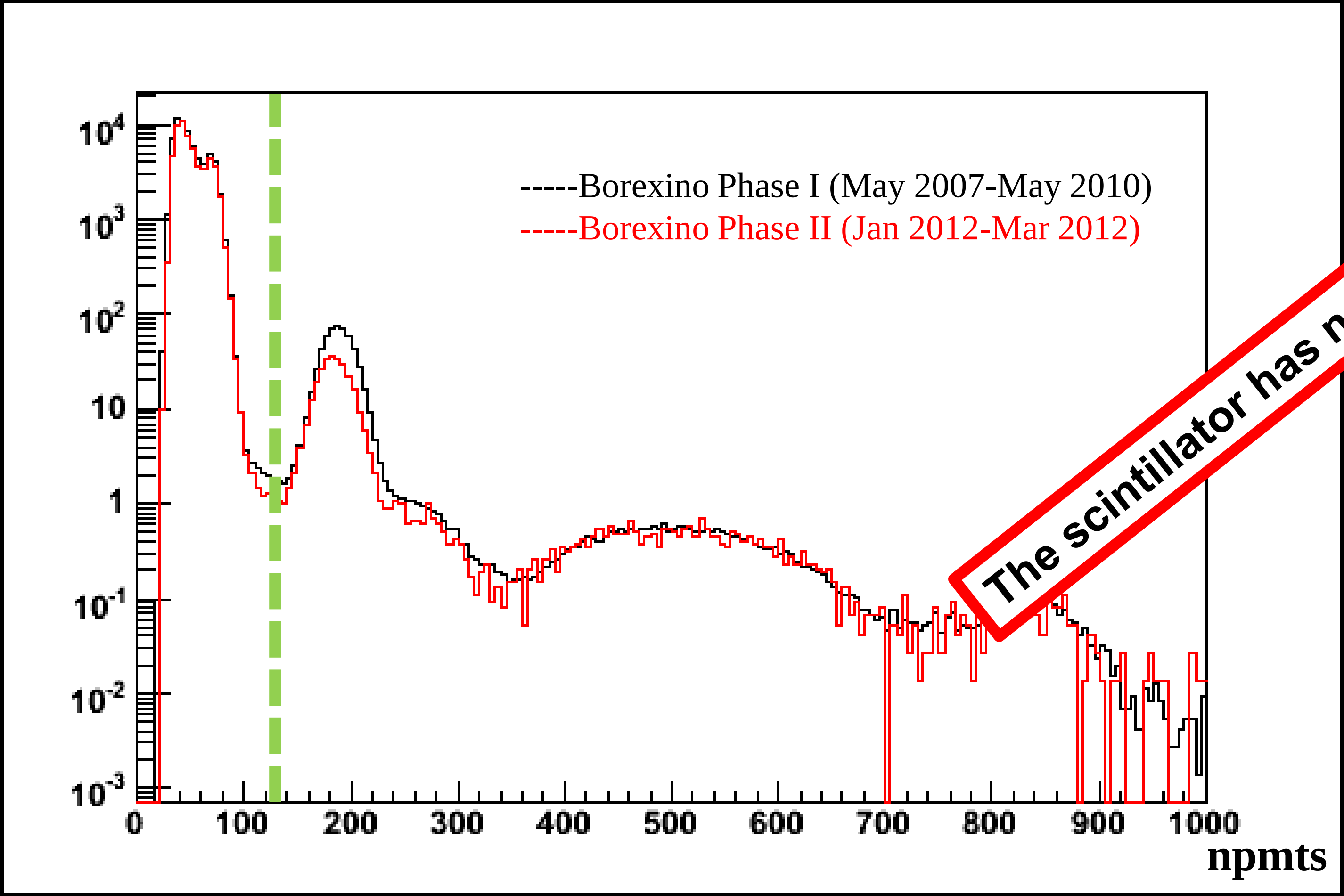

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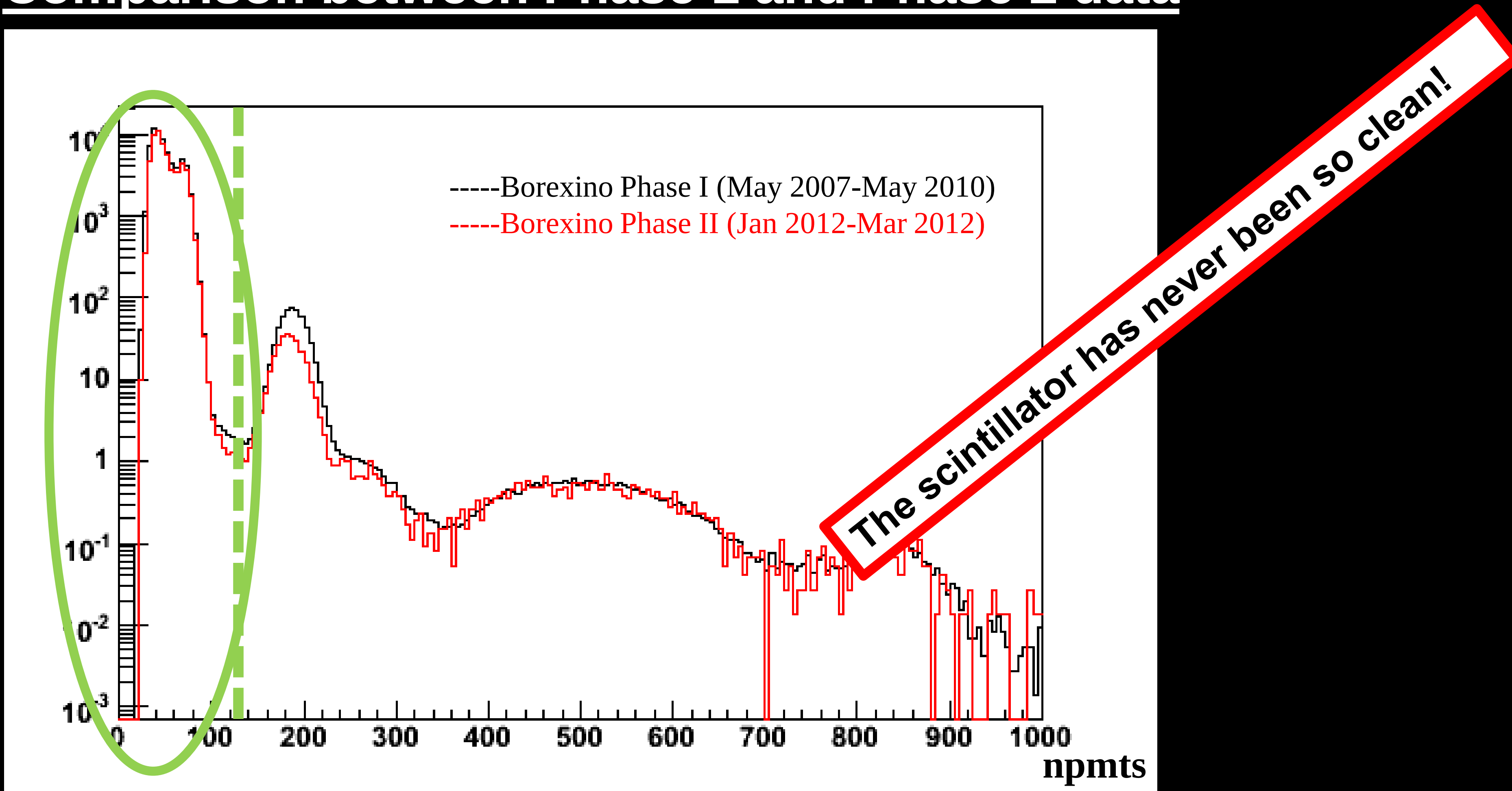

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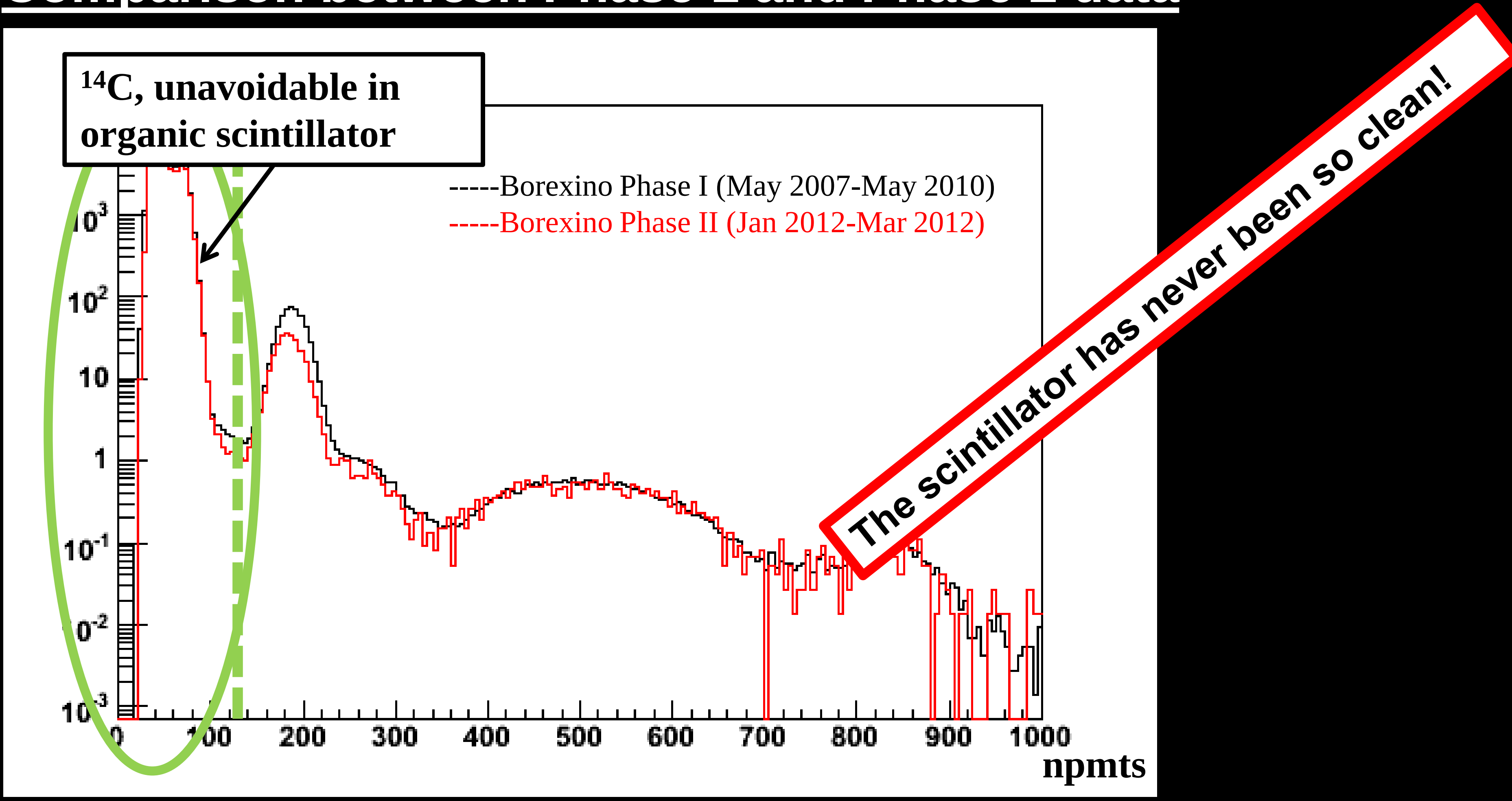

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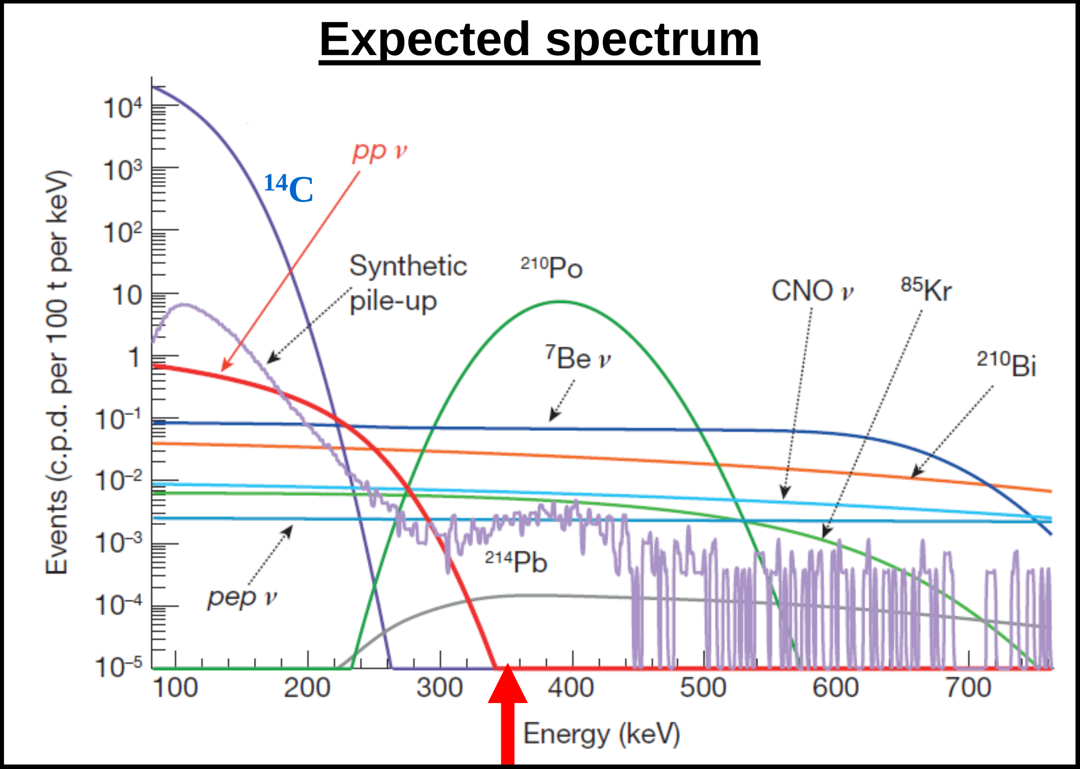

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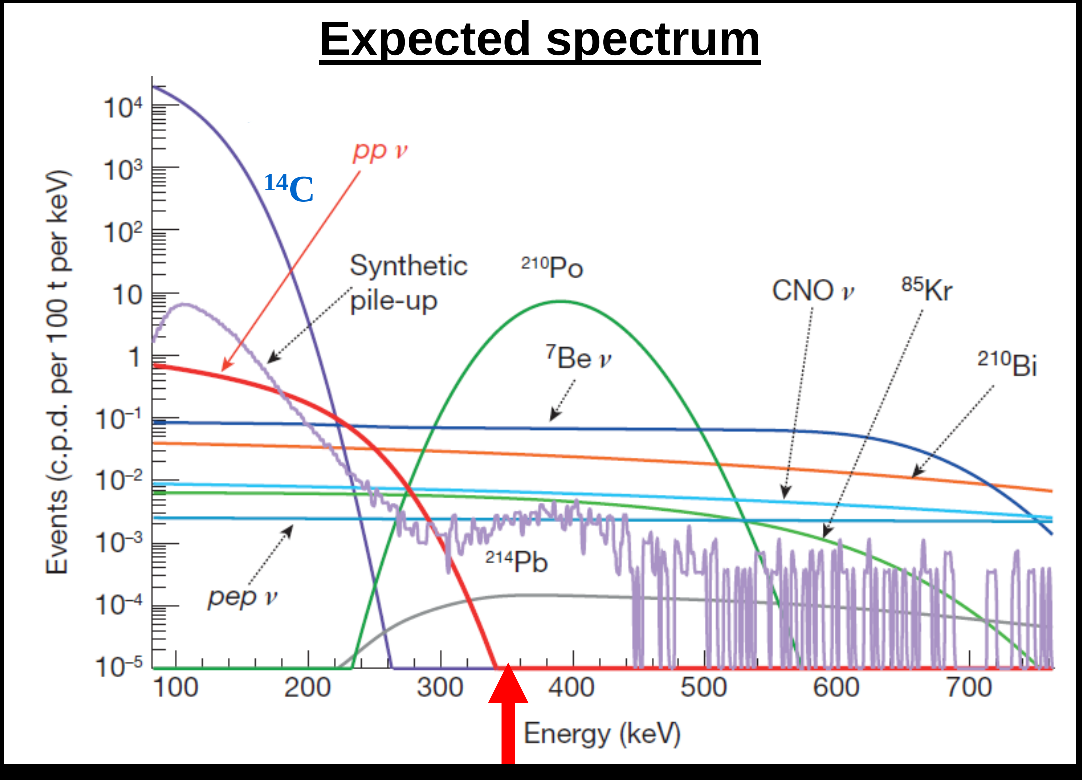

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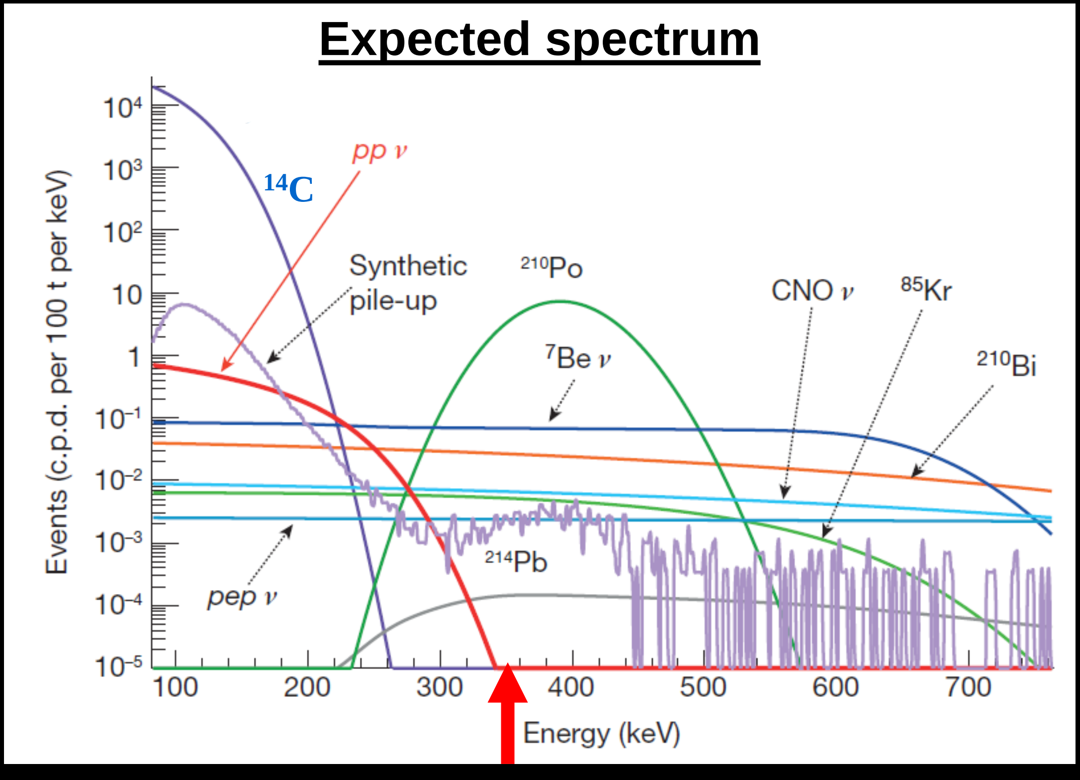

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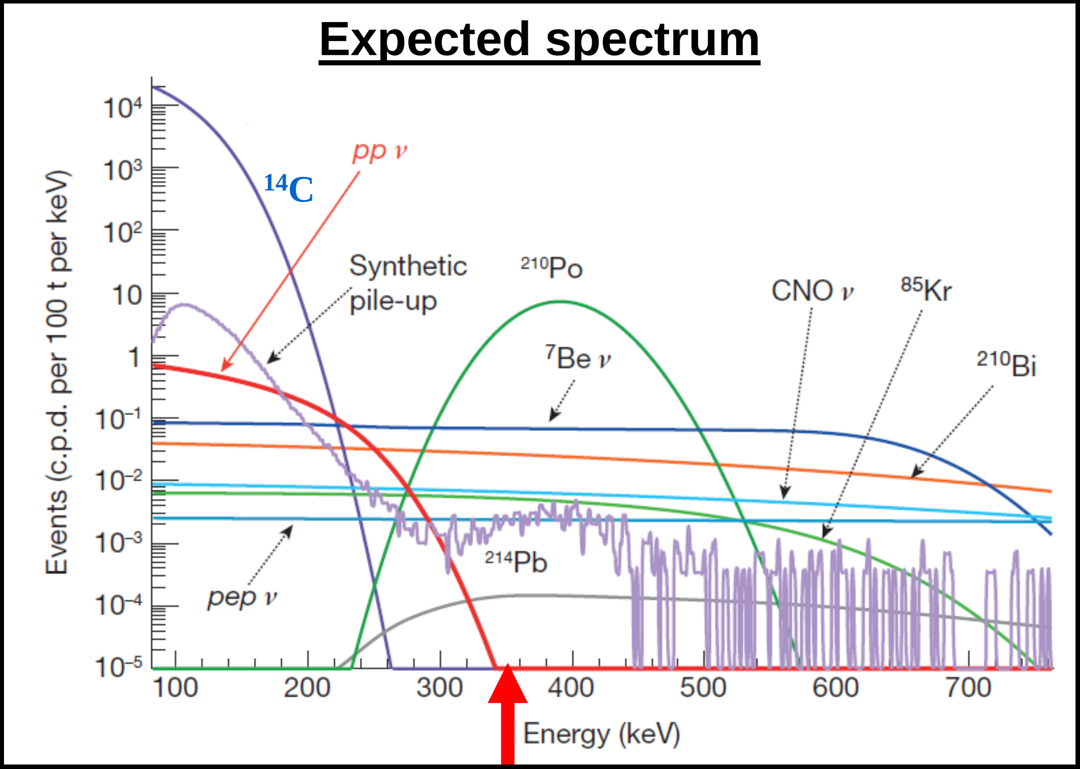

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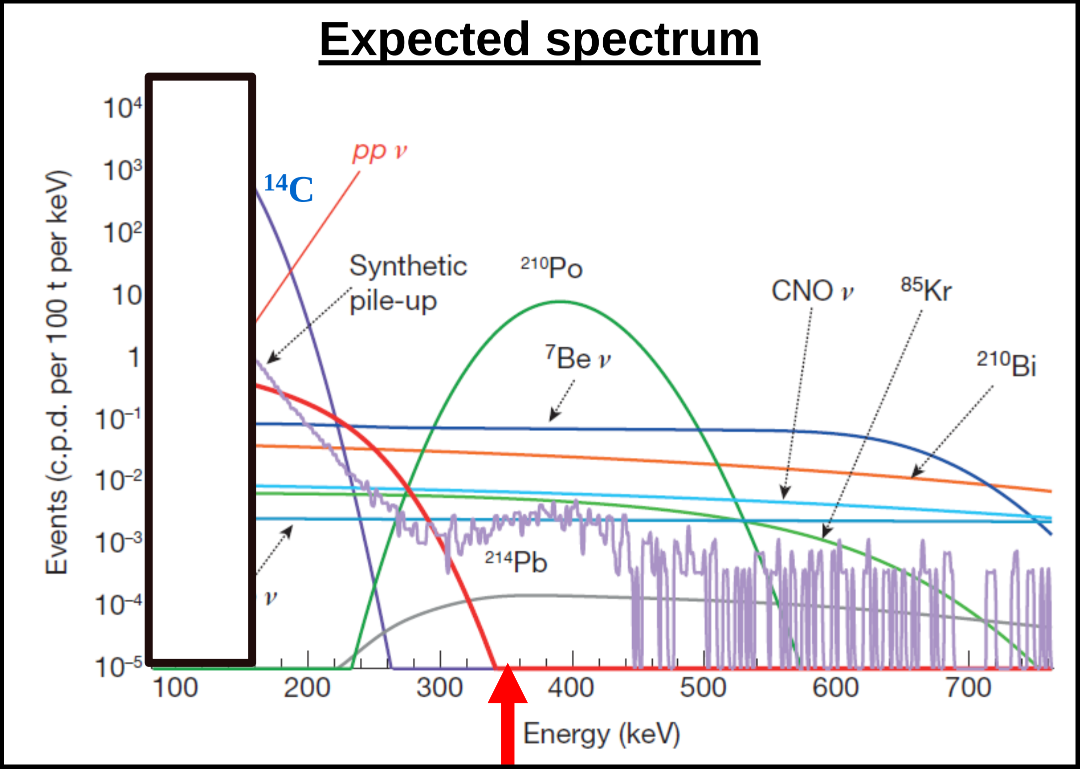

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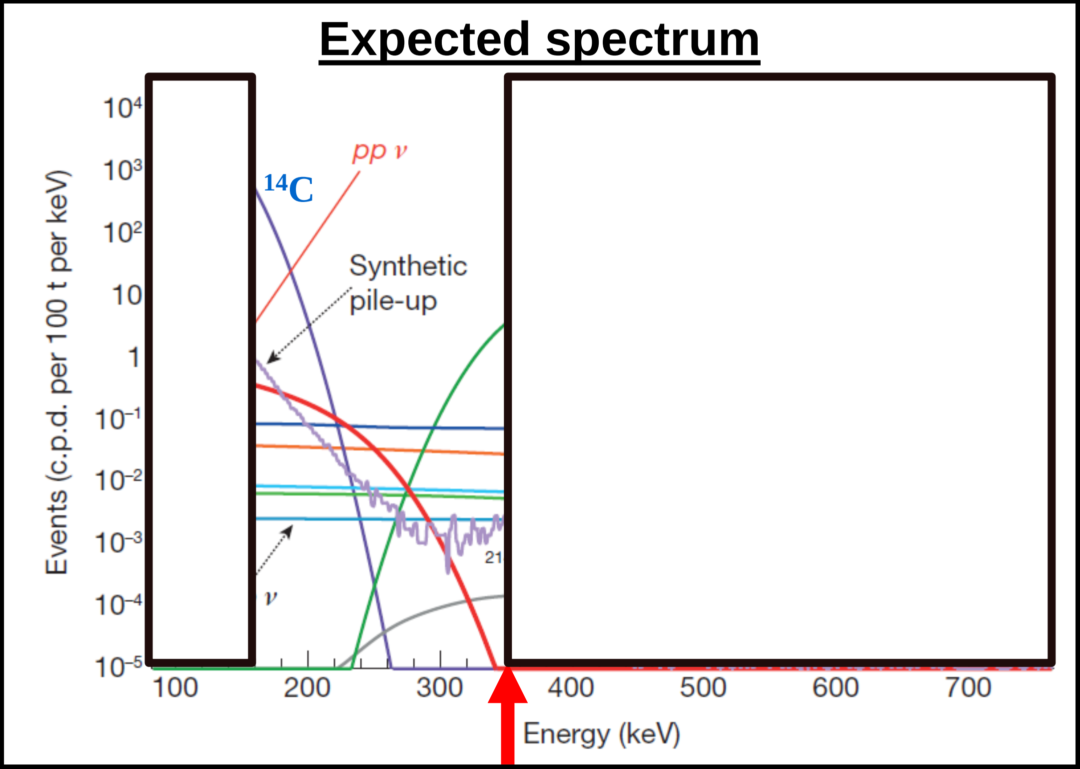

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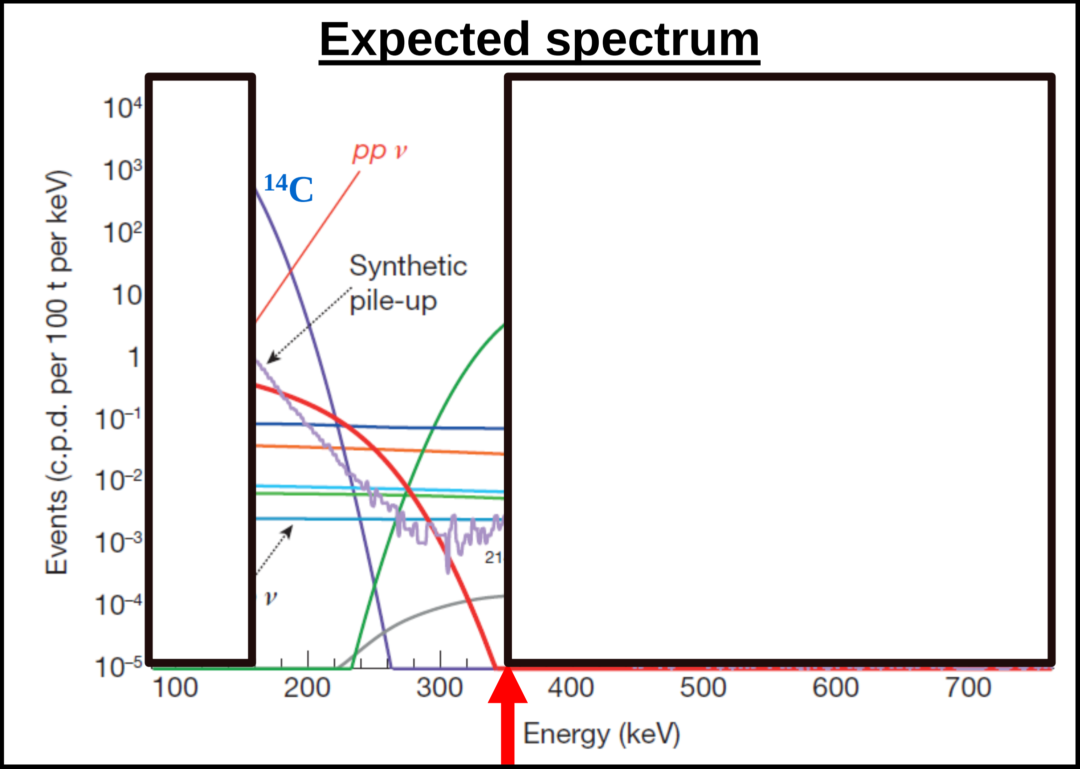

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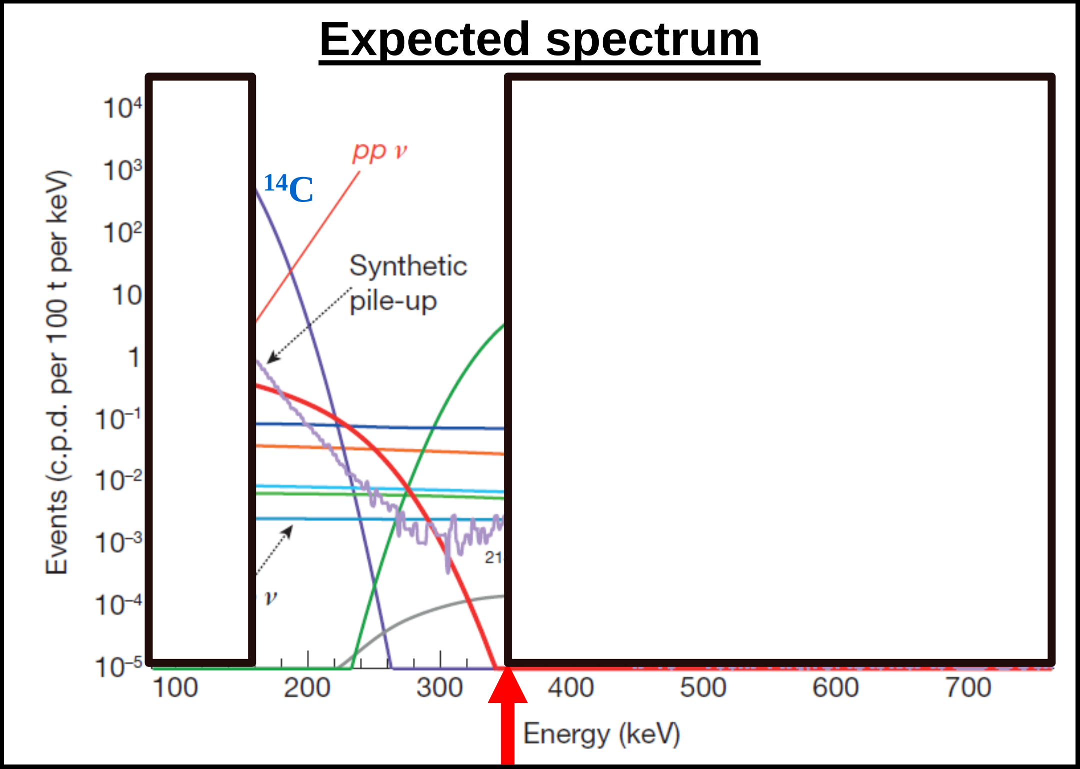

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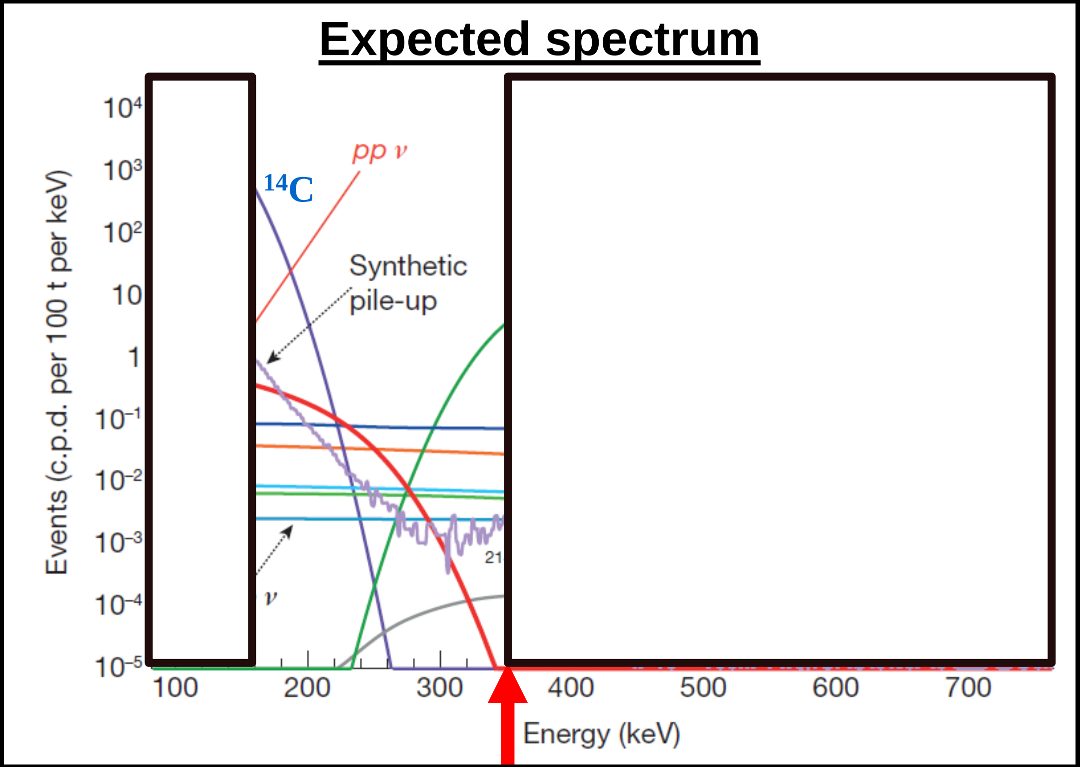

A spectral fit is needed to disentangle the contributions of signal and background;

It is crucial to know precisely the spectral shapes of signal and backgrounds;

Search for pp-neutrinos: challenges

Spectral shapes are affected by the detector response:

- Spectral deformation (both signal and backgrounds) due to several effects (threshold, dark noise);
- Energy scale and resolution issues at low energies (quenching..);

Detector response at low energy assessed by combining calibration data and MonteCarlo simulations;

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Independent determination of the rate of the main backgrounds (^{14}C and pile-up) in order to constrain them in the fit;

- ^{14}C rate determined from an independent class of events less affected by the trigger threshold (2° cluster events);
- Pile-up rate and shape determined by a data-driven method (synthetic pile-up);

Search for pp-neutrinos : ^{14}C and pile-up

Search for pp-neutrinos : ^{14}C and pile-up

Independent determination of the ^{14}C rate: *2-nd cluster* events

- Events occurring in the last part of the acquisition window (triggered by the previous event);
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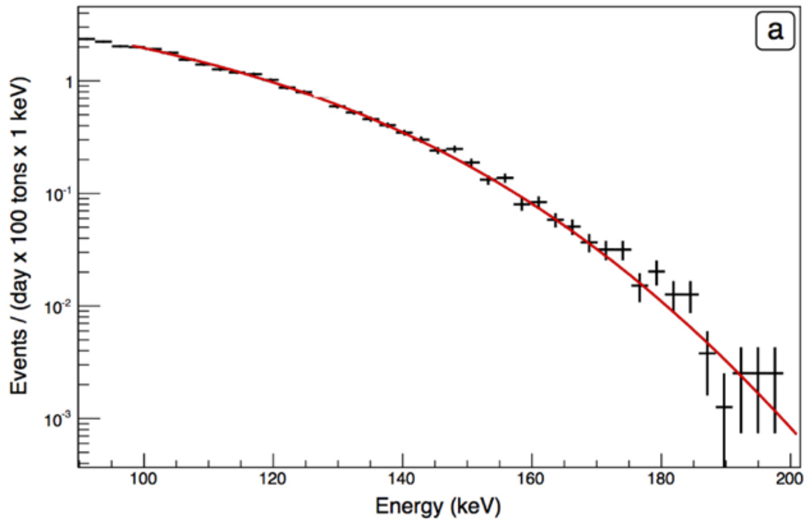
- **^{14}C rate = (40 ± 1)Bq/100tons**



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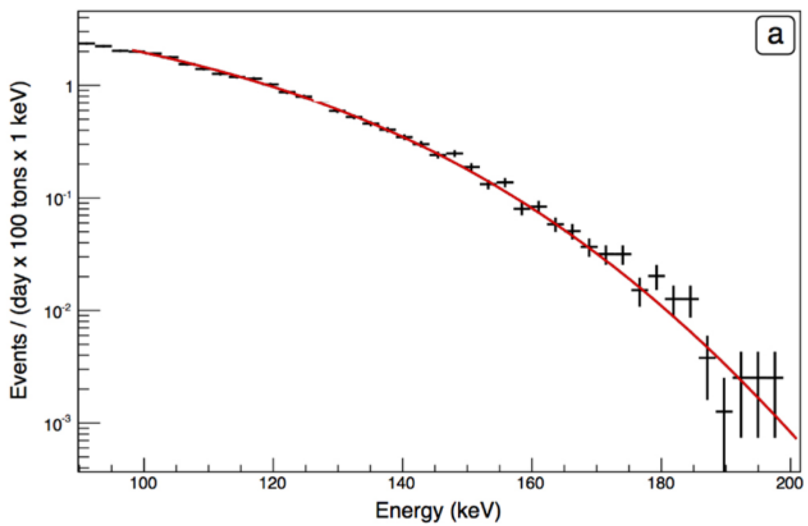
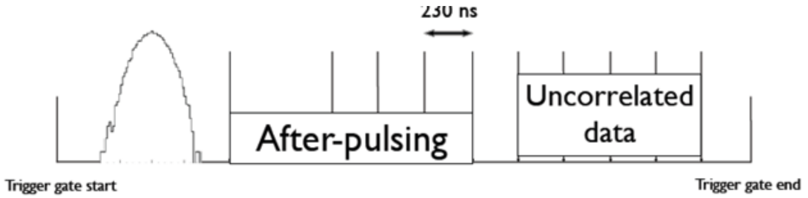
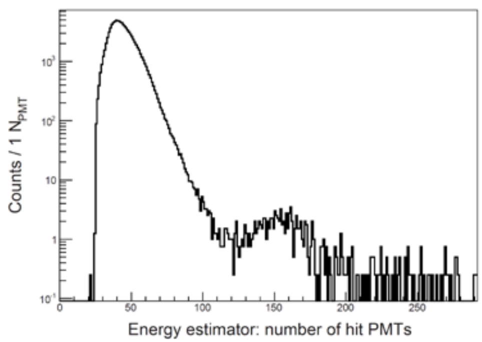


Independent determination of the pile-up shape and rate: *synthetic pile-up*

- Data-driven method;
- To construct pile-up, real-events are artificially overlapped with random data samples;





Pile-up rate(^{14}C -^{14}C)= (154 $\pm$10) cpd/100tons;

Search for pp-neutrinos: results

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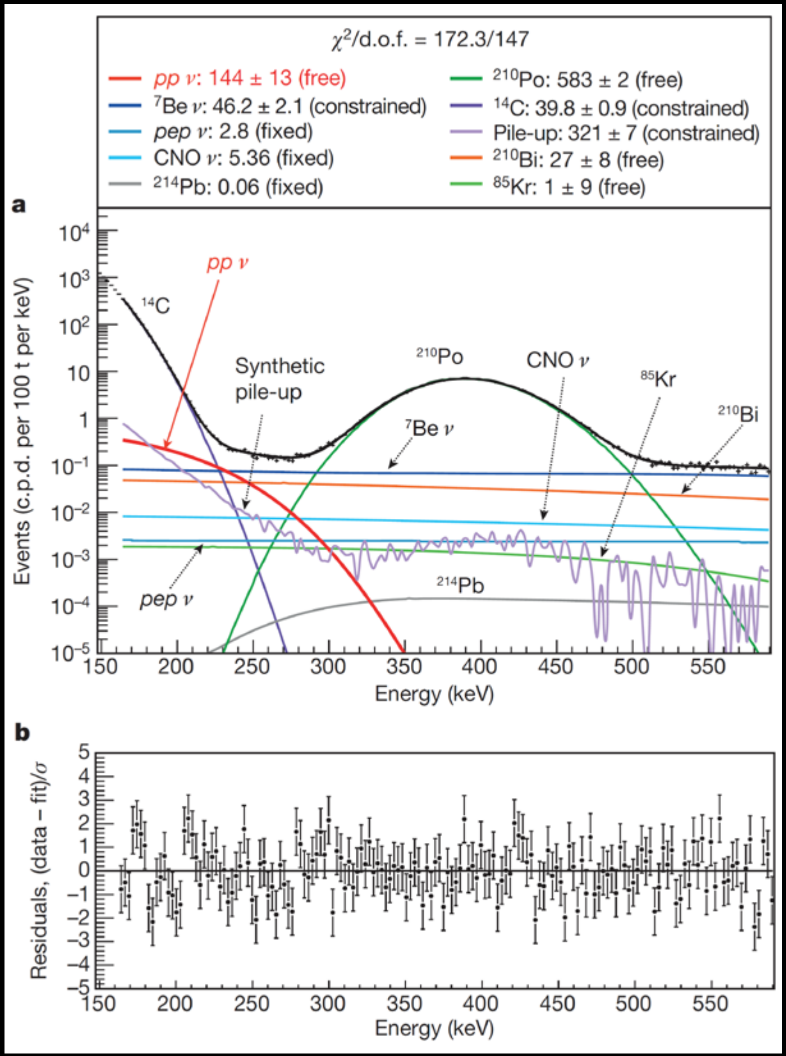

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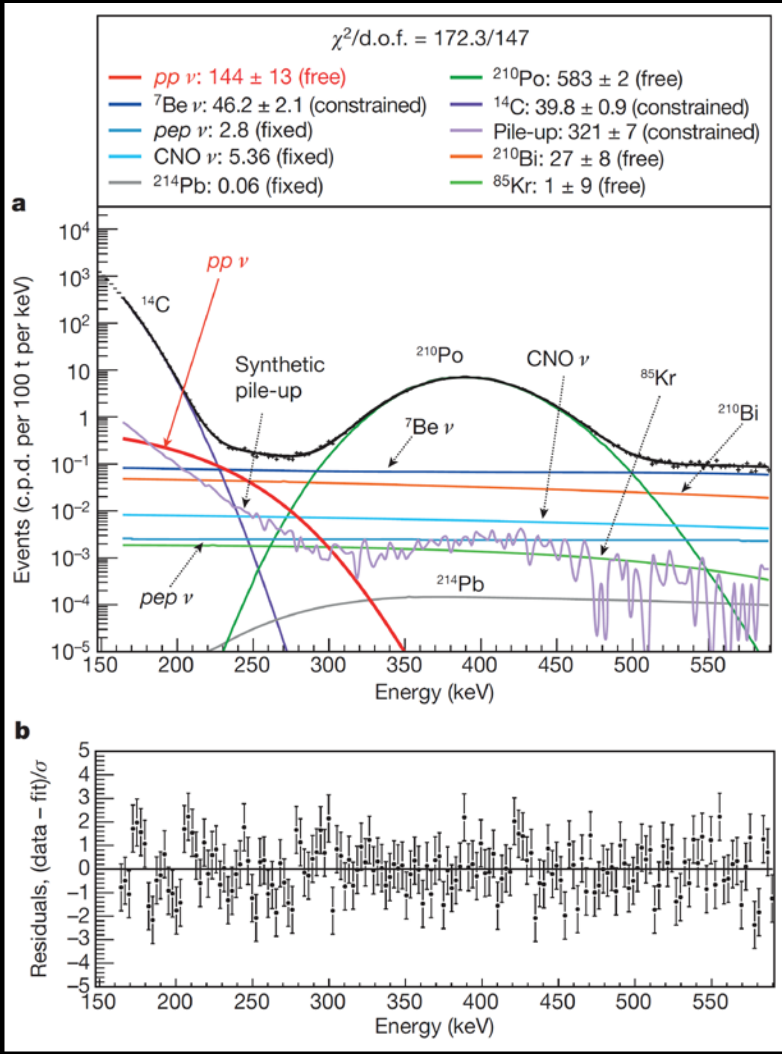

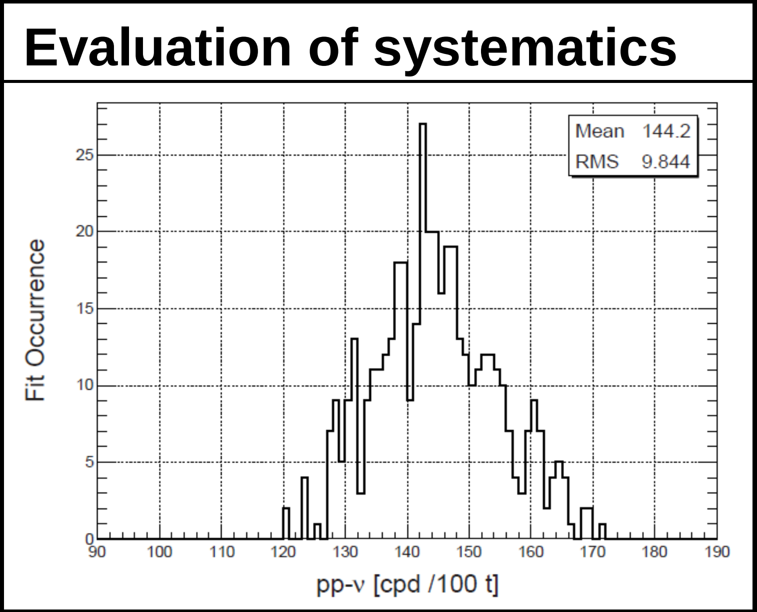

- Distribution of the best fit values for pp-rate obtained varying some of the fit conditions (fit range, energy estimator...)

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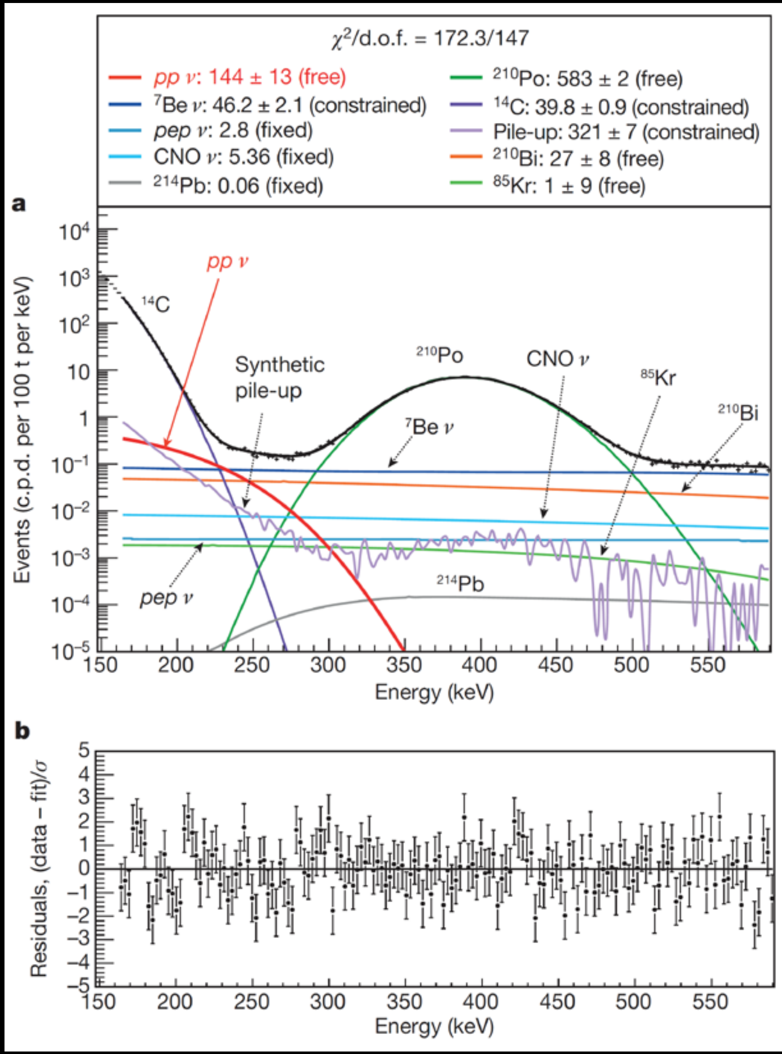
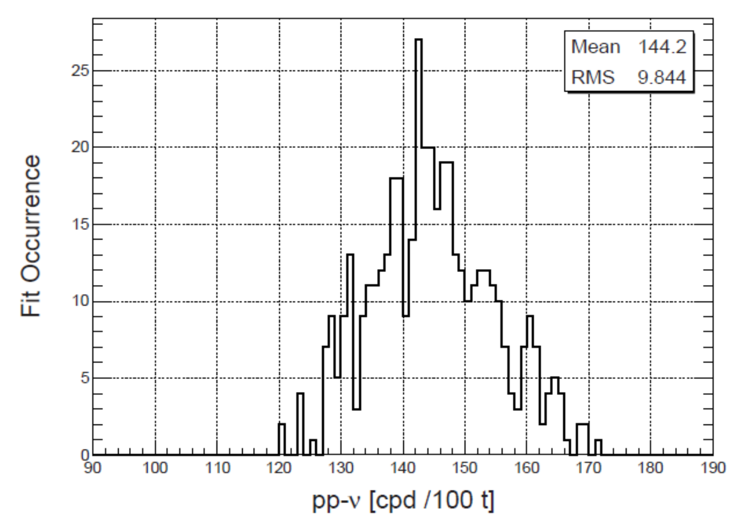


Evaluation of systematics



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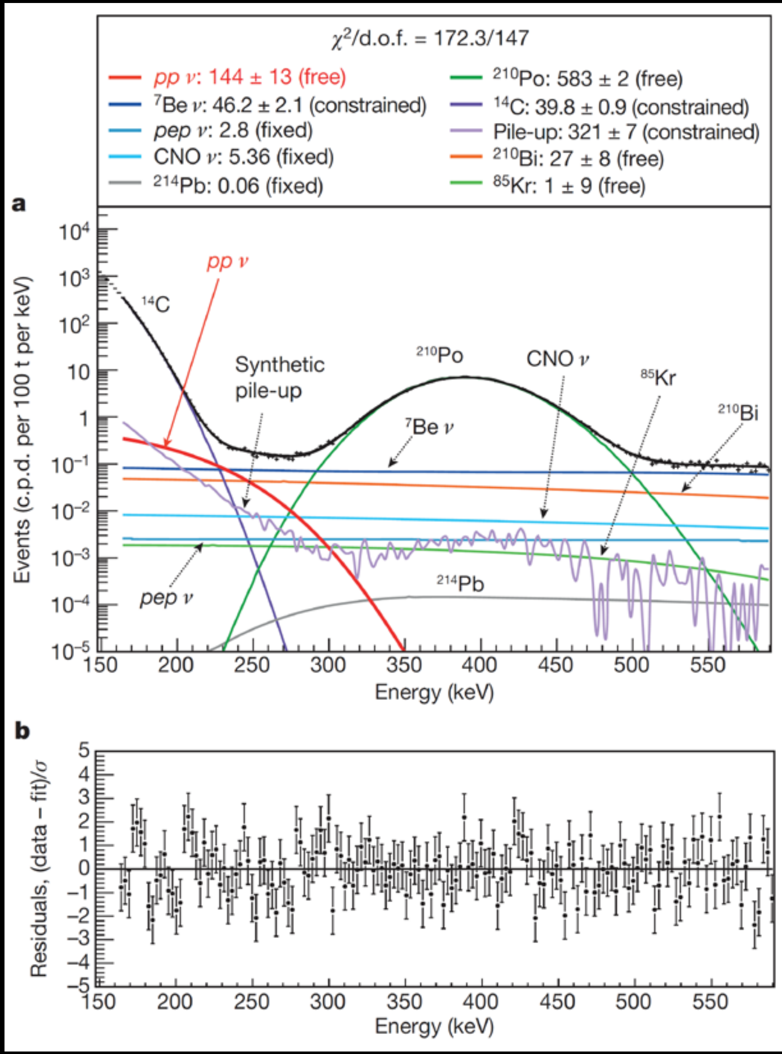

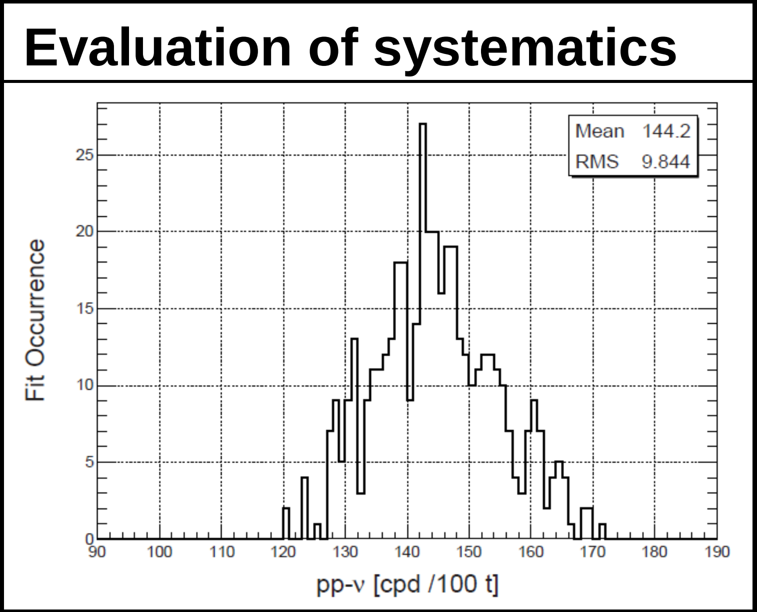

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Predicted rate for SSM (High Metallicity) + MSW-LMA = 131 ± 2 cpd/100tons

Results: pp neutrino flux

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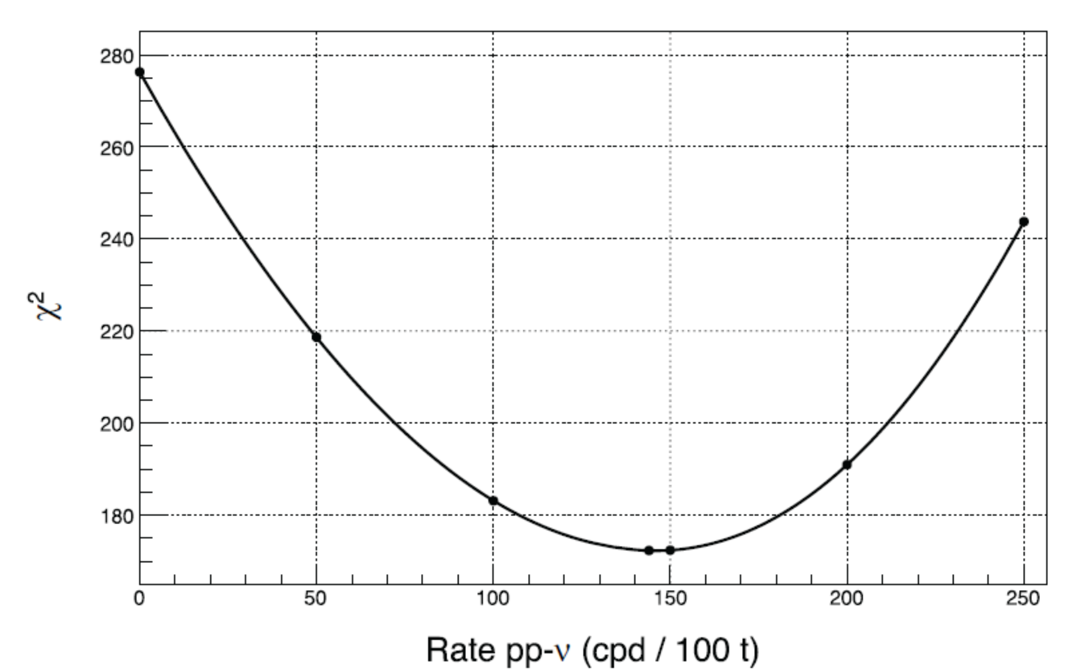

Zero pp count is excluded at 10σ

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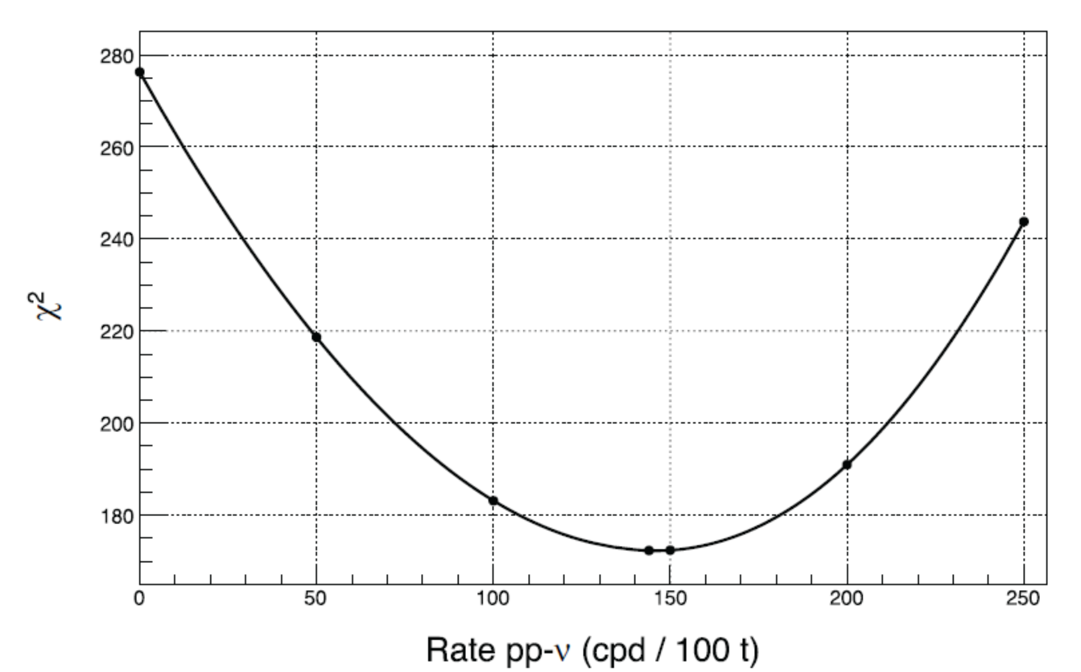

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$$\Phi_{pp} = \begin{cases} (6.6 \pm 0.7) \times 10^{10}\,\mathrm{cm}^{-2} s^{-1} & \text{measured} \\ (5.98 \pm 0.04) \times 10^{10}\,\mathrm{cm}^{-2} s^{-1} & \text{expected (high - Z)} \\ (6.03 \pm 0.04) \times 10^{10}\,\mathrm{cm}^{-2} s^{-1} & \text{expected (low - Z)} \end{cases}$$

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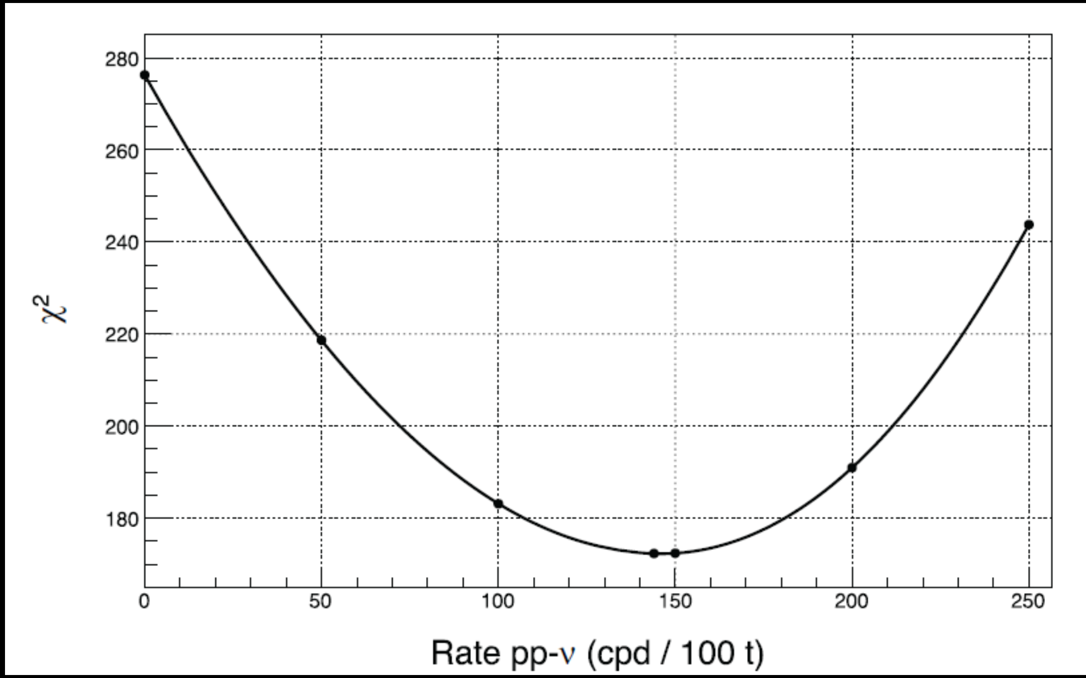

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Luminosity in neutrinos consistent with luminosity in photons

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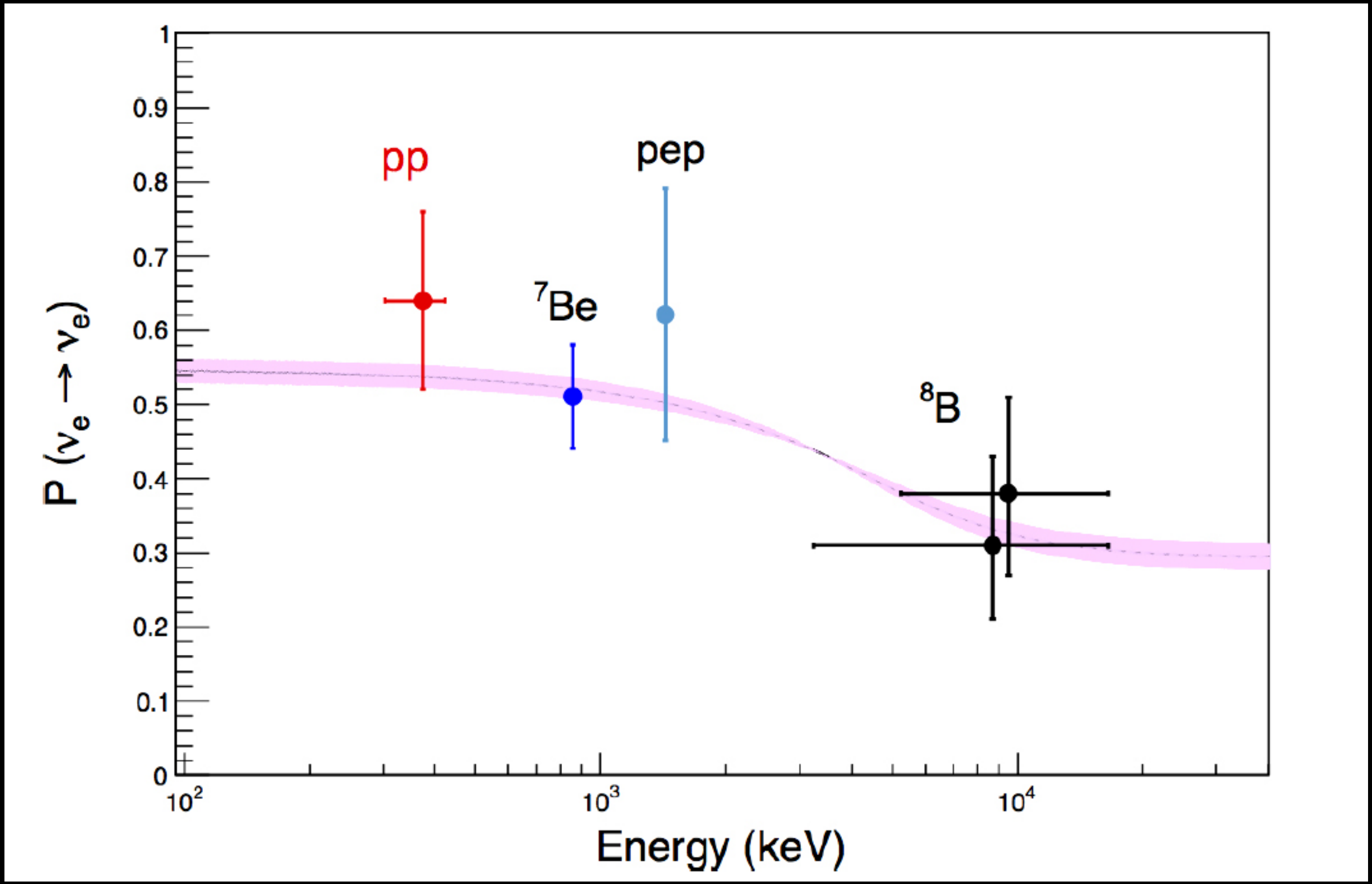

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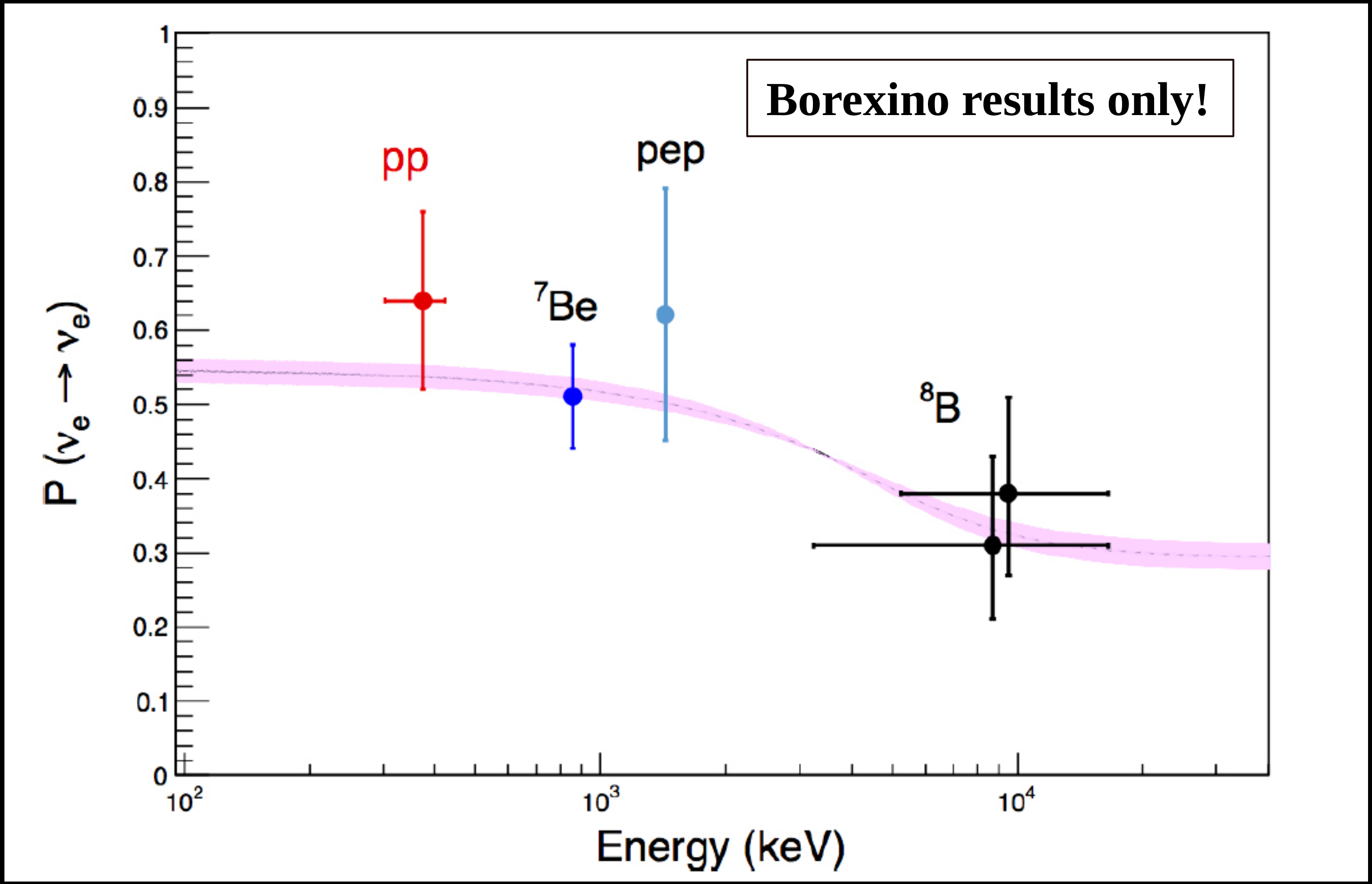
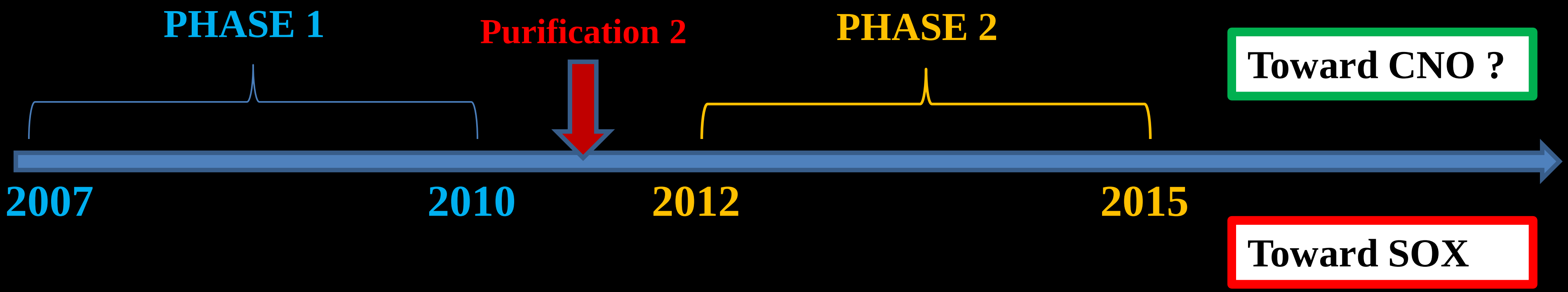


Conclusions and outlook: what next?



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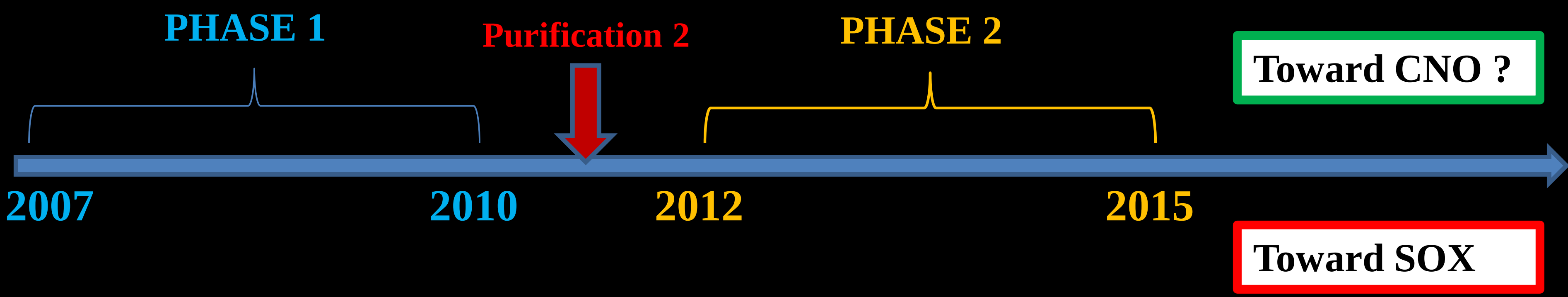

Complete analysis of Phase 2 data

- calibration campaign to further reduce systematic uncertainties;
- improved measurement of ^{7}Be ν (3% error? challenging!) and other solar neutrino families;
- Attempt to measure CNO ν: **very** challenging!

Sterile neutrino program (SOX)

- In 2016 the ^{144}Ce-^{144}Pr anti-neutrino source will arrive in Gran Sasso and the sterile neutrino program will start;

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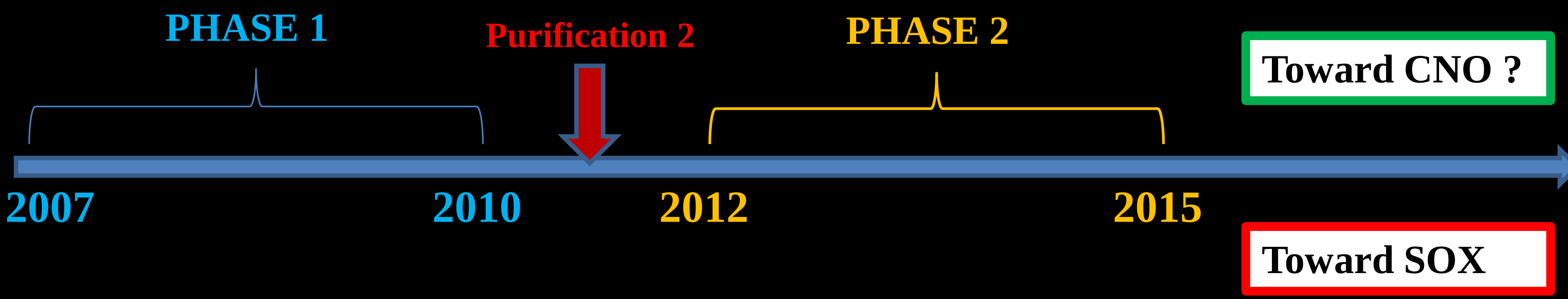

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the Borexino Collaboration

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Thank you!

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