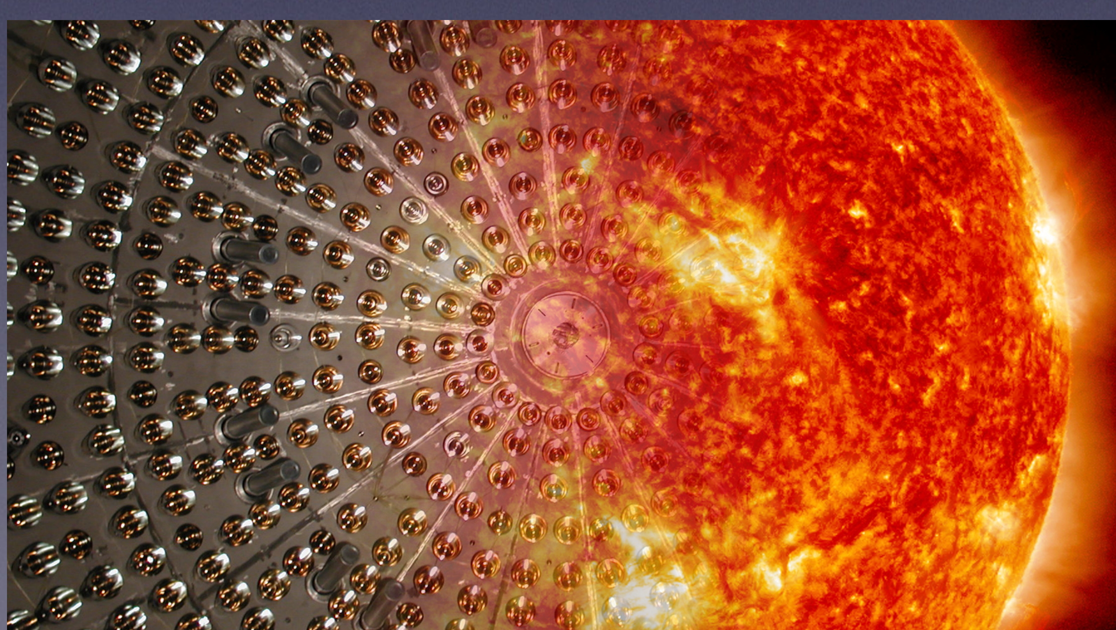
Neutrinos from the primary proton-proton fusion in the Sun



Marco Pallavicini
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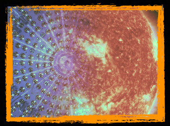
on behalf of Borexino Collaboration



Talk outline

- **Solar neutrino** physics AD 2014
  - A short introduction
  - Motivations for pp neutrino measurement
- Previous Borexino measurements on solar neutrinos
- Direct measurement of pp neutrinos
  - Technique
  - Result
  - Scientific implications

ARTICLE

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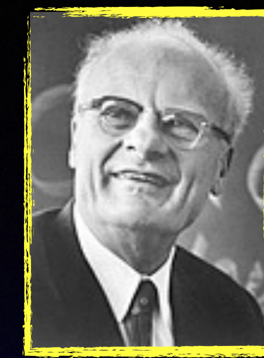
Neutrinos from the primary proton–proton fusion process in the Sun

Borexino Collaboration*

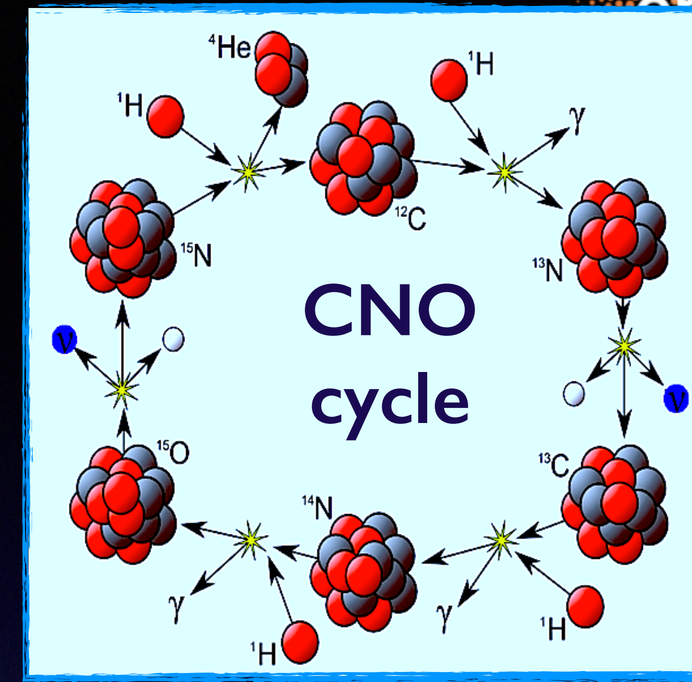
In the core of the Sun, energy is released through sequences of nuclear reactions that convert hydrogen into helium. The primary reaction is thought to be the fusion of two protons with the emission of a low-energy neutrino. These so-called *pp* neutrinos constitute nearly the entirety of the solar neutrino flux, vastly outnumbering those emitted in the reactions that follow. Although solar neutrinos from secondary processes have been observed, proving the nuclear origin of the Sun's energy and contributing to the discovery of neutrino oscillations, those from proton–proton fusion have hitherto eluded direct detection. Here we report spectral observations of *pp* neutrinos, demonstrating that about 99 per cent of the power of the Sun, 3.84×10^{33} ergs per second, is generated by the proton–proton fusion process.

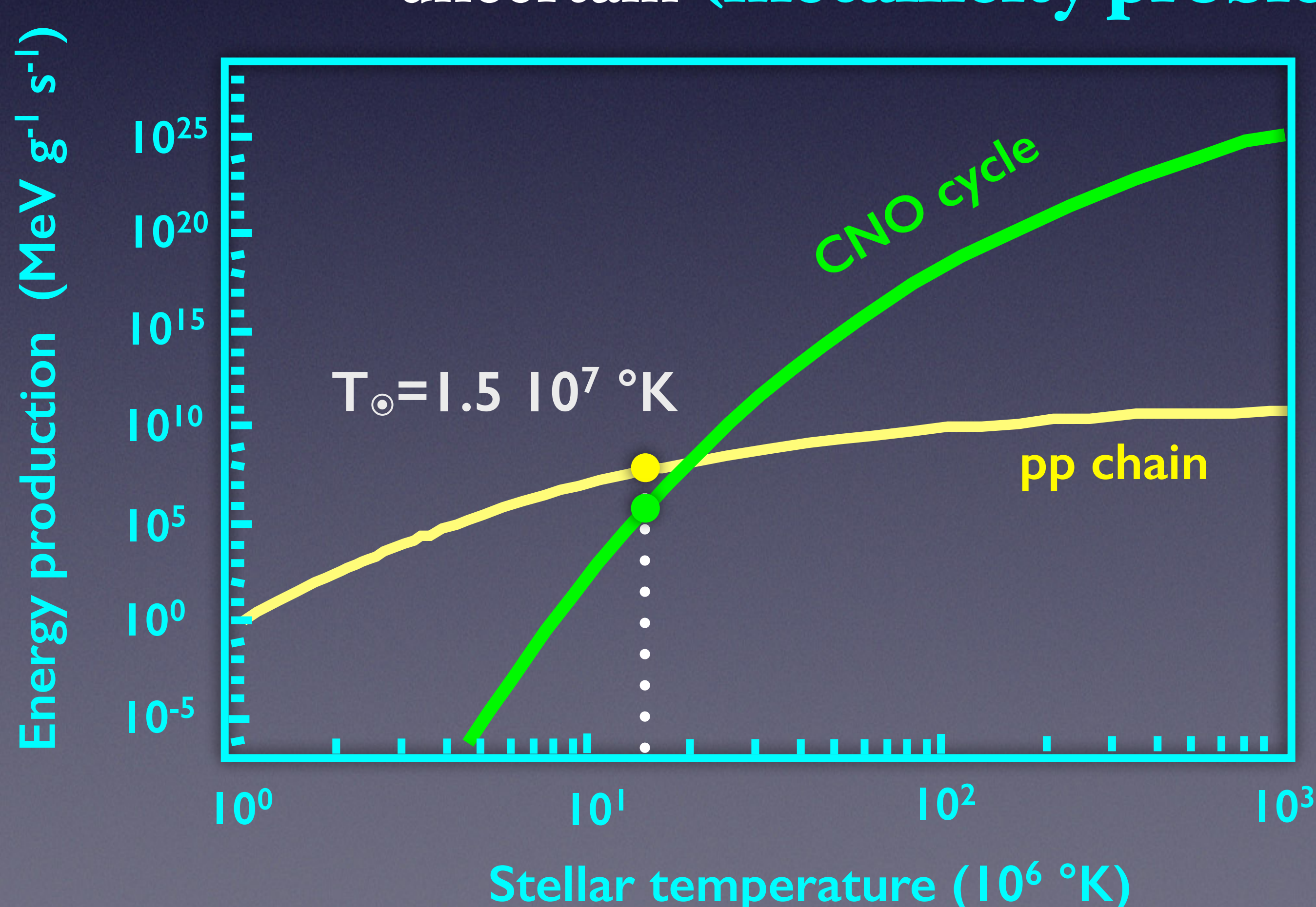
Solar neutrinos

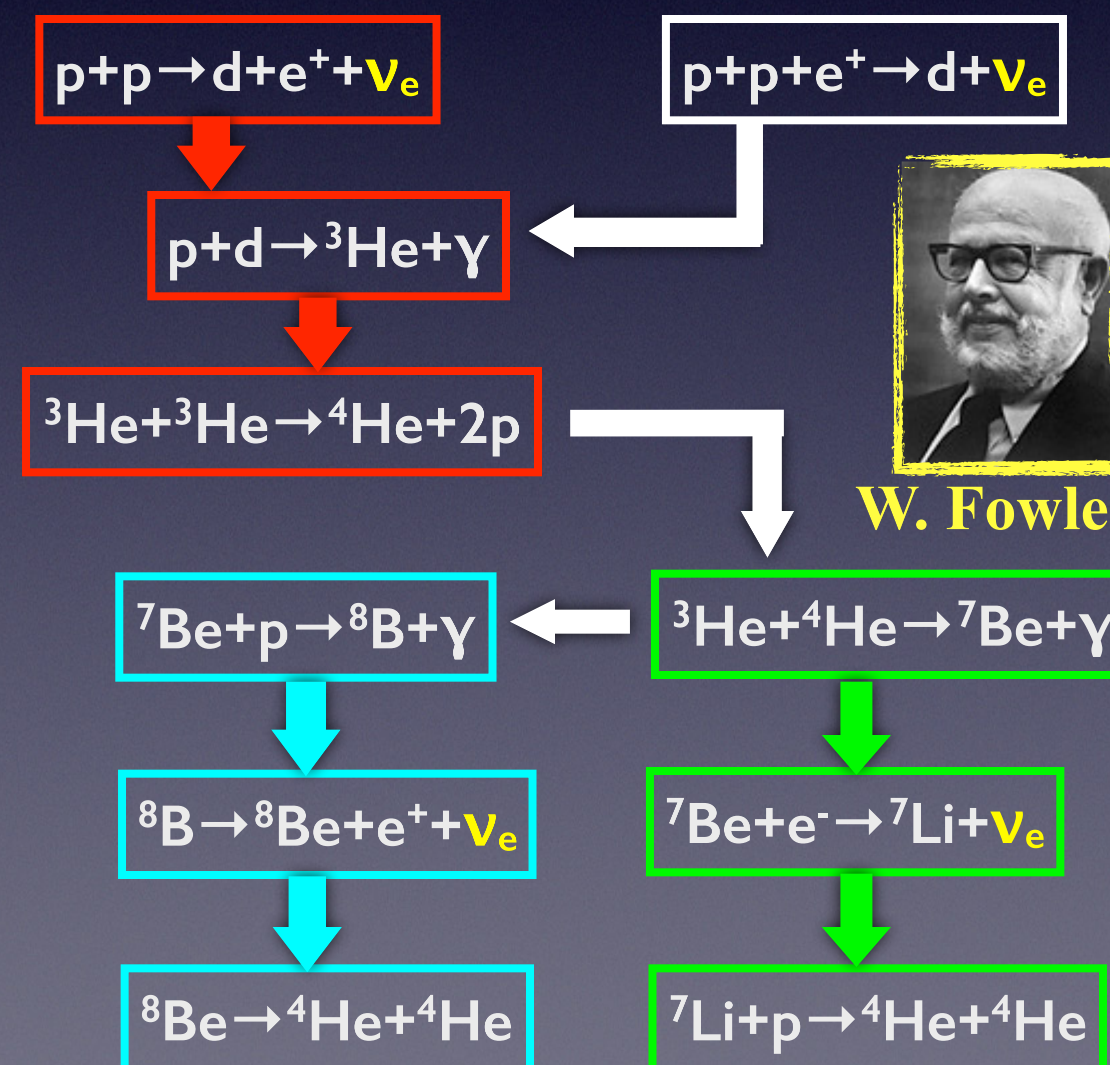
- Nuclear fusion feeds stars
  - **pp chain:** dominant in Sun-like main sequence stars
  - **CNO cycle:** dominant in more massive stars
    - The role of CNO in the Sun is still uncertain **(metallicity problem)**



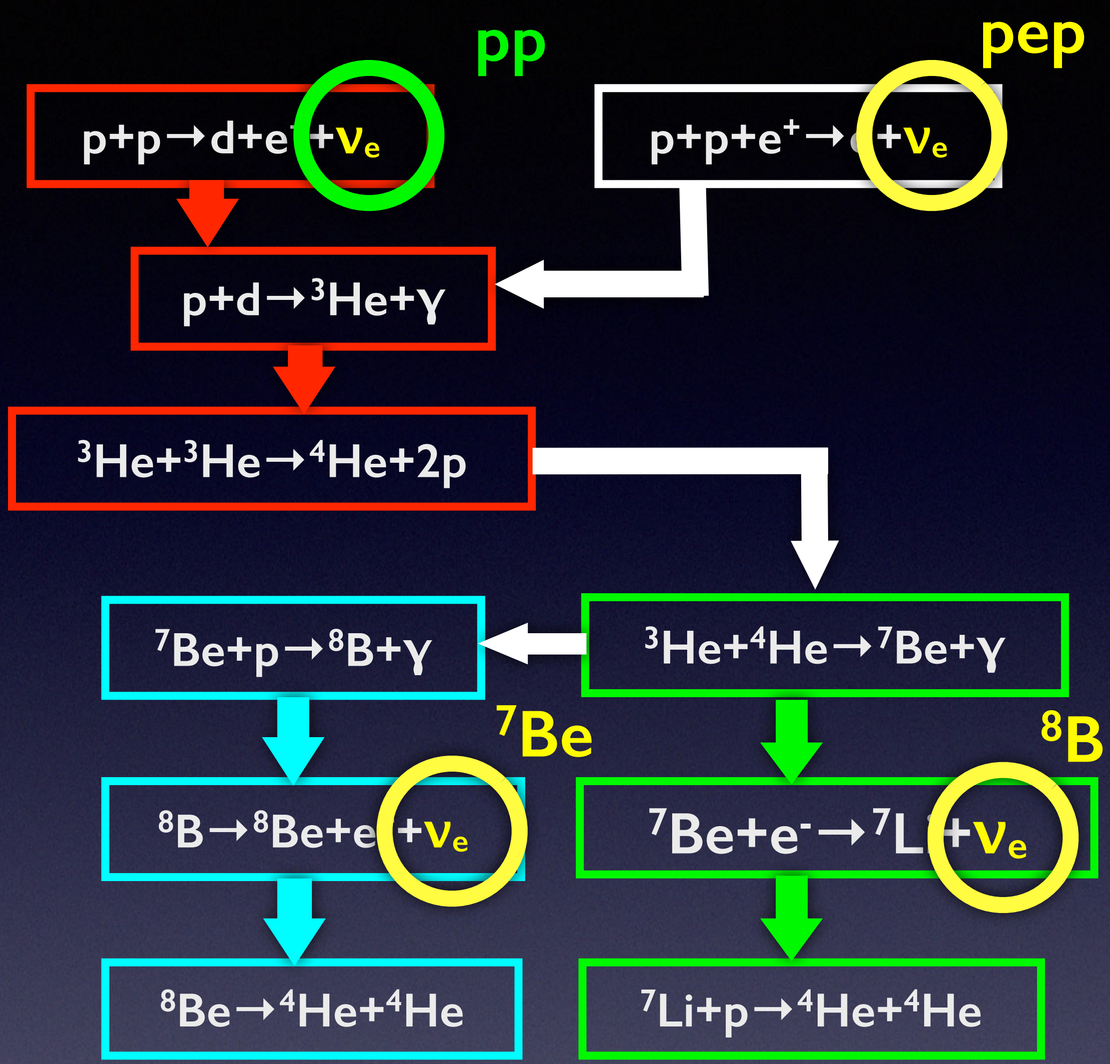
H. Bethe



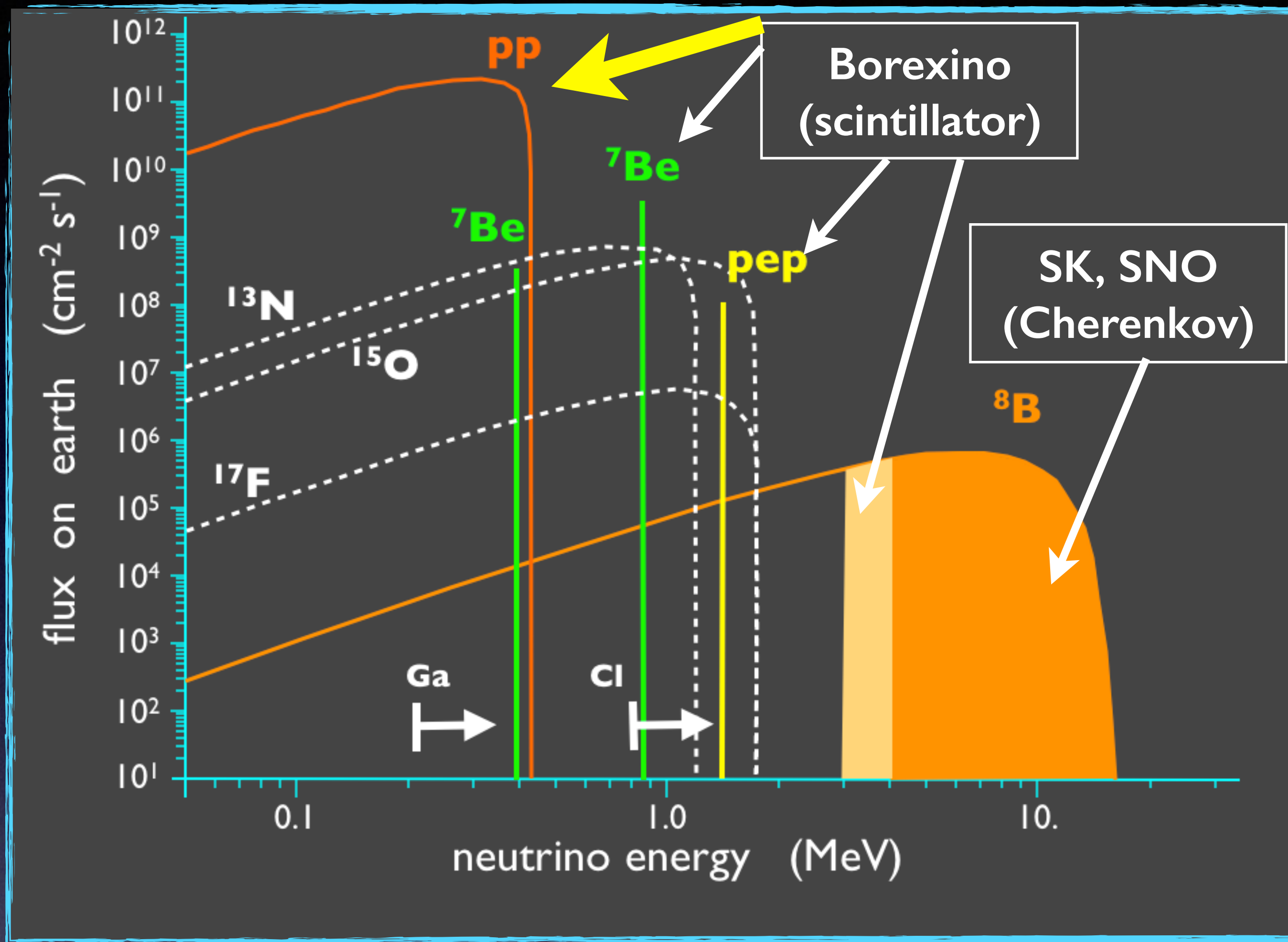


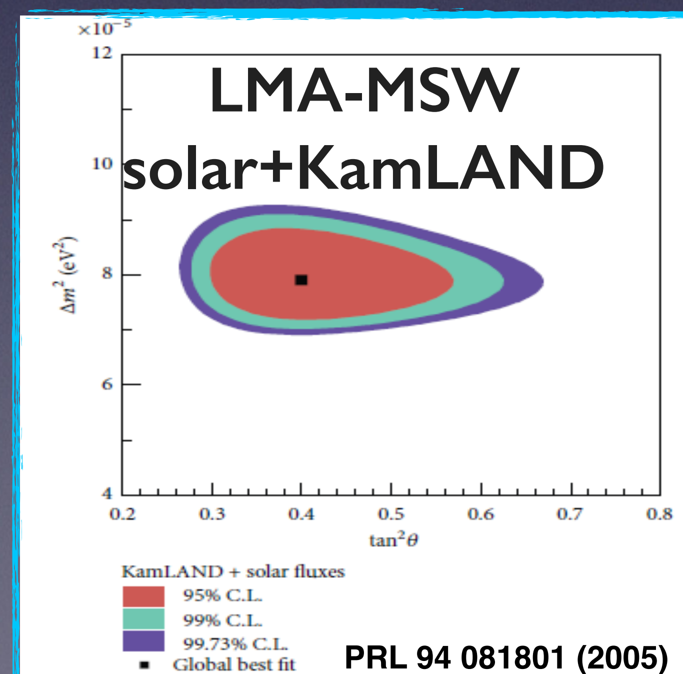


Solar neutrinos (2)



new





- **BUT**
  - Neutrinos **oscillate** from Sun to Earth (SNO, 2000)
  - **MSW-LMA** solution (solar data + KamLAND)
  - **Energy dependent P_{ee}**

Solar ν fluxes: metallicity

Source	High metallicity Flux [$cm^{-2}s^{-1}$] SSM-GS98	Low metallicity Flux [$cm^{-2}s^{-1}$] SSM-AGSS09	Old calculations Flux [$cm^{-2}s^{-1}$] SSM-GS98-2004
pp	$5.98(1\pm0.006)\times10^{10}$	$6.03(1\pm0.006)\times10^{10}$	$5.94(1\pm0.01)\times10^{10}$
pep	$1.44(1\pm0.012)\times10^{8}$	$1.47(1\pm0.012)\times10^{8}$	$1.40(1\pm0.02)\times10^{8}$
^{7}Be	$5.00(1\pm0.07)\times10^{9}$	$4.56(1\pm0.07)\times10^{9}$	$4.86(1\pm0.12)\times10^{9}$
^{8}B	$5.58(1\pm0.13)\times10^{6}$	$4.59(1\pm0.13)\times10^{6}$	$5.79(1\pm0.23)\times10^{6}$
^{13}N	$2.96(1\pm0.15)\times10^{8}$	$2.17(1\pm0.15)\times10^{8}$	$5.71(1\pm0.36)\times10^{8}$
^{15}O	$2.23(1\pm0.16)\times10^{8}$	$1.56(1\pm0.16)\times10^{8}$	$5.03(1\pm0.41)\times10^{8}$
^{17}F	$5.52(1\pm0.18)\times10^{6}$	$3.40(1\pm0.16)\times10^{6}$	$5.91(1\pm0.44)\times10^{6}$
Total CNO:	5.24×10^{8}	3.76×10^{8}	10.8×10^{8}

Aldo M. Serenelli *et al.* 2011 *ApJ* 743 24

Relative difference due to metallicity

ν	% diff
pp	0,8
pep	2,1
7	8,8
8	17,7
13	26,7
15	30
17	38,4

- **CNO flux** reduced by new cross section measurement of $^{14}N(p,\gamma)^{15}O$
- Better accuracy for the **$^{3}He(^{4}He,\gamma)^{7}Be$ cross section**
- New opacity calculations
- **New abundance** based on 3D models

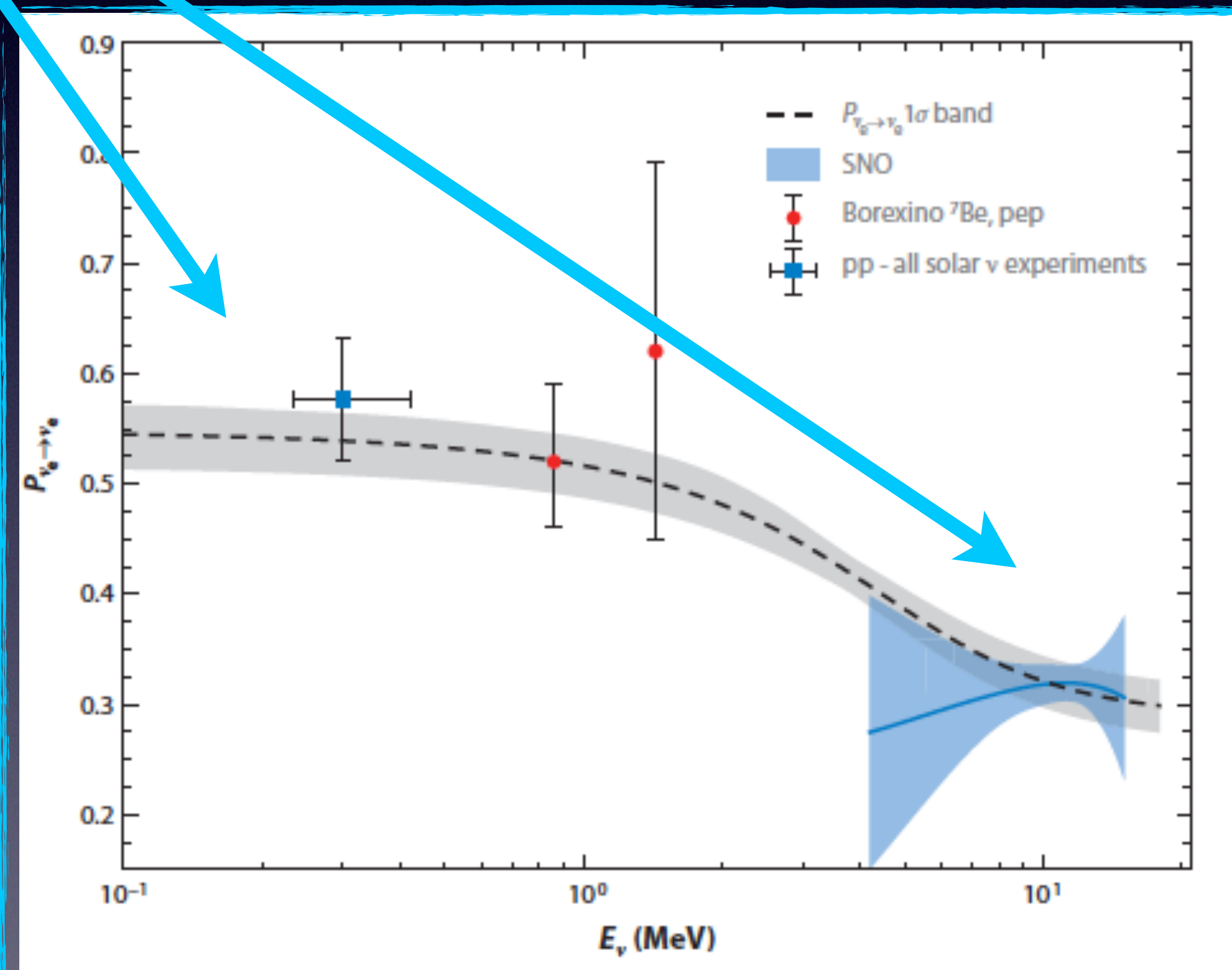
What may we still learn from solar ν ?

- **CNO cycle** is the most important on most stars
  - It depends on high Z catalyzers, so is directly linked to metallicity
- **Metallicity:** ^{7}Be, CNO and Luna-MeV may solve the issue
  - If low, eliosismology has severe problems
  - If high, standard solar formation model is wrong

- The **high precision** era of solar ν physics is coming!
- Comparison of % precision ν fluxes with photon flux may teach us a lot about solar physics
  - Are there other emitted particles (axions, sterile neutrinos, ?)
  - Is the Sun in steady state ?
    - Big science gain if we discover it is not !

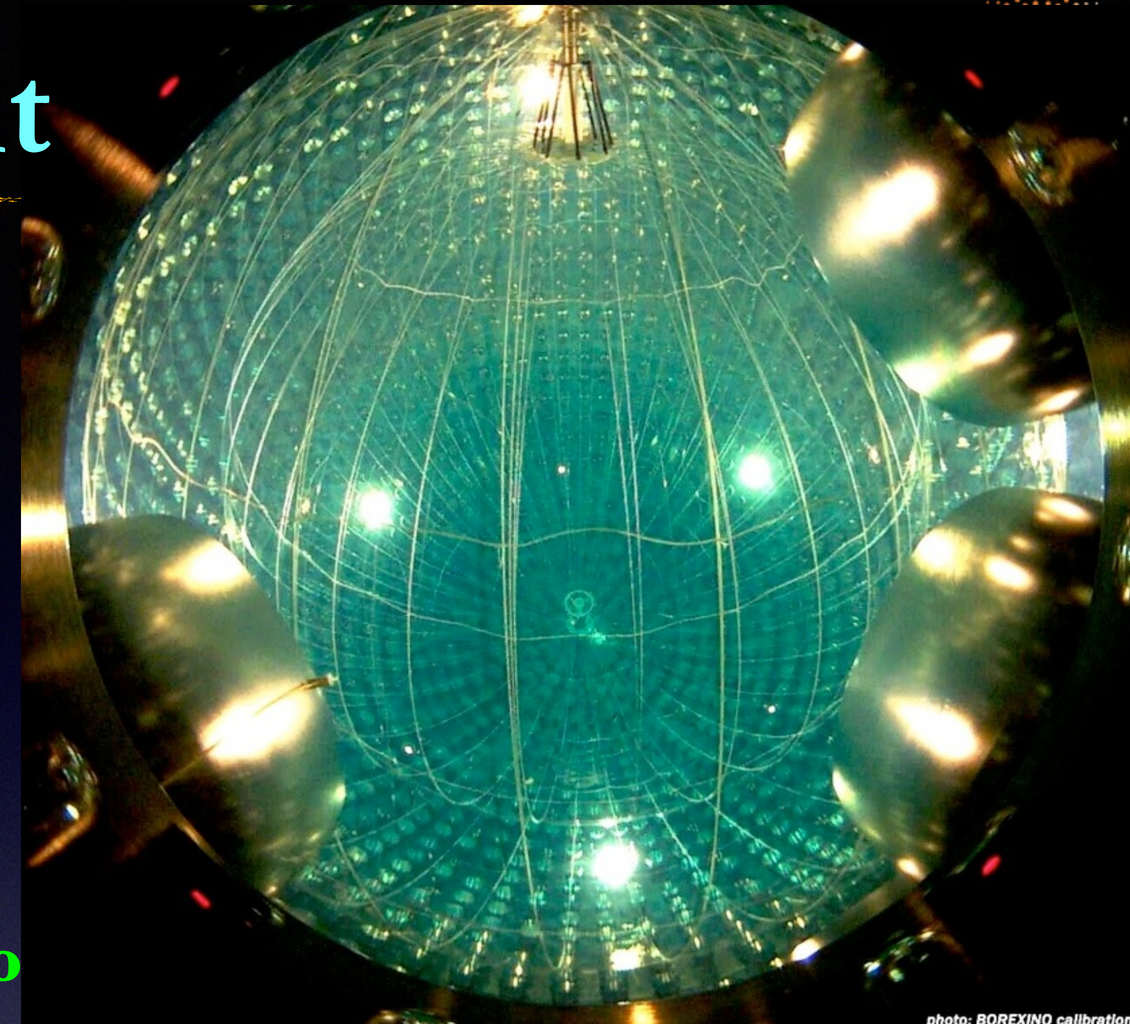
What may we still learn from solar ν ?

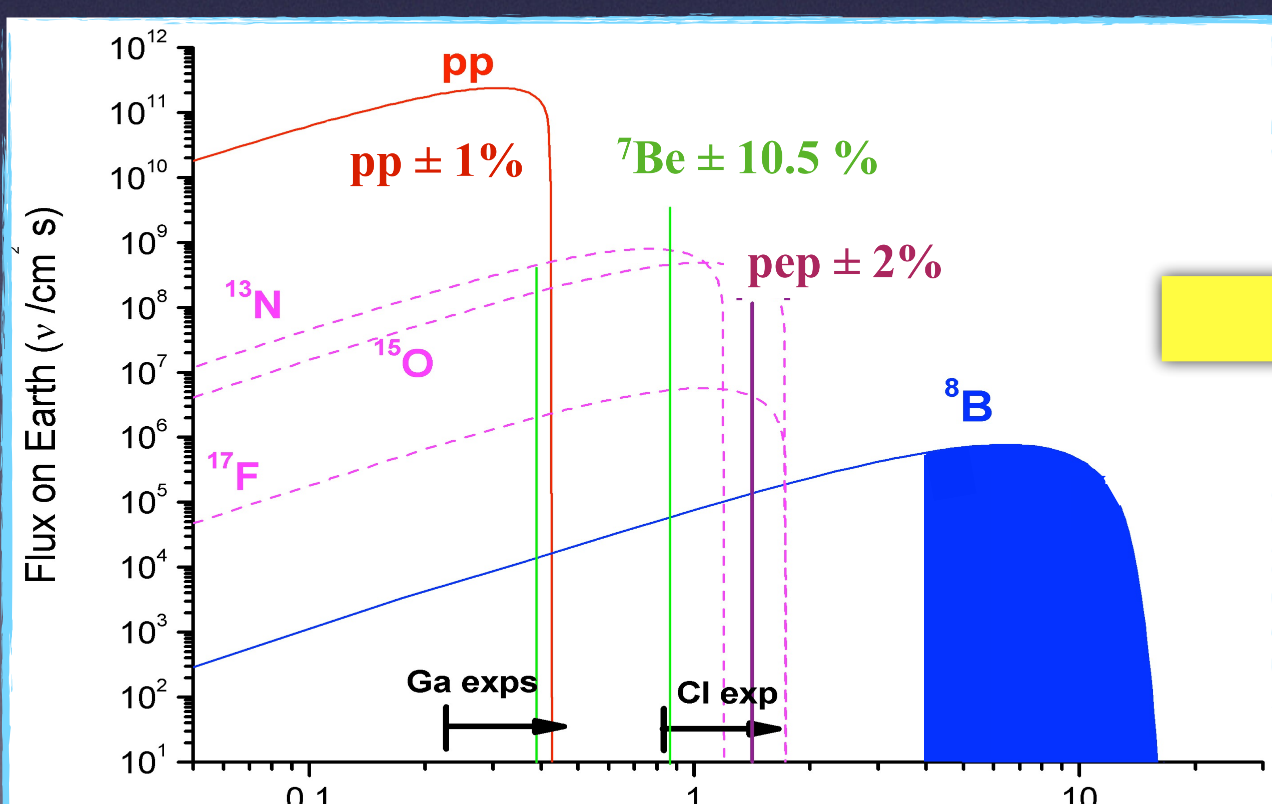
- MSW-LMA effect is **observed,** still with relatively large errors
  - **Probe of P_{ee} requires higher precision**
  - No evidence yet of **upturn** in ^{8}B neutrinos (see later)
  - Precision measurements will probe P_{ee} and constrain non-standard neutrino and solar physics

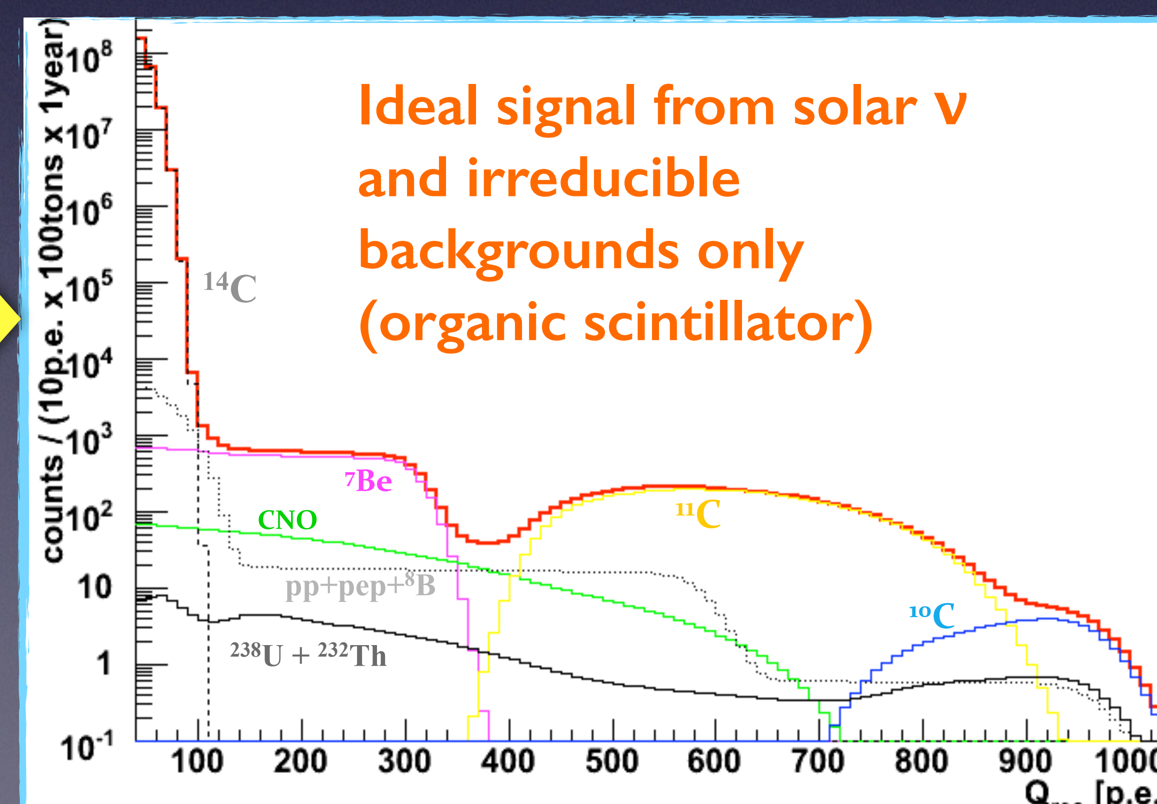


Borexino experiment

- Mainly, a **solar ν experiment:**
  - $\nu + e^- \rightarrow \nu + e^-$ in liquid scintillator
    - **Ultra-low background** obtained via **selection, shielding, and purifications**
    - Low energy threshold, good resolution, spatial reconstruction, and pulse shape ID
  - But also:
    - Geo-neutrinos, rare events, **sterile neutrino**

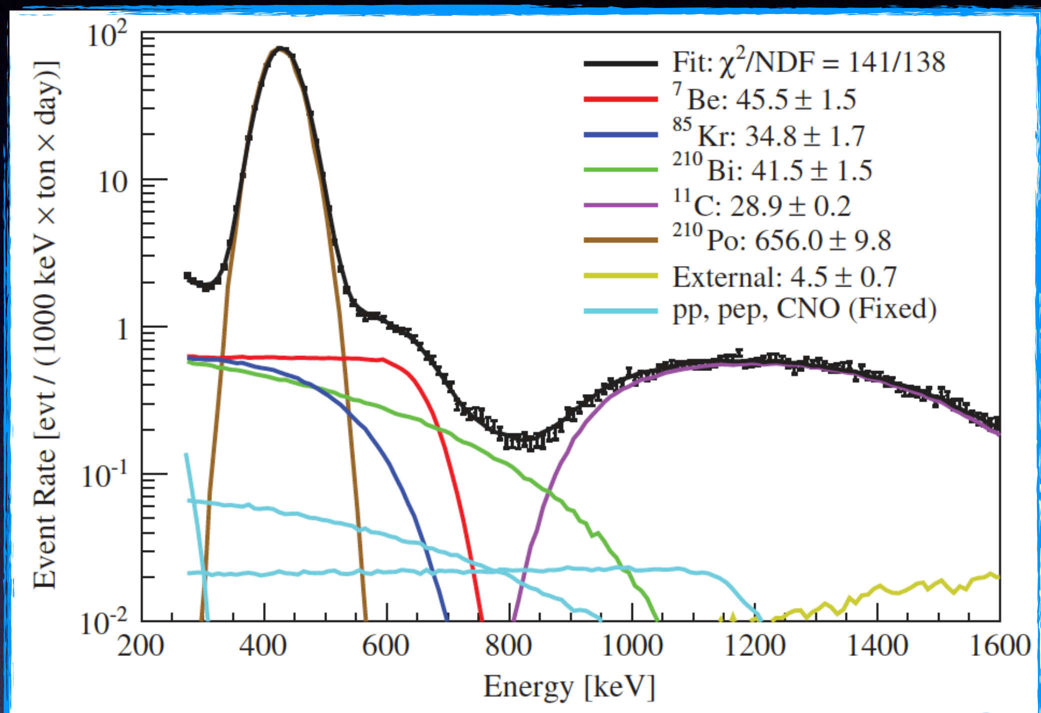






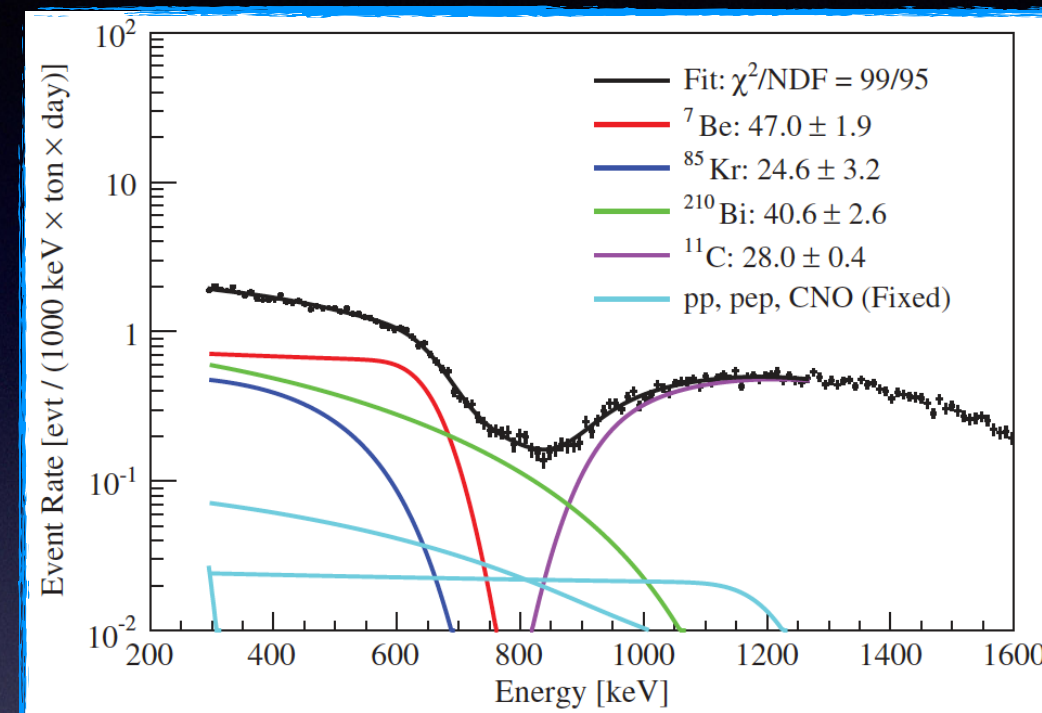
Measurement of ^{7}Be rate (2011)

Monte Carlo fit to the spectrum, without α/β subtraction of the ^{210}Po peak



Phys. Lett. B658:101-108, 2008
Phys. Rev. Lett. 101, 091302, 2008
Phys. Rev. Lett. 107, 141302, 2011

Analytical fit of the spectrum after α/β subtraction of ^{210}Po peak

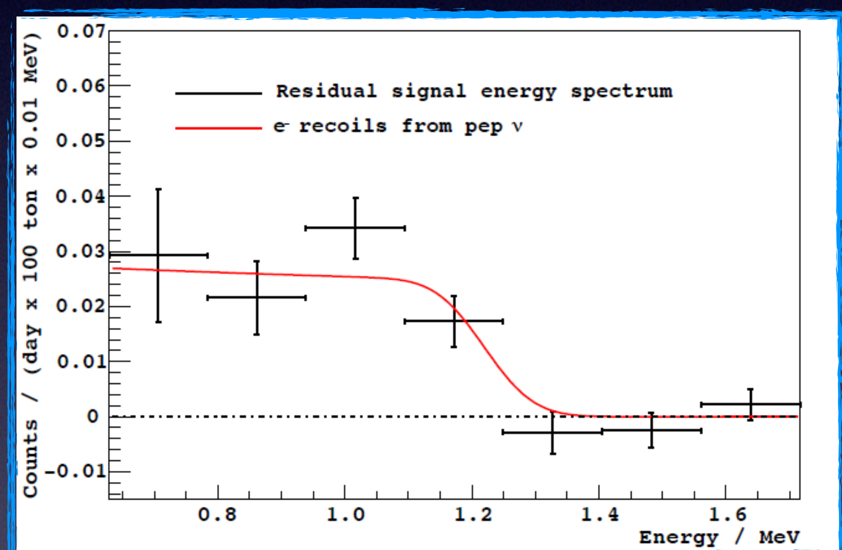


- Two methods:
  - Consistent results. Small difference included in systematic error.
  - Final rate (100 t target):
    - 46.0 ± 1.5 (stat) ± 1.5 (sys) c d^{-1}

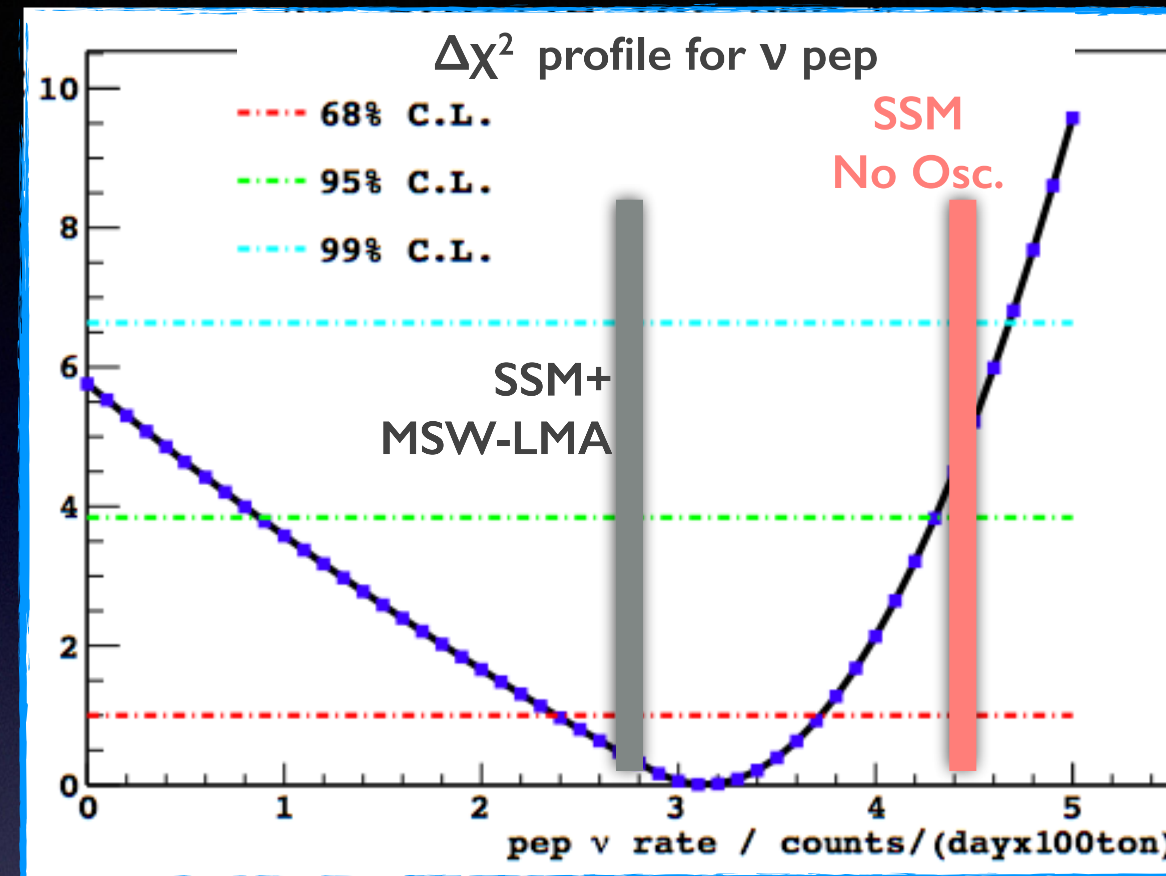
Source	%
Trigger (eff. and stability)	< 0.1
Live time	0,04
Scintillator density	0,05
Fiducial volume	+0.5 -1.3
Fit method	2
Energy response	2,7
Cuts efficiency	0,1
Total	**+3.4 -3.6**

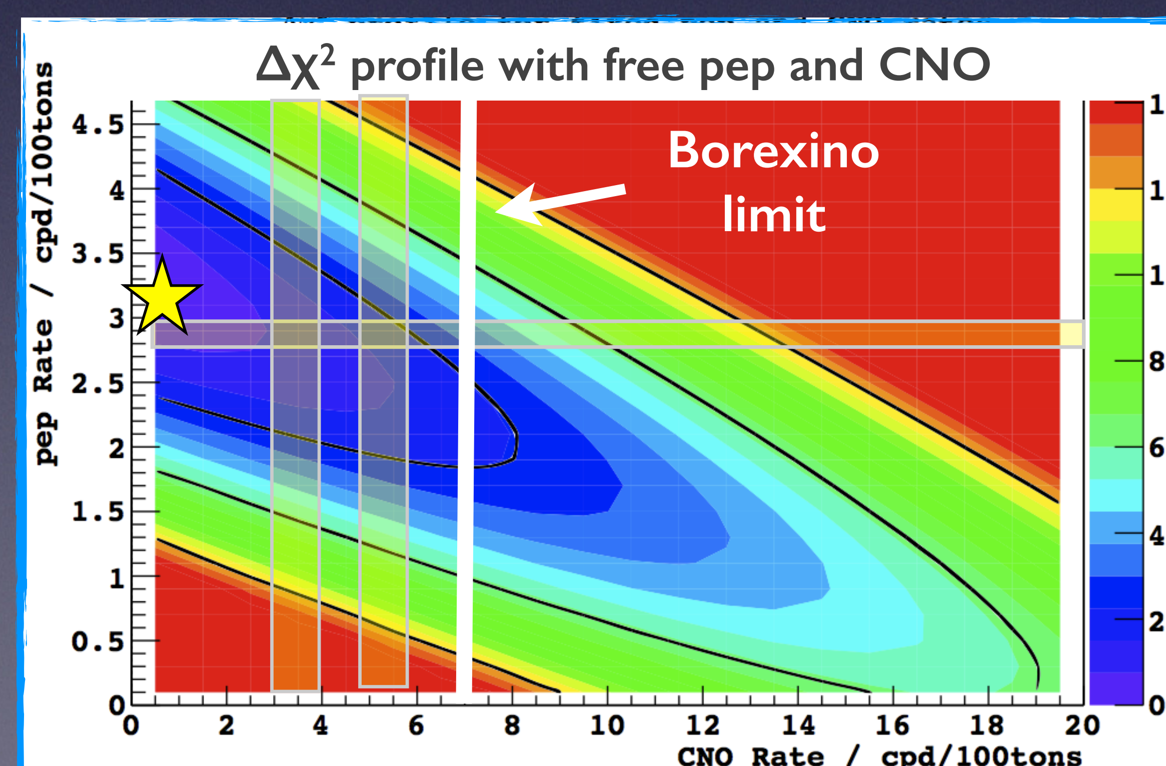
pep-cno: final result (2012)

- pep rate:
  3.1 ± 0.6(stat) ± 0.3(sys) cpd/100 t
  - No oscillations excluded at **97% c.l.**
  - **No ν pep excluded at 98%**



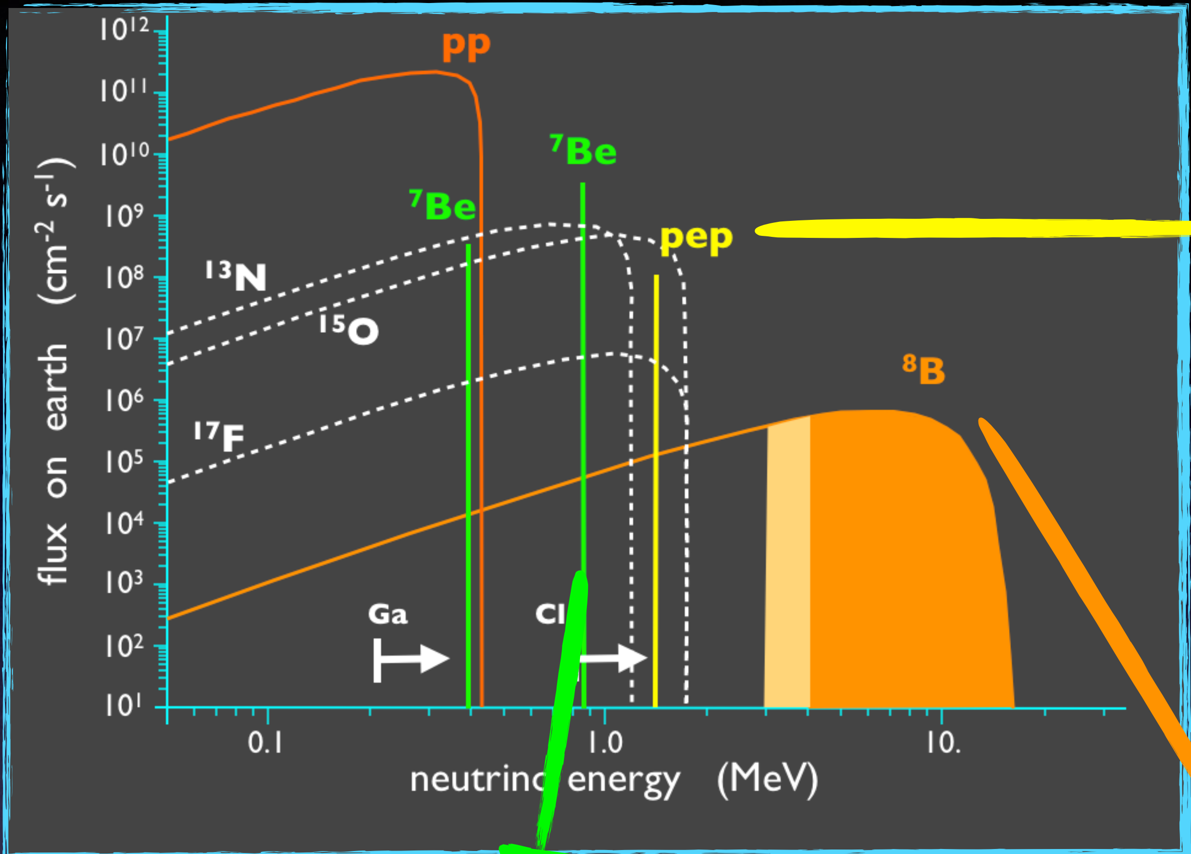
PRL 108, 051302 (2012)

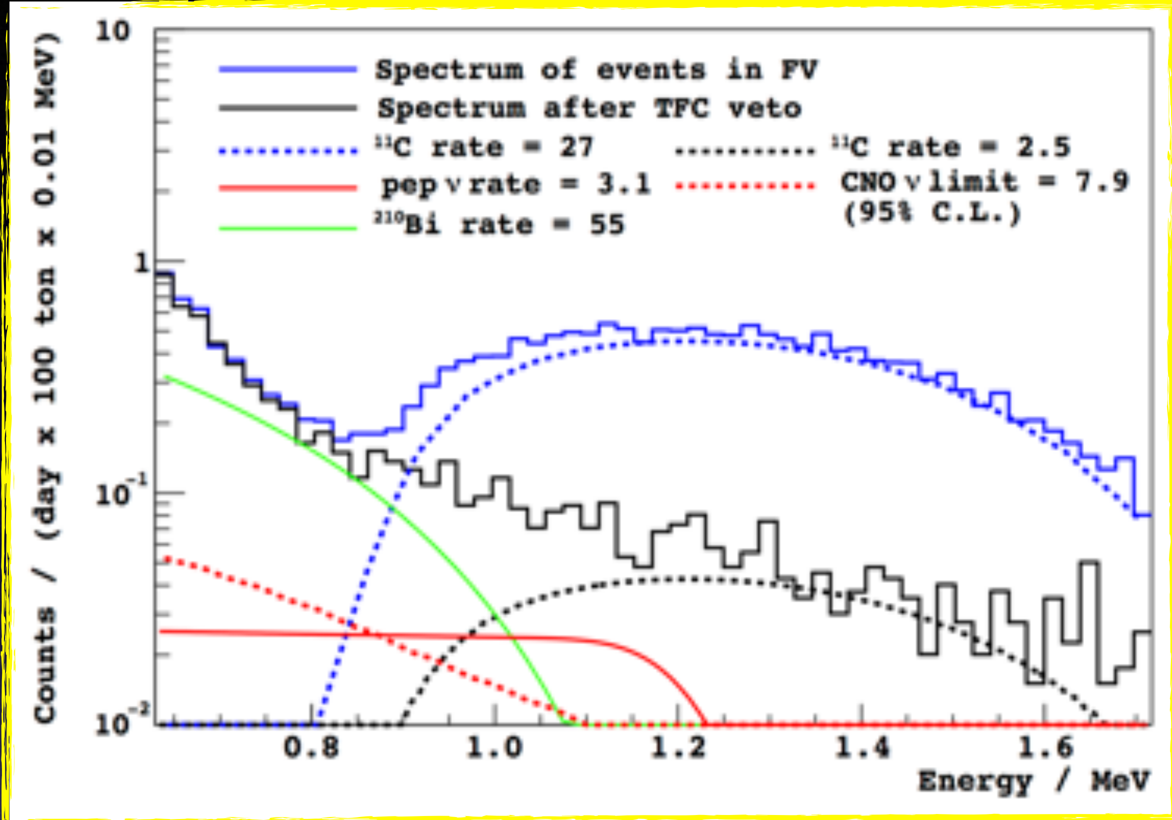




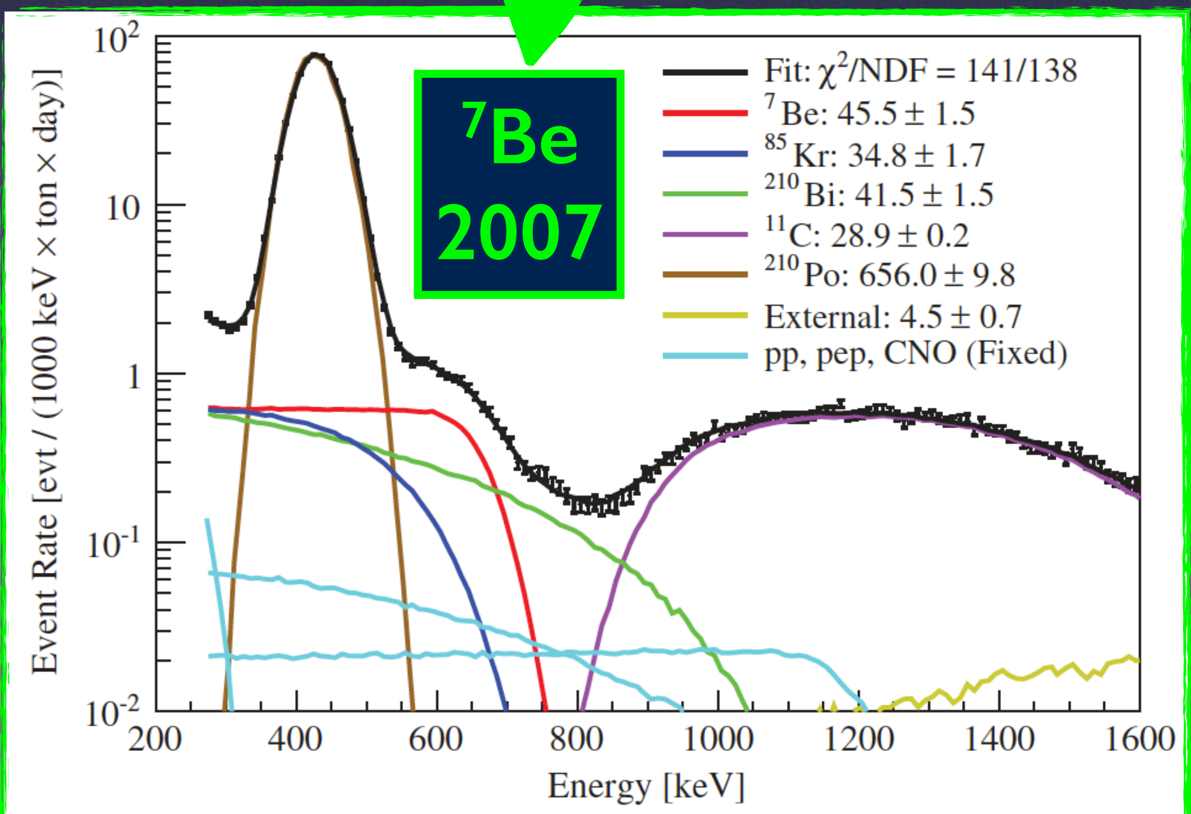
- Assuming MSW-LMA:
  - $\Phi_{pep} = 1.6 \pm 0.3\ 10^8\ cm^{-2}\ s^{-1}$
- CNO limit assuming pep @ SSM
  - CNO rate < 7.1 cpd/100 t (95% c.l.)

Previous Borexino measurements

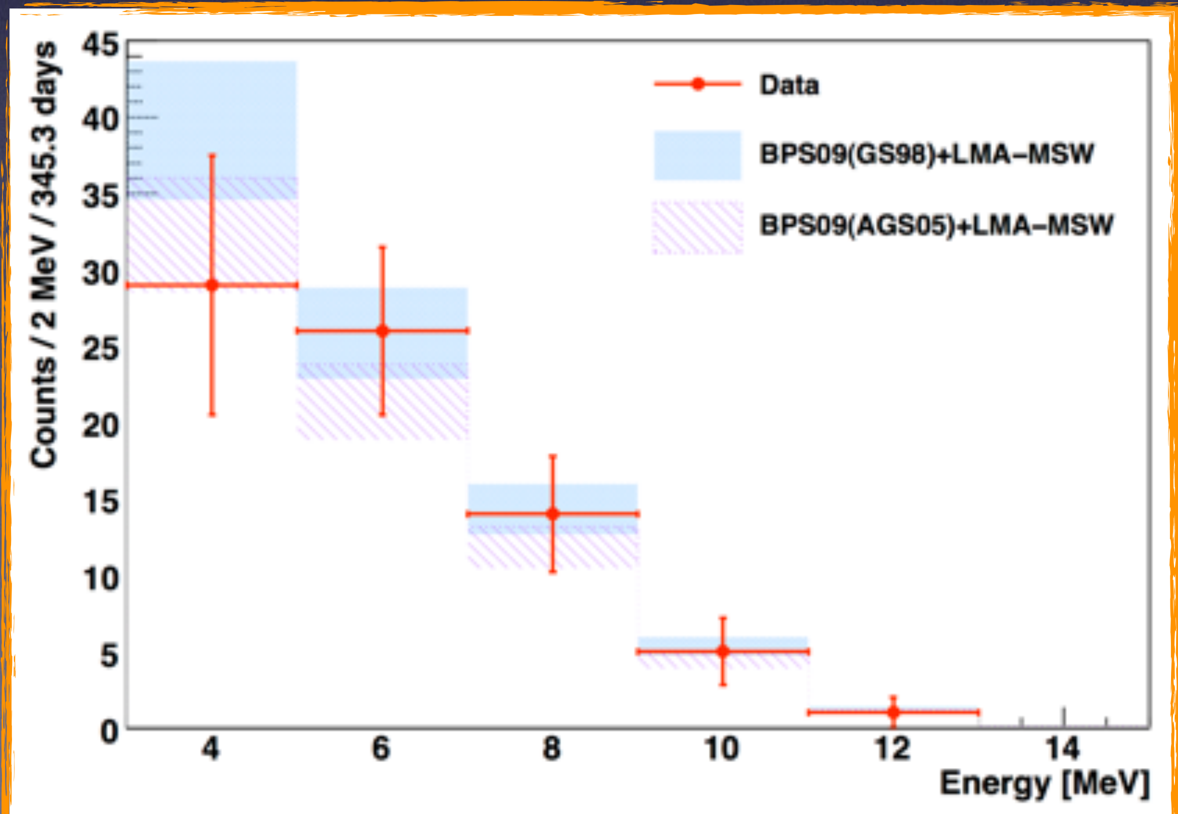




pep 2012



8B 2010

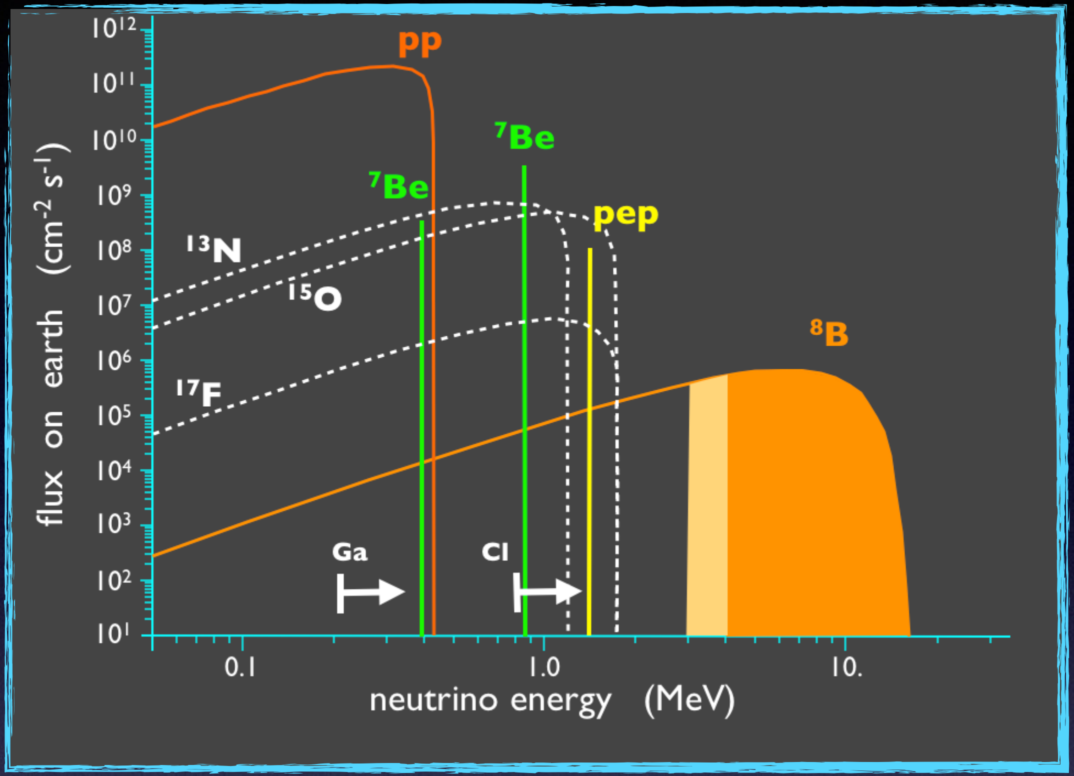


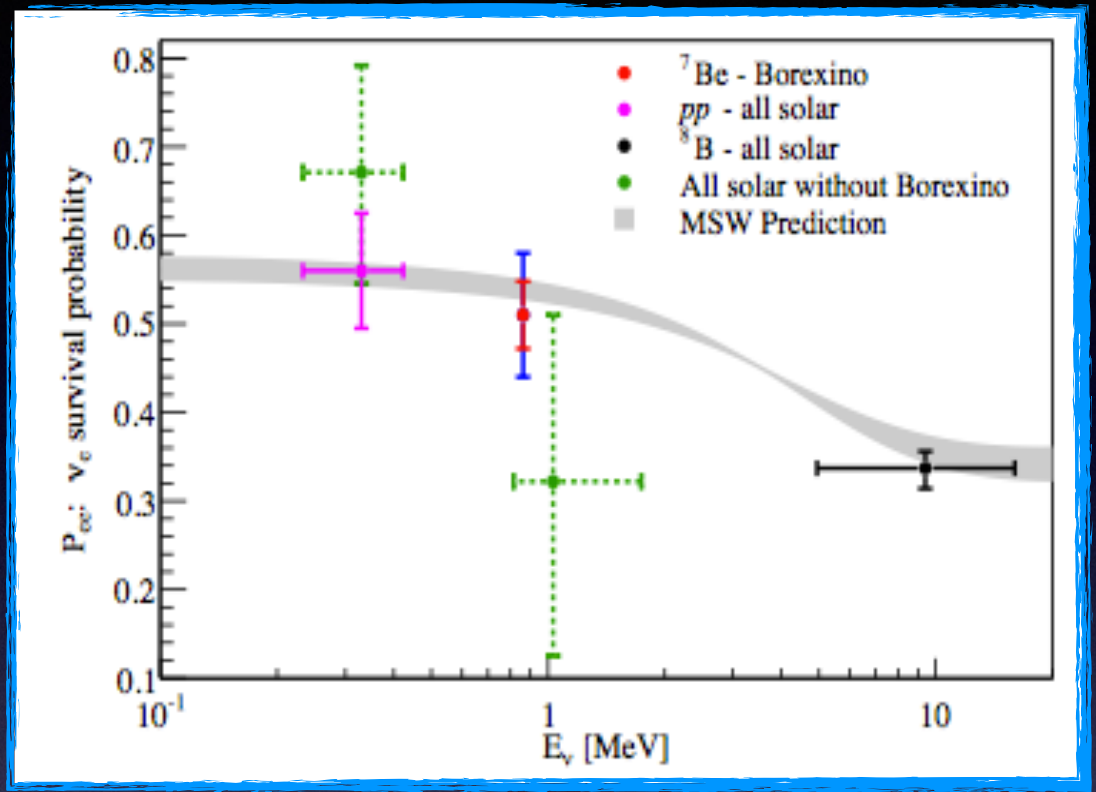
Background in phase 2 (2012-2014)

- We made an extensive purification by means of water extraction in loop

- ^{238}U
  - Searching for ^{222}Rn events (^{214}Bi-^{214}Po), **^{238}U < 1.2 10^{19} g/g**
  - At least a factor 20 better than in Phase 1
- ^{232}Th
  - Searching for ^{220}Rn events (^{212}Bi-^{212}Po), **^{232}Th < 1.2 10^{18} g/g**
  - At least a factor 10 better than in Phase 1
- ^{85}Kr
  - Currently **compatible with zero.** It was 35 cpd/100 t
- ^{210}Bi
  - Reduce down to ~ 20 cpd/100 t. It was ~ 60 cpd/100 t

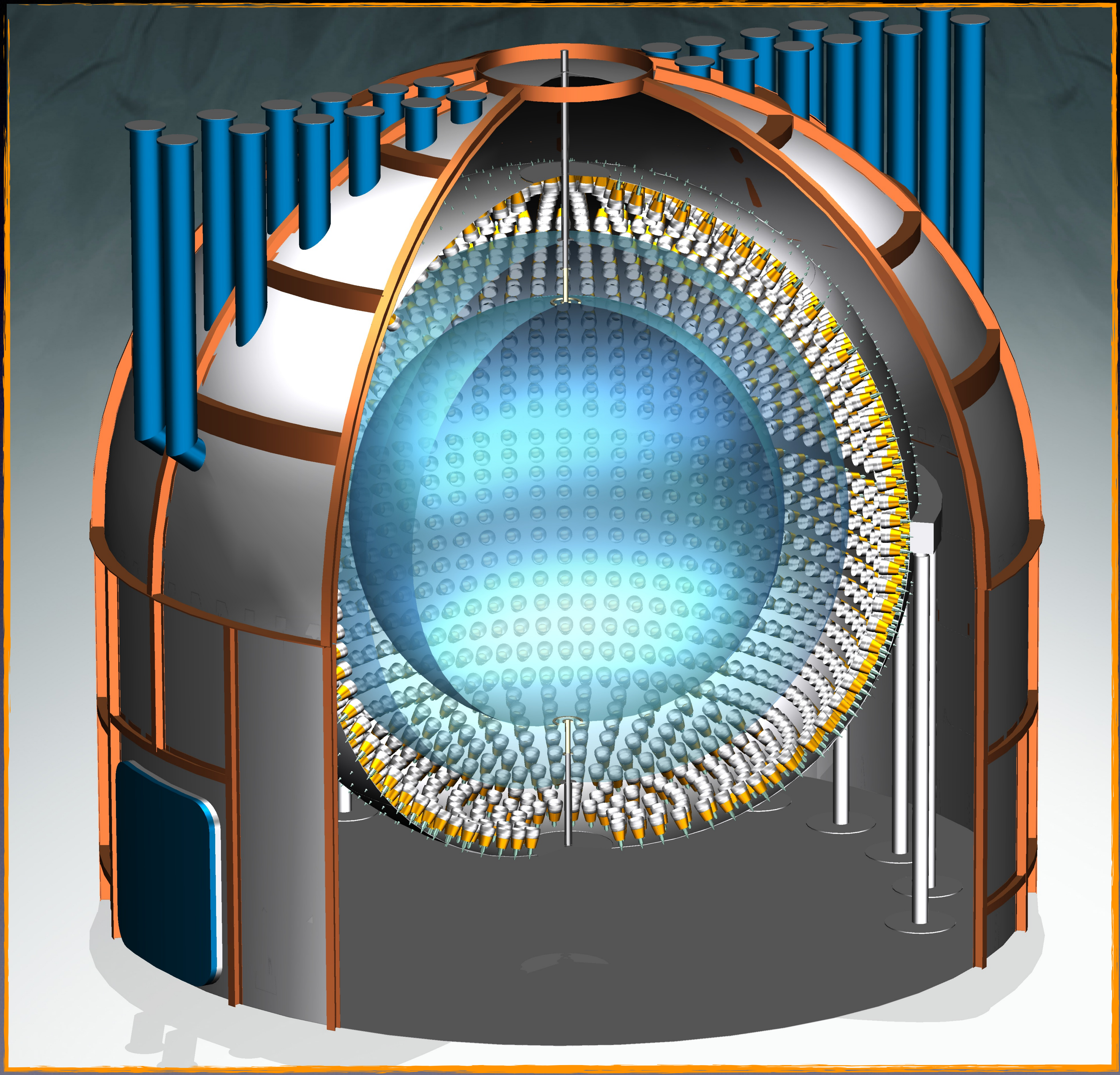
Why search for pp neutrinos ?



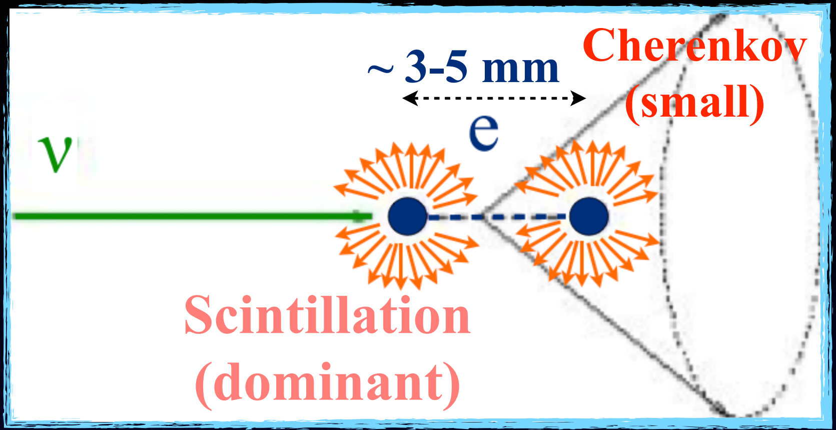


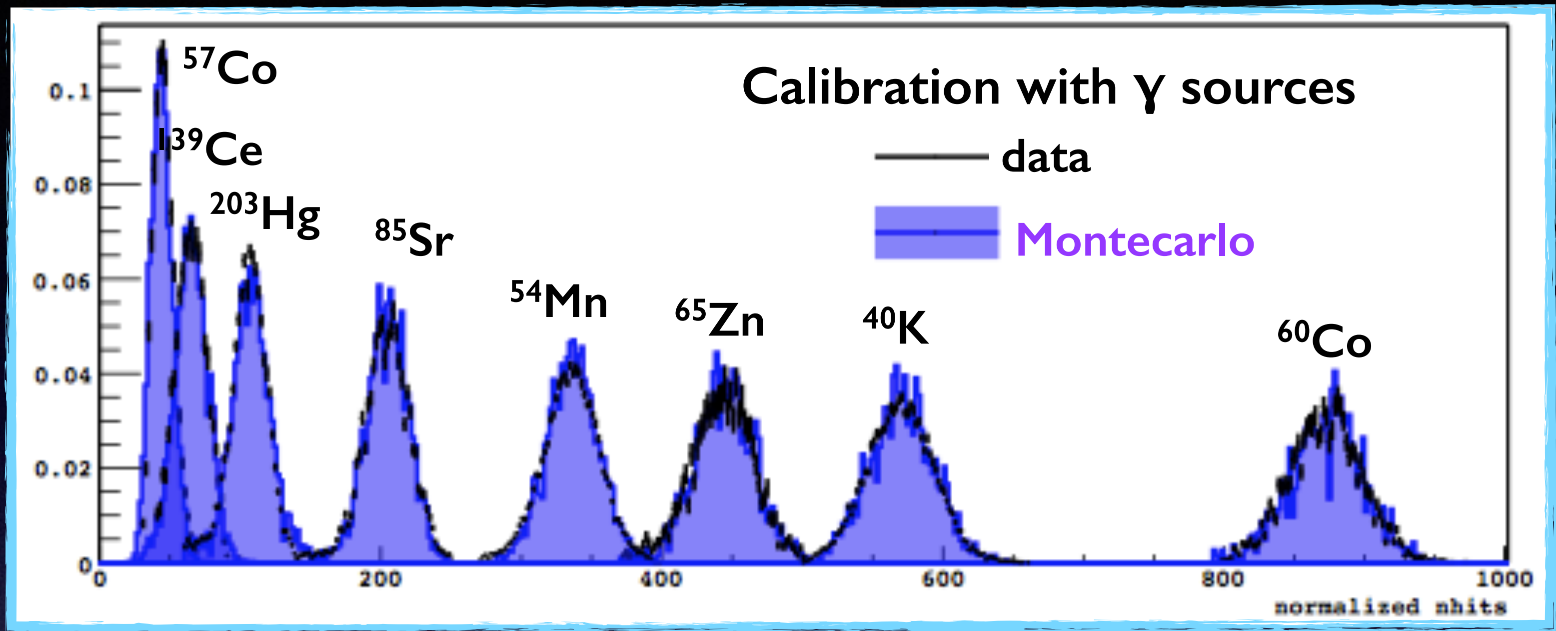
- They are the most important component, though lowest in energy
- They give directly the Sun's power in real time, allowing a comparison between neutrino luminosity and photon luminosity
  - Stability
  - Other particles i.e. axions or sterile
- They probe neutrino oscillations in vacuum (no MSW)

Borexino detector

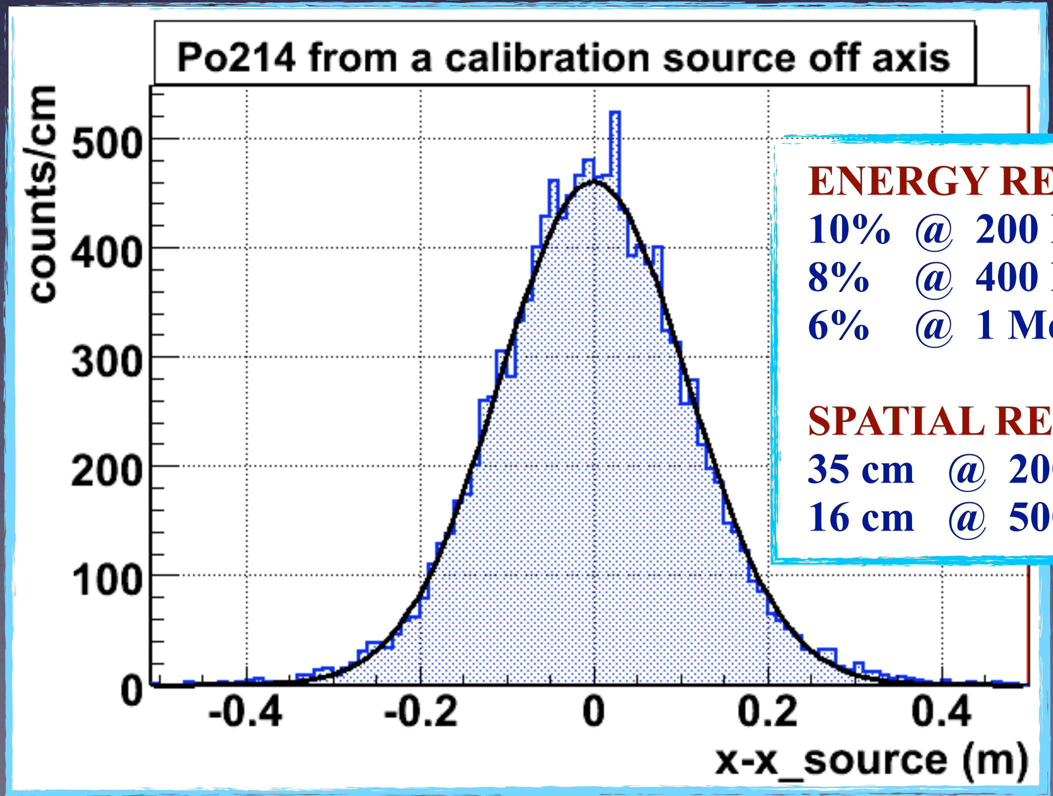


ν detection in Borexino





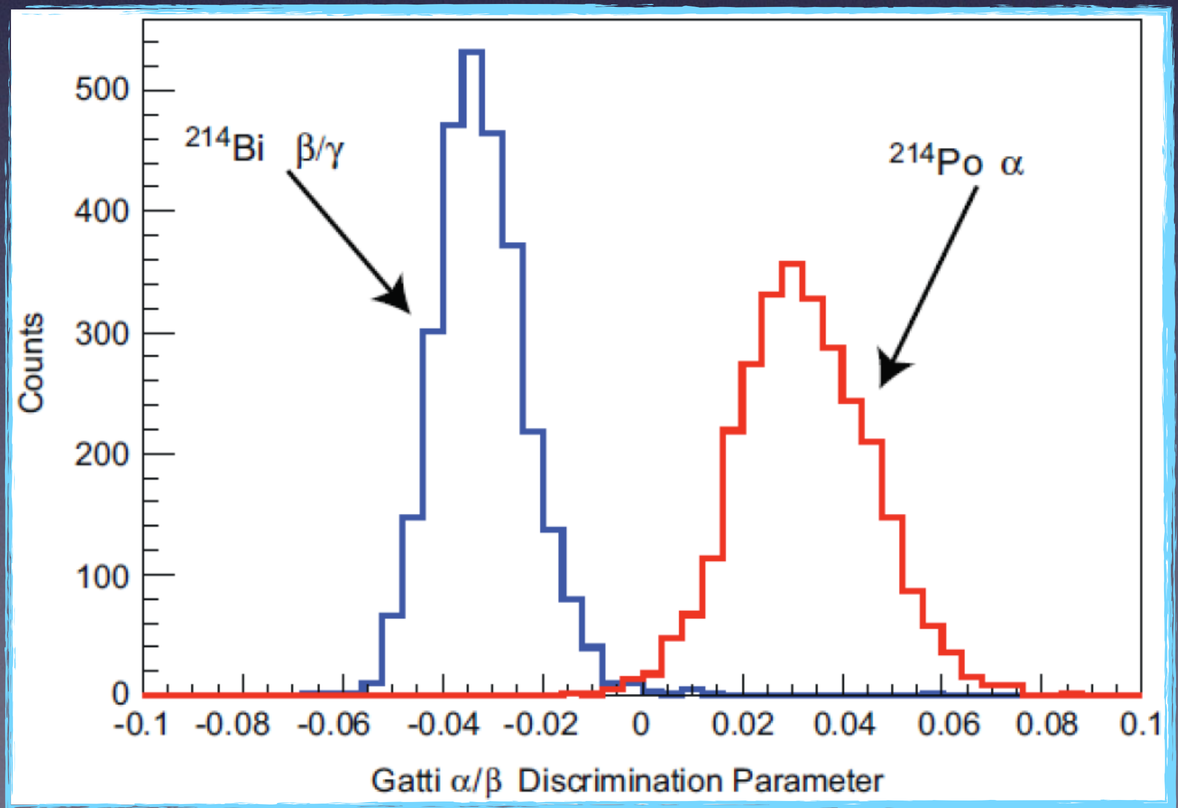
- Scintillation light
  - # of photons → energy
  - time of flight → position
  - pulse shape → α/β β+/β-



ENERGY RESOLUTION
10% @ 200 keV
8% @ 400 keV
6% @ 1 MeV

SPATIAL RESOLUTION
35 cm @ 200 keV
16 cm @ 500 keV

α / β separation (^{214}Bi - ^{214}Po)



Modelling scintillation

- Number of collected photoelectrons is only approximately linear with the deposited energy
  - In fact:
    - it depends on the particle (light quenching)
    - it is affected by many detector related effects (photon propagation, pmts, electronics, and trigger)

$$N_{ph} = Y_{scint} \times E \times Q(E)$$

$$Q(E) = \frac{1}{E} \int_0^E \frac{dE'}{1 + k_B \frac{dE}{dx}(E')}$$

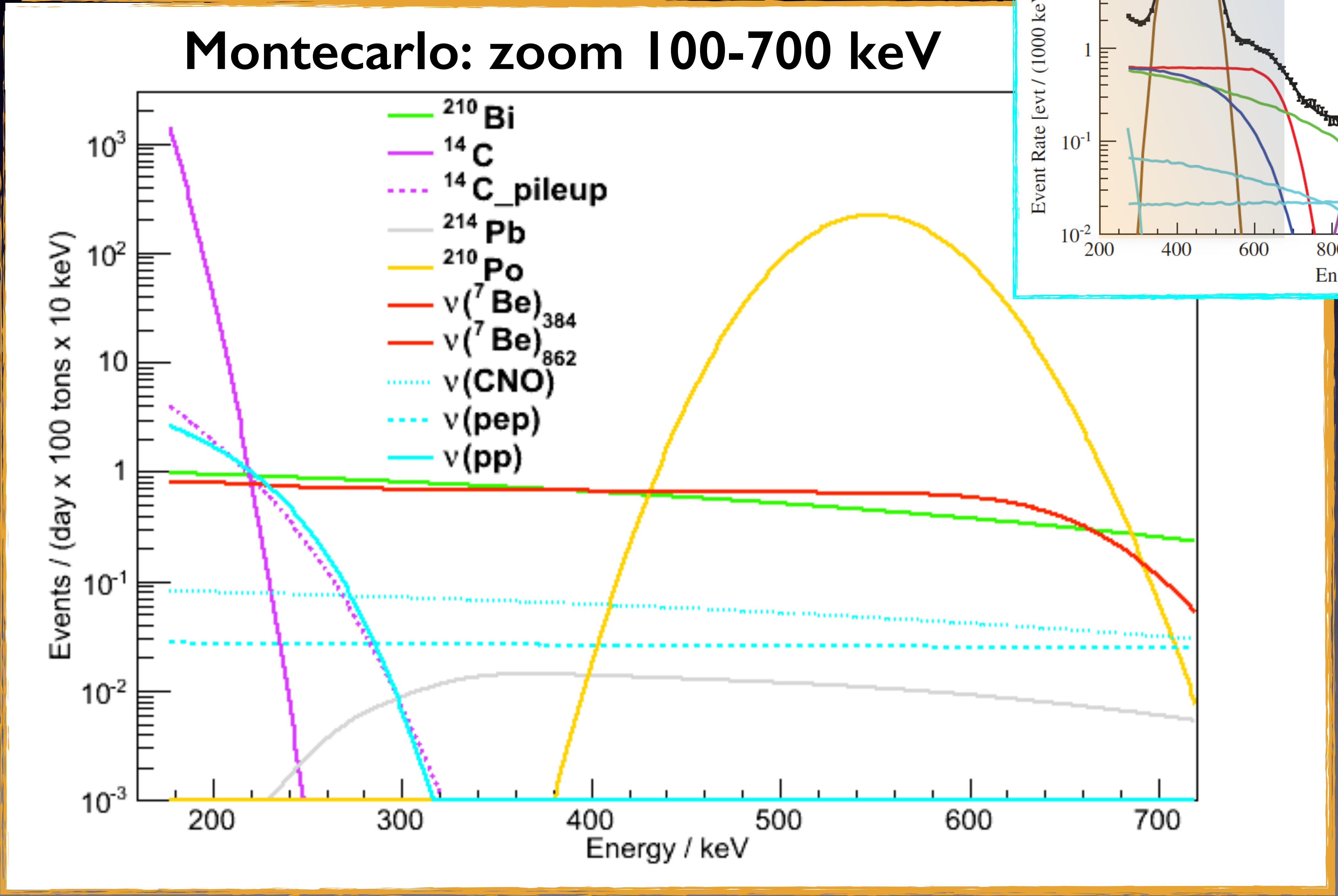
$$N_{pe} = Y_{det} \times E \times Q(E)$$

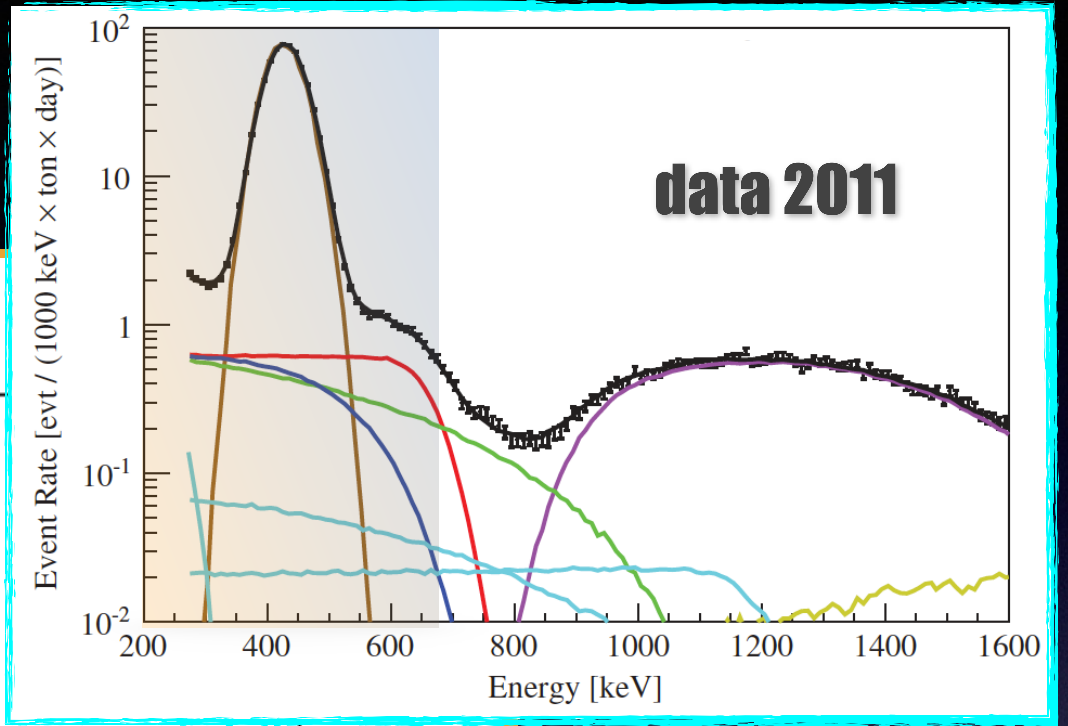
Data taking

- Trigger is generated when a minimum number of PMTs (typically 25) are hit within a 100 ns window
  - A 16 μs gate is open and all hits are collected
  - Hits closer in time than 140 ns in the same PMTs are lost, but the total charge is measured
- Energy estimator
  - Offline code searches for “clusters” in the gate, i.e. the list of hits presumably belonging to the physical event
    - For pp analysis, fixed length of 230 ns
    - Multiple photons in the same PMT are ignored to simplify statistical model (pp is low energy and the number of lost hits is small)

$$N_p = N_{tot}\left(1 - e^{-\frac{N_{pe}}{N_{tot}}}\right)$$

Neutrino signal and main backgrounds





Data selection and cuts

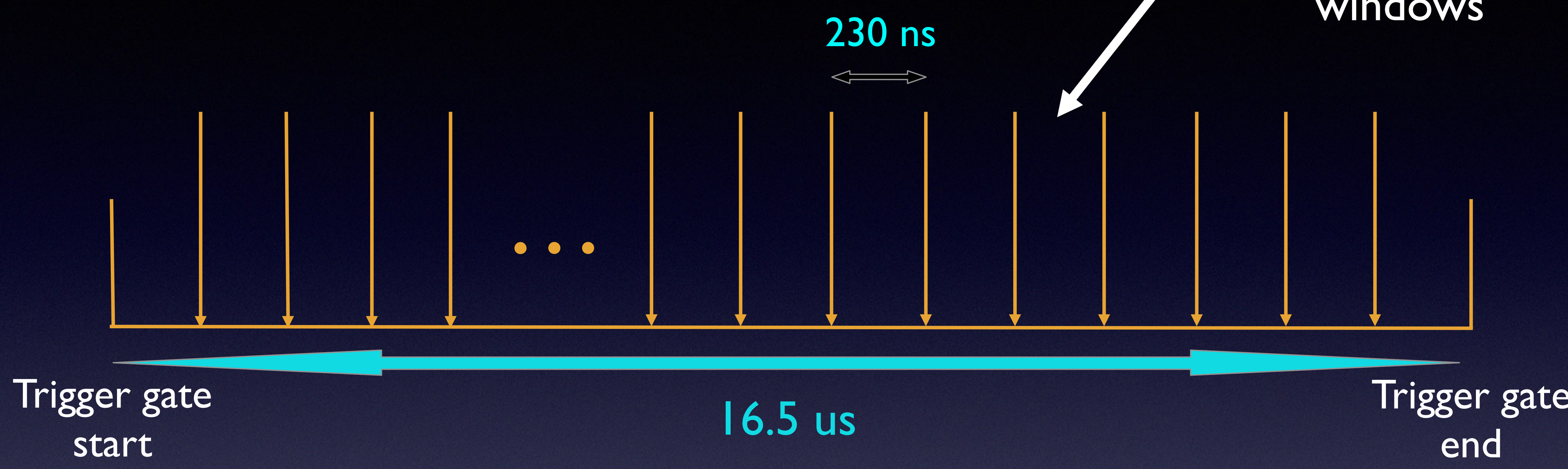
- Quality checks are applied and good runs are selected
  - Run validation
- Events are selected with specific cuts to reject
  - Muons
  - Electronic noise events
- Energy estimator and position is reconstructed
  - Events are selected in a fiducial volume
- All this is quite standard. we did the same for other solar neutrinos
  - **pp neutrinos, however, are difficult for three main reasons**

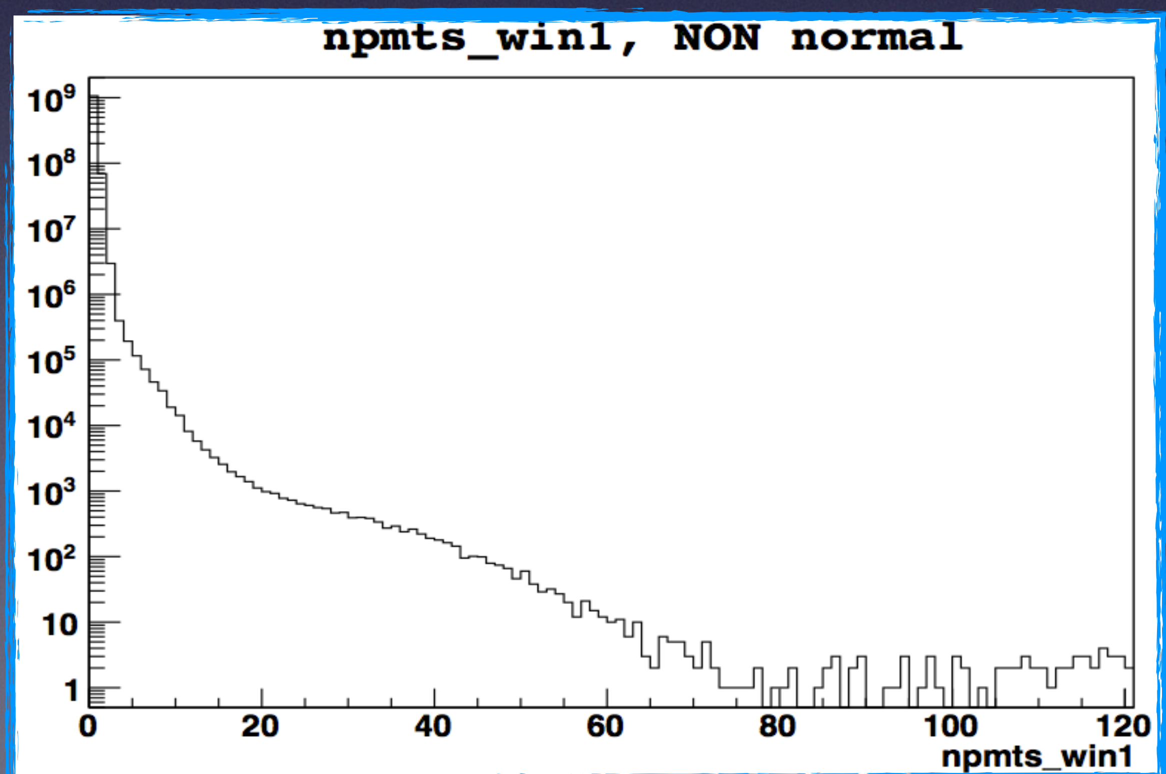
Challenges for pp ν detection

- **#1: dark noise**
  - Very low energy
    - pp recoil energy end point is **256 keV,** about **120 pmt hits**
    - **the dark noise of ~ 2000 PMTs cannot be ignored**
- **#2: ^{14}C β decay spectrum**
  - **Huge statistics,** fitting of the spectral shape not trivial
- **#3: ^{14}C pile-up**
  - The relatively huge rate of ^{14}C **(~ 100 Bq total)** makes p**ile-up probability sizeable** and pile-up effective spectrum **relevant for the measurement**

Challenge #1: dark noise

Count number of PMTs hit in each of these windows

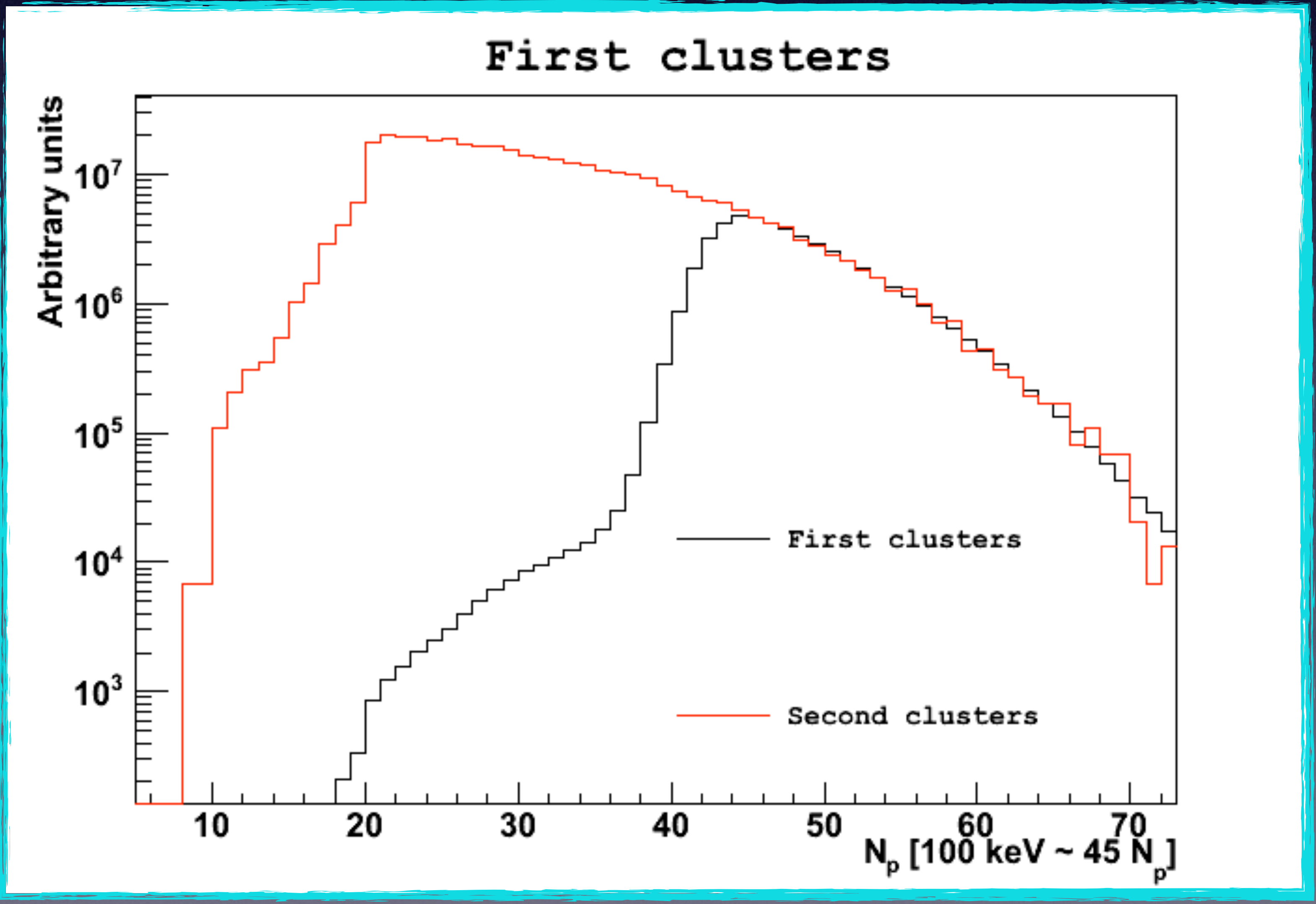




Challenge #2: ^{14}C spectral shape

- It is crucial to know the **exact rate of ^{14}C events**
  - **Problem:** it is not easy to measure trigger efficiency at very low energy, i.e. below 30-40 hits
  - **Solution:** use pile up events, i.e. events in the gate after triggering event

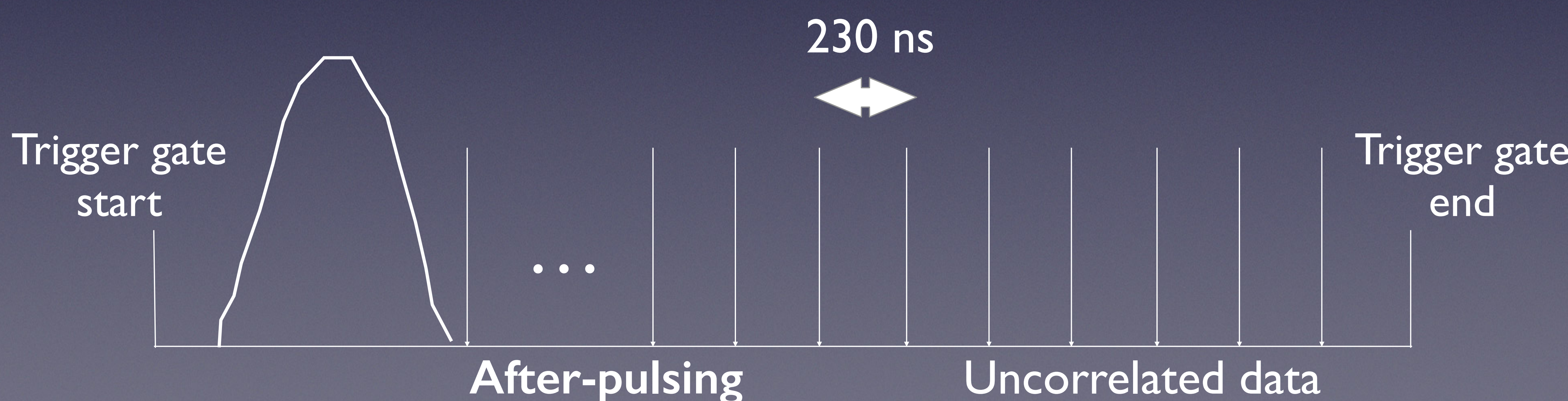
- Pile up events are not affected by hardware threshold effects
- They ARE, however, affected by reconstruction capability effects



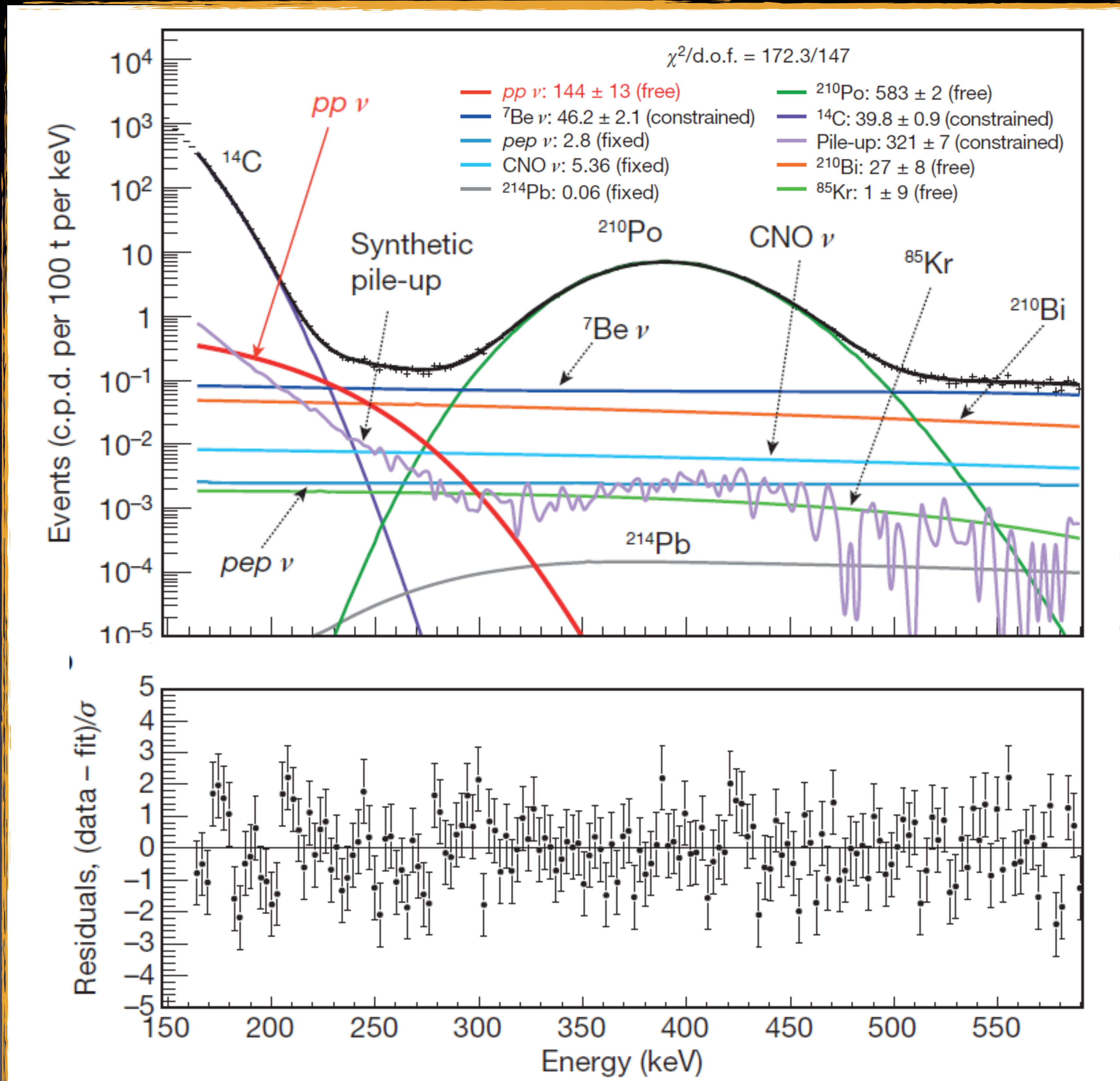
Challenge #3: pile up events

- **A few numbers:**
  - Rate of ^{14}C in scintillator: **R_C ~ 40 Bq / 100 t**
  - Borexino active mass: **M = 300 t**
  - Rate of ^{14}C pile up: **$r = (MR_C) \times R_C \times 230$ ns ~ 100 cpd / day**
    - pp expected rate: 130 cpd / 100 t

- Two independent methods used to measure pile-up spectrum
  - Overlap triggering events with other events in the same gate



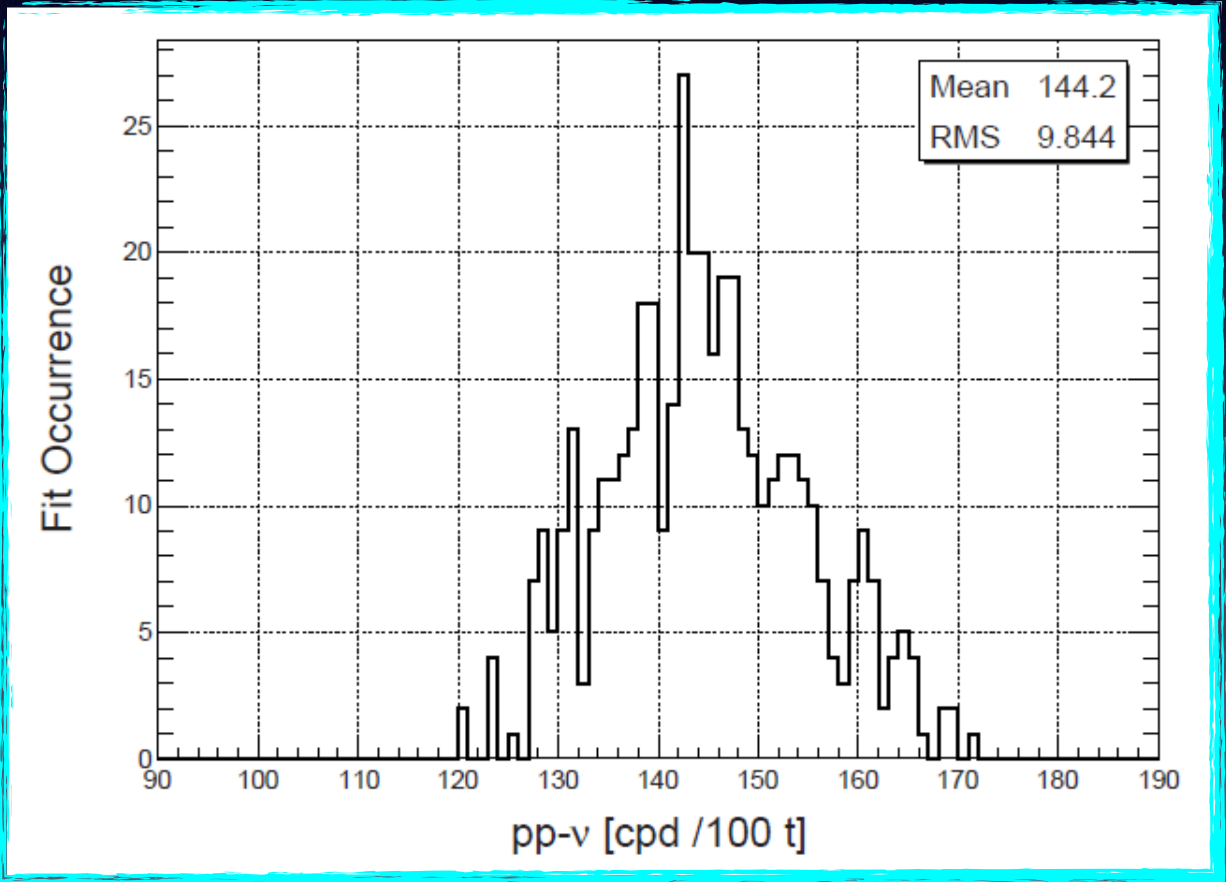
Fit results

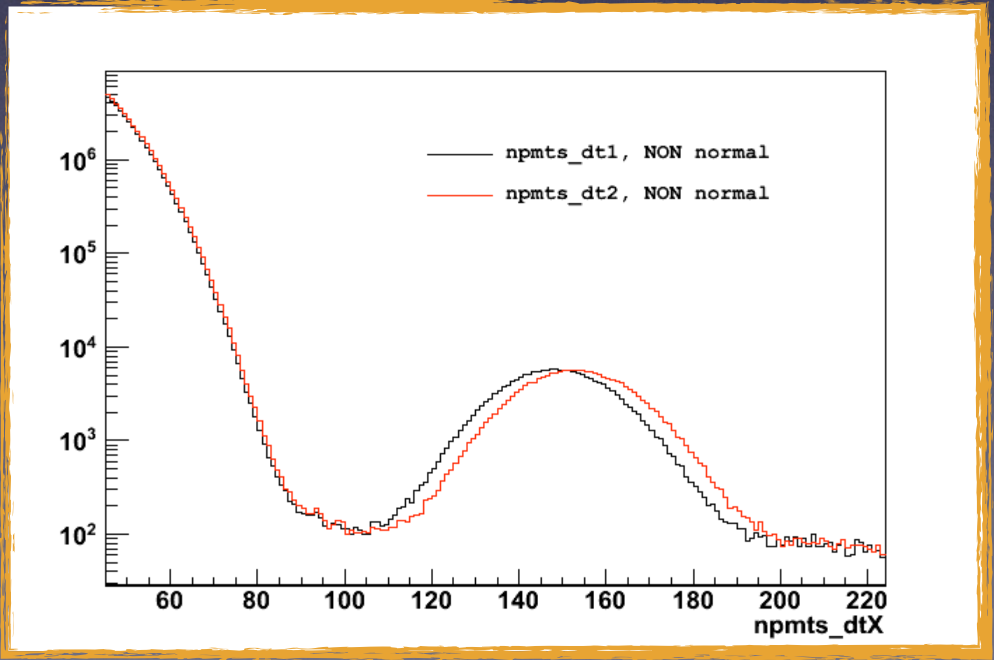


χ^2/d.o.f. = 172.3/147
pp ν: 144 ± 13 (free)
⁷Be ν: 46.2 ± 2.1 (constrained)
pep ν: 2.8 (fixed)
CNO ν: 5.36 (fixed)
²¹⁴Pb: 0.06 (fixed)
²¹⁰Po: 583 ± 2 (free)
¹⁴C: 39.8 ± 0.9 (constrained)
Pile-up: 321 ± 7 (constrained)
²¹⁰Bi: 27 ± 8 (free)
⁸⁵Kr: 1 ± 9 (free)
pp ν
¹⁴C
Synthetic pile-up
²¹⁰Po
CNO ν
⁸⁵Kr
²¹⁰Bi
⁷Be ν
pep ν
²¹⁴Pb
Events (c.p.d. per 100 t per keV)
Residuals, (data – fit)/σ
Energy (keV)

Systematics

- Systematic error is studied by varying fit conditions on all reasonable parameters within their known or data-constrained values
  - Distribution is peaked at ≈ 144 cpd / 100 t
- Main sources:
  - Pile-up : synthetic vs convolution
  - 7% — ^{85}Kr rate
  - 8% — Fiducial vol.: signal / background
  - 8% — Energy estimator

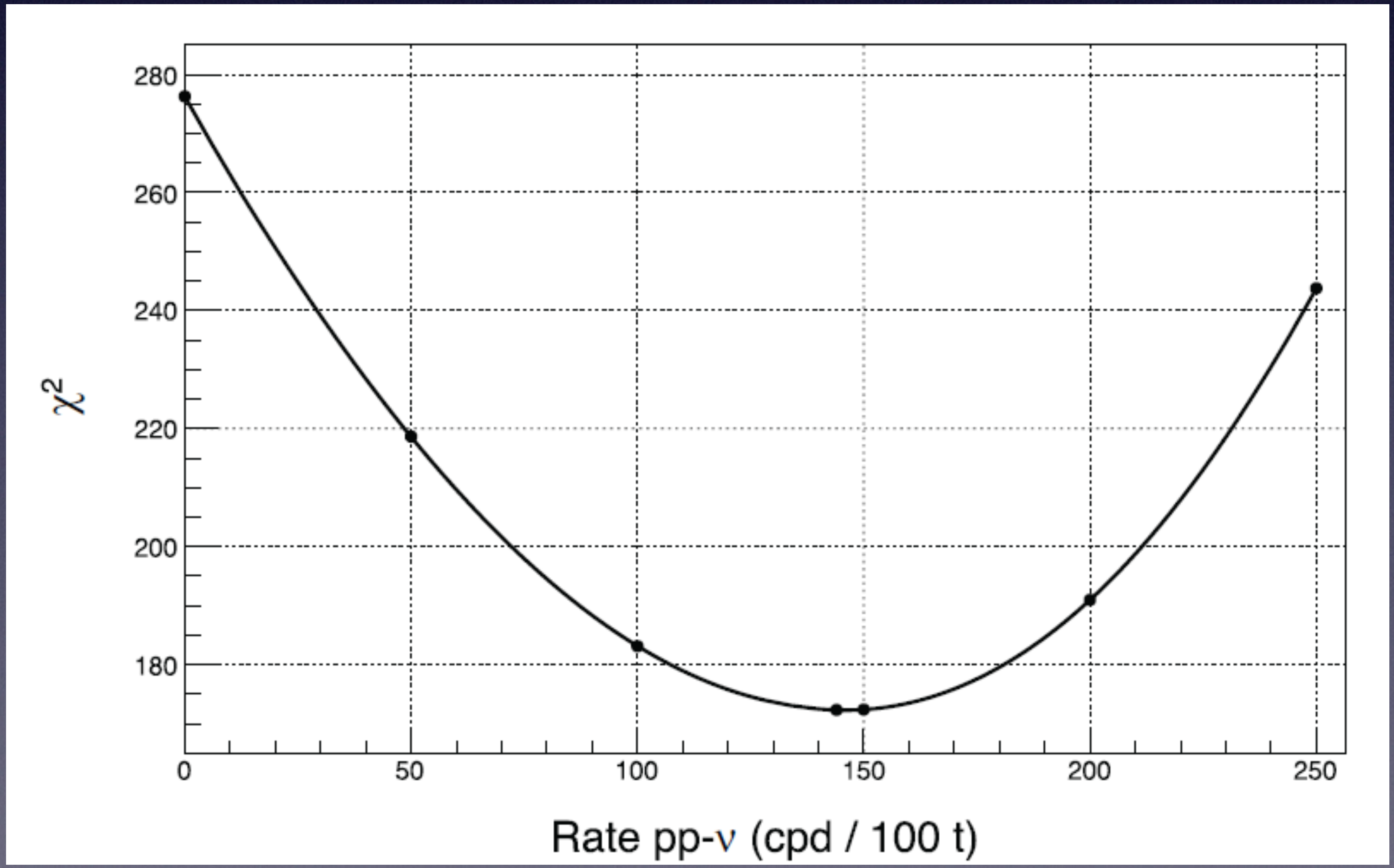




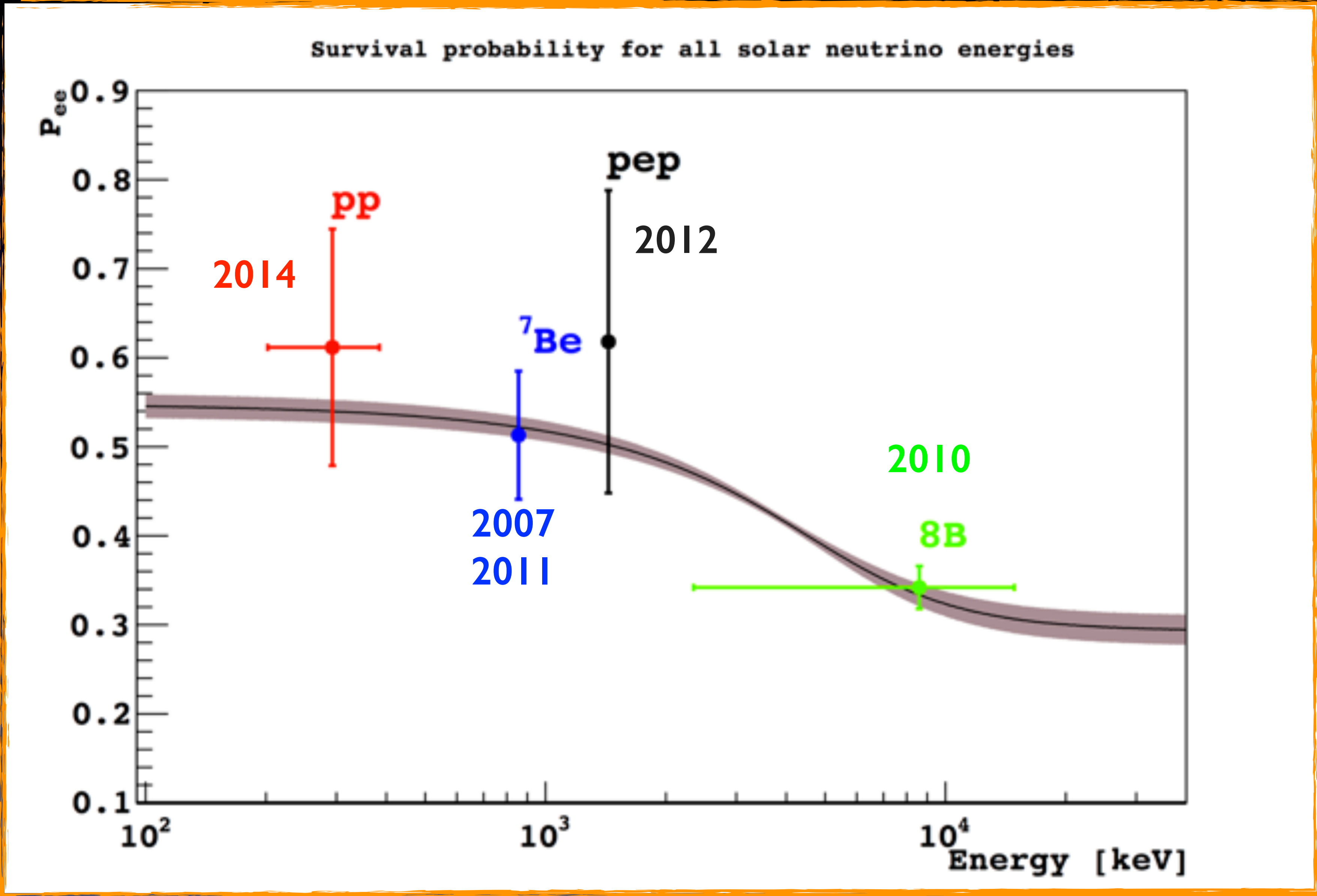
Final result

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

expected: (HM-SSM+LMA-MSW): 131 ± 2 cpd/100 t



7 years of Borexino



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

Stability of the Sun

- The pp neutrinos give a direct and real time measurement of Sun's power
  - 8 minutes delay for neutrinos
  - ~ 100 ky delay for photons

- Some ideas about the possibility to explain long term climate variation are related to variation of the Sun's activity

SCIENCE IDEAS

Solar Variability

Glacial Epochs, and Solar Neutrinos

by George A. Cowan and Wick C. Haxton

[Los Alamos Science, 1982]

Conclusion

- Borexino has been taking data for 7 years since 2007
  - ^{7}Be, ^{8}B, pep and now pp neutrinos have been measured
  - First neat geo-neutrino detection
  - CNO a dream ahead
    - Very challenging, maybe not possible

  - ^{7}Be, ^{8}B will likely be improved further

- The future:
  - SOX, Short Distance Neutrino Oscillations with Borexino
    - Search for sterile neutrinos
    - See A. Caminata talk today