Experimental detection of the CNO cycle

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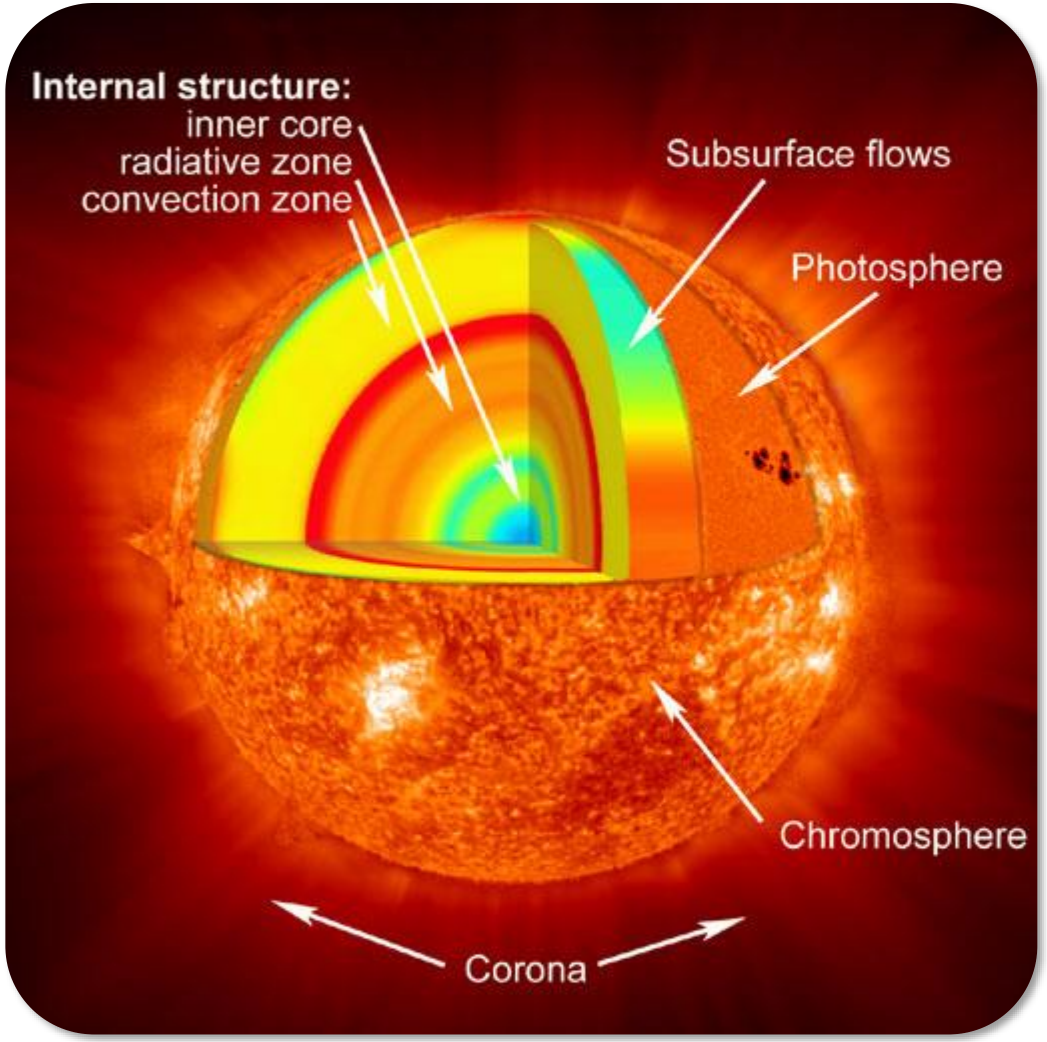
UJ Particle Physics Phenomenology and Experiments Seminar
Monday September 26th, 2022

How does the Sun shine ?

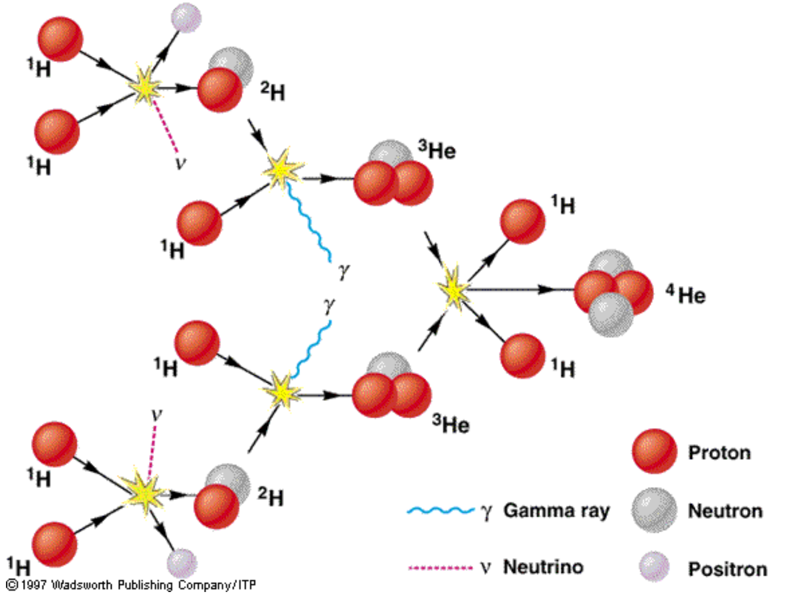
- we should not forget that *all energy* on this planet actually *comes* from the Sun

- In 1937, Gamov and von Weizsäcker suggested that the Sun is powered by a chain of nuclear reactions initiated by proton–proton fusion and leading to the production of ^{4}He. This idea was further developed by Bethe and Critchfield. At about the same time von Weizsäcker and independently Bethe proposed an alternative mechanism, namely the carbon–nitrogen–oxygen cycle (CNO cycle)

Solar ν as sensitive tool to test solar models



The three cycles of pp chain (*pp*-I, *pp*-II and *pp*-III) are each associated with a characteristic neutrino source. All three cycles begin with the fusion of two protons to form deuterium (^{2}H), through the ‘*pp*’ and ‘*pep*’ reactions.



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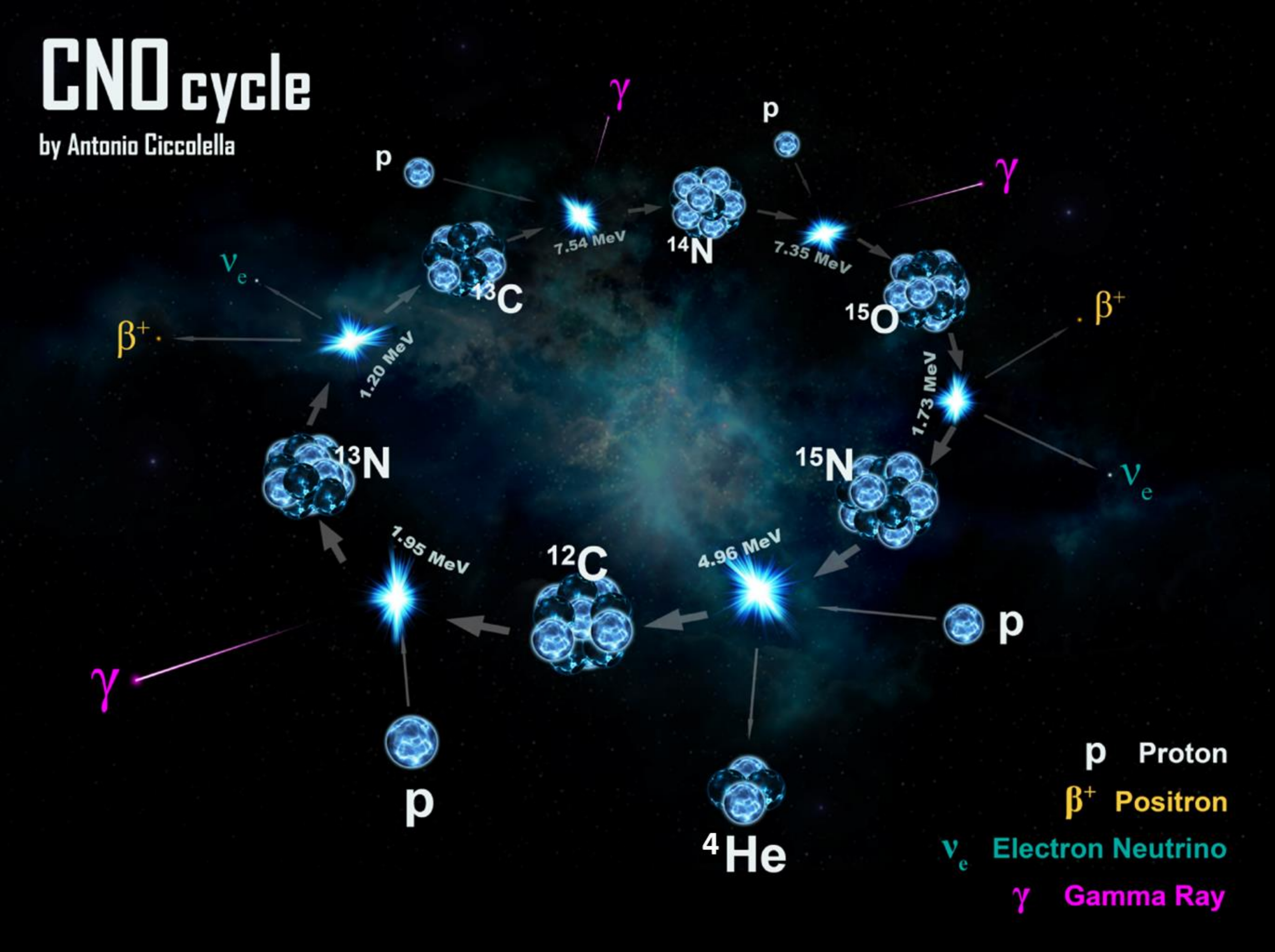
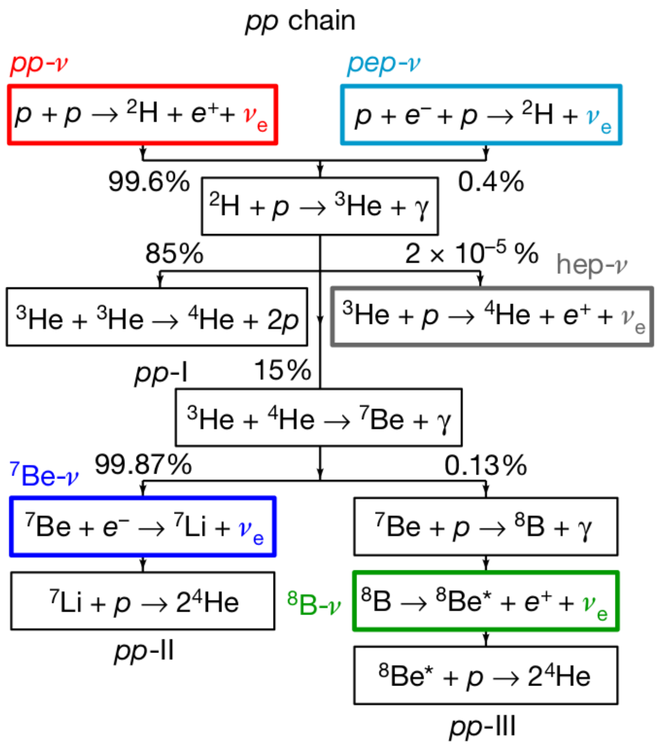
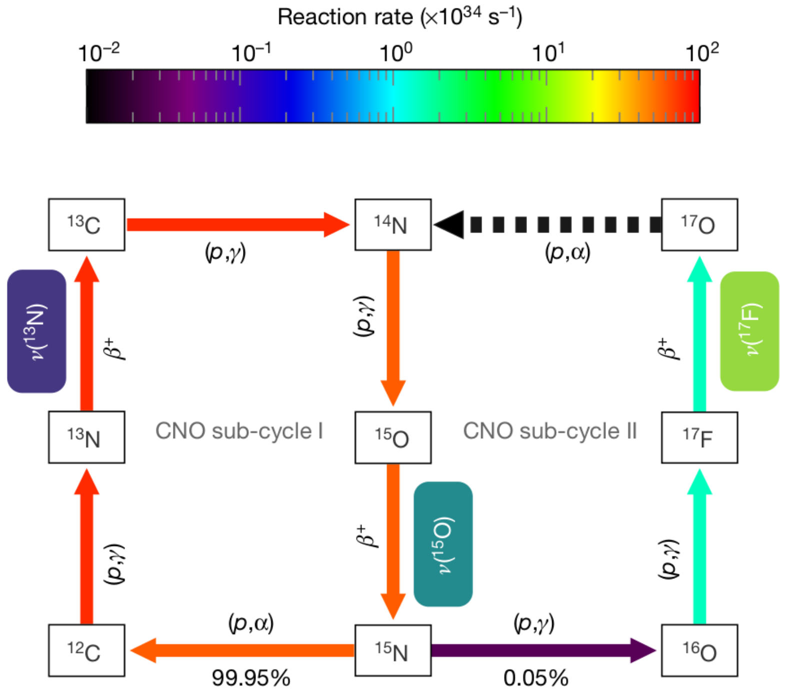
Original motivation of the first experiments on solar ν was to test the Standard Solar Model (SSM)

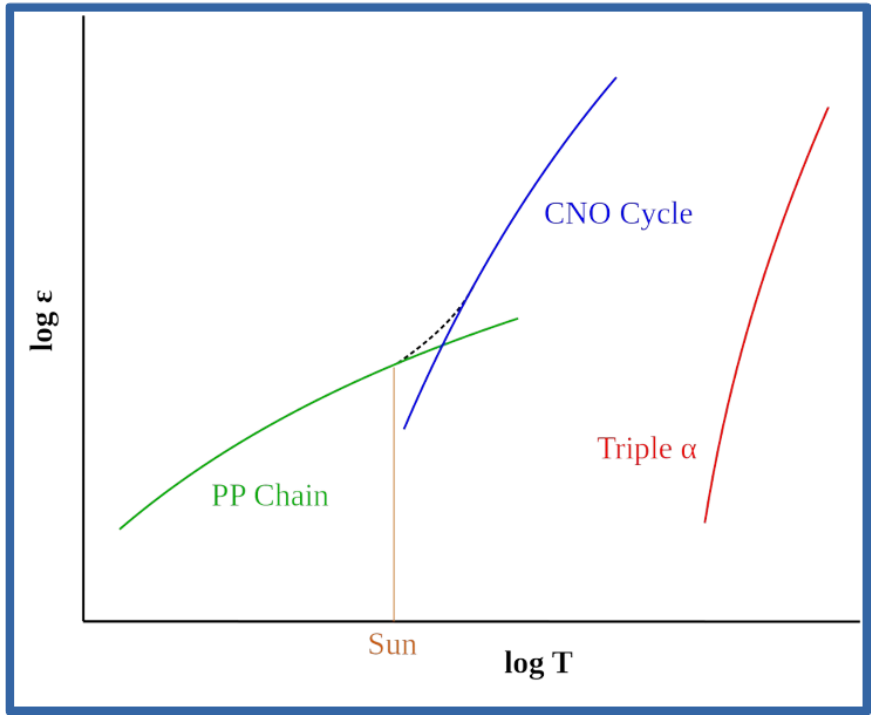


CNO cycle is a closed-loop chain of nuclear reactions catalysed by ^{12}C, ^{14}N and ^{16}O nuclei in which four protons are converted into ^{4}He.

PP vs CNO Competition







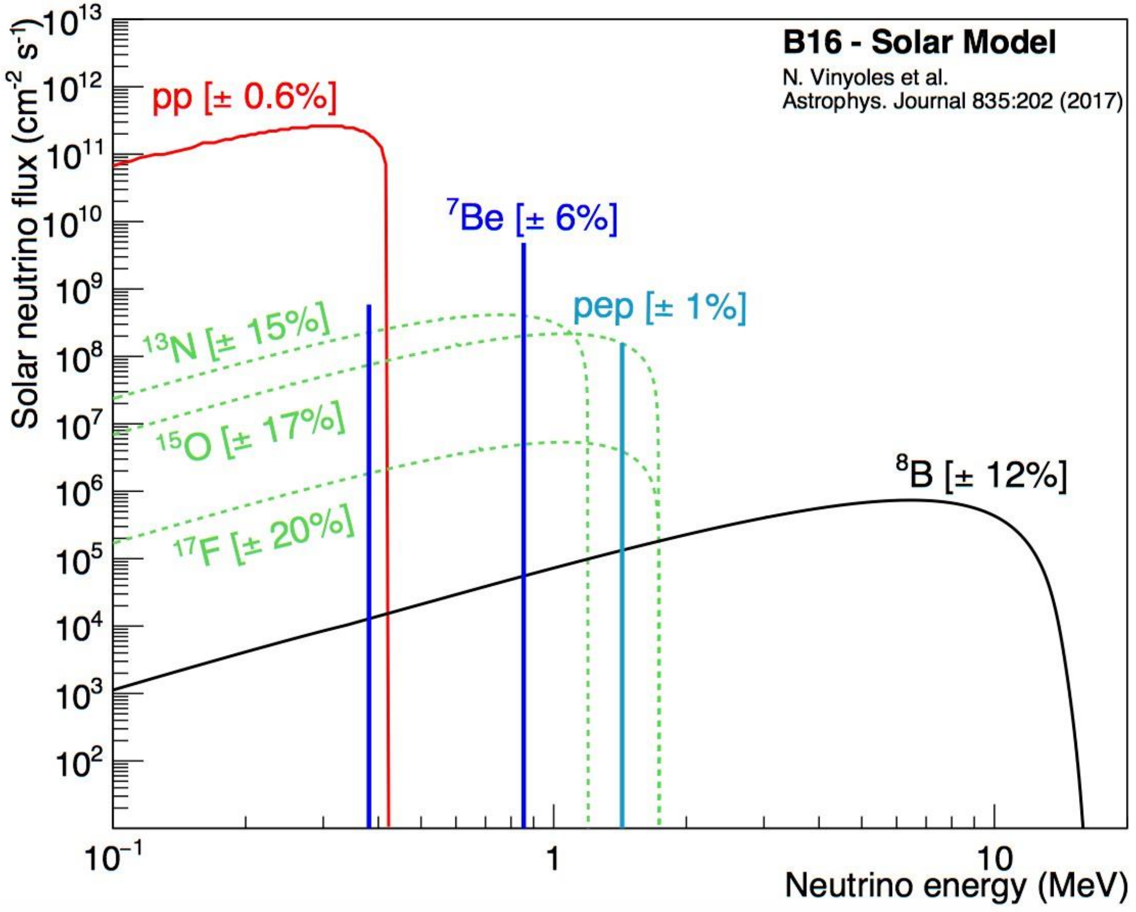
- Intense neutrinos from nuclear fusion in the Sun's core
- Majority (99%) from pp-chain with subdominant contribution from CNO cycle
- What's left in solar neutrinos?
  - Help understanding solar interior (metallicity problem)
- **Precision test of the MSW oscillation model**
  - Precise measurement of spectrum at the vacuum-to-matter transition region
  - Measurement of Day/Night asymmetry

The CNO cycle dominates in stars heavier than 1.3 M

Solar neutrinos as sensitive tool to test solar models: expected fluxes

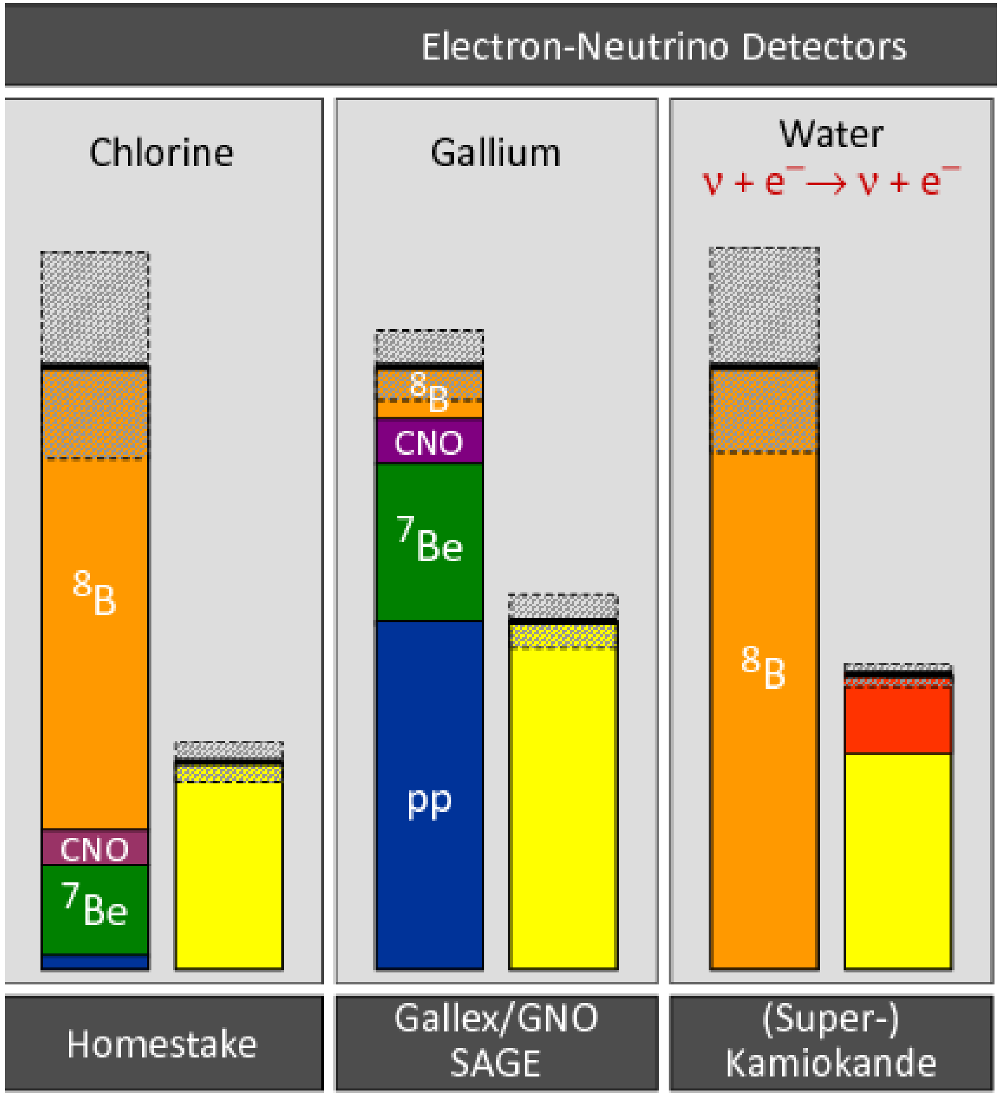
FLUX	B16-GS98
pp (10^{10} cm^{-2} s^{-1})	5.98(1±0.006)
pep (10^{8} cm^{-2} s^{-1})	1.44(1±0.01)
^{7}Be (10^{9} cm^{-2} s^{-1})	4.94(1±0.06)
^{8}B (10^{6} cm^{-2} s^{-1})	5.46(1±0.12)
^{13}N (10^{8} cm^{-2} s^{-1})	2.78(1±0.15)
^{15}O (10^{8} cm^{-2} s^{-1})	2.05(1±0.17)
^{17}F(10^{6} cm^{-2} s^{-1})	5.29(1±0.20)

N. Vinyoles et al.,
Astrophys. J. 835 (2017) 202



Original motivation of the first experiments on solar ν was to test the Standard Solar Model (SSM)

The solar neutrino problem: Homestake/Kamioka/Gallex-Sage



- Wrong experiments?
- Nuclear physics solution?
- If neutrinos are massive: flavour oscillations? ✓

(years: 1970-2000)

Solar Neutrino Problem:

Fluxes 1/2 or 1/3
of expectations!

The Borexino Collaboration

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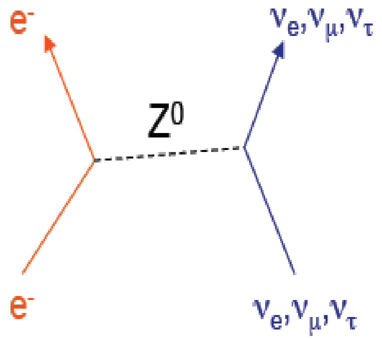
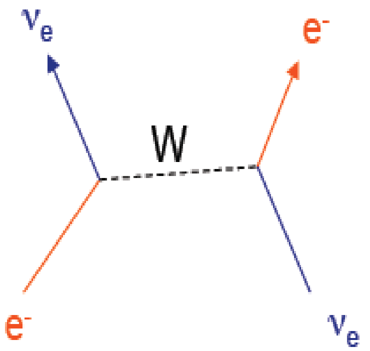
JAGIELLONIAN UNIVERSITY IN KRAKÓW

POLITECNICO MILANO 1863

BOREXINO Detector – Detection principle

- Neutrino elastic scattering on electrons of liquid scintillator: **$e^- + \nu \rightarrow e^- + \nu$;**
- Scattered electrons cause the scintillation light production;
- <u>Advantages</u>:
  - Low energy threshold (~ 0.2 MeV);
  - High light yield and a good energy resolution;
  - Good position reconstruction;
- <u>Drawbacks :</u>
  - Info about the ν directionality is lost;
  - ν-induced events can't be distinguished from the events of β/γ natural radioactivity;
  - The expected rate of solar neutrinos in 100 tons of BX scintillator is ~40 counts/day which corresponds to ~$5\cdot10^{-9}$ Bq/kg

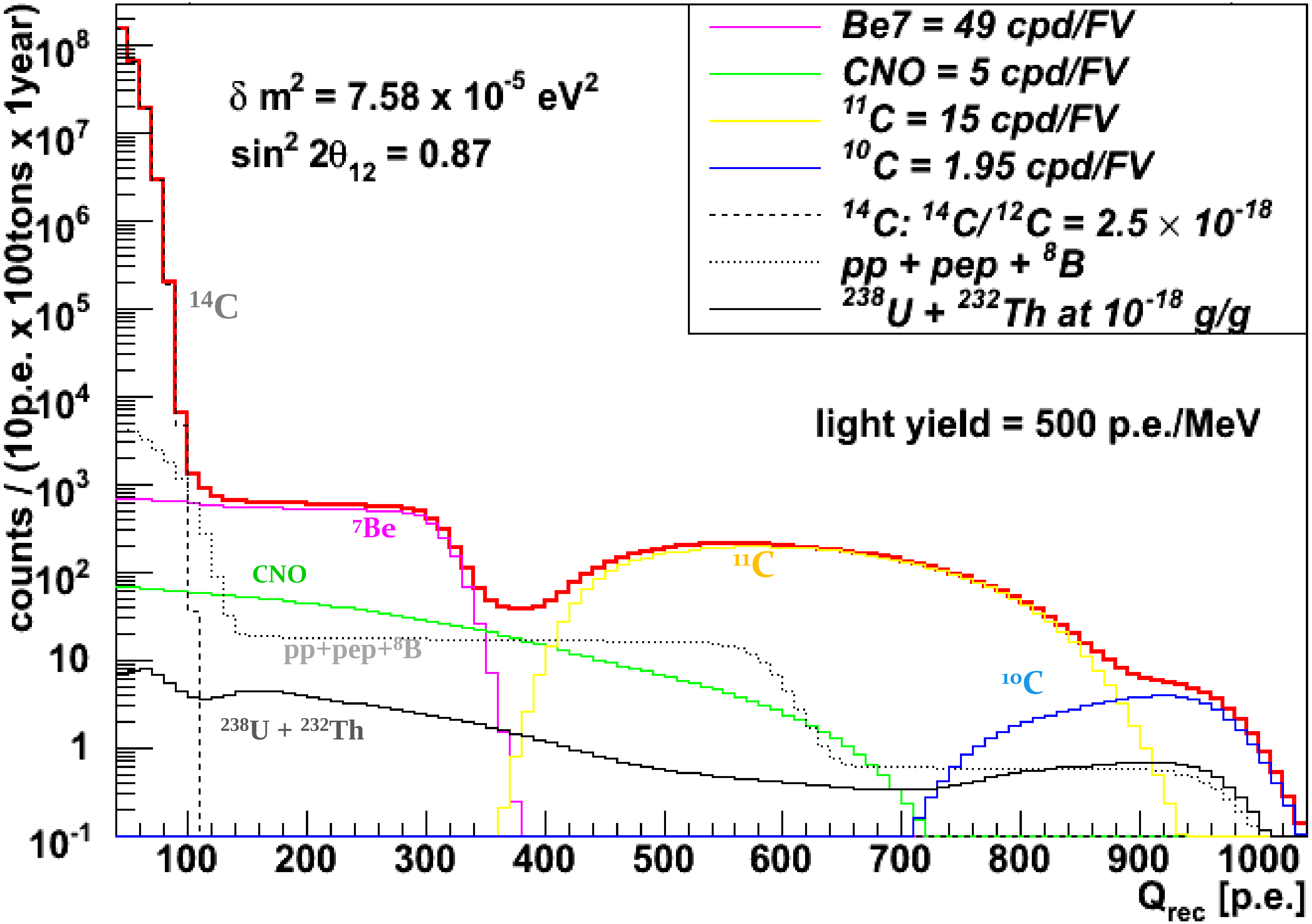




Extreme radiopurity is a must for a precision low energy neutrino spectroscopy.

E.g.:
- Rn in air ~ 10 Bq/kg
- Natural water ~ 10 Bq/kg
- Rn in Borexino ~ 1×10^{-10} Bq/kg

The expected signal and the irreducible background



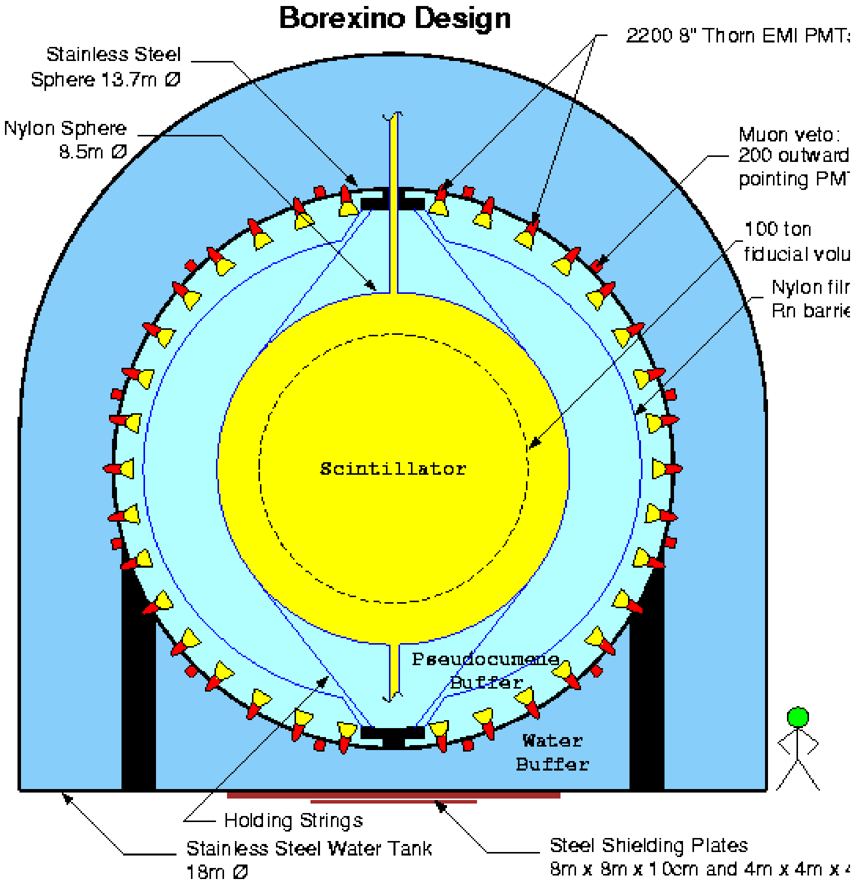
BOREXINO Detector

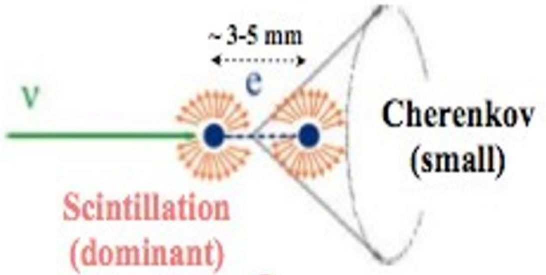
Core of the detector: 300 tons of liquid scintillator contained in a nylon vessel of 4.25 m radius (PC+PPO);

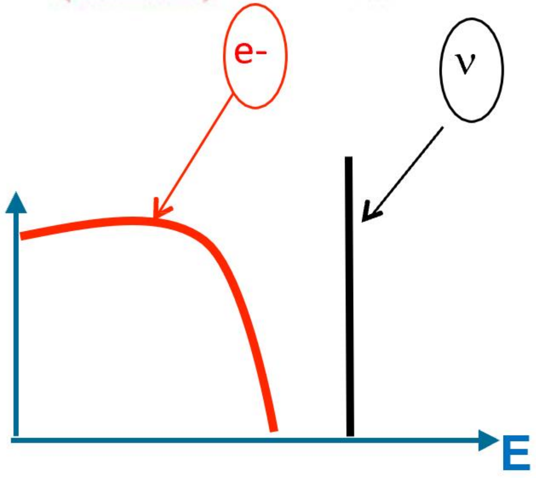
1st shield: 1000 tons of ultra-pure buffer liquid (pure PC) contained in a stainless steel sphere of 7 m radius;

2214 photomultiplier tubes pointing towards the center to view the light emitted by the scintillator;

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







We measure the energy carried away by the electron!

200 PMTs mounted on the SSS pointing outwards to detect light emitted in the water by muons crossing the detector;

Borexino is located inside the Gran Sasso mountain in Italy

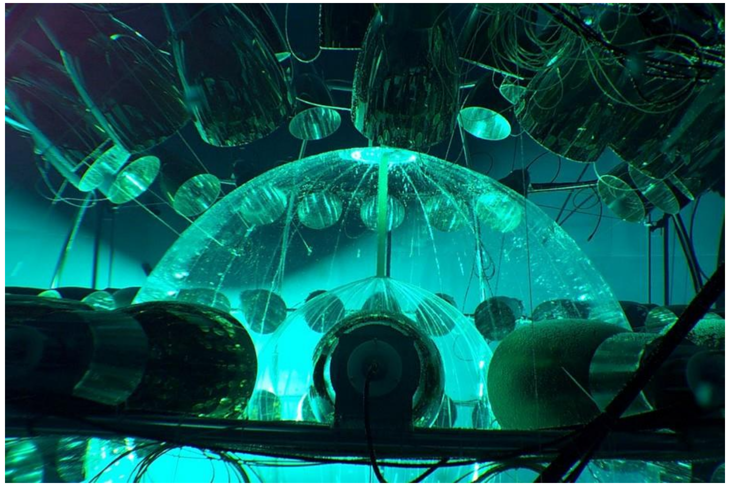
The Borexino Saga

1990: idea of a sub-Mev solar neutrino detector. A real time neutrino detection

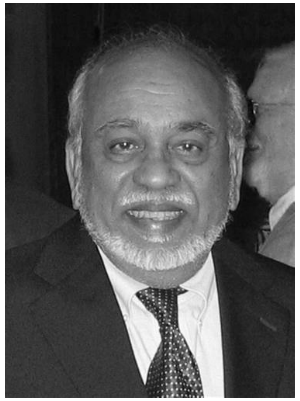
1995: CTF testing the record radiopurity
^{238}U, $^{232}Th < 10^{-16}$ g/g
$^{14}C/^{12}C < 10^{-18}$

1996-1997: Approval of the experiment

Mid-2007: Beginning of the datataking



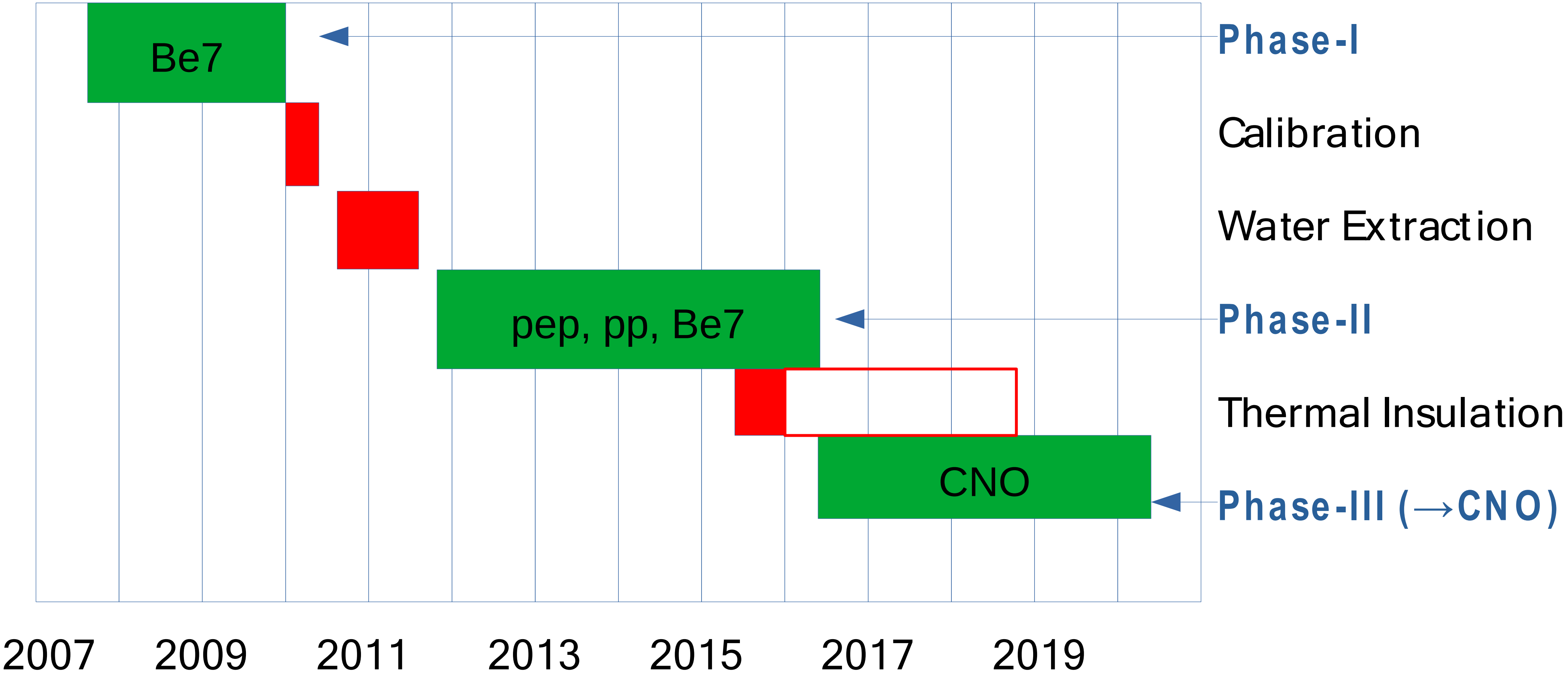
Gianpaolo Bellini



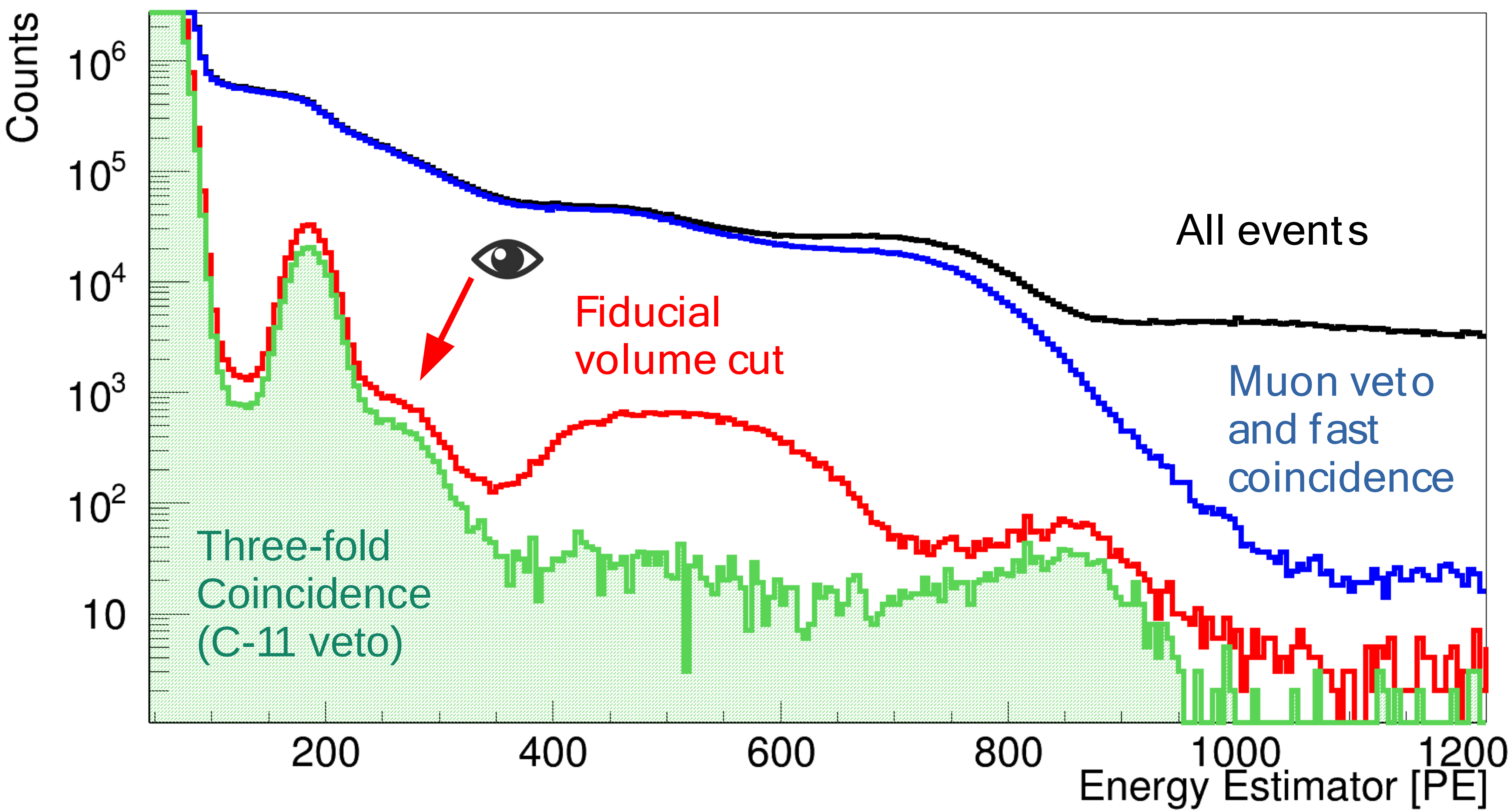
Raju Raghavan (1937-2011)

Great care in selecting radioupure materials (structure and scintillator) and unprecendented purification tecniques: distillation, N2 stripping, water extraction

The three ages of Borexino

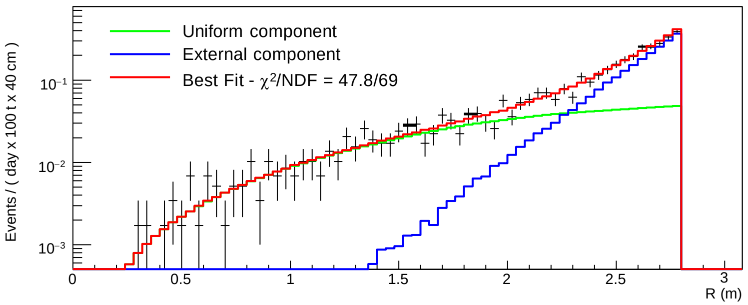


The Borexino Energy Spectrum

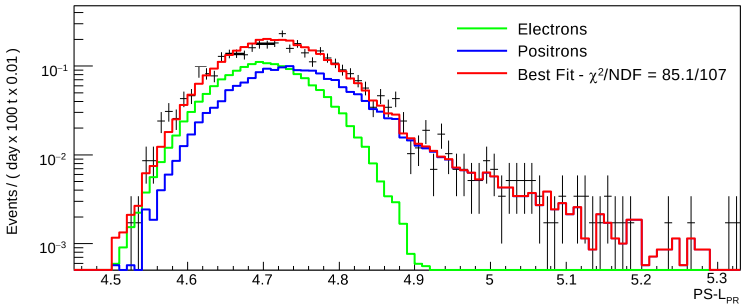


Results : example of multivariate fit of the data

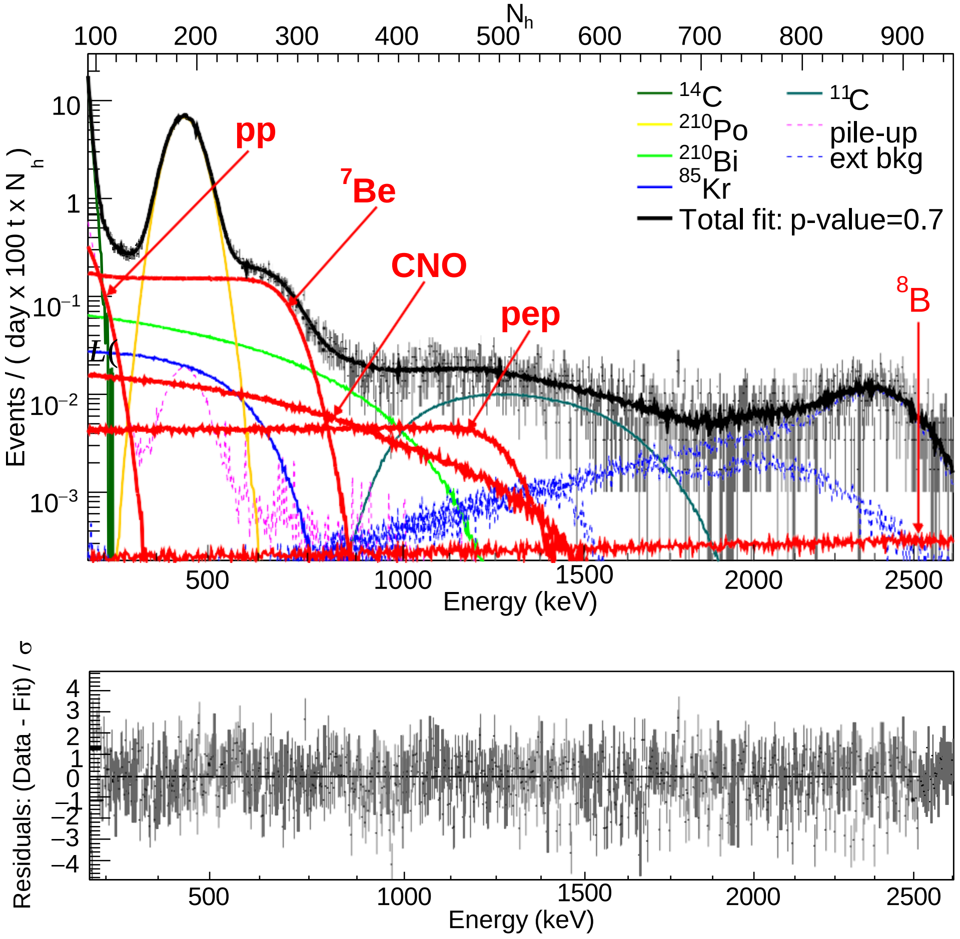
Radial distribution



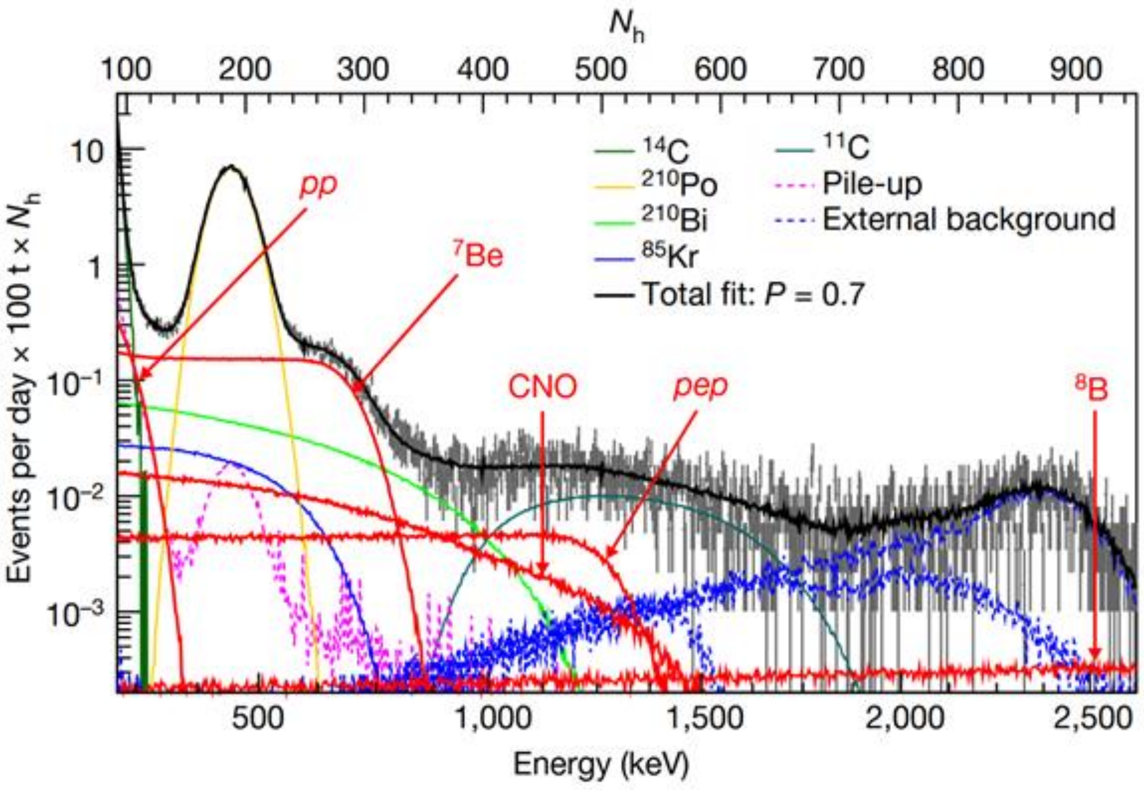
PS-L_{PR}



Energy spectrum



BOREXINO – real-time solar neutrino spectroscopy

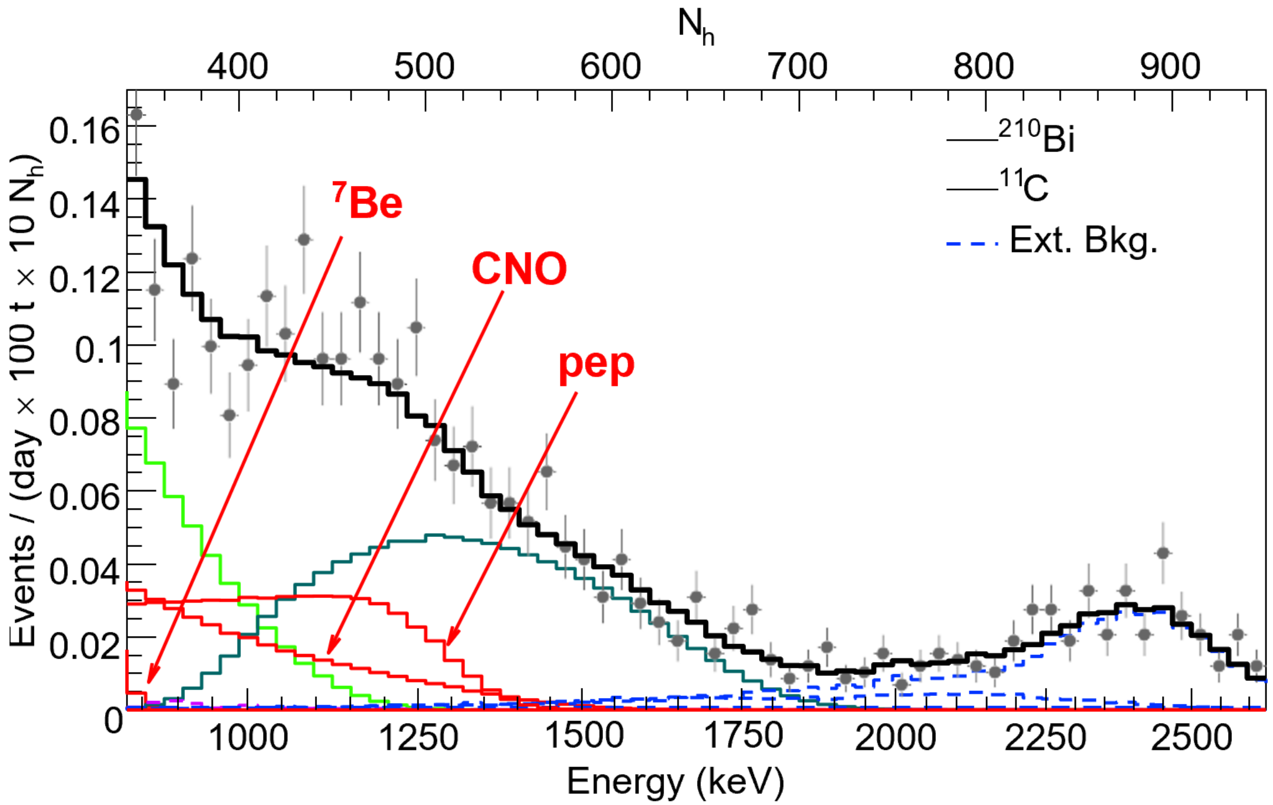


The Borexino Collaboration. *Comprehensive measurement of pp-chain solar neutrinos*. ***Nature* 562,** 505–510 (2018)

From the measured interacton rates and assuming HZ-SSM fluxes we get electron neutrino survival probability from 60 keV to >10 MeV.

Selected the innermost β-like events

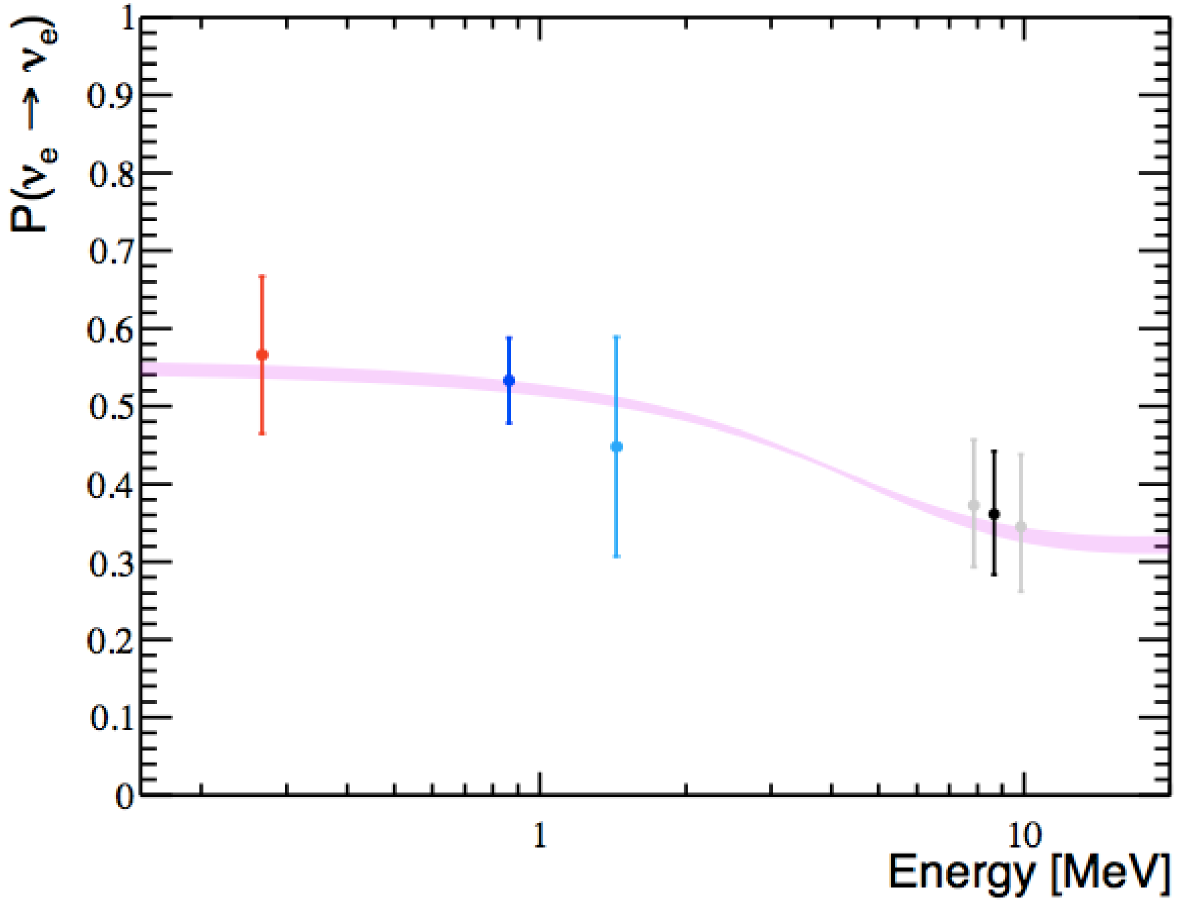
Radius <2.4 m Ps-LPR < 4.8



- P_{ee}(pp)= 0.57±0.10 P_{ee}(^{7}Be,862keV)= 0.53±0.05
- P_{ee}(pep)= 0.43±0.11 P_{ee}(^{8}B)= 0.37±0.08

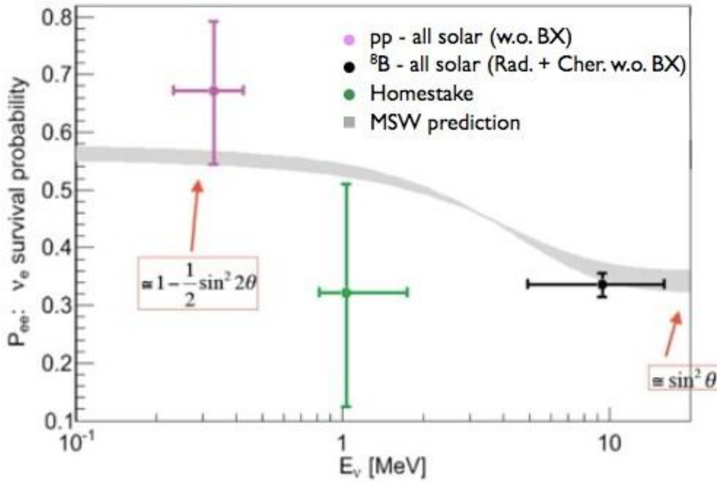
P_{ee}: Borexino impact

Borexino now



Pee - electron neutrino survival probability

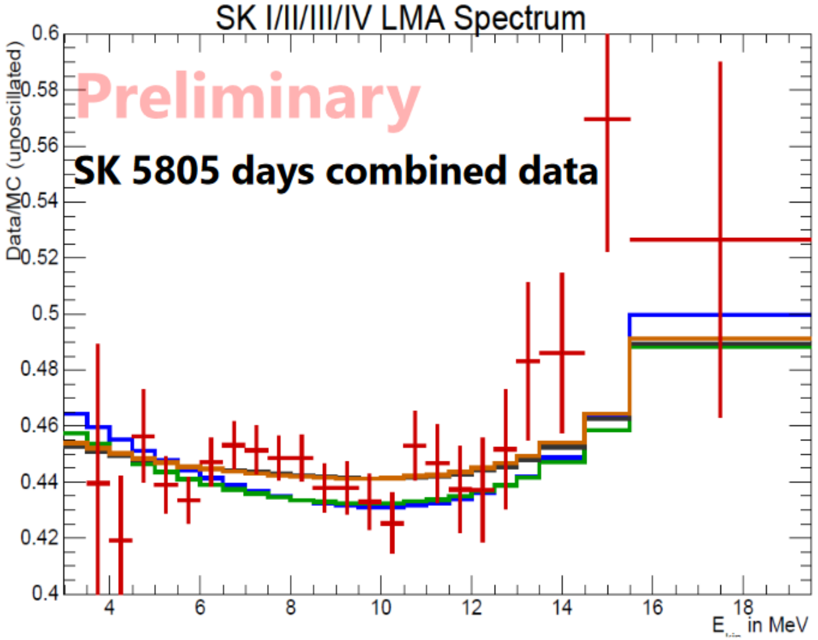
Before Borexino



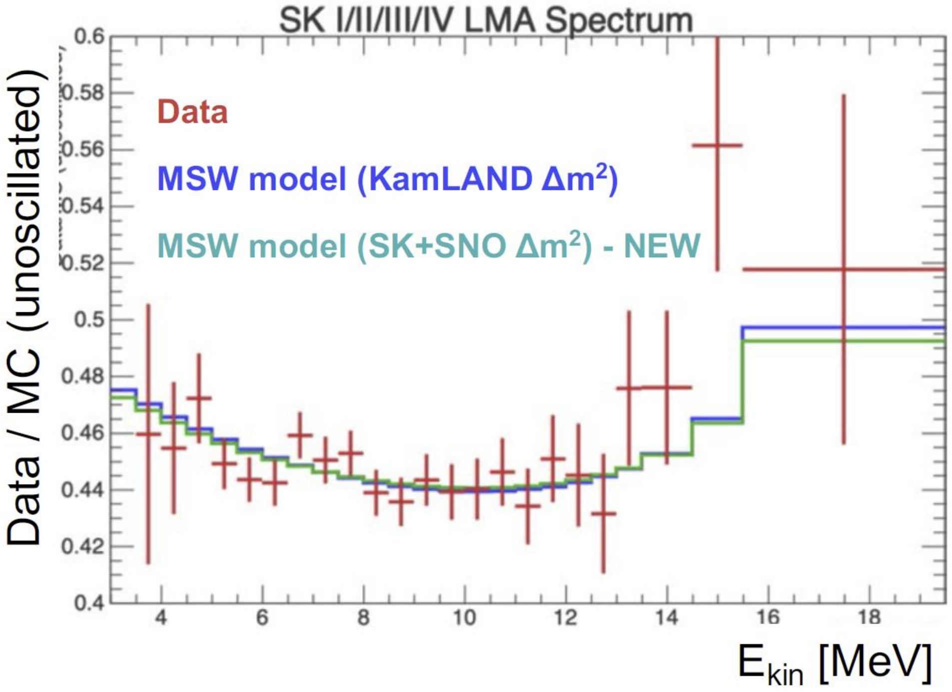
1. Borexino has measured the electron neutrino Pee in the *vacuum regime*, where, according to the MSW- LMA model, the vacuum dominates
2. The Borexino data allowed to probe the vacuum– matter transition from a single experiment.
3. Despite the uncertainty of the various points, that incorporate both the experimental errors and the SSM uncertainties, the experimental results seem in agreement with the predictions of the MSW-LMA model.

New spectrum and Day/Nigth asymemetry measurements to test MSW

- Energy dependent survival probability Pee



TAUP 2019 - Yuuki Nakano and for the Super-Kamiokande collaboration 2020 J. Phys.: Conf. Ser. 1468 012189



TAUP 2021 – Livia Ludhova talk: Solar and Geoneutrinos

- Day/Night effect

$$A_{DN}^{Fit} = (-3.6 \pm 1.6(stat) \pm 0.6(syst))\ \% \rightarrow A_{DN}^{Fit} = (-2.1 \pm 1.1)\ \%$$

Neutrino 2020 Yasuhiro Nakajima *Recent results and future prospects from Super-Kamiokande*

Data/MC ratio at E < 6 MeV slightly shifted upward

Shift of prediction due to improved detector simulation. Added statistics due to improved spallation cut.

Event migration due to new reconstruction

Day/Night asymmetry shift

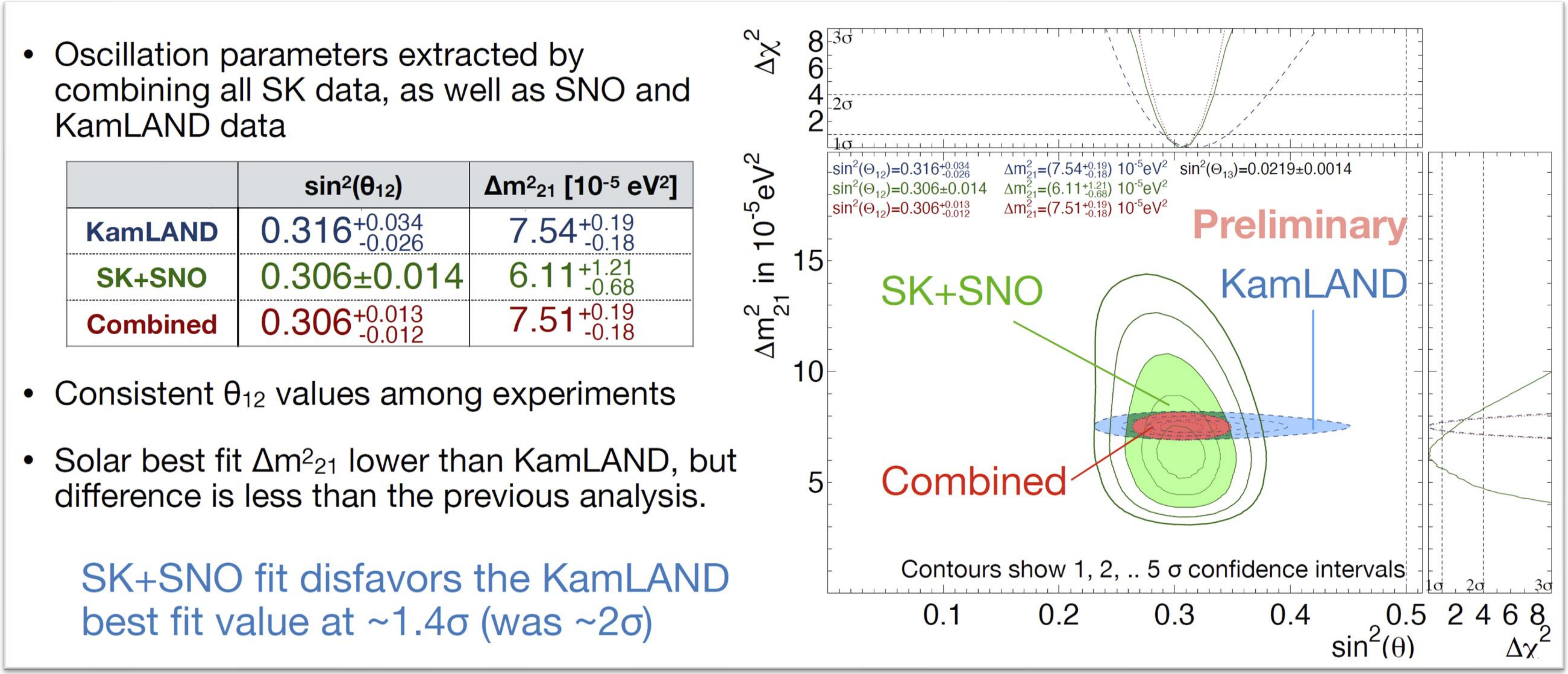
Previous analysis used data up to Feb 2014 (SK-IV: 1664 days)

Added ~1200 days of data fluctuated towards smaller D/N asymmetry

Both impacted to the shift of best fit Δm^2_{21}

SuperK - Oscillation Parameter Extraction

- use rate, spectral and day/night rate variation
- larger value of Δm^2 than before
- less tension (1.4 σ) with KamLAND (reactor antinu) -



- Oscillation parameters extracted by combining all SK data, as well as SNO and KamLAND data

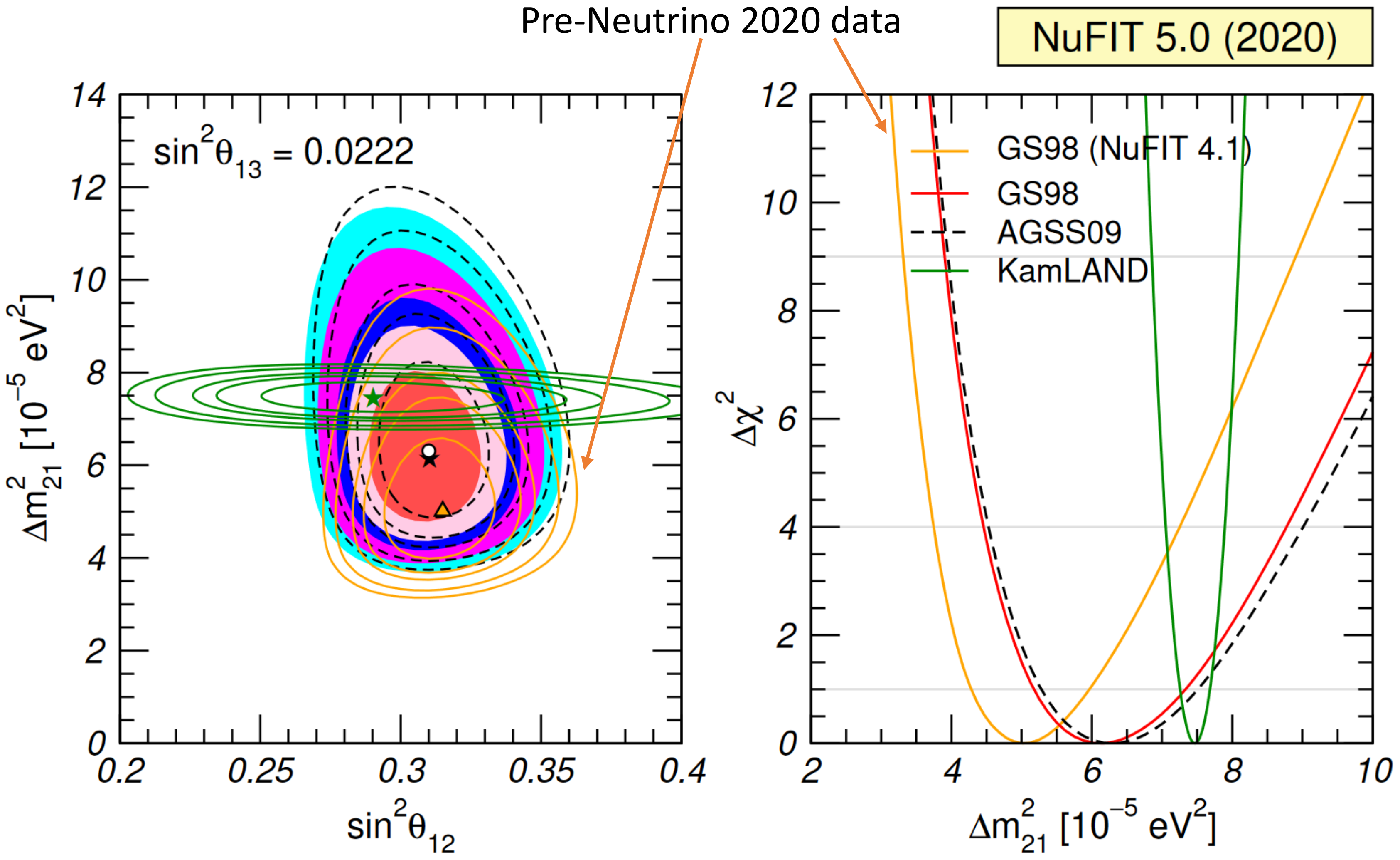
	$\sin^2(\theta_{12})$	Δm^2_{21} [10^{-5} eV^2]
KamLAND	$0.316^{+0.034}_{-0.026}$	$7.54^{+0.19}_{-0.18}$
SK+SNO	0.306 ± 0.014	$6.11^{+1.21}_{-0.68}$
Combined	$0.306^{+0.013}_{-0.012}$	$7.51^{+0.19}_{-0.18}$

- Consistent θ_{12} values among experiments
- Solar best fit Δm^2_{21} lower than KamLAND, but difference is less than the previous analysis.

SK+SNO fit disfavors the KamLAND best fit value at ~1.4σ (was ~2σ)

Yasuhiro Nakajima *Recent results and future prospects from Super-Kamiokande* Neutrino 2020

Resolved tension in the solar sector

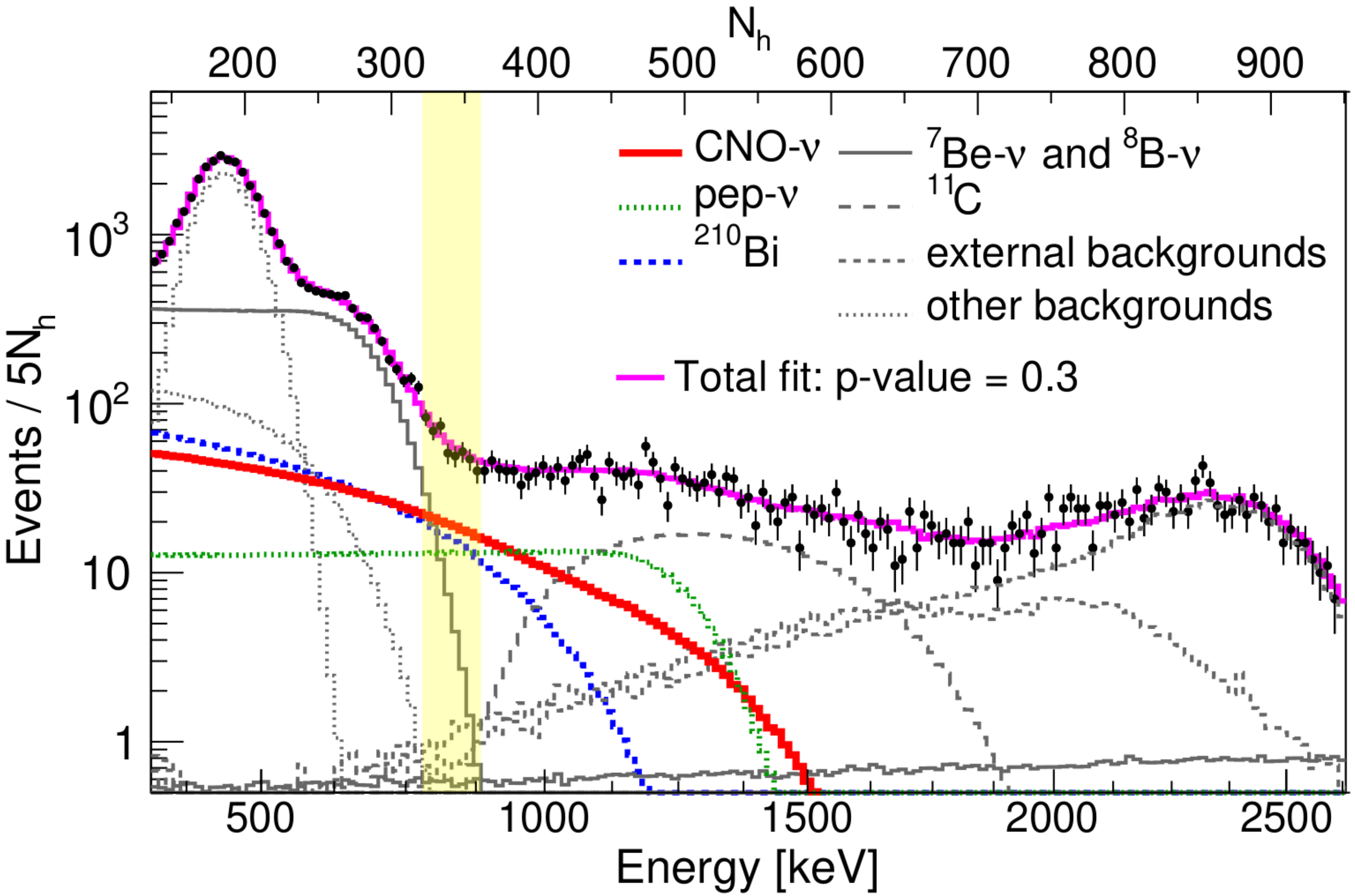


Pre-Neutrino 2020 data

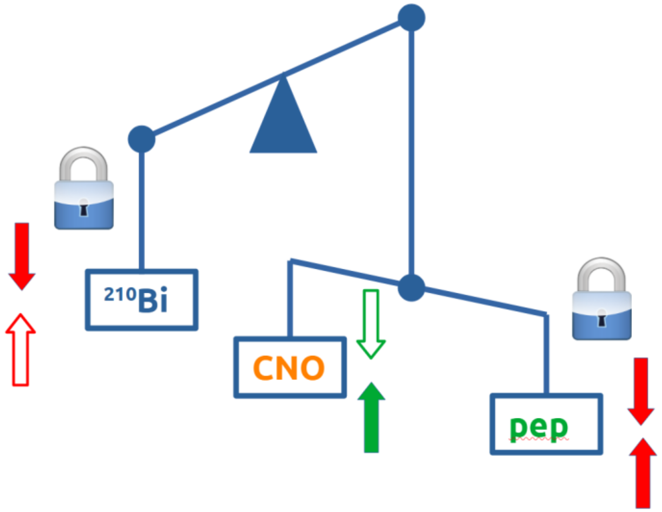
- With the new data the tension between the best fit Δm^2_{21} of KamLAND and that of the solar results has decreased.
- The best fit of KamLAND lies at 1.14σ in the analysis with the GS98 fluxes.
- This decrease in the tension is due to both, the smaller day-night asymmetry (and the slightly more pronounced turn-up in the low energy part of the spectrum which lowers it one extra unit.

Esteban, I., Gonzalez-Garcia, M., Maltoni, M. et al. *The fate of hints: updated global analysis of three-flavor neutrino oscillations.* J. High Energ. Phys. 2020, 178 (2020).

CNO - challenges

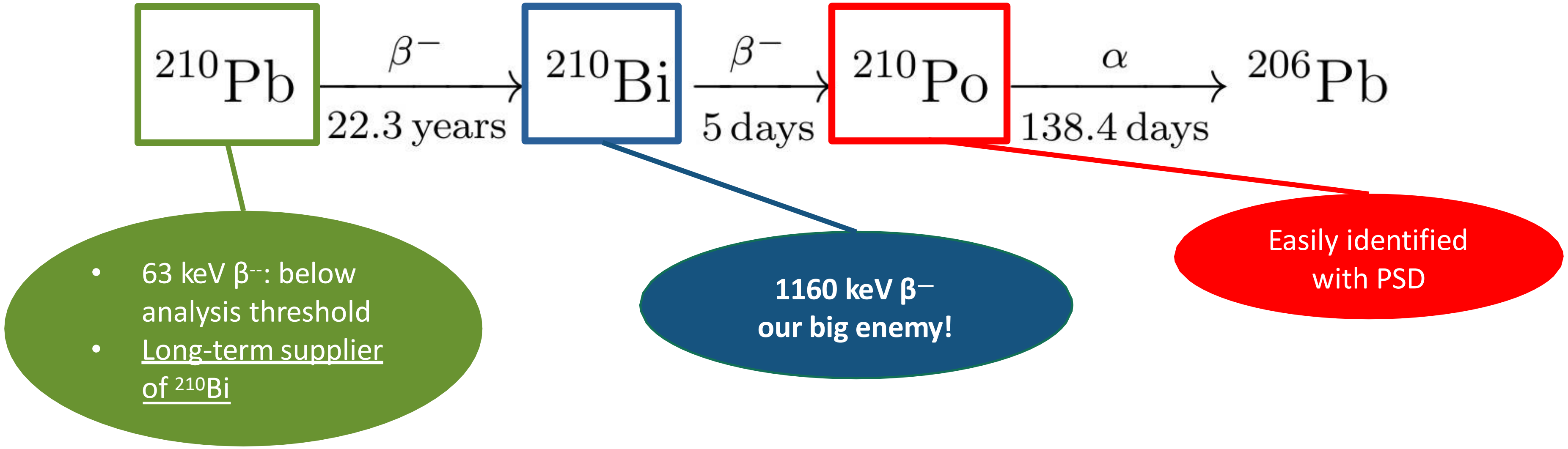


- *pep* rate: gaussian penalty at SSM prediction
- ^{210}Bi rate: semi-gaussian penalty at our upper limit



Strategy: independent constraint of pep and Bi-210

Strategy for ^{210}Bi constraint



$$\boxed{^{210}\mathrm{Pb}} \xrightarrow[22.3\,\text{years}]{\beta^-} \boxed{^{210}\mathrm{Bi}} \xrightarrow[5\,\text{days}]{\beta^-} \boxed{^{210}\mathrm{Po}} \xrightarrow[138.4\,\text{days}]{\alpha} {}^{206}\mathrm{Pb}$$

- 63 keV β^{--}: below analysis threshold
- <u>Long-term supplier of ^{210}Bi</u>

1160 keV β^-
our big enemy!

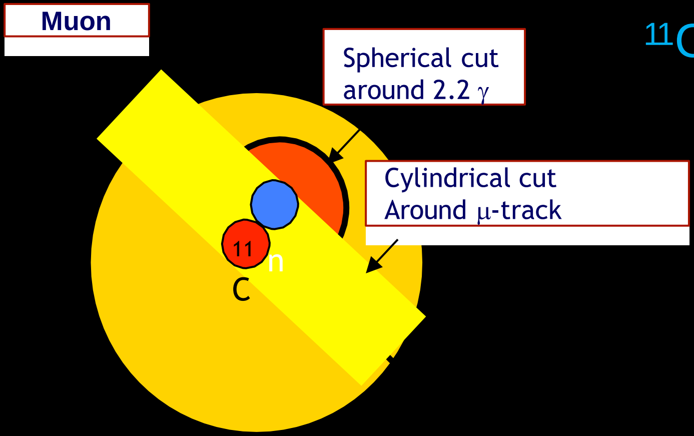
Easily identified
with PSD

Measuring ^{210}Po could allow to constraint ^{210}Bi

…

If only we had secular exquilibrium!

^{11}C cut: 1) the three fold coincidence



^{11}C is produced by muons together with neutron(s);

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

The likelihood that a certain event is ^{11}C is obtained using:

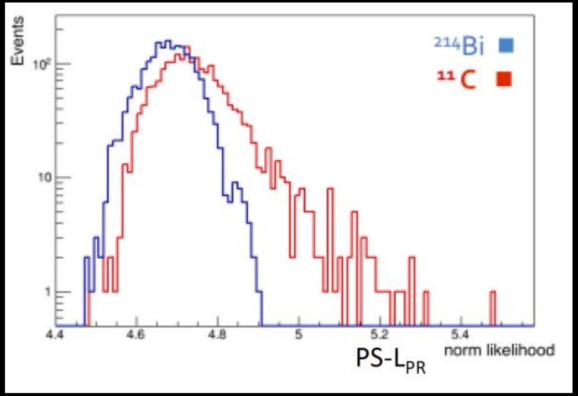
- Distance in space and time from the μ-track;
- Distance from the neutron;
- Neutron multiplicity;
- Muon dE/dx and number of muon clusters in an event;

The data-set is divided in two samples: one depleted in ^{11}C (TFC-subtracted) and one enriched in ^{11}C (TFC-tagged) which are simultaneously fit;

2) The β^+/β^- pulse-shape variable PS-L_{PR}:

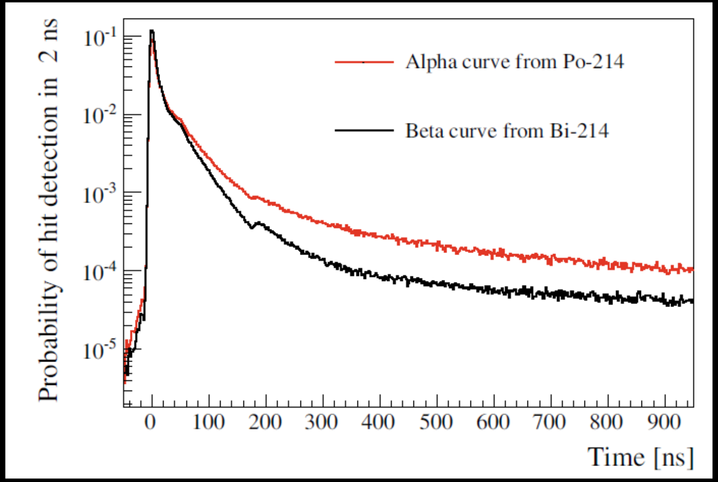
^{11}C decays β^+ : the probability density function (PDF) of the scintillation time profile is different for e^- and e^+ for two reasons:

- in 50% of the case e^+ annihilation is delayed by ortho-positronium formation (τ~3ns);
- e^+ energy deposit is not point-like because of the two annihilation gammas;



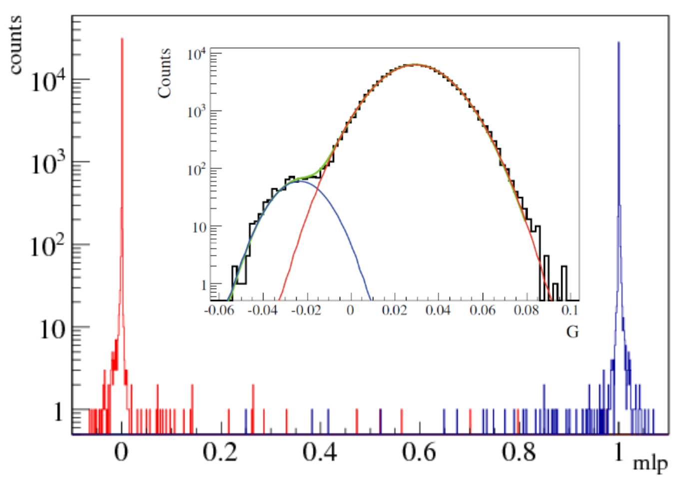
New discrimination parameter based on the output likelihood of the pos-reco alghoritm

α / β Discrimination with ANN



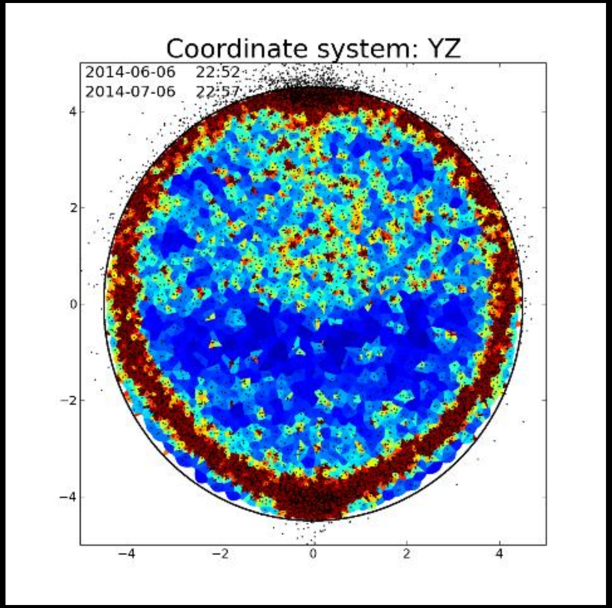
Solved problem of α discrimination from ^{210}Po (α)

Neural networks method

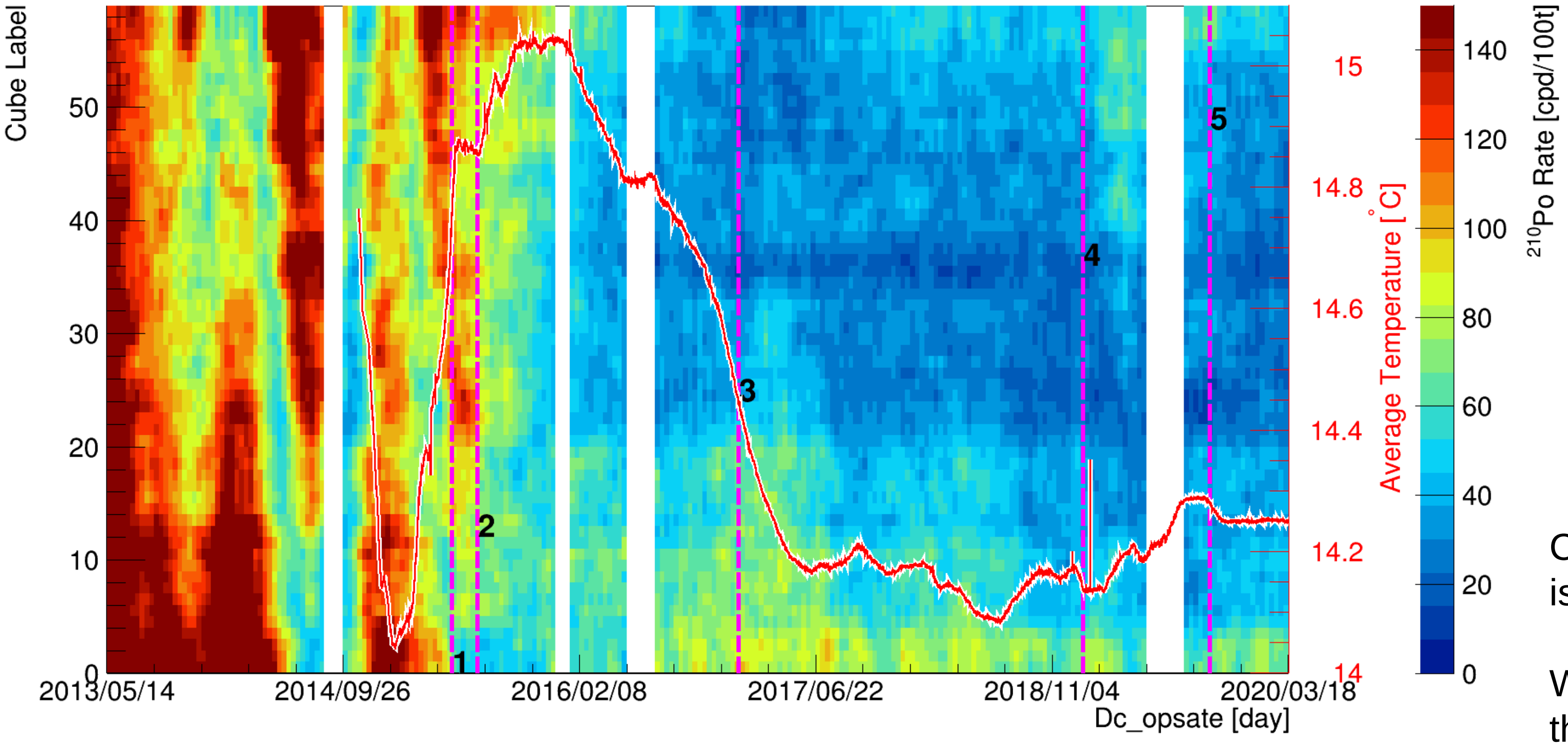


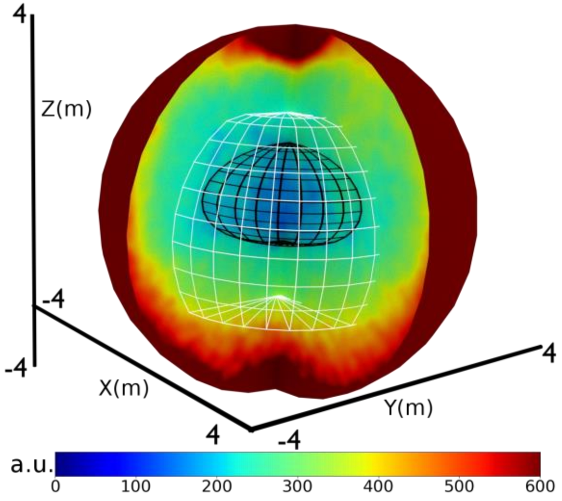
Galbiati, C., Misiaszek, M. & Rossi, N. Eur. Phys. J. A (2016) 52: 86.

Example of α/β for ^{214}Bi-^{214}Po



The Low Polonium Field



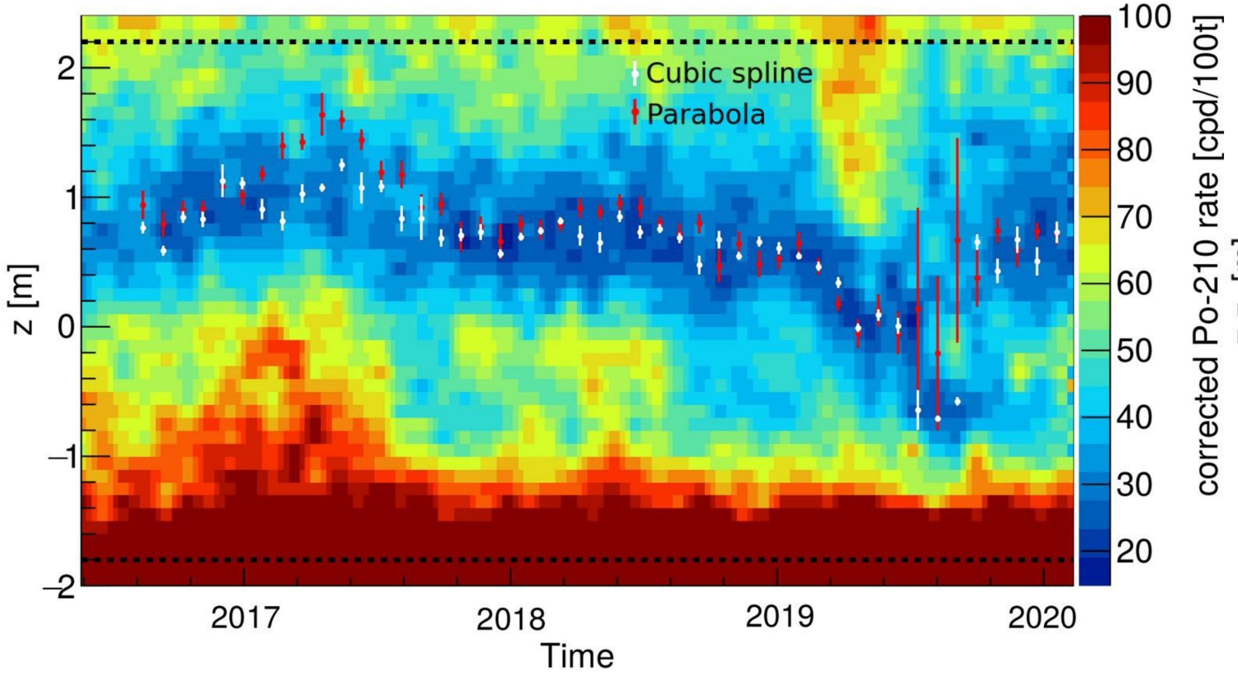


Clean region in the core of the detector is created: LPoF

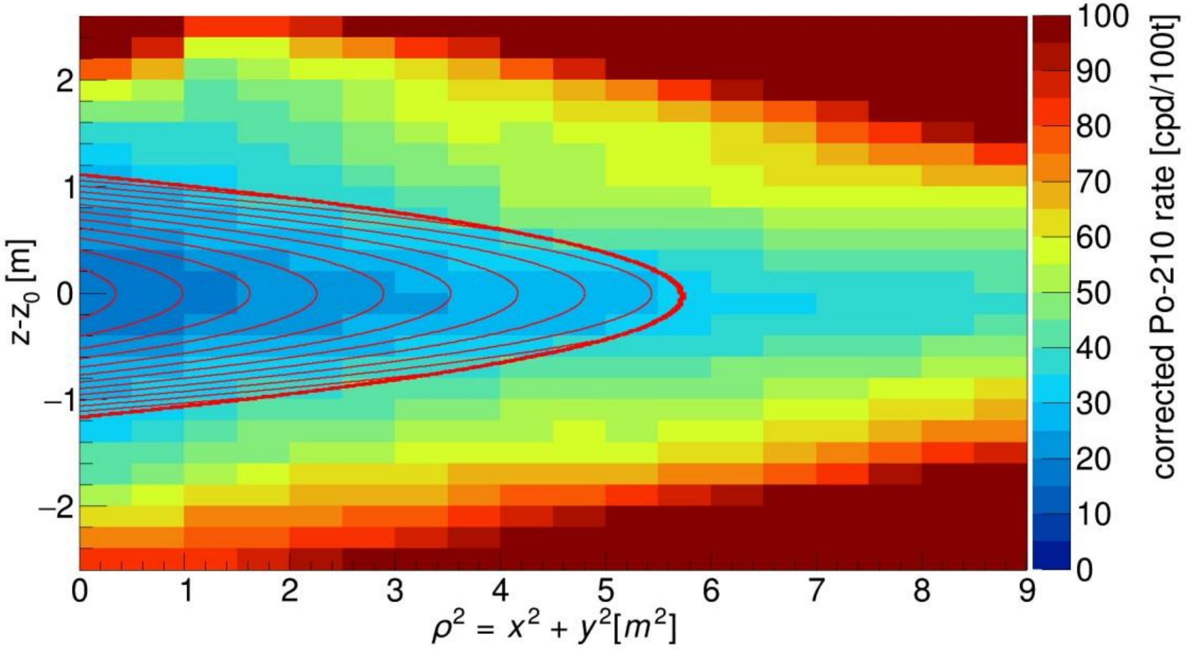
We extract the minimal ^{210}Po rate value, that is an upper limit on ^{210}Bi rate as a half-Gaussian constraint in the analysis

Bi < 11.5 +/- 1.04 cpd/100t (stat + sys)

$R(^{210}Po_{min}) = R(^{210}Bi) + R(^{210}Po_{vessel}) > R(^{210}Bi)$



Evolution of the Low Polonium Field



Low polonium field after blind alignment

Method (upper limit): 2D and 3D fits with paraboloidal model, model independent splines and steady diffution models. Bias crosscheck with Toy MC.

Bi < 11.5 +/- 1.04 cpd/100t (stat + sys)

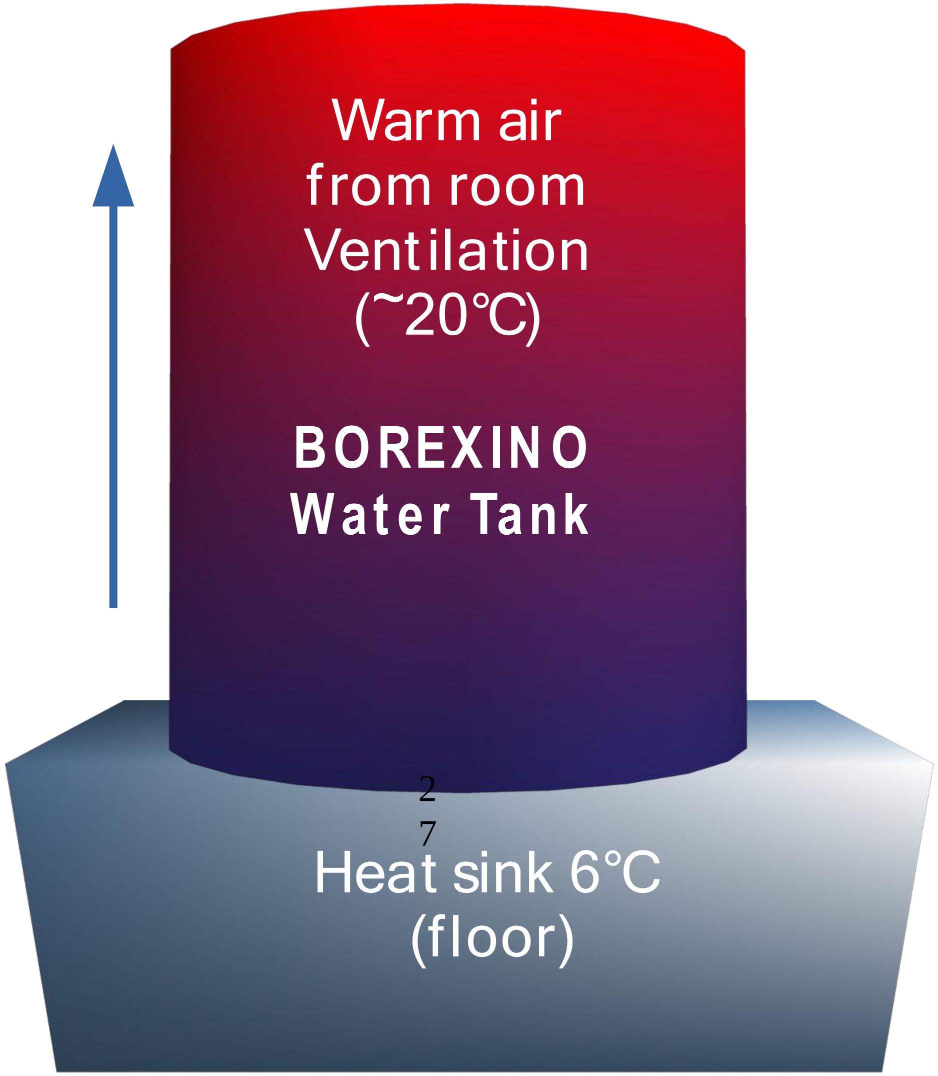
Thermal Insulation Program

Idea:

Strong and stable **vertical gradient** prevents convective motions

Milestones

2014: installation of temperature probes
Mid-2015: *beginning* of the insulation program
Late 2015: turning off of the *water recirculation system* in the water tank;
2016: first operation of the *active temperature control system* (ATCS)
Early 2019: change of the active control *set point*
Late 2019: installation and commissioning of the *hall C temperature control system.*

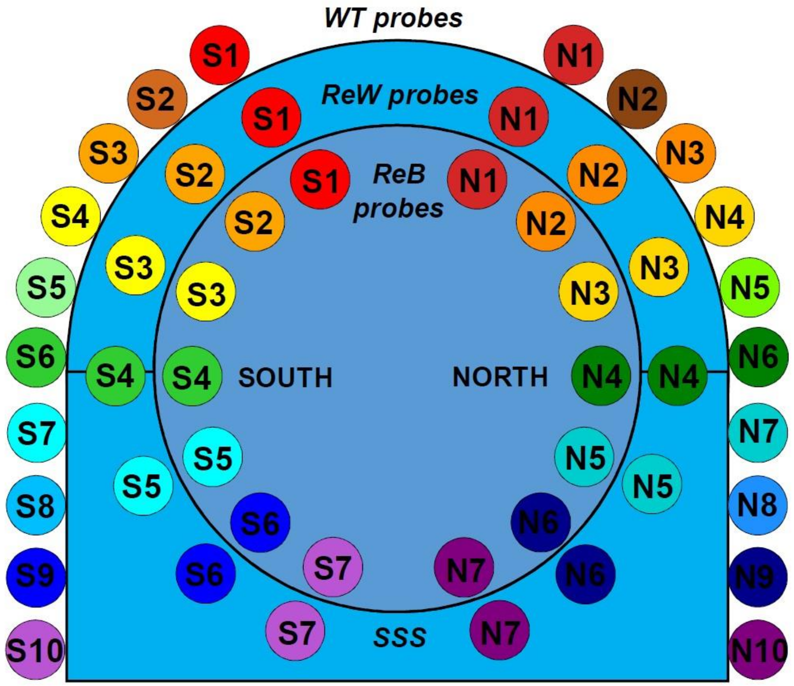


Warm air
from room
Ventilation
(~20℃)

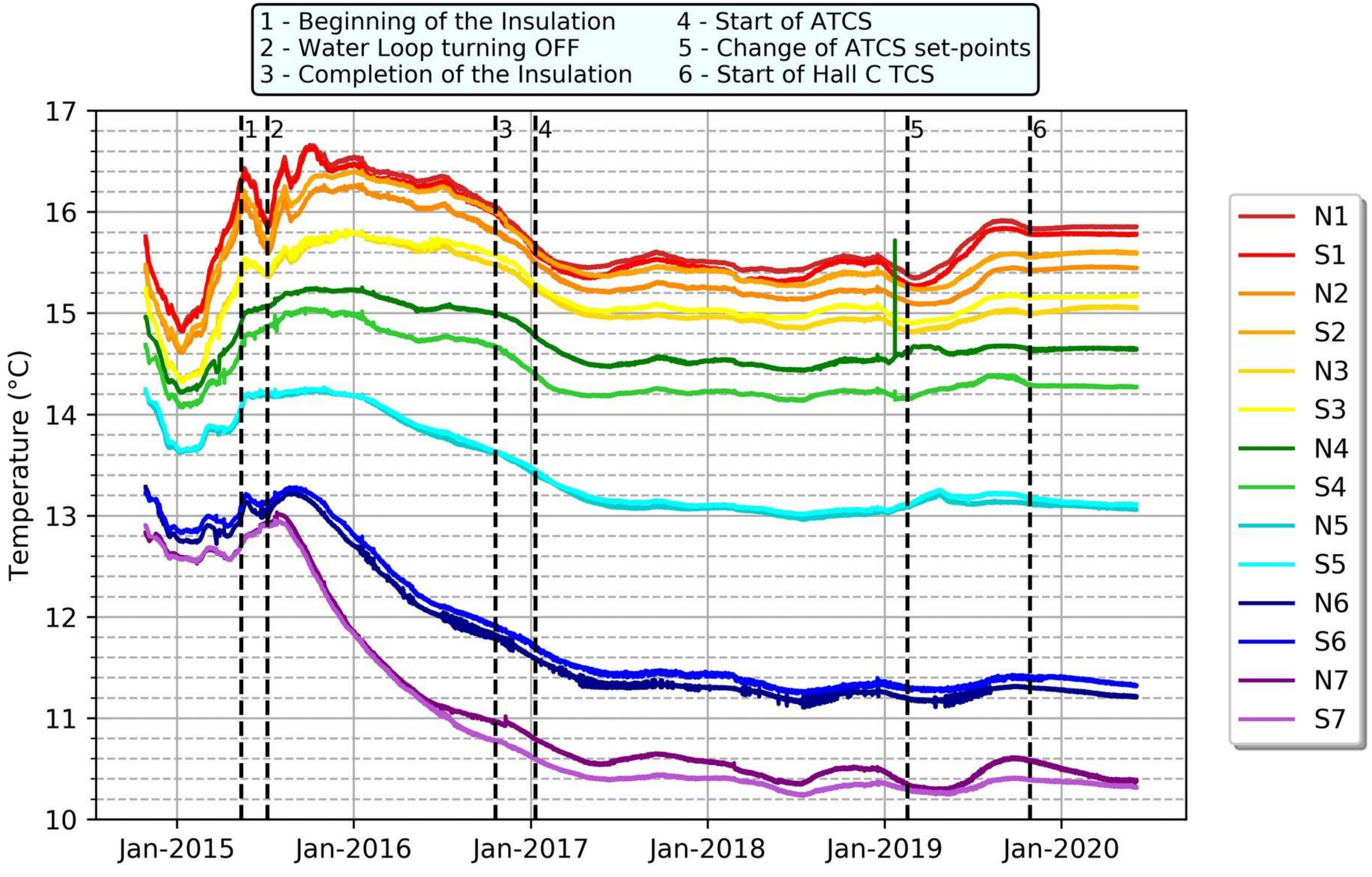
BOREXINO
Water Tank

Heat sink 6°C
(floor)

Effects on the temperatures



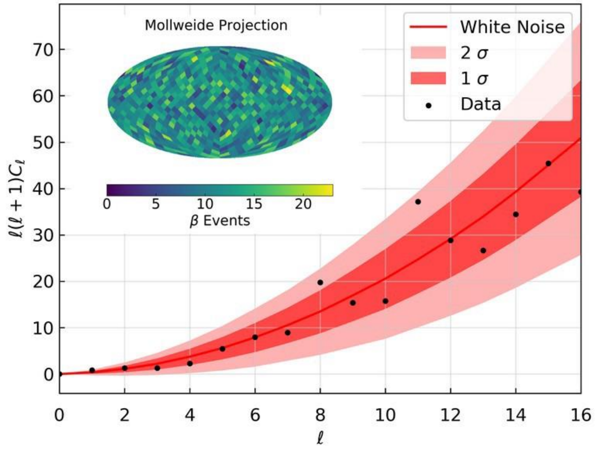
Temperature probes



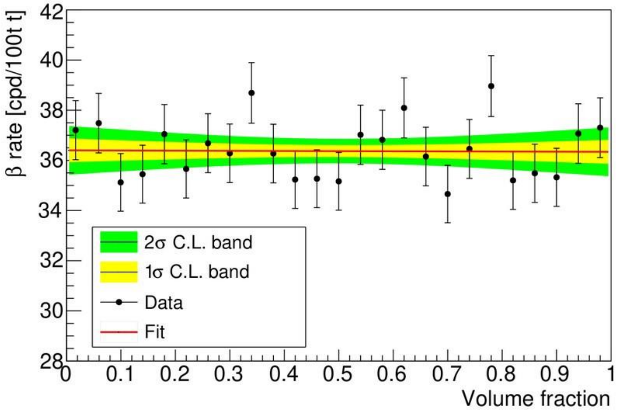
Probes closer to the inner detectors with thermal program milestones

Bi-210 Uniformity

Uniformity studies



Angular uniformity



Radial Uniformity

The ^{210}Bi upper limit can be extended over the full FV if and only ^{210}Bi is unifom

Unformity = Angular + Radial

Results: **uniform within error**.

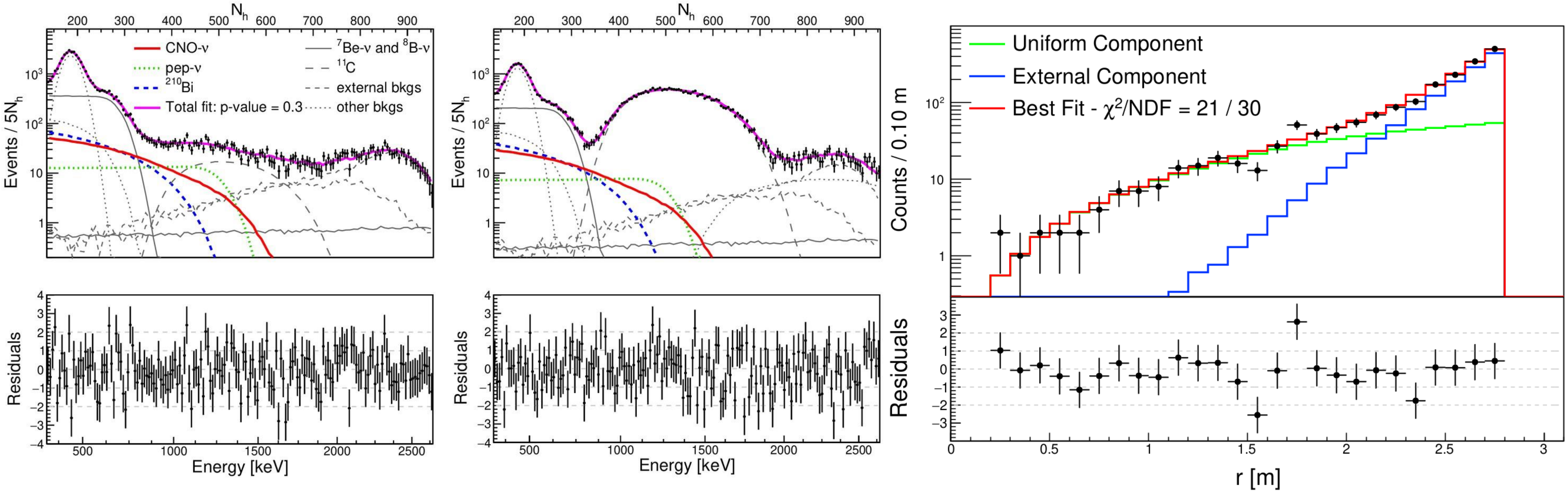
Sistematic uncertainty (uniformity): 0.78 cpd/100t

Supported by numerical fluid dynamic simulations.

^{210}Bi Stabel in time: ^{210}Pb leaching forml nylon is negligible

Final constraint: ^{210}Bi < 11.5 ± 1.3 cpd/100t

Multivariate Fit



Period: mid 2016, beginning of 2020 (Phase-III)

Energy window: 320-2640 keV

Pep constraint: 2.74 ± 0.04 cpd/100t (Gaussian)

^{210}B constraint: 11.5 ± 1.3 cpd/100t (1/2-Gaussian)

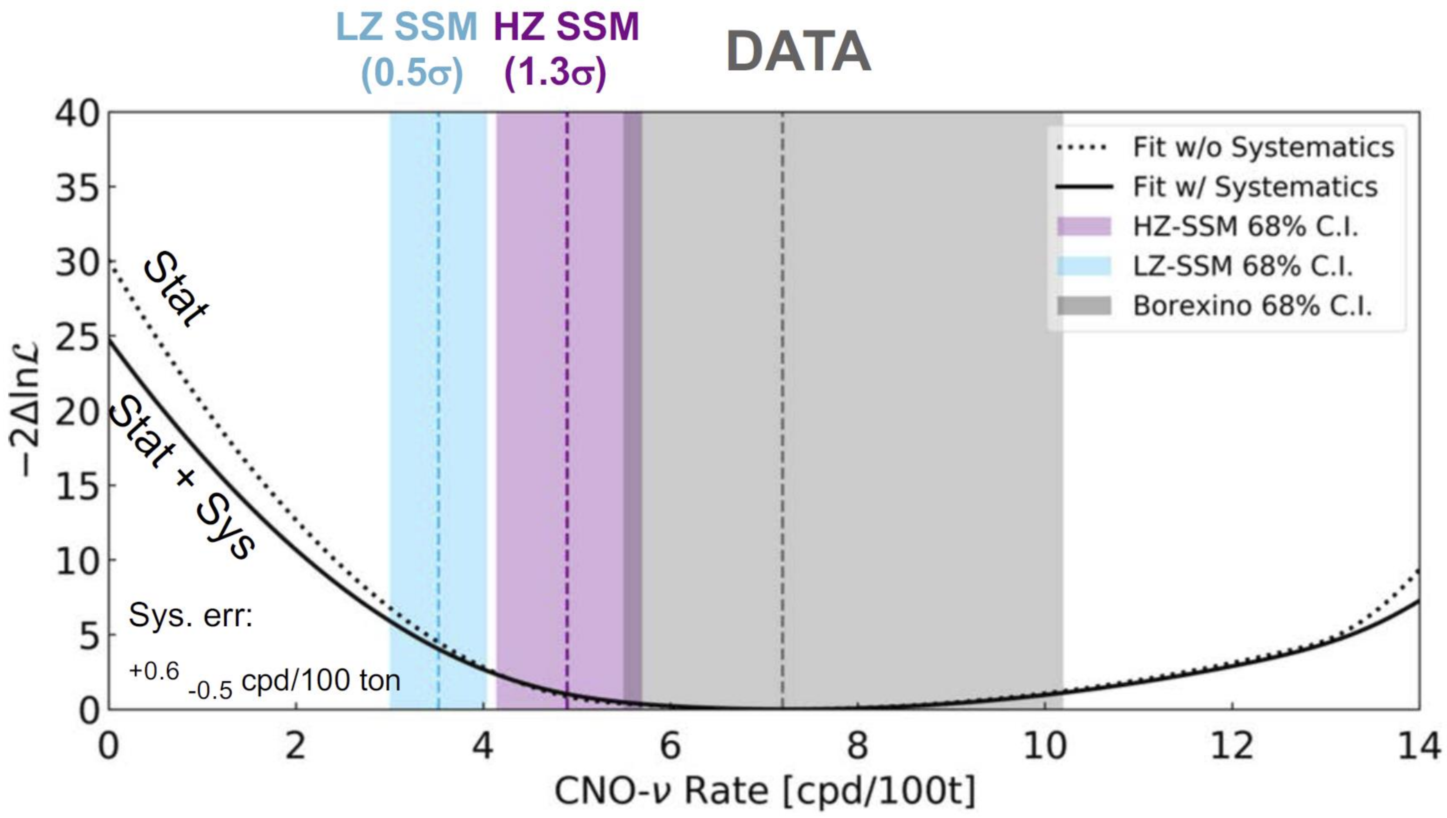
Method: MC multivariate fit

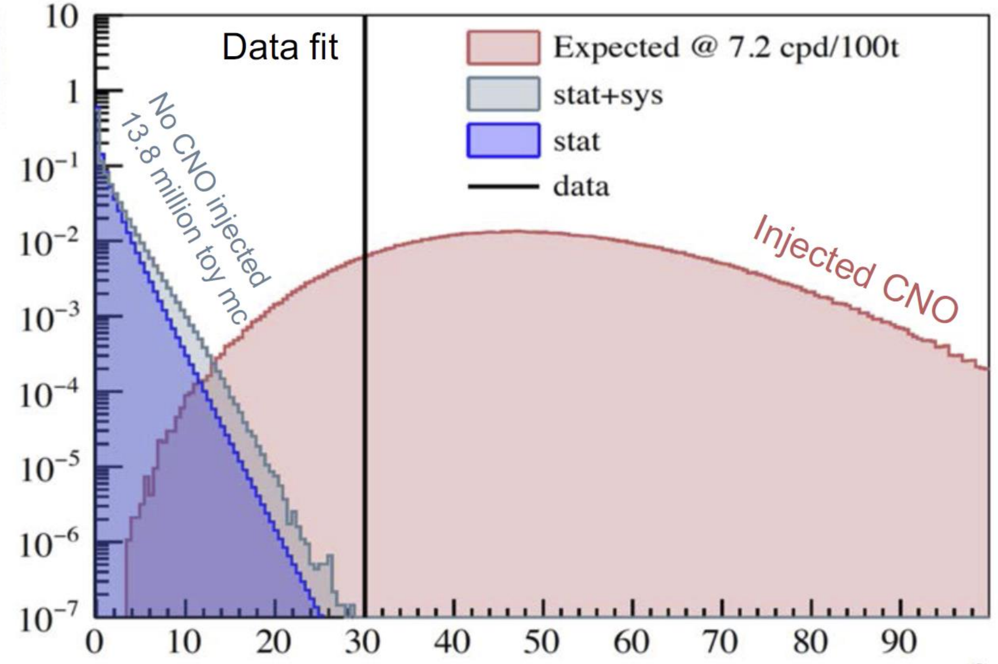
Result
(68% CL stat)

7.2 $_{-1.7}^{+2.9}$ cpd/100t

CNO fit results

The Borexino Collaboration. *Experimental evidence of neutrinos produced in the CNO fusion cycle in the Sun*. **Nature 587,** 577–582 (2020).





Nature 587 (2020) 577

$$q = -2\log\frac{\mathcal{L}(\mathrm{CNO}=0)}{\mathcal{L}(\mathrm{CNO})}$$

Result (68% CL stat + sys) = $R_{\mathrm{CNO}} = 7.2^{+3.0}_{-1.7}$ cpd/100 t

Φ(CNO with sys) = $7.0^{+3.0}_{-2.0} \times 10^{8}$ cm^{-2} s^{-1}

Null-hypothesis exclusion:
5σ significance at 99% CL

The international journal of science / 26 November 2020

outlook
Multiple myeloma

nature

CATCHING THE RAYS

Neutrino detector secures evidence of the Sun's secondary fusion cycle

Coronavirus
How Iceland subdued COVID-19 with science

Family planning
Research and invest in contraceptives that meet women's needs

Environment
The effect of noise and light pollution on US bird populations

Vol. 587 No. 7835
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Borexino

1. Borexino has been the first experiment probing **sub-MeV neutrinos in real-time,** and is still now **the unique experiment** able to proceed with these studies.
2. Borexino has measured for **the first time all pp chain nuclear reactions producing neutrinos**, measuring, in particular, simultaneously the pp, ^{7}Be, and pep neutrino flux, ^{8}B neutrinos with a low threshold and probing hep neutrinos.
3. These results paved the way to actual breakthroughs not only on Solar physics, but also on neutrino physics. **The ν_e survival probability in the vacuum regime is measured** for the first time by Borexino and the **vacuum–matter transition** has been probed by a single experiment. In addition, a number of non-standard neutrino interactions has been studied by Borexino with world leading limits.

Borexino

physicsworld
BREAKTHROUGH OF THE YEAR
2014

physicsworld
TOP 10
BREAKTHROUGH
2020

European Physical Society
PRIZE

The 2021 Giuseppe and Vanna Cocconi Prize
for an outstanding contribution to Particle Astrophysics and Cosmology

is awarded to the

Borexino Collaboration

for their ground-breaking observation of solar neutrinos from the pp chain and CNO cycle that provided unique and comprehensive tests of the Sun as a nuclear fusion engine.

Luc Bergé
President
European Physical Society

Thomas Gehrmann
Chair
EPS High Energy and Particle Physics Division

Mulhouse, France, 26 July 2021

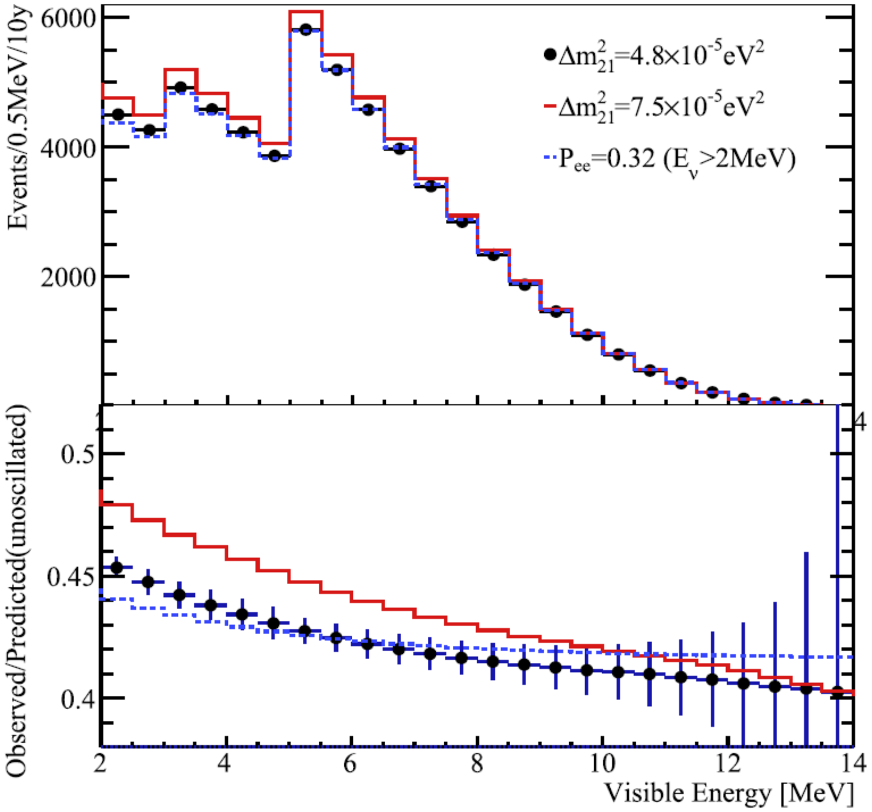
4. The detection of the CNO cycle closes a long history, which began in the 30s of the last century, when Hans Bethe and Carl Friedrich von Weizsacker, independently, proposed that the fusion of hydrogen in stars could also be catalyzed by nuclei heavier than He. Then the theory of energy generation hypothesizes that the CNO would be the primary channel for hydrogen burning in stars more massive than the Sun , and it is in fact the primary channel for hydrogen burning in the Universe. This hypothesis never received an observational confirmation until now, when Borexino **has observed CNO neutrinos** proving also that its contribution in the Sun is of the order of 1%.
5. When all solar neutrino fluxes measured by Borexino, including CNO, are combined, the LZ hypothesis is **disfavored at a level of 2.1σ.**
6. Again, thanks to the low intrinsic background, Borexino has **observed geo-neutrinos** with 5σ statistical significance and studied them to obtain Earth geo-physical and geo-chemical information.

Backup slides

Future detectors

JUNO

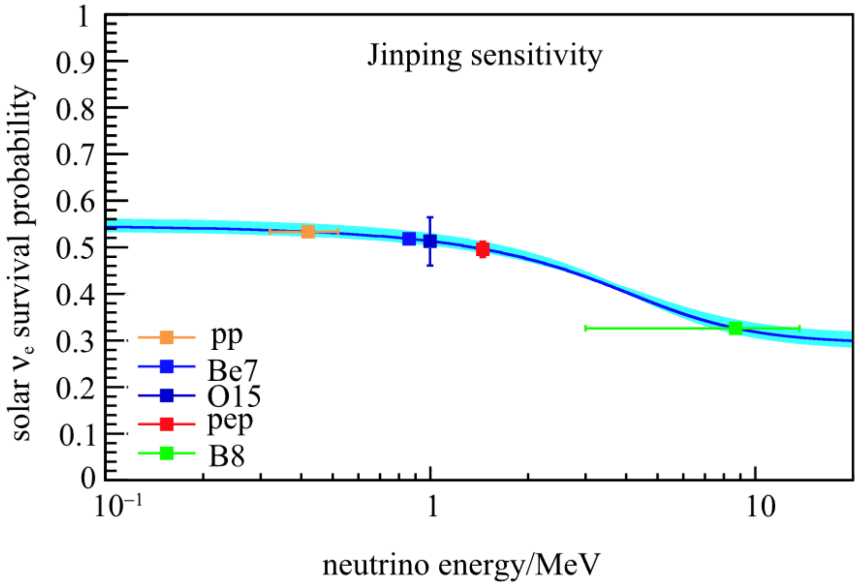
- 20 kt liquid scintillator
- excellent for B solar neutrino measurements,
- low-energy threshold,
- high energy resolution compared with water Cherenkov



Chinese Physics C 2021, Vol. 45 Issue(2) : 023004
DOI: 10.1088/1674-1137/abd92a

Jinping

- slow liquid scintillator
- total fiducial target mass of 2000 tons for solar neutrino



John F. Beacom *et al* 2017 *Chinese Phys. C* 41 023002

HyperKamiokande

- next generation large water Cherenkov detector
- water tanks provide the fiducial (total) volume of 0.19 (0.26) million metric tons