Experimental detection of the CNO cycle

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on behalf of the Borexino Collaboration

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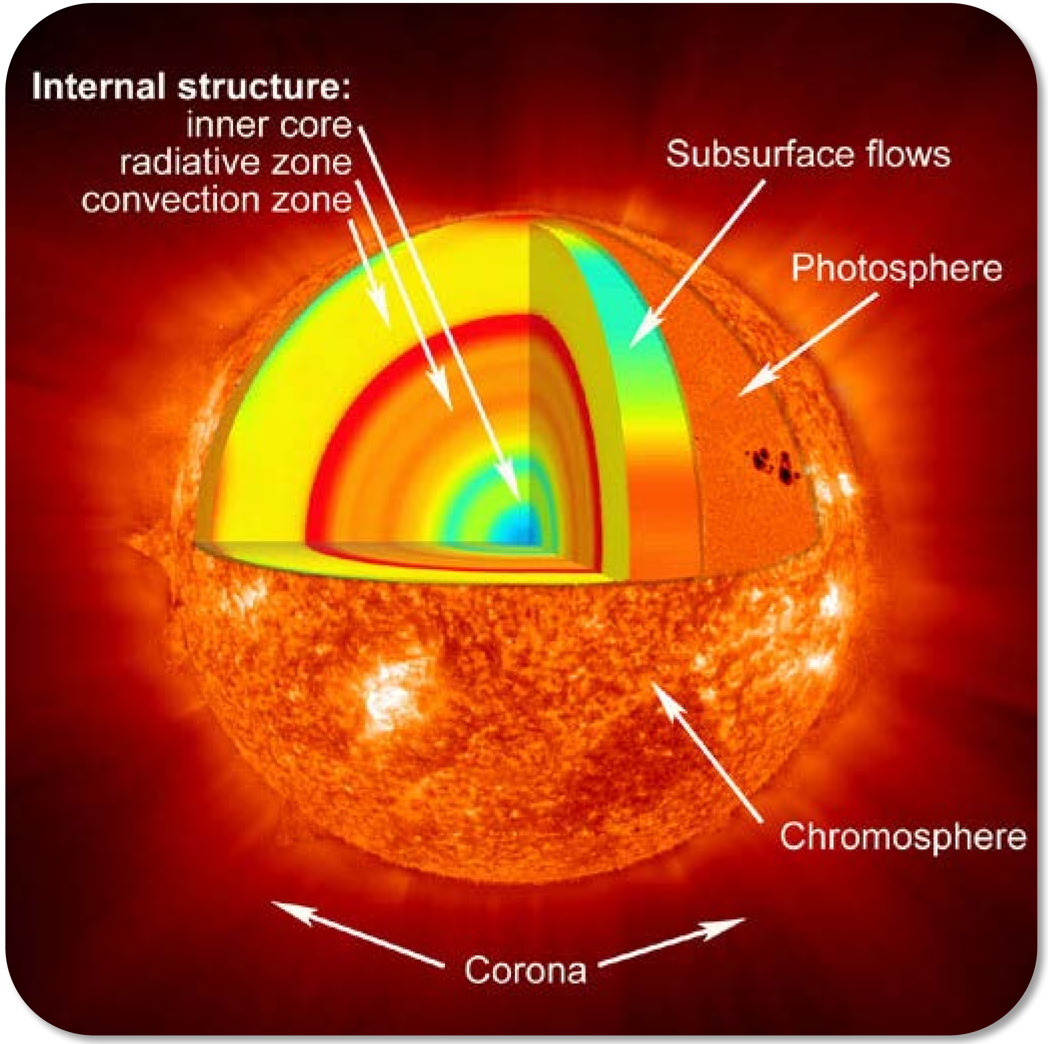
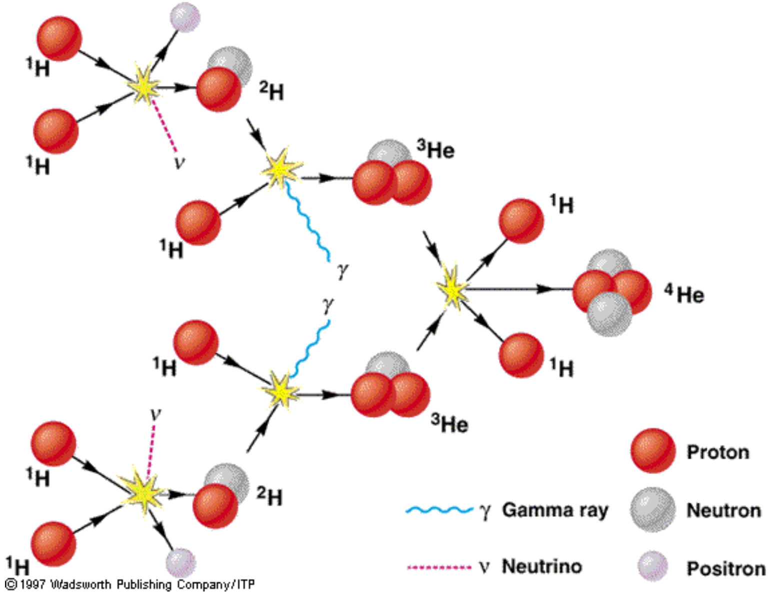
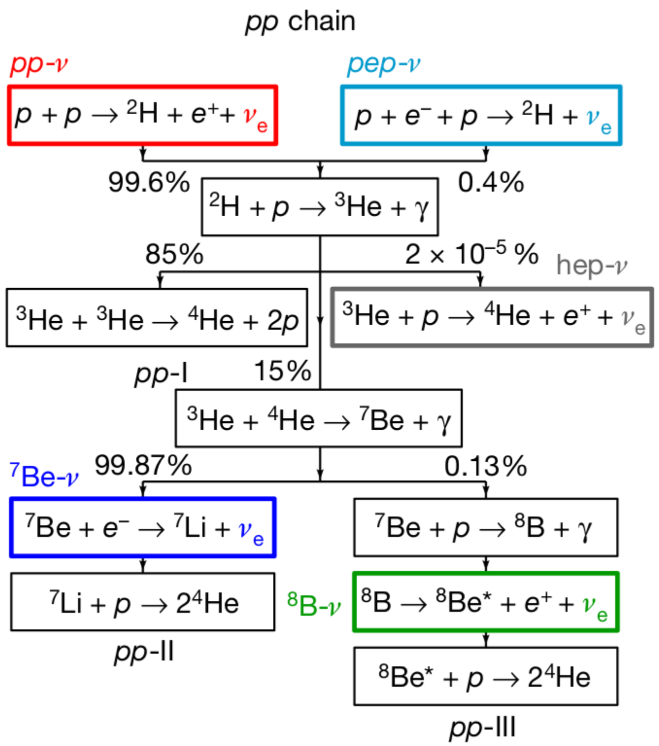
Solar ν as sensitive tool to test solar models

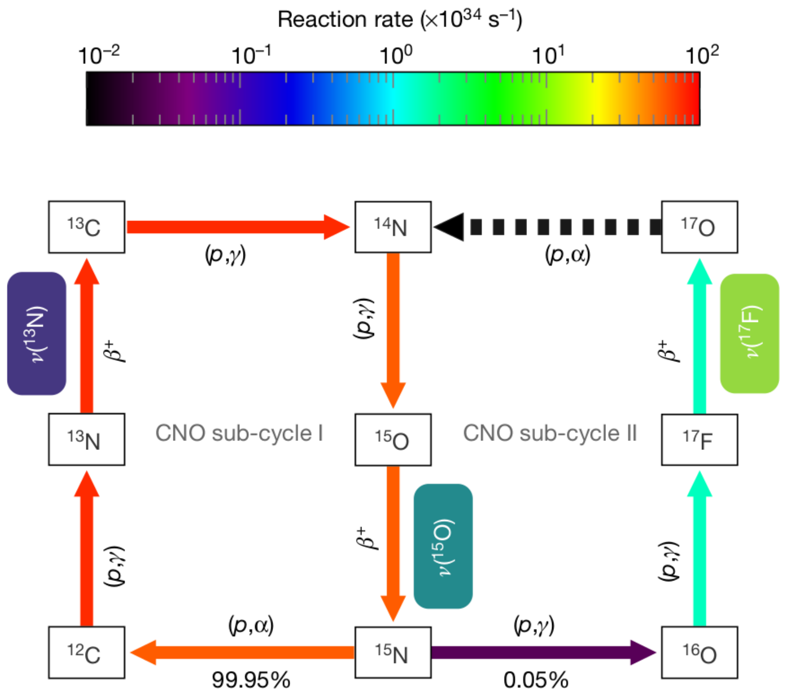


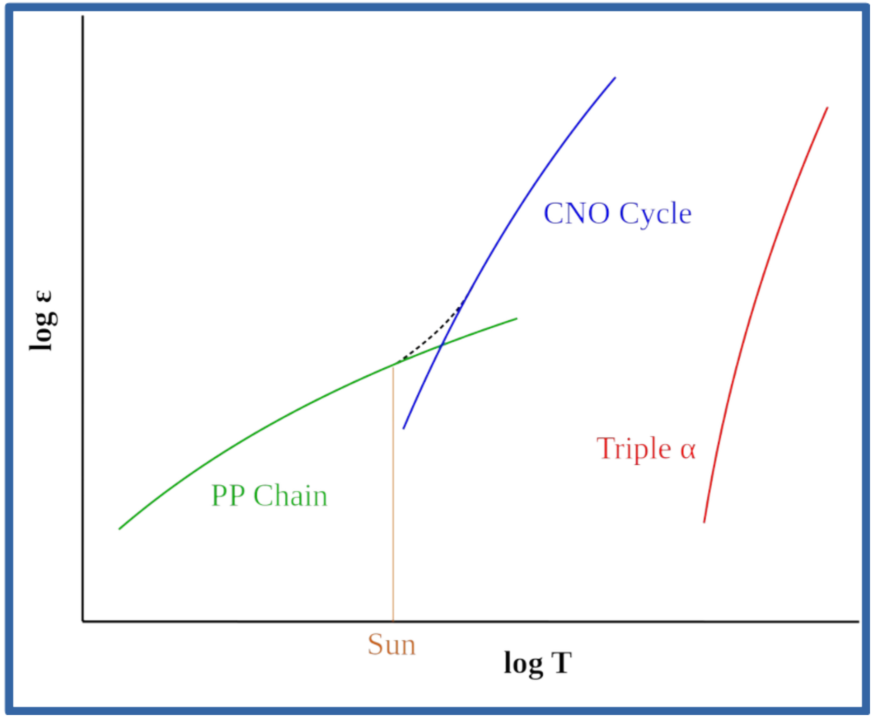
The three cycles of pp chain (*pp*-I, *pp*-II and *pp*-III) are each associated with a characteristic neutrino source. All three cycles begin with the fusion of two protons to form deuterium (^{2}H), through the '*pp*' and '*pep*' reactions.



PP vs CNO Competition







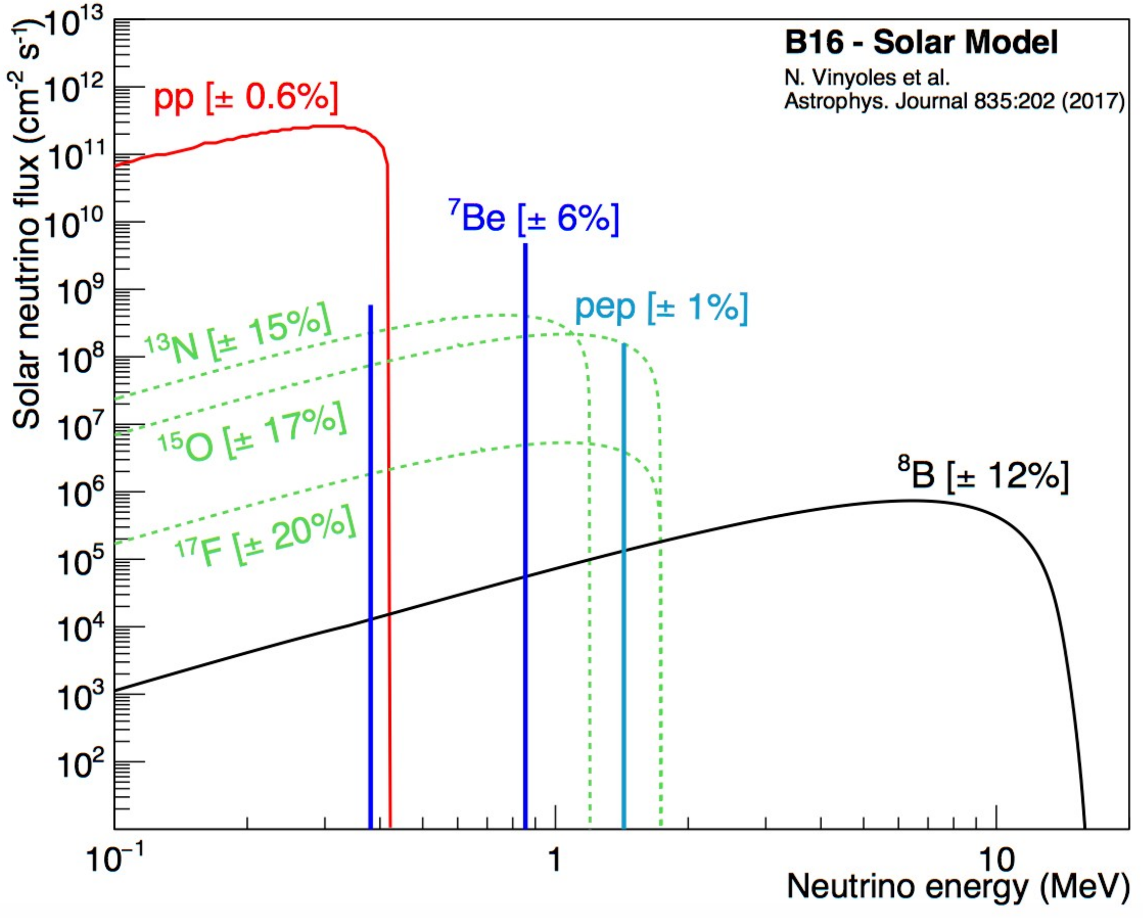
- Intense neutrinos from nuclear fusion in the Sun's core
- Majority (99%) from pp-chain with subdominant contribution from CNO cycle
- What's left in solar neutrinos?
  - Help understanding solar interior (metallicity problem)
- **Precision test of the MSW oscillation model**
  - Precise measurement 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)

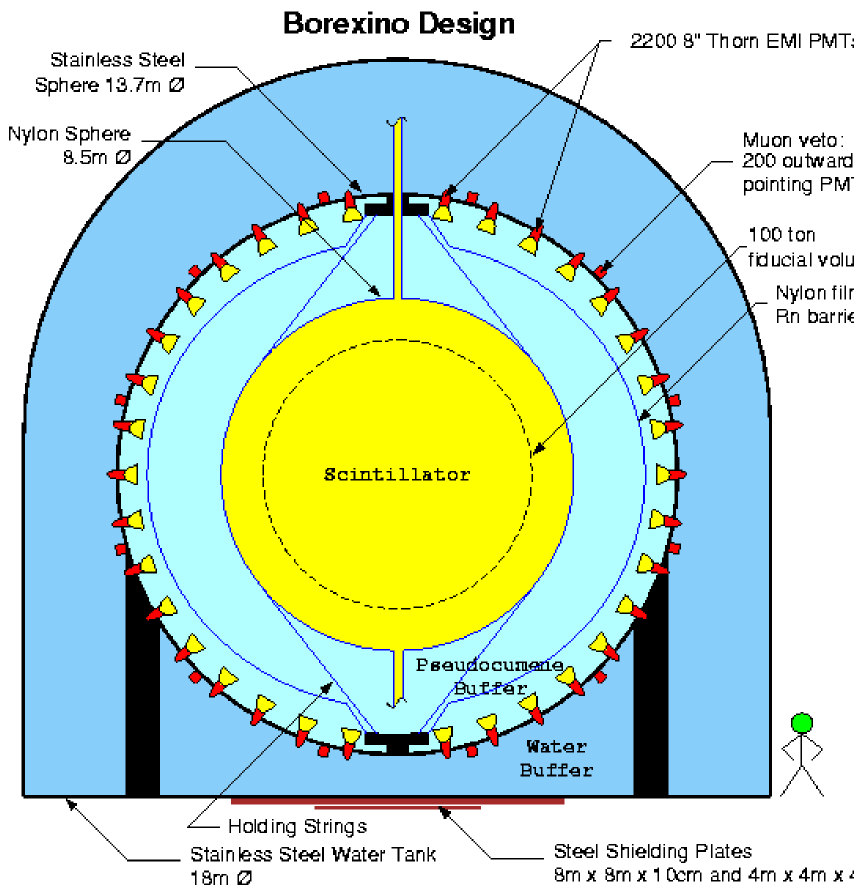
BOREXINO Detector

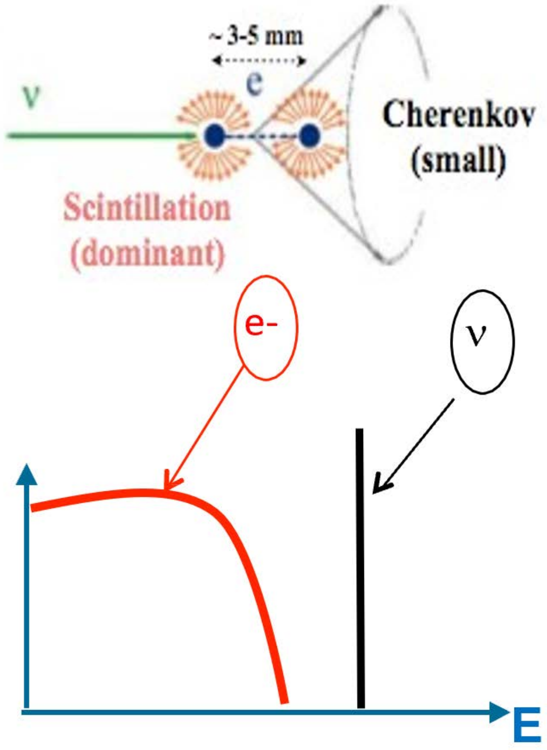
Core of the detector: 300 tons of liquid scintillator contained in a nylon vessel of 4.25 m radius (PC+PPO);

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;



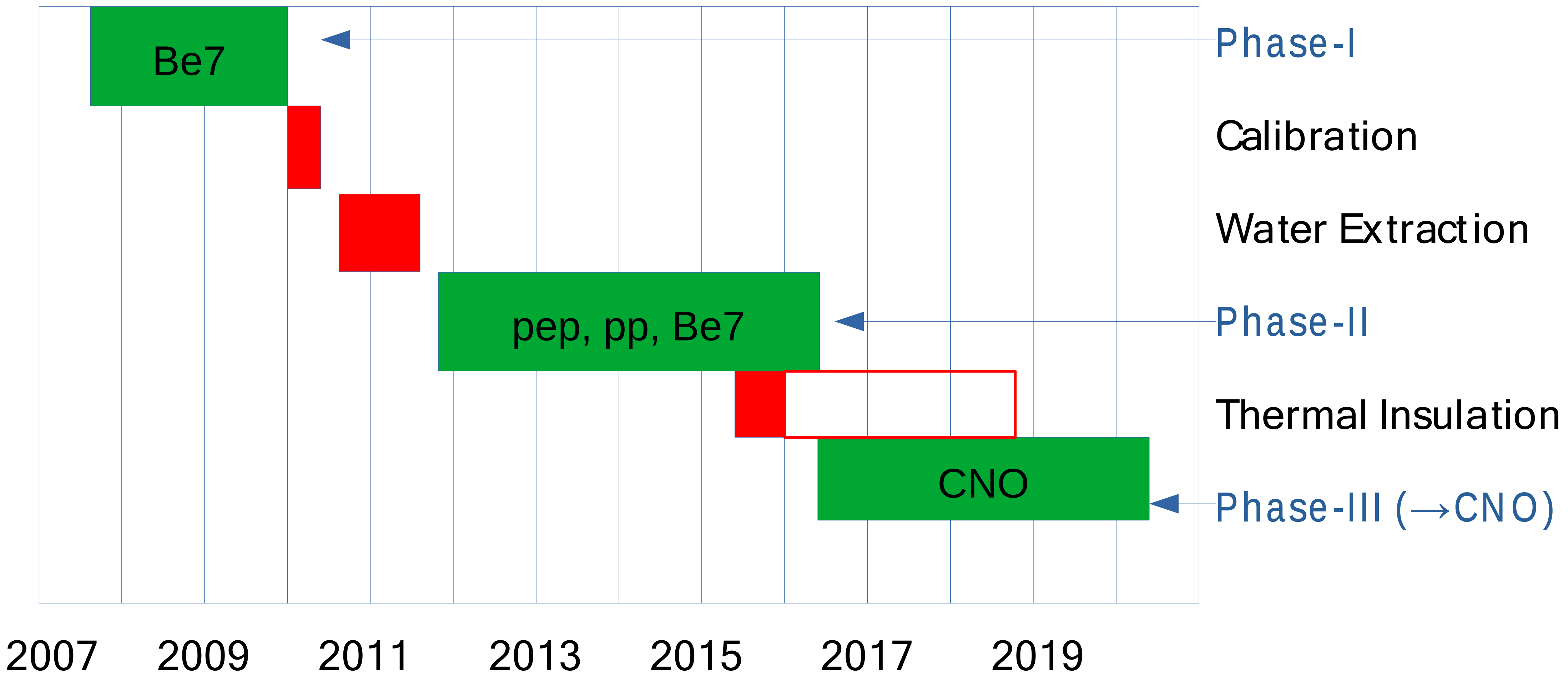


We measure the energy carried away by the electron!

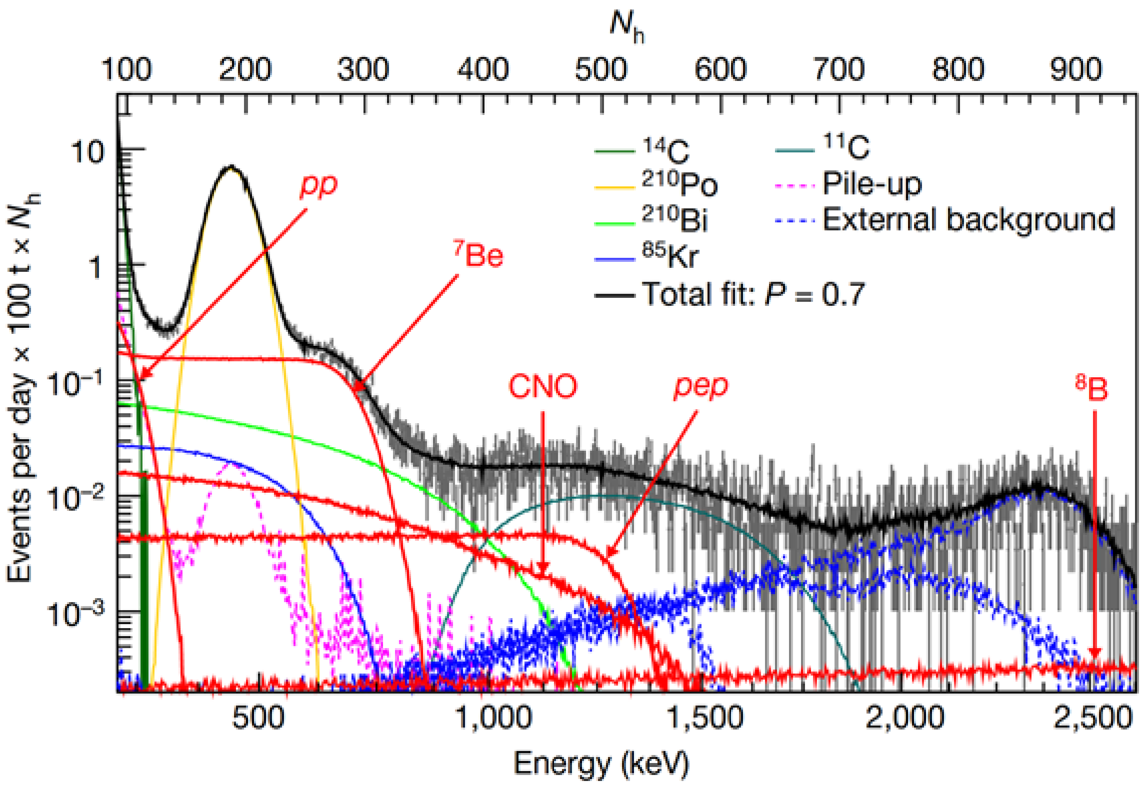
200 PMTs mounted on the SSS pointing outwards to detect light emitted in the water by muons crossing the detector;

Borexino is located inside the Gran Sasso mountain in Italy

The three ages of Borexino



BOREXINO – real-time solar neutrino spectroscopy

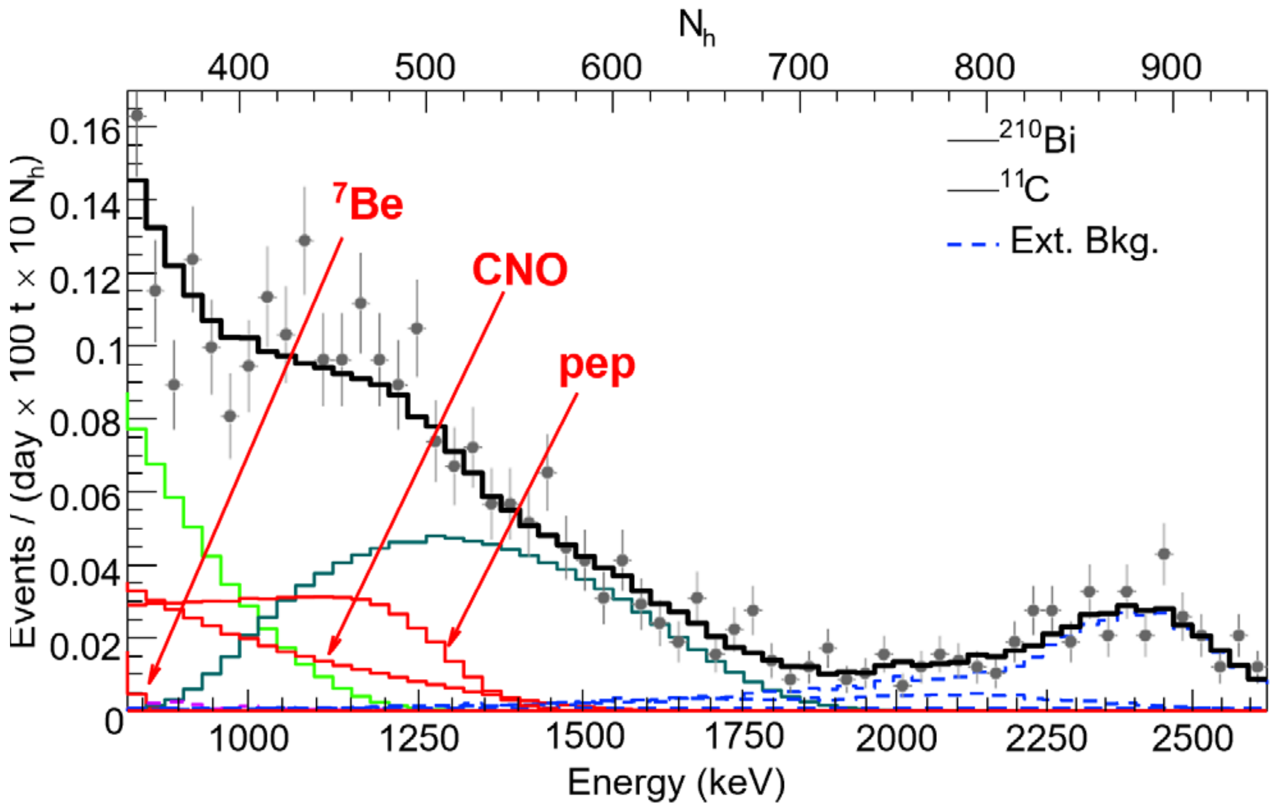


The Borexino Collaboration. *Comprehensive measurement of pp-chain solar neutrinos*. ***Nature* 562,** 505–510 (2018)

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

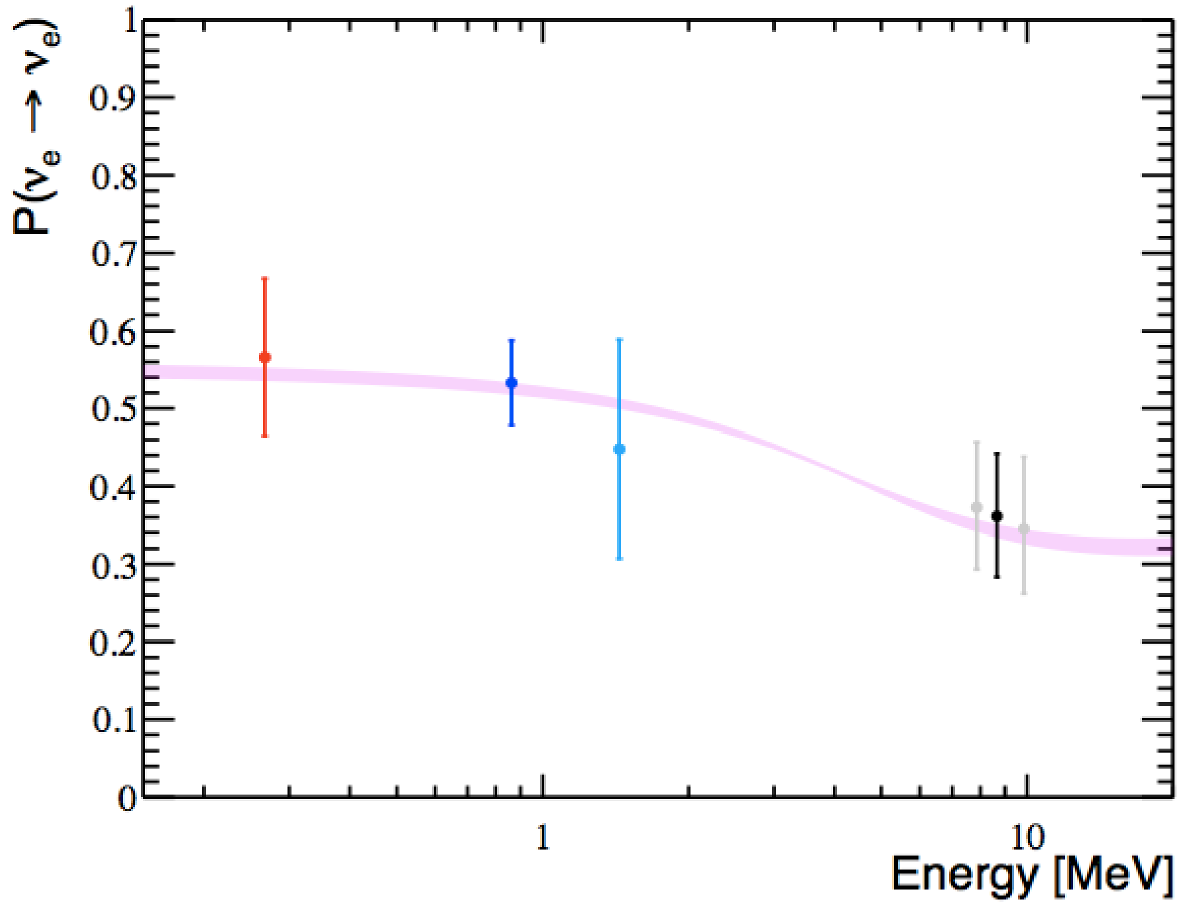
Radius <2.4 m Ps-LPR < 4.8



- 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

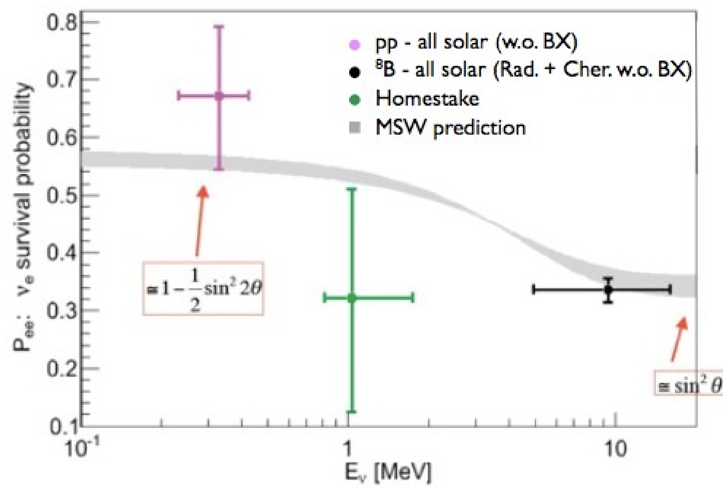
P_{ee}: Borexino impact

Borexino now



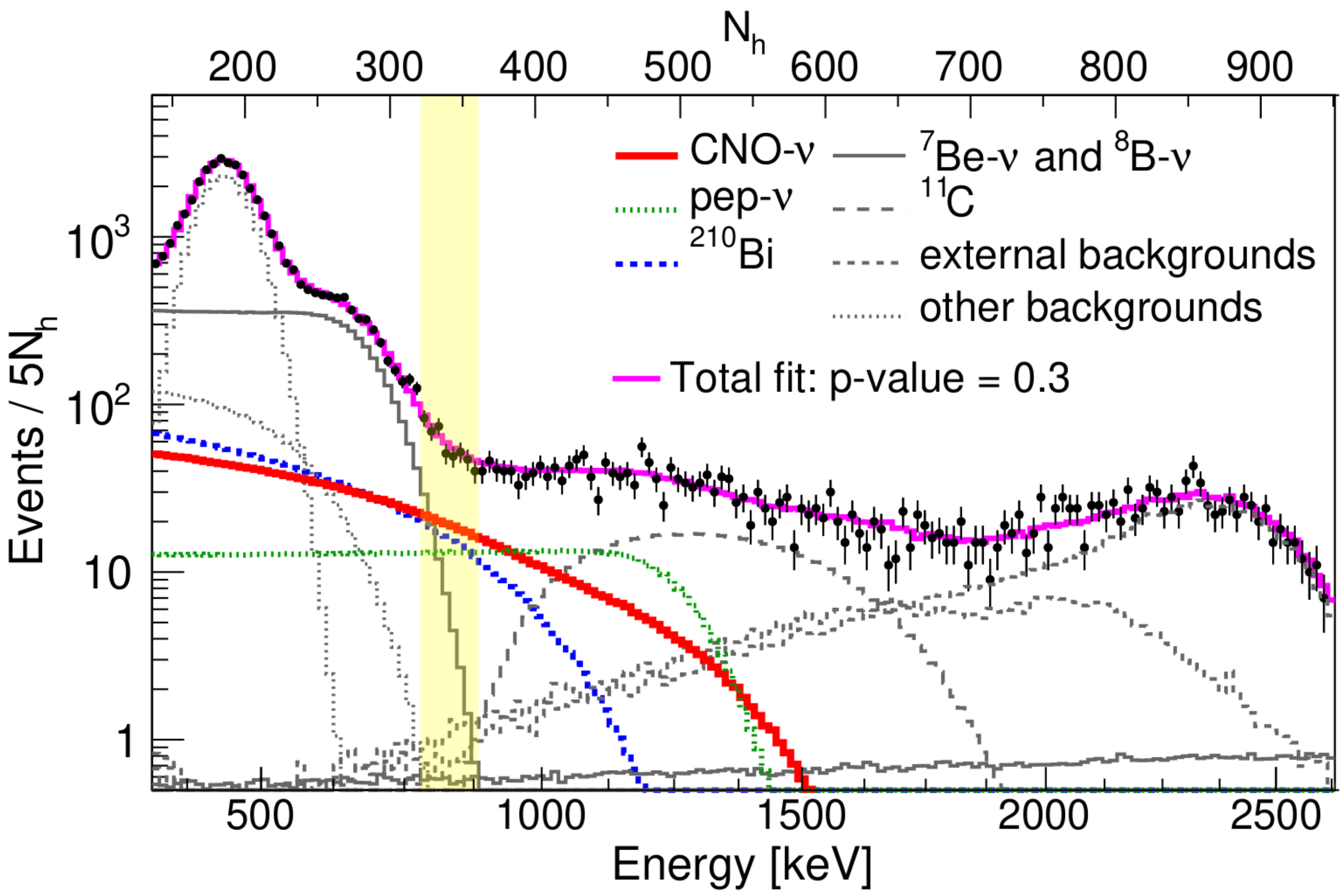
Pee - electron neutrino survival probability

Before Borexino

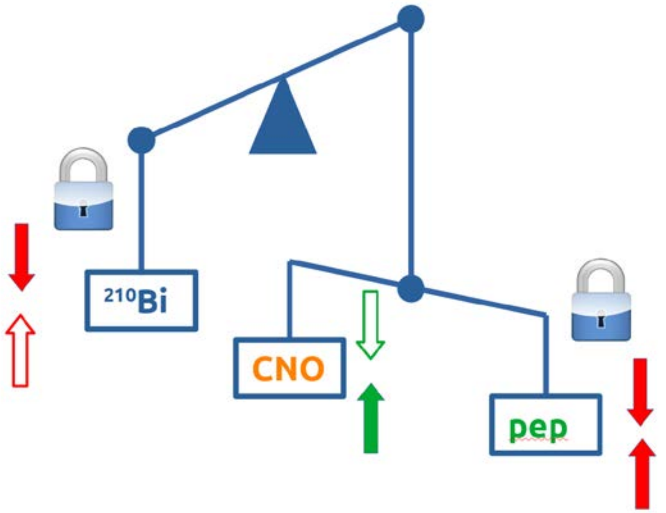


1. Borexino has measured the electron neutrino Pee in the *vacuum regime*, where, according to the MSW- LMA model, the vacuum dominates
2. The Borexino data allowed to probe the vacuum– matter transition from a single experiment.
3. Despite the uncertainty of the various points, that incorporate both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

CNO - challenges

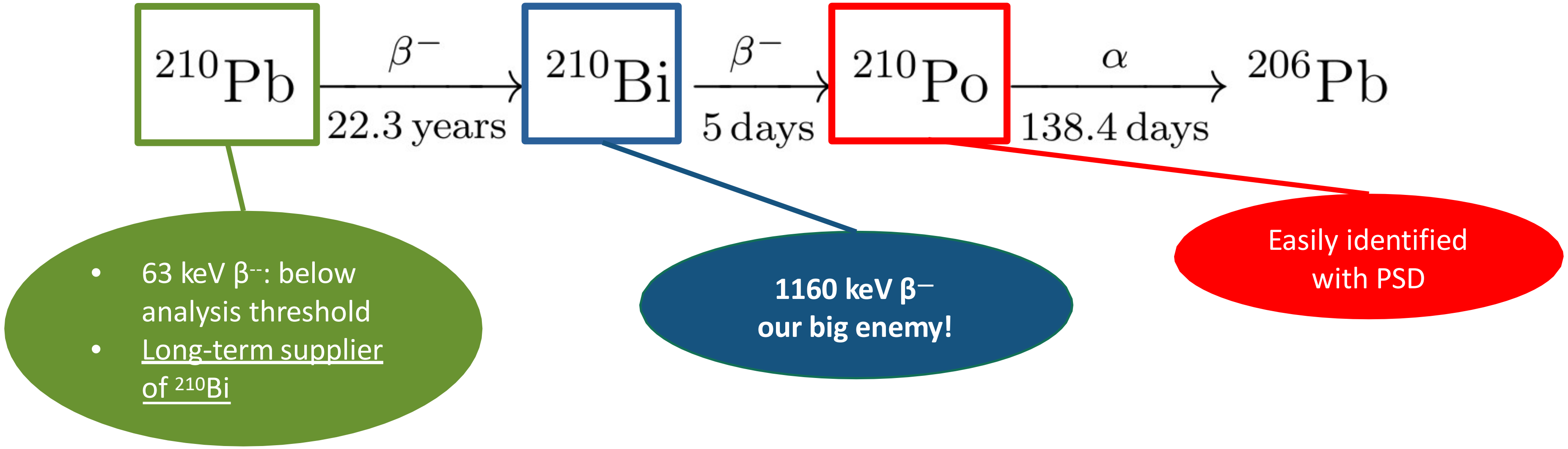


- *pep* rate: gaussian penalty at SSM prediction
- ^{210}Bi rate: semi-gaussian penalty at our upper limit



Strategy: independent constraint of pep and Bi-210

Strategy for ^{210}Bi constraint

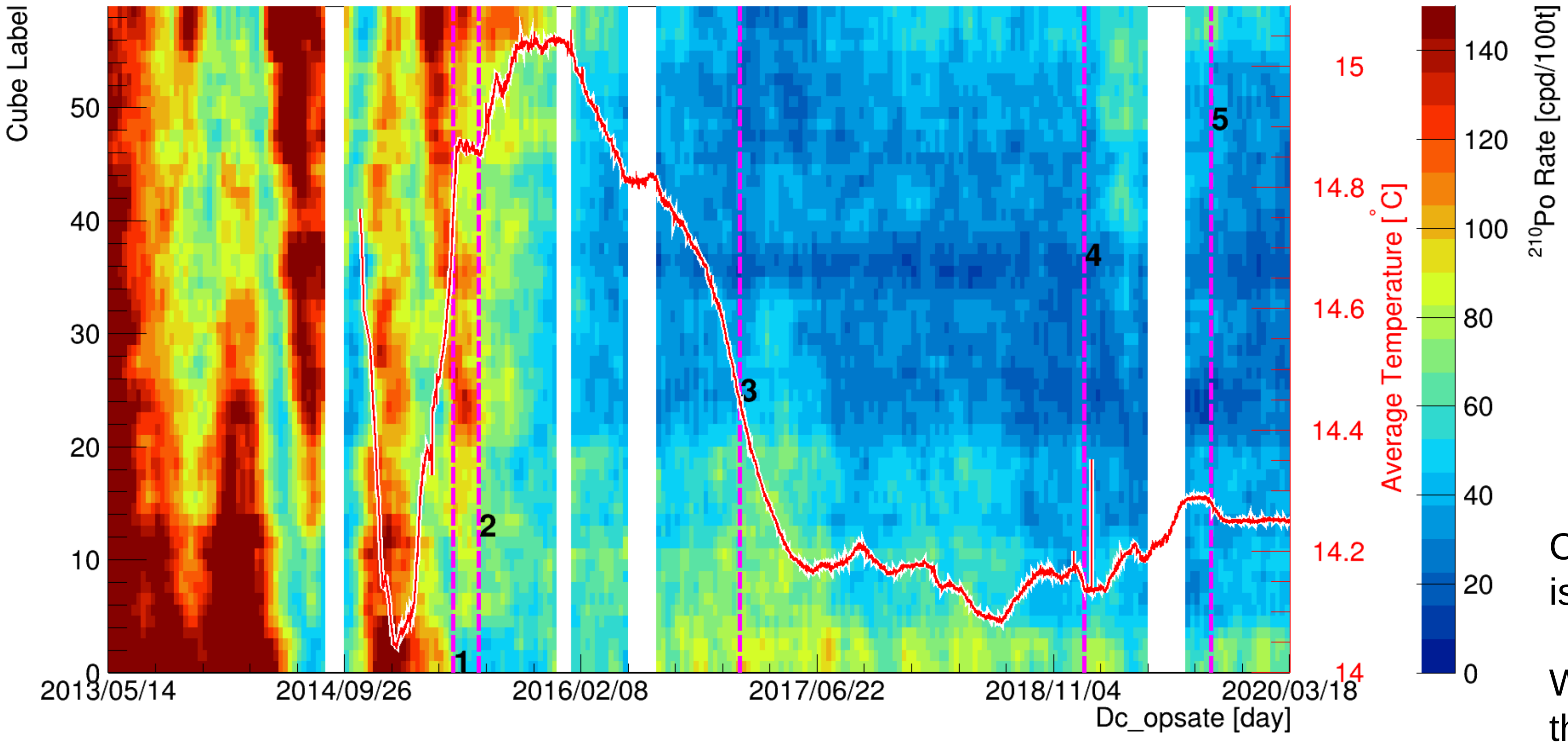


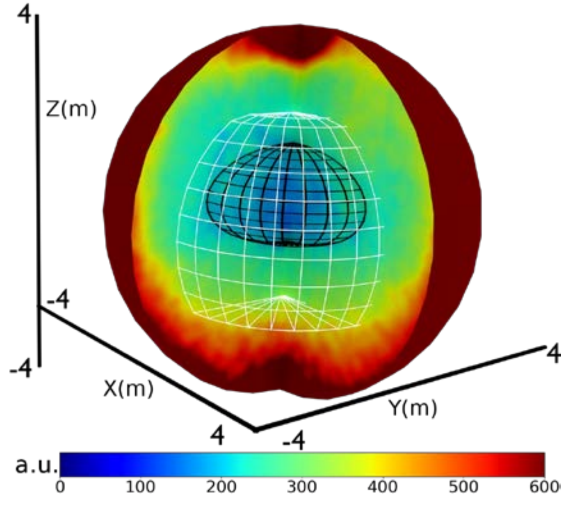
Measuring ^{210}Po could allow to constraint ^{210}Bi

…

If only we had secular exquilibrium!

The Low Polonium Field





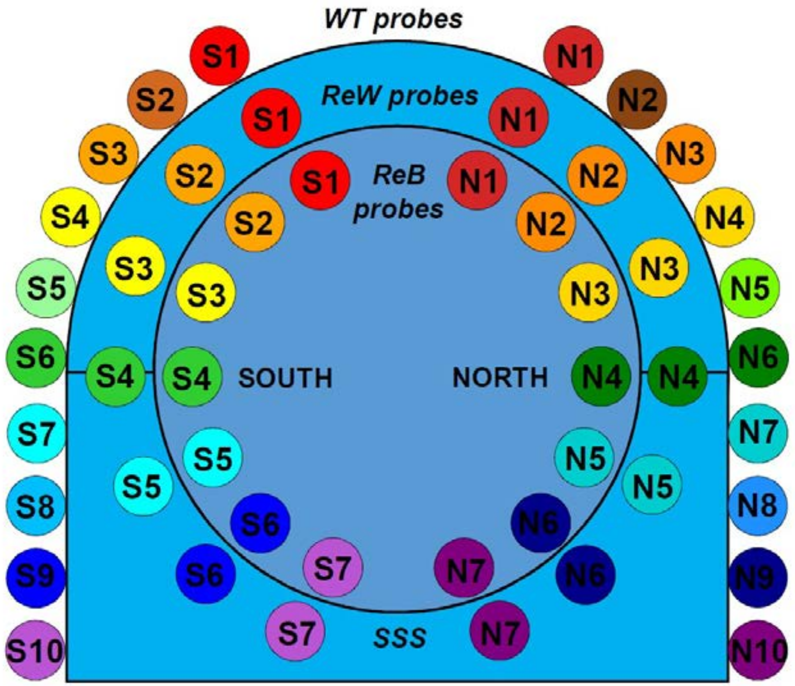
Clean region in the core of the detector is created: LPoF

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

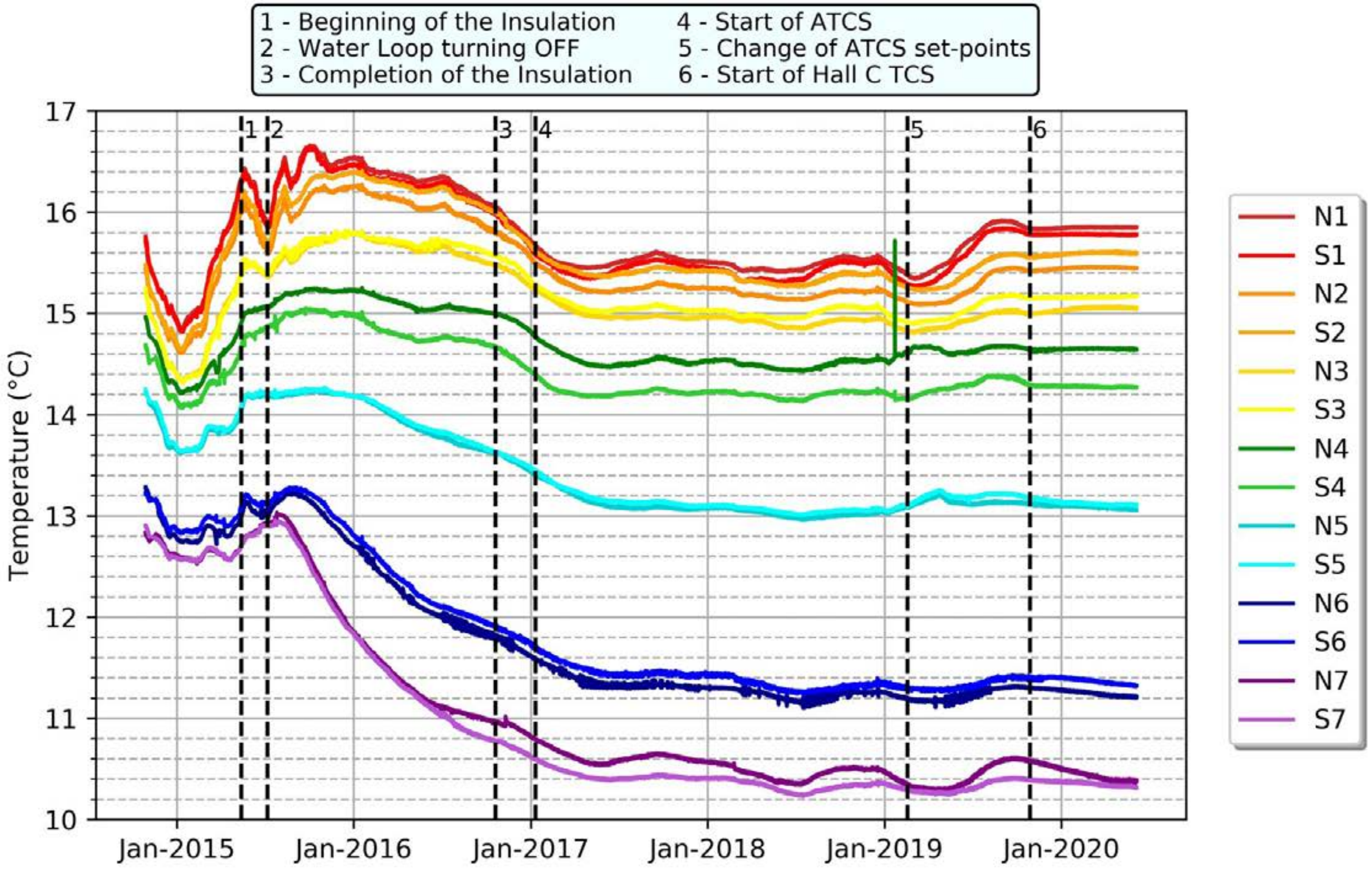
Bi < 11.5 +/- 1.04 cpd/100t (stat + sys)

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

Effects on the temperatures



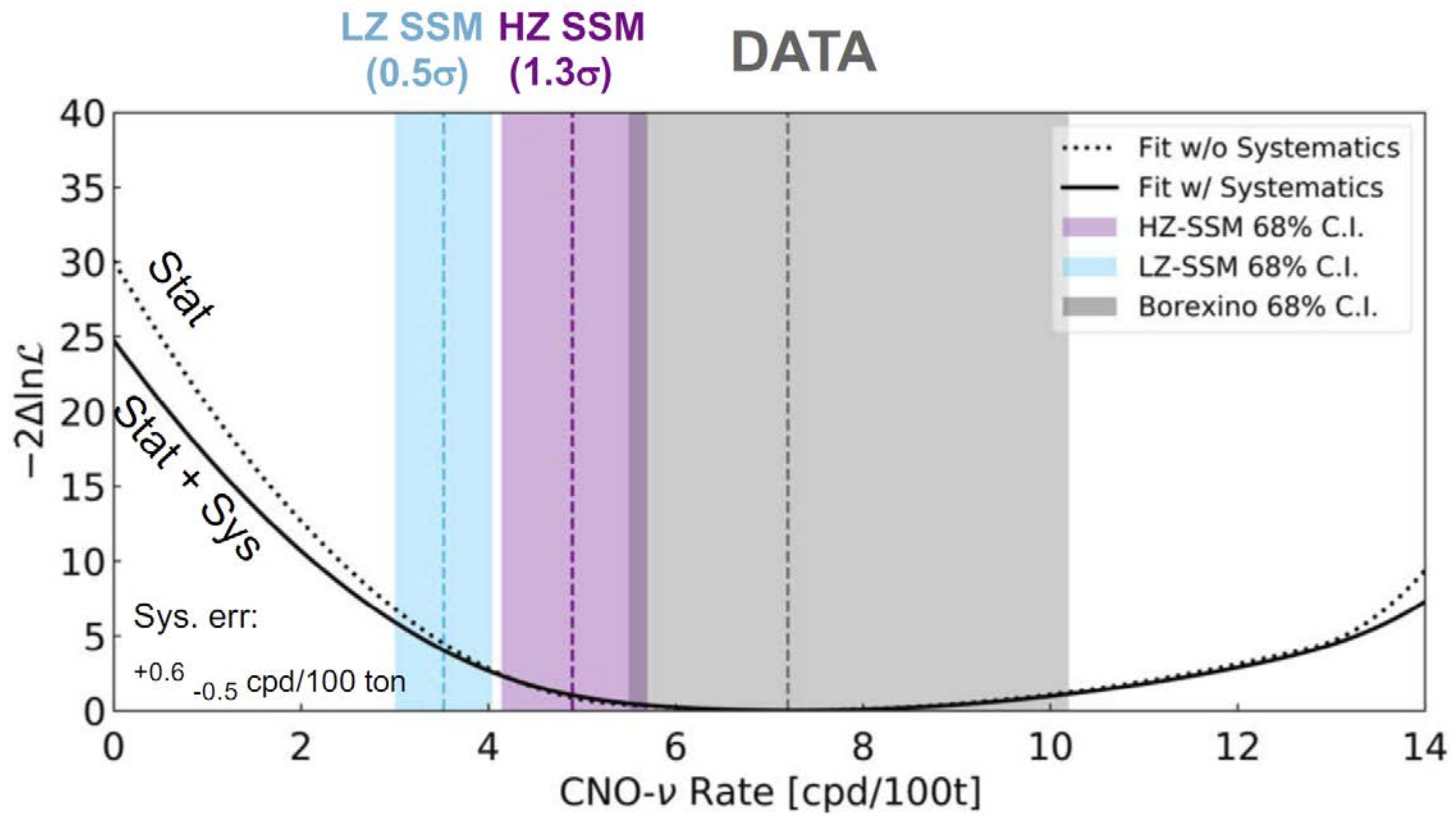
Temperature probes

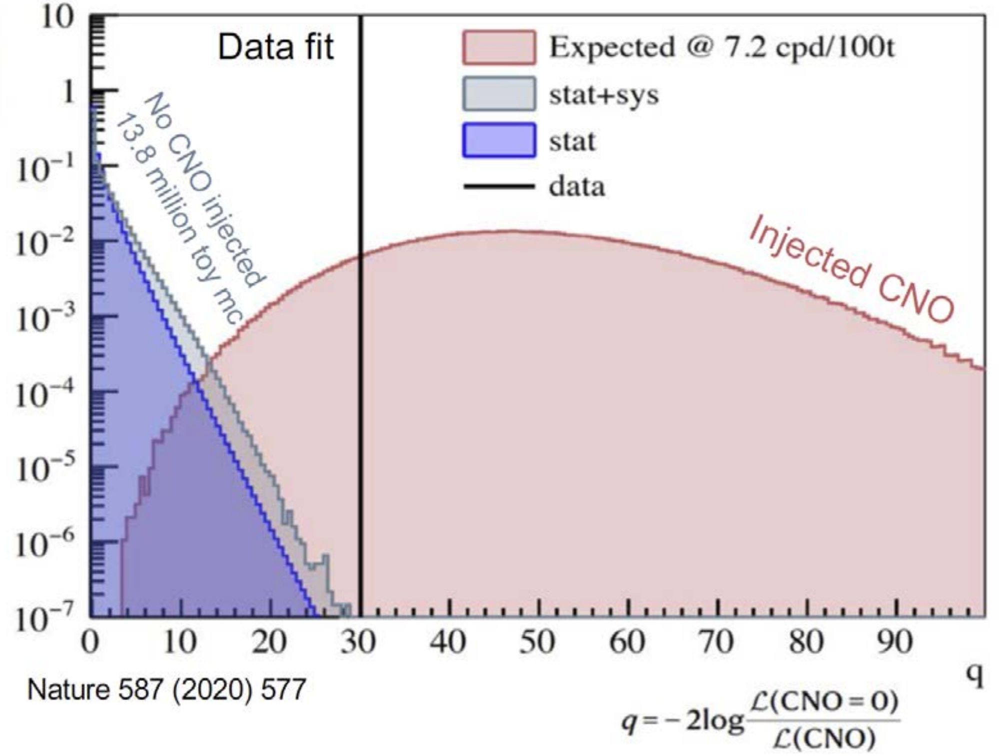


Probes closer to the inner detectors with thermal program milestones

CNO fit results

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





Result (68% CL stat + sys) = $R_{CNO} = 7.2^{+3.0}_{-1.7}$ 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

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

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.