Comprehensive measurement of *pp*-chain solar neutrinos in BOREXINO

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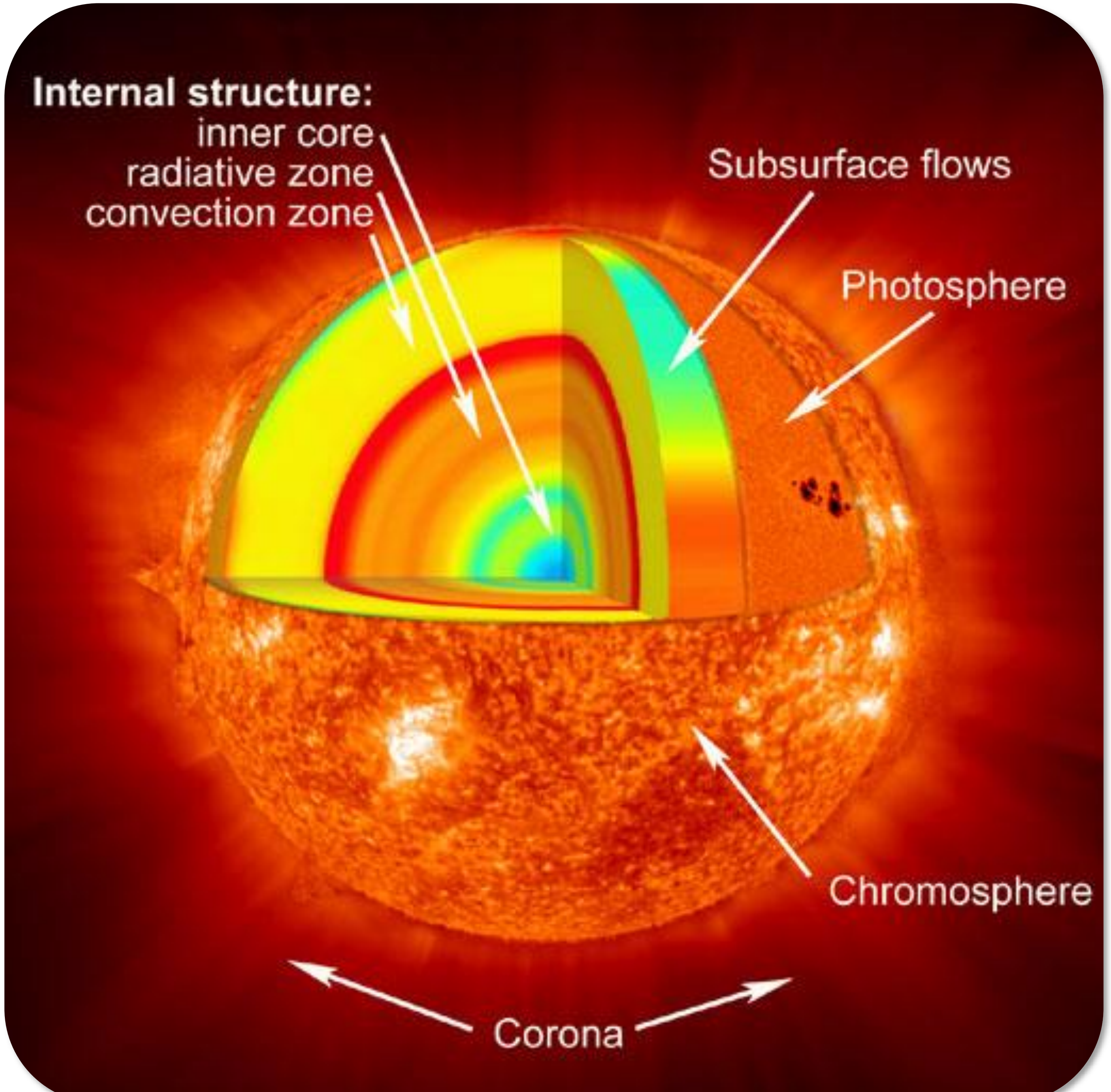
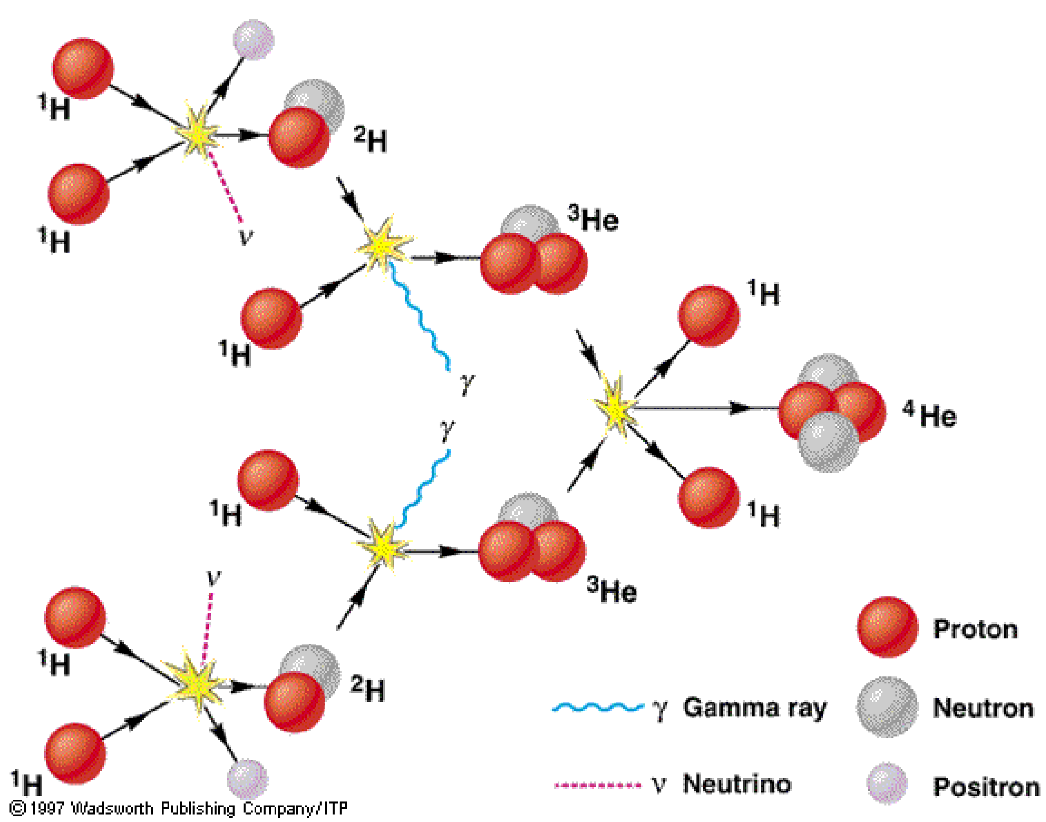
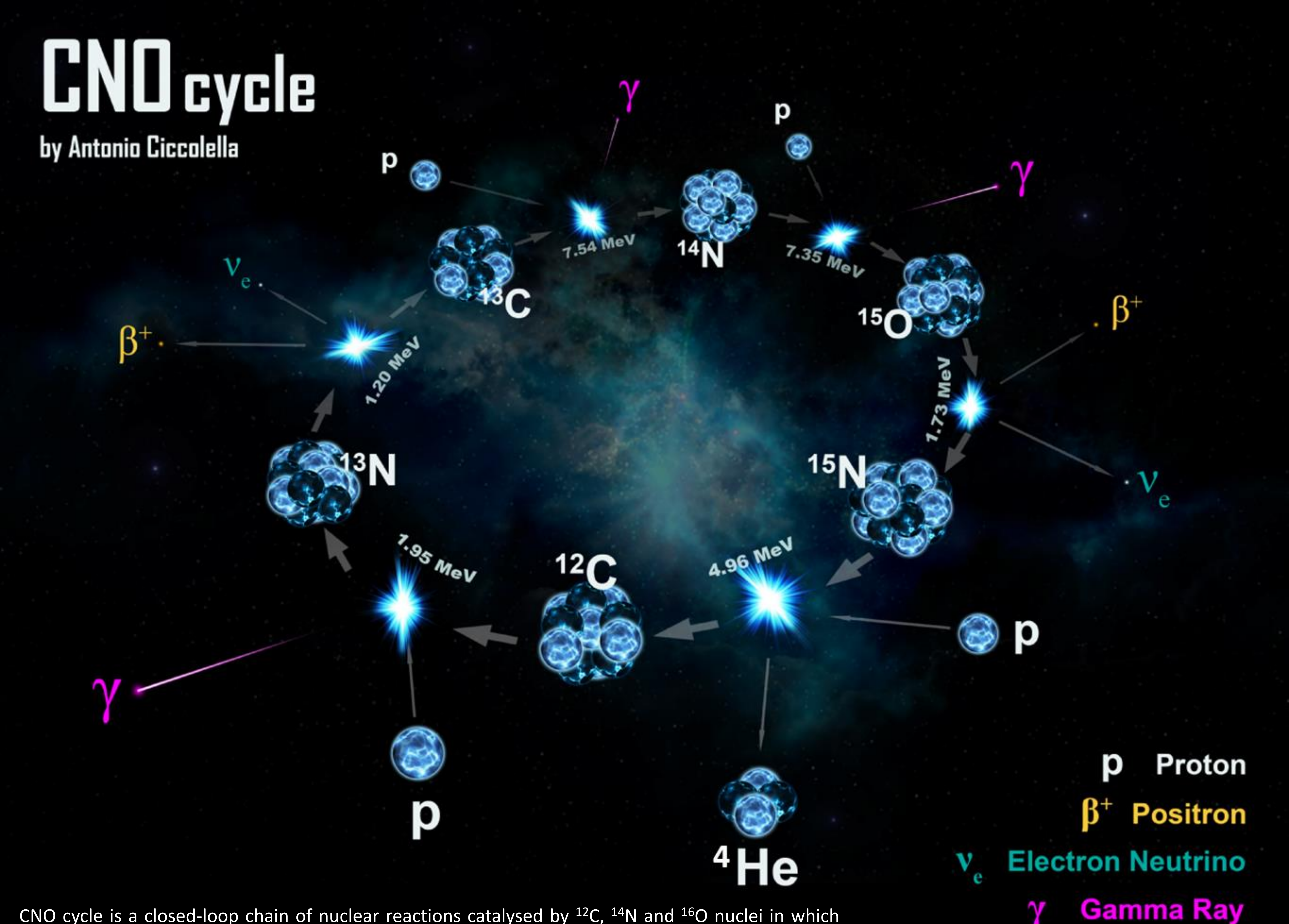
Solar ν as sensitive tool to test solar models



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.



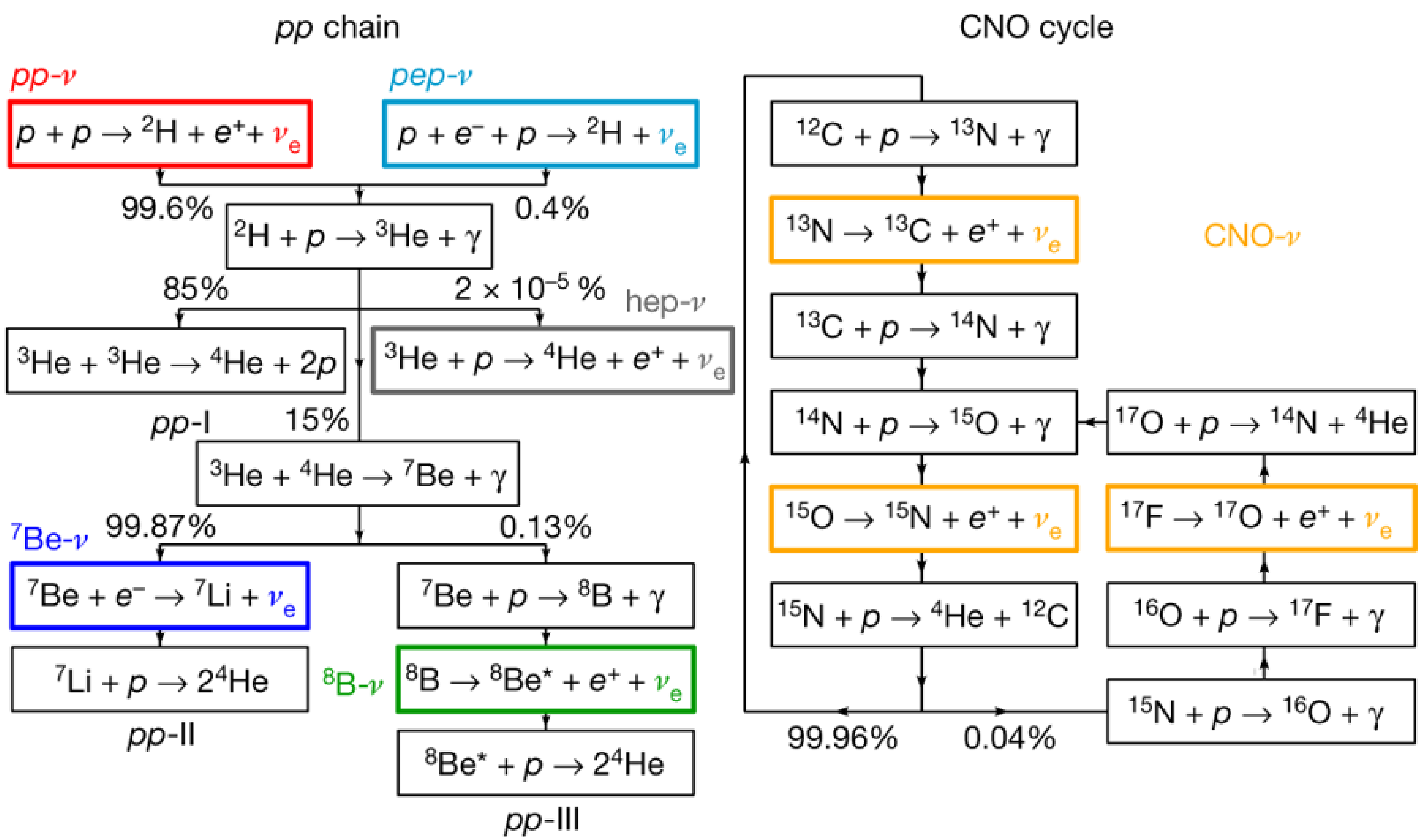


CNO cycle is a closed-loop chain of nuclear reactions catalysed by ^{12}C, ^{14}N and ^{16}O nuclei in which four protons are converted into ^{4}He.

Solar ν as sensitive tool to test solar models

pp chain: 99 % of Sun Energy

CNO cycle: <1 % of Sun Energy



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

The Borexino Collaboration

PRINCETON UNIVERSITY

INFN

UNIVERSITÀ DEGLI STUDI DI MILANO

LNGS

St. Petersburg Nuclear Physics Inst.

НИИЯФ МГУ

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

TUM

APC

UHH

JÜLICH FORSCHUNGSZENTRUM

UNIVERSITÀ DEGLI STUDI DI GENOVA

Virginia Tech

GRAN SASSO SCIENCE INSTITUTE
CENTER FOR ADVANCED STUDIES
Istituto Nazionale di Fisica Nucleare

TECHNISCHE UNIVERSITÄT DRESDEN

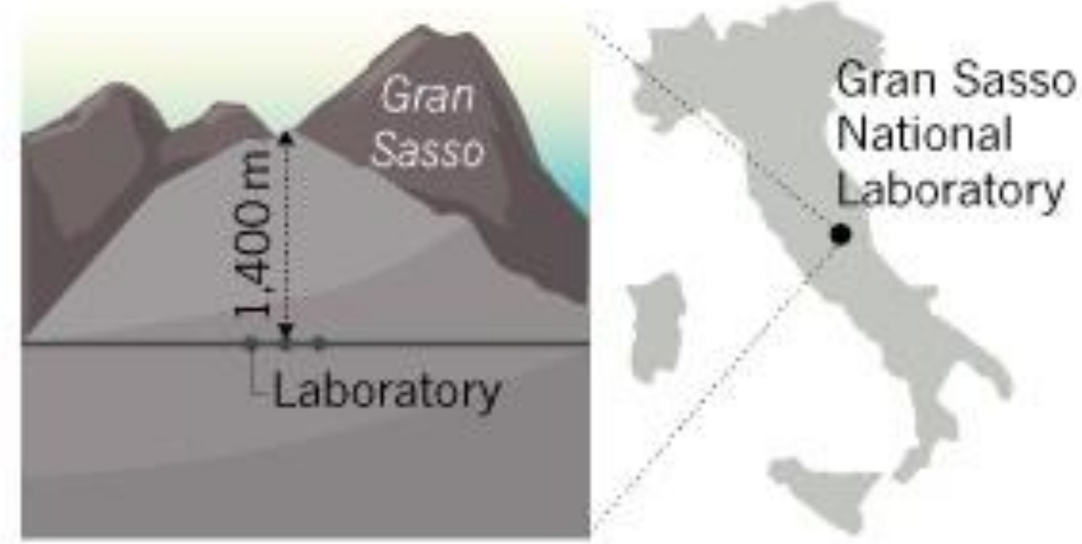
JAGIELLONIAN UNIVERSITY IN KRAKÓW

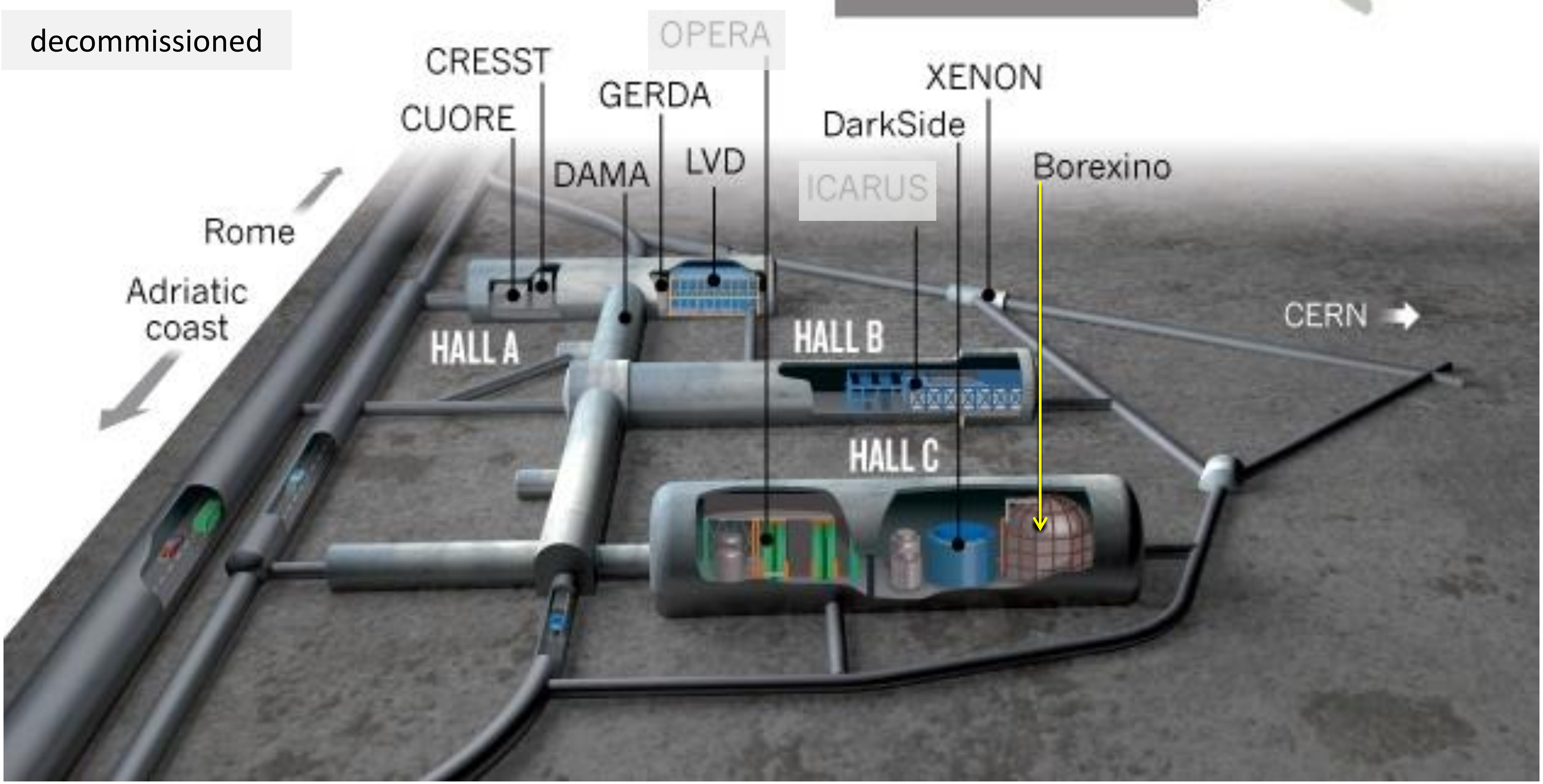
POLITECNICO MILANO 1863

Gran Sasso INFN underground laboratory

THE A, B AND C OF GRAN SASSO

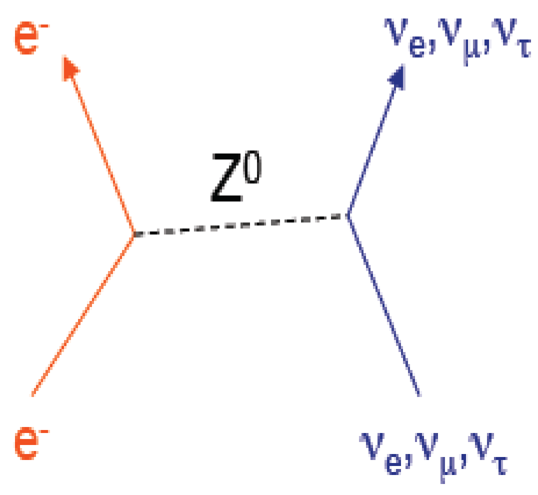
Experiments at the Gran Sasso National Laboratory are housed in and around three huge halls carved deep inside the mountain, where they are shielded from cosmic rays by 1,400 metres of rock.

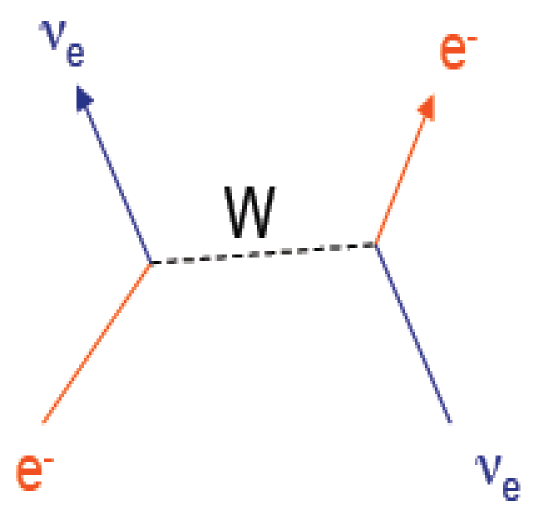




BOREXINO Detector – Detection principle

- 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 $\sim 5 \cdot 10^{-9}$ 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

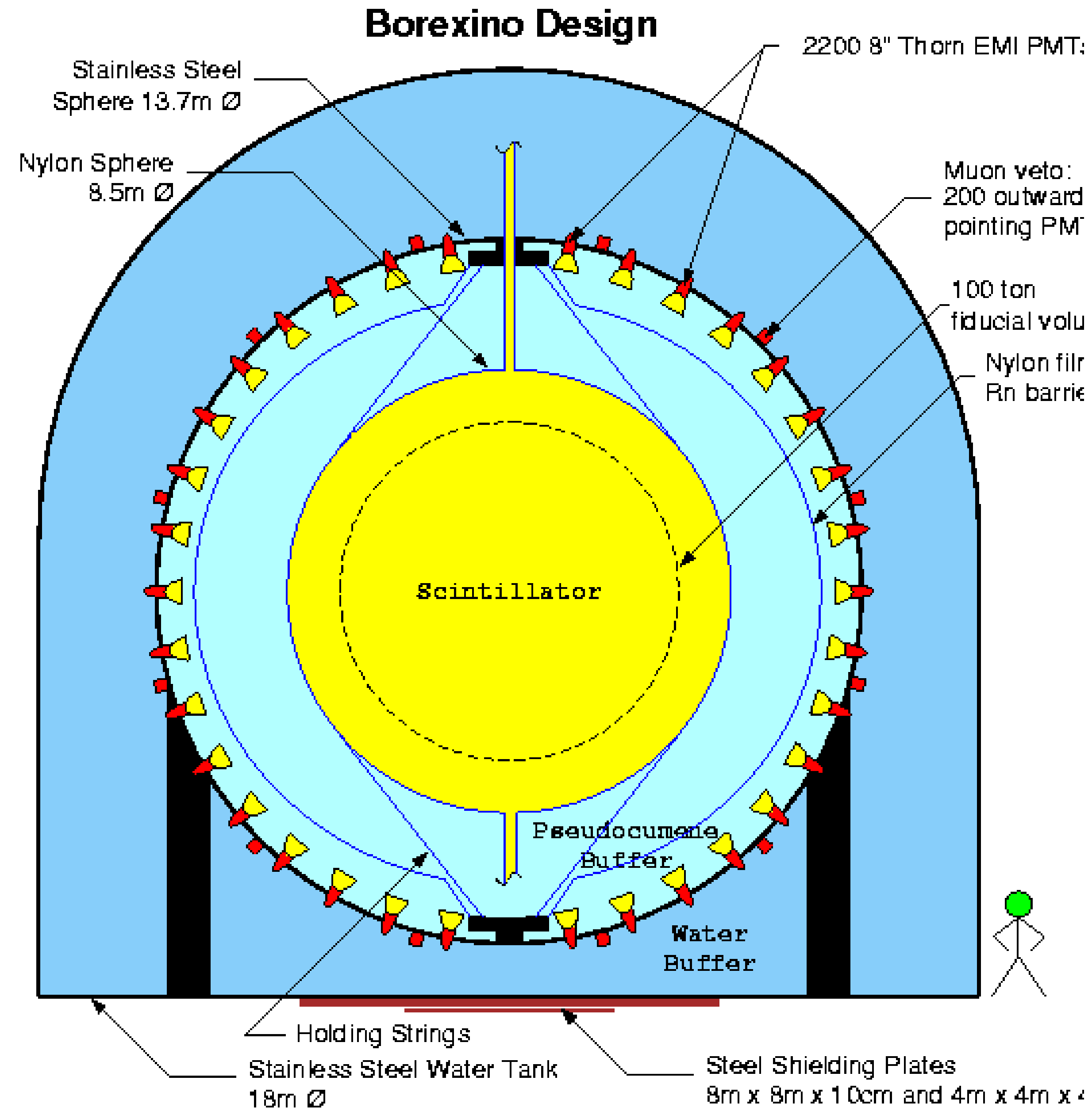
BOREXINO Detector

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;

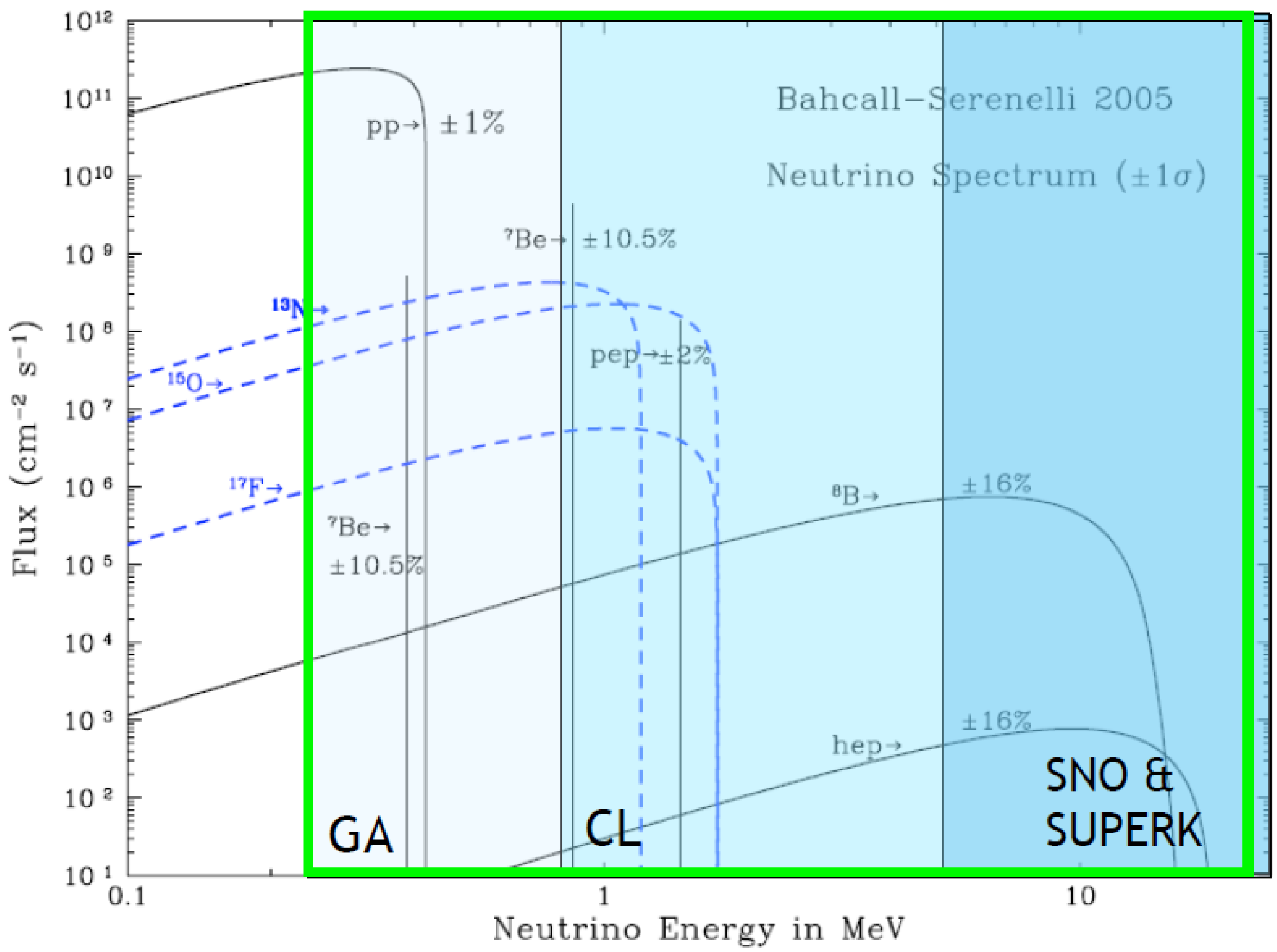
2nd shield: 2000 tons of ultra-pure water contained in a cylindrical dome;



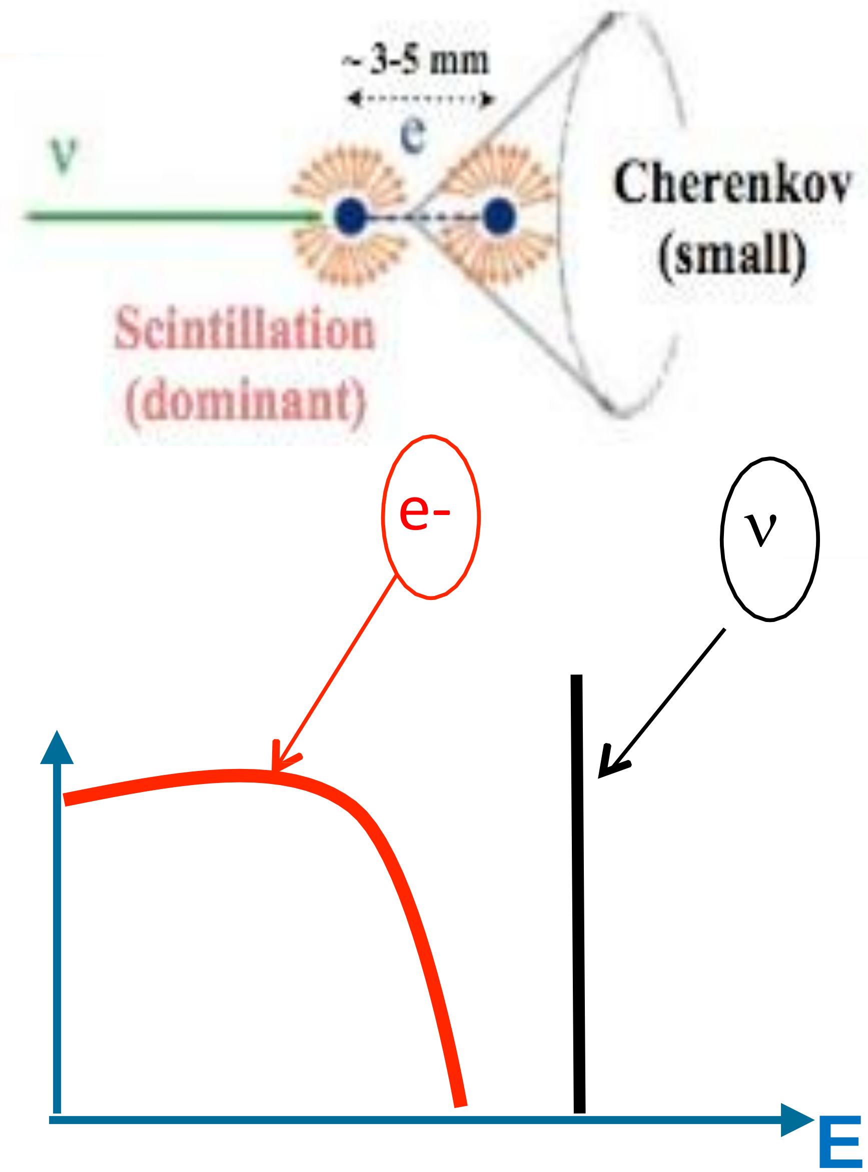
200 PMTs mounted on the SSS pointing outwards to detect light emitted in the water by muons crossing the detector;

Borexino is located inside the Gran Sasso mountain in Italy

Borexino goal: the measure in real time of the single ν components

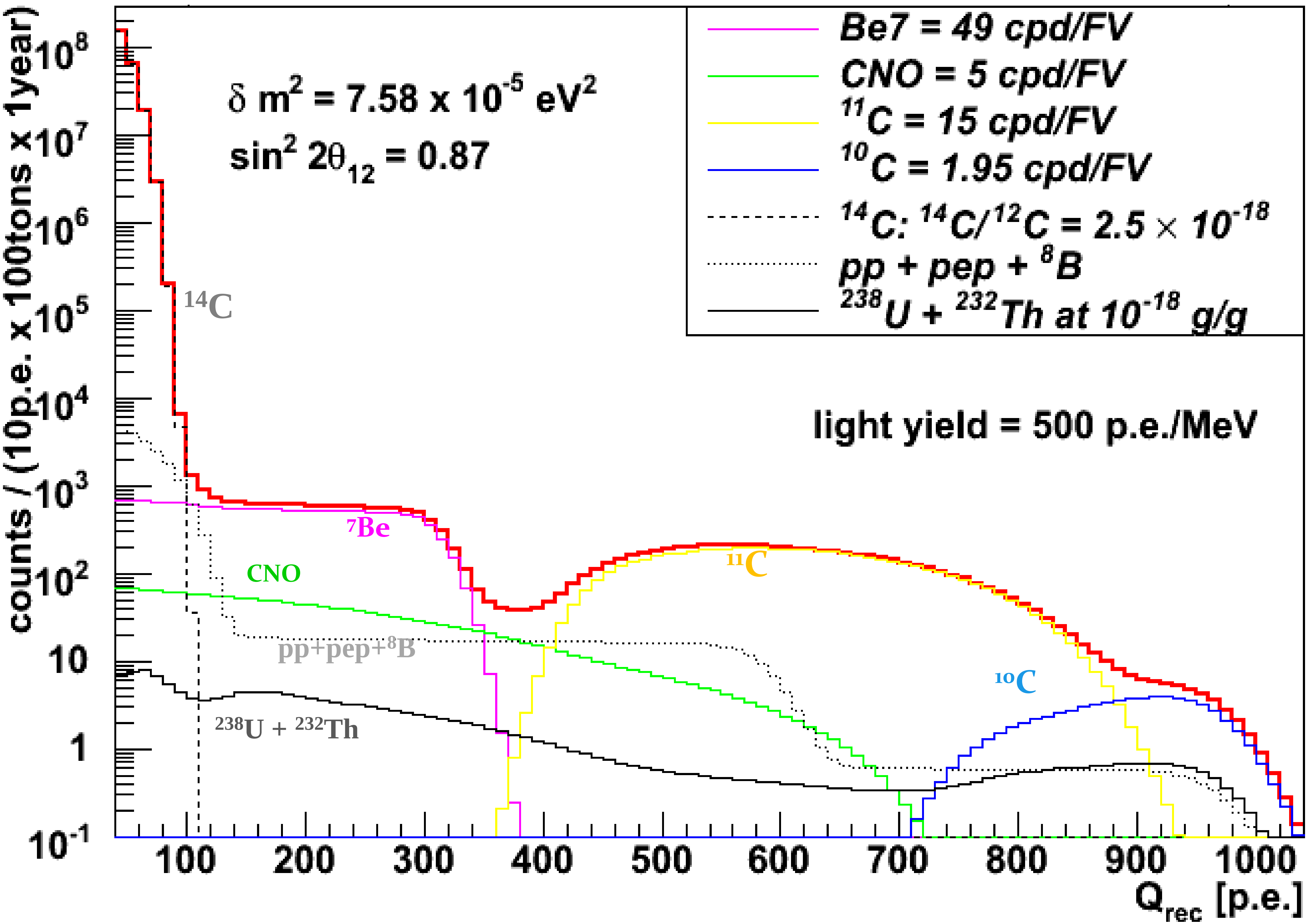


BOREXINO



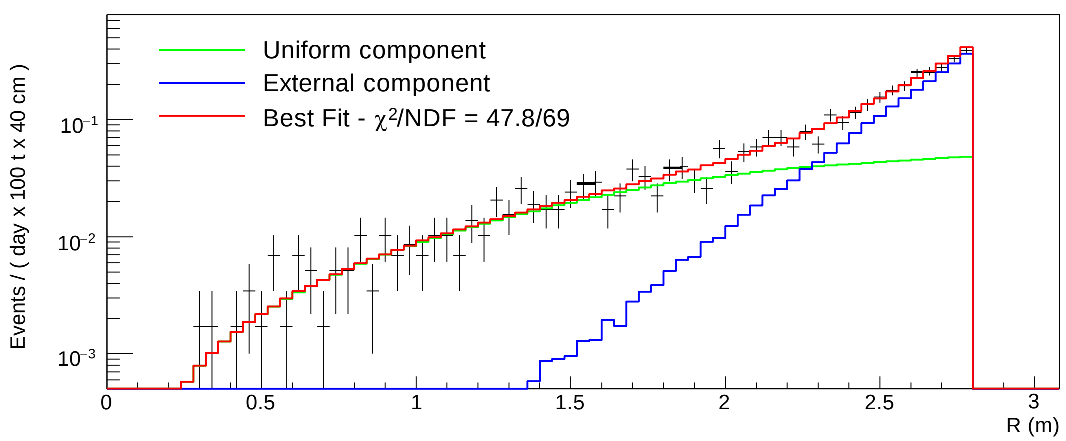
We measure the energy carried away by the electron!

The expected signal and the irreducible background

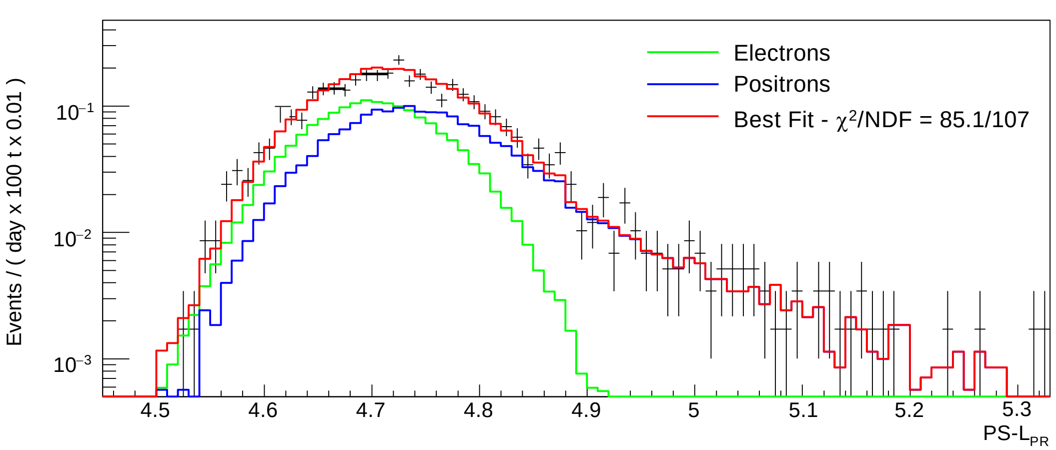


Results : example of multivariate fit of the data

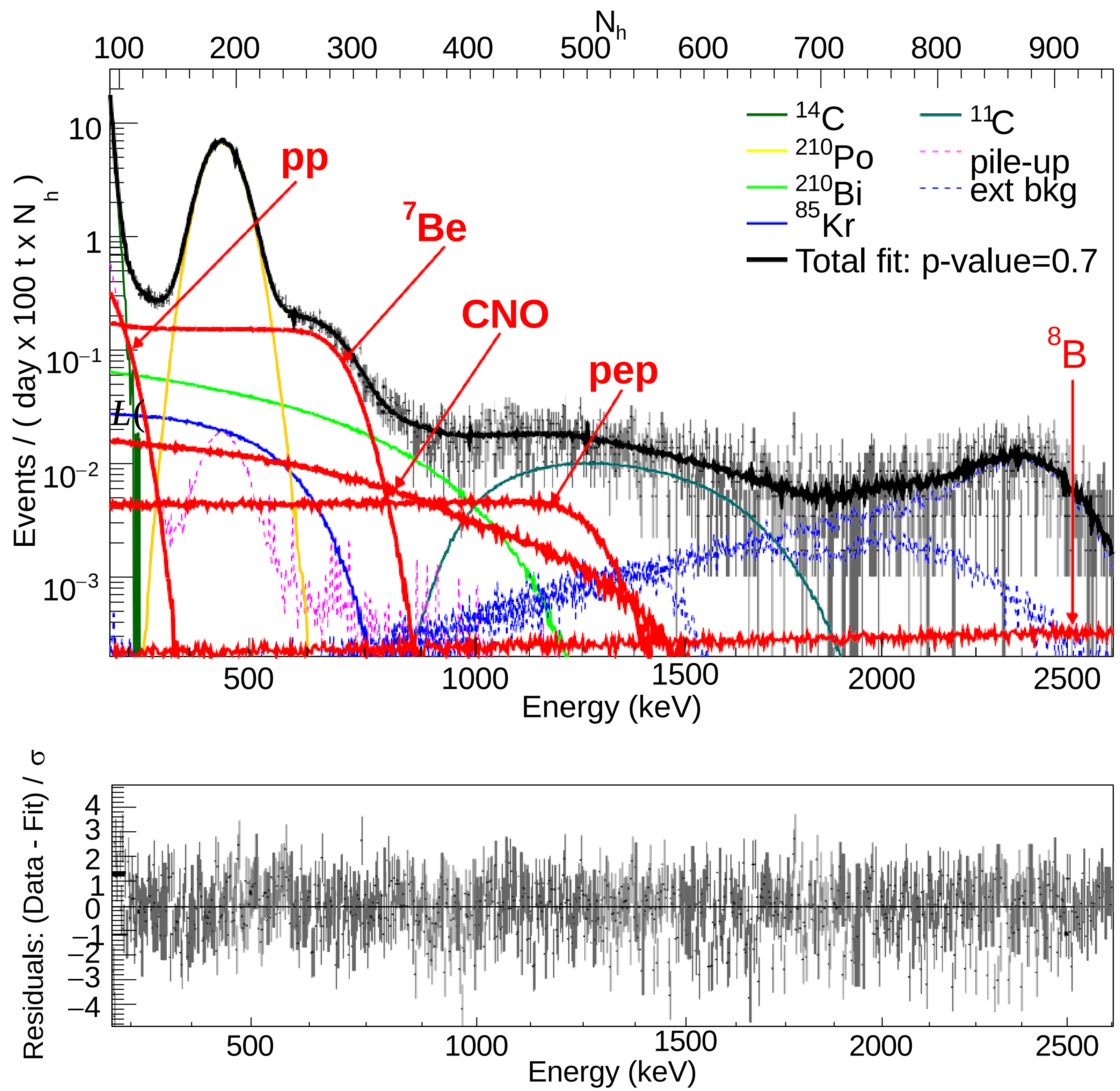
Radial distribution



PS-L_{PR}

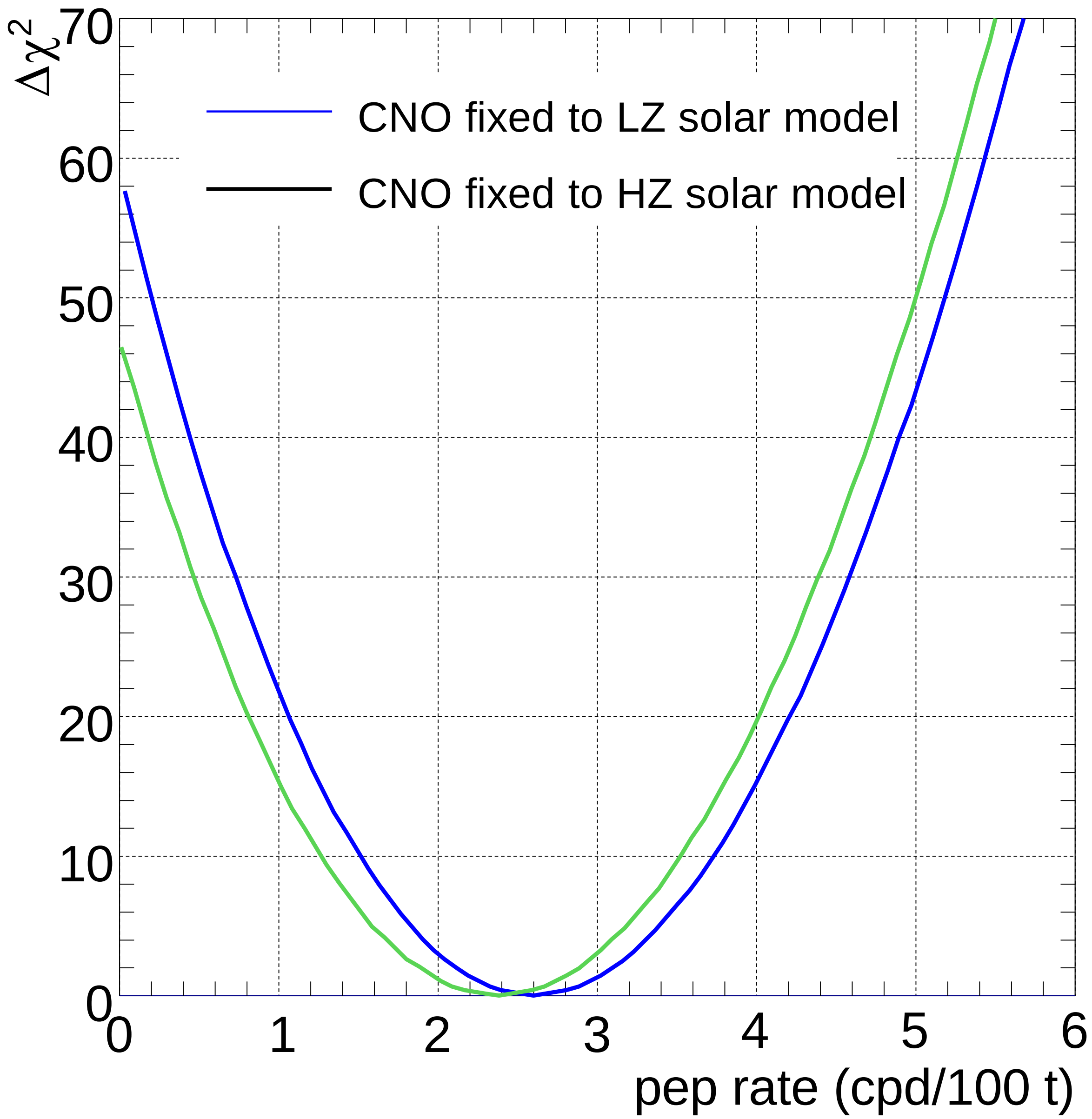


Energy spectrum

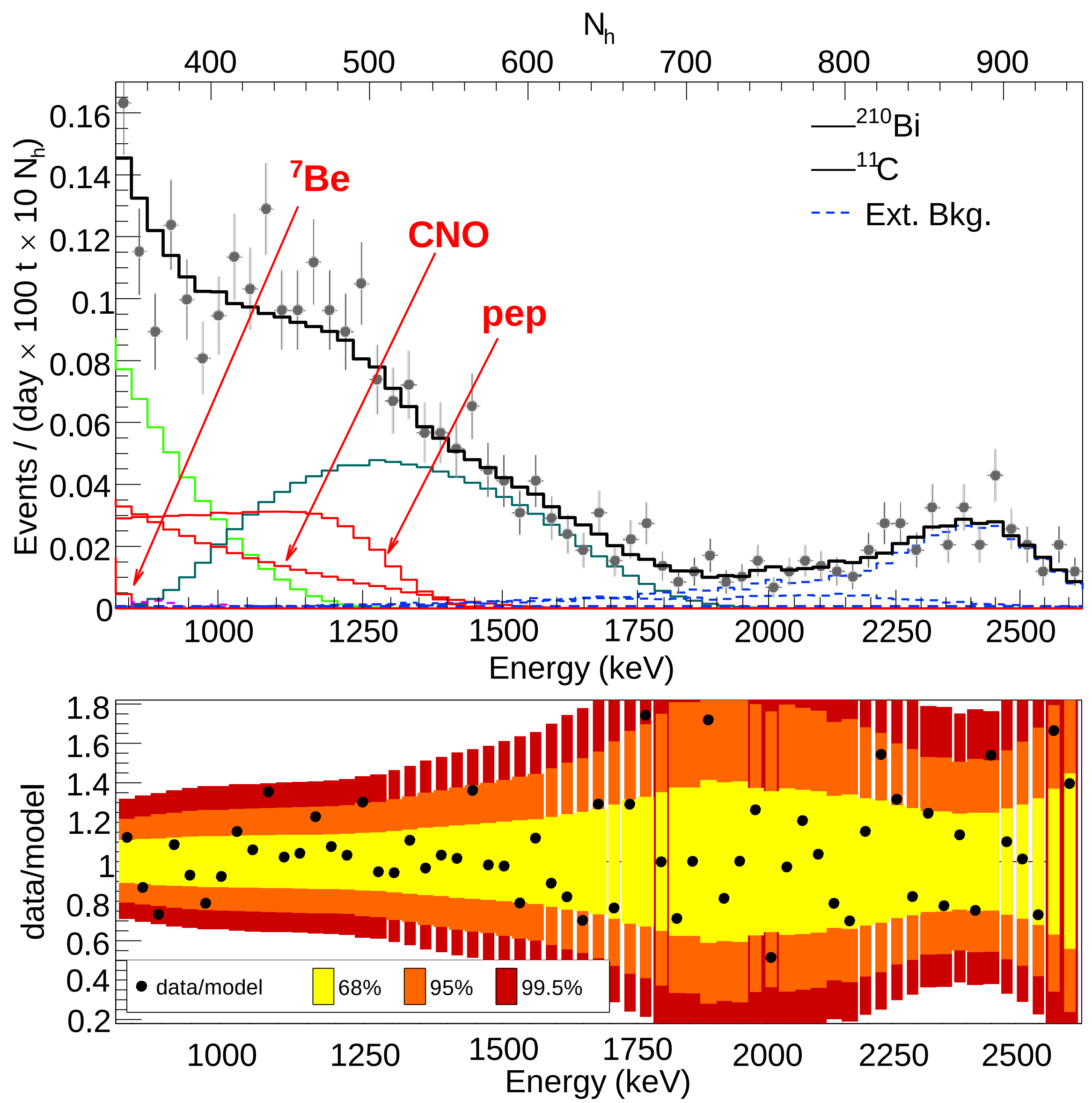


Evidence of pep solar ν at 5σ

Likelihood profile resulting from the multivariate fit
(*systematical uncertainties included*)



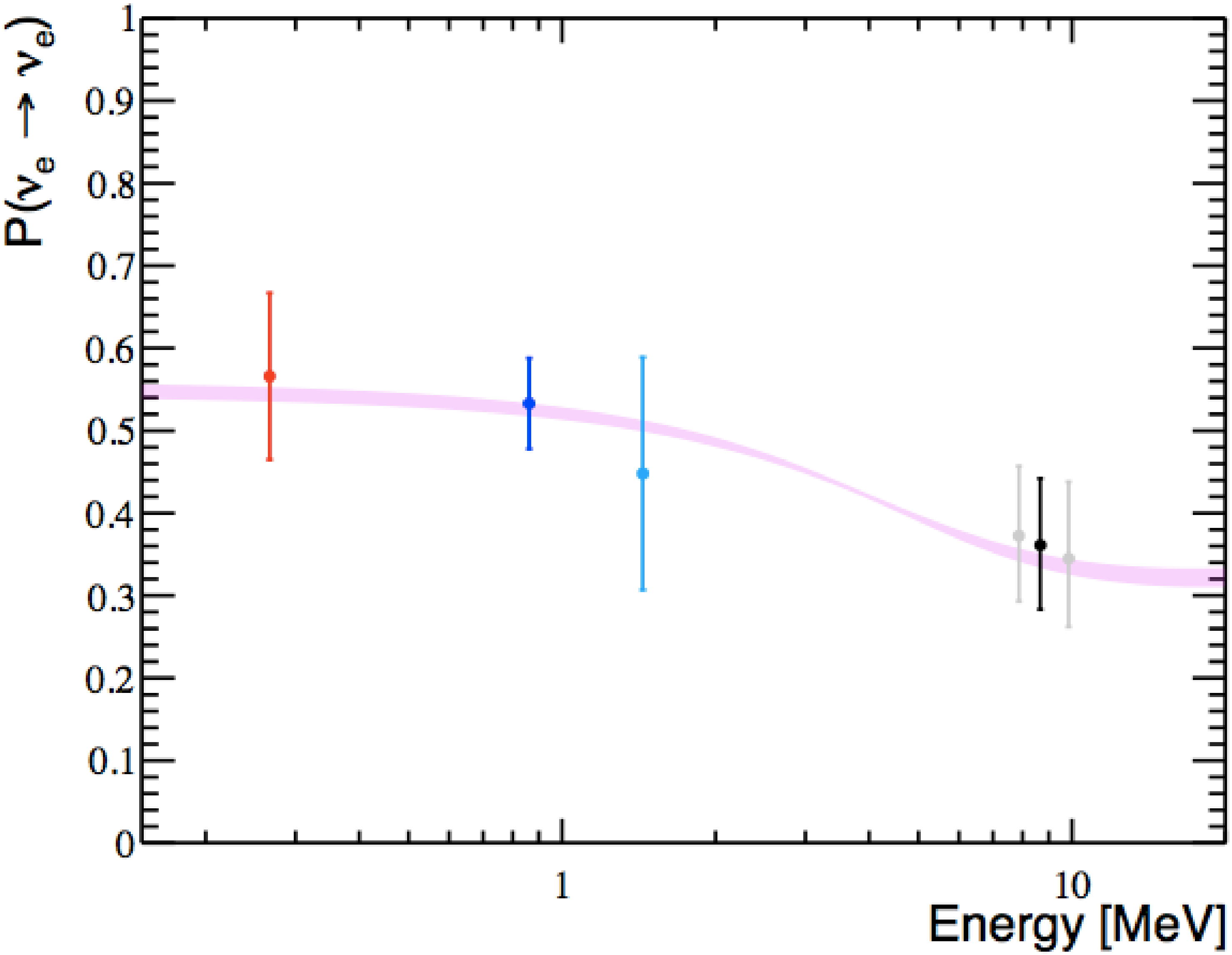
Selected the innermost β-like events
Radius <2.4 m Ps-LPR < 4.8



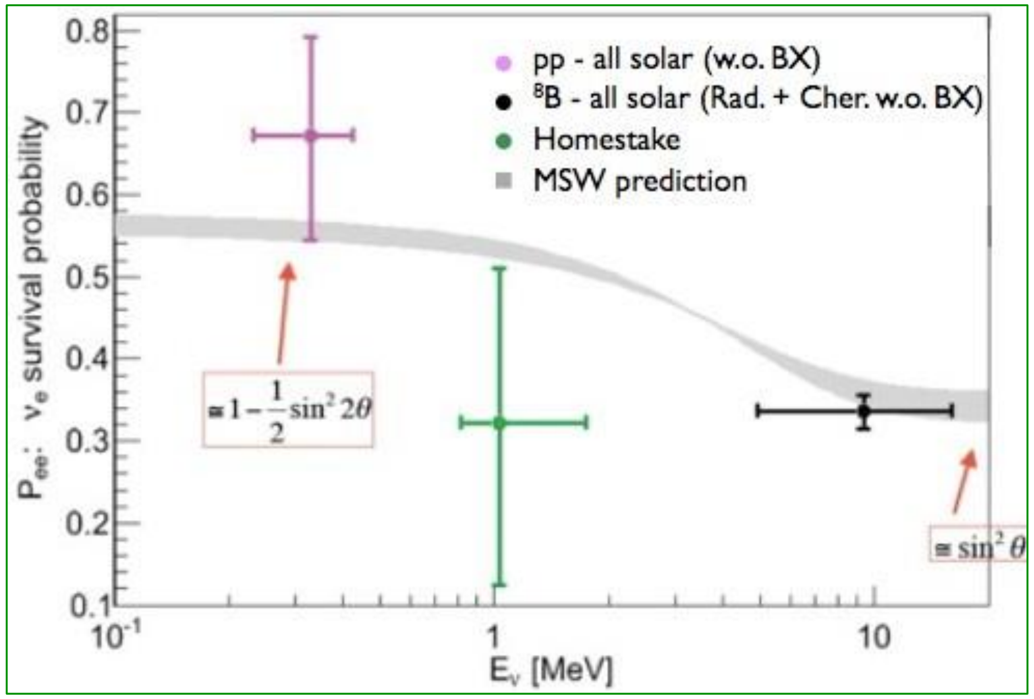
Neutrino survival probability

P_{ee}: Borexino impact

Borexino now



Before Borexino



From the measured interacton rates and assuming HZ-SSM fluxes we get:

- $P_{ee}(pp)=0.57\pm0.10$
- $P_{ee}(^7Be, 862keV)=0.53\pm0.05$
- $P_{ee}(pep)=0.43\pm0.11$
- $P_{ee}(^8B)= 0.36\pm0.08$ $\langle E_\nu \rangle=8.9$ MeV

BOREXINO – most recognized results

2008: Direct Measurement of the ^{7}Be Solar Neutrino Flux with 192 Days of BOREXINO Data
Phys. Rev. Lett. 101 (2008) 091302

2011: Precision Measurement of the ^{7}Be Solar Neutrino Interaction Rate in BOREXINO
Phys. Rev. Lett. 107 (2011) 141302

2012: First evidence of **pep** solar neutrinos by direct detection in BOREXINO
Phys. Rev. Lett. 108 (2012) 051302

nature International weekly journal of science

2014: Neutrinos from the primary proton–proton fusion process in the Sun
Nature 512 (2014) 383–386

2018: Comprehensive measurement of pp-chain solar neutrinos
Nature 562 (2018) 505–510

Summary & Outlook

With Phase-II data Borexino has entered the era of precision spectroscopy of solar neutrinos;
Thanks to its exceptional radiopurity, Borexino has gone well beyond its original goal providing a complete study of solar neutrinos from the entire proton-proton chain;

The newest results:

First simultaneous extraction of pp, pep and ^{7}Be neutrino rate from the same fit;

Improved precision in all flux measurements (notably ^{7}Be precision is now 2.7%);

New determination of the ^{8}B neutrino flux (precision increased by 55%);

> 5σ evidence of the pep neutrino signal;

The future : CNO ?