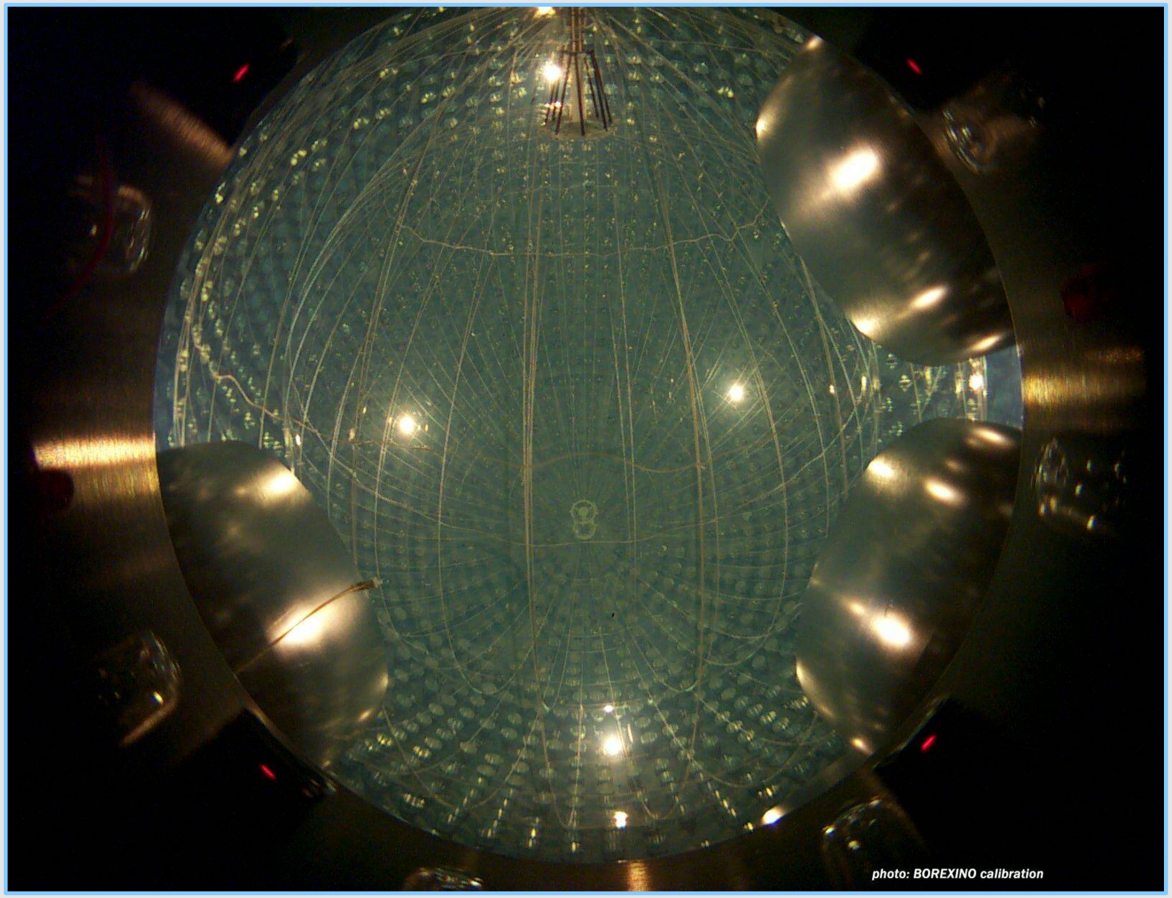
The Borexino experiment:
a sub-MeV solar neutrino observatory



CSQCD V @ LNGS

Chiara Ghiano
Laboratori Nazionali del Gran Sasso

Solar fusion reactions

$4p \rightarrow 4\,He + 2e + + 2\,\nu_e + 26.7$ MeV

pp-chain

>99% energy production

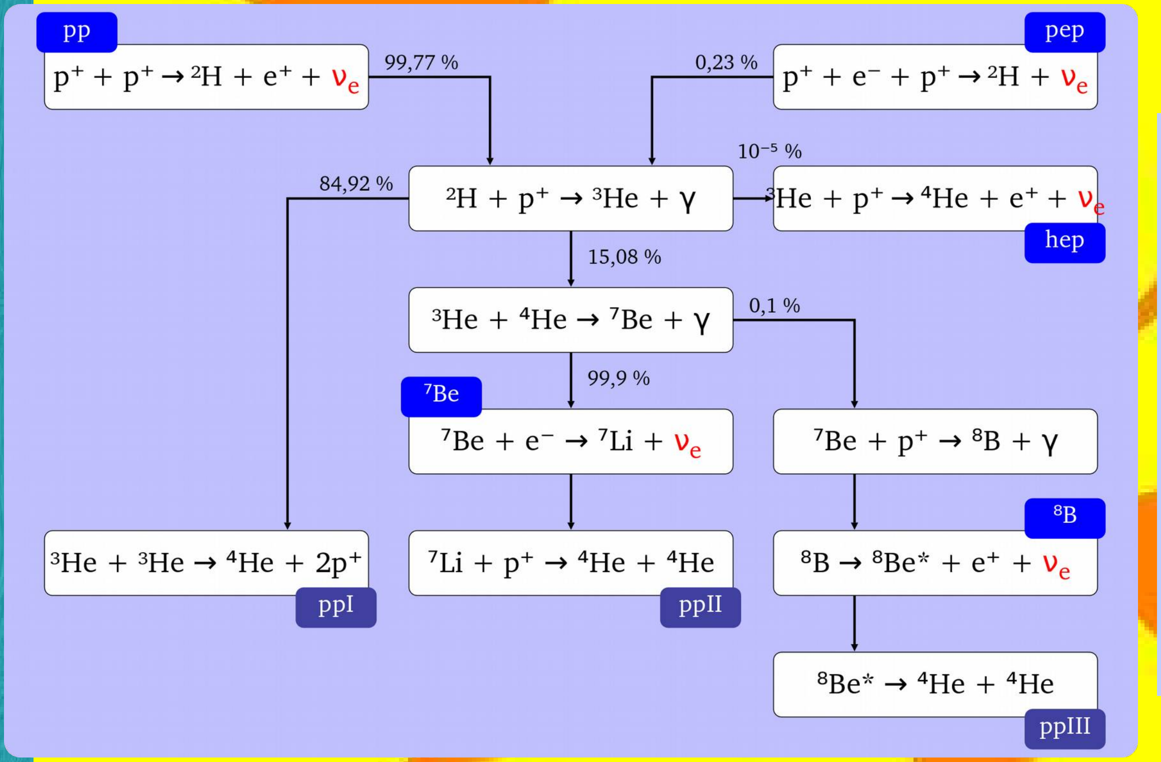
5 ν species

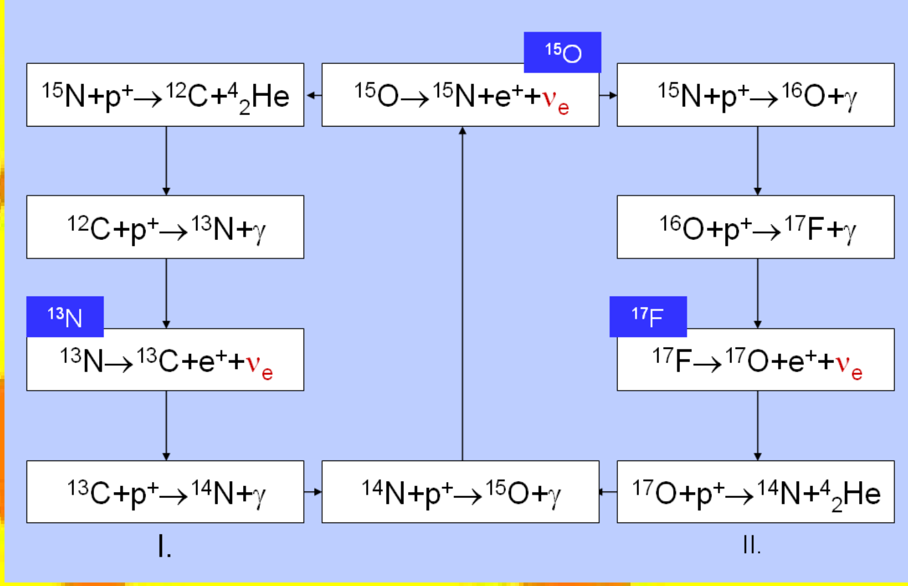
CNO-chain

contribute <1% energy production

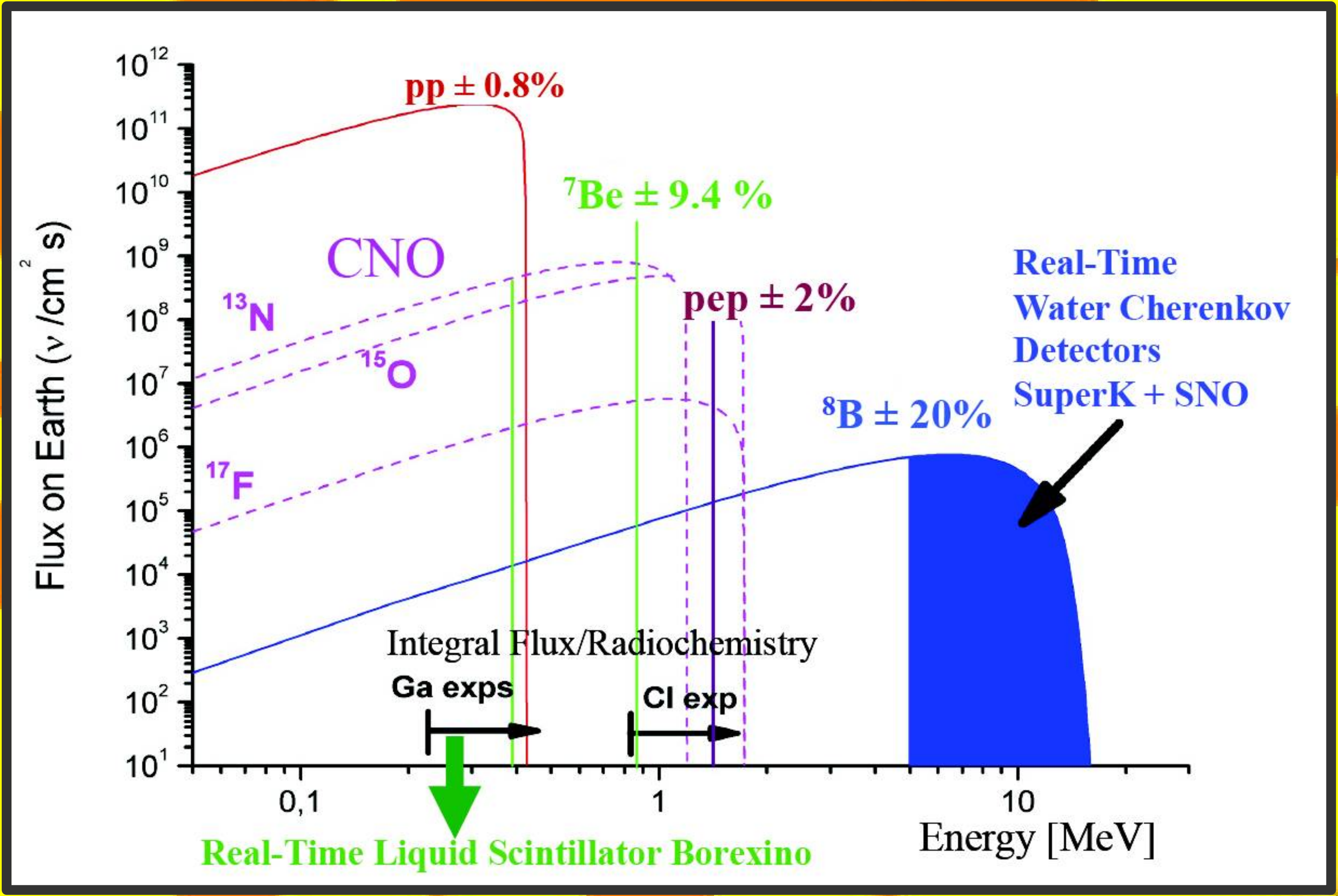
heavy star dominant

3 ν species





Solar electron neutrinos spectrum



Why measure solar neutrinos?
1_SOLAR AND STELLAR PHYSICS

- **Measure solar neutrino flux → test Solar Standard Model**
  Astro-ph probe: neutrinos allow to look at the Sun's core

- **Solve solar metallicity problem: tension between High Metalliciy (High Z) and Low Metallicity (Low Z) Solar Models**
  - High Z (GS) → older model, higher heavy element abundances, agrees with helioseismology measurments
  - Low Z (AGSS) → recent model based on new solar atmosphere optical spectroscopy measurments, lower heavy element abundances, in disagreement with helioseismology

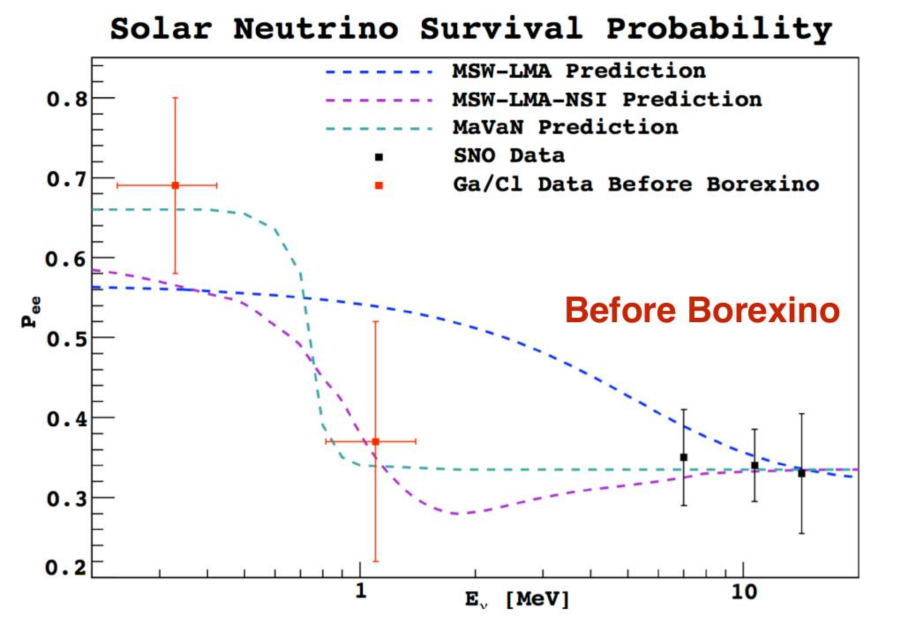
ν flux	GS98	AGSS09	Change from GS98 (%)
pp	$5.98\ (1\pm0.006)\ \times10^{10}$	$6.03\ (1\pm0.006)\ \times10^{10}$	0.8
pep	$1.44\ (1\pm0.012)\ \times10^{8}$	$1.47\ (1\pm0.012)\ \times10^{8}$	2.0
hep	$8.04\ (1\pm0.30)\ \times10^{3}$	$8.31\ (1\pm0.30)\ \times10^{3}$	3.4
^{7}Be	$5.00\ (1\pm0.07)\ \times10^{9}$	$4.56\ (1\pm0.07)\ \times10^{9}$	-8.8
^{8}B	$5.58\ (1\pm0.14)\ \times10^{6}$	$4.59\ (1\pm0.14)\ \times10^{6}$	-17.7
^{13}N	$2.96\ (1\pm0.14)\ \times10^{8}$	$2.17\ (1\pm0.14)\ \times10^{8}$	-26.7
^{15}O	$2.23\ (1\pm0.15)\ \times10^{8}$	$1.56\ (1\pm0.15)\ \times10^{8}$	-30.0
^{17}Fe	$5.52\ (1\pm0.17)\ \times10^{6}$	$3.40\ (1\pm0.16)\ \times10^{6}$	-38.4

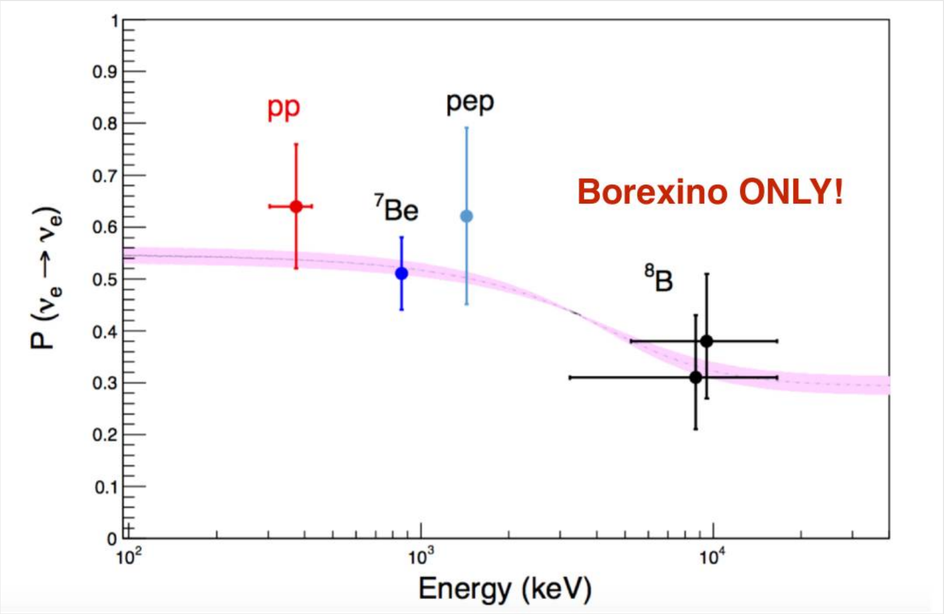
Serenelli, Haxton, Pena-Garay arXiv 1104.1639	CNO Flux ($10^{8}cm^{-2}s^{-1}$)
HIGH Z SSM	5.24 ± 0.84
LOW Z SSM	3.76 ± 0.60

Why to measure solar neutrinos today?
2_NEUTRINO PHYSICS

- ★ Borexino can measure the P_{ee} (electron neutrino survival probability) both in the matter-enhanced oscillation region and in the vacuum region.

- ★ Precision measurements of solar neutrino fluxes can help map out the transition region, sensitive to new physics.
  testing the LMA (Large Mixing Angle) – MSW Oscillation (matter effects) analysis solution to neutrino oscillations (energy dependent day/night effects)





Borexino physic program and results

Borexino is presently the only detector able to measure the solar neutrino interaction rate down to energies as low as ~ 150 keV and to reconstruct the energy spectrum of the events

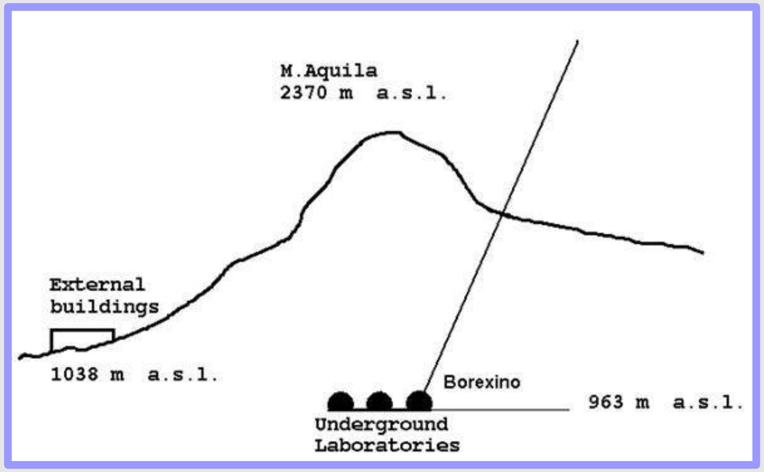
- ✔ First measurement of the interaction rate of the ^{7}Be 862 keV solar neutrinos with accuracy of the measurement has recently reached 5%
- ✔ Exclusion of any significant day-night asymmetry of the ^{7}Be solar neutrino flux
- ✔ First direct observation of the monoenergetic 1440 keV pep solar neutrinos
- ✔ Set of the strongest upper limit of the CNO solar neutrinos flux to date
- ✔ Measure of the ^{8}B solar neutrinos with an energy threshold of 3 MeV
- ✔ First direct measurement of the pp spectrum
- ✔ 4 σ geo-netrinos detection
- ✔ Detailed study of the cosmogenics in liquid scintillator

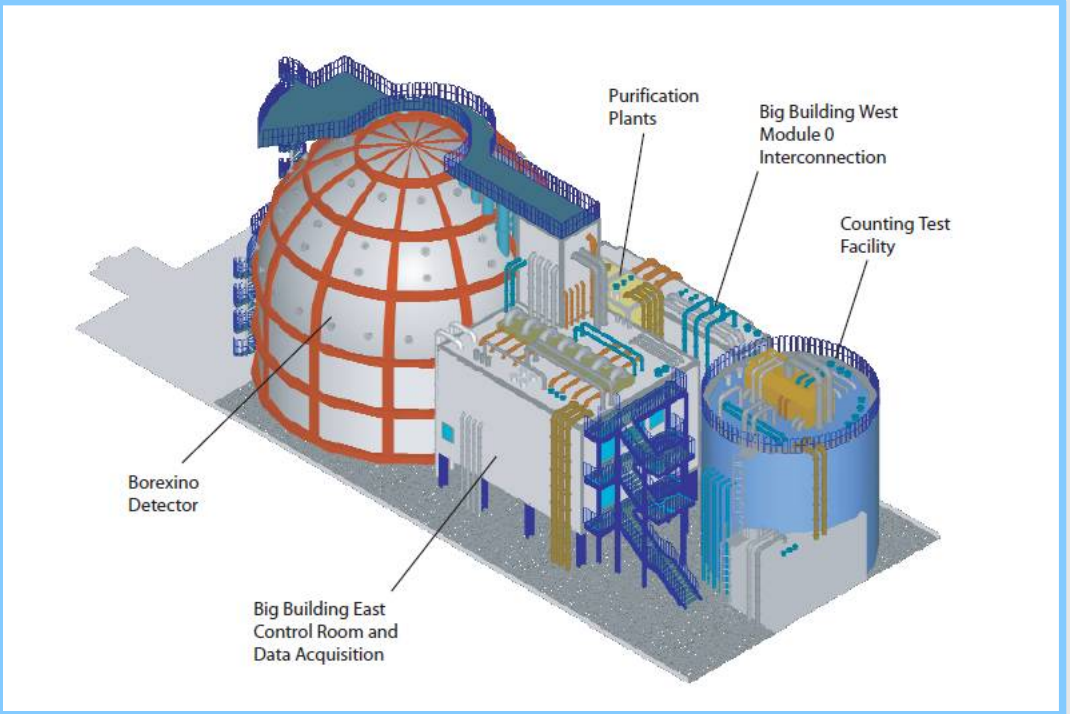
Experimental site

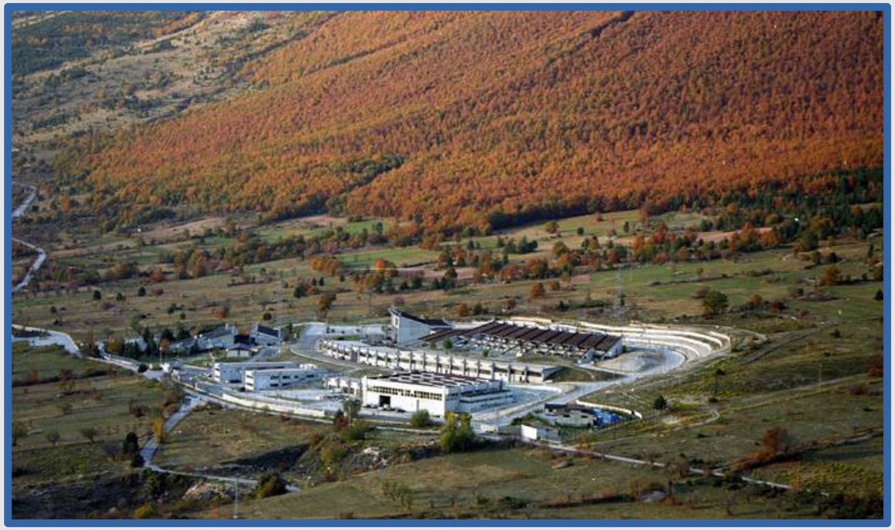
rock overburned 3800 m.w.e. ⇒ μ flux attenuation of 10^6
1.16 ± 0.03 μ/m 2 /hr
E_μ = 320 ± 4 ± 11 GeV

Radon ~100 Bq/m 3 in the air
neutron flux = 3.7±0.3 10^{2} m^{-2} s^{-1}

- External background:
  underground + graded shielding
- Internal background:
  accurate selection of materials +
  purification of the target mass

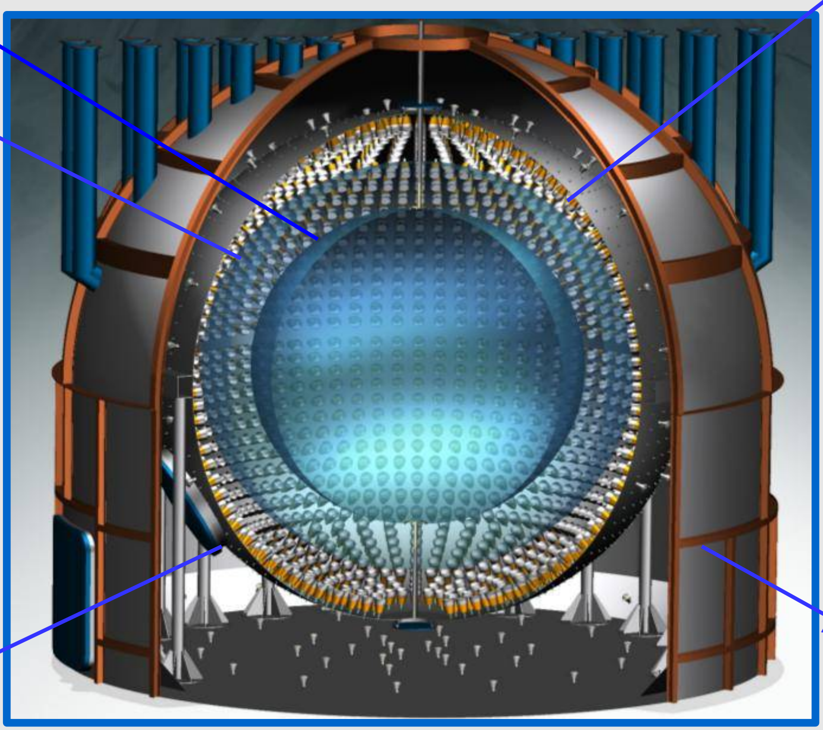






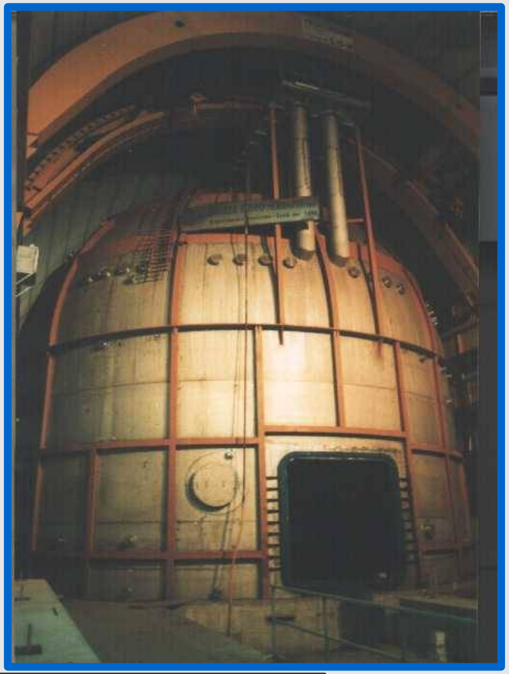
The BOREXINO detector

2212 8″ ETL 9351
PMTs mounted inside the SSS



Two Nylon balloons 150 μm thick
Inner Vessel
(8.5 m, V = 340 m³)
Filled with 278 tons of scintillator
(PC @ 1.5 g/l of PPO)
Inner Buffer (11.5 m)
filled with PC + DMP

Water Tank
(d=18 m, V = 2400 m³)
Shielding from γ and n.
Water Cerenkov detector
(Muon Veto) 208 PMTs



Stainless Steel Sphere
(d= 13.7 m, Volume = 1340 m³)

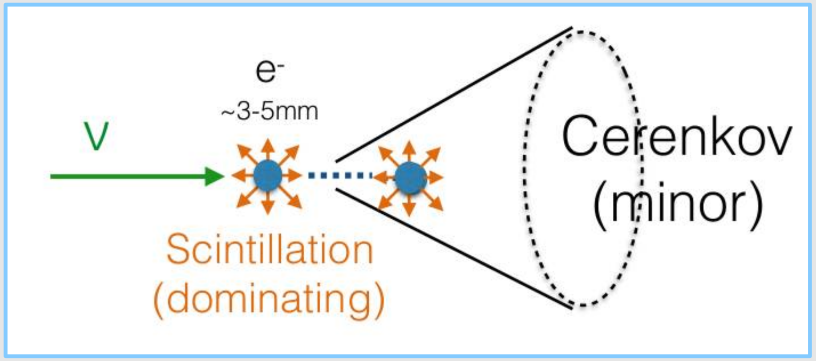
The Borexino signal

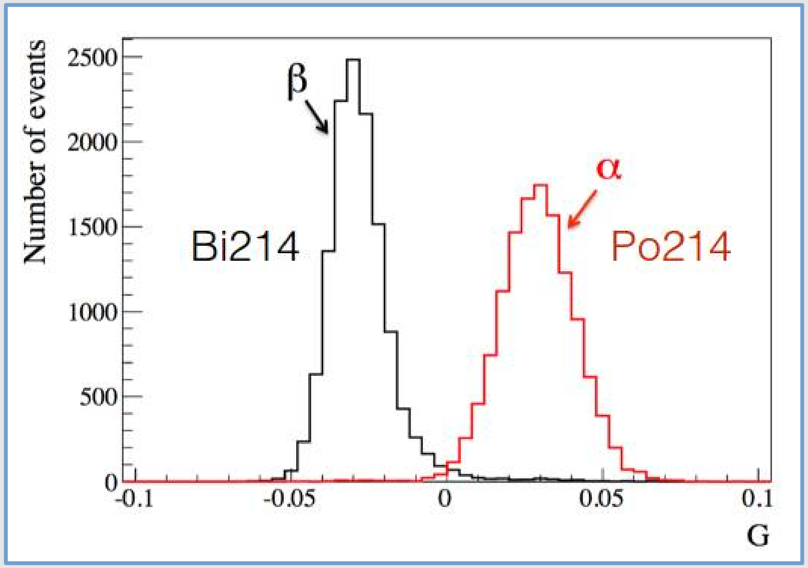
The Borexino PMTs detect the scintillation light produced by electrons scattered by neutrinos

- Very low energy threshold (~<100 keV)
- Good energy resolution ~ 5% @ 1MeV
- Photoelectron yield 500 pe/MeV
- Good position reconstruction by T.O.F. ~16cm @ 500keV
- For α and β+ we can apply the pulse shape discrimination
  Pulse shape α/β, β+/β-

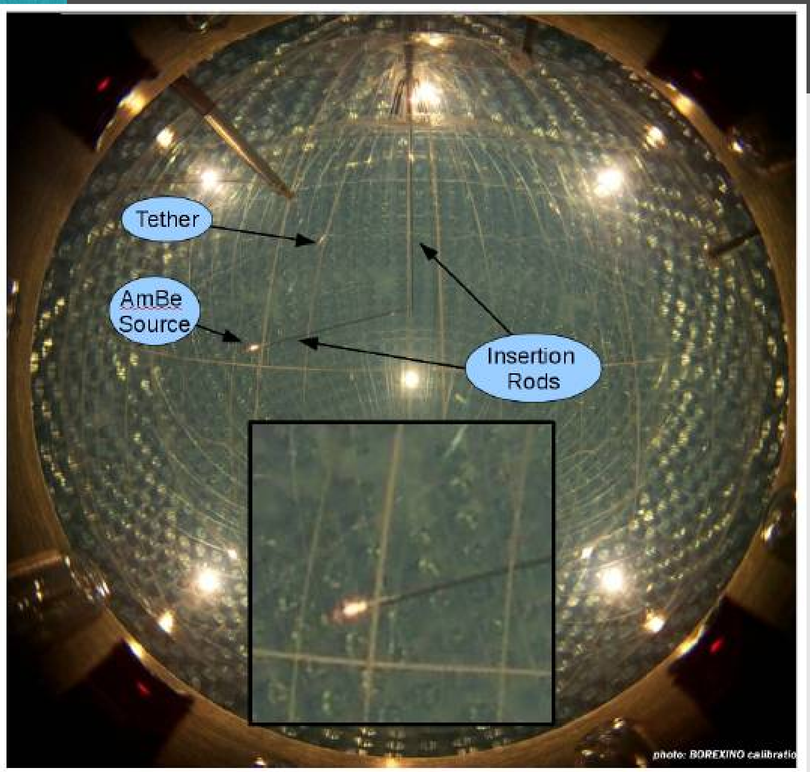
Drawbacks:

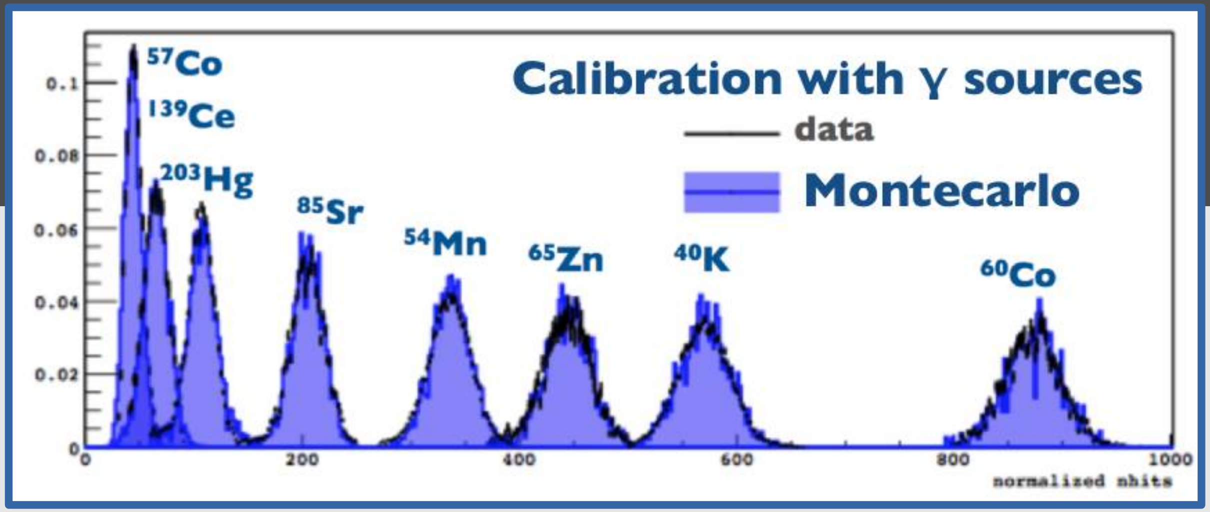
- No directionality
- Crucial point: Extreme low background required!!!

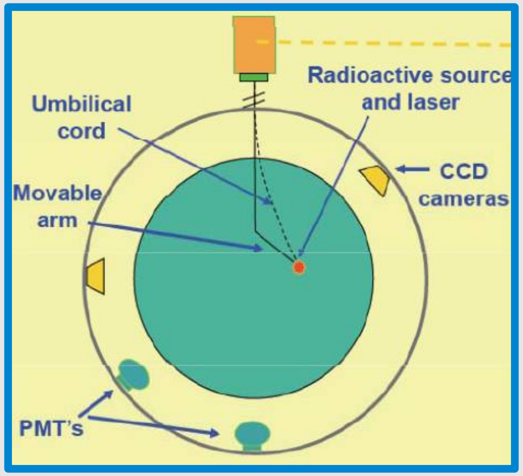




Calibrations







- **Energy response** as a function of position, particle type, and energy
- **Fiducial mass determination:** position reconstruction bias as a function of energy, position and particle type
- **Alpha beta discrimination efficiency** as a function of energy and position
- **Efficiency of a distance separation cut** for events assumed to occur at approximately the same location
- **Efficiency of the Borexino trigger** and its threshold

Signal and backgrounds

Expected ~50 events/day on 100ton of liquid scintillator from ^{7}Be neutrinos

→ **~ 6 10^{-9} Bq/kg**

But

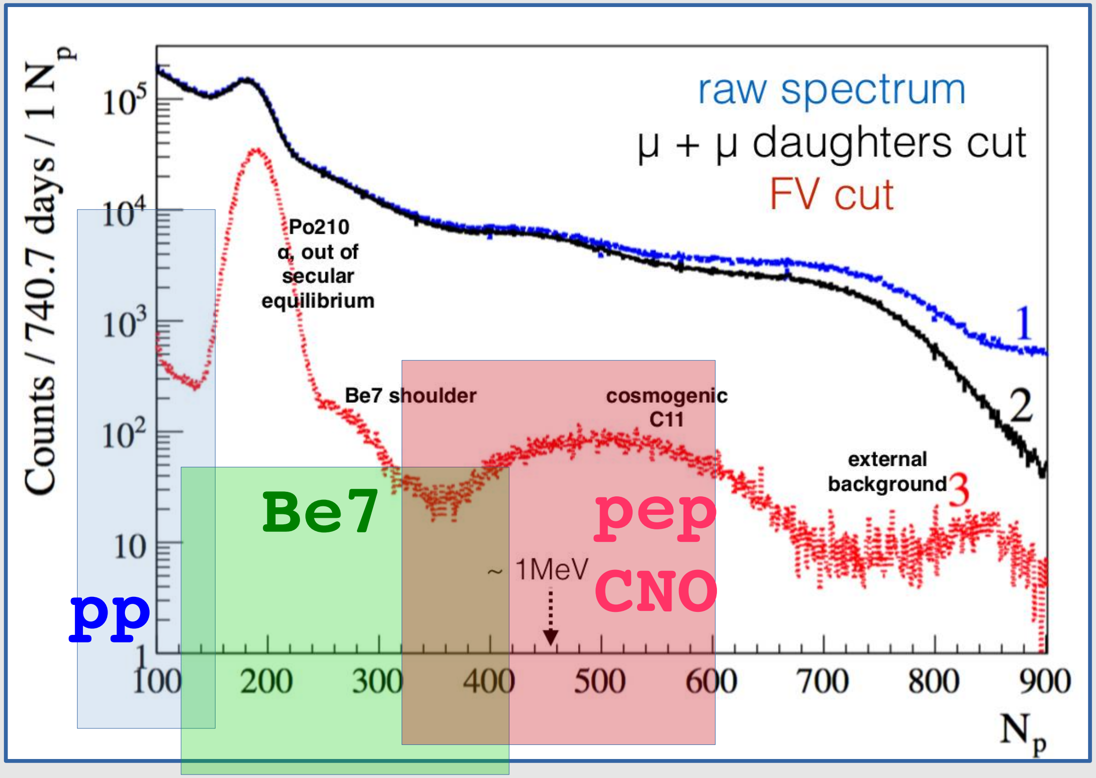
- Natural water is ~10 Bq/Kg in **^{238}U**, **^{232}Th** and **^{40}K**
- Air is ~10 Bq/m^3 in **^{39}Ar**, **^{85}Kr** and **^{222}Rn**
- Typical rock is ~100-1000 Bq/m^3 in **^{238}U**, **^{232}Th** and **^{40}K**

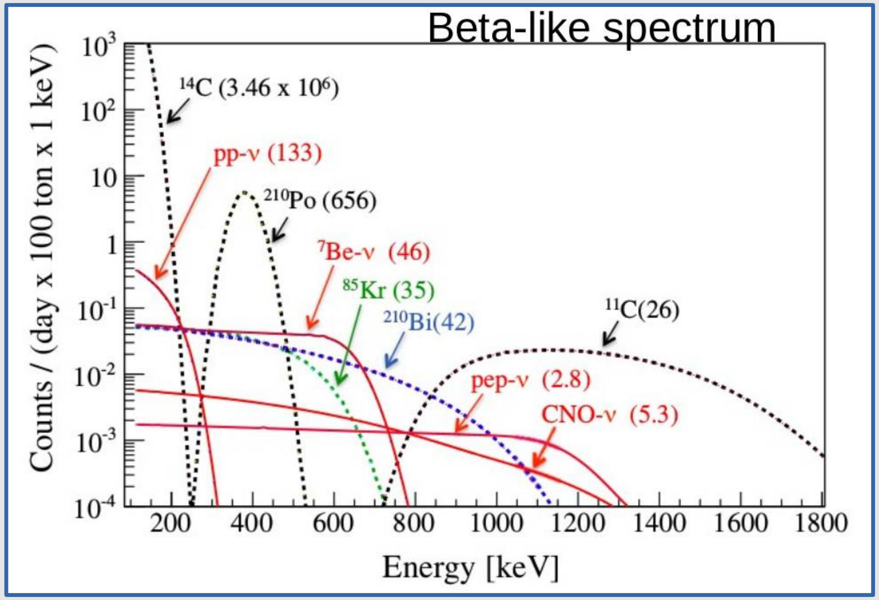
Borexino's scintillator must be 9/10 orders of magnitude less radioactive than anything on Earth!

Background issues

Source of contamination		Typical flux	Borexino requirements	Strategy (hardware)	Strategy (softw.)	Result phase 1	Result phase 2
μ	cosmic	~200 $s^{-1}m^{-2}$ @ sea level	< $10^{-10}s^{-1}m^{-2}$	Underground, water detector	Cherenkov PS analysis	< 10^{-10} eff > 0.9992	< 10^{-10} eff > 0.9992
γ	Rock	--	--	water	FV	negligible	negligible
γ	PMT, SSS	--	--	buffer	FV	negligible	negligible
^{14}C	Intrinsic PC	~ 10^{-12} g/g	~ 10^{-18} g/g	selectioon	threshold	~2 10^{18} g/g	~2 10^{18} g/g
^{238}U ^{232}Th	**Dust, metallic**	**10^{-5}-10^{-6} g/g**	**< 10^{-16} g/g**	**Distillation WE, filtration, mat. Selection, cleanliness**	**Tagging α/β**	**1.6+-0.1 10^{-17} g/g** **5.1+-1 10^{-18} g/g**	**< 9 10^{-19} g/g** **< 9 10 $^{-18}$ g/g**
^{7}Be	cosmogenic	~ 3 10^{-2} Bq/t	< 10^{-6} Bq/t	distillation	--	Not seen	Not seen
^{40}K	Dust, PPO	~2 10^{-6}g/g (dust)	< 10^{-18} g/g	Distillation , WE	--	Not seen	Not seen
^{210}Po	Surface cont. from ^{222}Rn		< 1c/d/t	Distillation , WE, filtration, cleanliness	fit	May '07 70 c/d/t Jan '10 ~1 c/d/t	< 1 c/d/t
^{222}Rn	Emanation from materials, rock	10 Bq/l air, water 100-1000 Bq rock	< 10 cpd 100 t	N_2 stripping cleanliness	Tagging α/β	< 1 cpd 100t	< 0.1 cpd 100t
^{39}Ar	Air, cosmogenic	17 mBq/m^3 (air)	< 1 cpd 100 t	N_2 stripping	fit	<< ^{85}Kr	<< ^{85}Kr
^{85}Kr	Air, nuclear weapons	1 Bq/m^3 (air)	< 1 cpd 100 t	N_2 stripping	fit	30 +-5 cpd/100t	< 7 cpd/100 t
^{210}Bi	Surface cont. from ^{220}Rn	--	--	Water extraction	fit	10-50 cpd/100t	~25

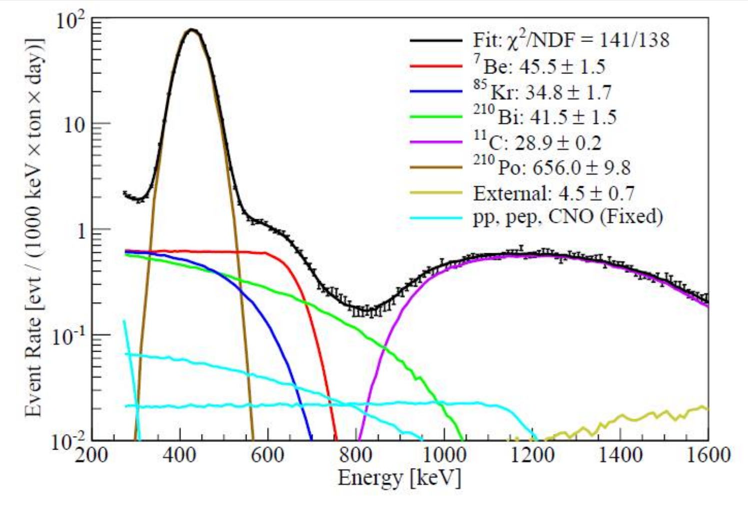
Borexino Spectrum



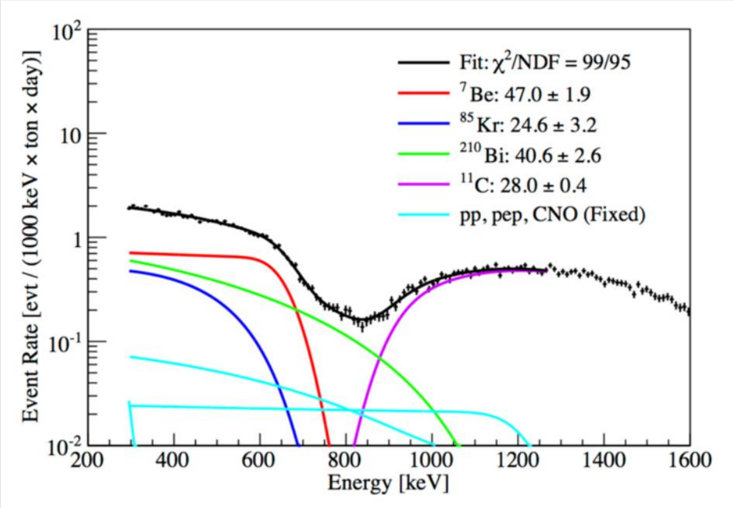


^{7}Be-ν (862 keV) rate @ 4.6% precision and absence of day- night asymmetry

Montecarlo fit, without Po210 removal



Analytical fit, with α/β statistical subtraction



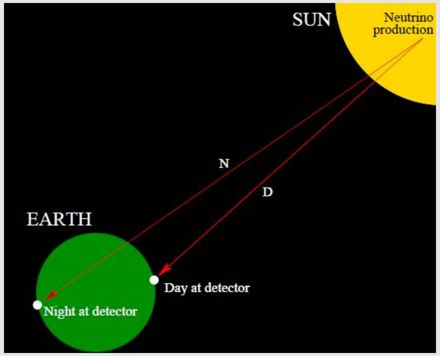
Resulting from a spectral fit of energy spectrum after selection cuts (Fiducial Volume, muon removal, shape Cuts)

862 keV Be7 neutrino flux result

$$46.0 \pm 1.5(\text{stat})^{+1.5}_{-1.6}(\text{syst})\ \text{counts}/(\text{day}\cdot 100\ \text{ton})$$

$$(3.10 \pm 0.15) \times 10^9\ \text{cm}^{-2}\text{s}^{-1}$$

Phys. Rev. Lett. **107**, 141302

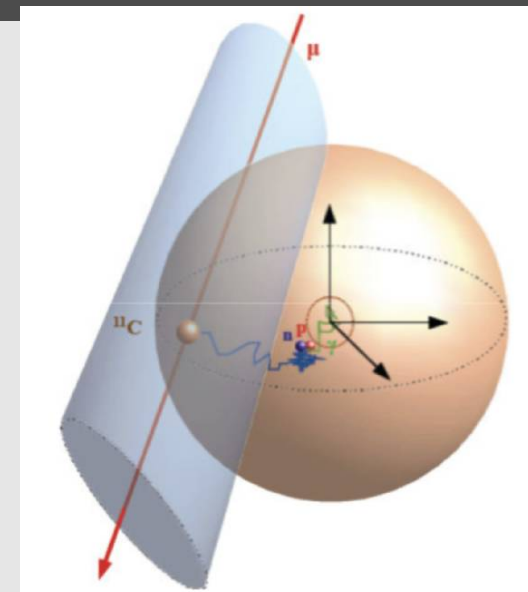


Absence of day- night asymmetry on Be7 flux

$$A_{dn} = 0.001 \pm 0.012\ (\text{stat}) \pm 0.007\ (\text{syst})$$

Physics Letters B 707 (2012) 22-26

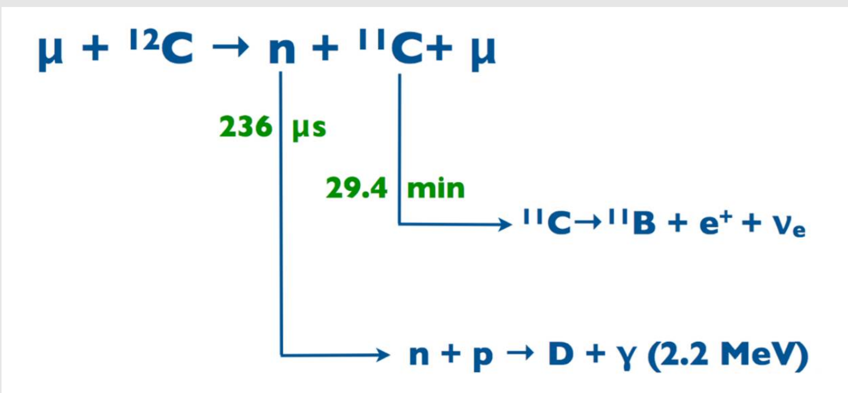
The first measurement of pep neutrinos and limit on the CNO neutrino flux

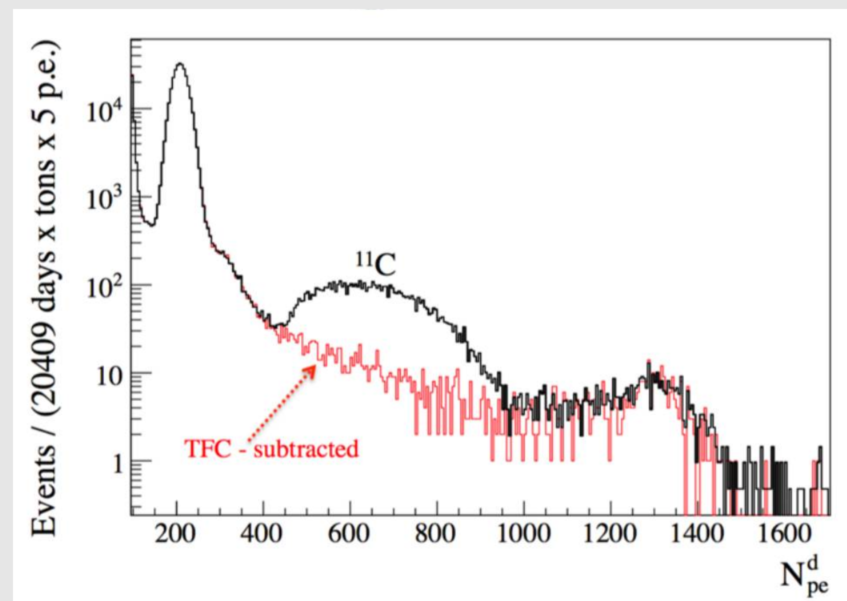


Key tools

- very low background in the FV

- suppression of cosmogenic ^{11}C (e^+) with τ = 29.4 min
  → Three fold coincidence: space-time veto removes 91% of ^{11}C payed with 48.5% loss of exposure
  ^{11}C rate: 27 → 2.5 cpd/100tons





- pulse shape analysis for β+/β- separation
  ^{11}C (e^+): positronium formation + annihilation

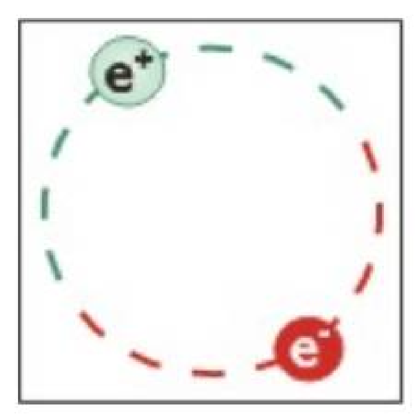
- radial analysis for disentangling external background

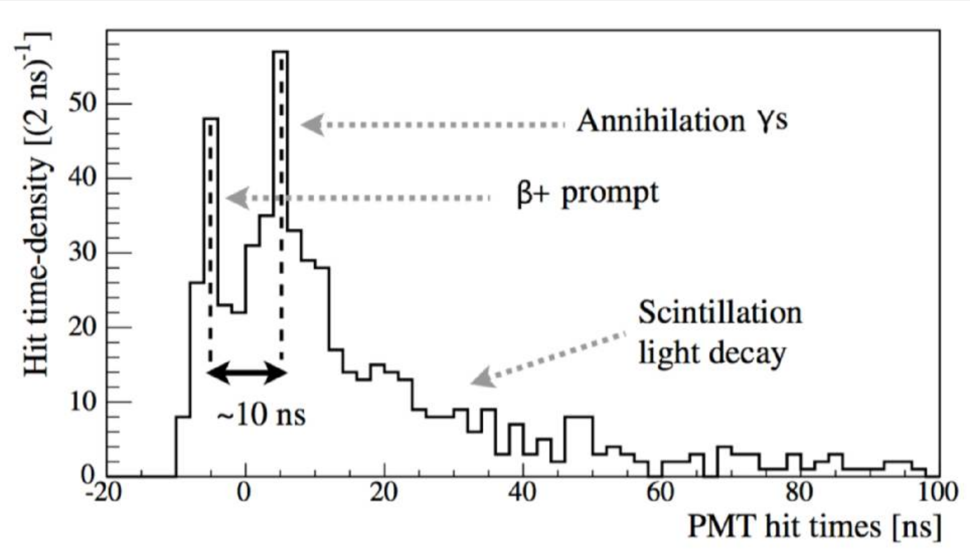
- multivariate fit procedure → simultaneous fit in 3 parameter space: energy spectra, pulse shape and radial distribution
  (sensitive to external background)

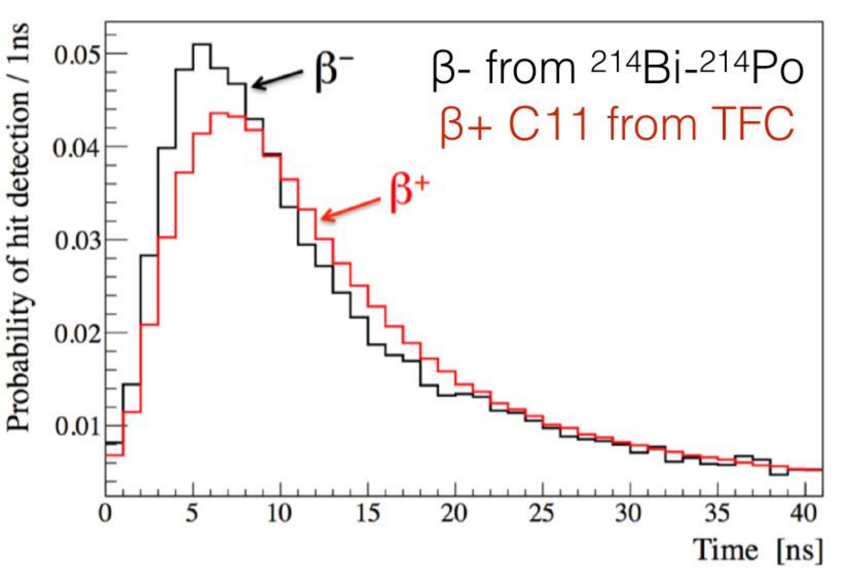
The first measurement of pep neutrinos: PSD

Pulse Shape Discrimination variables to discriminate $\beta^-\beta^+$ (^{11}C) events

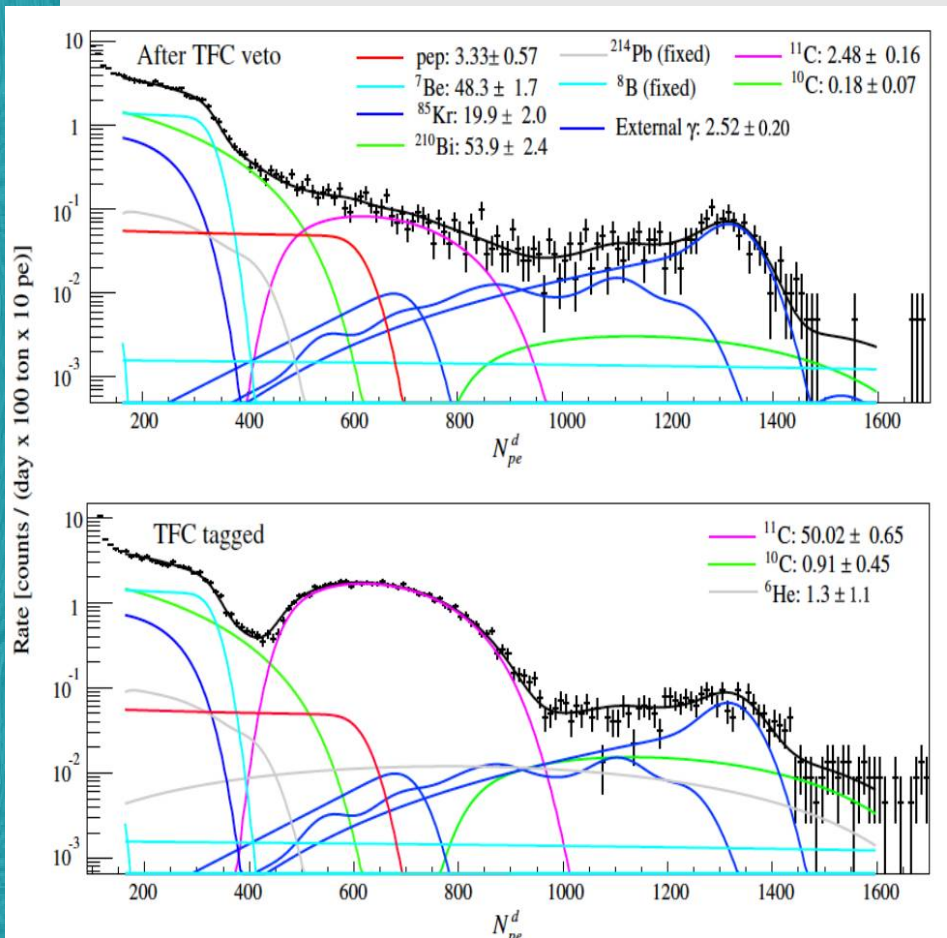
- e^+ can form ortho-positronium with ~50% probability and ~3ns lifetime in Borexino's scintillator
- this leads to the formation of different pulse shapes for electrons and positrons!
- Distribution of scintillation time signal for e+ delayed with rispect to e^-
  → different event topology
  → We use such difference to discriminate e^+/e^- events

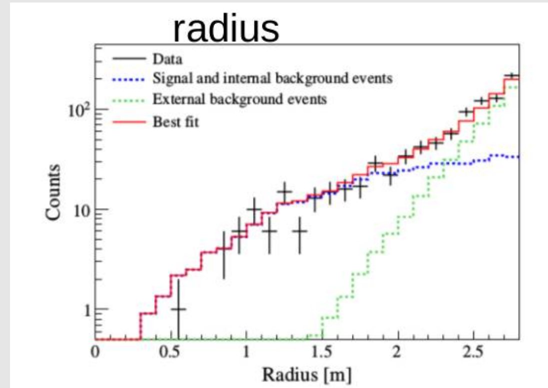


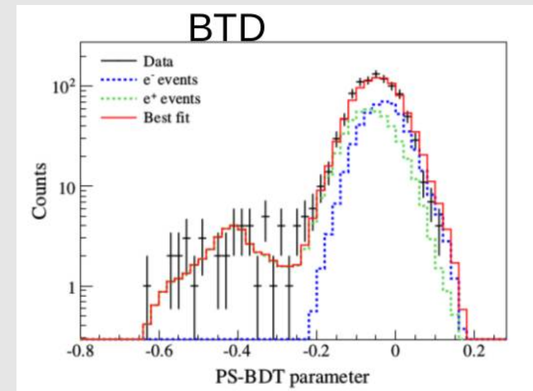




The first measurement of pep neutrinos and limit on CNO neutrinos







Multivariate Fit concept
- radial distribution
- beta +/- pulse shape
- TFC subtracted spectrum
- complementary spectrum

pep

$$(3.1 \pm 0.6_{\text{stat}} \pm 0.3_{\text{syst}}) \text{ counts/(day} \cdot 100 \text{ ton)}$$

$$(1.6 \pm 0.3) \times 10^{8} \text{ cm}^{-2}\text{s}^{-1}$$

Physical Review Letters 108, 051302 (2012)

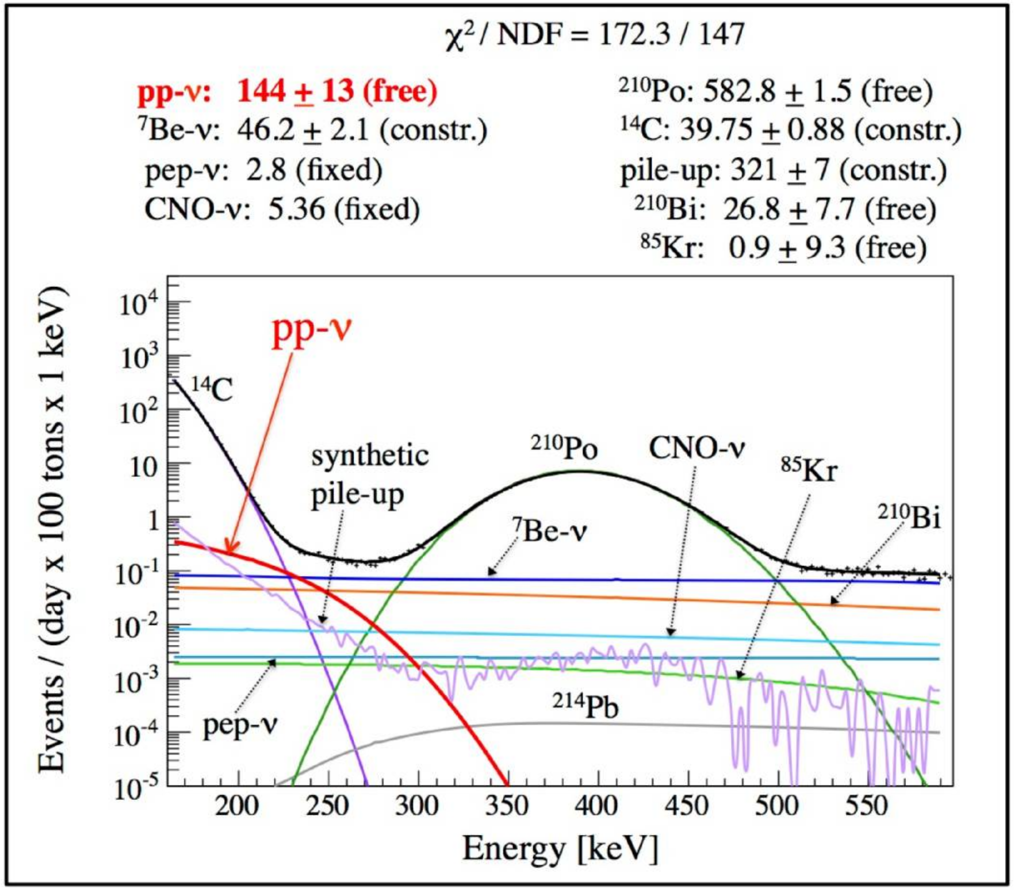
CNO

$$< 7.9 \text{ counts/(day} \cdot 100 \text{ ton)}$$

$$< 7.7 \times 10^{8} \text{ cm}^{-2}\text{s}^{-1} \text{ (95\% C.L.)}$$

Physical Review Letters 108, 051302 (2012)

The first real-time detection of pp-ν



144 ± 13 (stat.) ± 10 (syst.) c.p.d. per 100 t.

$$(6.6 \pm 0.7) \times 10^{10}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}.$$

Nature 512, 383-386 (28 August 2014)

The first direct observation of the low energy neutrinos coming from the "pp" fusion in the core of the Sun

- Fit of the energy distribution
- Selection criteria (maximize signal-to-noise):
  - removing residual backgrounds
  - remove electronic noise events
  - Fiducialization (~86 m^3)
- ^{14}C (156 keV): 2.7 x 10^{-18} of ^{12}C (~40 Bq)
  - Independent measure of ^{14}C
  - pile-up due to the high rate
  - pile-up modelling through the synthetic pile-up (^{14}C-^{14}C mostly)

^8B neutrinos

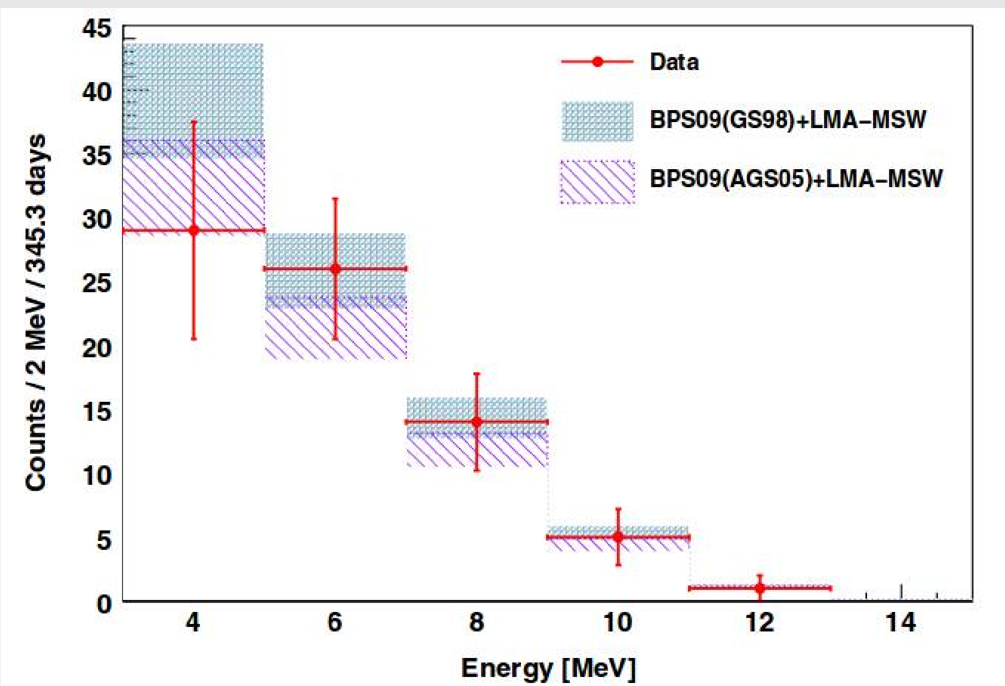
Borexino is small (compared to SK and SNO), but could measure ^8B neutrinos with an unprecedented low energy threshold (3MeV compared to 5MeV)

E > 3 MeV

0.22 ± 0.04(stat) ± 0.01(syst) cpd/100t

	Threshold [MeV]	$\Phi^{ES}_{^8B}$ [10^6 cm^{-2} s^{-1}]
SuperKamiokaNDE I	5.0	$2.35 \pm 0.02 \pm 0.08$
SuperKamiokaNDE II	7.0	$2.38 \pm 0.05^{+0.16}_{-0.15}$
SNO D_2O	5.0	$2.39^{+0.24}_{-0.23}{}^{+0.12}_{-0.12}$
SNO Salt Phase	5.5	$2.35 \pm 0.22 \pm 0.15$
SNO Prop. Counter	6.0	$1.77^{+0.24}_{-0.21}{}^{+0.09}_{-0.10}$
Borexino	3.0	$2.4 \pm 0.4 \pm 0.1$
Borexino	5.0	$2.7 \pm 0.4 \pm 0.2$

Phys.Rev.D82:033006,2010



Cut	Counts 3.0–16.3 MeV	Counts 5.0–16.3 MeV
All counts	1932181	1824858
Muon and neutron cuts	6552	2679
FV cut	1329	970
Cosmogenic cut	131	55
^{10}C removal	128	55
^{214}Bi removal	119	55
^{208}Tl subtraction	90 ± 13	55 ± 7
^{11}Be subtraction	79 ± 13	47 ± 8
Residual subtraction	75 ± 13	46 ± 8
Final sample	75 ± 13	46 ± 8
BPS09(GS98) ^8B ν	86 ± 10	43 ± 6
BPS09(AGS05) ^8B ν	73 ± 7	36 ± 4

Borexino history

PHASE 1 (2007-2010)

Solar neutrinos

- ^{7}**Be** υ: 1st observation + precise measurement
- Day/Night asimmetry
- **pep** υ: 1st observation
- ^{8}**B** υ
- **CNO** υ: best limit

- Geoneutrinos evidence > 4.5 σ

PHASE 2 (2012- end of 2016)

Improved radiopurity:
Internal radioactive backgrounds much lower than in Phase-I

- ^{85}Kr compatible with 0
- ^{210}Bi reduced (factor ~3)
- ^{232}Th and ^{238}U negligible

Solar neutrinos

- **pp** υ: first real time observation

Geoneutrinos

- 5.9 σ

Future plans

What Solar is going on now:

1) Better accuracy for the solar neutrinos (^{7}Be, pep, pp, ^{8}B)

2) Effort to measure CNO neutrinos

- ^{210}Bi independent constraint from the ^{210}Po decay
- Temperature stabilization for preventing ^{210}Po mixing→ thermal insulation
- further purification campaign

3) 3-4 months long calibration campaign ahead

4) SOX project:
short distance oscillations with Borexino

→ Search for sterile neutrinos with a strong ^{144}Ce-^{144}Pr antineutrino generator.