Recent Results from Borexino

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on behalf of the Borexino Collaboration

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Technische Universität München

The Borexino Collaboration

UNIVERSITÀ DEGLI STUDI DI MILANO

INFN

LNGS

PRINCETON UNIVERSITY

UNIVERSITÀ DEGLI STUDI DI GENOVA

NATIONAL RESEARCH CENTER "KURCHATOV INSTITUTE"

St. Petersburg Nuclear Physics Inst.

Technische Universität München

SKOBELTSYN INSTITUTE OF NUCLEAR PHYSISCS
LOMONOSOV MOSCOW STATE UNIVERSITY

Virginia Tech

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

UNIVERSITÀ DEGLI STUDI DI FERRARA

JÜLICH FORSCHUNGSZENTRUM

JINR Dubna

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

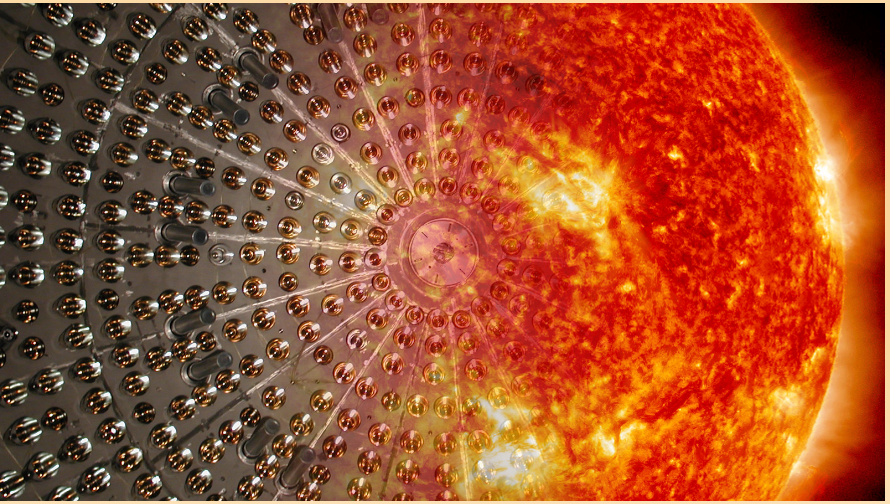
TECHNISCHE UNIVERSITÄT DRESDEN

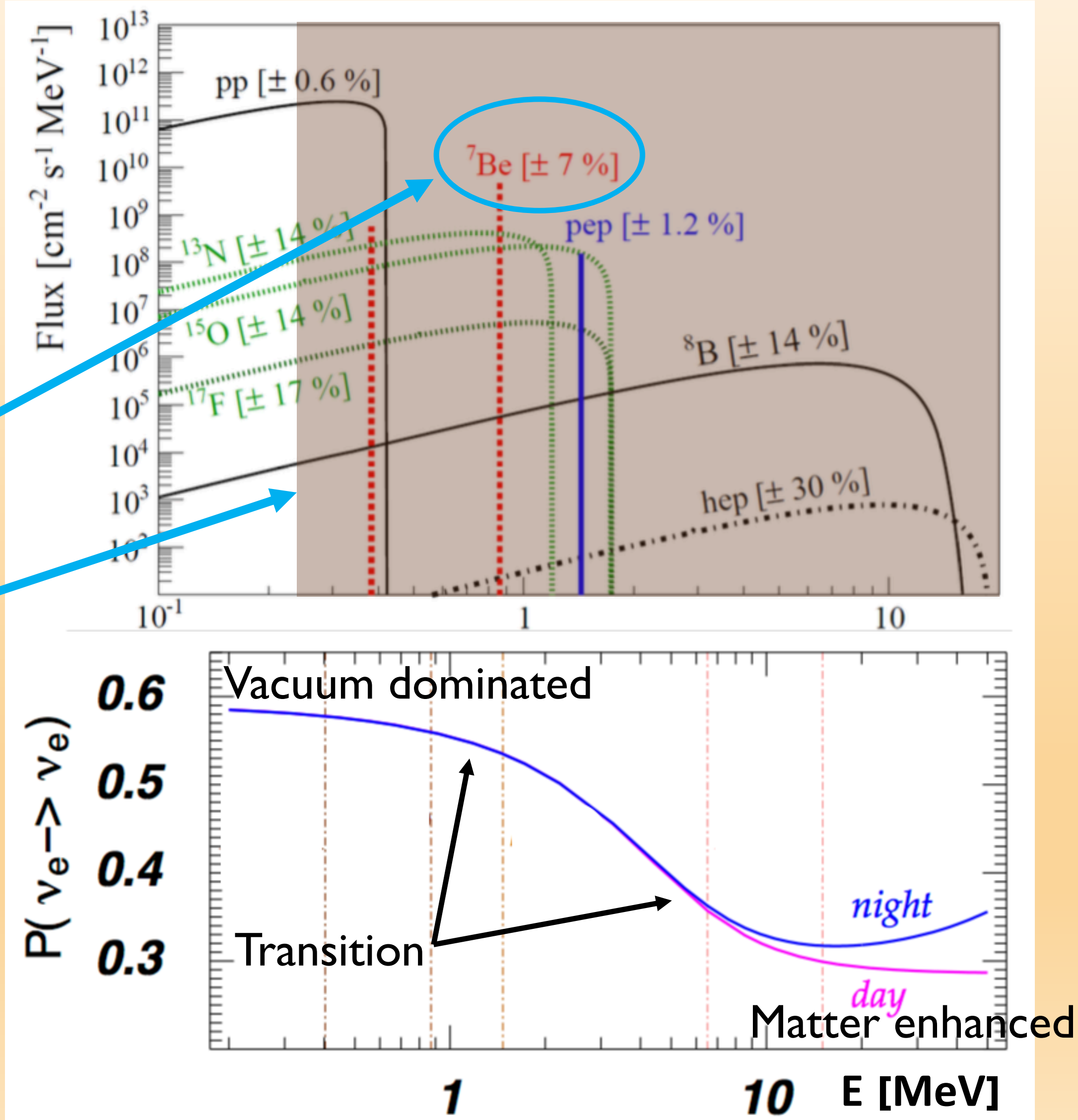
Why Borexino?

Neutrinos produced in solar fusion processes:
- Test solar modelling (ASTRO -)
- Study of neutrino oscillations (PARTICLE - PHYSICS)

Experiment design goal:
$^{7}\mathrm{Be}$-ν

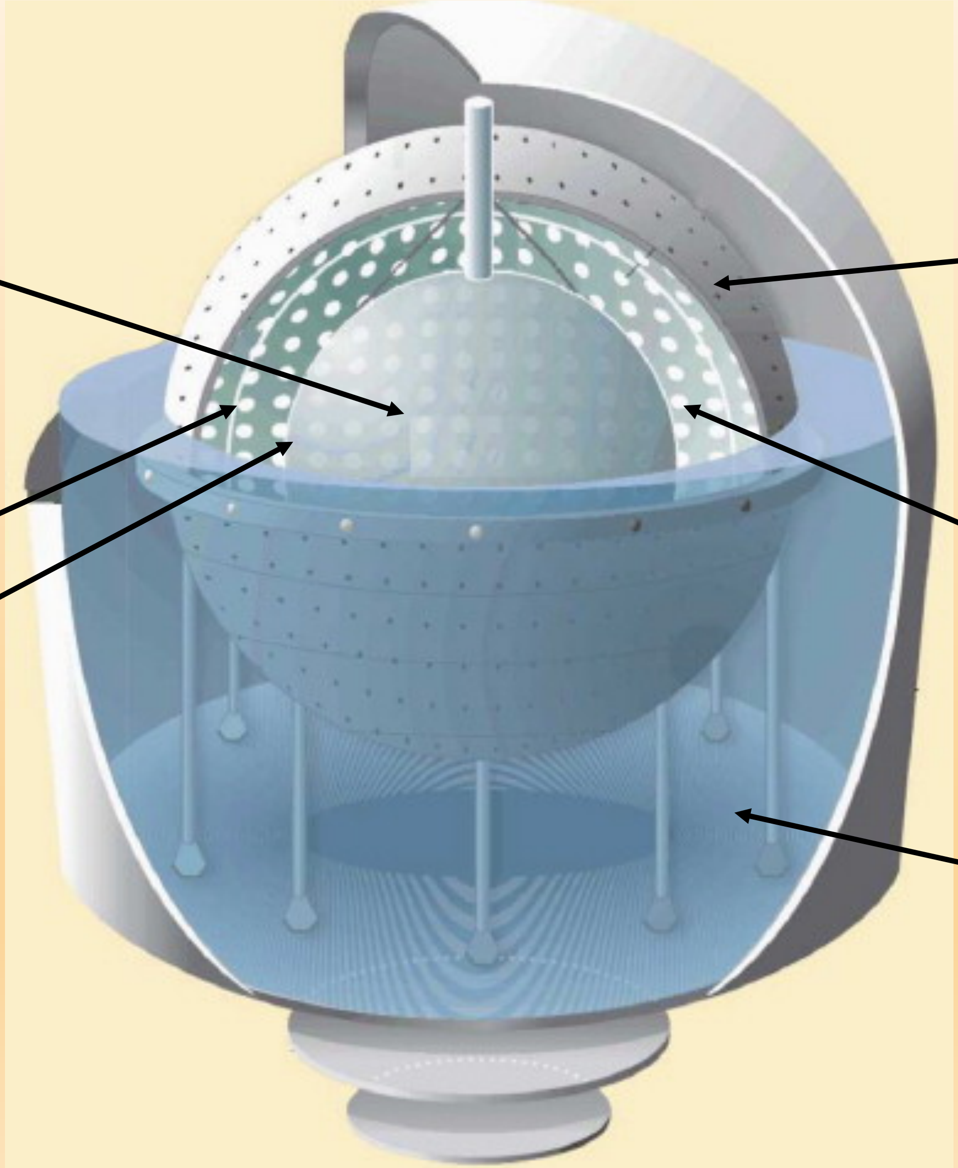
Design threshold:
~250 keV





The Borexino Detector

Located at LNGS



Scintillator Core:
270 t PC + PPO (1.5 g/l)

Nylon Vessels:
125 μm thick
Inner: 4.25 m radius
Outer: 5.50 m radius
(radon shield)

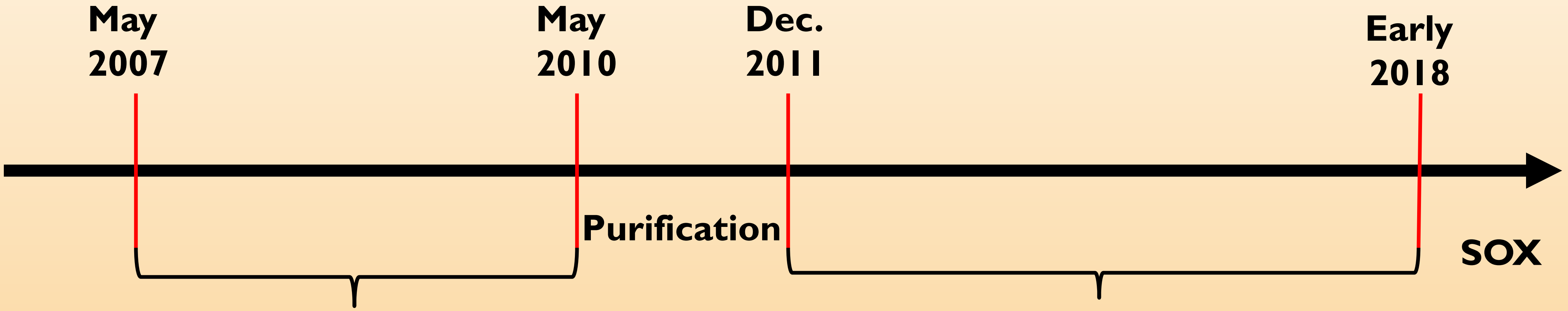
Detection reaction:
Neutrino – Electron scattering
$\nu + e^- \longrightarrow \nu + e^-$

Stainless Steel Sphere:
13.7 m diameter
2212 PMTs
34% optical coverage

Buffer Region:
~1000 t PC + DMP light quencher

Water Tank:
2.1 kt water
208 PMTs on floor and SSS
γ and fast neutron shield
μ veto detector

Borexino Time Line



Phase I:

First direct $^{7}\mathrm{Be}\ \nu$ measurement (2007)

$^{7}\mathrm{Be}\ \nu$ precision measurement (5%, 2011)

$^{8}\mathrm{B}\ \nu$ measurement above 3 MeV (2010)

First direct pep ν measurement (2012)

Strongest CNO limit (2012)

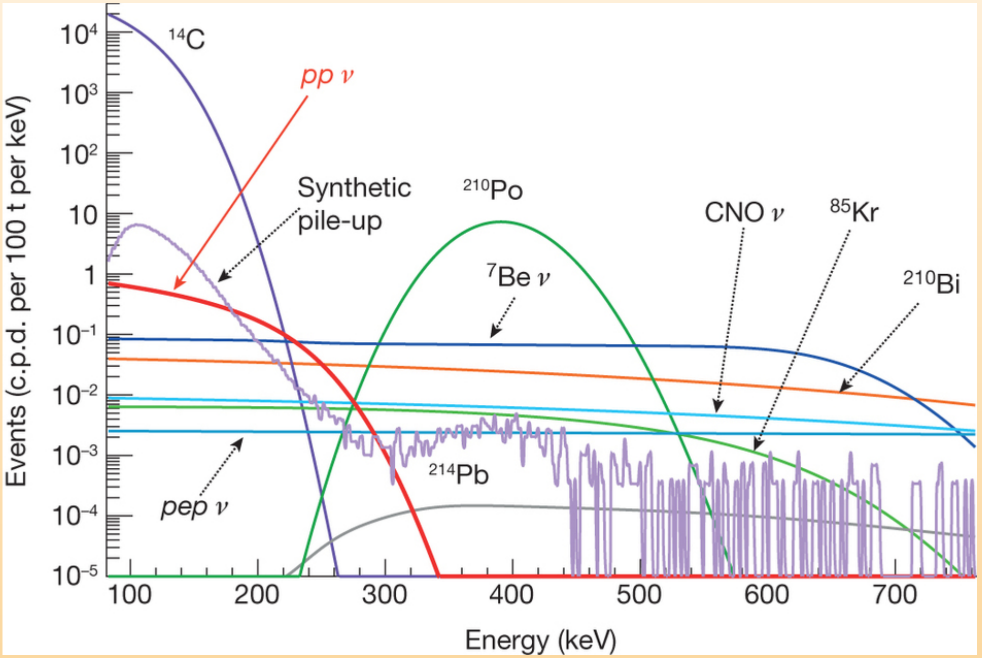
Geo ν observation (2010)

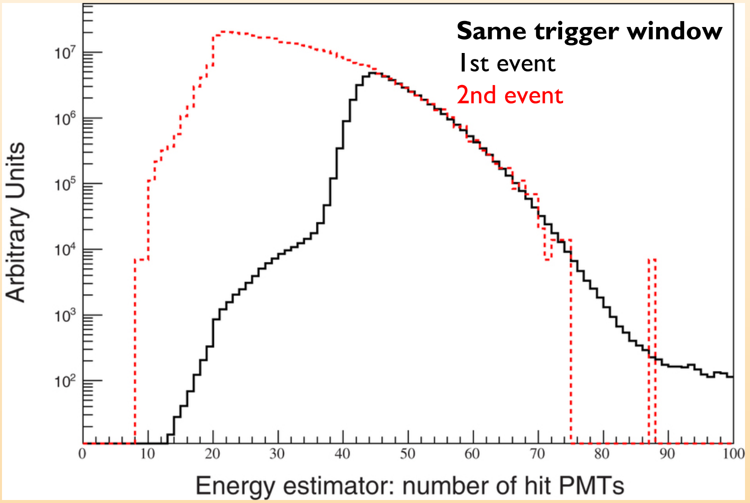
Phase II:

First direct pp ν measurement (2014)

Geo ν spectroscopy (2015)

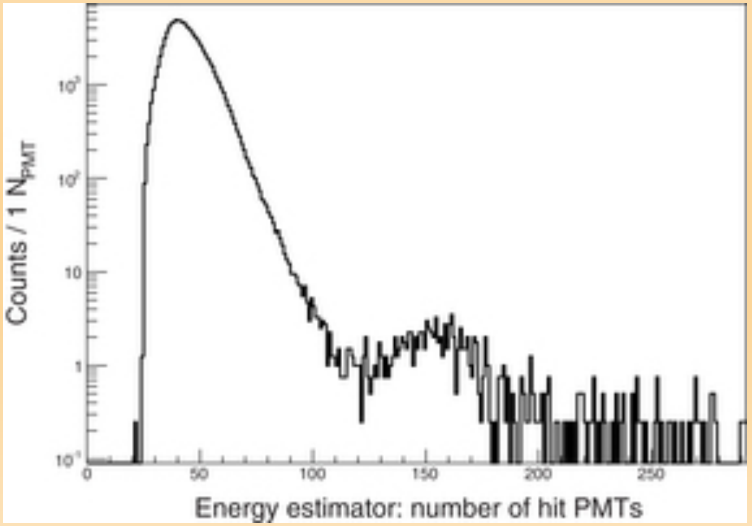
pp-ν Analysis





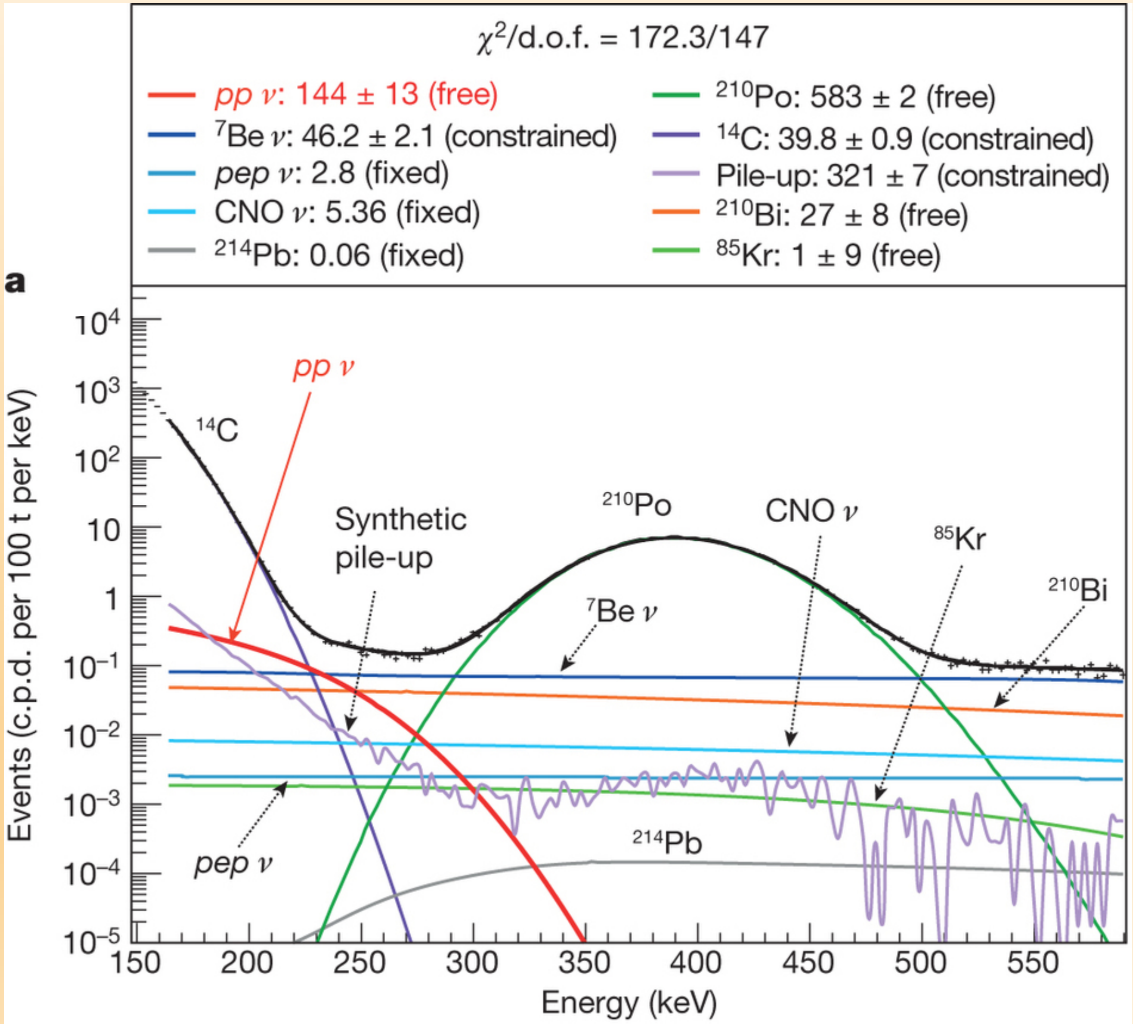
Independent constrain on $^{14}\mathrm{C}\ (40 \pm 1)$ Bq

Neutrino energy < 420 keV
Electron recoil energy < 264 keV
Analysis threshold: 165 keV
Radiochemical experiments: 233 keV threshold



Synthetic pile-up:
$^{14}\mathrm{C}+^{14}\mathrm{C}$, $^{14}\mathrm{C}+^{210}\mathrm{Po}$ ...

pp-ν Results

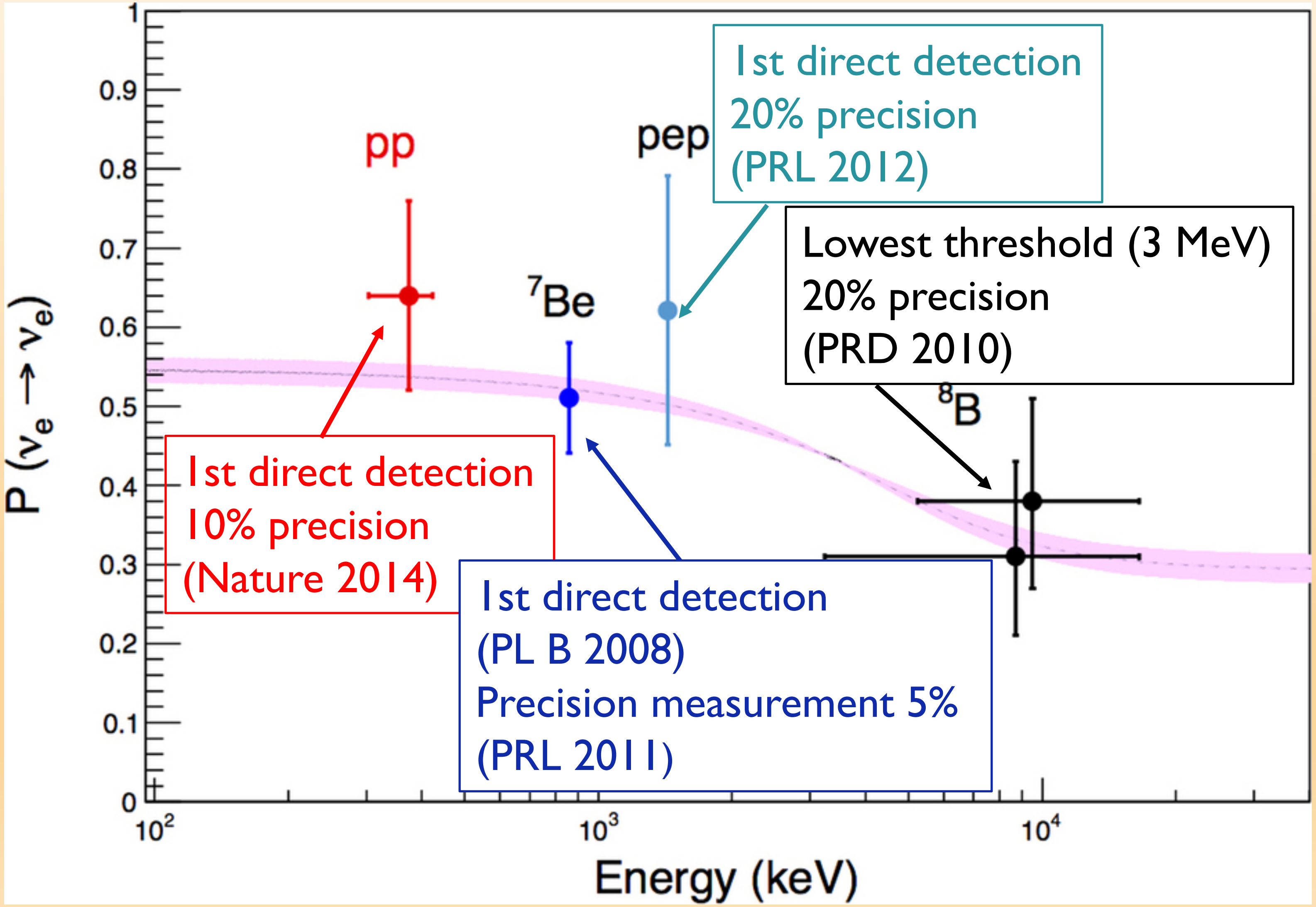


Measurement: 144 ± 13 cpd / 100 t
Expected: 131 ± 2 cpd / 100 t
Null hypothesis rejected at 10 σ

Measured Flux: $\Phi_{\text{pp}} = (6.6 \pm 0.7) \cdot 10^{10}\text{cm}^{-2}\text{s}^{-1}$

⟶ Confirms LMA-MSW
⟶ Confirms SSM – compatible with low & high metallicity
⟶ Future Borexino inspired experiments to reach uncertainty level
⟶ Confirms Sun‘s stability over 10^5 years

Borexino pp-Chain Neutrino Results



Solar Neutrino Results

Species	Rate [cpd / 100 t]	Flux $[\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	Reference
pp	$144 \pm 13 \pm 10$	$(6.6 \pm 0.7) \cdot 10^{10}$	Nature512(2014)7515
$^{7}\mathrm{Be}$	$46.0 \pm 1.5^{+1.5}_{-1.6}$	$(4.48 \pm 0.24) \cdot 10^{9}$	PRL107(2011)141302
pep	$3.1 \pm 0.6 \pm 0.3$	$(1.6 \pm 0.3) \cdot 10^{8}$	PRL108(2012)051302
$^{8}\mathrm{B}$	$0.22 \pm 0.04 \pm 0.01$	$(2.4 \pm 0.4 \pm 0.1) \cdot 10^{6}$	PRD82(2010)033006
CNO	< 7.9 (95% C.L.)	$< 7.7 \cdot 10^{8}$ (95% C.L)	PRL108(2012)051302

$^{7}\mathrm{Be}$:

1. Absence of day-night assymetry
2. Yearly modulation

Geo-neutrinos

Cosmogenic backgrounds:

1. Seasonal modulation of muon flux
2. Detailed studies of neutrons and cosmogenics

Rare processes: Best limit on e^{-} decay (2015)

Geo Neutrinos

Anti-neutrinos produced in radioactive decays in Earth‘s crust and mantle

Decay	Half life $[10^9 \mathrm{yr}]$	Maximum ν Energy [MeV]
$^{238}\mathrm{U} \rightarrow {}^{206}\mathrm{Pb}$+8 $^{4}\mathrm{He} + 6\mathrm{e} + 6\,\bar{\nu}_\mathrm{e}$	4,47	3.26
$^{232}\mathrm{Th} \rightarrow {}^{208}\mathrm{Pb}$+8 $^{4}\mathrm{He} + 6\mathrm{e} + 6\,\bar{\nu}_\mathrm{e}$	14.0	2.25
$^{40}\mathrm{K} \rightarrow {}^{40}\mathrm{Ca}$+e $+\ \bar{\nu}_\mathrm{e}$ (89%)	1.28	1.311

Detection via Inverse Beta Decay:

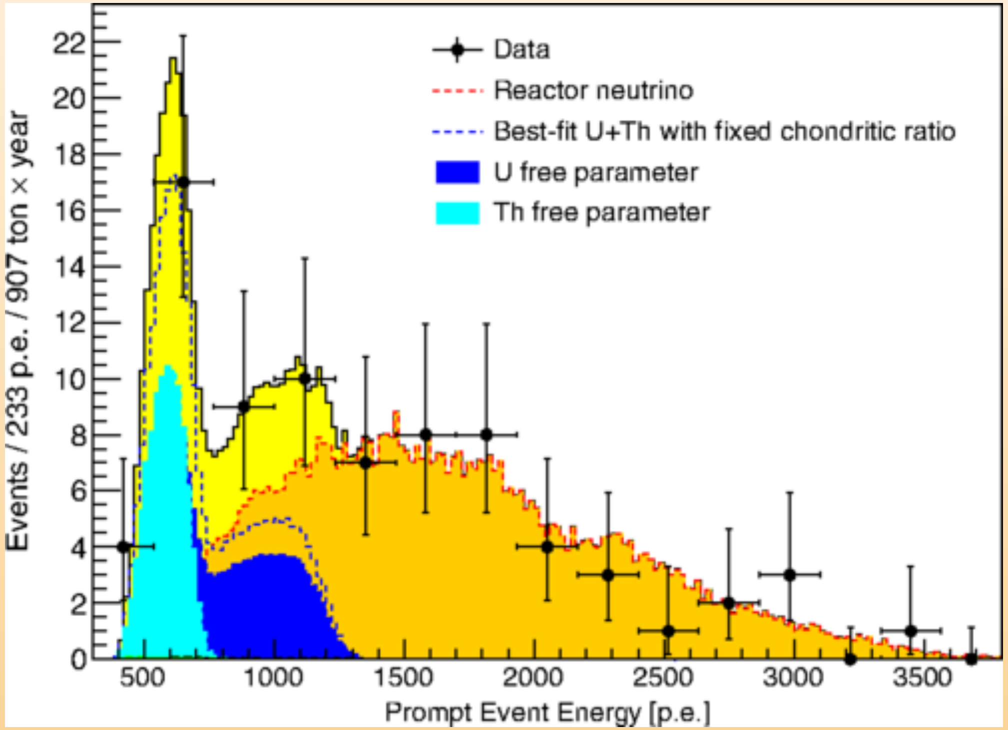
$$\bar{\nu}_\mathrm{e} + \mathrm{p} \rightarrow \mathrm{n} + \mathrm{e}^+ \left(\rightarrow 2\gamma\ (511\ \mathrm{keV\ each})\right)$$
$$\mathrm{n} + \mathrm{H} \rightarrow \mathrm{D} + \gamma\ (2.2\ \mathrm{MeV})$$

Signature: Prompt signal: e^+ annihilation
Delayed siganl: 2.2 MeV γ
Neutron capture time: ~250 μs

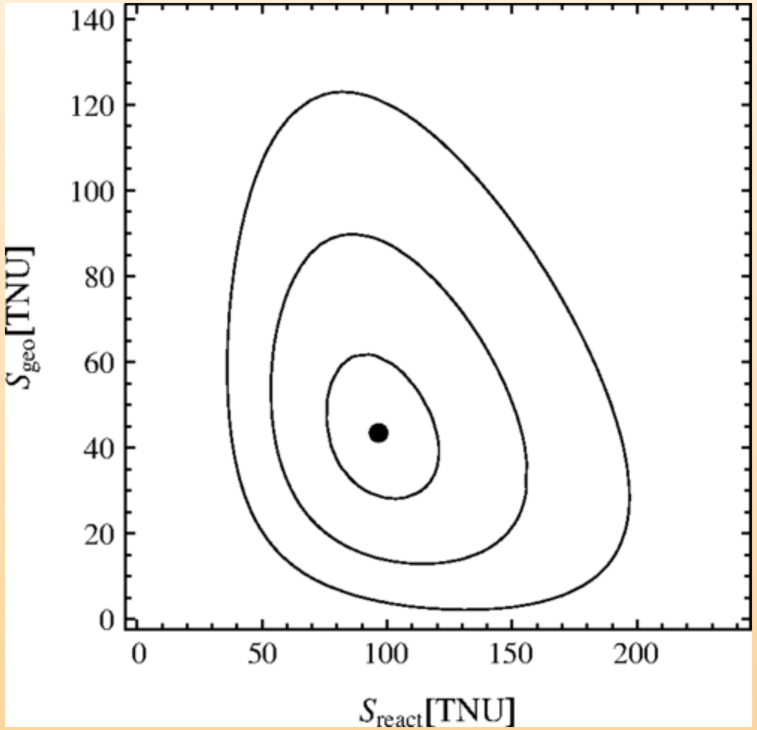
Detection Threshold: 1.8 MeV
$\longrightarrow$ K not visible
Th/U ratio 3.9 as from chondritic model

Distribution of long-lived radioisotopes & radiogenic heat contribution to total balance
Understand: Magnetic field, mantle convection, plate tectonics...

Geo Neutrinos: Results



Exposure: $(907 \pm 44)\ \mathrm{t \cdot yr}$
77 coincidences found
Background not caused by reactors: ~ 0.8 events



	Events	Flux [TNU]	Expected [TNU]
Reactor	$52.7^{+9.2}_{-9.3}$	$96.6^{+20.5}_{-19.2}$	(87 ± 4) (after oscillations)
Geo	$23.7^{+7.4}_{-6.3}$	$43.5^{+14.5}_{-12.8}$	Model dependent

(1 **T**errestrial **N**eutrino **U**nit = 1ev/yr/10^{32}protons)

1,2,3 σ contours
Null hypothesis rejected at 5.9 σ

Geo Neutrinos: Implications

$$S_{EXPECTED} = S_{LOCAL\ CRUST} + S_{REST\ OF\ CRUST} + S_{MANTLE}$$

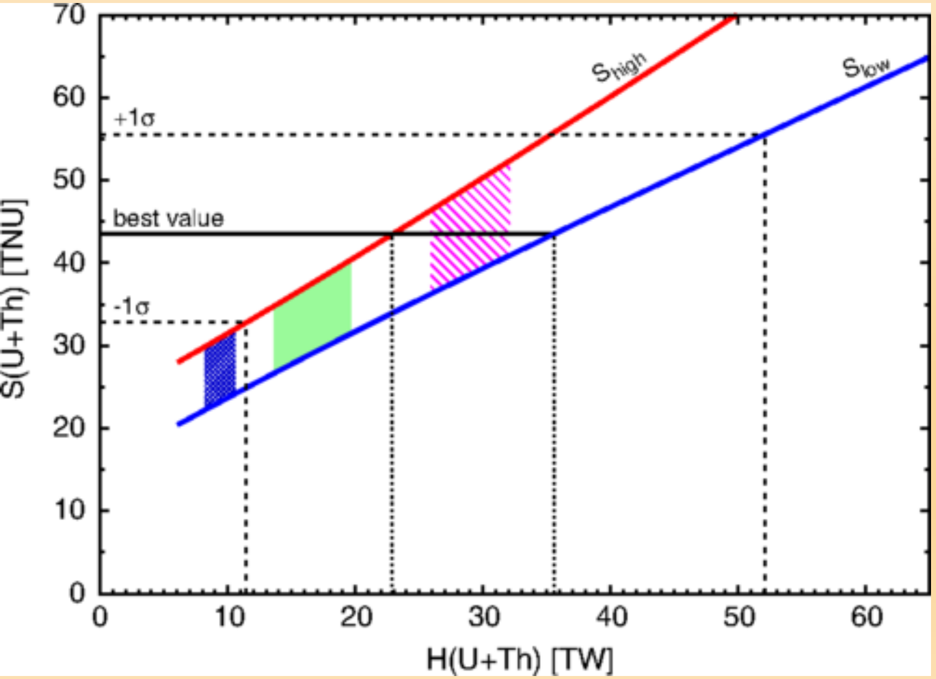
43.5 ± 11.1
(Measurement)

9.7 ± 1.3
(geological, -physical, -chemical study)

13.7 ± 2.5
(Model)

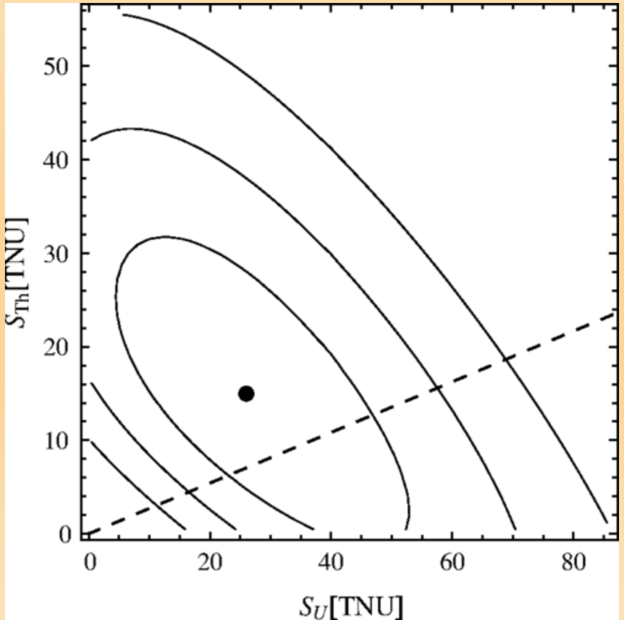
$\mathbf{20.9^{+15.1}_{-10.3}}$
(likelihood)

No mantle contribution excluded at 98% C.L.



Consistent with different BSE models

Possibility to dissentangle Th and U contributions & probe different models



Borexino Phase II: Goals & Prospects

^{7}Be flux: Uncertainty ~3% & seasonal modulation
pep flux: Evidence >3σ
^{8}B flux: Reduced threshold and uncertainty
pp flux: Possible update
Geo-neutrinos: Update
CNO flux: Improved limit & possibly first detection
→Probe solar metallicity

Model	CNO neutrino flux $[10^8 \mathrm{cm}^{-2}\mathrm{s}^{-1}]$	Expected count rate in Borexino [cpd / 100 t]
Low Z SSM	3.76 ± 0.60	~3.7
High Z SSM	5.24 ± 0.84	~5.3
Δ	28%	

Conclusions

- Almost full solar neutrino spectroscopy
- Leading limit on CNO neutrino flux
- Geo neutrino observation at 5.9 σ
- Made possible by unprecedentedly high radio-purity

Phase II: ~4.5 yr accumulated data + ~1.5 yr until start of SOX
6 yr of high quality data

- Phase II priority: Improved limit on CNO or measurement
- Huge effort made to control temperature & prevent convective motions
- Update of other solar neutrino fluxes & geo neutrinos

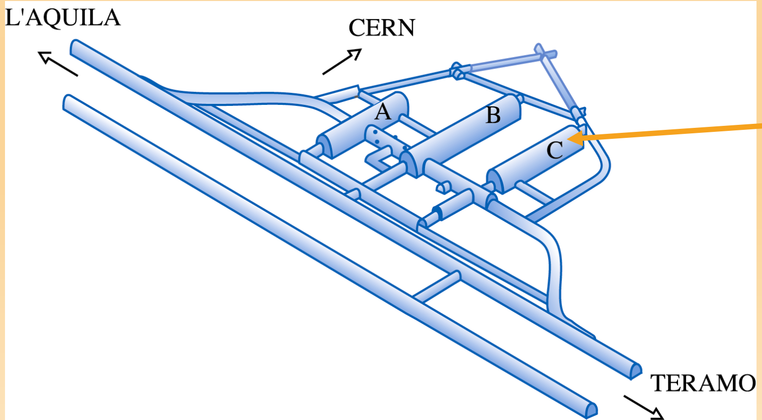
Additional Material

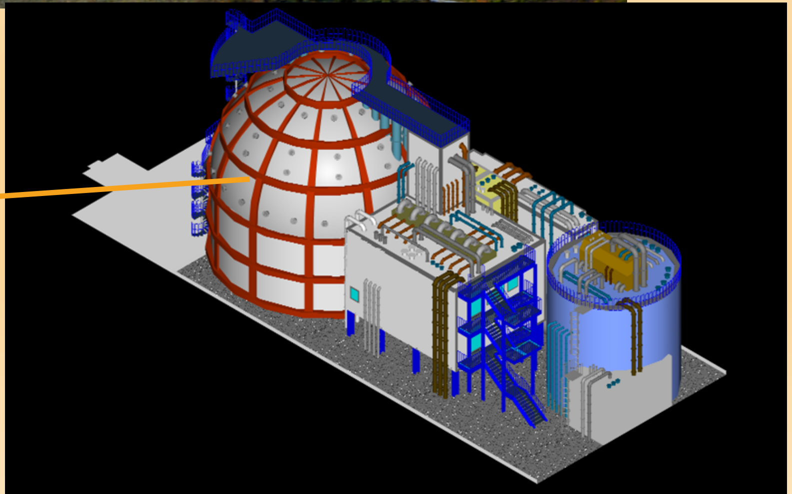
Thank you for your attention

Experimental Side

Laboratori **N**azionali del **G**ran **S**asso

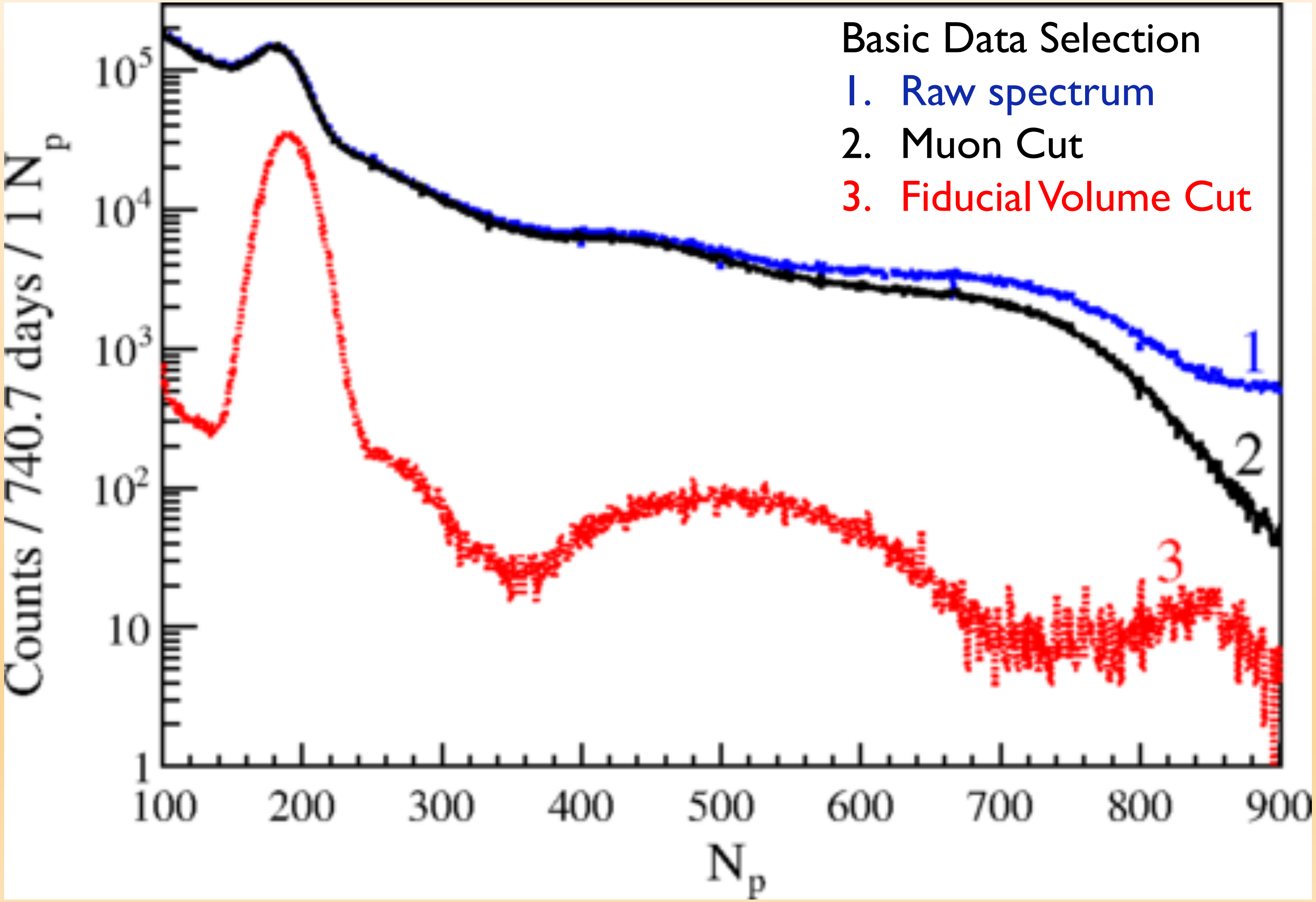
Underground labs accessible via highway tunnel





Located straight under Monte L'Aquila
Shielded by 3800 m.w.e.
Reduced μ flux by ~10^6

Borexino Energy Spectrum



Borexino Backgrounds

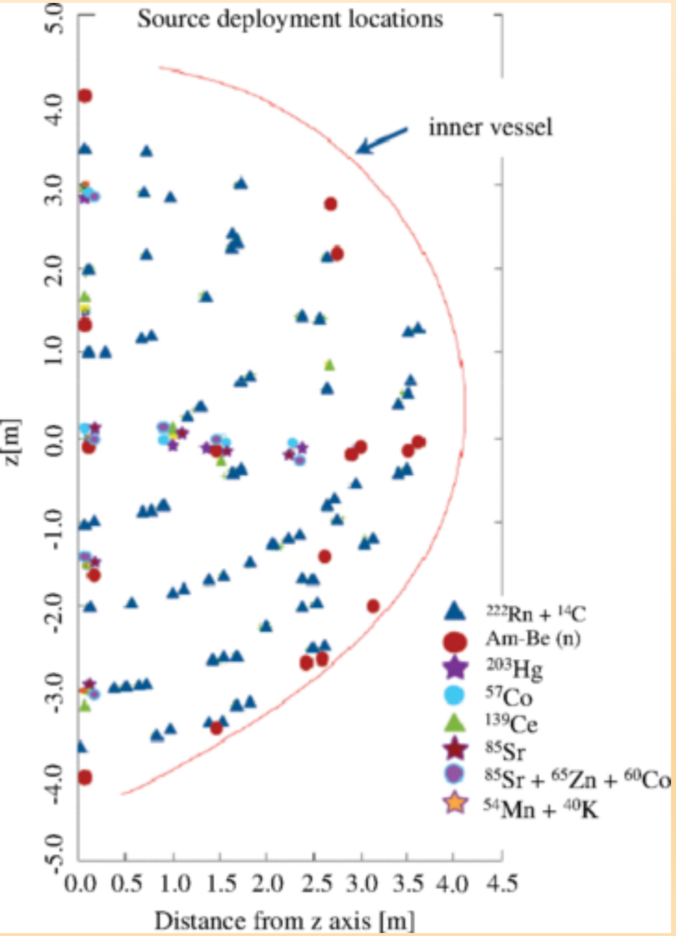
Borexino's inner scintillator core is the radio-cleanest spot on Earth!

Isotope	Before Purification	After Purification
$^{14}C/^{12}C$	$(2.69 \pm 0.06) \cdot 10^{-18}$	unchanged
^{85}Kr	(30 ± 5) cpd/100 t	$\leq$ 5 cpd/100 t
^{210}Po	~500 cpd/100 t	unchanged
^{210}Bi	~40cpd/100 t	~20 cpd/100 t

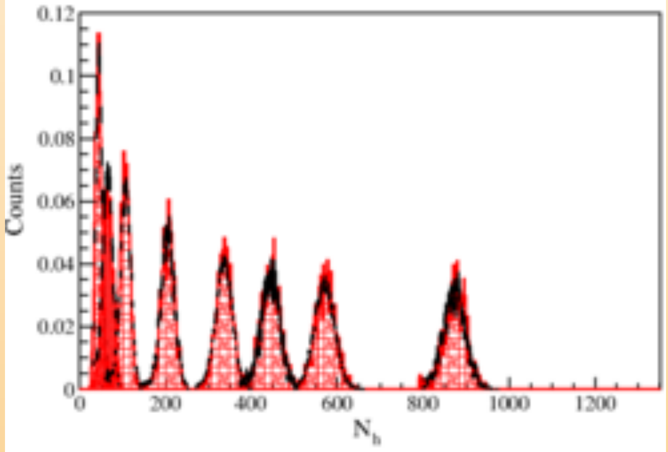
^{40}K, ^{39}Ar below detection limit
^{238}U, $^{232}Th < 10^{-18}$ g/g (unprecedented)
^{222}Rn ~1 cpd/100 t

Borexino Calibration Campaigns

2008 – 2011: 3 internal and 2 external calibration campaigns



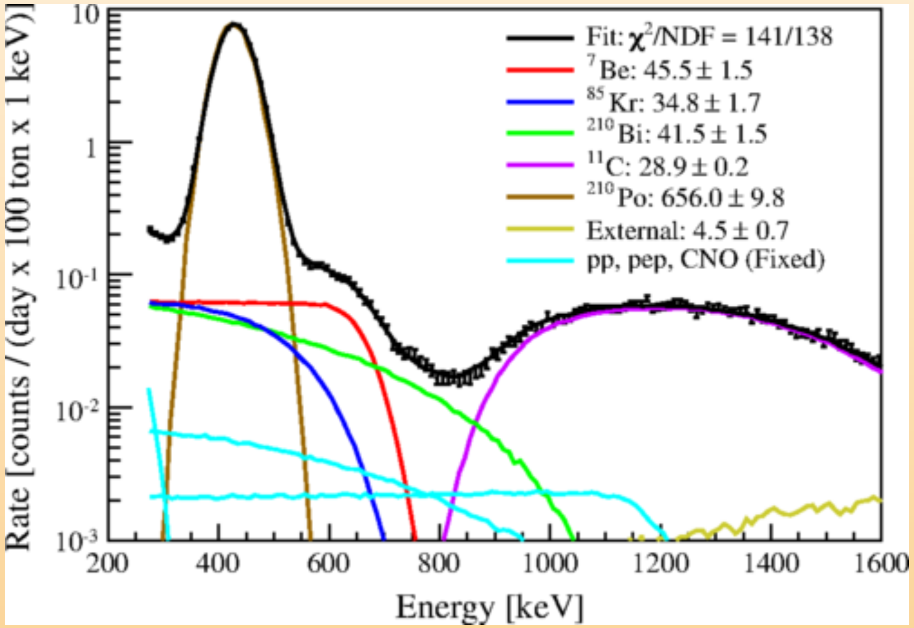
Energy calibration:
MC tuned with several γ sources
Resolution ~ **5%/$\sqrt{E}$ [MeV]**



Position Reconstruction:
Rn source in 182 positions
Fiducial volume **uncertainty 2%** (pp-analysis)

Calibration shall be repeated before end of Phase II (2017)

Cosmogenic ^{11}C Reduction – Three Fold Coincidence



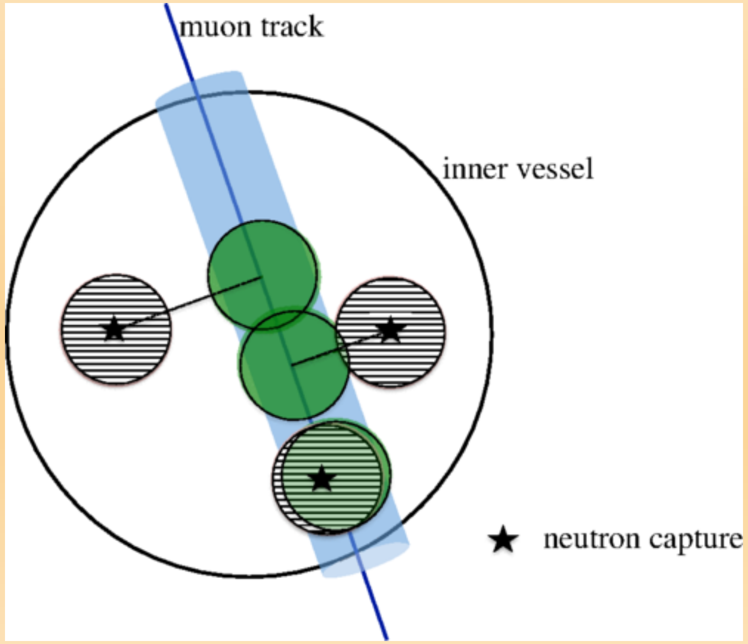
$$\mu + {}^{12}C \rightarrow \mu + {}^{11}C + n$$

$\tau = 29.4$ min

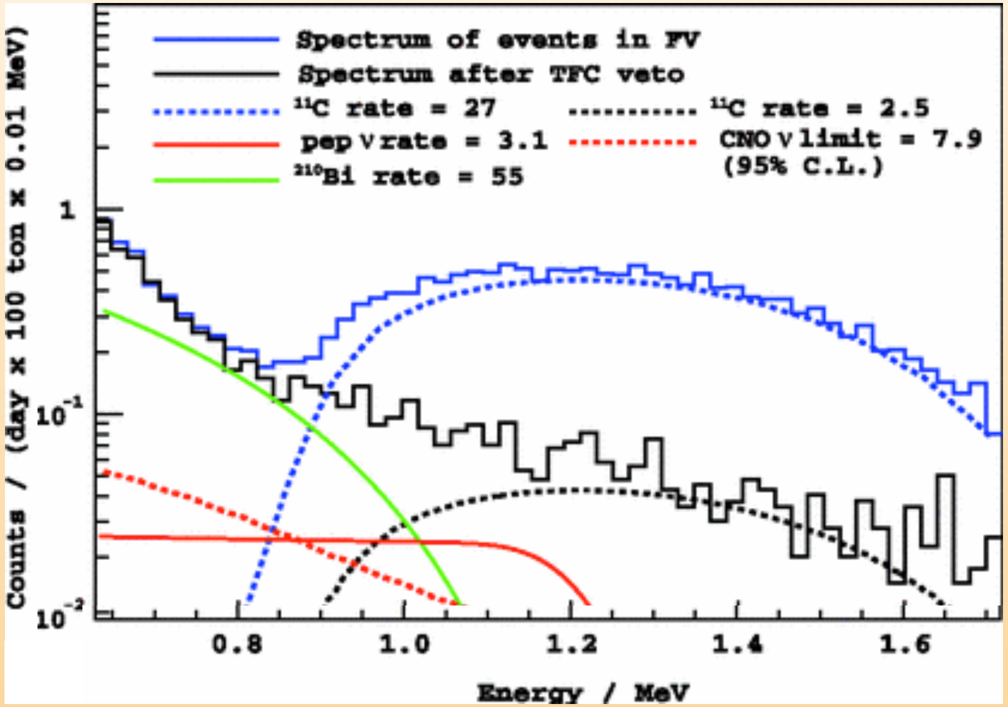
$\sim 250\ \mu s$

$$n + p \rightarrow D + \gamma(2.2\ MeV)$$

$${}^{11}C \rightarrow {}^{11}B + e^+ + \nu_e$$



Cosmogenic ^{11}C Reduction – Three Fold Coincidence



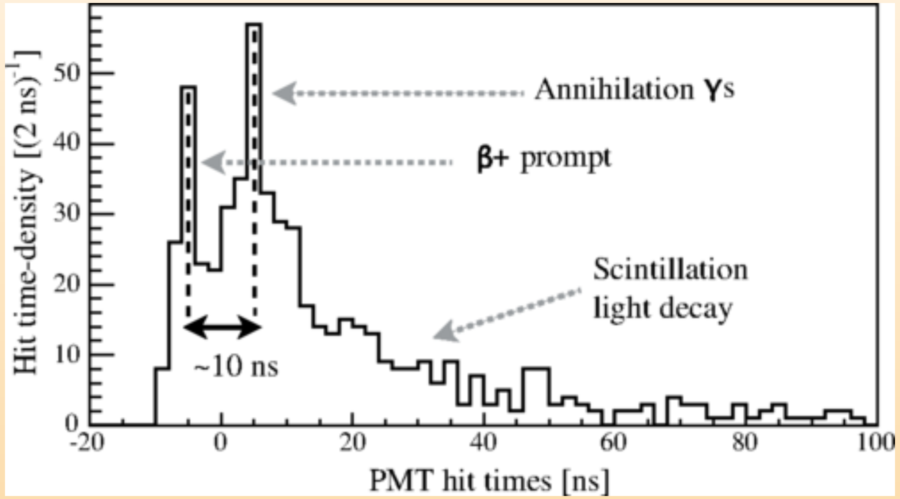
Already applied in Phase I pep neutrino analysis (2012): 90% ^{11}C reduction at ~50% surviving exposure

Phase II goal: Same or better ^{11}C reduction at ~65% surviving exposure

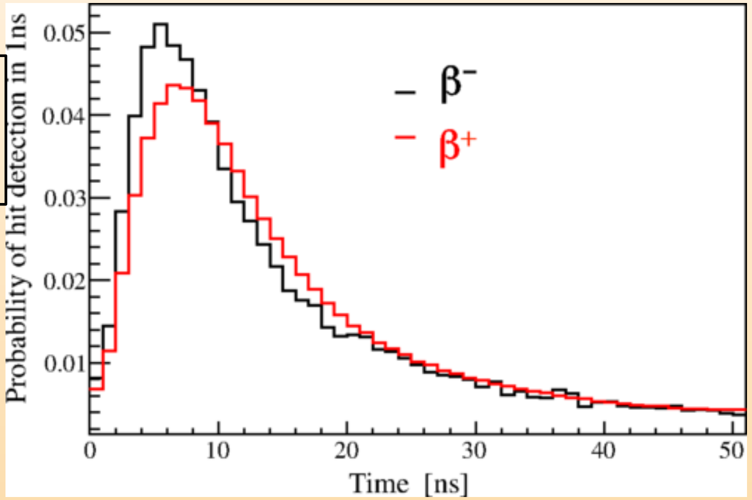
→Improved algorithms

→Stable and continouus DAQ (duty cycle >95%)

Pulse Shape Discrimination (e^+/e^-)

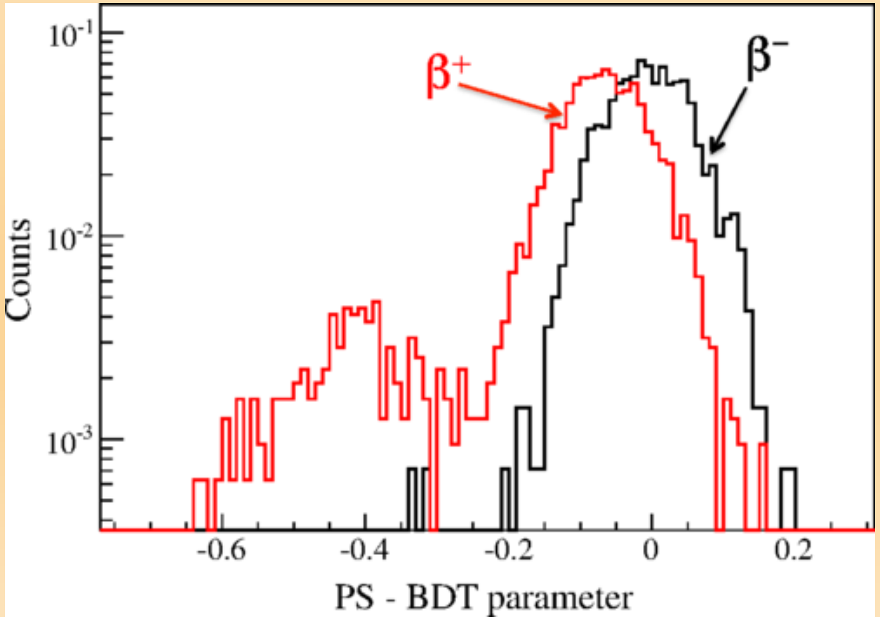


Difference in pulse shape of e^+ & e^-

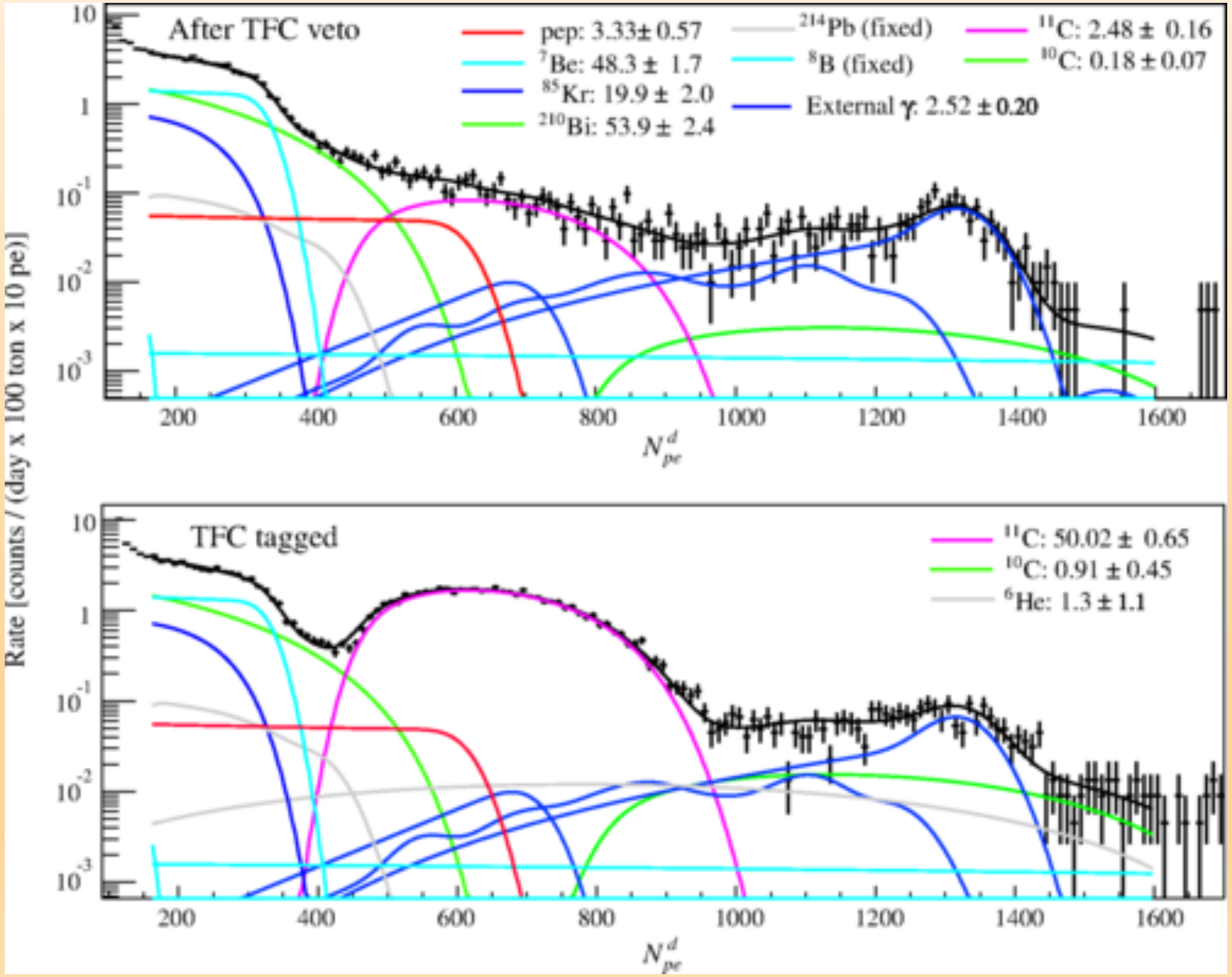


Delayed e^+annihilation signal through formation of ortho-positronium

Definition of **B**oosted **D**ecision **T**ree parameter to discriminate between e^+ & e^-



Fit Strategy

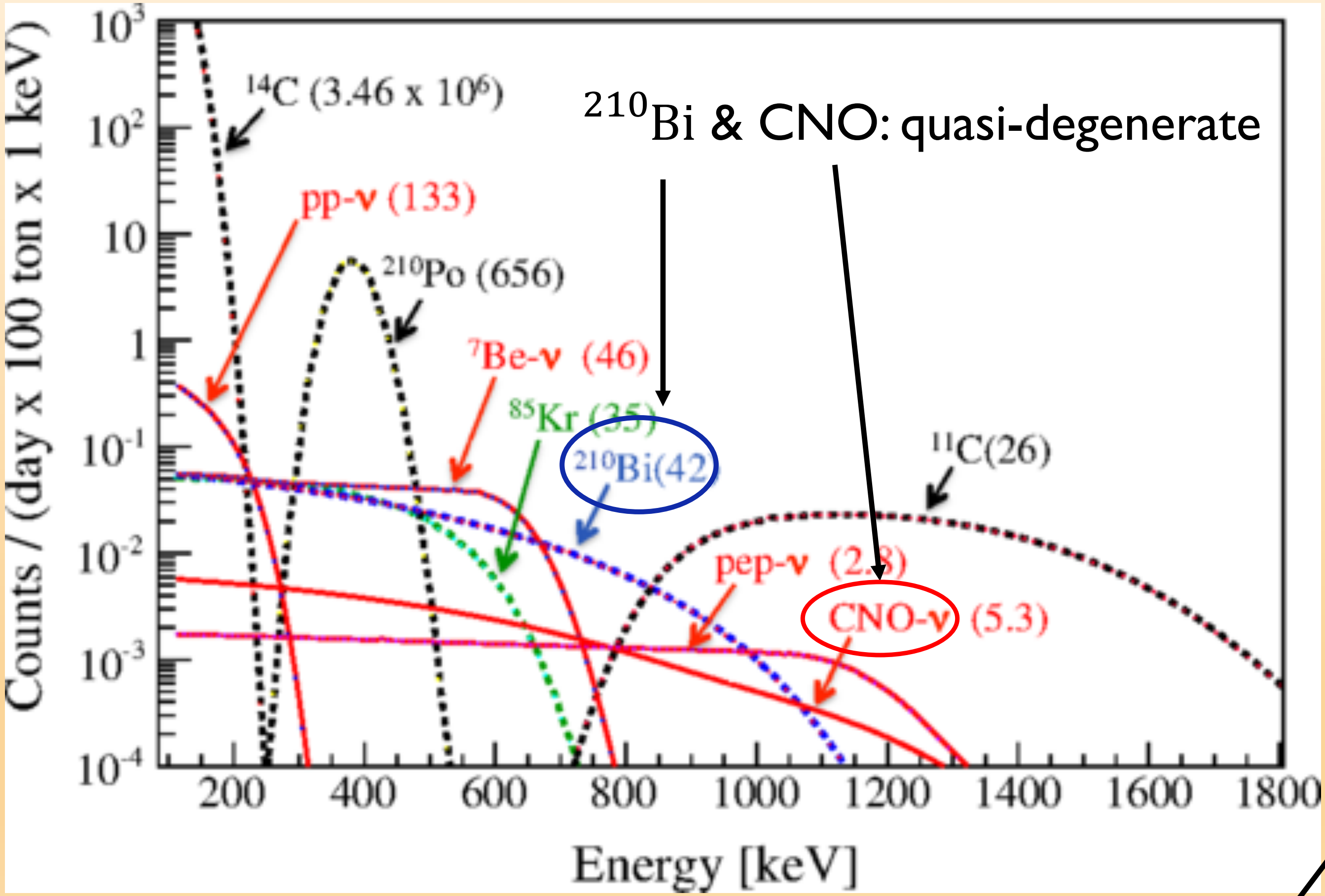


Multivariate maximum-likelihood fit:

1. TFC-subtracted energy spectrum
2. TFC-enhanced energy spectrum (complementary)
3. Radial event distribution
4. PS-BDT parameter (e^+/e^-)

Aiming to fit all components simultaneously:
(pp+ ^{7}Be+pep/CNO)

CNO & ^{210}Bi



^{210}Pb

β^- $T_{1/2} = 22.3$ yr, $E = 0.06$ MeV, $BR = 81\%$

^{210}Bi

β^- $T_{1/2} = 5.0$ d, $E = 1.2$ MeV

^{210}Po

α $T_{1/2} = 138.4$ d, $E = 5.3$ MeV

Clear α peak

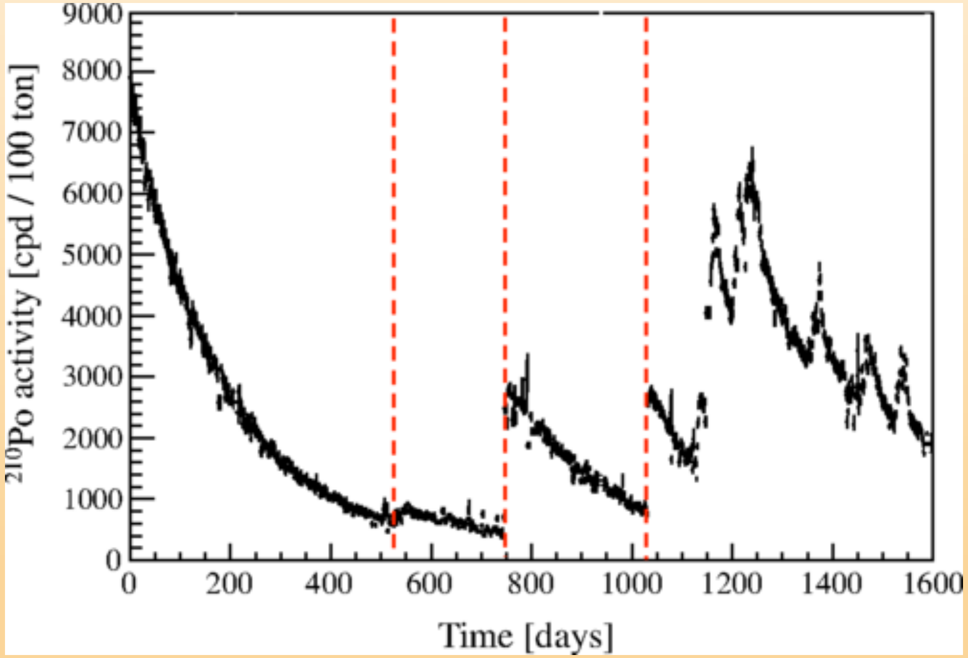
^{206}Pb

stable

Constrain ^{210}Bi from its daughter in secular equilibrium ^{210}Po

At least 10% precision
→Stability needed!

^{210}Po - Instabilities



Detector operations induce ^{210}Po contaminations
→No operations during Phase II data taking

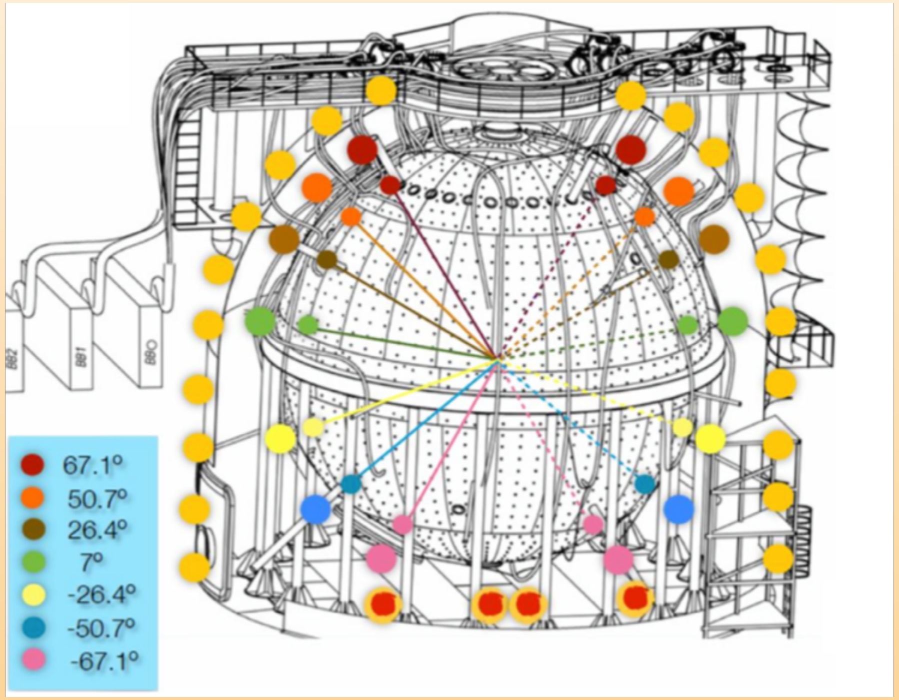
Equilibrium still broken:
Temperature changes induce ^{210}Po fluctuations
→Possibly due to convective currents

Complete fluidodynamic simulation of currents ongoing

Controlling the Temperature

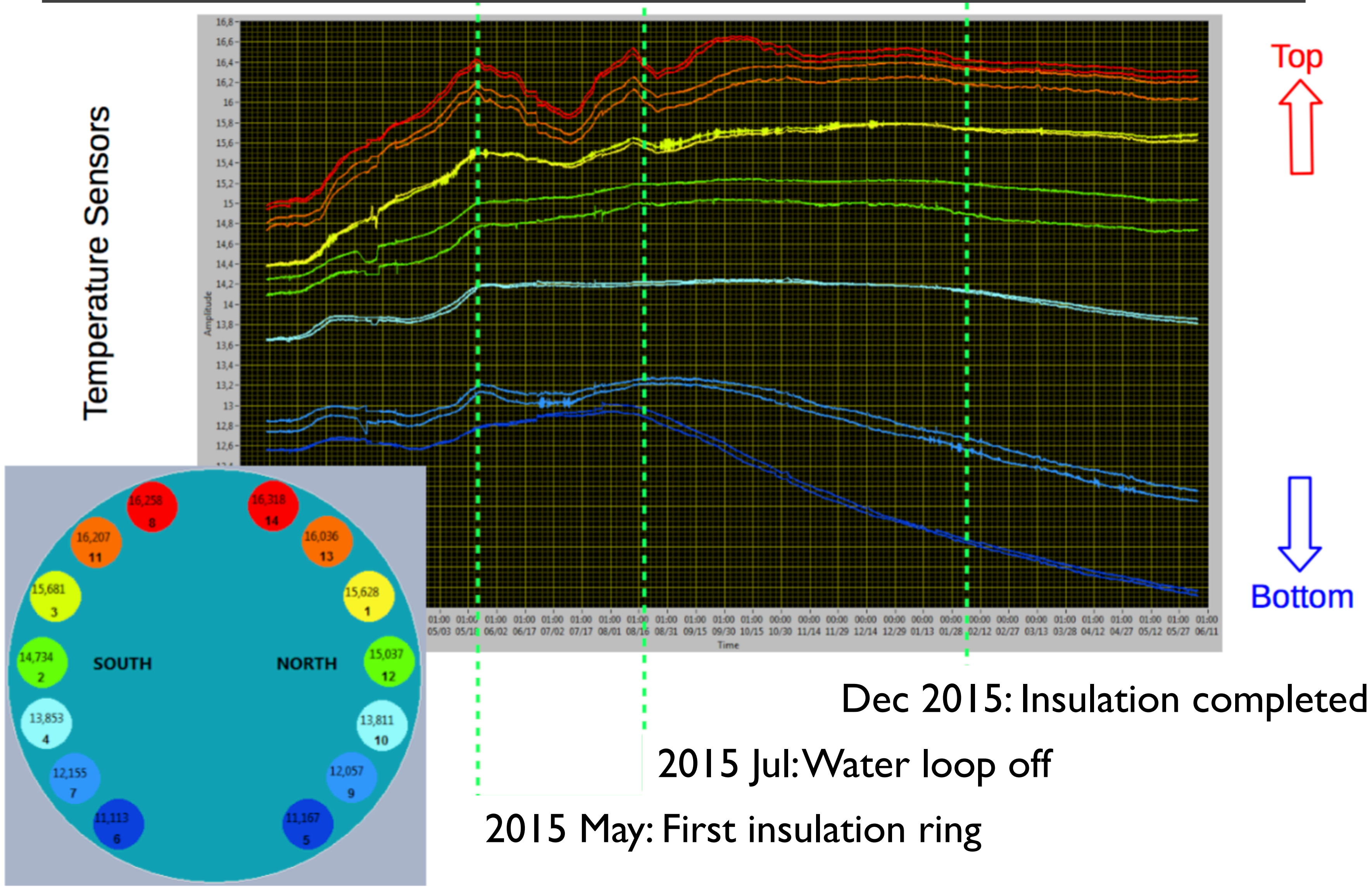
Thermal insulation of whole detector

- 20 cm mineral wool + reflective layer
- May to December 2015
- Active T controll installed to be activated at need



- 65 new calibrated T probes, internal and external installed
- 2 probes measuring T in Hall C
- 0.1 °C absolute accuracy
- 0.01 °C resolution stability

Temperature Stabilization



Impact on ^{210}Po