BOREXINO – the achievements and prospects

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on behalf of the BOREXINO Collaboration

Les Rencontres de Physique de la Vallée d'Aoste, 23.02-01.03 2014 La Thuile, Italy

Outline

- BOREXINO
- Phase I results
- Phase II physics
- Conclusions

BOREXINO Collaboration

INFN

Gran Sasso

Perugia

Max-Planck-Institut für Kernphysik

Heidelberg

Hamburg

Budapest

Milano

Genova

München

Kraków

Kurchatov Moscow

the Borexino Collaboration

JINR Dubna

Princeton

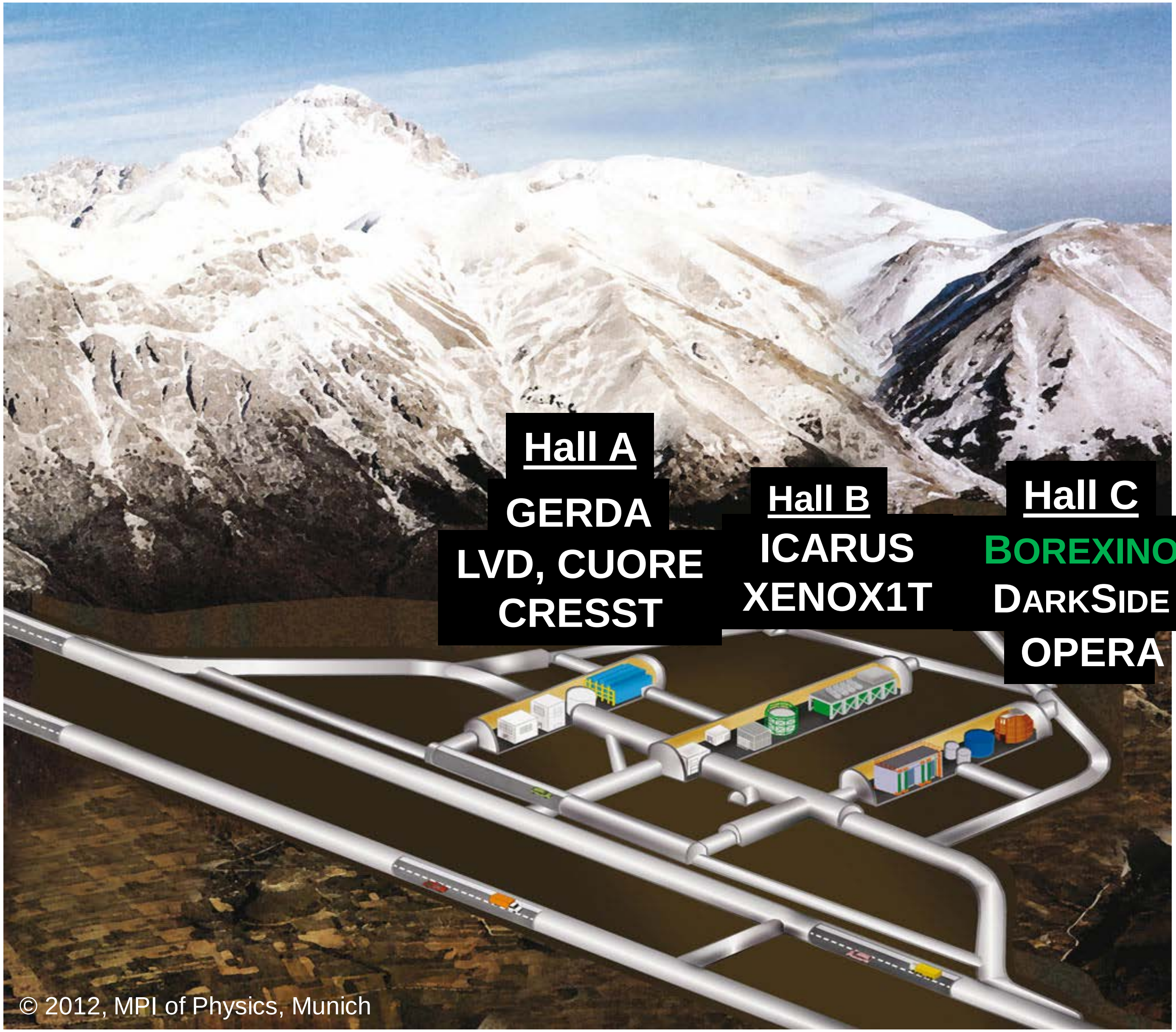
Virginia Tech

UMass Amherst

Paris

St. Petersburg

BOREXINO at LNGS



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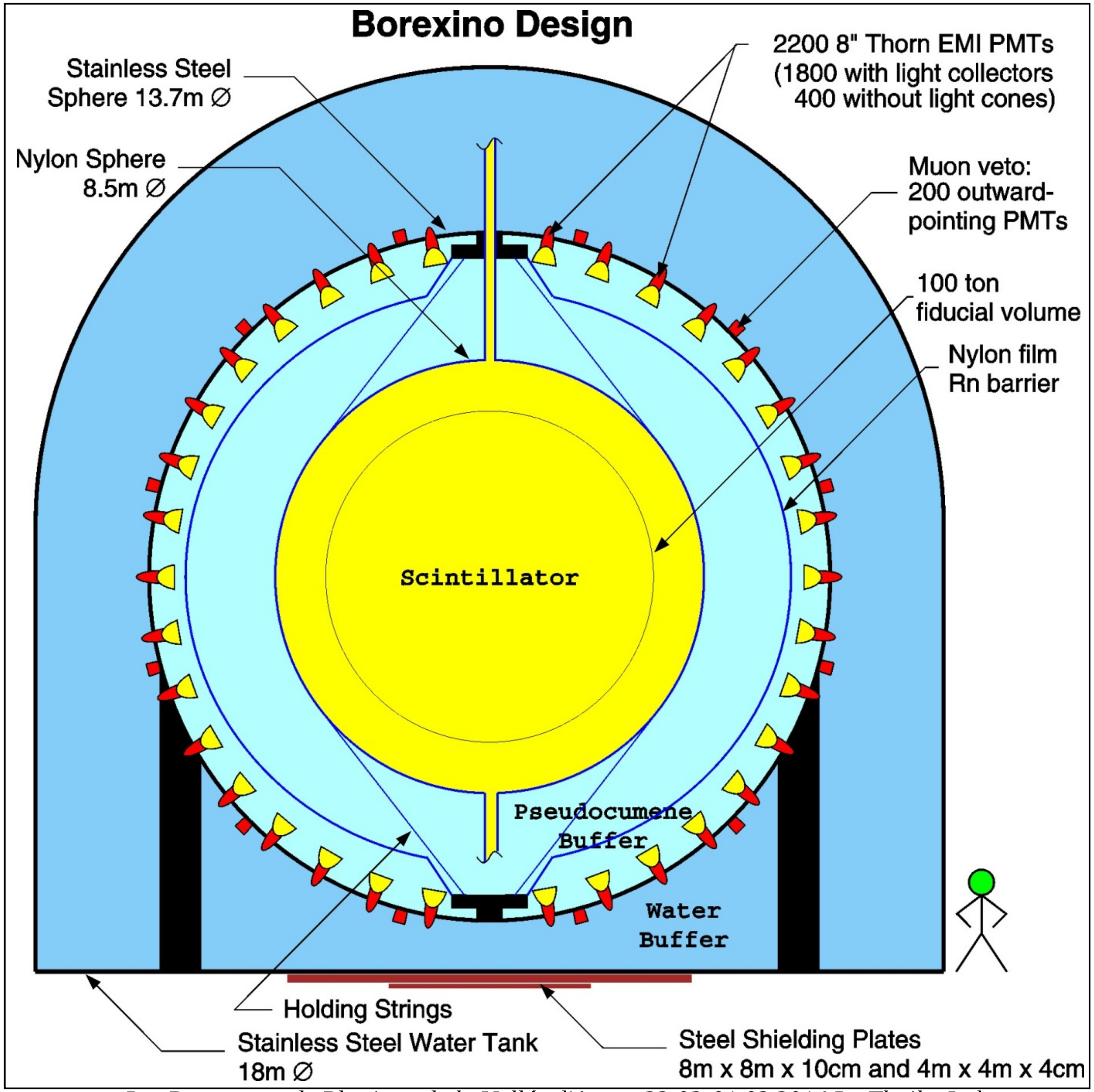
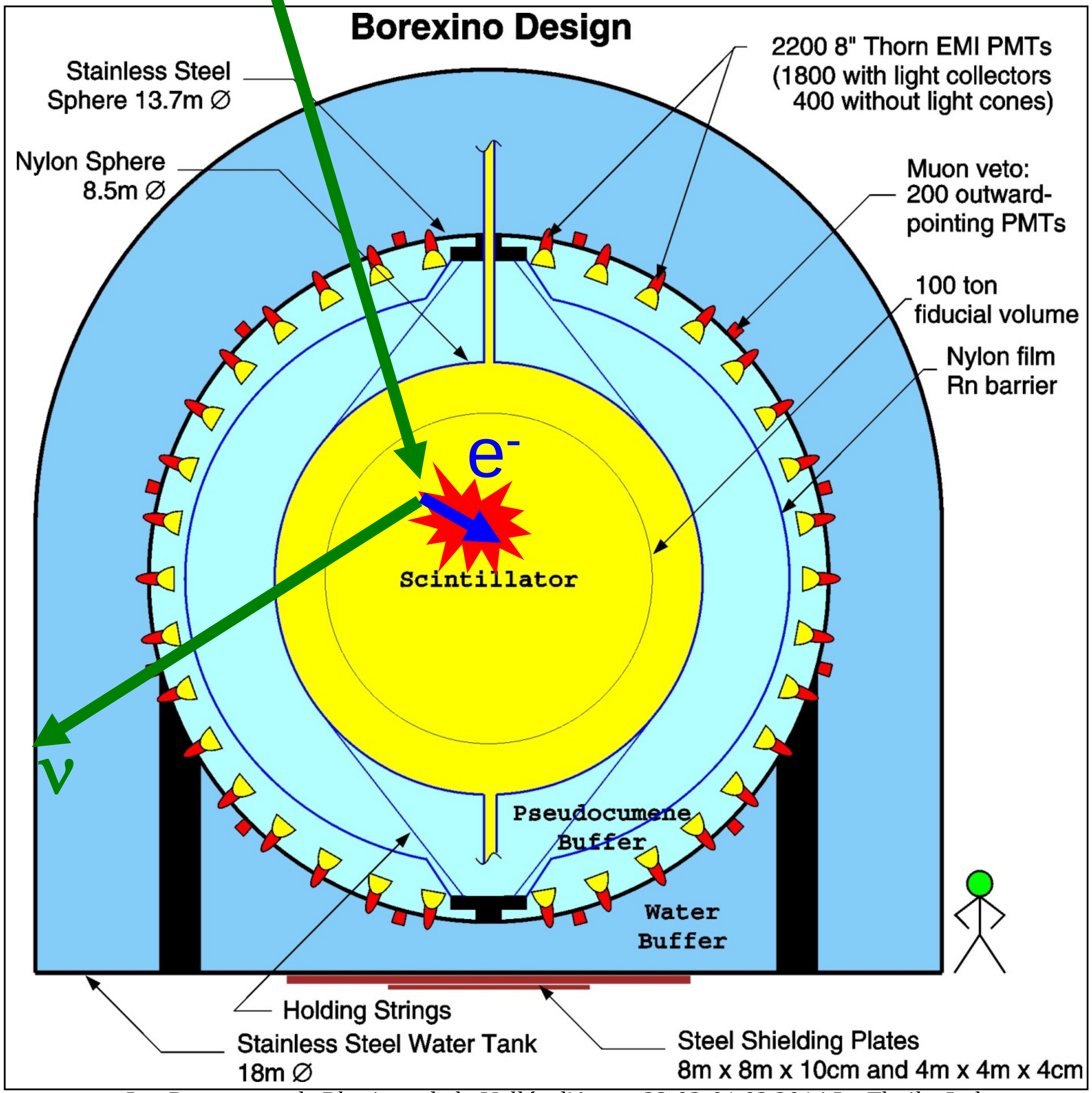
BOREXINO design



BOREXINO design



BOREXINO and solar neutrinos

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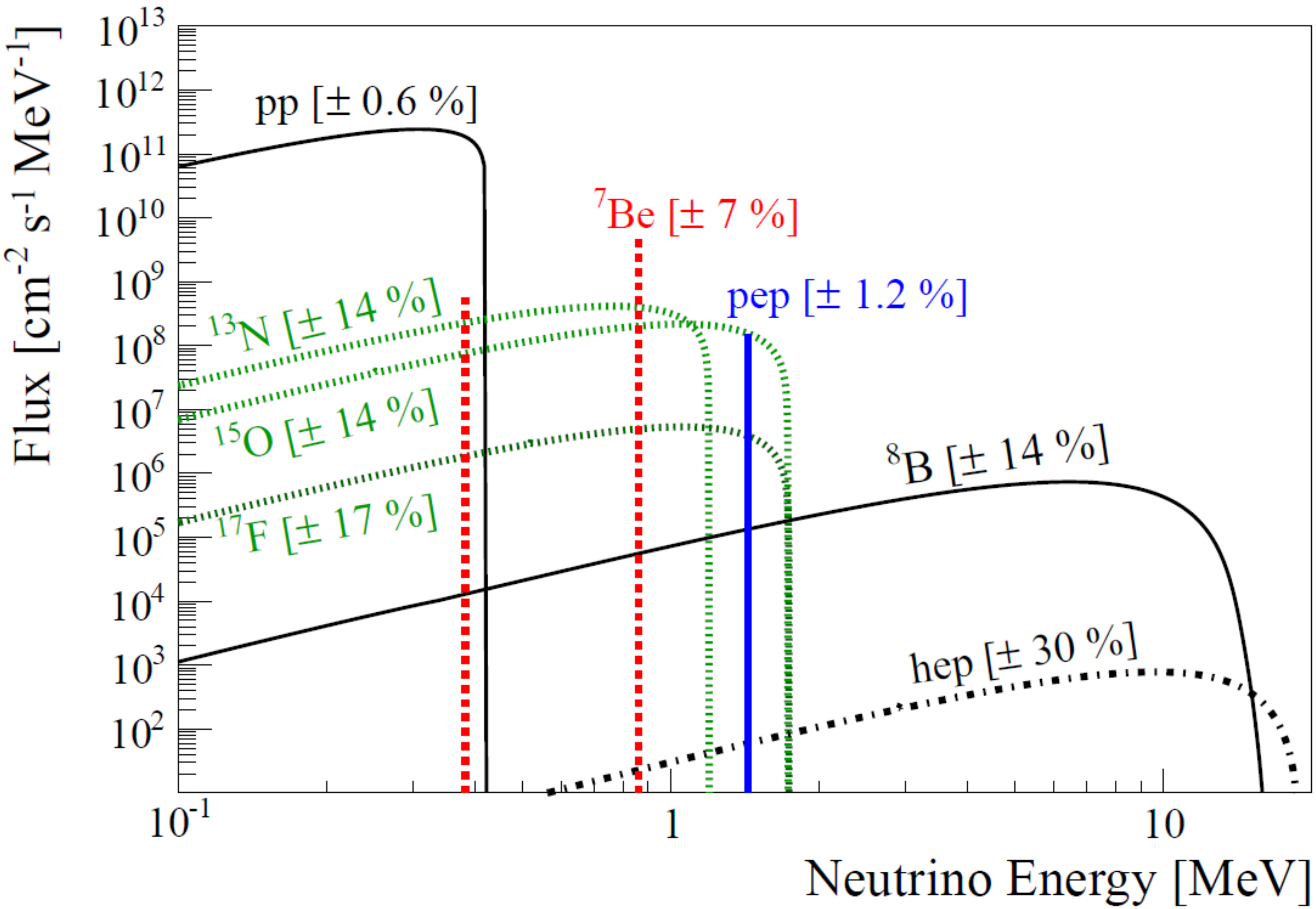
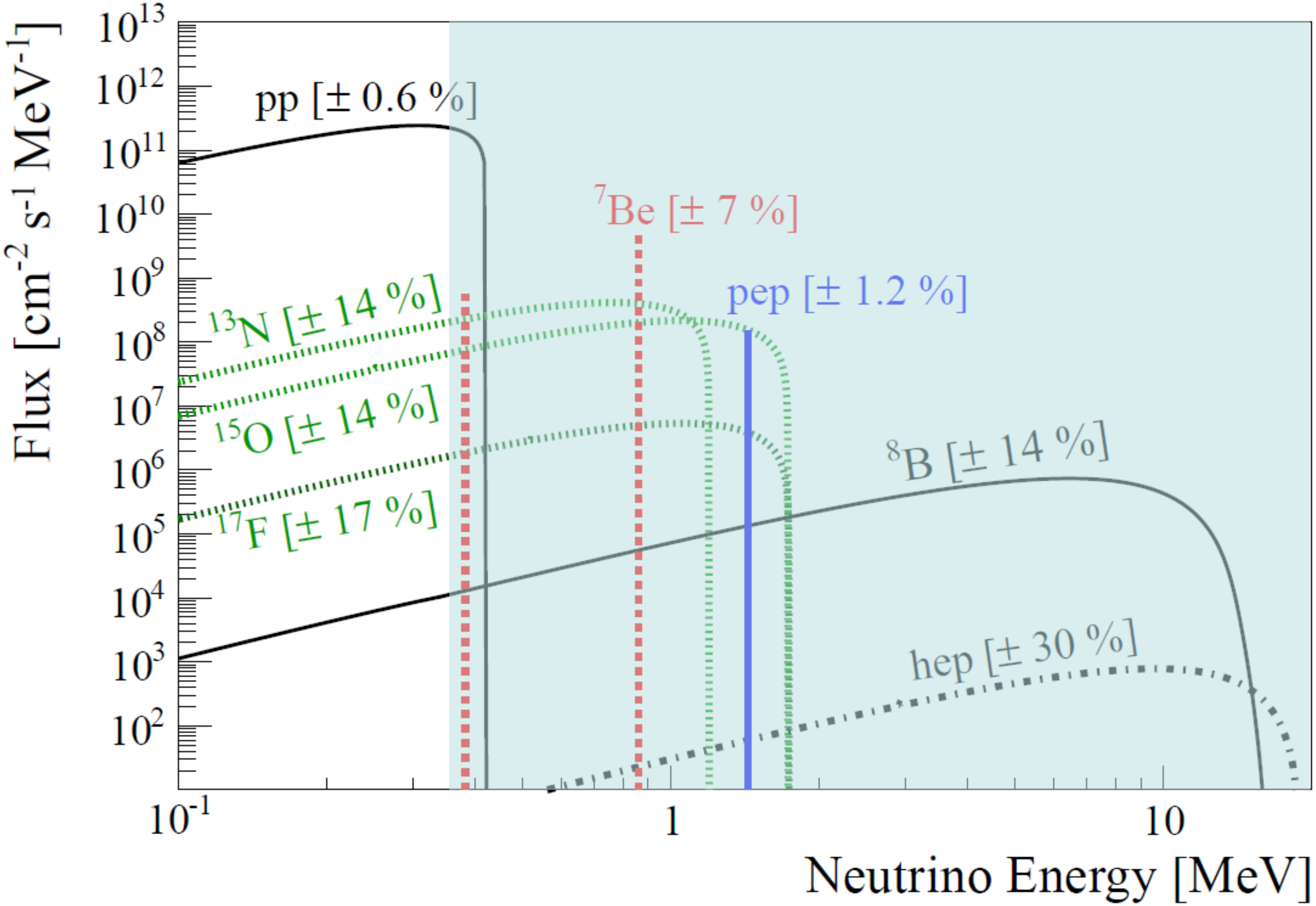
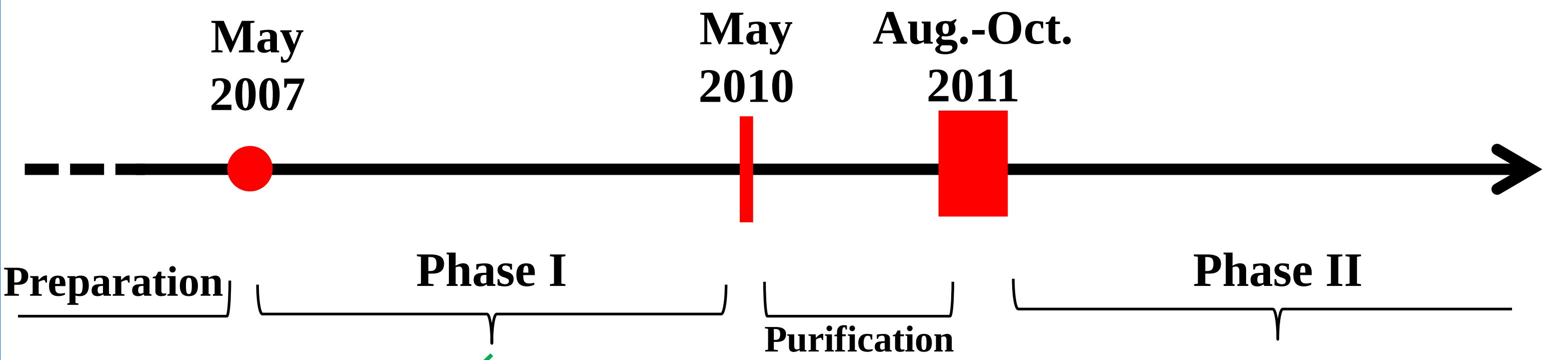


BOREXINO and solar neutrinos



BOREXINO at a glance



Phase I:

- (First) solar ^{7}Be-ν measurement
- ^{7}Be-ν day-night asymmetry
- Low-threshold ^{8}B-ν
- First pep-ν detection
- Best upper limit on CNO-ν
- First geo-ν observation at > 4σ
- Muon seasonal variations
- Limits on rare processes

Phase II:

- Measurement of pp-ν flux
- Measurement of CNO-ν flux
- Short-base ν oscillations: SOX

Phase I and Phase II:

- Neutrons and other cosmogenics
- ^{7}Be-ν seasonal modulation
- Updated geo-ν flux

BOREXINO radiopurity

In a nutshell: the radio-purest detector ever built

Isotope	**Specification for LS**	**Before purification**	**After purification**
^{238}U	$\leq 10^{-16}$ g/g	$(5.3 \pm 0.5)\cdot10^{-18}$ g/g	**< $0.8\cdot10^{-19}$ g/g**
^{232}Th	$\leq 10^{-16}$ g/g	$(3.8 \pm 0.8)\cdot10^{-18}$ g/g	**< $1.0\cdot10^{-18}$ g/g**
^{14}C/^{12}C	$\leq 10^{-18}$	$(2.69 \pm 0.06)\cdot10^{-18}$ g/g	unchanged
^{40}K	$\leq 10^{-18}$ g/g	$\leq 0.4\cdot10^{-18}$ g/g	unchanged
^{85}Kr	$\leq$ 1 cpd/100 t	(30 ± 5) cpd/100 t	$\leq$ 5 cpd/100 t
^{39}Ar	$\leq$ 1 cpd/100 t	<< ^{85}Kr	<< ^{85}Kr
^{210}Po	not specified	~ (70) 1 dpd/100 t	unchanged
^{210}Bi	not specified	(20) 70 dpd/100 t	**(20 ± 5) cpd/100 t**

^{7}Be neutrino flux

The flux of monoenergetic ^{7}Be neutrinos measured with 4.6 % precision

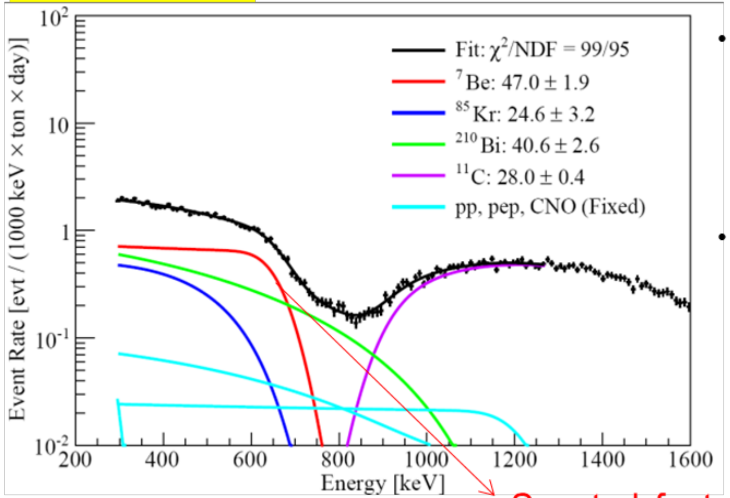
$$R = (46 \pm 1.5_{stat} \pm 1.6_{sys})\ \text{cpd/100 t}$$

Phys. Rev. Lett. 107, 141302 (2011)

$\phi_{Be} = (3.10 \pm 0.15) \times 10^9\ cm^{-2}s^{-1}$ $P_{ee} = 0.51 \pm 0.07$ at 0.862 MeV

- The final spectrum is fitted to a global signal plus background model to extract the value of the flux
- Two independent methods: MC based and the analytical one

740 live days



Spectral feature: compton-like edge from scattered electrons

- *First real time detection of ^{7}Be solar neutrinos by Borexino*

  Phys. Lett. B 658 (2008) 101-108 – data collected for 47.4 live days

  $R = 47 \pm 7_{stat} \pm 12_{sys}$ counts/(day·100 ton)

- *Direct Measurement of the ^{7}Be Solar Neutrino Flux with 192 Days of Borexino Data*

  Phys. Rev. Lett. 101 (2008) 091302

  $R = 49 \pm 3_{stat} \pm 4_{sys}$ counts/(day·100 ton)

BOREXINO

Phase I results

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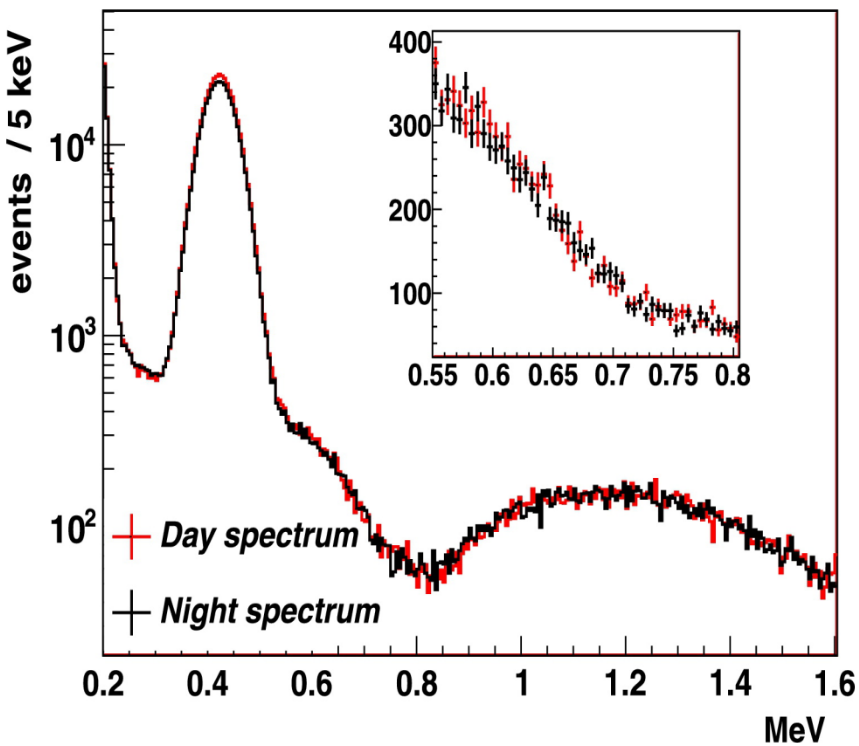
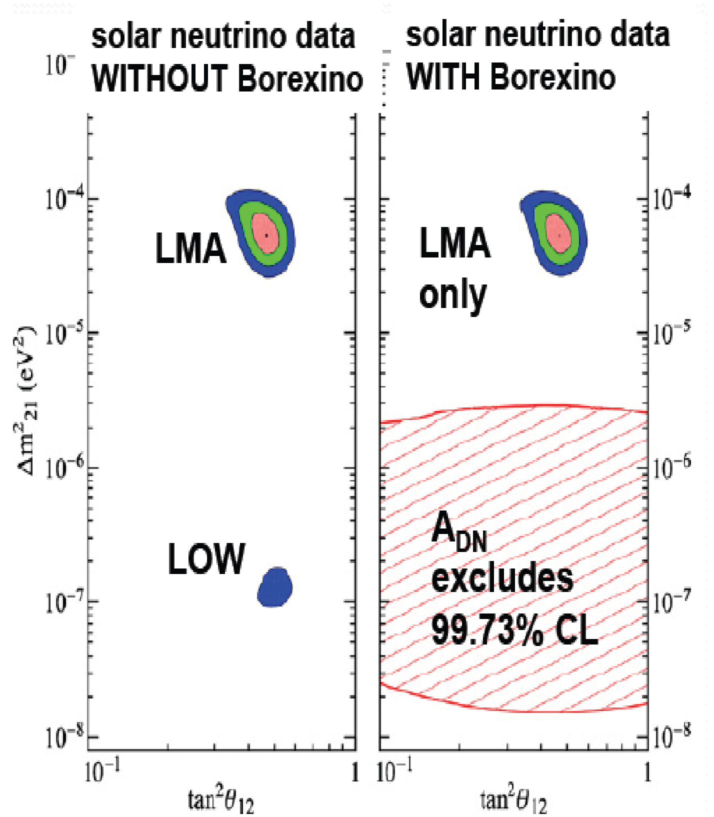
^{7}Be-ν flux day-night asymetry

$$A_{d\text{-}n} = 2\,(R_n - R_d)/(R_n + R_d) = 0.001 \pm 0.012_{stat} \pm 0.007_{sys}$$

In agreement with MSW-LMA, LOW region excluded at >8.5 σ with solar neutrinos only (no assumption of CPT symmetry)

Phys. Lett. B 707, 1 (2012) 22-26





pep and CNO-ν fluxes

- First observation of the flux of mono-energetic pep neutrinos

$$R = (3.1 \pm 0.6_{stat} \pm 0.3_{sys})\ \text{cpd/100 t}$$

$\Phi^{LMA}_{pep} = (1.6 \pm 0.3) \times 10^{8}\ cm^{-2}\ s^{-1}$ $P_{ee} = 0.62 \pm 0.17$ at 1.44 MeV

- Limit for CNO neutrinos obtained assuming the pep neutrino flux according to SSM,
- Strong correlation with ^{210}Bi in the fit

$$R < 7.1\ \text{cpd/100 t (95 \% C.L.)}$$

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

The strongest limit obtained up to date.
Not sufficient to solve the metallicity problem.

Phys. Rev. Lett. 108, 051302 (2012)

pep and CNO-ν fluxes

Three-fold coincidence technique

^{11}C is a produced by muons crossing BX

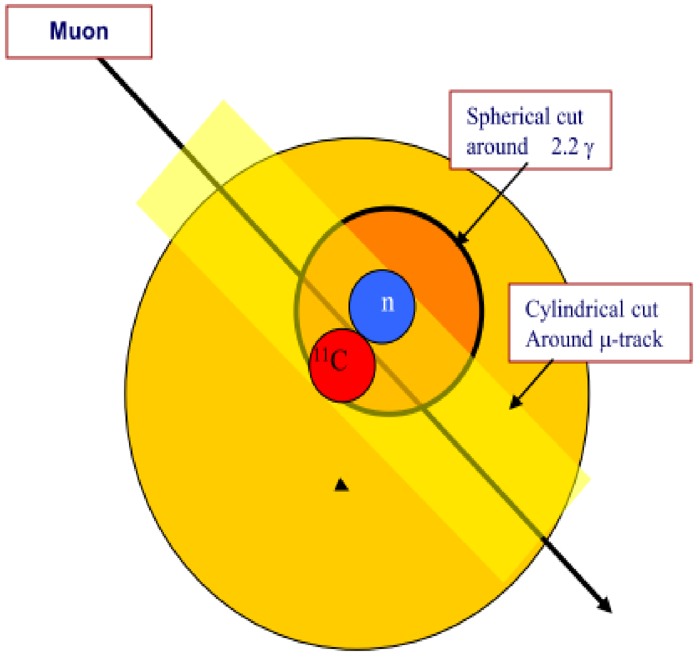
$$\mu + {}^{12}C \rightarrow \mu + {}^{11}C + n$$

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

$t \sim 30min$

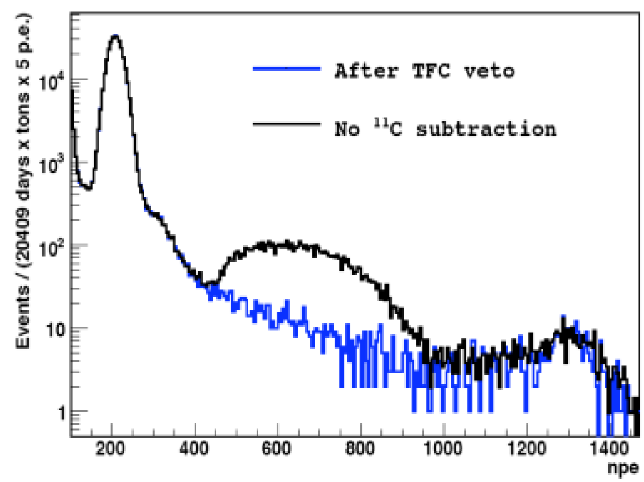
$$n + p \rightarrow d + \gamma$$

$\tau \sim 260 \mu s$



Optimal choice:

- Eliminates 91% of ^{11}C;
- Preserve 48.5% of livetime;



- ^{11}C from 27 counts/day/100tons to 2.5 counts/day/100tons

^{8}B neutrino flux

- BOREXINO is the first LS detector sensitive to ^{8}B neutrinos
- The energy threshold is limited by ^{208}Tl

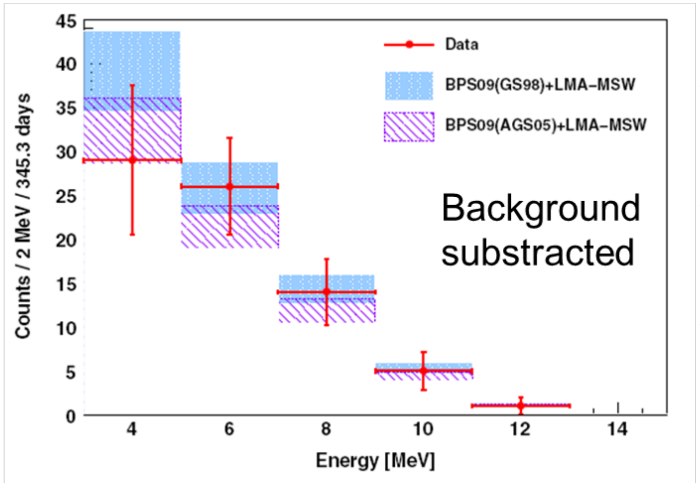
$$R = (0.22 \pm 0.04_{stat} \pm 0.01_{sys})\ \text{cpd/100 t} \quad E > 3\ \text{MeV}$$
$$R = (0.13 \pm 0.02_{stat} \pm 0.01_{sys})\ \text{cpd/100 t} \quad E > 5\ \text{MeV}$$

Phys. Rev. D82 (2010) 033006

$$\phi_B^{ES} = (2.4 \pm 0.4_{stat} \pm 0.1_{sys}) \times 10^6\ \text{cm}^{-2}\text{s}^{-1}$$

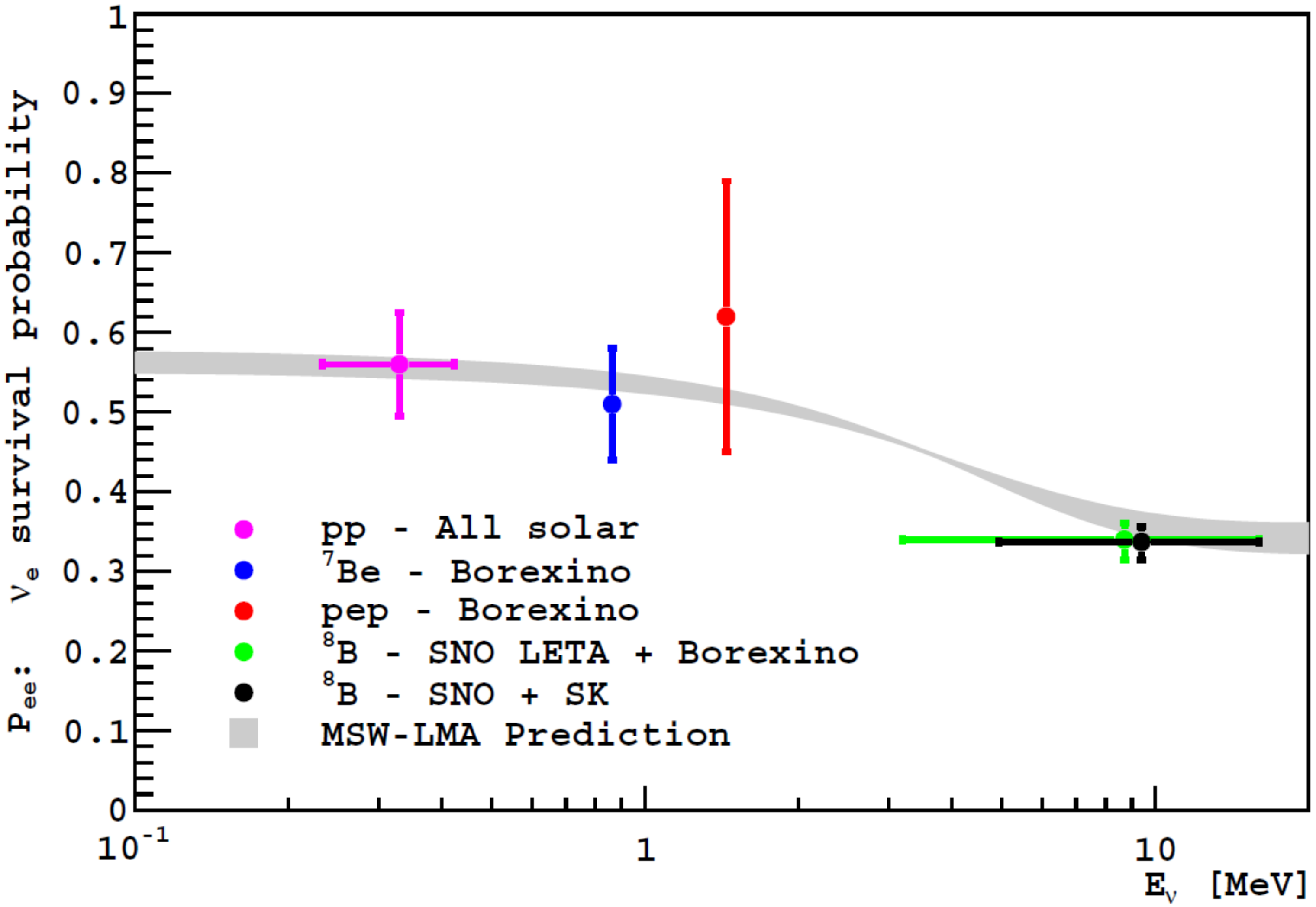
$$P_{ee} = 0.29 \pm 0.10 \ \text{at}\ \langle E \rangle = 8.9\ \text{MeV}$$

- Exposure: 345 days in 100 tons FV: Jul 2007 – Aug 2009
- no oscillation hypothesis excluded at 4.2σ



- the measurement of *ν-e* elastic scattering from ^{8}B solar neutrinos with 3 MeV energy threshold
- in agreement with measurements from SNO and SuperKamiokaNDE
- the first measurement of ^{8}B solar neutrinos in a liquid scintillator

P_{ee} after BOREXINO



^{7}Be-ν flux annual modulation

BOREXINO

Phase I results

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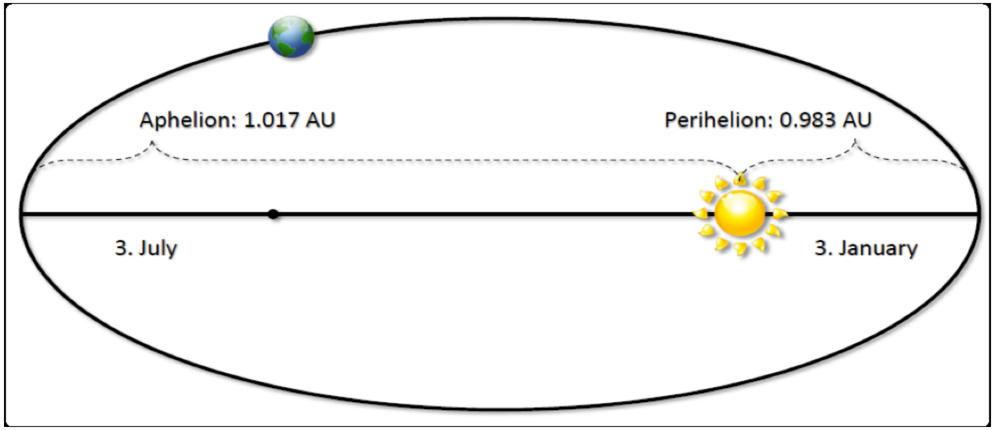

Due to Earth eccentricity $\varepsilon = 0.0167$ (maximum on January 3) one expects:
- Perihelion-Aphelion difference of ±7% in neutrino flux
- ^{7}Be neutrino rate variation between 47.5 and 44.5 cpd/100 ton

Very stable detector response (energy scale, PSD and position reconstruction) needed. Problem with unstable background from ^{210}Bi!

3 analysis methods applied (Phase I + II)
- Fit of the rate vs time
- Lomb Scargle analysis
- Empirical Mode Decomposition

No evidence for anomalous oscillations (3σ)

arXiv:1308.0443v1

BOREXINO Phase II Goals

- Improvement of ^{7}Be neutrino flux measurement (3%) and seasonal variations
- Precision pep neutrino measurement (> 3σ)
- Geo-neutrino flux measurement with higher statistics
- ^{8}B neutrino measurement with x4 statistics (aiming 10%)

- **pp-neutrino flux measurement**
  - first direct observation of neutrinos from the primary proton-proton fusion reaction taking place in the Sin's core
- **Measurement (or establishing stronger limits) on the CNO neutrino flux**
  - first confirmation of fusion process that powers most stars
  - can help resolve the solar "metallicity problem"
- **Measurements with artificial neutrino sources: Project SOX: Short distance Oscillations with BoreXino.**
  - search for sterile neutrino
  - measurement of neutrino magnetic moment
  - search for nonstandard neutrino interactions

Towards determination of CNO-ν

BOREXINO

Phase I results

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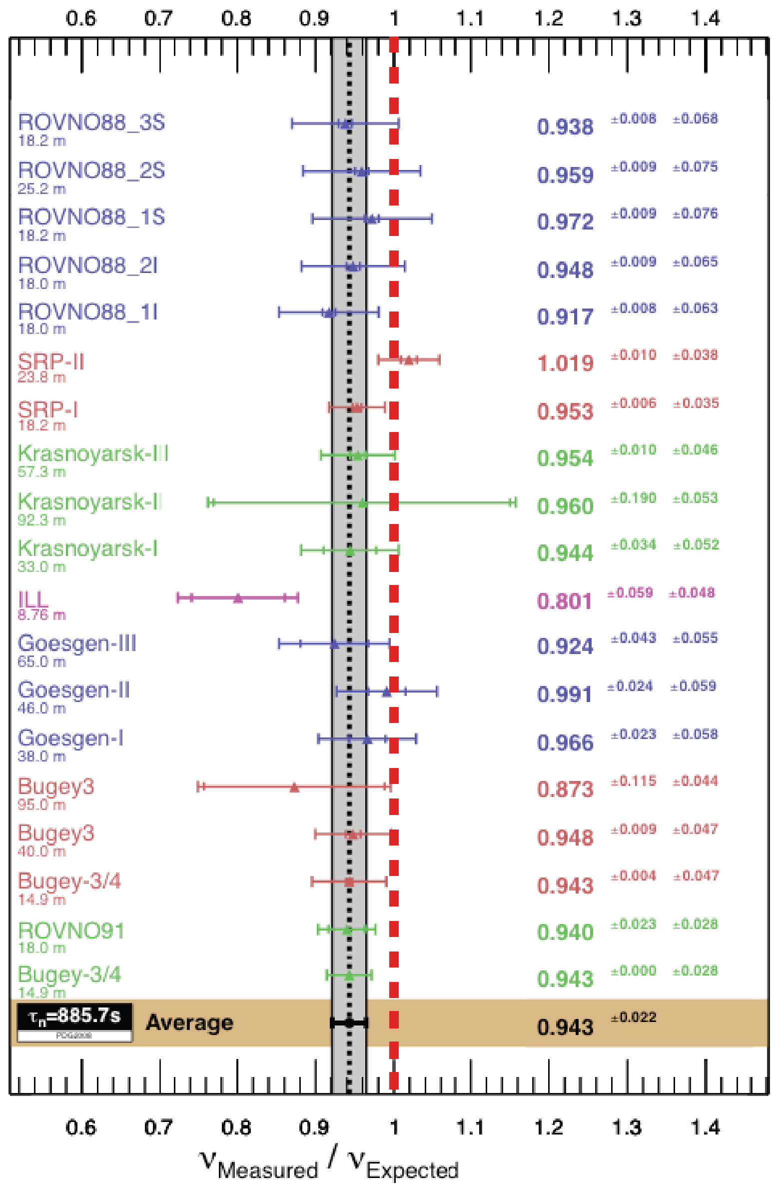
1. Lower ^{210}Bi background is required (additional purification)
   – CNO high metallicity rate is ~5 cpd/100 t
   – ^{210}Bi is still too high at ~20 cpd/100 t: reduction to 2 cpd/100 t is needed
2. Knowledge of energy spectrum of ^{210}Bi.
3. Improved energy calibration (±1 %)
4. Control of detector temperature (ΔT < 0.1 C/month)

Reactor neutrino anomaly



$\bar{\nu}_e$ Disappearance

The synthesis of published experiments at reactor-detector distances ≤ 100 m leads to a ratio R of observed event rate to predicted rate of

μ = 0.976 ± 0.024 (**OLD flux**)

With **NEW flux** evaluation, this ratio shifts to

μ = **0.943 ± 0.023**, **[2011 result]**

leading to a deviation from unity at 98.6% C.L.

$\chi^2_{min} = 19.6/18$

2013 result

μ = **0.936 ± 0.024**

χ^2_{min} / dof = 29.7 / 22

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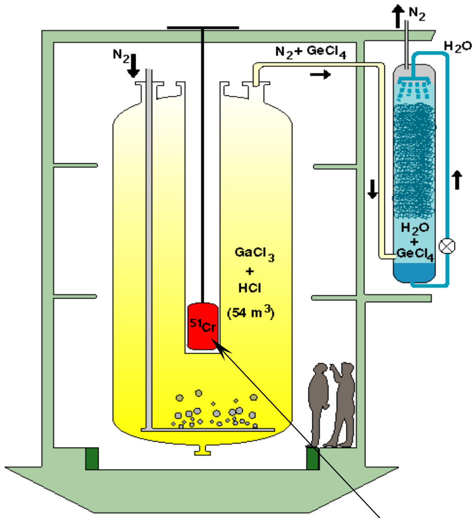
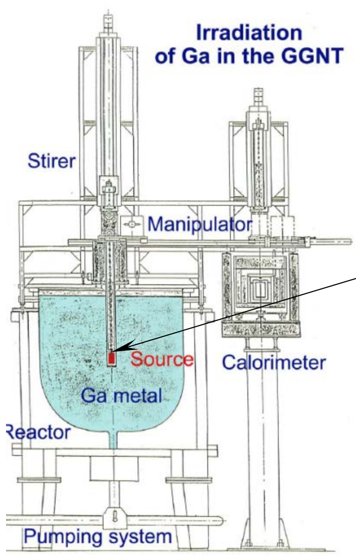
Ga anomaly

$$^{71}\mathrm{Ga} + \nu_e \rightarrow {}^{71}\mathrm{Ge} + e^-$$



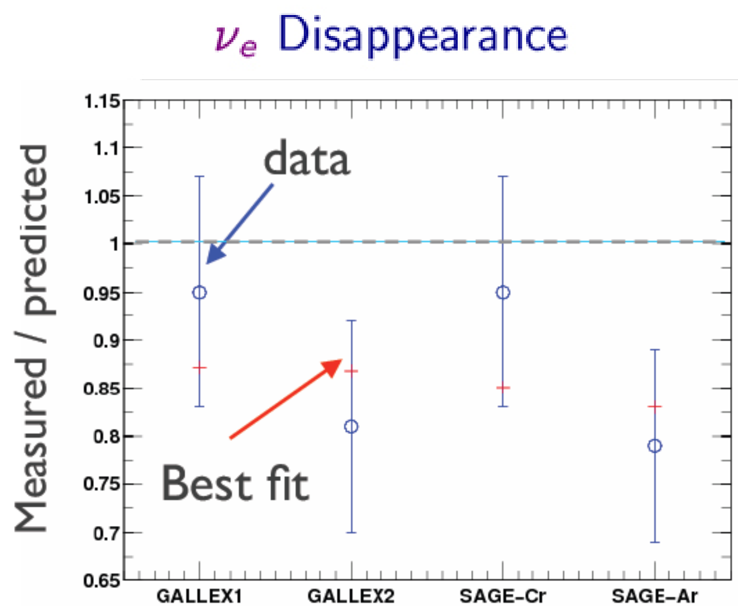
30.3 tons of Gallium in an aqueous solution : $GaCl_3$ + HCl

~ 65 PBq (^{51}Cr)
(1 PBq = 10^{15} ν/s)



~ 15 TBq (^{37}Ar)

30 to 57 tons of Gallium (metal) In 10 tanks



$\langle L \rangle_{\mathrm{GALLEX}} = 1.9\,\mathrm{m}$

$\langle L \rangle_{\mathrm{SAGE}} = 0.6\,\mathrm{m}$

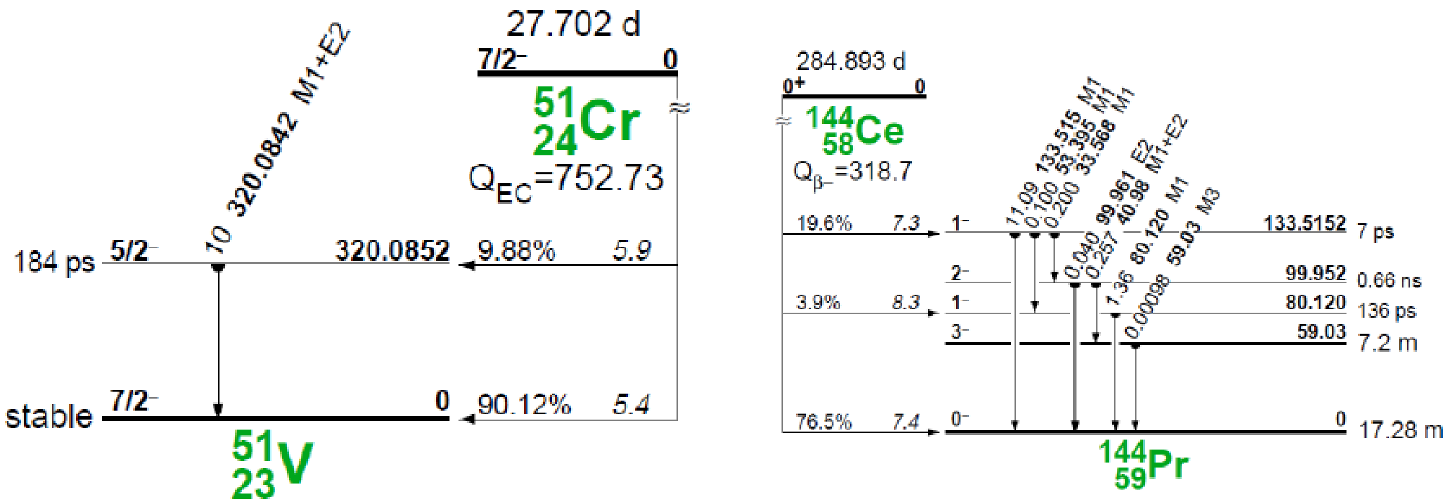
$\overline{R} = 0.76^{+0.09}_{-0.08}$

[Giunti, Laveder, PRC 83 (2011) 065504]

Haxton cross section with uncertainties

[Haxton, PLB 431 (1998) 110]

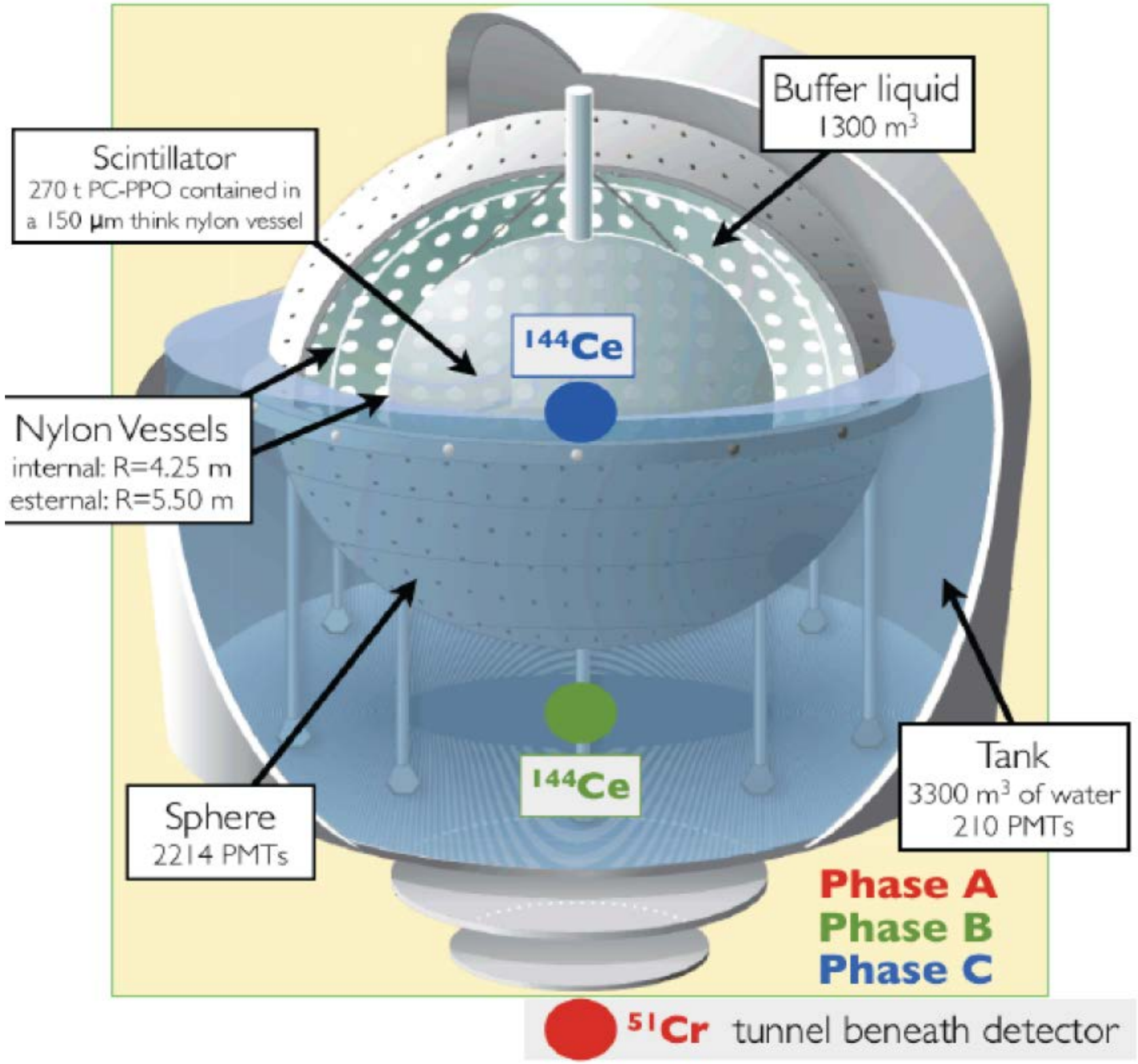
The SOX project: ν-sources



Source	decay	τ [days]	Energy [MeV]	Kg/MCi	W/kCi
^{51}Cr 200-400 PBq	e-capture (E_γ=0.32 MeV 10%)	40	0.7 90%	0.011	0.19
^{144}Ce-^{144}Pr 2-4 PBq	Fission product β^-	411	<2.9975 MeV 97.9%	0.314	7.6

The SOX project

$$P_{ee} = 1 - \sin^2 2\theta_{14} \sin^2 \frac{1.27\Delta m^2_{41}(eV^2)L(m)}{E(MeV)}$$



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The SOX project

BOREXINO

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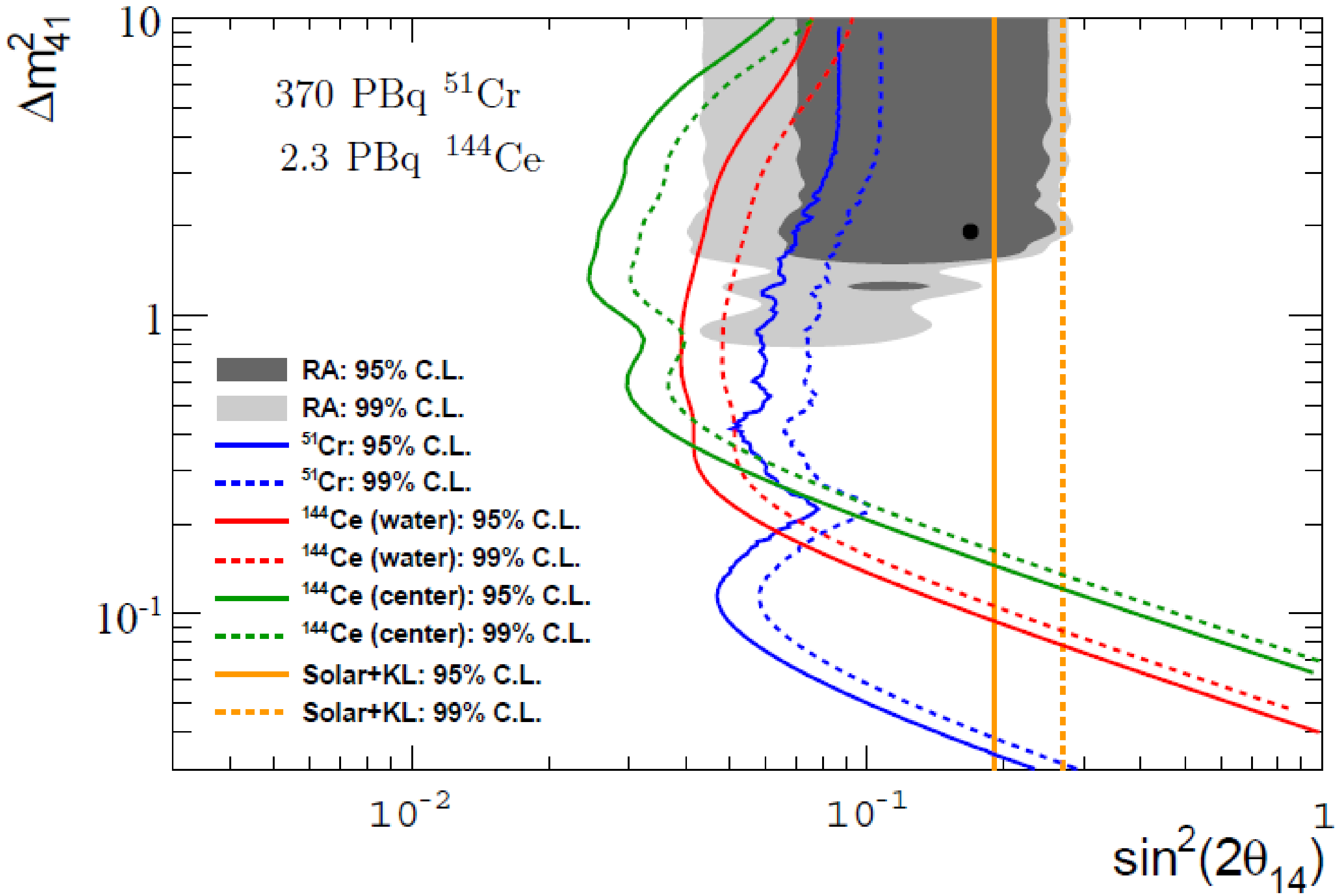
The SOX sensitivity



$\Delta(A_{Cr}) \sim 1$ %; $R_{Cr} \sim 15$ cm; $\Delta(FV) \sim 1$ %; $T_{1/2}$ signature
$\Delta(A_{Ce}) \sim 1.5$ %

Journal of High Energy Physics, 08 (2013) 038

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Conclusions

- BOREXINO achieved an unprecedented background level (still improving)
- In Phase I results over a broad range of neutrino energies obtained: ^{7}Be (<5%), ^{8}B, geo, pep, CNO limit…
- pp neutrino flux analysis well advanced
- Improvement on the CNO neutrino flux limit requires further background reduction (^{210}Bi)
- Promising future: search for sterile neutrinos with artificial sources (SOX funded and ongoing)

Backup slides

BOREXINO energy spectrum