Recent results from Borexino and prospects for the SOX experiment

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The Borexino detector

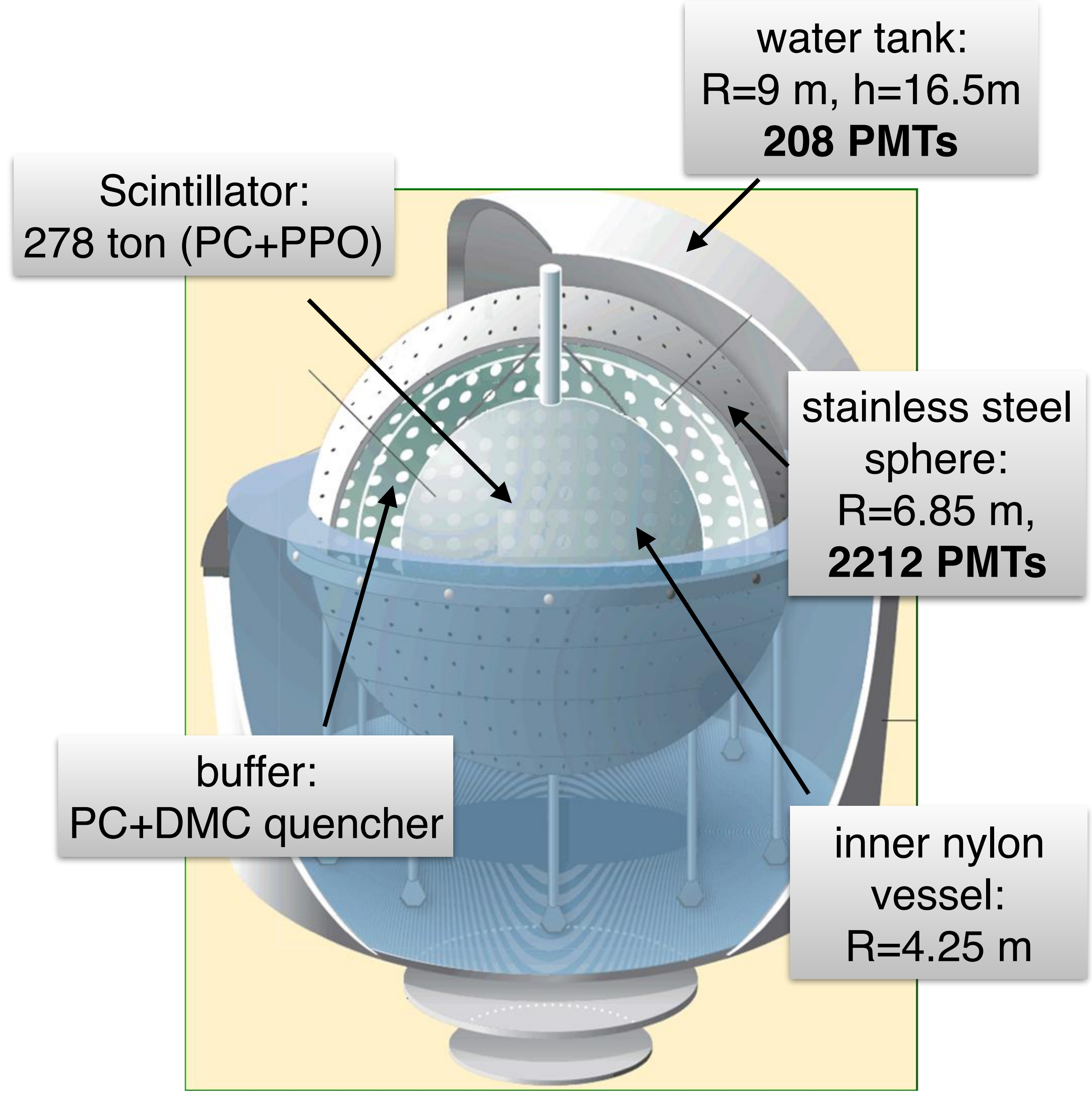
Gran Sasso Laboratory, Italy
(1400 m rock shielding, 3800 w.m.e.)

Light yield: ~500 photons/MeV

Hardware threshold: ~50 keV

Ultra-low radioactive background: over 10 orders of magnitude below typical radioactivity levels

Primary goal: real-time measurement of low-energy solar neutrinos



2007	Phase-I	2010	scintillator purification	2012	Phase-II	2017	2018	SOX

2007 – Solar neutrinos:
- ^{7}**Be, pep** flux
- limit on **CNO** flux

geo-neutrinos
neutrino magnetic moment (NMM)

2010 – record radio-purity level

2012 – Solar neutrinos:
- **pp** flux (new!)
- ^{7}**Be** seasonal modulation
- better results on ^{7}**Be, pep, CNO**

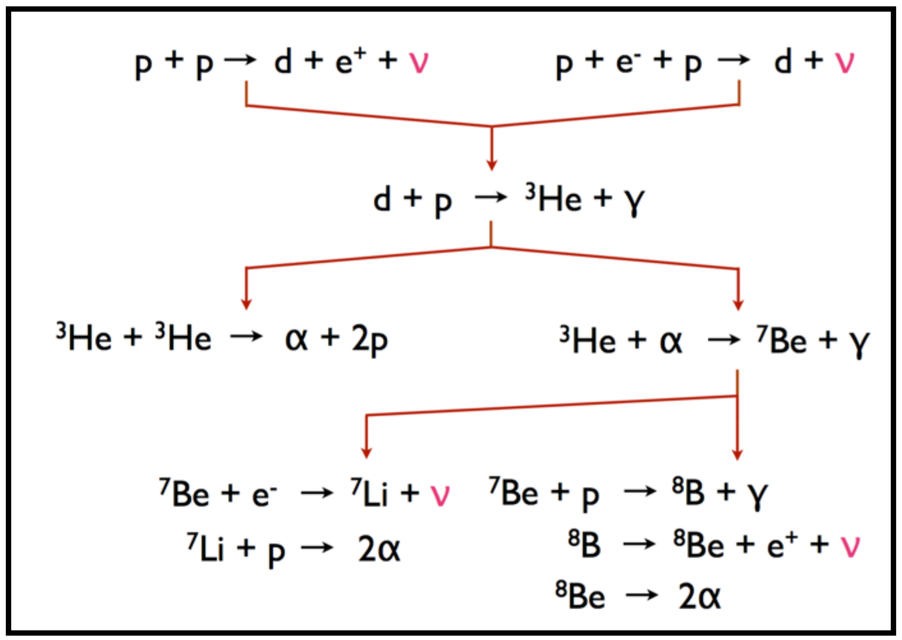
update on geo-neutrinos and NMM

2017

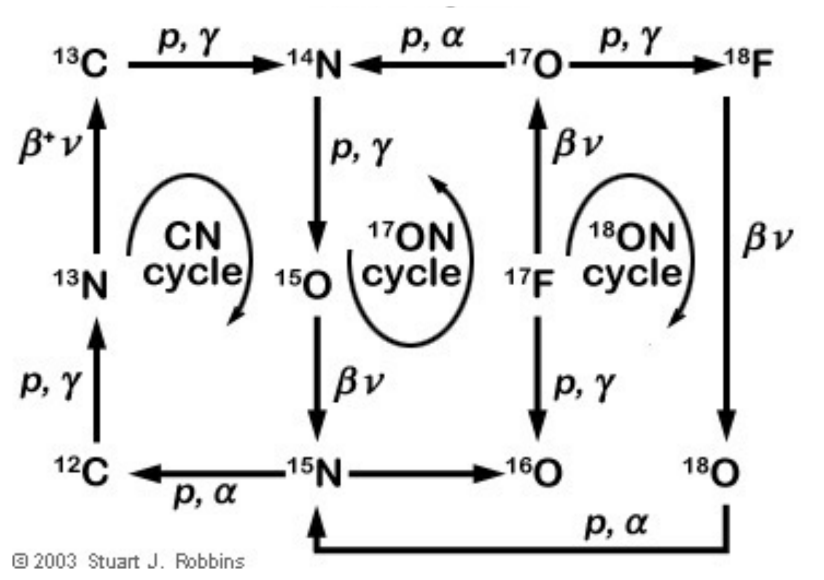
2018

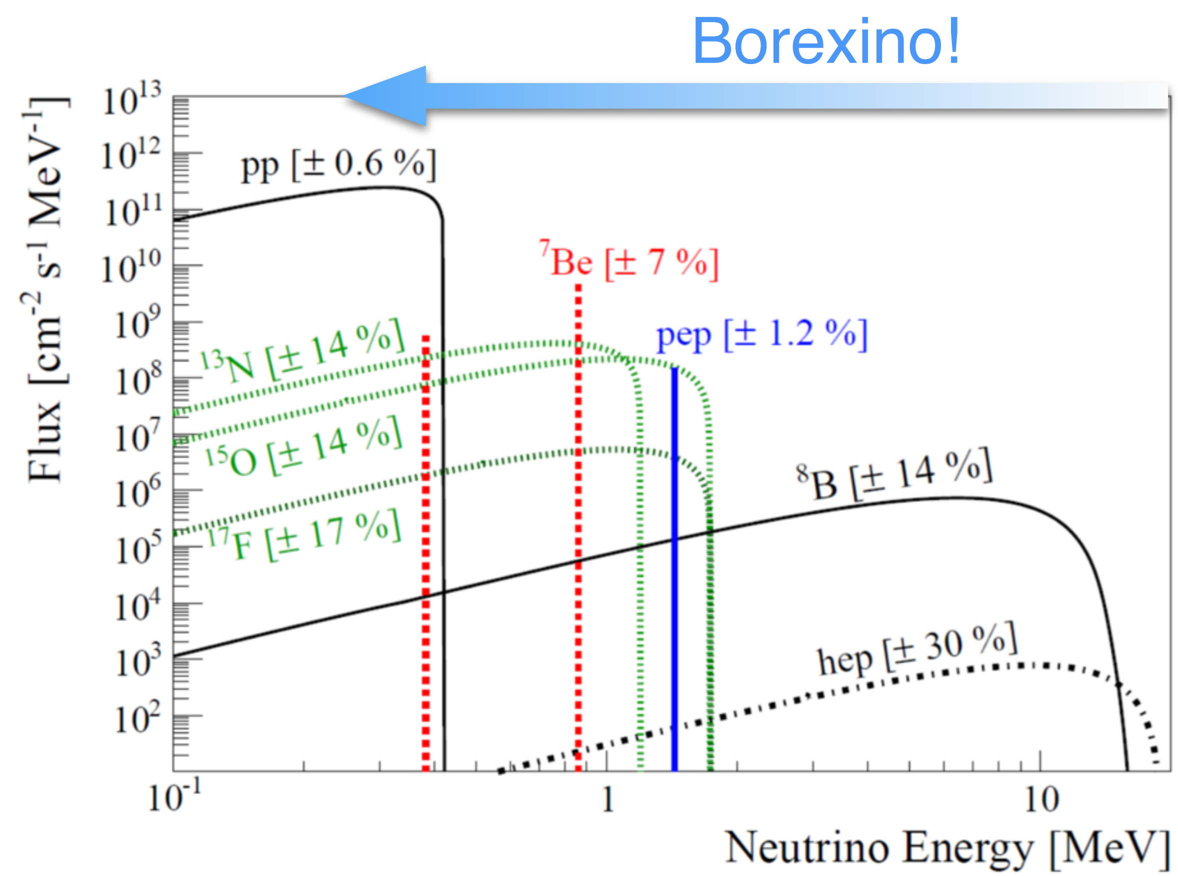
Solar neutrinos

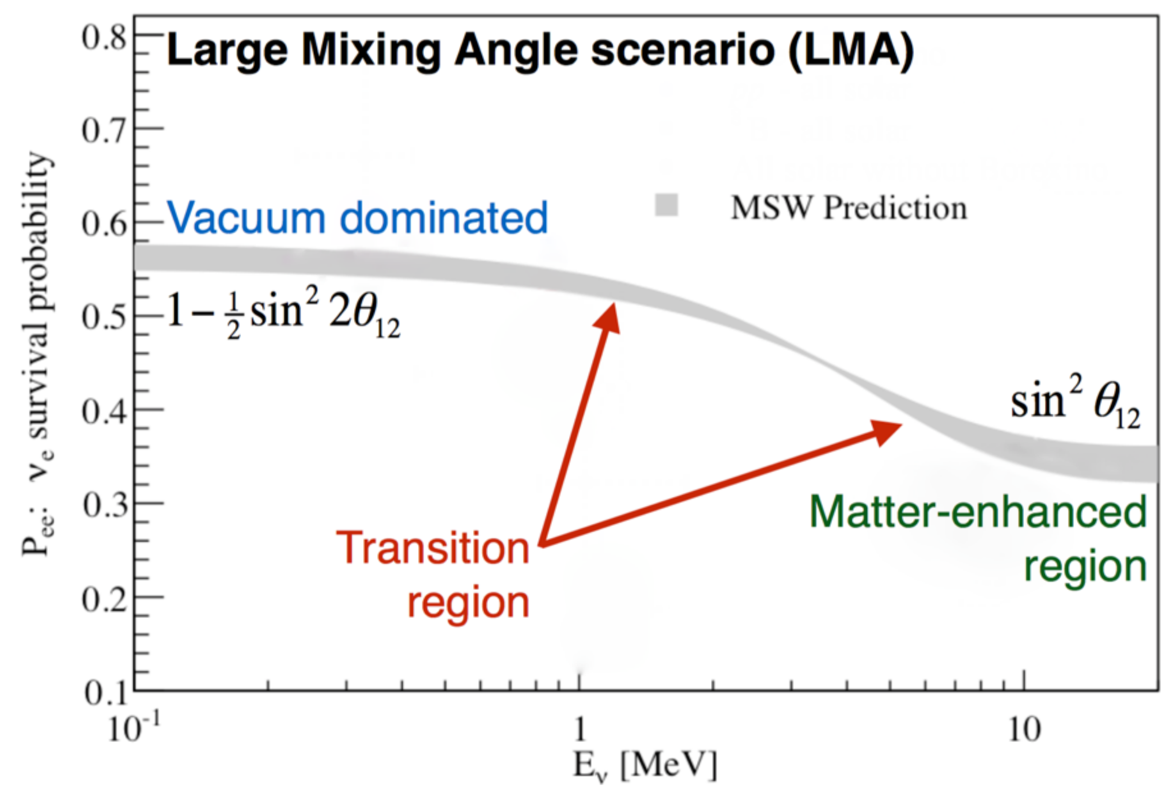
pp chain (~ 99% of the sun energy)



CNO cycle (<1% of the sun energy)







probes to test the Standard Solar Model (SSM), the Sun metallicity and the neutrino oscillations

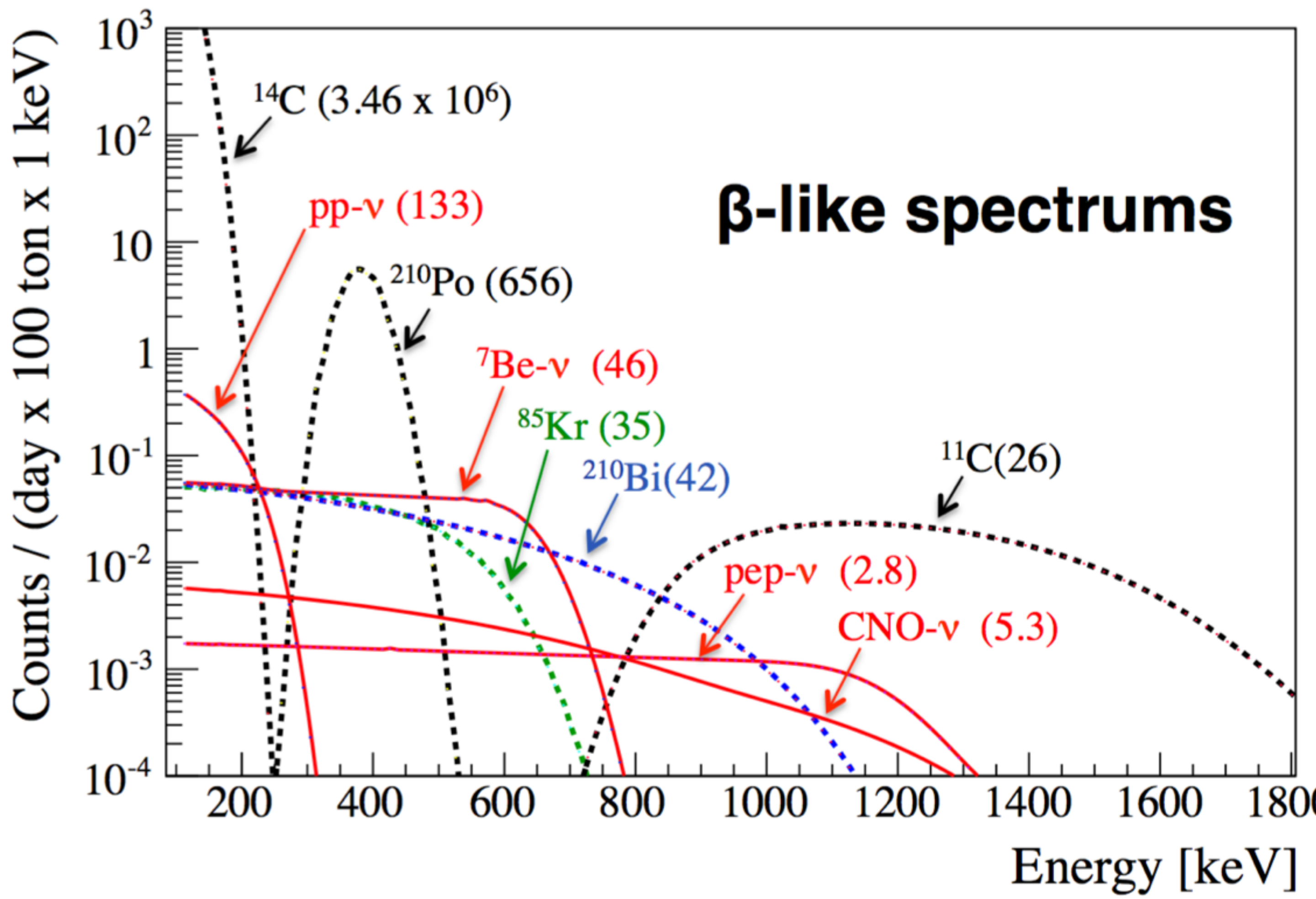
Solar neutrinos @ Borexino

Detection principle:
elastic scattering on electrons

$$\nu_x + e^- \rightarrow \nu_x + e^-$$

Indistinguishable from the natural radioactivity…

→ **extreme low background required!**

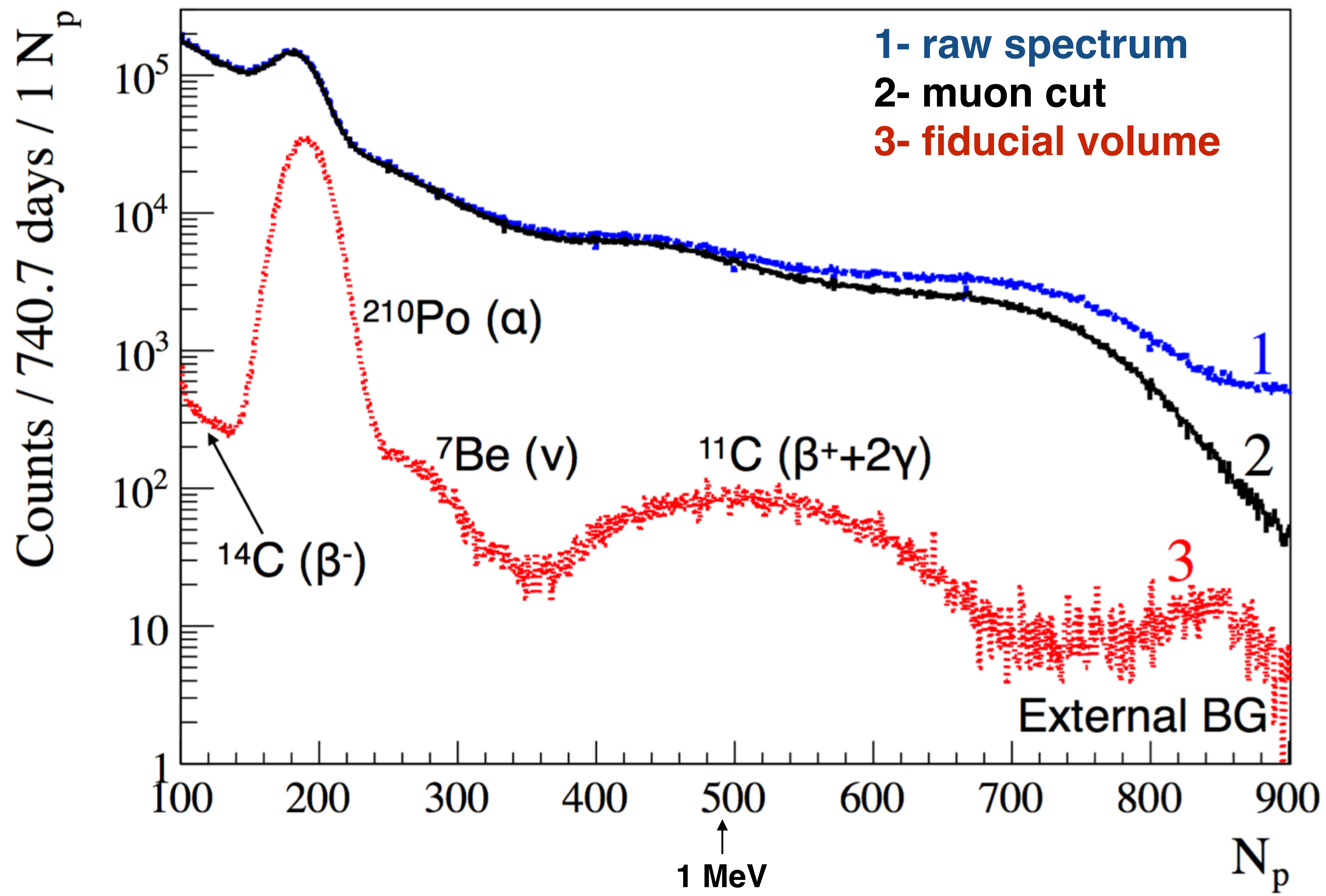


6 cycles of scintillator purification (2010-2011)

^{85}Kr: reduced by ~4.6
^{210}Bi: reduced by ~2.3
^{238}U: < 9.4 * 10^{-20} g/g (95% C.L.)
^{232}Th: < 5.7 * 10^{-19} g/g (95% C.L.)

+ ^{210}Po reduced by natural decay

Data selection



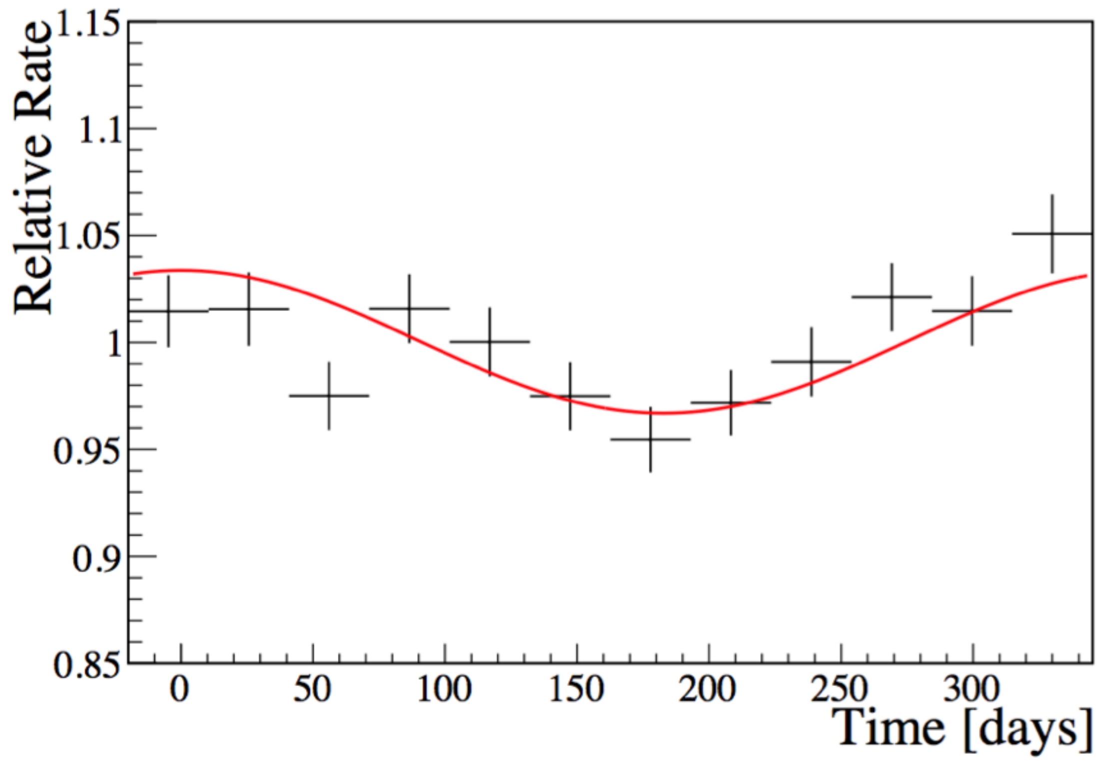
- ^{14}C: rate constraint and synthetic pile-up
- ^{214}Bi-^{214}Po: with alpha/ß discrimination
- ^{11}C: Three-Fold-Coincidence (TFC) discrimination
- Ext. BG: radial distribution

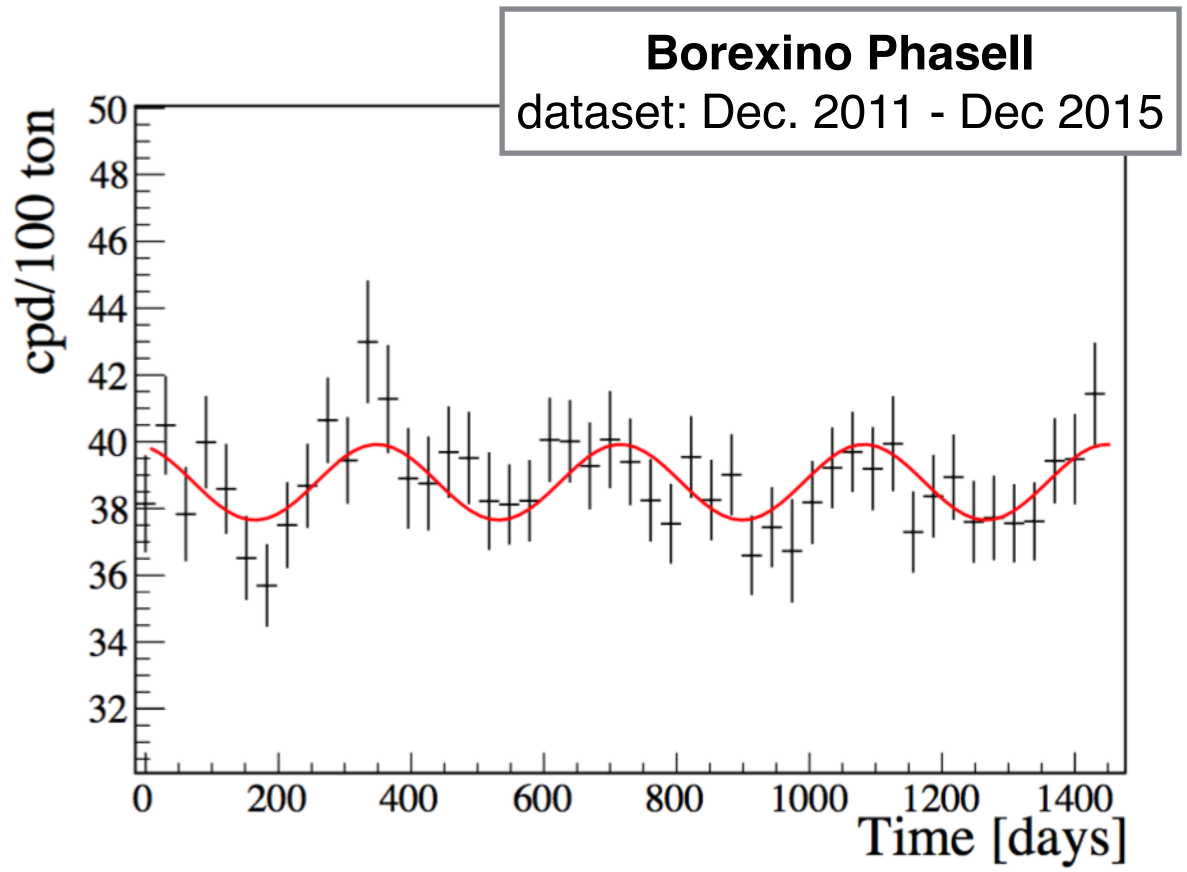
[arXiv:1308.0443]

Seasonal modulation of the ^{7}Be solar neutrino

3 methods used to analyse the periodical fluctuation on β-like signal from ^{7}Be ν_e:

- analytical fit to event rate
- Lomb-Scargle periodogram
- Empirical Mode Decomposition techniques





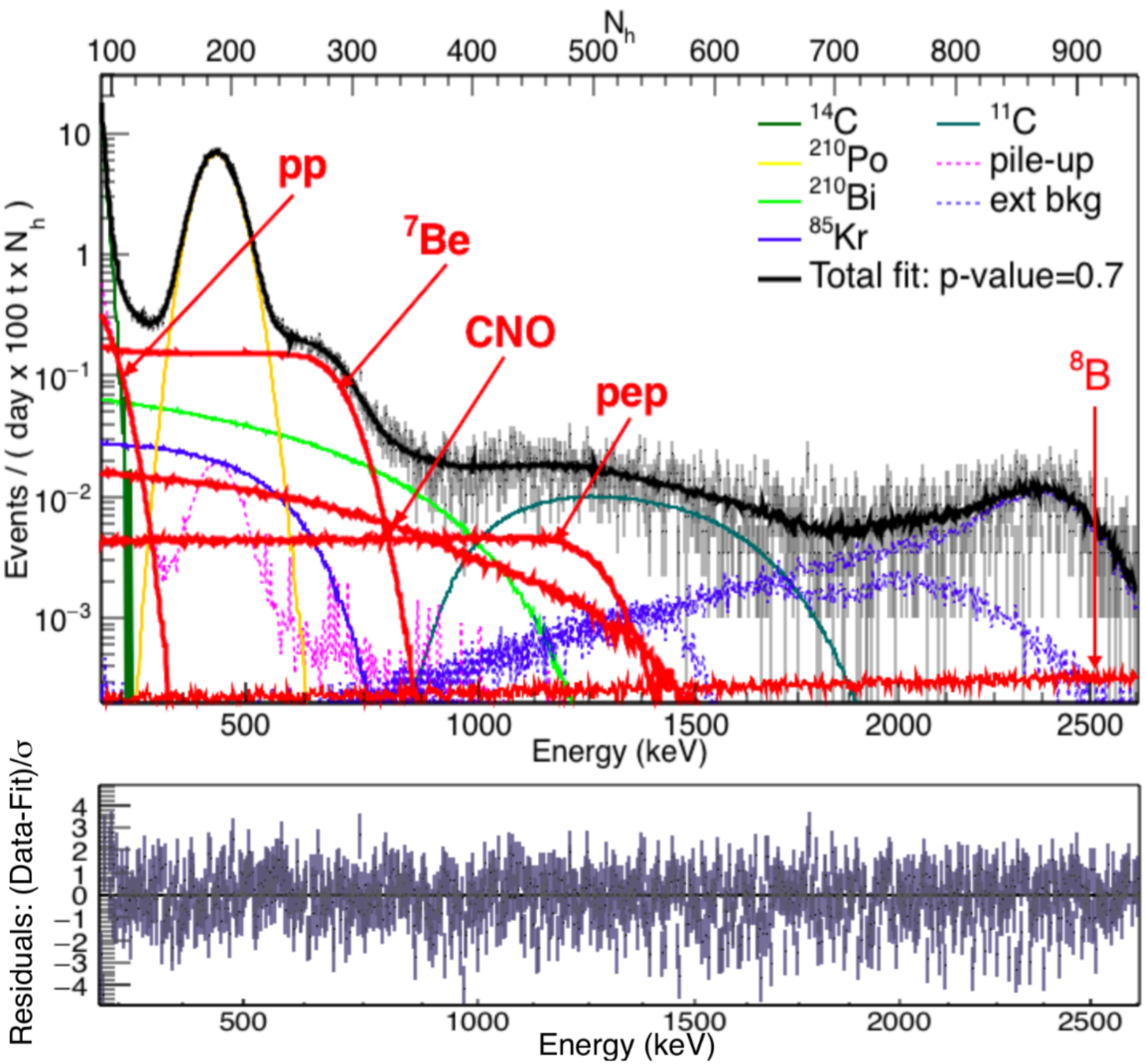
- **period, amplitude, and phase of the time evolution of the signal are consistent with its solar origin: T= 1 y, eccentricity = 0.0168 +- 0.0031**

- absence of an annual modulation is rejected at 99.99% C.L

[Astr. Phys. 92 (2017) 21]

Simultaneous spectroscopy of solar neutrinos

first global analysis of several solar neutrino components between 0.186 MeV and 2.927 MeV



Borexino PhaseII
dataset: Dec. 2011 - May 2016
exposure: 1291.51 days × 71.3 ton

Maximise a binned likelihood through a multivariate approach (TFC-tagged and TFC-subtracted energy spectrum, pulse shape, radial distribution)

2 complementary methods:

Analytical fit
- **model of the detector response (6 free parameters)**
- **possibility to describe unknown time variations**

Monte Carlo fit *[arXiv:1704.02291]*
- **detailed MC modeling tuned on calibrations data (PhaseI)**
- **sub% accuracy**

[arXiv:1707.09279]

Simultaneous spectroscopy of solar neutrinos

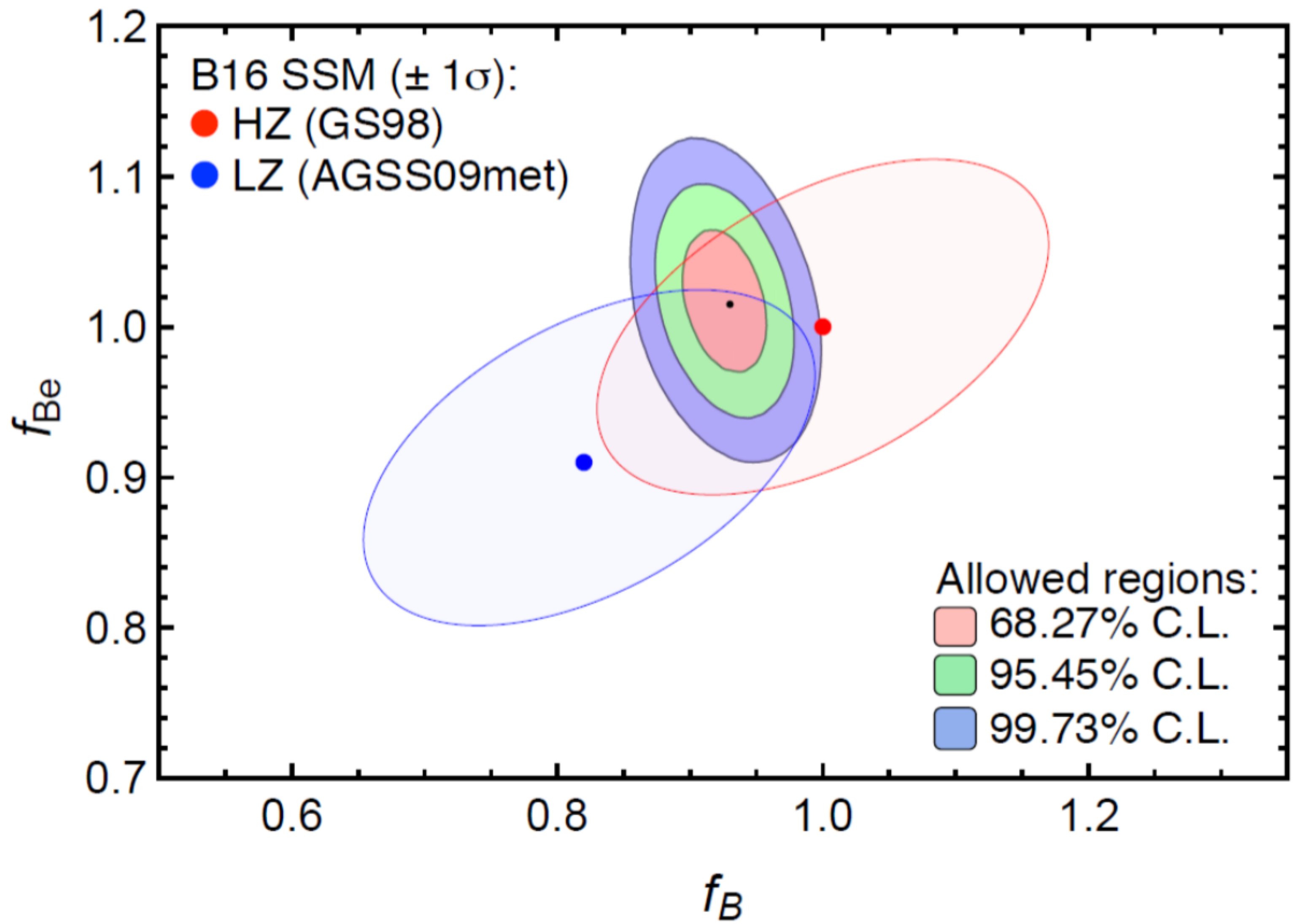
Rate in cpd/100 t and Flux in $cm^{-2}\ s^{-1}$

Solar ν	Borexino	B16(GS98)-HZ	B16(AGSS09)-LZ
pp	$134 \pm 10\ ^{+6}_{-10}$ $(6.1 \pm 0.5\ ^{+0.3}_{-0.5}) \times 10^{10}$	131.0 ± 2.4 $5.98\,(1 \pm 0.006) \times 10^{10}$	132.1 ± 2.3 $6.03\,(1 \pm 0.005) \times 10^{10}$
^{7}Be	$48.3 \pm 1.1\ ^{+0.4}_{-0.7}$ $(4.99 \pm 0.13\ ^{+0.07}_{-0.10}) \times 10^{9}$	47.8 ± 2.9 $4.93\,(1 \pm 0.06) \times 10^{9}$	43.7 ± 2.6 $4.50\,(1 \pm 0.06) \times 10^{9}$
pep (HZ)	$2.43 \pm 0.36\ ^{+0.15}_{-0.22}$ $(1.27 \pm 0.19\ ^{+0.08}_{-0.12}) \times 10^{8}$	2.74 ± 0.05 $1.44\,(1 \pm 0.009) \times 10^{8}$	2.78 ± 0.05 $1.46\,(1 \pm 0.009) \times 10^{8}$
pep (LZ)	$2.65 \pm 0.36\ ^{+0.15}_{-0.24}$ $(1.39 \pm 0.19\ ^{+0.08}_{-0.13}) \times 10^{8}$	2.74 ± 0.05 $1.44\,(1 \pm 0.009) \times 10^{8}$	2.78 ± 0.05 $1.46\,(1 \pm 0.009) \times 10^{8}$
CNO	< 8.1 (95% C.L.) $< 7.9 \times 10^{8}$ 95% C.L.)	4.91 ± 0.56 $4.88\,(1 \pm 0.11) \times 10^{8}$	3.52 ± 0.37 $3.51\,(1 \pm 0.10) \times 10^{8}$

- **pp** interaction rate obtained with a 30% better precision wrt previous results
- **^{7}Be** ν known with a better precision than the theoretical predictions for HZ-LZ solar model
- strongest evidence of **pep** ν (signal absence rejected at 5σ)
- current best limit on **CNO** ν

[arXiv:1707.09279]

Implications on the physics of the sun



- Borexino-KamLand Data combined
- HZ/LZ contour are 1σ theoretical prediction
- $fX = \Phi(X)/\Phi(X)_{HZ}$ in the axis are the reduced fluxes

with new ^{7}Be Phase-II results and ^{8}B from Borexino
[PRD 82 033006 (2010)]

Stay tuned: new ^{8}B measurement very soon!

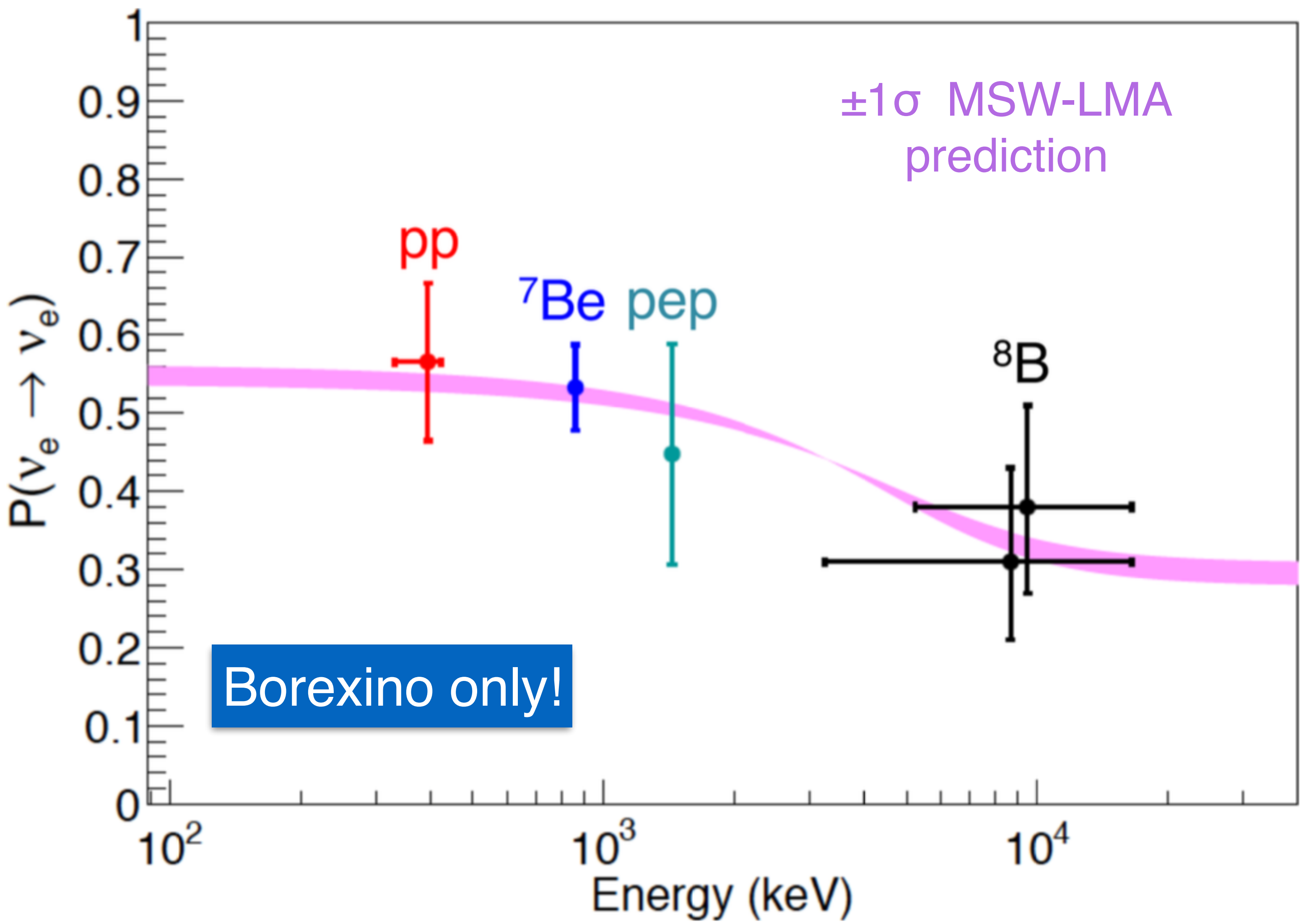
- discrimination between HZ/LZ solar models is now dominated by theoretical uncertainties

- a weak hint towards the HZ hypothesis

[arXiv:1707.09279]

Neutrino survival probability P_{ee} with Borexino

Survival probability of ν_e produced in the pp chain in the Sun



with new Phase-II results and ^{8}B from Borexino [PRD 82 033006 (2010)]

Stay tuned: new ^{8}B measurement very soon!

consistent with MSW-LMA (Mikheyev-Smirnov-Wolfenstein effect with Large Mixing Angle scenario)

consistent with SSM predictions —> sun has been stable for the past 10^5 years

[arXiv:1707.09279]

Update of the effective neutrino magnetic moment (NMM)

- **minimal extension of SM**: NMM proportional to neutrino mass

  —> $\mu_\nu < 10^{-18}\ \mu_B$ ~ 7-8 orders of magnitude lower than existing experimental limits

- **further extension of SM and new physics**: NMM proportional to lepton mass

  —> expectations reach the level of the the current experimental limits!

Neutrino-electron elastic scattering: most sensitive test for NMM search

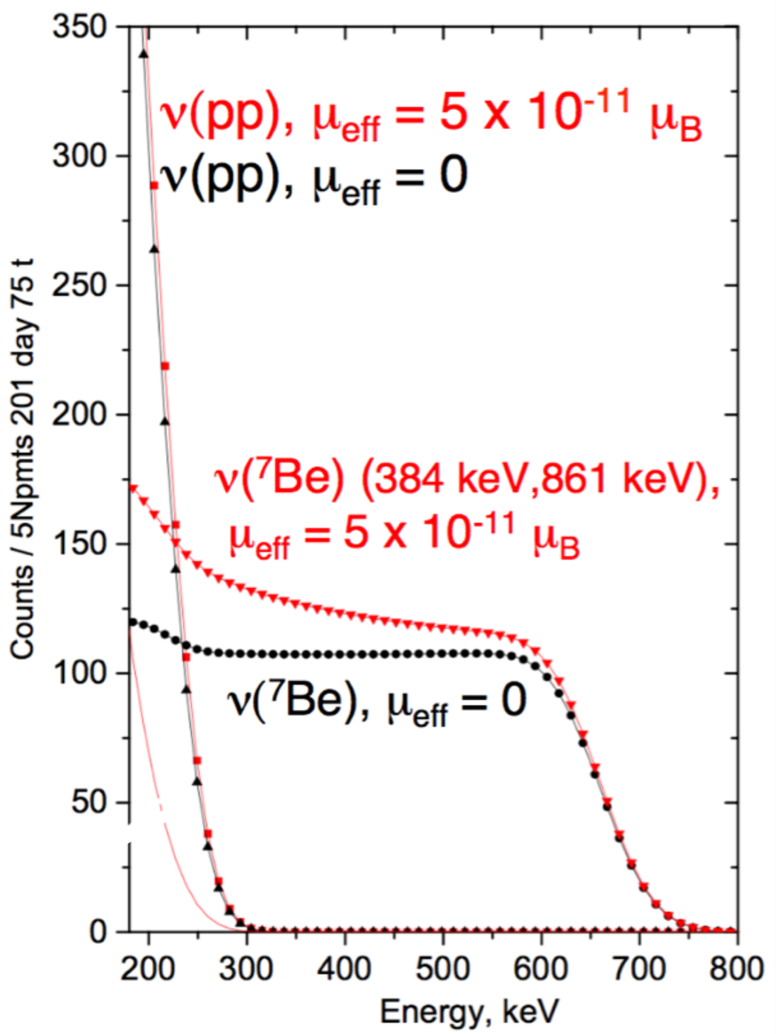
$$\frac{d\sigma_{EM}}{dT_e}(T_e, E_\nu) = \pi\, r_0^2\, \mu_{eff}^2 \left(\frac{1}{T_e} - \frac{1}{E_\nu}\right)$$

the spectrum of the scattered electron is influenced mostly at low E

^{7}Be ν: strong change of the shape (high sensitivity to NMM)

pp ν: the change of the shape is almost equivalent to the change of normalisation

—> constraints on the sum of the solar neutrino fluxes (from radiochemical gallium experiments) is applied



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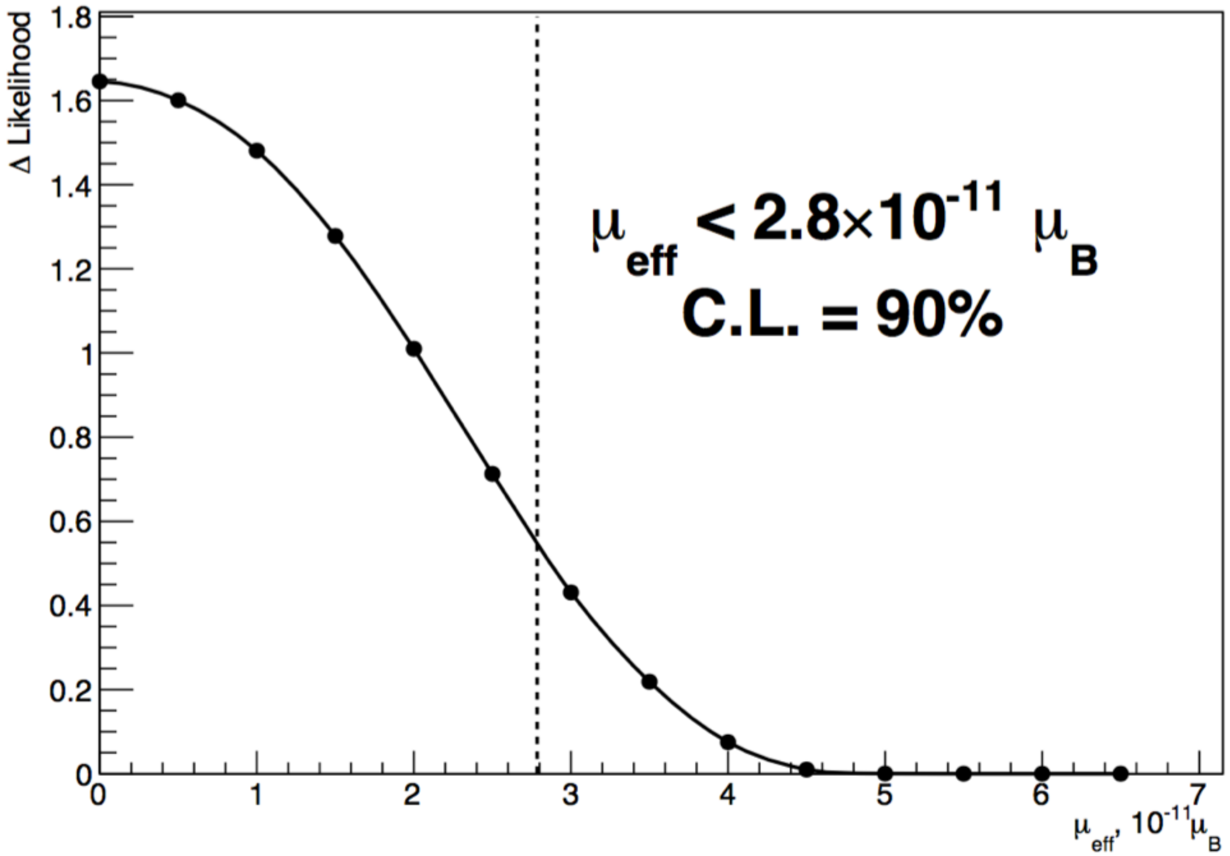


Borexino PhaseII
dataset: Dec. 2011 - May 2016
exposure: 1291.51 days × 71.3 ton

using the most conservative mass hierarchy, a 90% C.L. limit on each contribution can be obtained by setting other two to zero:

$\mu_e < 3.9\cdot10^{-11}\mu_B$, $\mu_\mu < 5.8\cdot10^{-11}\mu_B$,
$\mu_\tau < 5.8\cdot10^{-11}\mu_B$

[arXiv:1707.09355]

experiment/authors	source	$\times10^{-11}\mu_B$ [90% C.L.]
GEMMA [*Phys. Part. Nucl. Lett. 10 (2013) 139*] TEXONO [*PRD. 75 (2007) 012001*]	reactor anti-ν_e	$\mu_e<2.9$ $\mu_e<7.4$
Raffelt & Dearborn [*PRD 37 (1988) 2*] Arcea-Díaz et al. [*Astr. Phys. 2015 1*]	astrophysical (red giant cooling)	$\mu_e<0.3$ $\mu_e<0.22$
Super-K [*PRL 93 (2004) 021802*]	solar ^{8}B ν_e other solar + KamLand	$\mu_{eff}<36$ $\mu_{eff}<11$
Borexino (**old**) [*PRL 101 (2008) 091302*] Borexino (**new**)	solar ^{7}Be ν_e solar ^{7}Be + pp ν_e	$\mu_{eff}<5.4$ $\mu_{eff}<2.8$

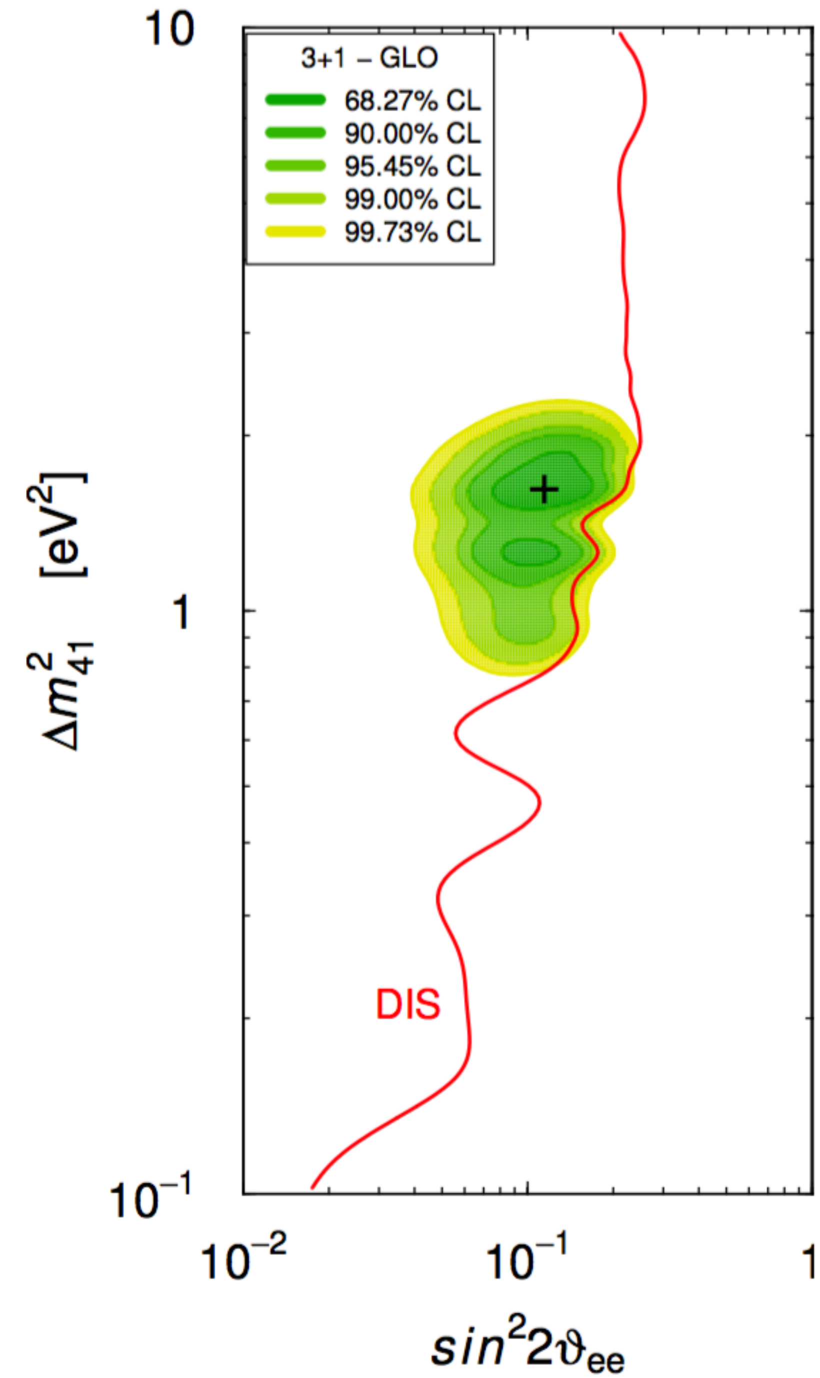
SOX - Short distance neutrino Oscillations with boreXino

several experimental anomalies found in ν_e /anti-ν_e appearance/disappearance experiments

Accelerator anomaly: ~ 3.8σ
LSND: Appearance of anti-ν_e in anti-ν_μ beam
Confirmed by MiniBooNE which registered ν_e and ν_μ beam

Gallium anomaly: ~ 2.8σ
Deficit observed in ν_e coming from ^{51}Cr and ^{37}Ar

Reactor anti-ν_e anomaly: ≈ 3.0σ
Re-evaluation of reactor antineutrino spectra results.
Observed rate deficit in all short-baseline (L = 10 – 100 m)



[PRD 88 (2013) 073008]

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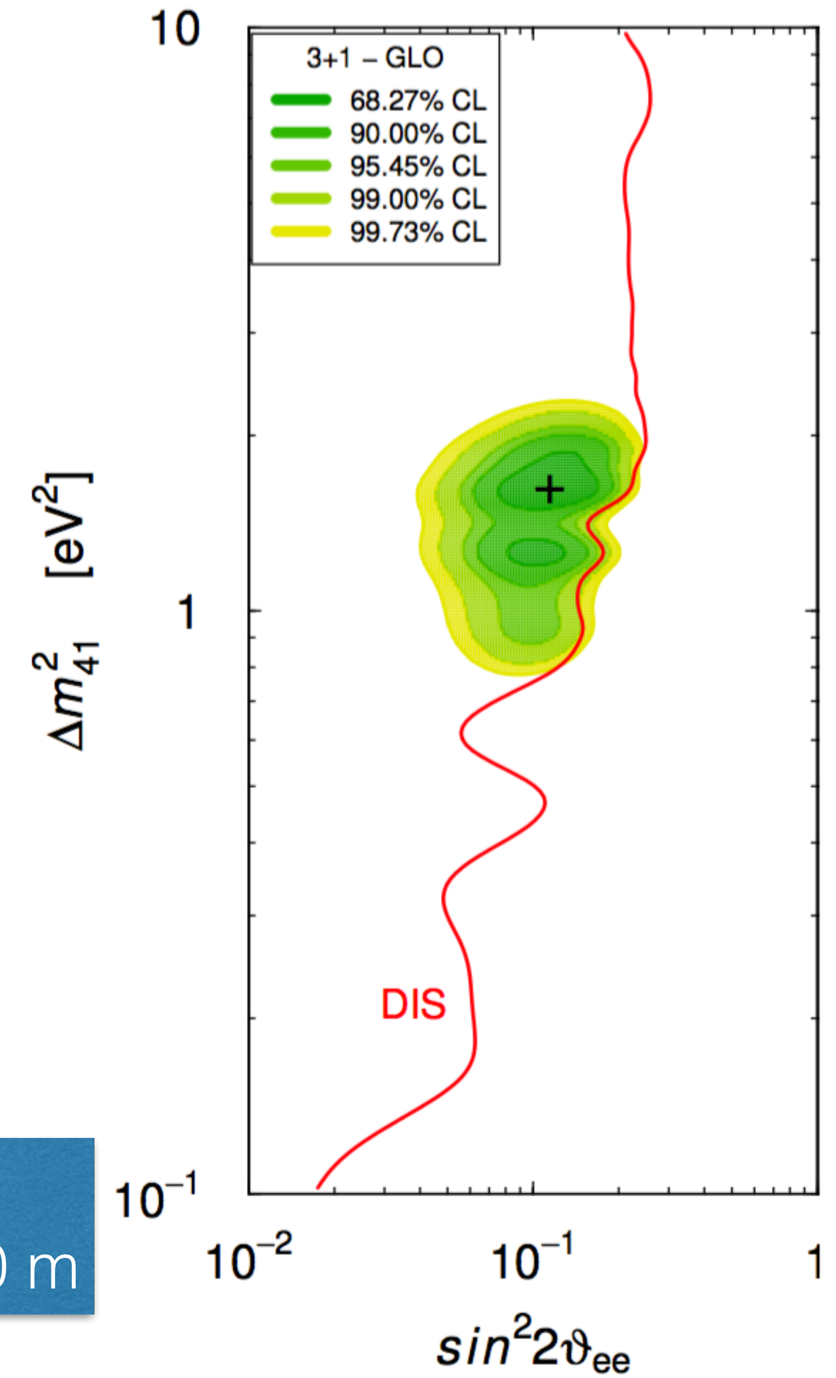
Reactor anti-ν_e anomal
Re-evalu ... eutrino spectra results.
Observed ... deficit in all short-baseline (L = 10 – 100 m)

weakened by Daya Bay recent results

possible solution: a sterile neutrino state with $\Delta m^2 \sim 1$ eV^2
[global fit gives $0.82 < \Delta m^2 < 2.14$ eV^2 (3σ)]
not yet updated after Daya Bay results: arXiv:1704.01082

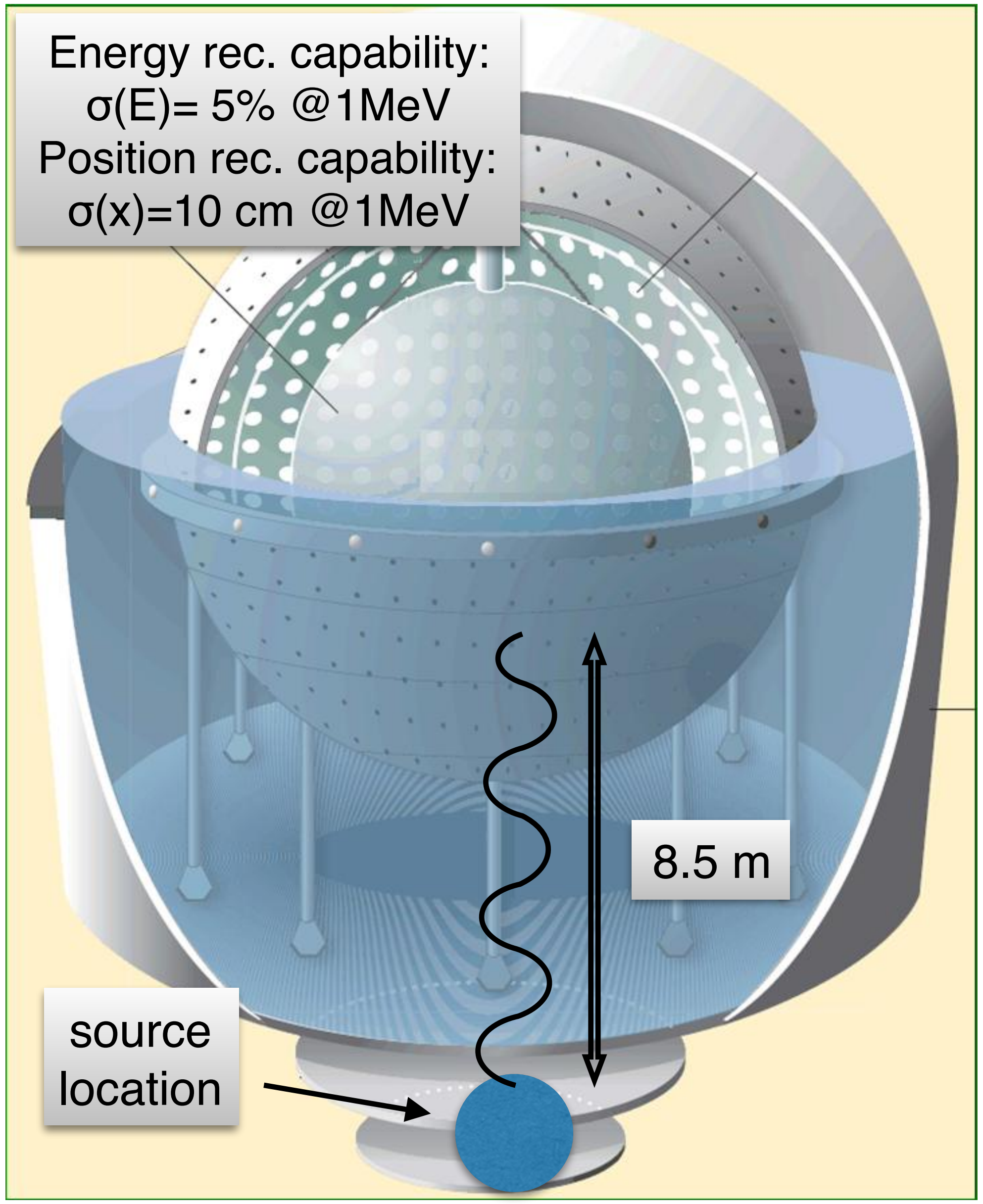
To be sensitive to $\Delta m^2 \sim 1$ eV^2:
neutrino source with E~1-10 MeV, located at a distance L~1-10 m

→ radioactive source under Borexino!



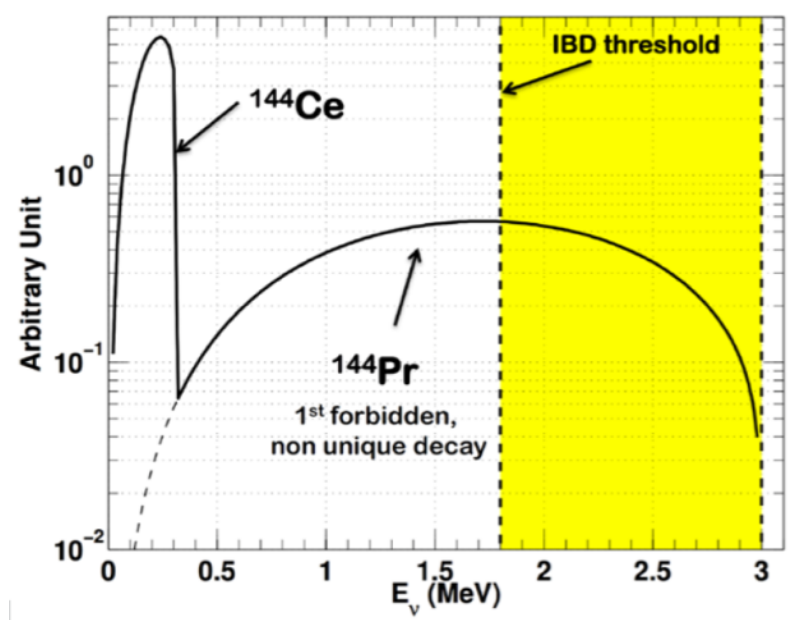
[PRD 88 (2013) 073008]

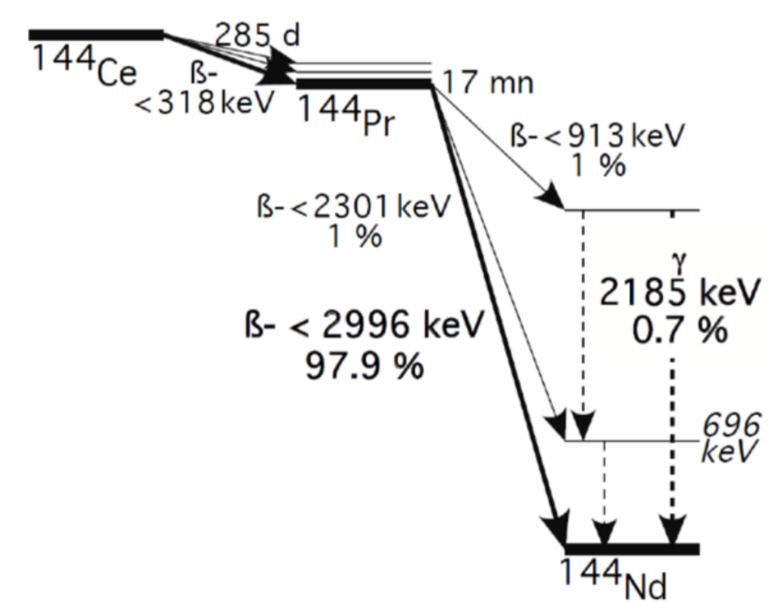
SOX - setup



^{144}Ce - ^{144}Pr anti-ν_e source:

- E_{ν_e}<2.99 MeV, τ~411 days
- initial activity ~ 100-150 kCi
- expected ~10^4 events in 1.5 years
- extraction from nuclear fuel (Mayak facility, Russia)
- 2.3ton Tungsten-alloy shield for high-energy γ





- 2 calorimeter setups to determine source activity (tested and fully functional)
- anti-ν_e spectral measurements from 3 independent apparatus

Source Pros:
no source background, deep underground, known neutrino spectrum, small size

SOX - source transportation

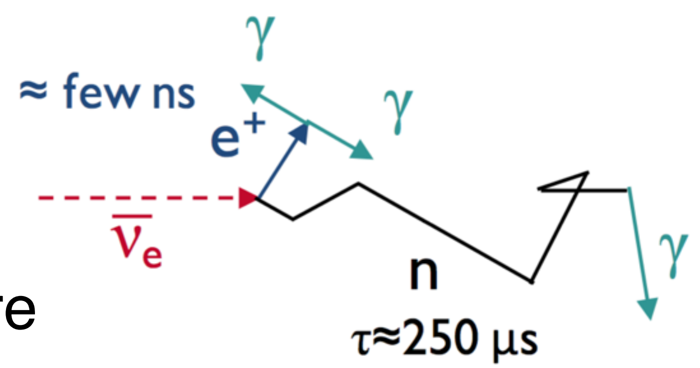
Source Cons: very hard to produce, transport, authorise

transportation from Mayak to Gran Sasso Laboratory and within the Lab. planned in detail

the **source production** will be finished by the end of 2017
data taking will start at the latest April 2018

SOX - detection mechanism and analysis

detection mechanism: $\overline{\nu}_e + p \rightarrow n + e^+$



→ prompt (e^+) and delayed (n capture): clear coincidence signature
→ almost background free (20 events/yr)

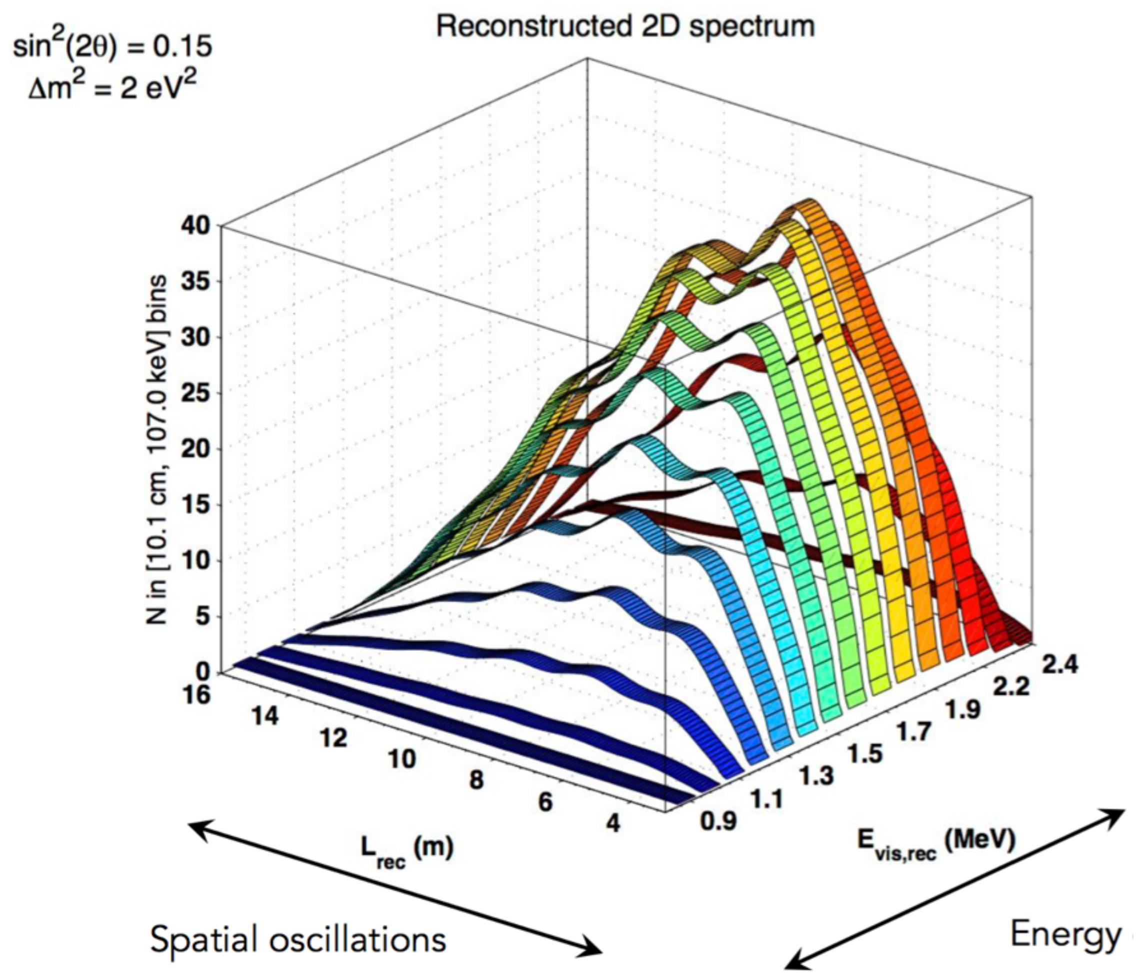
two techniques:

total counts (rate analysis)
standard disappearance experiment

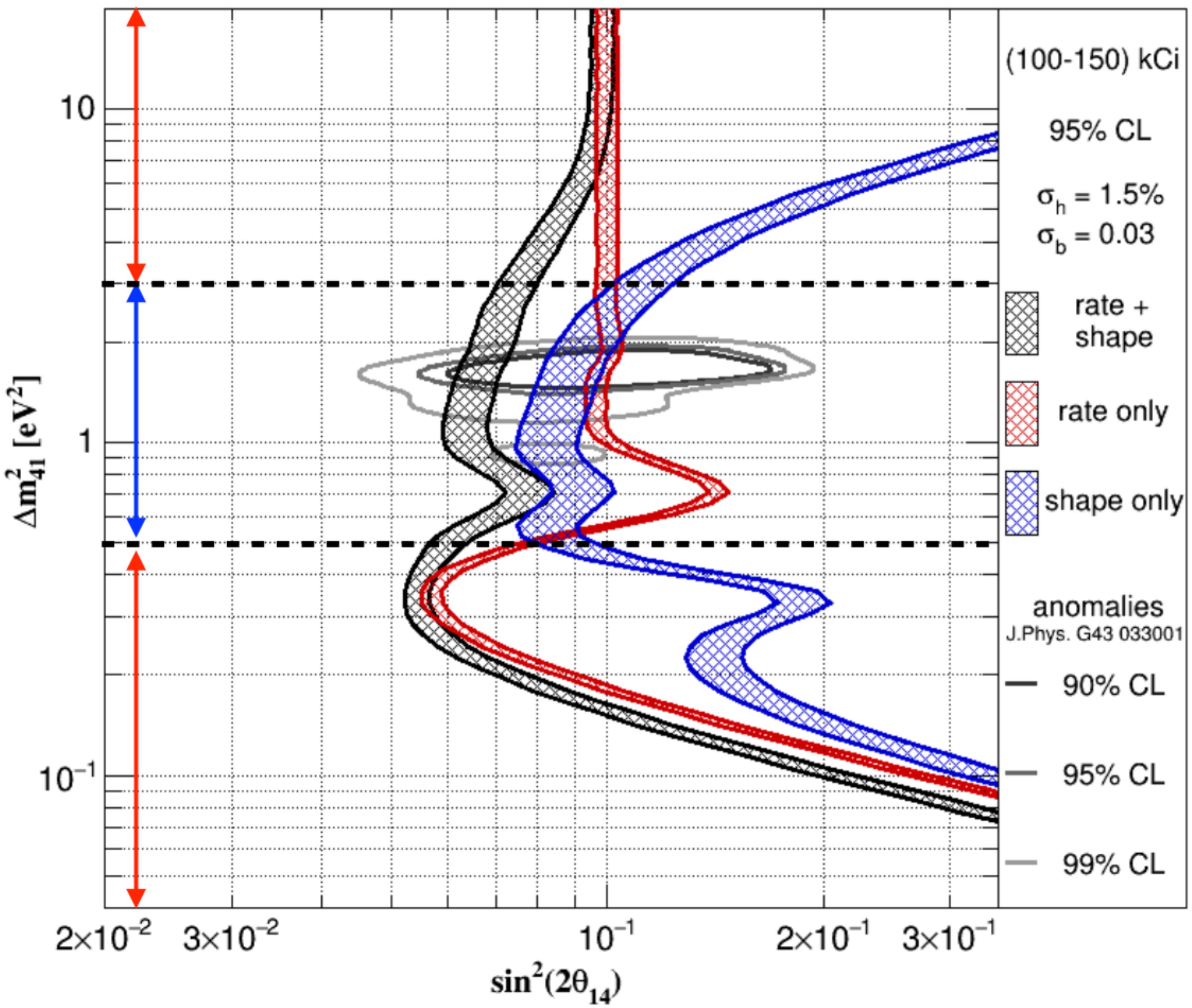
the activity of the source and the anti-ν_e spectrum must be known precisely!

spatial waves (shape analysis)
oscillation pattern in (E,L) plane

the anti-ν_e spectrum must be known but knowledge of the source activity not necessary!



SOX - Sensitivity



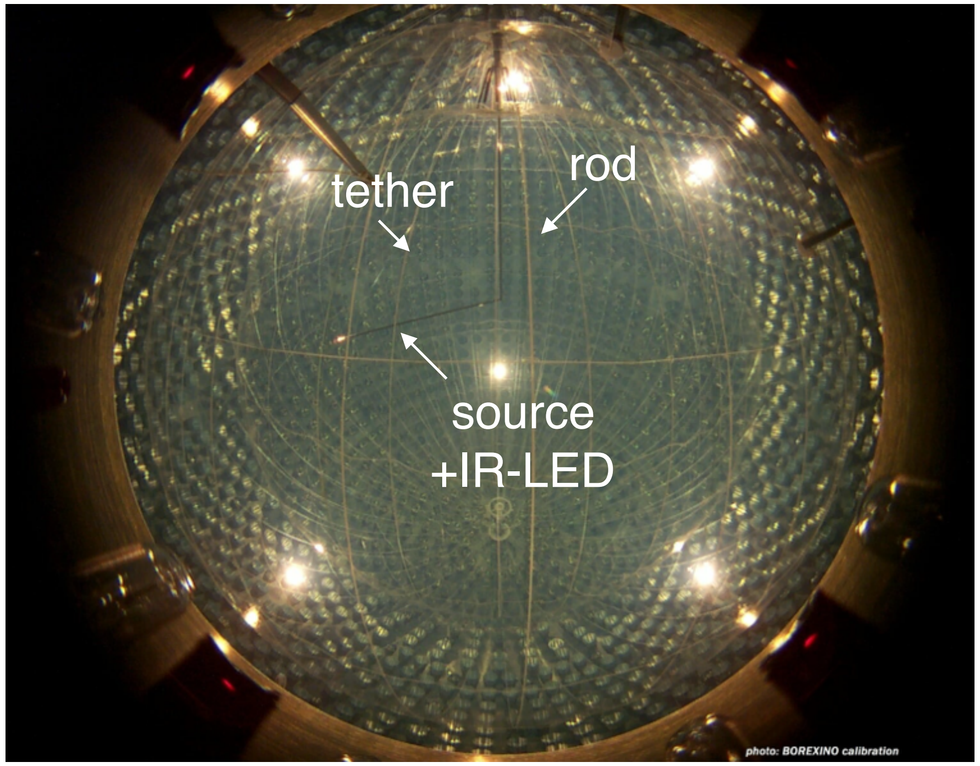
assuming:
σ=0.015 on activity meas.
σ=0.03 on spectrum meas.

0.1 <Δm^2<5 eV^2 best sensitivity window

rate + shape analysis:

almost the whole anomaly region could be excluded

SOX - calibration campaign



use well-tested Borexino calibration system:

➡ insertion of sources via interconnecting rods

➡ source location system composed of 6 CCD cameras looking for the position of a IR-LED attached to the source

➡ clean room and glove box for all manipulation to avoid perturbing the radio-purity of the detector

different source types and scans in the whole active volume

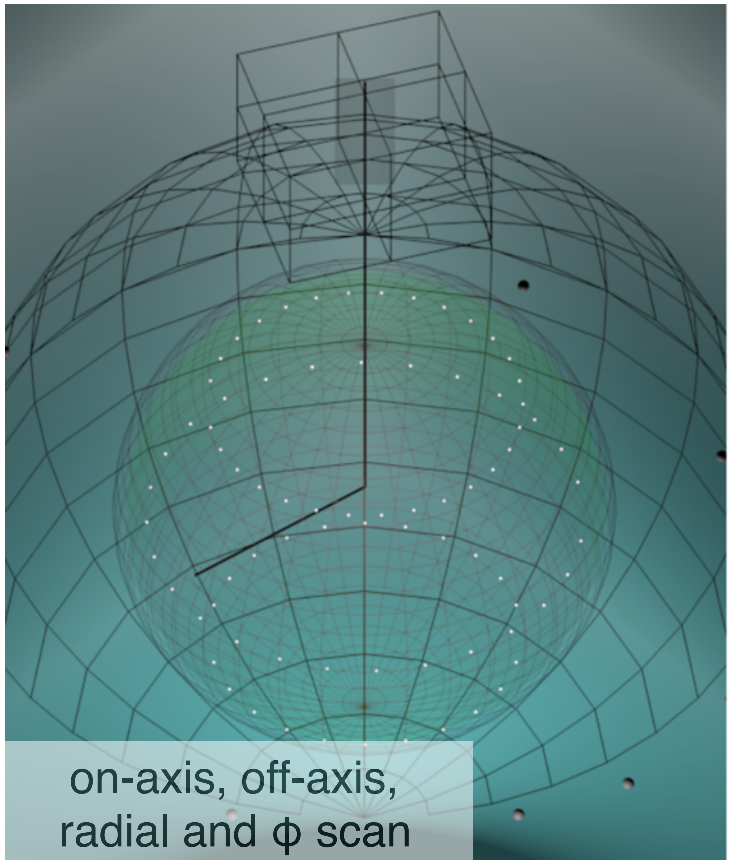
- map energy and position response precisely (^{222}Rn and mono-energetic γ sources)

- map the neutron and positron detection efficiency, especially at the vessel border (^{241}Am-^{9}Be, ^{68}Ga-^{68}Ge sources)

- tune the Monte Carlo

- test the new trigger for SOX

scheduled for this fall



Conclusion and prospects

- Borexino is now running into a precision spectroscopy phase, testing solar models and helping to solve the metallicity issue
- Phase-II results have improved accuracy compared to Phase-I thanks to new fitting tools and to the highly reduced background
- new upper limit on the effective neutrino magnetic moment (at the level of GEMMA's result)

further new results:

- testing neutrino excess from LIGO events (Gravitational Waves) [arXiv:1706.10176]
- neutrino-GRB correlation: best limits on all-flavours ν fluence below 7 MeV [Astro. Phys. 86 (2017) 11]

Next steps:

- **improved measurement of solar ^{8}B at low threshold (>3MeV)**
- **struggle to improve CNO sensitivity**
- **investigation of anomalous oscillatory behaviour in neutrinos with SOX**

The Borexino and SOX Collaborations

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backup

FIT: systematic uncertainty sources

Source of uncertainty	*pp* −%	*pp* +%	^{7}Be −%	^{7}Be +%	*pep* −%	*pep* +%
Fit method (analytical/MC)	-1.2	1.2	-0.2	0.2	-4.0	4.0
Choice of energy estimator	-2.5	2.5	-0.1	0.1	-2.4	2.4
Pile-up modeling	-2.5	0.5	0	0	0	0
Fit range and binning	-3.0	3.0	-0.1	0.1	1.0	1.0
Fit models (see text)	-4.5	0.5	-1.0	0.2	-6.8	2.8
Inclusion of ^{85}Kr constraint	-2.2	2.2	0	0.4	-3.2	0
Live Time	-0.05	0.05	-0.05	0.05	-0.05	0.05
Scintillator density	-0.05	0.05	-0.05	0.05	-0.05	0.05
Fiducial volume	-1.1	0.6	-1.1	0.6	-1.1	0.6
Total systematics (%)	-7.1	4.7	-1.5	0.8	-9.0	5.6

Update of the geo-neutrinos measurement

$\bar{\nu}_e$ produced by β decays of long-lived isotope in the interior of the Earth (^{238}U, ^{232}Th chains, and ^{40}K)

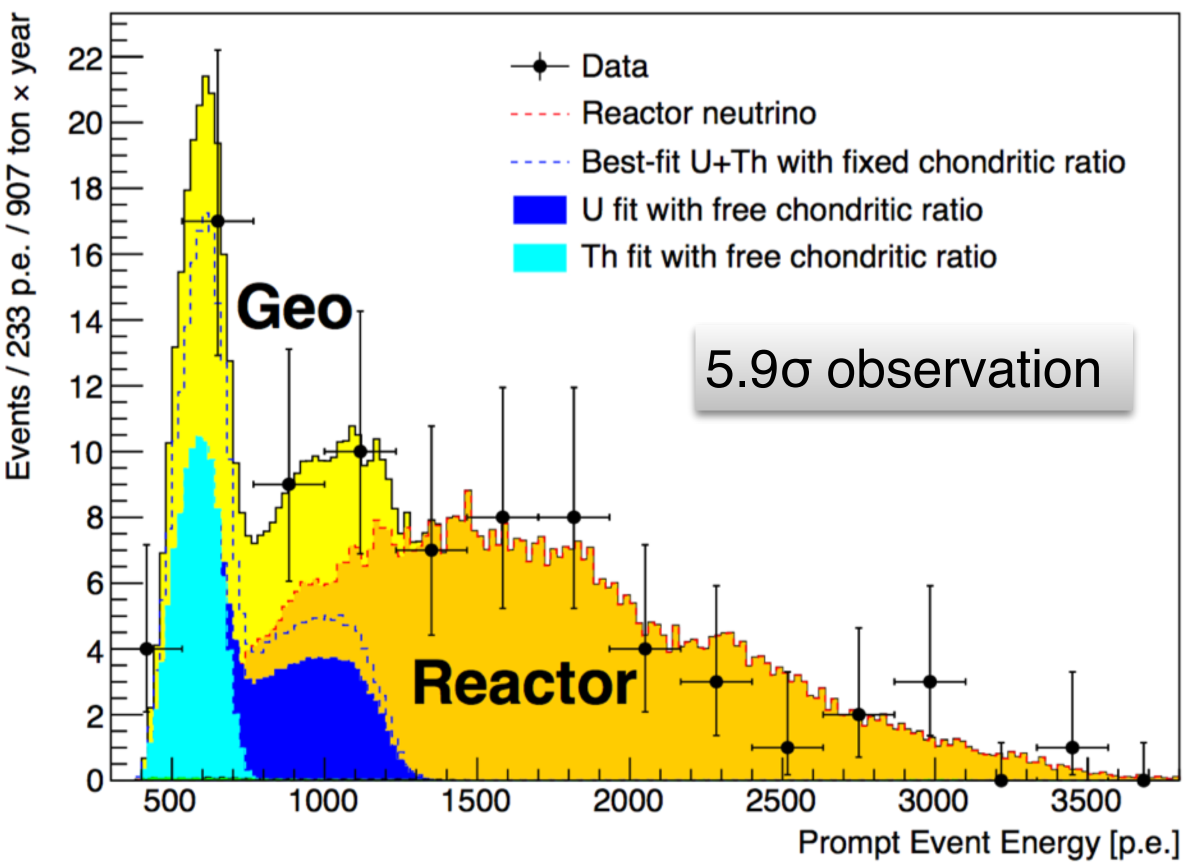
detection mechanism: inverse beta decay

$$\overline{\nu}_e + p \rightarrow n + e^+$$

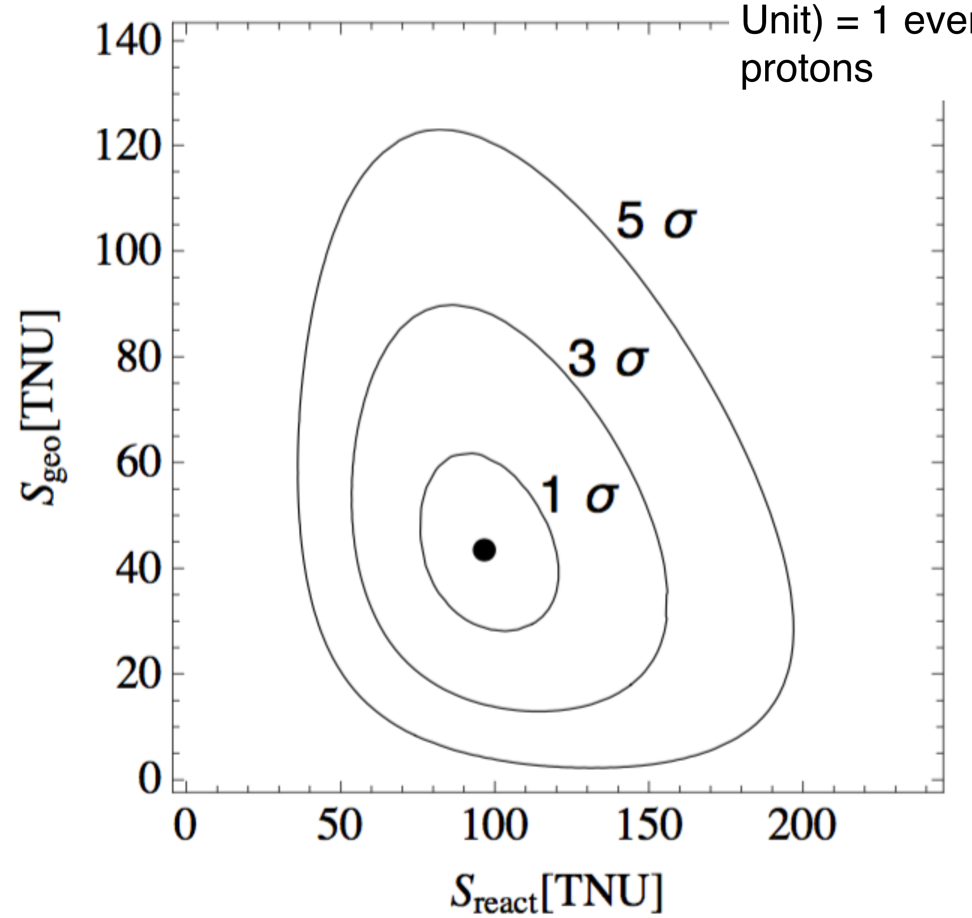
dataset: Dec. 2007 - March 2015
exposure: 2055.9 days × 71.3 ton

chondritic model is assumed: m(Th)/m(U) = 3.9

Log-Likelihood fit: Geo-neutrinos out of Reactor neutrinos



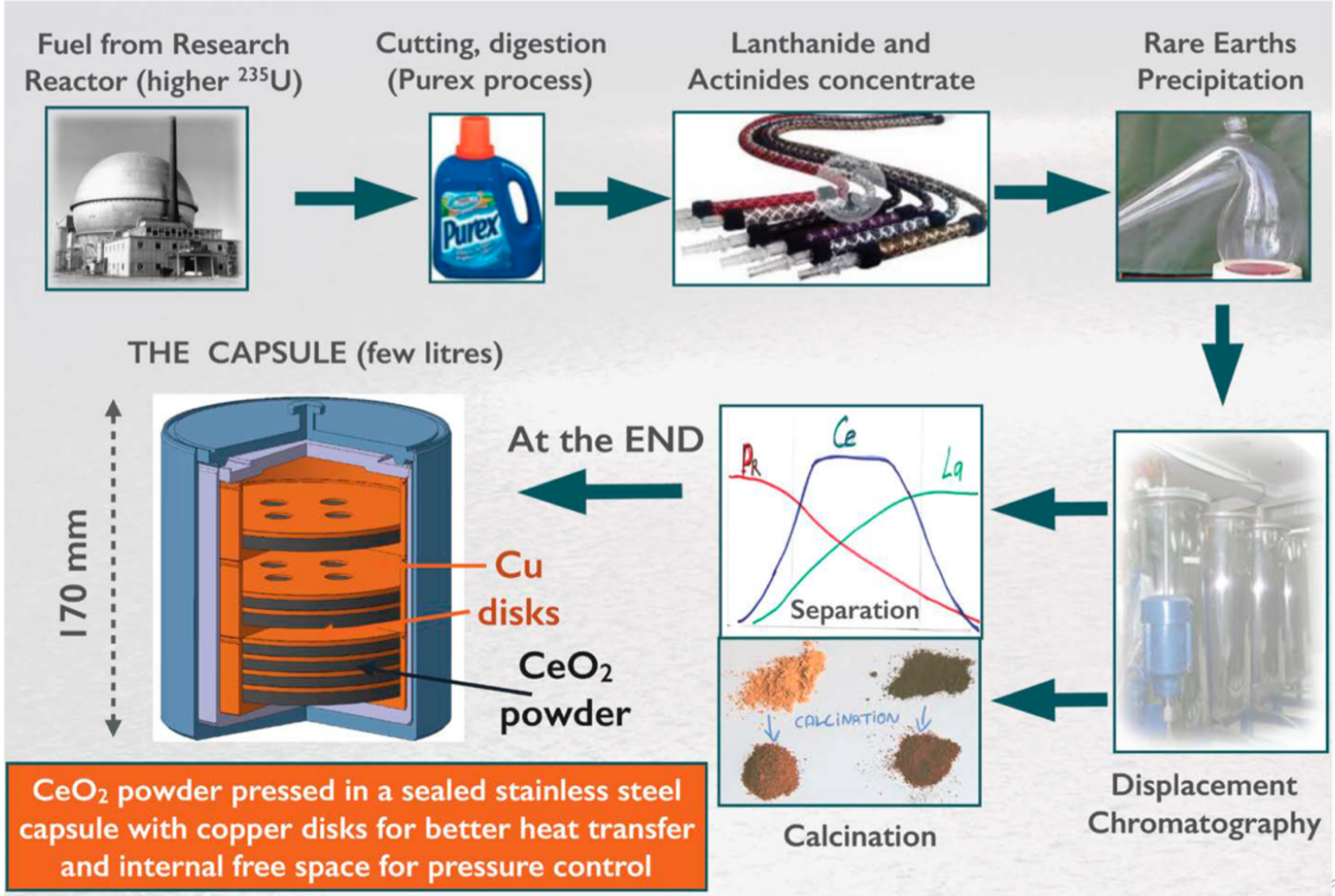
1 TNU (Terrestrial Neutrino Unit) = 1 event/year/10^{32} protons



A geo-neutrino signal from the mantle is obtained at 98% C.L.

[PRD92(2015)031101(R)]

SOX: source production, shielding and radioactive impurities

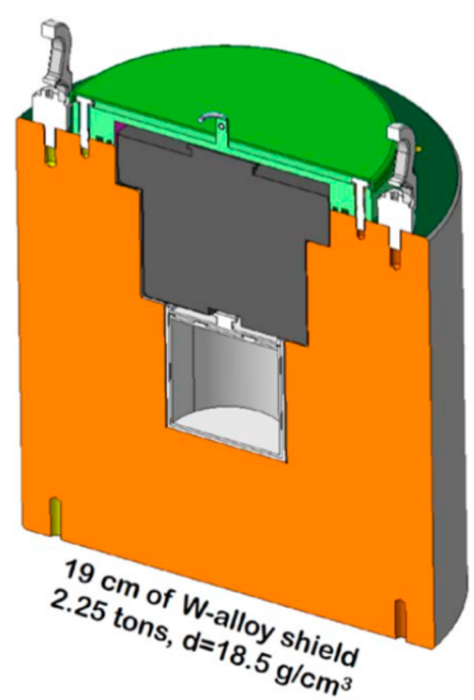


γ **radiation of ^{144}Ce itself must be fully shielded**

Strict constrains on the CeO_2 powder:

- γ rate: $< 10^{-5}$ Bq/Bq w.r.t. ^{144}Ce
- n rate: $< 10^{-5}$ Bq/Bq w.r.t. ^{144}Ce (max 10^5 s^{-1})
- A long list of nuclei to check! (γ, α, ICPMS, n)
- Power from impurities 10^{-3} W/W w.r.t. ^{144}Ce

^{22}Na, ^{44}Ti-^{44}Sc, ^{49}V, ^{54}Mn, ^{55}Fe, ^{57}Co, ^{60}Co, ^{63}Ni, ^{65}Zn, ^{68}Ge-^{68}Ga, ^{90}Sr-^{90}Y, ^{91}Nb, ^{93m}Nb, ^{106}Ru-^{106}Rh, ^{101}Rh, ^{102}Rh, ^{102m}Rh, ^{108m}Ag, ^{110m}Ag, ^{109}Cd, ^{113m}Cd, ^{119m}Sn, ^{121m}Sn, ^{125}Sb, ^{134}Cs, ^{137}Cs, ^{133}Ba, ^{143}Pm, ^{144}Pm, ^{145}Pm, ^{146}Pm, ^{147}Pm, ^{145}Sm, ^{151}Sm, ^{150}Eu, ^{152}Eu, ^{154}Eu, ^{155}Eu, ^{148}Gd, ^{153}Gd, ^{157}Tb, ^{158}Tb, ^{171}Tm, ^{173}Lu, ^{174}Lu, ^{172}Hf-^{172}Lu, ^{179}Ta, ^{178m}Hf, ^{194}Os-^{194}Ir, ^{192m}Ir, ^{193}Pt, ^{195}Au, ^{194}Hg-^{194}Au, ^{204}Tl, ^{210}Pb$\rightarrow^{206}$Pb, ^{207}Bi, ^{208}Po, ^{209}Po, ^{228}Ra$\rightarrow^{208}$Pb, ^{227}Ac$\rightarrow^{207}$Pb, ^{228}Th$\rightarrow^{208}$Pb, ^{232}U$\rightarrow^{208}$Pb, ^{235}Np, ^{236}Pu-^{232}U, ^{238}Pu$\rightarrow^{230}$Th, ^{239}Pu, ^{240}Pu, ^{241}Pu-^{241}Am, ^{241}Am, ^{242m}Am-^{230}Th, ^{243}Cm$\rightarrow^{235}$U, ^{244}Cm, ^{248}Bk-^{244}Am, ^{249}Bk-^{249}Cf, ^{248}Cf, ^{249}Cf, ^{250}Cf, ^{252}Cf, ^{252}Es, ^{254}Es-^{250}Bk.



Calibration campaign - Details

Main reaction for SOX: **anti-ν_e + p → n+e^+**

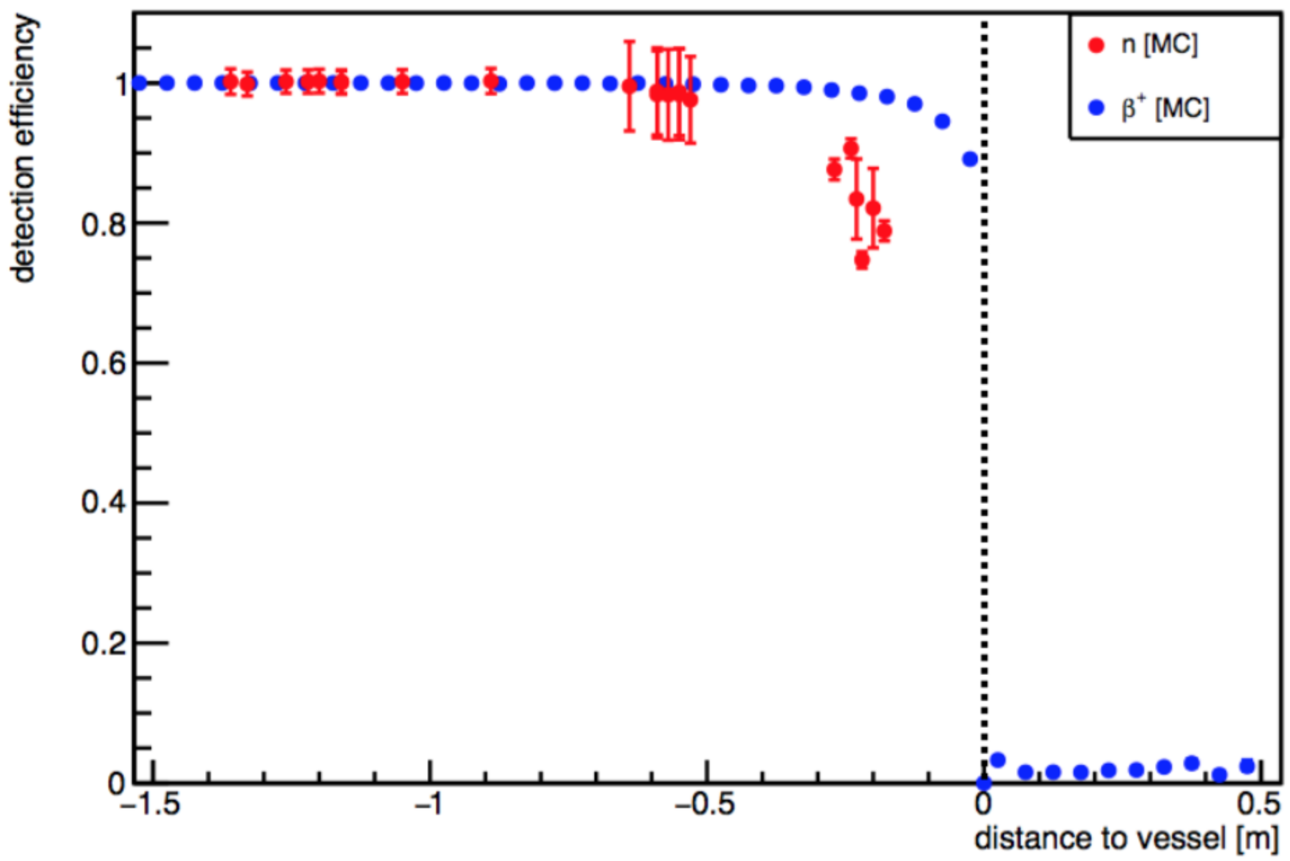
→ higher energies (IBD threshold: 1.8 MeV) wrt solar neutrinos

→ n and e+ are not point-like events

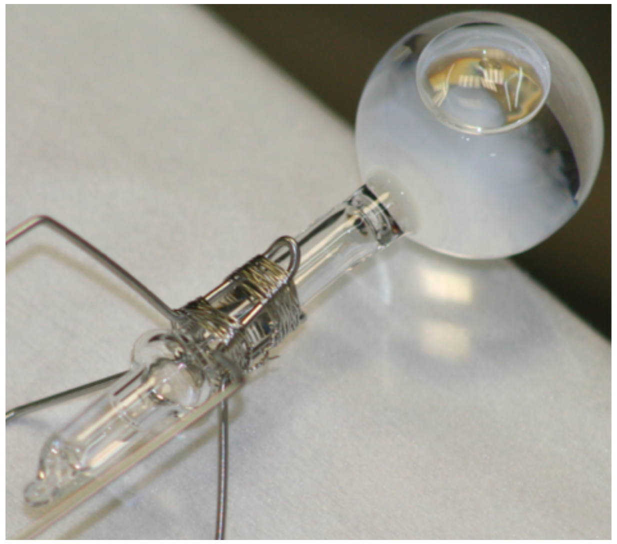
→ very clean signature: fiducial volume will be enlarged

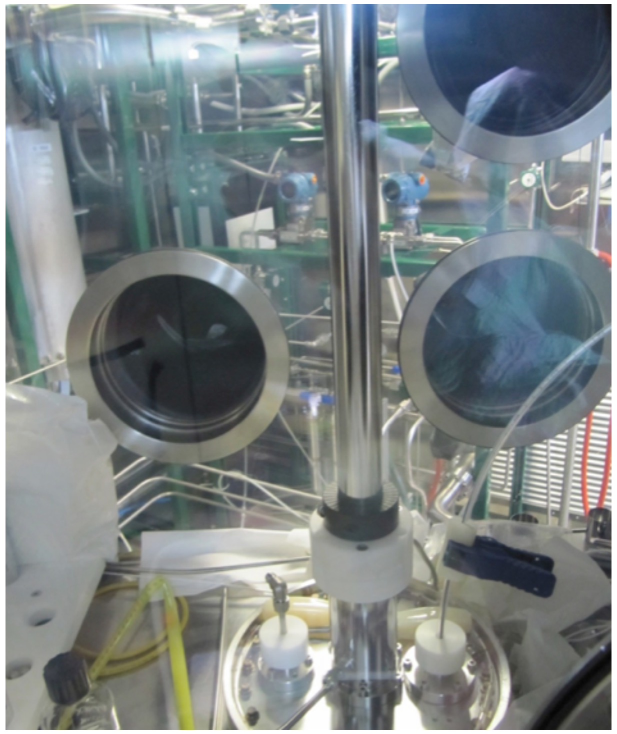
border effects must be understood very well

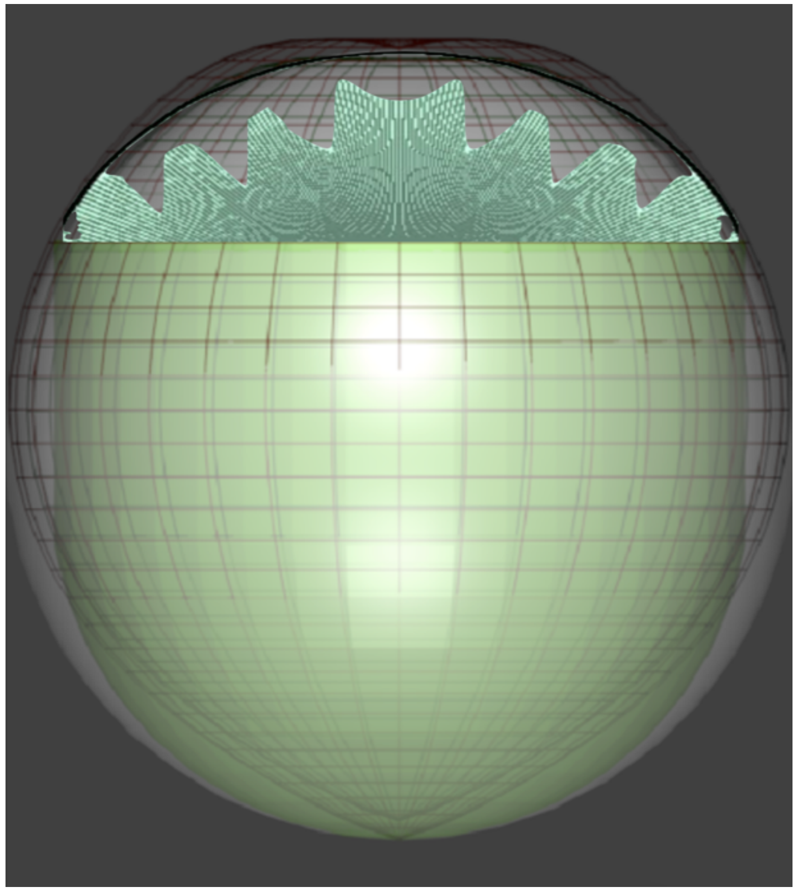
map the detection efficiency, especially at the vessel border



Calibration campaign - Details







Source	Type	E [MeV]	scan
$^{241}\mathrm{Am}^{9}\mathrm{Be}(+^{\mathrm{nat}}\mathrm{Ni})$	n	0-9	on-axis, off-axis radial, ϕ
$^{222}\mathrm{Rn}$	α	5.5, 6.0, 7.4	on-axis, off-axis, ϕ
	γ	0-3.2	on-axis, off-axis, ϕ
$^{68}\mathrm{Ge} -^{68}\mathrm{Ga}$	β^+	0-1.9 (+1.02)	on-axis, off-axis radial, ϕ
$^{85}\mathrm{Sr}$, $^{54}\mathrm{Mn}$, $^{65}\mathrm{Zn}$, $^{40}\mathrm{K}$	γ	0.5, 0.8, 1.1, 1.5	on-axis
$^{60}\mathrm{Co}$-$^{108m}\mathrm{Ag}$	γ	1.2-1.3, 0.4-0.6-0.7	on-axis