http://ifirse.icise.vn/nugroup/conf/nufrontier2018/index.html

Latest Phase-II results and **Prospects** of CNO neutrino detection with **BOREXino**

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International symposium on neutrino frontiers 2018
@ ICISE center, Quy Nhon, Vietnam 16–19 July 2018

BOREXINO COLLABORATION

UNIVERSITÀ DEGLI STUDI DI MILANO

INFN Istituto Nazionale di Fisica Nucleare

LNGS

PRINCETON UNIVERSITY

UNIVERSITÀ DEGLI STUDI DI GENOVA

NATIONAL RESEARCH CENTER "KURCHATOV INSTITUTE"

St. Petersburg Nuclear Physics Inst.

TUM Technische Universität München

University of Houston

JAGIELLONIAN UNIVERSITY IN KRAKÓW

JÜLICH Forschungszentrum

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UHH Universität Hamburg

НИИЯФ МГУ SKOBELTSYN INSTITUTE OF NUCLEAR PHYSICS LOMONOSOV MOSCOW STATE UNIVERSITY

University of Massachusetts Amherst 1863

Joint Institute for Nuclear Research

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

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Outline

- Introduction
- **Full pp-chain** solar neutrino
- Prospects for **CNO** solar neutrino
- Geo-neutrinos
- Conclusion

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- Introduction to Borexino experiment
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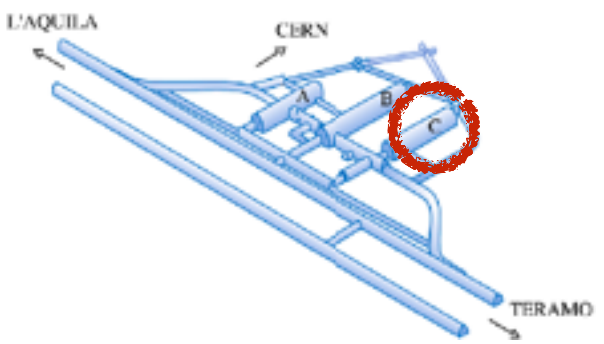
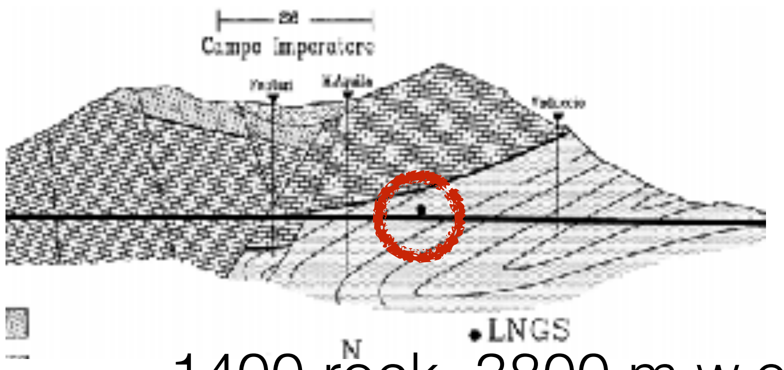
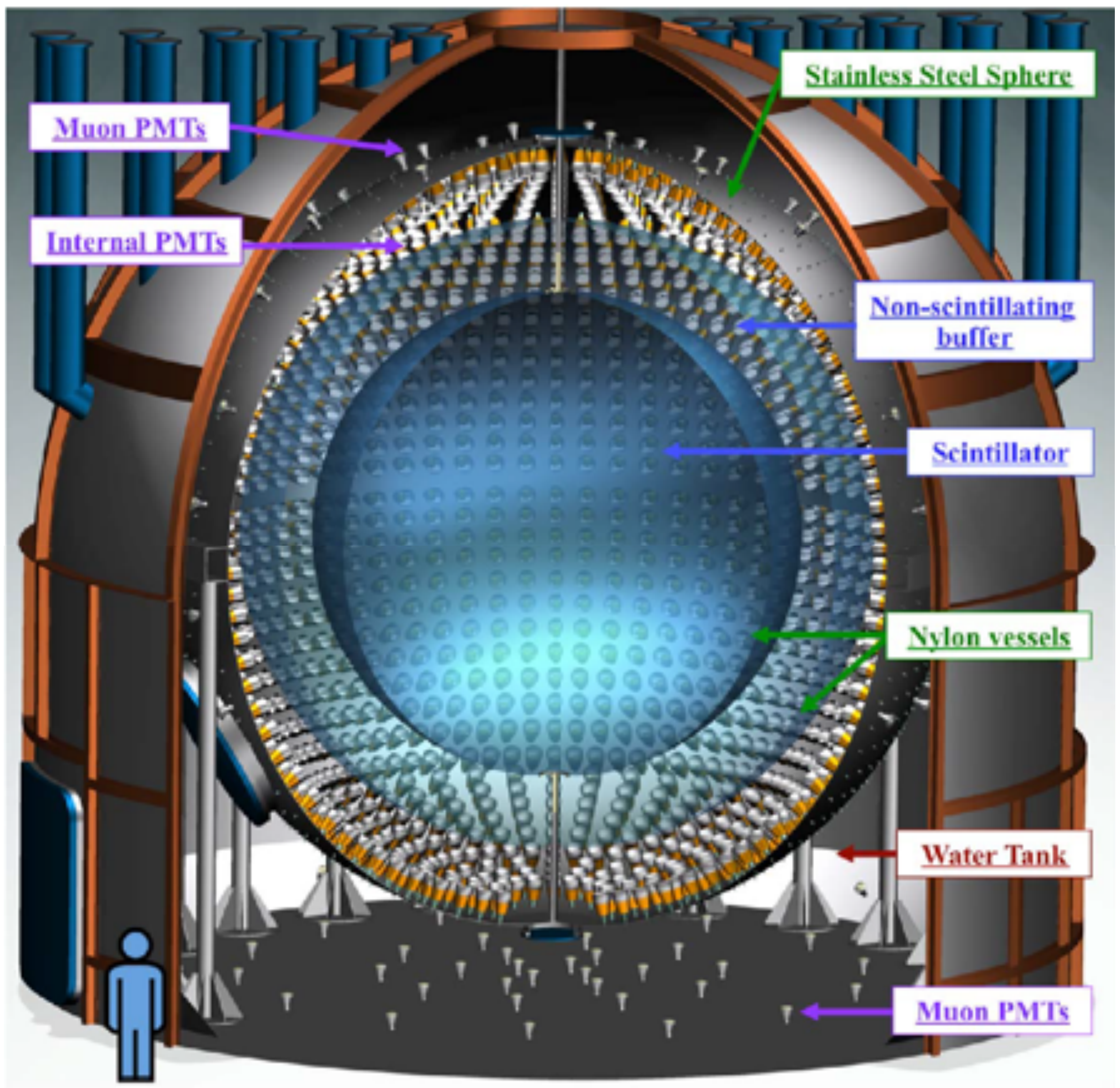
Borexino experiment





1400 rock, 3800 m.w.e.



- @ LNGS, 3800 m.w.e.
- **Center detector**:
  - Liquid scintillator + PMTs
- **Important characteristics**
  - σ_E 5%, σ_V 10 cm @ 1 MeV
  - IV ~300 ton, FV ~75 ton
  - LS ^{238}U, ^{232}Th ~ 10^{-19} g/g

Physics Program

2007 May-2010 May	2010-2011	2011 Dec-now
Phase-I	Purification + Calibration	**Phase-II**

Be7 Phys. Rev. Lett. 107, 141302 (2011)
pep Phys. Rev. Lett. 108, 051302 (2012)
pp Nature 512, 383-386 (28 August 2014)
3 MeV B8 Phys.Rev.D82:033006 (2010)
geo-neutrino PLB 687, 299-340 (2010)
Day-night symmetry PLB 707-1,22-26, (2012)
…

pp+Be7+pep+CNO arxiv 1707.09279
8B arxiv 1709.00756
neutrino magnetic moment PRD 96, 091103 (2017)
gravitational wave ApJ 850-21 (2017)
Be7 seasonal modulation AP, 92, 21-29 (2017)
gamma ray burst AP, 86, 11-17, (2017)
electric charge conservation PRL 115,231802(2017)
geo-neutrino PRD 93, 031101 (2015)
…

Outline

- Borexino experiment
- **Full** pp-chain solar neutrino
- Prospects for CNO solar neutrino
- Geo-neutrinos
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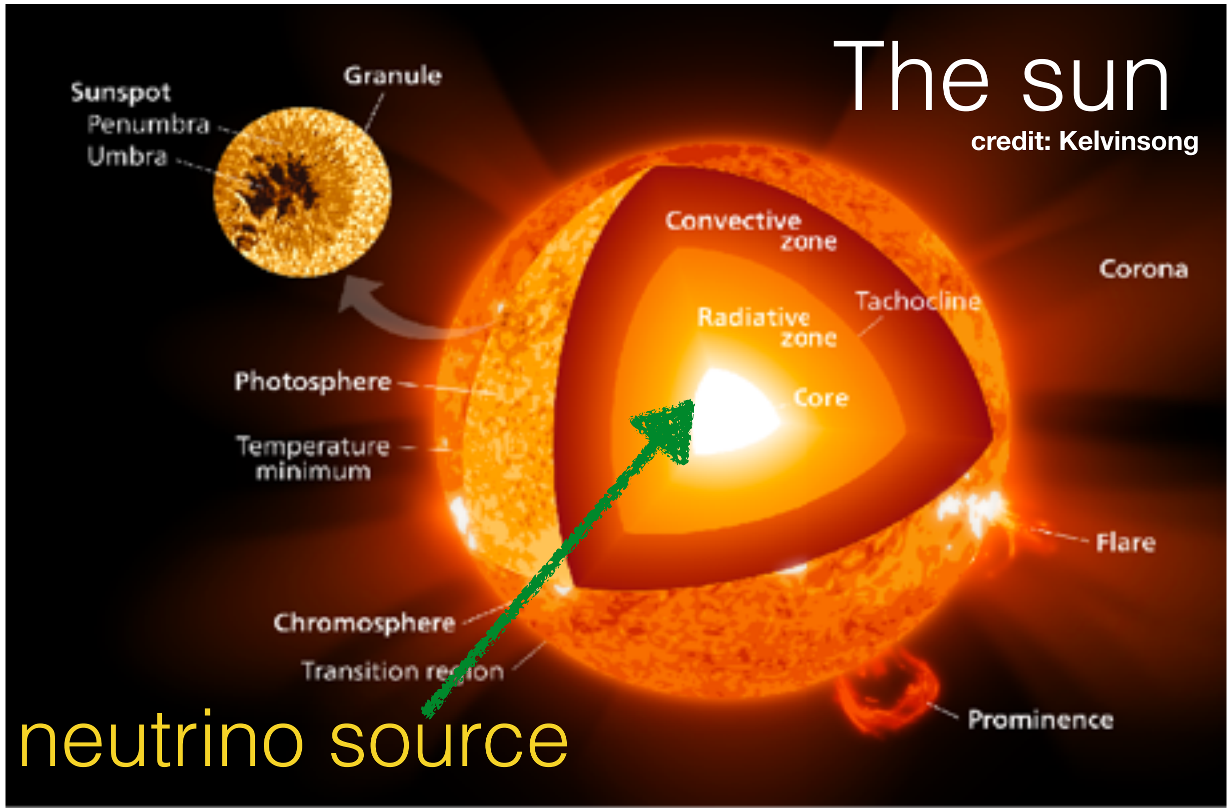
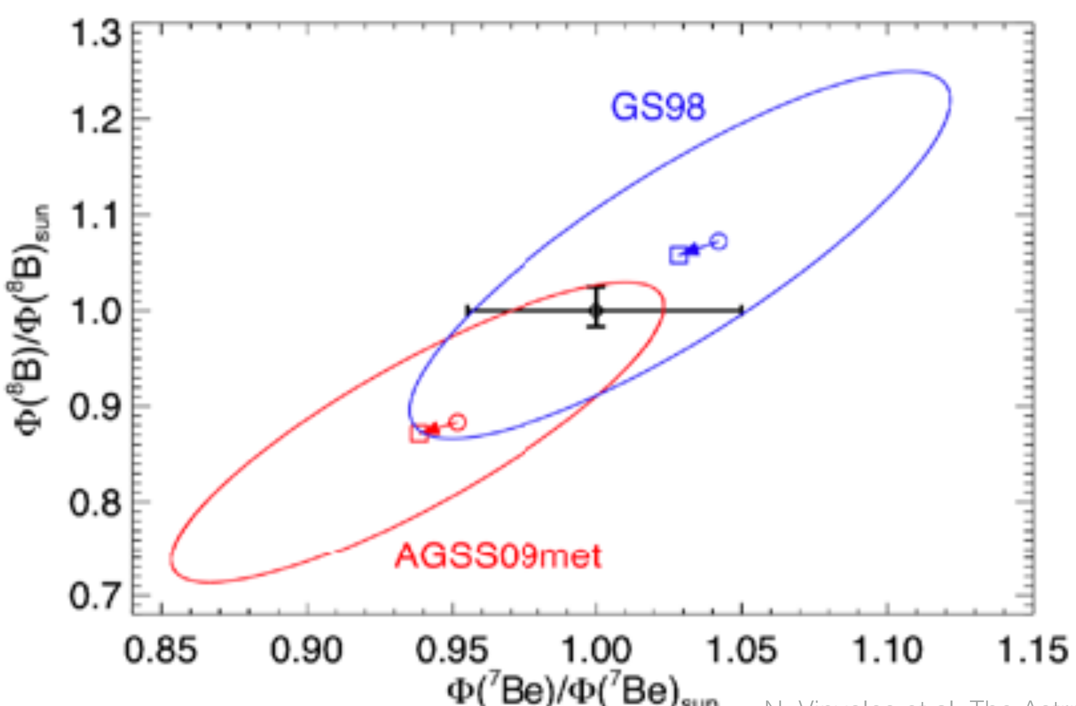
Why Solar neutrinos?



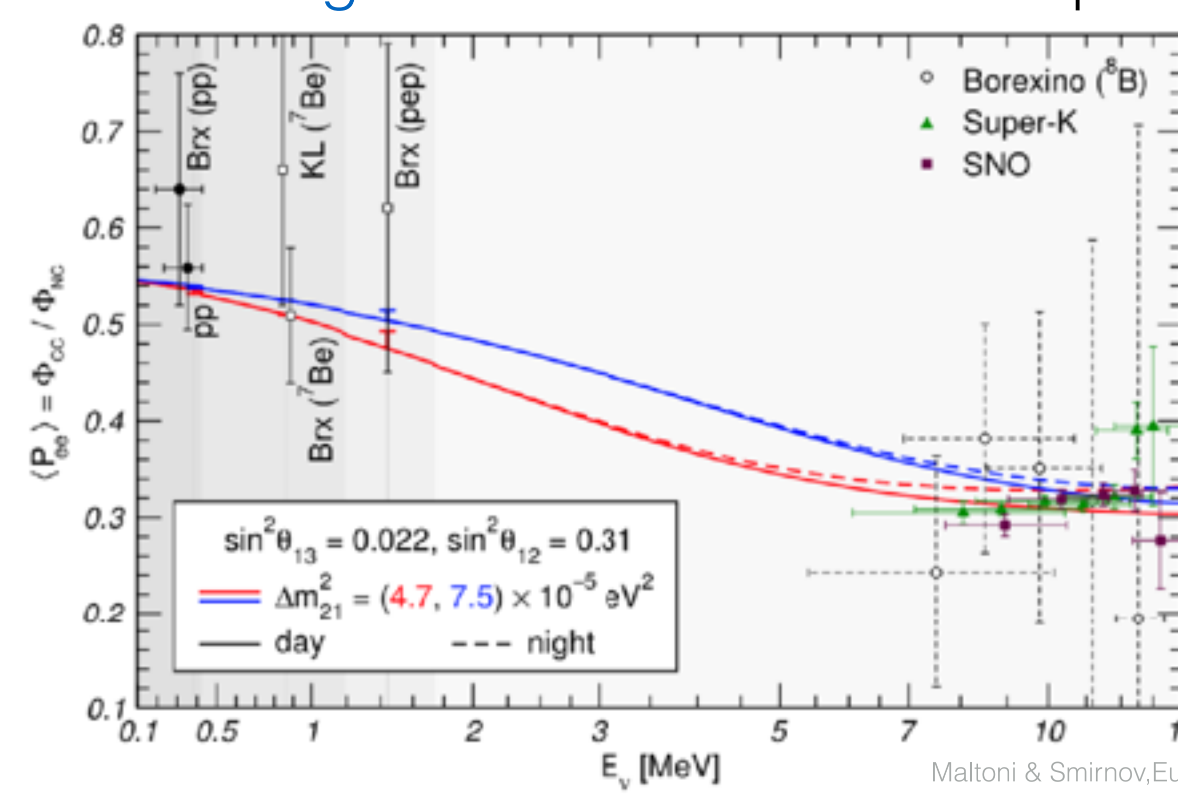
- Solar neutrino is produced in the **core region of the sun**. => study the core of the sun
- Solar neutrino propagate through **ultra-high-density region** and become **flavor-stable** => study MSW resonance

Two solar metallicity models



N. Vinyoles et al. The Astrph. Journ. 835 1 (2017) Improoved model

Solar vs global MSW-LMA survival prob.



Maltoni & Smirnov,Eur.Phys.J.2016

Full pp-chain solar neutrino

Borexino experimental results

Solar ν	Rate (cpd/100 t)	Flux ($cm^{-2}s^{-1}$)	Flux –SSM predictions ($cm^{-2}s^{-1}$)
pp	$134 \pm 10^{+6}_{-10}$	$(6.1 \pm 0.5^{+0.3}_{-0.5}) \times 10^{10}$	$5.98(1. \pm 0.006) \times 10^{10}$ (HZ) $6.03(1. \pm 0.005) \times 10^{10}$ (LZ)
^{7}Be	$48.3 \pm 1.1^{+0.4}_{-0.7}$	$(4.99 \pm 0.11^{+0.06}_{-0.08}) \times 10^{9}$	$4.93(1. \pm 0.06) \times 10^{9}$ (HZ) $4.50(1. \pm 0.06) \times 10^{9}$ (LZ)
pep (HZ)	$2.43 \pm 0.36^{+0.15}_{-0.22}$	$(1.27 \pm 0.19^{+0.08}_{-0.12}) \times 10^{8}$	$1.44(1. \pm 0.009) \times 10^{8}$ (HZ) $1.46(1. \pm 0.009) \times 10^{8}$ (LZ)
pep (LZ)	$2.65 \pm 0.36^{+0.15}_{-0.24}$	$(1.39 \pm 0.19^{+0.08}_{-0.13}) \times 10^{8}$	$1.44(1. \pm 0.009) \times 10^{8}$ (HZ) $1.46(1. \pm 0.009) \times 10^{8}$ (LZ)
$^8B_{HER\text{-}I}$	$0.136^{+0.013+0.003}_{-0.013-0.003}$	$(5.77^{+0.56+0.15}_{-0.56-0.15}) \times 10^{6}$	$5.46(1. \pm 0.12) \times 10^{6}$ (HZ) $4.50(1. \pm 0.12) \times 10^{6}$ (LZ)
$^8B_{HER\ II}$	$0.087^{+0.080+0.005}_{-0.010-0.005}$	$(5.56^{+0.52+0.33}_{-0.64-0.33}) \times 10^{6}$	$5.46(1. \pm 0.12) \times 10^{6}$ (HZ) $4.50(1. \pm 0.12) \times 10^{6}$ (LZ)
$^8B_{HE}$	$0.223^{+0.015+0.006}_{-0.016-0.006}$	$(5.68^{+0.39+0.03}_{-0.41-0.03}) \times 10^{6}$	$5.46(1. \pm 0.12) \times 10^{6}$ (HZ) $4.50(1. \pm 0.12) \times 10^{6}$ (LZ)
CNO	< 8.1 (95 % C.L.)	$< 7.9 \times 10^{8}$ (95 % C.L.)	$4.92(1. \pm 0.11) \times 10^{8}$ (HZ) $3.52(1. \pm 0.10) \times 10^{8}$ (LZ)
hep	<0.002 (90% C.L.)	$<2.2 \times 10^{5}$ (90 % C.L.)	$7.98(1. \pm 0.30) \times 10^{3}$ (HZ) $8.25(1. \pm 0.12) \times 10^{3}$ (LZ)

One experiment,
all solar pp-chain ν

- Covering 0.2 MeV to 17 MeV
- Main challenge:
  - **clean LS**
  - High precision **calibration**
  - Good **stability** of the det.
  - Genuine **MC** in large E range

Unprecedented radio-purity level

2007-2010: **Phase-I**

^{238}U 5x10^{-18} g/g

^{232}Th 3x10^{-18} g/g

^{210}Pb ~2x10^{-24} g/g

^{85}Kr ~20 cpd/100ton

2010-2012

Purification + Calibration

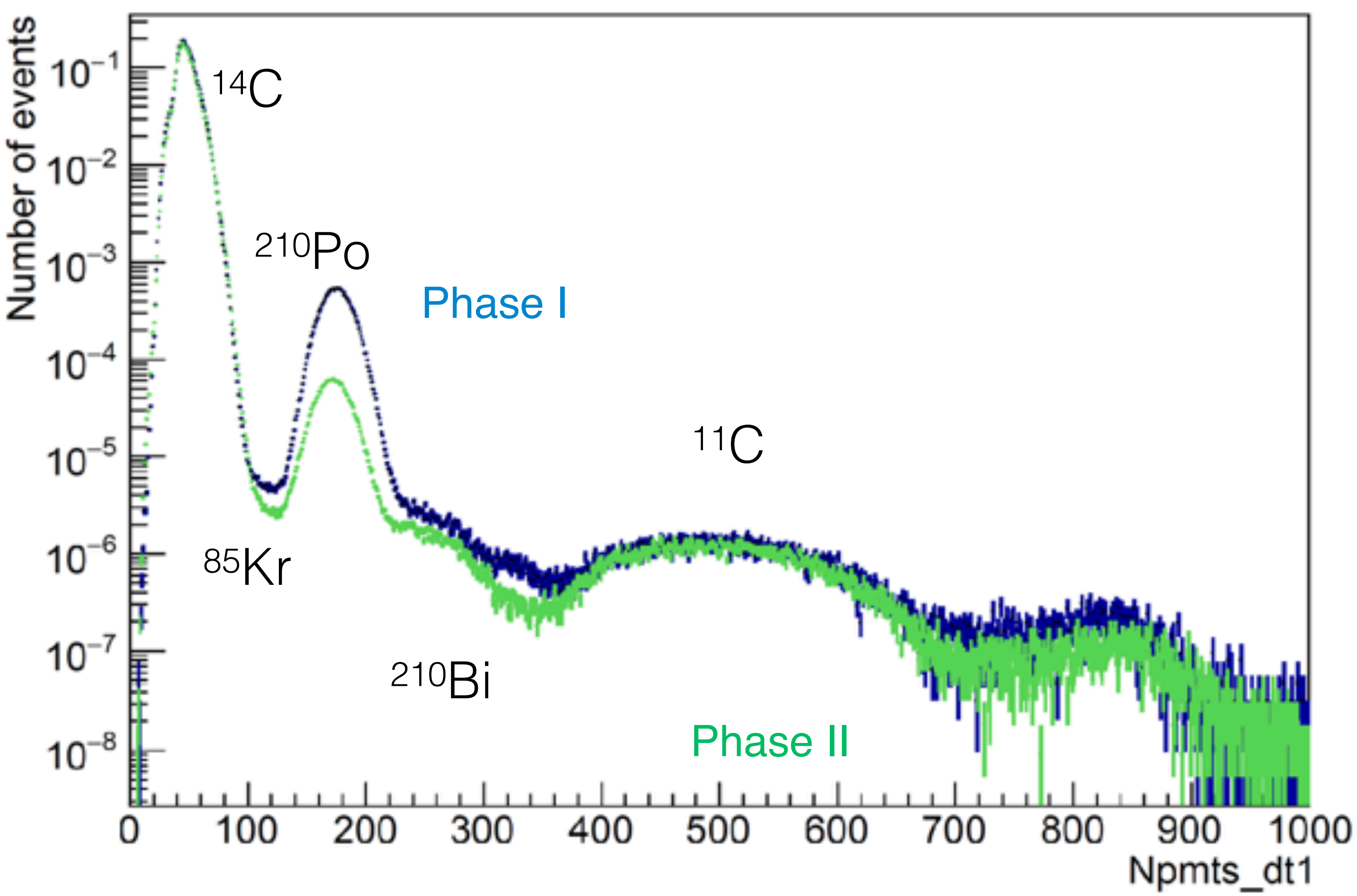
2012-now: **Phase-II**

^{238}U <9.4x10^{-20} g/g

^{232}Th <5.7x10^{-19} g/g

^{210}Pb ~9x10^{-26} g/g

^{85}Kr ~5 cpd/100ton



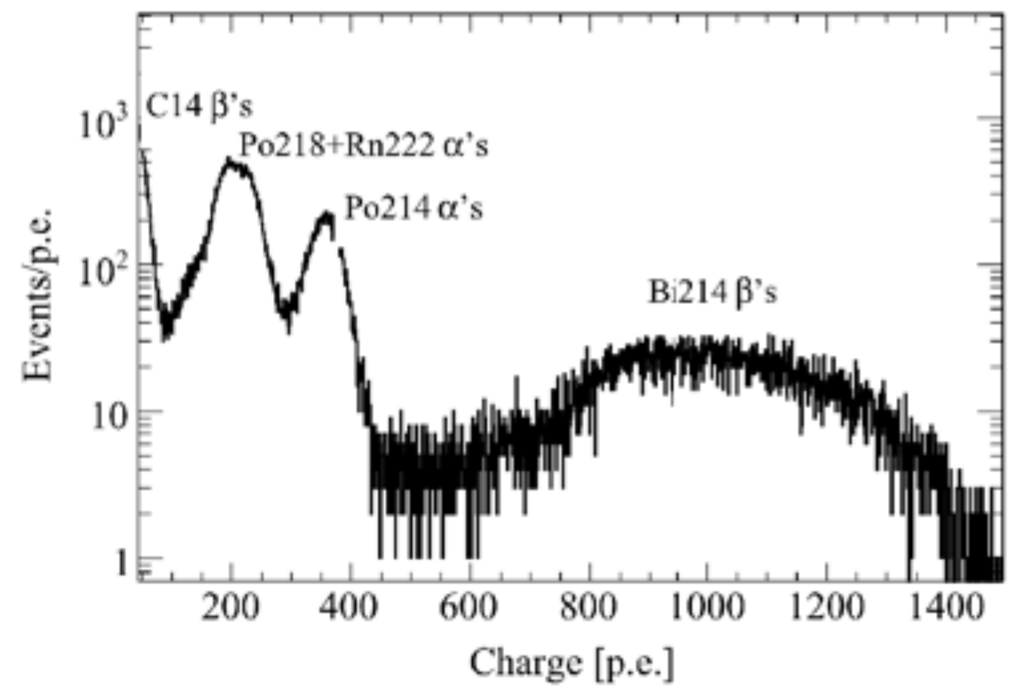
^{238}U<1.2x10^{-12} Bq/kg

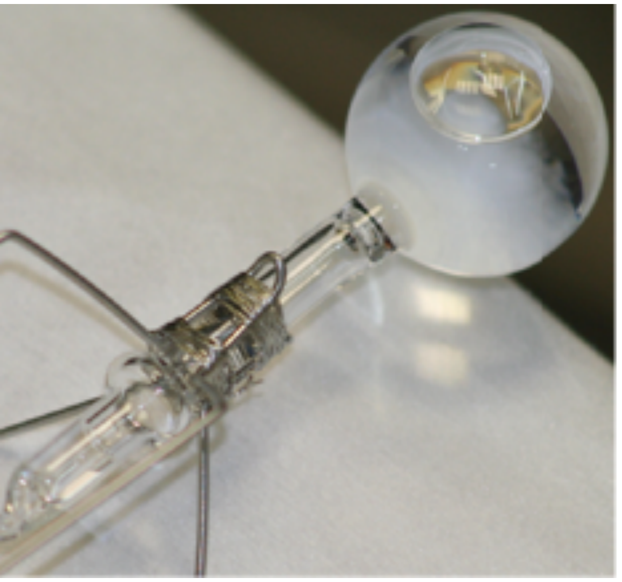
mineral water ~10 Bq/kg

=> 10^{-13} reduction

Internal Calibration

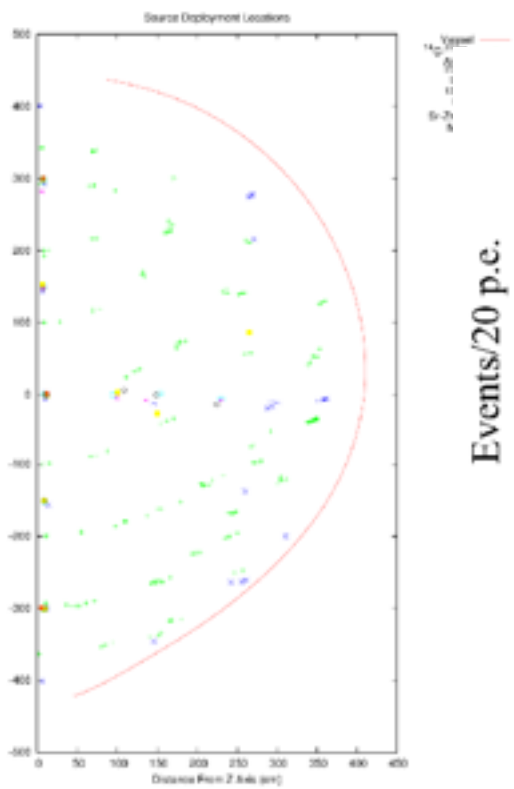
Source	Type	E [MeV]	Position	Motivations	Campaign
^{57}Co	γ	0.122	in IV volume	Energy scale	IV
^{139}Ce	γ	0.165	in IV volume	Energy scale	IV
^{203}Hg	γ	0.279	in IV volume	Energy scale	III
^{85}Sr	γ	0.514	z-axis + sphere R=3 m	Energy scale + FV	III,IV
^{54}Mn	γ	0.834	along z-axis	Energy scale	III
^{65}Zn	γ	1.115	along z-axis	Energy scale	III
^{60}Co	γ	1.173, 1.332	along z-axis	Energy scale	III
^{40}K	γ	1.460	along z-axis	Energy scale	III
^{222}Rn+^{14}C	β,γ	0-3.20	in IV volume	FV+uniformity	I-IV
	α	5.5, 6.0, 7.4	in IV volume	FV+uniformity	
^{241}Am^{9}Be	n	0-9	sphere R=4 m	Energy scale + FV	II-IV
394 nm laser	light	-	center	PMT equalization	IV

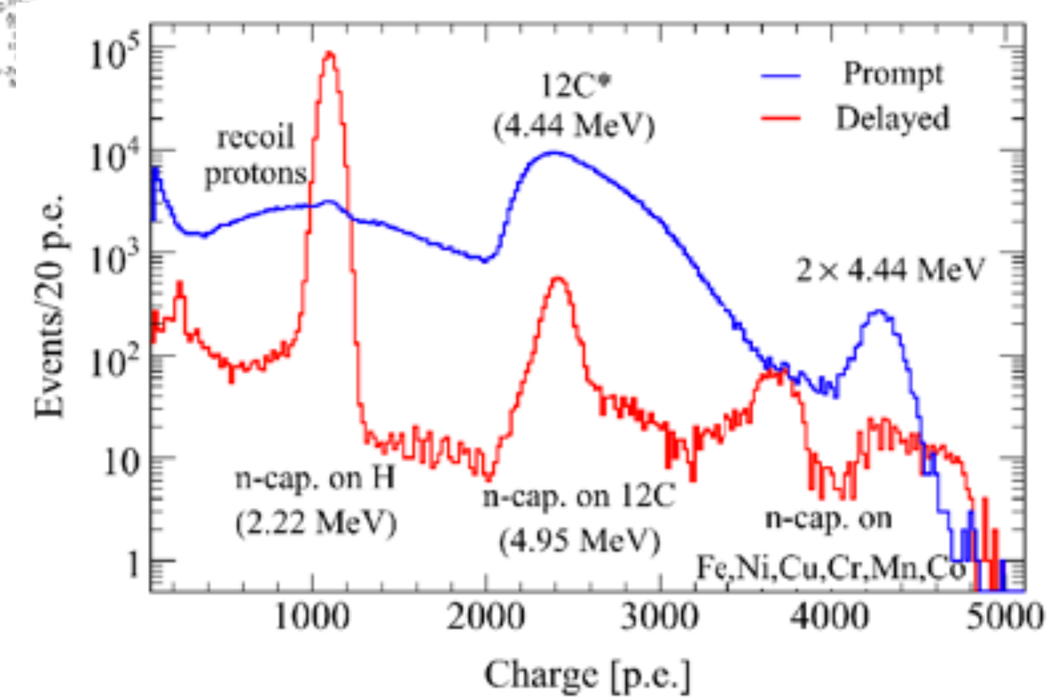




^{203}Hg γ source

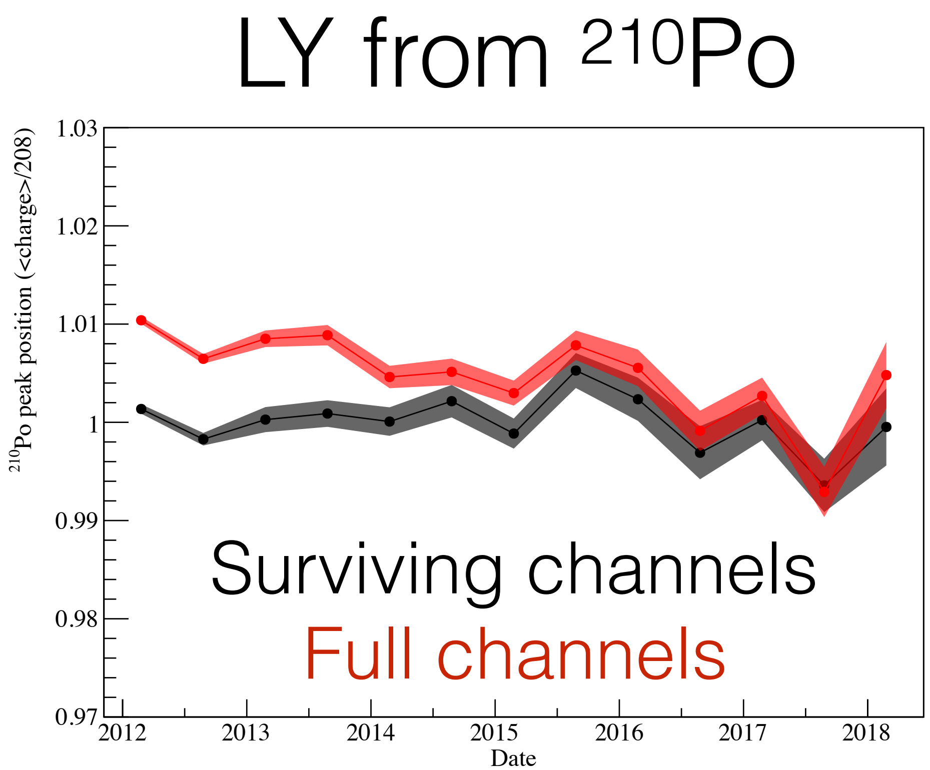
^{241}Am^{9}Be

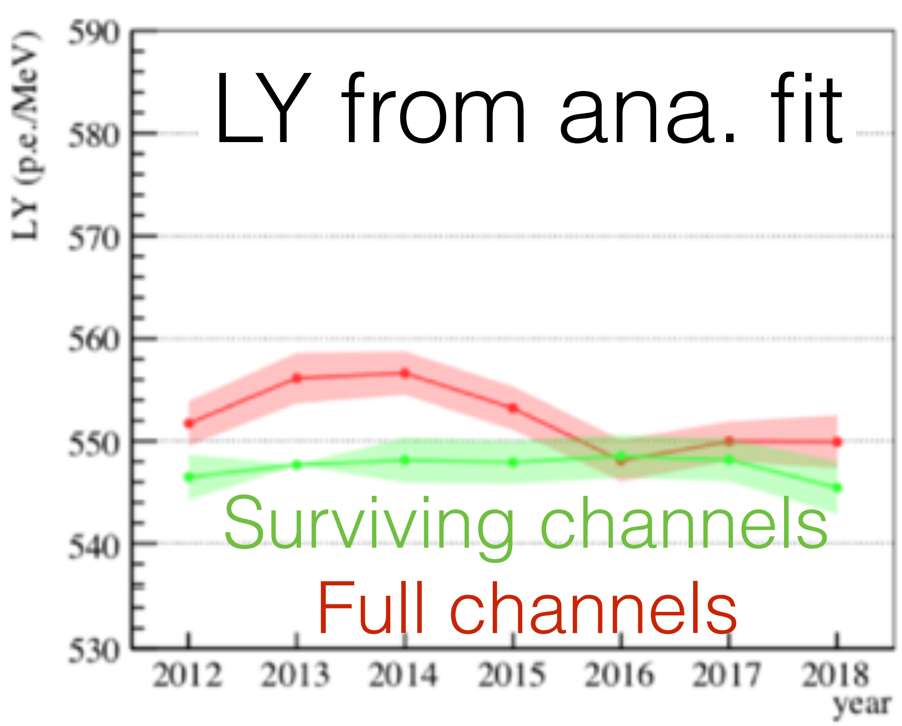




JINST 7 (2012) P10018

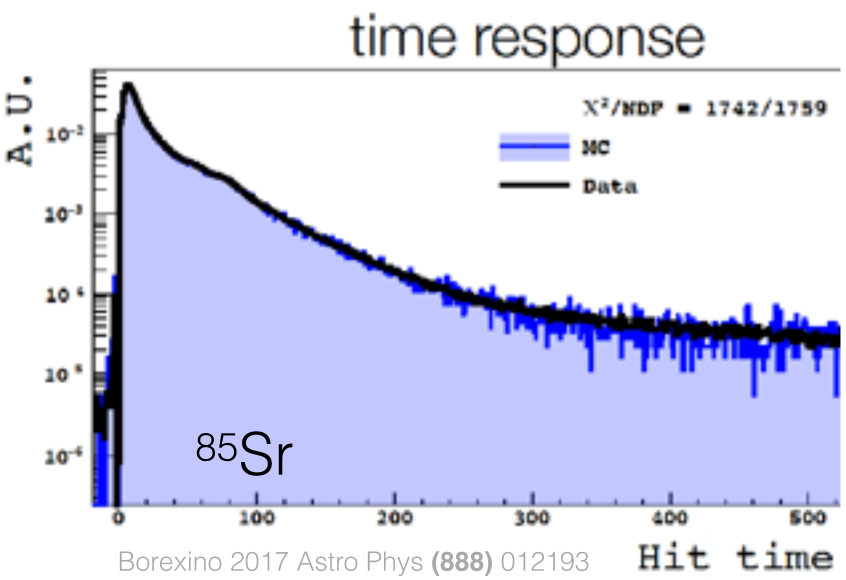
Known stability of detector



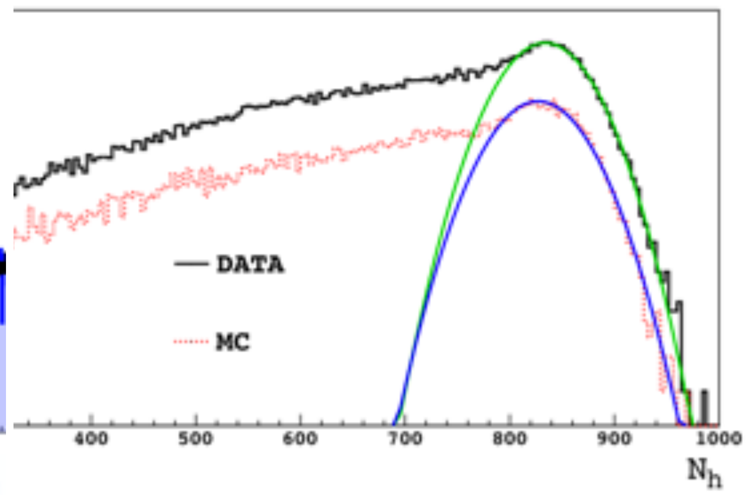


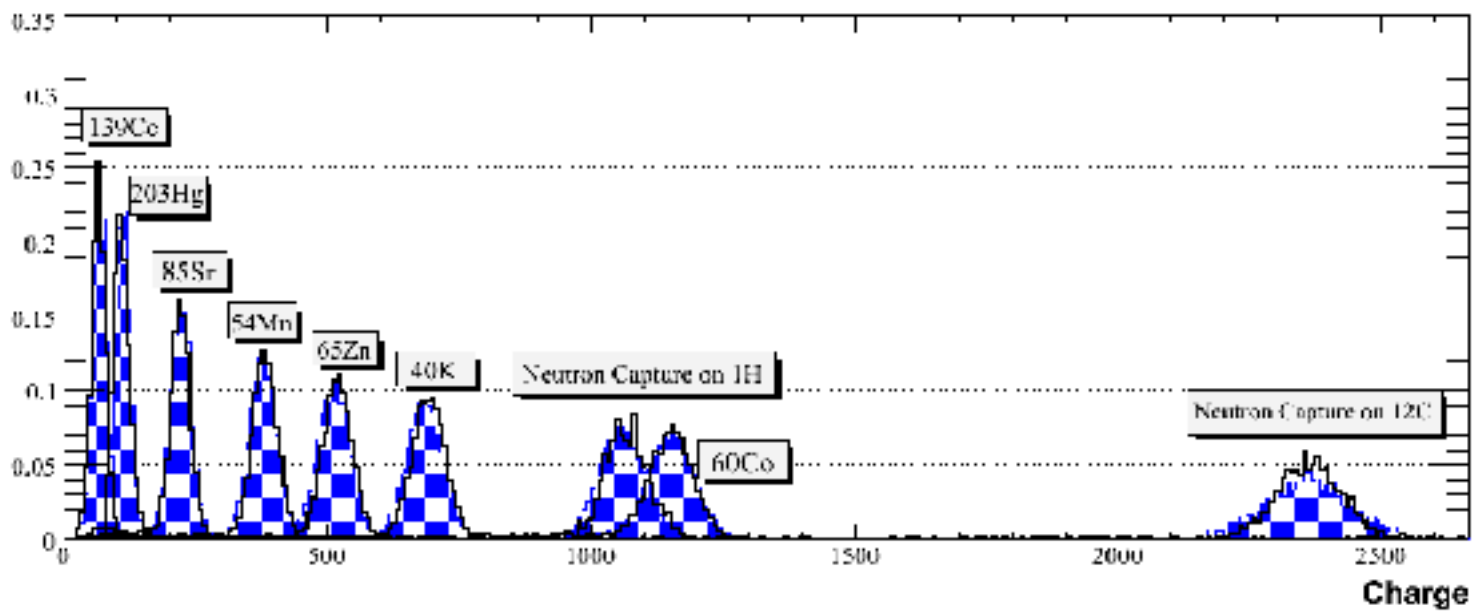
- No frequent calibration
- Contamination based monitoring: **^{14}C, ^{210}Po and ^{11}C**. **Analytical fit** as a cross-check.
- **Liquid scintillator** is **stable**.
- **Good PMT**(top 1000) is **stable**.
- 3% / year PMT loss introduced nontrivial energy scale decrease
    - Light yield is decreasing due to degrading of worse PMTs.

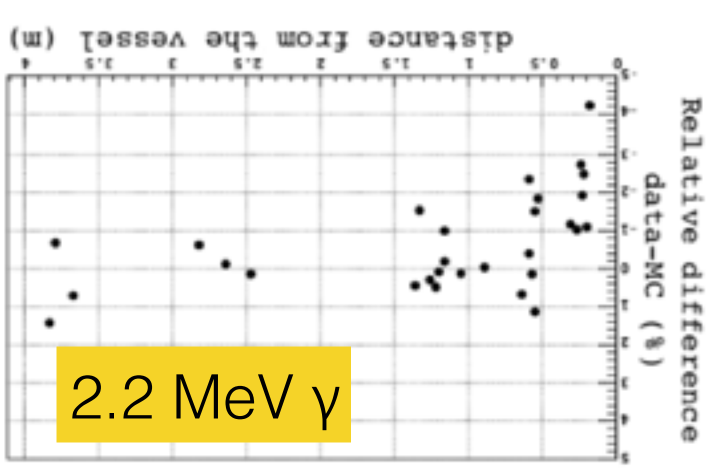
MC tuning

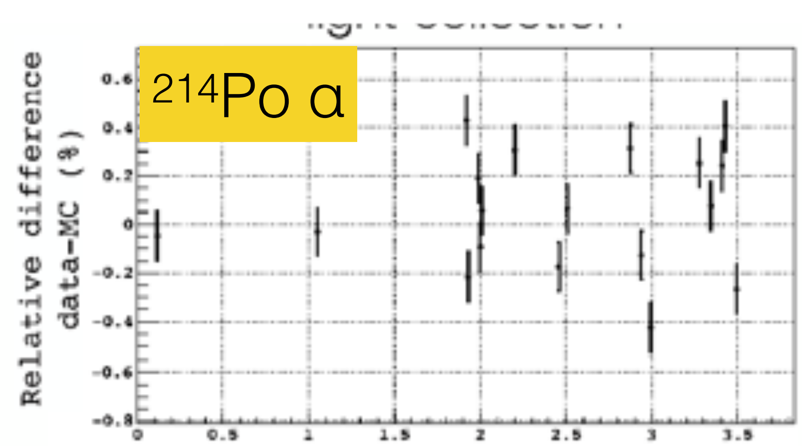


Borexino 2017 Astro Phys **(888)** 012193





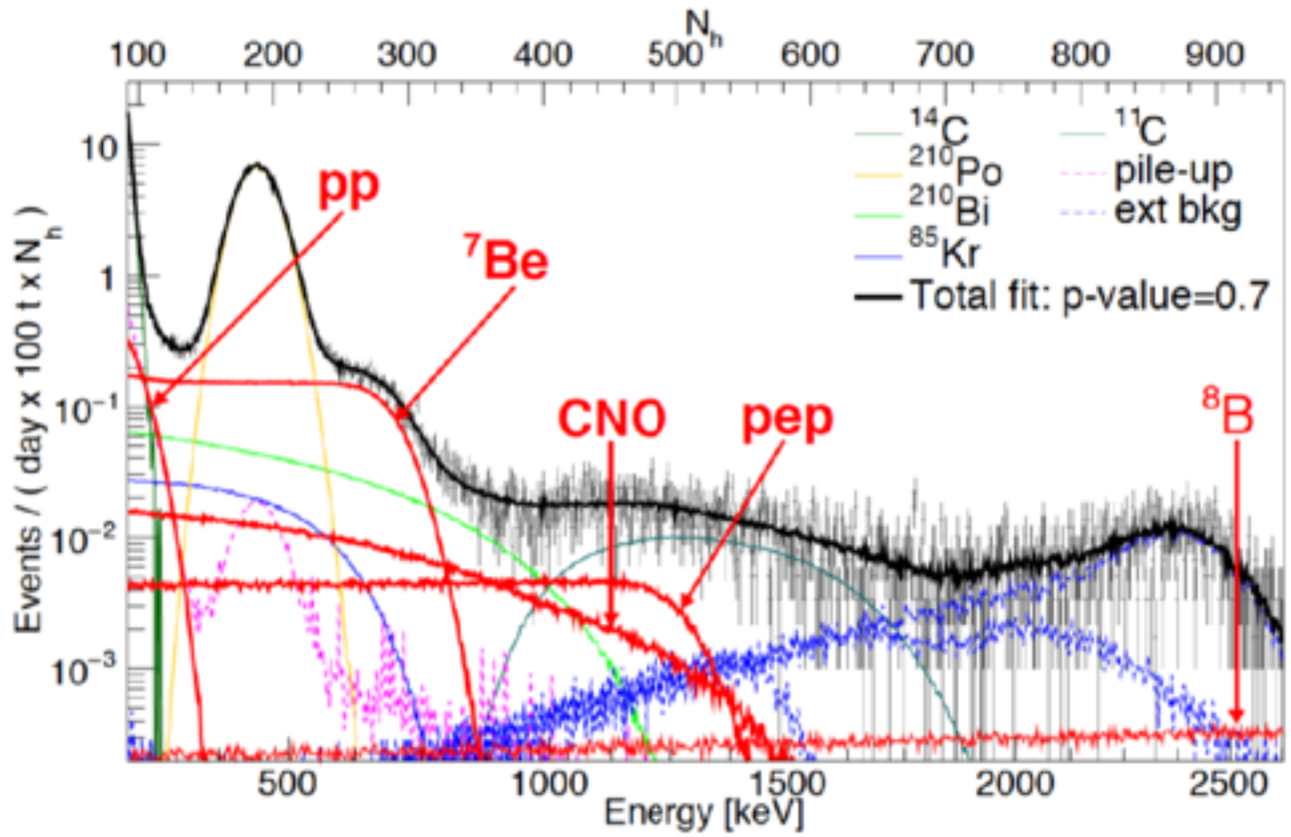




- Tuned on **calibration**
- **Temporal stability** tracked according to ^{14}C etc.
- **center region** E, dE/dr , V agreement within 1%
- **periphery** dE/dr 1.9%

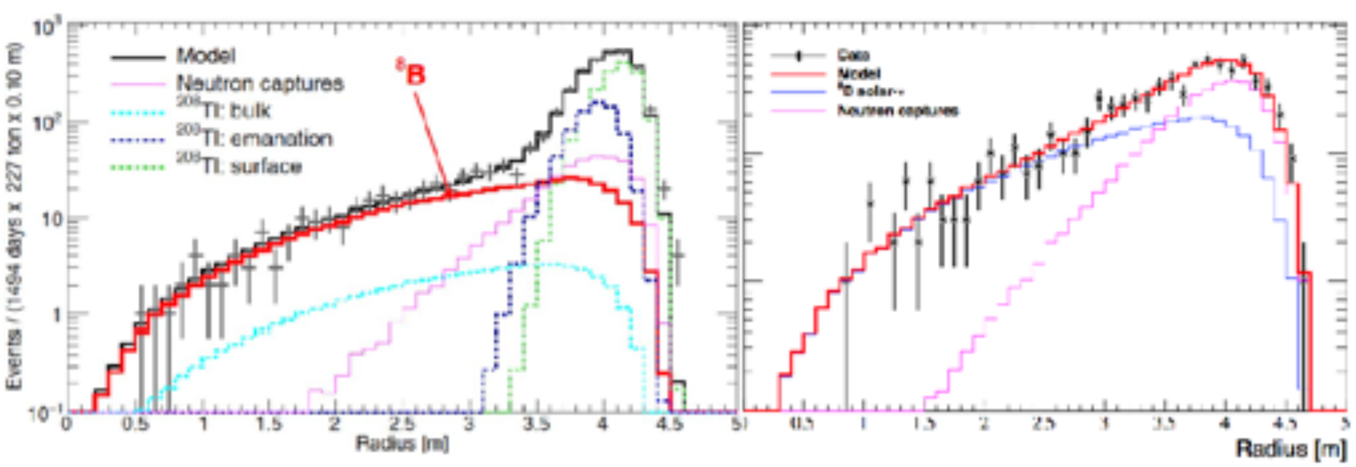
[1] M. Agostini, et al. "The Monte Carlo simulation of the Borexino detector," Astropart. Phys., vol. 888, p. 012193, Oct. 2017.

Analysis Overview



Low Energy Region (LER)

- **MultiVariate fit**
  - **Energy + Radius + PS**
- **0.19 ~ 2.93 MeV**



How Energy Region (HER)

- **Radial spectral fit**
- HER-I **3.2~5.7 MeV**
- HER-II **5.7~17 MeV**

LER: ^{11}C + natural decay

HER-I: n capture γ+ ^{208}Tl

HER-II: n capture γ

Background (LER)	rate (Bq/100 t)
^{14}C(0.156 MeV, β^-)	[40.0 ± 2.0]

Background (LER)	rate (cpd/100 t)
^{85}Kr (0.687 MeV, β^-) (internal)	6.8 ± 1.8
^{210}Bi (1.16 MeV, β^-) (internal)	17.5 ± 1.9
^{11}C (1.02-1.98 MeV, β^+) (internal)	26.8 ± 0.2
^{210}Po (5.3 MeV, α) (internal)	260.0 ± 3.0
^{40}K (1.460 MeV, γ) (external)	1.0 ± 0.6
^{214}Bi (<1.764 MeV, γ) (external)	1.9 ± 0.3
^{208}Tl (2.614 MeV, γ) (external)	3.3 ± 0.1

Background (HER-I)	rate (cpd/227.8 t)
μ, cosmogenics, ^{214}Bi (internal)	$[6.1^{+8.7}_{-3.1} 10^{-3}]$
(α , n) (external)	0.224 ± 0.078
^{208}Tl(5.0 MeV, β^-, γ) (internal)	[0.042 ± 0.008]
^{208}Tl(5.0 MeV, β^-, γ) (emanated)	0.469 ± 0.063
^{208}Tl(5.0 MeV, β^-, γ) (surface)	1.090 ± 0.046

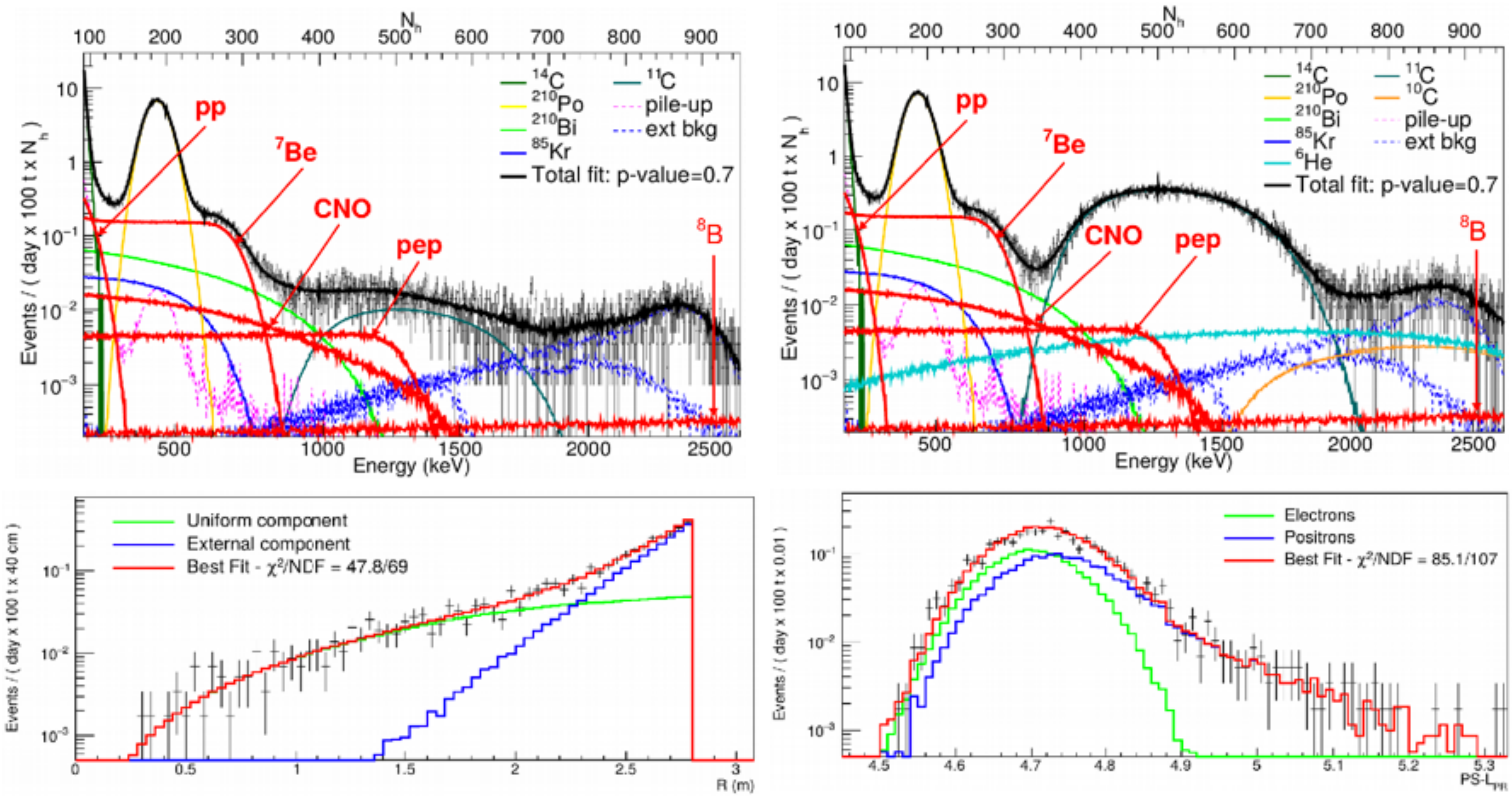
Background (HER-II)	rate (cpd/266.0 t)
μ, cosmogenics (internal)	$[3.8^{+14.6}_{-0.1} 10^{-3}]$
(α , n) (external)	0.239 ± 0.022

LER Highlight: analytical det. response

$$M : f(E) \mapsto g(\text{charge}) = \int_0^{E_{\text{end}}} \mathrm{d}E \cdot f(E) \cdot \text{RPF}\left[\text{charge}; \mu(E), \text{var}(\mu)\right]$$

- Analytical shape of spectrum of mono-energetic events
  - **Momentum based approximation**
  - Match the average (energy scale + non-linearity model)
  - Match the variance (energy resolution model)
  - … (—> simplified)
  - More: “Mask”, “pile-up” etc…
- We can simplify because
  - Borexino response is simple: small FV in center, low energies => no irregular tail
  - We are not sensitive.. => small systematics
  - **Fit full MC to get the bias introduced in simplification**

LER Highlight: Multi-Variate analysis

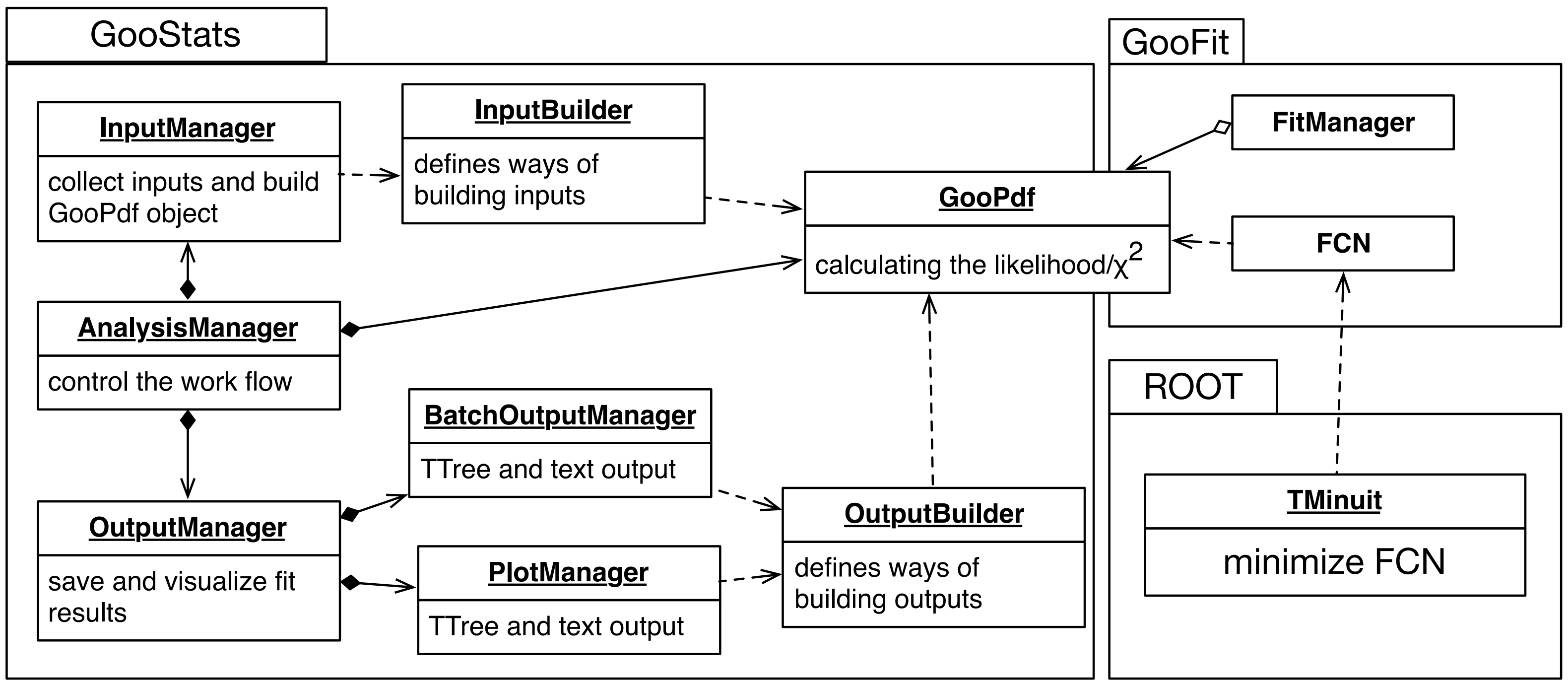


$$\mathcal{L}_{\mathrm{MV}}\left(\vec{\theta}\right) = \mathcal{L}_{\mathrm{TFC-sub}}\left(\vec{\theta}\right) \cdot \mathcal{L}_{\mathrm{TFC-tagged}}\left(\vec{\theta}\right) \cdot \mathcal{L}_{\mathrm{RD}}\left(\vec{\theta}\right) \cdot \mathcal{L}_{\mathrm{PS}}\left(\vec{\theta}\right)$$

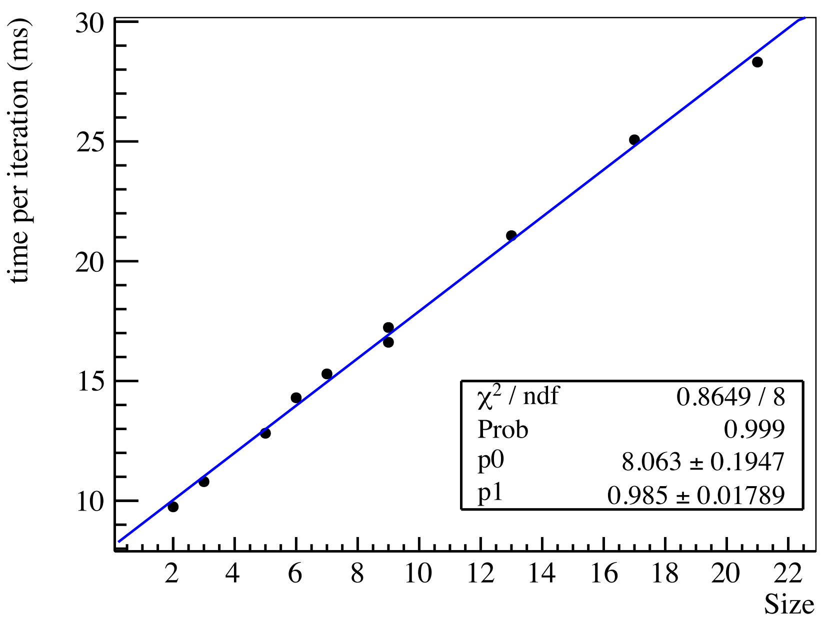
- Scaling factor introduced to remove bias.

[1] S. Davini, "Measurement of the pep and CNO solar neutrino interaction rates in Borexino-I," Eur. Phys. J. Plus, vol. 128, no. 8, p. 89, Aug. 2013.

LER Highlight: GPU accelerated fitter

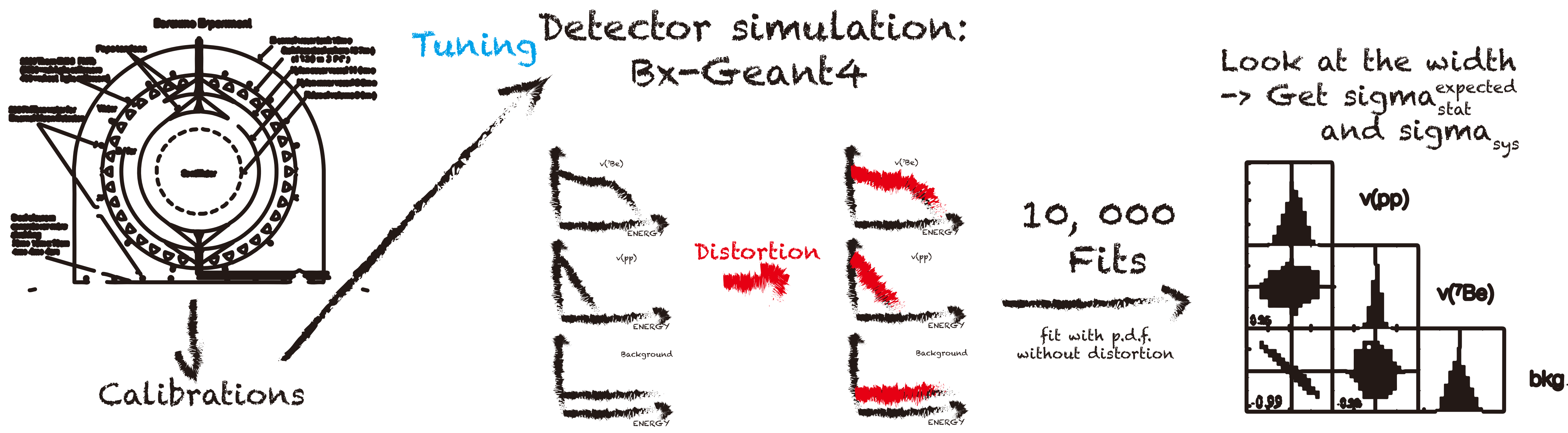


- **GooStats[1]: middle layer** between GooFit (GPU minimization engine) and (Borexino) analysis module



- **Parallelize** the computation of likelihood
- Borexino module: **Speed up more than 1000. Multivariate fit from days to minutes**
- Low overhead: Execution time linearly scales with problem size

[1] Ding, Xuefeng. (2018, May 19). GooStats, a multivariate spectrum fitting analysis package for particle physics accelerated by graphic processing units (Version v1.2.0). Zenodo. http://doi.org/10.5281/zenodo.1217007



- Fit spectrum **w/ and w/o** distortion => **width of best fit**
- Inject deformations according to **MC tuning precision**
- Consider: **Detector response** (energy scale, uniformity of the energy response, pulse-shape discrimination shape), and **theoretical shape**

Systematic uncertainties

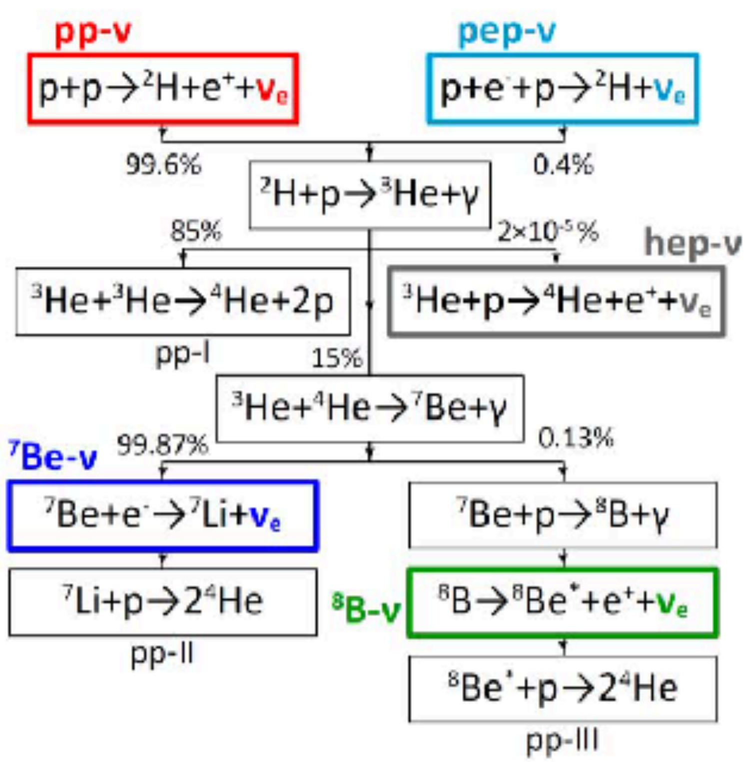
Systematic errors in the *LER* analysis						
	pp neutrinos		7Be neutrinos		*pep* neutrinos	
Source of uncertainty	-%	+%	-%	+%	-%	+%
Fit models (see text)	-4.5	+0.5	-1.0	+0.2	-6.8	+2.8
Fit method (analytical/MC)	-1.2	+1.2	-0.2	+0.2	-4.0	+4.0
Choice of the energy estimator	-2.5	+2.5	-0.1	+0.1	-2.4	+2.4
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
Inclusion of the 85Kr 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**

Systematic errors in the *HER* analysis (8B neutrinos)						
	HER-I		*HER-II*		*HER* (tot)	
Source of uncertainty	-%	+%	-%	+%	-%	+%
Target Mass	-2.0	+2.0	-2.0	+2.0	-2.0	+2.0
Energy scale	-0.5	+0.5	-4.9	+4.9	-1.7	+1.7
z-cut	-0.7	+0.7	0	0	-0.4	+0.4
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
Total systematics (%)	**-2.2**	**+2.2**	**-5.3**	**+5.3**	**-2.7**	**+2.7**

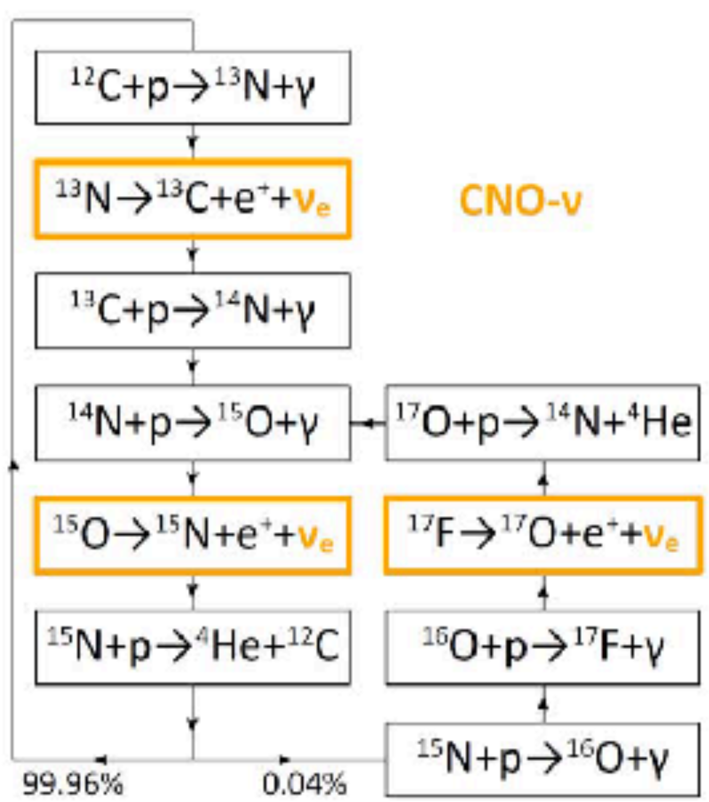
LER **HER**

Unique results on **solar physics**

pp chain



CNO cycle

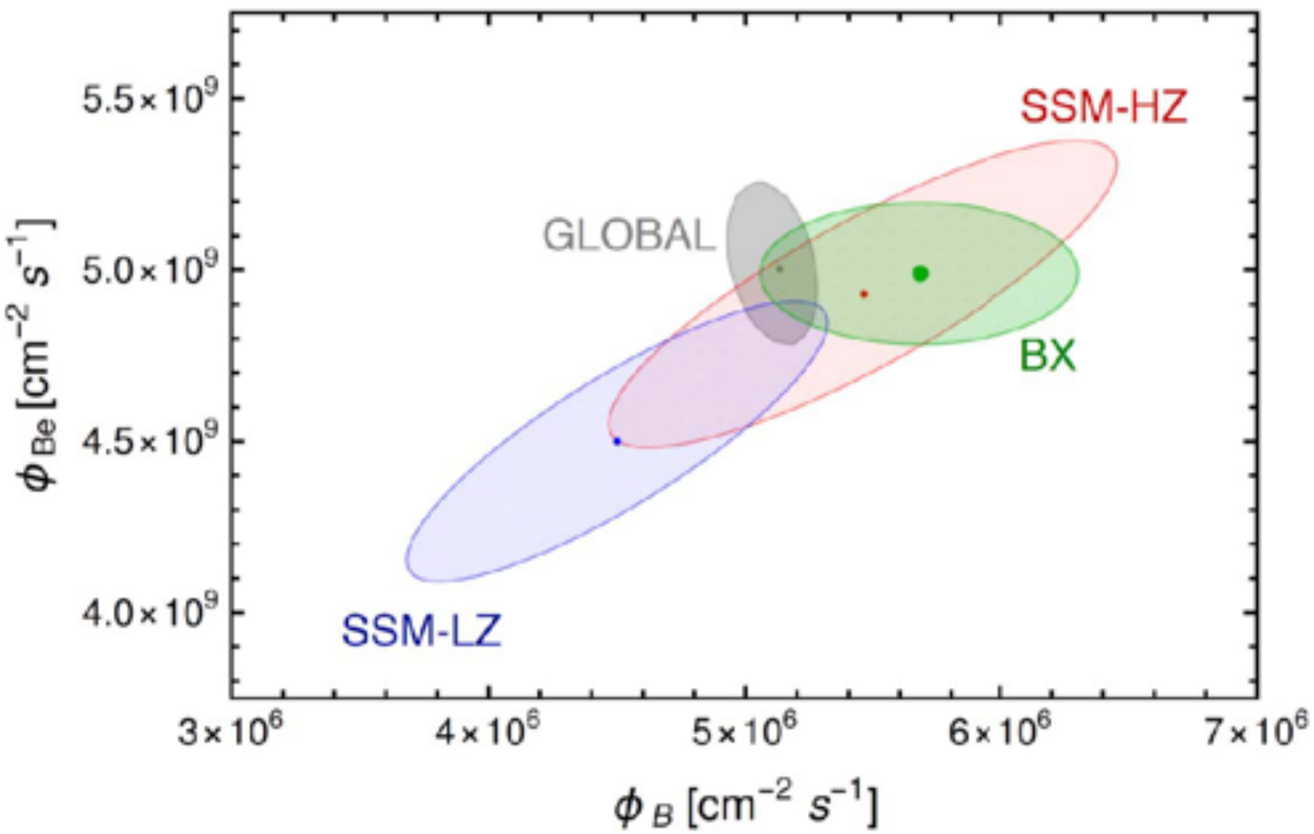


- We measured the luminosity from neutrino to be **$(3.89^{+0.35}_{-0.42})\times10^{33}$erg/s**,
- **Consistent** with results from photons $(3.846\pm0.015)\times10^{33}$ erg/s

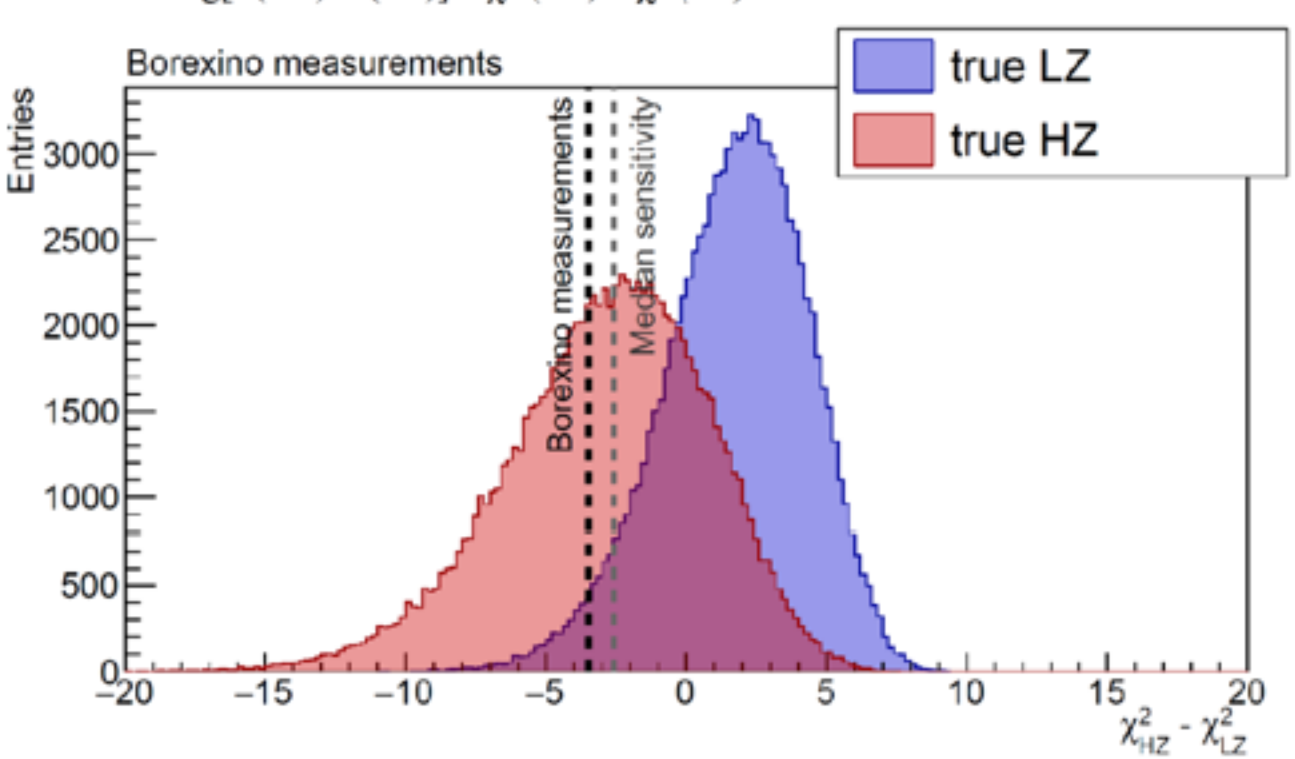
$$R=2\Phi(^{7}\mathrm{Be})/[\Phi(pp)-\Phi(^{7}\mathrm{Be})]$$

- pp-I vs pp-II B.R. **$0.178^{+0.027}_{-0.023}$**
- **Consistent** with both HZ (0.180±0.011) and LZ (0.161±0.010) model

Results on **solar neutrino flux**

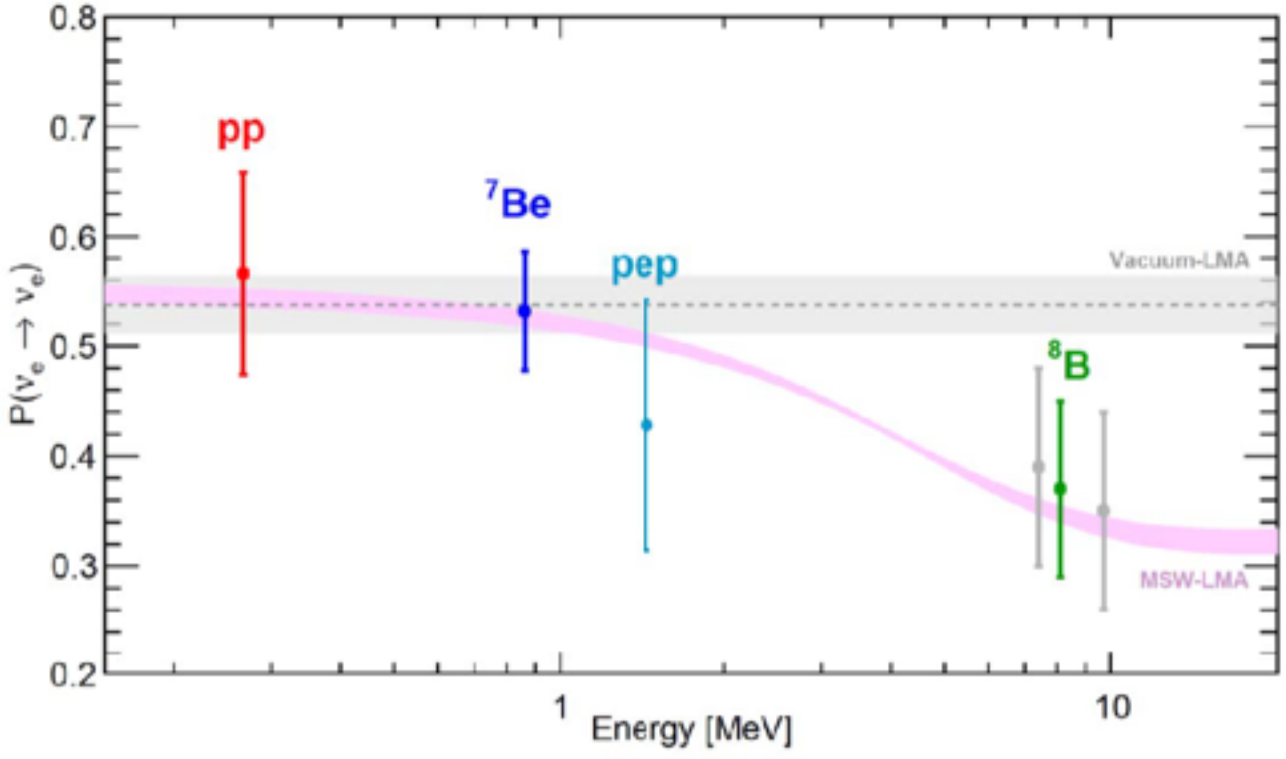


$t = -2\log[\mathcal{L}(HZ)/\mathcal{L}(LZ)] = \chi^2(HZ) - \chi^2(LZ)$

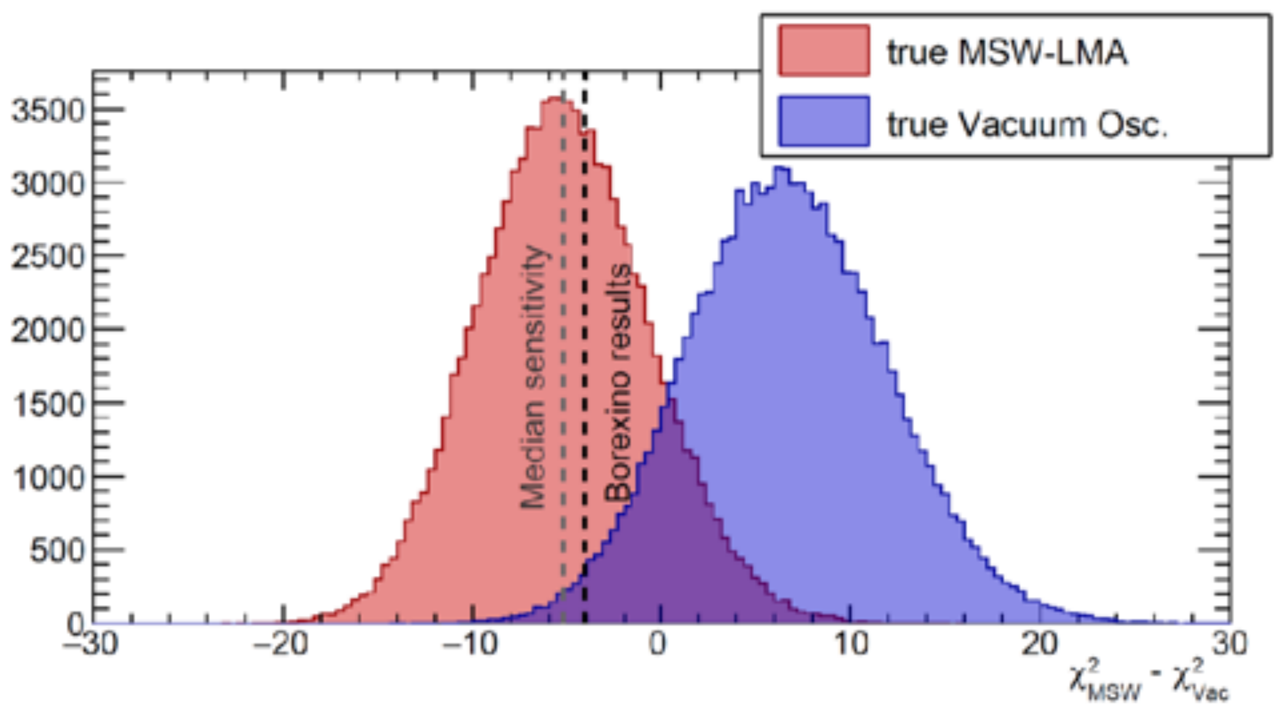


- Precision on ν(^{7}Be) 3% is better than the model precision 7%
- With Borexino results alone we **reject LZ model at 96.6% C.L.**, slightly better than the expected median sensitivity 93.8%.
- Including superK etc. both models are compatible

Results on P_{ee}



$t = -2\log[\mathcal{L}(MSW)/ \mathcal{L}(vacuum)] = \chi^2 (MSW) - \chi^2 (vacuum)$

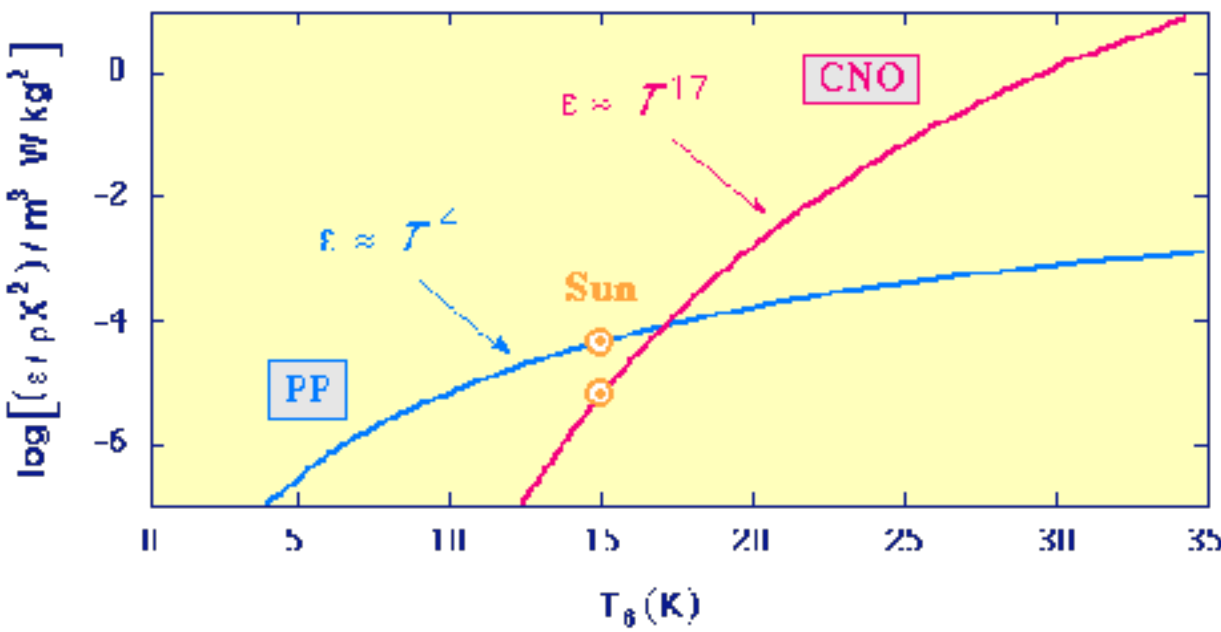


- Including uncertainty from theoretical flux prediction
- With Borexino results alone we **reject Vacuum-LMA model at 98.2% C.L.**,

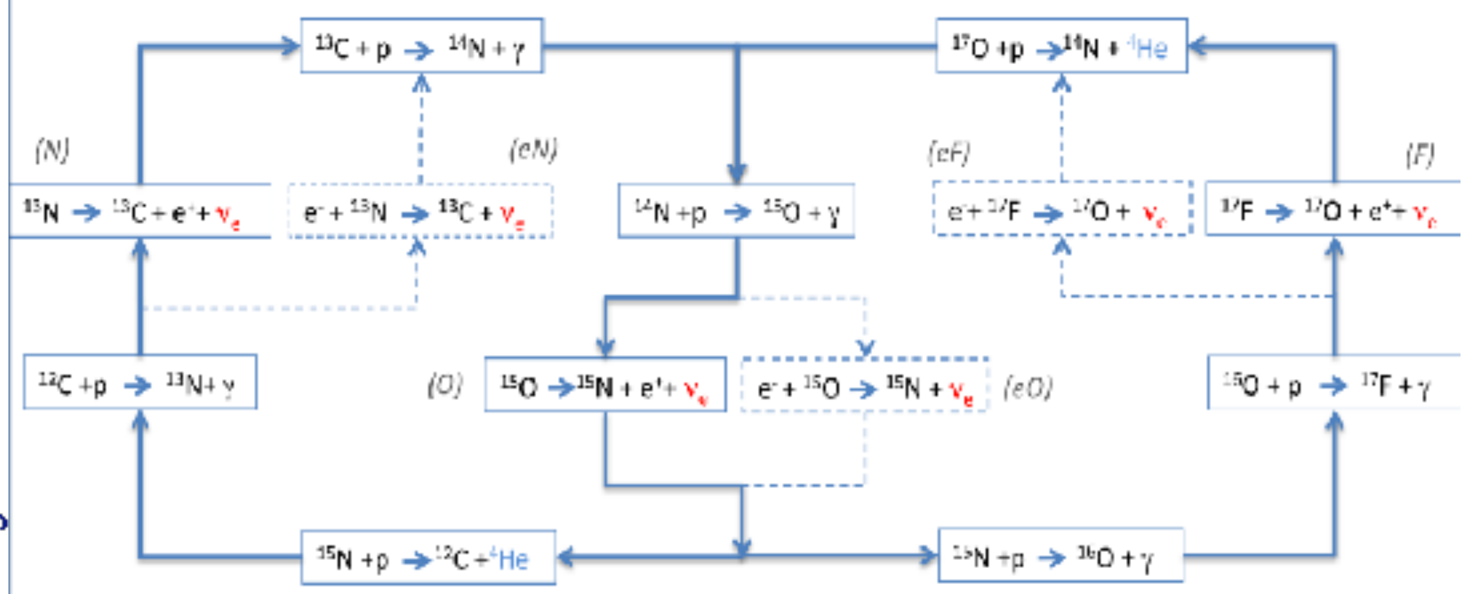
Outline

- Borexino experiment
- Full pp-chain solar neutrino
- Prospects for CNO solar neutrino
- Geo-neutrinos
- Conclusion

What is "CNO"? Why to study it?



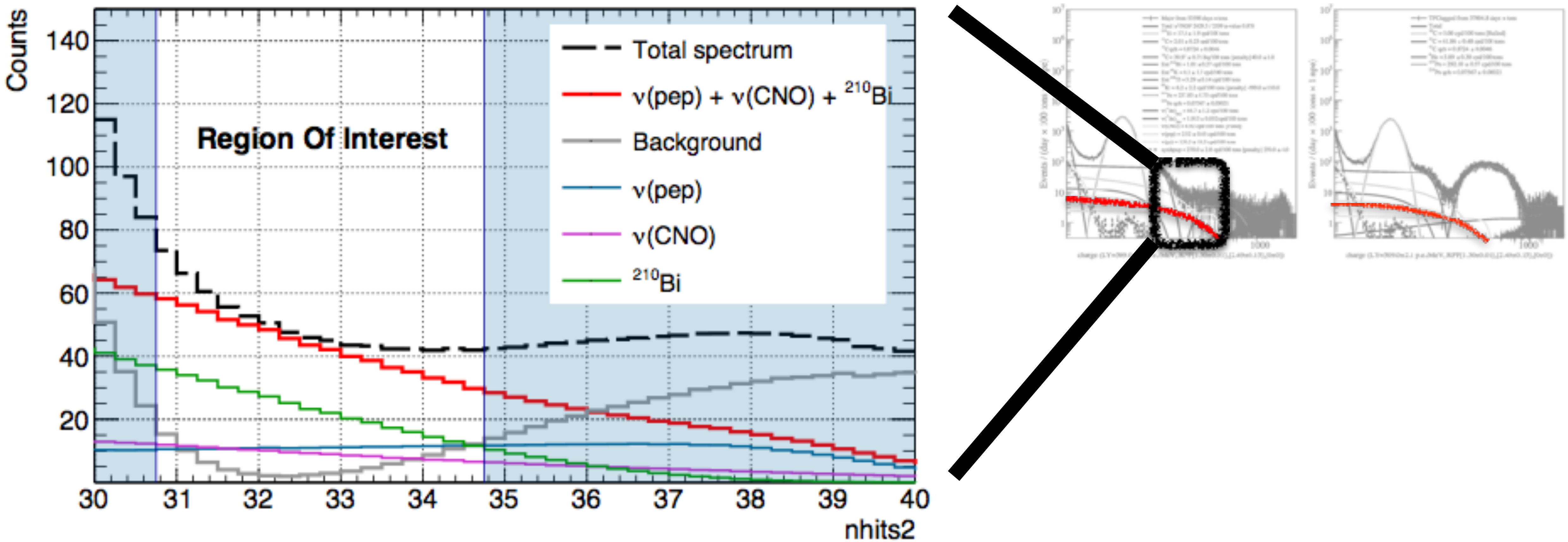
http://csep10.phys.utk.edu/astr162/lect/energy/cno-pp.html



The Sun and solar neutrinos, Neutrino 2016. F. L. Villante. U. L'Aquil & INFN-LNGS

- C, N, O as catalyst for 4p->^{4}He+.. fusion
- Major fusion energy source when temperature is high: more massive star or late stage of star
- **Only in theory**, CNO ν never observed
- Also can **distinguish metallicity** (if one day we measure it to 5%)

CNO: counting experiment



- Hardly distinguish pep, CNO and ^{210}Bi: only know the sum
- Constrain pep and **^{210}Bi** to measure CNO

pp/pep ratio → pep

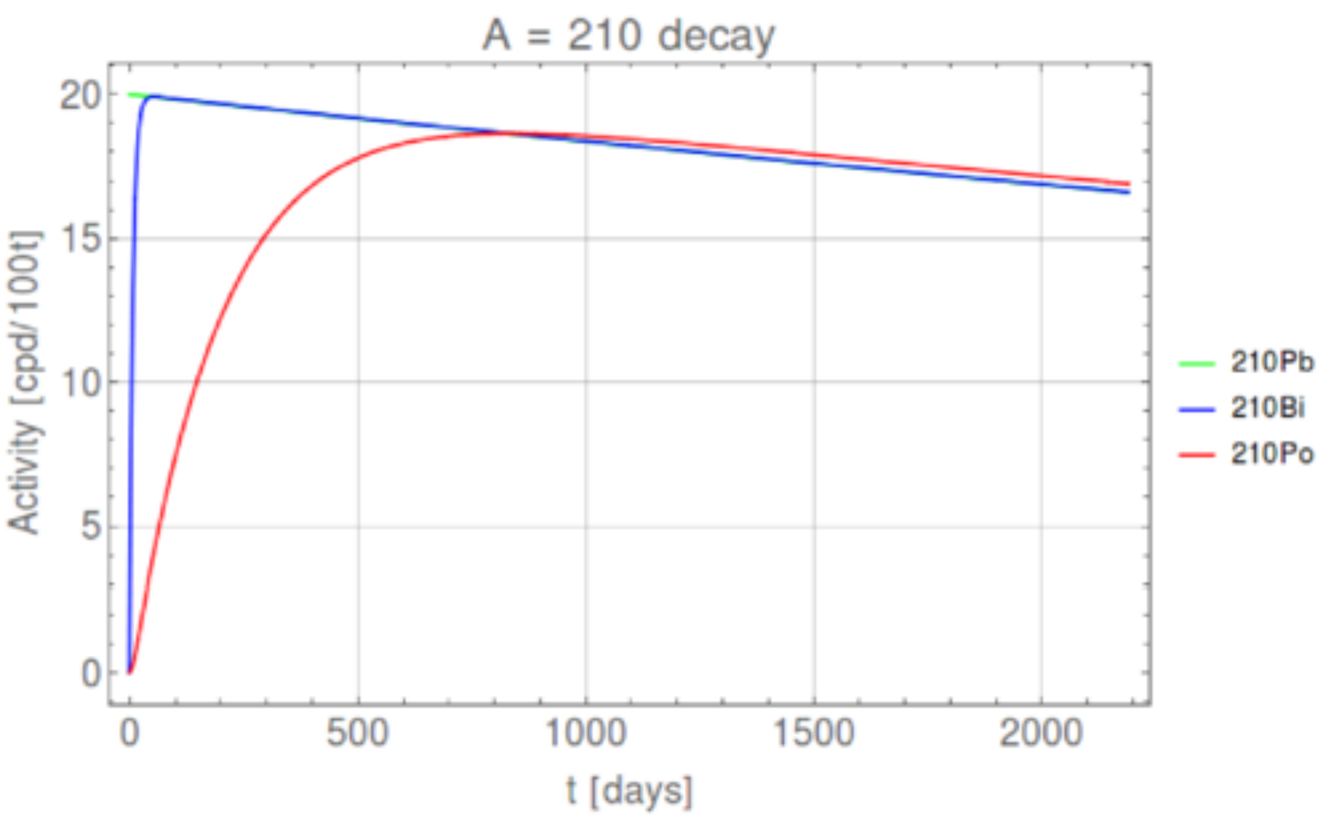
^{210}Po tagging → ^{210}Bi ← *Challenging!*

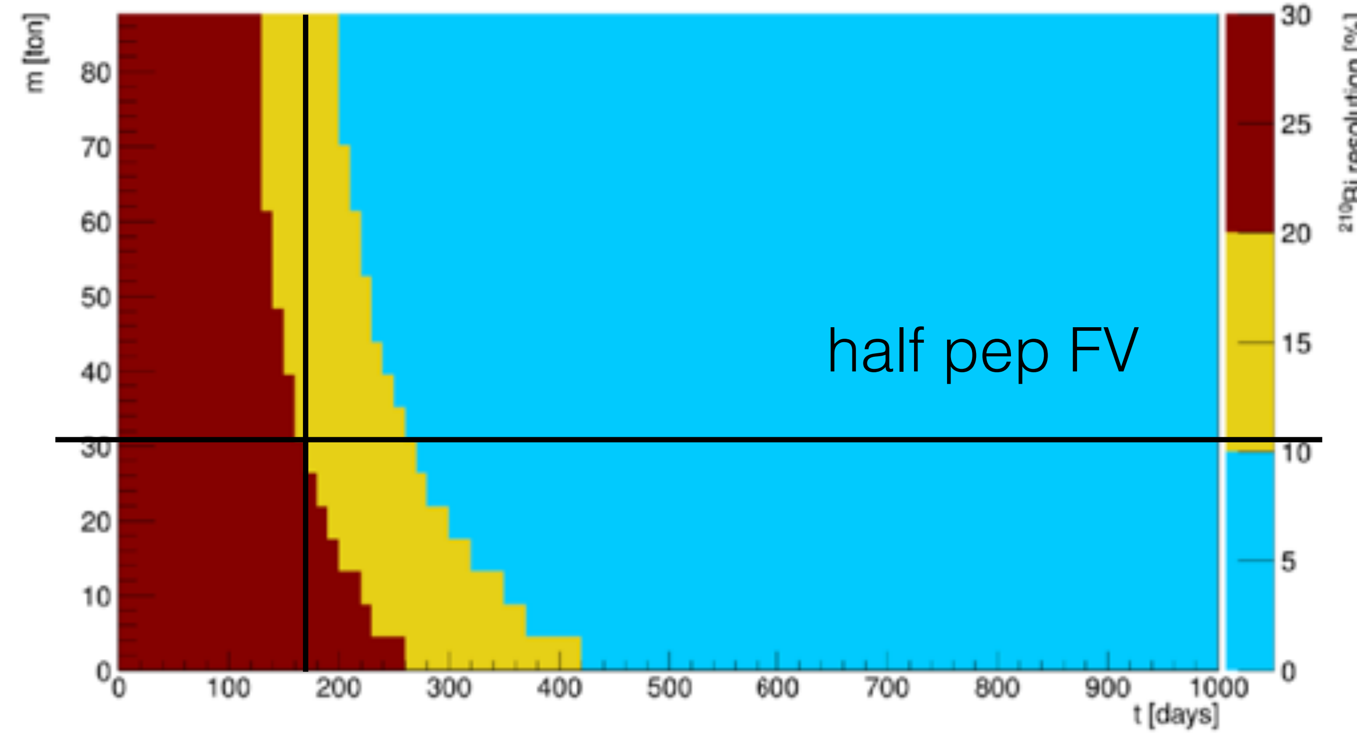
How weak?

1.00*CNO -1.04*Bi210 -0.15*pep =	6.60±11.34	CNO vs ^{210}Bi
1.00*CNO+ 1.06*Bi210 -0.65*pep =	21.01± 1.53	CNO vs pep
1.00*CNO+ 0.60*Bi210+ 2.51*pep =	23.05± 0.57	counting

- Diagonalizing the cov. matrix => **get shape precision**
- **σ(CNO-^{210}Bi) ~ 11 cpd/100t**
- **R(CNO) ~ 5 cpd/100t**

Measure ^{210}Bi from ^{210}Po

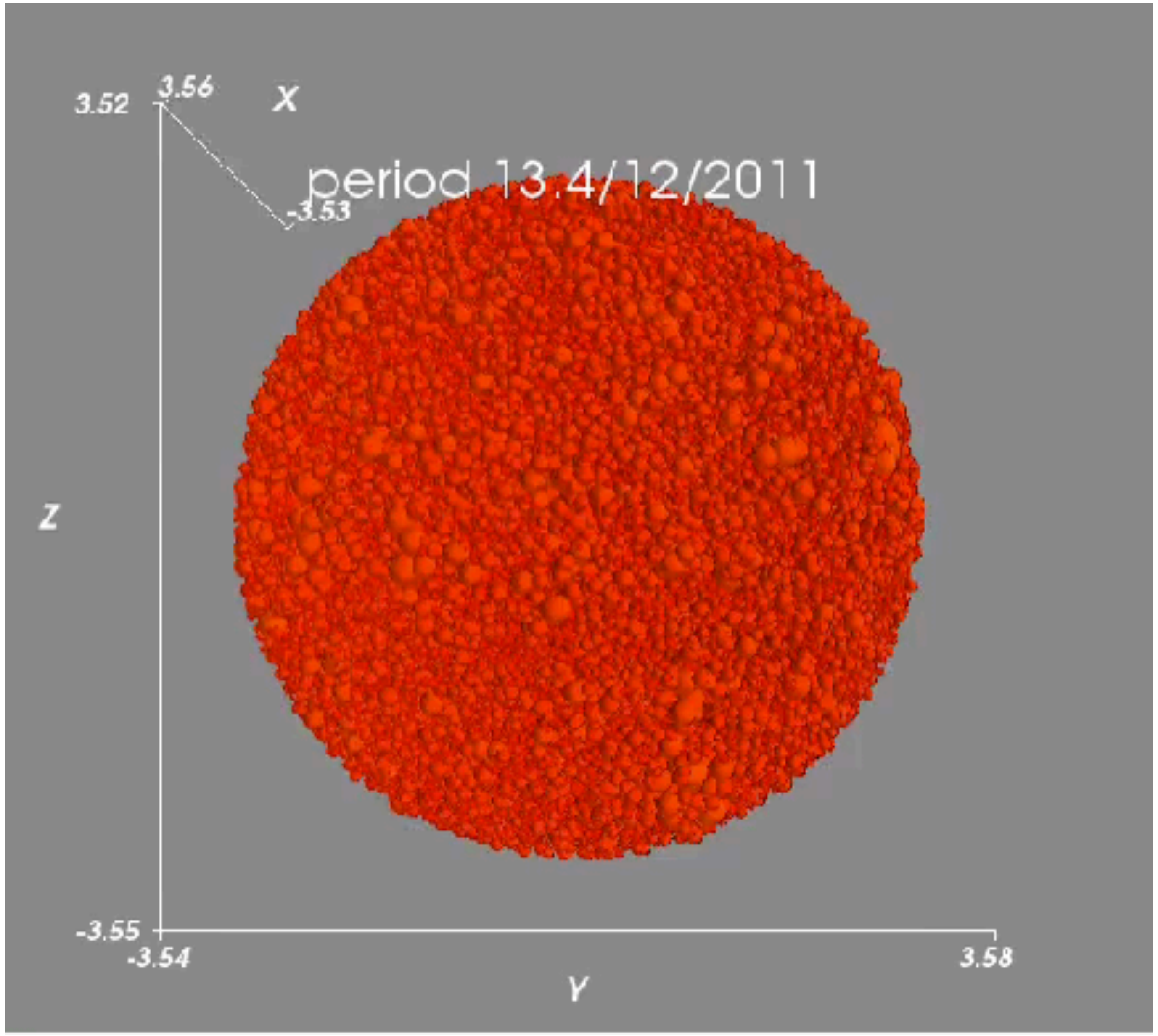




- When ^{210}Pb -> ^{210}Bi -> ^{210}Po reaches secular equilibrium, ^{210}Bi can be measured with ^{210}Po (α)
- With 30 ton FV ~ 6 months ^{210}Bi can reach 10% precision (statistical).

Diffusion **Convection**

$$\frac{\partial X_{\mathrm{Po}}}{\partial t} = X_{\mathrm{Bi}} \cdot \lambda_{\mathrm{Bi}} - X_{\mathrm{Po}} \cdot \lambda_{\mathrm{Po}} + \nabla \cdot (D_{\mathrm{Po}} \cdot \nabla X_{\mathrm{Po}} - \vec{v} X_{\mathrm{Po}})$$



- Temperature instability induces convective current
- Convection makes local ^{210}Po concentration contaminated by extra component

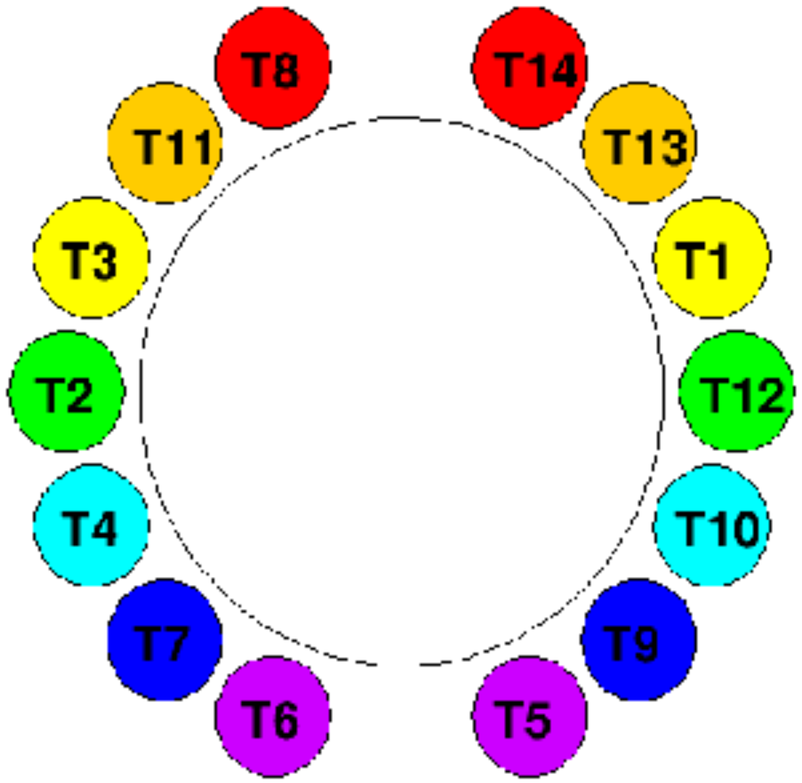
Thermal insulation etc.

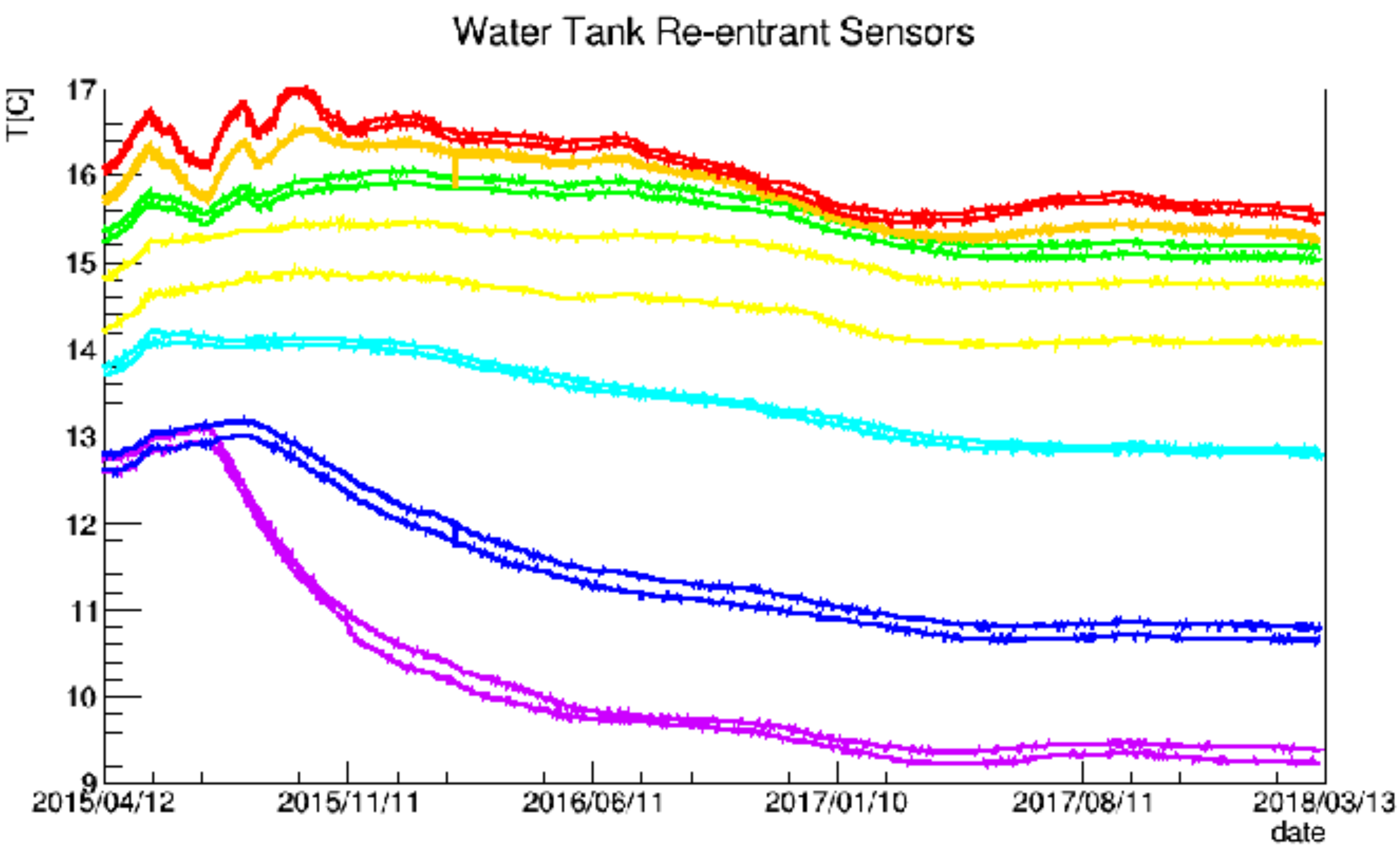
Before insulation

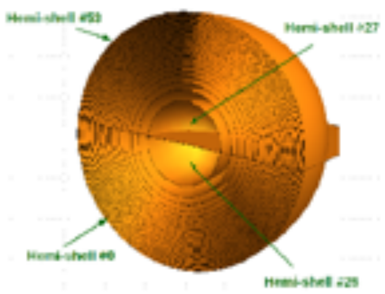
During insulation

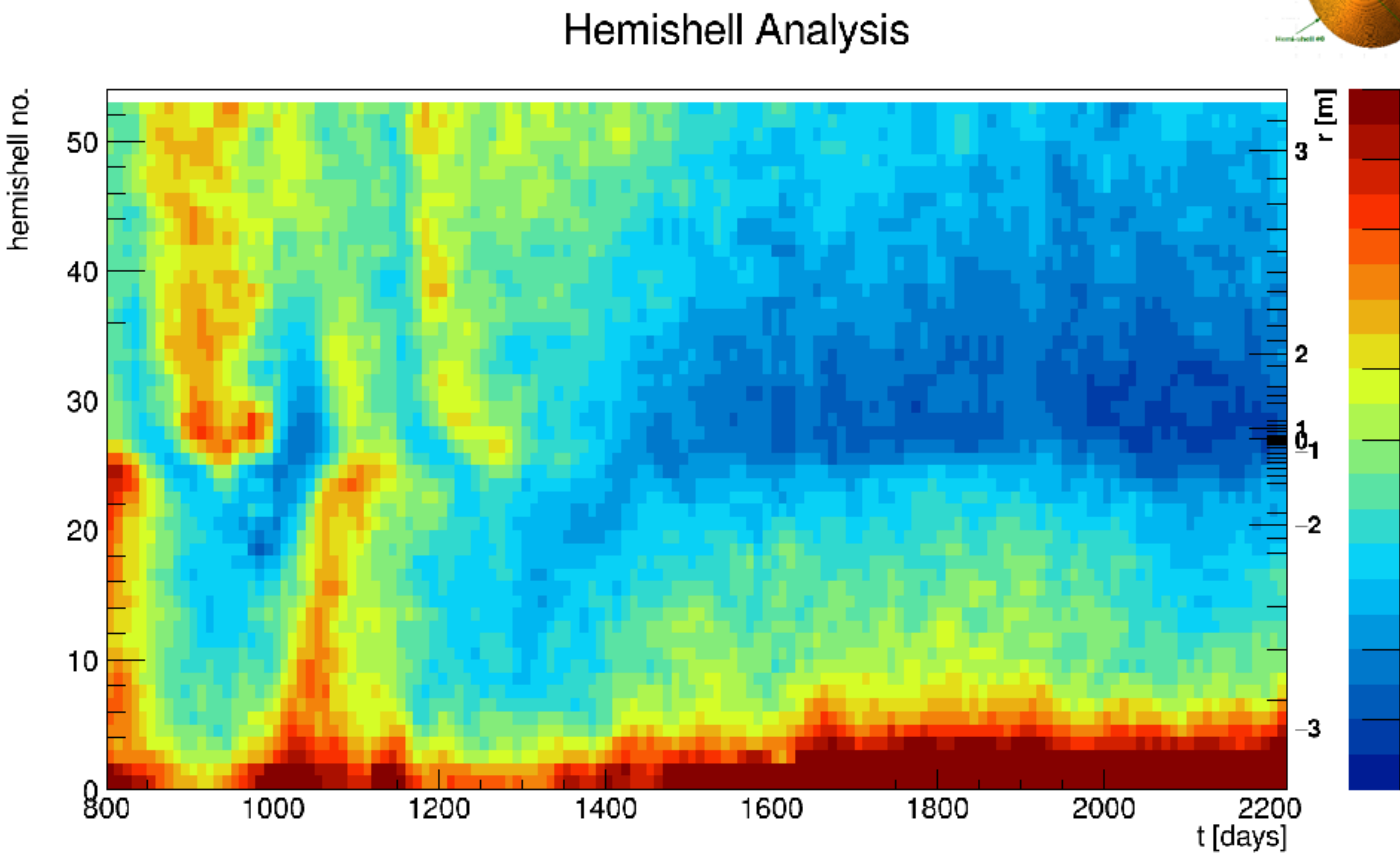
- 20 cm Rockwool dressed to maximize the temperature gradient and stabilize the detector's stratification in order to **reduce** convective transport of ^{210}Po from the **periphery** to the **FV**
- **Detector** wide and **experiment hall** wide Heating system

Temperature profile history

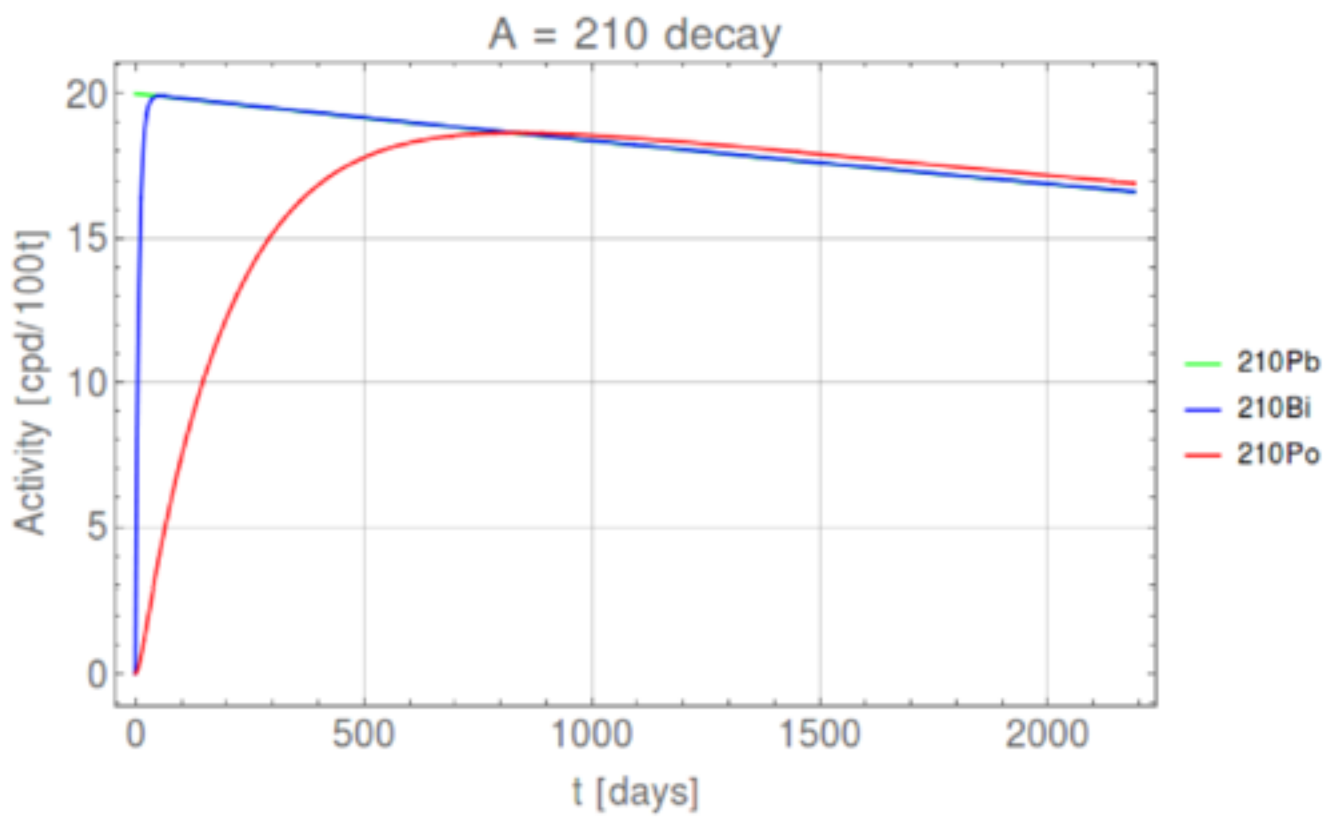


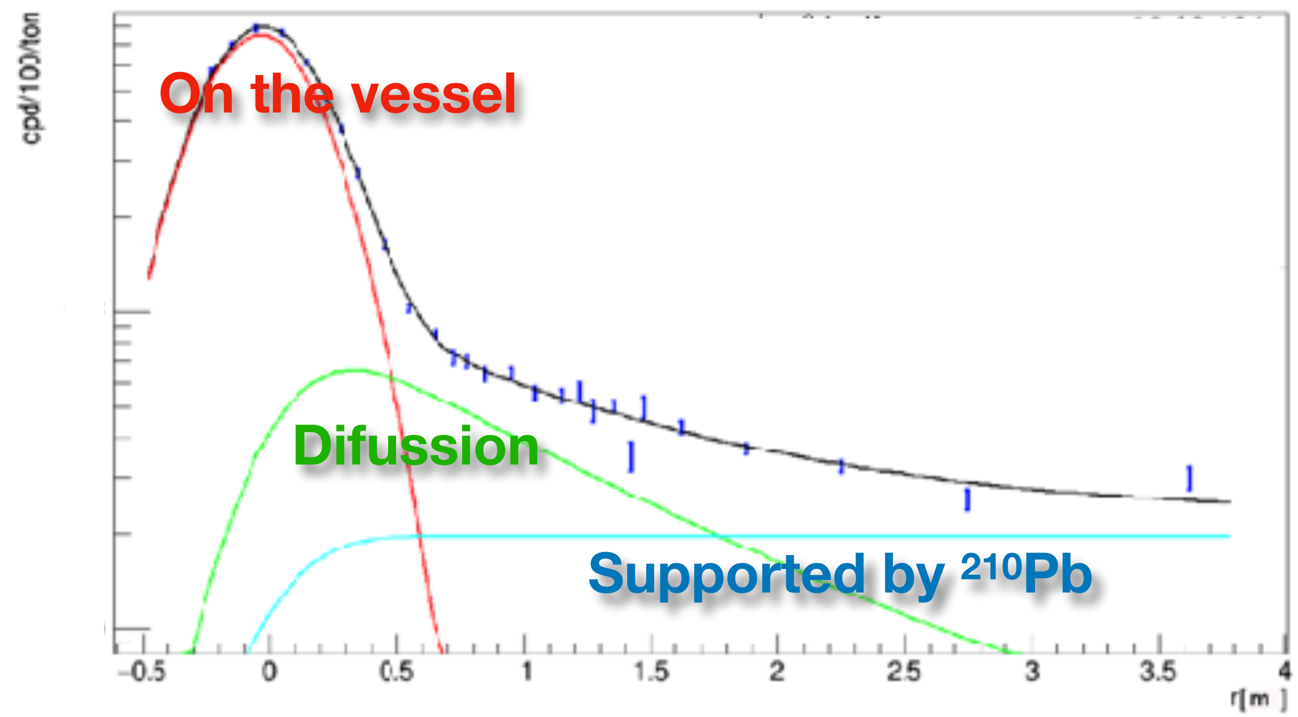





Hemishell Analysis
hemishell no.
0
10
20
30
40
50
800
1000
1200
1400
1600
1800
2000
2200
t [days]
r [m]
3
2
1
0
-1
-2
-3

Extract ^{210}Bi

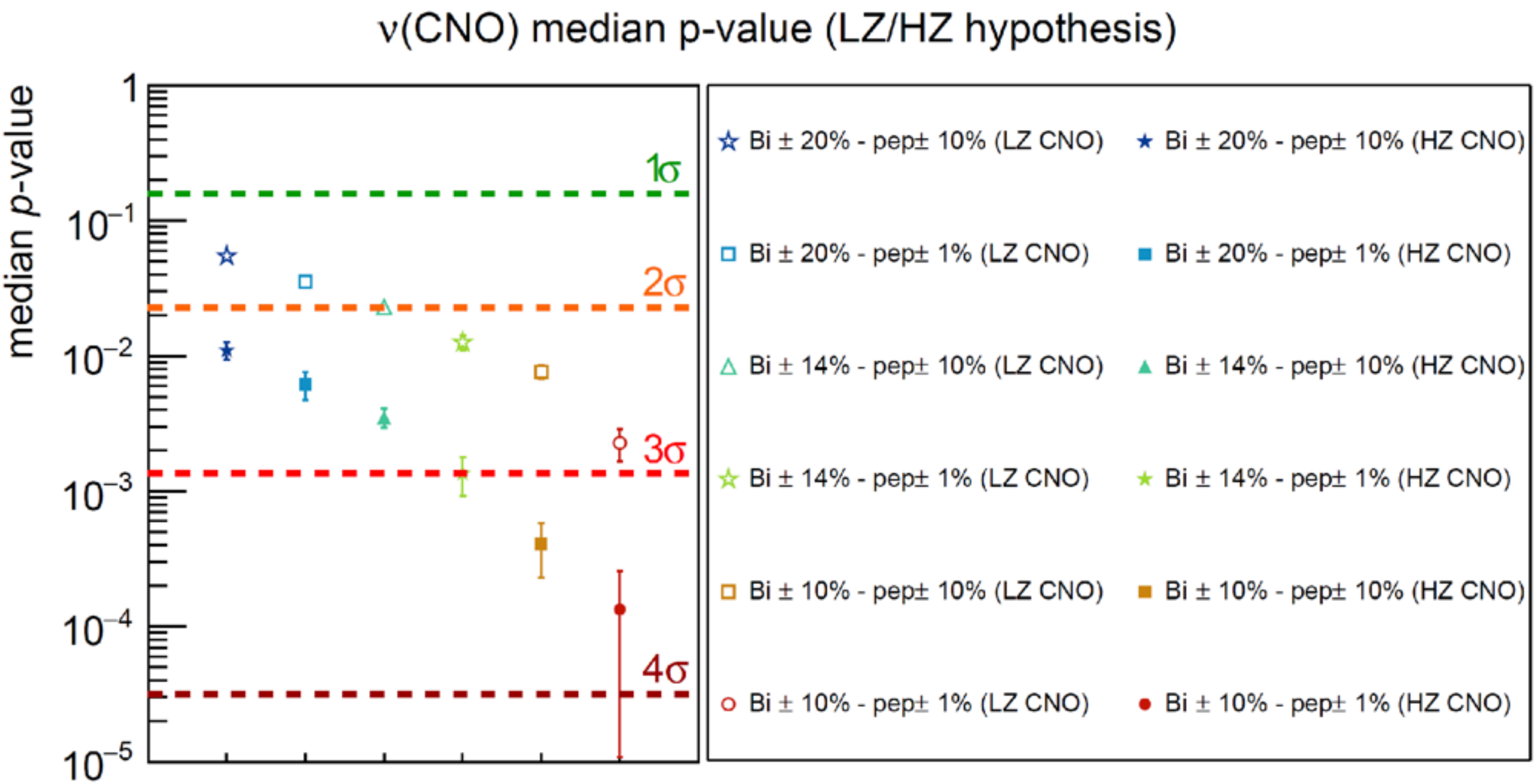




- Define **clean** region, then do temporal fit to extract ^{210}Bi
- **Residual convection component**: systematics. Study is still ongoing to evaluate its magnitude. Radial fit can provide cross-check.

Expected CNO sensitivity

- Assuming pep and ^{210}Bi constraint of certain precision



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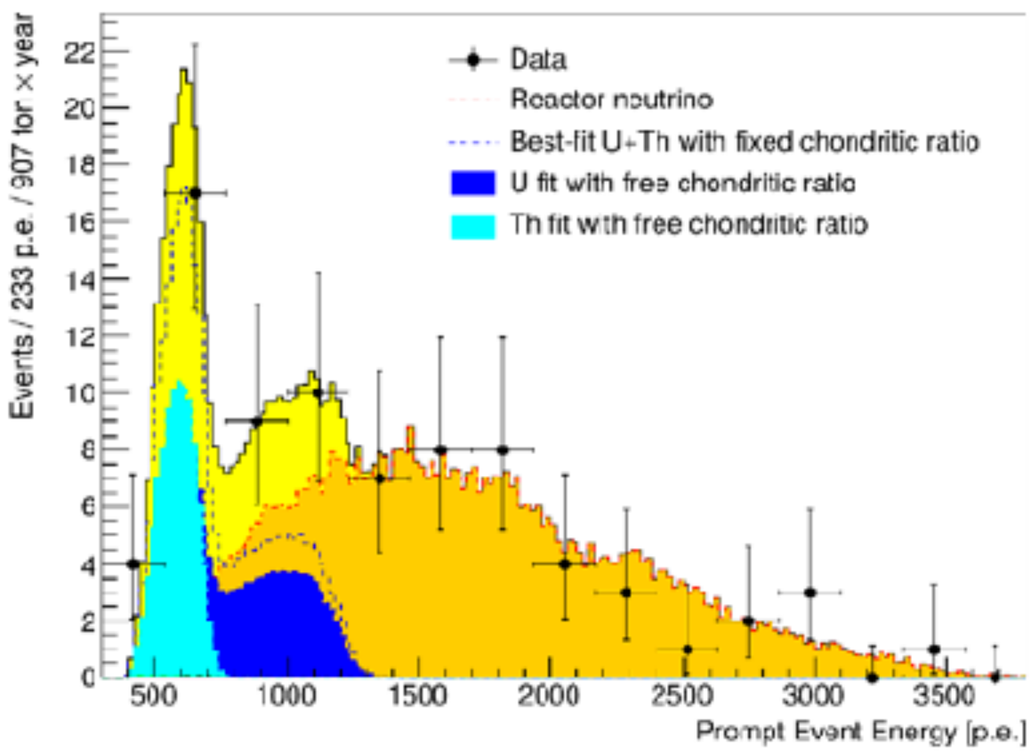
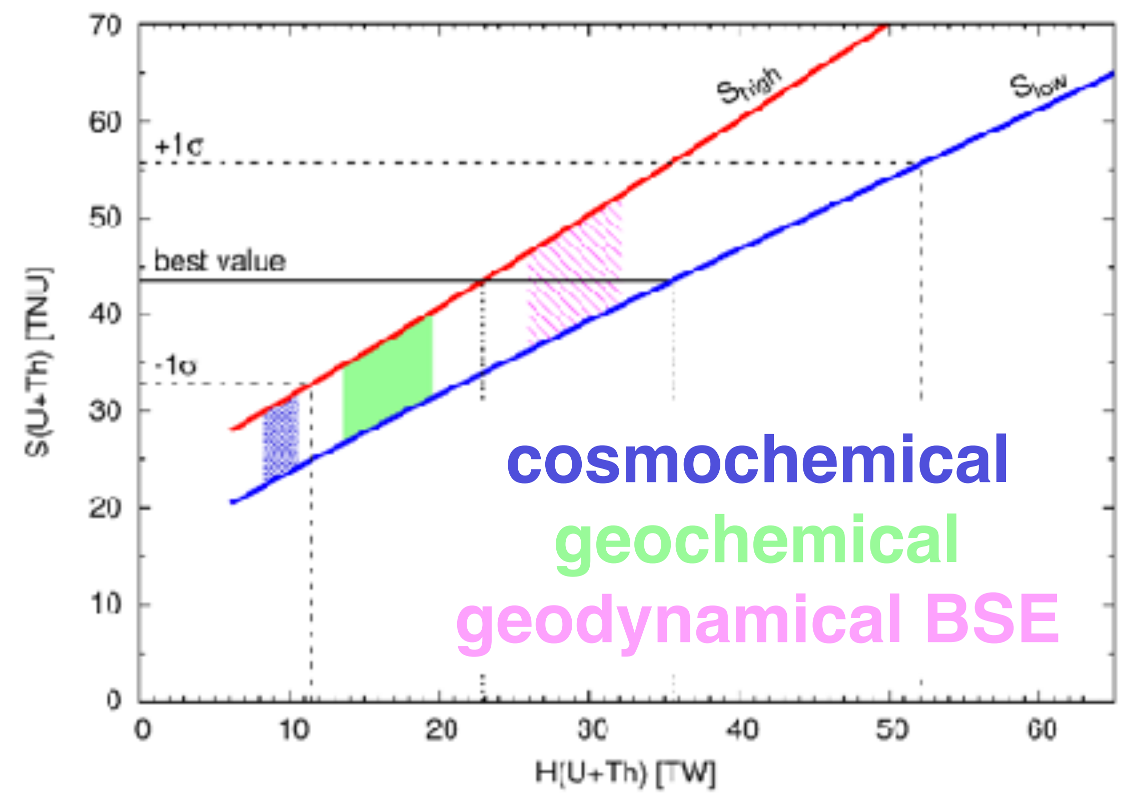
Geo-neutrinos





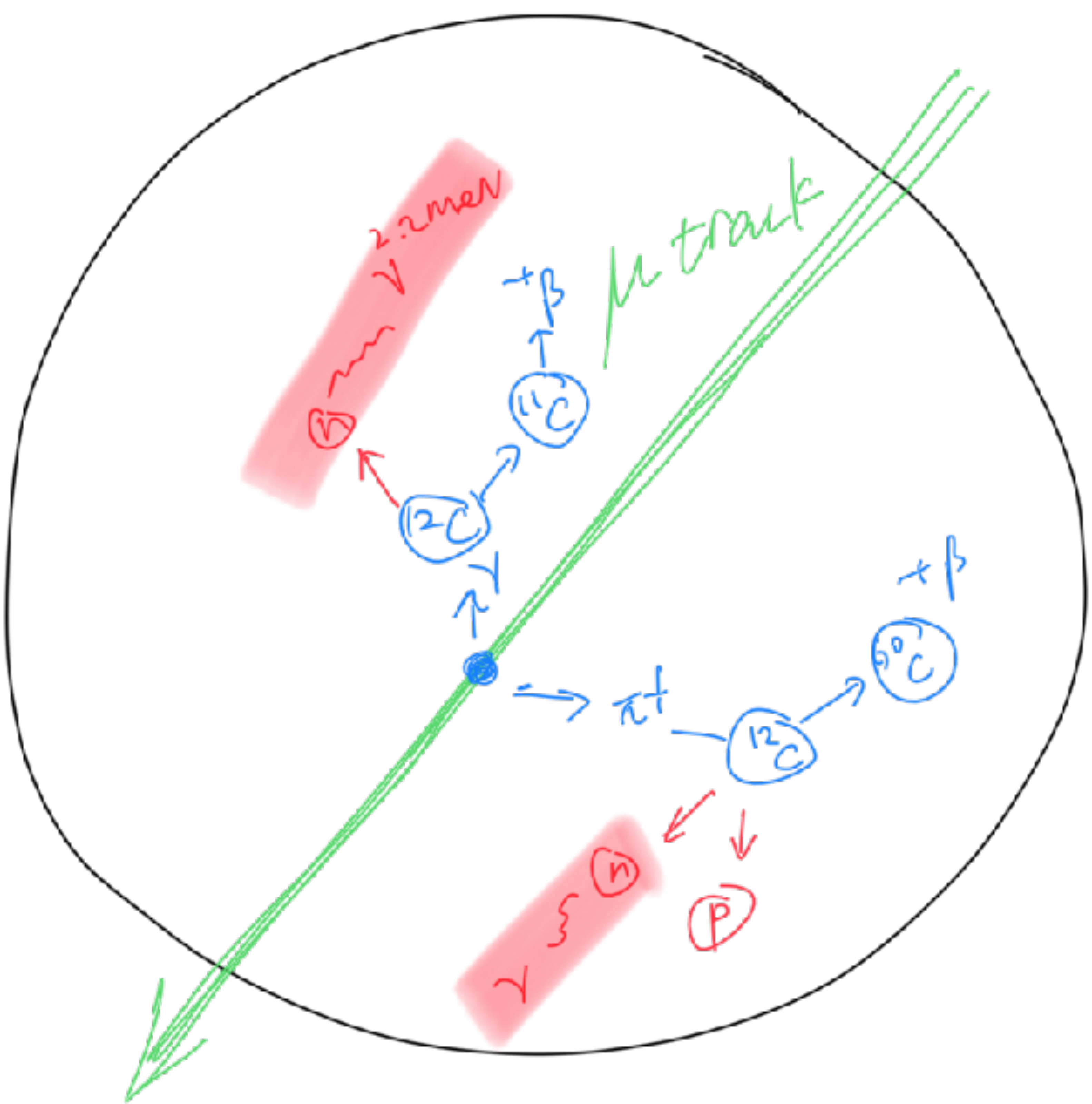
- 2056 days data (907 ton x year), 77 candidate
- $S_{geo}=23.7^{+6.5}_{-5.7}$(stat)$^{+0.9}_{-0.6}$(sys) TNU (**5.9 σ**, m(Th)/m(U)=3.9)
- geochemical and geodynamical BSE **fully compatible**, cosmochemical rejected at **1 σ** level
- Geo-neutrinos from mantle observed at **98% C.L.**

Conclusions

- Borexino reported simultaneous measurement of **full** pp-chain solar neutrinos.
- Significant improvement achieved in **stabilizing** detector stratification and **reducing** convection current.
- With 10% ^{210}Bi measurement, the median sensitivity of CNO neutrinos is **~3.7 σ (HZ) or ~2.8 σ (LZ)**
- With 2056 days of data, we observed geo-neutrino at 5.9σ C.L. and observed mantle geo-neutrino at 98% C.L.

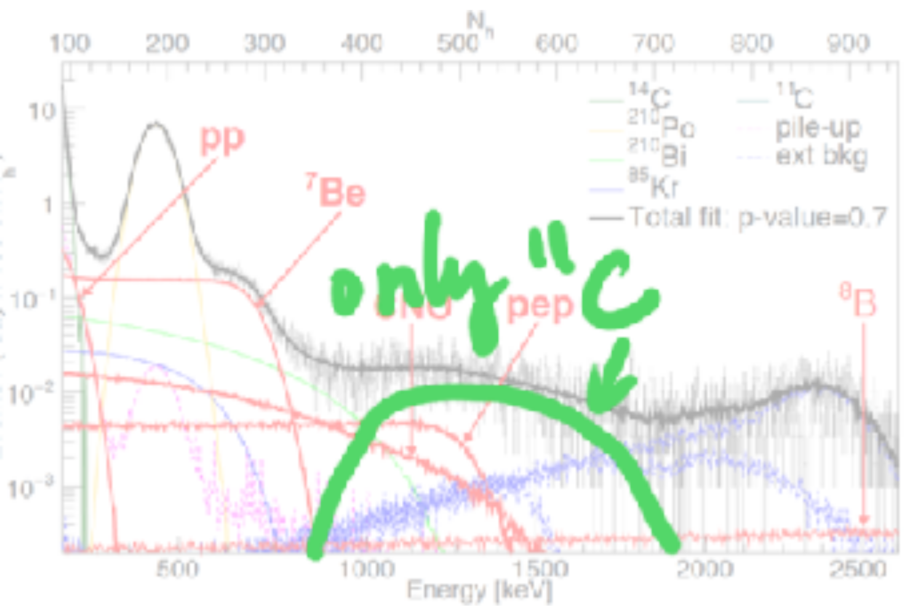
Backup

TFC cosmogenic veto

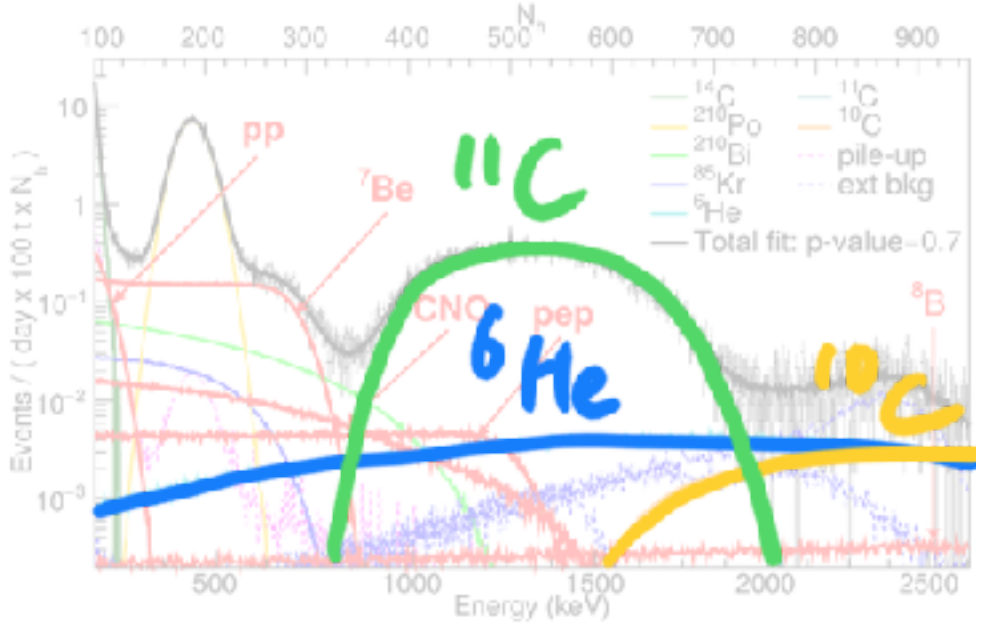


- Production of **$^{11}C/^{10}C$** is associated with production of **neutron**

TFC cosmogenic veto



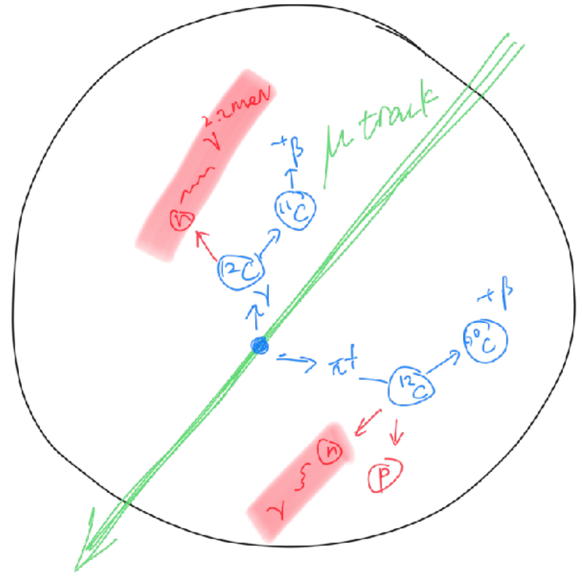
LER-A



LER-B

Background	HER-I rate [10^{-4} cpd/100 t]
Fast cosmogenics	13.6 ± 0.6
Muons	1.2 ± 0.1
Neutrons	0.72 ± 0.02
^{10}C	9.5 ± 14.1
^{11}Be	$0^{+36.3}_{-0.0}$
^{214}Bi	2.2 ± 1.0
Total	$27.2^{+38.9}_{-14.1}$

HER-II



- μ track + spoliation neutron + cosmogenic
- LER: (remove 92±4% ^{11}C, energy fit)
  - **^{6}He** (no neutron associated) also suppressed
- HER: (remove 92.5^{+7}_{-20}% ^{10}C, temporal fit)
  - **^{11}Be** (no neutron associated) also suppressed