

Strategy for CNO solar neutrino detection with Borexino

Lake Louise Winter Institute – Feb 13, 2019

Daive Basilico on behalf of the Borexino collaboration

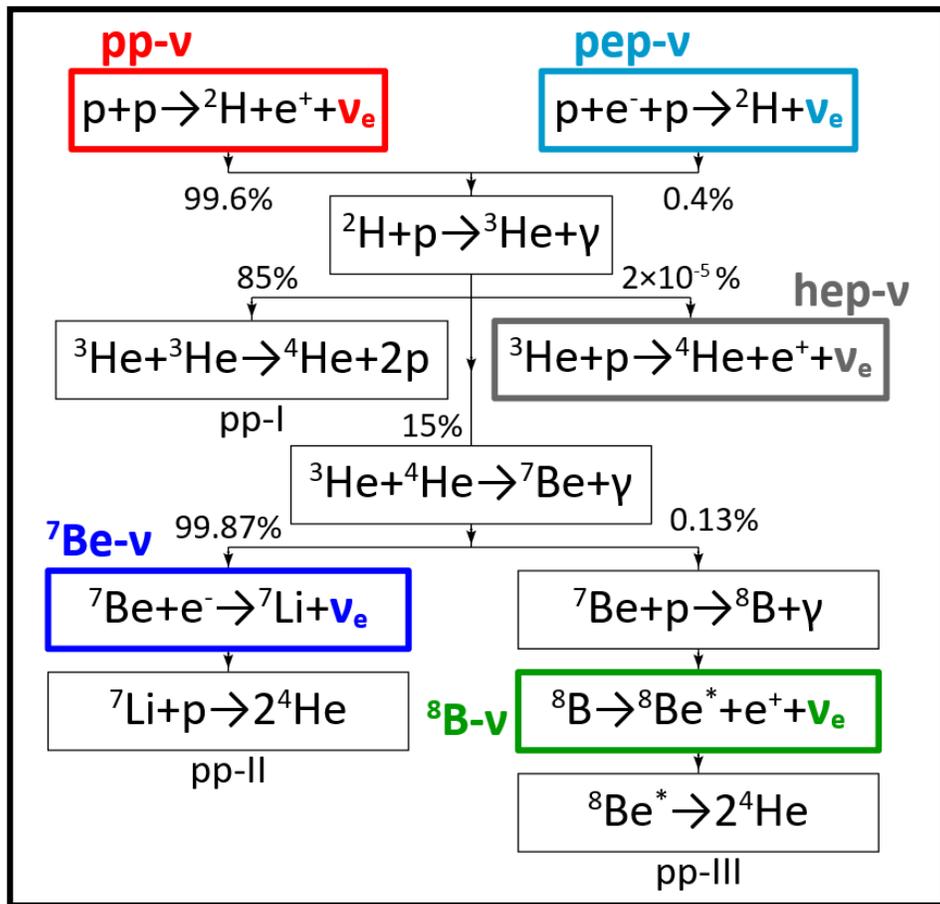


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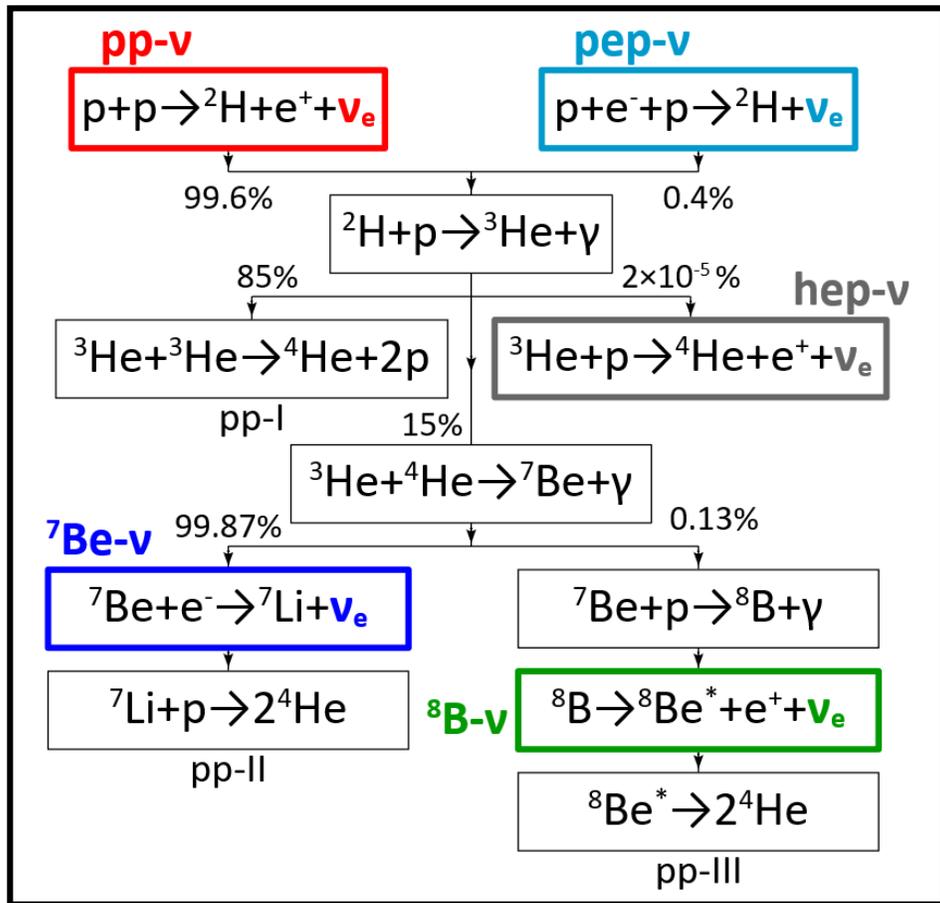
Solar neutrinos

- Sun shines thanks to nuclear reaction sequences
→ neutrino emission
- “Photography” of the Sun’s core
- **pp chain:** dominant for Sun-like stars (99% luminosity)

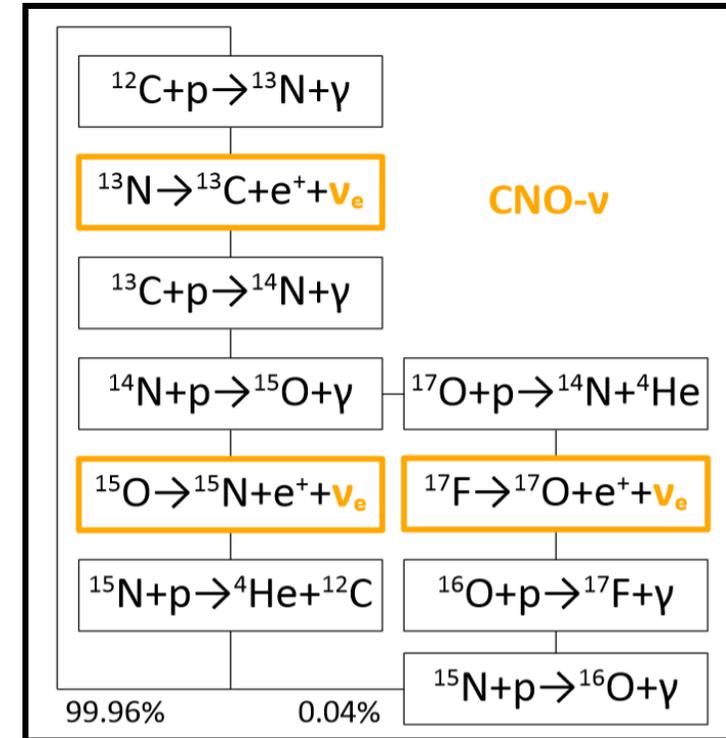


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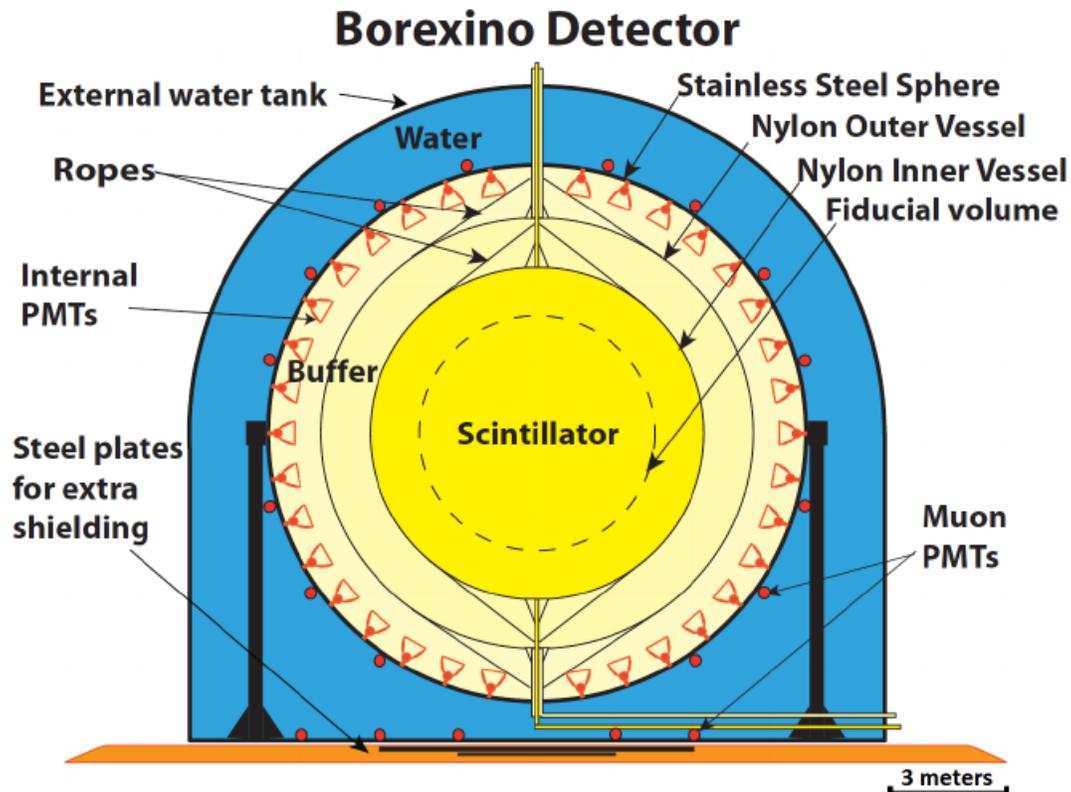


CNO cycle: 1% for the Sun, dominant for massive stars

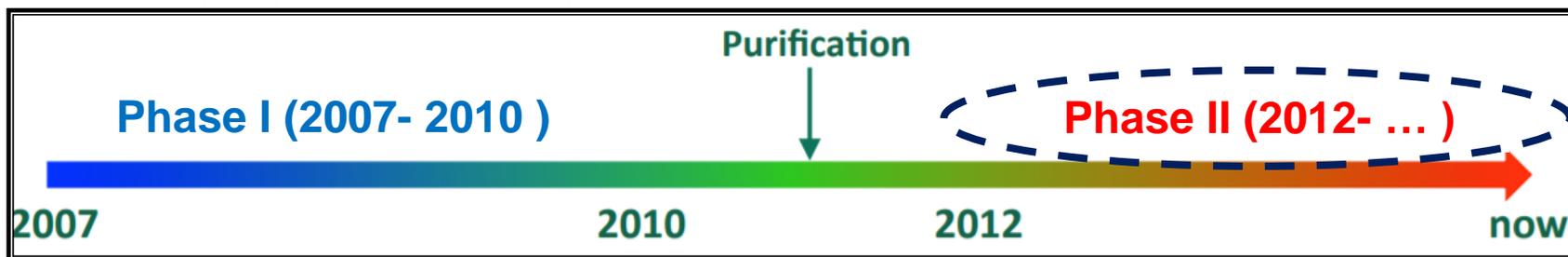


Still undetected!

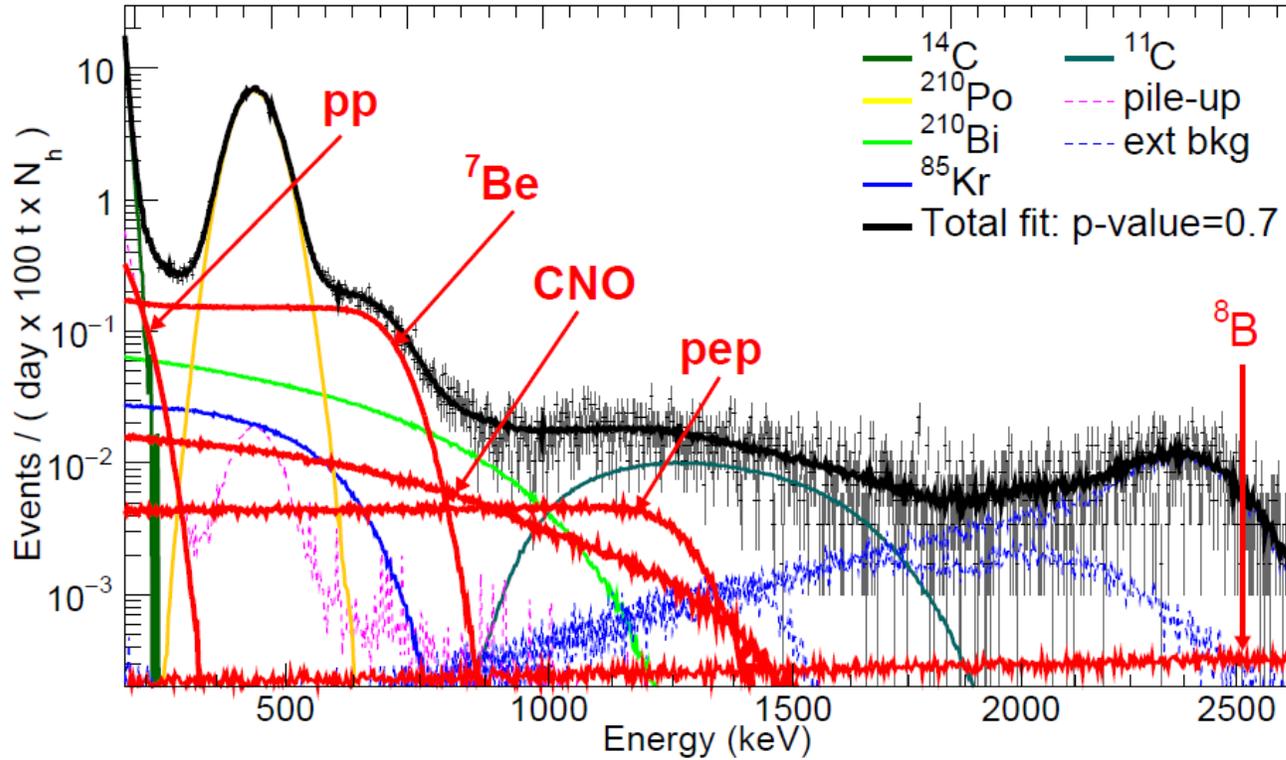
Borexino



- Data taking from 2007 @ LNGS
- Main goal: solar ν measurements with 300 ton of ultrapure liquid scintillator
- Extremely low radioactivity levels
- Elastic scattering: $\nu_x + e^- \rightarrow \nu_x + e^-$ $x = e, \mu, \tau$
- 2000 photomultipliers (PMTs):
 - Arrival time of detected photons \rightarrow Position
 - Number of detected photons \rightarrow Energy



Solar neutrino spectroscopy with Borexino



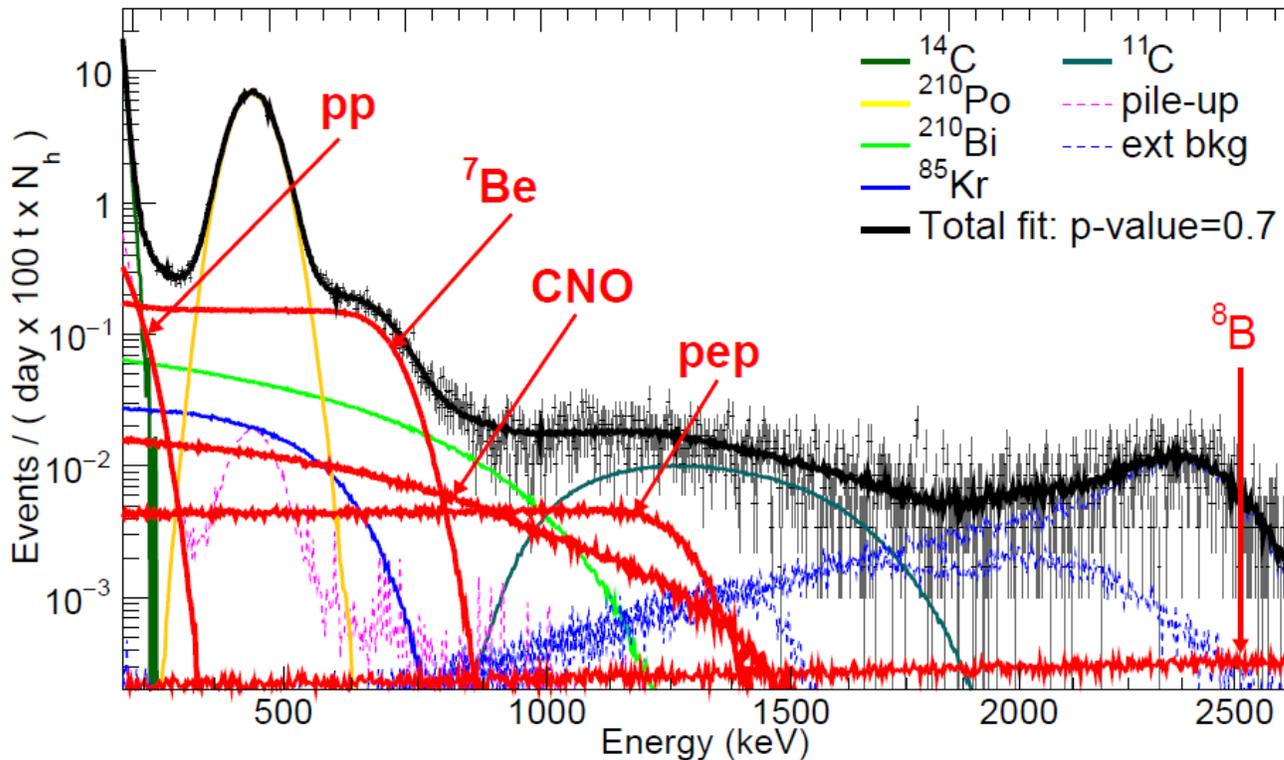
Solar neutrino spectroscopy: simultaneous fit of all the low energy neutrino solar rates (**pp, ⁷Be, pep + upper limit for CNO**)

→ multivariate analytical and Monte Carlo fit (see Davide D'Angelo's talk)

Latest Borexino CNO flux upper limit

$$\Phi(\text{CNO } \nu) < 7.9 \cdot 10^8 \text{ cm}^{-2} \text{ s}^{-1} \text{ (95\% C. L.)}$$

Solar neutrino spectroscopy with Borexino



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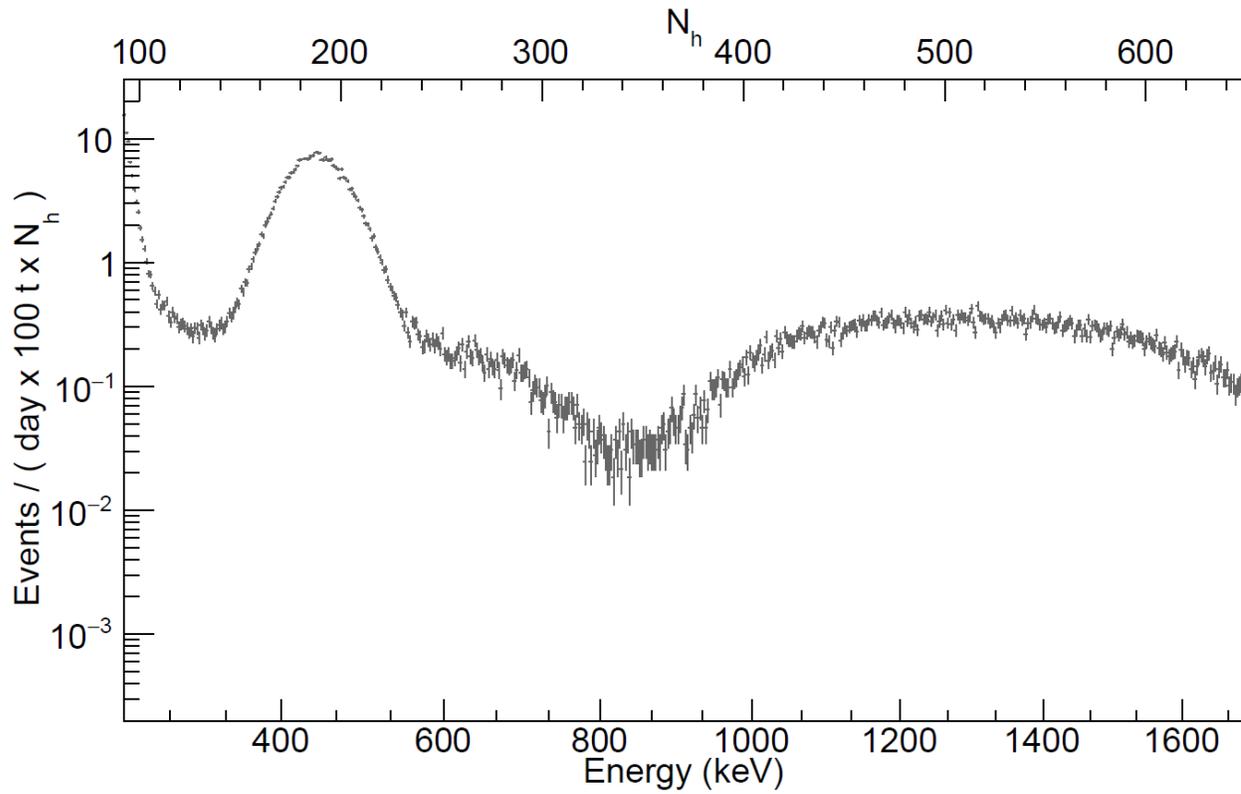
$$\Phi(\text{CNO } \nu) < 7.9 \cdot 10^8 \text{ cm}^{-2} \text{ s}^{-1} \text{ (95\% C. L.)}$$

Why a CNO ν measurement is so difficult?

- 1) Low rate
- 2) No distinguishable spectral features
- 3) Anticorrelation with ^{210}Bi and pep ν

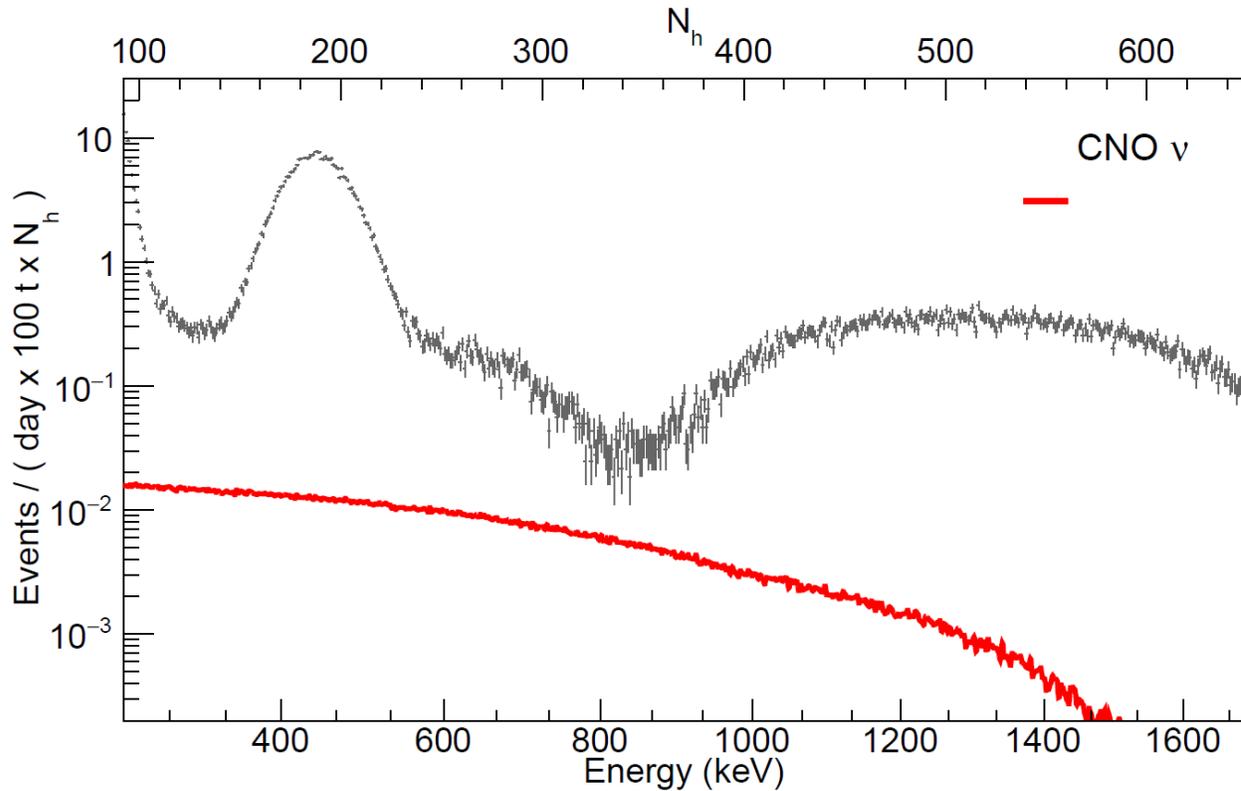
} shape

CNO ν – pep ν – ^{210}Bi anticorrelation



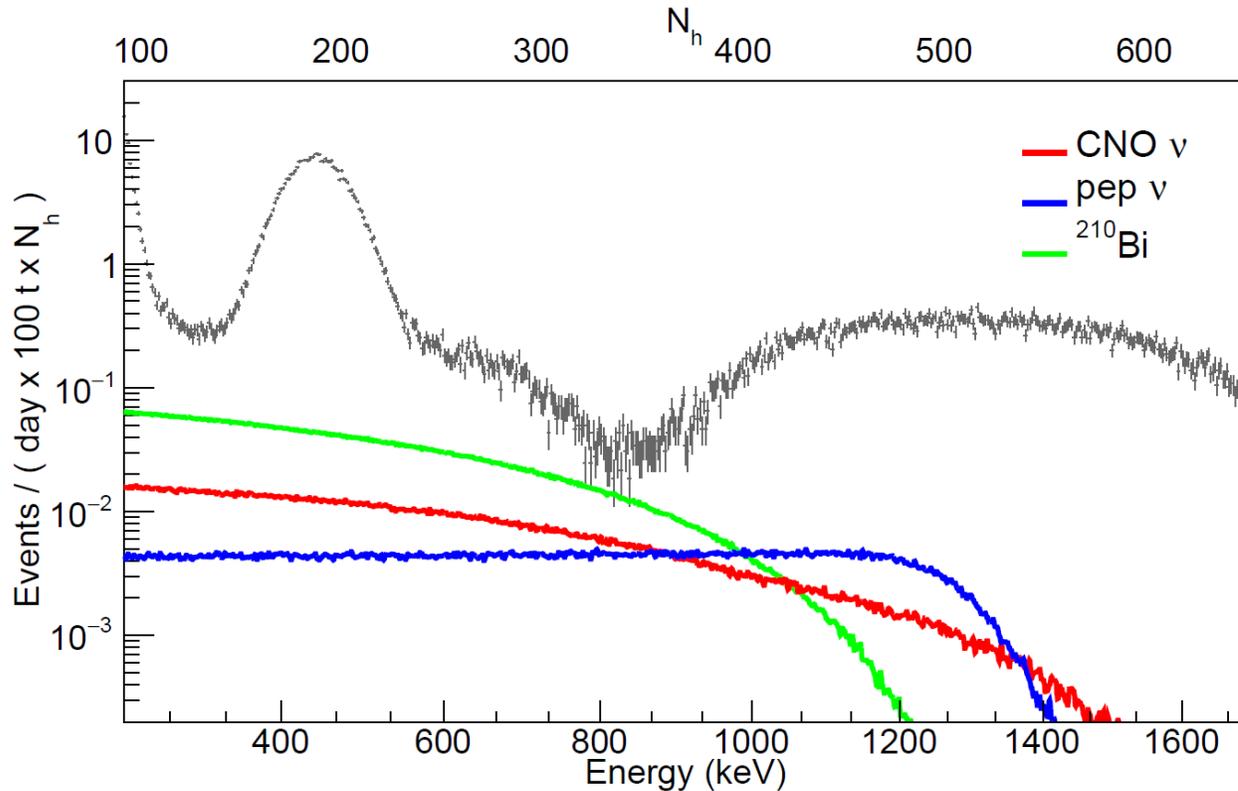
- Borexino data

CNO ν – pep ν – ^{210}Bi anticorrelation



- Borexino data
- CNO ν expected spectrum

CNO ν – pep ν – ^{210}Bi anticorrelation



- Borexino data
- CNO ν expected spectrum
- ^{210}Bi spectrum
- pep ν spectrum

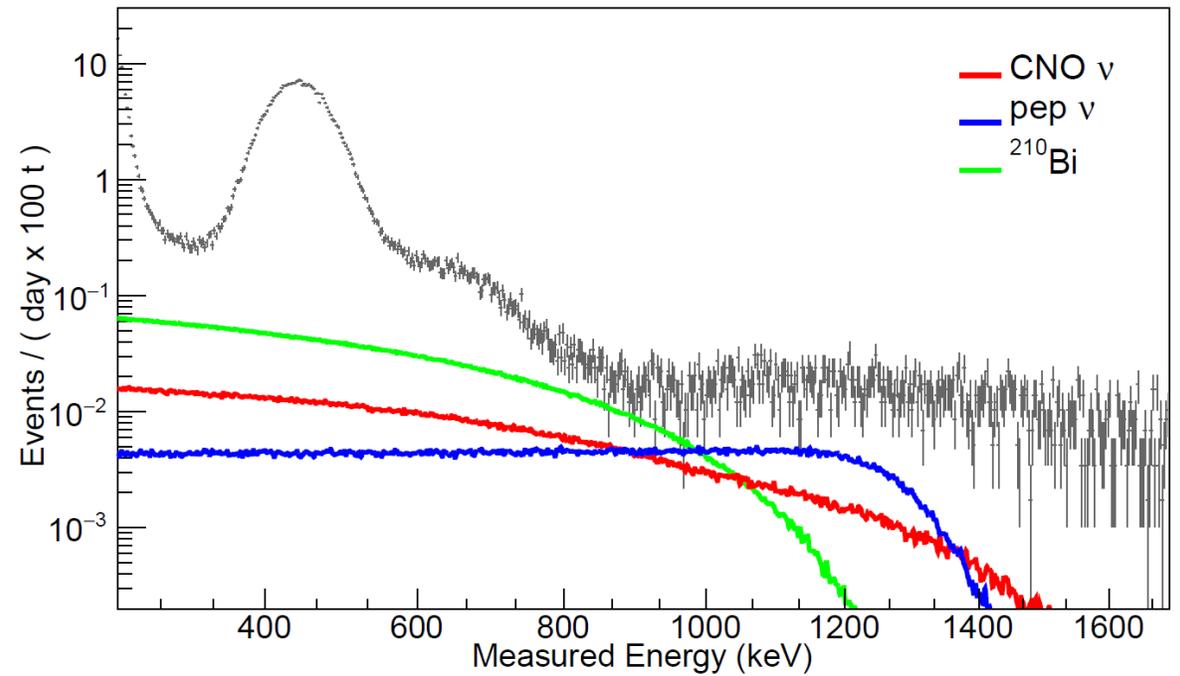
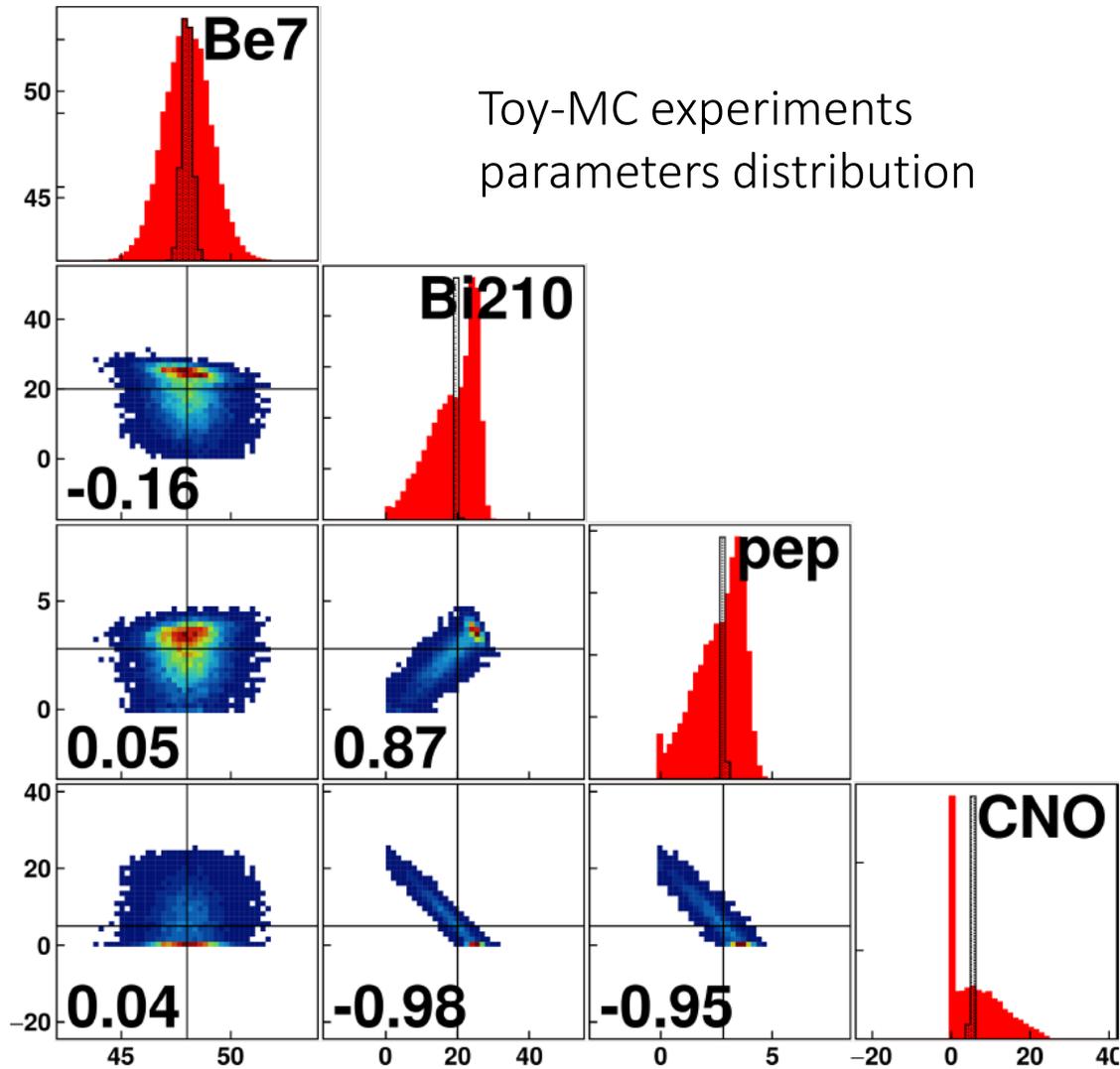
Strict anticorrelation between
CNO ν , pep ν and ^{210}Bi

The spectral fit returns only the
sum of the two components, if
both are left free!

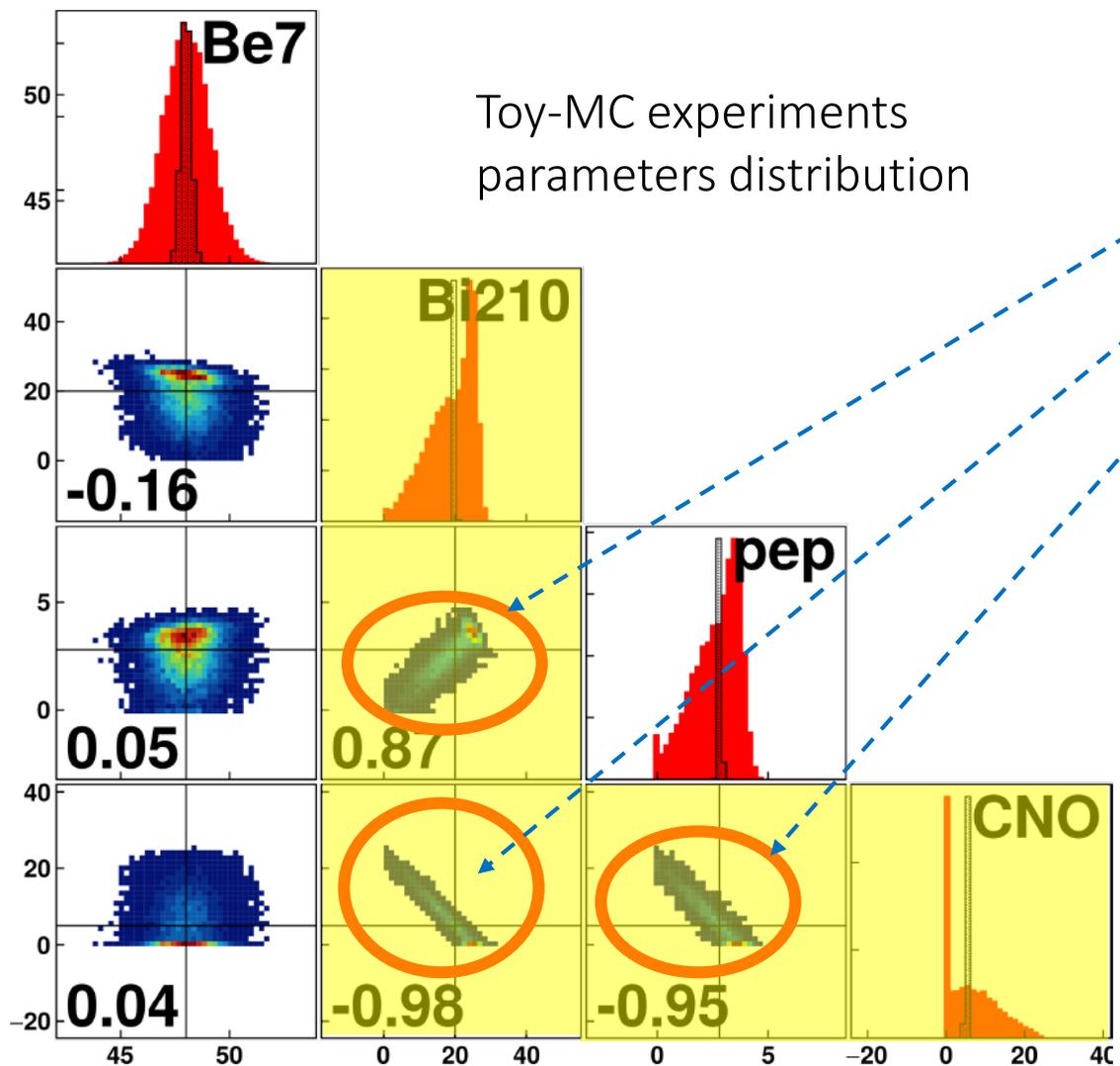
Note also the low rate:

- $R(\text{CNO } \nu)_{\text{expected}} \sim 3\text{-}5 \text{ cpd}/100\text{ton}$
- $R(^{210}\text{Bi}) \sim 20 \text{ cpd}/100\text{ton}$
- [$R(\text{pep}) \sim 2.7 \text{ cpd}/100\text{ton}$]

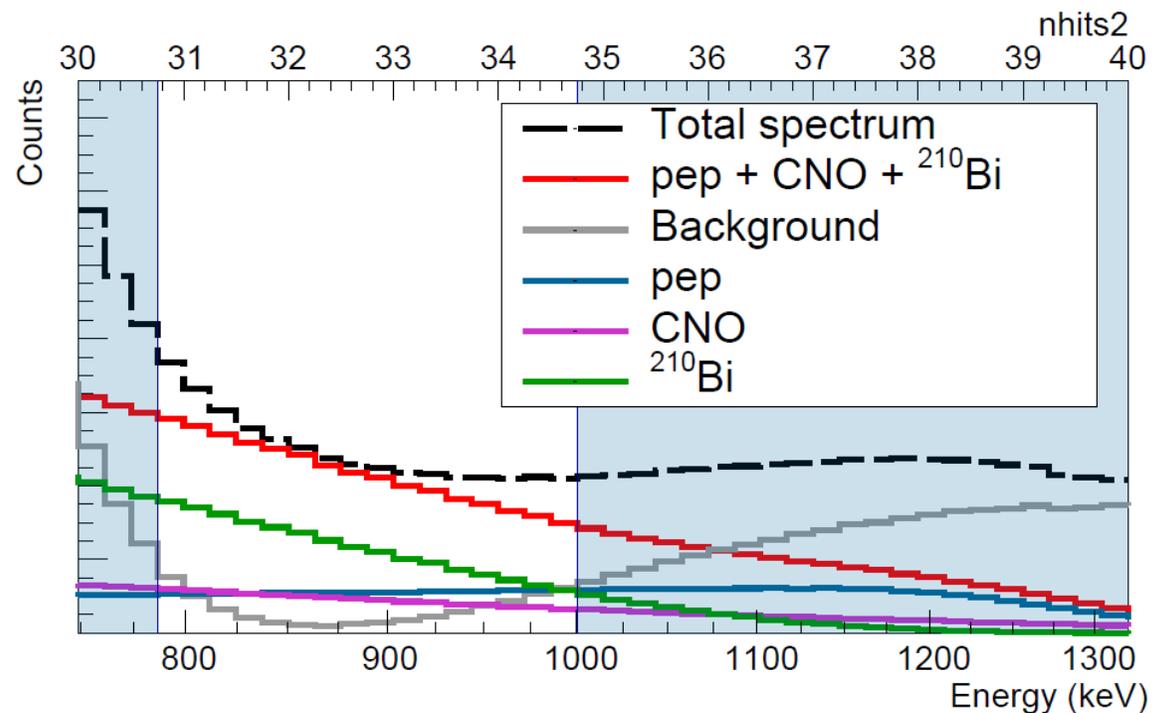
CNO ν – pep ν – ^{210}Bi anticorrelation



CNO ν – pep ν – ^{210}Bi anticorrelation



Strict anticorrelation between CNO ν , pep ν and ^{210}Bi



CNO ν – pep ν – ^{210}Bi anticorrelation

We need **two constraints independent** from the spectral fit

1. pep ν : pp/pep luminosity
2. ^{210}Bi : ^{210}Po tagging

Counting analysis (+ shape information)

i : signal or bkg component

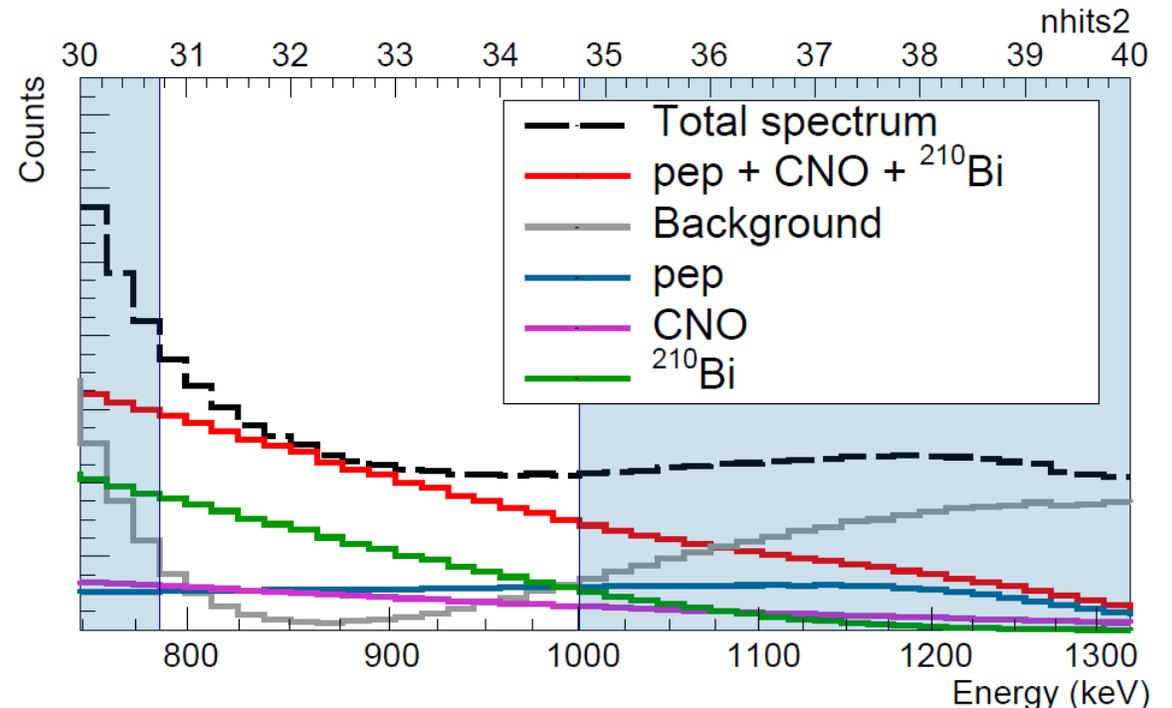
R_i : rate

σ_i : uncertainty on rate

f_i : fraction of events

$$N_{tot} \propto R_{CNO} f_{CNO} + R_{210Bi} f_{210Bi} + R_{pep} f_{pep}$$

$$\sigma_{CNO} \propto \frac{\sigma_{N_{tot}}}{f_{CNO}} \oplus \frac{f_{210Bi}}{f_{CNO}} \sigma_{210Bi} \oplus \frac{f_{pep}}{f_{CNO}} \sigma_{pep}$$



pep ν constraint → the solar luminosity constraint

L_{\odot} : solar luminosity at the earth's surface

d : average earth-sun distance

Sum over the neutrino reactions

$$\frac{L_{\odot}}{4\pi d^2} = \sum_i \alpha_i \Phi_i$$

Φ_i : pp and CNO neutrino fluxes

α_i : coefficients for the energy provided to the star by nuclear fusion reactions

Assumptions:

- Only pp chain and CNO cycle fuel the Sun
- The Sun is in dynamical equilibrium in 10^5 years timescale: ($L_{\odot} = \text{const.}$)

pep ν constraint → the solar luminosity constraint

L_{\odot} : solar
 luminosity at the
 earth's surface

$$\frac{L_{\odot}}{4\pi d^2} = \sum_i \alpha_i \Phi_i \approx \alpha_{pp} \Phi_{pp}$$

Φ_i : pp and CNO
 neutrino fluxes

L_{\odot} known at 0.4% level
 α_i known at 10^{-5} level

$\Phi(pp)$ known
 at 1% level

+

$\Phi(pep)$ known at
 $\approx 1\%$ level

pp and pep reactions:
 same matrix element

pp) $p + p \rightarrow d + e^+ + \nu_e$
 pep) $p + e^- + p \rightarrow d + \nu_e$

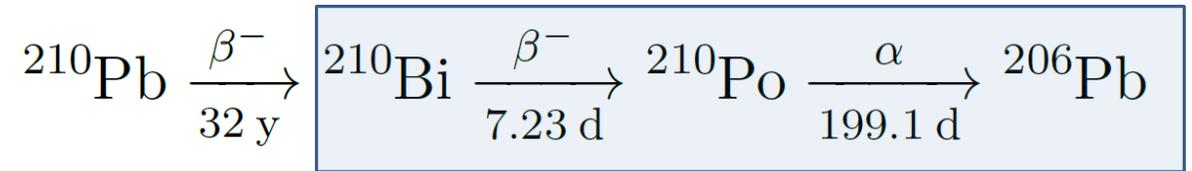
$\Phi(pp)/\Phi(pep)$
 known at <1%
 level

^{210}Bi constraint: from ^{210}Po to ^{210}Bi

Independent estimation of ^{210}Bi rate

^{210}Bi - ^{210}Po analysis:

Extract the ^{210}Bi decay rate in Borexino through the ^{210}Po decay rate features

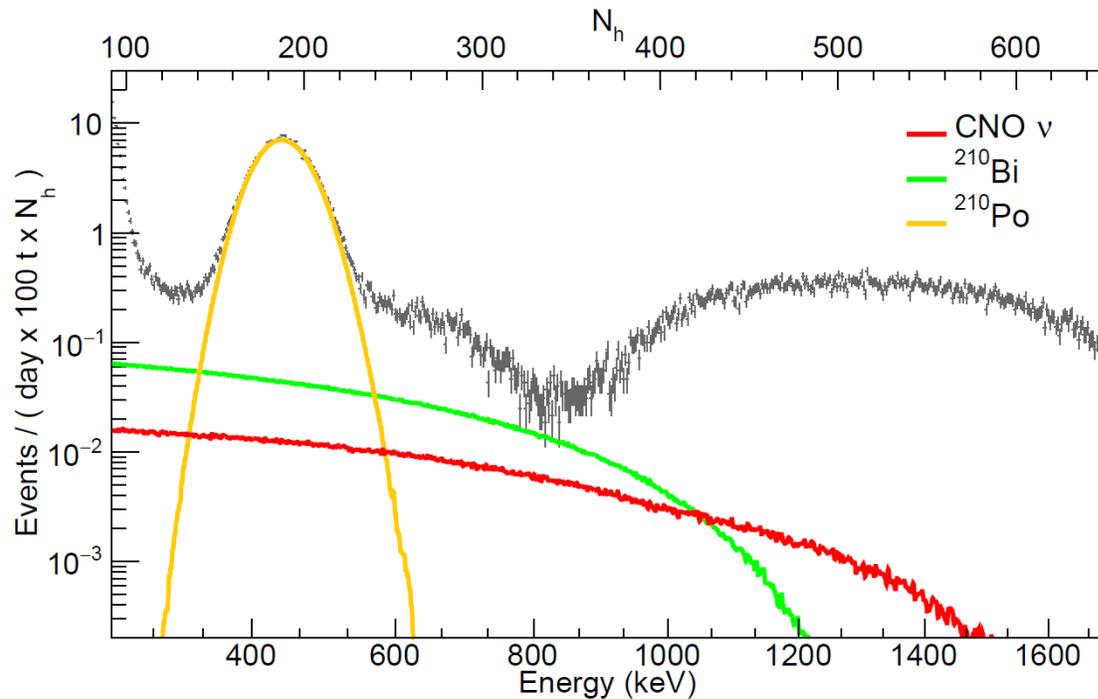
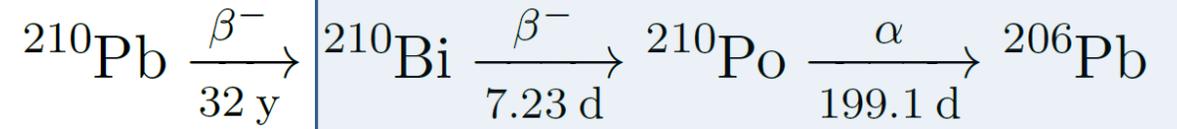


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^{210}Po is “easier” to identify wrt ^{210}Bi :

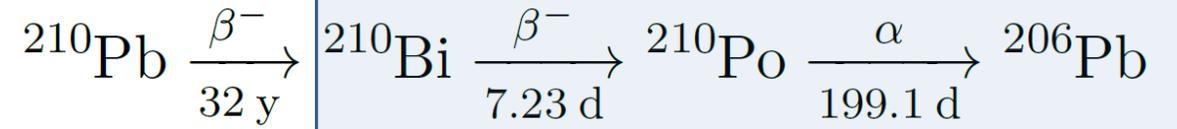
- Monoenergetic decay → “gaussian” peak
- α decay → pulse shape discrimination

^{210}Bi constraint: from ^{210}Po to ^{210}Bi

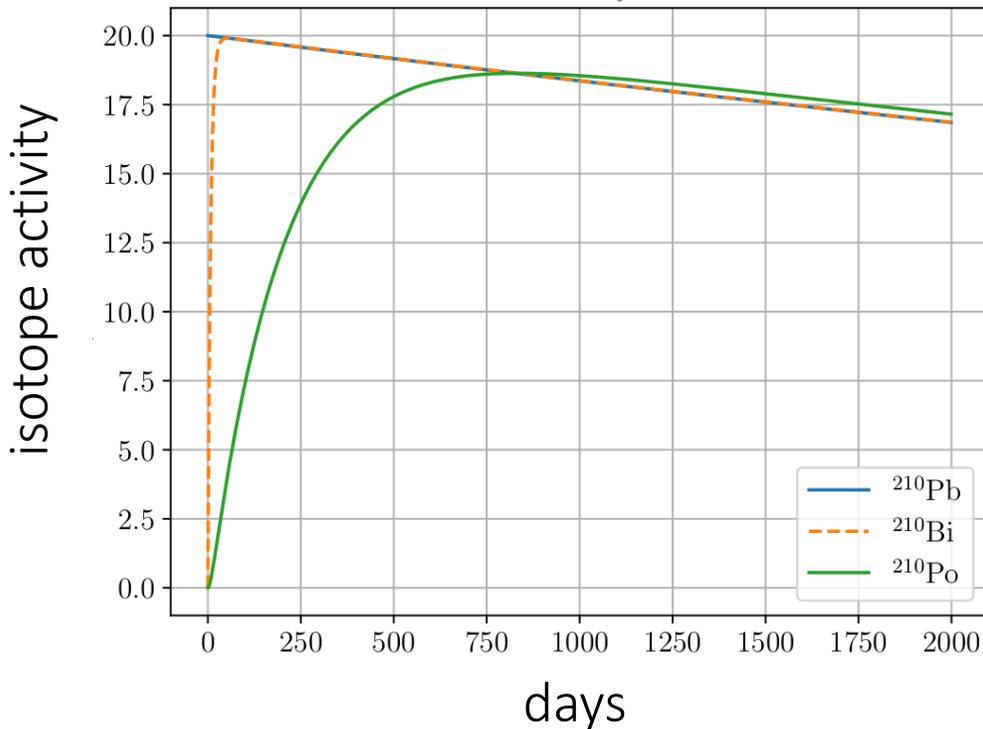
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A=210 decay chain

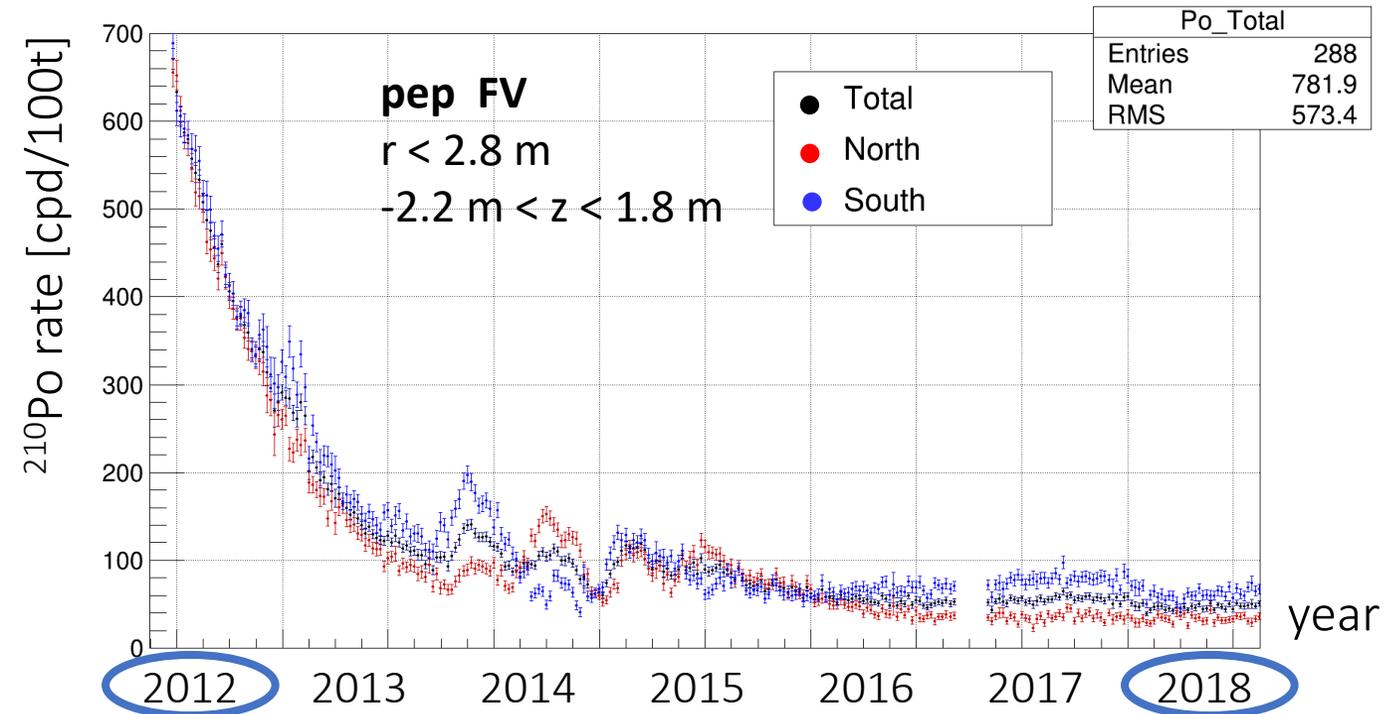


^{210}Po is “easier” to identify wrt ^{210}Bi :

- Monoenergetic decay \rightarrow “gaussian” peak
- α decay \rightarrow pulse shape discrimination

If the ^{210}Bi is in radioactive equilibrium with ^{210}Po , an independent measurement of the latter decay rate gives directly the ^{210}Bi one (**secular equilibrium scenario**)

^{210}Po rate evolution in time



Decreasing trend:

^{210}Po out of equilibrium!

(1400 cpd/100ton at beginning of 2012)

Irregular/“oscillating” trends: possibly due to scintillator temperature variations (seasonally correlated)

$$R_{\text{Po}}(t) = (A - B)e^{-t/\tau_{\text{Po}}} + B$$

$$\tau_{\text{Po}} \approx 200 \text{ days}$$

A: “unsupported term”, out of equilibrium

B: “supported term”, directly related to the ^{210}Bi parent



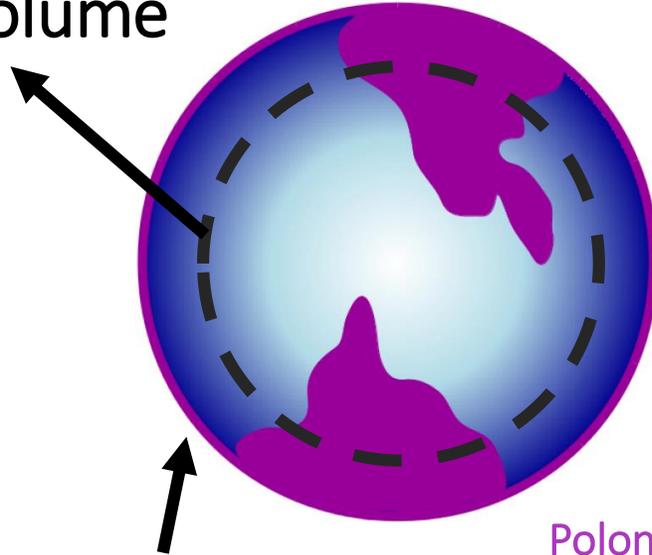
Waiting for the plateau! ($t \rightarrow \infty$)

Core of the analysis: understand the validity and the features of this relation, quantifying this B-term.

Diffusion and convection

^{210}Po moves in the scintillator because of the temperature gradient

Fiducial Volume



Inner Vessel

Polonium on IV and moving through convection

Pure exponential decay is prevented by the presence of strong convective motions (purple blobs), caused mostly by the seasonal temperature change.

$$\partial_t \rho(r) = D \nabla^2 \rho(r) - \frac{\rho(r)}{\tau_{\text{Po}}} \longrightarrow \rho(r) = \rho_0 \frac{\sinh(r/\lambda)}{r/\lambda}$$

Diffusion length
 $\lambda = \sqrt{D \tau_{\text{Po}}} \approx 20 \text{ cm}$

How to contrast the temperature variations?

Thermal insulation



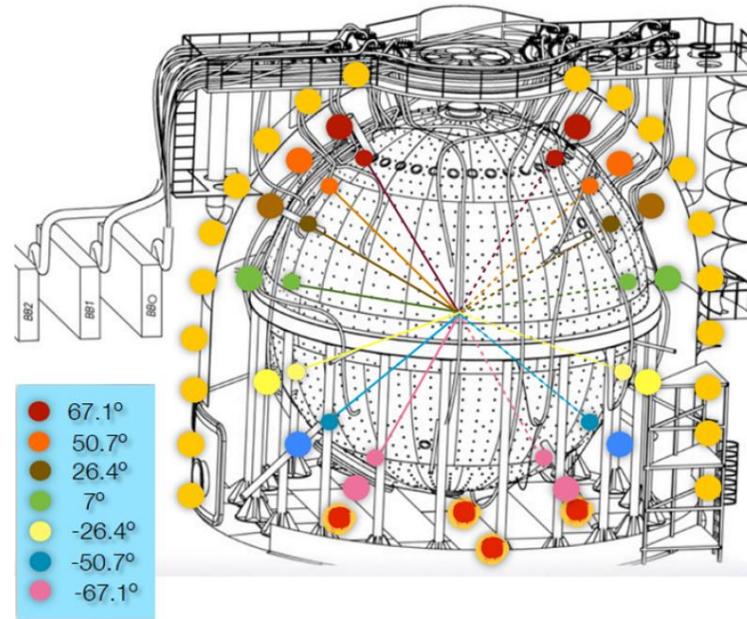
- Double layer of mineral wool
- Active Gradient Stabilization System
- Hall C Temperature Stabilization

How to contrast the temperature variations?

Thermal insulation



Temperature control system
(monitoring)



54 temperature probes

- Double layer of mineral wool
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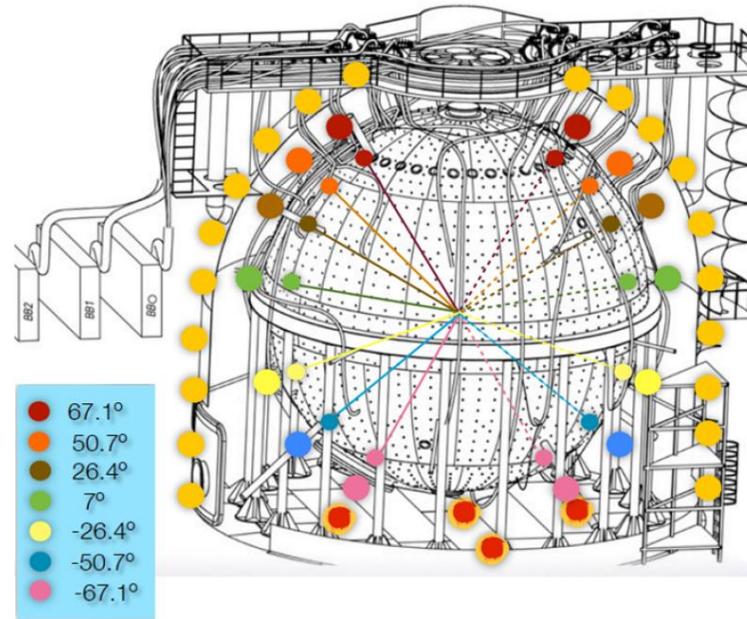
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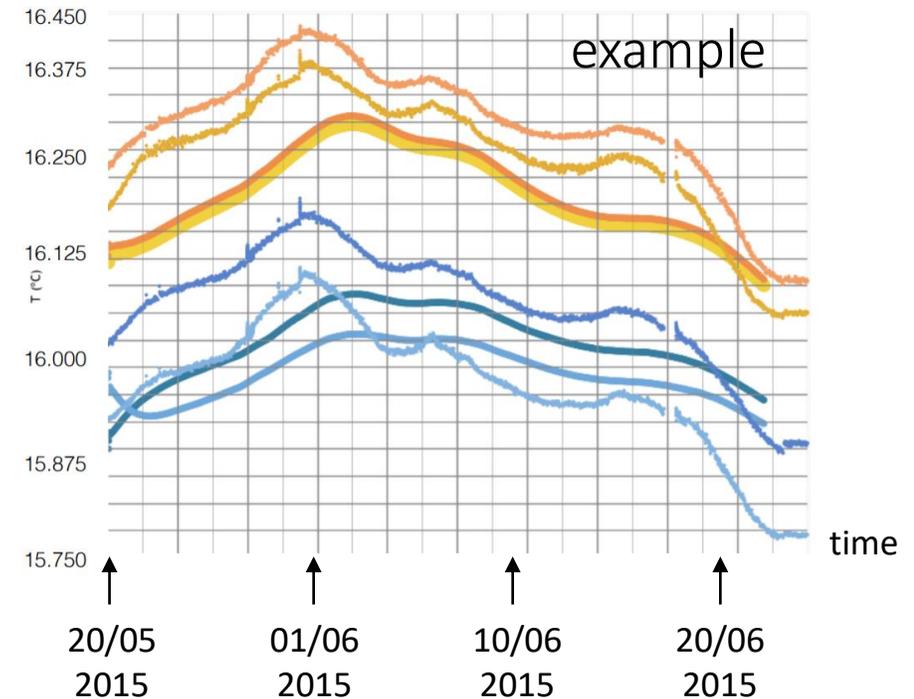
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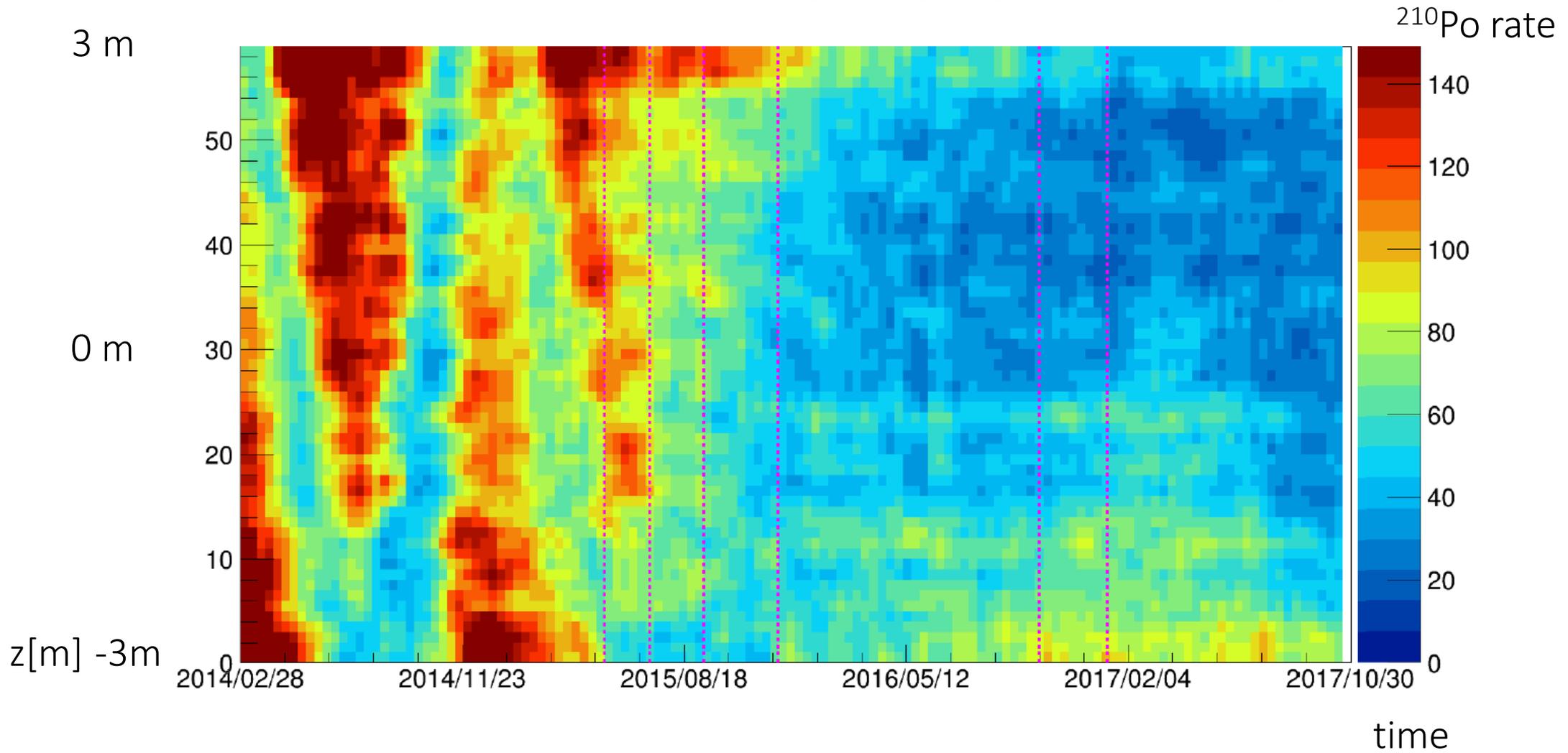


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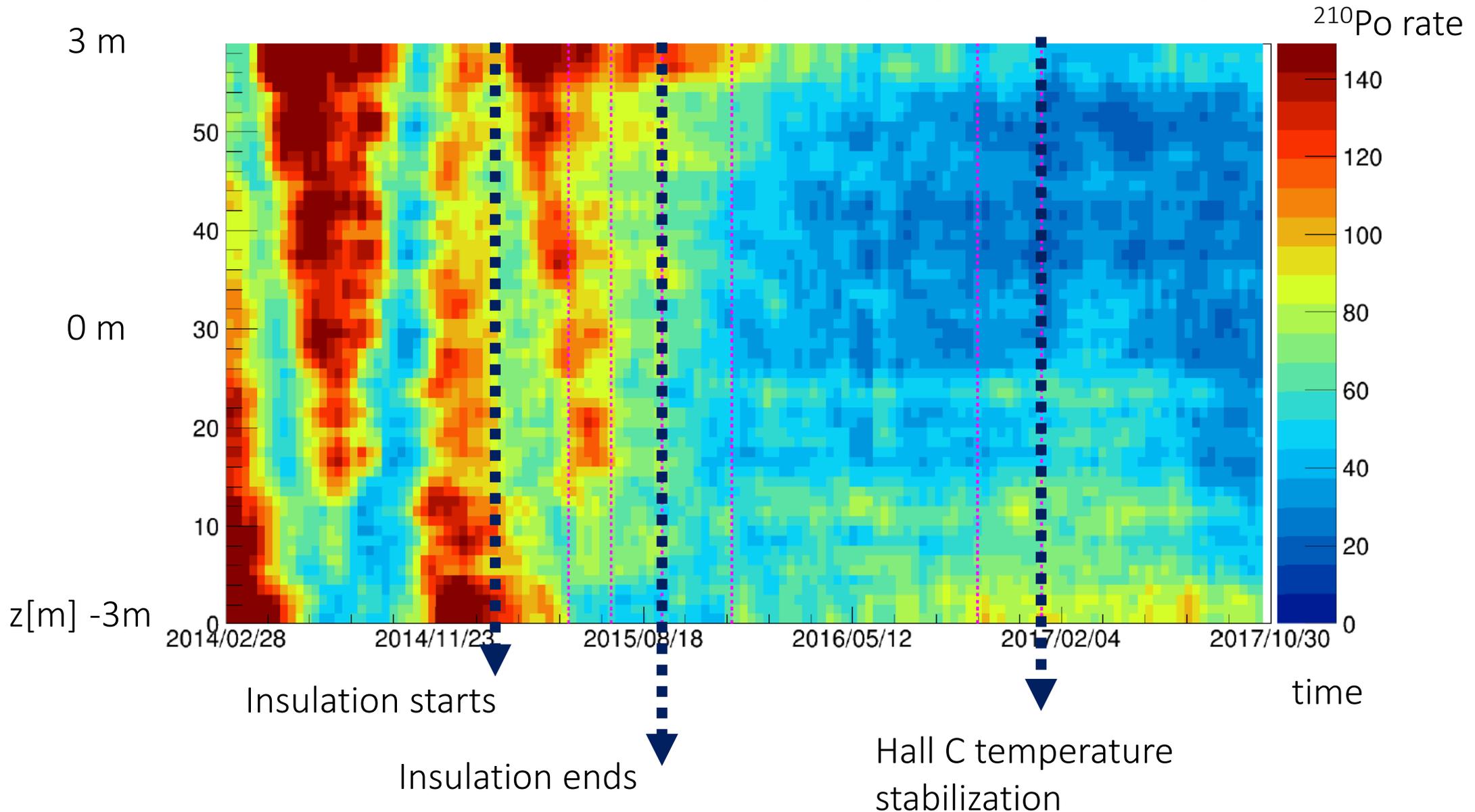
Fluidodynamics simulations



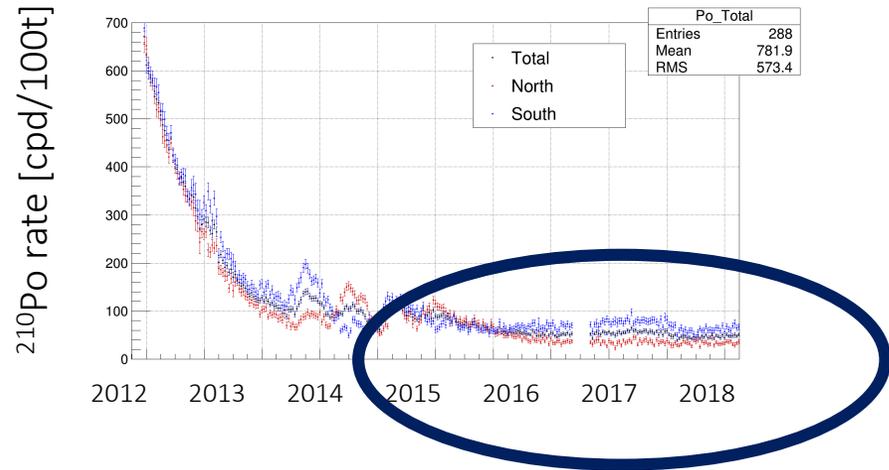
^{210}Po rate – Insulation effects



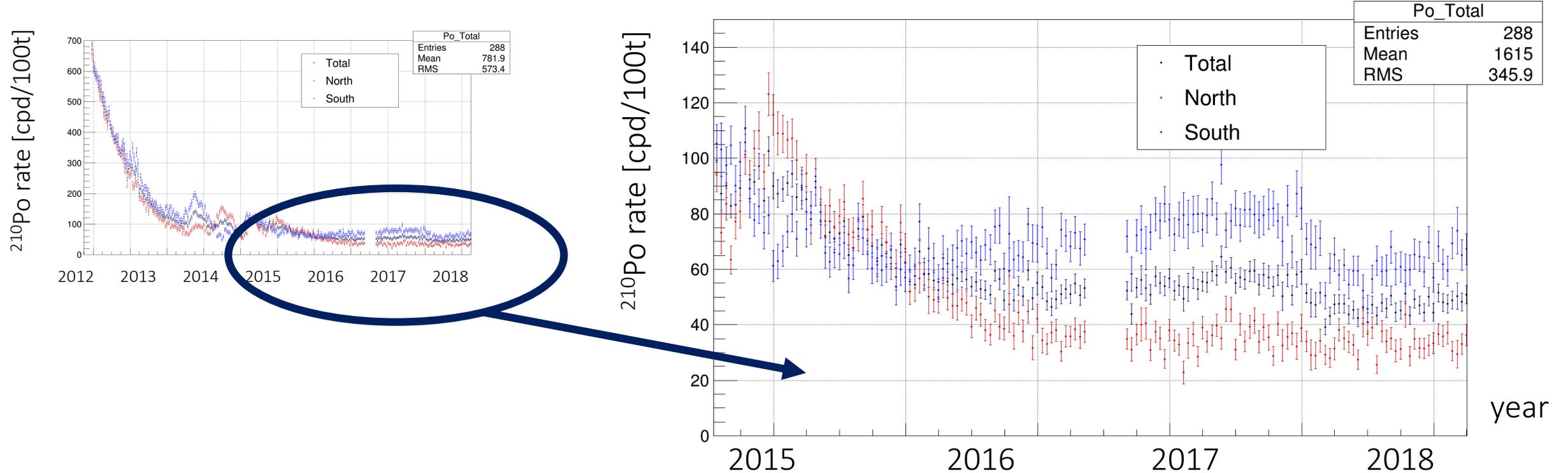
^{210}Po rate – Insulation effects



^{210}Po rate vs time: from 2015 until now



^{210}Po rate vs time: from 2015 until now



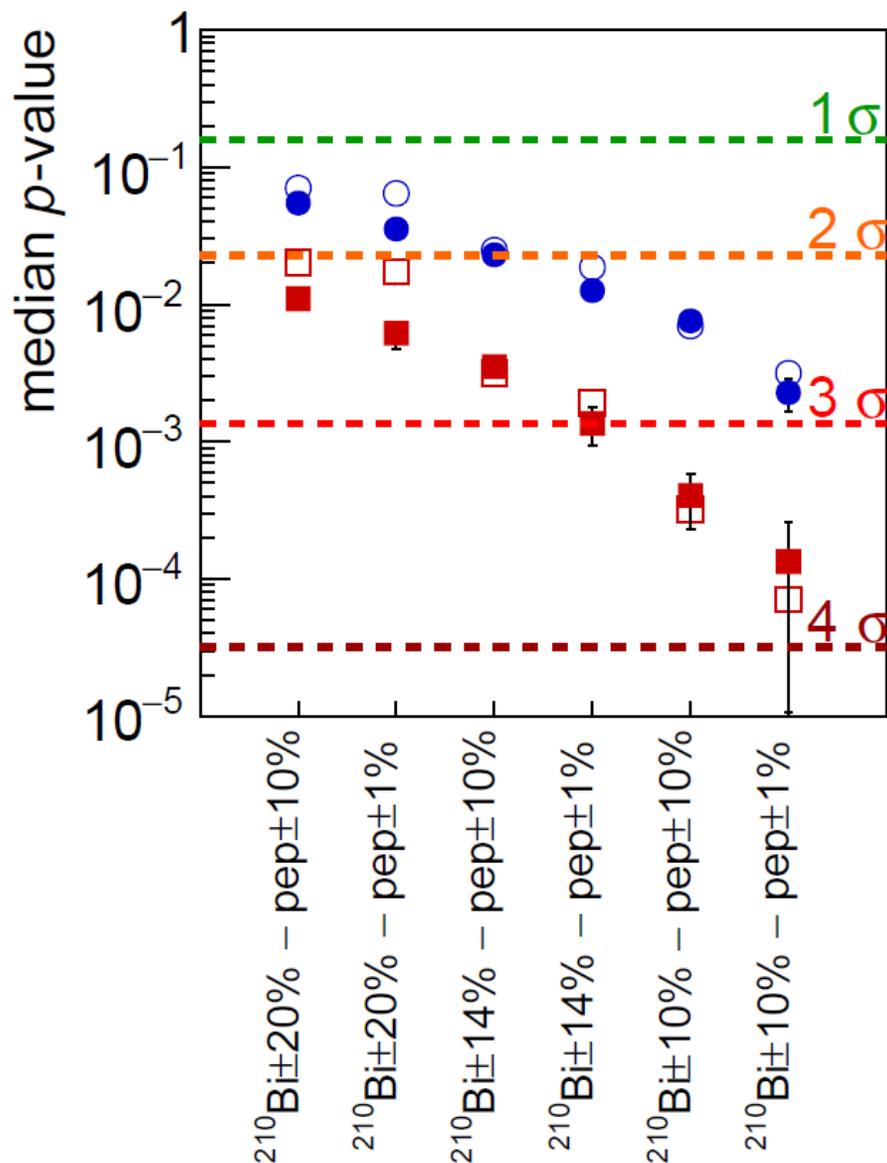
From 2016 on:

- Global rate decrease
- Second-order effects/oscillations appearing
- Less convective motions, more homogeneity



Ongoing analysis

Sensitivity to CNO ν detection



= what level of precision on the background do we need?

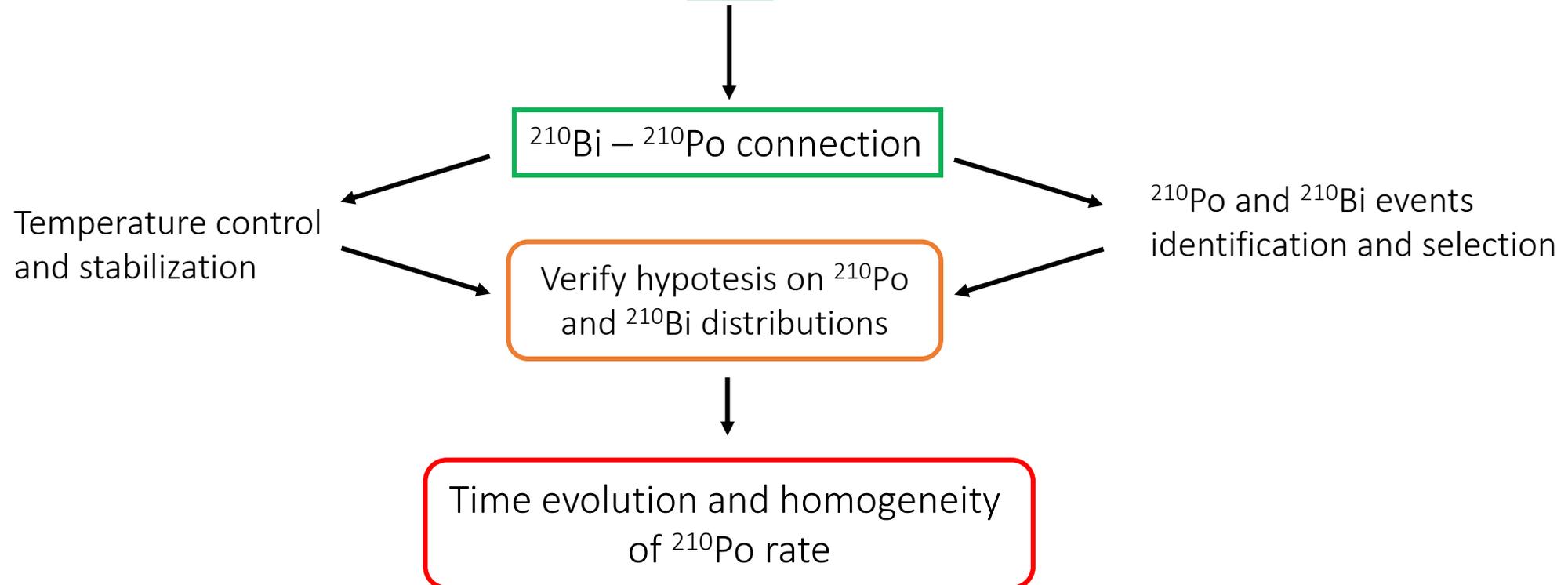
- Low metallicity – rate only analysis
- Low metallicity - rate + shape analysis
- High metallicity – rate only analysis
- High metallicity – rate + shape analysis

- Discovery power evaluated performing an hypothesis test based on a profile likelihood test statistics
- Shape constraints are useful especially when combined with weak rate constraints
- (High metallicity would help!)

For 3σ evidence, with a ^{210}Bi rate $\approx 15\text{-}20$ cpd/100t, at least we need $\sigma_{210\text{Bi}} \approx 10\%$

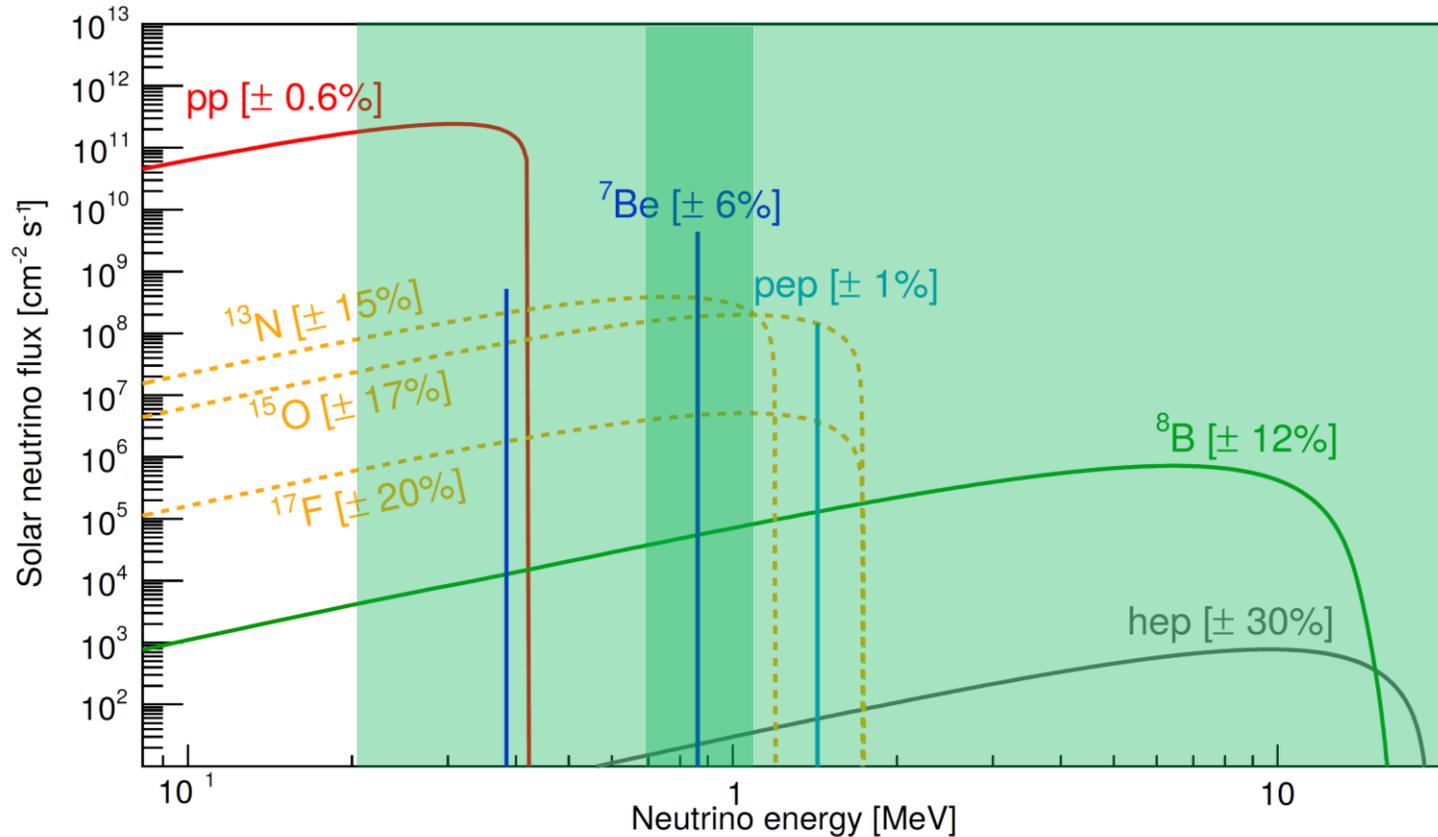
Summary

- In principle, Borexino has the required sensitivity to detect CNO ν flux at a 3σ level: the goal is $\sigma_{210\text{Bi}} \approx 10\%$
- The analysis is mainly based on counting the events
 - Independent constraints on pep and ^{210}Bi rates play a crucial role to reduce σ_{CNO}



Thank you!

Solar neutrinos – energy spectrum



- Expected emitted spectrum
- Standard Solar Model B16
- Borexino:
 - Initial main goal:
 ν ^7Be measurement
 - Achieved goals:
all ν species from pp chain

Solar neutrinos

Astrophysics: solar models, metallicity...

Particle physics: flavor oscillations, NSI...

The ^{210}Bi - ^{210}Po analysis in a nutshell

1. ^{210}Po events **filtering** and selection
2. Definition of **spatial regions**
 - Z slices
 - “Radial shells”
3. Study of the **supported *B-term***:
 - Fit in time for each defined region
 - B-term as a function of the spatial coordinate (“z” or “distance from IV”)

^{210}Po events filtering

1. Bxfilter (alpha.cc module)
2. Main cuts:
 - Energy (NPmtsDt1_GeoNorm)
 - Alpha/beta: MLP variable
 - Inner Fiducial Volume (Std: $|z| < 1.67\text{m}$, $r < 2.5\text{m}$)

