The Borexino heritage: pp and CNO solar ν

University of Manchester - via ZOOMLand
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Marco Pallavicini
Università degli Studi di Genova and INFN

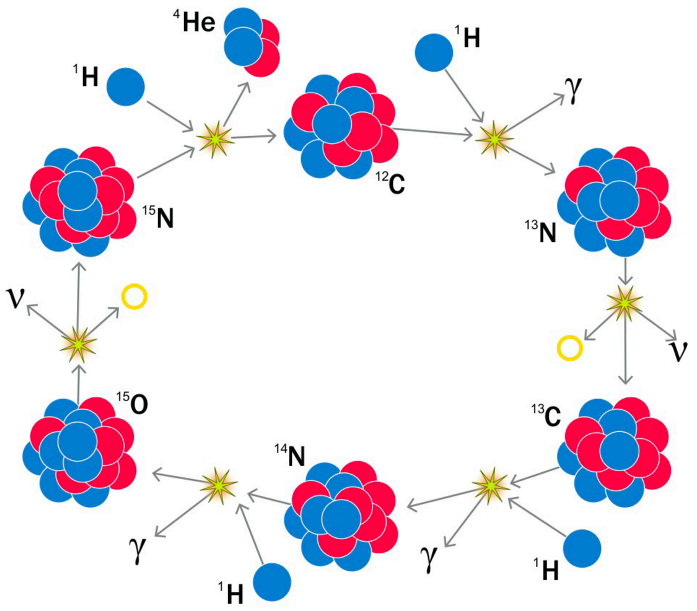
INFN
Istituto Nazionale di Fisica Nucleare

Talk overview

- **Science**
  - Solar and geo-neutrinos

- **Technology:** the most radio-pure detector ever built

- **Results**
  - The *pp chain* and the **MSW mechanism**
  - Intermezzo: **geo-neutrinos**
  - The *CNO cycle*
    - Challenges, Strategy, Results



- Conclusions and prospectives

A touch of history

- The question concerning the **energy source feeding the Sun** (and stars) is as ancient as humankind

- Hot scientific debate in the late XIX century
  - Know sources (chemistry, gravity) **cannot sustain the Sun long enough** for **geology** and **biology**
    - Controversy between Lord Kelvin and Charles Darwin

- **1920: Francis Aston** invents the **mass spectrometer** and proves that the ^{4}He atom is lighter than 4 H atoms

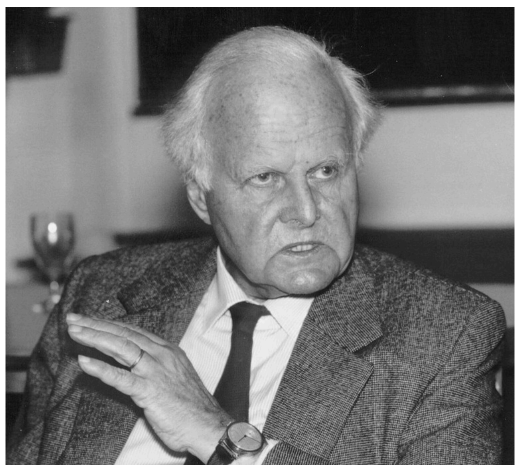
- **1920:** In a famous address to the British Association for the Advancement of Science **Arthur Eddington** points out that the **conversion of hydrogen into helium would provide easily enough energy,** adding prophetic words:

"If, indeed, the sub-atomic energy in the stars is being freely used to maintain their great furnaces, it seems to bring a little nearer to fulfilment our dream of controlling this latent power for the well-being of the human race---or for its suicide"

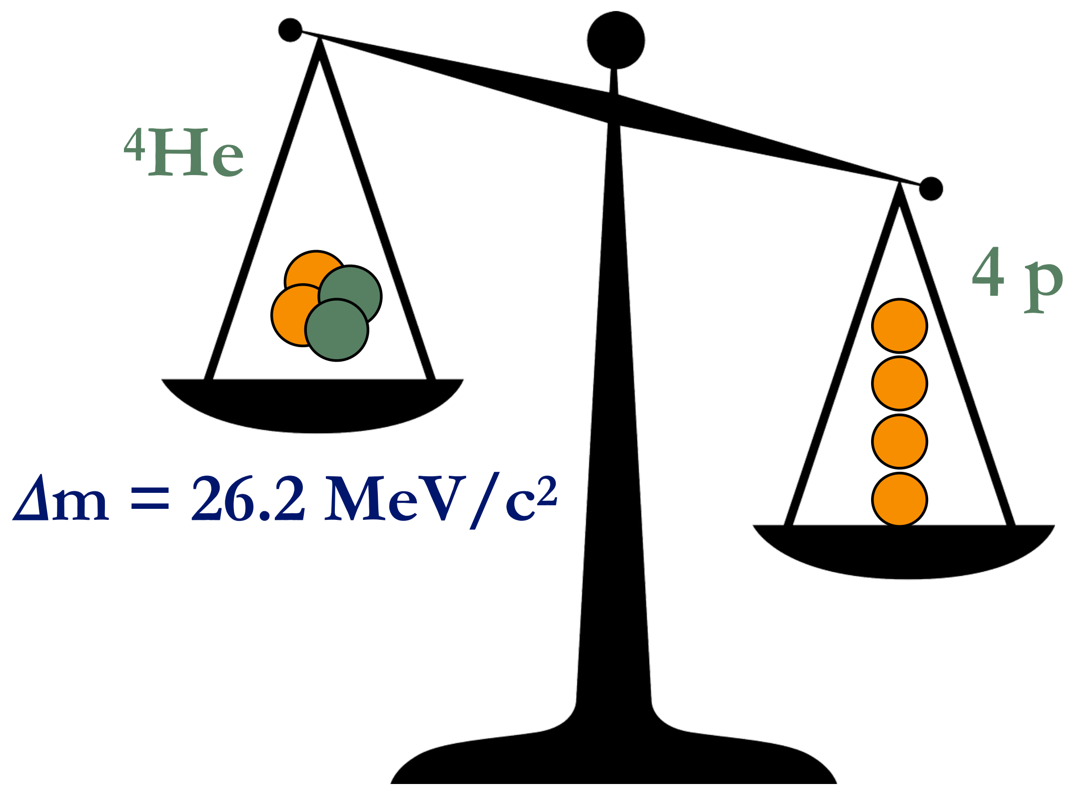
Stars energy source

- The long standing debate about **solar** (and other stars) **energy source** was ***theoretically*** solved in 1938

F. W. Aston - 1920
A.S. Eddington Observatory 43 (1920), Nature (1920)



Carl F. von Weizsäcker

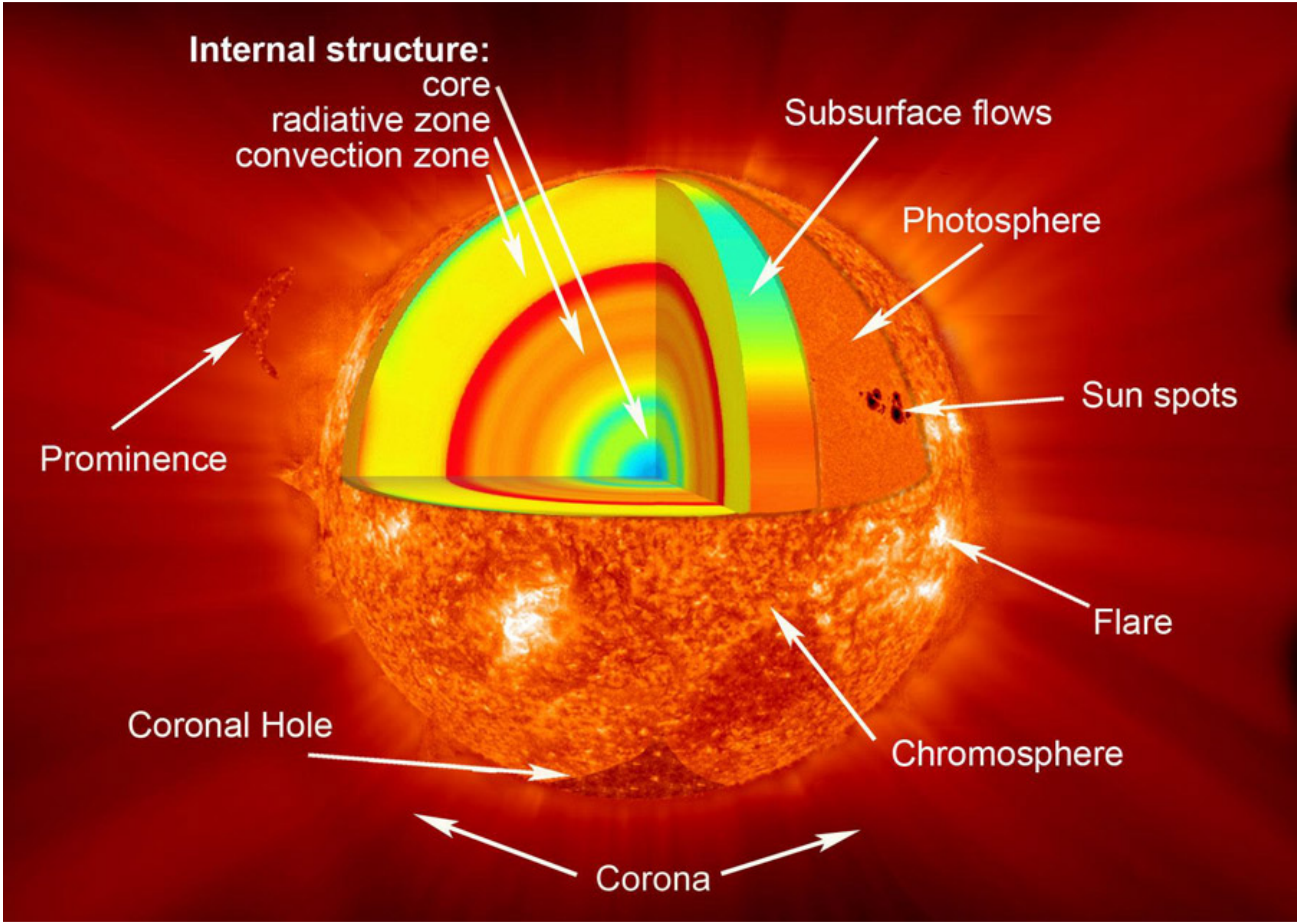


Hans Bethe (Nobel 1967)

- Hydrogen burning through **two** fusion paths:
  - **The pp chain,** initiated by **direct pp fusion**
  - **The CNO cycle, catalysed** by the presence of **C**, **N** and **O** in the core

- Initially, CNO was (wrongly) believed to be dominant in the Sun because of the poorly known solar core temperature

The structure of the Sun



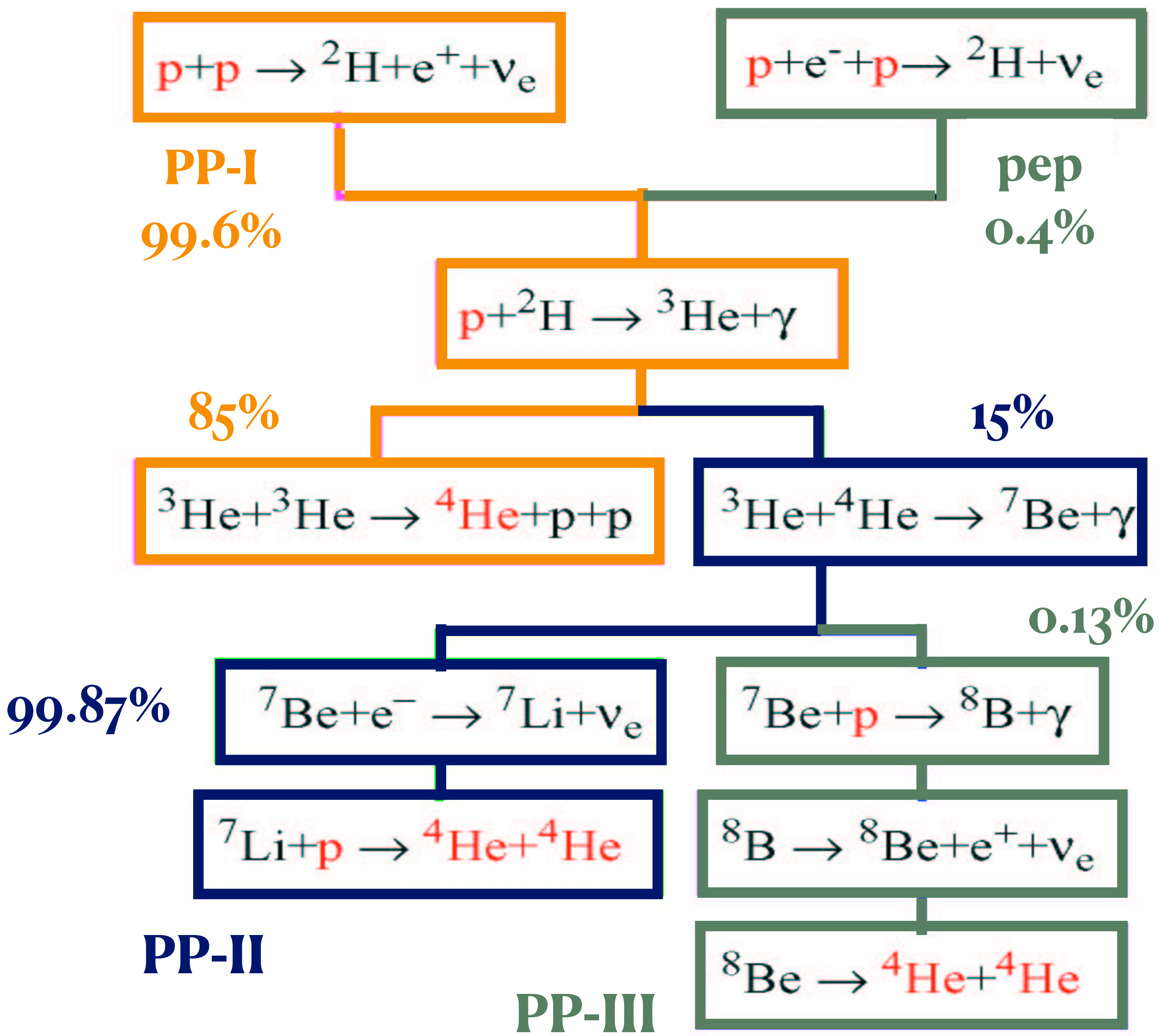
Solar neutrinos from hydrogen burning

A.S. Eddington Observatory 43 (1920), Nature (1920)

Bethe & Critchfield 1938

pp chain

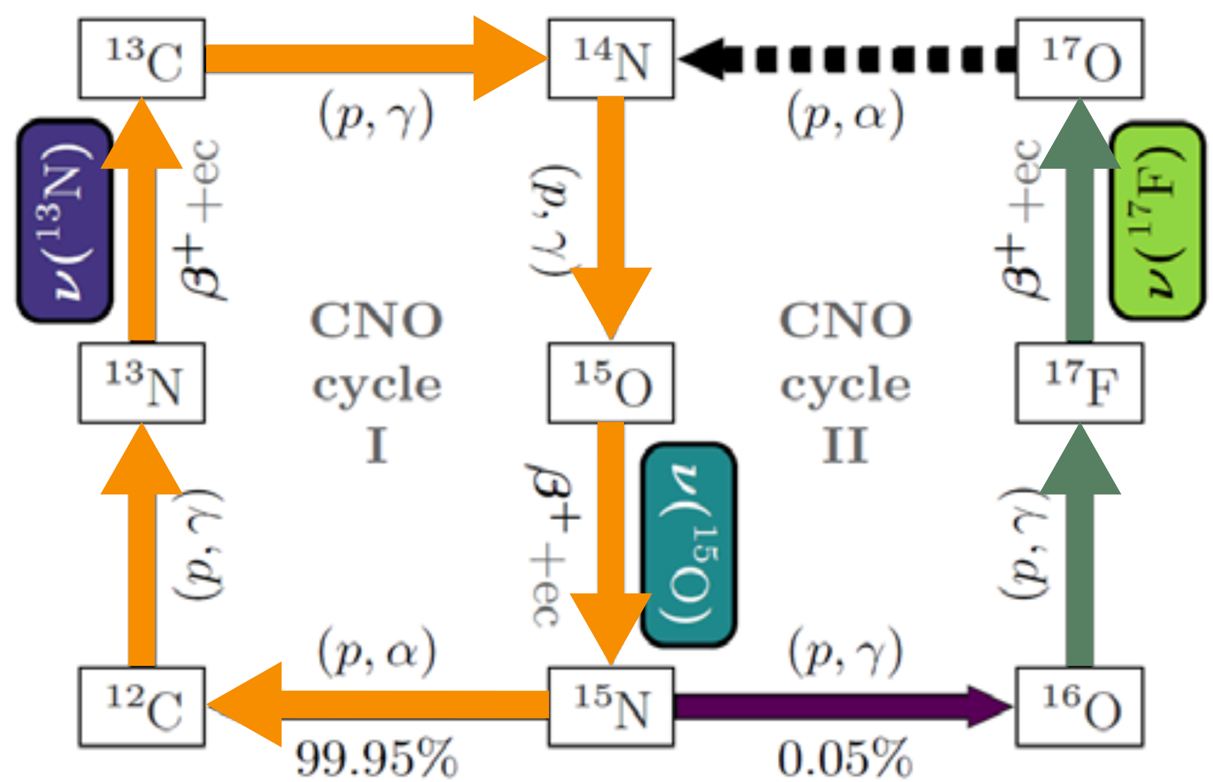
(99% energy)



CNO cycle

(~ 1% energy)

Weizsäcker (1937, 1938), Bethe (1939)



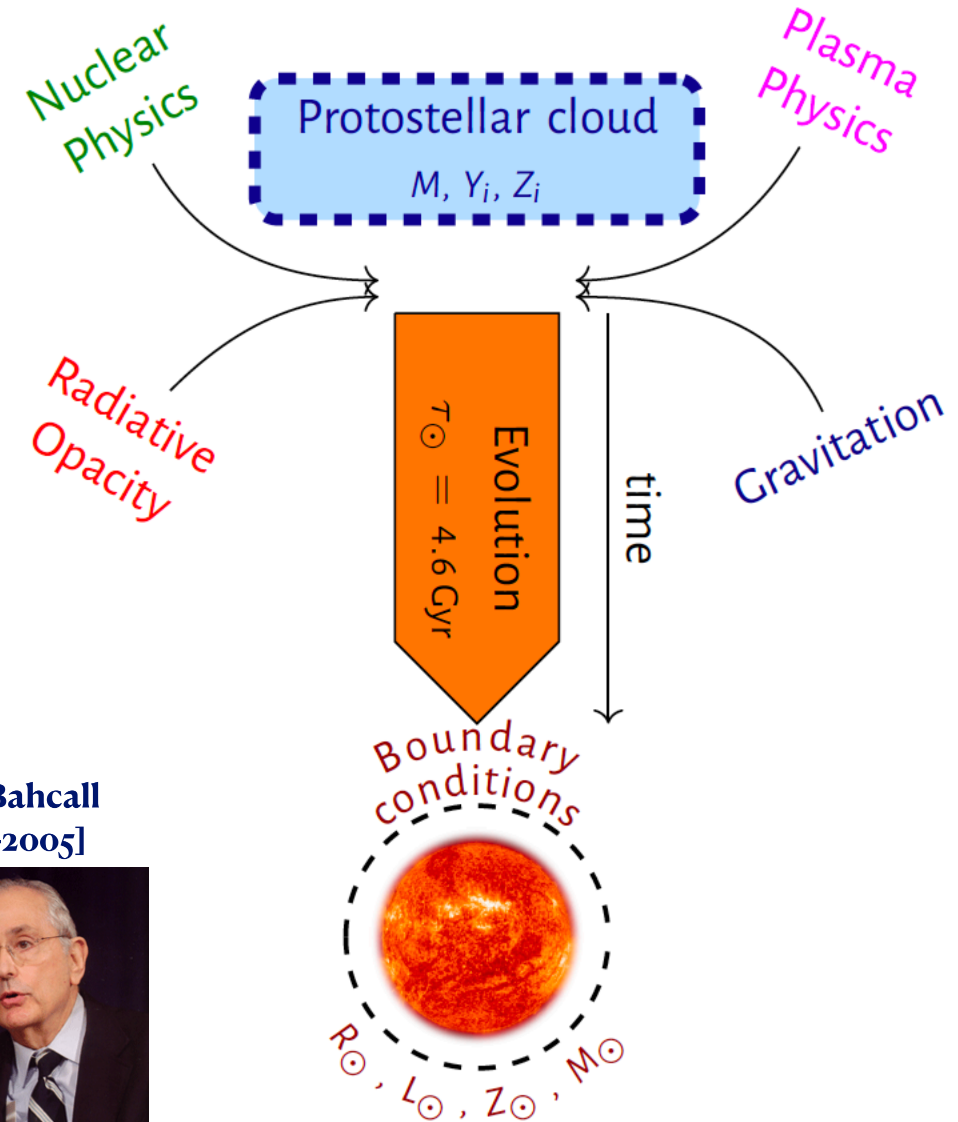
${}^{12}C$ is the main catalyst

CNO-II is suppressed in the Sun

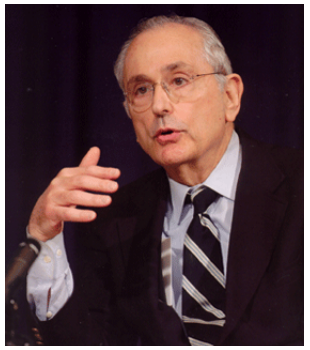
REACTION	ENERGY YIELD	2% of E in NEUTRINOS
$4p \rightarrow {}^4He + 2e^+ + 2\nu_e$	$24.7\ MeV + 2m_ec^2$	$< E_\nu >= 0.53\ MeV$

The Standard Solar Model

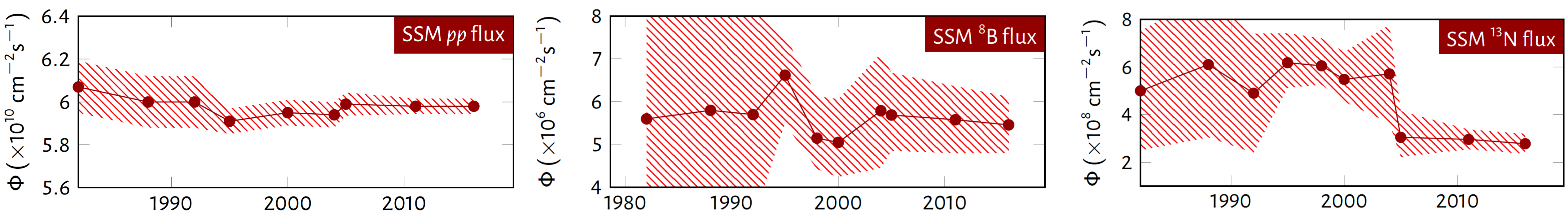
- **The observable is the Sun we see now,** which depends on a **complex evolution process**
  - Gravity
  - **Composition**: X (hydrogen), Y (helium), , Z ("metals")
  - Radiative **opacity** and plasma physics
  - Temperature and density profiles
  - Energy transport: radiative until 0.71 $R_\odot$, then convective
- Todays conditions act as boundary conditions
  - Two crucial **observables:**
    - Elio-seismology
    - **Solar neutrinos**



John Bahcall
[1934-2005]

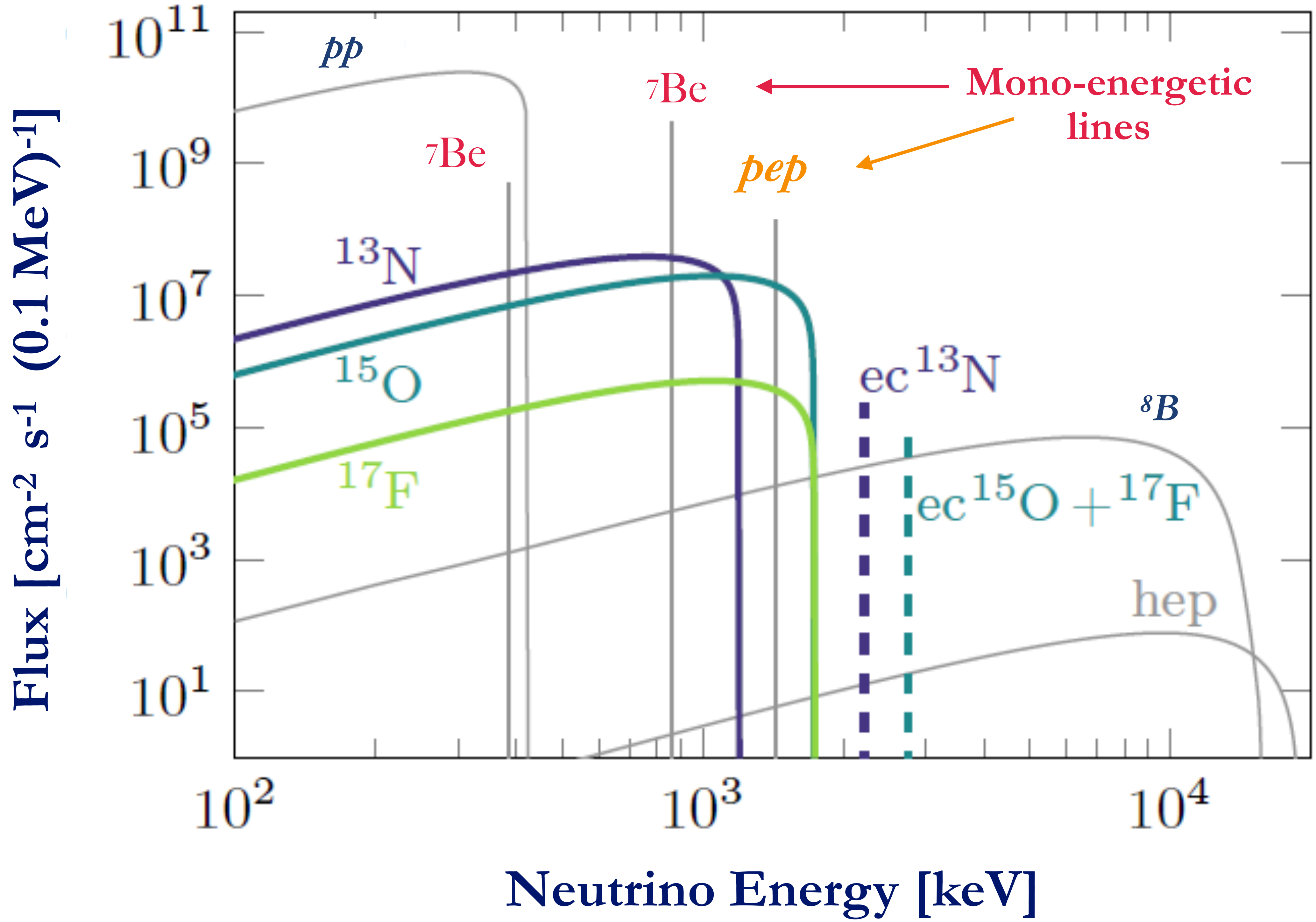


- The model as well has evolved (better cross sections, opacity and diffusion models)



Neutrino spectrum from the SSM

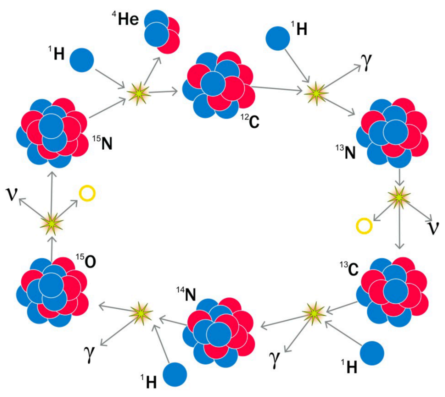
$L_\odot = 3.846 \pm 0.015 \; 10^{26}$ W

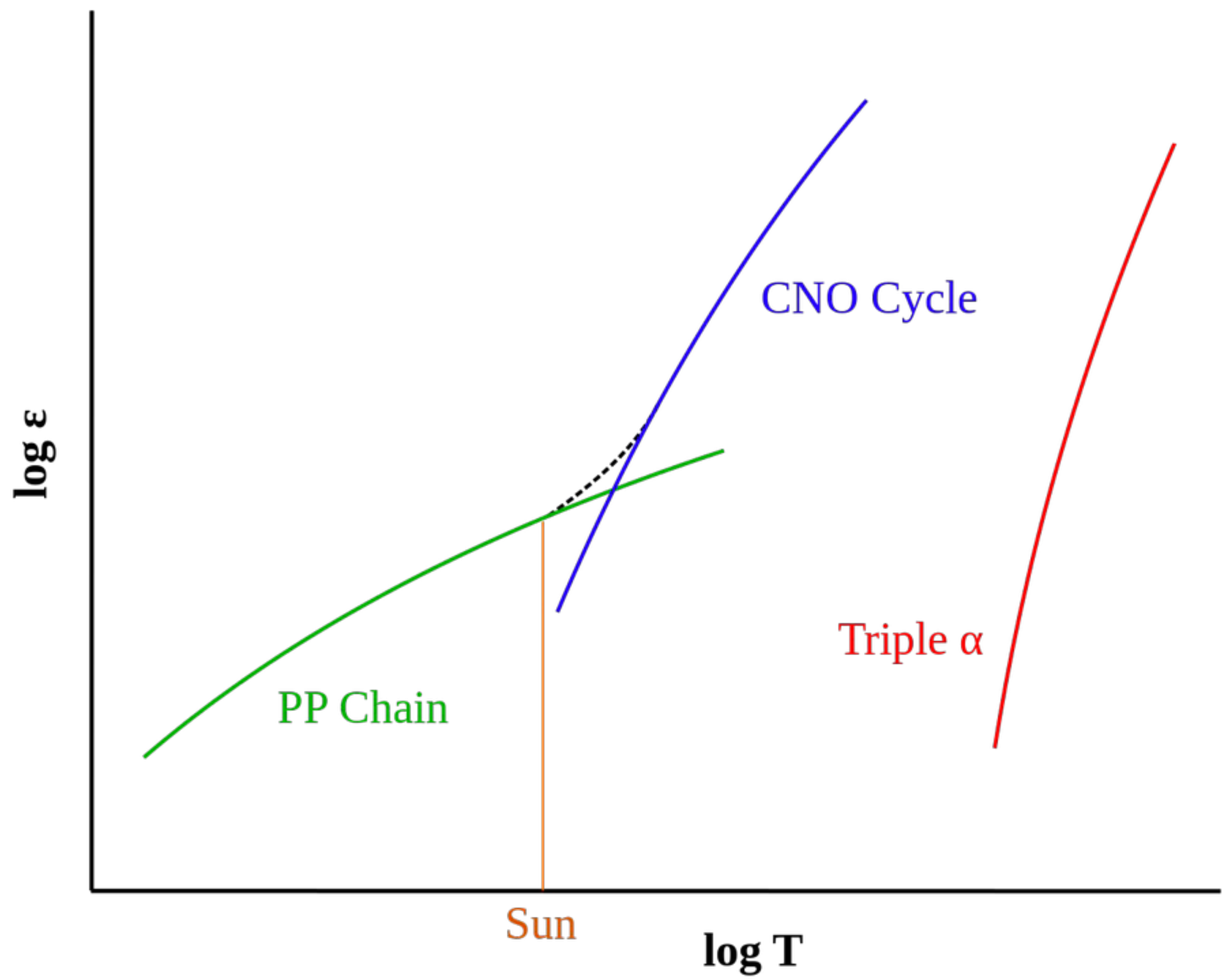


N. Vinyoles et al., The Astrophysical Journal (2017), 835:202 Feb. 1st. doi:10.3847/1538-4357/835/2/202

CNO relevance

- **CNO is dominant in stars heavier than 1.3 M ⊙**
  - **Never directly observed** before Borexino
  - Crucial for stellar evolution and nucleosynthesis in the Universe
- Also, a **unique probe** of core's chemical composition
  - CNO role in the Sun poorly understood **("metallicity problem")**



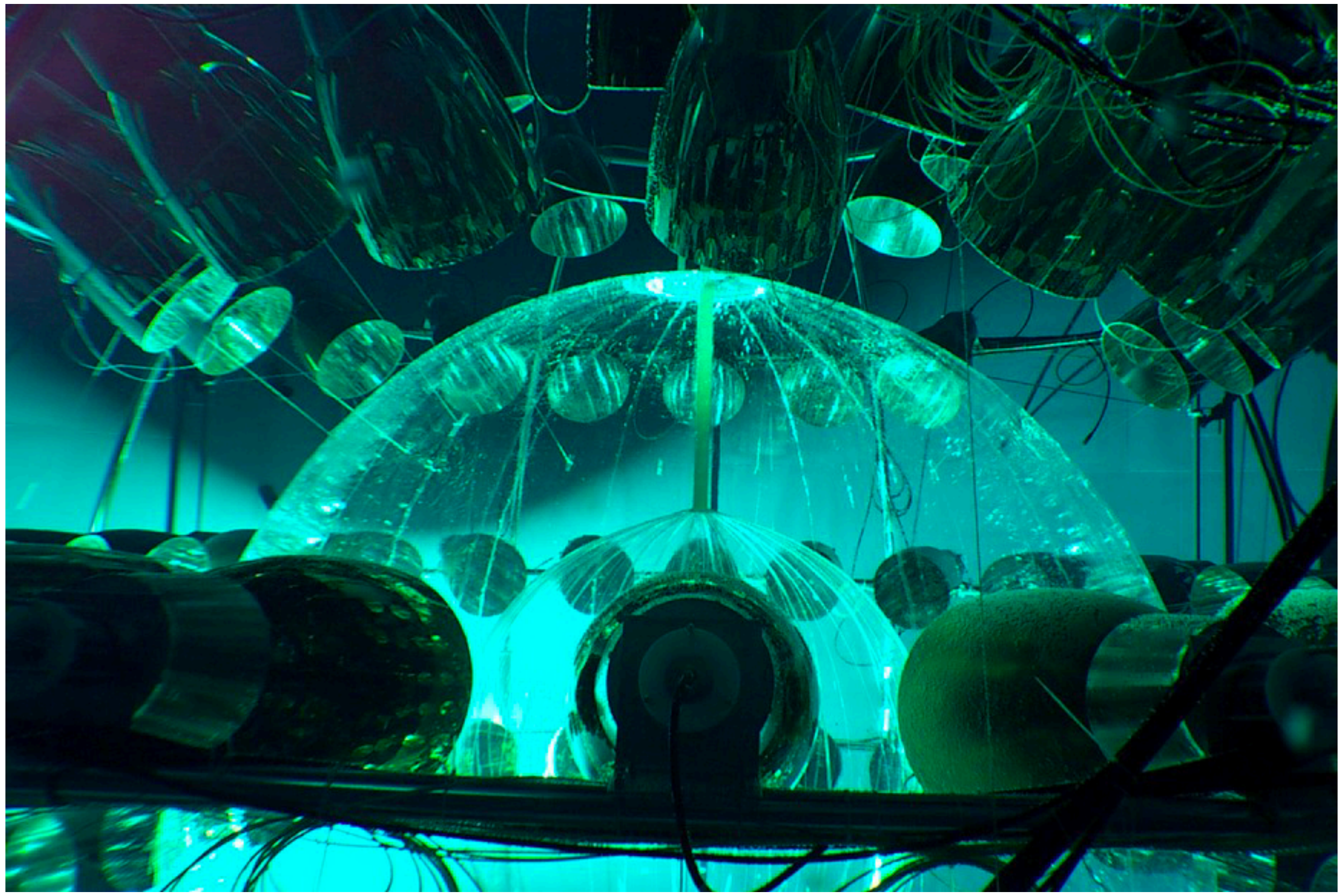


The CNO cycle is the most important mechanism of **hydrogen burning** of the Universe

The long journey of Borexino

- **1990: BOREX** idea abandoned, in favour of **elastic scattering on e^-**
  - A **smaller** detector was needed, **BOREX(ino)** was born!

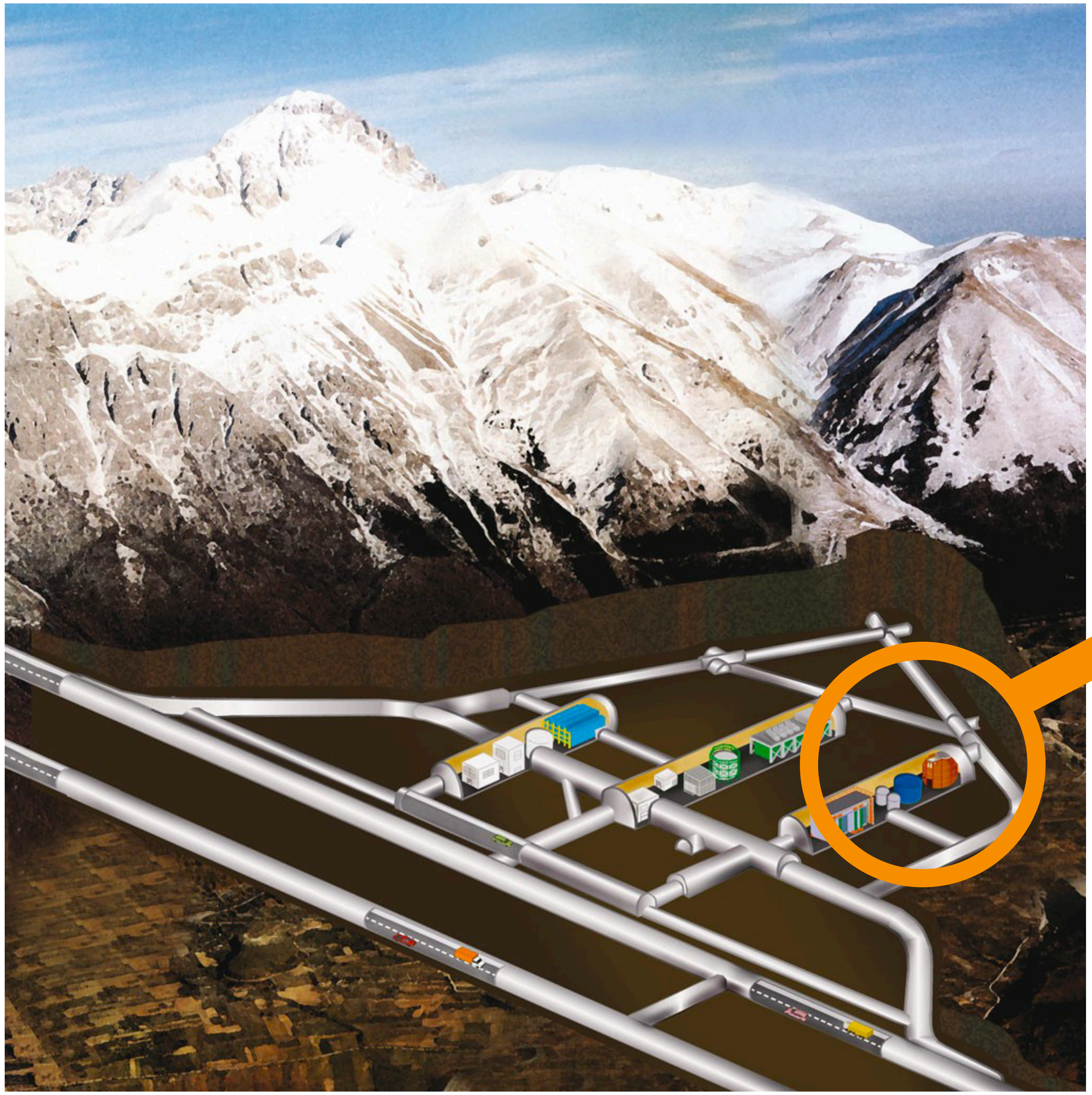
The Counting Test Facility at LNGS



- **1992-1995:** prototype and R&D
- **1995:** the CTF at LNGS proves that Borexino can be done !
  - Record radio-purity was measured (at that time):
    - **^{238}U and ^{232}Th below 10^{-16} g/g**
    - **^{14}C/^{12}C below 10^{-18}**
- **1996-2007:** construction, with great care, and some environmental hurdles…
- **2007:** data taking begins. Still continuing today, with no stops.

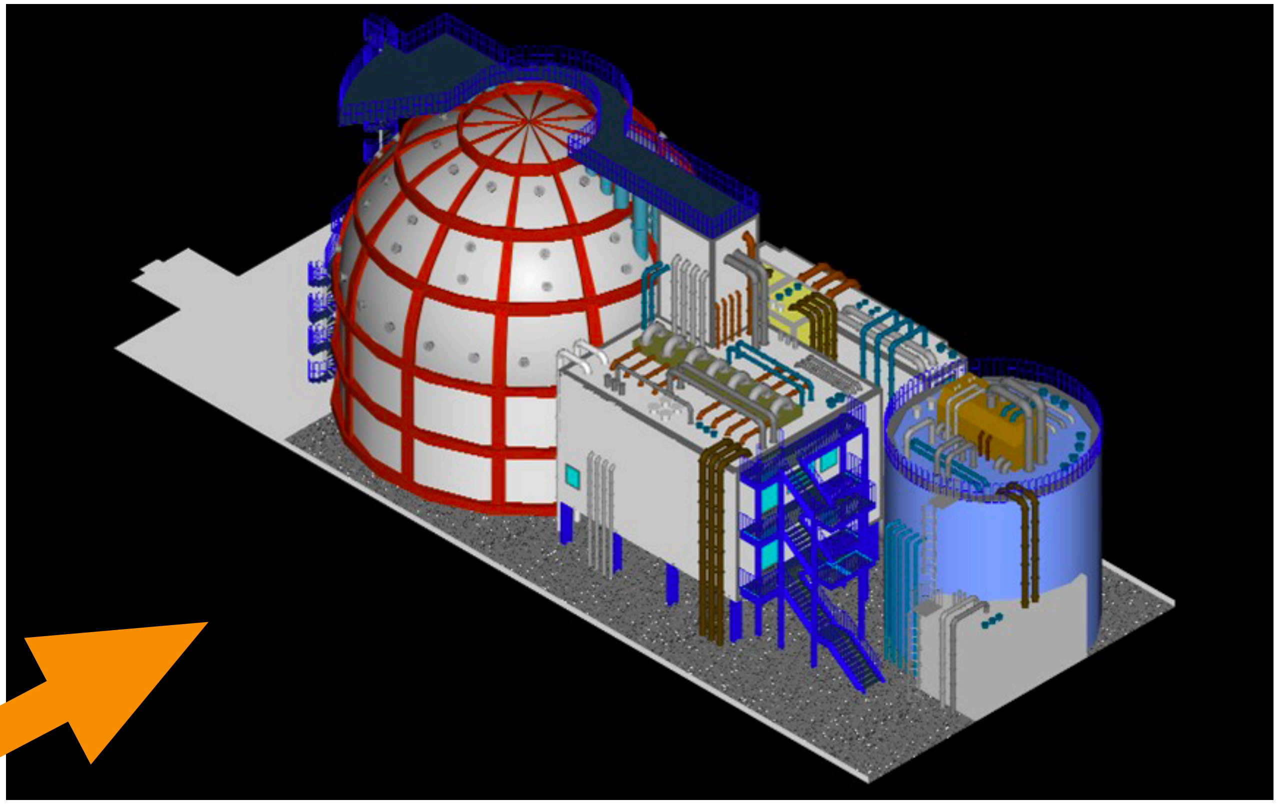
Founders

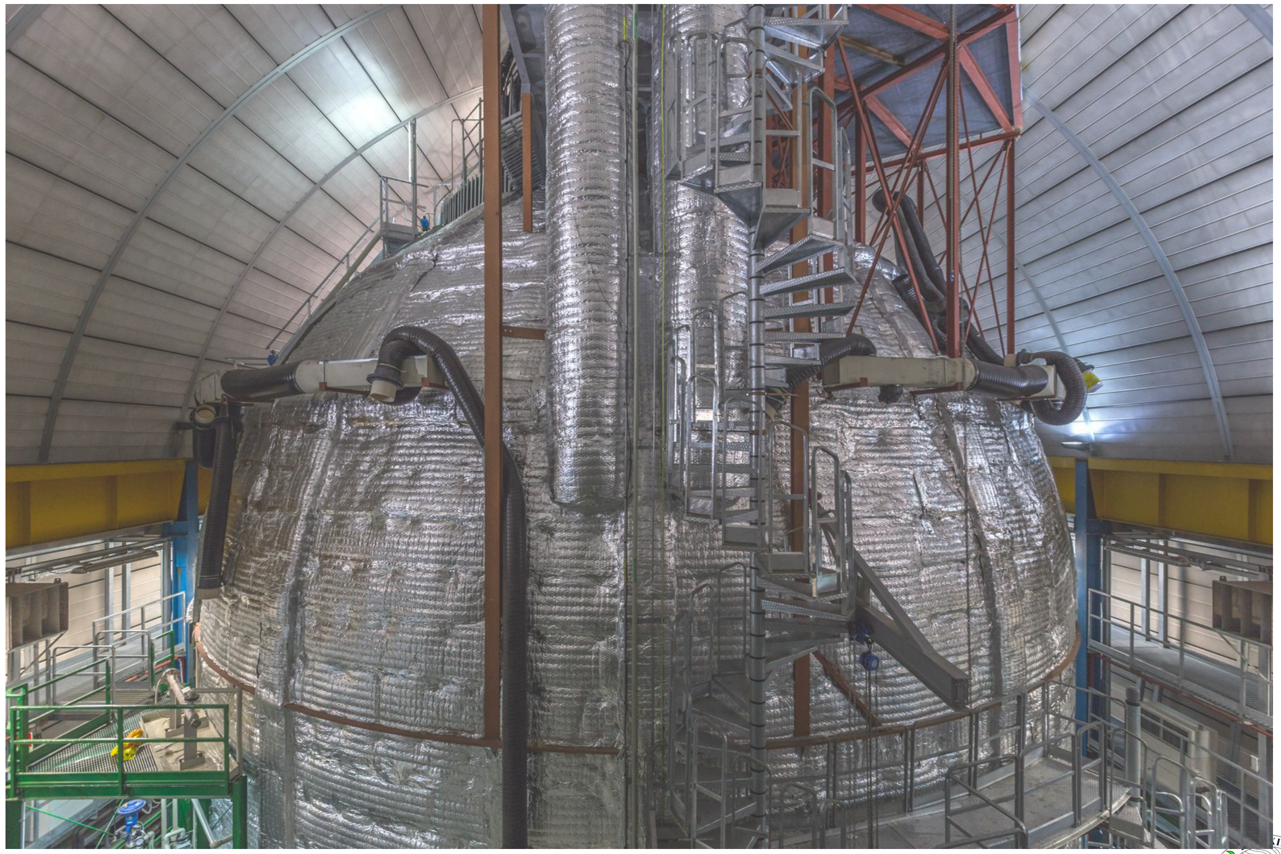
Borexino location



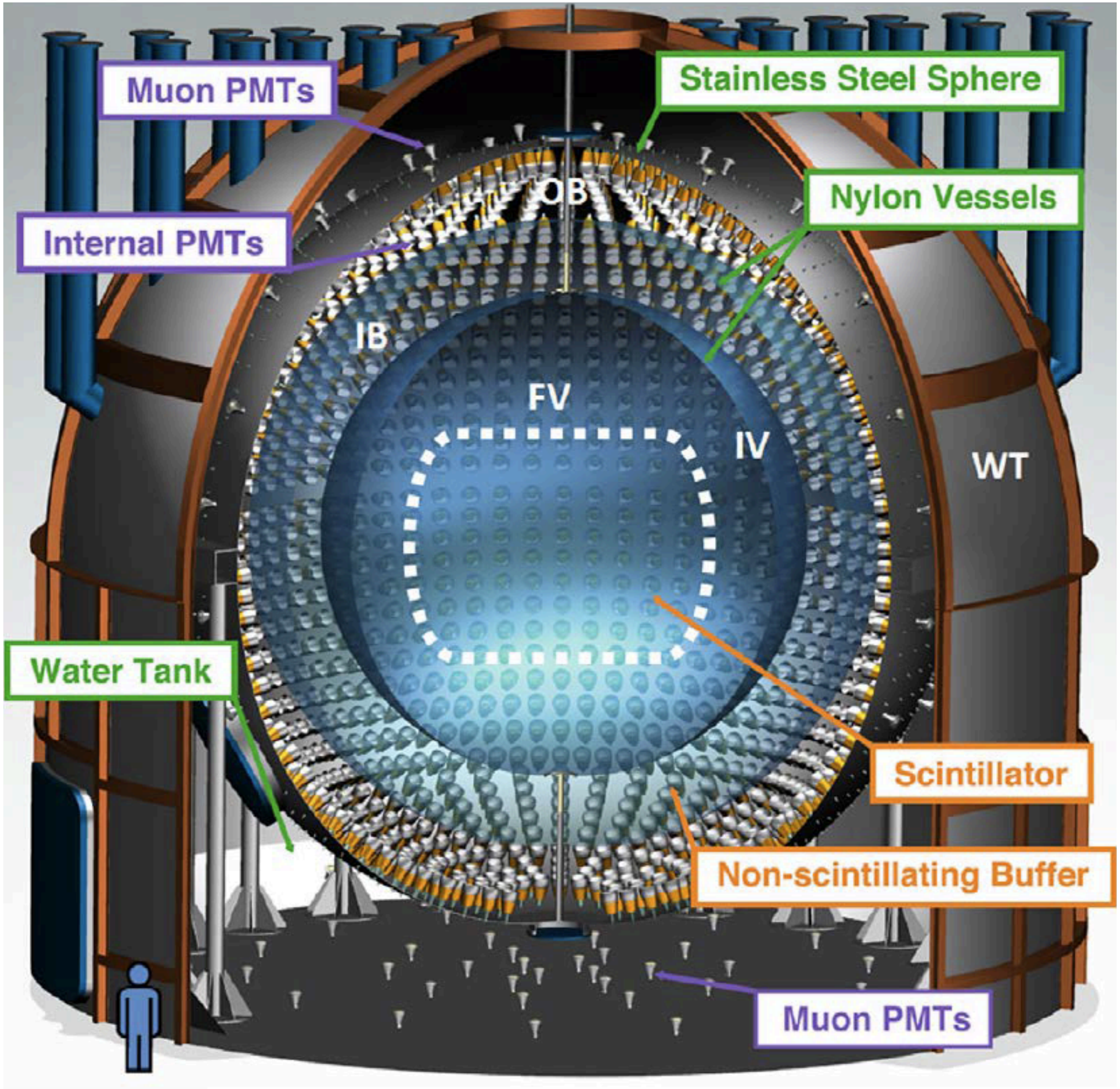
Laboratori Nazionali del Gran Sasso
(Hall C)

Rock: 3.800 m w.e. – muon flux ~ 25 m^{-2} d^{-1}

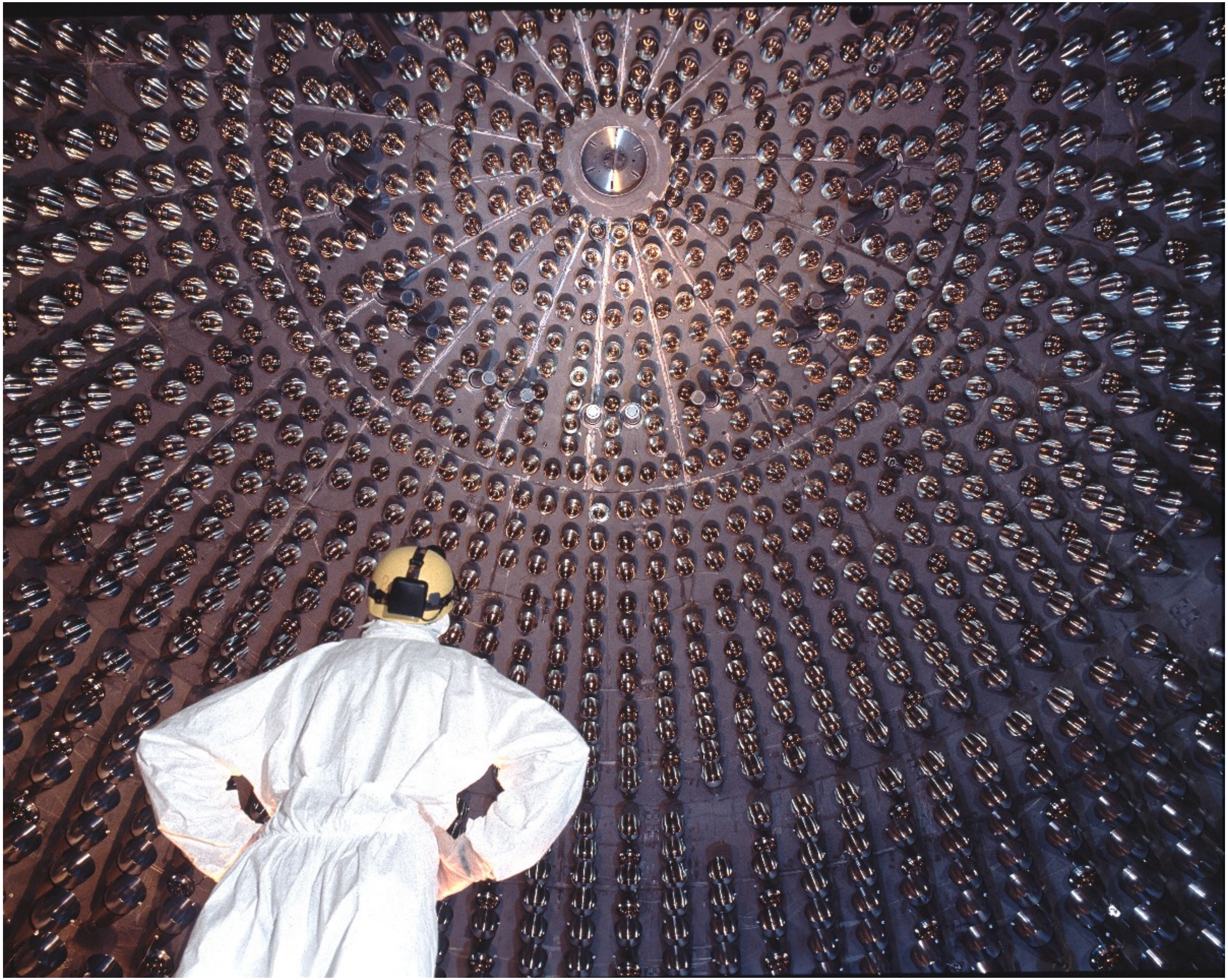




The detector

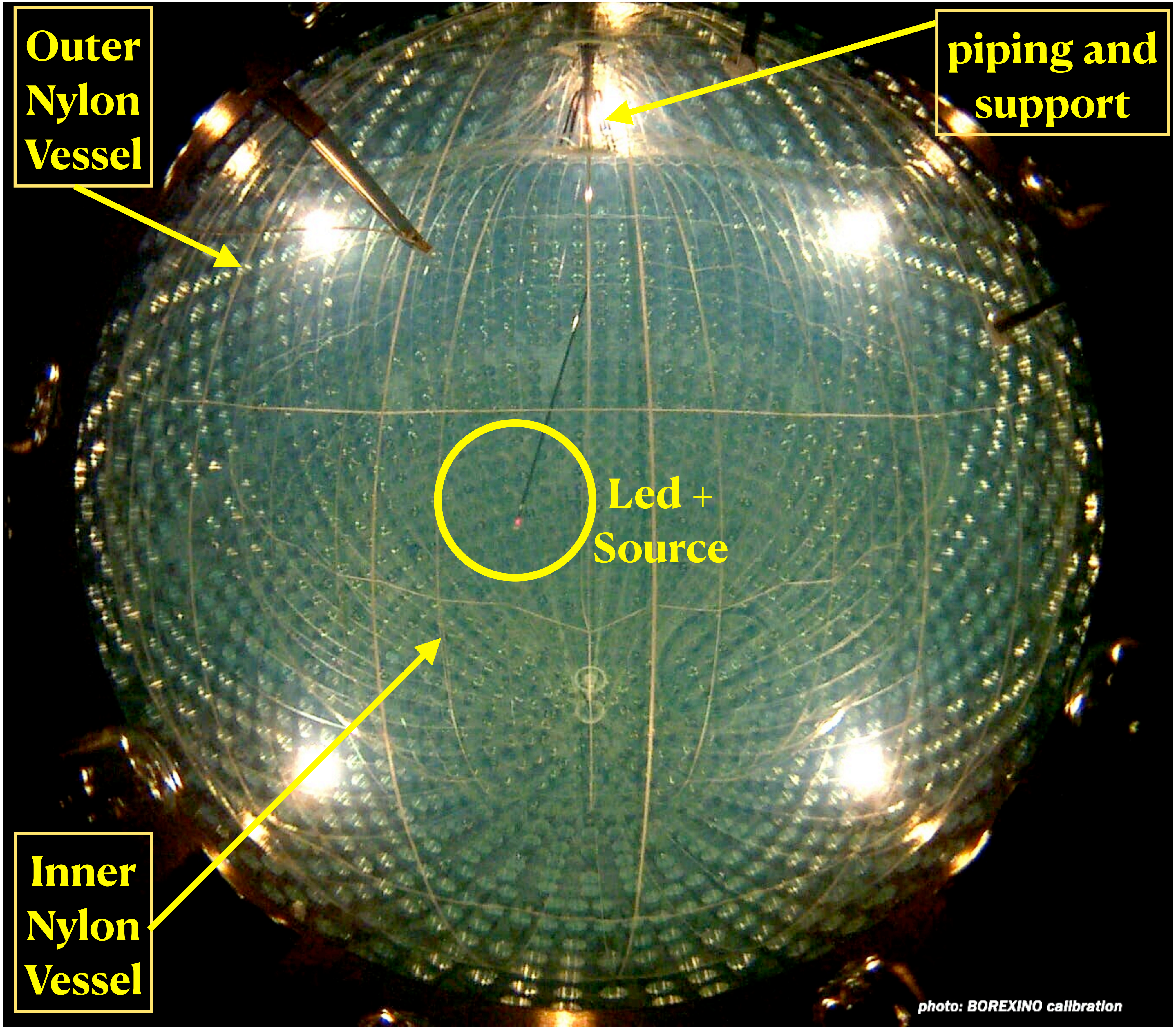


Internal view, empty



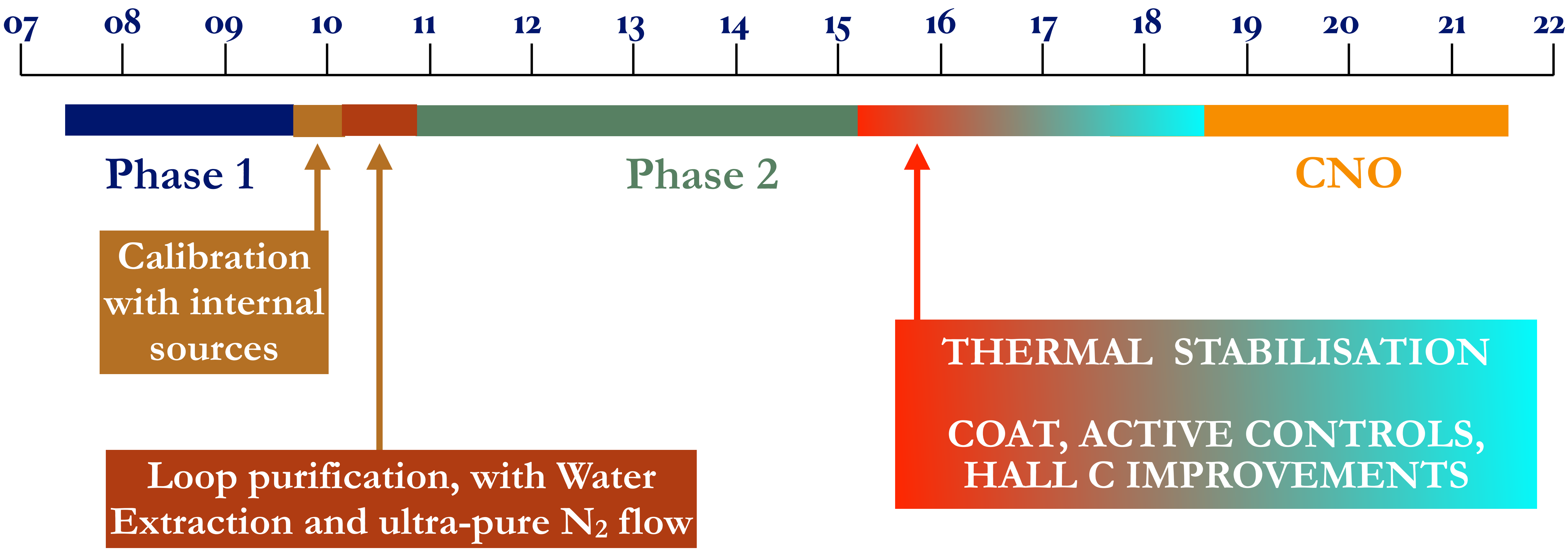
Internal view: inflated vessels (with N_2)

Internal view, filled, during calibration in 2009



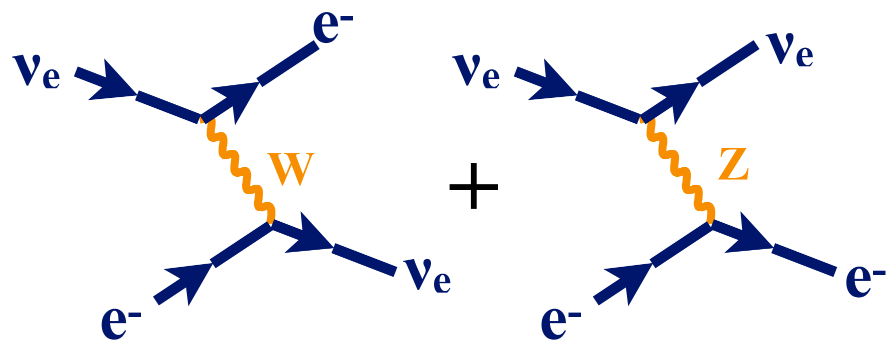
2007-2020

- 3 data taking periods
  - **Phase I** (2007-2009): first detections
  - **Phase II** (2011-2017): pp chain precise measurements
  - **Phase III** (2018-2020): **CNO measurement**

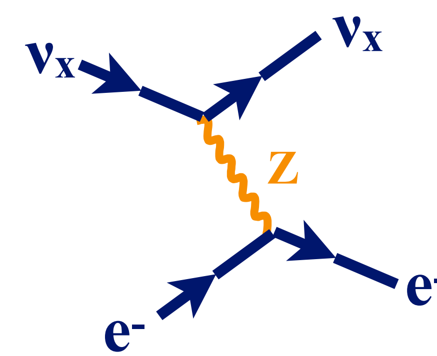


Neutrino detection in Borexino (I)

- Elastic scattering on e⁻: detects **all ν** flavours, with a **larger cross-section for ν_e**

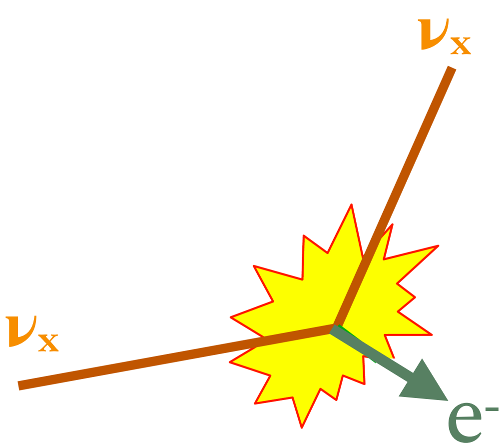


$$\xi = \sin^2\theta_W \simeq 0.23$$



$$\sigma(\nu_e e^-) = \frac{G_F^2 s}{\pi}\left[\left(\frac{1}{2}+\xi\right)^2 + \frac{\xi^2}{3}\right]$$

9.5 10^{-45} cm^2 @ 1 MeV

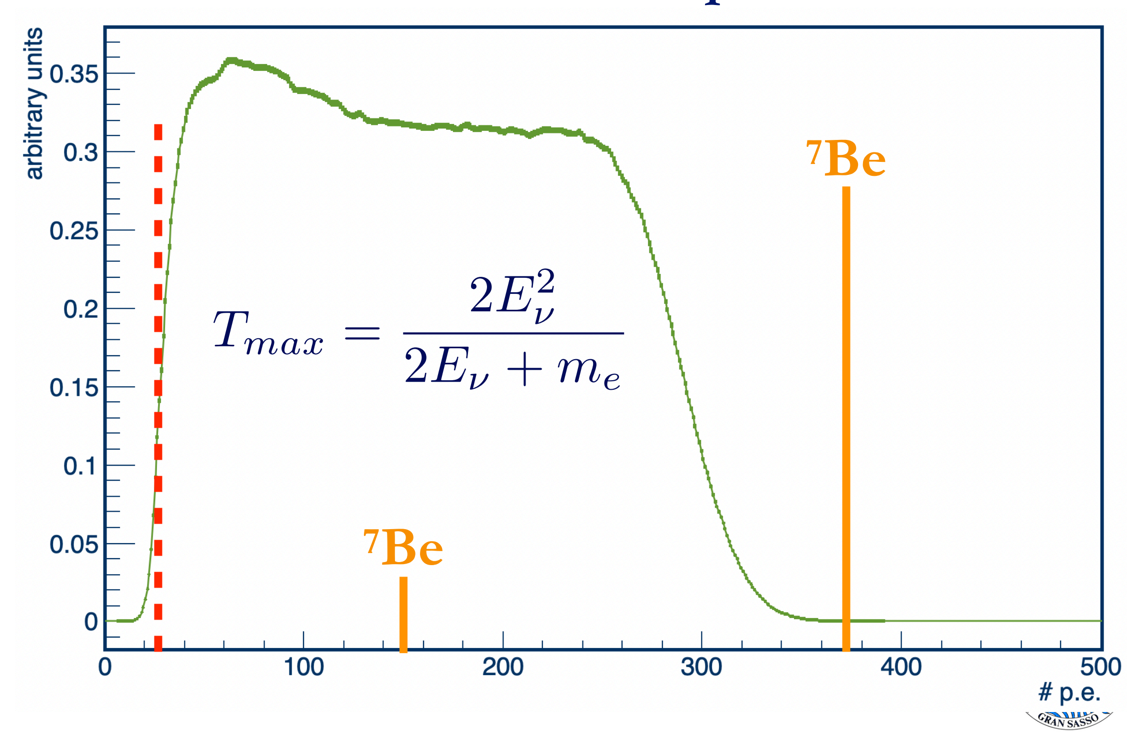


$$\sigma(\nu_x e^-) = \frac{G_F^2 s}{\pi}\left[\left(\frac{1}{2}-\xi\right)^2 + \frac{\xi^2}{3}\right]$$

1.8 10^{-45} cm^2 @ 1 MeV

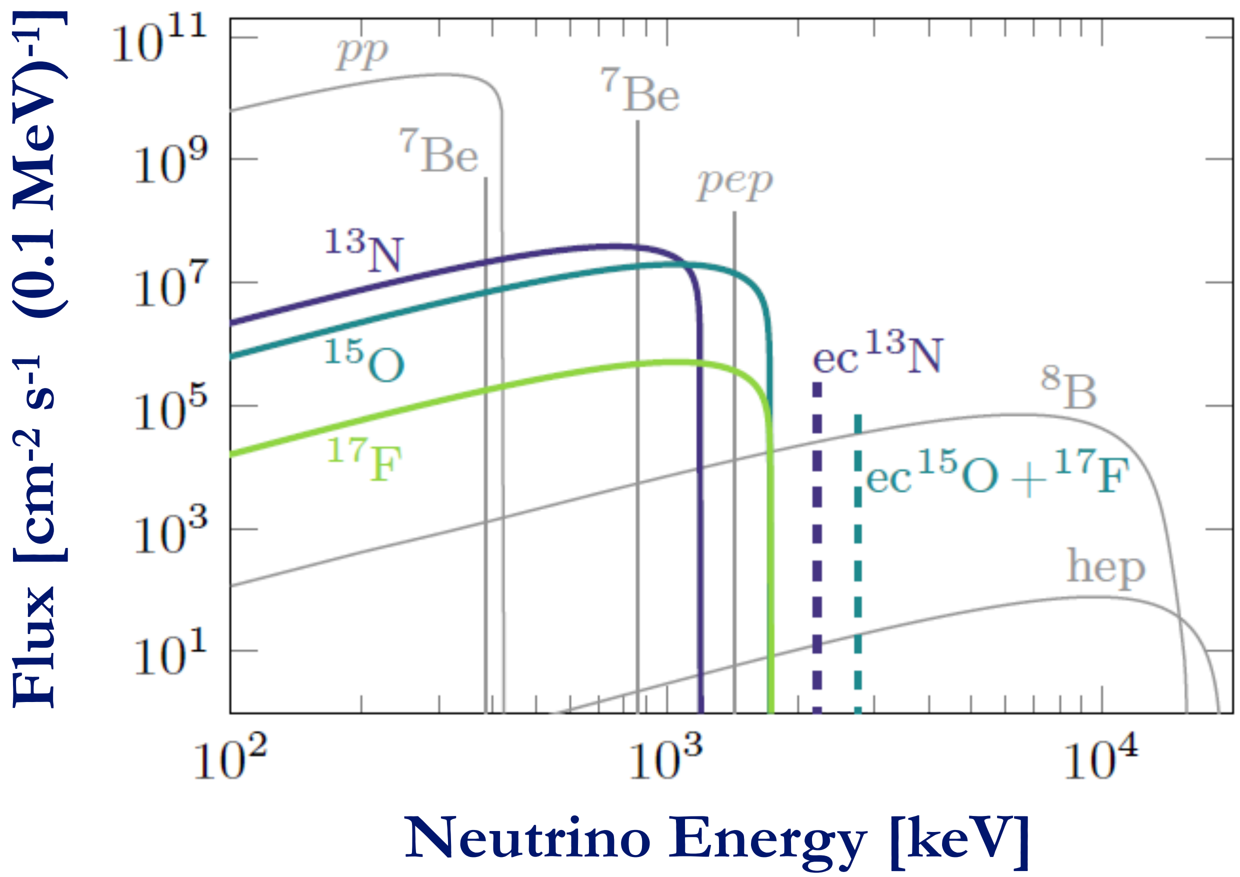
- The e⁻ is scattered in the **liquid scintillator:**
  - **path:** **few mm**
  - **physics thresh.:** **very small**
  - **triggering thresh.:** **~40 keV** (dep.)
  - **analysis thresh.:** **~ 200 keV**

SIGNATURE: 'Compton' shoulders

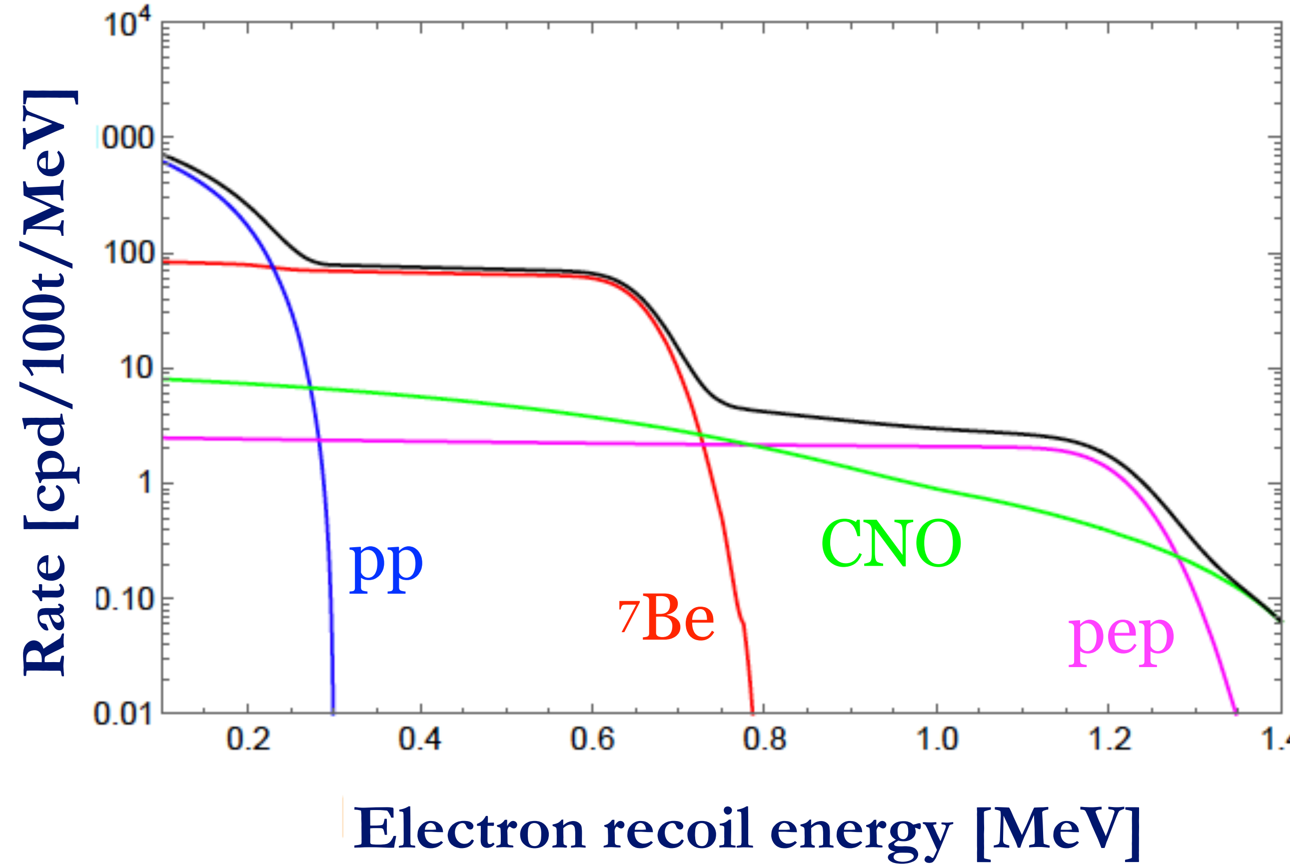


Neutrino detection in Borexino (II)

SOLAR NEUTRINO SPECTRUM



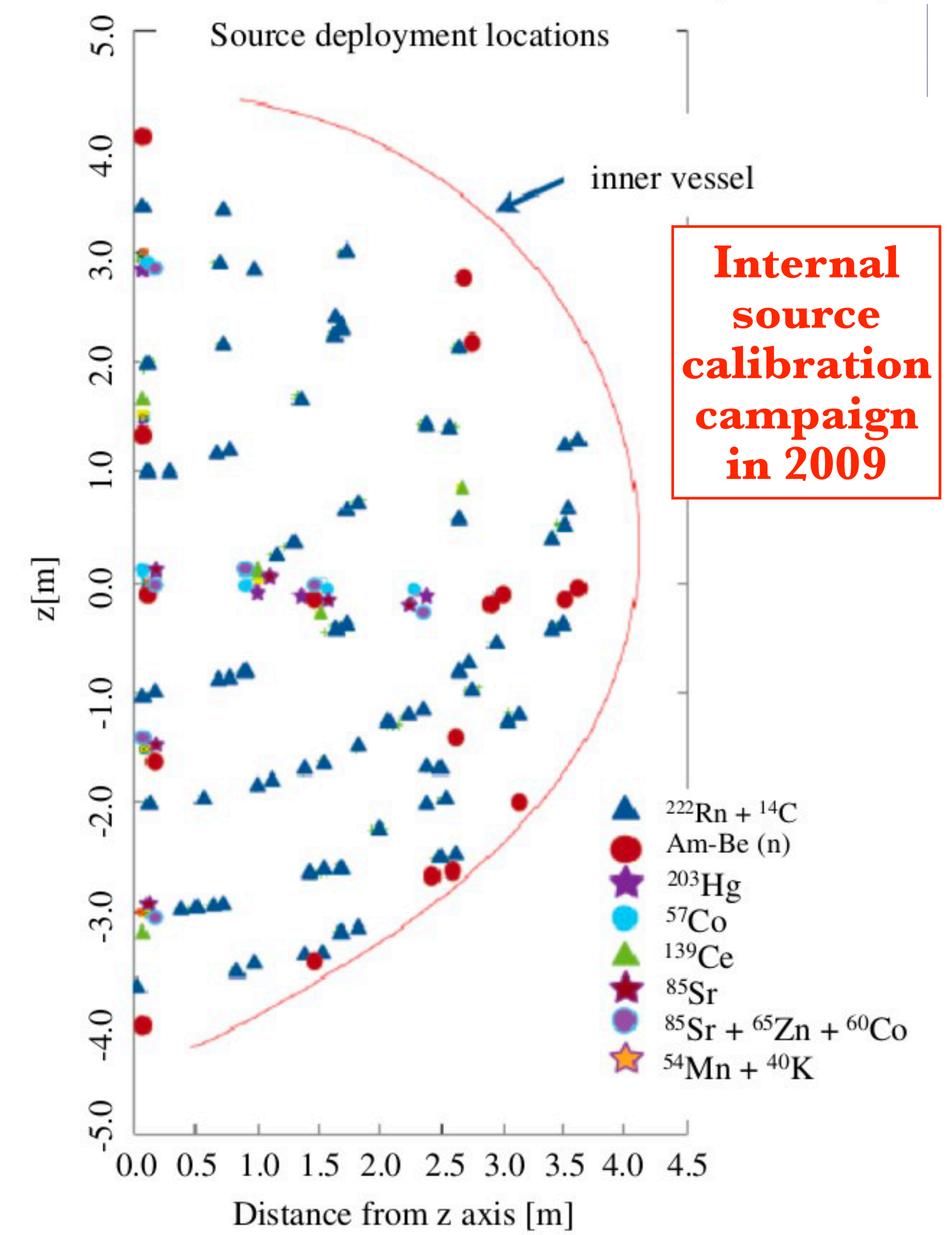
DETECTION RATE IN BOREXINO



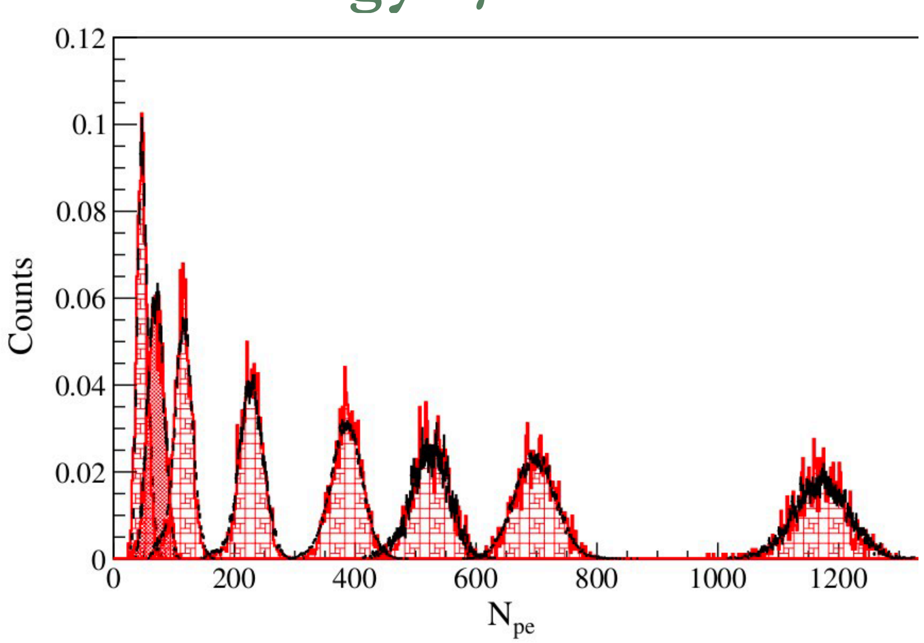
Source	Count Rate [cpd/100t/d]	Comments on detection	First detection in BX
^{7}Be	~ 48	Clear signature on the shoulder	2007
^{8}B	< 1	Small, but high energy, low background	2010
pep	~ 3	Weak signature on top of ^{11}C	2012
pp	~ 140	Low energy, partially covered by ^{14}C	2014
CNO	~ 5	Small signal, migrating background (see talk)	2020
hep	Not measurable today	Signal too low, mostly covered by ^{8}B	never

Detector response

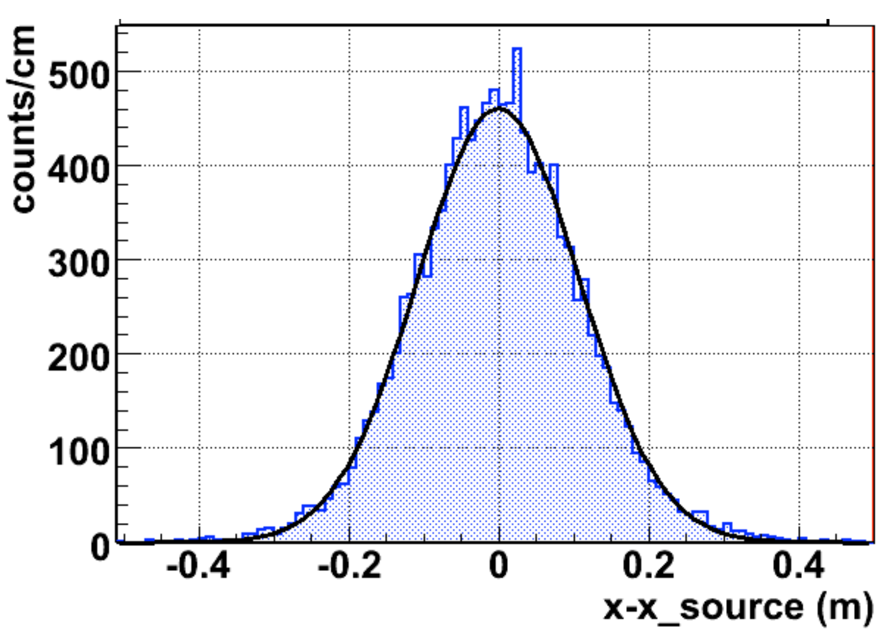
- Large liquid scintillator signal yields:
  - # photo-electrons:
    - **energy: 6% @ 1 MeV**
  - time-of-flight:
    - **position: ~11 cm @ 1 MeV**
  - pulse shape:
    - very good α/β and (weak) β^+/β^- **discrimination**



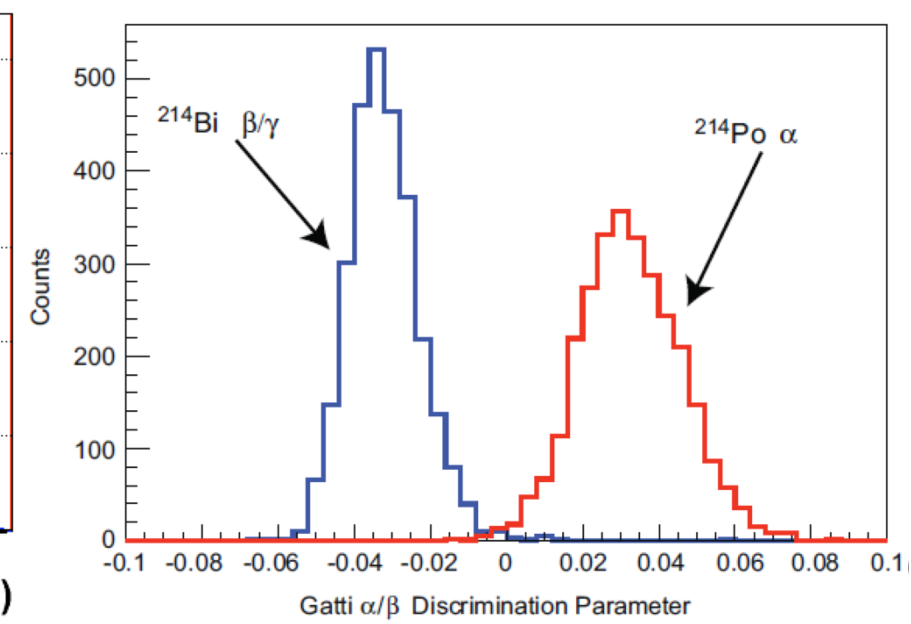
Energy: γ sources



Position: ^{214}Po



α/β: ^{214}Bi - ^{214}Po



Fighting backgrounds

- **Quasi-point-like energy deposits mimic neutrino events**

EXTERNAL

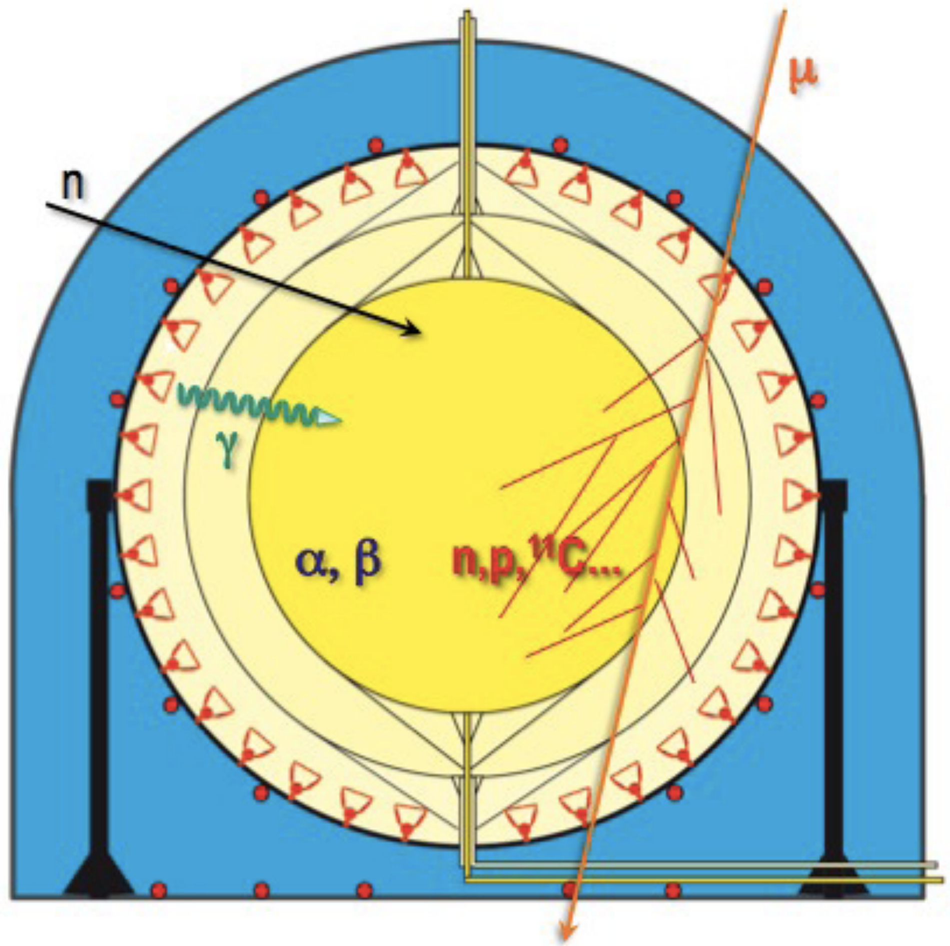
- γs (and n) from environment and detector materials (PMTs and SSS, mostly)

A tiny amount reaches FV

INTERNAL

- α and β emitters dissolved in the scintillator

^{14}C, ^{238}U, ^{232}Th, ^{40}K, ^{39}Ar, ^{7}Be, …
^{85}Kr, ^{210}Pb, ^{210}Po



COSMOGENIC

- Residual muons produce long living isotopes (μs to days range)

^{11}C, ^{8}He, ^{9}C, ^{9}Li, ….

MIGRATING

- Detaching from Nylon Vessel and transported by convection into the FV

^{210}Po, ^{222}Rn

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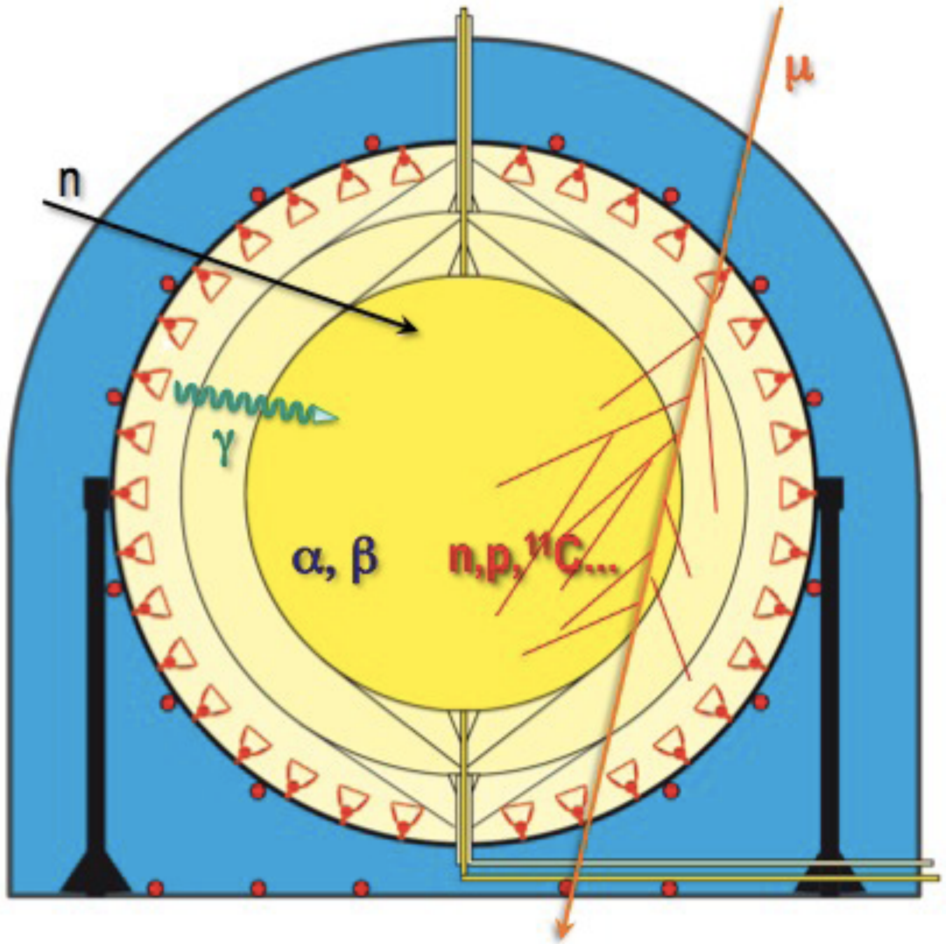

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^{210}Po, ^{222}Rn

FIGHTING STRATEGY

- Shielding, muon tagging and tracking
- Material selection (steel, PMTs, nylon)
- Nylon vessel (material selection, clean construction, no air exposure)

Fighting backgrounds

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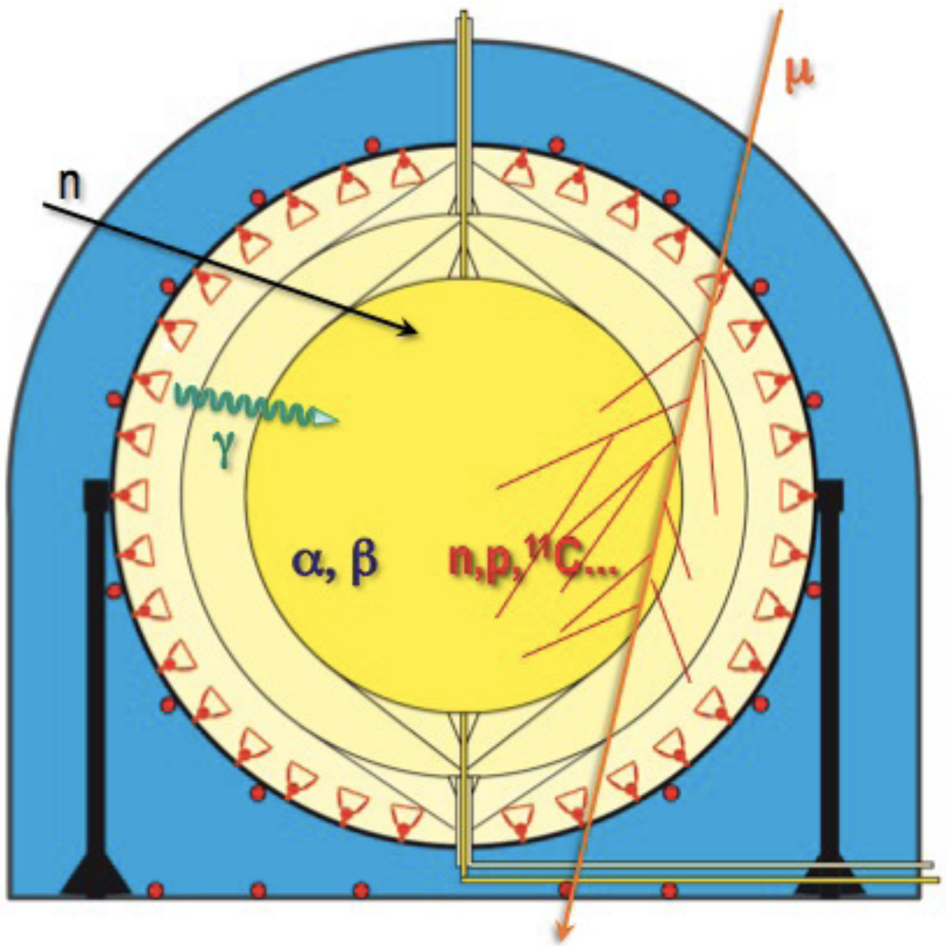

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MIGRATING

- Detaching from Nylon Vessel and transported by convection into the FV

^{210}Po, ^{222}Rn

FIGHTING STRATEGY

- Selection of PC vendor for low ^{14}C, dedicated plant, and custom transportation
- **Distillation** of PC, **Water Extraction** of PC+PPO solution
- Development of **low Ar and Kr N_2** to remove dissolved contaminants
- Extreme cleanliness of plants, carefully designed filling procedures

A long story made short!

Fighting backgrounds

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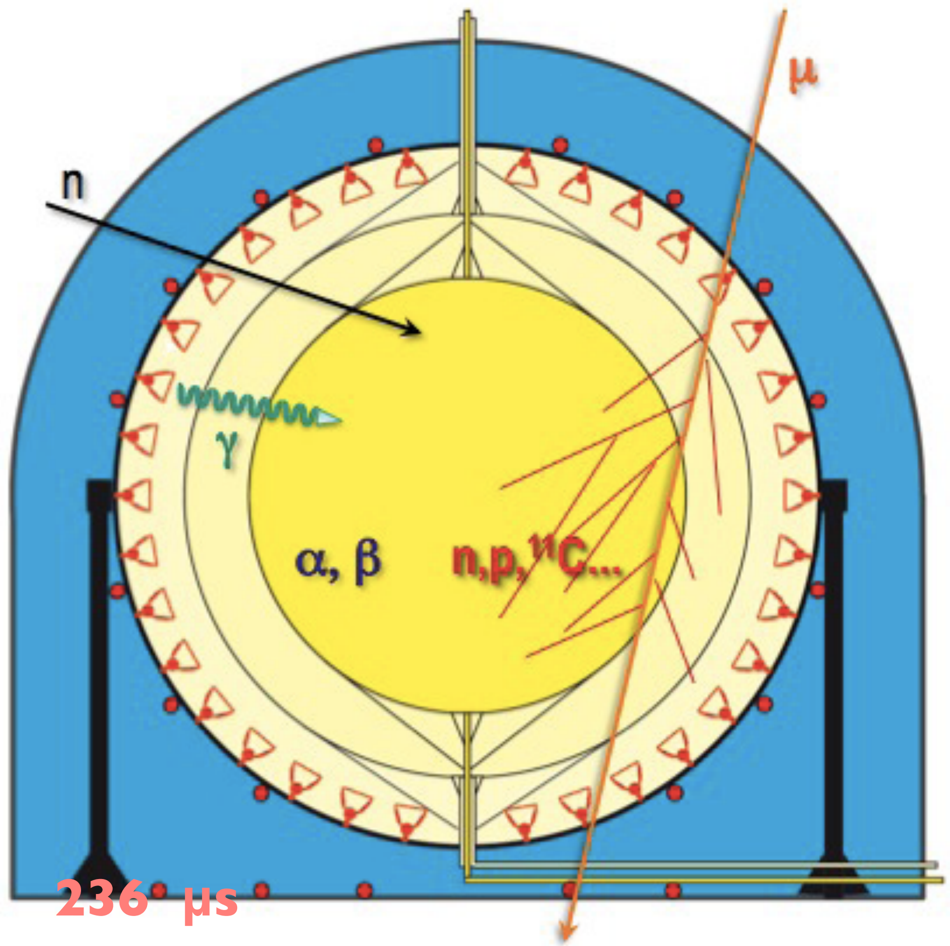

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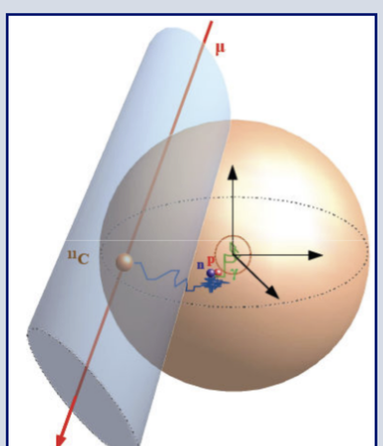
FIGHTING STRATEGY



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

29.4 min

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

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

236 µs

Other isotopes: removed by "after muon" veto cuts

Fighting backgrounds

- Quasi-point-like energy deposits mimic neutrino events

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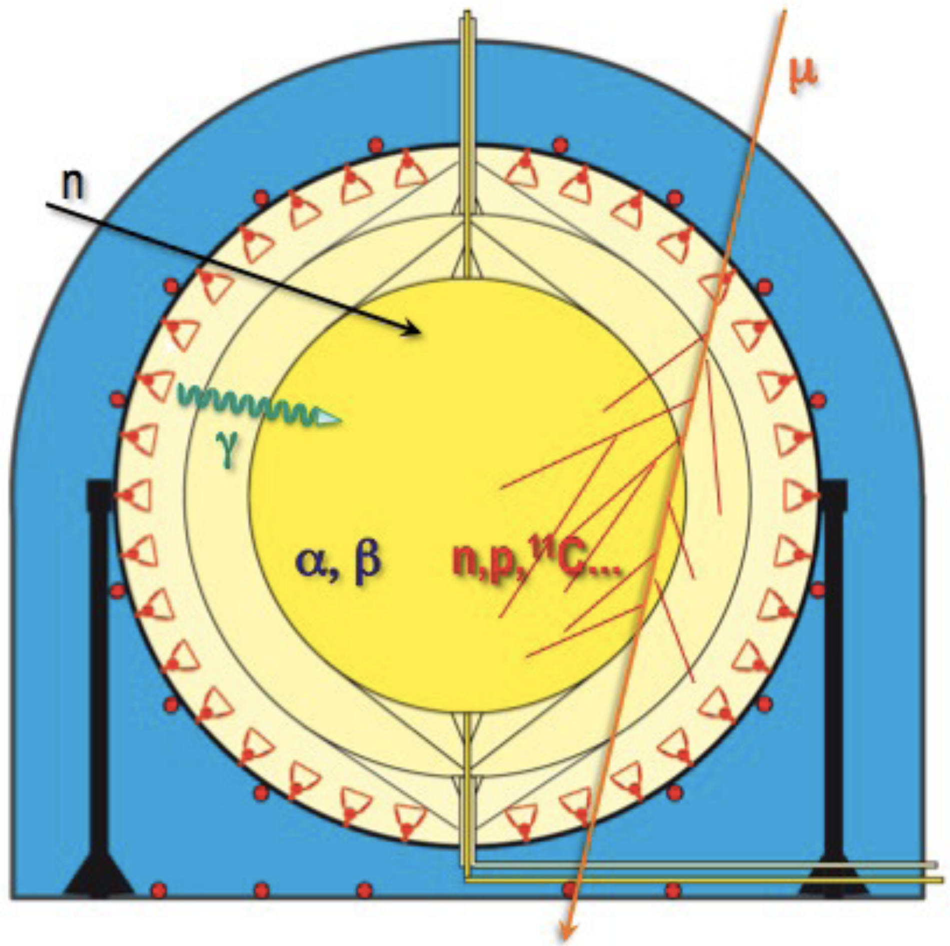

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MIGRATING

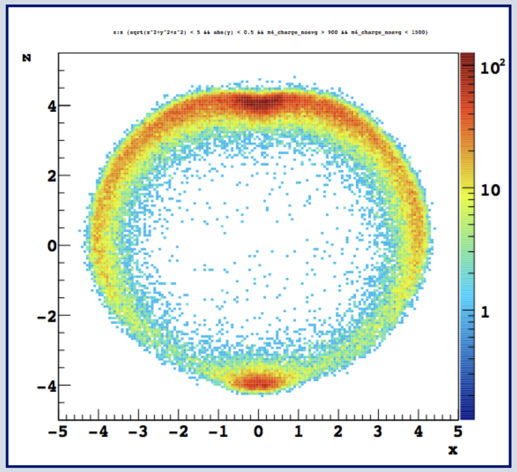
- Detaching from Nylon Vessel and transported by convection into the FV

^{210}Po, ^{222}Rn

FIGHTING STRATEGY

- Isotopes detaching from IV may reach the FV
  - ^{210}Po (chiefly) and ^{222}Rn daughters
- Leaching rate (chemistry) and speed (convection currents)
  - Only if they live long enough!

See later



Signals and backgrounds

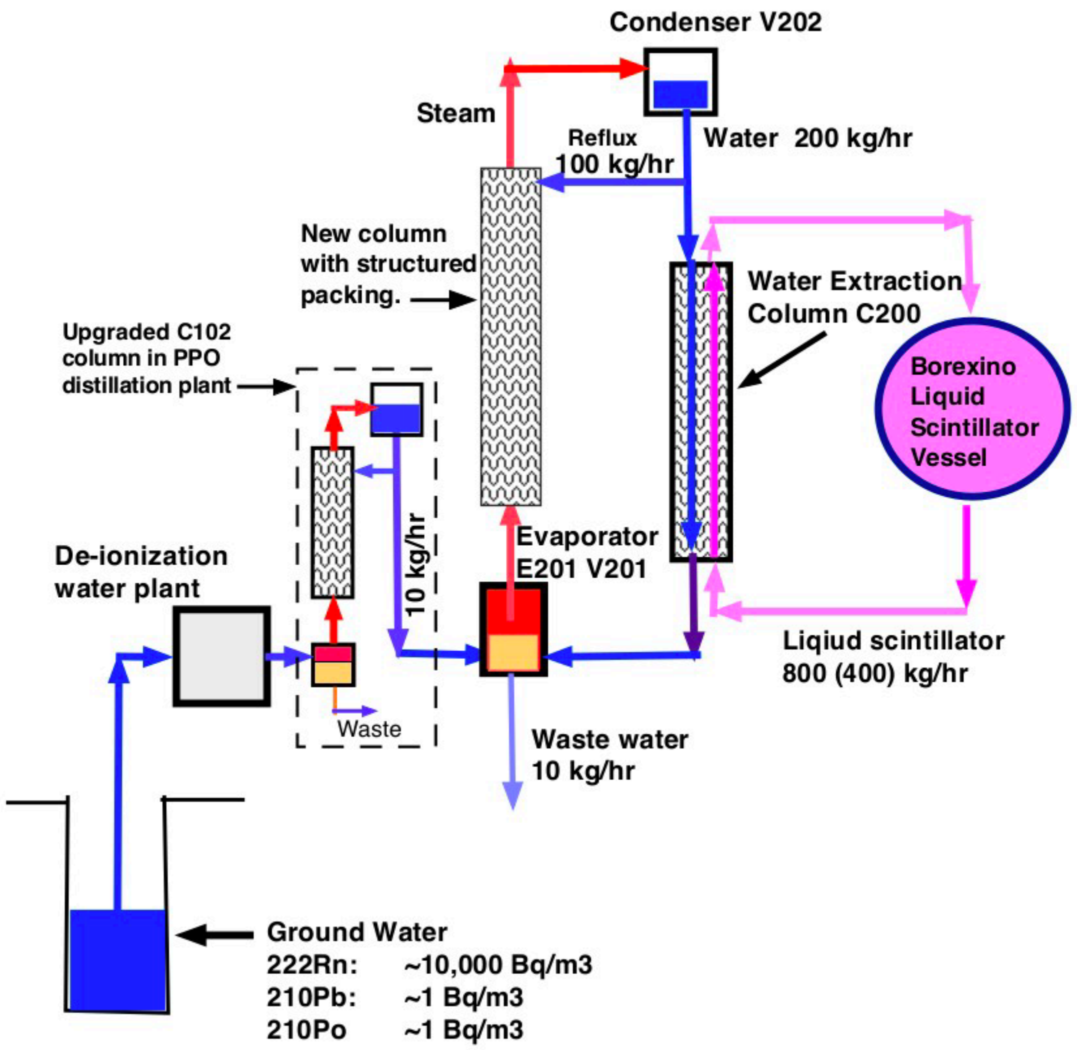
- ν **signal:** ~140 cpd/100 t (pp) and ~50 cpd/100 t (^{7}Be). The others are smaller. **CNO ~ 5 cpd/100 t;**
  - Compare with:
    - **Good mineral water, air:** ~ 10 Bq/kg ⟹ 8.6 10^{10} cpd/100 t

      Must be **10 orders of magnitude** better than "clean" materials.

Isotope	Requirement	Technique	Phase I	Phase II
^{14}C	< 10^{-17} g/g	selection		
^{238}U	< 10^{-16} g/g	Distillation, W.E.	1.6±0.1 10^{-17} g/g	< 9.4 10^{-20} g/g
^{232}Th	< 10^{-16} g/g	Distillation, W.E.	5.1±1 10^{-18} g/g	< 5.7 10^{-19} g/g
^{85}Kr	A few cpd/100 t	N_2 flow	~30 cpd/100 t	~ 5 cpd/100 t
^{40}K, ^{39}Ar	A few cpd/100 t	Distillation, N_2 flow	Not visible	Not visible
^{210}Po	Not too critical	Distillation, W.E.		
^{210}Bi (^{210}Pb)	A few cpd/100 t	Distillation, W.E.	~40 cpd/100 t	~10 cpd/100 t

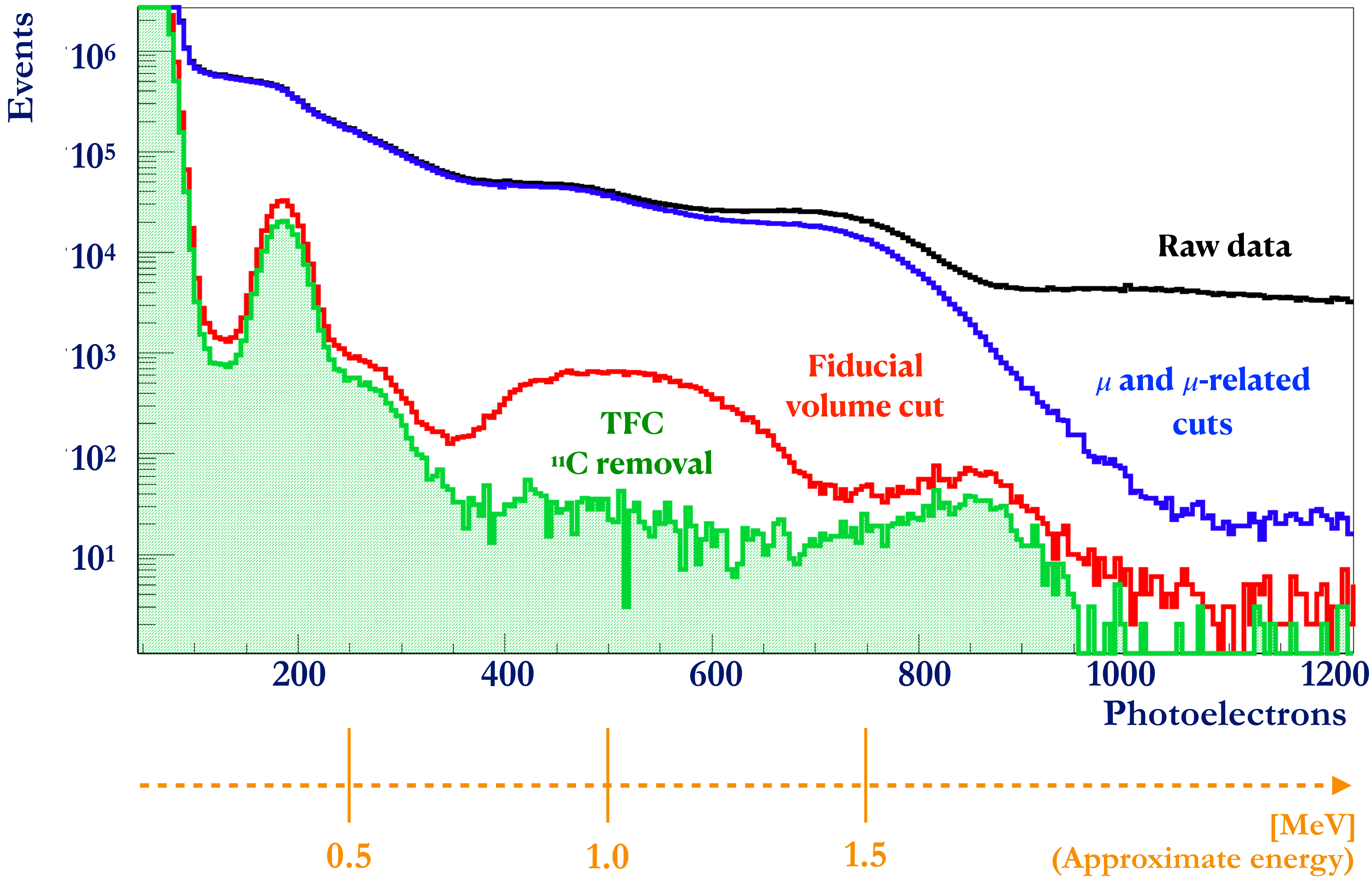
Purification campaign 2010-2011

- **A key step toward pp and CNO ν**
  - Water Extraction
    - Turbulent mixing with ultra-clean water to remove ions, much more soluble in water
  - Low Ar-Kr N_2 bubbling
    - Turbulent mixing with N_2 flow, to remove dissolved gasses
- **Very successful** on ^{238}U, ^{232}Th (chain heads), ^{210}Bi and ^{85}Kr

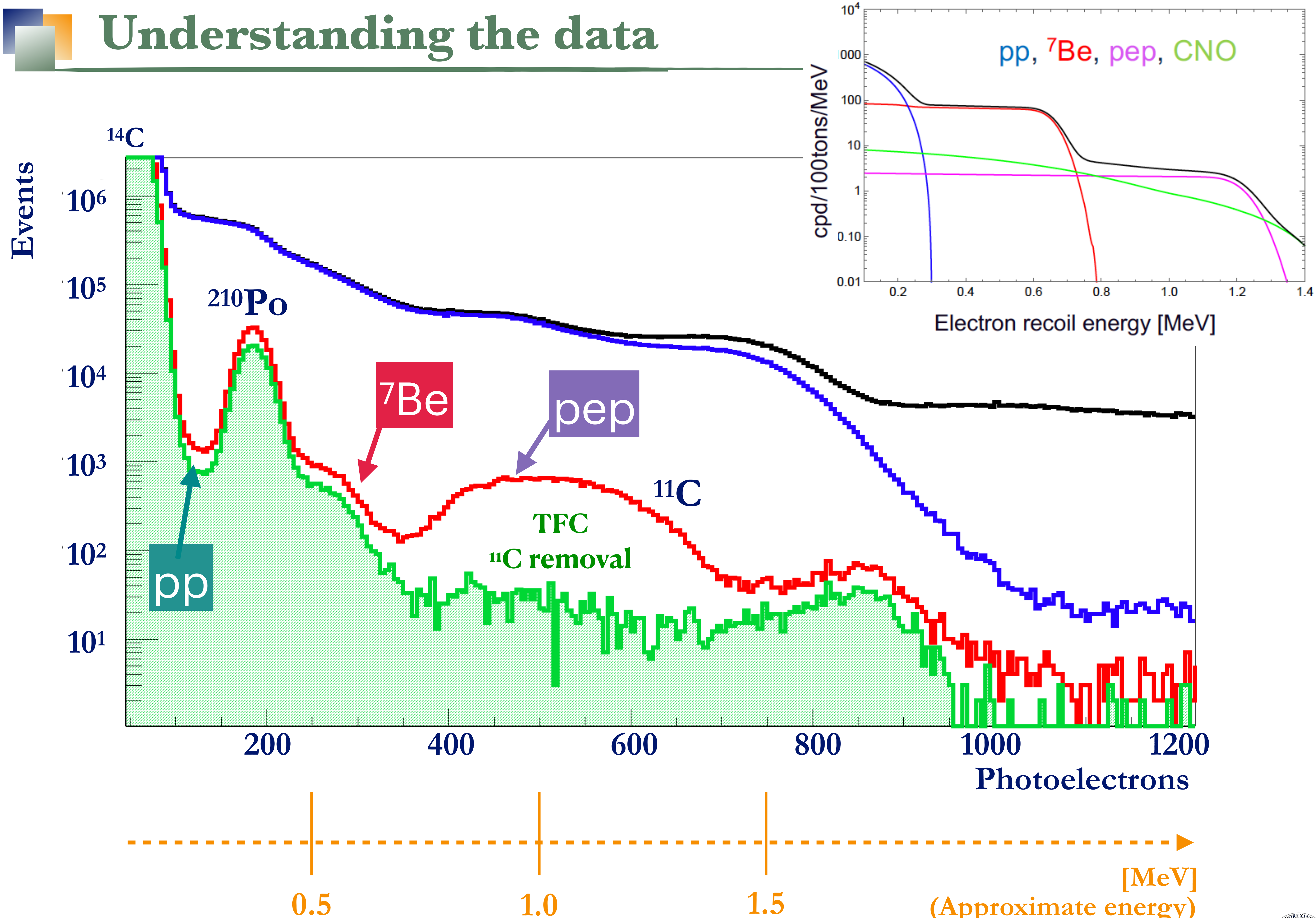


Isotope	2007-2010	2012-2020
^{238}U	1.6 ± 0.1 10^{-17} g/g	< 9.4 10^{-20} g/g
^{232}Th	5.1 ± 1 10^{-18} g/g	< 5.7 10^{-19} g/g
^{85}Kr	~ 30 cpd/100 t	~ 5 cpd/100 t
^{210}Bi	~ 40 cpd/100 t	~ 10 cpd/100 t

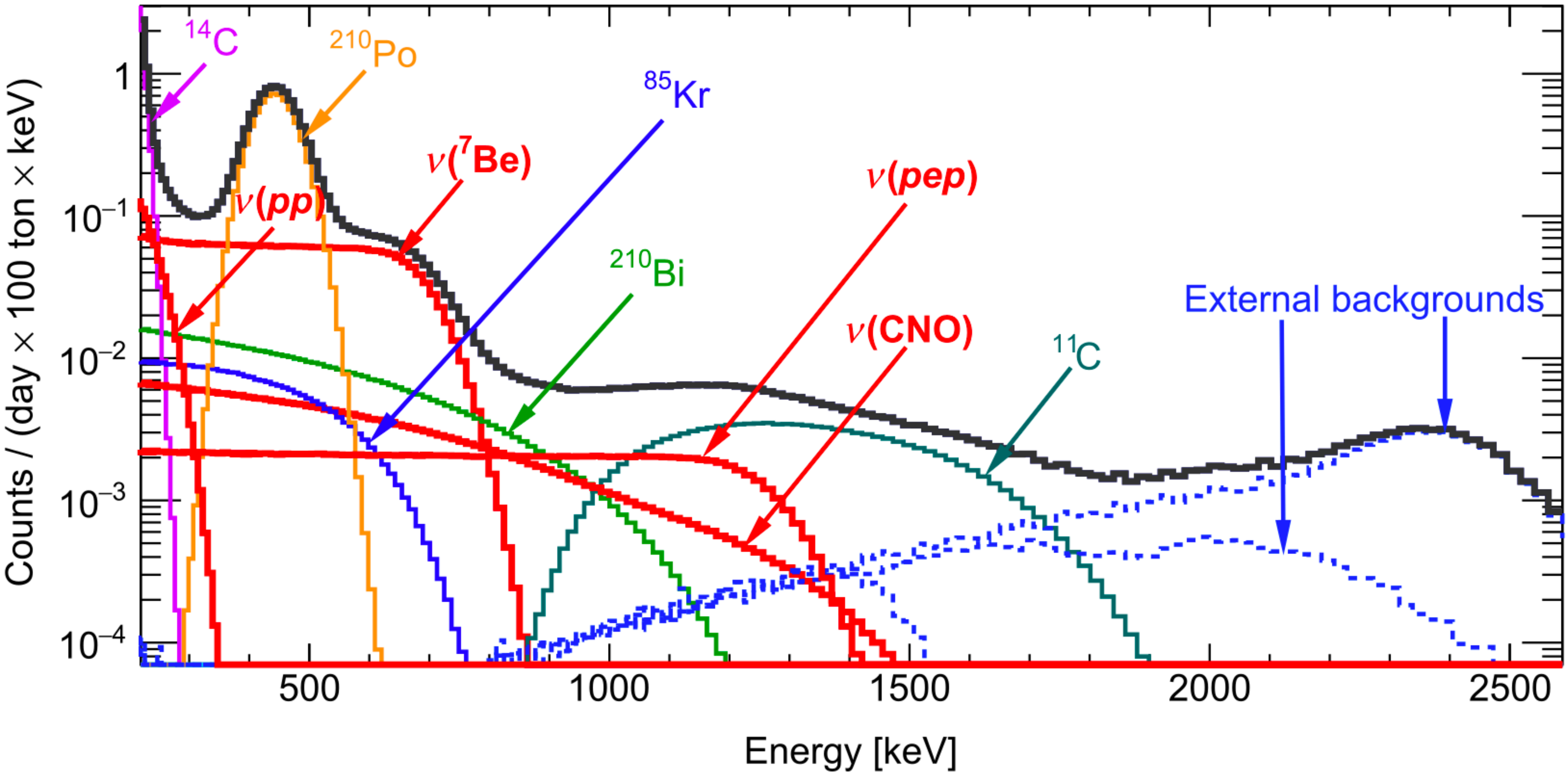
Understanding the data



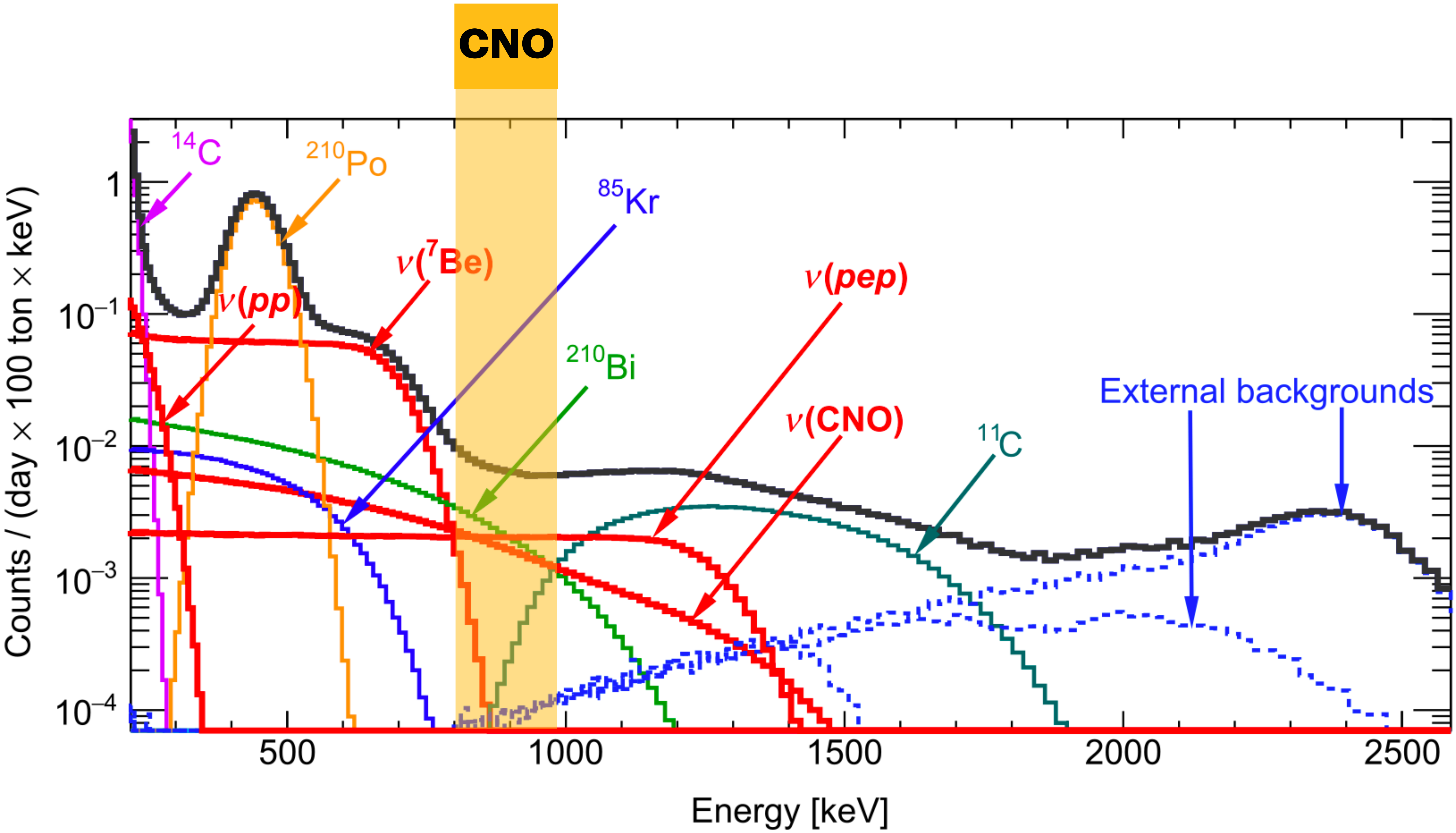
Understanding the data



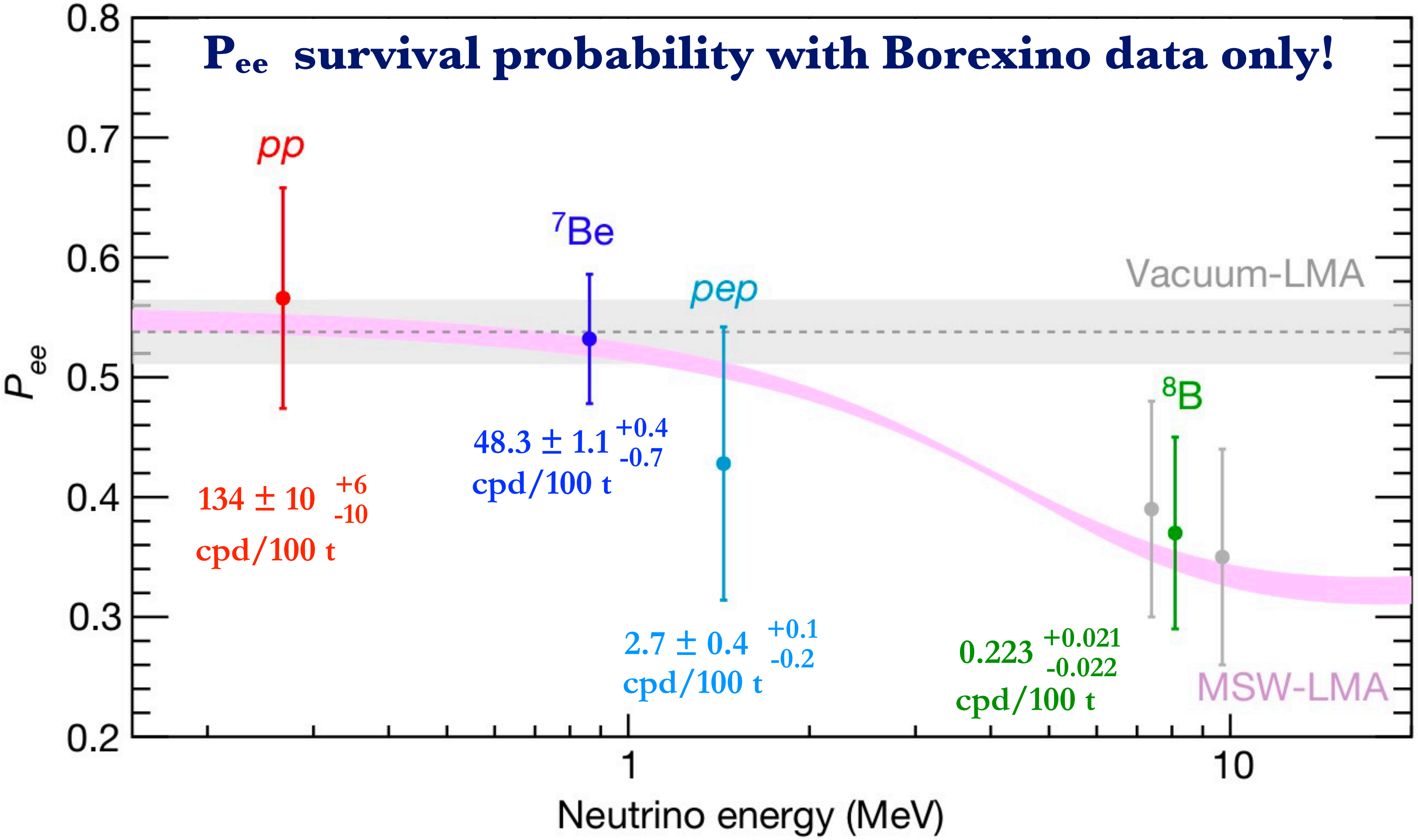
Spectral components: fit



Spectral components



Summary of pp chain study (2007-2018)



Comprehensive chain:
Nature 562 (2018) 7728, 505.
Phys. Rev. D (2019)

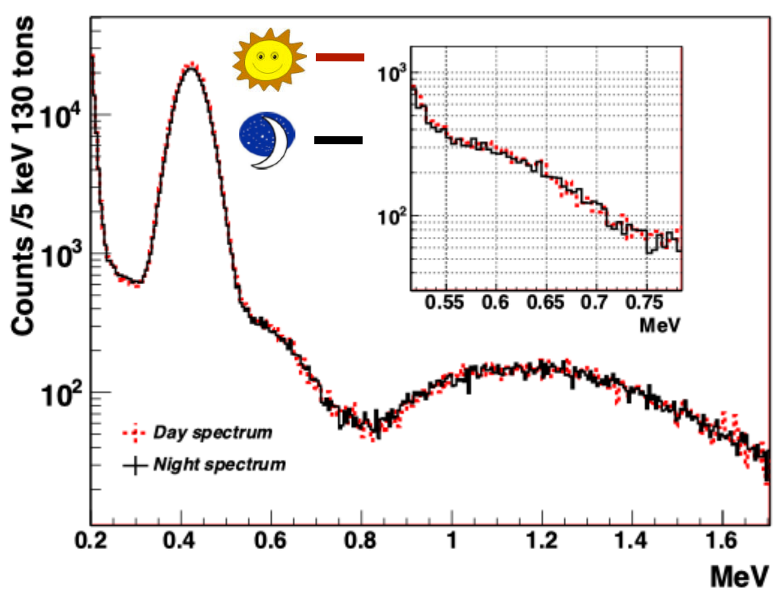
pp:
Nature 512 (2014) 7515, 383.

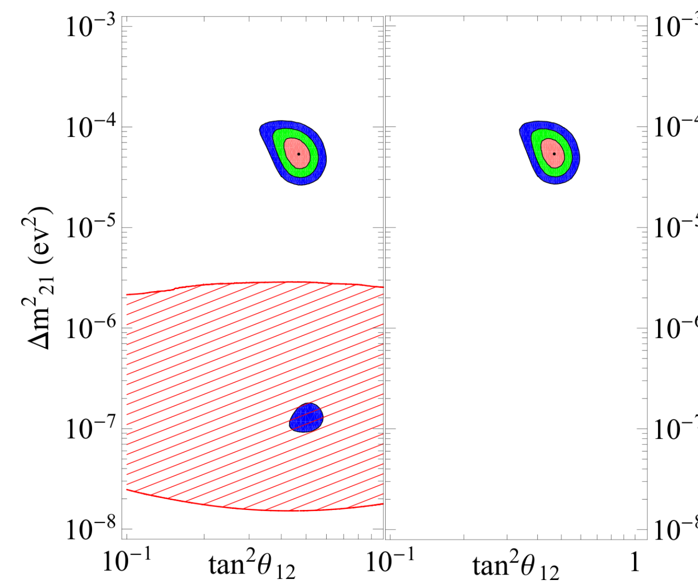
^{7}Be:
Phys. Lett. B658 (2008) 101
PRL 107 (2011) 141302

pep:
PRL 108 (2012) 051302

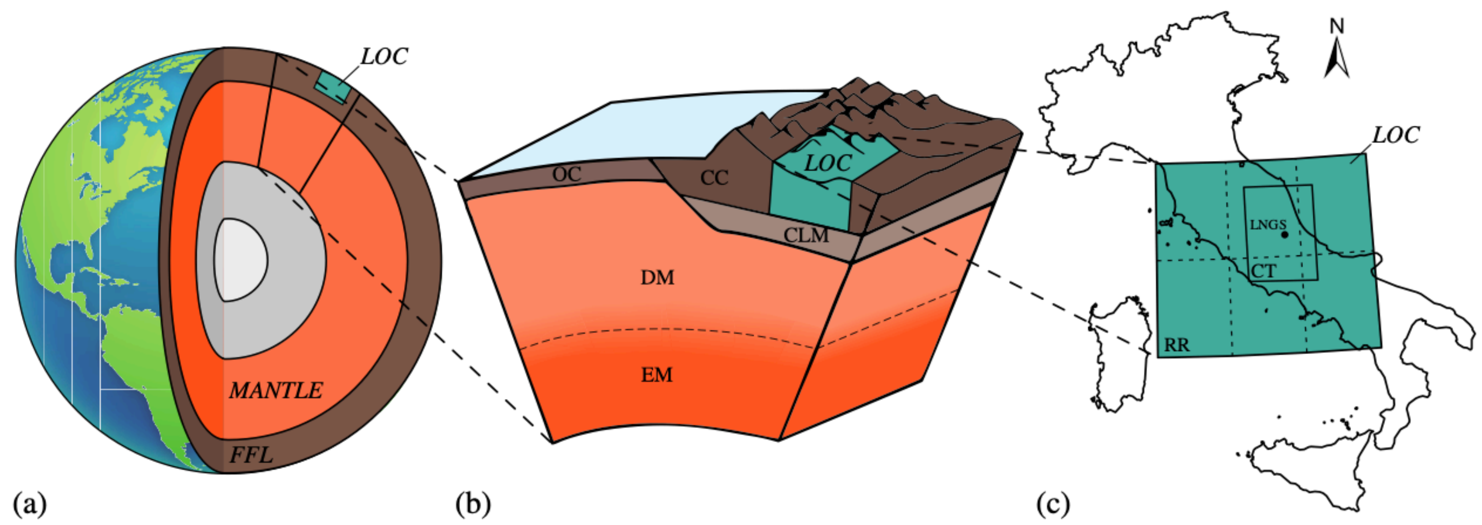
^{8}B:
Phys. Rev. D82 (2010) 033006

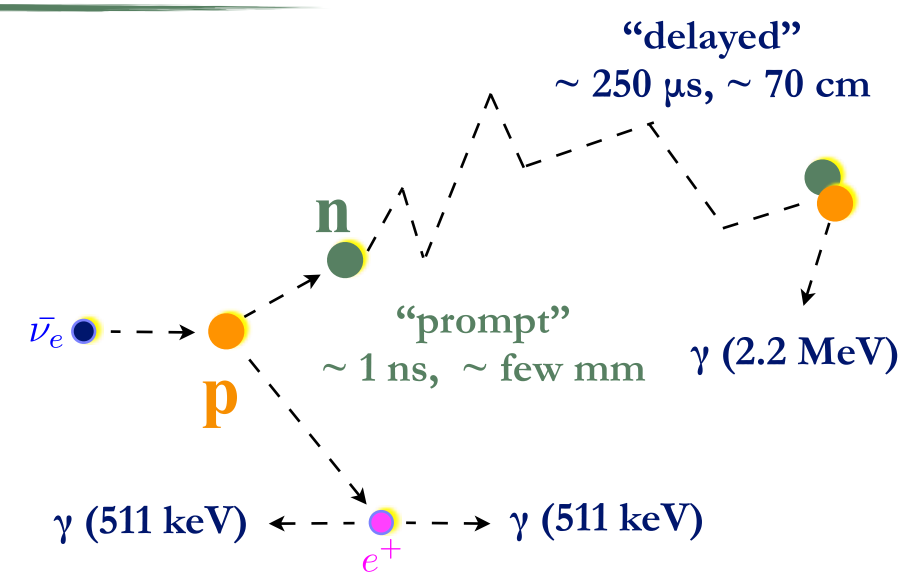
No day-night ^{7}Be: confirmation of LMA [Phys. Lett. B707 (2012) 401.]



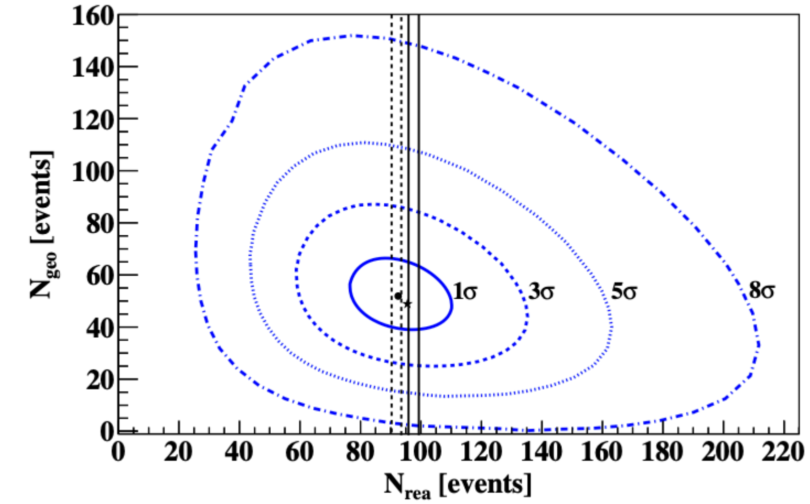


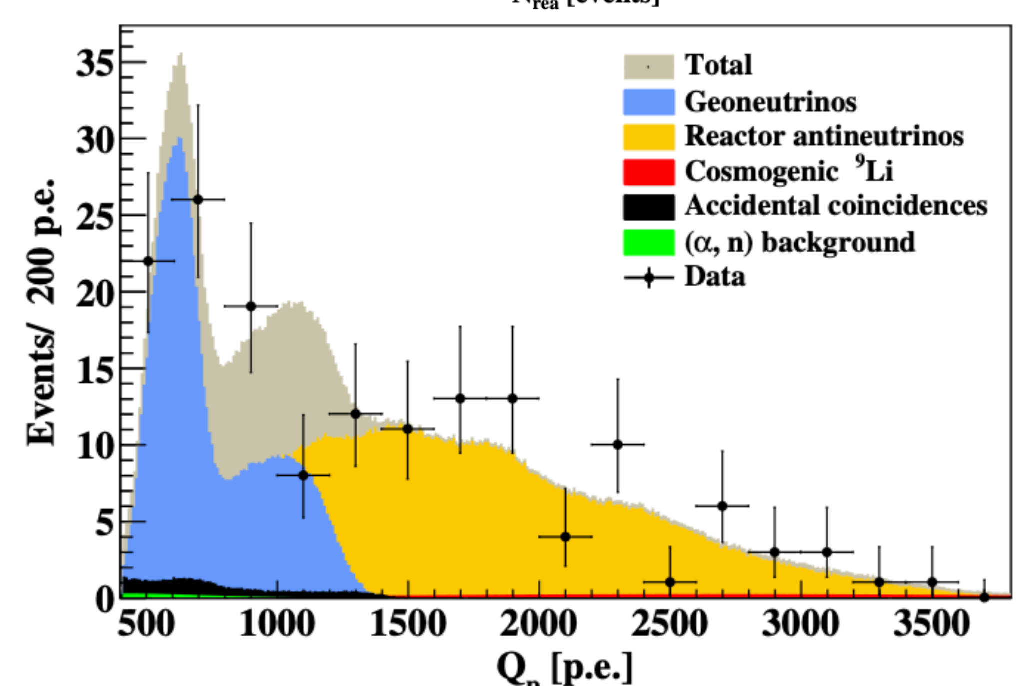
Intermezzo: ν from the Earth





- **Data:**
  - Exposure: **3262,7 days** ($1.29 \pm 0.05 \; 10^{32}$ protons x year)
  - Very low non-neutrino background, thanks to radio-purity
    - Background: **8.3 events TOTAL in ~ 10 years** (cosmogenic and accidentals)
    - Background from reactor anti-$\boldsymbol{\nu}$, quite low in Italy.
- **Key results:**
  - Signal: $52.6^{+9.4}_{-8.6}$ (stat)$^{+2.7}_{-2.1}$ (sys) [^{238}U & ^{232}Th] (>8 σ)
  - 99% C.L. evidence of **contribution from the mantle**
  - Radiogenic heat from ^{238}U and ^{232}Th: **24.6 ± 11 TW**
  - No geo-reactor



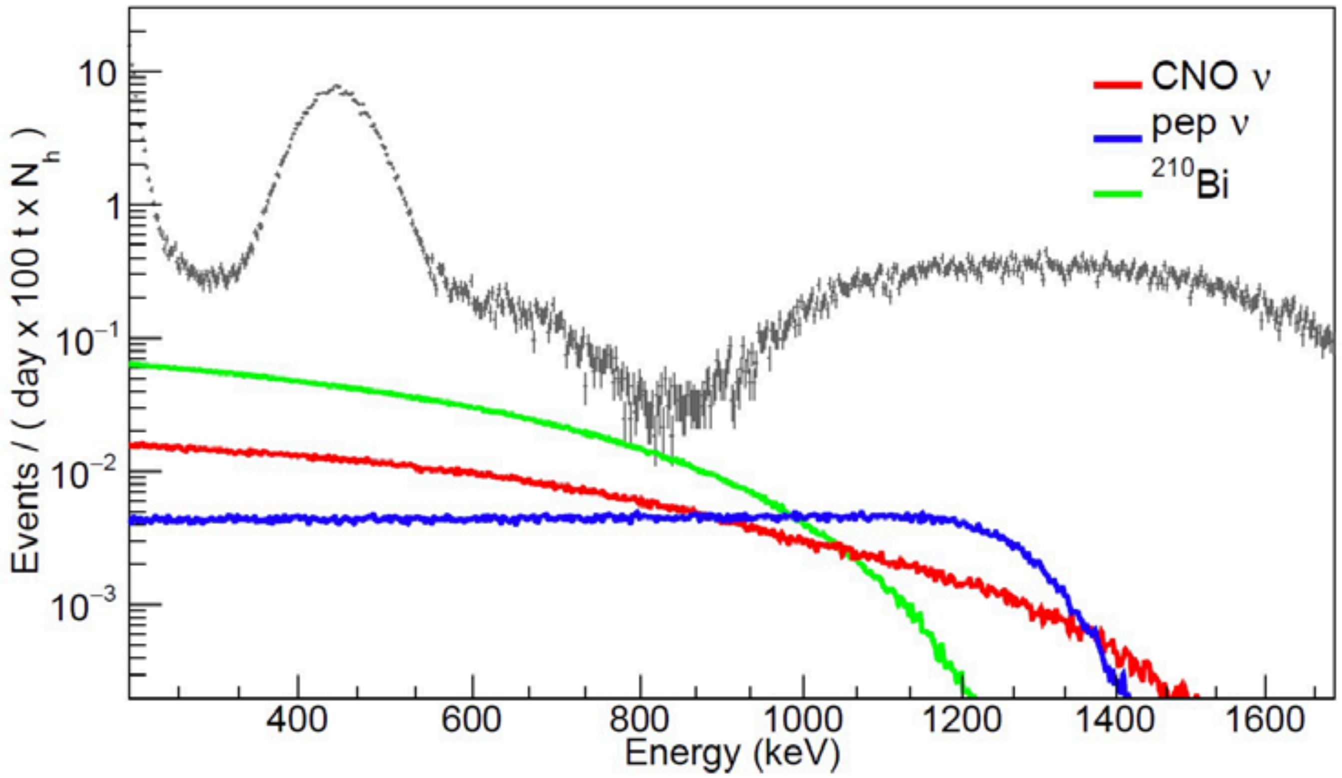


Phys. Lett. B 687 (2010) 299-304 • e-Print: 1003.0284 [hep-ex]
Phys. Rev. D 92 (2015) 3, 031101 • e-Print: 1506.04610 [hep-ex]
Phys. Rev. D 101 (2020) 1, 012009 • e-Print: 1909.02257 [hep-ex]

Chasing CNO

- CNO measurement was hard:
  - The signal is much smaller than pp and ^{7}Be
  - CNO, pep, and ^{210}Bi are highly correlated in the fit
    - Spectral fit gives CNO+^{210}Bi, if both left free
  - **To measure CNO, you must independently fix the other two**
    - **pep:** determined at 1.4 % by luminosity; very solid constraint
    - **^{210}Bi: the key point.** You must measure it independently.

J. Bergströmet al., JHEP, 2016:132, 2016

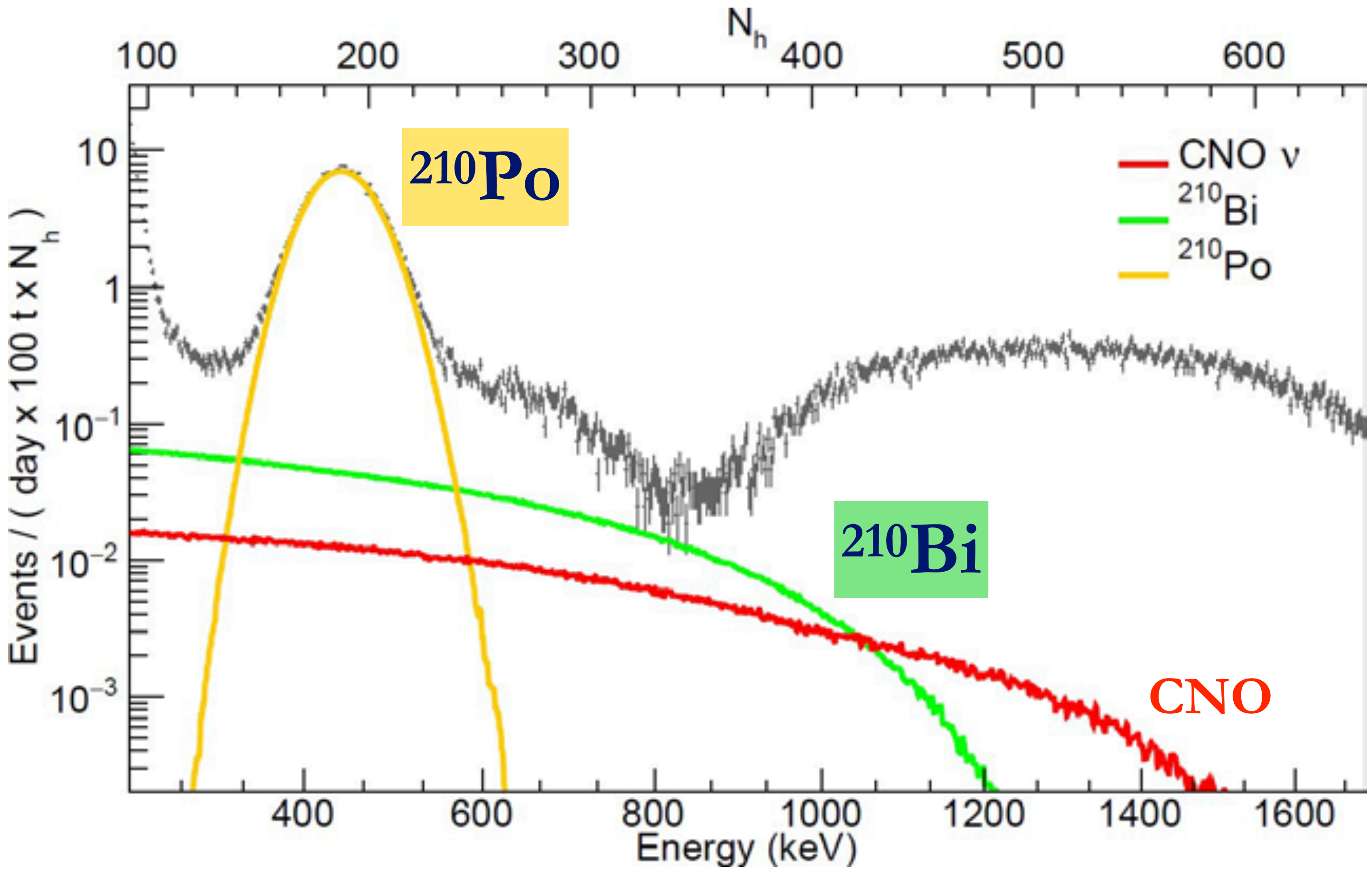


How to fix ^{210}Bi ?

- Decay chain: $^{210}Pb \xrightarrow[32y]{\beta^-[63\ keV]} {}^{210}Bi \xrightarrow[7.23d]{\beta^-[1161\ keV]} {}^{210}Po \xrightarrow[199.1d]{\alpha\ [5.40\ MeV]} {}^{206}Pb$

  ^{238}U end

  - In principle, it is easy: you measure ^{210}Po peak and you get ^{210}Bi



- **BUT:**
  - ^{210}Po peak was **much higher** than measured ^{210}Bi
    - **Out-of-equilibrium ^{210}Po** background in the scintillator
    - ^{210}Po count rate was also not a pure exponential with the expected life-time: there was **evidence of ^{210}Po migrating from the vessel** surface into the FV by convection
  - Key questions:
    - **Is ^{210}Bi (i.e. ^{210}Pb) also migrating ? (N.B. ^{210}Pb is not visible)**
    - **Can you stop ^{210}Po migration or make it slow enough ?**

Fighting migrating background

- **Basic idea:**
  - diffusion is slow: $\dot{\rho}(\vec{r},t) = D\,\nabla^2\rho(\vec{r},t) - \frac{\rho_0}{\tau_{Po}}$

    DIFFUSION LENGTH $\lambda = \sqrt{D\tau_{Po}} \simeq 20\ cm$

    - With no convection (i.e. by diffusion only) **^{210}Po decays before reaching FV**
  - if you slow down **convective currents** enough, all ^{210}Po will decay before reaching FV and affect ^{210}Bi determination

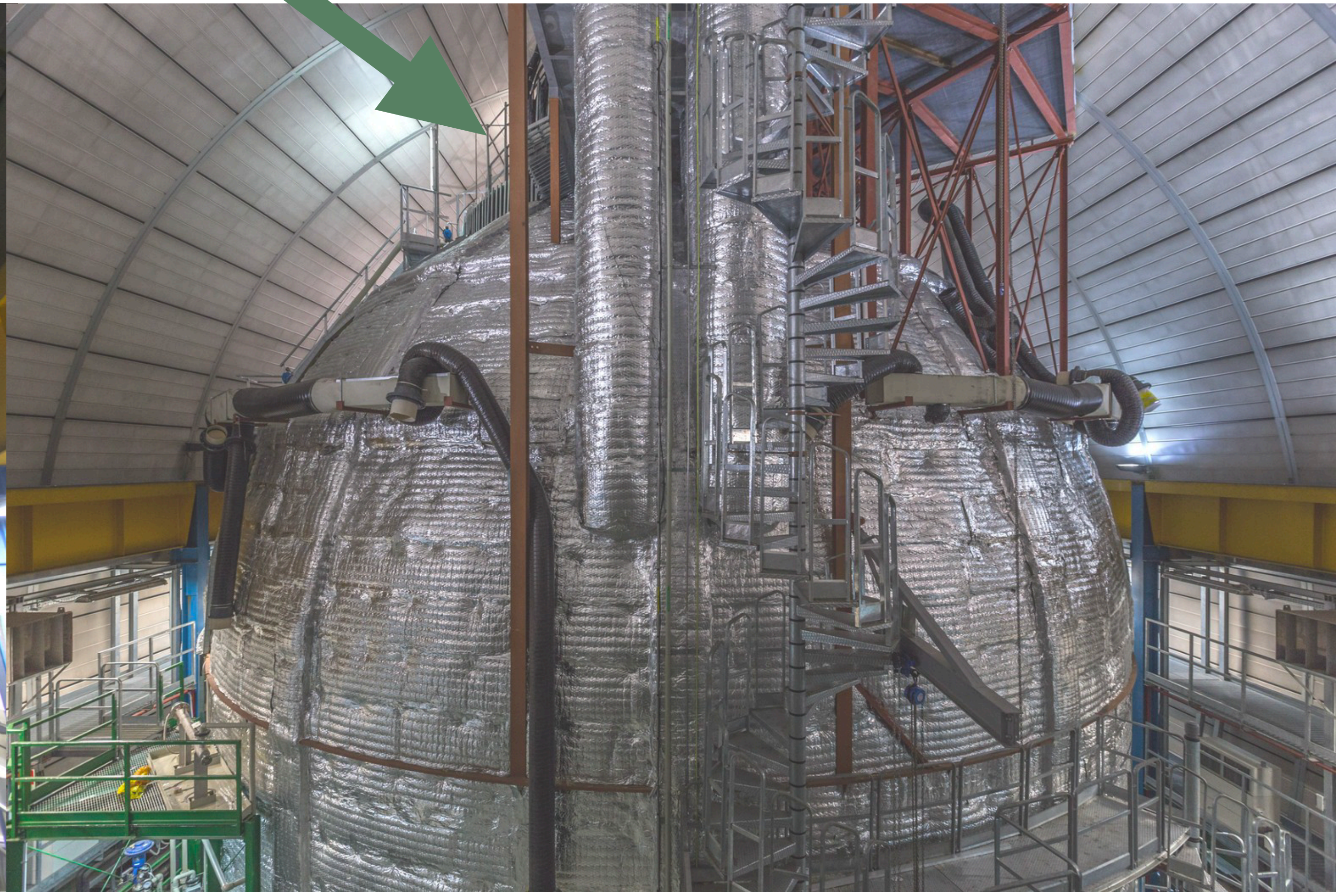
- Strategy:
  - Allow ^{210}Po out-of-equilibrium to decay
    - 2010 purification campaign did not remove all ^{210}Po
      - It DID reduce ^{210}Bi, i.e. parent ^{210}Pb
  - Act with passive and active systems on the thermodynamics of the detector to slow down convective currents
    - **A coat** (2015): Double layer of mineral wool. Thermal conductivity down to 0.03 W/m/K
    - **Active system controlling the top temperature** (ACTS, 2016)
      - Fine tuning in early 2019
    - Thermal control of **Hall C as well** (late 2019)

Thermal insulation (2015)

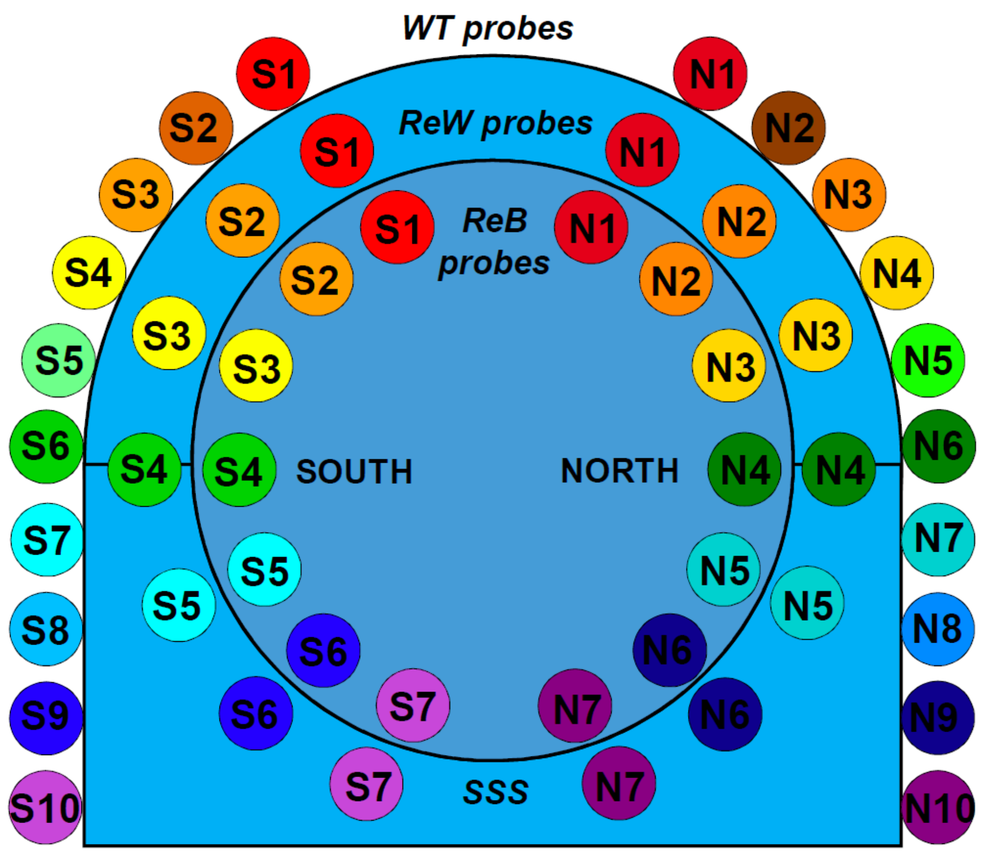
On top: copper coils under insulation with controlled water flow (2016)

Before

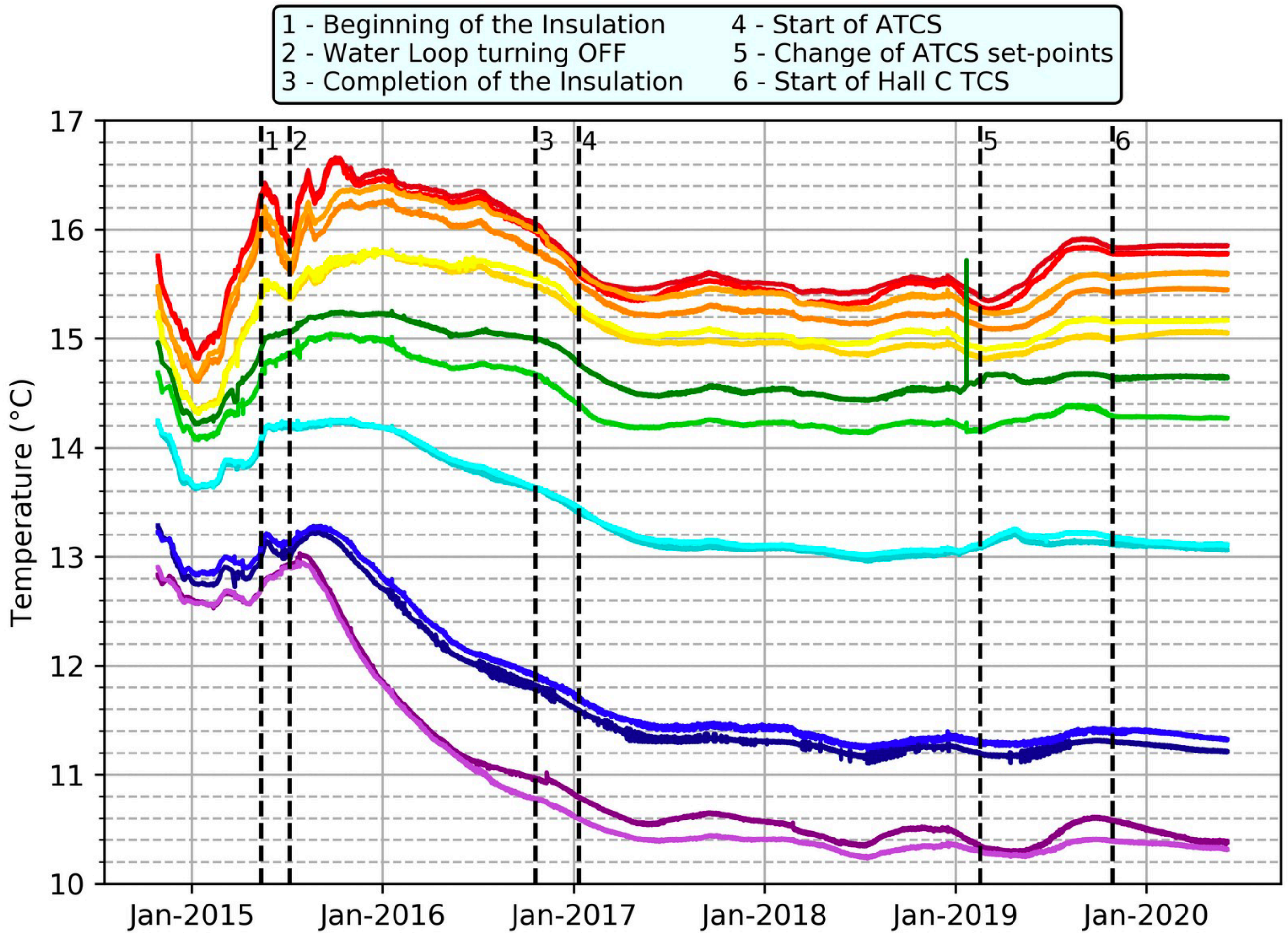
After



Effect on temperatures

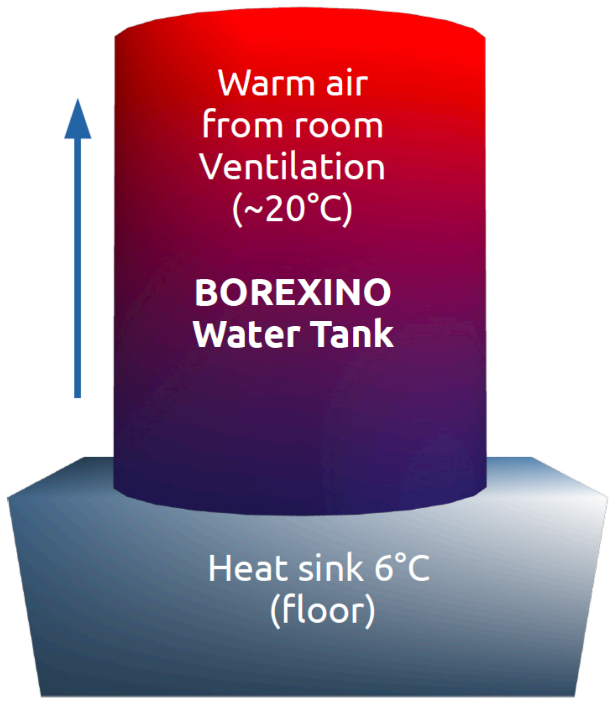


Distribution of T probes

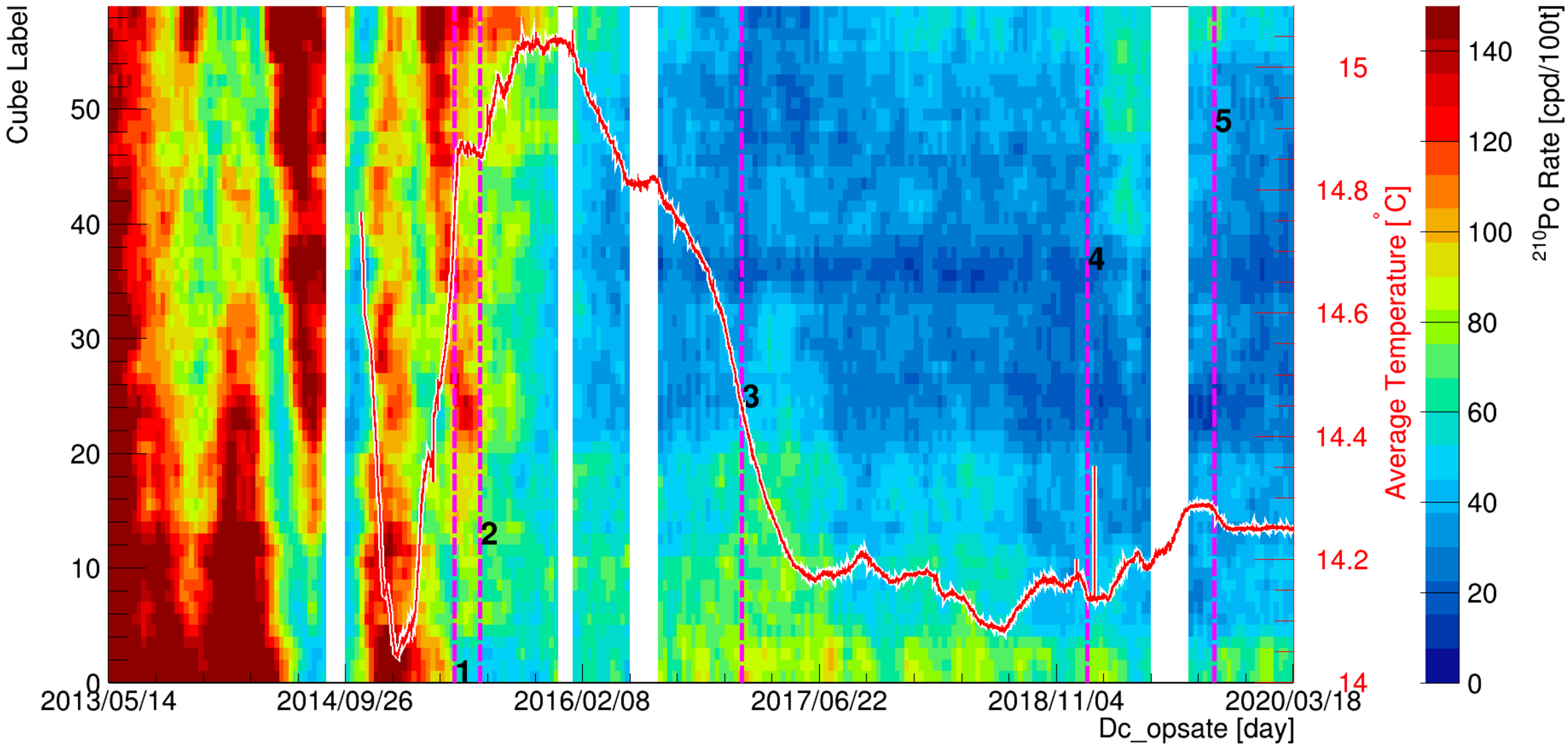


T vs Time

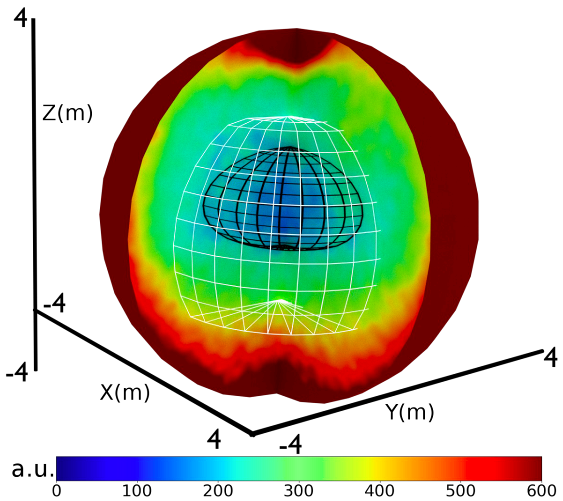
- Two important notes:
  - stability was achieved because the **LNGS floor is colder (~ 6 °C) than air (~20 °C in Hall C)**
    - This yields the **right vertical gradient** to stop convection
  - the time constant is very slow. Years to get stability, still in progress.



Evolution of ^{210}Po

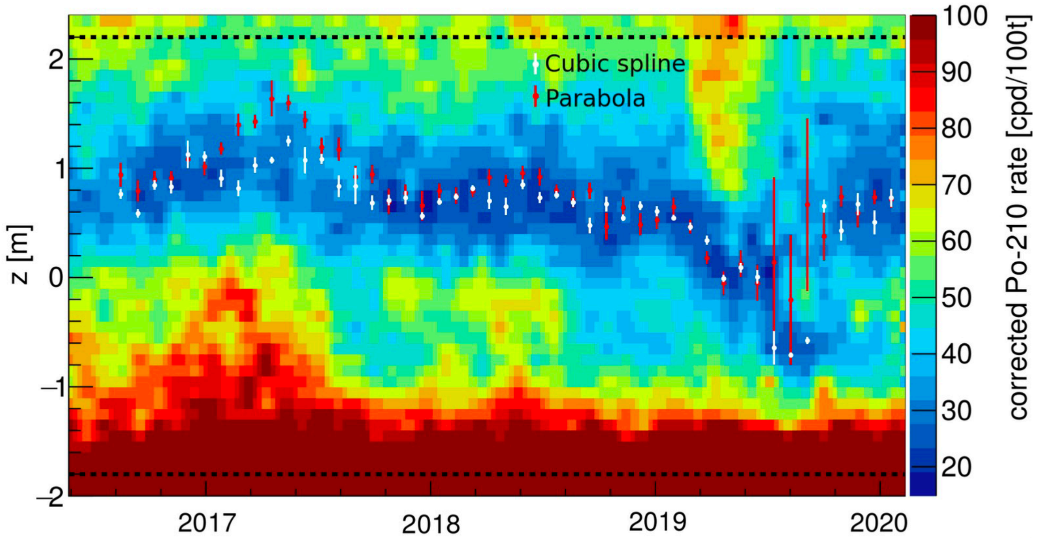


The low ^{210}Po "field" and ^{210}Bi upper limit

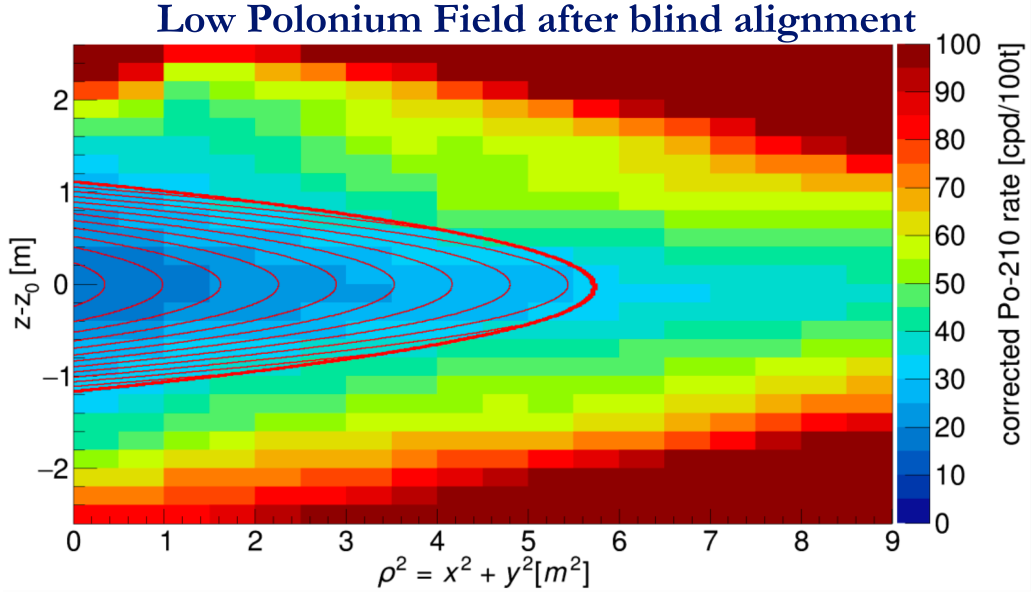


- The minimum is at **z = + 80 cm**
- From this minimum, we get an **upper limit on ^{210}Bi**
- To get a measurement, we would need to know that is a "true" minimum, which we cannot claim yet
  - **But we can claim observation !**

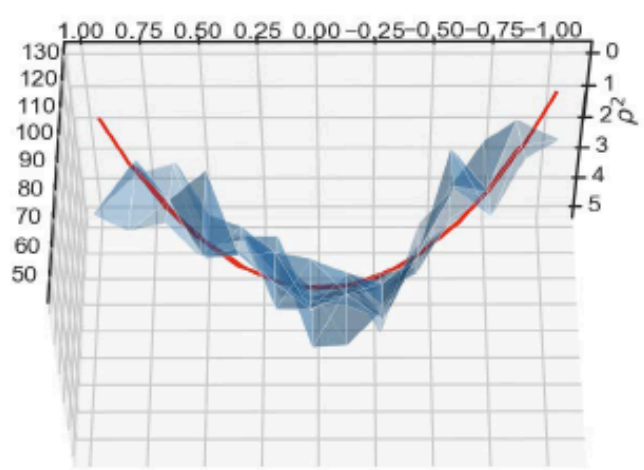
Evolution of the Low Polonium Field



Low Polonium Field after blind alignment

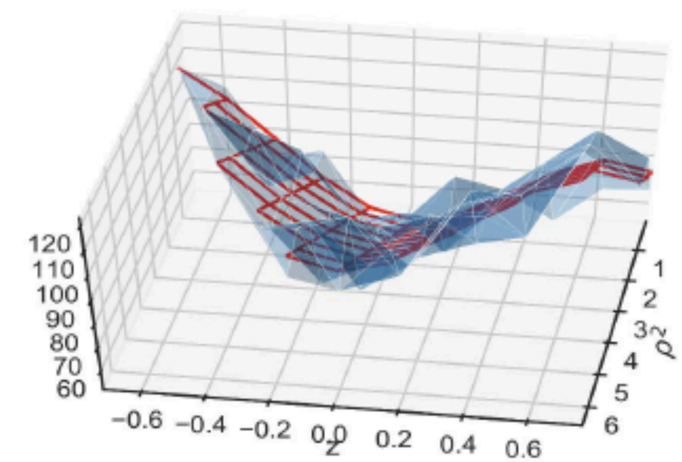


PARABOLOID



$$R_{Po} = R_{min\epsilon}\left[1 + \frac{\rho^2}{a^2} + \frac{(z - z_0)^2}{b^2}\right]$$

SPLINE FIT



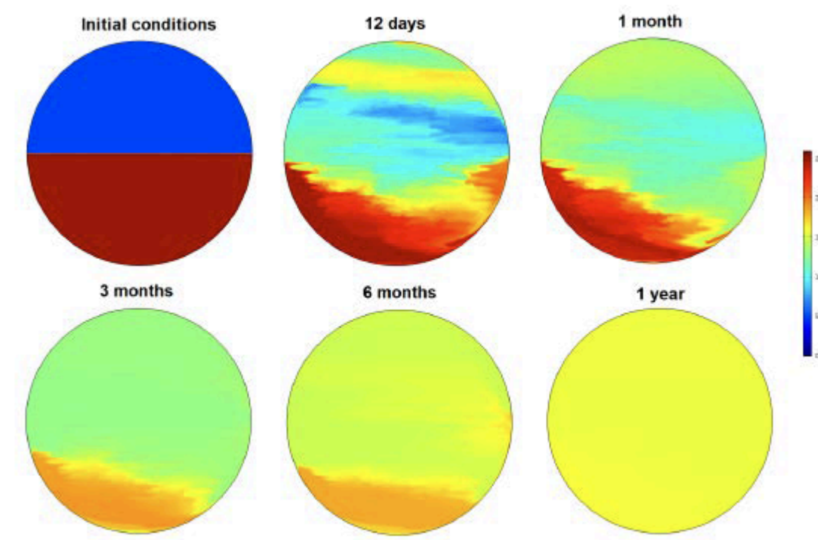
Two consistent methods for fitting the aligned LPoF and find the minimum

^{210}Bi < 11.5 ± 1.04 cpd/100t (stat+sys)

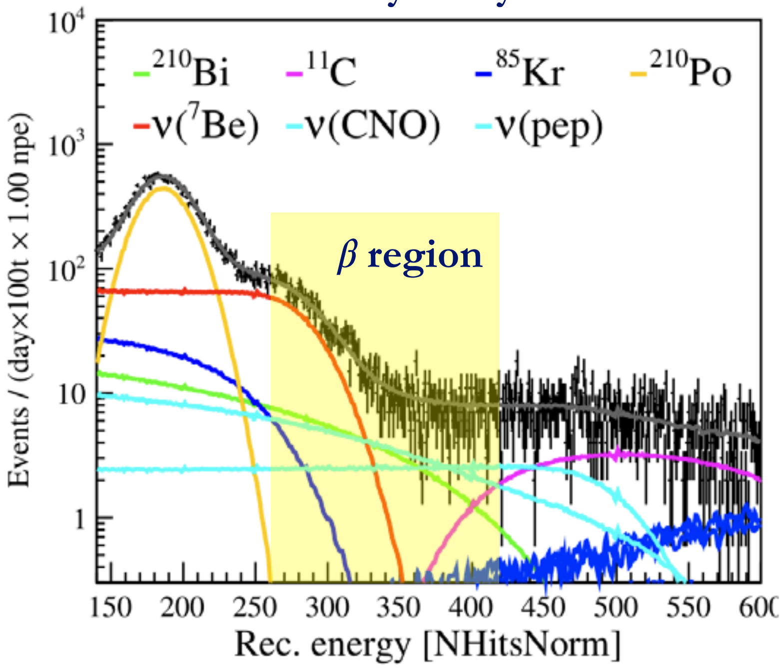
^{210}Bi uniformity and stability

- We got the ^{210}Bi upper limit in the LPoF over a short period of time
  - BUT: **CNO fit must be done on the whole FV and more data**
- **OK if you prove that ^{210}Bi (i.e. ^{210}Pb) is stable and uniform**
  - **Stability:** checked by looking at "β region" over time
    - No evidence of change of ^{210}Bi component (i.e. ^{210}Pb leaching from IV)
    - Small variations attributed conservatively to ^{210}Bi
  - **Uniformity:** angular and radial distributions carefully studied
    - Uniform within error. **0.78 cpd/100t** added to error.
    - Fluid dynamics confirms it

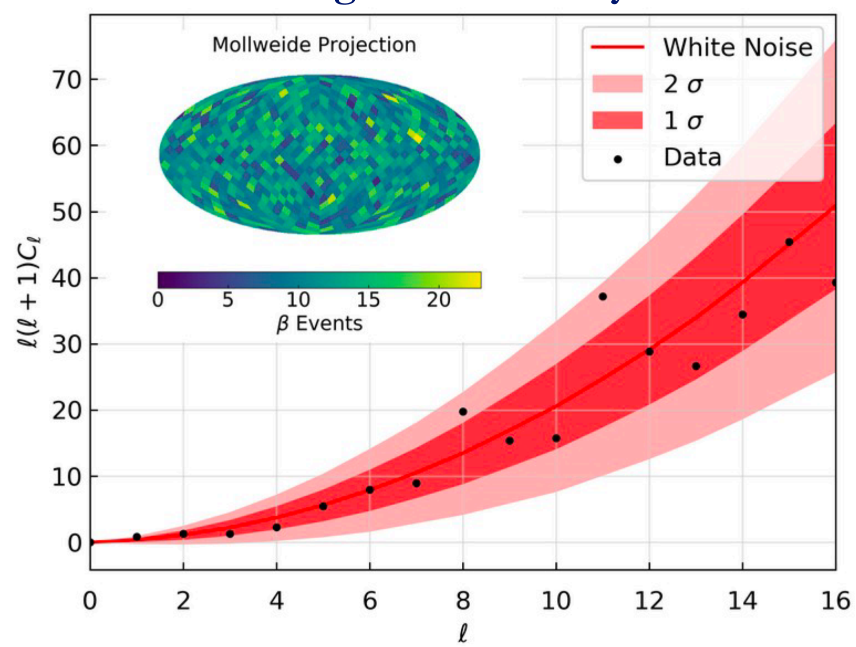
Full uniformity reached in 1 y [3D simulation]



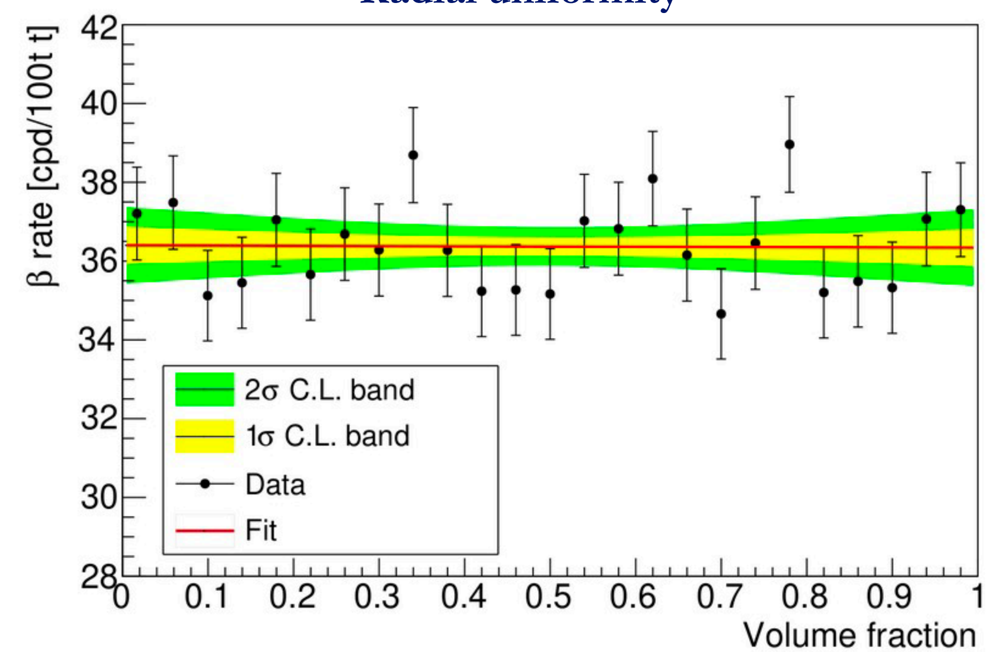
Stability study



Angular uniformity



Radial uniformity

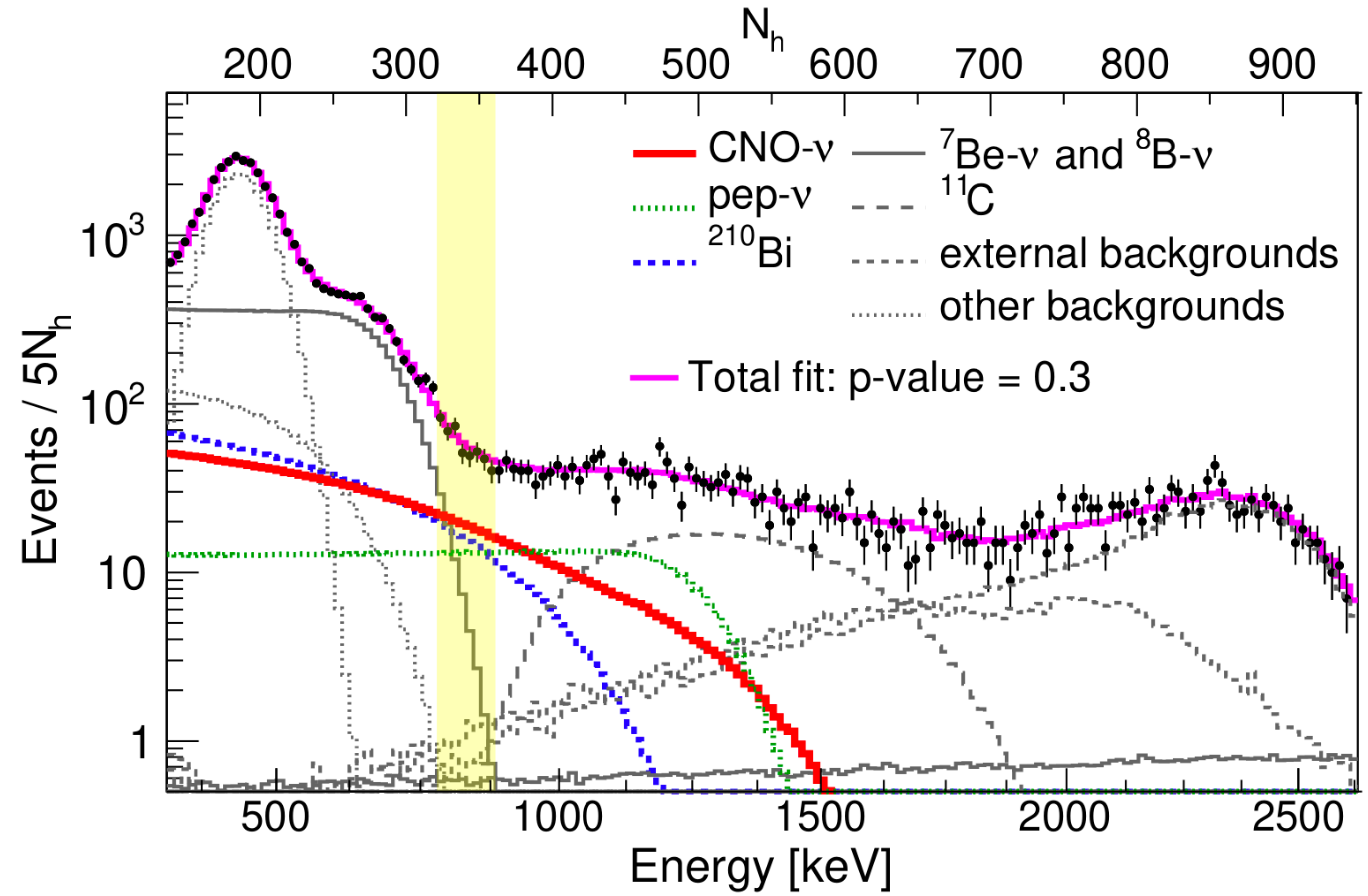


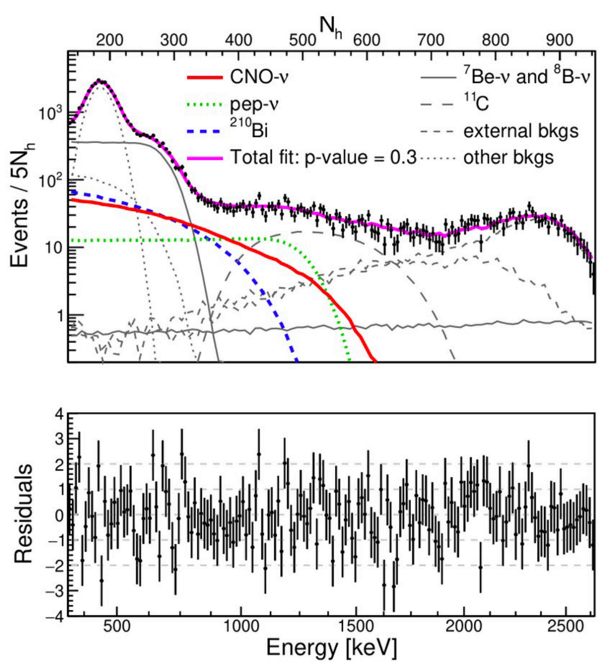
- The final constraints that **breaks degeneracy** with CNO:

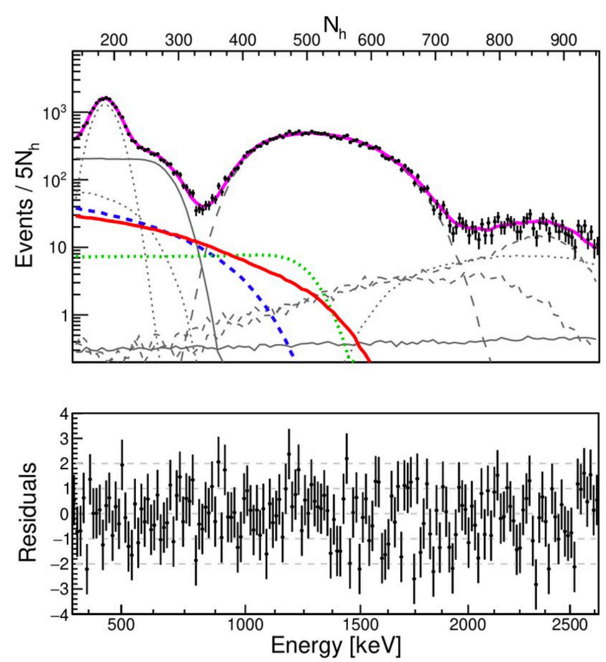
^{210}Bi < 11.5 ± 1.3 cpd/100t

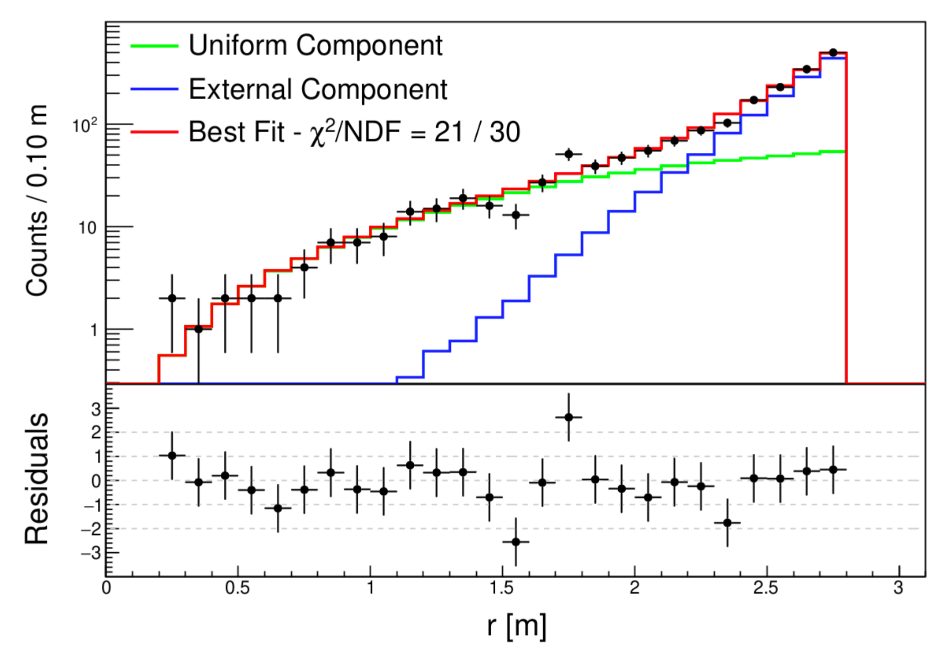
CNO analysis and multi-variate fit

- Key elements
  - pep symmetric penalty from luminosity: ± 1.4 %
  - ^{210}Bi asymmetric penalty (upper limit): 11%
  - Multivariate fit on MC distributions using:
    - Spectrum
    - TFC subtracted spectrum
    - Radial distribution
  - Cross check with simple counting analysis and analytical fits (confirming results)



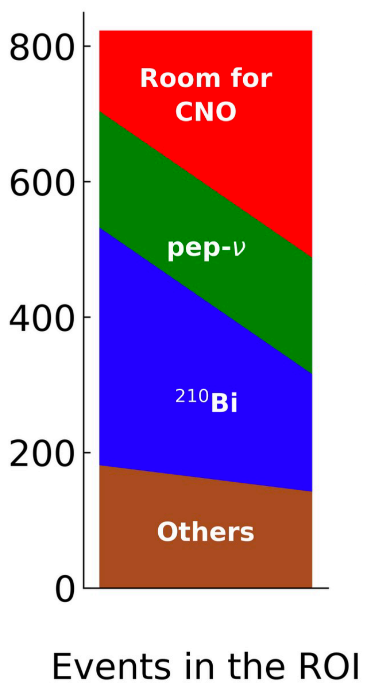


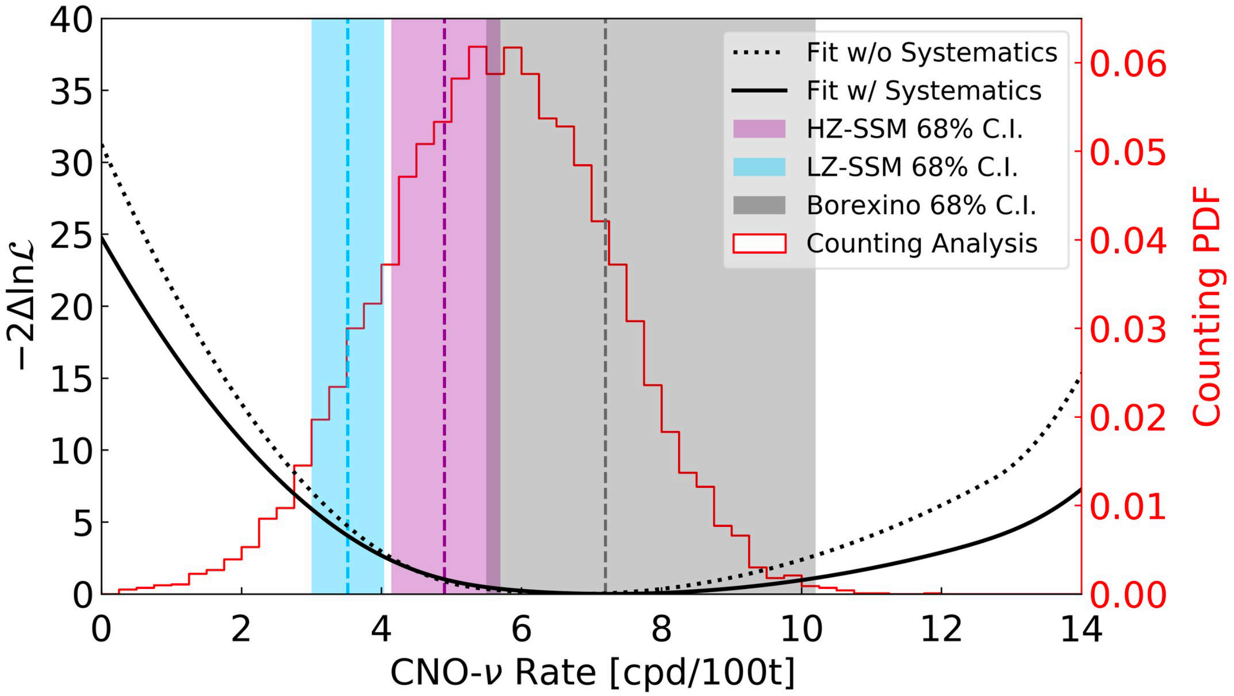




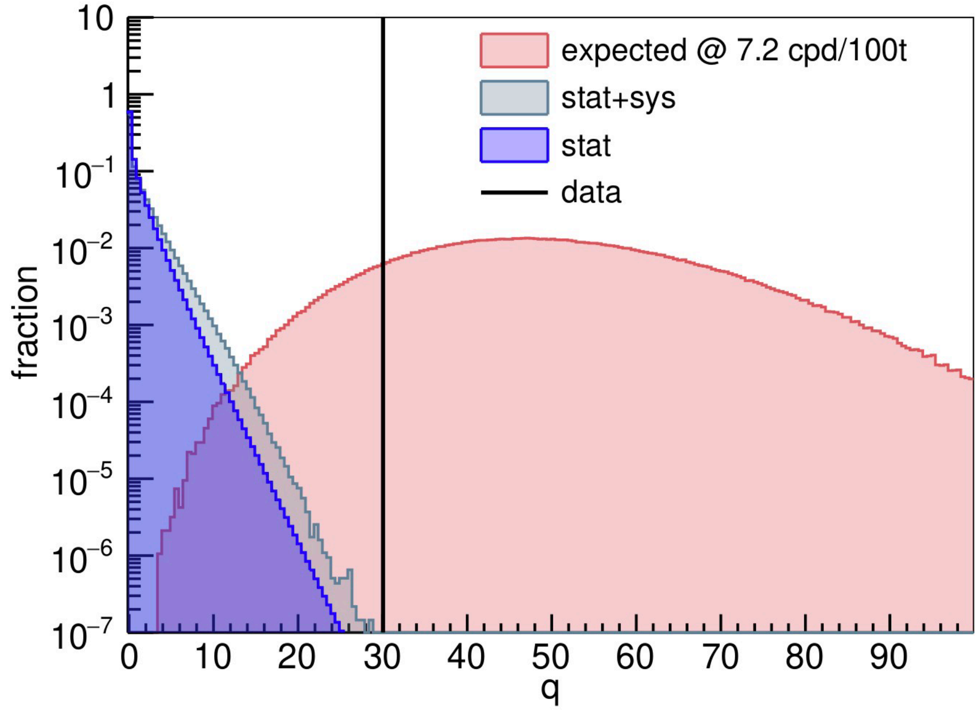
Result (68% CL stat) 7.2 - 1.7 + 2.9 cpd/100t

Final result: observation of CNO





Result (68% CL stat + sys) = 7.2 - 1.7 + 3.0 cpd/100t



CNO in [5.5 - 10.2] cpd/100 t (68% CL)

- Systematics:
  - Response, resolution, spectral shapes and
  - LY: σL = -0.5, σR +0.6 (5.1 σ significance)
- Significance
  - Hypothesis test with 13.8 x 10^6 pseudo-experiments
  - Hypothesis CNO=0 excluded at 5.0σ (99%CL)
- Model compatibility
  - \- 0.5σ (HZ)
  - \- 1.3σ (LZ)
  - \- LZ disfavoured at 2.1σ including other
- Fluxes from pp-chain (Borexino only)

Conclusions

- It's been a **long journey,** with a hard beginning, a nice "crescendo" of beautiful results, and a great final!
  - All solar neutrino components (except *hep*) either discovered or measured
    - **MSW test** through the ***pp chain***
    - Precise test of the standard solar model
    - **CNO neutrinos!**
  - A clean measurement of **geo-neutrinos,** free of reactor background
  - Some interesting upper limits of rare events (not covered in this talk)

- After **30 years** since the beginning, Borexino will be drained in 2021
  - **Leaving a precious heritage,** as I hope I did convince you today.

- We could not make SOX, very unfortunately, but that is science.

- **It was a fantastic journey**

THANKS !!!