Solar Neutrinos from CNO cycle and most recent results from Borexino

Virtual La Thuile via ZOOMLand
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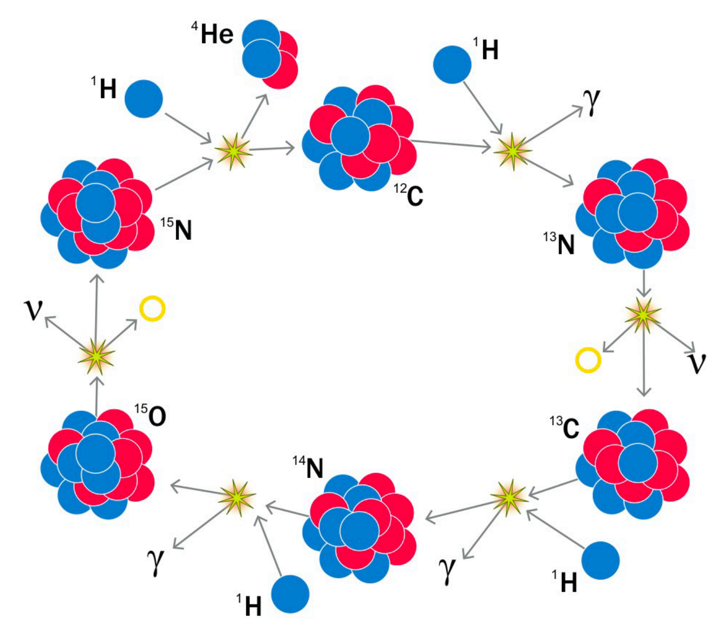
Talk overview

- **Science**
  - Solar (and geo) neutrinos

    Not covered, sorry

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

- **Results**
  - The ***pp chain*** and the **MSW mechanism**
  - The ***CNO cycle***
    - Challenges, Strategy, Results

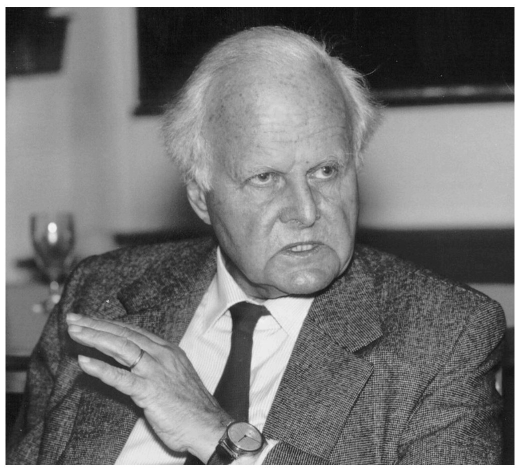


- Conclusions and prospectives

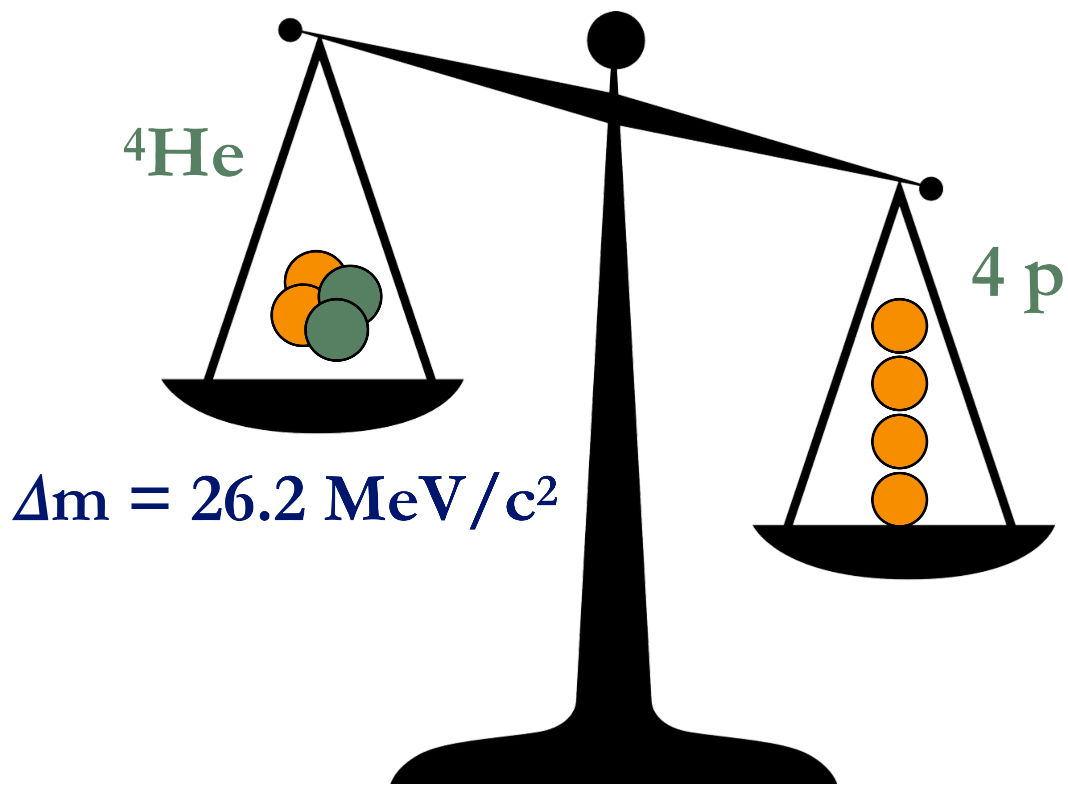
Stars energy source

- 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

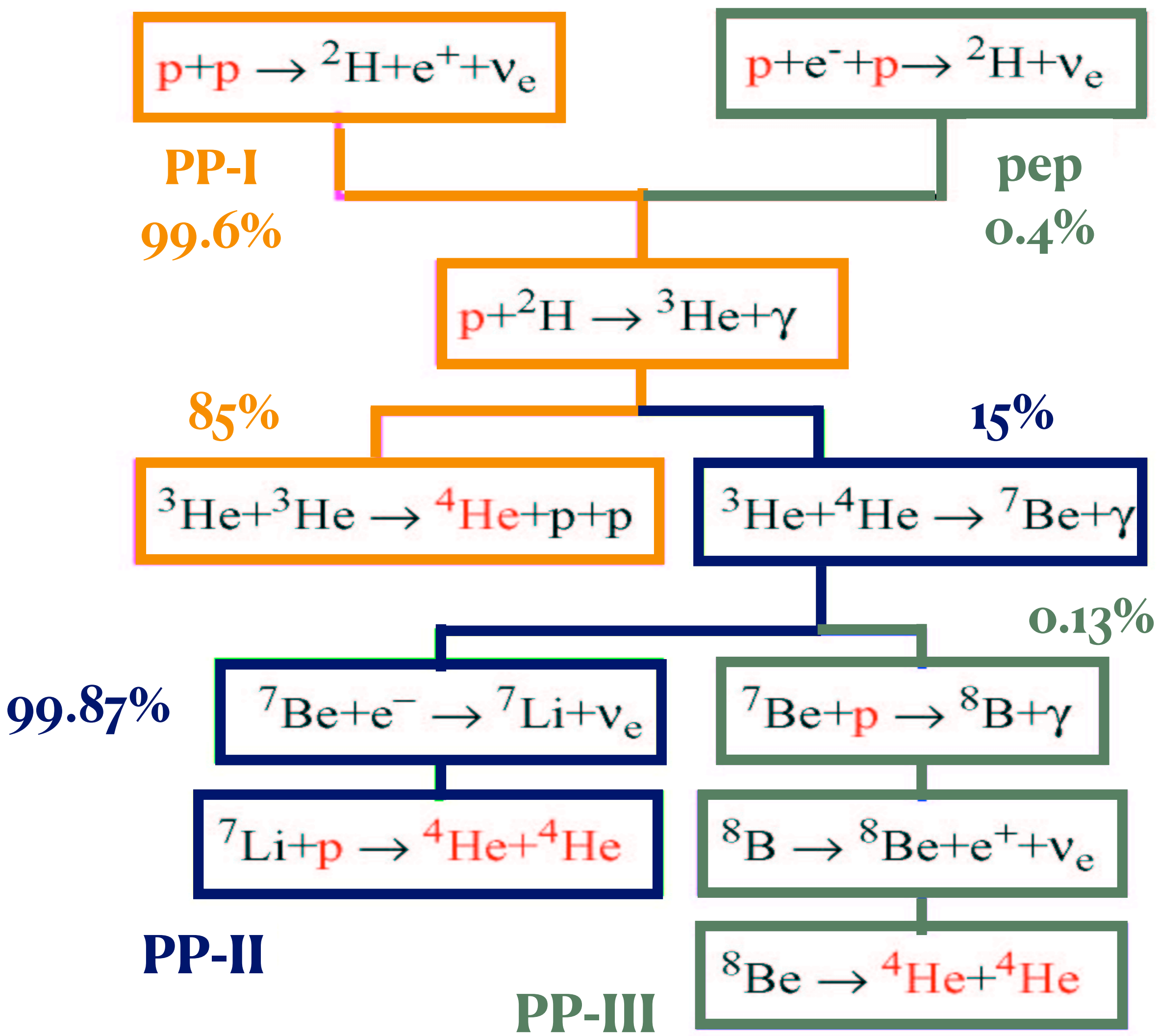
- Initially, CNO was (wrongly) believed to be dominant in the Sun because of the poorly known solar core temperature

Solar neutrinos from hydrogen burning

pp chain

(99% energy)

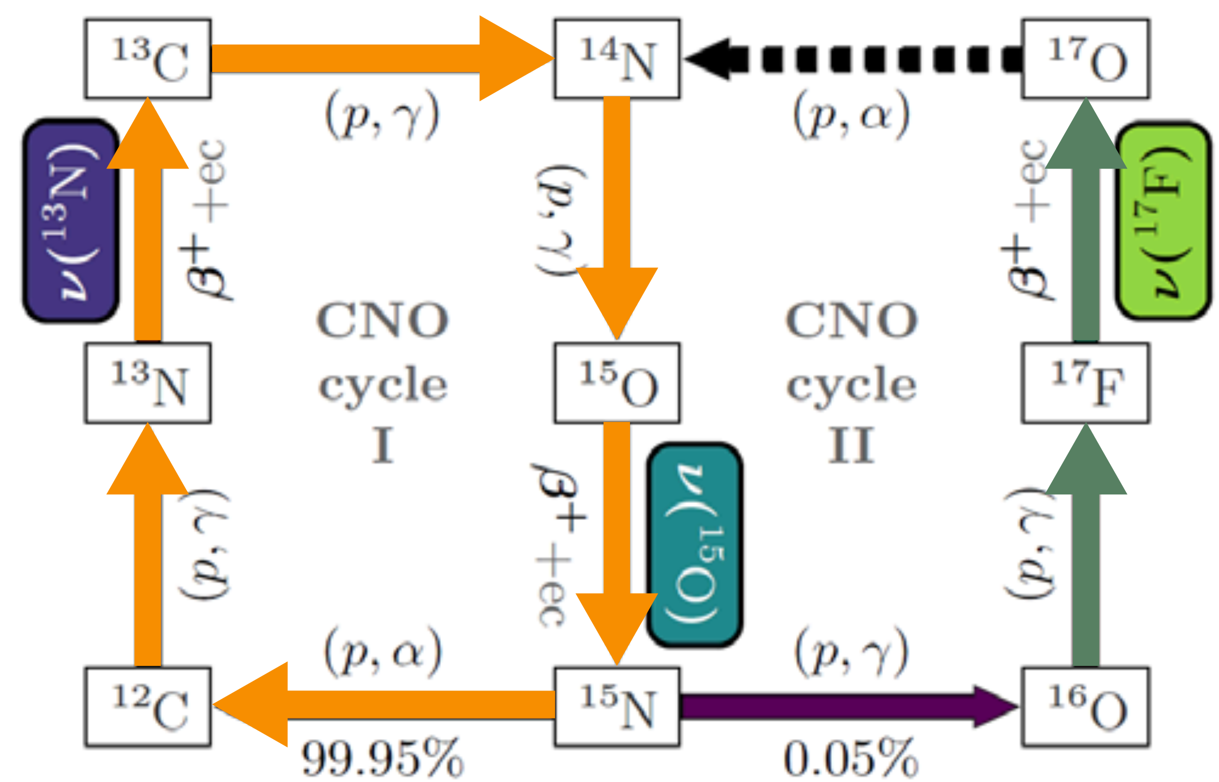
Bethe & Critchfield 1938



CNO cycle

(~ 1% energy)

Weizsäcker (1937, 1938), Bethe (1939)



^{12}C is the main catalyst

CNO-II is suppressed in the Sun

REACTION

$$4p \rightarrow {}^{4}He + 2e^{+} + 2\nu_e$$

ENERGY YIELD

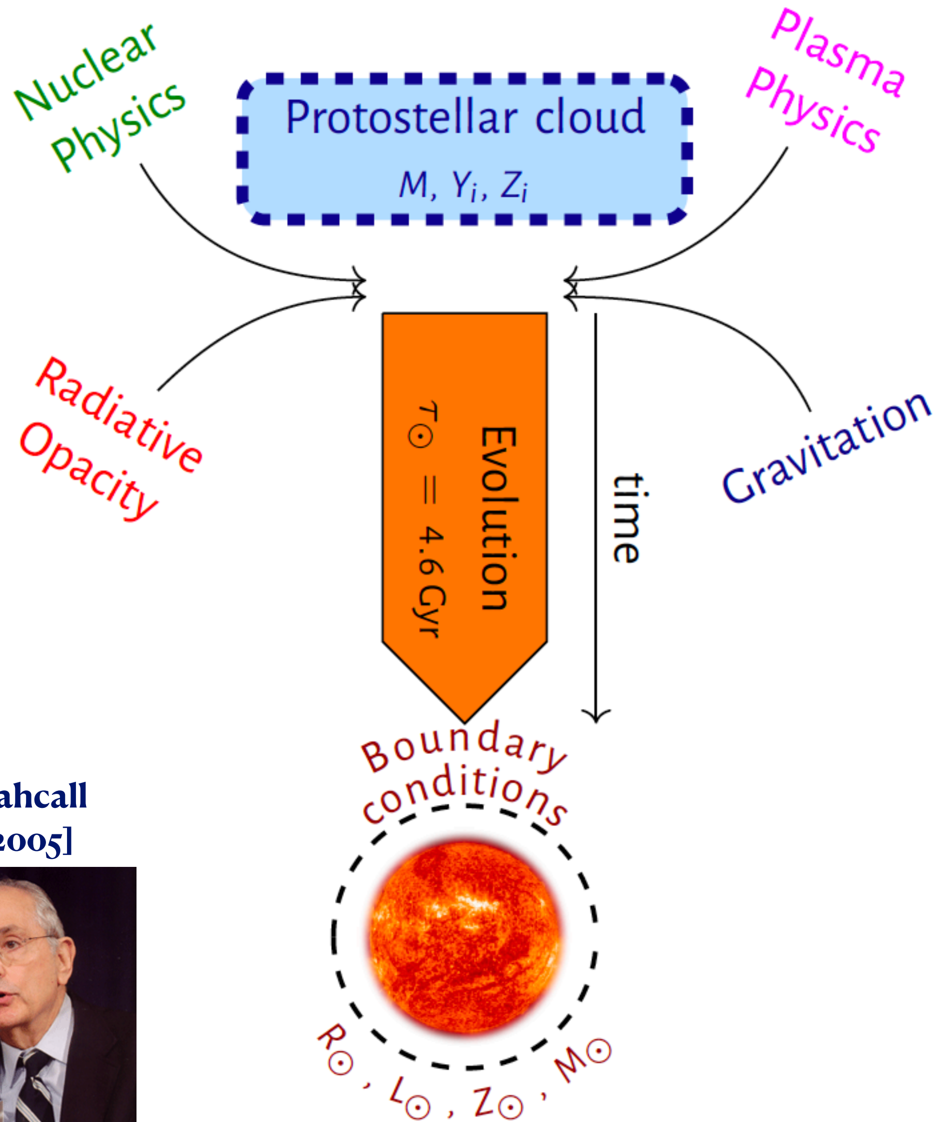
$$24.7\ MeV + 2m_e c^2$$

2% of E in NEUTRINOS

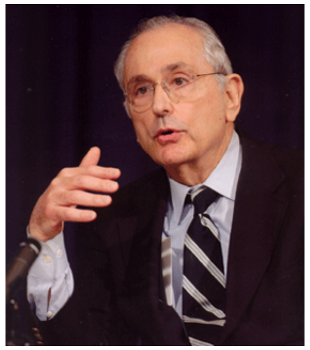
$$< E_\nu >= 0.53\ MeV$$

The Standard Solar Model

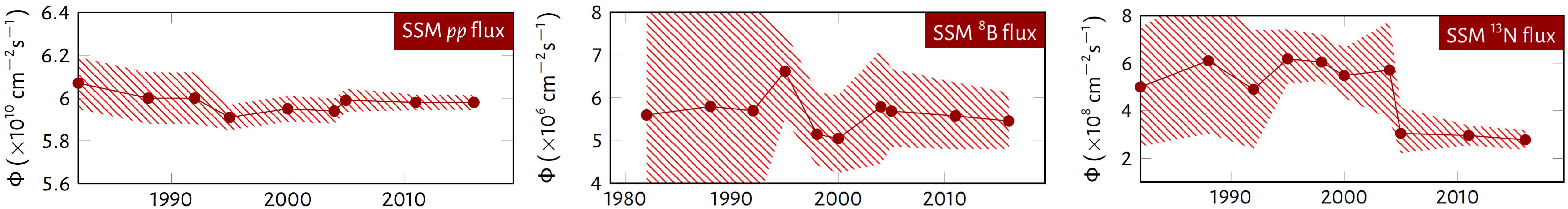
- **The observable is the Sun we see now,** which depends on a **complex evolution process**
  - Gravity
  - **Composition**: X (hydrogen), Y (helium), , Z (“metals”)
  - Radiative **opacity** and plasma physics
  - Temperature and density profiles
  - Energy transport: radiative until 0.71 $R_\odot$,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



John Bahcall [1934-2005]

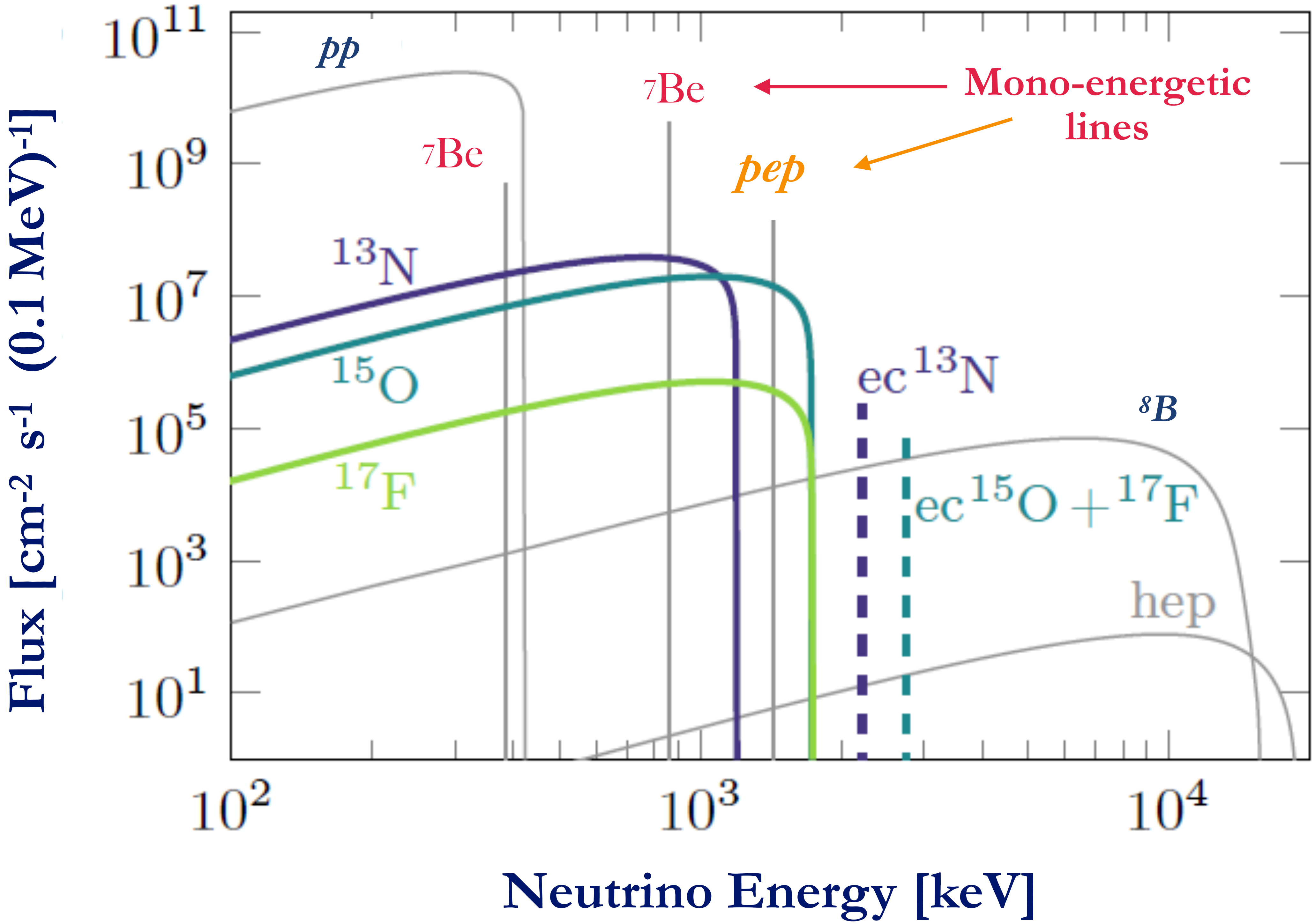


- The model as well has evolved (better cross sections, opacity and diffusion models)



Neutrino spectrum from the SSM

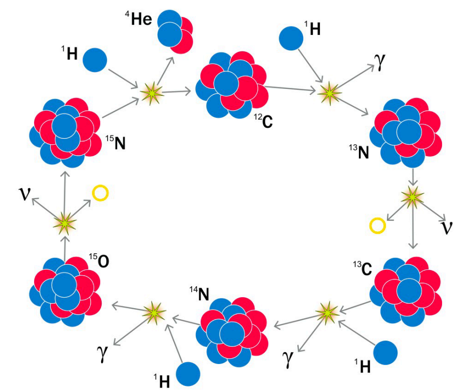
$L_\odot = 3.846 \pm 0.015\ 10^{26}$ W

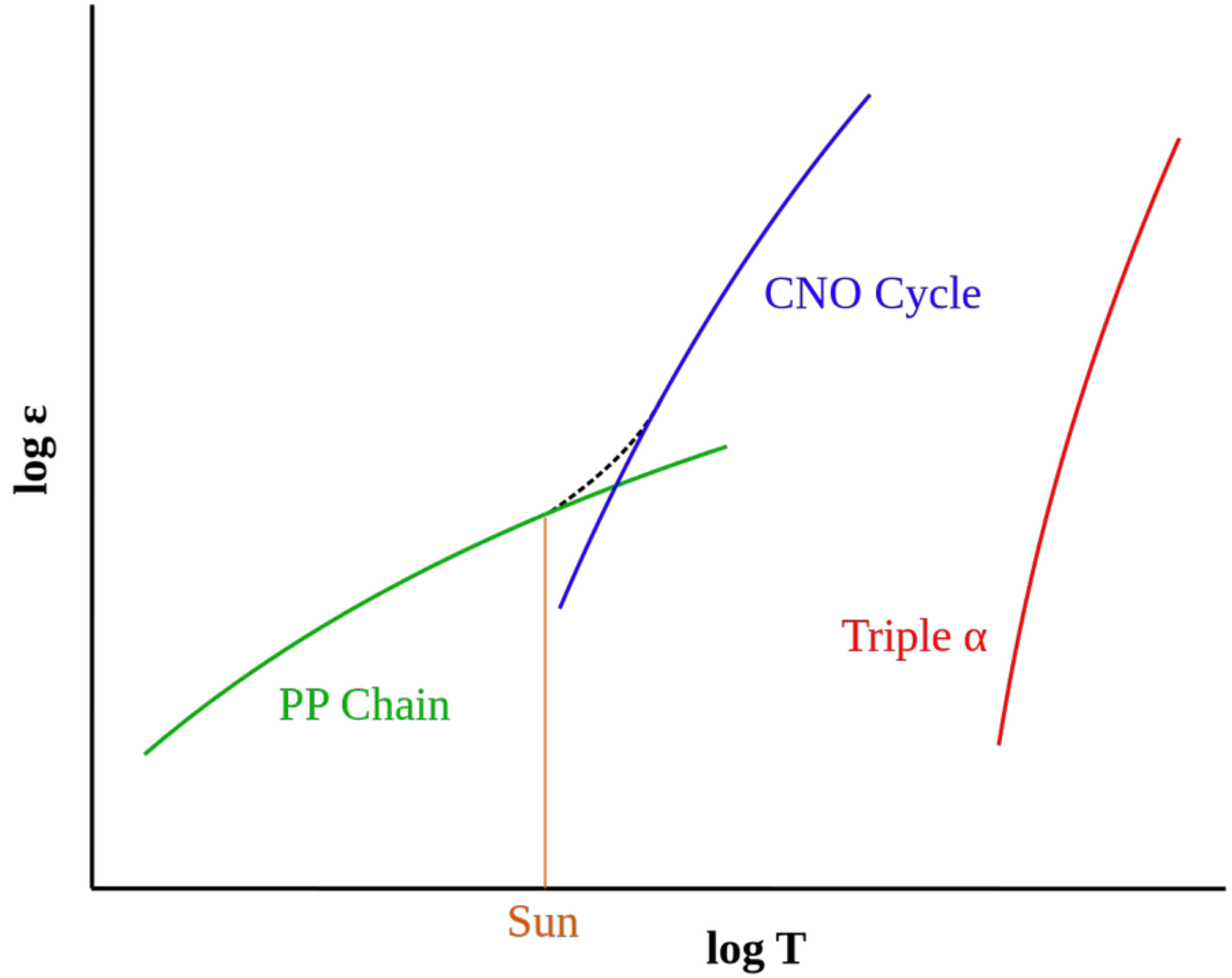


N. Vinyoles et al., The Astrophysical Journal (2017), 835:202 Feb. 1st. doi:10.3847/1538-4357/835/2/202

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")**



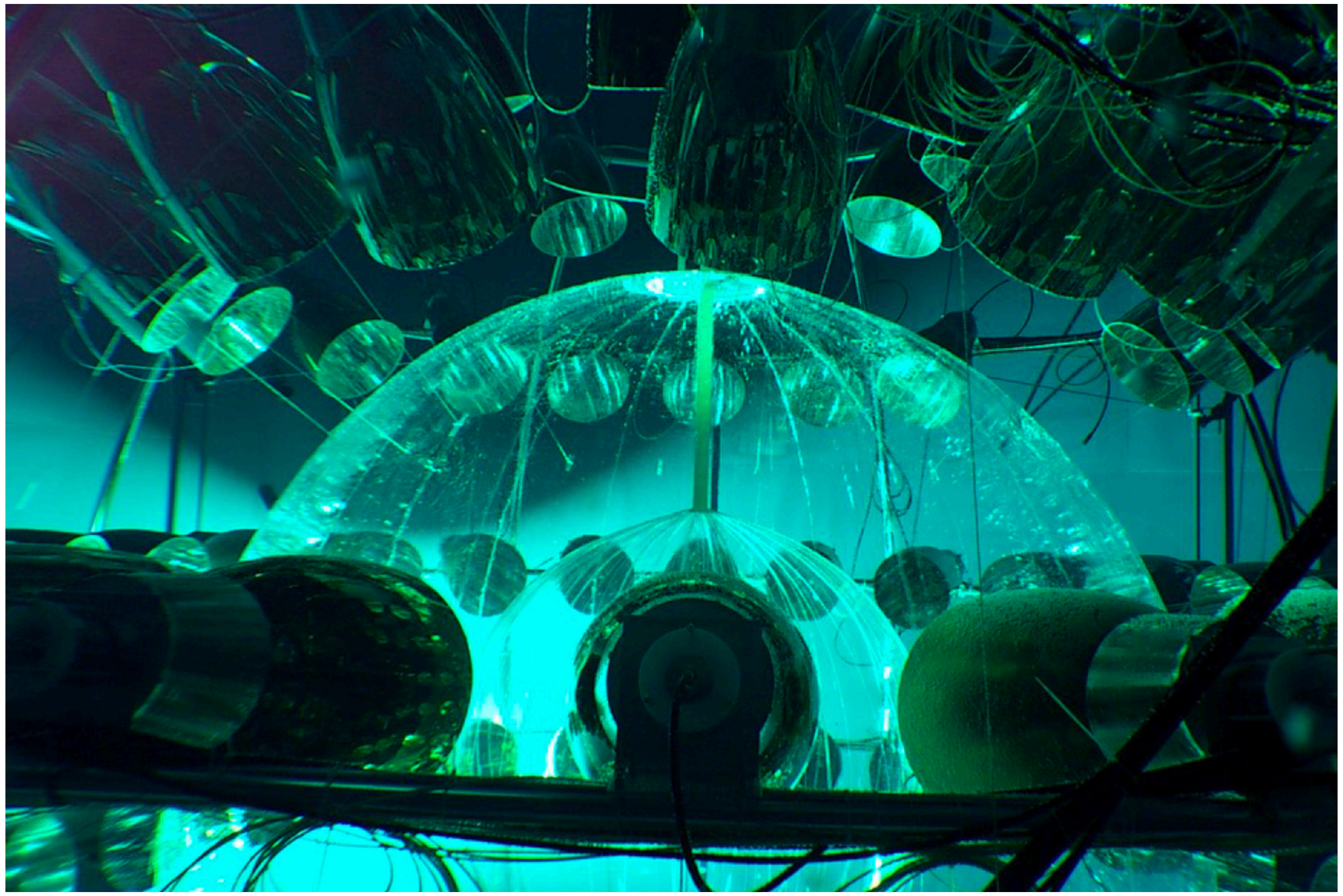


The CNO cycle is the most important mechanism of **hydrogen burning** of the Universe

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!

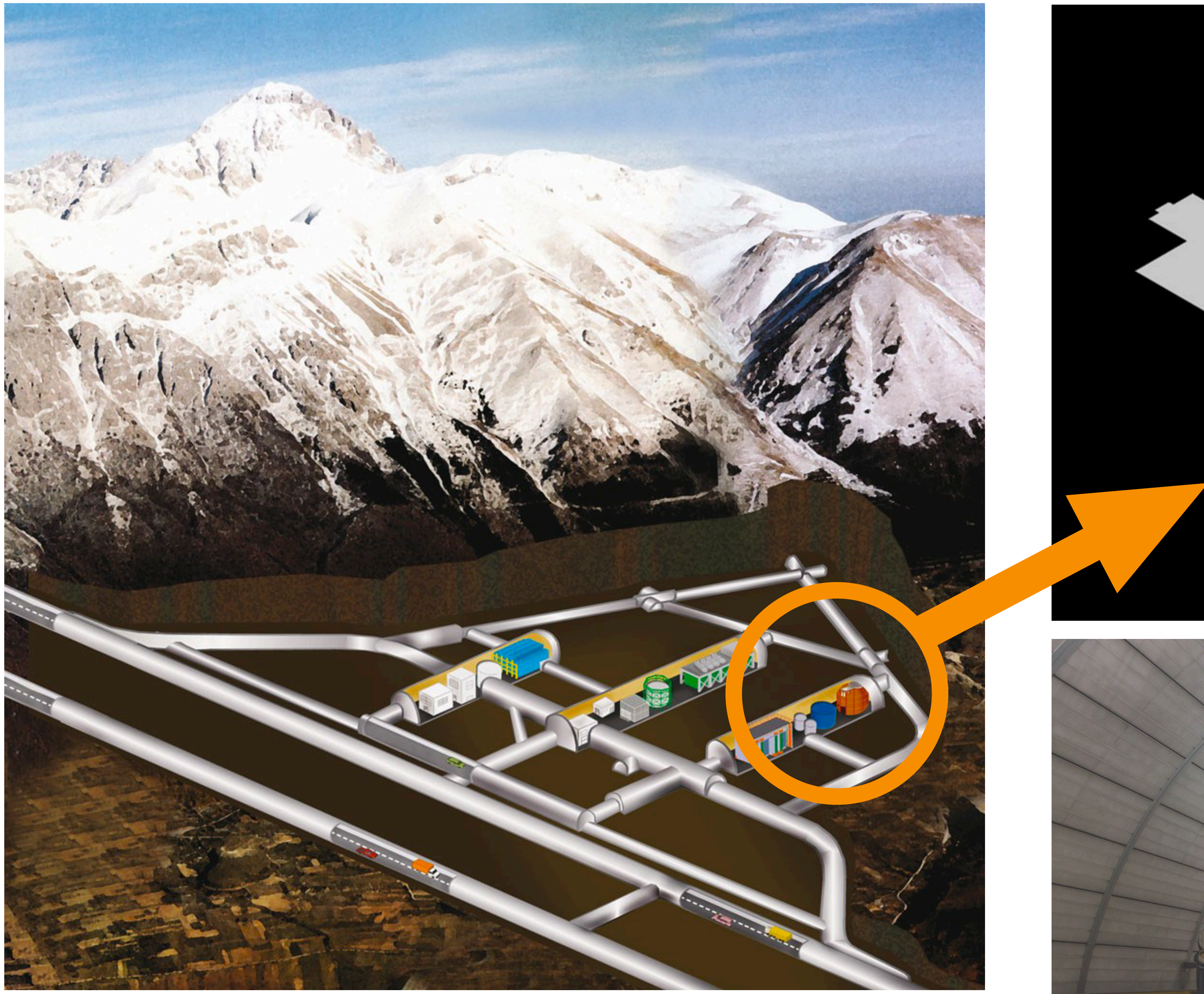
The Counting Test Facility at LNGS

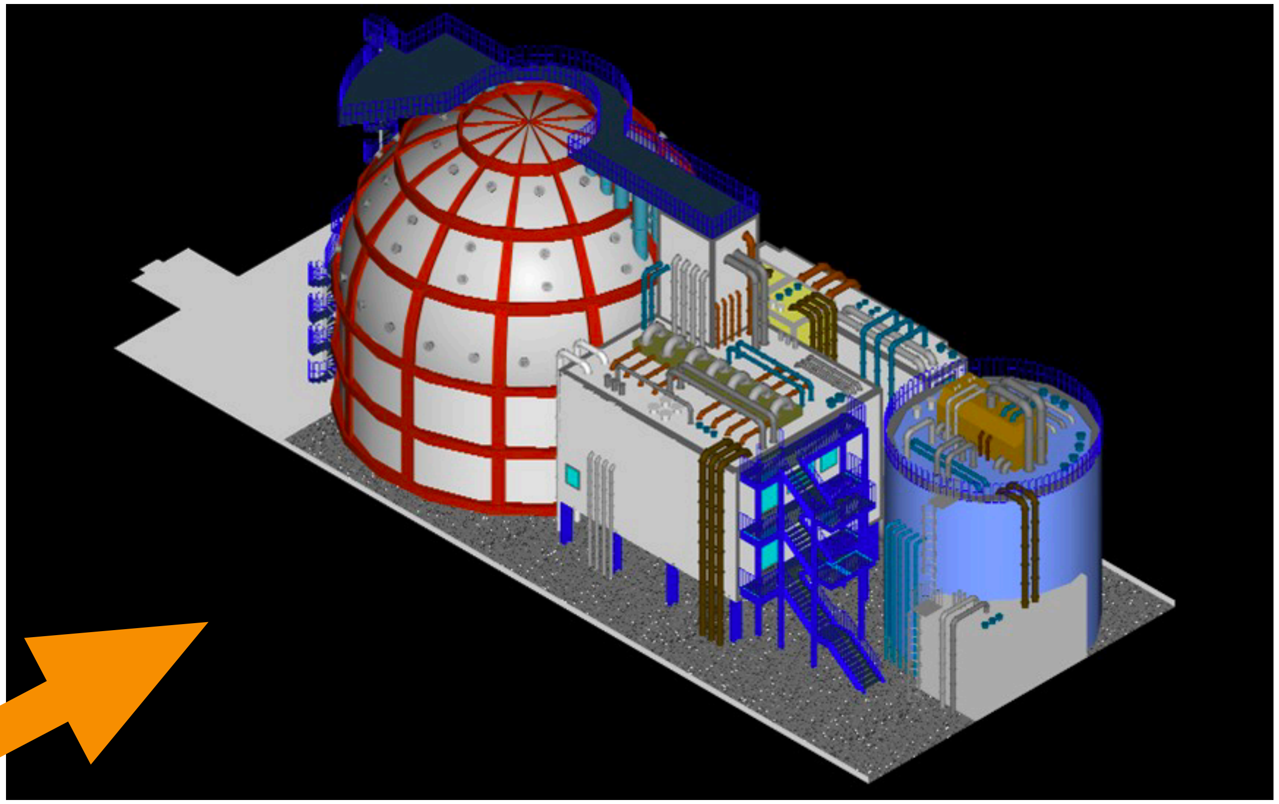


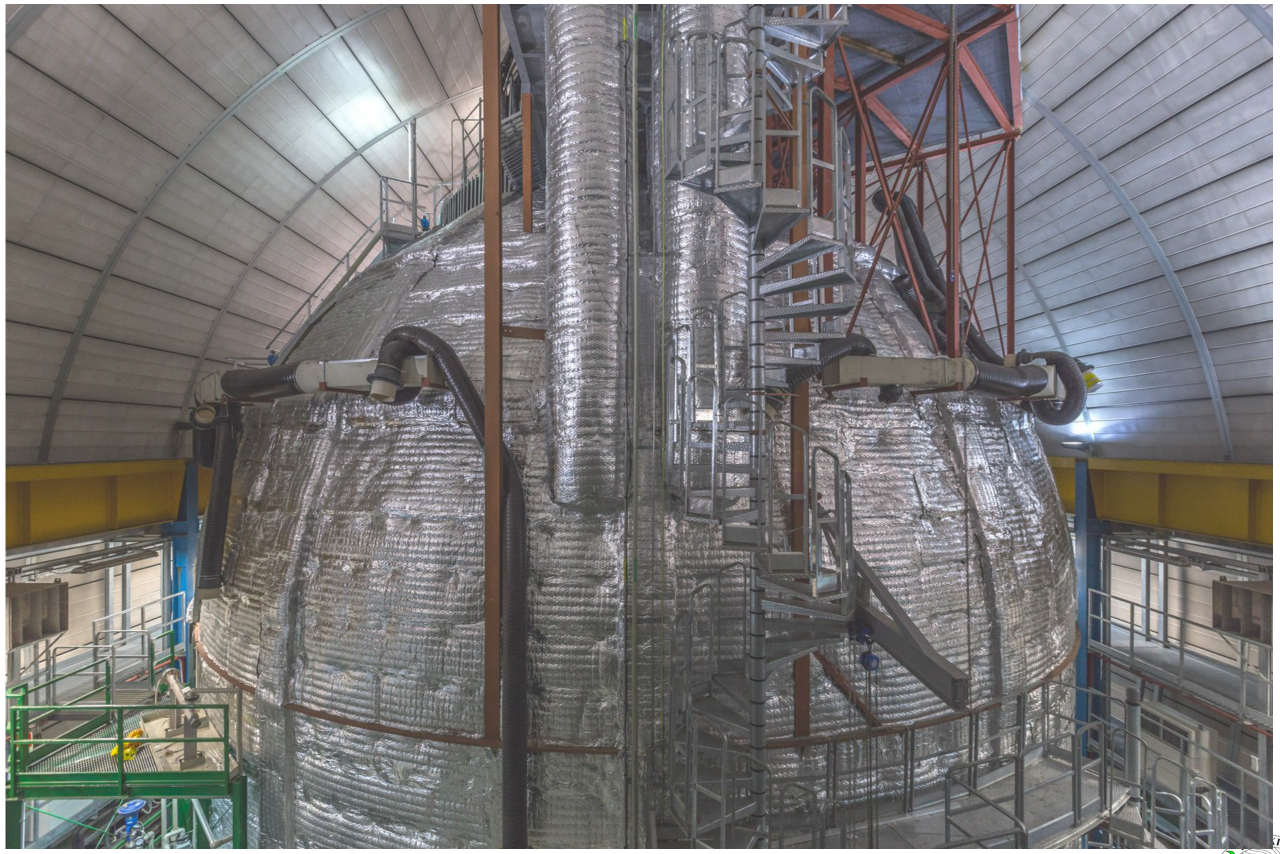
- **1992-1995:** prototype and R&D
- **1995:** the CTF at LNGS proves that Borexino can be done !
  - Record radio-purity was measured (at that time):
    - **^{238}U and ^{232}Th below 10^{-16} g/g**
    - **^{14}C/^{12}C below 10^{-18}**
- **1996-2007:** construction, with great care, and some environmental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

Founders

Borexino location



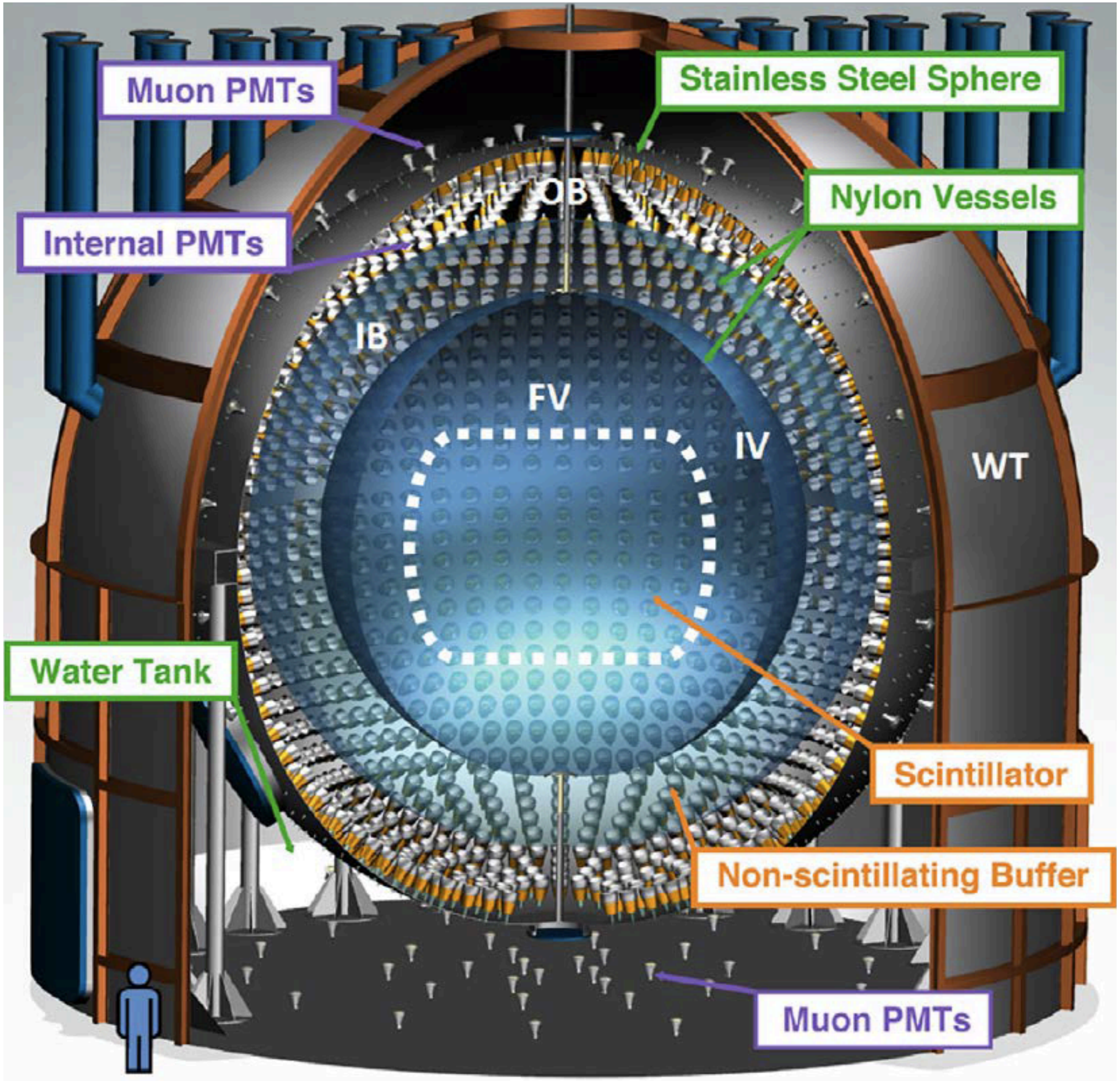




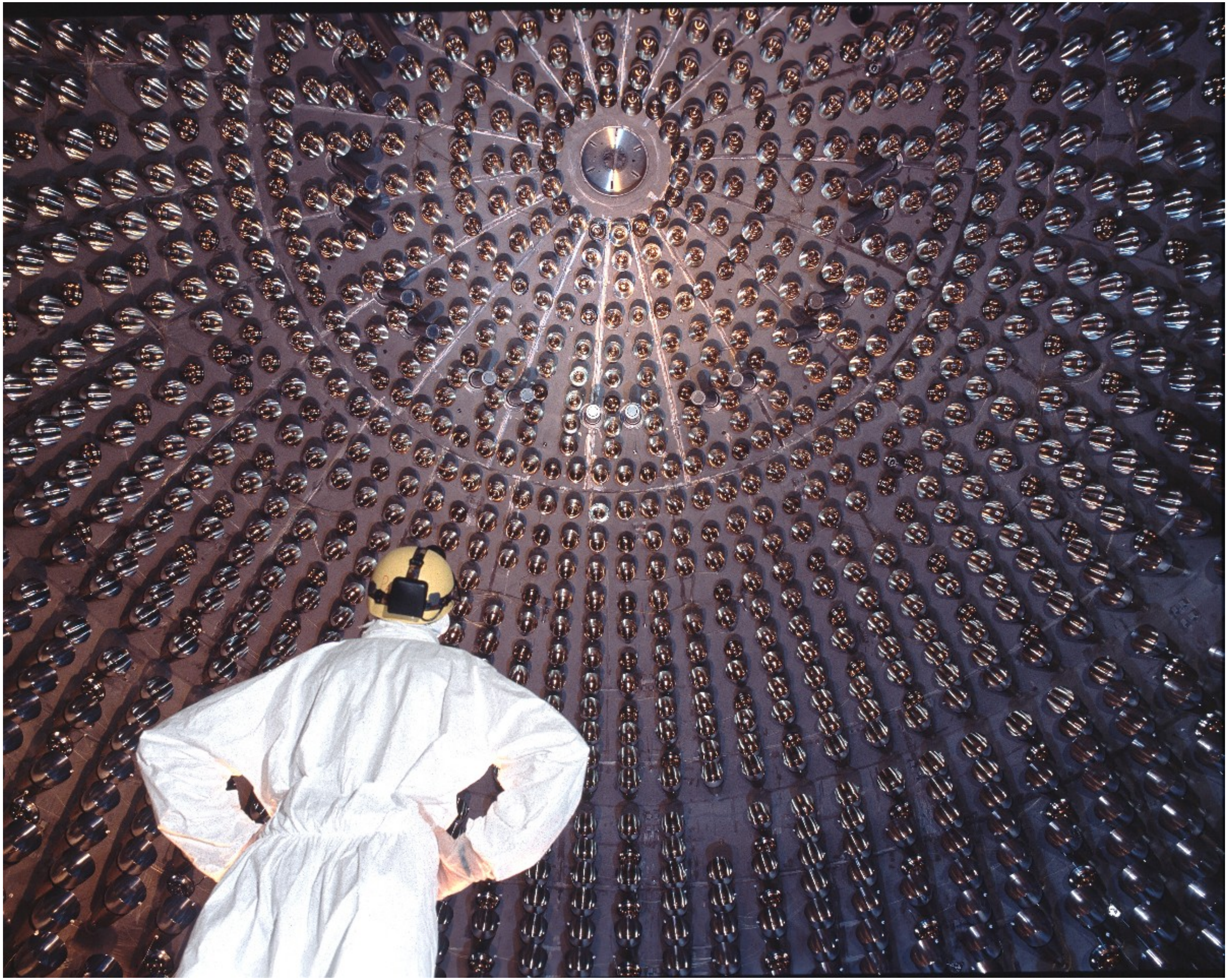
Laboratori Nazionali del Gran Sasso
(Hall C)

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

The detector

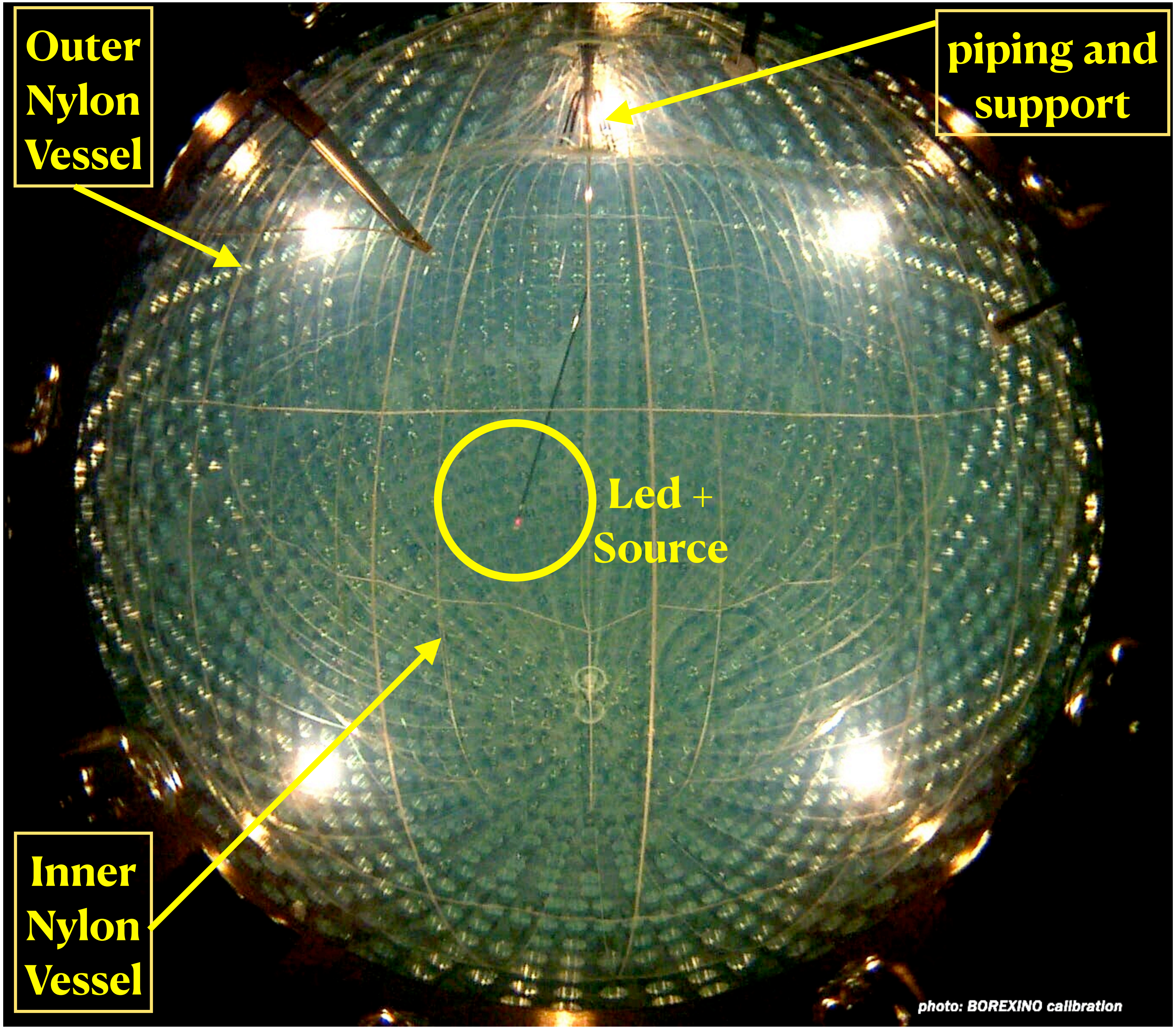


Internal view, empty



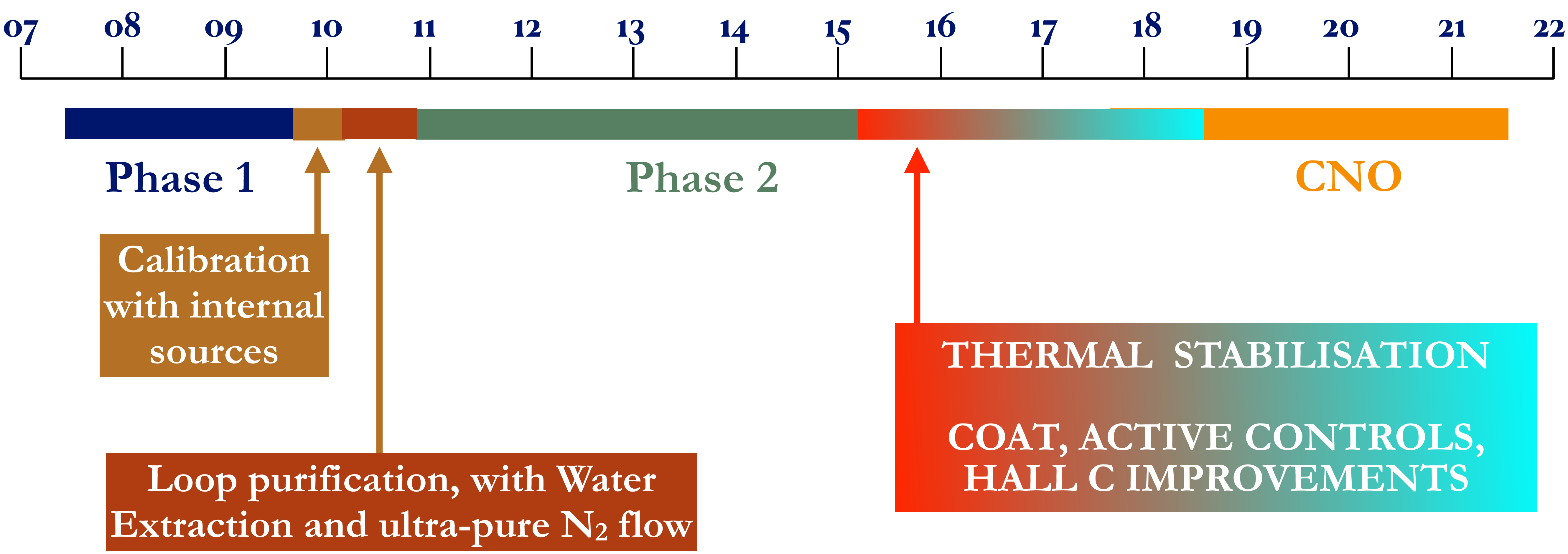
Internal view: inflated vessels (with N_2)

Internal view, filled, during calibration in 2009



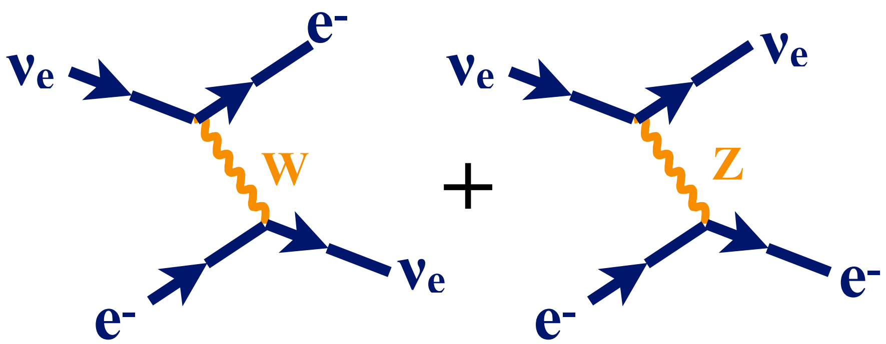
2007-2020

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

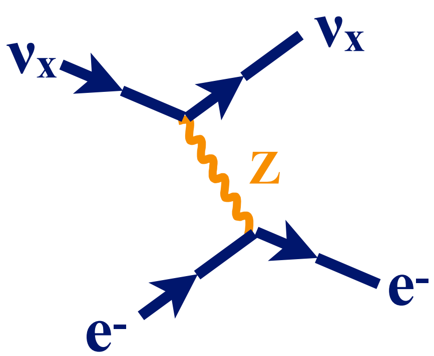


Neutrino detection in Borexino (I)

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

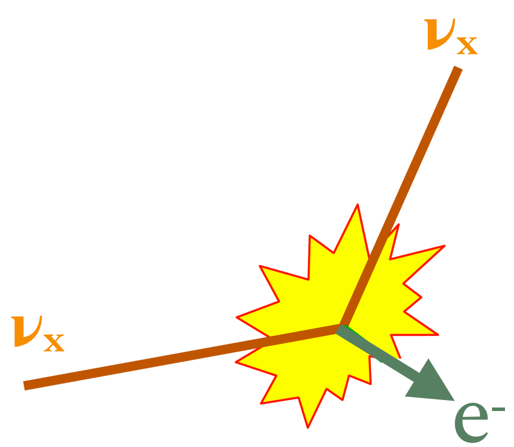


$$\xi = \sin^2\theta_W \simeq 0.23$$



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

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

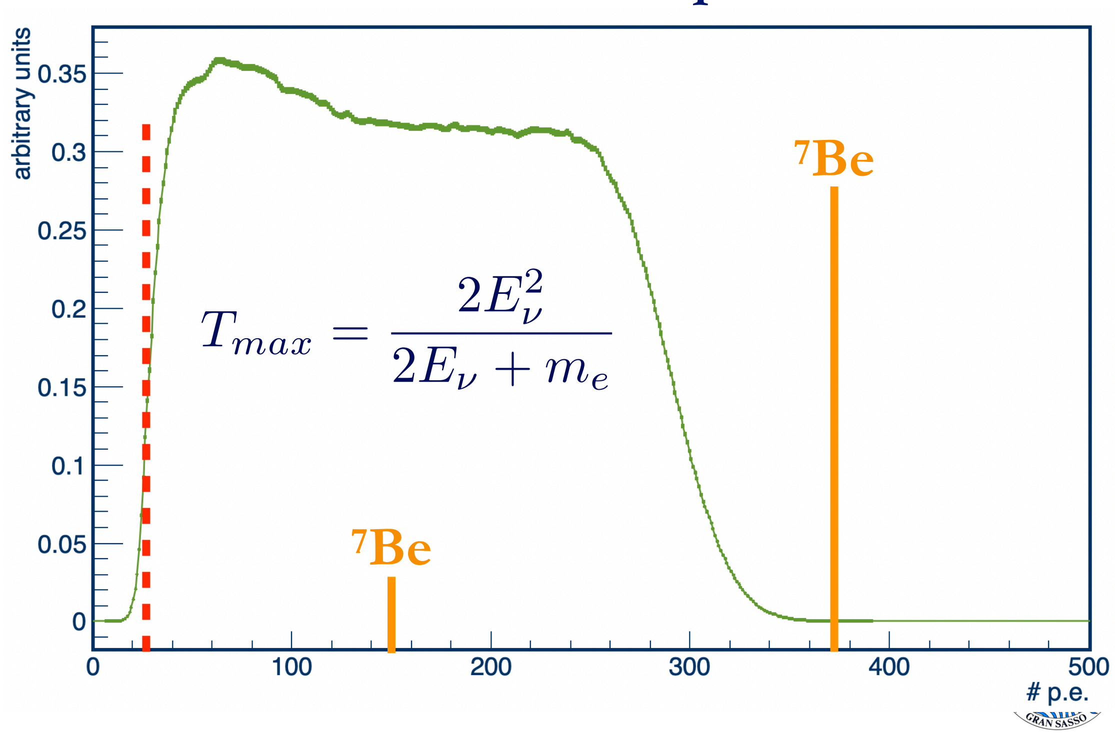


$$\sigma(\nu_x e^-) = \frac{G_F^2 s}{\pi}\left[\left(\frac{1}{2}-\xi\right)^2+\frac{\xi^2}{3}\right]$$

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

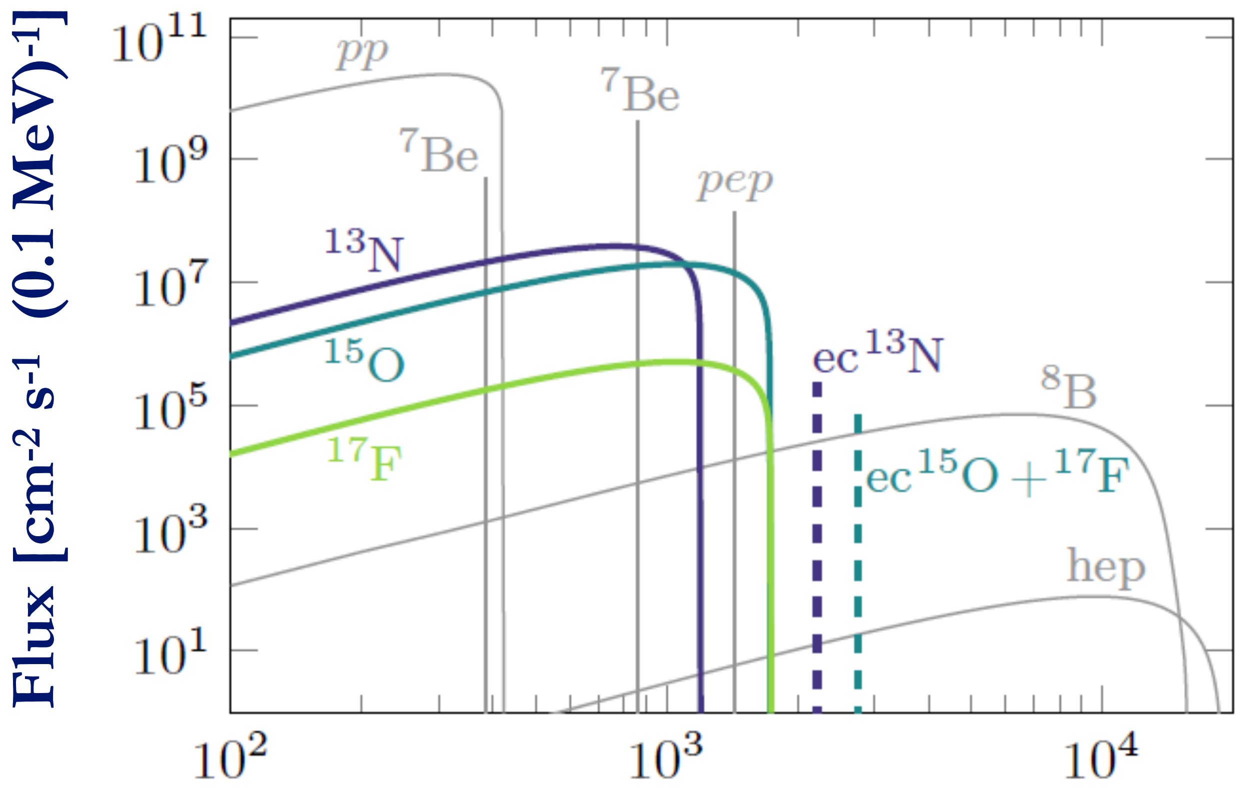
- The e⁻ is scattered in the **liquid scintillator:**
  - **path:** **few mm**
  - **physics thresh.:** **very small**
  - **triggering thresh.:** **~40 keV** (dep.)
  - **analysis thresh.:** **~ 200 keV**

SIGNATURE: 'Compton' shoulders

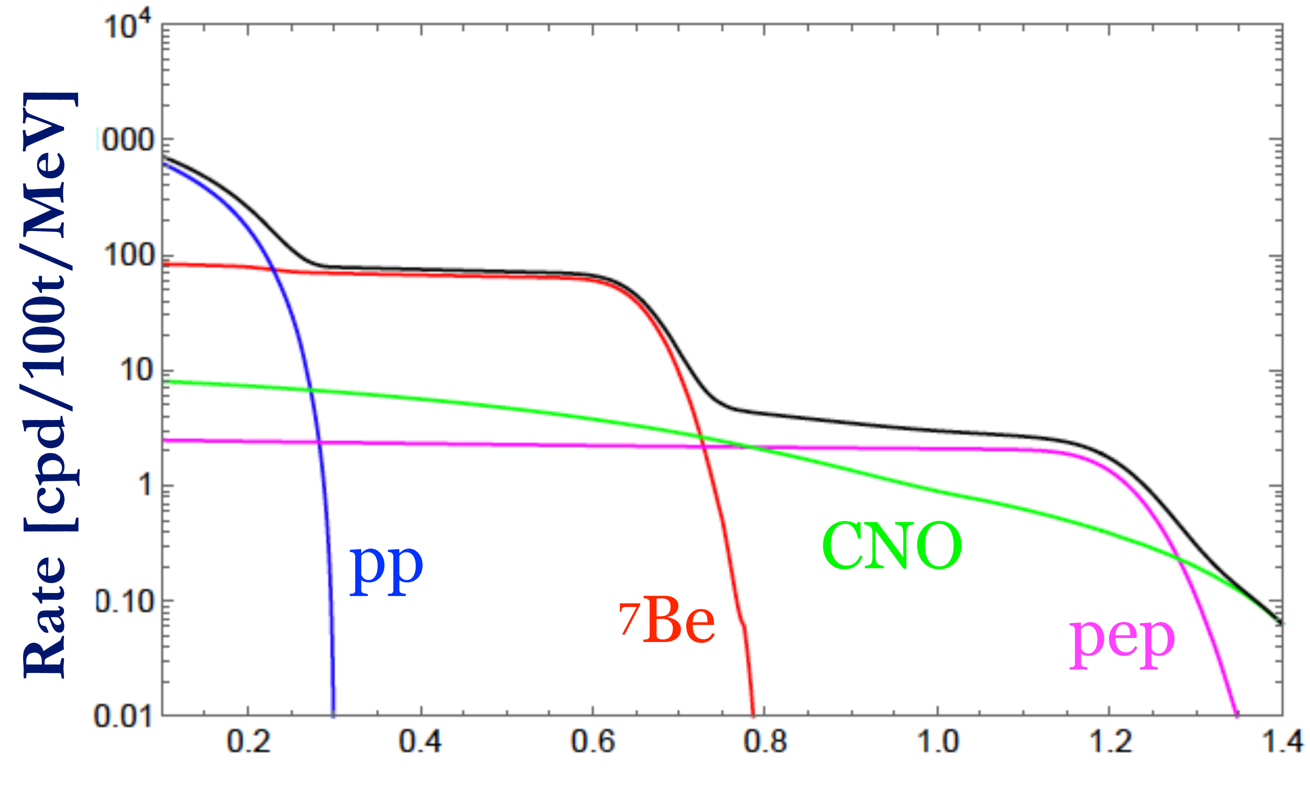


Neutrino detection in Borexino (II)

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

Fighting backgrounds

- Quasi-point-like energy deposits mimic neutrino events

EXTERNAL

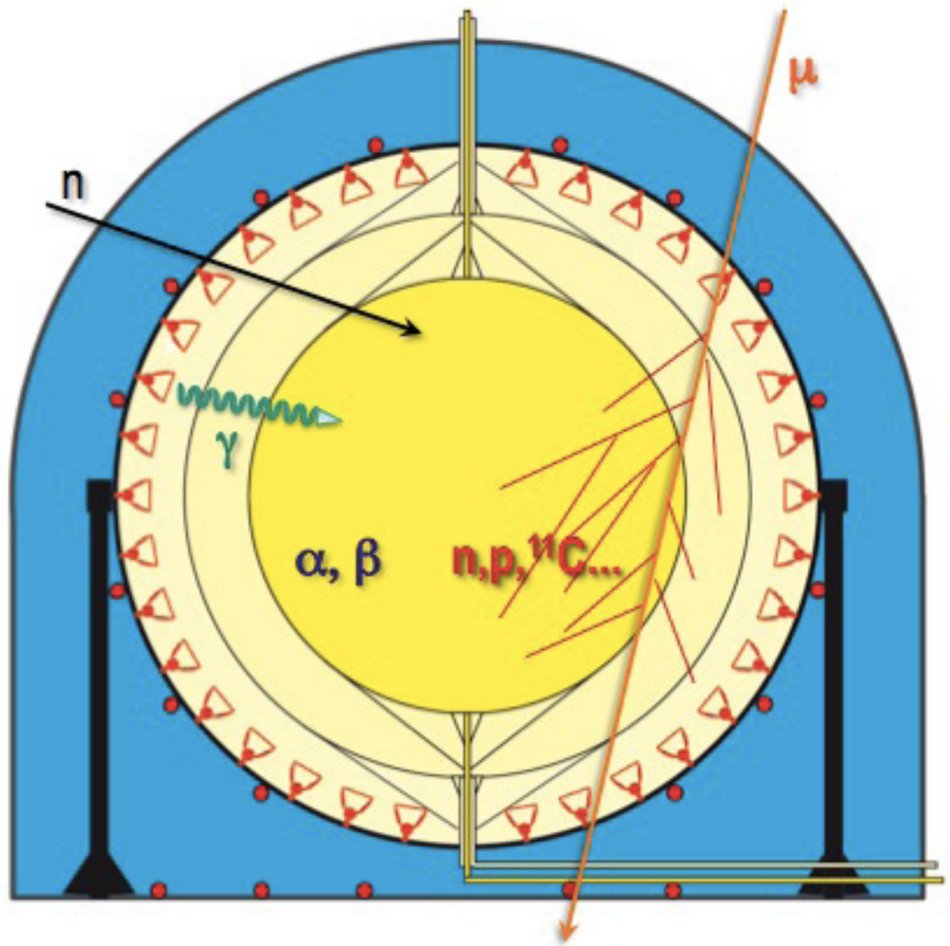
- γs (and n) from environment and detector materials (PMTs and SSS, mostly)

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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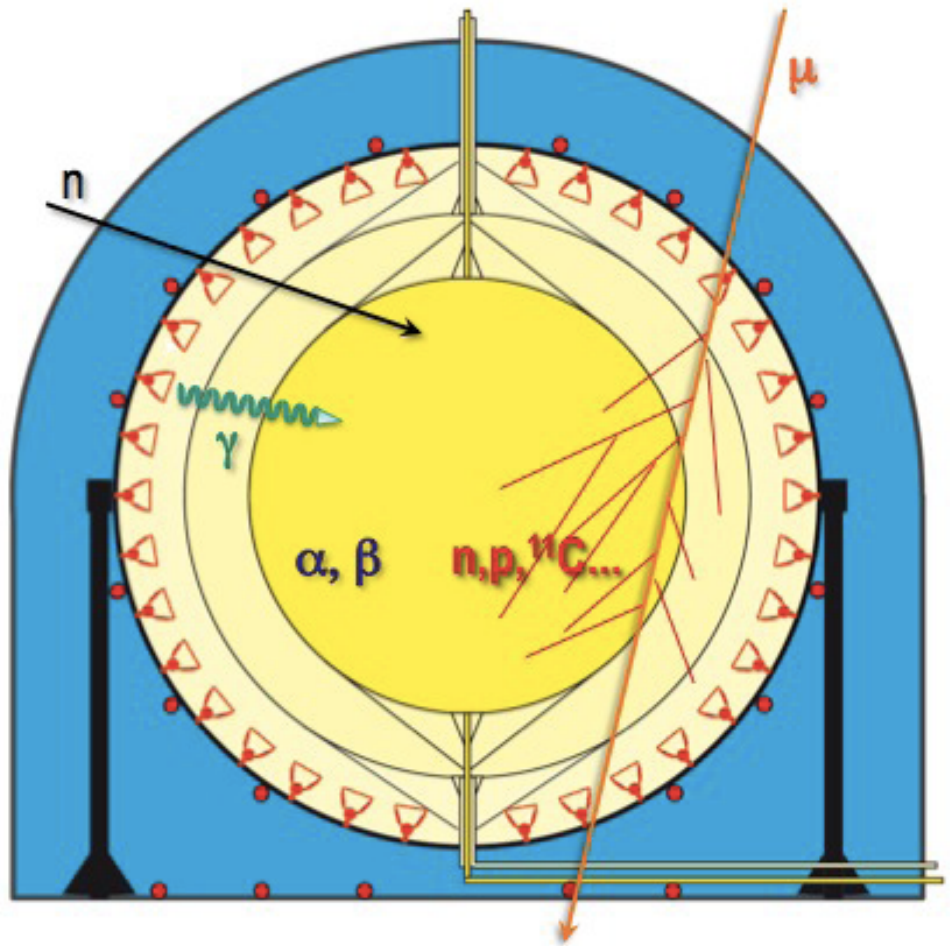

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^{210}Po, ^{222}Rn

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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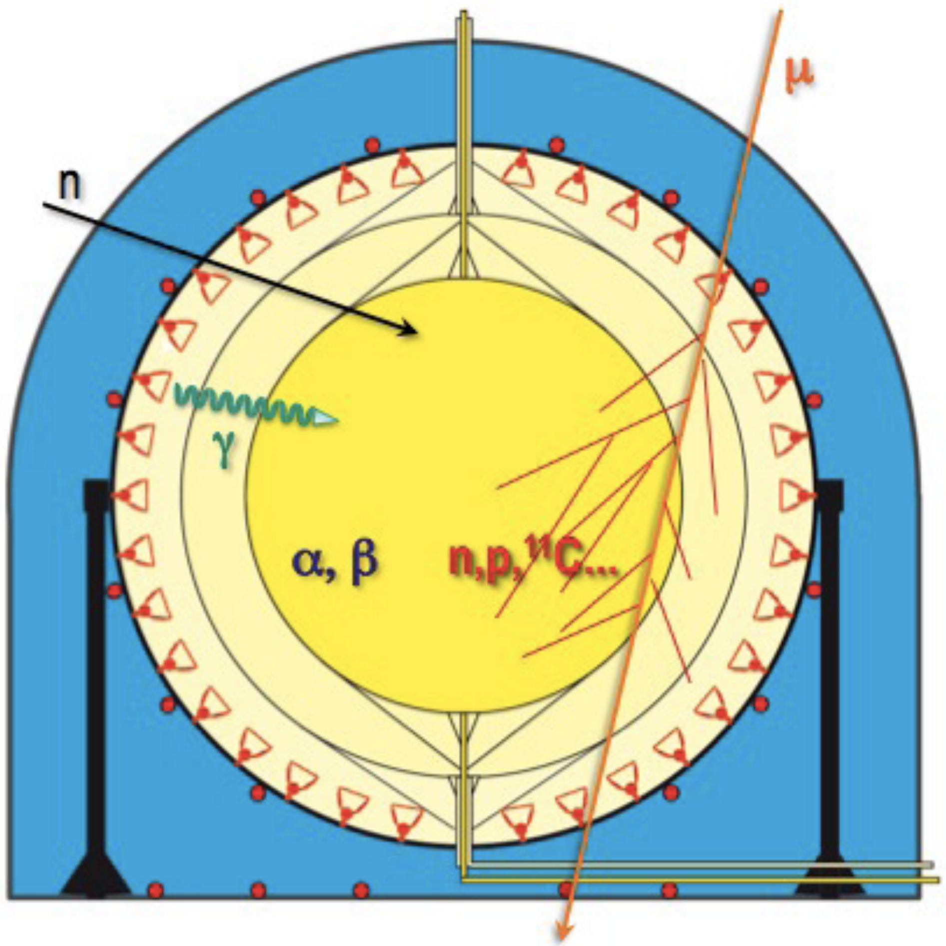

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^{11}C, ^{8}He, ^{9}C, ^{9}Li, ….

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

- Quasi-point-like energy deposits mimic neutrino events

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INTERNAL

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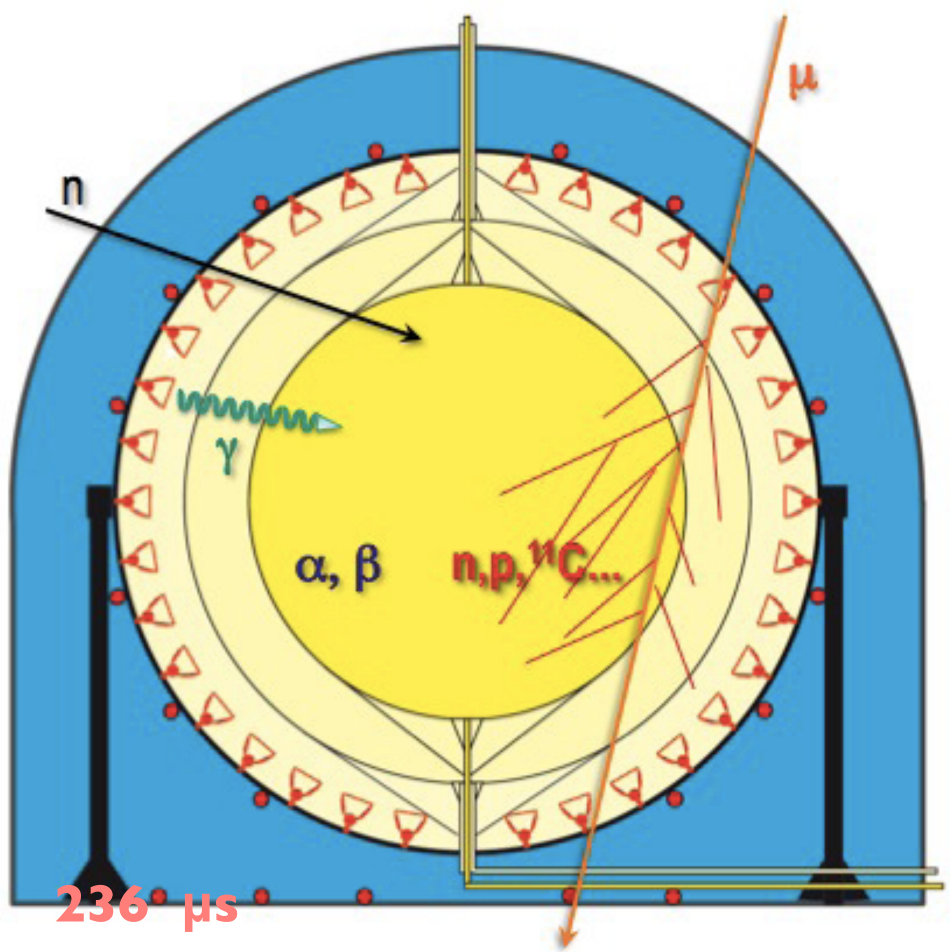

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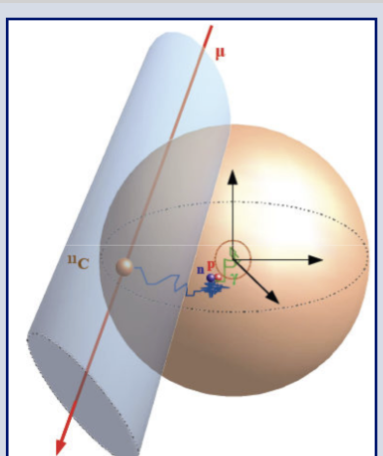

FIGHTING STRATEGY

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

29.4 min

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

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

236 μs

Other isotopes: removed by "after muon" veto cuts

Fighting backgrounds

- Quasi-point-like energy deposits mimic neutrino events

EXTERNAL

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

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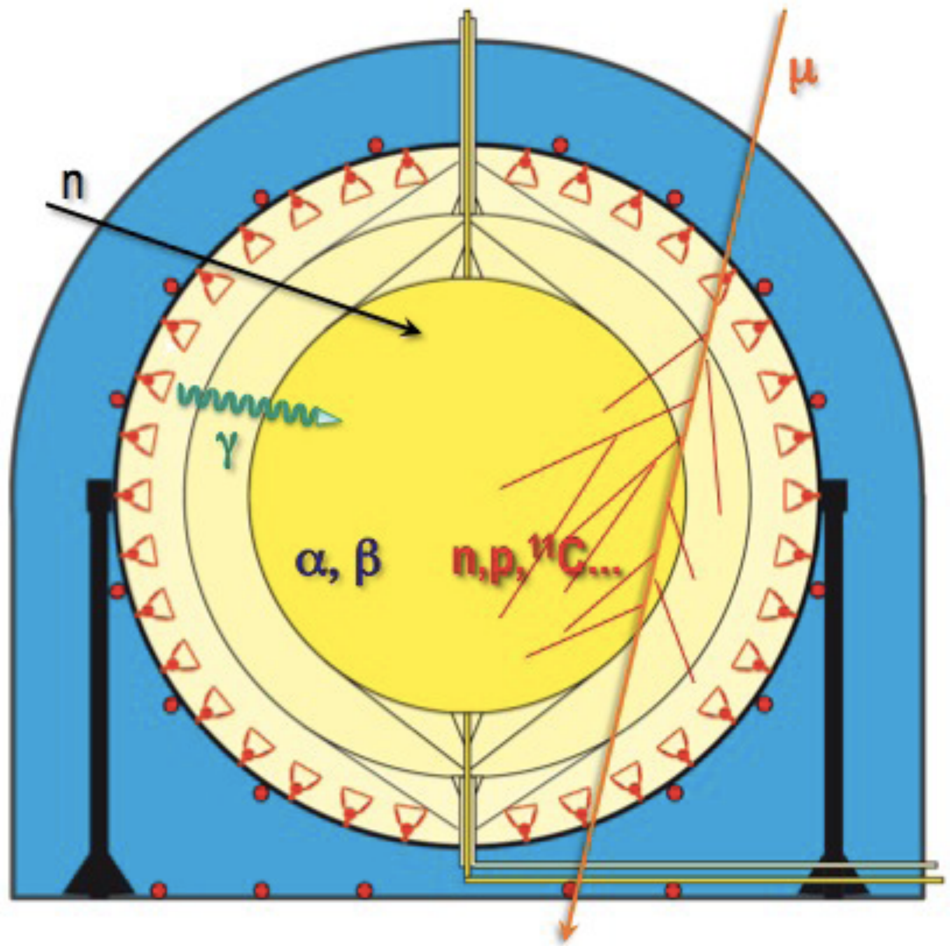
INTERNAL

- 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

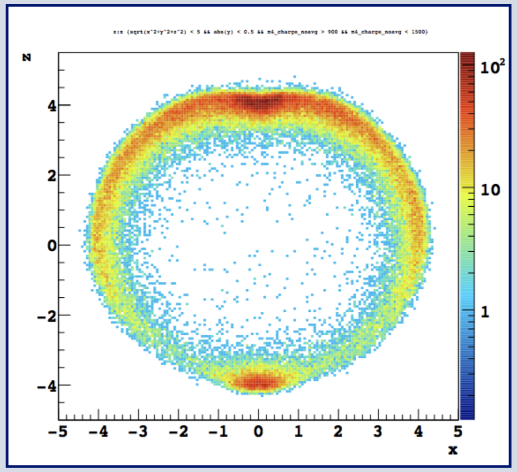
- Detaching from Nylon Vessel and transported by convection into the FV

^{210}Po, ^{222}Rn

FIGHTING STRATEGY

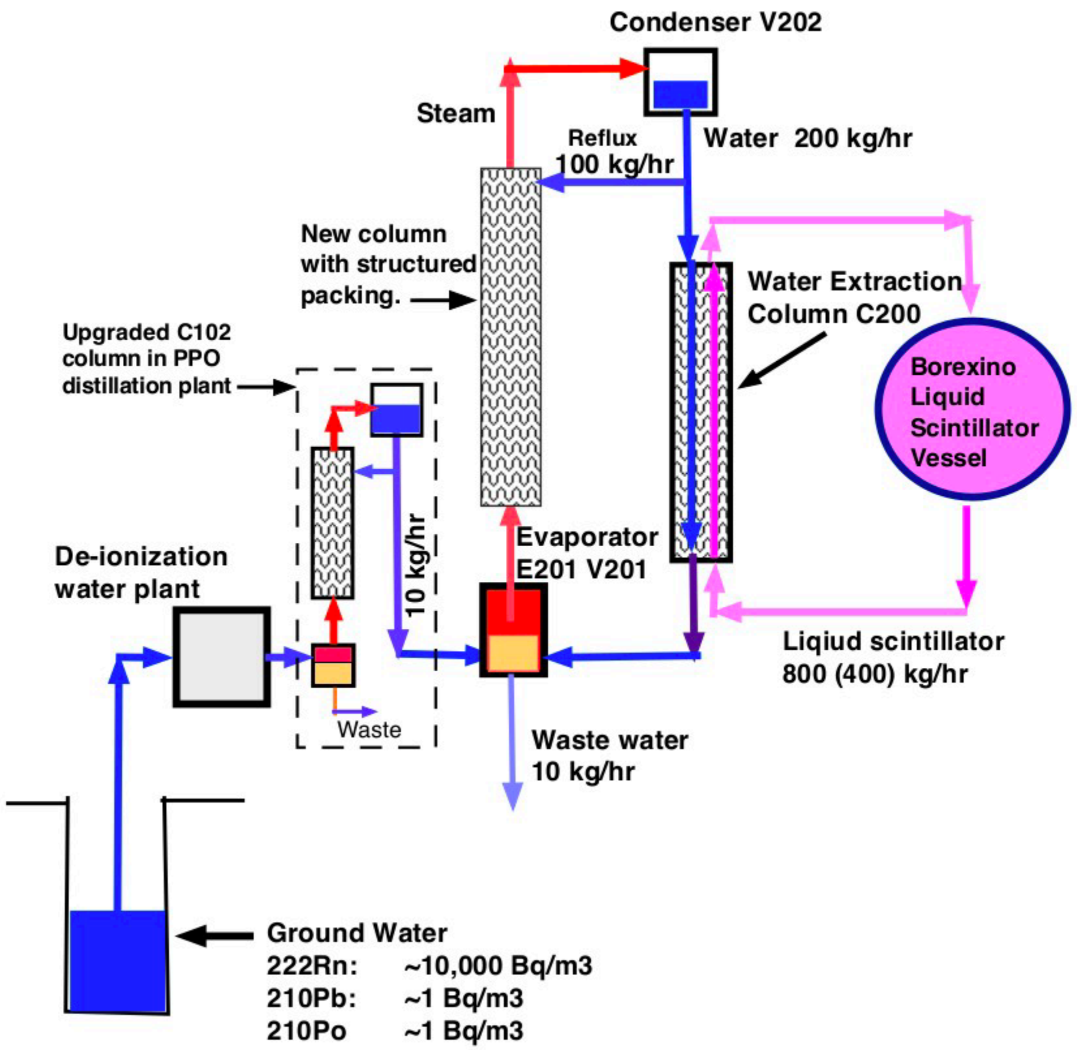
- Isotopes detaching from IV may reach the FV
  - ^{210}Po (chiefly) and ^{222}Rn daughters
- Leaching rate (chemistry) and speed (convection currents)
  - Only if they live long enough!

See later



Purification campaign 2010-2011

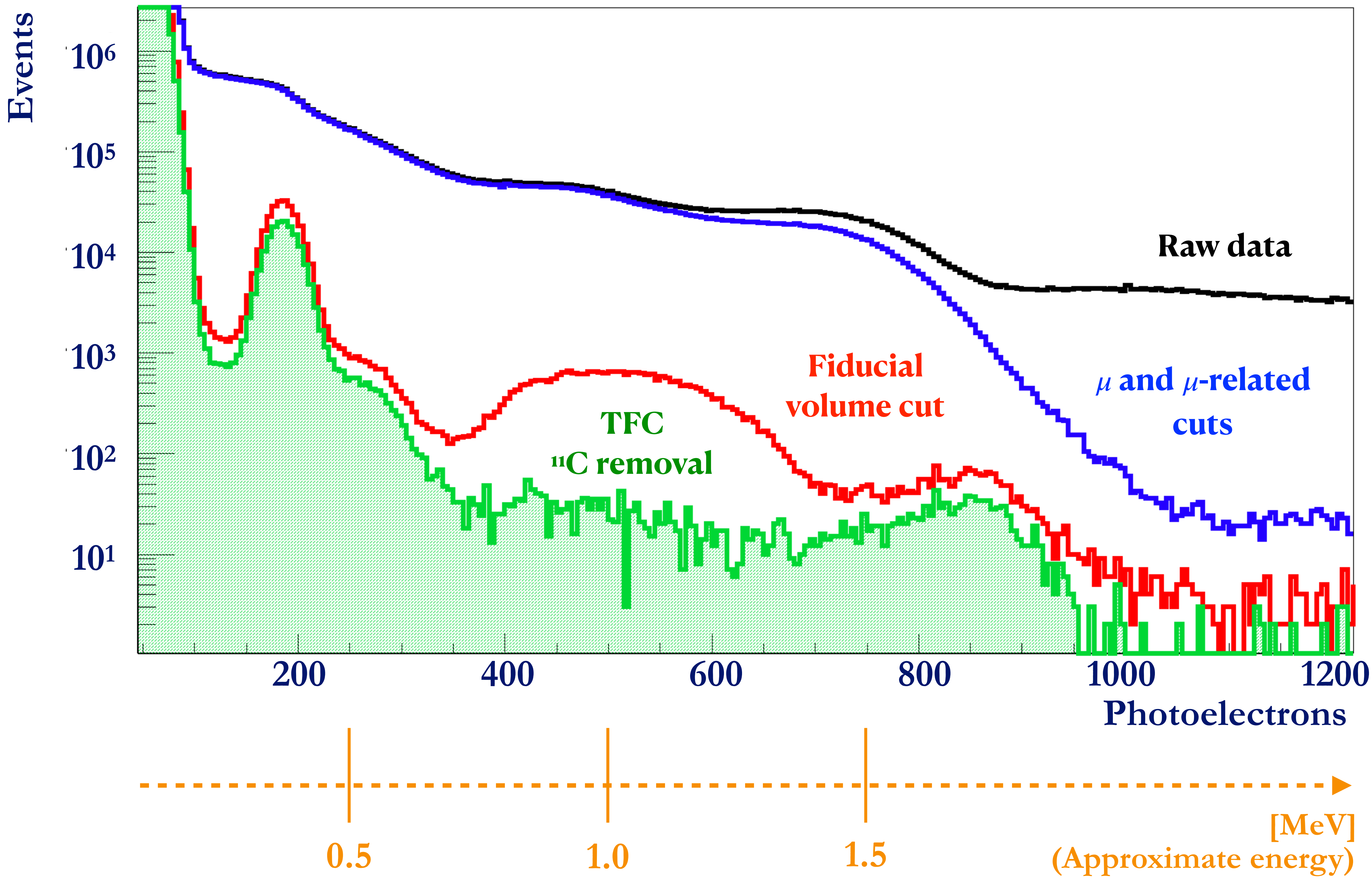
- **A key step toward pp and CNO ν**
  - Water Extraction
    - Turbulent mixing with ultra-clean water to remove ions, much more soluble in water
  - Low Ar-Kr N_2 bubbling
    - Turbulent mixing with N_2 flow, to remove dissolved gasses



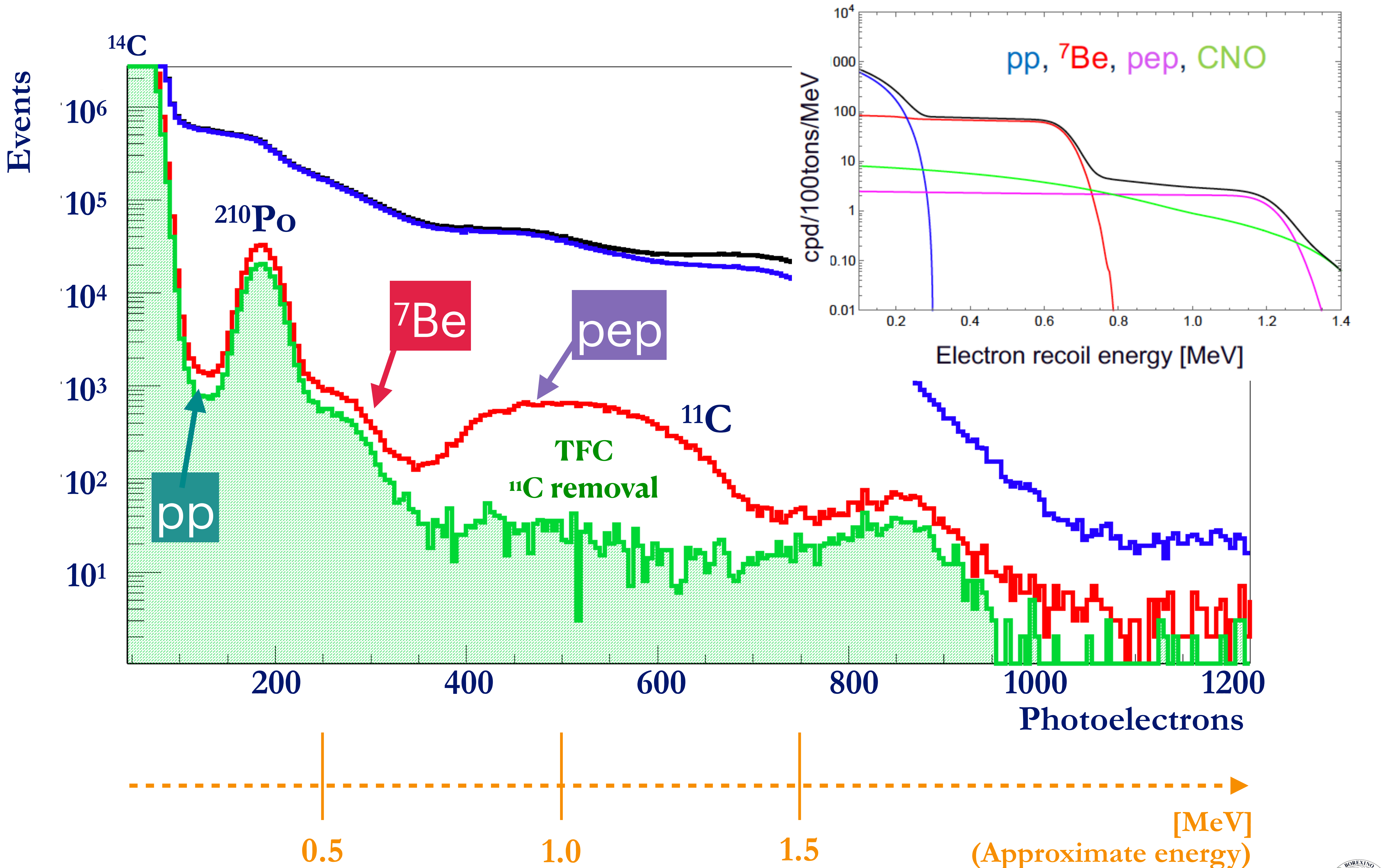
- **Very successful** on ^{238}U, ^{232}Th (chain heads), ^{210}Bi and ^{85}Kr

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

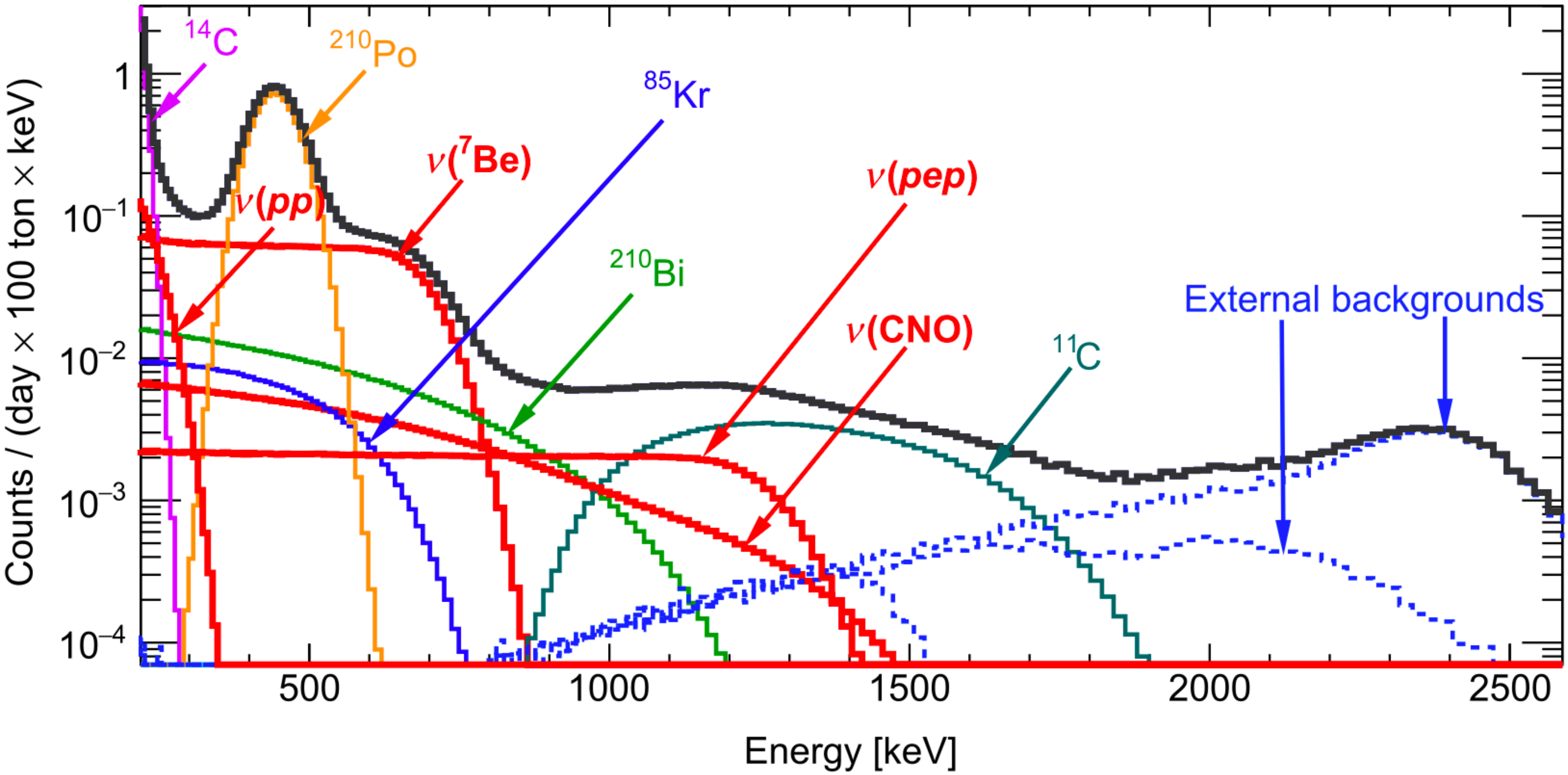
Understanding the data



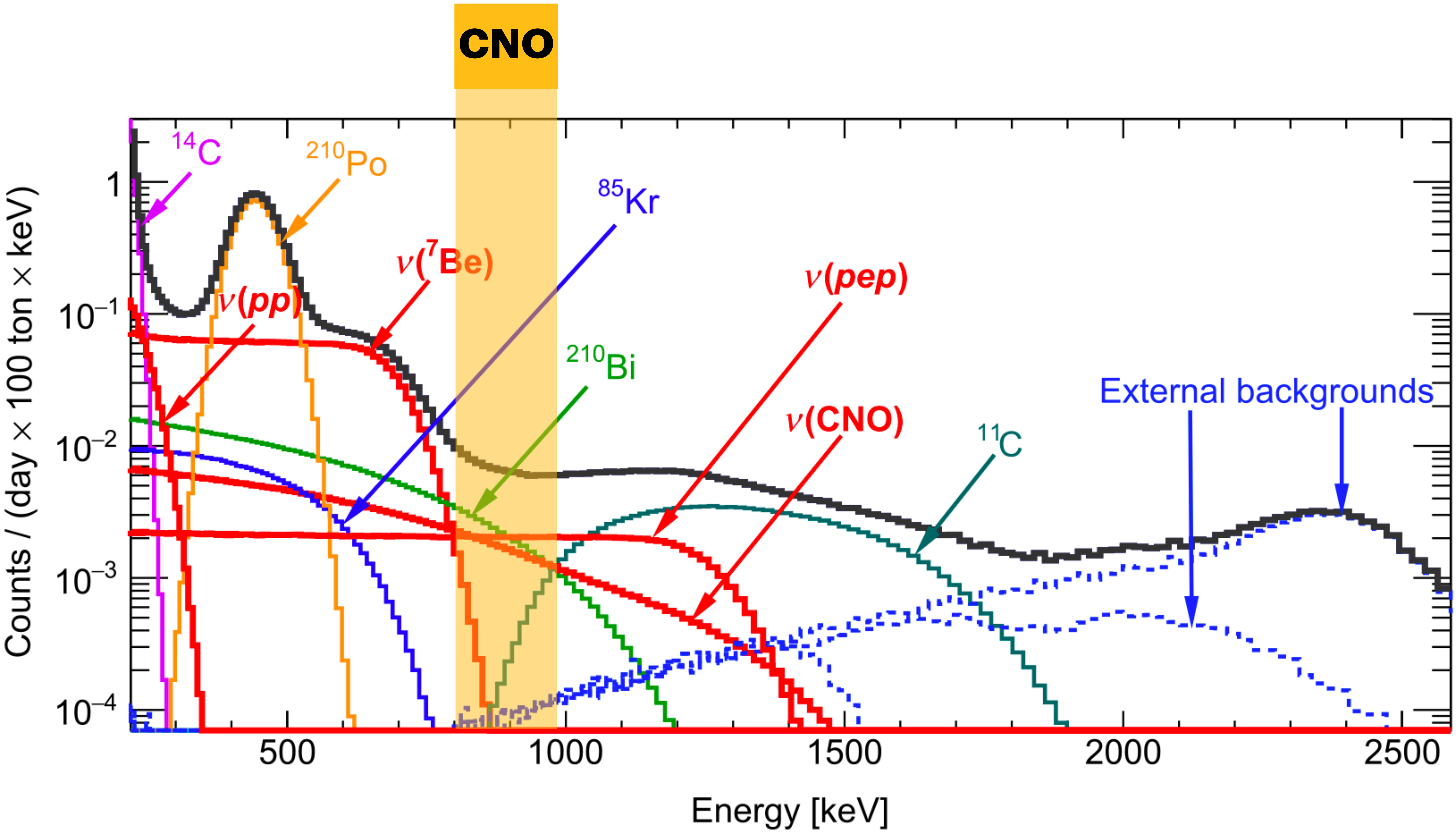
Understanding the data



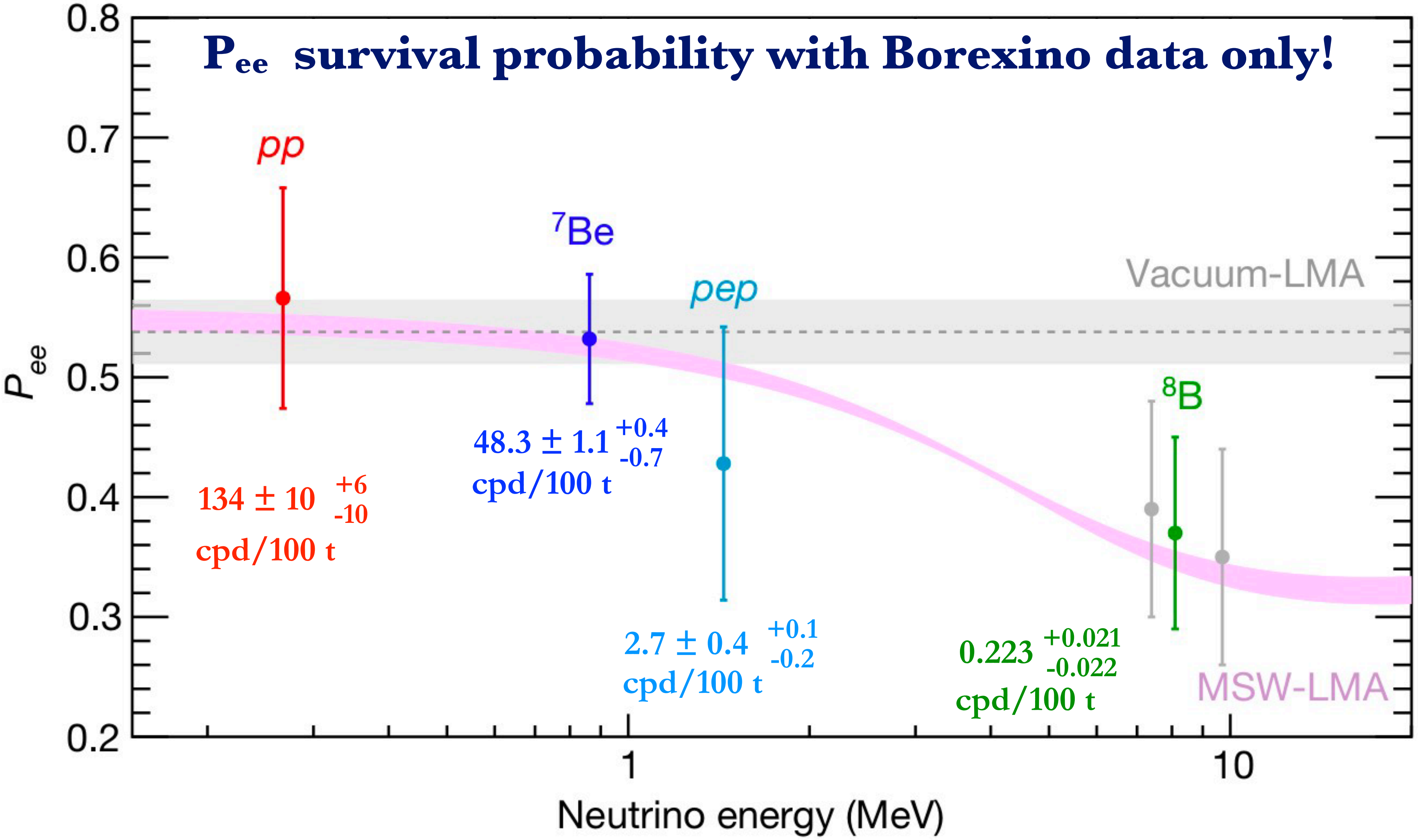
Spectral components: fit



Spectral components



Summary of pp chain study (2007-2018)



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

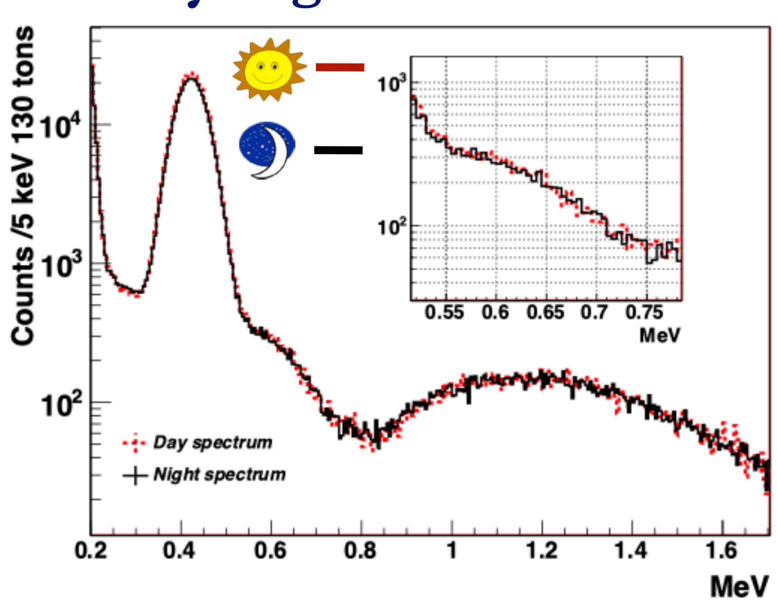
pp:
Nature 512 (2014) 7515, 383.

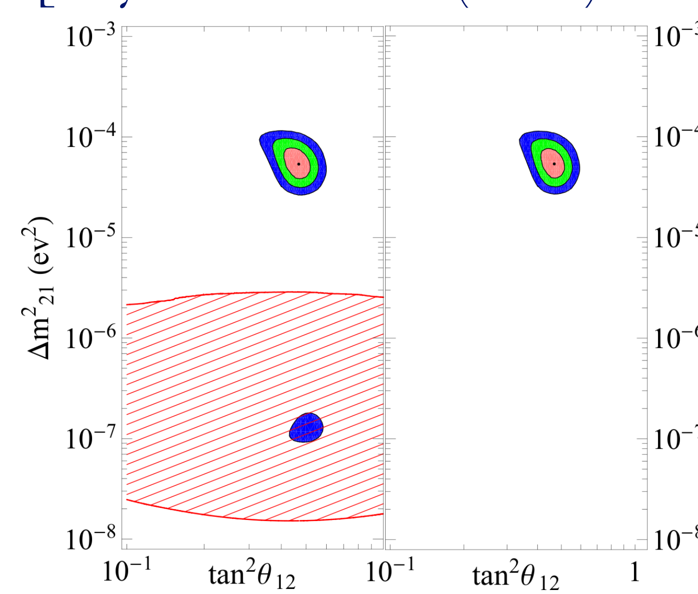
^{7}Be:
Phys. Lett. B658 (2008) 101
PRL 107 (2011) 141302

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.]

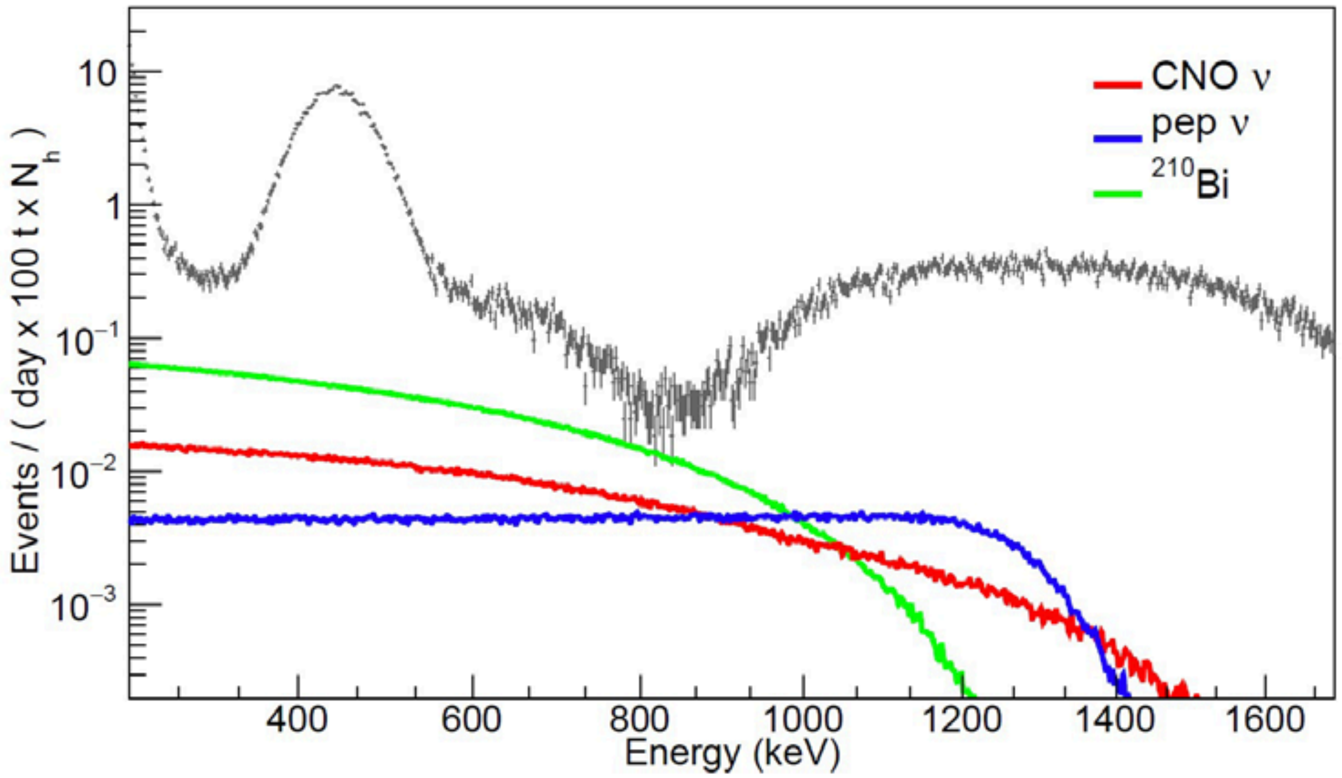




Chasing CNO

- 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

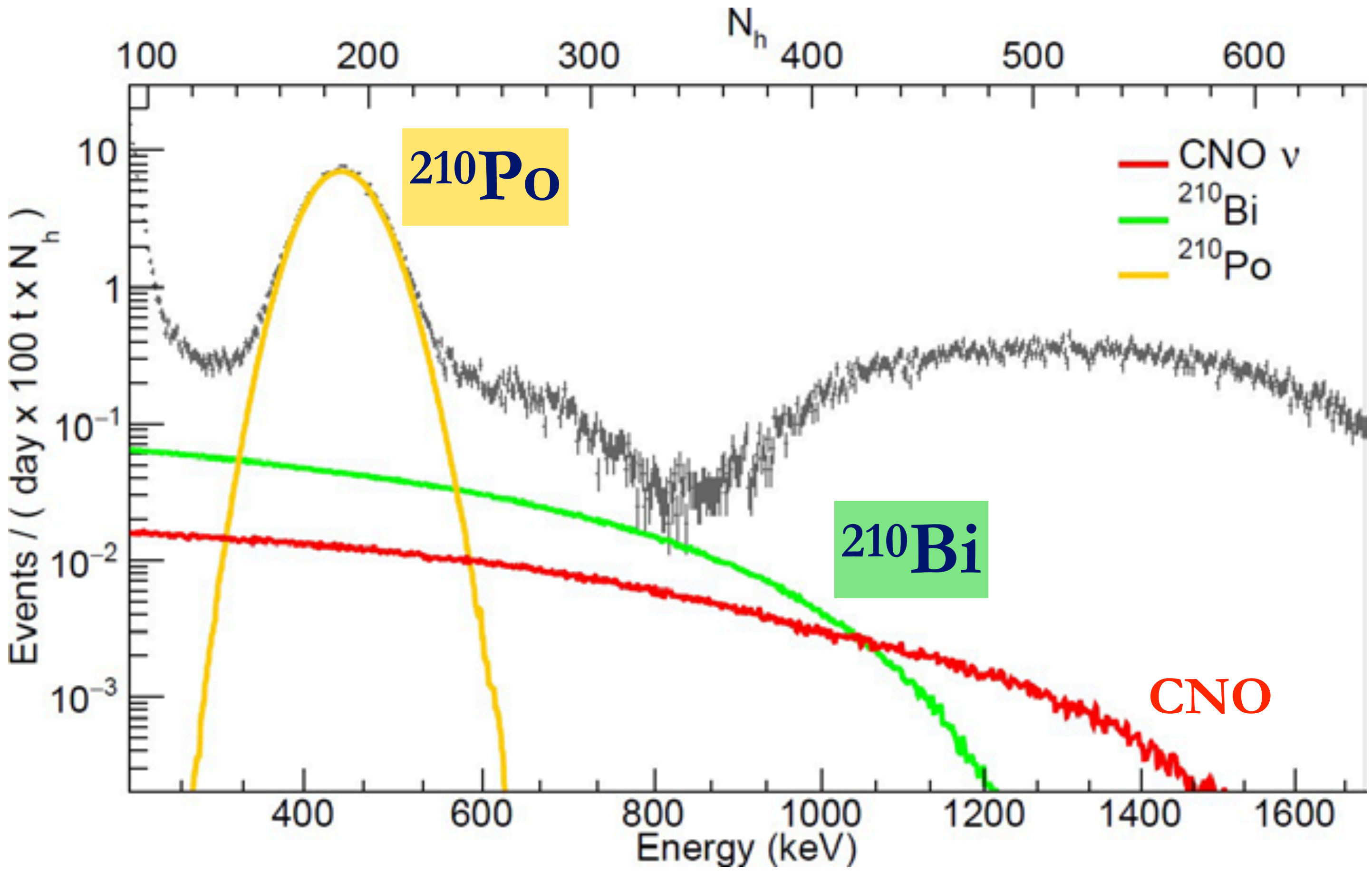


How to fix ^{210}Bi ?

- 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

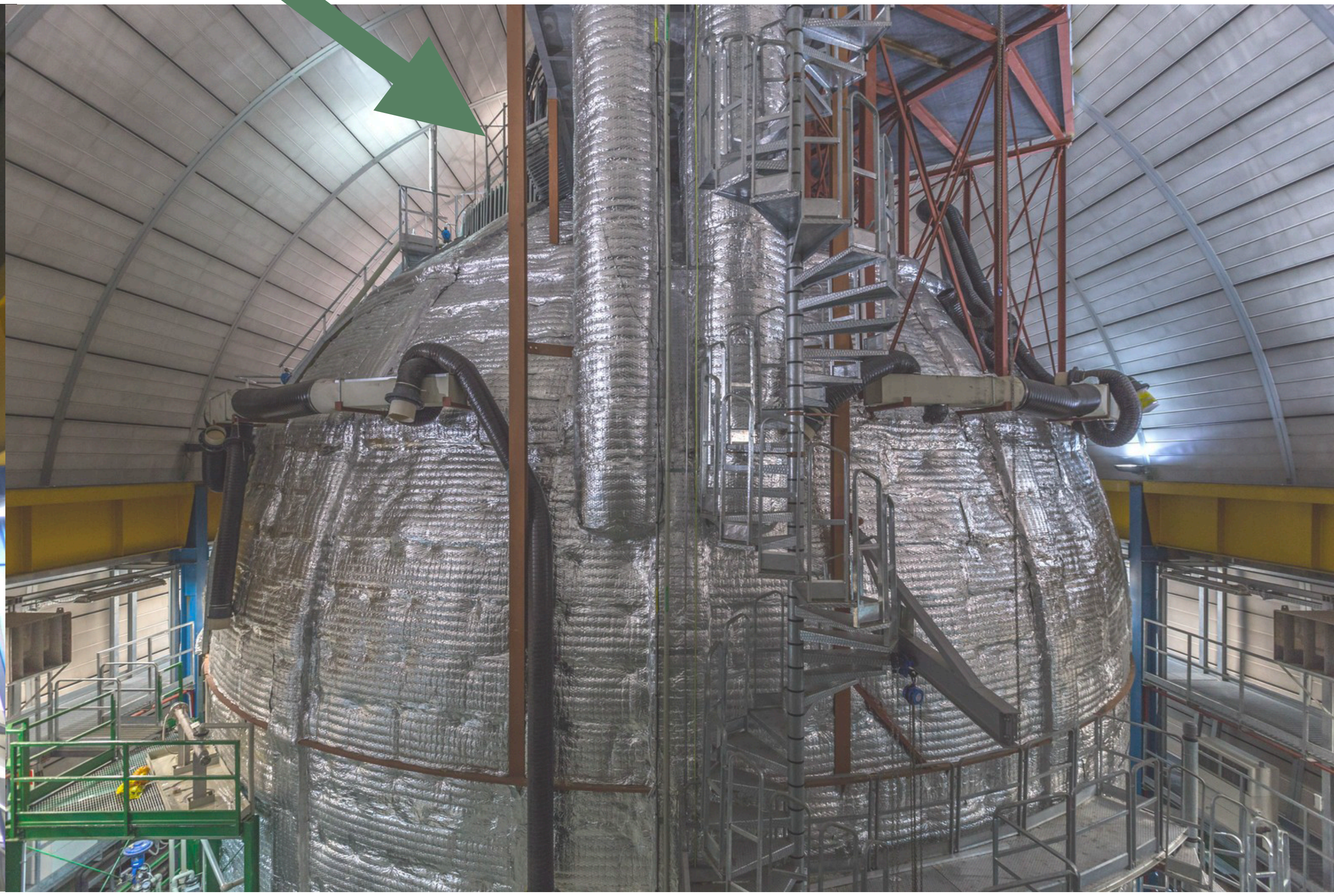
- Strategy:
  - Allow ^{210}Po out-of-equilibrium to decay
    - 2010 purification campaign did not remove all ^{210}Po
      - It DID reduce ^{210}Bi, i.e. parent ^{210}Pb
  - Act with passive and active systems on the thermodynamics of the detector to slow down convective currents
    - **A coat** (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)

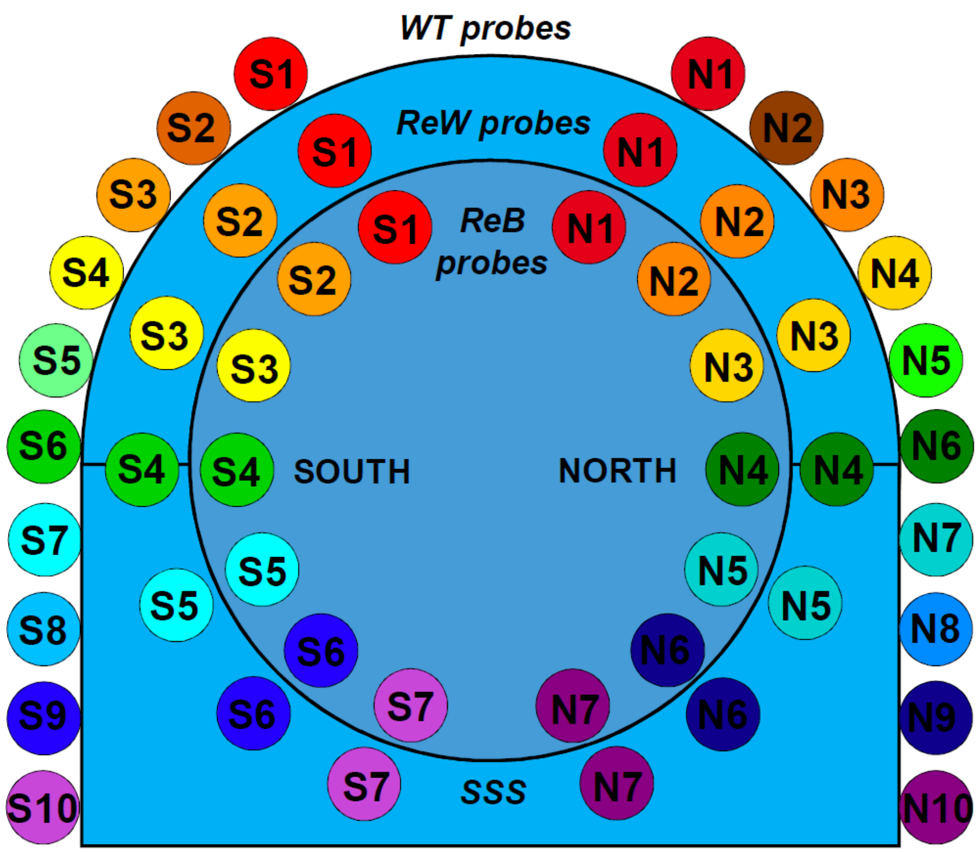
On top: copper coils under insulation with controlled water flow (2016)

Before

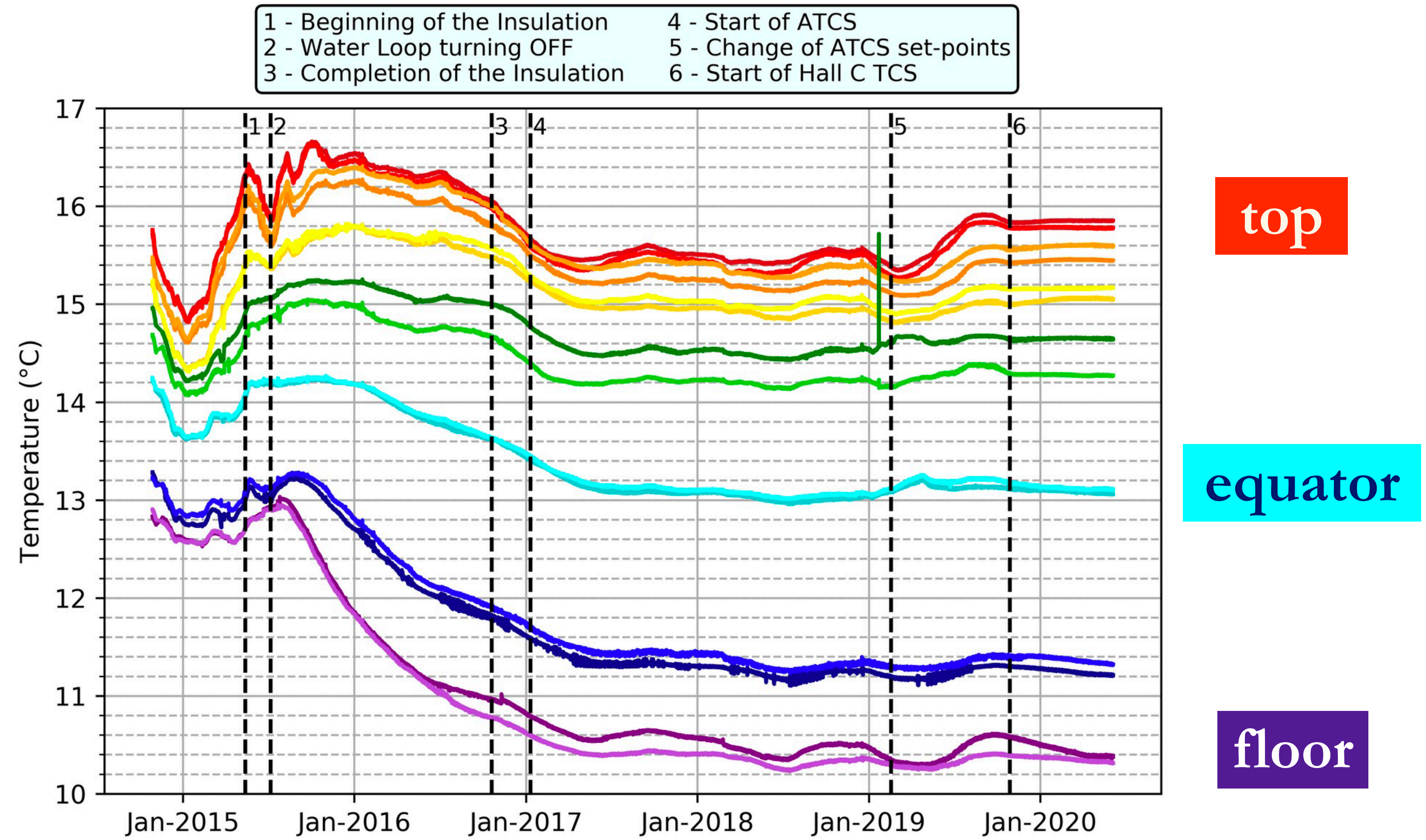
After



Effect on temperatures

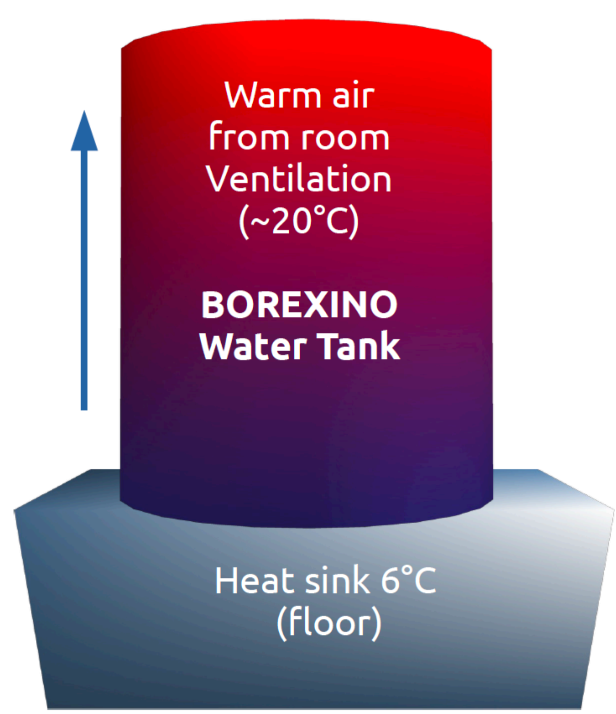


Distribution of T probes

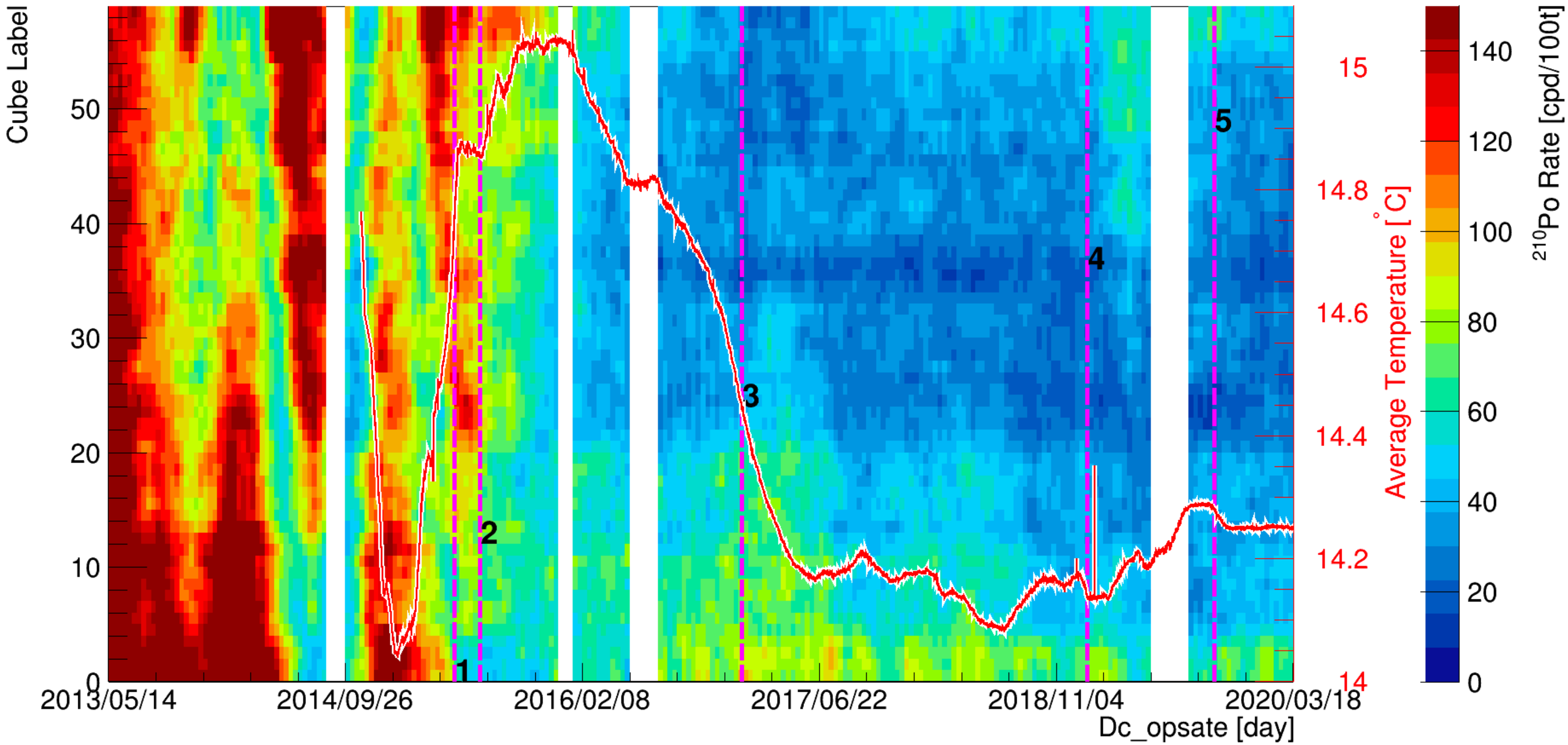


T vs Time

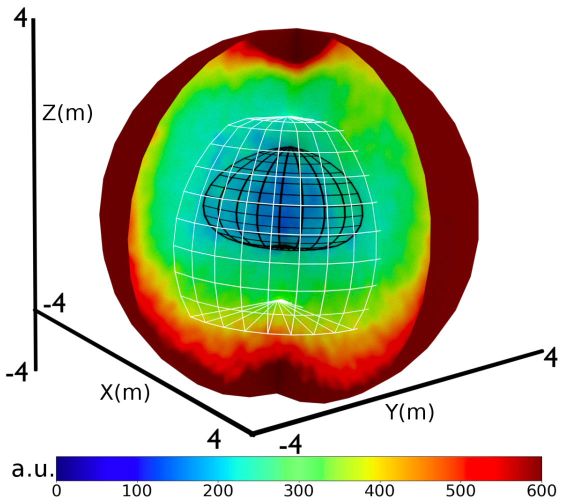
- Two important notes:
  - stability was achieved because the **LNGS floor is colder (~ 6 °C) than air (~20 °C in Hall C)**
    - This yields the **right vertical gradient** to stop convection
  - the time constant is very slow. Years to get stability, still in progress.



Evolution of ^{210}Po

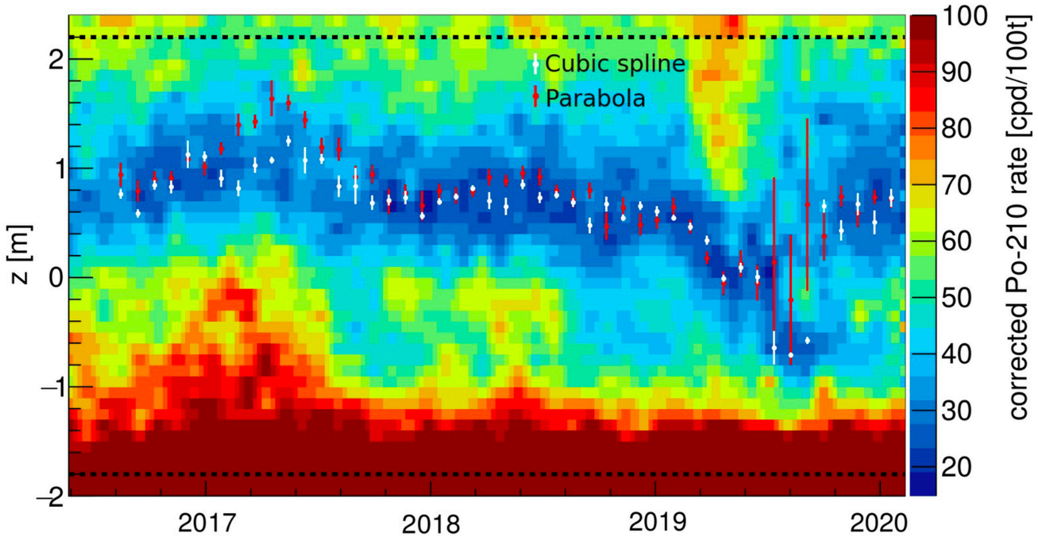


The low ^{210}Po "field" and ^{210}Bi upper limit

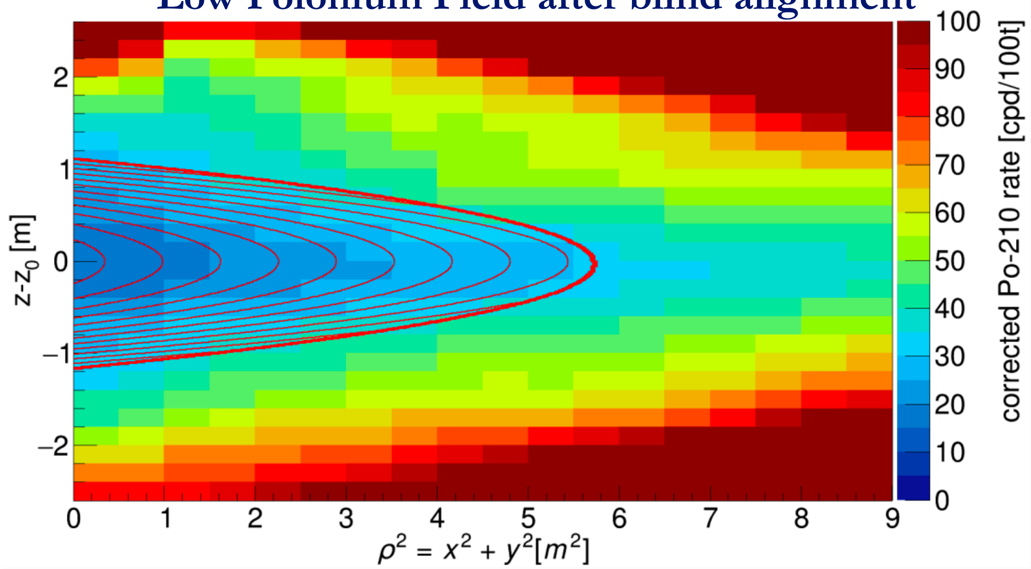


- The minimum is at **z = + 80 cm**
- From this minimum, we get an **upper limit on ^{210}Bi**
- To get a measurement, we would need to know that is a "true" minimum, which we cannot claim yet
  - **But we can claim observation !**

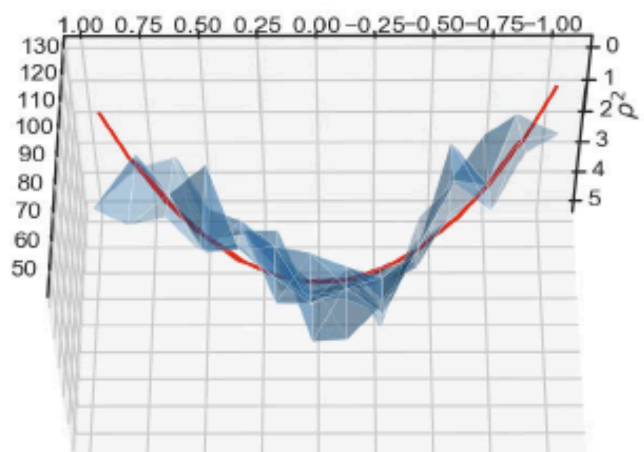
Evolution of the Low Polonium Field



Low Polonium Field after blind alignment

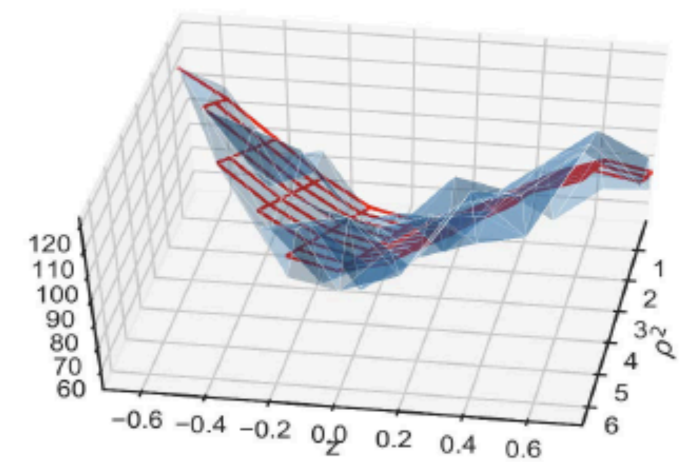


PARABOLOID



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

SPLINE FIT



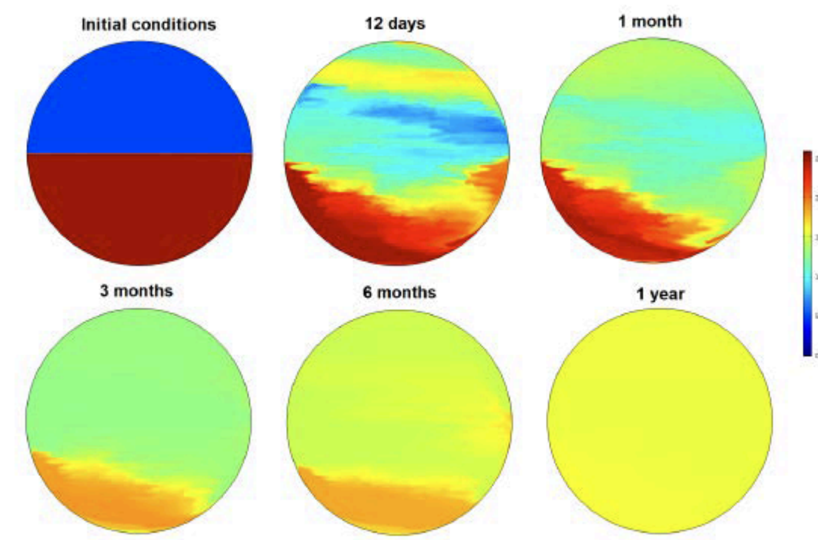
Two consistent methods for fitting the aligned LPoF and find the minimum

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

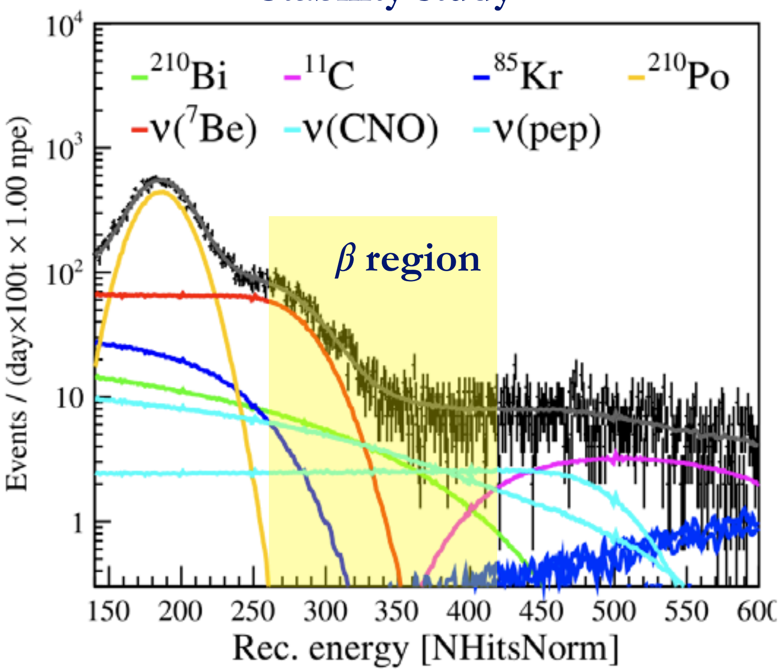
^{210}Bi uniformity and stability

- 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

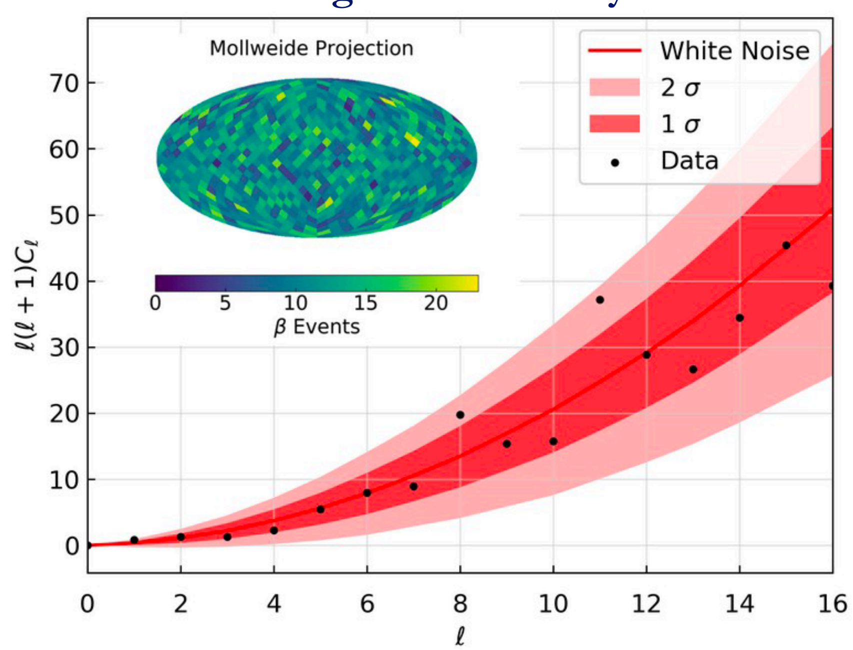
Full uniformity reached in 1 y [3D simulation]



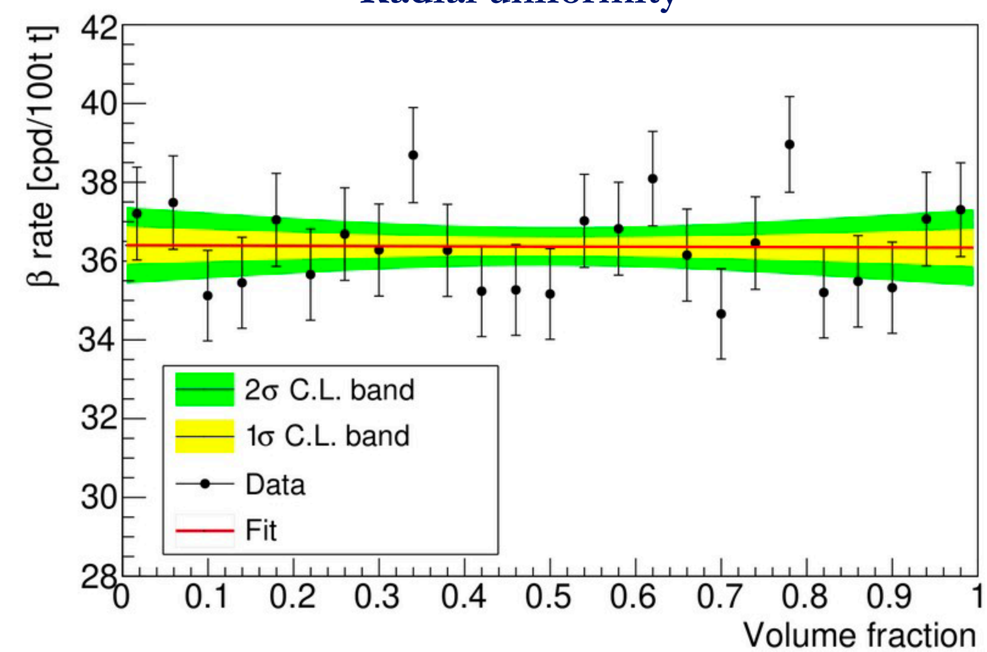
Stability study



Angular uniformity



Radial uniformity

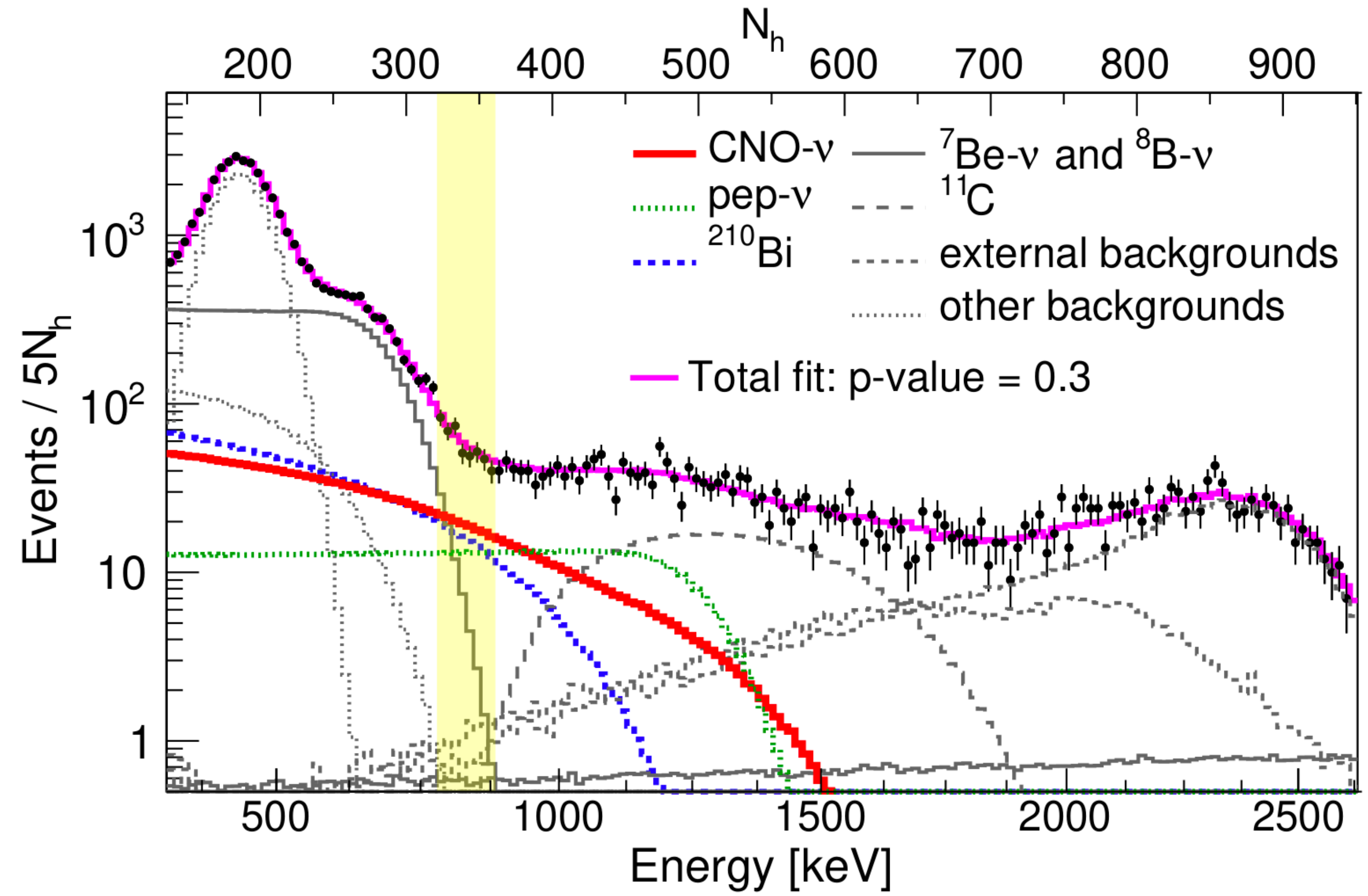


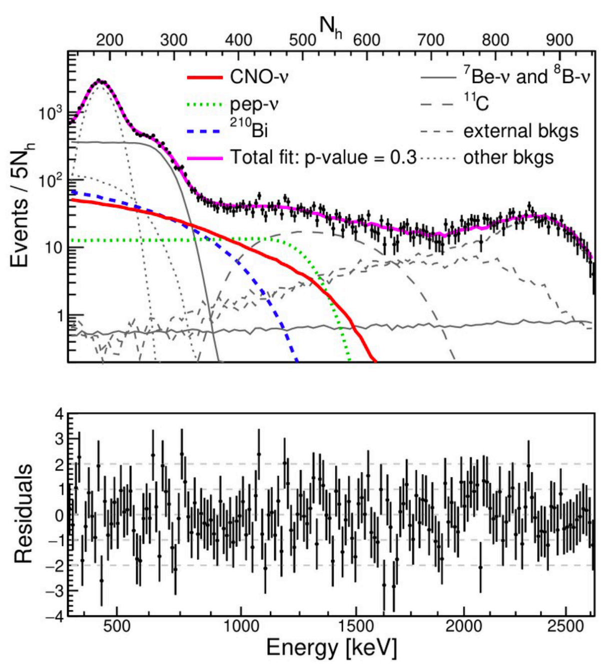
- The final constraints that **breaks degeneracy** with CNO:

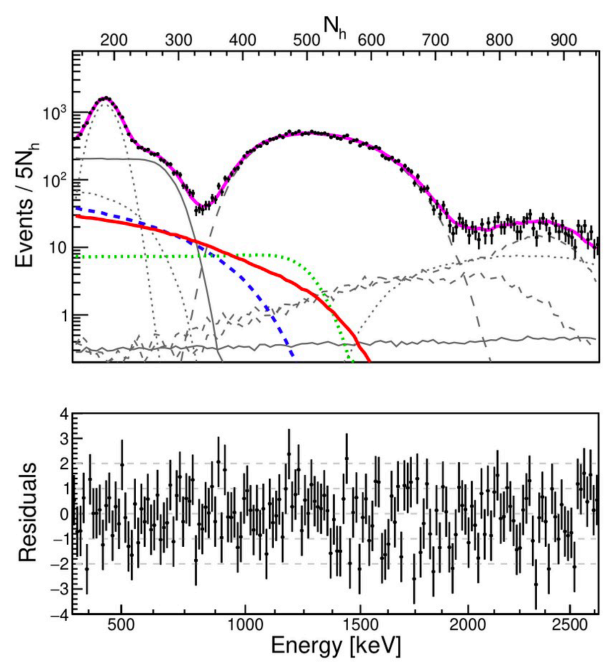
^{210}Bi < 11.5 ± 1.3 cpd/100t

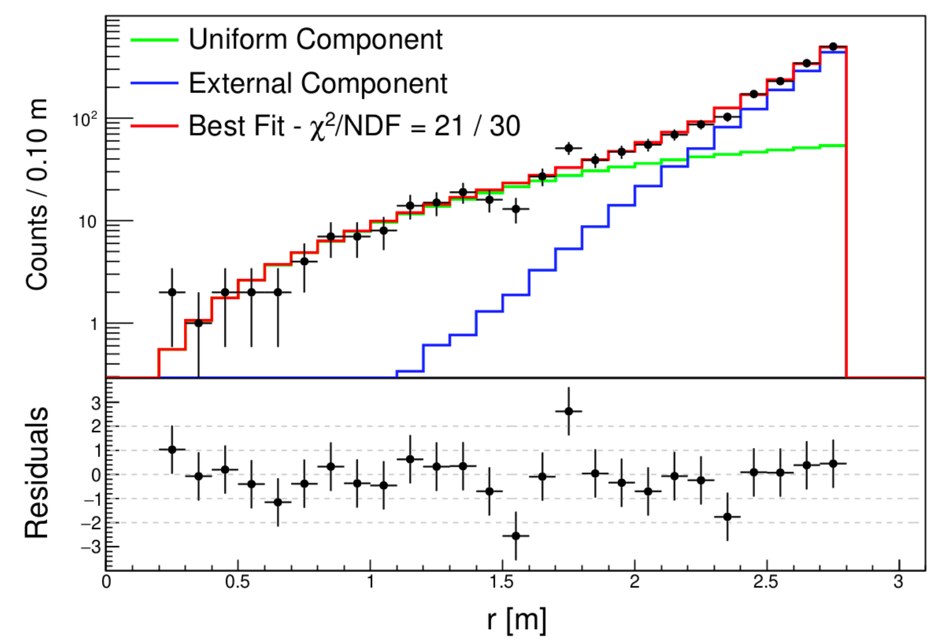
CNO analysis and multi-variate fit

- 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)



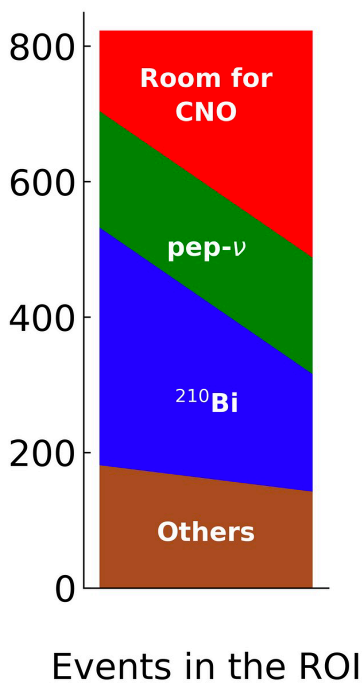


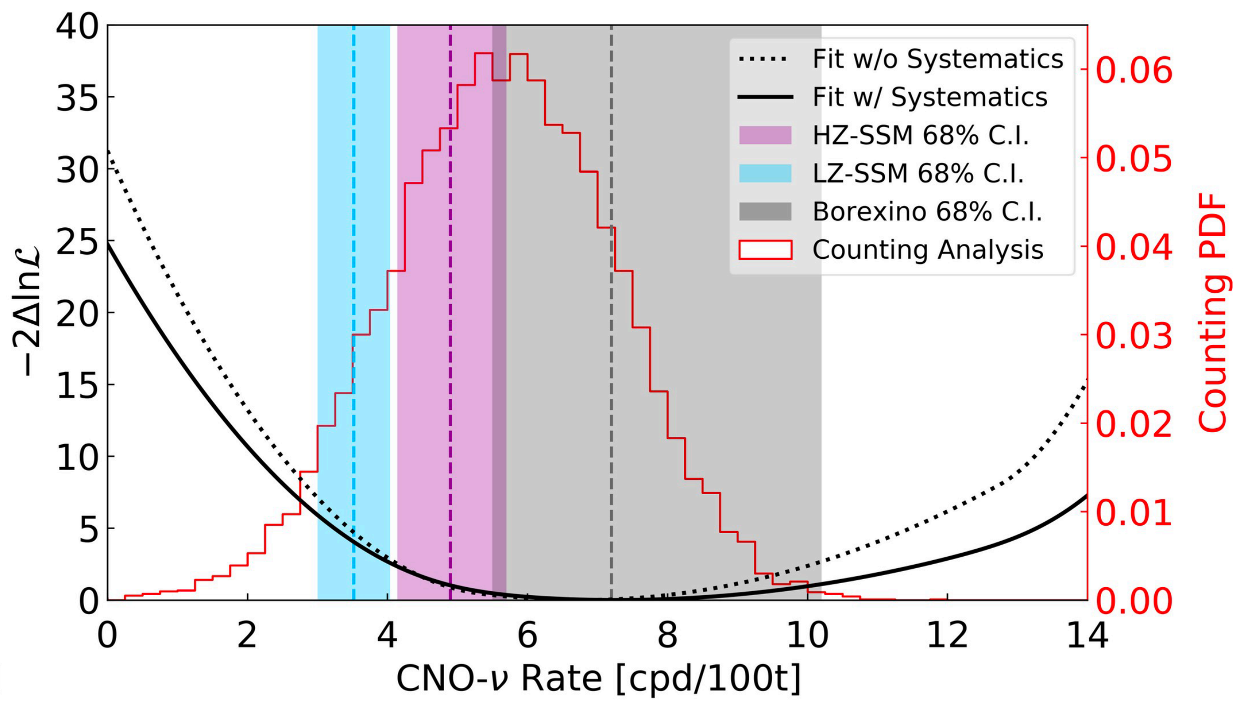




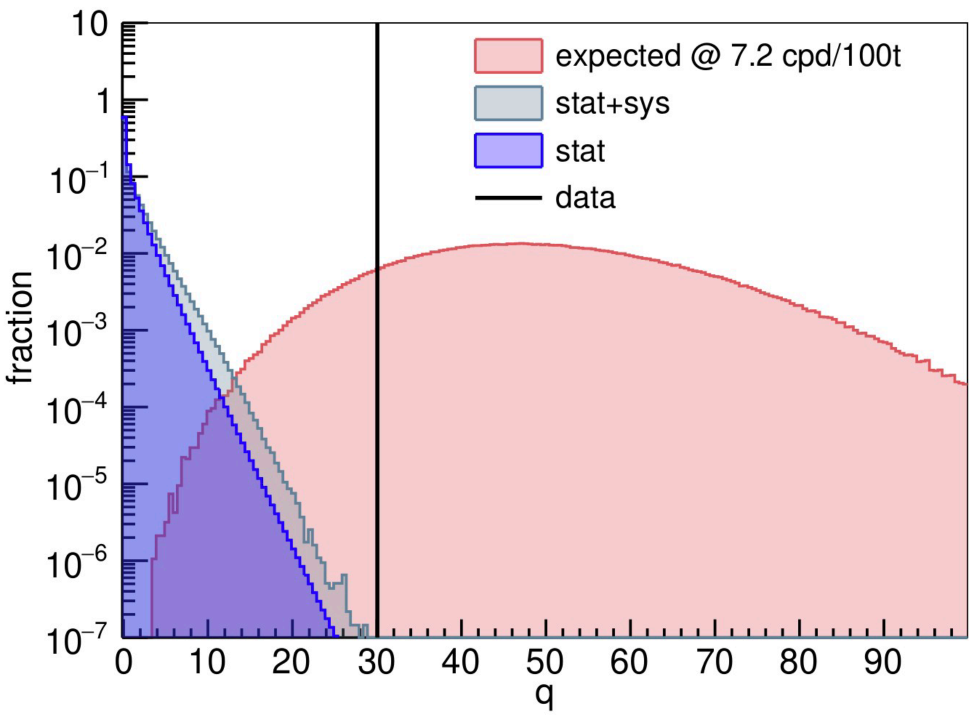
Result (68% CL stat) 7.2 - 1.7 + 2.9 cpd/100t

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 !!!