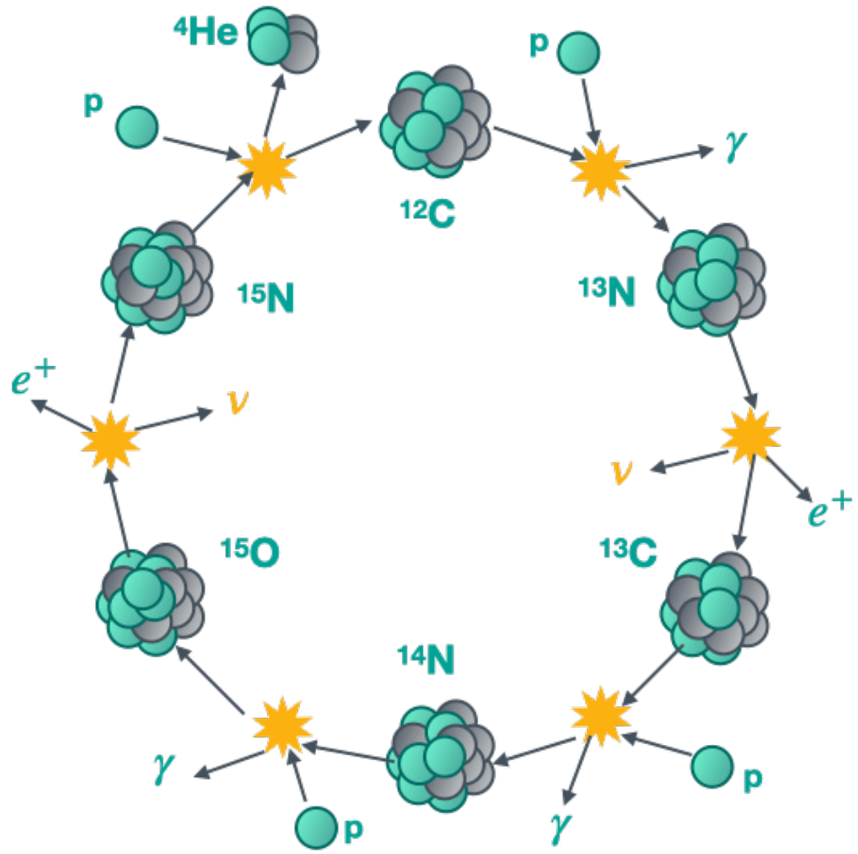


Reaching for the Sun: First Evidence of CNO Neutrinos

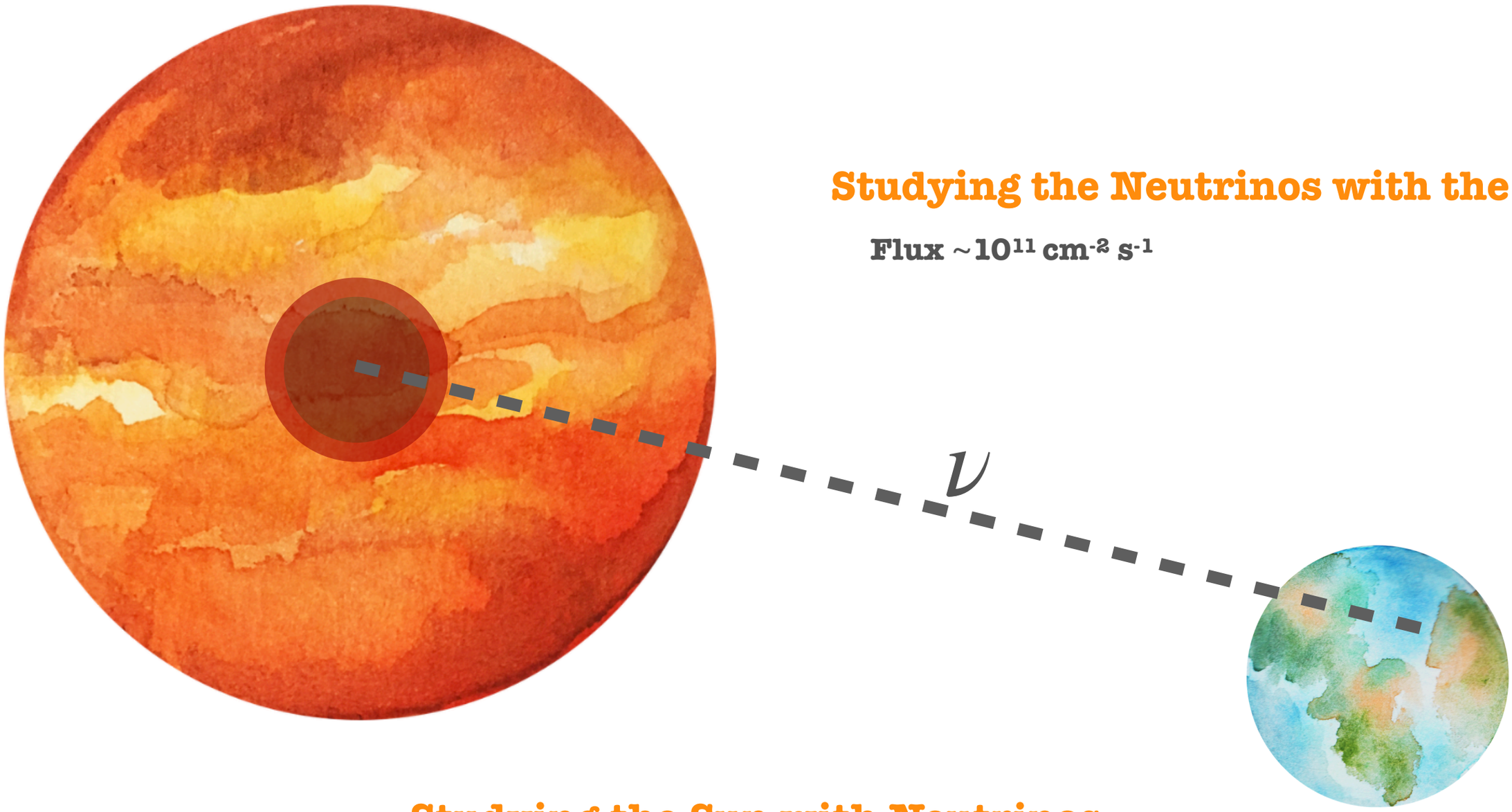
Zara Bagdasarian[1,2] for the Borexino collaboration

[1] University of California Berkeley (USA),
previously [2]Forschungszentrum Jülich (Germany)

Fermilab Neutrino Seminar Series
September 17th, 2020

Solar neutrinos - a window into the core of the Sun

Solar neutrinos - a window into the core of the Sun



Studying the Neutrinos with the Sun

Flux ~10^{11} cm^{-2} s^{-1}

Studying the Sun with Neutrinos

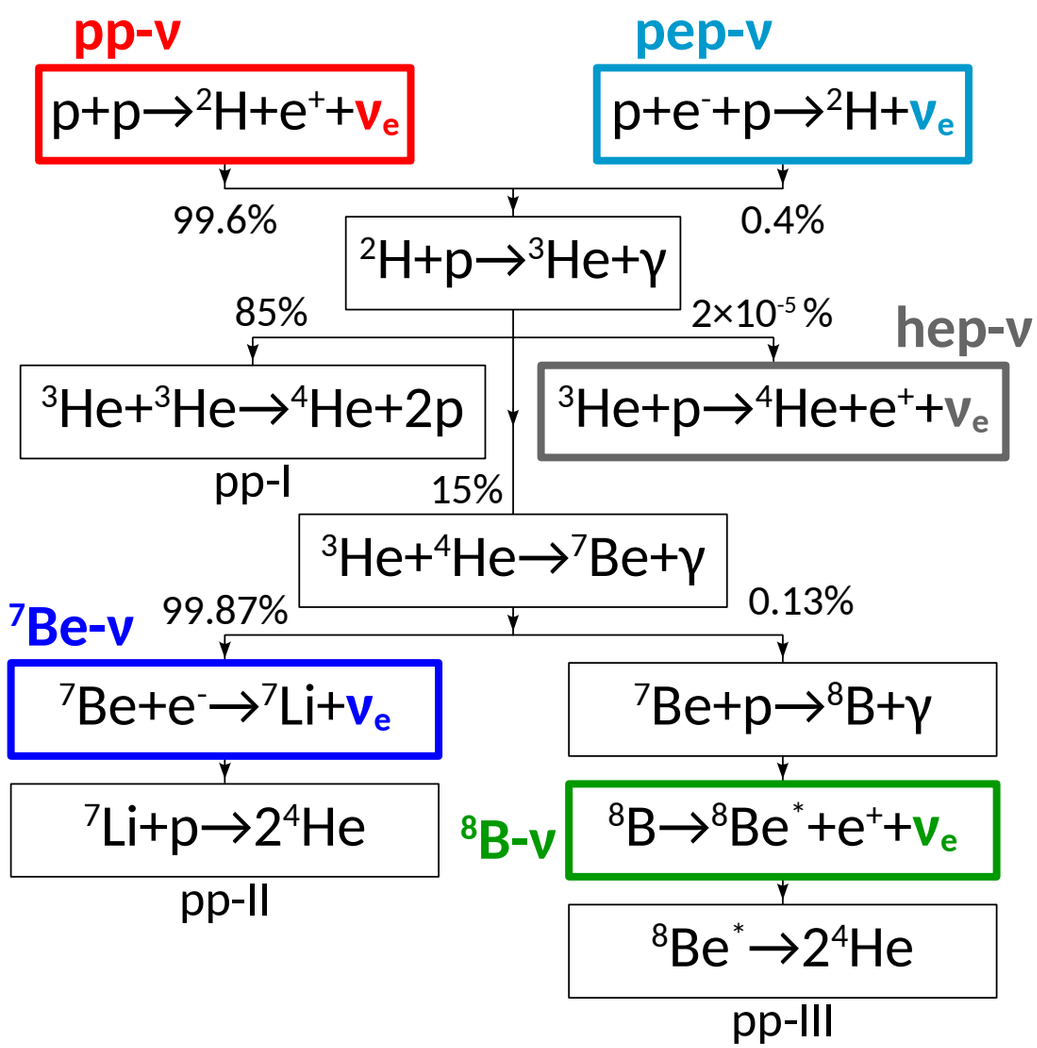
The only direct probe of nuclear process in the core

Fusion processes in the Sun

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

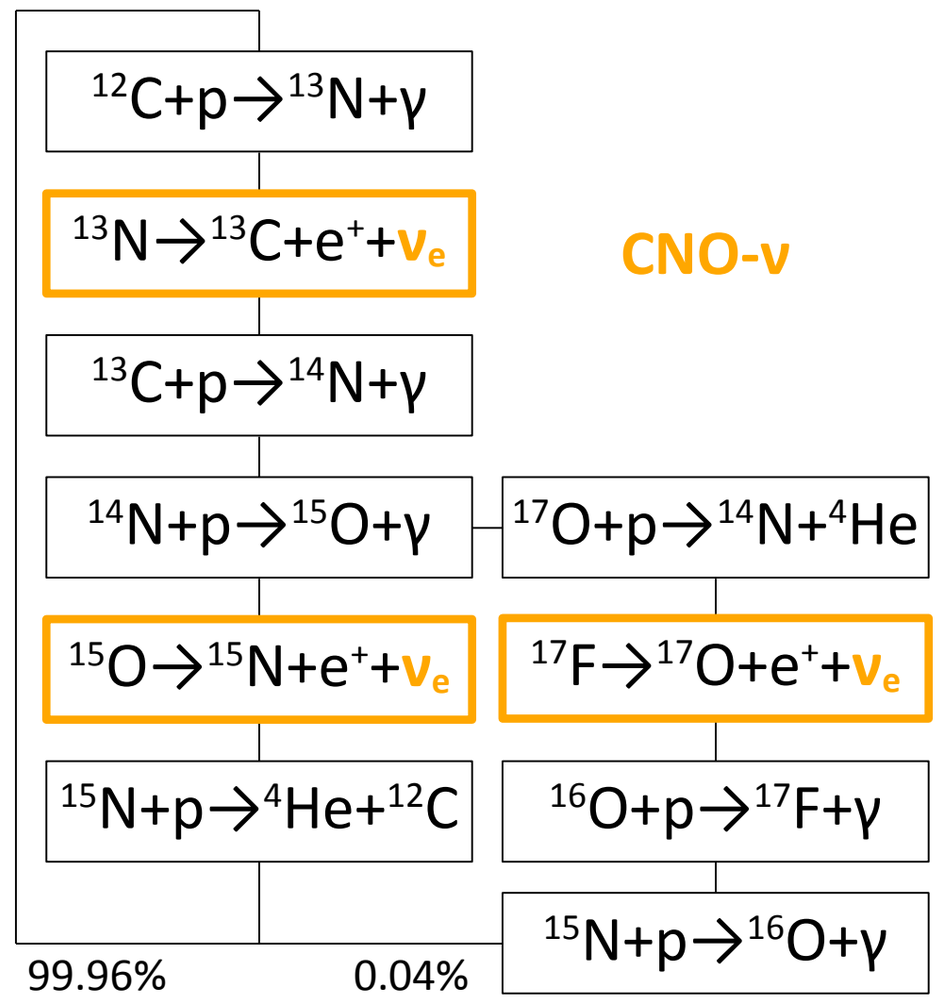
Released energy ~26 MeV

pp chain reaction (~99%)



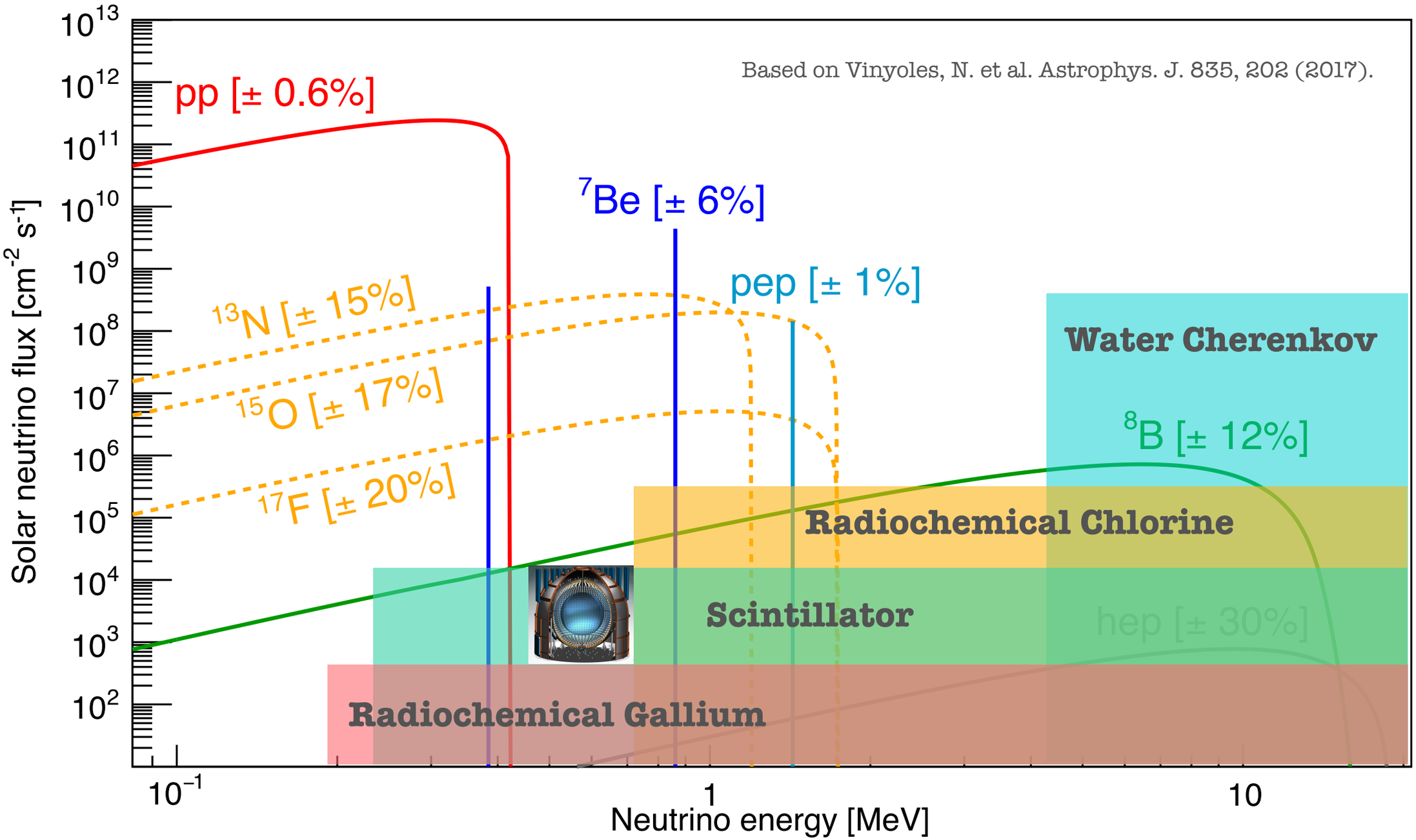
Bethe&Critchfield (1938)

CNO cycle (<1%)



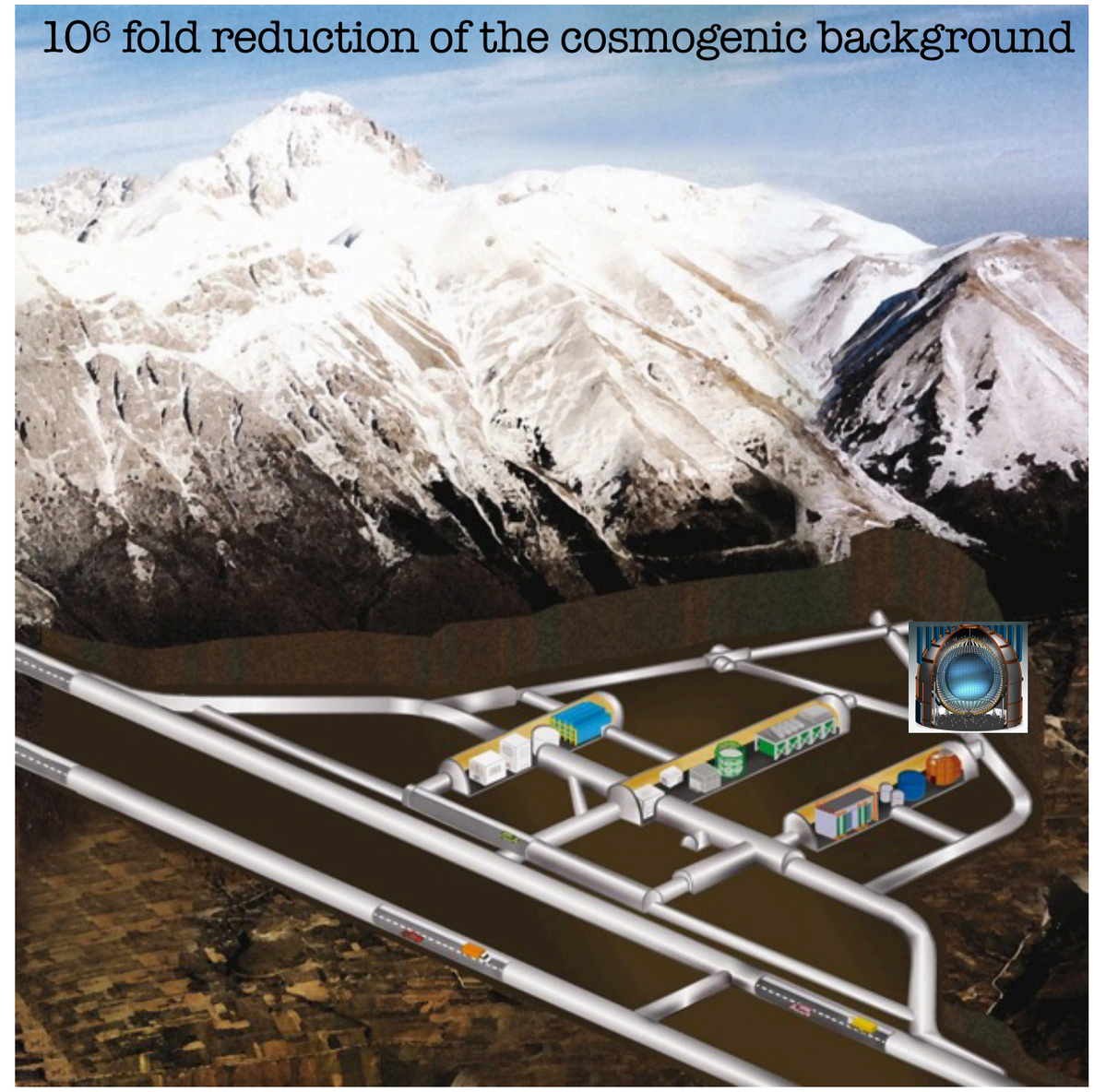
Weizsäcker (1937, 1938), Bethe (1939)

Solar Neutrinos Flux on Earth



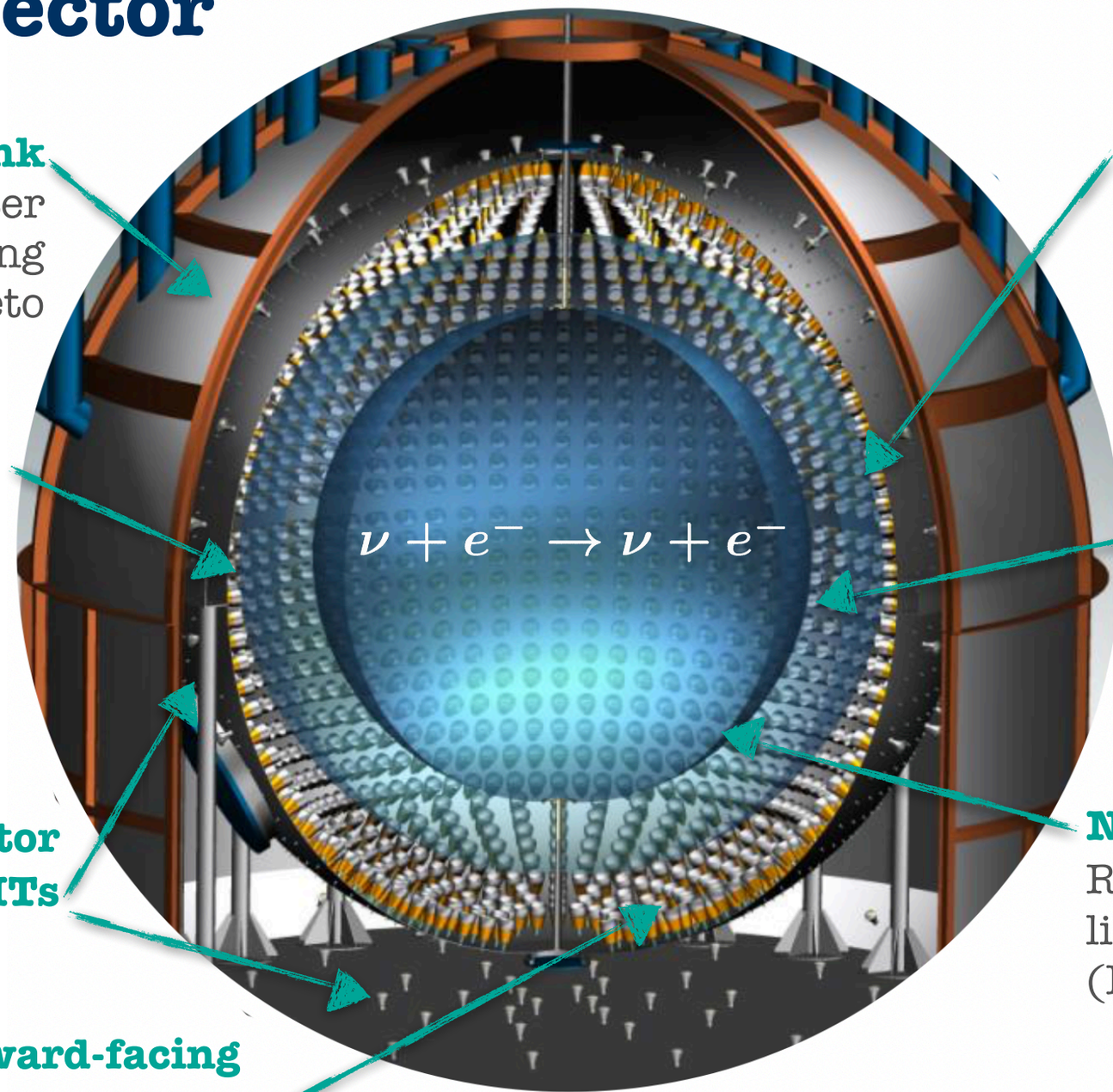
Borexino @ Laboratori Nazionali del Gran Sasso

Gran Sasso,
Apennines,
Abruzzo, Italy



Laboratori Nazionali del Gran Sasso (LNGS)

Borexino Detector



Water tank
R = 9 m, 2.1 kt water
Shielding
Cherenkov muon veto

Nylon Outer Vessel
R = 5.5 m
Barrier for ^{222}Rn
from steel, PMTs etc.

Stainless Steel Sphere
R = 6.85 m
PMTs support
Buffer + scintillator
container

Buffer
Pseudocumene (PC) +
DMP quencher

208 Outer Detector PMTs

Nylon Inner Vessel
R = 4.25 m, ~ 300 t of
liquid scintillator
(PC/PPO solution)

2212 Inward-facing PMTs

- Unprecedented scintillator radiopurity
- Low-energy threshold
- High light yield

- Good energy and position resolution
- Particle discrimination
- No directionality

Borexino achievements and goals

Purification I — 2007

Purification II — 2010, 2012

Thermal insulation — 2016

Phase I (2007-2010)

Phase II (2012-2016)

Phase III (2016-2020)

- ν (^{7}Be) flux [1-3]
- ν (^{8}B) flux [4]
- ν (pep) flux [5]
- ν (CNO) limit [5]
- Limit on NMM [1]

Improved radiopurity:

- ^{85}Kr: reduced by ~4.6
- ^{210}Bi: reduced by ~2.3
- Th and U negligible (~10^{-19} g/g)

- ν (pp) flux [6]
- **New results on the solar fluxes***
- Neutrino magnetic moment limit
- Correlations with gravitational wave signals
- **Non-standard interactions (NSI)**

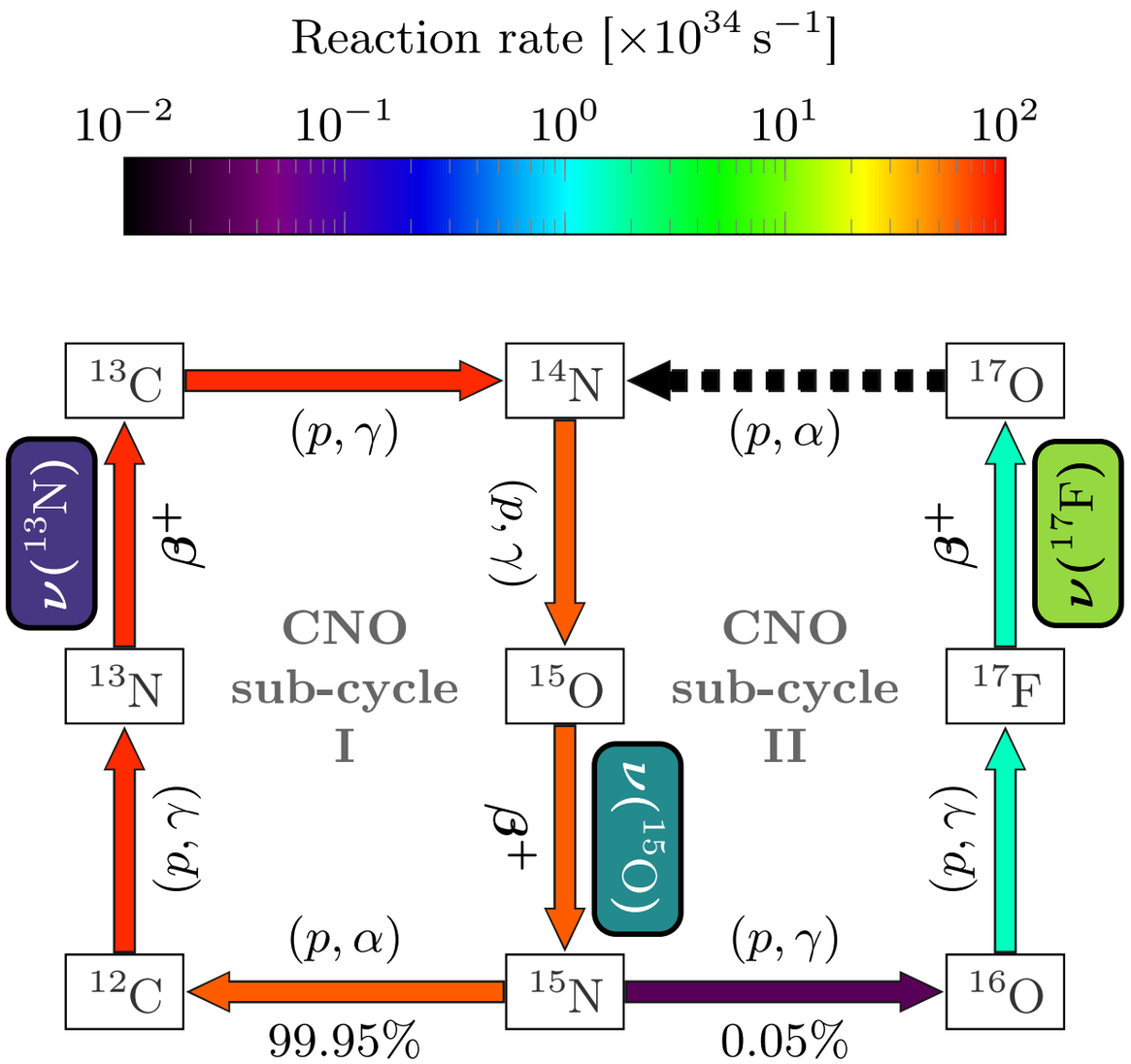
- **CNO detection**

- **Geoneutrinos latest update**

***Nature 496 (2018) 505.**

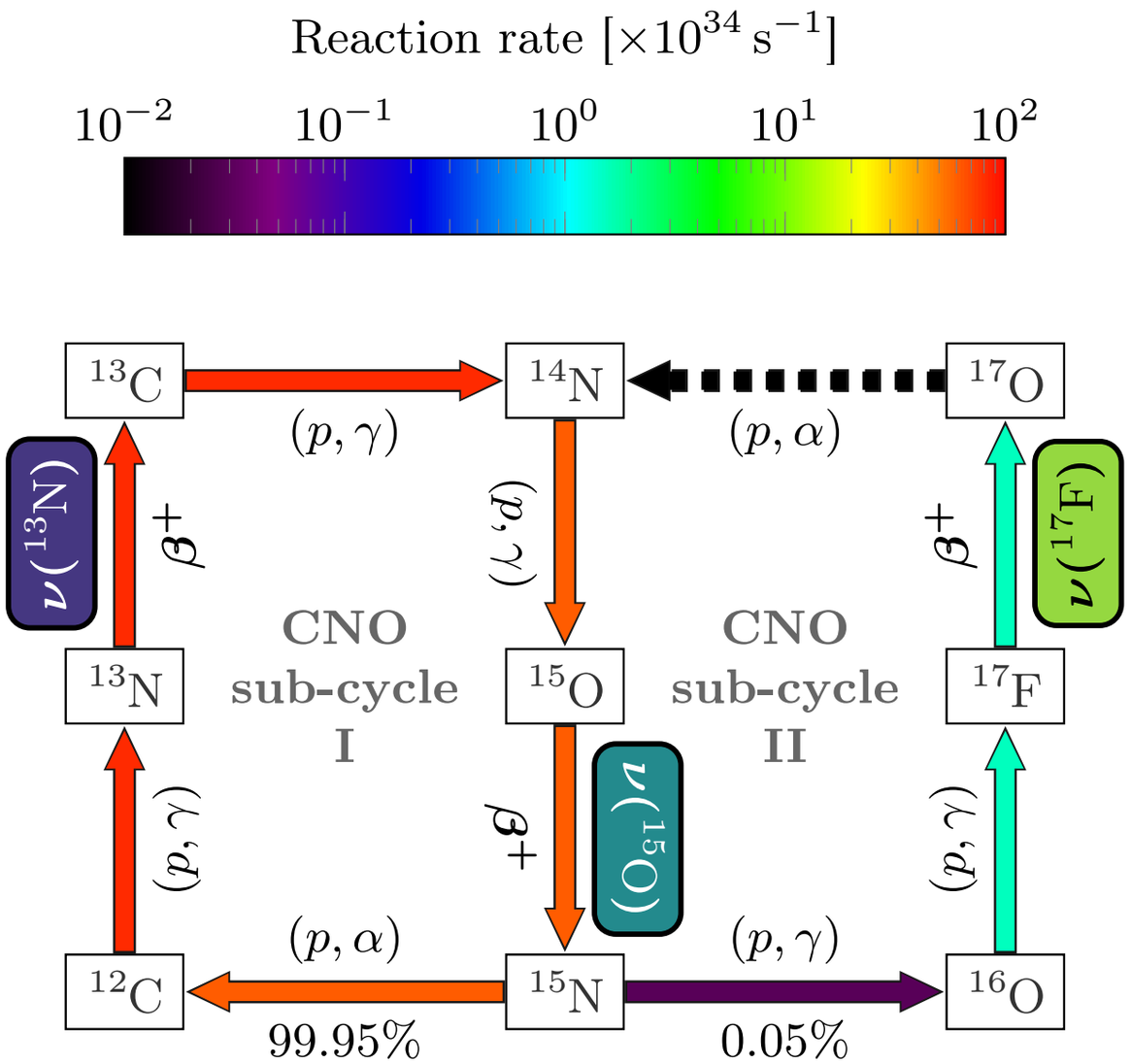
[1] DOI: 10.1103/PhysRevLett.101.091302; [2] DOI: 10.1016/j.physletb.2007.09.054; [3] DOI: 10.1103/PhysRevLett.107.141302; [4] DOI: 10.1103/PhysRevD.82.033006; [5] DOI: 10.1103/PhysRevLett.108.05130; [6] Nature 512 (2014) 383.

CNO neutrinos search motivation



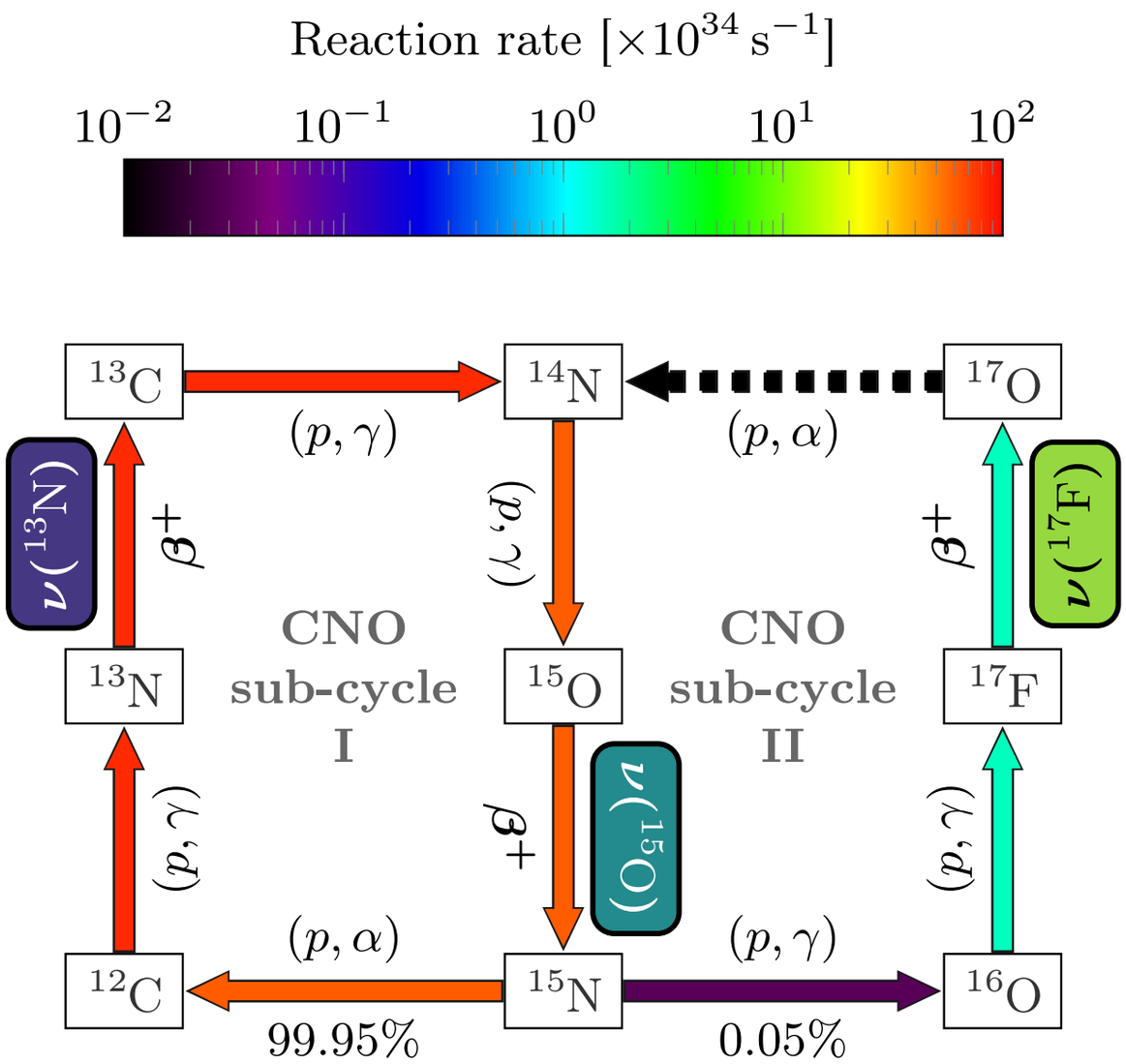
- **Proof of principle** of star energy production via CNO cycle
- Important for astrophysics studies of the Sun and **heavier stars** where the process is expected to be **dominant**

CNO neutrinos search motivation



- **Proof of principle** of star energy production via CNO cycle
- Important for astrophysics studies of the Sun and **heavier stars** where the process is expected to be **dominant**
- Large number of massive stars and their rapid evolution -> **the primary mechanism** for the stellar conversion of hydrogen into helium **in the Universe.**

CNO neutrinos search motivation



Solar ν	Expected Flux (HZ)	Expected Flux (LZ)	Difference (HZ-LZ)/HZ
CNO [10^8 cm^{-2} s^{-1}]	4.88 (1± 0.11)	3.51 (1± 0.11)	**28.1%**

- **Proof of principle** of star energy production via CNO cycle
- Important for astrophysics studies of the Sun and **heavier stars** where the process is expected to be **dominant**
- Large number of massive stars and their rapid evolution -> **the primary mechanism** for the stellar conversion of hydrogen into helium **in the Universe.**
- Sensitive to **Sun core metallicity (Z) problem**: almost 30% difference in predictions from high (HZ) vs low (LZ) Standard Solar Models
- Two-fold dependence on Z: **indirectly through core temperature and opacity** (as for the pp-chain solar neutrinos) + **directly dependent on the amount of carbon and nitrogen.**

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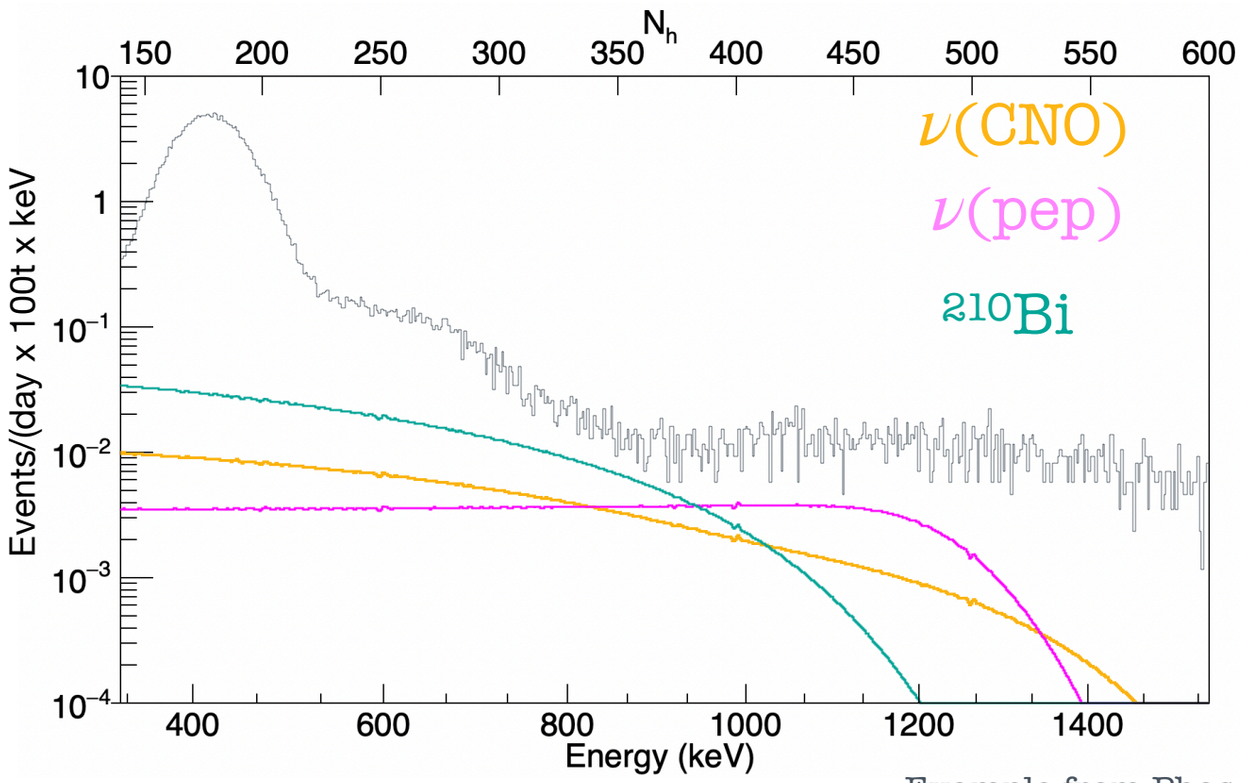
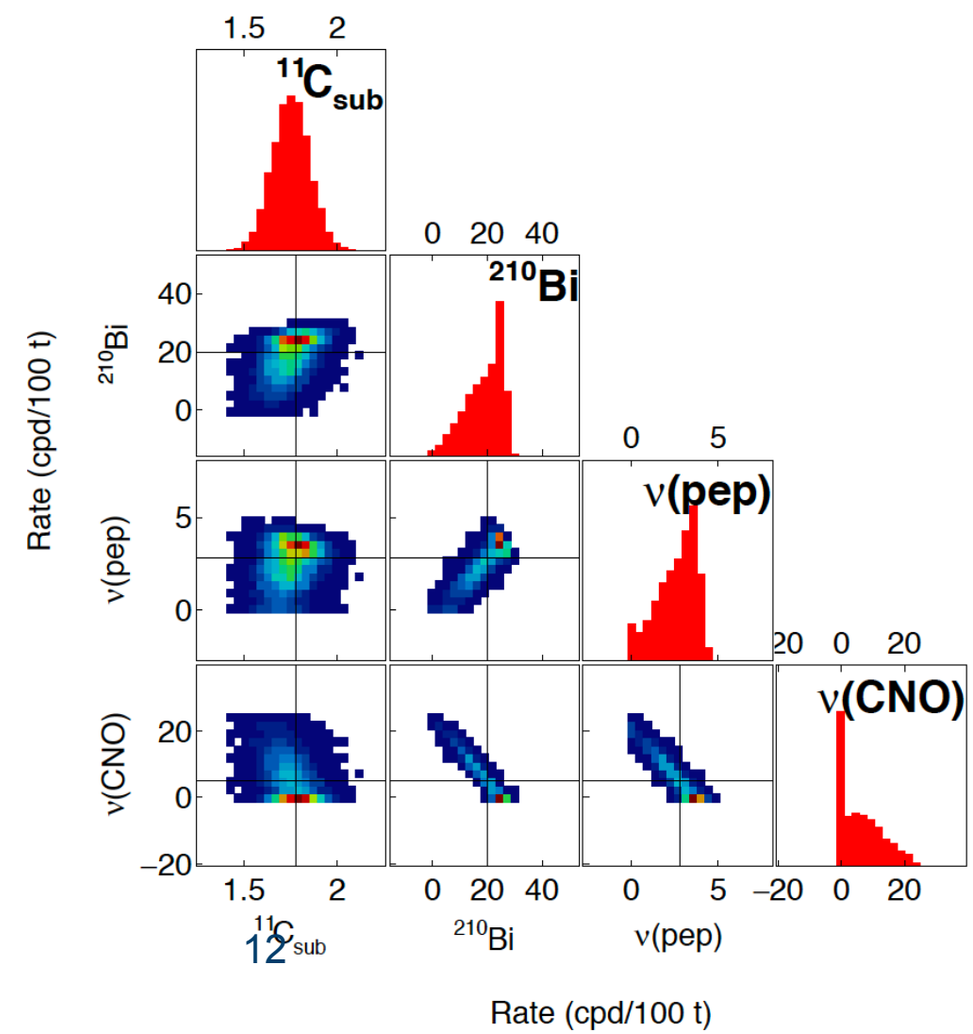
Challenges to measure CNO neutrinos

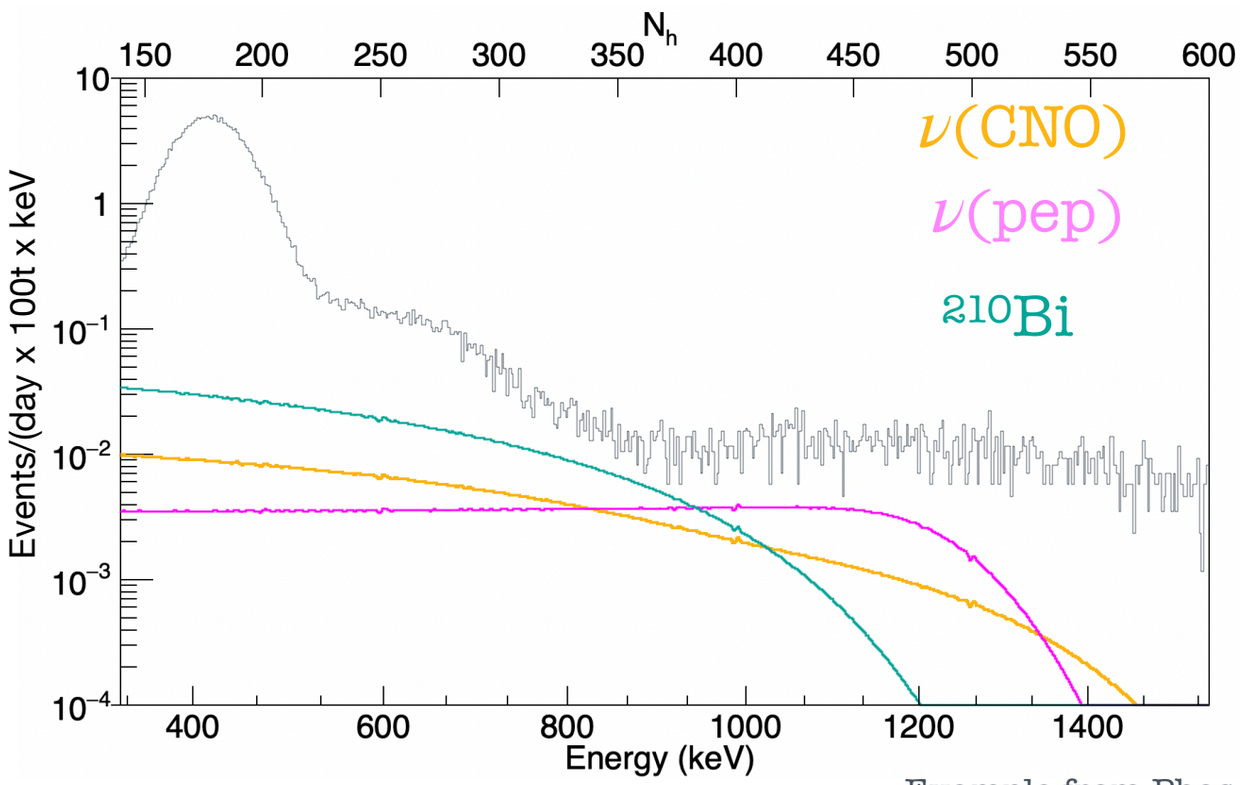


Example from Phase II

- Low rate of ν(CNO)~ 3-5 cpd/100ton
- Shape similar to ^{210}Bi and ν(pep)
- Strong correlations → need independent constraints:

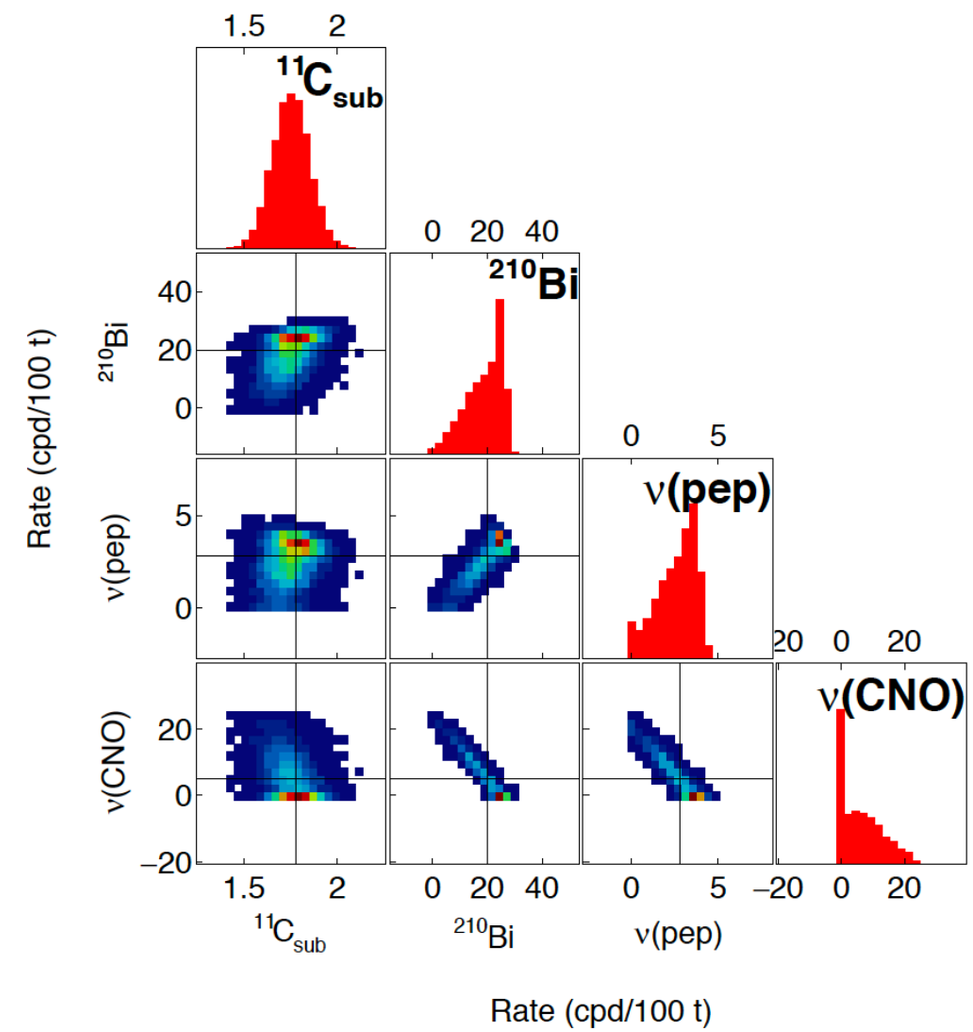


Challenges to measure CNO neutrinos



Example from Phase II

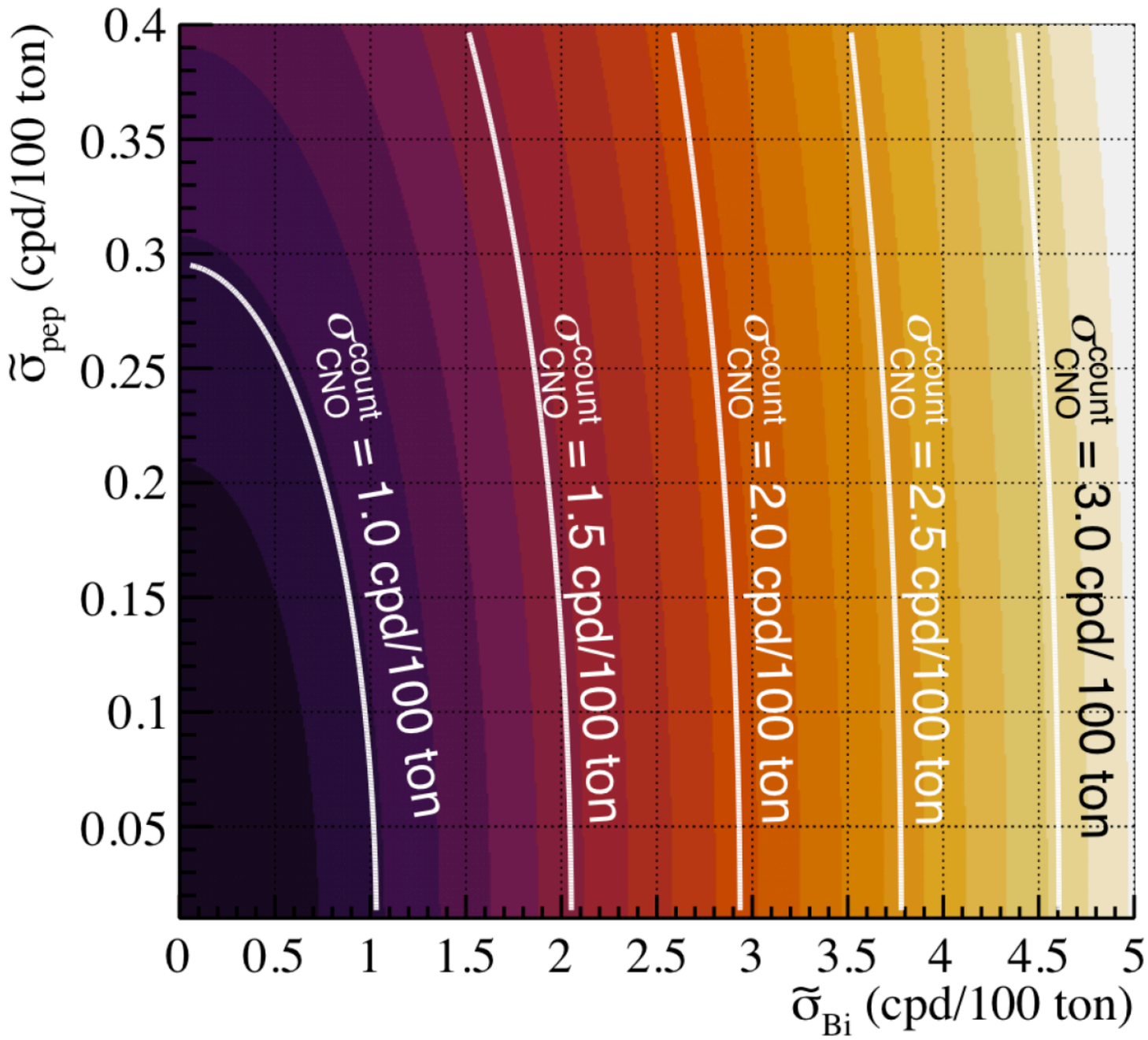
- Low rate of ν(CNO)~ 3-5 cpd/100ton
- Shape similar to ^{210}Bi and ν(pep)
- Strong correlations → need independent constraints:
  - ^{210}Bi: link with ^{210}Po (next many slides
  - ν(pep): solar luminosity constraint



The pep flux can be constrained at the 1.4 % level through the solar luminosity constraint coupled with robust assumptions on the pp to pep neutrino rate ratio, existing solar neutrino data, and the most recent oscillation parameters.

Bergström et al https://doi.org/10.1007/JHEP03(2016)132
F. Vissani https://doi.org/10.1142/11384

Sensitivity studies - Constraints expected impact

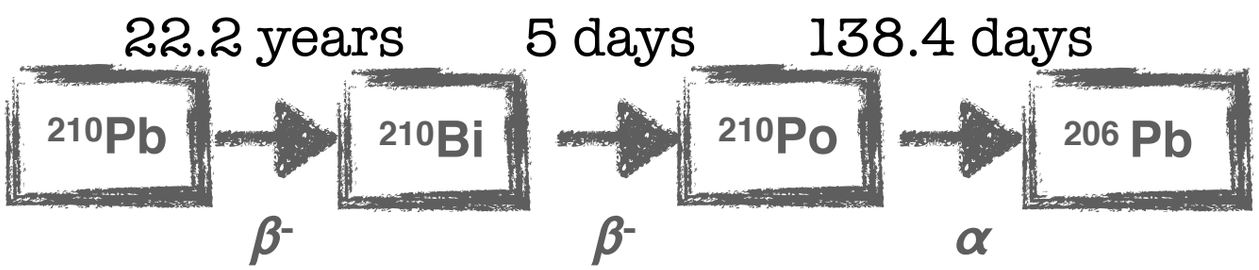


- **for a given ^{210}Bi constraint, no strong dependence of CNO measurement uncertainty on the value of pep constraint**
- **^{210}Bi constraint is much more crucial**

The quest for CNO is turned into

the quest of ^{210}Bi

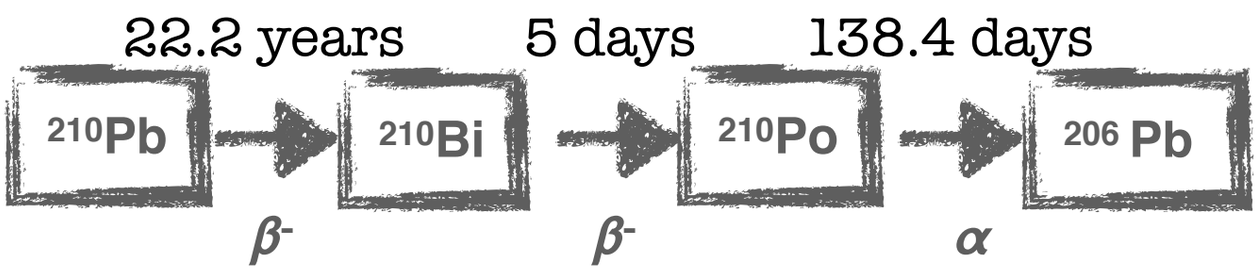
^{210}Bi challenge



^{210}Bi constraint from ^{210}Po measurement

At secular equilibrium the rate of ^{210}Bi is equal to that of ^{210}Po

^{210}Bi challenge



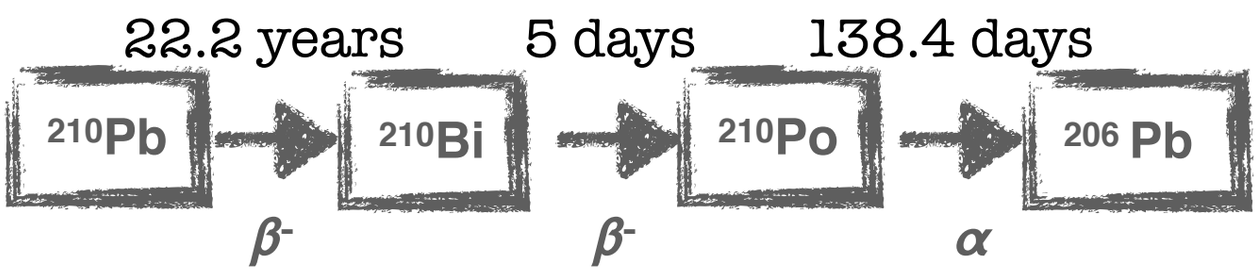
^{210}Bi constraint from ^{210}Po measurement

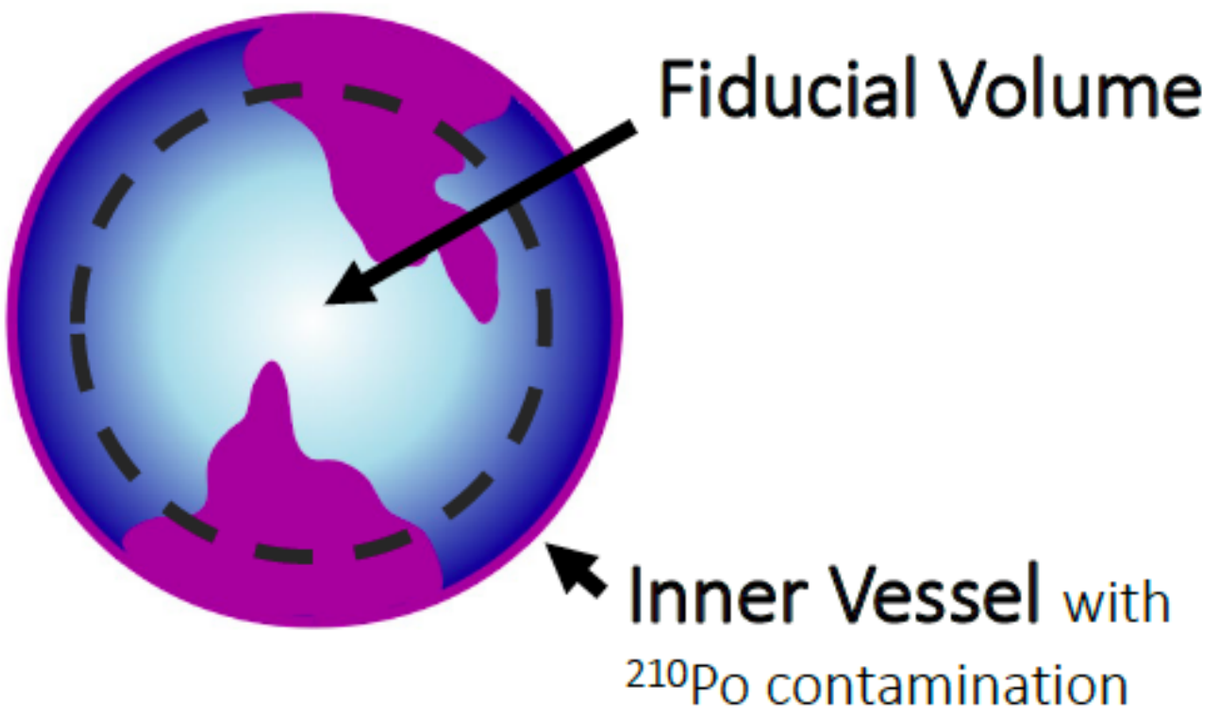
At secular equilibrium the rate of ^{210}Bi is equal to that of ^{210}Po

^{210}Po identification advantages:

- Monoenergetic decay → "gaussian" peak
- α-decay → pulse shape discrimination

^{210}Bi challenge





$$R(^{210}\mathrm{Po}_{\mathrm{min}}) = R(^{210}\mathrm{Bi}) + R(^{210}\mathrm{Po}^{\mathrm{V}})$$

^{210}Bi constraint from ^{210}Po measurement

At secular equilibrium the rate of ^{210}Bi is equal to that of ^{210}Po

^{210}Po identification advantages:

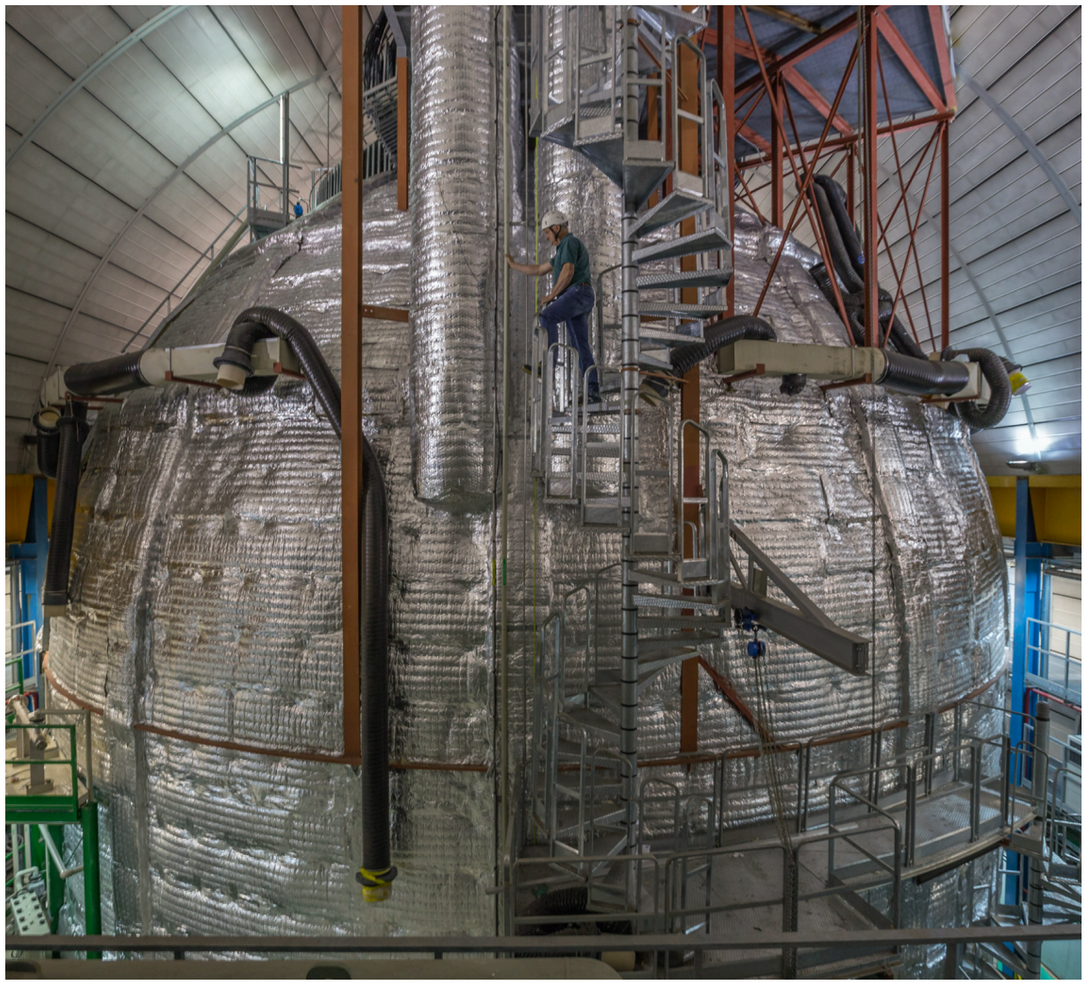
- Monoenergetic decay → "gaussian" peak
- α-decay → pulse shape discrimination

^{210}Po stability challenges:

- the intrinsic value is perturbed by the presence of strong convective motions, caused mostly the seasonal and man-made temperature change in the experimental hall
- Need thermal insulation to stop convective motions

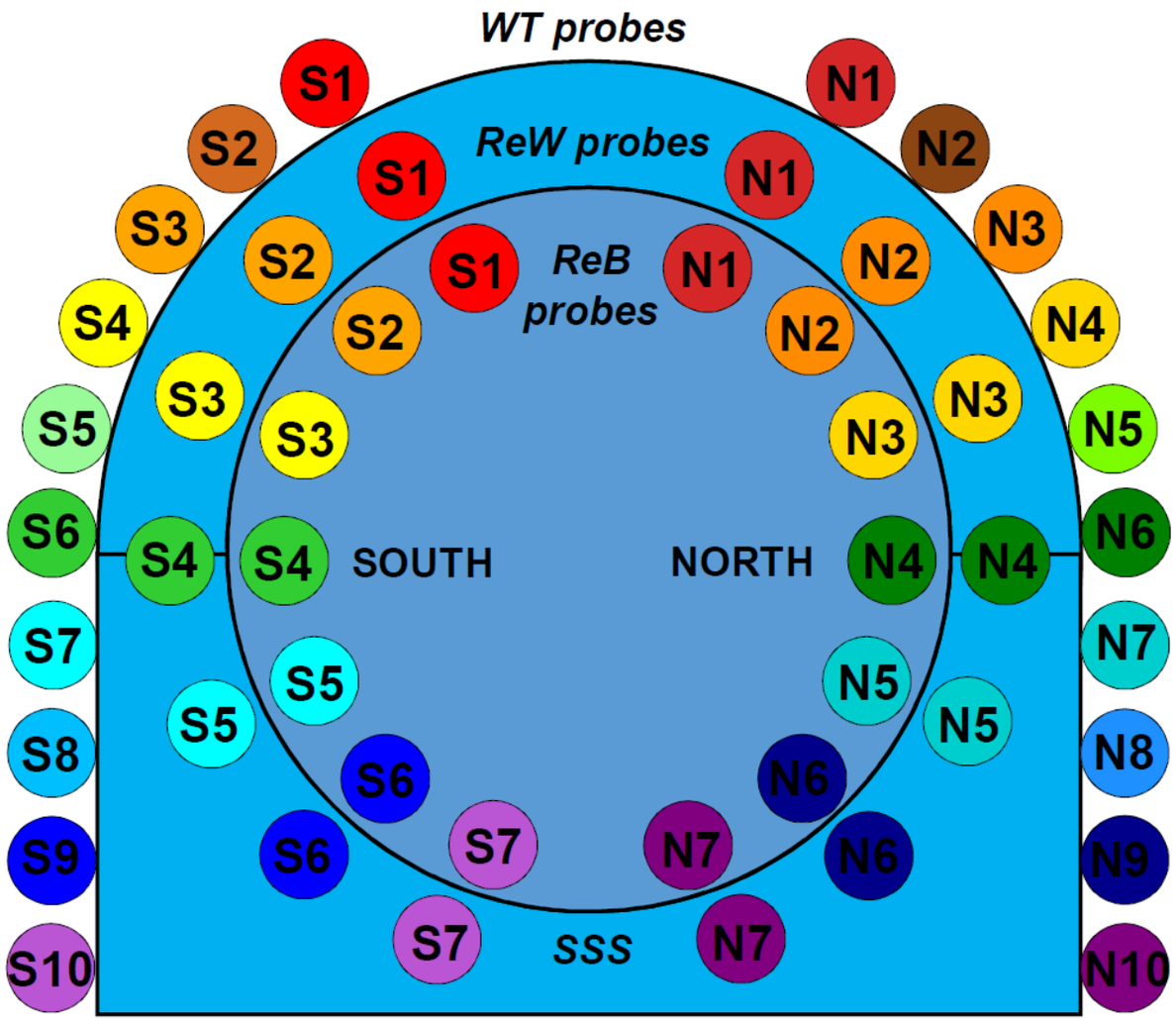
Hardware campaign: monitor, understand, suppress

Thermal insulation with double layer of mineral wool (900m²) & Active Gradient Stabilization System (2014-2016)



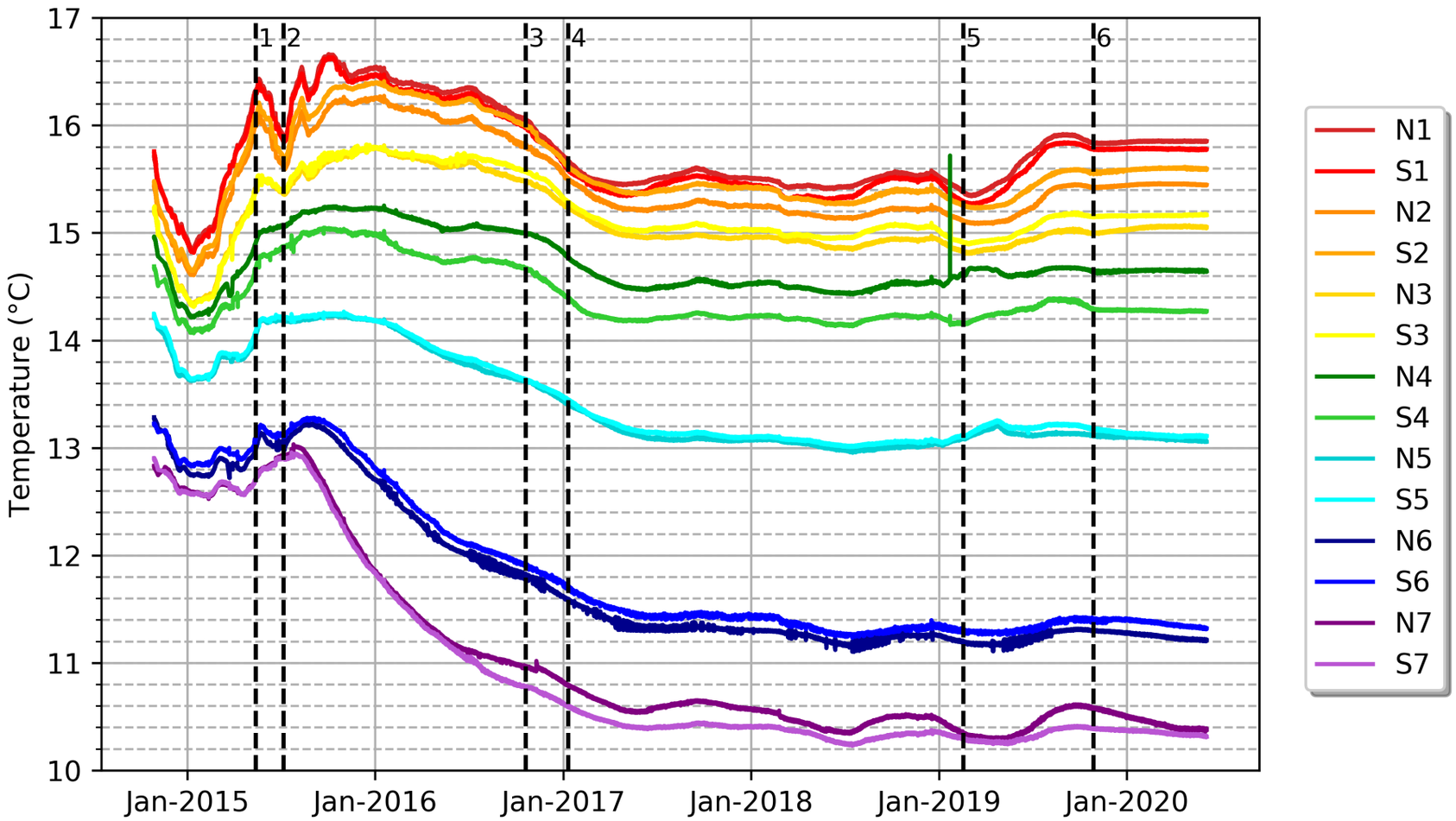
(thermal conductivity down to 0.03W/m/K)

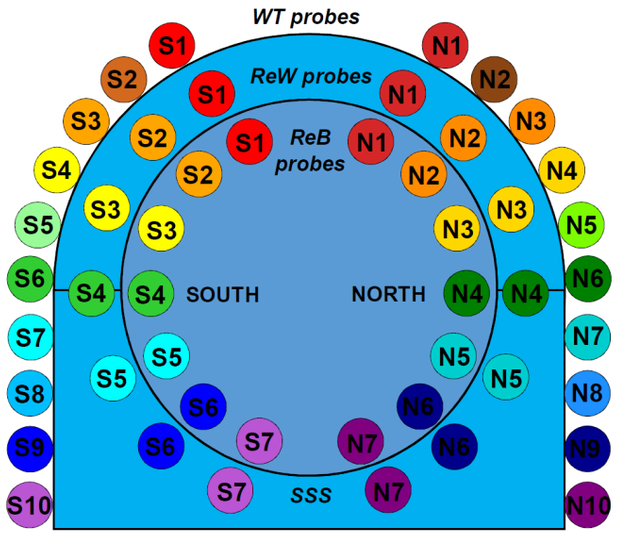
Temperature probes (2014-2015)



66 probes with 0.07°C resolution

Hardware campaign: monitor, understand, suppress





- **Fluid dynamical simulations**
- **Hall C Temperature Stabilization**
- **Achieved excellent temperature stability with the establishment of a clear temperature gradient**

1. Beginning of the insulation
2. Water recirculation off
3. Completion of the insulation
4. Start of active control temperature system (ACTS)
5. Change of ACTS set points
6. Start of hall C temperature control system

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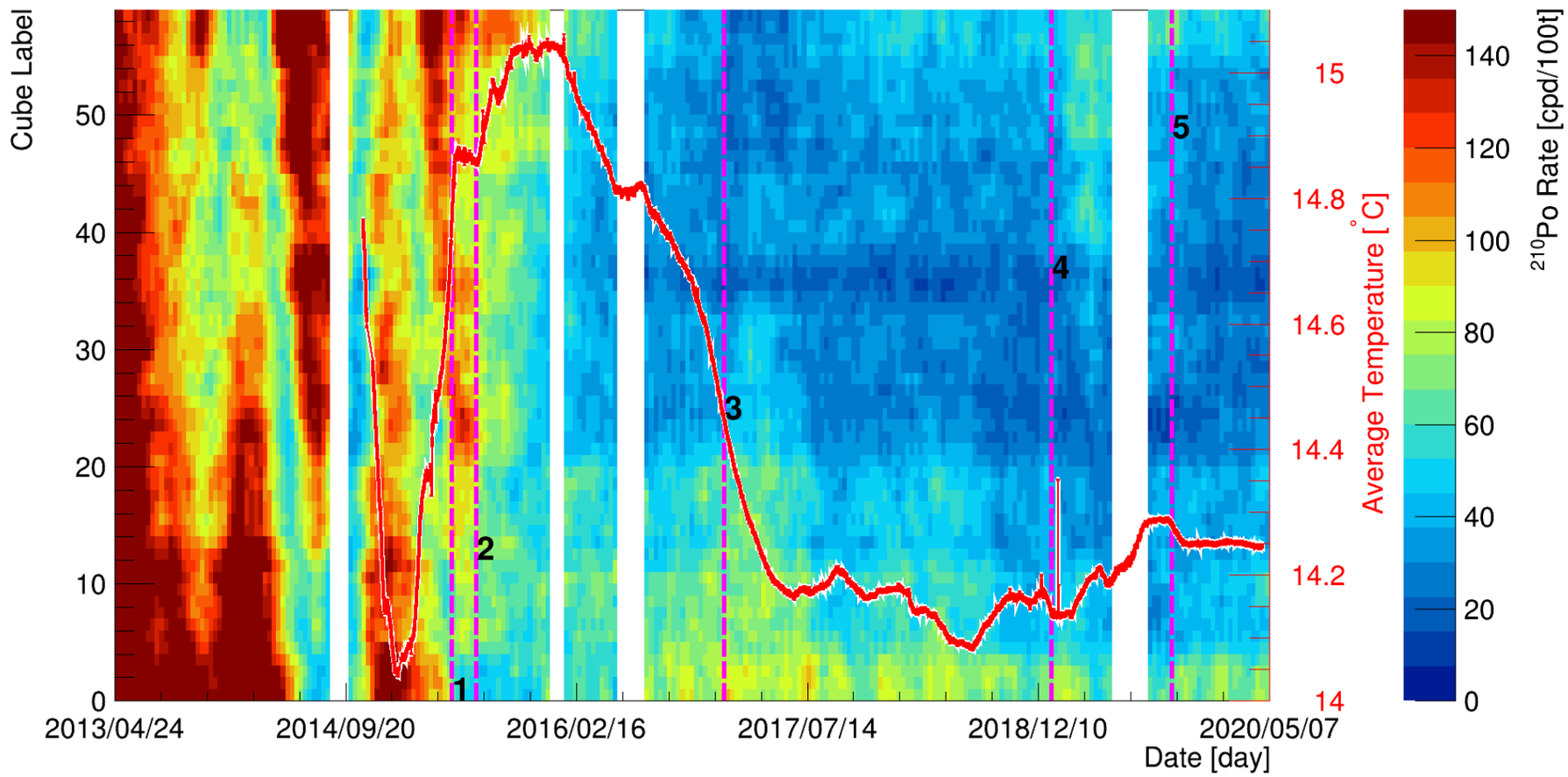
^{210}Po mapping



Convective motions before insulation

1. Beginning of the insulation
2. Water recirculation off
3. Completion of the insulation

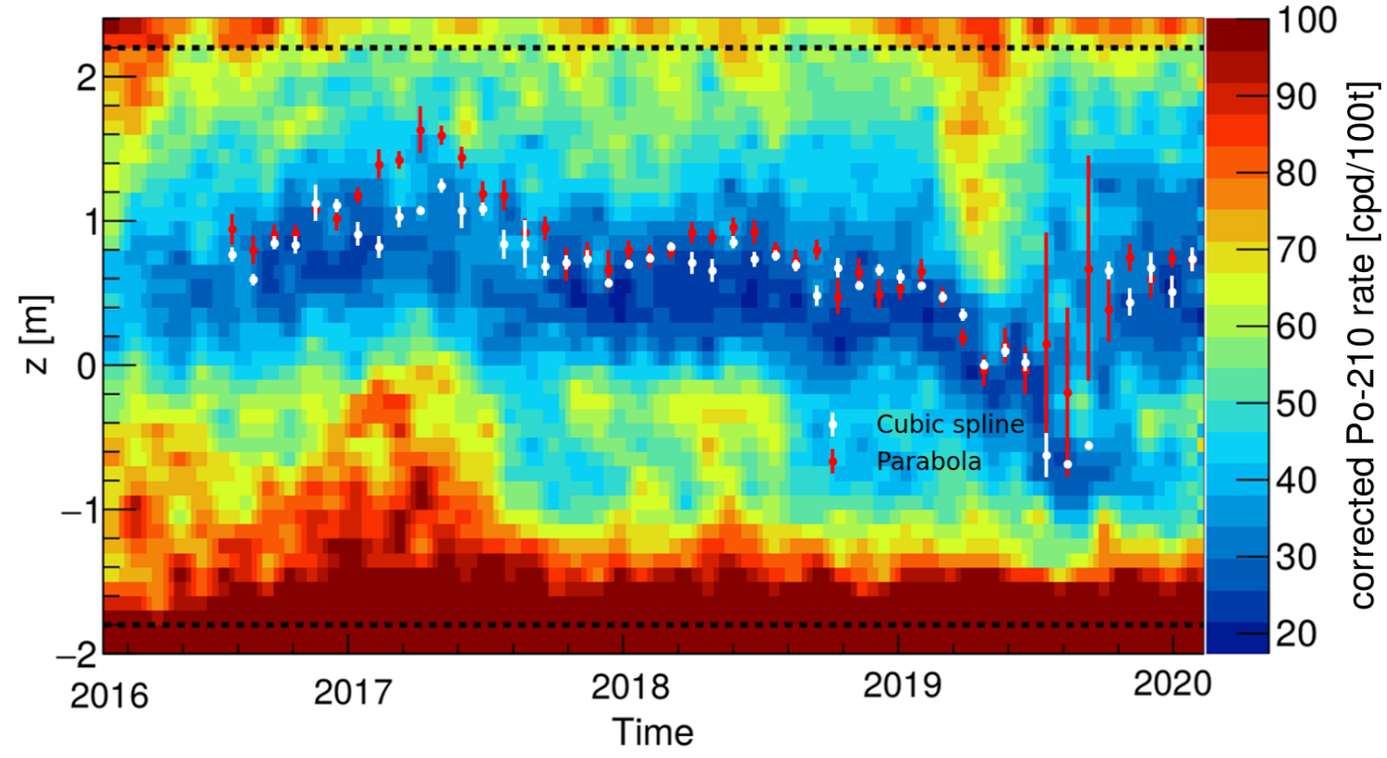
Stabilized after insulation

4. Start of active control temperature system (ACTS)
5. Change of ACTS set points

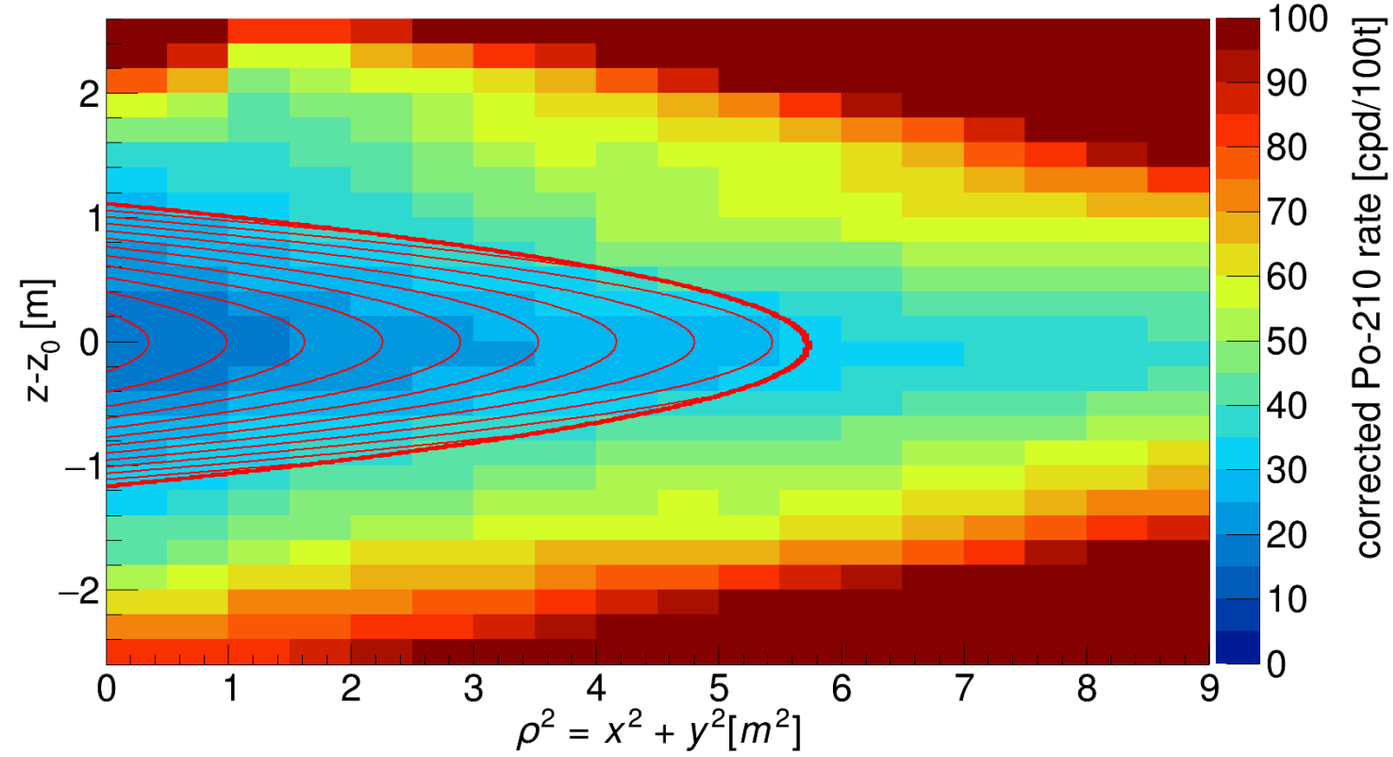
"Low Polonium Field" (20 tons) from which we can infer the intrinsic ^{210}Po and hence the ^{210}Bi

Low ^{210}Po field analysis

- Paraboloidal/spline fit over one/ two-month periods
- Extract z position of ^{210}Po minimum over time
- Align data using previous month center position
  - 1. Paraboloid
  - 2. Paraboloid along x-y + Cubic spline along z
- Po rate in LPoF = supported Po + slowly decaying convective Po

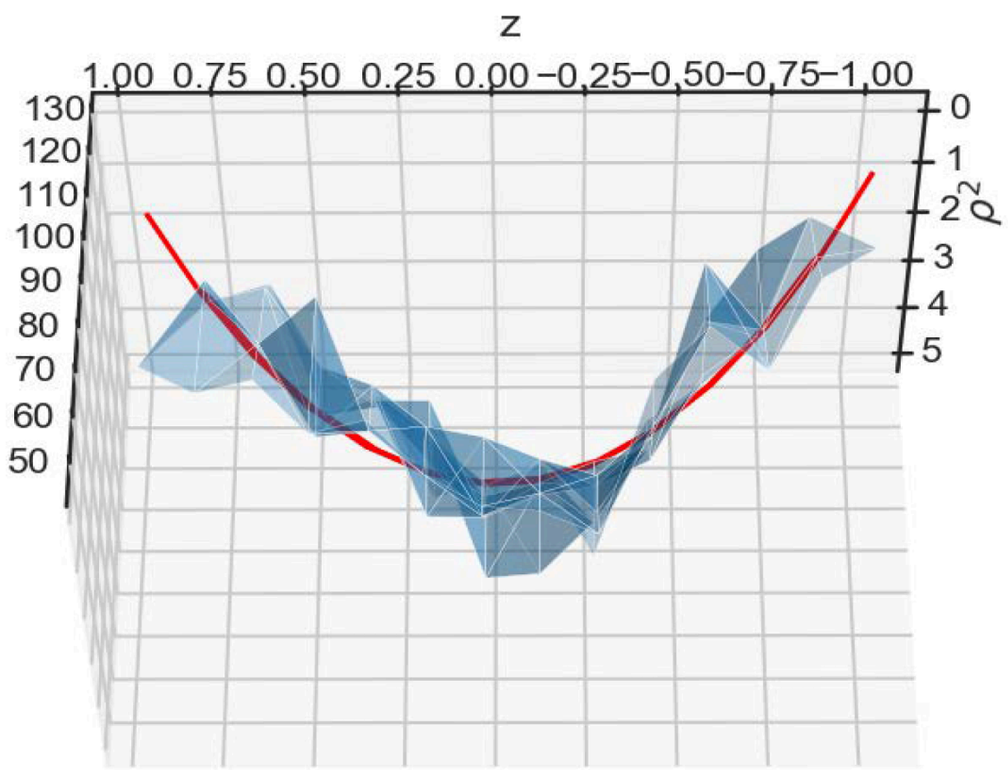


20t, center at ~80 cm above equator (moves very slowly) free of convective motions, resembling an ellipsoid with rotational symmetry along the x-y plane.

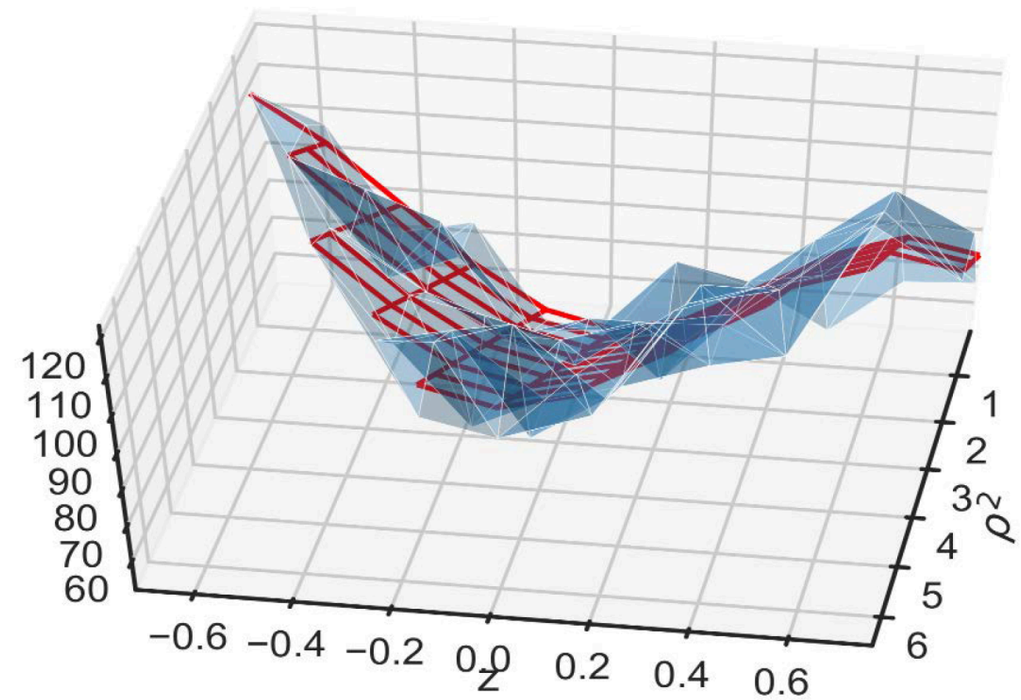


^{210}Po spatial distribution fits

Paraboloidal fit



Paraboloidal along x-y + Cubic spline along z

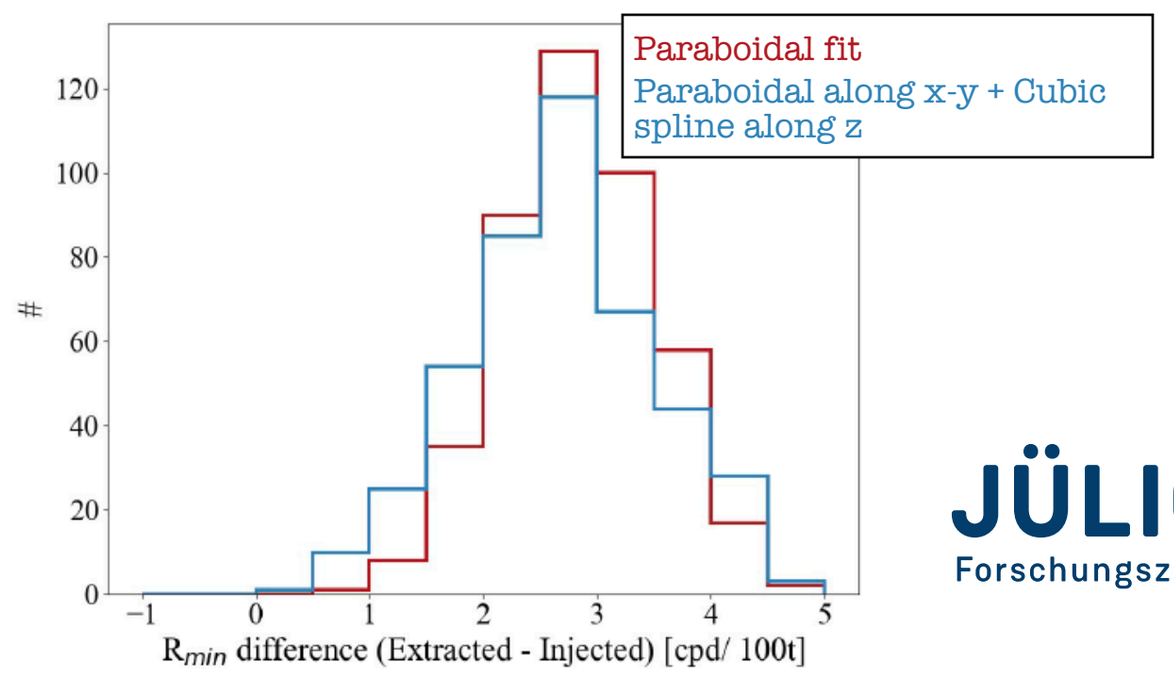


$$R(^{210}Po) = R_{min}\varepsilon \cdot \left(1 + \frac{\rho^2}{a^2} + \frac{(z - z_0)^2}{b^2}\right) + R_\beta$$

Complex structure along the z axis are accounted with a spline model within a Bayesian framework

Toy MC validation:
Datasets of 2 years livetime each with supported and convective ^{210}Po

No negative bias in both methods → **conservative ^{210}Bi upper limit** → no false enhancement of CNO rate



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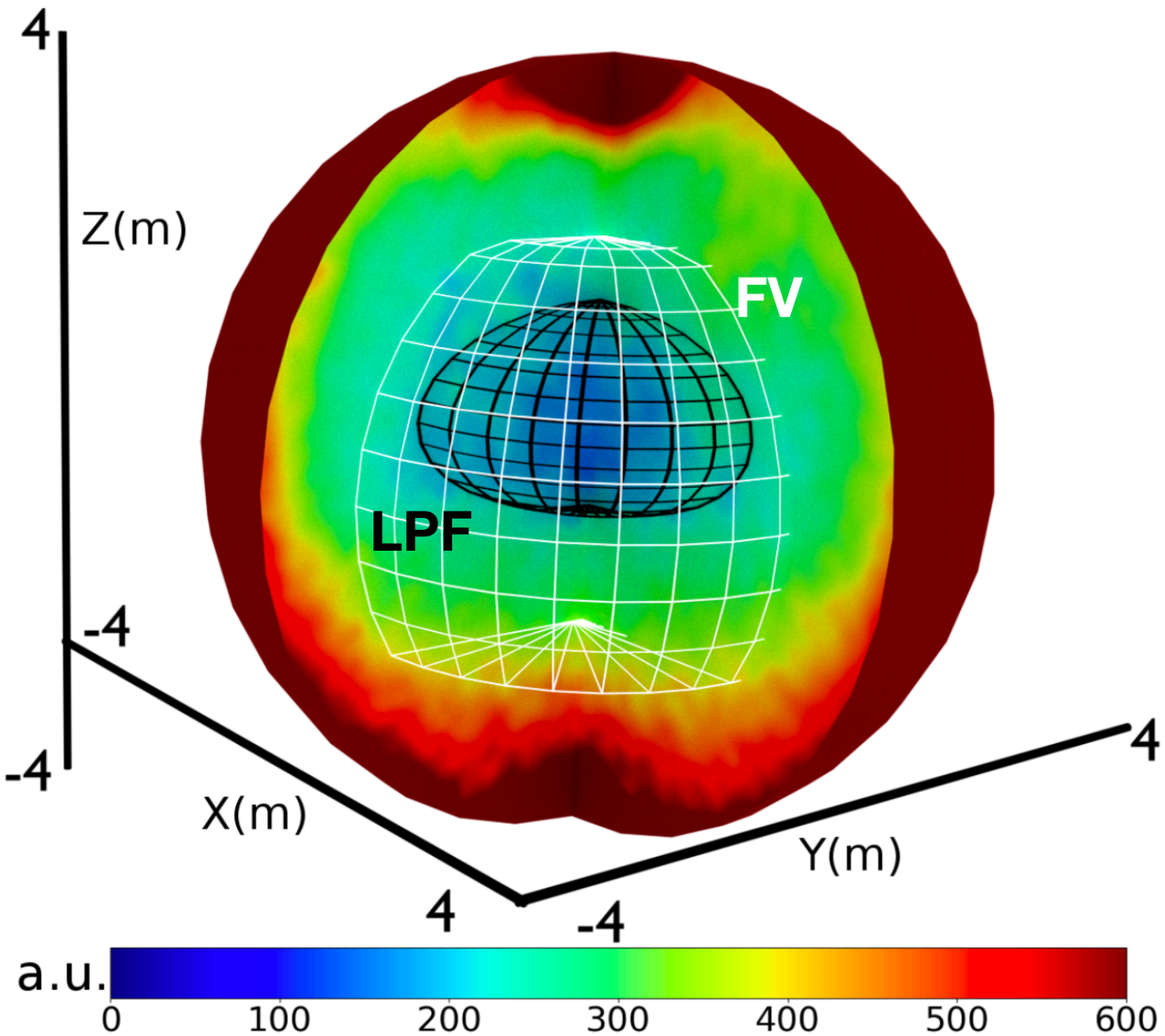
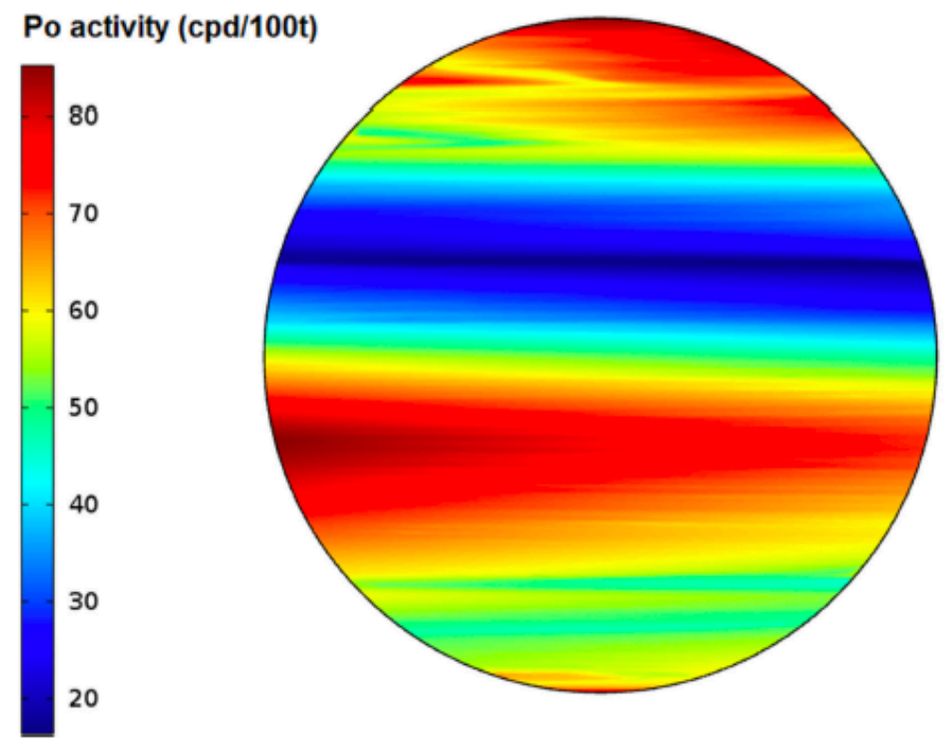
Low ^{210}Po field

20t, center at 80 cm above equator (moves very slowly)



Remarkable agreement with expectations from fluid dynamics simulations

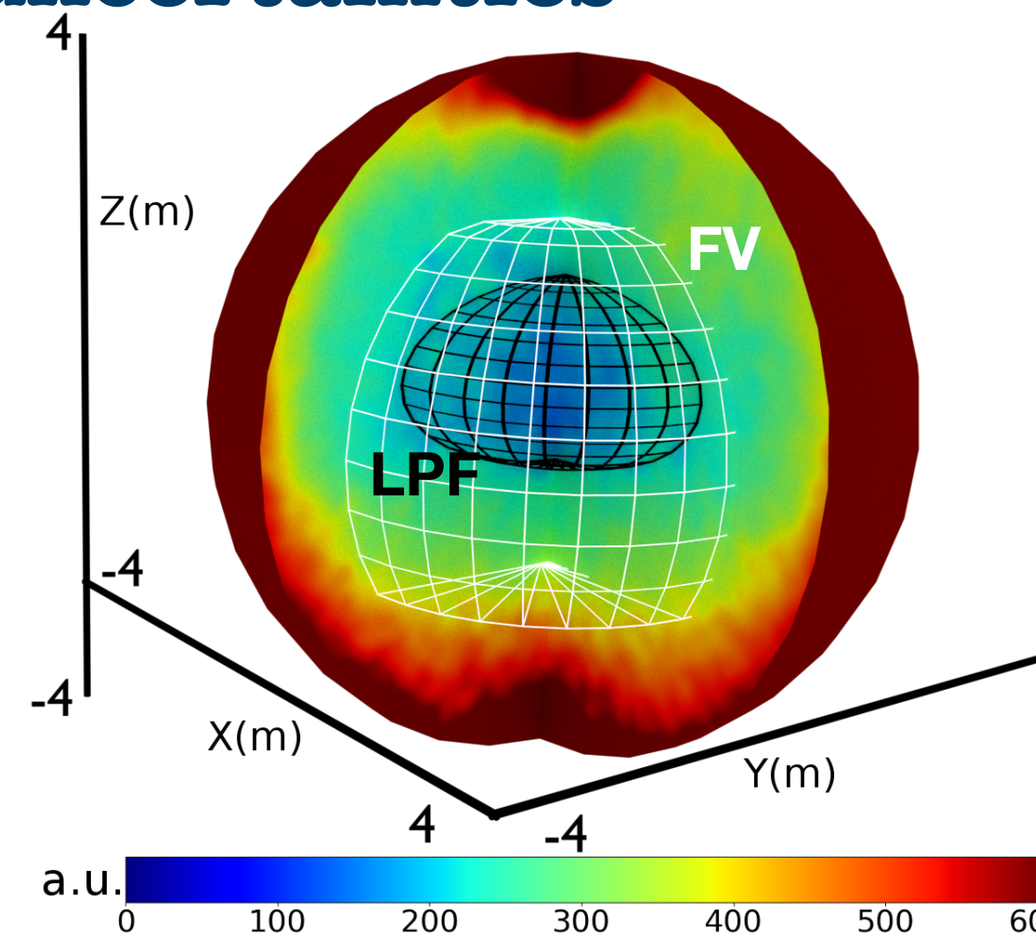


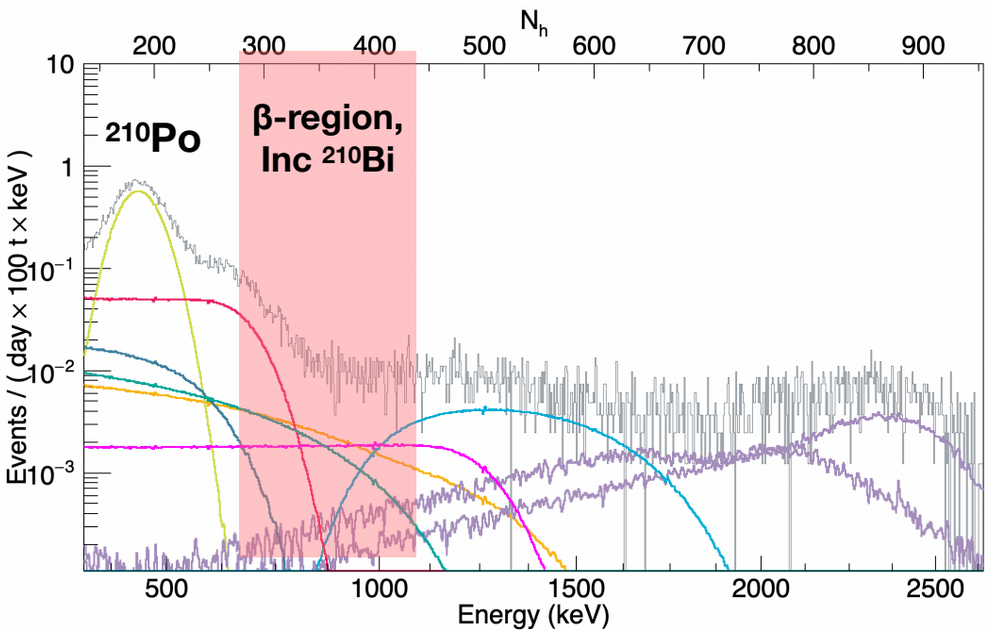
"Low Polonium Field" (20 tons) from which we can infer the intrinsic ^{210}Po and hence the ^{210}Bi

^{210}Bi assessment systematic uncertainties

- ^{210}Bi constraint based on 20t region analysis
- CNO analysis: implicitly extrapolating the ^{210}Bi constraint from the LPoF to the larger FV mass (70t)
- Precision level of ^{210}Bi uniformity in the FV → systematic to the ^{210}Bi constraint

Selection of β-like events
- Stability in time
- Uniformity in space

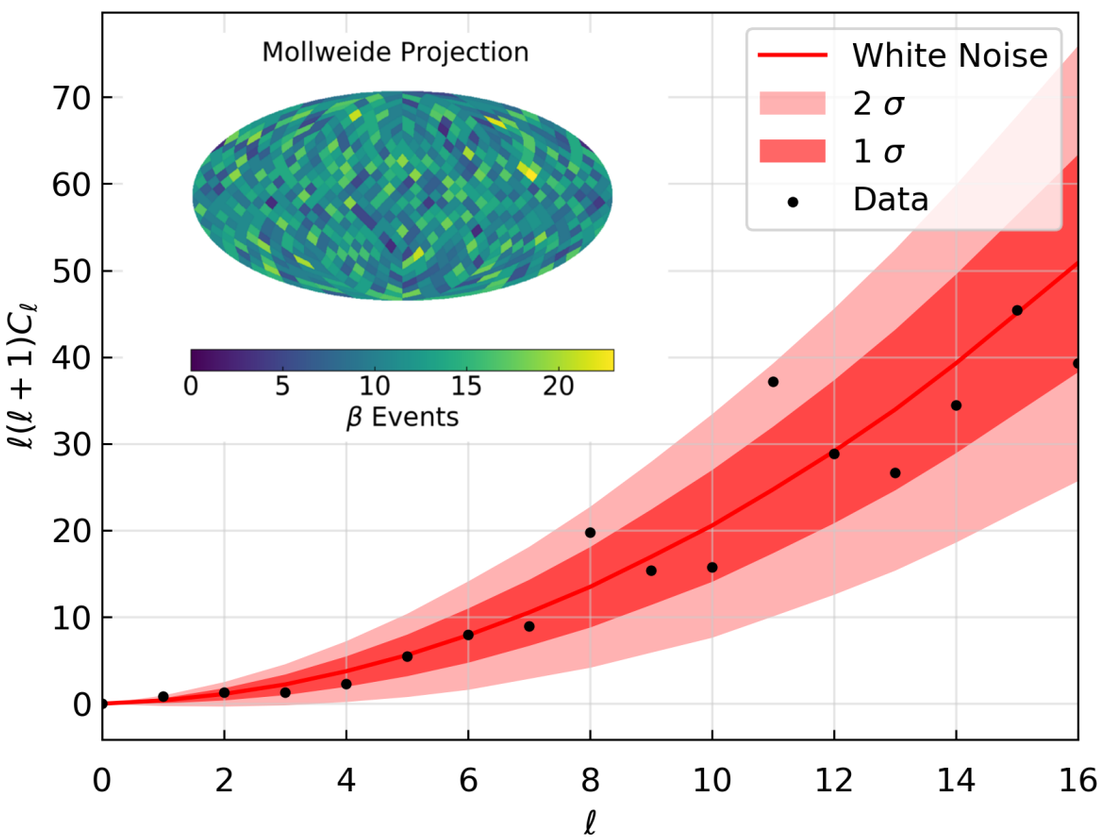




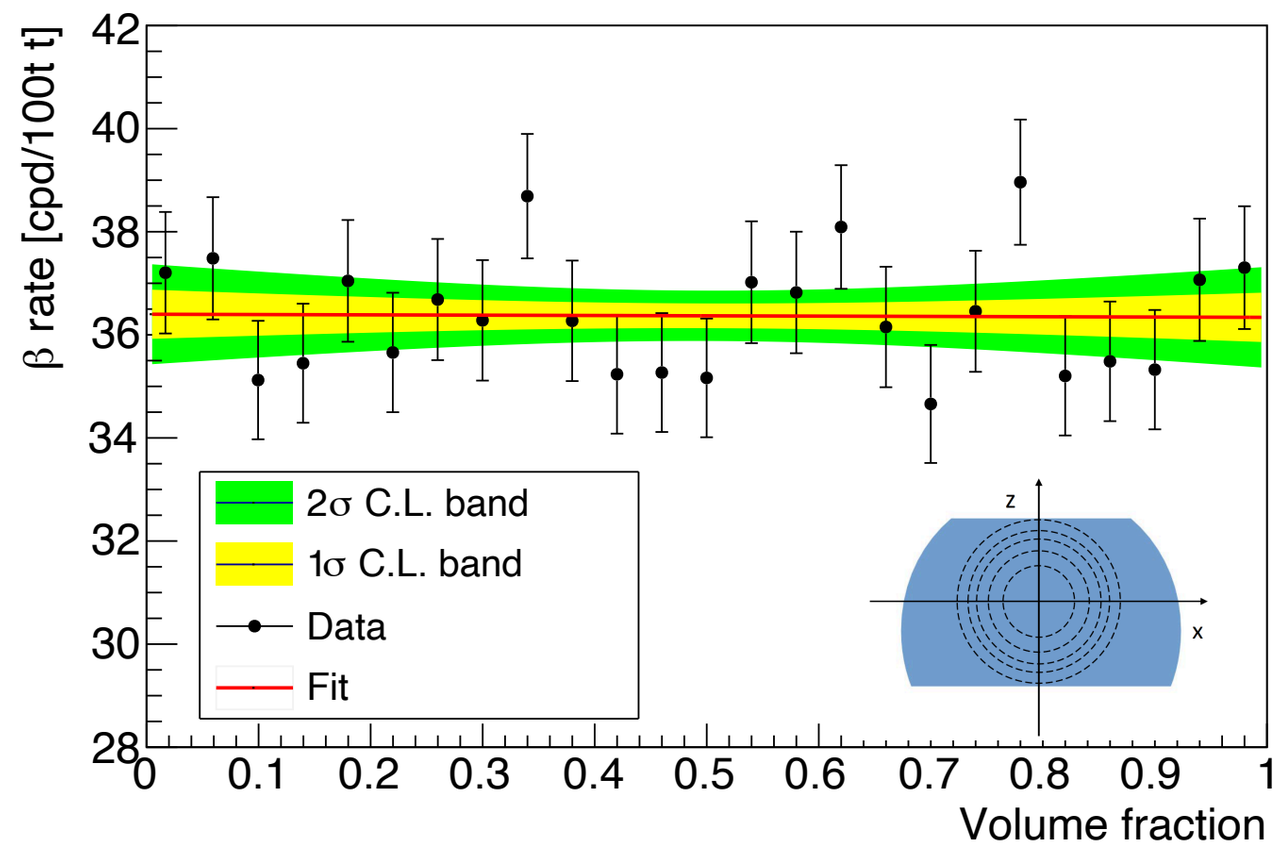
Analyzing β spatial distribution of events in a large energy range (above ^{210}Po-α)
→ ~75% neutrinos
→ ~15% ^{210}Bi
→ ~10% ^{11}C and ^{85}Kr
Rate variations are attributed to ^{210}Bi events (conservative approach)

^{210}Bi systematic uncertainties: spatial uniformity

^{210}Bi angular distribution



^{210}Bi radial distribution



Radial shell analysis
σ^{sys}(rad) = 0.51 cpd/100 t

Spherical harmonic decomposition
σ^{sys}(ang) = 0.59 cpd/100 t

Overall ^{210}Bi spatial uniformity systematics: 0.78 cpd/100t

^{210}Bi assessment inc. systematic uncertainties

- No evidence of any relevant time variation besides the expected annual modulation due to solar neutrinos of 3.3% (Be-ν's contribute >60% to the β rate in the selected energy windows).
- Systematics from mass of the fit region of ^{210}Po data: 0.4 cpd/100t
- Uncertainty due to estimation of leak of β-events in ^{210}Po region using pulse-shape discrimination: 0.3 cpd/100t

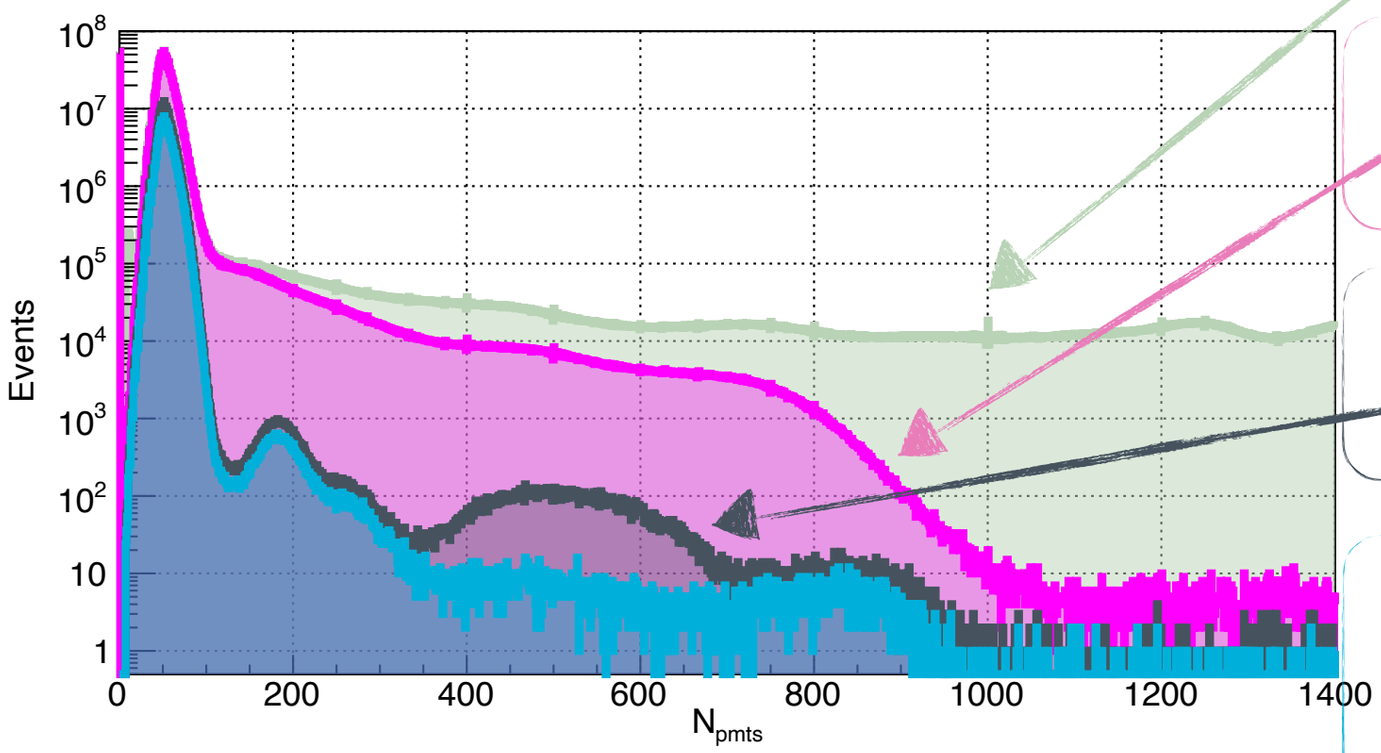
R_{min} (cpd/100t)	σ_{fit}	σ_{mass}	$\sigma_{binning}$	$\sigma_{Bi_homogenu}$	$\sigma_{\beta leak}$	σ_{total}
11.5	0.88	0.36	0.31	0.78	0.3	**1.3**

- Rmin(^{210}Po) may be overestimated because of residual ^{210}Po from the vessel
  -> Upper limit on ^{210}Bi rate:

$R(^{210}Bi) \leq (11.5 \pm 1.3)$ cpd/100 t

Phase-III dataset

☀ **Dataset:** July 2016 - February 2020
☀ **Exposure:** 1071,95 days x 71.3 tons



Data selection main steps:

All data

muon and muon daughter cuts:
300 ms after crossing muons

Fiducial volume (FV) cut:
R<2.8 m; -1.8m <z<2.2m

Three fold coincidence tag (^{11}C veto)
-> ^{11}C depleted energy spectrum

Three fold coincidence tag (^{11}C veto)

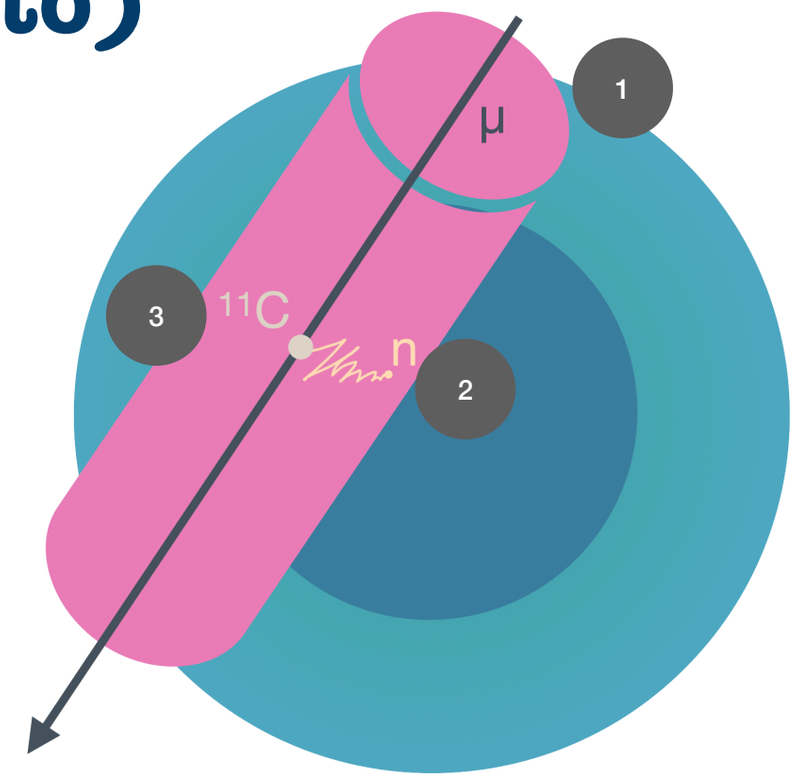
Cosmogenic background

Calculate for each event the likelihood to be **^{11}C** through the three fold coincidence:

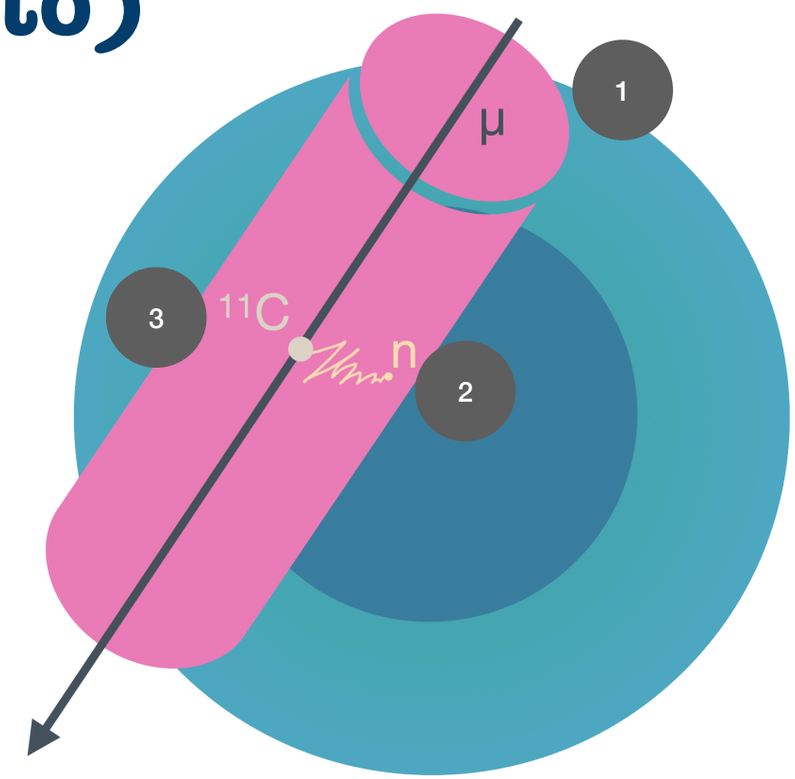
$$\mu + {}^{12}C \rightarrow \mu + {}^{11}C + n \quad (1)$$

$$n + p \rightarrow D + \gamma_{(2.2\ MeV)} \quad (250\ \mu s) \quad (2)$$

$${}^{11}C \rightarrow {}^{11}B + e^{+} + \nu_e \quad (\sim 30\ min) \quad (3)$$



Three fold coincidence tag (^{11}C veto)



Cosmogenic background

Calculate for each event the likelihood to be **^{11}C** through the three fold coincidence:

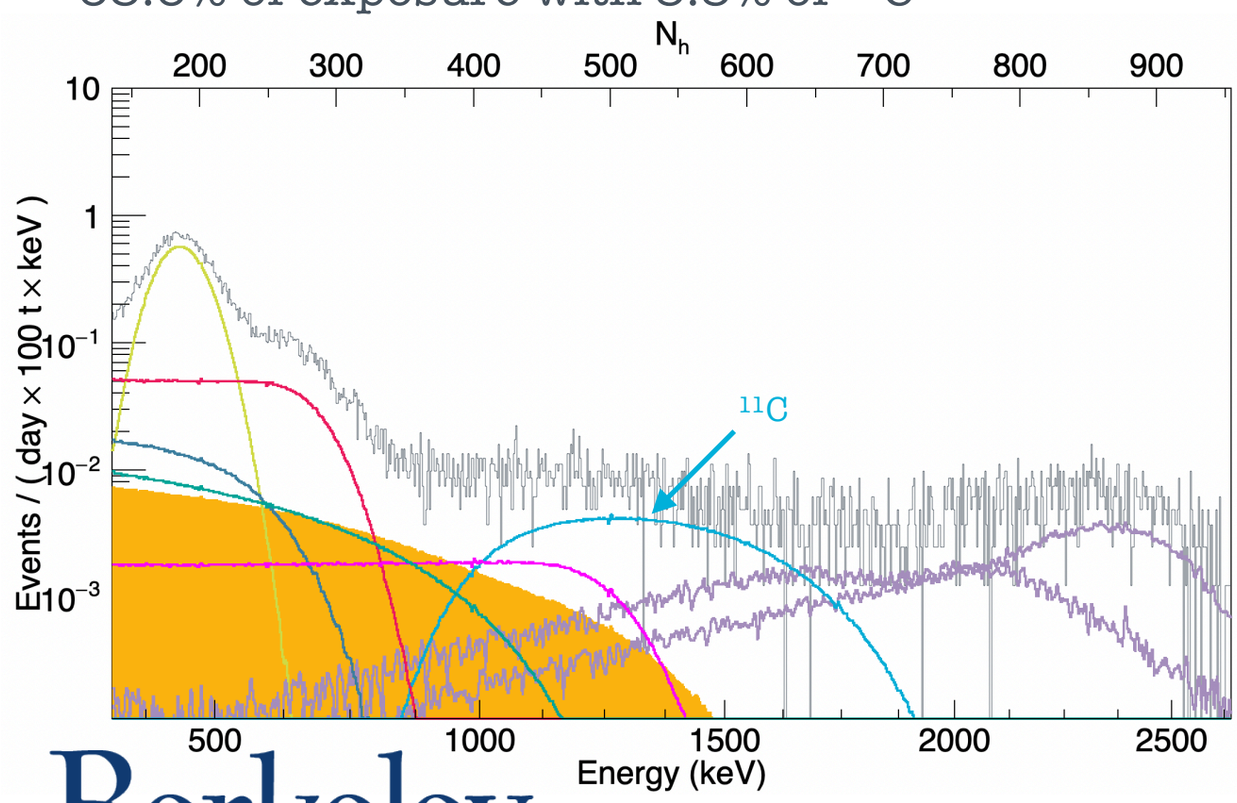
$$\mu + {}^{12}C \rightarrow \mu + {}^{11}C + n \quad (1)$$

$$n + p \rightarrow D + \gamma_{(2.2\ MeV)} \quad (250\ \mu s) \quad (2)$$

$${}^{11}C \rightarrow {}^{11}B + e^{+} + \nu_e \quad (\sim 30\ min) \quad (3)$$

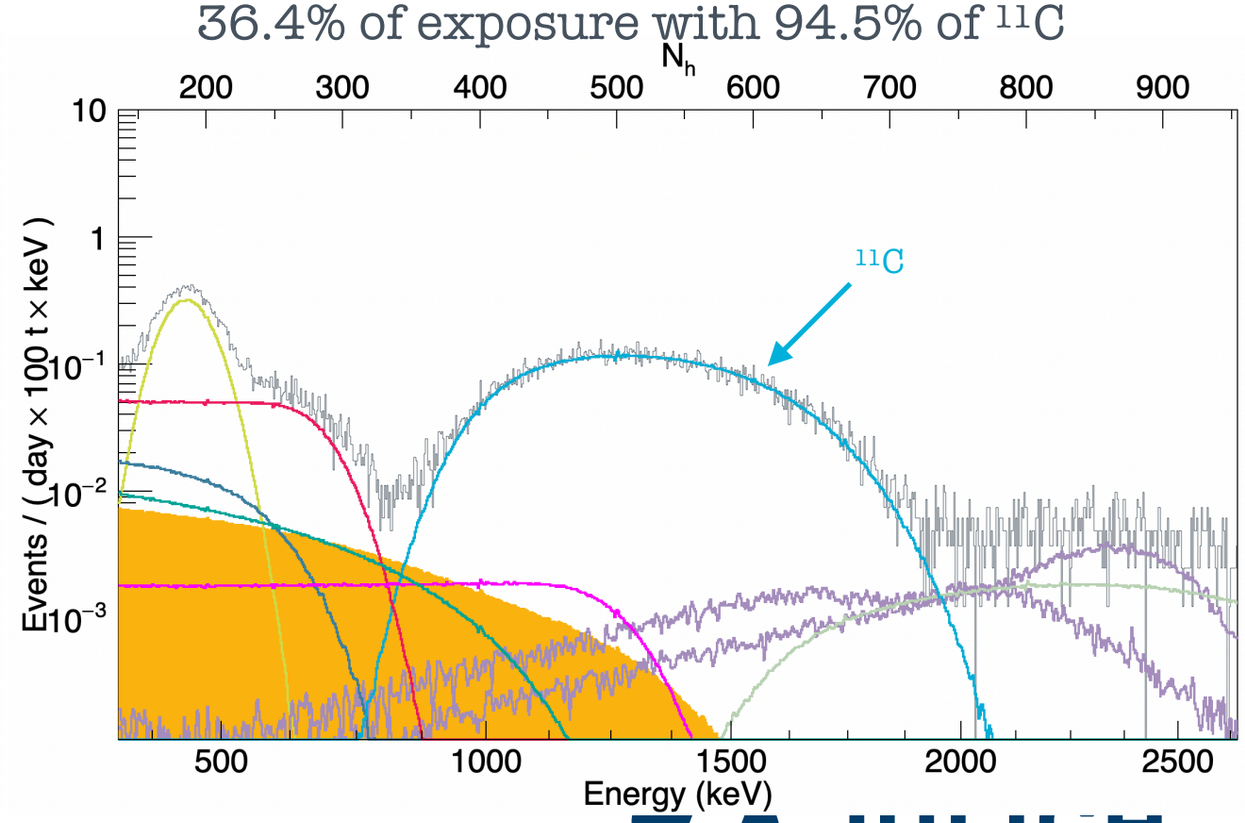
☀ **^{11}C depleted energy spectrum:**

63.6% of exposure with 5.5% of ^{11}C



☀ **^{11}C enriched spectrum**

36.4% of exposure with 94.5% of ^{11}C



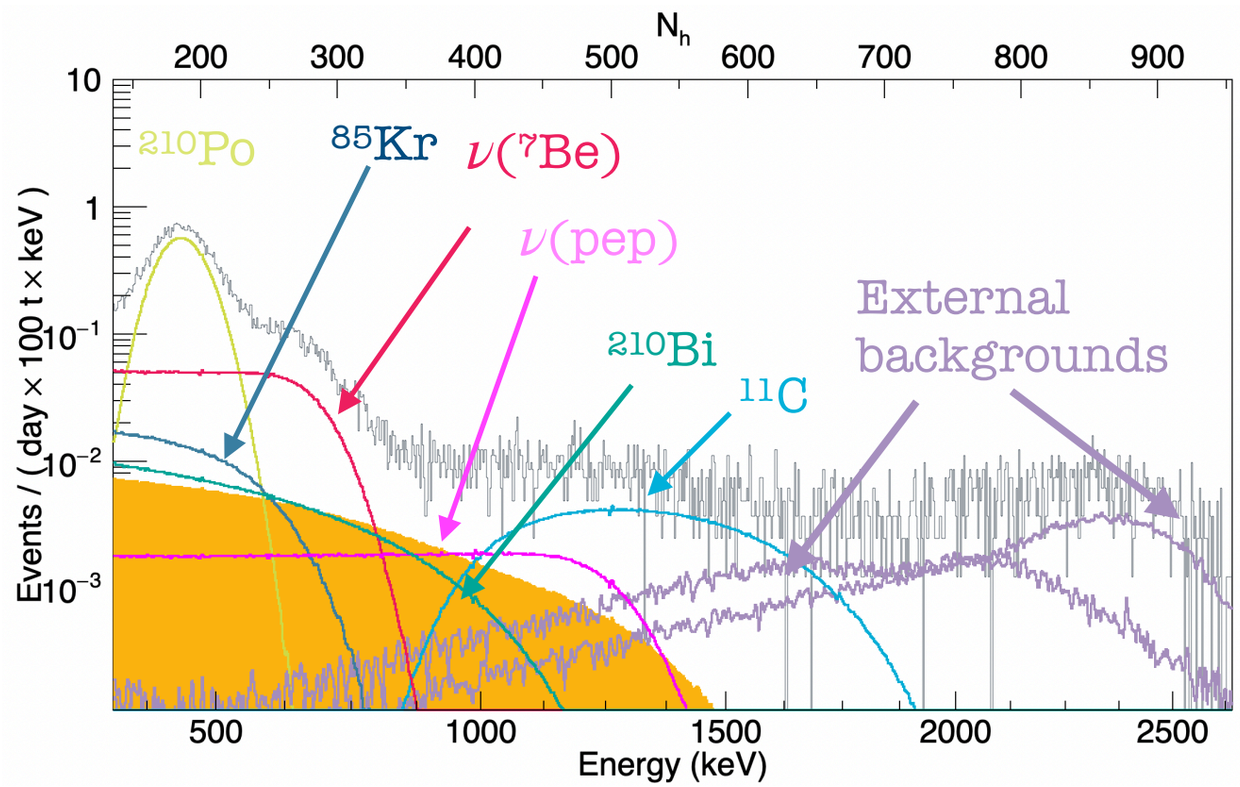
Other Backgrounds

Internal backgrounds :

After purifications: **^{232}Th** and **^{238}U** negligible (~10^{-19} g/g),
^{85}Kr (6.8 ± 1.8) cpd/100t;(Phase-II value) **^{210}Bi**
^{210}Po - the only α-decay background, **key to** its parent, **^{210}Bi, constraint**

External backgrounds

γs from **^{208}Tl, ^{214}Bi, ^{40}K** - efficient reduction by fiducial volume selection + radial dependence



Solar neutrinos

Yesterday's signal = today's background:
pp-chain neutrinos: **ν(pp), ν(^{7}Be), and ν(pep)**

Monte Carlo Probability Density Functions production

Solar neutrinos pre-steps:

Primary solar neutrino spectra → Survival Probability Elastics scattering cross section → Recoiled electron energy with radiative corrections

All components:

Generating all species + uniform electrons (flat in energy) in the full Borexino Monte Carlo

Scintillation light generation and propagation, electronics response, and energy and position reconstruction

Applying selection cuts:

- Uniform electron sample → PDFs for uniform (MC e-) and external backgrounds radial distributions
- External backgrounds → PDFs for all neutrinos and backgrounds energy spectra
- All other components → PDFs for all neutrinos and backgrounds energy spectra

Normalised with the fraction of events passing the cuts to the number of events generated in FV

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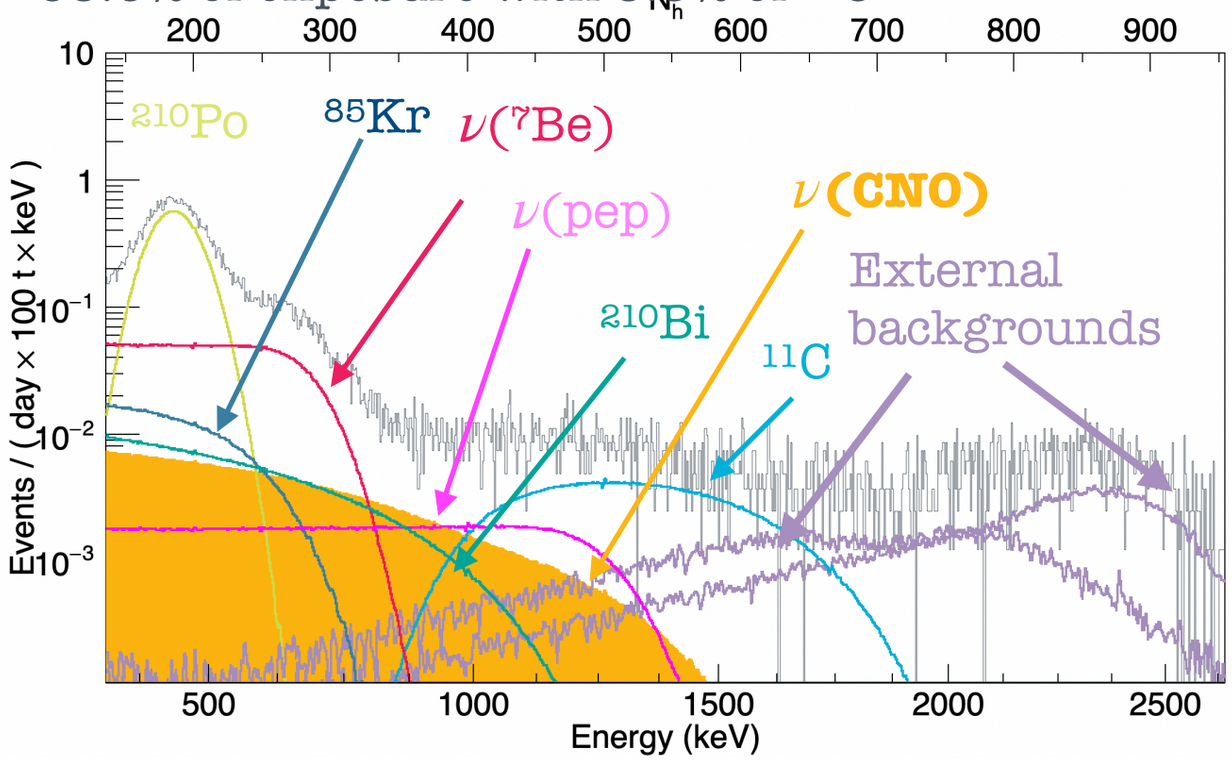
Multivariate Spectral Fit

$$\mathcal{L}_{MV}(\theta)=\mathcal{L}_{dep}(\theta)\cdot\mathcal{L}_{enr}(\theta)\cdot\mathcal{L}_{Rad}(\theta)$$

- **^{11}C depleted energy spectrum:**

63.6% of exposure with 5.5% of ^{11}C



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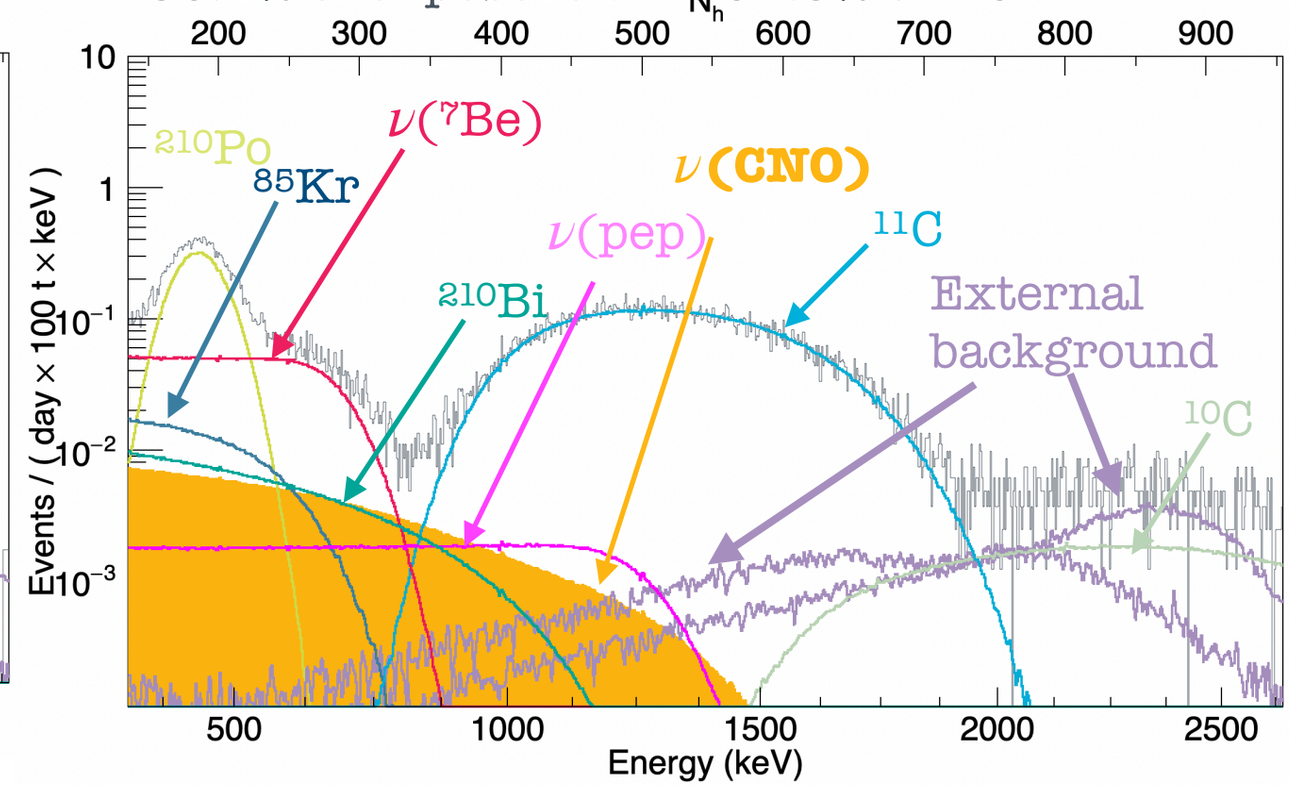
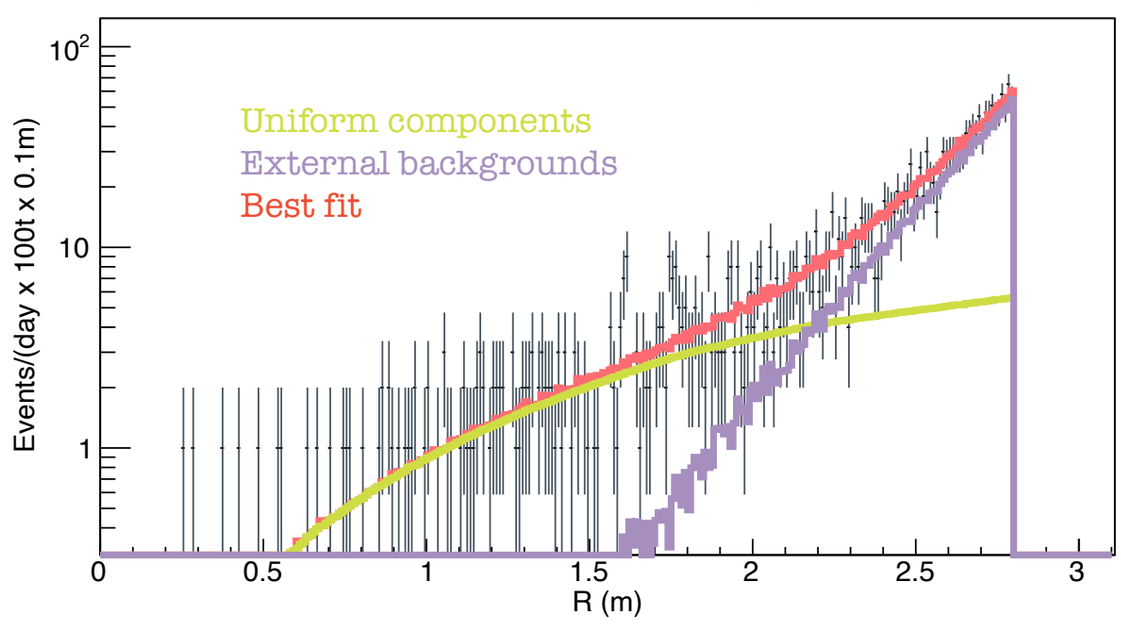


- **Radial distribution:**
  Improve disentanglement of external from the internal contaminants



Constraints:

ν(pep) = 2.74 ± 0.04 cpd/100t

^{210}Bi (upper limit): 11.5 ± 1.3 cpd/100t

All other components free

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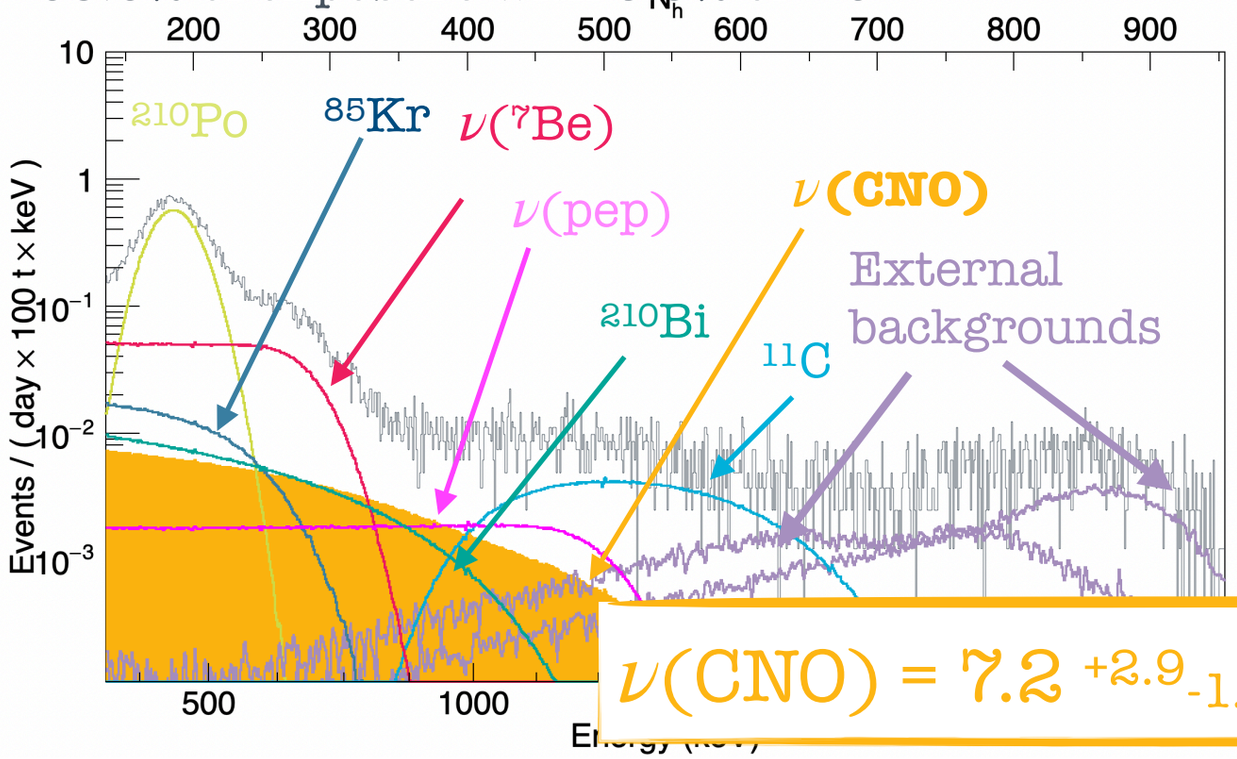

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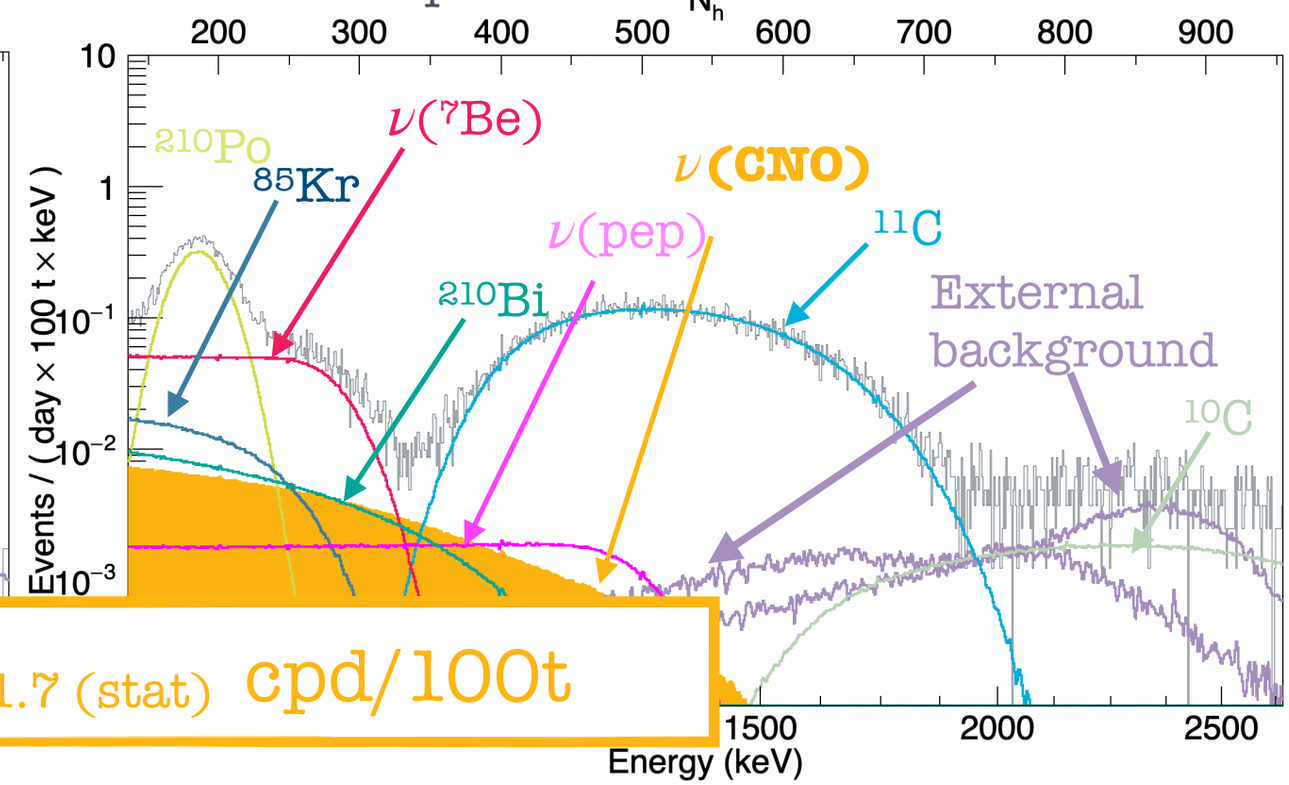
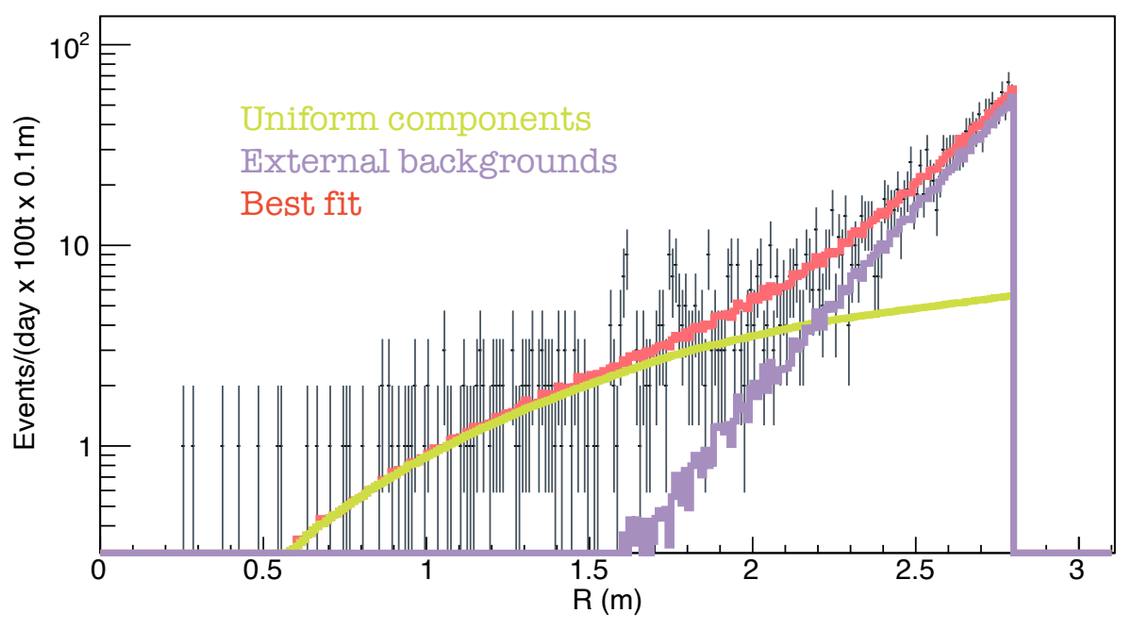


ν(CNO) = 7.2 $^{+2.9}$-1.7 (stat) cpd/100t

- **Radial distribution:**
  Improve disentanglement of external from the internal contaminants



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All other components free

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Integrating systematic uncertainties

Fit configurations:

Ranges, binning
~2500 fits
Negligible

^{210}Bi decay spectrum shape

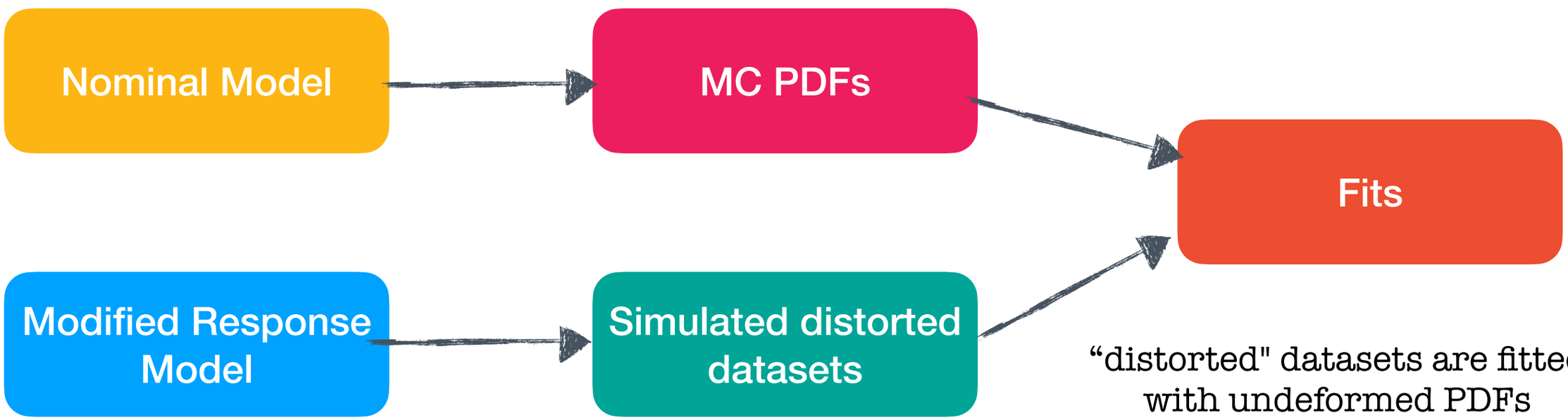
Additionally considered:

- (H. Daniel. Nucl. Phys. 31 p.293, 1962)
- A.Grau Carles and A.Grau Malonda. Nuclear Physics A, 596(1) p.83, 1996.
- I.E. Alekseev et al. arxiv:2005.08481.

Detector response

Vary detector response parameters within range allowed by calibration

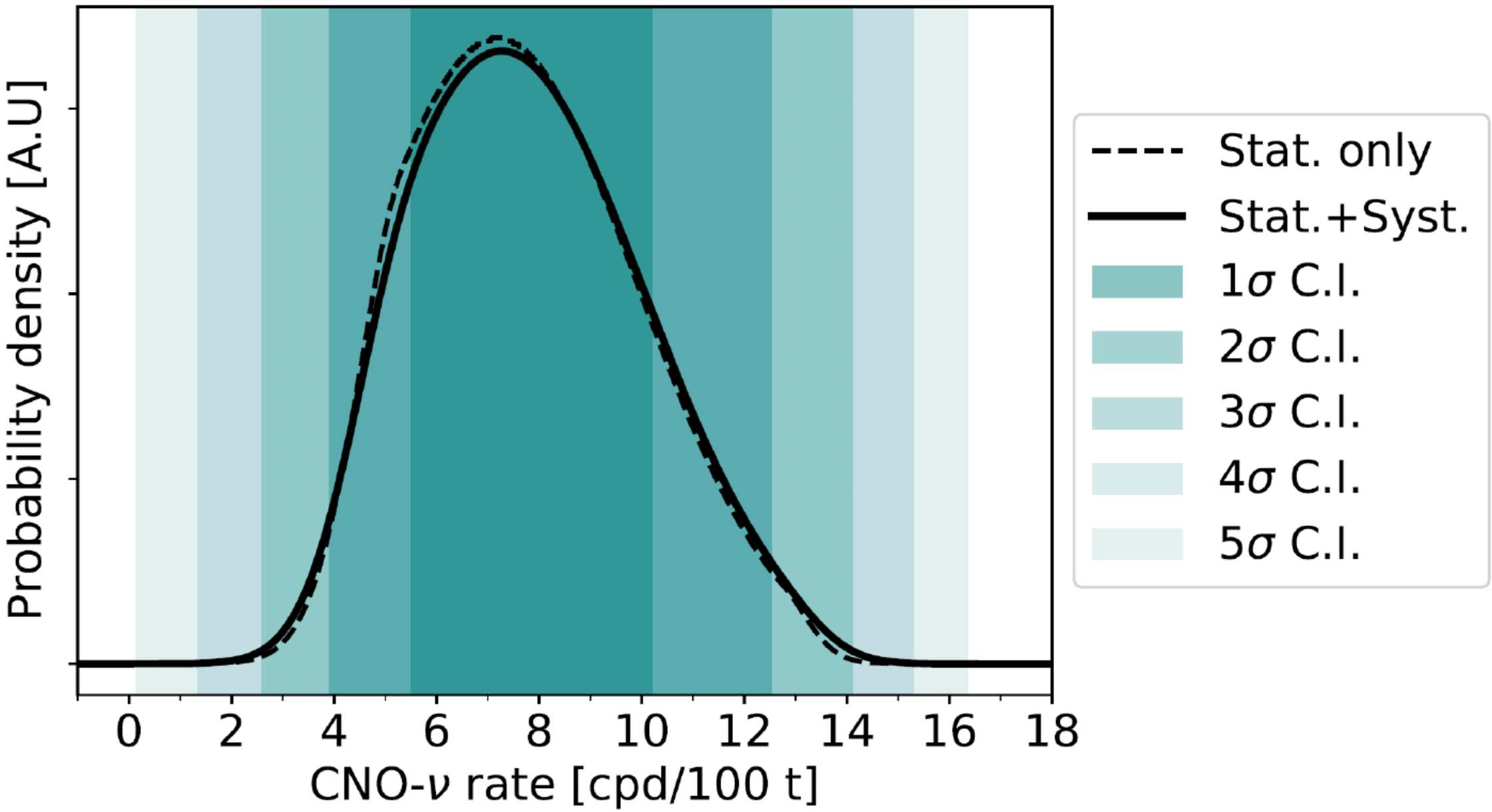
- Energy scale (0.23%)
- non-uniformity (0.28%)
- non-linearity (0.4%)



"distorted" datasets are fitted with undeformed PDFs

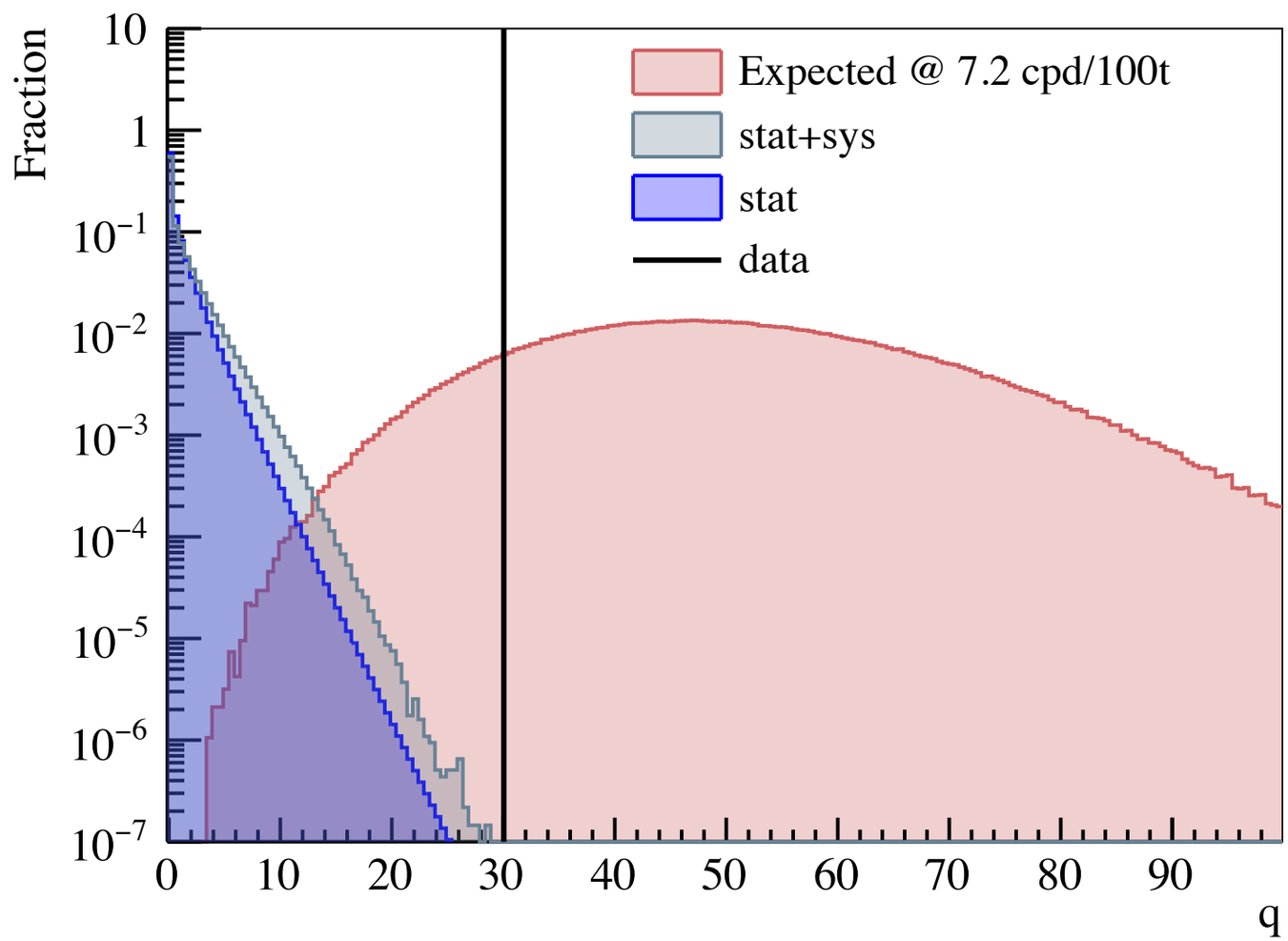
CNO systematic error due to a mismatch between real and modified PDFs:
-0.5/+0.6 cpd per 100 t

Results: Quintiles from normalized likelihood



Results: Significance of CNO detection

What if there was no CNO?
Null hypothesis



Profile Likelihood ratio test statistics:

$$q = -2log\frac{L(CNO = 0)}{L(CNO)}$$

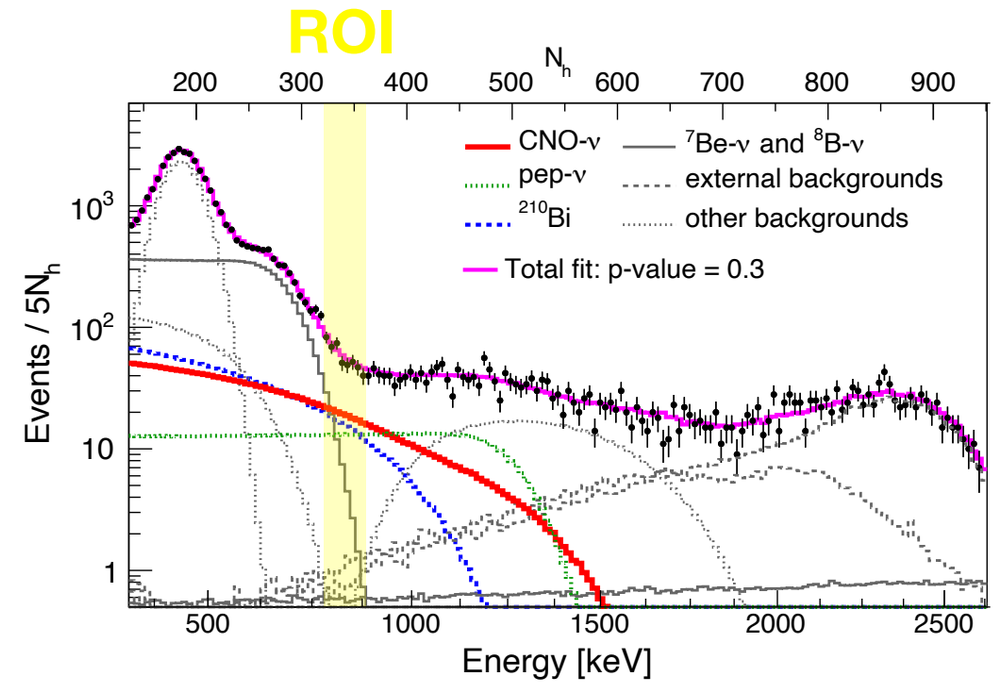
Generating **~15 million "distorted" datasets with no CNO injected** and analysed as regular data ("distorted" datasets are fitted with undeformed PDFs)

q_0 (data) = 30.04

No CNO hypothesis disfavored with ≥ 5σ significance

Results: Counting analysis cross check

- Choose the energy window which maximizes CNO signal to background (Region of Interest, ROI)
- Count the events in ROI
- Subtract all identified background events, estimated based on external constraints (pep, 210Bi) and spectral fit (analytical on Npe) results



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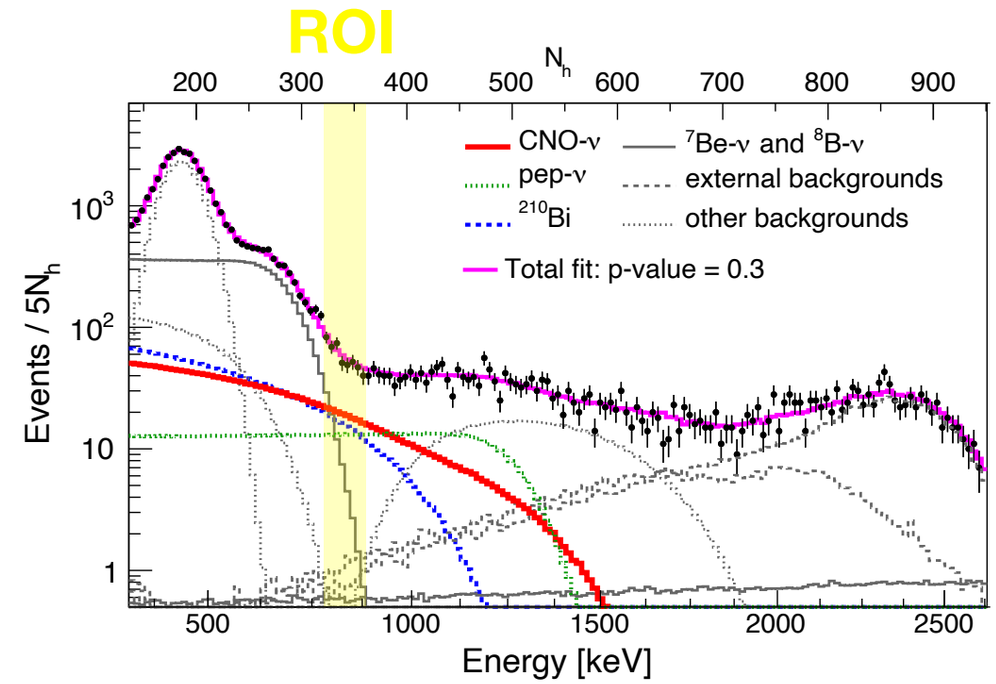
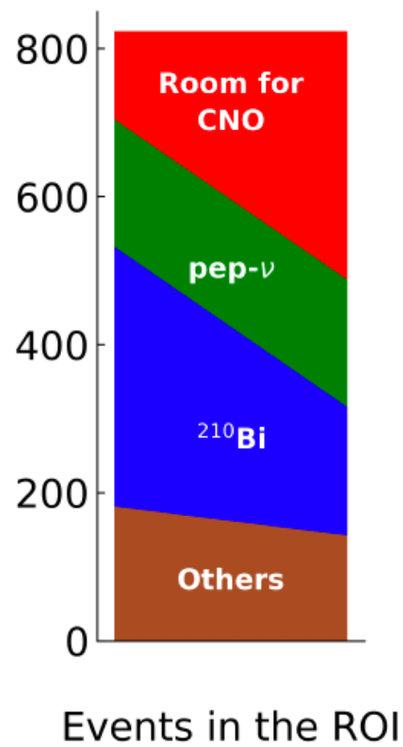
- Detector response systematics accounted varying the of events inside the ROI for each component



Specie (S_i)	Events
N	823 ± 28.7
^{210}Bi	261 ± 29.6
$\nu(pep)$	171.7 ± 2.4
$\nu(^{7}\mathrm{Be})$	86.8 ± 2.6
^{11}C	57.9 ± 5.8
Others	15.6 ± 1.6
$\sum_i S_i$	593.5 ± 30.4
$N - \sum_i S_i$	229.5 ± 41.8



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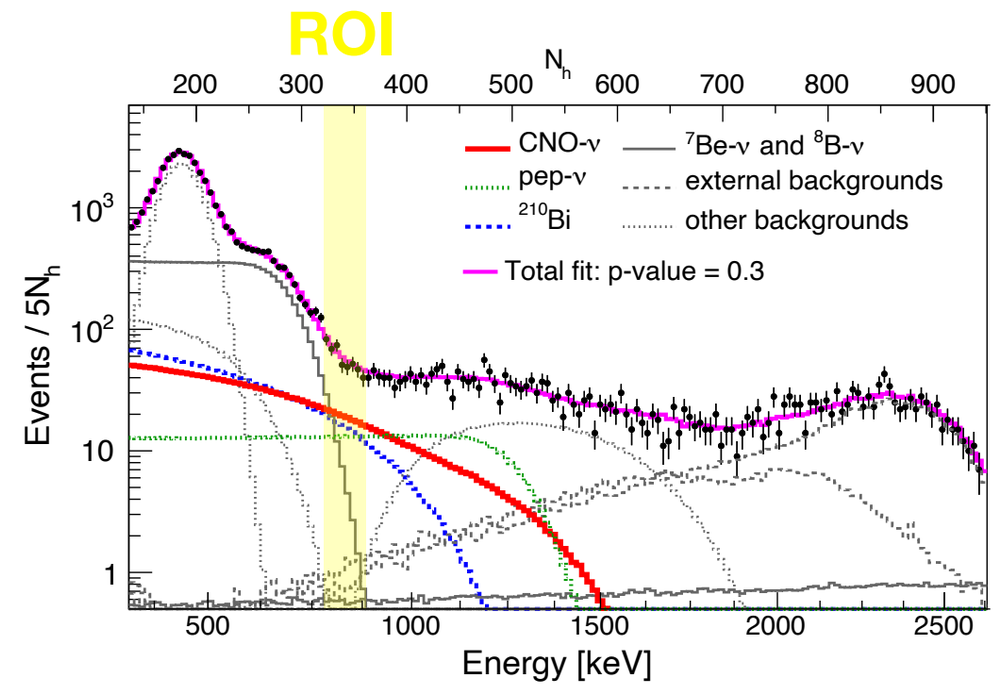

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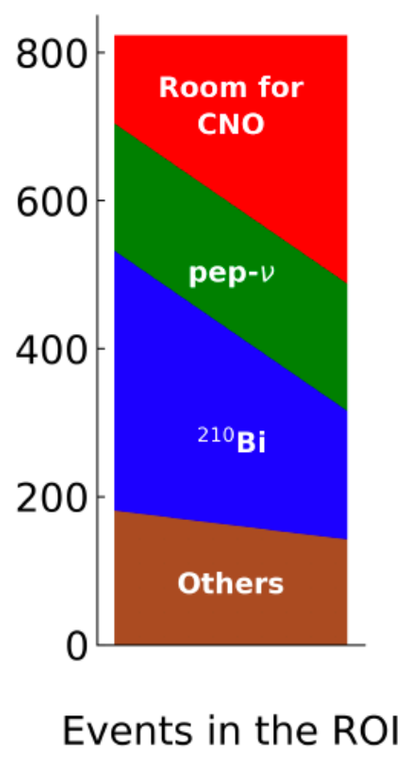
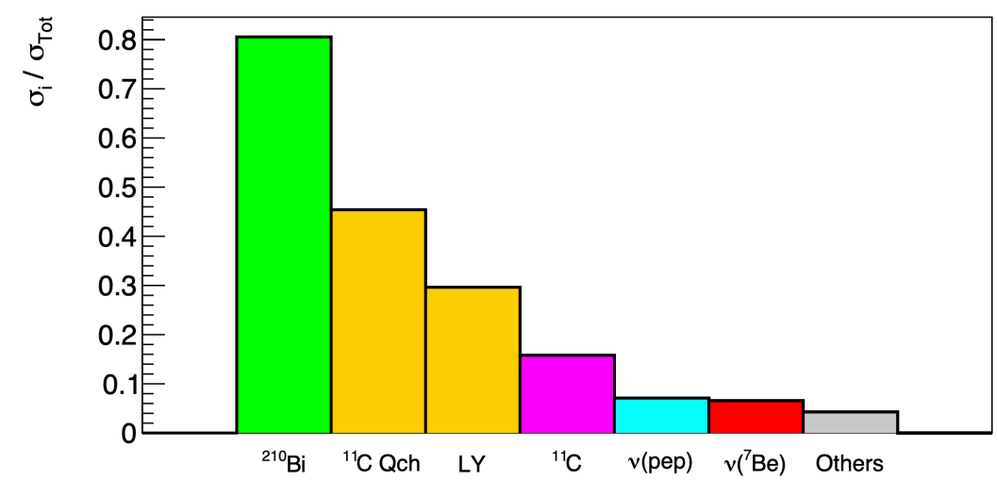
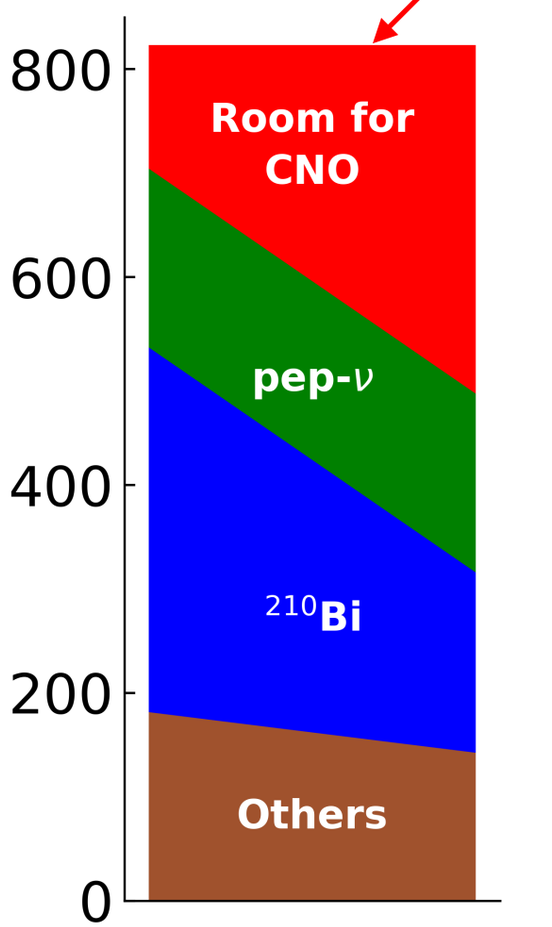
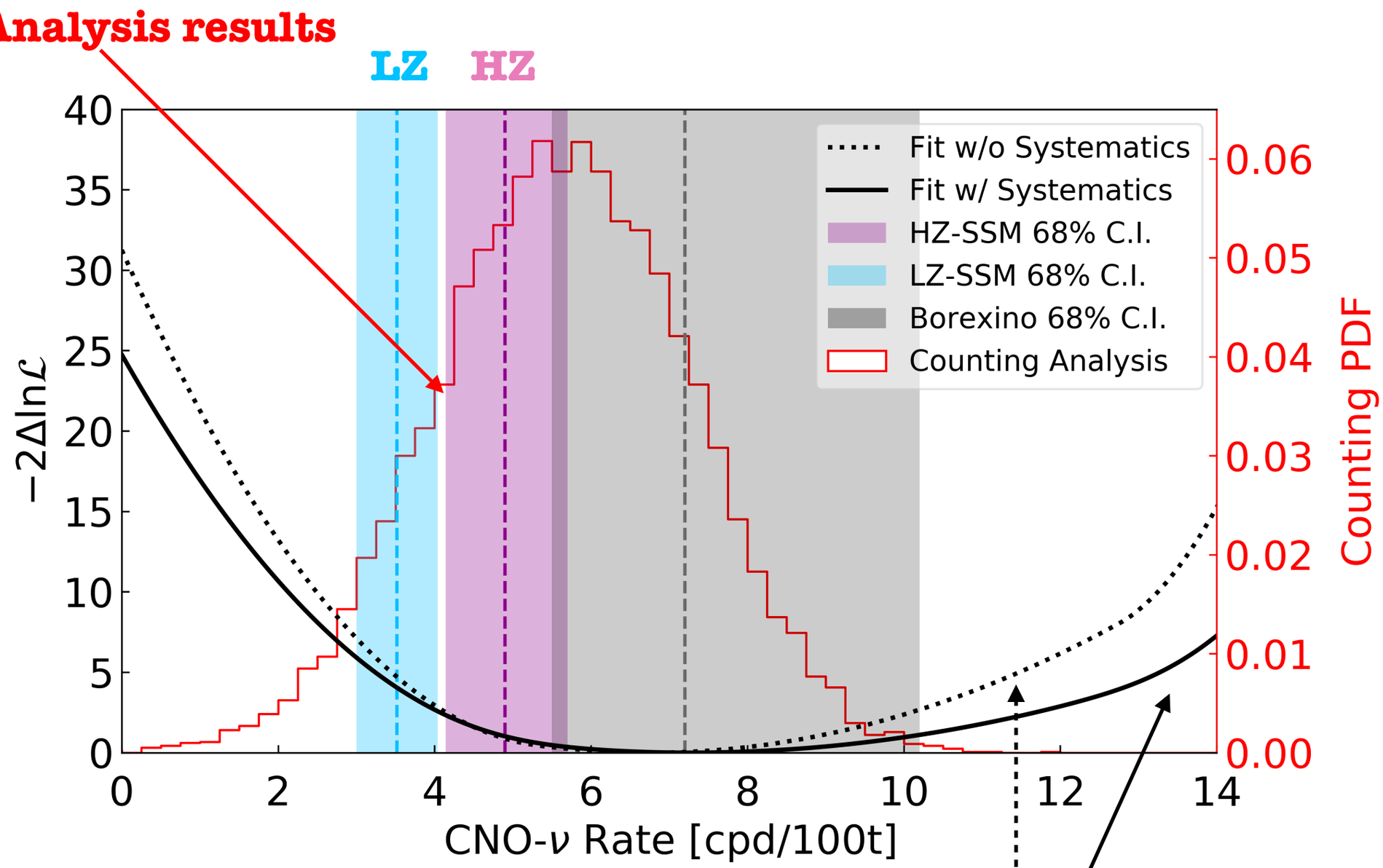


Major contributions of systematics comes from ^{210}Bi and detector response parameters such as ^{11}C quenching and light yield:



Results: Summary





Mutlivariate fit results

- ^{210}Bi determination - the biggest systematics for both counting and multivariate fit
- Compatible results

Summary

Borexino has gone well beyond its original goal

The undeterred, several years long effort to thermally stabilize the detector:

- First detection of neutrinos from the CNO-cycle in the Sun with 5σ significance

Borexino has completely unraveled the two helium fusion processes powering the Sun

BOREXINO COLLABORATION

UNIVERSITÀ DEGLI STUDI DI MILANO

INFN Istituto Nazionale di Fisica Nucleare

LNGS

PRINCETON UNIVERSITY

UNIVERSITÀ DEGLI STUDI DI GENOVA

Virginia Tech

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

NATIONAL RESEARCH CENTER "KURCHATOV INSTITUTE"

St. Petersburg Nuclear Physics Inst.

Technische Universität München

University of Houston

Universität Hamburg

JAGIELLONIAN UNIVERSITY IN KRAKÓW

JÜLICH Forschungszentrum

POLITECNICO MILANO 1863

SKOBELTSYN INSTITUTE OF NUCLEAR PHYSICS LOMONOSOV MOSCOW STATE UNIVERSITY

UNIVERSITÀ DEGLI STUDI DI FERRARA

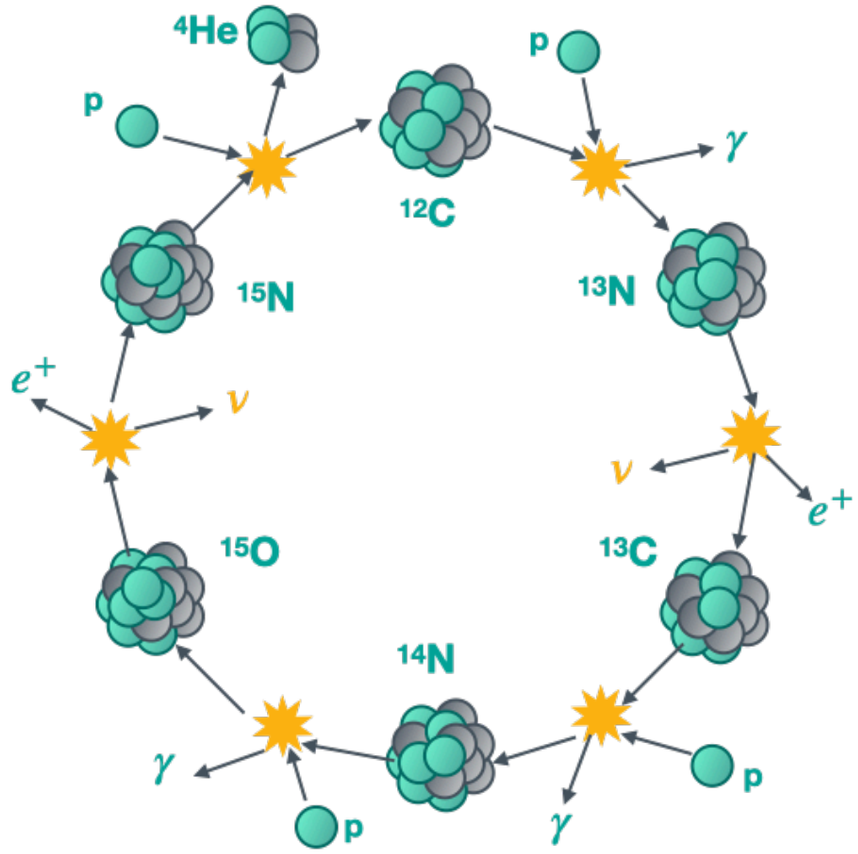
TECHNISCHE UNIVERSITÄT DRESDEN

Joint Institute for Nuclear Research

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

Dedication to Simone Marcocci

(1989-2019)



QUESTIONS ARE WELCOME

now

or later

@ZaraBagdasarian

zara.bagdasarian@berkeley.edu