PRINCETON UNIVERSITY

First measurement of CNO solar neutrinos

Xuefeng Ding

Physics department, Princeton University, Princeton, NJ 08544, USA

BOREXINO GRAN SASSO

BNL seminar 2020 07 23

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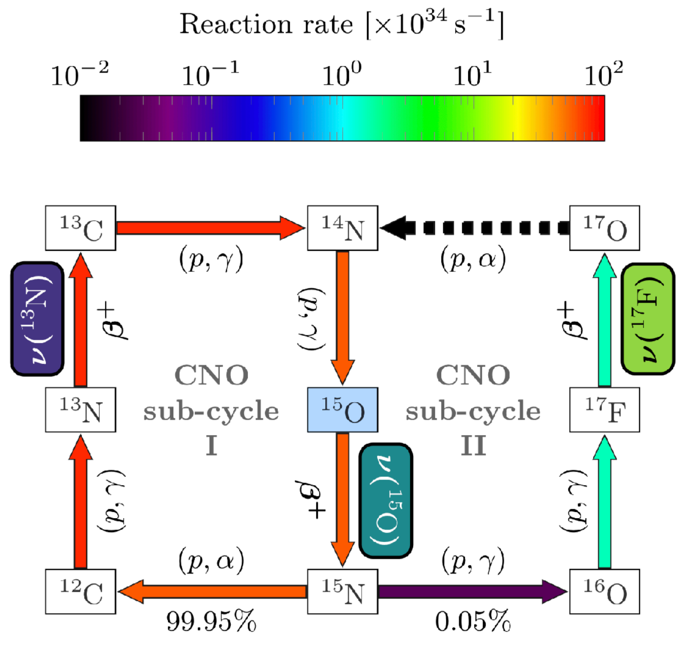
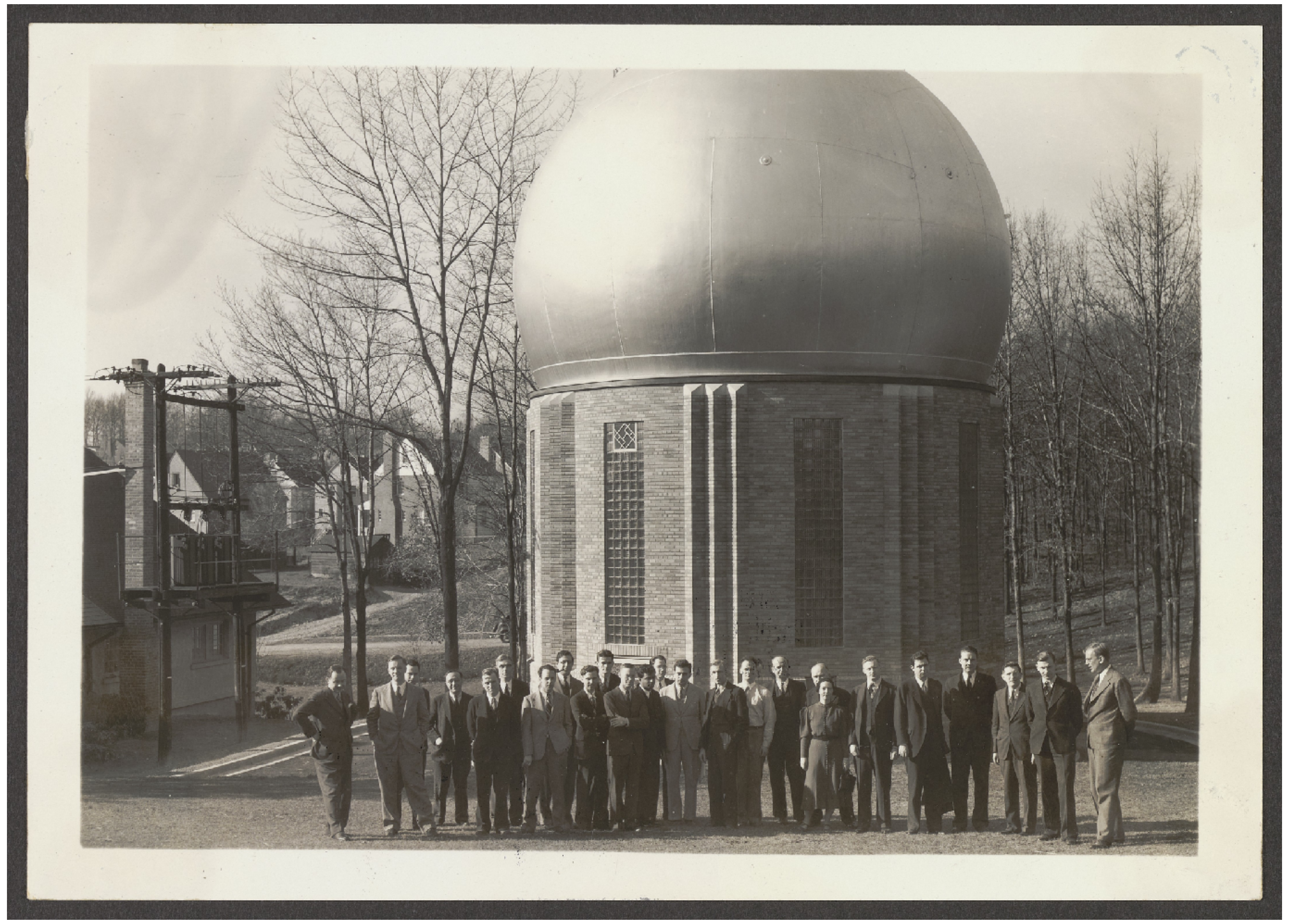
The carbon-nitrogen-oxygen (CNO) cycle



When do we first looked at how the Sun shines?



- On March 17, 1938, fourth annual Washington Conference of Theoretical Physics was held in the Carnegie Institute and George Washington University's. How the Sun shines was brought into discussion.
  - One year before, Carl Friedrich von Weizsäcker proposed the energy comes from p+p-> $^2D + e^+ + \nu_e$
  - By the end of the conference, Bethe came up with subsequent processes that ^2D are converted to ^4He
  - After the conference, Bethe started to think about one question: What about heavier stars?

H. Bethe: discovery of CNO cycle mechanism

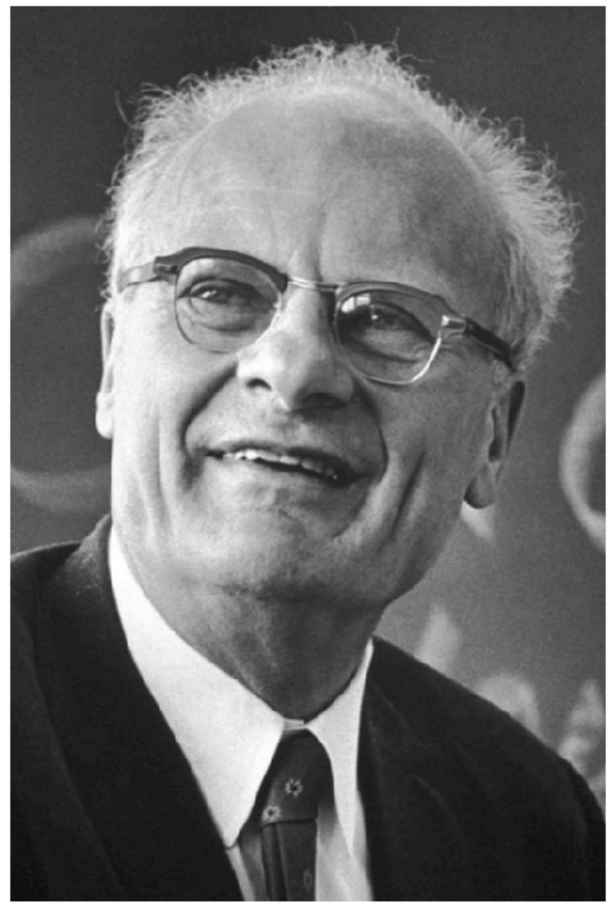


Photo from the Nobel Foundation archive.

Hans Albrecht Bethe

Prize share: 1/1

The Nobel Prize in Physics 1967 was awarded to Hans Albrecht Bethe "for his contributions to the theory of nuclear reactions, especially his discoveries concerning the energy production in stars."

MARCH 1, 1939 PHYSICAL REVIEW VOLUME 55

Energy Production in Stars*

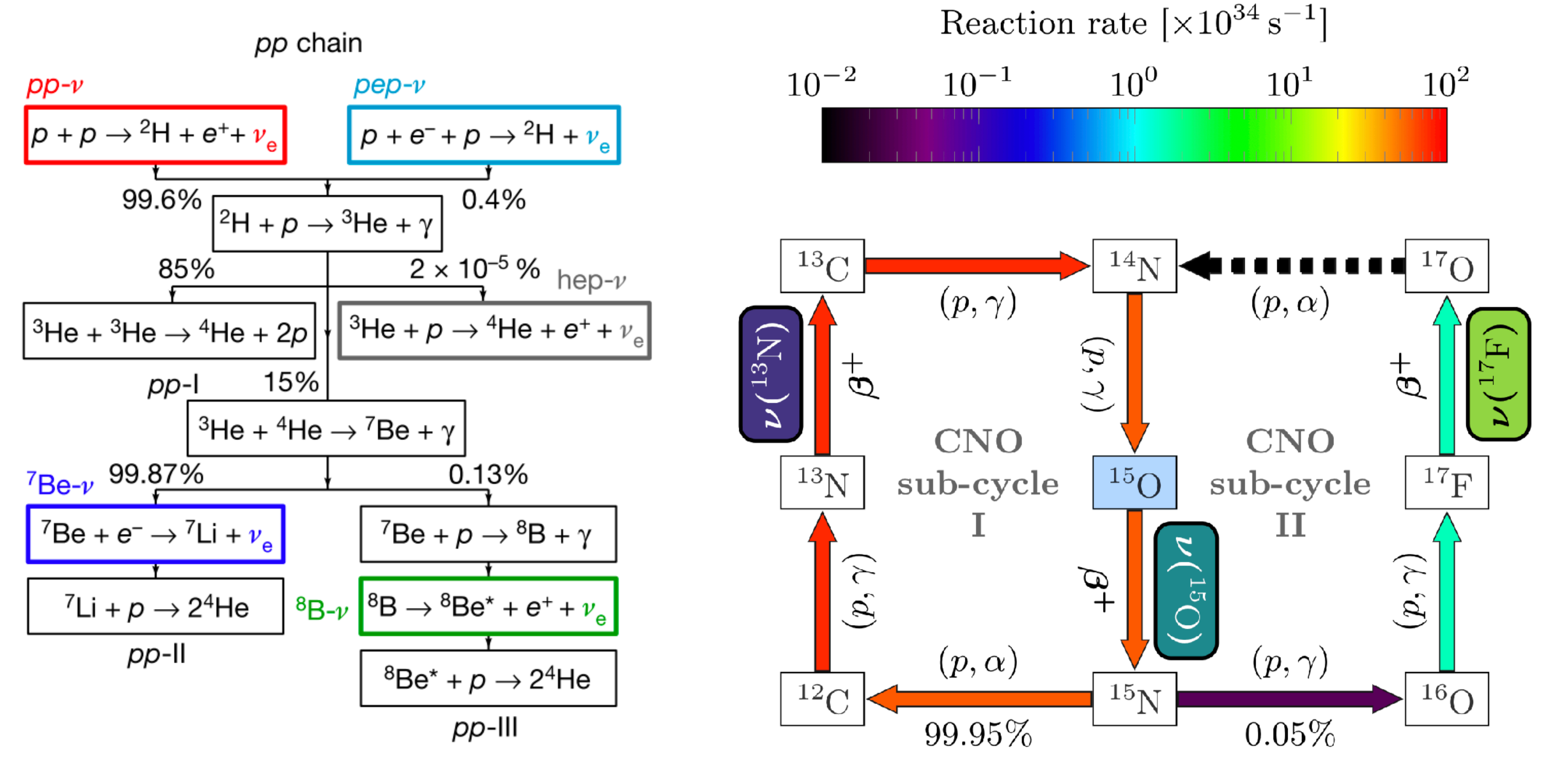
H. A. BETHE
Cornell University, Ithaca, New York

(Received September 7, 1938)

It is shown that the *most important source of energy in ordinary stars is the reactions of carbon and nitrogen with protons*. These reactions form a cycle in which the original nucleus is reproduced, *viz.* $C^{12}+H=N^{13}$, $N^{13}=C^{13}+\epsilon^{+}$, $C^{13}+H=N^{14}$, $N^{14}+H=O^{15}$, $O^{15}=N^{15}+\epsilon^{+}$, $N^{15}+H=C^{12}+He^{4}$. Thus carbon and nitrogen merely serve as catalysts for the combination of four protons (and two electrons) into an α-particle (§7).
The carbon-nitrogen reactions are unique in their ... integration of the Eddington equations gives 19. For the brilliant star Y Cygni the corresponding figures are 30 and 32. This good agreement holds for all bright stars of the main sequence, but, of course, not for giants.
For fainter stars, with lower central temperatures, the reaction $H+H=D+\epsilon^{+}$ and the reactions following it, are believed to be mainly responsible for the energy production. (§10)
It is shown further (§5–6) that *no elements heavier than*

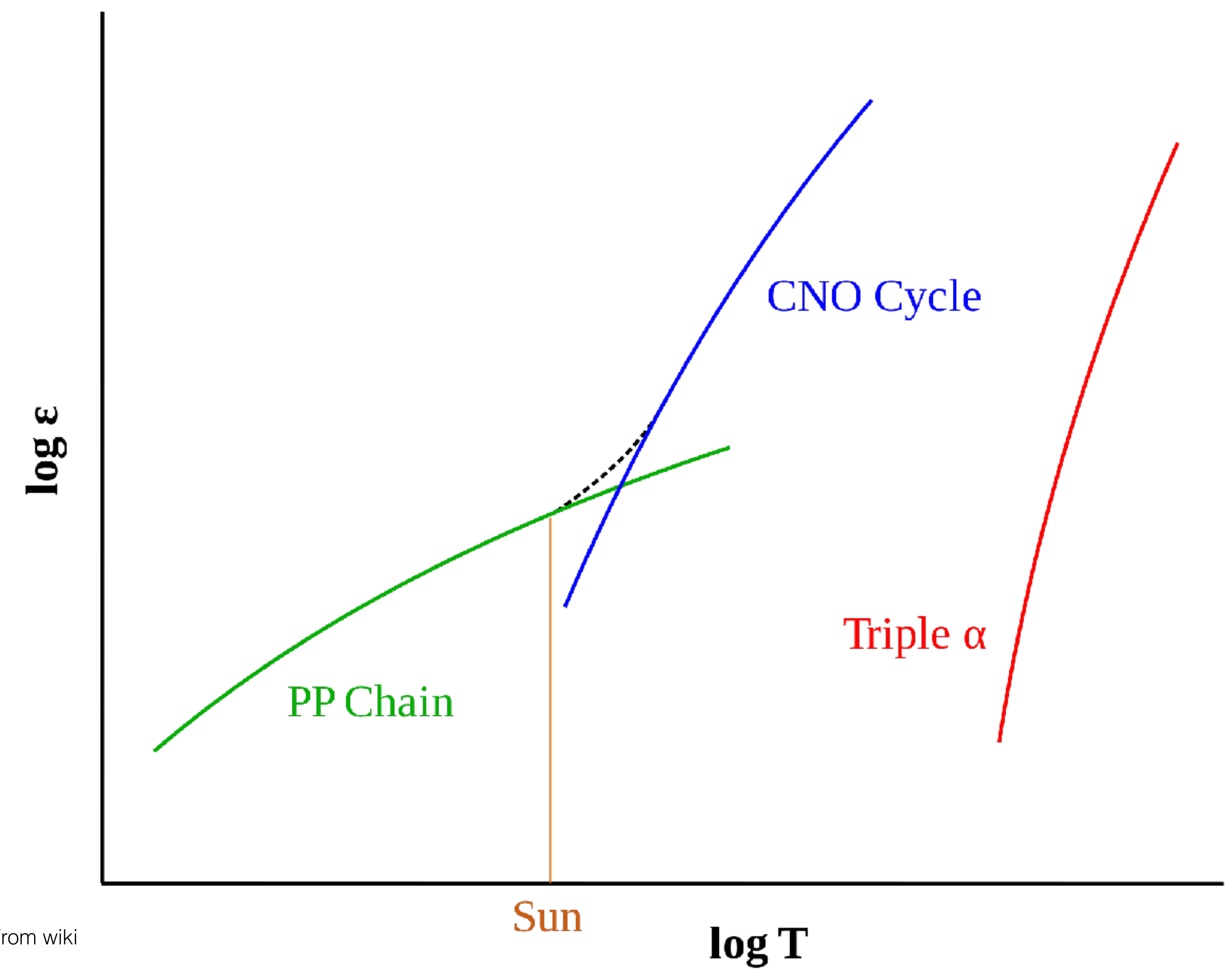
- Six month after the conference, H. Bethe submitted an article on energy production in stars with the CNO cycle process. His contribution was awarded Nobel prize in 1967.

Five proton fusion channels in the Sun



Comprehensive measurement of pp-chain solar neutrinos, BOREXINO, 2018, Nature

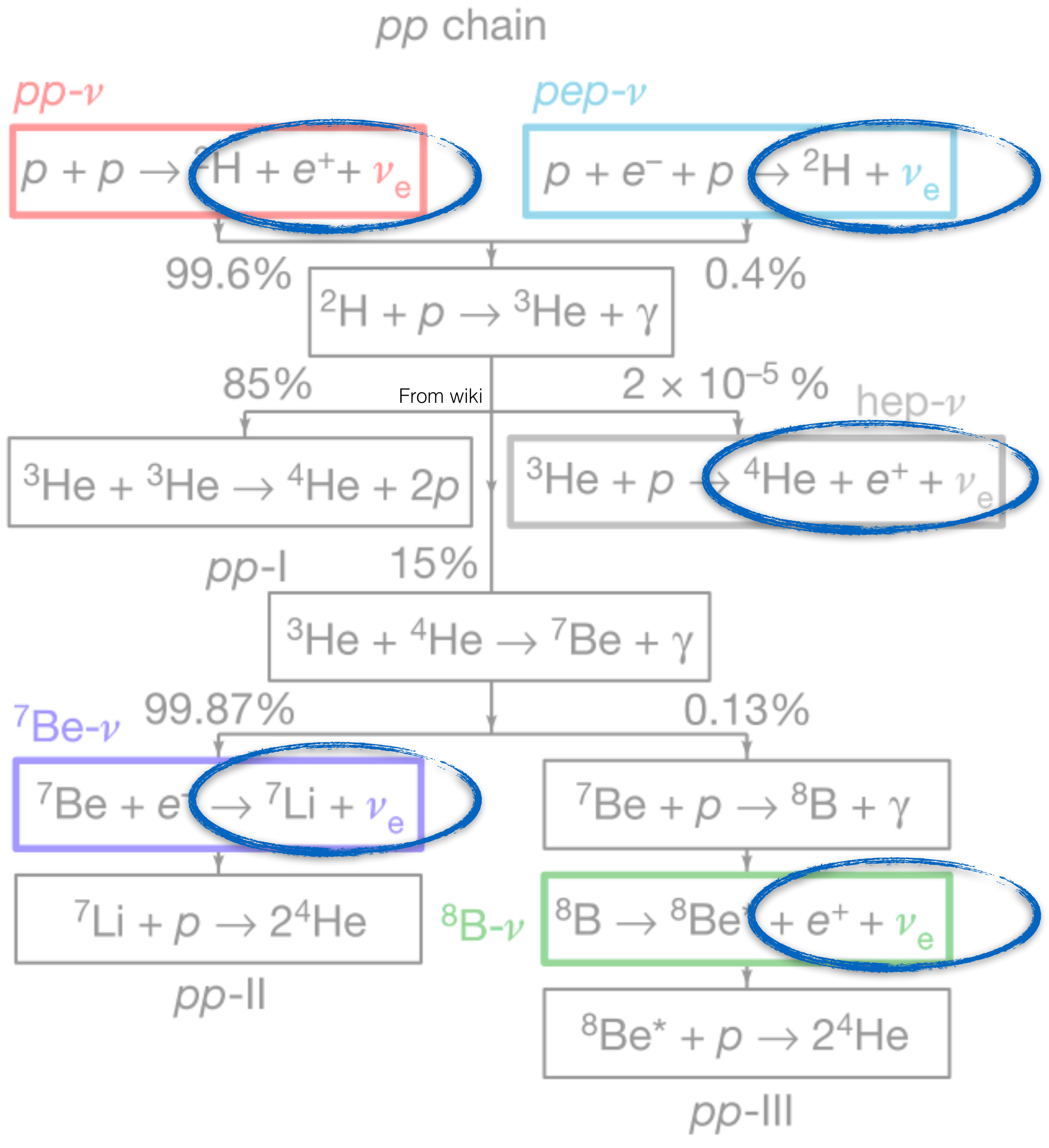
First Direct Experimental Evidence of CNO neutrinos, BOREXINO, 2020, hep-ex/2006.15115



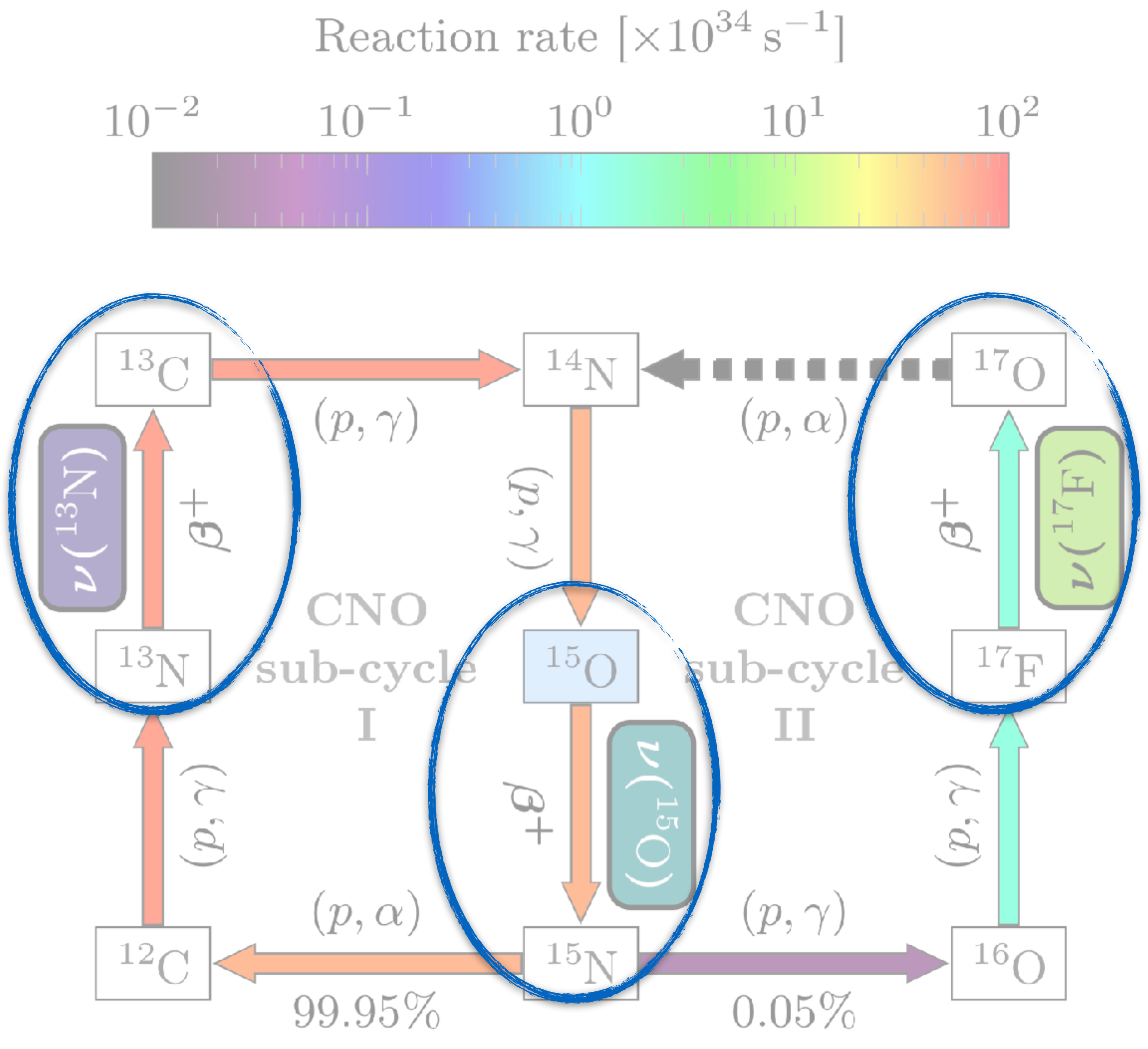
From wiki

- Standard Solar Model: Three pp chains and two CNO cycles are active in the Sun.
- CNO cycle contributes 1% energy in the Sun and remains hypothetical until this work.

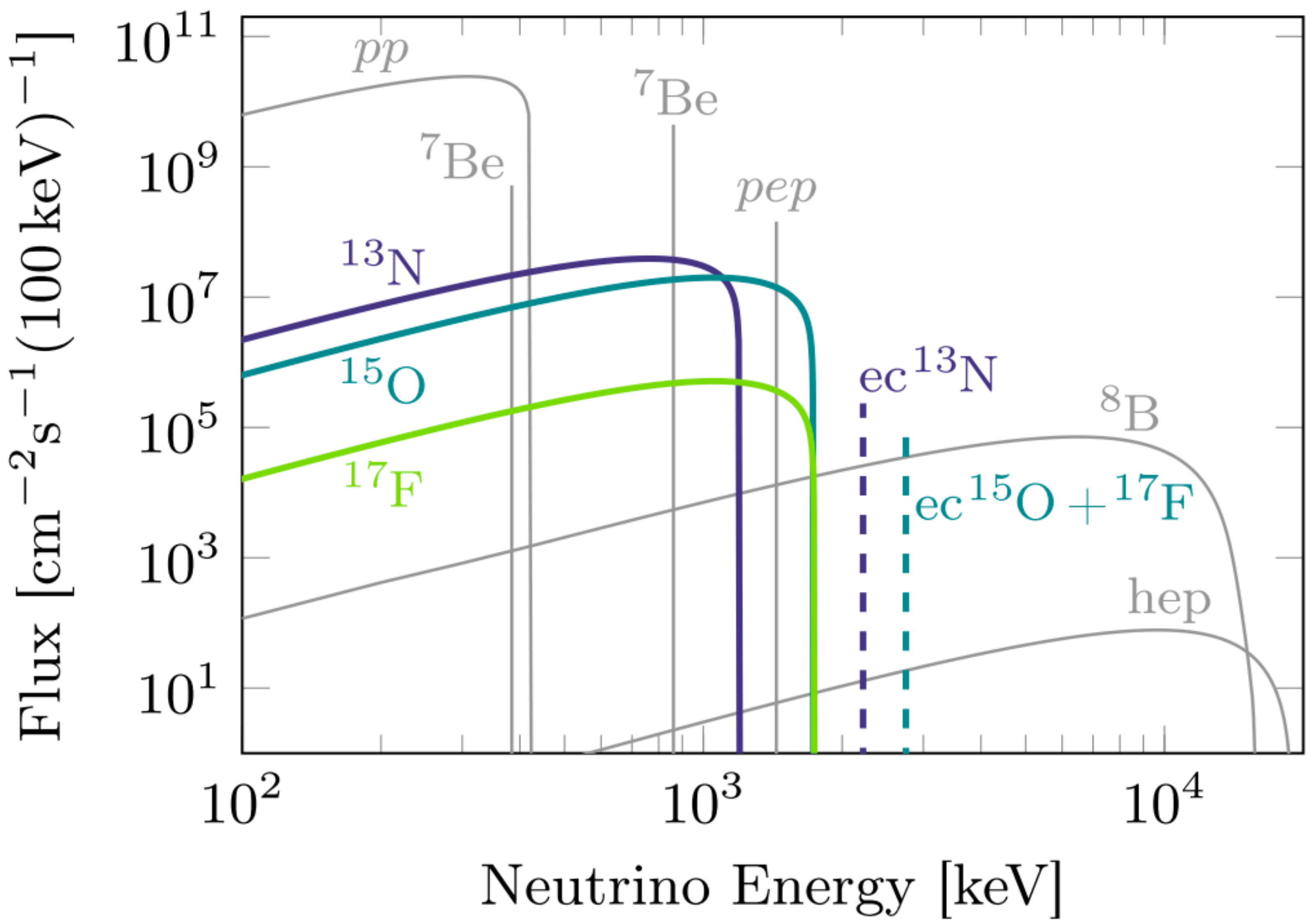
Neutrinos from proton fusion



Comprehensive measurement of pp-chain solar neutrinos, BOREXINO, 2018, Nature



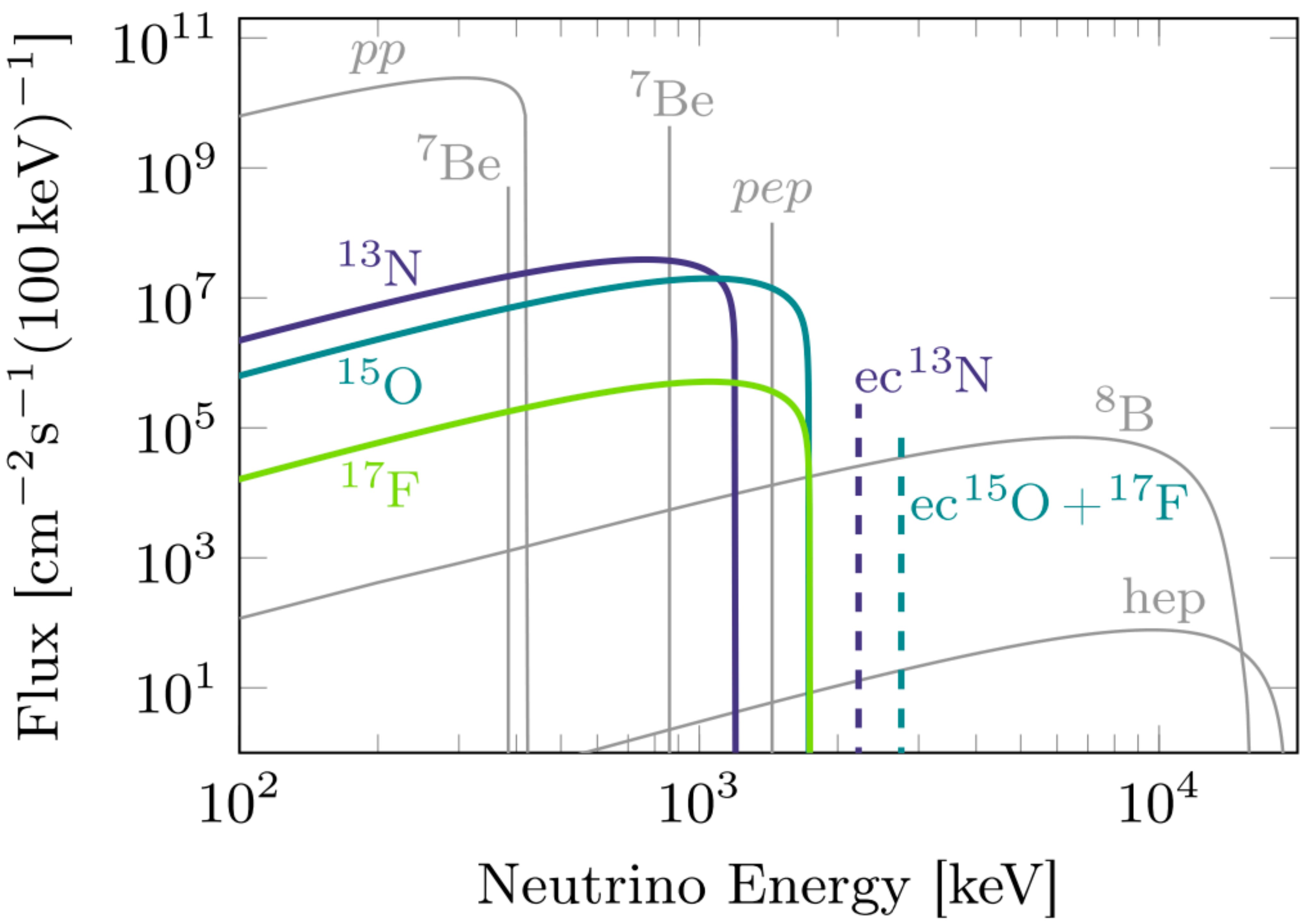
First Direct Experimental Evidence of CNO neutrinos, BOREXINO, 2020, hep-ex/2006.15115



- Neutrinos are produced during β^+ decay and electron capture.
- They are named as *pp*, *pep*, ^{7}Be, ^{8}B, *hep*, and CNO (^{13}N+^{15}O+^{17}F) solar neutrinos.

Previous measurement of solar neutrino fluxes

- We have *pp*, *pep*, ^{7}Be, ^{8}B, *hep*, and CNO (^{13}N+^{15}O+^{17}F) solar neutrinos.



- Radiochemical: Chlorine, Gallex/GNO, SAGE
  - Only weight sum of neutrino flux is given
- Elastic Scattering: Super-K, SNO, BOREXINO
  - Neutrino fluxes measured separately
  - Super-K, SNO: ^{8}B and *hep* (limit)
  - Borexino: *pp*, *pep*, ^{7}Be, ^{8}B, *hep* (limit), and CNO (limit)
- pp chain (except *hep*) was fully measured. **CNO cycle was not observed yet**

Measurement by Borexino Phase-II (2018)

Article | Published: 24 October 2018

Comprehensive measurement of *pp*-chain solar neutrinos

The Borexino Collaboration

Nature **562**, 505–510(2018) | Cite this article

6838 Accesses | **32** Citations | **223** Altmetric | Metrics

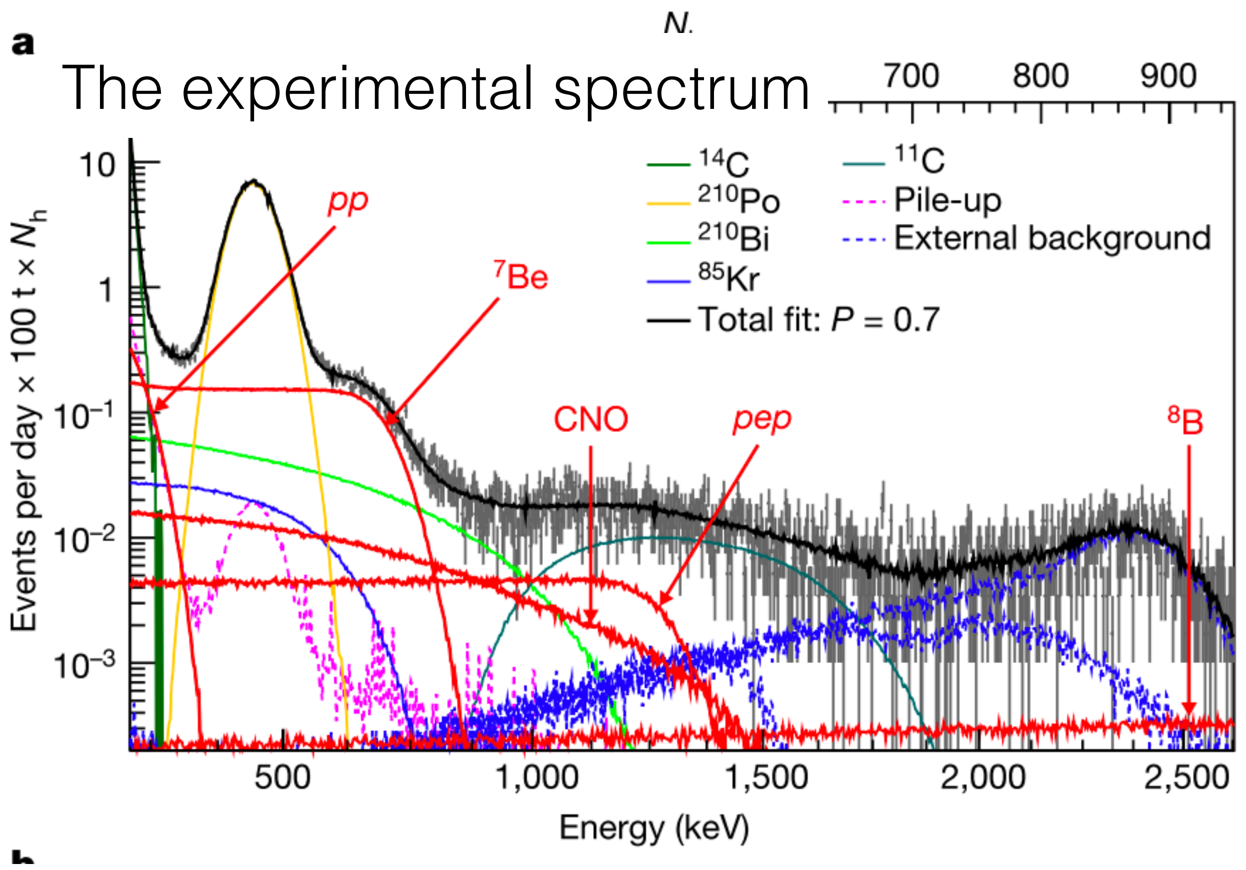


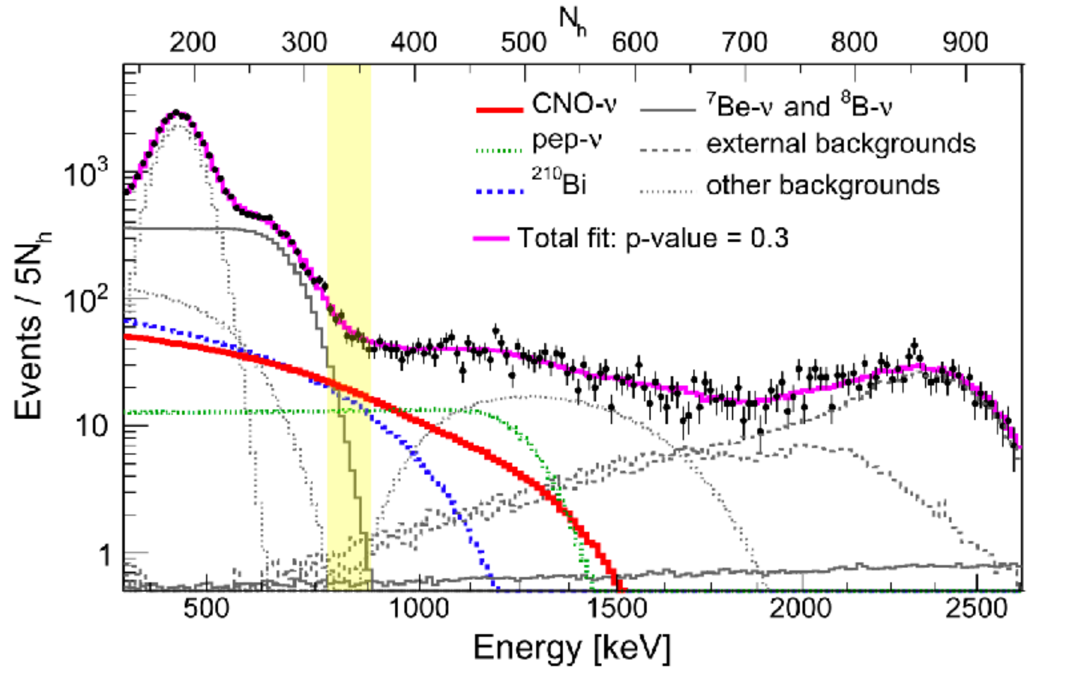
Table 2 | Borexino experimental solar-neutrino results

Solar neutrino	Rate (counts per day per 100 t)	Flux (cm^{-2} s^{-1})	Flux–SSM predictions (cm^{-2} s^{-1})
pp	$134 \pm 10^{+6}_{-10}$	$(6.1 \pm 0.5^{+0.3}_{-0.5}) \times 10^{10}$	$5.98(1.0 \pm 0.006) \times 10^{10}$ (HZ) $6.03(1.0 \pm 0.005) \times 10^{10}$ (LZ)
^{7}Be	$48.3 \pm 1.1^{+0.4}_{-0.7}$	$(4.99 \pm 0.11^{+0.06}_{-0.08}) \times 10^{9}$	$4.93(1.0 \pm 0.06) \times 10^{9}$ (HZ) $4.50(1.0 \pm 0.06) \times 10^{9}$ (LZ)
pep (HZ)	$2.43 \pm 0.36^{+0.15}_{-0.22}$	$(1.27 \pm 0.19^{+0.08}_{-0.12}) \times 10^{8}$	$1.44(1.0 \pm 0.01) \times 10^{8}$ (HZ) $1.46(1.0 \pm 0.009) \times 10^{8}$ (LZ)
pep (LZ)	$2.65 \pm 0.36^{+0.15}_{-0.24}$	$(1.39 \pm 0.19^{+0.08}_{-0.13}) \times 10^{8}$	$1.44(1.0 \pm 0.01) \times 10^{8}$ (HZ) $1.46(1.0 \pm 0.009) \times 10^{8}$ (LZ)
$^{8}B_{HER-I}$	$0.136^{+0.013+0.003}_{-0.013-0.003}$	$(5.77^{+0.56+0.15}_{-0.56-0.15}) \times 10^{6}$	$5.46(1.0 \pm 0.12) \times 10^{6}$ (HZ) $4.50(1.0 \pm 0.12) \times 10^{6}$ (LZ)
$^{8}B_{HER-II}$	$0.087^{+0.080+0.005}_{-0.010-0.005}$	$(5.56^{+0.52+0.33}_{-0.64-0.33}) \times 10^{6}$	$5.46(1.0 \pm 0.12) \times 10^{6}$ (HZ) $4.50(1.0 \pm 0.12) \times 10^{6}$ (LZ)
$^{8}B_{HER}$	$0.223^{+0.015+0.006}_{-0.016-0.006}$	$(5.68^{+0.39+0.03}_{-0.41-0.03}) \times 10^{6}$	$5.46(1.0 \pm 0.12) \times 10^{6}$ (HZ) $4.50(1.0 \pm 0.12) \times 10^{6}$ (LZ)
CNO	<8.1 (95% C.L.)	$<7.9 \times 10^{8}$ (95% C.L.)	$4.88(1.0 \pm 0.11) \times 10^{8}$ (HZ) $3.51(1.0 \pm 0.10) \times 10^{8}$ (LZ)
hep	<0.002 (90% C.L.)	$<2.2 \times 10^{5}$ (90% C.L.)	$7.98(1.0 \pm 0.30) \times 10^{3}$ (HZ) $8.25(1.0 \pm 0.12) \times 10^{3}$ (LZ)

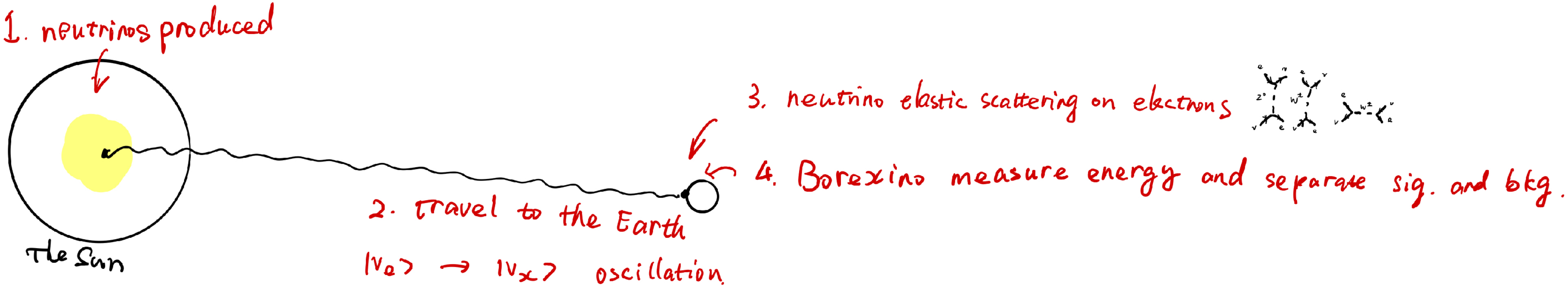
Measured neutrino rates (second column): for *pp*, ^{7}Be, *pep* and CNO neutrinos we quote the total counts without any threshold; for ^{8}B and hep neutrinos we quote the counts above the corresponding analysis threshold. Neutrino fluxes (third column) are obtained from the measured rates assuming the MSW-LMA oscillation parameters[19], standard neutrino–electron cross-sections[27] and a density of electrons in the scintillator of $(3.307 \pm 0.003) \times 10^{31}$ electrons per 100 t. All fluxes are integral values without any threshold. The result for *pep* neutrinos depends on whether we assume HZ or LZ SSM predictions to constrain the CNO neutrino flux. The last column shows the fluxes predicted by the SSM for the HZ or LZ hypotheses[18].

- 1291 day (2011 Dec—2016 May) x 71 t data are analyzed
- Whole pp-chain (except *hep*) detected.
- **CNO cycle was not observed yet.**

Detection of CNO solar neutrinos with Borexino

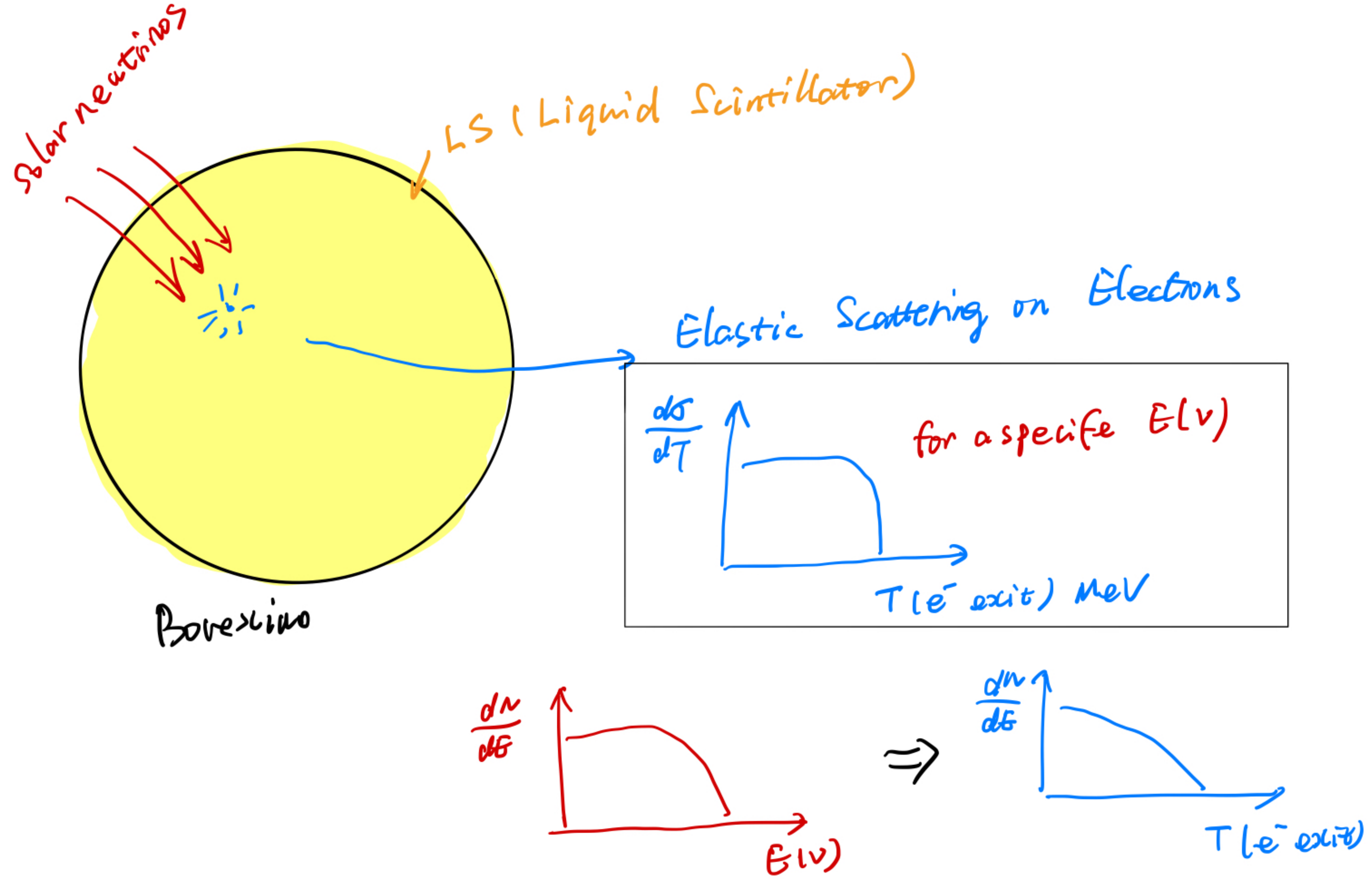


The principle of neutrino detection of Borexino

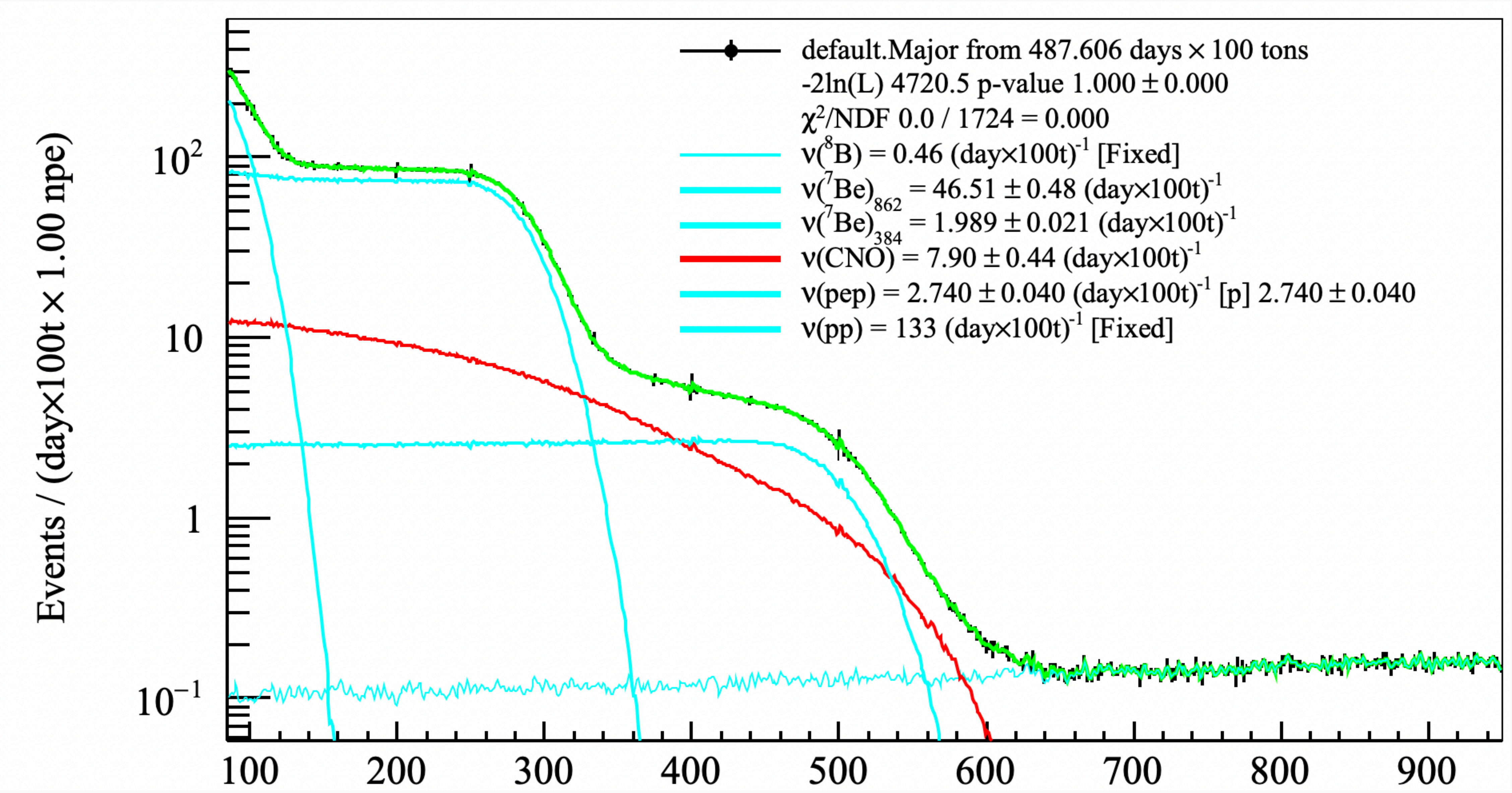


1. Neutrinos are produced in the core of the Sun
2. Neutrinos propagate to the Earth. Part of electron neutrinos transform to muon/tau neutrinos.
3. Neutrinos elastically scattering on electrons in Borexino
4. Borexino measures the recoil-electron energy (signal).
5. Borexino obtain event energy distribution, and separate signals and backgrounds.

Borexino detects the **recoil electron** of neutrino ES



Recoil electron energy distribution



- Borexino measures the energy of recoil electrons of solar neutrinos elastic scattering on electrons.
- The recoil electron energy distribution is **different** from the neutrino energy distribution.

Background reduction by purification

- Scintillator repurification between July 2010 — August 2011.
- Six cycles of “water extraction” and “nitrogen tripping” were used.
- Significant reduct achieved.

Low Background Methods in Undergroup Astroparticle Physics. Frank Calaprice. TAUP 2017

Isotope	Initial impurity	Final impurity
^{85}Kr	30 cpd/100t	<5 cpd/100t
	Reduced: >6	
^{238}U (^{226}Ra) ^{214}Bi - ^{214}Po	5.3x10^{-18} gU/g Reduced: >77	<8x10^{-20} gU/g <0.8 c/100t/y
^{238}U (^{226}Ra) ^{214}Bi - ^{214}Po	5.3x10^{-18} gU/g Reduced: >77	<8x10^{-20} gU/g <0.8 c/100t/y
^{232}Th ^{212}Bi-^{212}Po	3.8(8)x10^{-18} gTh/g Reduced: >3	<1x10^{-18} gTh/g <0.8 c/100t/y
^{210}Bi	70 cpd/100t Reduced: x4	17.5 cpd/100t
^{210}Po	Increased in first 2 cycles 20 →45 cpd/t Plant contaminants?	Decreased during Cycles 4-6 return to ~20 cpd/t and decaying.

e and Underground Physics

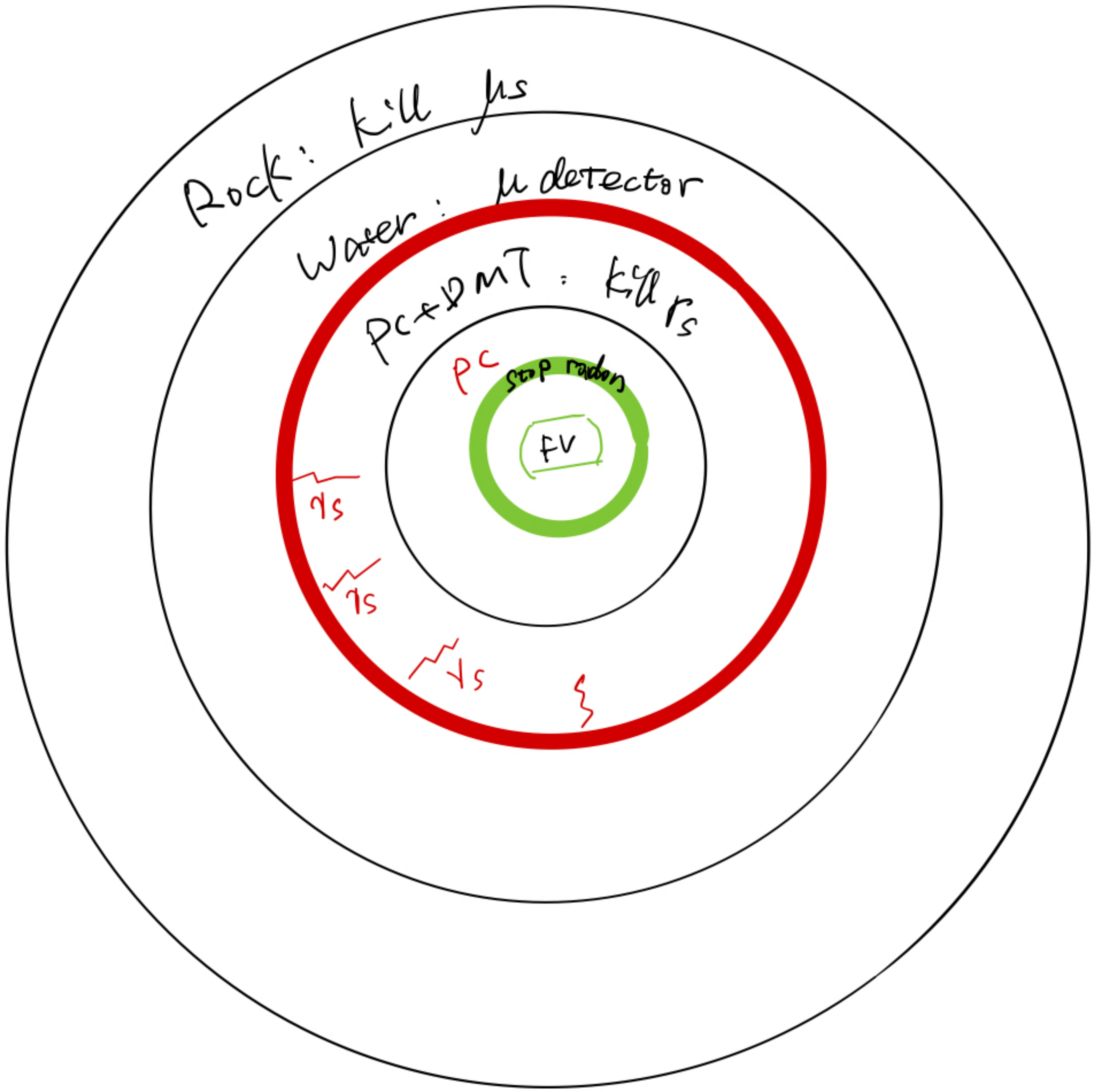
The low background nylon vessel

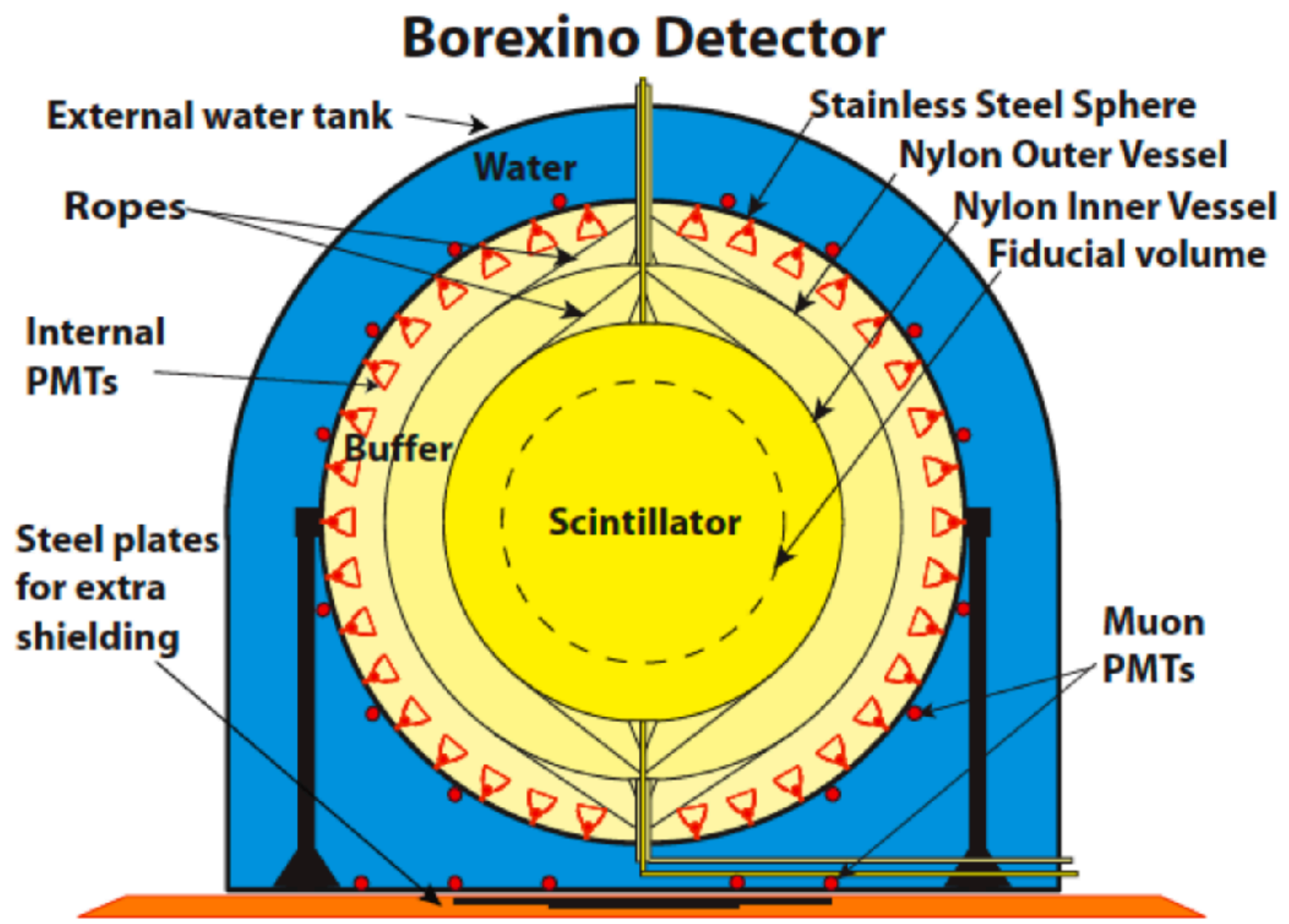
- Very low background nylon film made at Princeton University.
- Original consideration was thick acrylic walls emits too much gamma bkg.
- Later: decay daughters in the film gain kinetic energy, detach from the film, and migrate into the FV with convection currents.

Prototypes of the nested nylon vessels @ Jadwin Gymnasium at Princeton University

The nylon scintillator containment vessels for the Borexino solar neutrino experiment, J. Benziger et al. NIM, 2007

Background reduction by shielding



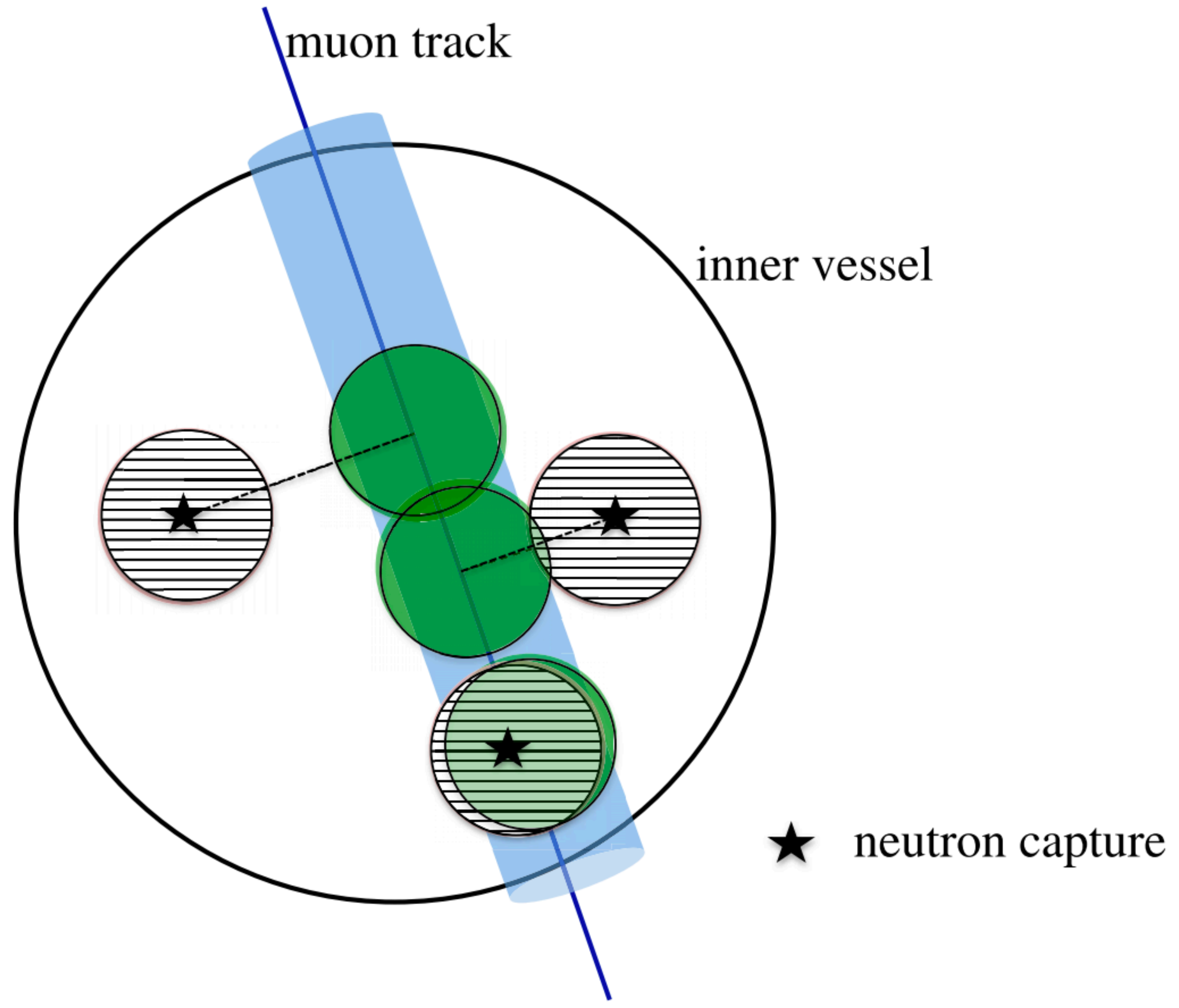


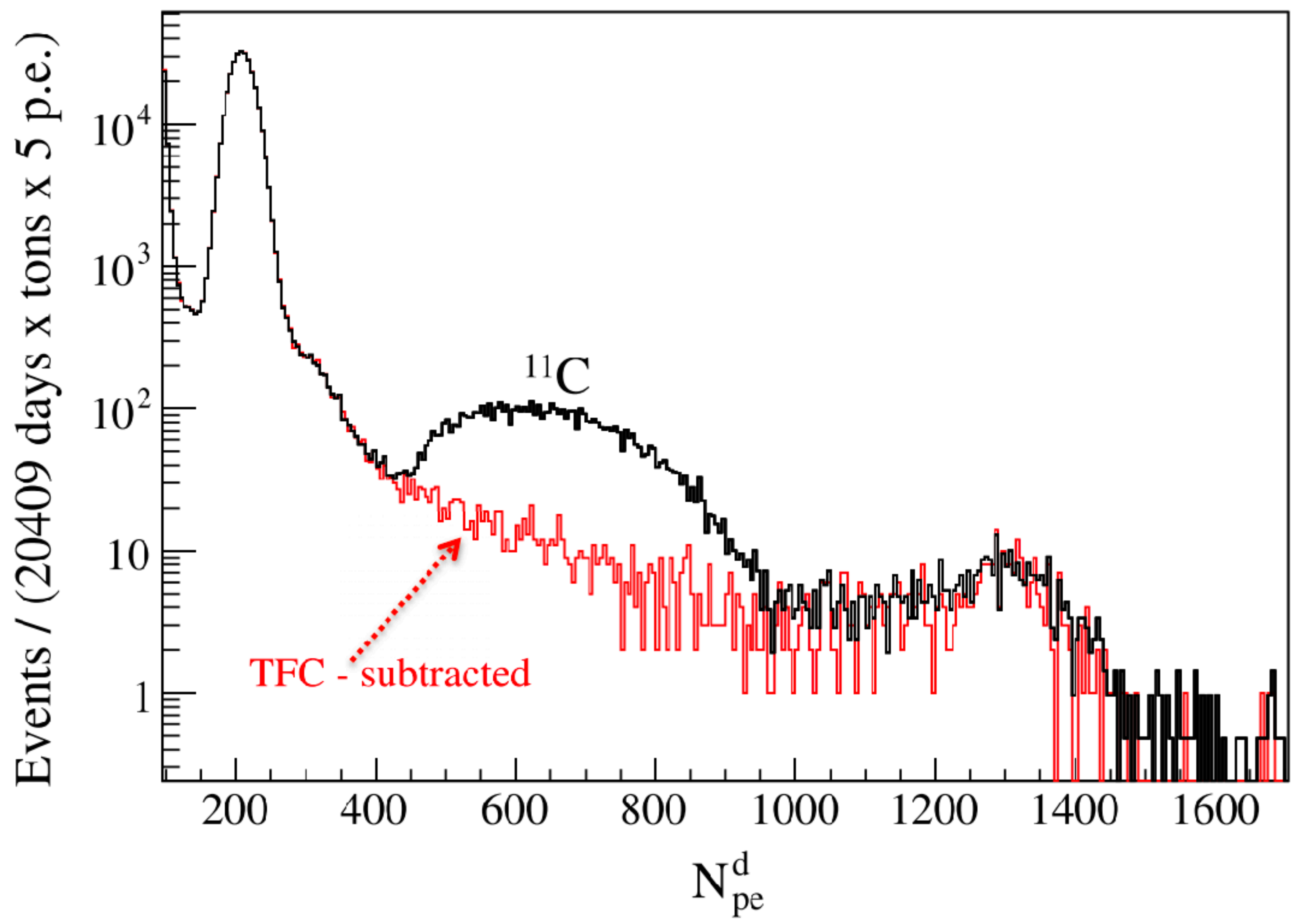
First detection of solar neutrinos from CNO cycle with Borexino. G. Ranucci. Neutrino 2020

Entrance of Gran Sasso tunnel

- Outmost: 3800 w.m.e. rock as shield against **muons**
- Second band: water Cherenkov detector vetoing **muons**
- Third band: PC+DMP buffer kills **gammas** from PMTs
- Nylon between fourth and fifth band: stop **radon**
- Innermost: FV cut further removes **gammas** from PMTs

Backgrounds reduction through analysis

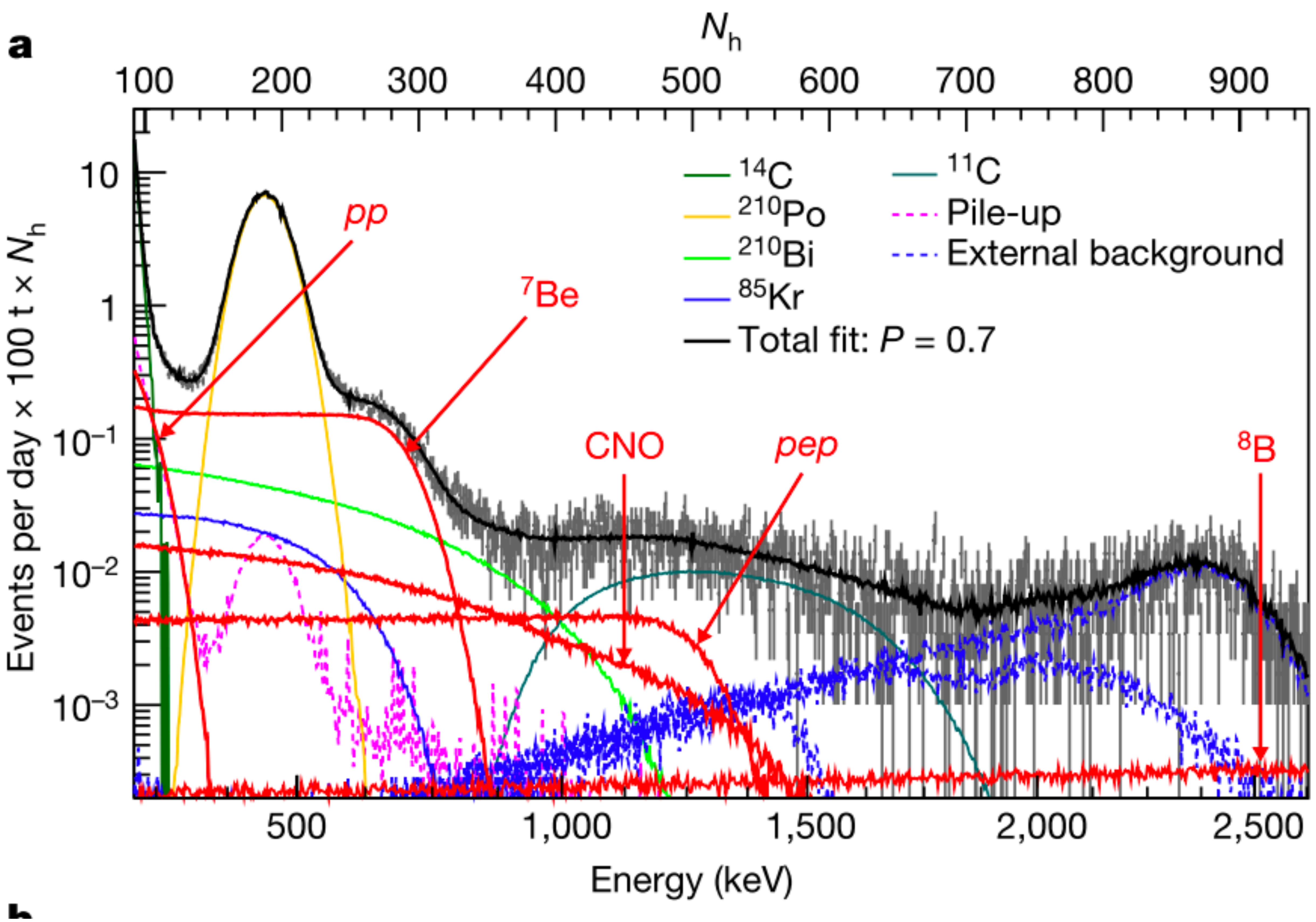




Final results of Borexino Phase-I on low-energy solar neutrino spectroscopy, BOREXINO, 2014, PRD

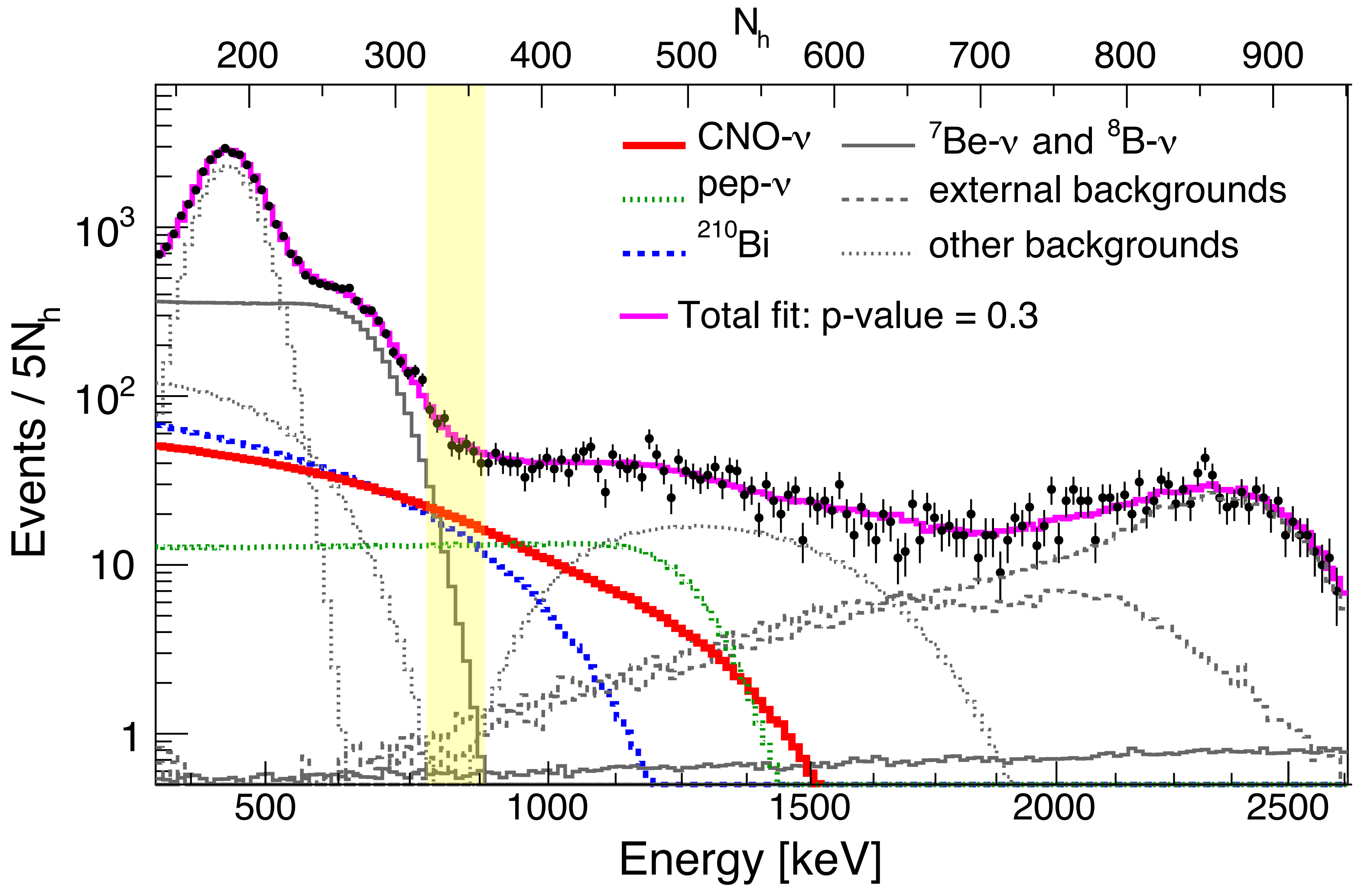
- ^{11}C are suppressed by three-fold-coincidence (TFC, muon + neutron + ^{11}C) cut.
  - ✦ ^{11}C are mainly produced through ^{12}C(γ/π,n)^{11}C etc. γ/π are from muons. Most ^{11}C are produced with a neutron.
  - ✦ We build a likelihood from distance & delay to nearest muons & neutrons and reduce ^{11}C rate by ~93%

Seven backgrounds of the Borexino detector

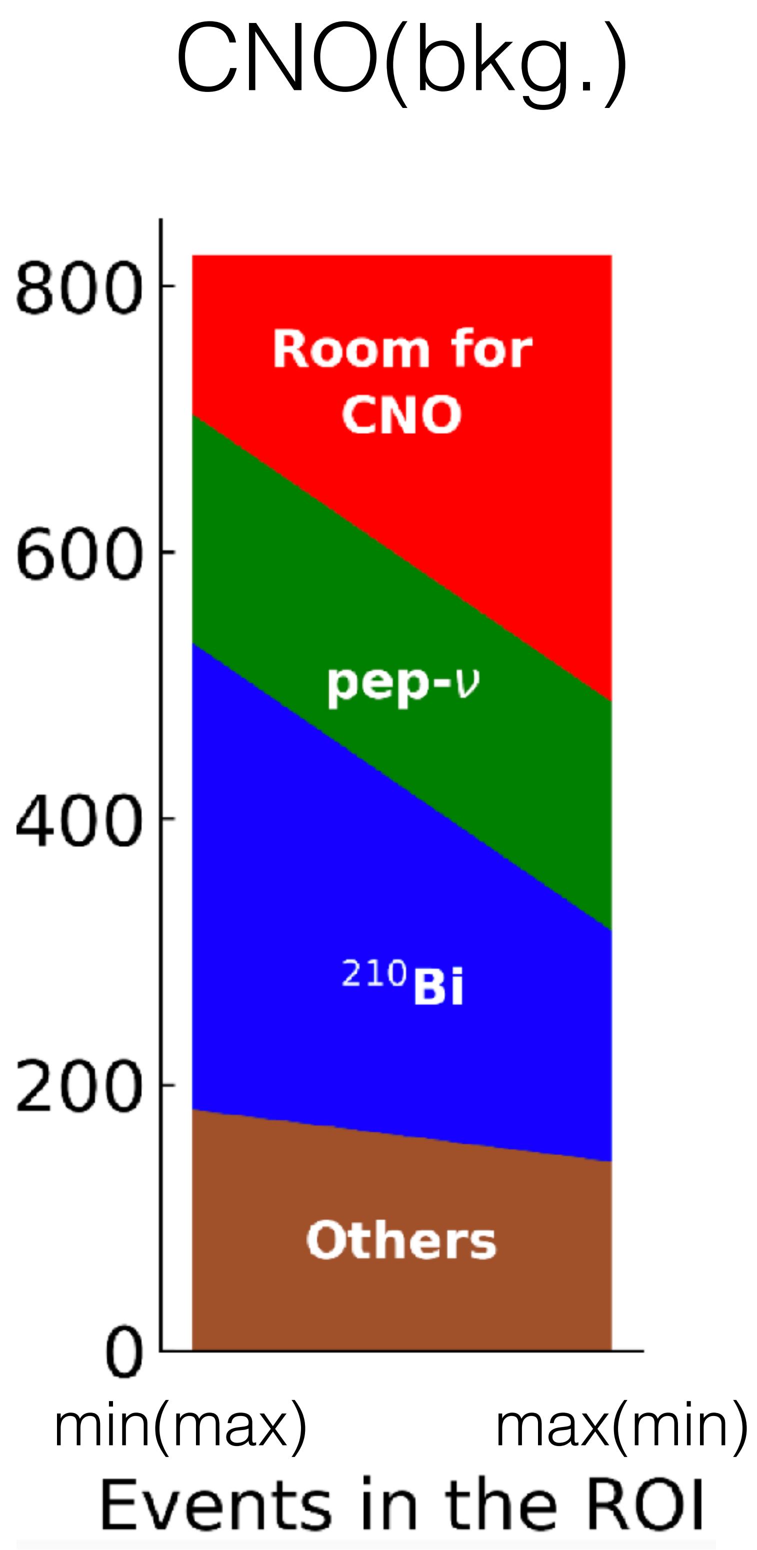


1. ^{14}C. Cosmogenic. τ=5730 years
2. ^{210}Po. Decay descendant of ^{210}Pb
3. ^{210}Bi. Decay daughter of ^{210}Pb
4. ^{85}Kr. From Atom bombs. In the air.
5. ^{11}C. Cosmogenic. τ=20 mins
6. pile-up. As its name.
7. Ext. γ from ^{208}Tl, ^{234}Th, and ^{40}K in PMTs

Important backgrounds for CNO



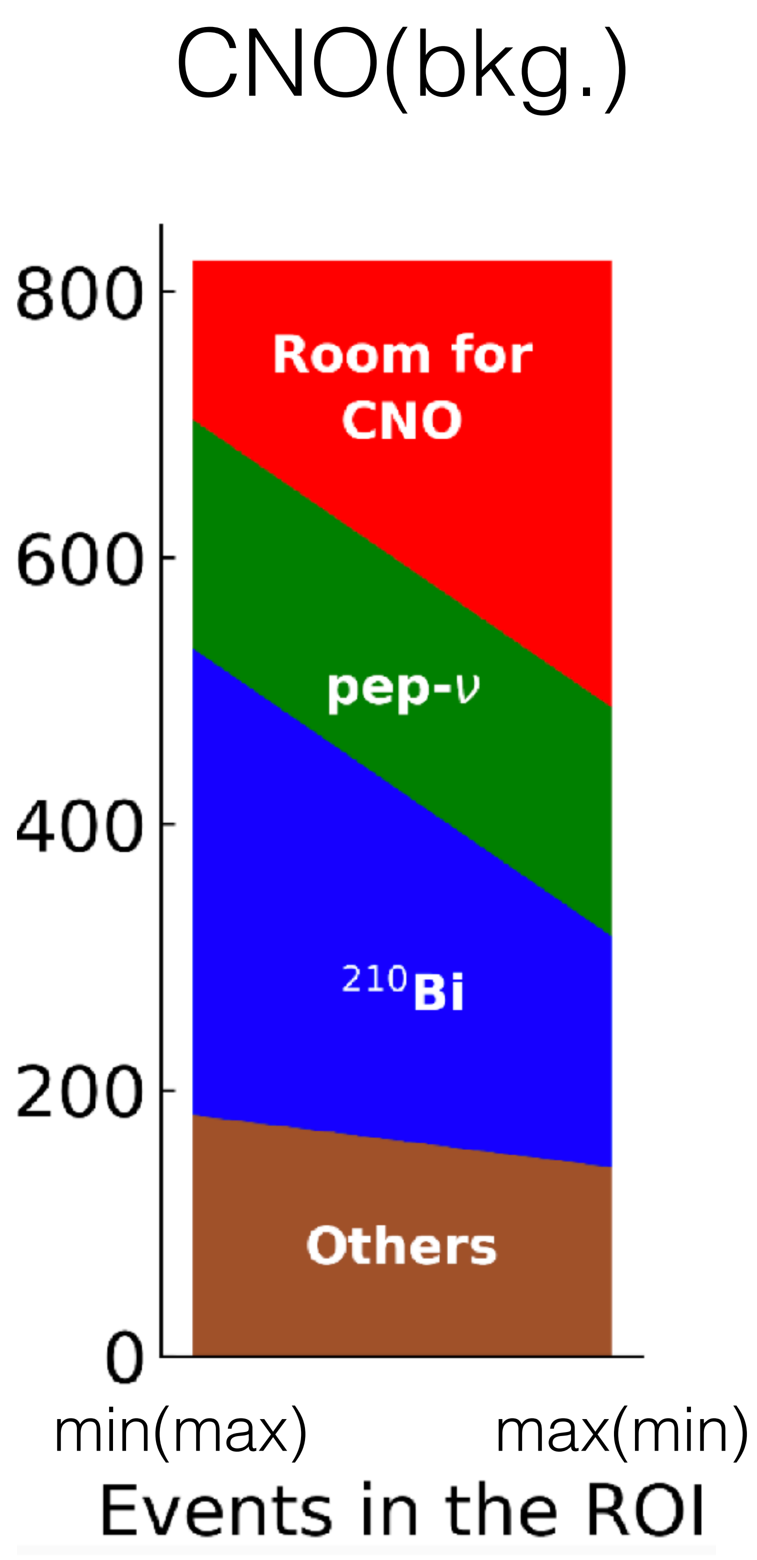
First detection of solar neutrinos from CNO cycle with Borexino. G. Ranucci. Neutrino 2020



First Direct Experimental Evidence of CNO neutrinos, BOREXINO, 2020, hep-ex/2006.15115

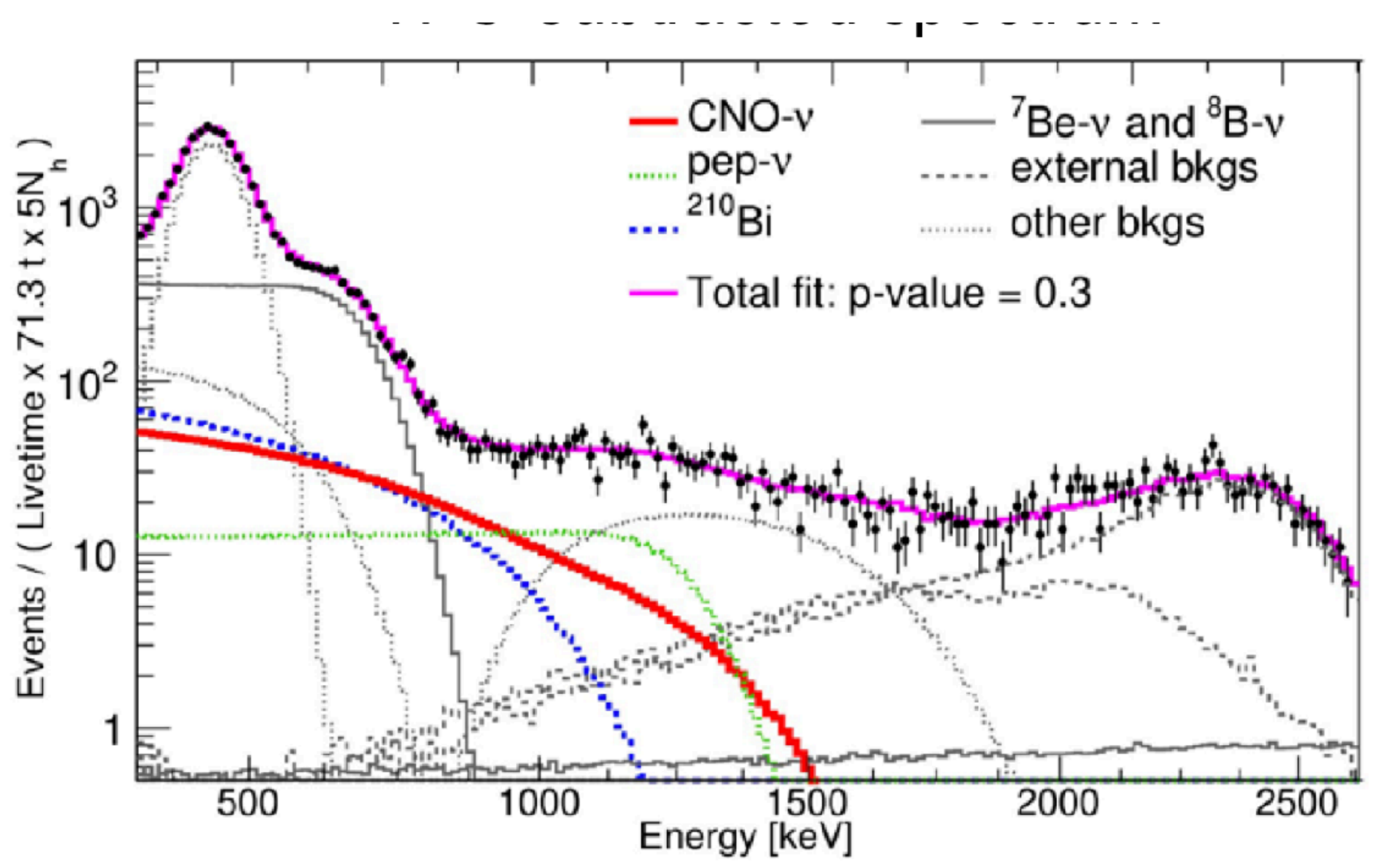
- ROI: around 0.8—0.9 MeV
- ~90% CNO ν + *pep* ν + ^{210}Bi
- ~10% ^{7}Be ν + ^{11}C + ext. ^{40}K γ etc.

Measure ext. ^{40}K, ^{11}C, internal ^{40}K, and ν(^{7}Be)

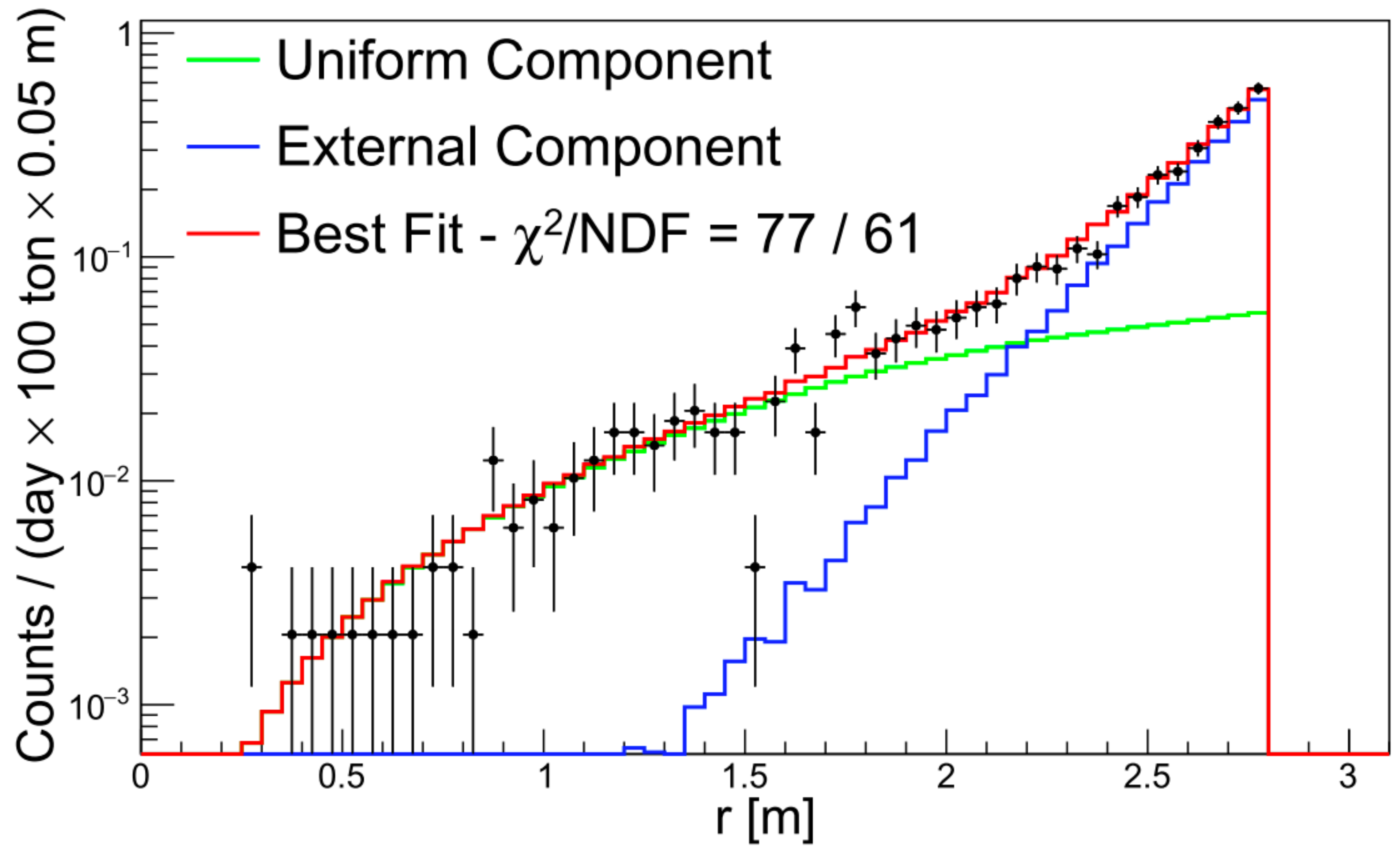


First Direct Experimental Evidence of CNO neutrinos, BOREXINO, 2020, hep-ex/2006.15115

Others = ^{7}Be ν + ^{11}C + ext. ^{40}K γ etc.



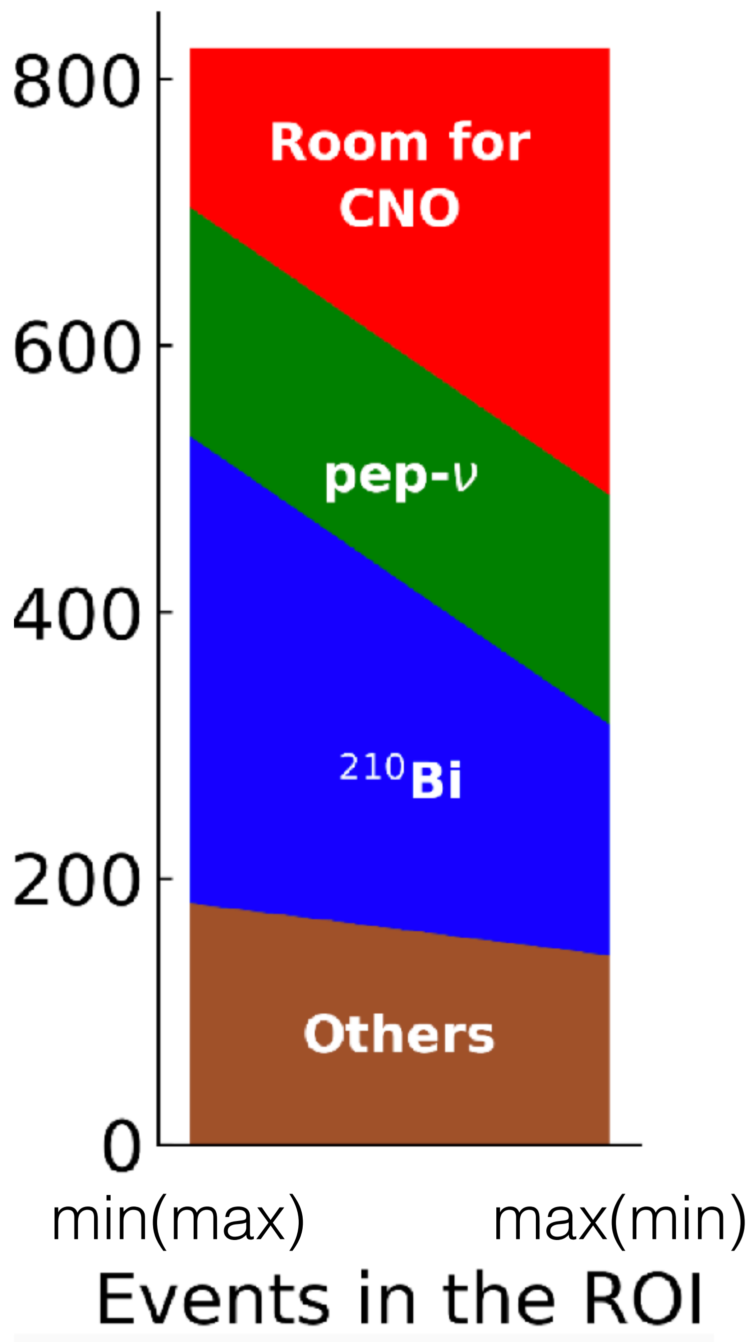
First Direct Experimental Evidence of CNO neutrinos, BOREXINO, 2020, hep-ex/2006.15115



First Direct Experimental Evidence of CNO neutrinos, BOREXINO, 2020, hep-ex/2006.15115

- Around 10% of ROI.
- Ext ^{208}Tl/^{232}Th/^{40}K γ: by event **position** distribution.
- ^{11}C: by **energy** distribution. Peak shape.
- Internal ^{40}K: by **energy** distribution. Double peak shape (beta + EC). Negligible.
- ^{7}Be ν: by **energy** distribution. Heaviside-step-function like shape.

CNO(bkg.)



First Direct Experimental Evidence of CNO neutrinos, BOREXINO, 2020, hep-ex/2006.15115

Regular Article - Theoretical Physics | Open Access | Published: 18 March 2016

Updated determination of the solar neutrino fluxes from solar neutrino data

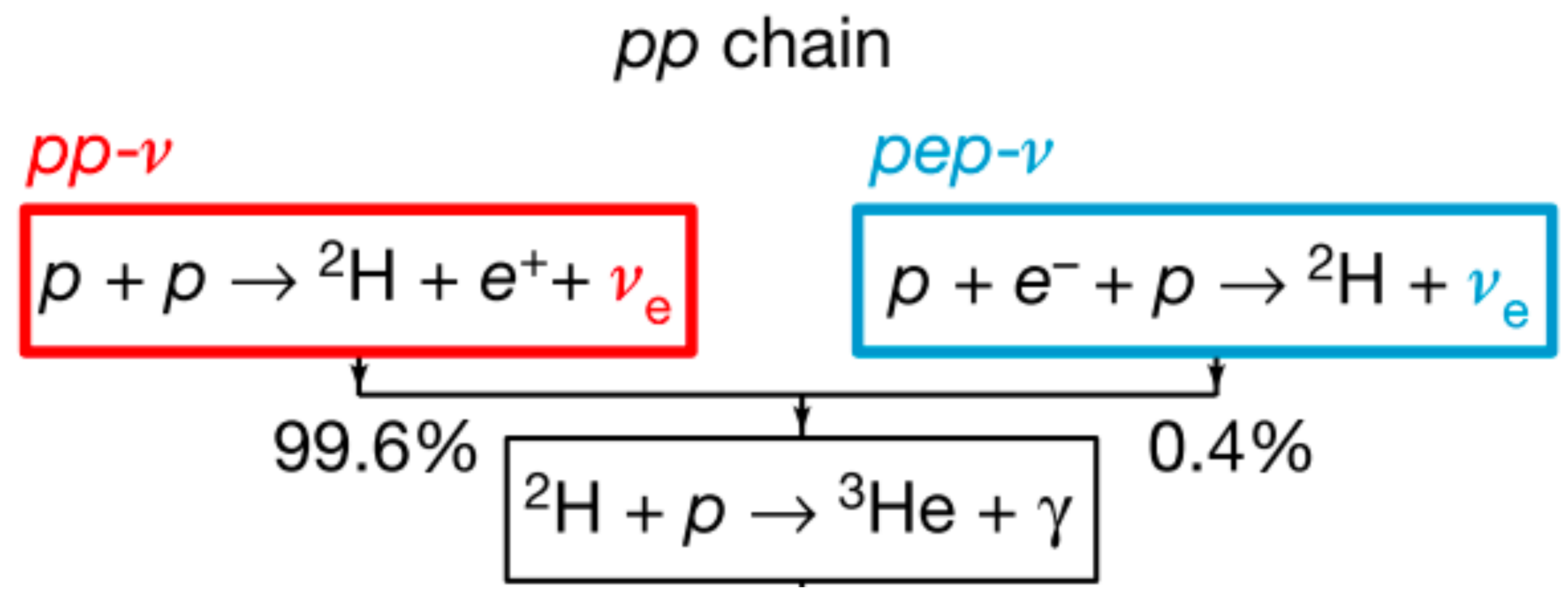
Johannes Bergström, M. C. Gonzalez-Garcia, Michele Maltoni, Carlos Peña-Garay, Aldo M. Serenelli & Ningqiang Song

Journal of High Energy Physics **2016**, Article number: 132 (2016) | Cite this article

362 Accesses | **33** Citations | **2** Altmetric | Metrics

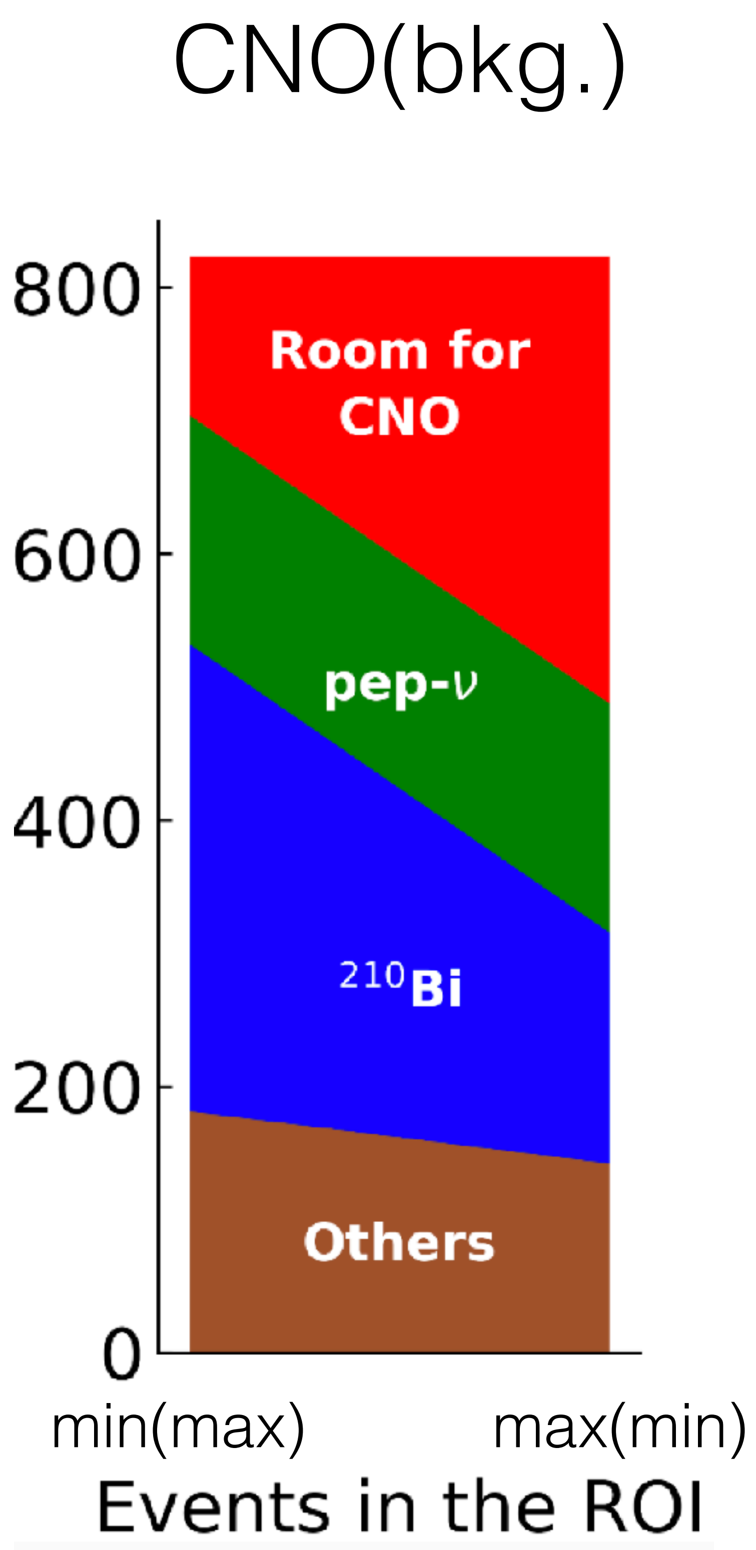
$$0.9800 \times \varphi_{\mathrm{pp}} + 0.0939 \times \varphi_{\mathrm{Be}} + 0.0092 \times \varphi_{\mathrm{CNO}} + \\ + 0.0089 \times \varphi_{\mathrm{pep}} + \text{small terms} = 6.379 \times (1 \pm 0.4\%)$$

Luminosity constraint and entangled solar neutrino signals, F. Vissani, 2018

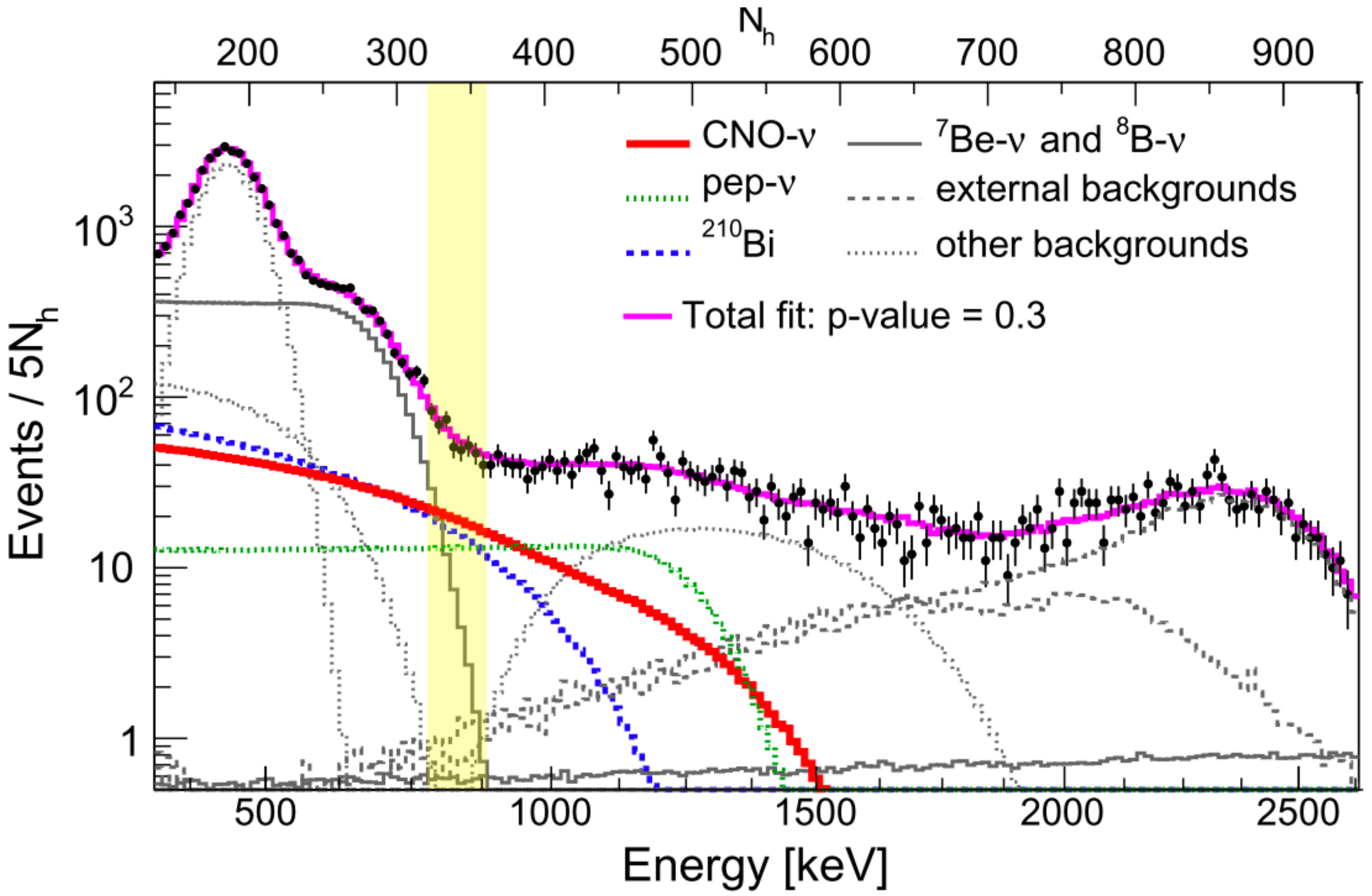


- ~30% of ROI
- From global fit.
  - Luminosity constraint constraints pp. Need also ^{7}Be etc.
  - pp/pep ratio: known from nuclear physics
- Standard MSW P_{ee} used.

Challenges of constraining ^{210}Bi



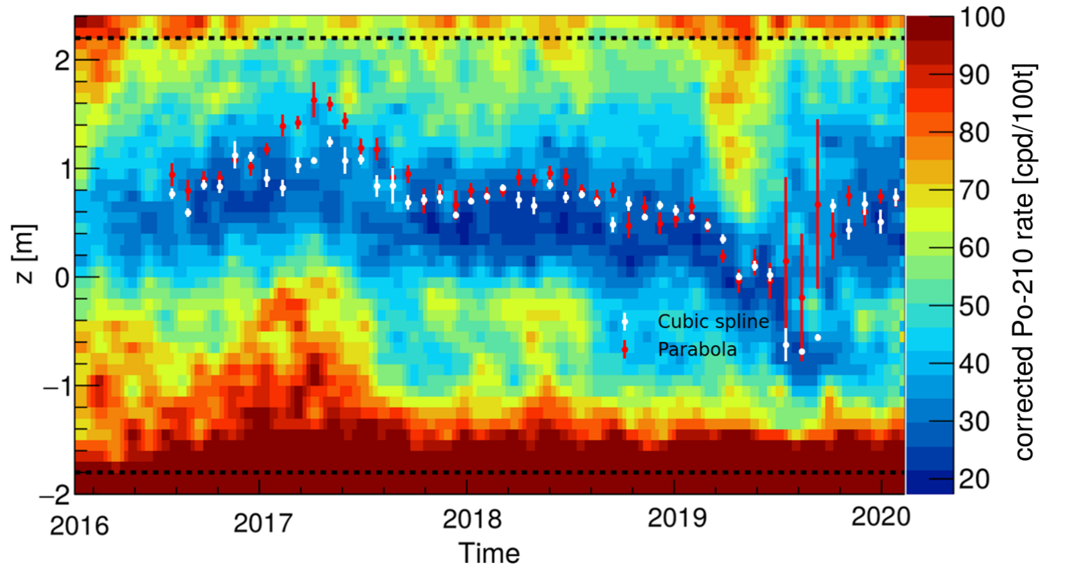
First Direct Experimental Evidence of CNO neutrinos, BOREXINO, 2020, hep-ex/2006.15115



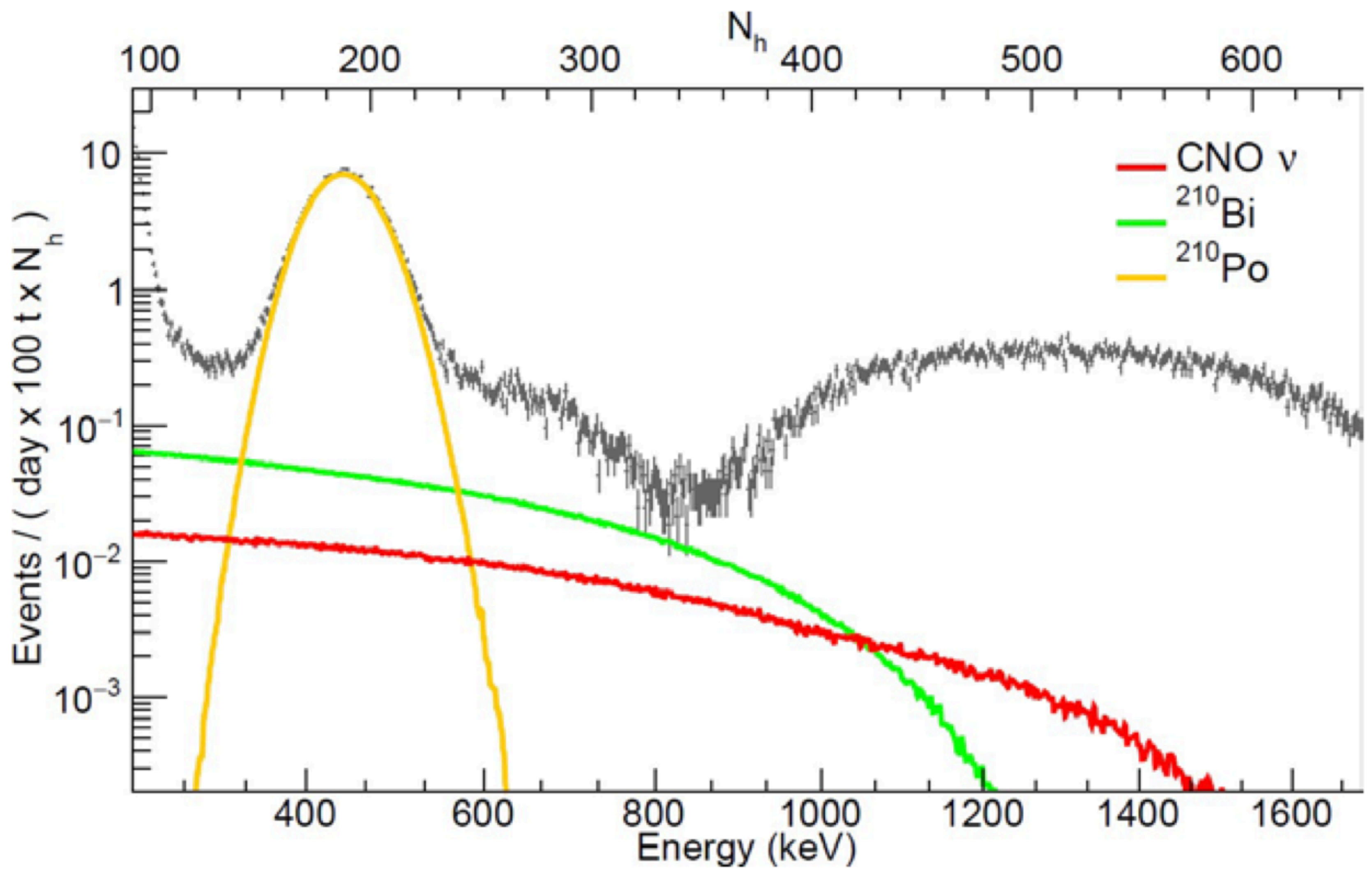
- ~30% of ROI
- **Very similar shape compared with CNO**. Difficult to separate through shape.
- Need to be measured independently.
- Solution: LPoF method.

Low-Polonium-Field (LPoF) analysis

To measure ^{210}Bi

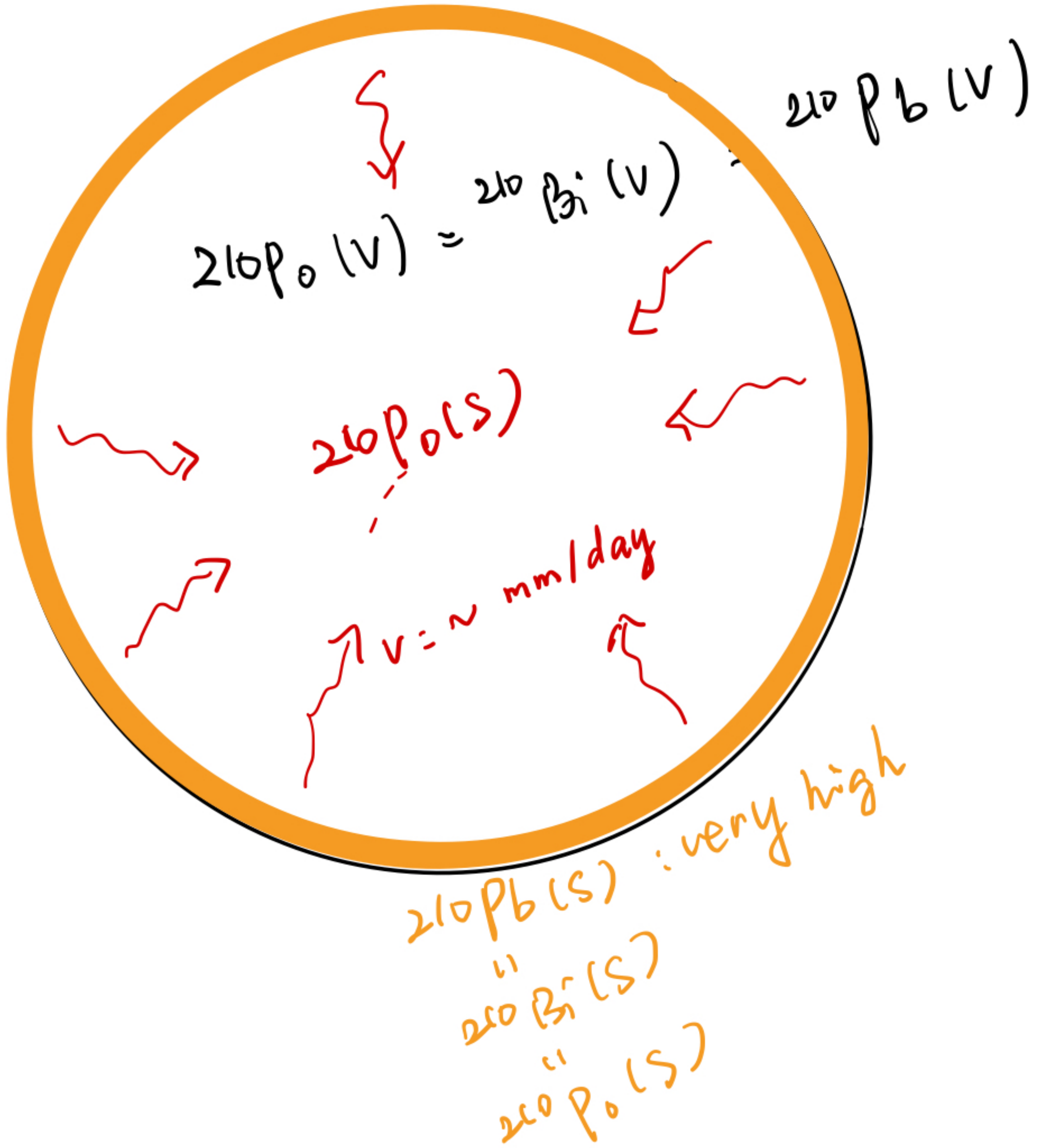


$$^{210}\mathrm{Pb} \xrightarrow[32\ \mathrm{y}]{\beta^-} {}^{210}\mathrm{Bi} \xrightarrow[7.23\ \mathrm{d}]{\beta^-} {}^{210}\mathrm{Po} \xrightarrow[199.1\ \mathrm{d}]{\alpha} {}^{206}\mathrm{Pb}$$



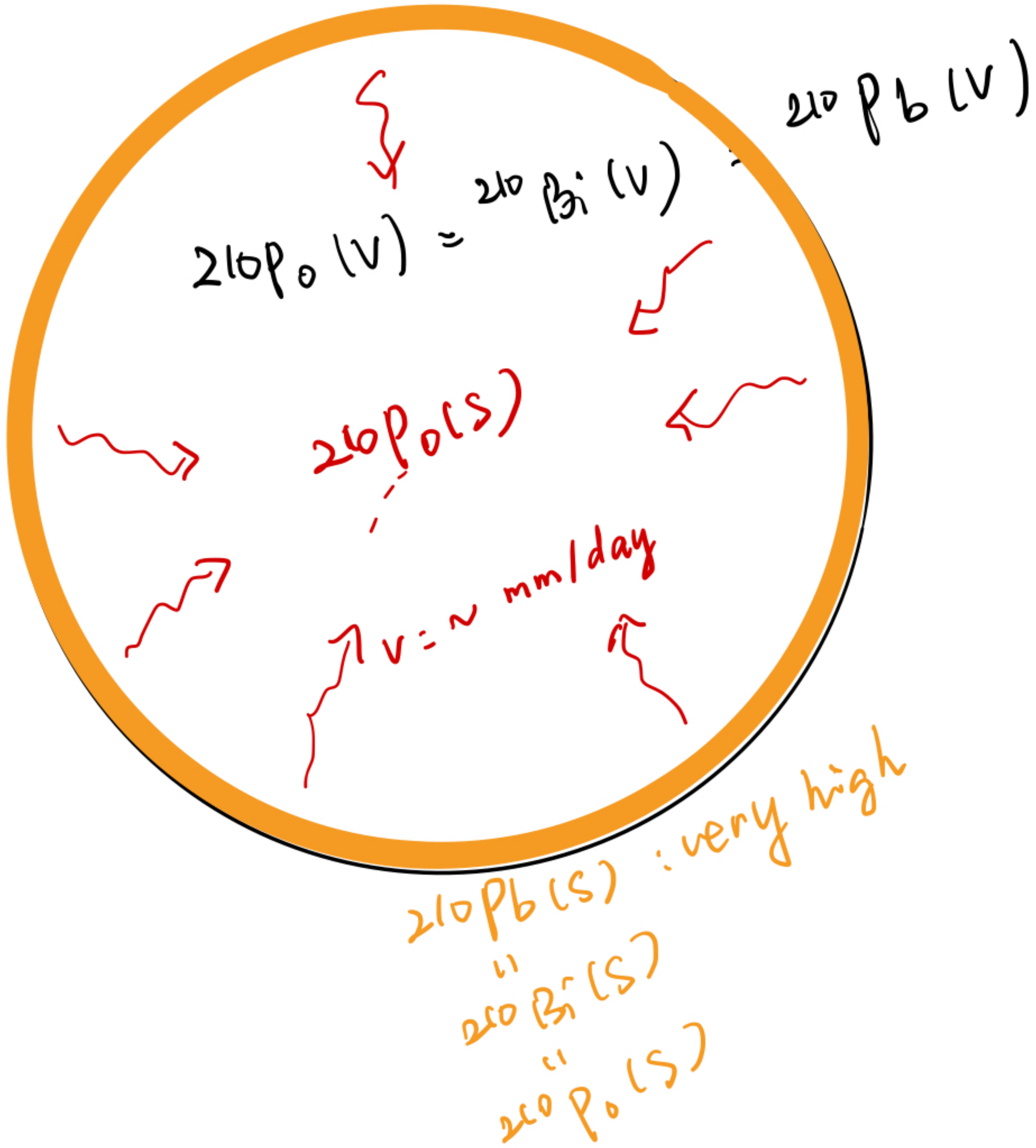
- When ^{210}Pb—^{210}Bi—^{210}Po reaches secular equilibrium, **their rates are equal.**
- ^{210}Po rate can be measured precisely. ^{210}Po decay through α decay. ^{210}Po events can be selected event-by-event using an α/β discriminator.

^{210}Po(Surface) and ^{210}Po(Volume)



- ^{210}Pb are present both in the liquid scintillator (hereinafter as ^{210}Pb(Volume)) and the surface of nylon vessel (hereinafter as 210Pb(Surface)).
  - It is supposed ^{210}Pb are deposited into the nylon during the first fill, when ^{210}Pb is not removed by purification yet.
- **We need only R(^{210}Po(V)) = R(^{210}Bi(V)) = R(^{210}Pb(V))**
- ^{210}Po(S) is background and need to be suppressed.

Suppress ^{210}Po(Surface)



- ^{210}Po(S) need to travel a few meters to reach FV.
- Suppress convection, ^{210}Po(S) will decay halfway, and ^{210}Po(S, FV) will reduce.
- Solution: Keep the detector thermal condition stable to suppress convection.

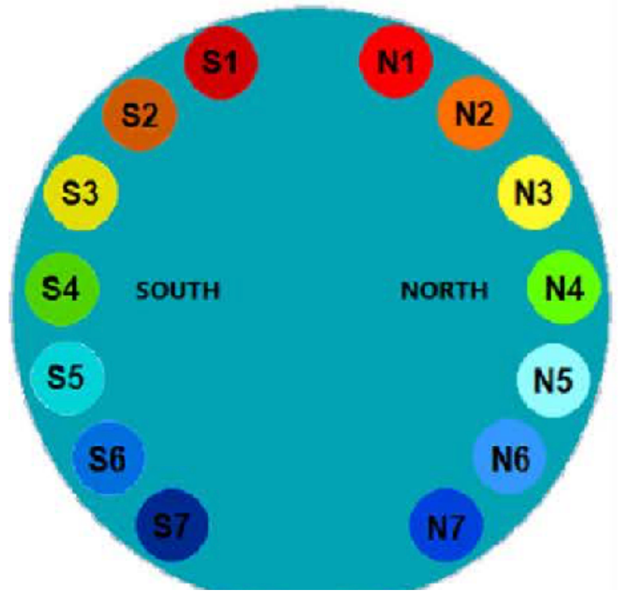
Six years of efforts to stabilize thermal condition

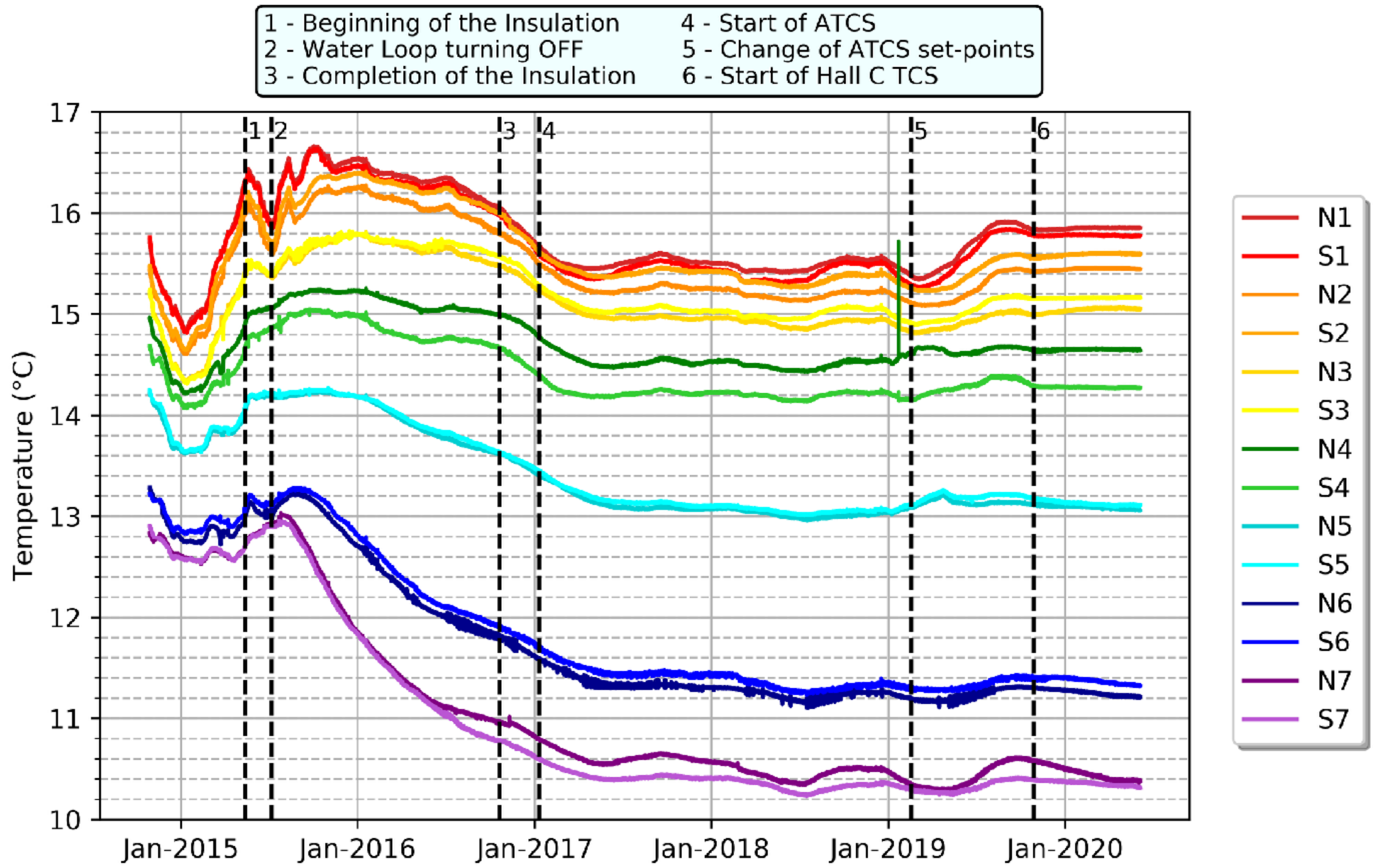
First Direct Experimental Evidence of CNO neutrinos, BOREXINO, 2020, hep-ex/2006.15115

Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment
Volume 964, 1 June 2020, 163801

Fluid-dynamics and transport of ^{210}Po in the scintillator Borexino detector: A numerical analysis

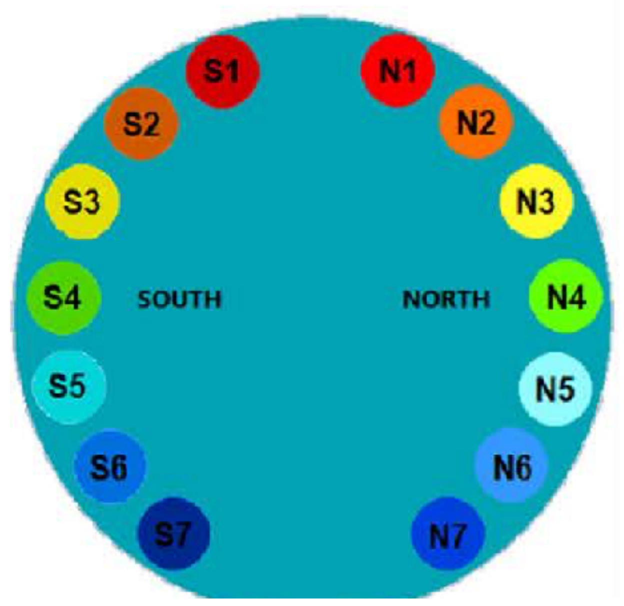
V. Di Marcello [a], D. Bravo-Berguño [b, 1], R. Mereu [c], F. Calaprice [d], A. Di Giacinto [a], A. Di Ludovico [d], Aldo Ianni [a], Andrea Ianni [d], N. Rossi [a], L. Pietrofaccia [d]

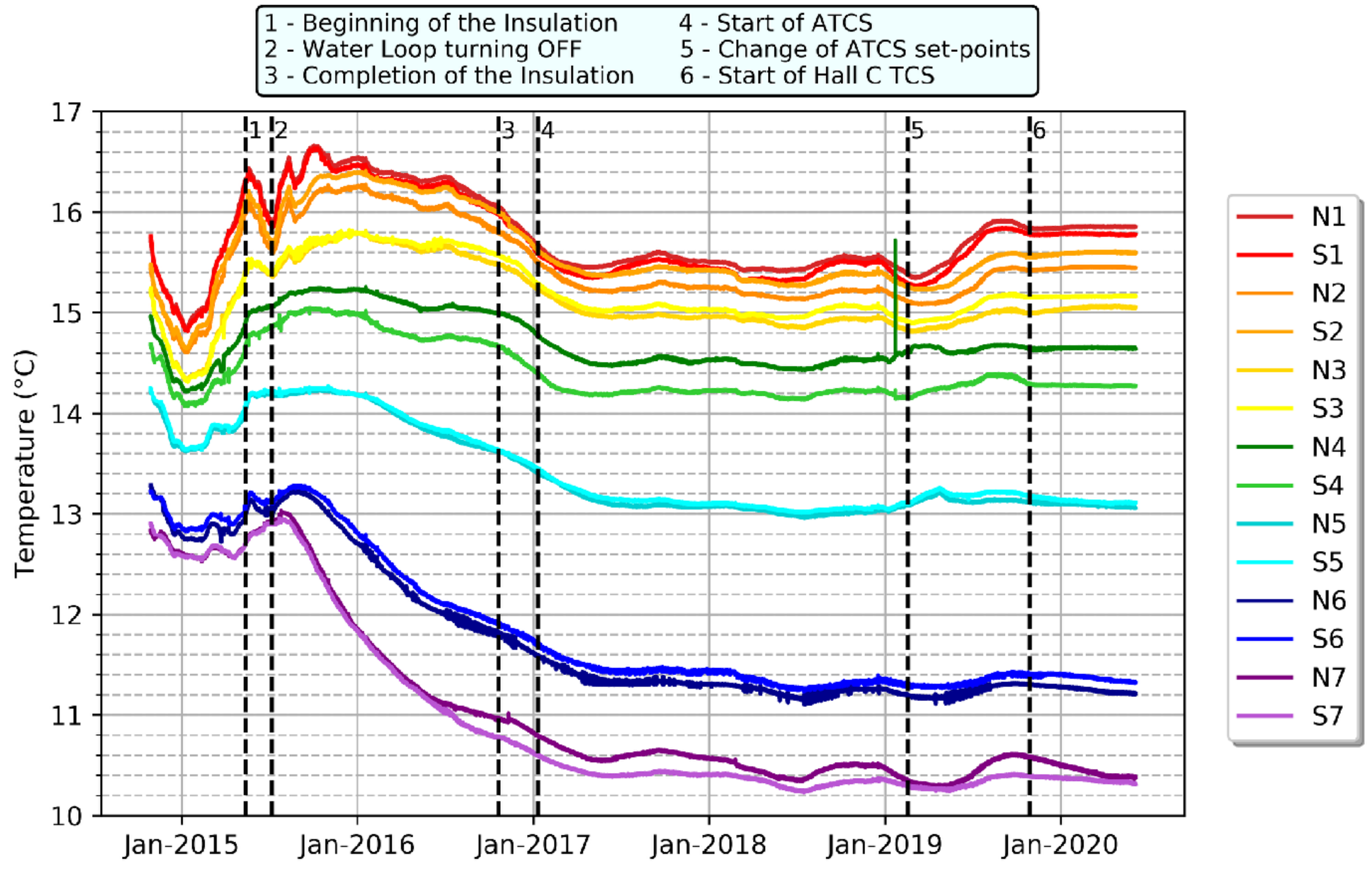




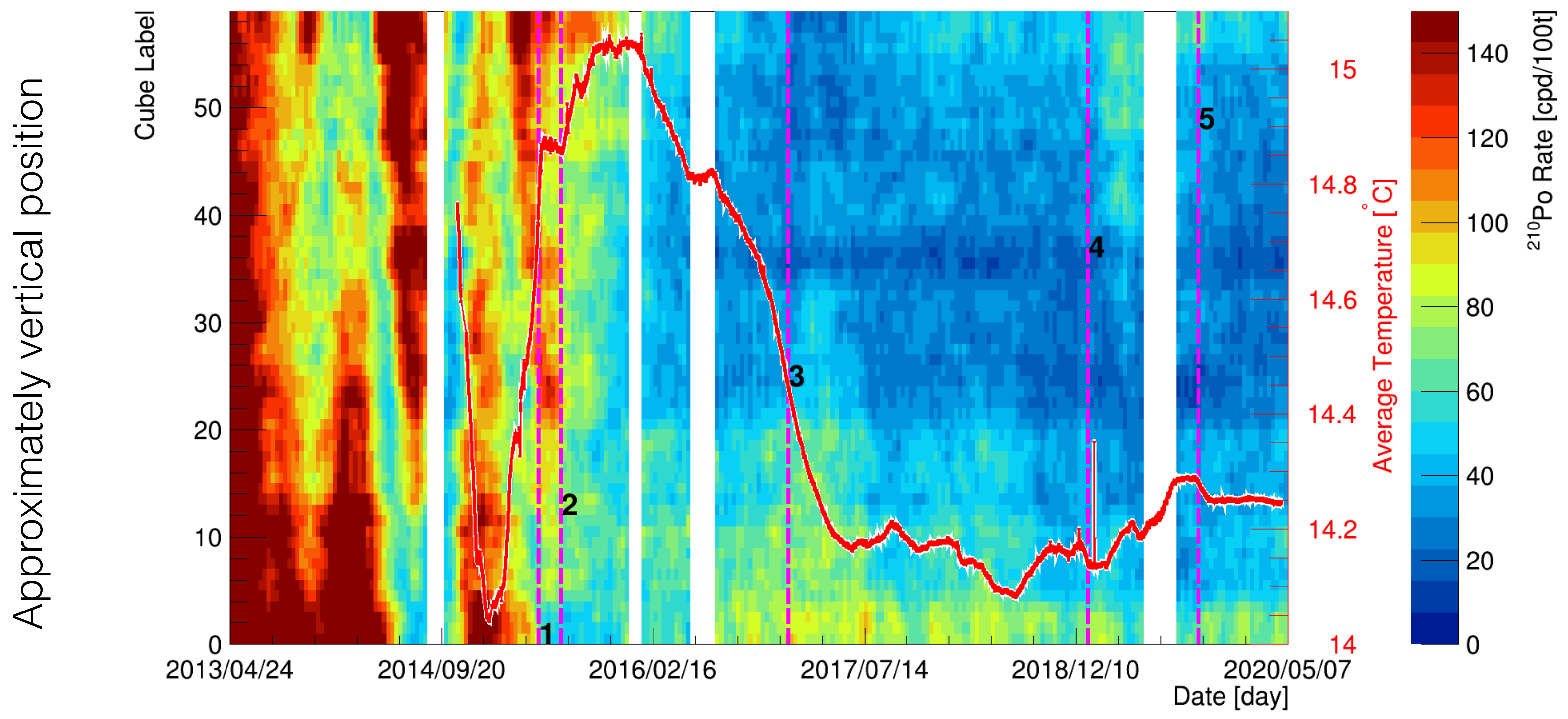
First Direct Experimental Evidence of CNO neutrinos, BOREXINO, 2020, hep-ex/2006.15115

- Double layer of mineral wool for insulation & Active Temperature Control System (ATCS) (2014—2016)
- Temperature Probes (2014—2016)
- Fluid dynamical simulations
- Hall C Temperature stabilization (2019)





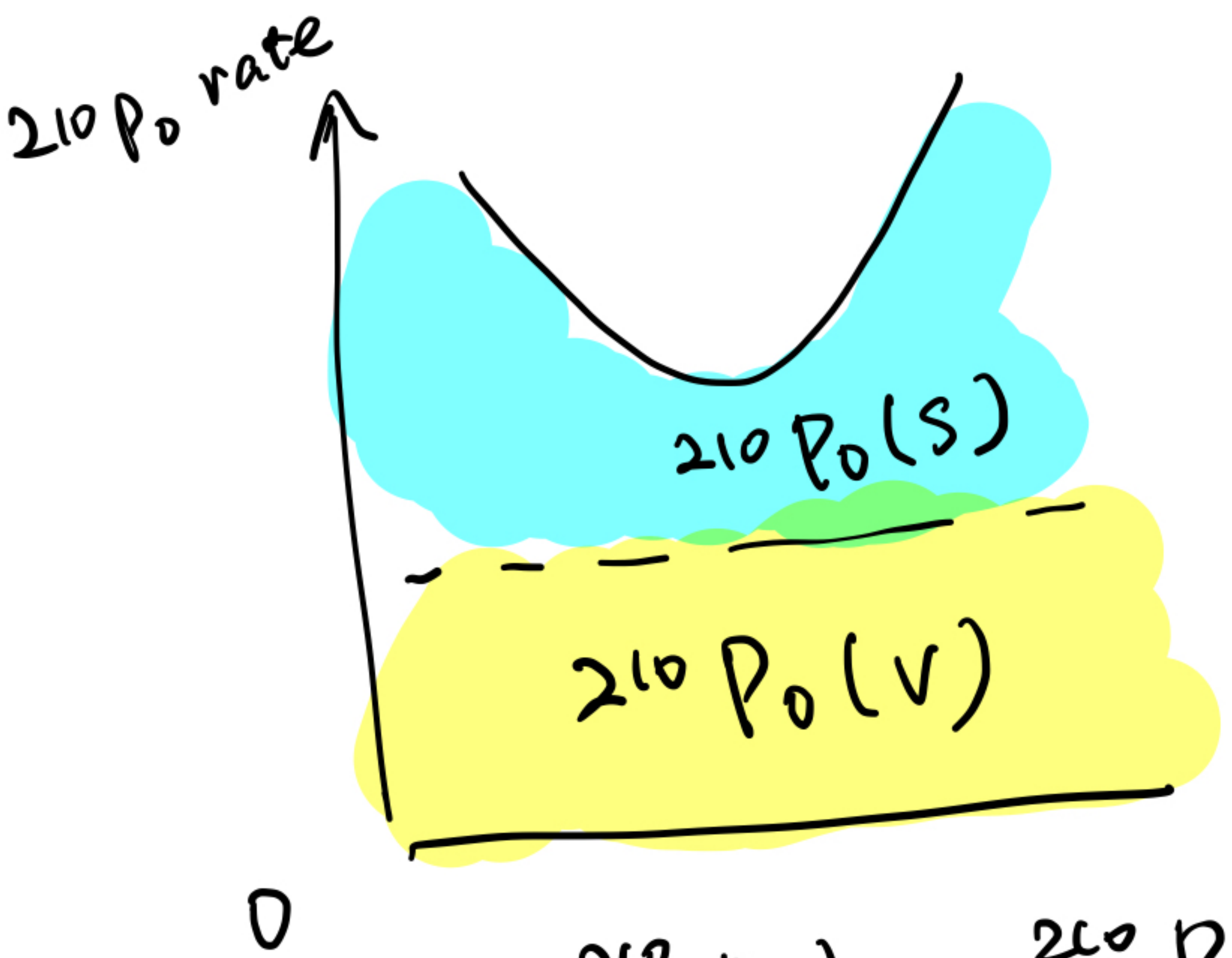
First Direct Experimental Evidence of CNO neutrinos, BOREXINO, 2020, hep-ex/2006.15115



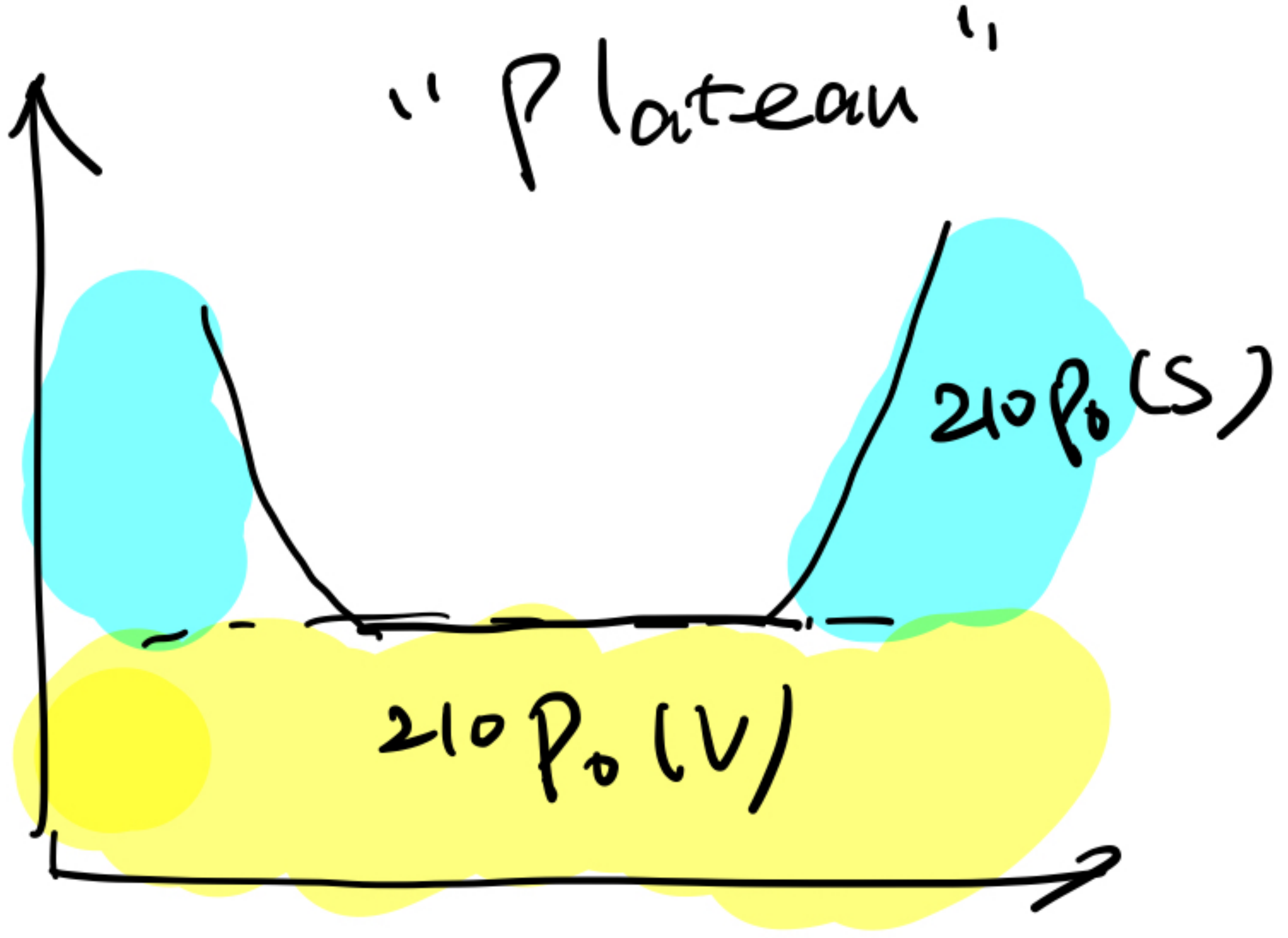
First Direct Experimental Evidence of CNO neutrinos, BOREXINO, 2020, hep-ex/2006.15115

- Temperature (top) much more stable after insulation & ATCS between 2017 Jan and 2019 Jan.
- Convection current suppressed, and less ^{210}Po(S) migrate into FV, and lower ^{210}Po rate (bottom).

Our case

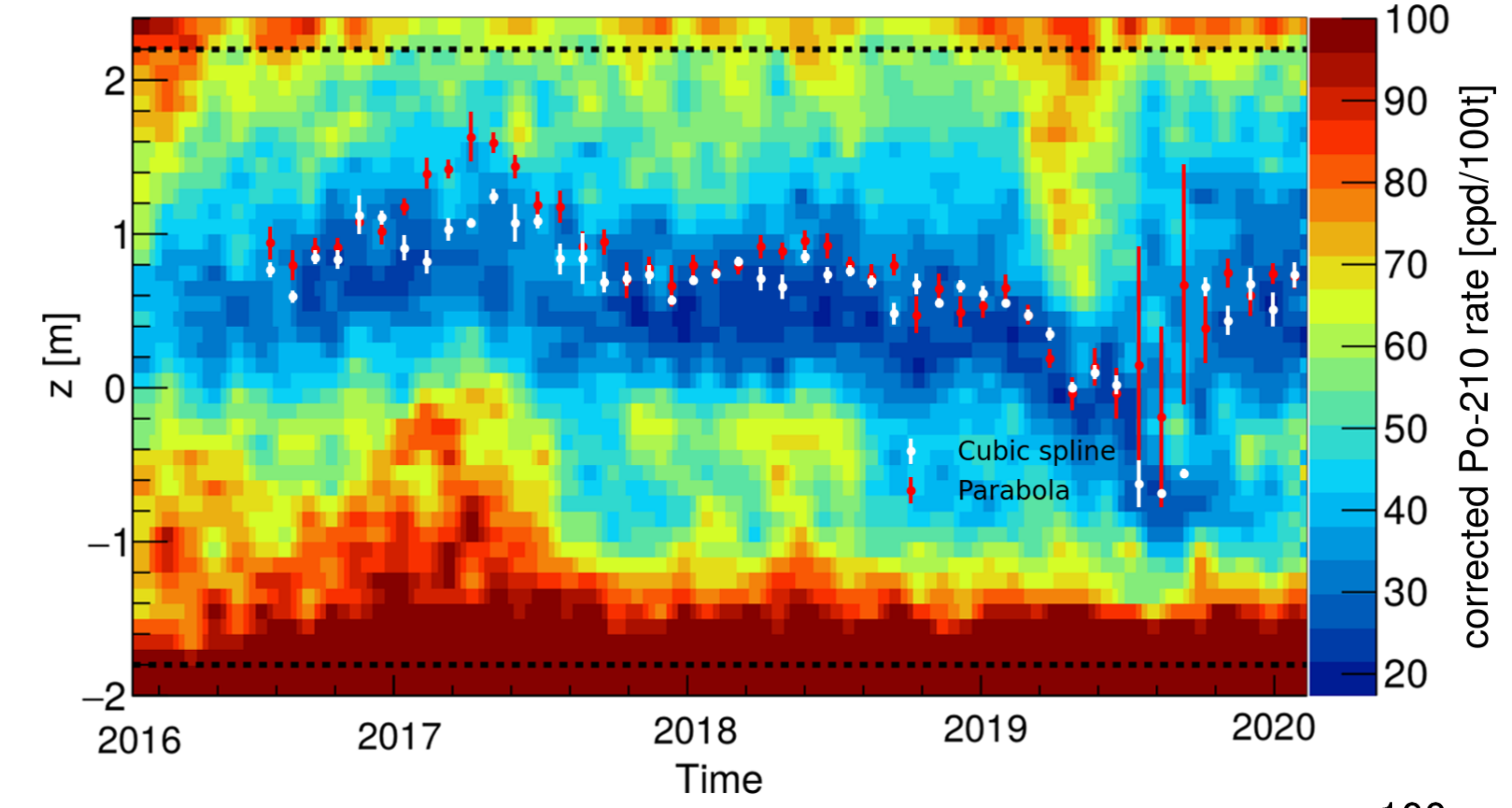


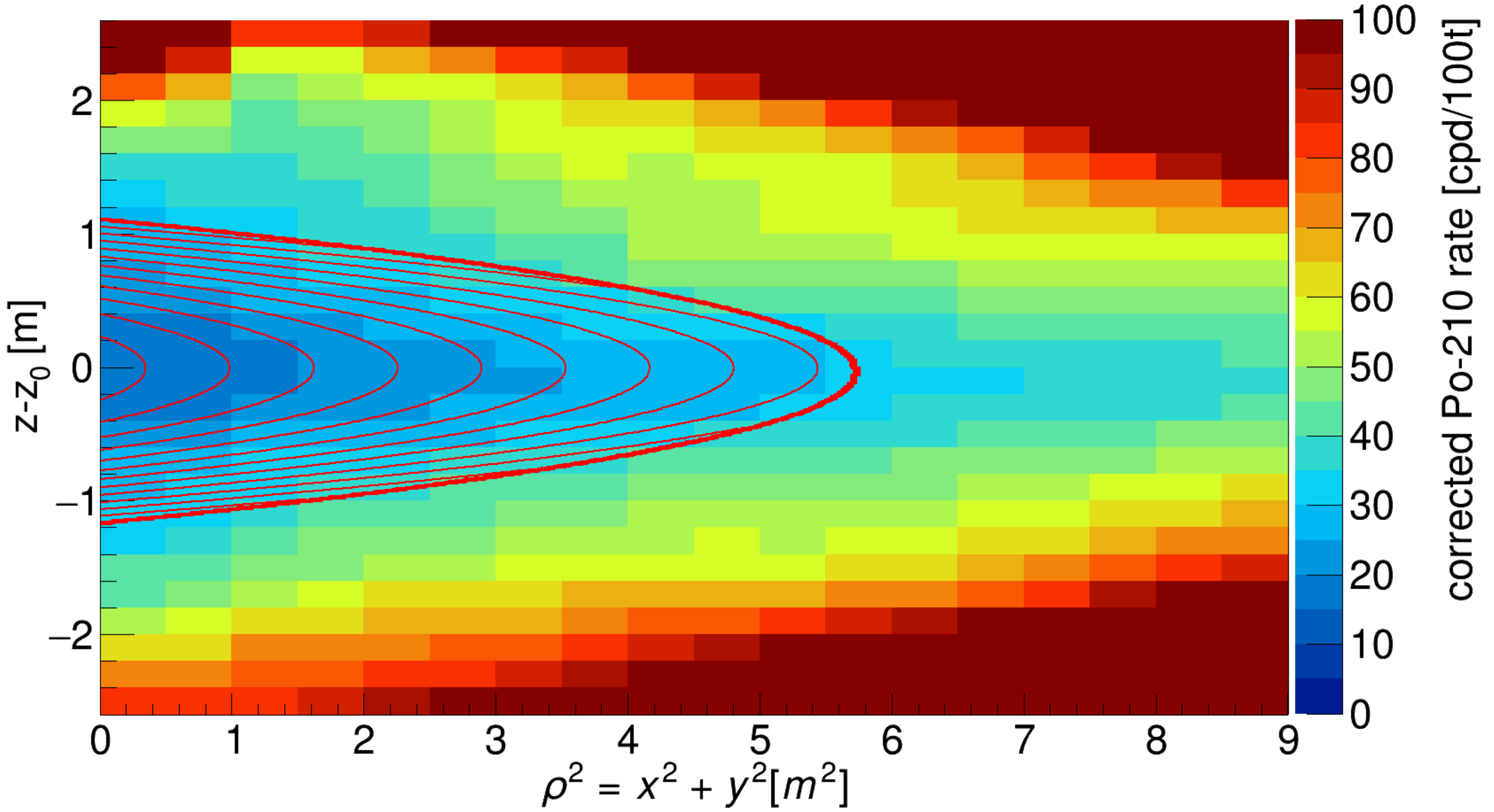
$$\min(^{210}Po) \geq {}^{210}Po(V)$$



$$\min(^{210}Po) = {}^{210}Po(V)$$

Breakthrough: Low Polonium Field (LPoF) analysis

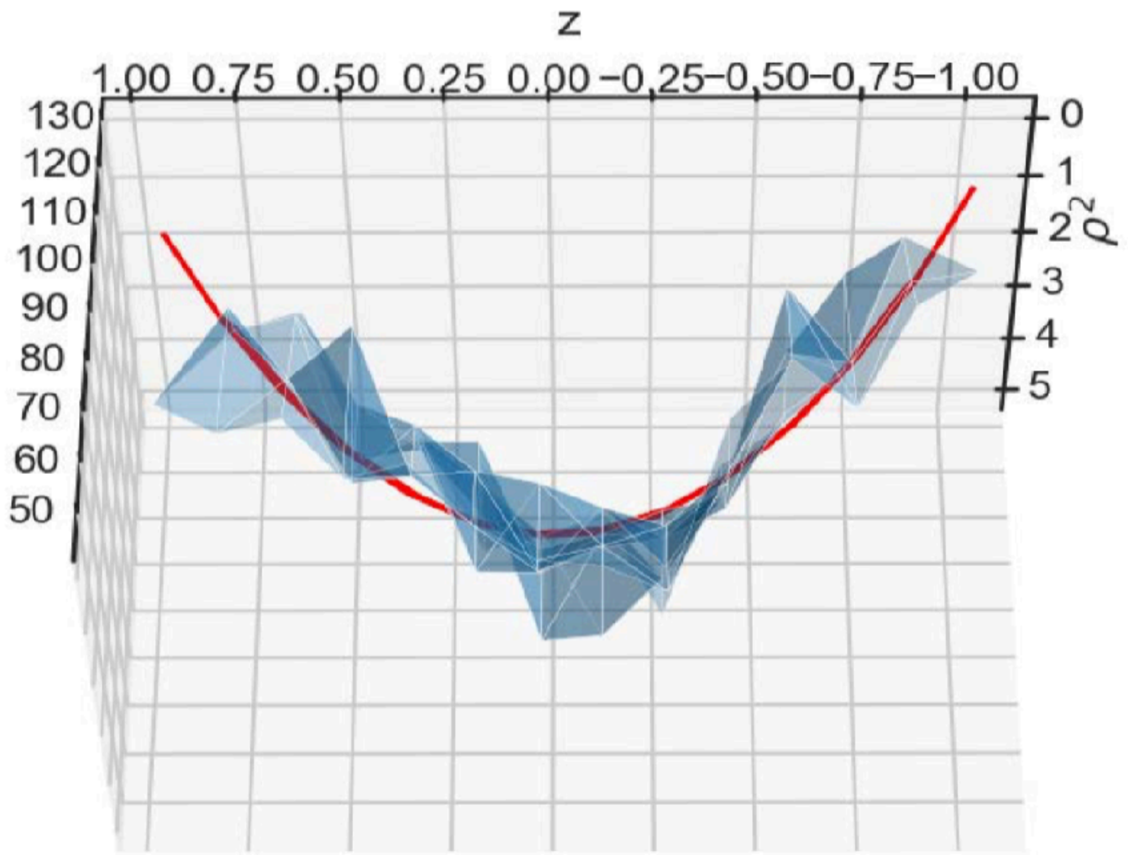




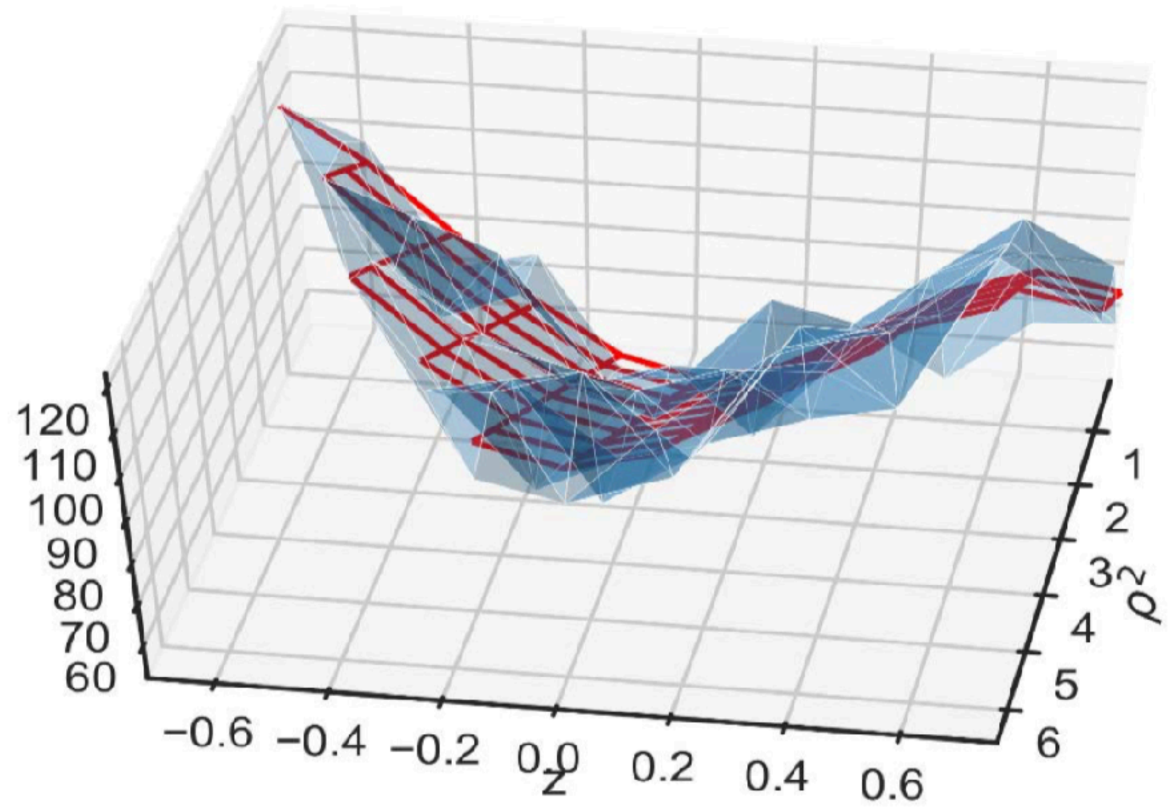
- LPoF: **Get minimum of R(^{210}Po)**
- Align dataset vertically for the minimum calibrated by minimum of previous month (blind alignment)
  - Fit dataset splitter in one month with parabolic/spline functions to obtain the minimum position.
- Fit merged dataset with parabolic/ spline functions.

Result of LPoF analysis

Paraboloid



Spline fit:

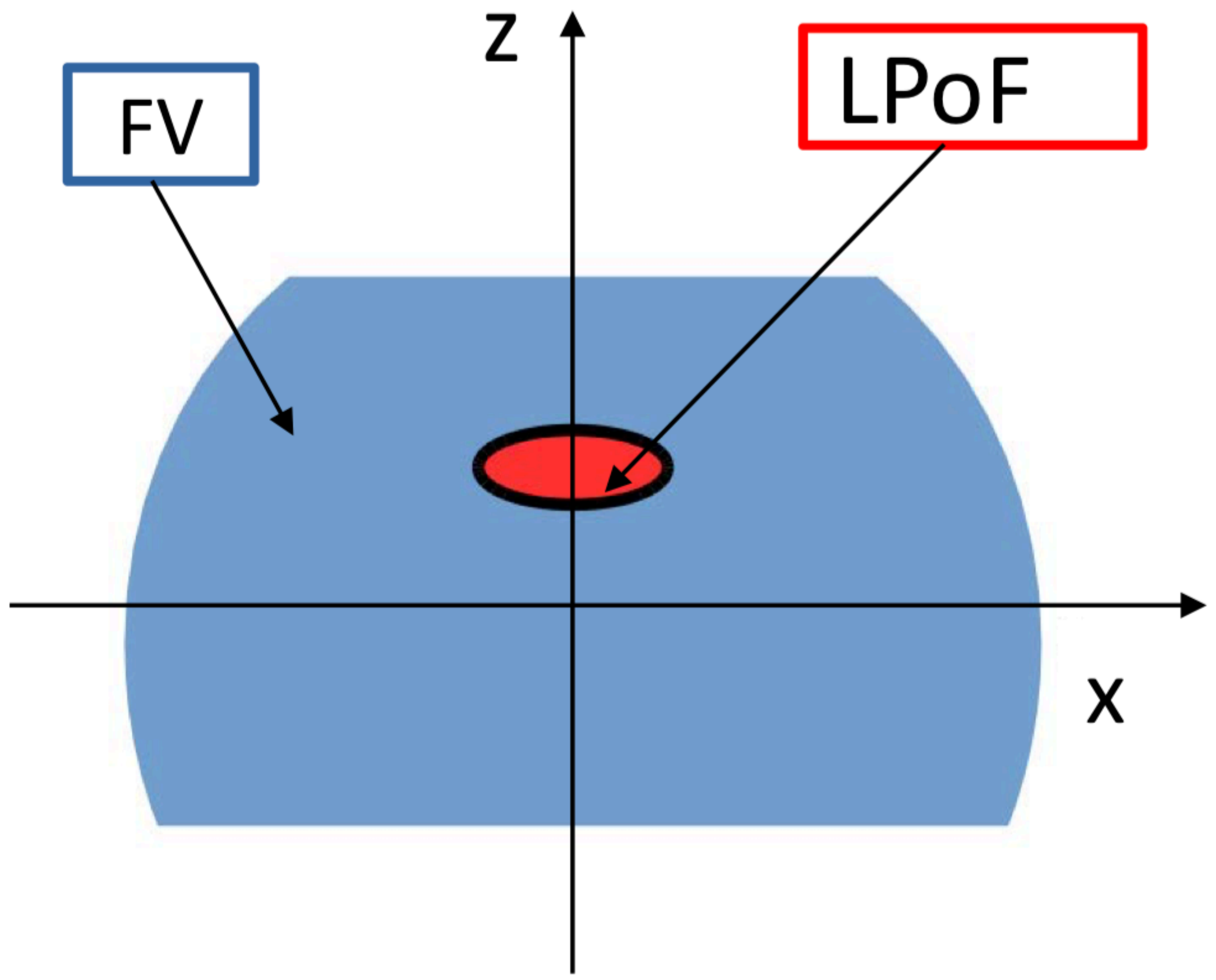


Fit model

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

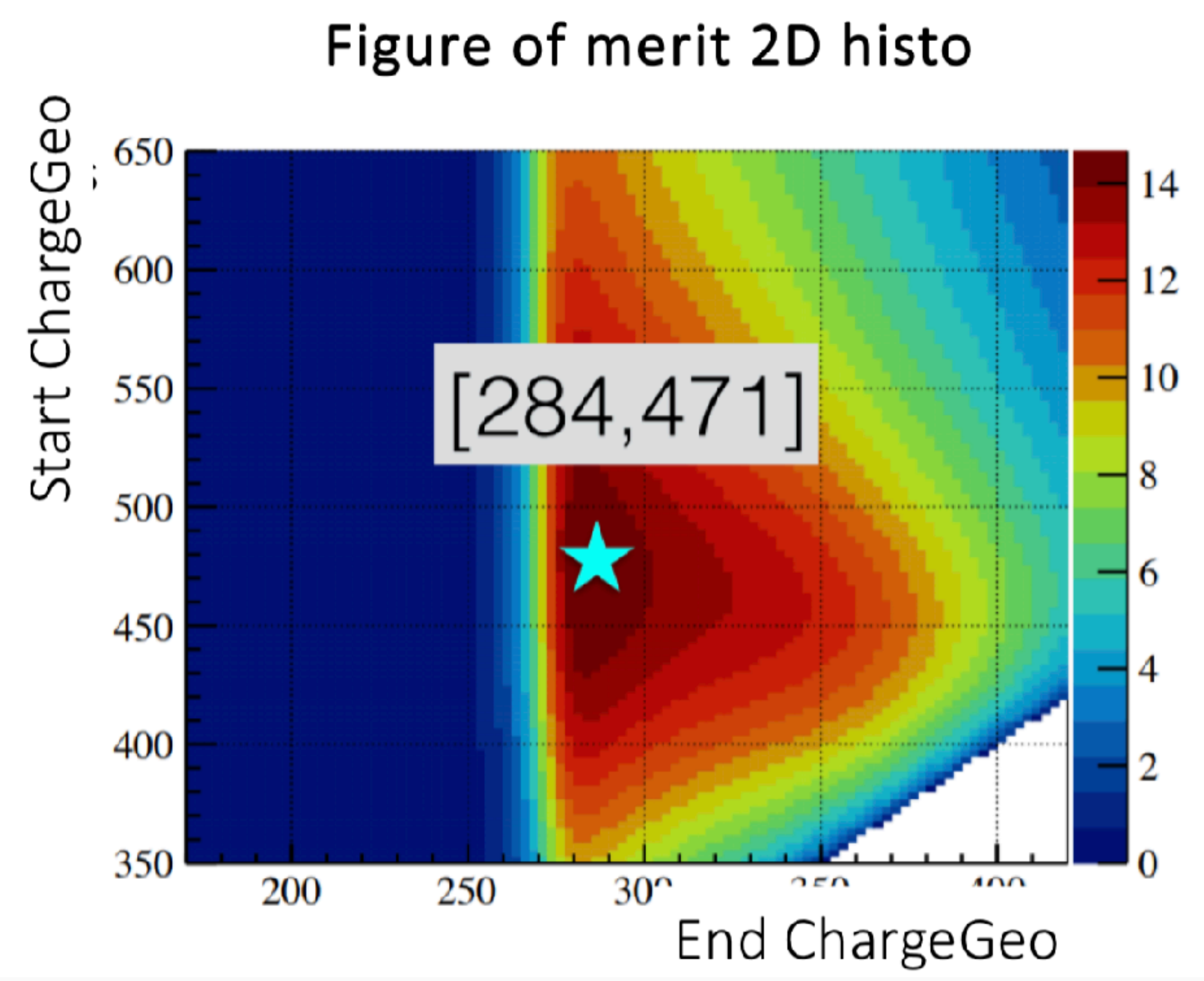
R_{min}(cpd/100t)	σ_{fit}	σ_{mass}	$\sigma_{binning}$	σ ^{210}Bi homog.	$\sigma_{\beta\ leak}$	σ_{Total}
11.5	0.88	0.36	0.31	See next slides	0.30	See next slides

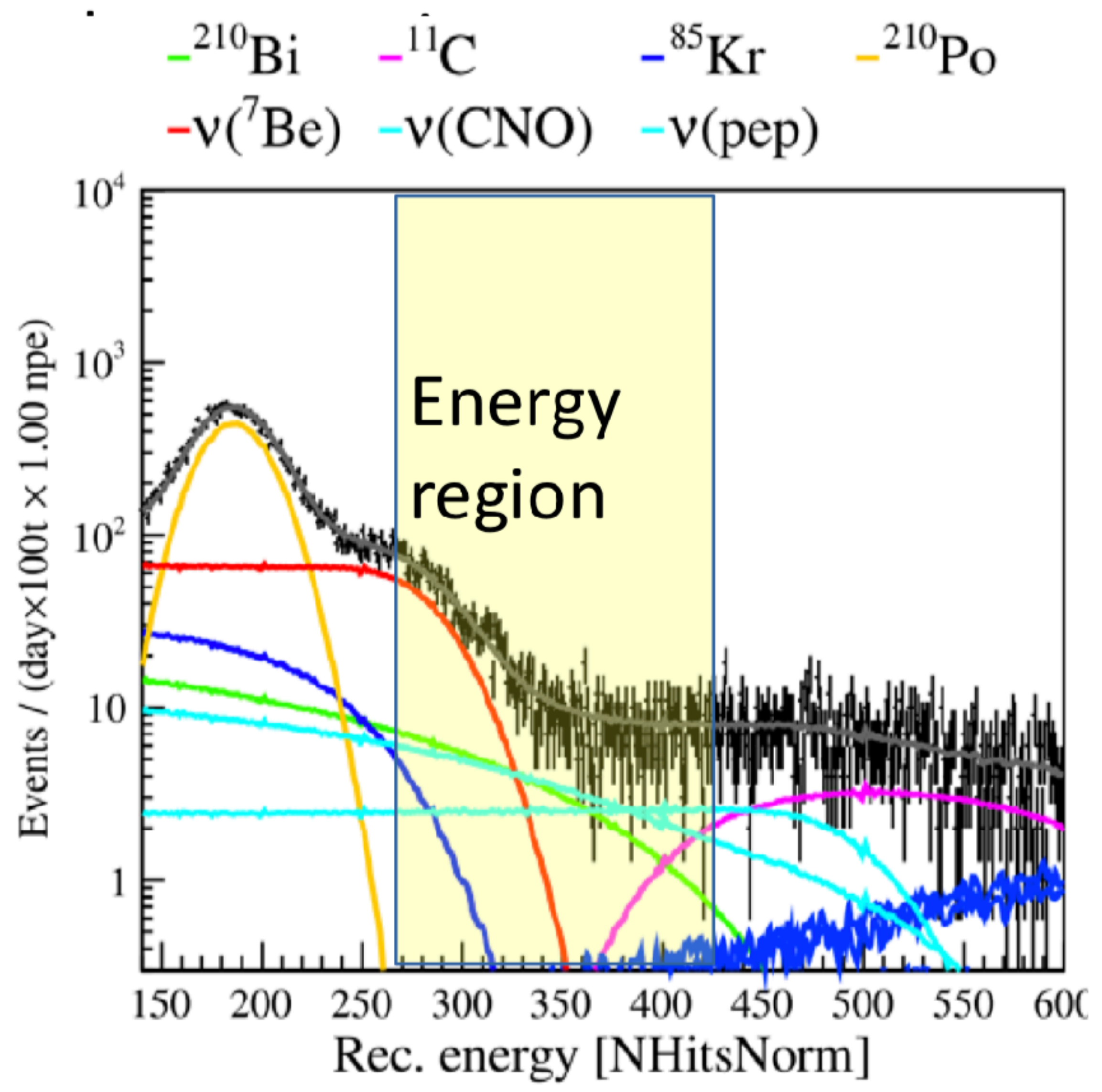
^{210}Bi homogeneity systematics



- LPoF provides the R(^{210}Bi) at the minimum of a 20 ton region (fit range used by LPoF).
- Assume R(^{210}Bi, FV) = R(^{210}Bi, LPoF)
- Spatial Inhomogeneity of R(^{210}Bi) introduce bias.

^{210}Bi homogeneity systematics based on Obi-wan





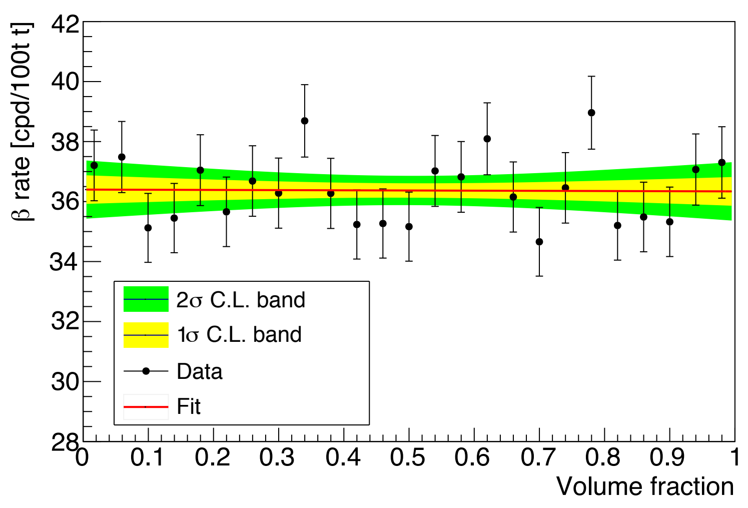
- Obi-wan = Optimized Bismuth window analyzer
- Obi-wan is optimized based on S/sqrt(S+B) of ^{210}Bi
- ~75% neutrinos, ~15% ^{210}Bi, ~10% ^{11}C and ^{85}Kr
- Inhomogeneity of Obi-wan is a conservative estimate of inhomogeneity of ^{210}Bi.

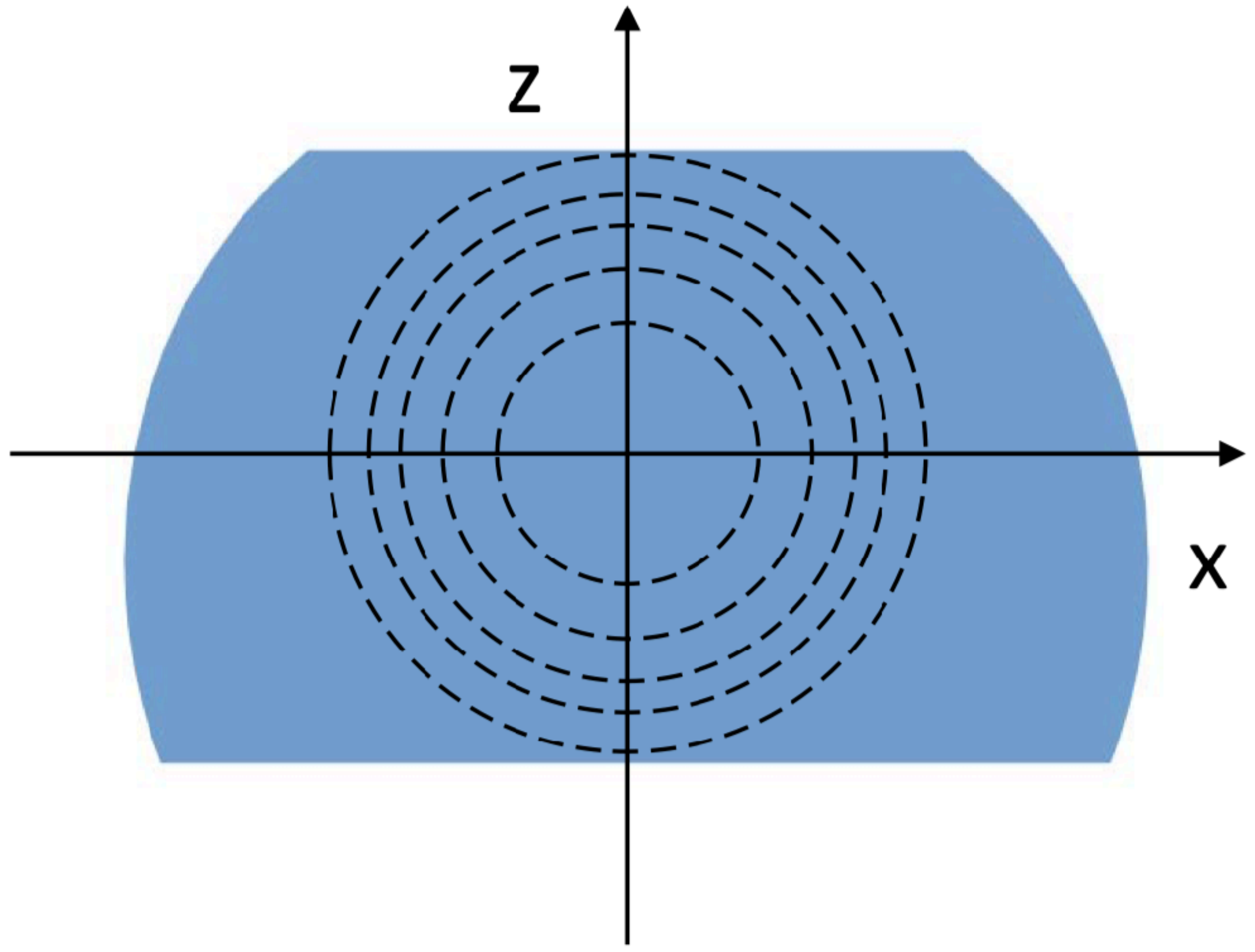
^{210}Bi homogeneity systematics based on Obi-wan

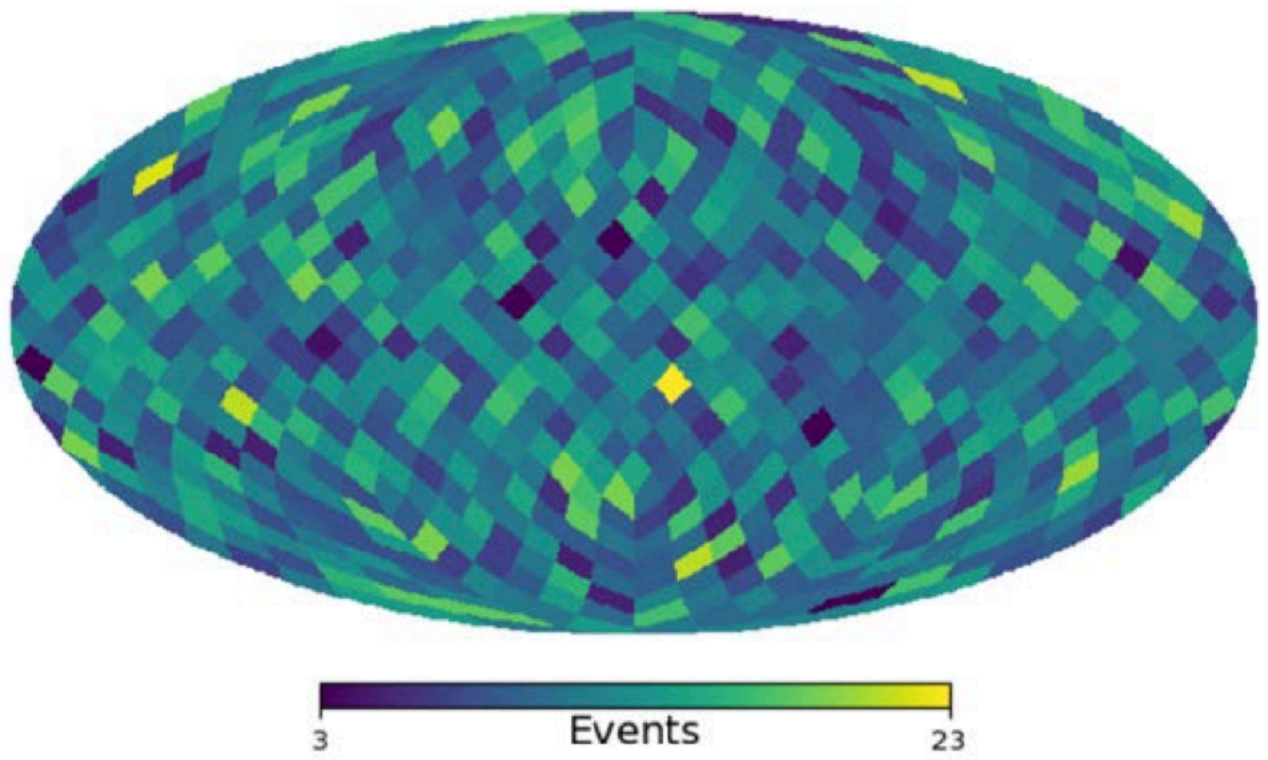
Radial β analysis + Angular β analysis

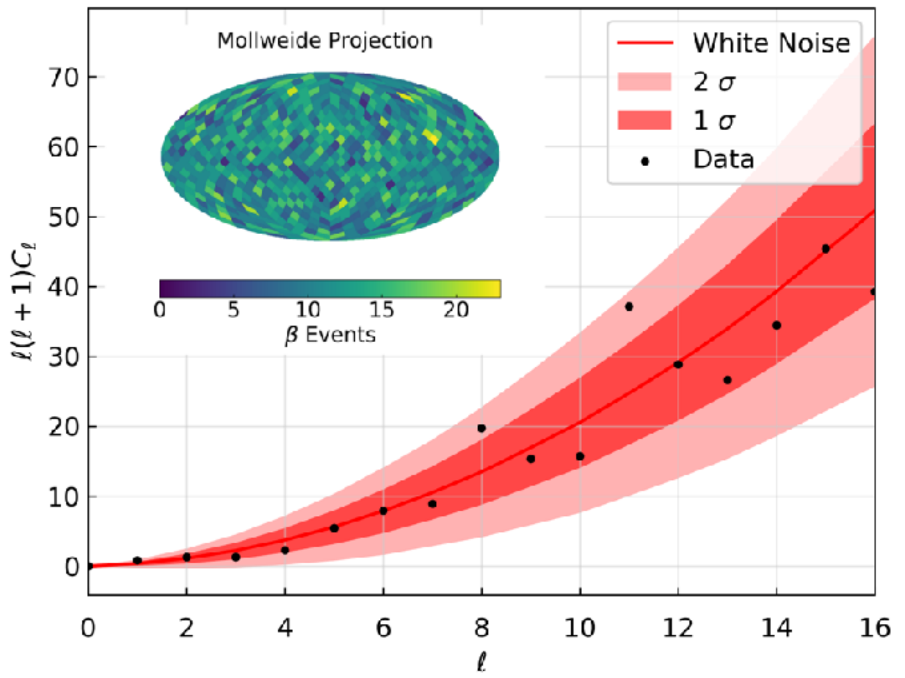
Radial shells

Spherical harmonics decomposition







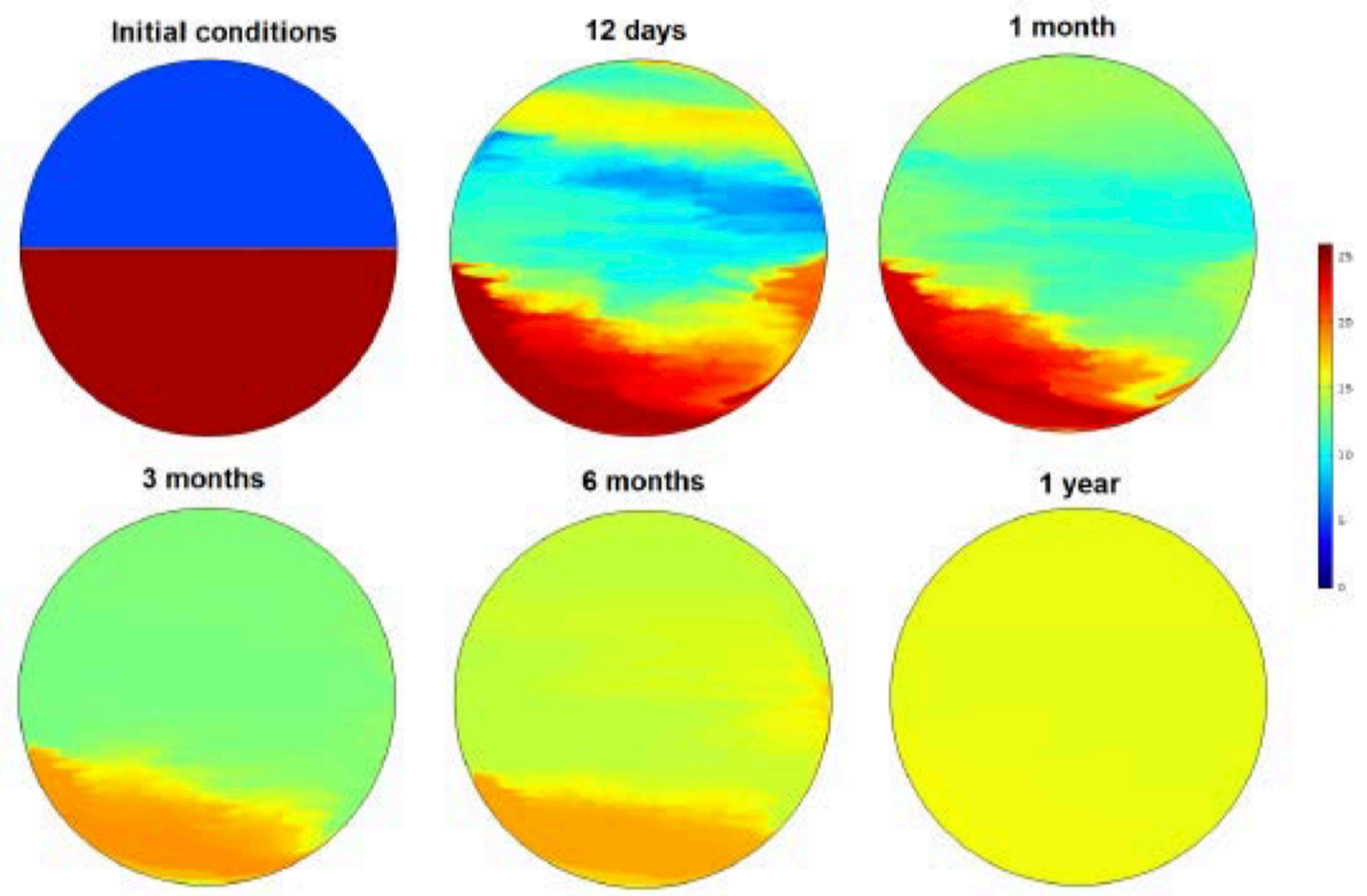


0.51 cpd/100t

0.59 cpd/100t

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

Further proof of ^{210}Bi homogeneity



- ^{210}Bi activity evolution is simulated according to estimated convection current.
- Before the insulation, the convection is very strong.
- Even if ^{210}Bi is completely at the top in the beginning, after one year it will be completely mixed.

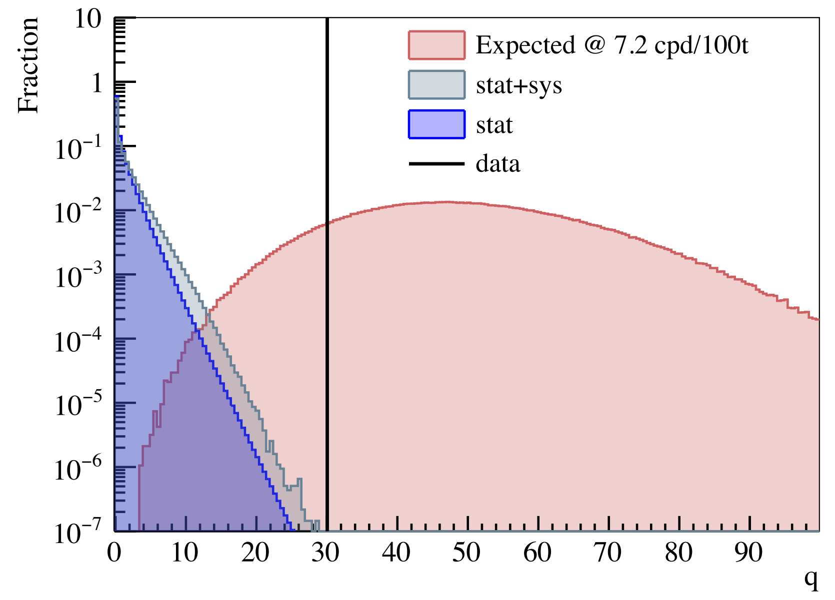
Result of LPoF analysis

- $R(^{210}Bi) + R(^{210}Po(S)) = 11.5 \pm 1.3$ cpd/100t
- $R(^{210}Po(S)) \geq 0$

Or

- $R(210Bi) \leq 11.5 \pm 1.3$ cpd/100t

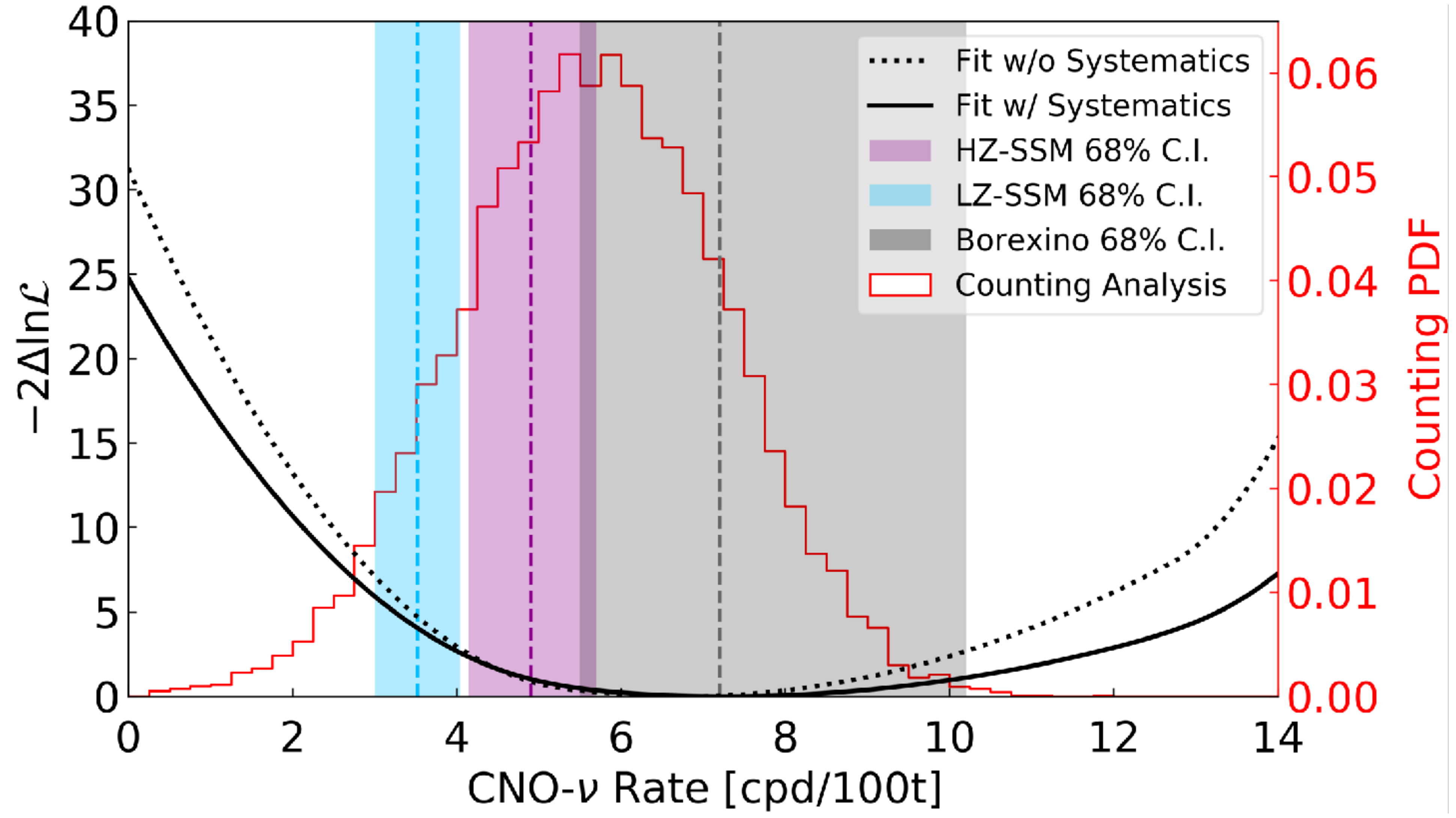
Statistical analysis



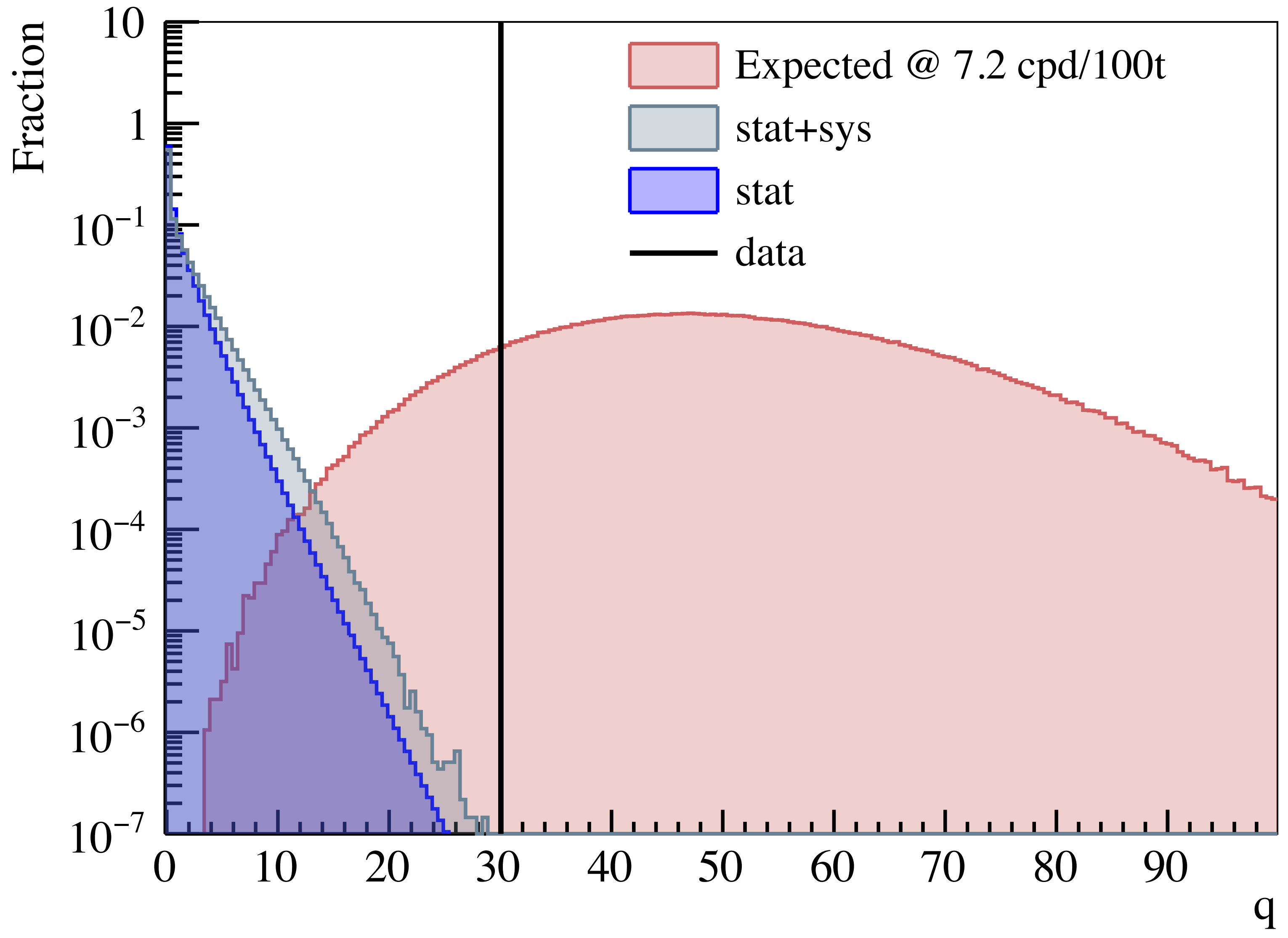
The Statistical analysis

- The statistical analysis has two objectives
  - Evaluate the confidence interval (counting + MV fit)
  - Evaluate the discovery significance (hypothesis test)

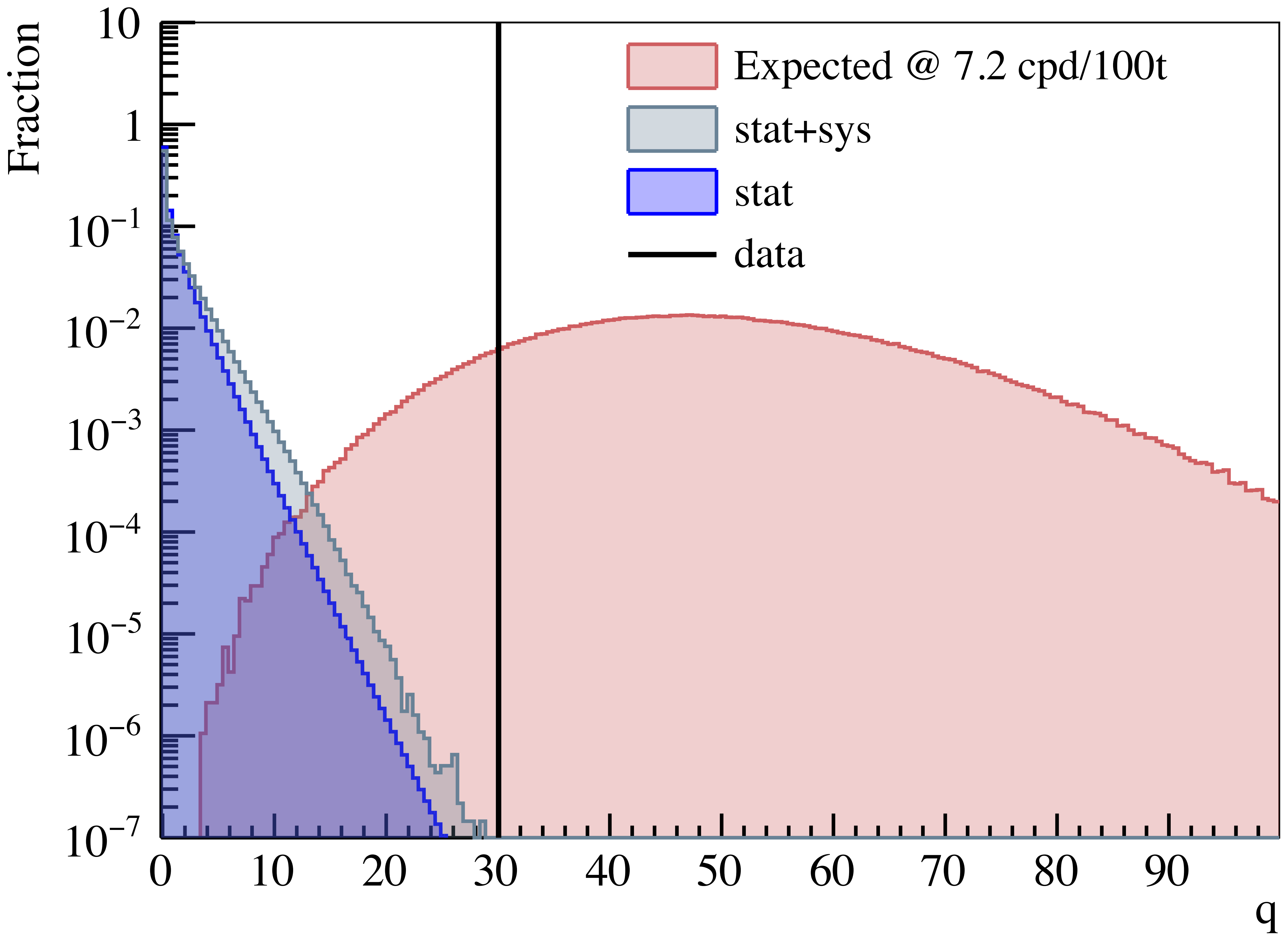
Confidence interval



Discovery significance

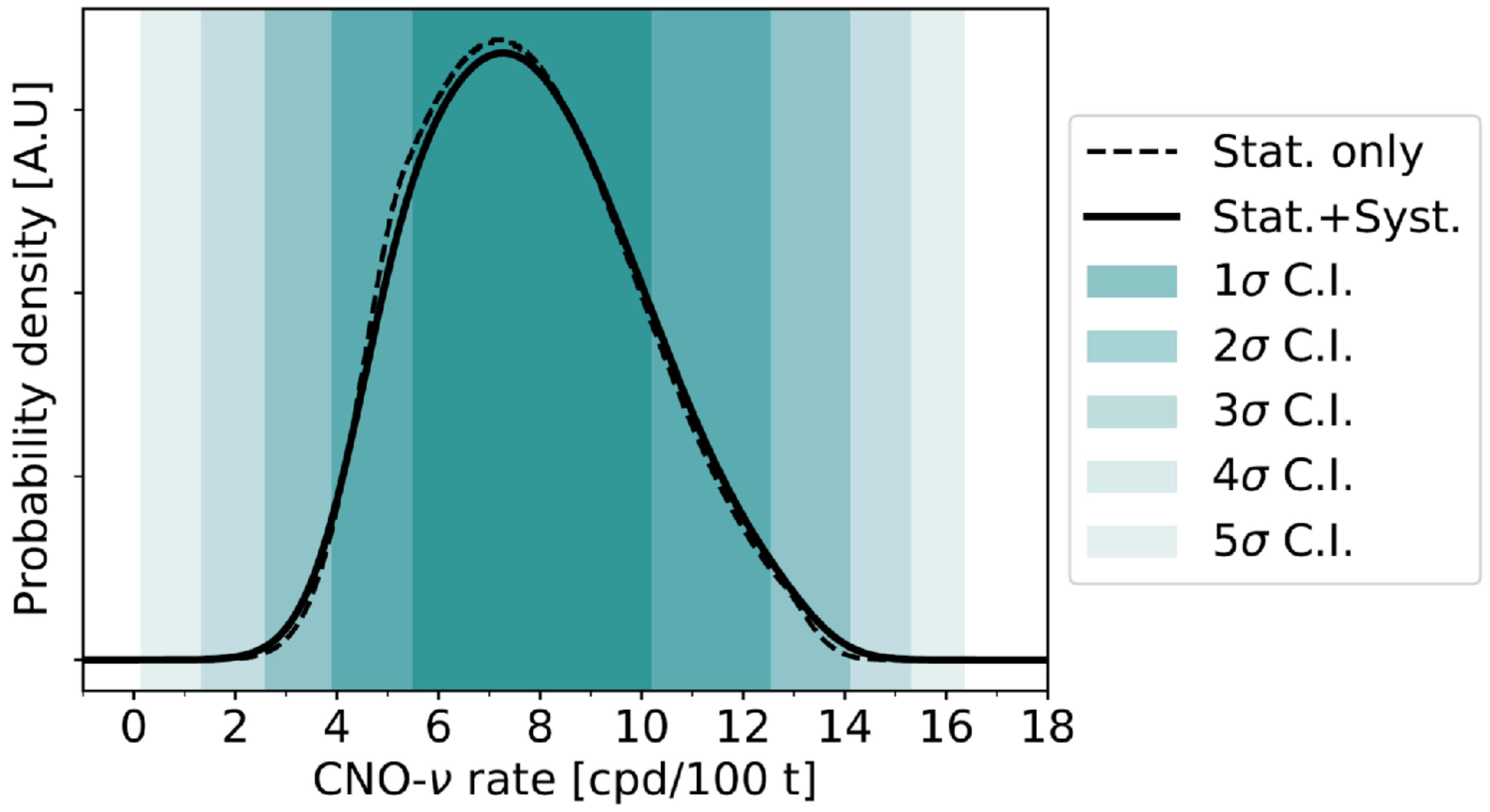


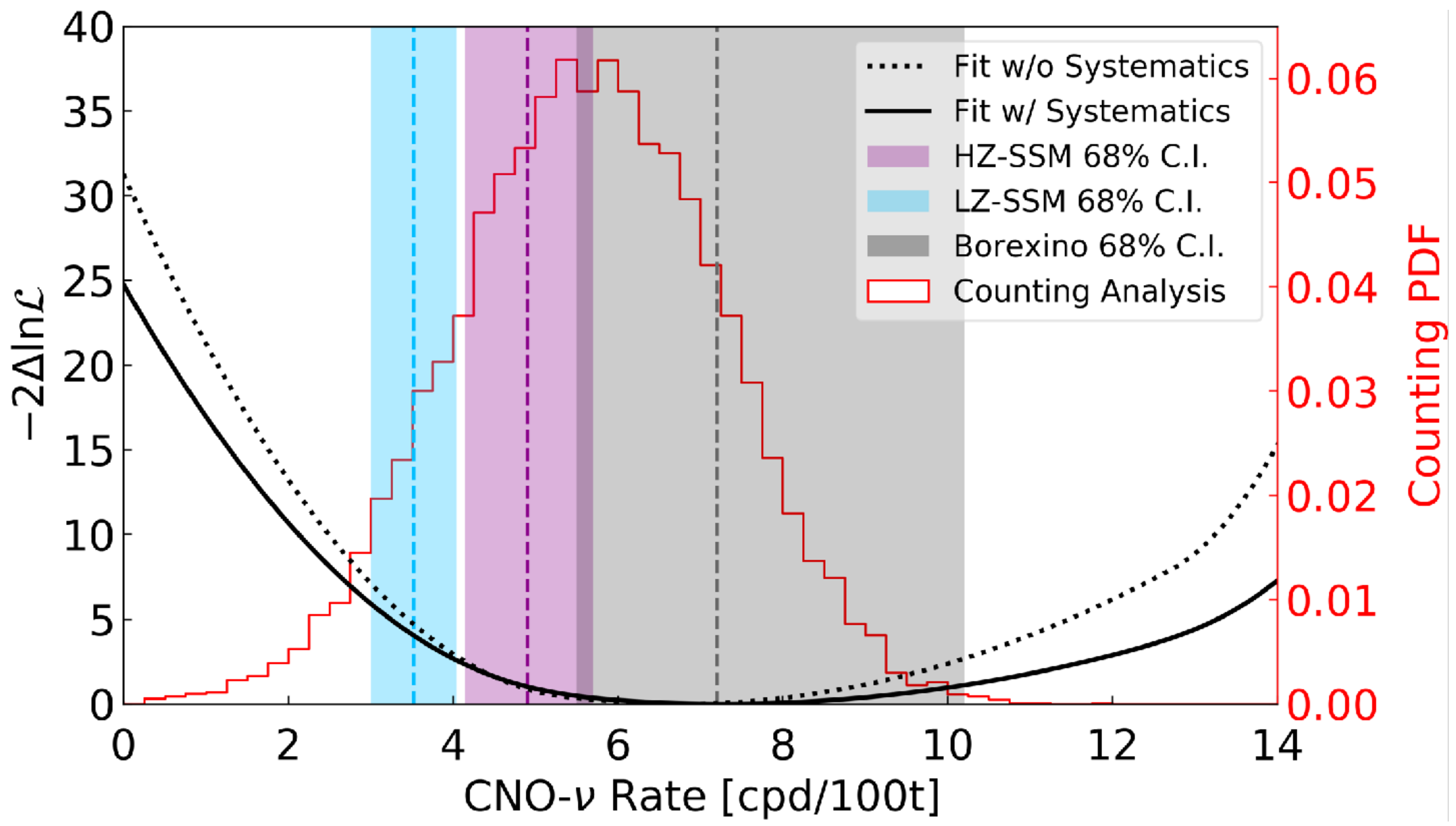
The discovery significance



- Test statistic ***q*** = profile likelihood = -2ln[L(no CNO) / L(CNO free)]
- Get **q of data** (= 30.05)
- Get distribution of q assuming **null hypothesis** (no CNO) with and without systematics using Monte Carlo method
  - Due to use of “half-gaussian” pull term, or the “upper limit”, Cowan’s fomula does not apply (half-chisquare)
  - When systemics uncertainty is included, distribution is completely unknown.
  - To prove 5 sigma, we need to show the p-value is less than 2.8×10^{-7}. We simulated 13.8 million datasets. No event above q(data). So p-value of data is less than 5 sigma significance at 99% C.L.

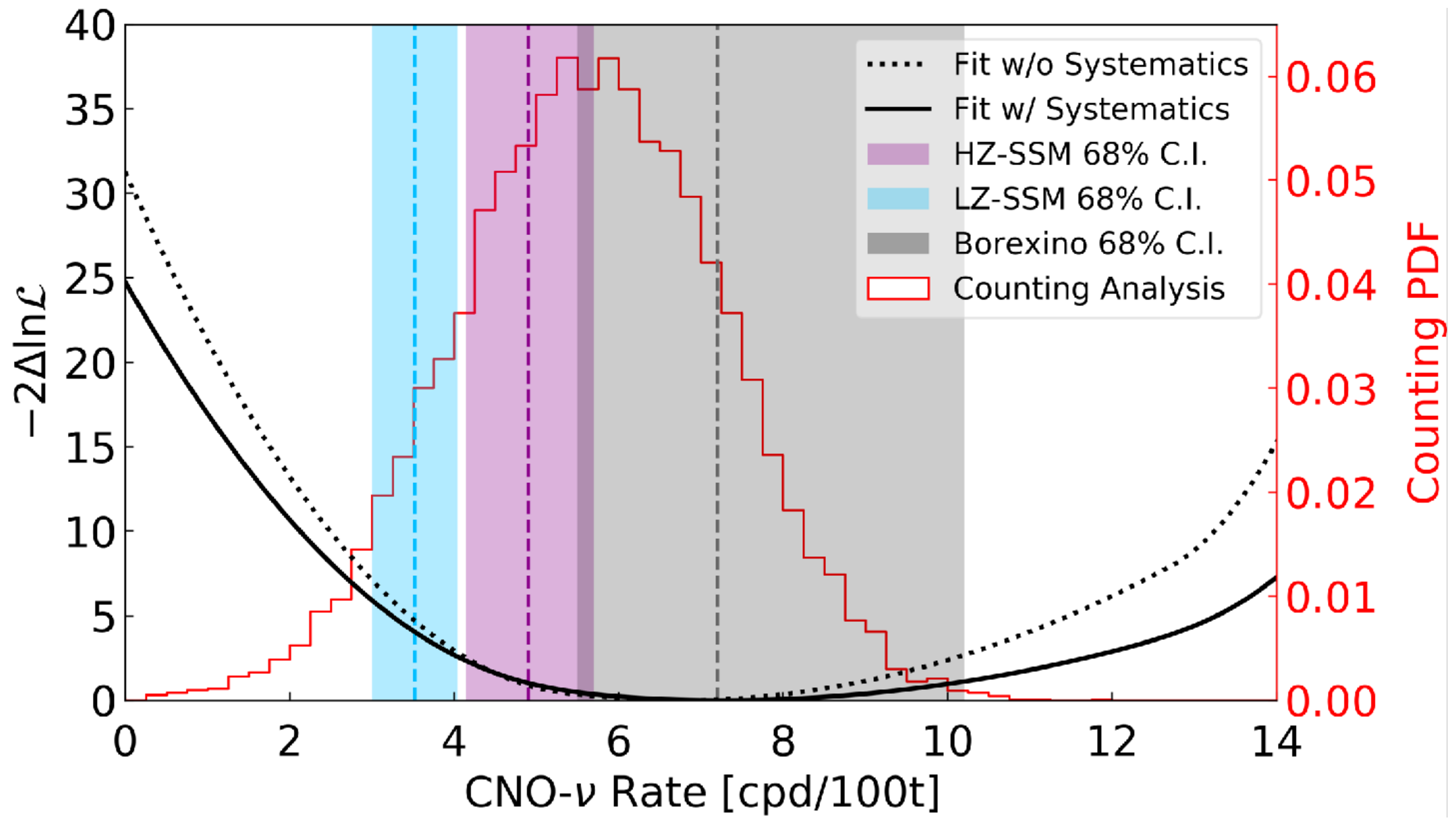
The confidence interval — Multivariate fit





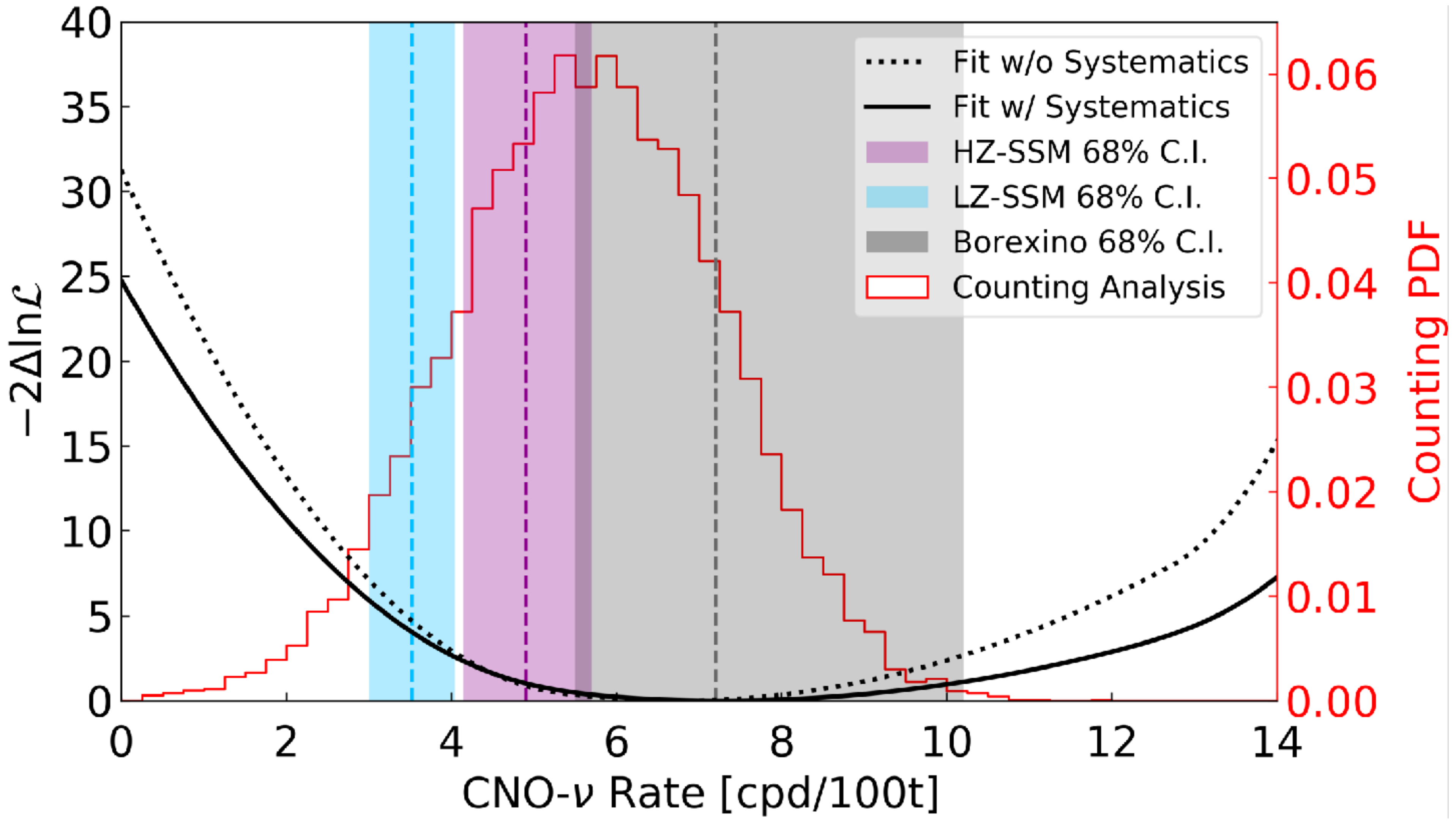
- Scan the test statistic over the CNO rate q(CNO).
- Convert q(CNO) to the P.D.F. of CNO rate according to p = C*exp(LL).
- Get 68% quantile as the 1 sigma Confidence Interval (C.I.)
- Smear the P.D.F. of CNO with systematic uncertainty ($_{-0.5}^{+0.6}$ cpd/100t)
- Get 68% quantile of the smeared P.D.F. as 1 sigma C.I. including systematic uncertainty.

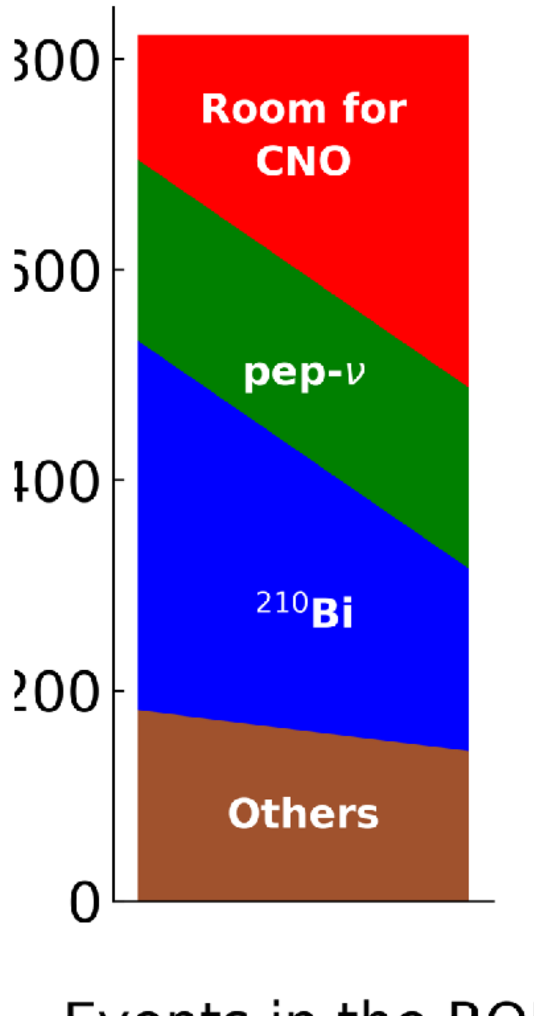
Why asymmetric likelihood profile?



- The likelihood on the left is steep.
  - When CNO goes down, ^{210}Bi need to increase, but limited by the LPoF.
  - When CNO goes high, ^{210}Bi decrease, but ^{210}Po(S) can make up the LPoF.

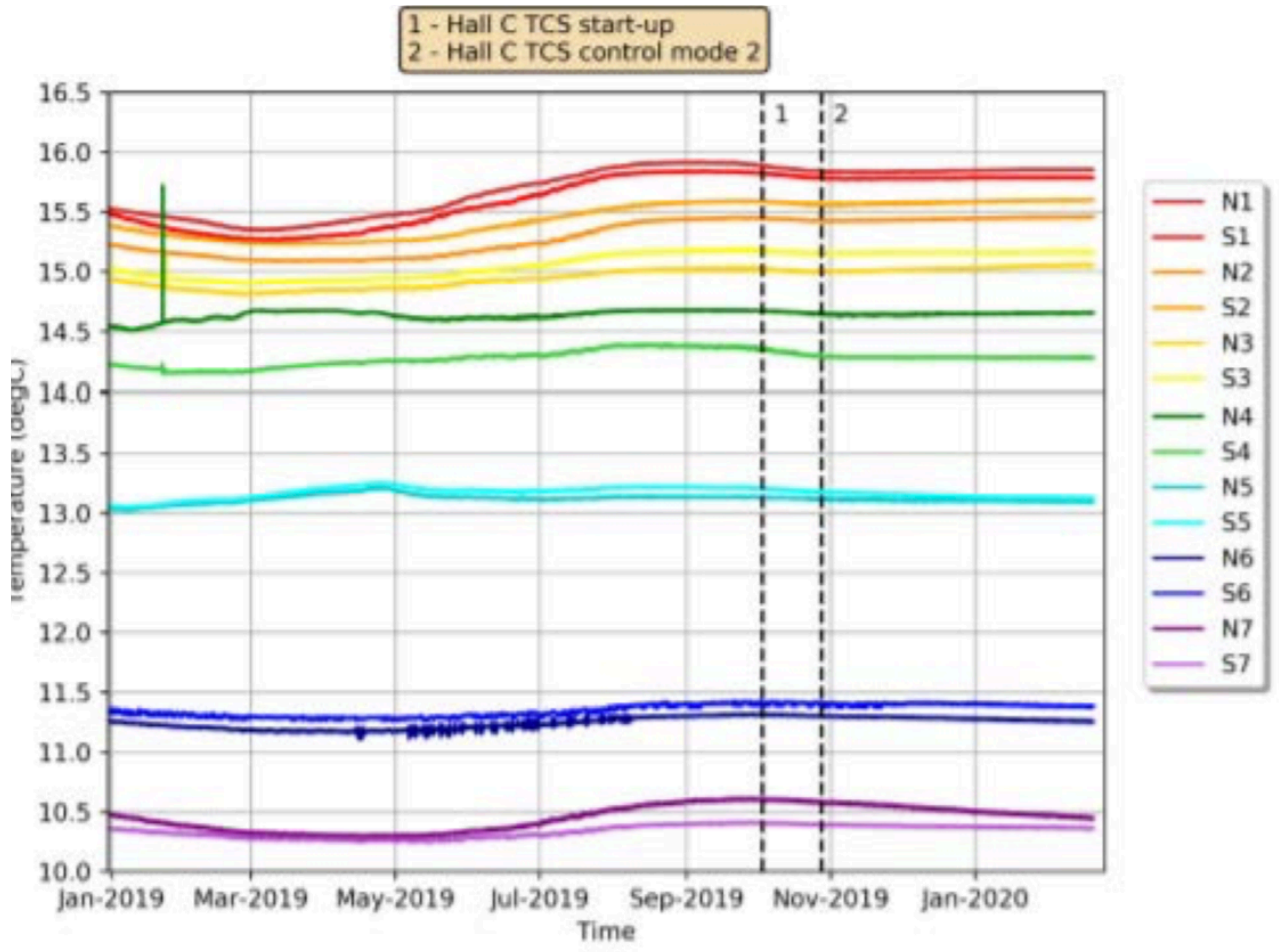
The confidence interval — Counting analysis

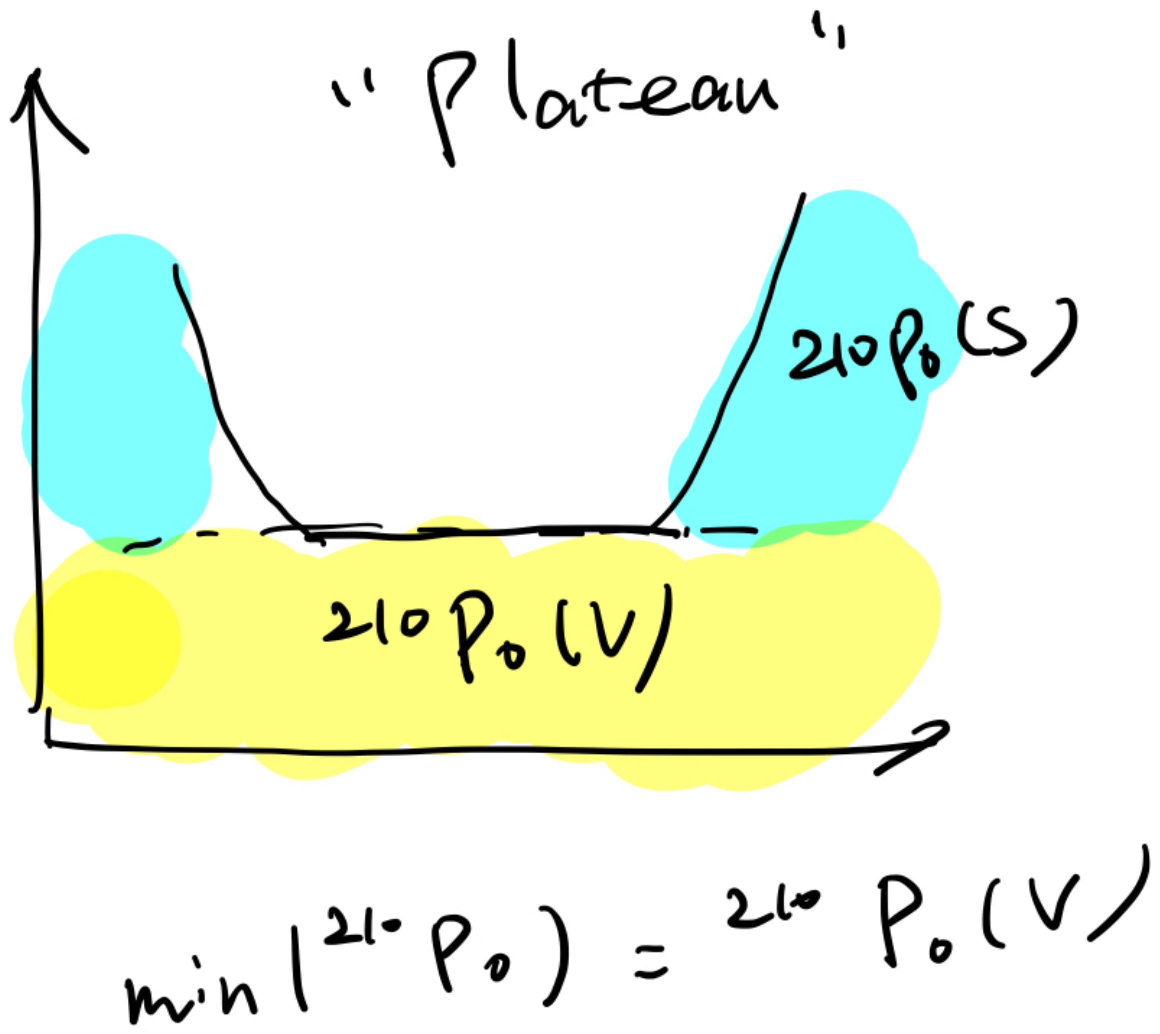




Species (S_i)	Events	Fraction
N	823 ± 28.7	
^{210}Bi	261.5 ± 29.6	0.31
ν(pep)	171.7 ± 2.4	0.21
$\nu(^7$Be)	86.8 ± 2.6	0.10
^{11}C	57.9 ± 5.8	0.07
Others	15.6 ± 1.6	0.02
$\sum_i S_i$	593.5 ± 30.4	0.71
$N - \sum_i S_i$	229.5 ± 41.8	0.29

- Count number of events in ROI
- Subtract background randomly according to determined value. For ^{210}Bi, conservatively subtract follow Gaussian distribution 11.5 ± 1.3.
- Obtained distribution of rate of residual events can be used to evaluate the confidence interval of CNO neutrinos.
- Straightforward and robust.

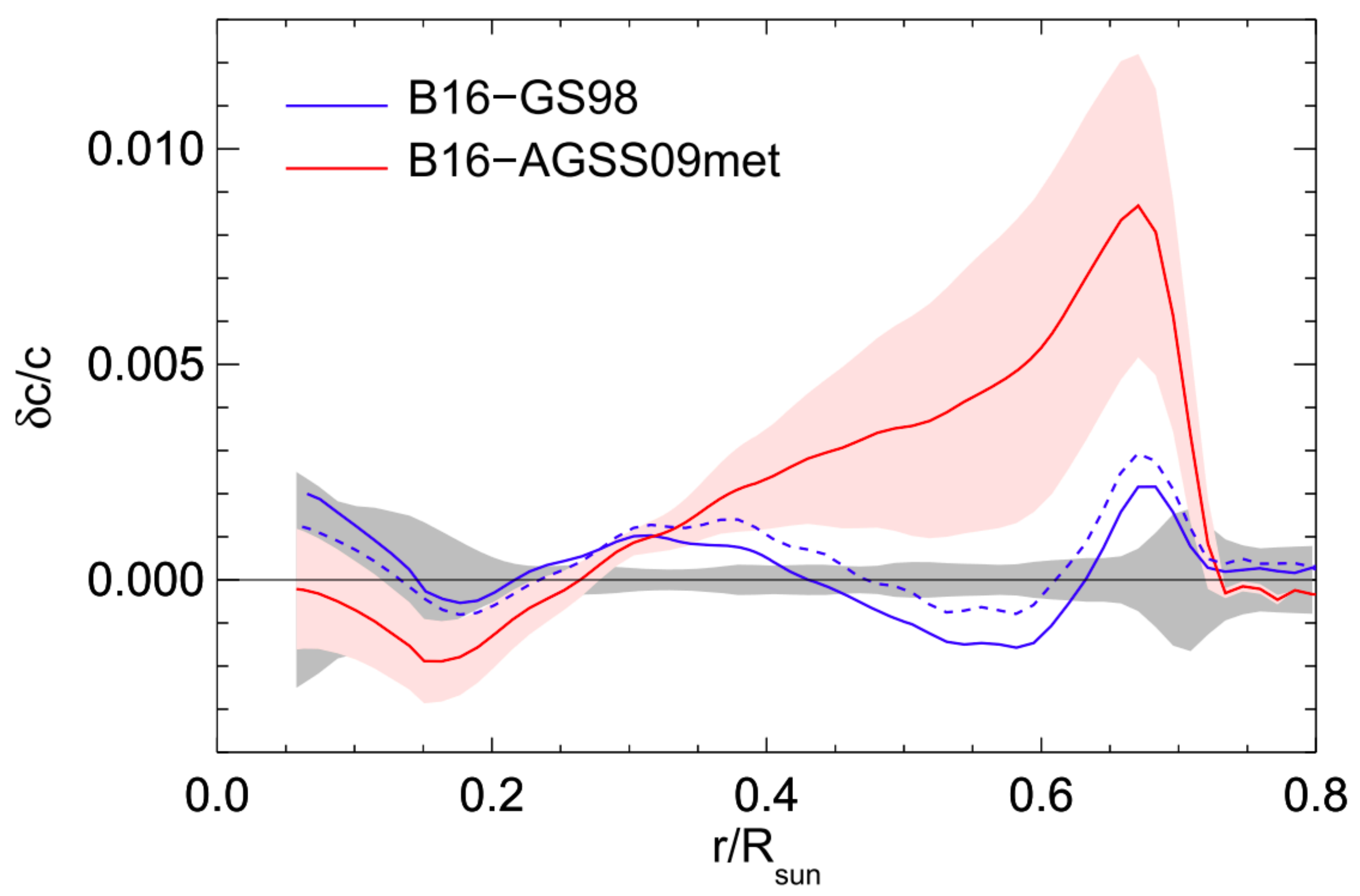




- Extremely stable temperature after installation of new system last November.
- If convection is further suppressed, "plateau" is seen, we measure ^{210}Bi rate, rather than giving an upper limit.
- CNO will be measured (confidence interval significantly improved).

How about metallicity problem?

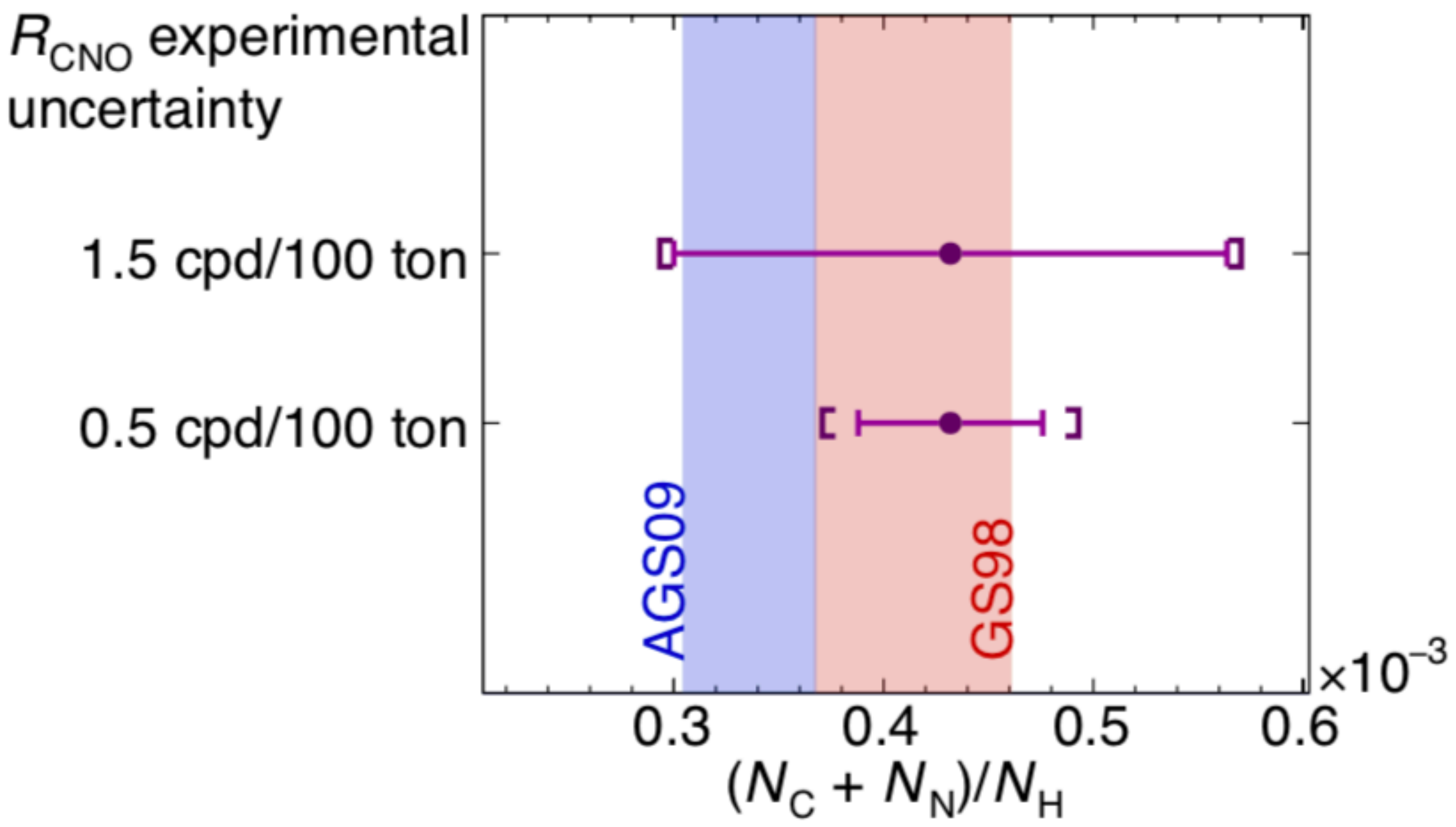
Sound speed by HZ/LZ/helioseismology



- The “solar metallicity problem”: the refined 3D model proposed in 2009 lost agreement with helioseismology data.
- Only metallicity (mass fraction of elements heavier than helium) is different between two models.
- Need to modify the opacity to restore the agreement.
- Neutrino flux measurements may provide hints

Use CNO to measure C & N abundances

(Expected, MC only)

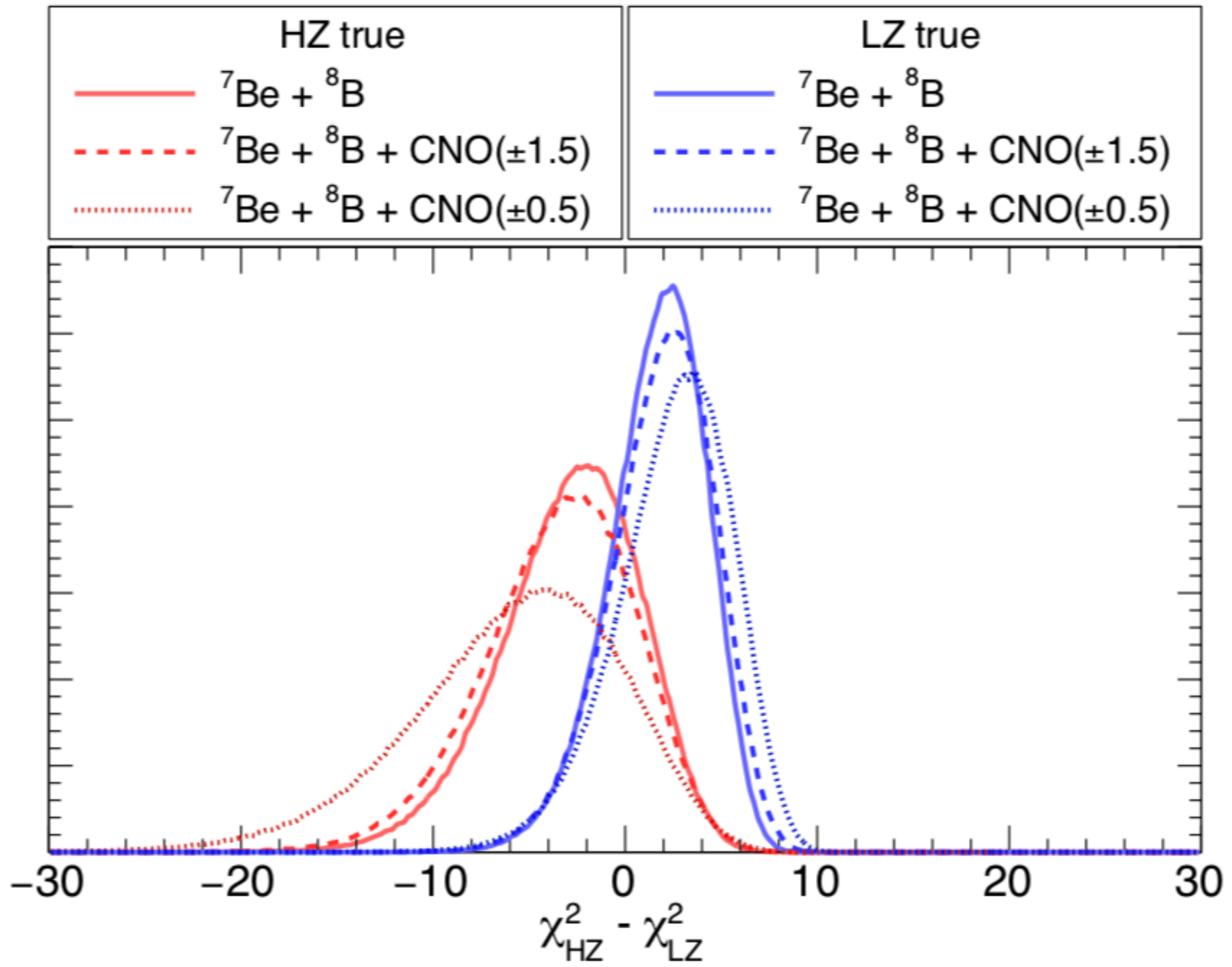


Sensitivity to neutrinos from the solar CNO cycle in Borexino, arXiv 2005.12829

- pp-chain solar neutrino fluxes depend on solar core temperature
- CNO cycle solar neutrino fluxes depend on temperature + C & N abundances.
- Combine two to measurement C & N abundances directly

Use CNO to do hypothesis test

(Expected, MC only)

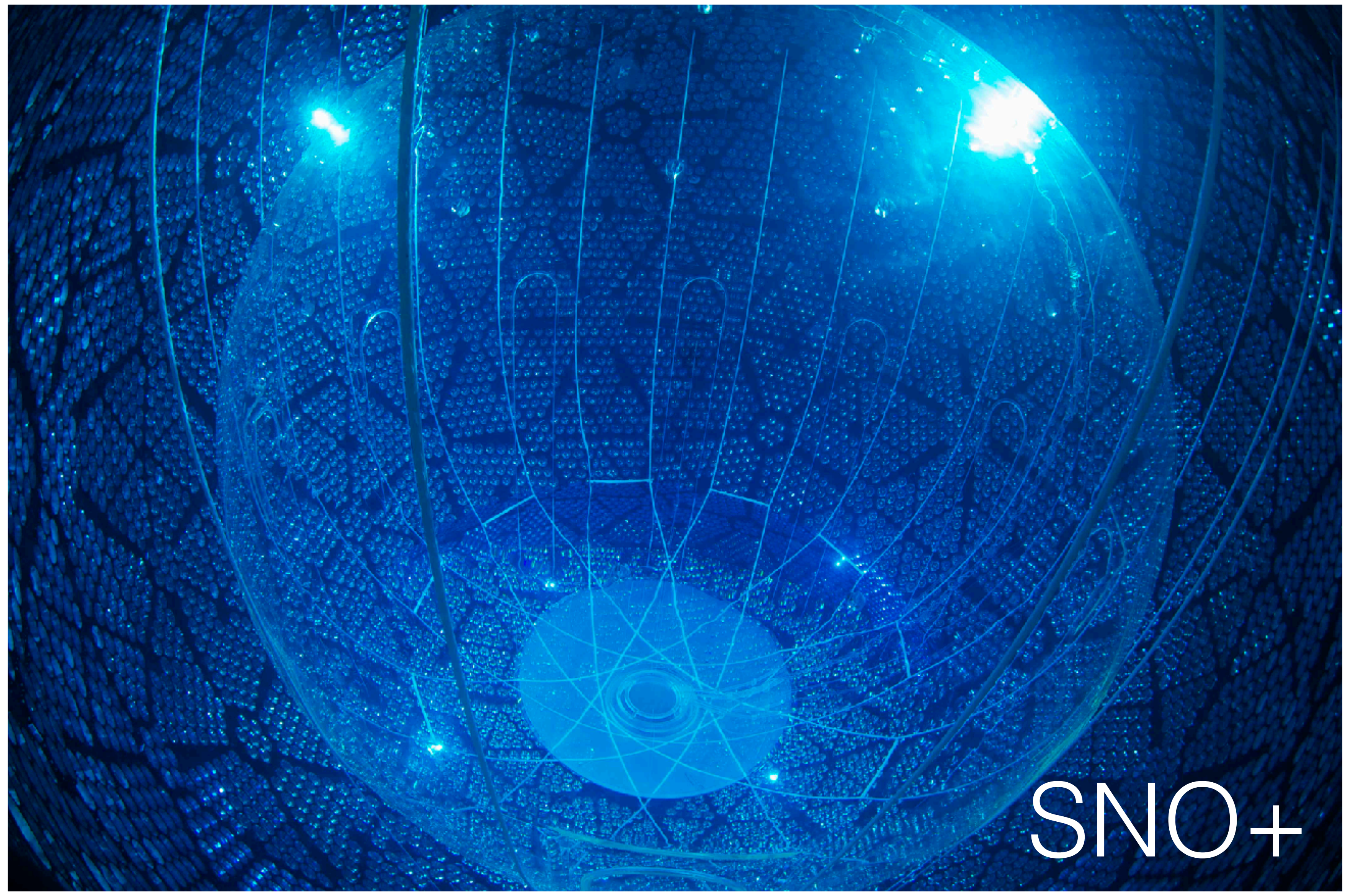


Sensitivity to neutrinos from the solar CNO cycle in Borexino, arXiv 2005.12829

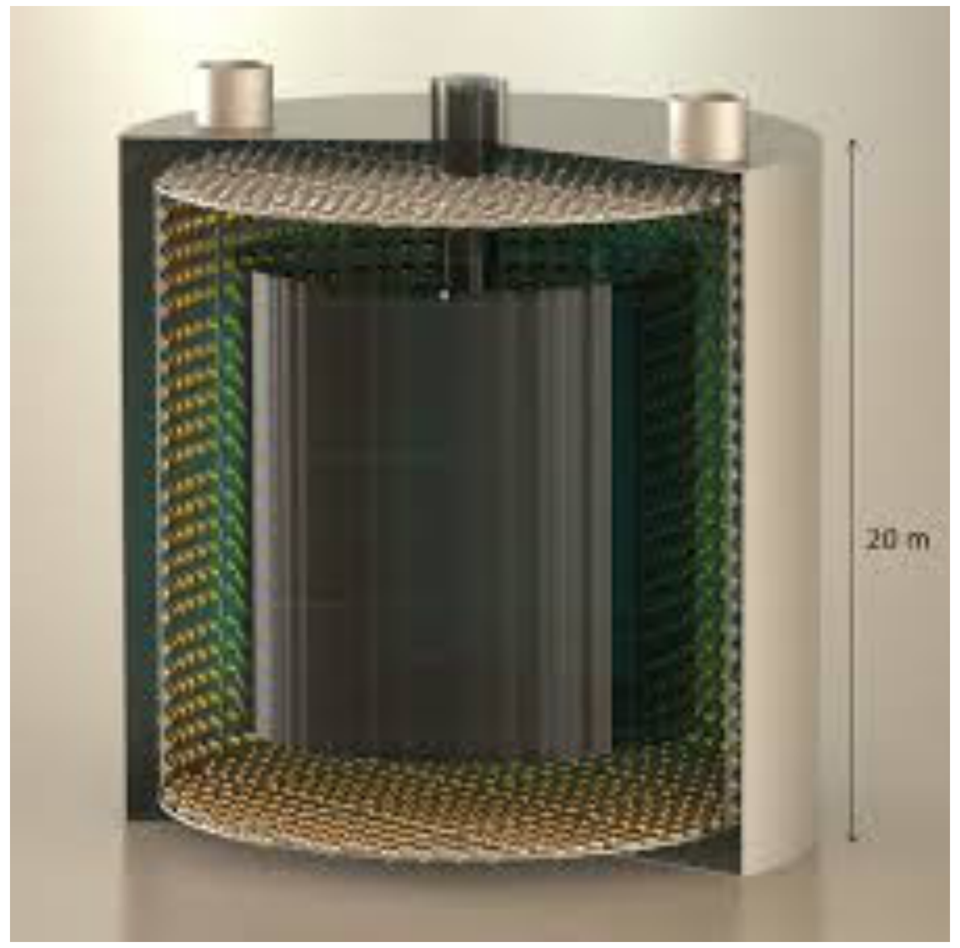
Solar ν	B16(GS98)-HZ cpd/100 ton	B16(AGSS09)-LZ cpd/100 ton	Borexino Results cpd/100 ton
pp	131.1 ± 1.4	132.2 ± 1.4	$134 \pm 10^{+6}_{-10}$
^{7}Be	47.9 ± 2.8	43.7 ± 2.5	$48.3 \pm 1.1^{+0.4}_{-0.7}$
pep	2.74 ± 0.04	2.78 ± 0.04	$2.43 \pm 0.36^{+0.15}_{-0.22}$(HZ)
			$2.65 \pm 0.36^{+0.15}_{-0.24}$ (LZ)
CNO	4.92 ± 0.78	3.52 ± 0.52	< 8.1 (95% C.L.)

- Standard hypothesis test

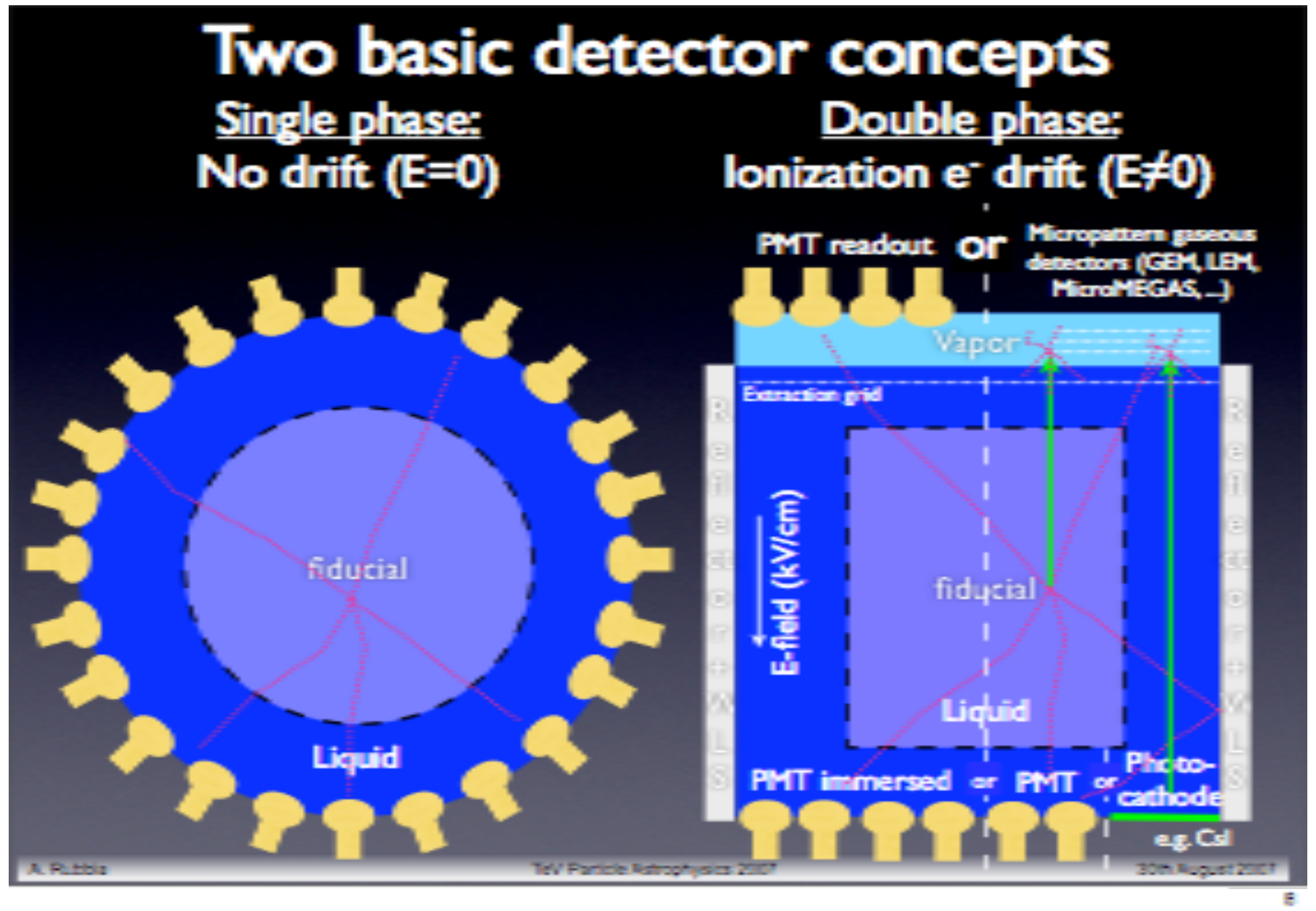
Future experiments



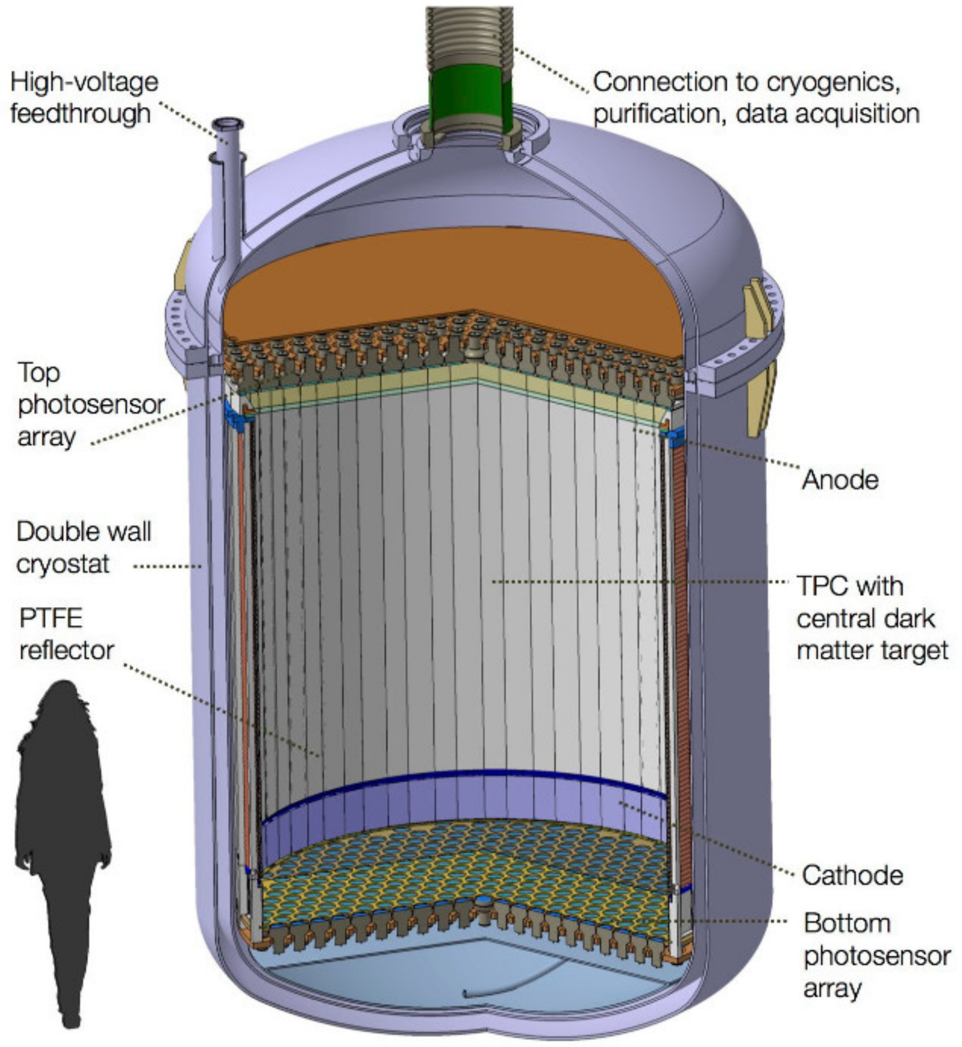
Jingping Neutrino Experiment



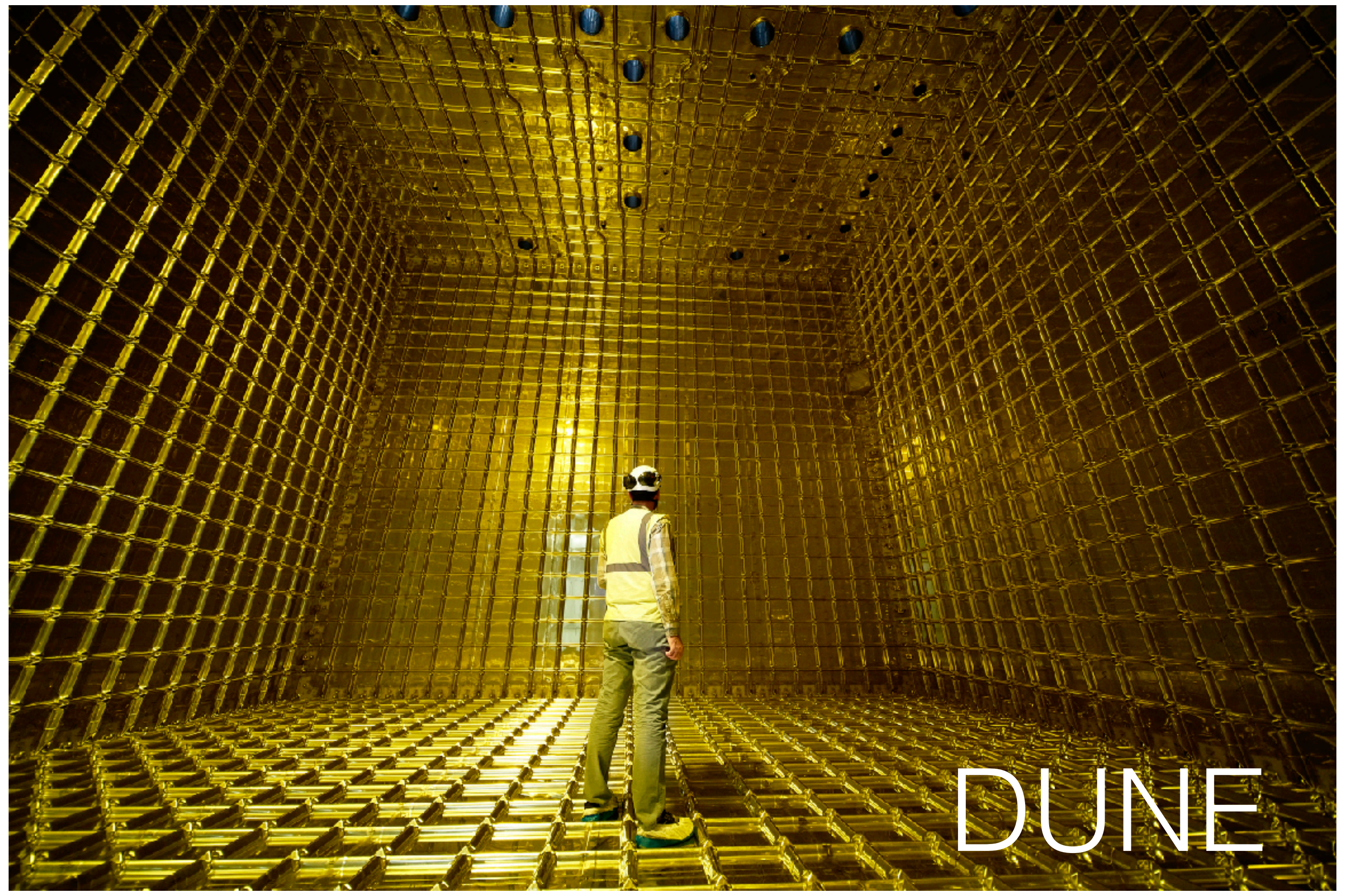
- SNO+: existing, deep
- JPNE: directionality
- LAr/LXe: no ^{11}C, high energy resolution



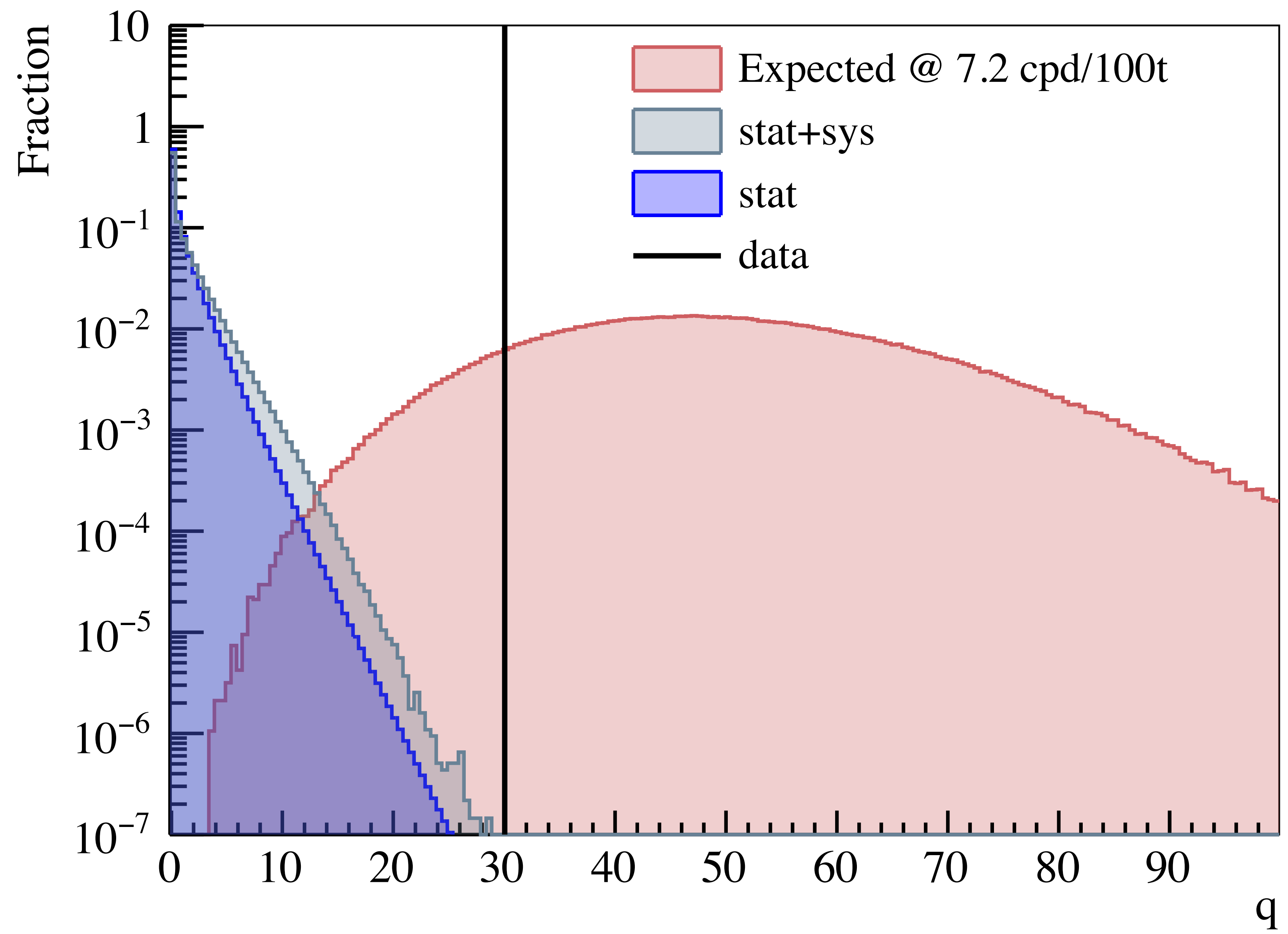
ARDM

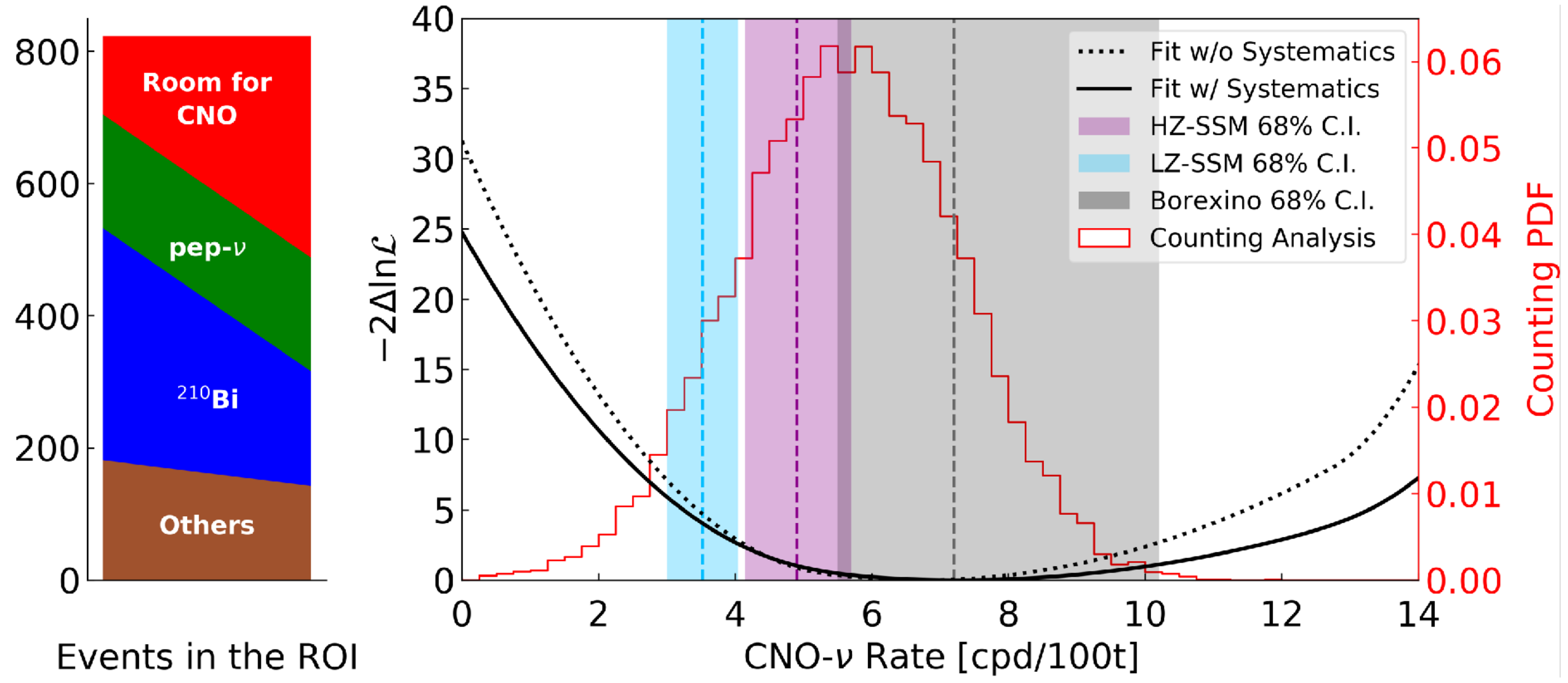


DARWIN



Conclusions



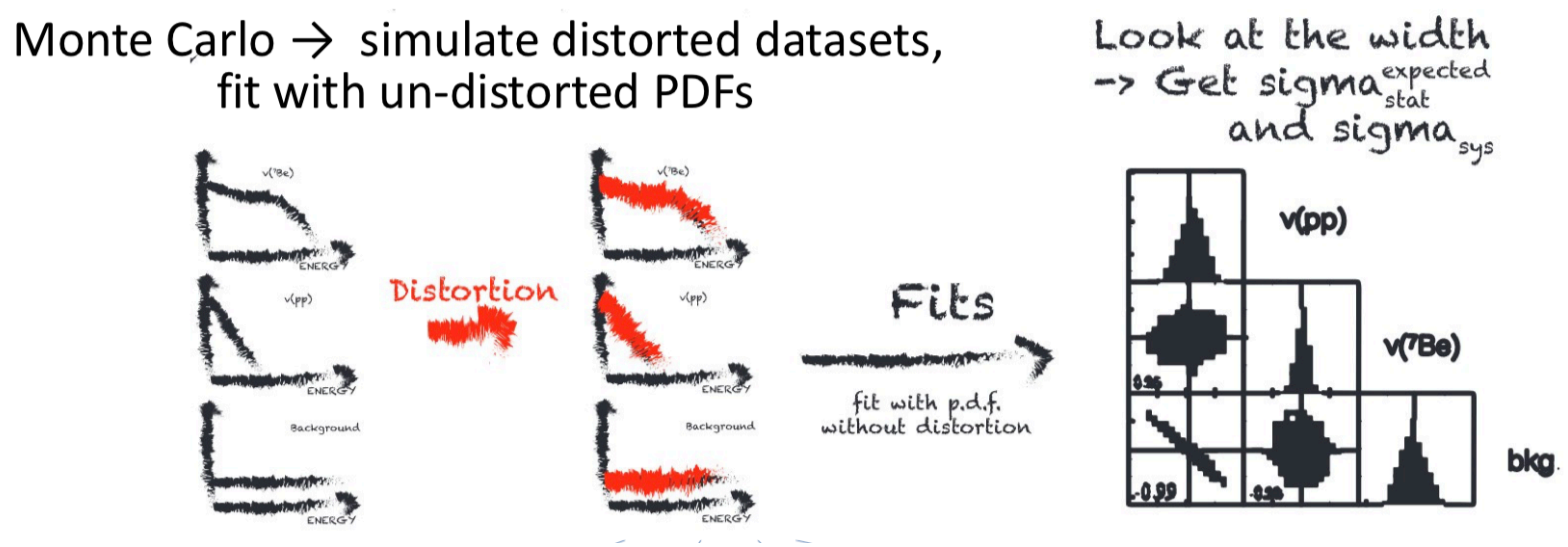


- With LPoF analysis, we obtained an upper limit of ^{210}Bi
- Based on this result, we evaluate discovery significance to no CNO hypothesis is more than 5 sigma at 99 C.L. **It is first detection of CNO solar neutrinos.** Finally proves CNO cycle proposed by H. Bethe 80 years ago.
- We measured CNO neutrino flux to be

$$7.0^{+3.0}_{-2.0} \times 10^8 \ cm^{-2}s^{-1}$$

Backup

The systematic uncertainty



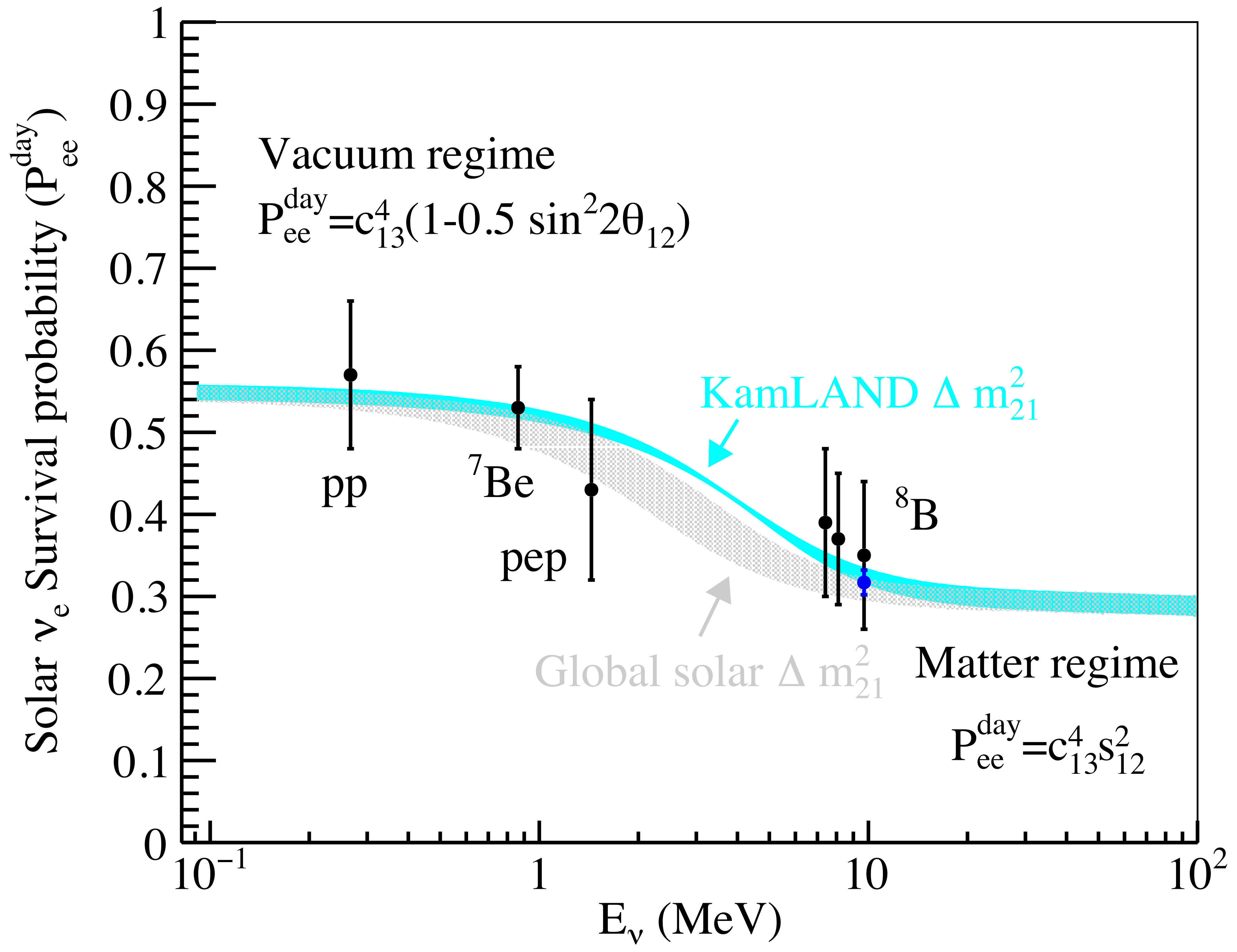
- Using the Cousins & Highland, or hybrid frequentist-Bayesian method.
  - Define list of known inaccuracy type and magnitude (energy function, LY 0.23%, non-uniformity 0.28% and NL 0.4%; ^{11}C deformation 2.3%; ^{210}Bi shape 18%)
  - Simulate distorted datasets and fit with un-distorted PDF
  - Subtract quadratically width of distribution of results with 0-systemics.

The Neutrino Oscillation

$$P_{ee} = |\langle \nu_e | \nu(t_E) \rangle|^2 = \sum_j |U^m_{ej}(n^0)|^2 |U_{ej}|^2.$$

Production in the solar core

Detection in vacuum



- When detected, part of solar electron neutrinos has oscillated into muon/tau neutrinos.
- Historically known as the “solar neutrino problem”. Nobel prize in 2015.