BOREXINO: EXPERIMENTAL EVIDENCE OF NEUTRINOS PRODUCED IN THE CNO FUSION CYCLE IN THE SUN

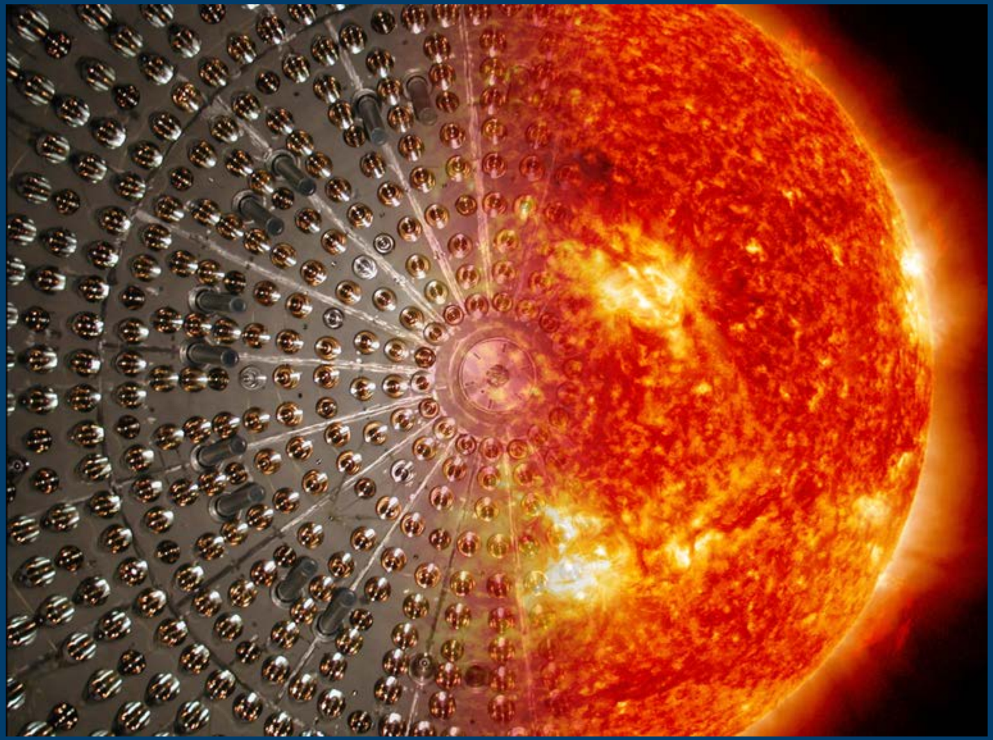
LIVIA LUDHOVA

FOR THE BOREXINO COLLABORATION

IKP-2, FORSCHUNGSZENTRUM JÜLICH

AND RWTH AACHEN UNIVERSITY,

GERMANY



DECEMBER 4TH, 2020

7TH KAT STRATEGY MEETING

OUTLINE

1. Solar neutrinos
2. Borexino detector
3. Borexino solar neutrino analysis

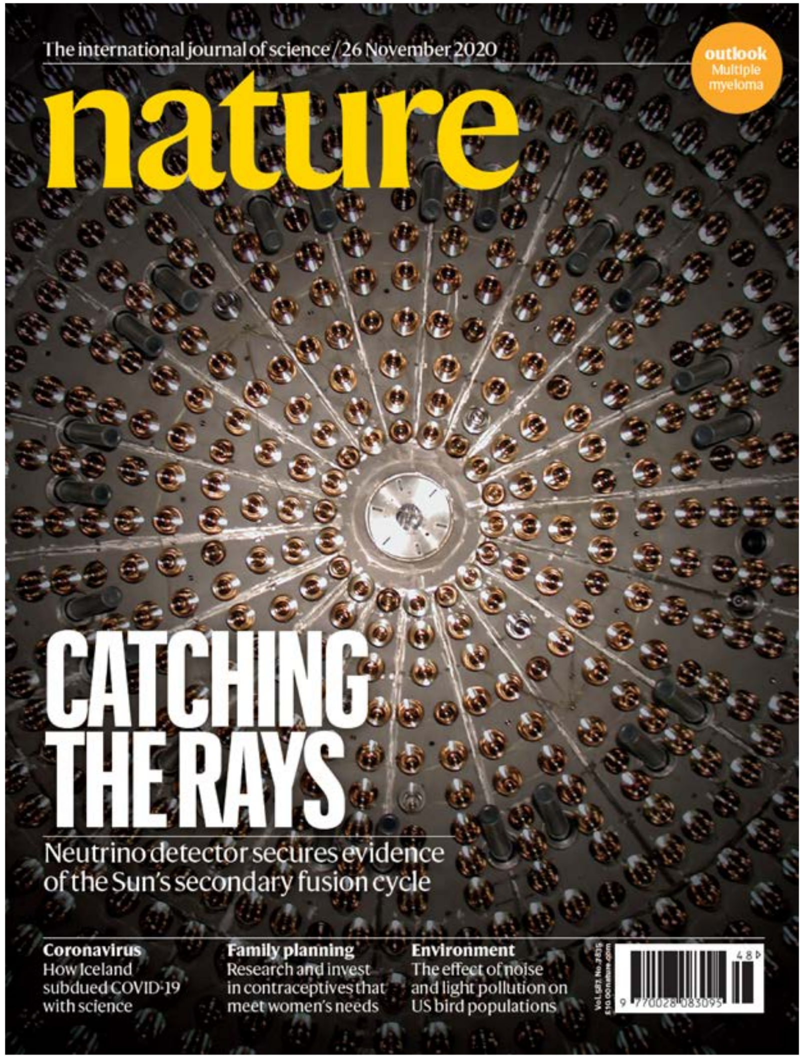
    ✓ pp fusion chain

    ✓ latest news:

    the first observation

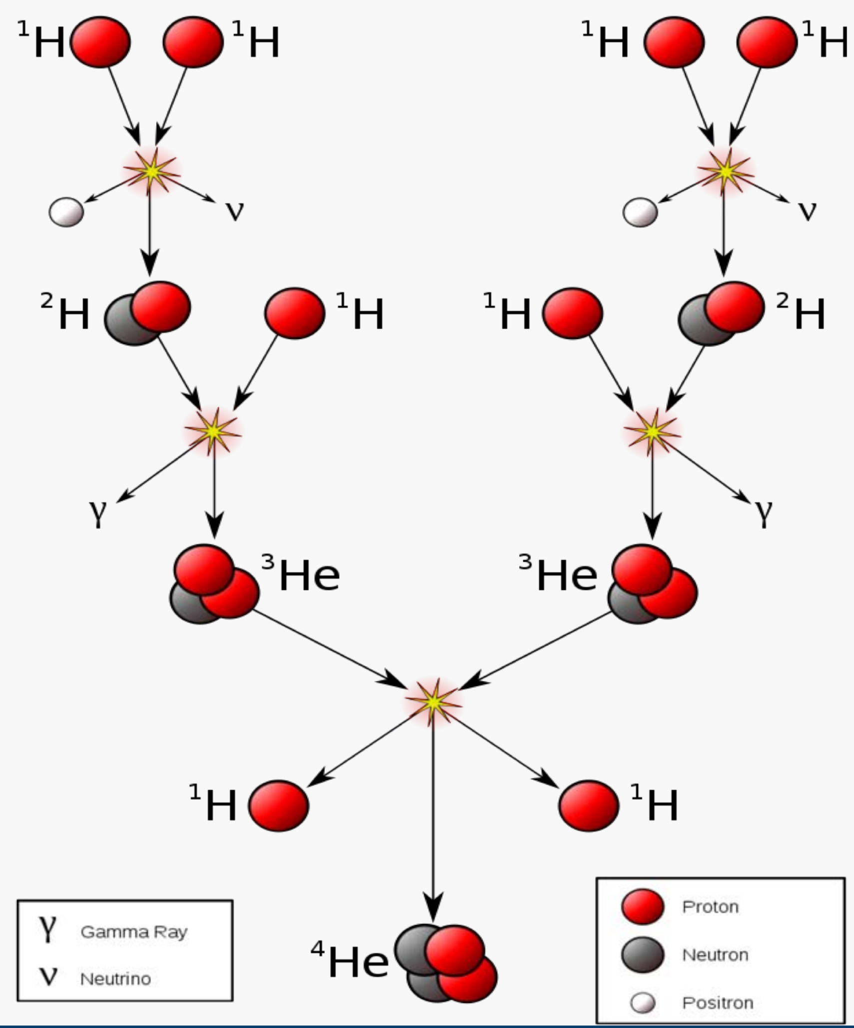
    of CNO cycle solar neutrinos

    published in Nature few days ago: 25/11/2020

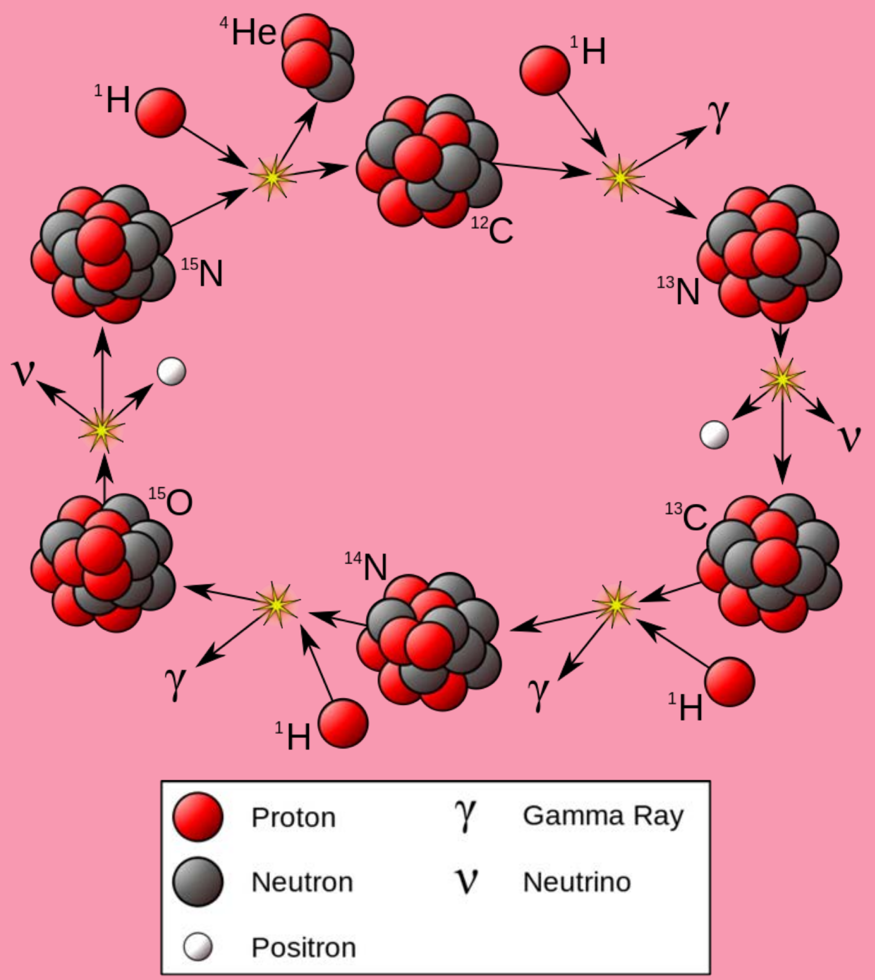


HYDROGEN-TO-HELIUM FUSION IN THE SUN

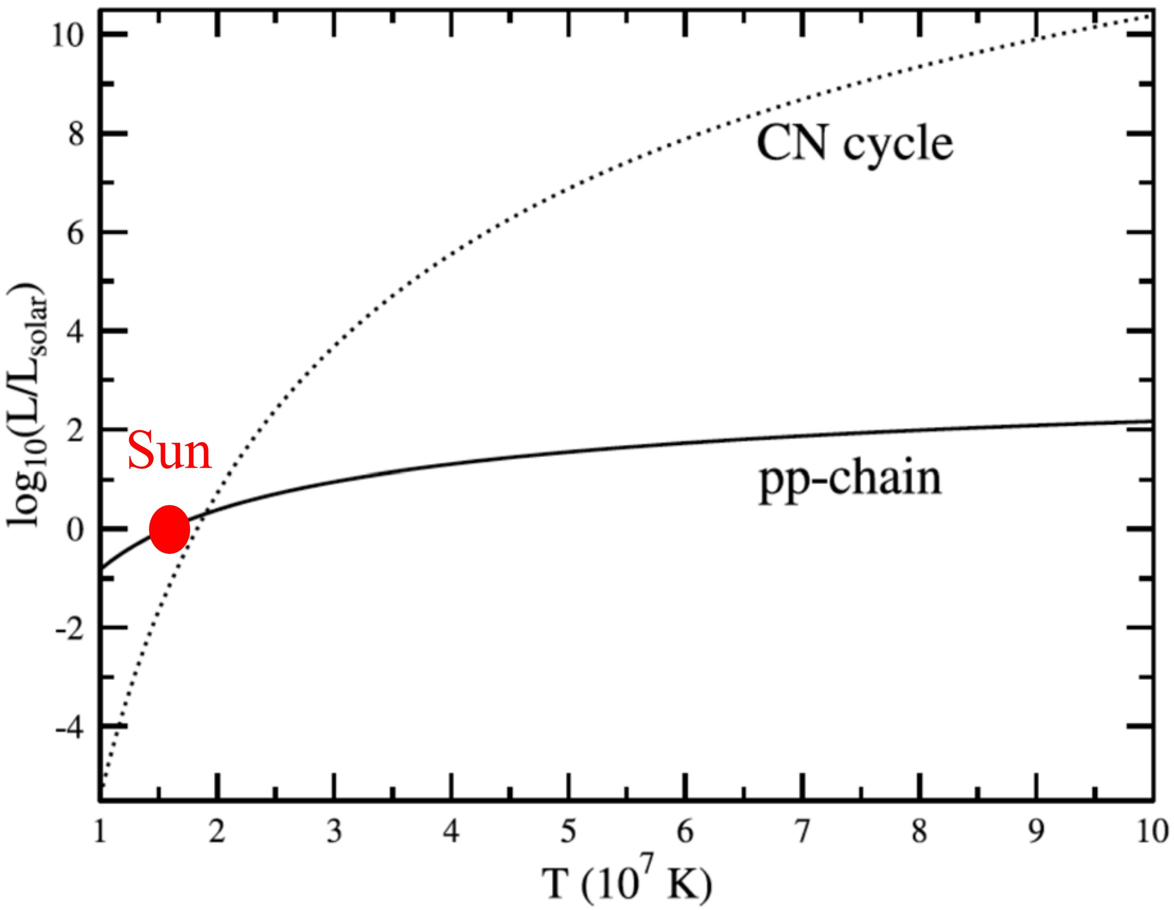
pp-cycle: ~99% solar energy



CNO-cycle: < 1% solar energy



CNO CYCLE VS PP CHAIN IN THE STARS

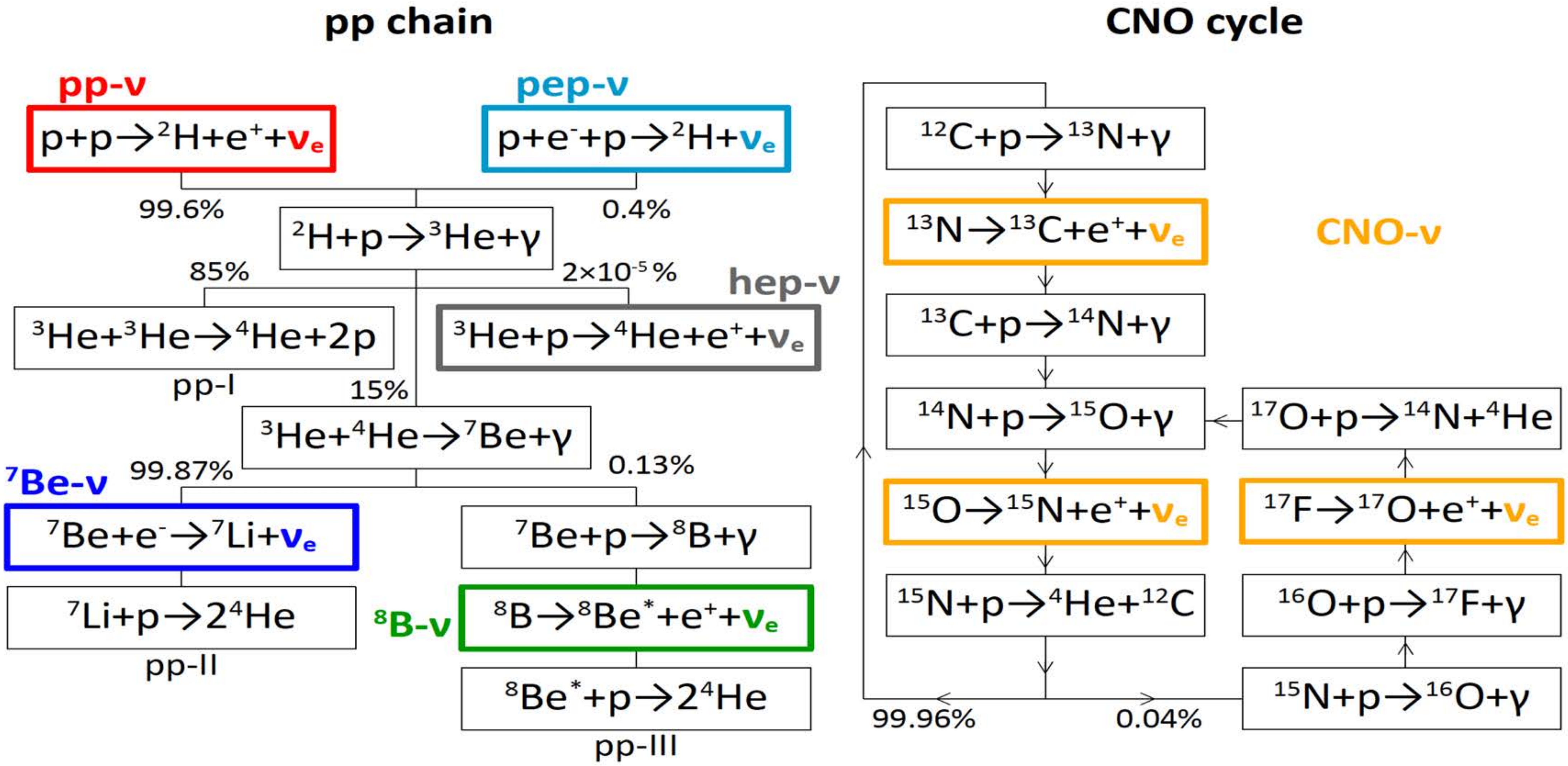


Haxton & Serenelli: The Astrophysical J. 687 (2008) 678

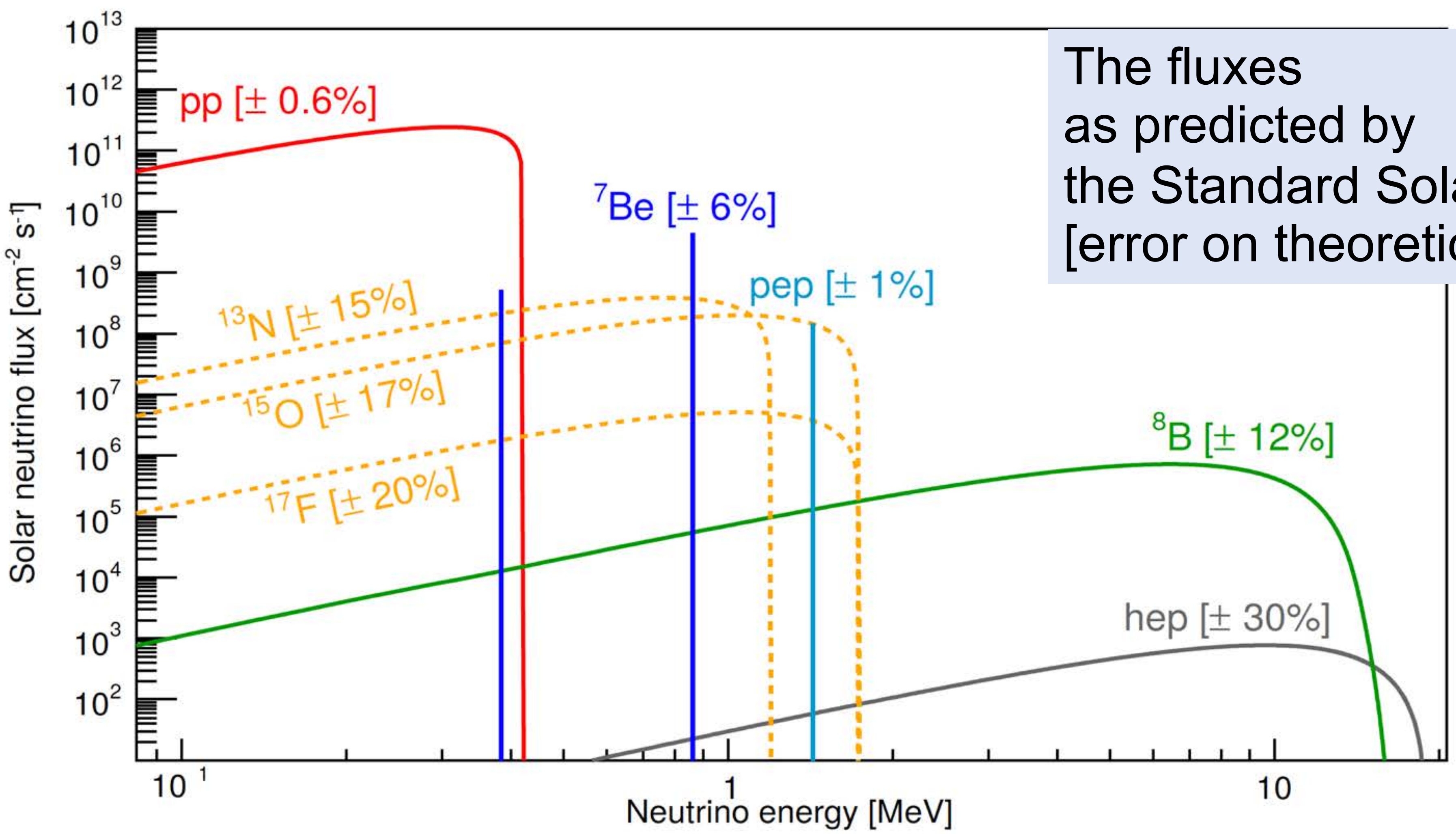
In massive stars,
having higher temperature in their cores,
the CNO cycle is the dominant energy source.

That makes
the CNO fusion cycle
the main Hydrogen-to-Helium conversion process in the stars

SOLAR NEUTRINOS FROM THE PP AND CNO



ENERGY SPECTRUM OF SOLAR NEUTRINOS



The fluxes
as predicted by
the Standard Solar Model
[error on theoretical prediction]

SOLAR NEUTRINOS AND WHY TO STUDY THEM

Neutrino physics

- Solar mixing angle θ_{12} and global fits of **neutrino oscillation parameters**
- Testing LMA-MSW predictions and matter effects: **electron flavour survival probability as f(E_ν)** and its upturn
- Searches for **Non-standard Neutrino Interactions**

Solar and stellar physics

- Direct probe of **nuclear fusion**
- Photon vs neutrino luminosity: testing **thermodynamical stability** of the Sun
- **Standard Solar Models**
  - ✓ Metallicity problem

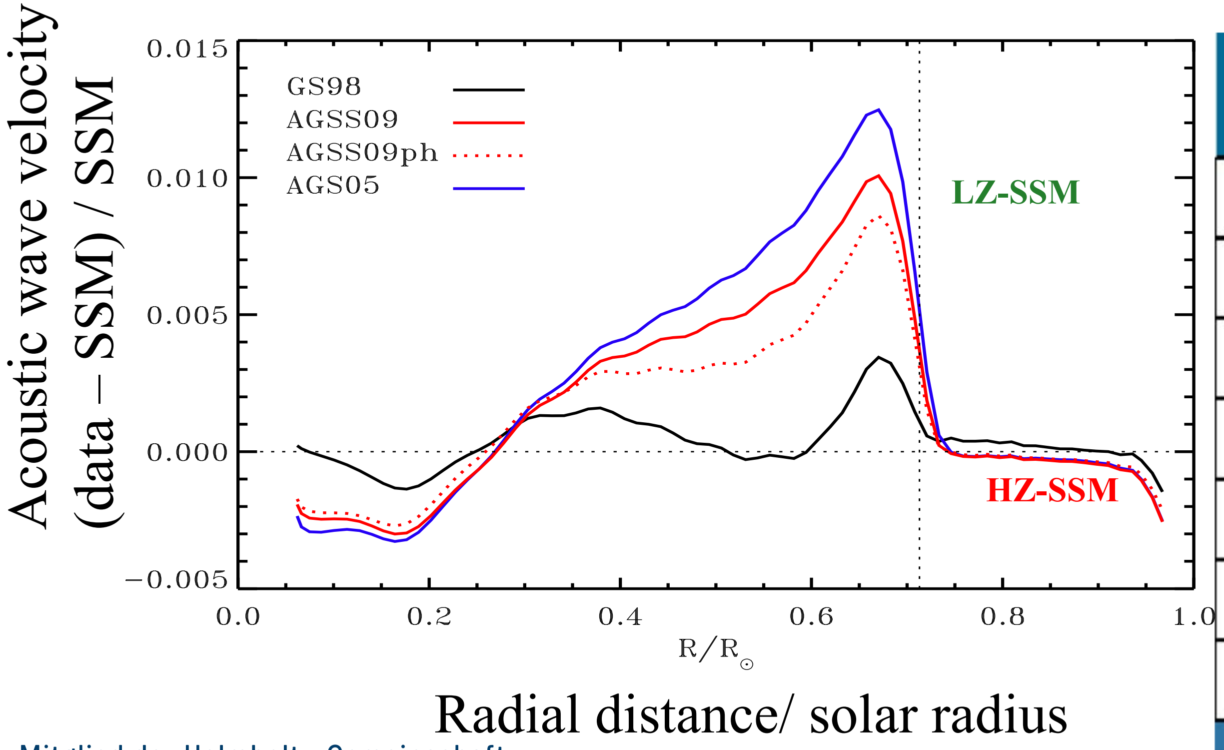
SOLAR METALLICITY PROBLEM

Metallicity is an input to the SSM, that influences the neutrino flux prediction.
- opacity -> temperature -> cross sections
- CNO -> direct influence through C, N, O

Z = abundance of heavy elements: C, N, O, Ne, Mg, Si, Ar, Fe
X = abundance of H and He

High-Metallicity HZ-SSM = B16 SSM with an older GS98 metallicity input
Low-Metallicity LZ SSM = B16 SSM with a newer AGSS09met input

The new low metallicity inputs, based on the new spectroscopic data and 3D models of the solar atmosphere, spoil the previous agreement of the SSM (with older high metallicity inputs) with the helio-seismological data.



FLUX	B16-GS98	B16-AGSs09met	DIFF. (HZ-LZ)/HZ
pp (10^{10} cm^{-2} s^{-1})	5.98(1±0.006)	6.03(1±0.005)	-0.8%
pep (10^{8} cm^{-2} s^{-1})	1.44(1±0.01)	1.46(1±0.009)	-1.4%
^{7}Be (10^{9} cm^{-2} s^{-1})	4.94(1±0.06)	4.50(1±0.06)	8.9%
^{8}B (10^{6} cm^{-2} s^{-1})	5.46(1±0.12)	4.50(1±0.12)	17.6%
^{13}N (10^{8} cm^{-2} s^{-1})	2.78(1±0.15)	2.04(1±0.14)	26.6%
^{15}O (10^{8} cm^{-2} s^{-1})	2.05(1±0.17)	1.44(1±0.16)	29.7%
^{17}F(10^{6} cm^{-2} s^{-1})	5.29(1±0.20)	3.26(1±0.18)	38.3%

N. Vinyoles et al., Astrophys. J. 836 (2017) 202

BOREXINO COLLABORATION

~100 scientists from

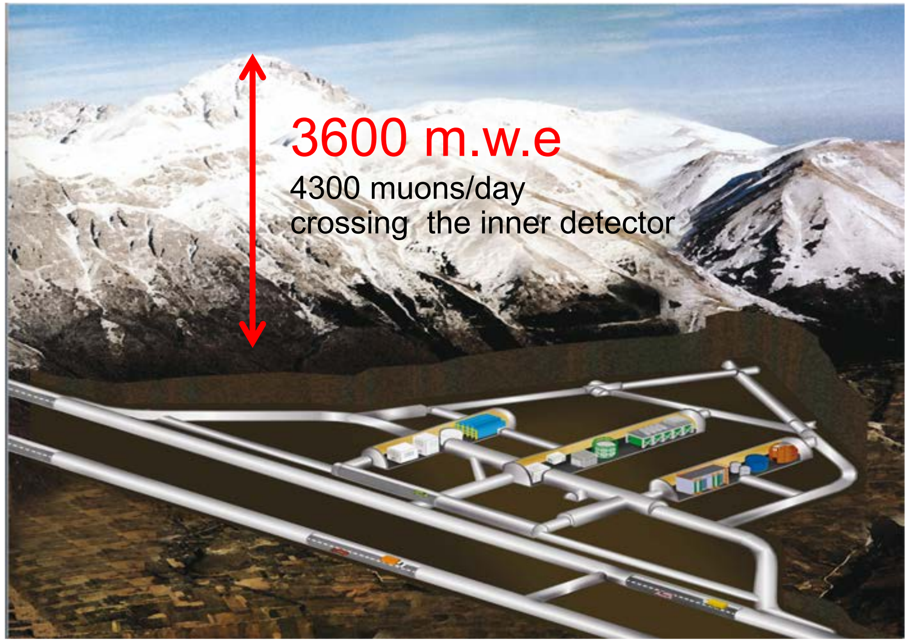
- Italy
- Germany

Forschungszentrum Jülich
JGU Mainz
RWTH Aachen
TU Dresden
TU München

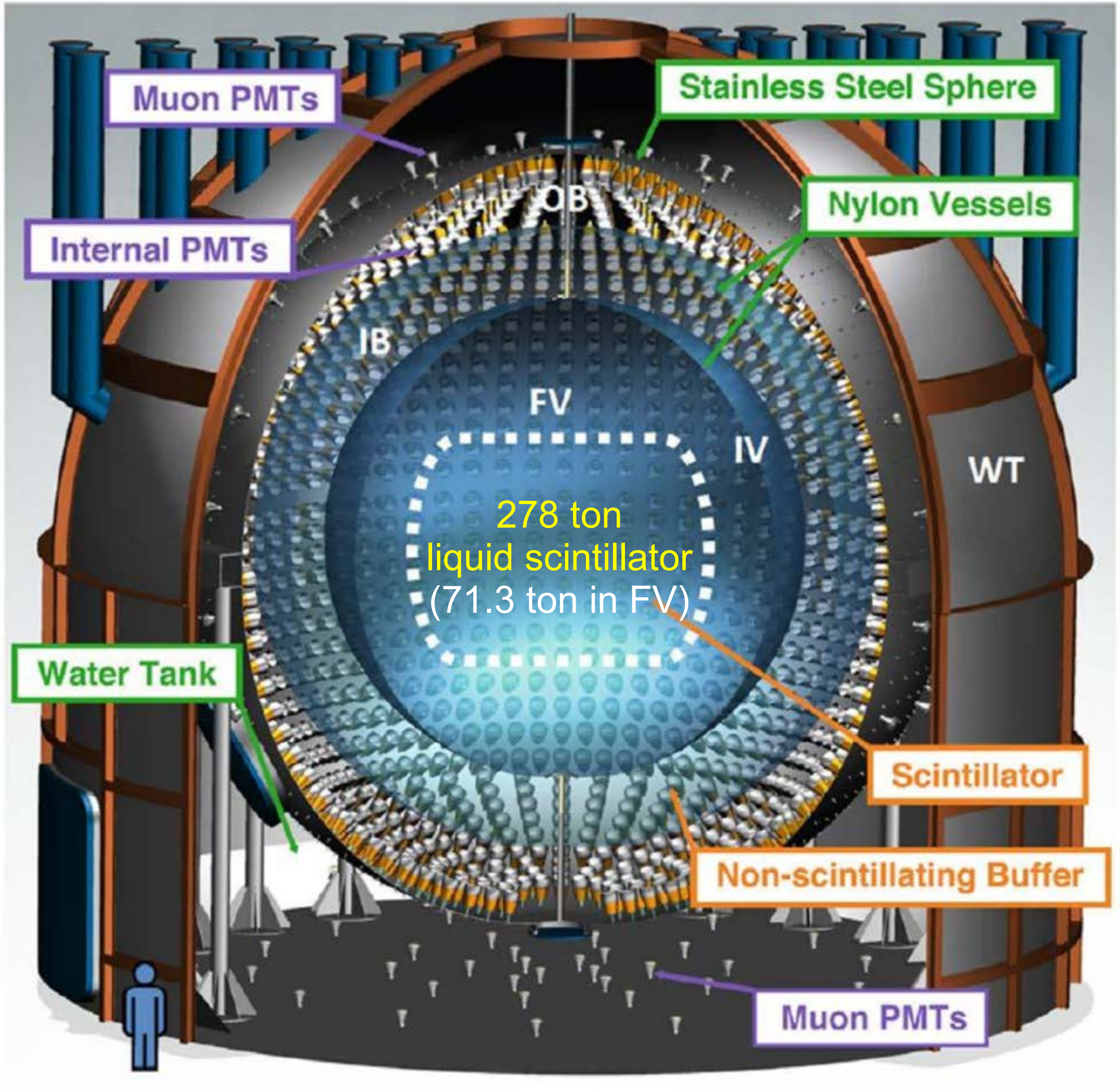
- USA
- Russia
- France
- Poland

BOREXINO DETECTOR

Laboratori Nazionali del Gran Sasso, Italy

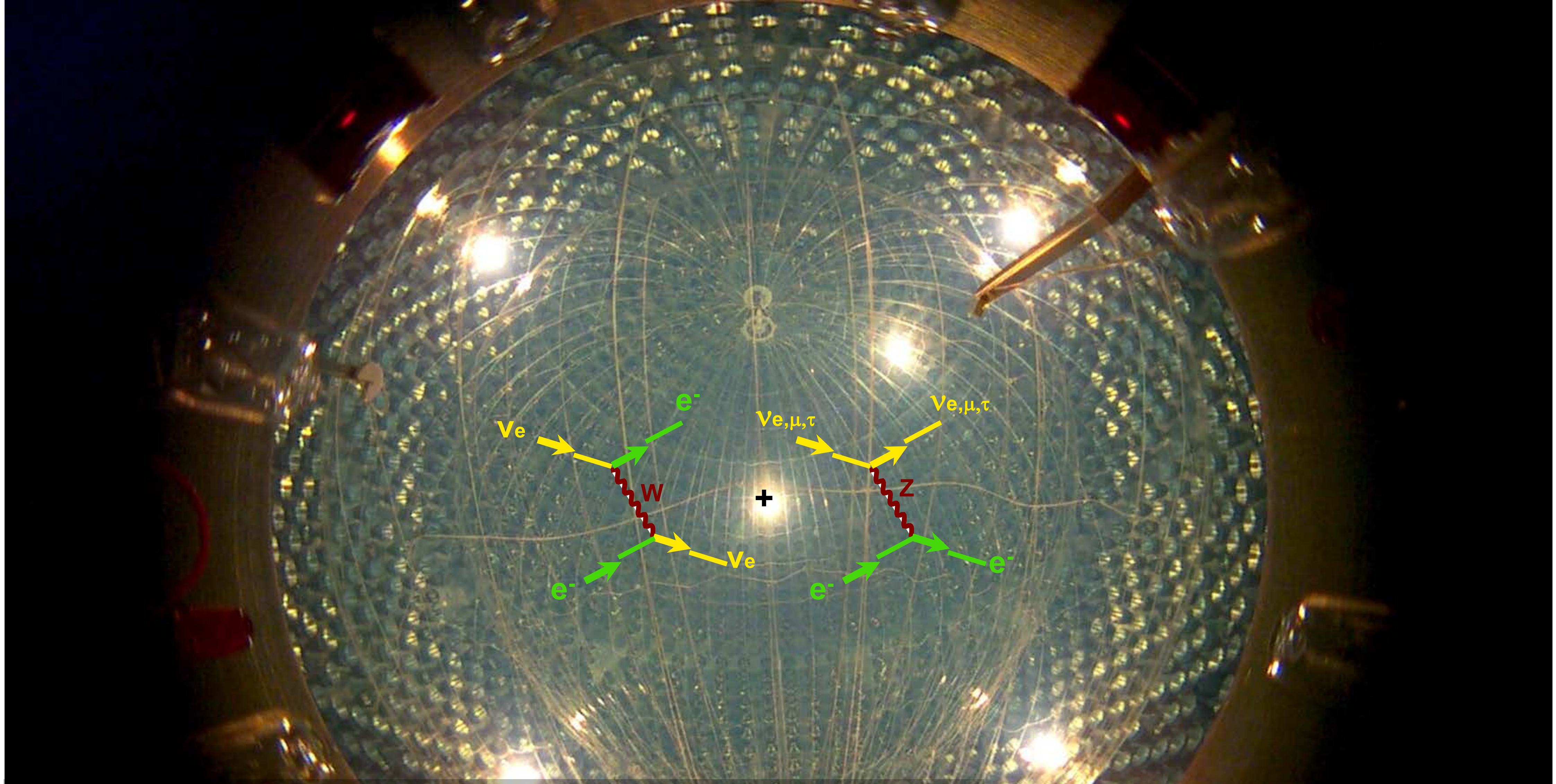


- **the world's radio-purest LS detector**
  $< 9 \times 10^{-19}$ g(Th)/g , $< 8 \times 10^{-20}$ g(U)/g
- **~500 photoelectrons / MeV**
- energy reconstruction: 5 keV (5%) @ 1 MeV
- position reconstruction: 10 cm @ 1 MeV
- pulse shape identification (α/β, e^+/e^-)



Operating since 2007

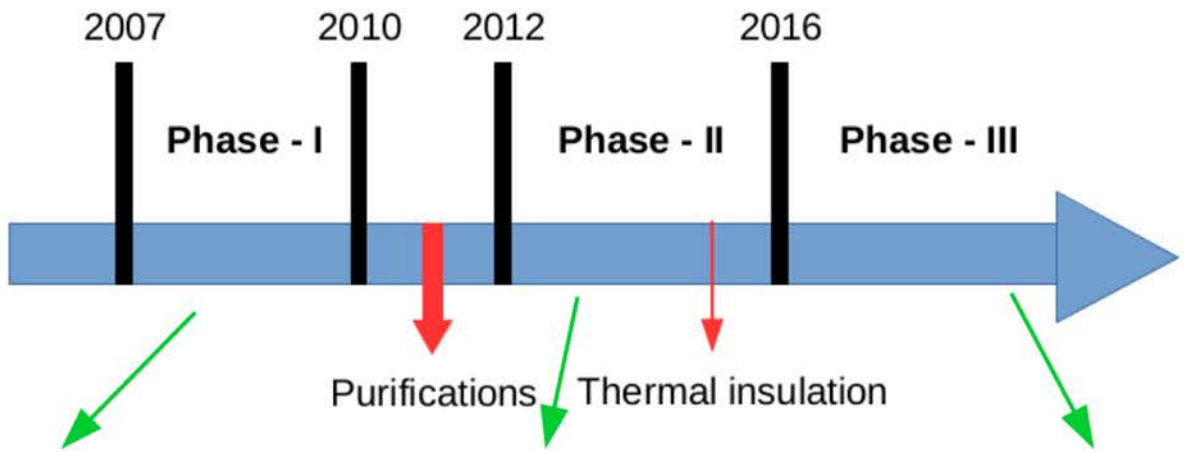
More about detector in:
NIM A600 (2009) 568



Solar neutrino detection: SINGLES

- Elastic scattering of electrons
- No threshold
- All flavours (cross section for ν_e ~6x higher)

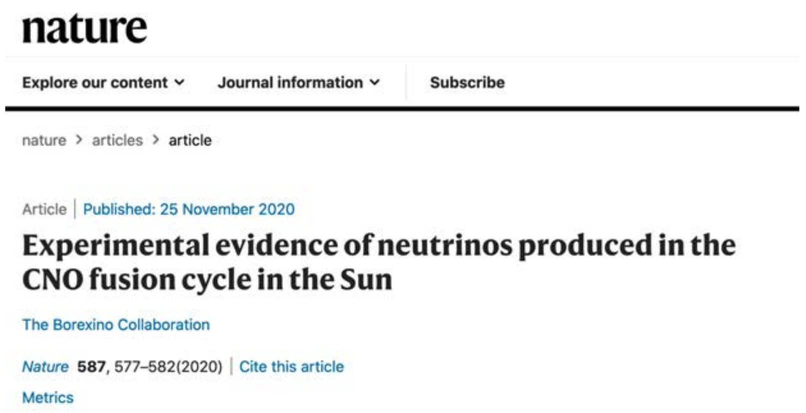
BOREXINO TIMELINE AND RESULTS



- First observation and precise measurement of ^{7}Be ν
- First observation of *pep* ν, ^{8}B ν with low threshold
- Give the best limit of CNO ν

- Precise measurement of *pp* ν
- First complete study of all components of the pp-chain

CNO observation
NATURE 25/11/2020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Article | Published: 25 November 2020

Experimental evidence of neutrinos produced in the CNO fusion cycle in the Sun

The Borexino Collaboration

Nature **587**, 577–582(2020) | Cite this article

Metrics

- Geoneutrinos (2010, 2013, 2015, 2019)
- Search for solar, astro anti-ν (2011)
- Test of electric charge conservation (2015)
- Limit on ν-magnetic moment (2017)
- Search for solar axions (2008, 2012)
- Search for coincidence with GRB's (2016)
- Search for coincidence with GRB's (2016)
- Search for coincidence with GW's (2017)

BOREXINO PP-CHAIN RESULTS

ARTICLE

Nature Oct 25th 2018

https://doi.org/10.1038/s41586-018-0624-y

Spectroscopy of all pp-cycle neutrinos at once

Low Energy Region (LER) 0.19 – 2.93 MeV:

pp (9.5%), **^{7}Be** (2.7%), ***pep*** (>5σ)

High Energy Region (HER) 3.2 – 16 MeV:

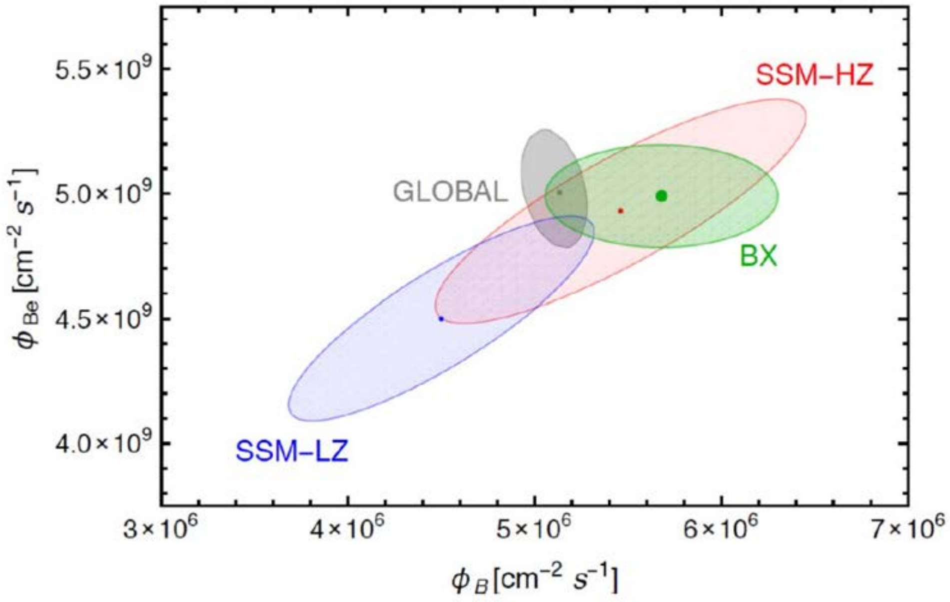
^{8}B (3 MeV threshold, 8%)

- First Borexino limit on **hep** neutrinos
- Limit on **CNO cycle** neutrinos
- Neutrino and photon luminosity in agreement

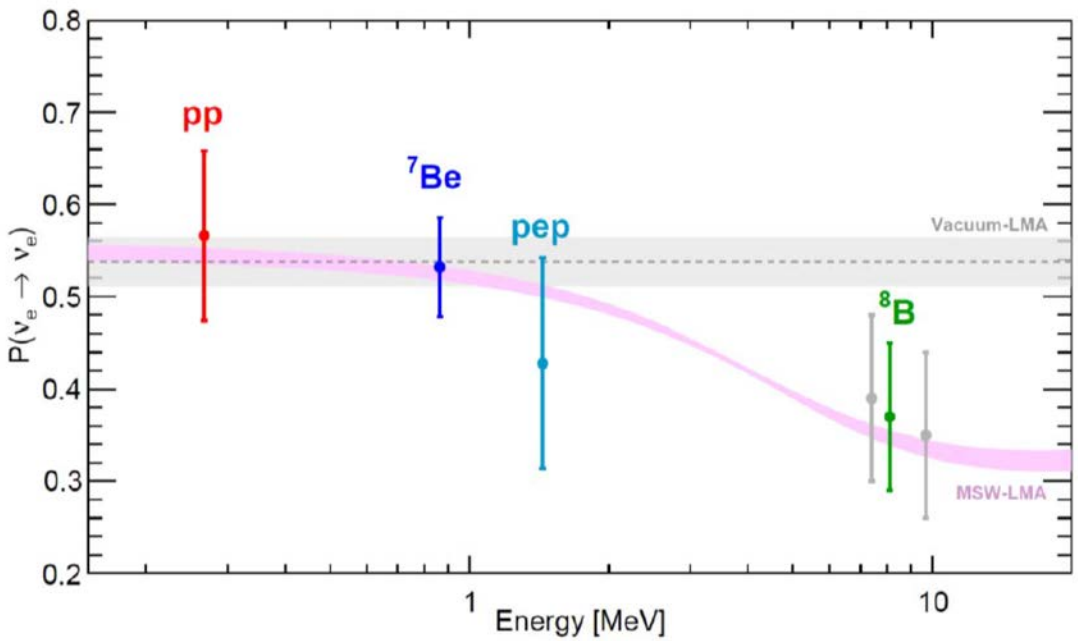
Comprehensive measurement of *pp*-chain solar neutrinos

The Borexino Collaboration*

- Indication towards **HZ Standard Solar Models**
- BR(pp_{II}/pp_{I})=<^{3}He+^{4}He>/<^{3}He+^{3}He> = 0.18±0.03
- Survival probabilities at different energies in both vacuum and matter domains
- **Vacuum-LMA model excluded at 98.2% CL**



Solar ν		Rate [cpd/100 t]
pp	1.3x	$134 \pm 10^{+6}_{-10}$
^{7}Be	1.8x	$48.3 \pm 1.1^{+0.4}_{-0.7}$
pep (HZ)		$2.43 \pm 0.36^{+0.15}_{-0.22}$
pep (LZ)	1.6x	$2.65 \pm 0.36^{+0.15}_{-0.24}$
$^8B_{HE-I}$		$0.136^{+0.013+0.003}_{-0.013-0.003}$
$^8B_{HE-II}$		$0.087^{+0.080+0.005}_{-0.010-0.005}$
$^8B_{HE}$	>2x	$0.223^{+0.015+0.006}_{-0.016-0.006}$

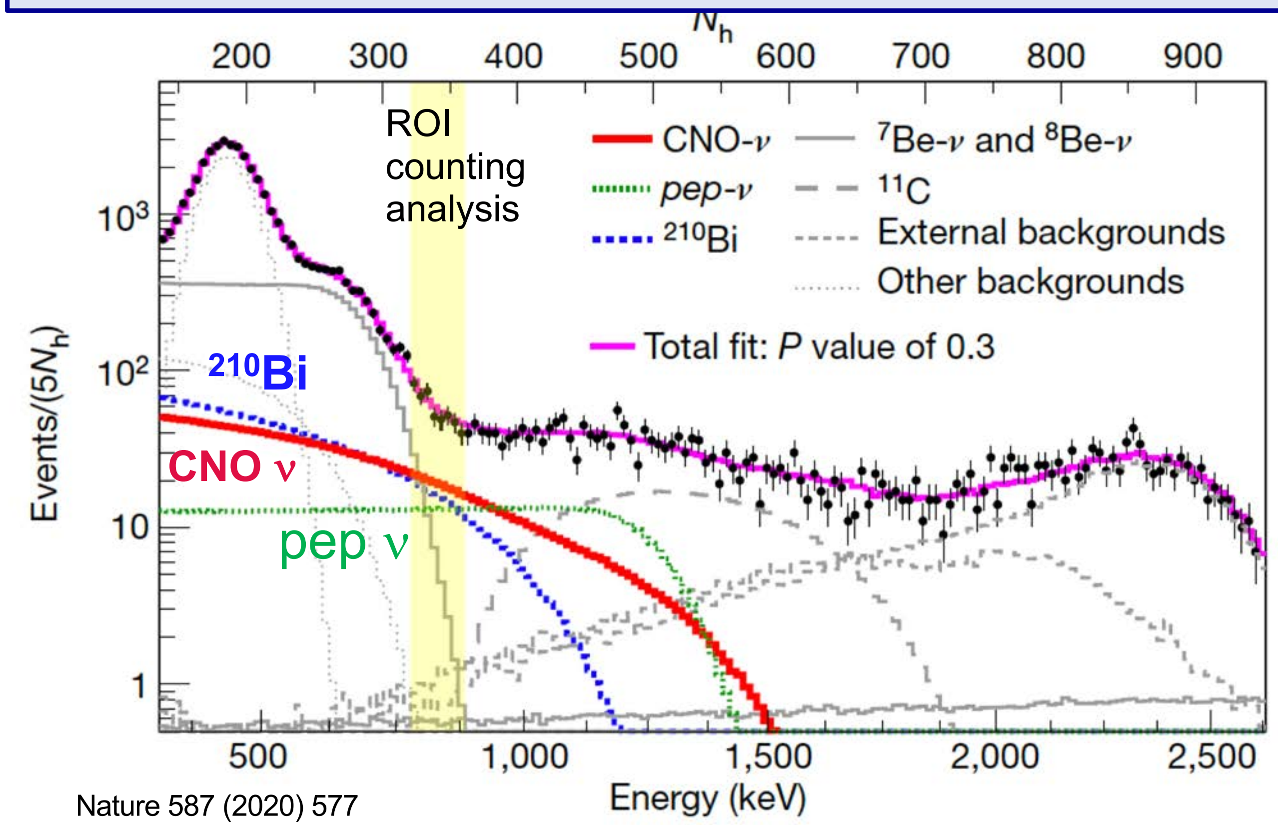


CHALLENGES TO MEASURE CNO NEUTRINOS

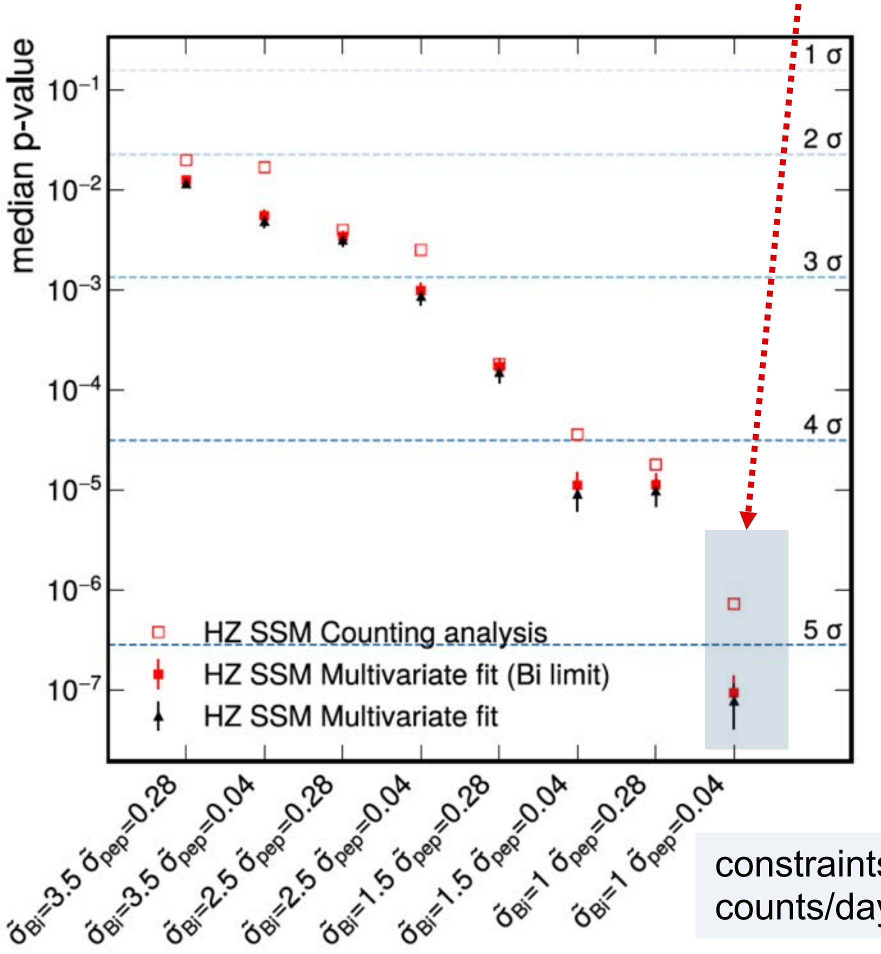
- Low rate (3-5 counts/day/100 ton of liquid scintillator)
- No prominent spectral features
- **Correlation with**
  - ✓ **pep solar neutrino: 1.4%** constraint from the solar luminosity and global fit of solar data without Bx Phase III
  - ✓ ^{210}Bi contamination of liquid scintillator: CHALLENGE

Expected sensitivity 4-5σ for the HZ-SSM and conditions achieved in Phase III

(Eur. Phys. Jour. C (2020) 1091)



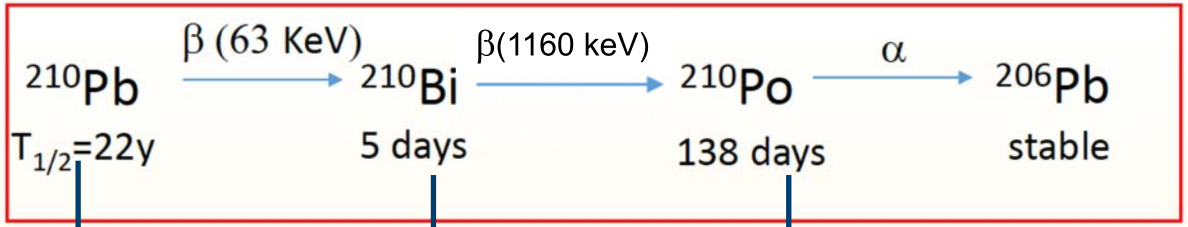
Nature 587 (2020) 577



constraints in counts/day/100 t)

BOREXINO STRATEGY TO CONSTRAIN 210-BISMUTH

F. Villante et al., Phys. Lett. B 701 (2011)



- contaminant of the scintillator
- long-lasting source of ^{210}Bi
- below the analysis threshold

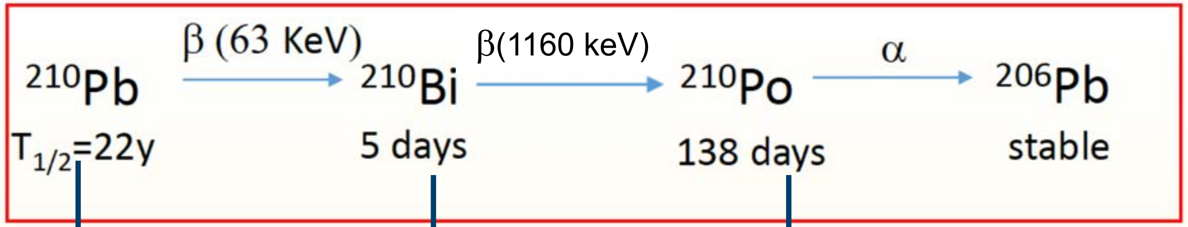
anti-correlated background to CNO

- **event-by-event identification using** MLP α/β pulse shape discriminator

Assuming **secular equilibrium**, all these **rates are the same**

BOREXINO STRATEGY TO CONSTRAIN 210-BISMUTH

F. Villante et al., Phys. Lett. B 701 (2011)



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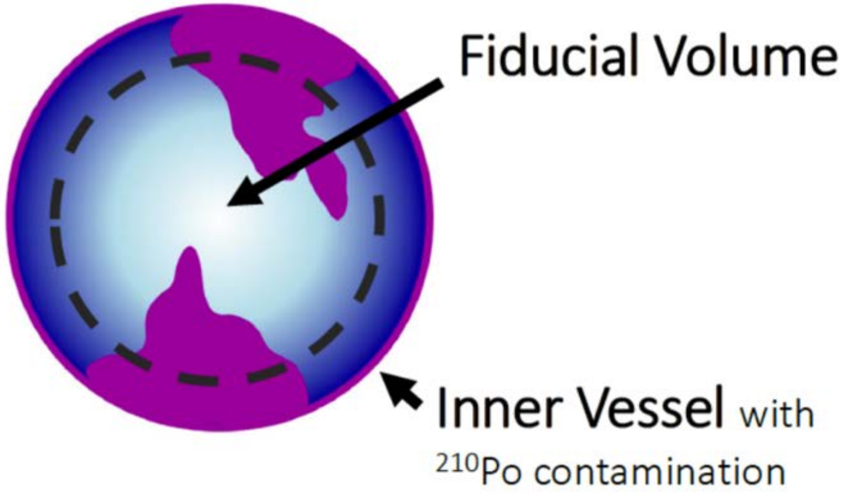

Problem: seasonal convective currents bringing ^{210}Po from the nylon vessel to the fiducial volume of the analysis; **breaking the secular equilibrium**

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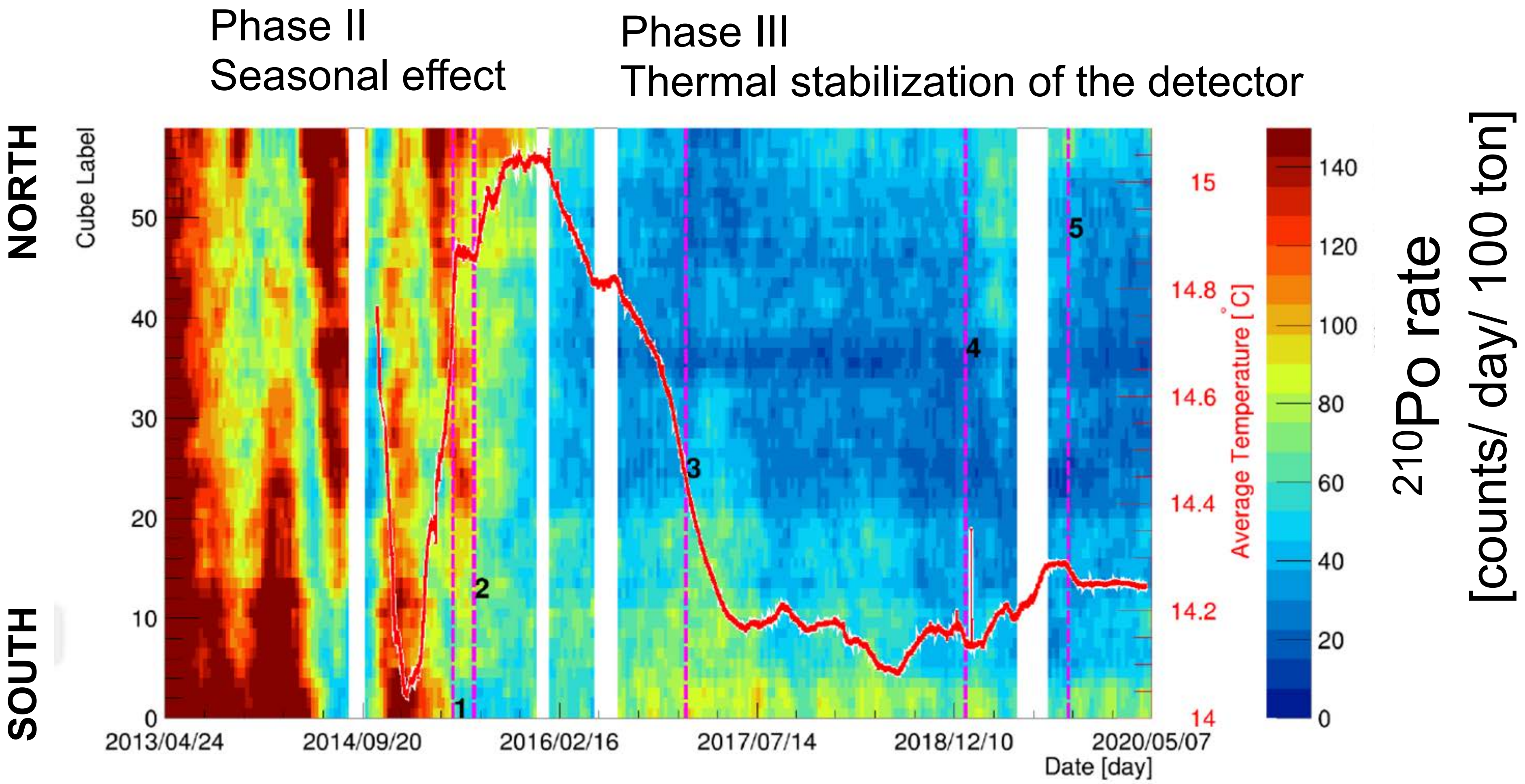
TEMPORAL EVOLUTION OF 210-POLONIUM RATE



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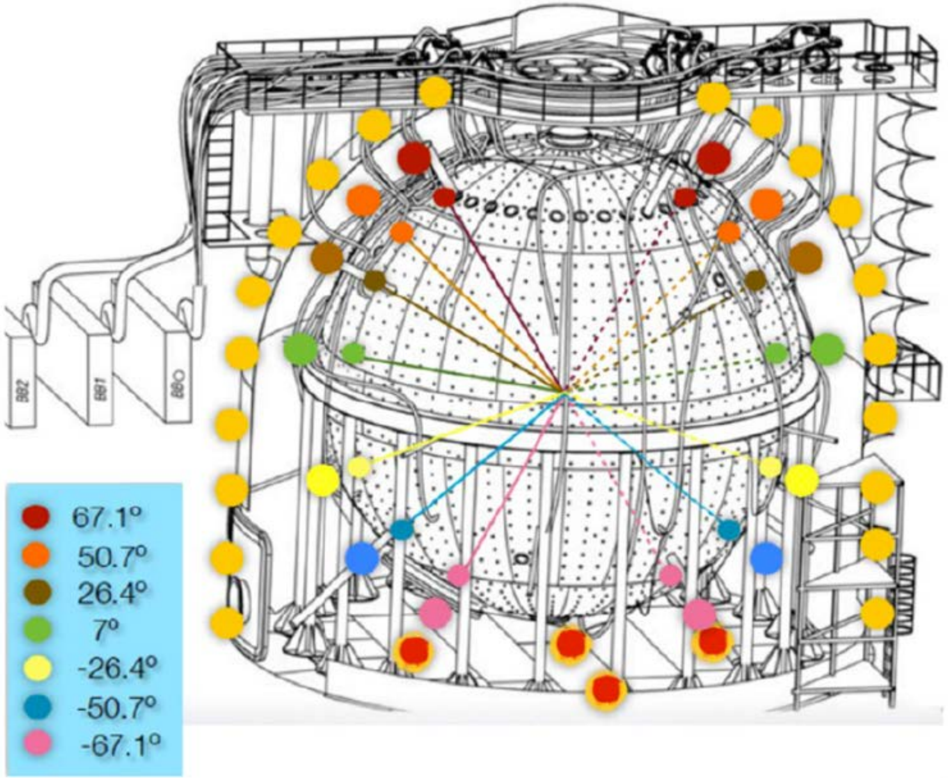
SOLUTION: THERMAL STABILIZATION OF THE DETECTOR

Thermal insulation with mineral wool

Temperature probes and active temperature control



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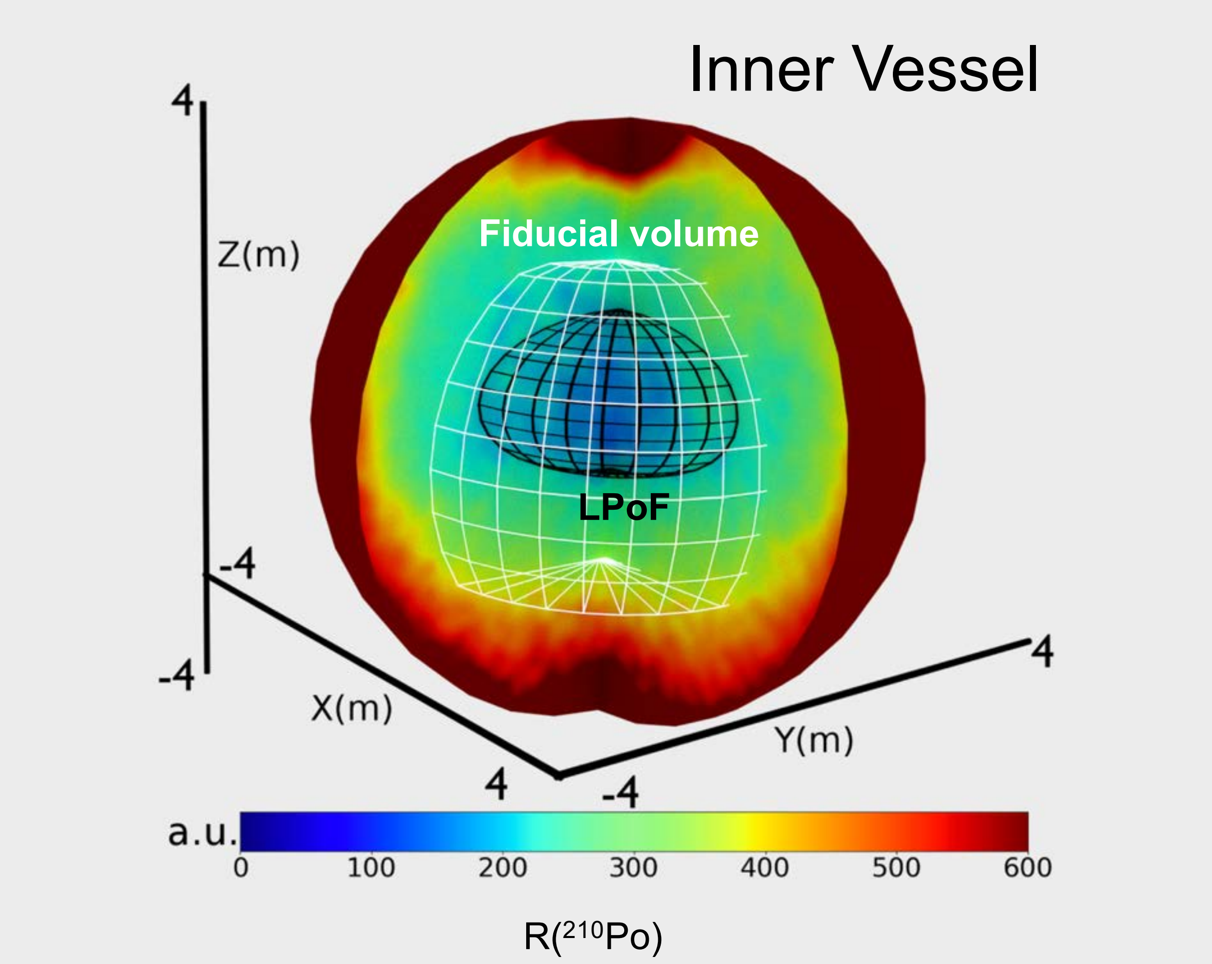
LOW POLONIUM FIELD (LPoF)



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1. Clean region in the core of the detector is created: LPoF

2. We extract the minimal ^{210}Po rate value, that is an upper limit on ^{210}Bi rate

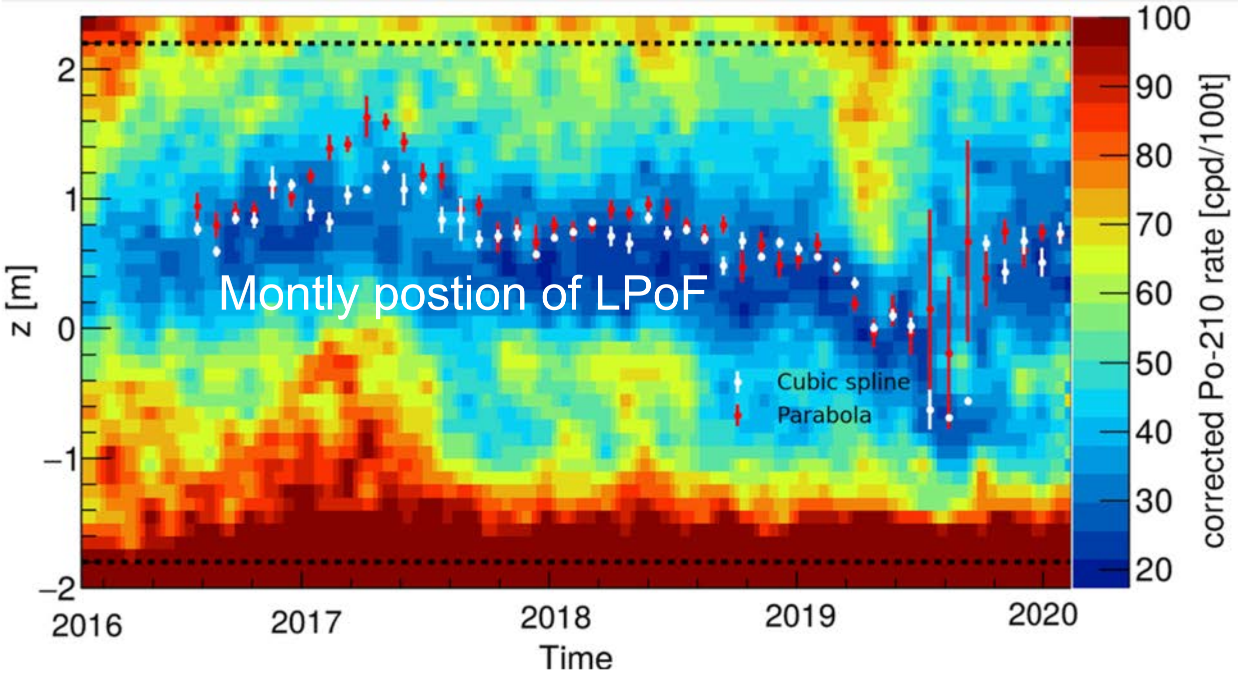
$$R(^{210}Po_{min}) = R(^{210}Bi) + R(^{210}Po^{vessel}) < R(^{210}Bi)$$

3. Check that the R(^{210}Bi) is homogeneous in the whole fiducial volume of the analysis (include non-homogeneity in the sys error)

4. Use **upper limit on R(^{210}Bi)** as a half-Gaussian constraint in the analysis

LOW POLONIUM FIELD – POSITION AND FIT

Slow movement of the LPoF along z



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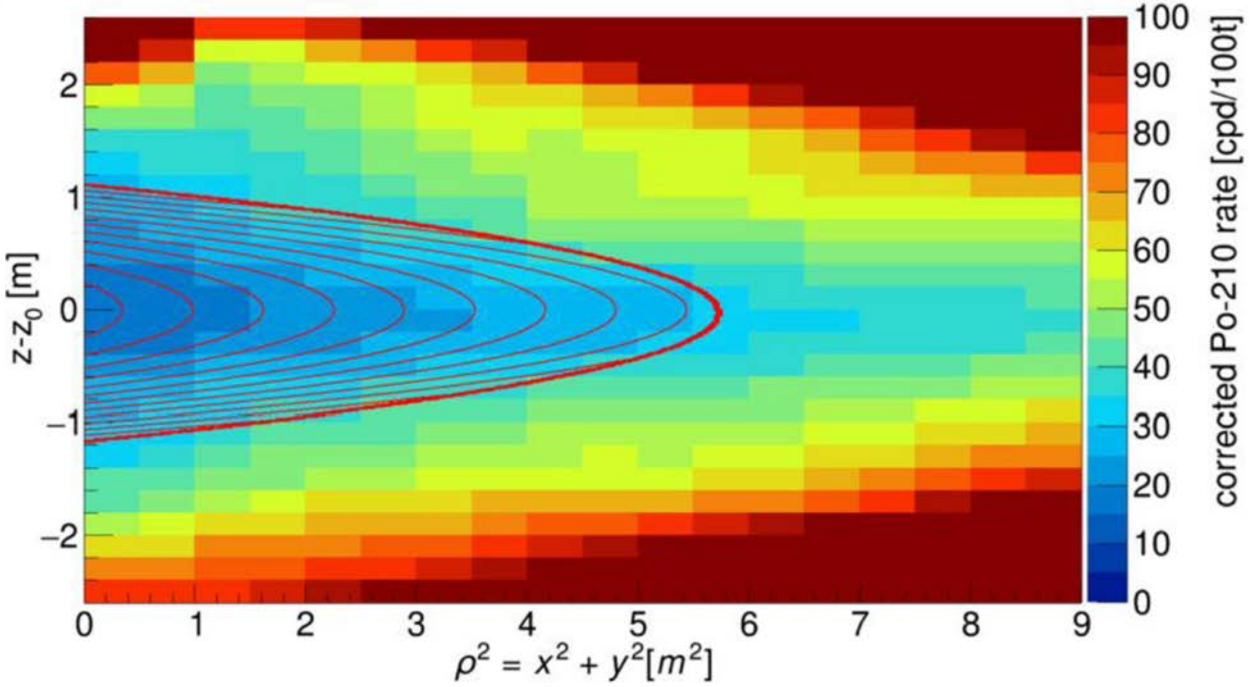
Fit of the aligned LPoF data



$$\frac{d^2R(^{210}\mathrm{Po})}{d(\rho^2)dz} = [R(^{210}\mathrm{Po}_{min})\epsilon_E\epsilon_{MLP} + R_\beta] \times \left(1 + \frac{\rho^2}{a^2} + \frac{(z-z_0)^2}{b^2}\right)$$

R(^{210}Bi) $\leq$ (11.5 $\pm$ 1.3) counts / day / 100 ton
including all systematic errors

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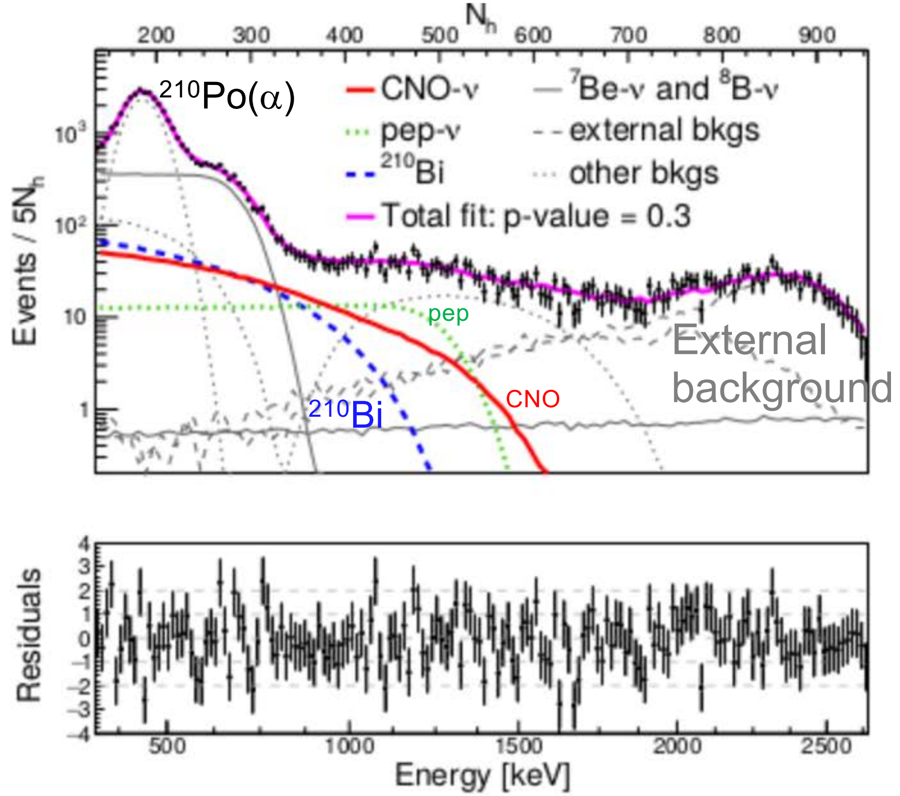
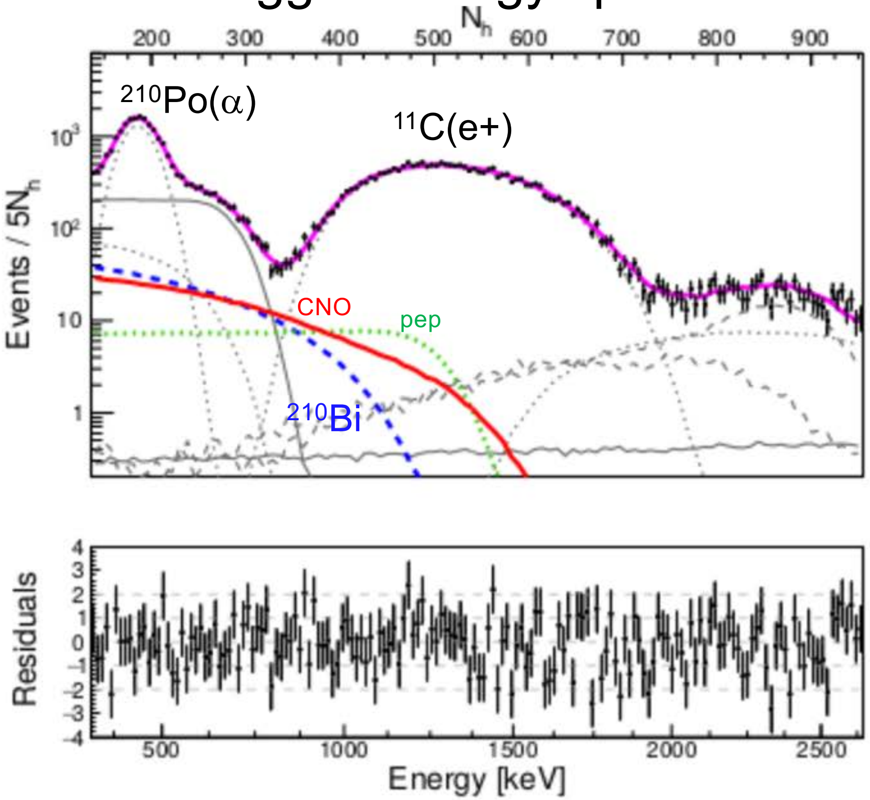
MULTIVARIATE SPECTRAL FIT WITH THREE-FOLD COINCIDENCE (TFC) TO TAG ^{11}C

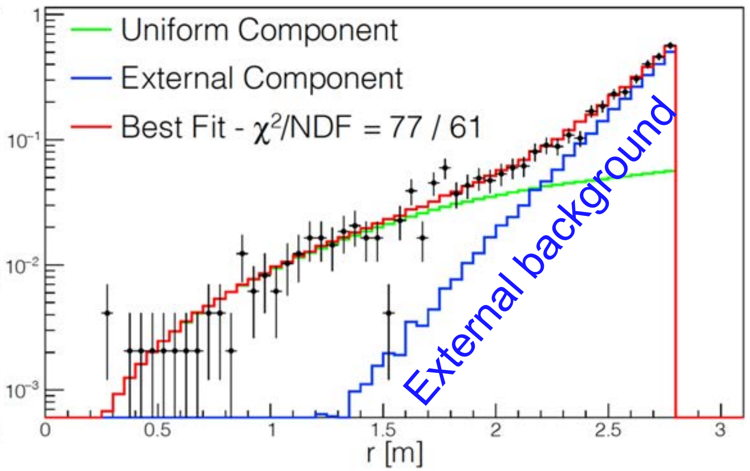
^{11}C subtracted energy spectrum



^{11}C tagged energy spectrum



Radial distribution



Constraints in the fit:
R(pep) = (2.74 + 0.04) cpd/100 t
R(^{210}Bi) < (11.5 $\pm$ 1.3) cpd/100 t

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

$^{11}C \rightarrow {}^{11}B + e^+ + \nu_e$
$\tau \sim$ 30 min

$n + p \rightarrow d + \gamma$ (2.2 MeV)
$\tau \sim$ 260 μs

$$\mathcal{L}_{MV}(\vec{\theta}) = \mathcal{L}_{sub}^{TFC}(\vec{\theta})\, \mathcal{L}_{Tag}^{TFC}(\vec{\theta})\, \mathcal{L}_{Radial}(\vec{\theta})$$

Phase III data (July 2016 – Feb 2020)
with exposure 1072 days x 71.3 ton

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FIT AND COUNTING ANALYSIS RESULTS

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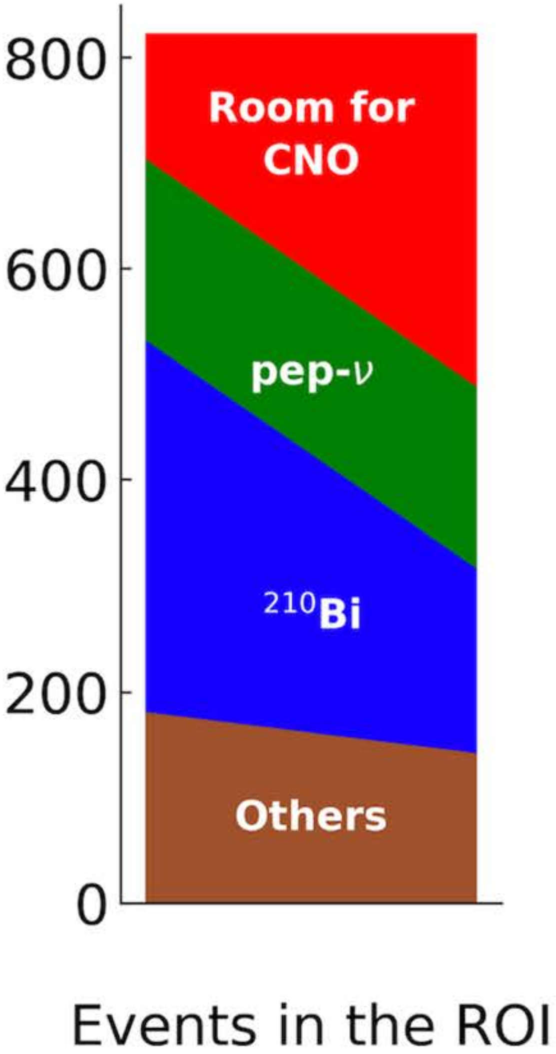

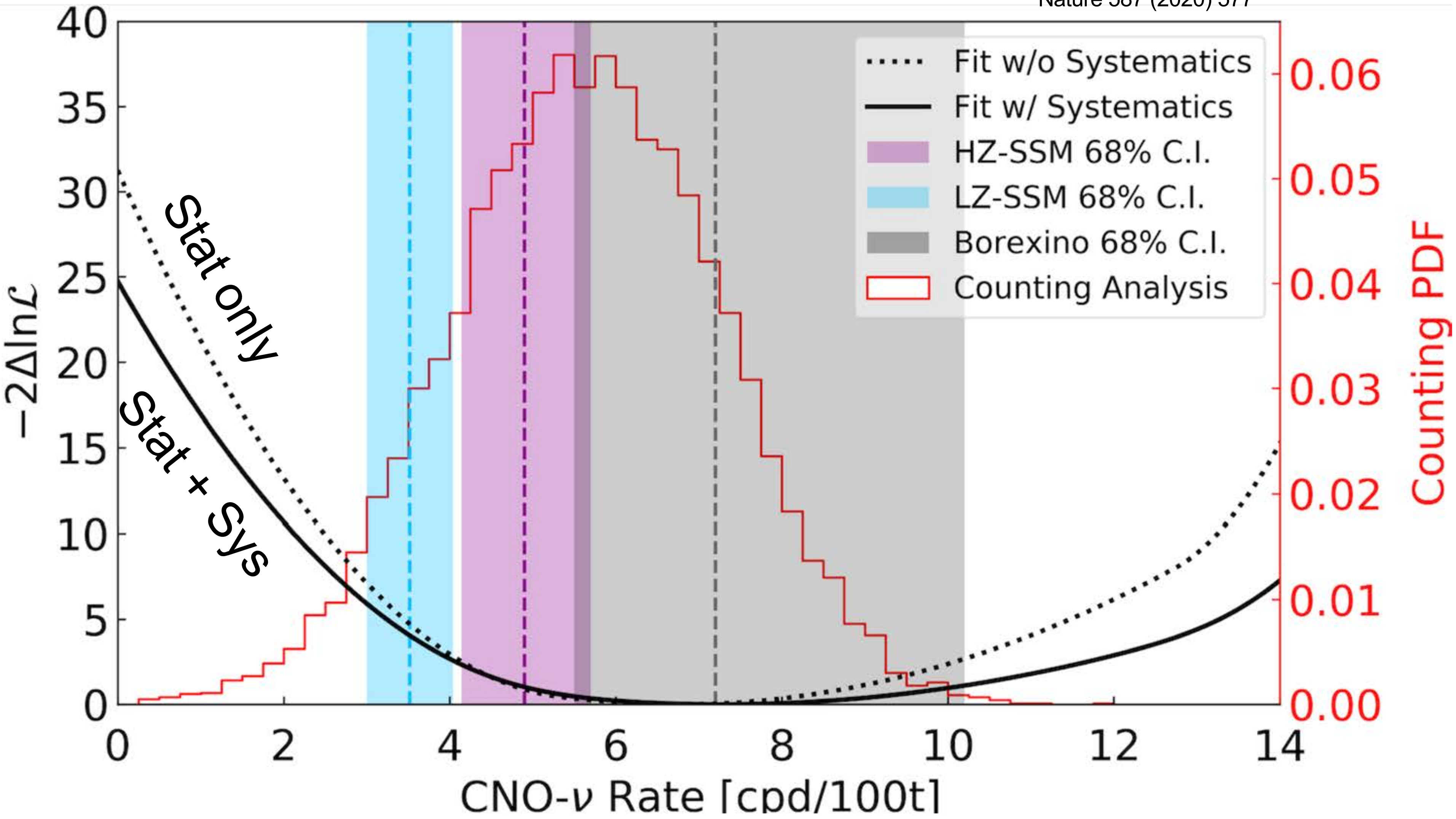

$R(CNO) = 7.2^{+3.0}_{-1.7}$ counts / day / 100 ton

including systematic errors $^{+0.6}_{-0.5}$ cpd/100 ton

FIT AND COUNTING ANALYSIS RESULTS

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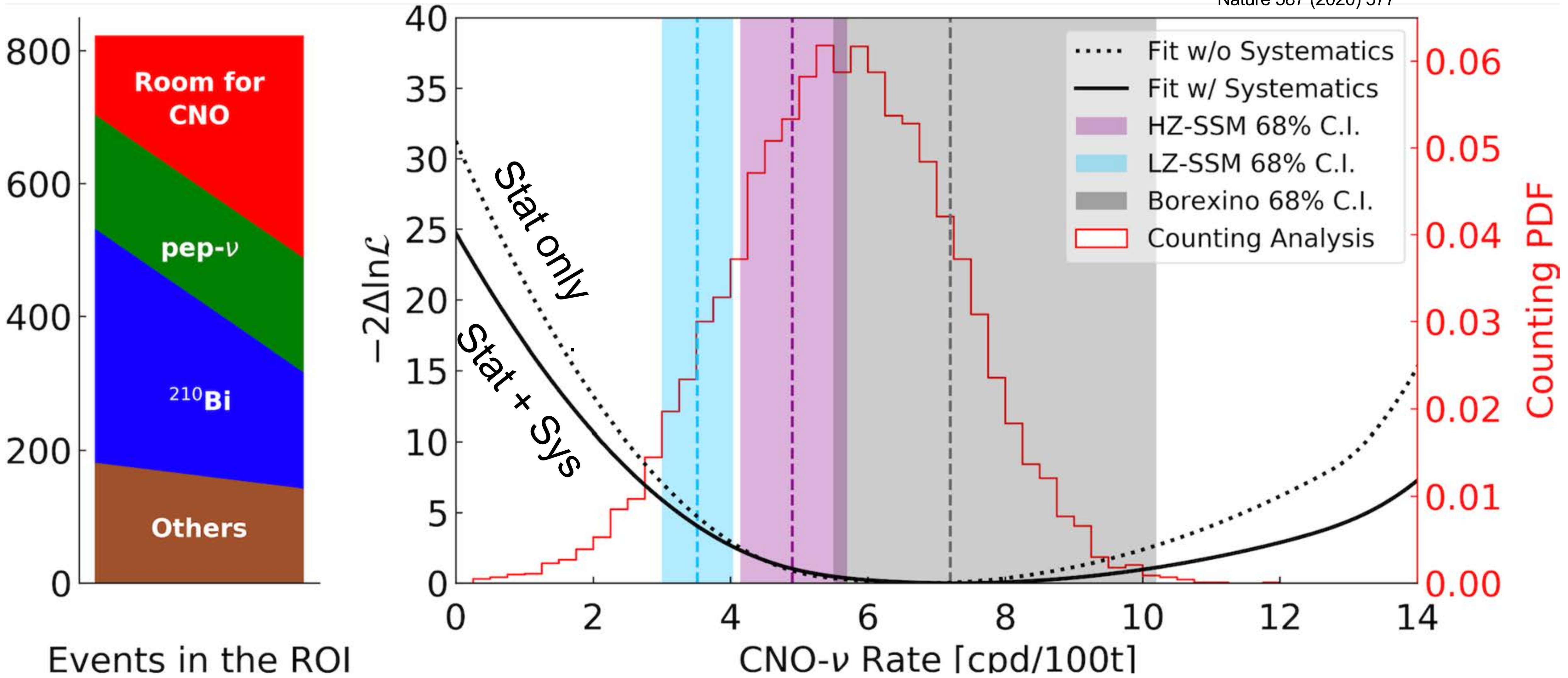
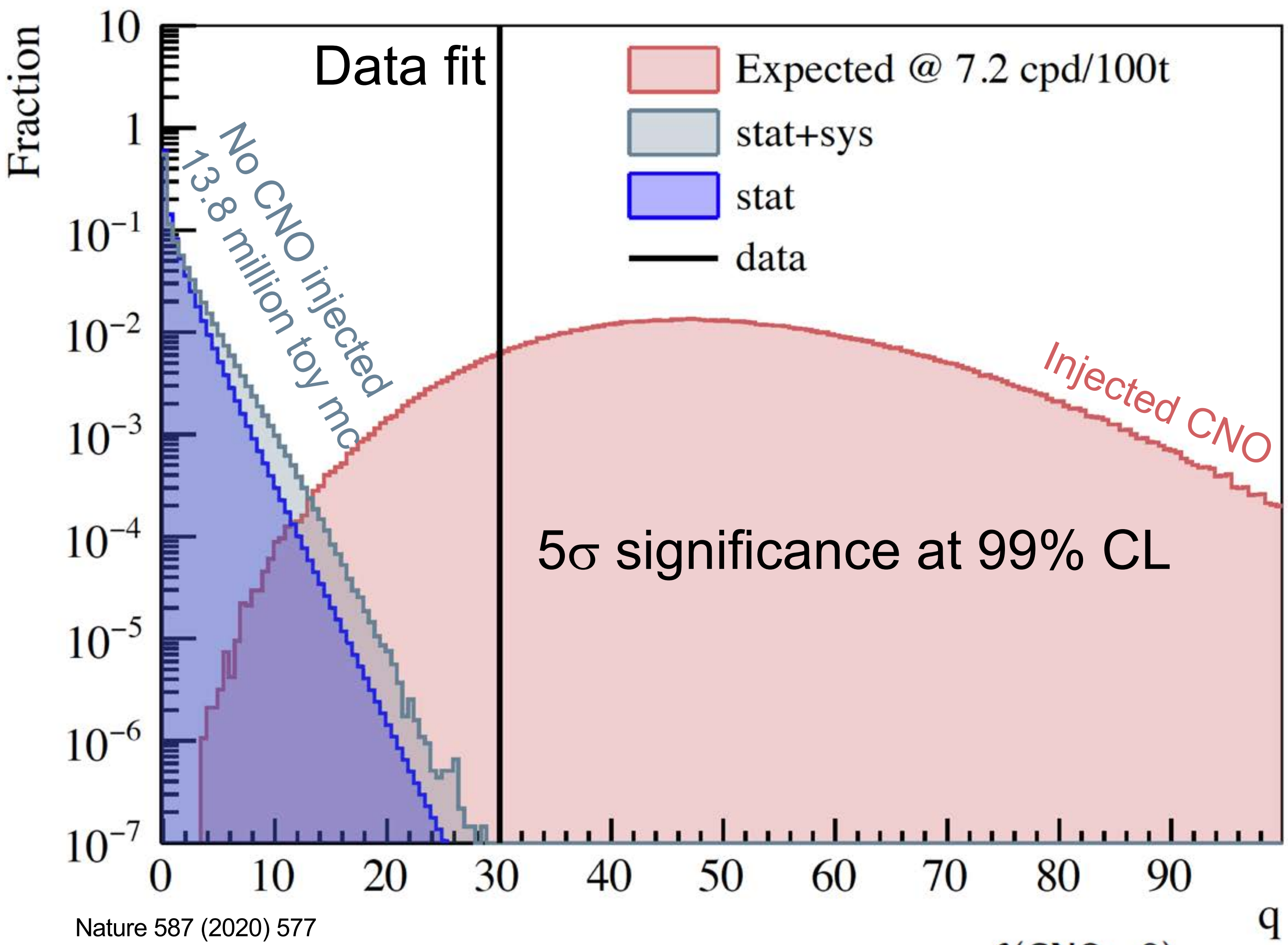


$\Phi(\mathrm{CNO}) = 7.0^{+3.0}_{-2.0} \times 10^{8}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$
including systematic errors

SIGNIFICANCE OF THE RESULT WITH TOY MONTE CARLO



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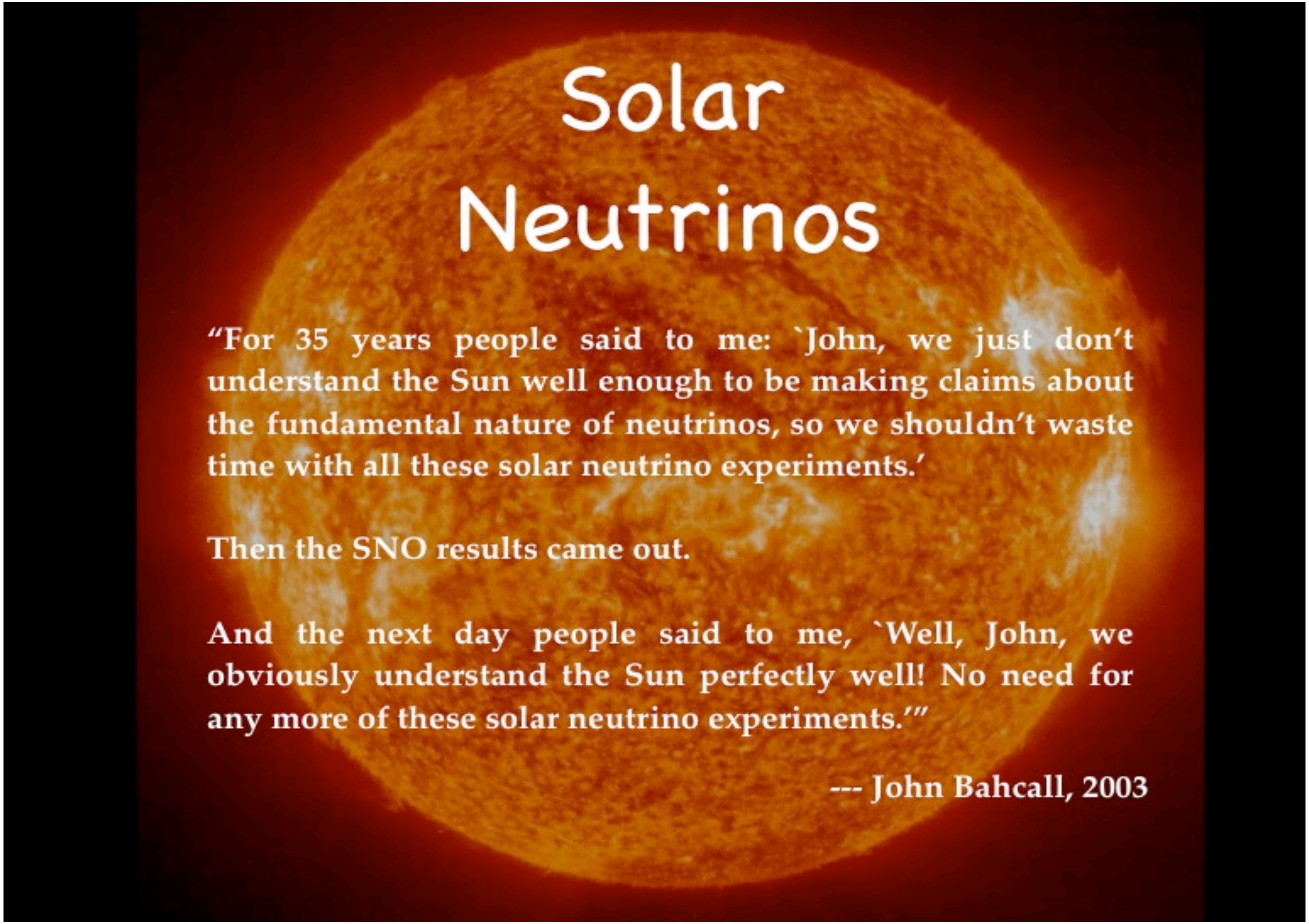
$$q = -2\log\frac{\mathcal{L}(CNO=0)}{\mathcal{L}(CNO)}$$

SUMMARY AND OUTLOOK

- Borexino has experimentally confirmed the existence of the CNO fusion cycle in Nature using the Phase III data (July 2016 – Feb 2020)

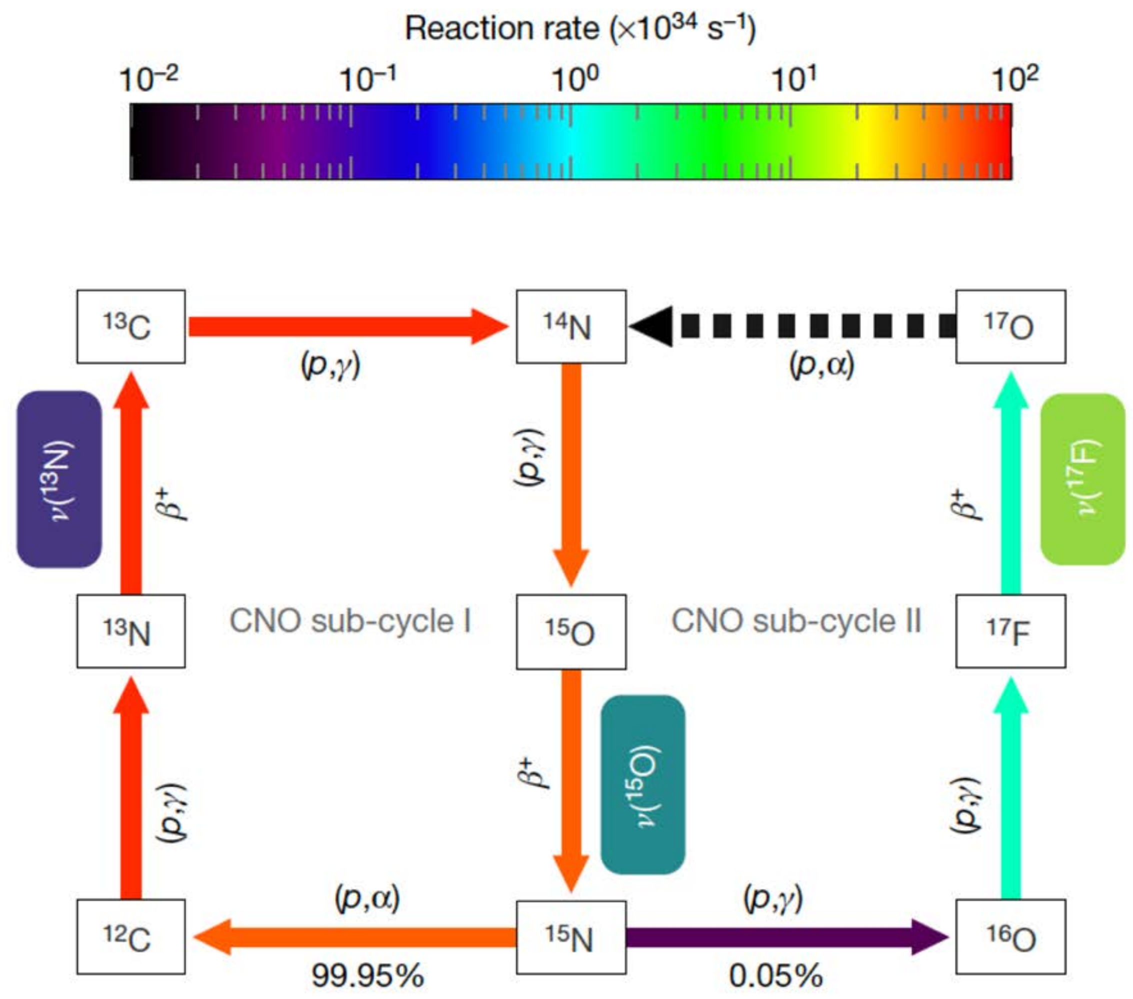
- More precise measurements are needed for solving the solar metallicity puzzle

- Borexino will stop data taking in 2021:
  more precise measurement is very hard but not fully excluded


Solar
Neutrinos
"For 35 years people said to me: `John, we just don't understand the Sun well enough to be making claims about the fundamental nature of neutrinos, so we shouldn't waste time with all these solar neutrino experiments.'
Then the SNO results came out.
And the next day people said to me, `Well, John, we obviously understand the Sun perfectly well! No need for any more of these solar neutrino experiments.'"
--- John Bahcall, 2003

Thank you!

Backup slides



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THREE-FOLD COINCIDENCE (TFC) TO TAG ^{11}C

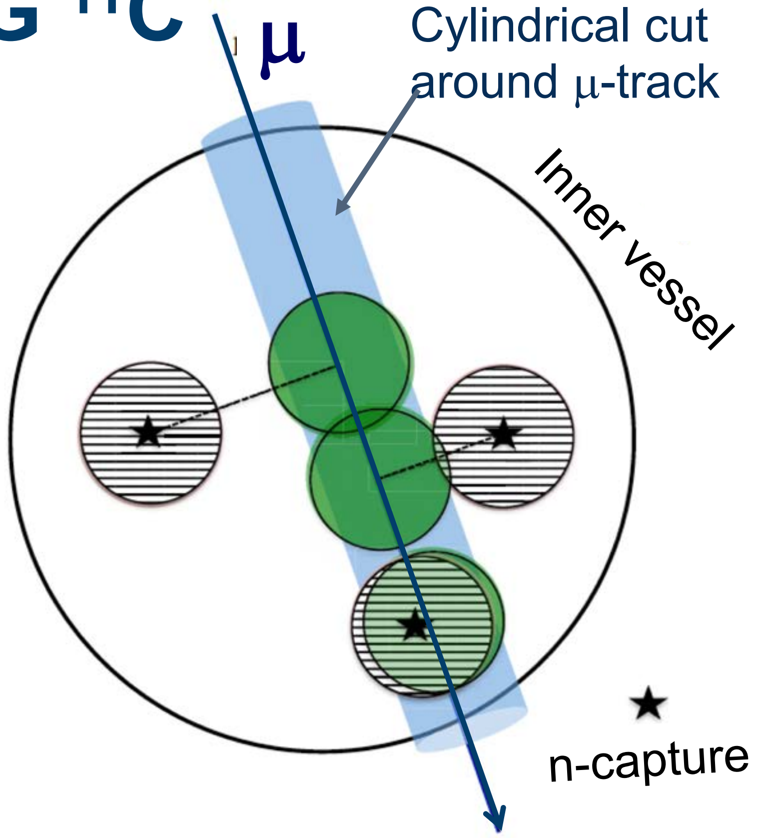
Critical for *pep* and CNO neutrinos

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

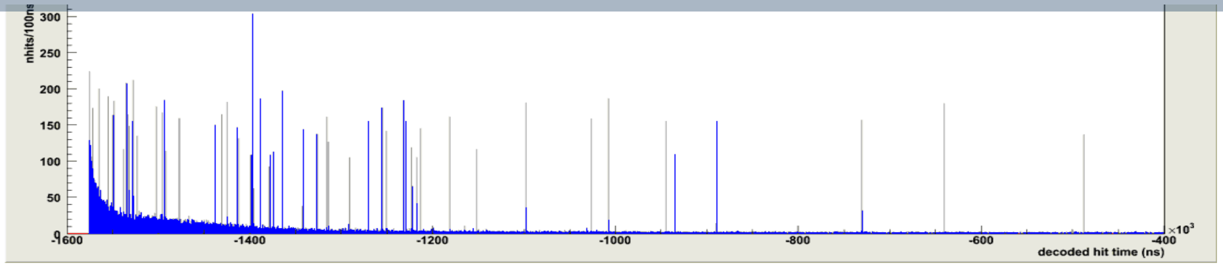
${}^{11}C \rightarrow {}^{11}B + e^{+} + \nu_e$
$\tau \sim 30$ min

$n + p \rightarrow d + \gamma$ (2.2 MeV)
$\tau \sim 260\ \mu s$

Muon detection ε = 99.992%:
- Outer Detector triggers
- Cluster of hits in Outer Detector data
- Pulse-shape of Inner Detector data



Neutron detection: after each ID μ, 1.6 ms gate is opened to detect neutrons: example with several tens of neutrons.

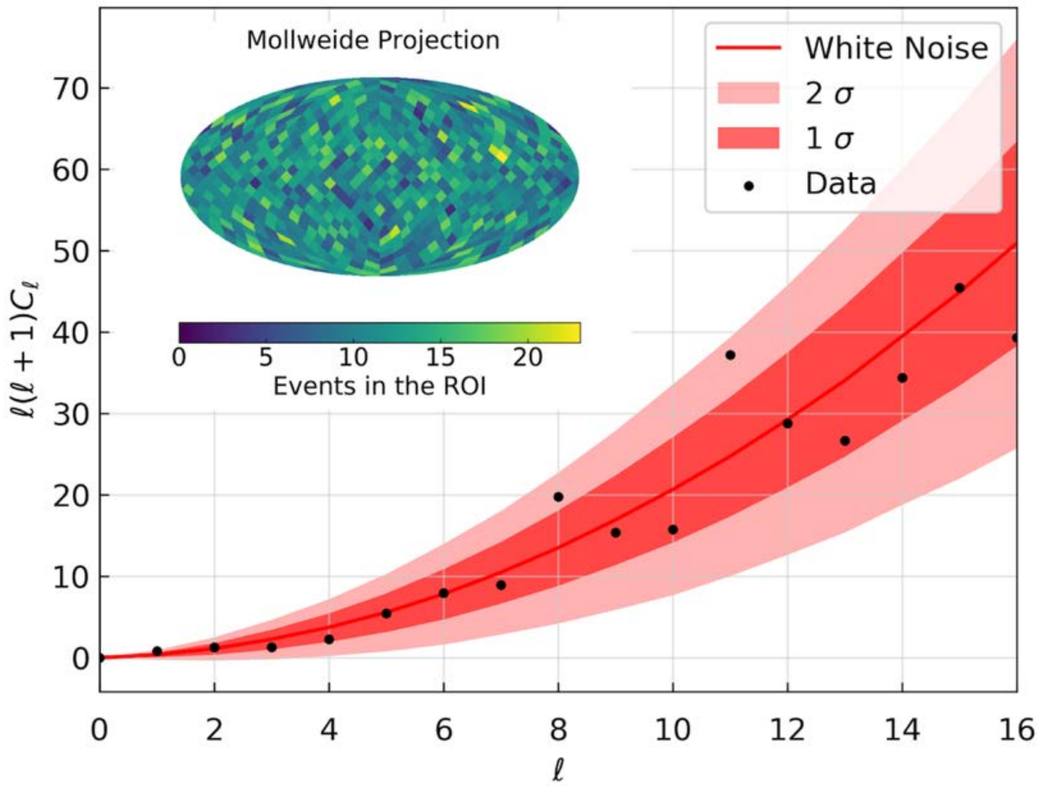


Likelihood that a certain event is ^{11}C uses in input time and space correlations between subsequent muons and cosmogenic neutrons.

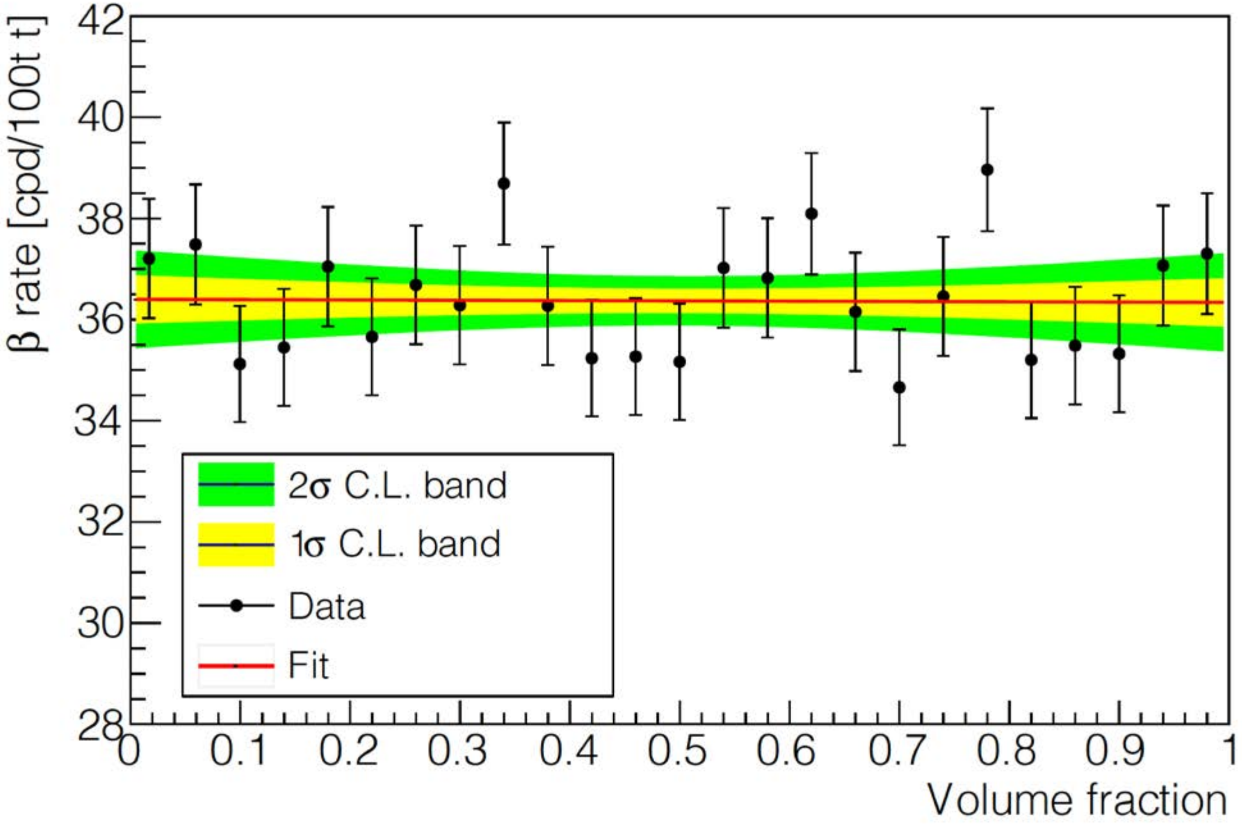
Exposure divided to 2 categories:
TFC-tagged (36% of exposure, 92% of ^{11}C)
TFC-subtracted (64% of exposure, 8% of ^{11}C)

210-BISMUTH HOMOGENEITY IN THE FIDUCIAL VOLUME

Angular homogeneity ±0.59 cpd/100 t



Radial homogeneity ±0.52 cpd/100 t



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SYSTEMATIC ERROR

On ^{210}Bi upper limit

$R\,(\mathrm{Po_{min}})$	σ_{fit}	σ_{mass}	σ_{bin}	$\sigma^{hom.}_{angular}$	$\sigma^{hom.}_{radial}$	σ^{leak}_{β}	σ_{tot}
11.5	0.88	0.36	0.31	0.59	0.52	0.30	1.30

- σ_{fit}: paraboloidal/spline fit uncertainty
- σ_{mass}: LPoF mass uncertainty
- σ_{bin}: Uncertainty due to binning (used 1 or 2 months)
- $\sigma^{hom.}_{angular}$ and $\sigma^{hom.}_{radial}$: see previous slide
- $\sigma^{leak.}_{\beta}$: R_β uncertainty (β leakage)

On the fit CNO rate

- from the fiducial volume defiinition, lifetime, scintillator density - NEGLIGIBLE
- fit conditions (binning etc) with 2500 data fits – NEGLIGIBLE
- light yield stability, non-linearity of the energy scale and resolution based on the calibration data and using ^{210}Po and ^{11}C standard candles, shape on the ^{210}Bi energy spectrum $^{+0.6}_{-0.5}$ cpd/100 t