Lake Louise Winter Institute 2022
20-25 February, 2022

Borexino:
Recent results and outlook on the final data

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Physics at the interface: Energy, Intensity, and Cosmic frontiers
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Synopsis

- Solar fusion and solar neutrinos
- The Borexino detector
- Summary of Borexino legacy results
- Recent results:
  - CNO neutrinos
  - sub-MeV directionality
- The final say

Why solar neutrinos?

- Solar neutrinos: one of the success stories of 20th century physics
    - Direct messengers of the nuclear thermo-fusion machinery in its core
    - Probes of its chemical composition and thermal profile

- Vehicles for the discovery of lepton flavor conversion (‘neutrino oscillations’)
    - -> neutrino mass
    - Probe for more new physics

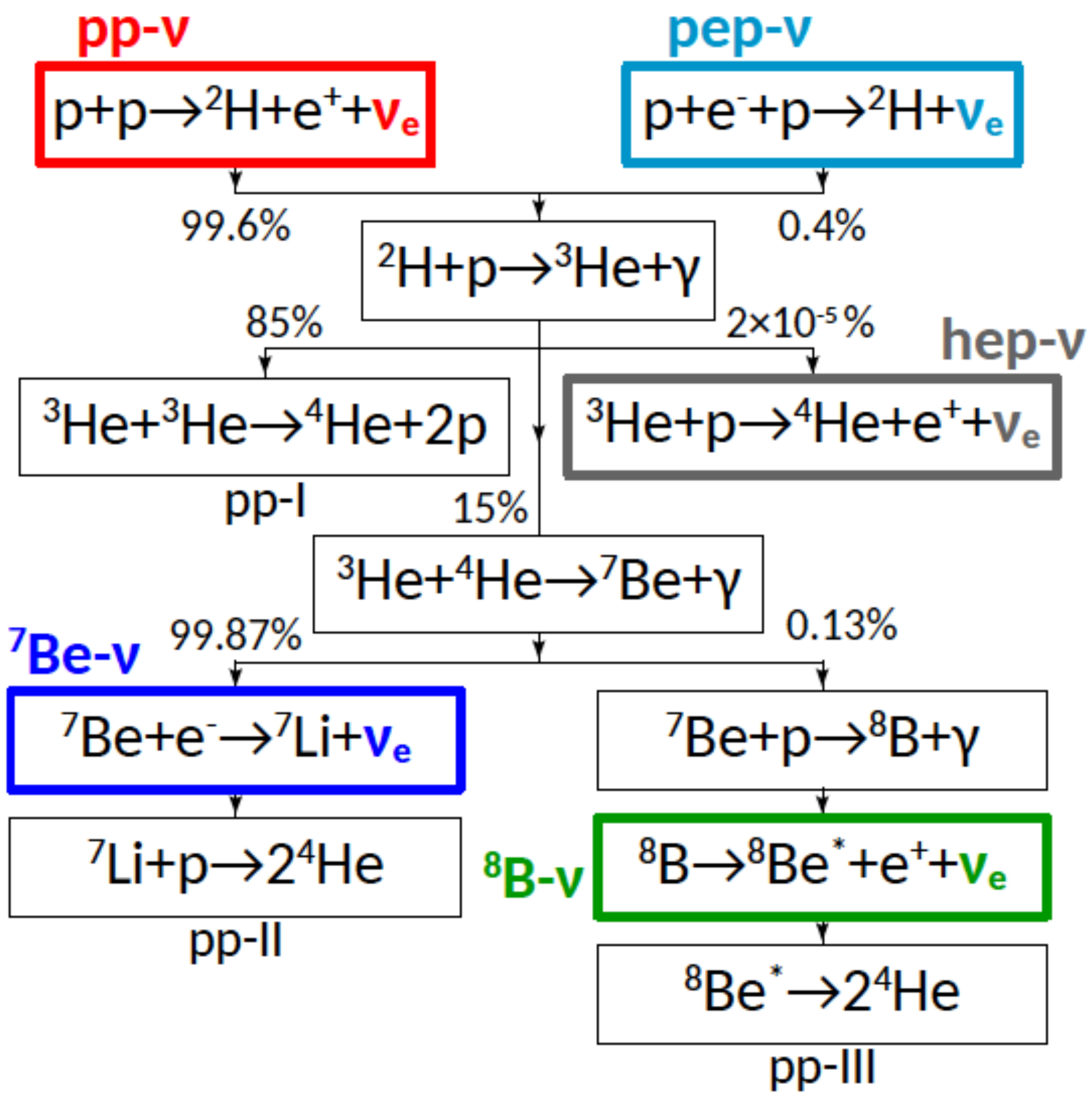
Solar neutrinos from two nuclear fusion processes

$$\boxed{4p \to {}^4He = 2e^+ + 2\nu_e + (24.7 + 2m_ec^2)\ \mathrm{MeV}}$$

(~2% of the total energy)

$$\langle E_\nu \rangle \sim 0.53\,\mathrm{MeV}$$

pp chain (~ 99%)



pp-ν

$p+p \to {}^2H+e^+ +\nu_e$

pep-ν

$p+e^- +p \to {}^2H+\nu_e$

99.6%

0.4%

${}^2H+p \to {}^3He+\gamma$

85%

2×10^{-5}%

hep-ν

${}^3He+{}^3He \to {}^4He+2p$

pp-I

${}^3He+p \to {}^4He+e^+ +\nu_e$

15%

${}^3He+{}^4He \to {}^7Be+\gamma$

^{7}Be-ν

99.87%

0.13%

${}^7Be+e^- \to {}^7Li+\nu_e$

${}^7Li+p \to 2{}^4He$

pp-II

${}^7Be+p \to {}^8B+\gamma$

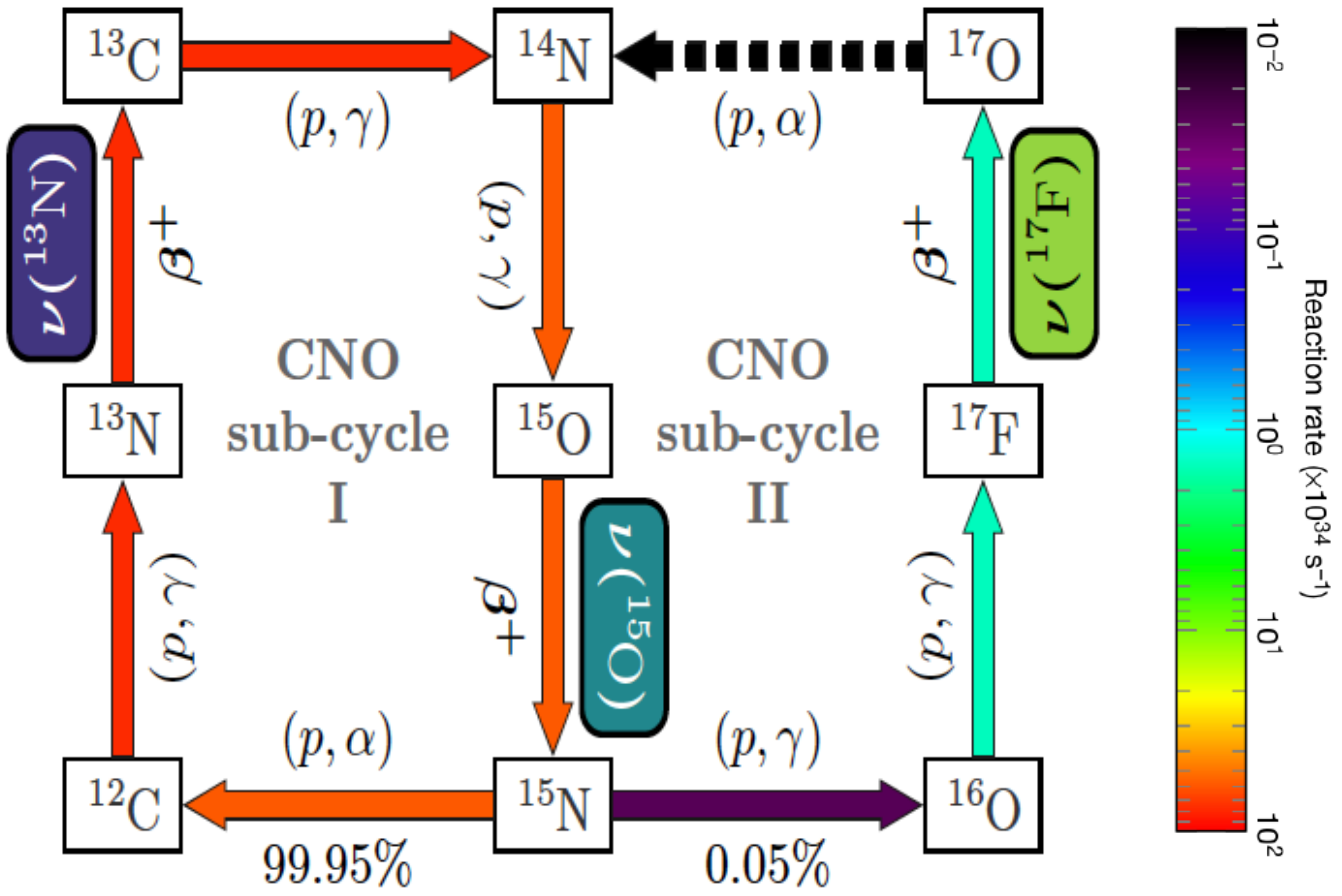
^{8}B-ν

${}^8B \to {}^8Be^* +e^+ +\nu_e$

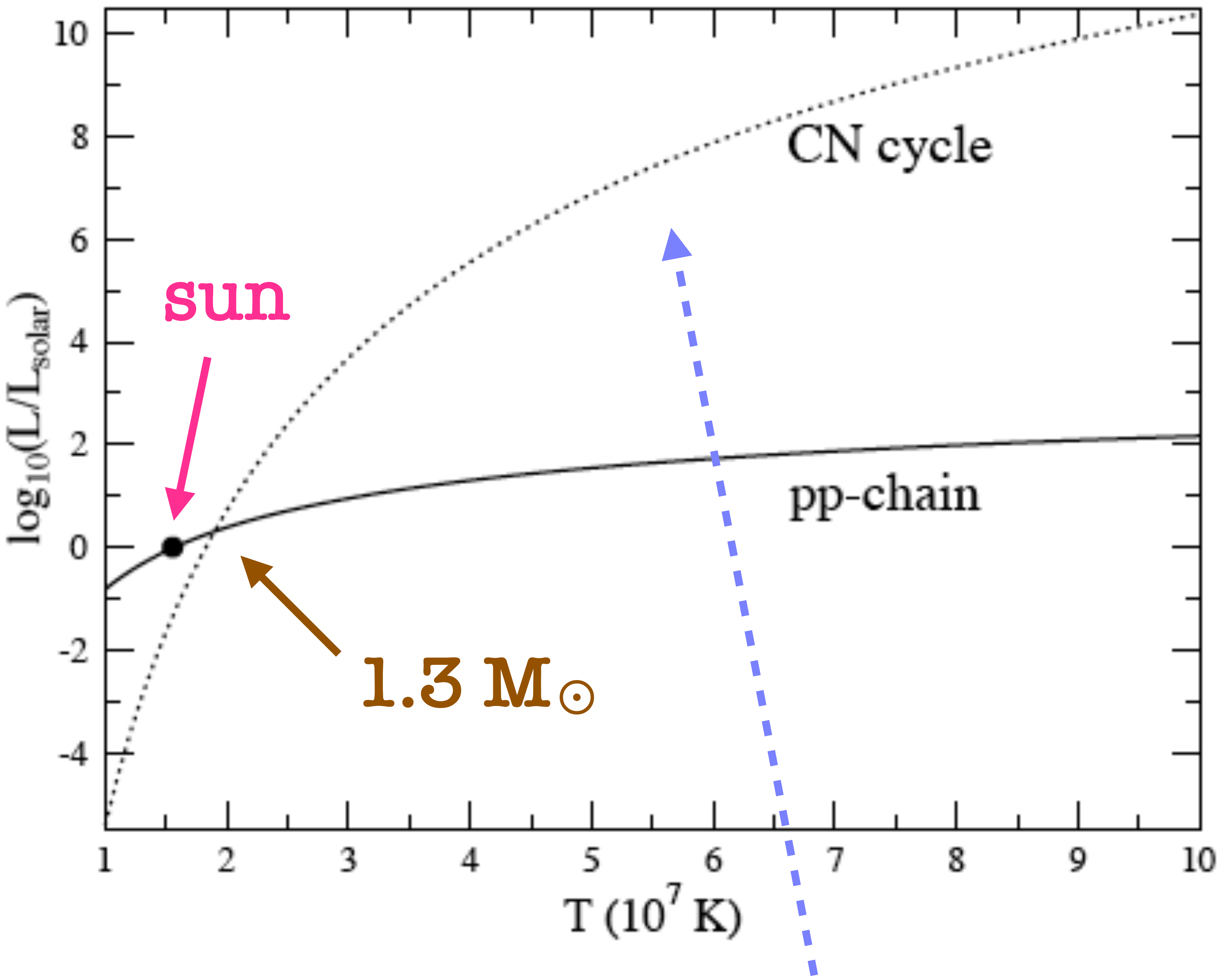
${}^8Be^* \to 2{}^4He$

pp-III

CNO cycle (~ 1%)



Meanwhile, in heavier stars …



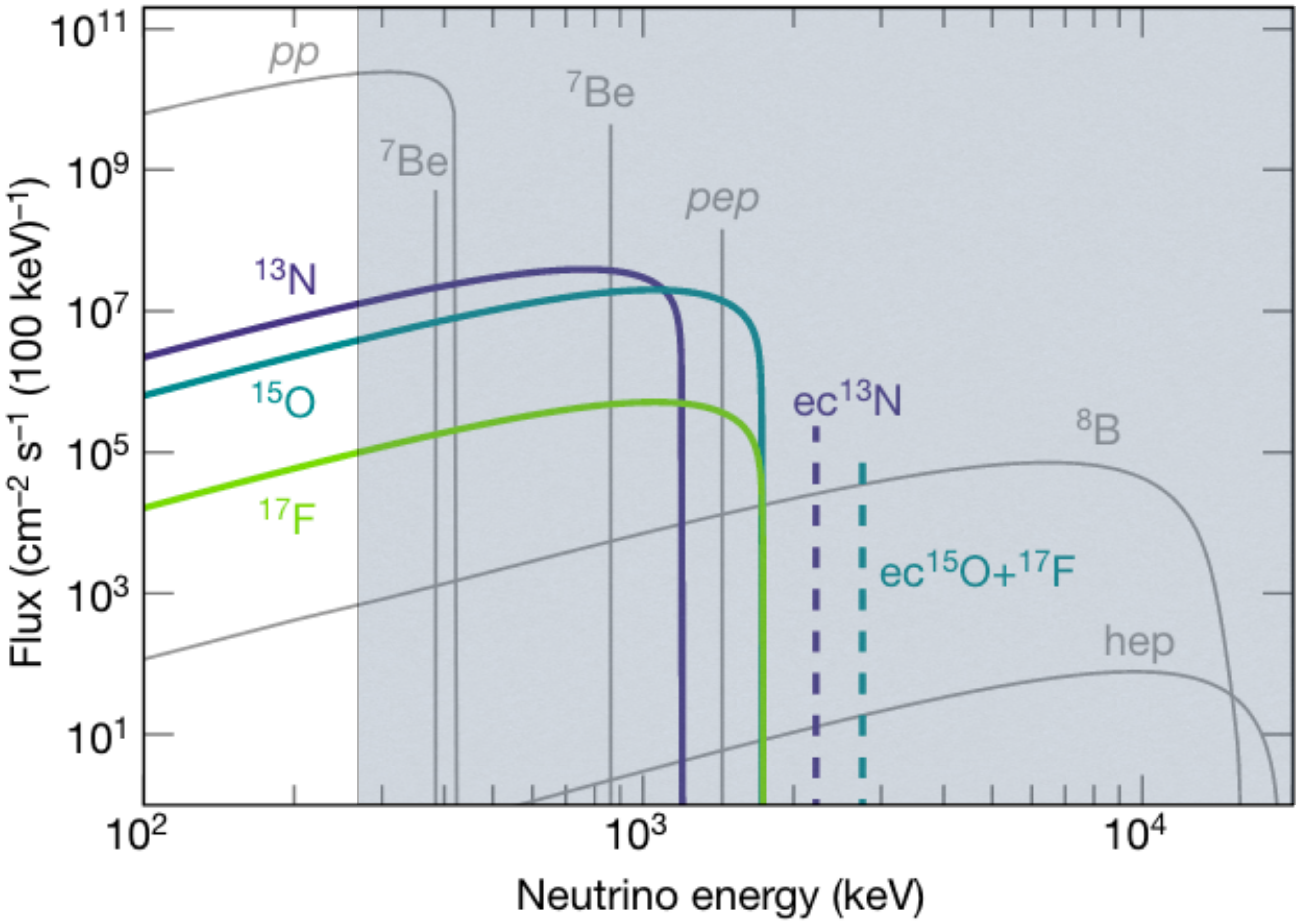
in heavier stars the gravitational pressure favors CNO fusion of protons

$$L_\odot = (3.846 \pm 0.015) \times 10^{53}\ \mathrm{erg/s}$$

$$\frac{L_\odot}{4\pi(A.U.)^2} = \sum_i a_i \phi_i^\nu$$

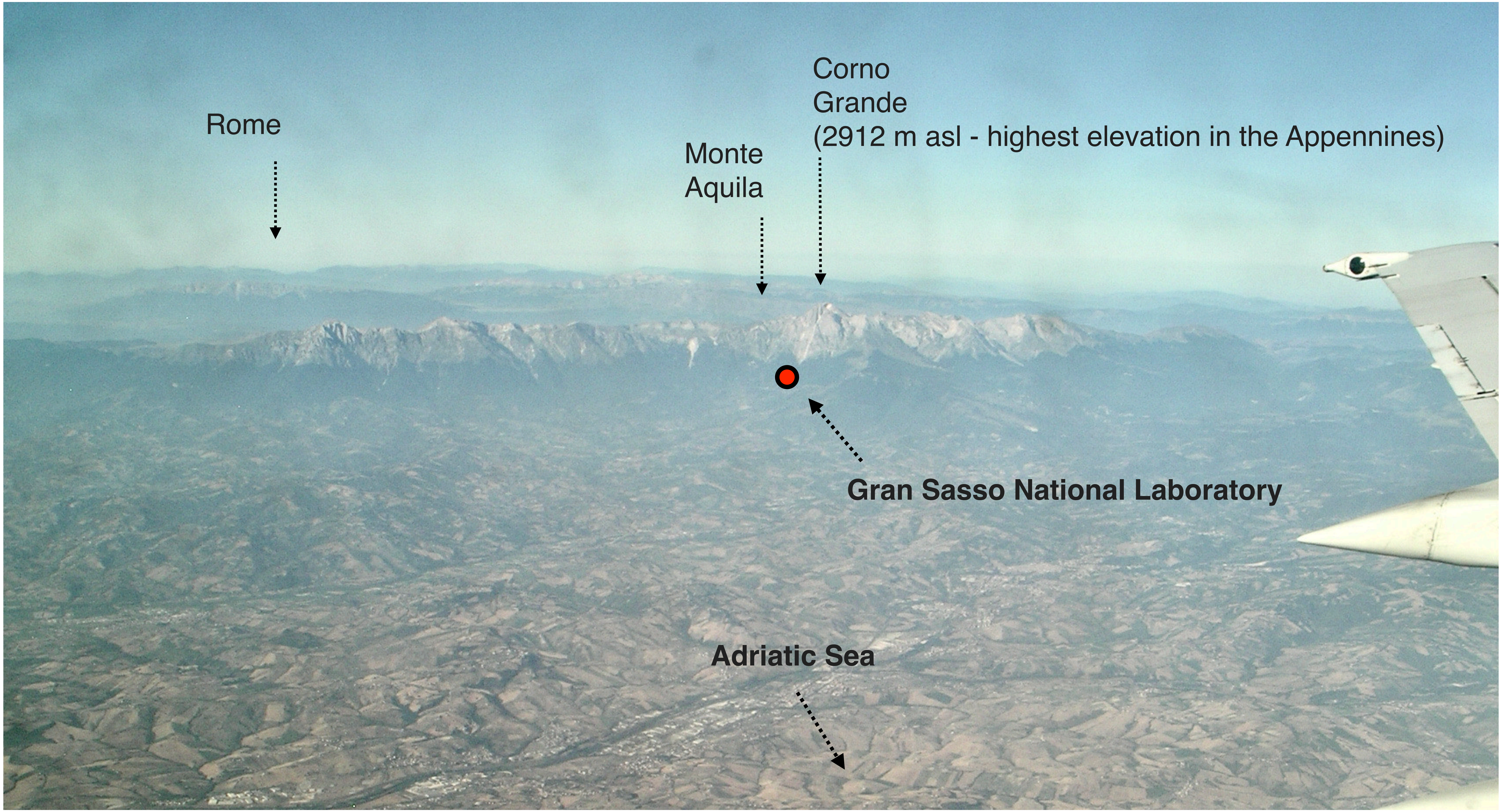
CN neutrinos considered the dominant energy producing process in many stars

Solar neutrino spectrum (Bahcall et al.)



- Exquisite understanding of fusion processes in the Sun
- Experimental precision in some cases better than theoretical uncertainties
- Solar metallicity (for elements with Z>2) not yet fully pinpointed
- Current models disagree:
  - High Z vs. Low Z
  - CNO neutrinos can provide the answer

The stage — the Gran Sasso massif, Italy



Rome

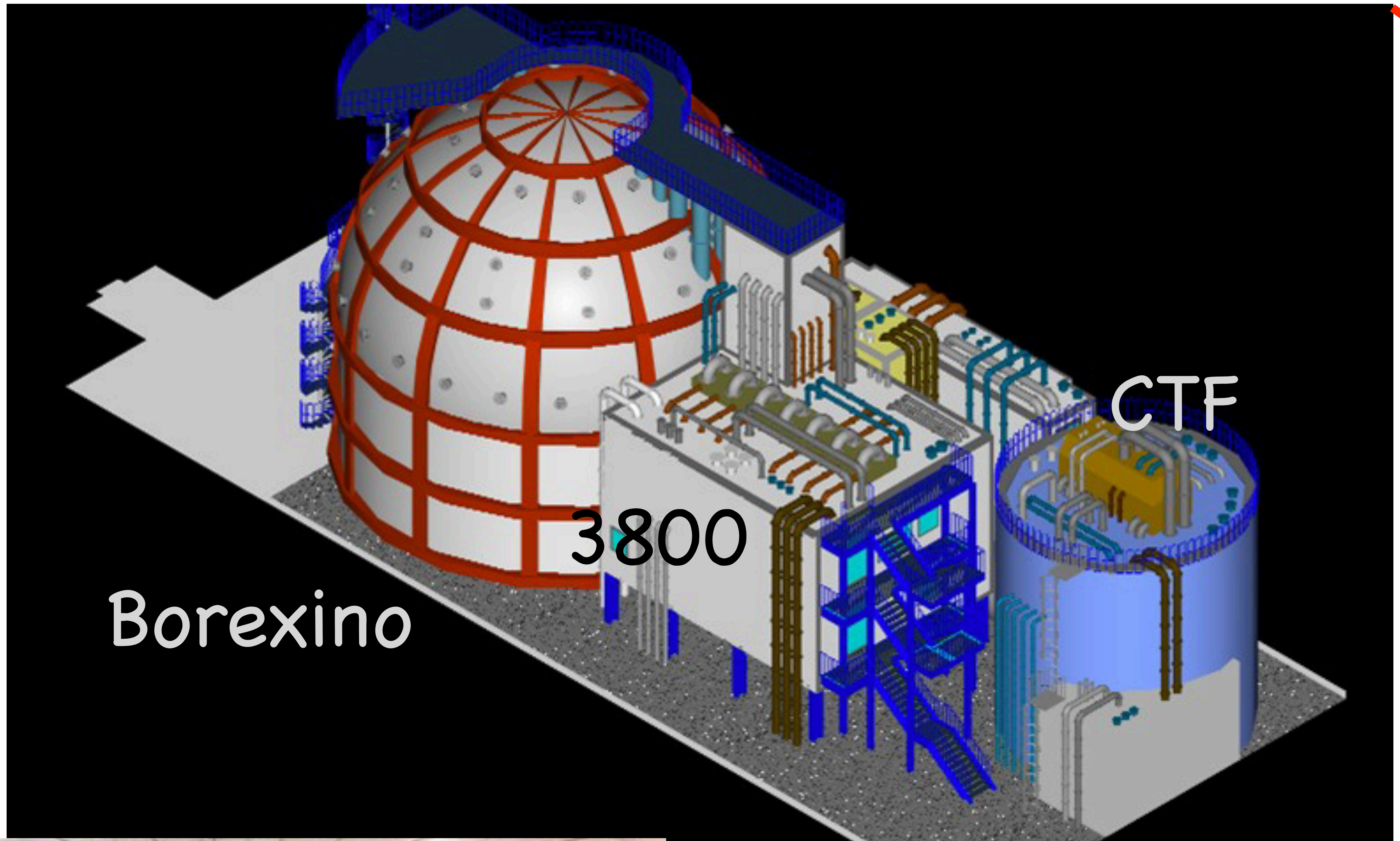
Monte Aquila

Corno Grande (2912 m asl - highest elevation in the Appennines)

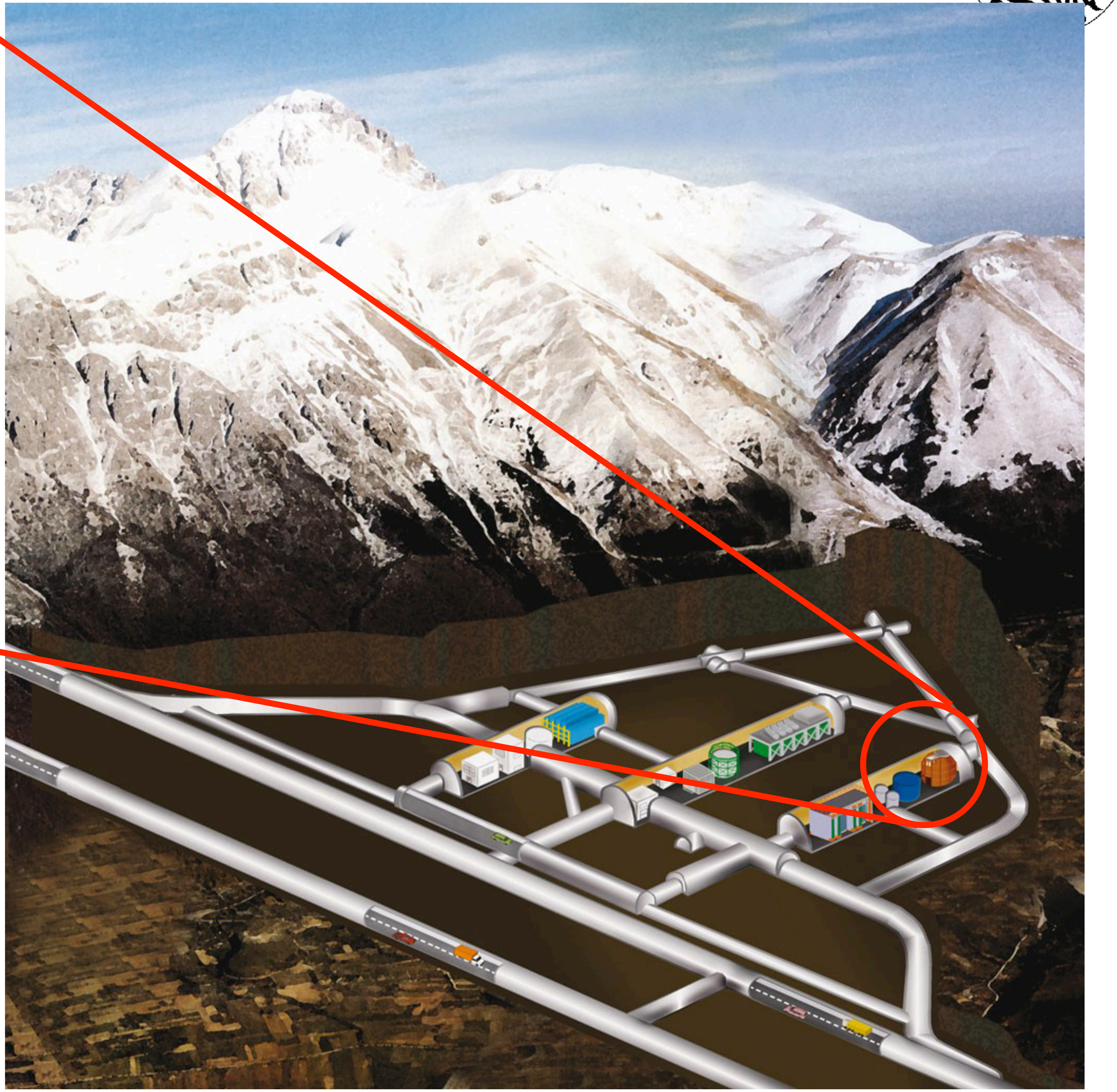
Gran Sasso National Laboratory

Adriatic Sea

Hall C @ LNGS



3800 m.w.e.
ca. 1 muons/m^2/h



the Borexino detector

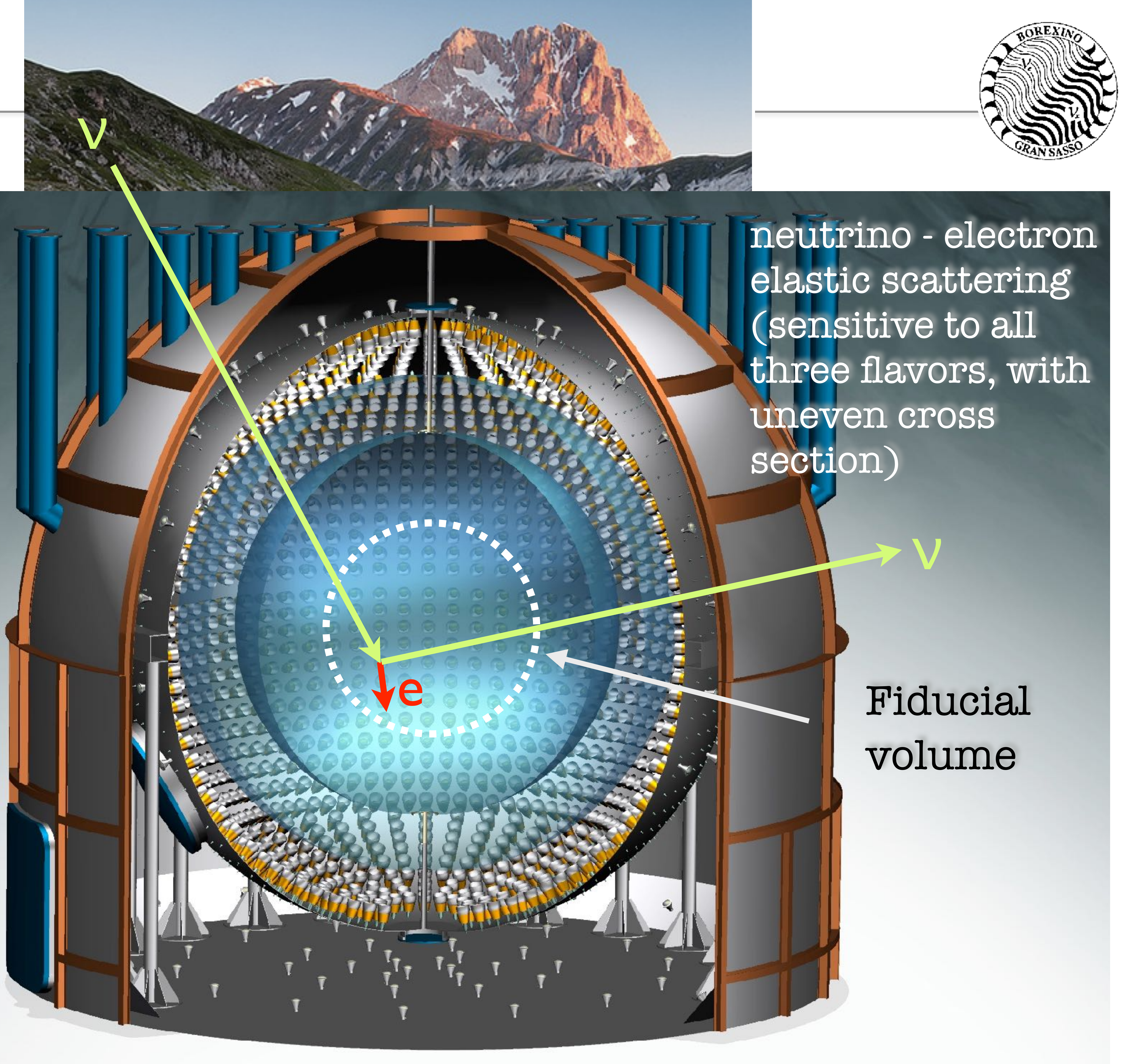
Scintillator:
280 t PC+PPO (1.5g/l) in a 125 μm thick
Inner nylon vessel (R=4.25m)

Buffer region:
PC+DMP quencher (5g/l) 4.25m<R<6.75m

Outer nylon vessel:
R=5.50m (^{222}Rn Barrier)

Stainless Steel Sphere:
R=6.75m,
2212 8" PMTs with light guides. 1350m^3

Water tank:
γ and n shield, μ water cherenkov detector
208 PMTs in water, 2100m^3

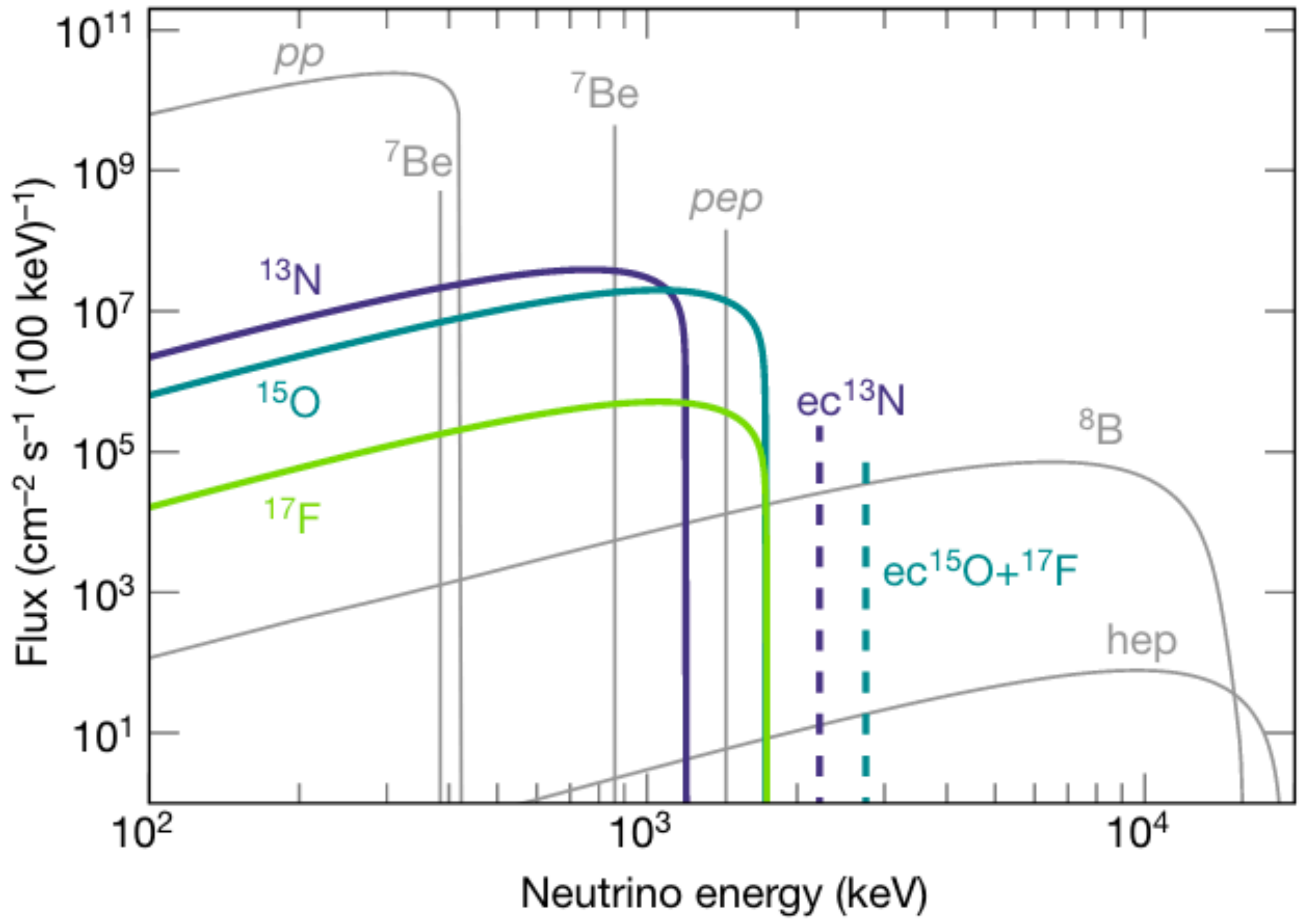


neutrino - electron elastic scattering (sensitive to all three flavors, with uneven cross section)

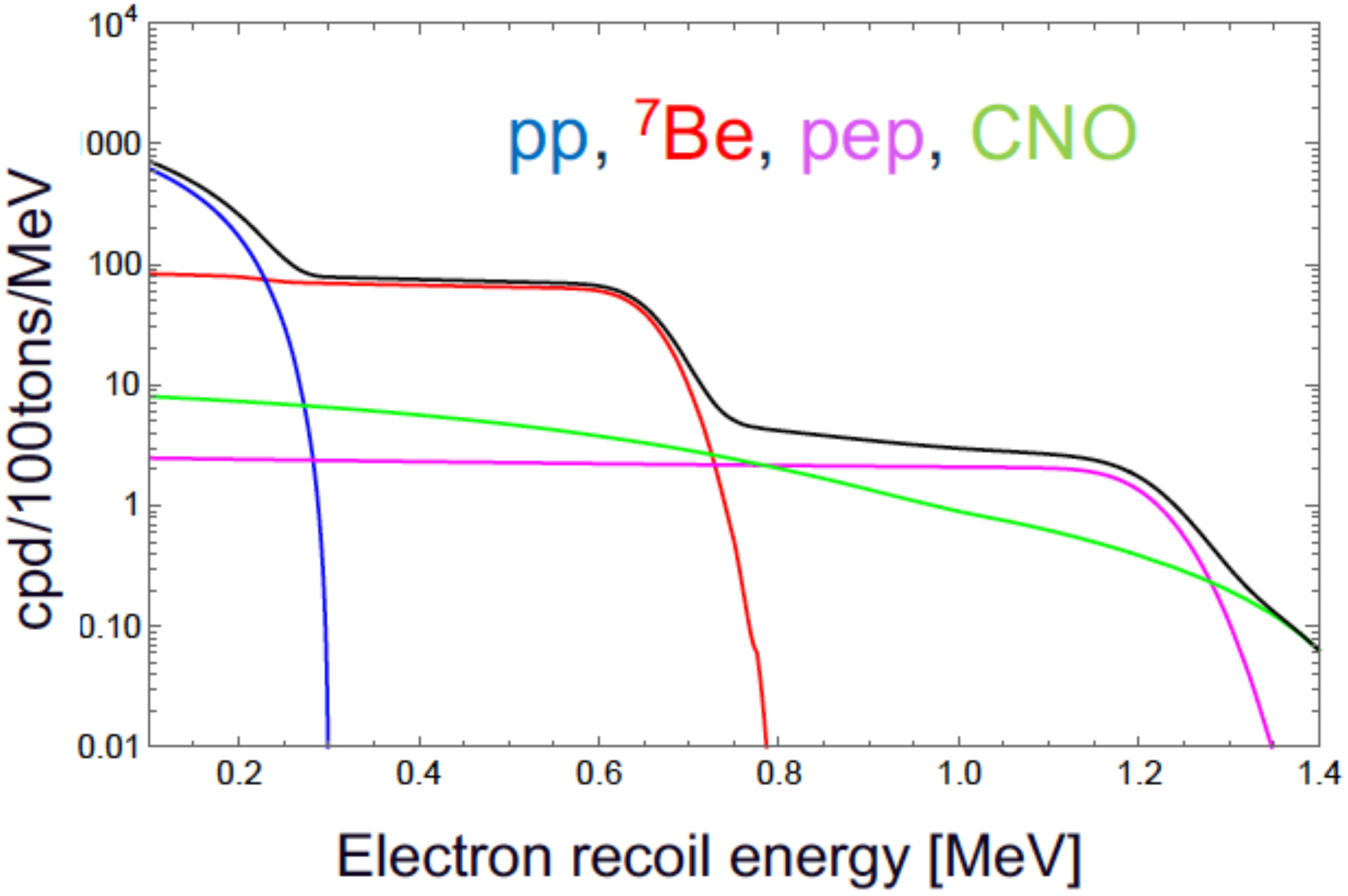
Fiducial volume

The Physics: solar neutrino spectrum

solar neutrino spectrum



solar neutrino-induced electron scattering spectrum in Borexino



Little directional information —> minimizing radioactivity is essential

The Borexino detector filled with liquid scintillator

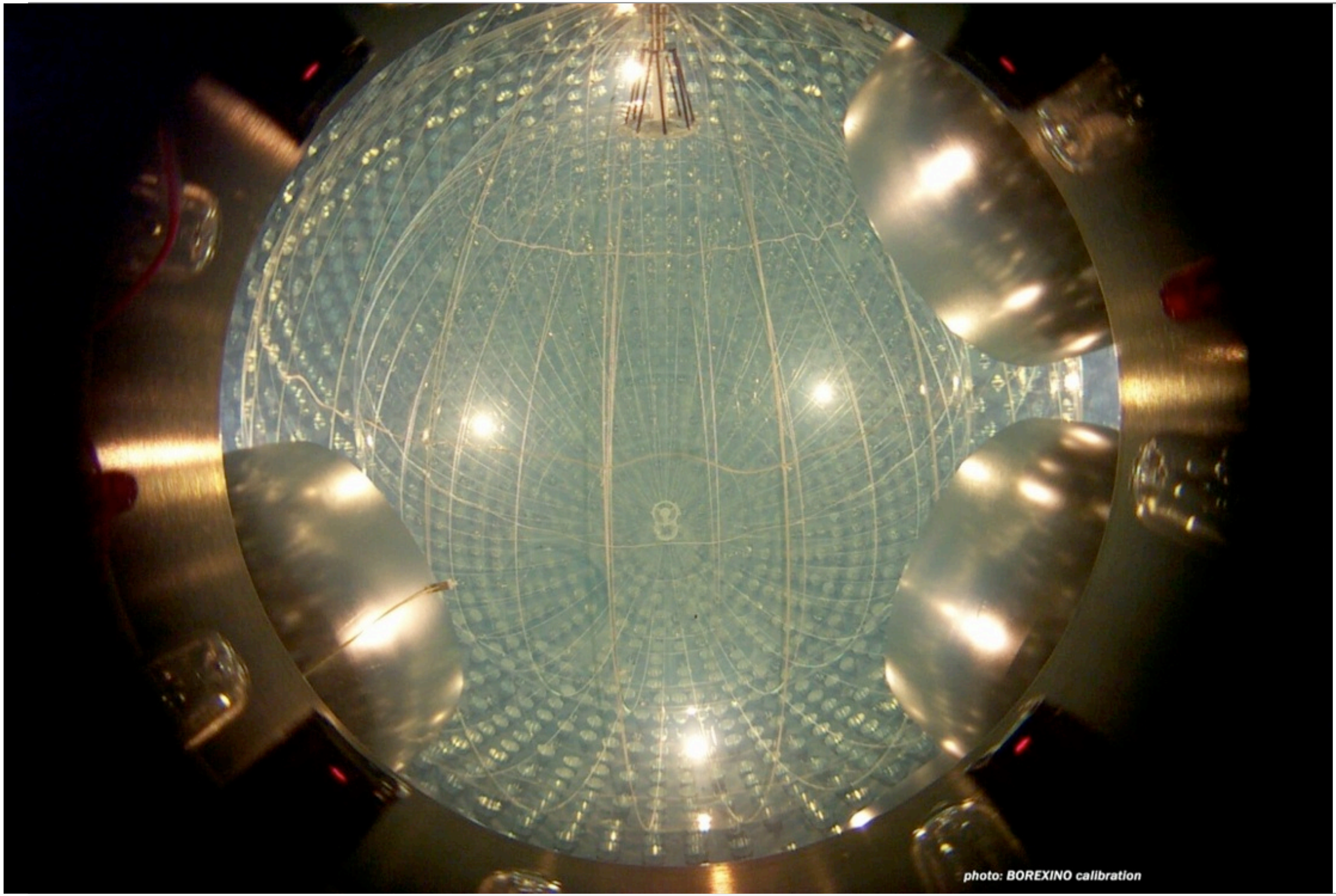


photo: BOREXINO calibration

detector filled on May 15, 2007

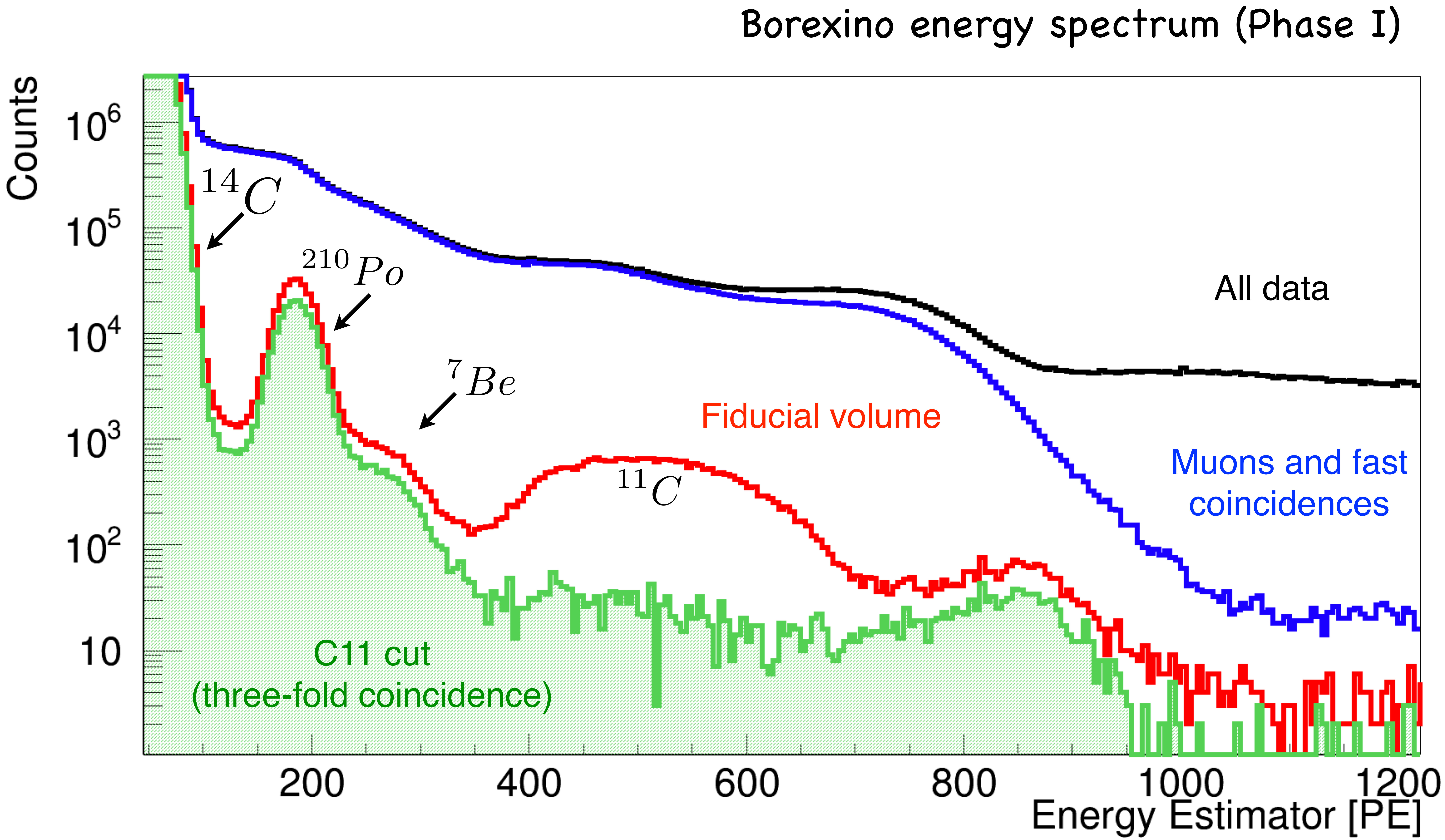
At 1 MeV:

$$\frac{\Delta E}{E} \sim 6\%$$

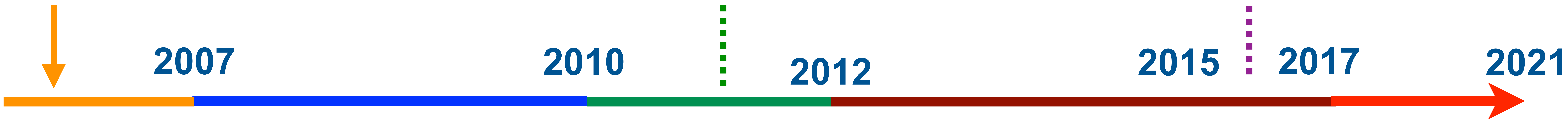
$$\sigma_{x,y,z} \sim 11\ cm$$

1238 active channels for the CNO neutrino measurement

Borexino data and basic selection cuts



Borexino timeline



Filling and initial purification

Purification II

Detector thermal insulation
Active temperature control
(detector and hall C)

Phase I (2007-2010)

- R(^{7}Be) – first
- D/N R(^{7}Be) – none
- R(pep) – first
- R(^{8}B) – first in LS
- R(CNO) – limit
- geo-neutrinos
- μ flux, cosmogenics
- search for exotics

6 cycles LS water extraction purification

- ^{85}Kr: reduced by ~4.6
- ^{210}Bi: reduced by ~2.3
- Th and U negligible:
  - ^{238}U: < 9.4×10^{-20} g/g
  - ^{232}Th: < 5.7×10^{-19} g/g

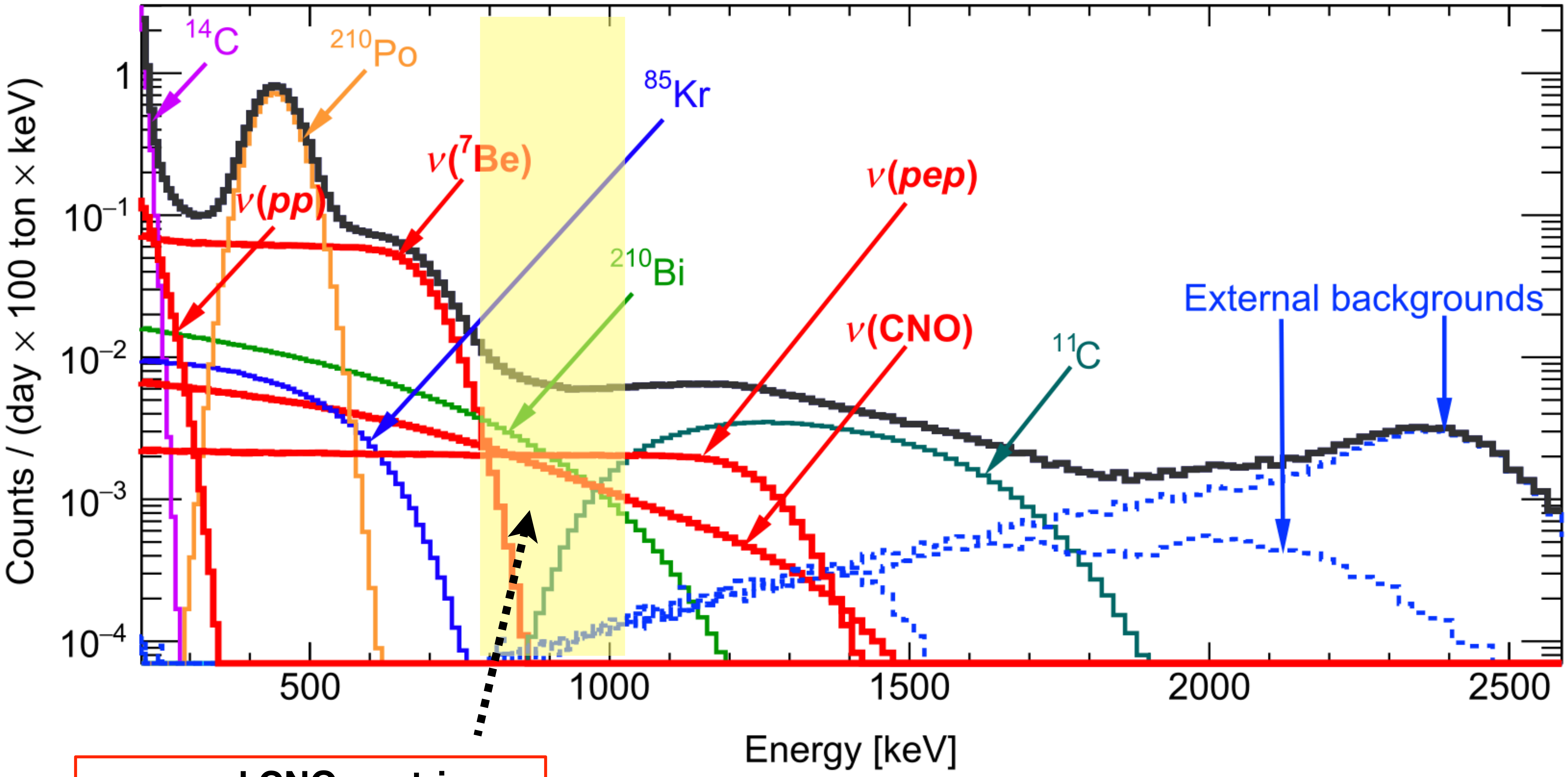
Phase II (2012-2016)

- R(pp) – first spectral
- seasonal R(^{7}Be)
- Comprehensive pp chain (pp, pep, ^{7}Be)
- Improved R(^{8}B)
- geo-neutrinos – 5σ
- ν magnetic moment

Phase III

- R(CNO) – first
- sub-MeV directional

Decomposing the spectrum



pep and CNO neutrinos most visible here

CNO, pep, ^{210}Bi highly correlated

Borexino Phase 2 results (2010-2016)

Nature 562, 505 (2018)
PRD 101, 062001 (2020)

252 ton-yr exposure	**Phase II BX results (cpd/100t)**	**Bx flux ($cm^{-2}\,s^{-1}$)**	**SSM (HZ/LZ) ($cm^{-2}\,s^{-1}$)**
pp	$134 \pm 10^{+6}_{-10}$ **10%**	$(6.1 \pm 0.05^{+0.3}_{-0.5}) \times 10^{10}$	$5.98(1 \pm 0.006) \times 10^{10}$ $6.03(1 \pm 0.005) \times 10^{10}$
^{7}Be	$48.3 \pm 1.1^{+0.4}_{-0.7}$ **2.7%**	$(4.99 \pm 0.11^{+0.06}_{-0.08}) \times 10^{9}$	$4.93(1 \pm 0.06) \times 10^{9}$ $4.50(1 \pm 0.06) \times 10^{9}$
pep	(HZ) $2.43 \pm 0.36^{+0.15}_{-0.22}$ (LZ) $2.65 \pm 0.36^{+0.15}_{-0.24}$ **5σ**	$(1.27 \pm 0.19^{+0.08}_{-0.12}) \times 10^{8}$ $(1.39 \pm 0.19^{+0.08}_{-0.13}) \times 10^{8}$	$1.44(1 \pm 0.01) \times 10^{8}$ $1.46(1 \pm 0.01) \times 10^{8}$
^{8}B	$0.223^{+0.015}_{-0.016} \pm 0.06$	$(5.68^{+0.39}_{-0.41} \pm 0.03) \times 10^{8}$	$5.46(1 \pm 0.12) \times 10^{6}$ $4.50(1 \pm 0.12) \times 10^{6}$
hep	<0.002 (90% C.L.)	$<2.2 \times 10^{5}$	$7.89(1 \pm 0.30) \times 10^{3}$ $8.25(1 \pm 0.30) \times 10^{3}$
CNO	<8.1 (95% C.L.)	$<7.9 \times 10^{8}$	$4.88(1 \pm 0.12) \times 10^{8}$ $3.51(1 \pm 0.12) \times 10^{8}$

solar metallicity controversy (HZ and LZ models differ by almost 30% for the CNO neutrino flux)

precision and reach beyond design goals of the experiment

The solar metallicity puzzle

- The solar metallicity is important:
  - Catalysts to CNO process
  - Affects plasma opacity, indirectly affecting the core T and modifying the density profile and evolution

- Discrepancy between solar properties predicted by HZ and LZ input values:
  - LZ favored by spectroscopy
  - HZ favored by helioseismology

pep and 210Bi constraints

pep

- pp/pep ratio (from nuclear physics)
- Solar luminosity constraint (0.4%)
- Oscillation parameters from global fit
- Relatively independent on CNO neutrinos

--> 1.4%

^{210}Bi

$$^{210}\mathrm{Pb} \xrightarrow[22.3\,\mathrm{years}]{\beta^-} {}^{210}\mathrm{Bi} \xrightarrow[5\,\mathrm{days}]{\beta^-} {}^{210}\mathrm{Po} \xrightarrow[138.4\,\mathrm{days}]{\alpha} {}^{206}\mathrm{Pb}$$

- Assume equilibrium in the A=210 decay sequence
- Affected by convective mixing of ^{210}Po from periphery -> requires thermal stabilization
- ^{210}Po minimum or plateau at the center

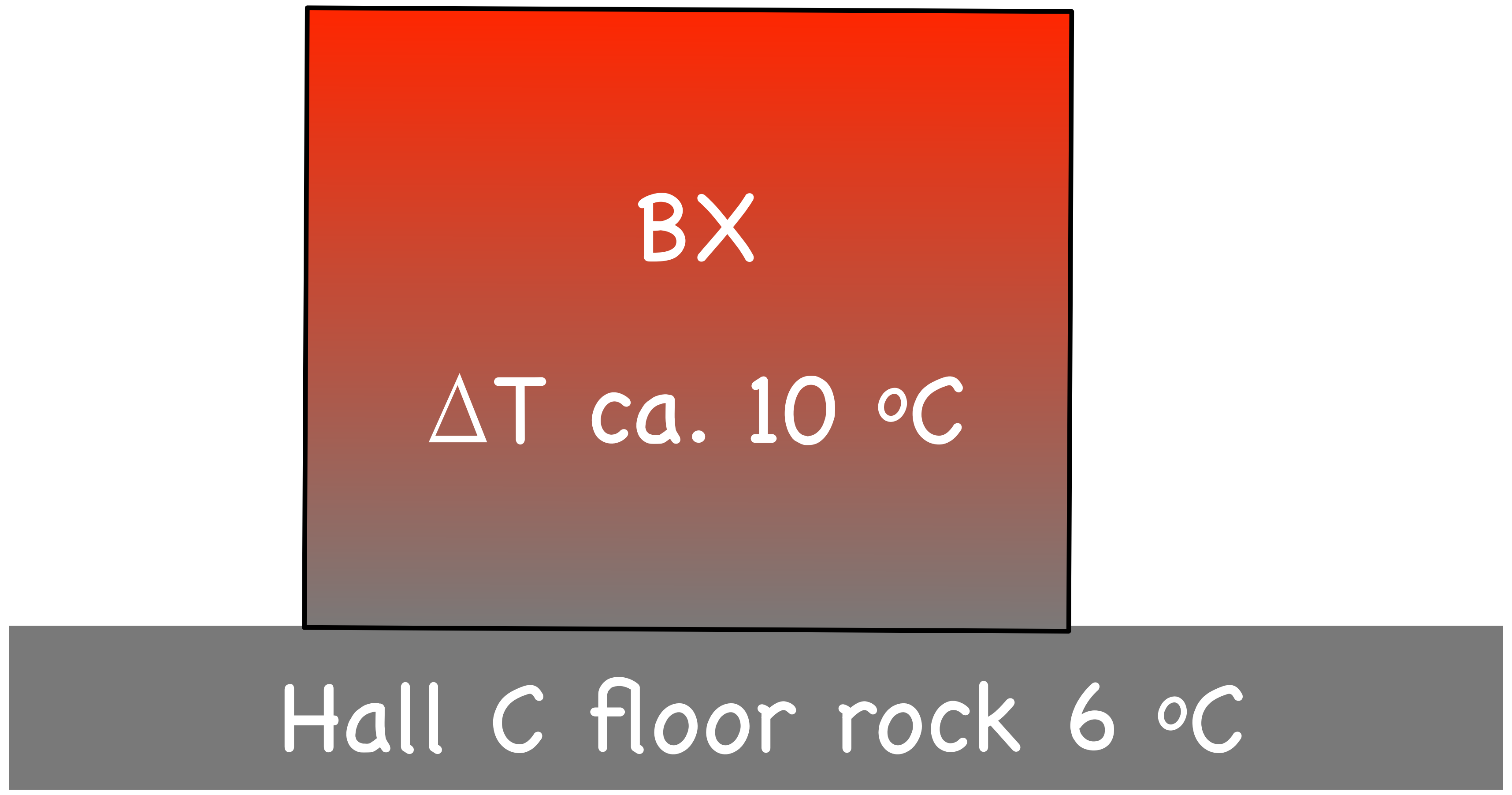
Thermal stabilization of the detector

2014 — Installation of T probes

2015-2016 — Thermal insulation of the water tank

2017 — active T control system atop water tank

2019-2020 — Hall C air T control system

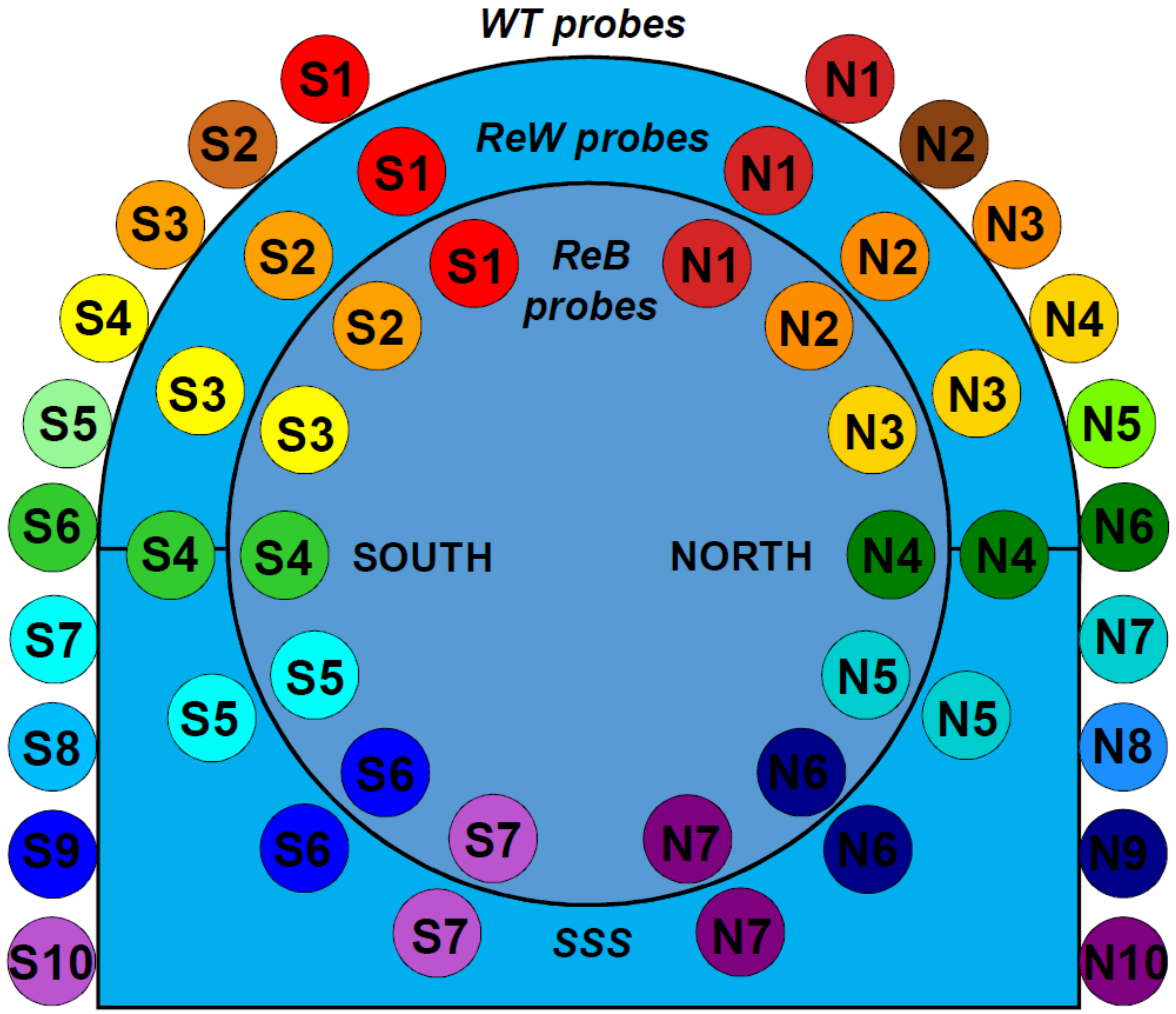


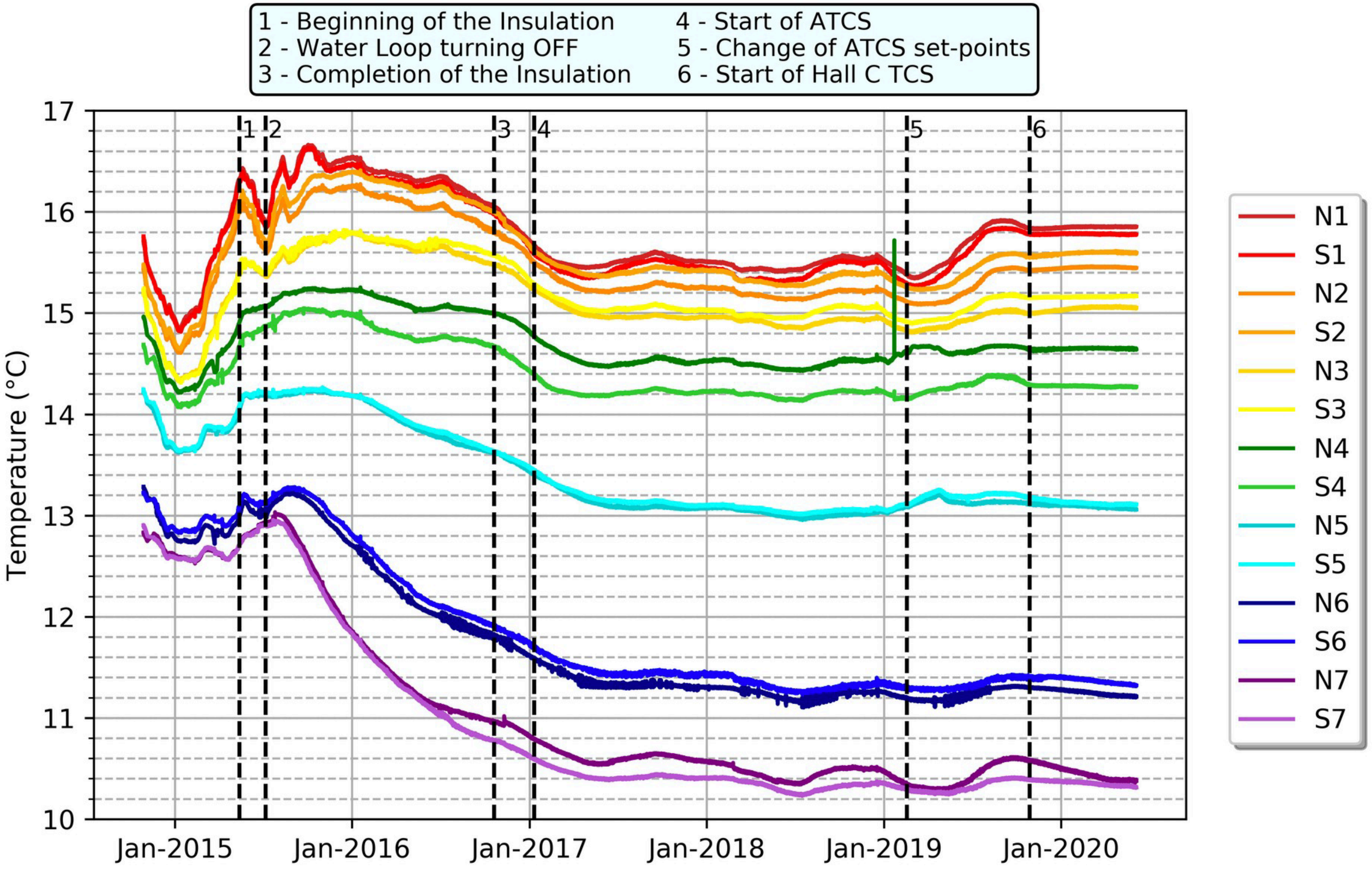
BX

ΔT ca. 10 °C

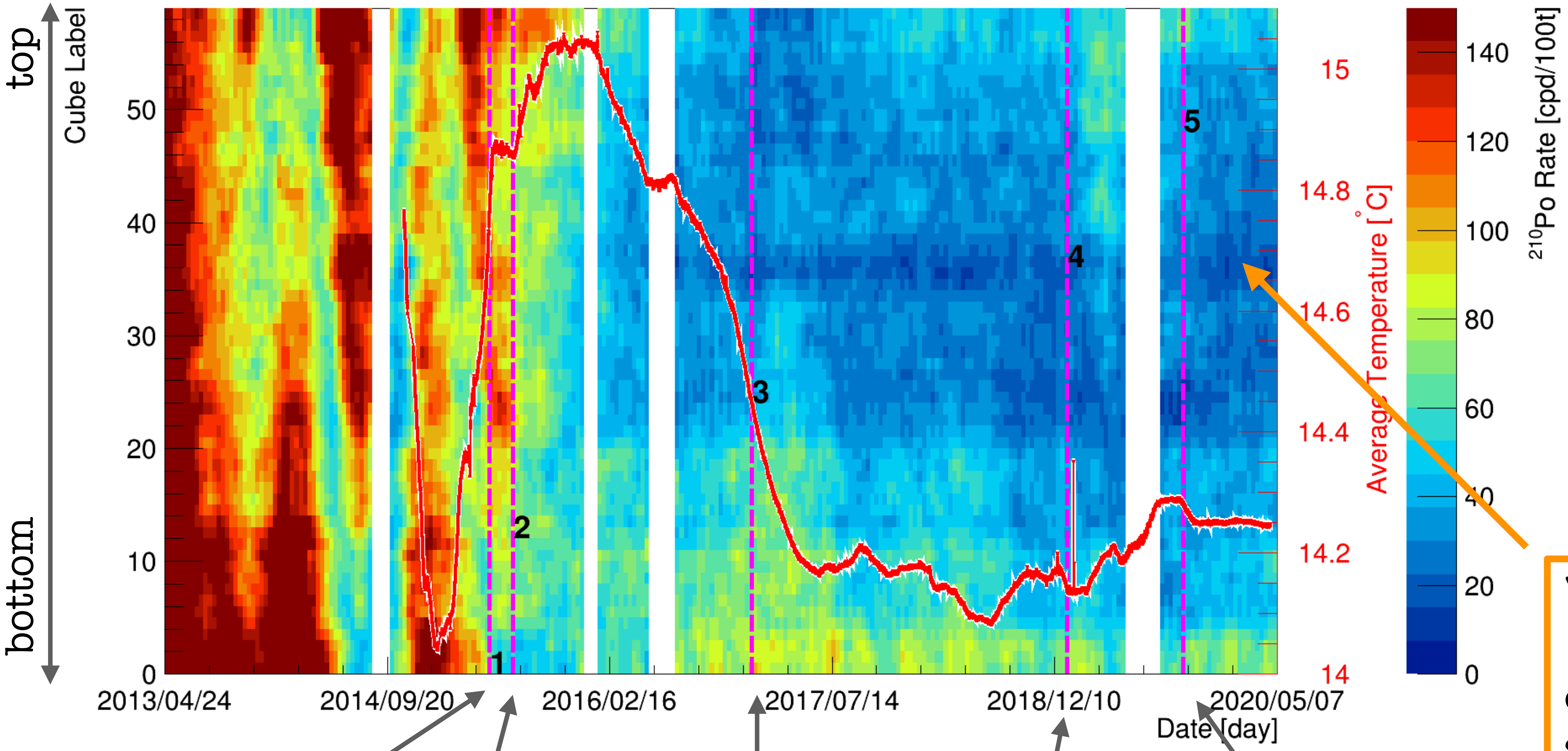
Hall C floor rock 6 °C

Temperature stabilization timeline





^{210}Po trend vs time



thermal insulation begins

water recirculation loop off

upper detector T control on

setpoint adjustment

T control of Hall C air

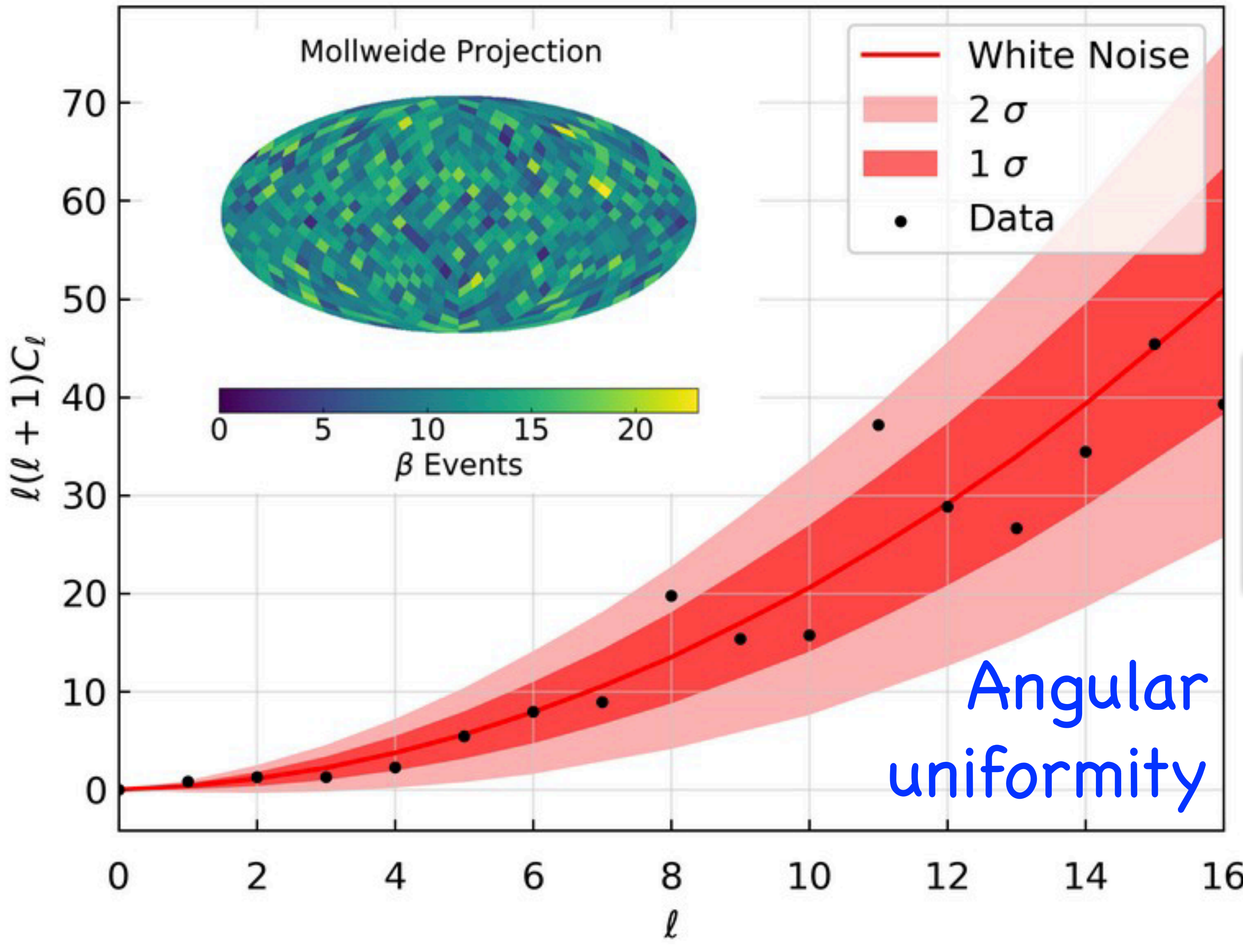
^{210}Po activity (in cpd/100t) within the inner 3-meter radius sphere of scintillator, binned in 3 tonne cubes

"Low Polonium Field region, 20 tonnes, just above the equator (observed layering successfully modeled with fluid simulations)

The Low Polonium Field analysis

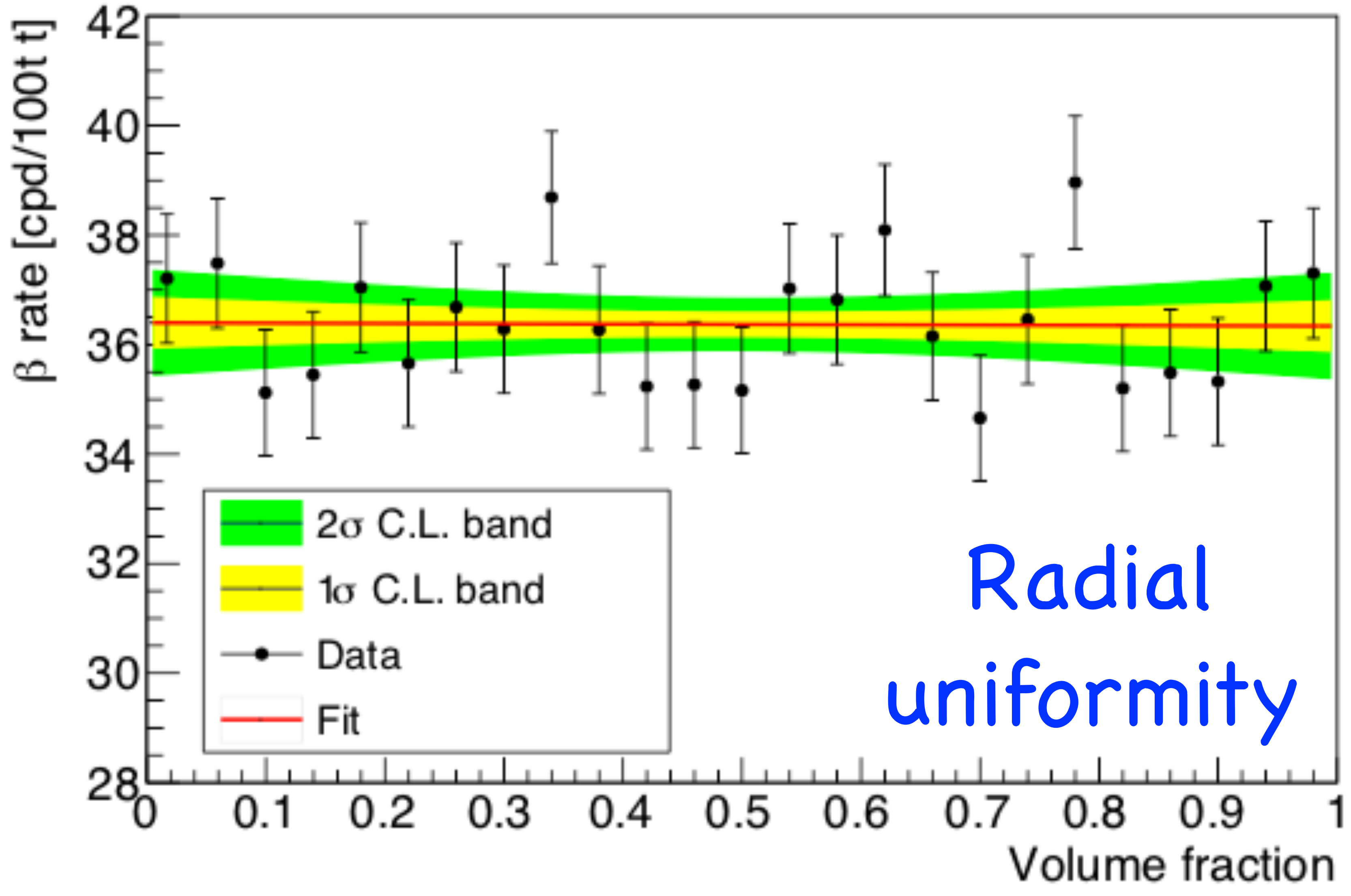
- The ^{210}Po minimum found with 20 tonnes of scintillator
- Extrapolation of the ^{210}Bi upper limit to 70 tonnes requires ^{210}Bi spatial uniformity and time stability
- This is done by selecting β-like events in an energy range where ^{210}Bi (pep, CNO) events dominate
  (i.e. in the 'valley' between ^{7}Be and ^{11}C)
  - radial and angular uniformity
  - time stability (no leaching from vessel)

R(^{210}Bi) ≤ 11.5±1.3 cpd/100t



Angular uniformity

σ^{sys}(ang)
0.59 cpd/100t

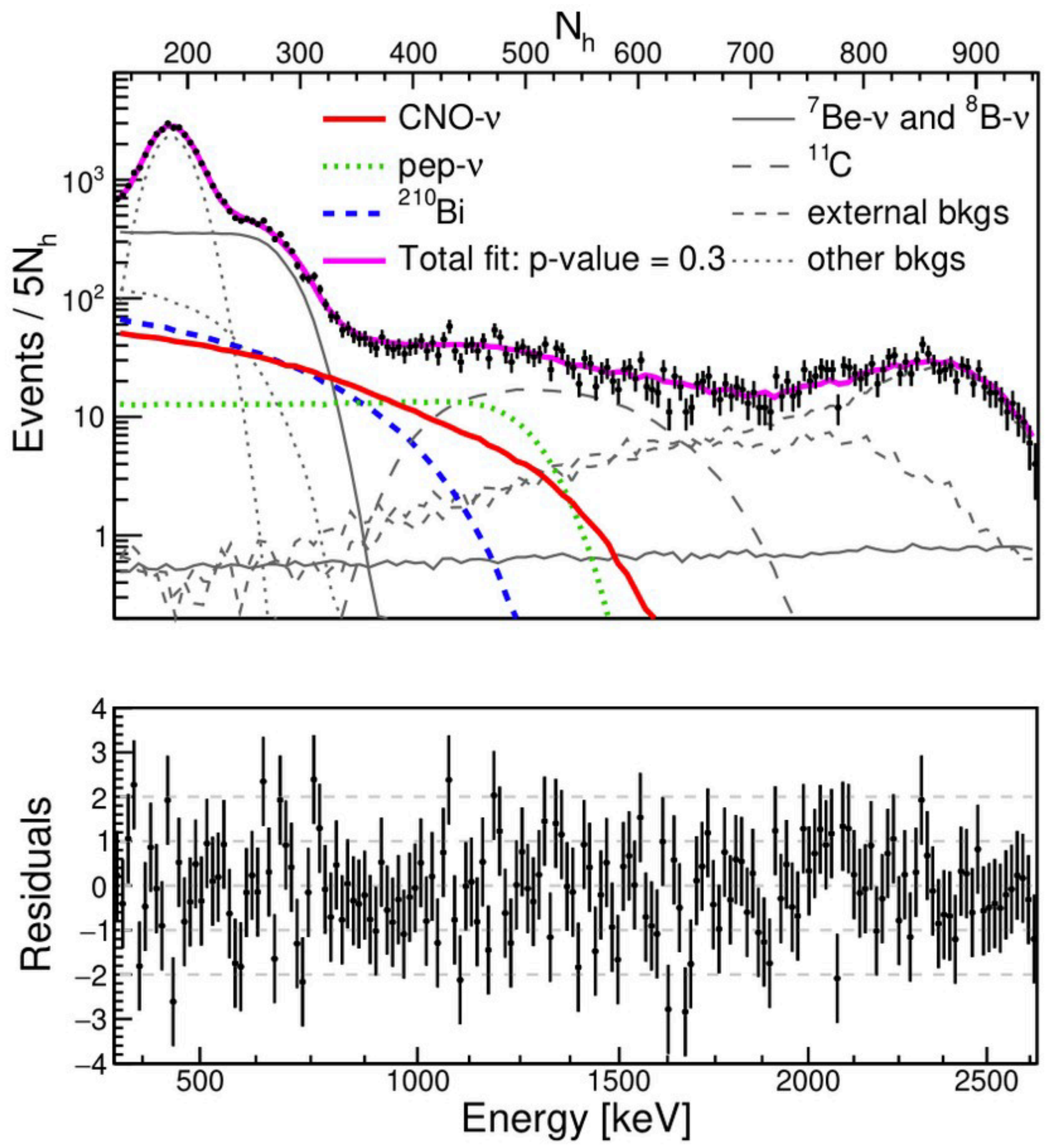


Radial uniformity

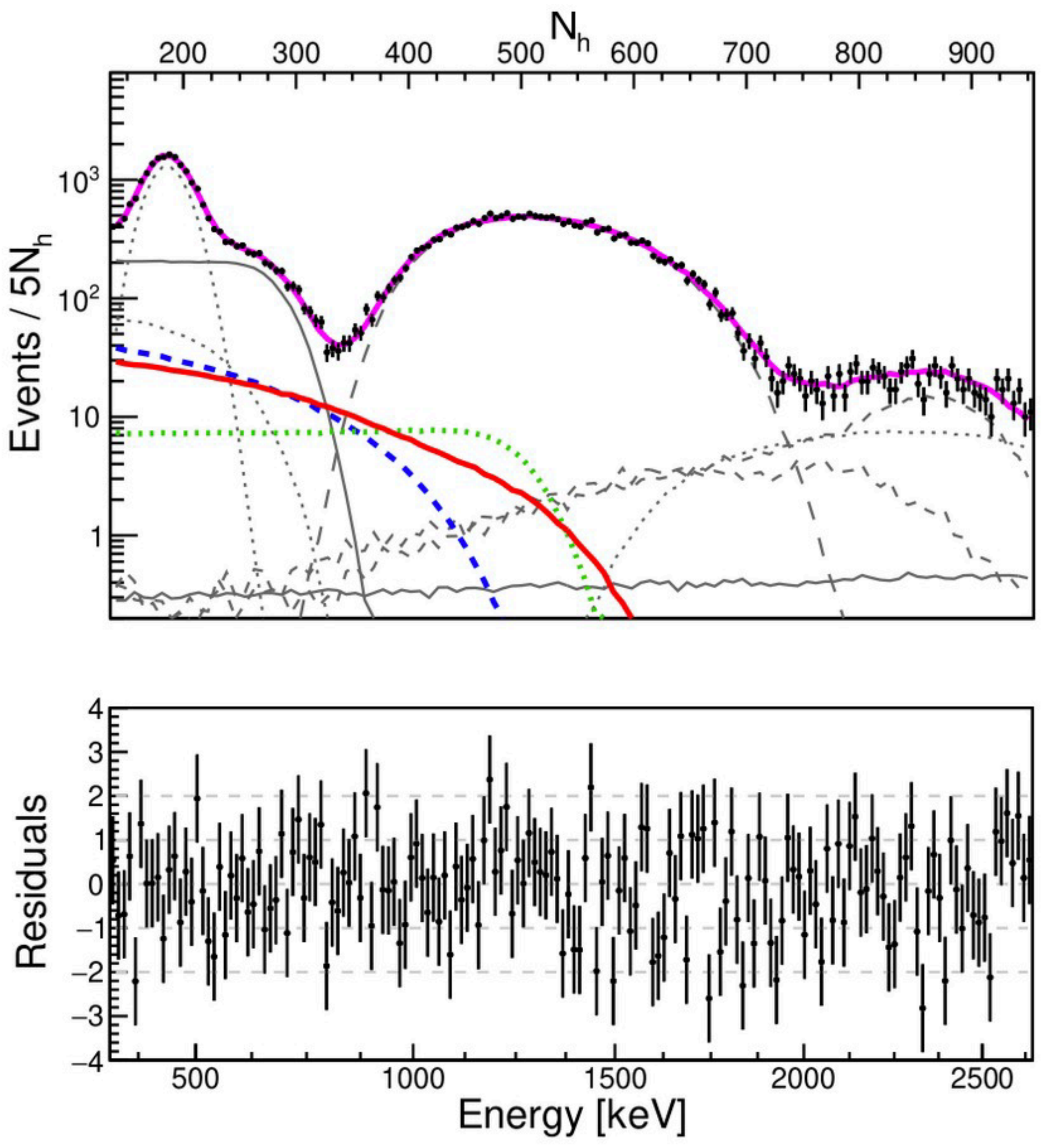
σ^{sys}(rad)
0.51 cpd/100t

Multi-variate fit

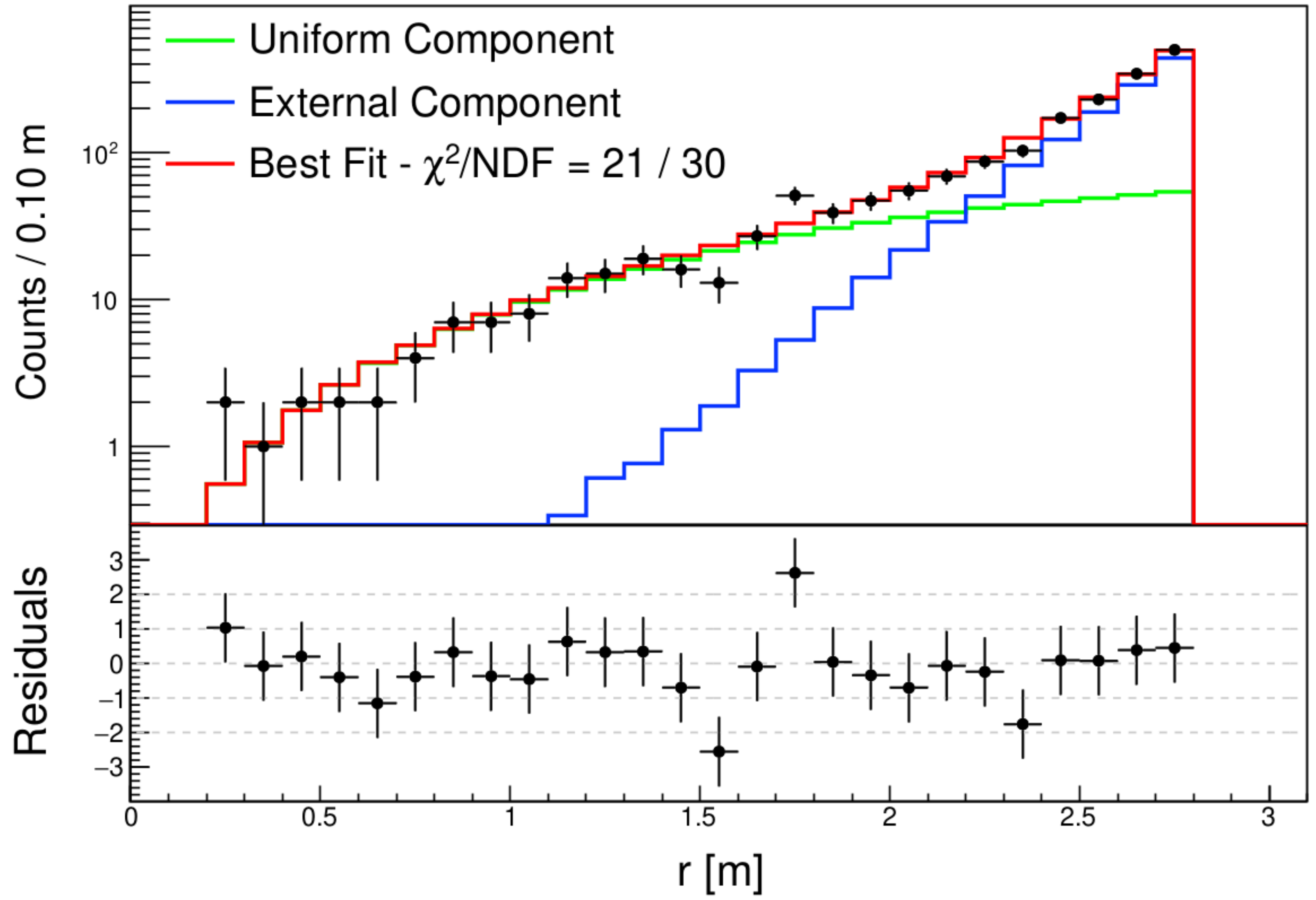
TFC-subtracted
(^{11}C-depleted)



TFC-tagged
(^{11}C-enriched)



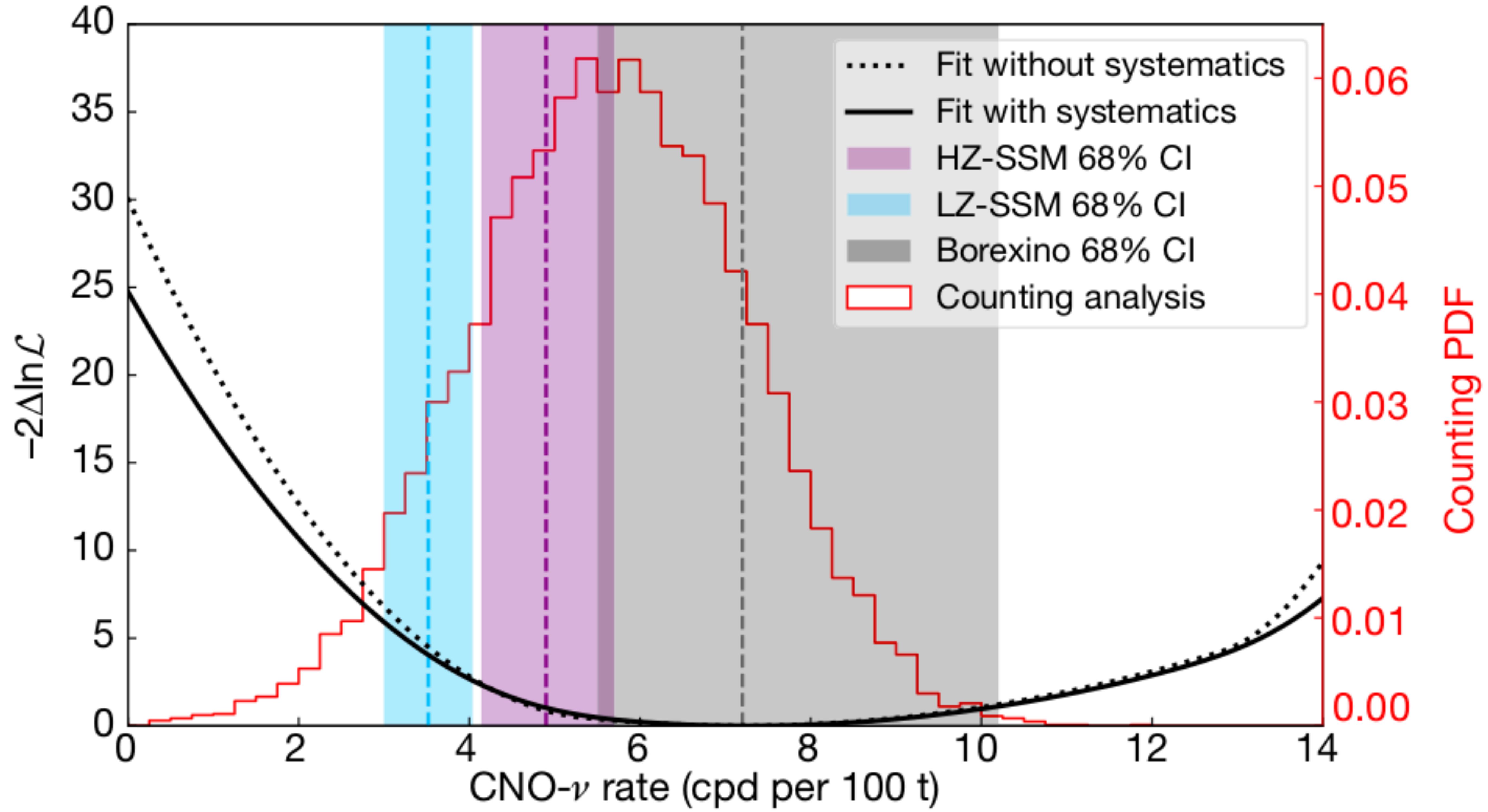
Radial distribution



$R(CNO) = 7.2^{+3.0}_{-1.7}$ cpd/100t

- The ^{210}Bi background constraint is an upper limit, reflected in the asymmetric uncertainty
- CNO to be considered an experimental lower limit

CNO neutrino measurement



No CNO neutrino hypothesis rejected with a significance of 5.0σ at 99% C.L.

$R(CNO) = 7.2^{+2.9}_{-1.7}{}^{+0.6}_{-0.5}$ cpd/100t

Result confirmed at 3.5σ by counting analysis (R = 5.6+/-1.6 cpd/100t)

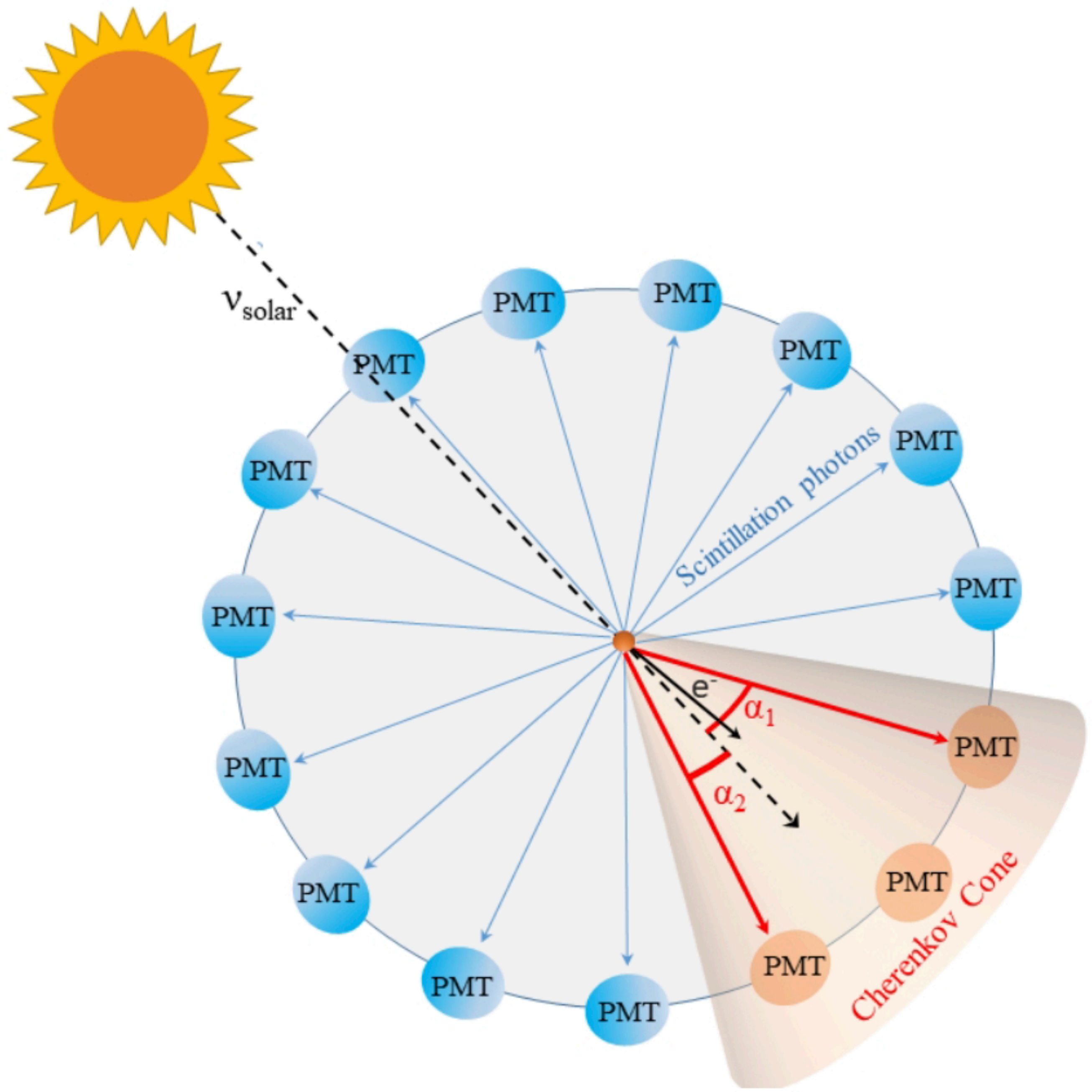
Current summary of Borexino results (2020)

Nature 562, 505 (2018)
PRD 101, 062001 (2020)
Nature 587, 577 (2020)

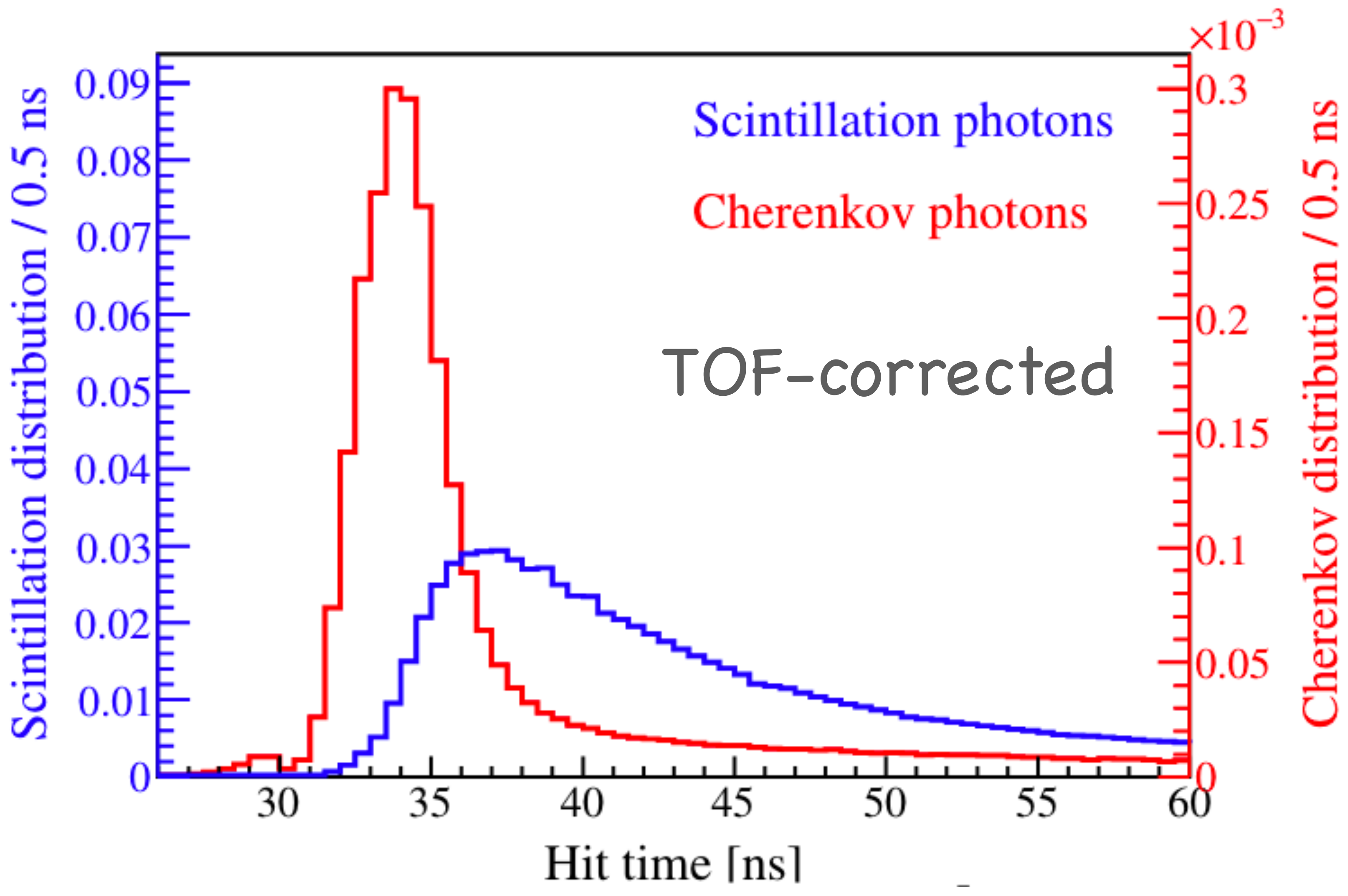
	BX results (cpd/100t)	**Bx flux ($cm^{-2}\,s^{-1}$)**	**SSM (HZ/LZ) ($cm^{-2}\,s^{-1}$)**
pp	134^{+12}_{-14} 10%	$6.1(1\pm0.10)\times10^{10}$	$5.98(1\pm0.006)\times10^{10}$ $6.03(1\pm0.006)\times10^{10}$
^{7}Be	$48.3^{+1.2}_{-1.3}$ 2.7%	$5.0(1\pm0.027)\times10^{9}$	$4.93(1\pm0.06)\times10^{9}$ $4.50(1\pm0.06)\times10^{9}$
pep	$2.43^{+0.39}_{-0.42}$ $2.65^{+0.39}_{-0.42}$ 16%	$1.27(1\pm0.17)\times10^{8}$ $1.39(1\pm0.16)\times10^{8}$	$1.44(1\pm0.01)\times10^{8}$ $1.46(1\pm0.01)\times10^{8}$
^{8}B	$0.223^{+0.016}_{-0.017}$ 8%	$5.68(1\pm0.076)\times10^{8}$	$5.46(1\pm0.12)\times10^{6}$ $4.50(1\pm0.12)\times10^{6}$
hep	<0.002 (90% C.L.)	$<2.2\times10^{5}$	$7.89(1\pm0.30)\times10^{3}$ $8.25(1\pm0.30)\times10^{3}$
CNO	$7.2^{+3.0}_{-1.7}$ 5σ	$7.0^{+3.0}_{-2.0}\times10^{8}$	$4.88(1\pm0.12)\times10^{8}$ $3.51(1\pm0.12)\times10^{8}$

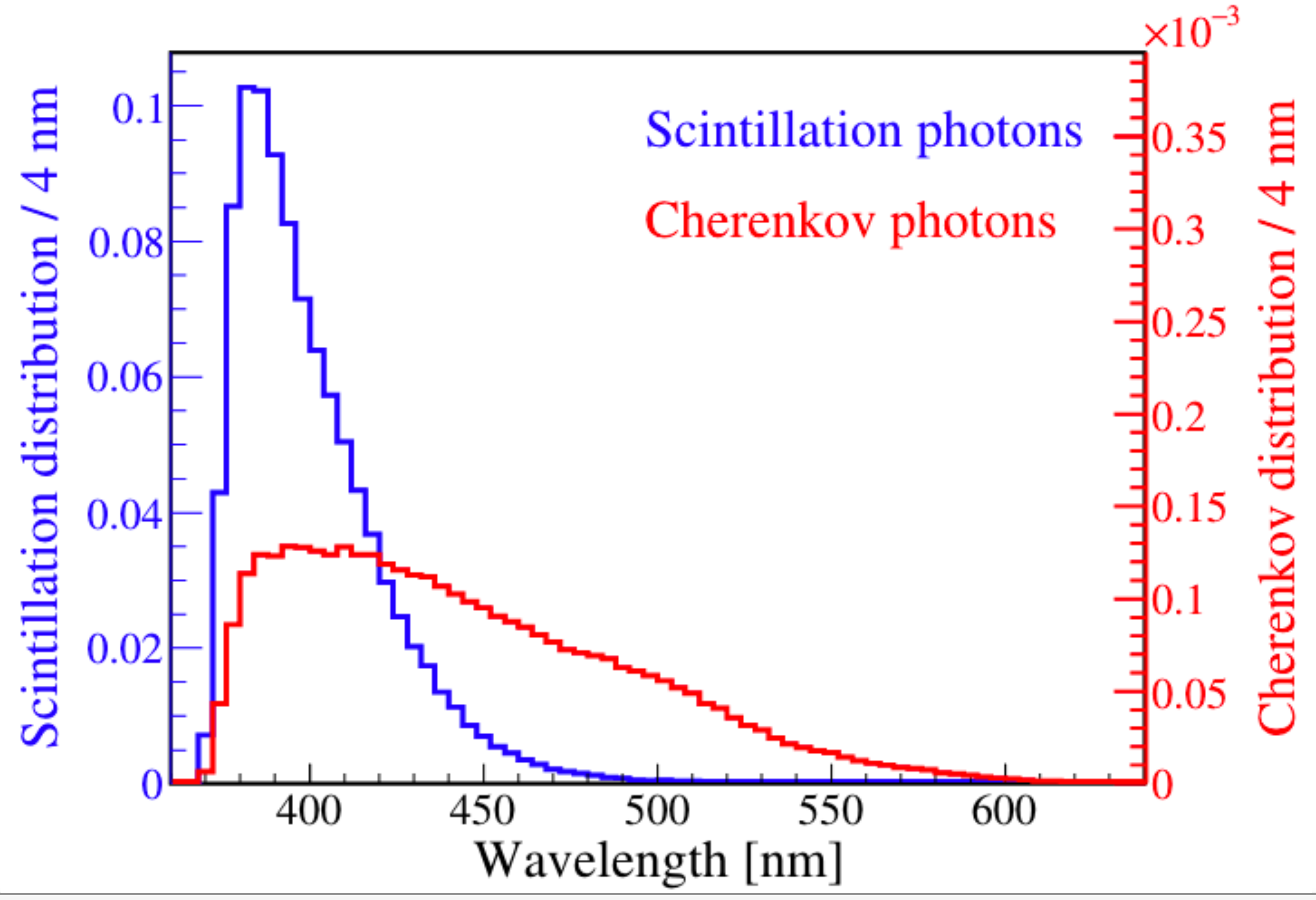
Directionality signature for sub-MeV neutrinos

arXiv:2112.1186, 2109.04770



- Correlate individual photon arrival time of events to the known position of the Sun (Correlated and Integrated Directionality (CID) technique)
- Extract the (feeble, <0.5%) Cherenkov signal using their faster hit time pattern (after TOF correction)
- Cherenkov light emitted for events >160 keV
- Include group velocity correction for Cherenkov photons





- Cherenkov photons that are absorbed and re-emitted are included in scintillation population
- Cherenkov detected above 370 nm

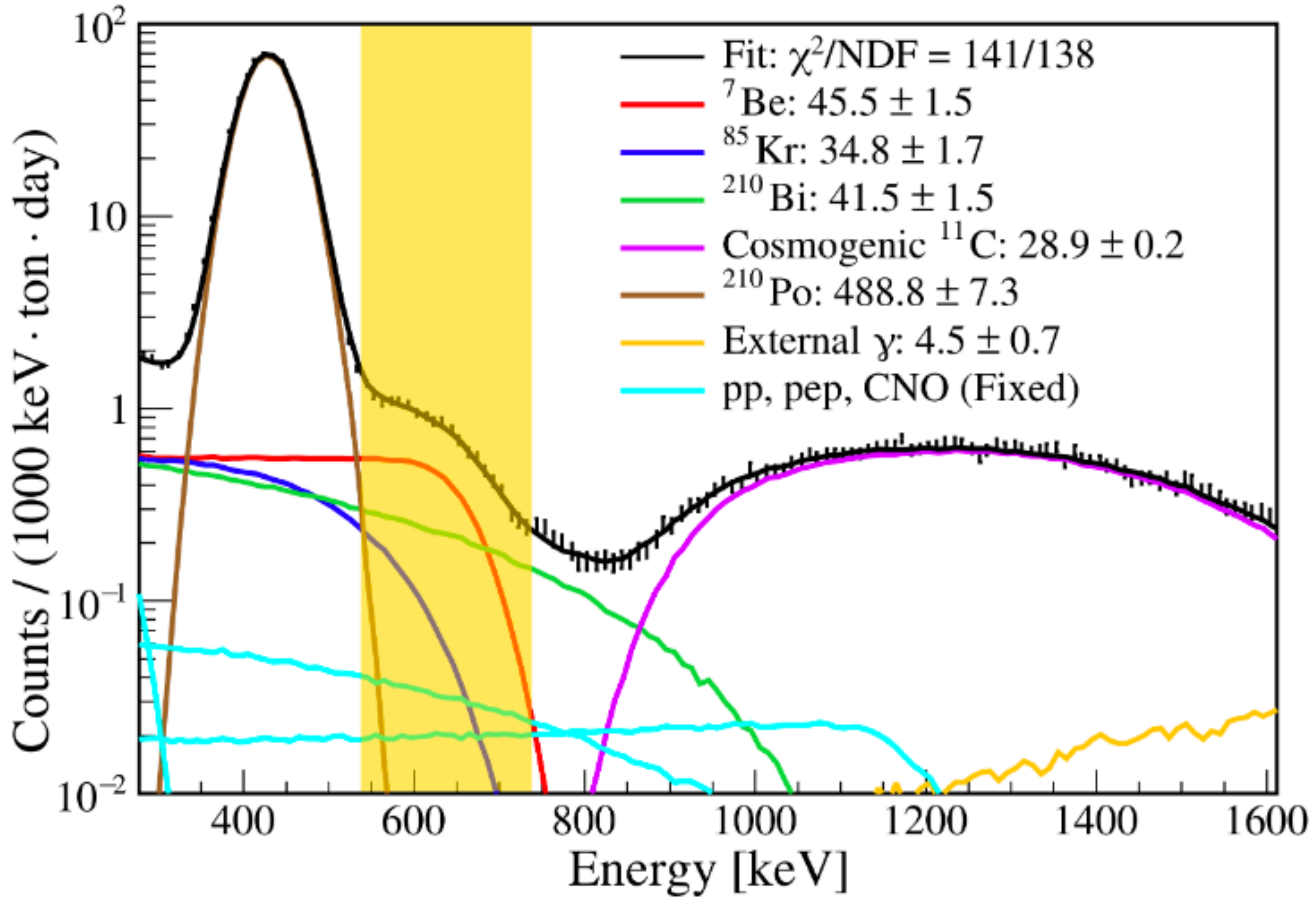
Directional measurement of sub-MeV neutrinos

arXiv:2112.1186, 2109.04770

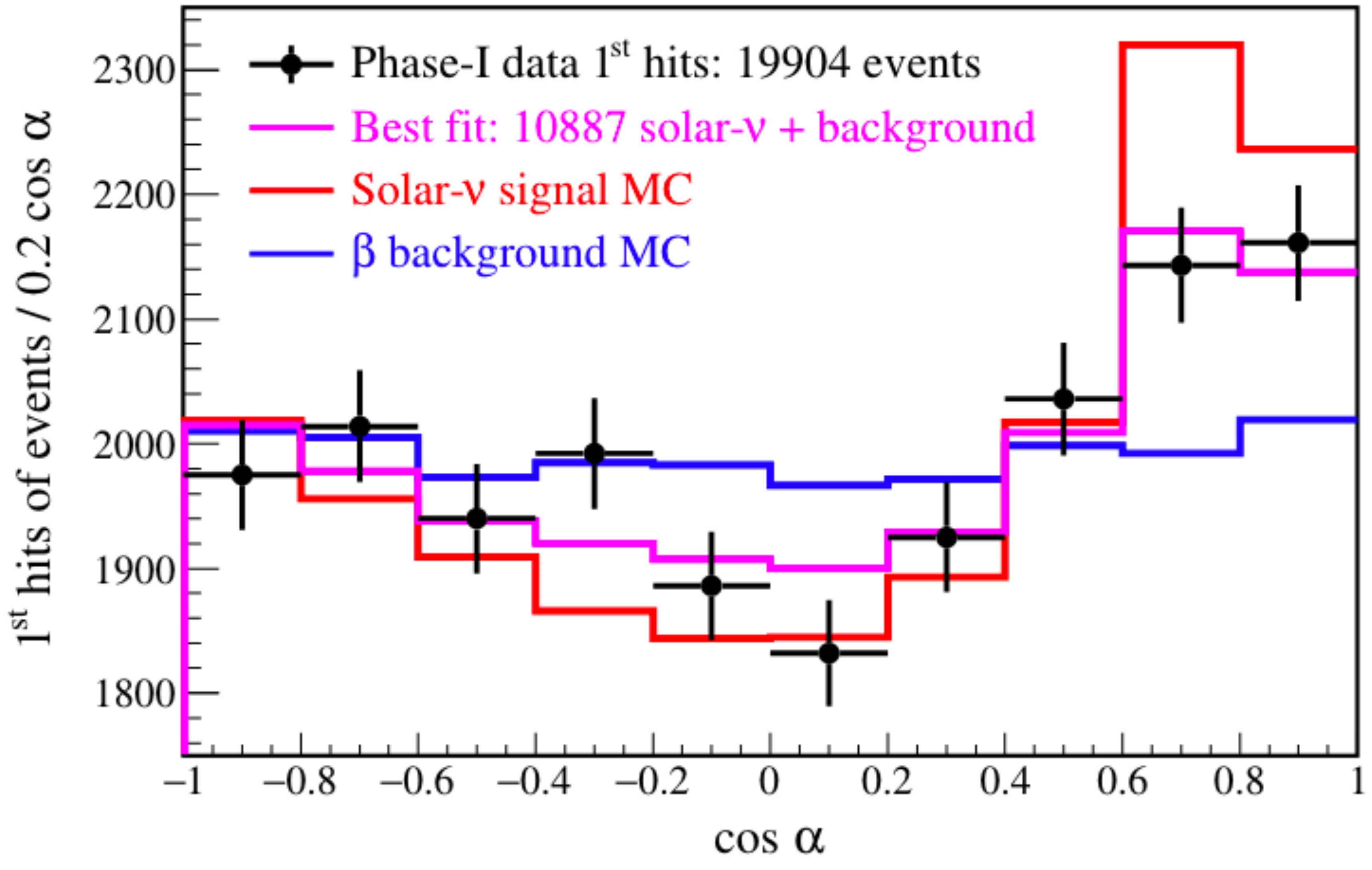
- Verify method with gamma calibration sources
- Select Phase-I data in the Be-7 Compton shoulder energy range: E = 0.54 - 0.74 MeV

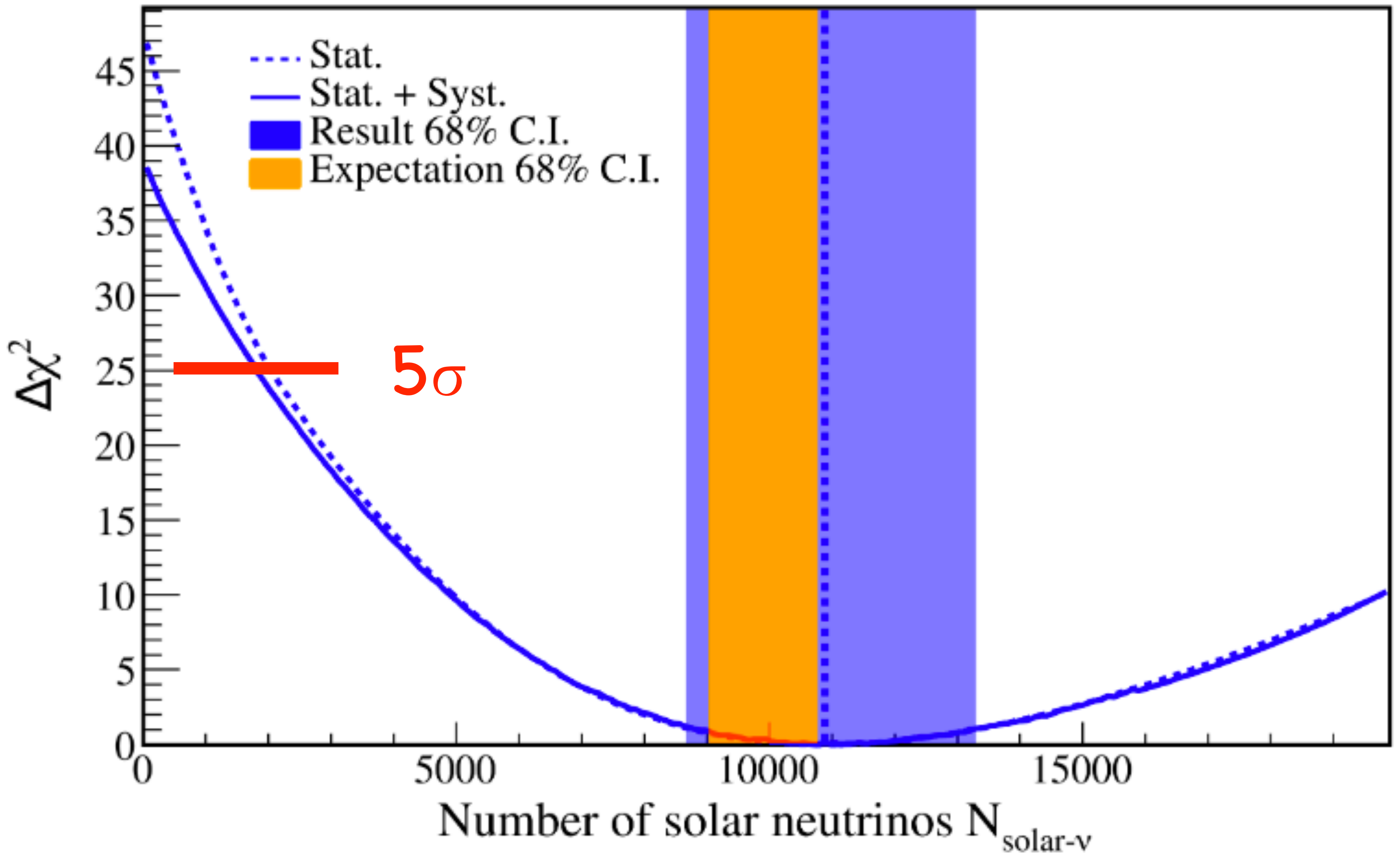
$$N_{solar-\nu} = 10887^{+2386}_{-2103}(stat) \pm 947(syst) \quad (68\%\ C.L.)$$

$$R(^7Be)_{CID} = 51.6^{+13.9}_{-12.5}\ cpd/100t$$

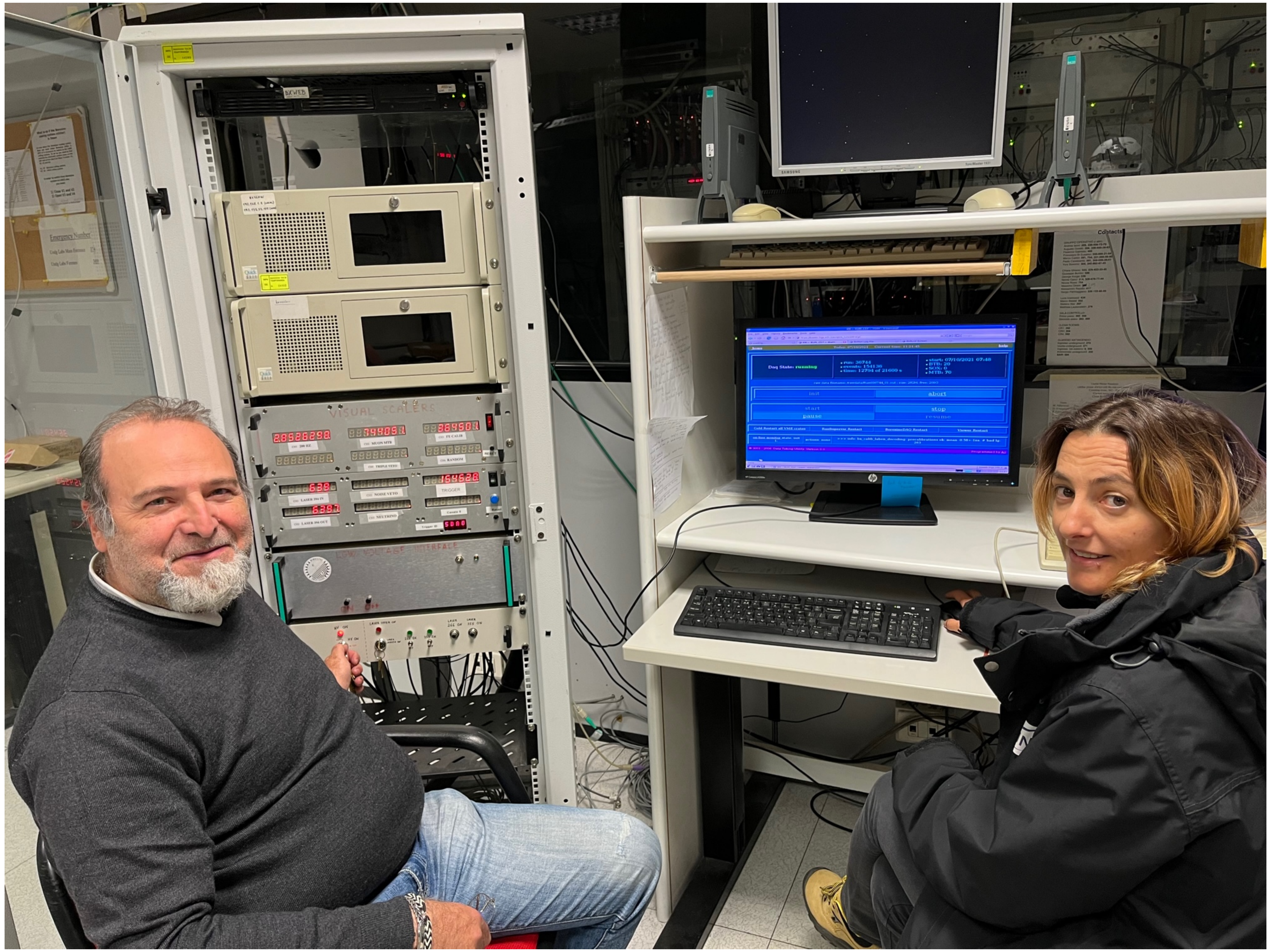


- No-solar neutrino excluded >5σ
- Rate of solar ν interactions consistent with SSM





October 4, 2021 — end of data-taking



Chiara Ghiano and Massimo Orsini turn off the DAQ and the PMT high voltage one last time

The swan's song: is the solar metallicity within reach?

$R(CNO) = 7.2^{+2.9}_{-1.7}{}^{+0.6}_{-0.5}$ cpd/100t

- HZ/LZ compatible at 0.5σ / 1.3σ
- LZ disfavored at 2.1σ when including pp-chain neutrino fluxes (Borexino only)

- Measured ^{210}Bi background is an upper limit, obtained from the minimum of the low-^{210}Po field distribution
- Borexino has another year of data with an ever more stable detector
- Looking for the onset of a minimum 'plateau' in the low-polonium field that would indicate the true ^{210}Po contamination of the scintillator
- Combined with higher statistics it could yield a CNO measurement sufficient to determine the metallicity of the Sun's core

The Borexino collaboration

UNIVERSITÀ DEGLI STUDI DI MILANO

INFN Istituto Nazionale di Fisica Nucleare

LNGS

PRINCETON UNIVERSITY

UNIVERSITÀ DEGLI STUDI DI GENOVA

NATIONAL RESEARCH CENTER "KURCHATOV INSTITUTE"

St. Petersburg Nuclear Physics Inst.

TUM Technische Universität München

STUDIUM GENERALE CIVITATIS PERUSII A.D. MCCCVIII

JAGIELLONIAN UNIVERSITY IN KRAKÓW

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APC

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UNIVERSITY OF MASSACHUSETTS AMHERST 1863

Joint Institute for Nuclear Research

TECHNISCHE UNIVERSITÄT DRESDEN

RWTH AACHEN UNIVERSITY

in memoriam

Cristina Arpesella
Martin Deutsch
Burkhard Freudiger
Andrei Martemianov
Sandro Vitale
Raju Raghavan
Steve Kidner
Hervé de Kerret
Corrado Salvo
Oleg Zaimidoroga
Simone Marcocci

and John Bahcall

with thanks and recognition to many historical collaborators and friends

Summary and Outlook

- Solar neutrinos essential to prove solar fusion and discover neutrino oscillations
- Borexino has precisely mapped the pp solar chain and measured CNO neutrinos, unraveling all solar energy-producing mechanisms and a key process in heavier stars (as predicted by Bethe and Weizsäcker in the 1930s) -> one last result to come …
- Borexino has recently demonstrated that it is possible to extract directional information from sub-MeV neutrino interactions in scintillator (foundational for future experiments)
- Borexino has pioneered low-radioactivity techniques which have defined a new standard for rare-event physics, shaping the career of many young scientists in the process

physicsworld BREAKTHROUGH OF THE YEAR 2014

physicsworld TOP 10 BREAKTHROUGH 2020