— The Borexino legacy —
from the solar neutrino puzzle to the detection of CNO solar neutrinos

Neutrino University Seminar
Fermilab, July 7, 2022

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UMass Amherst
Amherst Center for Fundamental Interactions
Physics at the interface: Energy, Intensity, and Cosmic frontiers
University of Massachusetts Amherst

Foreword

Borexino began more than 30 years ago (!) to

- uncover the mysterious behavior of (solar) neutrinos
- precisely understand how the sun shines.

This is a personal account of an ambitious physics experiment that has been a defining part of my research career since graduate school.

I will present a summary of the main scientific milestones from Borexino, as well as some of the latest results.

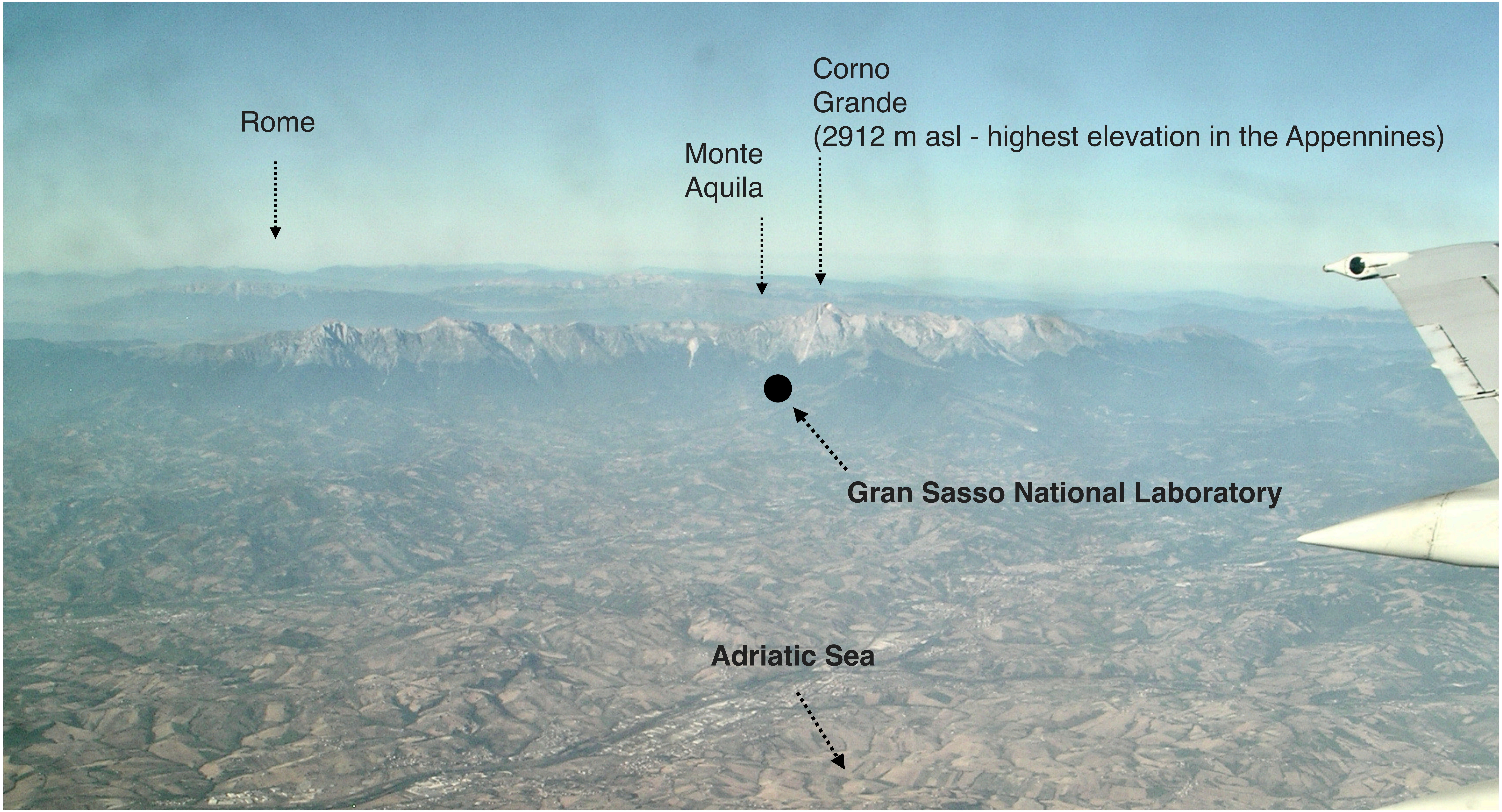
I include a personal selection of events surrounding the purely scientific journey. Any misrepresentation is entirely the responsibility of the presenter.

Synopsis

- Prologue
- Neutrinos and the Sun
    - Solar fusion and solar neutrinos
    - Neutrino oscillations
- Borexino: why, when, who, how, what
    - (the making of) the detector
    - Borexino legacy results
    - Most recent results
- Outlook: the final say?

Nun, god of the waters of chaos, lifts the barque of the sun god Ra (represented by both the scarab and the sun disk) into the sky at the beginning of time (Book of the Dead of Anhai1050 BC)

The stage — the Gran Sasso massif, Italy



The characters of this story

The ancestors
- Neutrinos
- The Sun

Soldiers, priests, heroes, and chorus
- The Borexino collaboration

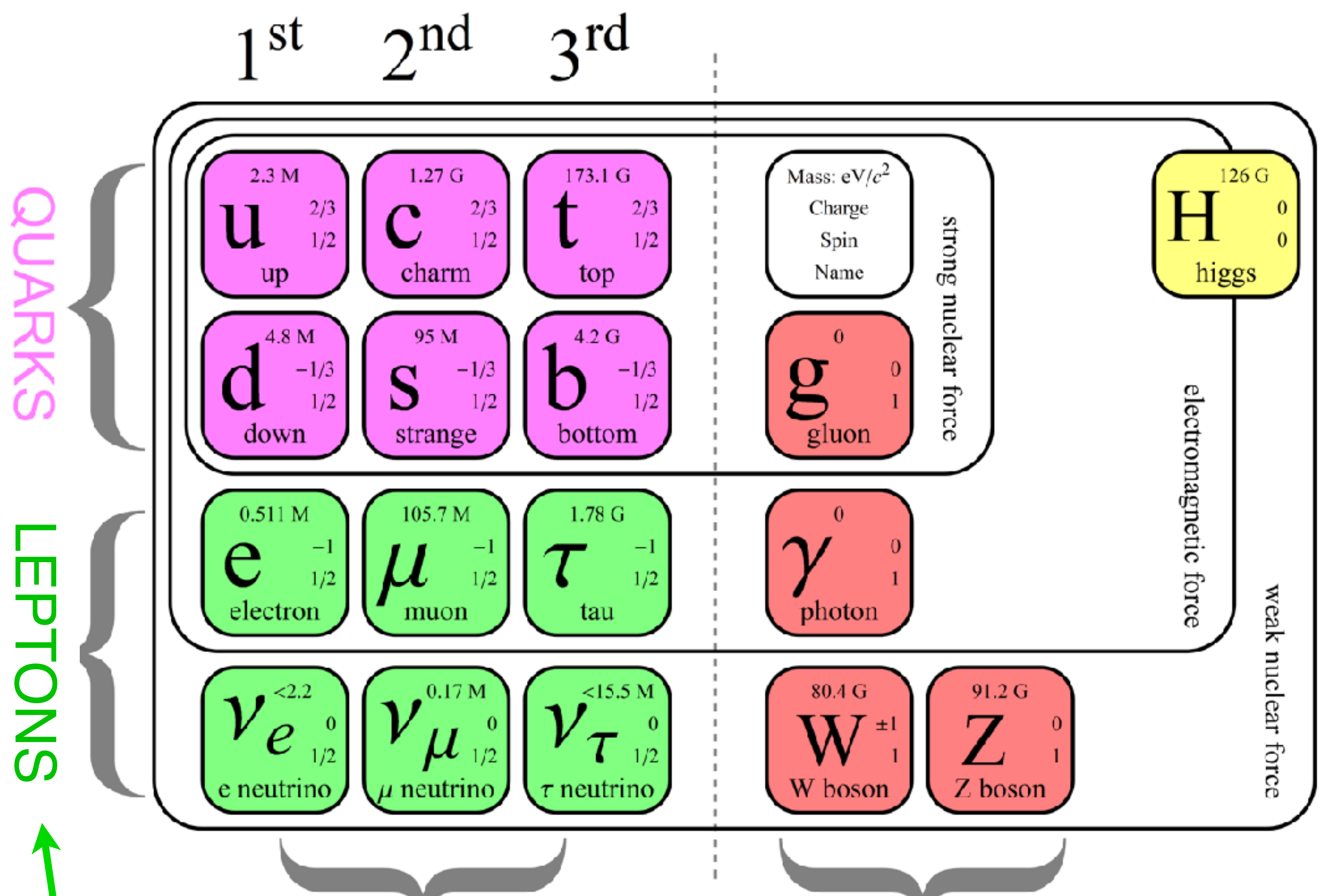
The temple:
the Borexino detector
- The scintillator
- The nylon vessel
- Photomultipliers
- The fluid

The cardinal virtues
- Light yield
- Timing resolution
- Cleanliness
- Radio-purity

The villains
- U, Th, K
- γ rays
- Muons
- Rn + Progeny

The Olympus
- The Borexino results!

Fundamental particles in the Standard Model

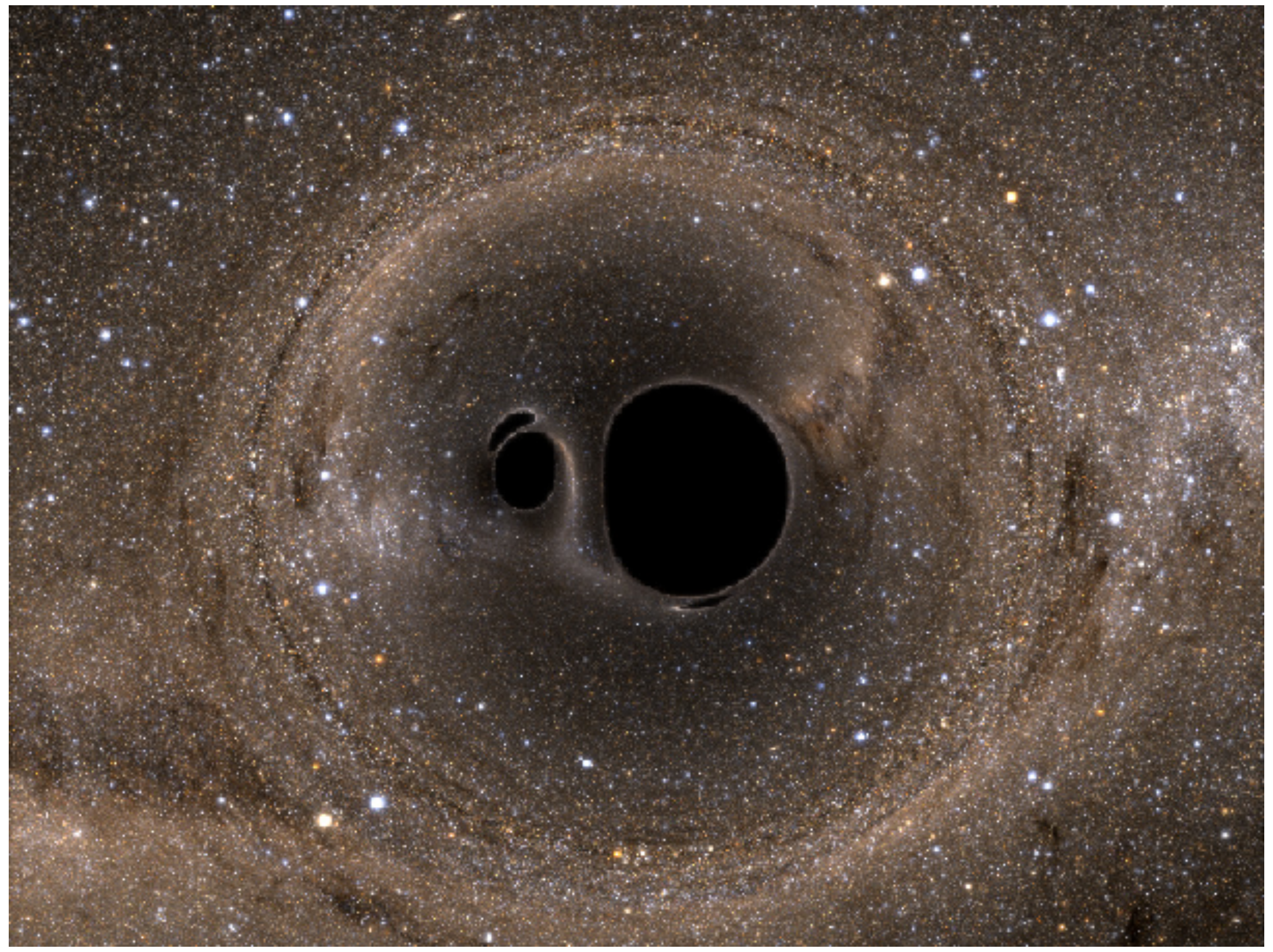


massless neutrinos

LEPTON NUMBER

and ANTI-FERMIONS

the SM successfully describes the results of ~all particle physics experiments to date

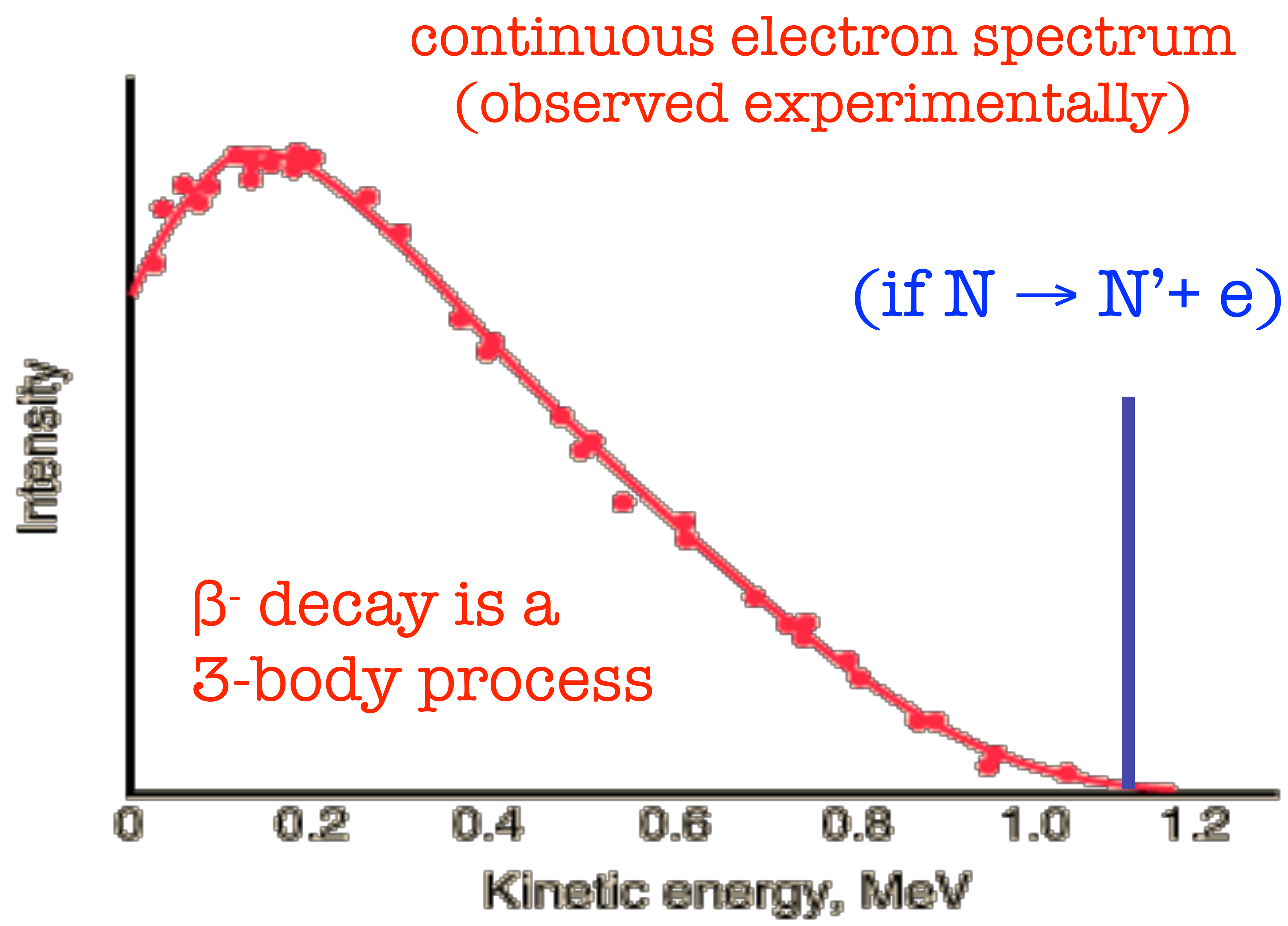


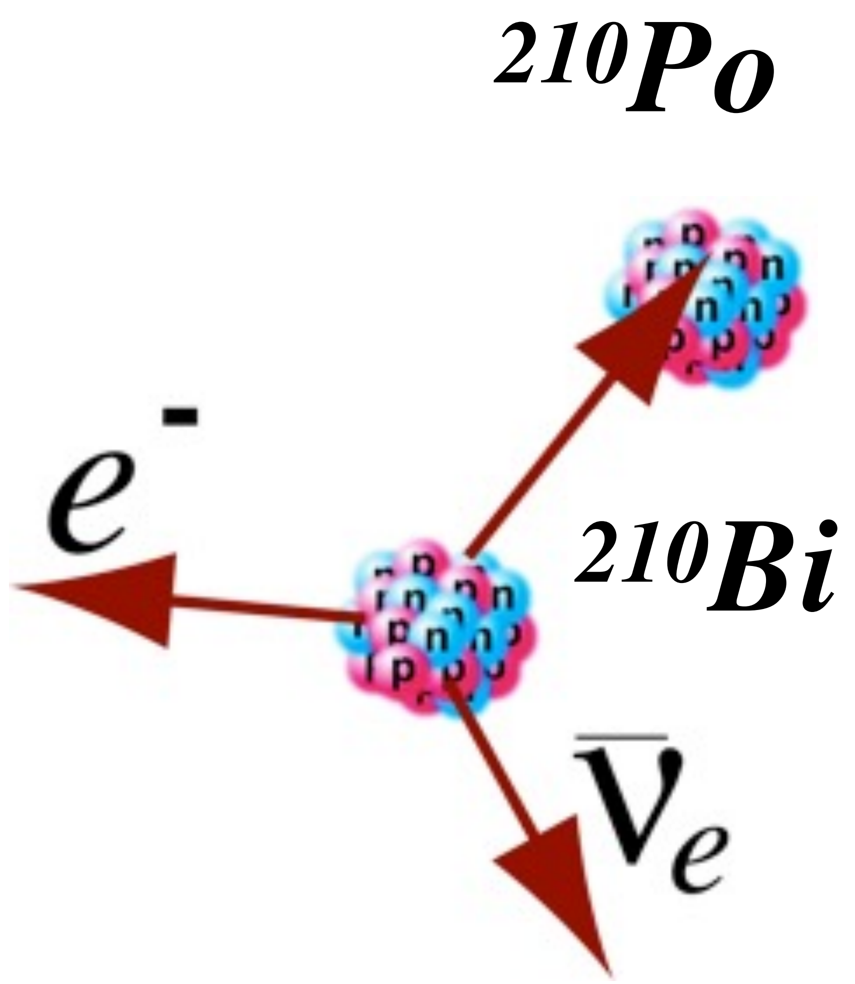
the discovery of gravitational waves is a striking confirmation of general relativity

(Massless graviton)

1930: (why) are energy and angular momentum

Neutrino physics began … without neutrinos!





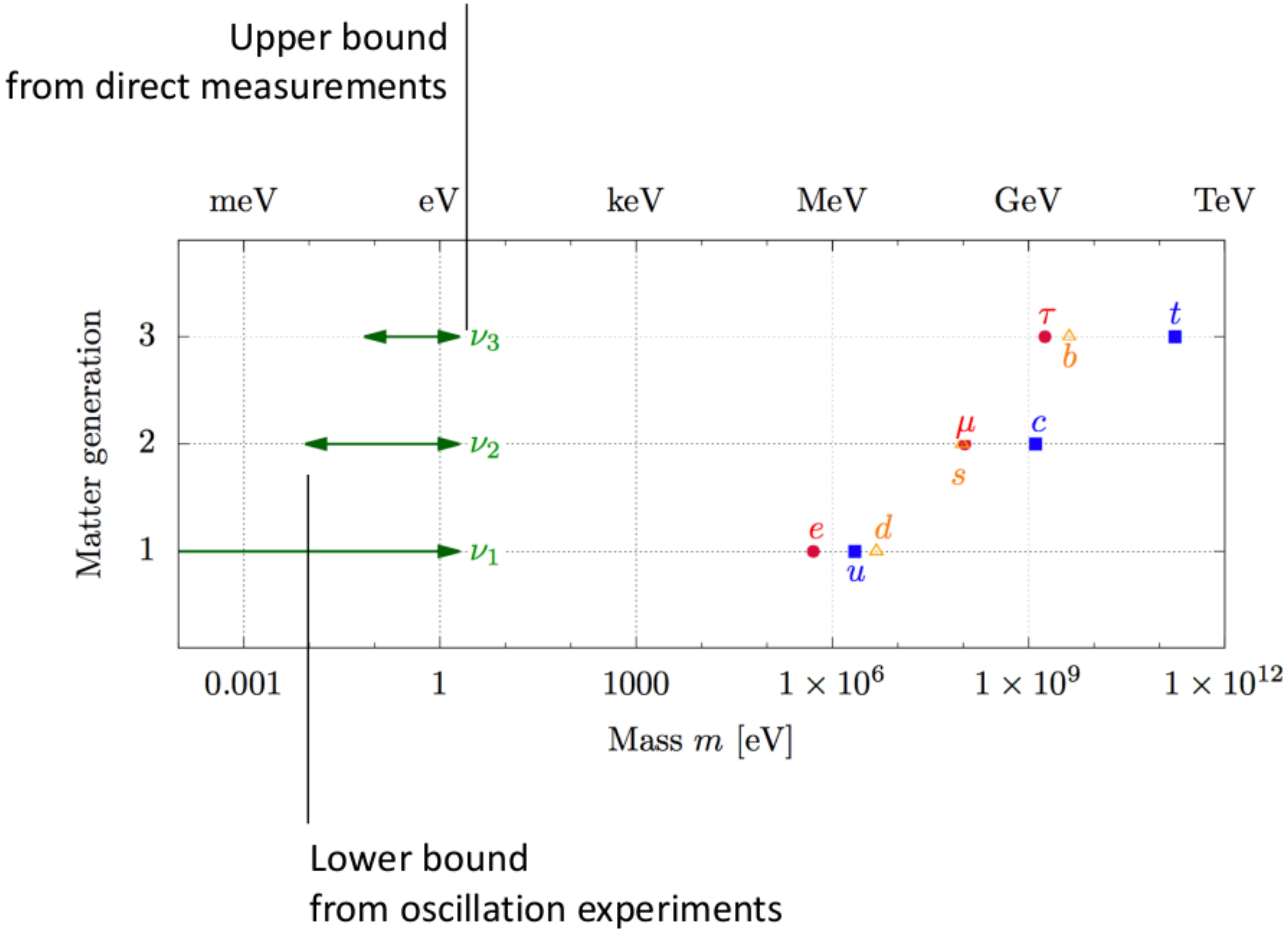
$$s = \frac{1}{2}$$

$$\underset{(1^-)}{\overset{Z=83}{{}^{210}Bi}} \longrightarrow \underset{(0^+)}{\overset{Z=84}{{}^{210}Po}} + e^- \; (+\bar{\nu}_e)$$

"I have hit upon a desperate remedy to save the "exchange theorem" of statistics and the law of conservation of energy"

"Oh, It's well better not to think to this at all, like new taxes"

Today's questions: neutrino mass



- Why are neutrinos so light?
- What is the scale of neutrino mass?
- How do neutrinos acquire mass?
- How are neutrino masses ordered?

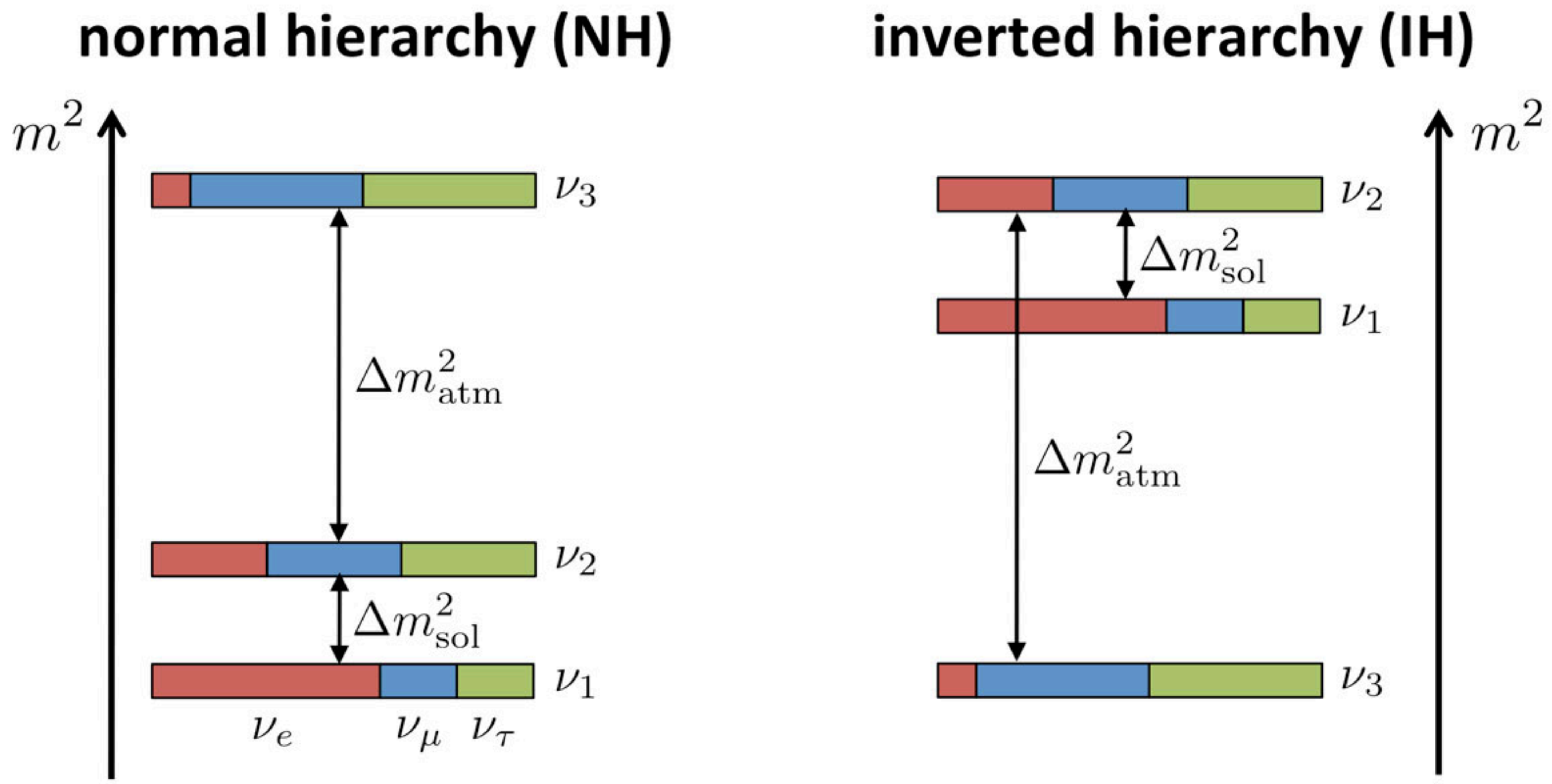


Figure from SNOWMASS neutrino colloquium by S. Mertens

First neutrino detection — 1956

~MeV antineutrinos from the Savannah River nuclear reactor

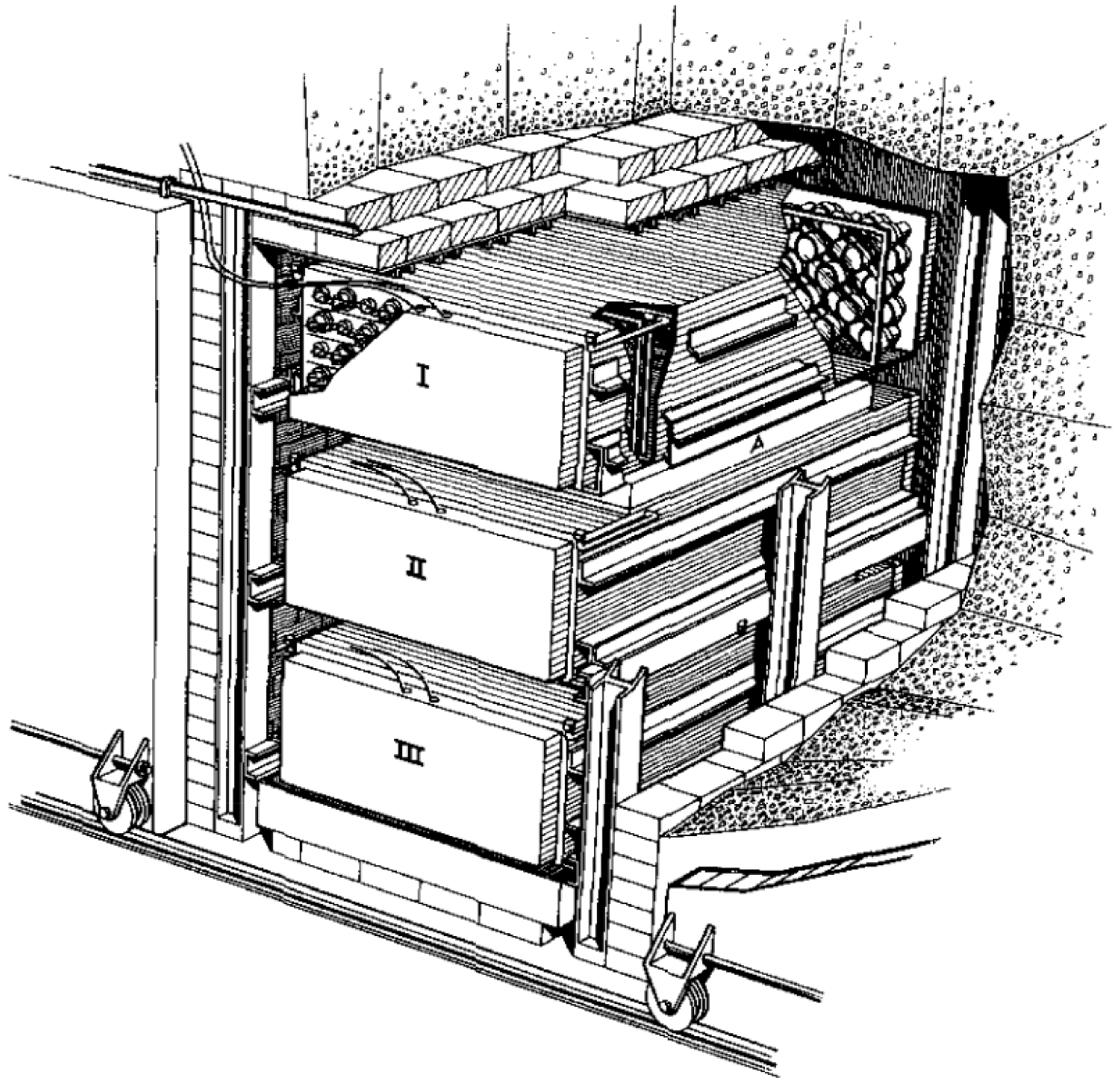
Inverse beta decay reaction

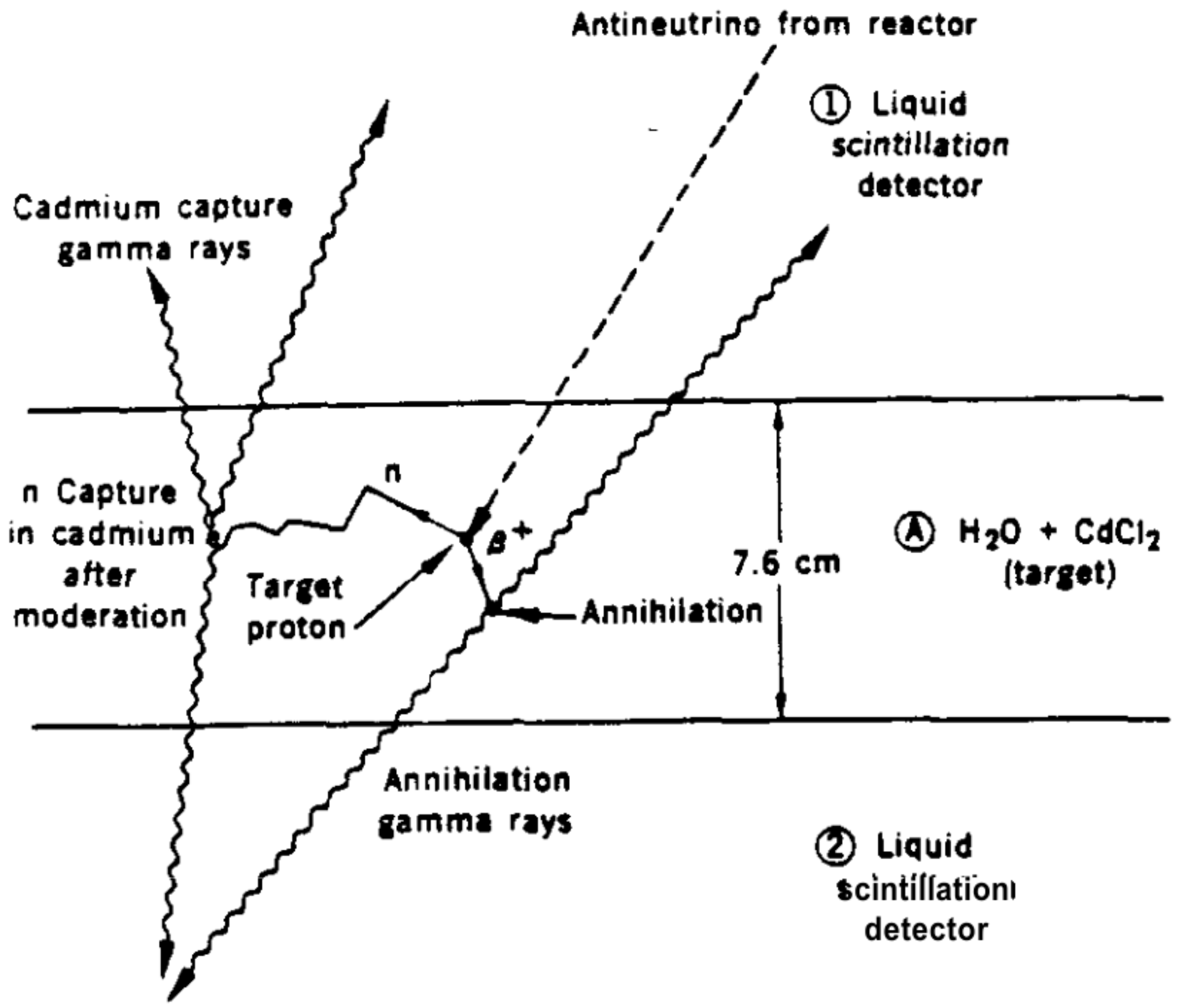
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

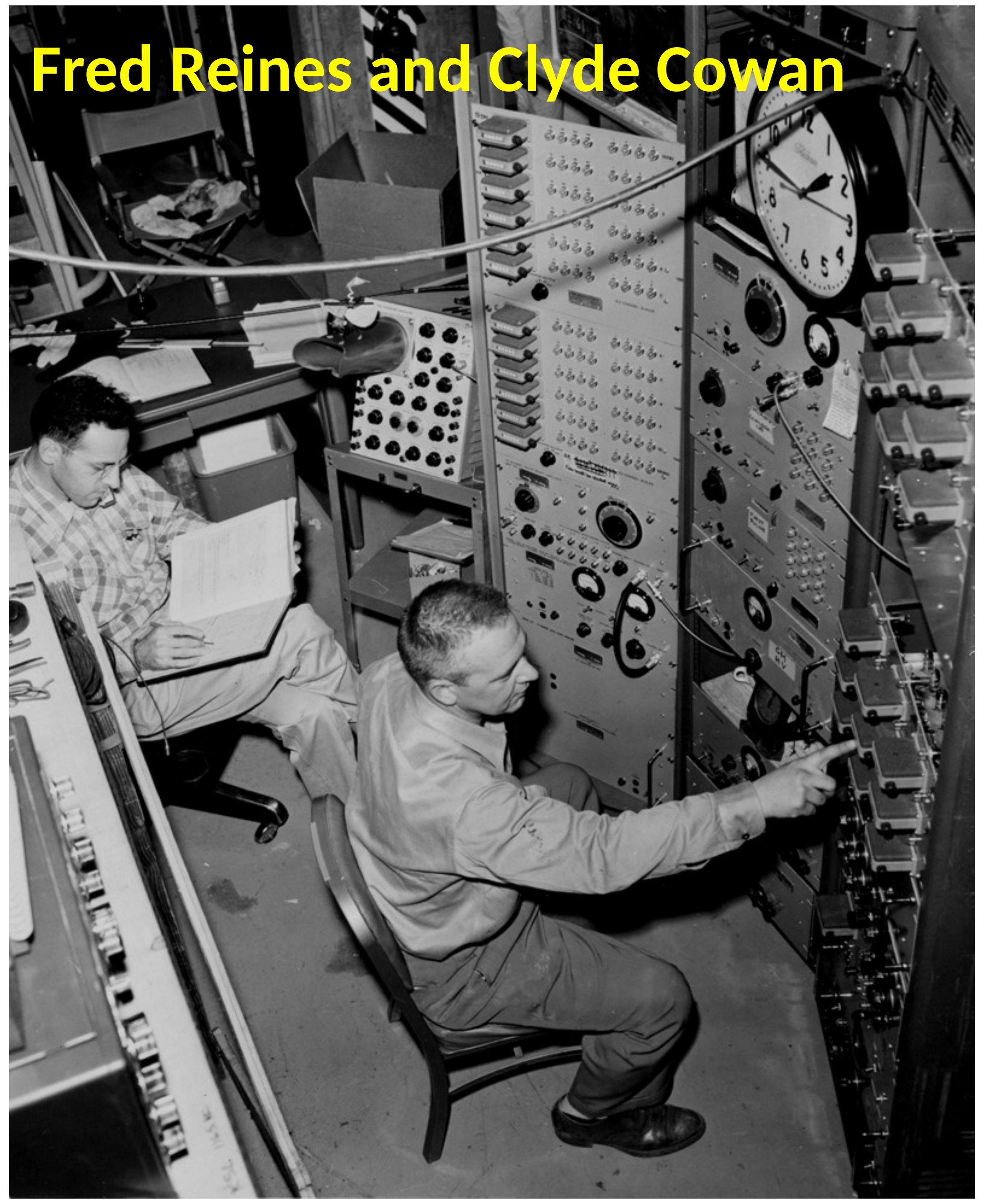
$$\sigma \sim 10^{-44}\ cm^2$$

Neutron capture de-excitation photons

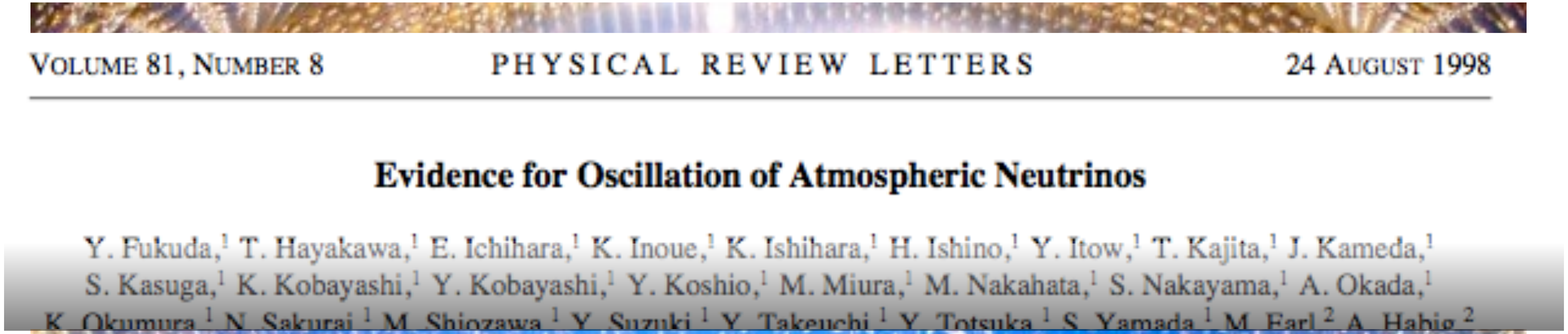
Time-coincidence eliminates backgrounds





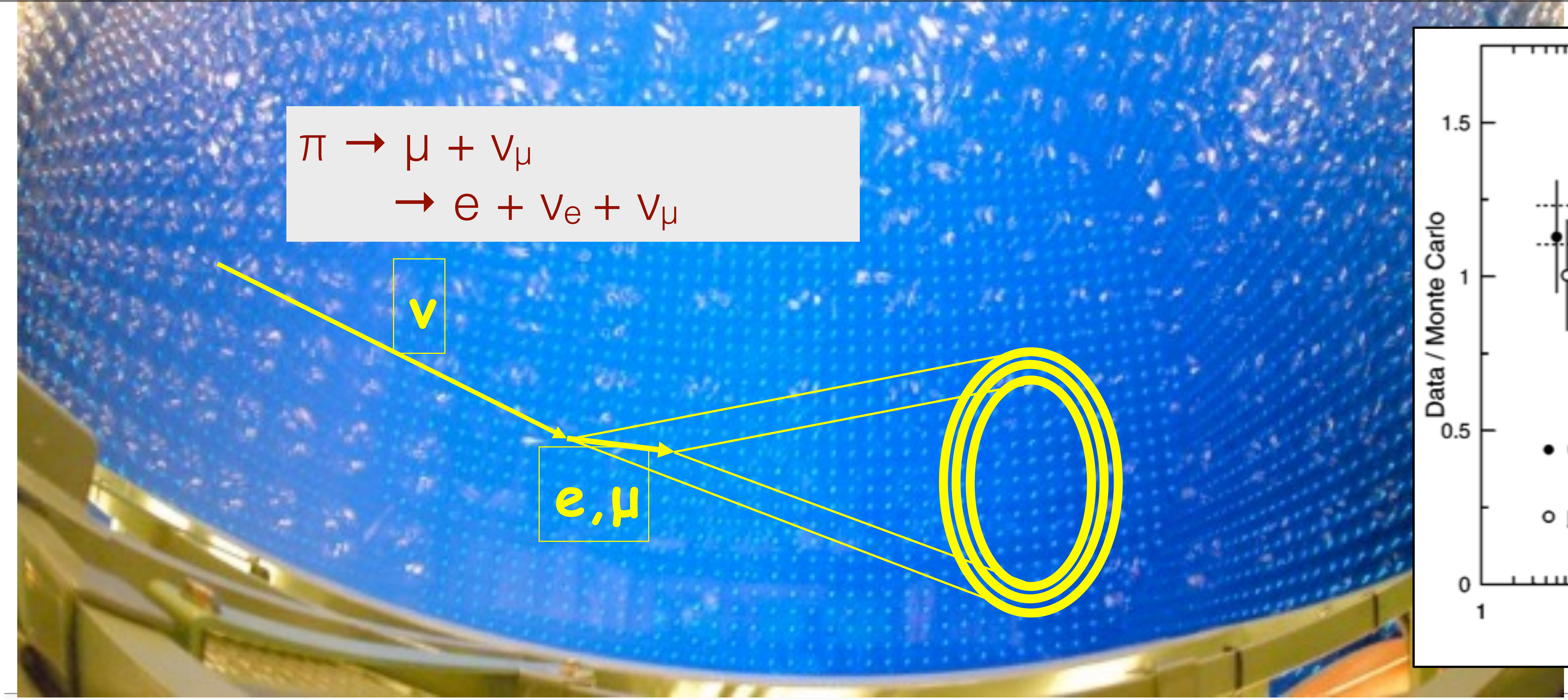


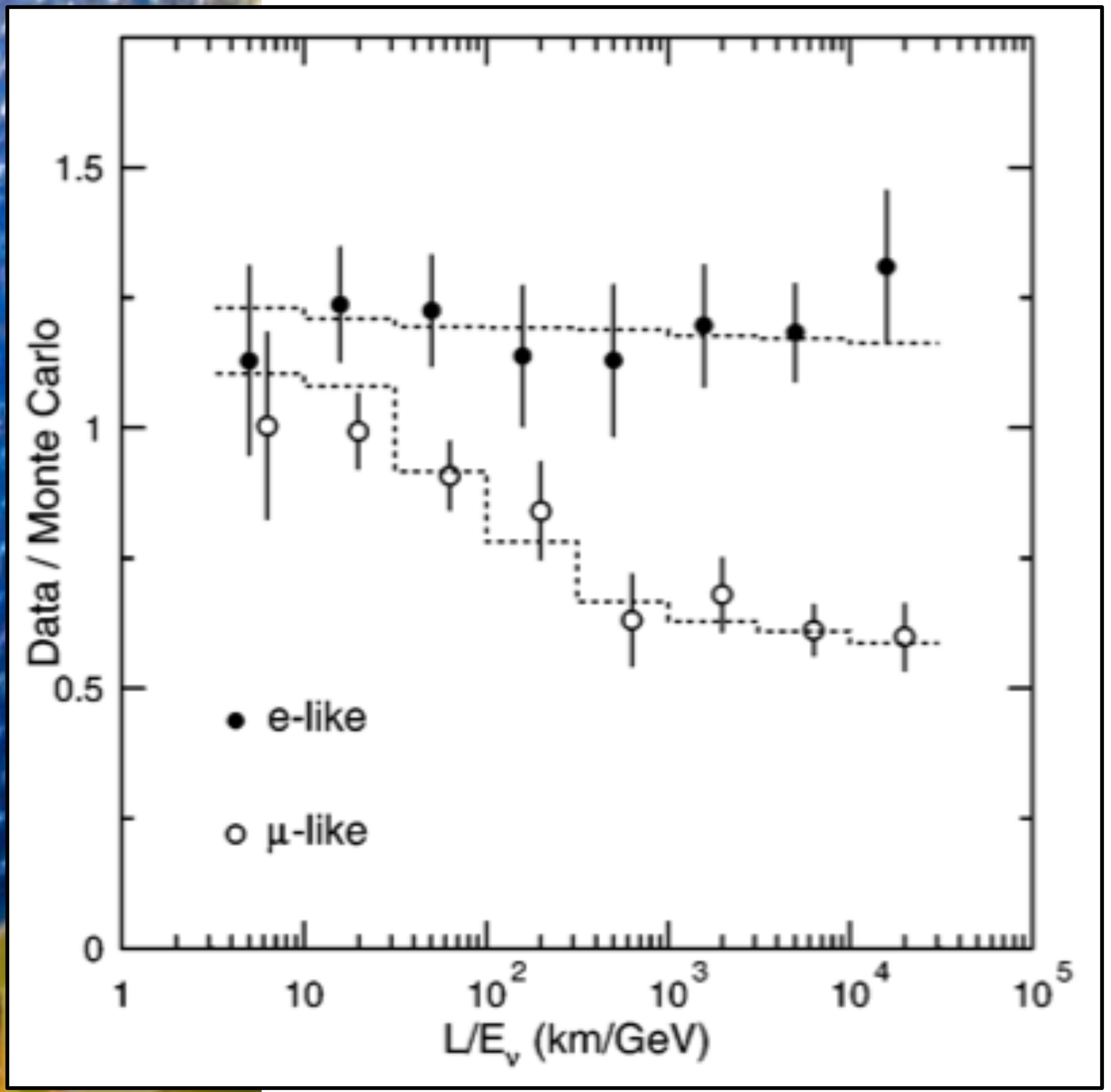
1998 — Atmospheric neutrinos oscillations -> massive neutrinos


VOLUME 81, NUMBER 8 PHYSICAL REVIEW LETTERS 24 AUGUST 1998

Evidence for Oscillation of Atmospheric Neutrinos

Y. Fukuda,[1] T. Hayakawa,[1] E. Ichihara,[1] K. Inoue,[1] K. Ishihara,[1] H. Ishino,[1] Y. Itow,[1] T. Kajita,[1] J. Kameda,[1] S. Kasuga,[1] K. Kobayashi,[1] Y. Kobayashi,[1] Y. Koshio,[1] M. Miura,[1] M. Nakahata,[1] S. Nakayama,[1] A. Okada,[1] K. Okumura,[1] N. Sakurai,[1] M. Shiozawa,[1] Y. Suzuki,[1] Y. Takeuchi,[1] Y. Totsuka,[1] S. Yamada,[1] M. Earl,[2] A. Habig,[2]





Neutrinos: a pillar in the development of the Standard Model

1930 — rescue of conservation of energy and angular momentum (Pauli, postulating a new particle)

1934 — first theory of weak interactions (Fermi)

1935 — prediction of 2ν double beta decay (Göppert-Meyer)

1937 — Majorana neutrinos in 0νββ decay (Majorana, Racah, Furry)

1937/1939 — mechanism for solar fusion (Bethe, von Weiszäcker)

1956 — first neutrino detection at the Savannah River reactor (Reines, Cowan)

1956/1957 — prediction/discovery of parity non-conservation, neutrino left-handed helicity (Lee + Yang / C.S. Wu, Goldhaber)

1958 — neutrino-antineutrino oscillations proposed (Pontecorvo)

1962 — discovery of muon neutrinos (Lederman, Schwartz, Steinberger)

early 1970's — detection of solar neutrinos at Homestake (Davis, Bahcall) (more after the late '80s —> solar neutrino puzzle)

1973 — discovery of weak neutral currents (Gargamelle at CERN)

1987 — detection of Supernova neutrinos (KamiokaNDE, IMB)

1998 — discovery of atmospheric neutrino oscillations (SuperK, T. Kajita)

2002 — discovery of solar neutrino oscillations (SNO, A. McDonald)

post-2002 — precision neutrino oscillation physics (mixing angles, mass splittings)

2005/2010 — detection of geo-neutrinos (KamLAND, Borexino)

2013 — discovery of extra-galactic neutrinos, multi-messenger astrophysics (IceCube)

2015 — coherent neutrino scattering on nuclei (COHERENT)

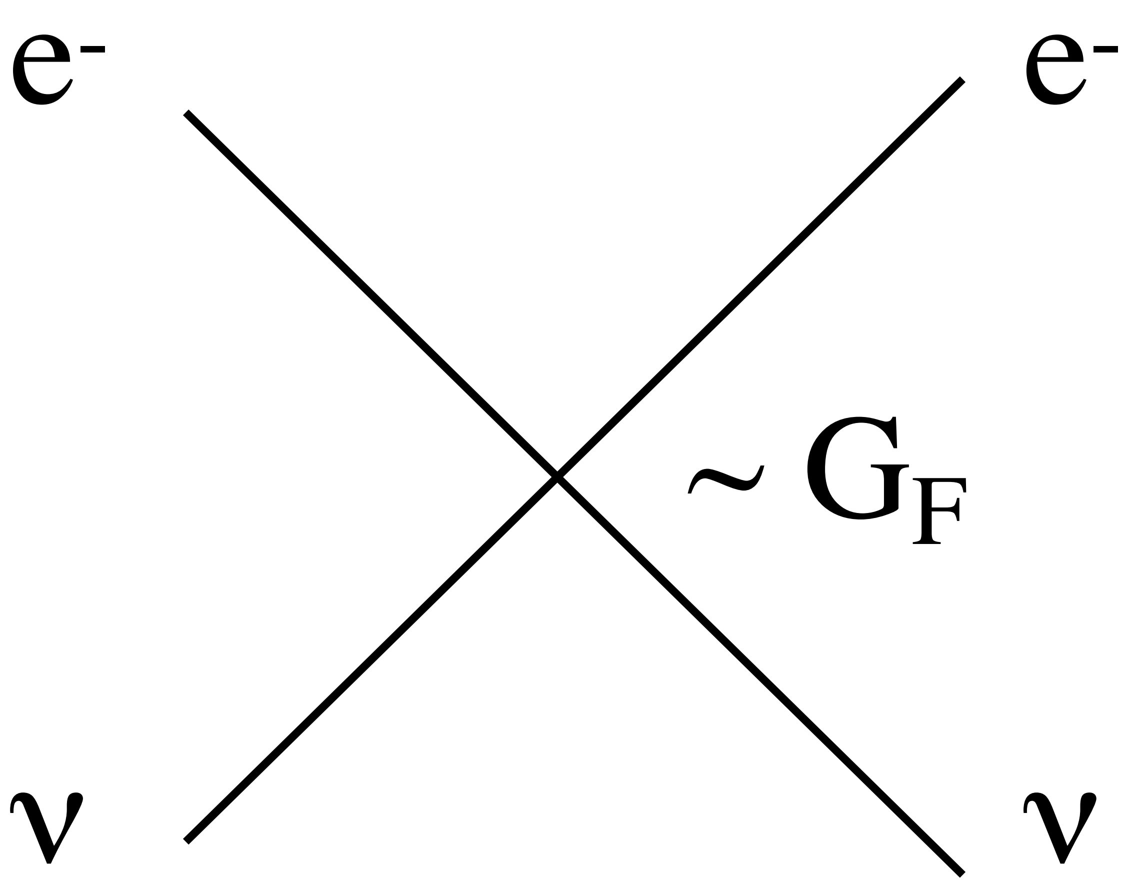
2014, 2020 — detection of solar pp neutrinos, CNO neutrinos (Borexino)

the 'Nobel-est' of particles
4 prizes (3 FPE)
8 scientists

- *Fundamental symmetries*
- *Precision measurements*
- *Applied physics*

Really hard to detect, especially at low energy

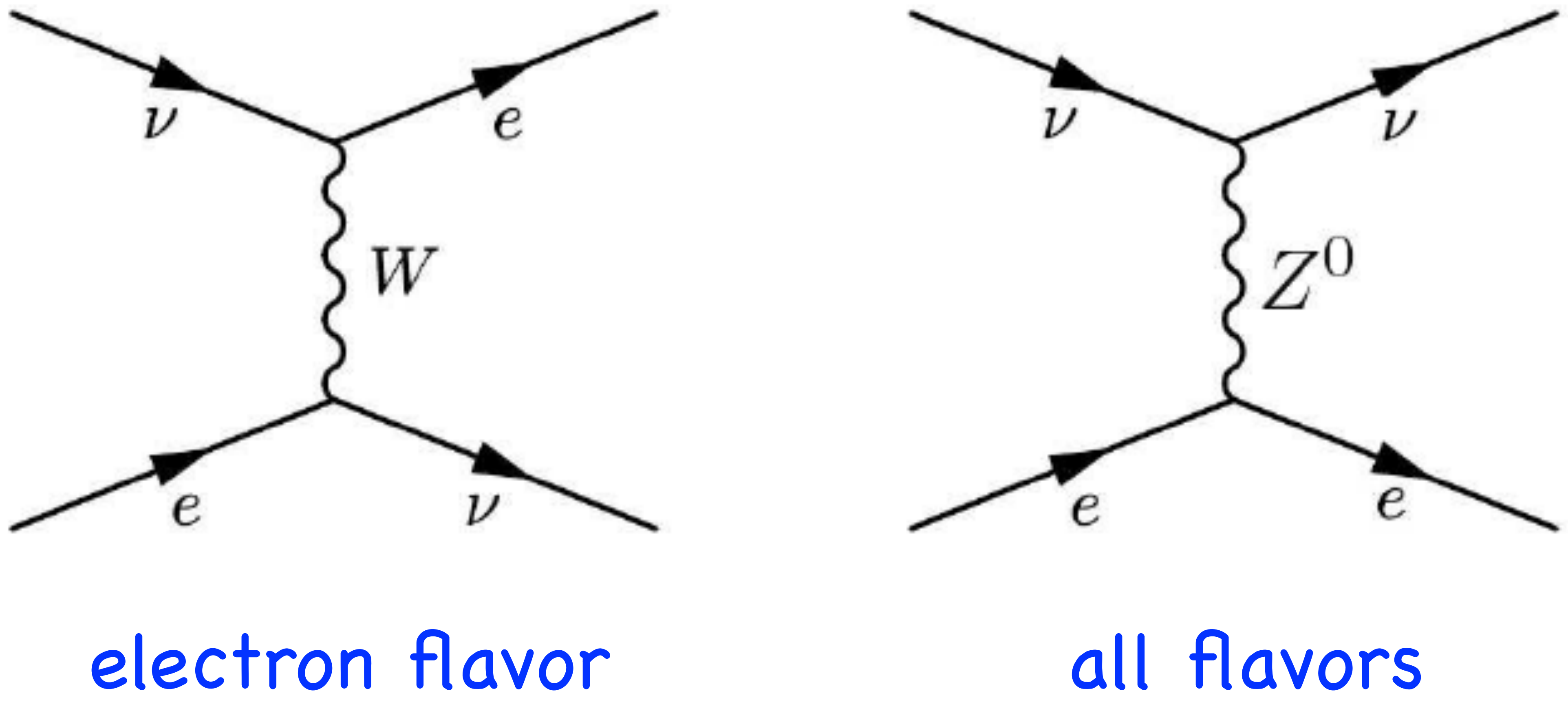
1934
Fermi develops the theory of weak interactions (four-fermion interactions)



neutrino-electron elastic scattering cross section at 1 MeV

$$\sigma = \frac{G_F^2 s}{\pi}(\hbar c)^2 = 2.3 \cdot 10^{-44} cm^2$$

very clean, yet evanescent probe

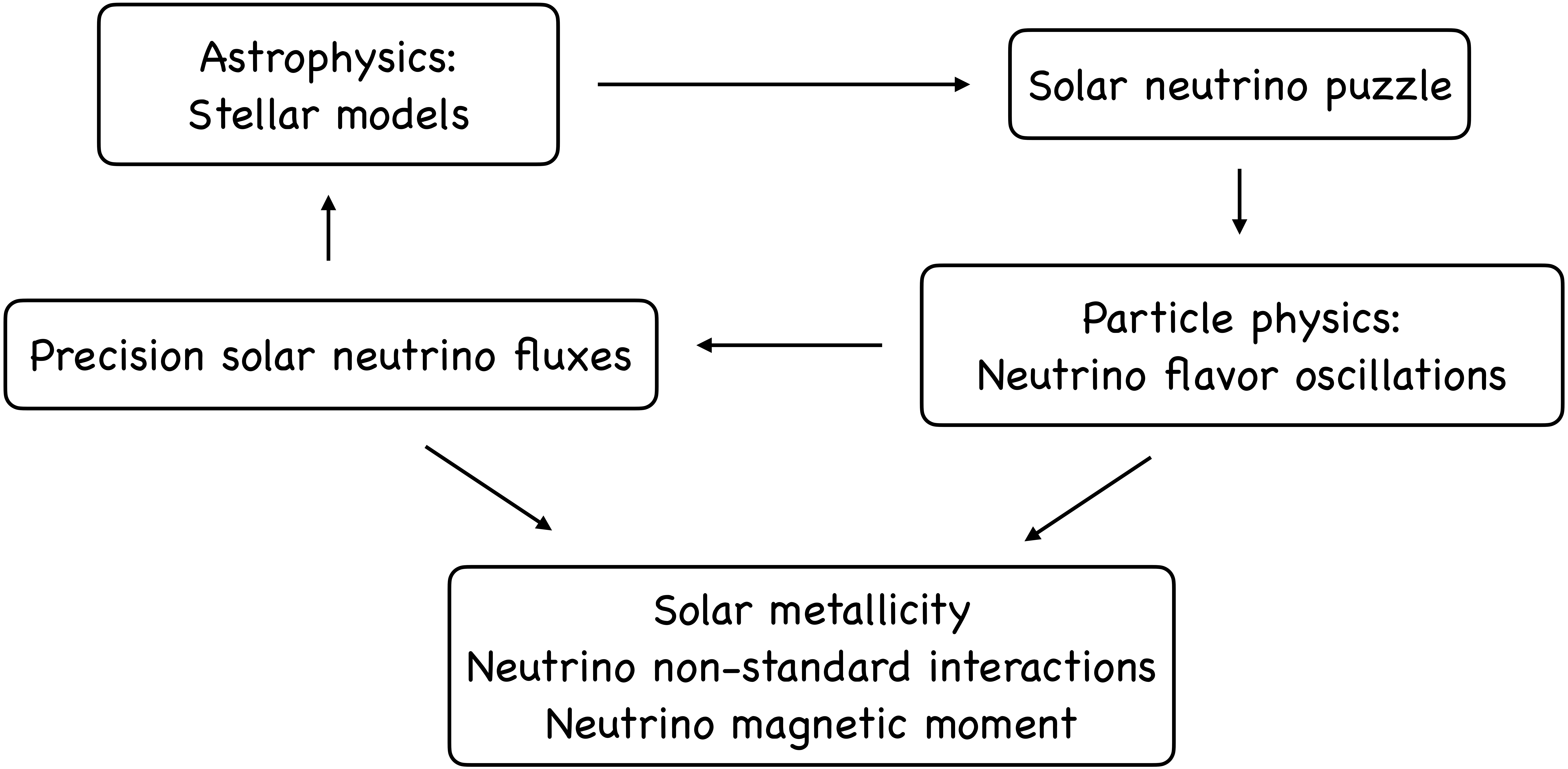


Why solar neutrinos?

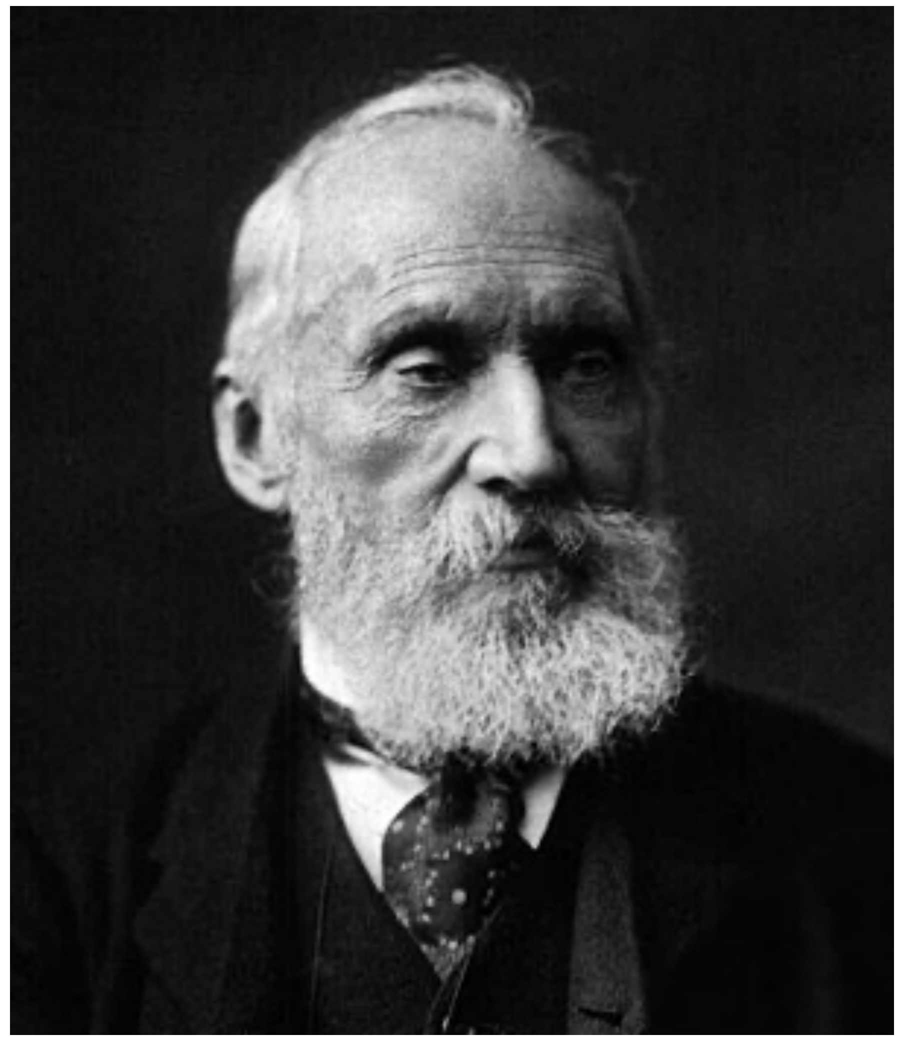
- Solar neutrinos: one of the success stories of 20th century physics
  - Direct messengers of the nuclear thermo-fusion machinery in its core
  - Probes of its chemical composition and thermal profile

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

Solar neutrinos — an iterative success story

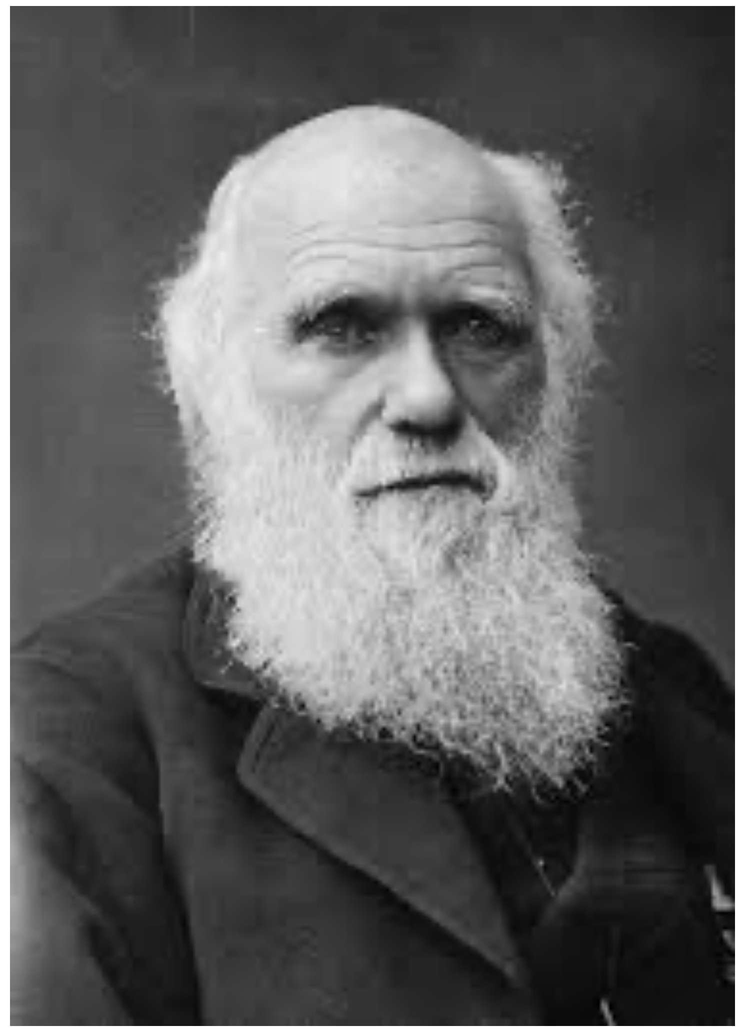


A 'heated' debate (XIX century)



- William Thomson (Lord Kelvin) estimated that the Sun's heating came from gravitational collapse
- Age of the Sun < 20 Myears (in the absence of other sources)
- Incidentally, the discovery of radioactivity on Earth did not revert his estimate for the Sun's age

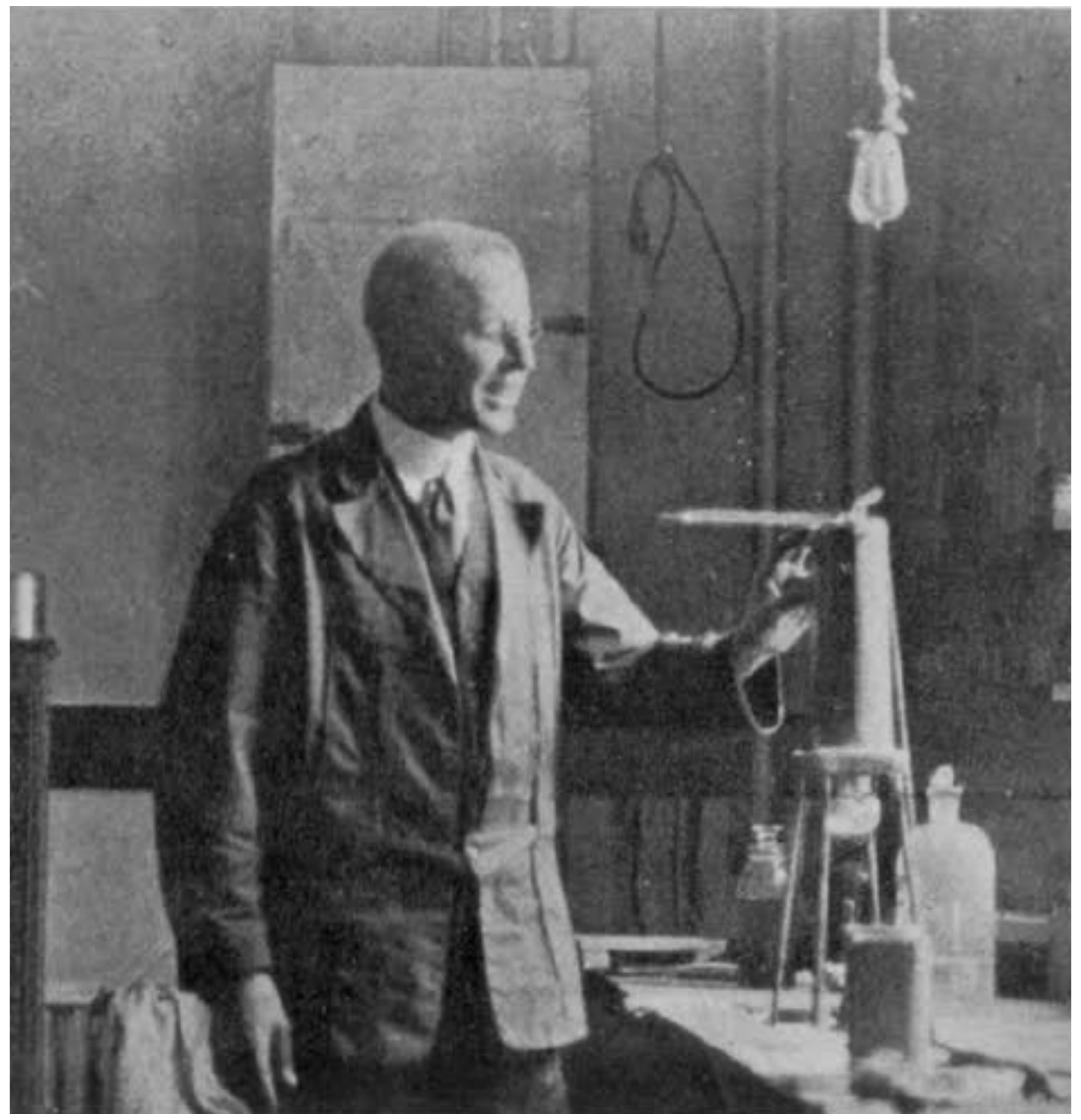
- Charles Darwin's studies on the origin and evolution of species on Earth (1859->) led to a discrepancy on the age of Earth between biology+geology and physics known at that time
- In general, "we are far from knowing enough to tell"
- ==> Age of the Earth > 300 Myears



Towards a shifted paradigm requiring new physics

- Discovery of radioactivity in 1895-6 (Röntgen, Becquerel) and follow-up studies by Marie and Pierre Curie and Ernest Rutherford provided the alternative power source missing in Lord Kelvin's model, who remained steady behind his estimates

- In 1899, TC Chamberlain allowed for the possibility that atoms were complex systems locking up enormous amounts of energy, which could be let free by the extreme conditions inside the Sun.



- Radioactive dating of rocks --> 1907.
- Amherst-native Bertram Boltwood
- Uranium -> Lead decay series (another 'cycle' of science!)
- ==> Age of the Earth 300-2,200 Myears
- (current dating with this technique yields 4.4 Gyears)

The solution (1937-39)

- Explaining the Sun's age > billions of years required a yet unknown source

  —> Nuclear fusion

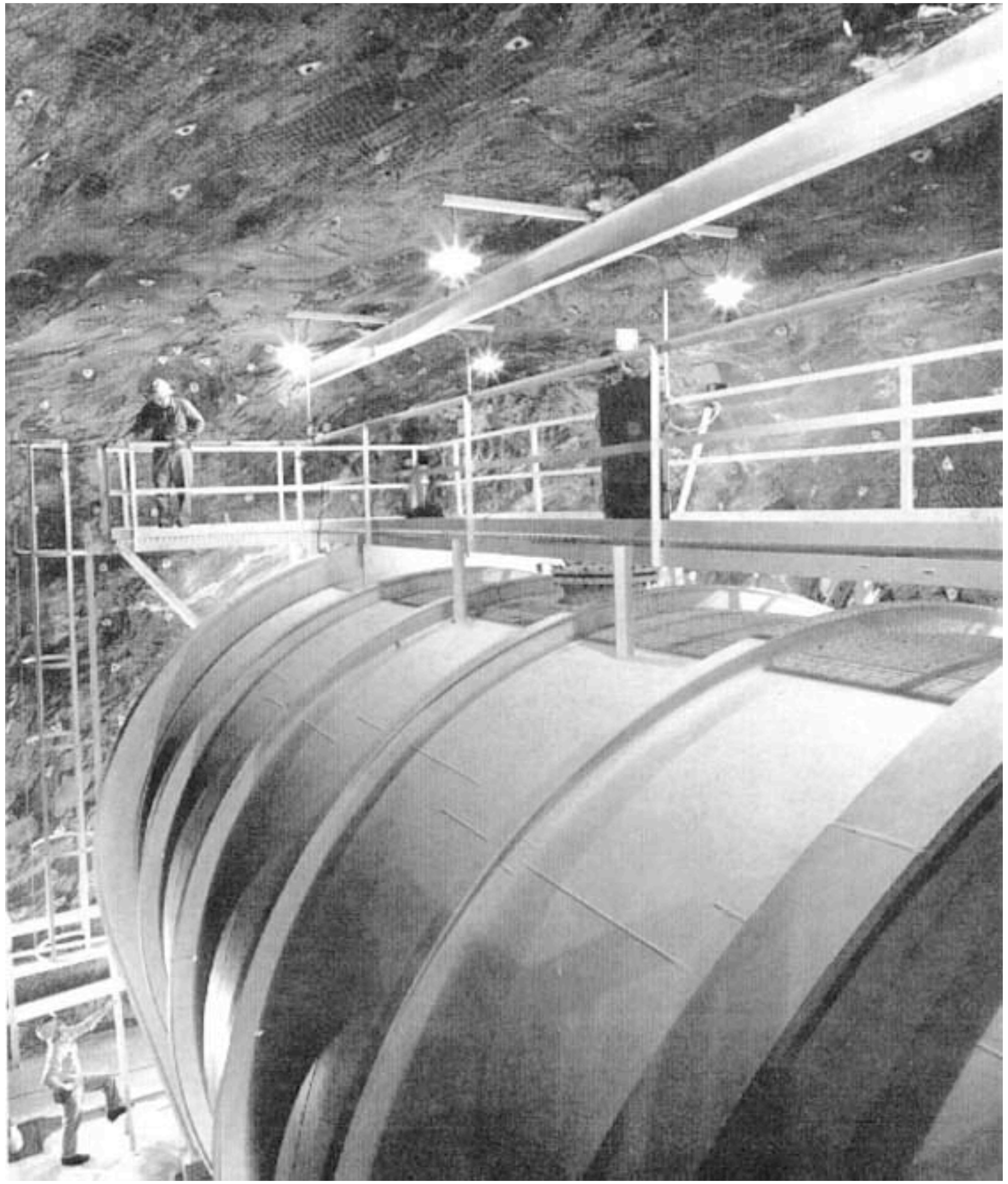
Carl Friedrich von Weizsäcker, Hans Bethe and others:

- Fusion of protons -> Helium
- $E=mc^2$ -> $\Delta m = 0.7\%$
- Age of the Sun = approx. 5 Gyears

Two mechanisms:

- Proton-proton (pp) chain
- Carbon-Nitrogen-Oxygen (CNO) cycle

Solar neutrino detection



- Homestake Mine, Lead SD, 1400 m underground
- 615 tons of perchloroethylene (C_2Cl_4)

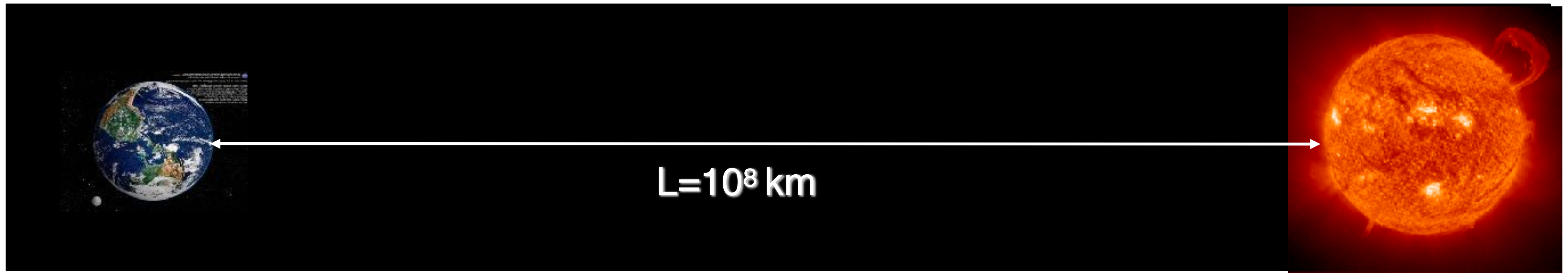
$^{37}Cl + \nu$ --> $^{37}Ar + e$

~one ^{37}Ar atom produced every 2 days !

$$\sigma \sim 10^{-42} \ \ cm^2$$

proved that there are nuclear fusion reactions in the sun

observed only ~1/3 of the expected flux



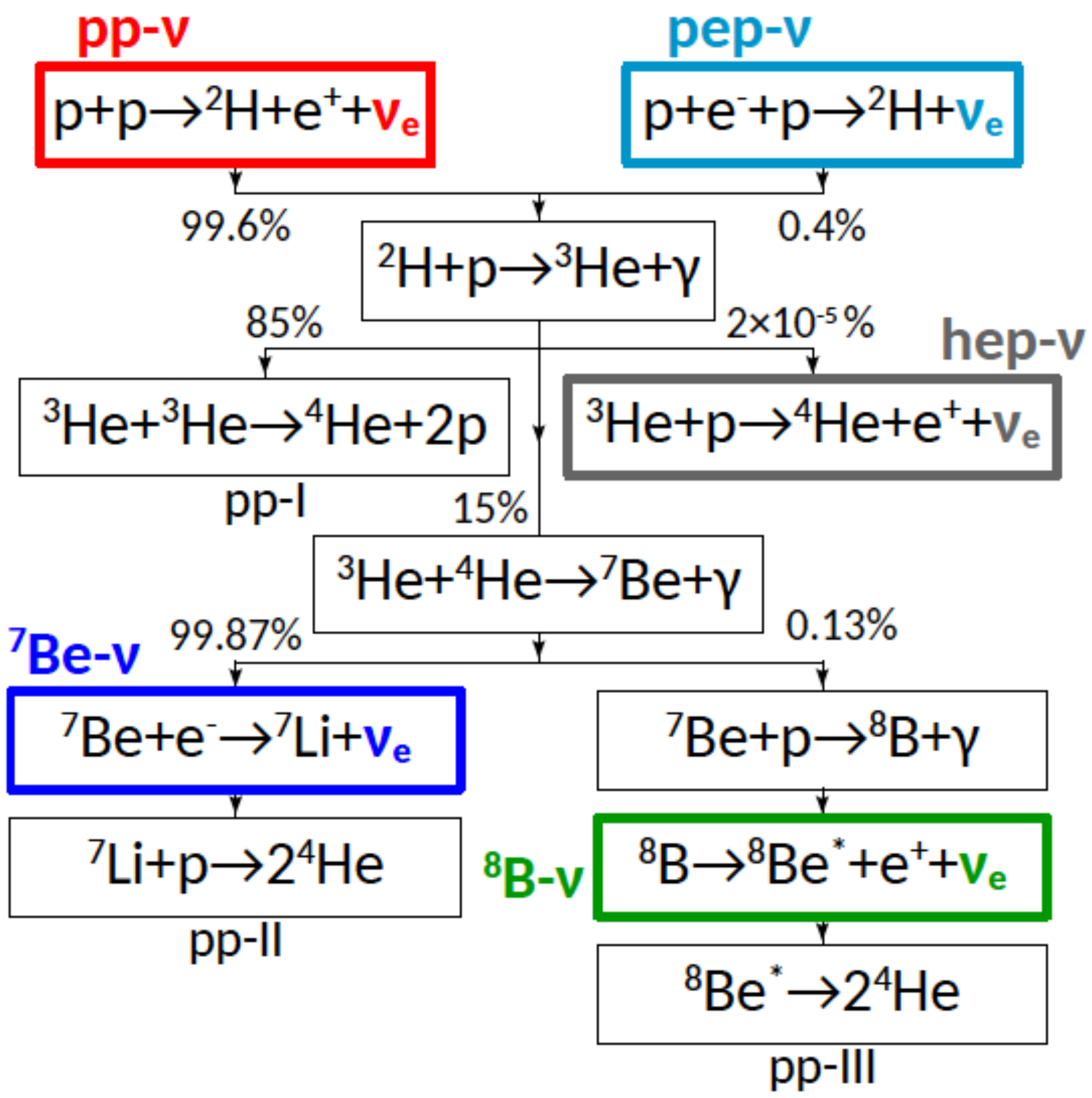
Solar neutrinos

$$4p \rightarrow {}^4He = 2e^+ + 2\nu_e + (24.7 + 2m_e c^2)\ \mathrm{MeV}$$

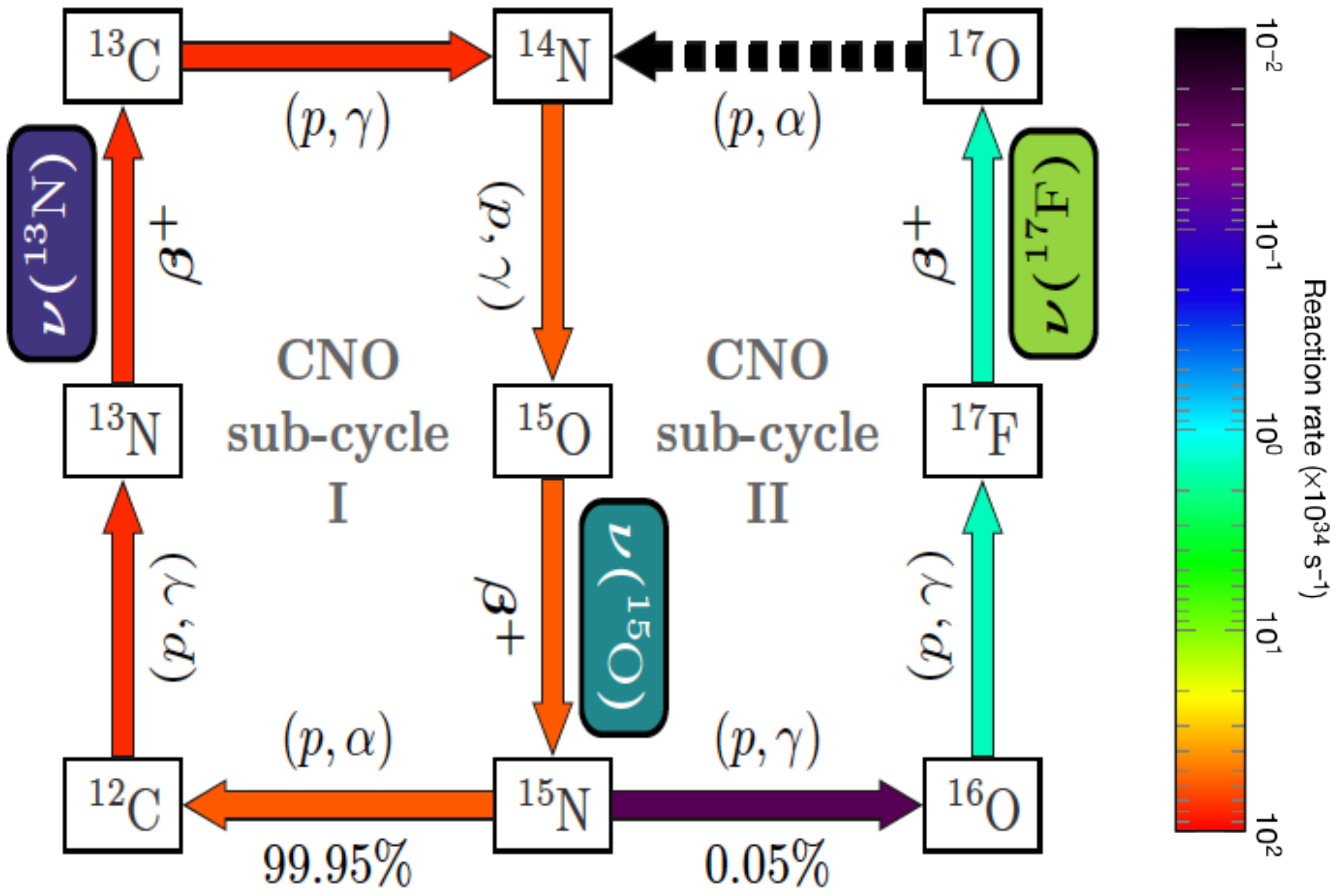
(~2% of the total energy)

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

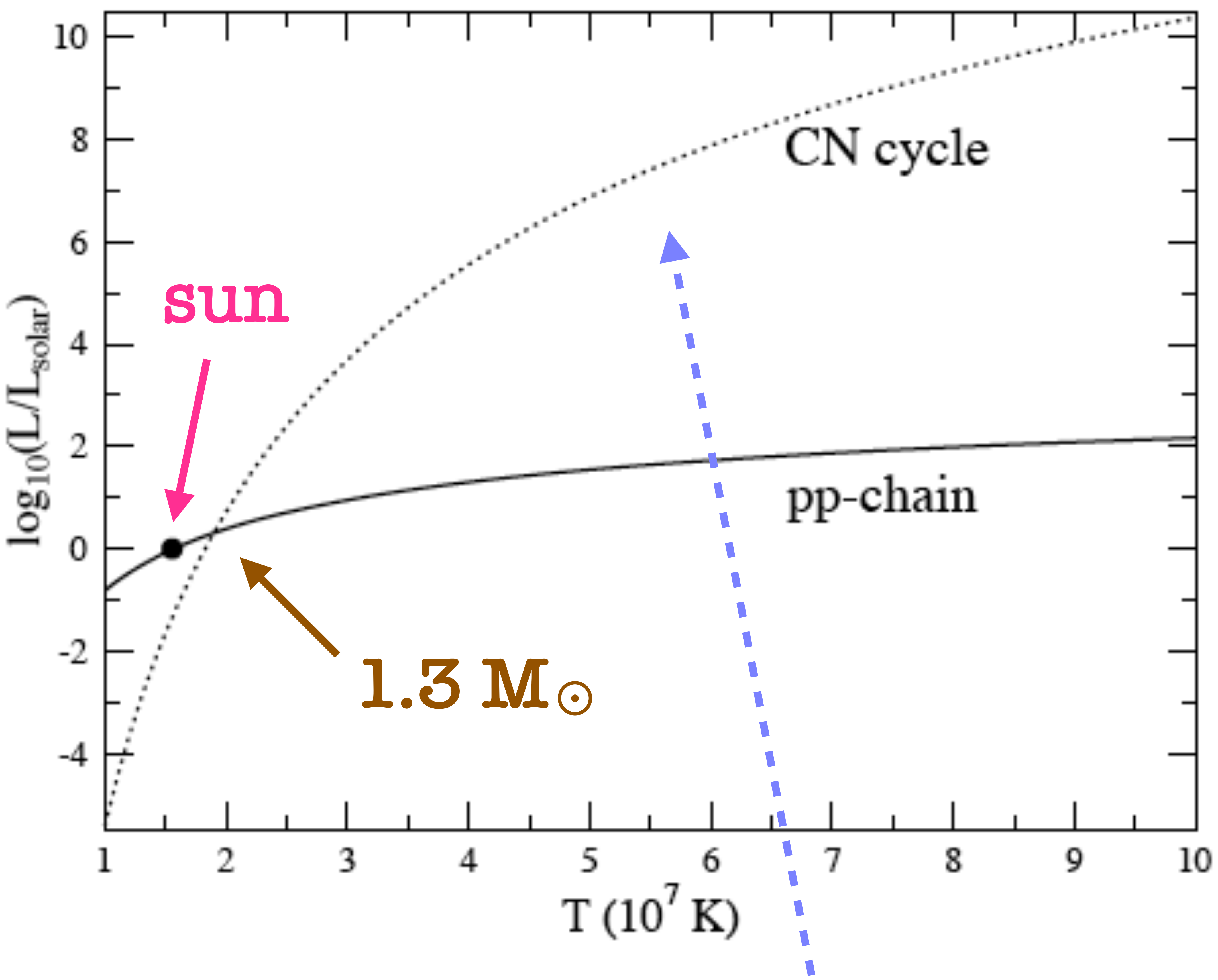
pp chain (~ 99%)



CNO cycle (~ 1%)



Meanwhile, in heavier stars …



in heavier stars the gravitational pressure favors CNO fusion of protons

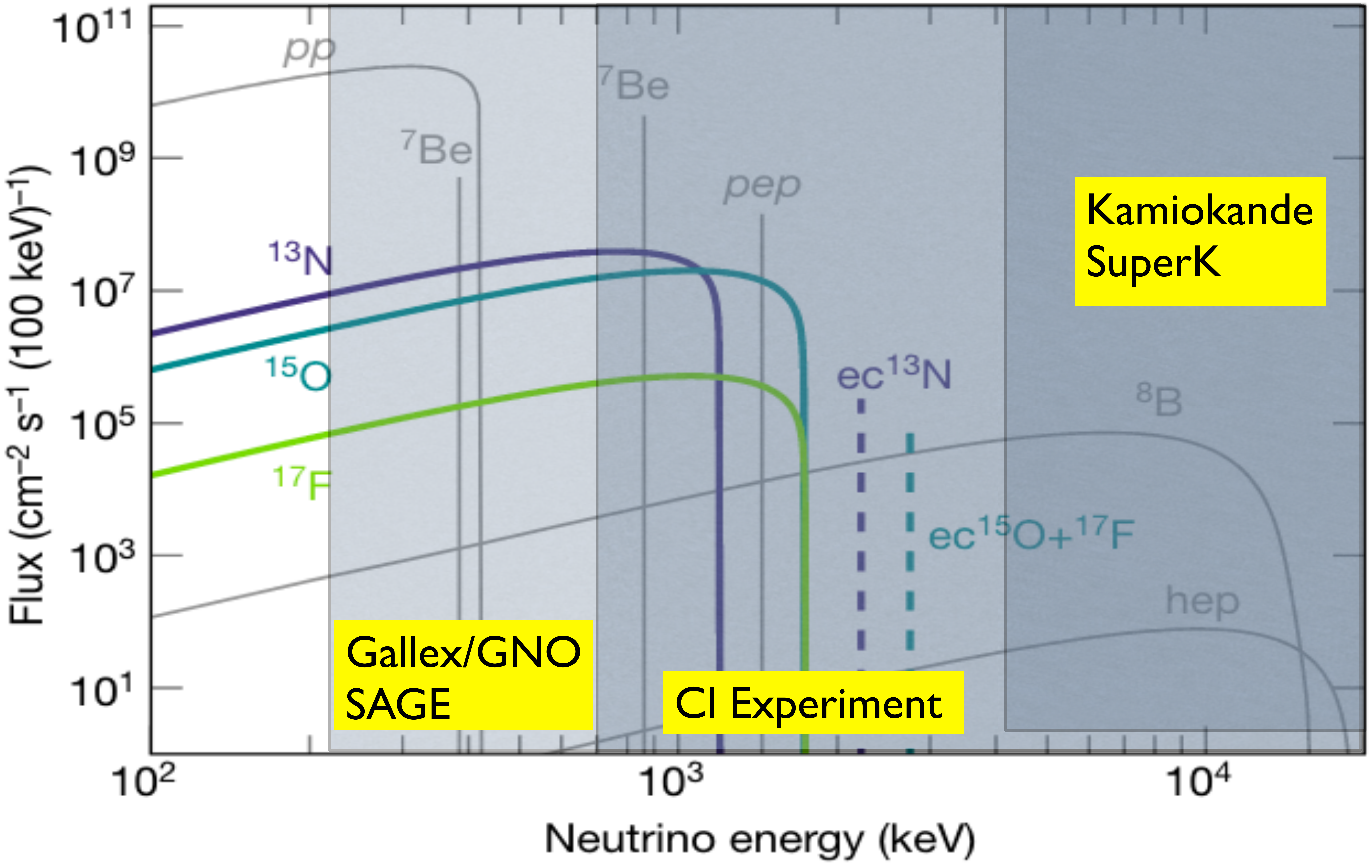
$L_\odot = (3.846 \pm 0.015) \times 10^{53}$ erg/s

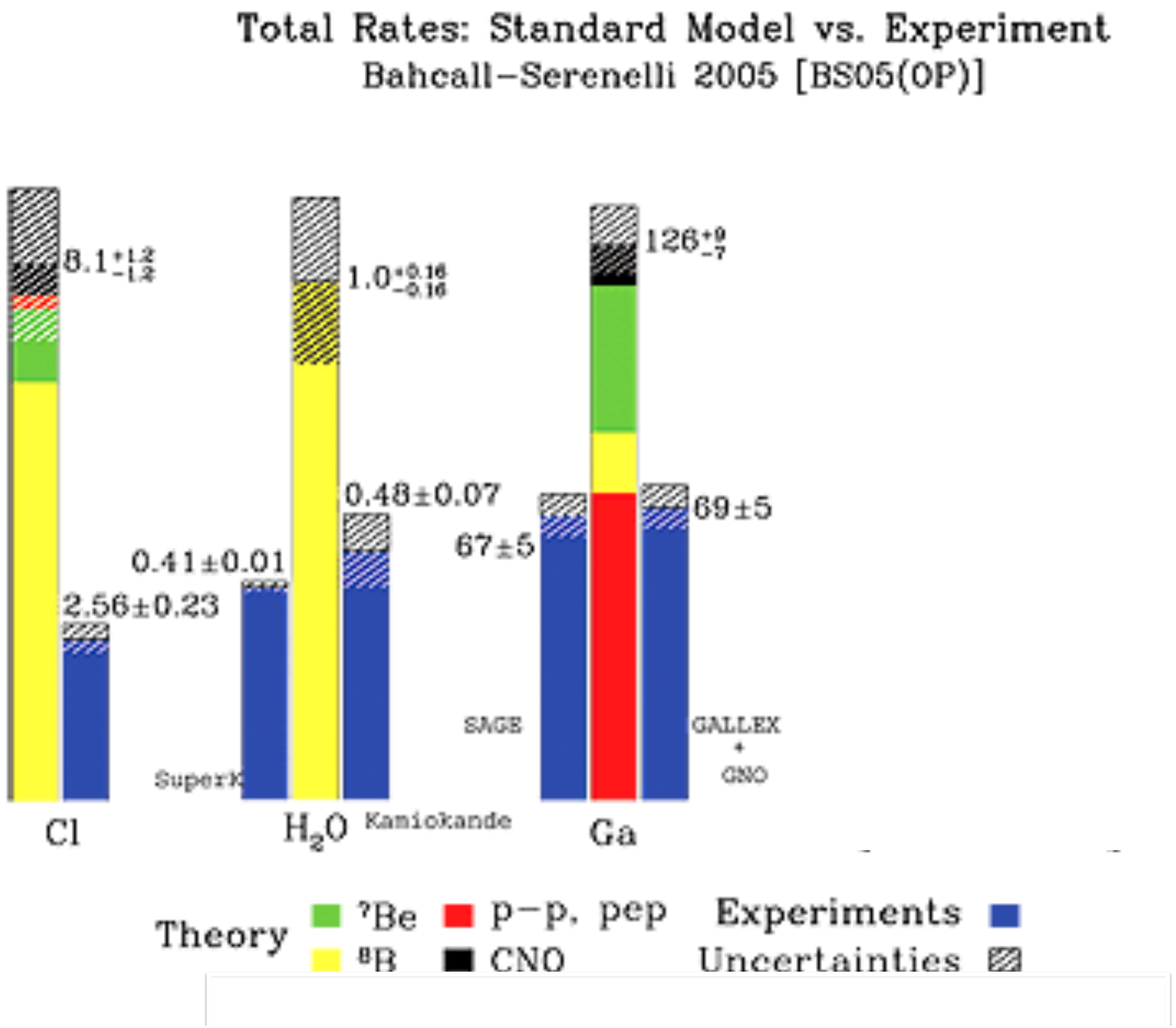
$$\frac{L_\odot}{4\pi(A.U.)^2} = \sum_i a_i \phi_i^\nu$$

CN neutrinos considered the dominant energy producing process in many stars

Solar neutrino puzzle

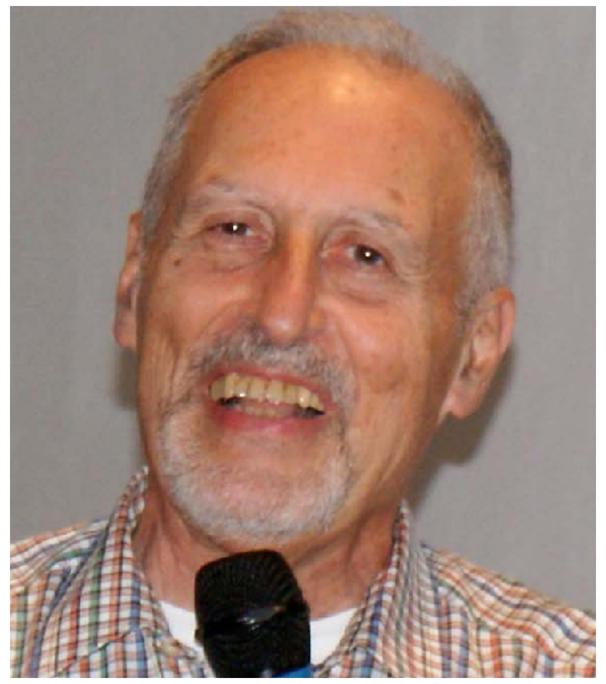
No room left for
^{7}Be neutrinos!

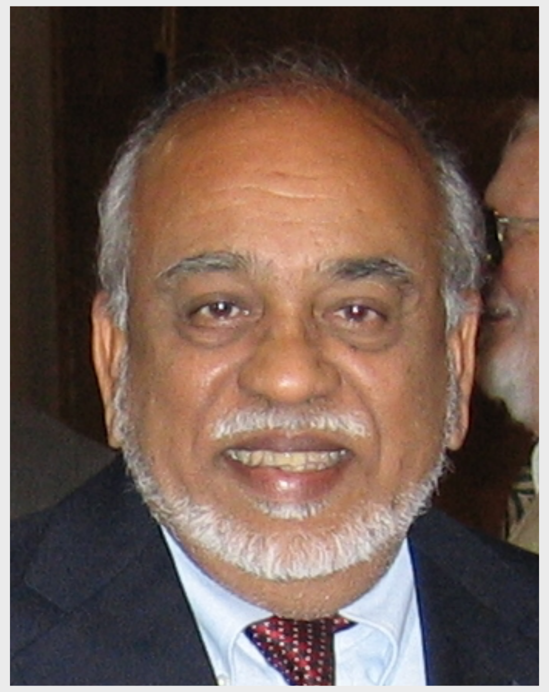




Borexino: the beginning

- Proposed in the early 90s by:
  Gianpaolo Bellini (Milan),
  Frank Calaprice (Princeton)
  Raju Raghavan (Bell Labs)





- Initially Borex (for ^{8}B neutrinos, radiochemical), it morphed into a low-energy (<1 MeV), real-time liquid scintillator experiment -> measure 'missing' ^{7}Be neutrinos
- Key challenge: intrinsic radiopurity

BOREXINO
at Gran Sasso

Proposal for a real time detector for low energy solar neutrinos

Volume 1
August 1991

P. Trincherini
C.C.R. Euratom, ISPRA, (VA) - Italy.

G. Alimonti, R. Bassini, G. Bellini, S. Bonetti,
S. Brambilla, M. Campanella, W. Cavaletti., P. D'Angelo,
M. di Corato, M. Giammarchi, D. Giove, D. Giugni, P. Inzani,
I. Iori, S. Malvezzi, L. Manduci, I. Manno, E. Meroni,
A. Moroni, L. Perasso, F. Ragusa, G. Ranucci, G. Salmini,
R. Scardaoni, D. Torretta, V. Torri, P. Ullucci
Physics Dept. of the University and INFN
Milano - Italy

T. Kovacs, J. Mitchell, P. Raghavan, R.S. Raghavan
AT&T Bell Laboratories
Murray Hill NJ - U.S.A.

P. Benetti, B. Bertotti, G. Cecchet, A. De Bari,
A. Minoia, L. Pezzotti, A. Perotti
Physics Dept. of the University and INFN
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B. Alpat, F. Elisei, G. Levi, G. Mantovani
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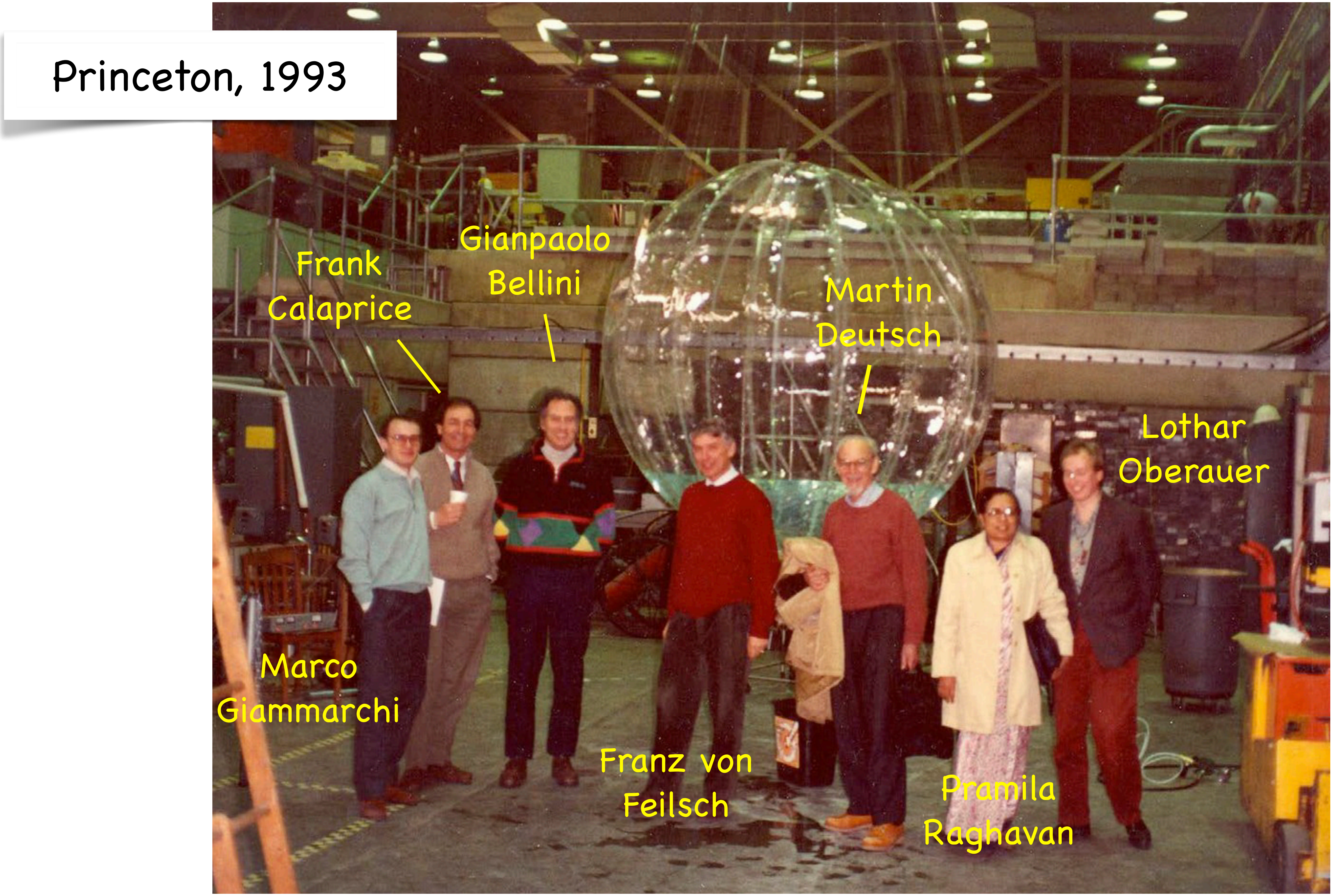
J. Cilc, J. Dostal, Michael Finger, Miroslav Finger,
Z. Janout, F. Kubalek, M. Tomasek
Charles University, Prague
The Czech Technical University, Prague - Czechoslovakia

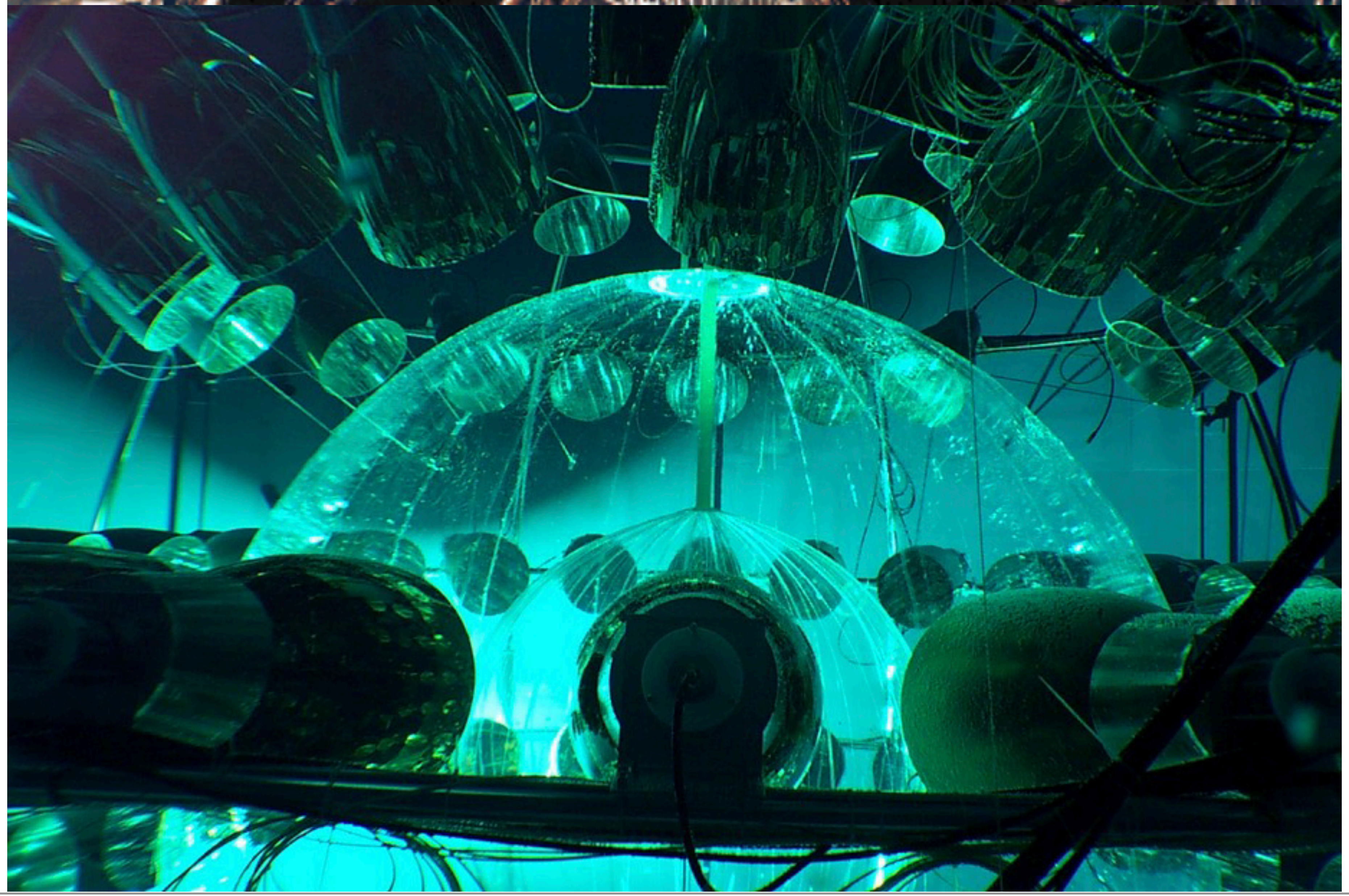
F.P. Calaprice
Physics Dept., Princeton University
Princeton NJ - U.S.A.

Borexino: early days



The Counting Test Facility (CTF) (1995-2001)

- 4-tonne test facility
- Record scintillator radio purity:
  - ^{232}Th, ^{238}U < 10^{-16} g/g
  - $^{14}C/^{12}C = 2 \times 10^{-18}$
- Nylon vessel concept for scintillator containment



Ideas ahead of their time

VOLUME 72, NUMBER 10 PHYSICAL REVIEW LETTERS 7 MARCH 1994

New Approach to the Search for Neutrinoless Double Beta Decay

R. S. Raghavan

AT&T Bell Laboratories, Murray Hill, New Jersey 07974

(Received 9 November 1993)

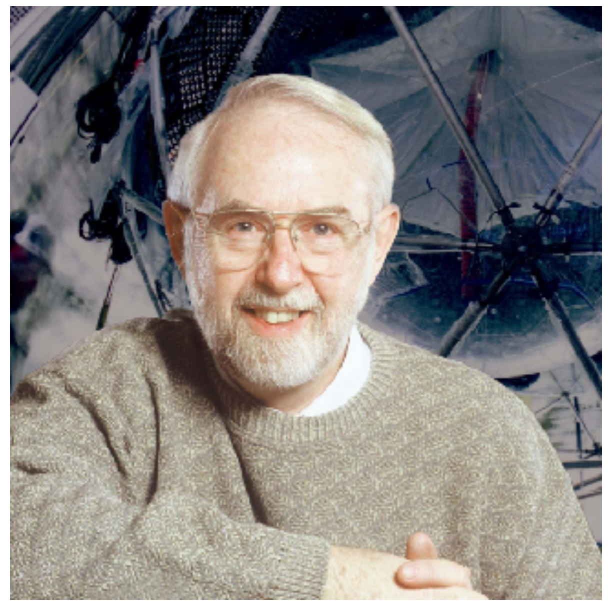
Sub-eV Majorana neutrino masses $\langle m_\nu \rangle$, can be explored by a new approach to neutrinoless double β decay using ^{136}Xe in a Xe gas-loaded, multiton liquid scintillator installed in a very low background detector such as the Kamiokande facility. With enriched ^{136}Xe, a readily implementable, 10 ton detector experiment can establish an $\langle m_\nu \rangle = 0.45$ eV at 3σ in 1 yr (or exclude an $\langle m_\nu \rangle < 0.23$ eV in 2 yr). A 100 ton detector can extend the limit to $\langle m_\nu \rangle < 0.1$ eV, compared with the present limit of $\langle m_\nu \rangle < 1.3$ eV.

KamLAND-Zen
arXiv:2203.02139

(Dated: March 7, 2022)

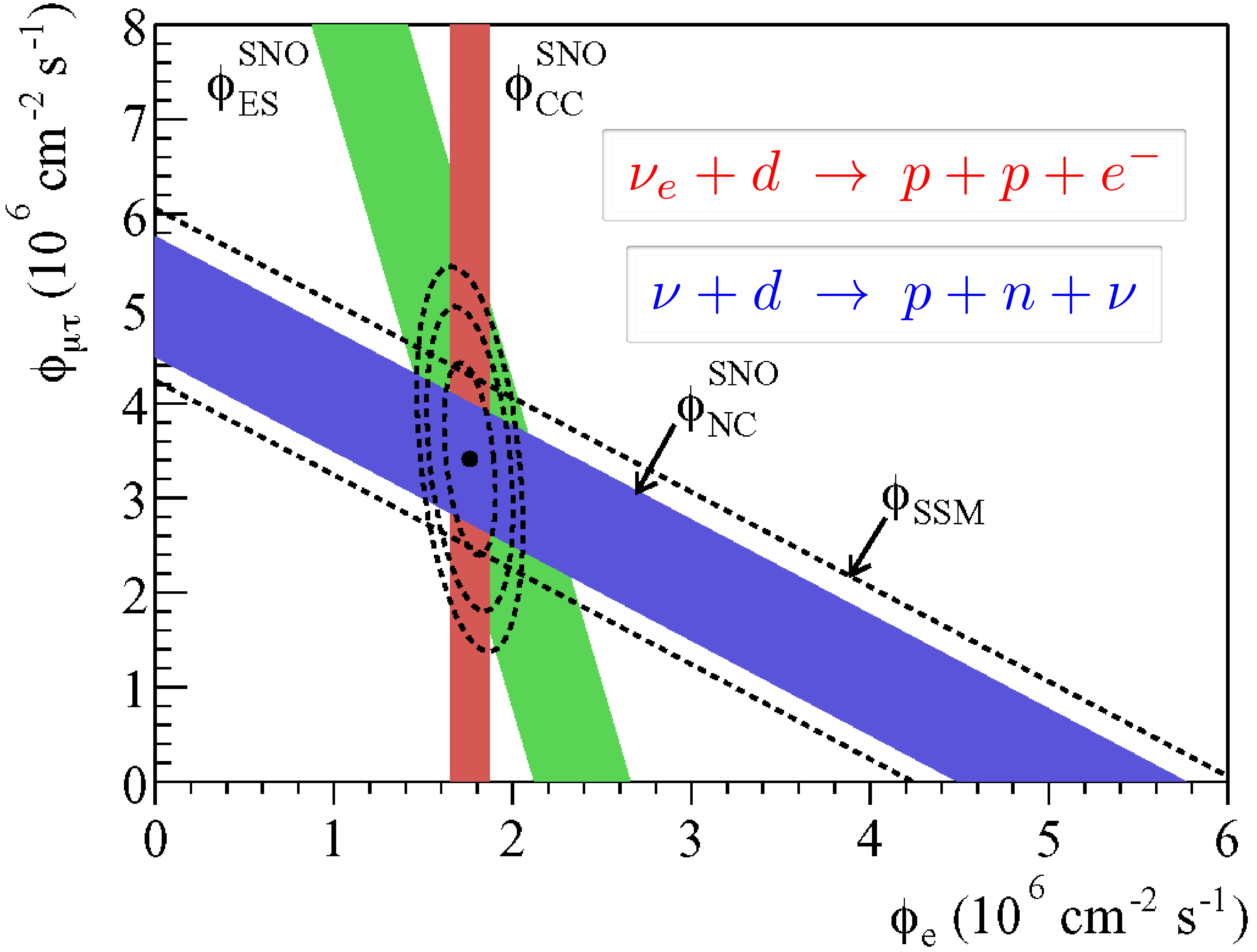
The KamLAND-Zen experiment has provided stringent constraints on the neutrinoless double-beta ($0\nu\beta\beta$) decay half-life in ^{136}Xe using a xenon-loaded liquid scintillator. We report an improved search using an upgraded detector with almost double the amount of xenon and an ultra-low radioactivity container, corresponding to an exposure of 970 kg yr of ^{136}Xe. This new data provides valuable insight into backgrounds, especially from cosmic muon spallation of xenon, and has required the use of novel background rejection techniques. We obtain a lower limit for the $0\nu\beta\beta$ decay half-life of $T^{0\nu}_{1/2} > 2.3 \times 10^{26}$ yr at 90% C.L., corresponding to upper limits on the effective Majorana neutrino mass of 36 – 156 meV using commonly adopted nuclear matrix element calculations.

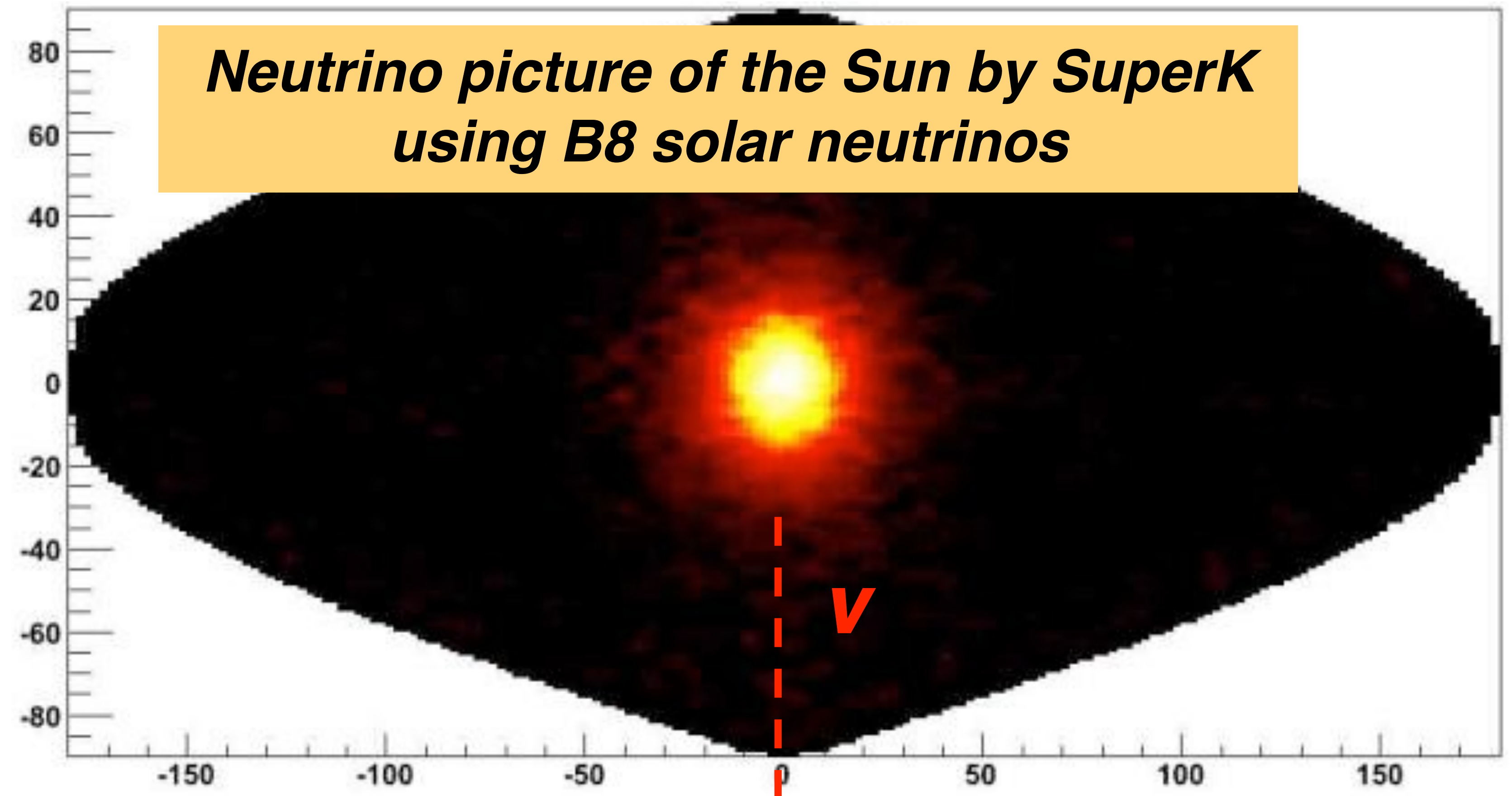
Solar ν oscillations (SNO)

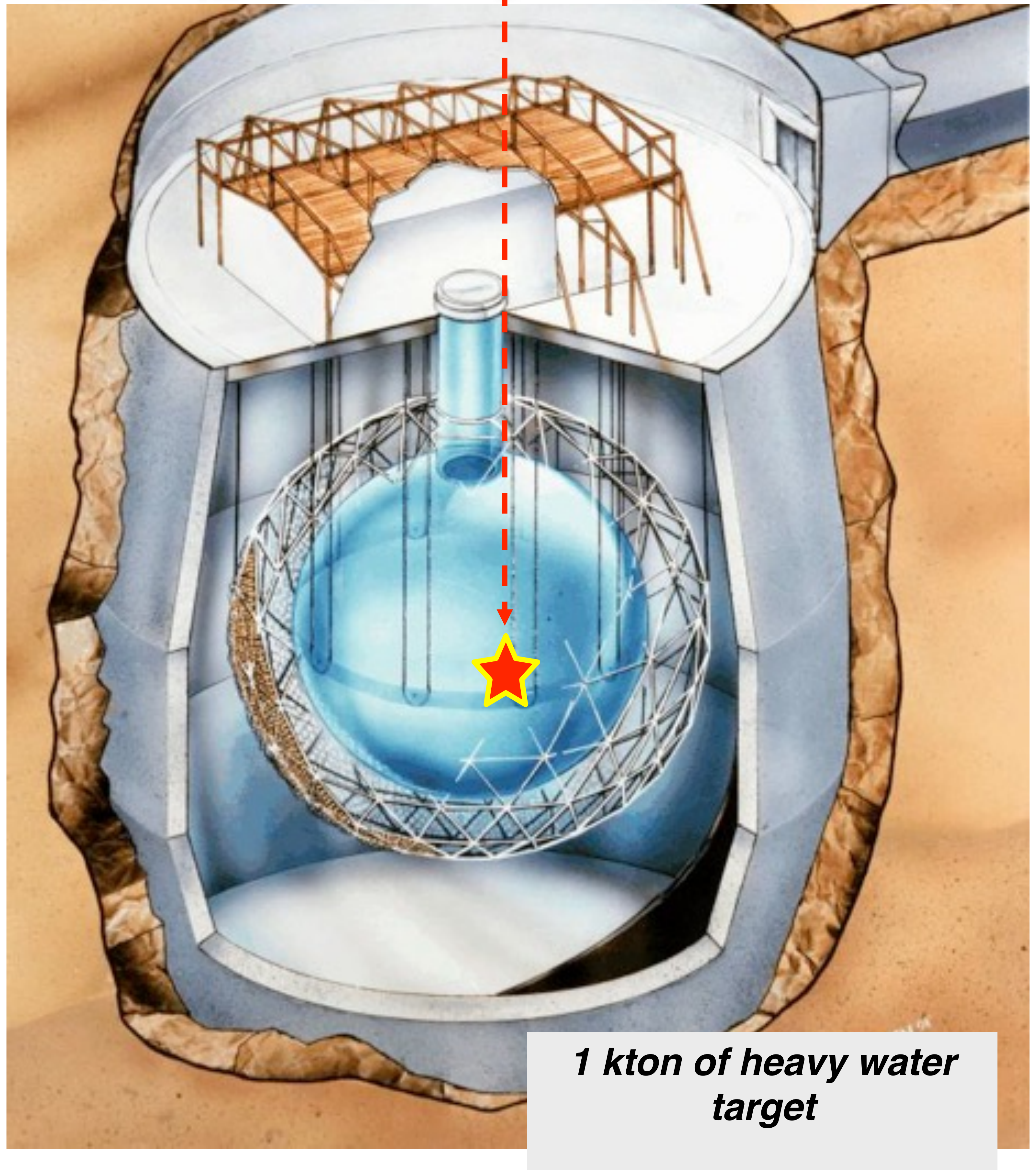


by exploiting 2 different reactions on deuterium, the SNO experiment proved that ν_e produced in fusion reactions in the sun have turned (oscillated) into $\nu_{\mu,\tau}$ when they are detected on earth

Phys. Rev. Lett. 89, 011301 (2002)







Solar neutrino puzzle

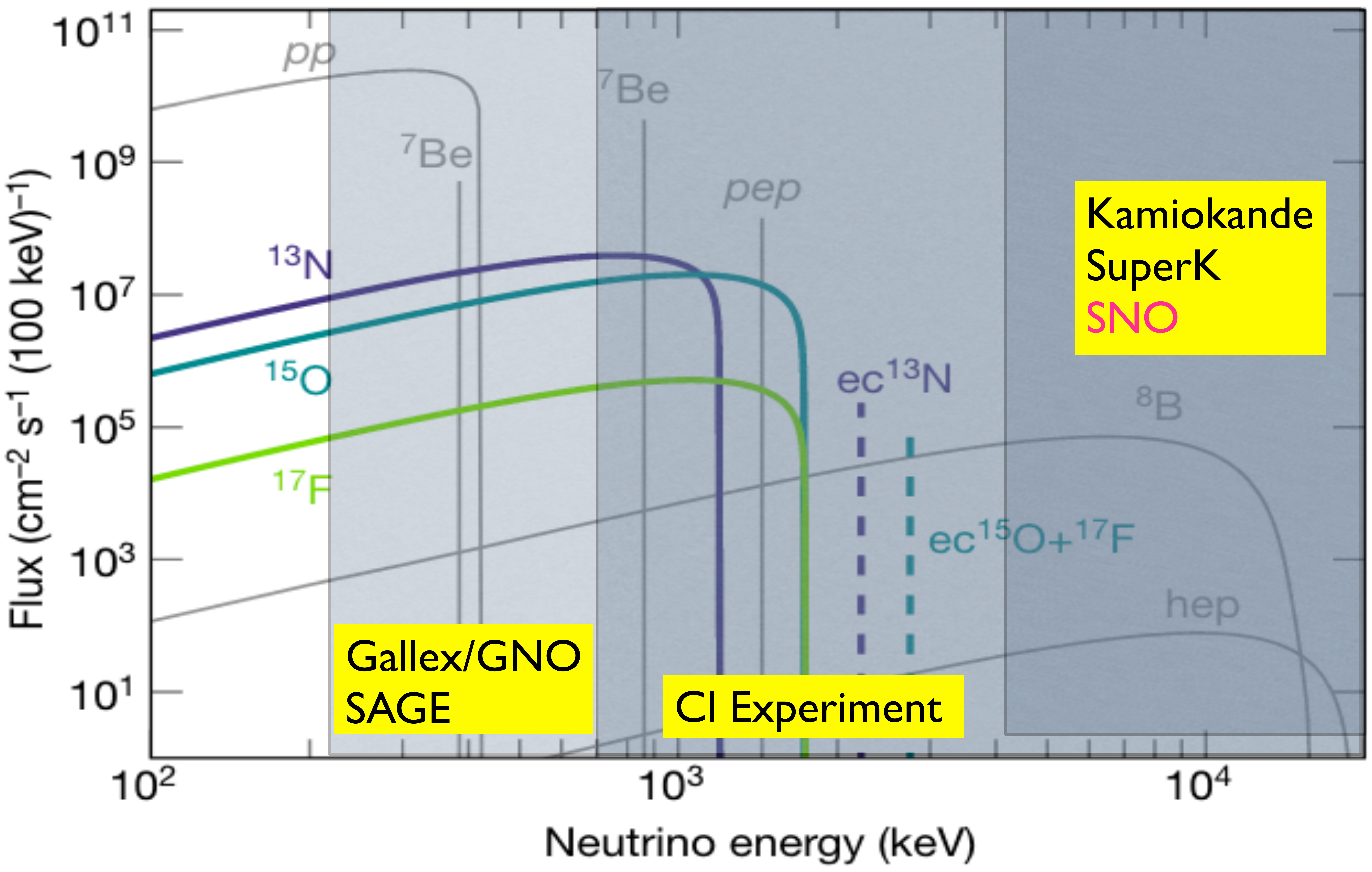
gallium → ~1/2

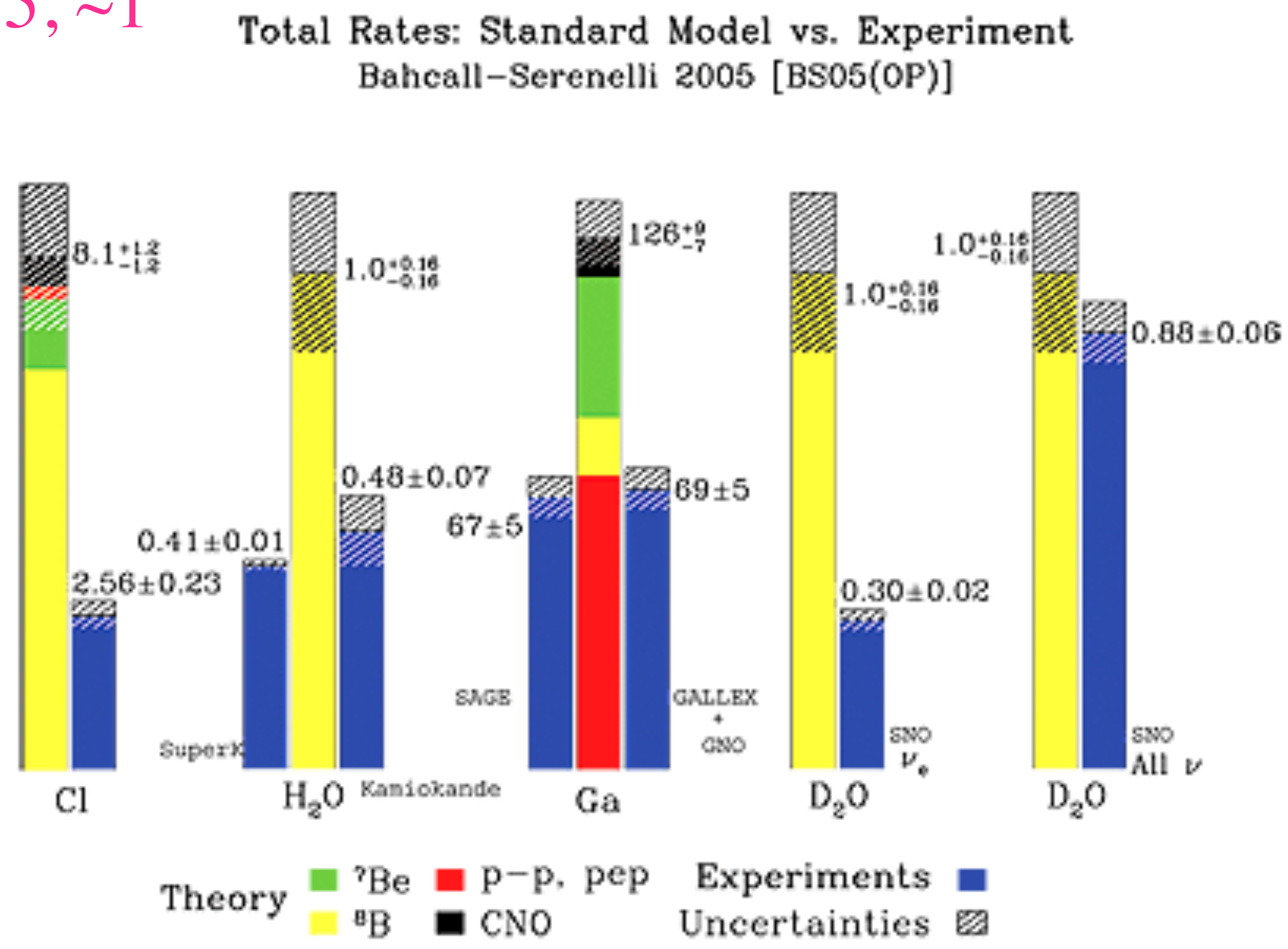
water → ~2/5

chlorine → ~1/3

D_2O → ~1/5, ~1

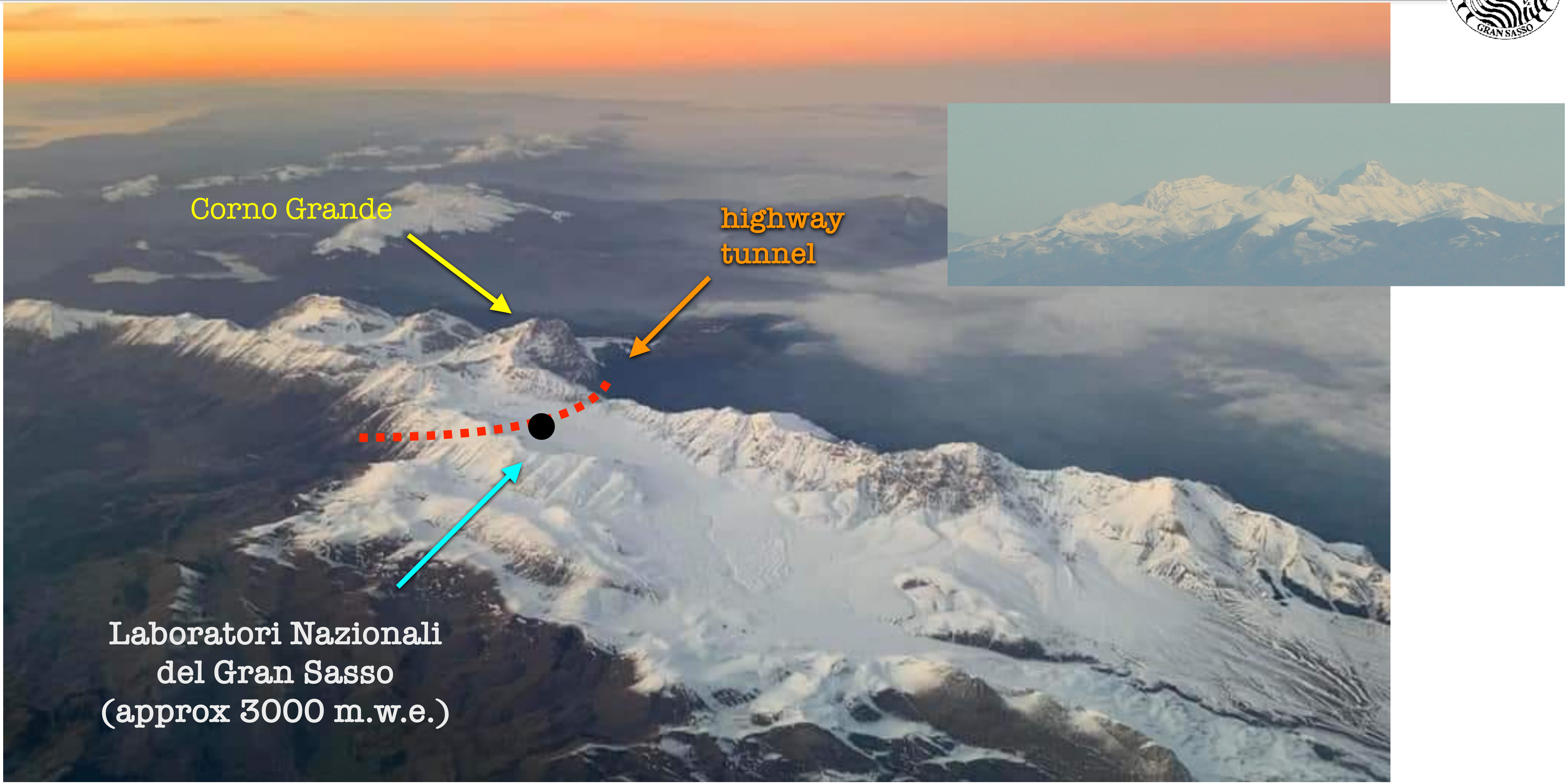
No room left for ^{7}Be neutrinos!



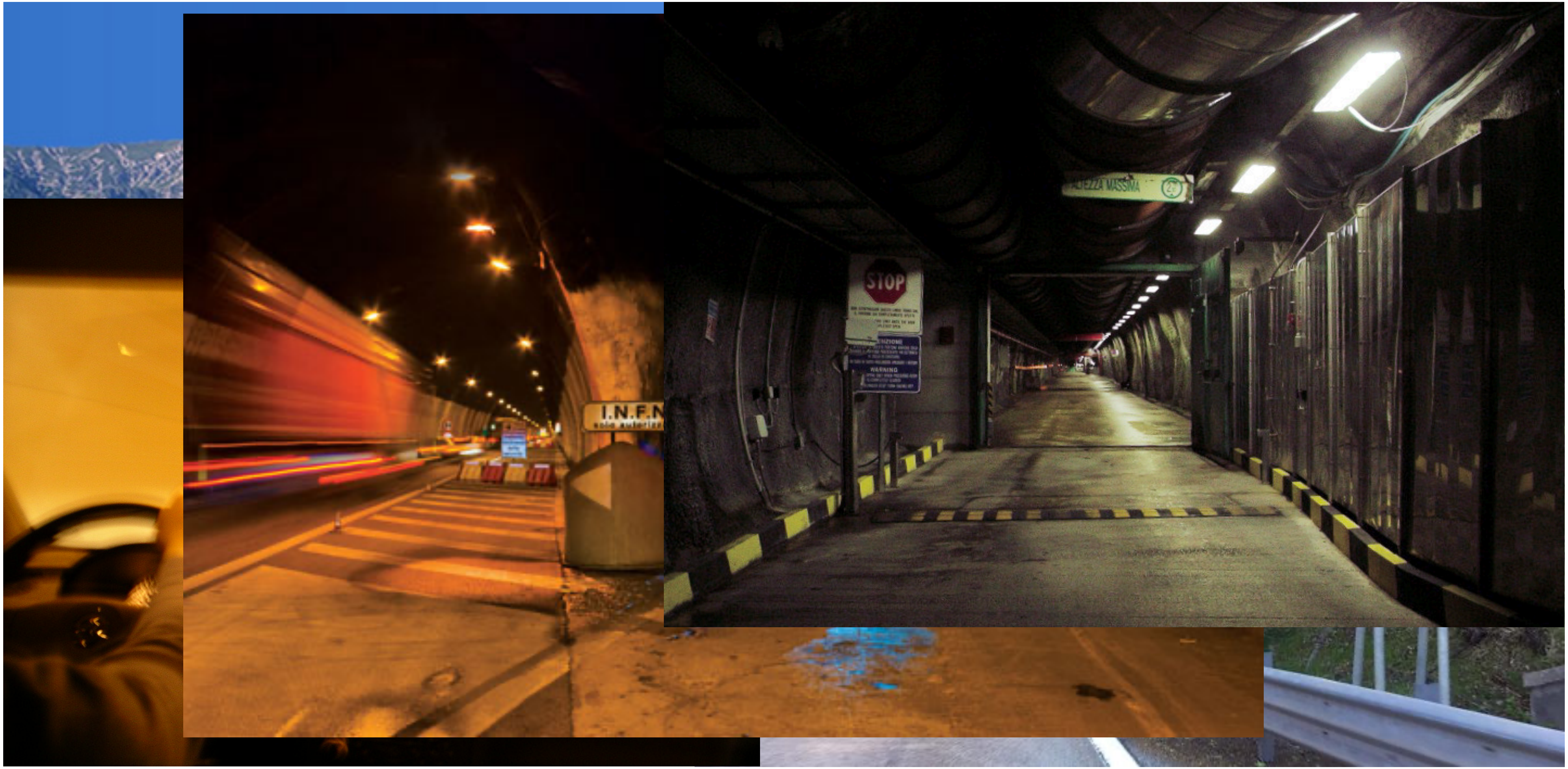


neutrino oscillations!

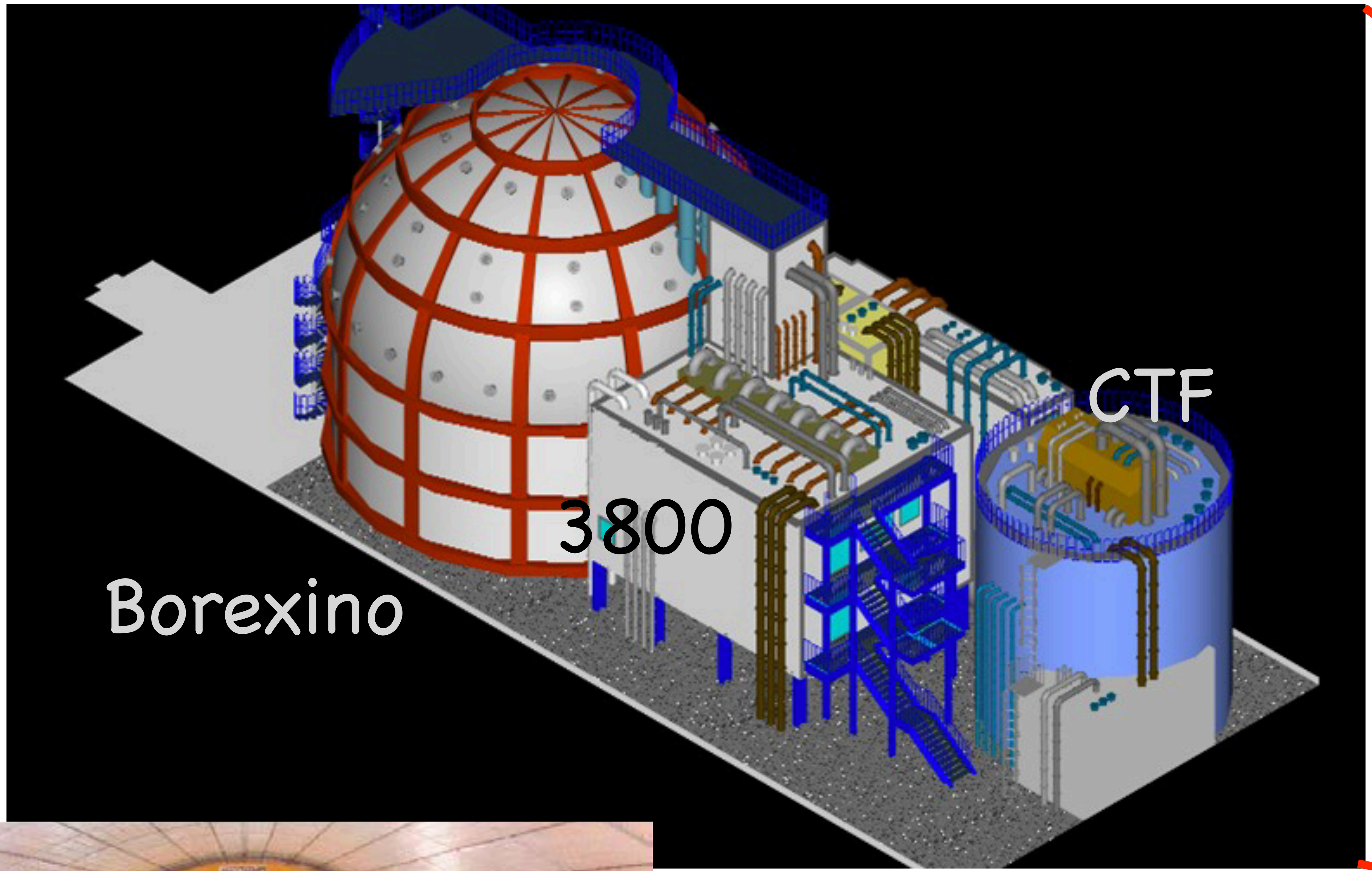
Back to Gran Sasso

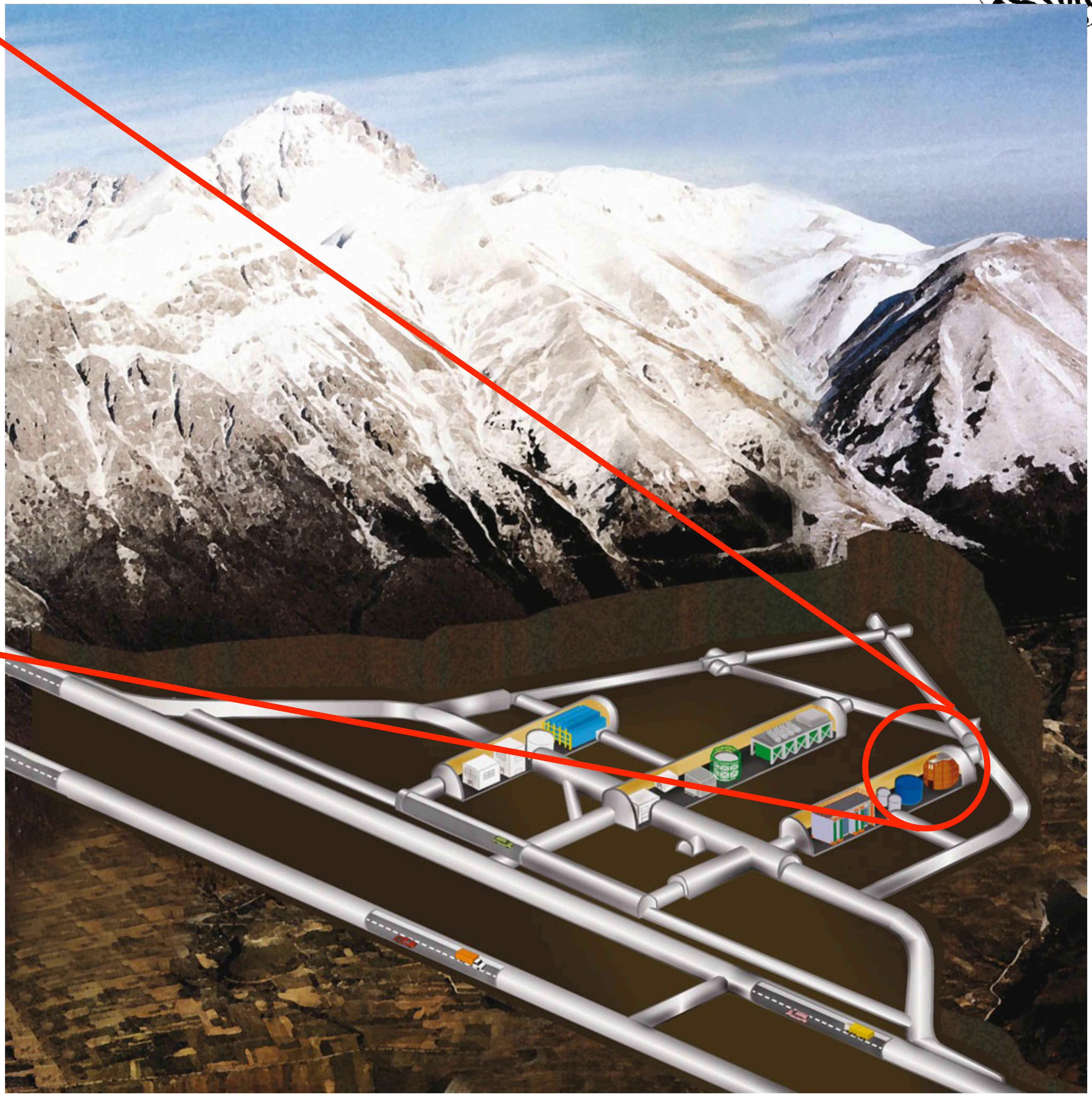


Into the tunnel, deep underground



Hall C @ LNGS





3800 m.w.e.
ca. 1 muons/m²/h

the Borexino detector

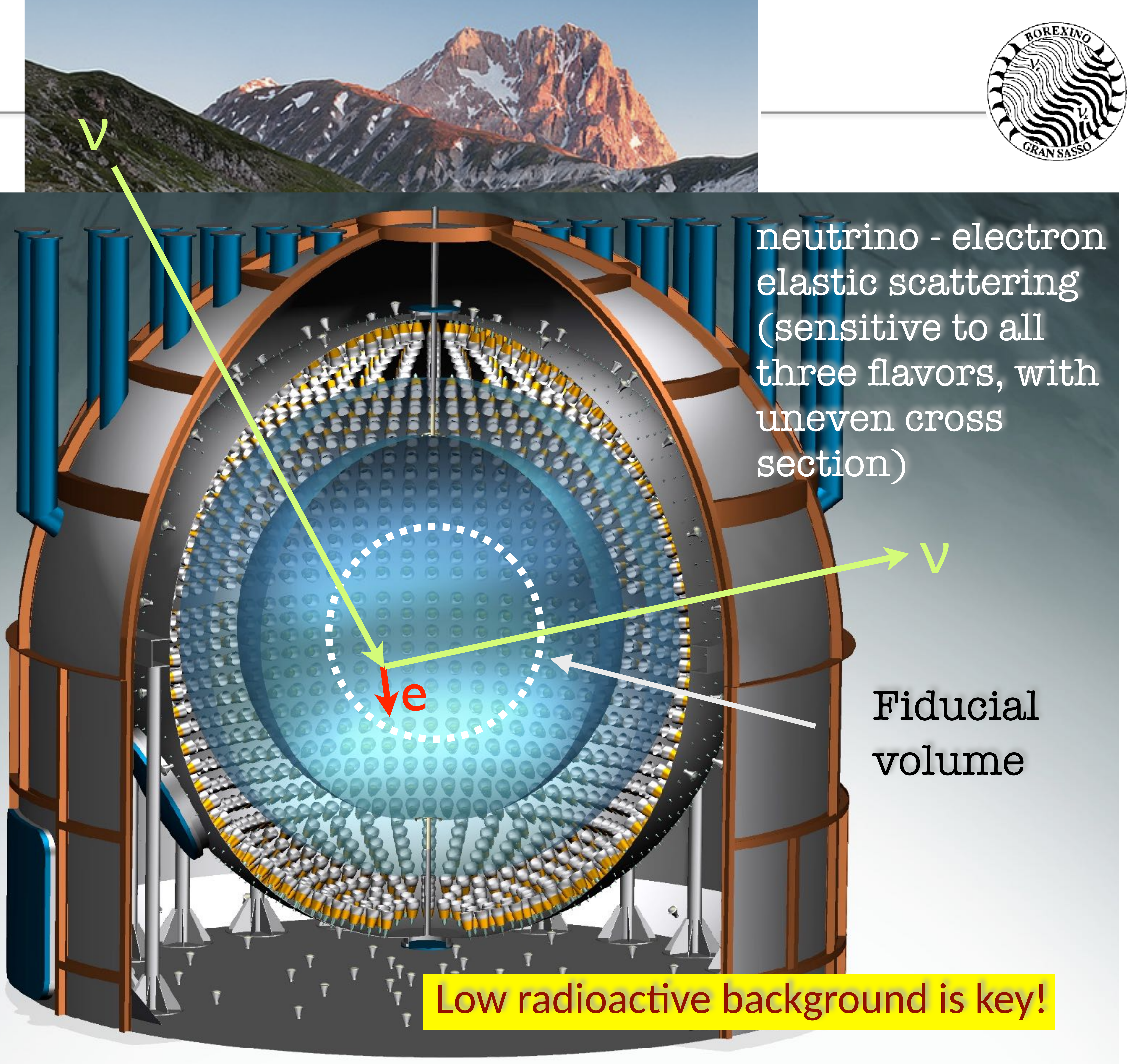
Scintillator:
280 t PC+PPO (1.5g/l) in a 125 μm thick
Inner nylon vessel (R=4.25m)

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

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

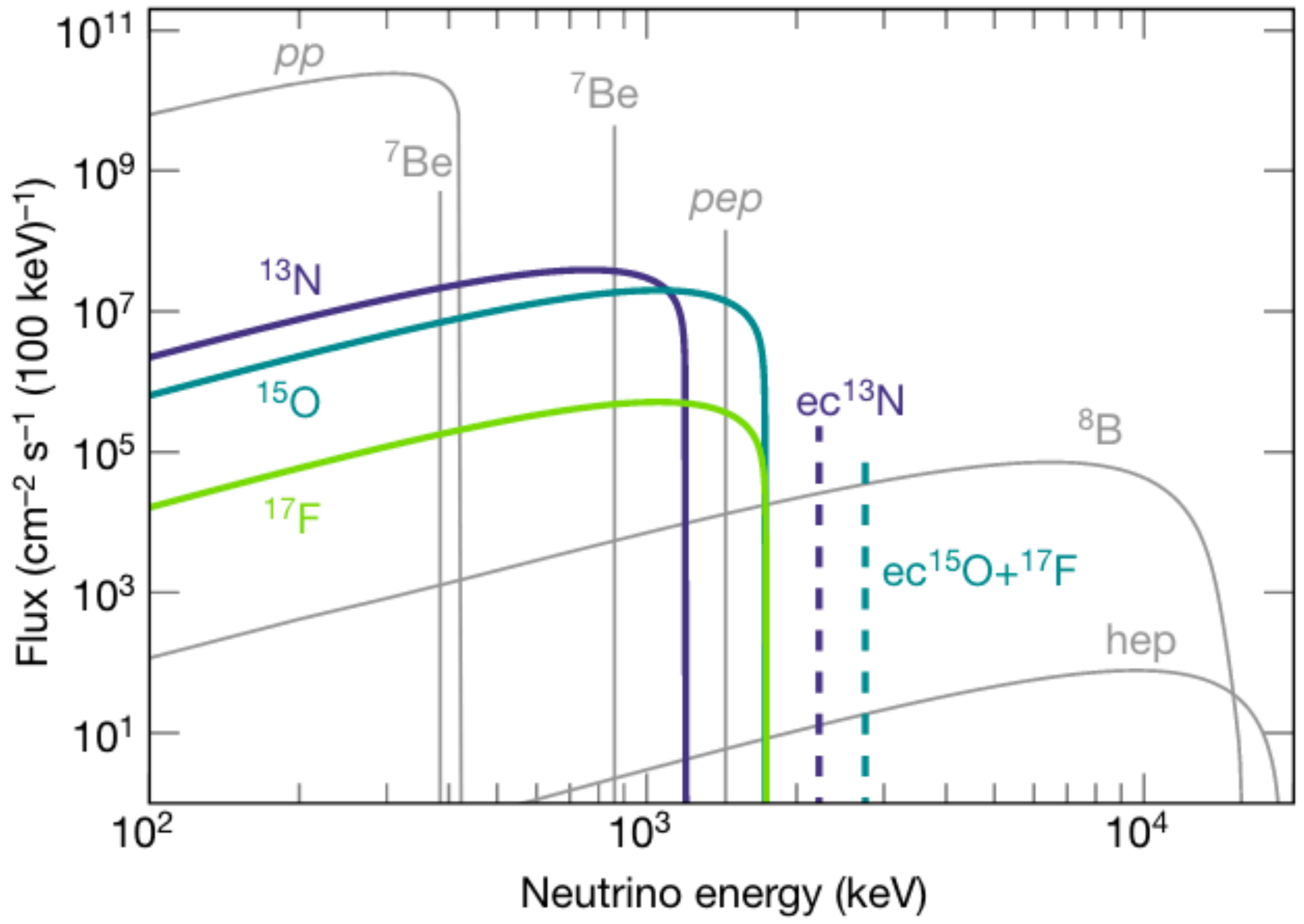
Stainless Steel Sphere:
R=6.75m,
2212 8” PMTs with light guides. 1350m^3

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

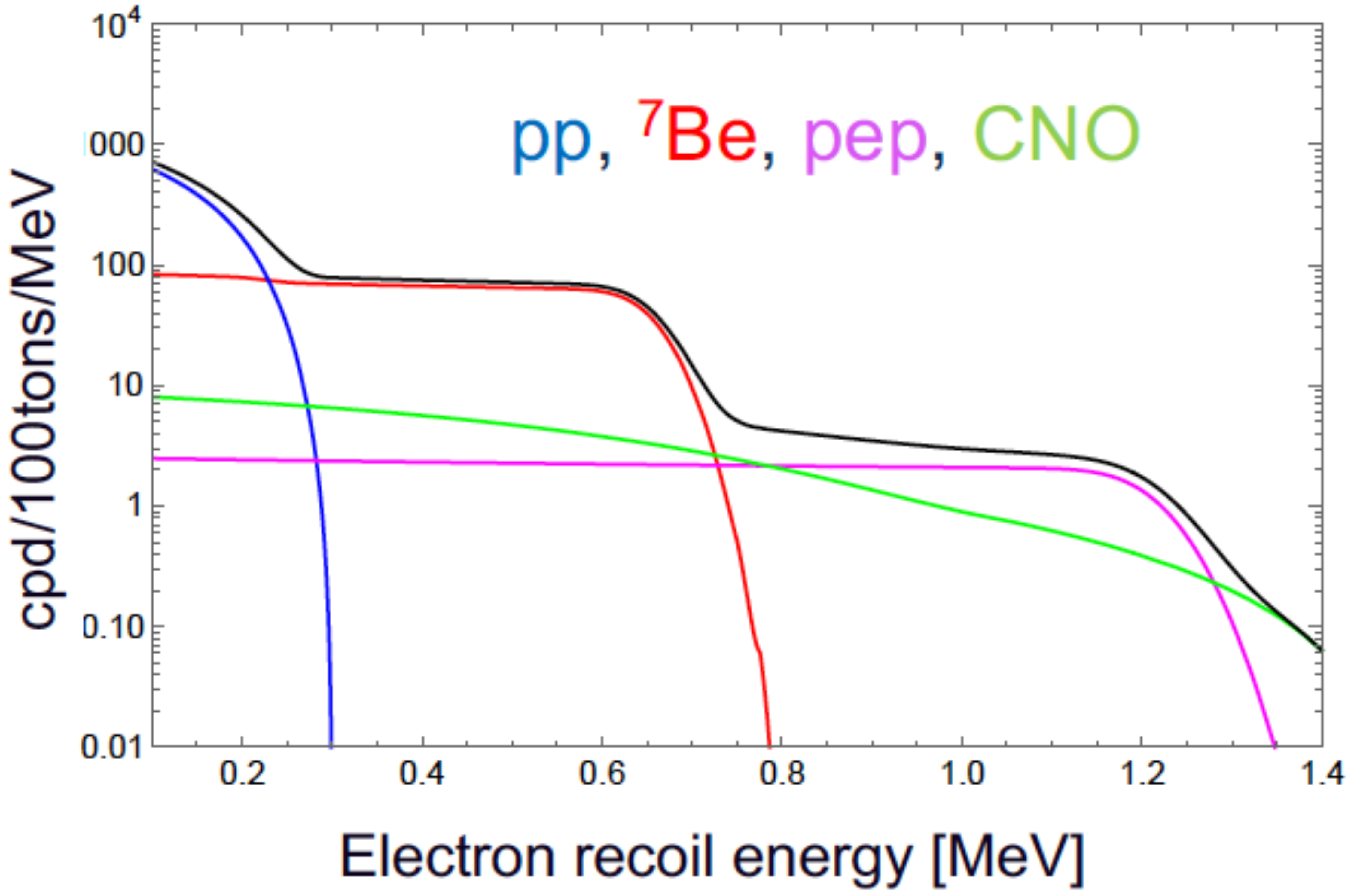


The Physics: solar neutrino spectrum

solar neutrino spectrum

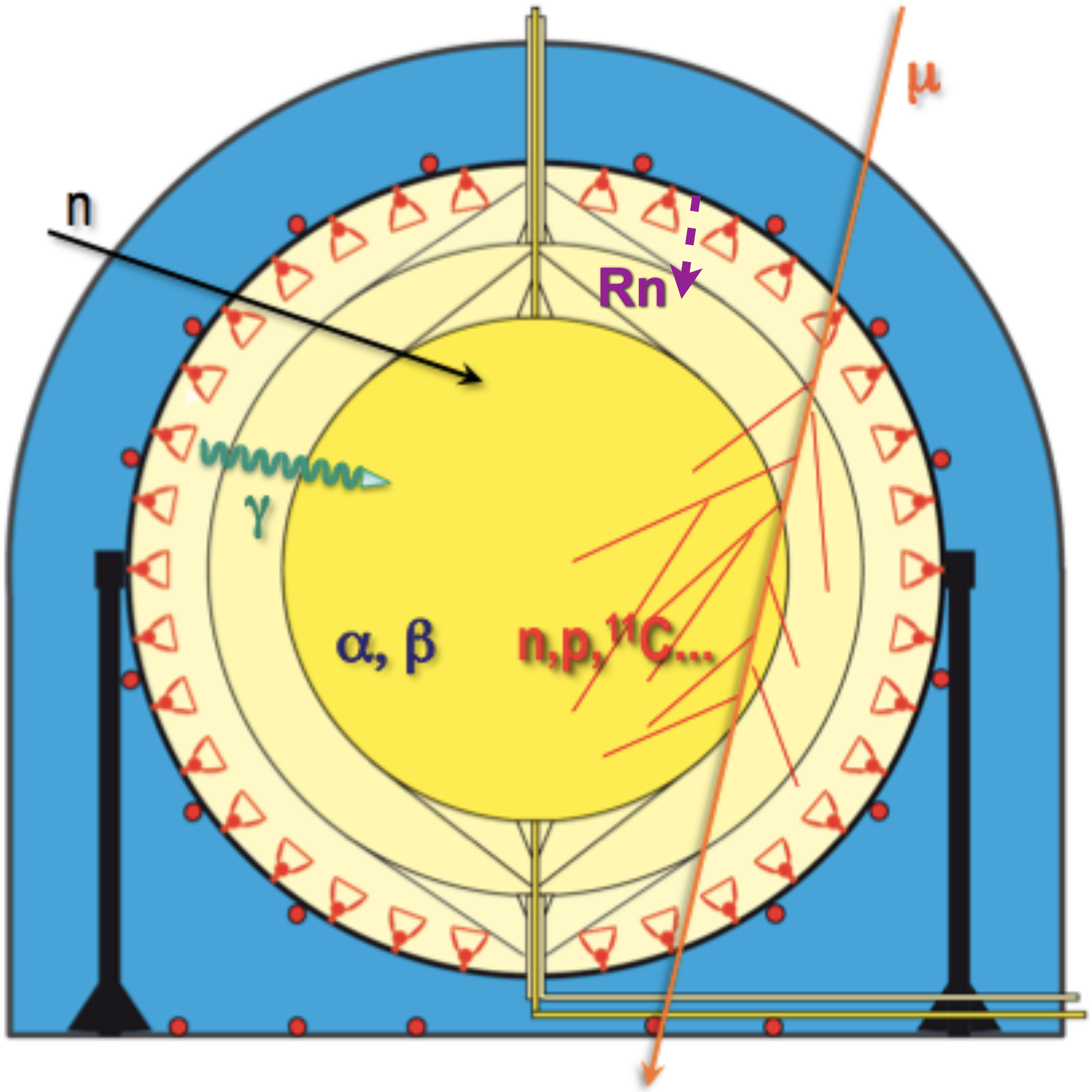


solar neutrino-induced electron scattering spectrum in Borexino



Little directional information —> minimizing radioactivity is essential

Known backgrounds



internal radioactivity
traces of radioisotopes in the scintillator (U,Th,^{40}K)

external γ rays
from fluid buffer, steel sphere, PMT glass and light concentrators (^{40}K,^{208}Tl,^{214}Bi)

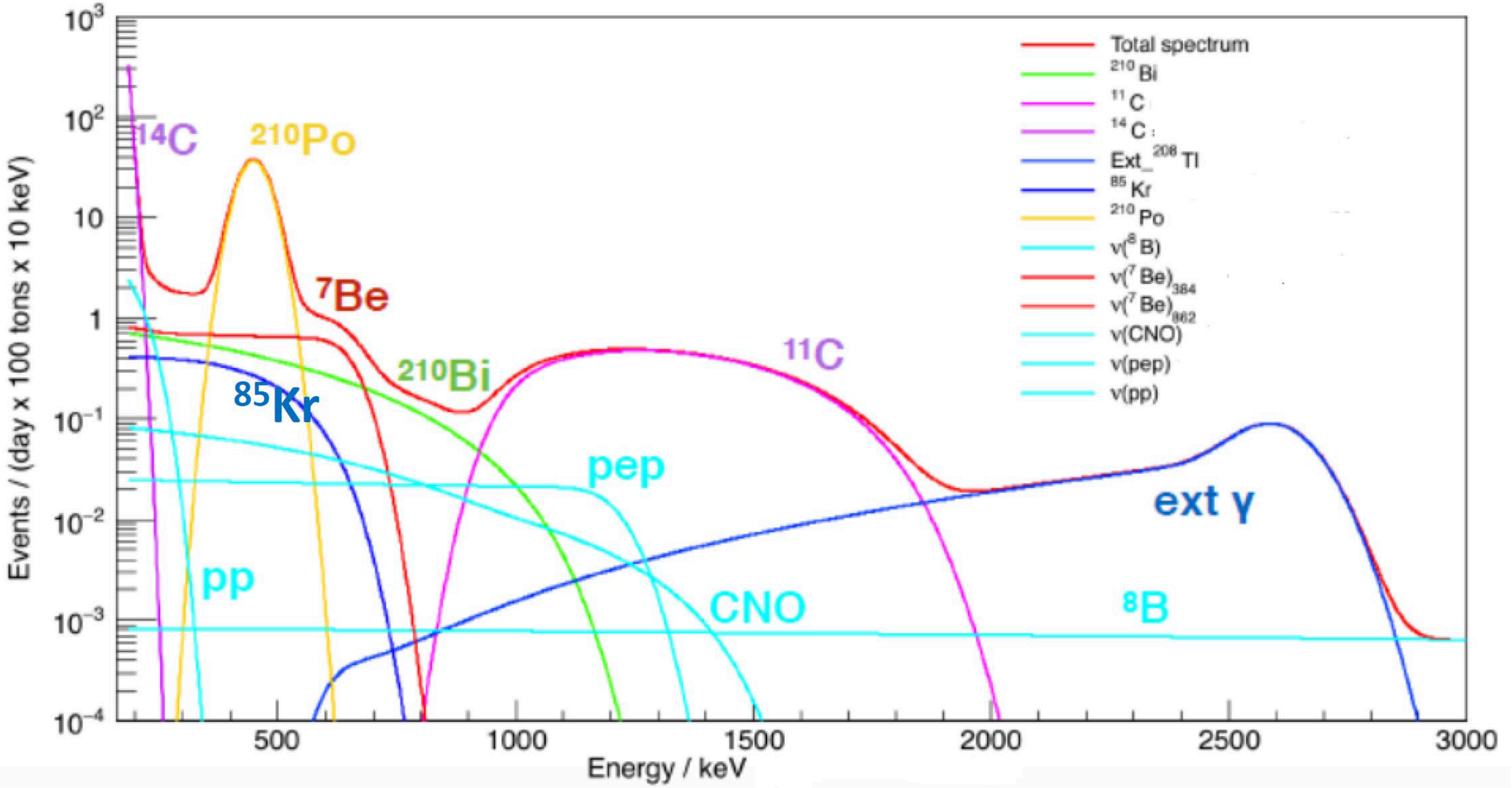
radon emanation
from the PMTs and steel sphere

cosmic muons
and their secondaries

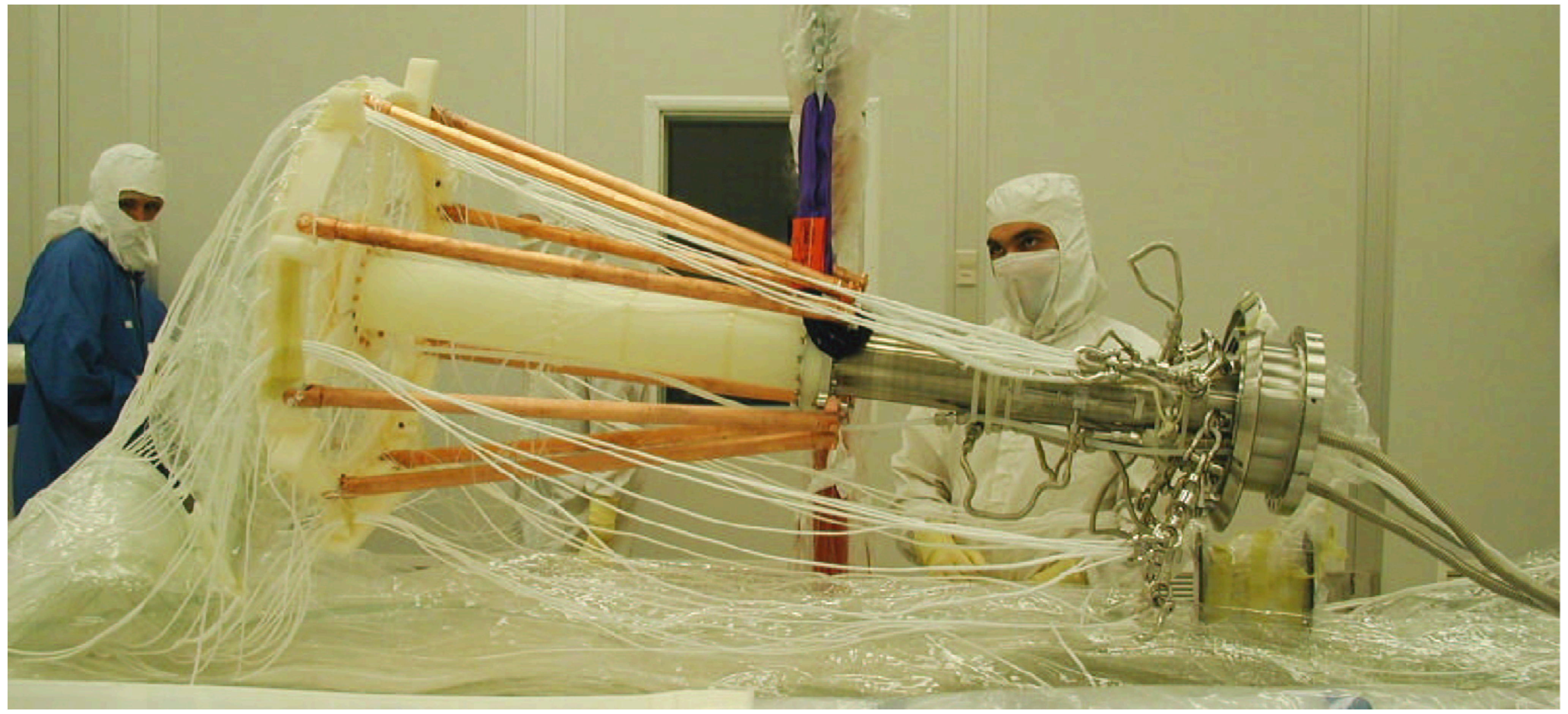
cosmogenics
neutrons and radionuclides from μ spallation and hadronic showers

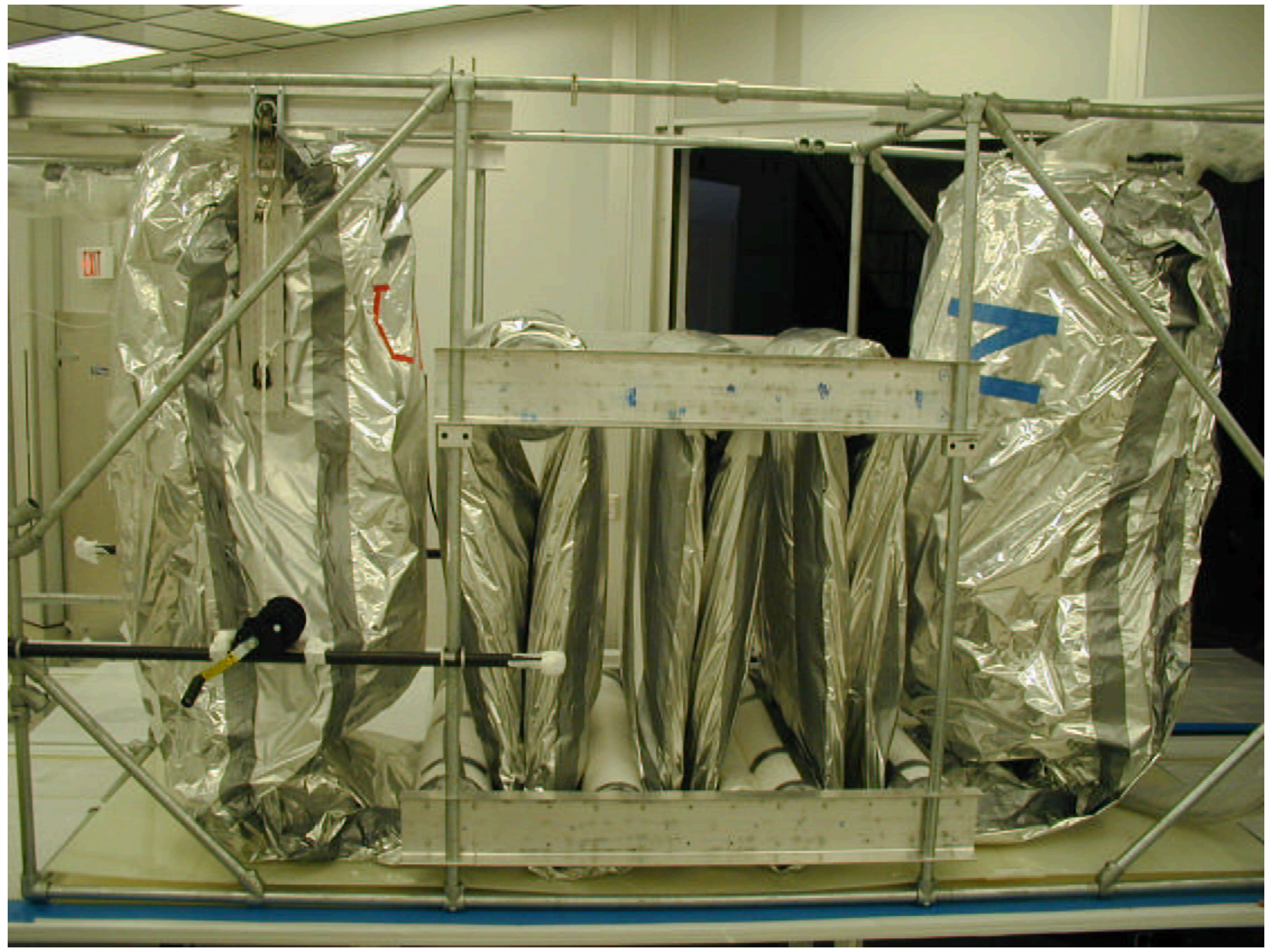
fast neutrons
from external muons

Decomposing the spectrum



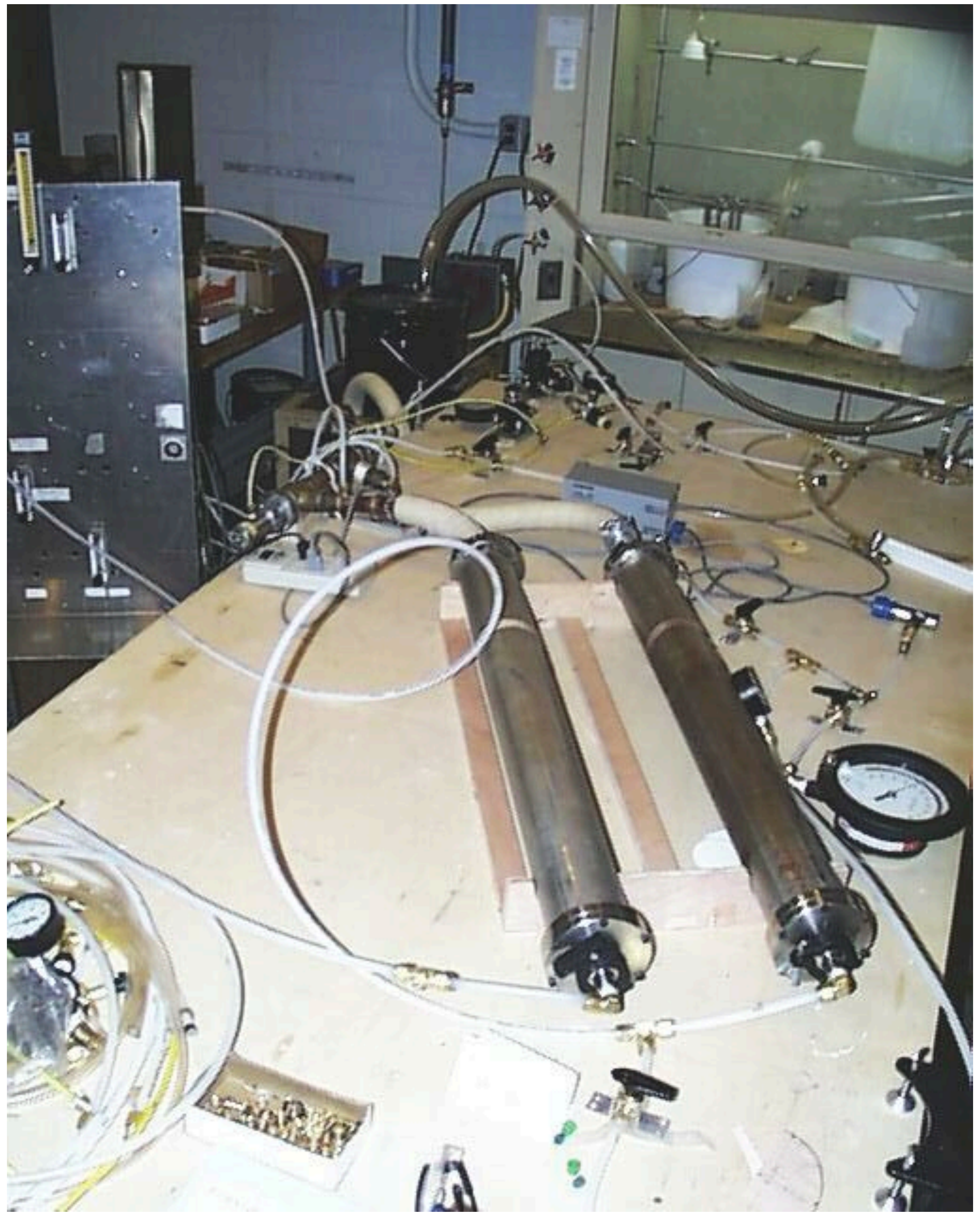
Vessel construction at Princeton



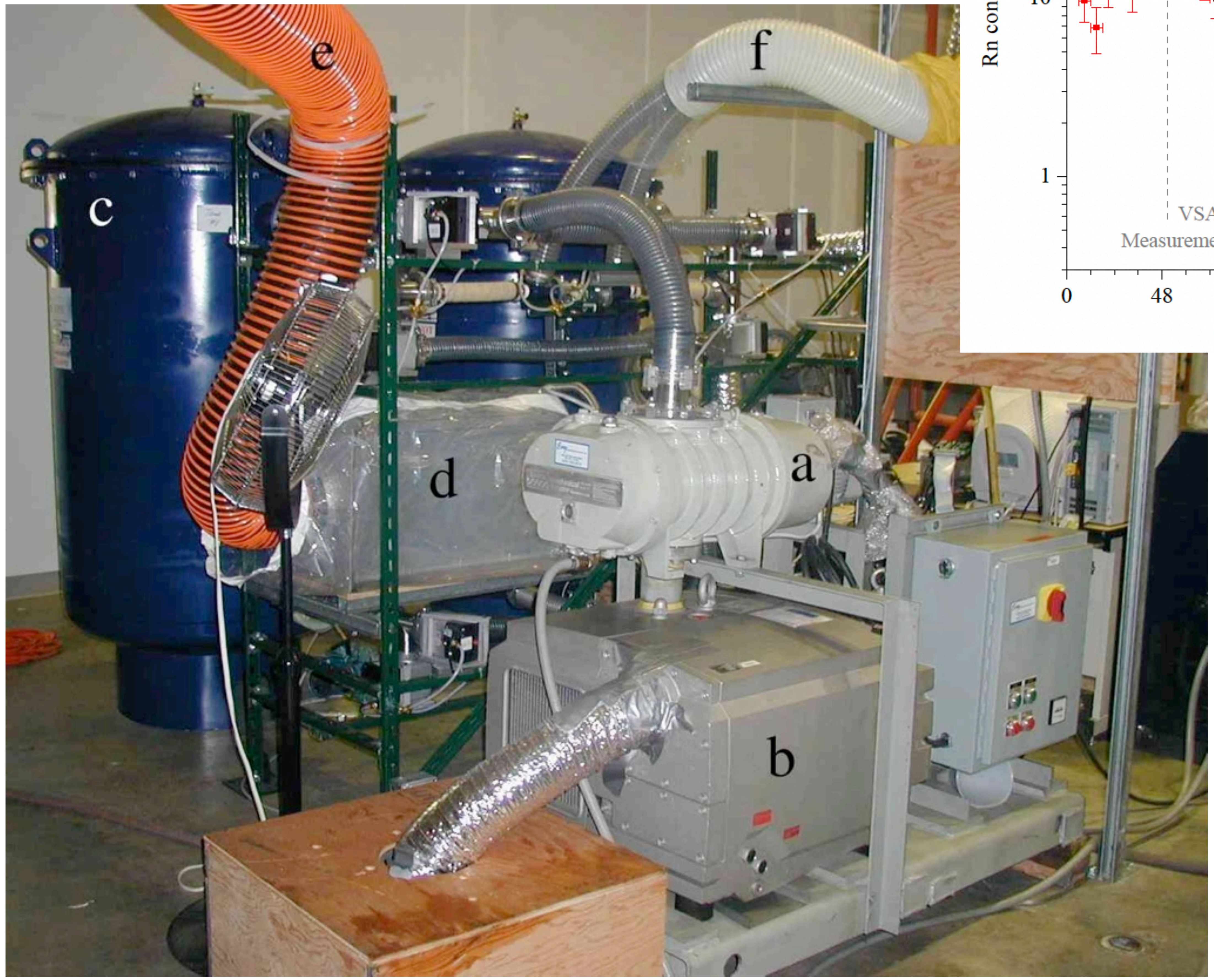


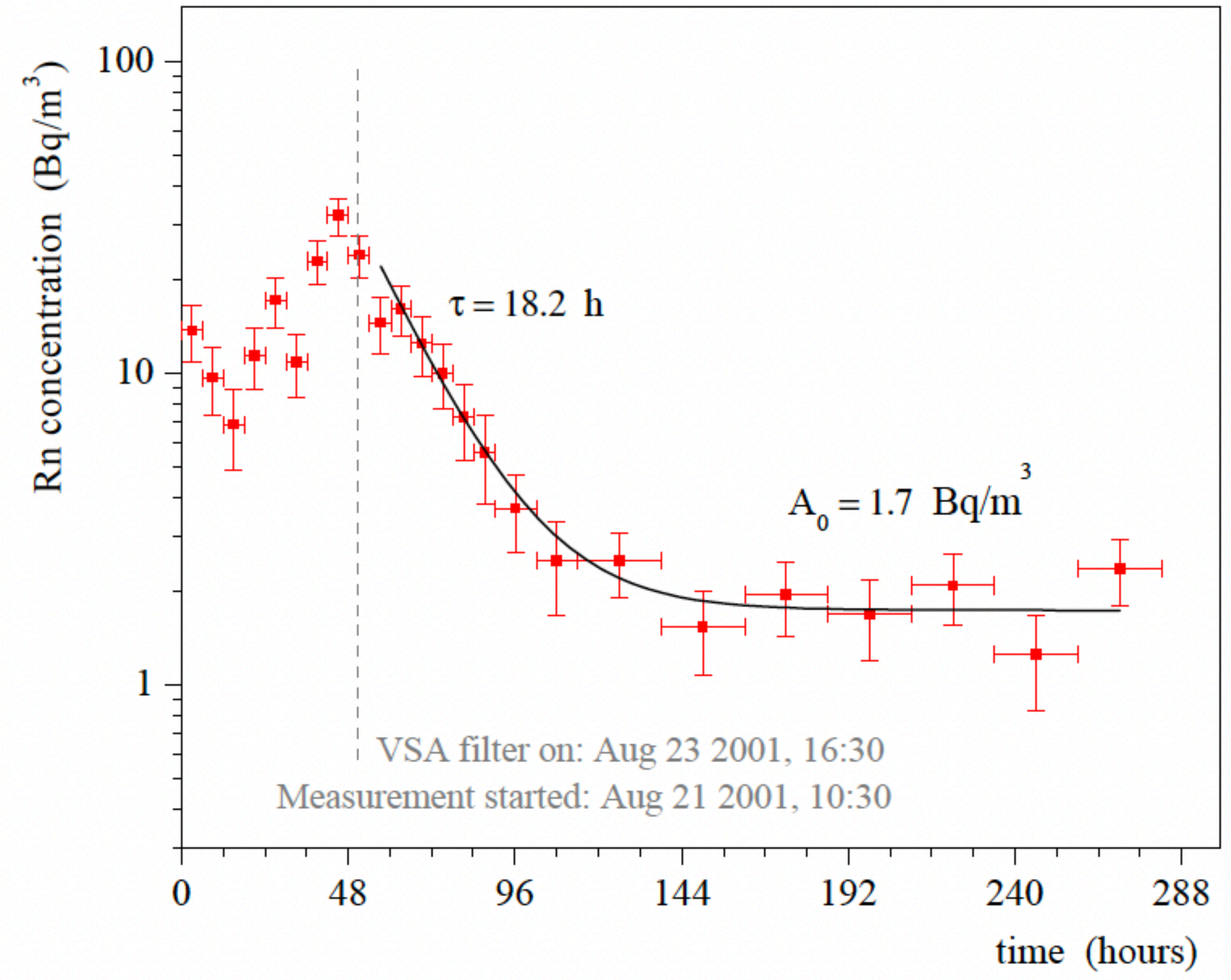
The radon scrubber: concept — prototype — build — run

PhD — year 1



PhD — year 2





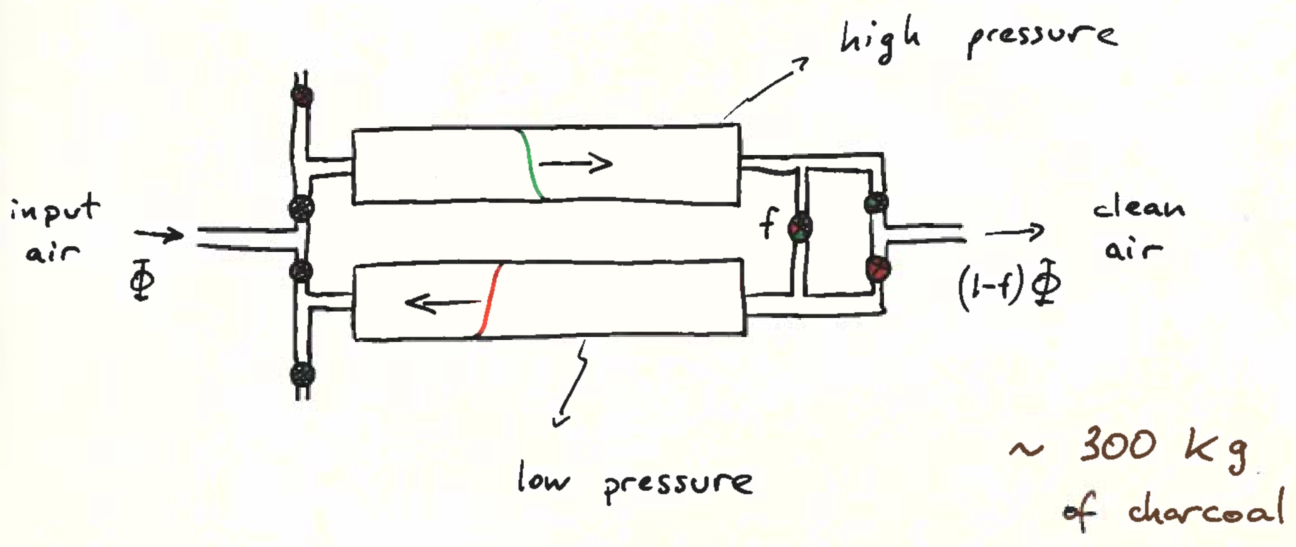
- Nylon vessels built in radon-mitigated clean room, the first of its kind
- Now relatively commonplace in our field

My first talks

BX collaboration meeting, Jan 1999

Charcoal-based PSA (Pressure Swing Adsorption) system

→ compact
→ cost effective



RADON PURIFICATION IN PRINCETON

A. POCAR
T. SHUTT
E. DEHAAS
J. BENZIGER
F. CALAPRICE

Borexino Collaboration Meeting, 16 Jan '99

Progress in Radon Removal from Air

A. Pocar, J. Benziger, F. Calaprice, N. Darnton, E. deHaas, F. Loeser, T. Shutt
Princeton University

March 25, 1999
APS Centennial Meeting

- Air Radon Content for the Princeton Clean Room
- PSA (VSA) System
- Current Development
- Plan for the Future Months

A. Pocar et al. | Progress in Radon Removal from Air | March 25, 1999

APS Centennial March 1999

The Radon Filtering VSA System

A. Pocar, J. Benziger, F. Calaprice, E. deHaas, E. Harding, T. Shutt

Princeton University

Radon Backgrounds in Rare–Event Experiments, Neutrino 2000
Sudbury, 14th June 2000

Neutrino 2000

Conclusions

A small–scale VSA radon filter has been operated and radon reductions of 10^4 have been achieved

A large–scale VSA system for supplying air to the cleanroom where the assembly of the Borexino nylon vessels will take place has been designed to achieve radon reductions $\geq 10^3$

Preliminary results, if confirmed, show that plateout of radon daughters on nylon and subsequent washoff into the scintillator are far from the "worst case" scenario

A VSA device could be used as a radon concentrator to continuously monitor the activity of the cleanroom air once the air–filtering system is operational

Particle counting, pickling and passivation

Particulate contamination in Borexino subsystems

Frank Calaprice

November 3, 1999

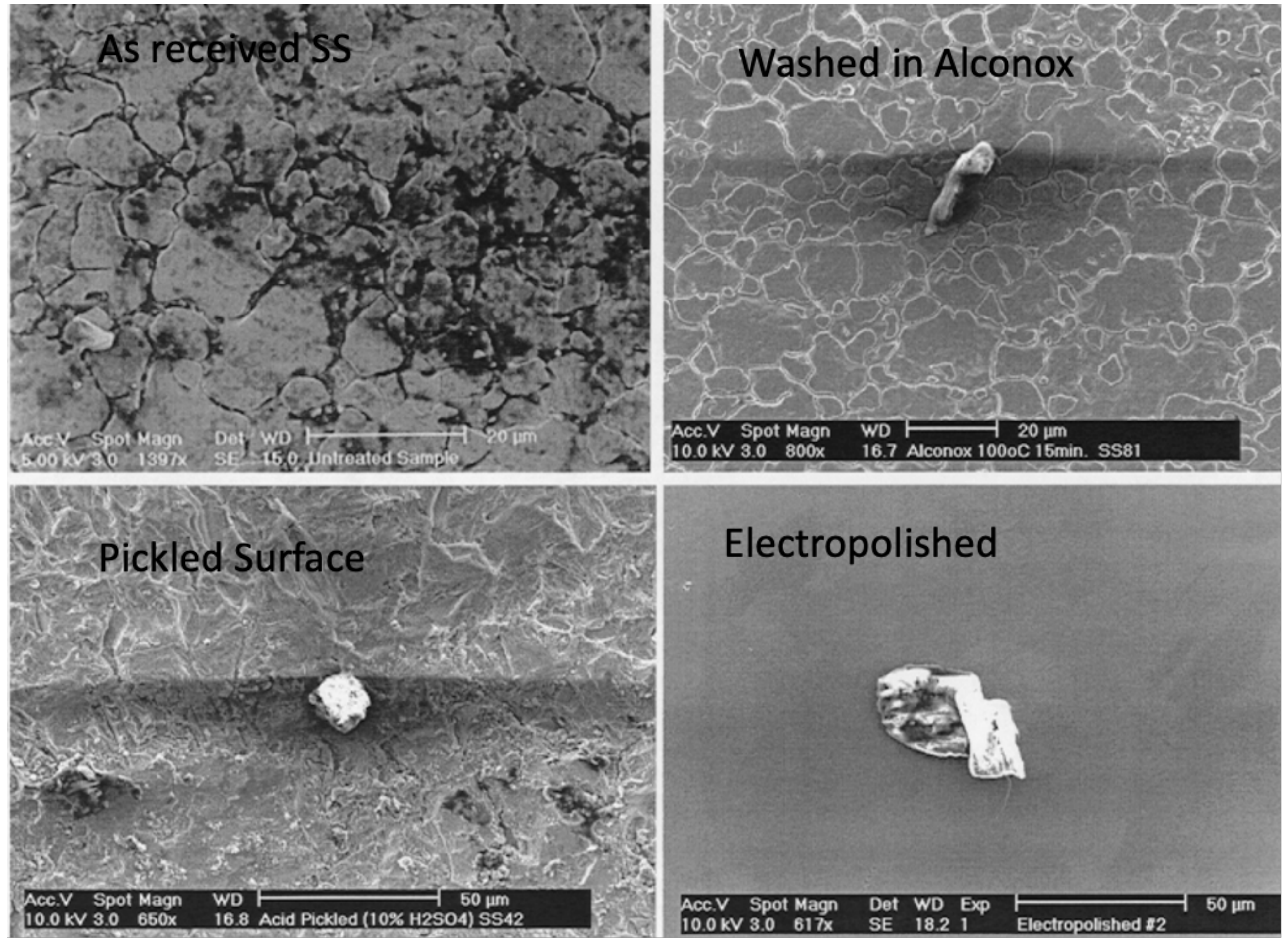
The following are some sketchy notes I made in an effort to better understand the requirements for cleanliness levels of various scintillator sub-systems for Borexino, particularly the new purification skid system. In addition I tried to determine what standard measurement methods could be applied to establish the cleanliness levels of the systems.

METRIC
11 April 1994
MIL-STD-1246C

SUPERSEDING
MIL-STD-1246B
4 SEPTEMBER 1987

MILITARY STANDARD

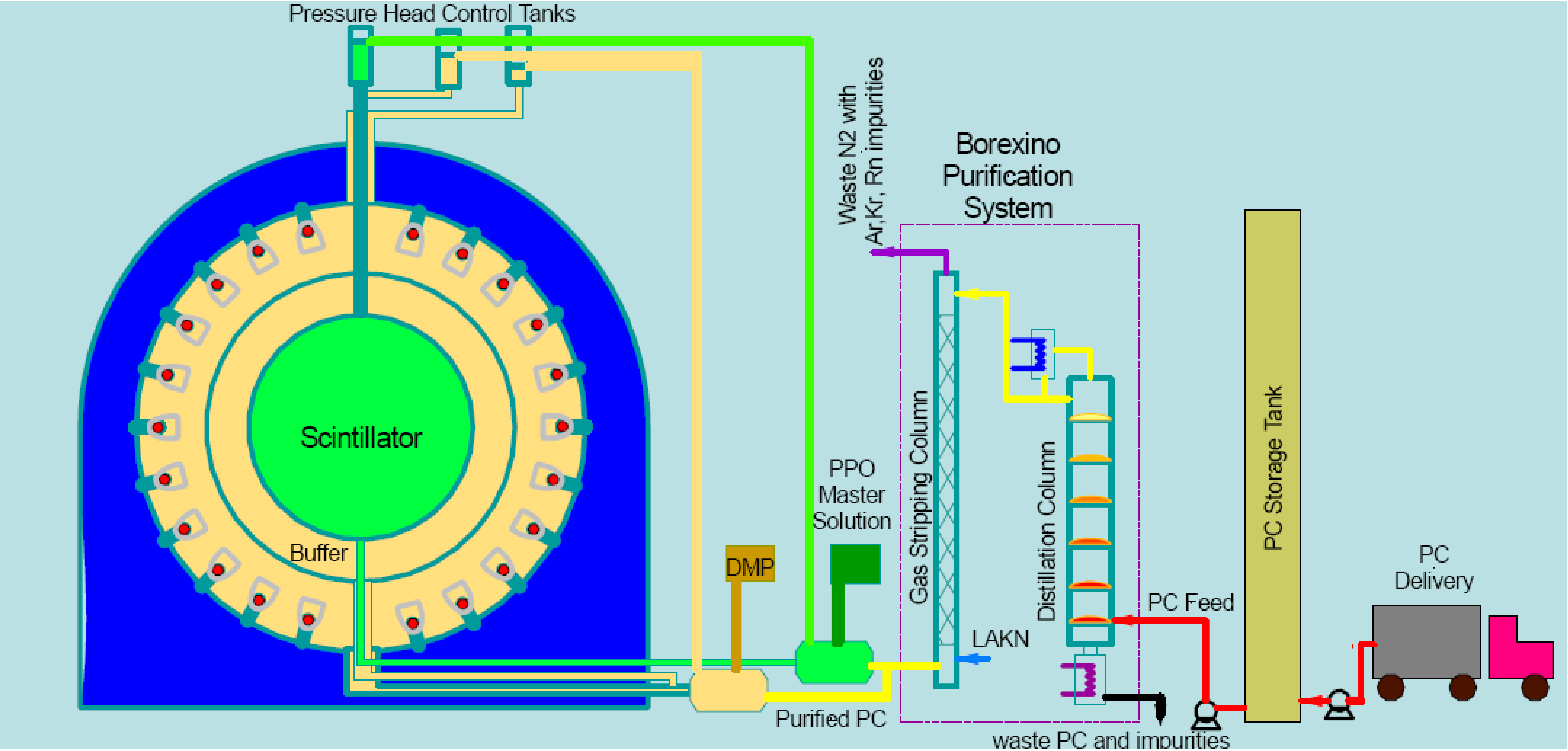
PRODUCT CLEANLINESS LEVELS
AND
CONTAMINATION CONTROL PROGRAM



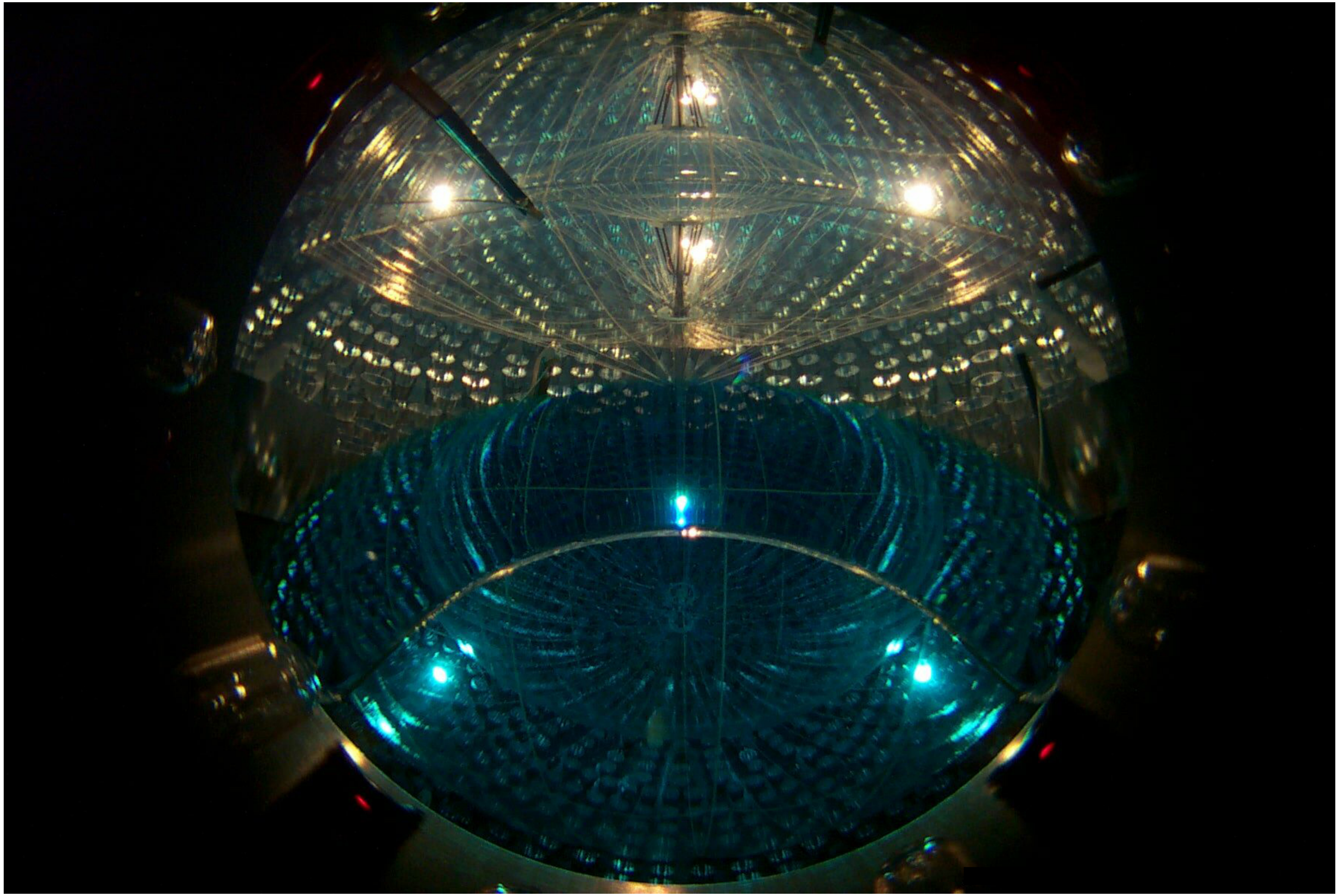
The Borexino PMTs and nylon vessels

- Optical coverage approx. 35%

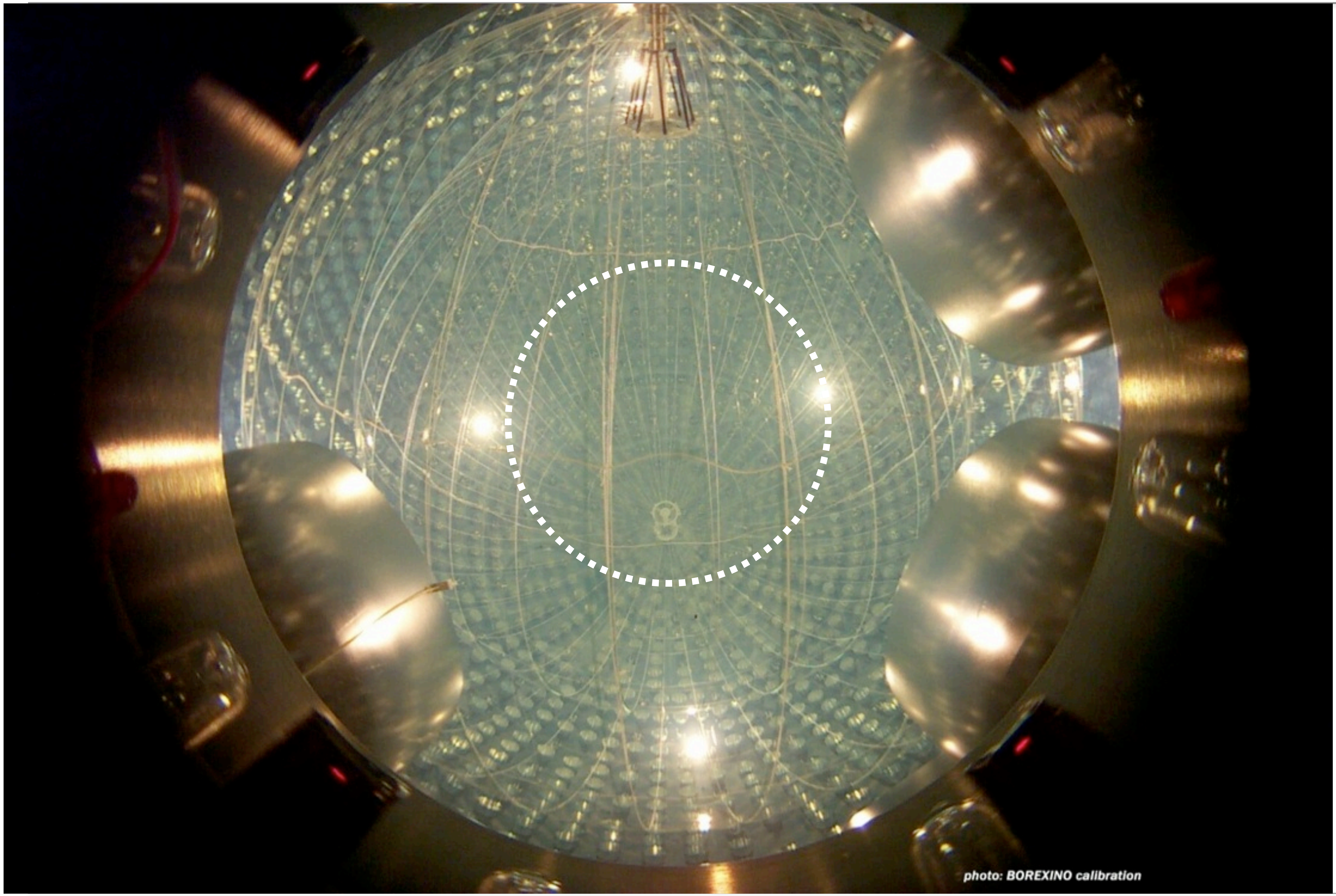
Scintillator filling



Scintillator filling



The Borexino detector filled with liquid scintillator



detector filled on May 15, 2007

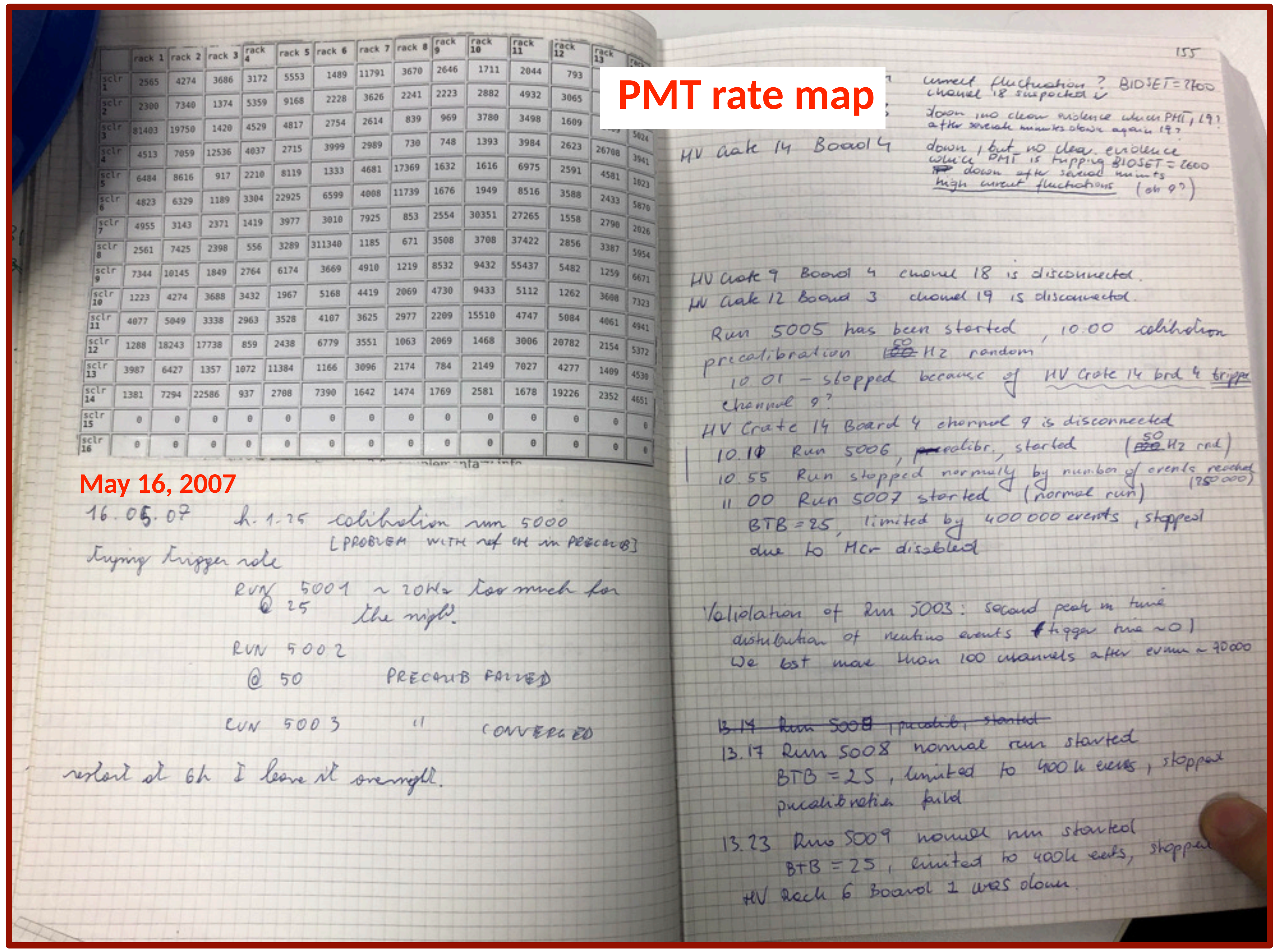
At 1 MeV:

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

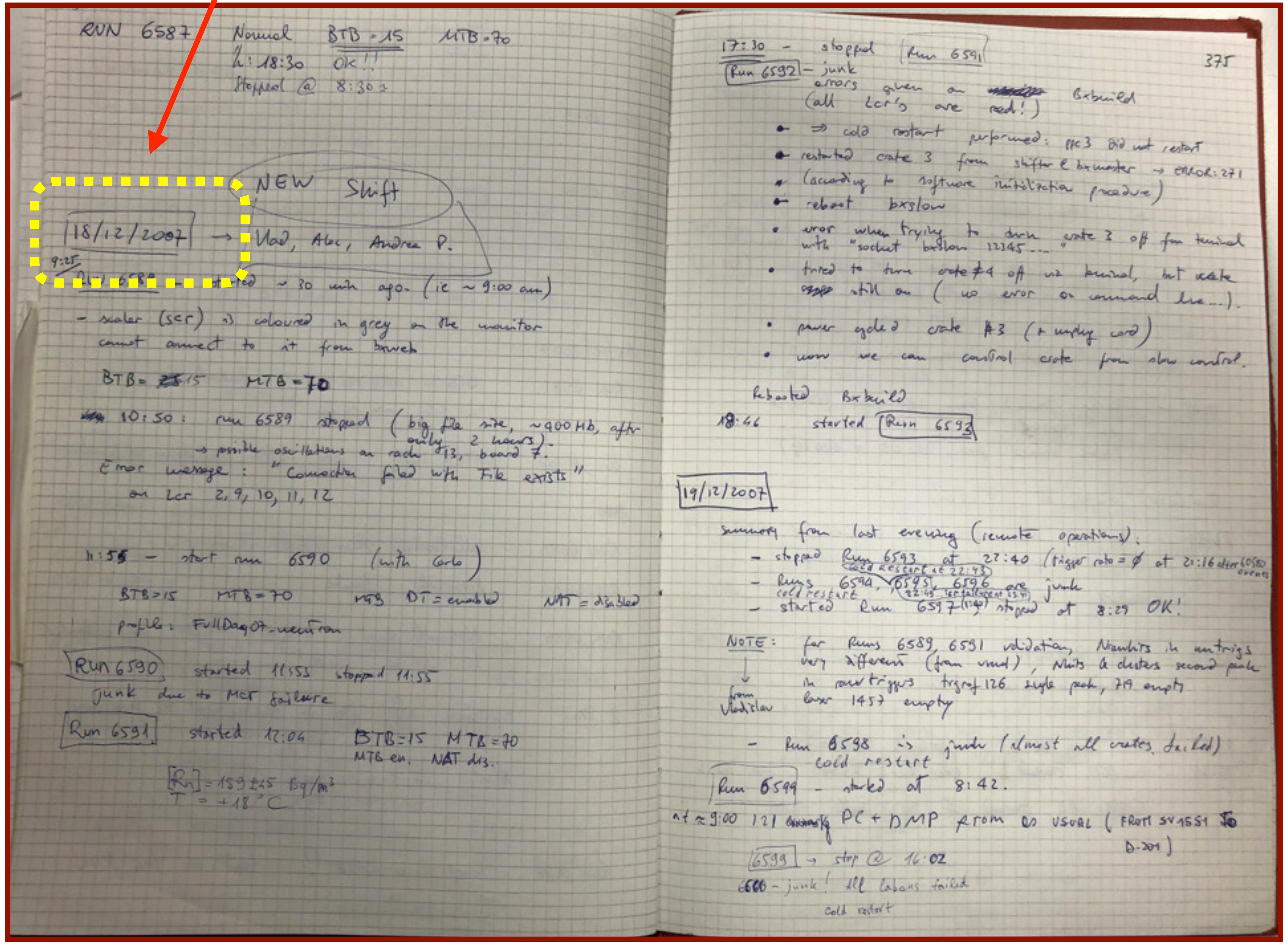
$$\sigma_{x,y,z} \sim 11\ cm$$

1238 active channels for the CNO neutrino measurement

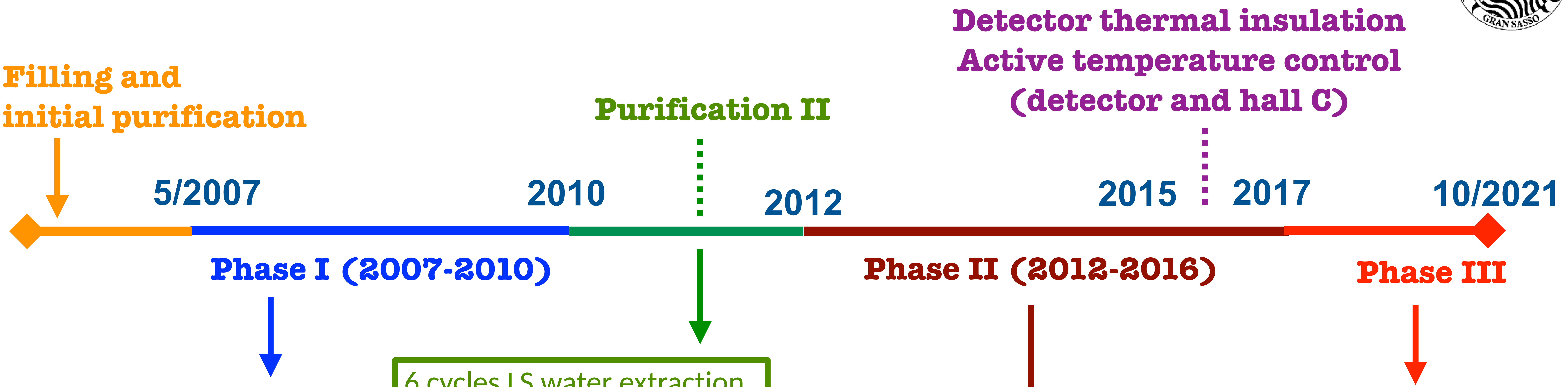
My first logbook entry!



Winter break shift!



Borexino timeline



- 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

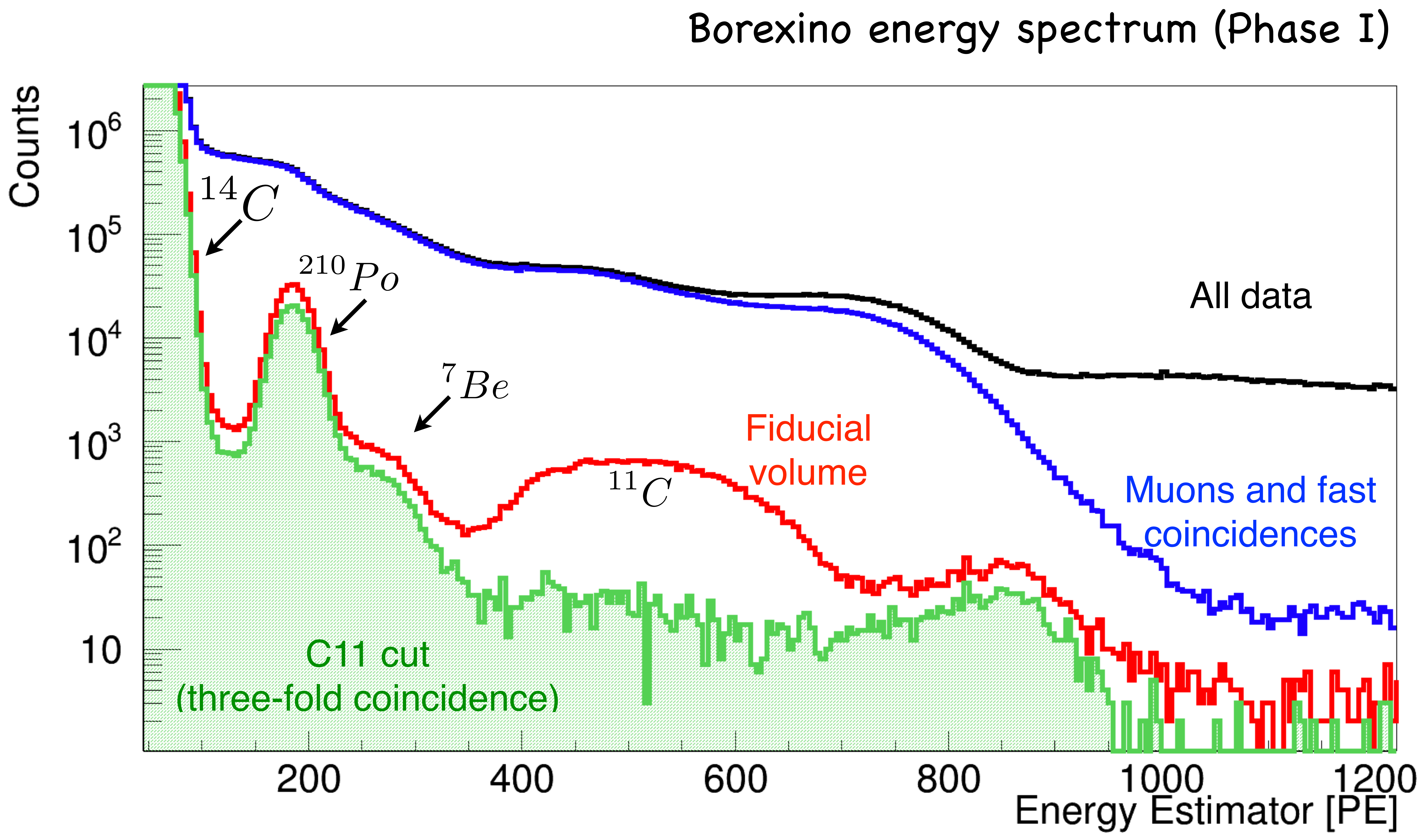
6 cycles LS water extraction purification

- ^{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

- 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

- R(CNO) — first
  — refined
- Hint of HZ
- sub-MeV directional
- Precision annual modulation

Borexino data and basic selection cuts



L’Aquila earthquake — April 6, 2009

Borexino Phase 2 results (2010-2016)

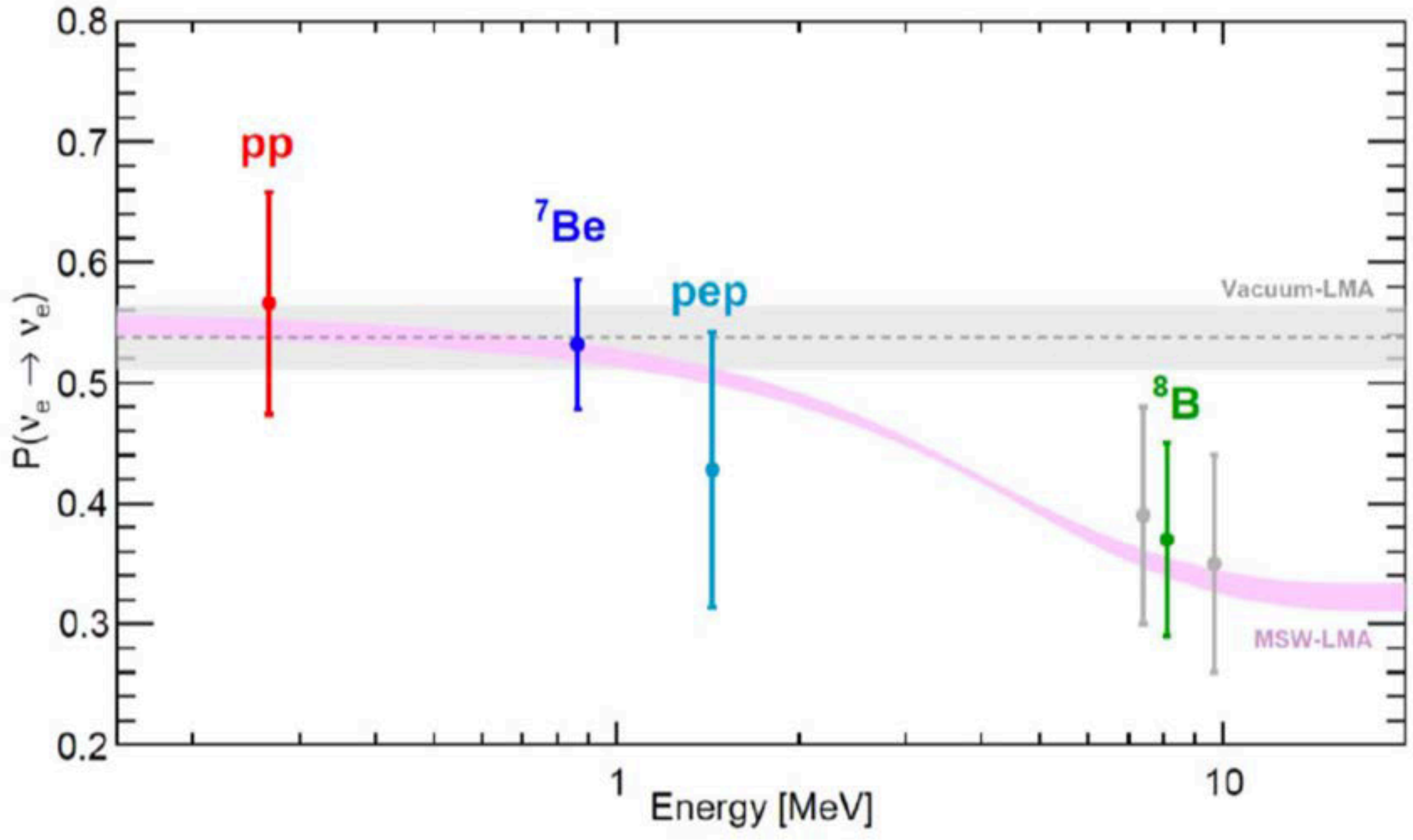
Nature 562, 505 (2018)
PRD 101, 062001 (2020)

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%**	$(6.1 \pm 0.05^{+0.3}_{-0.5}) \times 10^{10}$	$5.98(1\pm0.006)\times10^{10}$ $6.03(1\pm0.005)\times10^{10}$
^{7}Be	$48.3 \pm 1.1^{+0.4}_{-0.7}$ **2.7%**	$(4.99 \pm 0.11^{+0.06}_{-0.08})\times10^{9}$	$4.93(1\pm0.06)\times10^{9}$ $4.50(1\pm0.06)\times10^{9}$
pep	(HZ) $2.43 \pm 0.36^{+0.15}_{-0.22}$ (LZ) $2.65 \pm 0.36^{+0.15}_{-0.24}$ **5σ**	$(1.27 \pm 0.19^{+0.08}_{-0.12})\times10^{8}$ $(1.39 \pm 0.19^{+0.08}_{-0.13})\times10^{8}$	$1.44(1\pm0.01)\times10^{8}$ $1.46(1\pm0.01)\times10^{8}$
^{8}B	$0.223^{+0.015}_{-0.016} \pm 0.06$	$(5.68^{+0.39}_{-0.41} \pm 0.03)\times10^{8}$	$5.46(1\pm0.12)\times10^{6}$ $4.50(1\pm0.12)\times10^{6}$
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	<8.1 (95% C.L.)	$<7.9\times10^{8}$	$4.88(1\pm0.12)\times10^{8}$ $3.51(1\pm0.12)\times10^{8}$

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

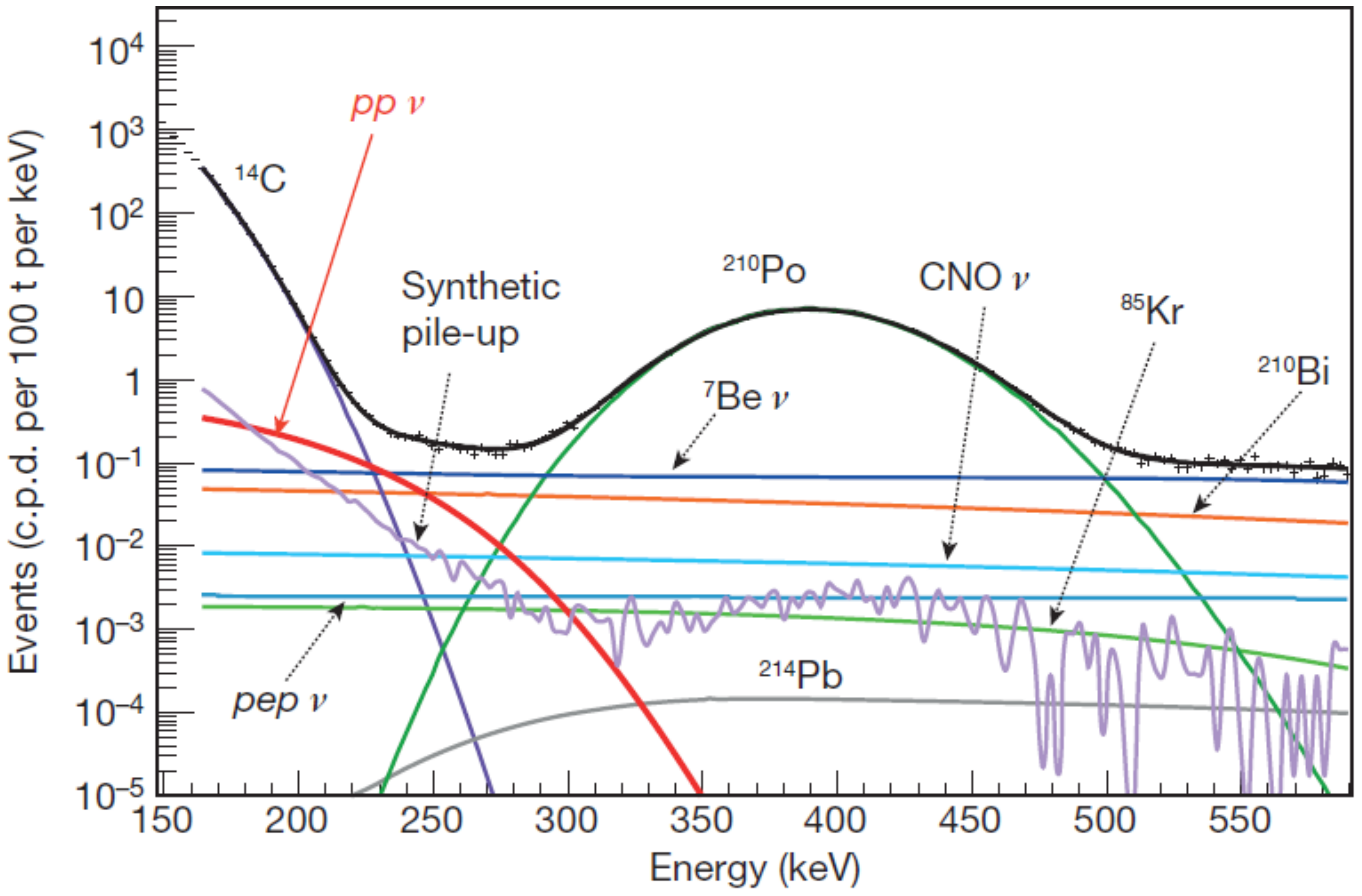
precision and reach beyond design goals of the experiment

Solar neutrino survival probability



Significance of the first pp neutrino measurement

Directly test the time stability of the Sun (time scale 10^5 years), which is a crucial assumption in the Standard Solar Model



SCIENCE IDEAS

Solar Variability

Glacial Epochs, and Solar Neutrinos

by George A. Cowan and Wick C. Haxton

Physics World (IOP)
Top 10 2014
Breakthroughs

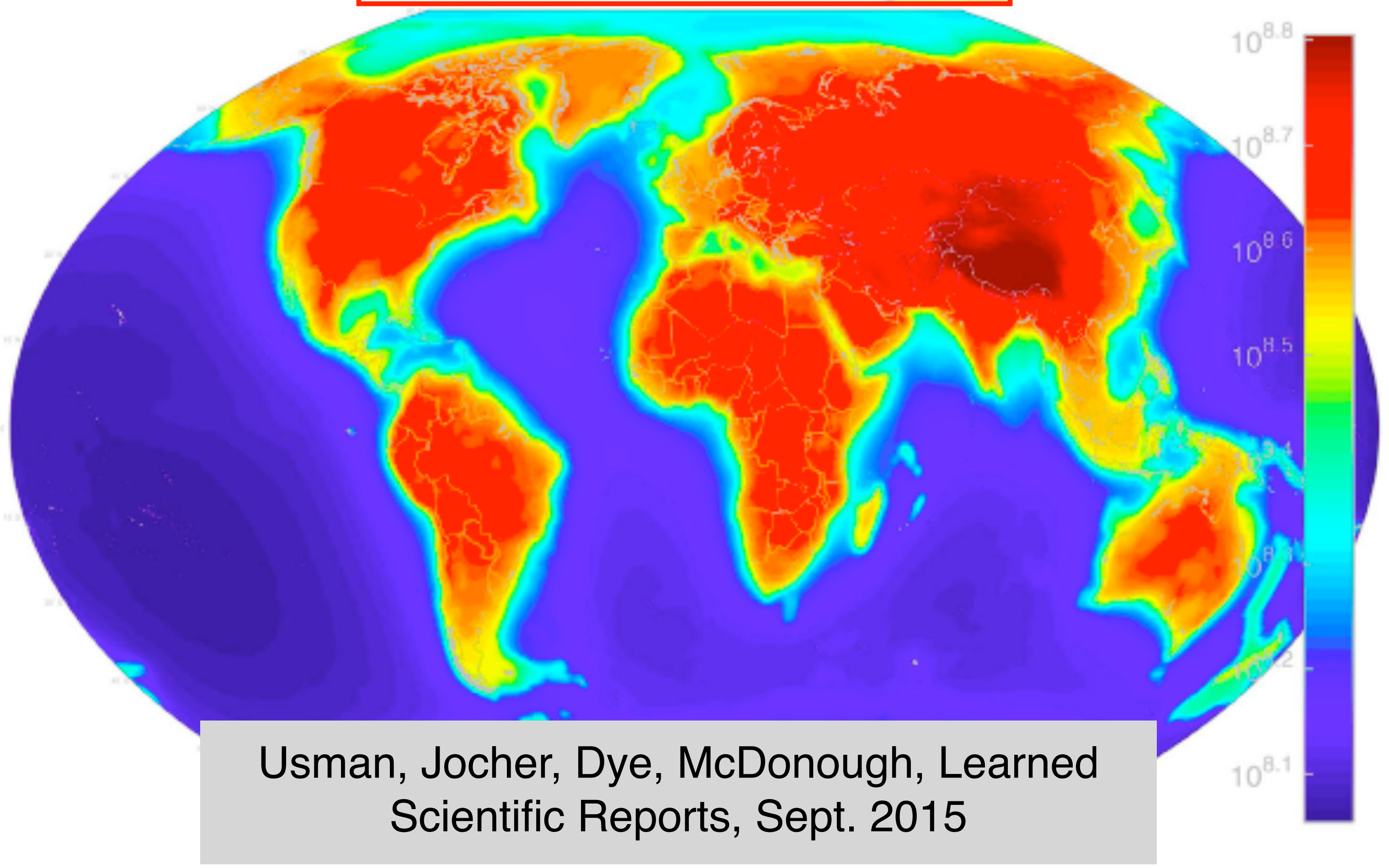
UMass grad student Keith Otis co-led the analysis

Geo-neutrinos (3262.74 days)

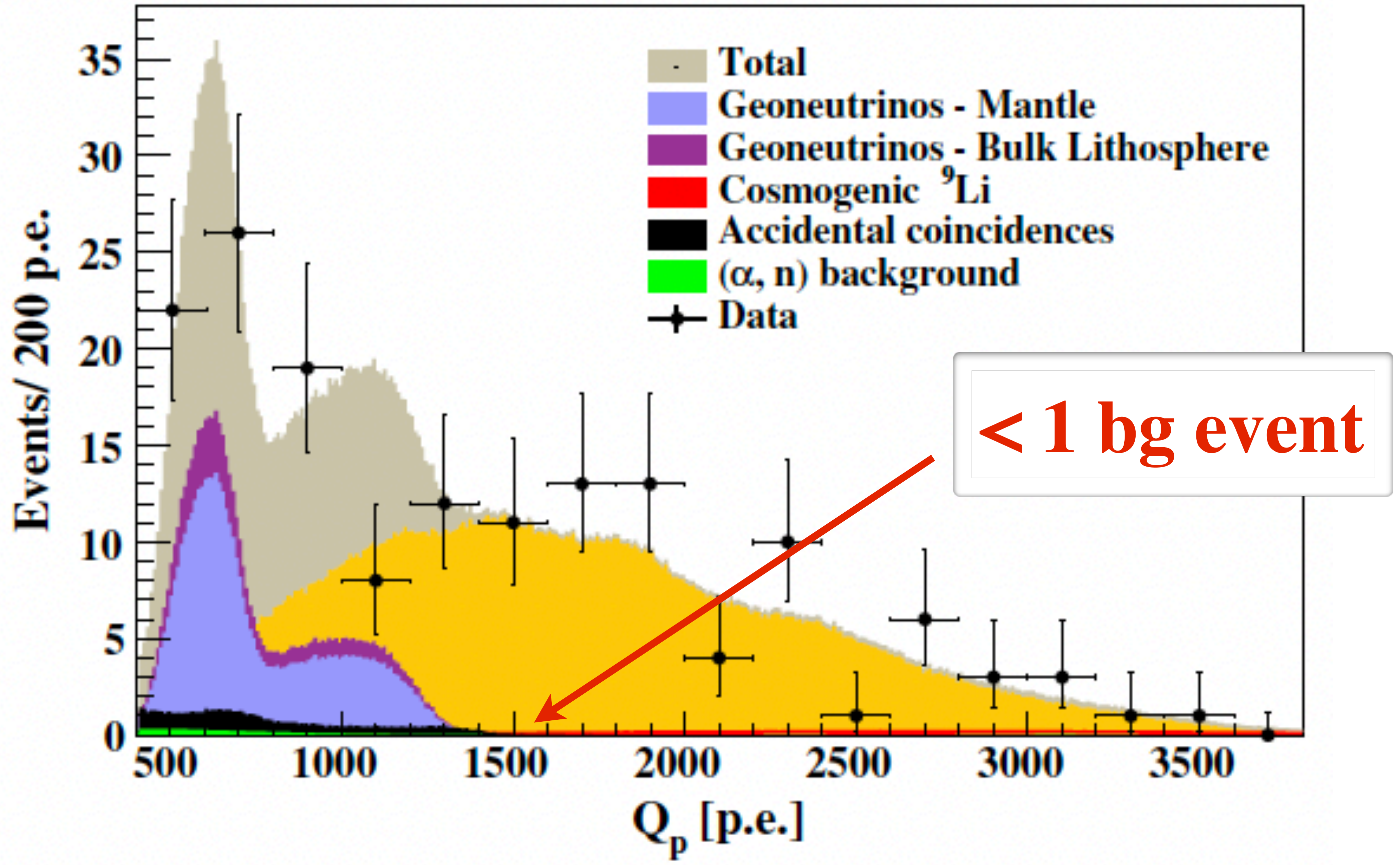
[PRD 101 012009 (2020)]

- Anti-neutrinos associated with beta decays in the Earth
- Detected via IBD, characteristic coincidence
  - ^{232}Th and ^{238}U chains
  - ^{40}K (below IBD threshold)
- Observed by two experiments:
  - First reported by KamLAND ('05), then '11, '13
  - Borexino published in '10, '13, '15

$\Phi_\nu \sim 10^6$ cm^{-2} s^{-1}



Usman, Jocher, Dye, McDonough, Learned Scientific Reports, Sept. 2015



extremely low background allows for a measurement even with low statistics

Detected antineutrinos from the earth mantle

The solar metallicity puzzle

- Metallicity: abundance of elements with Z>2 (C, N, O, Ne, Mg, Si, S,Ar, Fe…)
- Metallicity is obtained from spectroscopic measurement of the photosphere and from studies of meteorites —> Long sequence of Spectroscopic measurements

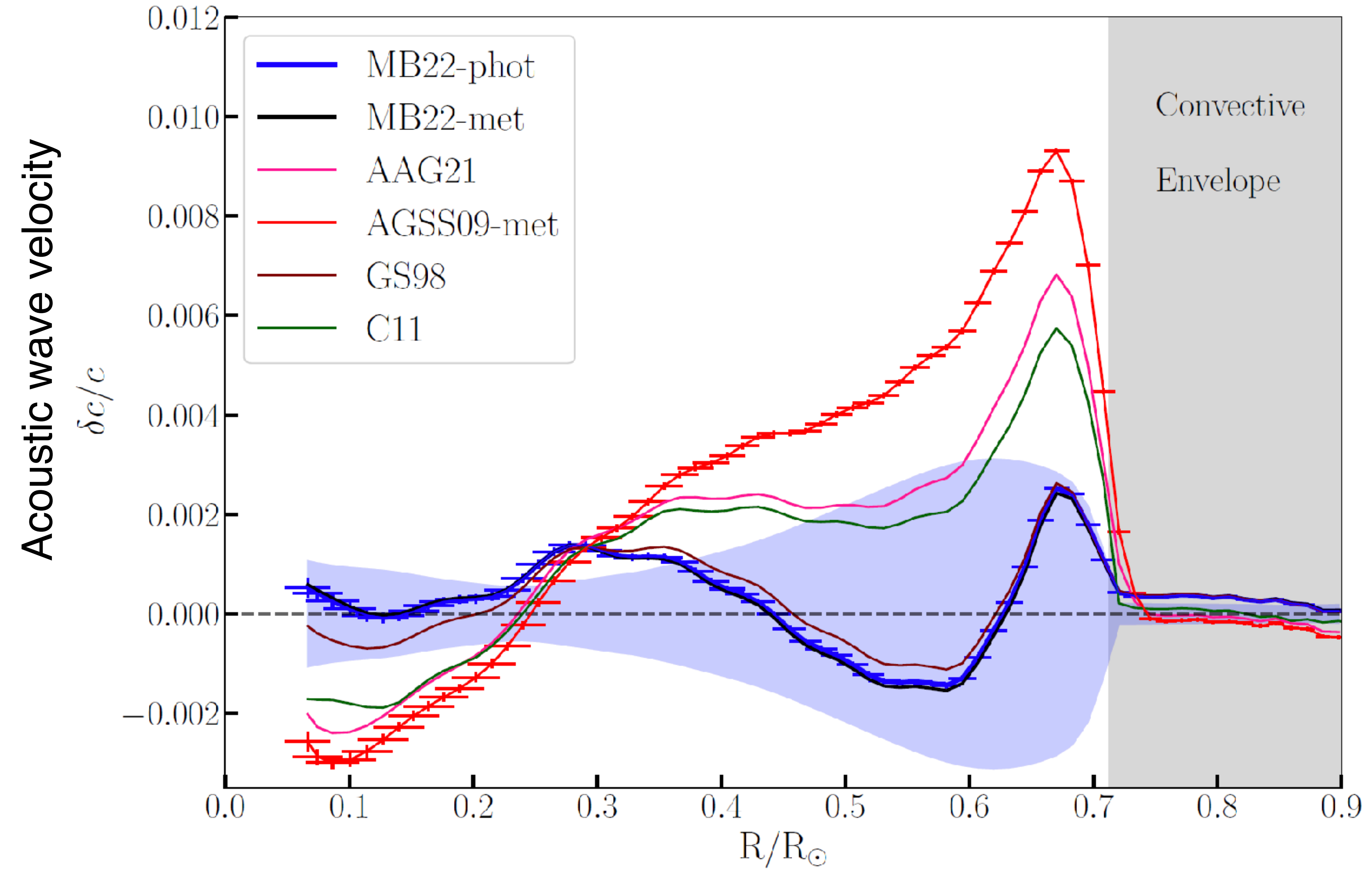
- Metallicity is an input to the Standard Solar Models (SSMs)
  - SSMs are calibrated to reproduce the measured photospheric chemical mixture at the present-day solar age;
  - Metallicity influences opacity which in turn affects the solar core temperature profile
  - Thus metallicity influences significantly the output of the Standard Solar Model

- Two observables:
  - Helioseismology (sound wave propagation on the surface)
  - Solar neutrinos (CNO flux depends directly on metallicity)

The solar metallicity and solar neutrinos

- SSMs with HZ (LZ) input agree (disagree) with helioseismological measurements

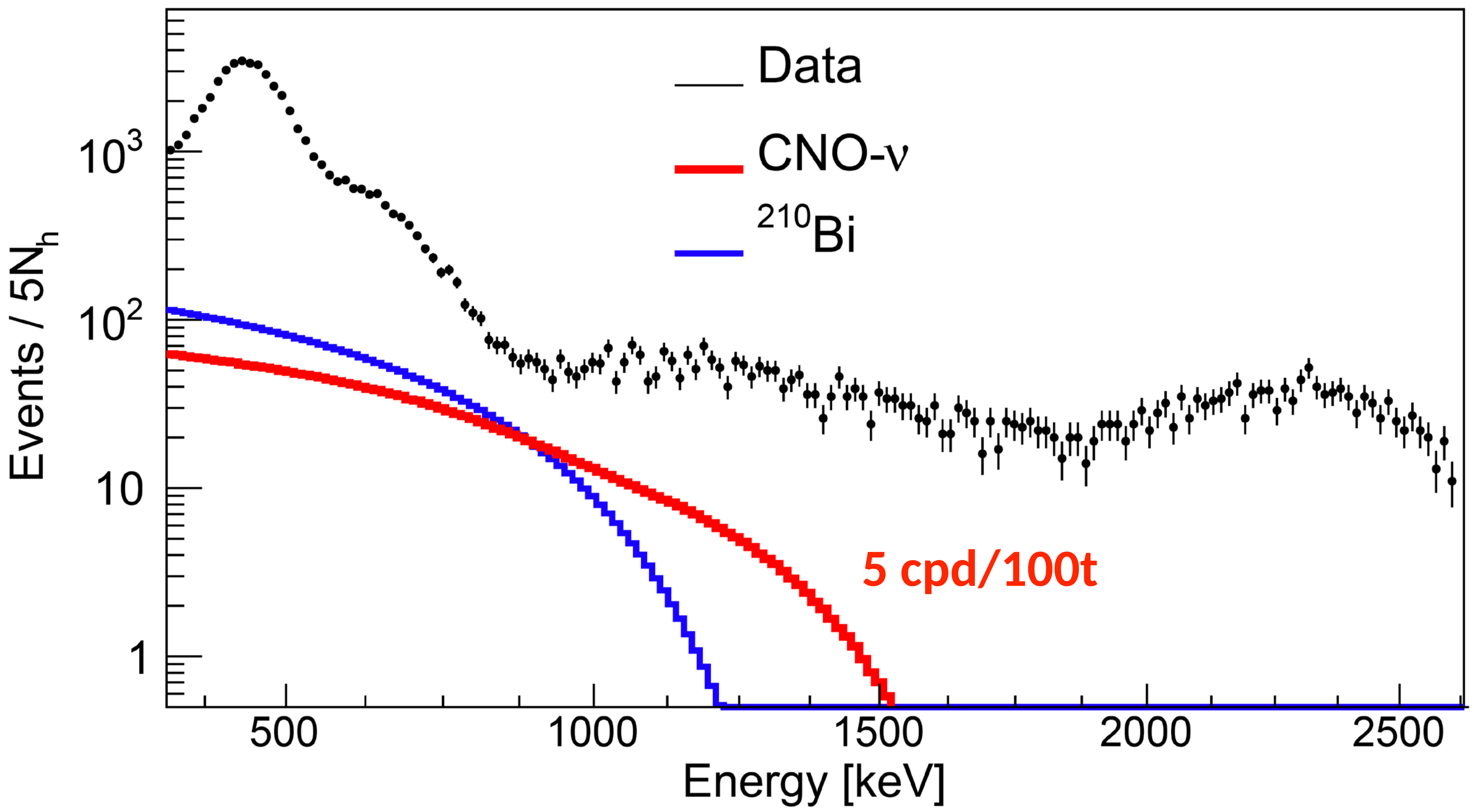
- All solar neutrino fluxes depend on T
- CNO flux directly depend on C,N abundance



Radial distance/ solar radius

	FLUX	Dependence on T	SSM-/HZ (1)	SSM-/LZ(2)	DIFF. (HZ-LZ)/HZ
pp chain	pp (10^{10} cm^{-2} s^{-1})	$T^{-0.9}$	5.98(1±0.006)	6.03(1±0.005)	-0.8%
pp chain	pep (10^{8} cm^{-2} s^{-1})	$T^{-1.4}$	1.44(1±0.01)	1.46(1±0.009)	-1.4%
pp chain	^{7}Be (10^{9} cm^{-2} s^{-1})	T^{11}	4.94(1±0.06)	4.50(1±0.06)	8.9%
pp chain	^{8}B (10^{6} cm^{-2} s^{-1})	T^{24}	5.46(1±0.12)	4.50(1±0.12)	17.6%
CNO cycle	^{13}N (10^{8} cm^{-2} s^{-1})	T^{18}	2.78(1±0.15)	2.04(1±0.14)	26.6%
CNO cycle	^{15}O (10^{8} cm^{-2} s^{-1})	T^{20}	2.05(1±0.17)	1.44(1±0.16)	29.7%

Extracting the CNO signal



Data set
Jan 2017 –sep 2021
(after selection cuts)

^{210}Bi and CNO are highly degenerate

^{210}Bi needs an independent constraint

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%

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

^{210}Bi

- 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

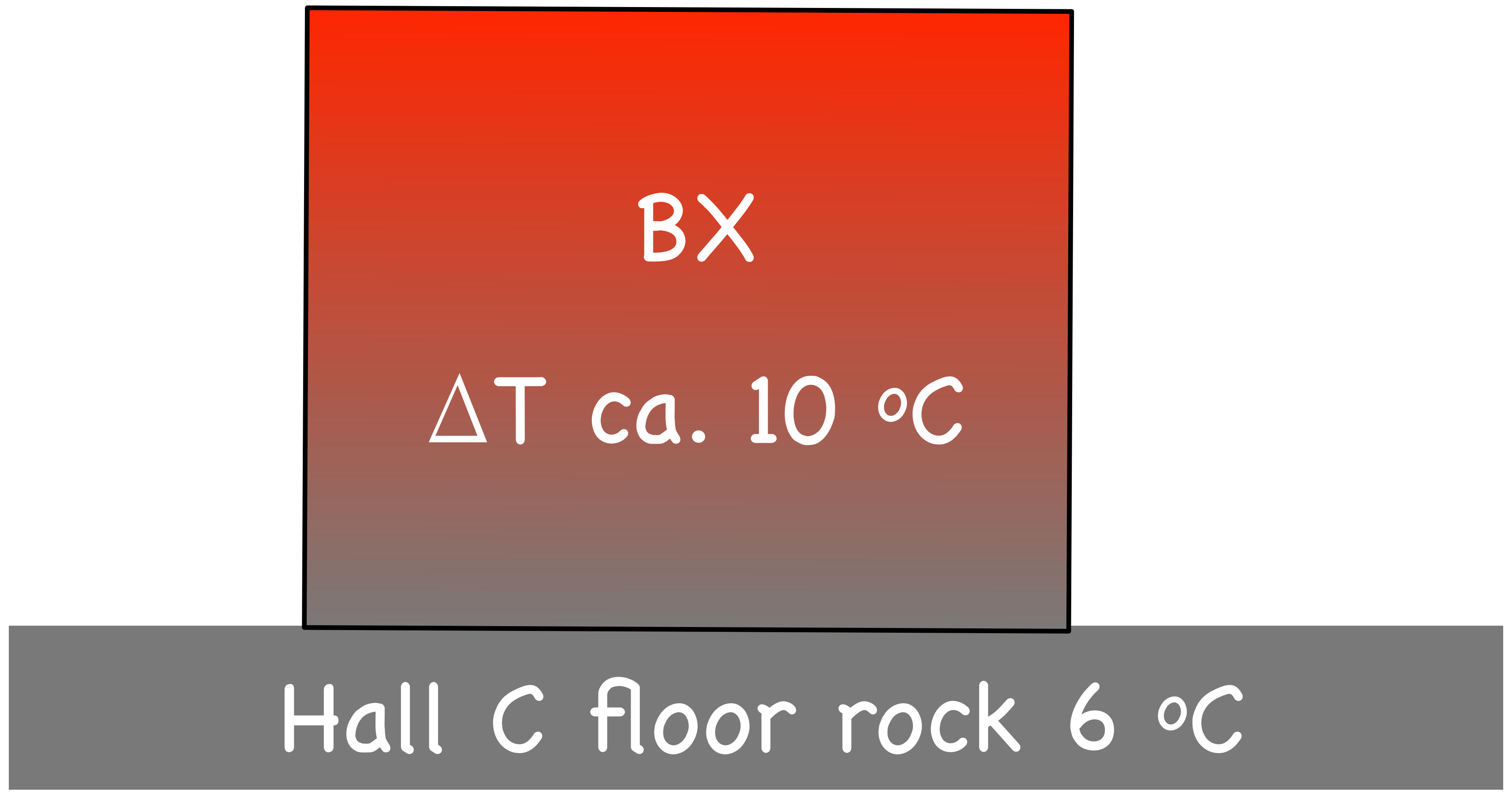
Thermal stabilization of the detector

2014 — Installation of T probes

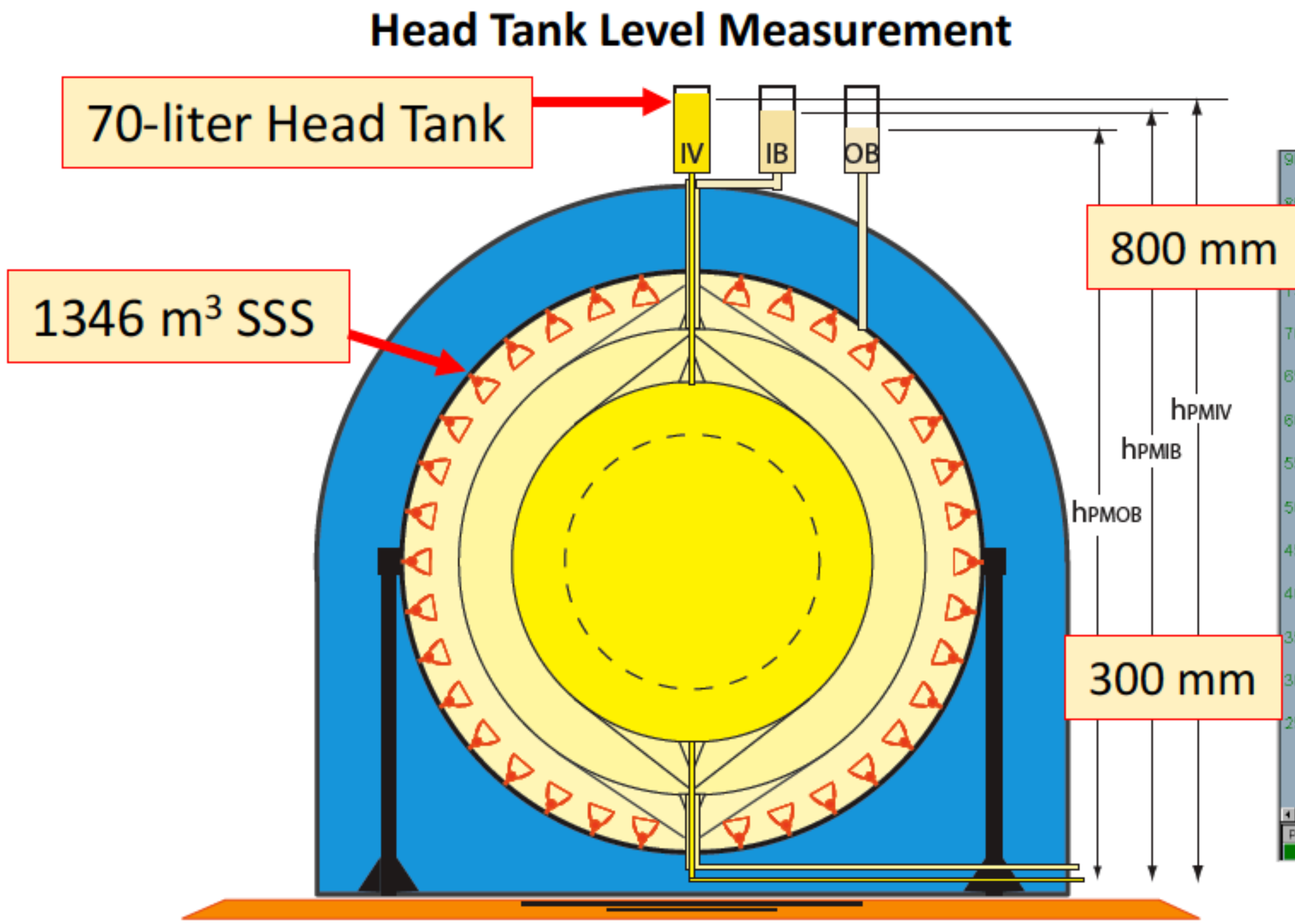
2015-2016 — Thermal insulation of the water tank

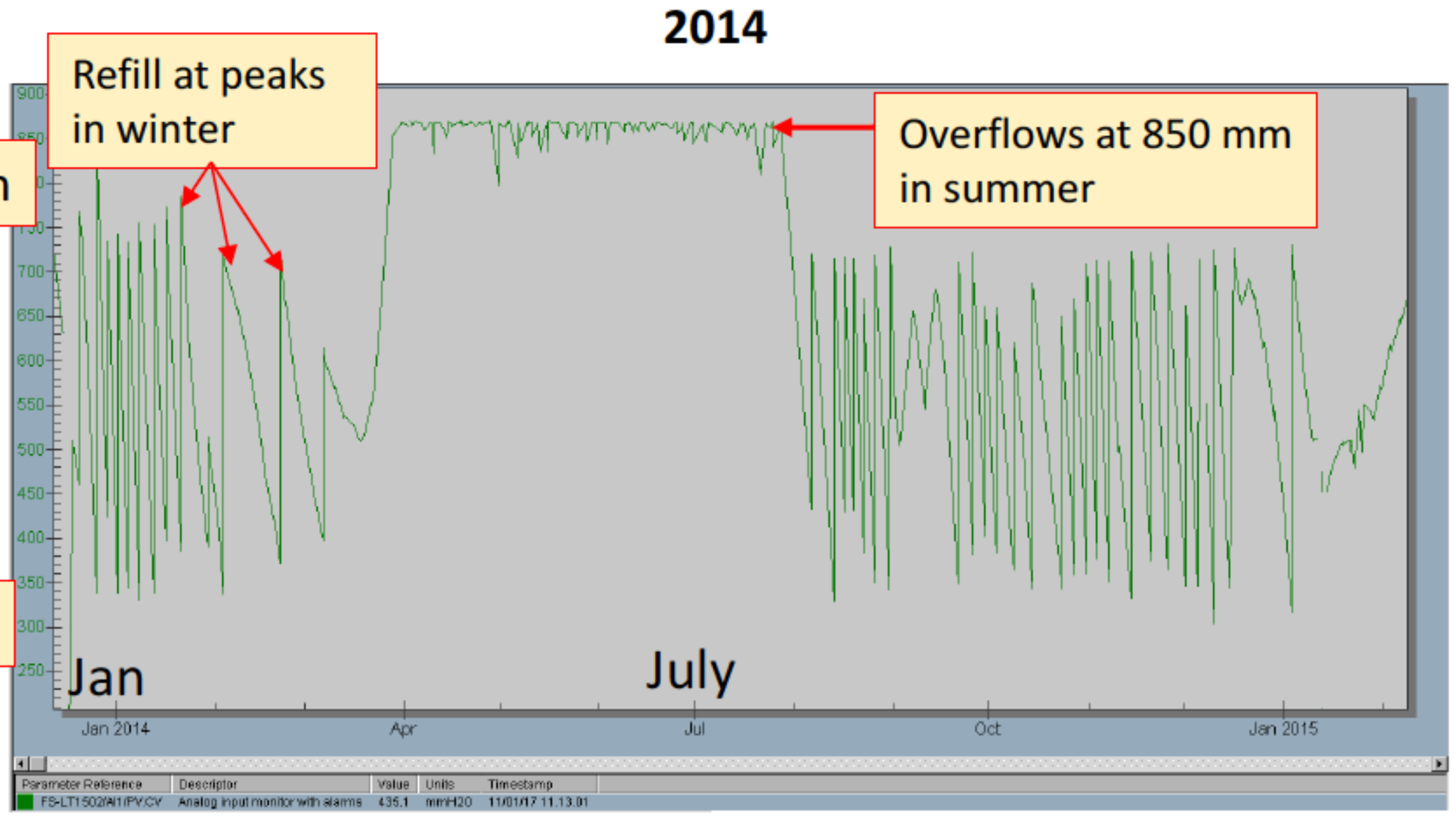
2017 — active T control system atop water tank

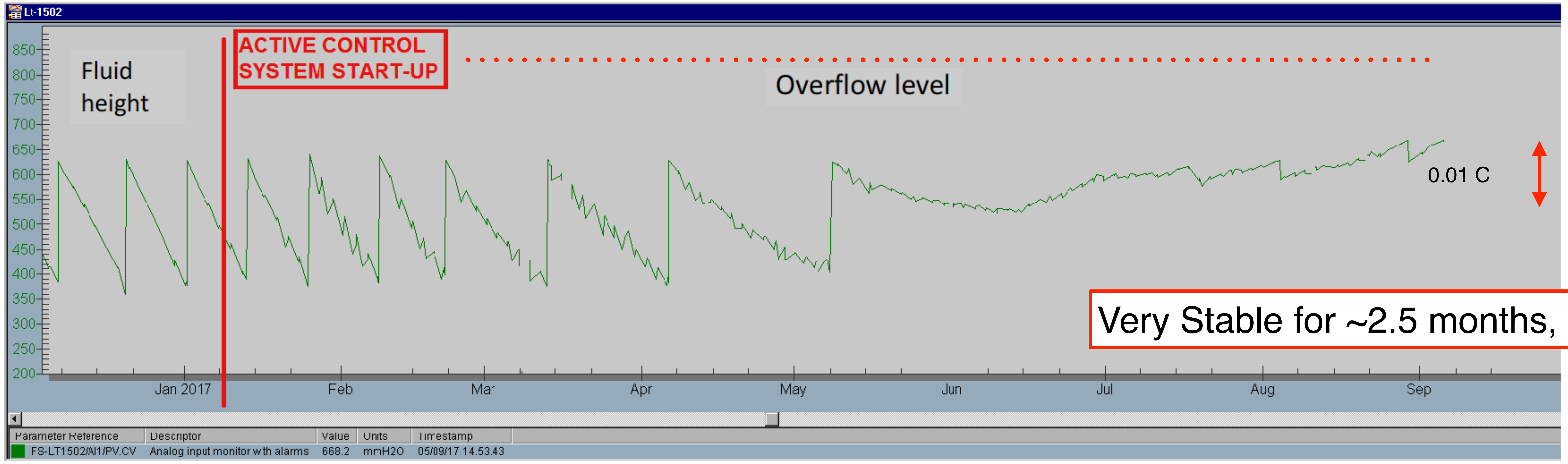
2019-2020 — Hall C air T control system



Borexino: a very sensitive thermometer!

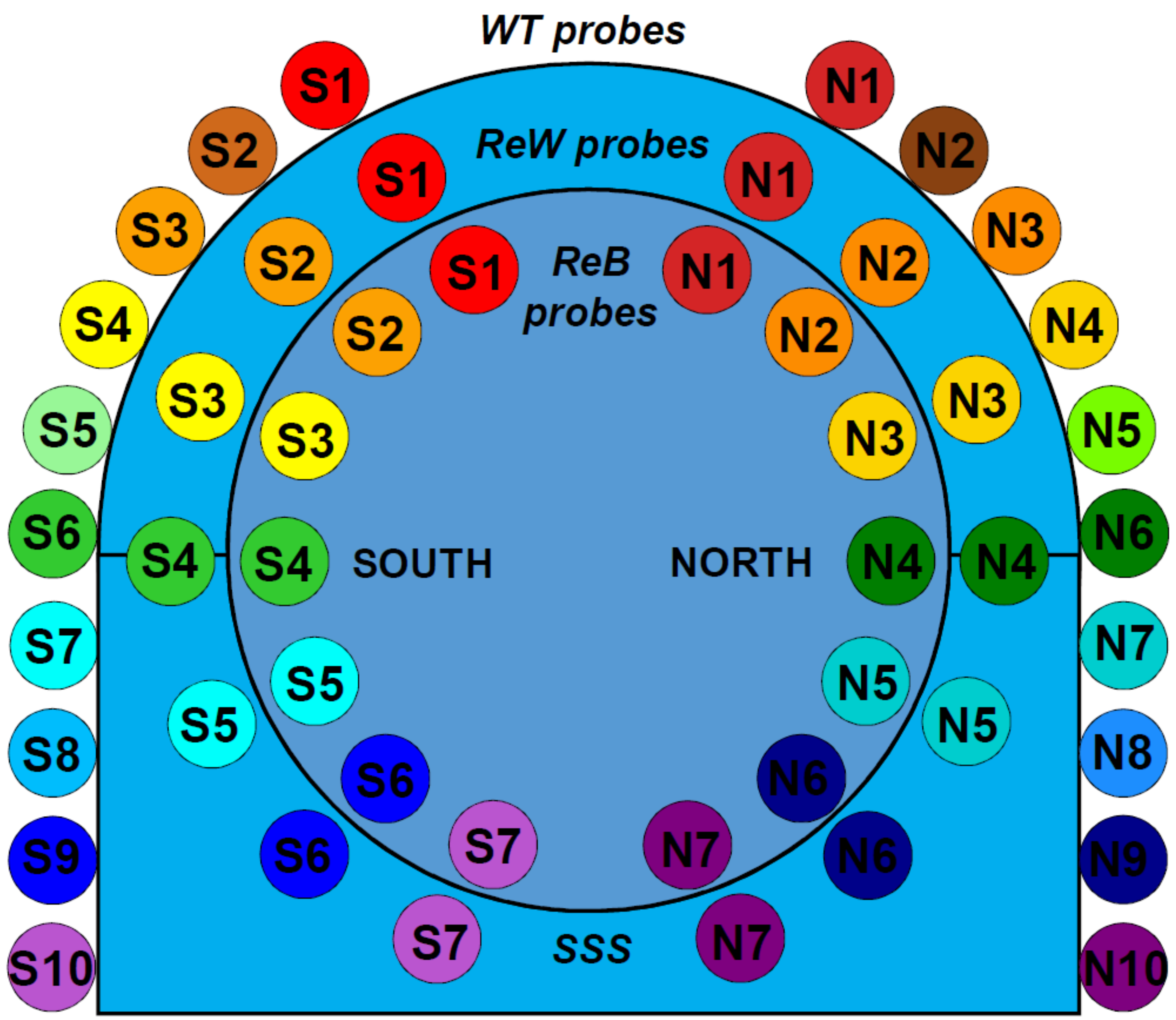


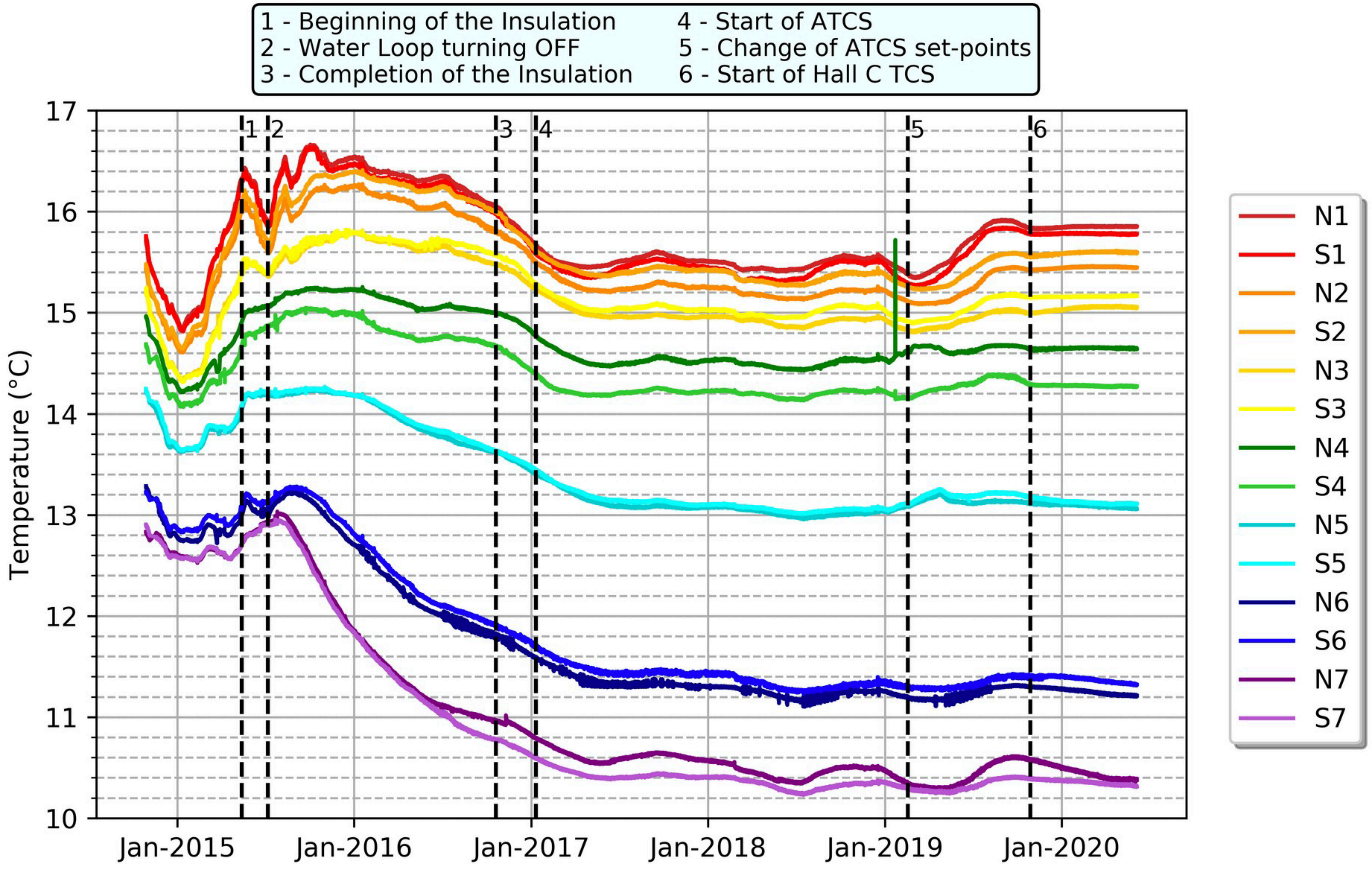




Very Stable for ~2.5 months, helped by warm summer

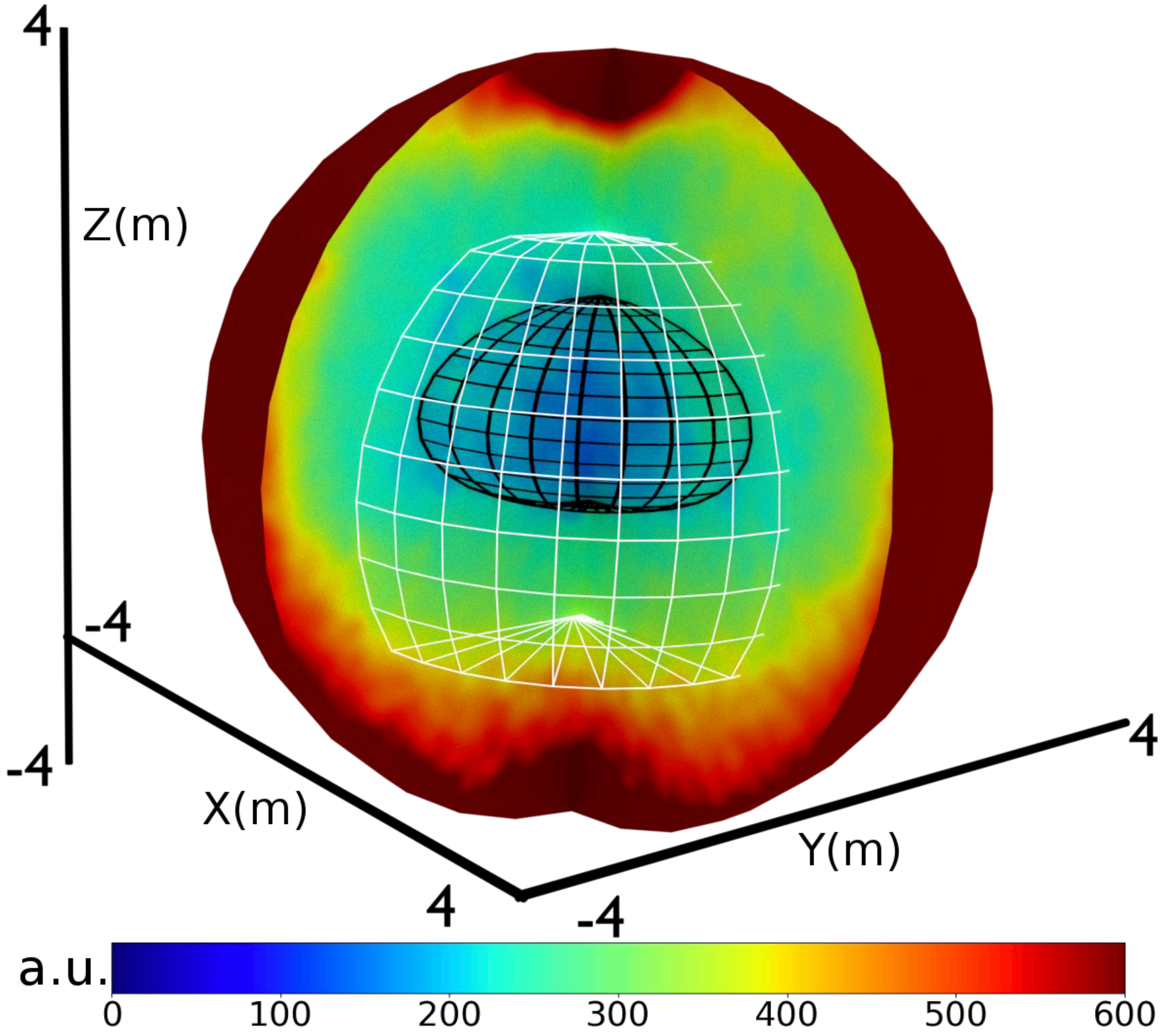
Temperature stabilization timeline

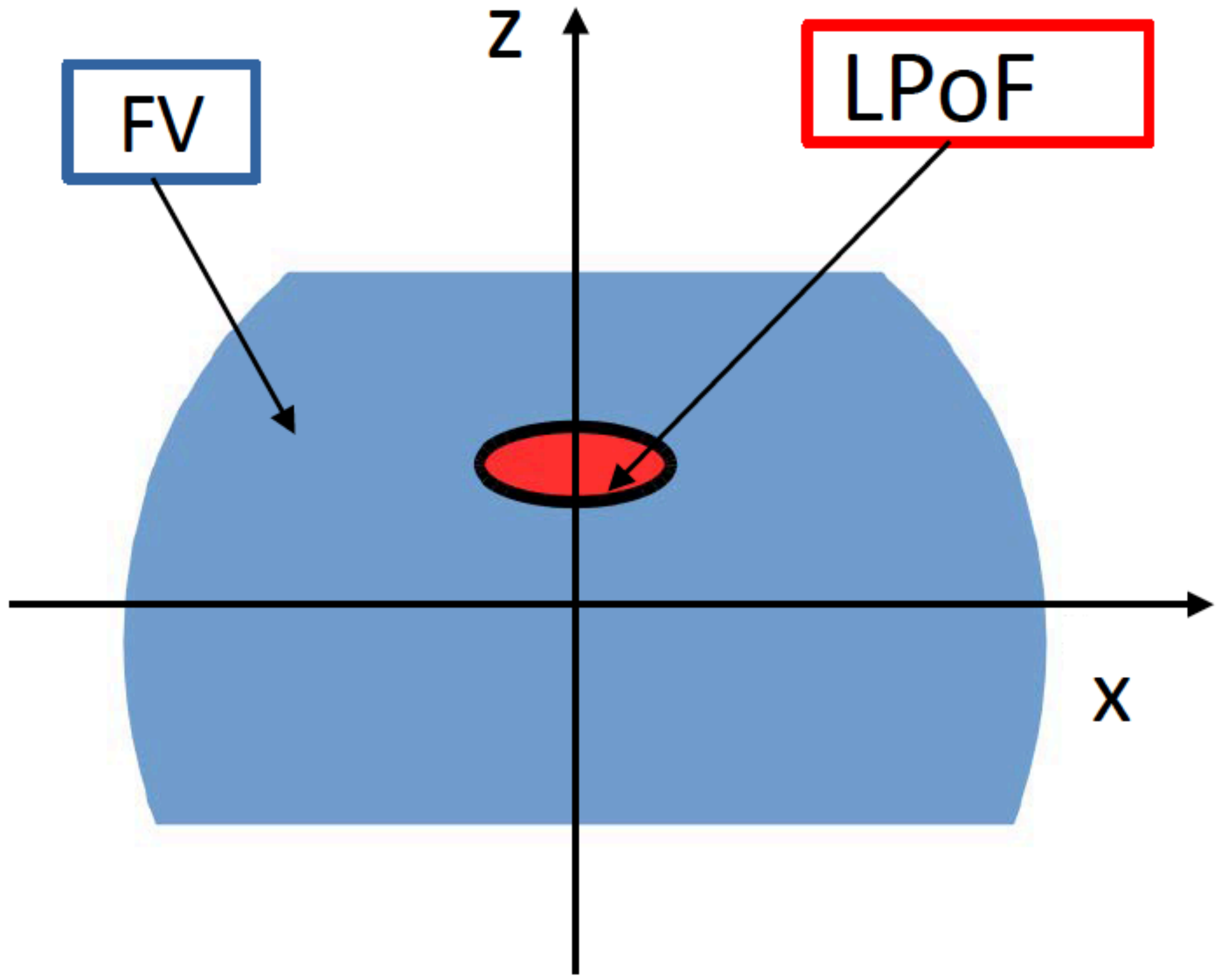




The Low Polonium Field Volume

^{210}Po has a minimum at z=+80 cm above the equator (20 tonnes)



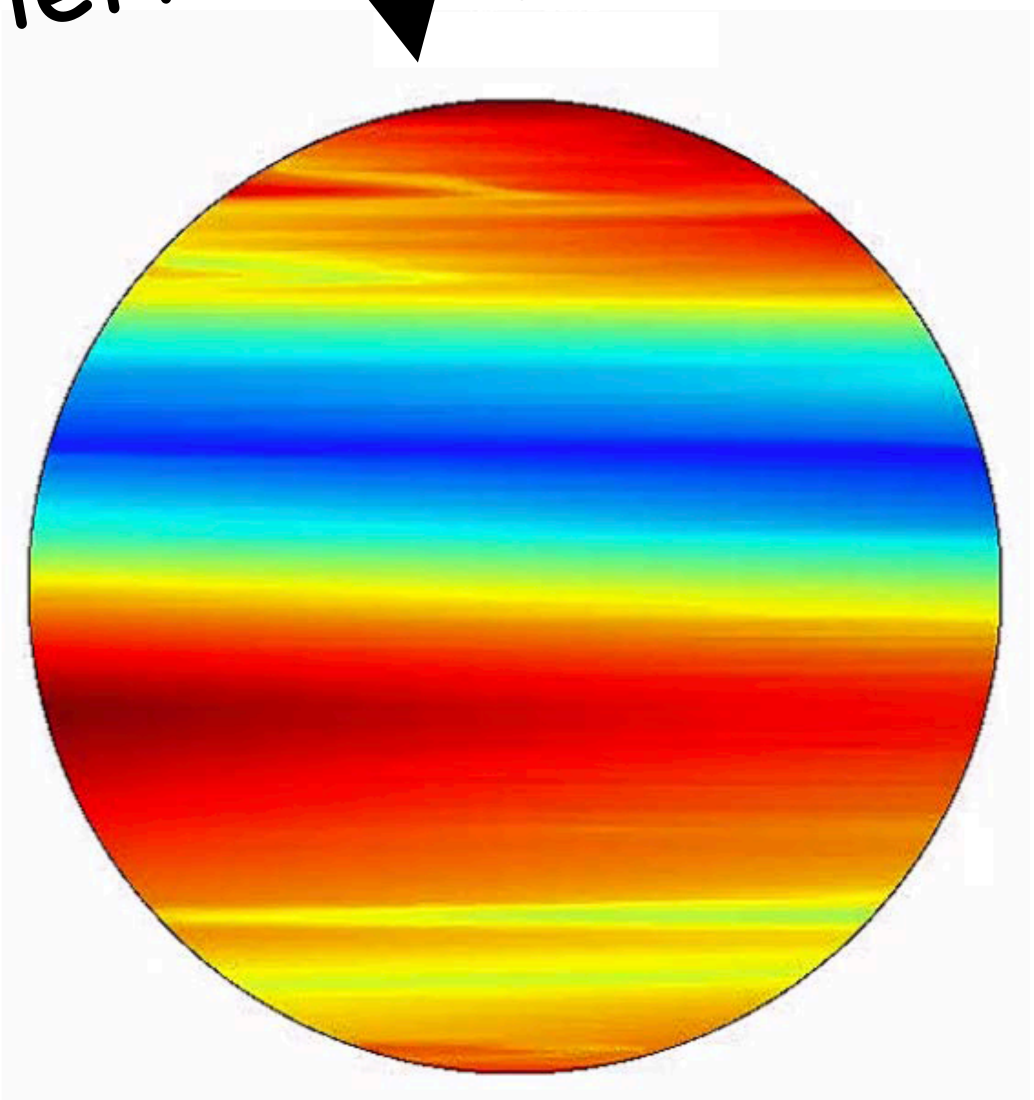


$R(^{210}Po\ min)$ =

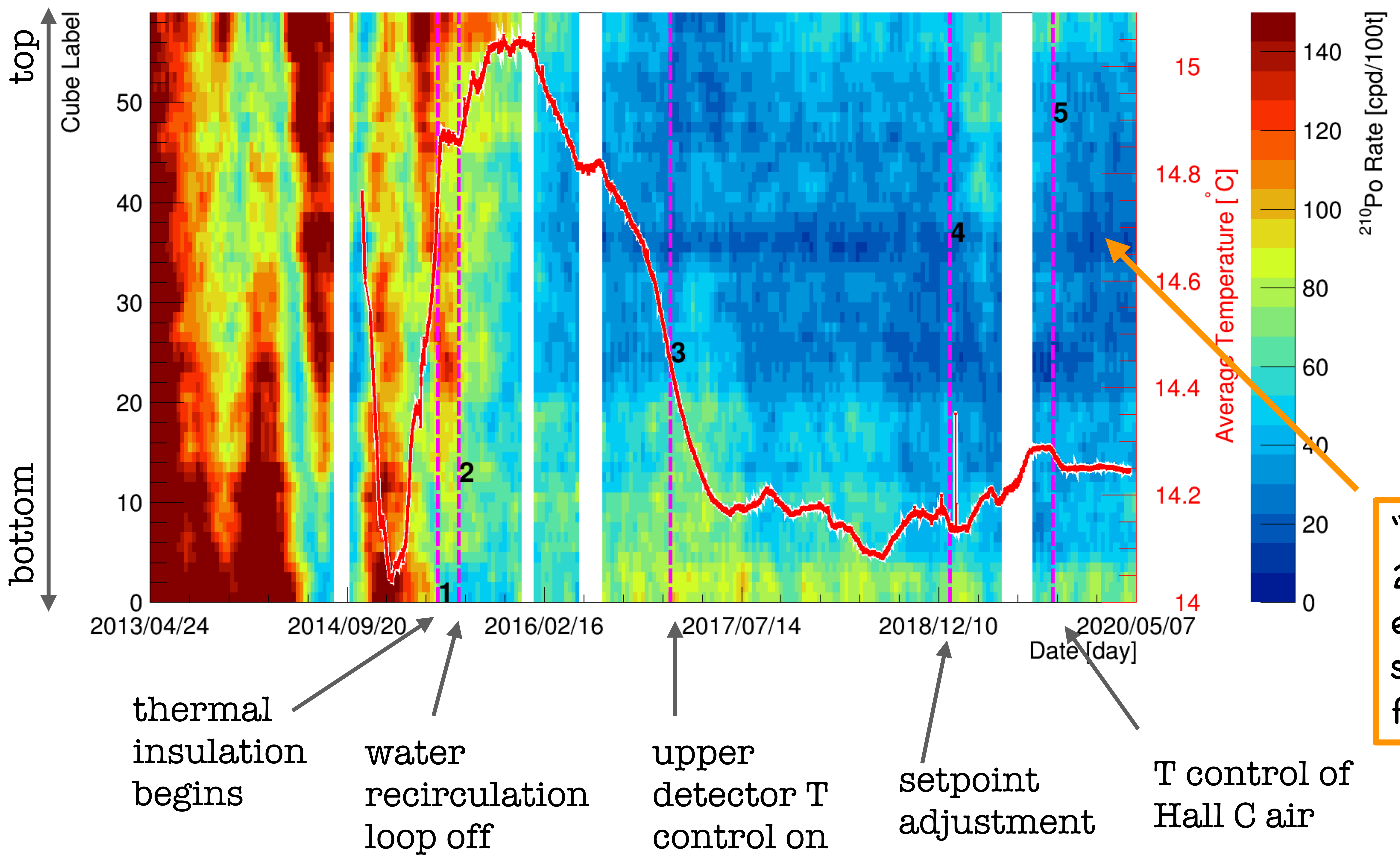
= $R(^{210}Bi)$ + R(from vessel)

≥ $R(^{210}Po$ intrinsic)

numerical fluid simulations



^{210}Po trend vs time — UPDATE

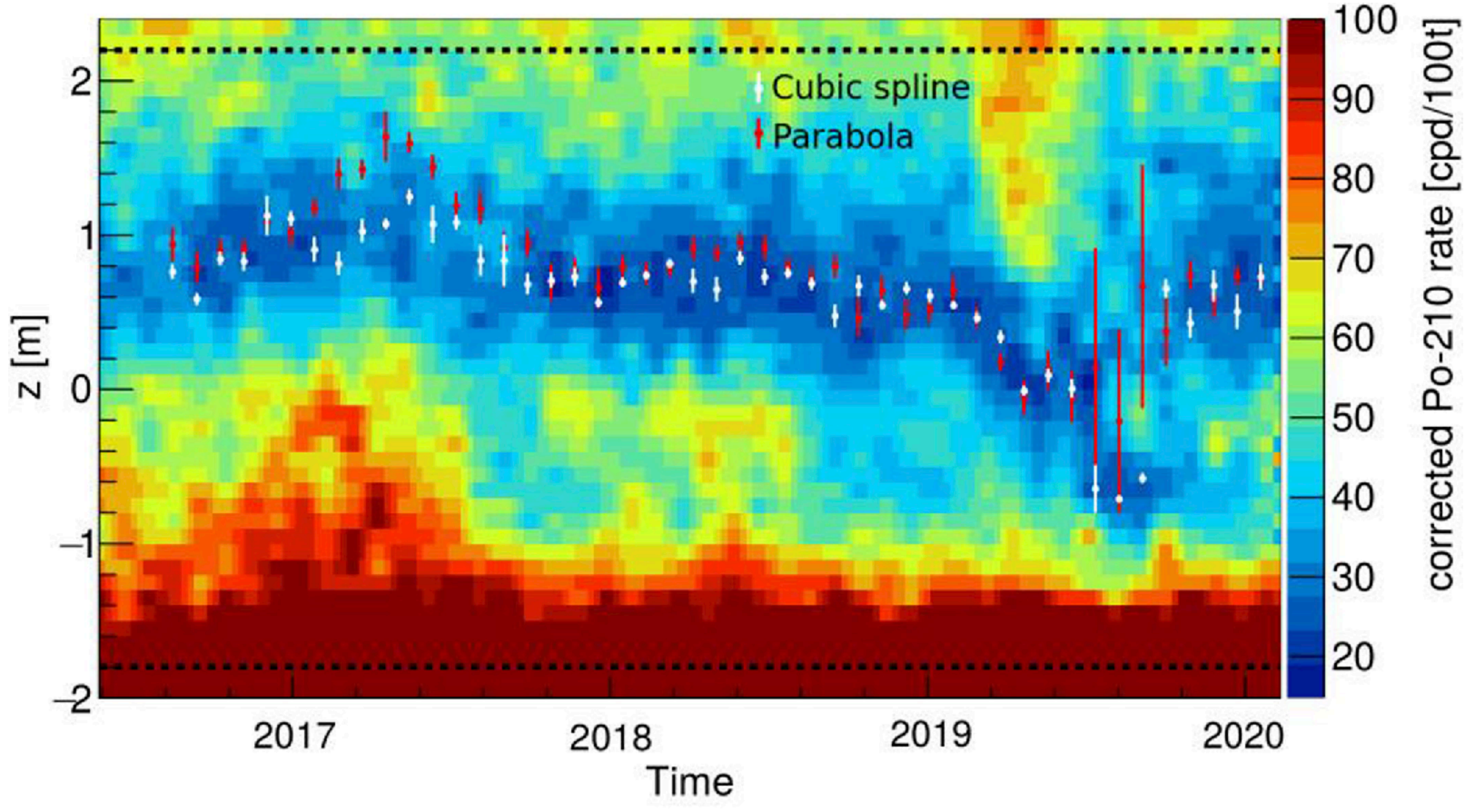


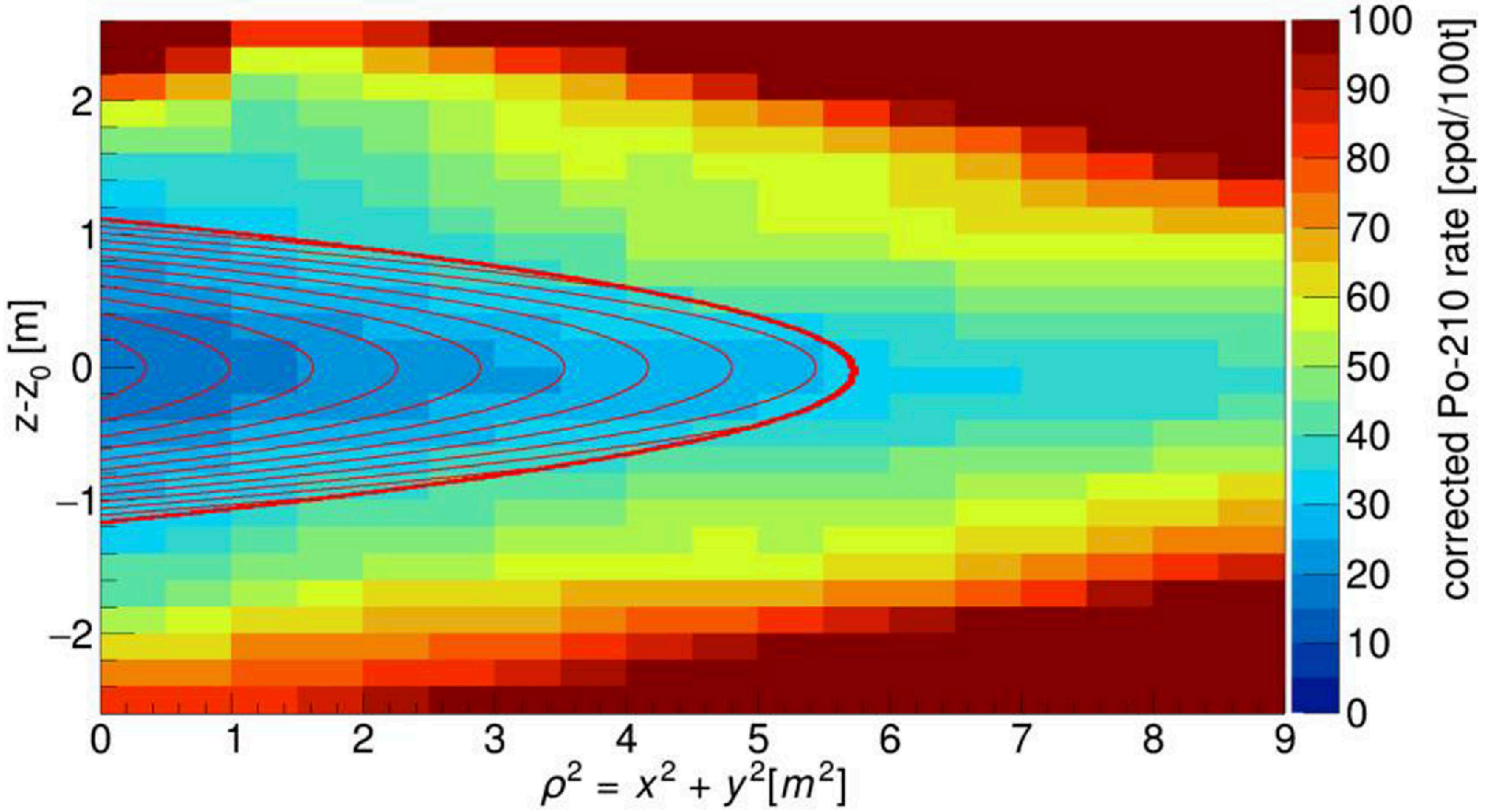
^{210}Po activity (in cpd/100t) within the inner 3-meter radius sphere of scintillator, binned in 3 tonne cubes

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

The Low Polonium Field analysis

- The Low Polonium (LPoF) field region moves very slowly with time
- The centroid of the LPoF is established monthly via two methods (paraboloid/ cubic spline fits)
- Monthly data is aligned (blind procedure), identifying a 20 tonne LPoF volume
- The ^{210}Po minimum establishes **an upper limit for ^{210}Bi**
- Assess ^{210}Bi spatial (radial and angular) and time stability

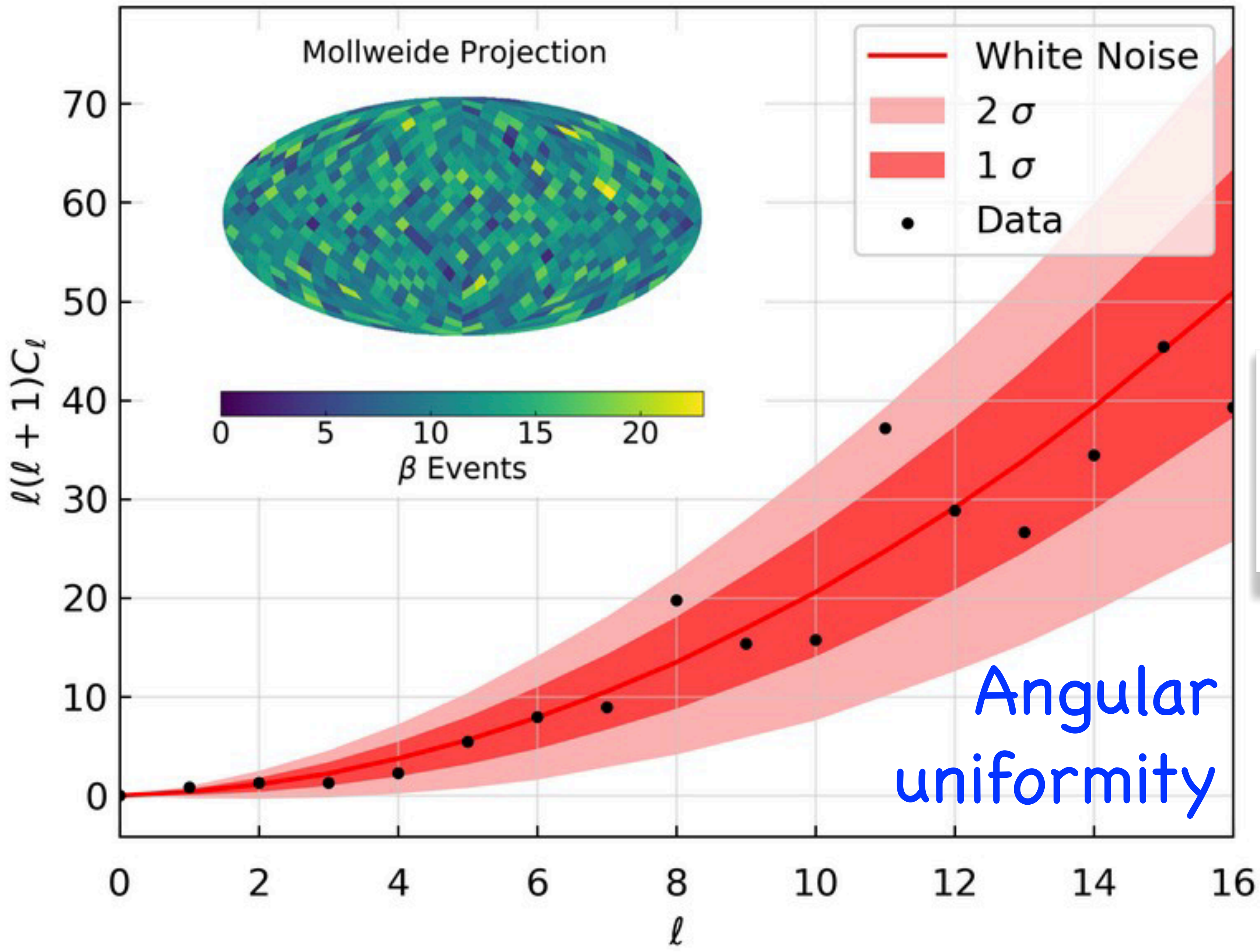




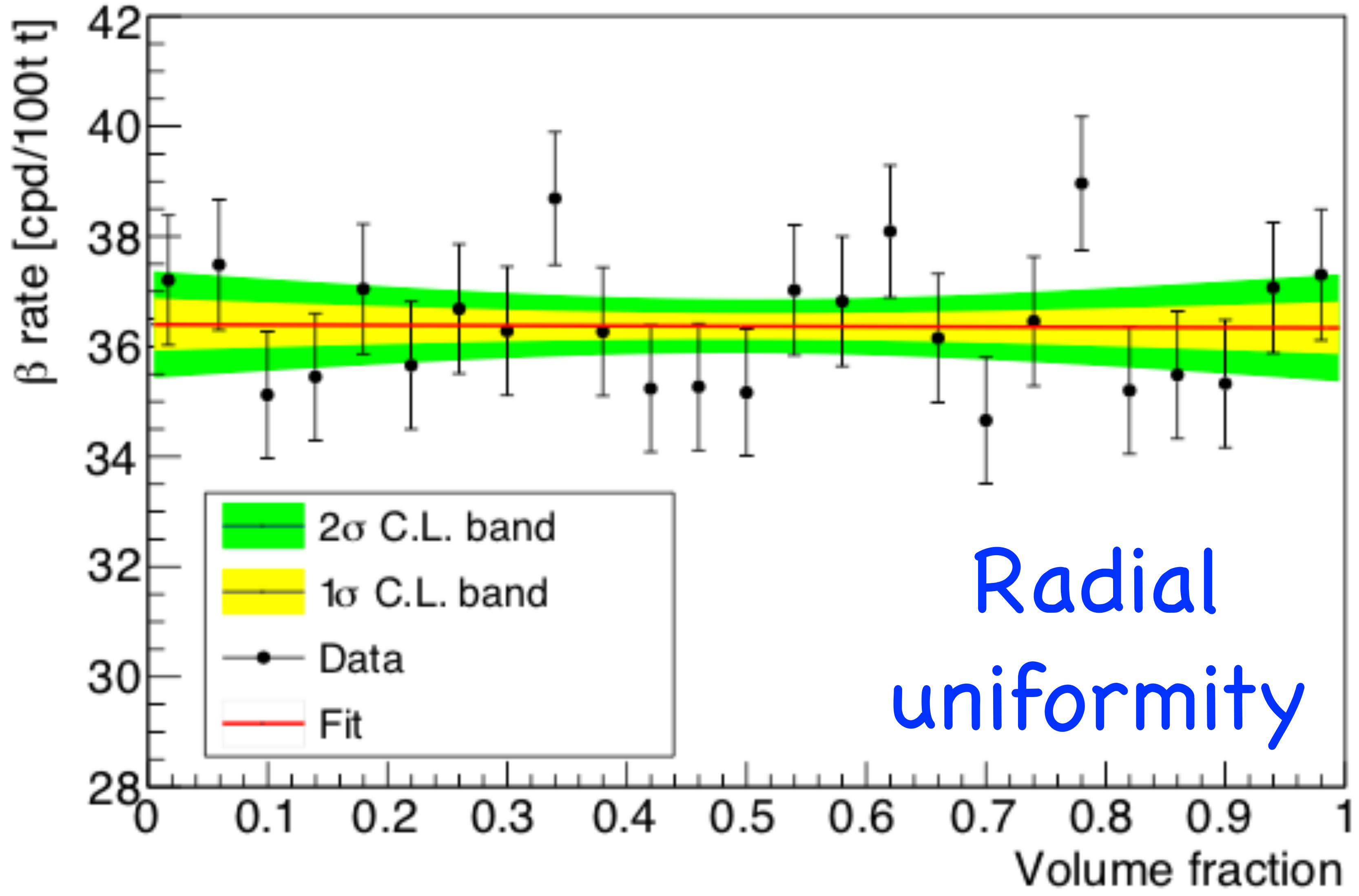
$\sigma_{stat}(R_{min}(^{210}Po))$
0.88 cpd/100t

The Low Polonium Field analysis

- 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)



σ^{sys}(ang)
0.59 cpd/100t

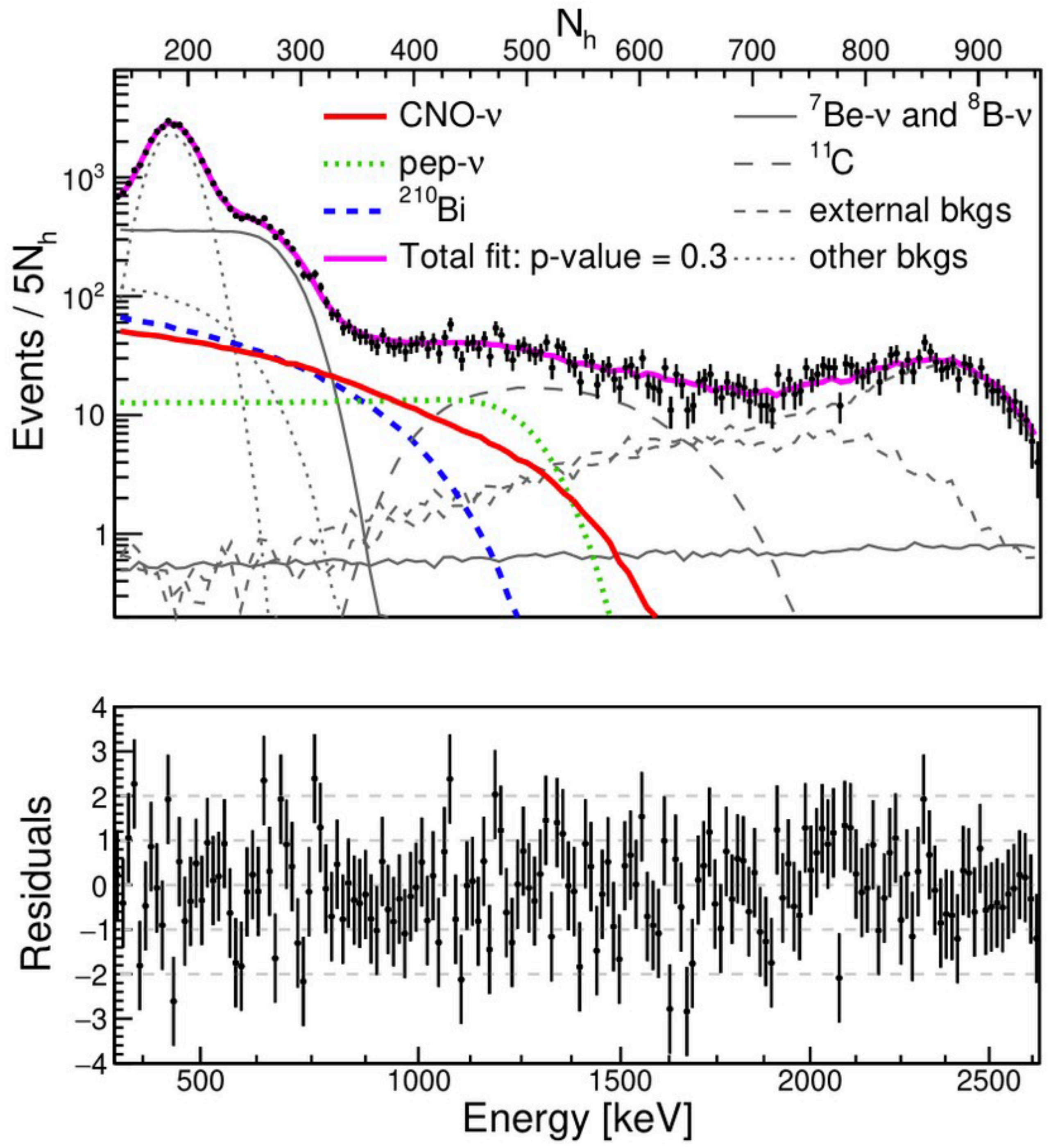


σ^{sys}(rad)
0.51 cpd/100t

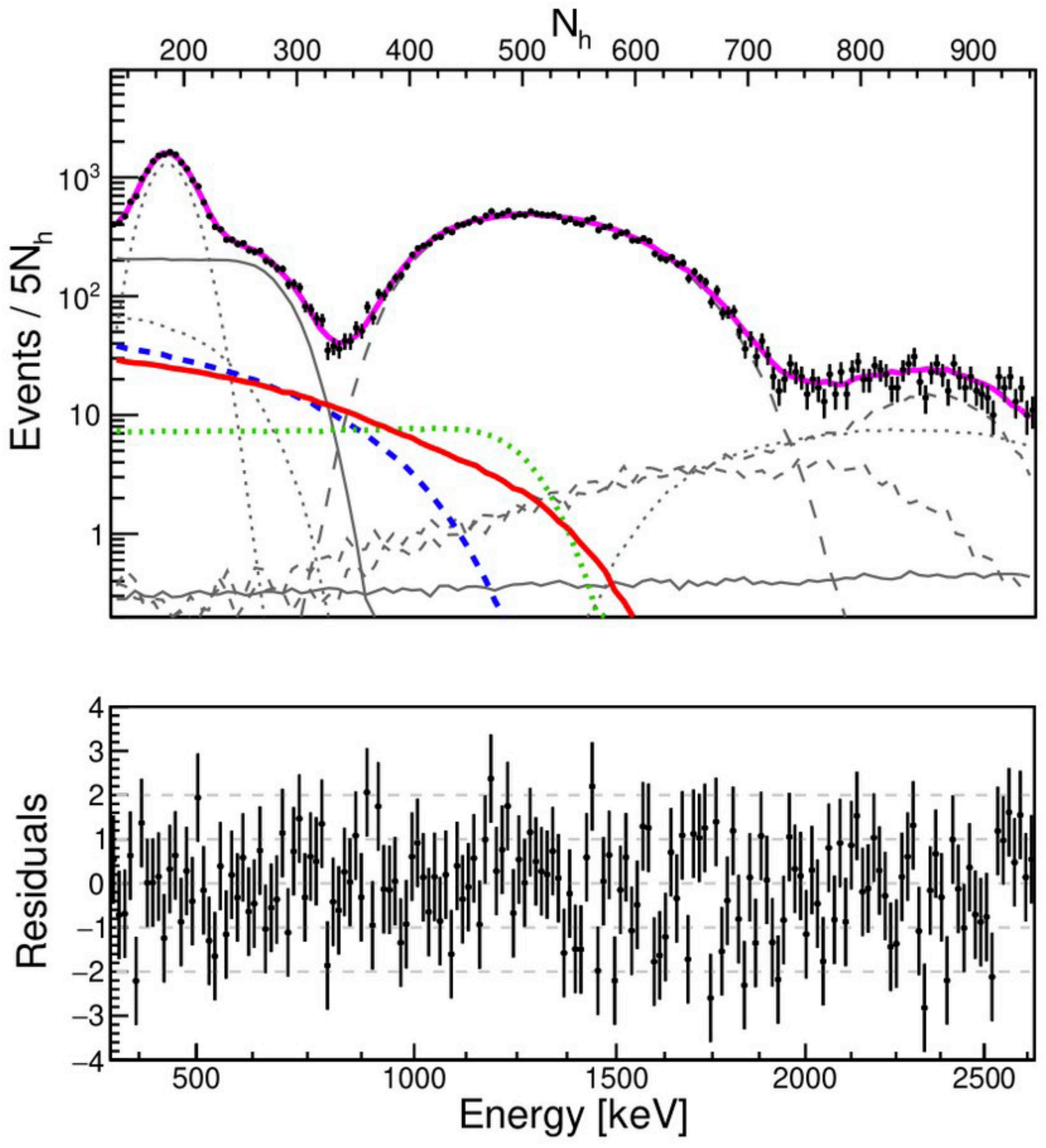
R(^{210}Bi) ≤ 11.5±1.3 cpd/100t

Multi-variate fit -> 1st observation of (solar) CNO neutrinos

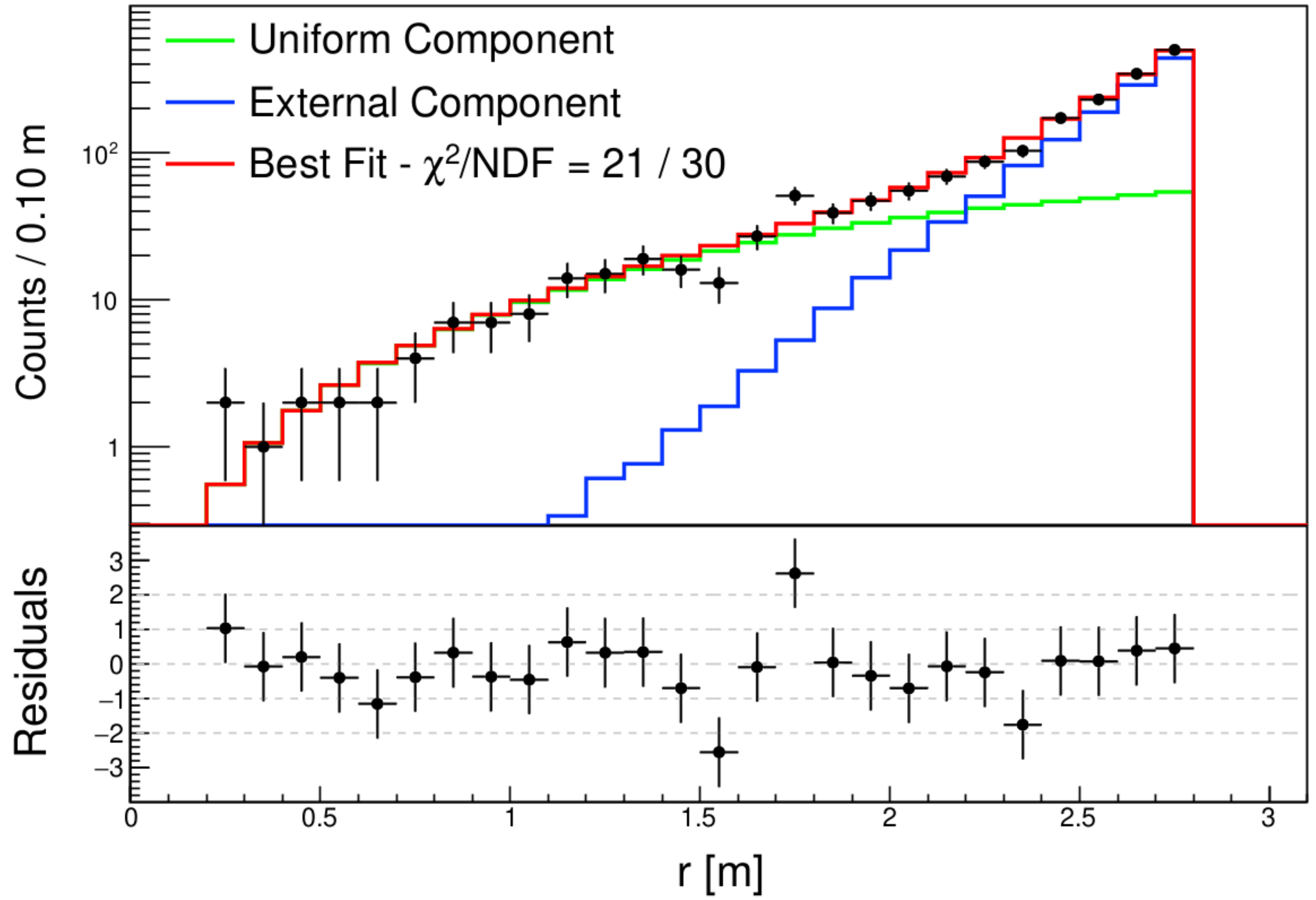
TFC-subtracted
(^{11}C-depleted)



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



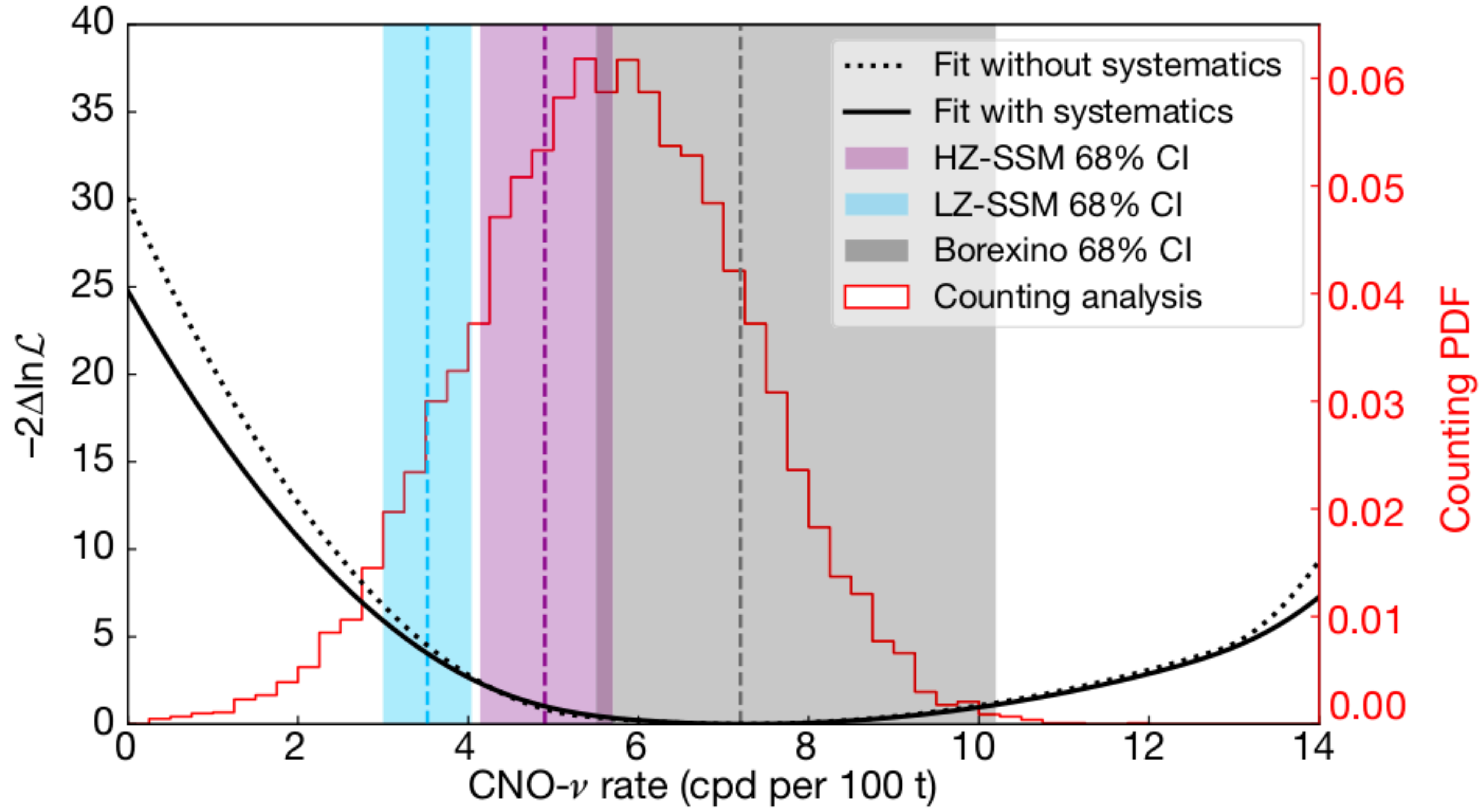
Radial distribution



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

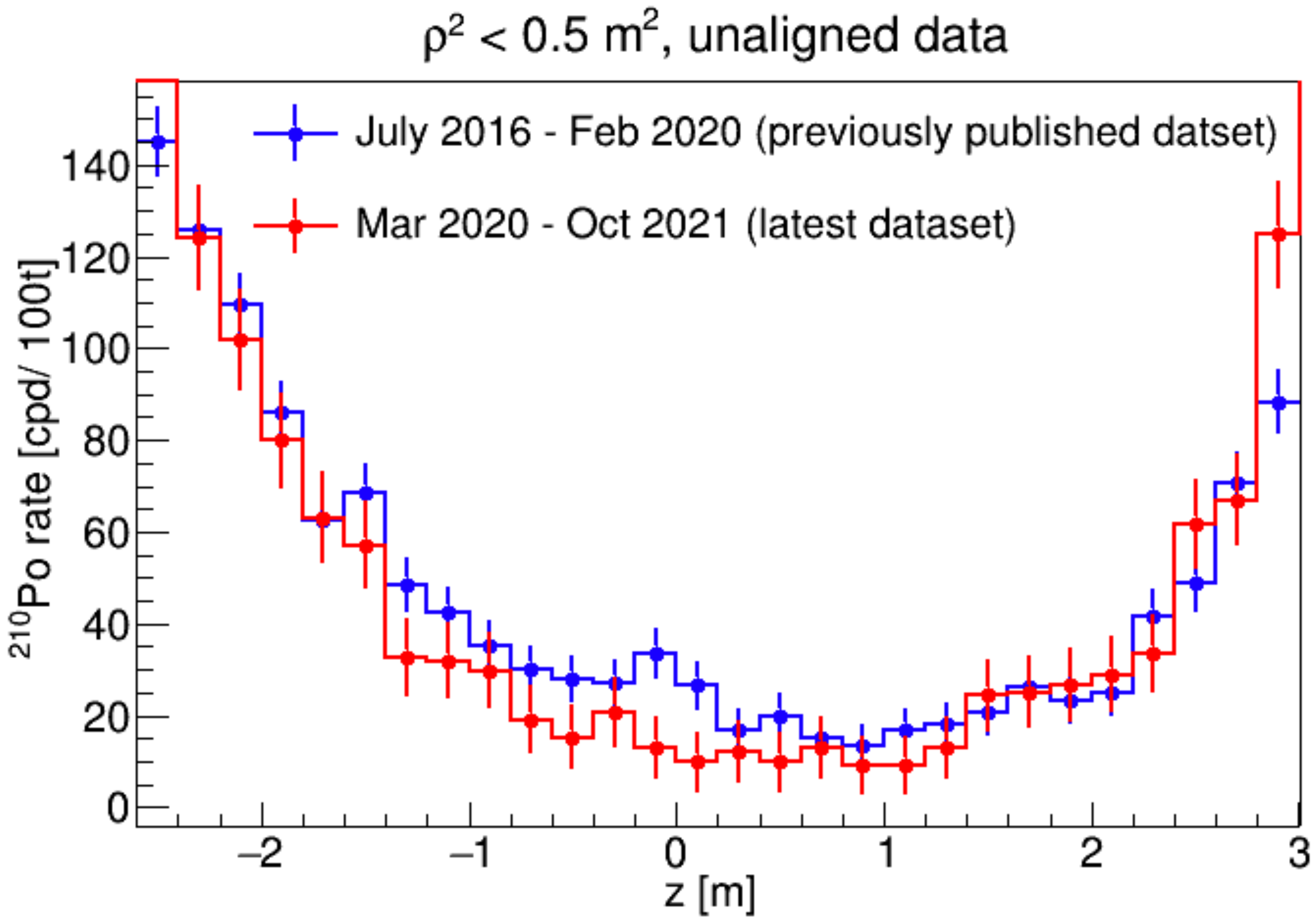


No CNO neutrino hypothesis rejected with a significance of 5.0σ at 99% C.L.

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

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

Improved ^{210}Bi constraint with entire Phase III dataset



R(210Bi) < 10.8 +/- 1.0 counts/d/100t

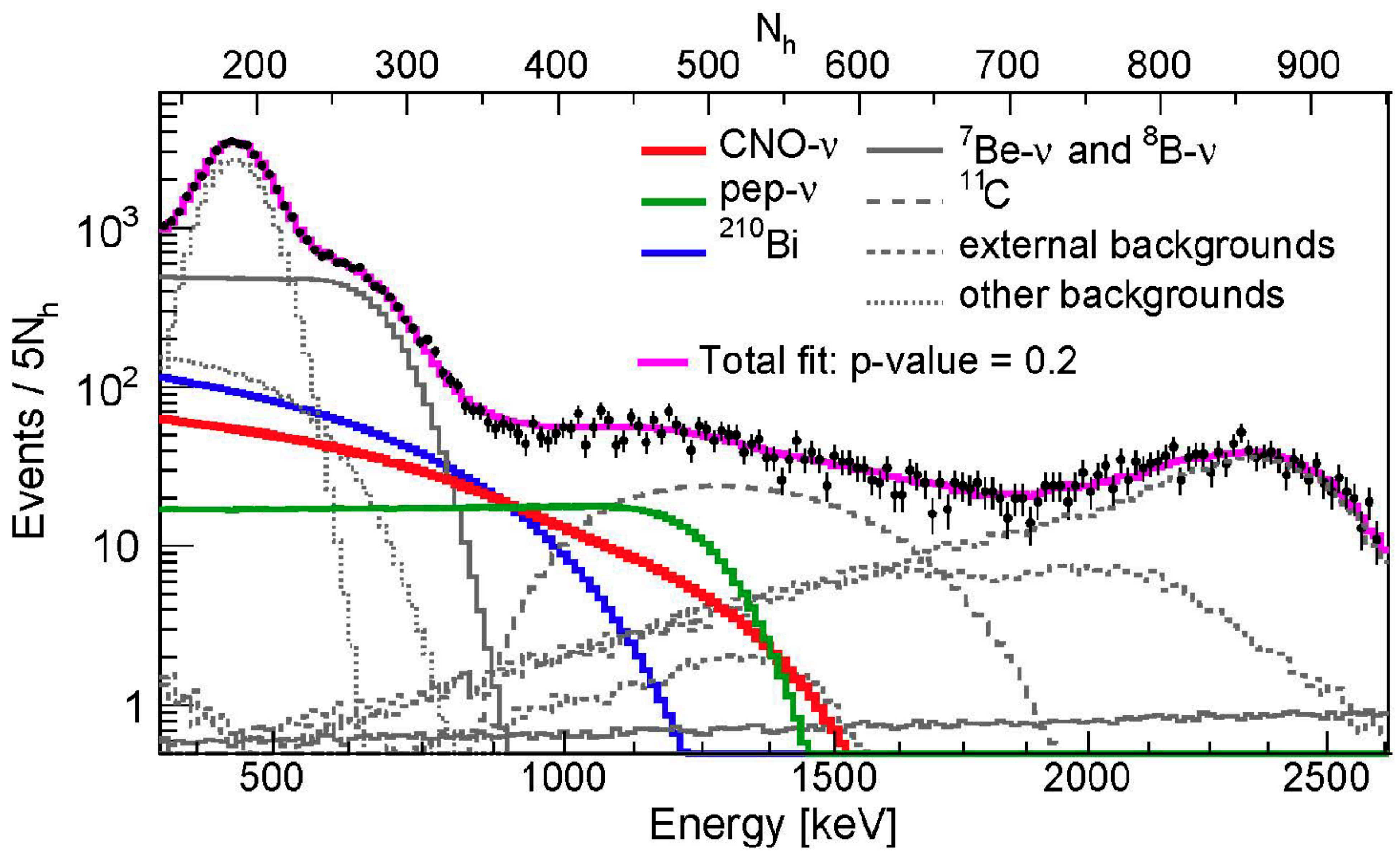
Perform multivariate fit:
— energy
— radial distribution

— Constrain 210Bi to this upper limit (asymmetric penalty)

— pep constrained by global analysis of solar data + luminosity constraint

— all other signals and backgrounds are free parameters

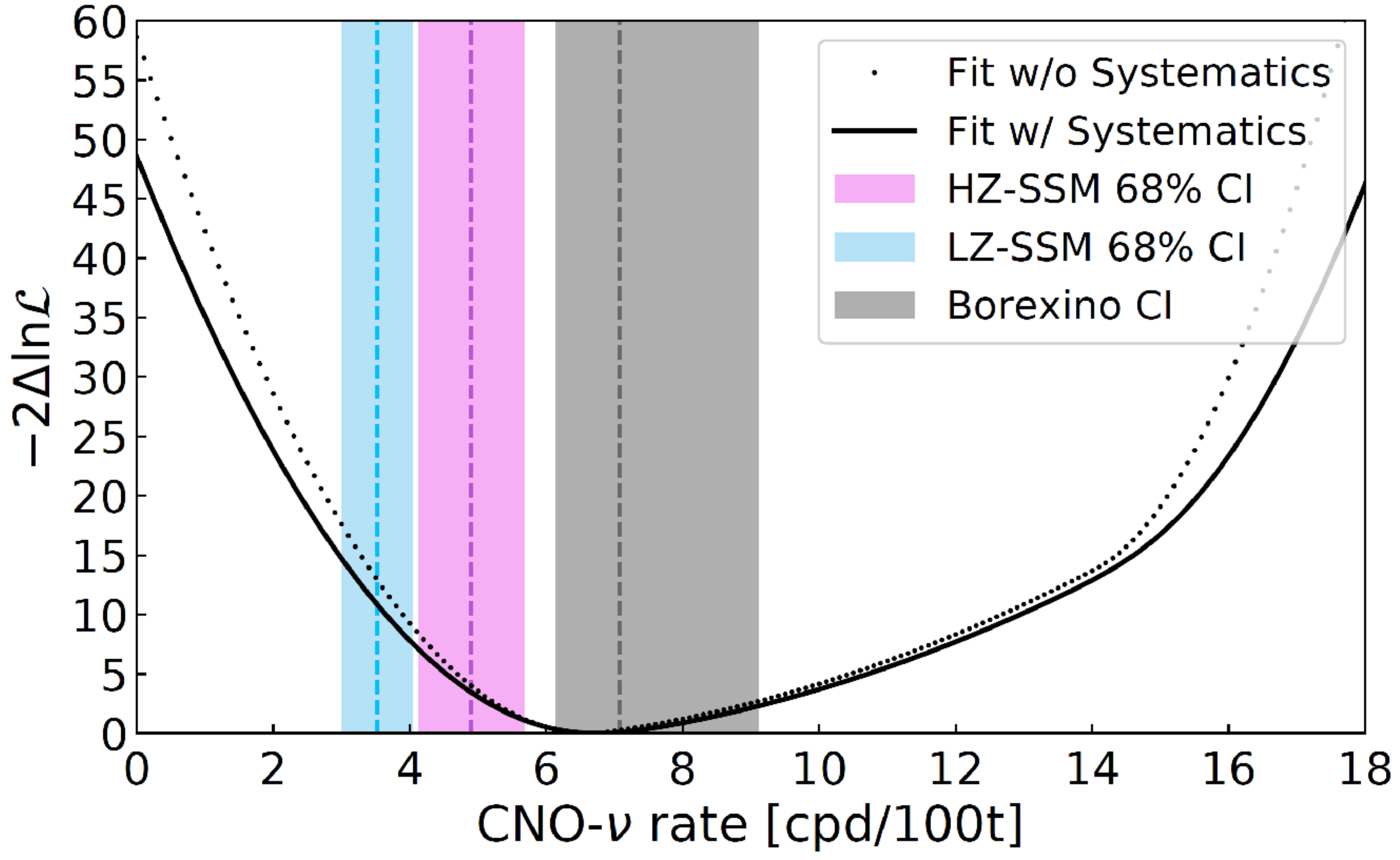
Improved CNO neutrino detection (2022)



Results (including sys errors)

Rate(CNO)= 6.7 $^{+2.0}_{-0.8}$ cpd/100t

ϕ(CNO)= 6.6 $^{+2.0}_{-0.9}$ x 10^8 ν cm $^{-2}$ s $^{-1}$



Included systematics:

- **Systematics on the method to extract the ^{210}Bi upper limit** (included in the error of the constraint);
- **Systematics on uniformity of ^{210}Bi** (included in the error on the constraint);
- **Fit condition:** we have performed the fit in 2500 different conditions → negligible;
- **Ratio between O and N neutrinos:** Systematics due to the fact that we fix the N/O ratio in the CNO spectral shape→negligible;
- **Systematic associated to non perfect energy pdfs: -0.4 +0.5 cpd/100t** (stability in time of light yield (estimated with neutrons), linearity (from calibrations), non-uniformity (from calibrations and neutrons), systematic on the ^{210}Bi spectral shape

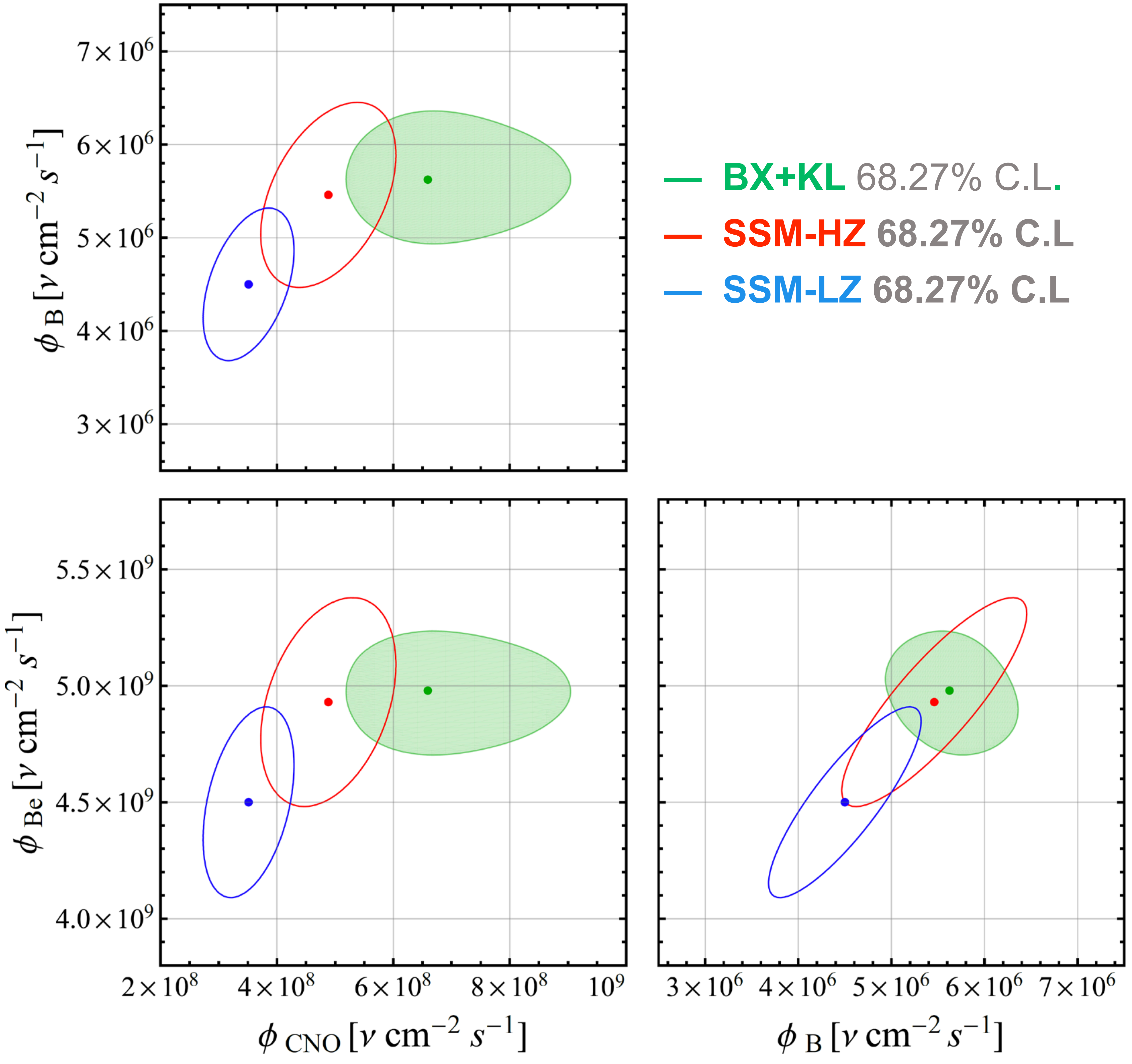
Summary of Borexino solar results (2022)

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	$6.7^{+2.0}_{-0.8}$ 7σ	$6.6^{+2.0}_{-0.9}\times10^{8}$	$4.88(1\pm0.12)\times10^{8}$ $3.51(1\pm0.12)\times10^{8}$

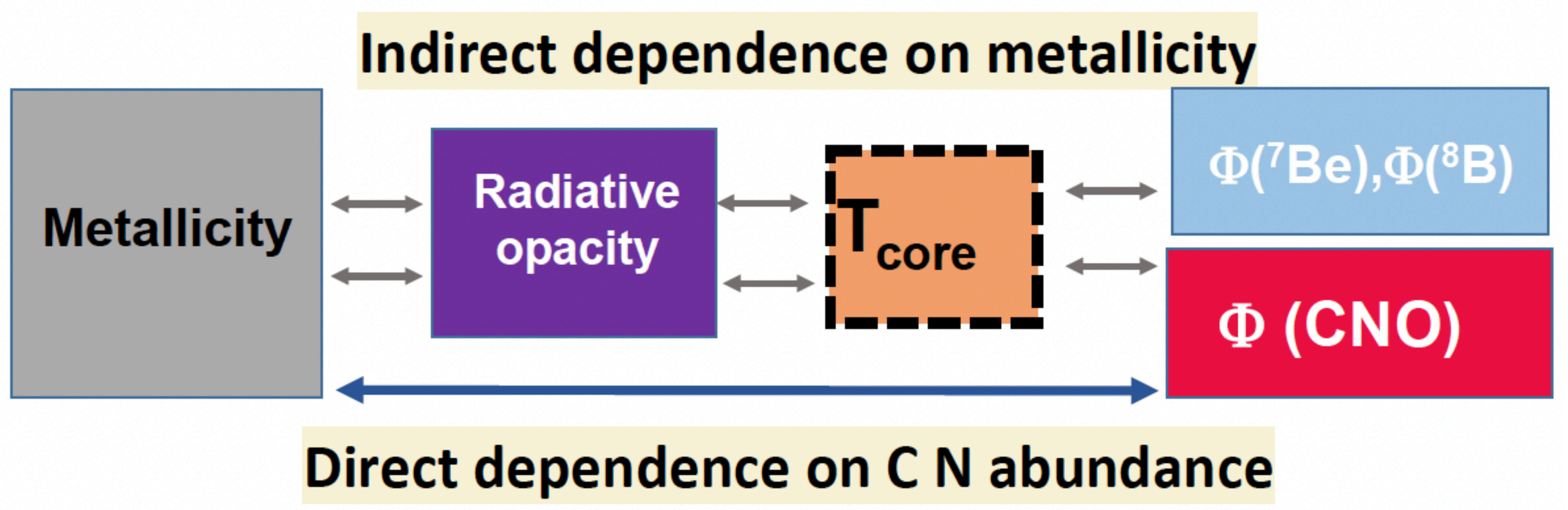
Implications of the improved CNO measurement

- **Borexino results only (8B, 7Be,CNO) +KamLAND**;
- Φ(Be), Φ(B) and Φ(CNO), together with θ_{12} and Δm^2_{12} are free parameter of the fit;
- The results agree well with the output of SSM-HZ(1) model, while feature a small tension with the SSM-LZ(2) model (p= 0.018);
- This small tension is created mostly (but not only) by the addition of the CNO result (p-value goes from 0.196 —> 0.018);



*(1) SSM-HZ= B16-GS98: Vinyoles et al. Astr.J. 835 (**2017**) 202 + Grevesse et al., SpaceSci.Rev. **(1998)** 85*
*(2) SSM-LZ= B16-AGS009met: Vinyoles et al. Astr.J. 835 (**2017**) 202 + A. Serenelli et al., Astr. J. 743,(2011)24*

C and N abundances



$$\Phi_B/\Phi_B{}^{SSM} \propto (T_c/T_c{}^{SSM})^{\tau_B} \qquad (\tau_B = 24)$$

$$\Phi_O/\Phi_O^{SSM} \propto \frac{n_{CN}}{n_{CN}^{SSM}} \times (T_c/T_c{}^{SSM})^{\tau_O} \qquad (\tau_O = 20)$$

- Use $\Phi(^8B)$ as a thermometer for the solar core
- A weighted $\Phi(^{15}O)/\Phi(^8B)$ ratio minimizes the uncertainties due to opacity and other input parameters of the SSM

$$\frac{(\Phi_O/\Phi_O{}^{SSM})}{(\Phi_B/\Phi_B{}^{SSM})^k} \propto \frac{n_{CN}}{n_{CN}^{SSM}} \left(\frac{T_c}{T_c{}^{SSM}}\right)^{\tau_O - k\tau_B}$$

$(k = \tau_O/\tau_B \sim 1.83)$

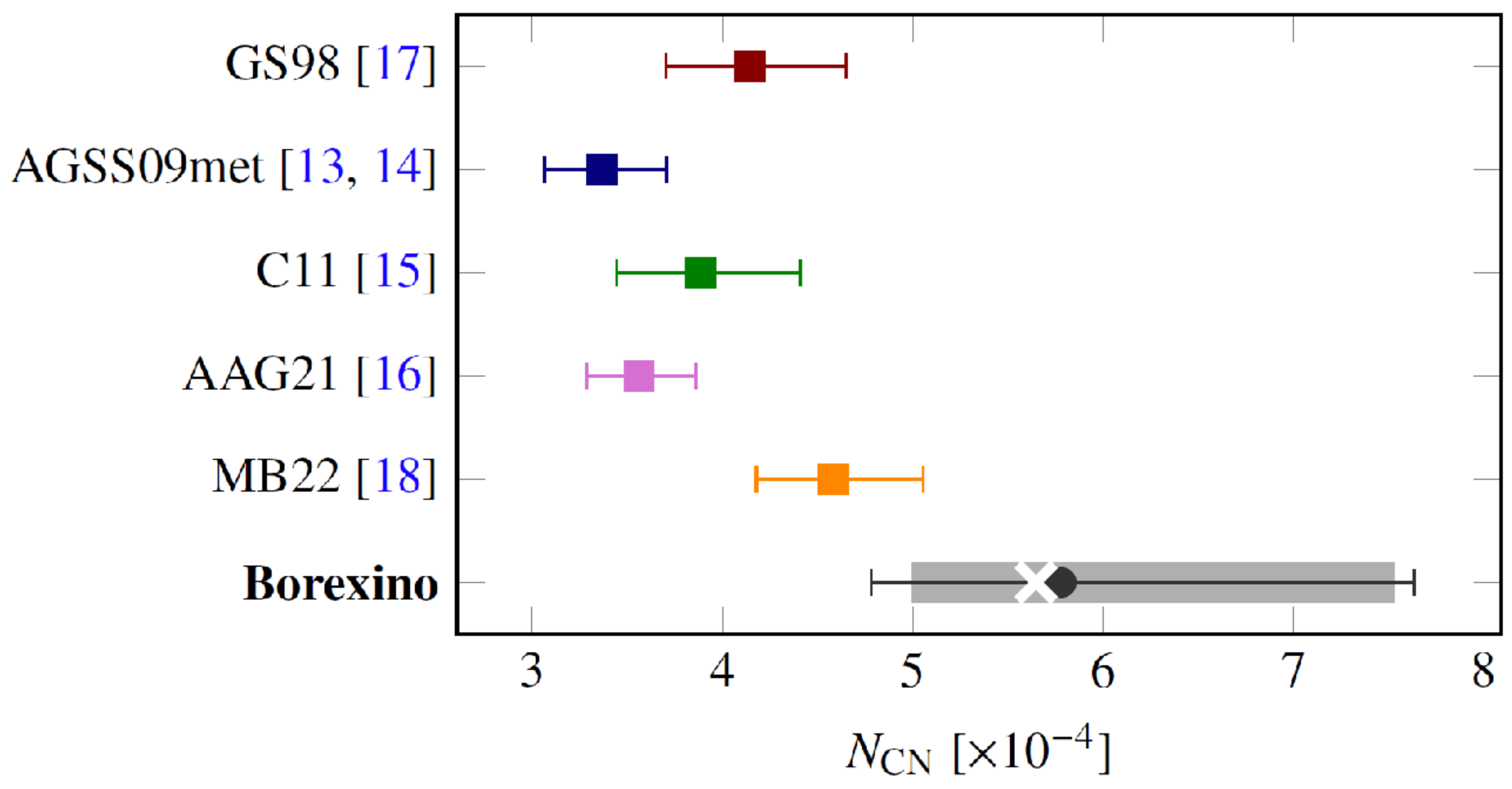
- Optimal value of k = 0.769: $\dfrac{N_{CN}}{N_{CN}^{SSM}} = \dfrac{(\Phi_O/\Phi_O^{SSM})}{(\Phi_B/\Phi_B^{SSM})^{0.769}}$

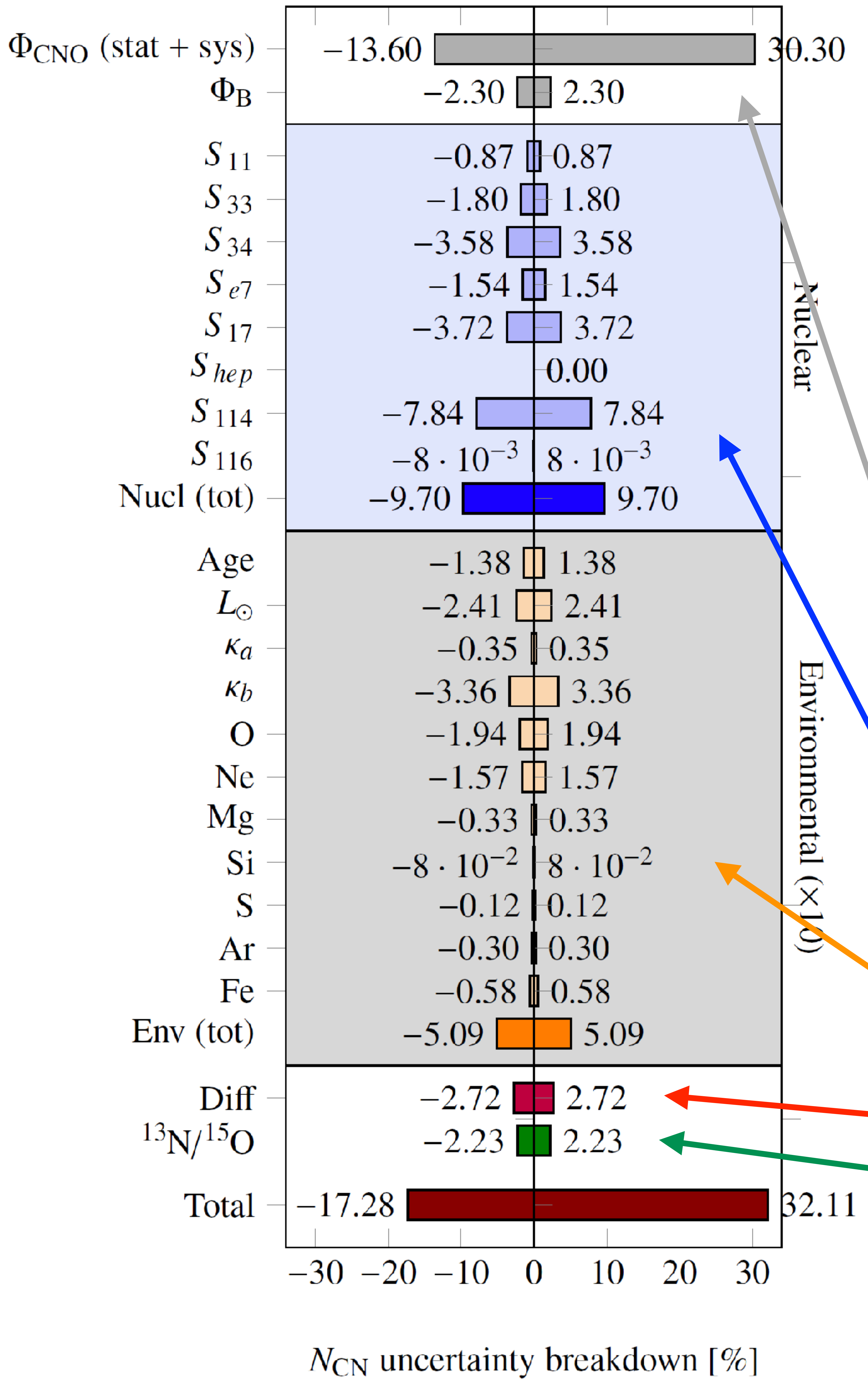
- N.B.: with this procedure we extract directly the abundance on the surface;
- In fact, the procedure relies on partial derivatives with respect to the photosphere composition;

C and N abundances

- Insert Φ_B from global analysis
- Calculating Φ_O from the CNO flux, assuming the SSM O/N ratio

$$N_{CN} = (5.78^{+1.85}_{-1.00}) \times 10^{-4}$$





Contributions to the error:

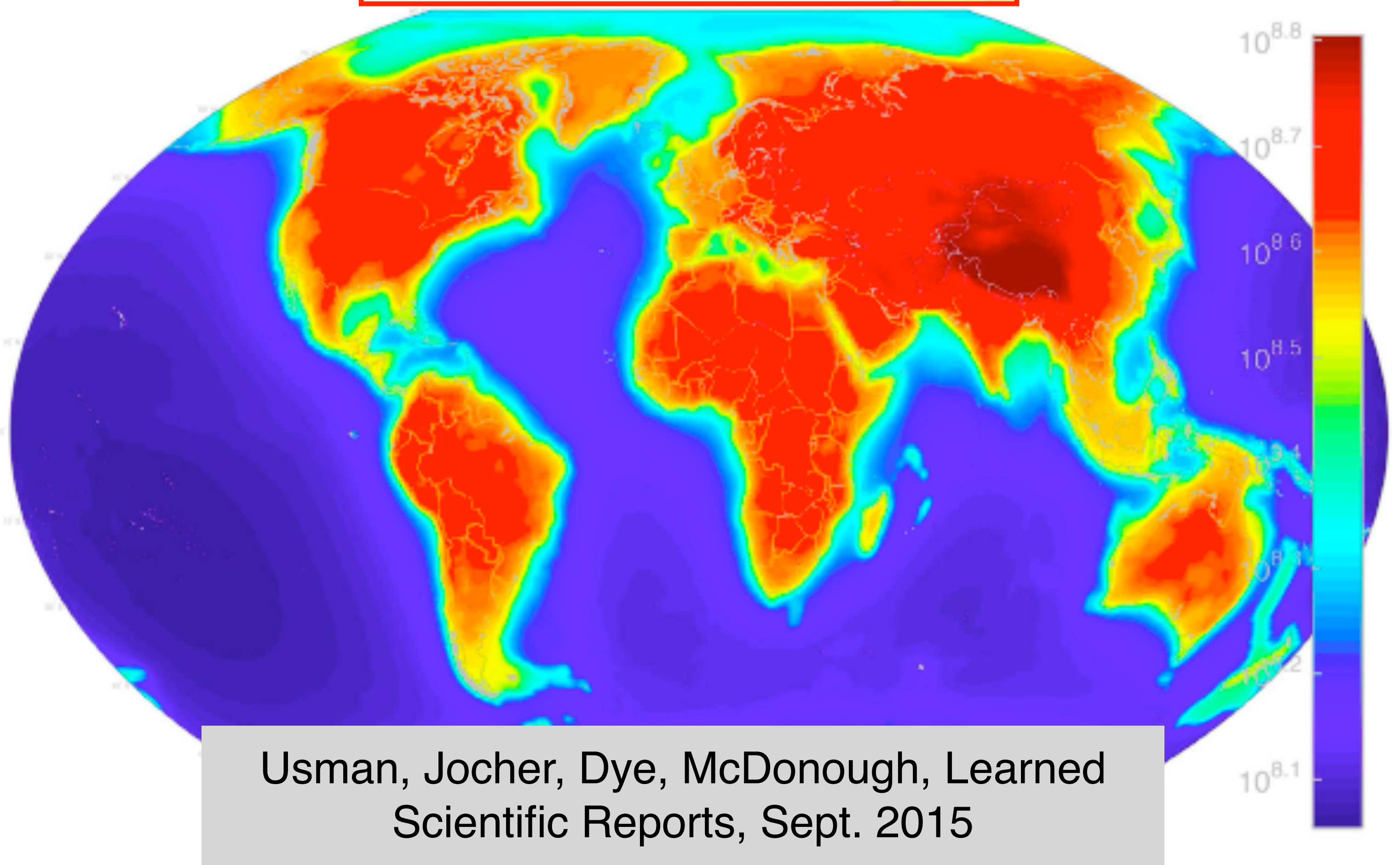
- CNO measurement: +30% -14%;
- 8B flux: +/-2.3%
- Nuclear: +/-9.7%
- Environm: 0.5% (small by construction)
- Diffusion: 2.7%
- N/O ratio: 2.2%

Geo-neutrinos (3262.74 days)

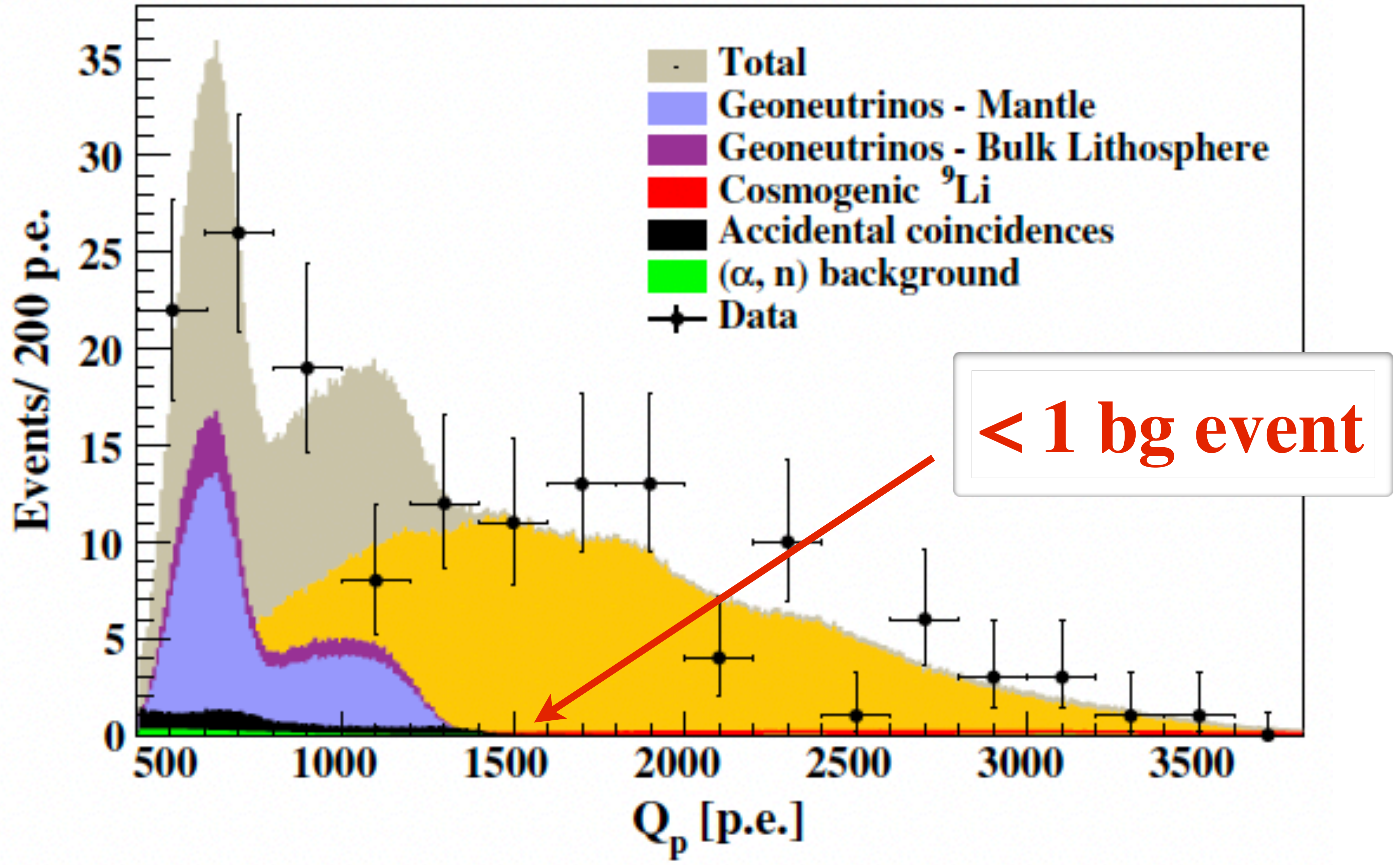
[PRD 101 012009 (2020)]

- Anti-neutrinos associated with beta decays in the Earth
- Detected via IBD, characteristic coincidence
  - ^{232}Th and ^{238}U chains
  - ^{40}K (below IBD threshold)
- Observed by two experiments:
  - First reported by KamLAND ('05), then '11, '13
  - Borexino published in '10, '13, '15

$\Phi_\nu \sim 10^6\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$



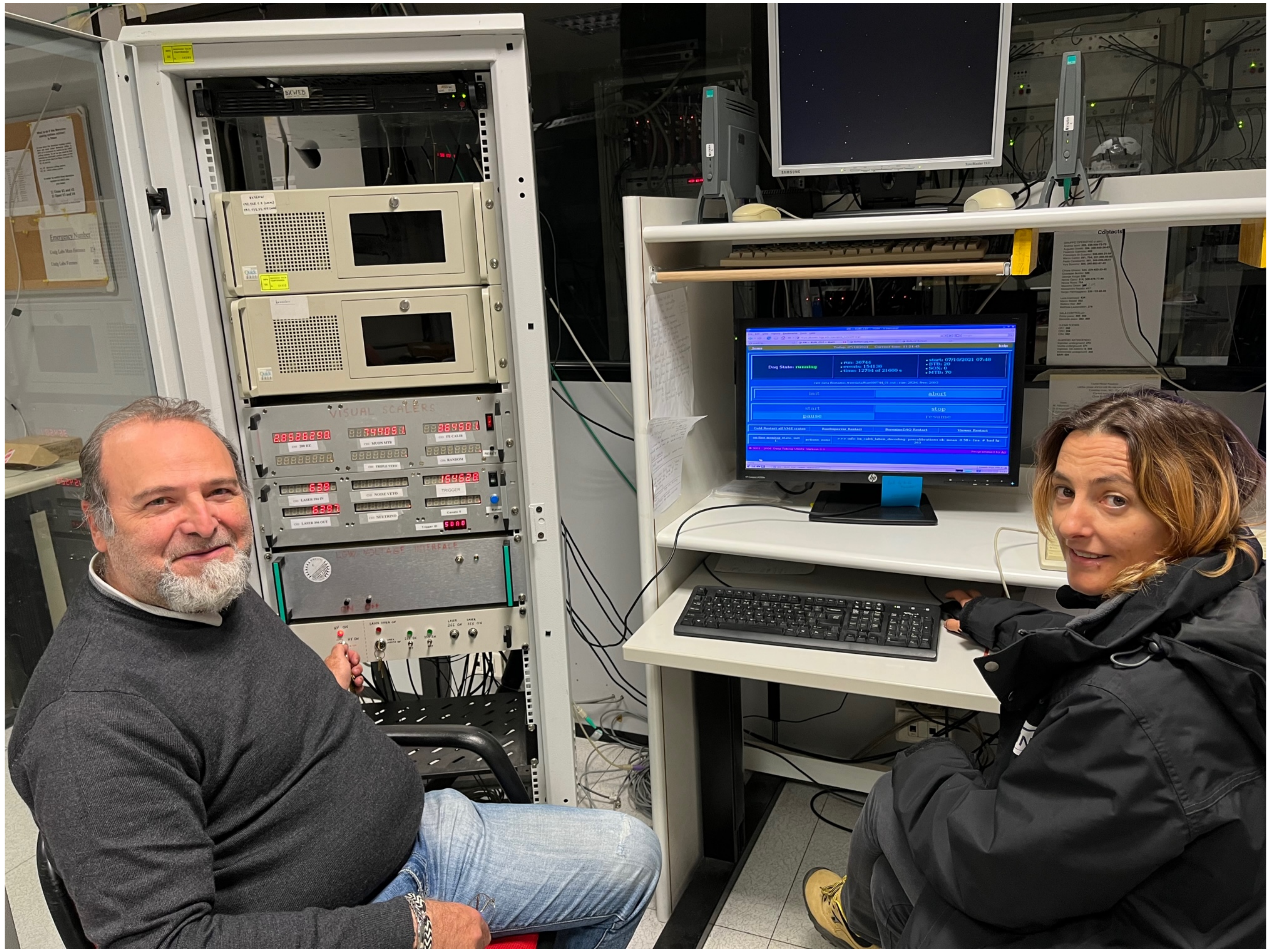
Usman, Jocher, Dye, McDonough, Learned
Scientific Reports, Sept. 2015



extremely low background allows for a measurement even with low statistics

Detected antineutrinos from the earth mantle

October 4, 2021 — end of data-taking



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

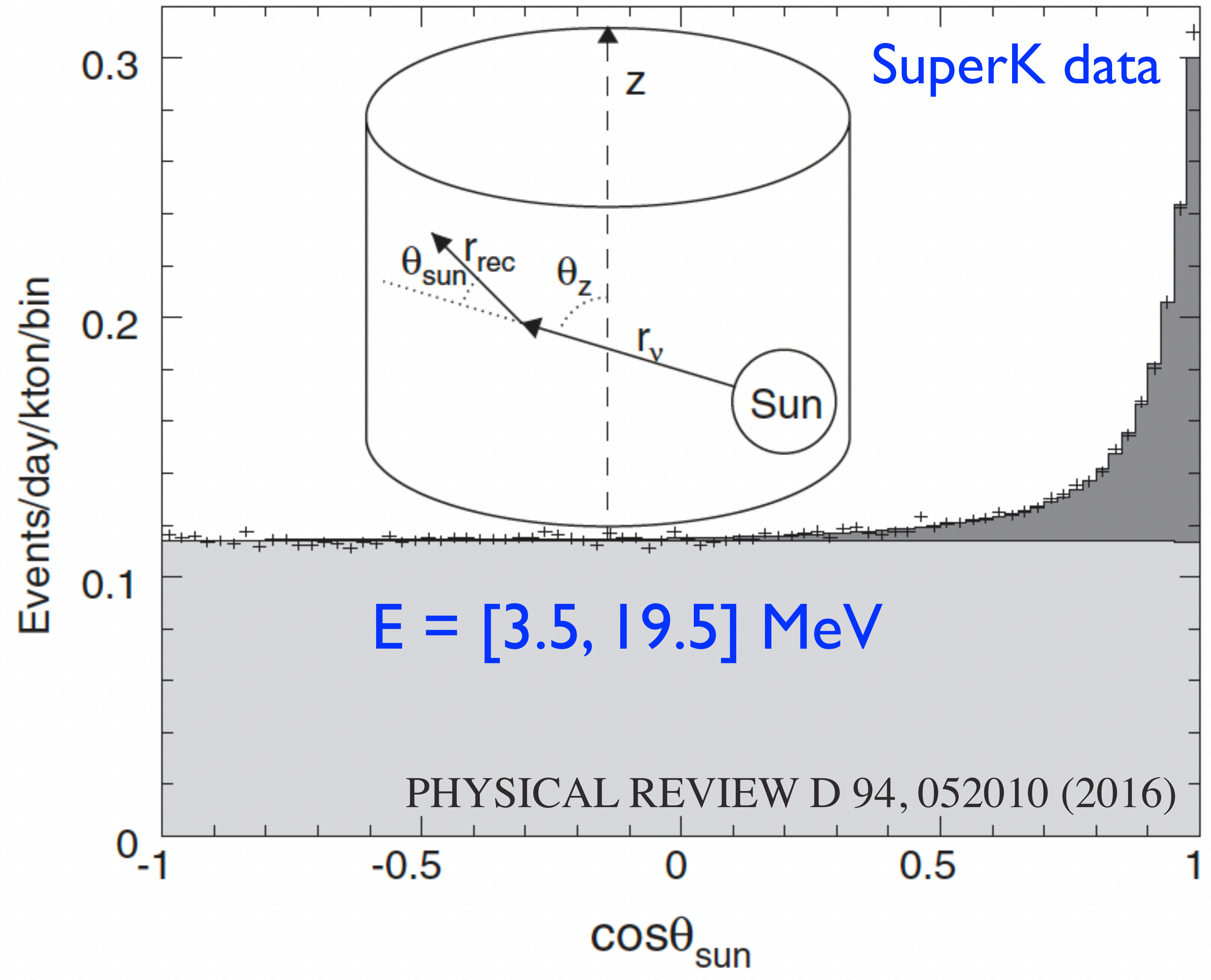
The Borexino detector has been drained of its scintillator (as of June 2022)

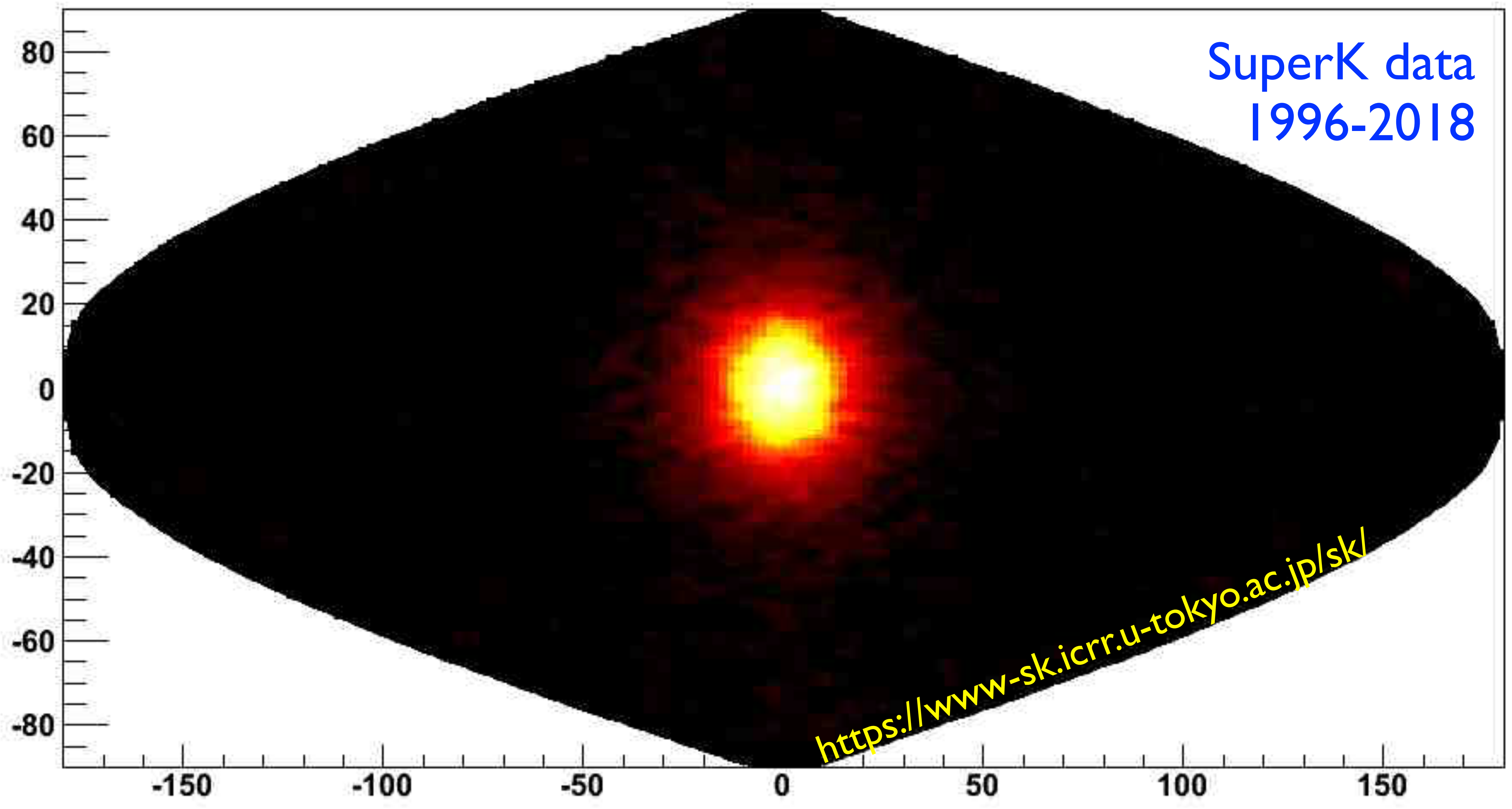
Reallocation of some of the Borexino infrastructure is currently being discussed

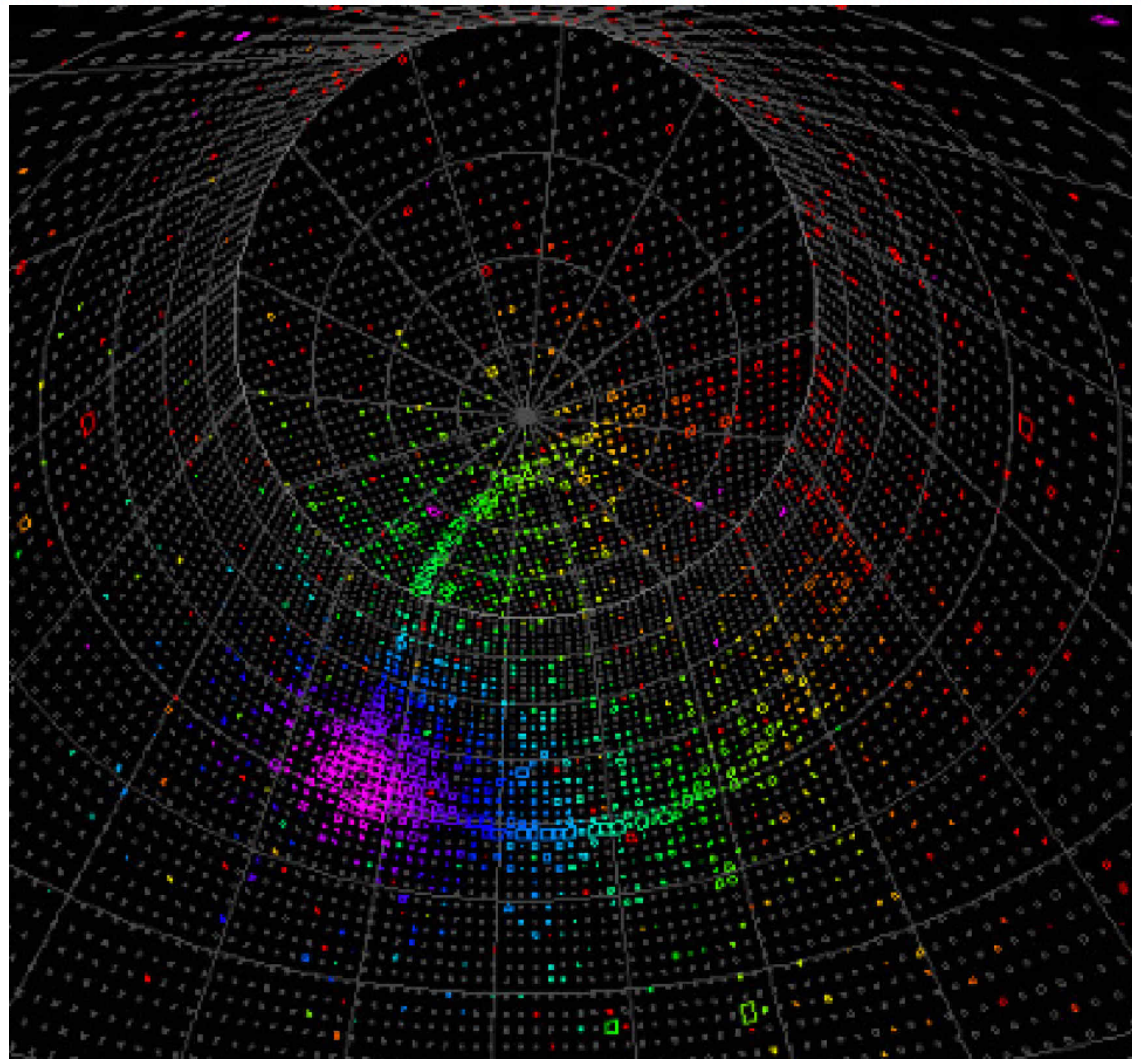
Analysis of data still ongoing

Directional neutrino signature

- Cherenkov detectors (Kamiokande, SuperK, SNO/SNO+) preserve directional information of the incoming neutrino
- Few MeV threshold
- Excellent transparency + ring imaging



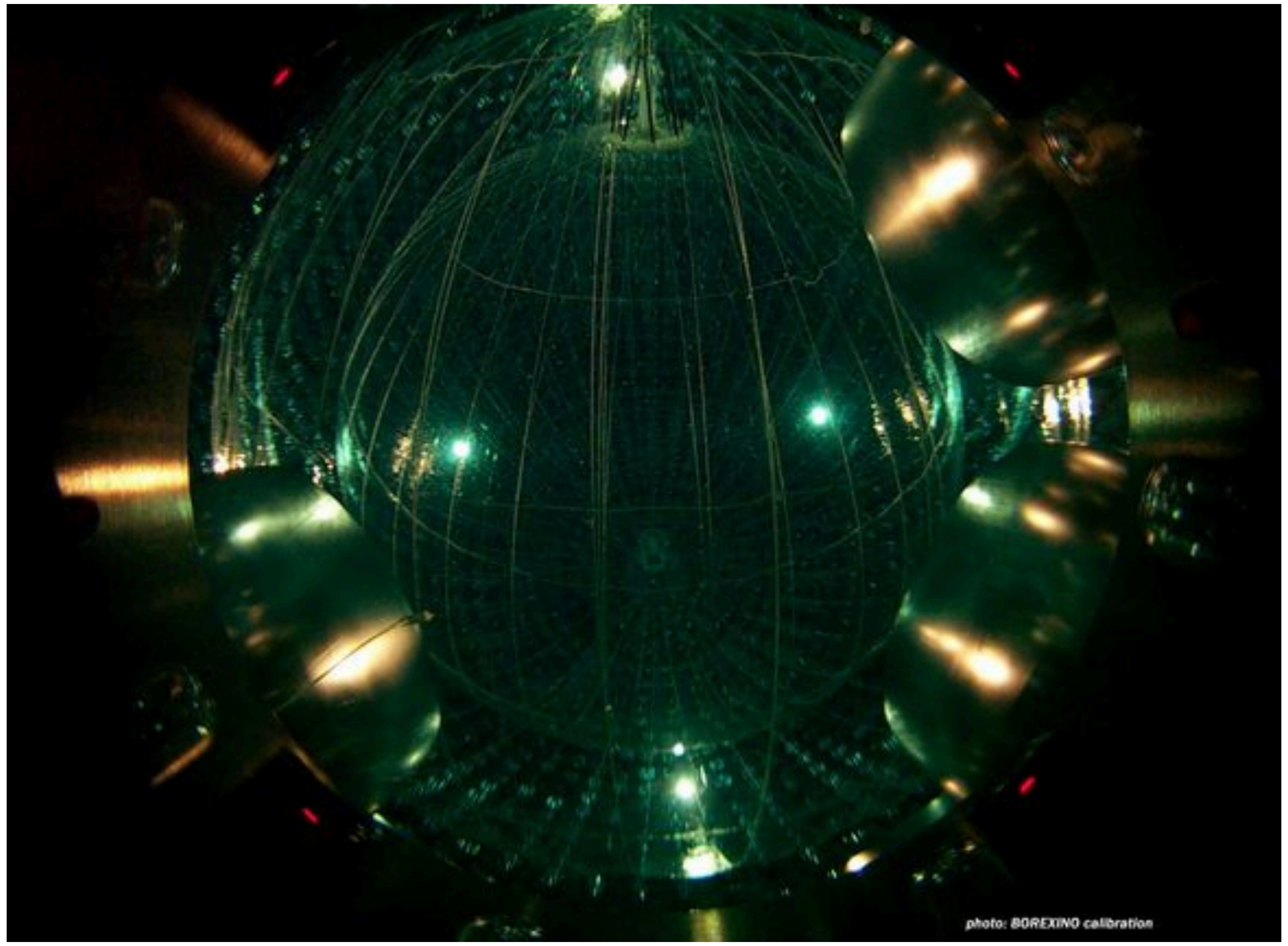




Directional signature at MeV energy in liquid scintillator

- Scintillator detectors: Borexino, KamLAND, JUNO
- Scintillation is isotropic -> directional information (mostly) lost
- High light yield (500 p.e./MeV) -> low energy threshold

  - Cherenkov light is still present, but much less intense than scintillation
    - Faster
    - Directional
    - Different spectrum

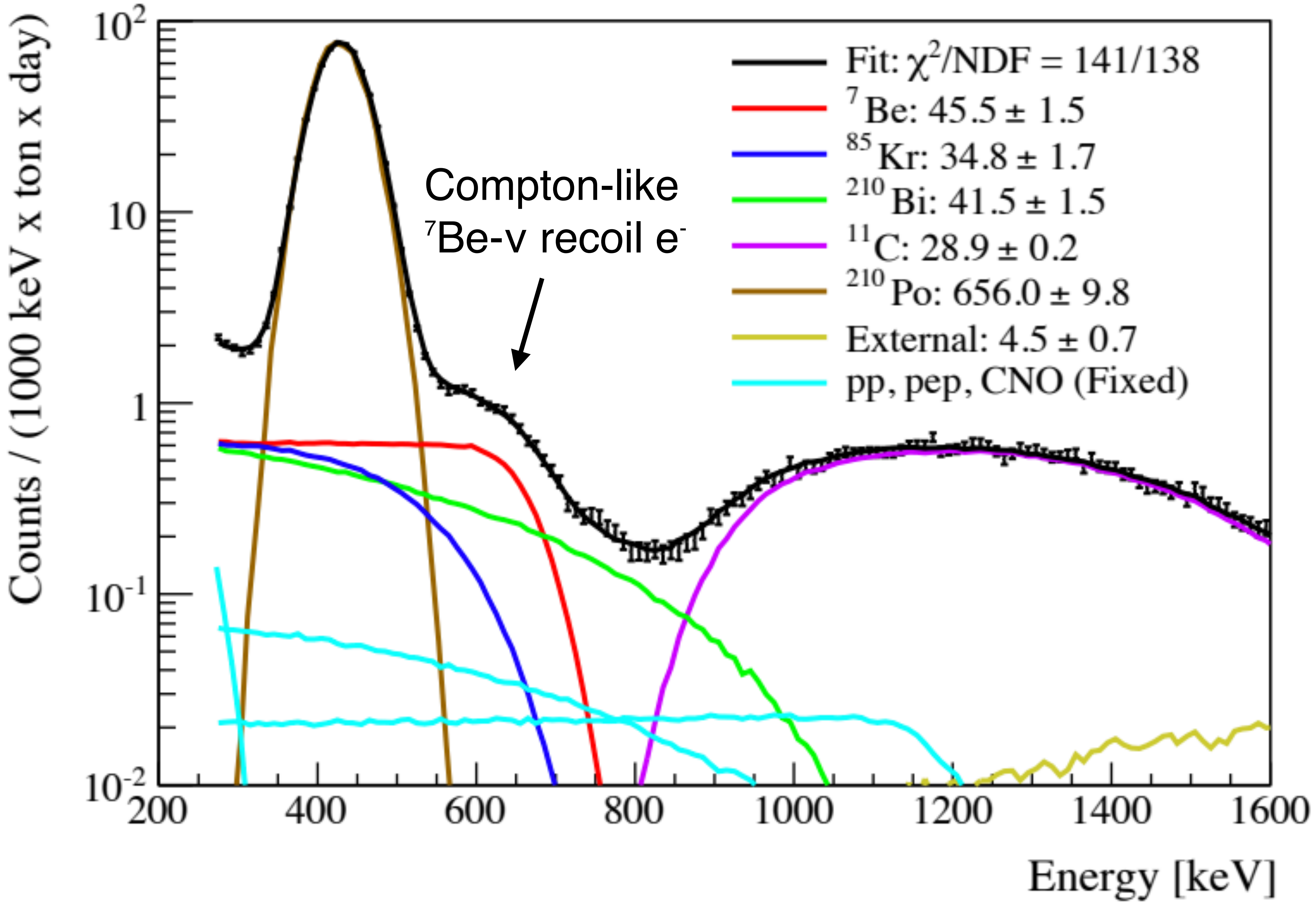


Directional signature of MeV solar neutrinos in Borexino

- Neutrino-electron elastic scattering
- LS molecule excitation is mostly converted into scintillation
  - >99.5% of detected photons
  - Isotropic
- Electrons with enough recoil energy (velocity) emit Cherenkov light in LS
  - >0.16 MeV
  - <0.5% of detected photons
  - directional

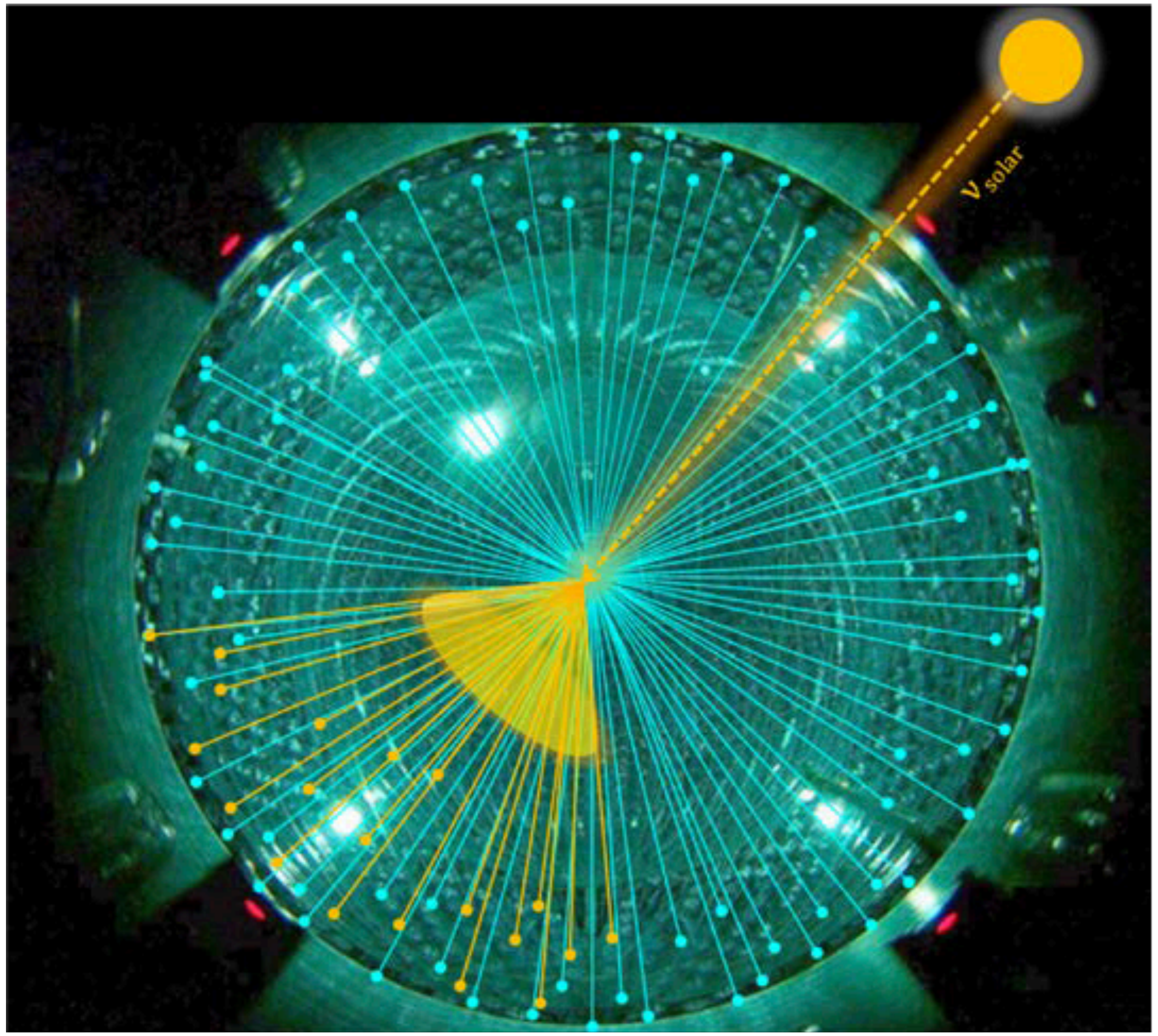
$$\nu + e^- \rightarrow \nu + e^-$$

Phys. Rev. D 89, 112007



Borexino Phase 1

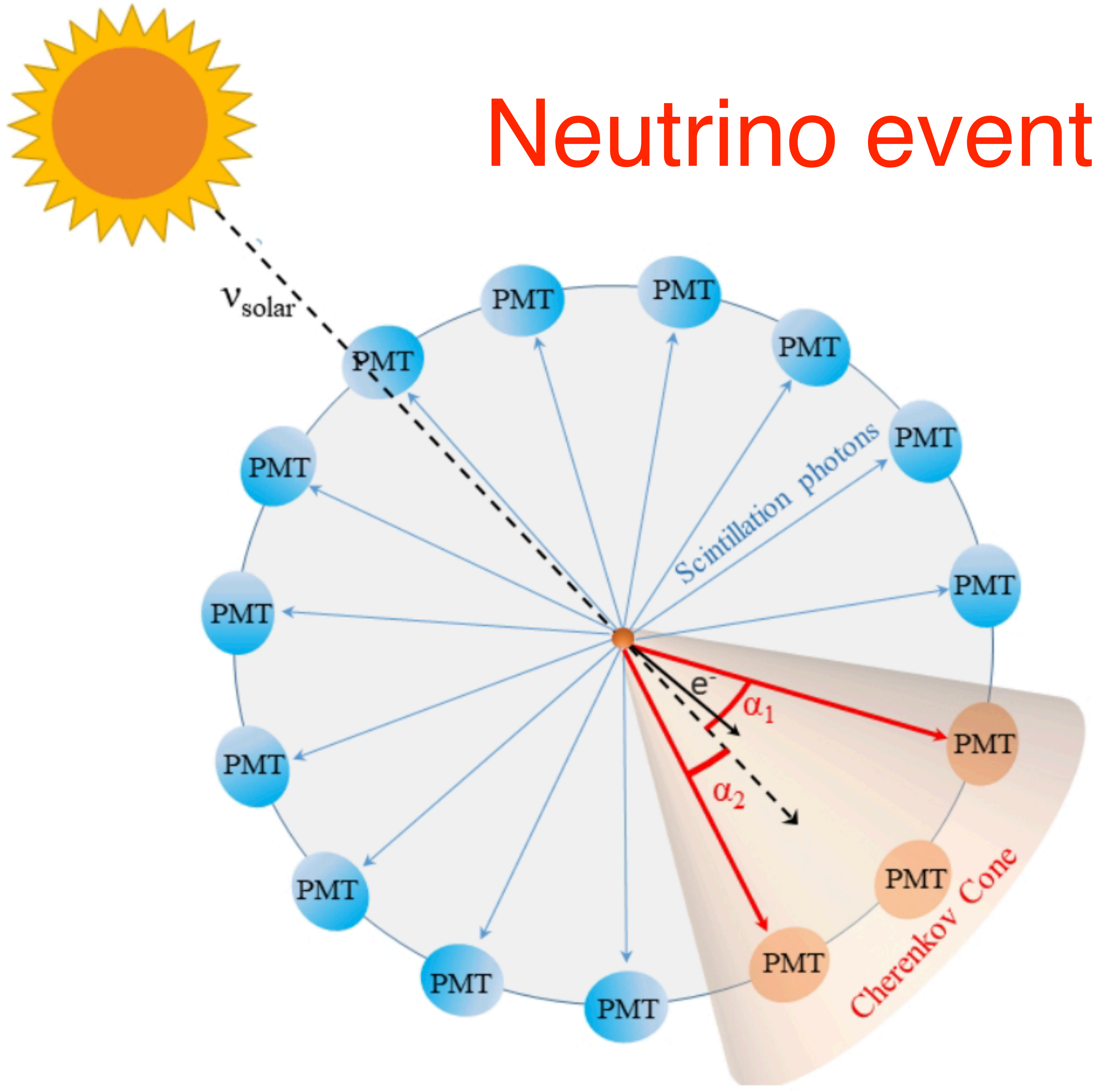
Correlated and Integrated Directionality (CID)



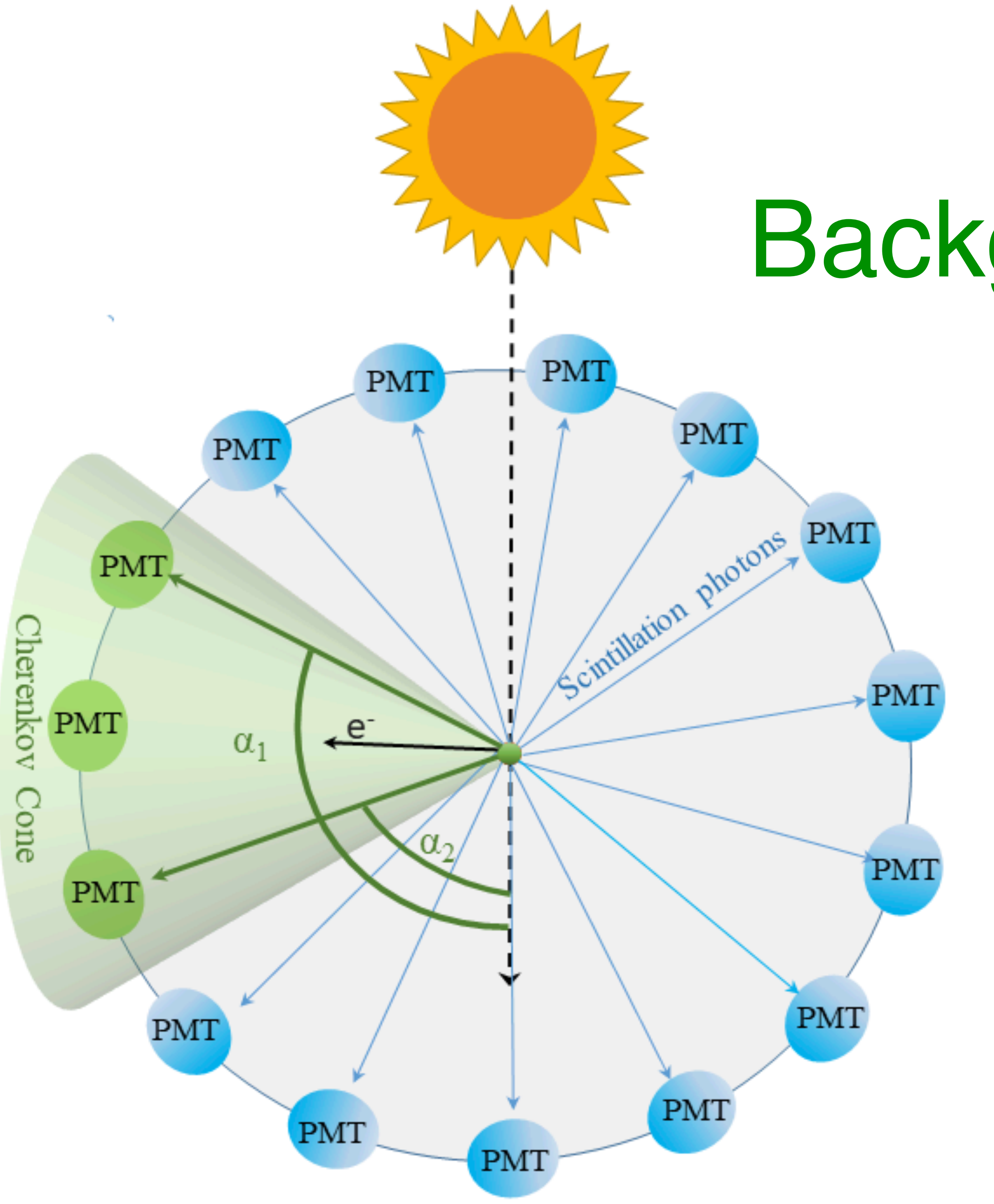
- Correlate individual photon arrival time of each event to the known position of the Sun
- Electrons recoiling with large energy transfer retain directional information
- Extract the (feeble, <0.5%) Cherenkov signal using their faster hit time pattern (after TOF correction and group velocity correction)
- Event-by-event directional reconstruction not possible (1-2 Cherenkov p.e./event)
- Combine individual PMT hits from many events -> statistical separation via different angular distribution

Correlated and Integrated Directionality (CID)

Neutrino event



Background event



Cherenkov hits correlated to Sun position

Non-flat cosα distribution
(peak at cosα ~0.75)

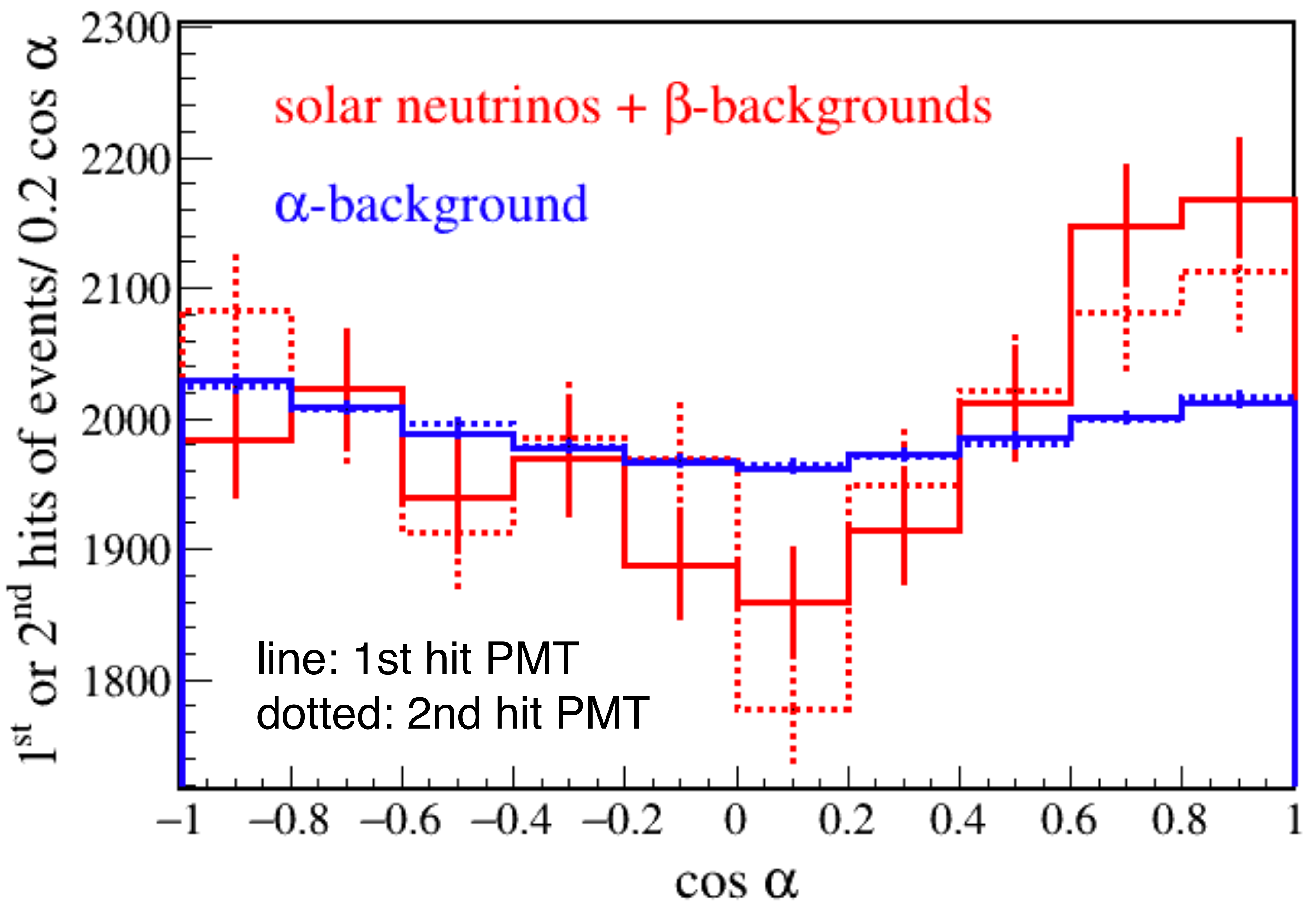
No correlated with the position of the Sun

Flat cosα distribution

cos α = <neutrino direction, reco photon direction>
reco photon direction = hit PMT position – reco event position

PRL128.091803(2022)
PRD105.052002(2022)

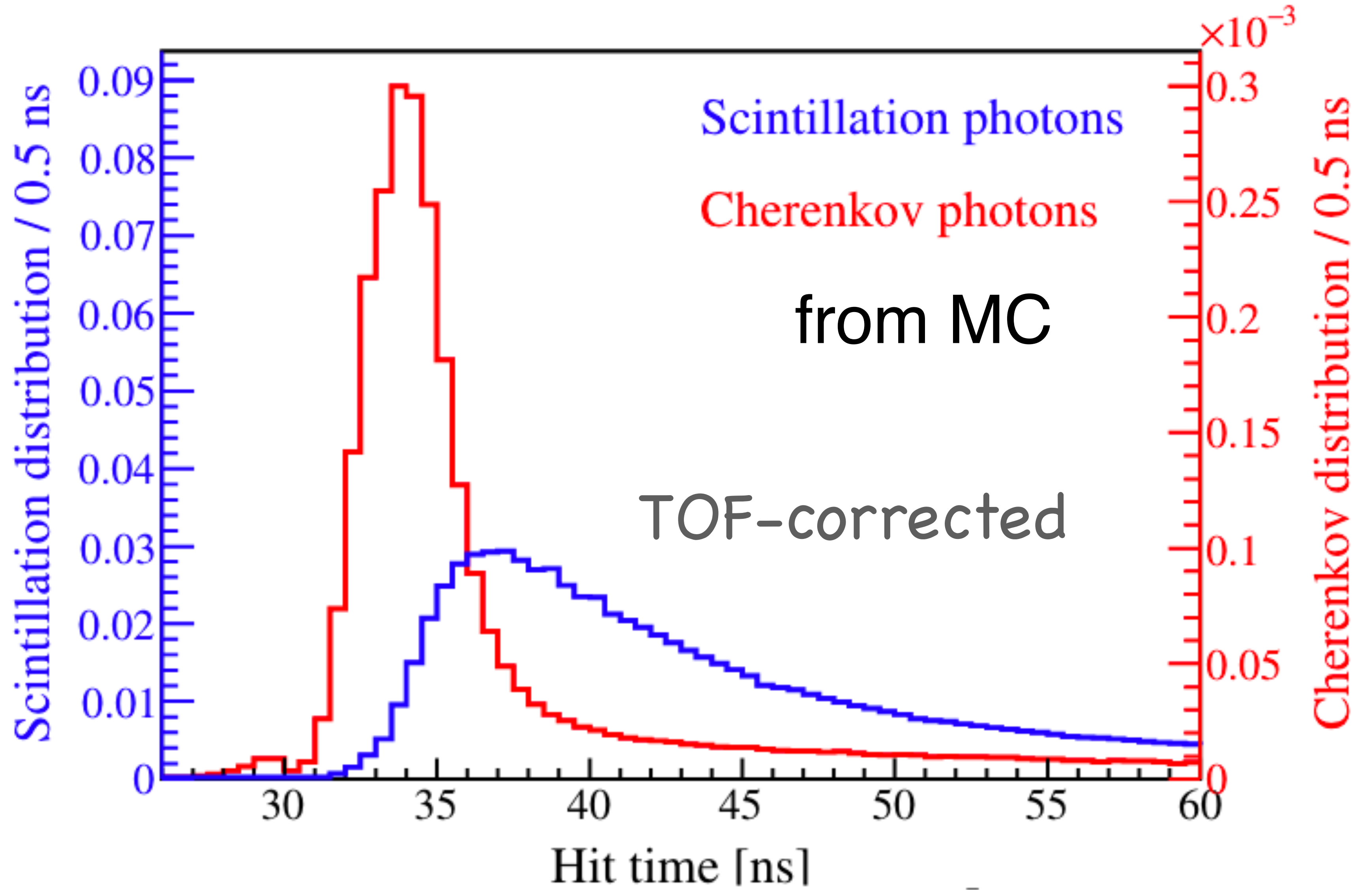
A first look: alpha background

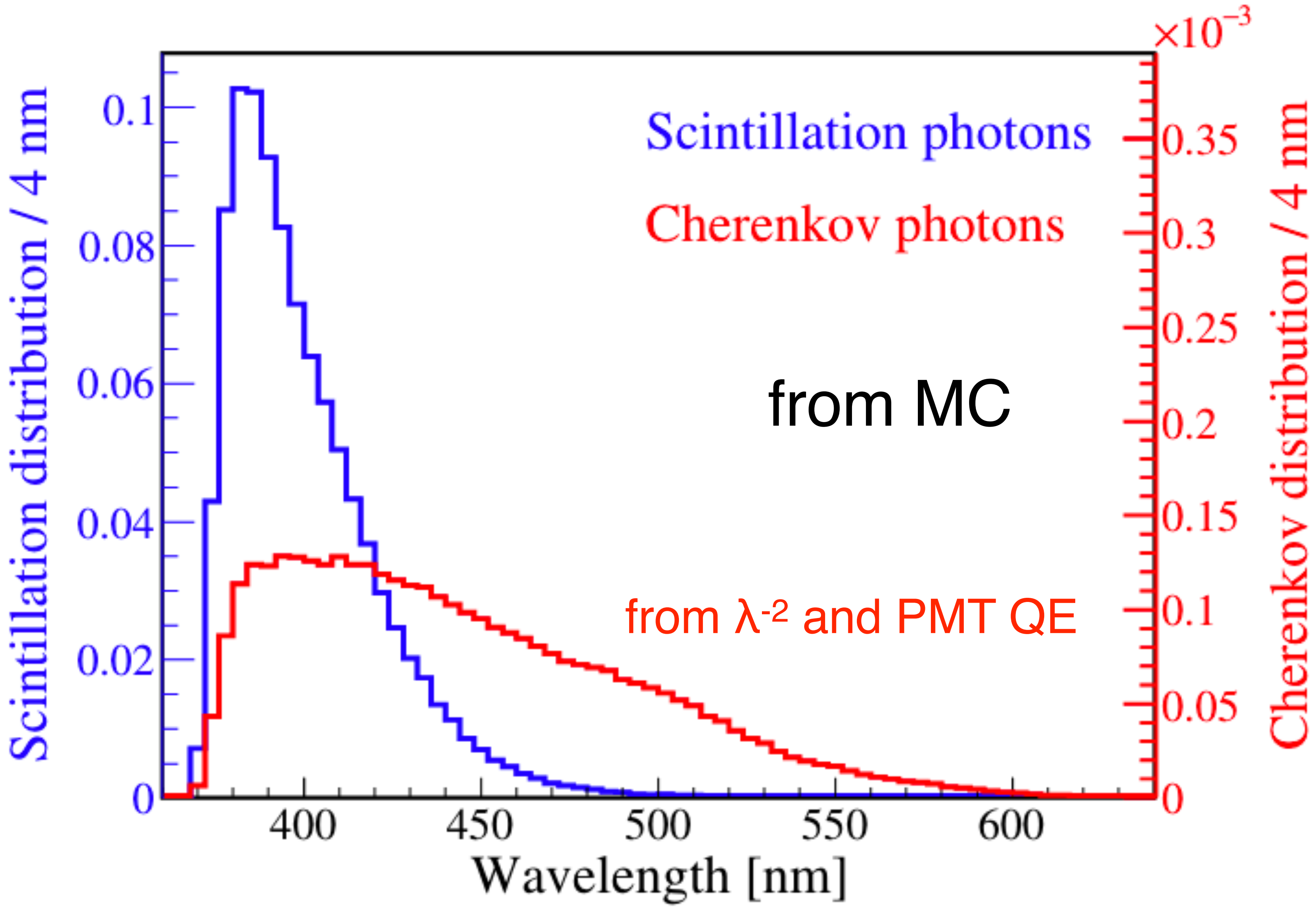


- α/β discrimination via PSD
- 530-740 keV β's
  - 7Be, pep, CNO; also 210Bi, 85Kr
  - Peaked distribution
- 400 keV α's (equivalent electron energy)
  - Flat distribution

PRL128.091803(2022)
PRD105.052002(2022)

Cherenkov group velocity correction





Emission time difference:

- Cherenkov: prompt
- Scintillation: ns emission + decay time
- Cherenkov photons that are absorbed and re-emitted are included in scintillation population

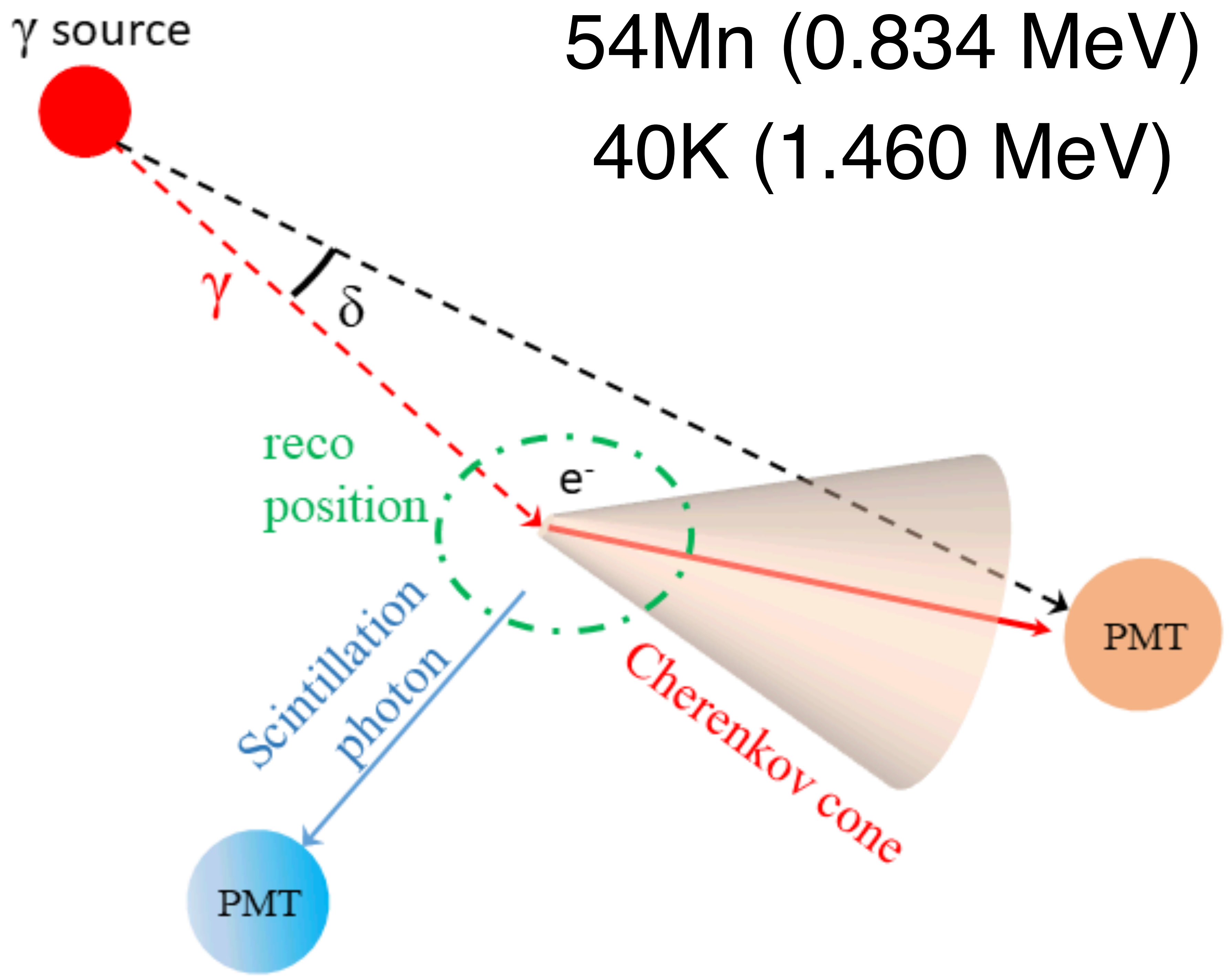
- Cherenkov detected above 370 nm
- Wavelength-dependent group velocity in LS
- Group velocity correction (gv_{Ch}) in MC:

$$t_{corr} = t - gv_{Ch} \times L = t - (\Delta n_{Ch}/c) \times L$$

t: MC PMT hit time L: MC photon track length

PRL128.091803(2022); PRD105.052002(2022)

Cherenkov group velocity correction with source calibrations



54Mn (0.834 MeV)

40K (1.460 MeV)

- γ sources with known position
- Compton-scattered electrons
- -> $\cos\delta$
- Reconstruction of the direction of the γ-ray is a major source of uncertainty

PRL128.091803(2022); PRD105.052002(2022)

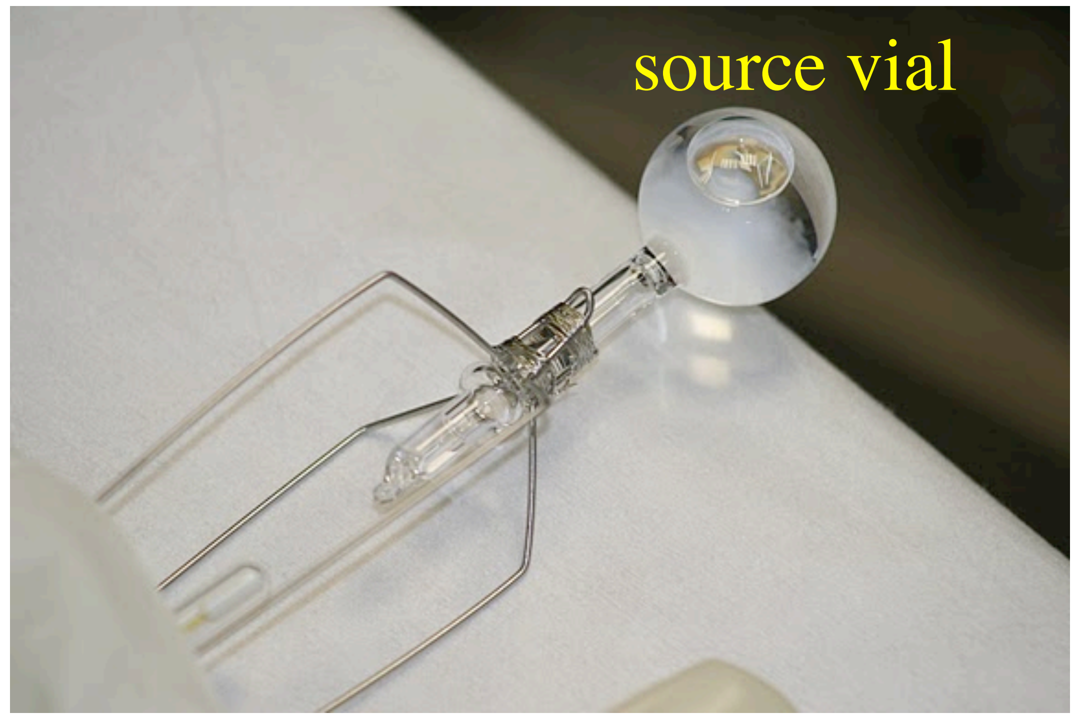
Calibrations (Phase I)

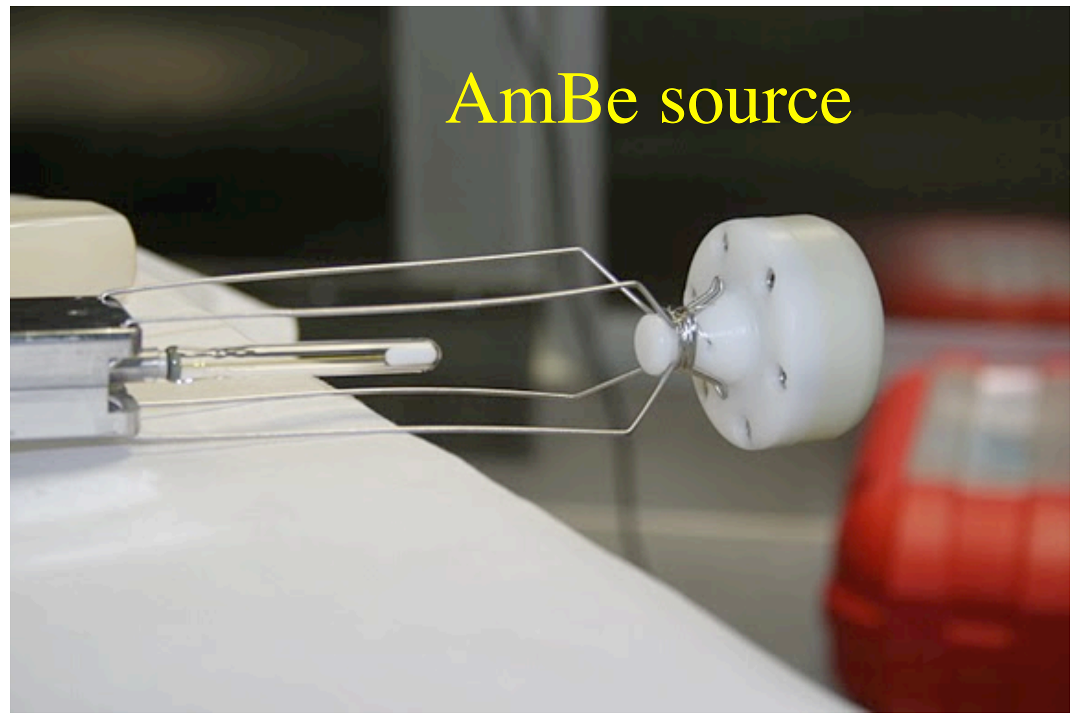
	γ								β		α	n		
	^{57}Co	^{139}Ce	^{203}Hg	^{85}Sr	^{54}Mn	^{65}Zn	^{60}Co	^{40}K	^{14}C	^{214}Bi	^{214}Po	n-p	n +^{12}C	n+Fe
energy (MeV)	0.122	0.165	0.279	0.514	0.834	1.1	1.1, 1.3	1.4	0.15	3.2		2.226	4.94	~7.5

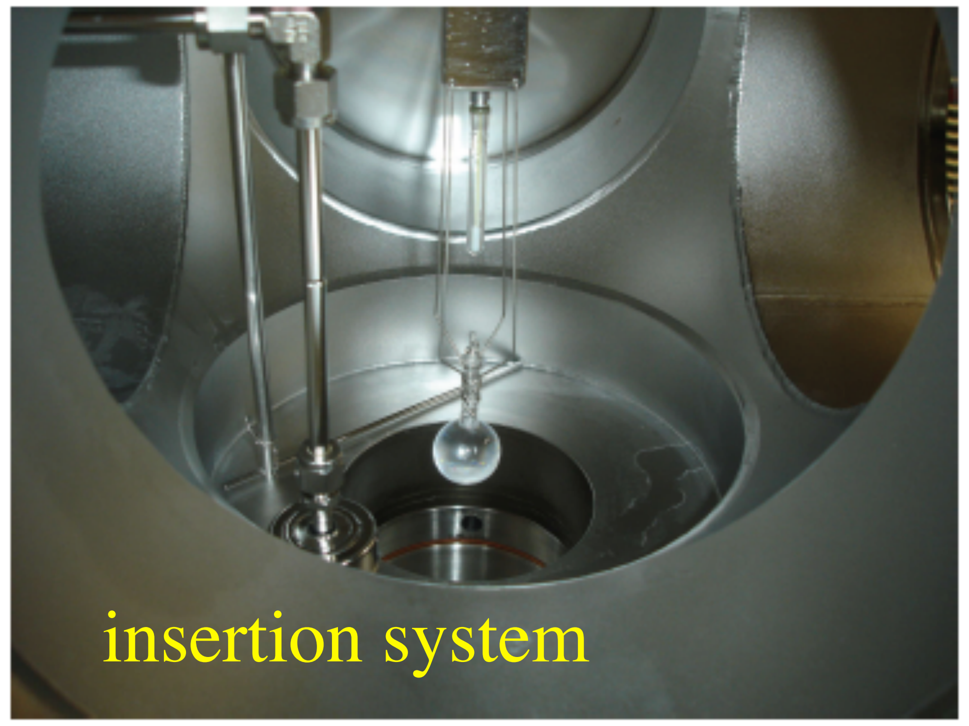
spiked water vial

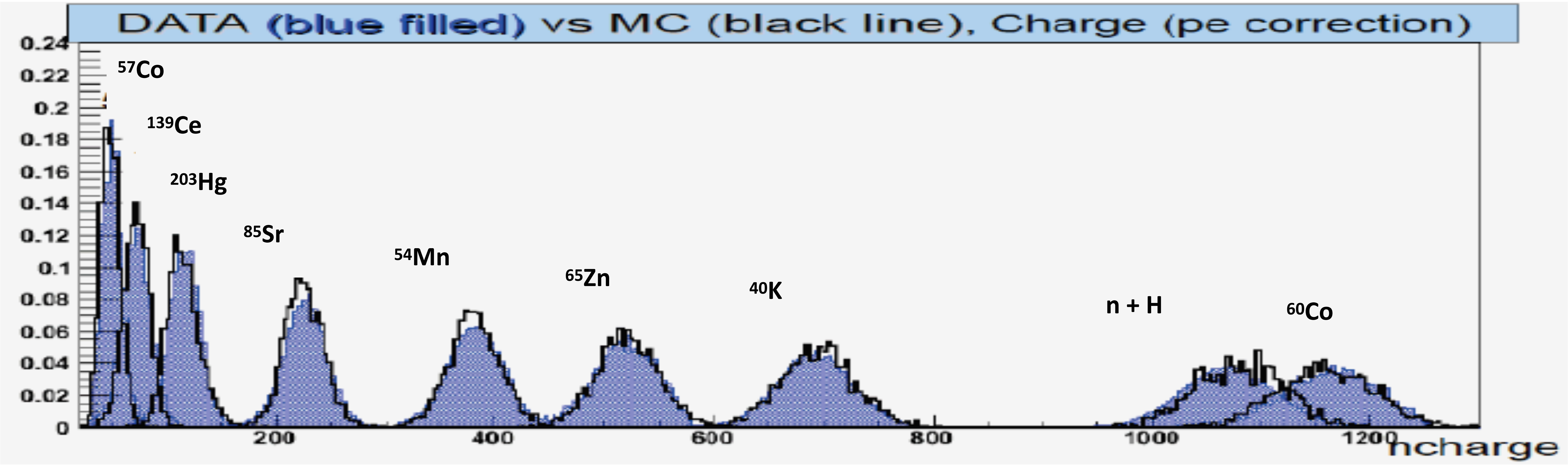
spiked scintillator vial

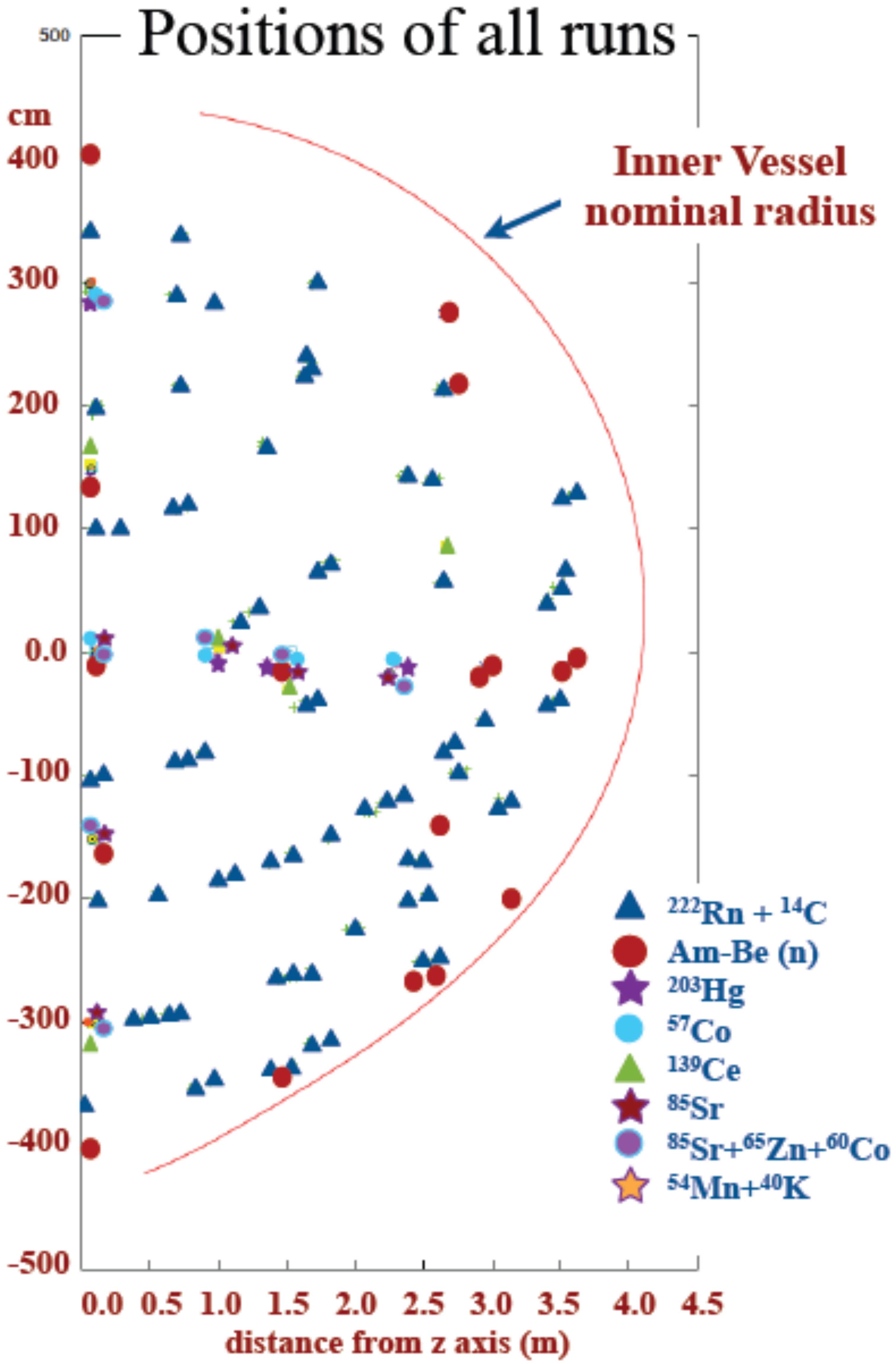
AmBe



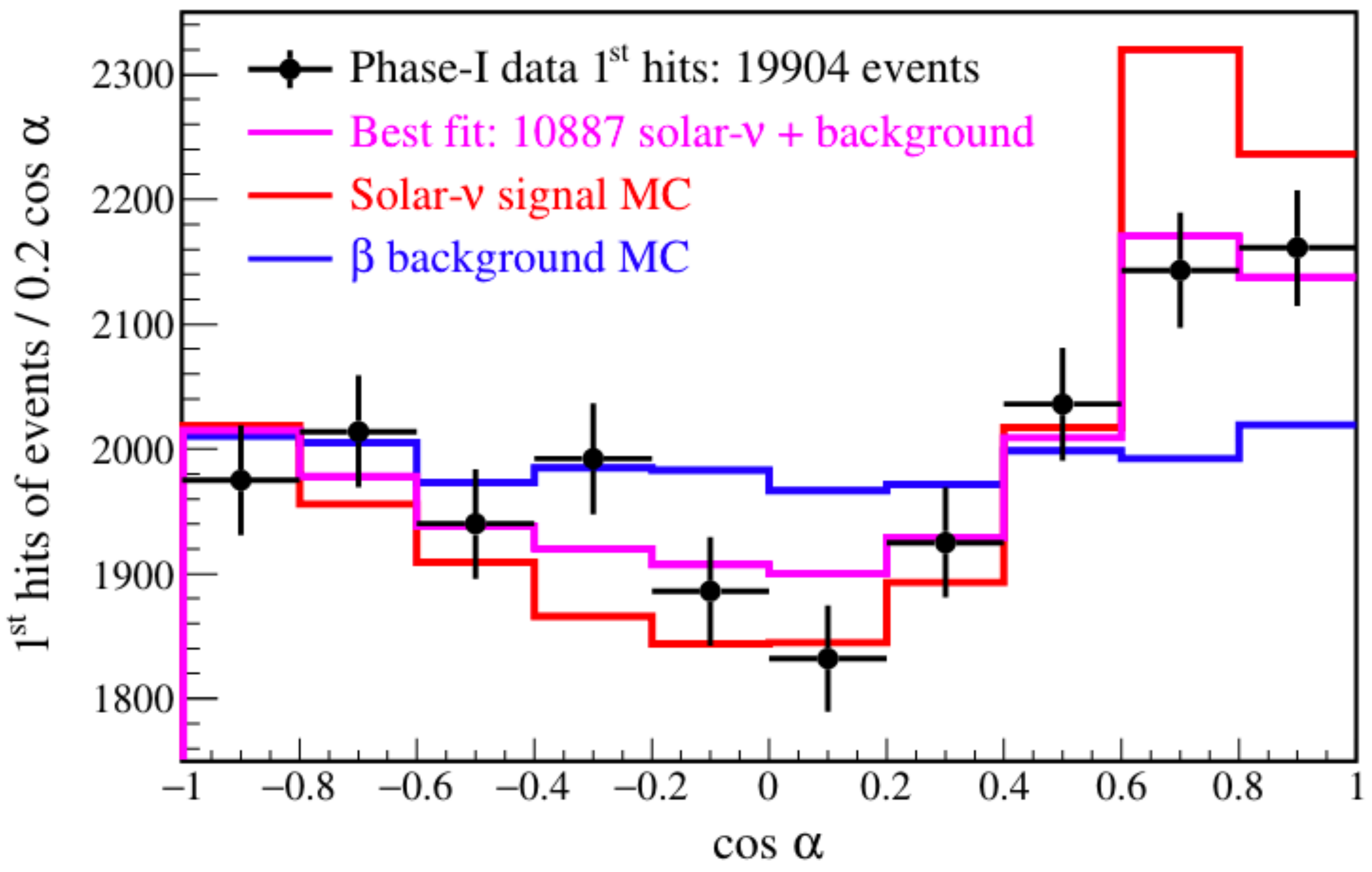


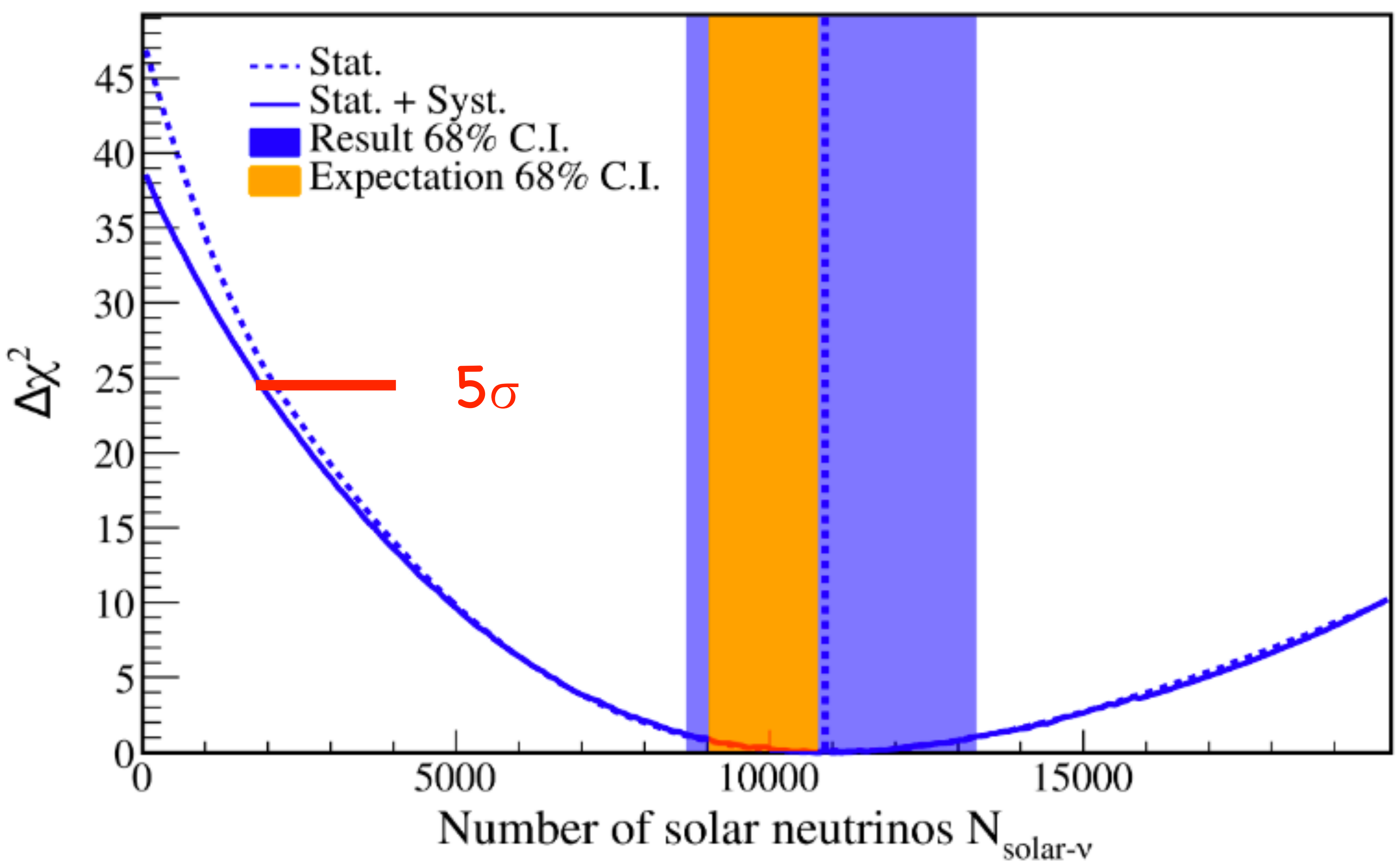






First directional measurement of sub-MeV neutrinos





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

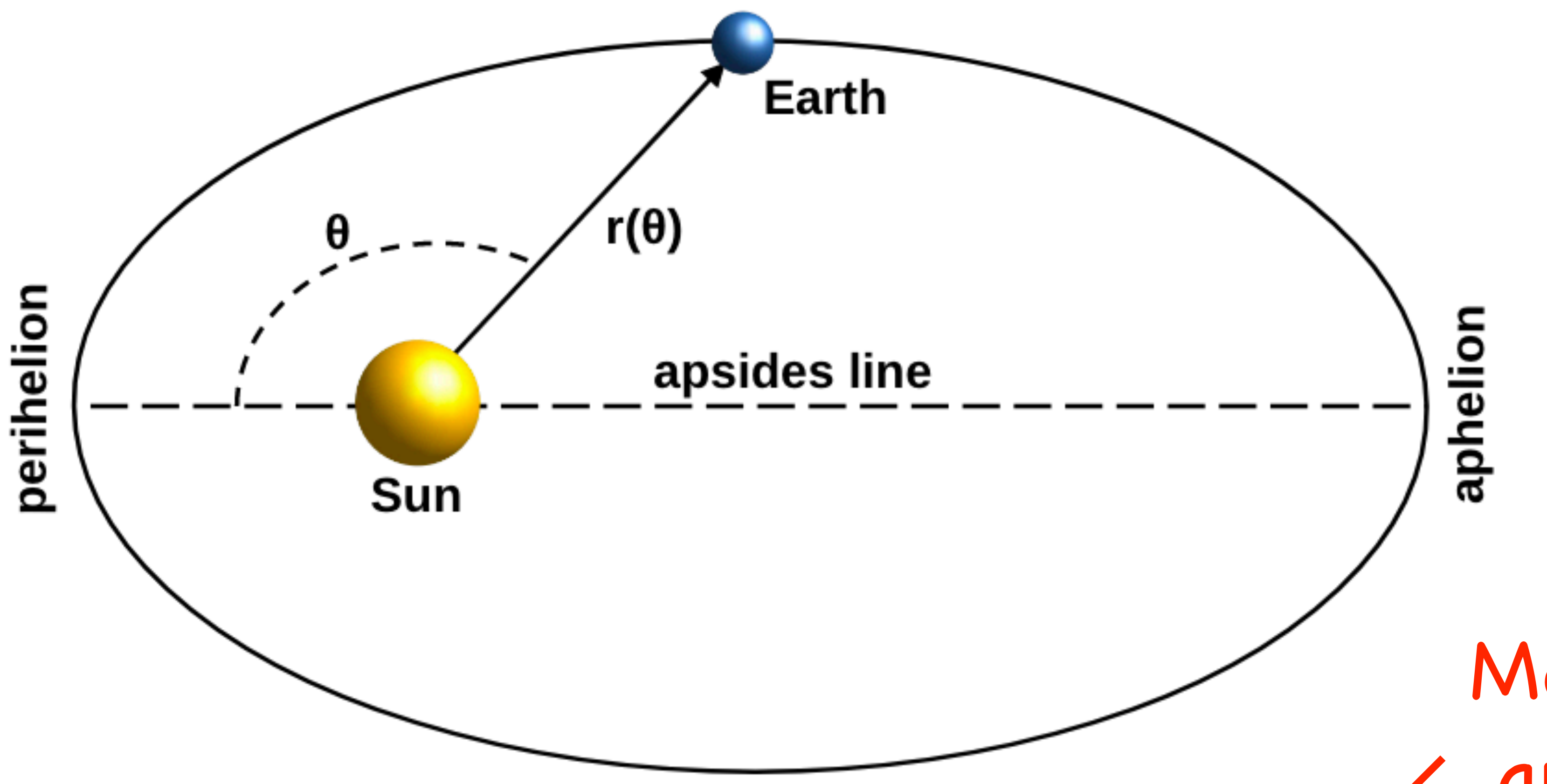
$$R(^{7}Be)_{CID} = 51.6^{+13.9}_{-12.5}\ cpd/100t$$

PRL128.091803(2022)
PRD105.052002(2022)

- No-solar neutrino excluded >5σ (>1814 neutrinos)
- Rate of solar ν consistent with SSM
- 10187 (+541,-1127) neutrinos expected

Earth's orbit with neutrinos (>5σ)

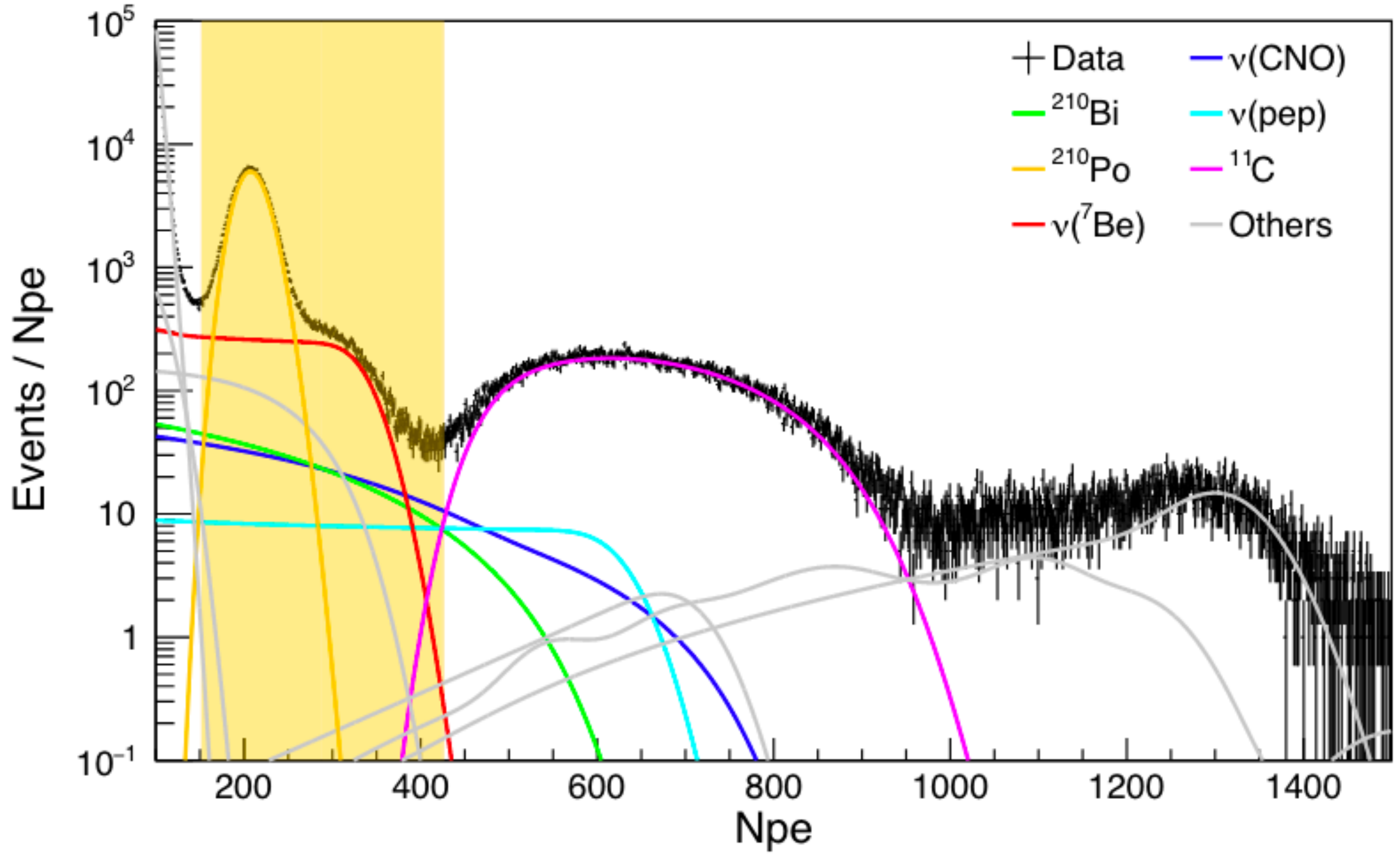
arXiv:2204.07029



$$r(\theta) = \frac{\bar{r}(1-\epsilon^2)}{1+\epsilon\cos(\theta)}$$

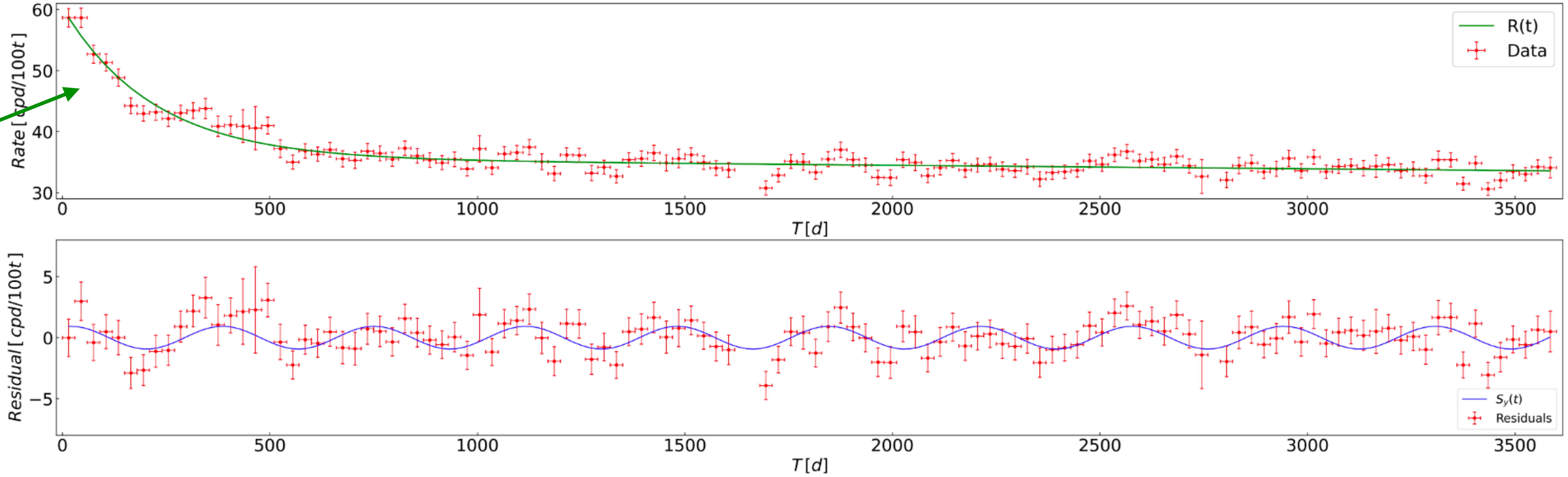
Modulation amplitude

$$\Phi(t) \approx \frac{\Phi_0}{\bar{r}^2}\left[1 + 2\epsilon\cos(\omega_y(t-t_0))\right]$$



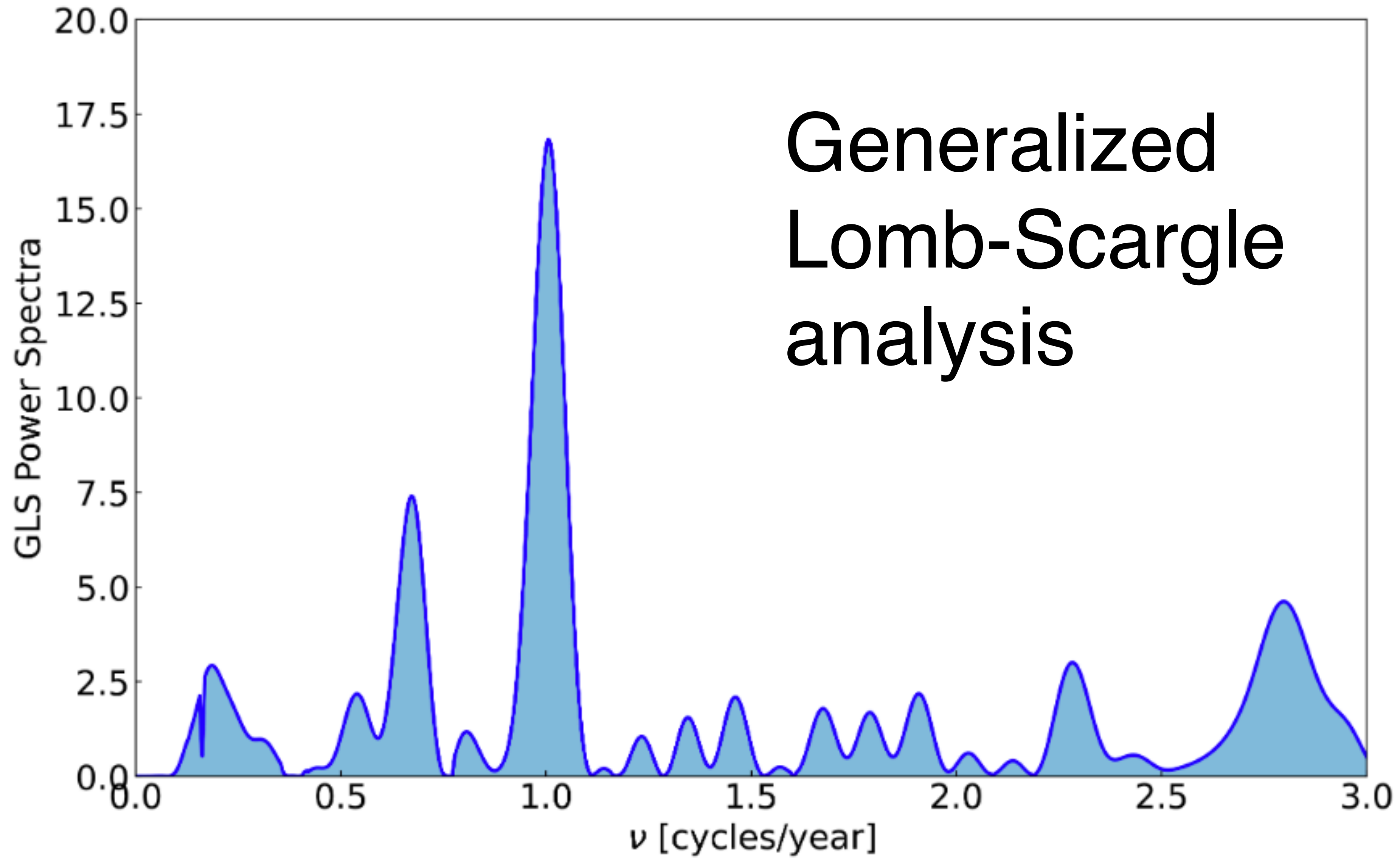
Secular (unmodulated) components:

- ^{210}Po leakage
- Bg non-uniform mixing
- External bg leakage from slow vessel deformation
- ^{85}Kr ?

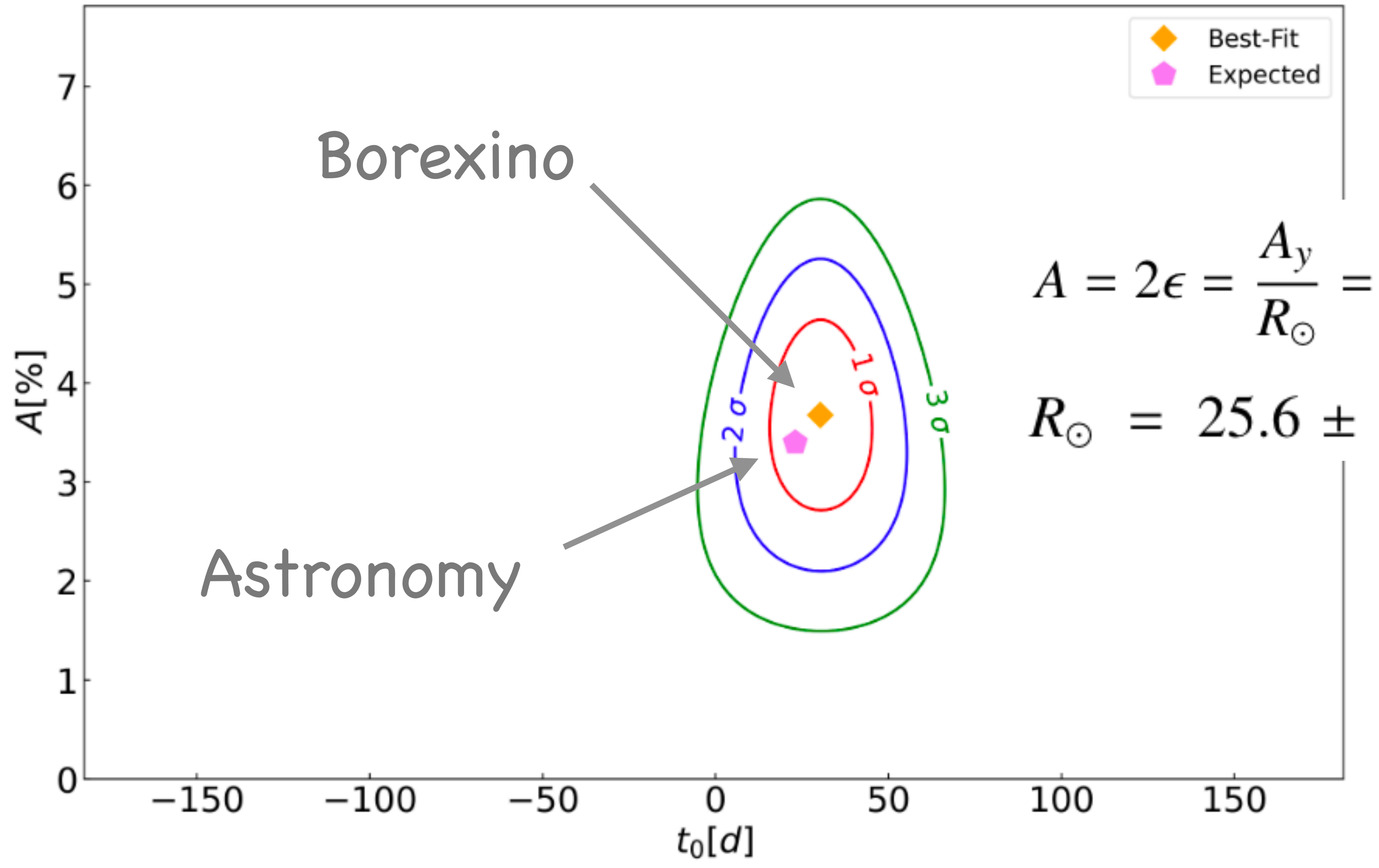


Earth's orbit with neutrinos (>5σ)

arXiv:2204.07029

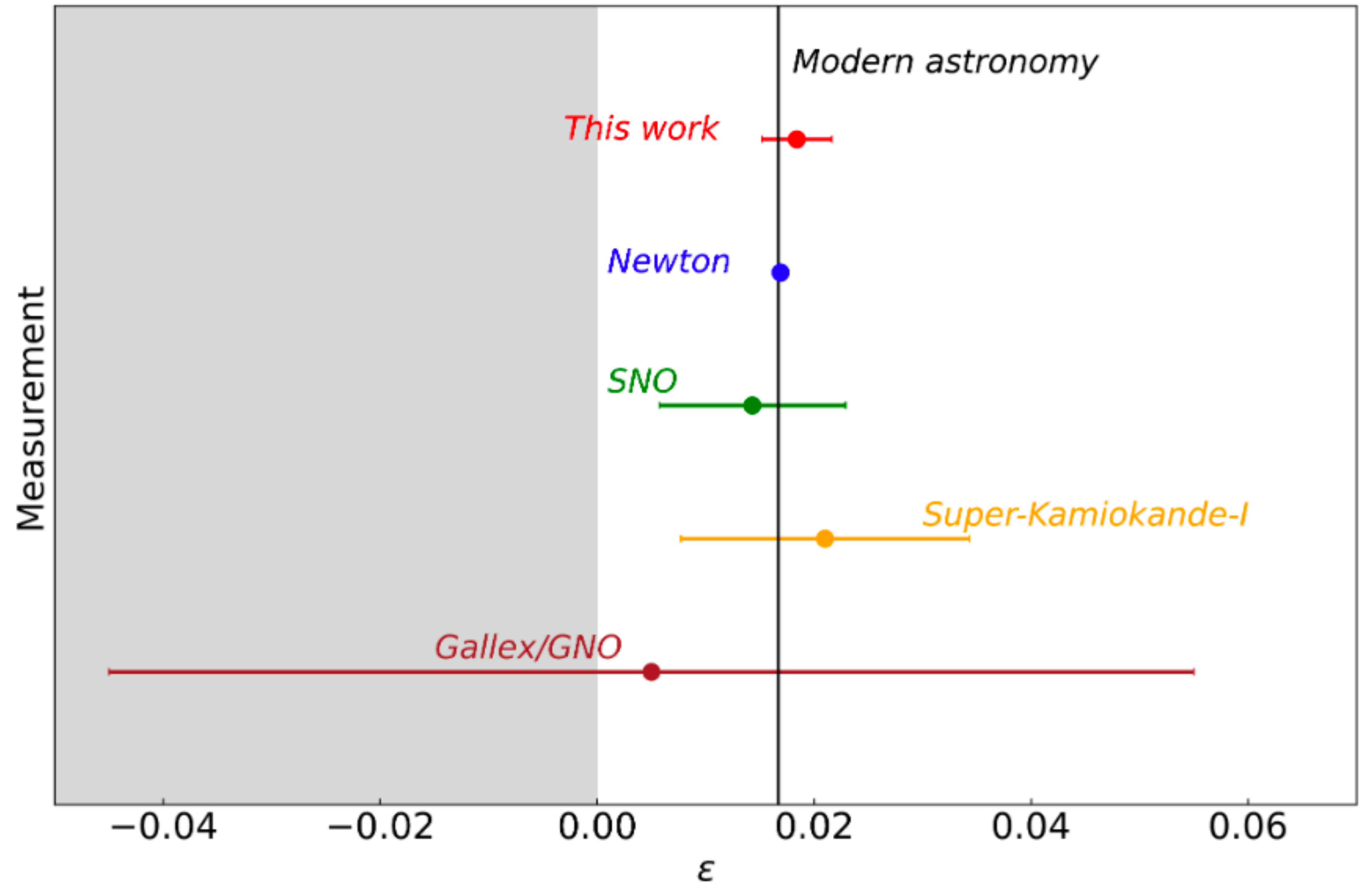


- 1-year peak is the only one with significant power
- Neutrino-only 5σ detection of the orbital modulation of the solar neutrino interaction rate



$$A = 2\epsilon = \frac{A_y}{R_\odot} = (3.68 \pm 0.65)\%,$$

$$R_\odot \;=\; 25.6 \pm 1.27 \;\; \text{cpd/100t}$$



The Borexino collaboration

in memoriam

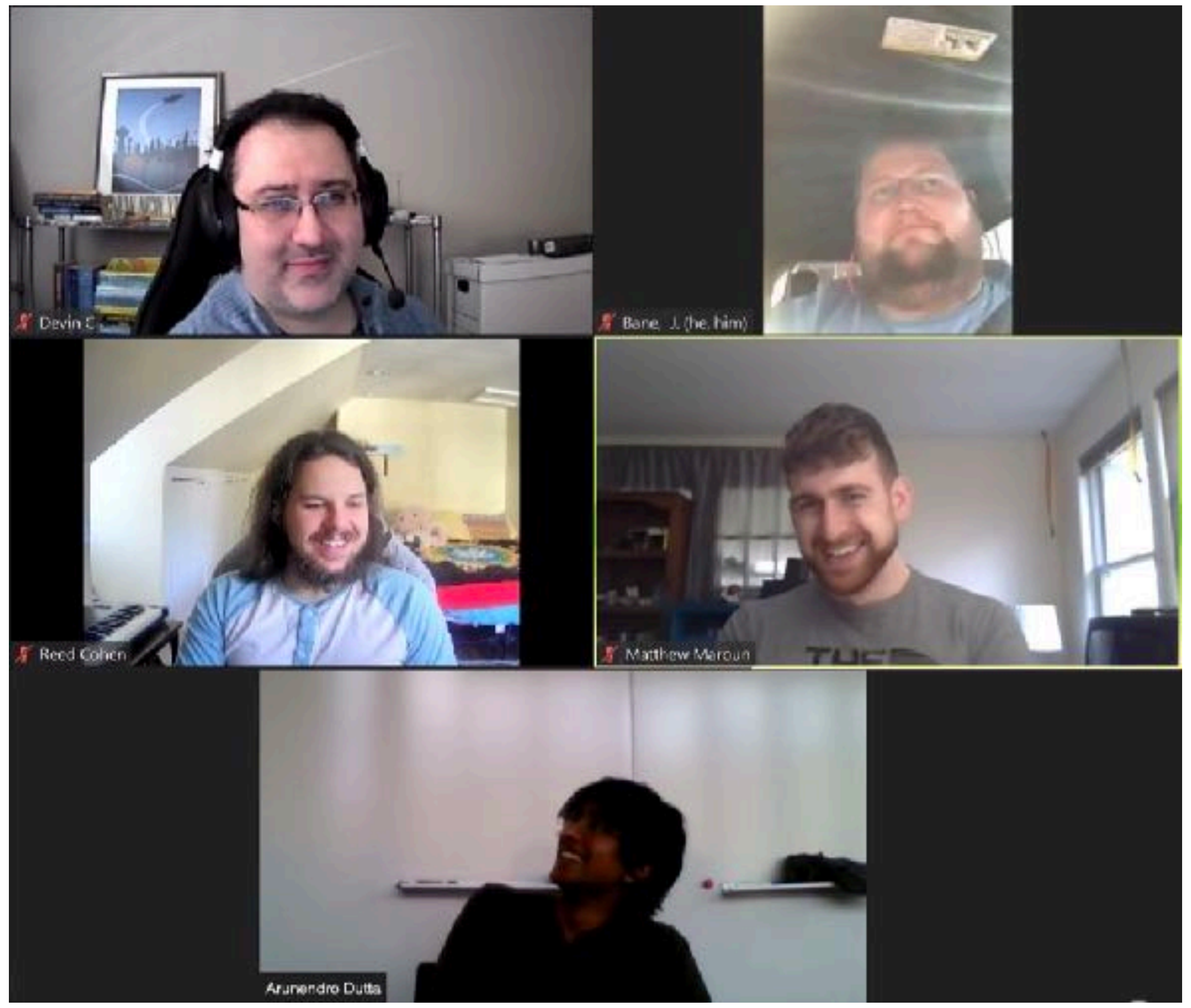
Cristina Arpesella
Martin Deutsch
Burkhard Freudiger
Andrei Martemianov
Sandro Vitale
Raju Raghavan
Steve Kidner
Hervé de Kerret
Corrado Salvo
Oleg Zaimidoroga
Simone Marcocci

and John Bahcall

with thanks and recognition to many historical collaborators and friends

Thanks to the members of my group!

https://blogs.umass.edu/pocar



While they are not involved in Borexino directly, they allow me to be here today to tell you the Borexino story with the peace of mind that the lab is in good hands!

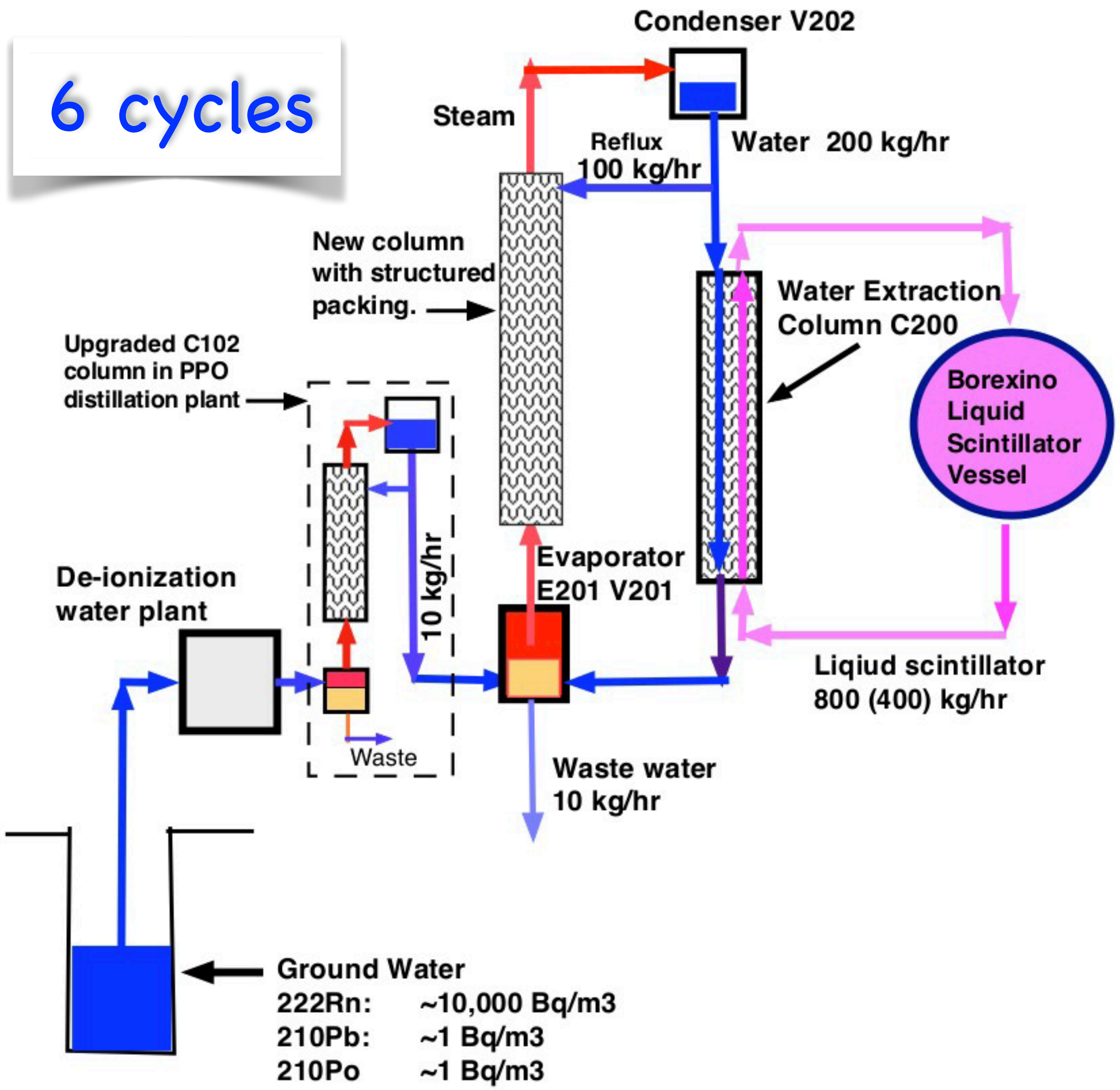
Borexino: summary and legacy

- 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 providing a hint on a high metallicity sun
- 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



Scintillator 2nd purification: water extraction (2010-11)

6 cycles



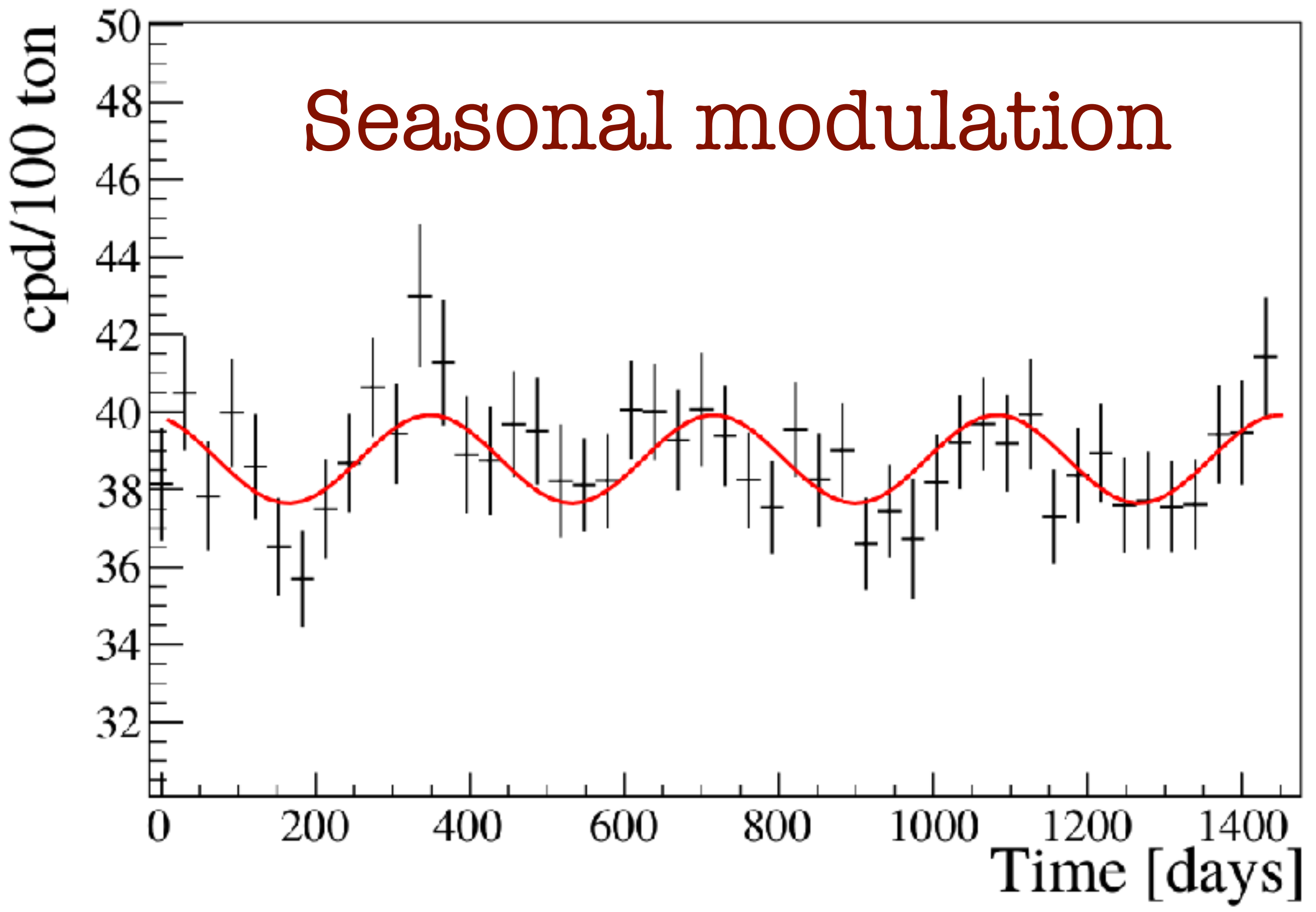
	Before [cpd/100t]	After [cpd/100t]
^{210}Bi	~40	~10
^{85}Kr	~30	~5
^{210}Po	>2000	<30 (decay)

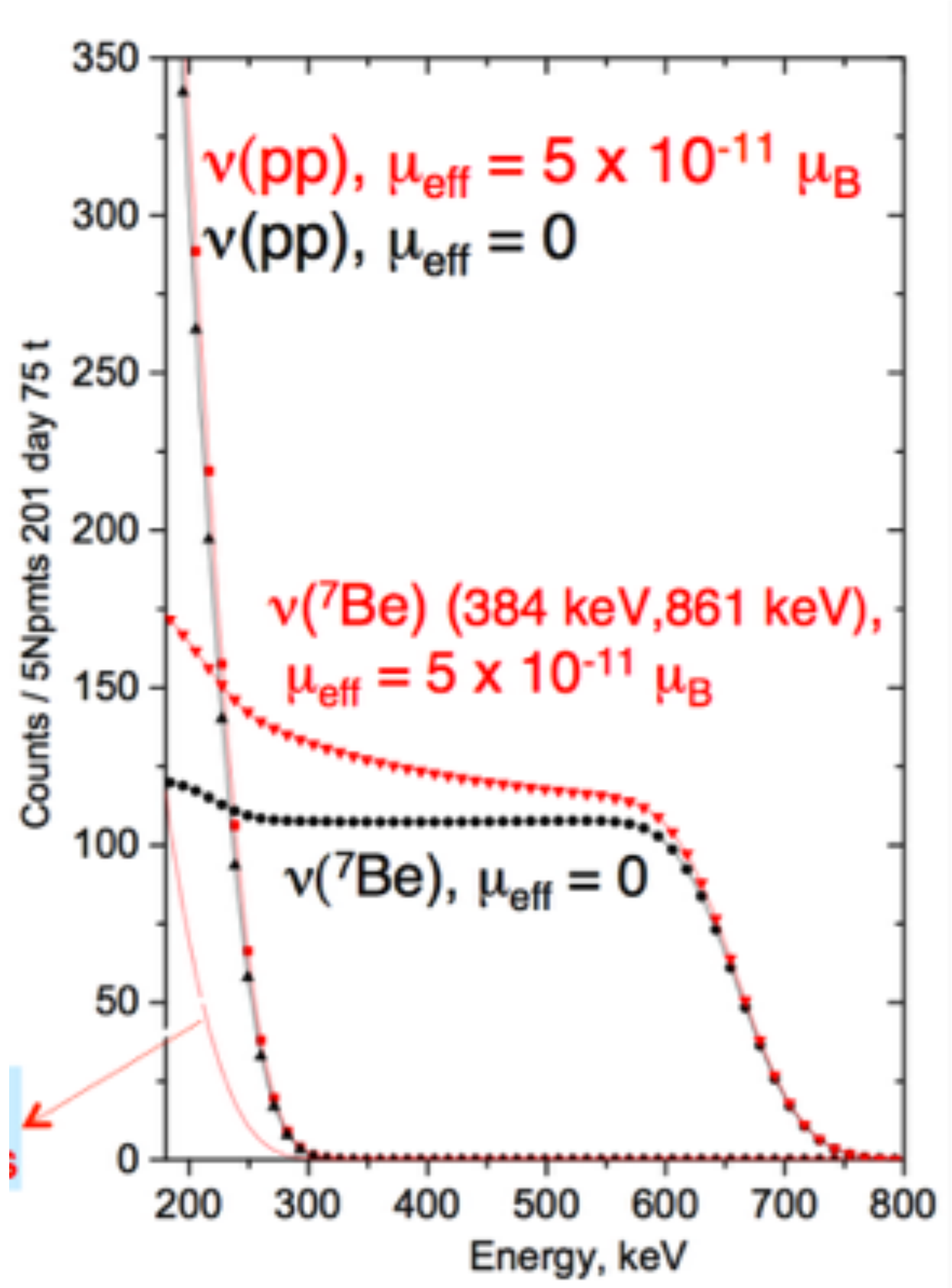
[1 cpd/100t ~ 0.1 nBq/kg]

- ^{232}Th,^{238}U < 10^{-18} g/g
- ^{39}Ar,^{40}K < 1 cpd/100t
- ^{222}Rn ca. 1 cpy/100t (3×10^{-4} nBq/kg)

Significance of Be-7 neutrino measurement

- Be-7 neutrinos are not missing in the end
- Strong confirmation of the neutrino oscillation paradigm





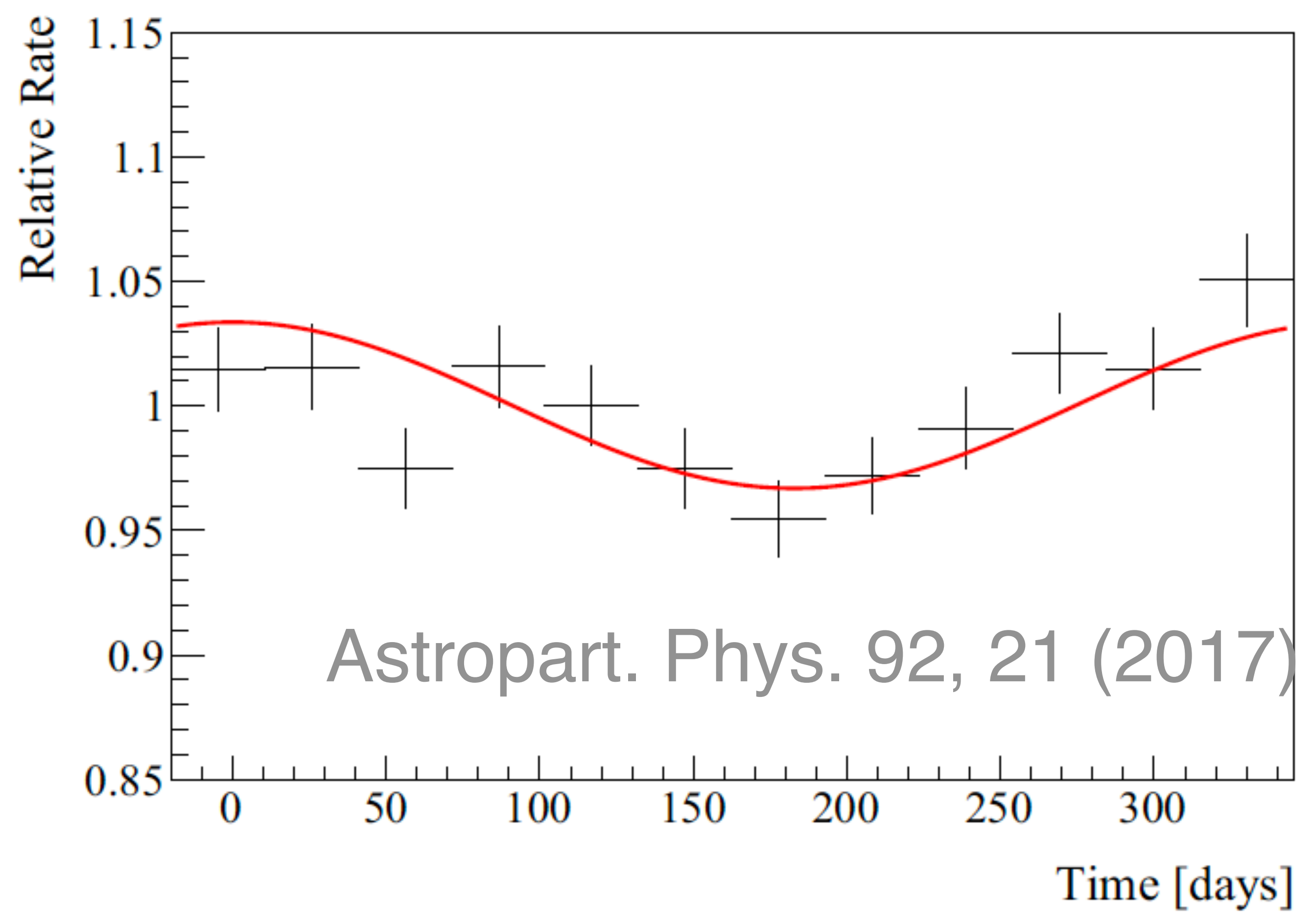
- Low-energy sensitivity allows searches for exotic physics
- Best limit on the neutrino magnetic moment:

$$\mu_{eff} < 2.8 \times 10^{-11} \mu_B \quad (90\%\ C.L.)$$

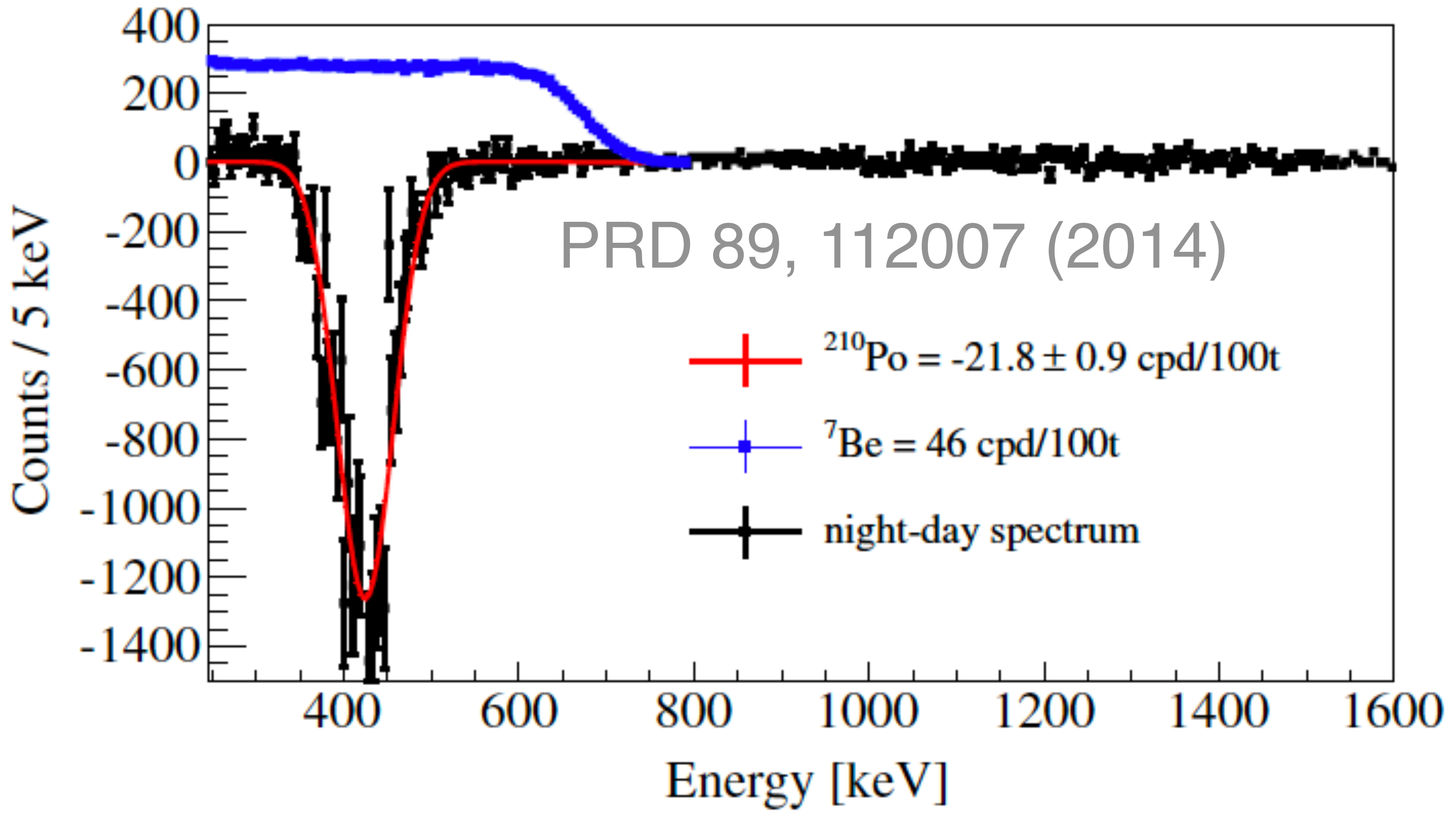
Low energy neutrinos and flavor oscillations

- The detection of ^{7}Be neutrinos is a further, independent confirmation of neutrino flavor conversion and the
- The absence of day-night asymmetry in the ^{7}Be solar neutrinos interaction rate strongly confirms the MSW-LMA neutrino oscillation solution

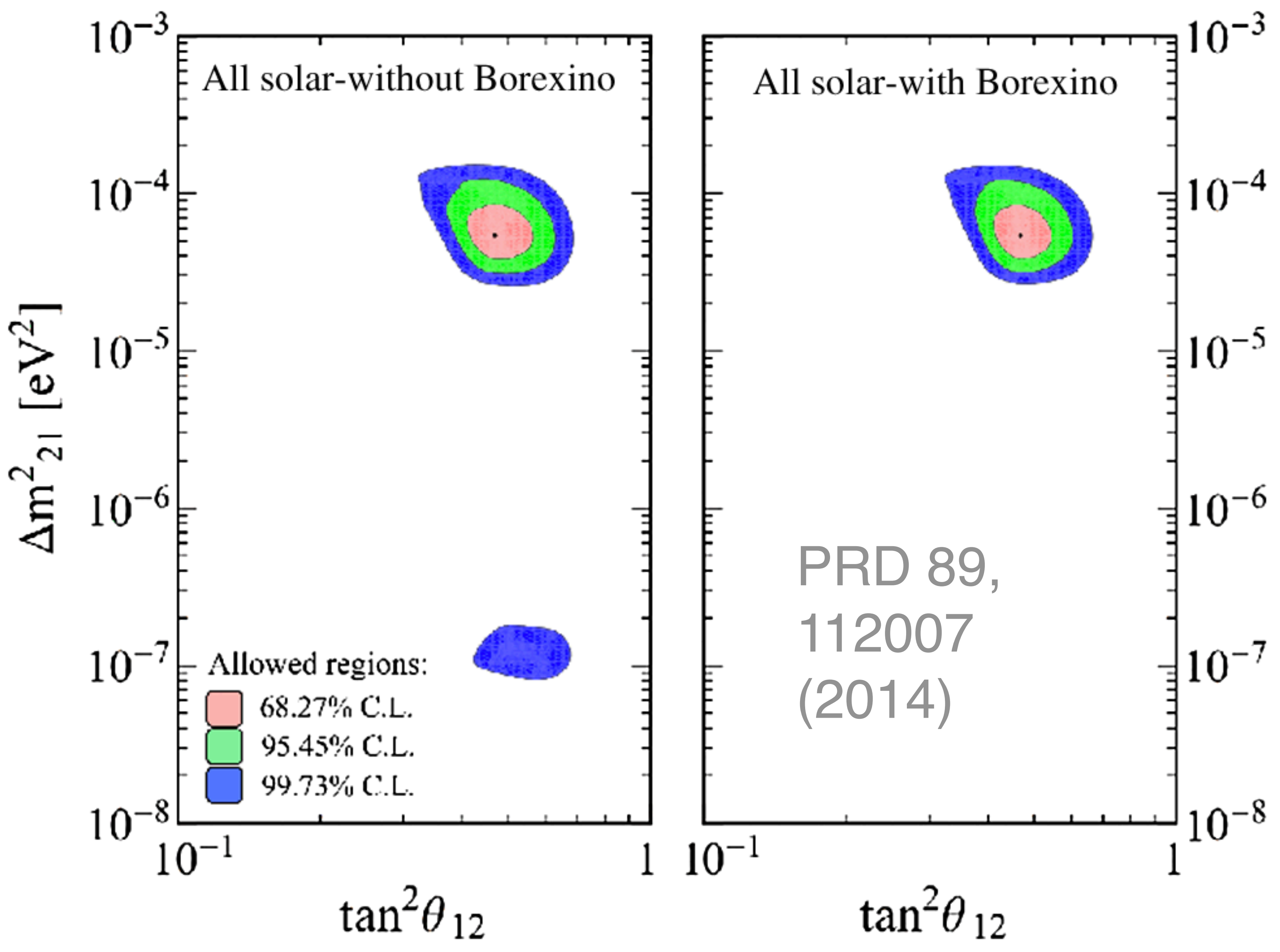
Annual modulation



night-day spectrum



Oscillation parameters



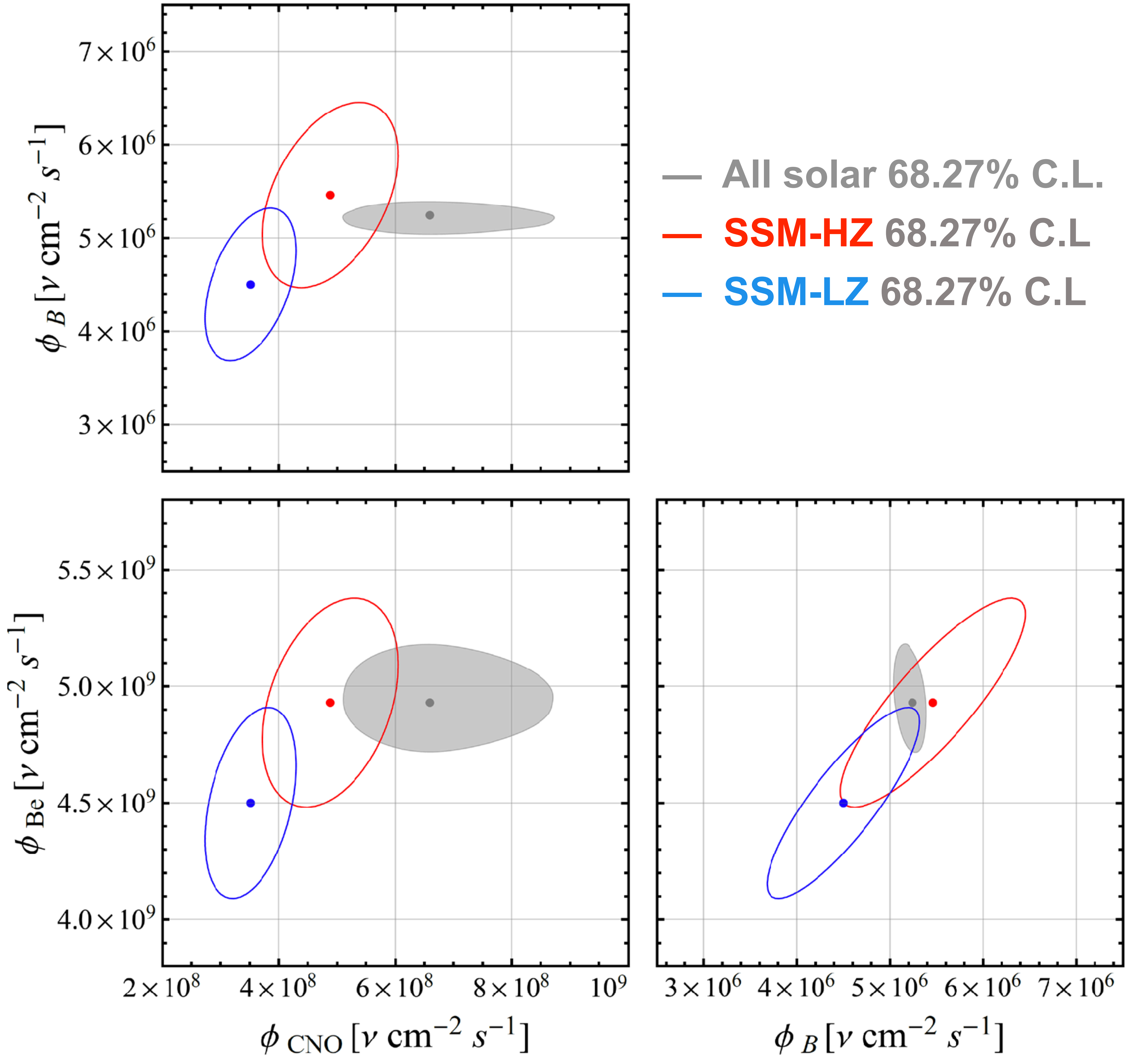
Implications of the improved CNO measurement

- **We include the CNO result in a global analysis of all solar neutrino data +KamLAND**;

- Φ(Be), Φ(B) and Φ(CNO), together with θ_{12} and Δm^2_{12} are free parameter of the fit;

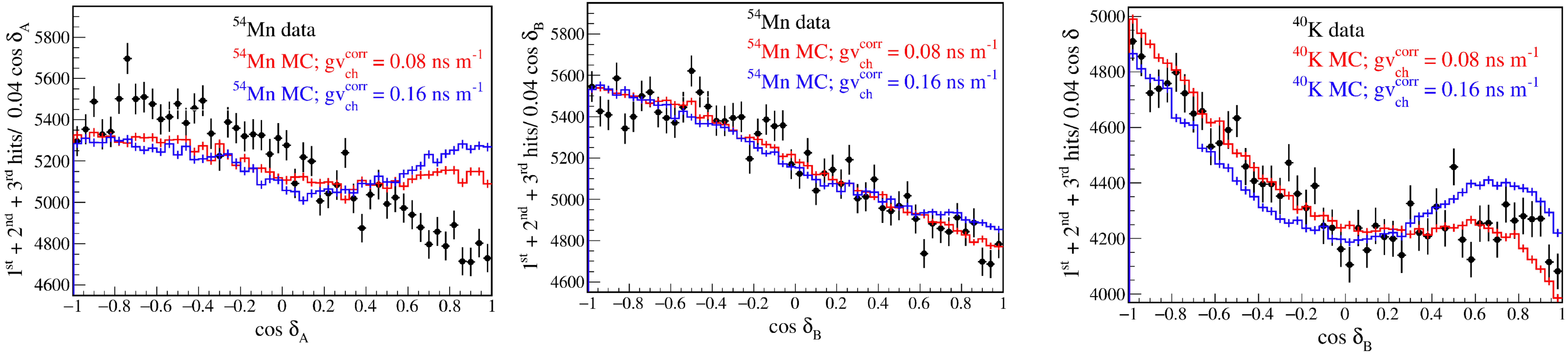
- The results agree well with the output of SSM-HZ[(1)] model, while feature a small tension with the SSM-LZ[(2)] model (p= 0.028);

- This small tension is created by the addition of the CNO result (p-value goes from 0.327 —> 0.028);



*(1) SSM-HZ= B16-GS98: Vinyoles et al. Astr.J. 835 (**2017**) 202 + Grevesse et al., SpaceSci.Rev. **(1998**) 85*
*(2) SSM-LZ= B16-AGS009met: Vinyoles et al. Astr.J. 835 (**2017**) 202 + A. Serenelli et al., Astr. J. 743,(2011)24*

Cherenkov group velocity correction: calibration



- Data and MC have subtle differences in hit time distribution
- Early hits heavily contribute to position reconstruction
- Data/MC difference in cosδ
- Need to adjust the position reconstruction PDF in MC
- Tweak position reco on 54Mn data (align all gv_Ch)
- Apply new reco to 40K data (more Cherenkov photons) -> sensitivity to gv_Ch)

gv_{Ch} = 0.108±0.039 ns/m

Δn_{Ch} = 0.032±0.01

$n_{new} = n - \Delta n_{Ch}$ = 1.55 - 0.03 = 1.52

(2% effect)

PRL128.091803(2022); PRD105.052002(2022)