中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

Seeing the Sun with neutrinos

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Neutrino Summer School
2025.07.03 Seminar

Short bio of me @ dingxf.cn

Xuefeng Ding

Associate Research Fellow

IHEP-CAS

@ 知乎 CV

- Hi! Glad to see u. I study the Sun, the reactor, and AI.
- I love writing **pop science (in Chinese)**, take a look!
- For 3rd (this Sep) undergraduate, check our **training program (科创计划) @ IHEP**. **DDL is Jul. 18th, 2024**, be hurry.

Experience

- Associate Research Fellow
  from 2023-02-01 to
  IHEP-CAS (Beijing)
- Postdoc Research Associate
  from 2019-05-09 to 2022-12-31
  Princeton University (Princeton)

Education

- PhD in Astro-particle Physics, 2019
  GSSI (L'Aquila) and SISSA (Trieste)
- MSc in Theoretical Physics, 2015
  Wuhan University (Wuhan)
- BSc in Physics Base classes, 2012
  Wuhan University (Wuhan)

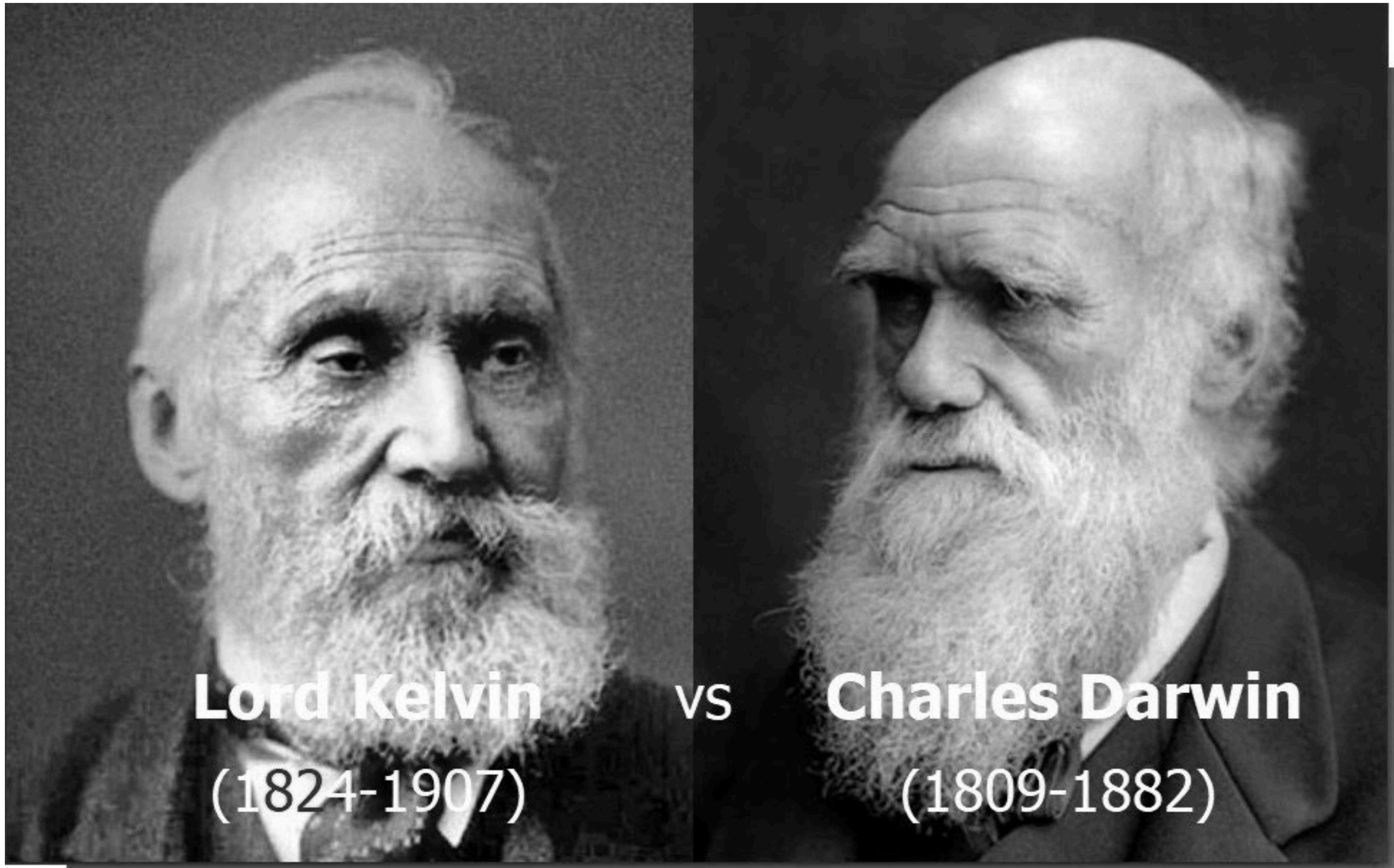
My 17 years 2008-2025

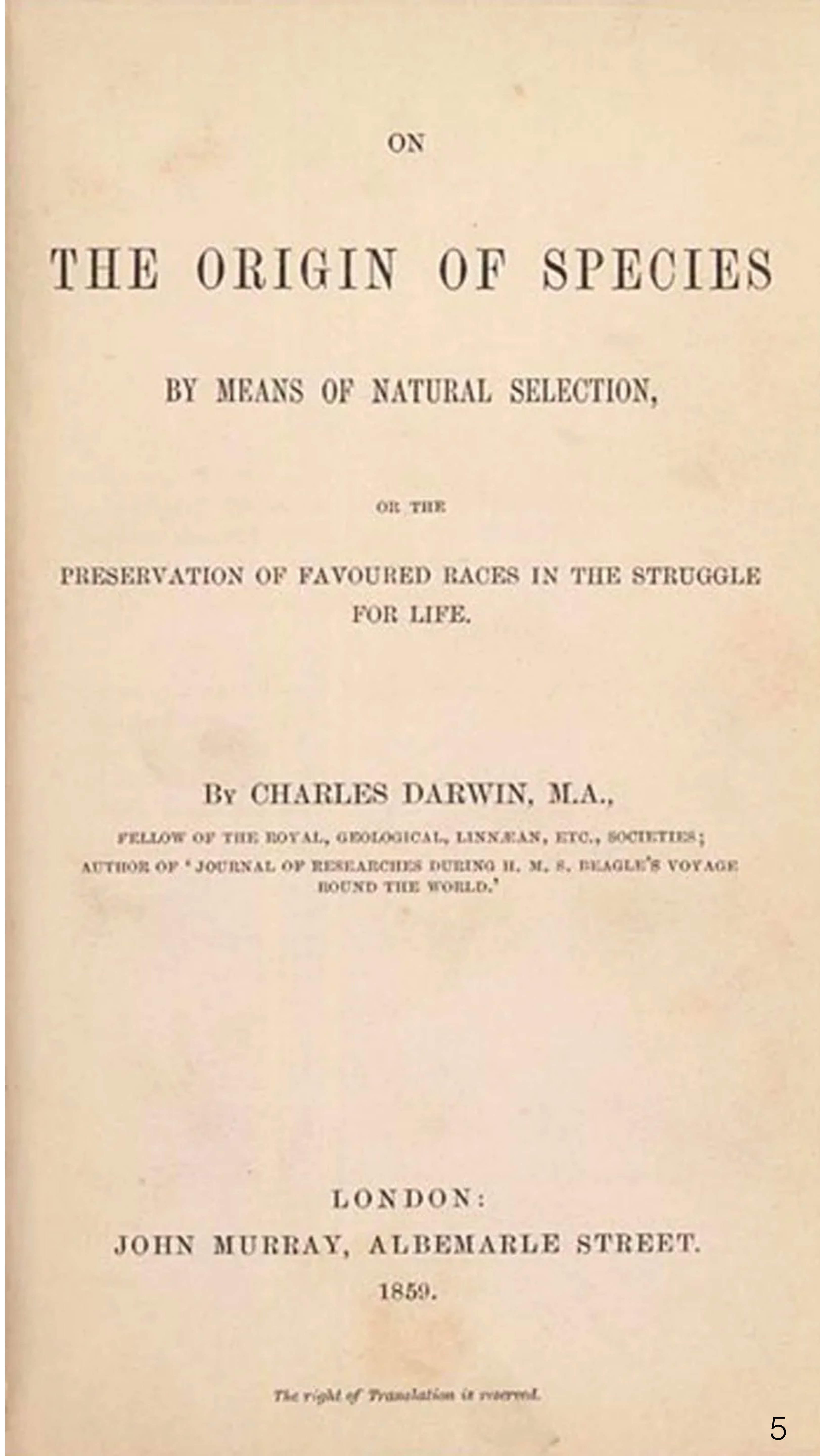
- 2008-2012 Lots of small projects
- 2012-2015 Simulation, optical models, Daya Bay and JUNO
- 2025-2019 Measurement of ^{7}Be solar neutrinos, Borexino
- 2019-2022 Measurement of CNO solar neutrinos, Borexino
- 2023-now JUNO reactor and solar neutrino physics and GasTPC R&D

➢ Prepare for the future, and be innovative (and fun) for now.


Sunspot
Penumbra
Umbra
Granule
Solar wind
Convective zone
Corona
Tachocline
Radiative zone
Photosphere
Core
Temperature minimum
Flare
Chromosphere
Transition region
The Sun
All features drawn to scale
Prominence

1859 达尔文：太阳寿命>3亿年
1862 开尔文：<3000万年




ON

THE ORIGIN OF SPECIES

BY MEANS OF NATURAL SELECTION,

OR THE

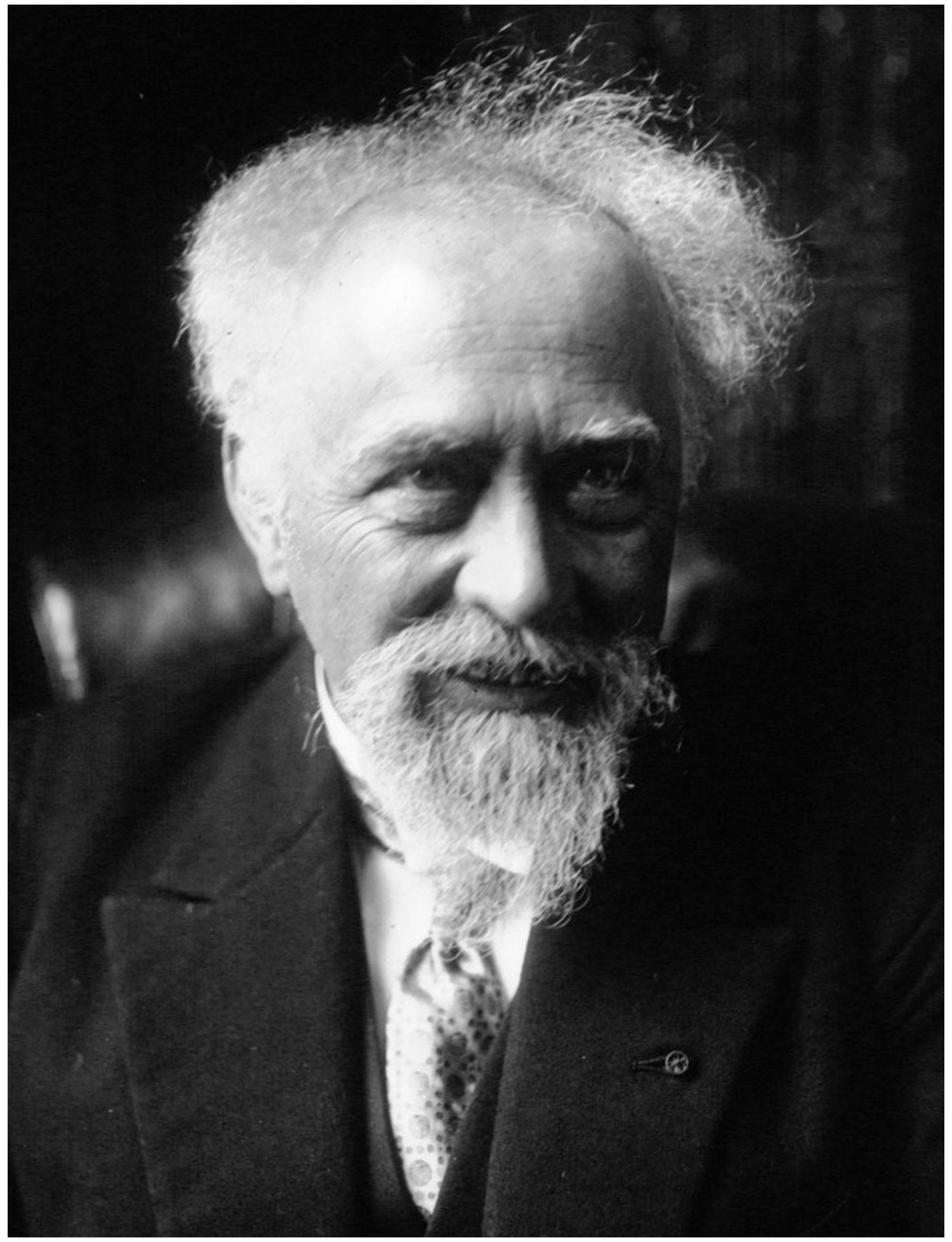
PRESERVATION OF FAVOURED RACES IN THE STRUGGLE FOR LIFE.

By CHARLES DARWIN, M.A.,

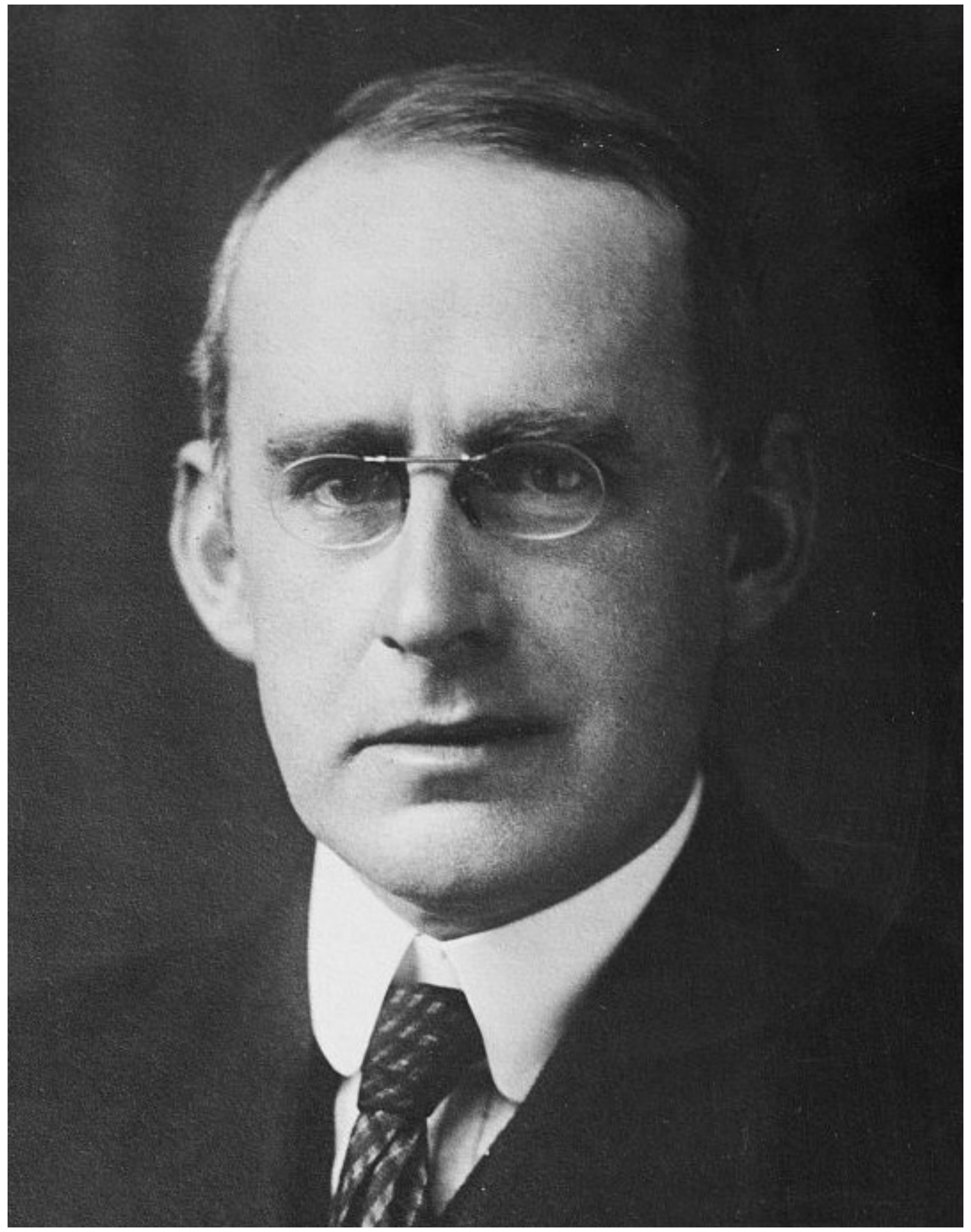
FELLOW OF THE ROYAL, GEOLOGICAL, LINNÆAN, ETC., SOCIETIES;
AUTHOR OF 'JOURNAL OF RESEARCHES DURING H. M. S. BEAGLE'S VOYAGE ROUND THE WORLD.'

LONDON:
JOHN MURRAY, ALBEMARLE STREET.
1859.

The right of Translation is reserved.

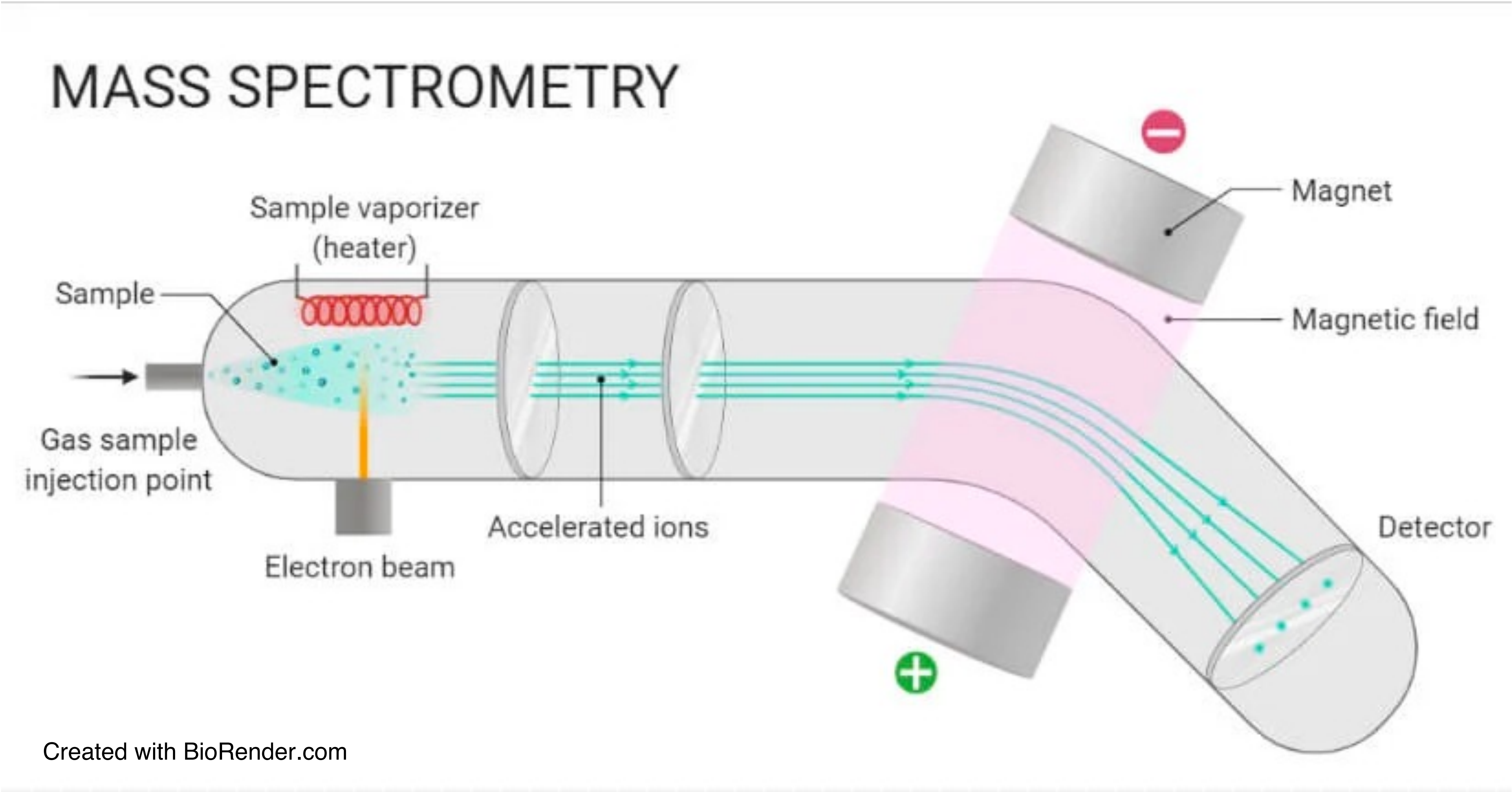


Jean Baptiste Perrin
(1870-1942)



Arthur Eddington
(1882-1944)

1920 太阳能量来自聚变



贝特与恒星能量来源

The Nobel Prize in Physics 1967

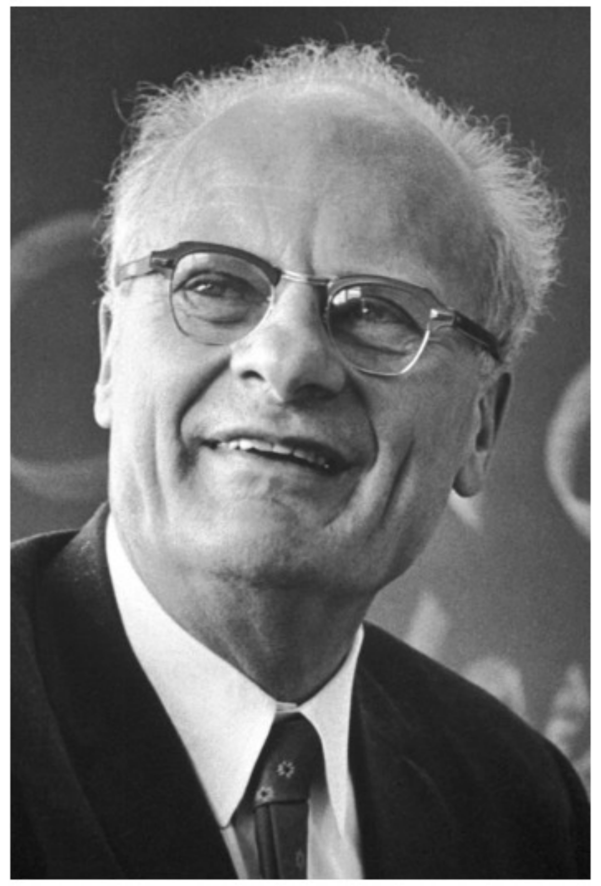
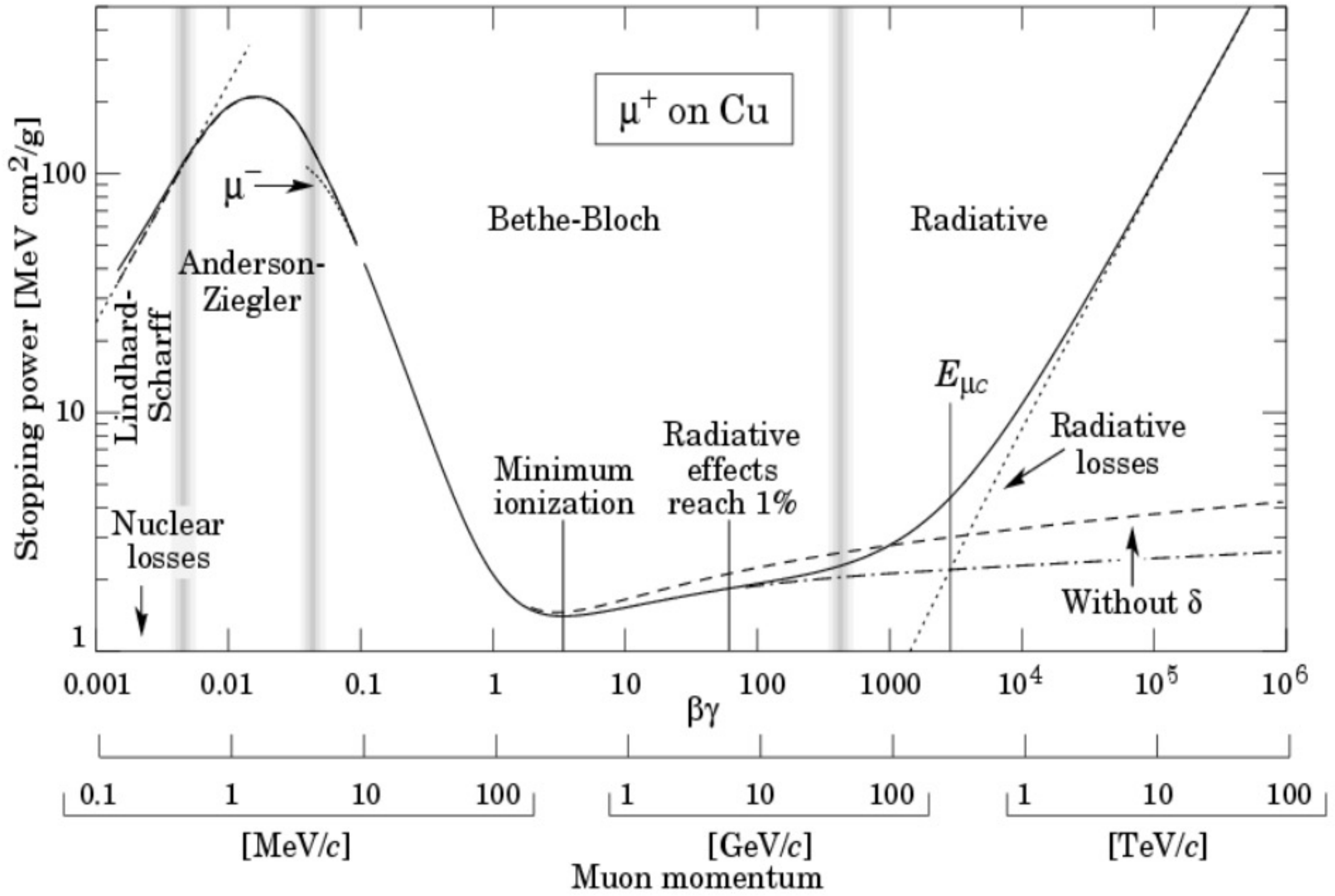


Photo from the Nobel Foundation archive.

Hans Albrecht Bethe

Prize share: 1/1



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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

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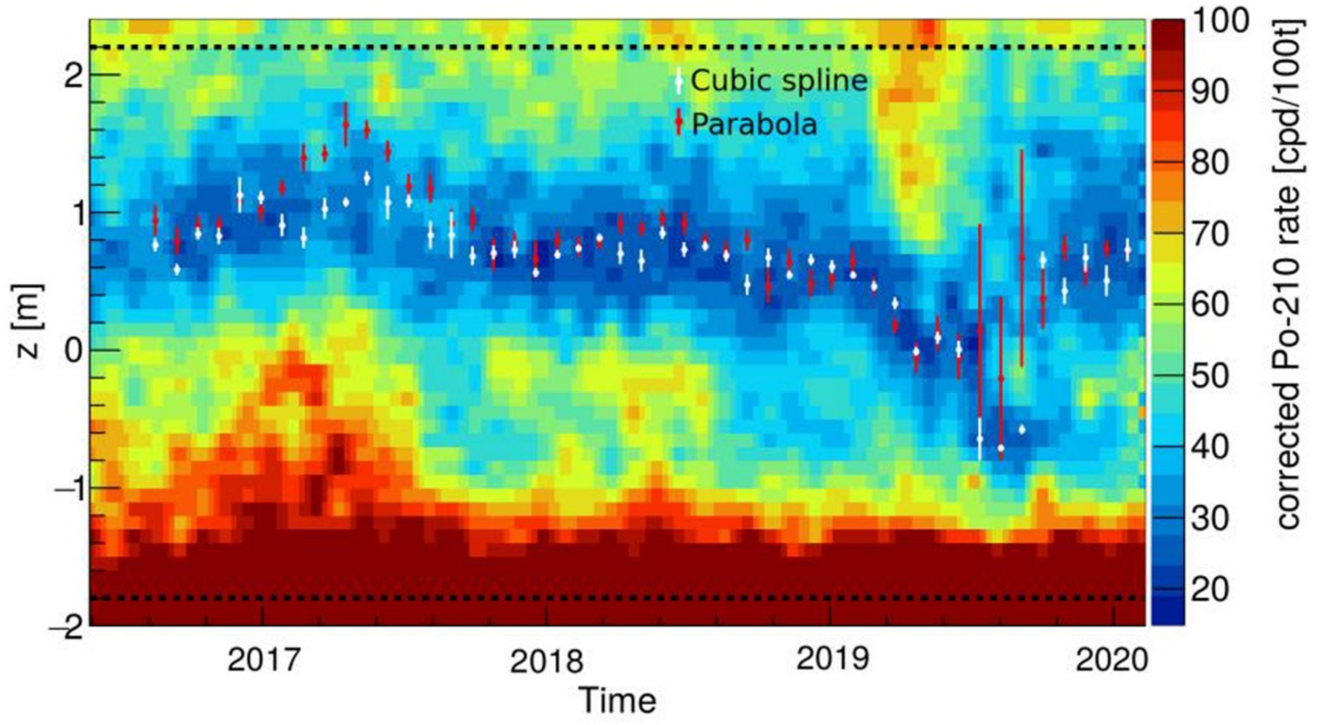
Abstract

For most of their existence, stars are fue
proceeds via two processes that are wel
chain and the carbon–nitrogen–oxygen
fusion processes in the solar core are th
complete spectroscopic study of neutri

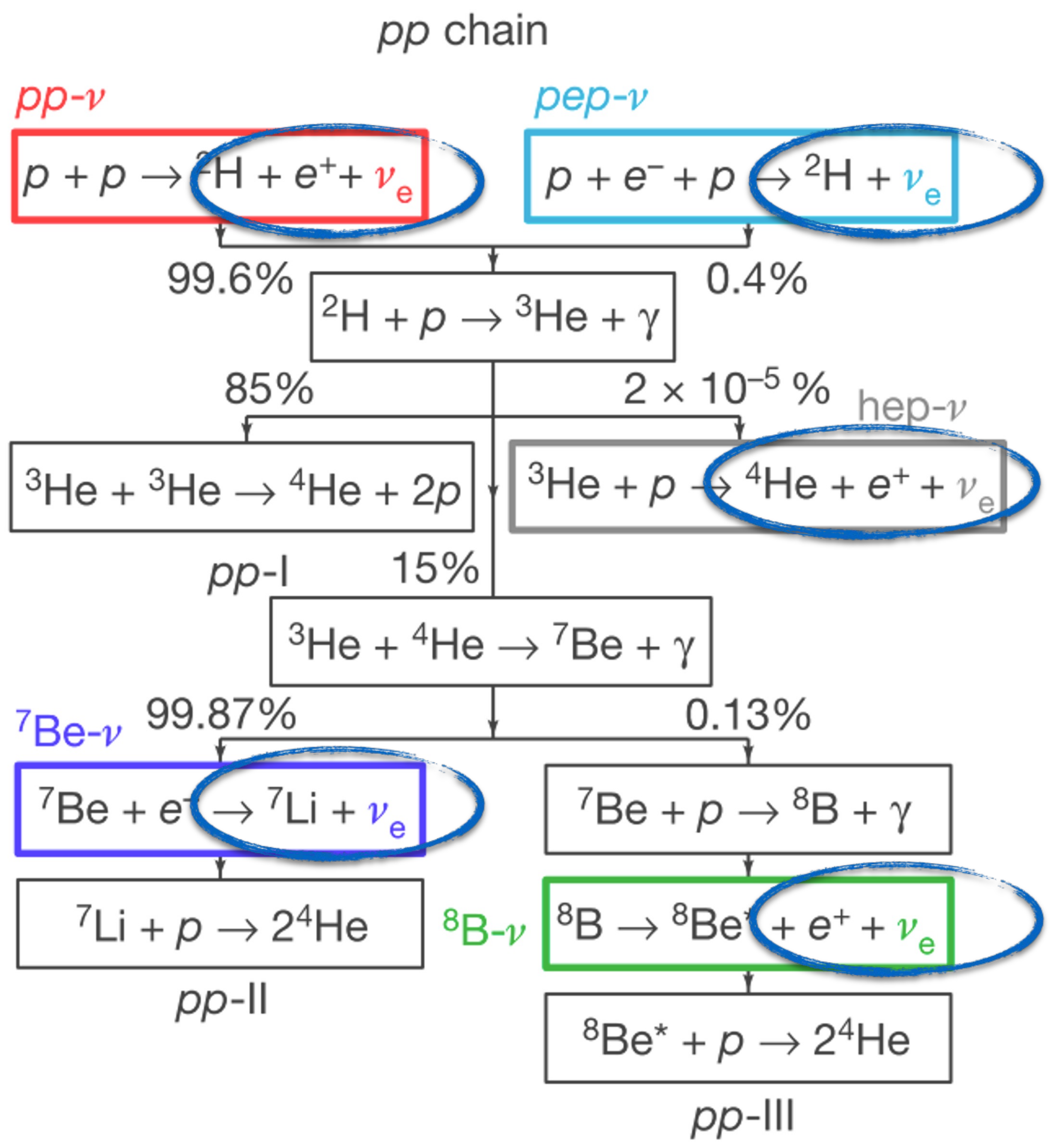


The Nobel Prize in Physics 1967 was awarded to Hans Albrecht Bethe "for his contributions to the theory of nuclear reactions, especially his discoveries concerning the energy production in stars"

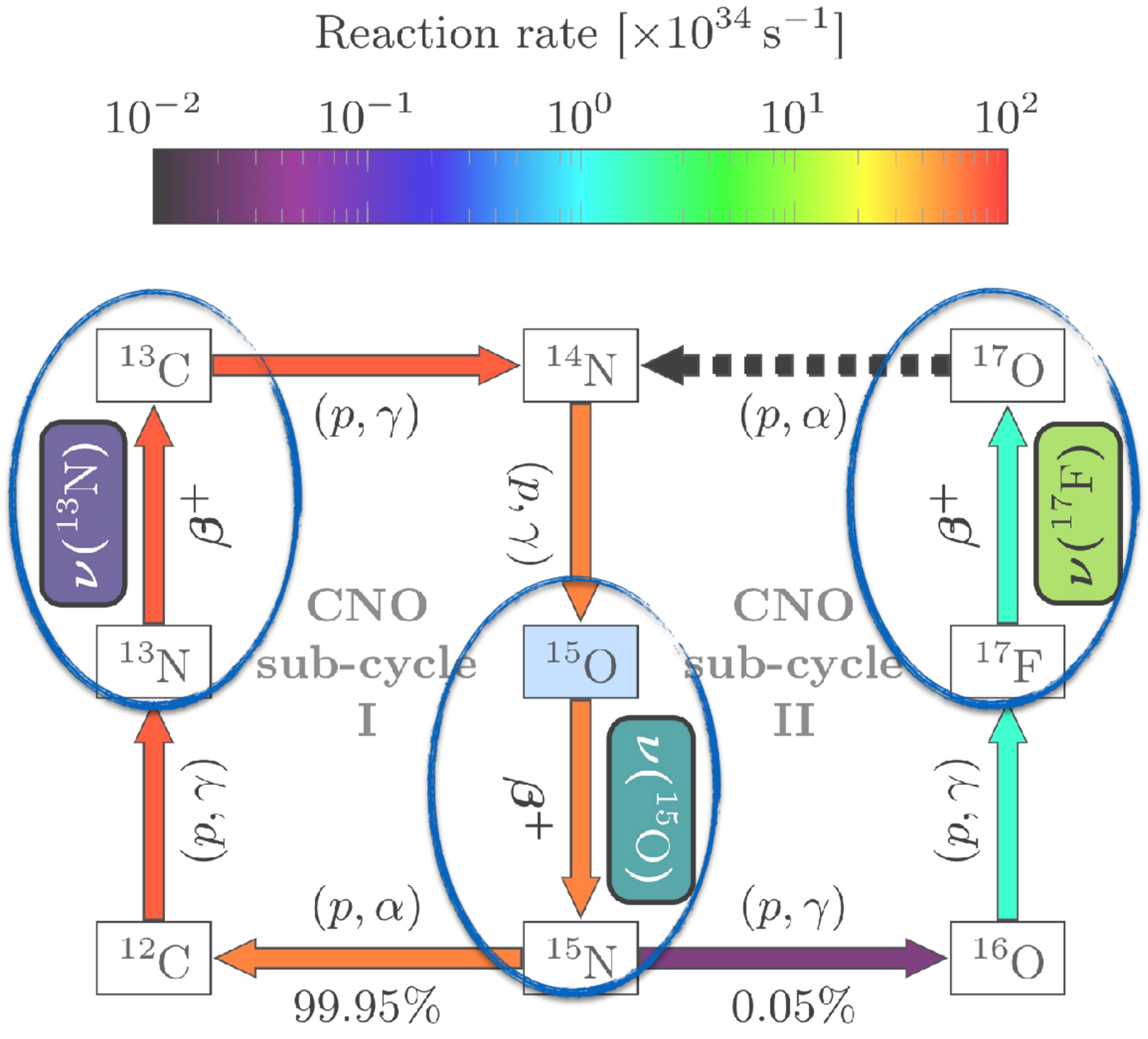
To cite this section
MLA style: The Nobel Prize in Physics 1967. NobelPrize.org. Nobel Prize Outreach AB 2023. Thu. 31 Aug 2023. <https://www.nobelprize.org/prizes/physics/1967/summary/>

After *Kristallnacht*, Bethe's mother had become afraid to remain in Germany. Taking advantage of her Strasbourg origin, she was able to emigrate to the United States in June 1939 on the French quota, rather than the German one, which was full.[61] Bethe's graduate student Robert Marshak noted that the New York Academy of Sciences was offering a $500 prize for the best unpublished paper on the topic of solar and stellar energy. So Bethe, in need of $250 to release his mother's furniture, withdrew the CNO cycle paper and sent it in to the New York Academy of Sciences. It won the prize, and Bethe gave Marshak $50 finder's fee and used $250 to release his mother's furniture. The paper was subsequently published in the *Physical Review* in March. It was a breakthrough in the understanding of the stars, and would win Bethe the Nobel Prize in Physics in 1967.[62][60] In 2002, at age 96, Bethe sent a handwritten note to John N. Bahcall congratulating him on the use of solar neutrino observations to show that the CNO cycle accounts for approximately 7% of the Sun's energy; the neutrino observations had started with Raymond Davis Jr., whose experiment was based on Bahcall's calculations and encouragement, and the note led to Davis's receiving a share of the 2002 Nobel Prize.[63]

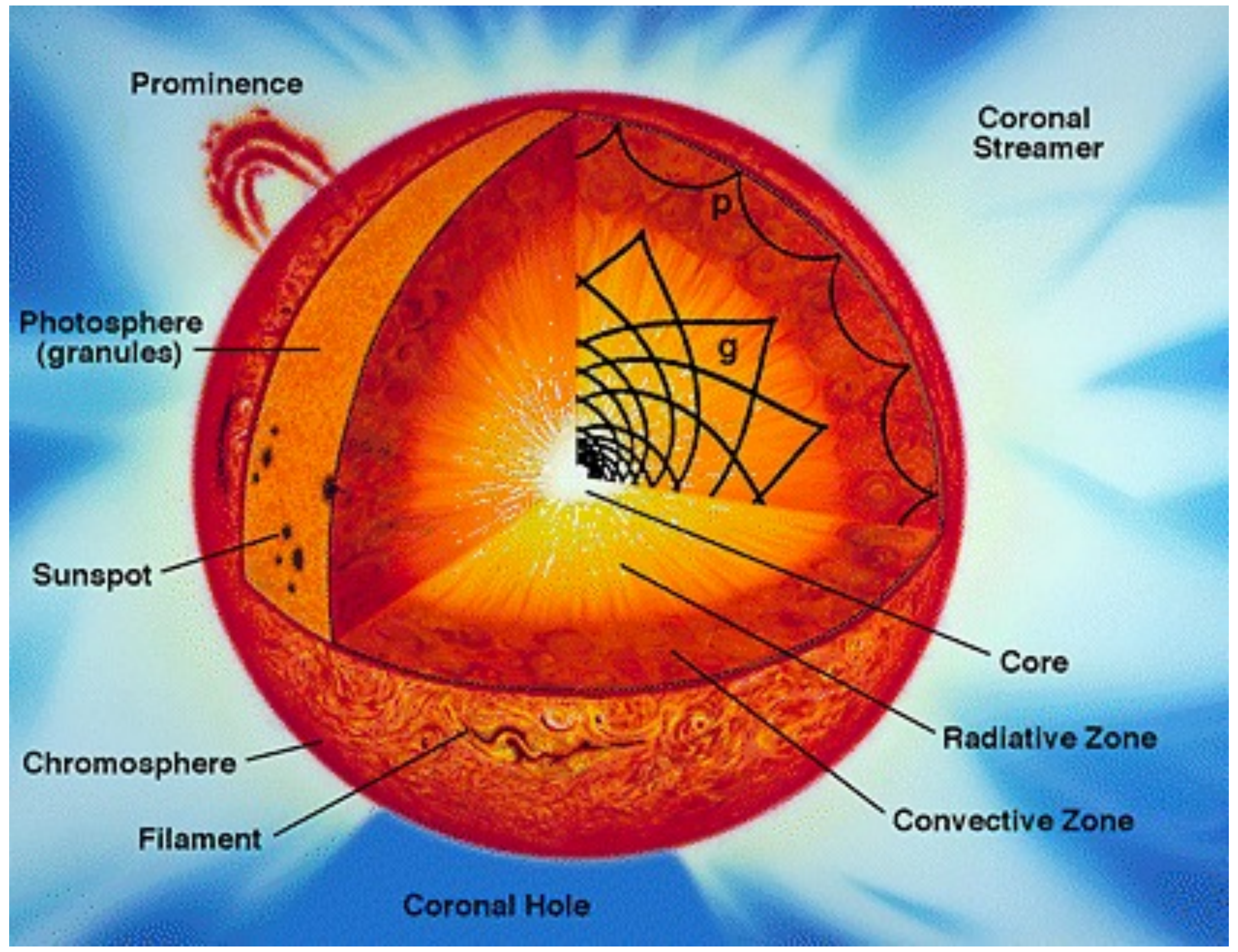
1930s 质子-质子链与碳氮氧循环过程

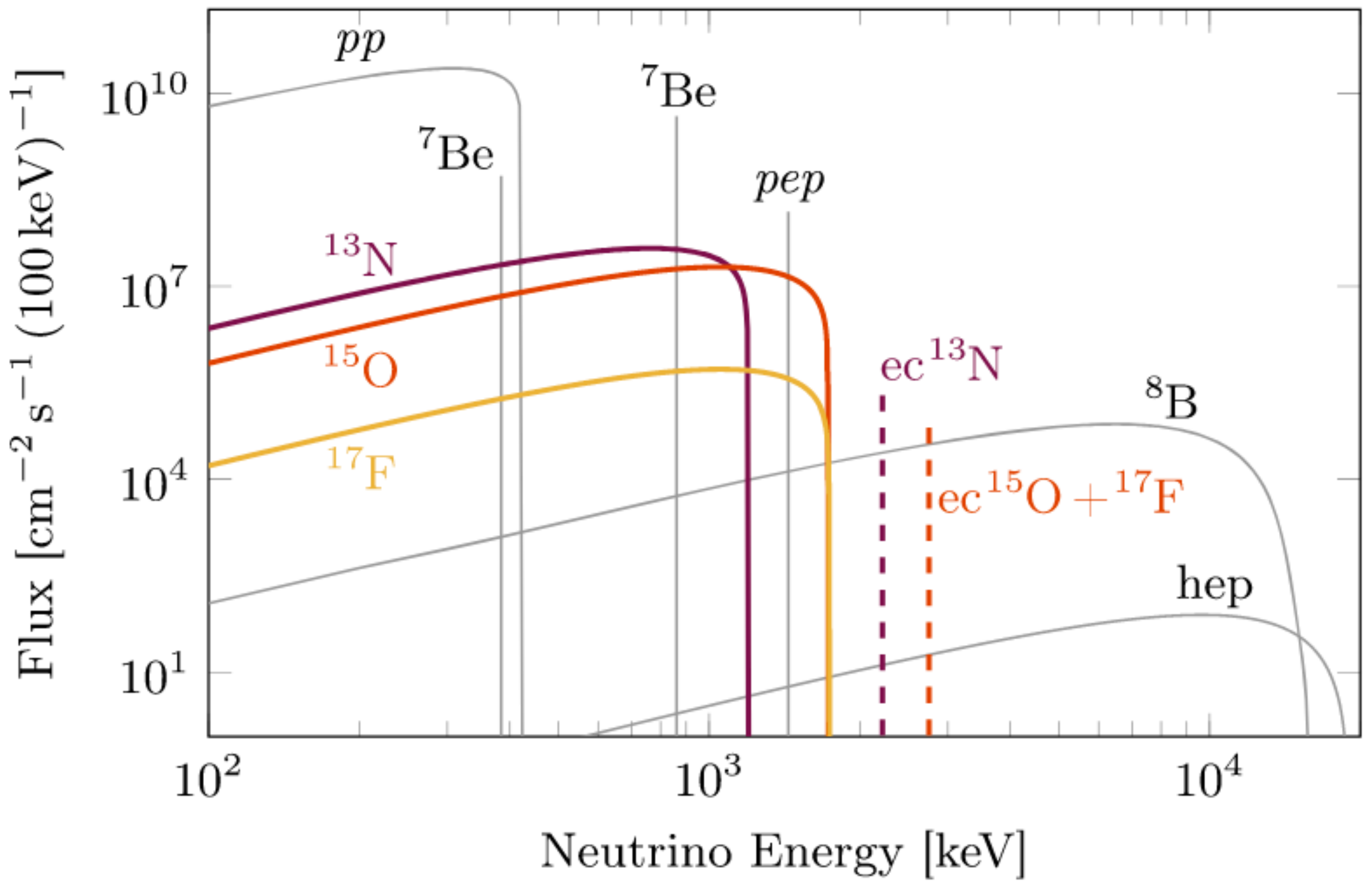


Comprehensive measurement of pp-chain solar neutrinos, BOREXINO, 2018, Nature



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





Agostini, M., K. Altenmüller, S. Appel, V. Atroshchenko, Z. Bagdasarian, D. Basilico, G. Bellini, et al. "Sensitivity to Neutrinos from the Solar CNO Cycle in Borexino." *European Physical Journal C* 80, no. 11 (November 26, 2020): 1091. https://doi.org/10.1140/epjc/s10052-020-08534-2.

- Bethe & Weizsäcker 太阳能源为两种氢核聚变过程
- 聚变过程会放出中微子

nature

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Article | Published: 25 November 2020

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

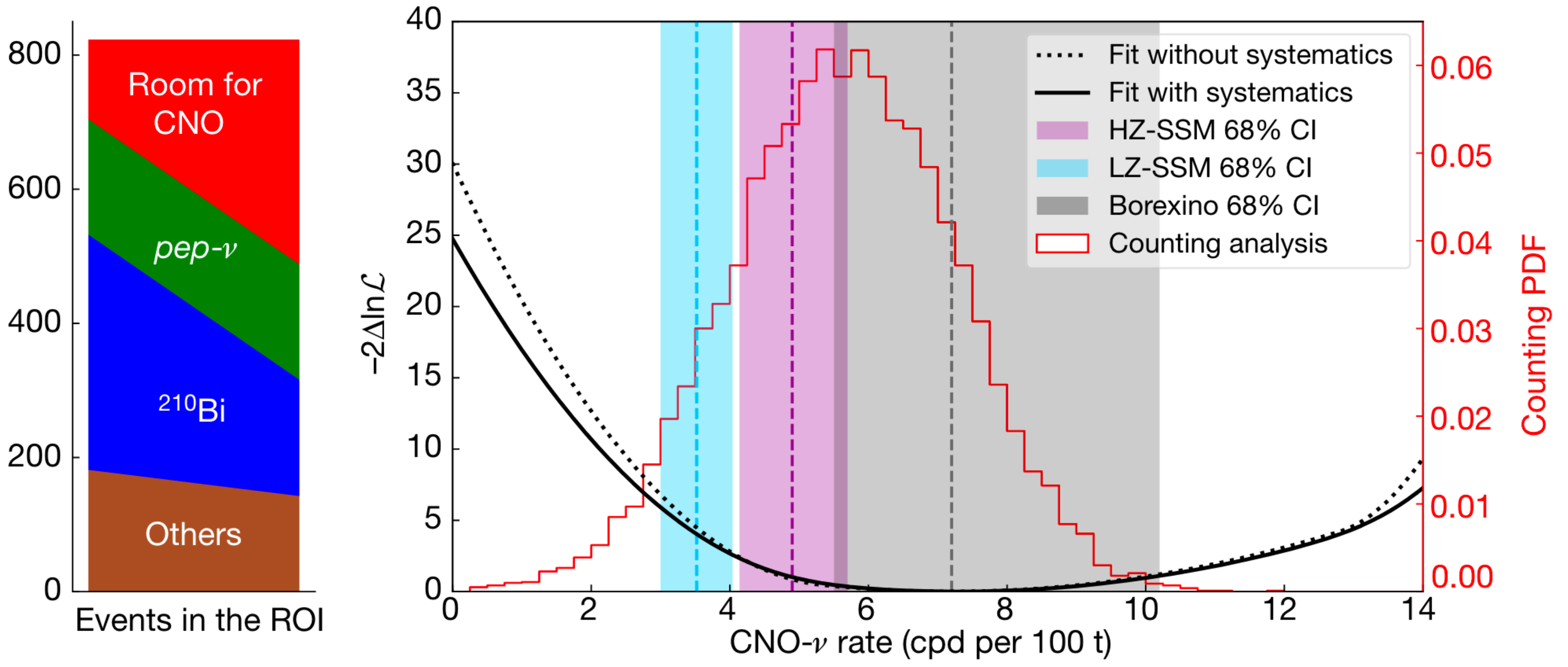
The Borexino Collaboration

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

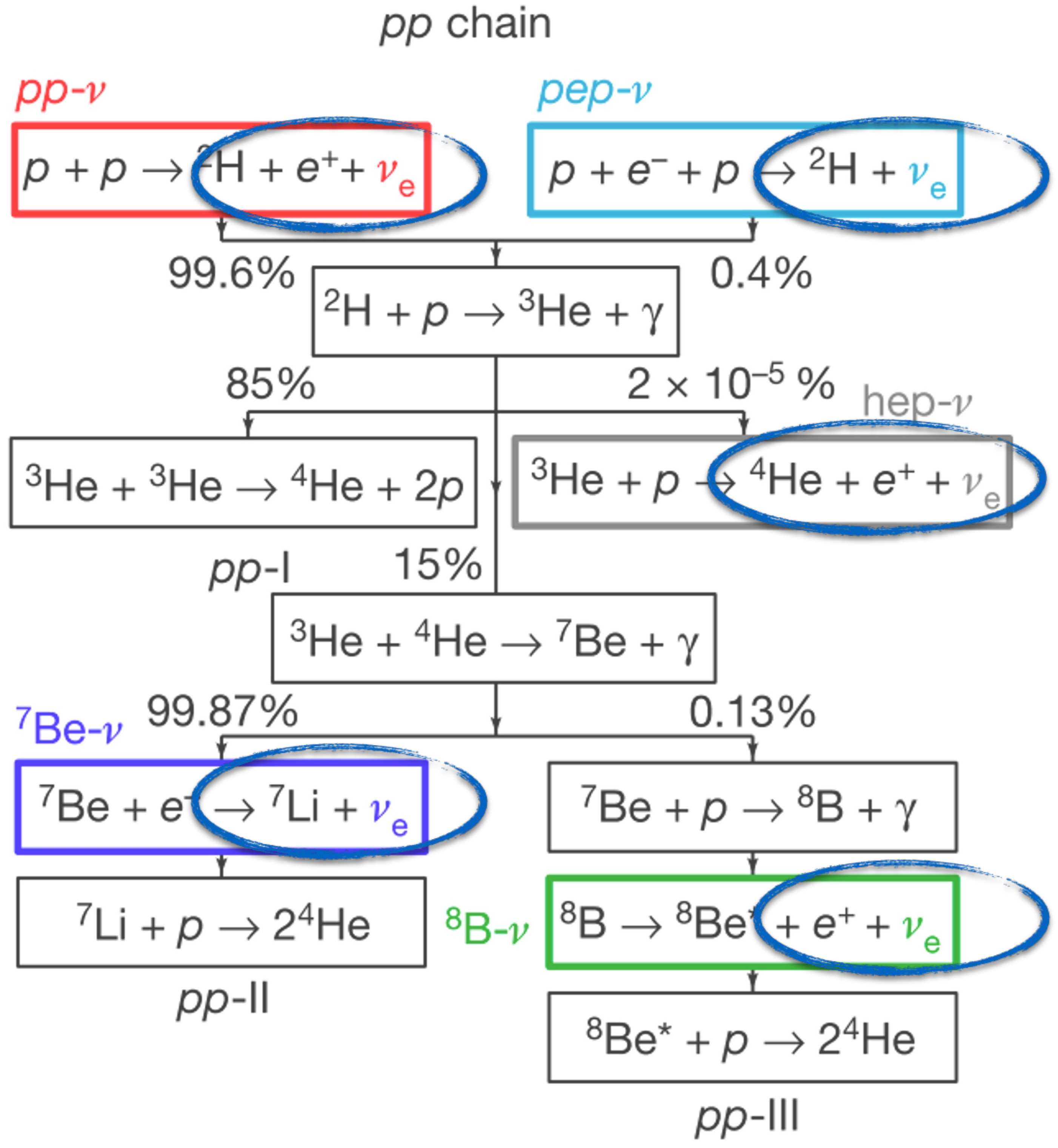
14k Accesses | **137** Citations | **902** Altmetric | Metrics

G. & V. Cocconi Prize 2021 - EPS

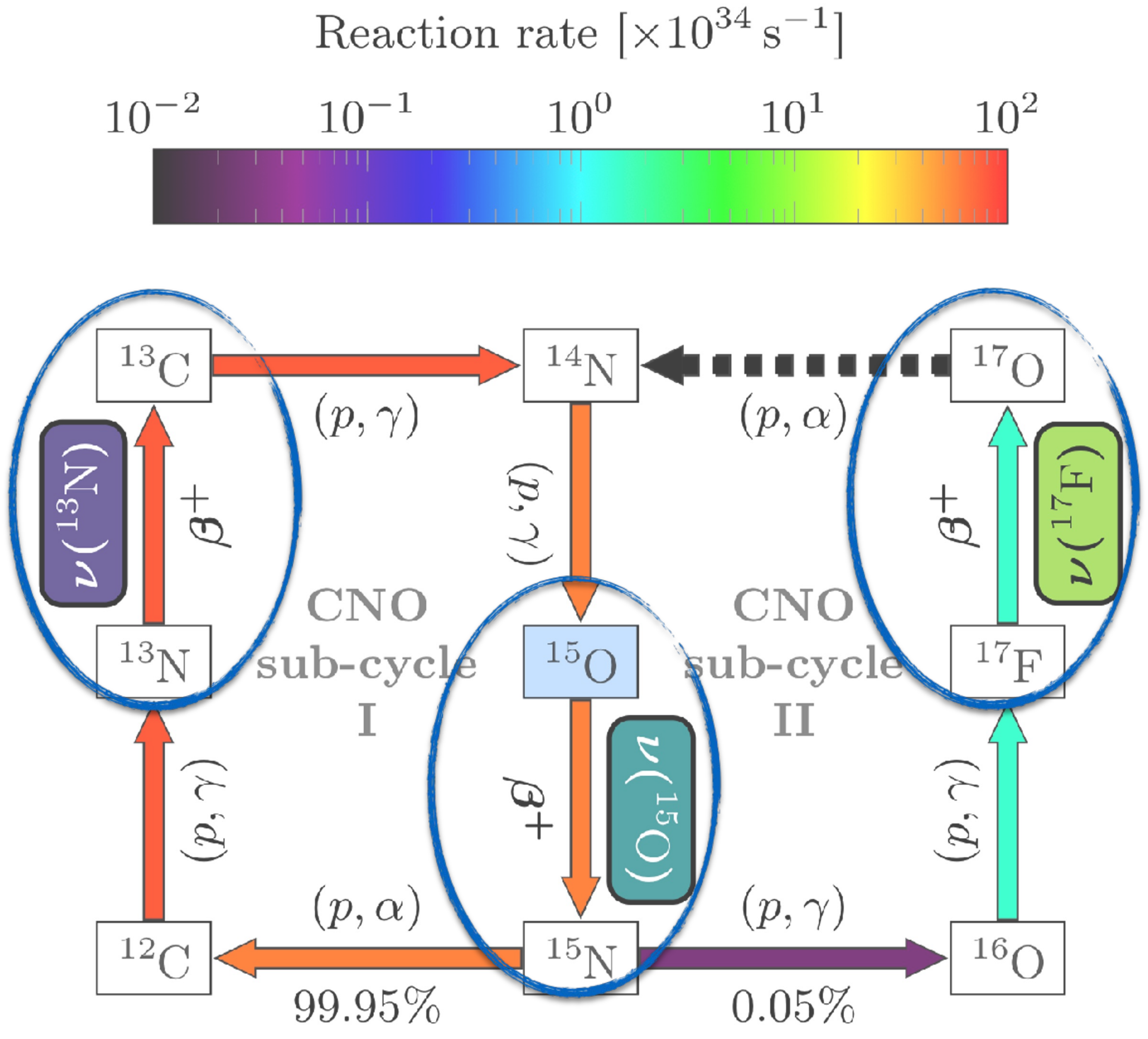
physicsworld TOP 10 BREAKTHROUGH 2020



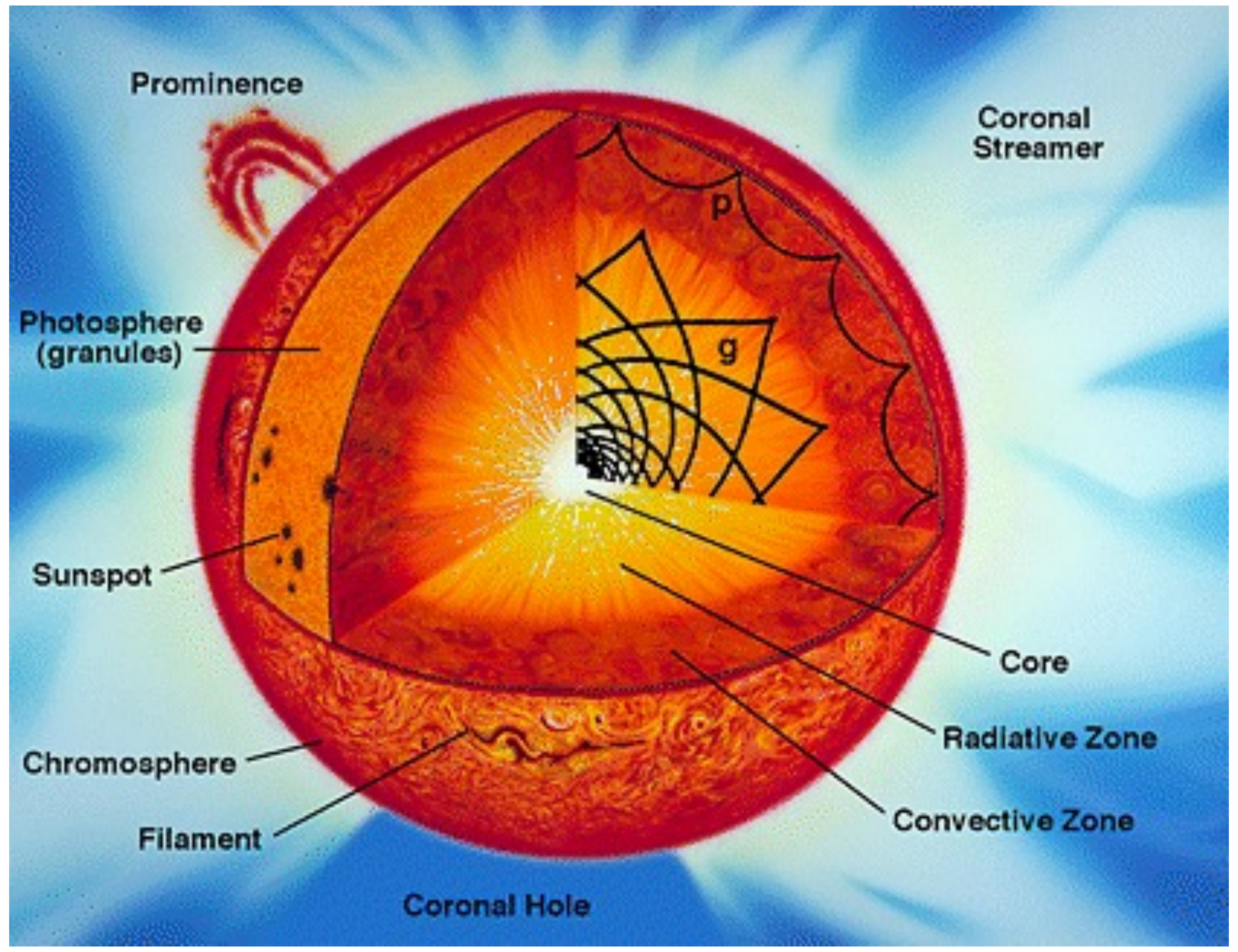
Basics about solar neutrinos

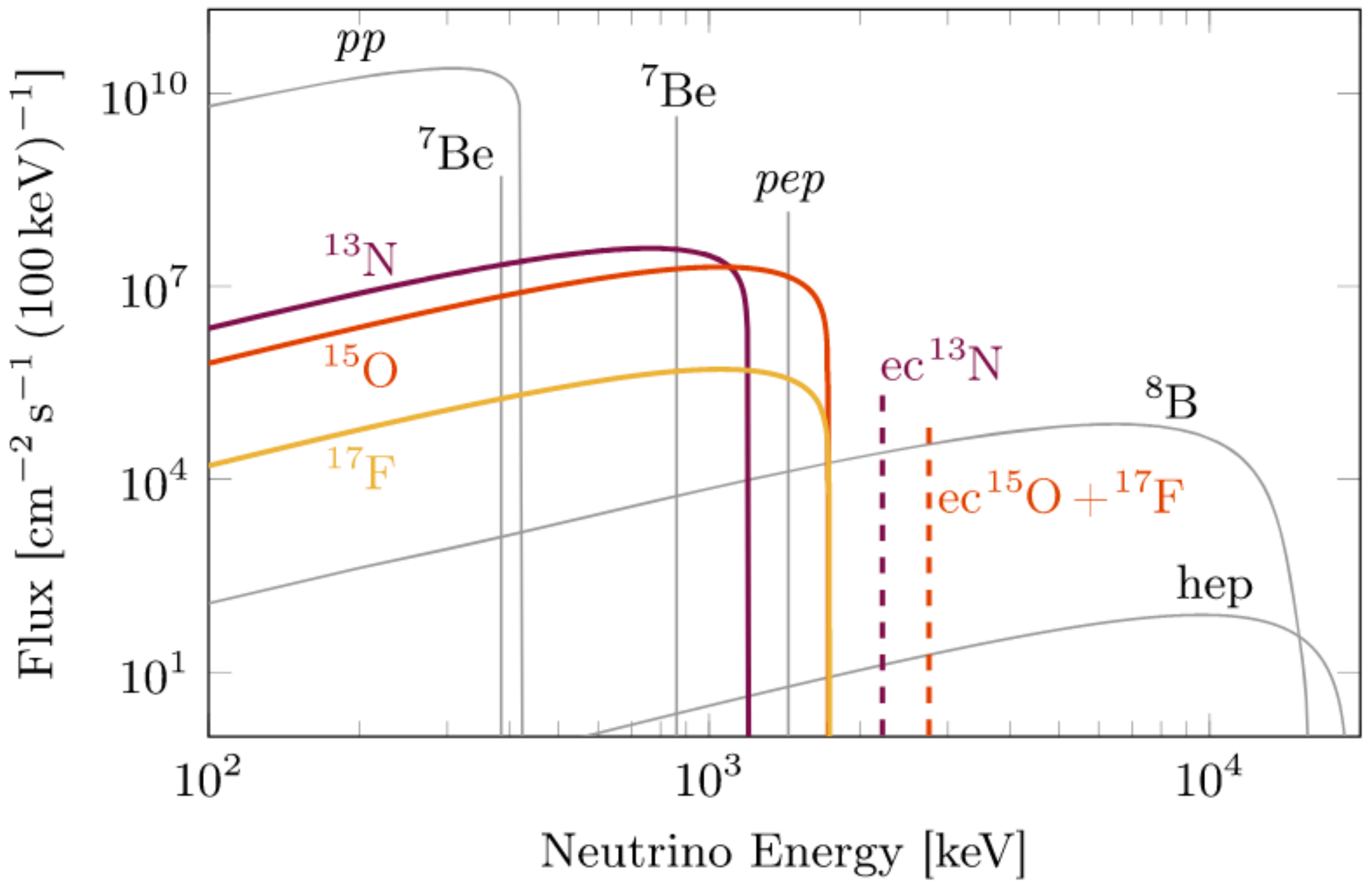


Comprehensive measurement of pp-chain solar neutrinos, BOREXINO, 2018, Nature



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

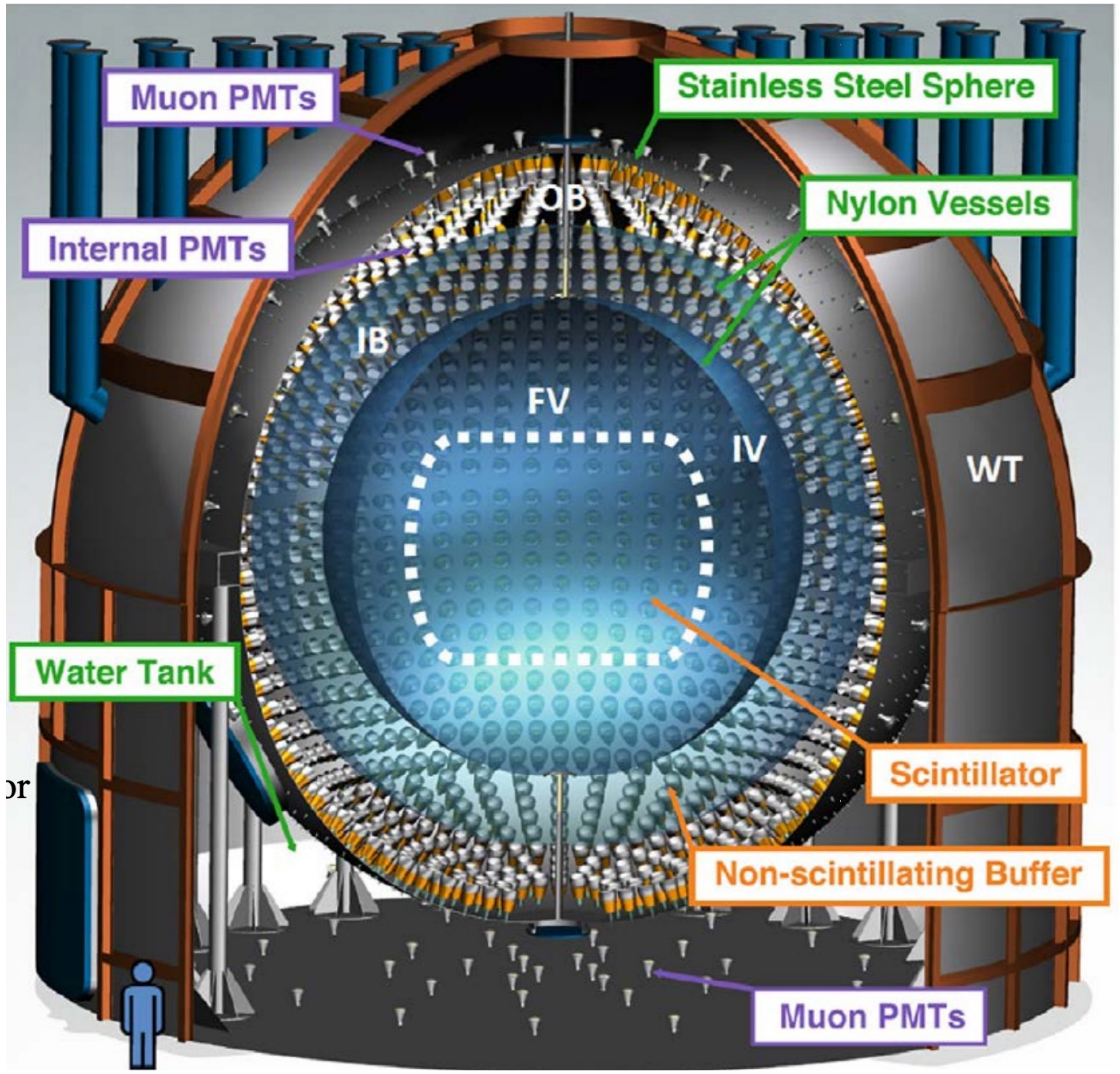




Agostini, M., K. Altenmüller, S. Appel, V. Atroshchenko, Z. Bagdasarian, D. Basilico, G. Bellini, et al. "Sensitivity to Neutrinos from the Solar CNO Cycle in Borexino." *European Physical Journal C* 80, no. 11 (November 26, 2020): 1091. https://doi.org/10.1140/epjc/s10052-020-08534-2.

- Two types of $4H \Rightarrow {}^4He$: pp-chain and CNO-cycle.
- Solar neutrinos are produced during the fusion.

Borexino detector



- Located at hall C of LNGS, Italy.
- Active volume 280 tons of liquid scintillator
- Detect solar neutrinos via elastic scattering off electrons of the scintillator, threshold at 60 keV

Physics program of Borexino

2007 May-2010 May

Phase-I

Be7 Phys. Rev. Lett. 107, 141302 (2011)
pep Phys. Rev. Lett. 108, 051302 (2012)
pp Nature 512, 383-386 (28 August 2014)
3 MeV B8 Phys.Rev.D82:033006 (2010)
geo-neutrino PLB 687, 299-340 (2010)
Day-night symmetry PLB 707-1,22-26, (2012)
…

2010-2011
Purification +
Calibration

2011 Dec-2016 May

Phase-II

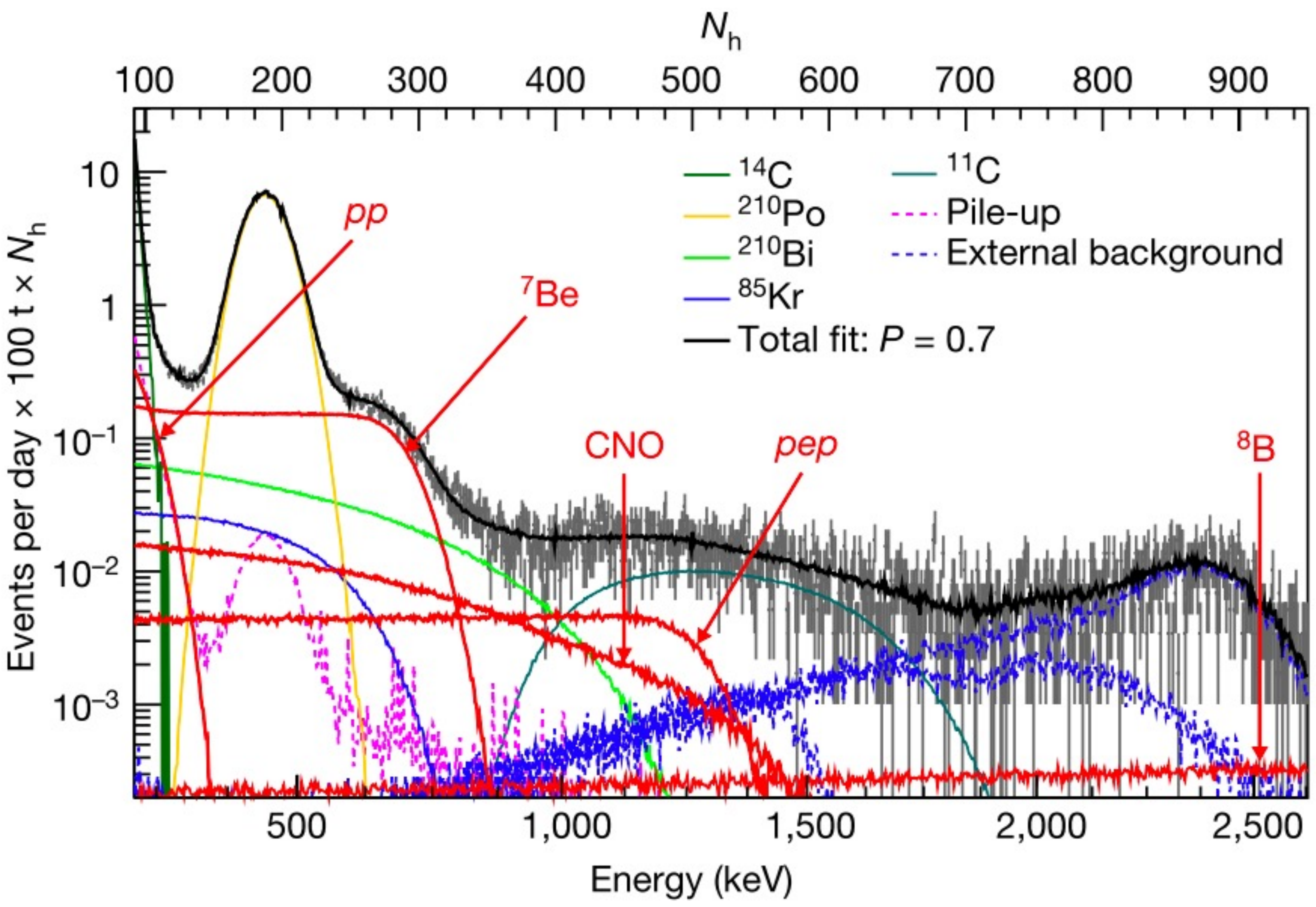
pp+Be7+pep+CNO+^{8}B Nature 2018, PRD 100, 082004, PRD 101.062001
neutrino magnetic moment PRD 96, 091103 (2017)
gravitational wave ApJ 850-21 (2017)
Be7 seasonal modulation AP, 92, 21-29 (2017)
gamma ray burst AP, 86, 11-17, (2017)
electric charge conservation PRL 115,231802(2017)
geo-neutrino PRD 93, 031101 (2015)
…

2016 June - 2021 October

Phase-III

Experimental evidence of CNO neutrinos, Nature 2020
Sensitivity to CNO neutrinos, EPJC 80, 10912020
Search for low energy neutrinos from astrophysical sources, ApJ 102509, 2020
…

Signals and backgrounds in Borexino



- Recoil electron induced by solar neutrinos (*pp*, ^{7}Be, CNO, *pep*, ^{8}B)
- Internal natural radioactivity (^{210}Po, ^{210}Bi, ^{85}Kr)
- External natural radioactivity
- Cosmogenic radioactivity (^{11}C)
- Pile-up

Unprecedented radiopurity

2007-2010: **Phase-I**

^{238}U $5\text{x}10^{-18}$ g/g

^{232}Th $3\text{x}10^{-18}$ g/g

^{210}Pb ~$2\text{x}10^{-24}$ g/g

^{85}Kr ~20 cpd/100ton

2010-2012

Purification + Calibration

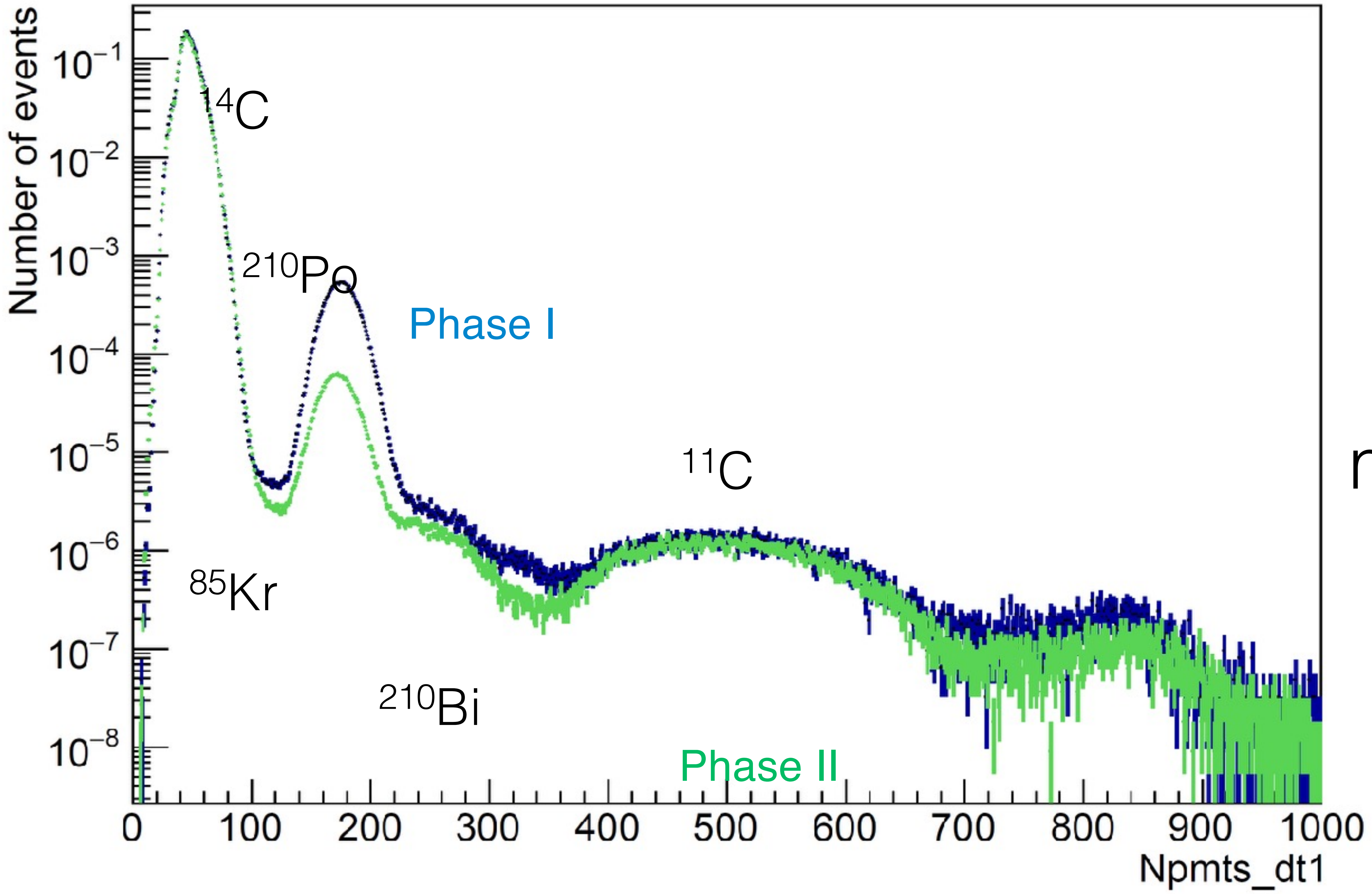
2012-now: **Phase-II**

^{238}U <$9.4\text{x}10^{-20}$ g/g

^{232}Th <$5.7\text{x}10^{-19}$ g/g

^{210}Pb ~$9\text{x}10^{-26}$ g/g

^{85}Kr ~5 cpd/100ton



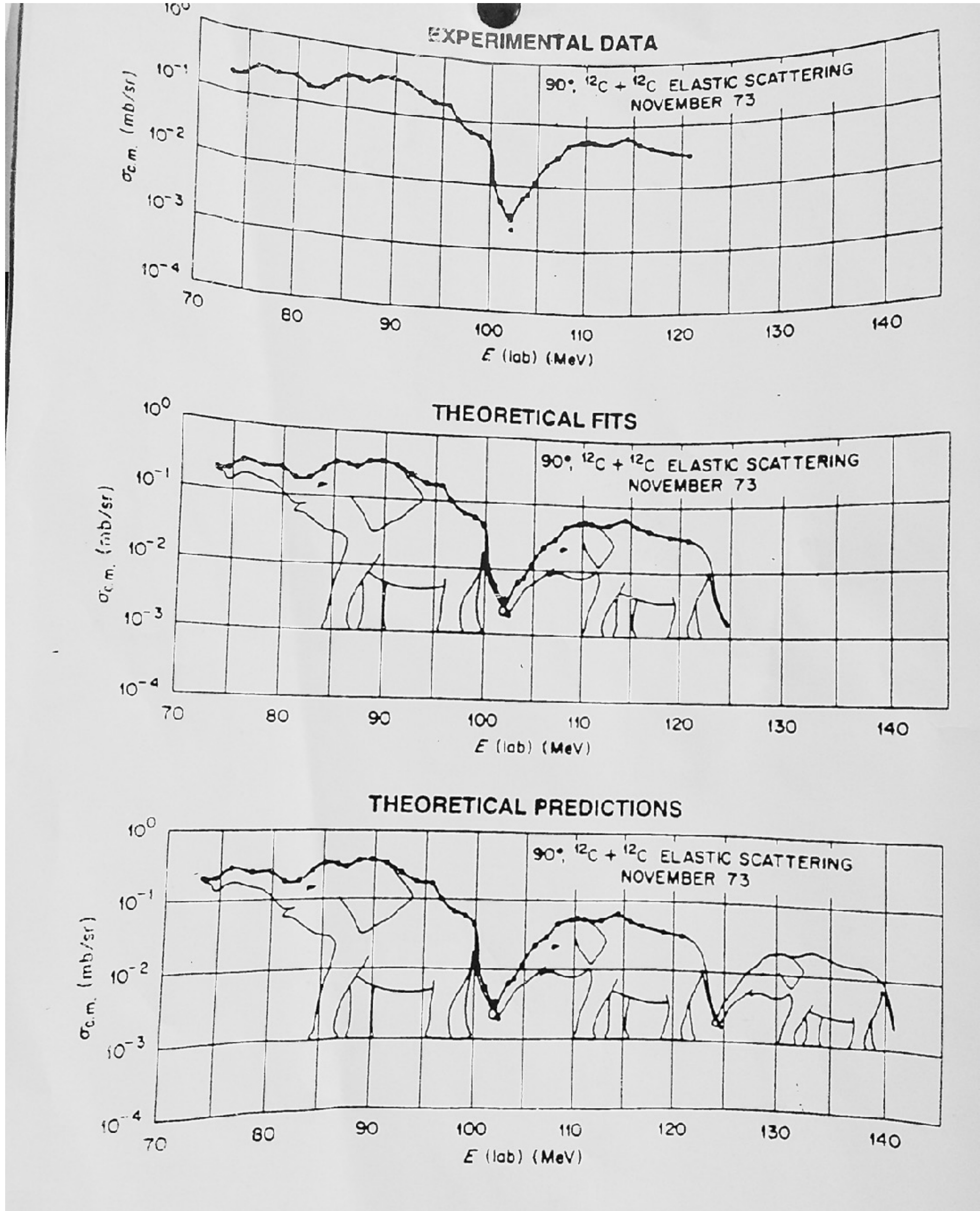
^{238}U<$1.2\text{x}10^{-12}$ Bq/kg

mineral water ~10 Bq/kg

=> 10^{-13} reduction

Work1: Fit, and GPU

The art of fitting



The process of fitting data, as seen by Subramanian Raman in *Science with a Smile.*

- Give me 8 parameters, I can fit an elephant

Published Online: May 2010 Accepted: October 2009

Drawing an elephant with four complex parameters

American Journal of Physics 78, 648 (2010); https://doi.org/10.1119/1.3254017

- Occam's Razor: free it if you are sensitive

Jürgen Mayer
- Max Planck Institute of Molecular Cell Biology and Genetics, Pfotenhauerstr. 108, 01307 Dresden, Germany

Khaled Khairy
more...

Impact factor ~ NIM/JINST

PDF ABSTRACT FULL TEXT FIGURES SUPPLEMENTAL CITED BY TOOLS SHARE METRICS

TOPICS
- Magnetic resonance imaging
- Fourier analysis
- Spectrum analysis
- Physicists

ABSTRACT

We define four complex numbers representing the parameters needed to specify an elephantine shape. The real and imaginary parts of these complex numbers are the coefficients of a Fourier coordinate expansion, a powerful tool for reducing the data required to define shapes.

Systematics of fitting from detector response

Method 1: fit with varying models

- MC: during each iteration of the fit, vary kb / absorption length spectrum etc. re-simulate and produce new pdf on the fly —> when one day computer is fast enough
    - ~200, 000 CPU x years per fit
- Full analytical: non-linearity + resolution models
    - ~2 hours per fit

Analytical Model of Detector Response

- Analytical shape of spectrum of mono-energetic events
  - Momentum based approximation
  - Match the average (energy scale + non-linearity model)
  - Match the variance (energy resolution model)
  - Match the skewness
  - … (—> simplified)
- We can simplify because
  - Borexino response is simple: small FV in center, low energies
  - We are not sensitive..
- Fit full MC to get the bias introduced in simplification

Detector response model: NL

$$M : f(E) \mapsto g(\text{charge}) = \int_0^{E_{\text{end}}} \mathrm{d}E \cdot f(E) \cdot \text{RPF}\left[\text{charge}; \mu(E), \text{var}(\mu)\right]$$


source: http://m.hnstrip.com/archives/view-1525-1.html

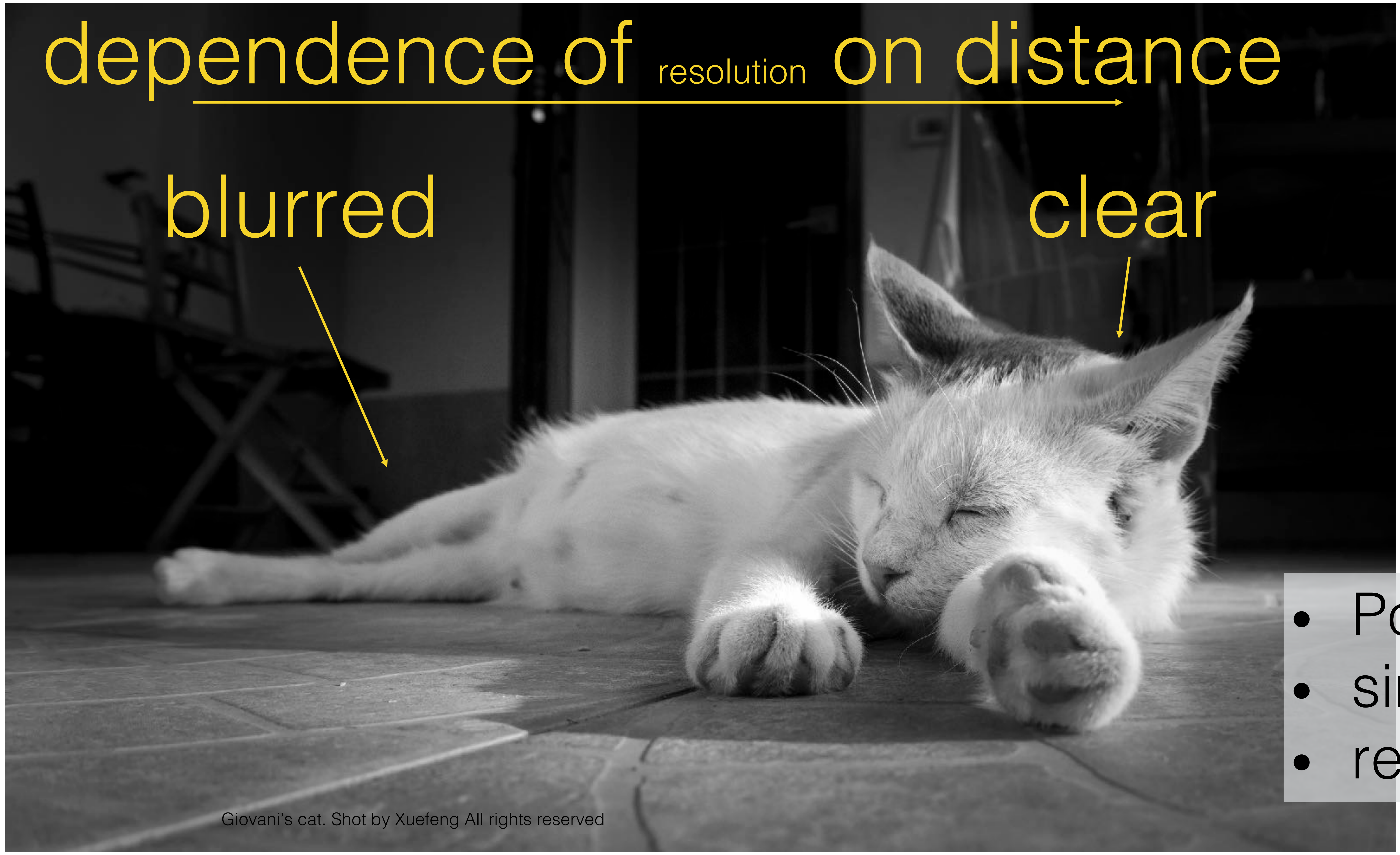
Energy scale + non-linearity:

scaling/streching/compressin
g

- Liquid scintilator: quenching, Cherenkov..
- More:Electronics, Clustering..

Detector response model: resolution

$$M : f(E) \mapsto g(\text{charge}) = \int_0^{E_{\text{end}}} \mathrm{d}E \cdot f(E) \cdot \mathrm{RPF}\left[\text{charge}; \mu(E), \mathrm{var}(\mu)\right]$$

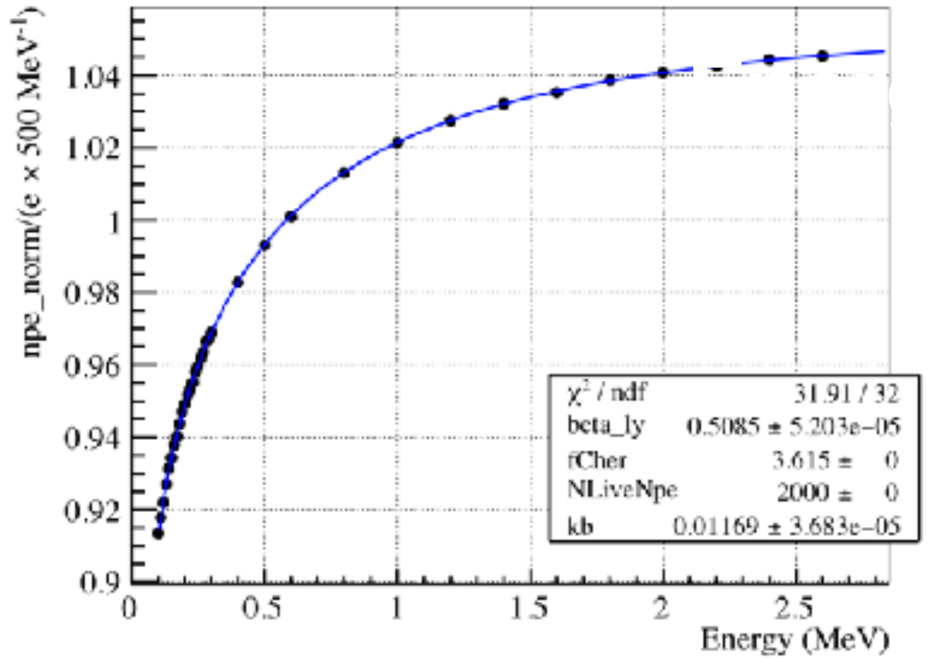


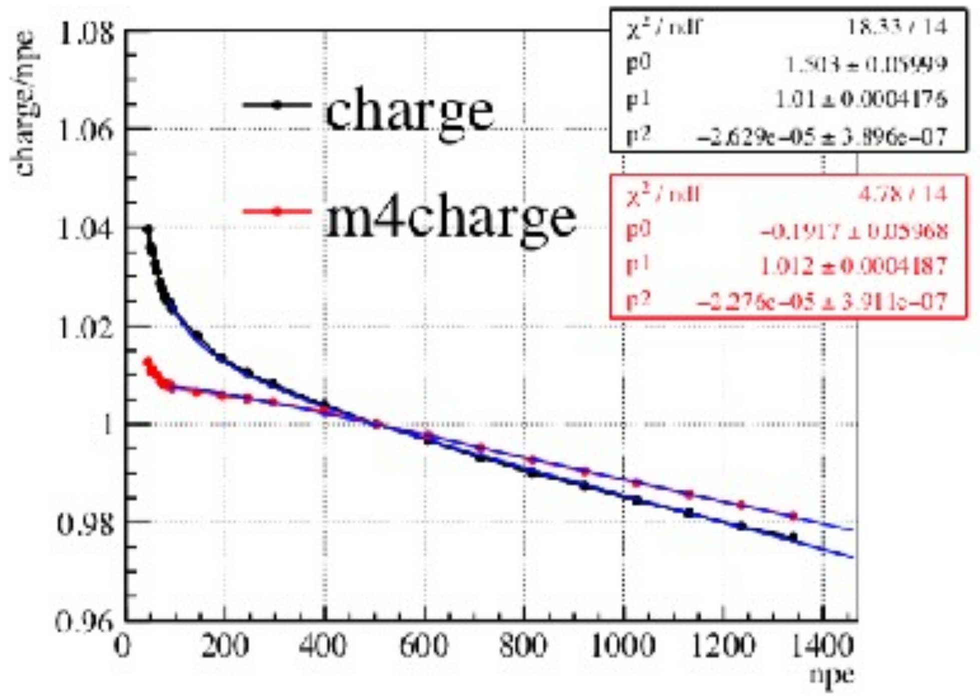
resolution

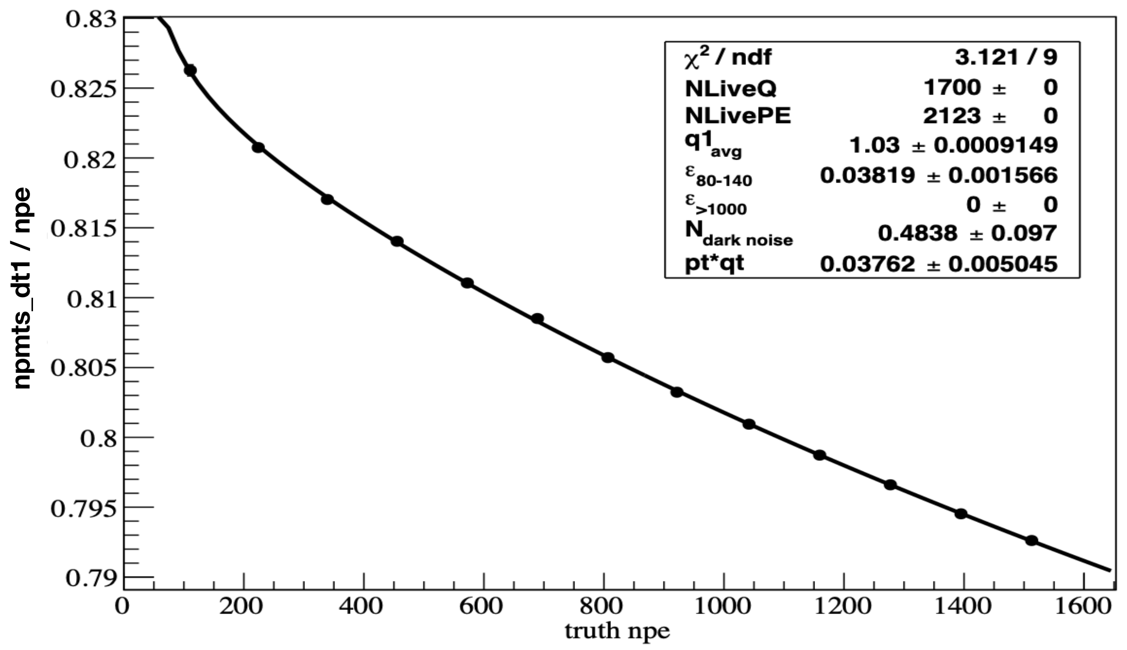
blur

- Poisson..
- single p.e. charge fluctuations..
- residual non-uniformity

Analytical Model — energy scale and non-linearity







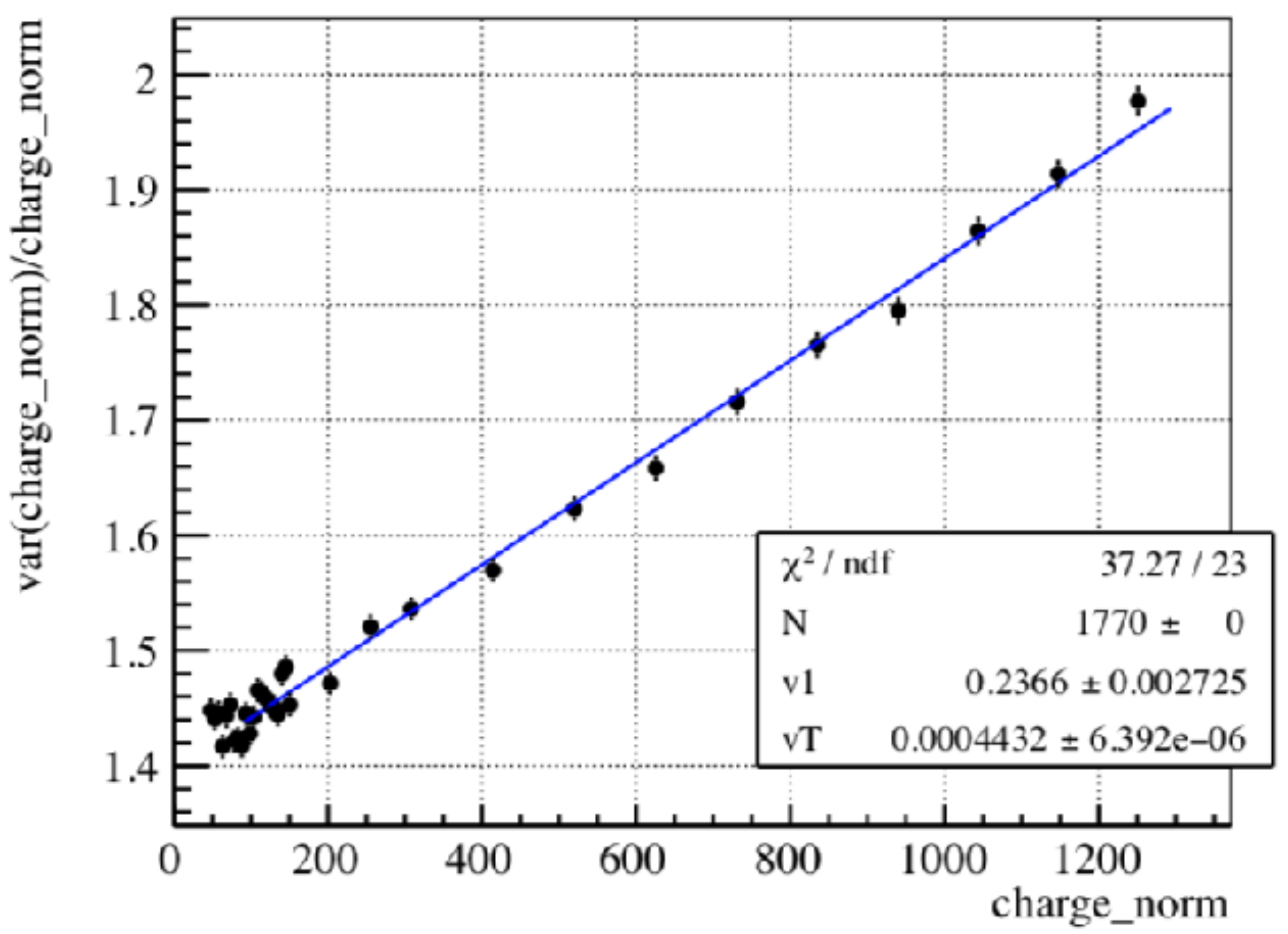
$$\mathrm{EToNpe}(E) = E \cdot \mathrm{Quenching}(k_b, E) \cdot \mathrm{LY_{ph}} \cdot \varepsilon_{\mathrm{scitillation}}(\mathrm{ph.} \to \mathrm{p.e.}) + \mathrm{N(Cherenkov\ ph.)} \cdot \varepsilon_{\mathrm{Cherenkov}}(\mathrm{ph.} \to \mathrm{p.e.})$$

$$\frac{\mathrm{charge}}{\mathrm{npe}} = \frac{p_{\mathrm{dn}} + (1 + p_{\mathrm{miscalib}}) \cdot \mathrm{npe} + p_{\mathrm{quadr}} \cdot \mathrm{npe}^{2}}{\mathrm{npe}}$$

$$\mathrm{NpeToNpmt(npe)} = \mathrm{NLiveT'} \cdot [1 - \exp(-\mu) \cdot (1 - pt \cdot \mu)]\,(1 - gc \cdot \mu)$$

$$\mu = \frac{\mathrm{npe}}{\mathrm{NLiveNpe'}} + \frac{N_{\mathrm{dark\ noise}}}{\mathrm{NLiveT'}}$$

Analytical Model — energy resolution model



$$\mathrm{var(charge\ )} = f_{\mathrm{eq}}(1+v_1)\cdot \mathrm{charge} \ + \frac{v_T}{2000}\cdot \mathrm{charge}\ ^2$$

- If you do not apply non-linearity correction, resolution dependence can be parameterized with physics parameter

Analytical Model — mono-energetic line shape

- Modified Gaussian

$$f(Q;\mu) = \frac{1}{\sqrt{2\pi}\sqrt{a+b\cdot Q}}\exp(-\frac{(Q-\mu+b)^2}{2(a+b\cdot Q)})$$

- Generalized gamma

$$f(Q;\mu) = \frac{2\beta^{\alpha}\mu^{2\alpha-1}}{\Gamma(\alpha)}\exp(-\beta\mu^2)$$

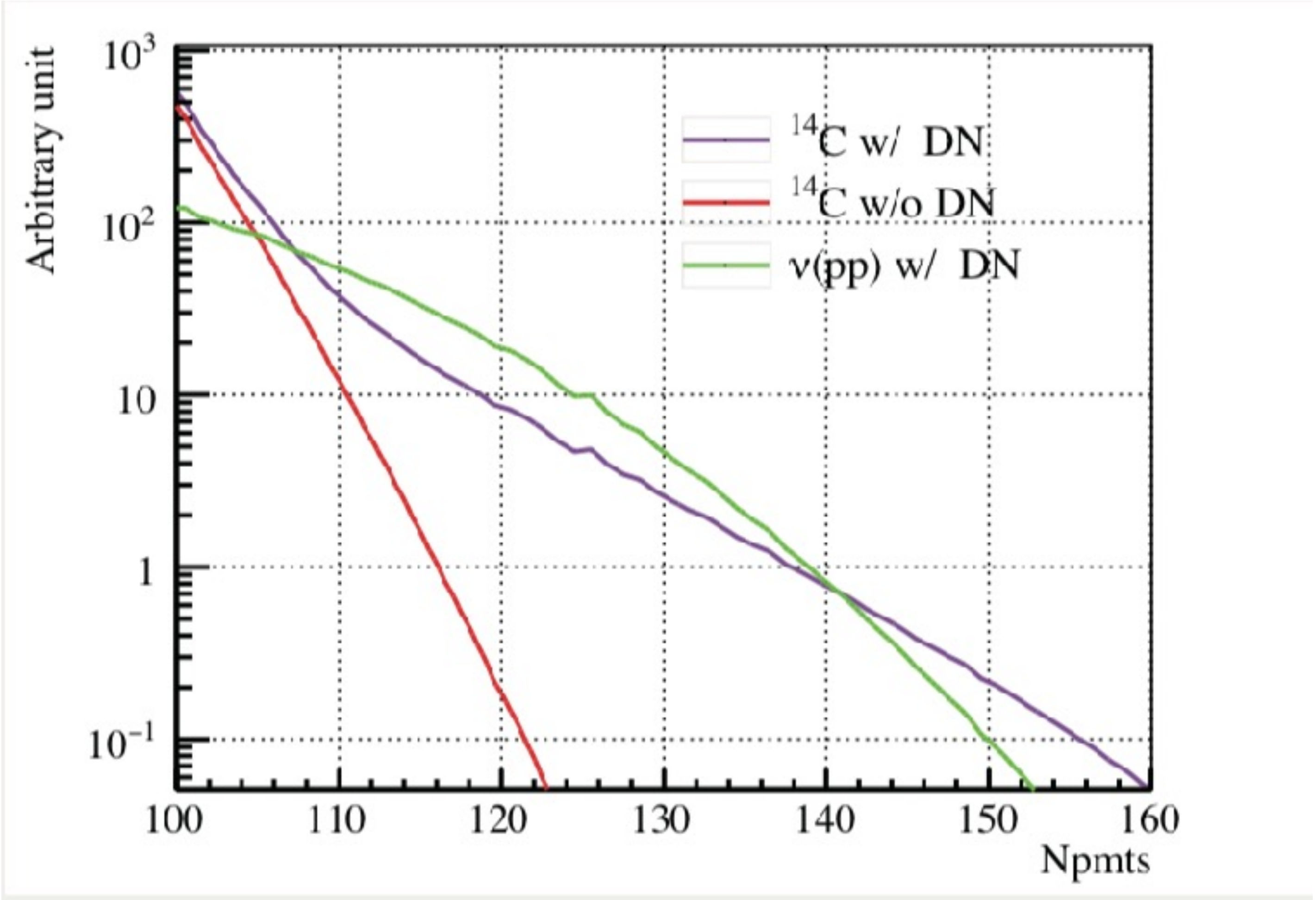
- Scaled Poisson

$$\text{Poisson}(x;\mu) = \frac{\mu^k}{\Gamma(k+1)}e^{-\mu}$$

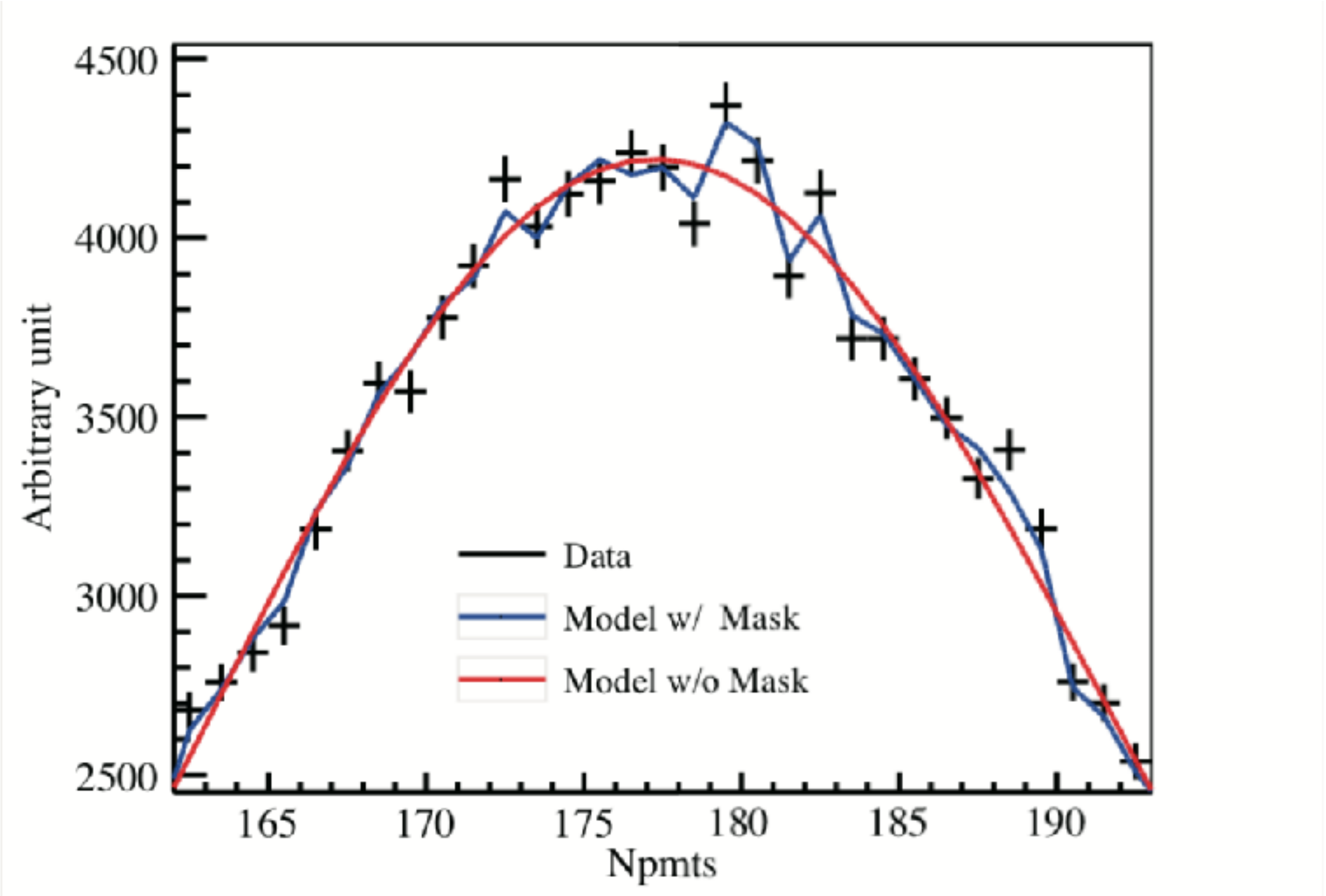
$$\text{RawSP}(x;\mu,\text{var}) = \frac{\text{Poisson}(\frac{x}{s},\frac{\mu}{s})}{s} \quad s = \frac{\text{var}}{\mu}$$

$$\text{SP}(x;\mu,\text{var}) = \frac{\text{RawSP}(x) + 4\cdot\text{RawSP}(x+0.5) + \text{RawSP}(x+1)}{6}$$

Analytical Model — More details



- Pile-up effect: Hits from more than one source piled up.
  - Dark noise, ^{14}C
  - Crucial background for *pp* analysis
- Solution: “Dark noise convolution”

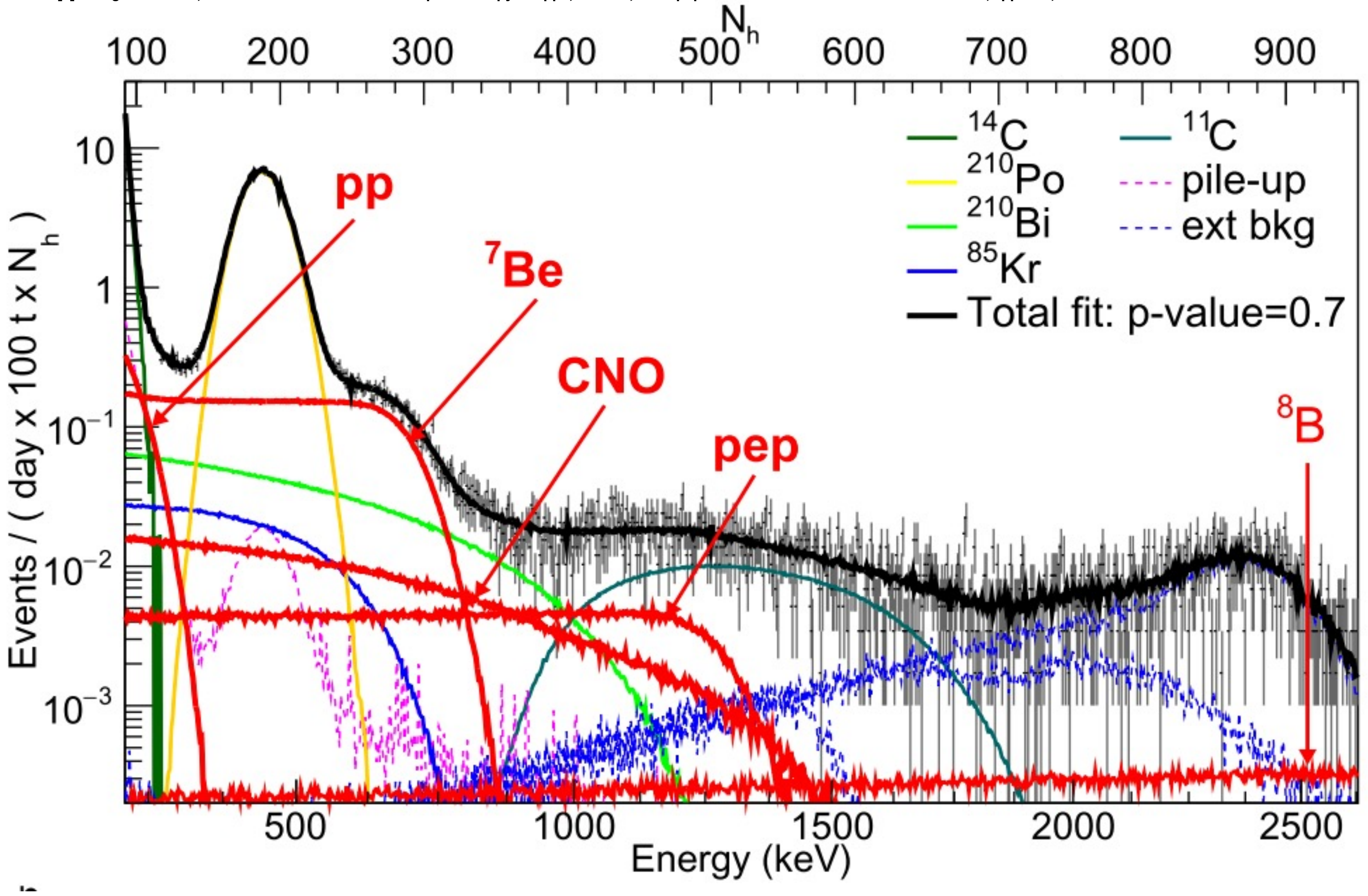


- Npmt is an integer variable
- Spikes appeared after normalization 2000/NLive
- **Solution: Apply “mask”**

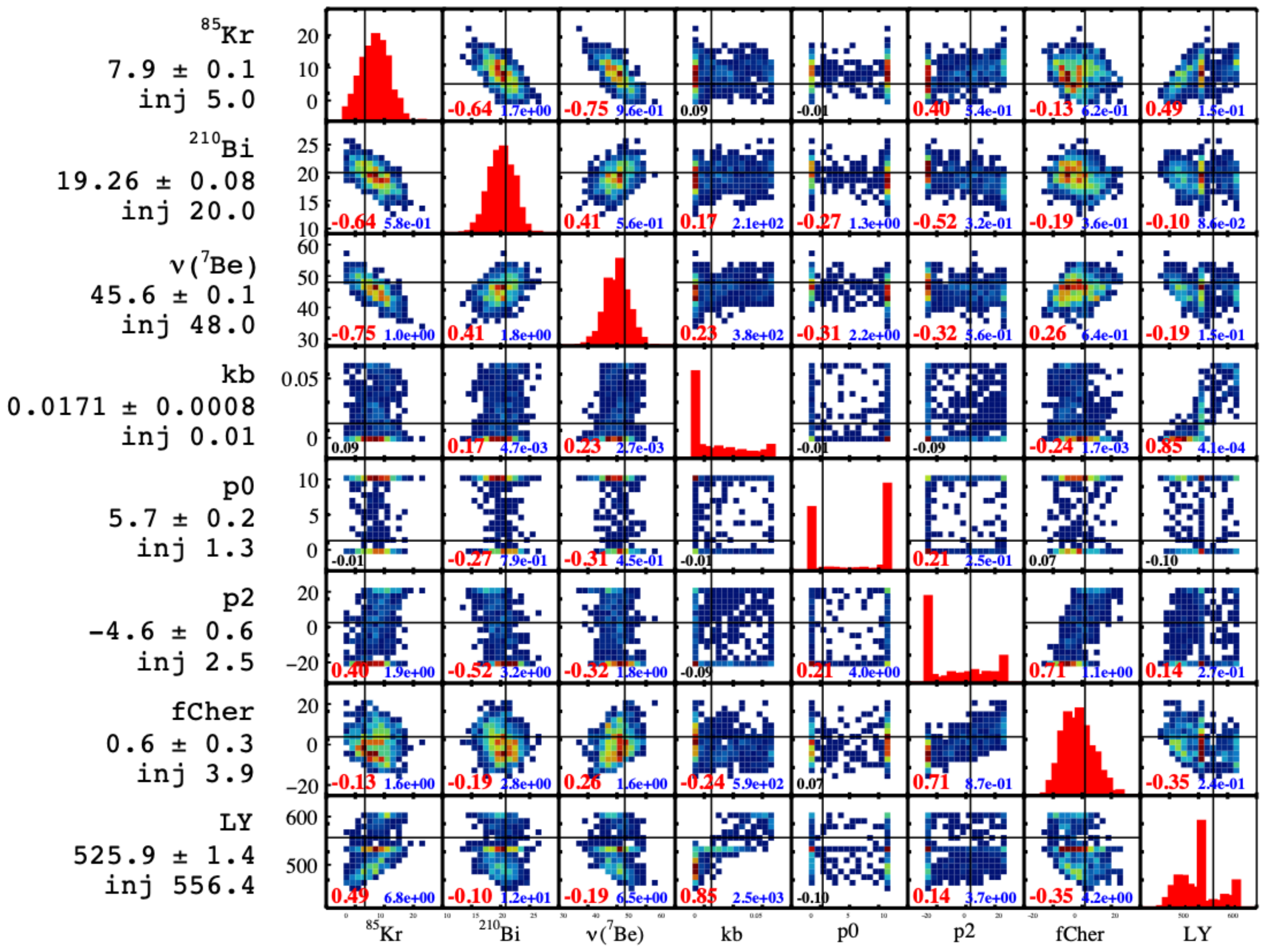
Results: correlation with NL/resolution

- Using full analytical response function, we can see the correlation with detector responses

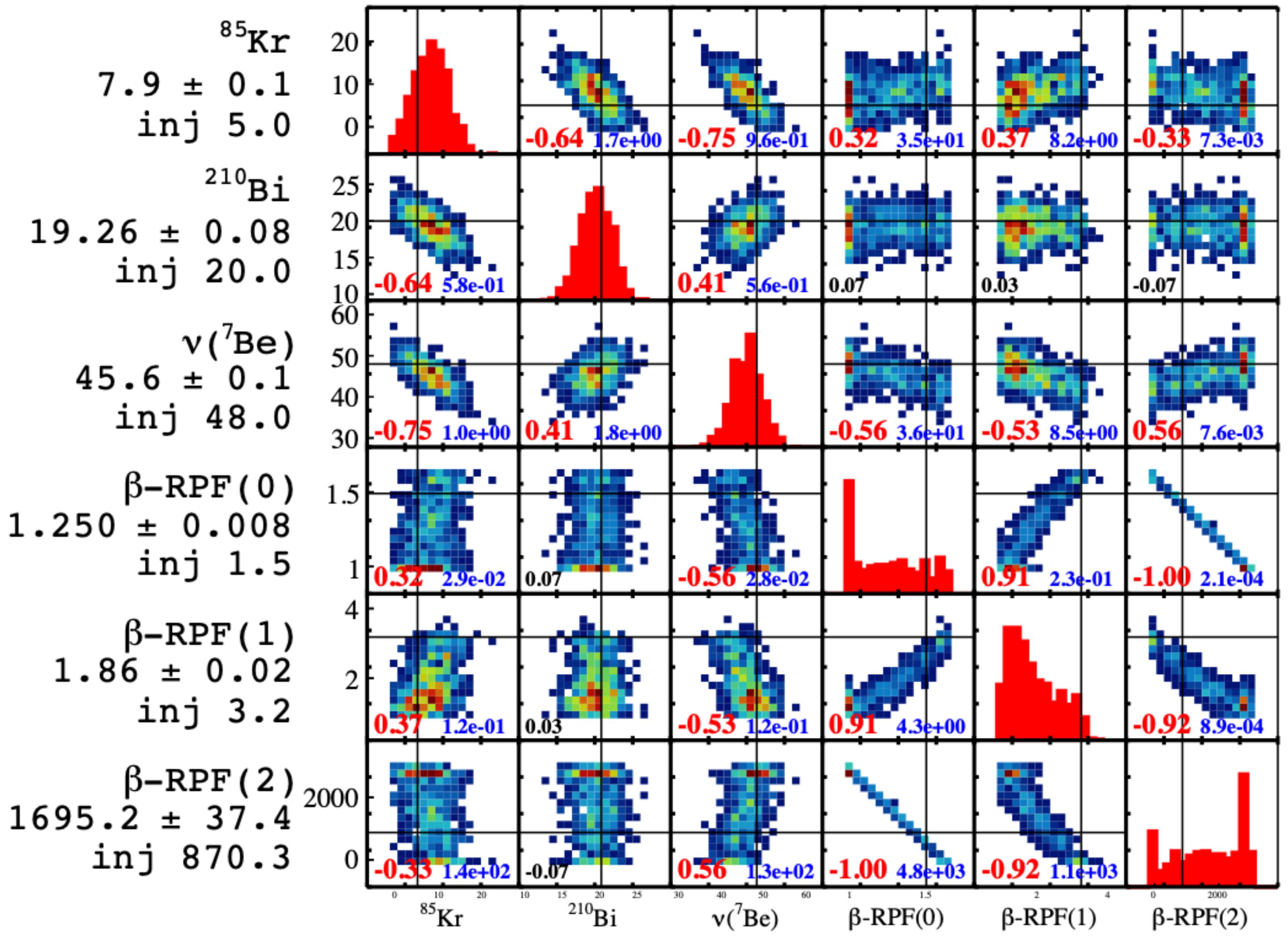
[1] M. Agostini *et al.*, “First Simultaneous Precision Spectroscopy of \$pp\$, \$^7\$Be, and \$pep\$ Solar Neutrinos with Borexino Phase-II,” pp. 1–8, Jul. 2017.



correlation with NL



correlation with res



GooStats: multivariate fitting package

- Speed multivariate up fitting with GPU.

May 19, 2018 **Software** **Open Access**

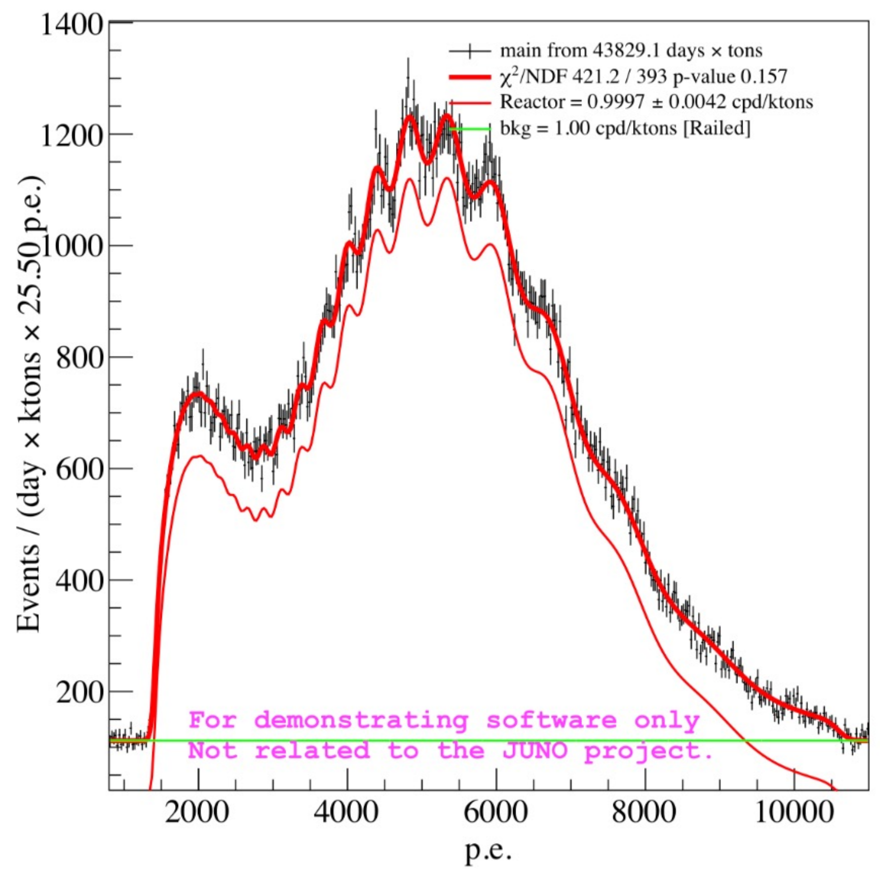
GooStats, a multivariate spectrum fitting analysis package for particle physics accelerated by graphic processing units

Ding, Xuefeng

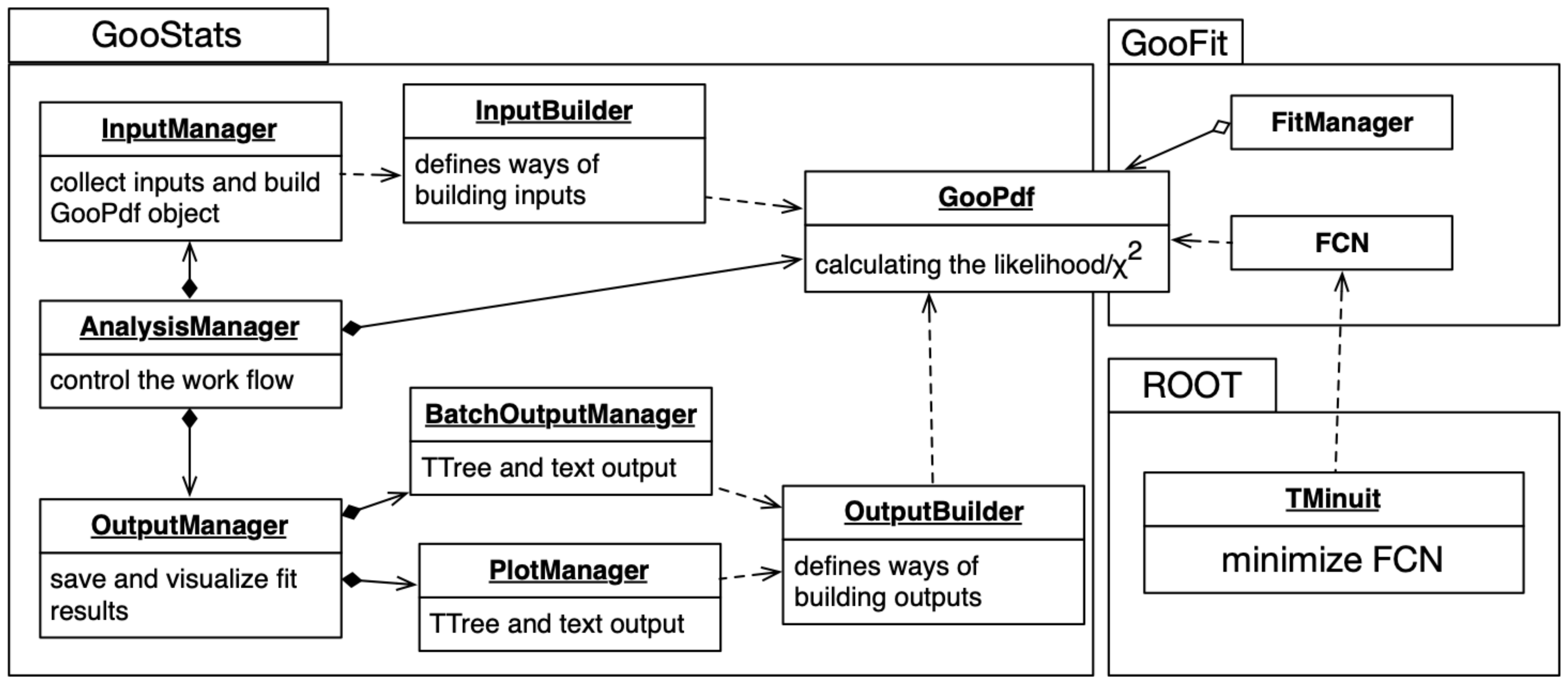
Contact person(s)

Ding, Xuefeng

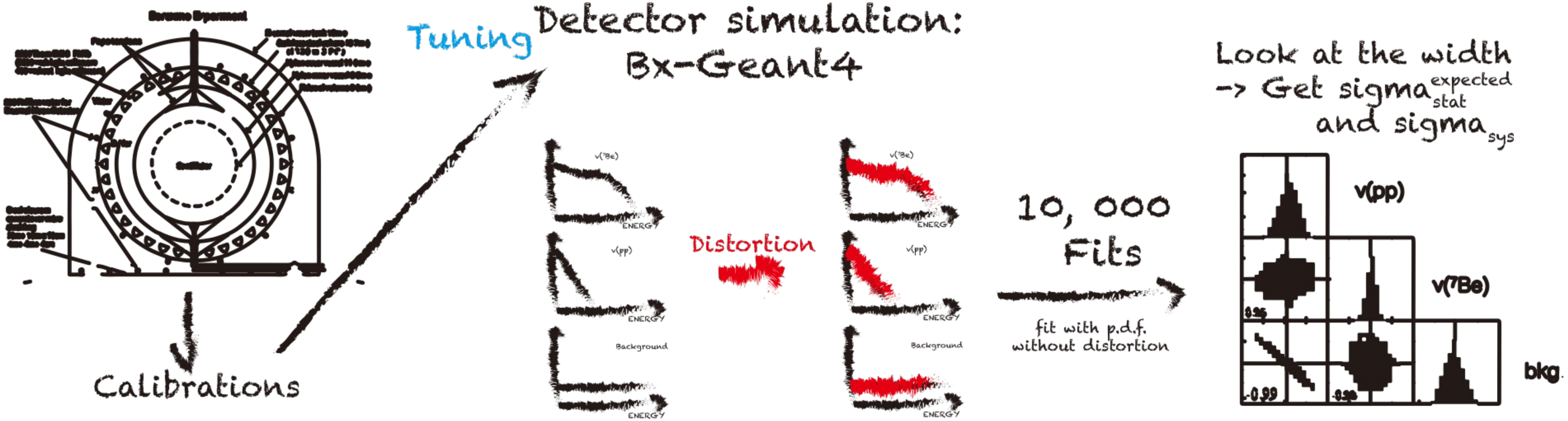
Publication date:
May 19, 2018
DOI:
DOI 10.5281/zenodo.1217007
Keyword(s):
multivariate GPU CUDA Fitting
Related identifiers:
Identical to:
https://github.com/GooStats/GooStats/releases/tag/v1.2.0




```
TFile**         test_tree.root
 TFile*         test_tree.root
  KEY: TTree    fit_result;1    Fit result of GooStats
root [2] fit_result->Show(0)
======> EVENT:0
 default.NReactor = 3.02987
 default.NReactor_err = 0.0159146
 default.Nbkg     = 1.02405
 default.Nbkg_err = 0.0162459
 default.U235     = 0.5
 default.U235_err = 0
 default.U238     = 0.2
 default.U238_err = 0
 default.Pu239    = 0.1
 default.Pu239_err = 0
 default.U241     = 0.2
 default.U241_err = 0
 default.LY       = 1300
 default.LY_err   = 0
 default.qc1      = 2.78788
 default.qc1_err  = 0
 default.qc2      = -0.528003
 default.qc2_err  = 0
 default.v1       = 0.3
 default.v1_err   = 0
 default.vT       = 5
 default.vT_err   = 0
 default.Reactor_dEvis = 1078.28
 default.Reactor_dEvis_err = 13.2291
 chi2             = 390.448
 NDF              = 397
 likelihood       = 1883.96
```



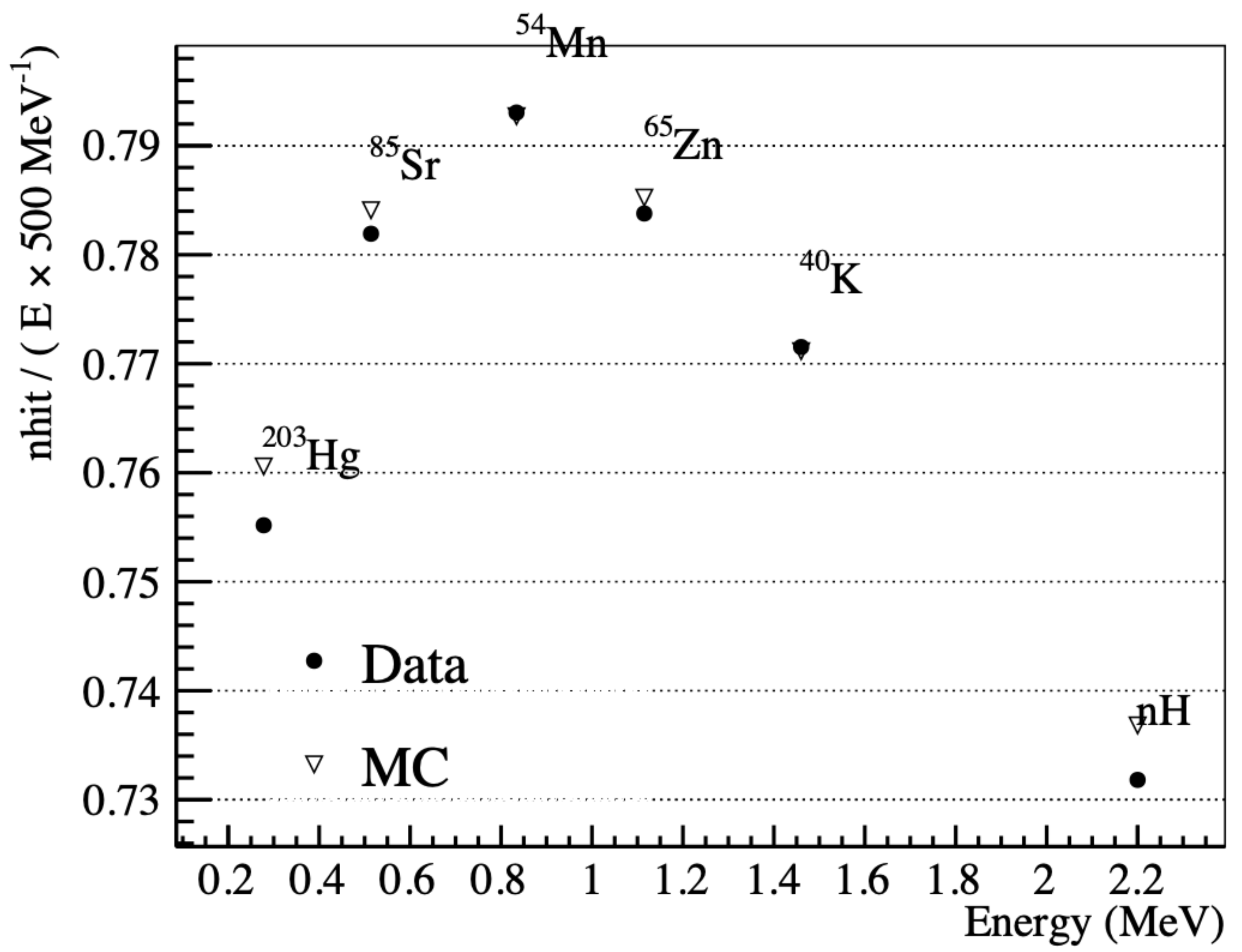
Method 2: Monte Carlo method

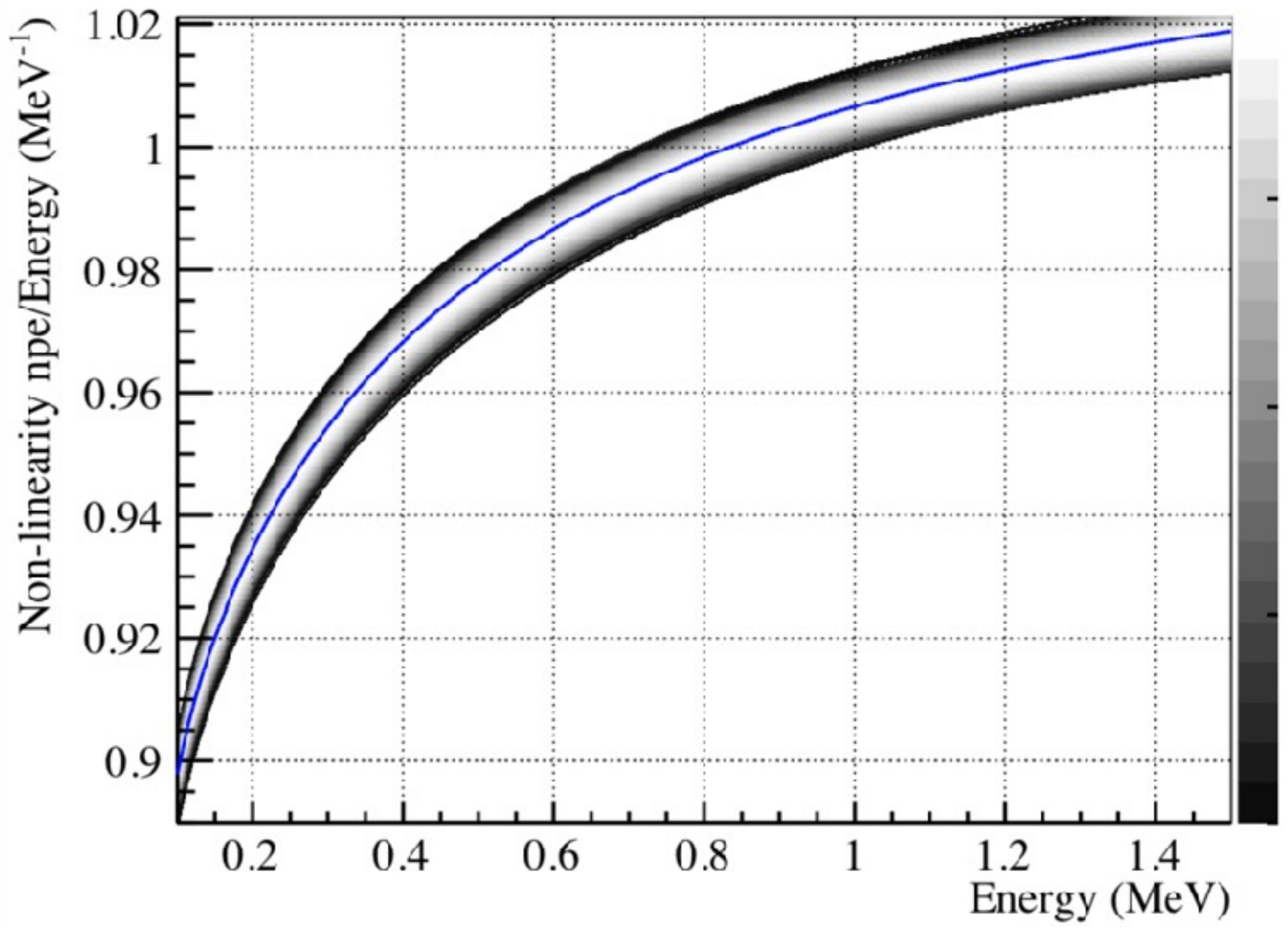


- pseudo-experiment spectra without distortion —> **statistical sensitivity**
- pseudo-experiment spectra with distortion —> **statistical** ⊕ **systematic**

Method 2 : Energy non-linearity related systematics

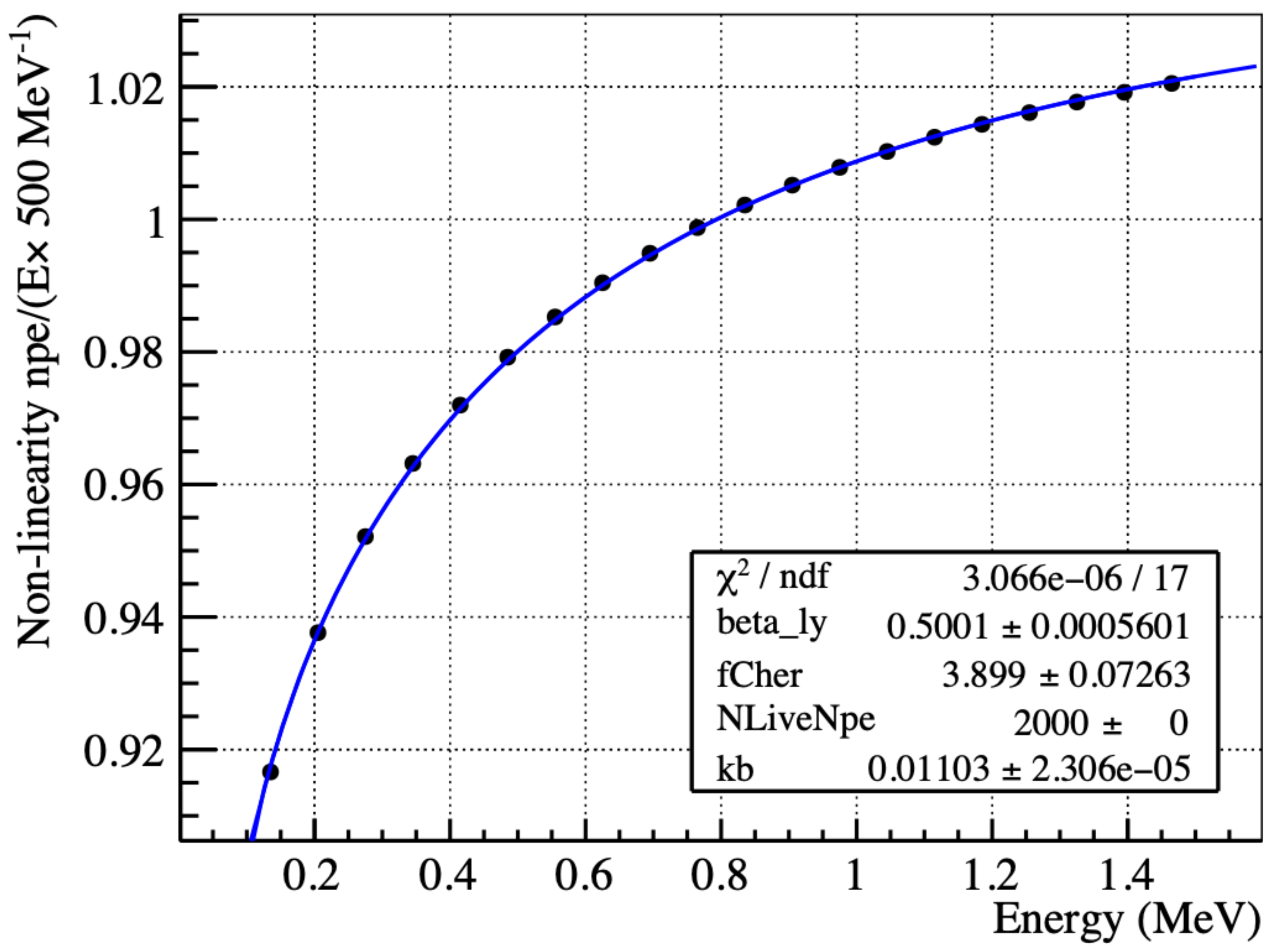
- **Determine 1-σ band of allowed NL**
  - Precision of MC (γ)
  - Assume same Precision of e^-/e^+
- **Generate the ensemble of models**
  - Find a presentation, say, E' = E (a+bE)
  - Decide the distribution of coordinate
  - Generate pseudo-experiment spectra and verify the density plot of sampled models

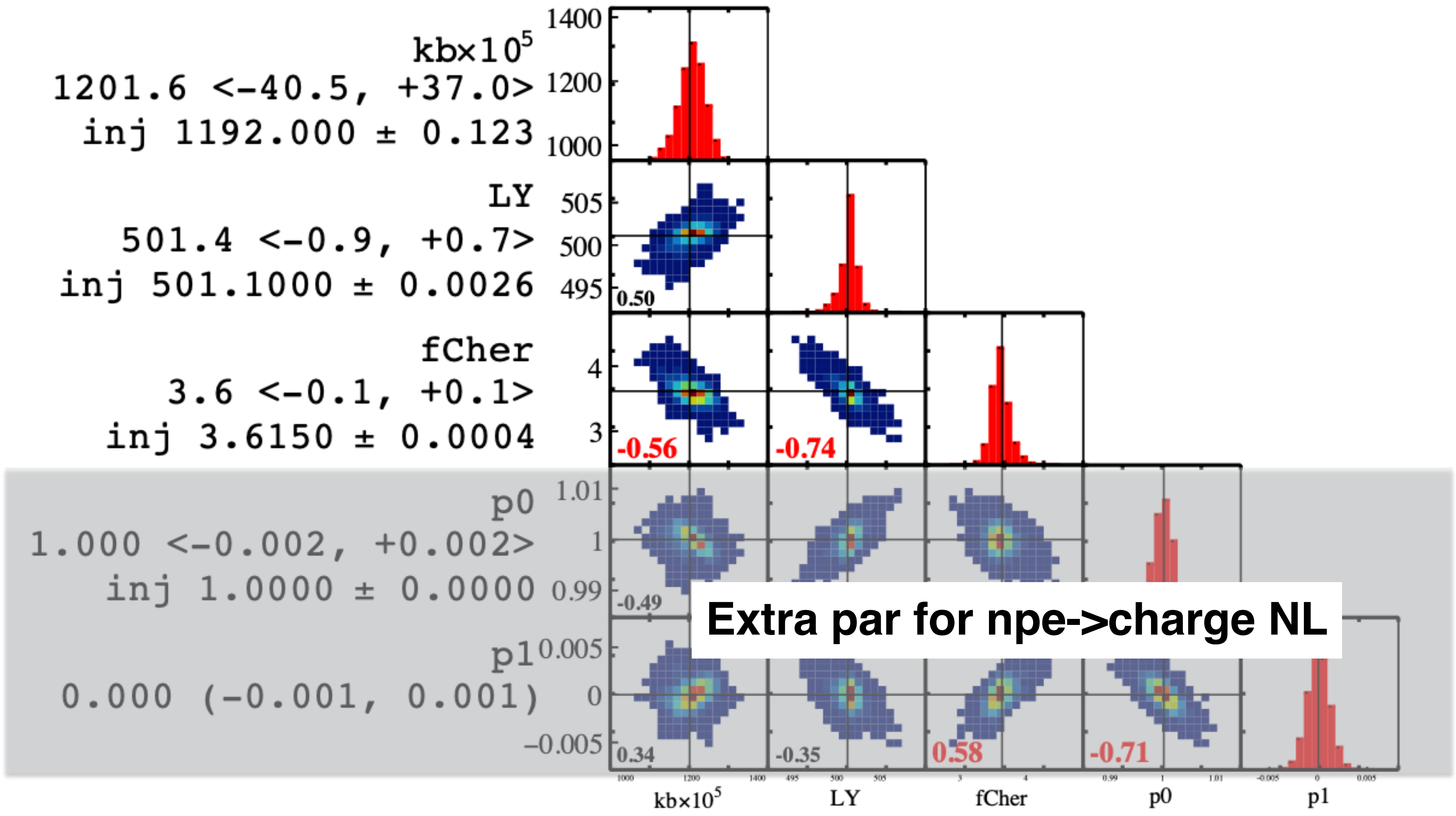




Phase-space of NL model ensemble

- Generate NL: **(MC NL)x(a+bE)**, vary **(a,b)**
- Fit NL with mu = **LY***[Qch(**kb**,E) + **fCher***Cherenkov(E)]
- Our ensemble covers certain phase-space of (kb,LY,fCher)





Summary: analytical vs MC
MC need a lot of fitting

So, GPU fitter would be nice

A few numbers..

- **For analytical pmt fitting.. how much speed up?**

	original fitter	GooStats	speed up
single fit + dn	**~ 1 hour**	**~4 seconds**	x600
complementary + dn	**~ 2 hours**	**~7 seconds**	x1000
dn+comp.+MV	unknown (**> 1 week**)	**~5 minutes**	> x2000

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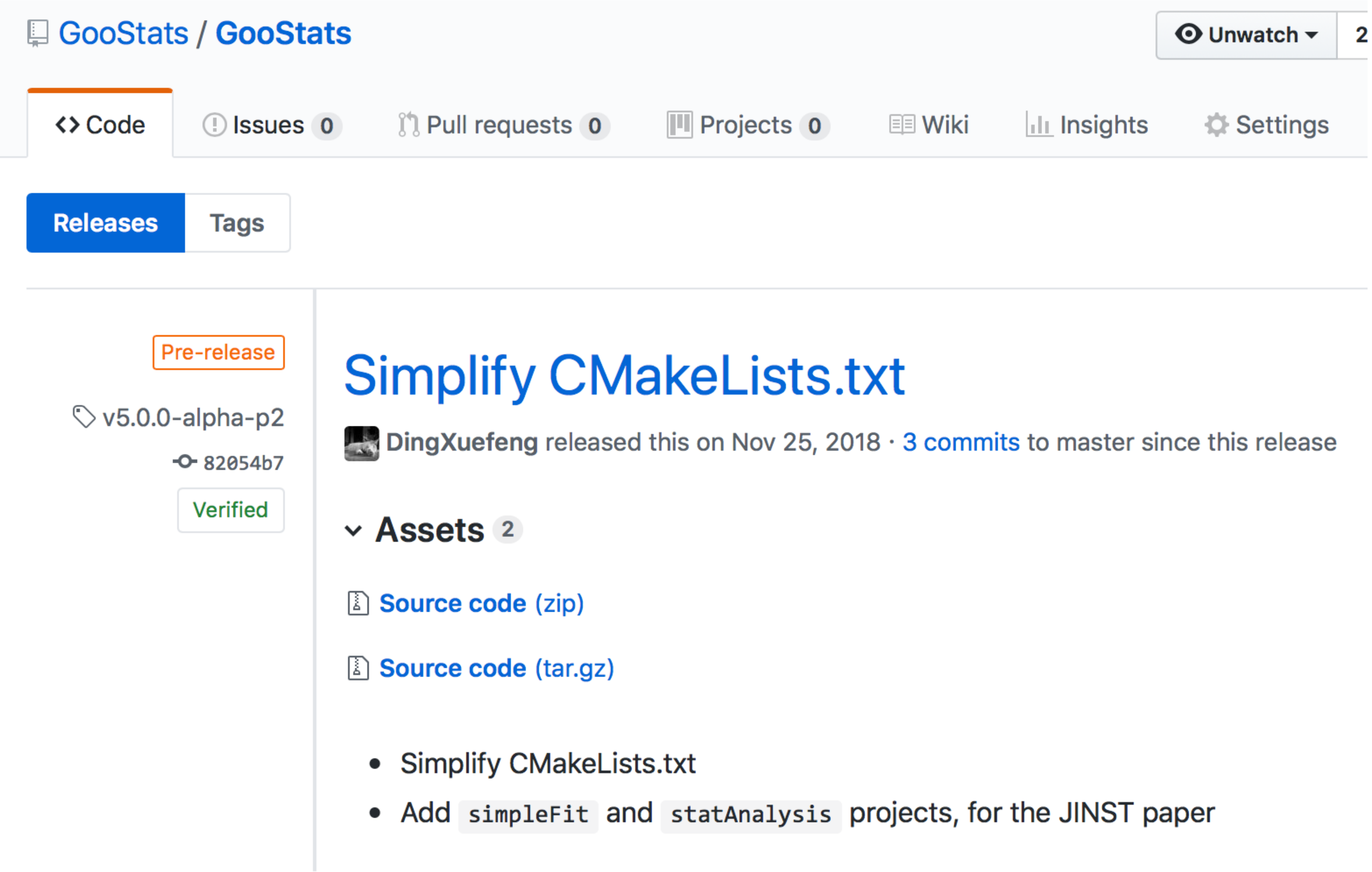
History & path

- 2016 Feb. Ilia: I added MINOS option so we can get precise error but it takes 8 hours.. me: hmm??
- 2017 New Year's Eve, GooStats v0.001
- 2017 Feb. 03 bx-GooStats-charge
- 2017 Mar. 19 bx-GooStats-MC-MV
- 2017 Mar. 23 bx-GooStats-npmt
- 2017 April Alina, Omer et al start to produce physics result with bx-GooStats

GooStats hosted on GitHub

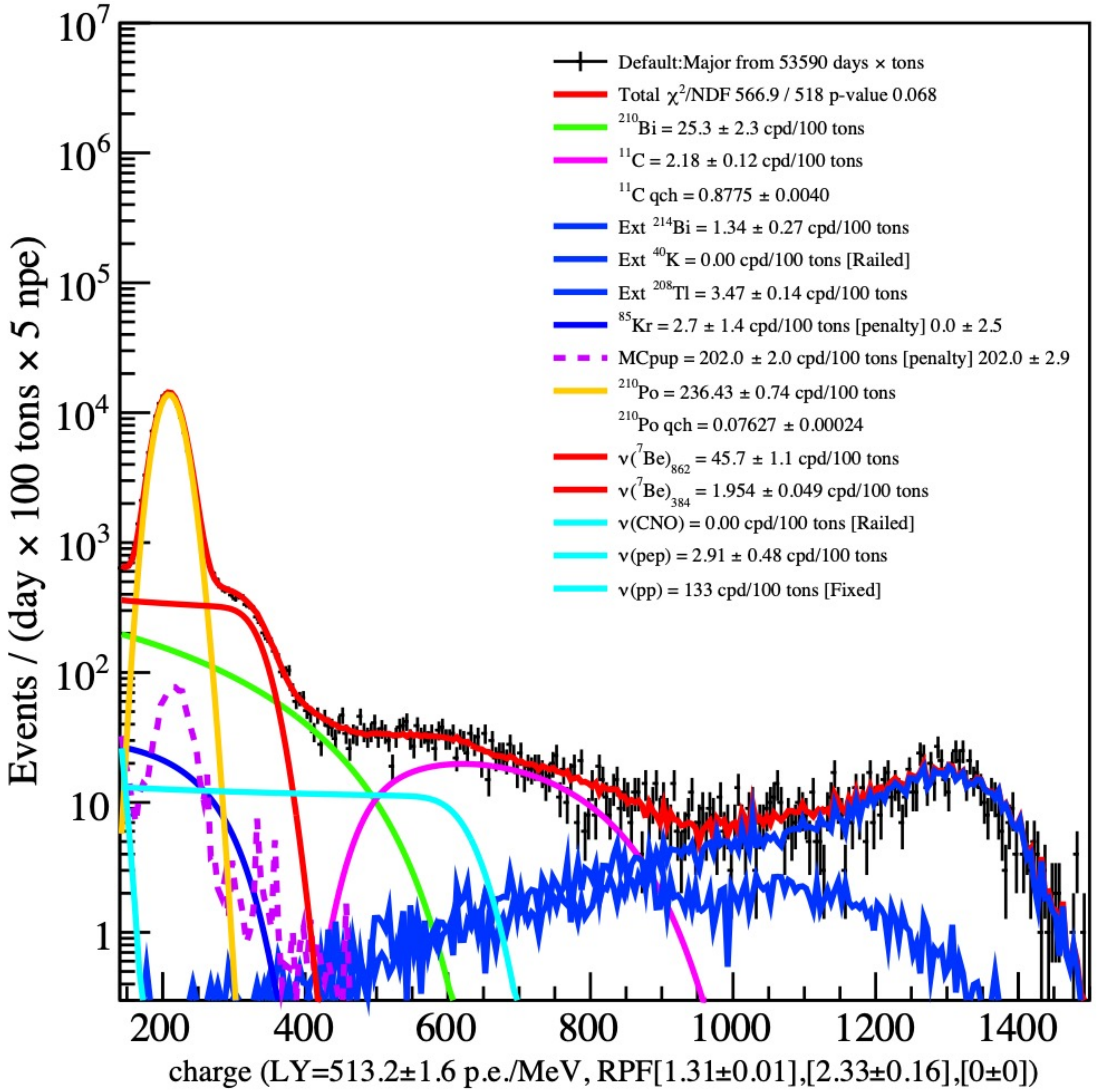
https://github.com/GooStats/GooStats.git

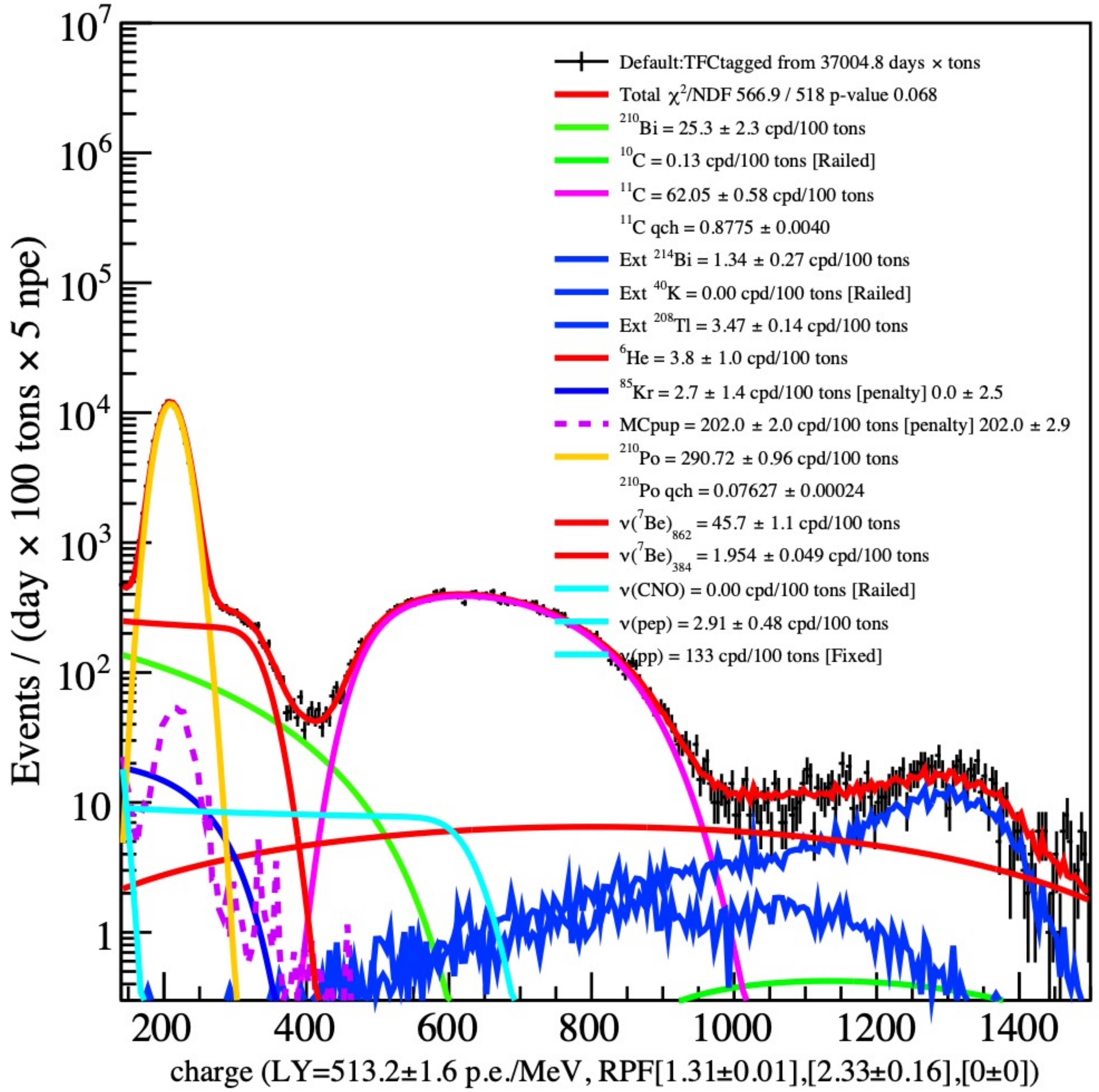


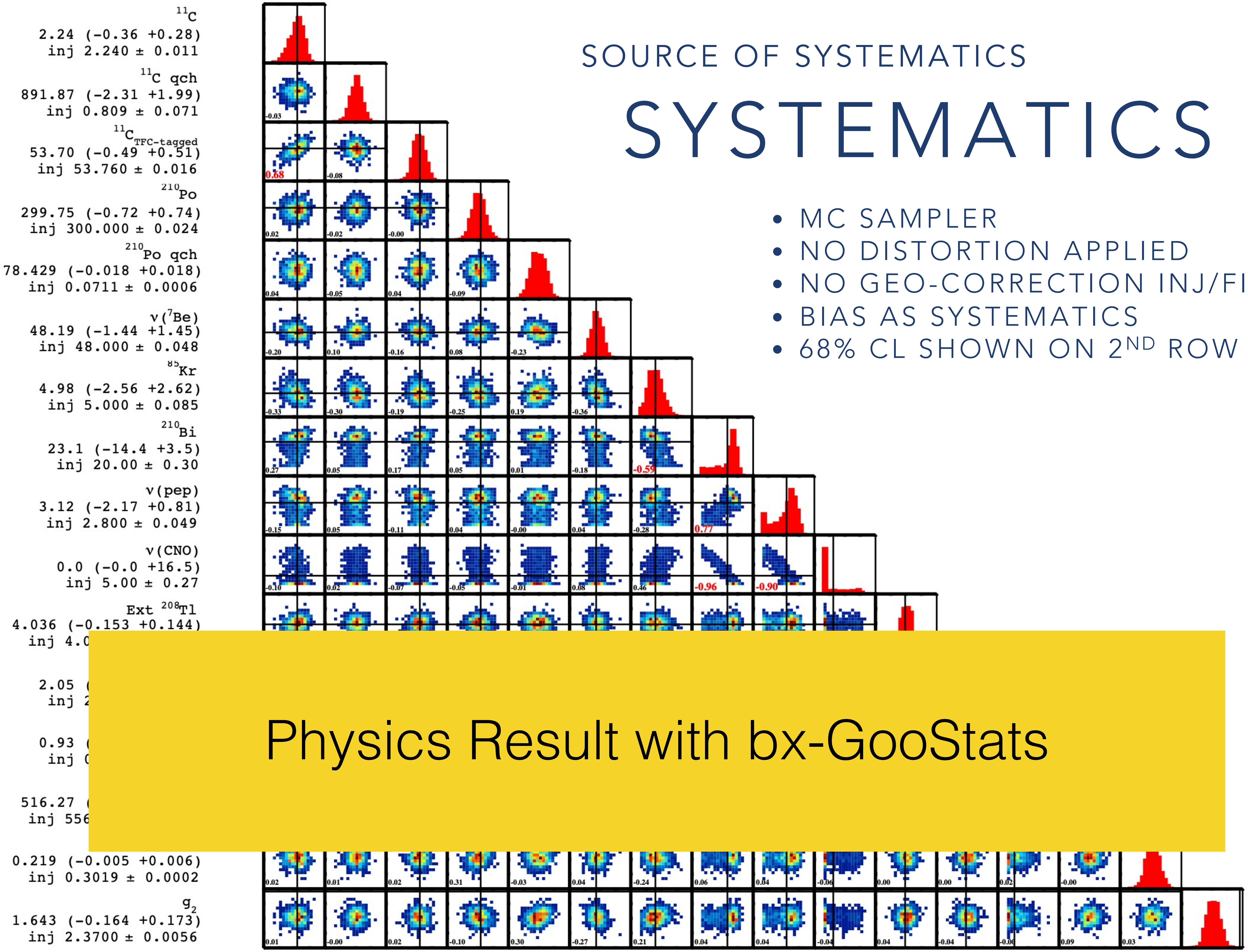
Git version tree

```
* | d73baa5 - (3 months ago) fix the logic in use_MC - Xuefeng Ding
* |   09a7ffd - (3 months ago) Merge branch 'MVfit_dev' into dingxf_dev - Xuefeng Ding
|\ \
| * | fc455c0 - (3 months ago) enable assert by building Debug. update startbin.. etc - Xuefeng Ding
| * | 4ec0eb4 - (3 months ago) bug fix: could not use static.. fix wrong start/end bin - Xuefeng Ding
| * | c8c08e4 - (3 months ago) now the logic is correct.. - Xuefeng Ding
| * | 3b6df49 - (3 months ago) bug fix: use memcp to symbol.. - Xuefeng Ding
| * | 12c2f9e - (3 months ago) bug fix: return -log(L). bug fix: MEMCPY_TO_SYMBOL is operating on symbol. you cannot pass th
* | |   c31cd18 - (3 months ago) Merge branch 'MVfit_dev' into dingxf_dev - Xuefeng Ding
|\ \ \
| |/ /
| * | 582d6e3 - (3 months ago) final bug fix. constant symbol cannot by passed. now you can run it - Xuefeng Ding
| * | 616ab96 - (3 months ago) can compile, yet cannot run. invalid device symbol - Xuefeng Ding
| * | cd67d09 - (3 months ago) add more infrustructure - Xuefeng Ding
| * |   3939786 - (3 months ago) Merge branch 'master' into MVfit_dev - Xuefeng Ding
| |\ \
| | |/
| * |   54cc966 - (3 months ago) Merge branch 'master' into MVfit_dev - Xuefeng Ding
| |\ \
| * | | 3b2c9a9 - (3 months ago) add infrustructure , yet cannot compile - Xuefeng Ding
| * | | 5085285 - (3 months ago) can compile - Xuefeng Ding
| * | |   845992f - (3 months ago) Merge branch 'master' into MVfit_dev - Xuefeng Ding
| |\ \ \
| * | | | 6fc1364 - (3 months ago) add MVPdf - Xuefeng Ding
| * | | | cb15b57 - (3 months ago) add MV fit - Xuefeng Ding
* | | | | b42b811 - (3 months ago) remove comparison with the old sun - Xuefeng Ding
| |_|_|/
|/| | |
* | | | a240d30 - (3 months ago) update ChangeLog - Xuefeng, Ding
* | | | d95969a - (3 months ago) update install_AgostiniPlot.sh - Xuefeng Ding (20170325_cvs_commit)
* | | | 95d287f - (3 months ago) update the instructions - Xuefeng Ding
```

Physics Result with bx-GooStats







SOURCE OF SYSTEMATICS

SYSTEMATICS

- MC SAMPLER
- NO DISTORTION APPLIED
- NO GEO-CORRECTION INJ/FIT
- BIAS AS SYSTEMATICS
- 68% CL SHOWN ON 2ND ROW

Physics Result with bx-GooStats

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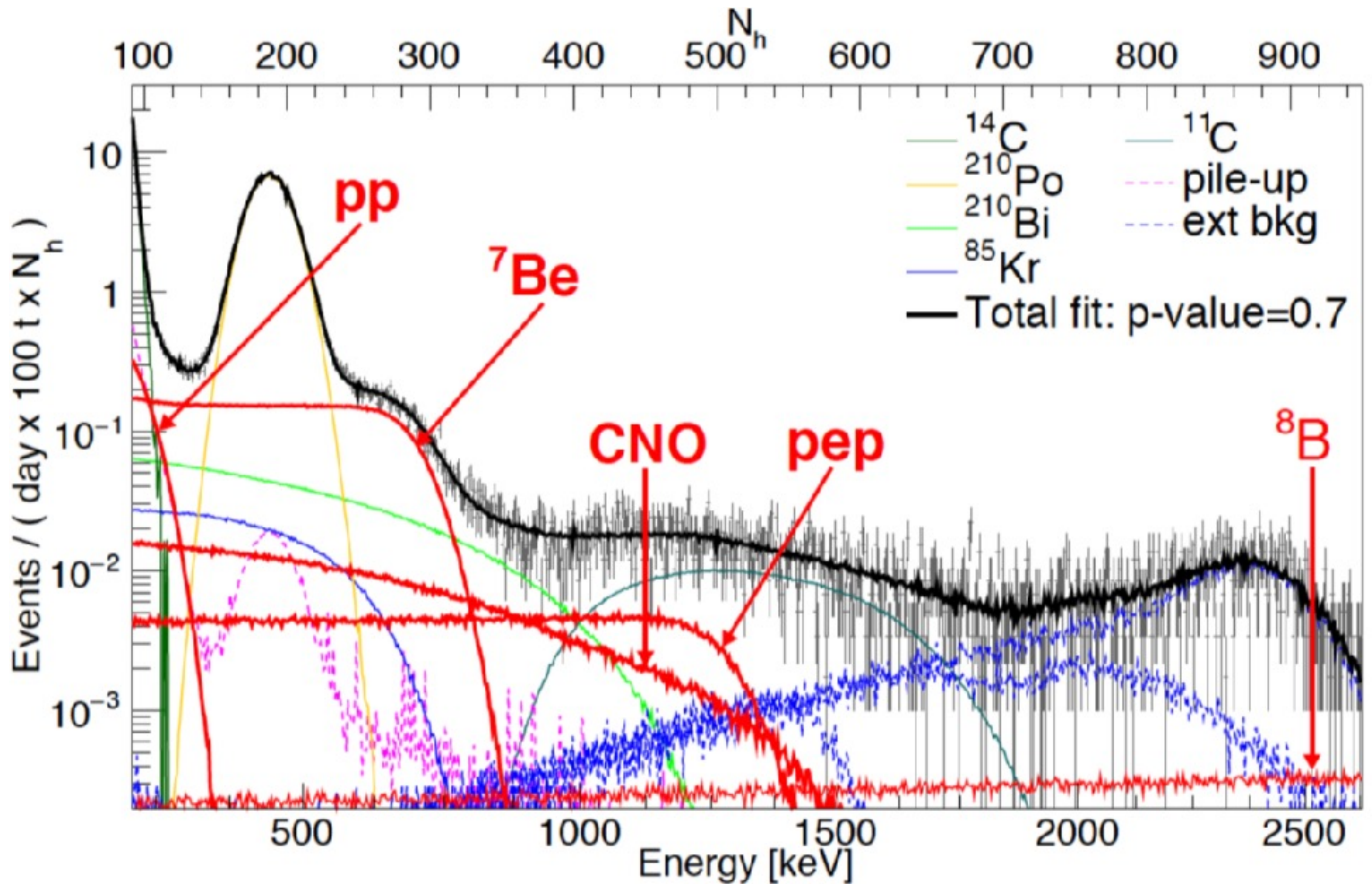
Contributions to **borex_phys** cluster

- **``AgosiniPlot'' correlation test**
  - 1000 fit x ~60 test (charge) = 60 day x 20 CPU
- **Normal fit**
  - Julich group: >4000 Analytical MultiVariate Fit
  - Pros: See result in 10 seconds
  - Cons: No time to eat sandwiches and watch Youtube anymore..

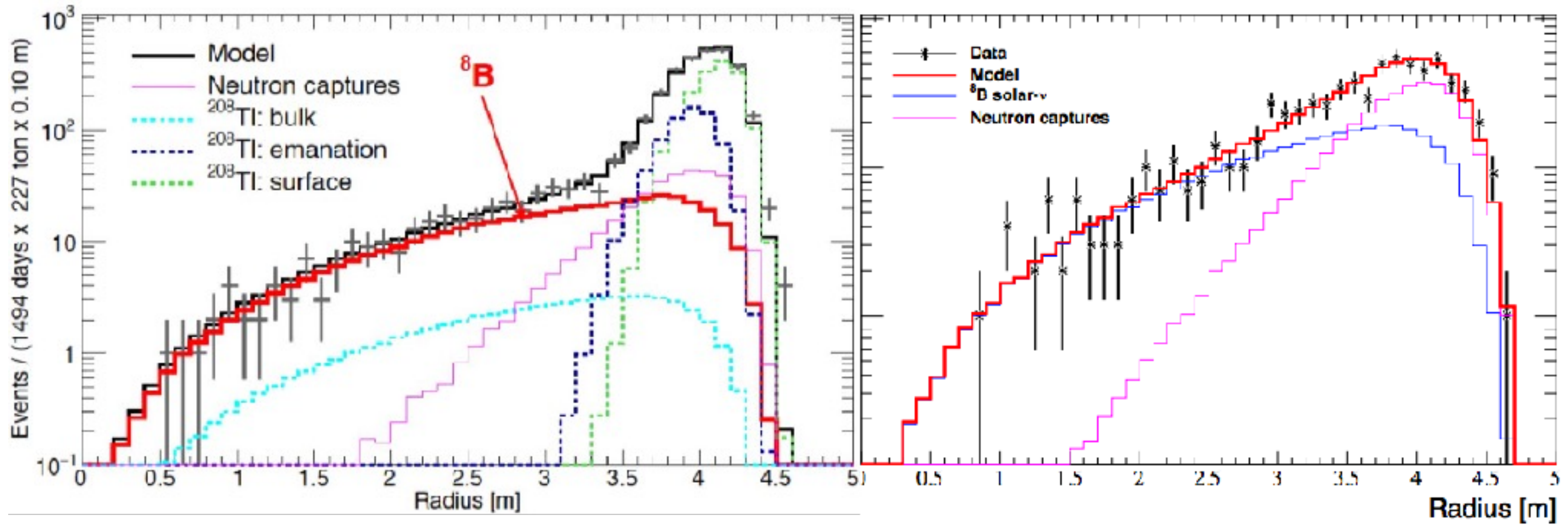
Borexino Phase-II result

Analysis Overview



Low Energy Region (LER)

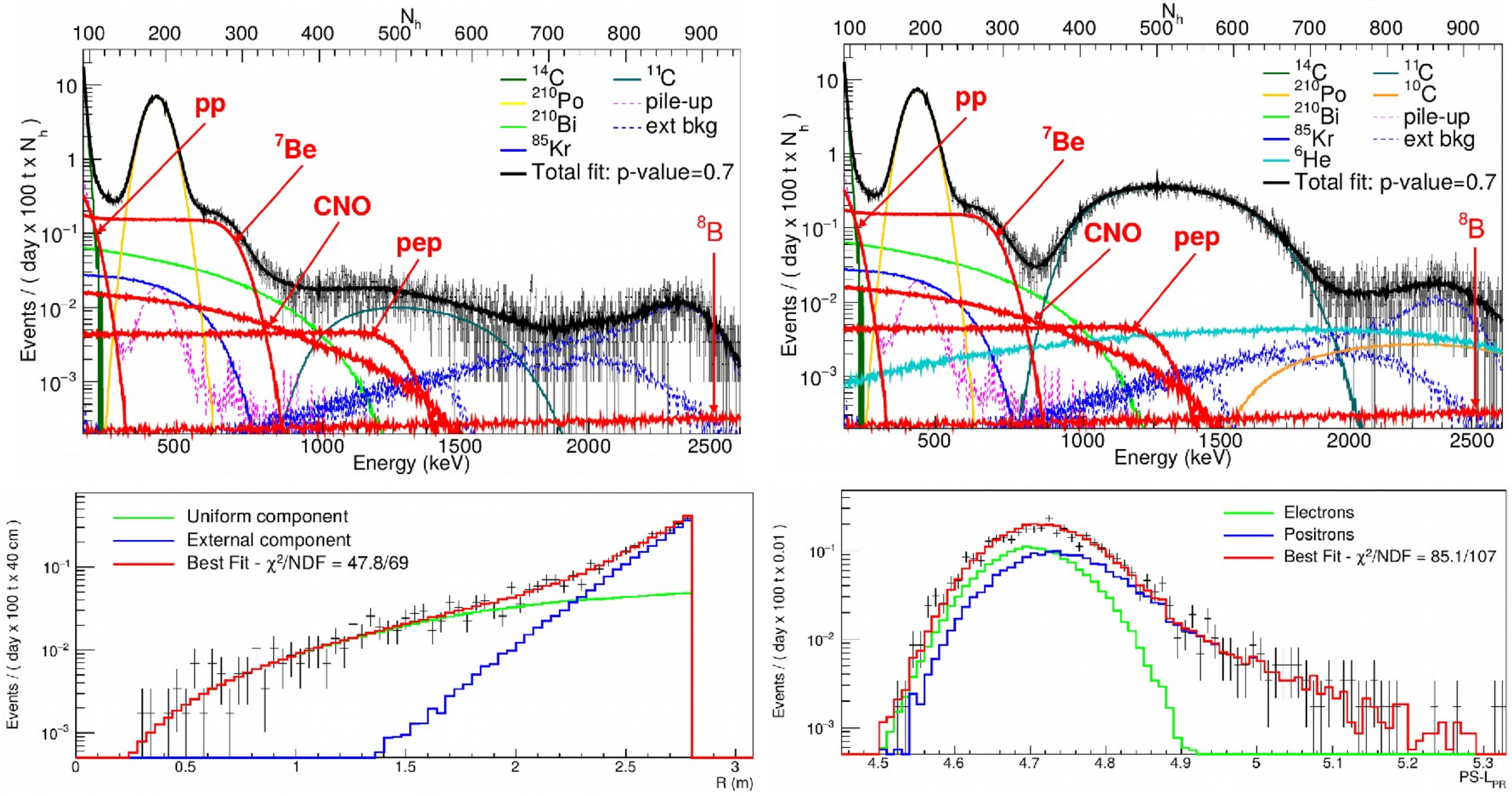
- **MultiVariate fit**
  - **Energy + Radius + PS**
- **0.19 ~ 2.93 MeV**



How Energy Region (HER)

- **Radial spectral fit**
- HER-I **3.2~5.7 MeV**
- HER-II **5.7~17 MeV**

LER Highlight: Multi-Variate analysis



$$\mathcal{L}_{\mathrm{MV}}\left(\vec{\theta}\right) = \mathcal{L}_{\mathrm{TFC-sub}}\left(\vec{\theta}\right) \cdot \mathcal{L}_{\mathrm{TFC-tagged}}\left(\vec{\theta}\right) \cdot \mathcal{L}_{\mathrm{RD}}\left(\vec{\theta}\right) \cdot \mathcal{L}_{\mathrm{PS}}\left(\vec{\theta}\right)$$

- Scaling factor introduced to remove bias.

[1] S. Davini, "Measurement of the pep and CNO solar neutrino interaction rates in Borexino-I," Eur. Phys. J. Plus, vol. 128, no. 8, p. 89, Aug. 2013.

Systematic uncertainties

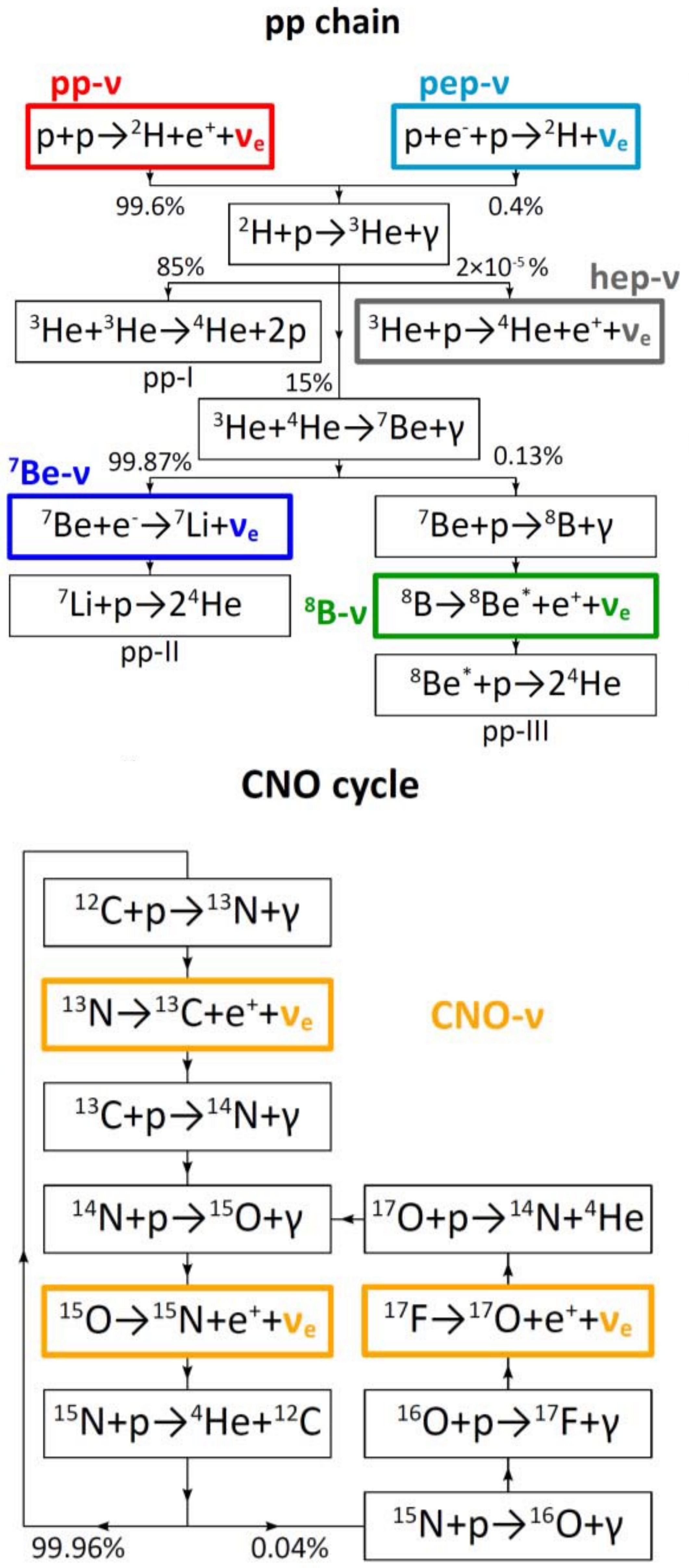
Systematic errors in the *LER* analysis						
	pp **neutrinos**		**7Be neutrinos**		***pep*** **neutrinos**	
Source of uncertainty	**-%**	**+%**	**-%**	**+%**	**-%**	**+%**
Fit models (see text)	-4.5	+0.5	-1.0	+0.2	-6.8	+2.8
Fit method (analytical/MC)	-1.2	+1.2	-0.2	+0.2	-4.0	+4.0
Choice of the energy estimator	-2.5	+2.5	-0.1	+0.1	-2.4	+2.4
Pile-up modeling	-2.5	+0.5	0	0	0	0
Fit range and binning	-3.0	+3.0	-0.1	+0.1	-1.0	+1.0
Inclusion of the 85Kr constraint	-2.2	+2.2	0	+0.4	-3.2	0
Live Time	-0.05	+0.05	-0.05	+0.05	-0.05	+0.05
Scintillator Density	-0.05	+0.05	-0.05	+0.05	-0.05	+0.05
Fiducial Volume	-1.1	+0.6	-1.1	+0.6	-1.1	+0.6
Total systematics (%)	**-7.1**	**+4.7**	**-1.5**	**+0.8**	**-9.0**	**+5.6**

Systematic errors in the *HER* analysis (8B neutrinos)						
	HER-I		***HER-II***		***HER*** **(tot)**	
Source of uncertainty	**-%**	**+%**	**-%**	**+%**	**-%**	**+%**
Target Mass	-2.0	+2.0	-2.0	+2.0	-2.0	+2.0
Energy scale	-0.5	+0.5	-4.9	+4.9	-1.7	+1.7
z-cut	-0.7	+0.7	0	0	-0.4	+0.4
Live time	-0.05	+0.05	-0.05	+0.05	-0.05	+0.05
Scintillator density	-0.05	+0.05	-0.05	+0.05	-0.05	+0.05
Total systematics (%)	**-2.2**	**+2.2**	**-5.3**	**+5.3**	**-2.7**	**+2.7**

LER

HER

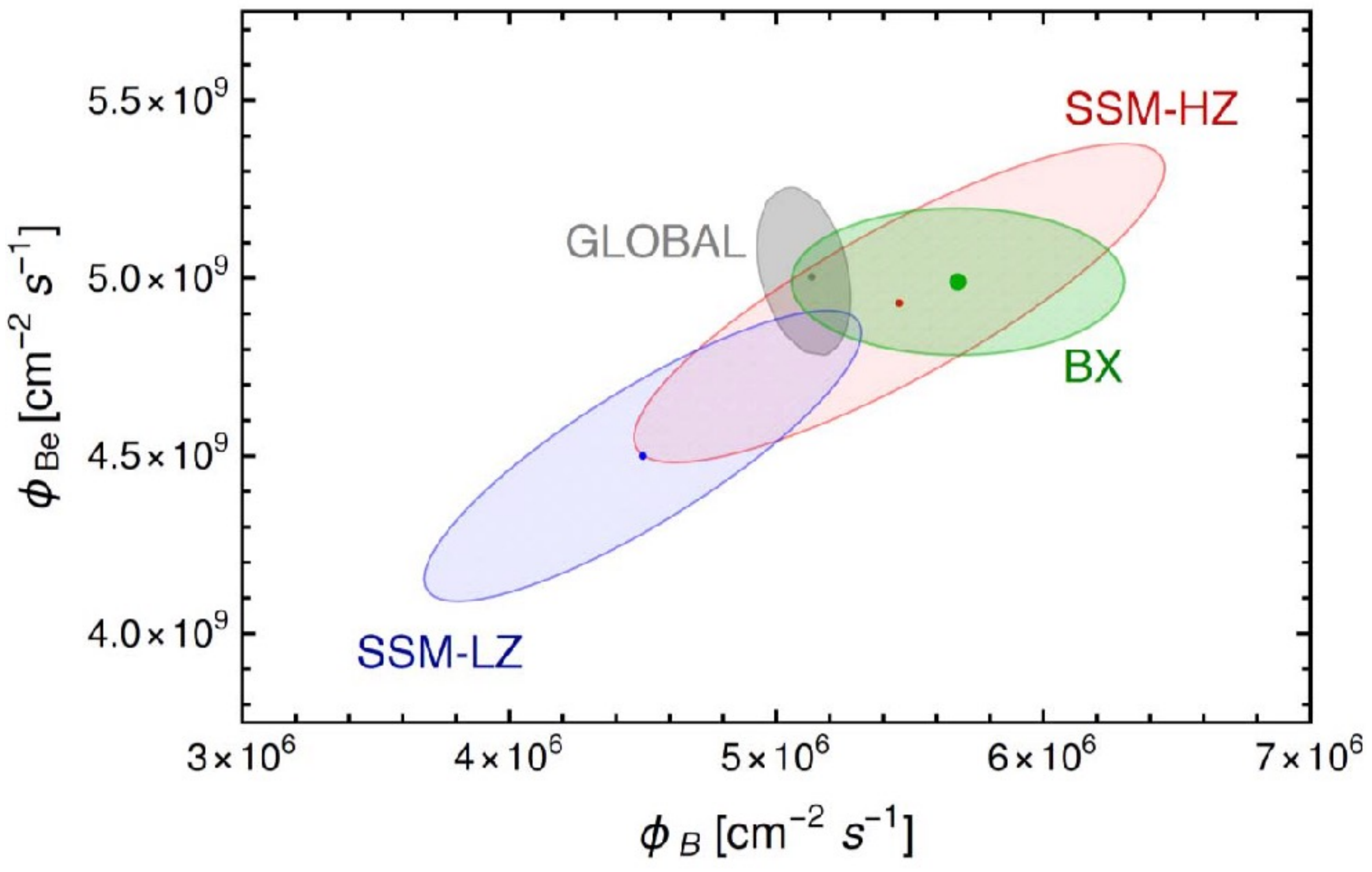
Unique results on **solar physics**

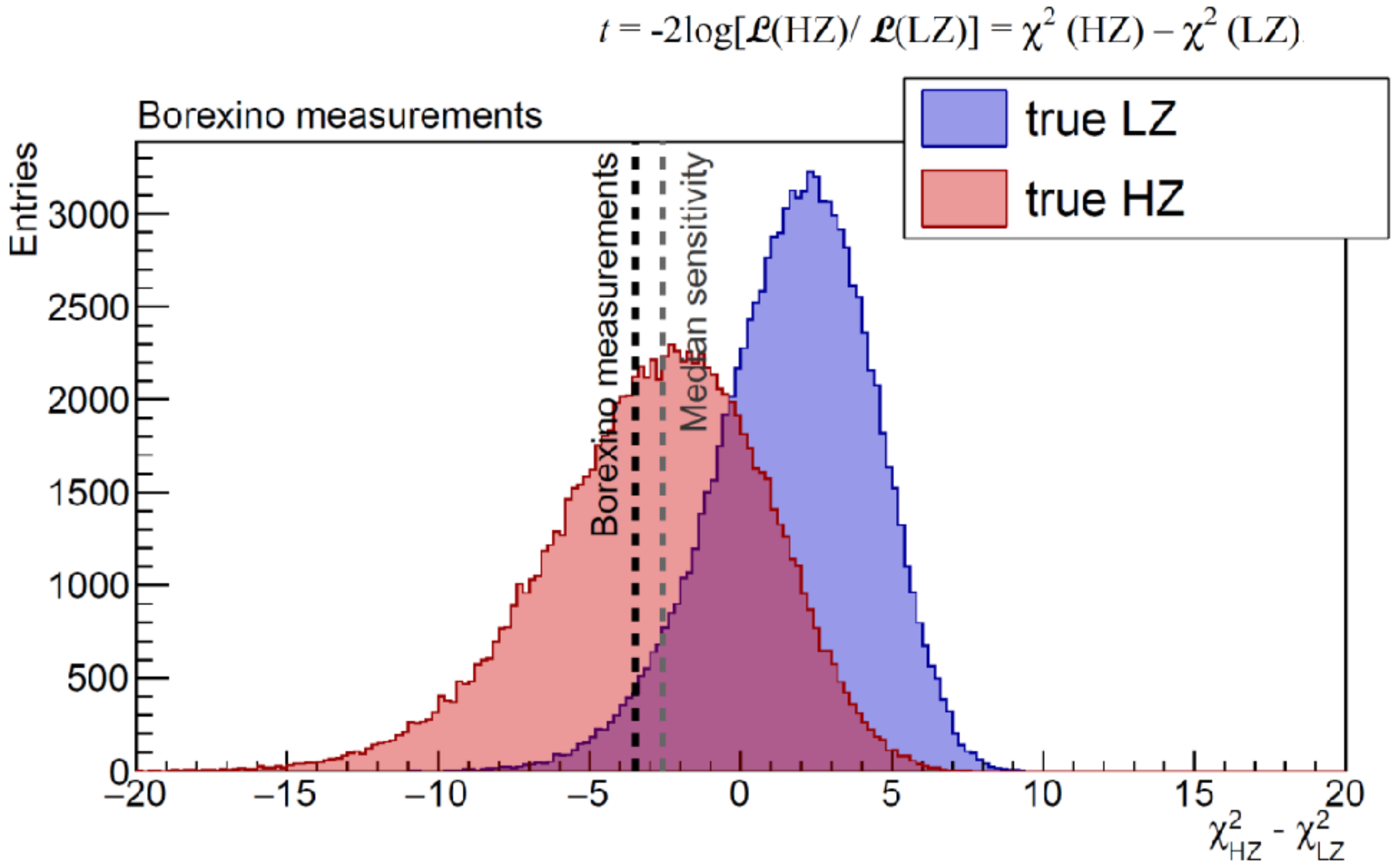


- We measured the luminosity from neutrino to be **$(3.89^{+0.35}_{-0.42})\times10^{33}$erg/s**,
- **Consistent** with results from photons $(3.846\pm0.015)\times10^{33}$ erg/s

$$R=2\Phi(^7\mathrm{Be})/[\Phi(pp)-\Phi(^7\mathrm{Be})]$$

- pp-I vs pp-II B.R. **$0.178^{+0.027}_{-0.023}$**
- **Consistent** with both HZ (0.180±0.011) and LZ (0.161±0.010) model

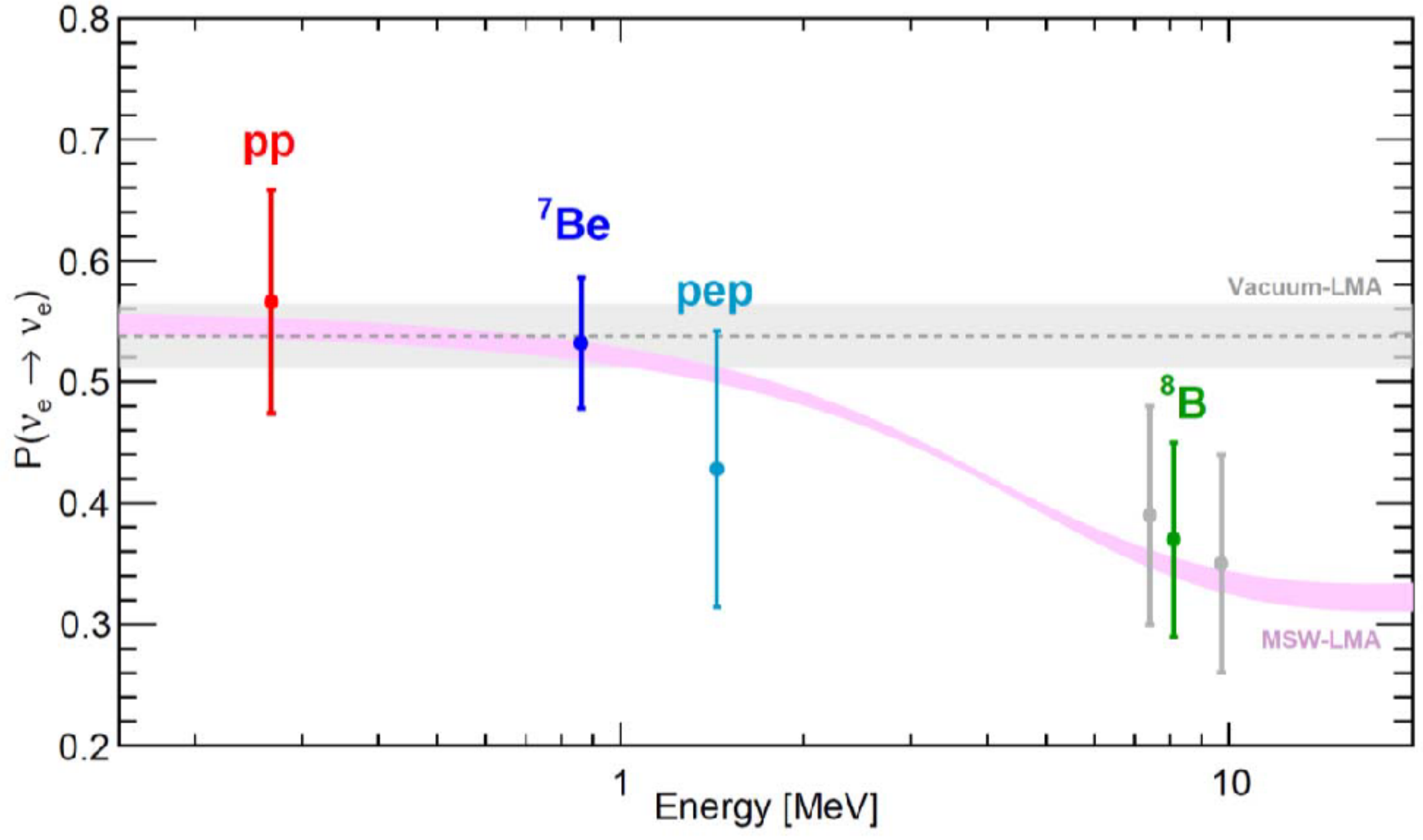


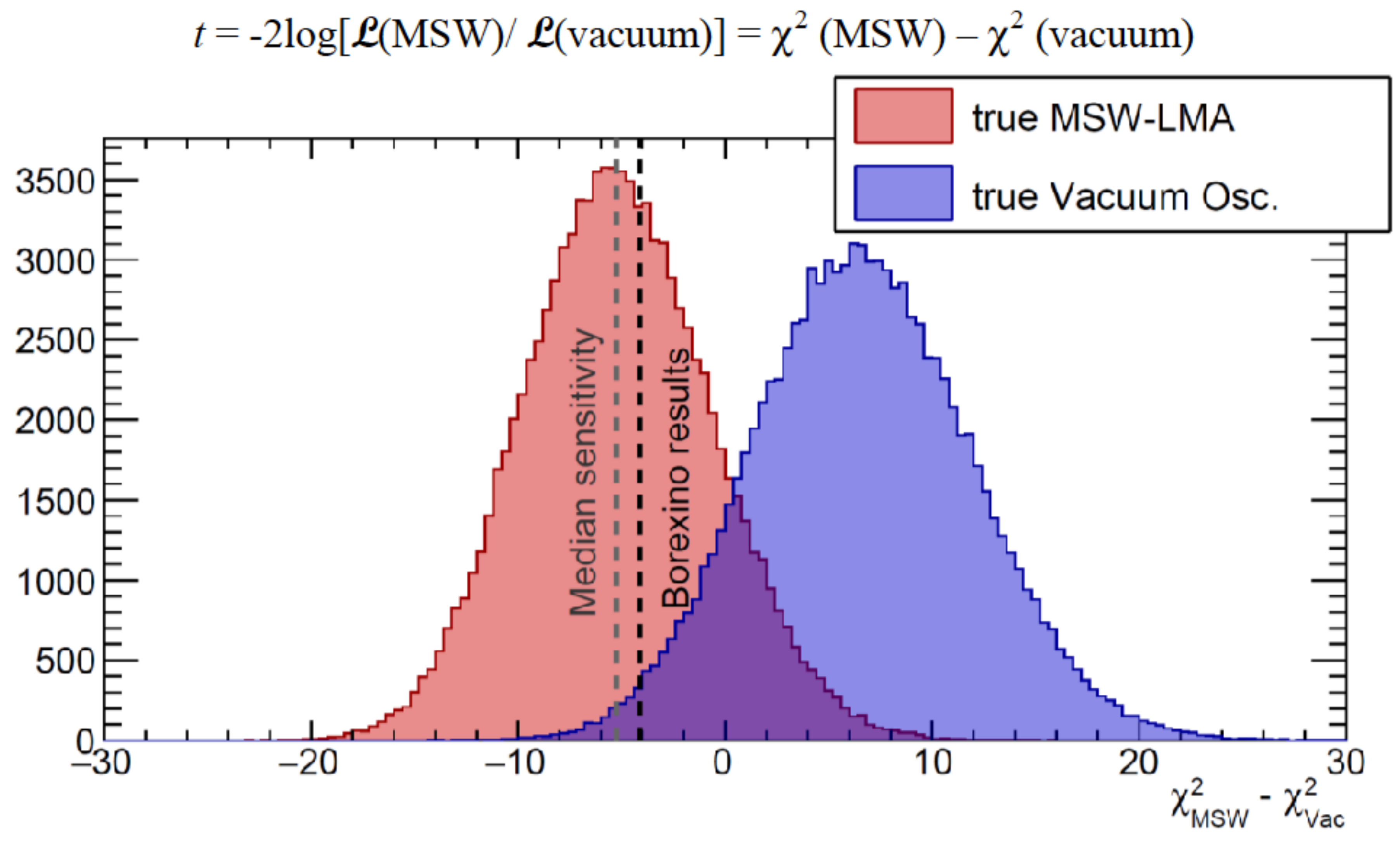


Results on **solar neutrino flux**

- Precision on ν(^{7}Be) 3% is better than the model precision 7%
- With Borexino results alone we **reject LZ model at 96.6% C.L.**, slightly better than the expected median sensitivity 93.8%.
- Including superK etc. both models are compatible

Results on P_{ee}





- Including uncertainty from theoretical flux prediction
- With Borexino results alone we **reject Vacuum-LMA model at 98.2% C.L.**,

How to model the Sun?

2.1.4 Full Set of Equations and Boundary Conditions

The complete set of standard equations describing the evolution of stars, and in particular of the Sun, is given by Eqs. (2.2), (2.5), (2.6), (2.10), (2.19) and the set of N Eqs. (2.42). Together, they form the system of $4 + N$ partial differential equations:

$$\frac{\partial r}{\partial m} = \frac{1}{4\pi r^2 \rho} \tag{2.43a}$$

$$\frac{\partial P}{\partial m} = -\frac{Gm}{4\pi r^4} \tag{2.43b}$$

$$\frac{\partial l}{\partial m} = \varepsilon_{\rm nuc} - \varepsilon_\nu + \varepsilon_{\rm gr} \tag{2.43c}$$

$$\frac{\partial T}{\partial m} = -\frac{GmT}{4\pi r^4 P} \begin{cases} \nabla_{\rm rad} & \text{radiative regions} \\ \nabla & \text{convective regions} \end{cases} \tag{2.43d}$$

$$\frac{\partial X_i}{\partial t} = \left.\frac{\partial X_i}{\partial t}\right|_{\rm conv} + \left.\frac{\partial X_i}{\partial t}\right|_{\rm mic} + \left.\frac{\partial X_i}{\partial t}\right|_{\rm nuc} \tag{2.43e}$$

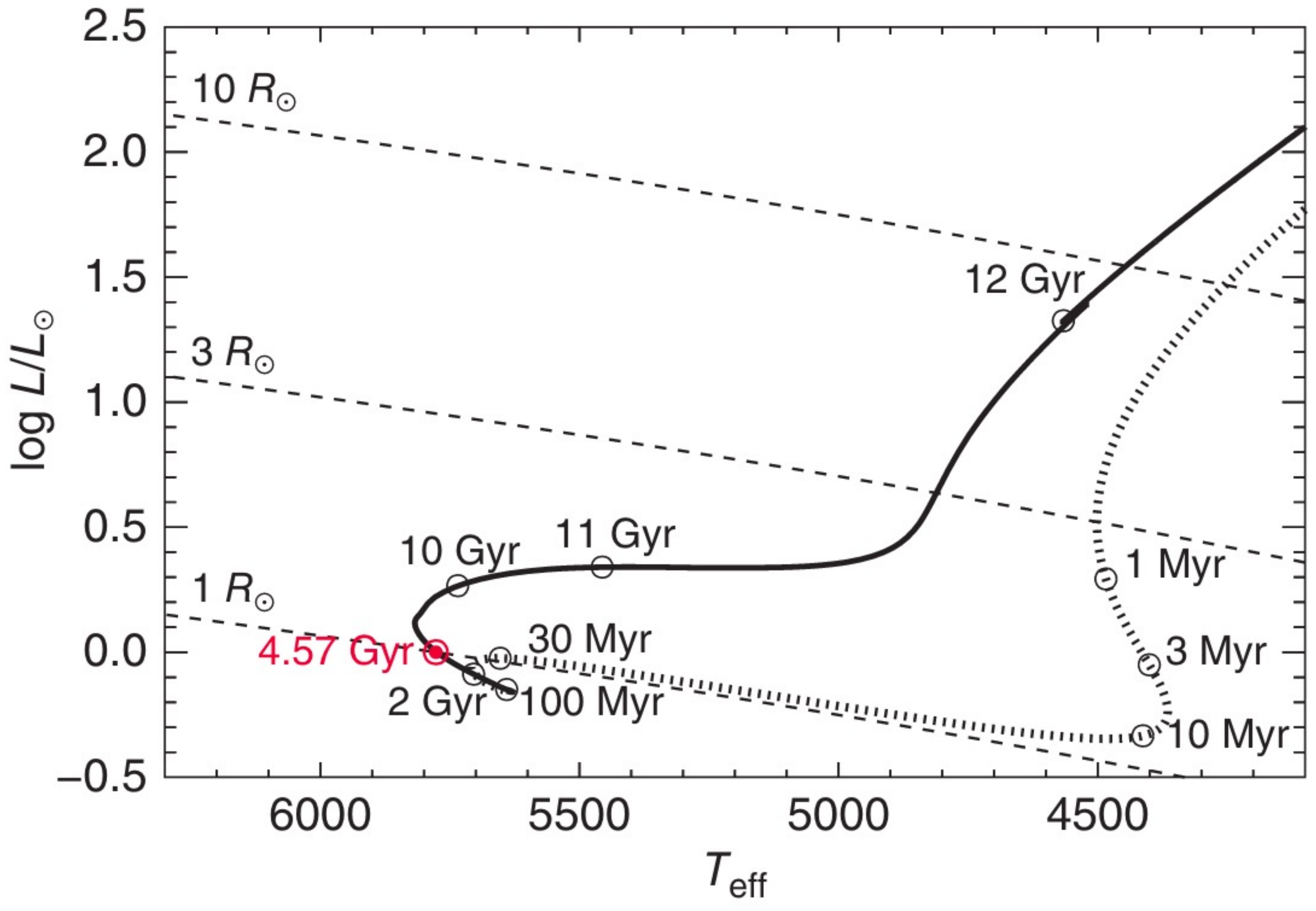
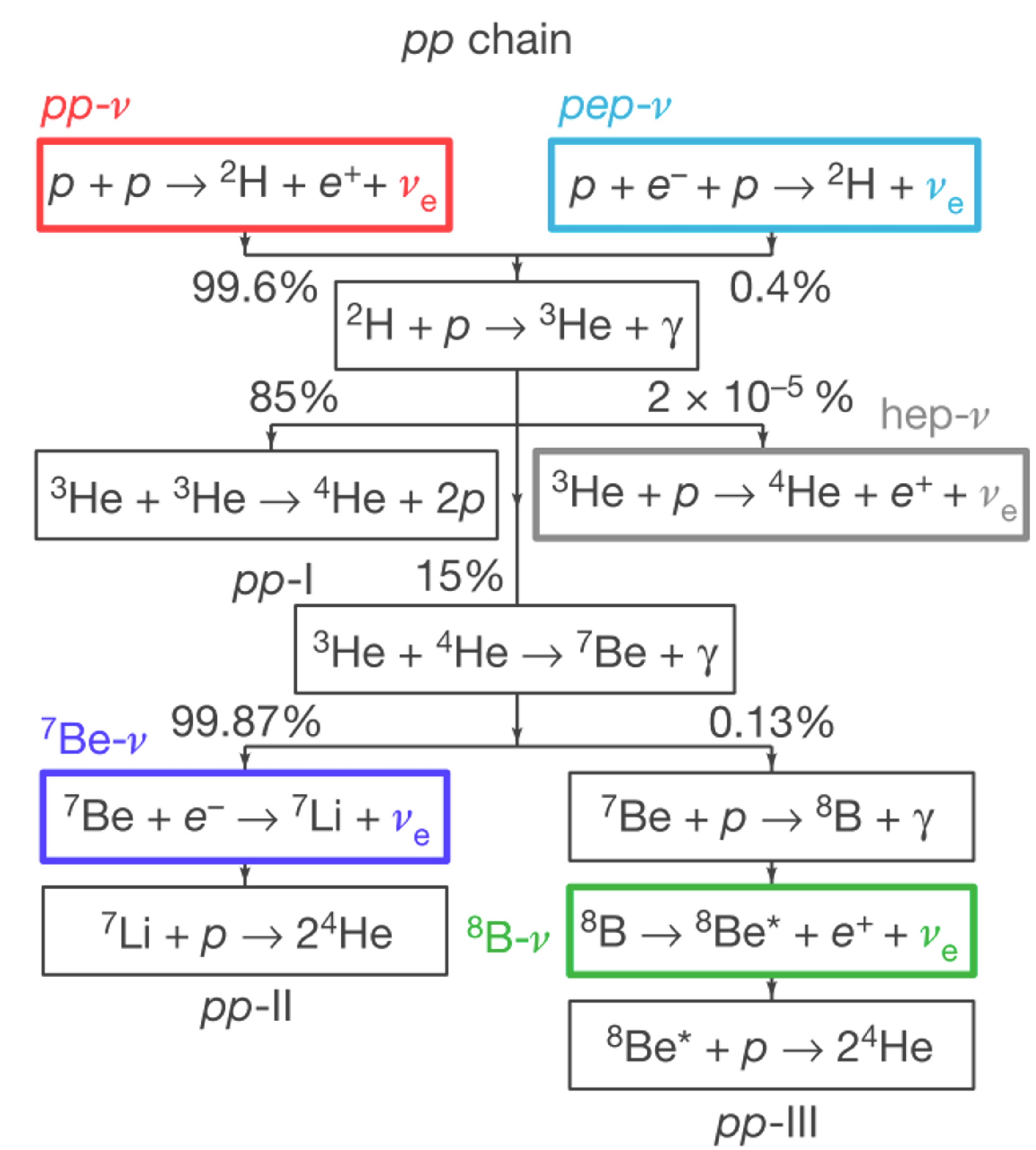


Figure 2.9 Hertzsprung–Russell diagram showing the evolution of a 1 $M_\odot$ stellar model. Curves of constant stellar radii are shown with dashed lines and the age of the model is indicated at several locations. The location of the present-day Sun is indicated with the ⊙ symbol, at $\tau_\odot$ = 4.57 Gyr. Pre-main sequence evolution is indicated with dashed lines.

Neutrinos produced in the Sun



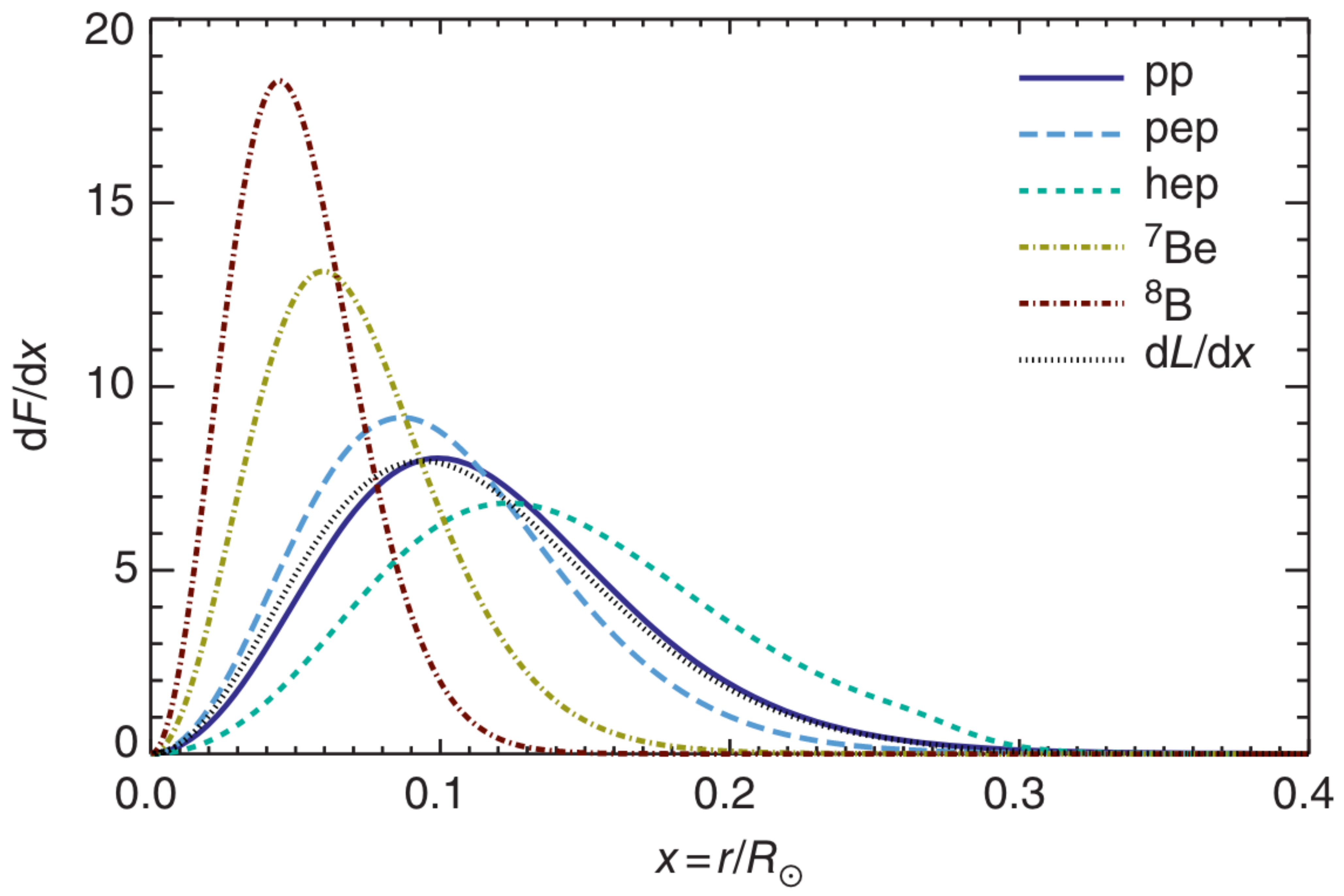
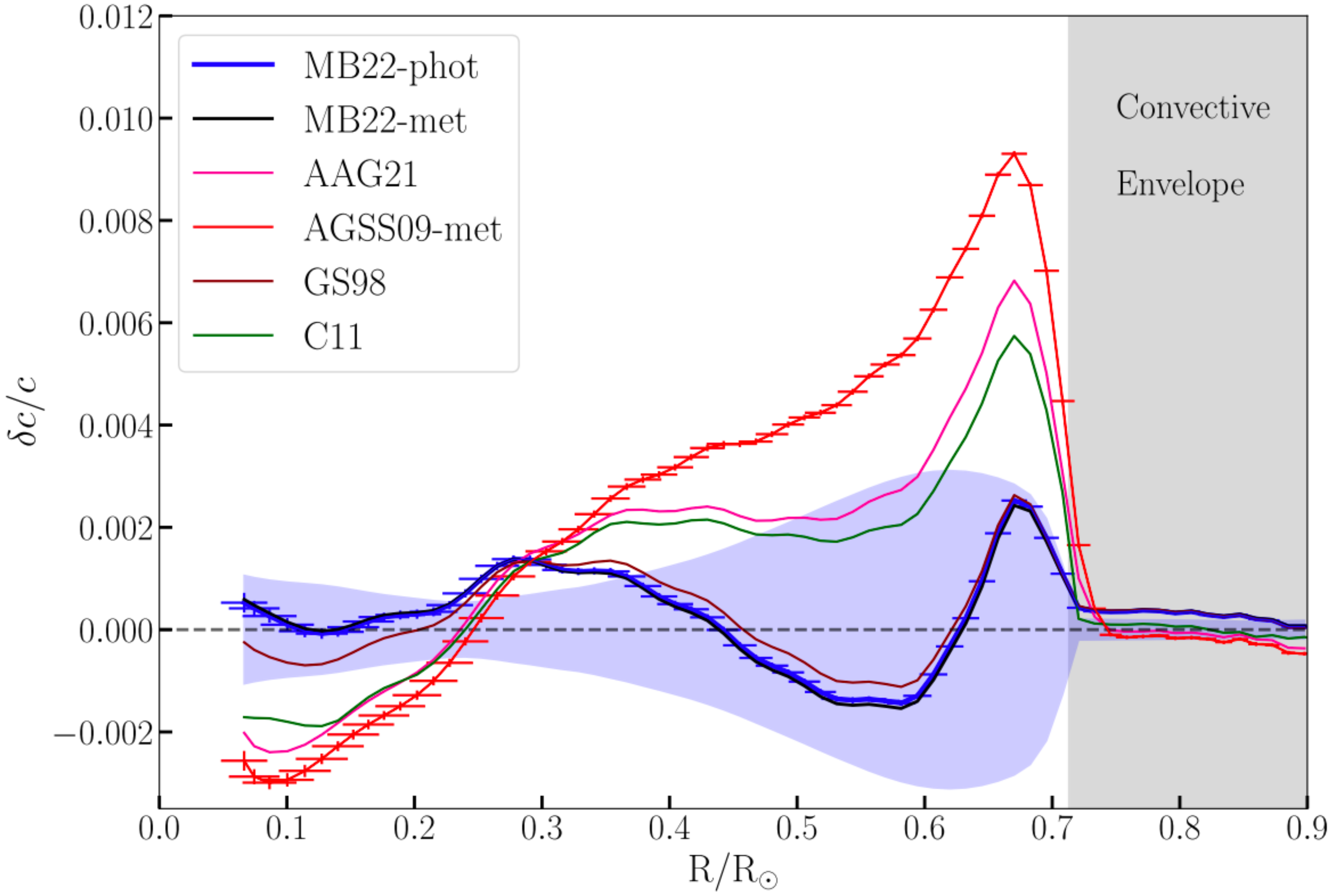


Figure 2.14 Distribution functions of the production of neutrinos in the pp chains and of the solar total luminosity.

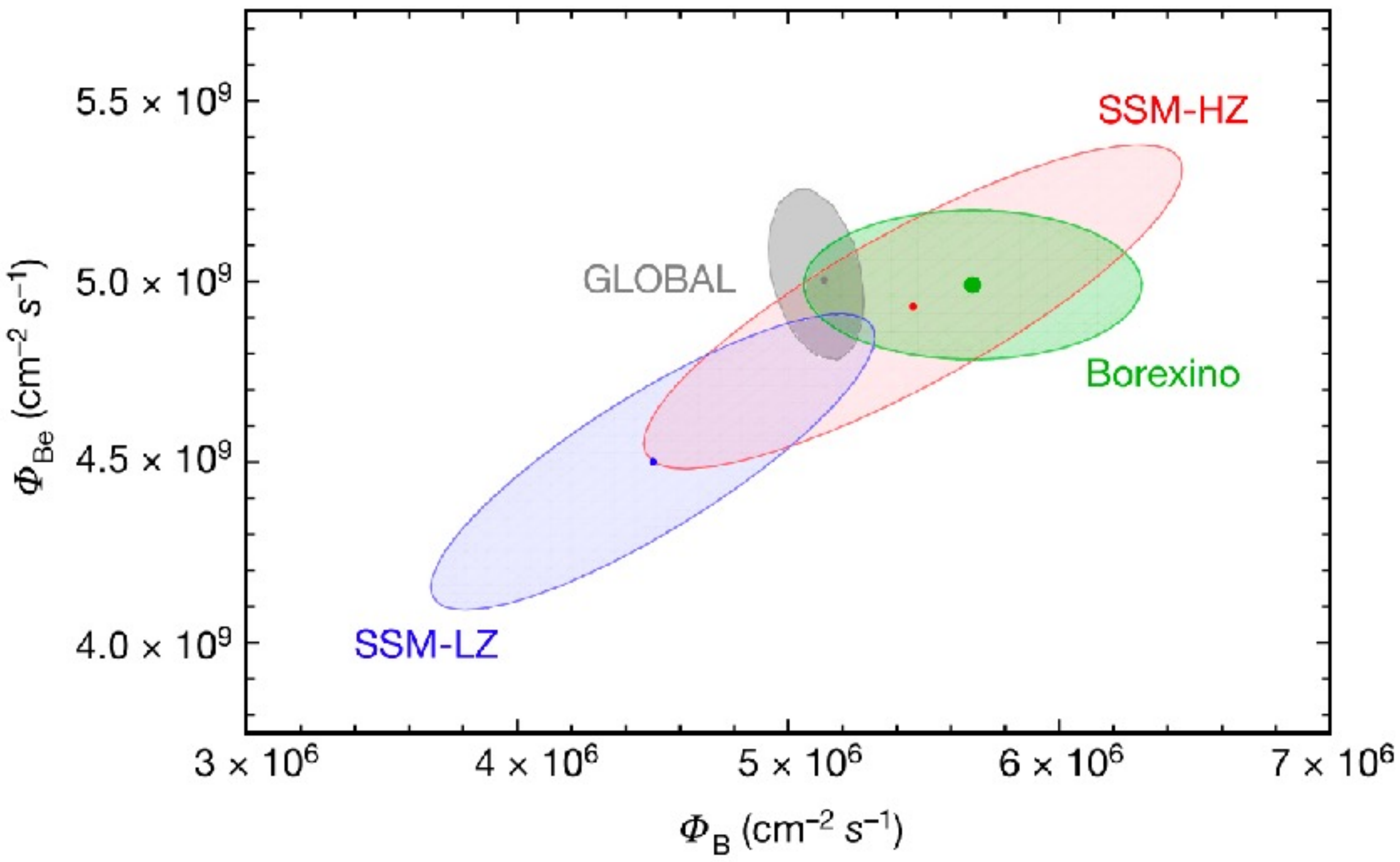
The metallicity problem

Sound speed profile



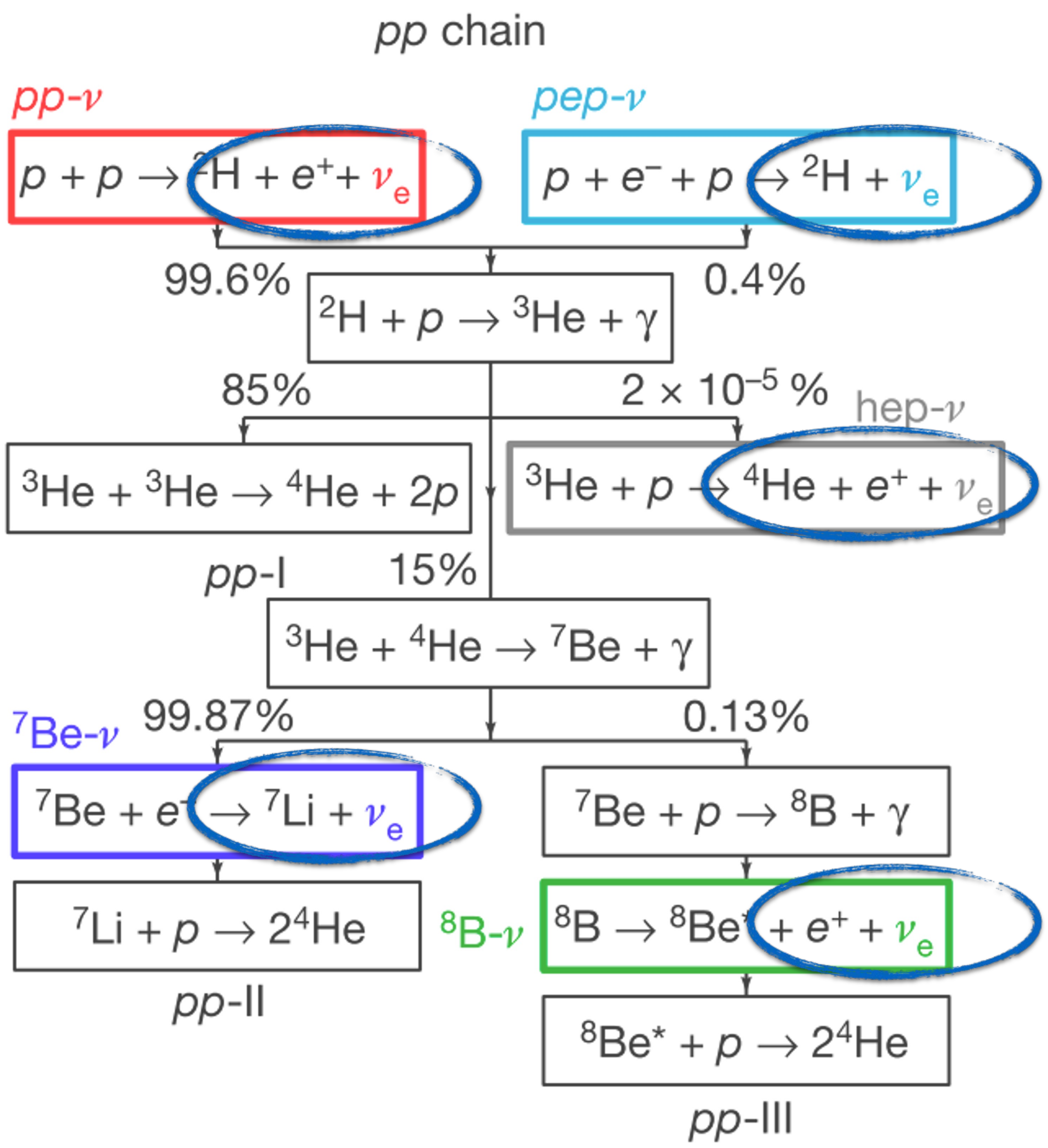
E. Magg et al. v2203.02255

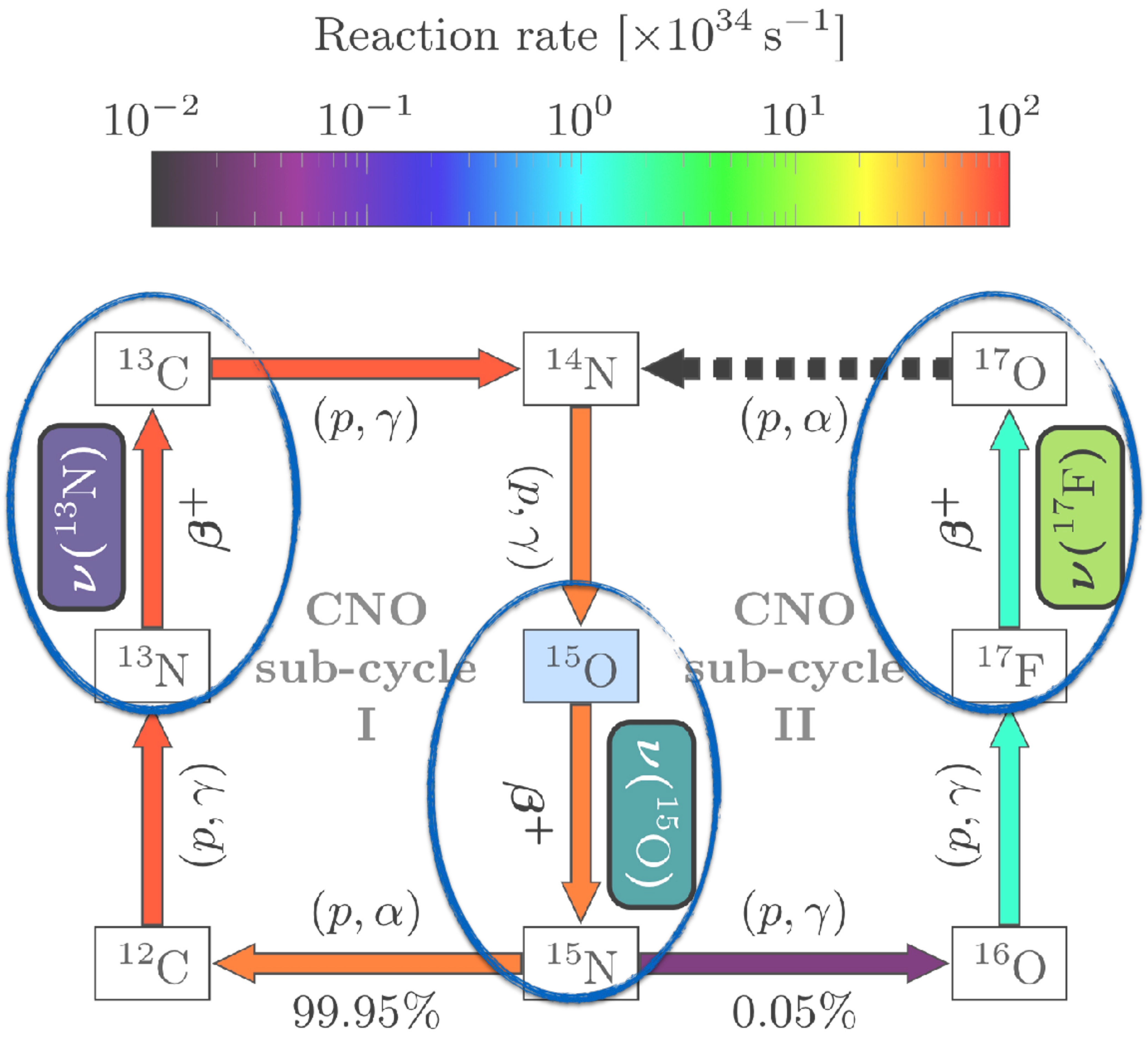
Solar neutrino fluxes



Borexino Collaboration (2018). Comprehensive measurement of pp-chain solar neutrinos. Nature, 562(7728), 505–510.

The pp-chain vs CNO-cycle





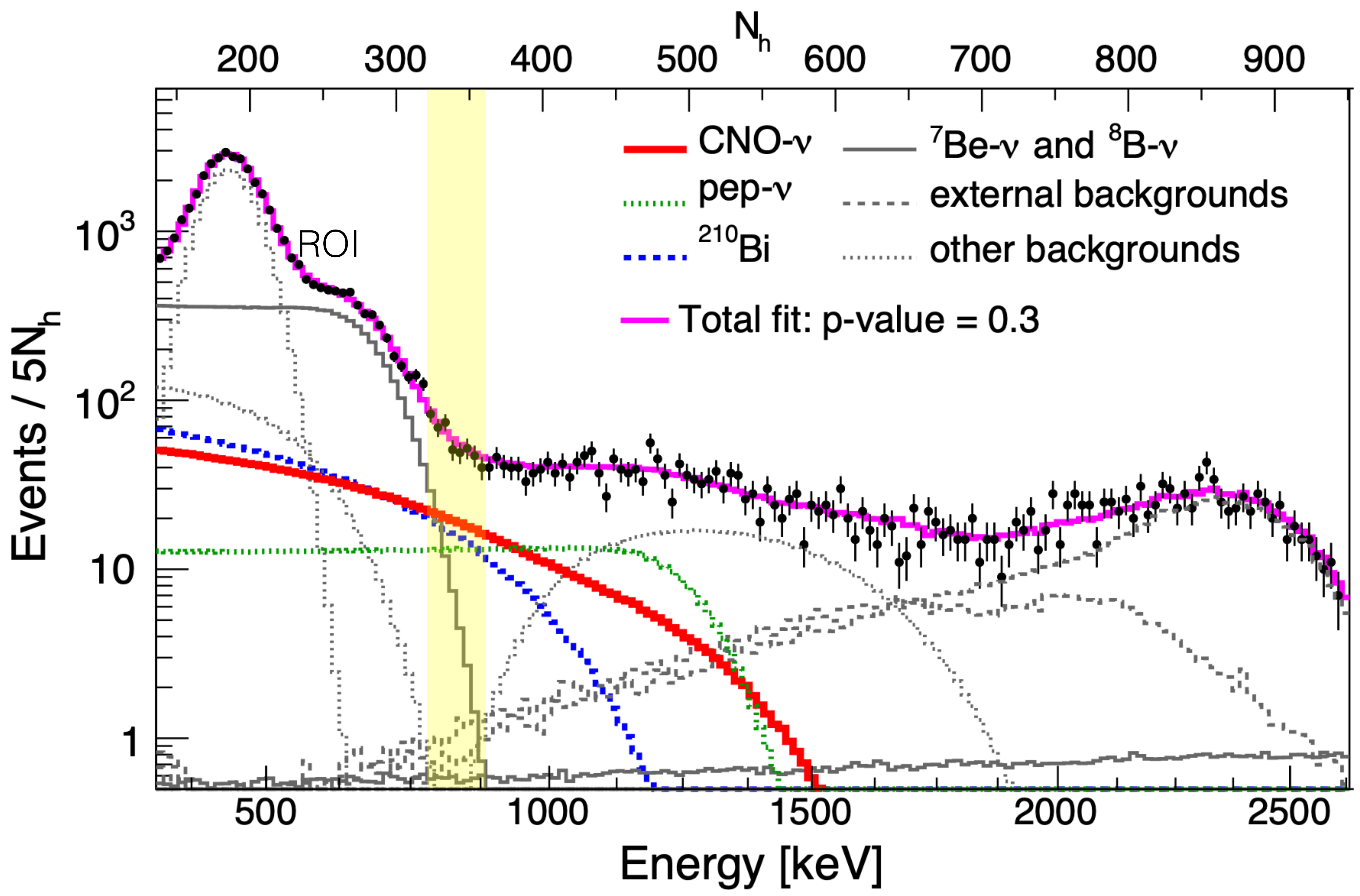
Comprehensive measurement of pp-chain solar neutrinos, BOREXINO, 2018, Nature

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

Borexino Phase-III: CNO

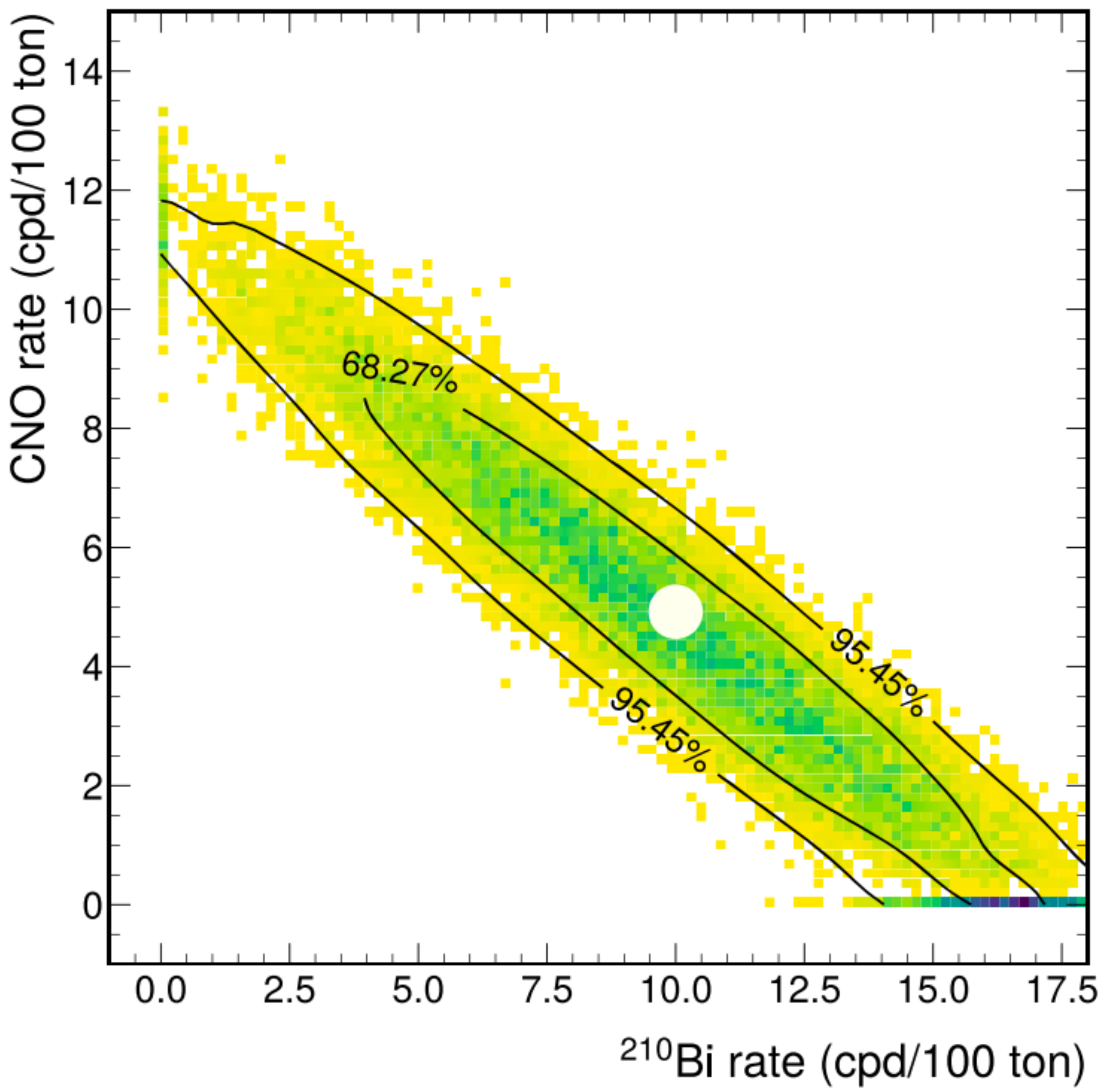
Measuring CNO with Borexino

Shape of CNO and ^{210}Bi



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

Fit results of CNO and ^{210}Bi of toy MC datasets

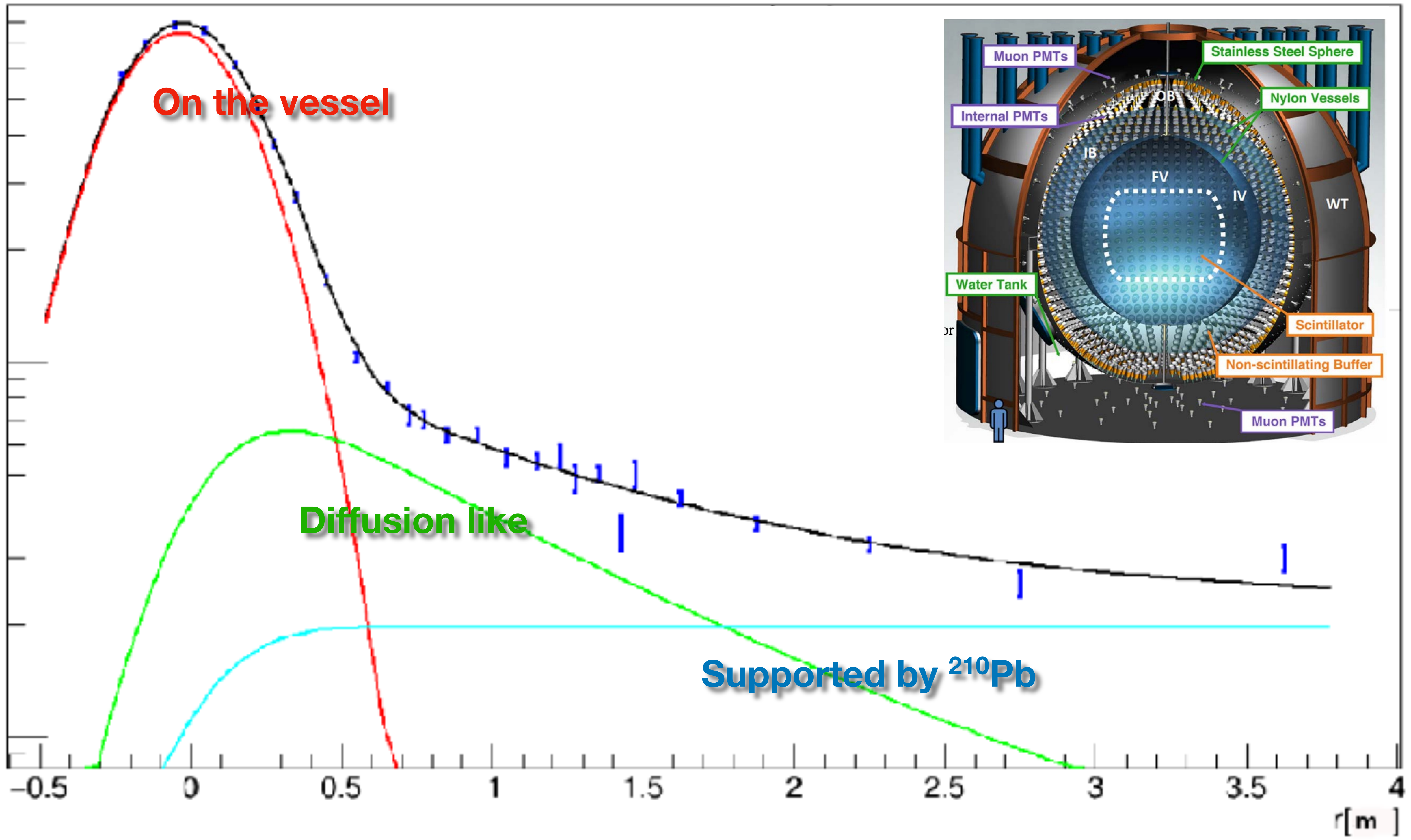


Borexino Collaboration. (2020). Sensitivity to neutrinos from the solar CNO cycle in Borexino. European Physical Journal C, 80(11). https://doi.org/10.1140/epjc/s10052-020-08534-2

- Bulk sensitivity from 0.8—1 MeV. With pep fixed, 0.6 ^{210}Bi+CNO is known well.
- **Once ^{210}Bi is determined, CNO will be measured.**

How to measure ^{210}Bi

Distribution of ^{210}Po events



- ^{210}Po is the decay daughter of ^{210}Bi;
- ^{210}Bi = ^{210}Po @ secular equilibrium;
- Extra ^{210}Po brought into FV by convection & migration:

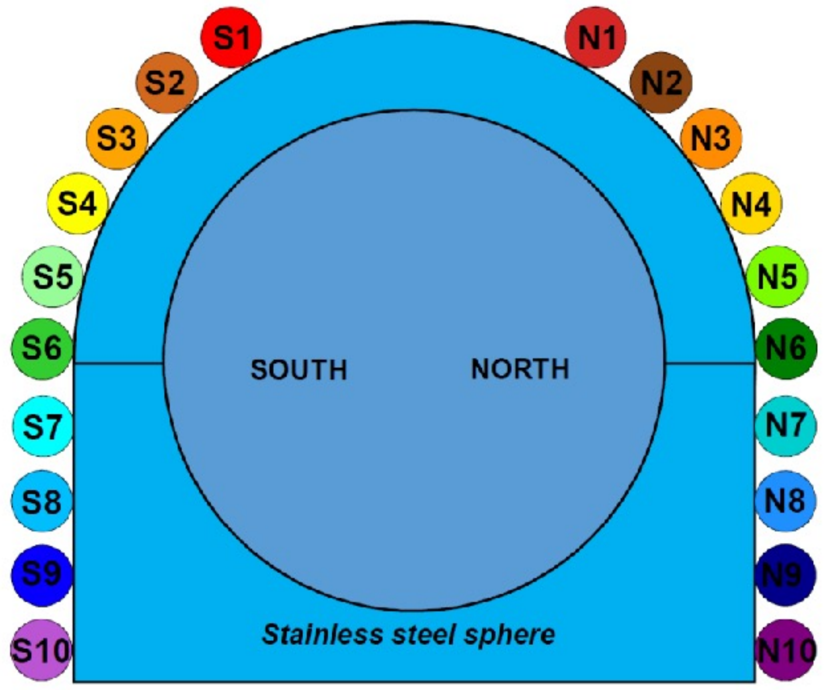
R(^{210}Bi) < R(^{210}Po) + migrated ^{210}Po

Efforts to suppress the convection motion.

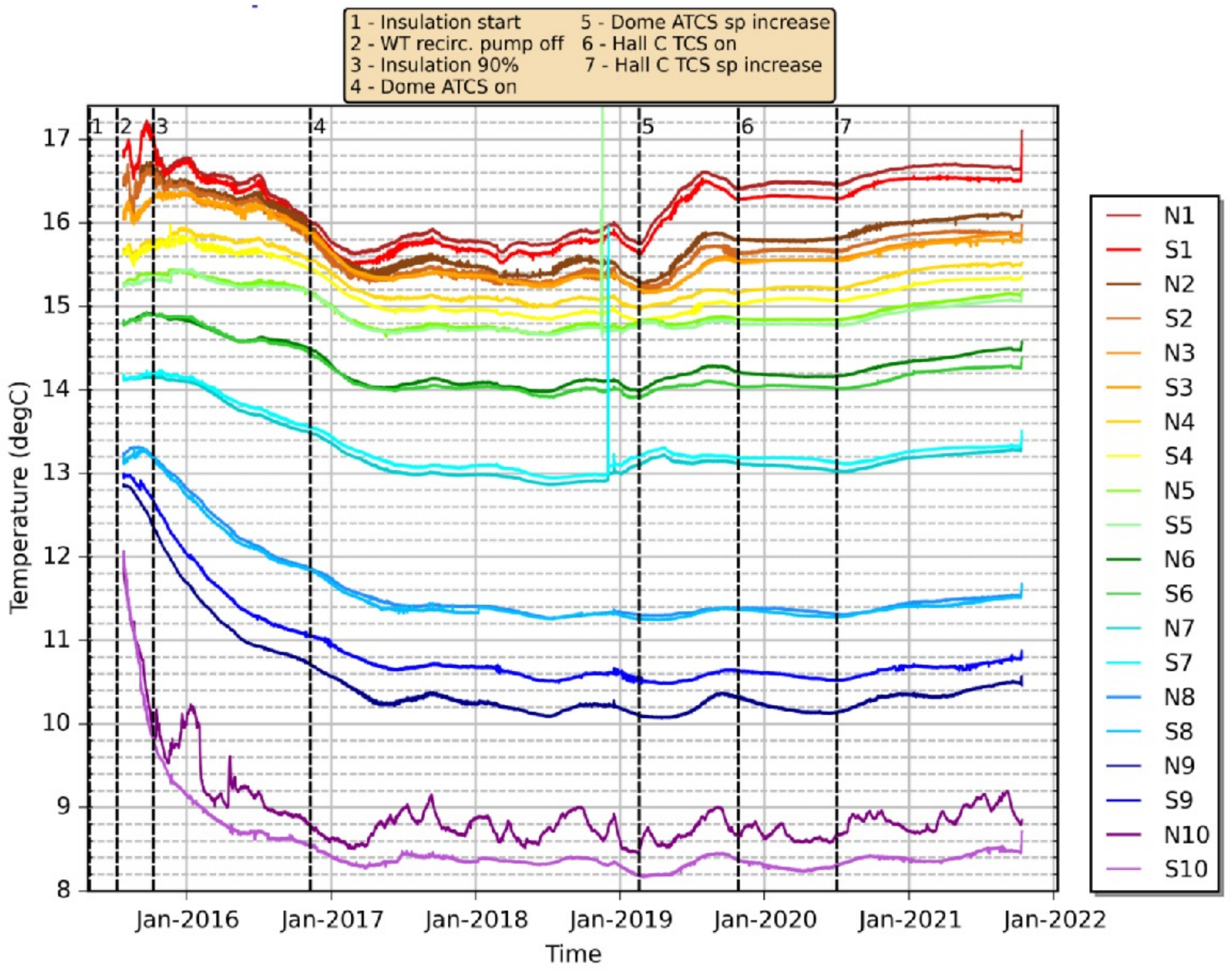
Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment
Volume 964, 1 June 2020, 163801

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

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



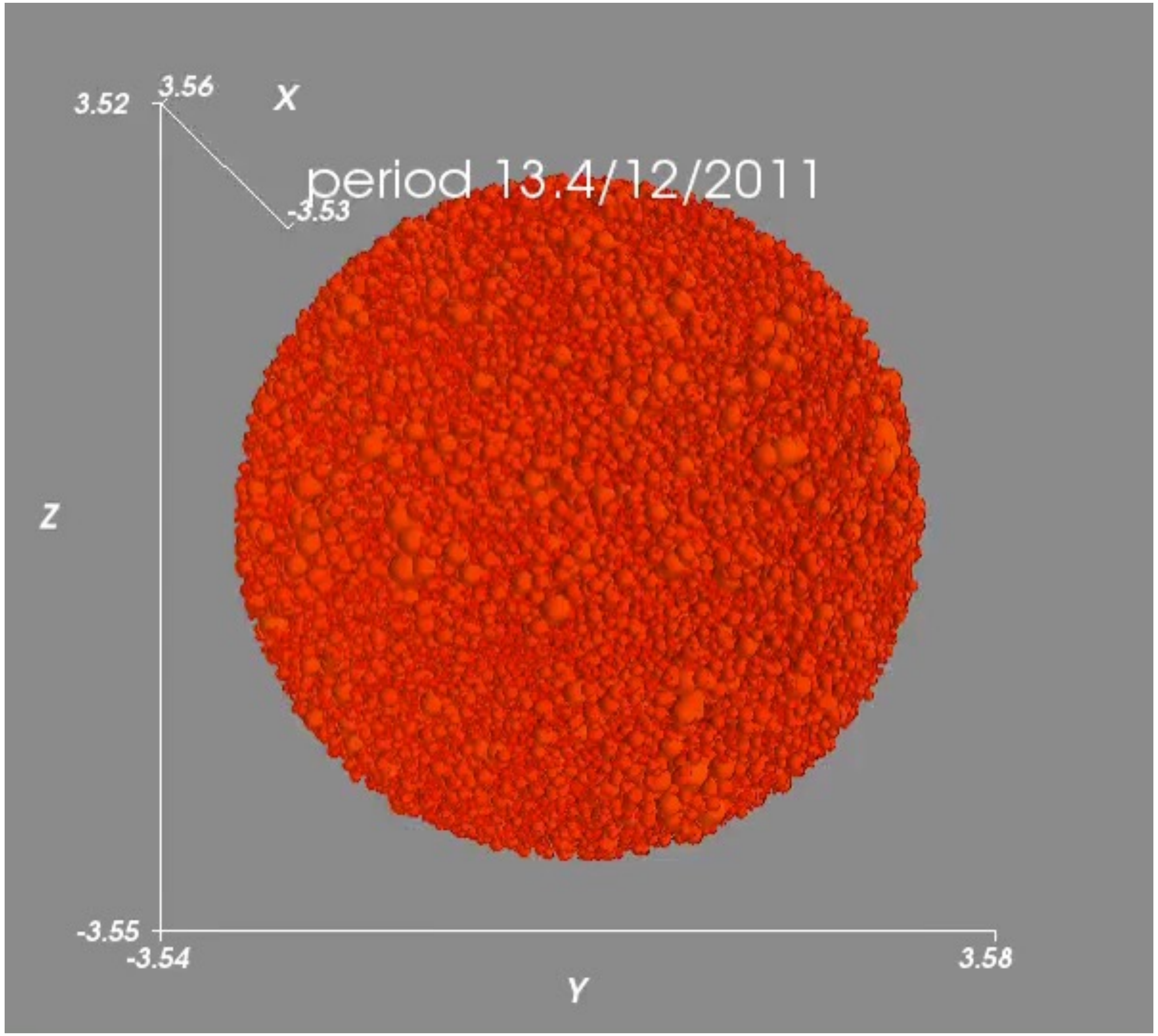
/2006.15115



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

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

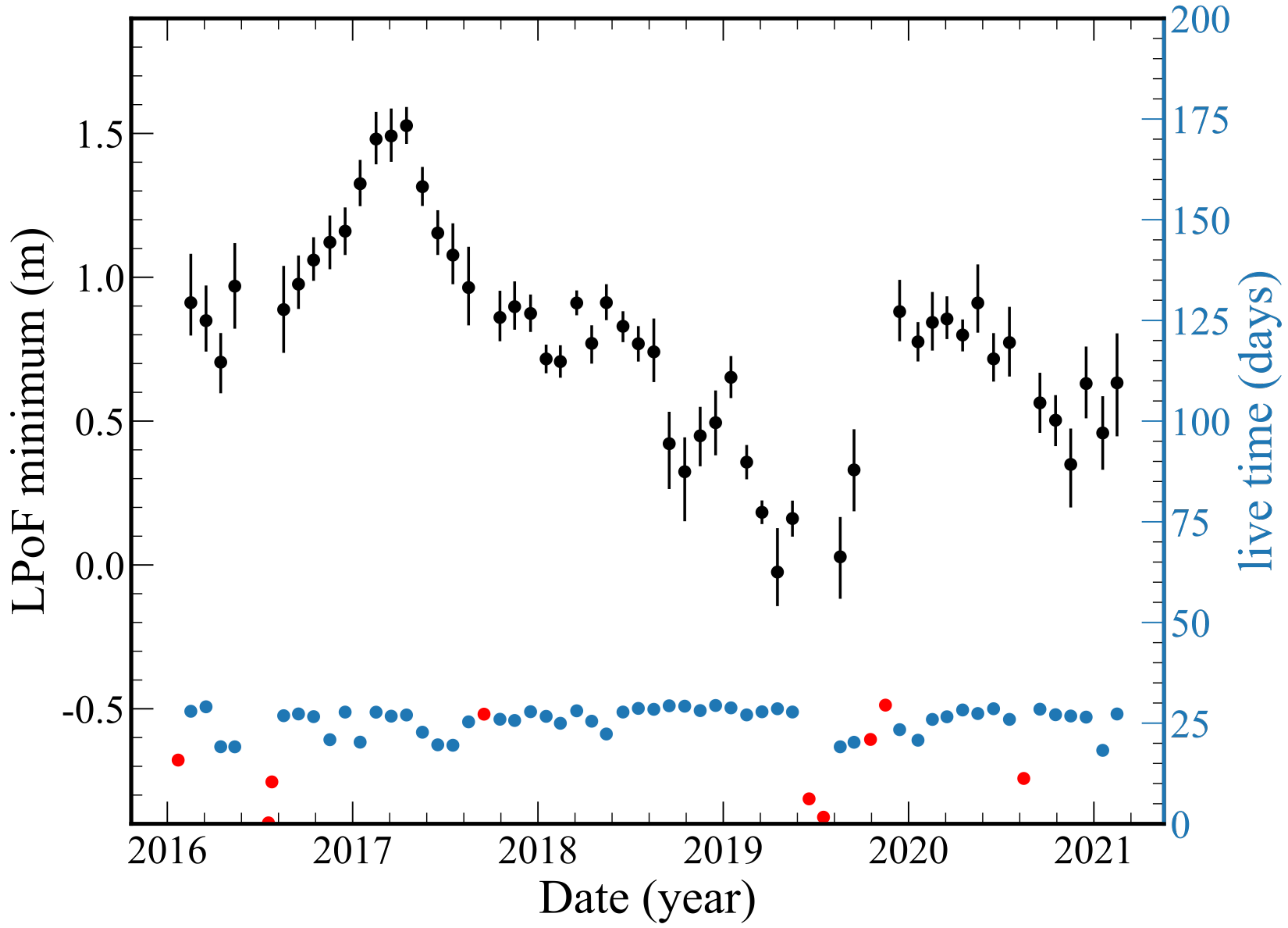
Formation of Low Polonium Field (LPoF)



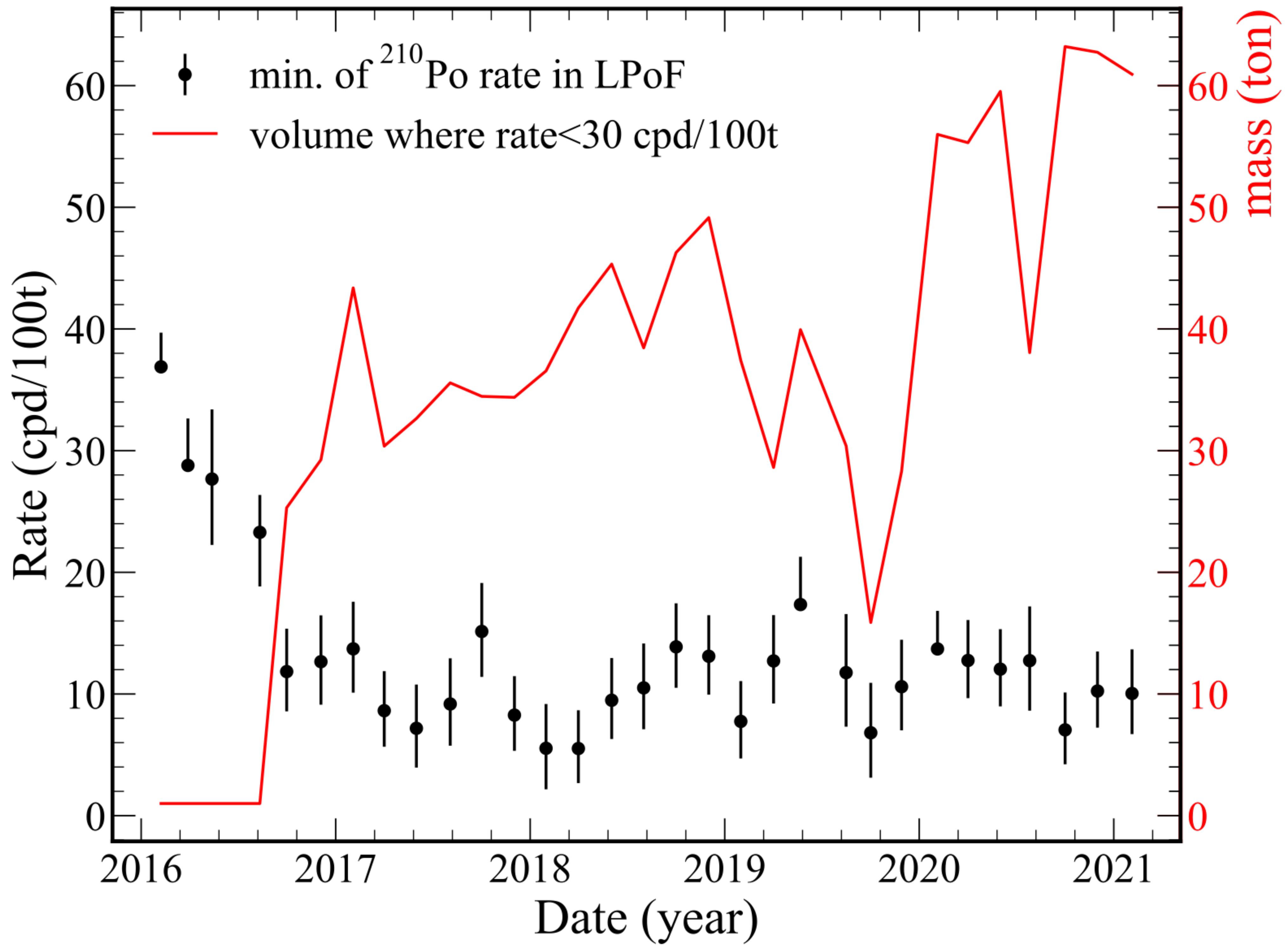
- Large cold dot: low rate; Small hot dot: high rate
- 2011-2013: high rate of ^{210}Po left after purification
- 2014-2016: seasonal up and down of low Polonium region (LPoF)
- After 2016: **LPoF relatively stable**

Behavior of Low Polonium Field

Position



Rate



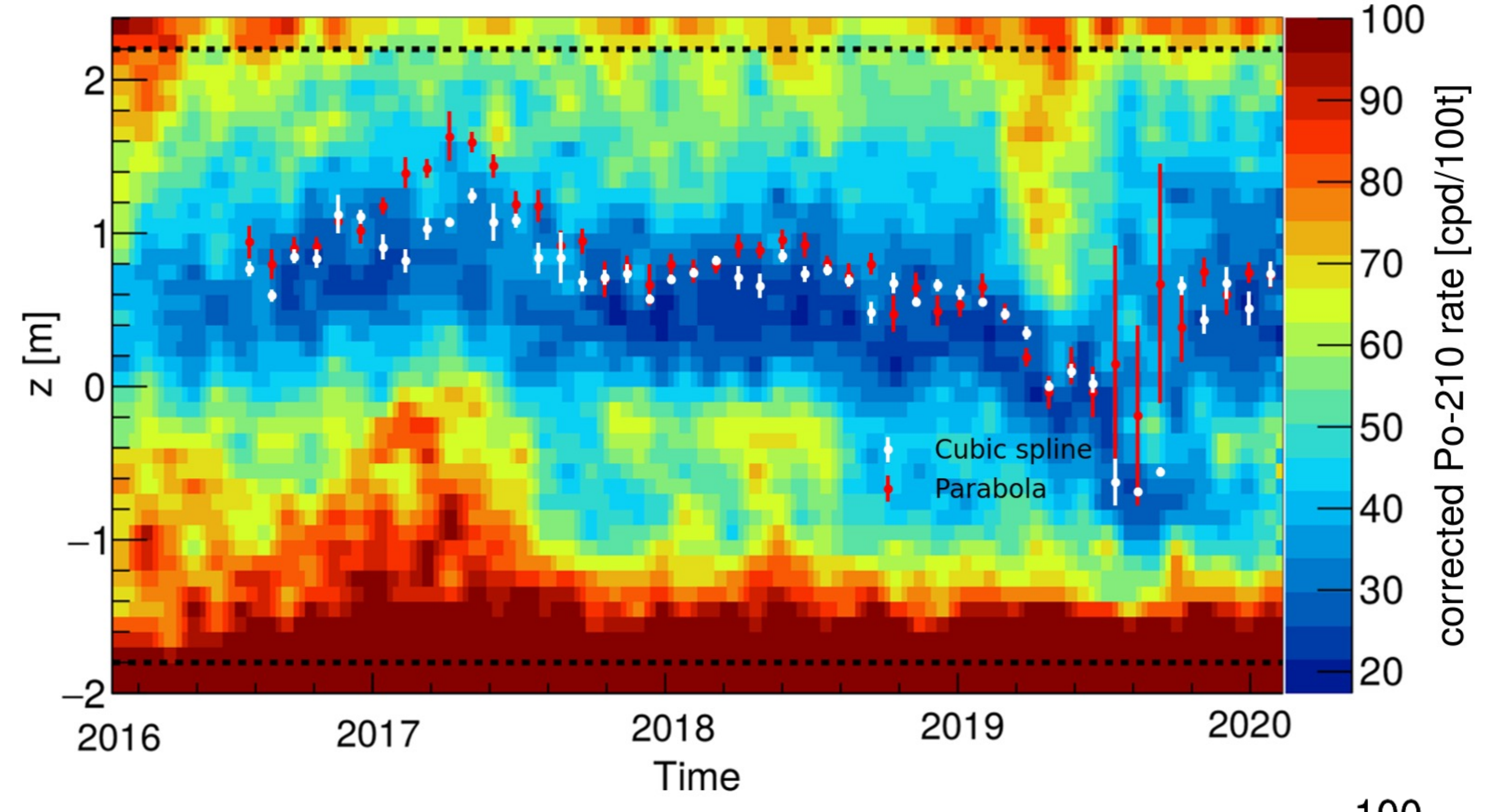
- Relatively stable, but still moving
- Rate @ minimum stable, maybe convection free

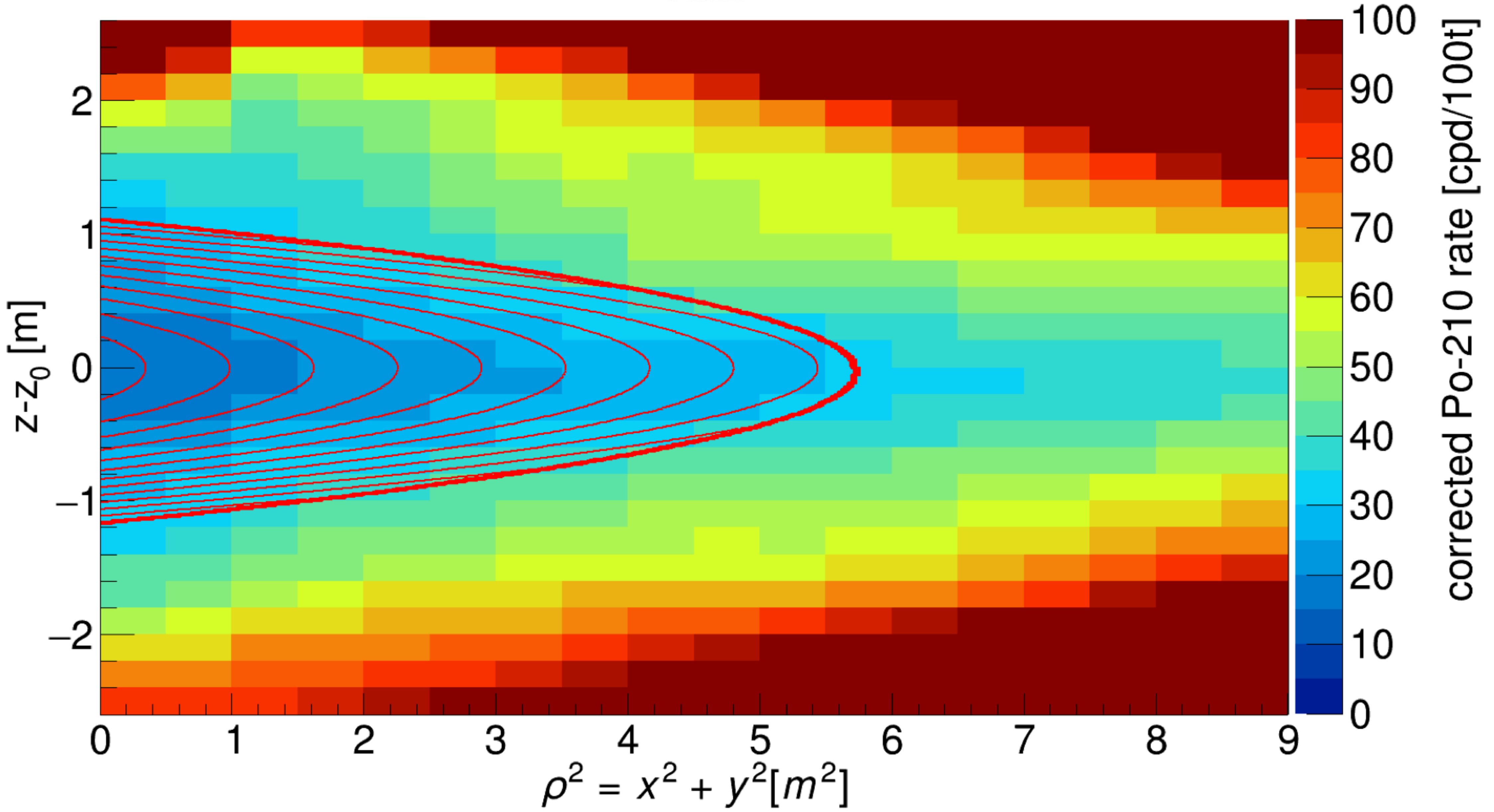
https://characters.fandom.com/wiki/Bambi

Blind Aligned Merged parabolic Bubble fIt

(BAMBI)

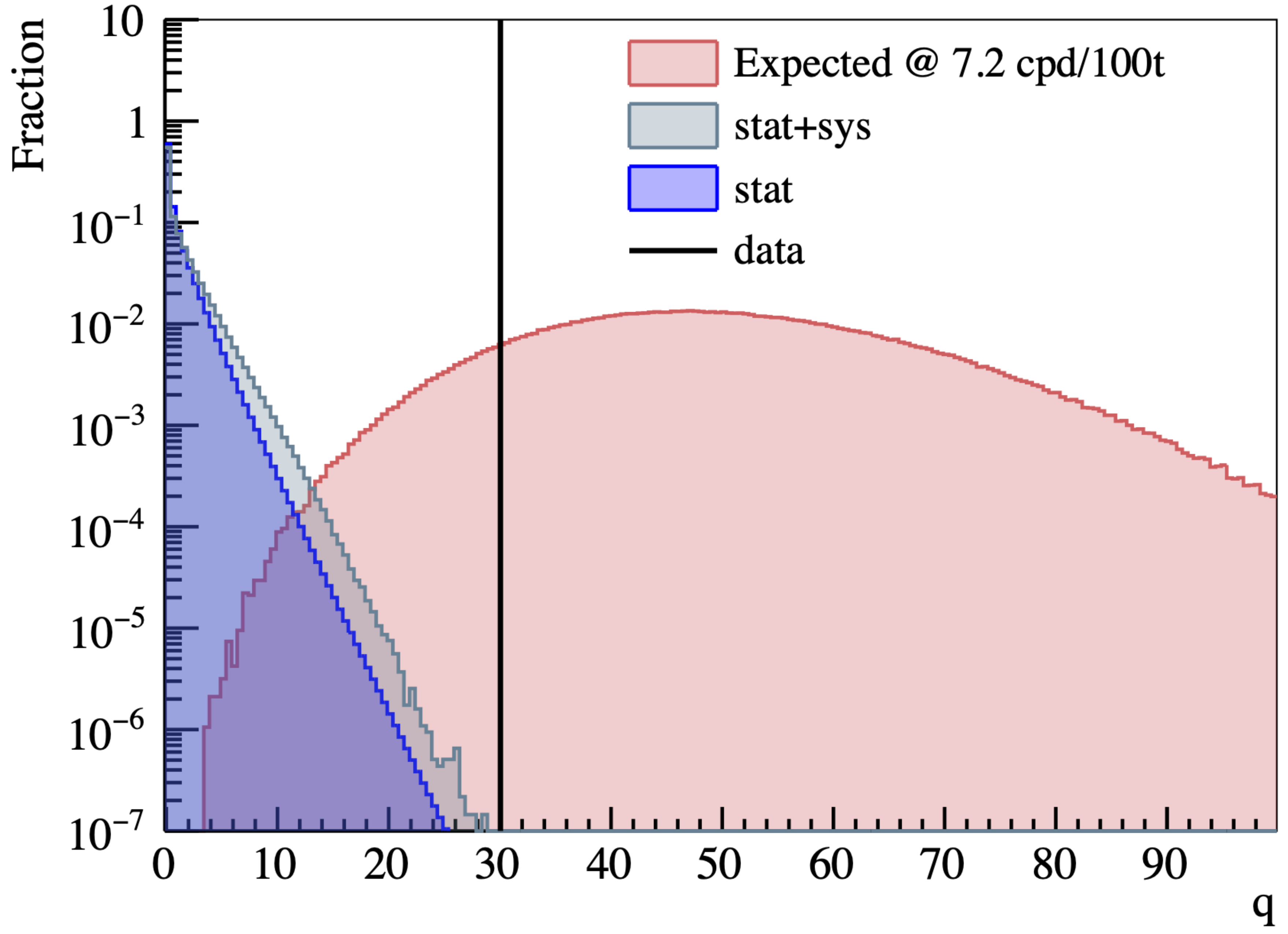
Low Polonium Field (LPoF) analysis

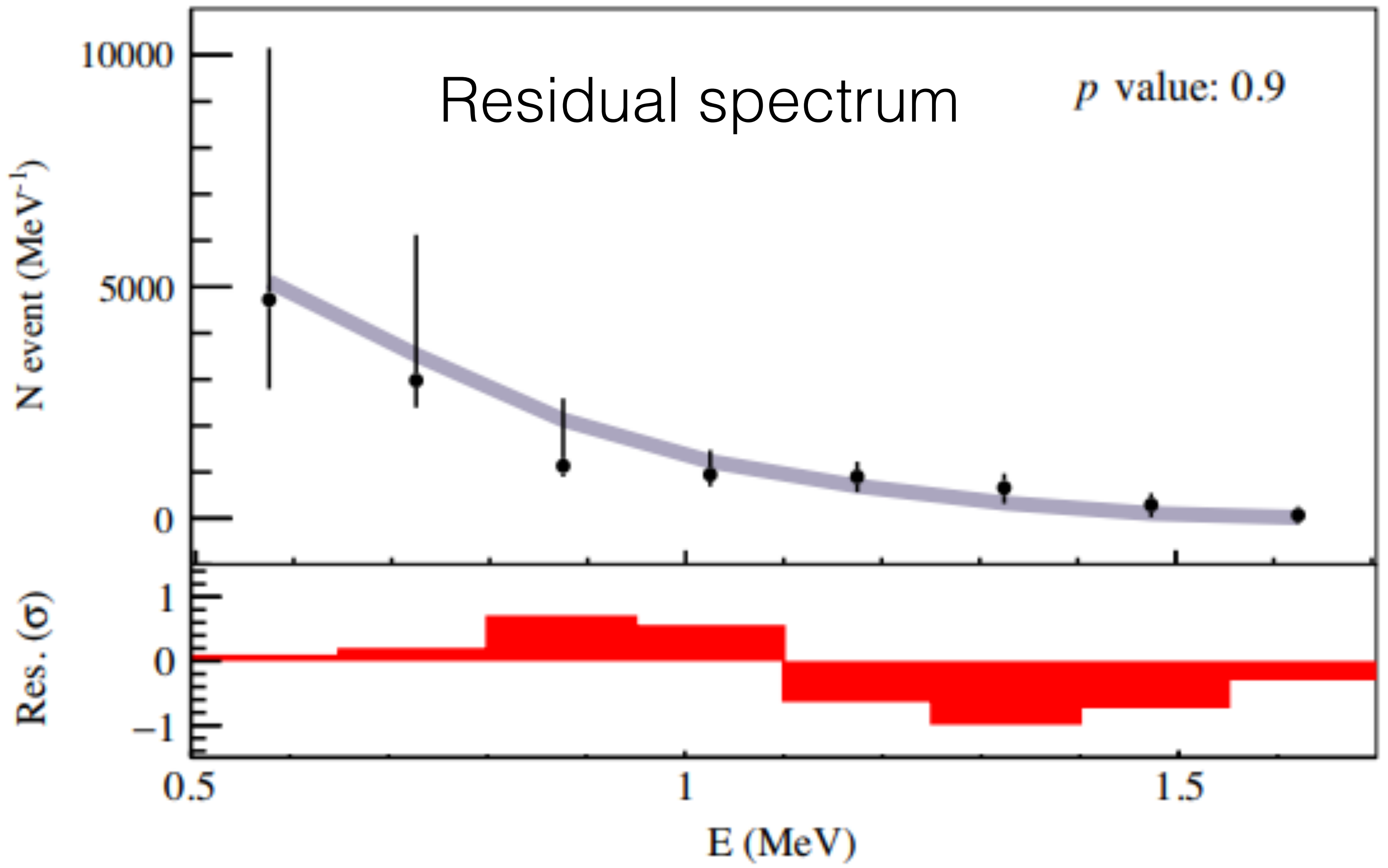




- Residual convection remains
- Low Polonium Field formed at center
- Correct movement of LPoF (Blind alignment)
- Fit event distribution in a bubble shape region in 2D with parabolic functions (bubble fit)
- Previous analyses: no correction, 1D fit; (2σ =>5σ)

Test against no-CNO hypothesis

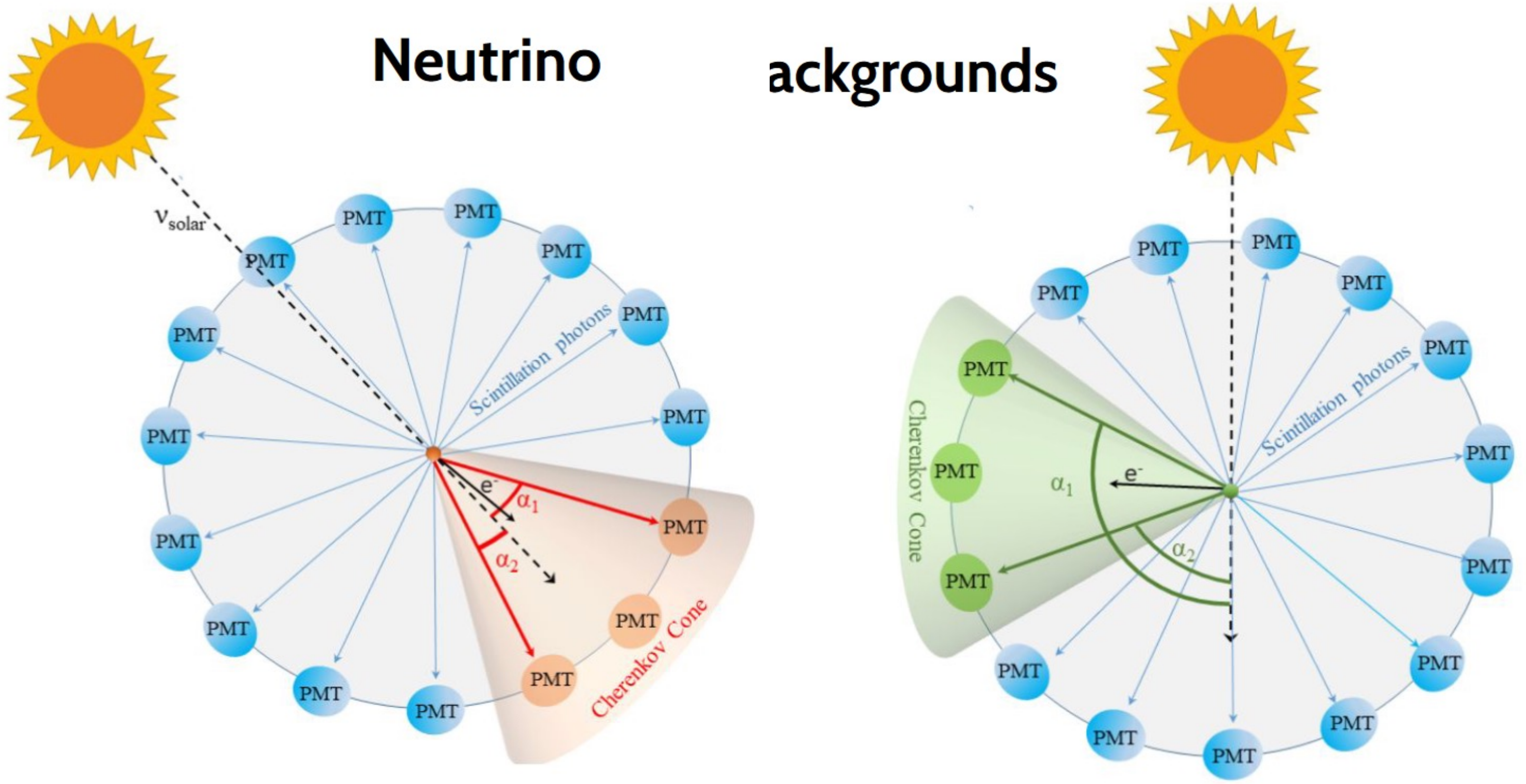


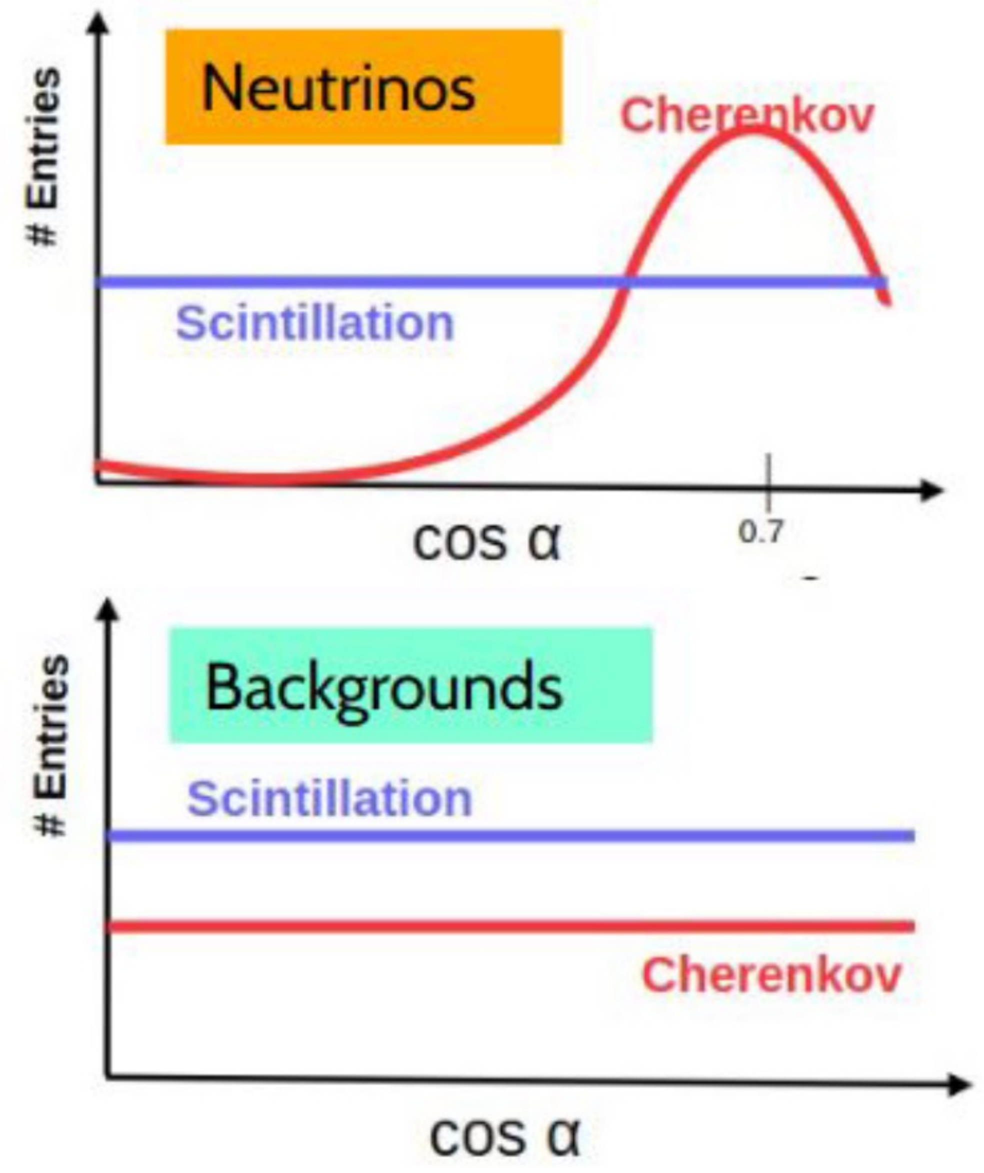


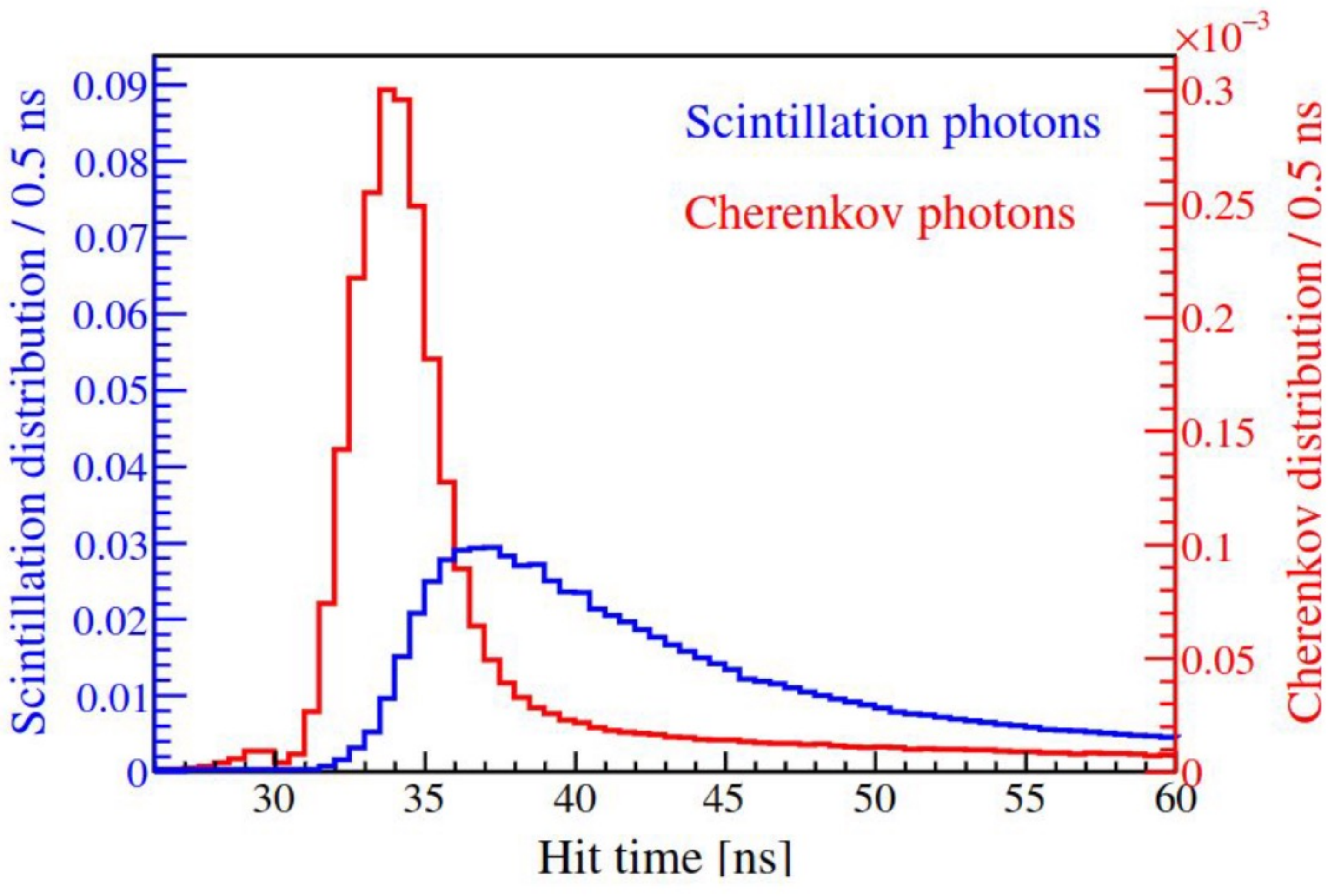
- Profile likelihood as the test statistic
- Use toy-MC method to get the distribution of test statistic. Evaluated p-value has statistical uncertainty.
- Simulated & Fitted 14million dataset
- **5 σ* rejection of no-CNO hypothesis**

*Evaluated with toyMC method and it's >5σ at 99% C.L.

Technology of Correlated and Integrated Directionality (CID)

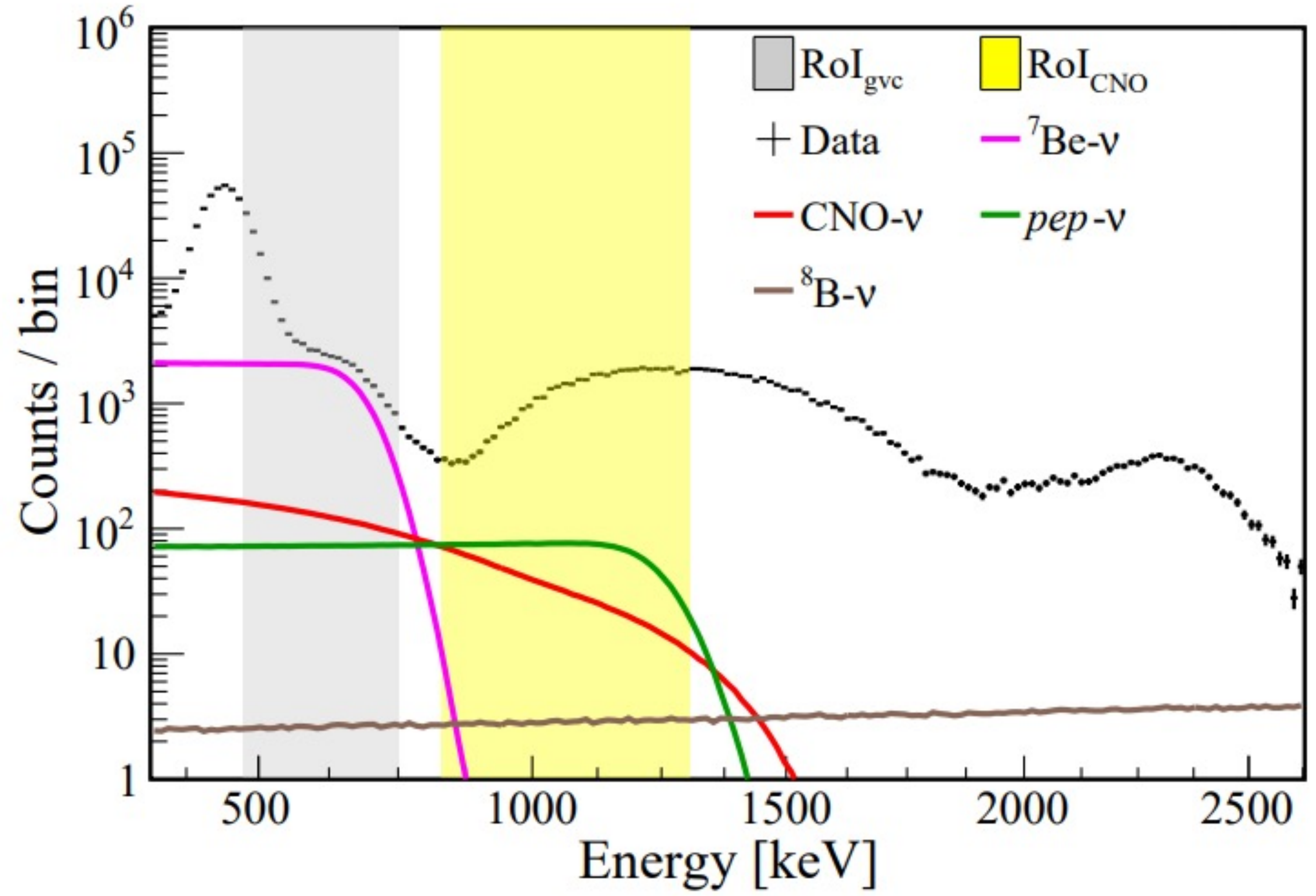


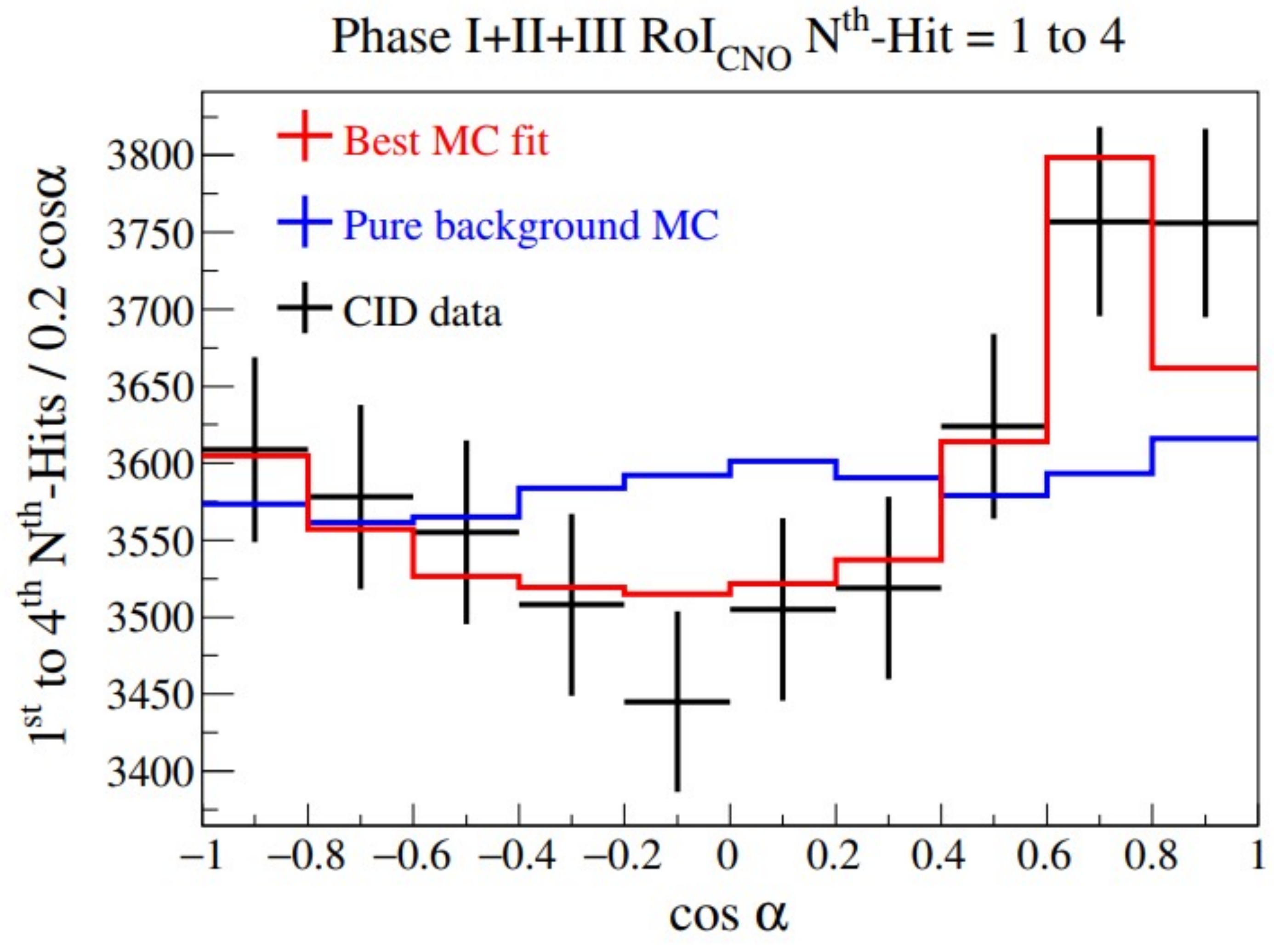




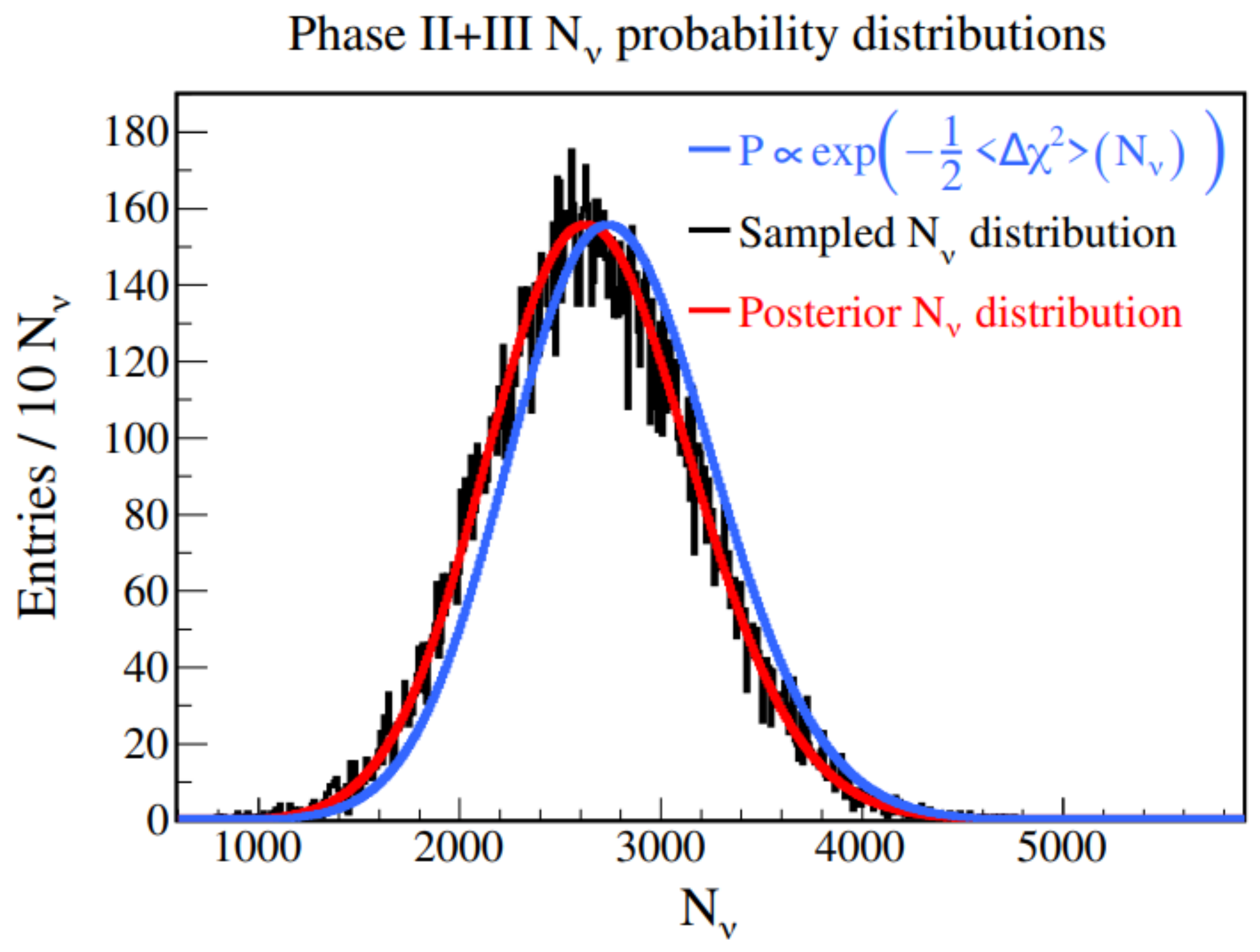
- Use integrated hit-level directional distribution to distinguish between solar events and uniform backgrounds.
- Discriminate Cherenkov photons and Scintillation photons with hit order.

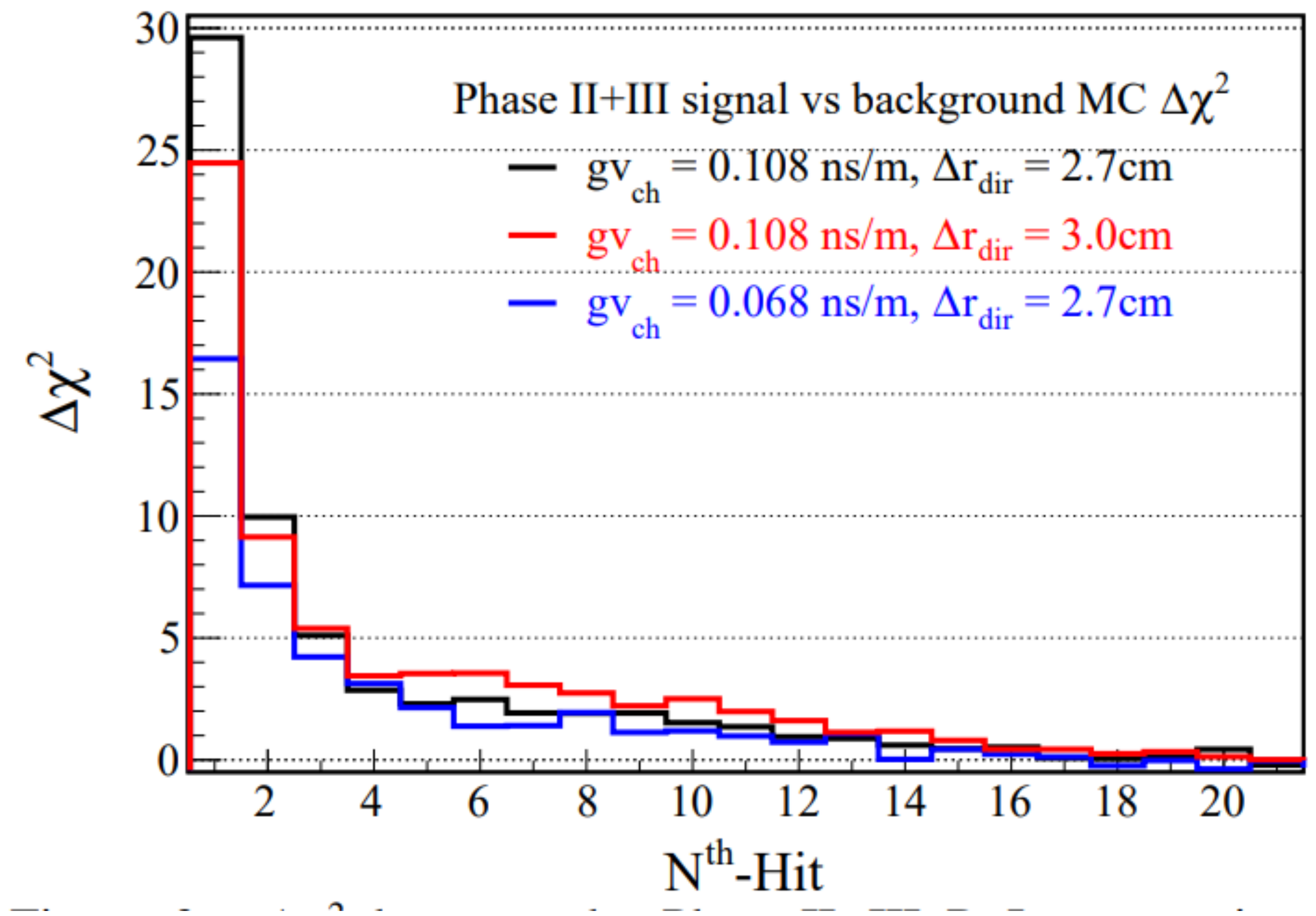
Borexino CNO with CID only

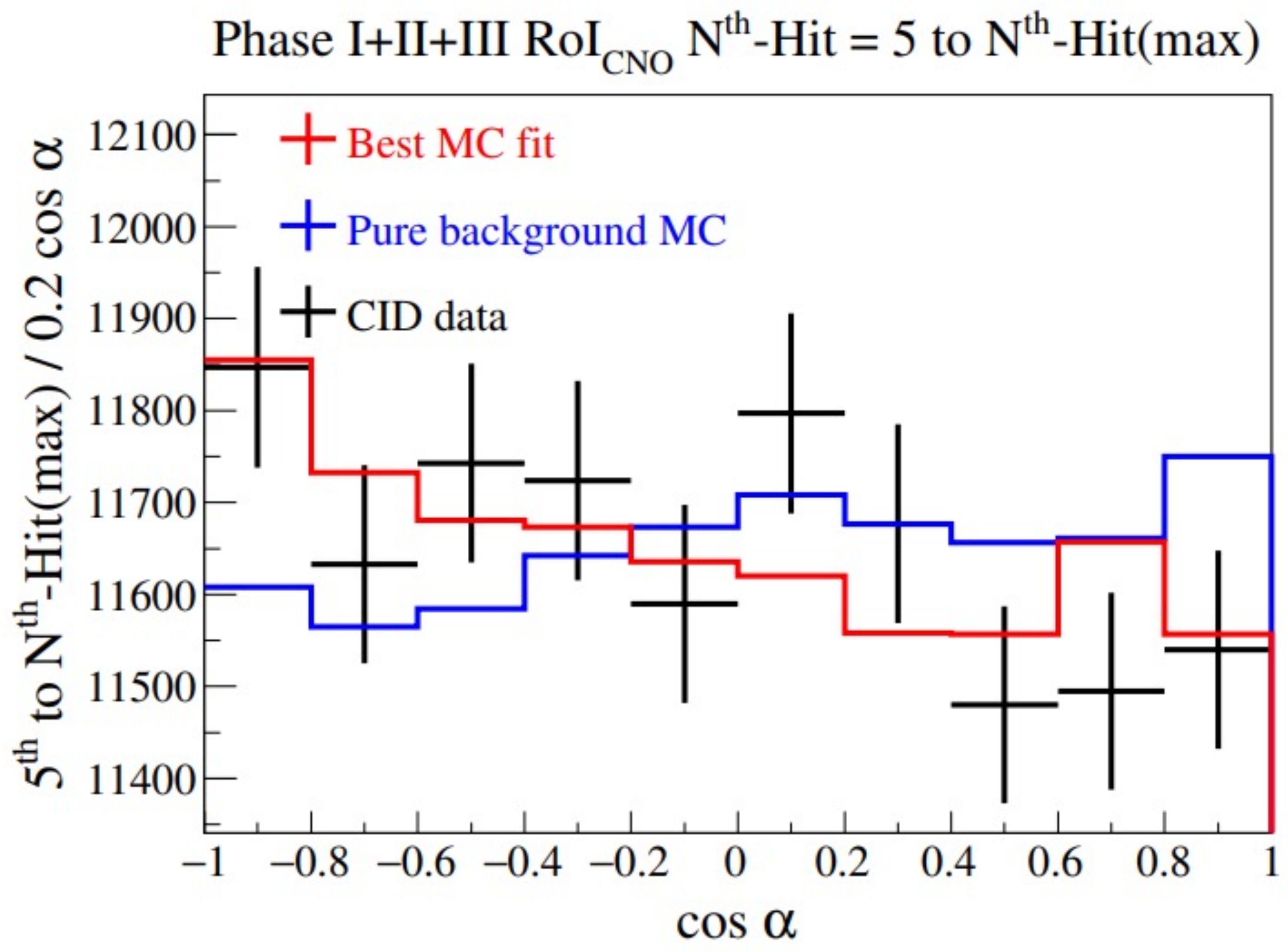




(a)



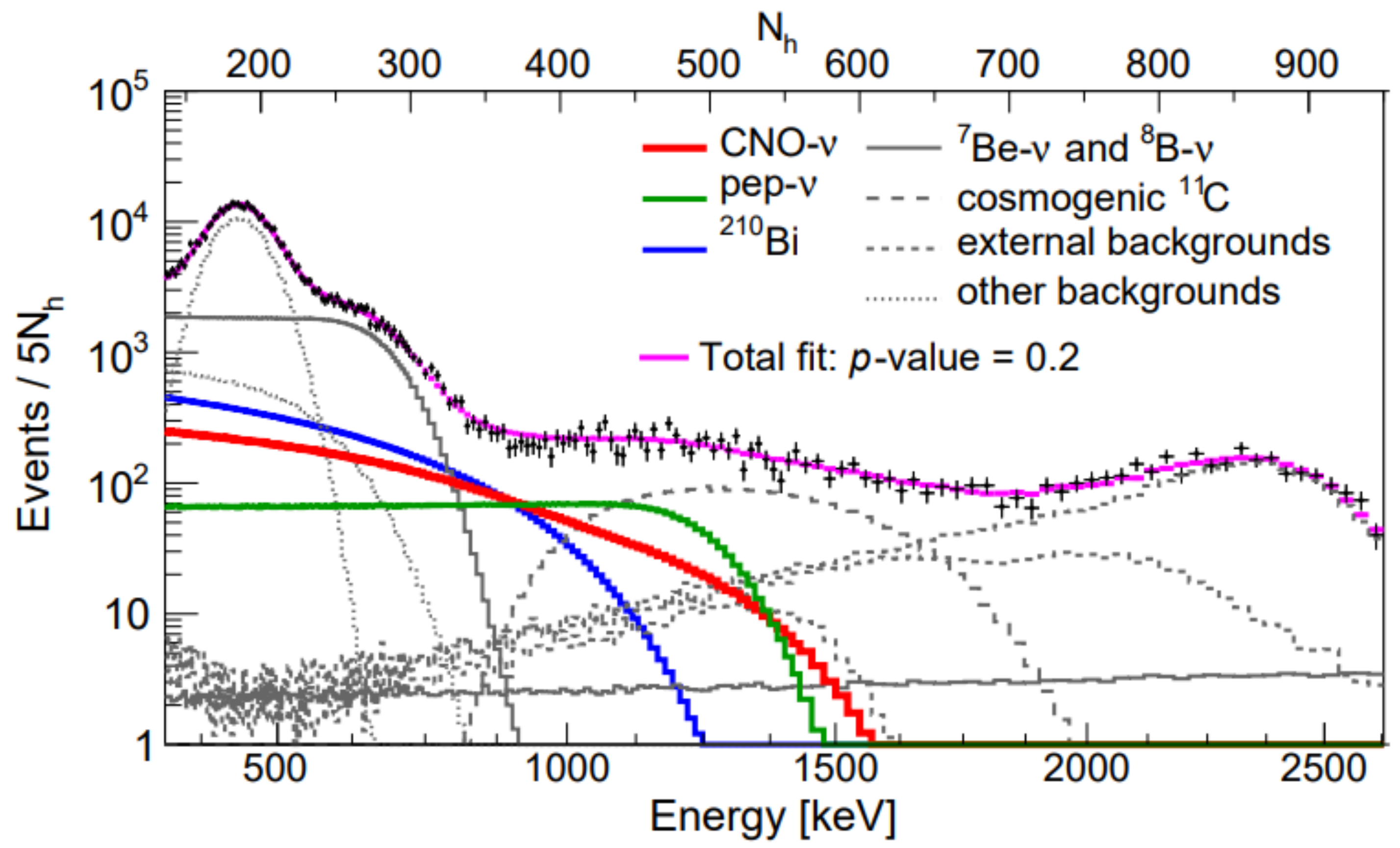


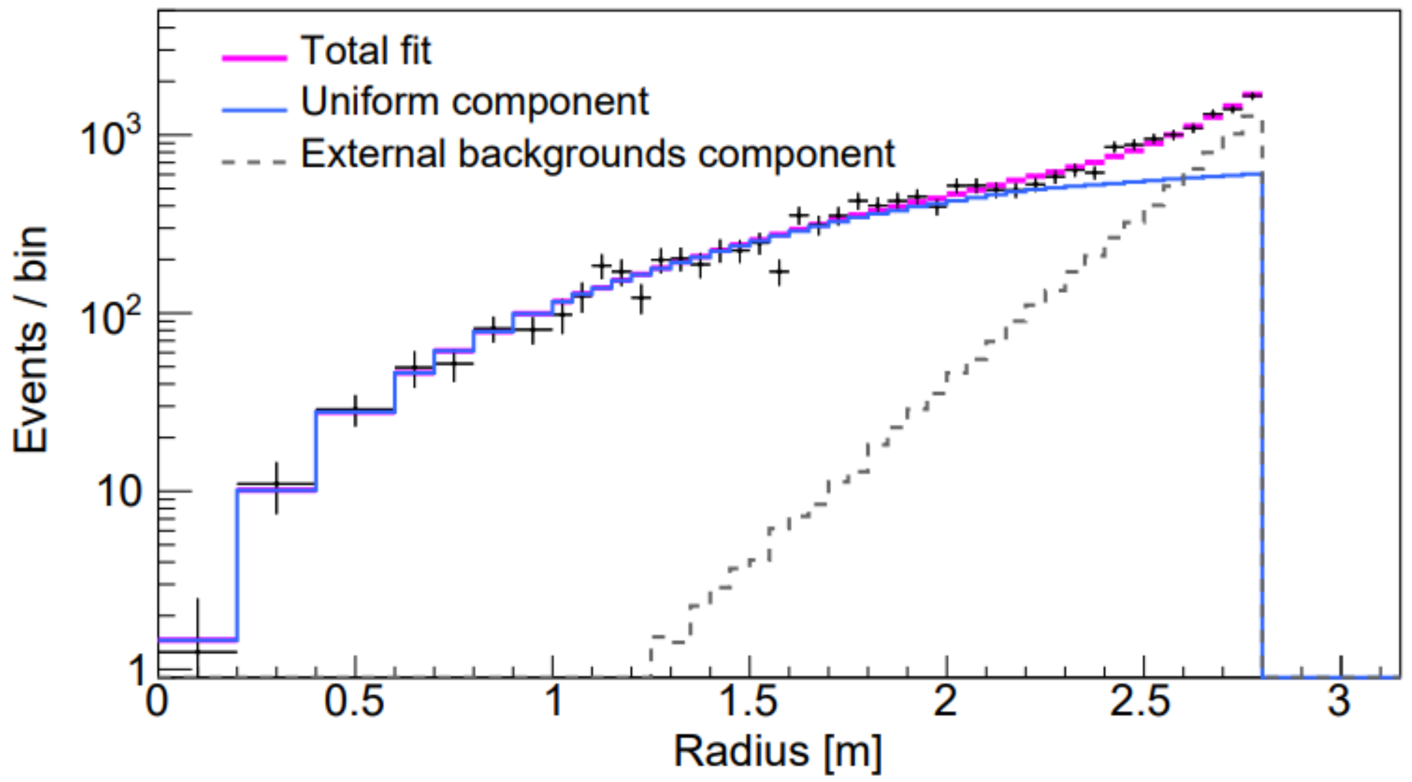


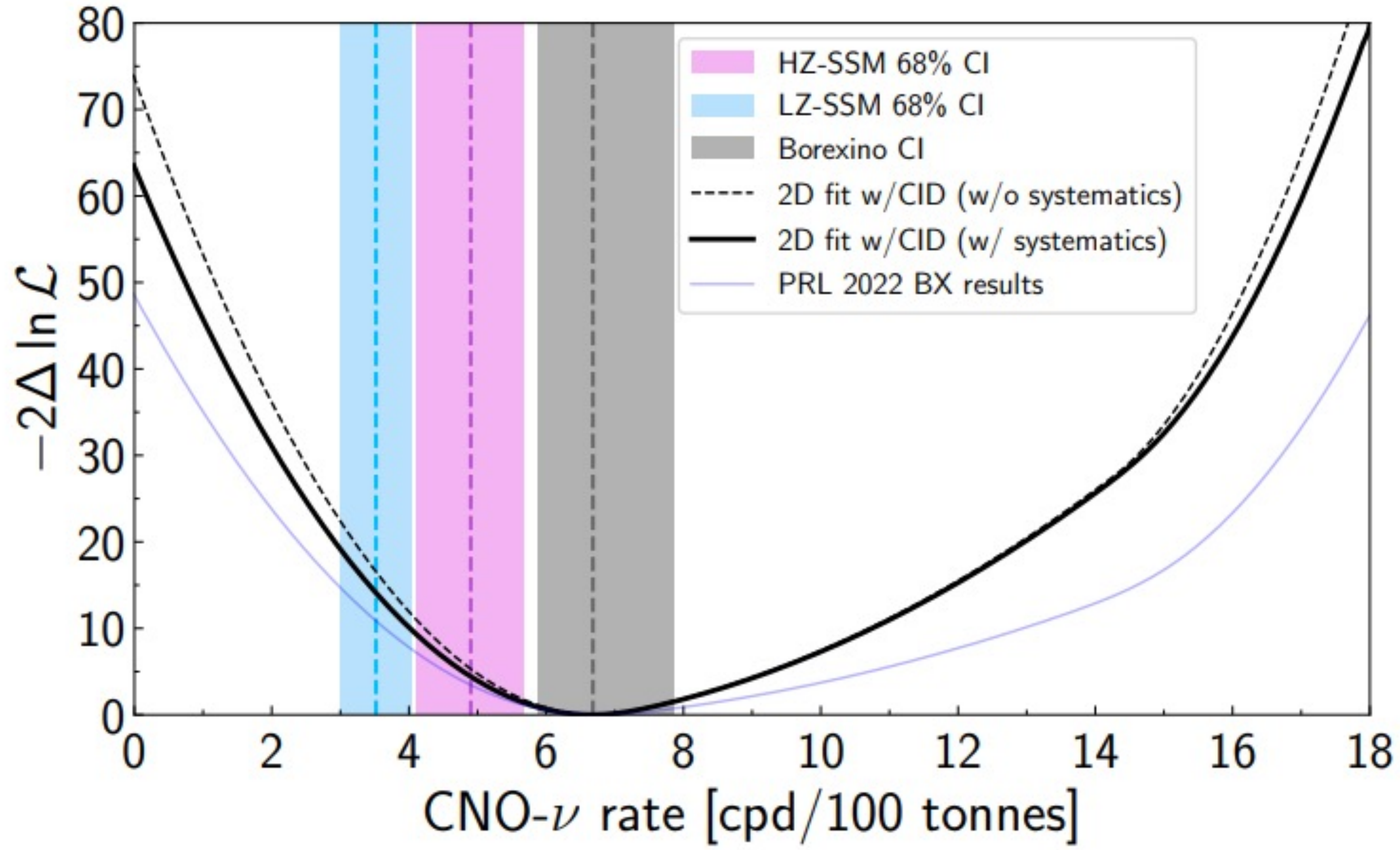
- CID with events in the CNO region of interest, $7.2^{+2.8}_{-2.7}$ cpd/100t
- Consistent with fit results.
- See Final results of Borexino on CNO solar neutrinos, arXiv:2307.14636 [hep-ex]

Borexino CID + MV fit

$$\mathcal{L}_{\mathrm{MV+CID}} = \mathcal{L}_{\mathrm{MV}} \cdot \mathcal{L}_{\mathrm{pep}} \cdot \mathcal{L}_{^{210}\mathrm{Bi}} \cdot \mathcal{L}^{\mathrm{P-I}}_{\mathrm{CID}} \cdot \mathcal{L}^{\mathrm{P-II+III}}_{\mathrm{CID}} \qquad (4)$$



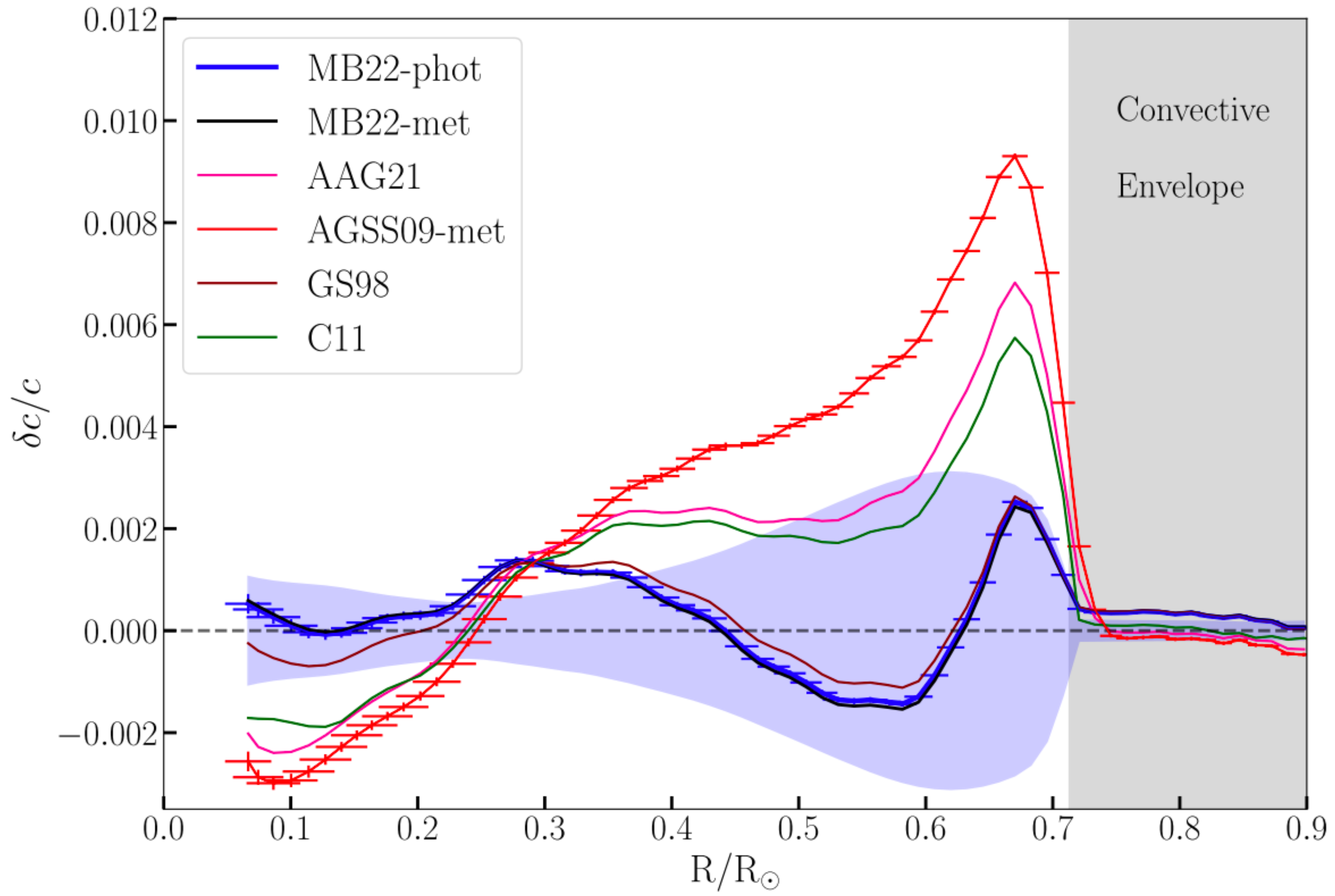




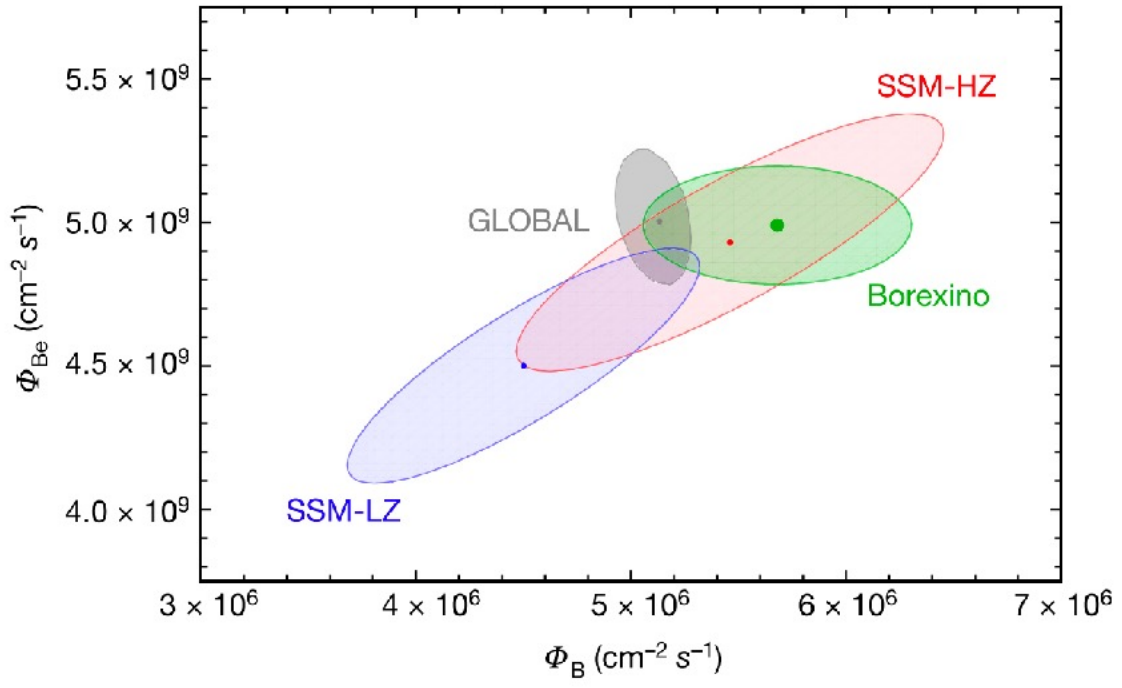
- Combining MV fit, CID analysis, Borexino obtained CNO as $6.7^{+1.2}_{-0.8}$ cpd/100t
- See Final results of Borexino on CNO solar neutrinos, arXiv:2307.14636 [hep-ex]

Solar abundance problem and Solar neutrinos

Sound speed profile

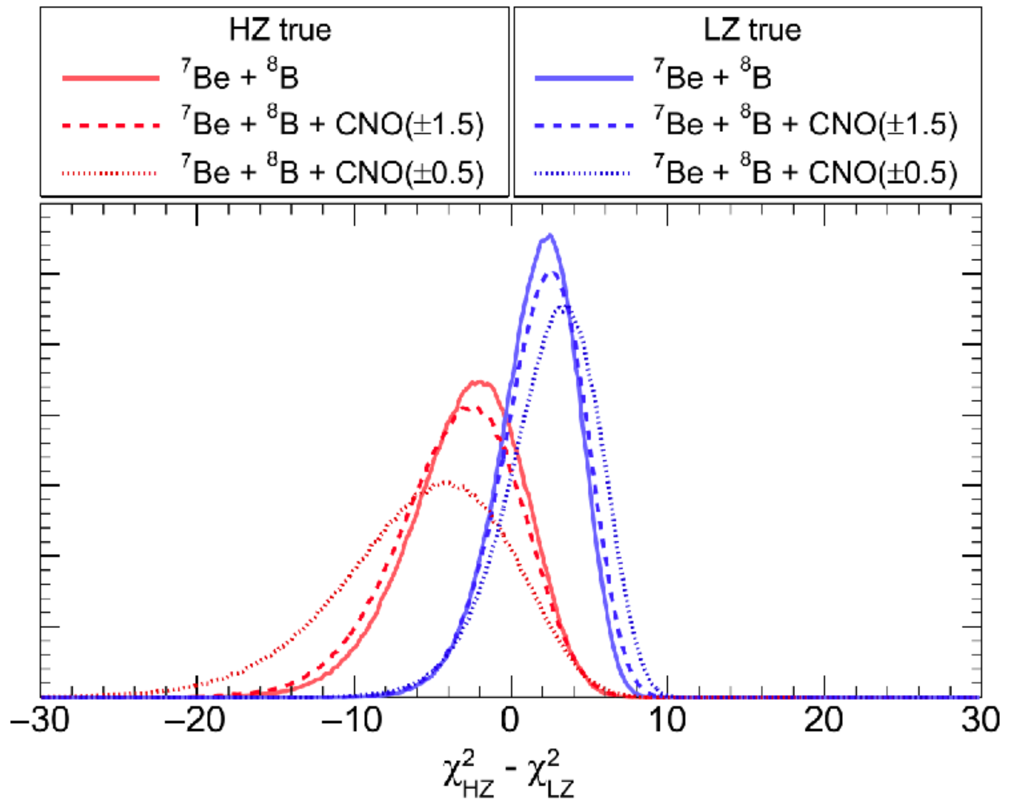


E. Magg et al. v2203.02255



Solar neutrino fluxes

Borexino Collaboration (2018). Comprehensive measurement of pp-chain solar neutrinos. Nature, 562(7728), 505–510.



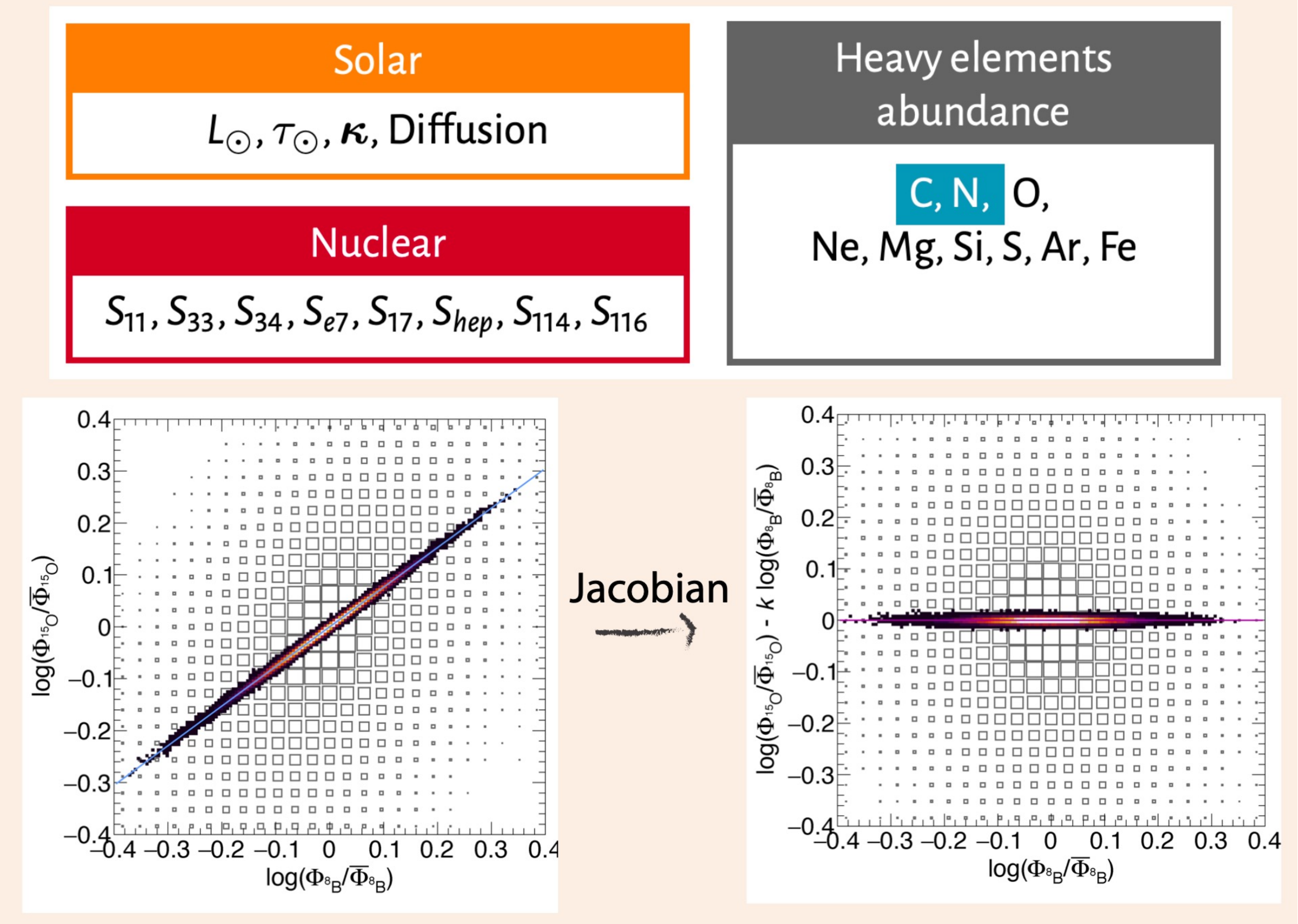
Hypothesis test against SSM-HZ/LZ

Borexino Collaboration. (2020). Sensitivity to neutrinos from the solar CNO cycle in Borexino. EPJC, 80(11).

- Volatile metal abundances is reconstructed from absorption lines.
- Various (say, HZ vs LZ) models exists. Neutrino fluxes can be used to test them.

pp-chain + CNO-cycle cancellation

- SSM inputs
  - Environmental, impact T_c (core temperature) Solar parameters, Heavy metal abundance;
  - Nuclear, not impacting T_c Nuclear matrix element
- If we modify "env without CN", T_c is modified,
  ln Φ(^{8}B) vs ln Φ(^{15}O) graph fall on the diagonal line
- If we modify also nuclear + CN: Environmental, impact T_c
  ln Φ(^{8}B) vs ln Φ(^{15}O) move away from diagonal
- Jacobian **Φ(^{8}B) vs Φ(^{15}O)** => **ln Φ(^{8}B) vs ln Φ(^{8}B)-κ ln Φ(^{15}O)**
  - **ln Φ(^{8}B)-κ ln Φ(^{15}O)** insensitive to "env without CN";
  - **ln Φ(^{8}B)-κ ln Φ(^{15}O)** (almost) only depend on nuclear + CN



Definitions

$\{Q\}$: SSM outputs $\quad q_i = Q_i/Q_i^{SSM}$

$\{\beta\}$: SSM inputs $\quad x_i = \beta_i/\beta_i^{SSM}$

$$\alpha(i,j) : \frac{\partial \ln q_i}{\partial \ln x_j}$$

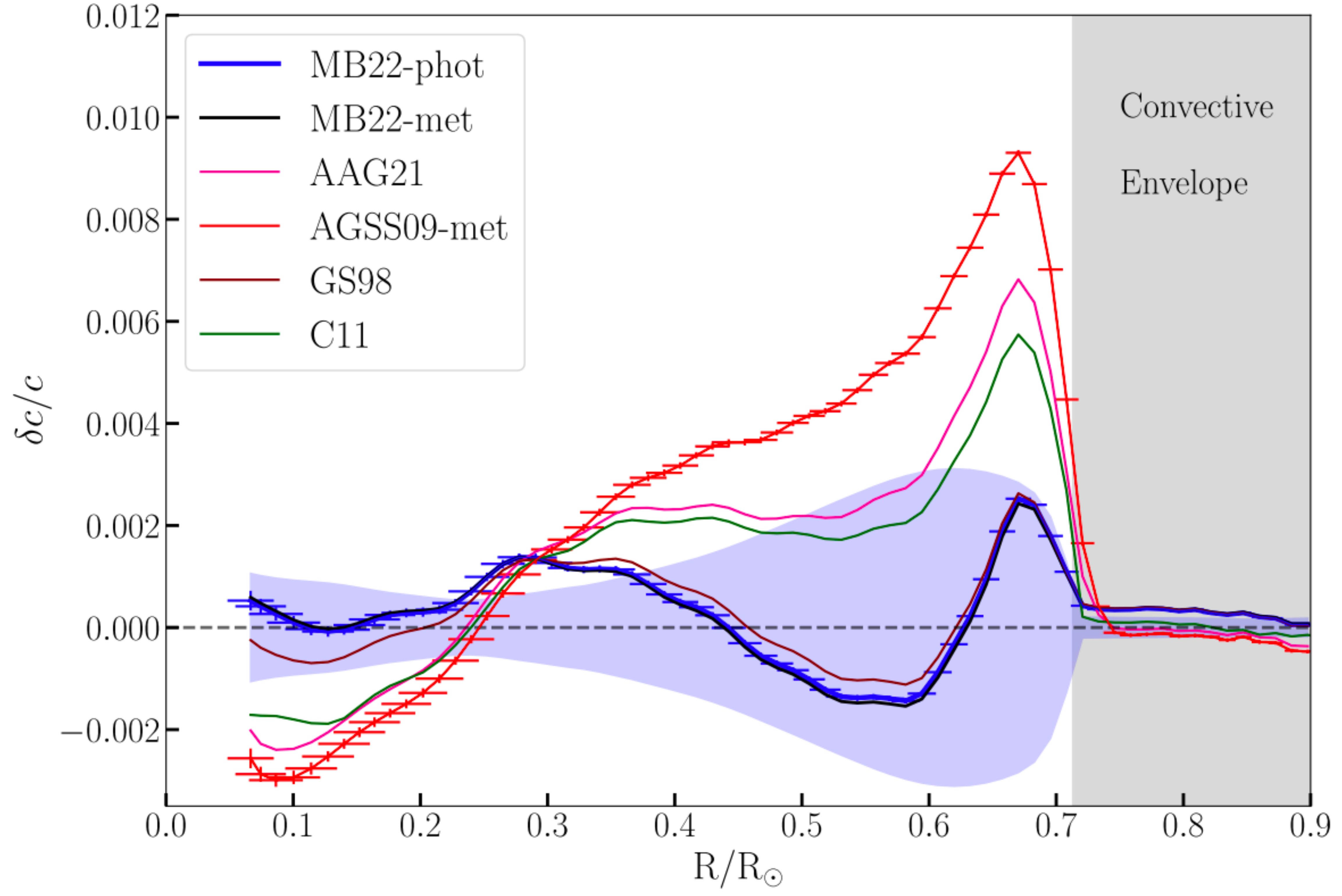
$$q_i = \prod_j^{sol} (x_j)^{\alpha(i,j)} \cdot \prod_j^{nucl} (x_j)^{\alpha(i,j)} \cdot \prod_j^{met} (x_j)^{\alpha(i,j)}$$

find κ which minimize Var

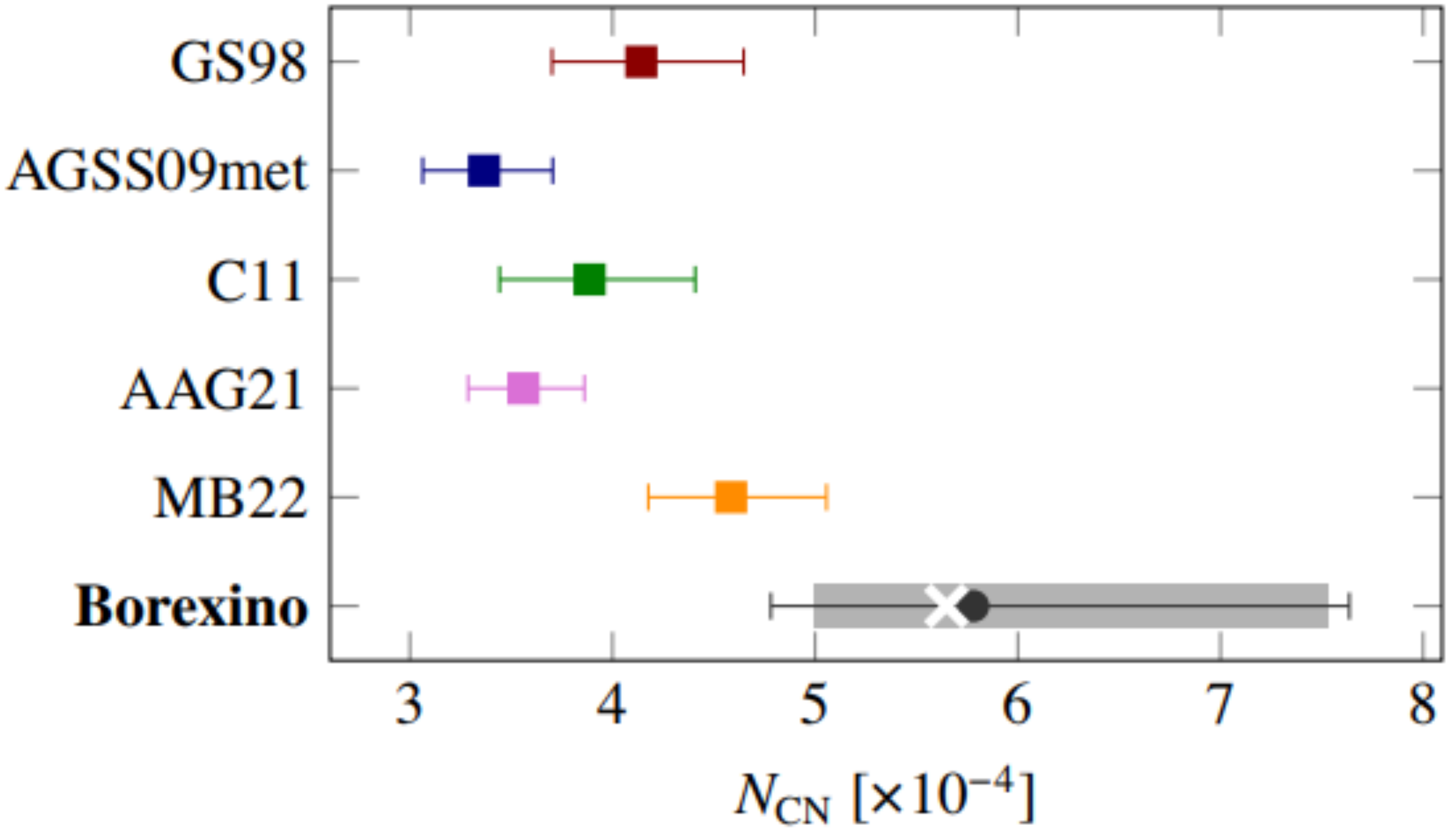
$$\mathrm{Var}\left[\frac{\varphi_{^{15}O}}{\varphi_{^8B}^k}\right] = \sum_j^{env} \left[\alpha(^{15}O, j) - k\alpha(^8B, j)\right]^2 \cdot (\delta x_j)^2$$

Results: CN abundance from solar neutrinos

Comparison on sound speed
(E. Magg et al. v2203.02255)



Comparison on CN abuandance (Borexino, PRL 2022)

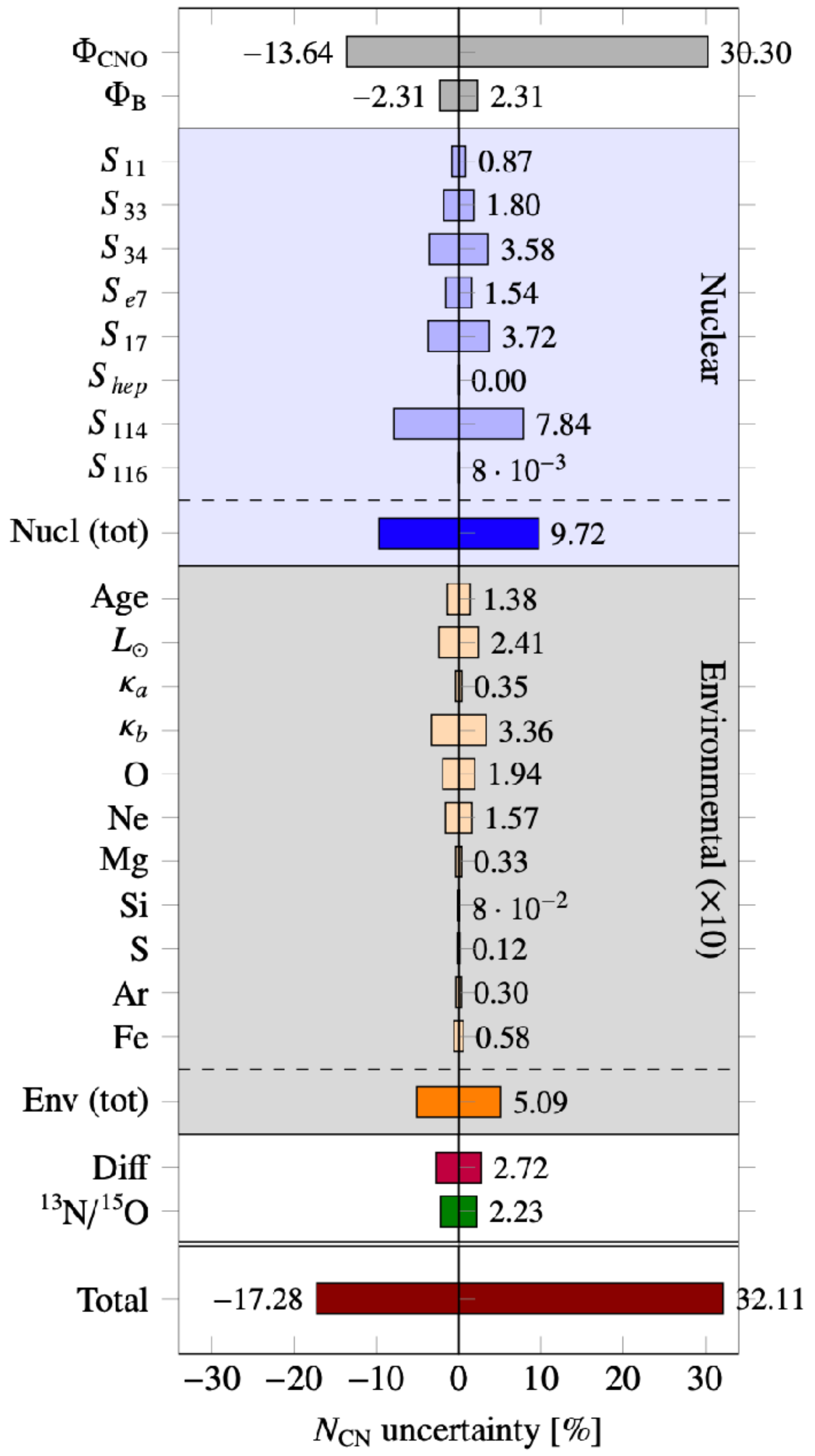


More to expect?

- DARWIN claimed may measure pp neutrinos at 0.15% level with 300ty (DARWIN, EPJC 80, 1133, 2020).
  - May be used together with luminosity to constrain CNO neutrino flux (Francesco Vissani, Solar Neutrinos, 121-141, 2019)
- Metallicity measurement limited by fusion cross-section measurement. To be updated. LUNA-MV
- Next generation experiments may establish evidence of solar neutrinos from *hep* branch (SoLAr).

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

Francesco Vissani, Luminosity constraint and entangled solar neutrino signals , Solar Neutrinos, pp. 121-141 (2019)



systematics in measurement of metallicity using solar neutrinos

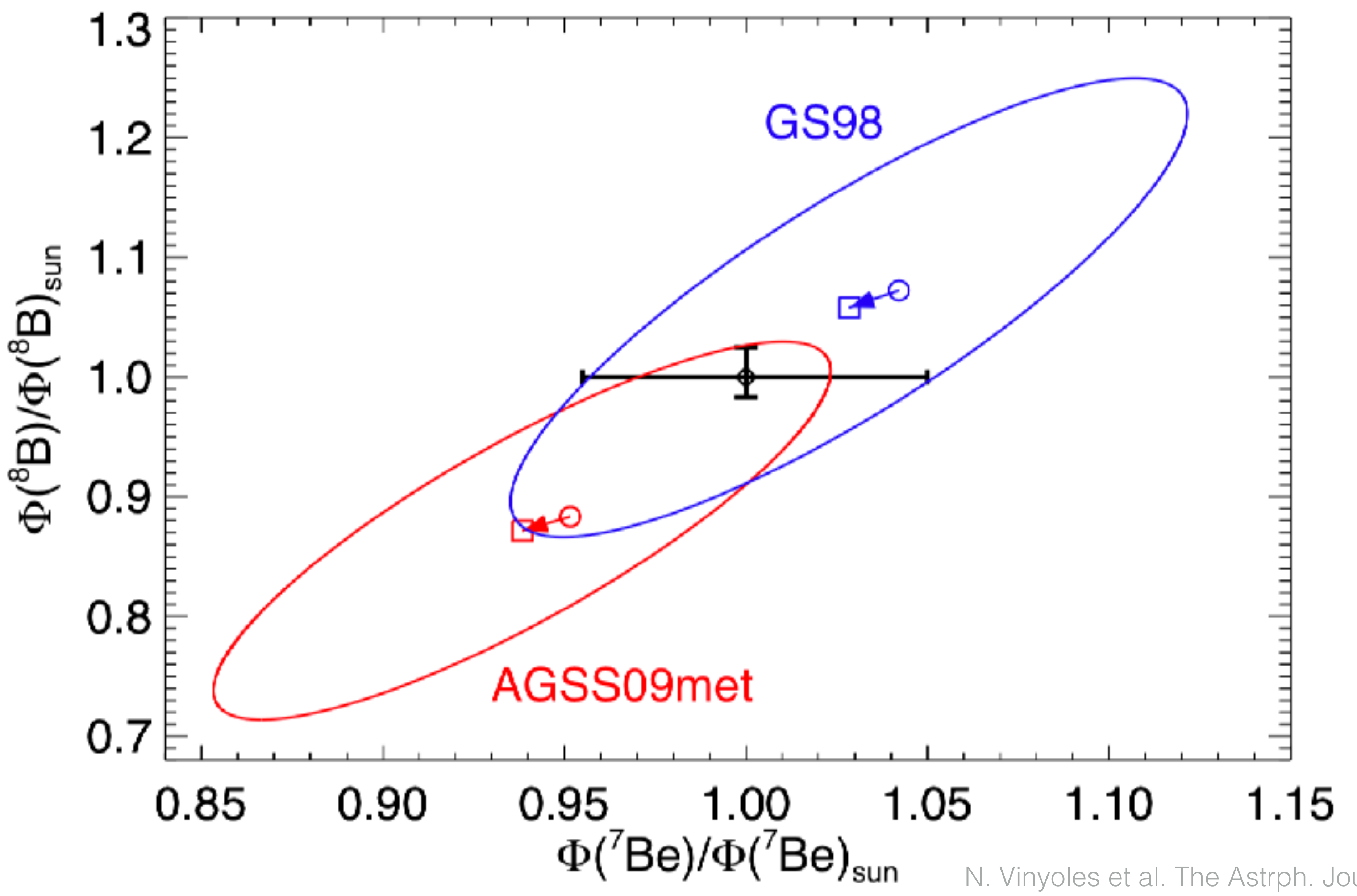
(From talk of Borexino on Neutrino 2022)

JUNO

Why solar neutrinos for JUNO

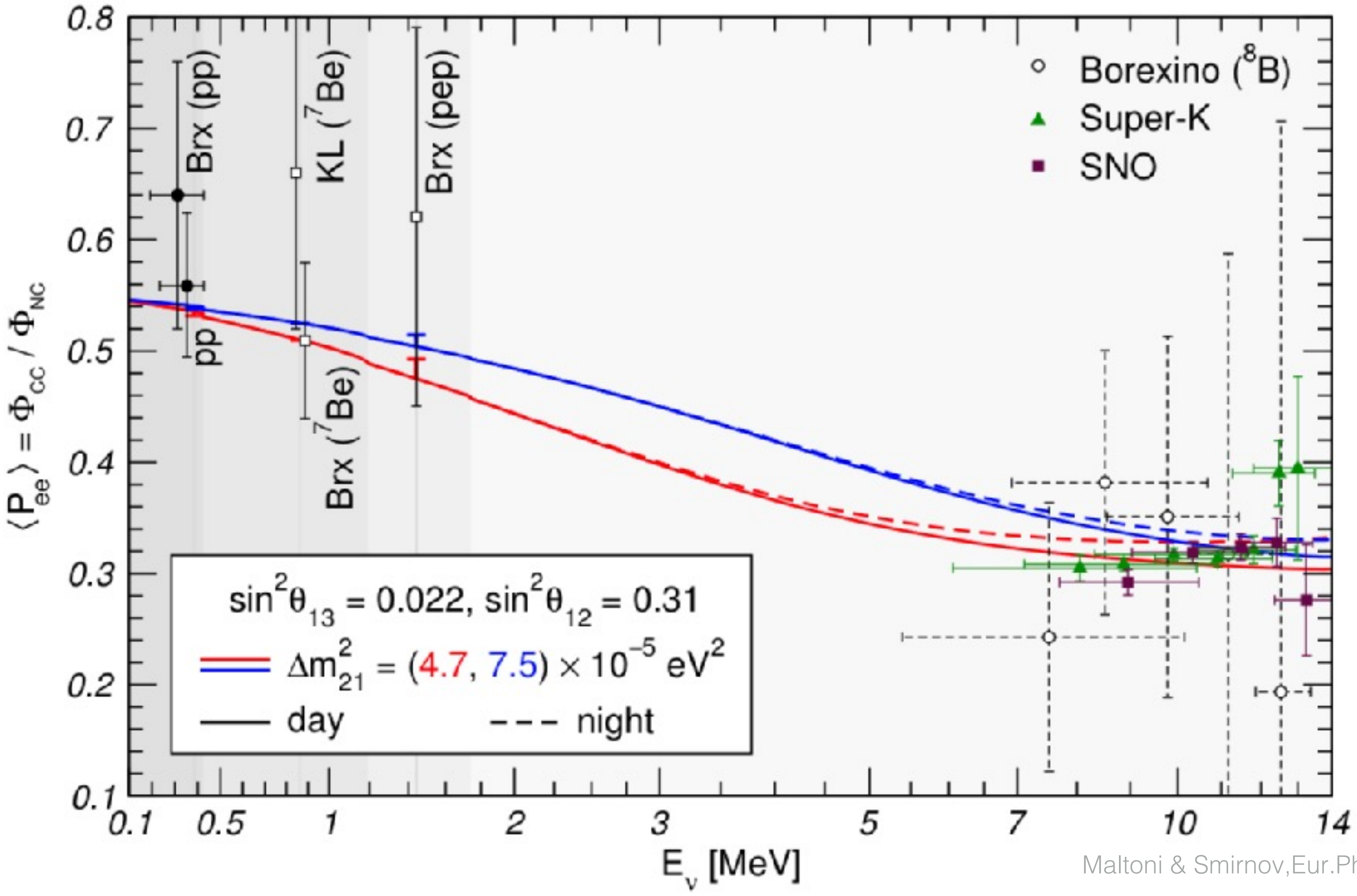
- Solar neutrino is produced in the **core region of the sun**. => study the core of the sun
- Solar neutrino propagate through **ultra-high-density region** and become **flavor-stable** => study MSW resonance

Two solar metallicity models



N. Vinyoles et al. The Astrph. Journ. 835 1 (2017) Improoved model

Solar vs global MSW-LMA survival prob.



Maltoni & Smirnov,Eur.Phys.J.2016

The MSW effect

- Matter effect: additional “potential” term.
- Solar neutrinos: no “oscillation” due to averaging.

$$i \frac{\mathrm{d}}{\mathrm{d}x} \Psi_\alpha = \mathcal{H}_\mathrm{F} \Psi_\alpha . \tag{9.54}$$

This equation has the structure of a Schrödinger equation with the effective Hamiltonian matrix $\mathcal{H}_\mathrm{F}$ in the flavor basis given by

$$\mathcal{H}_\mathrm{F} = \frac{1}{2E} \left(U \mathbb{M}^2 U^\dagger + \mathbb{A} \right) . \tag{9.55}$$

In the case of three-neutrino mixing, we have

$$\Psi_\alpha = \begin{pmatrix} \psi_{\alpha e} \\ \psi_{\alpha\mu} \\ \psi_{\alpha\tau} \end{pmatrix} , \qquad \mathbb{M}^2 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix} , \qquad \mathbb{A} = \begin{pmatrix} A_\mathrm{CC} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} , \tag{9.56}$$

where

$$A_\mathrm{CC} \equiv 2 E V_\mathrm{CC} = 2\sqrt{2} E G_\mathrm{F} N_e . \tag{9.57}$$

$$\overline{P}^{\text{adiabatic}}_{\nu_e \to \nu_e} = \frac{1}{2} + \frac{1}{2} \cos 2\vartheta^{(\mathrm{i})}_\mathrm{M} \cos 2\vartheta ,$$

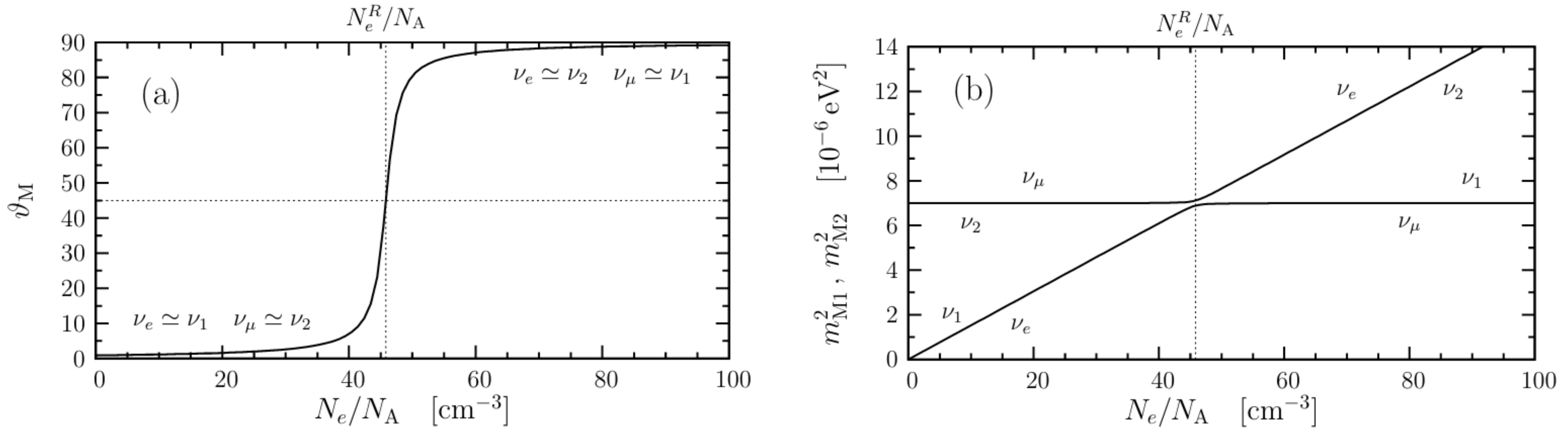
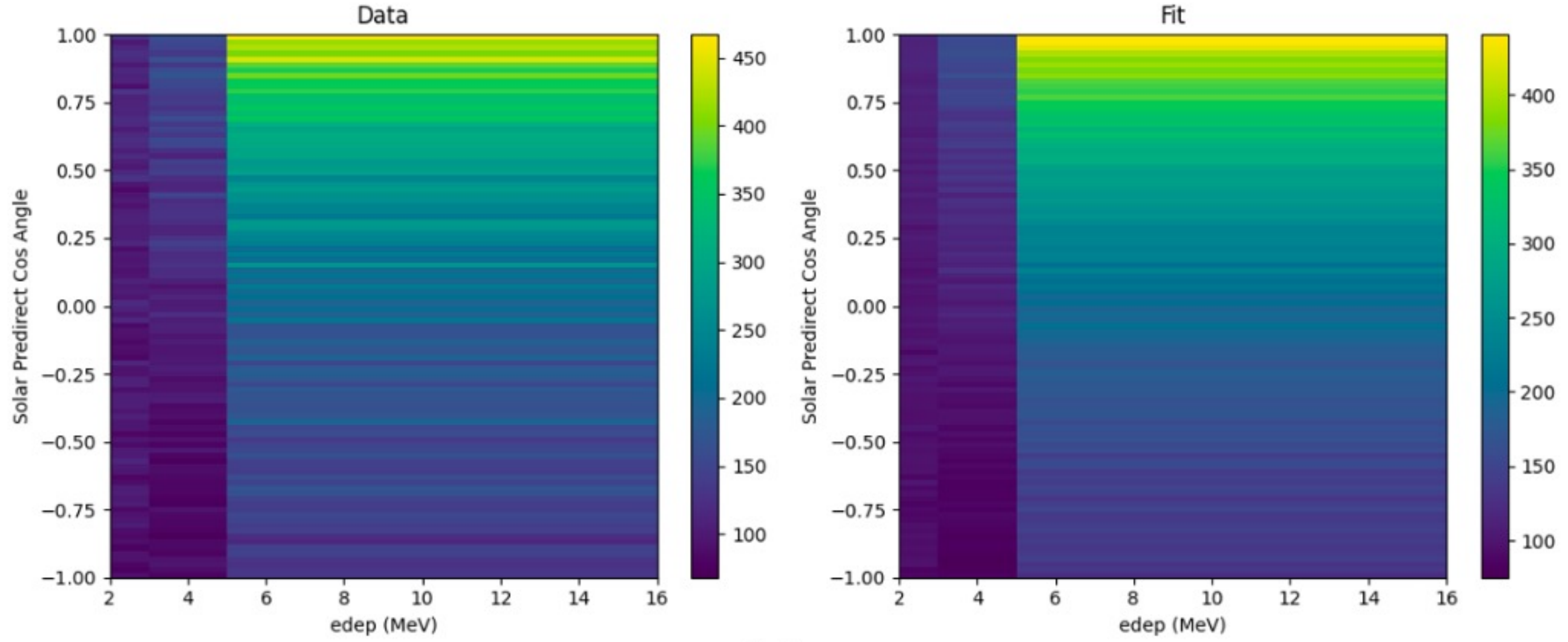


FIG. 9.2. Effective mixing angle ϑ_M (a) and the effective squared-masses $m^2_{\mathrm{M}1}$, $m^2_{\mathrm{M}2}$ (b) in matter as functions of the electron number density N_e divided by the Avogadro's number N_A, for $m_1 = 0$, $\Delta m^2 = 7 \times 10^{-6}\,\mathrm{eV}^2$, $\sin^2 2\vartheta = 10^{-3}$ and $E = 1\,\mathrm{MeV}$. $N_e^\mathrm{R} \equiv \Delta m^2 \cos 2\vartheta / 2\sqrt{2} E G_\mathrm{F}$ is the electron number density at the resonance, where $\vartheta_\mathrm{M} = 45°$.

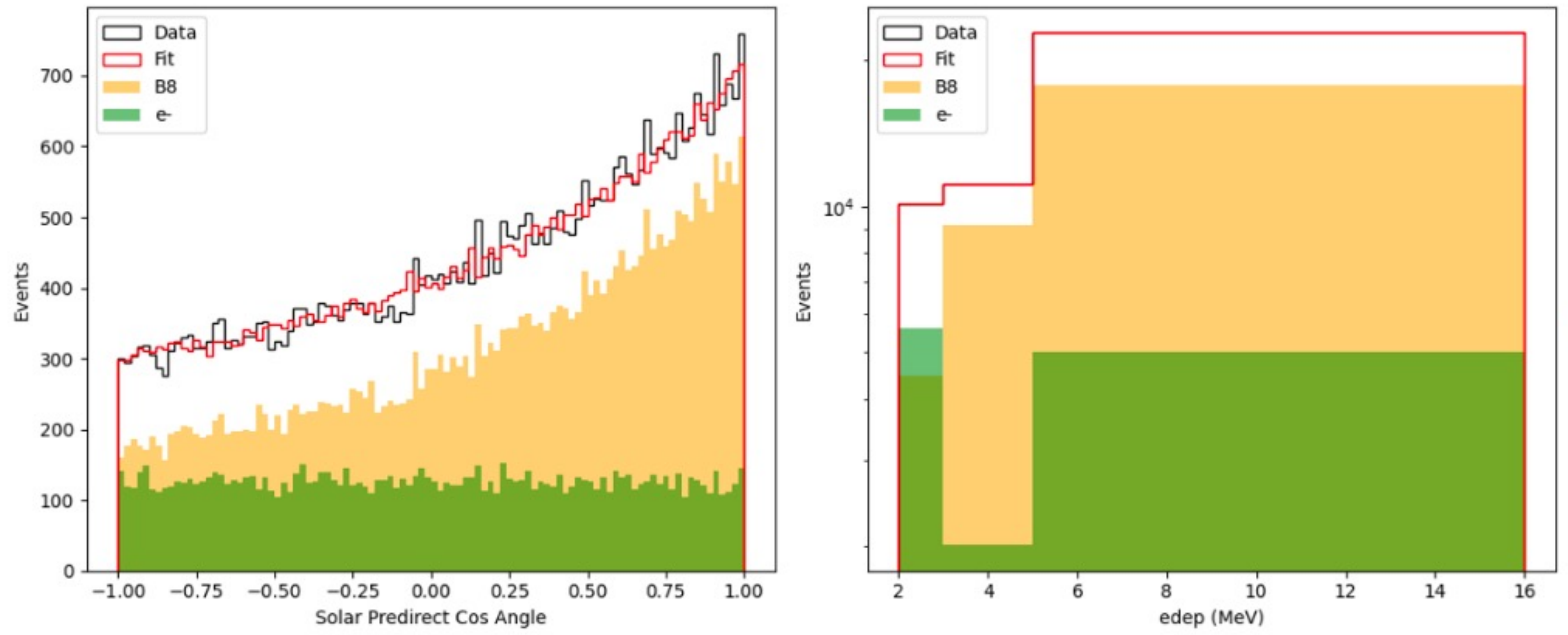
^{8}B太阳中微子灵敏度分析

结合方向重建的二维拟合

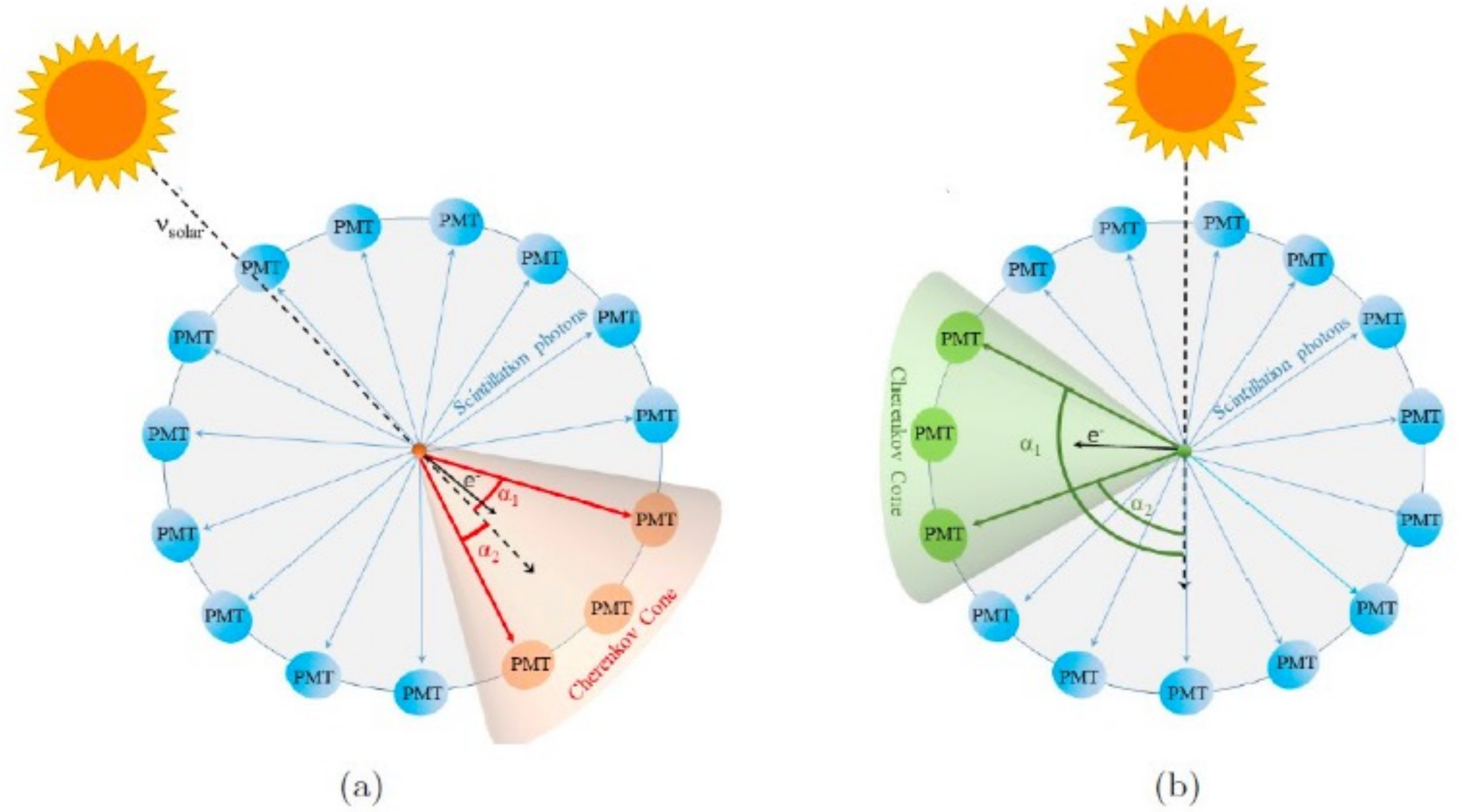
$$F_{\text{cost}} = \sum_{i,j}^{N,M}(-\lambda_{ij} + k_{ij}log(\lambda_{ij}) - log(k_{ij}!))$$



(a)



(b)



拟合变量：

1. 事例重建方向与太阳方位夹角余弦（Solar cos angle)
2. 沉积能量 （edep)

与一维拟合相比，二维流强拟合相对误差降低，证明了方向信息能够有效提升^{8}B中微子的测量精度。

拟合结果：

Type	E (MeV)	Fit rate (cpd/kton)	Relative error
^{8}B	(2, 3)	0.340	0.161
	(3, 5)	0.404	0.063
	(5, 16)	0.586	0.027
e^-	(2, 3)	0.360	0.150
	(3, 5)	0.096	0.260
	(5, 16)	0.185	0.830

相对误差降低

12

基于深度学习的方向重建

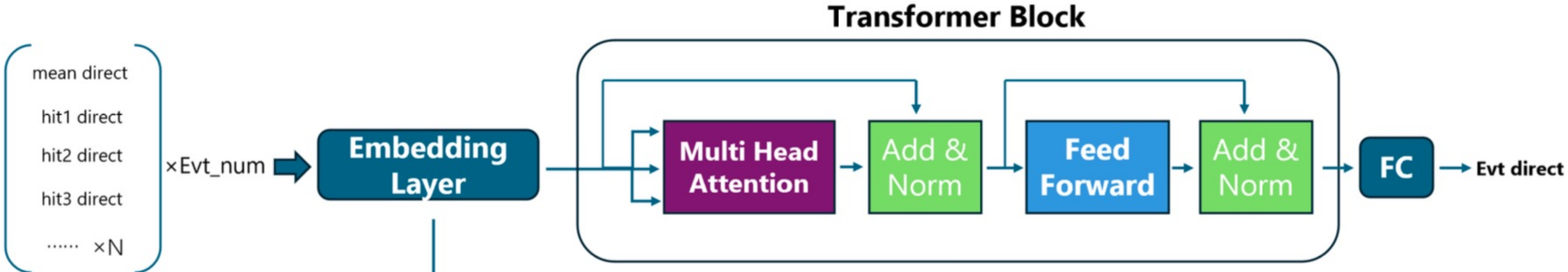
卷积神经网络

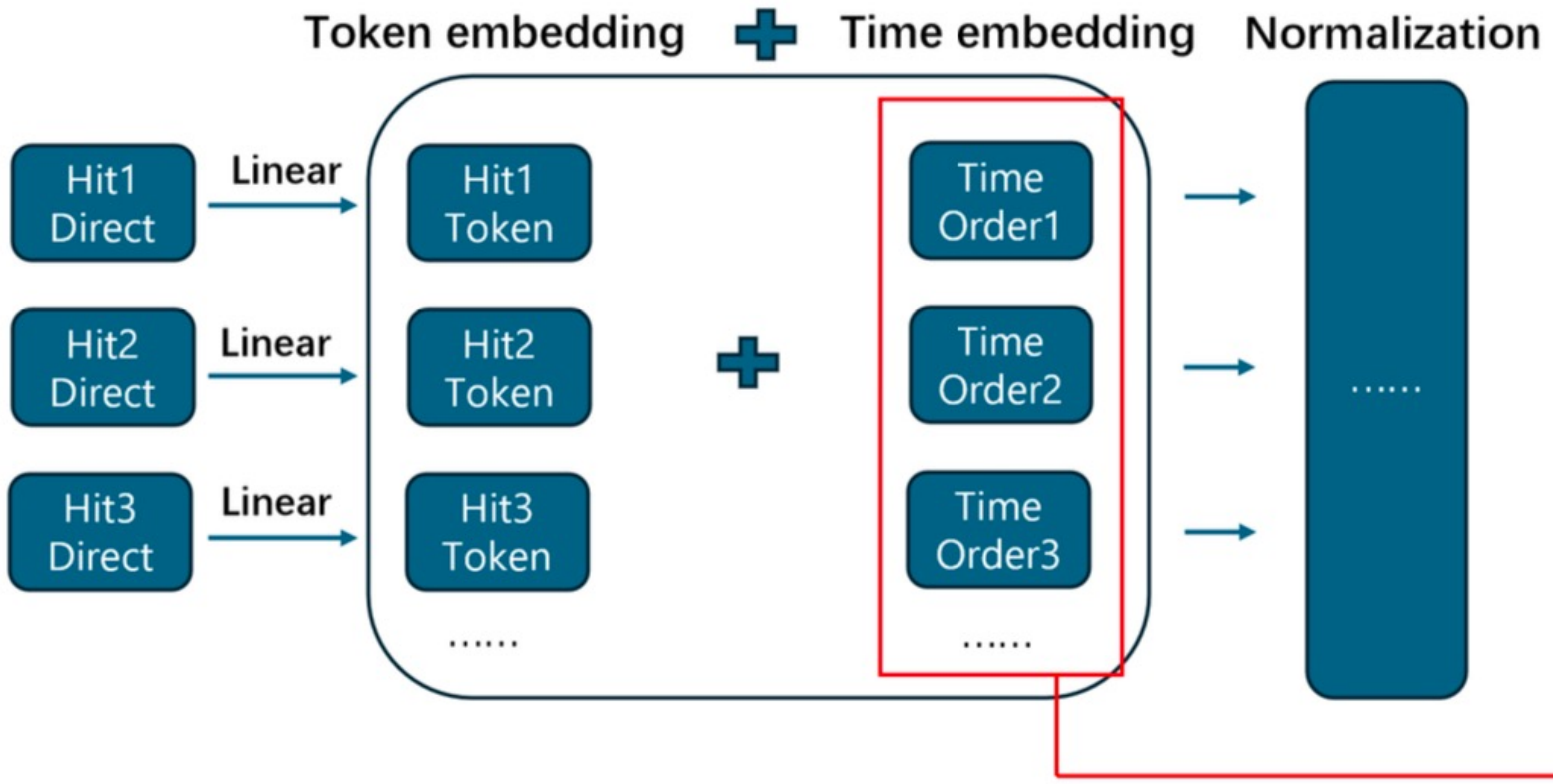
CRCP (CNN based)	
Input Layer	Conv2d-32 (9×9)
Feature Extraction Layers	Conv2d-64 (3×3)
	Conv2d-128 (3×3)
	Conv2d-256 (3×3)
	Conv2d-512 (3×3) Conv2d-512 (3×3)
Flatten Layer	
Fully Connected Layers	FC-128 FC-2
Total Parameters	2,826,754

ResNet-18	
Input Layer	Conv-64 (9×9)
Convolution Layer	Conv_x [3×3 64; 3×3 64] ×2
	Conv_x [3×3 128; 3×3 128] ×2
	Conv_x [3×3 256; 3×3 256] ×2
	Conv_x [3×3 512; 3×3 512] ×2
AvgPool & Fc-2	
Trainable parameters : 99,083,010	

基于深度学习的方向重建

Transformer模型





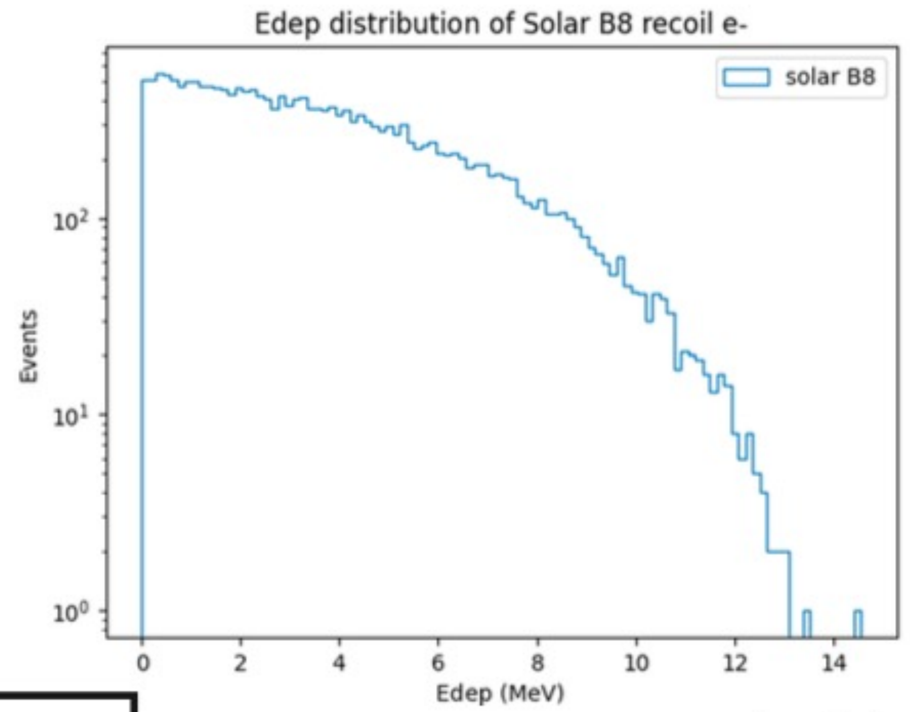
Hyper-Parameter	
embed_dim	64
multi_head	2
transformer block	1
ff_dim	128

$$TE_{(order,2i)} = \sin\left(\frac{order}{10000^{\frac{2i}{embed\ dim}}}\right)$$

$$TE_{(order,2i+1)} = \cos\left(\frac{order}{10000^{\frac{2i}{embed\ dim}}}\right)$$

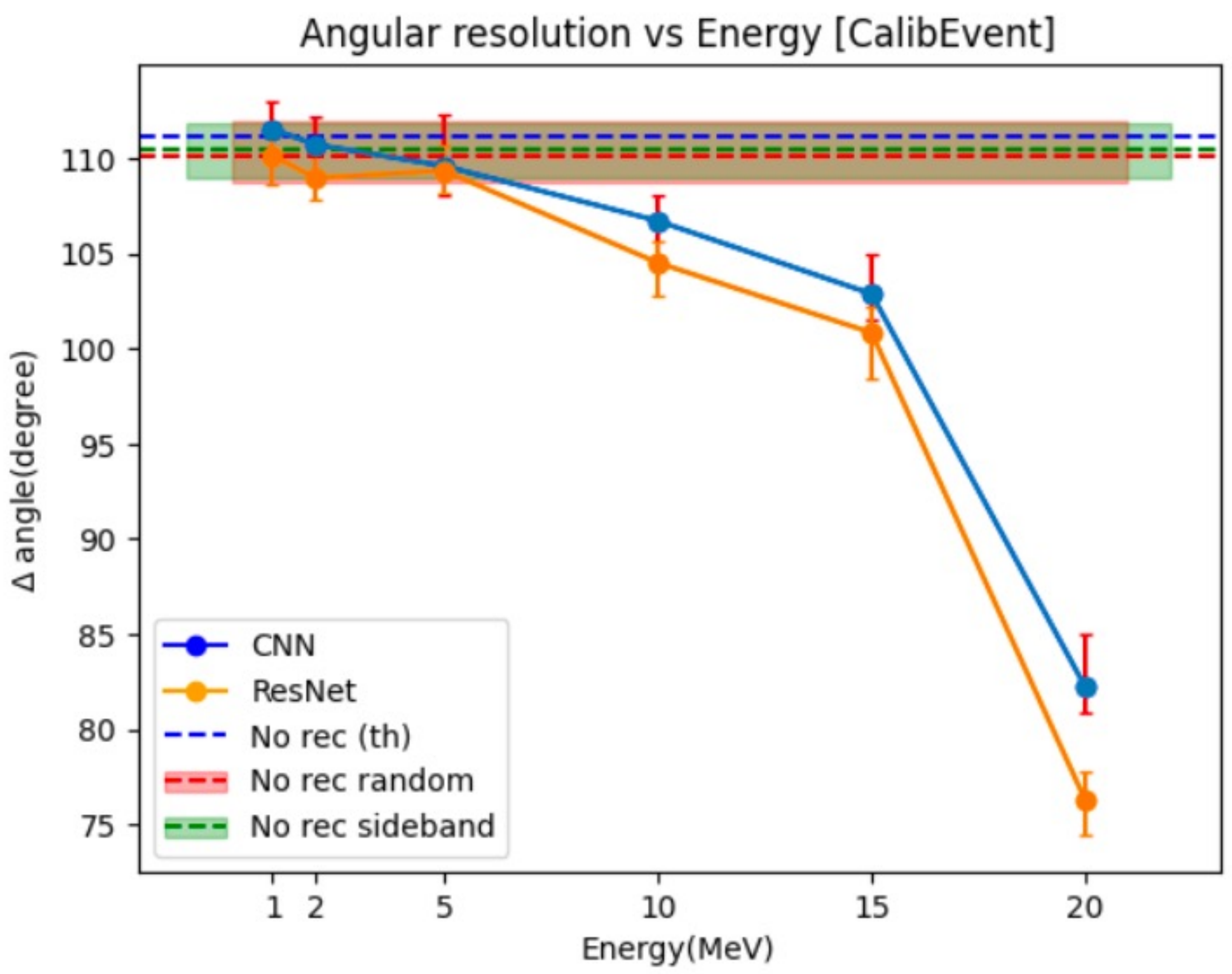
基于深度学习的方向重建

重建性能

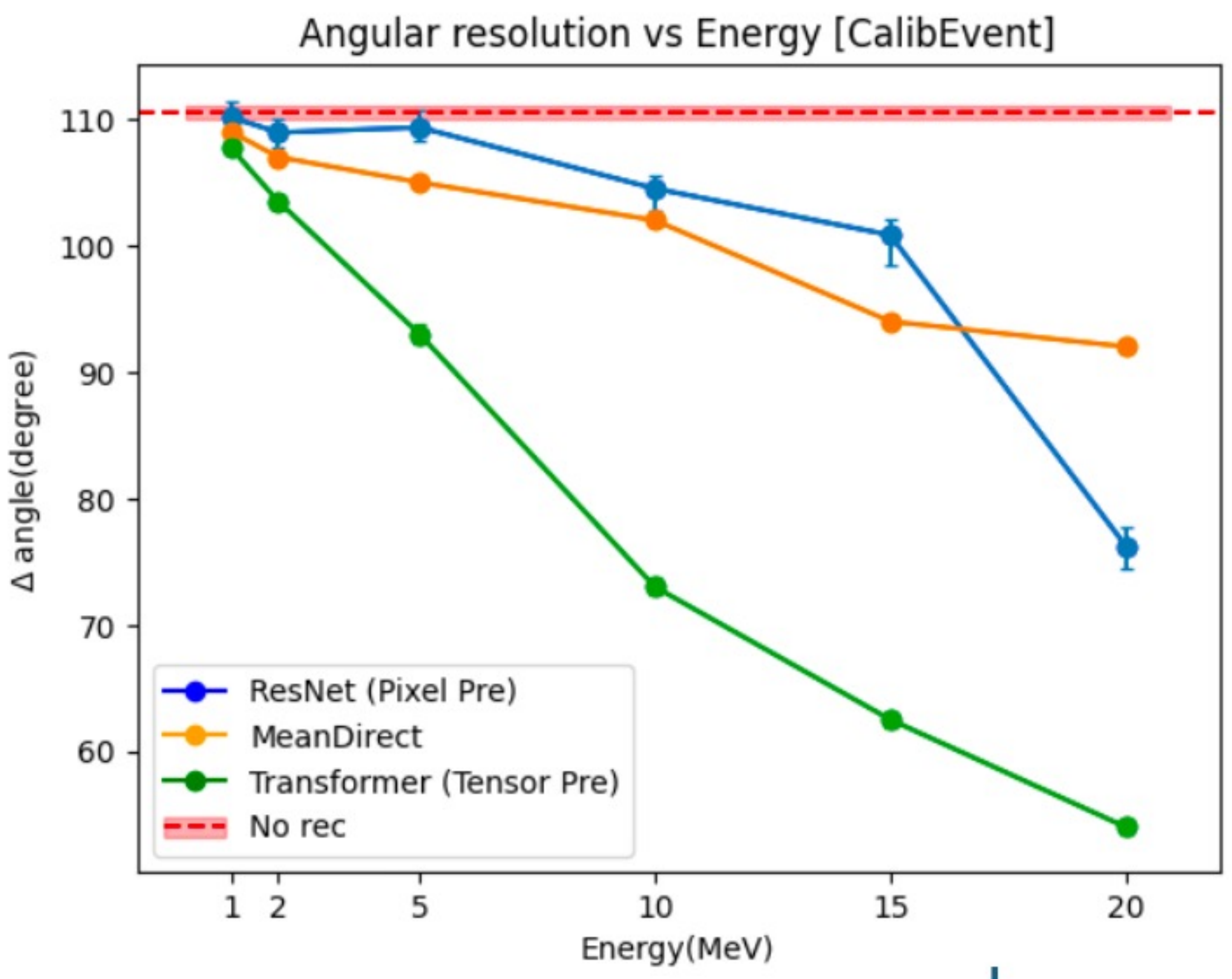


利用电子数据集验证性能：（角度重建精度越小，重建效果越好）

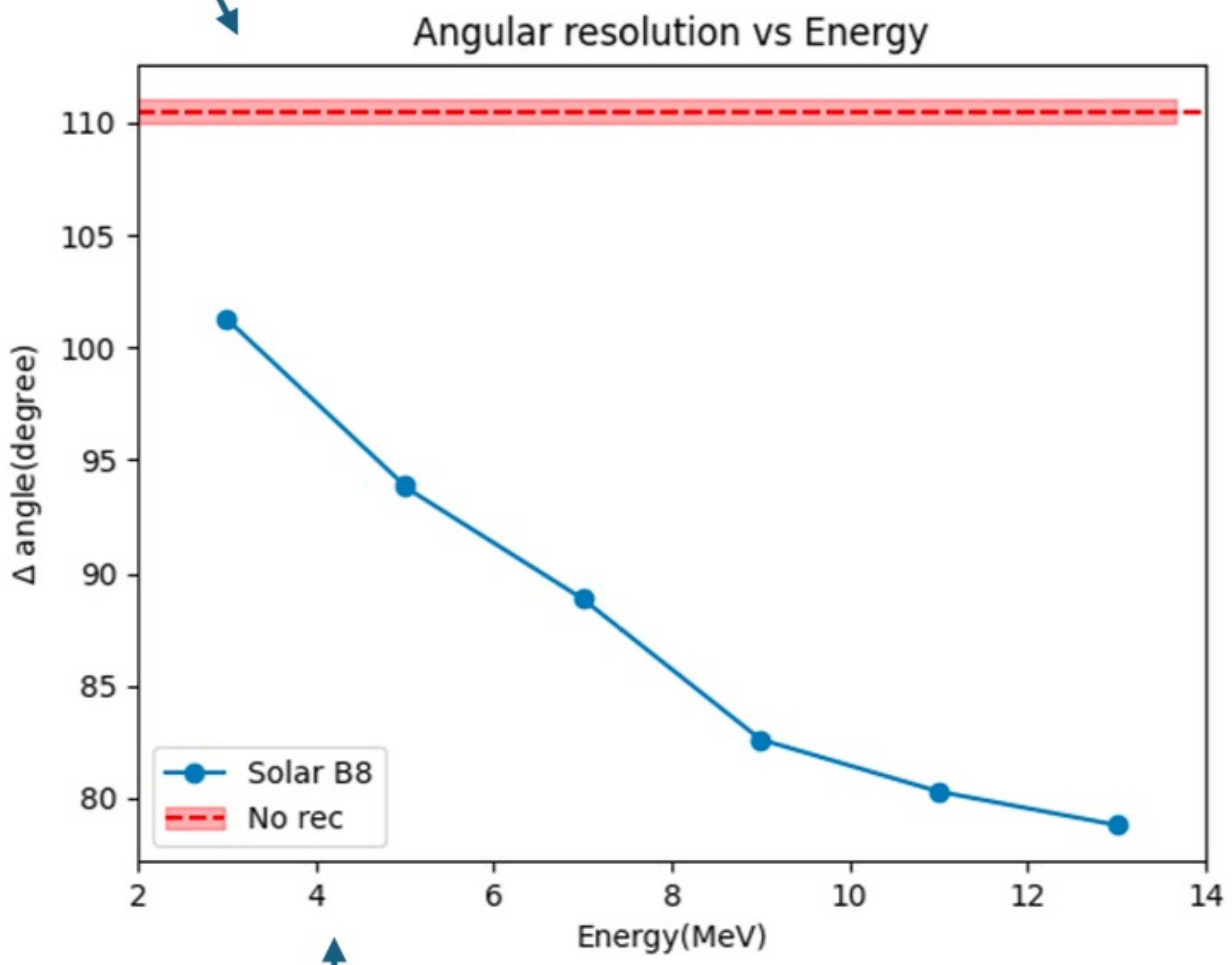
基于像素图预测的方向重建



基于数值矩阵的方向重建



^{8}B中微子事例方向重建



Energy：电子动能

Δangle：重建方向与实际方向间夹角一倍标准偏差值（重建角度精度）

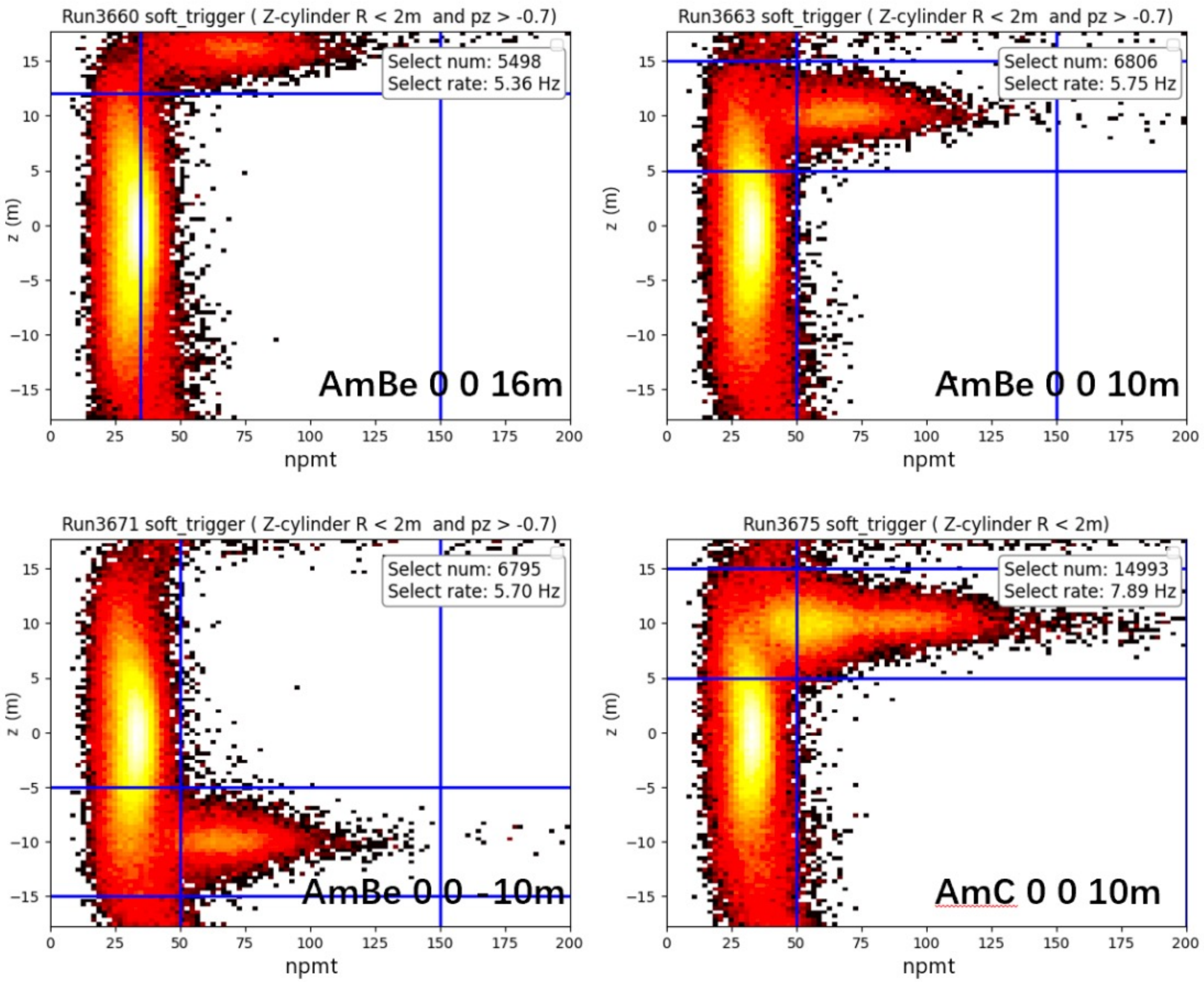
Transformer应用于^{8}B中微子事例重建

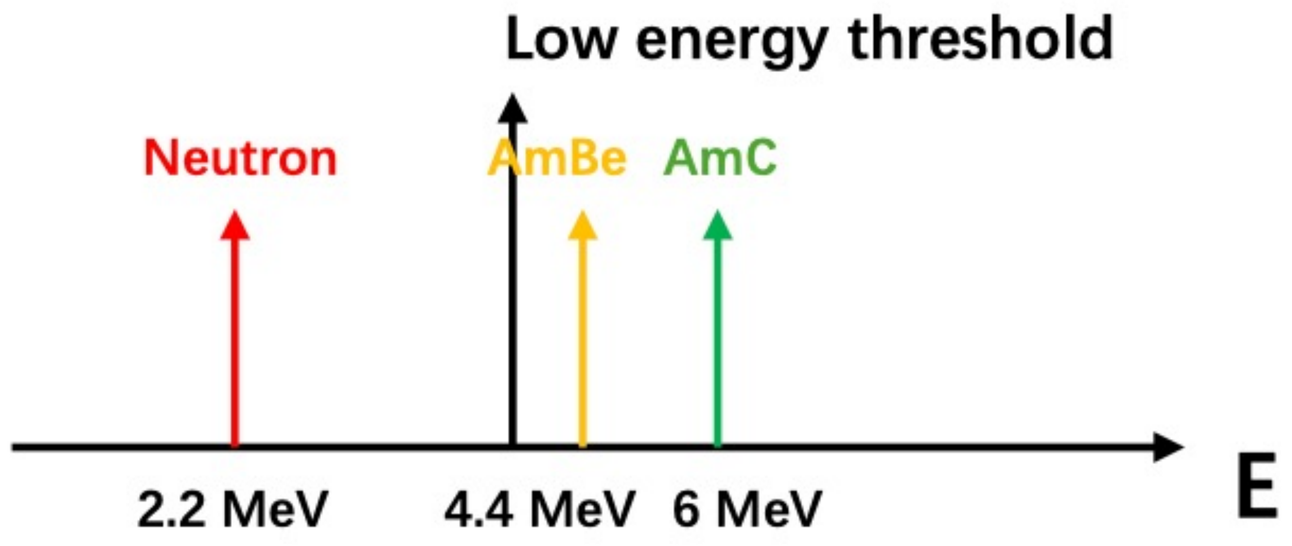
- **像素图识别法**：高能区表现良好，但低能区效果不明显。
- **Transformer算法**：1~20 MeV全能区的重建效果优越，整体优于传统方法和图像识别法，应用于^{8}B中微子事例同样有明显重建性能

JUNO水相真实数据分析

水相低能阈值测量

Am-Be和Am-C事例观测：



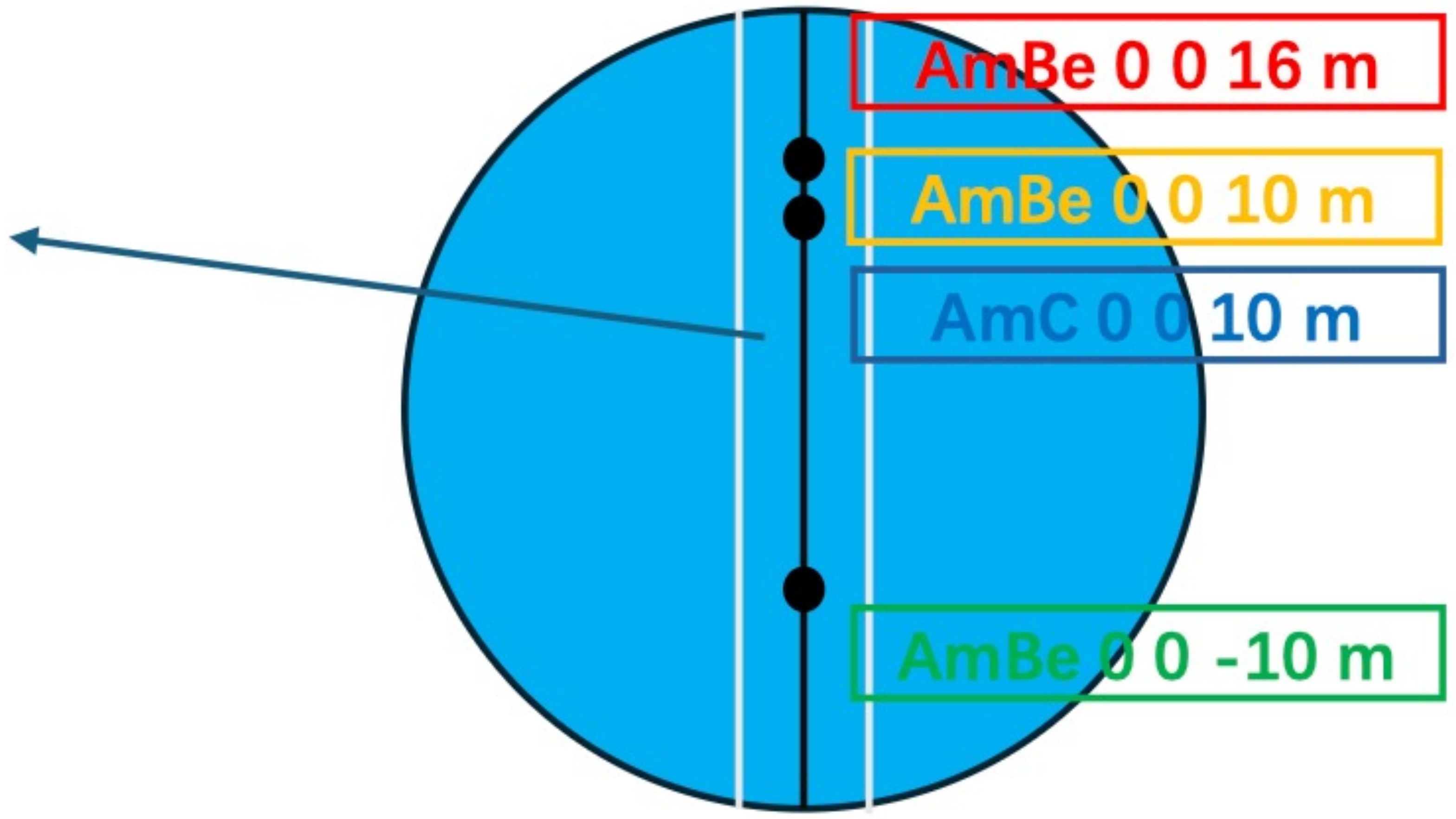


放射源衰变：

$$^{241}_{95}\mathrm{Am} \rightarrow {}^{237}_{93}\mathrm{Np} + {}^{4}_{2}\mathrm{He}$$

$$^{9}_{4}\mathrm{Be} + {}^{4}_{2}\mathrm{He} \rightarrow {}^{12}_{6}\mathrm{C} + {}^{1}_{0}\mathrm{n} \quad (4.4\,\mathrm{MeV}\,\gamma)$$

$$^{12}_{6}\mathrm{C} + {}^{4}_{2}\mathrm{He} \rightarrow {}^{15}_{7}\mathrm{N} + {}^{1}_{0}\mathrm{n} \quad (6.0\,\mathrm{MeV}\,\gamma)$$



观测到了Am-Be和Am-C事例，低能阈值降低至4 MeV。能量阈值越低，能够探测到的^{8}B能区范围越广。

JUNO水相真实数据分析

尝试寻找水相^{8}B中微子信号

真实数据中本底汇总：

Type	Target	Subtype	Cut strategy
Internal	Center Detector	^{238}U	npmt > 80
		^{232}Th	
		^{222}Rn	
External	Water Pool	^{238}U, ^{232}Th, ^{222}Rn	R < 14m
	PMT Glass	^{214}Bi, ^{208}Tl	
	Node & Bar	^{238}U, ^{232}Th, ^{40}K, ^{60}Co	
	Acrylic	^{238}U, ^{232}Th, ^{40}K	
Cosmogenic	Center Detector	^{6}He, ^{10}C, ^{11}C	npmt > 80
		^{12}B, ^{9}Li, ^{9}C, ^{8}Li, ^{8}B	muon track veto*
		^{11}Be	TFC veto*
Other	Center Detector	LS event	z < 10m
		Dark noise	npmt > 80
		Flasher	pz > 0.0 npmt > 80

(*号代表此策略未被应用于本研究)

取数日期：2.07 ~ 2.14
取数时间：共 ~100h（~4 days）

残余事例数：~3500 （预估^{8}B信号事例数：22）

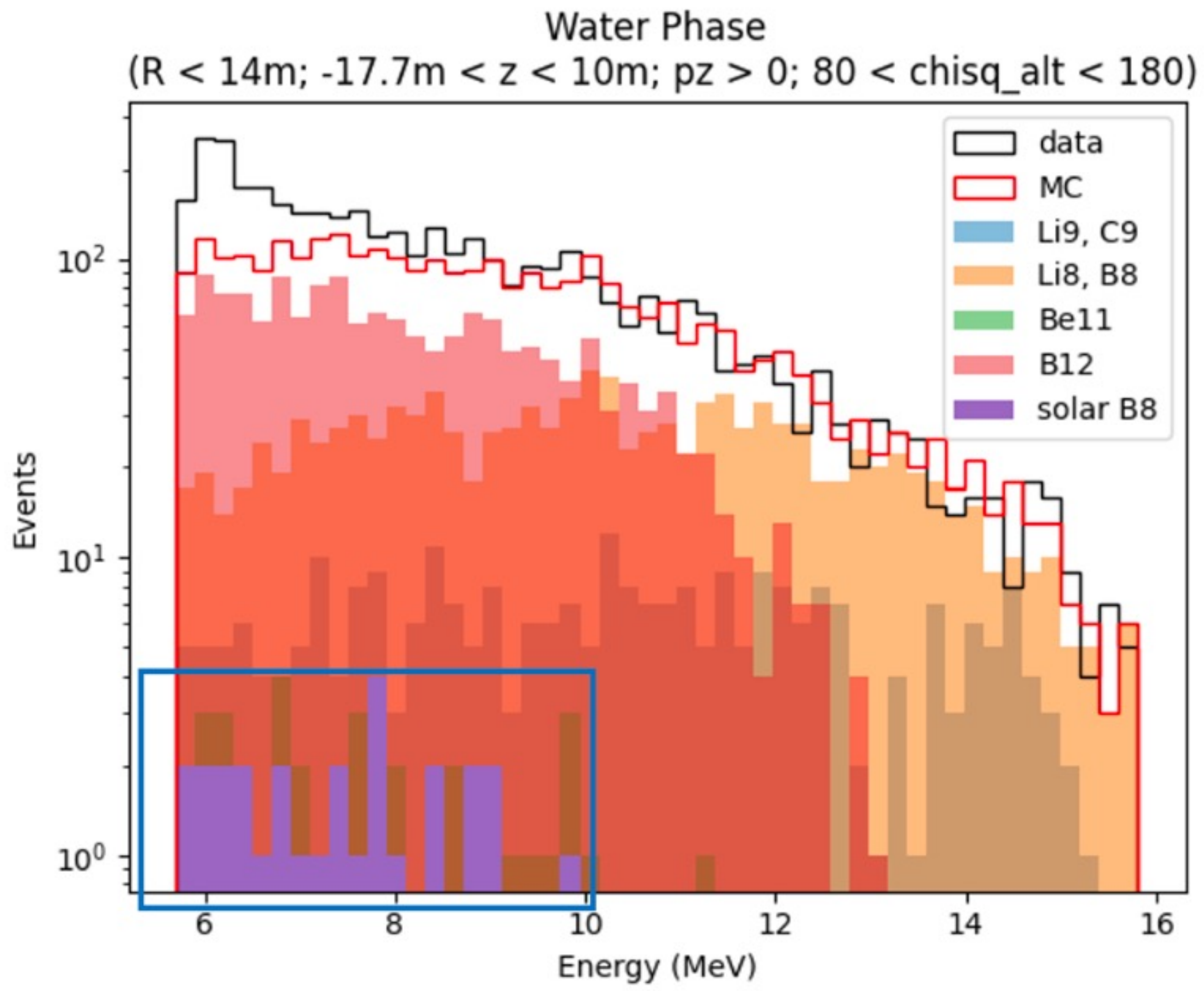
本底去除策略
效率估计

预期残余事例构成：

Type	Isotope	Events
Cosmogenic background	^{9}Li, ^{9}C	227
	^{8}Li, ^{8}B	972
	^{11}Be	34
	^{12}B	1297
Signal	Solar ^{8}B	22

(信噪比约1:150)

模拟与数据对比



残余事例中大部分为宇宙线本底，无法观测到明显的^{8}B中微子信号。

Summary

- Borexino: pp-chain + CNO-cycle are measured
- JUNO: Many opportunities