SOLAR NEUTRINOS: RECENT RESULTS AND PROSPECTS

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ON BEHALF OF THE SNO+ COLLABORATION
THANKS: SK, HK, DUNE, JUNO, THEIA, JNE, CLOUD

NEUTRINO 2024
XXXI INTERNATIONAL CONFERENCE ON NEUTRINO PHYSICS AND ASTROPHYSICS
JUNE 16-22, 2024 MILAN, ITALY

OUTLINE

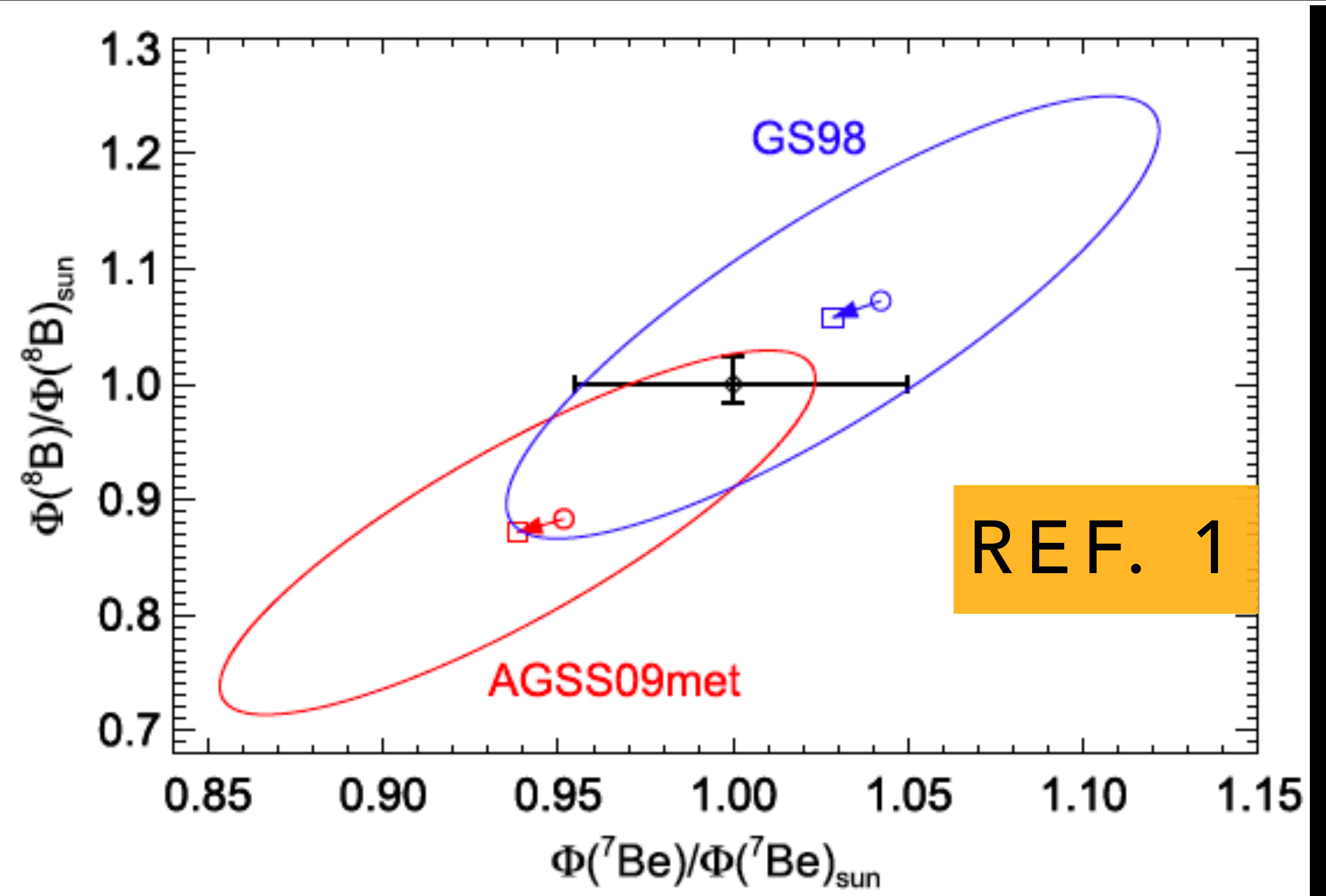
- Open questions in solar neutrino physics
- New and recent results
  - Super-Kamiokande
  - SNO+
- Prospects for large future experiments
  - Water: HK
  - LAr: DUNE
  - Scintillator: JUNO, JNE, Theia, CLOUD

See also opening talk on Borexino by Gianpaolo Bellini

And several posters, highlighted next

NEUTRINOS AS A PROBE OF THE SUN

- Solar neutrino observations
  - Sun burns via pp chain (99%), CNO cycle (1%) ✓
- Sun's composition still uncertain. Two classes of solar models high or low metallicity Z [abundances X: H, Y: He, Z: Li, …]
  - HighZ favored by helioseismology



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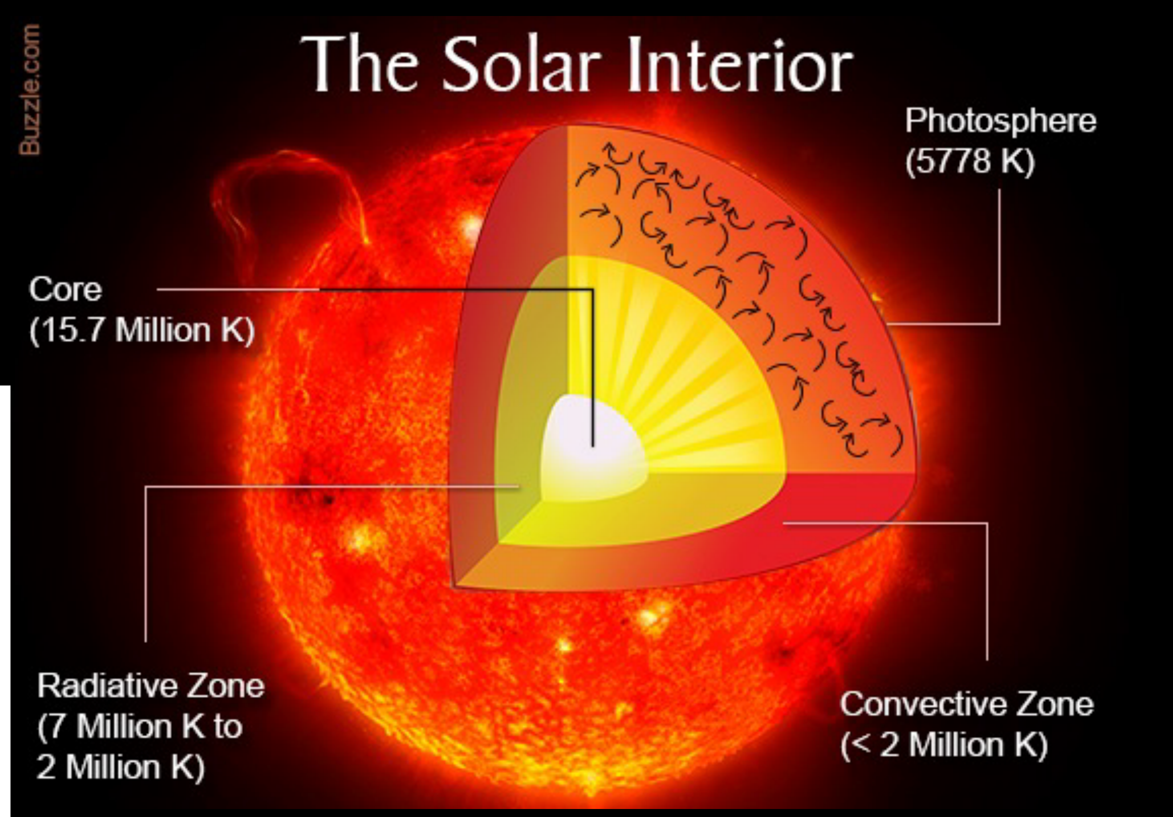
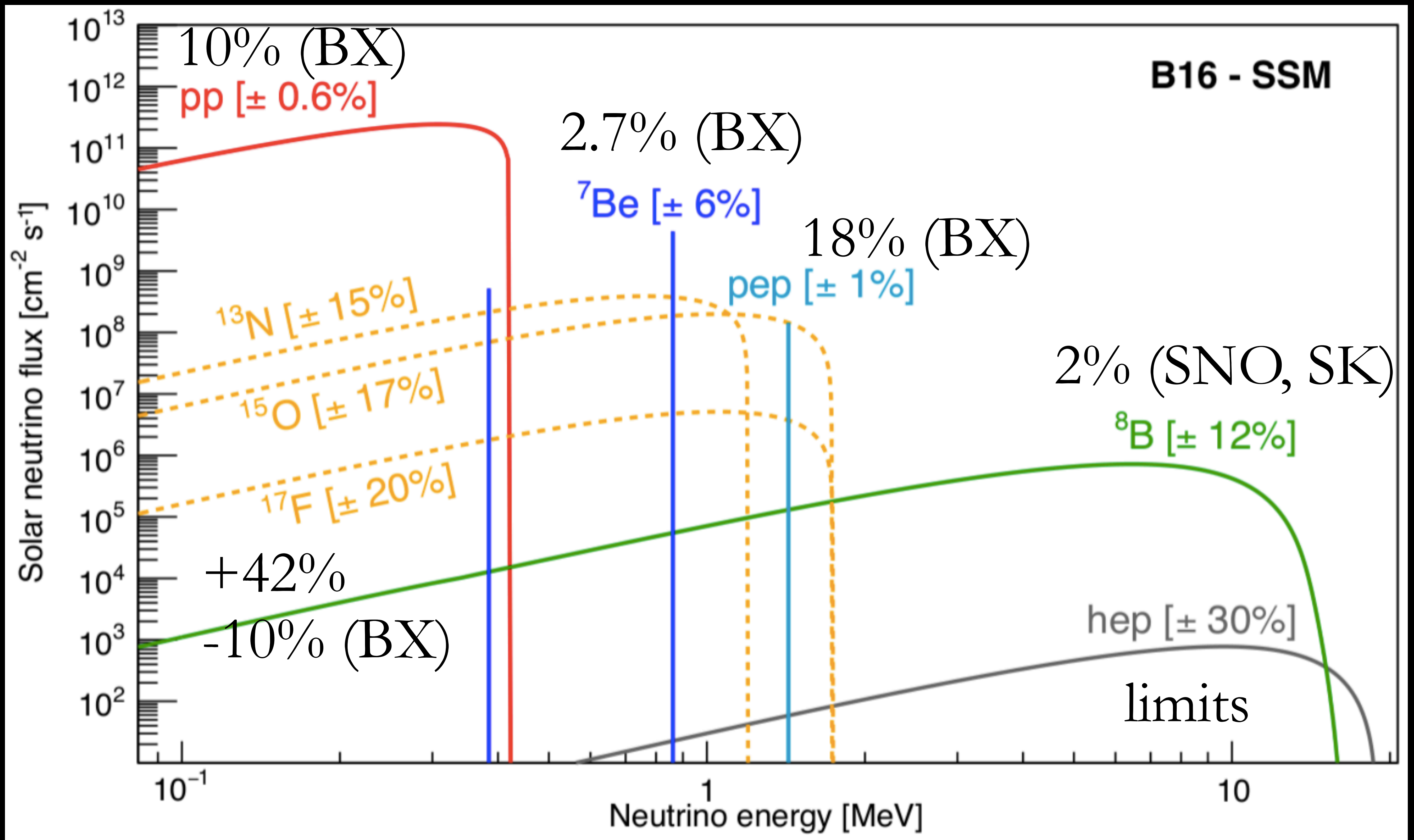
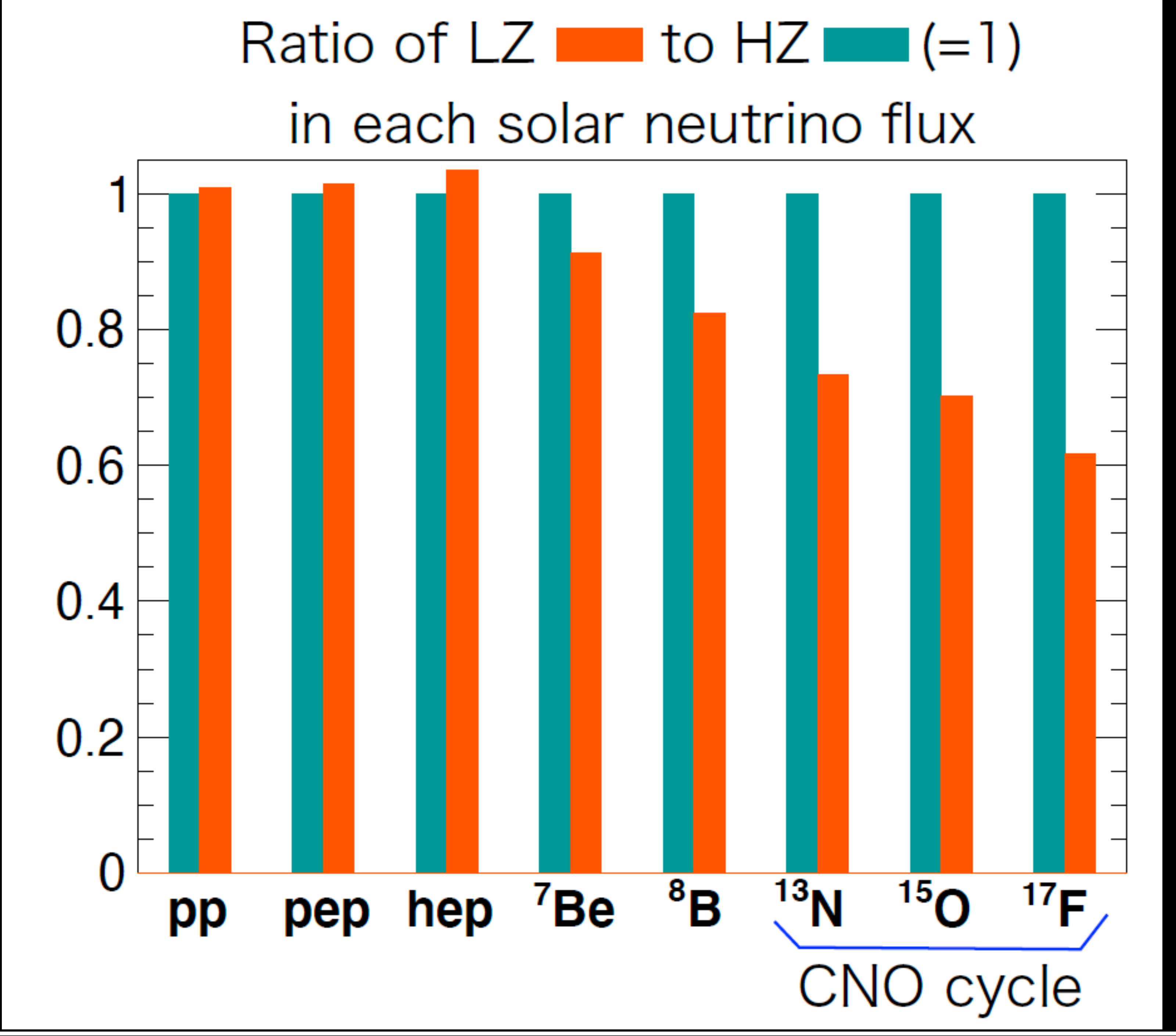




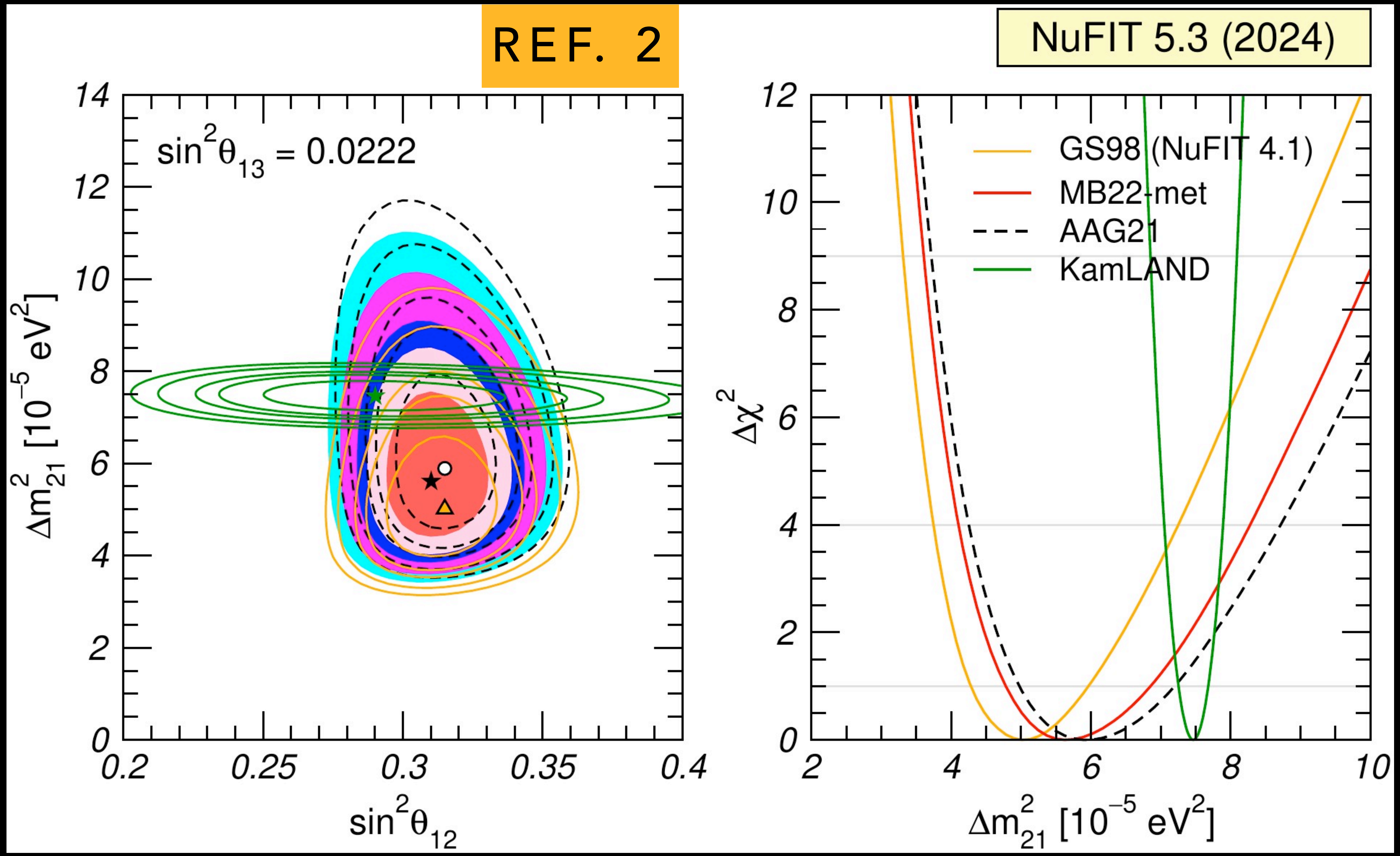
Questions ?

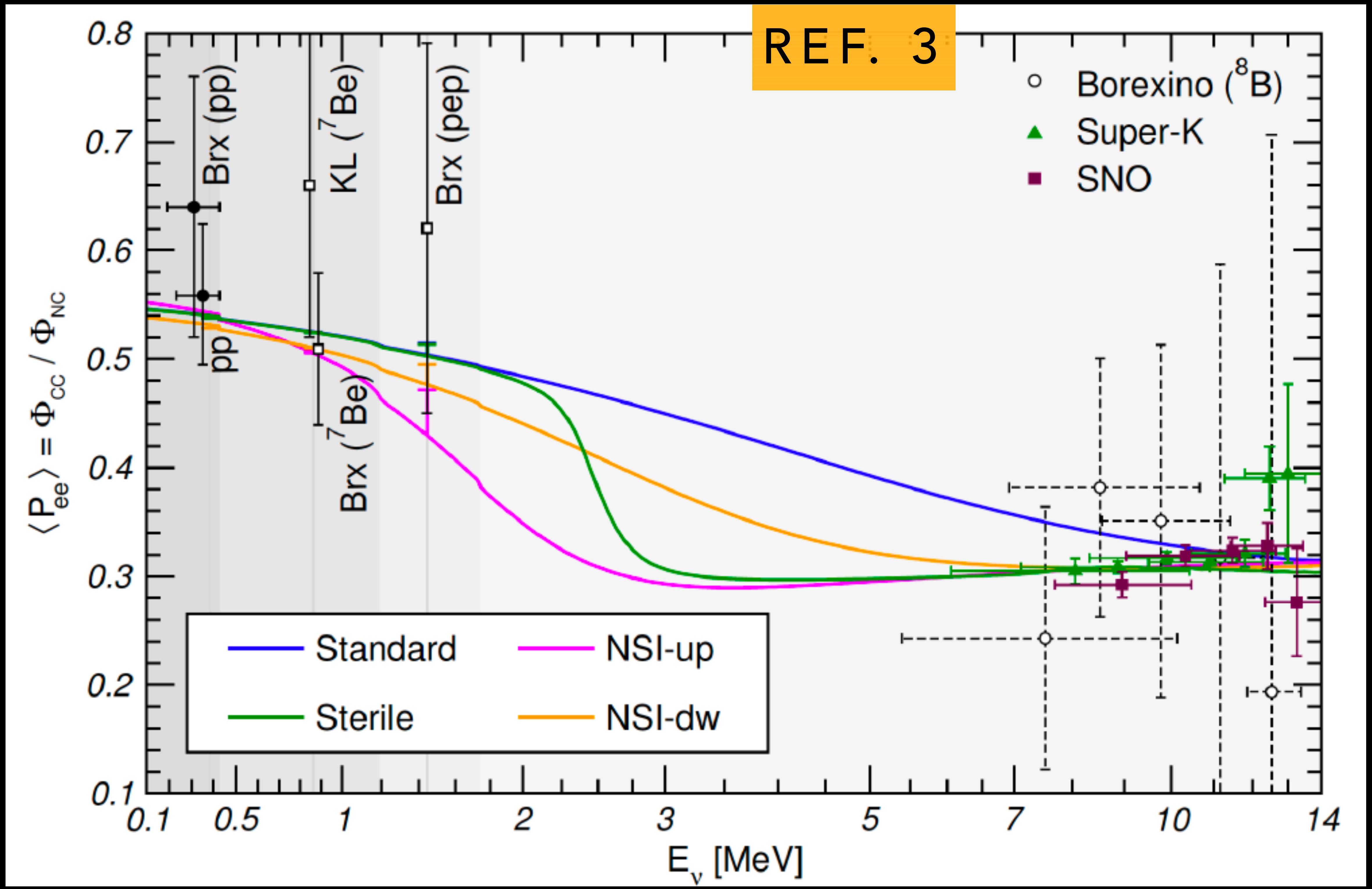
- HZ or LZ ?
- time variations/ correlations with solar events ?
- still missing hep flux



THE SUN AS A SOURCE OF NEUTRINOS

- High flux, pure ν_e source, large range of crossed densities
  - Sensitive to matter effects, sign of Δm^2_{21}. **MSW upturn and day-night hard to observe**
  - With SNO NC, precise measurement of Pee at ^{8}B energies: **tension with KamLAND**
  - Dependent on SSM otherwise, Pee still largely unconstrained in transition region: **NSI and other models still possible**





CURRENT EXPERIMENTS

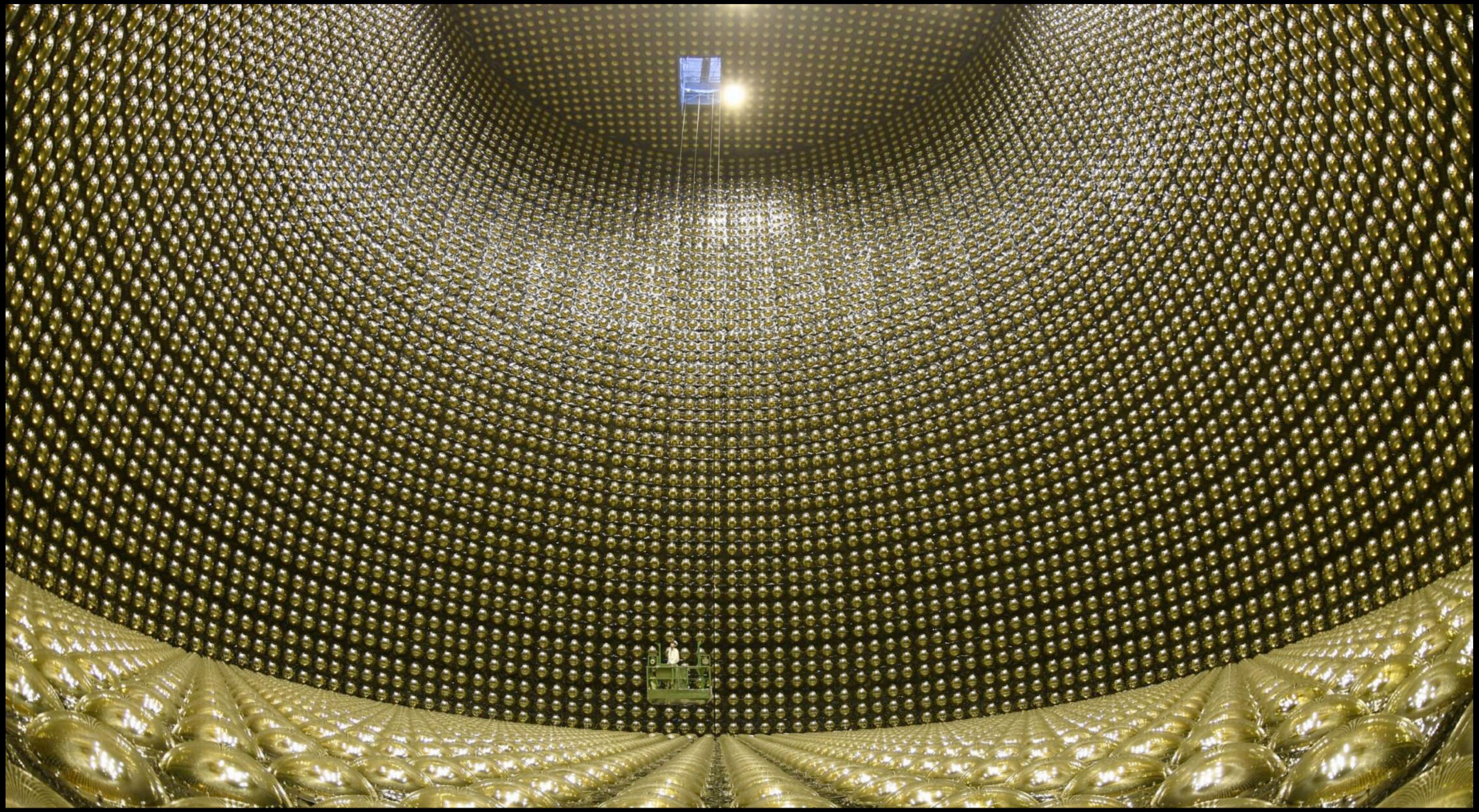
SUPER-KAMIOKANDE

SUPER-KAMIOKANDE

THANKS TO M. SMY

- Largest detector sensitive to solar neutrino energies: 22.5 kton fiducial
- Recently published: complete analysis of SK phases I - IV: over 20 years of data!!
  - Significant improvements in energy reconstruction and uncertaities
- Since 2020: SK-V (prep for Gd), SK-VI (0.01% Gd), SK-VII (0.03% Gd)

REF. 4,5



Phase	SK-I	SK-II	SK-III	SK-IV
Period (Start)	April '96	October '02	July '06	September '08
Period (End)	July '01	October '05	August '08	May '18
Livetime [days]	1,496	791	548	2,970
ID PMTs	11,146	5,182	11,129	11,129
OD PMTs	1,885	1,885	1,885	1,885
PMT coverage [%]	40	19	40	40
Energy thr. [MeV]	4.49	6.49	3.99	3.49

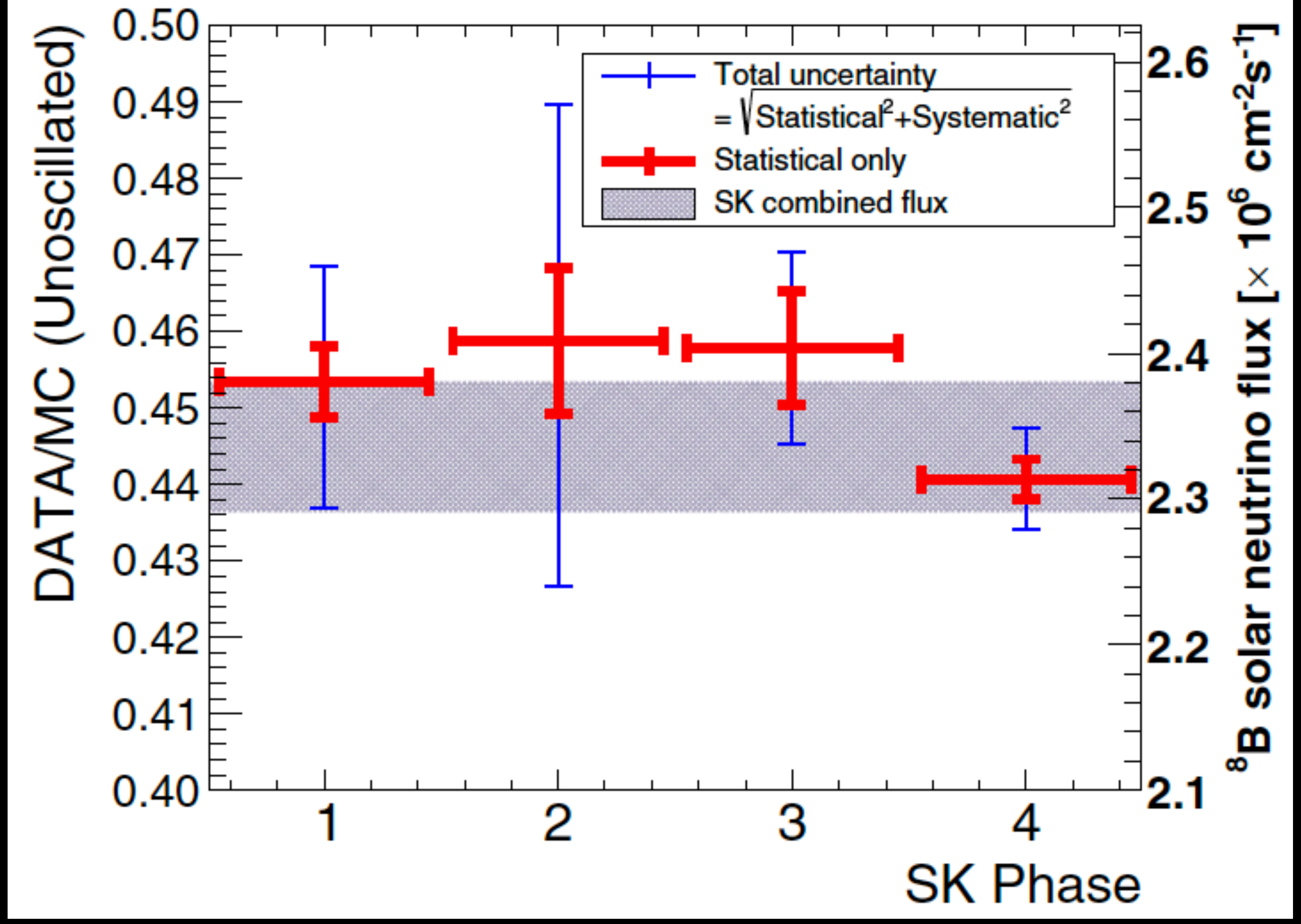
SUPERK ATMOSPHERIC NEUTRINO TALK: 668 / M. POSIADALA-ZEZULA

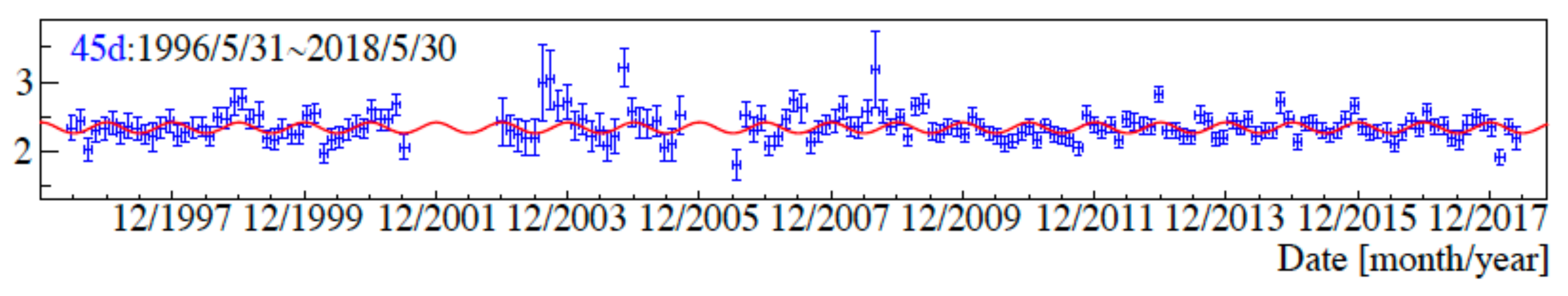
SUPERK SOLAR NEUTRINO POSTERS:
274 / A. YANKELEVICH
502 / Y. NAKANO

TIME VARIATIONS OF ^{8}B FLUX

REF. 4,5

Very precise rate measurement, consistent among various phases

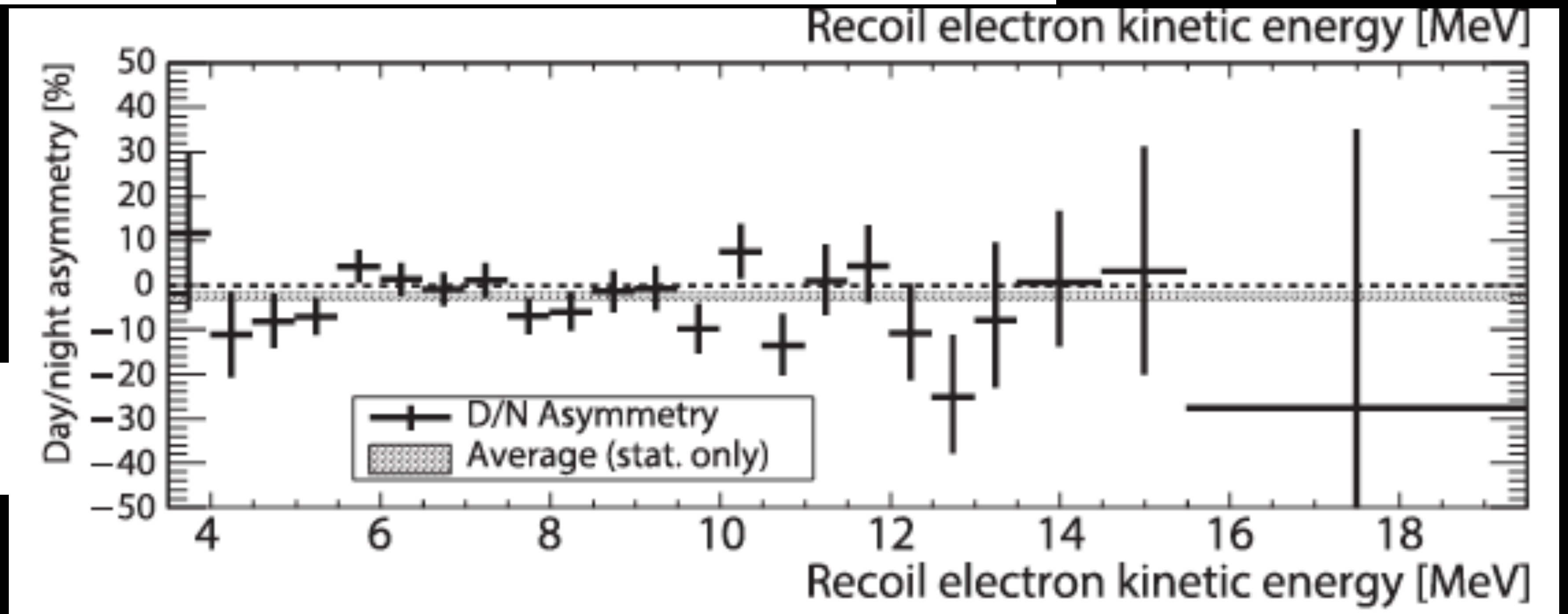




Day/night Asymmetry

SK-IV only, calc.

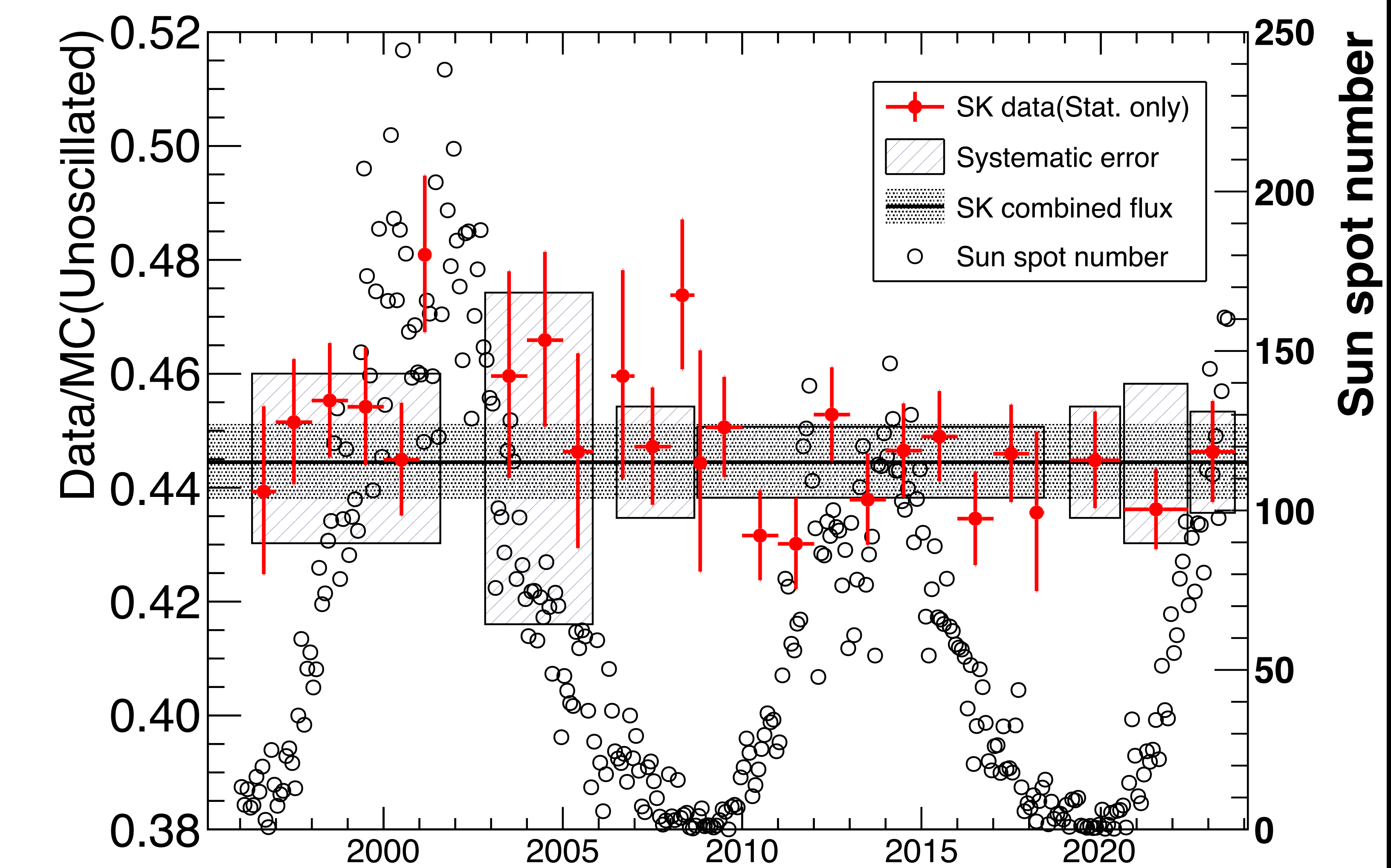
$$A_{\mathrm{D/N}}^{\mathrm{SK\text{-}IV,\ calc}} = -0.025 \pm 0.012(\mathrm{stat.}) \pm 0.014(\mathrm{syst.}).$$



SK I-IV combined fit, > 3 σ

$$A_{\mathrm{D/N}}^{\mathrm{SK,\ fit}} = -0.0286 \pm 0.0085\,(\mathrm{stat.}) \pm 0.0032\,(\mathrm{syst.}).$$

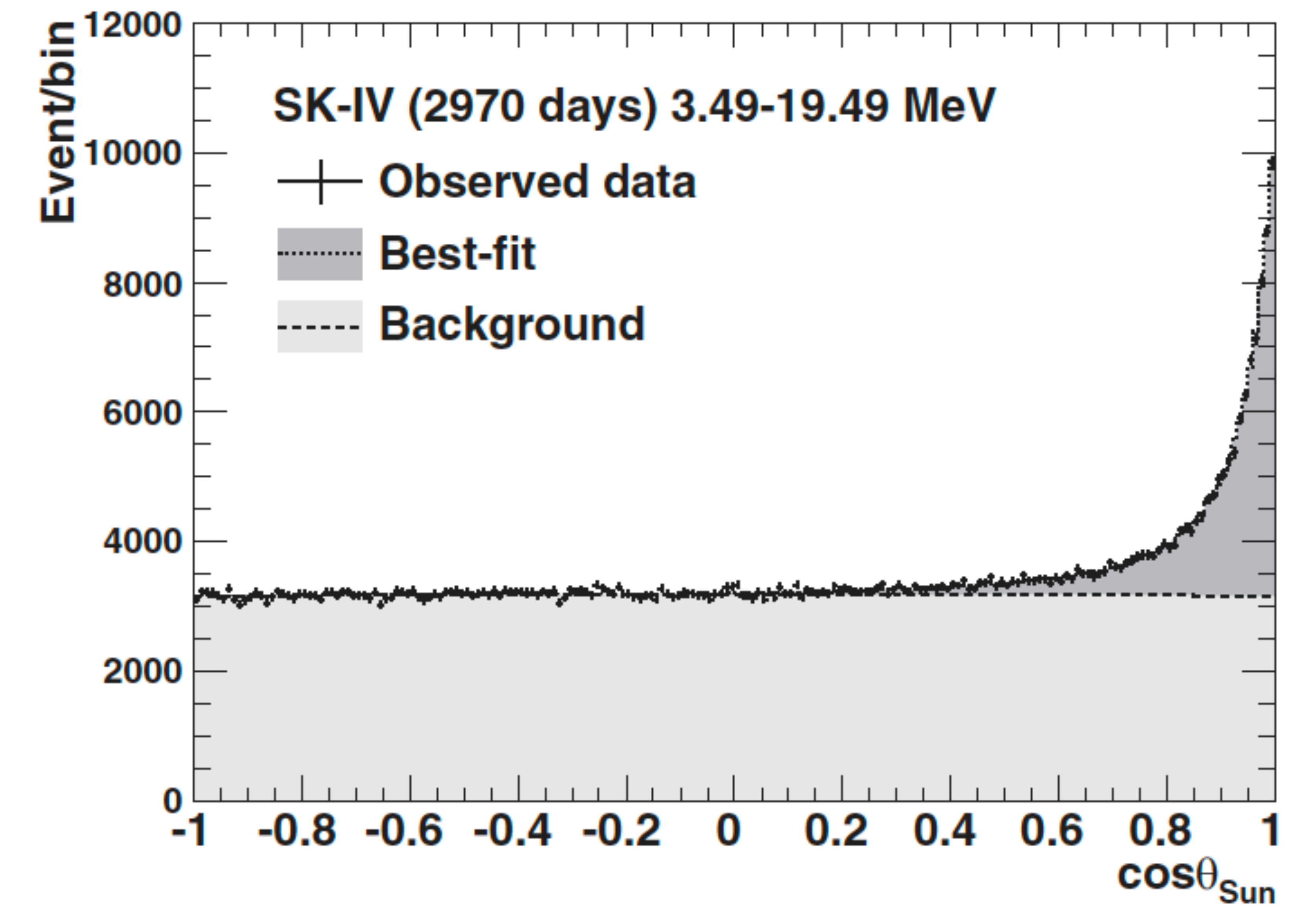
No statistically signicant time variations beyond eccentricity and day/night (compatible with MSW oscillations)



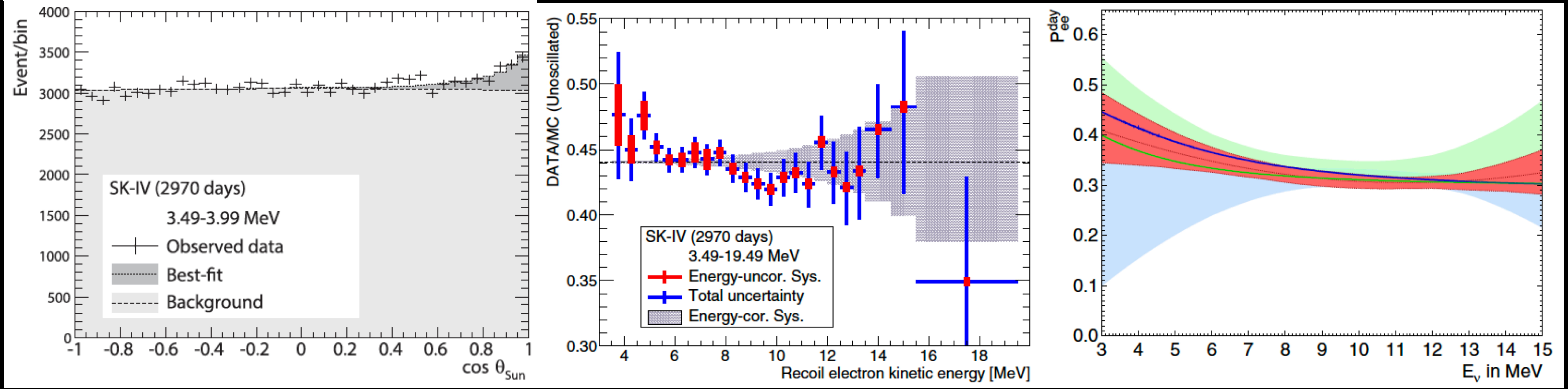
No sunspot correlation

^{8}B SOLAR NEUTRINO SPECTRUM

REF. 4

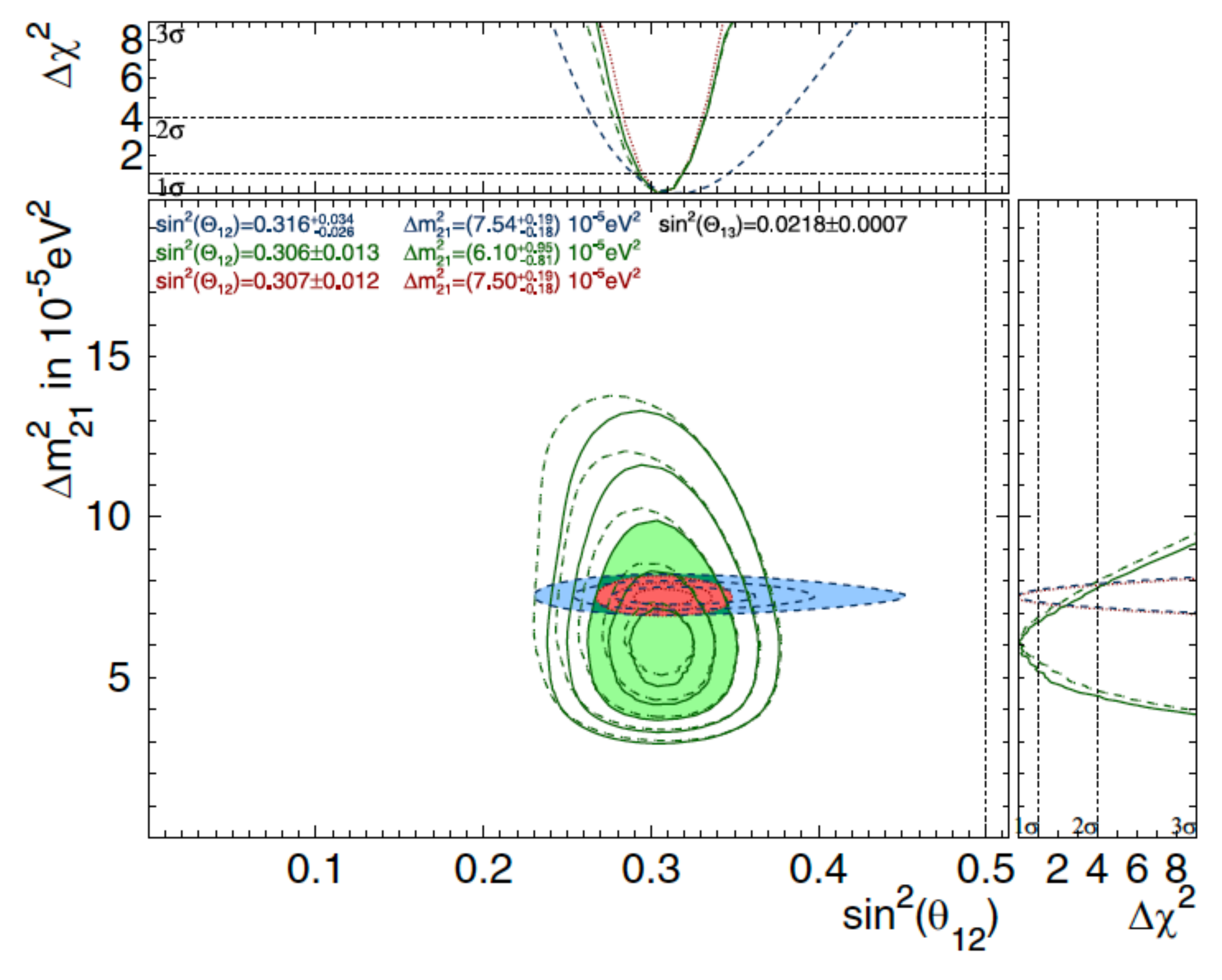


- Impressive precision, clear observation at 3.5 MeV threshold
- Spectrum still compatible with flat survival probability, but predicted low energy upturn is favored at 1.2 σ . Jointly with SNO data, at 2.1 σ.



SK OSCILLATIONS GLOBAL FIT

REF. 4



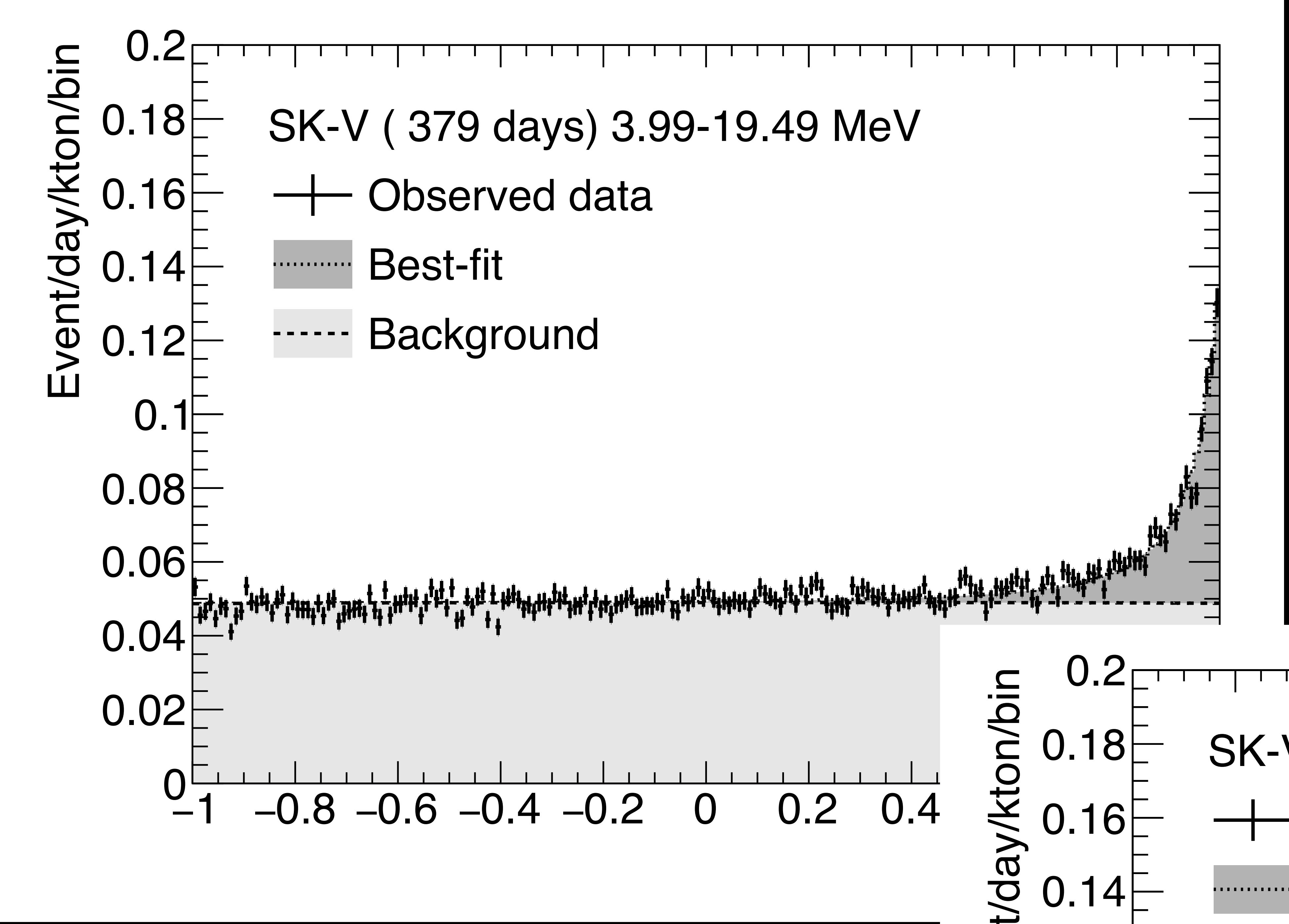
SK fit, fixed θ_{13}

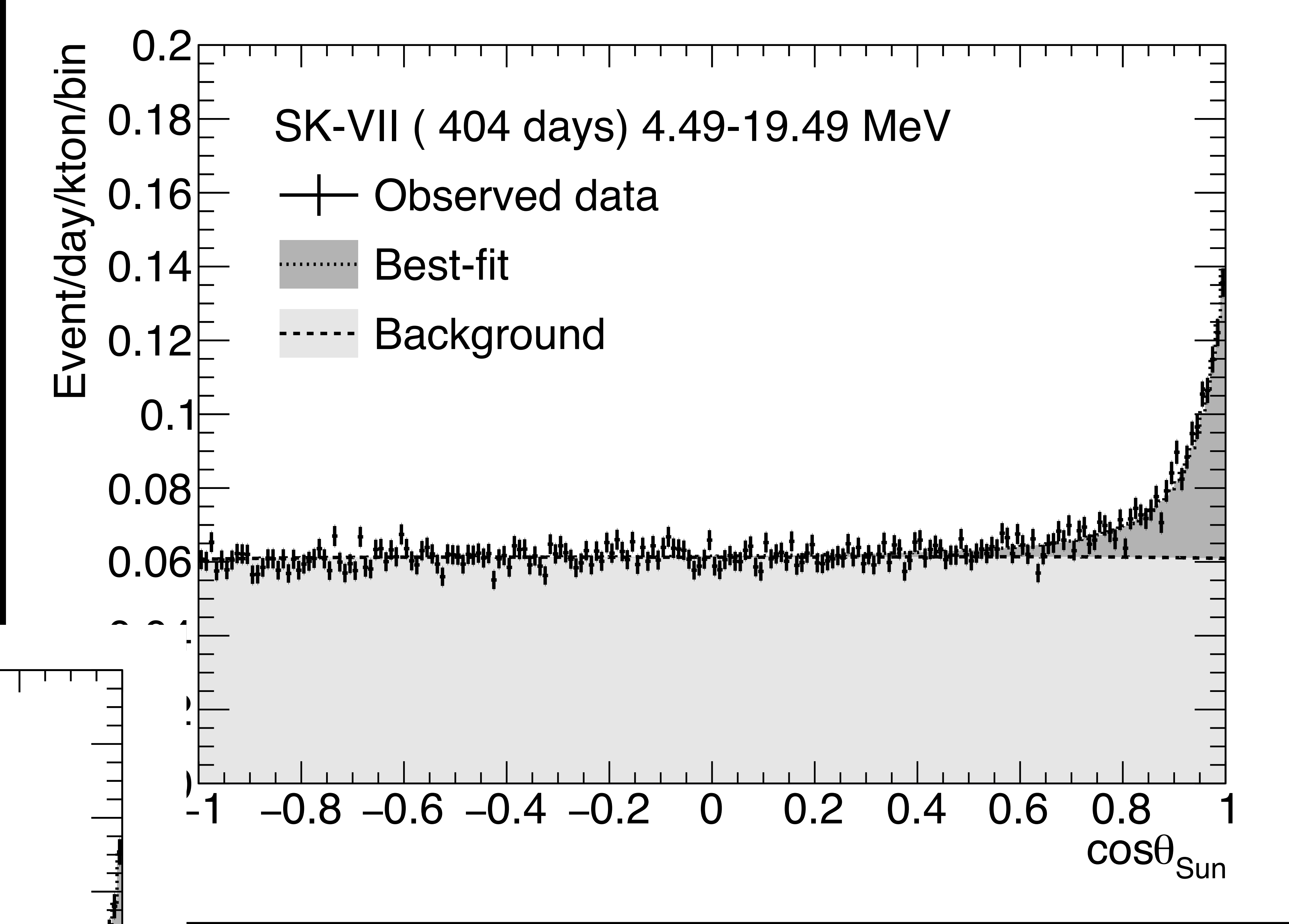
- Solar best-fit value updated to:

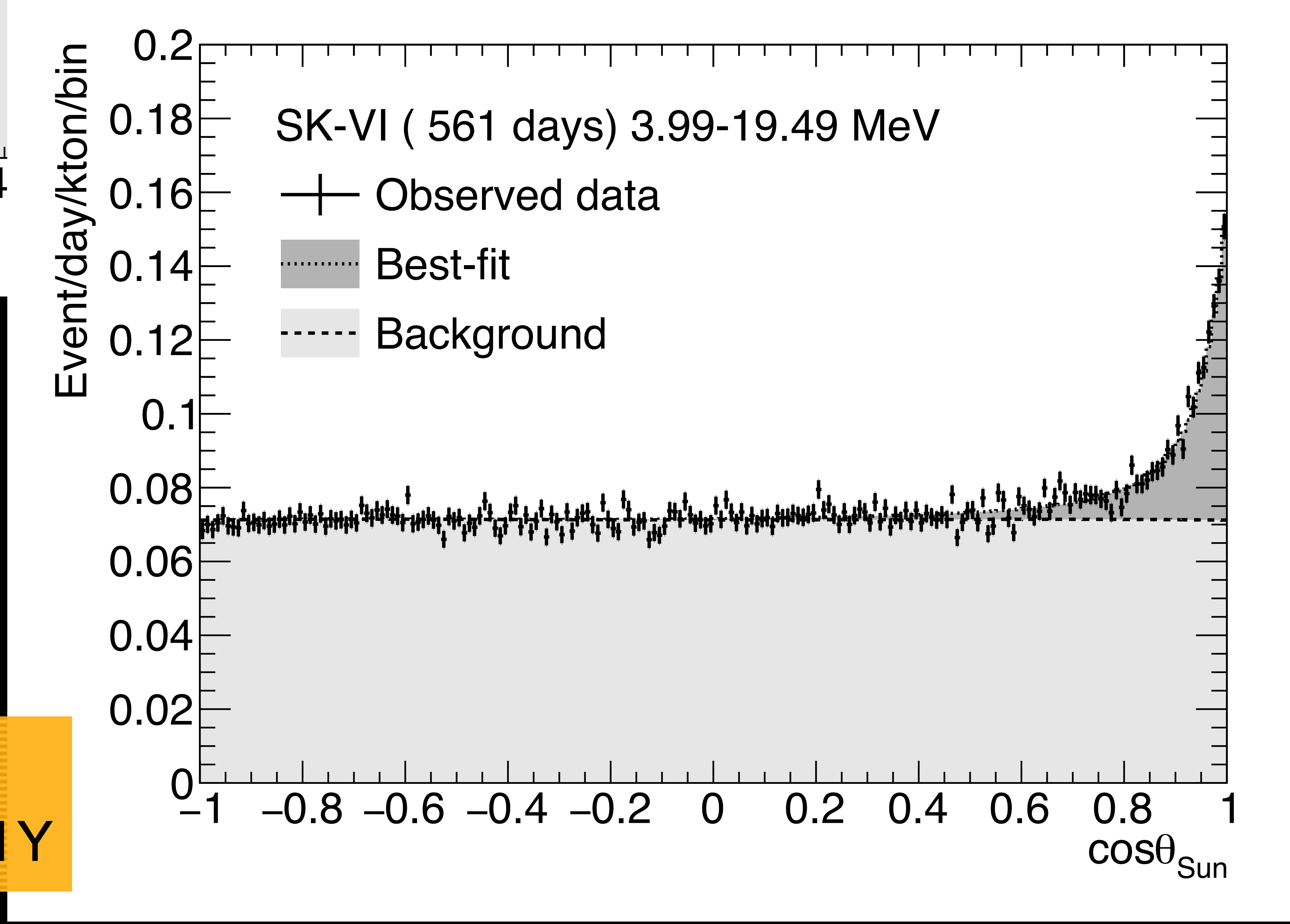
$$\Delta m^2_{21} = 6.10^{+0.95}_{-0.81} \times 10^{-5} eV^2$$

- ~1.5 σ away from KamLAND

NEW PHASES CONTINUE…







Higher backgrounds as expected, but 4 /4.5 MeV threshold is clearly possible !

VERY NEW RESULTS!
AGAIN, THANKS TO M. SMY

SNO+

Posters:

- 544 / D. Cookman / Measuring Solar Neutrino Oscillations in the SNO+ Detector
- 416 / G. Milton / First Indications of CC Solar Neutrino Interactions on Carbon-13
- 525 / S. Andringa / Reactor Antineutrino Oscillations and Geoneutrinos in SNO+

- 255 / A. Inácio and R. Hunt-Stokes / Time-based event discrimination methods for solar neutrino analyses in the SNO+ liquid scintillator phase
- 483 / J. Page / Event by Event classification of alpha-n and IBD Interactions at SNO+
- 593 / C. Hewitt and M. Anderson / Machine learning for fast event reconstruction in the SNO+ scintillator phase

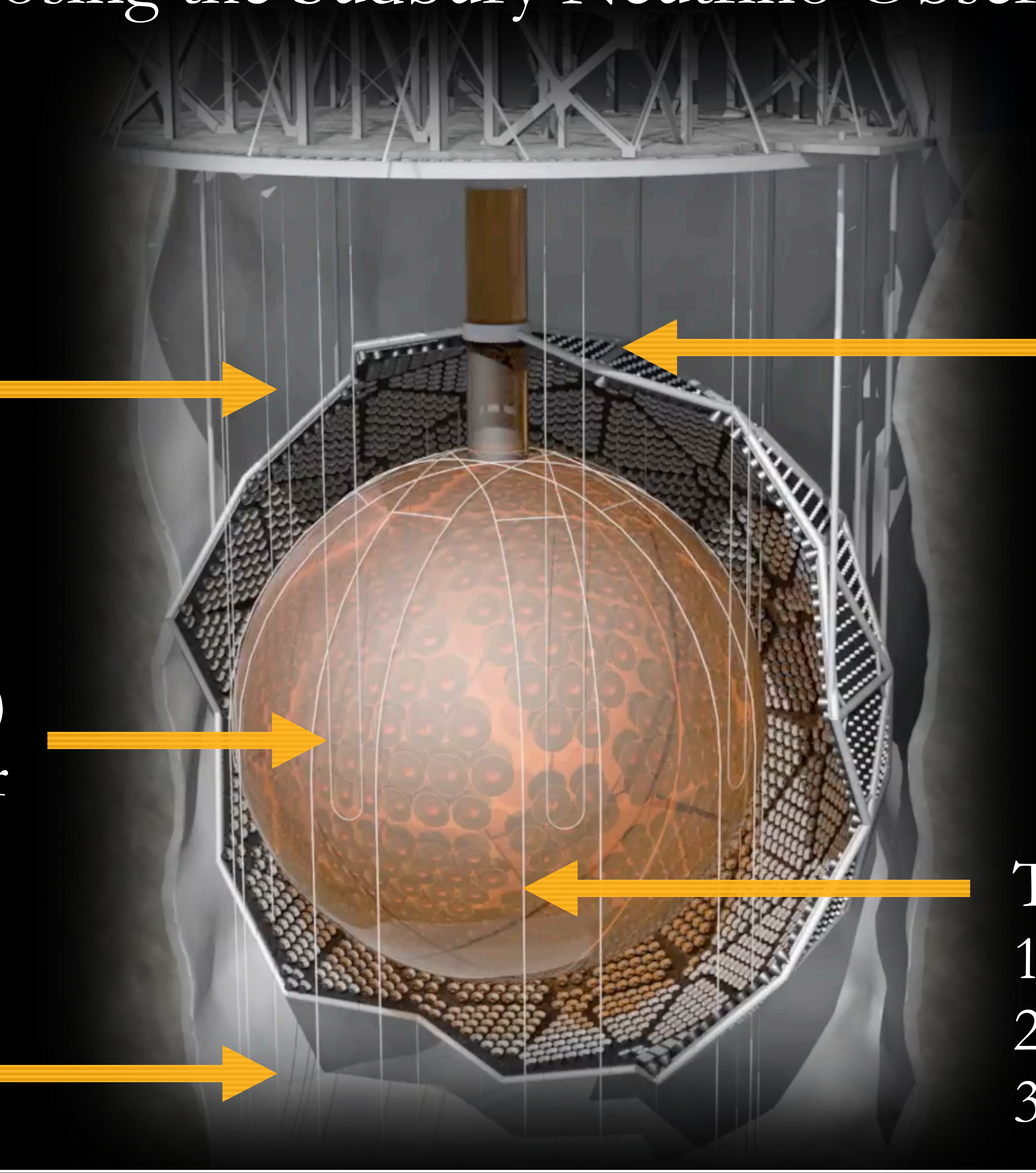
- 581 / B. Tam and S. Manecki / The SNO+ Tellurium Deployment Programme

THE SNO+ EXPERIMENT

Repurposing the Sudbury Neutrino Observatory (SNO) detector

2 km underground
~70 muons/day

Rope system
Hold-up and -down
Low Radioactivity



~9300 PMTs

Acrylic Vessel (AV)
12 m diameter

Ultra-Pure
Water

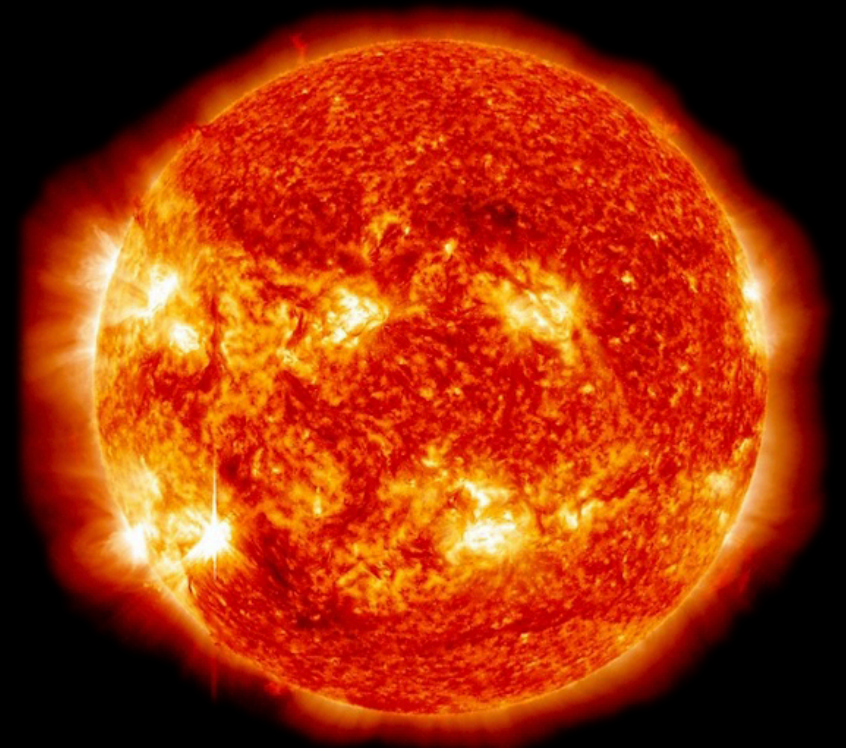
Purification plant

Target Material

1. Water: 905 tonnes
2. LAB Scintillator: 780 tonnes
3. Tellurium loading: +3.9 tonnes

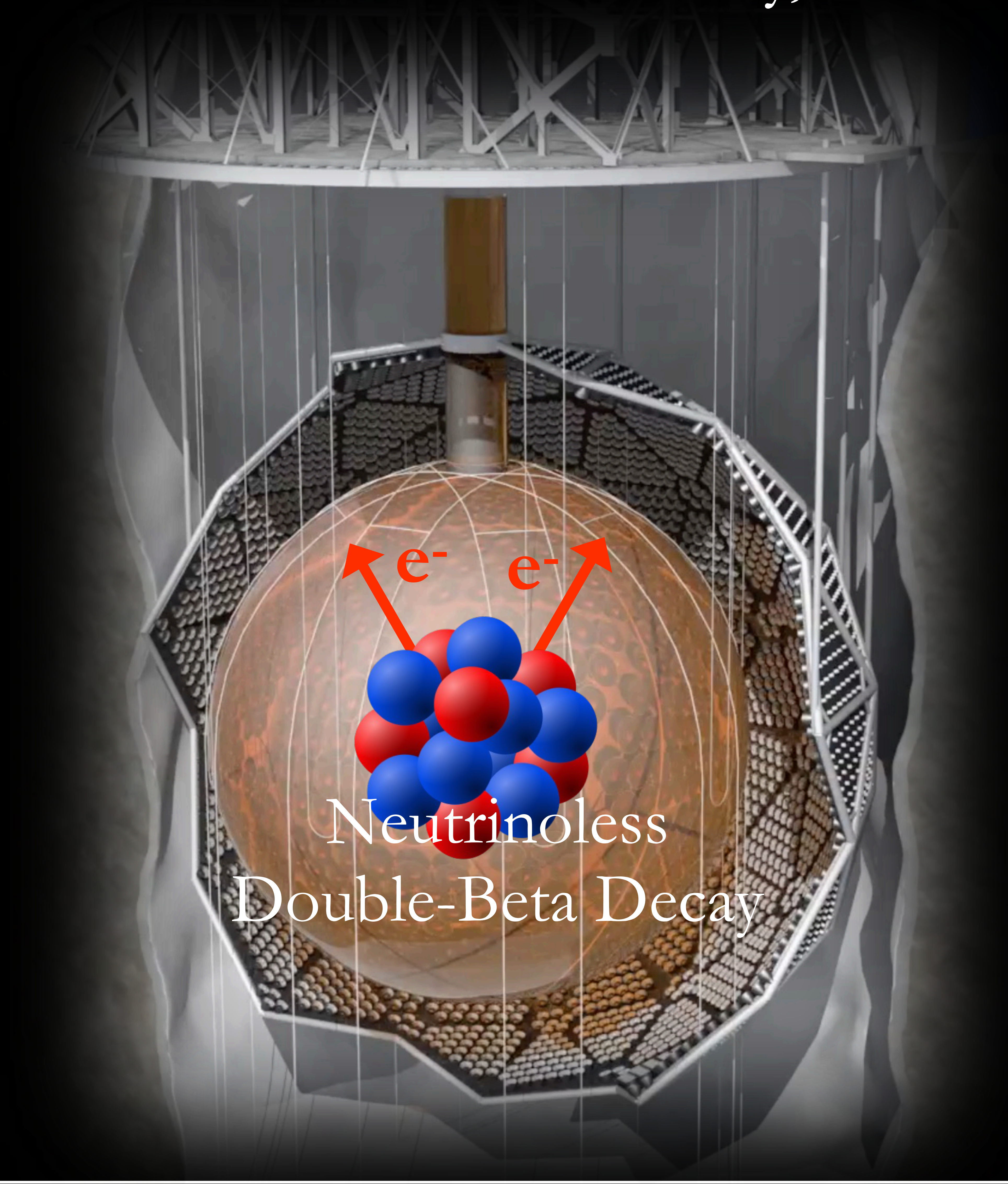
THE SNO+ EXPERIMENT

Multi-purpose experiment at SNOLAB - Sudbury, Ontario, Canada



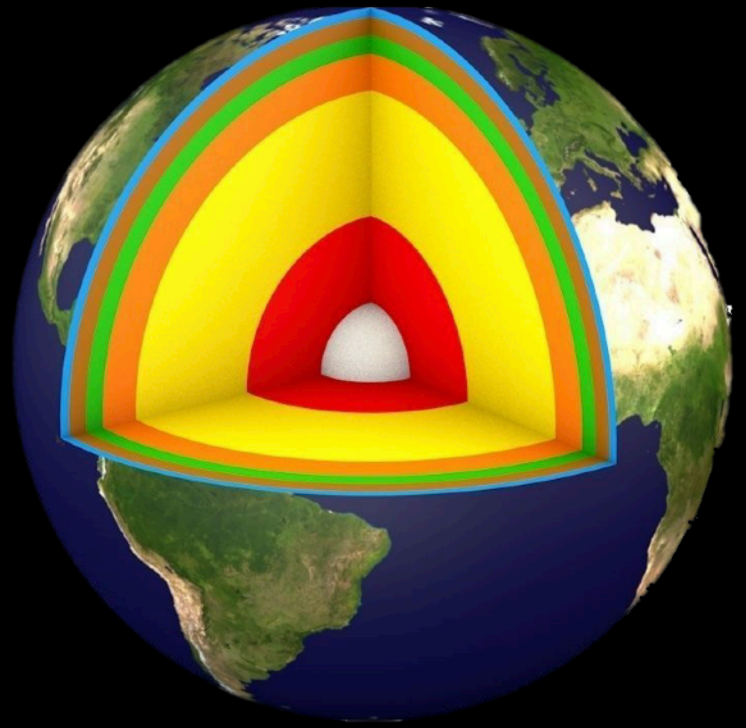
Solar Neutrinos

Reactor Neutrinos



Supernova Neutrinos
+ exotics

Geo-Neutrinos



SNO+ TIMELINE

2017 2018 2019 2020 2021 2022 2023 2024 2025

Water phase
- High Rn
- Low Rn

Partial fill phase
Scintillator over water.
Stop in fill due to Covid.

Scintillator phase
- Low PPO
- Nominal PPO
- Added bis-MSB

REF. 7

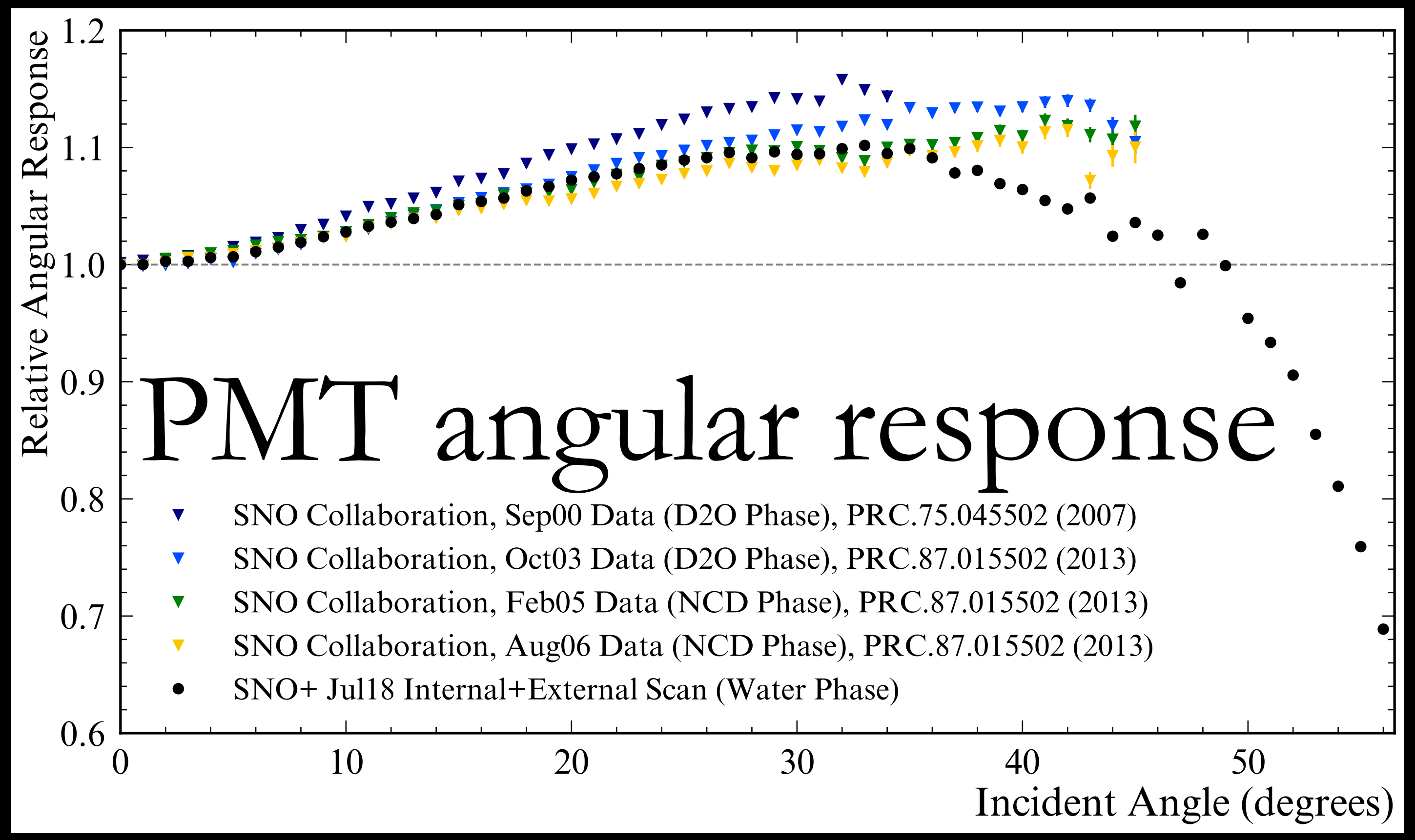
Next: Tellurium-loaded phase

REF. 8

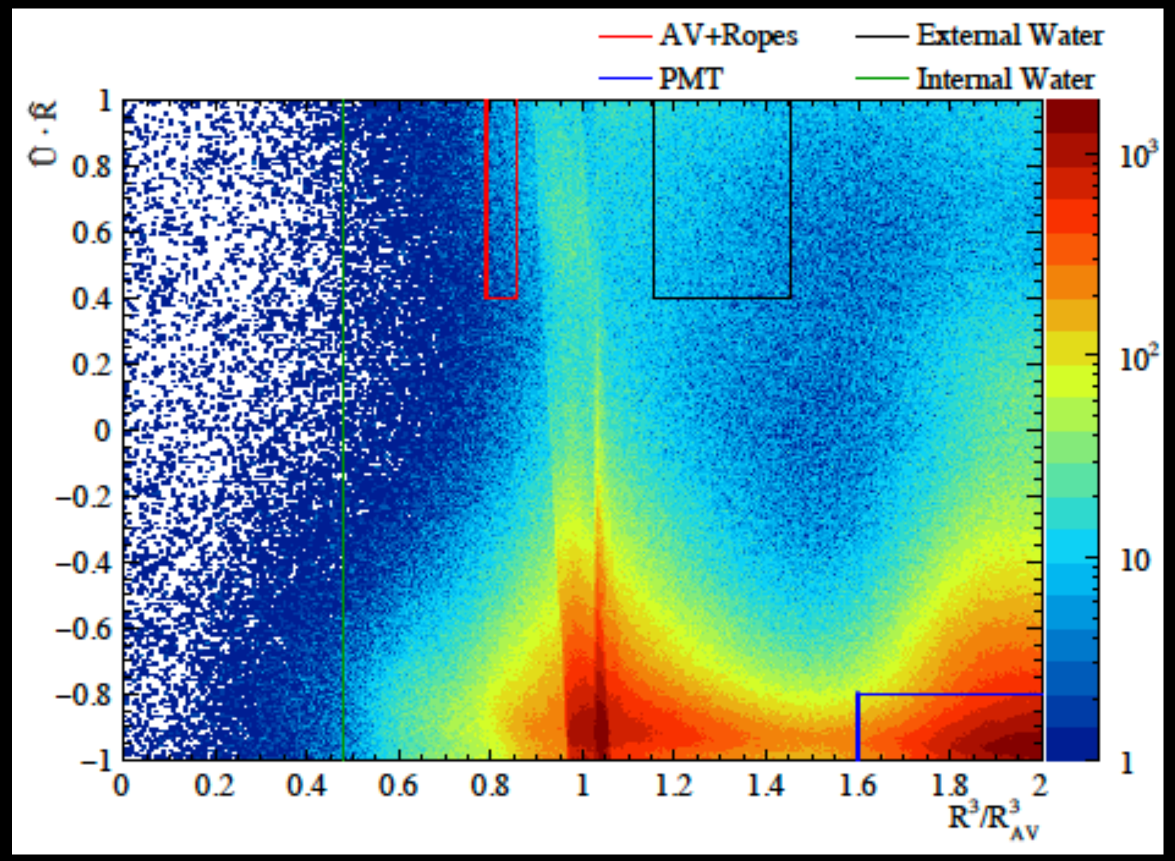
POSTER 581 / B. TAM, S. MANECKI

SNO+ PERFORMANCE

- Water Phase
  - Extensive calibrations: well-tuned detector model **REF. 9**
  - Constraints on external backgrounds: smaller than nominal

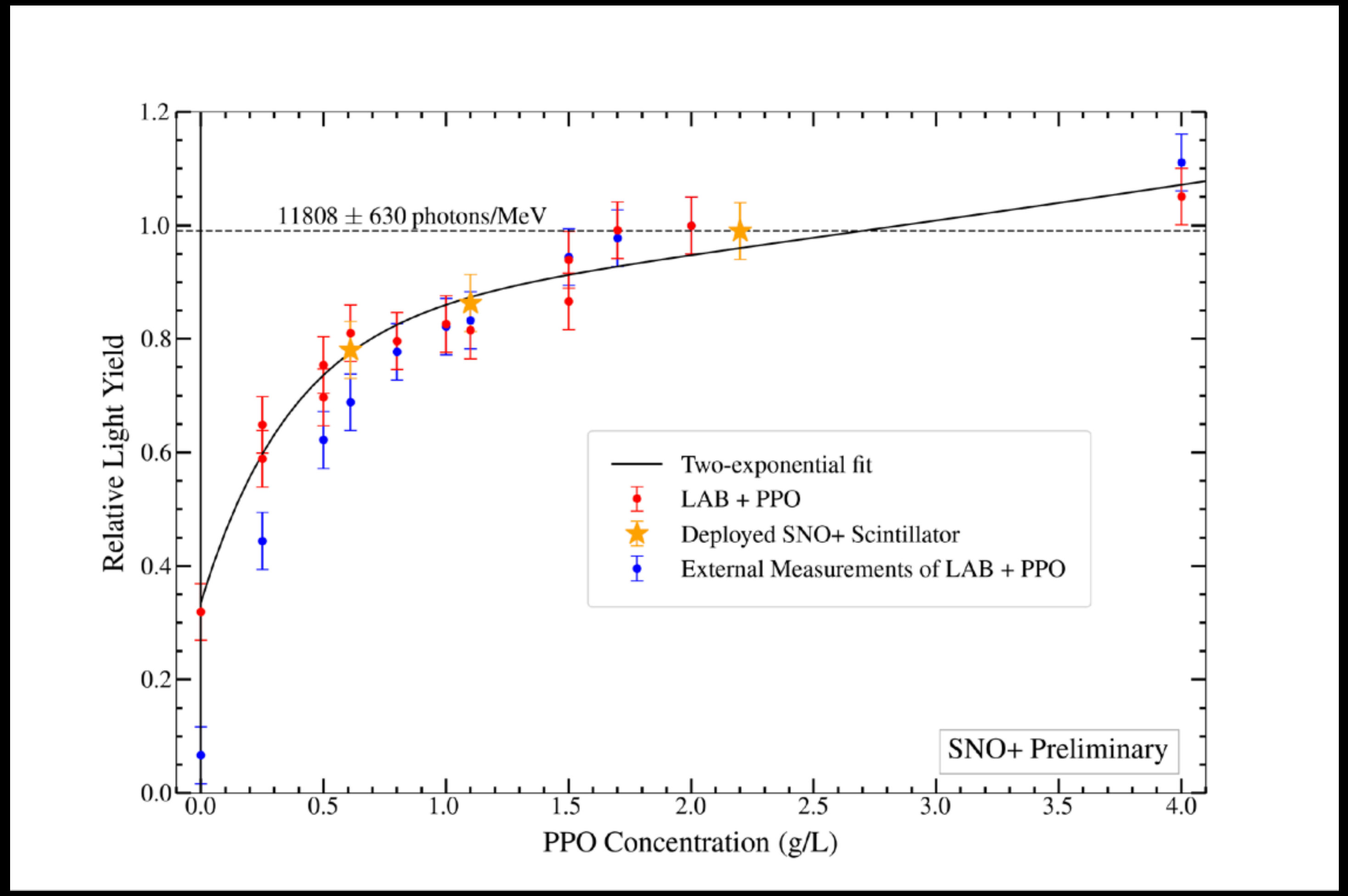


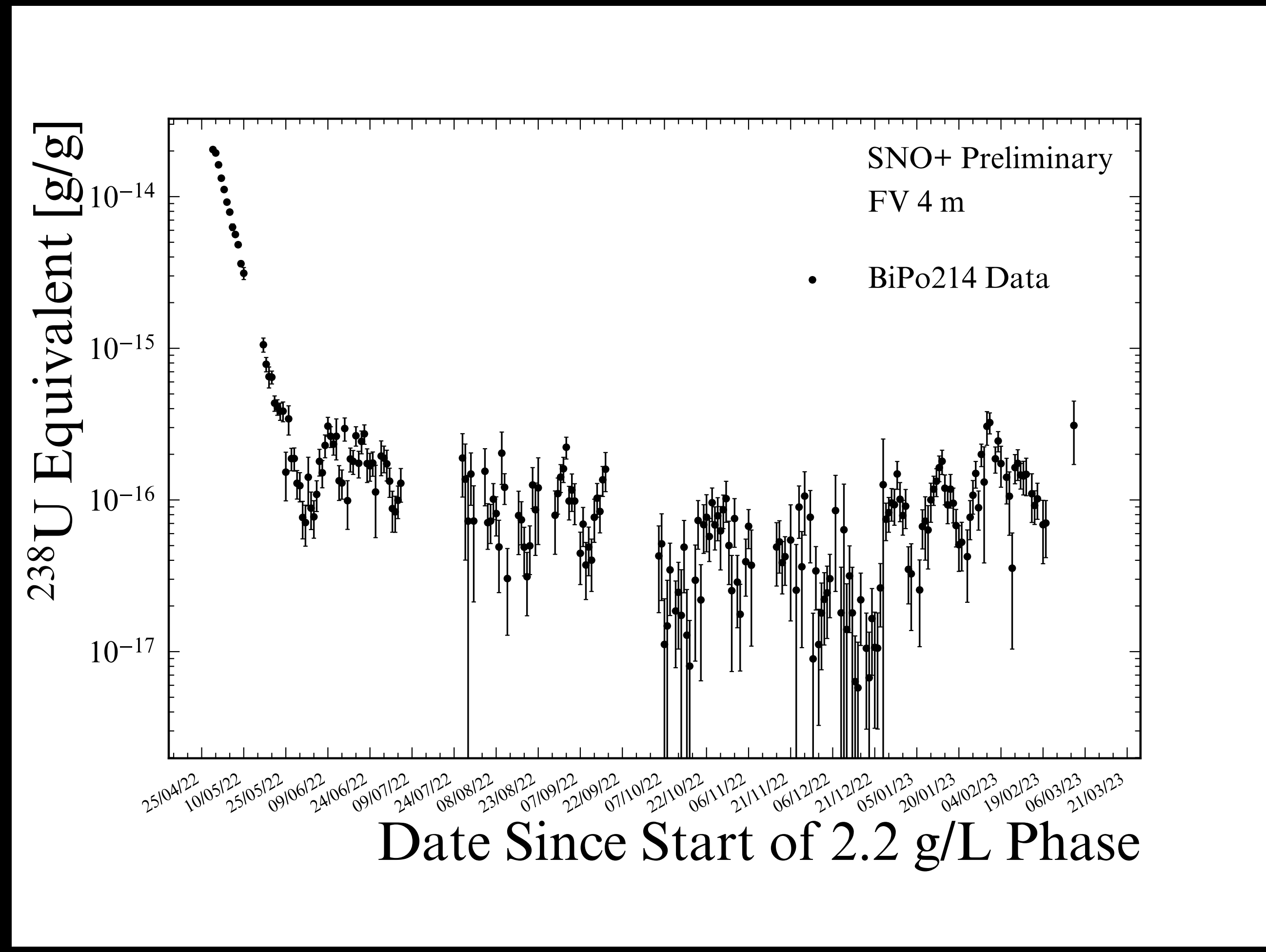
In/Out Direction



Radial Position

- Scintillator Phase
  - Tracking background and light levels throughout operations
  - High but decreasing level of Po210
  - BiPo214/212 segments of Uranium and Thorium chains at low level:
    - Eq. $^{238}U \sim 4.3\times10^{-17}$ g/g
    - Eq. $^{232}Th \sim 5.3\times10^{-17}$ g/g





SOLAR NEUTRINOS, WATER PHASE

- New analysis of 126.6 kt.days, including 190.3 days of low background data
  - Radon in water ~6×10^{-15} gU/g
  - Lowest background for water Cherenkov detectors > 5 MeV: 0.32 ± 0.07 ev/kt.days

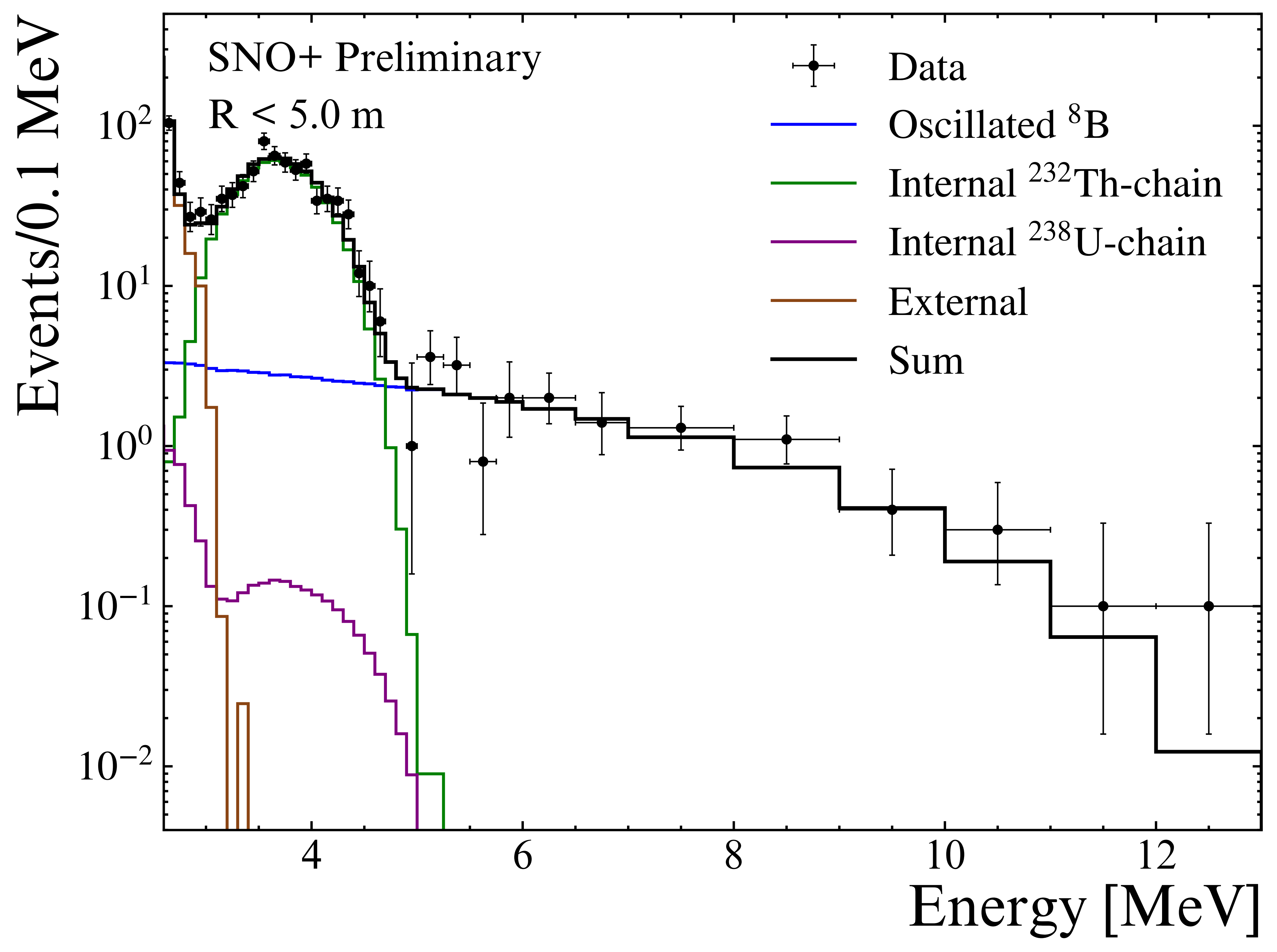
- Results
  - 3.5 MeV threshold, but large uncertainties in first bins
  - Best-fit flux consistent (inc. oscillations) with other experiments, and HZ and LZ solar models

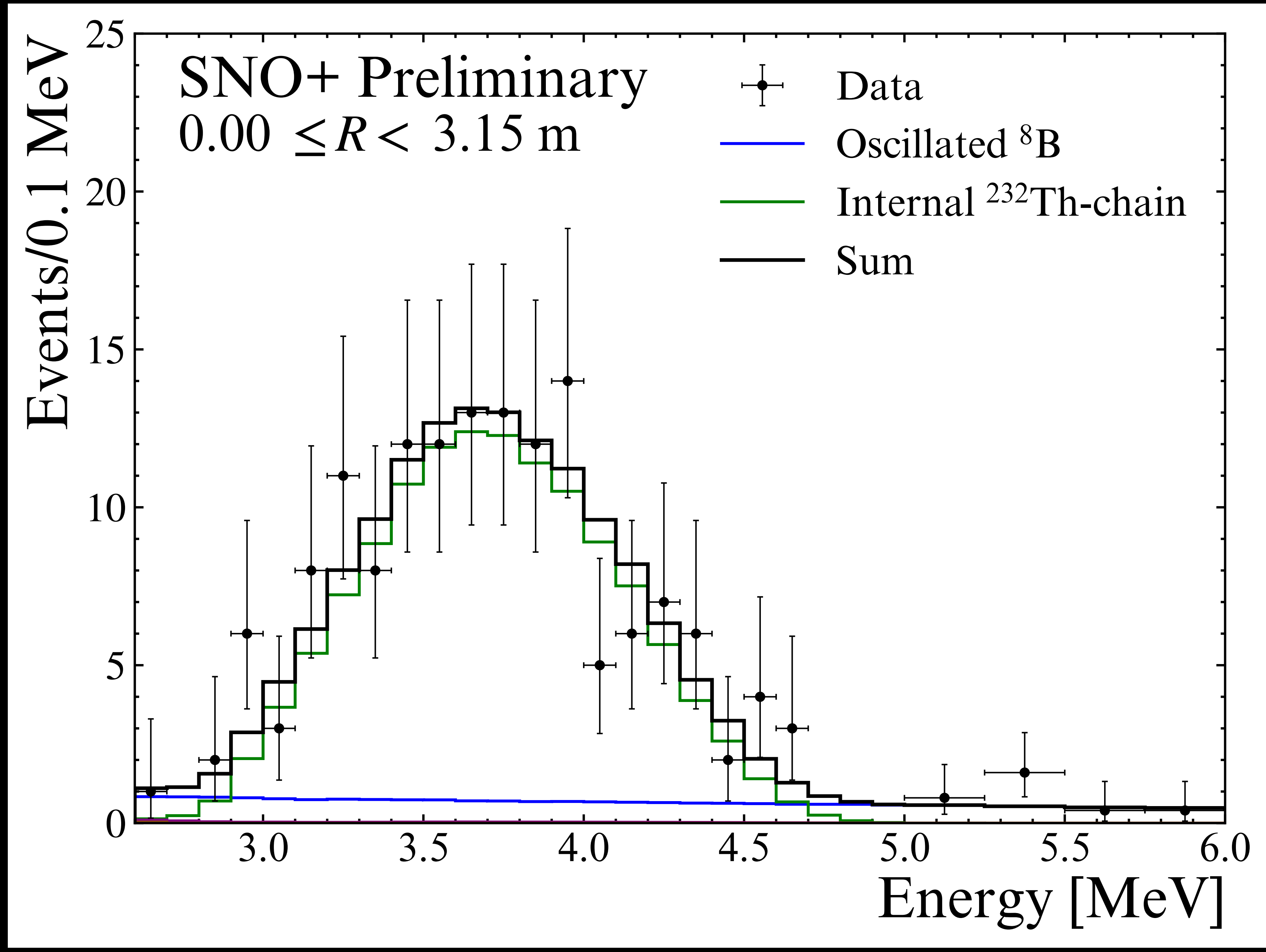
$$\left(5.36^{+0.41}_{-0.39}(\text{stat.})^{+0.17}_{-0.16}(\text{syst.})\right) \times 10^{6}\ \text{cm}^{-2}\text{s}^{-1}$$

SOLAR NEUTRINOS, SCINT. PHASE

POSTER 544 / D. COOKMAN

- Analysis of ^{8}B ES interactions in 138.9 live days of scint. data
- Fitted oscillation parameters compatible with global fits





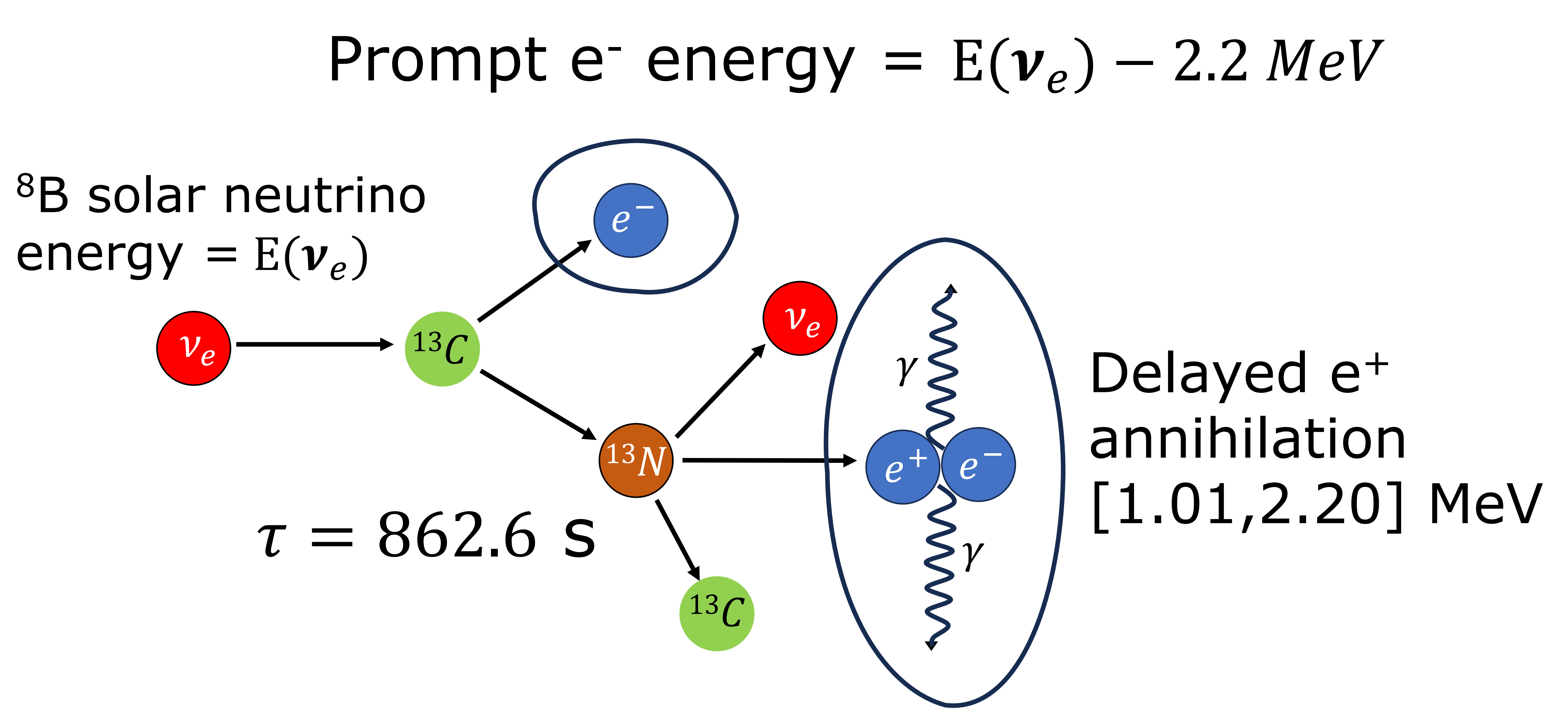
- Strict fiducial volume cut opens prospects for future sensitivity < 3 MeV !
- ^{232}Th still dominates 3-5 MeV regions, but multisite discriminant will help

POSTER 255 /A. INÁCIO, R. HUNT-STOKES

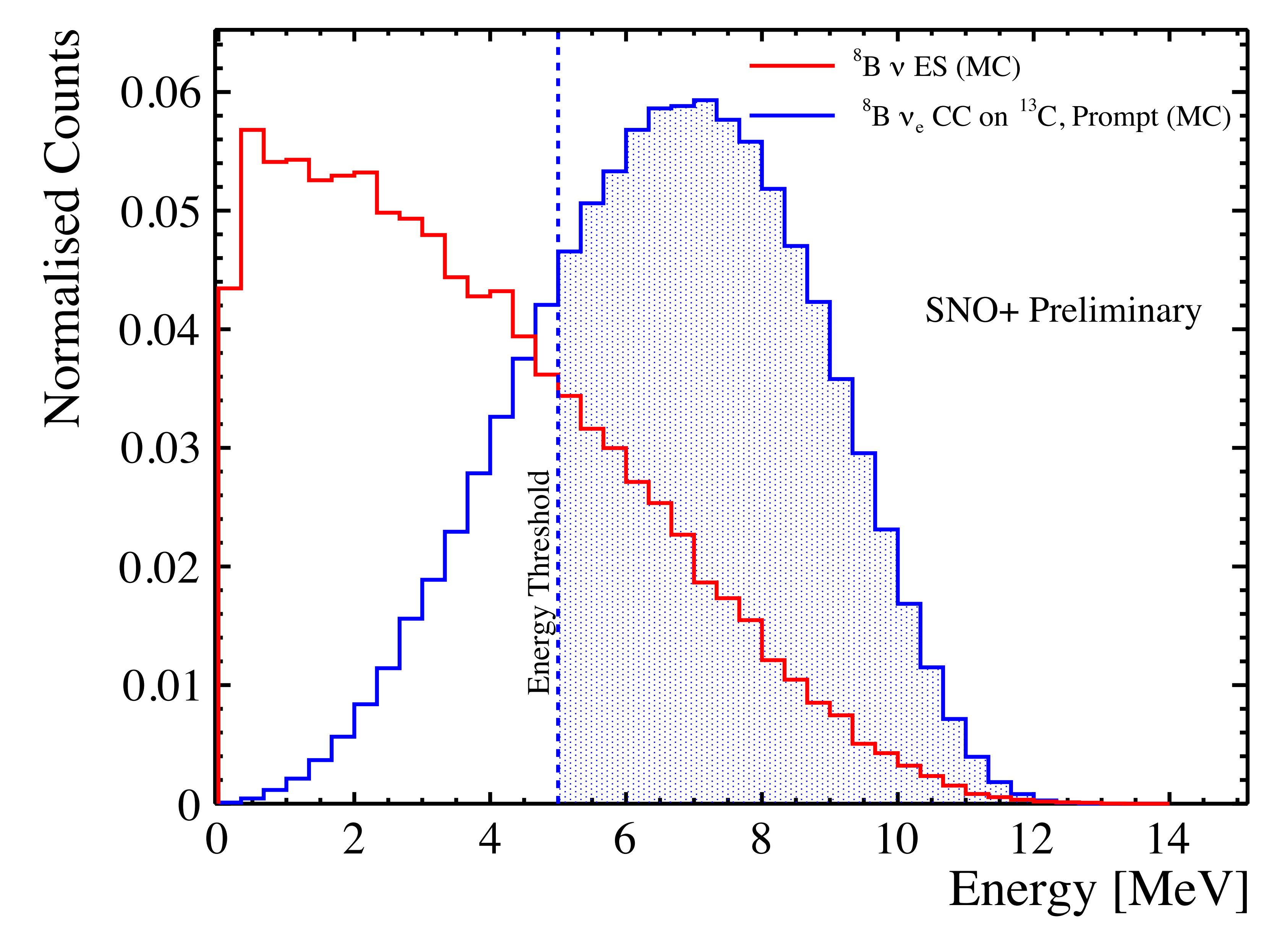
CHARGED CURRENT ON CARBON-13

$$\nu_e + {}^{13}C \rightarrow e^- + {}^{13}N$$

$$ {}^{13}N \rightarrow e^+ + \nu_e + {}^{13}C$$



- As yet unobserved reaction of electron neutrinos on Carbon-13 REF. 10
- Only 1.1% isotopic abundance, but cross section ~12× higher than ES at ^{8}B ν energies



- Cosmogenic backgrounds from ^{11}Be: negligible at SNOLAB depth
- Dominant accidental backgrounds determined by data-driven method
  - Randomly pick fake prompt , then search for delayed signal candidates

POSTER 416 / G. MILTON

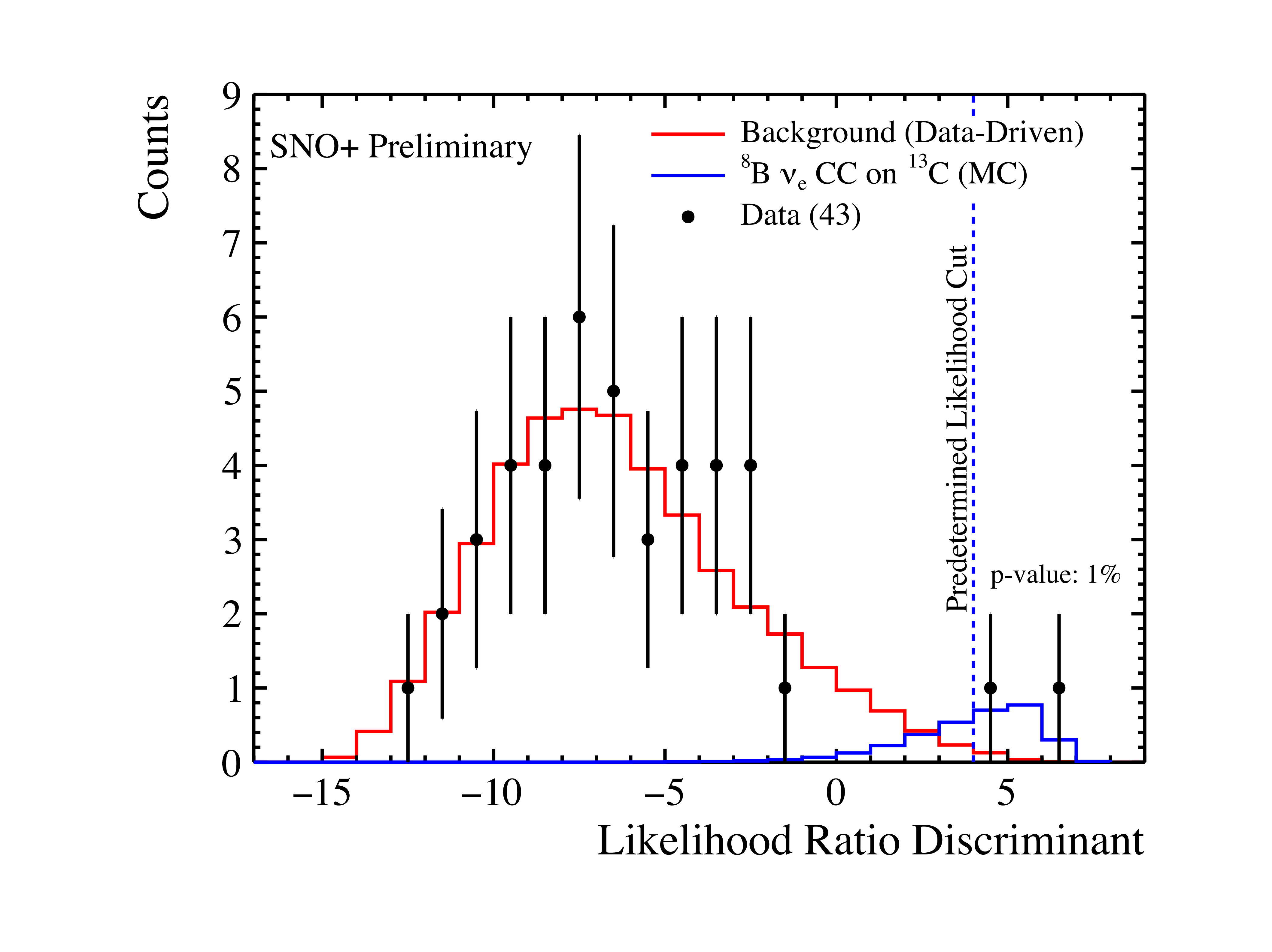
CC ON CARBON-13, RESULTS

- Cuts optimised prior to "blind box" opening:
  - Fiducial volume: R< 5.3 m
  - Prompt energy: 5.0 < E (e^-) < 15.0 MeV
  - Delayed energy: 1.14 < E (e^+) < 2.2 MeV
  - $\Delta R < 0.36$ m
  - $0.01 < \Delta T < 24$ min
  - Likelihood ratio analysis
    - Wider cuts on Delayed energy, ΔR, ΔT
    - Likelihood ratio discriminant> 4

EXPECTED	BOX	LIKELIHOOD
BACKGROUND	0.31	0.17
SIGNAL	1.83	1.79

150.51 live days

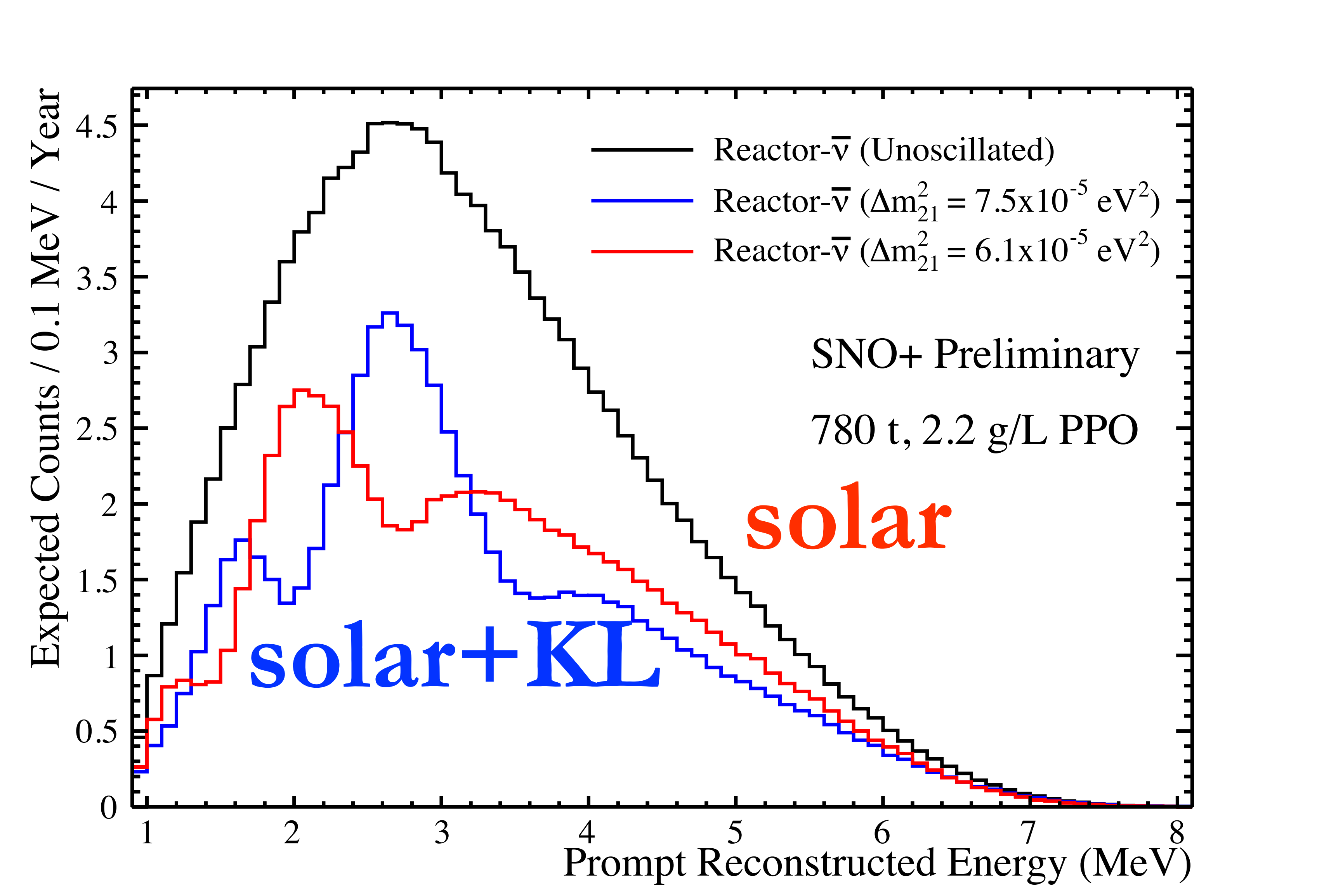
2 events found !



Indicative of a signal from ^{13}C CC interactions !

POSTER 416 / G. MILTON

REACTOR ANTINEUTRINOS ANALYSIS

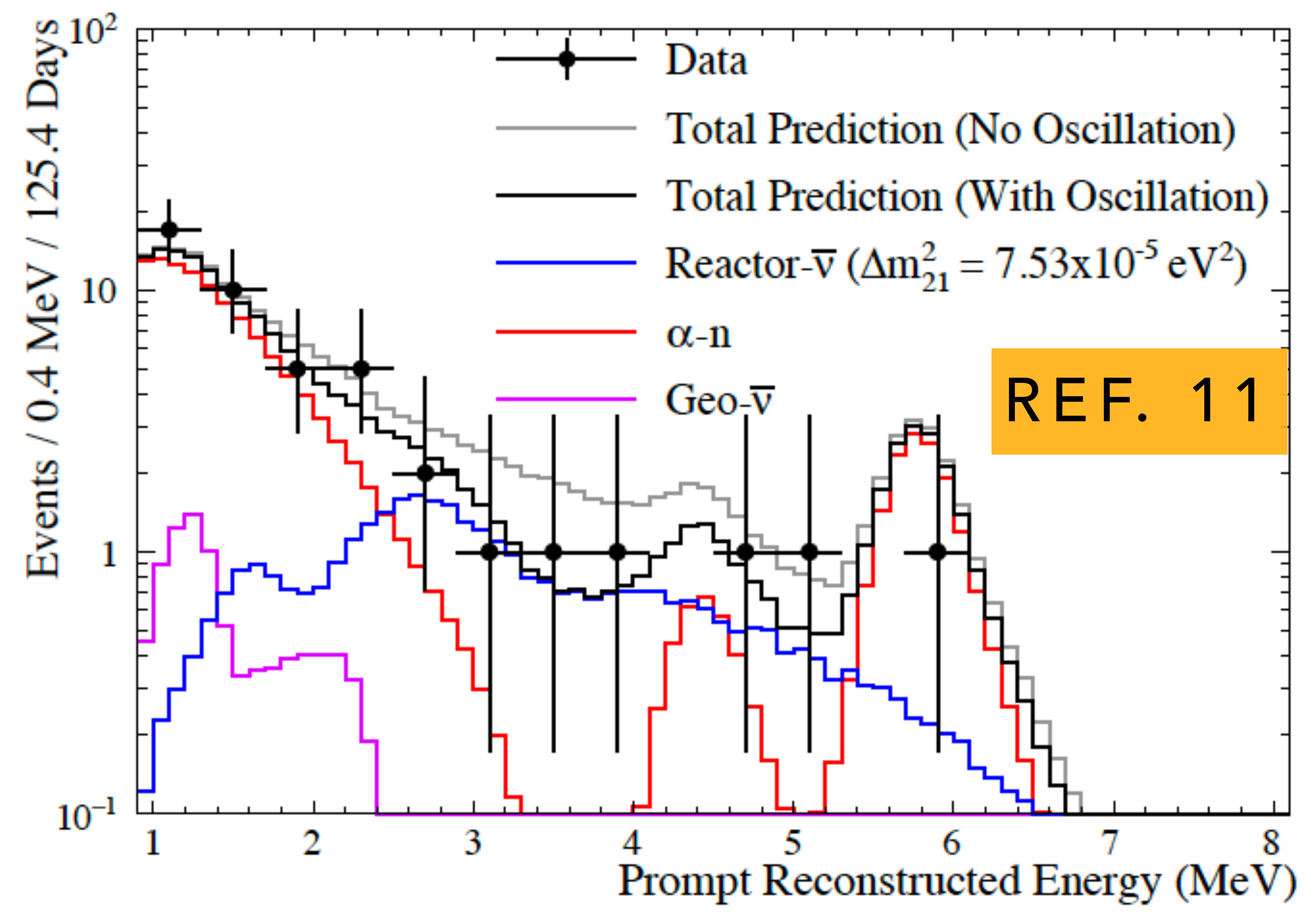


$$\bar{\nu}_e + p \rightarrow e^+ + n$$
$$n + p \rightarrow {}^2H + \gamma(2.2MeV)$$

- Prompt spectrum @ SNO+ with sharp features, due to few baselines
- Potential to shed light on solar-KamLAND tension

- Following first detection in a water Cherenkov detector, new results from partial and scint phases
- Main background: (α,n) reactions on ^{13}C
  - αs from high rate ^{210}Po decays
- Partial fill: 114 t.y exposure, 85 Hz of ^{210}Po
  - Stats and background-limited

POSTER 525 / S. ANDRINGA

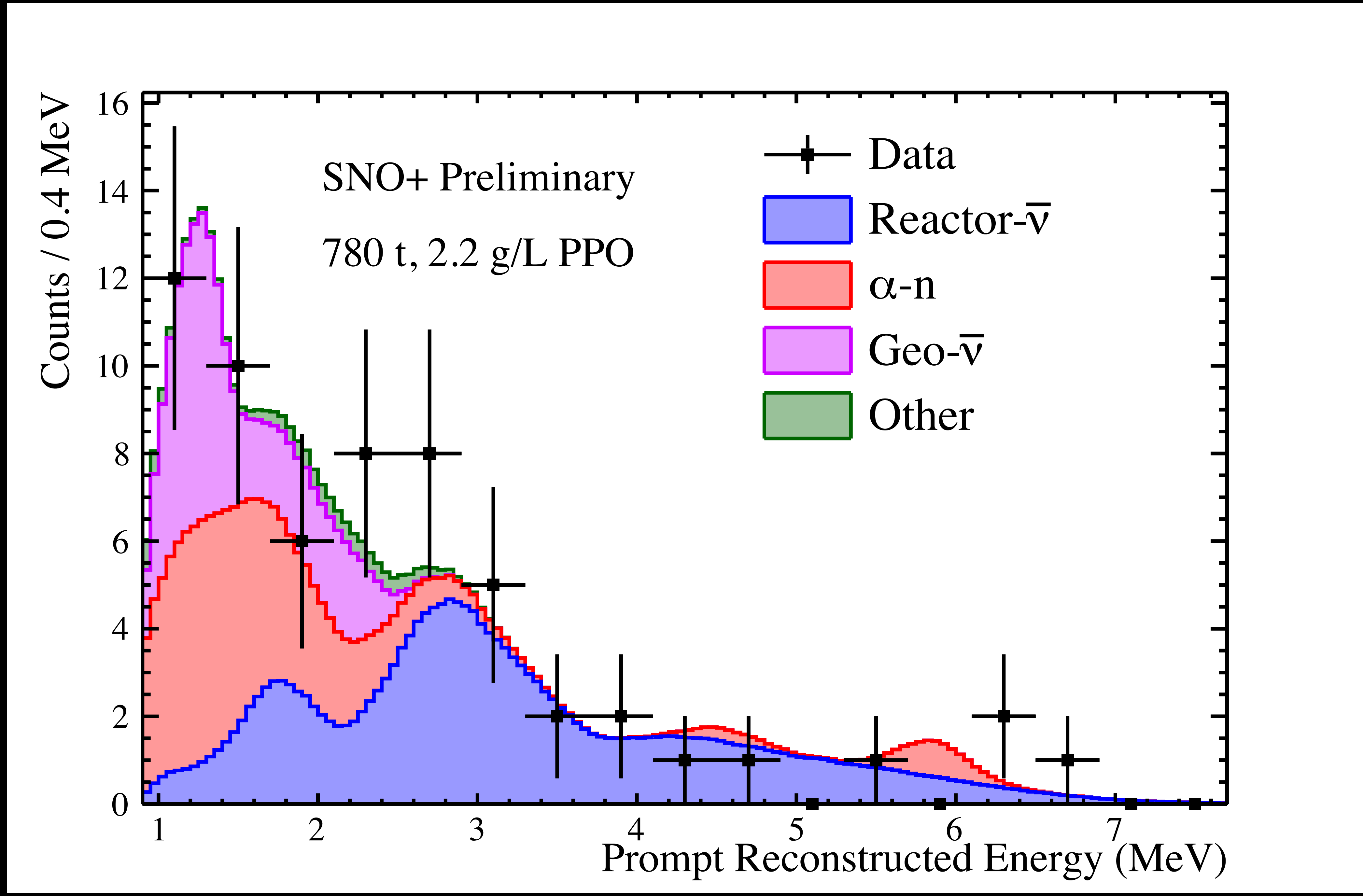


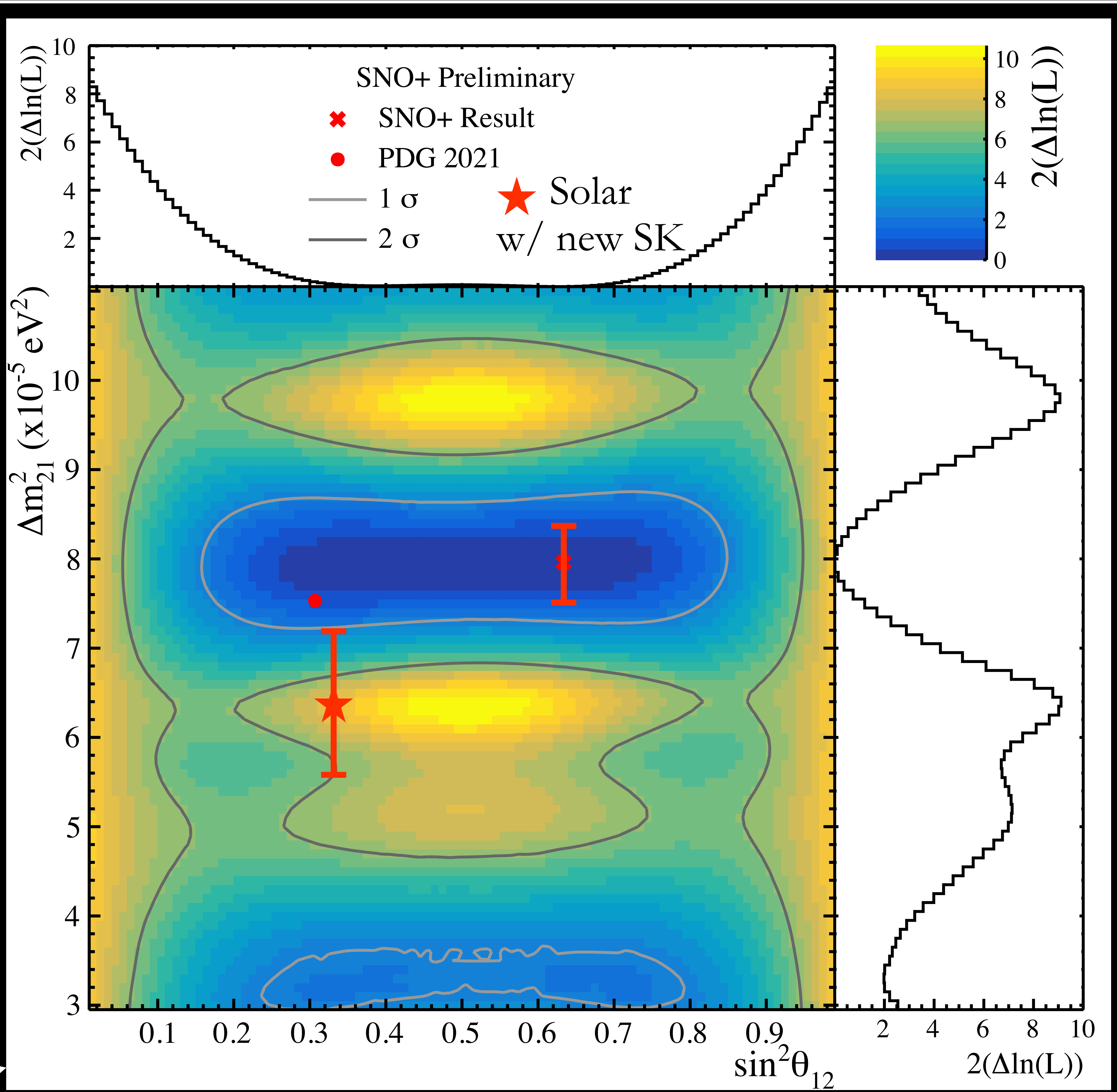
REF. 11

REACTOR ANTINEUTRINOS RESULTS

POSTER 525 / S. ANDRINGA

Scint. phase:
286 t.y
exposure,
38 Hz ^{210}Po





- Still stats limited, but lower (α,n) background
- Geo-nu 64+/- 44 TNU, will improve soon with (α,n) classifier POSTER 483/ J. PAGE
- Unconstrained oscillation fit

$$\Delta m^2_{21} = 7.96^{+0.48}_{-0.41} \times 10^{-5} eV^2$$

- ~1.3σ from solar only, <1σ from KL

FUTURE EXPERIMENTS

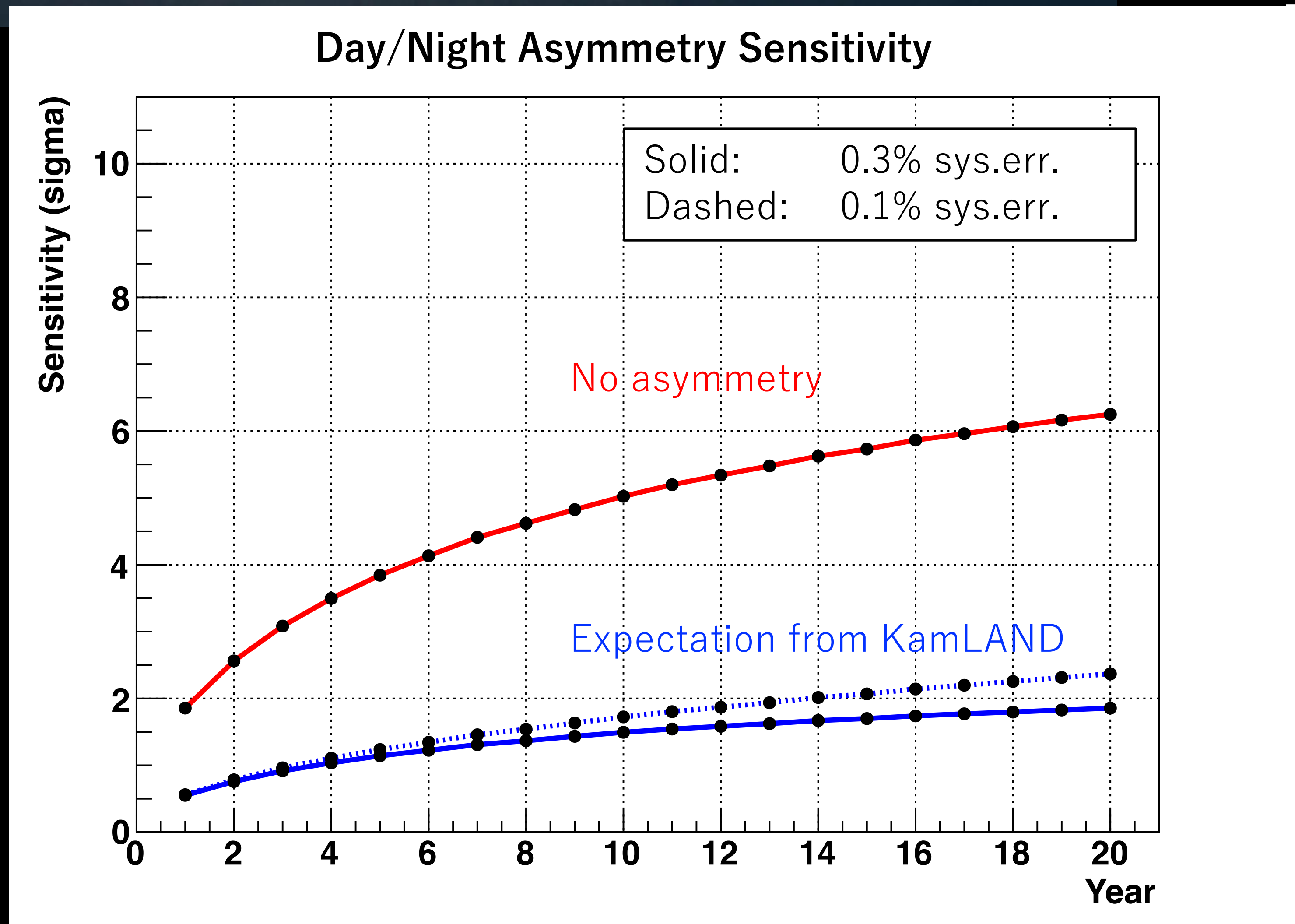
HYPER-KAMIOKANDE

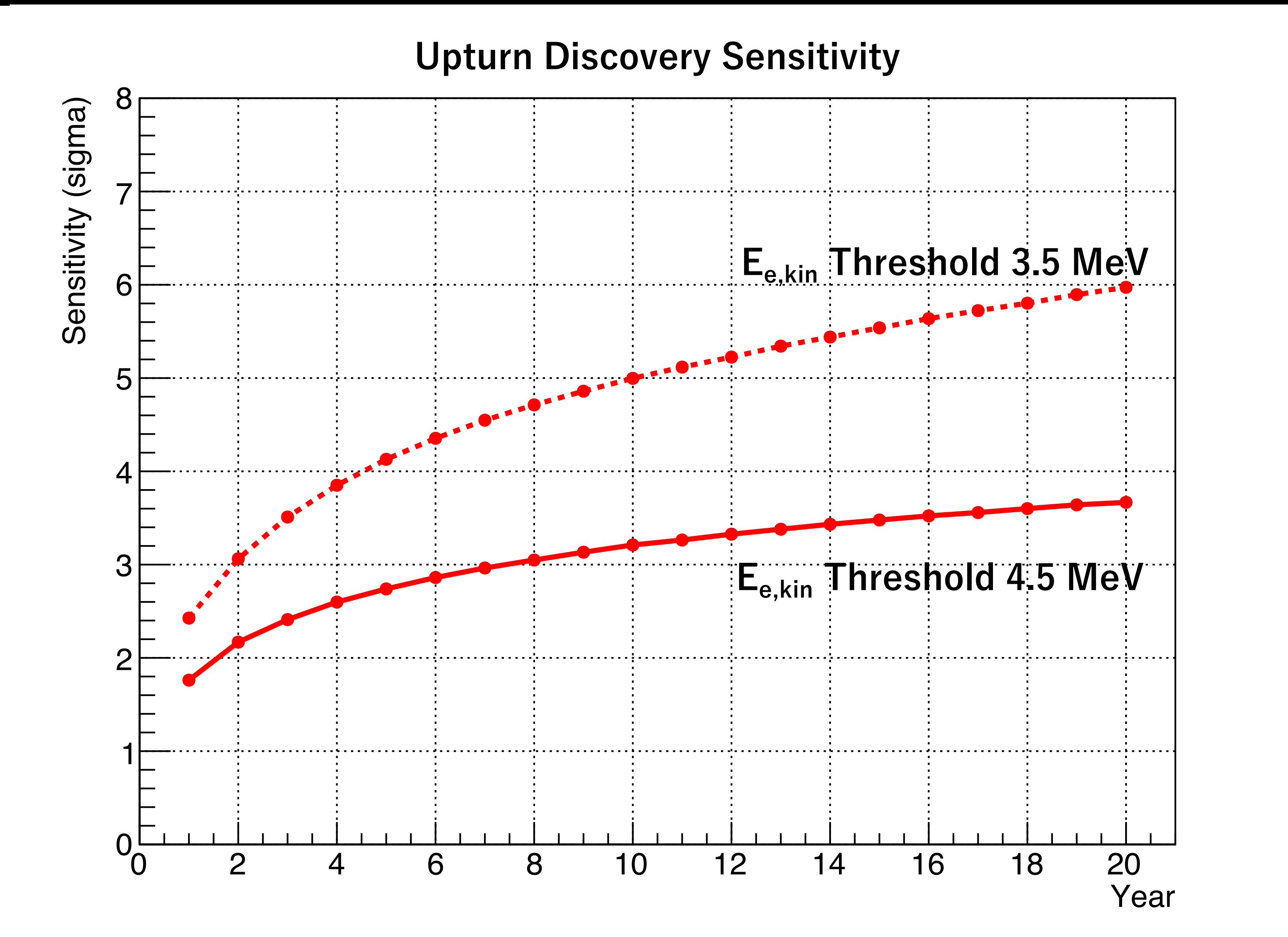
THANKS TO F. DI LODOVICO, S. MORIYAMA, T. YANO

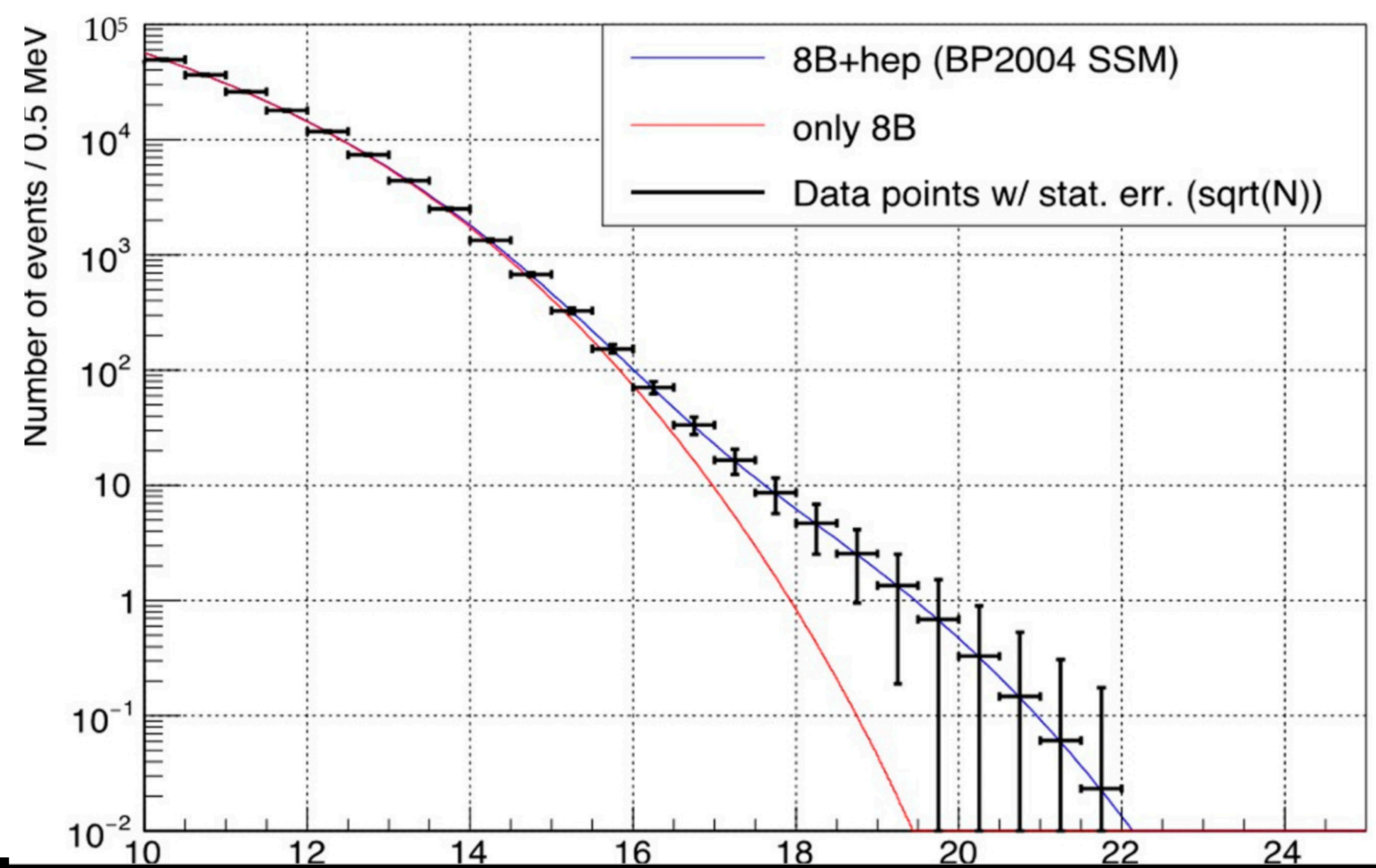
TALK 646/ S. MORIYAMA

- Largest ever (solar) neutrino detector, starting 2027
  - Less deep than SK: higher cosmogenic backgrounds, but have several methods to tag the showers
  - Huge statistics: ~5 ^{8}B ν/hour
    - If Δm^2_{21} is that of solar best fit, 5 σ on day-night effect.
    - If the threshold is 3.5 MeV, 5 σ on low energy upturn
    - 2-3 σ measurement of hep νs as well

REF. 12

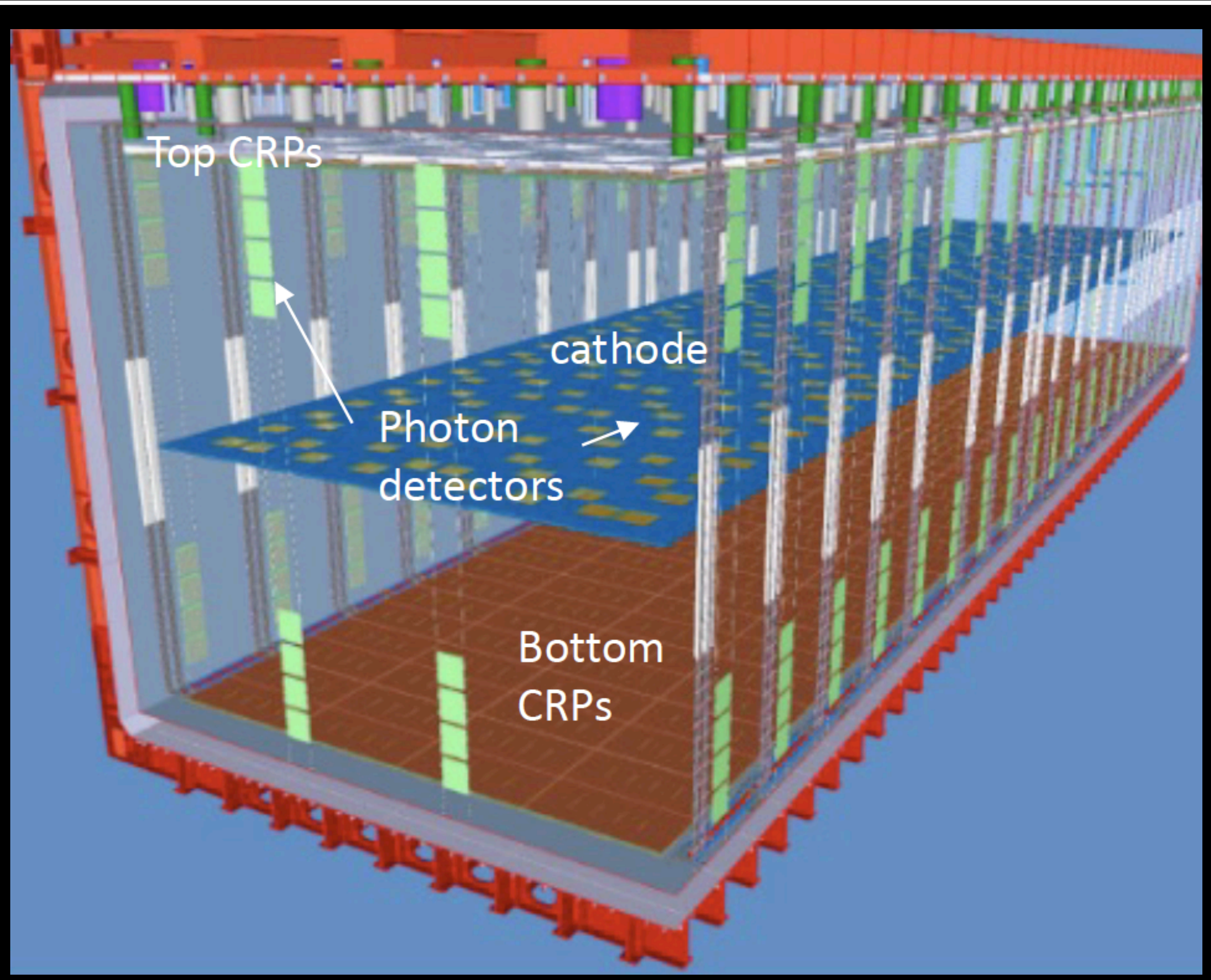




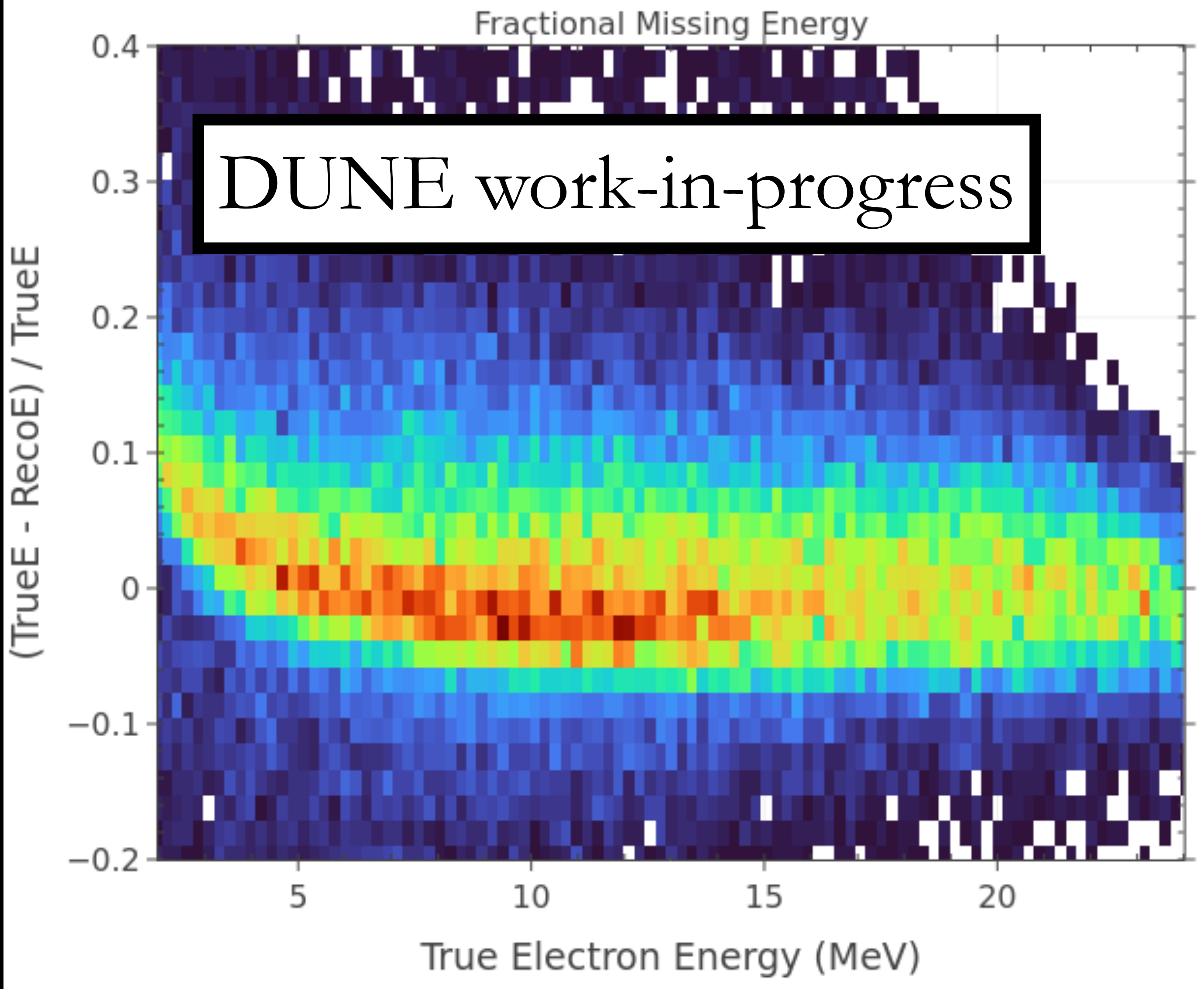


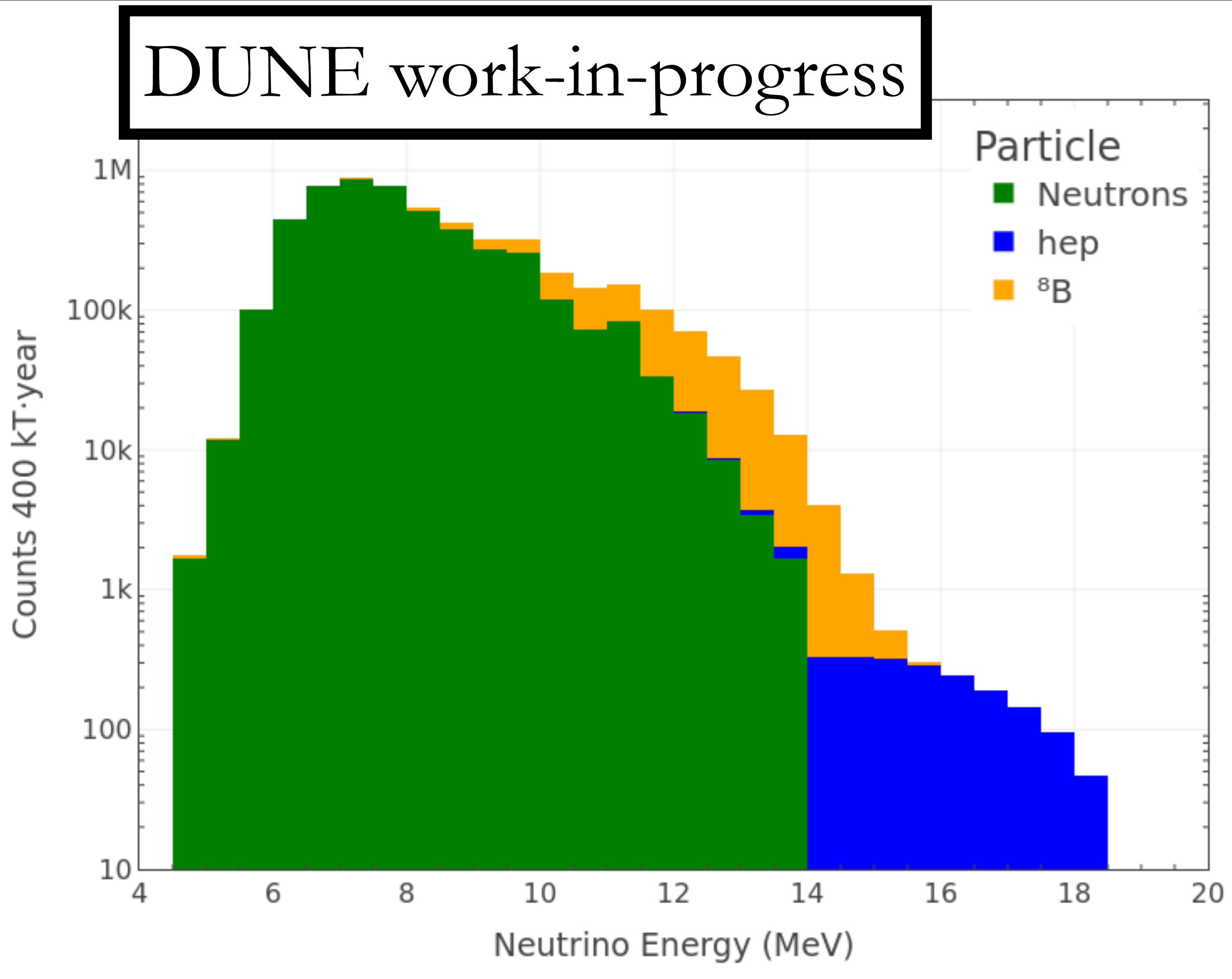
DUNE

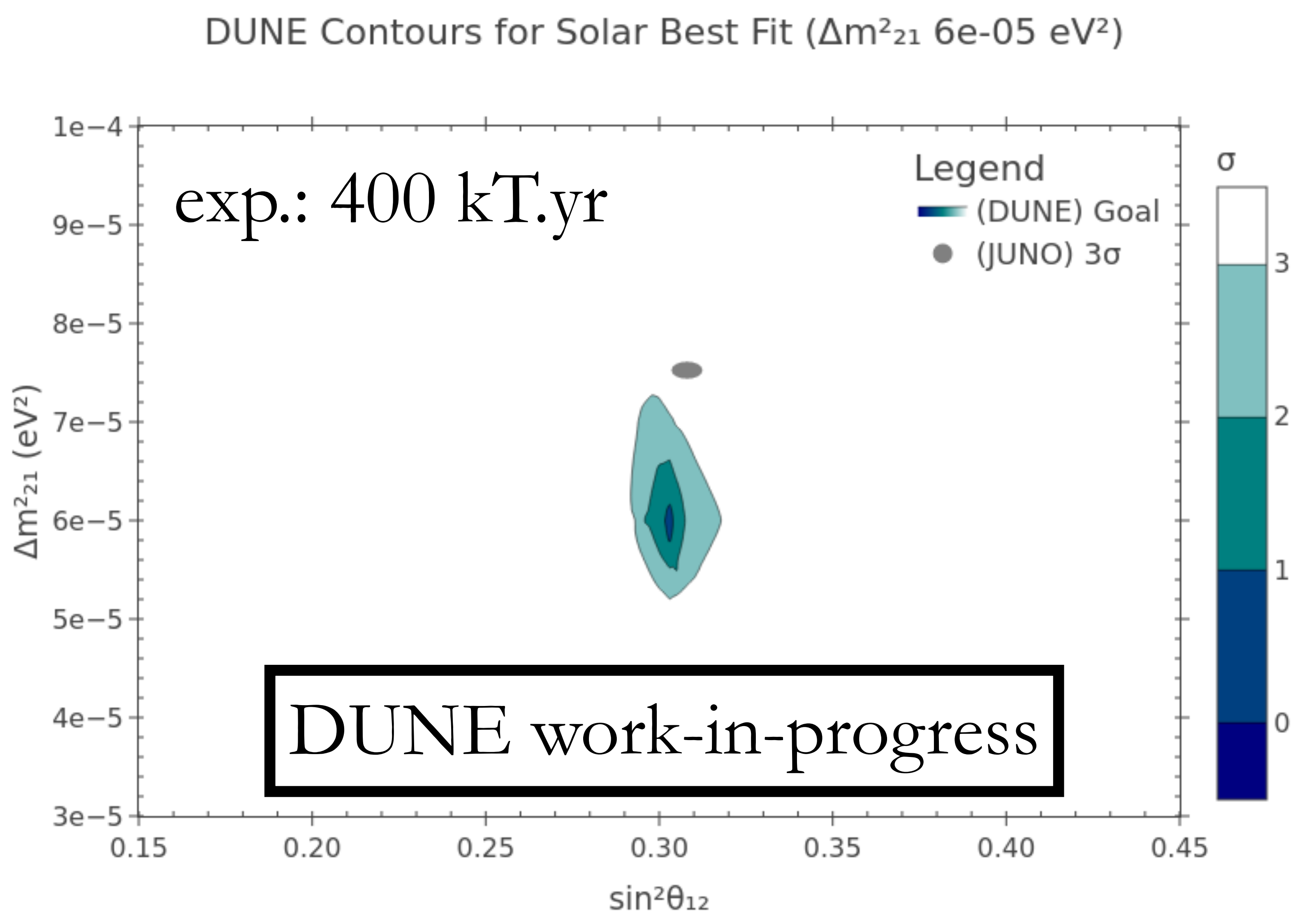
TALK 645/ C. MARSHALL
POSTER 87/ S. CORCHADO
THANKS TO
I. BOTELLA, C. CUESTA



- Phase-I, starting 2029
  - Two largest LAr TPCs ever built: ~27 kton active vol. (comb.)
  - Recent progress in low energy reconstruction: ~16% resolution
  - High ^{8}B stats → 3 σ solar/reactor Δm^2_{21} discrimination
  - High x-section on Ar, kinematics favorable for hep discovery
- Phase-II
  - very active R&D to improve LE performance



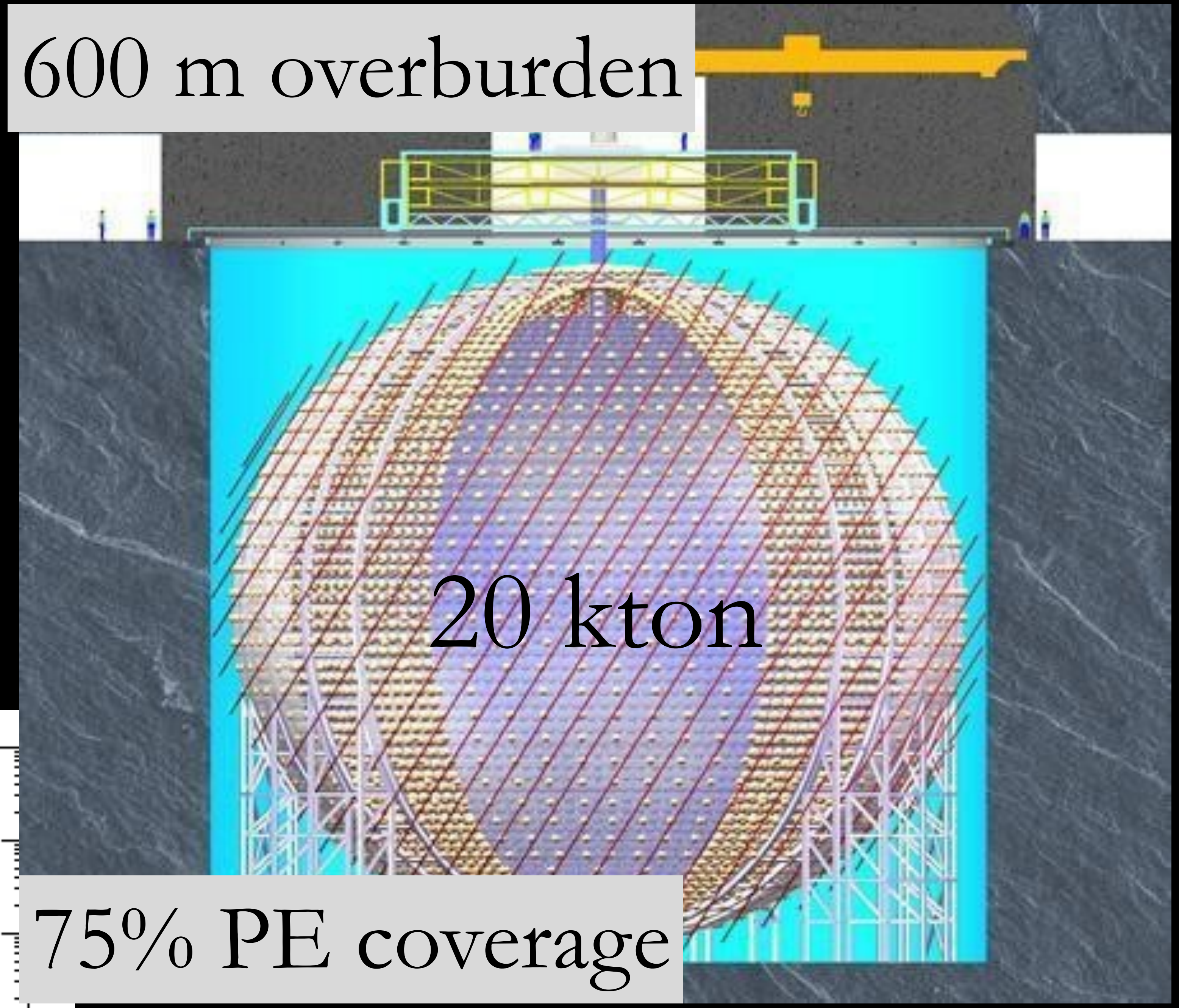


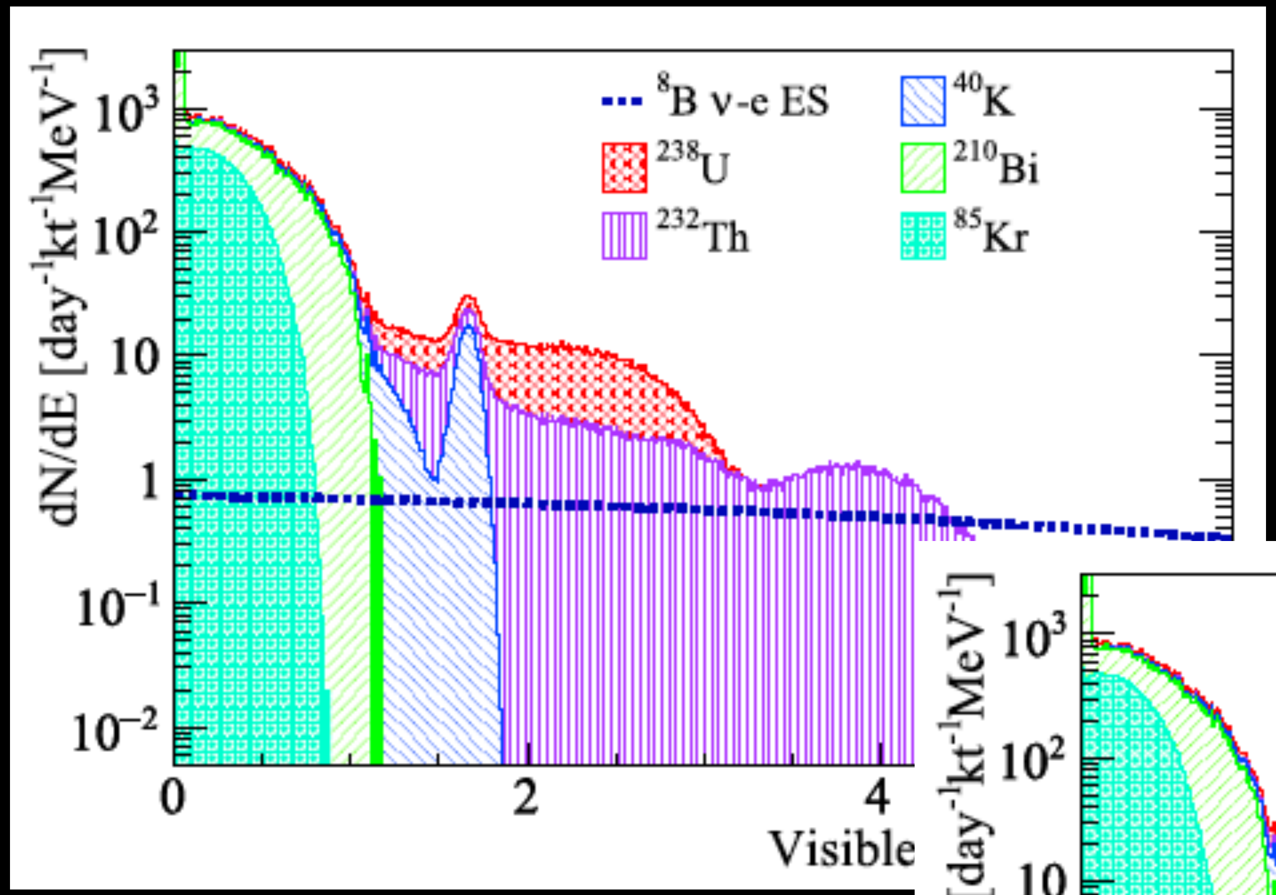


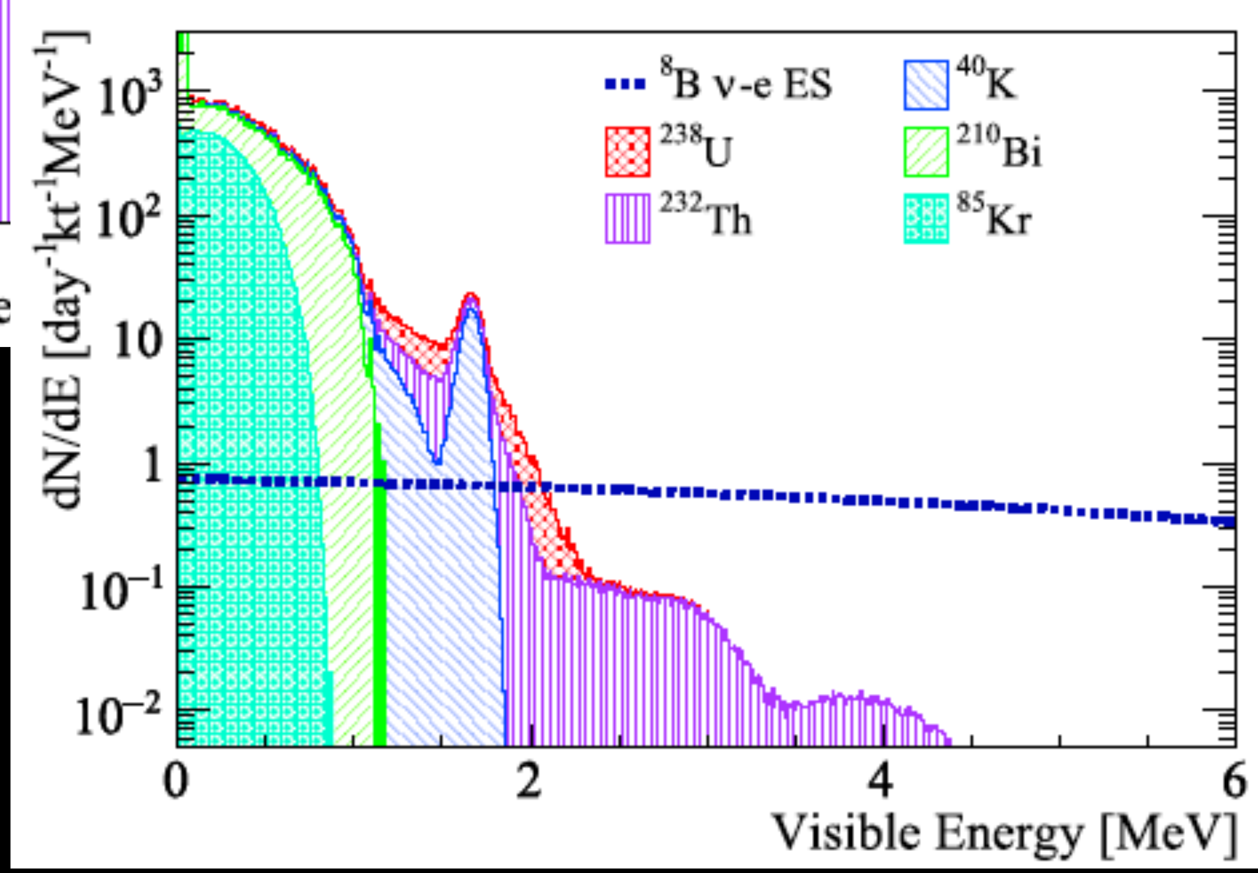
TALK 609/ J. CAO

THANKS TO G. RANUCCI

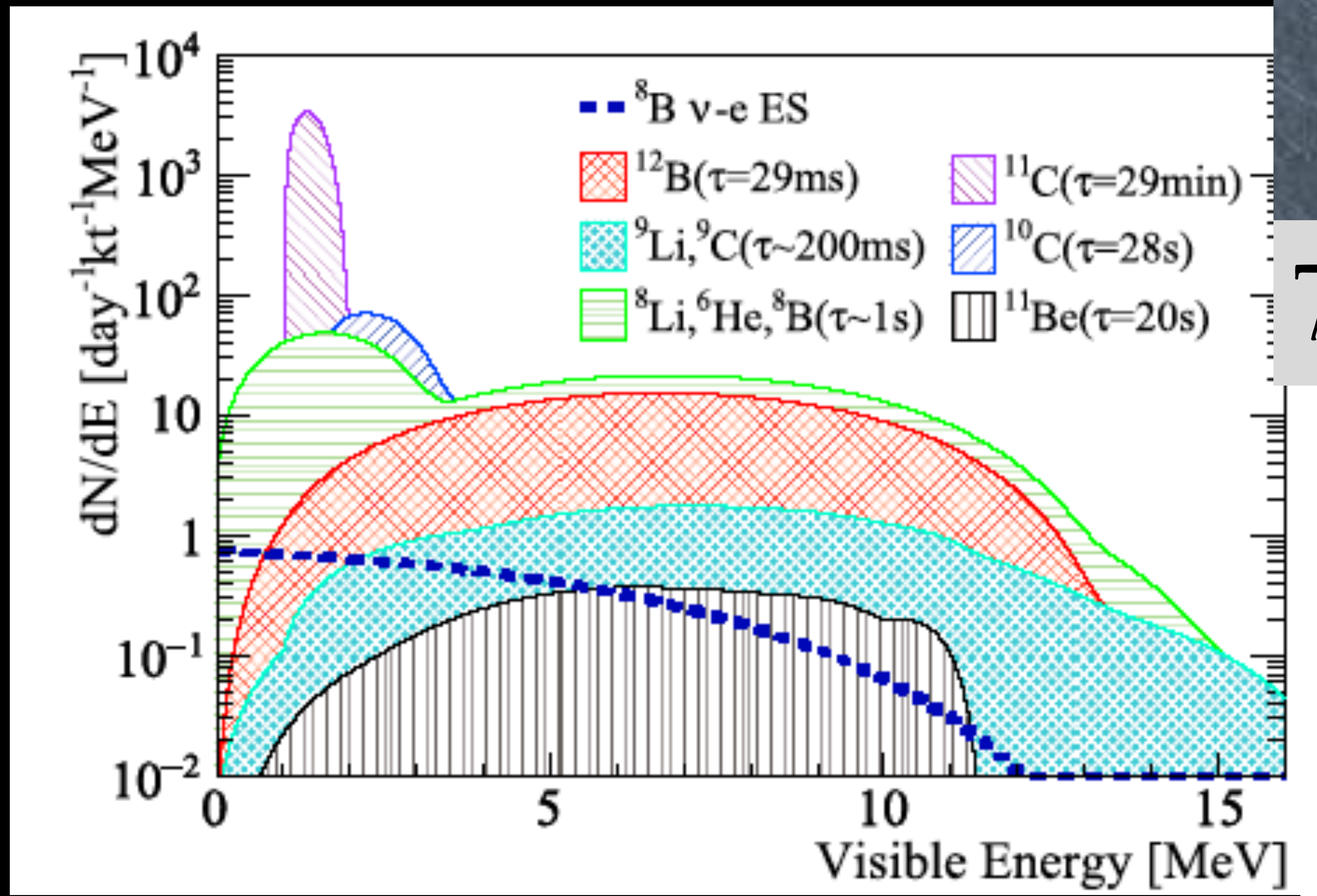
- Largest liquid scintillator detector, starting this year
  - Radiopurity control: materials 15% better than spec.
  - Scintillator purification similar to Borexino, goal to achieve 10^{-17} g/g in U/Th
  - High rate of cosmogenics (~7× more than Borexino): assuming similar tagging efficiencies

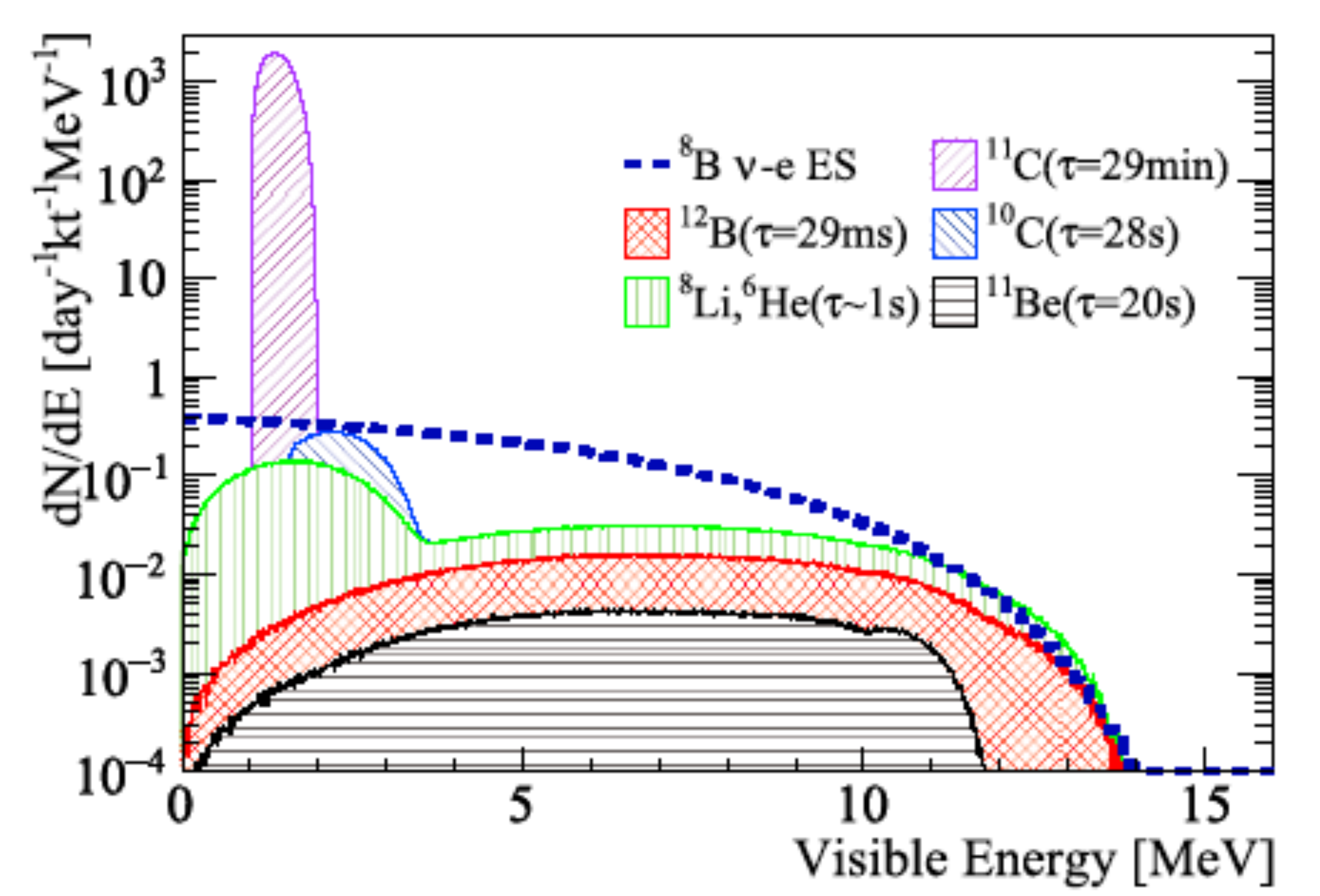






Assumed U/Th suppression



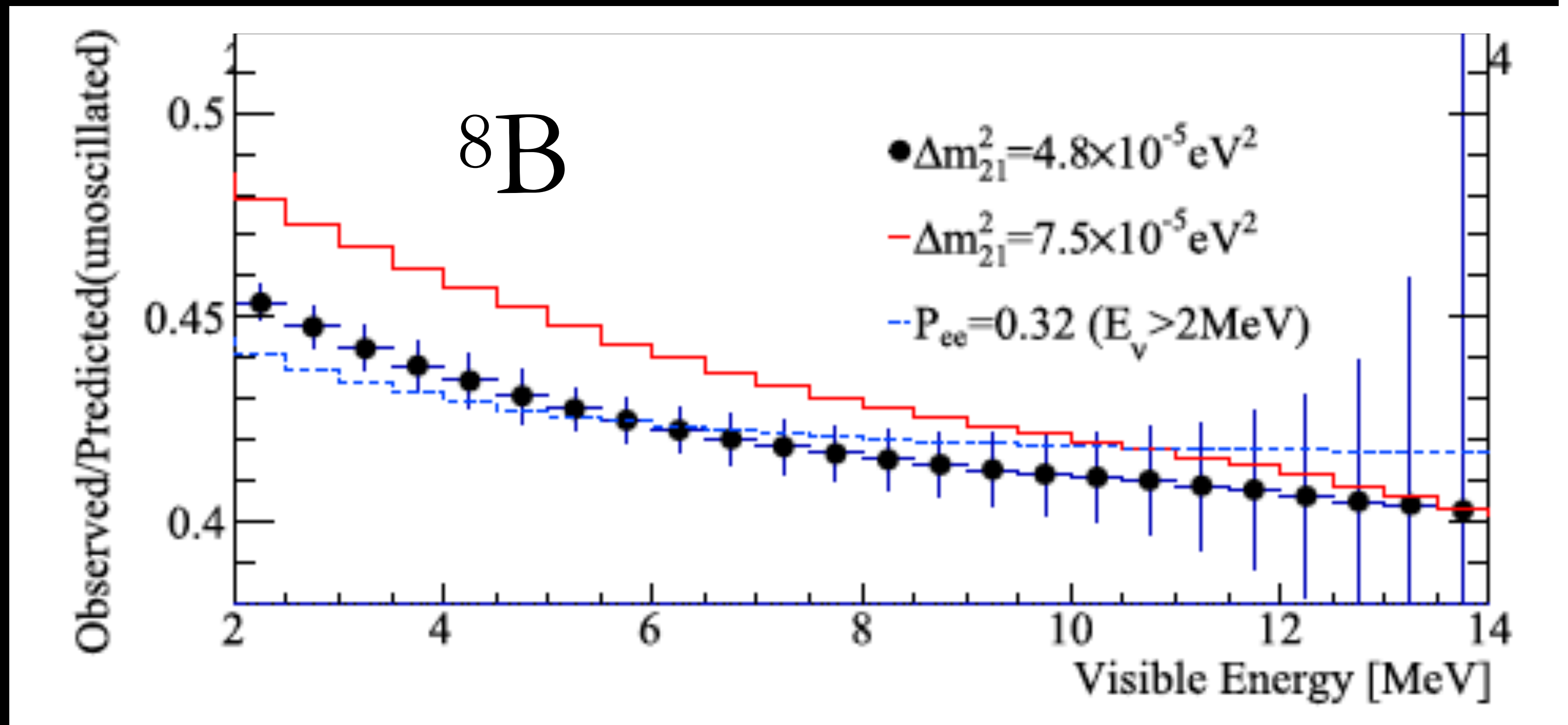


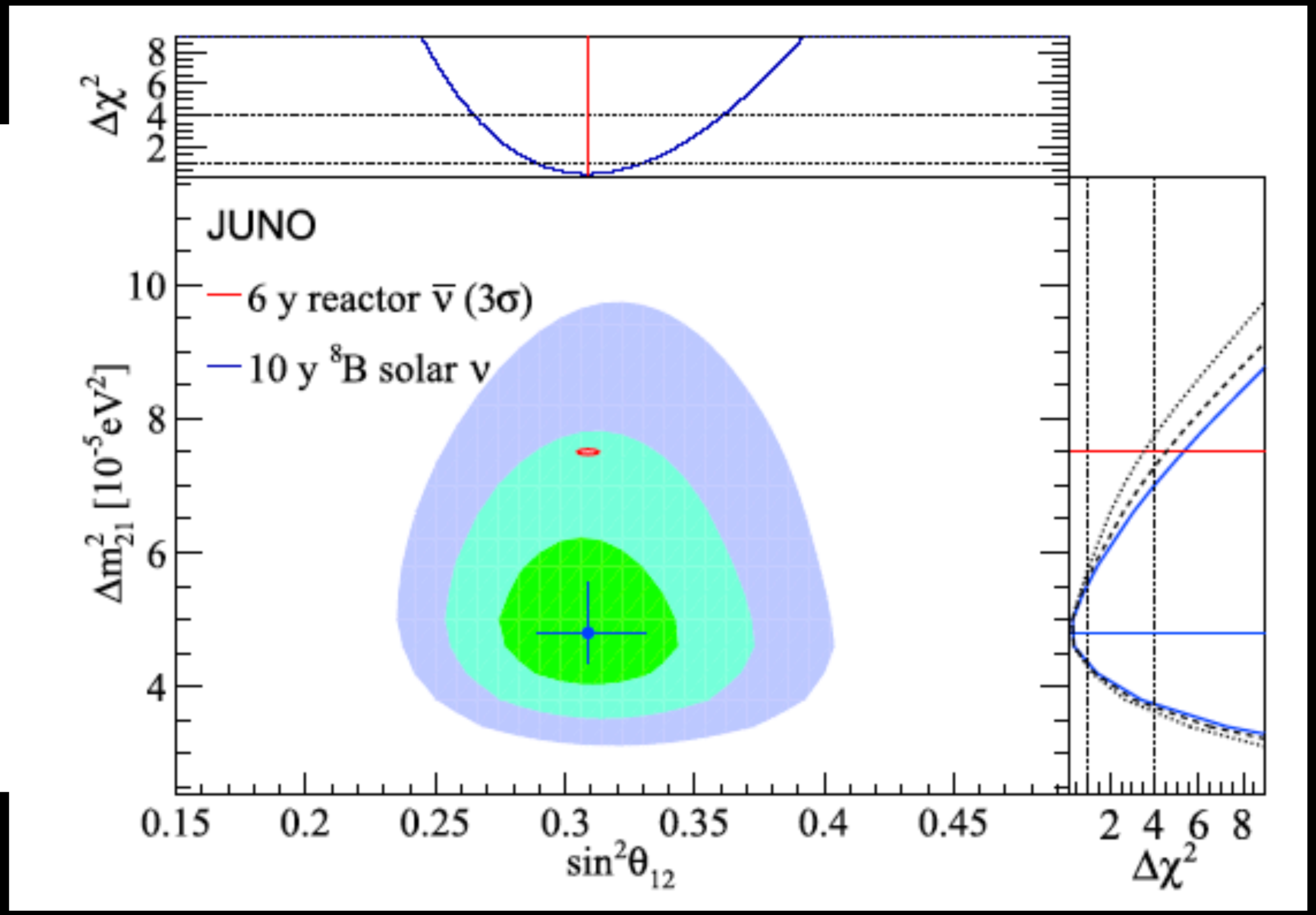
REF. 13

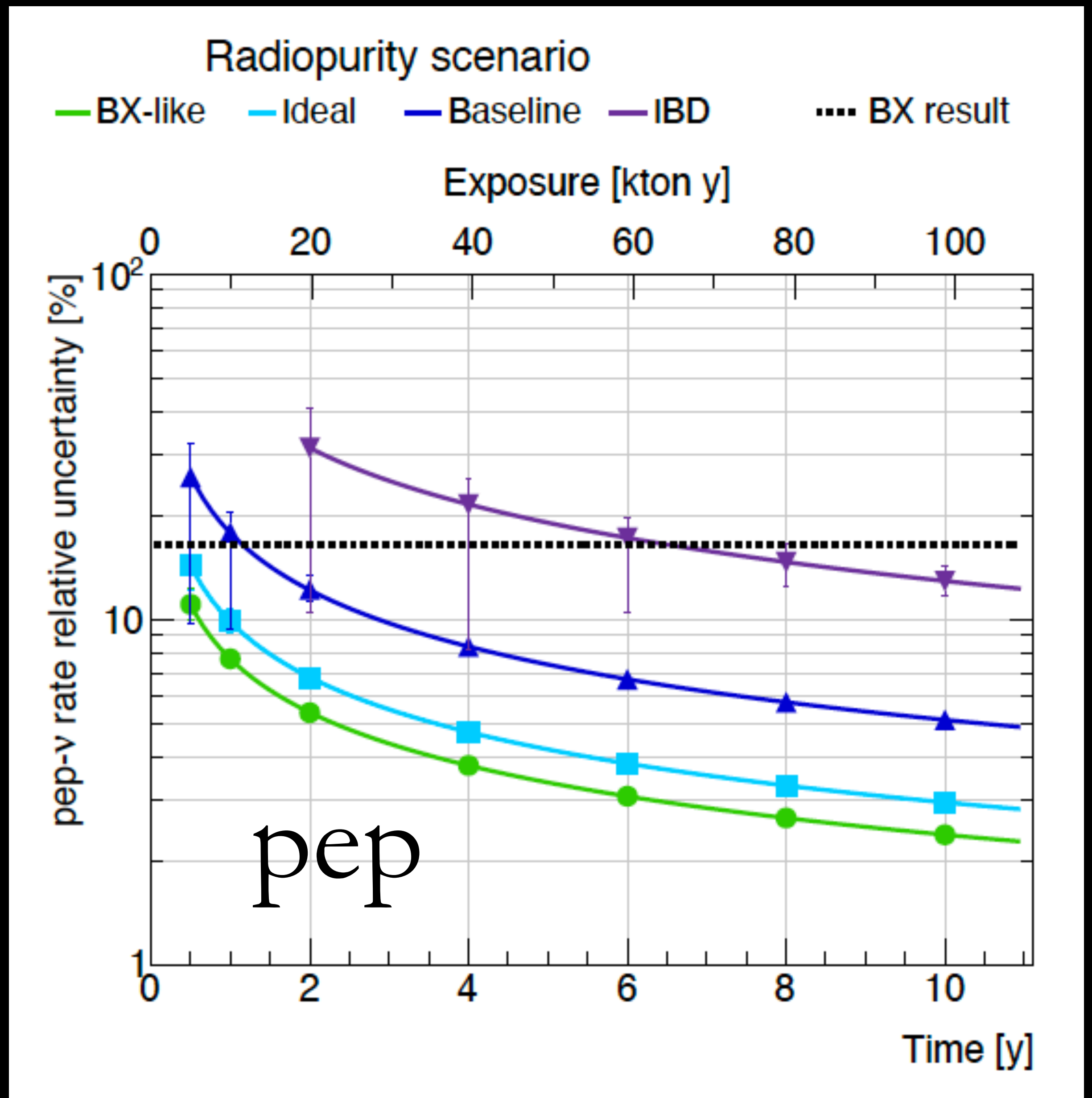
Assumed cosmogenics suppression

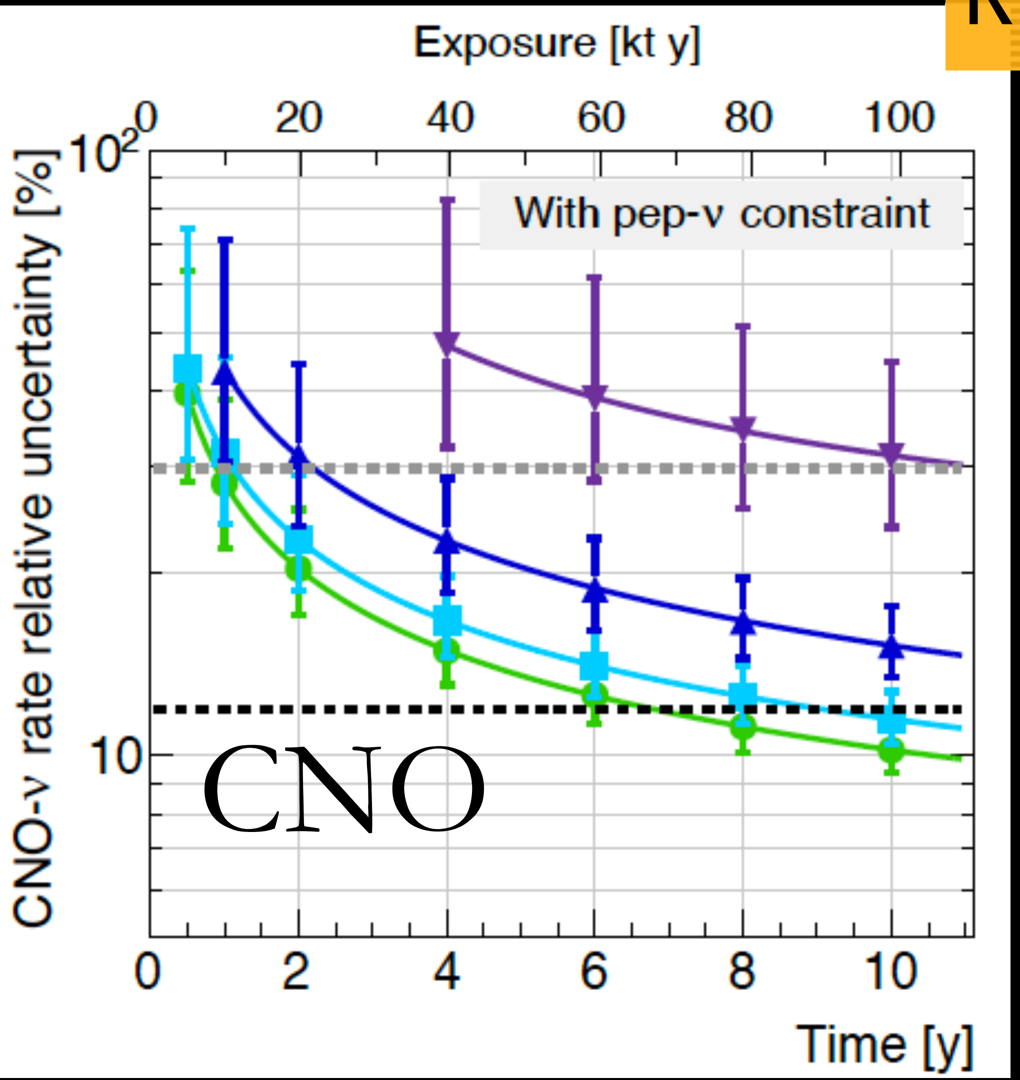
JUNO PROSPECTS ON SOLAR NEUTRINOS

- Low energy ^{8}B spectral measurement (+ day-night), constraining upturn and oscillation parameters
- ^{7}Be rate < 1%
- pep rate < 10%
- CNO similar to BX





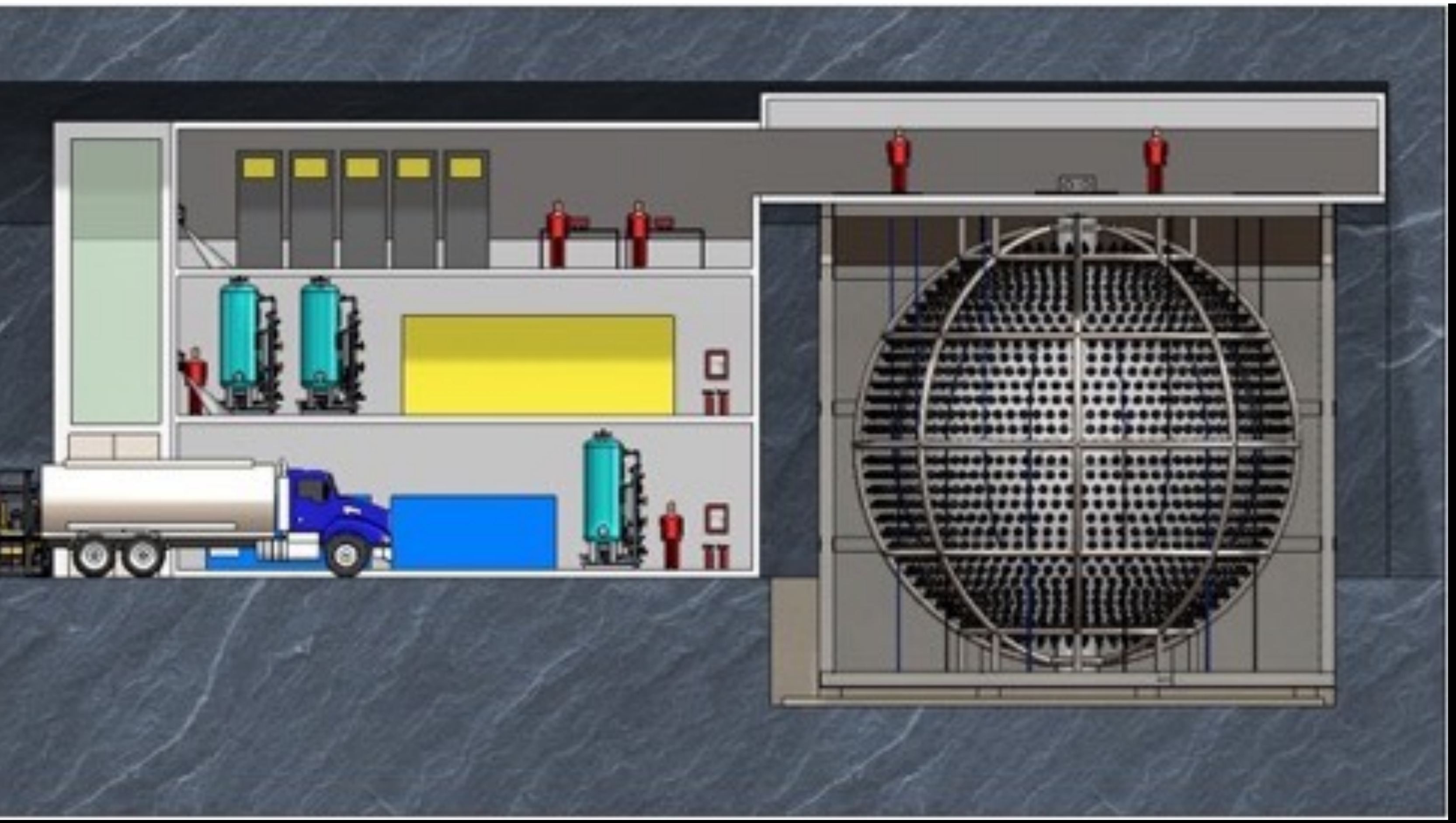




REF. 13

JUNO SOLAR NEUTRINO POSTERS:
240 / D. BASILICO, 286 / J. ZHAO,
330 / M. MALABARBA

THANKS TO
G. RANUCCI

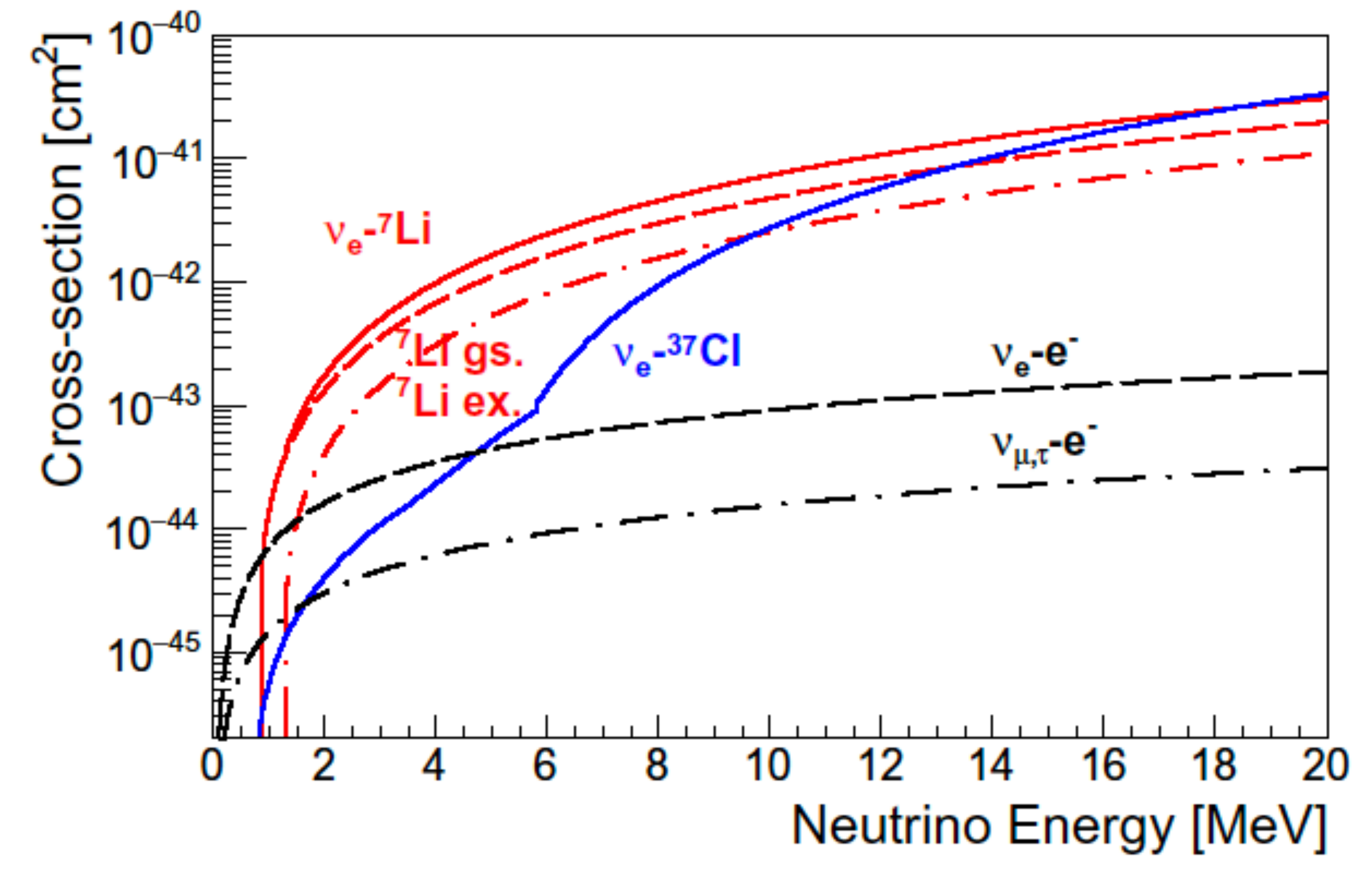


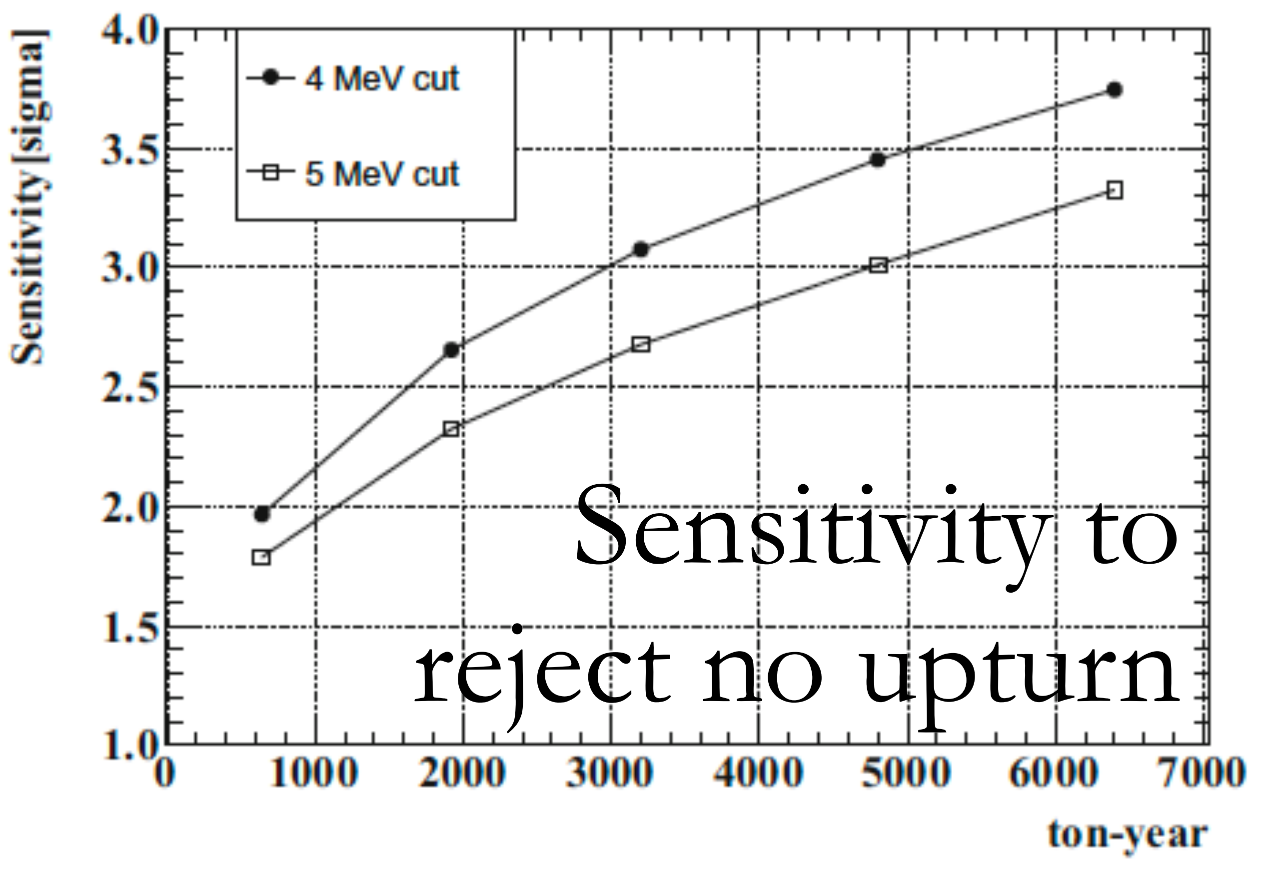
THANKS TO S. CHEN

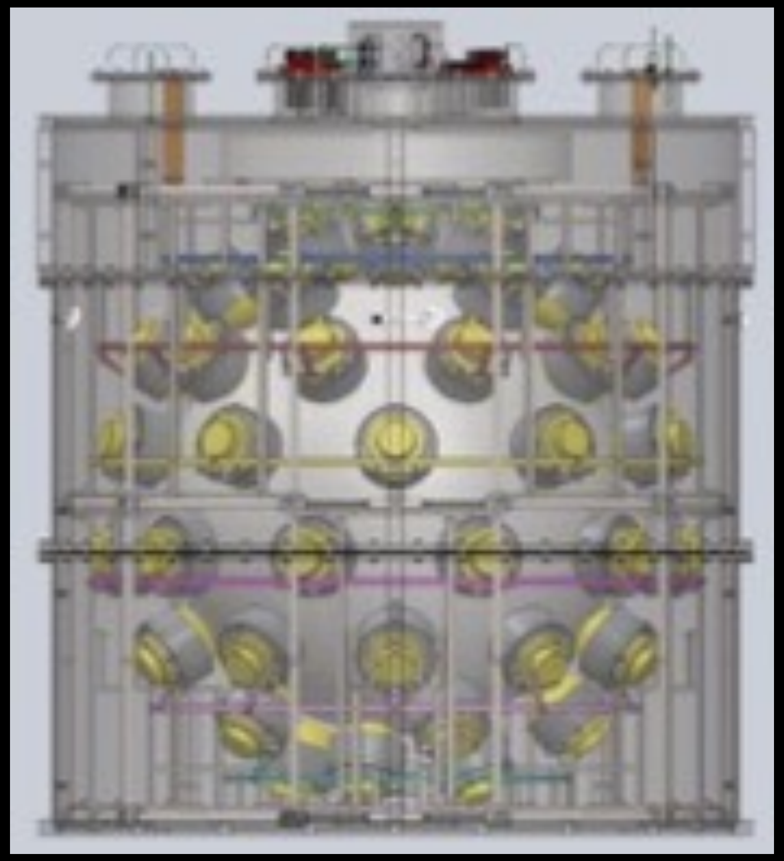
- China Jinping Underground Laboratory (CJPL), deepest UG lab in the world
- Cavity ready, construction soon
  - Acrylic vessel ~10 m diameter 500 m3
  - Target density +/- 20% (w/r to water). Start with water, then possibly slow-LS, LiCl-LS or TeLS or NdLS
- Currently testing new PMTs and electronics at 1 ton prototype

Data: end of 2026

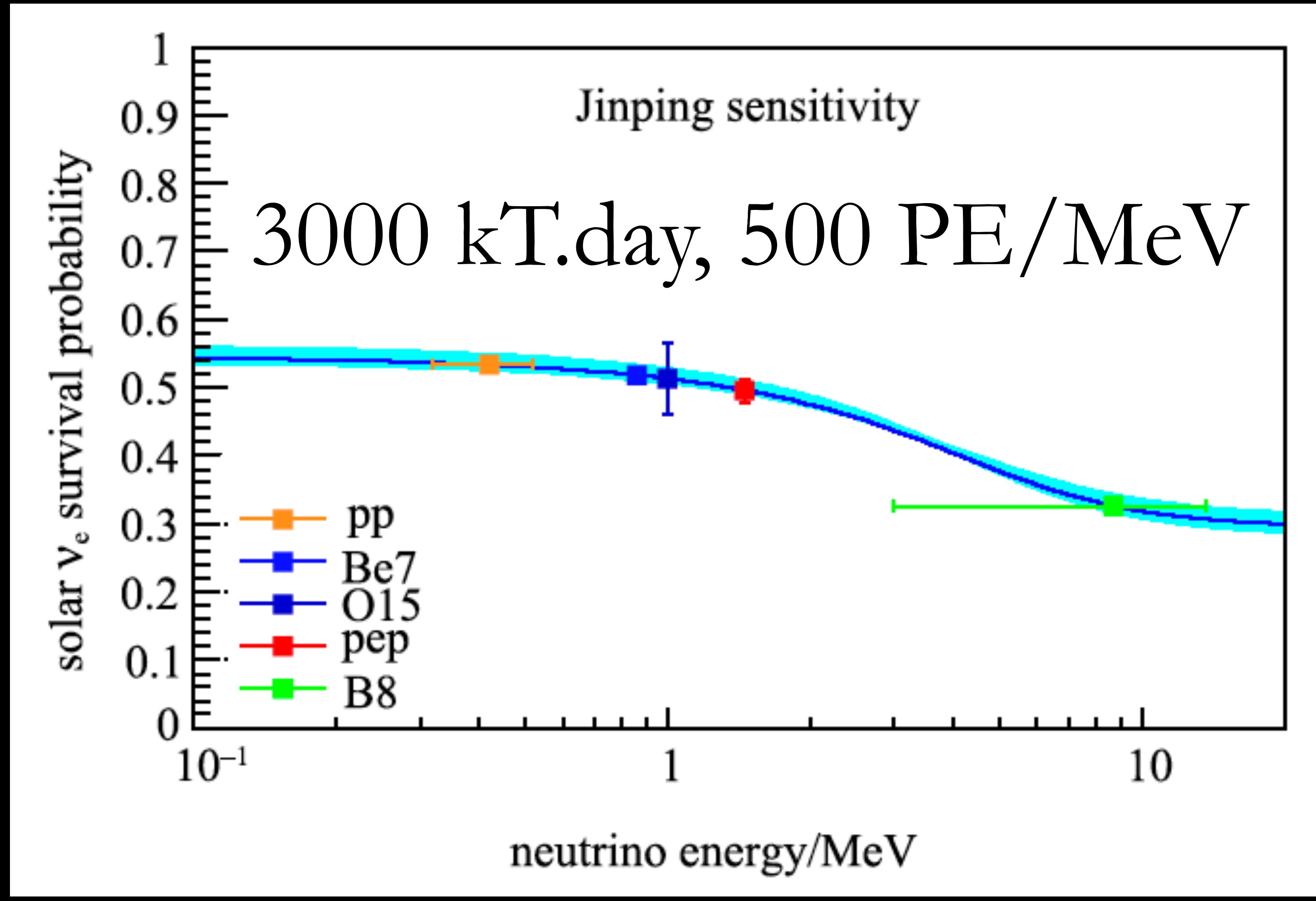
Possible Li loading





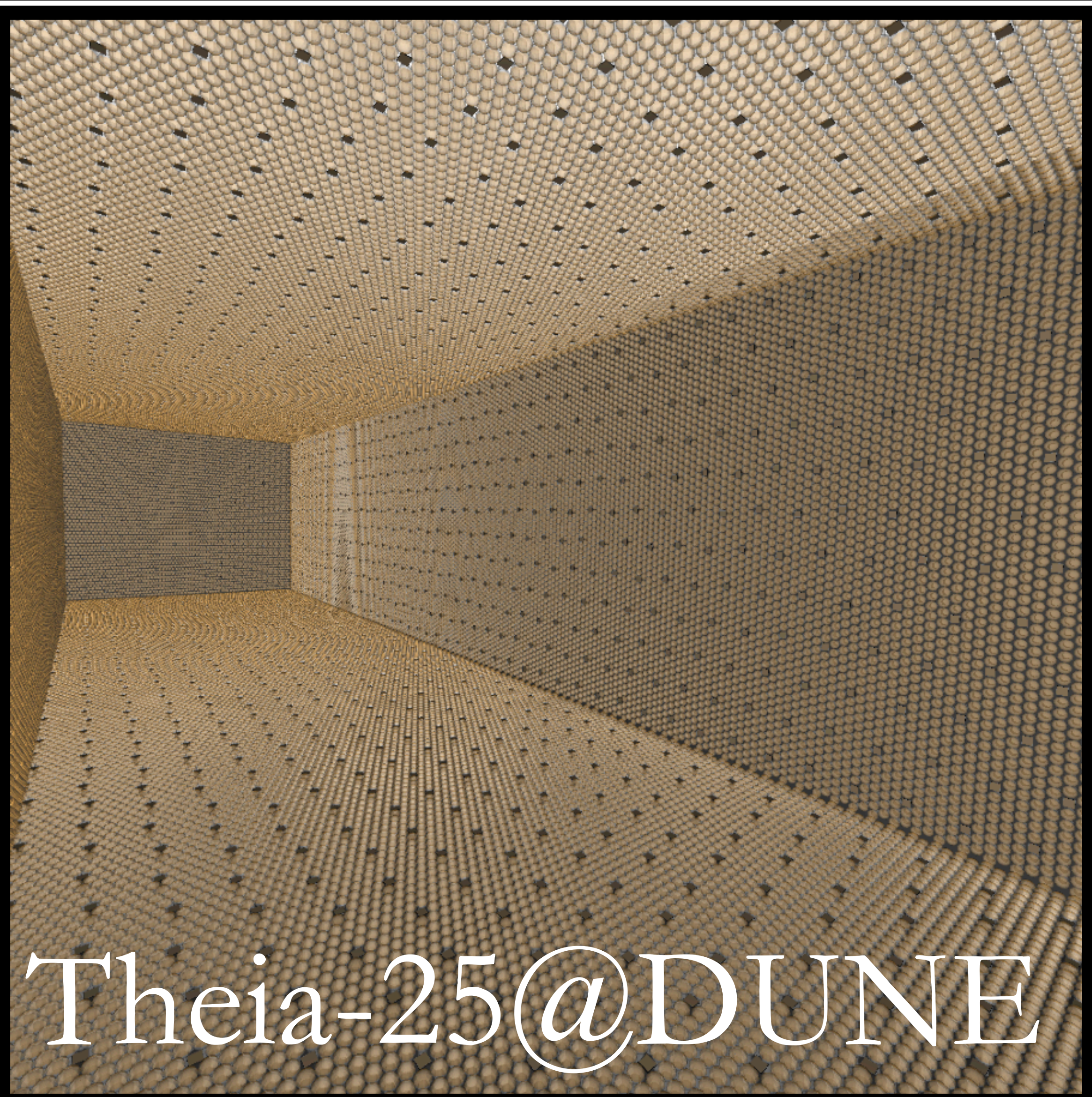


REF. 14, 15

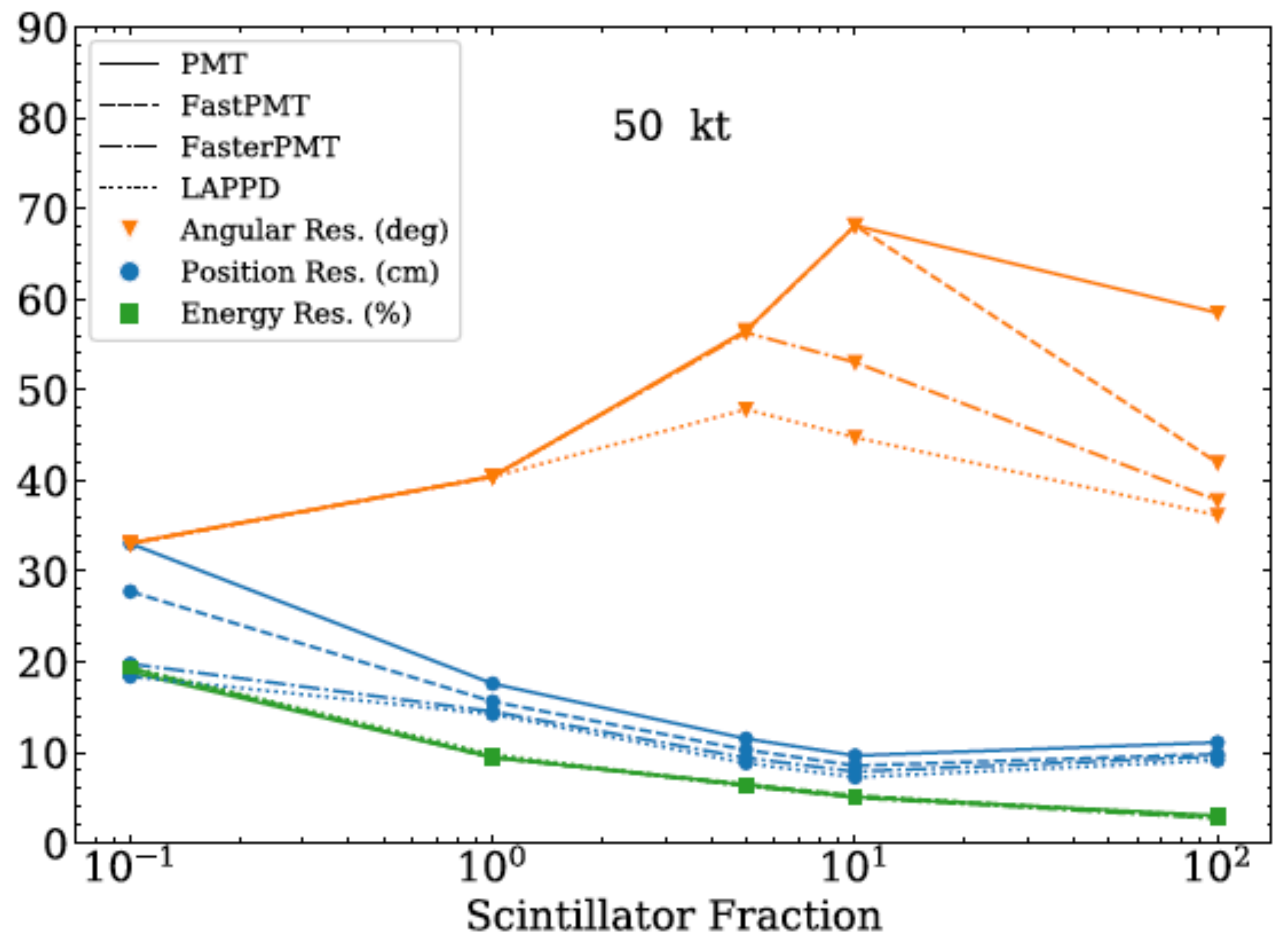


POSTERS 66, 114, 287, 307, 385, 491

POSTERS 578/ L. LEBANOWSKI, 596 / T. KAPTANOGLU



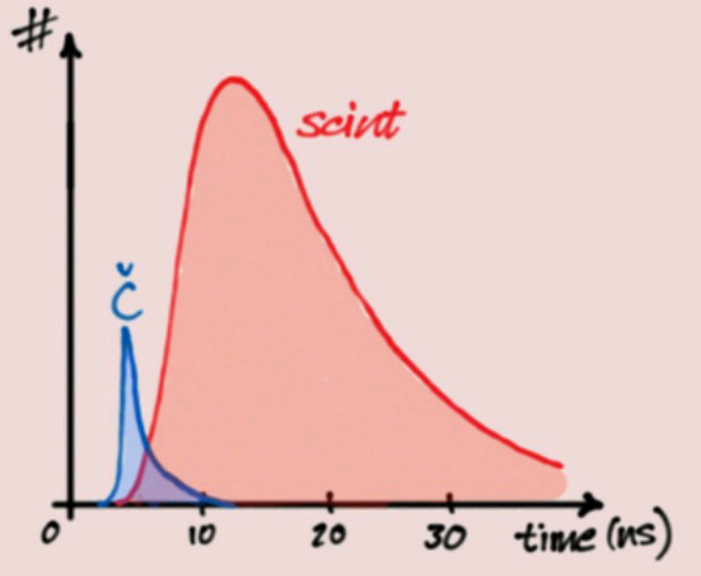
- Hybrid Cherenkov+scintilation detection combines high light yield and directionality
- R&D on Cherenkov/scintillation separation: fast sensors, slow scintillator, dichroicon (ANNIE, EOS, BUTTON)
- Targeting precision CNO and sensitive probe of vacuum/matter transition region.
  Directionality provides powerful discriminant



Timing

"instantaneous chertons" vs. delayed "scintons"

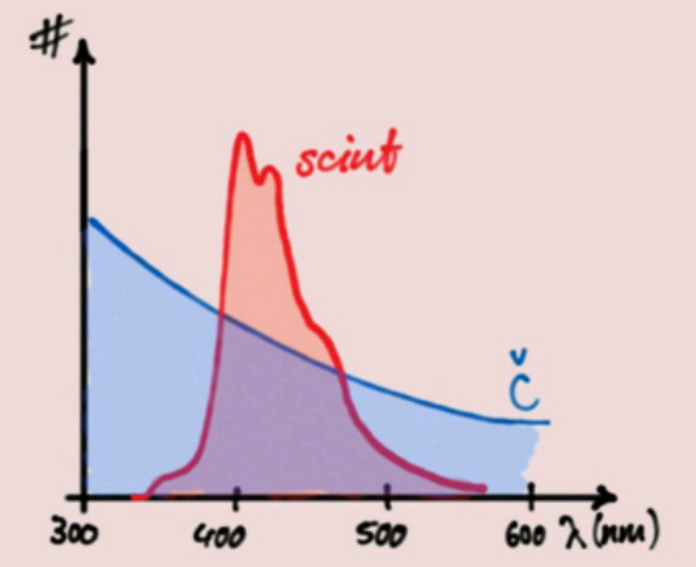
→ ns resolution or better



Spectrum

UV/blue scintillation vs. blue/green Cherenkov

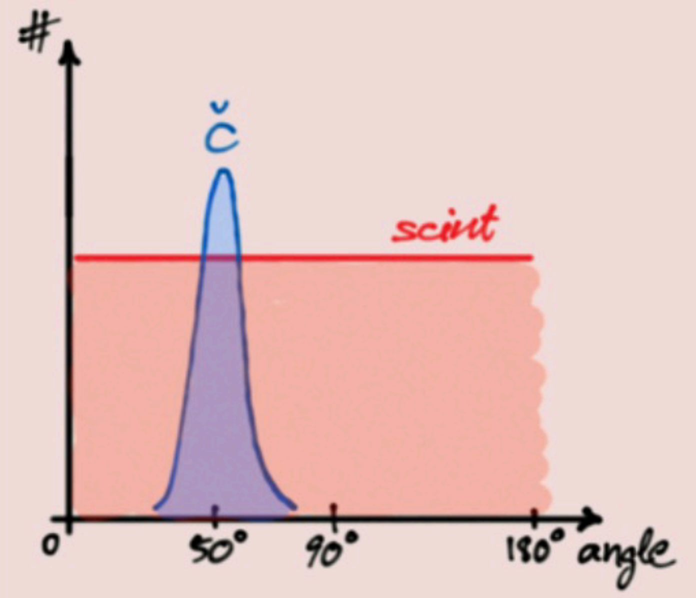
→ wavelength-sensitivity



Angular distribution

increased PMT hit density under Cherenkov angle

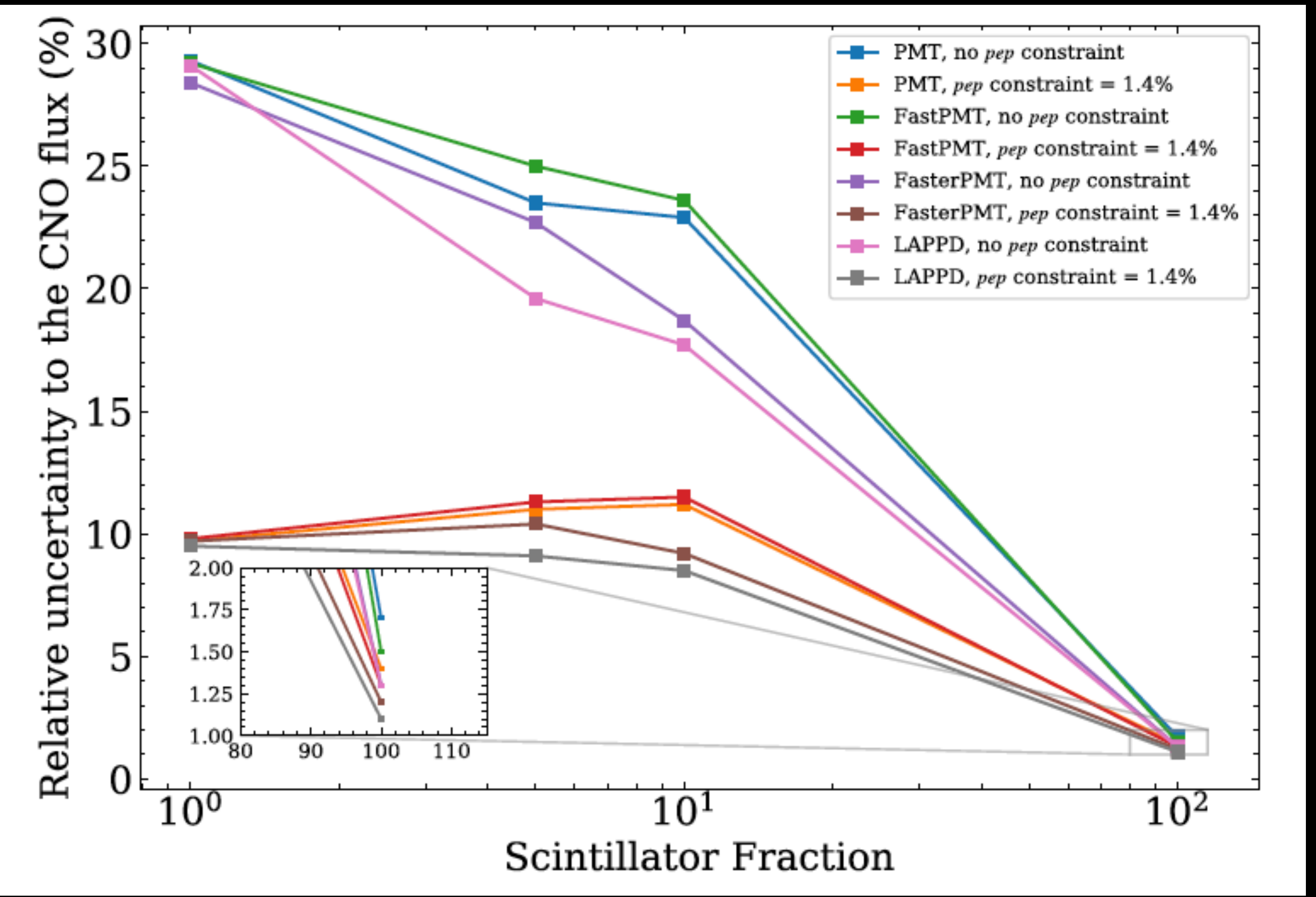
→ sufficient granularity



CNO precision well below 10%

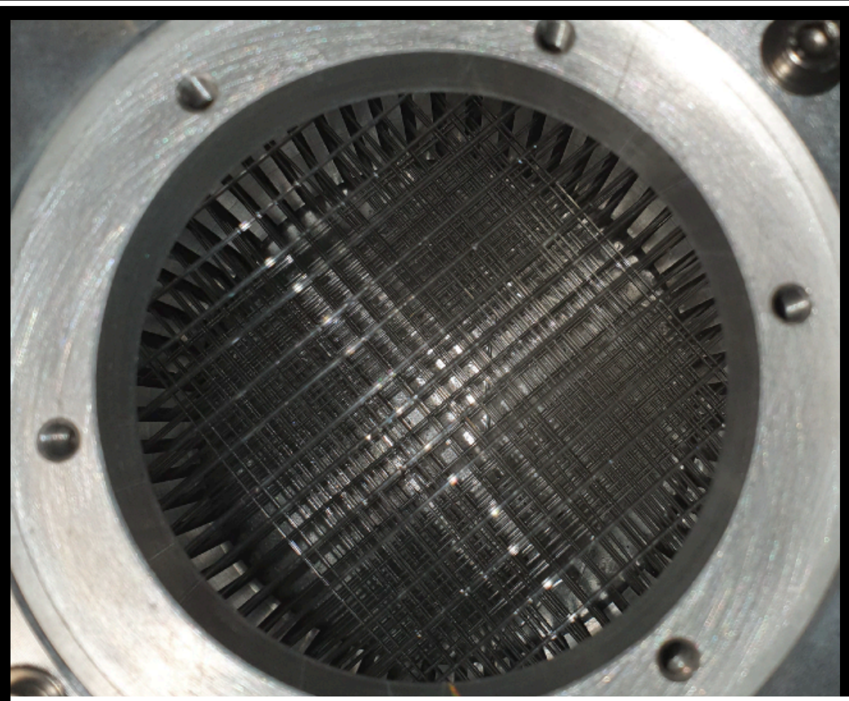
REF. 16,17

THANKS TO G. OREBI GANN



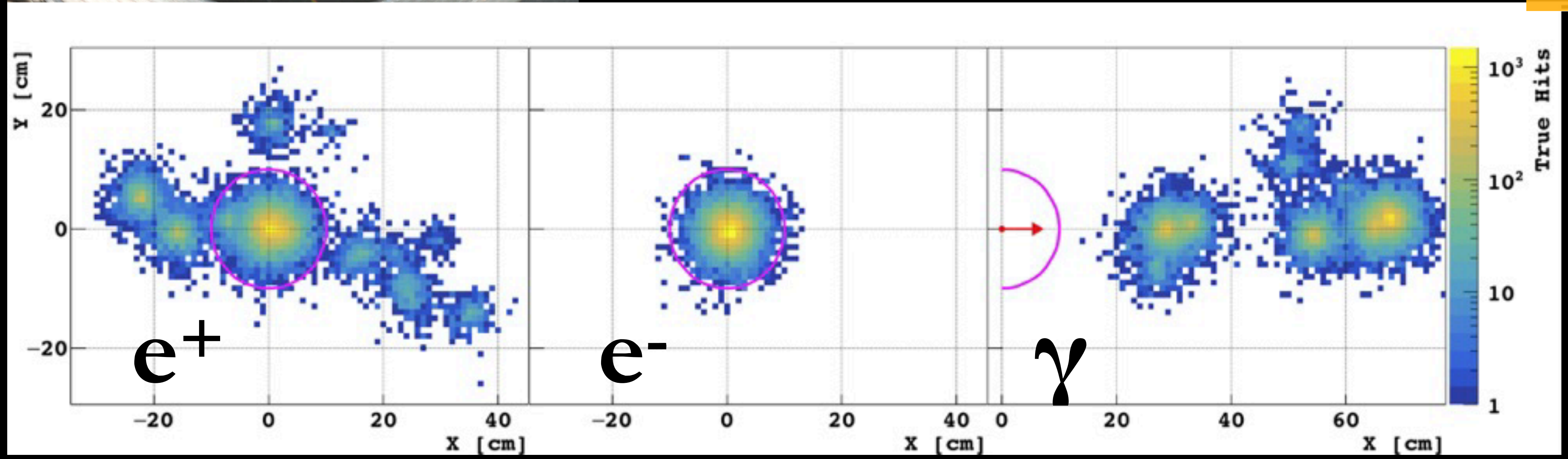
CLOUD/SUPERCHOOZ

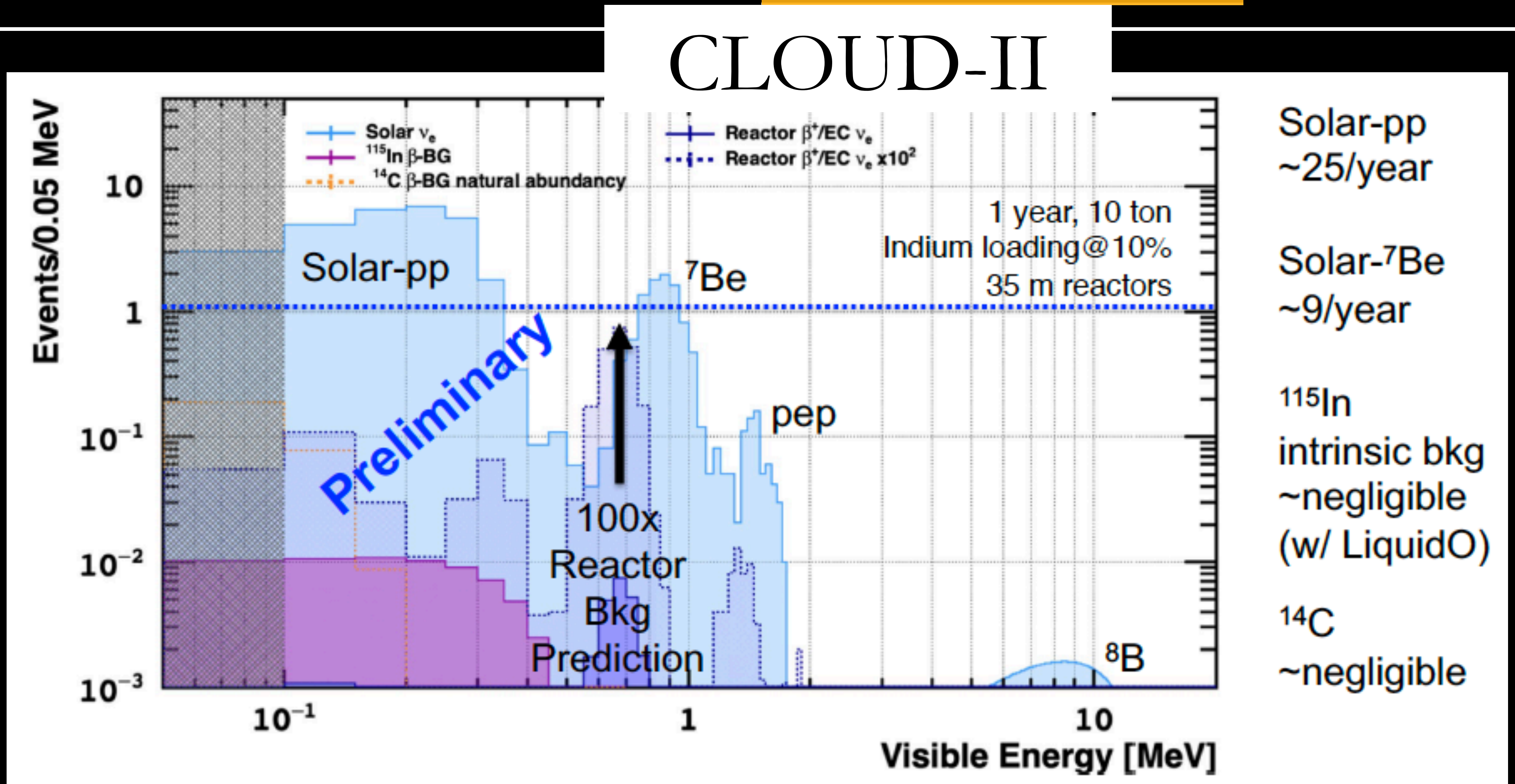
THANKS TO A. CABRERA

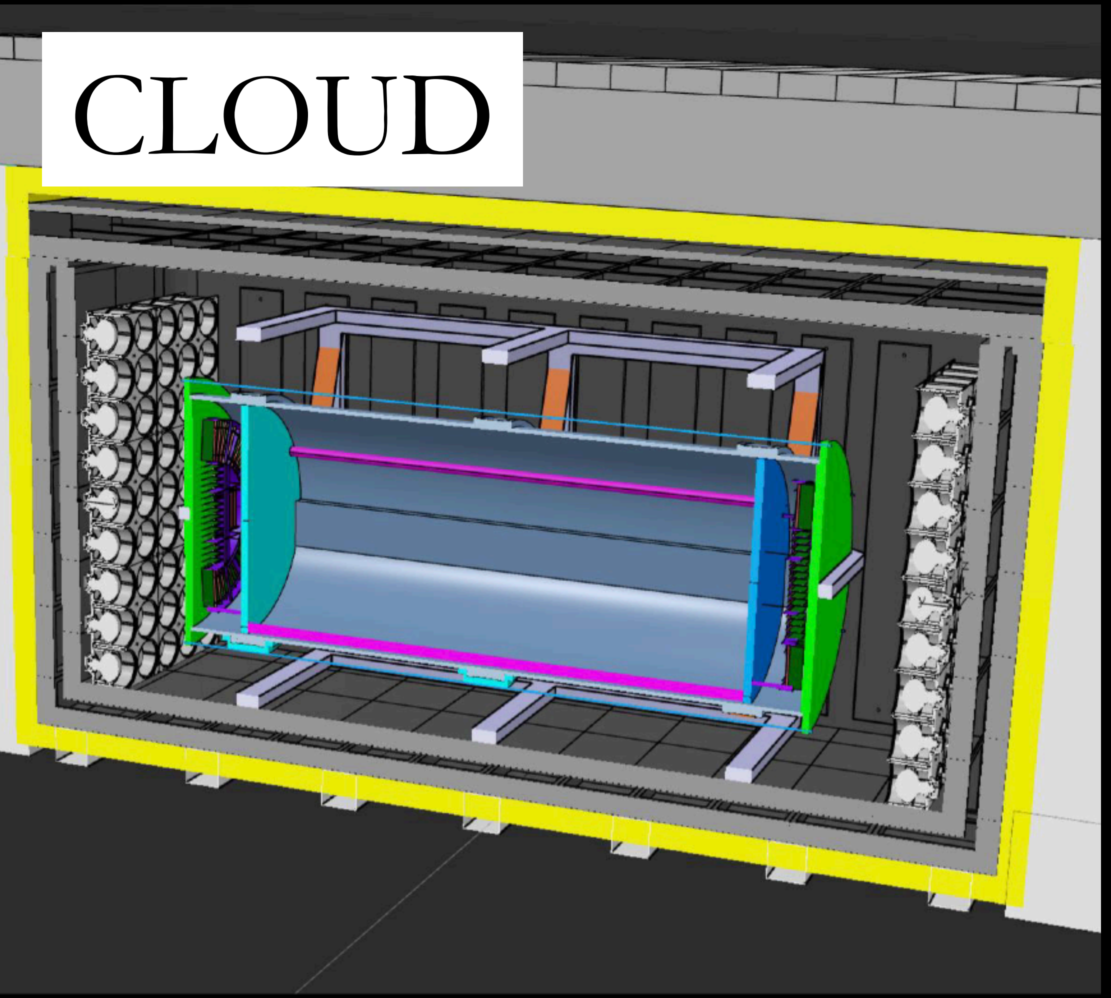


- LiquidO technology: opaque scintillator + optical fibers
  - < 1cm resolution
  - strong topology discrimination
  - no need for depth

REF. 18







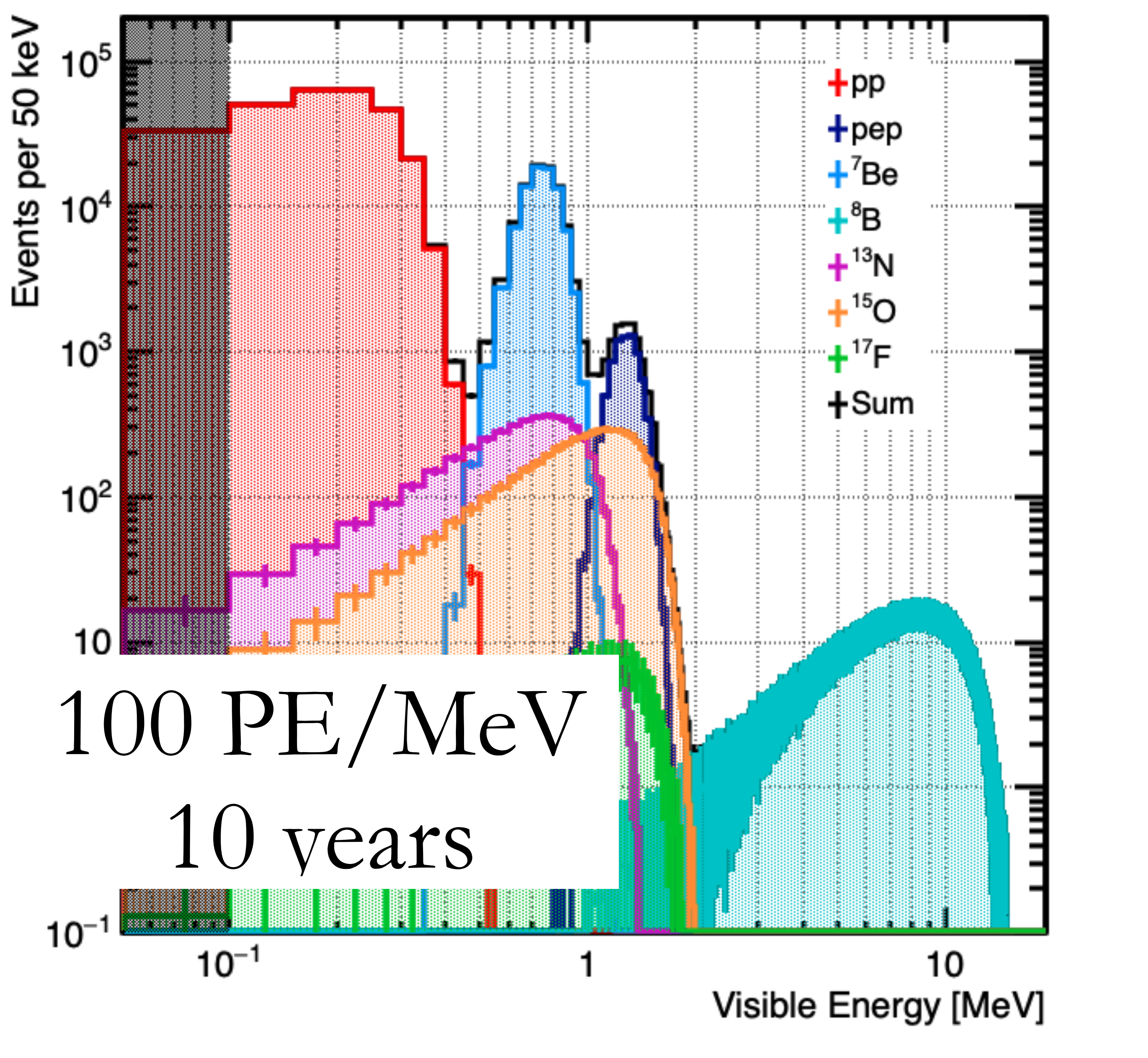
LiquidO + 10% Indium loading

$$\nu_e + {}^{115}In \rightarrow e^- + {}^{115}Sn^*$$
$$\hookrightarrow \gamma/e^- \,(116\ keV) + \gamma\,(497\ keV)$$

- CLOUD-II: 5 tons, 200 PE/MeV, at surface, 35 m from reactor (Chooz-B), ≲2029
- Super-Chooz: 10 kton, depth 100 m (Chooz-A)

POSTER 635 / R. GAZZINI

Super-Chooz



OUTLOOK

OUTLOOK

- Brilliant (pun intended!) history of solar neutrino physics is not over yet
- New/recent results from Super-Kamiokande and SNO+
  - SK: high stats, low threshold, day/night provide strong constraints on oscillations
  - SNO+: lowest backgrounds for ^{8}B ν >5 MeV in water, new results for ^{8}B ES in scint., first indication of CC reaction on ^{13}C, new results with reactor antineutrinos
- Future very large detectors
  - huge increase in stats: upturn, day-night, possible observation of hep (HK, DUNE)
  - future liquid scintillator detectors will improve at low energies too, with varied strategies
    - large volume, high purity (JUNO)
    - deepest location and scintillator loading (JNE)
    - directionality (Theia)
    - topology discrimination and scintillator loading (CLOUD)

ACKNOWLEDGMENTS

SNO+ Collaboration

- Thanks to the whole SNO+ Collaboration and to many colleagues that provided results, updates, insights and clarifications on the other experiments:
  - SK: M. Smy
  - HK: F. Di Lodovico, S. Moriyama, T. Yano
  - DUNE: C. Cuesta, I. Botella, S. Corchado
  - JUNO: G. Ranucci
  - Theia: G. Orebi Gann
  - Jinping: S. Chen
  - CLOUD: A. Cabrera

fct Fundação para a Ciência e a Tecnologia — REPÚBLICA PORTUGUESA

Supported by FCT, Portugal , project PTDC/FIS-PAR/2679/2021

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- [16] Theia Collab., Eur. Phys. J. C 80, 416 (2020)
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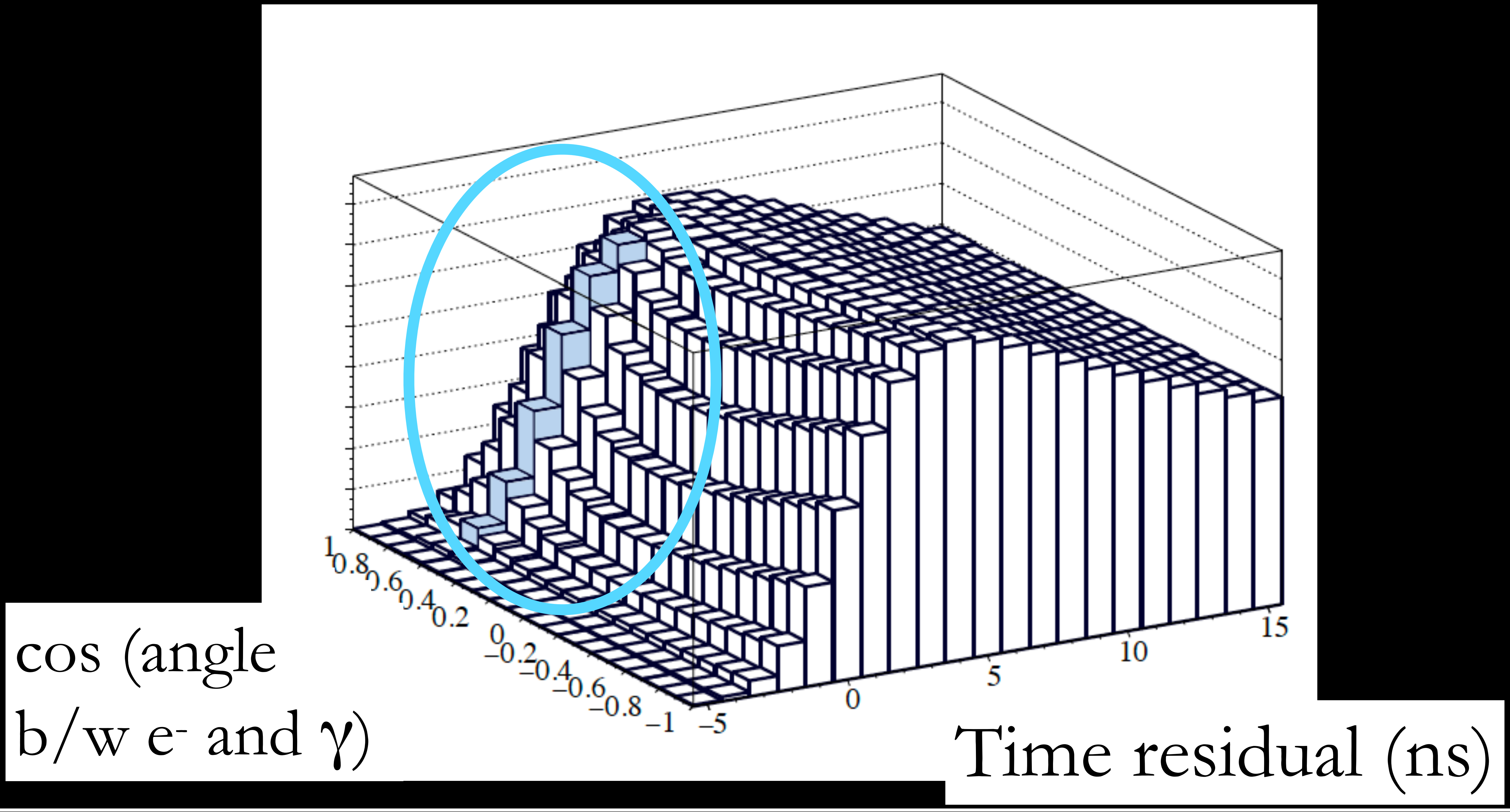
- [18] LiquidO Collab., Commun.Phys. 4 (2021) 273

EXTRA

DIRECTIONALITY IN SCINTILLATOR

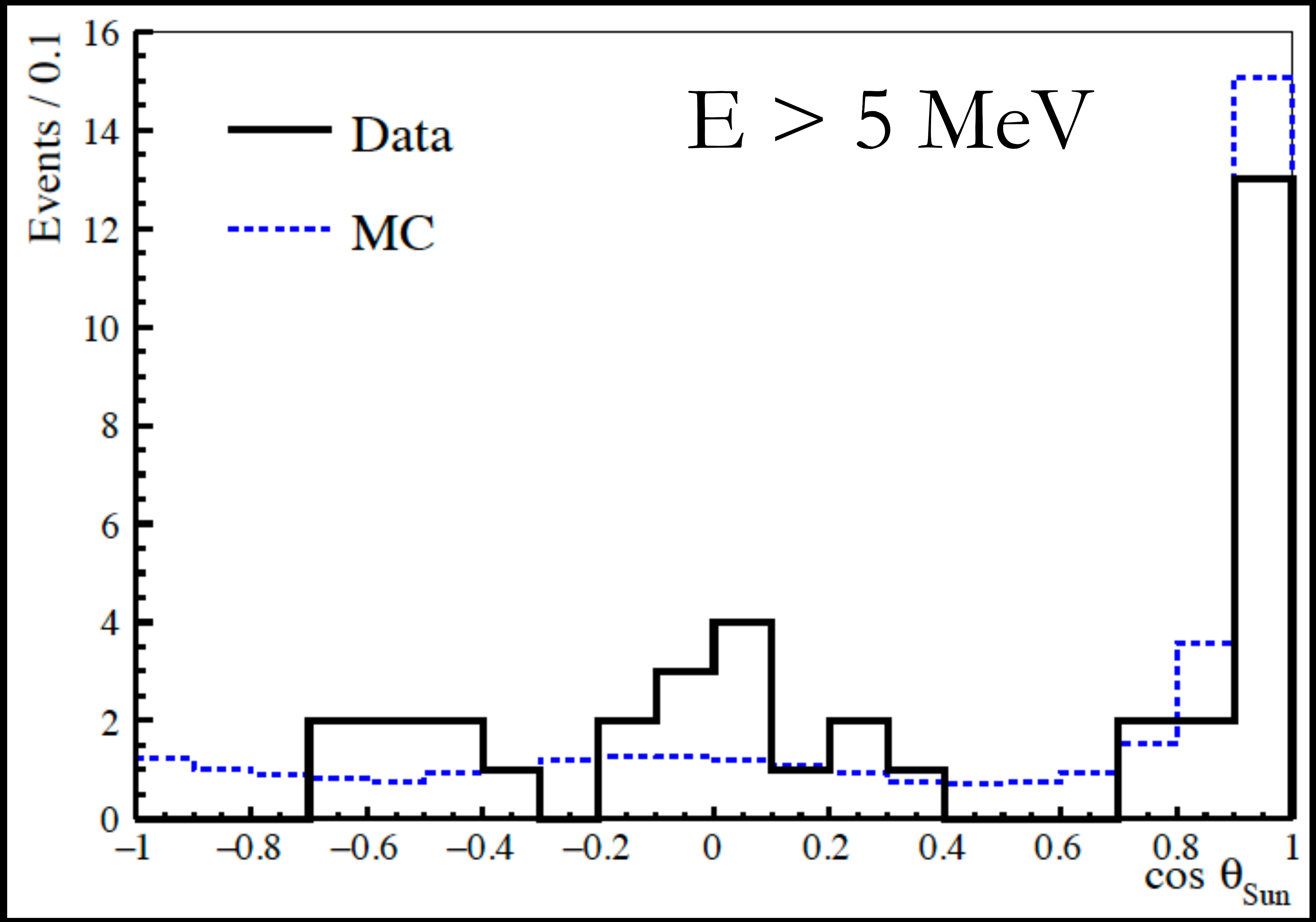
SNO+ Collab., Phys.Rev.D 109 (2024) 7, 072002

- Slow scintillation leads to good separation between Cherenkov and scintillation photons
- Early data with low PPO (0.6 g/L)
  - Reasonable light yield (300 pe/MeV)
  - Slow timing τ = 13. 5 ns (first comp.)



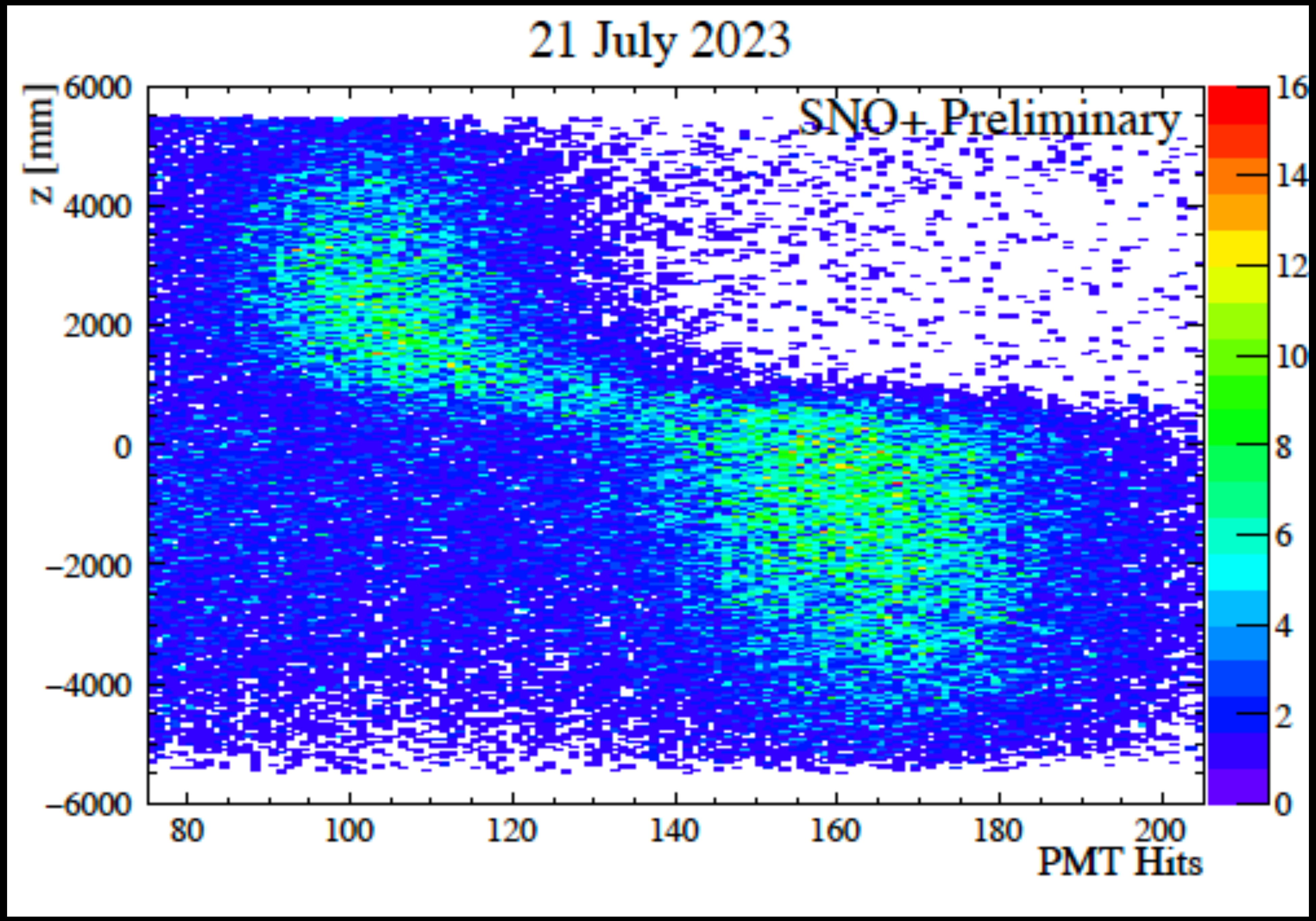
- Data from partial fill and early scint phases (23 and 15 kt-days)

[ref. 7]

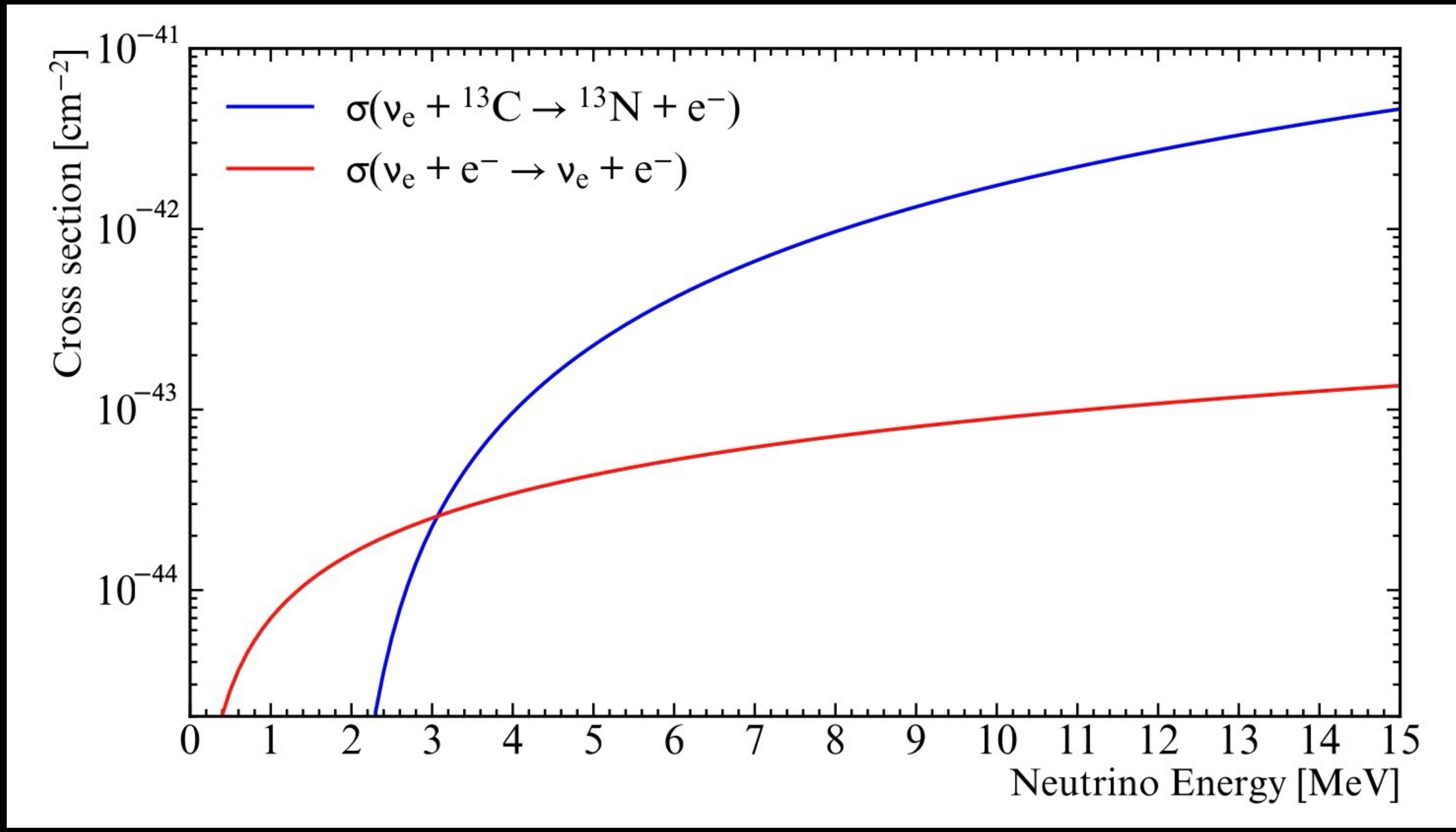


- First event-by-event reconstruction of direction in high light yield scintillator !

SNO+

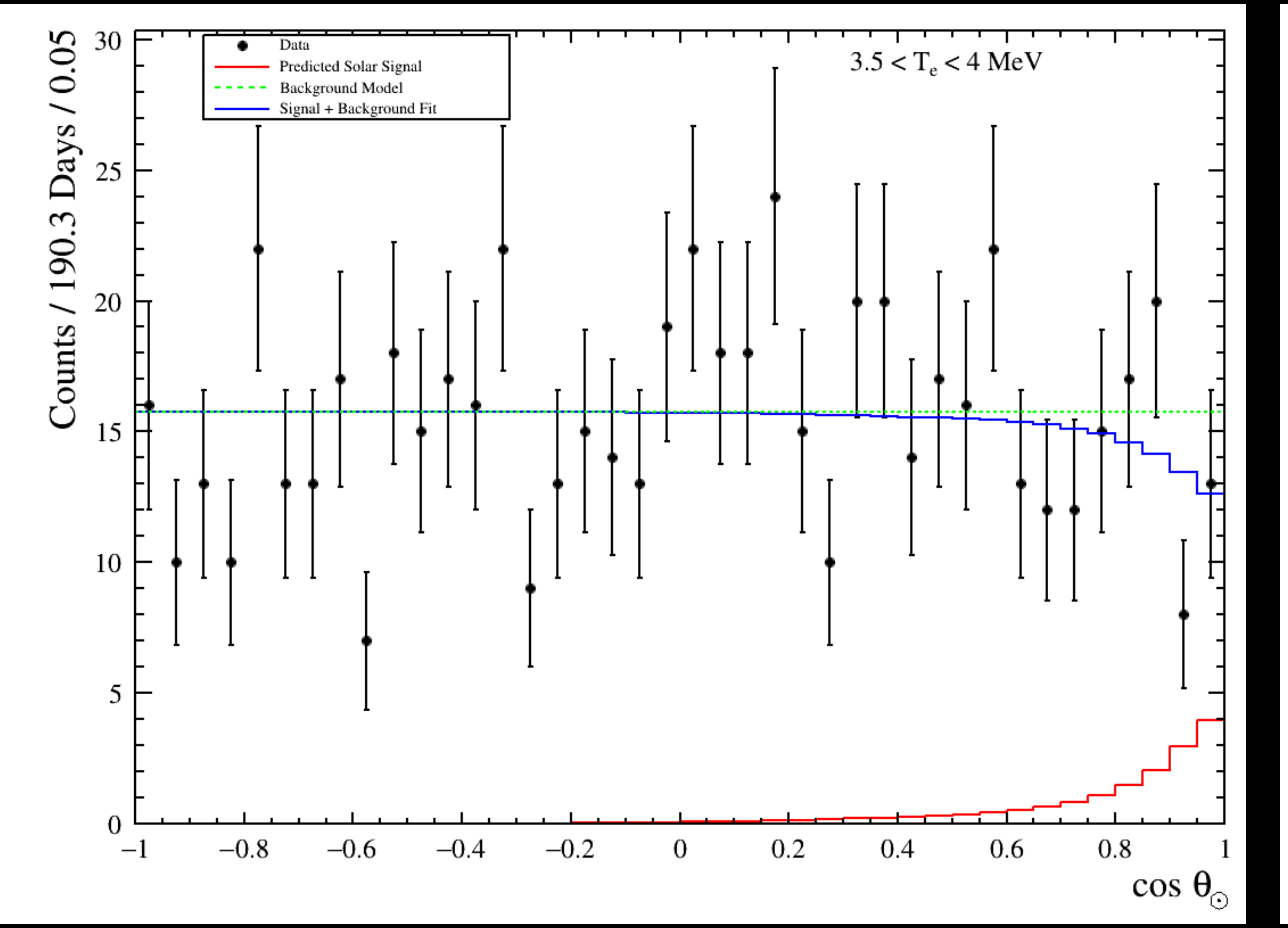


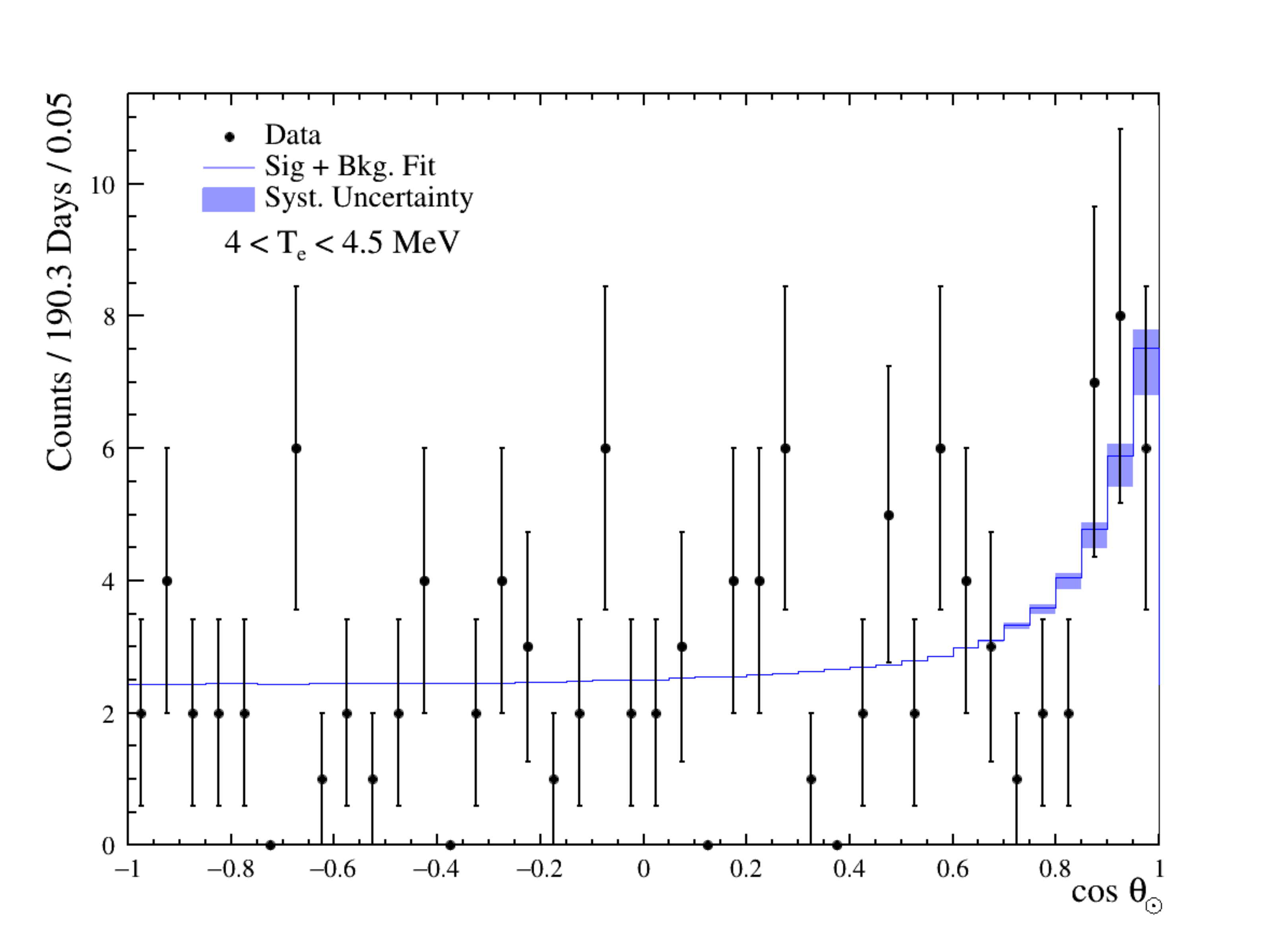
- Likelihood ratio:
  - Fiducial volume: R< 5.3 m
  - Prompt energy: 5.0 < E (e^-) < 15.0 MeV
  - Delayed energy: 1.0 < E (e^+) < 2.2 MeV
  - Delta R < 1 m
  - 0.01 < Delta T < 60 min
  - Likelihood ratio > 4

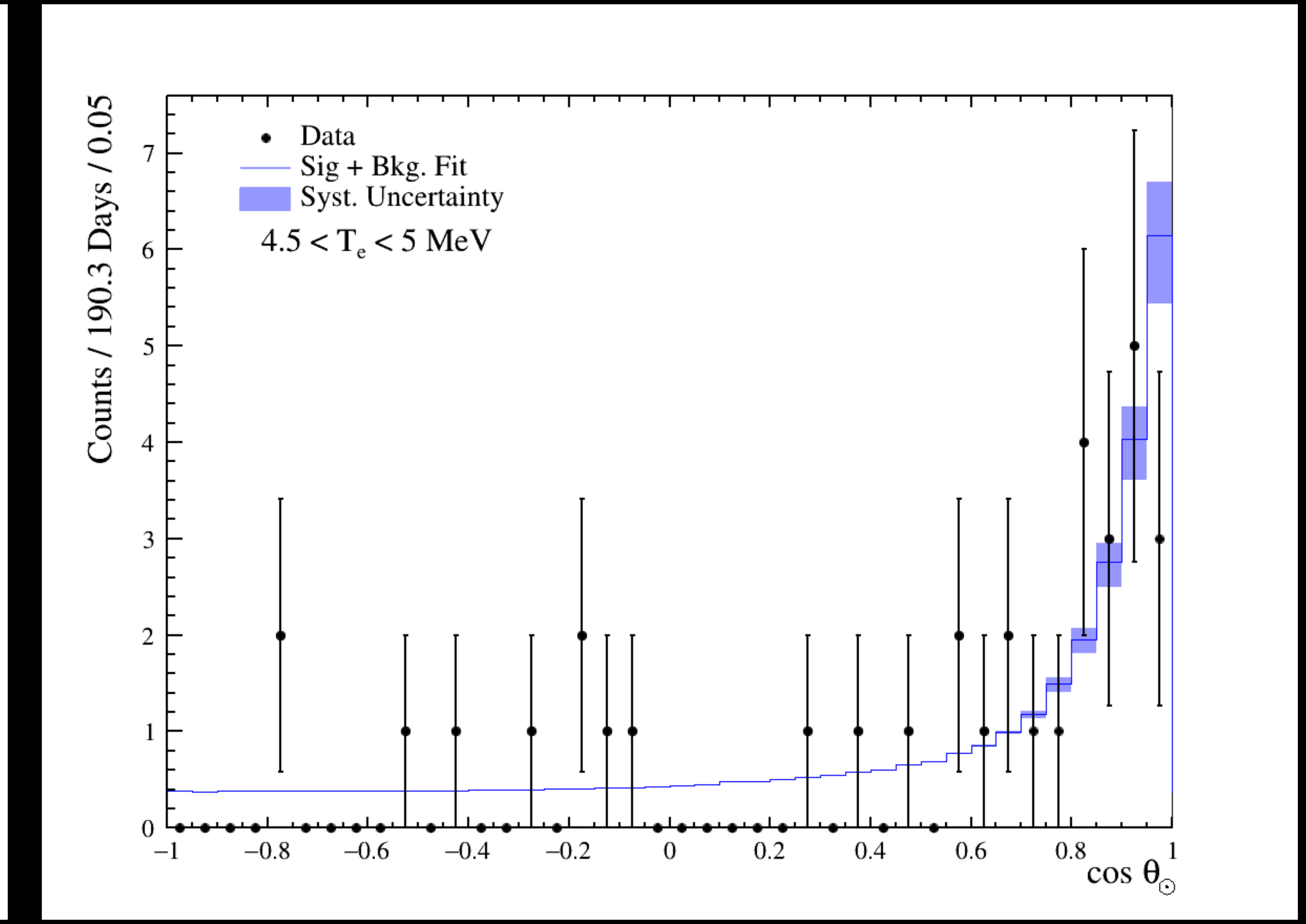


Observed events prompt energy: 10.7 and 8.1 MeV

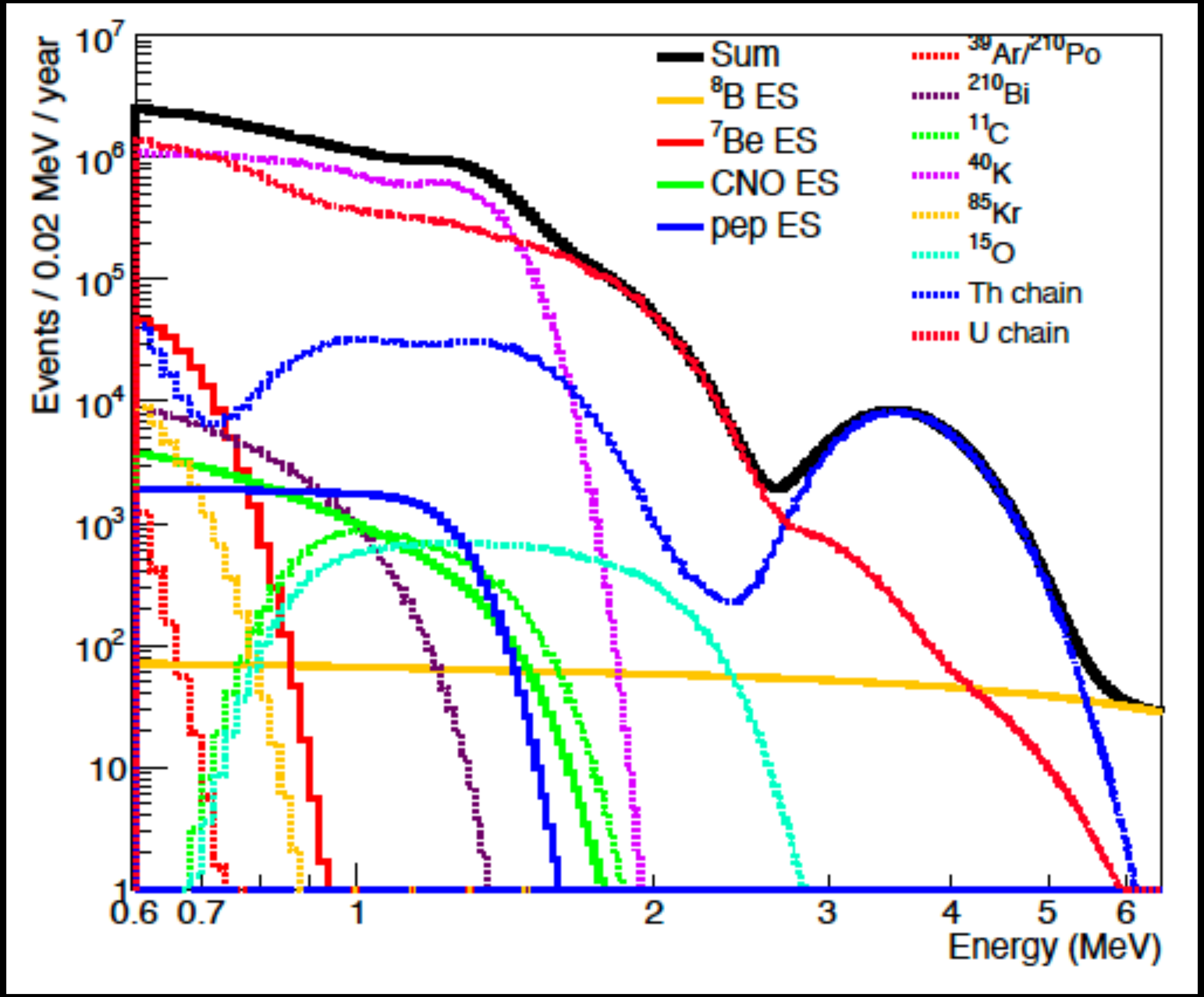
SNO+ SOLAR WATER PHASE



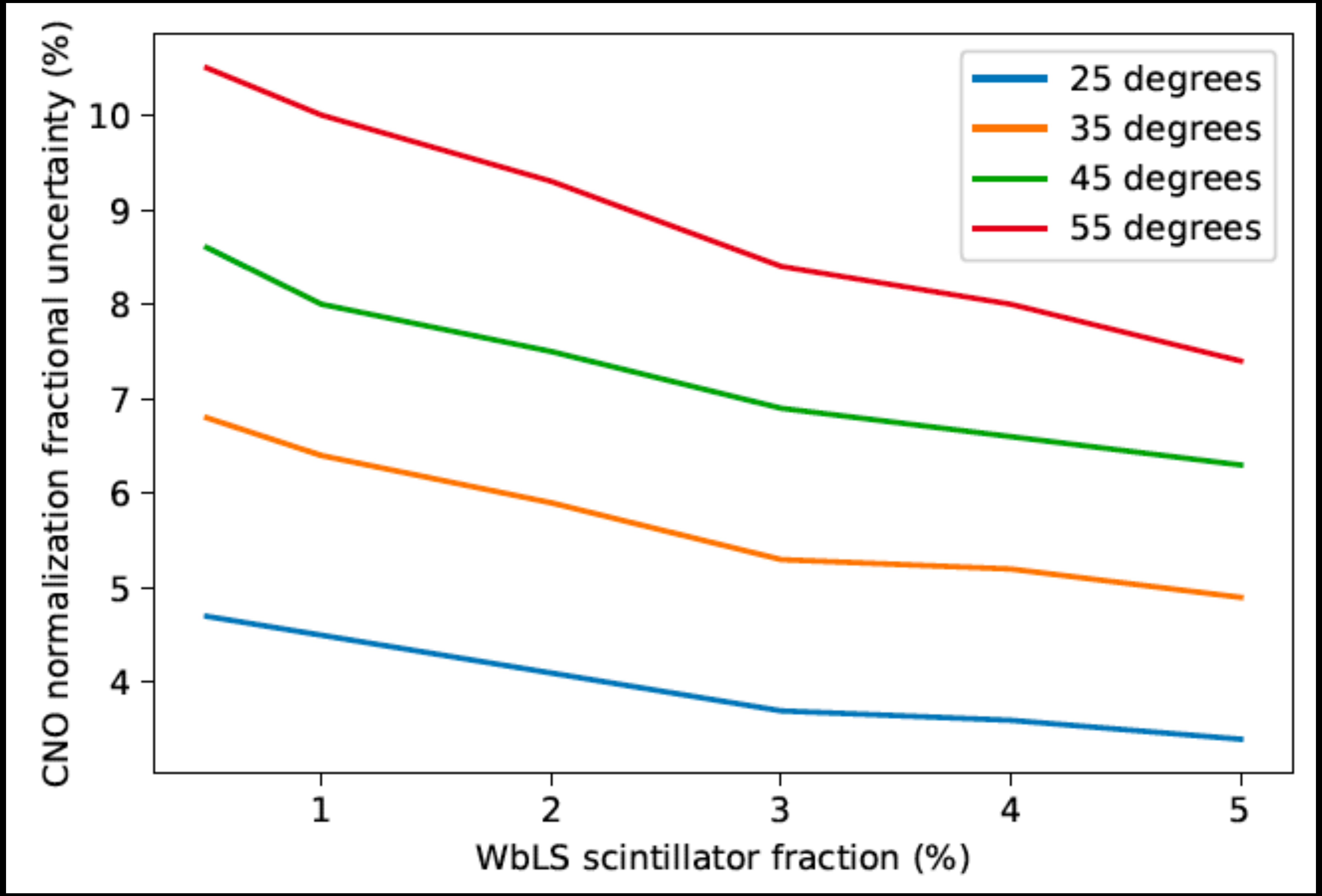




THEIA



Events / 0.02 MeV / year
Energy (MeV)
Sum
^{8}B ES
^{7}Be ES
CNO ES
pep ES
^{39}Ar/^{210}Po
^{210}Bi
^{11}C
^{40}K
^{85}Kr
^{15}O
Th chain
U chain



CNO normalization fractional uncertainty (%)
WbLS scintillator fraction (%)
25 degrees
35 degrees
45 degrees
55 degrees