JAVIER CARAVACA (SNO+ COLLABORATION)

SNO+ STATUS AND PROSPECTS

ICNFP
Crete - August 19

SNO+ IS A MULTIPURPOSE EXPERIMENT

MAIN GOAL: $0\nu\beta\beta$

NUCLEON DECAY

SOLAR NEUTRINOS

GEO & REACTOR NEUTRINOS

SUPERNOVA NEUTRINOS

EXOTIC AND OTHER PHYSICS

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EXOTIC AND OTHER PHYSICS

IN THIS TALK:

- **The SNO+ detector**
- **Results from water phase:**
  - **Invisible nucleon decay searches**
  - **B8 solar neutrino flux measurement**
  - **External background measurements**
- **Prospects of SNO+:**
  - **0νββ predicted sensitivity**
  - **Precise solar neutrino measurements**
  - **Detector status**

SNO+ APPARATUS

~2km depth (~6km.w.e)

~3 muons/hour

~9500 PMTs (54% optical coverage)

6m-radius, 10cm-thick UVT acrylic vessel

Clean room class 2000

Ultra-pure water buffer

SNO+ TIMELINE

~900 tonnes of water

SOLAR NEUTRINOS

NUCLEON DECAY

0νββ milestone: measure external backgrounds

May 2017 → Water phase started

Dec. 2016 Started taking commissioning data

WATER PHASE

2016

2017

SNO+ TIMELINE

Started filling with scintillator

SOLAR NEUTRINOS

NUCLEON DECAY

$0\nu\beta\beta$ milestone: measure external backgrounds

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We are here

2019 → Scintillator fill starts

SNO+ TIMELINE

~780 tonnes of LABPPO scintillator

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Dec. 2016 Started taking commissioning data

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SNO+ TIMELINE

~780 tonnes of LABPPO scintillator
+ ~4 tonnes natural tellurium (34% ^{130}Te)

SOLAR NEUTRINOS

NUCLEON DECAY

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0νββ

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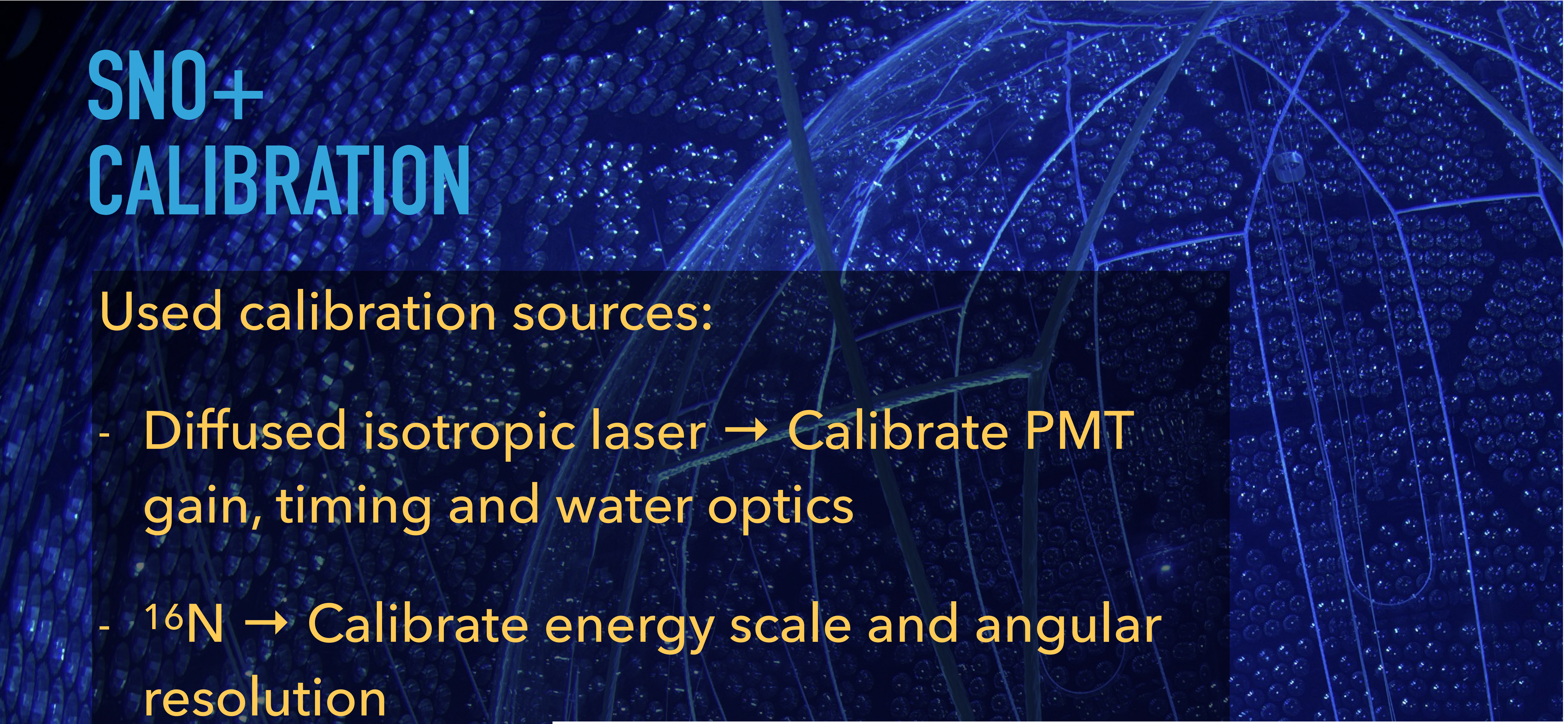
SNO+ CALIBRATION

Used calibration sources:

- Diffused isotropic laser → Calibrate PMT gain, timing and water optics

SNO+ CALIBRATION

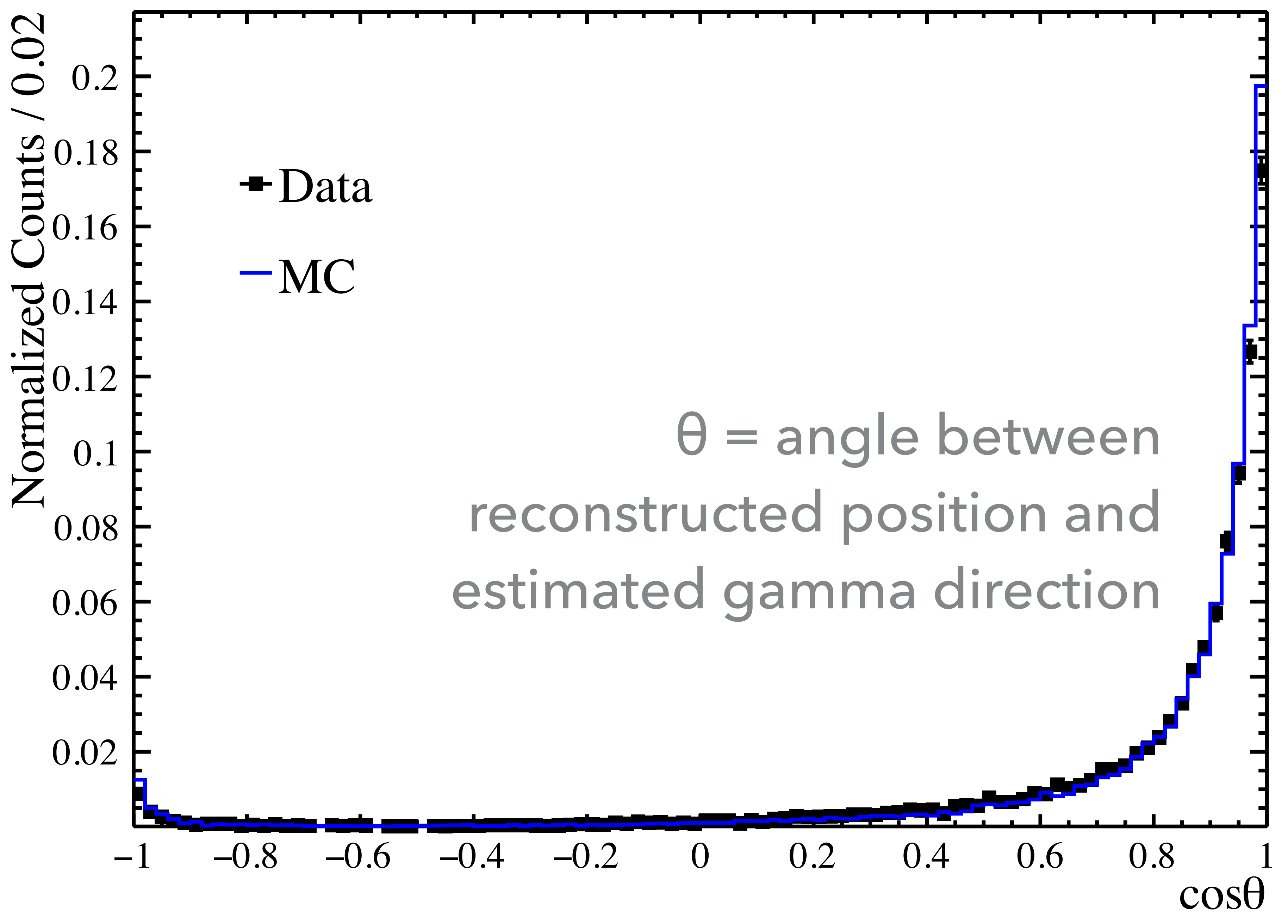


Used calibration sources:

- Diffused isotropic laser → Calibrate PMT gain, timing and water optics
- ^{16}N → Calibrate energy scale and angular resolution

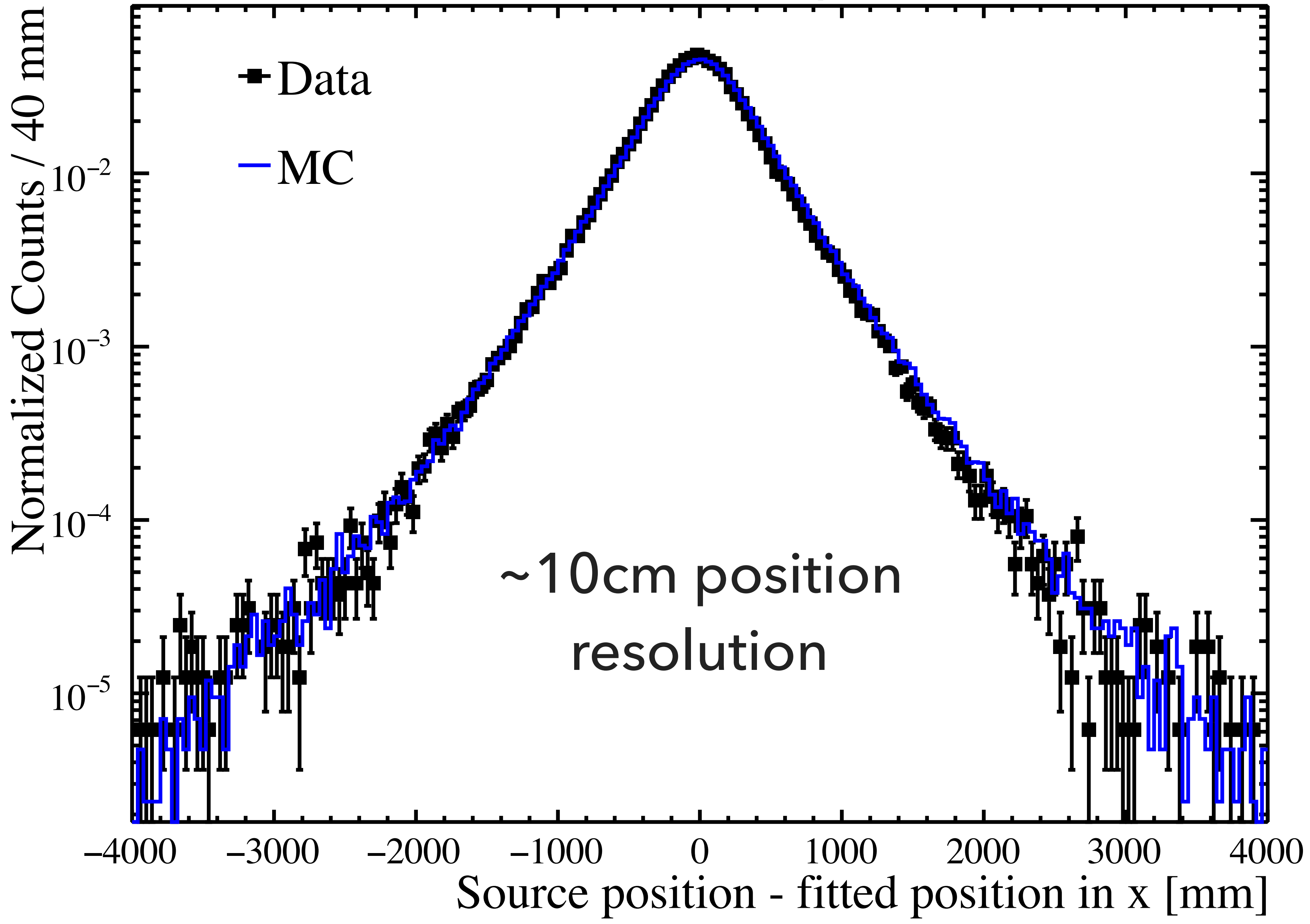
Energy threshold with water **~1MeV**

^{16}N reconstructed direction



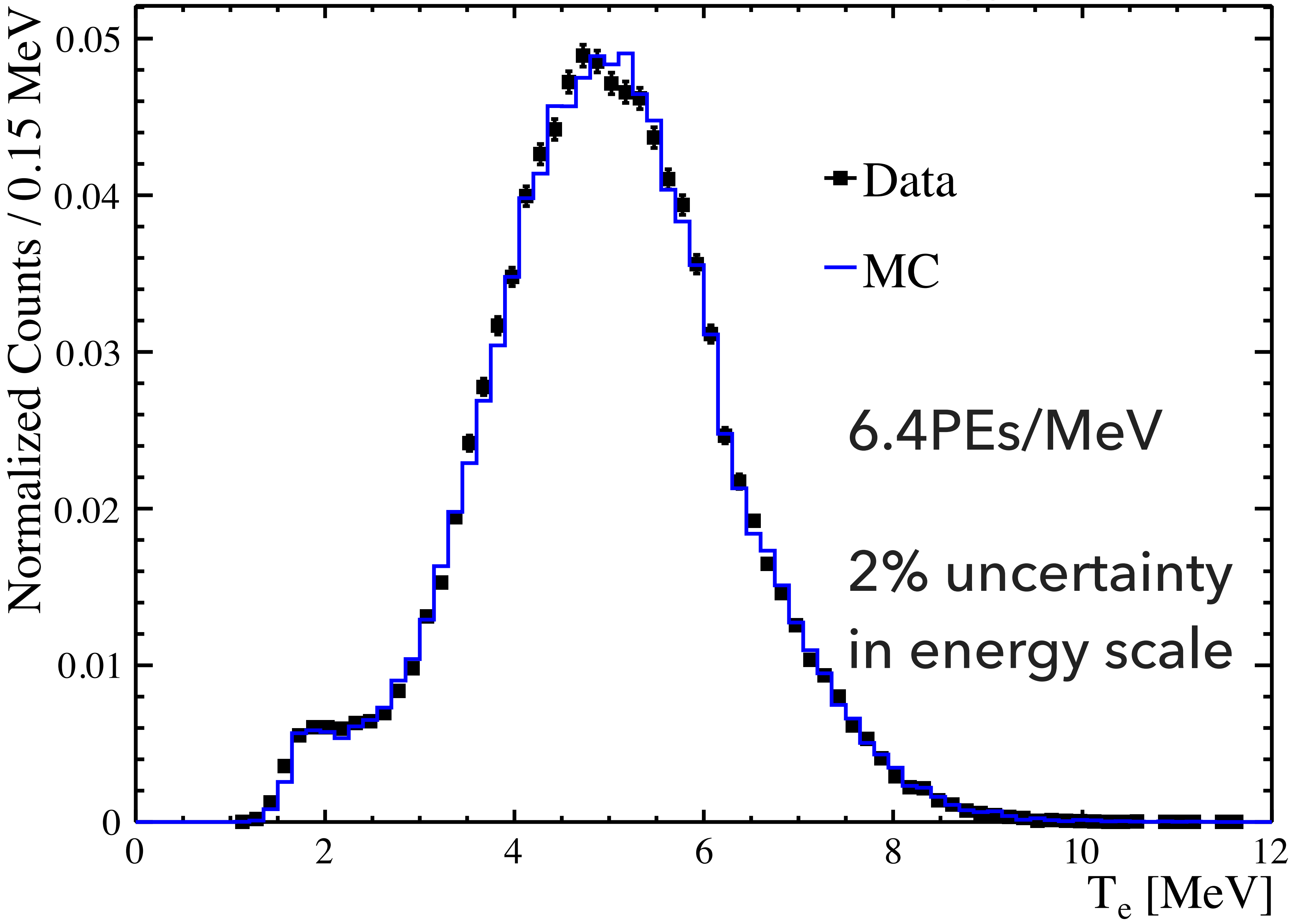
θ = angle between reconstructed position and estimated gamma direction

^{16}N reconstructed position



~10cm position resolution

^{16}N reconstructed energy



6.4PEs/MeV

2% uncertainty in energy scale

SNO+ CALIBRATION

Used calibration sources:

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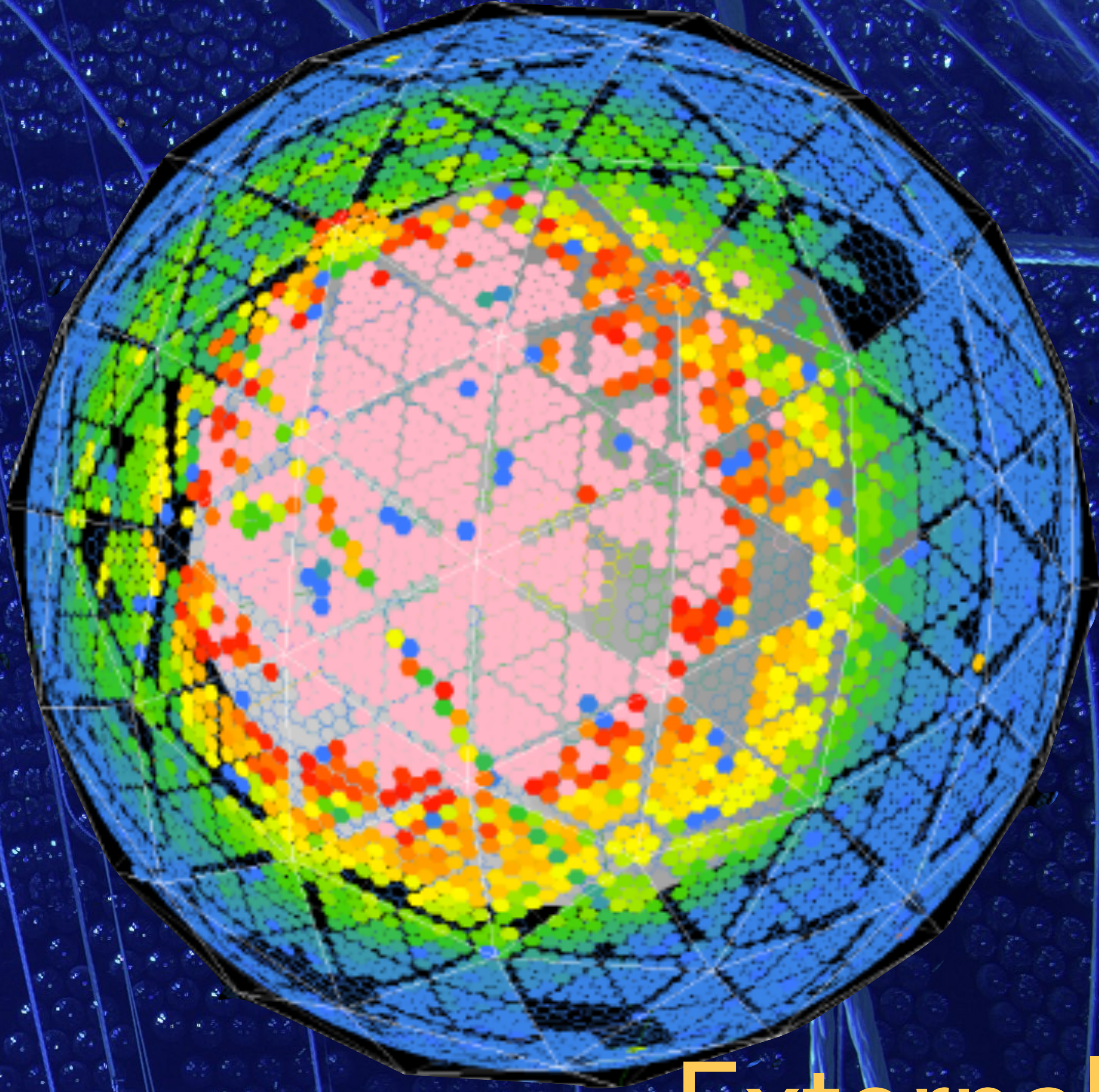
- Cherenkov source → Decouple optical microphysical parameters in scintillator and Te phase

SNO+ CALIBRATION

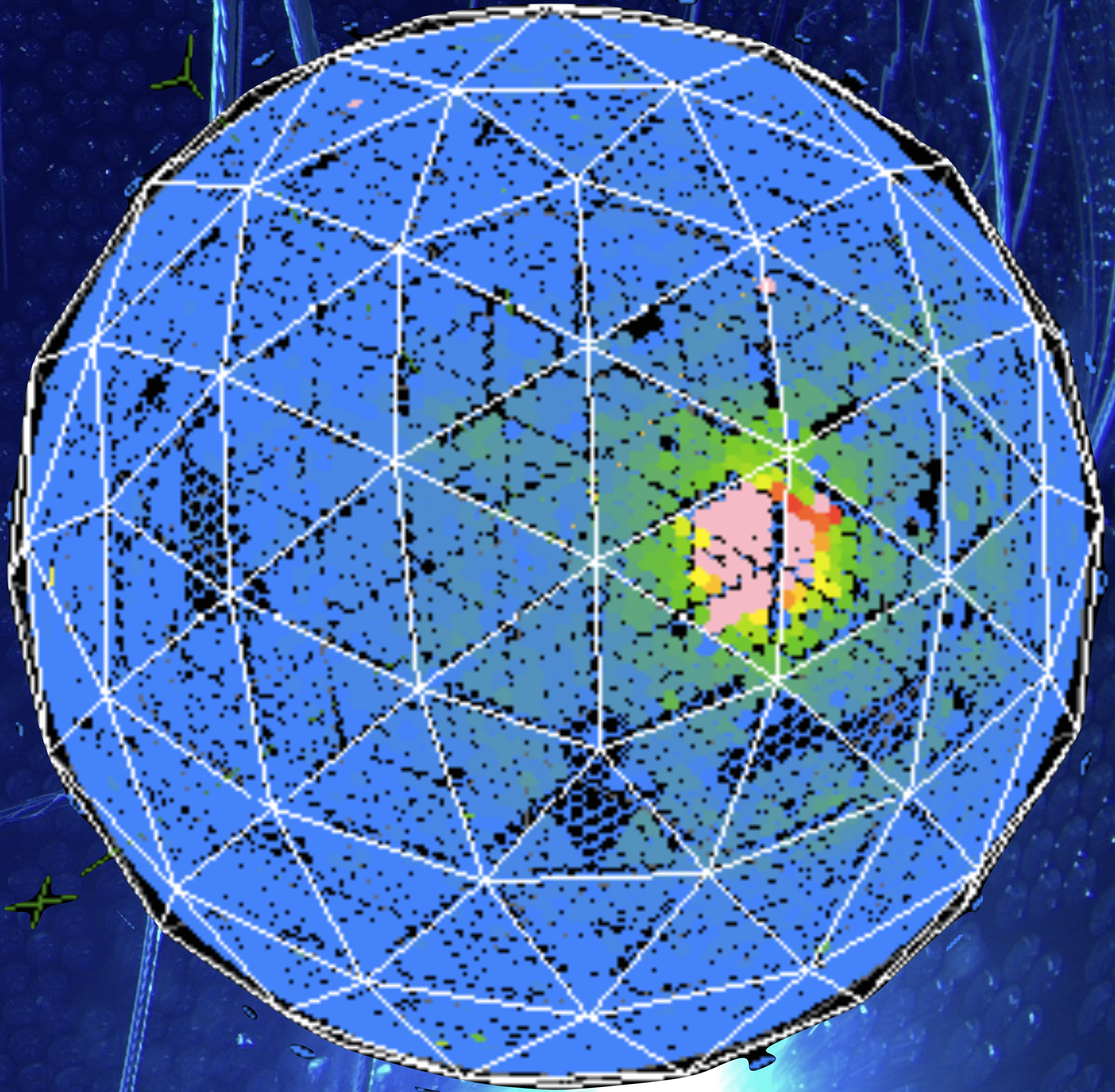
Used calibration sources:

- Diffused isotropic laser → Calibrate PMT gain, timing and water optics
- ^{16}N → Calibrate energy scale and angular resolution
- Cherenkov source → Decouple optical microphysical parameters in scintillator and Te phase
- External LED/Laser system → Further calibrate PMT and optics. Reduce risk of contamination due to source deployment

External LED event



External laser event



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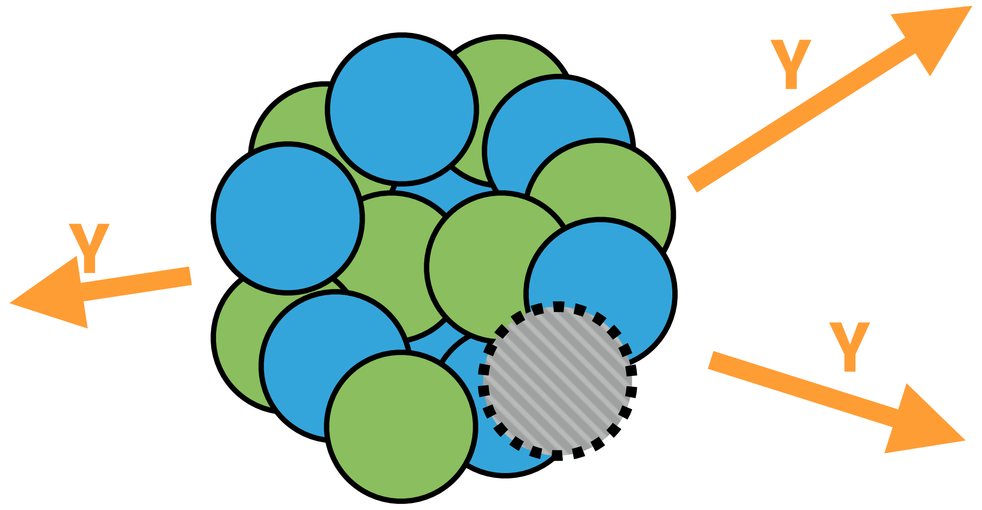
NUCLEON DECAY SEARCHES

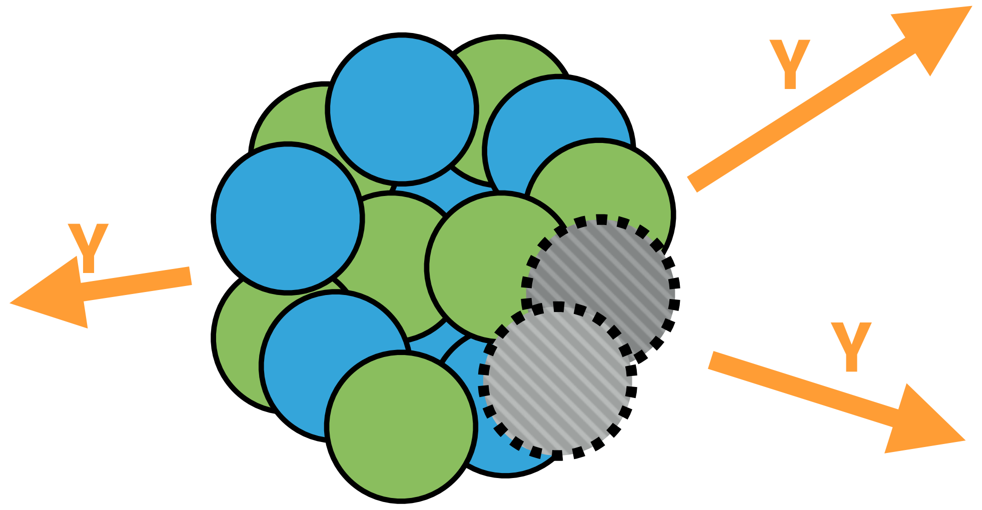
SNO+ WATER PHASE IS SENSITIVE TO INVISIBLE (DI)NUCLEON DECAYS LIFETIMES OF $\sim 10^{29}$ YEARS

- SK has world-leading limits for **visible** nucleon decays
- **Invisible** nucleon decay (e.g. N→3ν) yields de-excitation gammas above radioactive backgrounds
- We performed a model-independent search



$^{A}X \rightarrow {}^{A-1}X^{*} + \textit{invisible particle}$

$^{A-1}X^{*} \rightarrow {}^{A-1}X + \boldsymbol{\gamma}$**'s**



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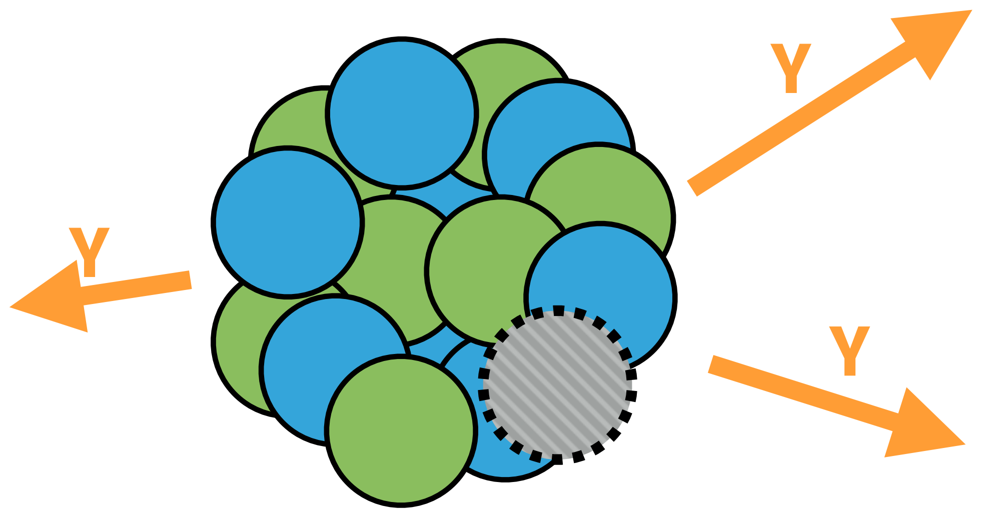

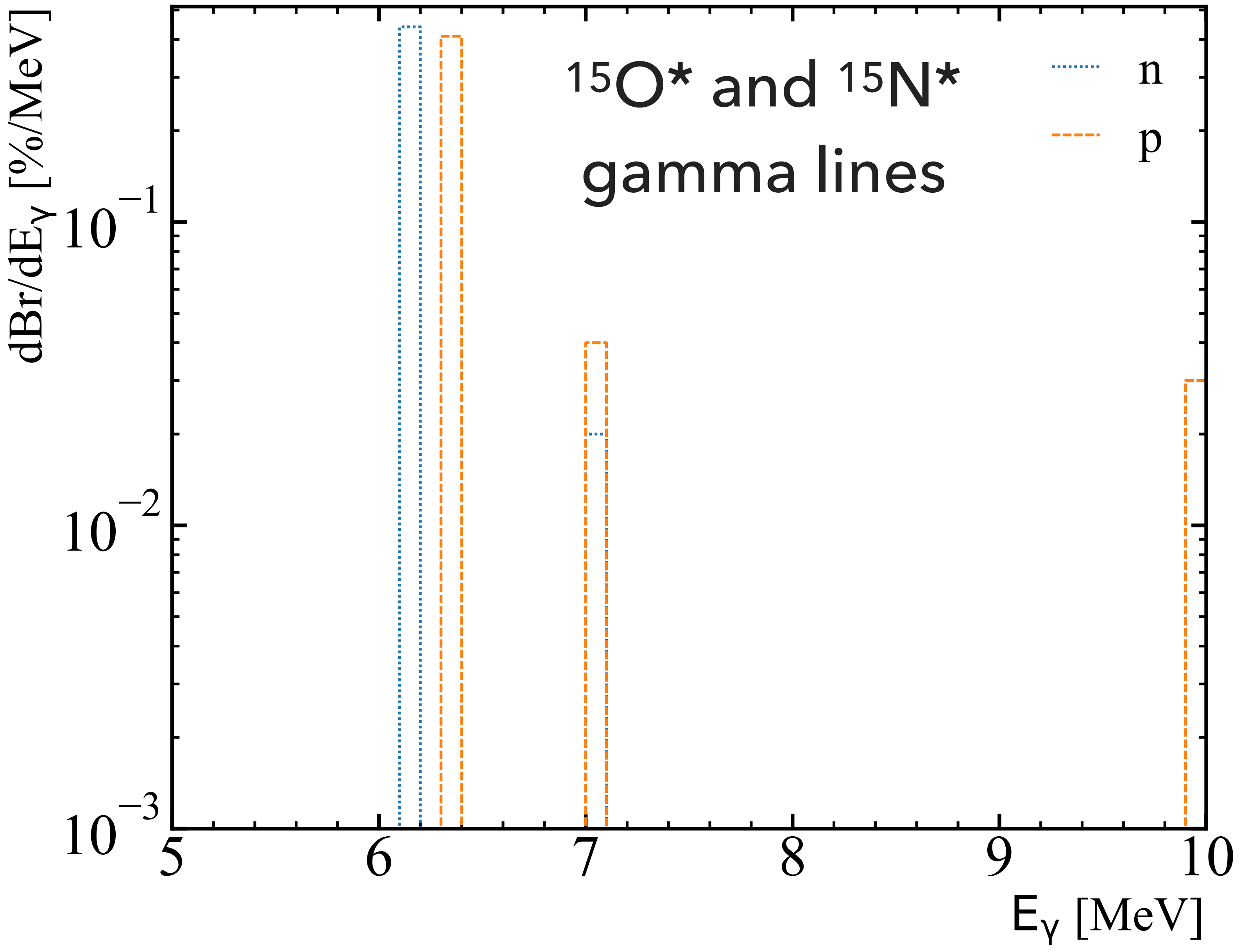

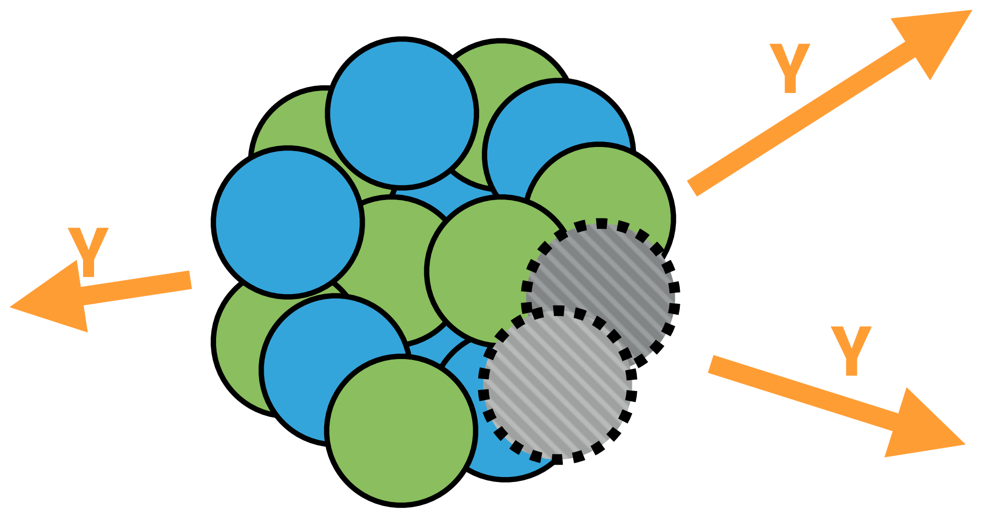

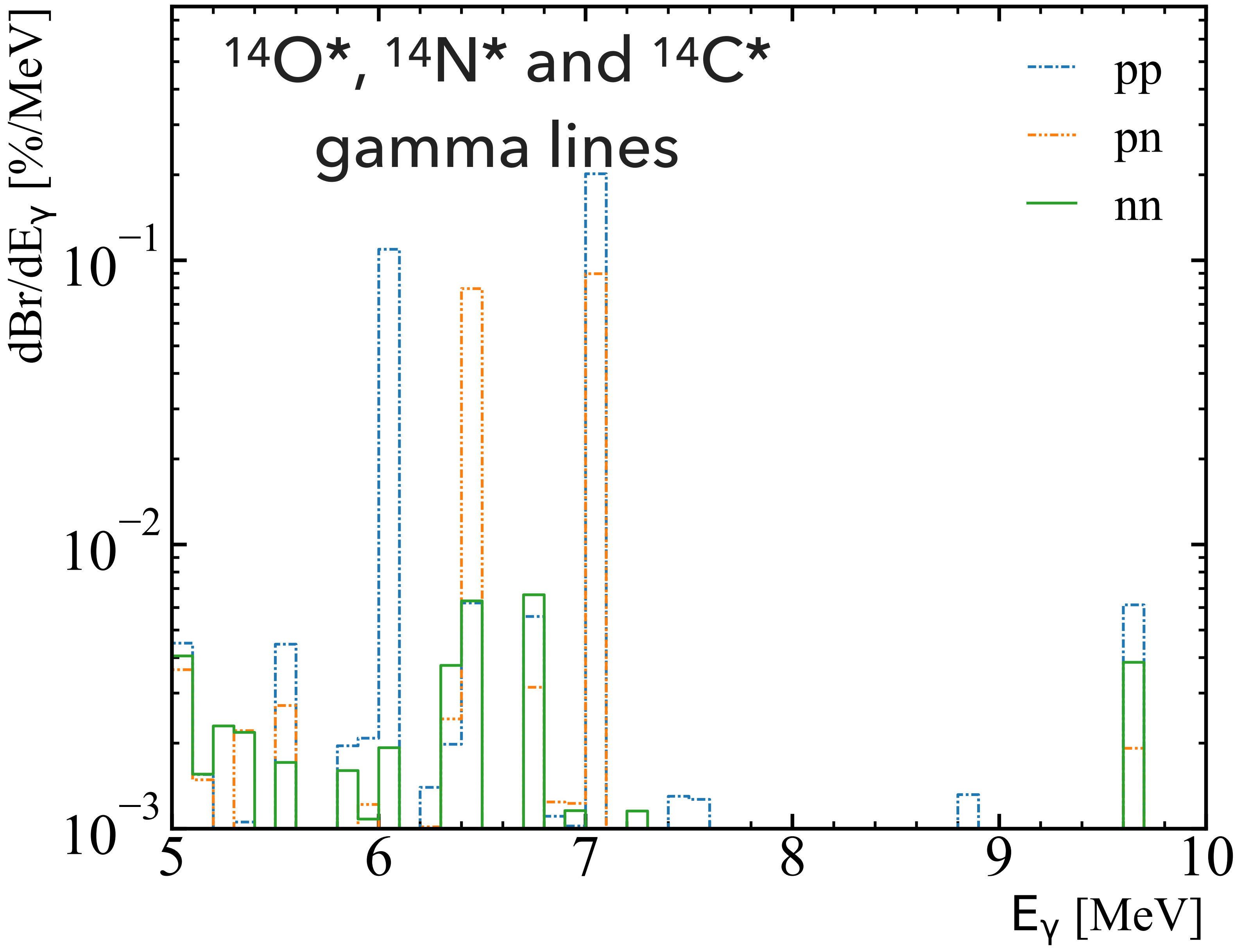

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$^{A-1}X^{*} \rightarrow {}^{A-1}X$ + **γ's**

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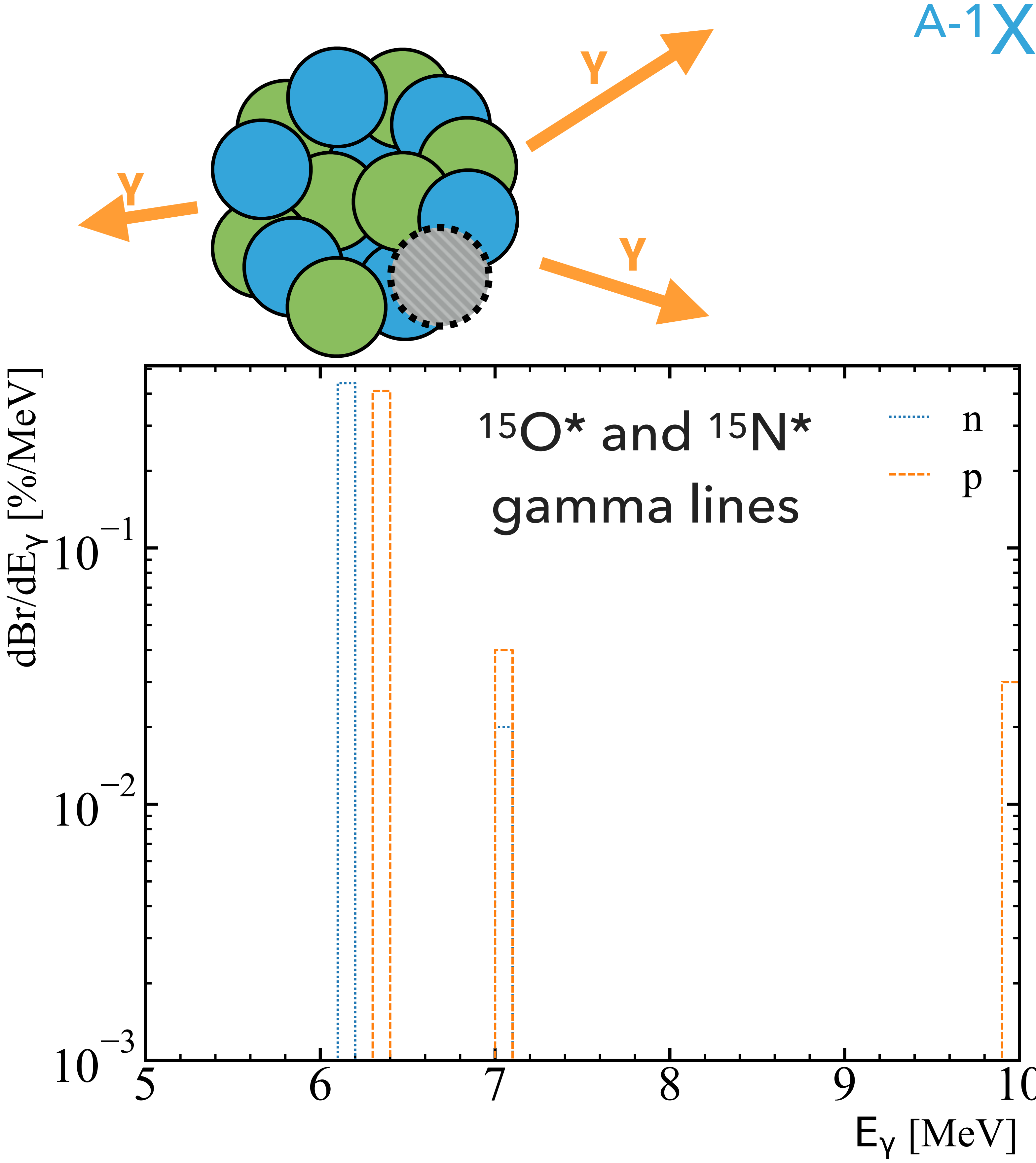
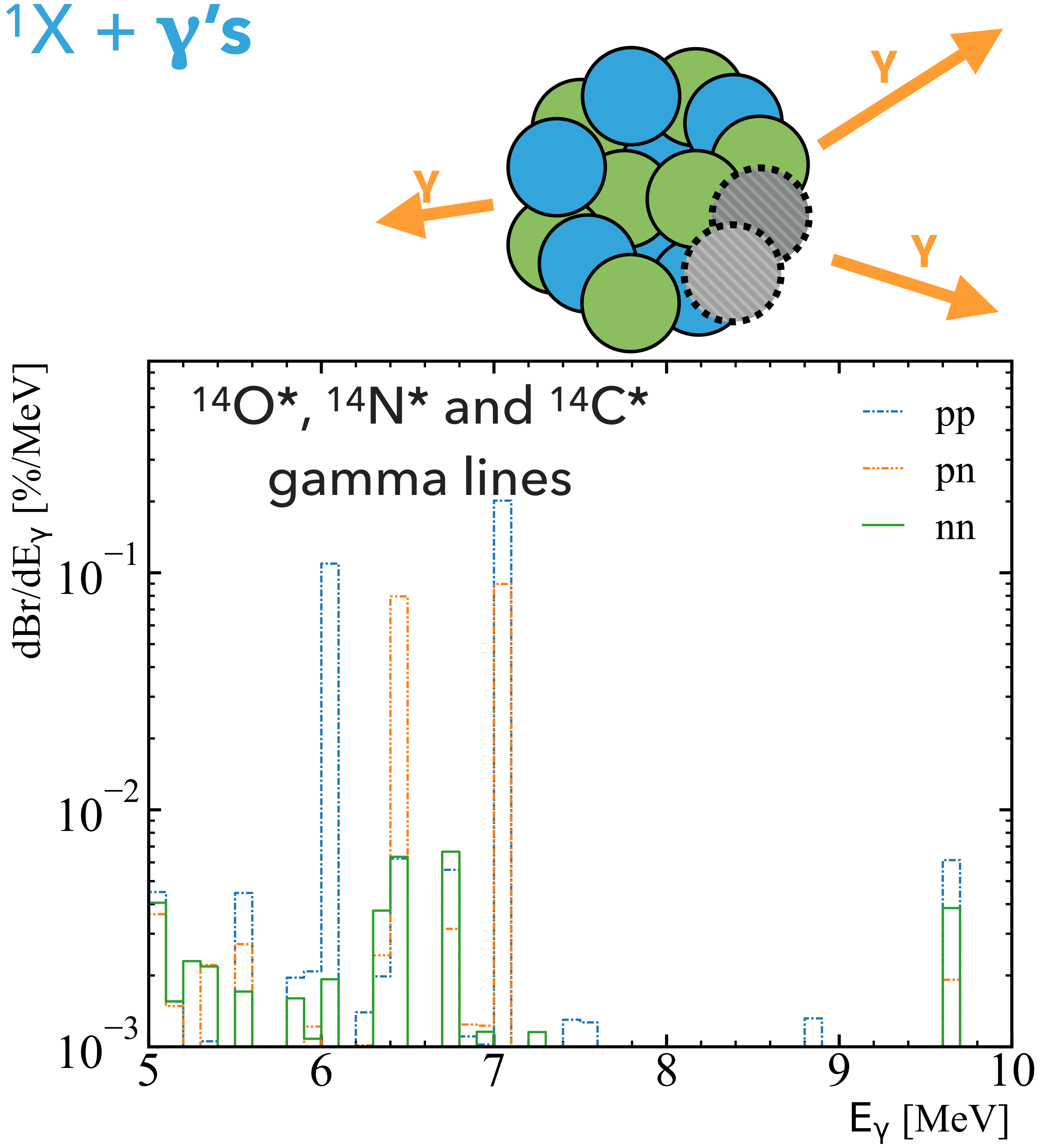


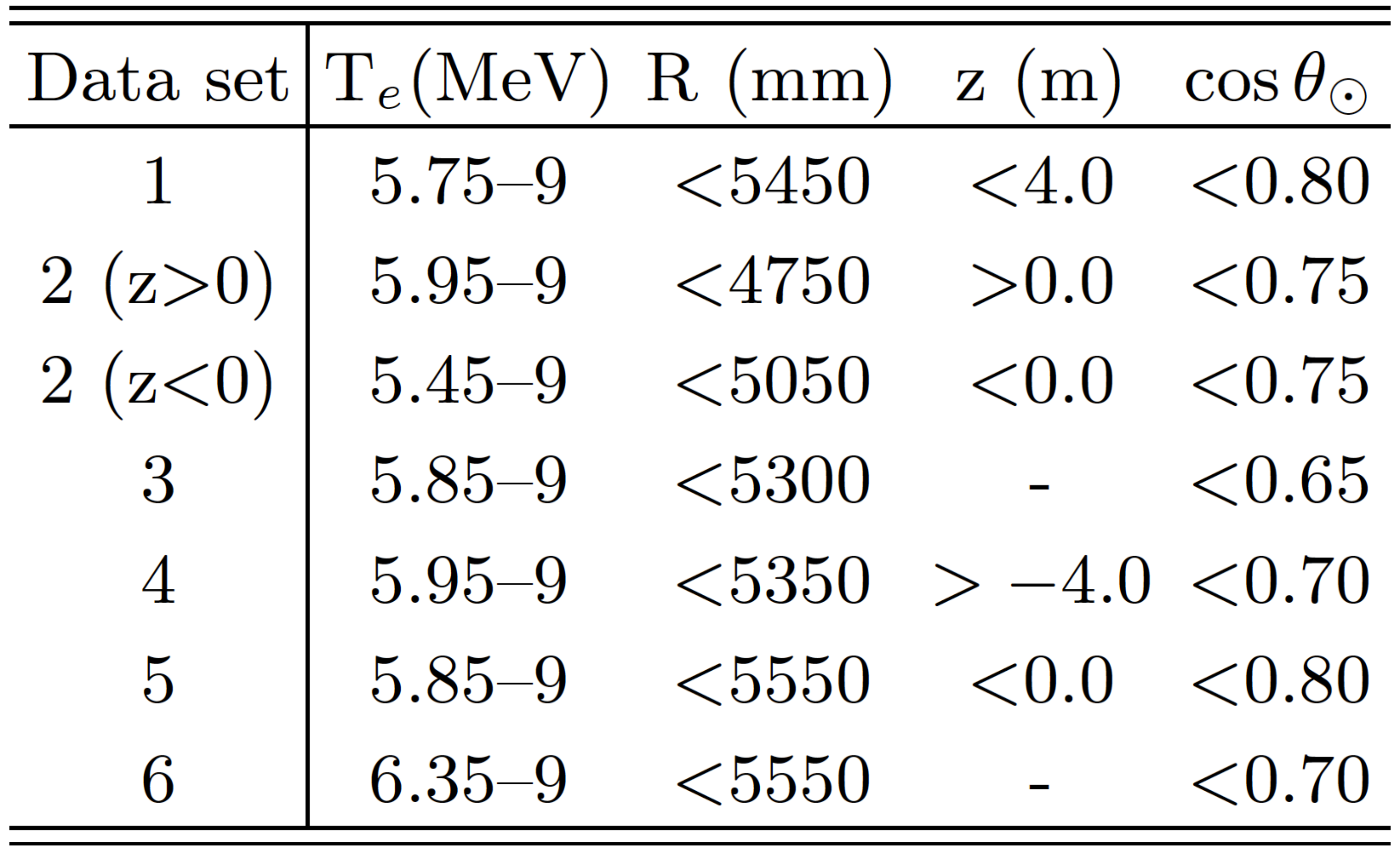


ONLY ~55 BACKGROUND EVENTS/YEAR AFTER SELECTION (ABOVE ~6MEV)

PERFORMED TWO INDEPENDENT ANALYSES:

COUNTING ANALYSIS

"CUT&COUNT" APPROACH



Data set	T_e(MeV)	R (mm)	z (m)	$\cos\theta_\odot$
1	5.75–9	<5450	<4.0	<0.80
2 (z>0)	5.95–9	<4750	>0.0	<0.75
2 (z<0)	5.45–9	<5050	<0.0	<0.75
3	5.85–9	<5300	-	<0.65
4	5.95–9	<5350	> -4.0	<0.70
5	5.85–9	<5550	<0.0	<0.80
6	6.35–9	<5550	-	<0.70

Time bins:
Dataset divided in 6 different background periods

Energy cut:
Reduces radioactive backgrounds

Fiducial volume:
Reduces external backgrounds

Sun direction:
Reduces solar neutrino background

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SPECTRAL ANALYSIS

MULTI-DIMENSIONAL LIKELIHOOD FIT

Observables:

- Energy
- Radial event position
- Sun direction
- Light isotropy
- Event direction

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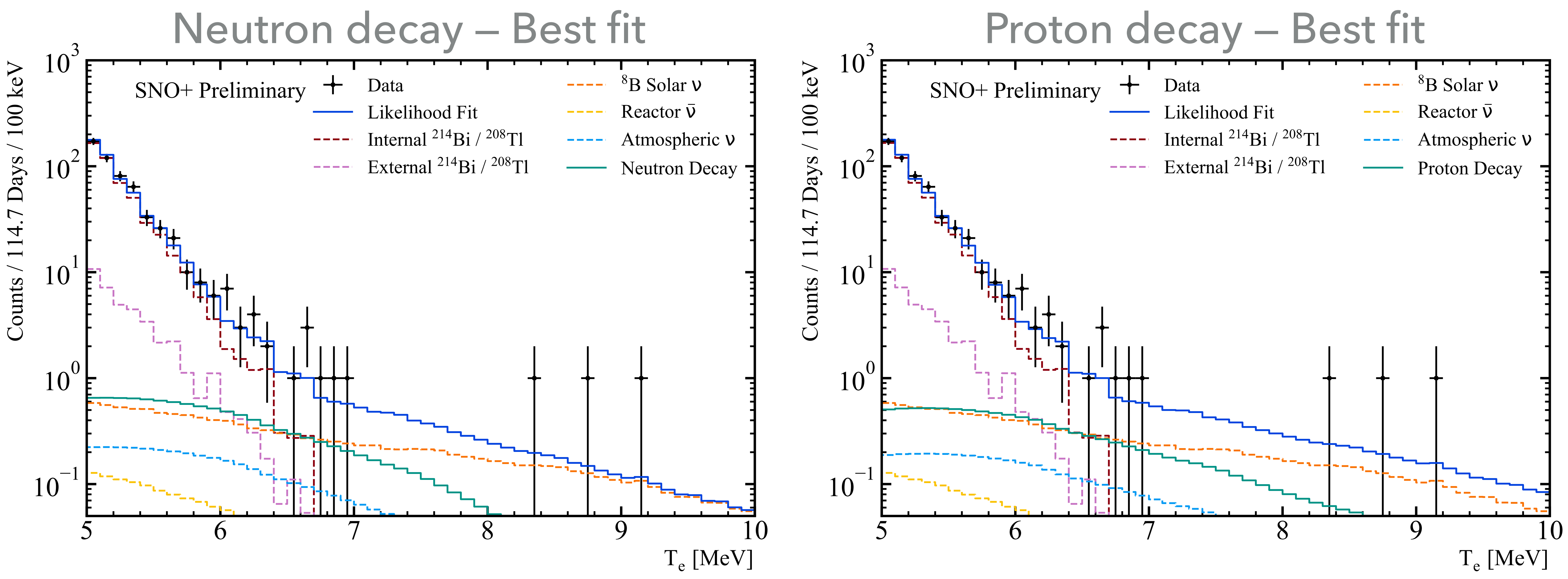
Neutron decay – Best fit

Proton decay – Best fit

Energy distributions

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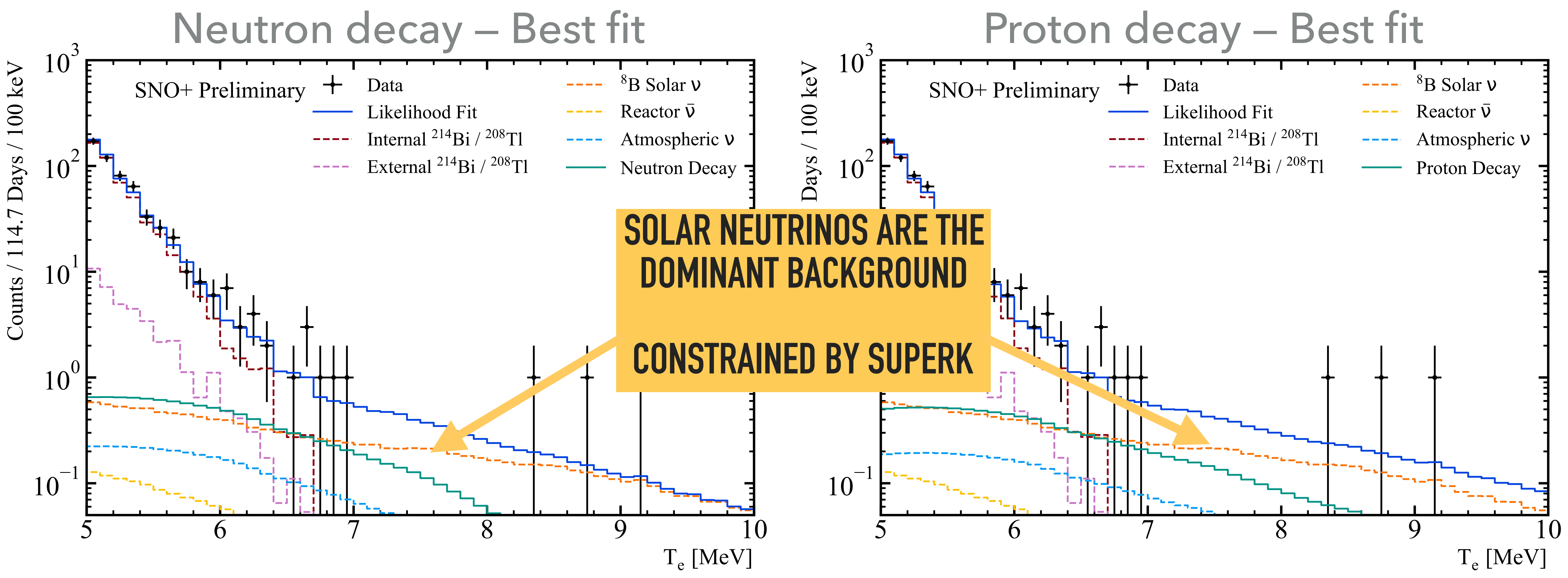

SOLAR NEUTRINOS ARE THE DOMINANT BACKGROUND

CONSTRAINED BY SUPERK

Energy distributions

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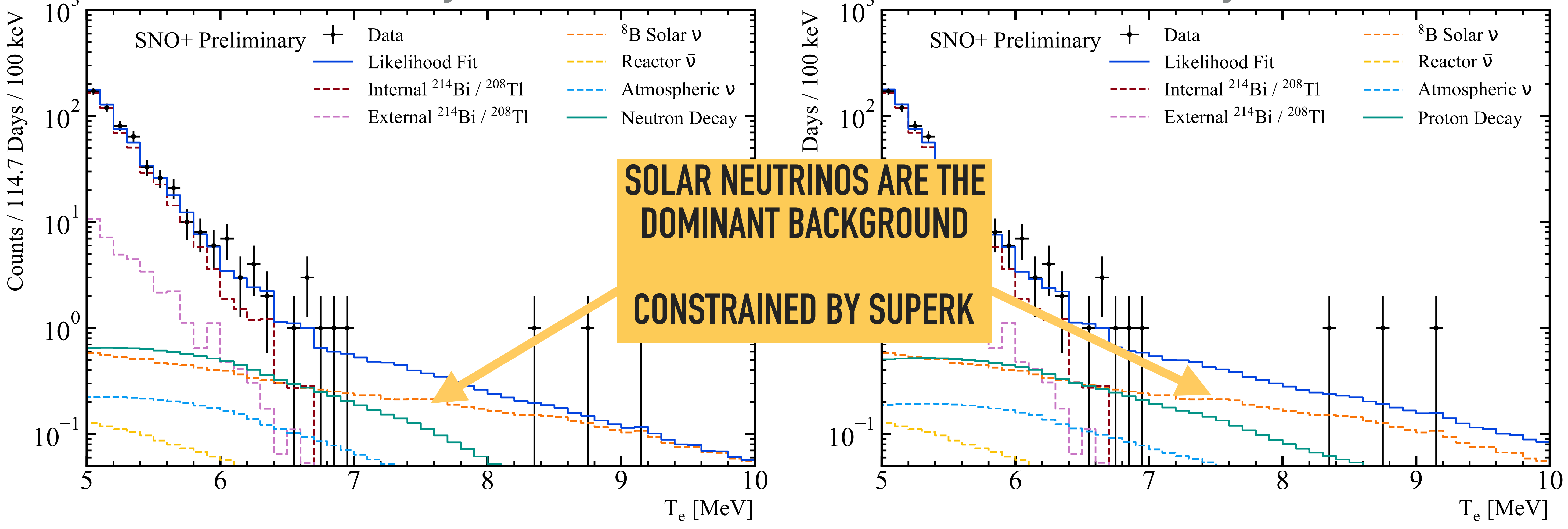
Proton decay – Best fit



SOLAR NEUTRINOS ARE THE DOMINANT BACKGROUND

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Energy distributions

UNCERTAINTY IN ENERGY RESOLUTION IS THE DOMINANT SYSTEMATIC

NO SIGNAL DETECTED → SET 90% C.L. LIFETIME LIMITS

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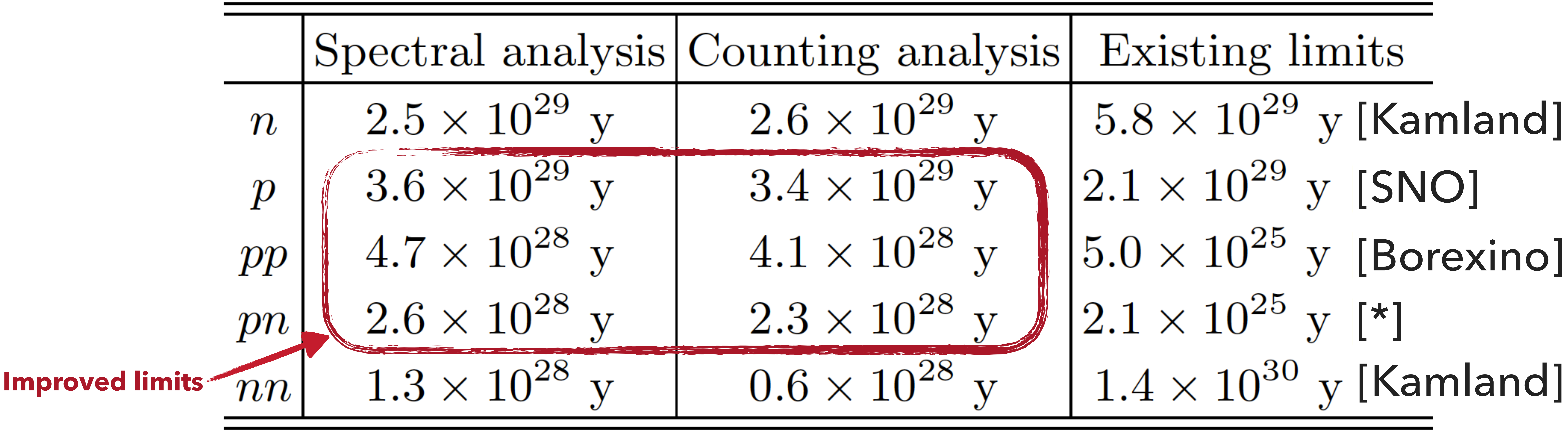

	Spectral analysis	Counting analysis	Existing limits
n	2.5×10^{29} y	2.6×10^{29} y	5.8×10^{29} y [Kamland]
p	3.6×10^{29} y	3.4×10^{29} y	2.1×10^{29} y [SNO]
pp	4.7×10^{28} y	4.1×10^{28} y	5.0×10^{25} y [Borexino]
pn	2.6×10^{28} y	2.3×10^{28} y	2.1×10^{25} y [*]
nn	1.3×10^{28} y	0.6×10^{28} y	1.4×10^{30} y [Kamland]

Improved limits

235 days-worth of data → currently x2 data available

[new analysis in preparation]

[*] V. Tretyak, V. Yu. Denisov, and Yu. G. Zdesenko, JETP Lett. **79**, 106 (2004), [Pisma Zh. Eksp. Teor. Fiz.79,136(2004)], arXiv:nucl-ex/0401022 [nucl-ex].

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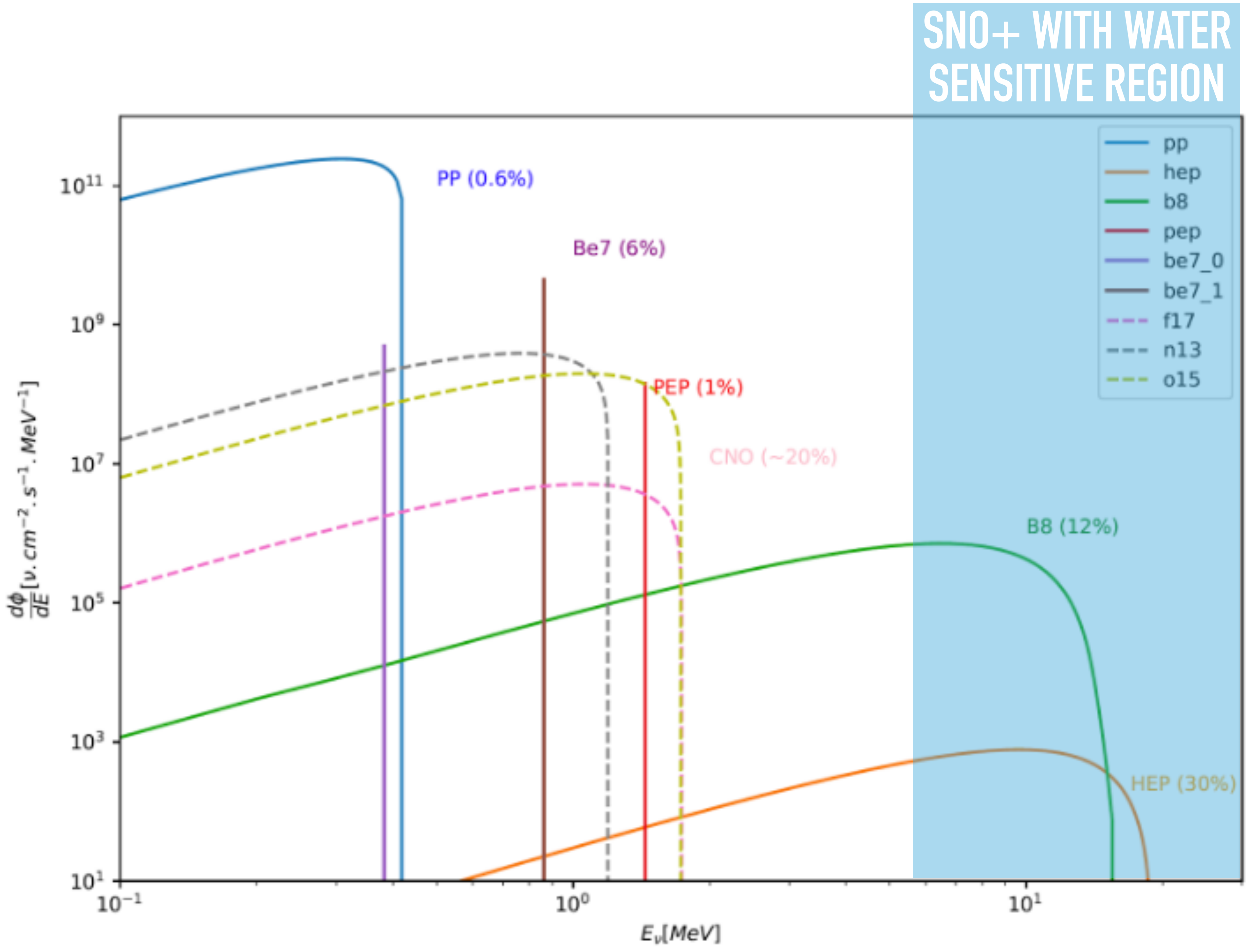
SOLAR NEUTRINOS IN WATER

MEASURED SOLAR B8 FLUX → COMPATIBLE WITH PREVIOUS MEASUREMENTS



VERY LOW BACKGROUNDS
→ SOLAR NEUTRINOS PEAK CLEARLY VISIBLE

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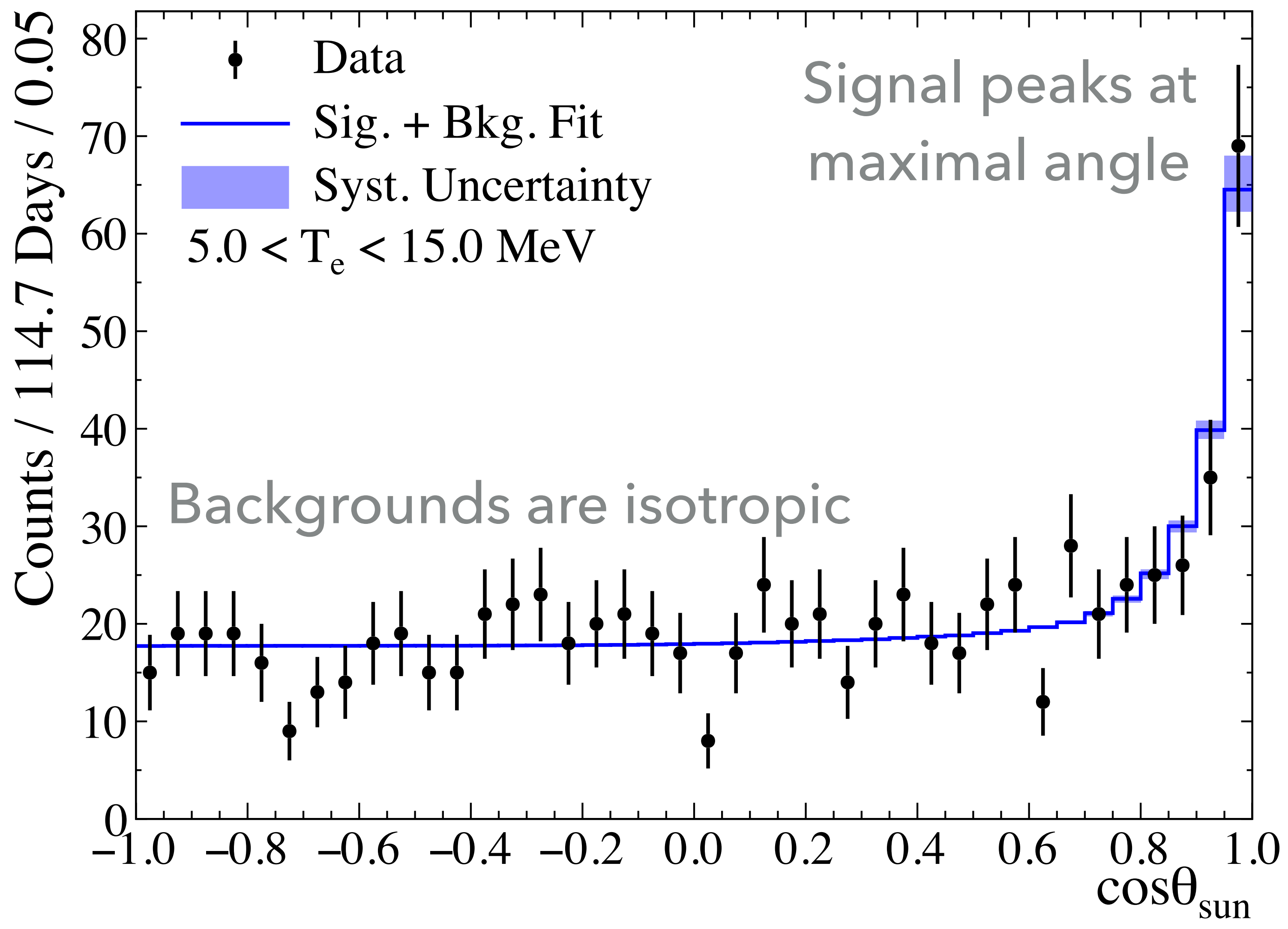
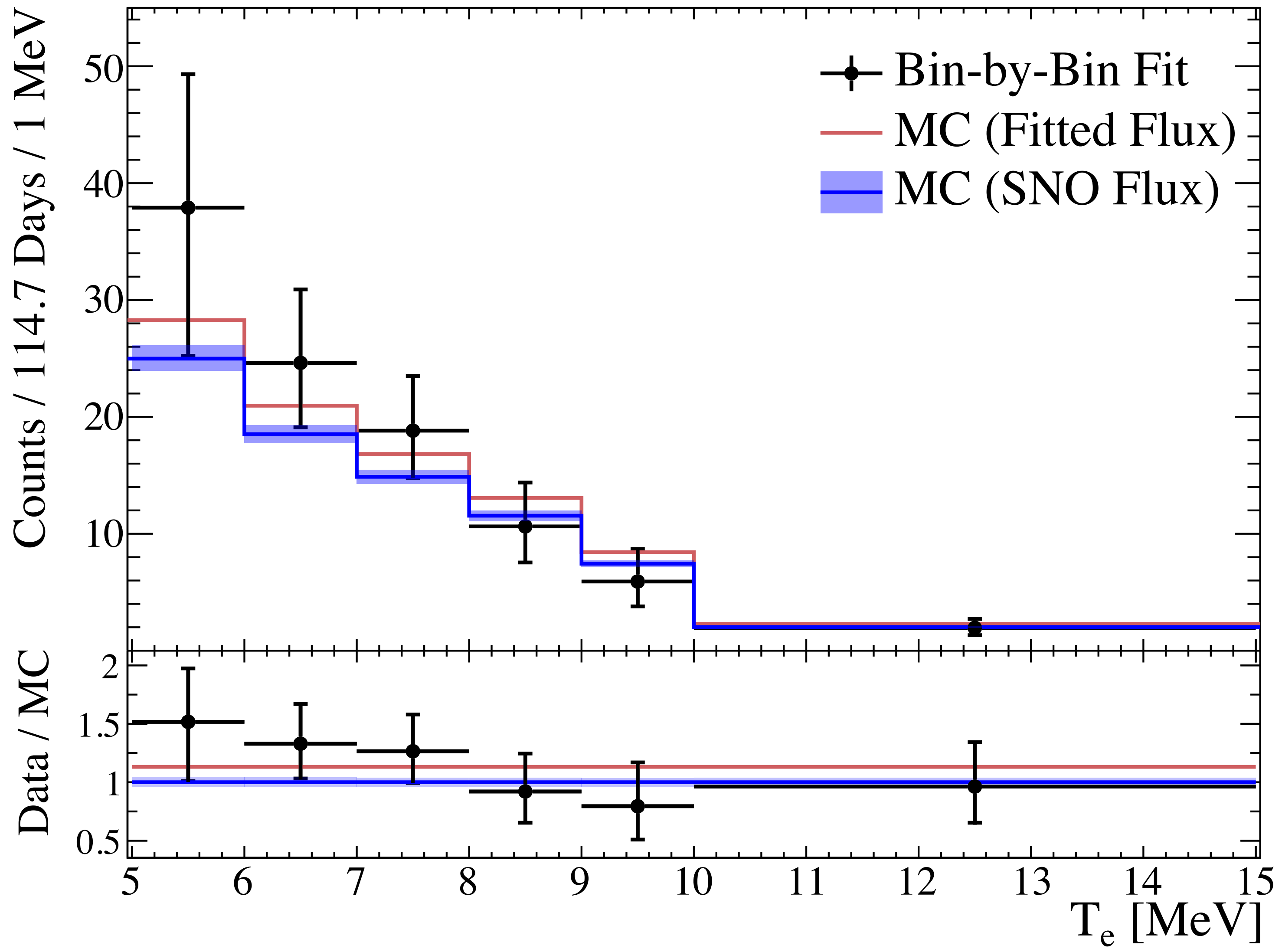
Angle between electron and Sun direction



Signal peaks at maximal angle

Backgrounds are isotropic

Electron kinetic energy distribution for background subtracted signal



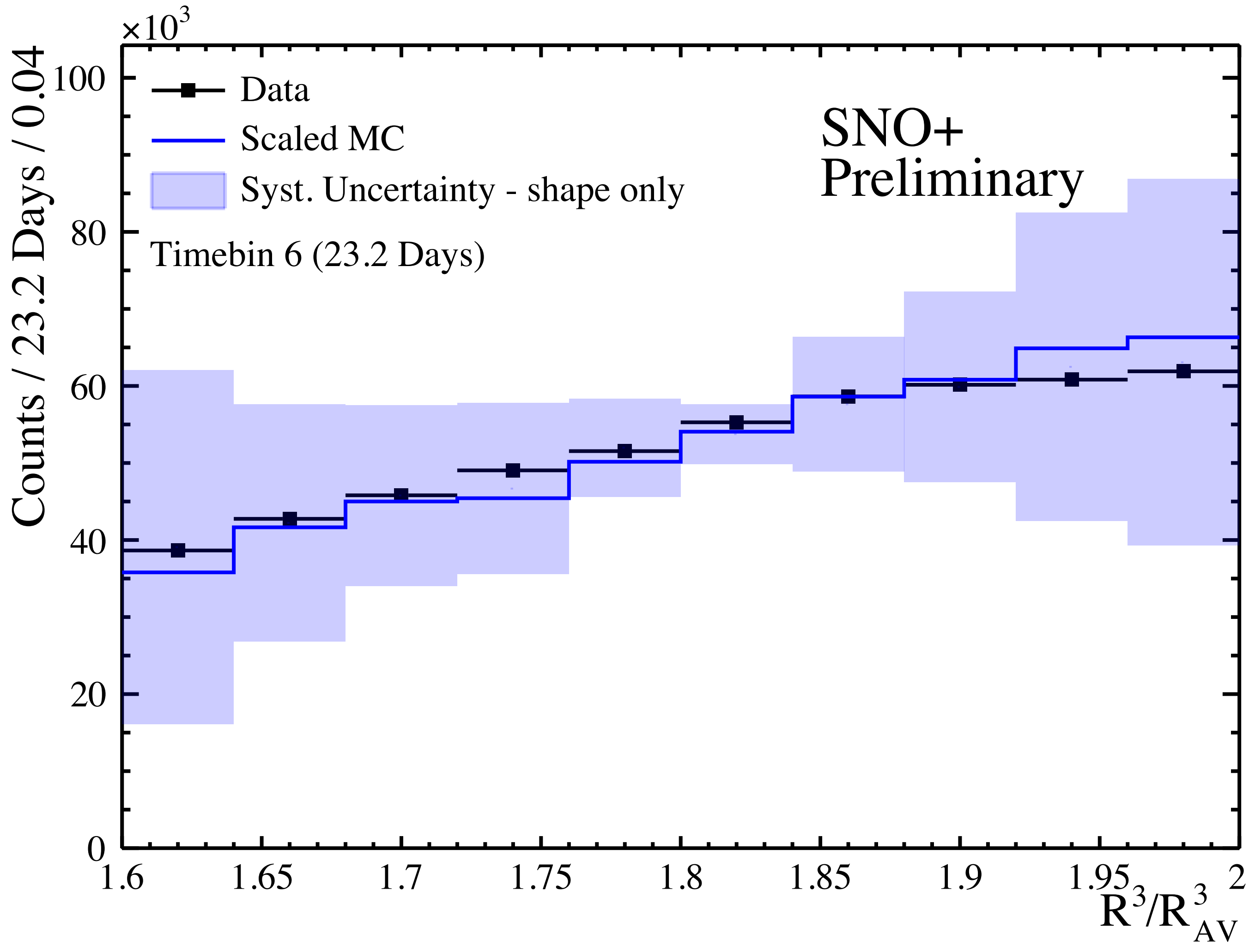
SNO+ (This work): $\Phi_{^8\mathrm{B}} = 5.95^{+0.75}_{-0.71}(\mathrm{stat.})^{+0.28}_{-0.30}(\mathrm{syst.}) \times 10^6\mathrm{cm}^{-2}\mathrm{s}^{-1}$

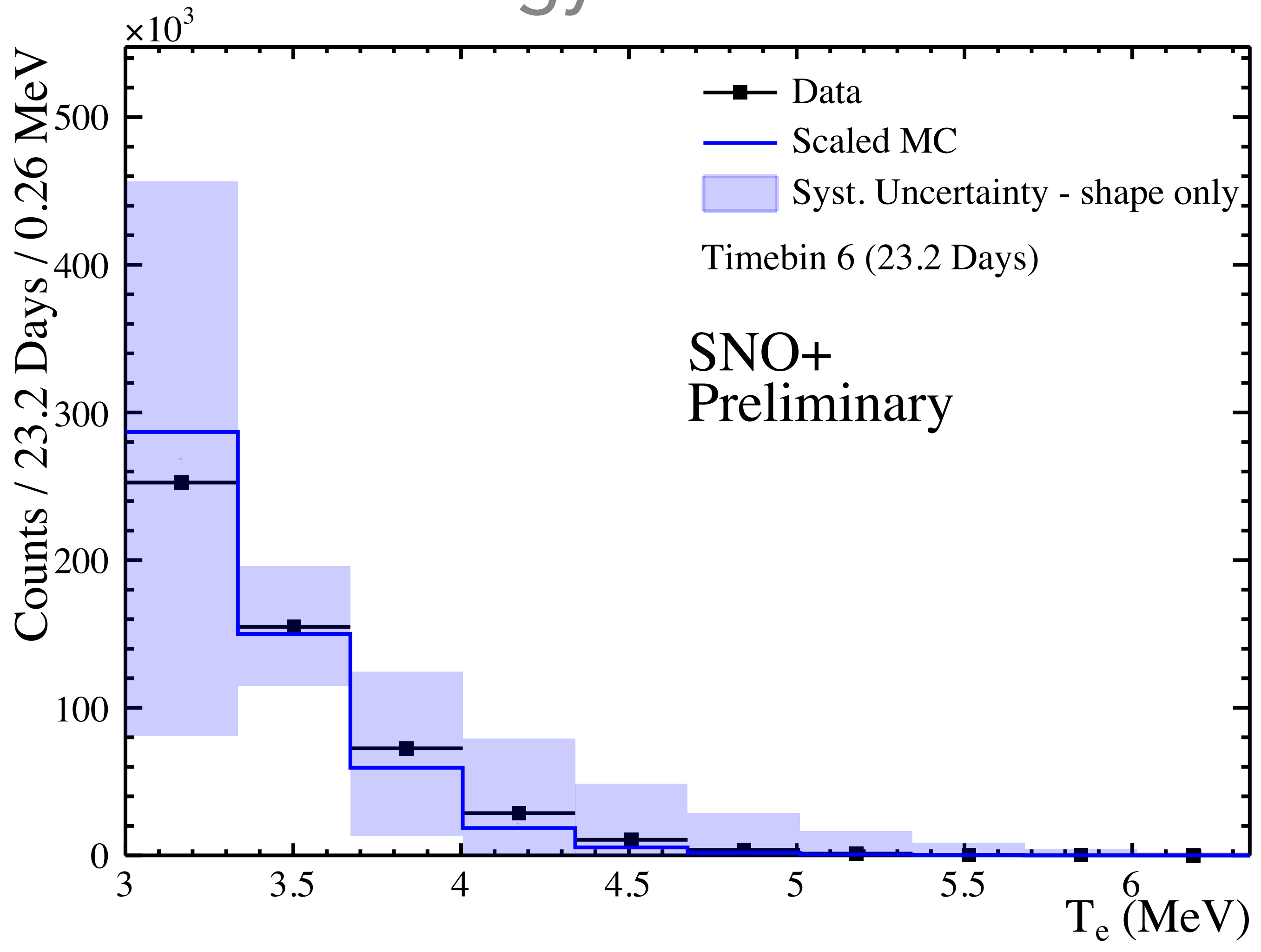
SNO: $\Phi_{^8\mathrm{B}} = (5.25 \pm 0.16(\mathrm{stat.})^{+0.11}_{-0.13}(\mathrm{syst.})) \times 10^6\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$

EXTERNAL BACKGROUNDS MEASUREMENTS

EXTERNAL BACKGROUNDS ARE COMPATIBLE WITH EXPECTATIONS

GAMMA BACKGROUND FROM PMTs


Radial distribution


Energy distribution

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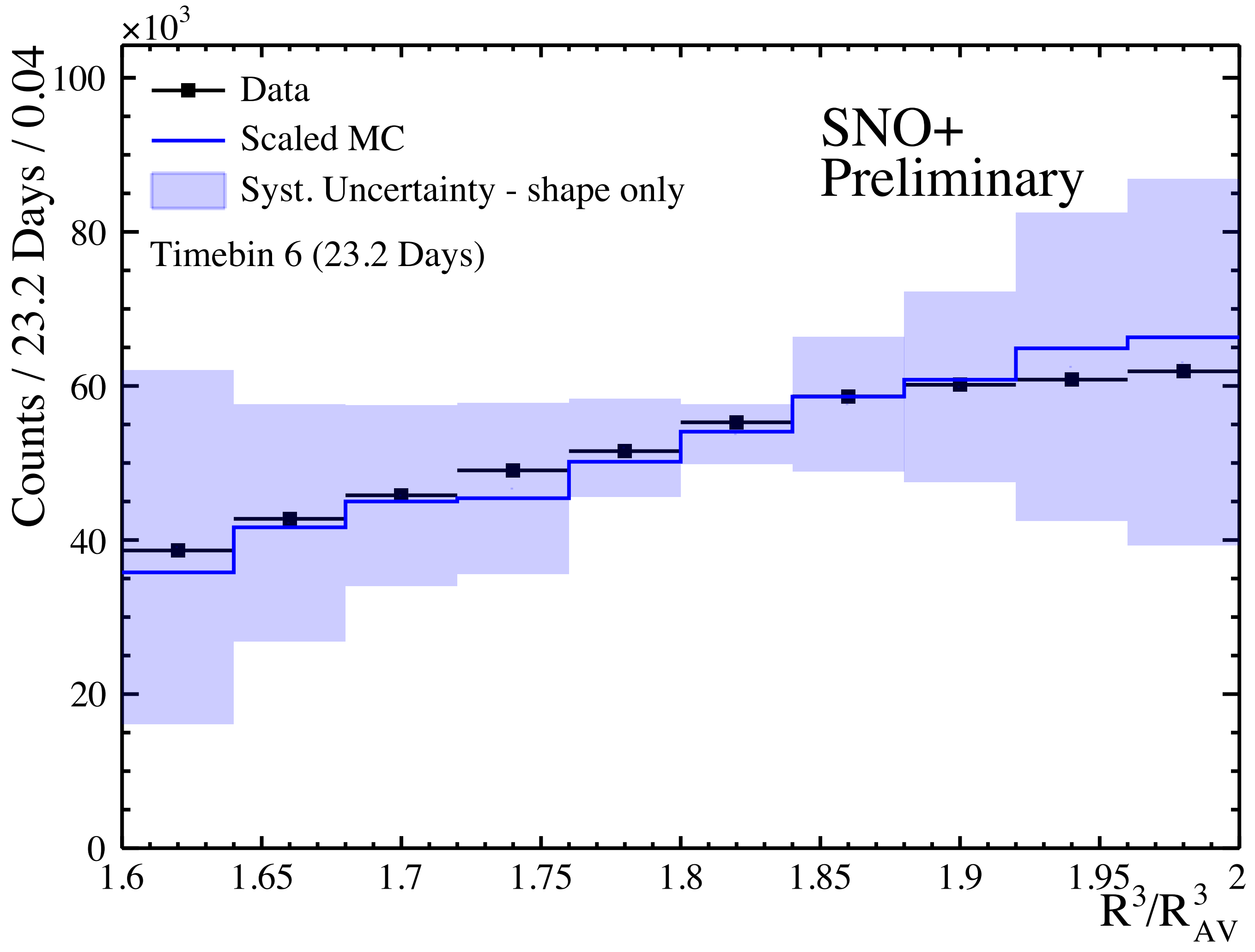

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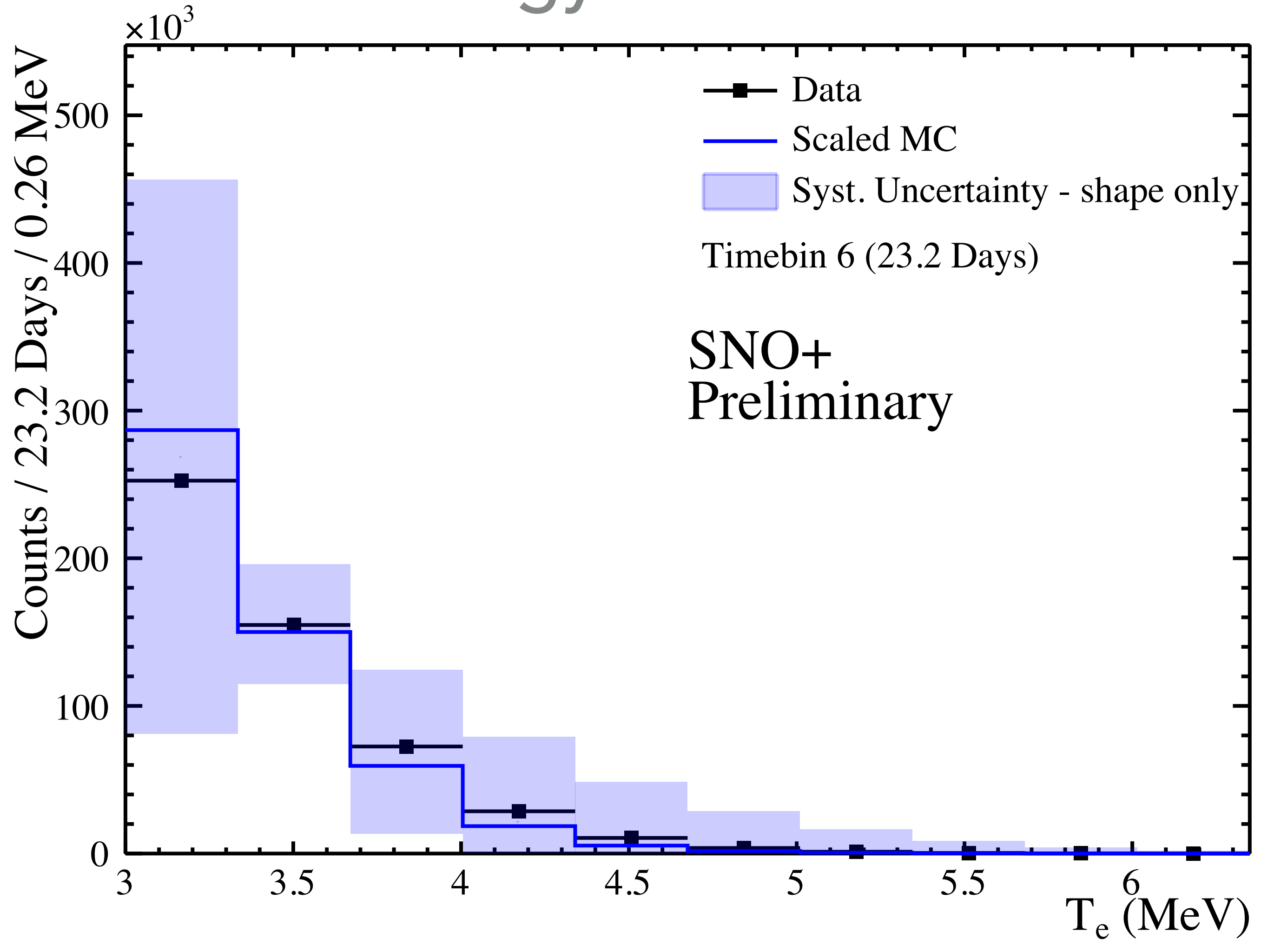
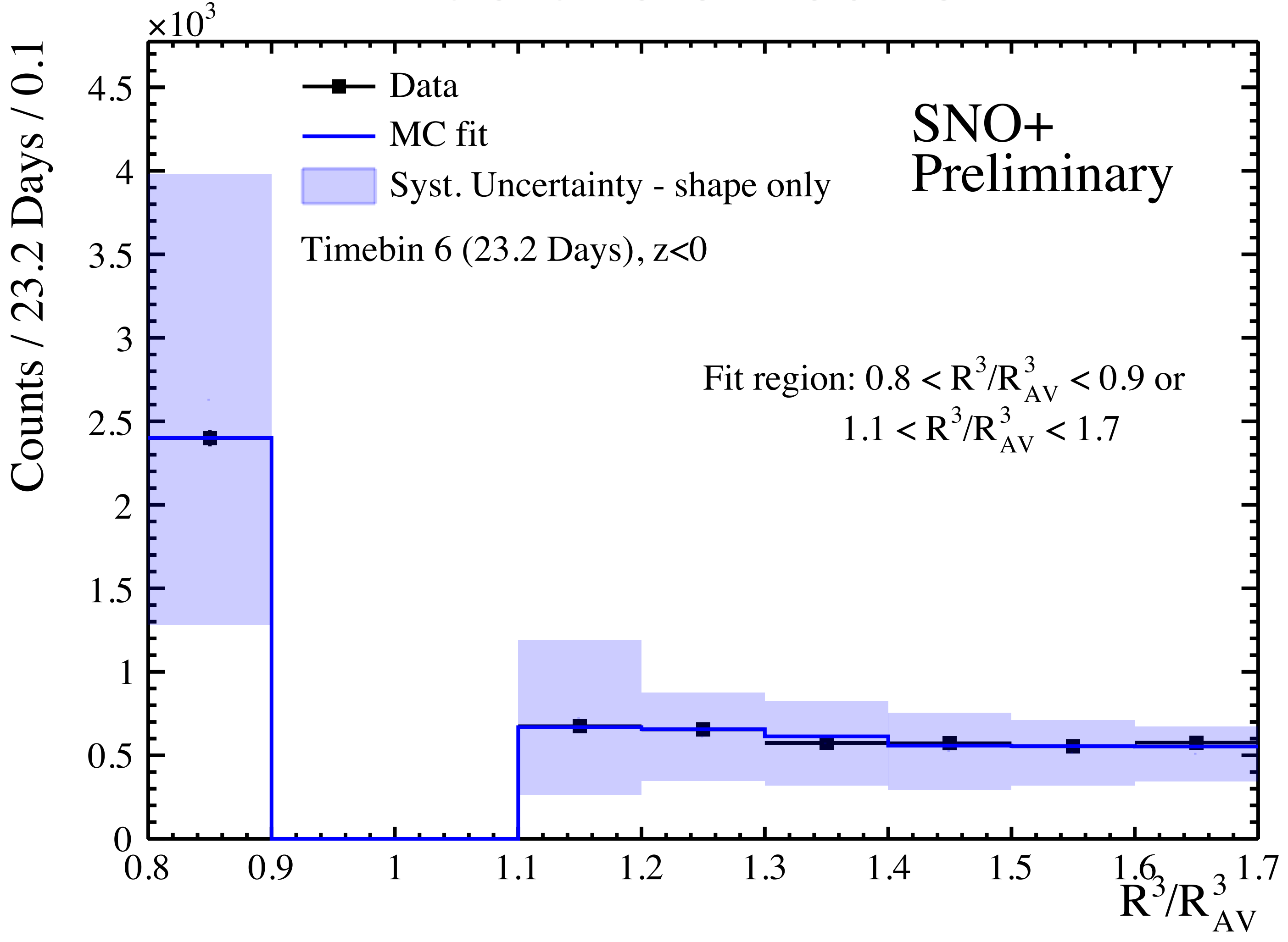


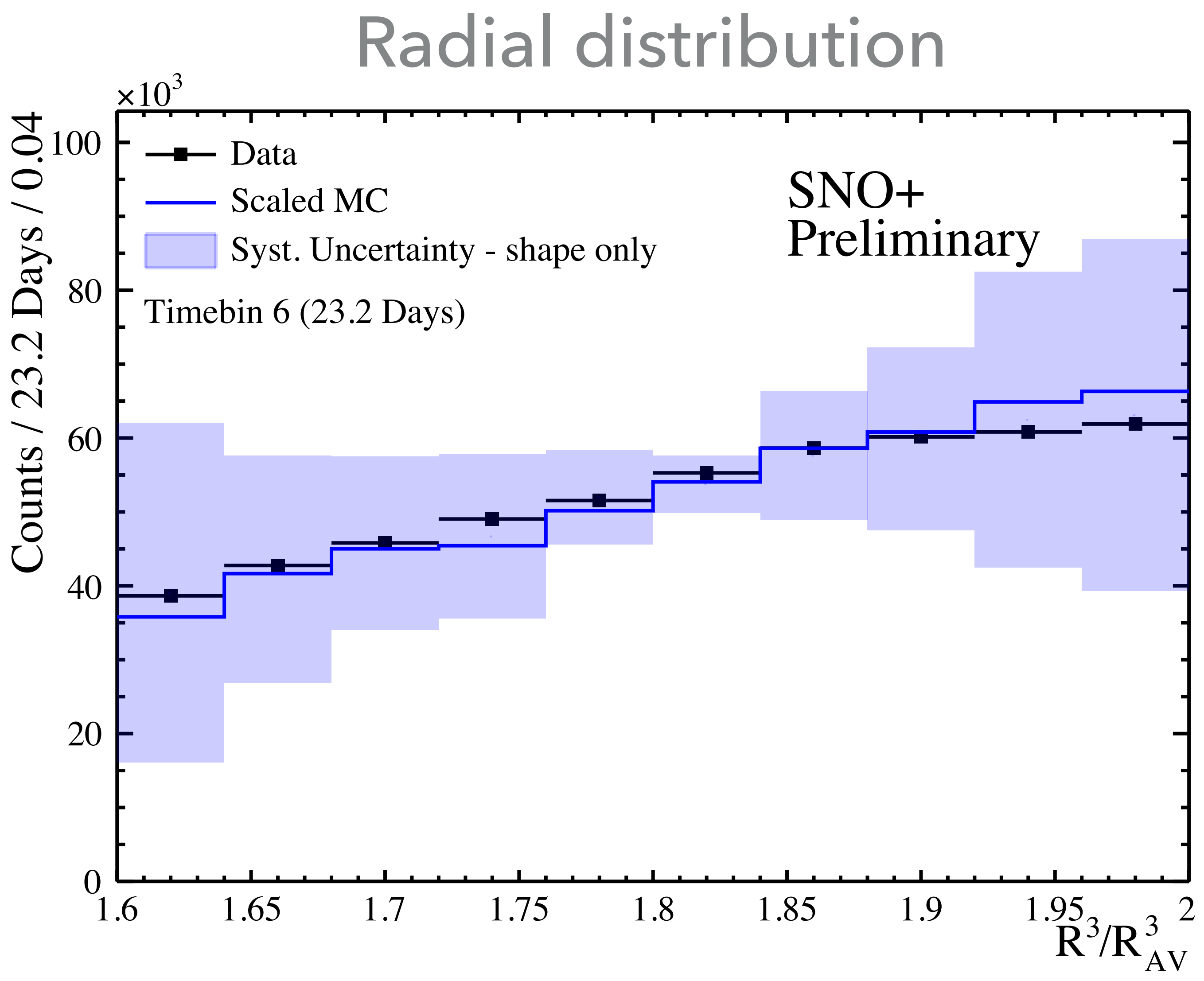
GAMMA BACKGROUND FROM WATER BUFFER AV AND ROPES

Radial distribution



EXTERNAL BACKGROUNDS ARE COMPATIBLE WITH EXPECTATIONS

GAMMA BACKGROUND FROM PMTs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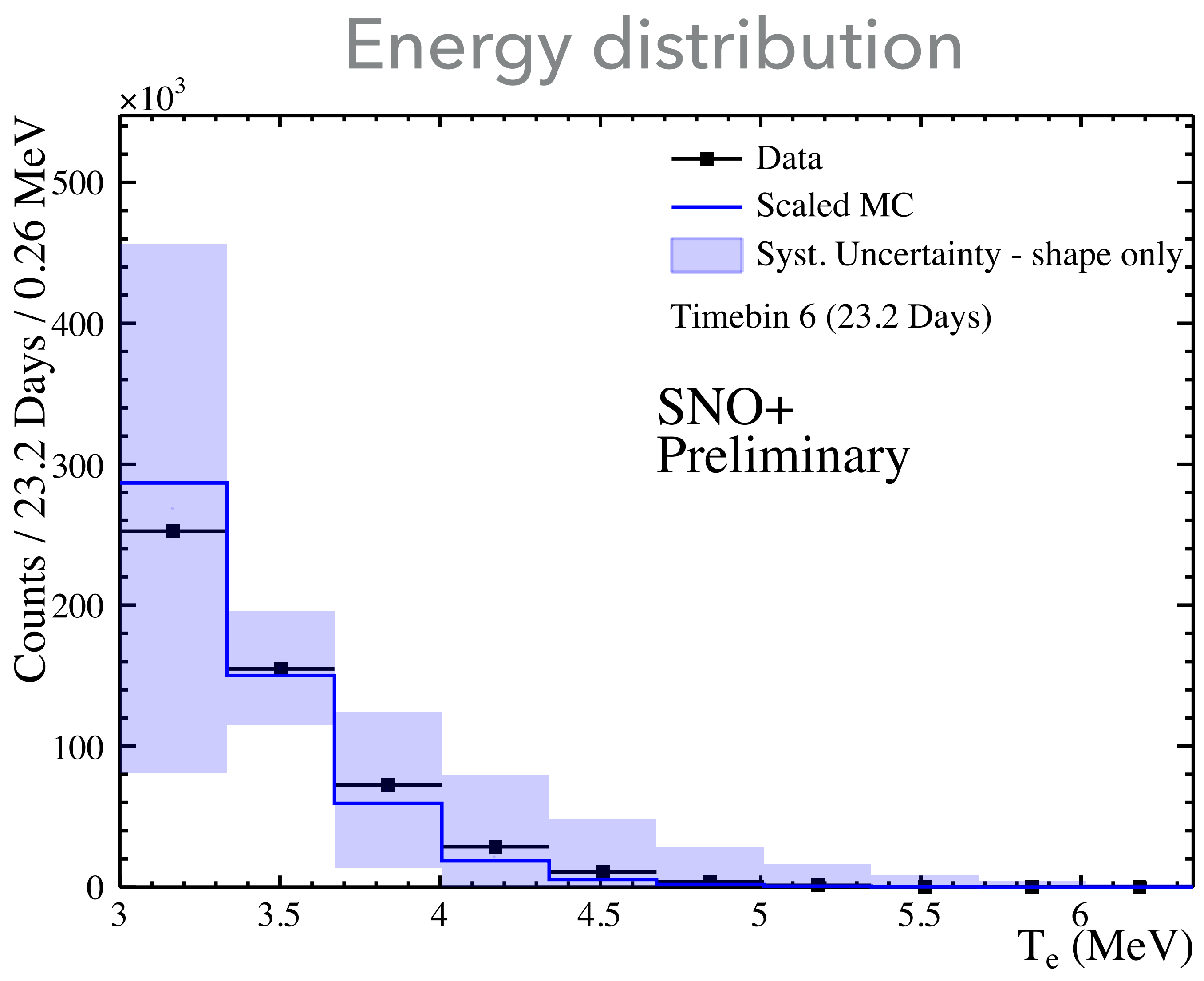
Energy distribution

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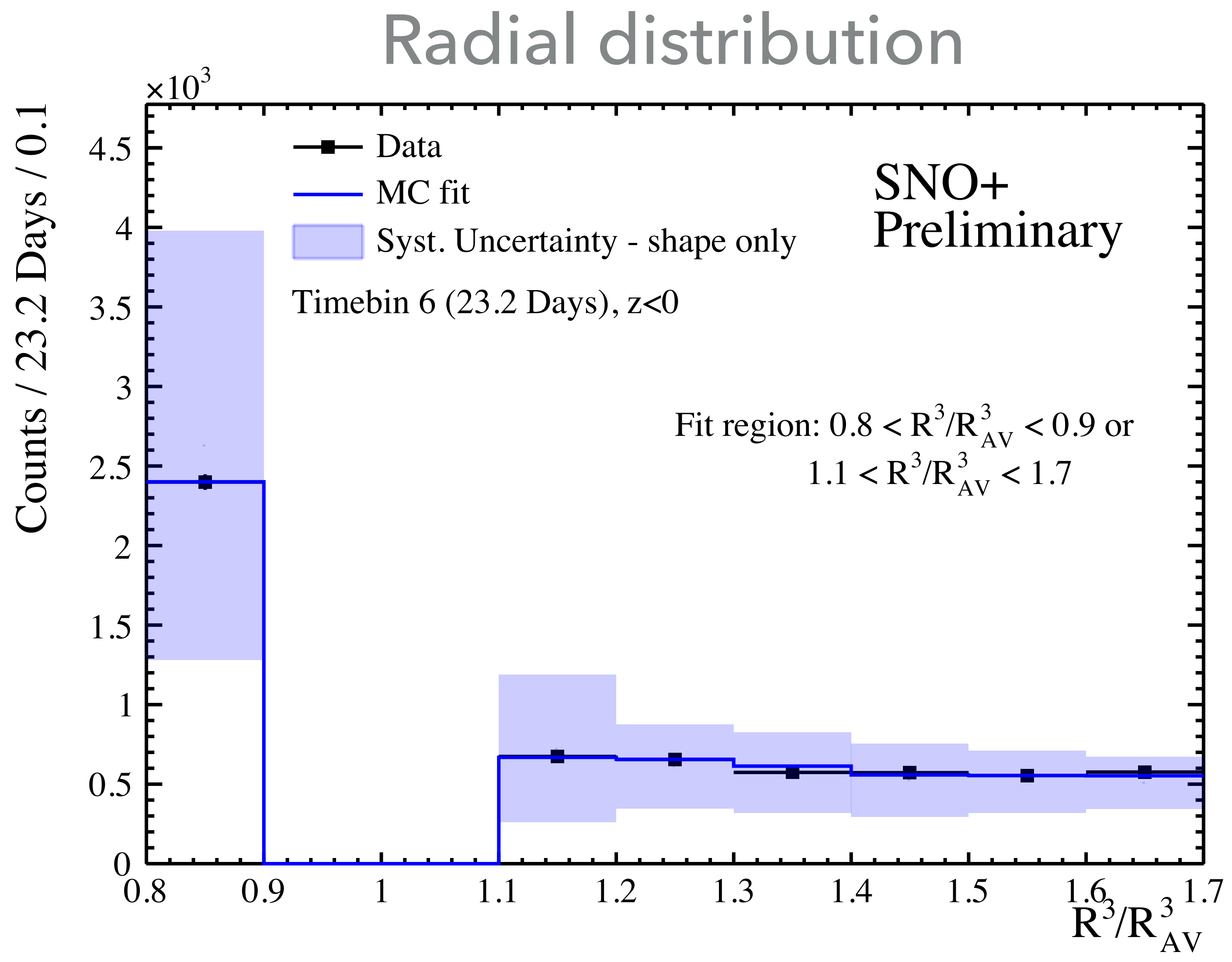

Radial distribution

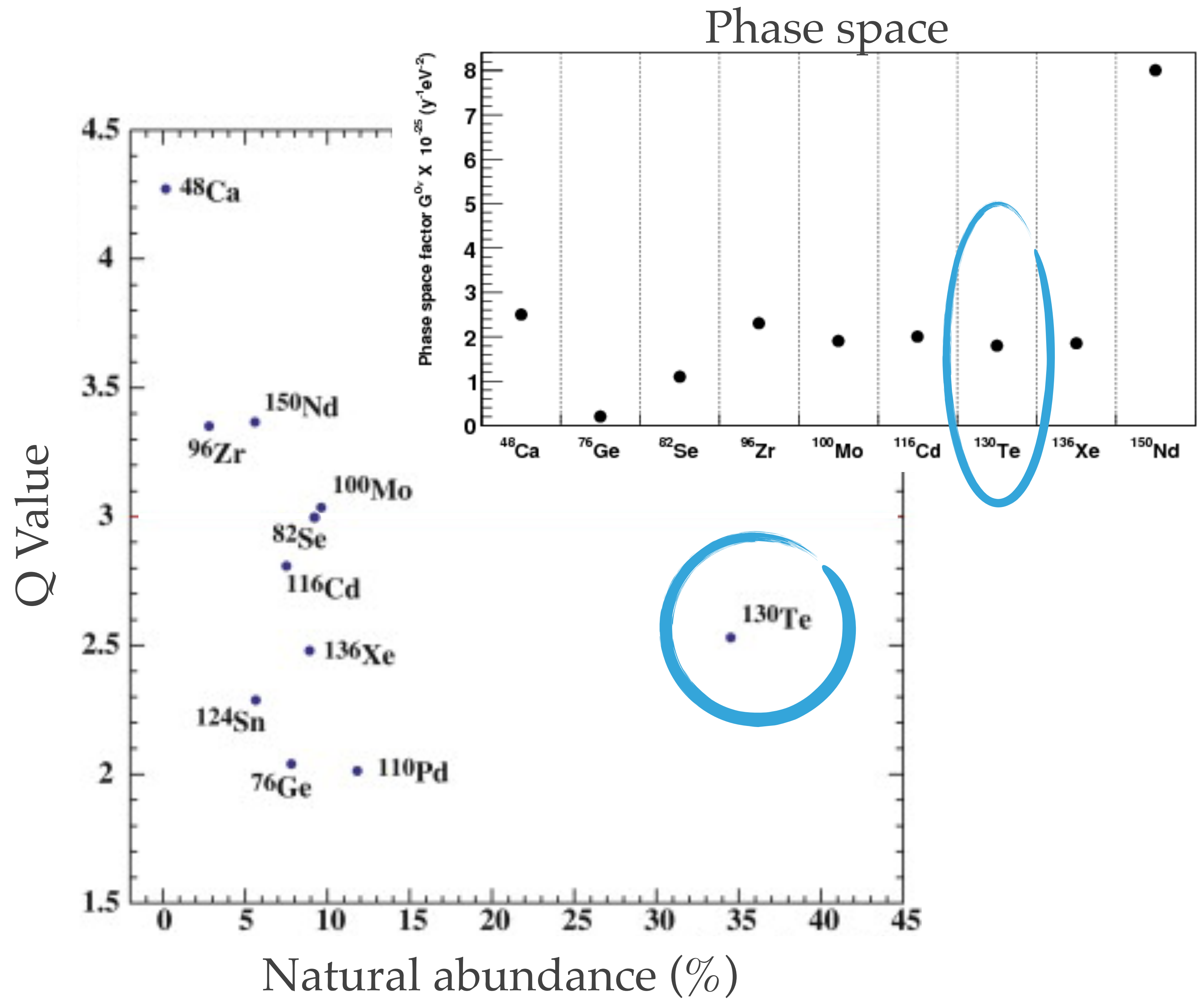
MEASUREMENT/EXPECTATION RATIO:

	Above equator	Below equator
AV+Ropes	$2.2 \pm 0.08^{+2.4}_{-1.9}$	$1.3 \pm 0.08^{+1.0}_{-0.9}$
Water buffer	$0.6 \pm 0.06^{+1.9}_{-0.6}$	$1.0 \pm 0.07^{+3.3}_{-1.0}$
PMT	$1.2 \pm 0.02^{+1.1}_{-0.5}$	$1.2 \pm 0.02^{+1.1}_{-0.5}$

OvBB

0νββ WITH TELLURIUM-130 IN LABPPO

1) Long 2νββ lifetime
2) Q value ~ 2.5MeV
3) 34% natural abundance
4) Phase space around average



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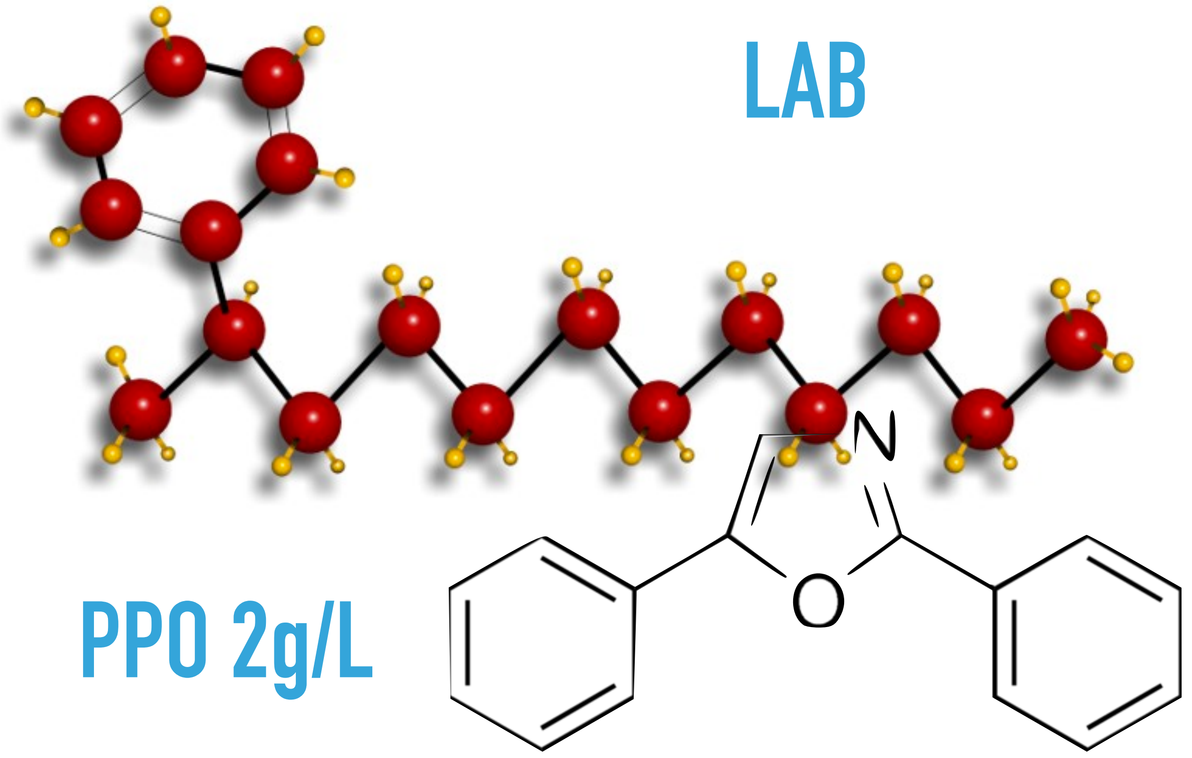
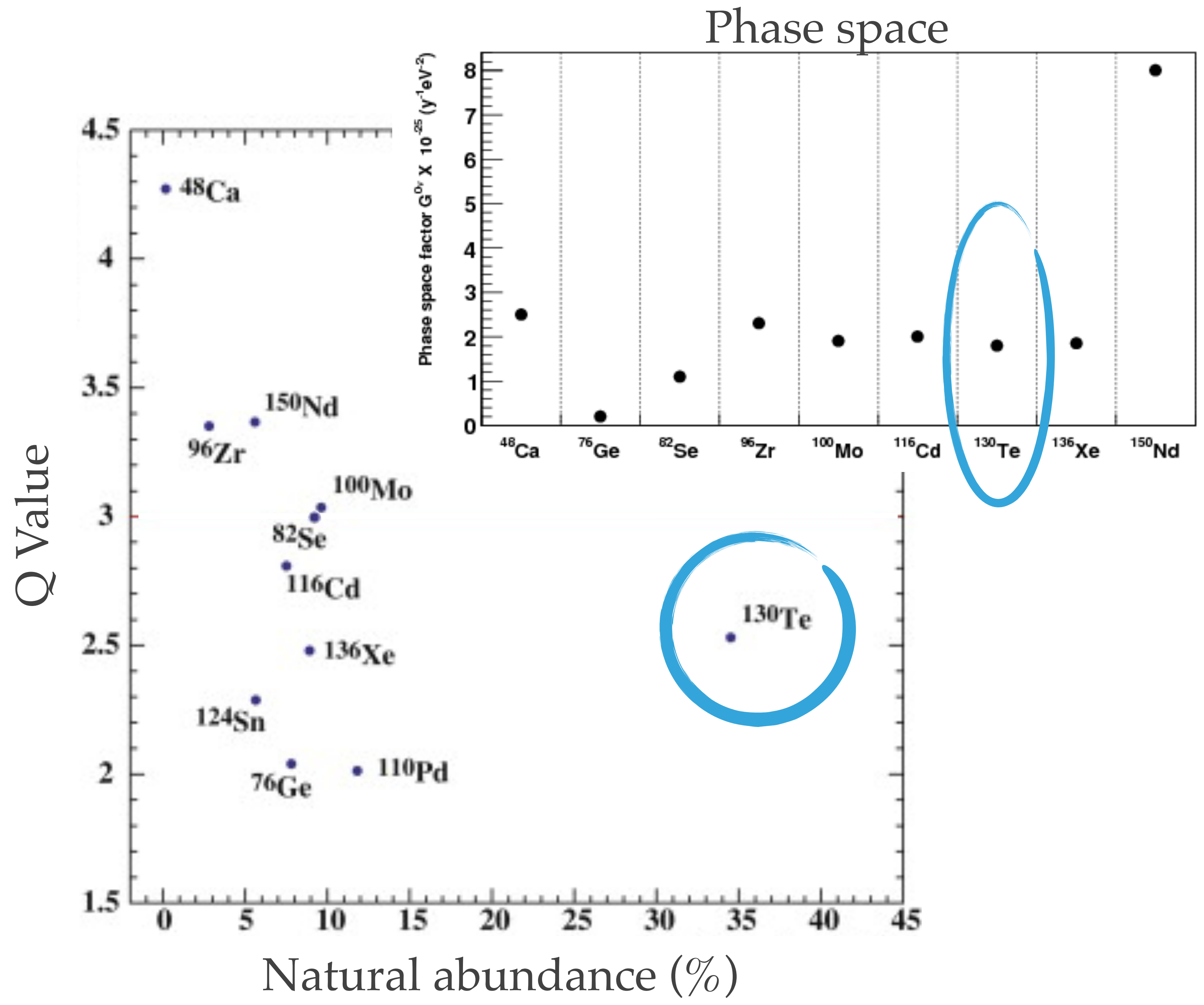
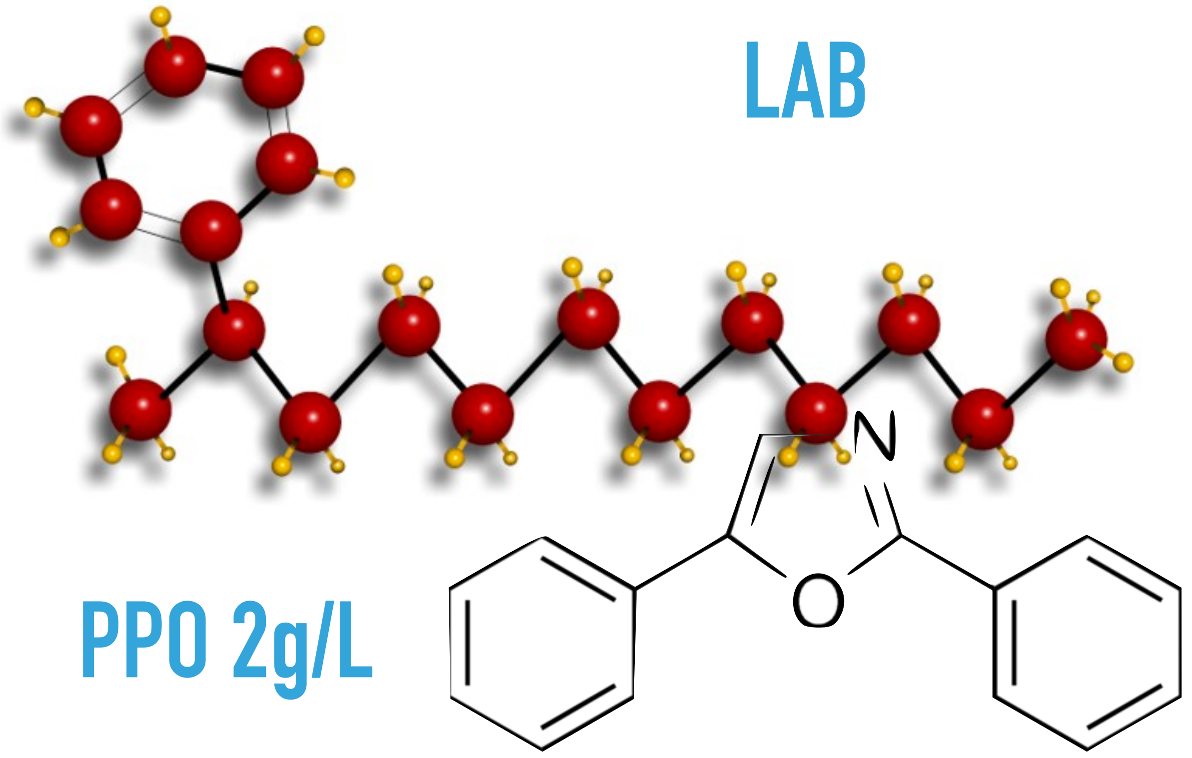


1) High light yield ~10000ph/MeV
2) Long attenuation length (~20m)
3) α/e pulse shape discrimination



0νββ WITH TELLURIUM-130 IN LABPPO

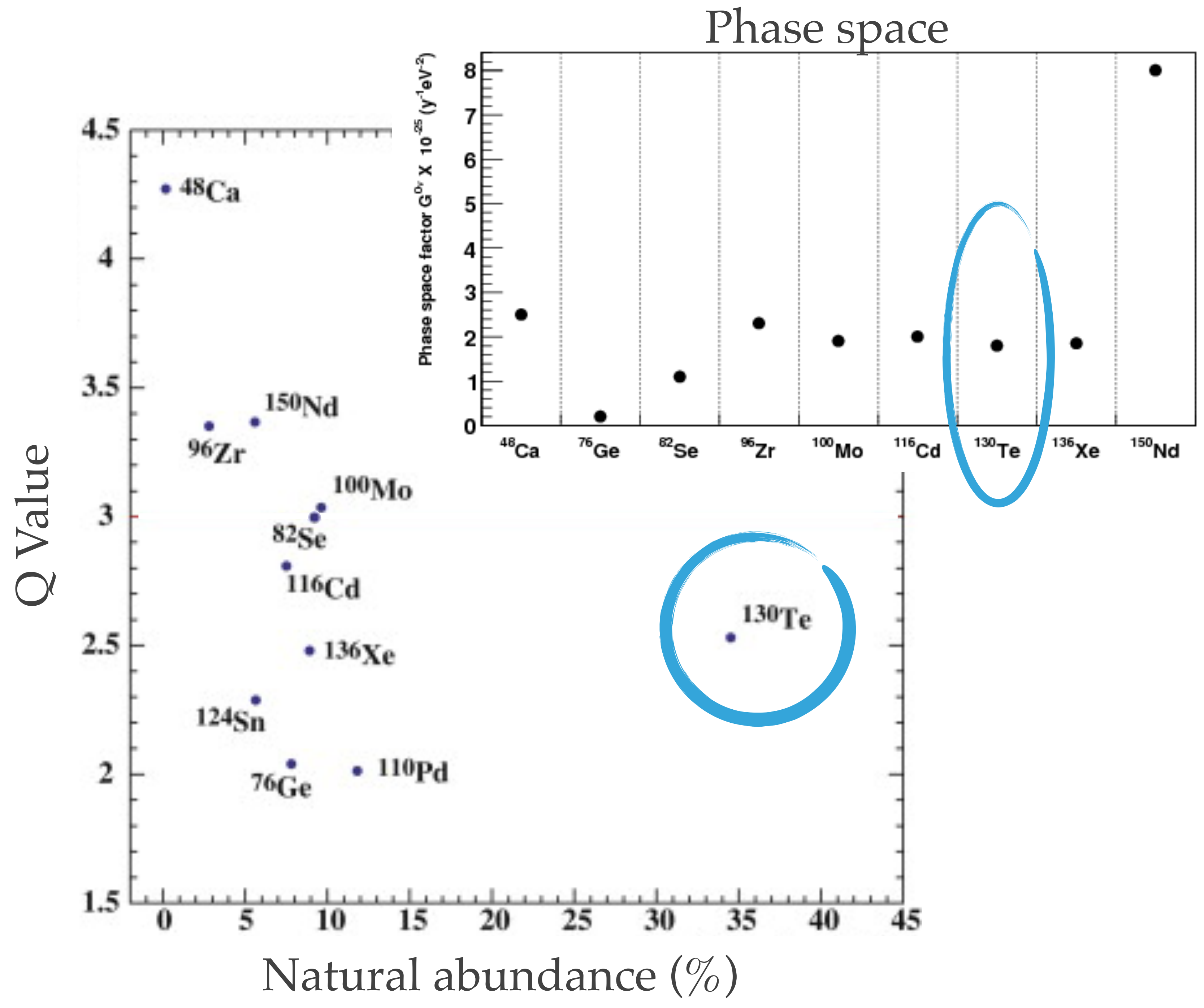
1) Long 2νββ lifetime
2) Q value ~ 2.5MeV
3) 34% natural abundance
4) Phase space around average



LAB

PPO 2g/L

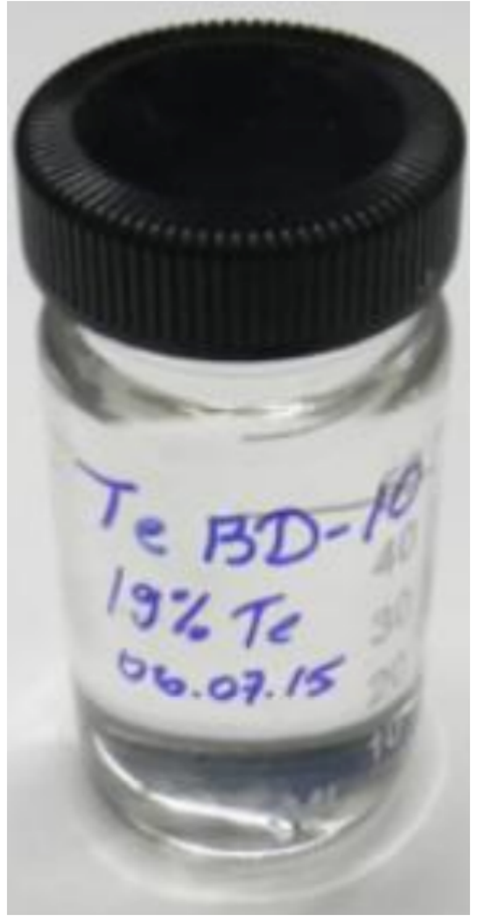
1) High light yield ~10000ph/MeV
2) Long attenuation length (~20m)
3) α/e pulse shape discrimination



Use DDA to stabilize mixture

COCKTAIL LOADED AT 0.5% NATURAL TELLURIUM →

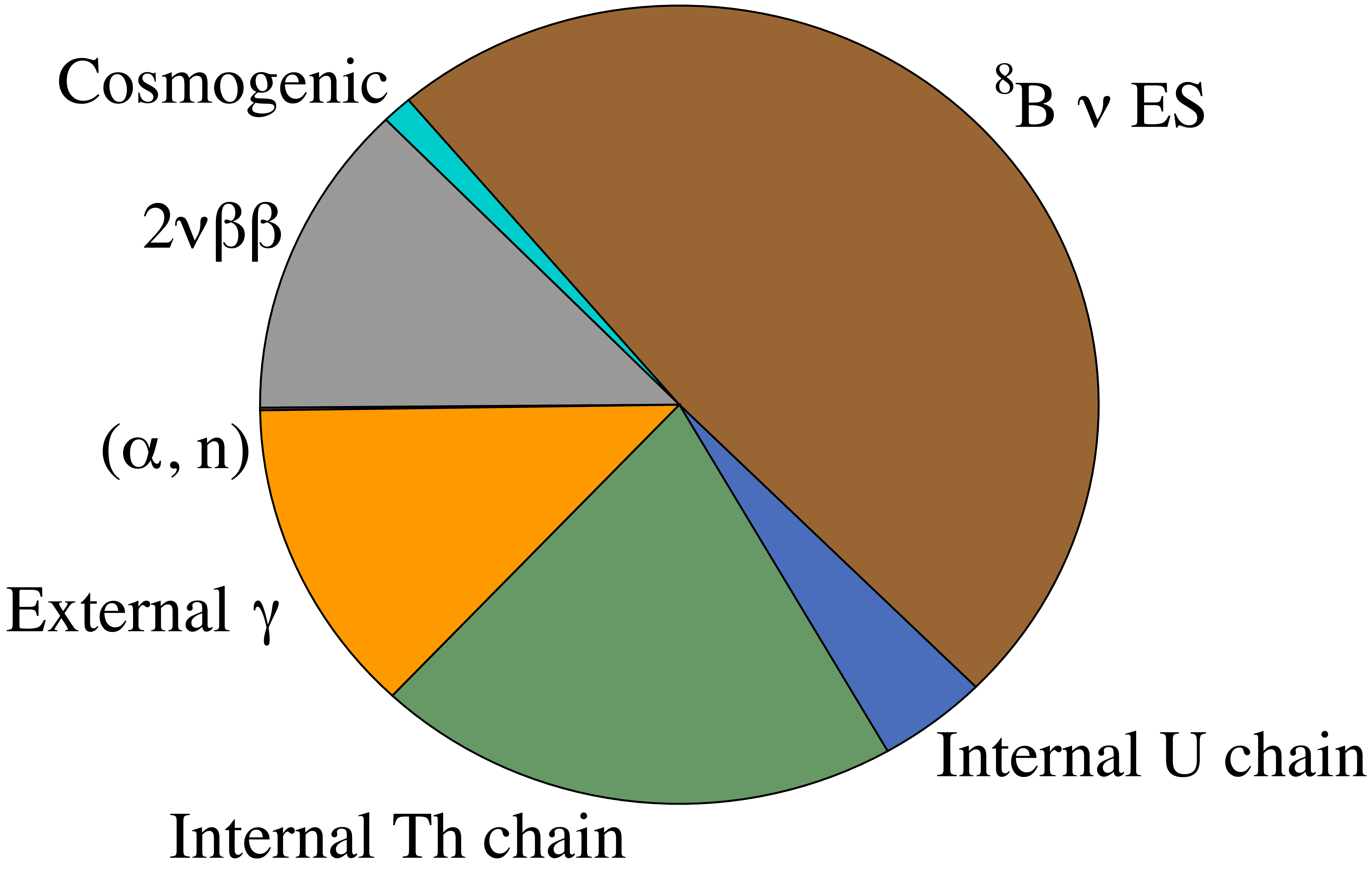
~400 PE/MeV → ~3% ENERGY RESOLUTION @2MeV



EXPECTED BACKGROUND

ASSUMING:
~10^{-15}g/g OF U
~10^{-16}g/g OF Th

Fiducial volume = 3.3m radius
ROI: 2.42 - 2.56 MeV [-0.5σ - 1.5σ]
Counts/Year: 9.47



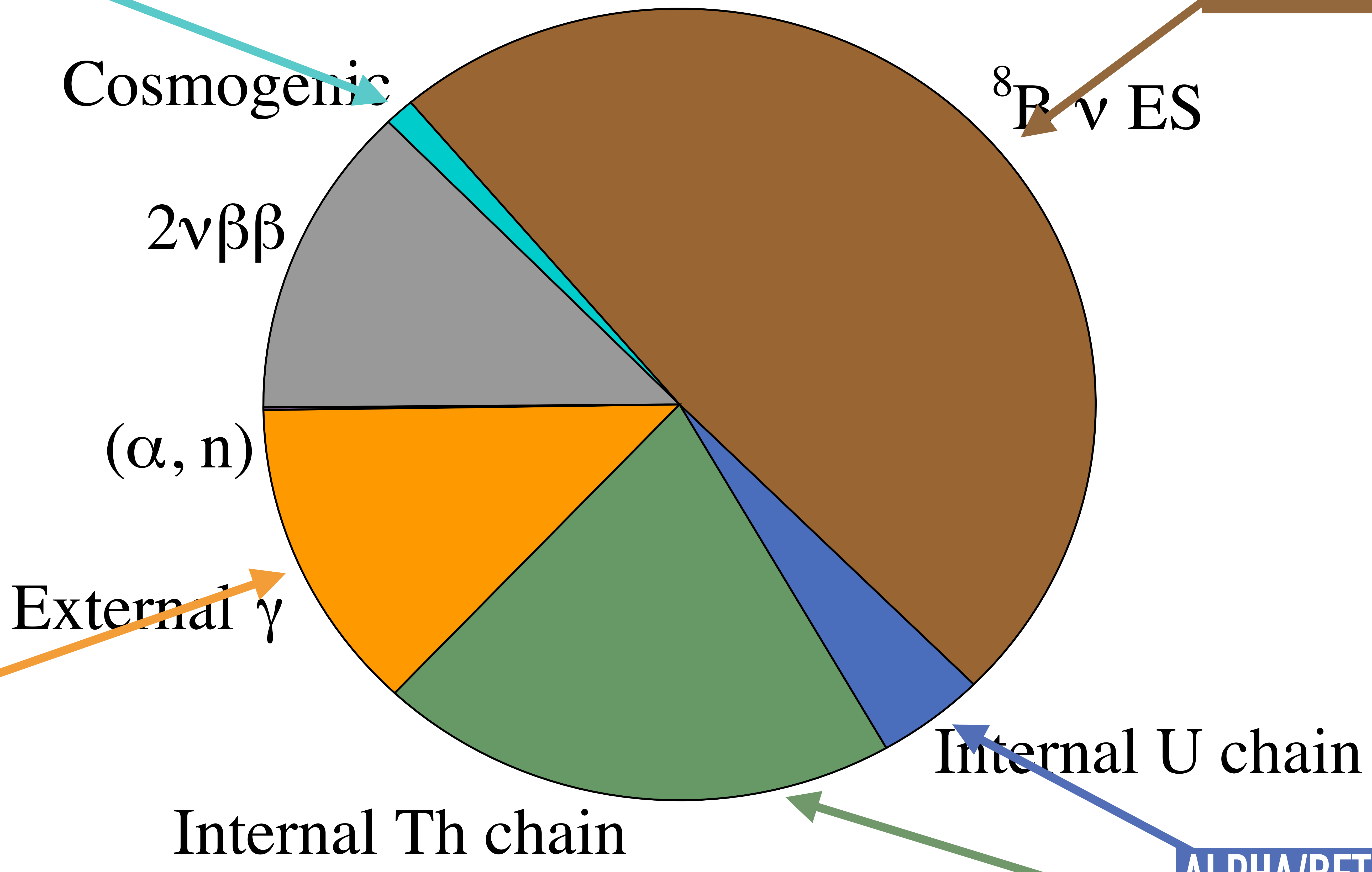
BACKGROUND REDUCTION TECHNIQUES

ASSUMING:
$\sim 10^{-15}$g/g OF U
$\sim 10^{-16}$g/g OF Th

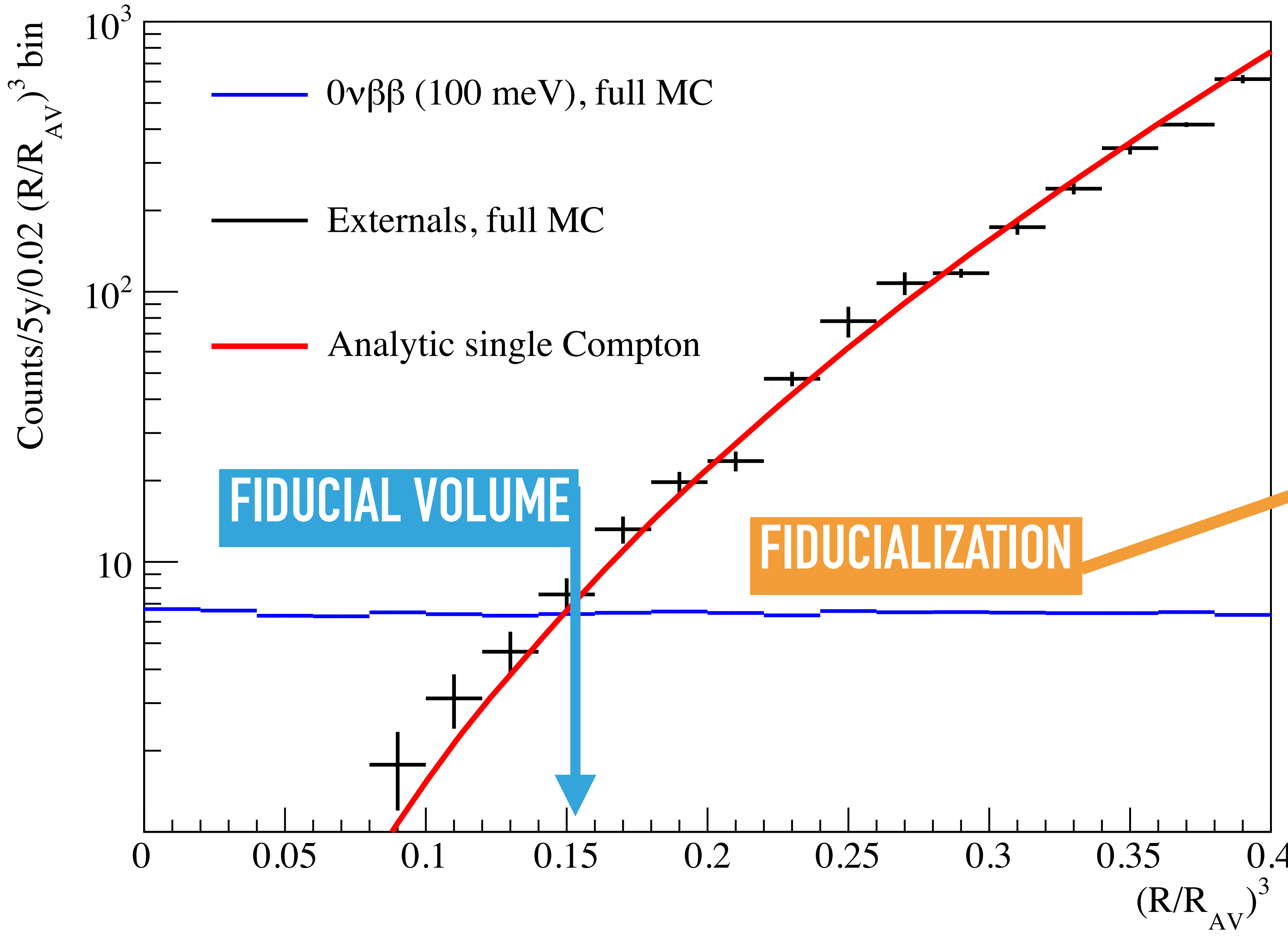
Fiducial volume = 3.3m radius
ROI: 2.42 - 2.56 MeV $[-0.5\sigma - 1.5\sigma]$
Counts/Year: 9.47

REDUCED BY SNOLAB DEPTH (~3 MUON/HOUR) AND TE UNDERGROUND STORAGE ('COOL-DOWN')

EXPLORING DIRECTIONALITY IN SCINTILLATOR



Radial distribution of external backgrounds vs 0νββ



FIDUCIAL VOLUME

FIDUCIALIZATION

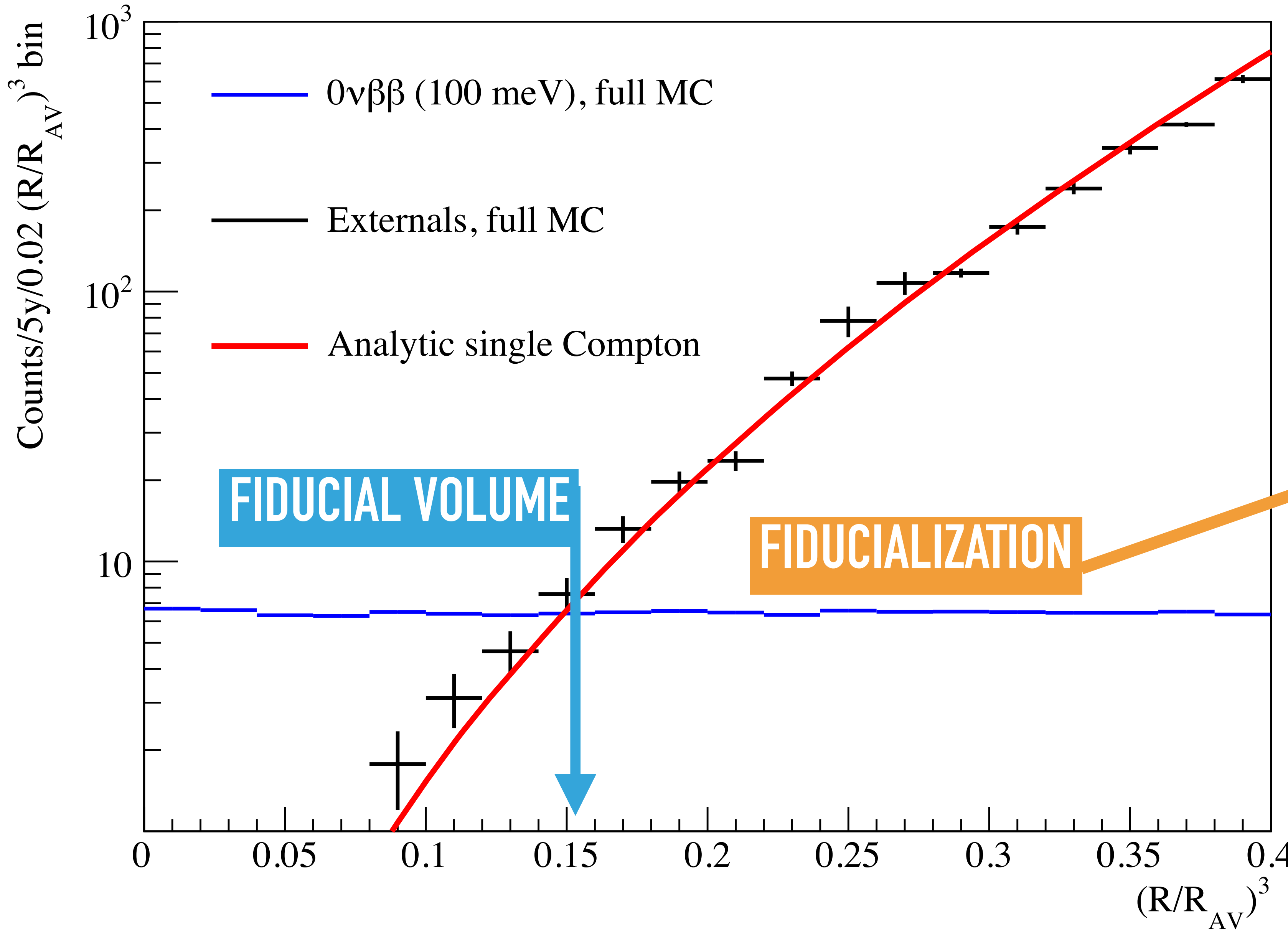
ALPHA/BETA SEPARATION
BIPO TAGGING

BACKGROUND REDUCTION TECHNIQUES

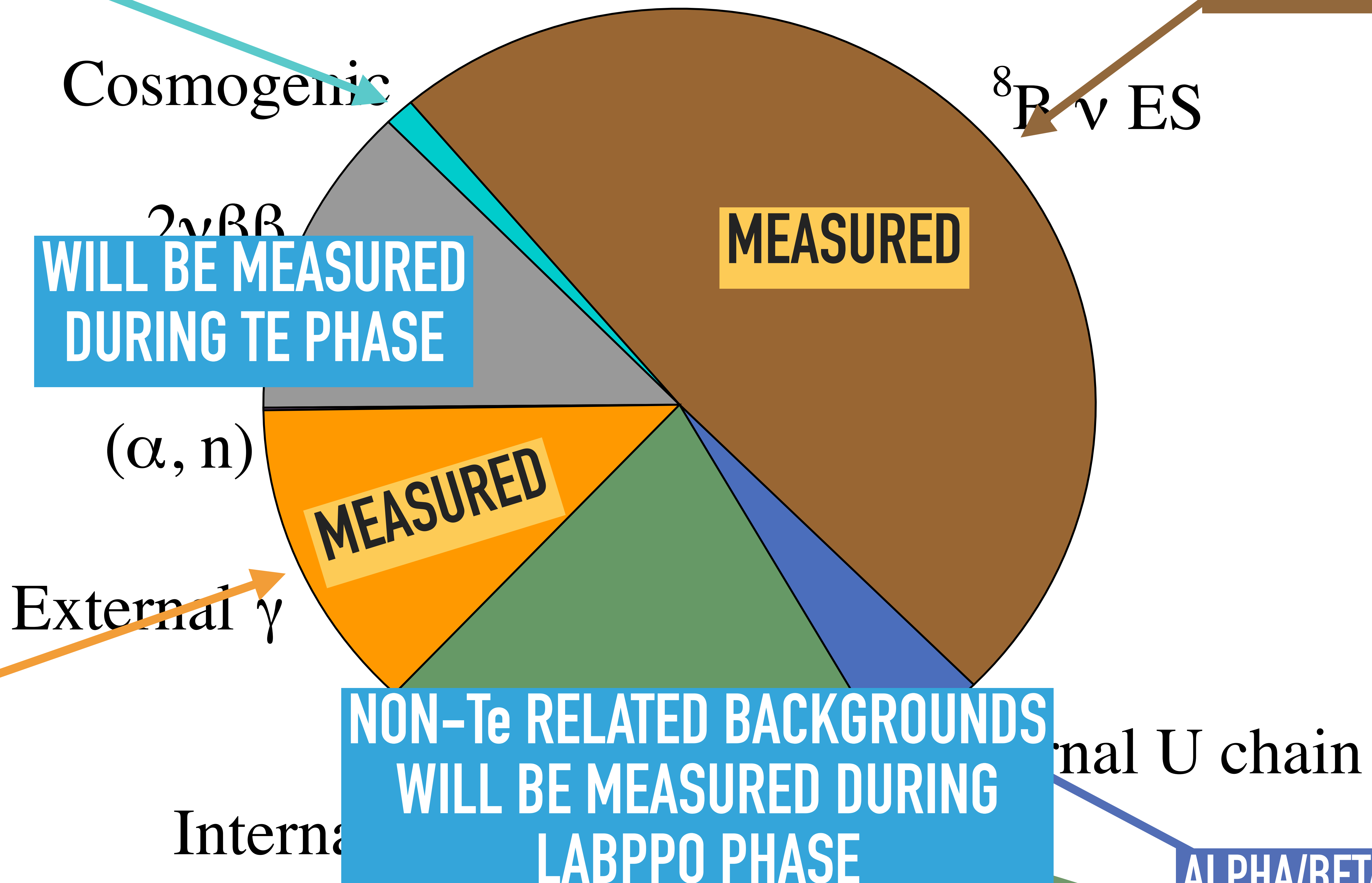
ASSUMING:
~10^{-15}g/g OF U
~10^{-16}g/g OF Th

Fiducial volume = 3.3m radius
ROI: 2.42 - 2.56 MeV [-0.5σ - 1.5σ]
Counts/Year: 9.47

Radial distribution of external backgrounds vs 0νββ



FIDUCIALIZATION



REDUCED BY SNOLAB DEPTH (~3 MUON/HOUR) AND TE UNDERGROUND STORAGE ('COOL-DOWN')

EXPLORING DIRECTIONALITY IN SCINTILLATOR

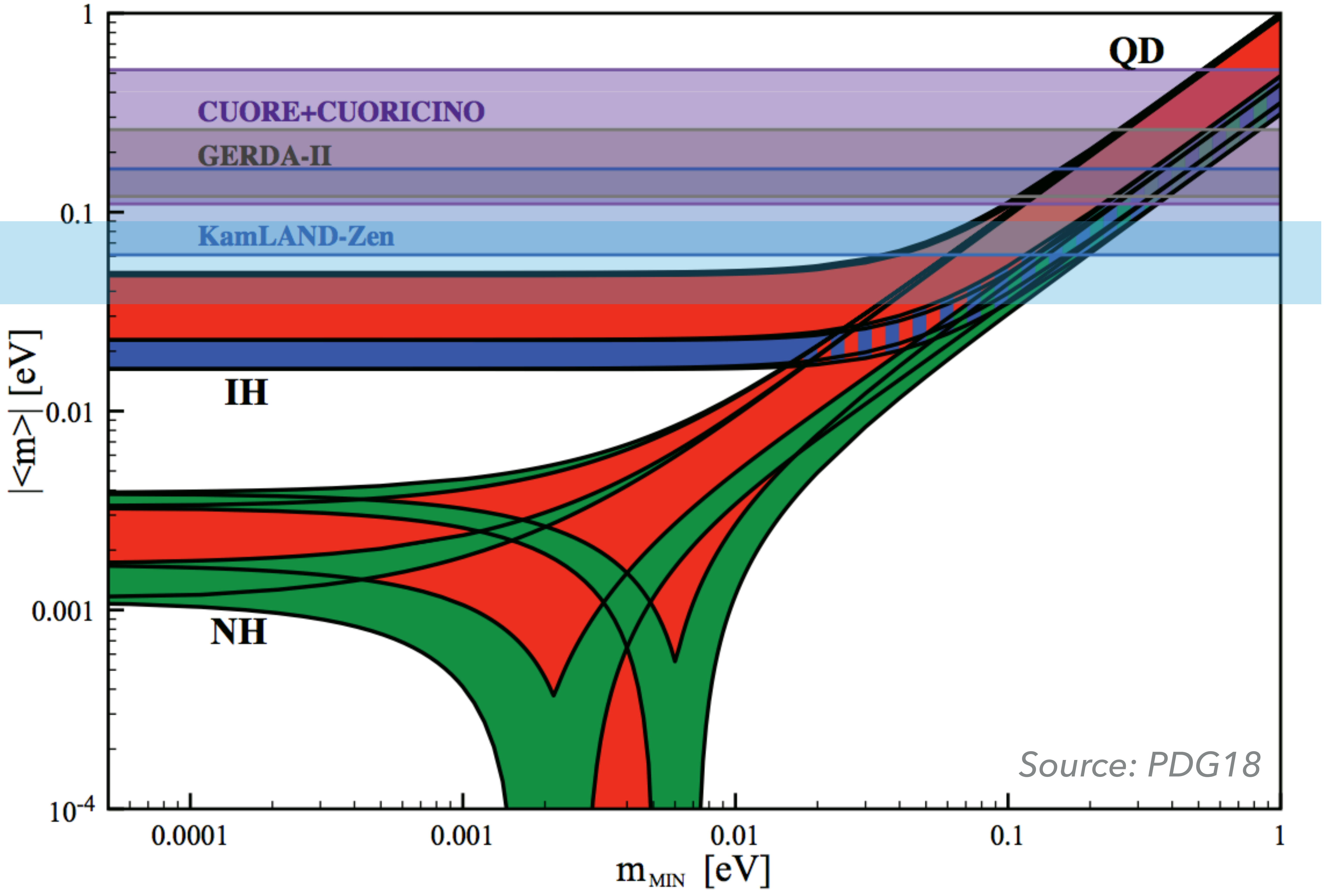
WILL BE MEASURED DURING TE PHASE

NON-Te RELATED BACKGROUNDS WILL BE MEASURED DURING LABPPO PHASE

ALPHA/BETA SEPARATION
BIPO TAGGING

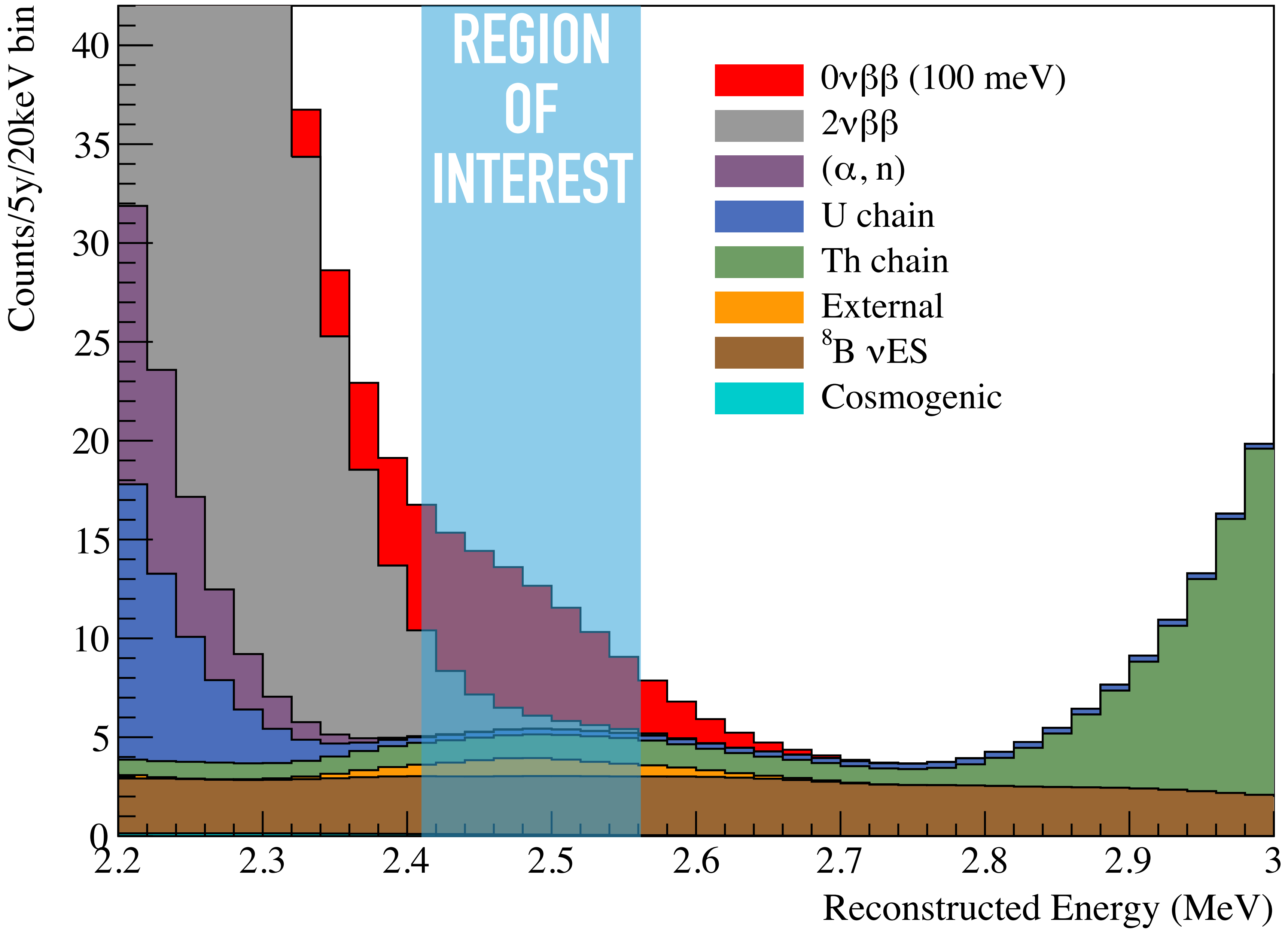
SENSITIVITY

SNO+ 5 YEARS:
$T_{1/2} > 2.1 \times 10^{26}$ YEARS
37meV < $m_{\beta\beta}$ < 89meV



Source: PDG18

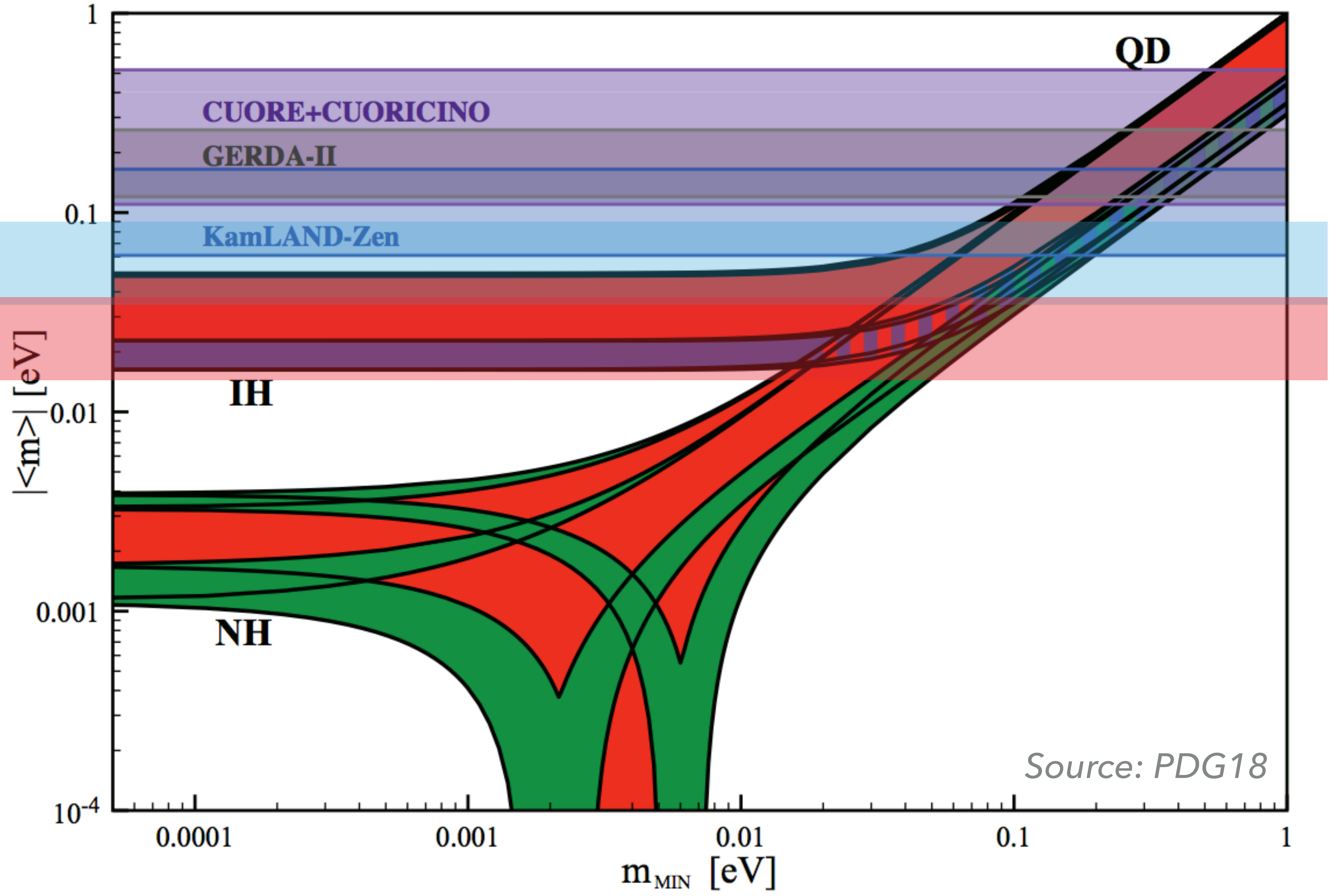
Expected energy distribution with nominal backgrounds



SENSITIVITY

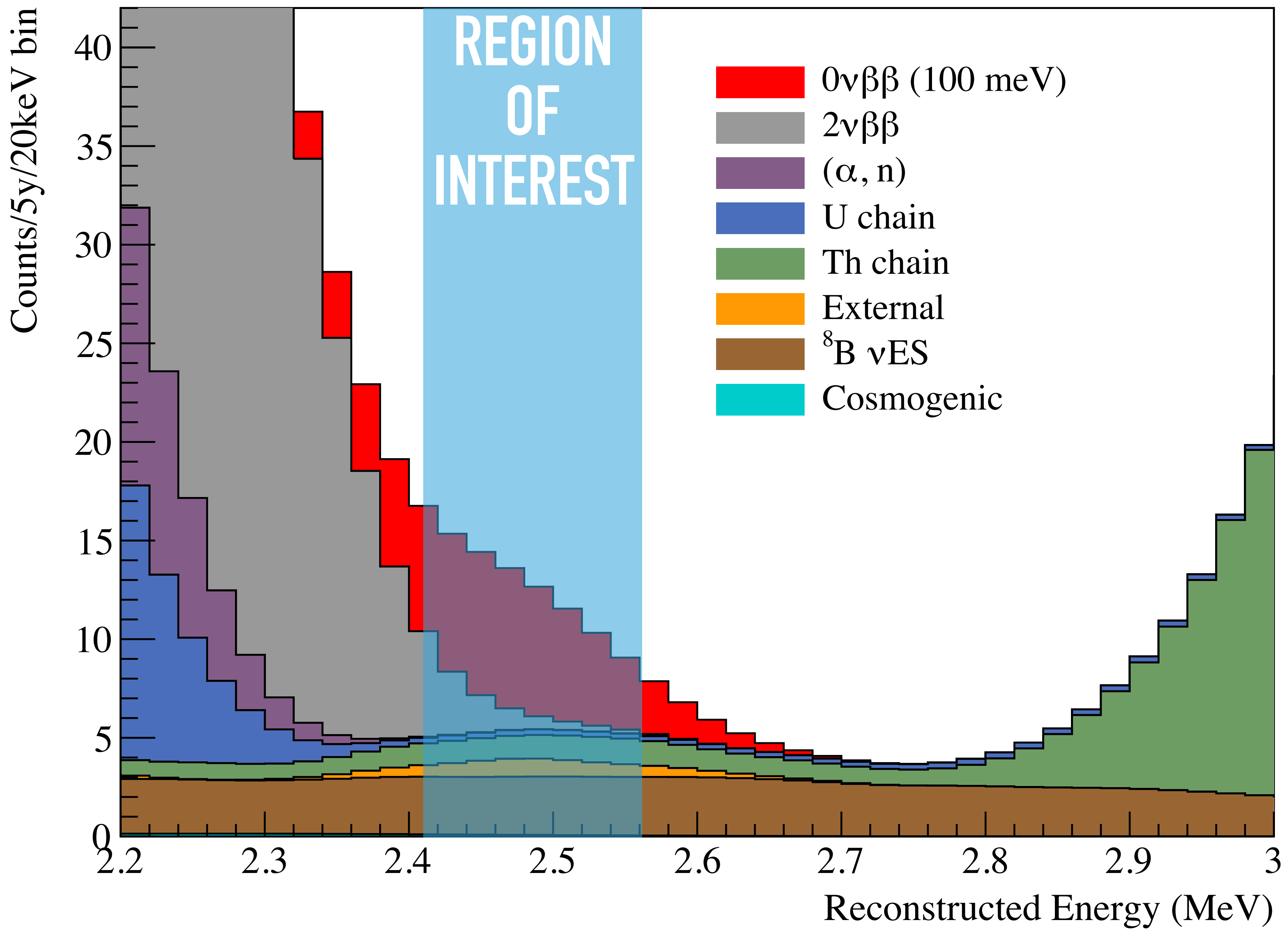
SNO+ 5 YEARS:
$T_{1/2} > 2.1 \times 10^{26}$ YEARS
37meV < $m_{\beta\beta}$ < 89meV

SNO+ PHASE II:
1) 4% TE
2) INCREASED LIGHT YIELD



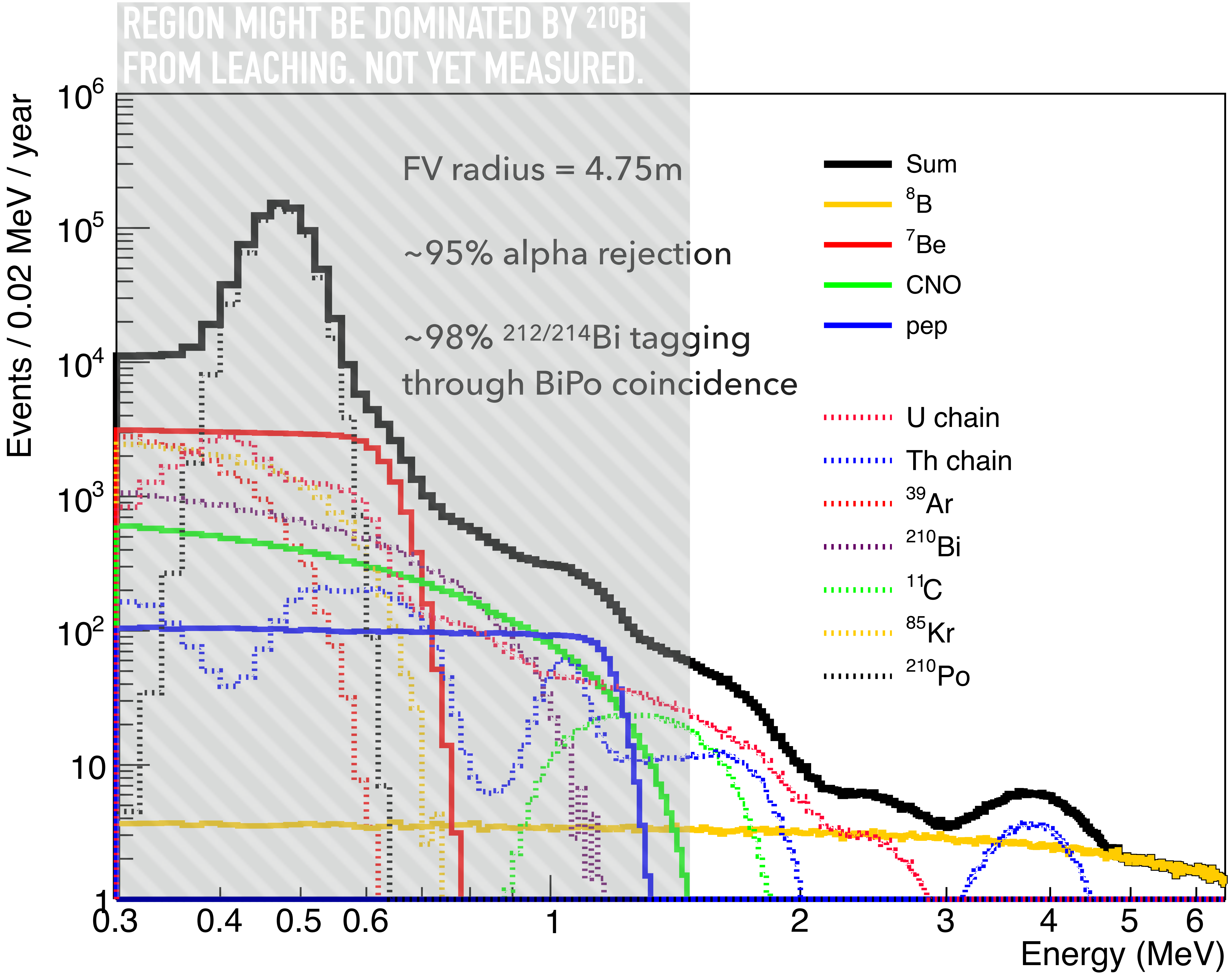
Source: PDG18

Expected energy distribution with nominal backgrounds



SOLAR NEUTRINOS IN LABPPO

SNO+ HAS POTENTIAL FOR PRECISE SOLAR NEUTRINO MEASUREMENTS



REGION MIGHT BE DOMINATED BY ^{210}Bi FROM LEACHING. NOT YET MEASURED.

FV radius = 4.75m

~95% alpha rejection

~98% $^{212/214}$Bi tagging through BiPo coincidence

- Solar neutrino experiment with lowest levels of ^{11}C
- Favorable scenario for precise PEP measurement and first CNO measurement
- Sensitivity highly depends on ^{210}Bi background level

DETECTOR STATUS

- Nitrogen cover gas installed → Currently registering the lowest external backgrounds since we started
- Scintillator plant commissioning finished → Filling vessel with scintillator and starting assessing internal background levels. Schedule delayed due to leaks search and repairs in scintillator plant.
- Tellurium purification plant commissioning ongoing → Done by beginning of 2020.

TELLURIUM STORED UNDERGROUND → COSMOGENICS 'COOL DOWN'

SUMMARY

- **SNO+ completed its water phase:**
  - Two physics analyses completed: invisible nucleon decay and solar neutrinos
  - Measured external backgrounds
  - More analyses to come: neutron production, anti-ν, etc.
- **SNO+ started pure scintillator phase:**
  - Low energy solar neutrino physics
  - Reactor and geo-neutrino physics
- **SNO+ will start deploying Te by 2020 to search for $0\nu\beta\beta$**

🇺🇸

- U. Pennsylvania
- U. Chicago
- U. C. Berkeley/LBNL
- U. Boston
- U. C. Davis
- BNL

🇨🇦

- U. Alberta
- Queen's University
- Laurentian University
- TRIUMF
- SNOLAB

🇵🇹

- LIP Lisboa
- LIP Coimbra

🇲🇽

Universidad Nacional
Autonoma de Mexico

🇩🇪

Technical University
Dresden

🇬🇧

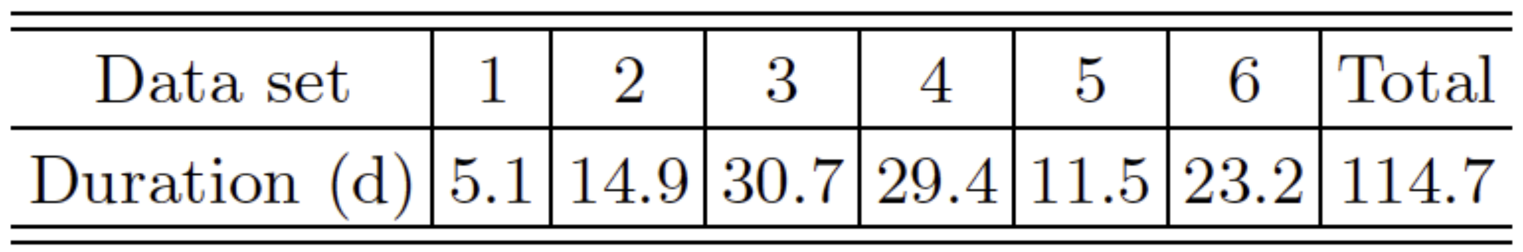
- Oxford University
- University of Sussex
- Liverpool University
- Lancaster University
- Queen Mary University of London
- Kings College London

August 10, 2019

SNO+

BACKUP

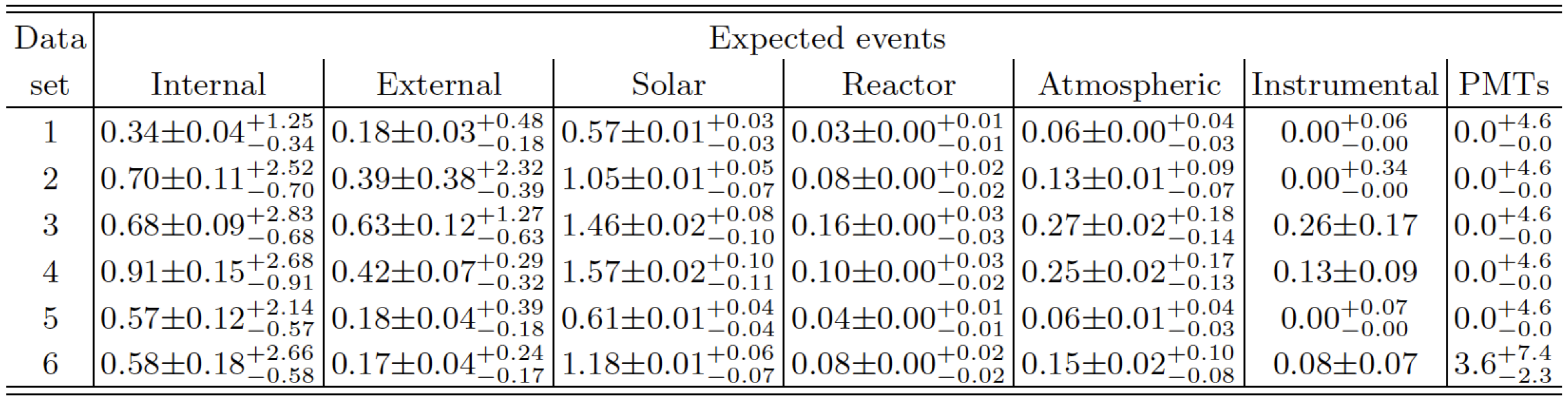
NUCLEON DECAY ANALYSIS DETAILS



Data set	1	2	3	4	5	6	Total
Duration (d)	5.1	14.9	30.7	29.4	11.5	23.2	114.7

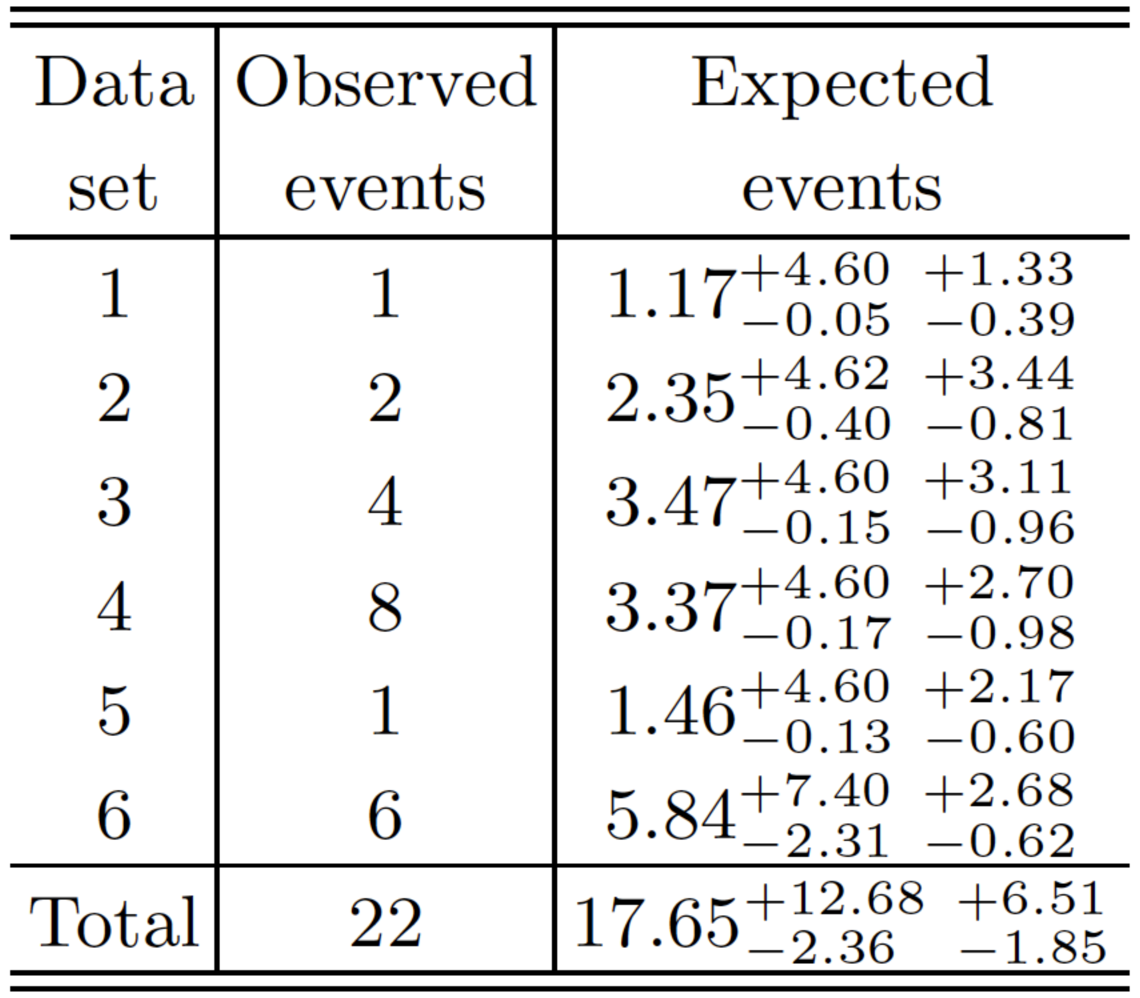
TABLE I. Live time within each data set, in days.

Background budget in water phase



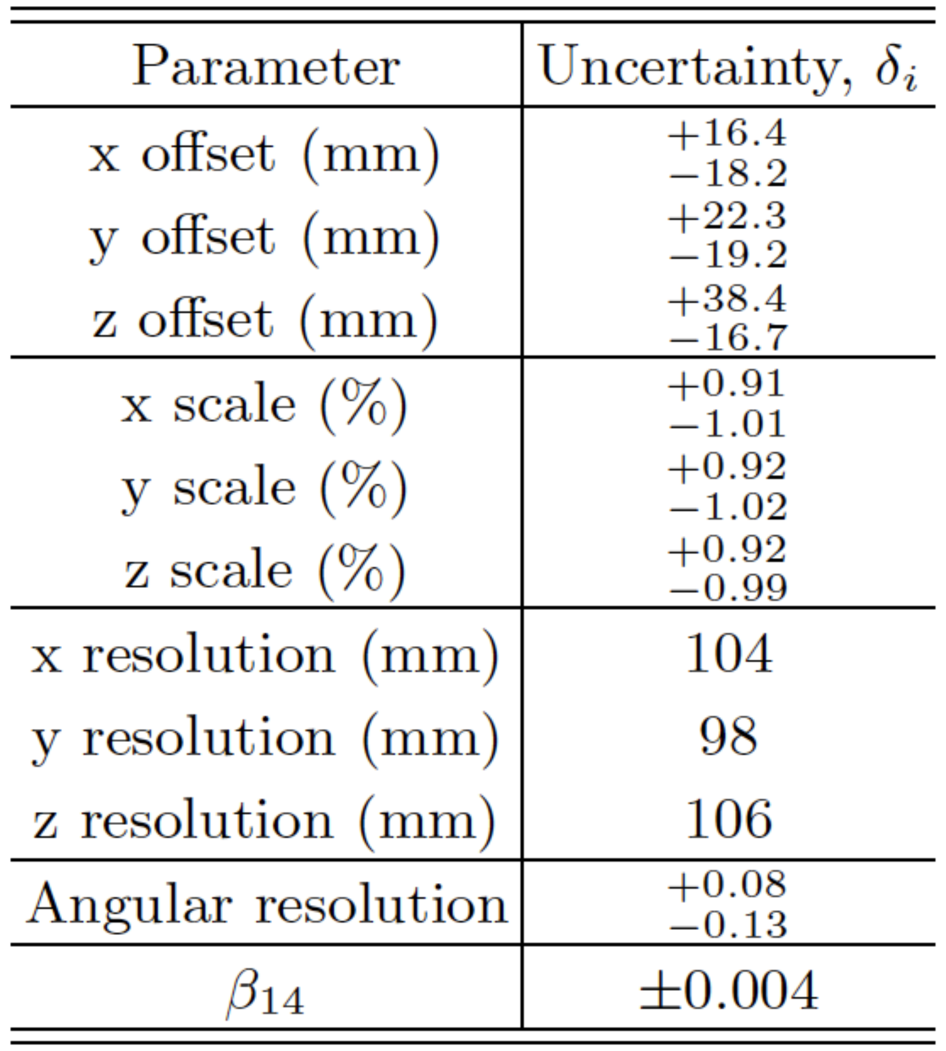
Data set	Expected events						
	Internal	External	Solar	Reactor	Atmospheric	Instrumental	PMTs
1	$0.34\pm0.04^{+1.25}_{-0.34}$	$0.18\pm0.03^{+0.48}_{-0.18}$	$0.57\pm0.01^{+0.03}_{-0.03}$	$0.03\pm0.00^{+0.01}_{-0.01}$	$0.06\pm0.00^{+0.04}_{-0.03}$	$0.00^{+0.06}_{-0.00}$	$0.0^{+4.6}_{-0.0}$
2	$0.70\pm0.11^{+2.52}_{-0.70}$	$0.39\pm0.38^{+2.32}_{-0.39}$	$1.05\pm0.01^{+0.05}_{-0.07}$	$0.08\pm0.00^{+0.02}_{-0.02}$	$0.13\pm0.01^{+0.09}_{-0.07}$	$0.00^{+0.34}_{-0.00}$	$0.0^{+4.6}_{-0.0}$
3	$0.68\pm0.09^{+2.83}_{-0.68}$	$0.63\pm0.12^{+1.27}_{-0.63}$	$1.46\pm0.02^{+0.08}_{-0.10}$	$0.16\pm0.00^{+0.03}_{-0.03}$	$0.27\pm0.02^{+0.18}_{-0.14}$	0.26 ± 0.17	$0.0^{+4.6}_{-0.0}$
4	$0.91\pm0.15^{+2.68}_{-0.91}$	$0.42\pm0.07^{+0.29}_{-0.32}$	$1.57\pm0.02^{+0.10}_{-0.11}$	$0.10\pm0.00^{+0.03}_{-0.02}$	$0.25\pm0.02^{+0.17}_{-0.13}$	0.13 ± 0.09	$0.0^{+4.6}_{-0.0}$
5	$0.57\pm0.12^{+2.14}_{-0.57}$	$0.18\pm0.04^{+0.39}_{-0.18}$	$0.61\pm0.01^{+0.04}_{-0.04}$	$0.04\pm0.00^{+0.01}_{-0.01}$	$0.06\pm0.01^{+0.04}_{-0.03}$	$0.00^{+0.07}_{-0.00}$	$0.0^{+4.6}_{-0.0}$
6	$0.58\pm0.18^{+2.66}_{-0.58}$	$0.17\pm0.04^{+0.24}_{-0.17}$	$1.18\pm0.01^{+0.06}_{-0.07}$	$0.08\pm0.00^{+0.02}_{-0.02}$	$0.15\pm0.02^{+0.10}_{-0.08}$	0.08 ± 0.07	$3.6^{+7.4}_{-2.3}$

Number of selected events

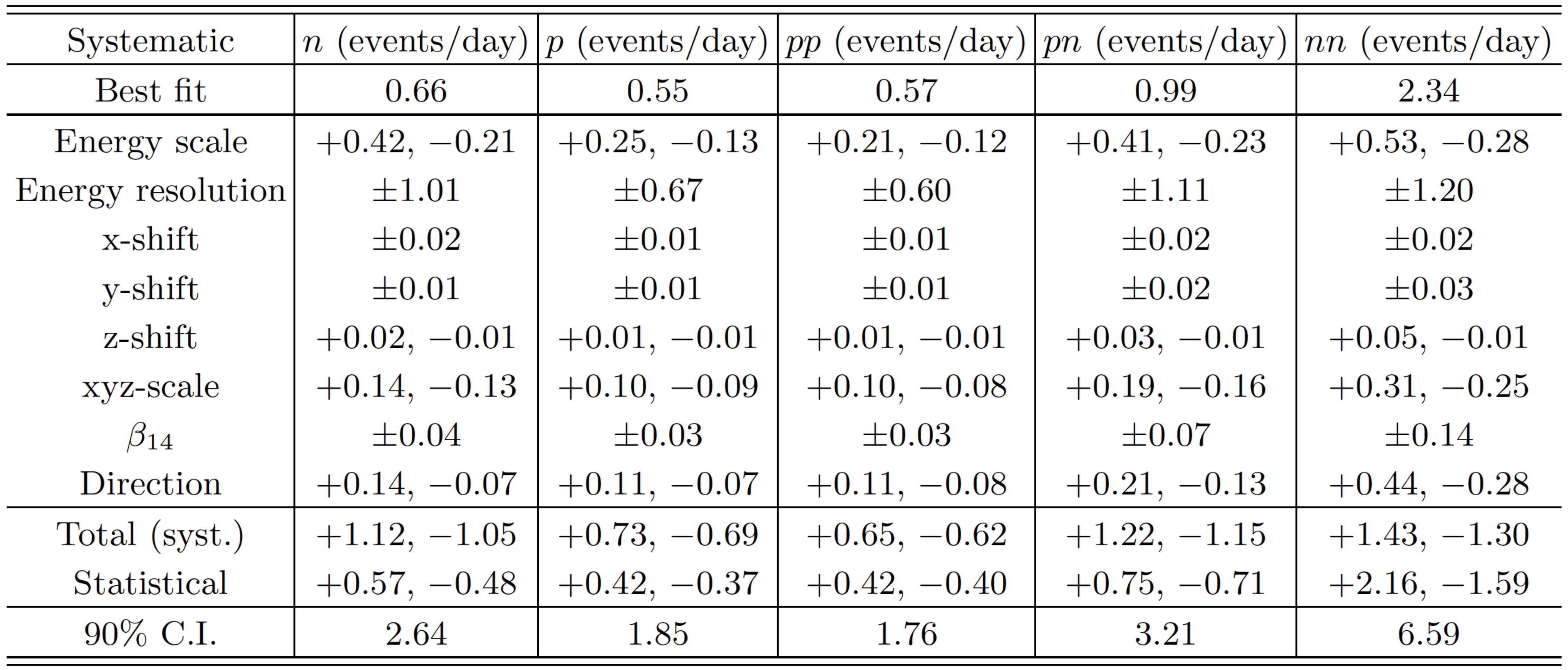


Data set	Observed events	Expected events
1	1	$1.17^{+4.60}_{-0.05}\ {}^{+1.33}_{-0.39}$
2	2	$2.35^{+4.62}_{-0.40}\ {}^{+3.44}_{-0.81}$
3	4	$3.47^{+4.60}_{-0.15}\ {}^{+3.11}_{-0.96}$
4	8	$3.37^{+4.60}_{-0.17}\ {}^{+2.70}_{-0.98}$
5	1	$1.46^{+4.60}_{-0.13}\ {}^{+2.17}_{-0.60}$
6	6	$5.84^{+7.40}_{-2.31}\ {}^{+2.68}_{-0.62}$
Total	22	$17.65^{+12.68}_{-2.36}\ {}^{+6.51}_{-1.85}$

Breakdown of impact of systematics uncertainties



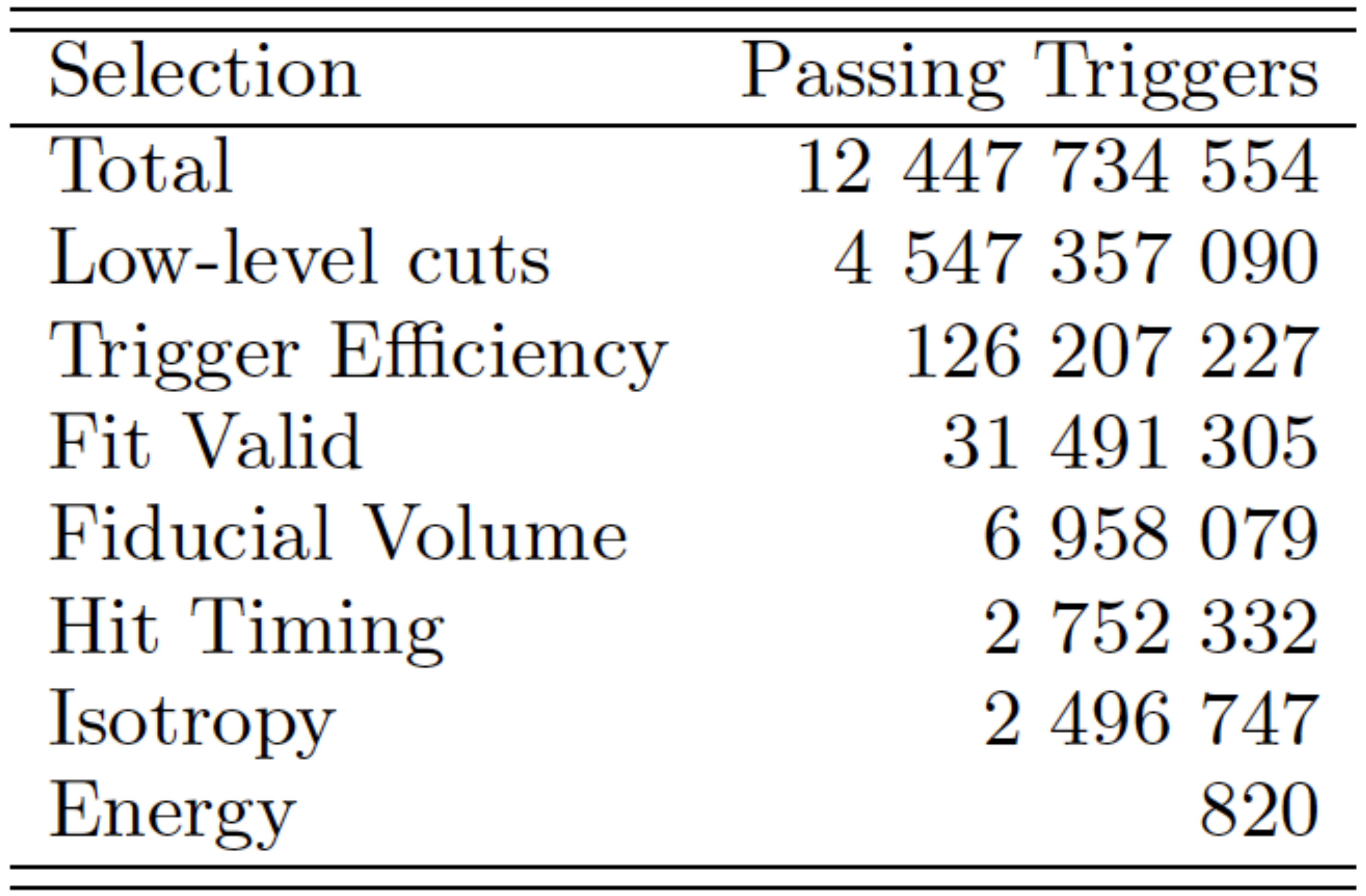
Parameter	Uncertainty, δ_i
x offset (mm)	${}^{+16.4}_{-18.2}$
y offset (mm)	${}^{+22.3}_{-19.2}$
z offset (mm)	${}^{+38.4}_{-16.7}$
x scale (%)	${}^{+0.91}_{-1.01}$
y scale (%)	${}^{+0.92}_{-1.02}$
z scale (%)	${}^{+0.92}_{-0.99}$
x resolution (mm)	104
y resolution (mm)	98
z resolution (mm)	106
Angular resolution	${}^{+0.08}_{-0.13}$
β_{14}	±0.004



Systematic	n (events/day)	p (events/day)	pp (events/day)	pn (events/day)	nn (events/day)
Best fit	0.66	0.55	0.57	0.99	2.34
Energy scale	+0.42, −0.21	+0.25, −0.13	+0.21, −0.12	+0.41, −0.23	+0.53, −0.28
Energy resolution	±1.01	±0.67	±0.60	±1.11	±1.20
x-shift	±0.02	±0.01	±0.01	±0.02	±0.02
y-shift	±0.01	±0.01	±0.01	±0.02	±0.03
z-shift	+0.02, −0.01	+0.01, −0.01	+0.01, −0.01	+0.03, −0.01	+0.05, −0.01
xyz-scale	+0.14, −0.13	+0.10, −0.09	+0.10, −0.08	+0.19, −0.16	+0.31, −0.25
β_{14}	±0.04	±0.03	±0.03	±0.07	±0.14
Direction	+0.14, −0.07	+0.11, −0.07	+0.11, −0.08	+0.21, −0.13	+0.44, −0.28
Total (syst.)	+1.12, −1.05	+0.73, −0.69	+0.65, −0.62	+1.22, −1.15	+1.43, −1.30
Statistical	+0.57, −0.48	+0.42, −0.37	+0.42, −0.40	+0.75, −0.71	+2.16, −1.59
90% C.I.	2.64	1.85	1.76	3.21	6.59

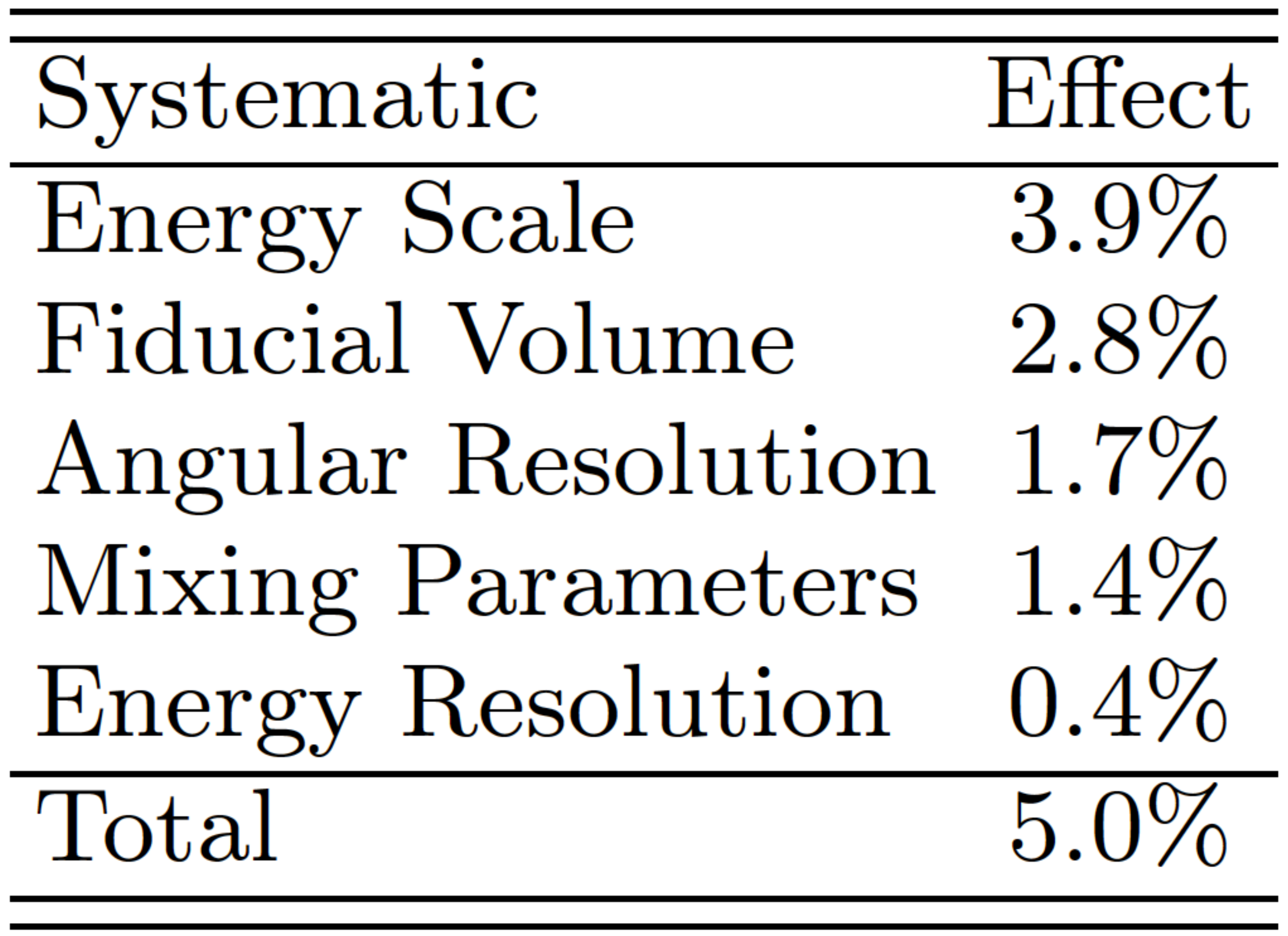
SOLAR NEUTRINO ANALYSIS DETAILS

Event selection



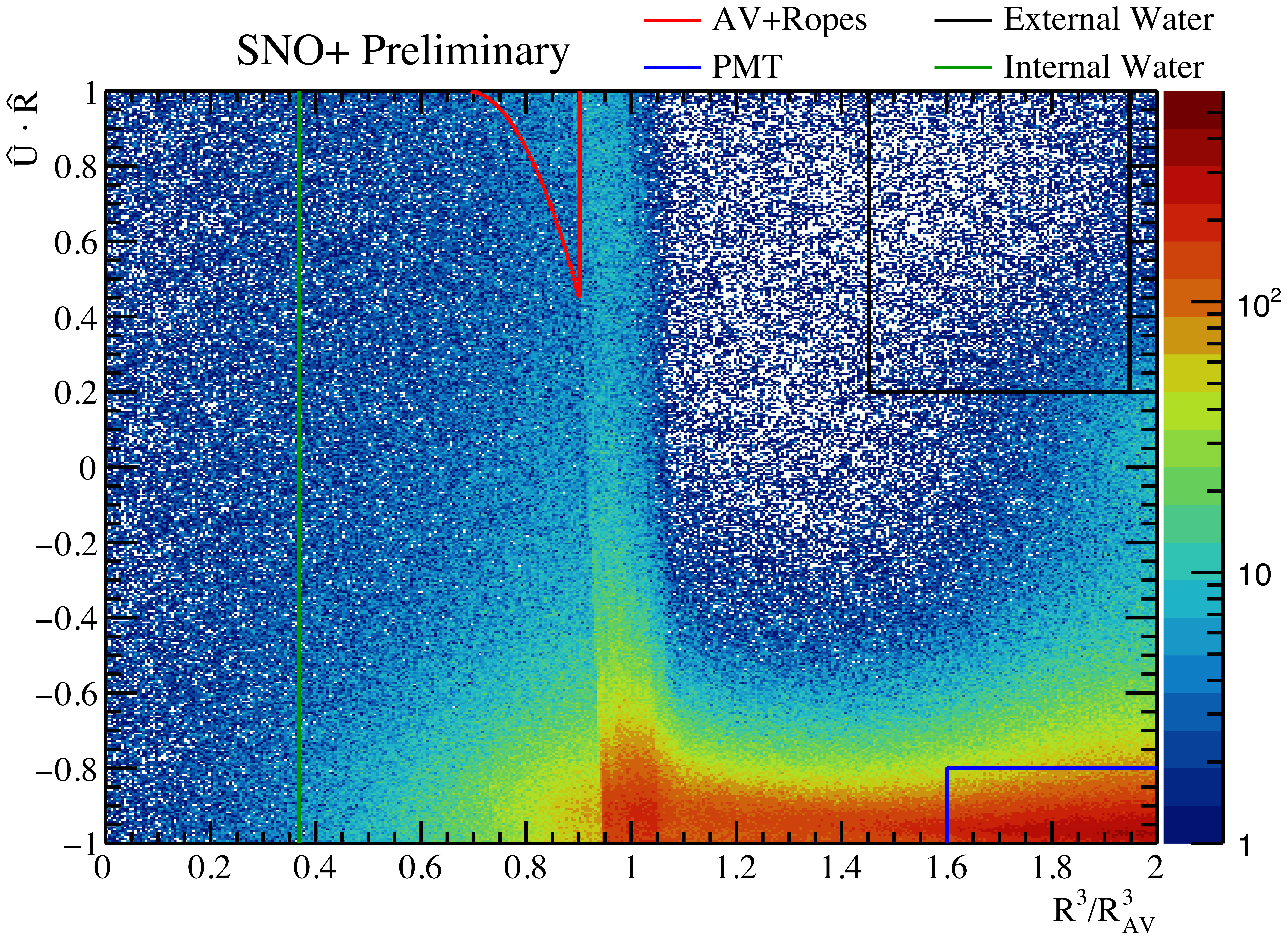
Selection	Passing Triggers
Total	12 447 734 554
Low-level cuts	4 547 357 090
Trigger Efficiency	126 207 227
Fit Valid	31 491 305
Fiducial Volume	6 958 079
Hit Timing	2 752 332
Isotropy	2 496 747
Energy	820

Systematics



Systematic	Effect
Energy Scale	3.9%
Fiducial Volume	2.8%
Angular Resolution	1.7%
Mixing Parameters	1.4%
Energy Resolution	0.4%
Total	5.0%

BACKGROUND ANALYSIS REGIONS



ANTI-NEUTRINOS DETECTION IN WATER

SNO+ IS ABLE TO DETECT NEUTRONS FROM AmBe SOURCE WITH ~47% EFFICIENCY