LIP Lisbon Thursday seminar
Lisbon, 28 November 2019

First results of the SNO+ experiment

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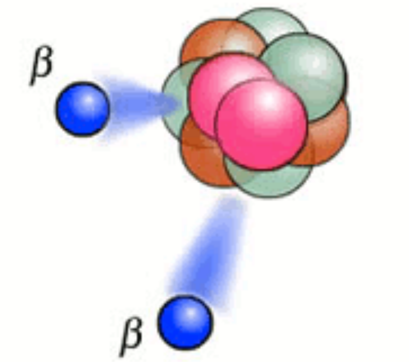
LIP Lisbon

OUTLINE

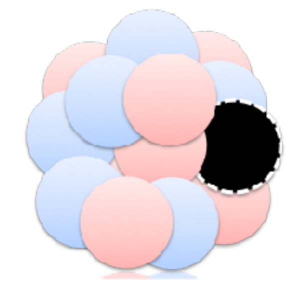
SNO+ is a multi-purpose detector



Neutrinoless double-beta decay of ^{130}Te

Geo and reactor anti-neutrinos

Solar neutrinos pep, CNO, low energy ^{8}B



Rare decays

Supernovae neutrinos

In this talk:

- The SNO+ detector
  - Structure
  - Calibration
- Results for the water phase:
  - Invisible nucleon decay
  - B8 solar neutrino flux measurement
  - External background measurements
- Prospects
  - Sensitivity for neutrinoless double-beta decay

WELCOME TO SUDBURY!

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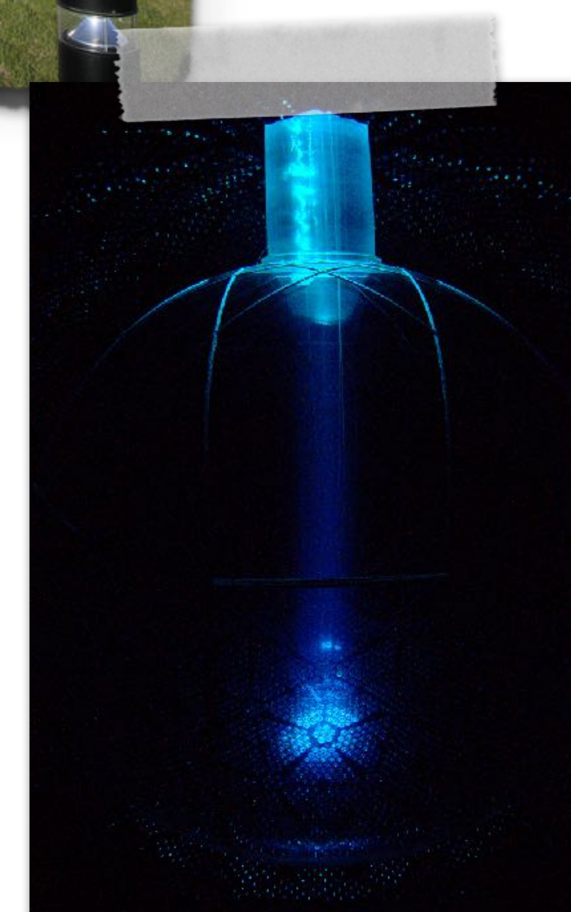
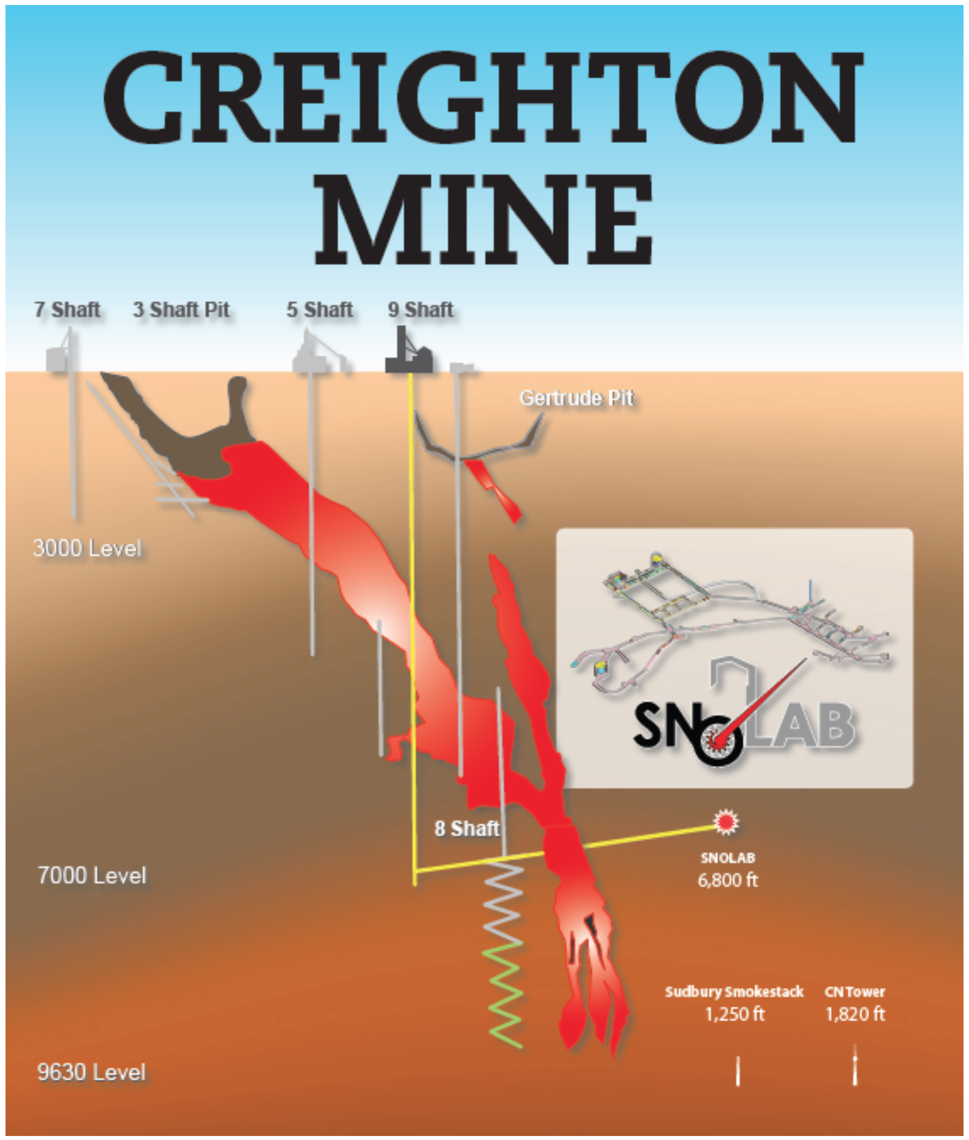
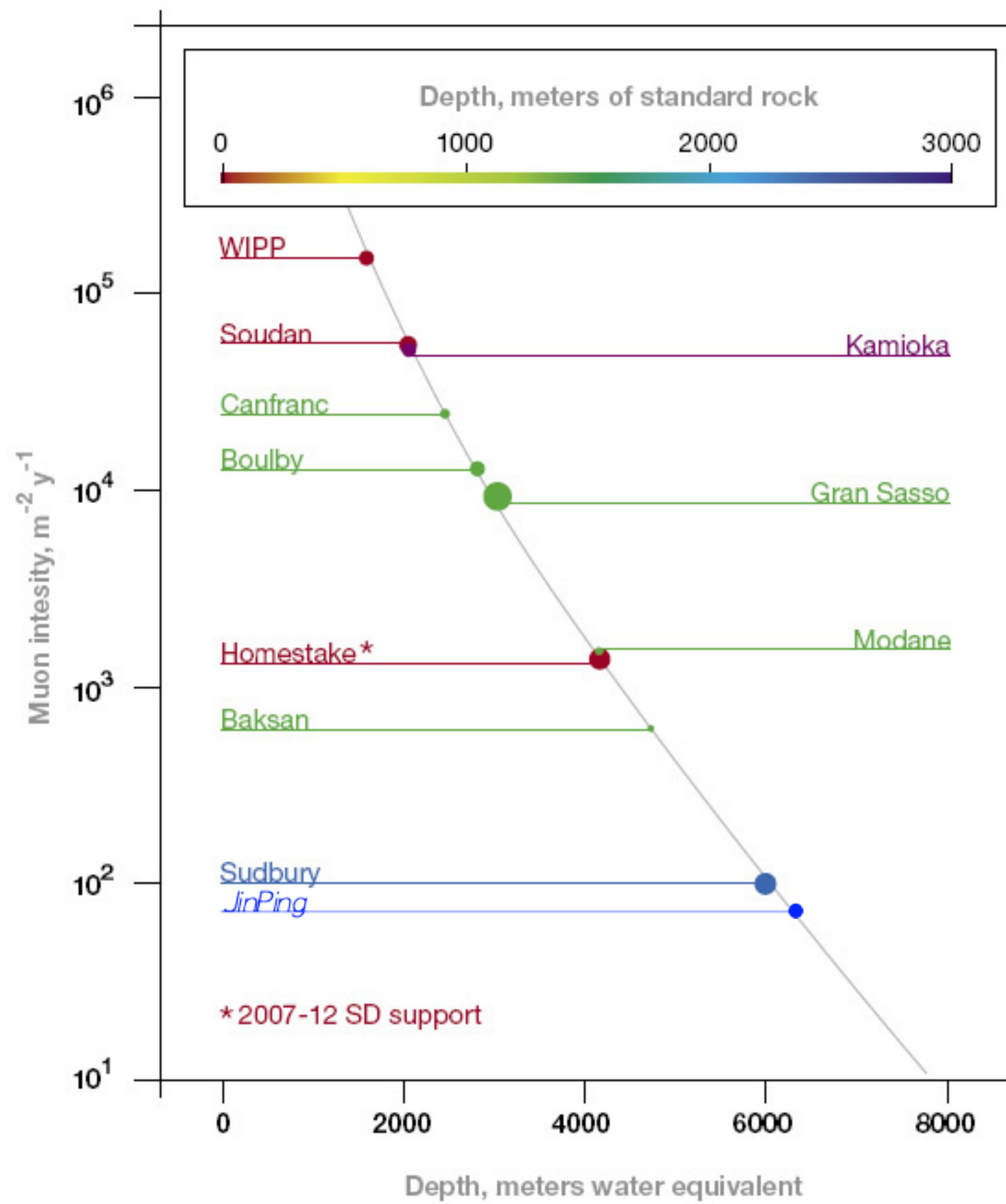


SNO+ Location



~70 Muons per day



Adapted from http://www.deepscience.org/contents/underground_universe_popup03.shtr

SNO+ DETECTOR

Main characteristics:

✳ Located 2 km underground at SNOLAB, Sudbury (Canada)

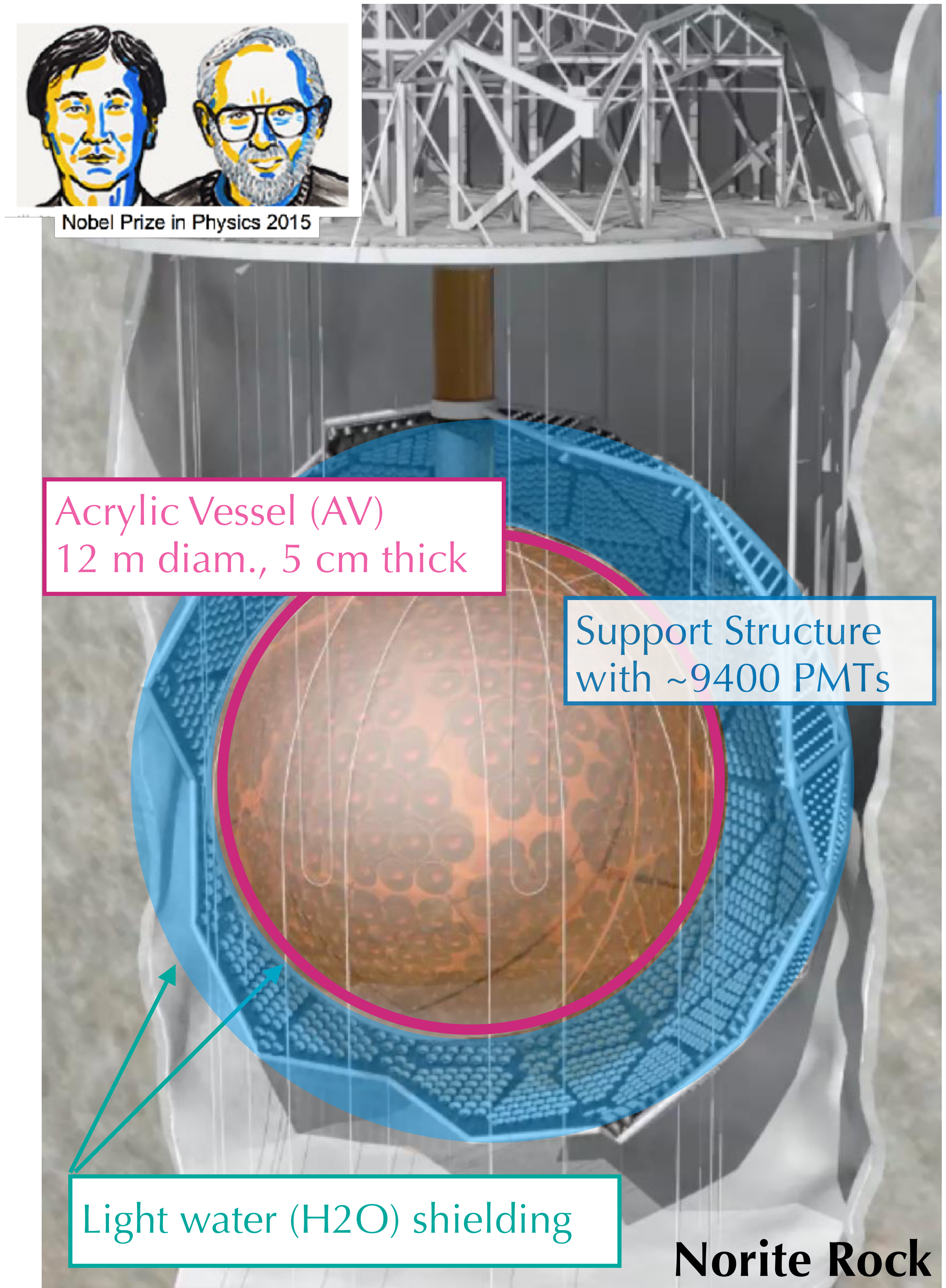
- Muon flux is reduced to ~3 μ/hr, low cosmogenic radiation

✳ Suspended in a cavern of 30.5 m height, full of ultra-pure water

- Shield against the radioactivity in the rock

✳ The 6 m radius acrylic vessel is kept in place by a high-purity hold-up and hold-down ropes system

✳ 9300 PMTs, placed on a 8 m support structure, provide 54% coverage of the detector area.

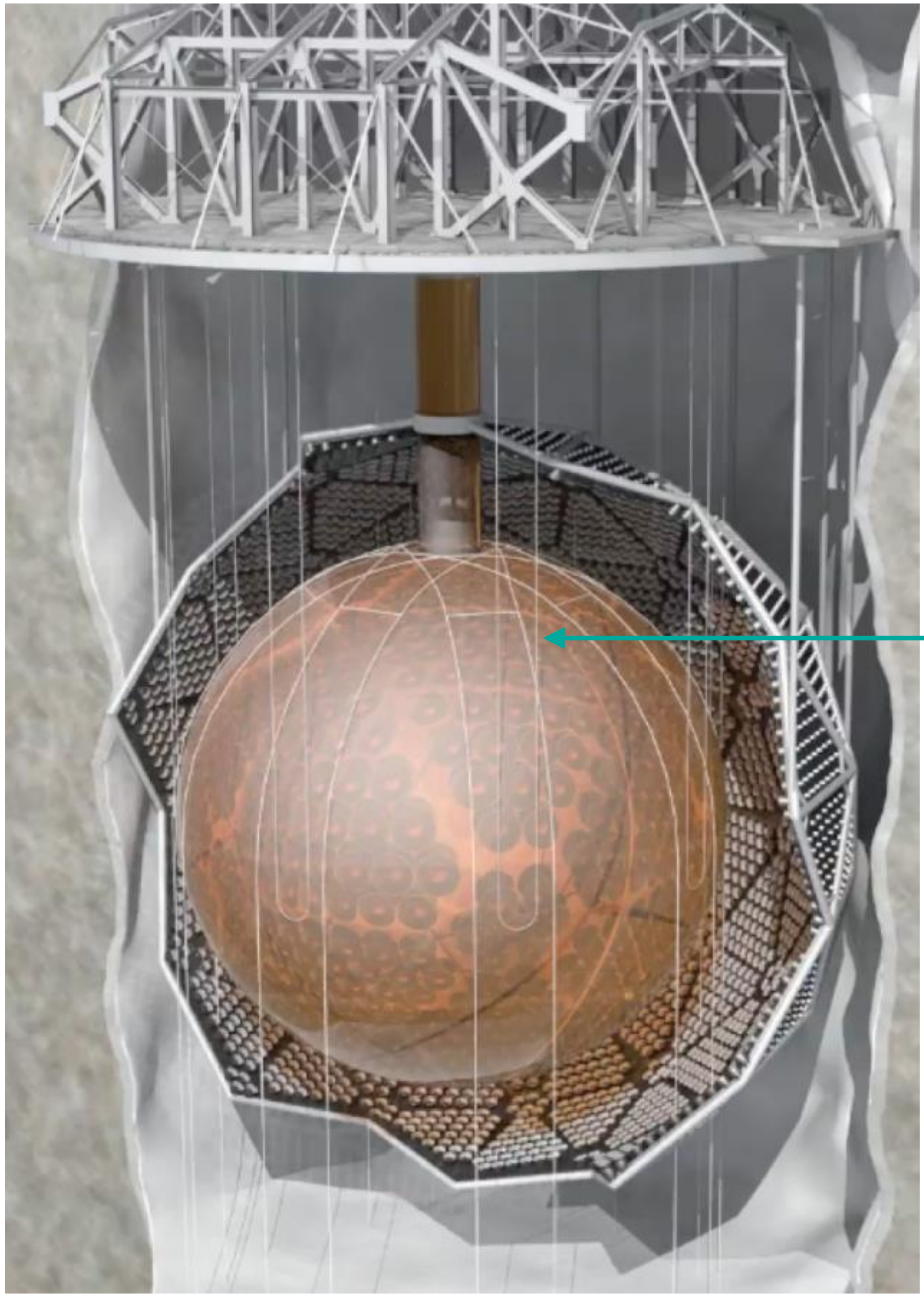


From SNO to SNO+

Upgraded DAQ

Upgraded Electronics

New Calibration system



Cover gas system
Limit Rn ingress

New hold-down ropes system
LS lighter than water

Repaired PMTs

Timeline

2016 2017 2018 2019

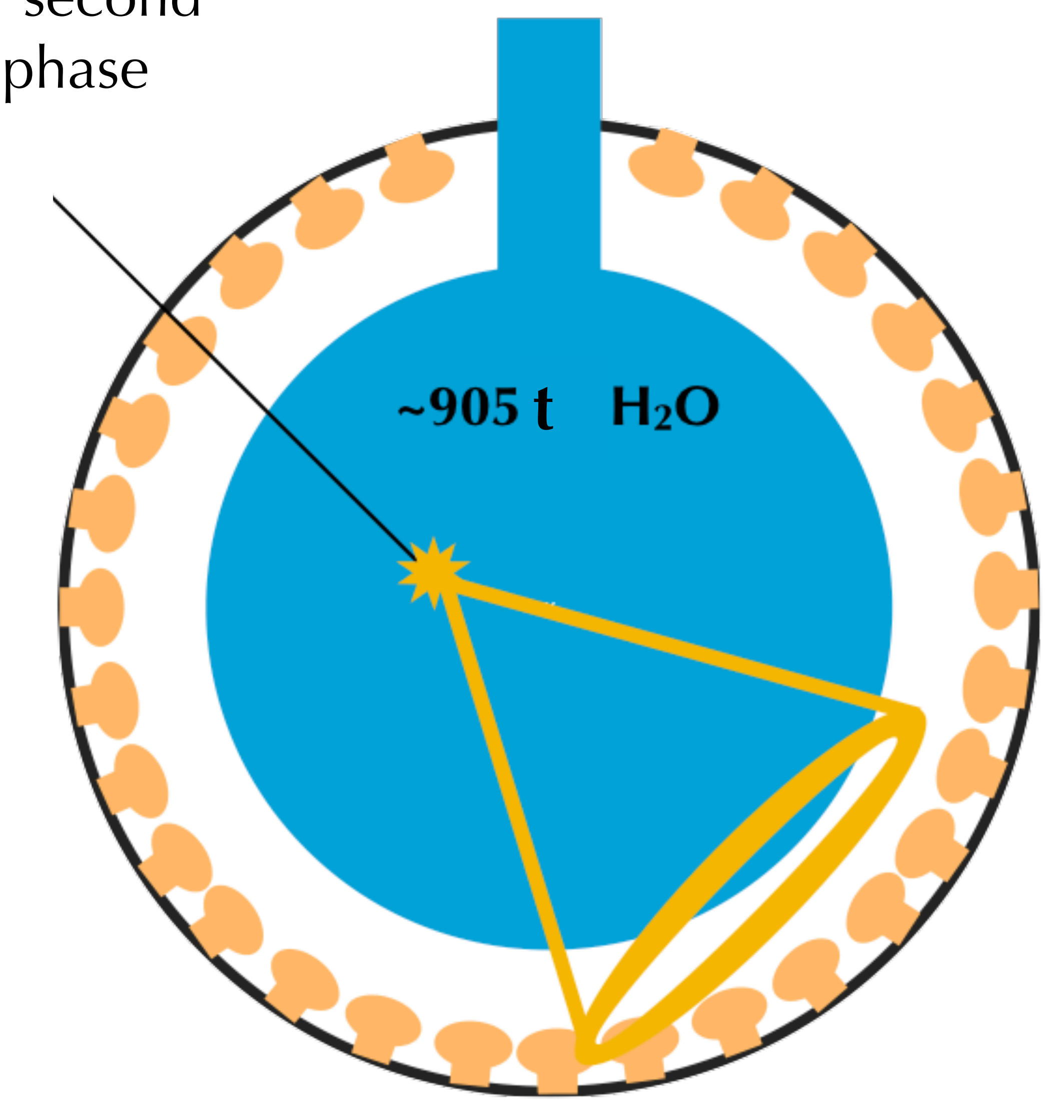
Dec.
Detector commissioning

May
Start of official data taking in water

Dec.
End of first water phase:

- Solar ^{8}B-ν flux
- Nucleon decay to invisible modes

July
End of second water phase



Timeline

2016 — 2017 — 2018 — 2019 — 2020 — 2021

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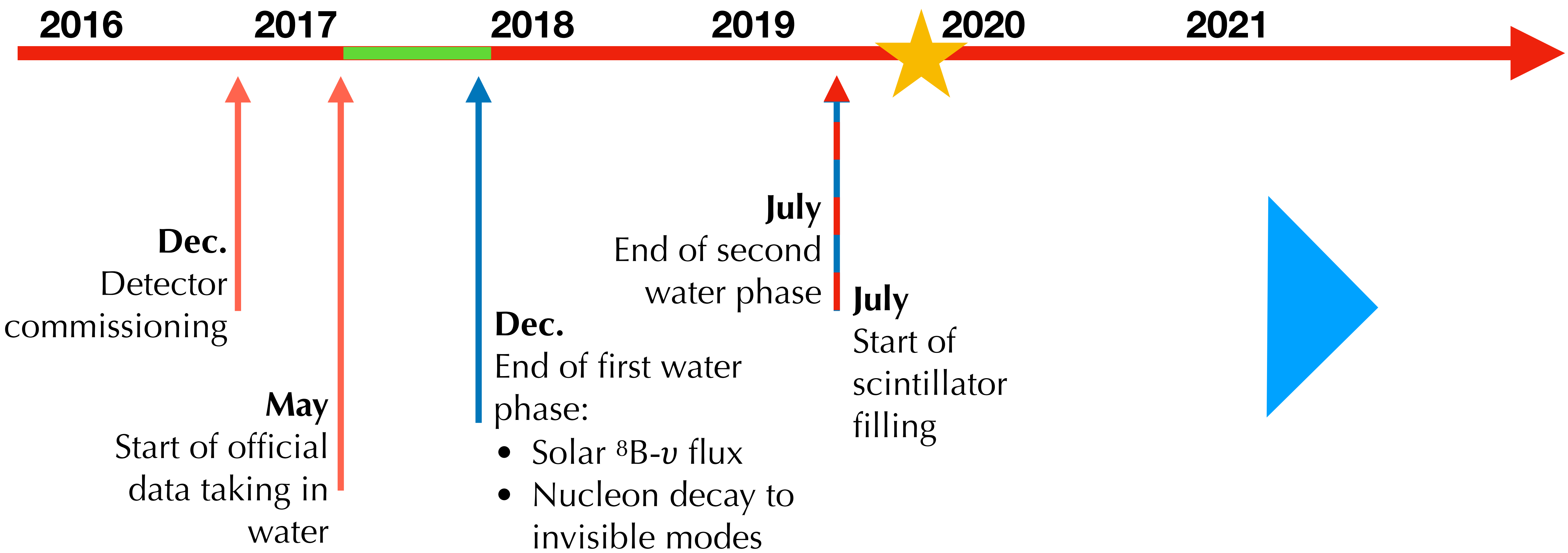
July
Start of scintillator filling

TIMELINE


2016
2017
2018
2019
2020
2021
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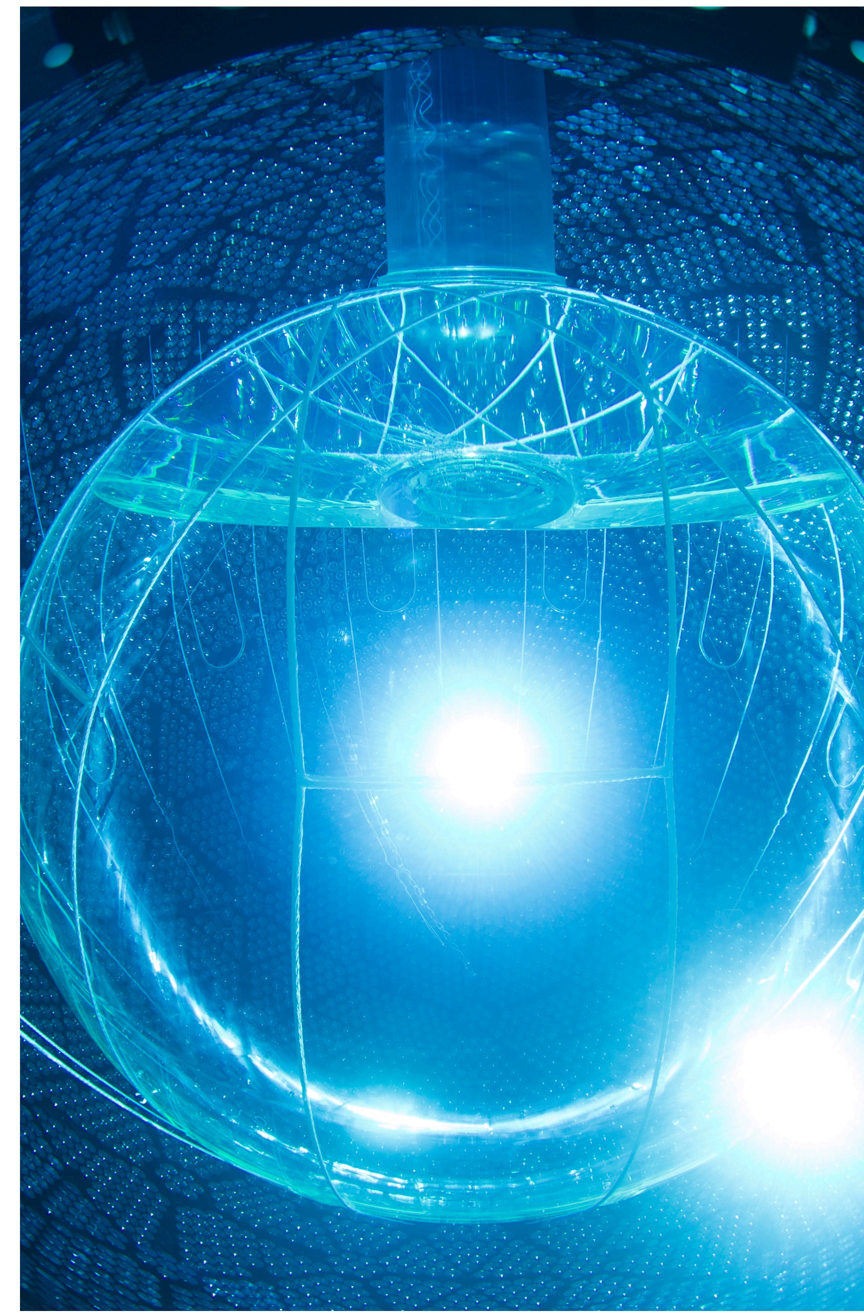

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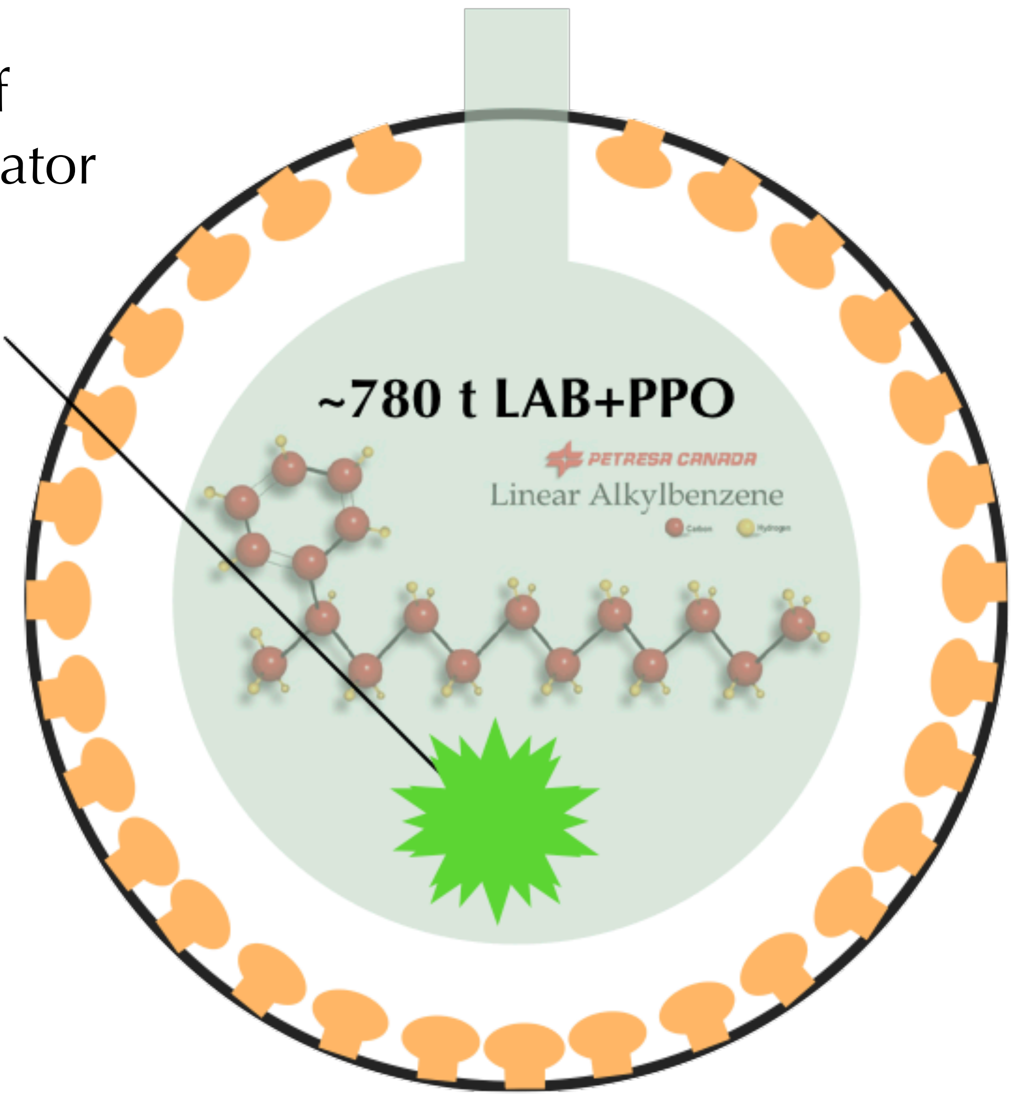

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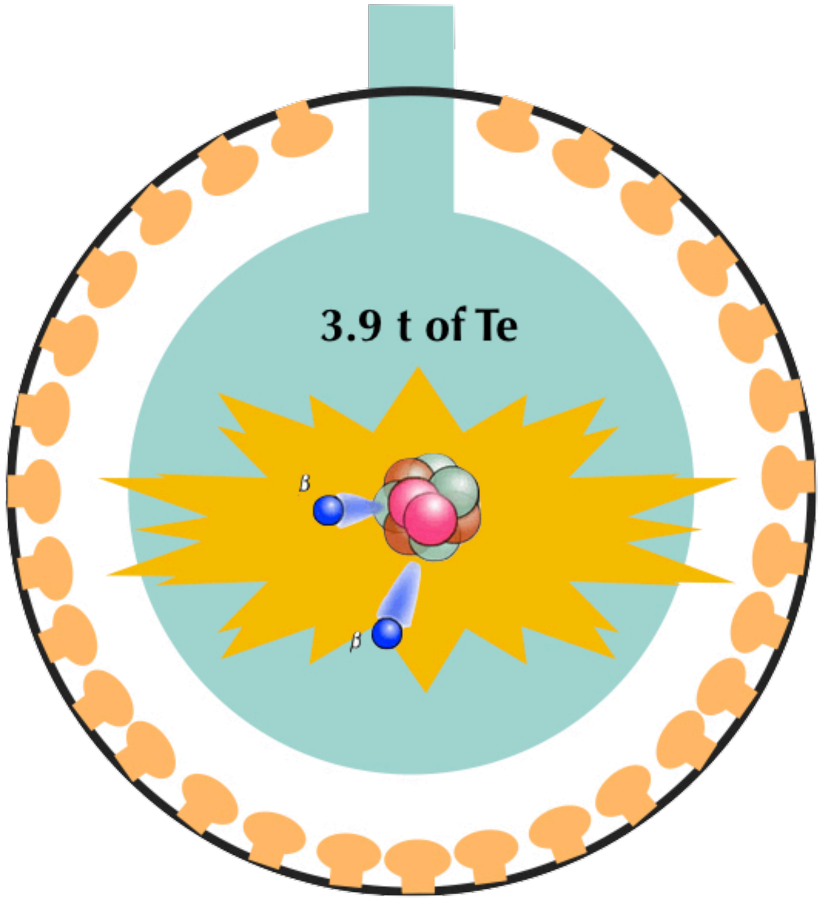
July
Start of scintillator filling

~2020
Start of scintillator loading with Te

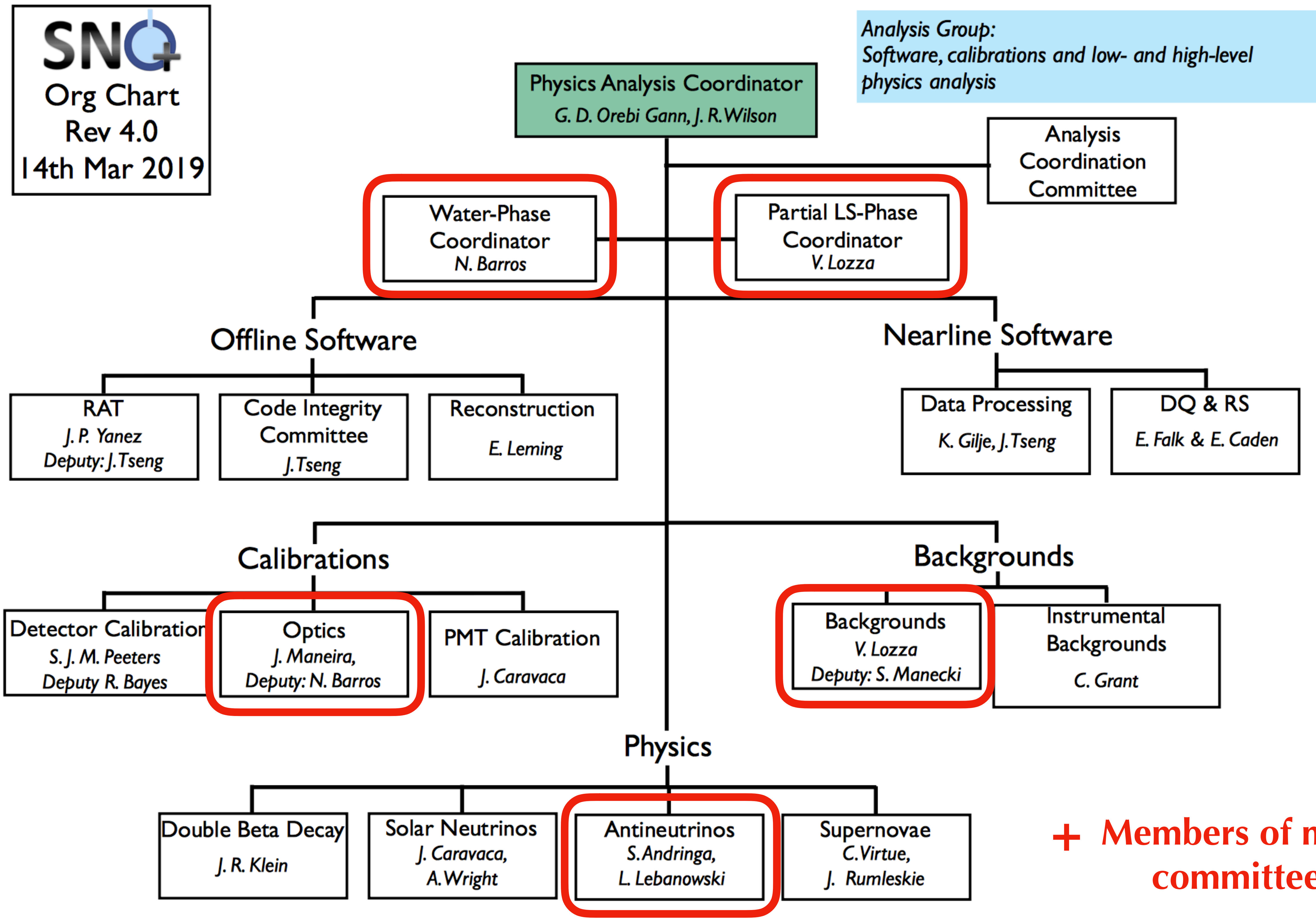


Physics goals & Phases

Goal	Water Phase **(2017-2019)**	Pure LS Phase **(Now)**	Te-loaded Phase **(2020)**
0νßß-decay			😎
^{8}B Solar neutrinos	X	X	X
Low-energy solar neutrinos		X	
Supernova neutrinos	X	X	X
Reactor anti-neutrinos	(X)	X	X
Geo anti-neutrinos		X	X
Exotic searches (i.e. nucleon decay)	X	X	X

SNO+ @ LIP

Past & Present



+ Members of many committees

SNO+ @ LIP

HARDWARE

- Delivered the systems for source deployment in SNO+
- Develop gamma calibration sources
- Develop the system for the optical calibration using fibers
- Installation of the optical fibers

DETECTOR CHARACTERIZATION

- Key role in the determination of the purity/cleanliness requirements for the various phases
- Delivered the optical calibration of the detector in water
- ….

ANALYSIS

- **Background analysis and daily background identification in water** and scintillator
- **Neutron analysis in water**
- **Anti-neutrino analysis in water** and scintillator

CODE & DATA

- High contribution to the development of the SNO+ code
- Important contribution to the reconstruction algorithms
- Responsible for the code documentation
- Delivered the data quality for SNO+
- Important contribution for data processing

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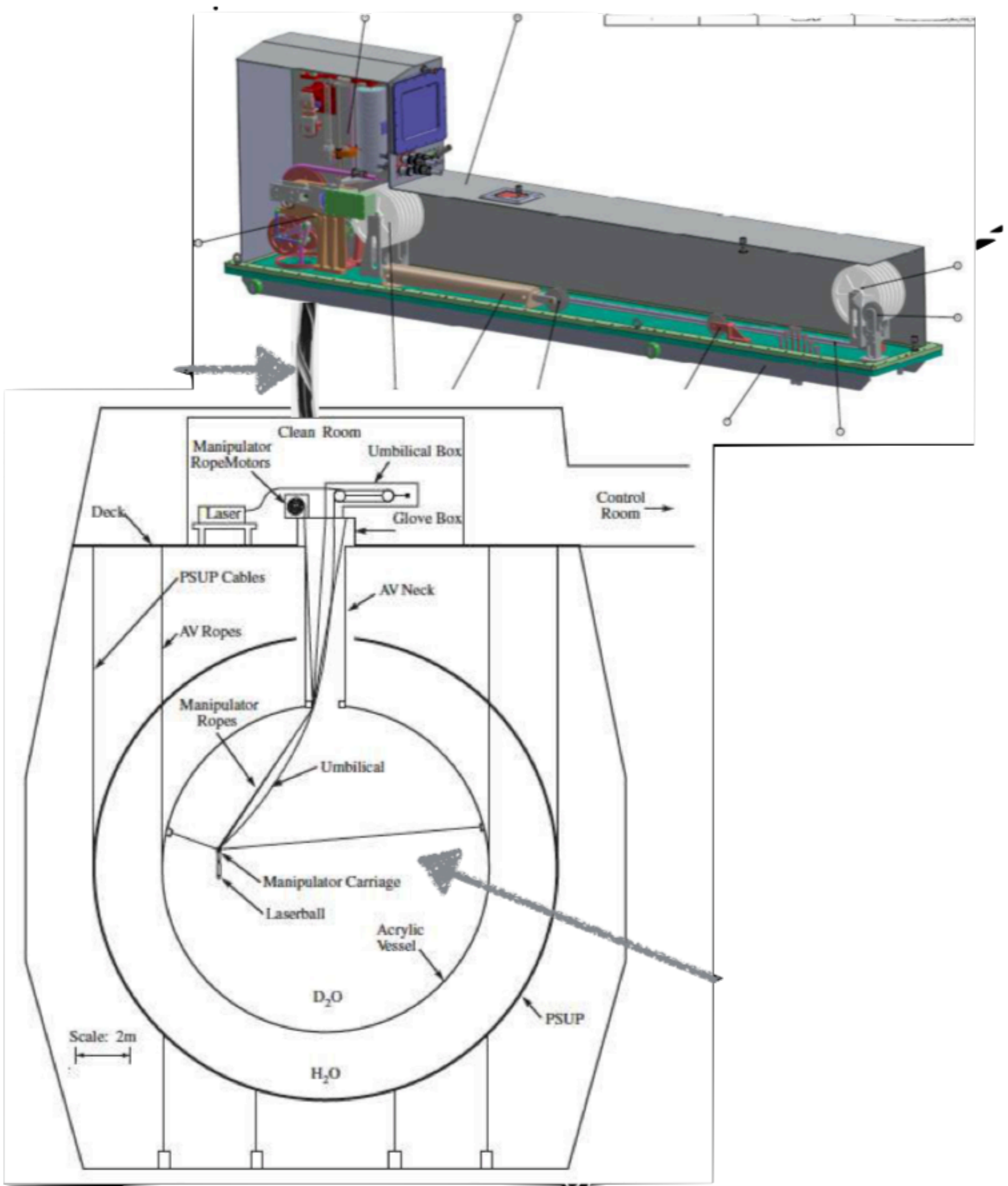
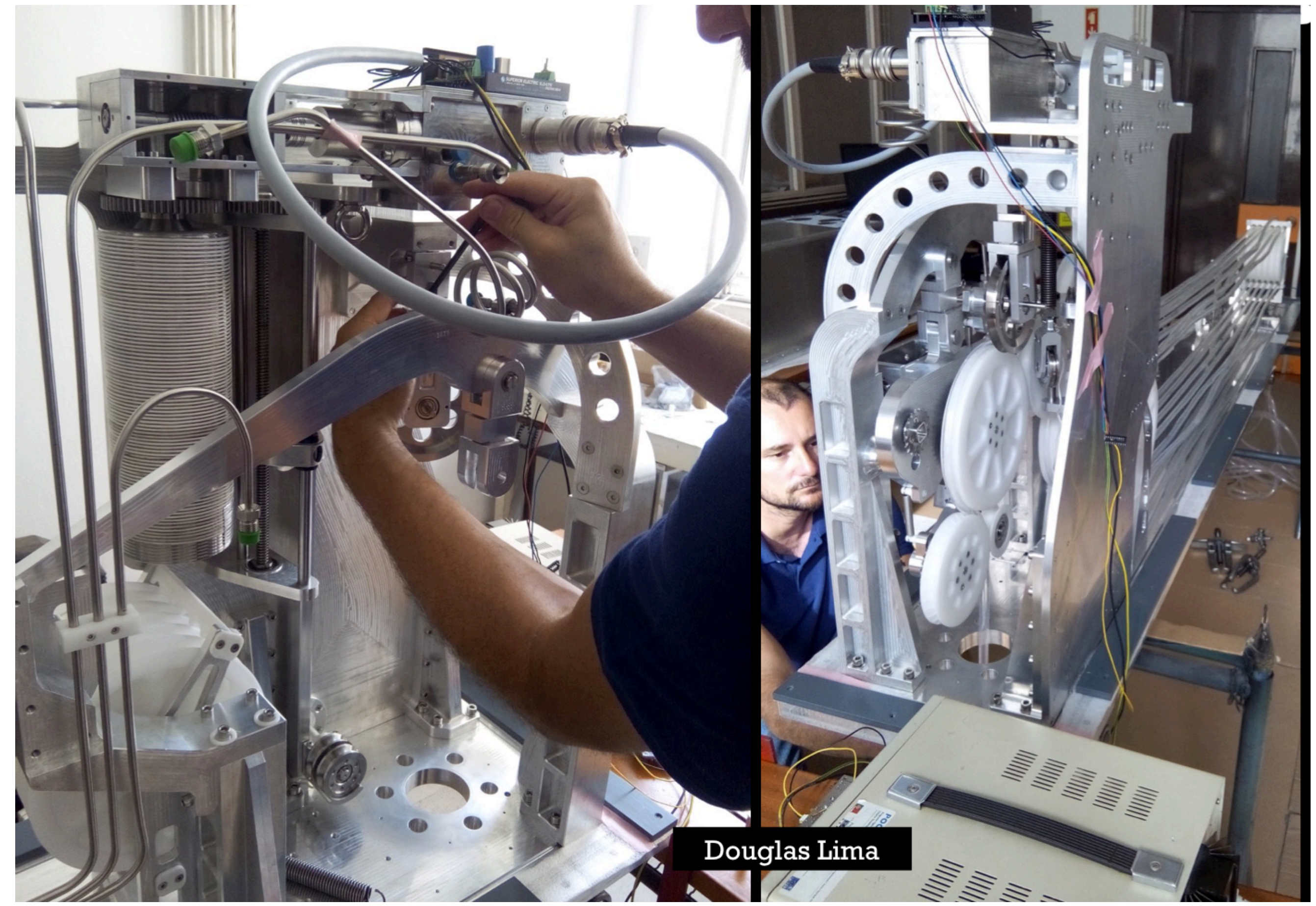
URM



Clean Room
Manipulator RopeMotors
Umbilical Box
Deck
Laser
Glove Box
Control Room
PSUP Cables
AV Neck
AV Ropes
Manipulator Ropes
Umbilical
Manipulator Carriage
Laserball
Acrylic Vessel
D_2O
PSUP
Scale: 2m
H_2O



Douglas Lima

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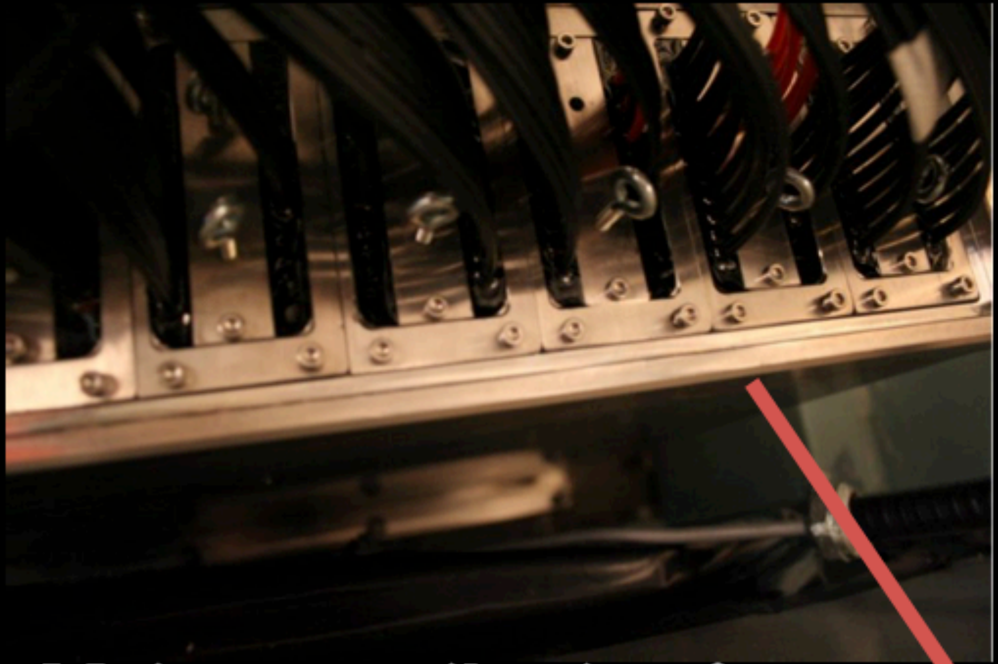
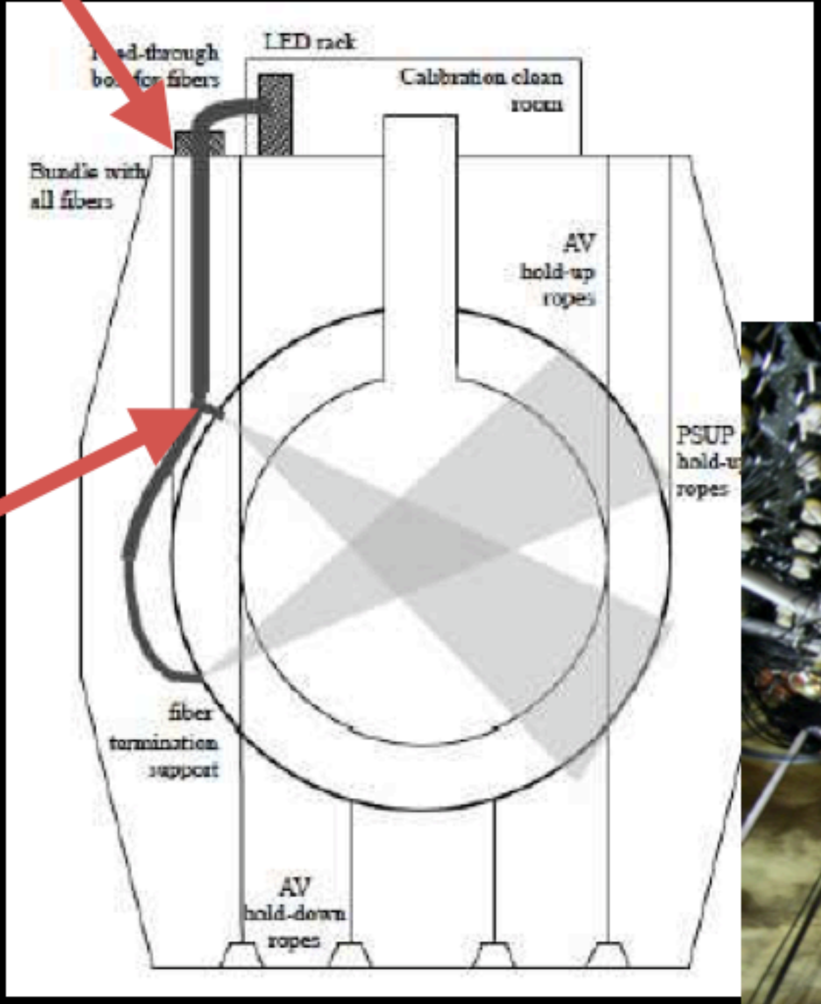
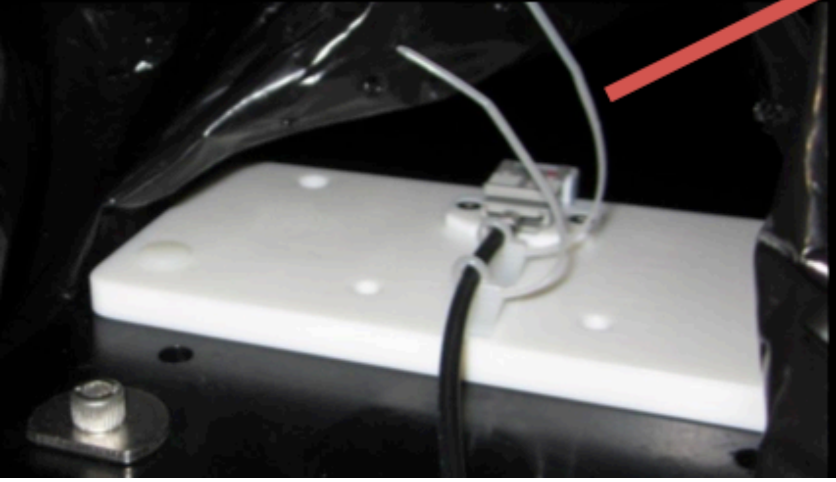
Fibers



- > 100 opt. fibers (most PMMA, some quartz)
- light injection with full coverage
- 92 LED channels, 3 lasers
- installed and working

- Major contribution from Portugal
  - all PMMA fibers
  - mechanical parts done at LIP-Coimbra





JM
Luís Gurriana

Calibration

Don't call the Nobel Committee just yet:
We forgot to calibrate the instruments
before the experiment...

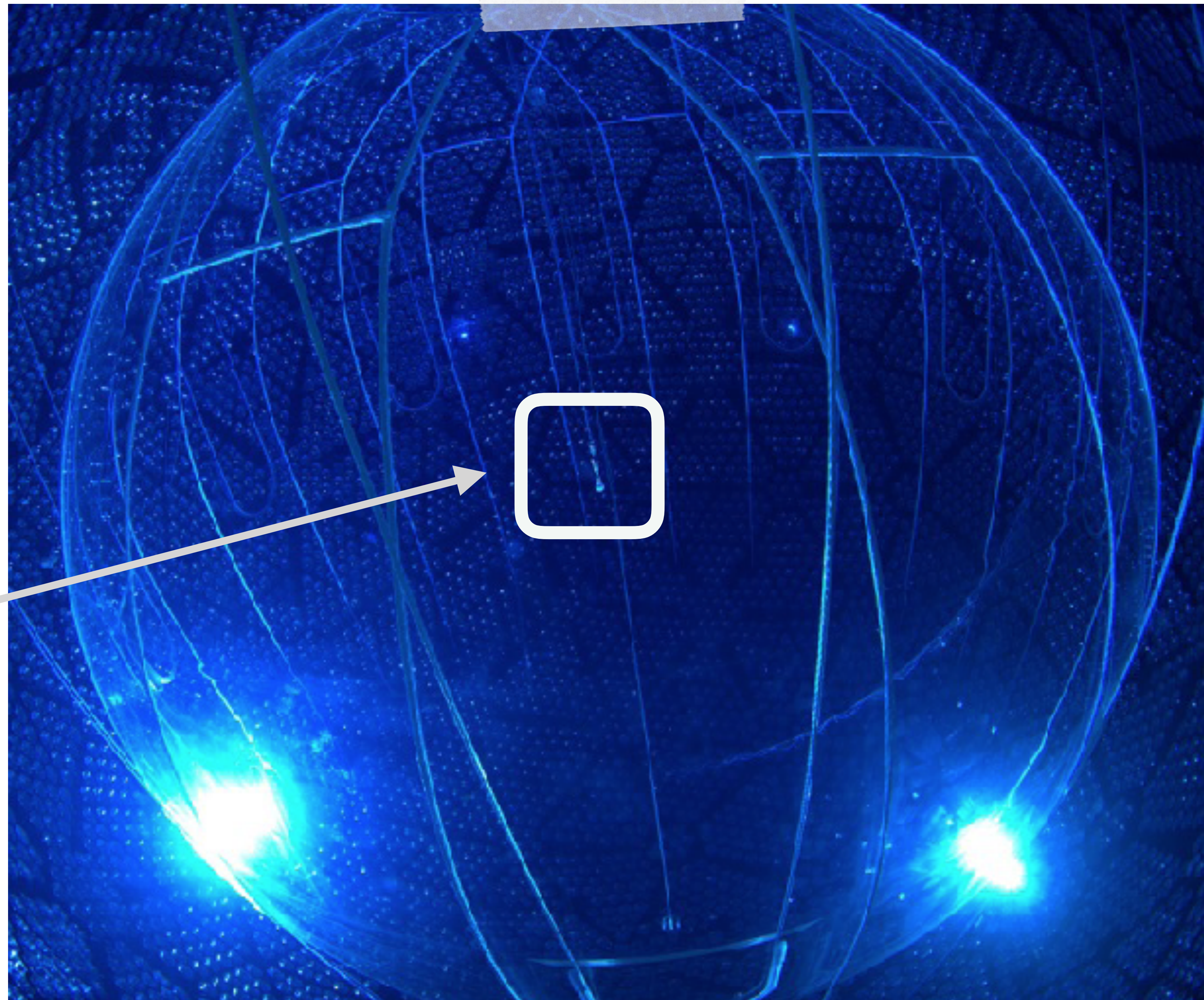
Main calibration sources used:

✴ Diffused isotropic laser

→ Calibrate PMT gain, timing and water optics

Laserball deployed inside the detector

Full characterization of the optical effects



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✳ ^{16}N gamma source
→ Calibrate energy scale and resolution

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

✳ ^{16}N gamma source
→ Calibrate energy scale and resolution

✳ AmBe neutron source
→ Calibrate the neutron response, energy scale

Water & Acrylic optics

✳ Parameters measured:

→ Internal water attenuation coefficients

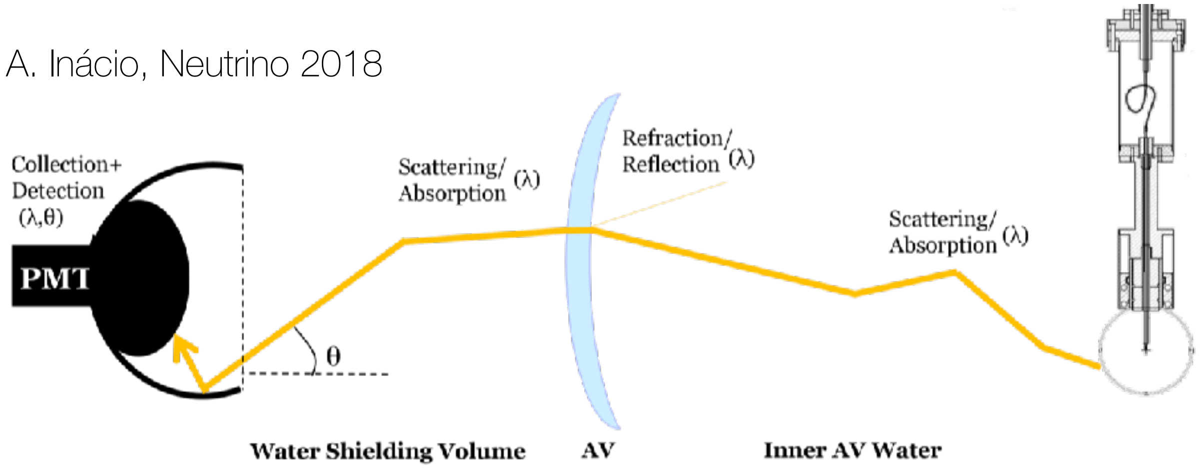
→ External water attenuation coefficients

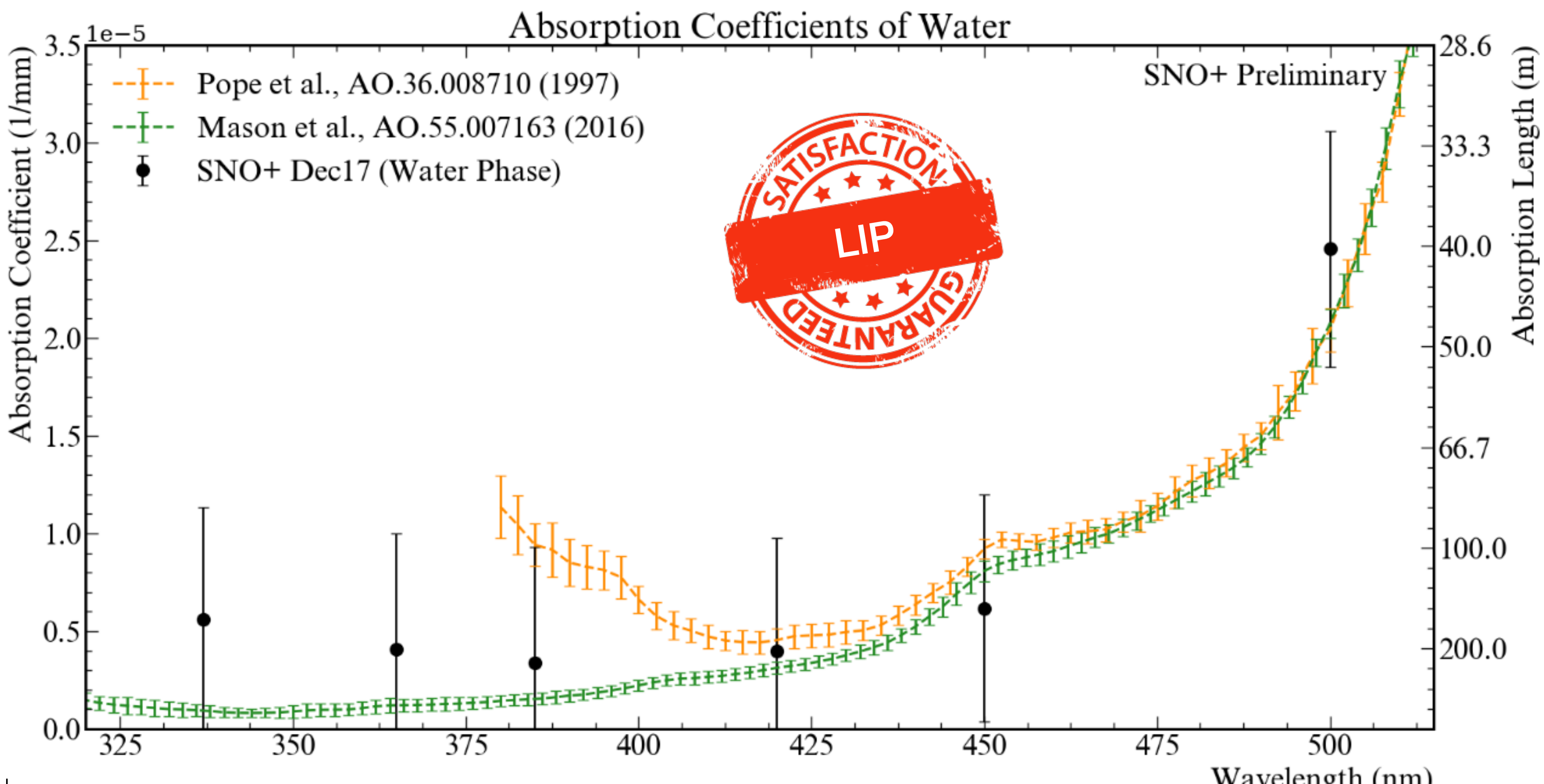
→ Laserball parameters

→ PMT angular response up to 45 degree

→ PMT efficiencies

A. Inácio, Neutrino 2018

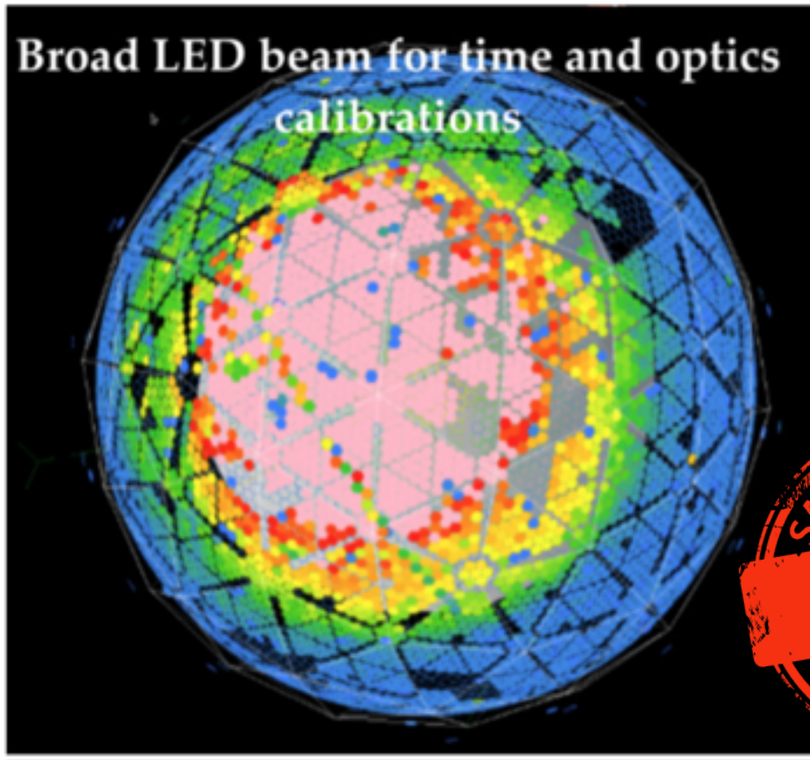


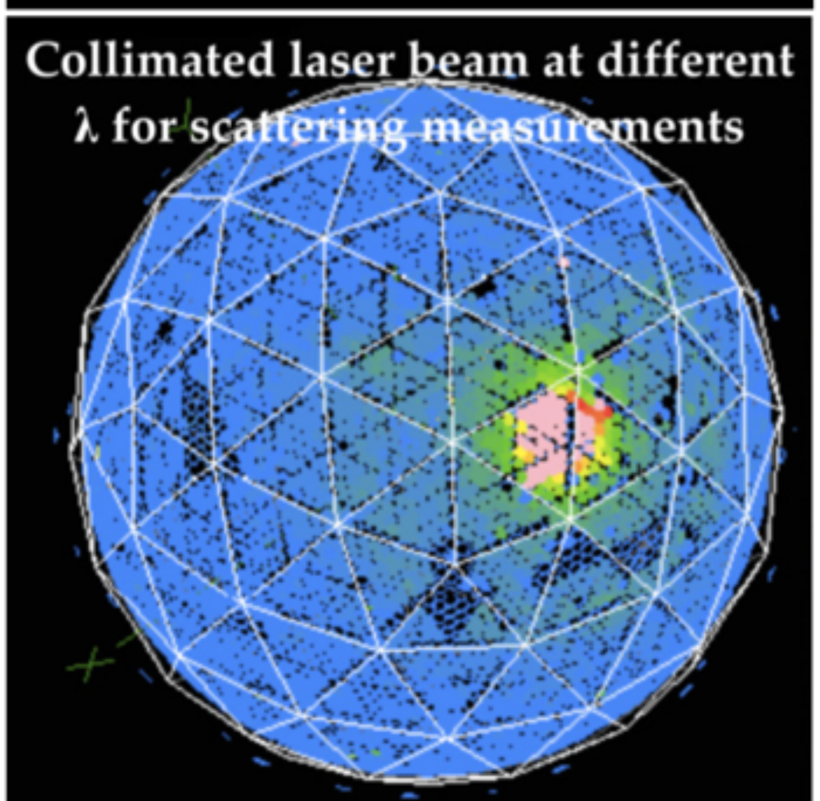


✳ Analysis entirely done by Ana Sofia

✳ Current status: use external scans to separate the acrylic and water optics

Other Optics Calibrations


Broad LED beam for time and optics calibrations

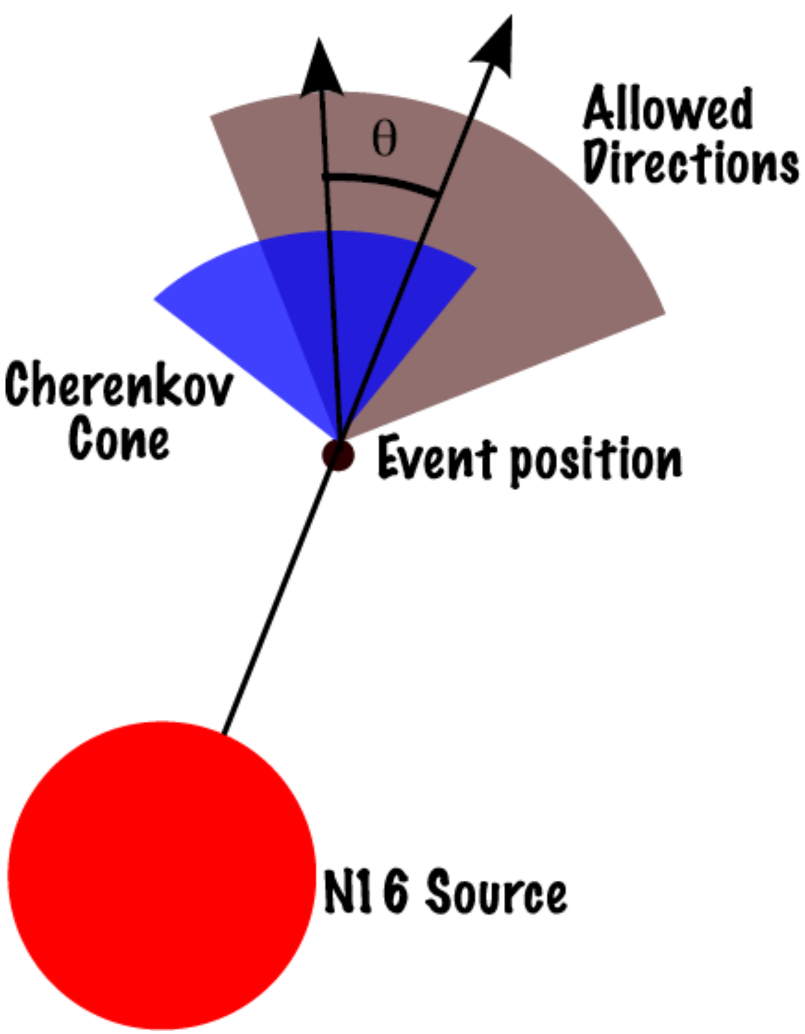

Collimated laser beam at different λ for scattering measurements

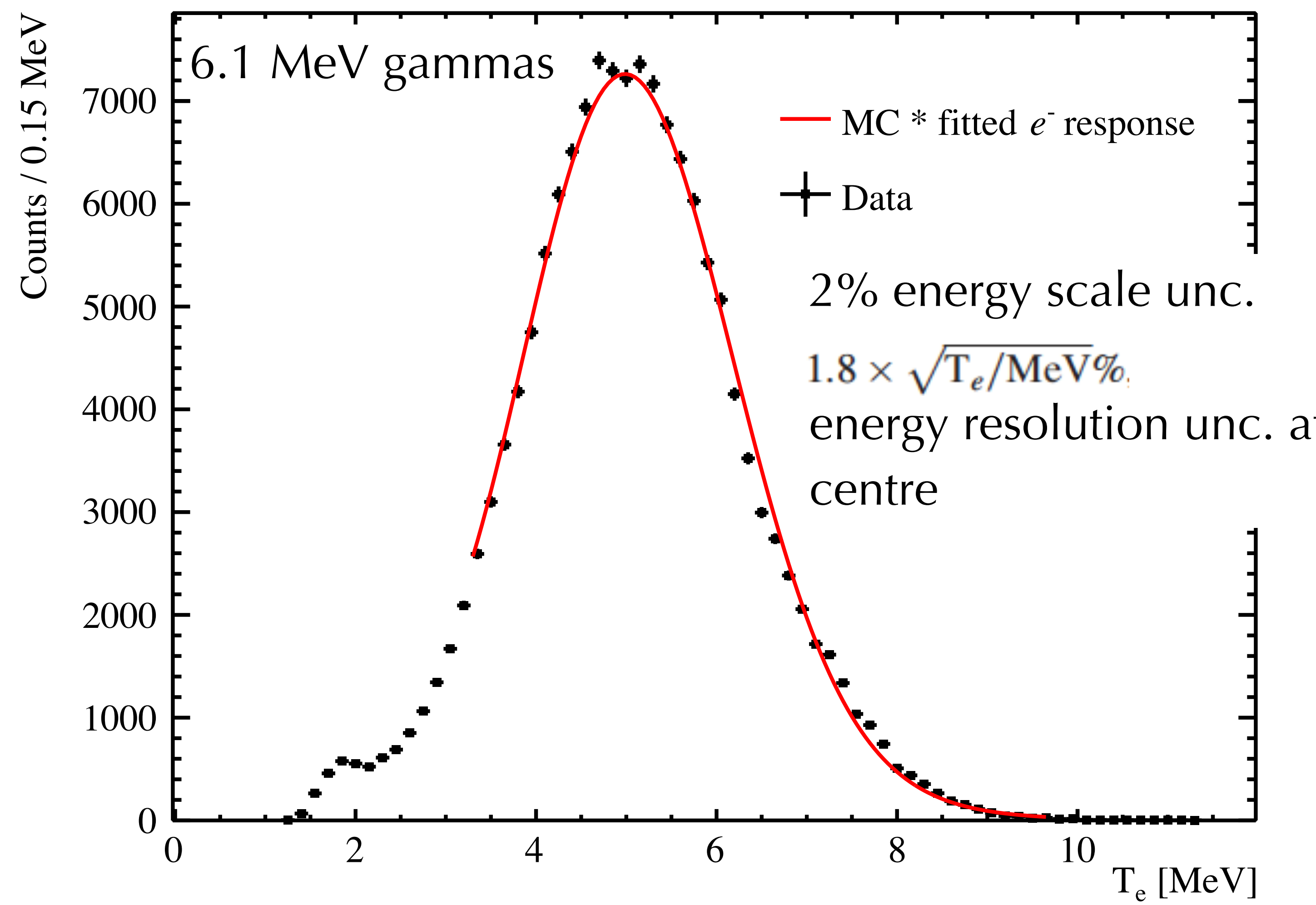
External LED/Laser system ➞ Further calibrate PMT and optics. Reduce risk of contamination due to source deployment

Cherenkov source ➞ Decouple optical microphysical parameters in scintillator and Te phase

Energy scale & Resolution

* Systematic uncertainties of energy scale and resolution are extracted from comparisons of fit values between data and MC





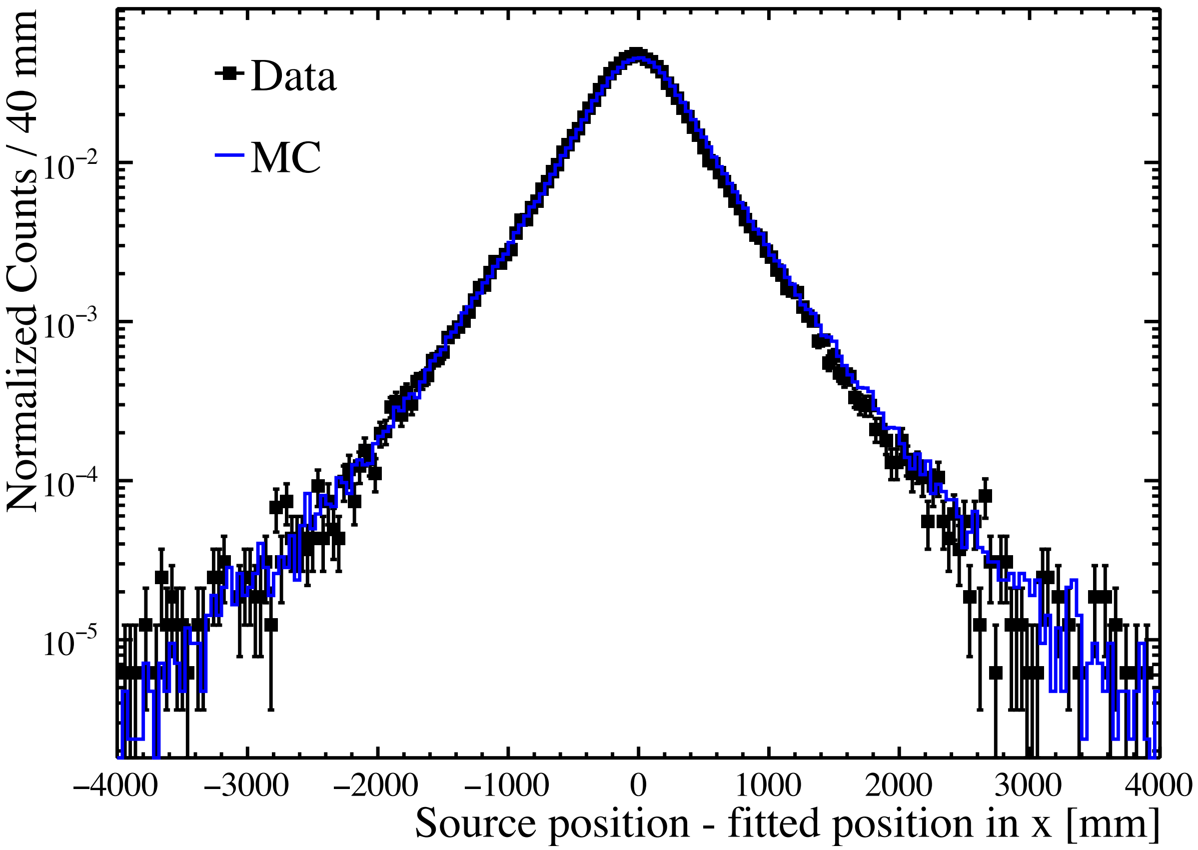
The fit is characterized in terms of:

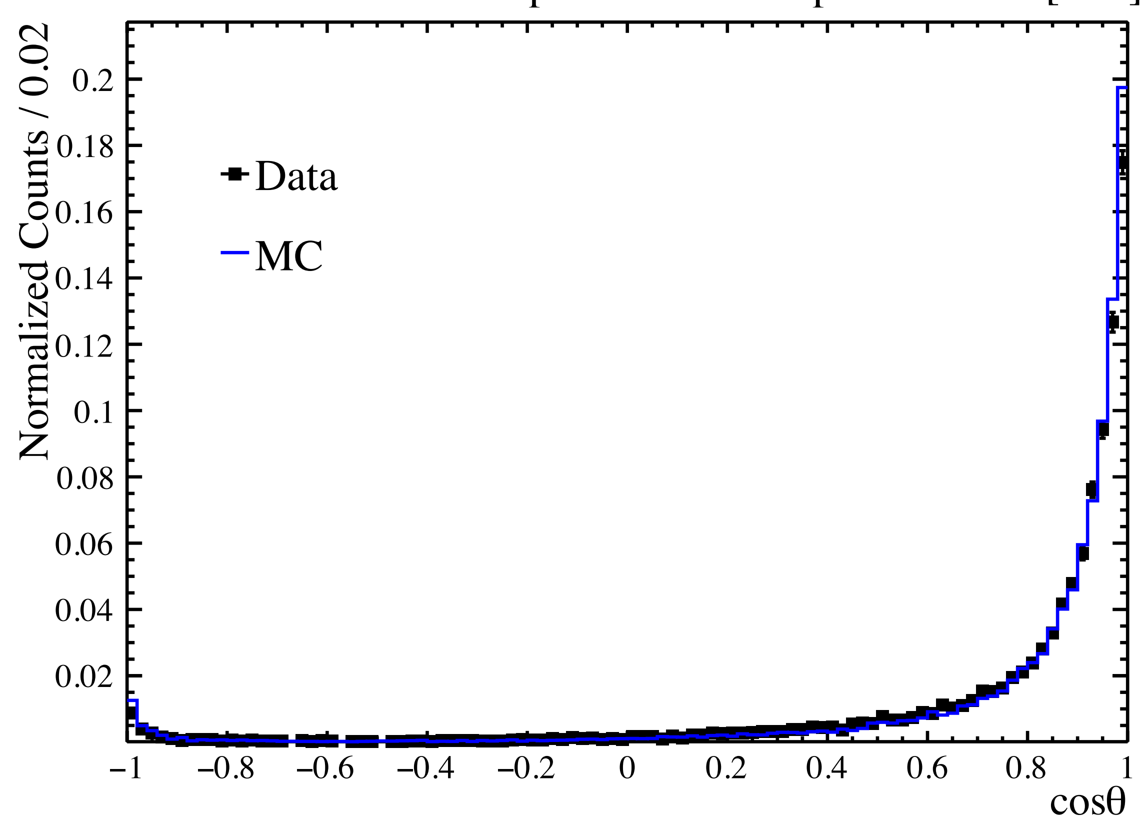
* scale = a linear correction to the energy
* resolution = relating to the width of the spectrum.

Vertex & Position Uncertainties

Fit with a distribution function representing the position of the first Compton electron, estimated from the Monte Carlo model, convolved with a Gaussian function and an exponential tail

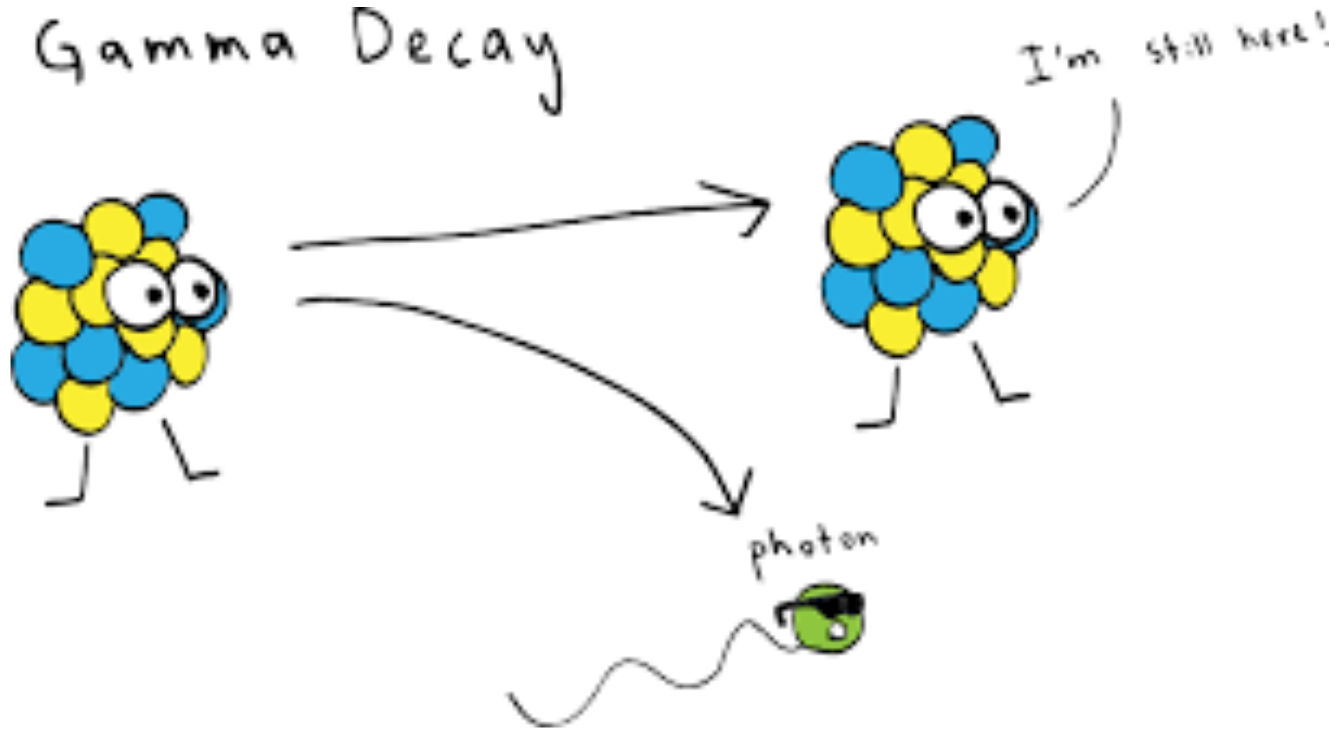
Parameter	Uncertainty, δ_i
x offset (mm)	$^{+16.4}_{-18.2}$
y offset (mm)	$^{+22.3}_{-19.2}$
z offset (mm)	$^{+38.4}_{-16.7}$
x scale (%)	$^{+0.91}_{-1.01}$
y scale (%)	$^{+0.92}_{-1.02}$
z scale (%)	$^{+0.92}_{-0.99}$
x resolution (mm)	104
y resolution (mm)	98
z resolution (mm)	106
Angular resolution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





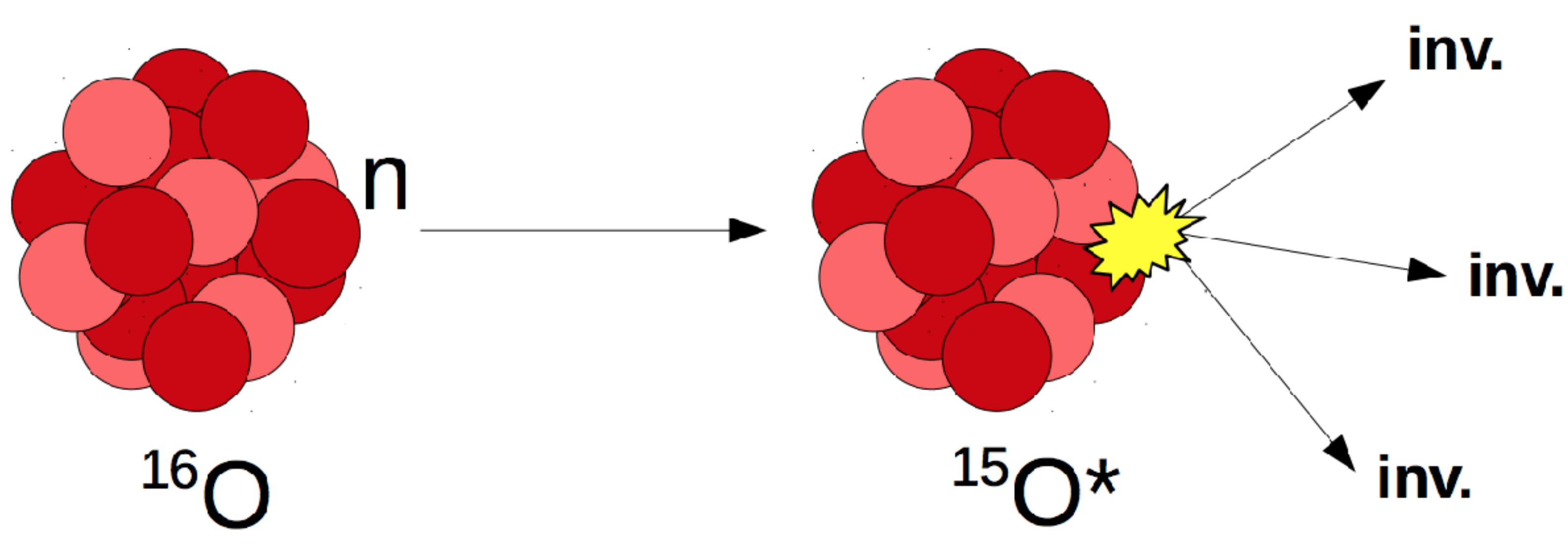
PHYS.REV. D 99, 032008 (2019)

NUCLEON DECAY



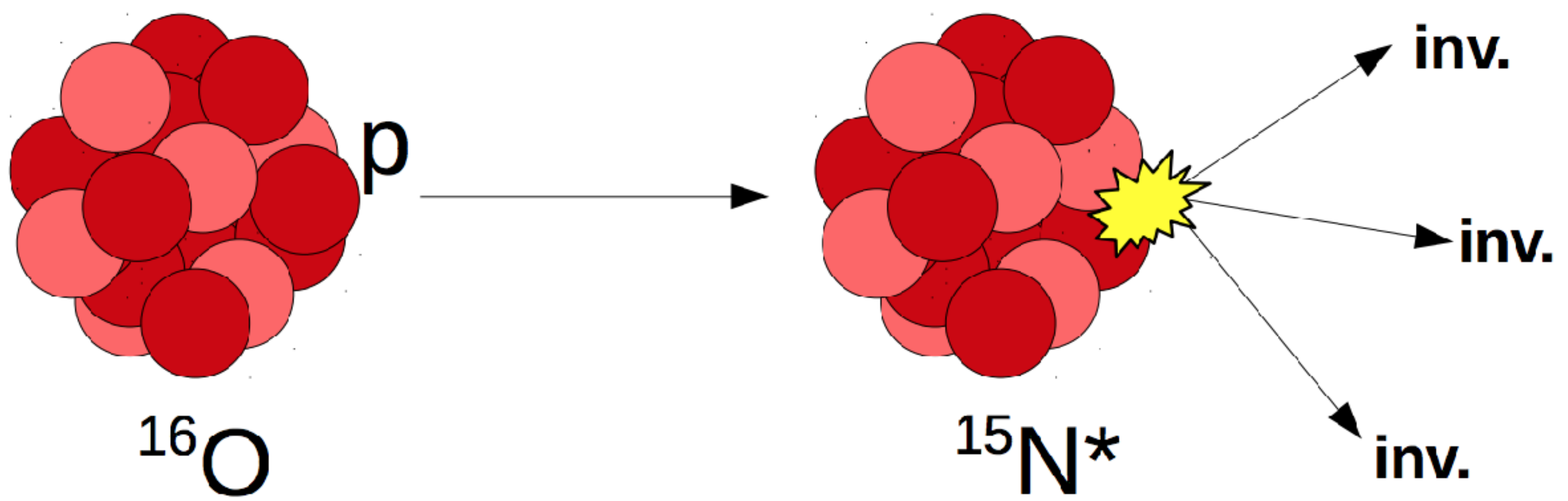
Nucleon Decay Searches

Phys. Rev. C 48, 1442



neutron → invisible
(e.g. n → 3ν)

De-excitation gammas:
- 6.32 MeV (41%)
- 7.01 MeV (4%)

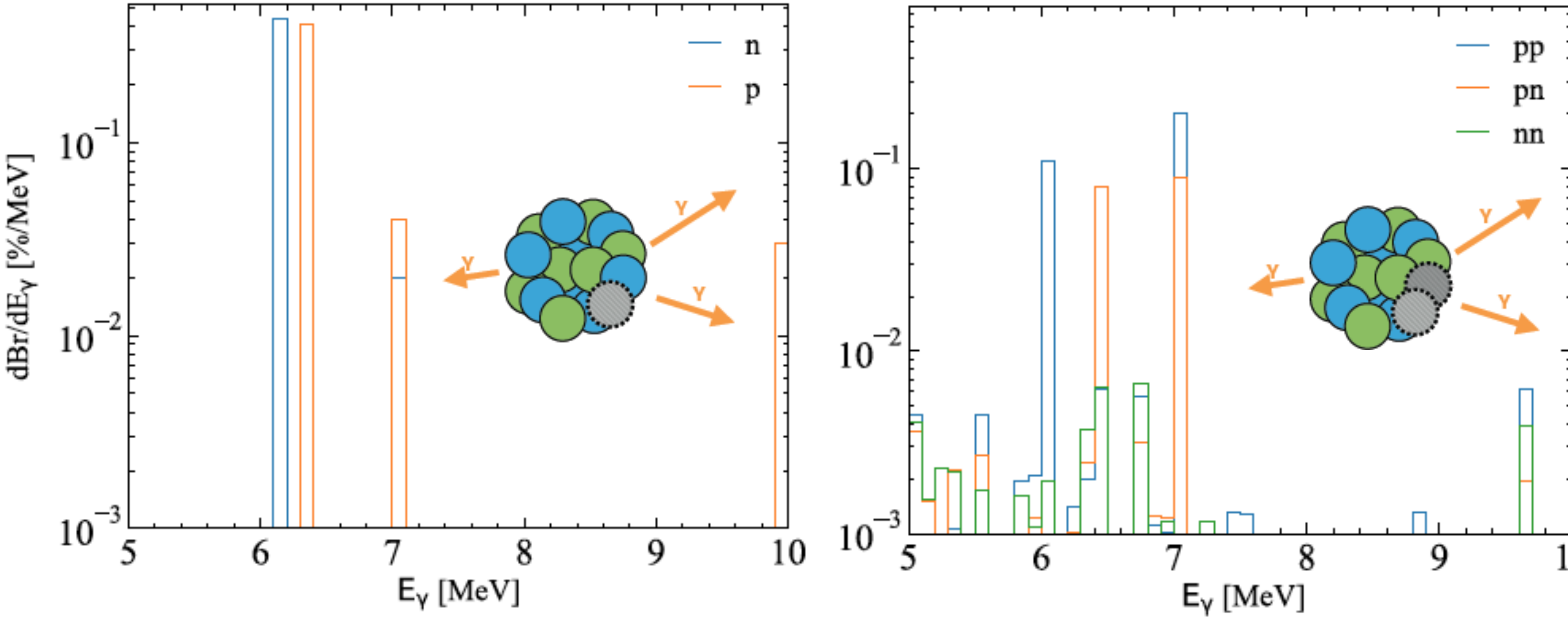


proton → invisible

De-excitation gammas:
- 6.18 MeV (44%)
- 7.03 MeV (2%)

V. Fisher, CIPANP 2018

Nucleon Decay Searches



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

Analysis of the first dataset: May - December 2017

- ✳ 235 days of data
  - detector live time = 95%
  - calibration or maintenance time = 16.9%
  - **not** pass data quality checks = 29.3%
  - instrumental effects, muon events, dead time = 2.4%

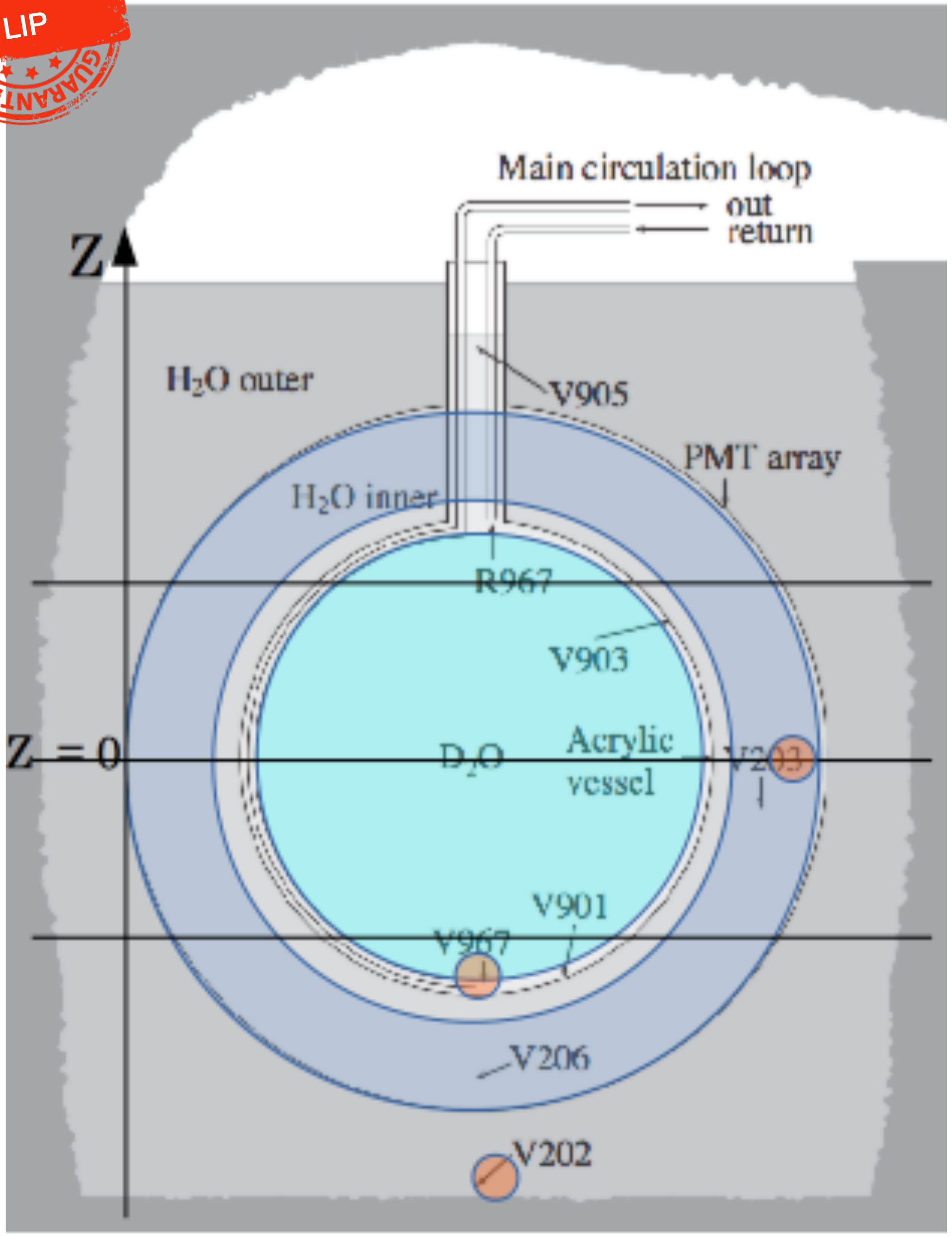
Overall 114.7 days ± 0.04%

Nucleon Decay Searches

- During the SNO+ water phase, significant work was done on commissioning the water processing and recirculation systems.
  - variation in Rn related background
  - data period has been divided in timebins with background levels were relatively stable
    - Background estimate for each + specific set of analysis cuts.
    - run-by-run MC production to account for variations in live channels

Nucleon Decay Searches

- Background characterisation
  - Study the time evolution of the event's density in order to identify hot regions and the potential cause of the localized increase
  - Divide the detector in 2 major regions: inner AV water (light blue) and outer AV water (dark blue)
  - Divide each region into 4 Z-zones
  - Correlated the effect of a variation in the background rate (Rn) to the water circulation route
  - Correlated the effect of a variation in the background rate to the various detector states (change in trigger thresholds, channels offline, …)
  - Define the cuts for the nucleon decay analysis

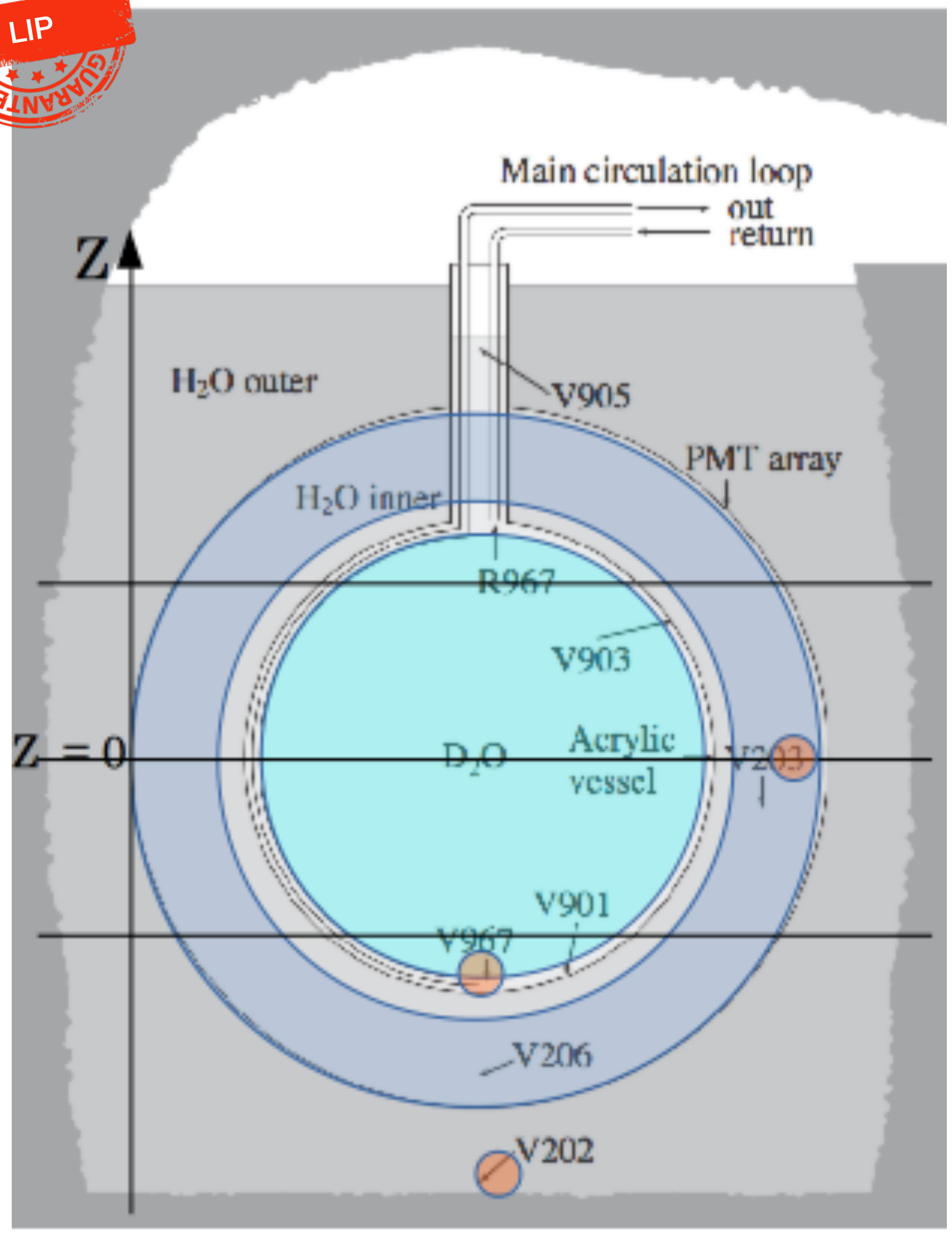


Ingress of recirculated (purified) water

Nucleon Decay Searches

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

- FV cut to reduce external backgrounds
  - Cut in radius and z
- Cut on solar direction reduces the solar neutrino background
  - other backgrounds are flat in $\cos\theta_\odot$



Ingress of recirculated (purified) water

Two independent blind analyses (remove [5-15]MeV):

Counting analysis

- Cut and count approach
  - Background analyses provides the expected counts in the ROI
- Upper limit on the number of signal decays:

$$\int_0^{S_{90\%}} \prod_k A(s\epsilon_k t_k + b_k)^{n_k} \times \mathrm{e}^{-(s\epsilon_k t_i + b_k)} \mathrm{d}s / n_k! = 0.9$$

timebin

observed events

expected background events

Spectral Analysis

Two independent blind analyses (remove [5-15]MeV):

Counting analysis

Data set	Observed events	Expected events
1	1	$1.17^{+4.60}_{-0.05}\ {}^{-0.39}_{+1.33}$
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	$17.65^{+12.68}_{-2.36}\ {}^{+6.51}_{-1.85}$

22 EVENTS SELECTED
[$17.65^{+14.25}_{-3.00}$ EXPECTED]

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Spectral Analysis

- Multi-dimensional LH fit
  - Observables:
    - Energy
    - Radial event position
    - Sun direction
    - Light isotropy
    - Event direction

Nucleon Decay Searches

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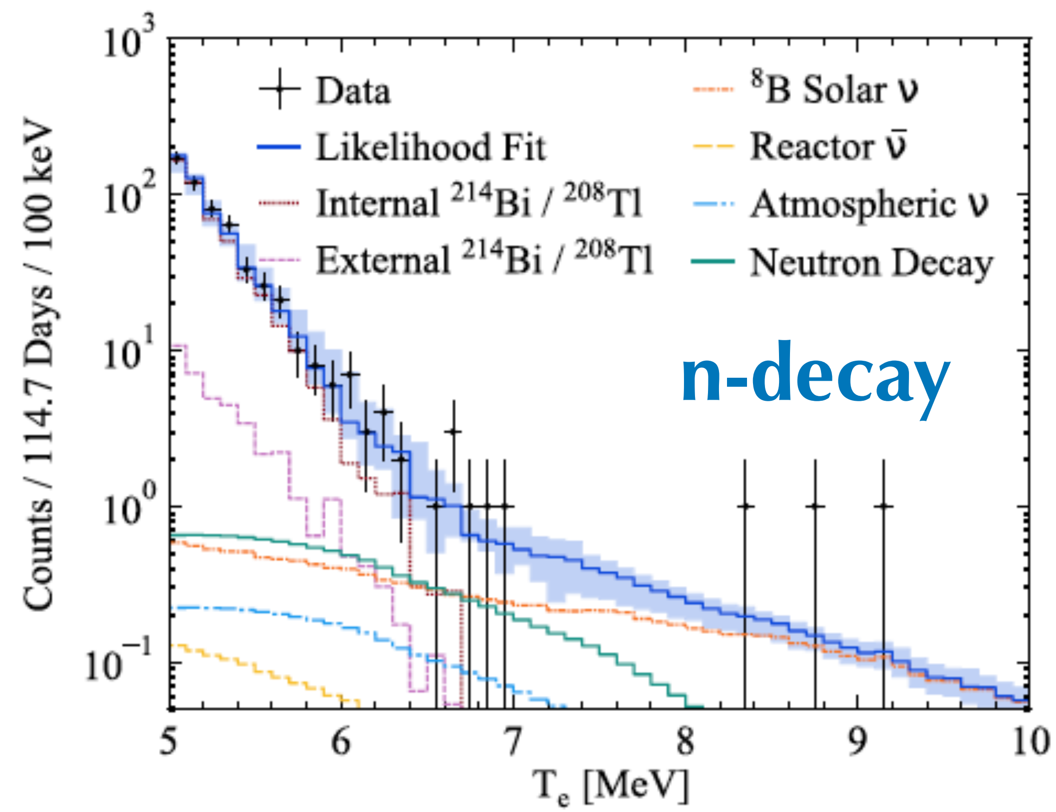


- Background included in the analysis:
  - solar neutrinos
  - reactor anti-neutrinos
  - atmospheric neutrinos
  - U & Th chain radioactivity

Nucleon Decay Searches

Results:

	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]

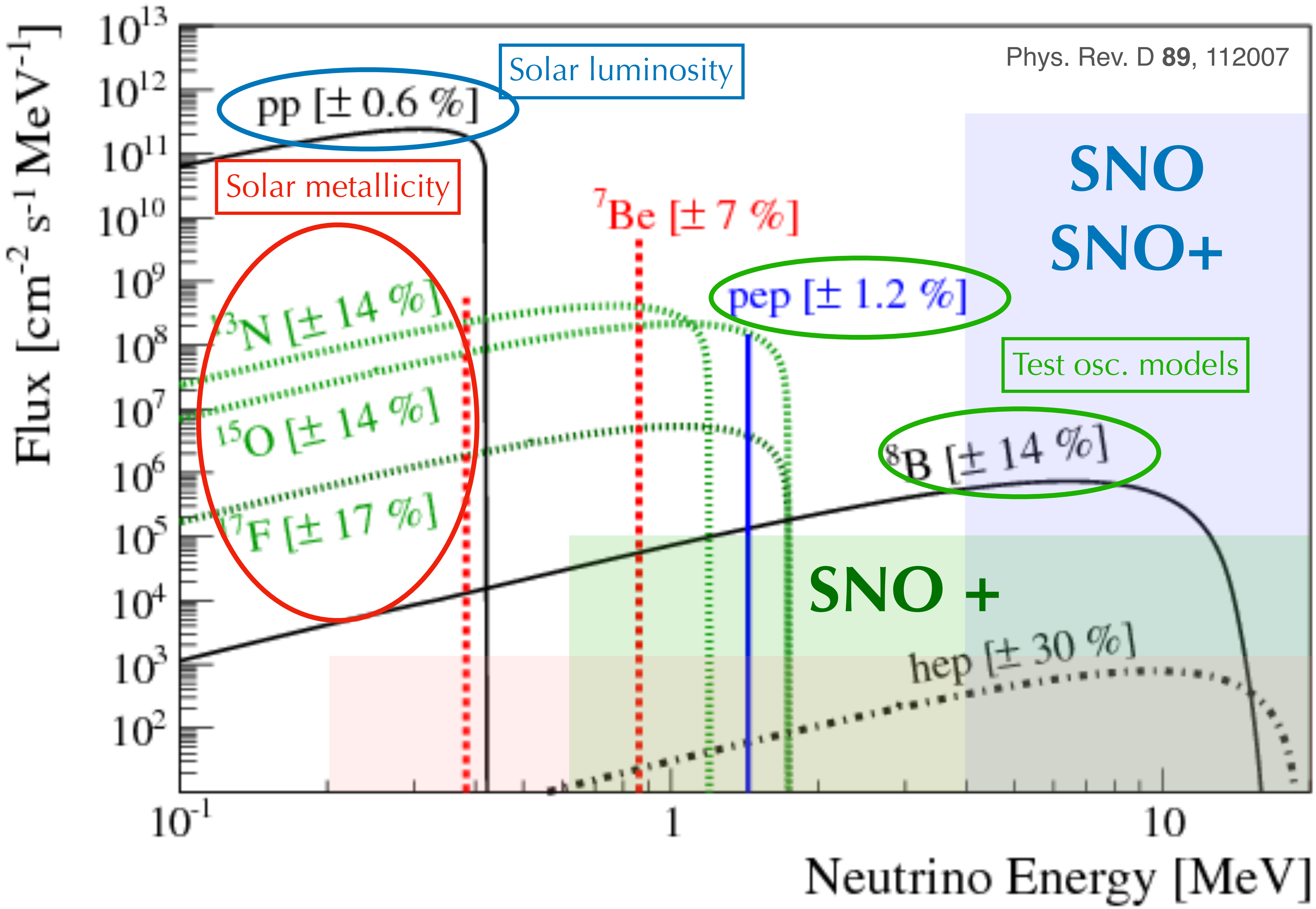
[*] = V. Tretyak, V. Yu. Denisov, and Yu. G. Zdesenko, JETP Lett. **79**, 106 (2004), [Pisma Zh. Eksp. Teor. Fiz.79,136(2004)], arXiv:nucl-ex/0401022 [nucl-ex].

Work in progress: Use the second part of low background water data to improve the limit on n!!!

PHYS.REV. D 99, 012012 (2019)

Solar Neutrinos

Measure of ⁸B solar neutrino flux



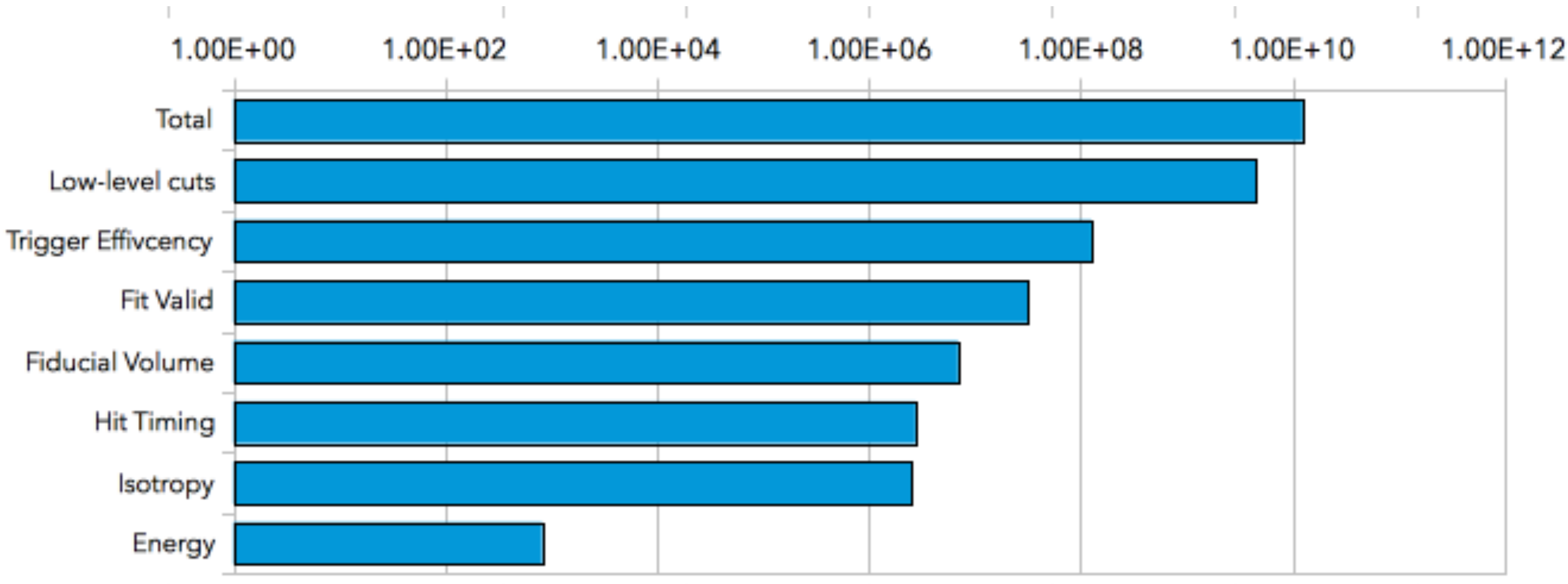
Measure of ^{8}B solar neutrino flux

- ✳ Region of interest [5-15] MeV
  - Extremely low background measurement
    - the deep UG location of SNOLAB highly reduces the muon and the muon induced background
  - **Elastic scattering** of electron by neutrinos (NC and CC)
  - Directional measurement (electrons keep the neutrino direction)

^{8}B Solar Neutrinos

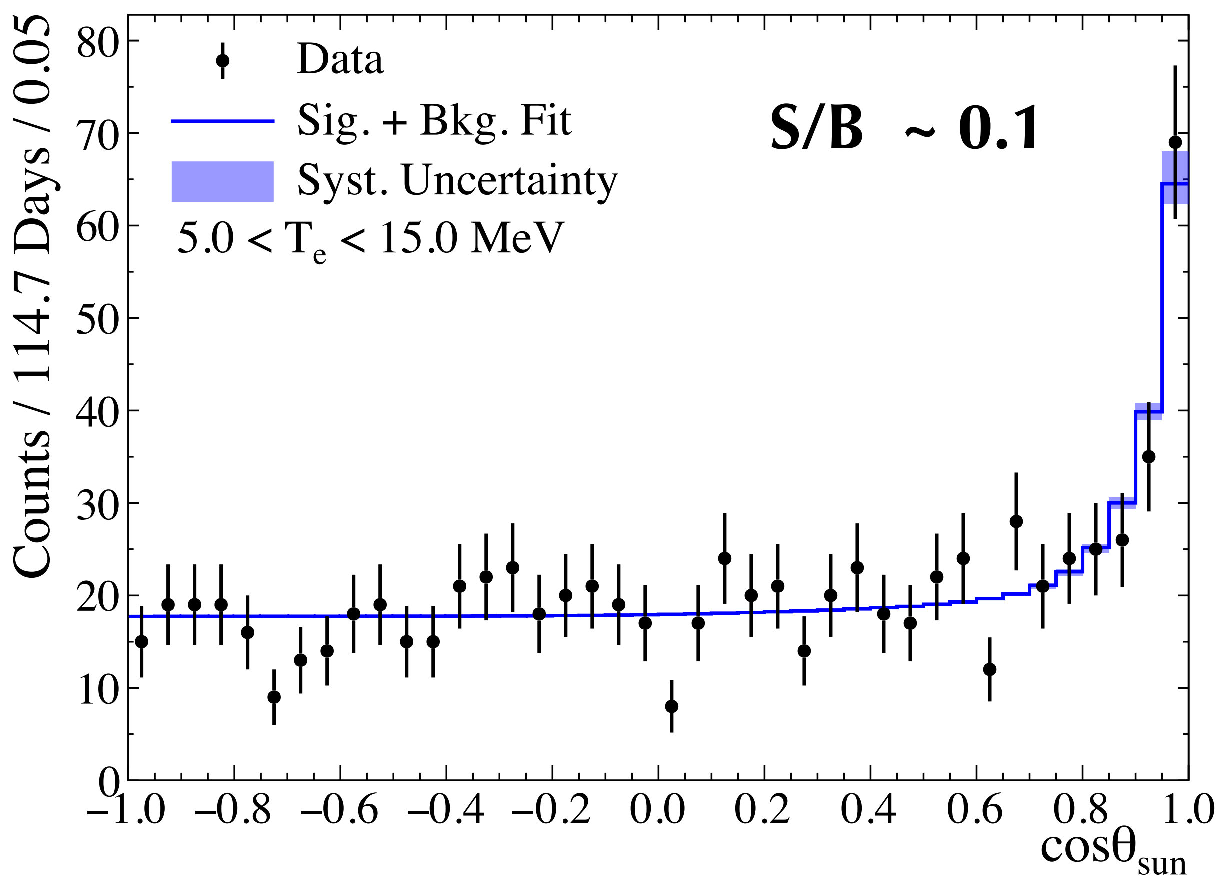
✳ Selection cuts to remove instrumental backgrounds

- FV cut of 5.3 m in radius to reduce the externals.

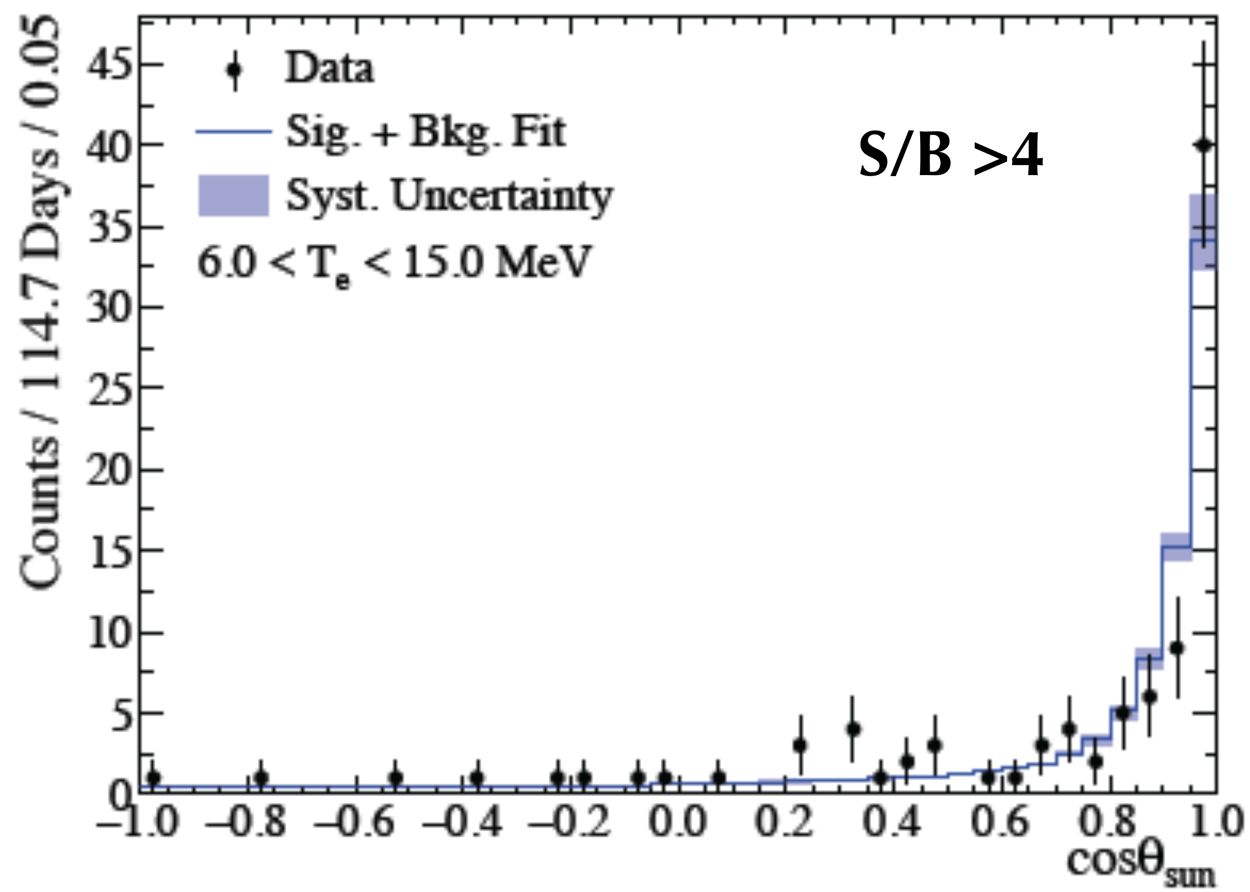


^{8}B Solar Neutrinos

Solar rate = 1.30 ± 0.18 events/kt-day
Background rate = 10.23 ± 0.38 events/kt-day



Solar rate = 1.03 $^{+0.13}_{-0.12}$ events/kt-day
Background rate = 0.25 $^{+0.09}_{-0.07}$ events/kt-day



^{8}B Solar Neutrinos

Solar rate = 1.30 ± 0.18 events/kt-day
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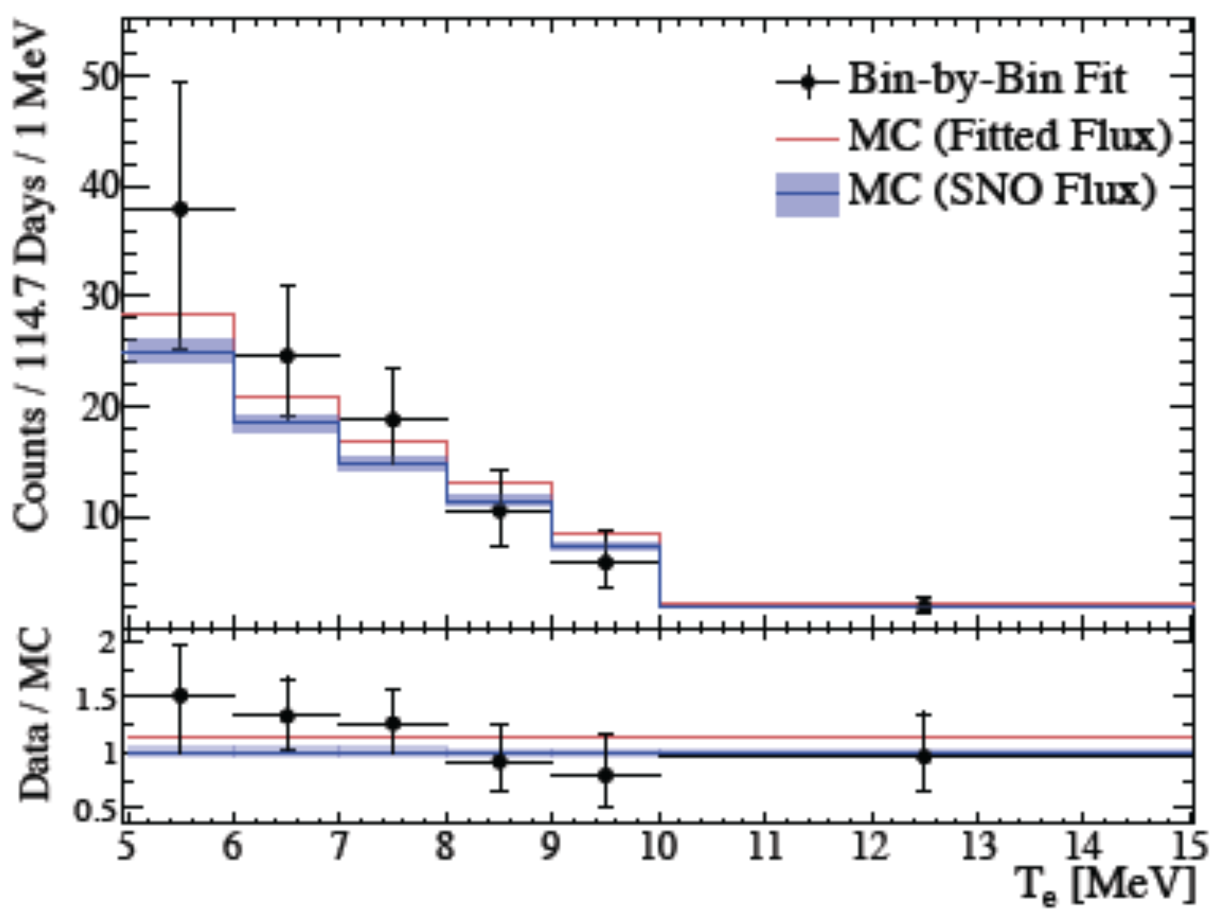


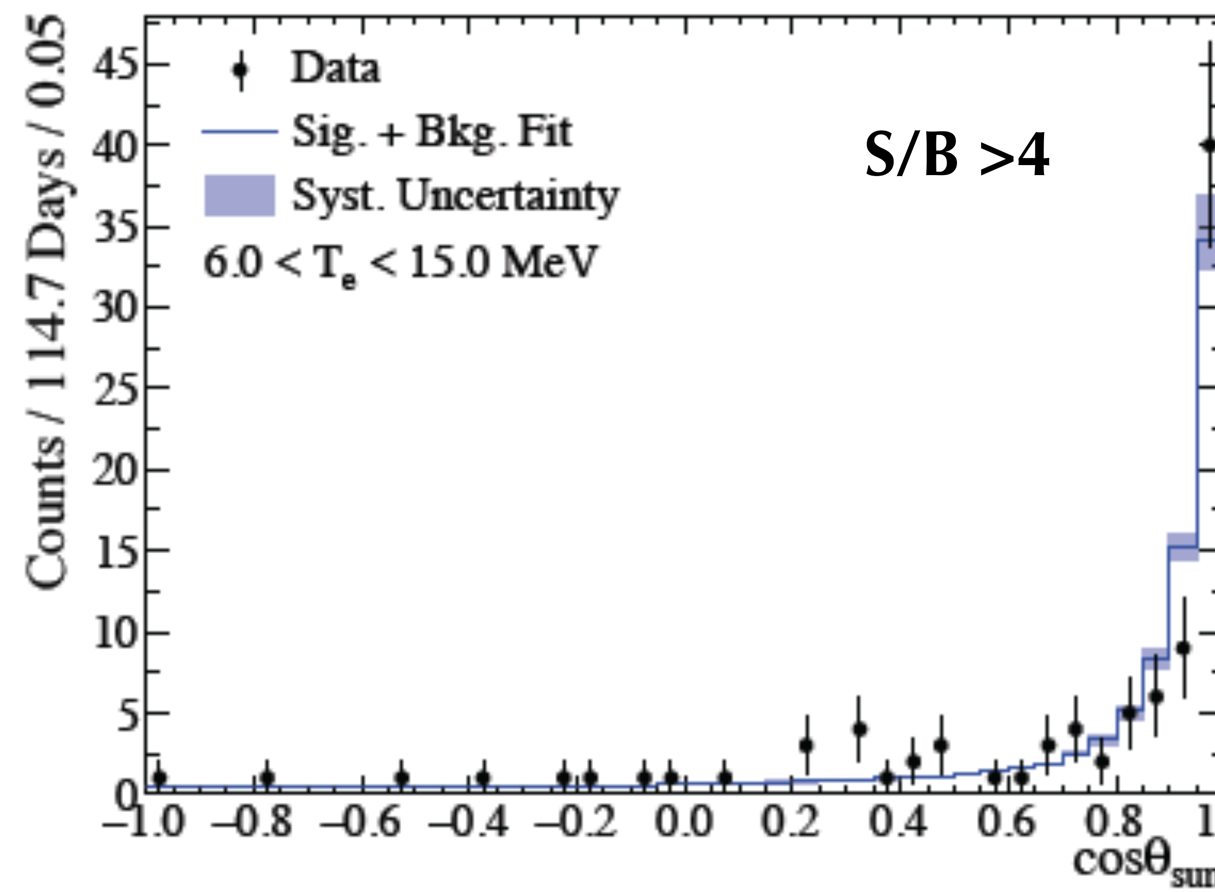
SNO+ (2019)

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

SNO

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

Solar rate = 1.03 $^{+0.13}_{-0.12}$ events/kt-day
Background rate = 0.25 $^{+0.09}_{-0.07}$ events/kt-day



S/B >4

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%

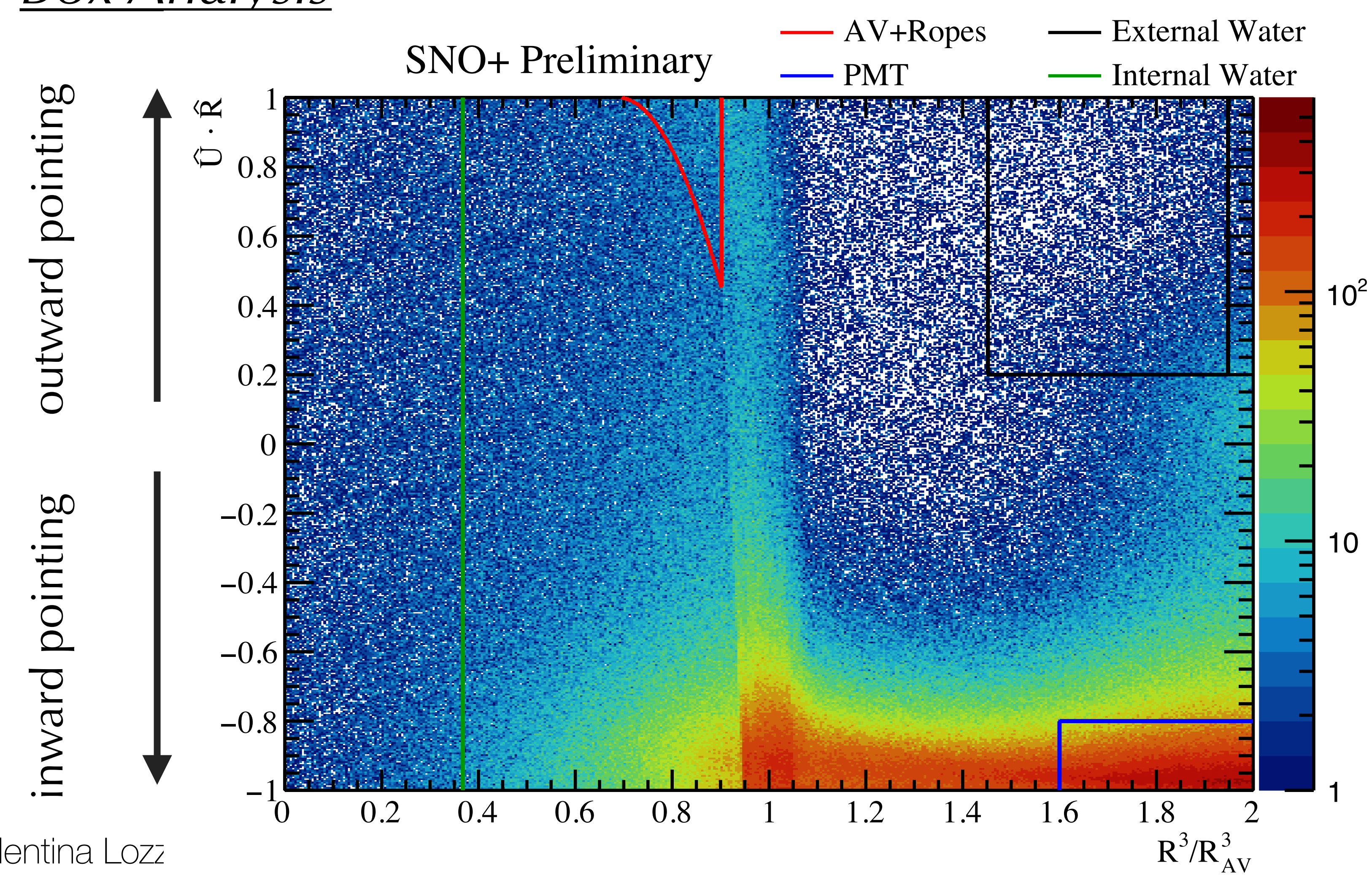
Background Measurement

External Backgrounds

- ✳ Measure the external background sources: purity level of PMTs, external water, acrylic vessel, ropes system.
- ✳ Measure the internal water purity for the nucleon-decay, solar and anti-neutrino study in water.

Event Selection:

- ✳ *Box Analysis*

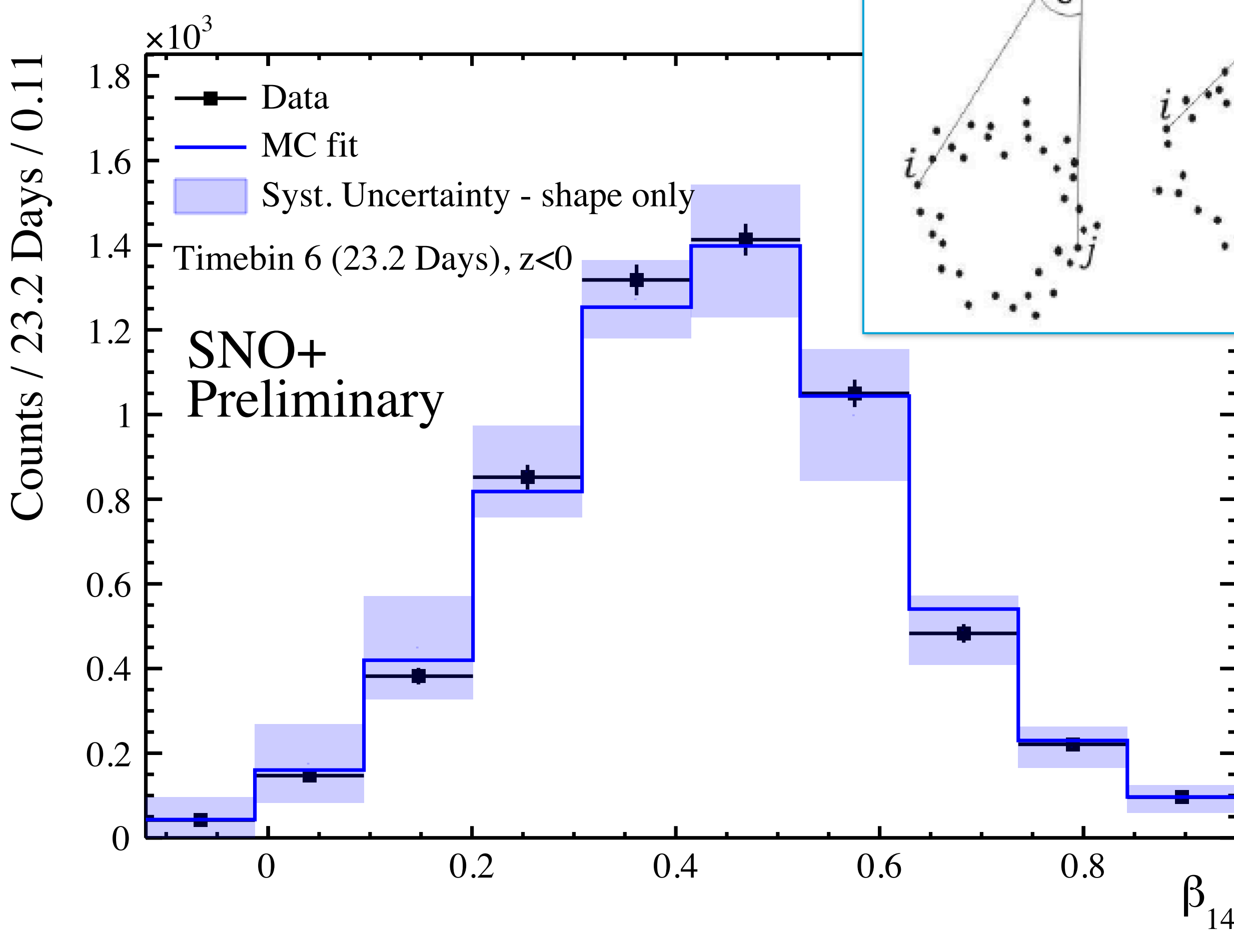


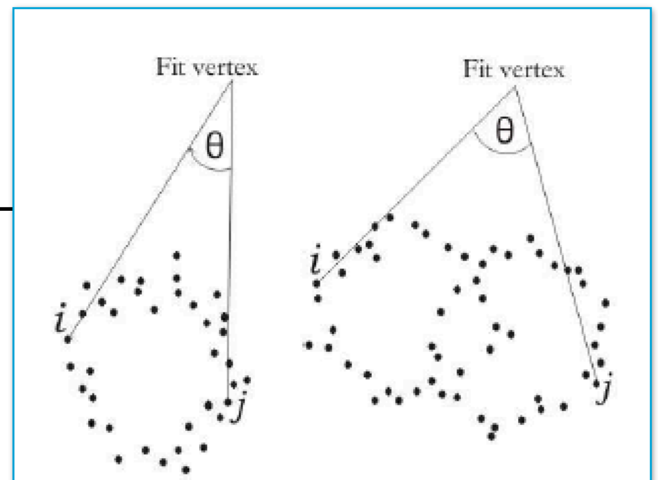
All Background	$-0.12 < \beta_{14} < 0.95$ ITR > 0.55 $3.0 < T_e < 6.35$
AV + Ropes	$0.69 < R^3/R^3_{AV} < 0.90$ $\hat{U} \cdot \hat{R} > 1.0 - 12 \times (R^3/R^3_{AV} - 0.69)^2$
External Water	$1.45 < R^3/R^3_{AV} < 1.95$ $\hat{U} \cdot \hat{R} > 0.2$
PMT	$1.6 < R^3/R^3_{AV} < 2.0$ $\hat{U} \cdot \hat{R} < -0.8$
Internal Water	$R^3/R^3_{AV} < 0.37$

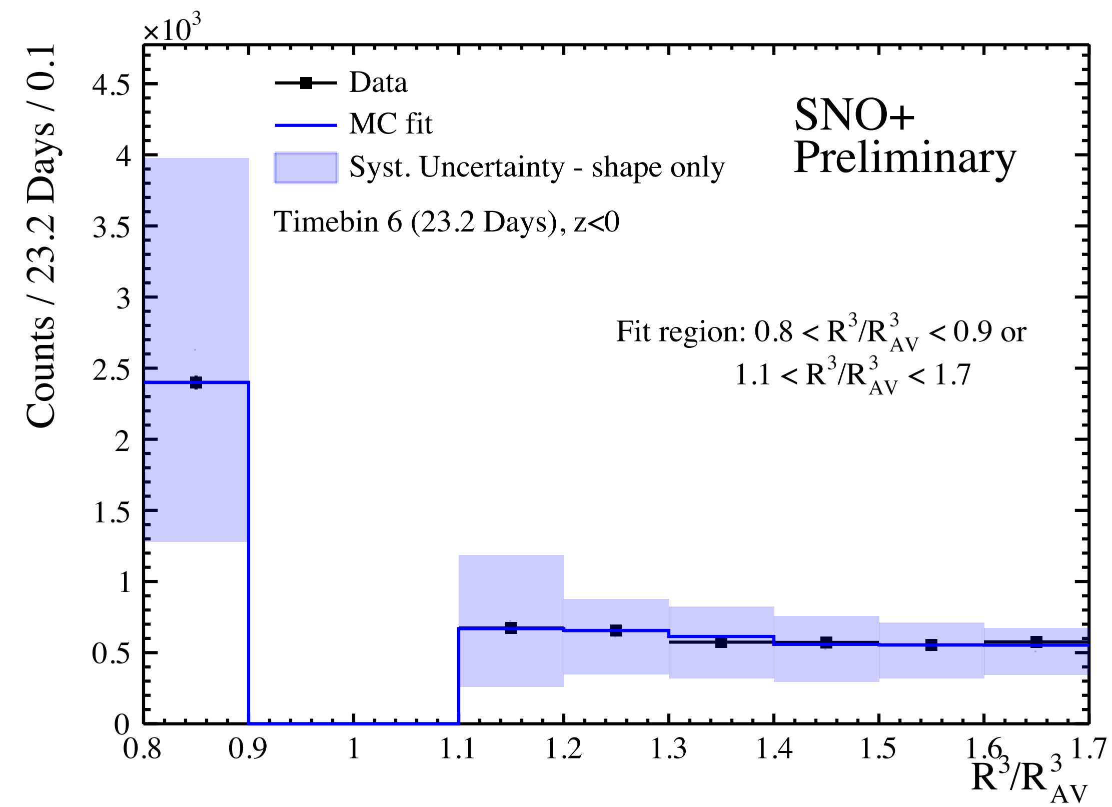
External Backgrounds

✴ *Likelihood Analysis*

- External radioactive sources:
  - Single region with a 2D fit in energy and isotropy
    - $1.1 < (R/R_{AV})^3 < 1.7$ or $0.8 < (R/R_{AV})^3 < 0.9$
    - $U.R > 0.5$



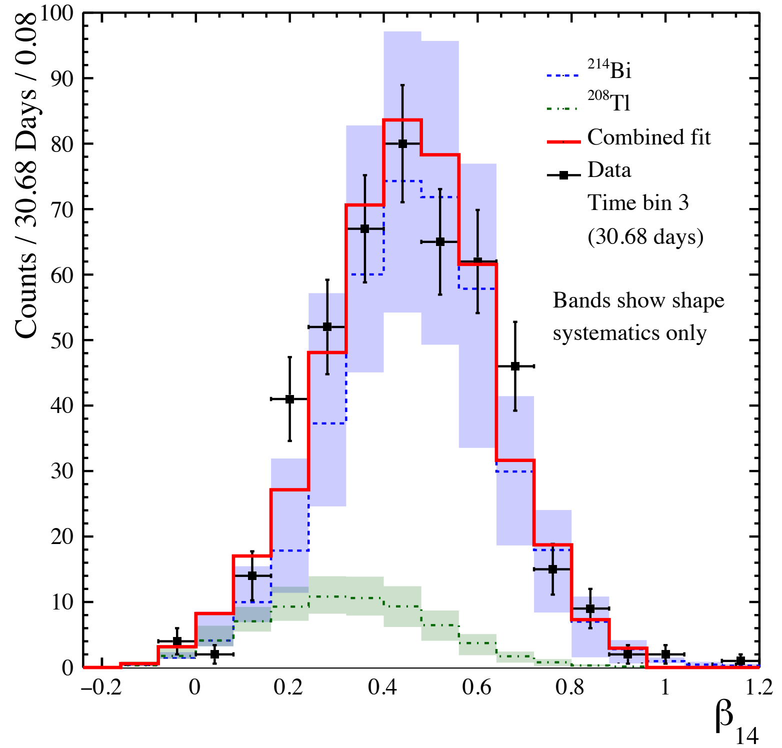




- Te = reconstructed kinetic energy
- ITR = In Time Ratio used to reject events with broad timing distributions

Internal Backgrounds

- Internal radioactive sources:
  - Single region with fit in isotropy
    - $(R/R_{AV})^3 < 0.37$



	AV water		Water shielding		AV		Ropes
	U	Th	U	Th	U	Th	Th
Period	$[\times 10^{-14}$ gU$/g_{H_2O}]$	$[\times 10^{-15}$ gTh$/g_{H_2O}]$	$[\times 10^{-13}$ gU$/g_{H_2O}]$	$[\times 10^{-14}$ gTh$/g_{H_2O}]$	$[\times 10^{-12}$ gU$/g_{AV}]$	$[\times 10^{-12}$ gTh$/g_{AV}]$	$[\times 10^{-9}$ gTh$/g_{\text{rope}}]$
1	$19.0 \pm 1.8^{+3.9}_{-3.7}$	$5.9 \pm 5.2^{+4.0}_{-5.9}$	$2.2 \pm 0.3^{+3.7}_{-1.3}$	$9.9 \pm 1.6^{+22.9}_{-9.7}$	$5.5 \pm 1.5^{+6.5}_{-5.5}$	$0.0^{+0.0}_{-0.0}\ ^{+1.1}_{-0.0}$	$0.0^{+0.0}_{-0.0}\ ^{+0.3}_{-0.0}$
2 ($z > 0$)	$48.5 \pm 3.1^{+11.7}_{-10.1}$	$34.5 \pm 13.7^{+11.2}_{-34.5}$	$86.9 \pm 1.1^{+103.2}_{-49.2}$	$207.7 \pm 6.4^{+449.9}_{-173.0}$	$33.0 \pm 16.4^{+60.8}_{-33.0}$	$12.5 \pm 2.4^{+33.9}_{-12.5}$	$2.8 \pm 0.5^{+7.7}_{-2.8}$
2 ($z < 0$)	$3.6 \pm 0.9^{+1.0}_{-0.7}$	$2.7^{+4.2}_{-2.7}\ ^{+1.3}_{-2.7}$	$16.3 \pm 0.4^{+24.4}_{-8.5}$	$39.8 \pm 2.8^{+134.8}_{-39.8}$	$7.7 \pm 5.5^{+24.4}_{-7.7}$	$3.7 \pm 1.2^{+11.0}_{-3.7}$	$0.9 \pm 0.3^{+2.5}_{-0.9}$
3	$8.7 \pm 0.7^{+2.4}_{-1.7}$	$8.3 \pm 3.1^{+3.0}_{-8.3}$	$1.7 \pm 0.1^{+2.5}_{-1.1}$	$9.3 \pm 0.5^{+19.1}_{-9.1}$	$1.2 \pm 0.9^{+7.9}_{-1.2}$	$0.0^{+0.3}_{-0.0}\ ^{+1.1}_{-0.0}$	$0.0^{+0.1}_{-0.0}\ ^{+0.3}_{-0.0}$
4	$19.4 \pm 1.0^{+5.8}_{-4.4}$	$9.4 \pm 4.1^{+6.5}_{-9.4}$	$0.6 \pm 0.1^{+1.2}_{-0.4}$	$10.6 \pm 0.6^{+19.3}_{-8.8}$	$0.3^{+0.8}_{-0.3}\ ^{+2.2}_{-0.3}$	$0.0^{+0.1}_{-0.0}\ ^{+0.5}_{-0.0}$	$0.0^{+0.0}_{-0.0}\ ^{+0.1}_{-0.0}$
5	$53.5 \pm 3.7^{+19.5}_{-14.3}$	$29.0 \pm 17.1^{+24.7}_{-29.0}$	$2.3 \pm 0.2^{+5.3}_{-1.6}$	$8.6 \pm 1.3^{+31.9}_{-8.6}$	$5.2 \pm 0.9^{+6.7}_{-5.2}$	$0.1^{+0.5}_{-0.1}\ ^{+0.3}_{-0.1}$	$0.0^{+0.1}_{-0.0}\ ^{+0.1}_{-0.0}$
6	$67.5 \pm 2.1^{+26.3}_{-20.8}$	$67.1 \pm 10.0^{+38.7}_{-67.1}$	$1.2 \pm 0.1^{+2.4}_{-0.8}$	$10.0 \pm 0.7^{+28.8}_{-10.0}$	$1.7 \pm 0.9^{+3.8}_{-1.7}$	$0.0^{+0.1}_{-0.0}\ ^{+1.0}_{-0.0}$	$0.0^{+0.0}_{-0.0}\ ^{+0.2}_{-0.0}$

Upcoming Results

Radioactive Backgrounds

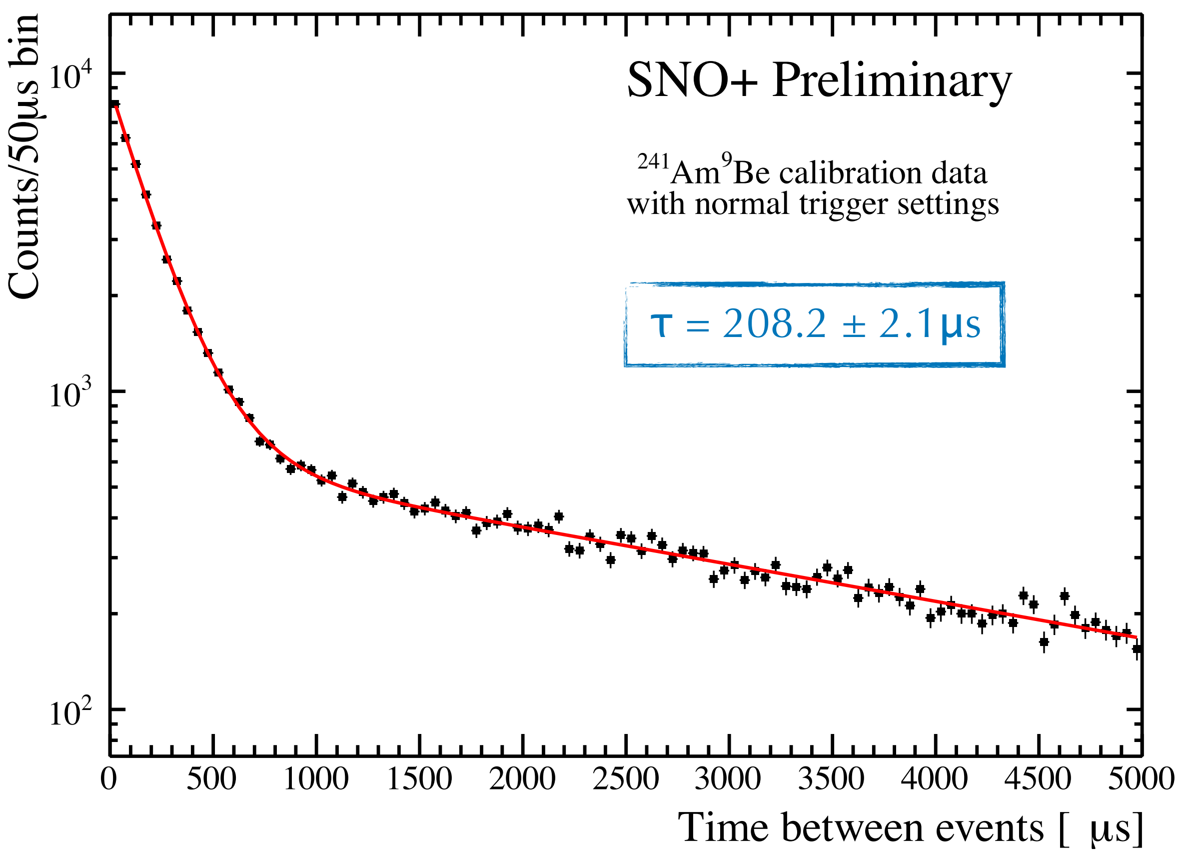
- Since October 2018 the top of the acrylic vessel is covered by a cover gas volume = volume filled with boiled-off nitrogen that reduces the Rn ingress of a factor larger than 10^4
  - Highly reduced U-chain background level allows a better identification and discrimination among background sources
  - In preparation = Measurement of external background source paper
    - Extremely important for all the follow-up phases.
- The data taking period is nearly twice the initial one
  - Increase the statistics for the nucleon decay search
  - Increase the statistics for the solar neutrino measurement at lower (<5 MeV) energy

Neutron Detection

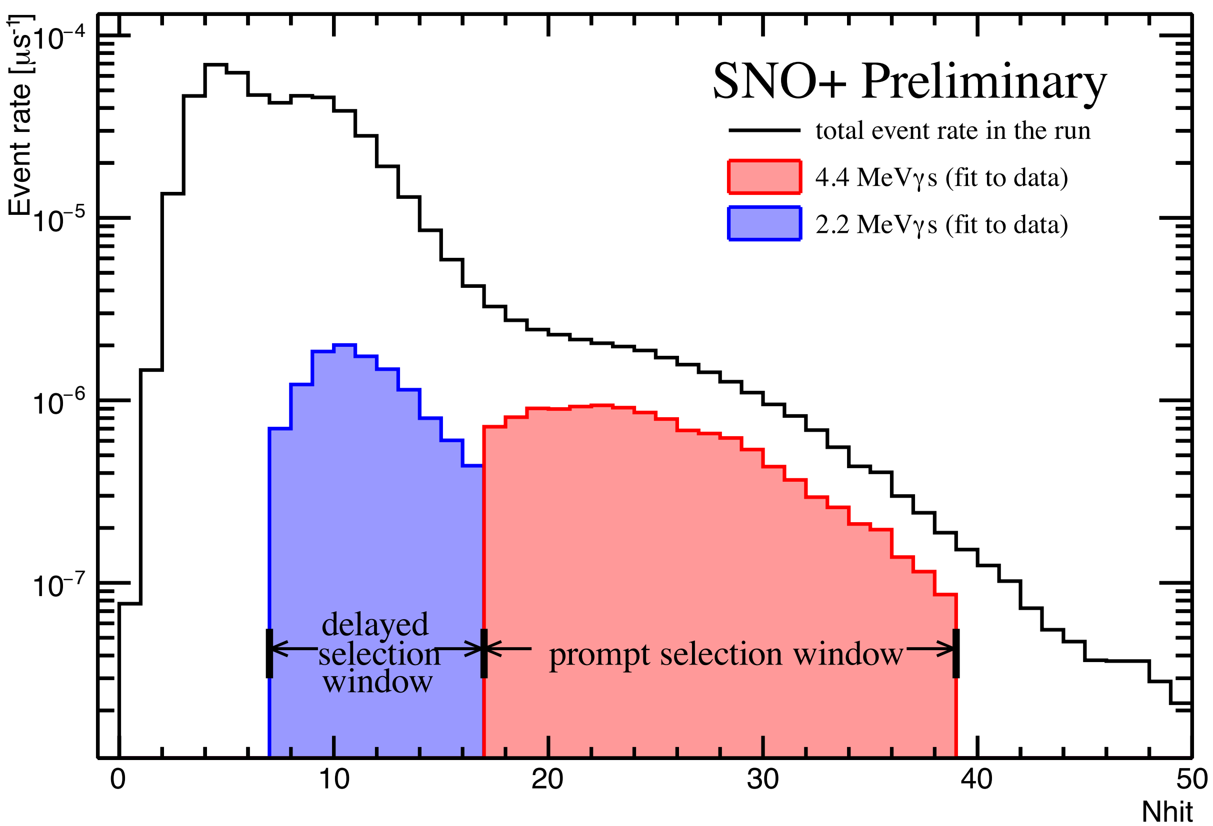
Deployment of AmBe source

- Neutron detection efficiency
- Neutron capture time

Efficiency for triggering on a neutron: 47%



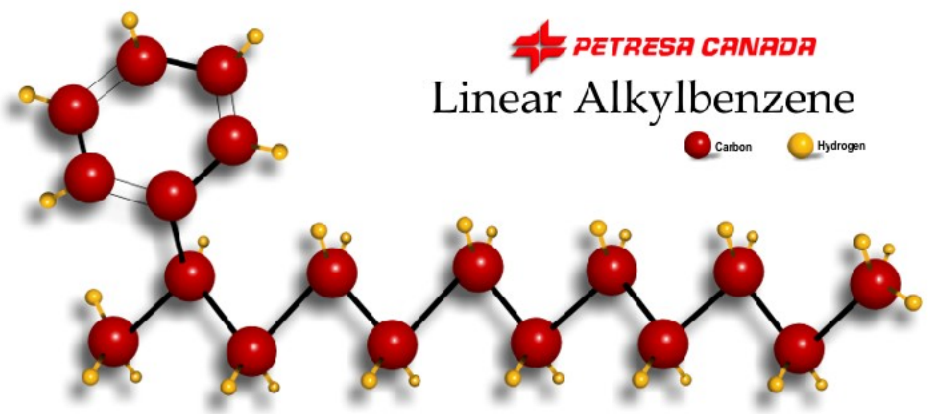
Simple coincidence analysis.
2-exponential fit: signal + random backg.



Signals extracted from the statistical analysis of coincidences (prompt 4.4 MeV γs and delayed 2.2 MeV γs) are compared to the total rate in this central AmBe run.

Future
SNO+

✳ Use of Tellurium



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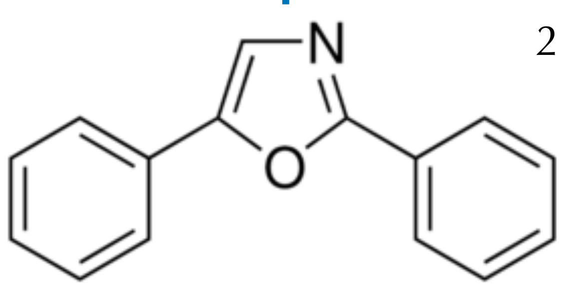
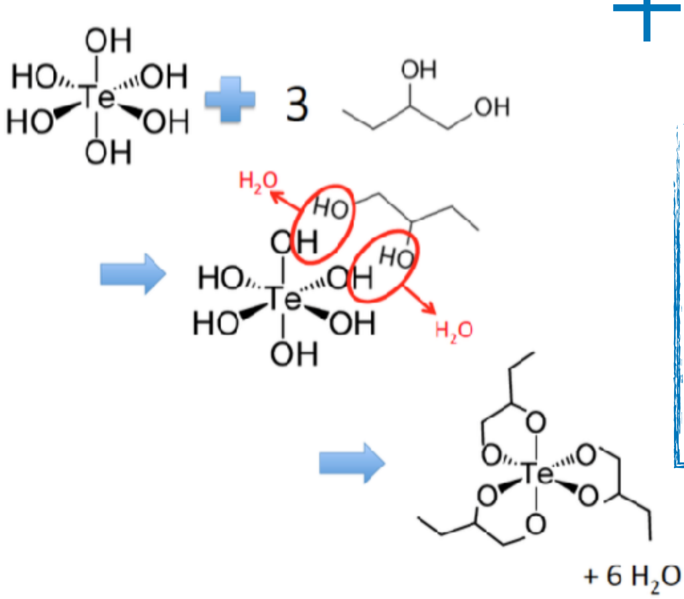


2 g/L PPO

+

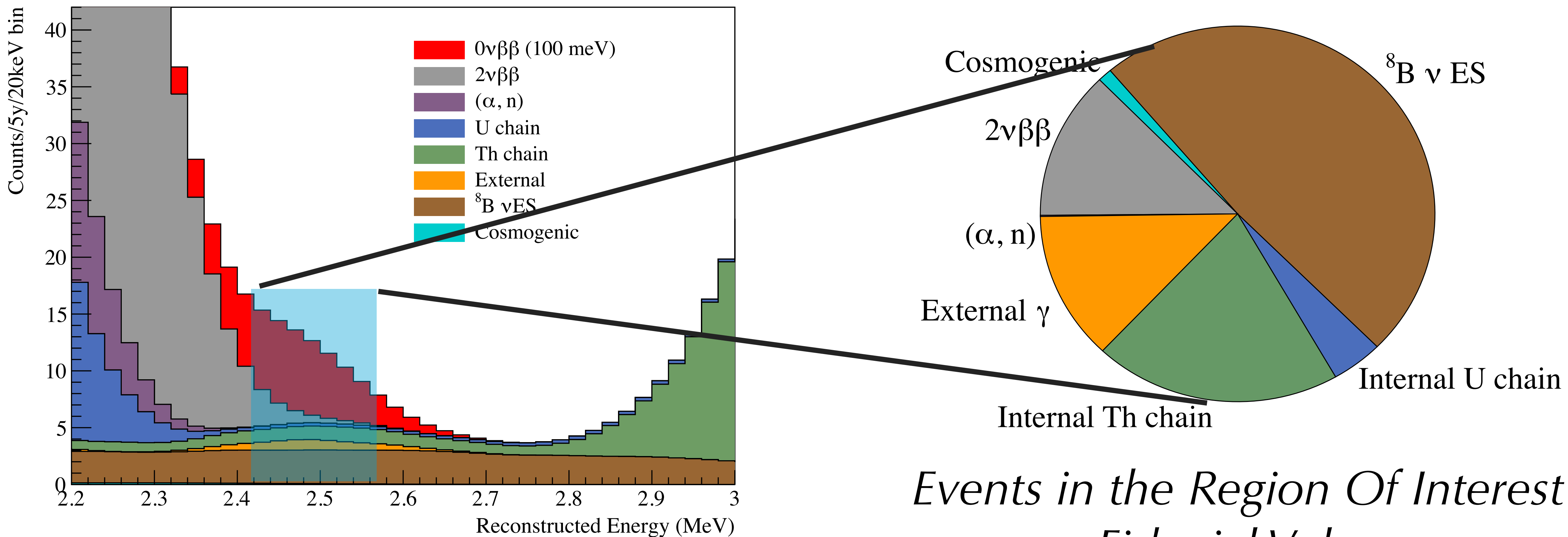


0.5% by mass natTe = 3900 kg

- Chemical compatibility with acrylic
- High light yield (~10,000 optical photons/MeV)
- High purity available
- Low scattering
- Good optical transparency
- Fast decay (different for betas and alphas)

- High natural abundance (34.08%)
- 2υββ $T_{1/2} = 8.2 \times 10^{20}$ yr
- Q-value = 2.53 MeV
- Good alpha/beta discrimination
- Long attenuation length
- High light yield
- No inherent optical absorption lines

Expected background



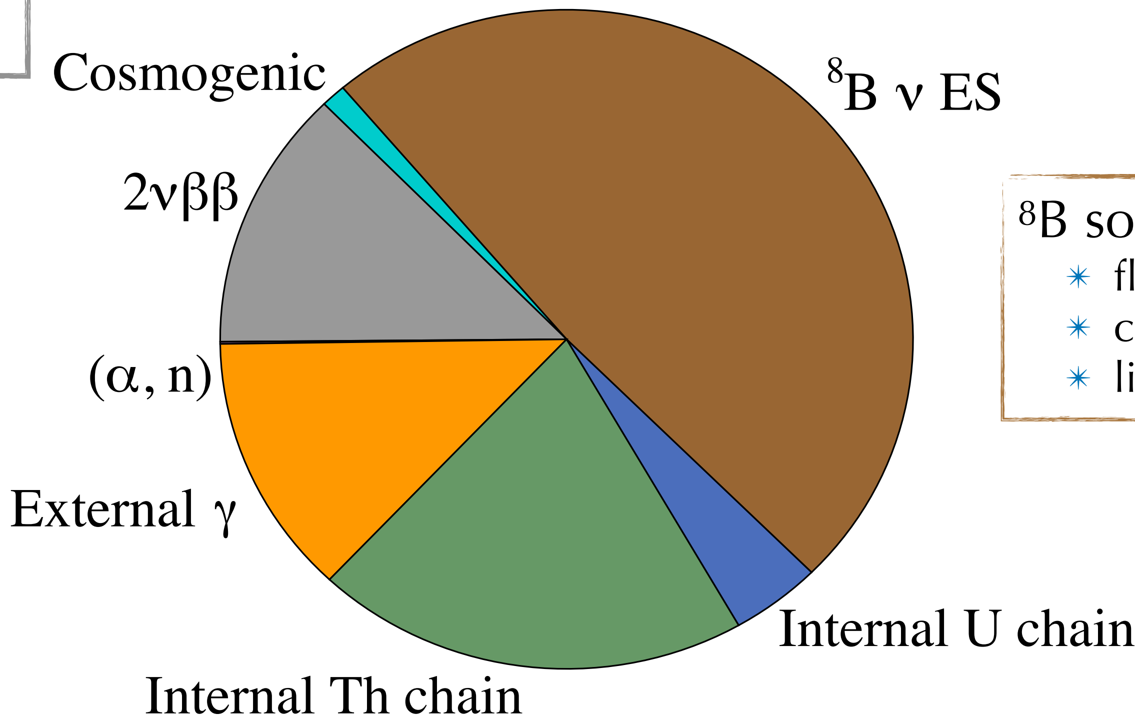
Events in the Region Of Interest
+ Fiducial Volume
9.47 events/yr

Expected background

Cosmogenic:
- ^{60}Co, ^{110m}Ag, ^{88}Y, ^{22}Na
- mitigation: purification + "cool-down" UG
- aimed: less than 1 ev/yr in ROI/FV

Two neutrino mode 2vßß:
- asymmetric ROI around the 0vßß signal
- limited by energy resolution

(a,n):
- alpha-capture on 13C/18O
- production of neutrons
- thermal neutron capture
- delayed coincidence tagging



^{8}B solar neutrinos:
- flat spectrum
- constrained by SNO/SK data
- limited by resolution

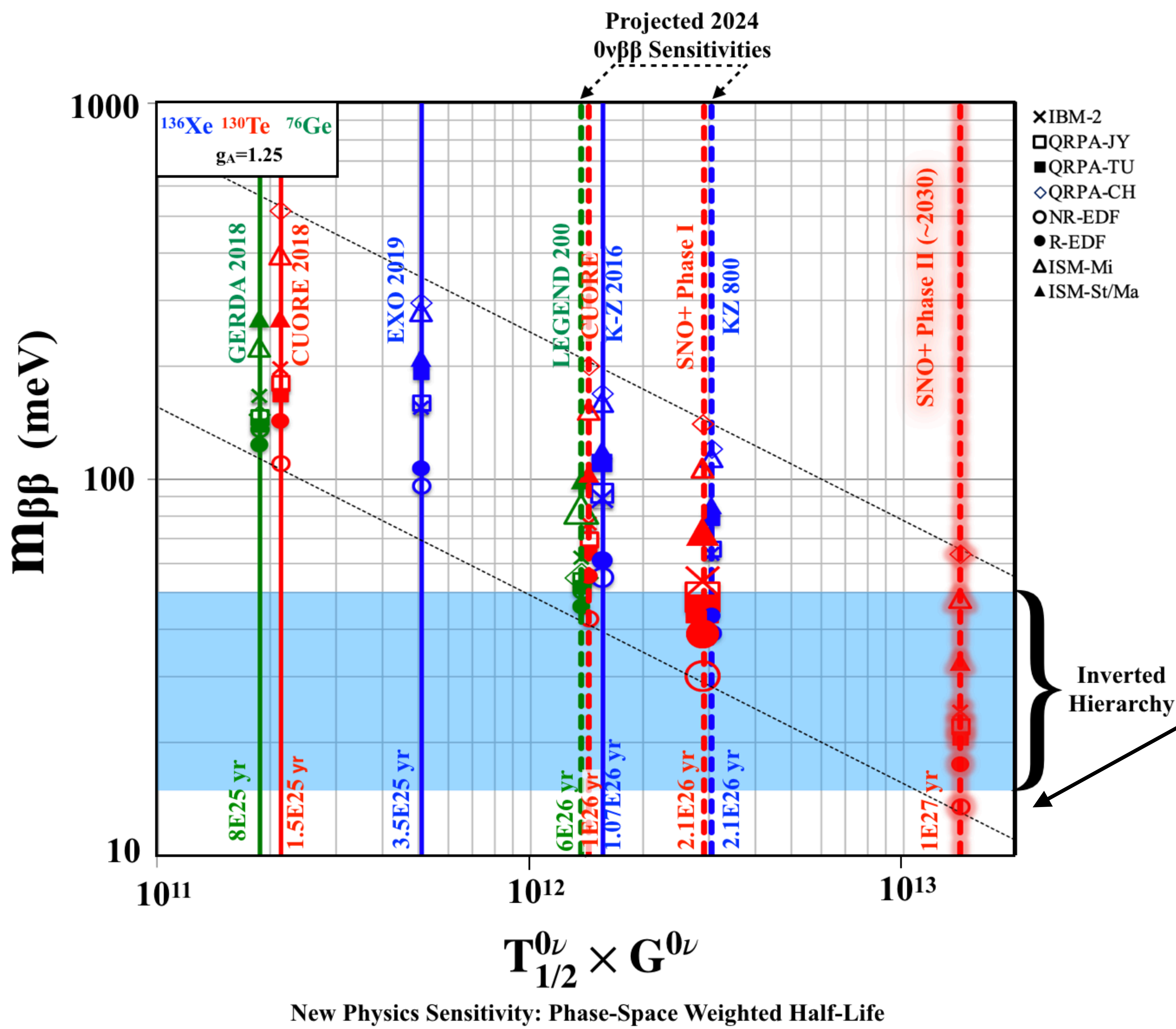
External gammas:
- from AV, ropes, water, PMTs
- fiducial volume (17%) cut

Internal U/Th chain:
- $^{214}BiPo$, $^{212}BiPo$
- ß – α delayed coincidence tagging + in-window rejection

	$T_{1/2}$ [yr]	$m_{0vßß}$ [meV]
0.5% Te, 5 yr	2.1×10^{26}	37 - 89

Future²
SNO+

Higher Loadings



Requires more than 20 t **isotope** loading

WHY TE-LOADED SCINTILLATOR?

$$m_{\beta\beta}^{-2} \propto T_{1/2}^{0\nu\beta\beta} \propto \frac{\varepsilon}{A}\sqrt{\frac{M \cdot t}{B \cdot \Delta E}}$$

To improve the sensitivity by a factor of 2, it is necessary an experimental improvement of 16

→

Requirements:
- **Large masses (volumes)**
- **High radio-purity**

✓ The loaded liquid scintillator technique is easily scalable
✓ ^{130}Te has a large natural abundance that doesn't require loadings
✓ Among the DBD isotopes is relative cheap (20 times cheaper than Xe)
✓ Annual production is ~150 t (Xe resources are very limited)

Summary

SNO+ completed its water phase:

- ✳ Two main physics papers published up to now:
  - invisible nucleon decay
  - ^{8}B solar neutrinos
- ✳ Measured external backgrounds
  - Paper in preparation
- ✳ More analyses to come:
  - neutron capture
  - anti-nu in water
- ✳ SNO+ started pure scintillator phase:
  - Low energy solar neutrinos
  - Reactor nd geo antineutrinos
- ✳ In 2020 we expect to deploy Te
  - Search for the neutrinoless double-beta decay

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LIP Lisboa

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University of Alberta
Queen's University
Laurentian University

TU Dresden

Boston University
BNL
University of California Berkeley
LBNL
University of Chicago
University of Pennsylvania
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University of Liverpool
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UNAM

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