Antineutrinos in the SNO+ water phase

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LIP seminar, April 2023

https://snoplus.ca/

https://lip.pt/

Outline

Introduction: historical context
- discovery of the neutrino and oscillations
- large neutrino detectors and SNO+
- SNO+ physics and reactor antuneutrinos

I - Calibration for antineutrino measurements
- the AmBe calibration source
- highest neutron capture efficiency
- neutron-proton capture cross-section

II - Seeing reactor antineutrinos in pure water
- the signal and main backgrounds
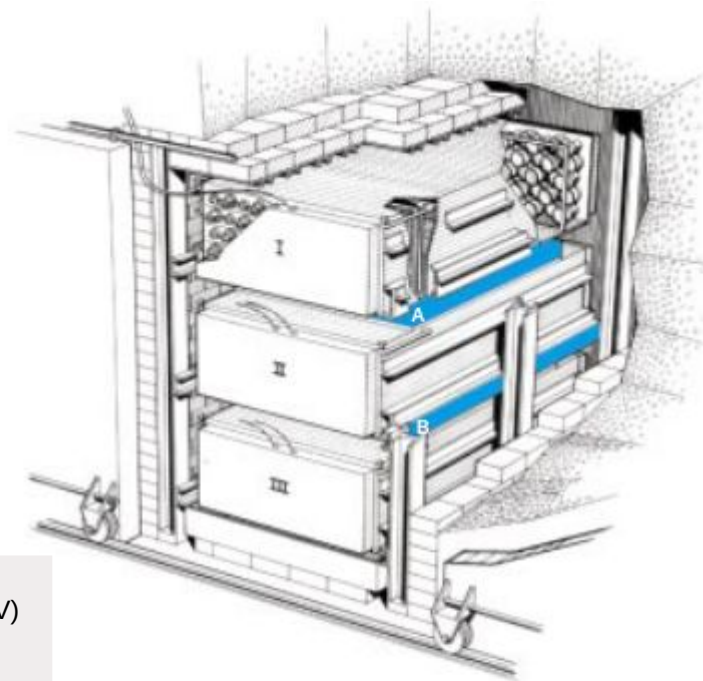- 3.5 sigma combined evidence
- putting it back into context

the neutrino discovery

25 years from the desperate remedy to the inverse beta decay

Neutron Beta Decay

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

Inverse Beta Decay

$$\bar{\nu} + p \rightarrow n + e^+$$
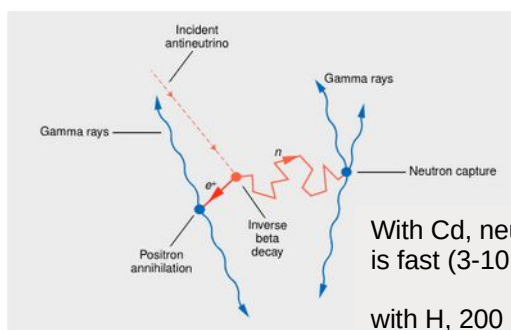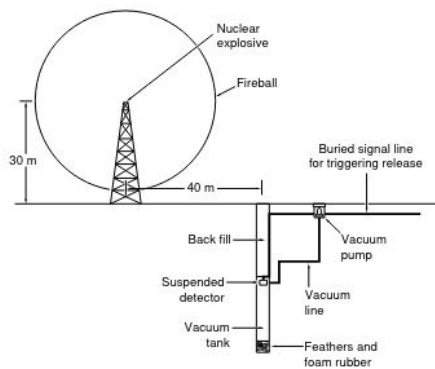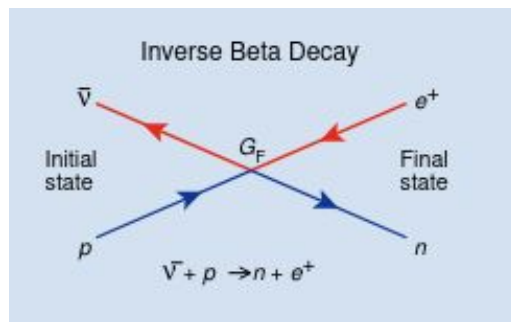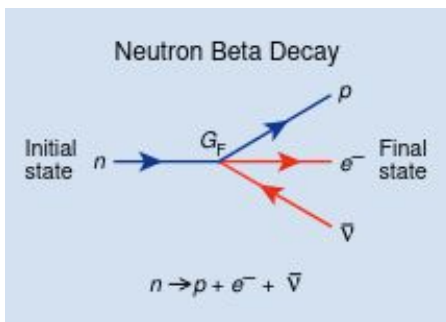
With Cd, neutron capture signal is fast (3-10 us) and high (9 MeV)

with H, 200 us and 2 MeV

A,B: 200 liters Water with Cadmium
I, II, III: 1400 liters of liquid scintilator, overseen by 110 PMTs
1 event / hour (5 times less with reactor off; signal / background~4)
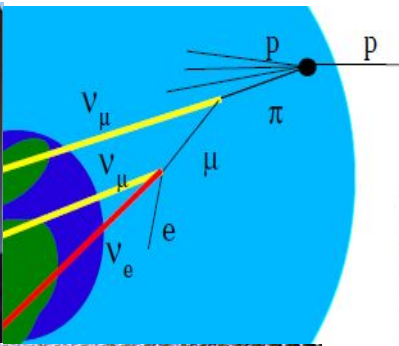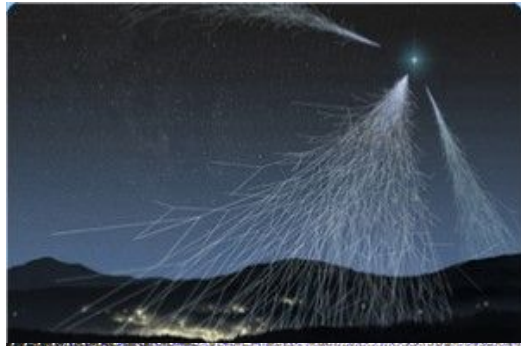Why not just water? Why not just scintillator?
Coincidence and anti-coincidence are the key ingredients

The Reines-Cowan Experiments: detecting the Poltergeist
LANL Report, LA-UR-97-2534-02
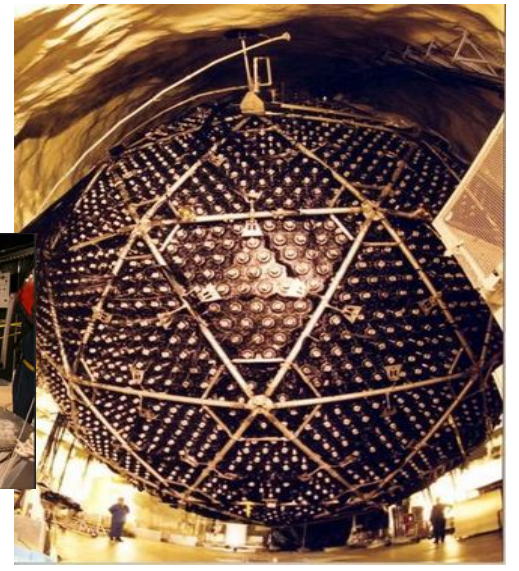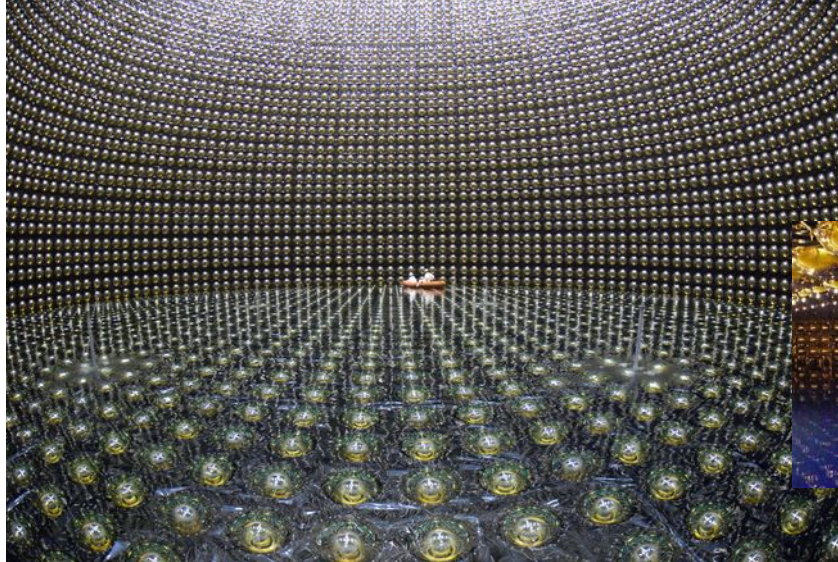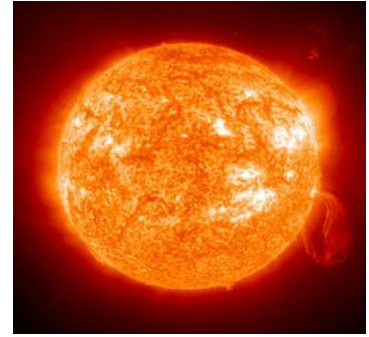
neutrino oscillations

from natural sources to human made neutrinos and back

underground labs for
shielding cosmic rays

very large (kton)
detectors, overviewed
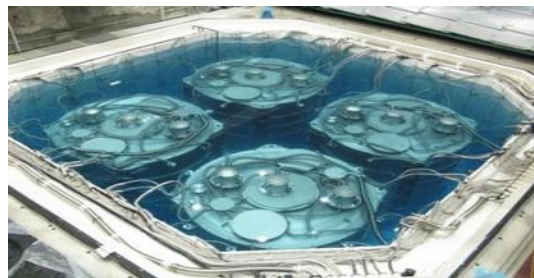by thousands of PMTs

very pretty sites :-)

neutrino oscillations

from natural sources to human made neutrinos and back
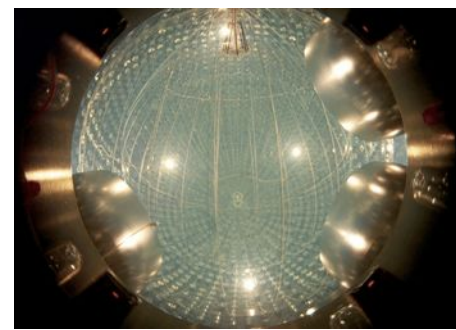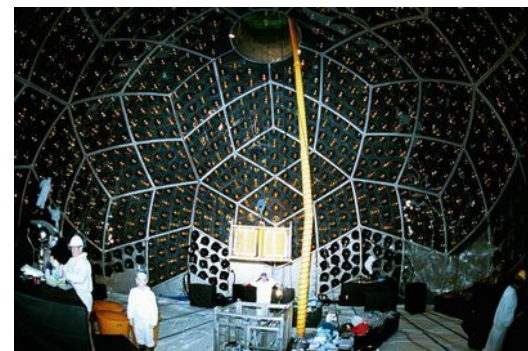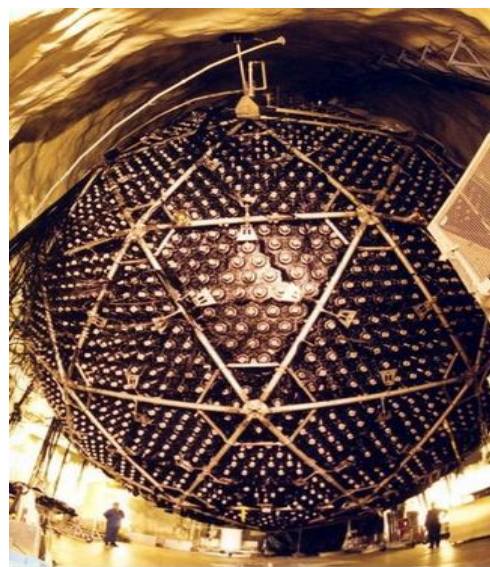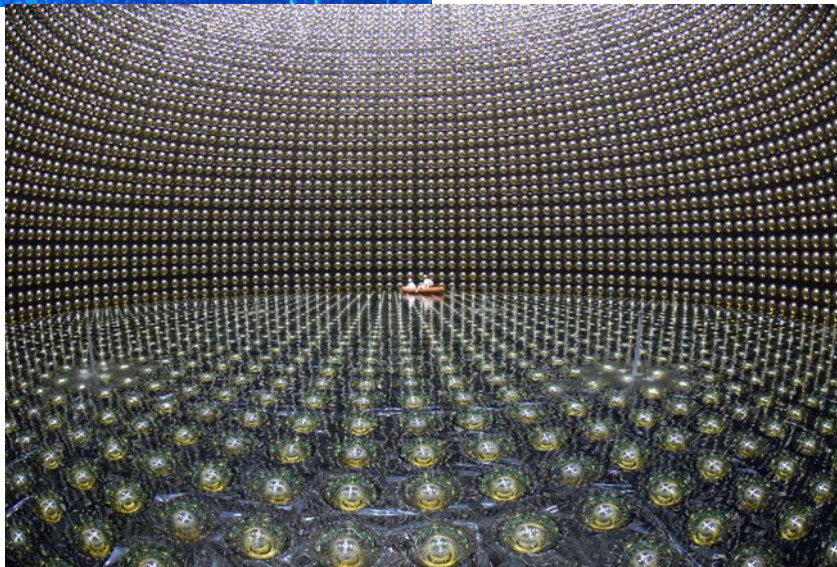
neutrino oscillations

from natural sources to human made neutrinos and back

SuperKamiokande
(GeV) atmospheric neutrinos

[muon (anti)neutrino disappearence]

K2K / T2K
(GeV) beam of muon (anti)neutrinos

SNO
(MeV) solar neutrinos

[electron neutrinos
change to others

NC in heavy water!]

KamLAND
(MeV) reactor
antineutrinos (150 km)

[compatible with solar]

IceCube

[more water]

Daya Bay
(MeV) reactor
antineutrinos (~1 km)

[last mixing angle]

Borexino

[solar electron nu
+ geo antinu]

neutrino physics in SNO(+)

from neutrino mass to neutrino mass mechanisms
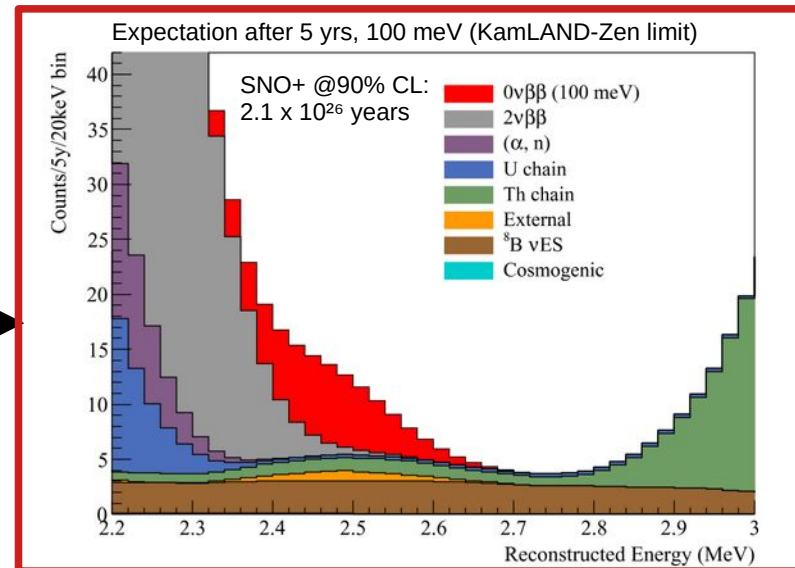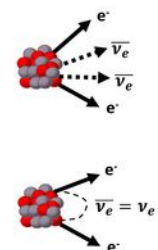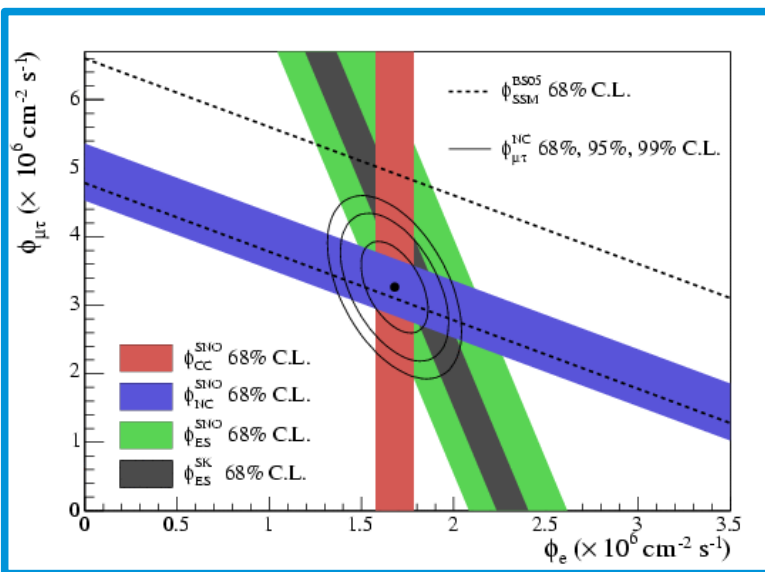
SNO
1kt D2O

Water Phase	Partial Fill	Scint Phase	Tellurium Phase	SNO++ ?
905 t H2O	H2O + LAB	780 t LAB	780 t LAB	More Tellurium?
			1.3 kg ^{130}Te	Other isotopes?
May 2017	March 2020	May 2022		
June 2019	Octob 2020	ongoing		

oscillations in SNO+

solar and reactor neutrinos in the same detector

reactor neutrinos in SNO+

solar neutrinos in SNO+
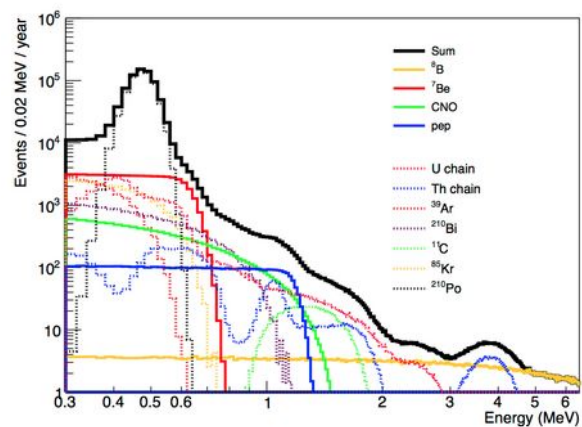
(note backgrounds,
no direction,
no coincidence tagging)
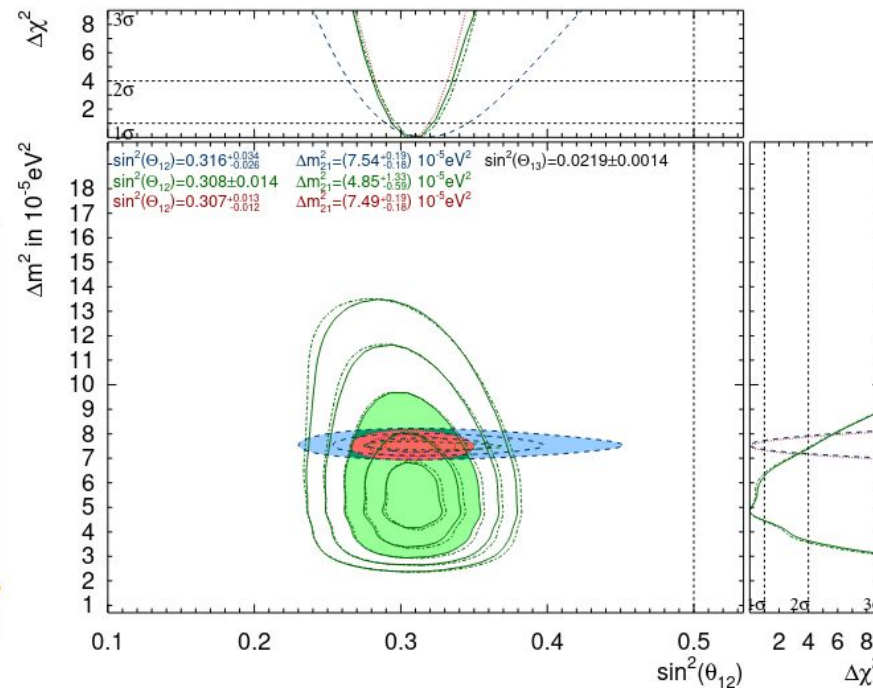
Solar Neutrino Measurements in SuperKamiokande IV

Phys.Rev.D.94.052010 (2016)
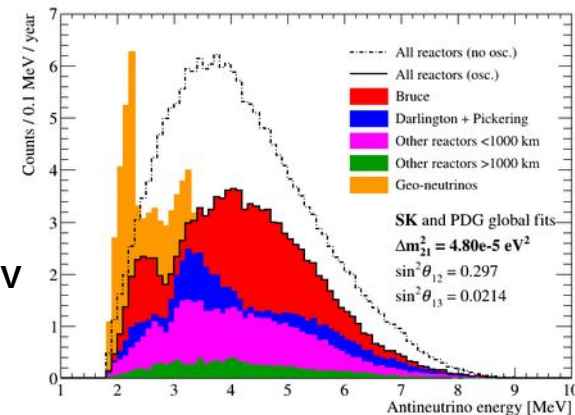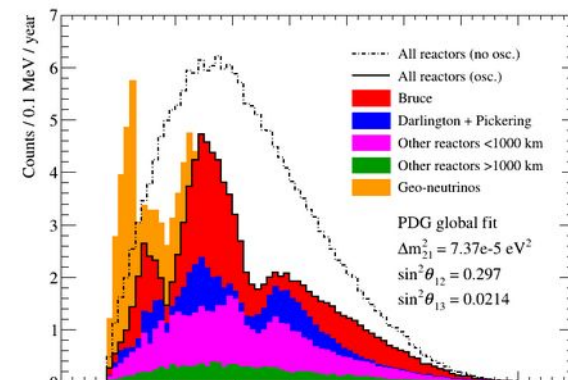
reactors around SNOLab

very clear oscillation pattern from 240 km and 350 km

Bruce at 240 km, Darlington+Pickering at 350 km in Canada (60% of flux)

CANDU (PHWR) reactors, with constant refuel, variations < 1%
thermal power modeled from hourly electrical power data

+ 100 (P/BWR) cores in the USA, with average baseline 620 km
thermal power from IAEA monthly average data (40% of flux)

	U-235	Pu-239	U-238	Pu-241
PHWR	0.52	0.42	0.05	0.01
P/BWR	0.57	0.39	0.08	0.06

Known biases corrected by scaling prediction, +-3% syst. unc.
(in water analysis the survival probability uncertainty is +- 4%)

$$Pee = 1 - \sin^2 2\theta \cdot \sin^2 (1.27\ \Delta m^2\ L/E)$$

the SNO+ detector

2070 m underground
@ SNOLAB, Canada

~ 3 muons / hour
(veto following 20 s)

active medium up to 6.0 m
(5.5 cm thick acrylic vessel)

> 9000 PMTs @ 8.5 m
(50 % optical coverage)

ultra-pure water for shielding
(+ 91 OWL PMTs)

access from the top deck
to the "neck" and outer water

scintillator lighter than heavy water
(1000 ton to 780 ton + 4 ton Te-nat):
new hold down rope systems

scintillator will have much higher rates:
electronic & DAQ upgrade

in adittion to water purification plant,
need also scintillator plants underground

cover gas-system was redesigned
higher purity calibration sources/systems

new simulation tool RAT, based on Geant4
and GLG4sim (from LS experiments)

+ an array of photographic camaras

the SNO+ detector

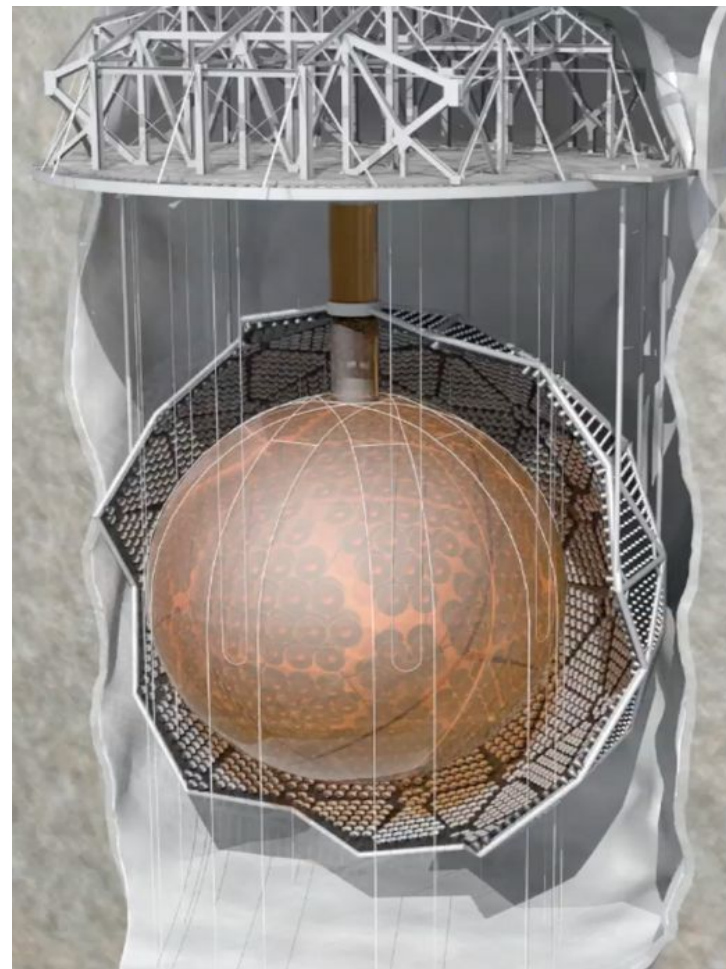

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the SNO+ water phase

first physics results
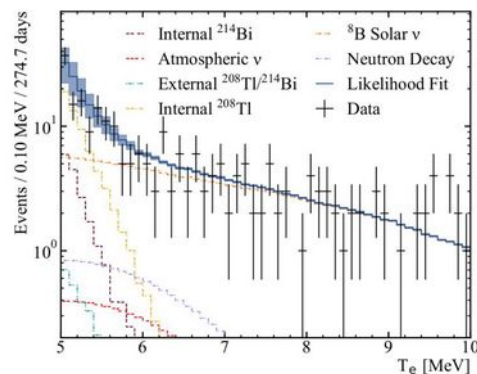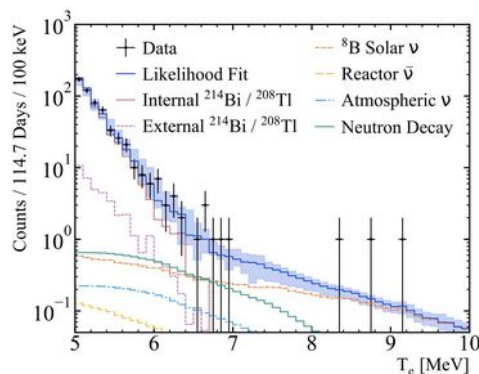
Search for invisible modes of nucleon decay

in water with the SNO+ detector

PRD 99, 032008 (2019) + PRD 105, 112012 (2022)

$\tau(n,p,pp,np \to inv) > 10^{28 / 29}$ years

(factor 3 improvement on previous results)
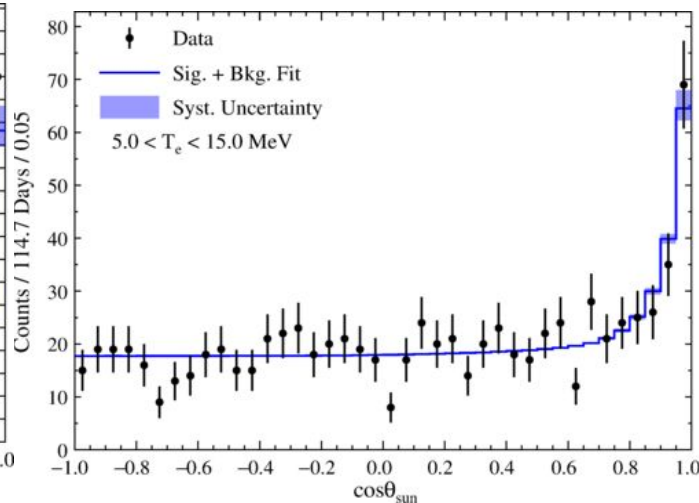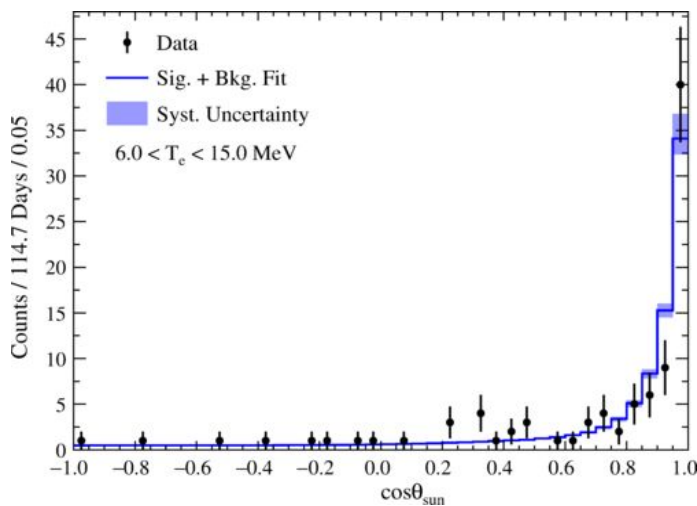
Measurement of the 8B solar neutrino flux

in SNO+ with very low backgrounds

PRD 99, 012012 (2019)

For reference, SNO LETA & SK IV go down to 3.5 MeV

the main limitation is from radioactive backgrounds

the SNO+ water phase

calibration for the water Cherenkov detector (and beyond)
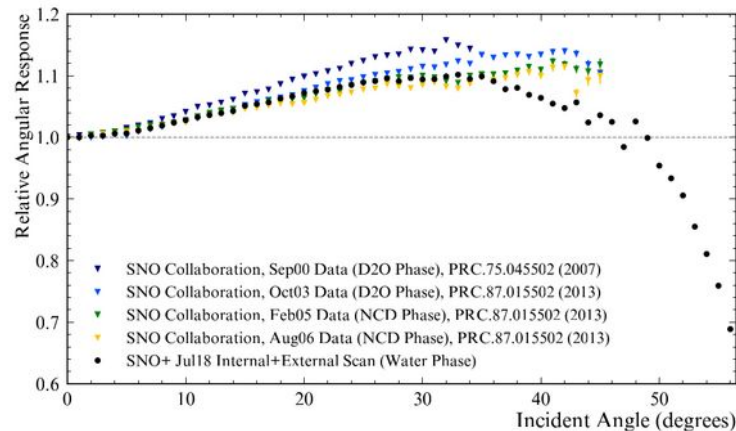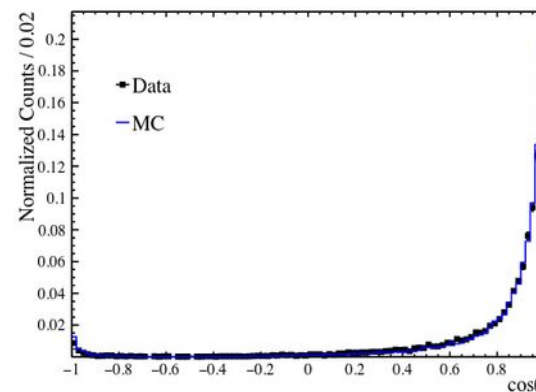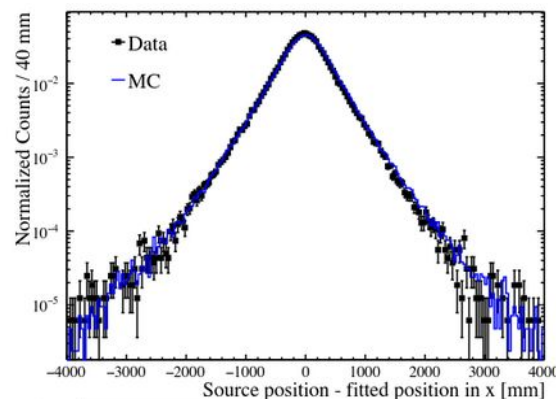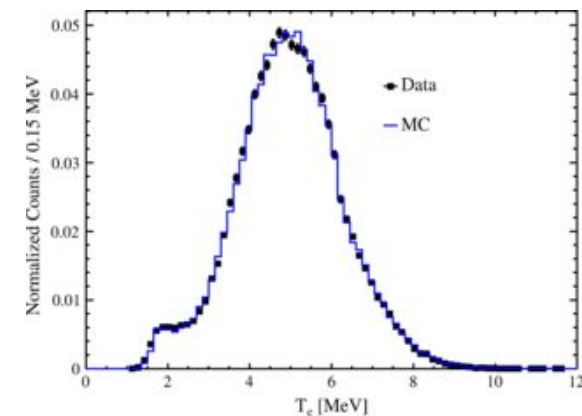
Laserball	- isotropic light, many wavelenghts
N16	- 6.1 MeV gamma (tagged by a beta)
AmBe	- 4.4 MeV and 2.2 MeV gammas (it is our *antineutrino* calibration source)

Optical calibration of the SNO+ detector in the water phase with deployed sources
JINST 16, P10021 (2021)

the calibration campaing

how to use our *antineutrino* / AmBe source
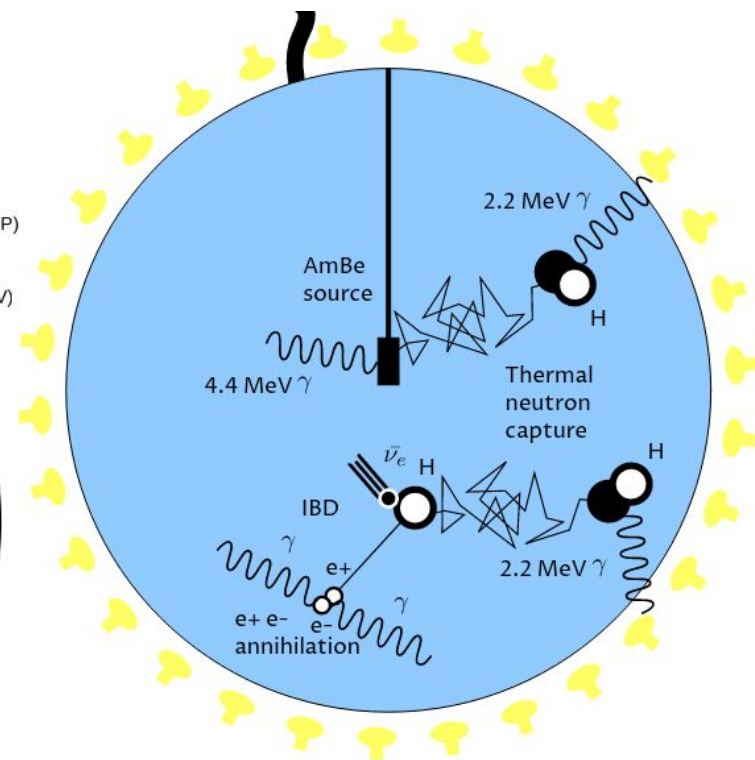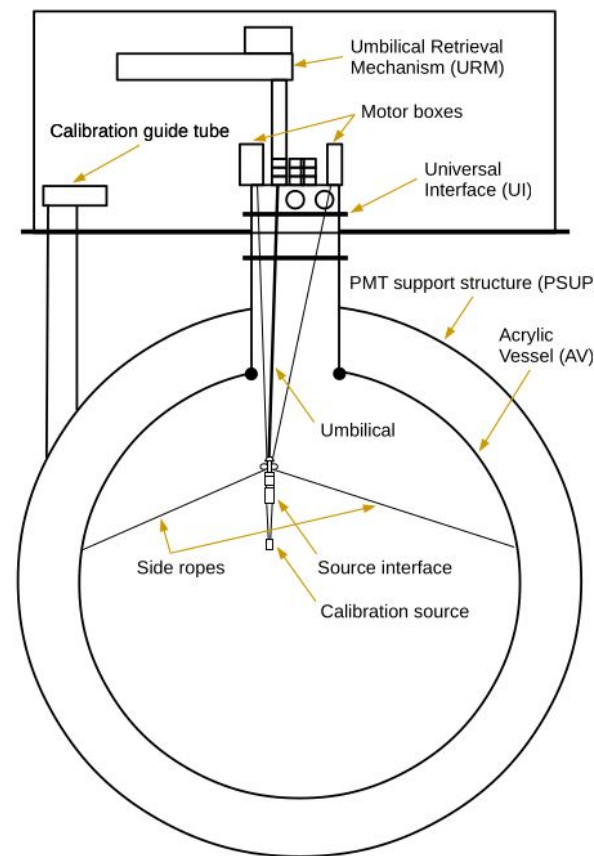
^{241}Am (alpha decays with T1/2 = 432 years)

^{9}Be (α,n) ^{12}C(*) with an efficiency of O(10^{-4})

^{9}Be (α,n) ^{12}C* -> ^{12}C + 4.4 MeV γ

n + p -> D* -> D + 2.2 MeV γ

(BR~40%, ^{12}C in ground state, no tag)

neutron capture in pure water

calibration campaigns of January 2018 and June 2018
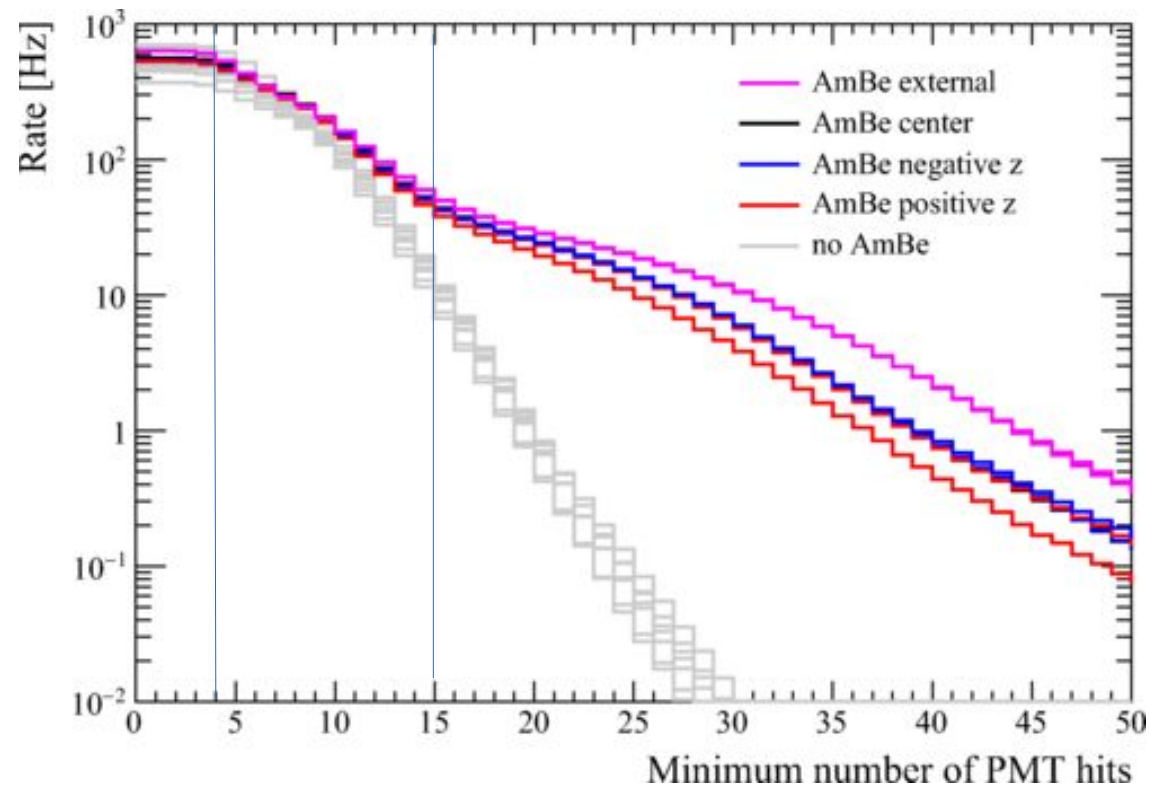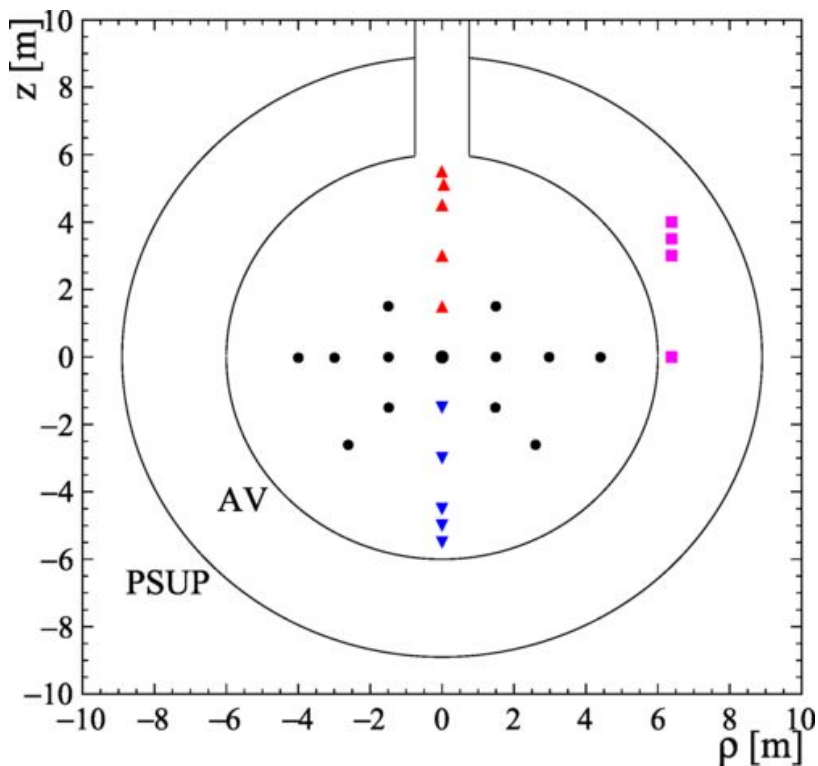
neutron capture in pure water

trigger efficiency close to 50% in the central water volume
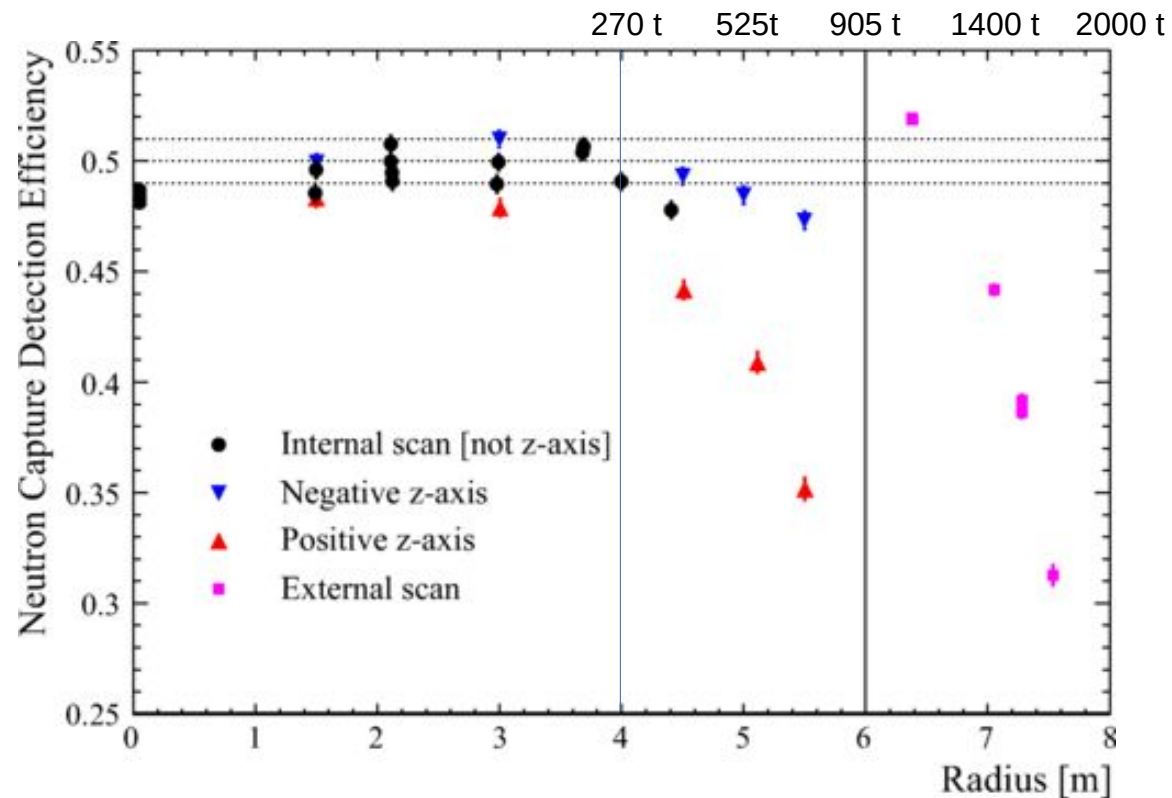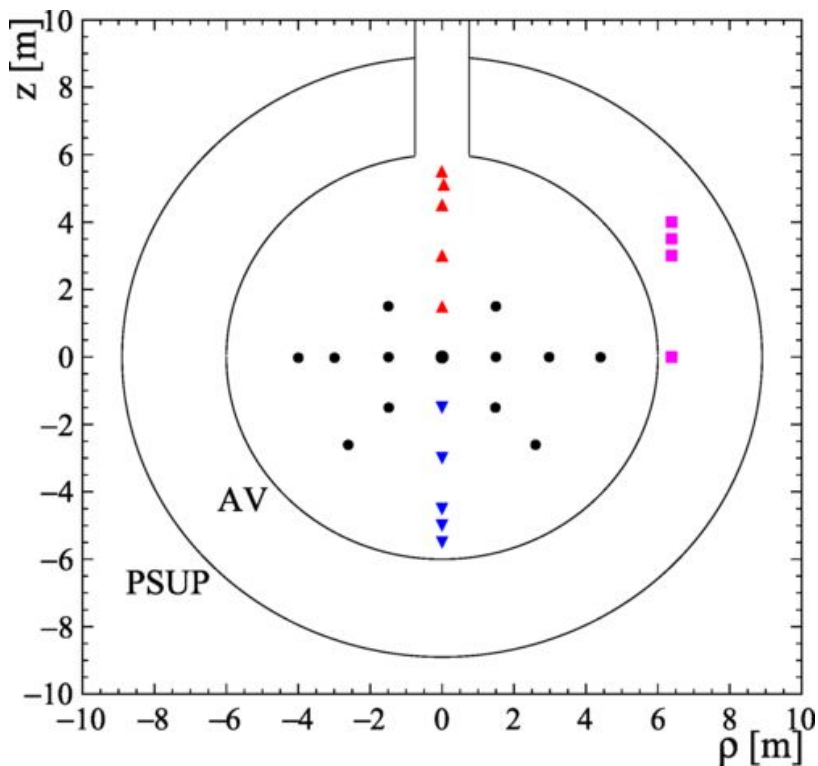
can also use a much larger water volume

coincidence analyses

extracting source signals from background

$\tau = \lambda^{-1} = (207.03 \pm 0.42)\ \mu s$

$P = (99.62 \pm 0.15)\%$ $E = (48.44 \pm 0.17)\%$

Counts/50 μs bin

- $N_p = 18, N_d = 5$
- $N_p = 15, N_d = 14$
- $N_p = 25, N_d = 4$

Time between events [μs]
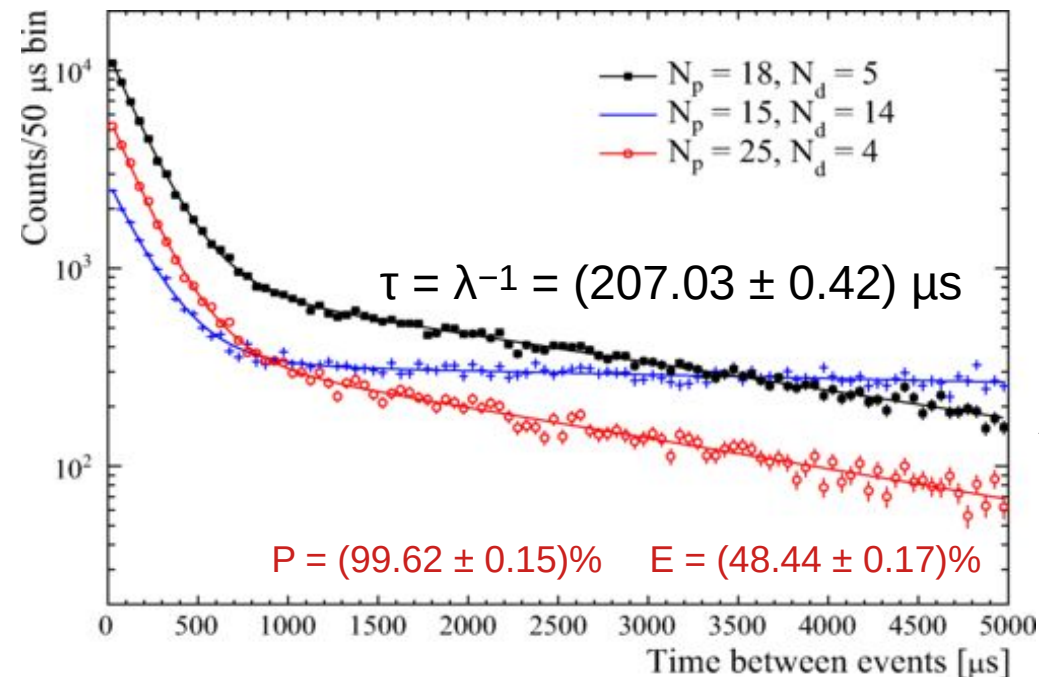
R_p, rate of single events, with $N_{hits} > N_p$
R_d, rate of single events, with $N_{hits} > N_d$

P_p, purity of prompt signal (4.4 MeV γ)
E_d, efficiency for delayed signal (2.2 MeV γ)

R_p P E : coincident events from the source
(1−P) + P (1−E) = (1−P E): random coincidence

λ + R_d: for both true and random coincidences
neutron capture time constant τ = 1 / λ

$$\frac{dN}{dt} = T \cdot R_p[PE \cdot (\lambda + R_d)\exp(-(\lambda + R_d)t) + (1 - PE)\cdot R_d \exp(-R_d t)]$$

coincidence analyses

extracting source signals from background
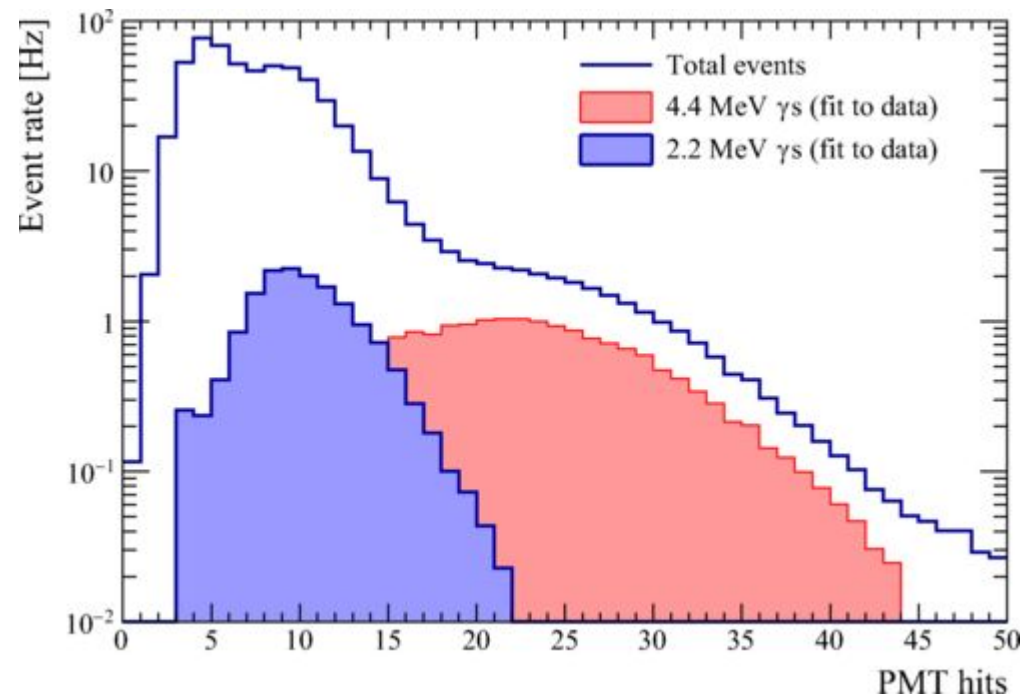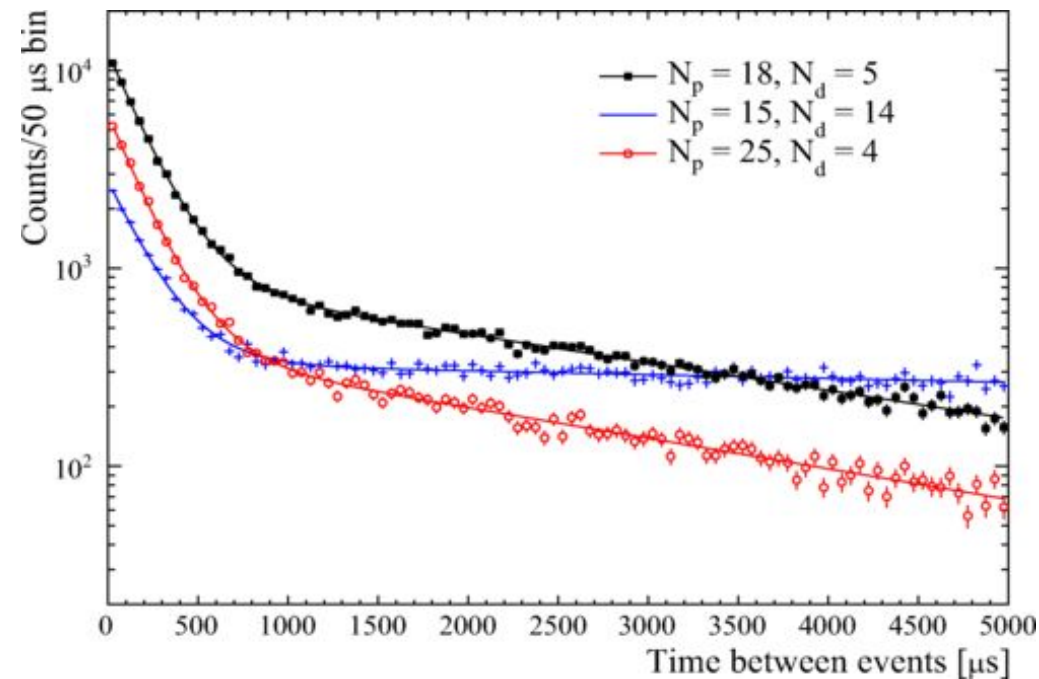
$$\frac{dN}{dt} = T \cdot R_p [PE \cdot (\lambda + R_d) \exp(-(\lambda + R_d)t) + (1 - PE) \cdot R_d \exp(-R_d t)]$$

n-p capture cross-section

a new precise measurement

	Efficiency [%]	τ [μs]
Fit result	48.44 ± 0.17	207.03 ± 0.42
Source encapsulation	0.43 ± 0.20	$-2.86^{+0.70}_{-0.54}$
Rate fluctuation	0.21 ± 0.29	$-1.78^{+0.23}_{-0.25}$
Final result	49.08 ± 0.39	$202.35^{+0.87}_{-0.76}$

202.6 ± 3.7 μs by SuperK
203.7 ± 2.8 μs by SuperK

$$\sigma_{H,t} = \frac{1}{\tau \, v_{n,t} \, n_H}$$

vn,t = 2200 m/s, Ek = 0.02530 eV
NH = 0.6680×10^{29} / m³

$$\sigma_{H,t} = 336.3^{+1.2}_{-1.5} \text{ mb}$$

Compatible to older measurements:

334.2±0.5 mb, Nucl. Phys. 74. 497 (1965)

332.6±0.7 mb, Phys. Rev. C 15, 1636 (1977)

Shoot strong neutron pulses into water and measure decay neutron spectra and temperature systematics negligible (ie, presented uncertainty is only statistical)

almost 50% trigger efficiency!
efficiency evaluated at detector center
reasonably flat up to R < 4 m
also usable in the external water

Measurement of neutron-proton capture in the SNO+ water phase   Phys. Rev. C 102, 014002 (2020)

Evidence of Antineutrinos from Distant Reactors Using Pure Water at SNO+   Physical Review Letters (130) 091801, 2023

coincidence tagging
coincidences in time, but also in space

$\tau = \lambda^{-1} = (207.03 \pm 0.42)$ μs

$\tau = \lambda^{-1} = (209 \pm 3)$ μs

4 delayed hits compatible
with the prompt position
(efficiency reduced by 2%
but purity increased 3.5 x)
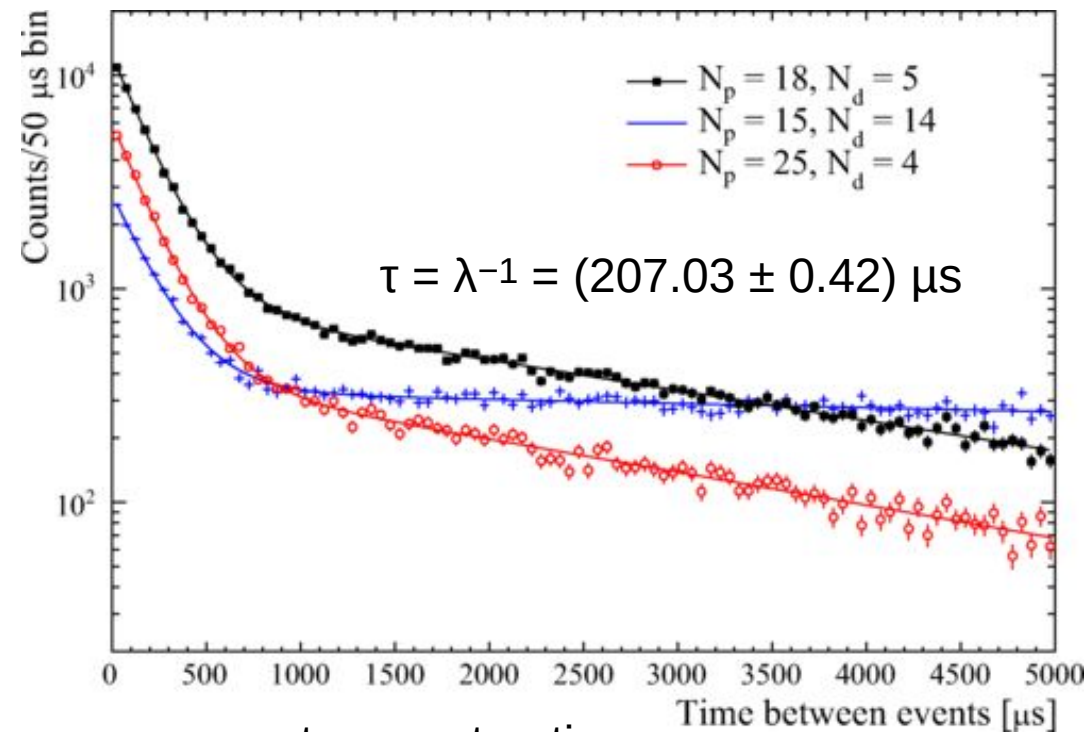
no event reconstruction,
just trigger level info
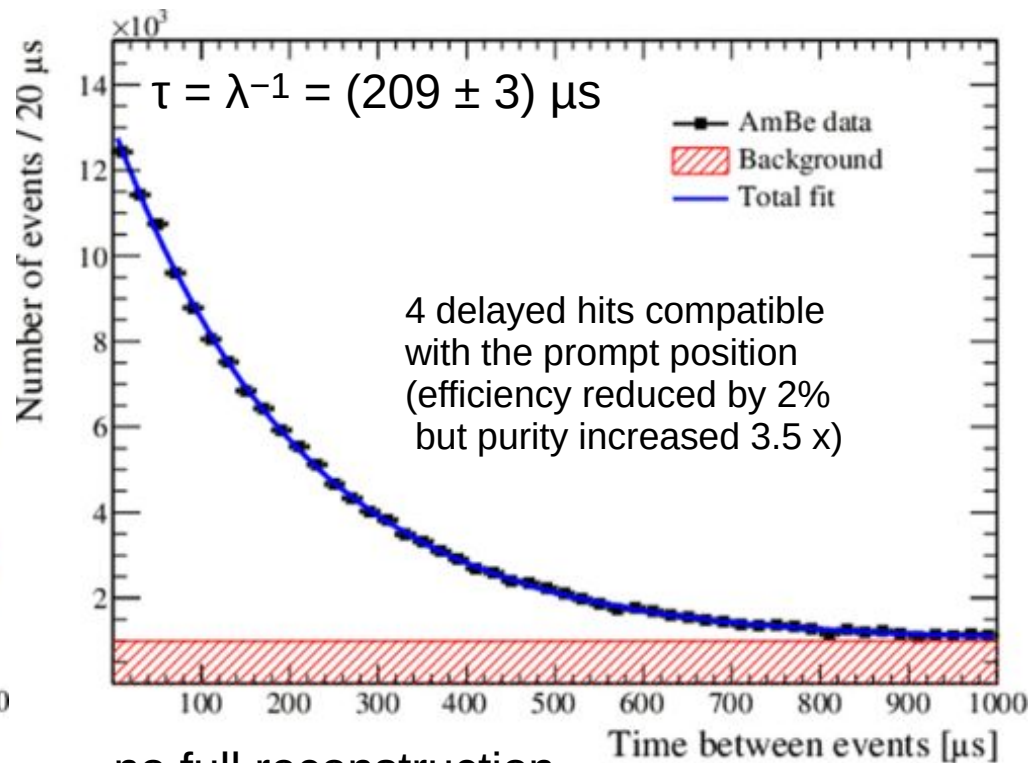
no full reconstruction,
base of SuperKamiokande delayed trigger

SK-IV dedicated trigger

coincidences in time, but also in space

60 kHz to read out all PMTs, search for coincidences with 200 ns
Super High Energy (~ 7.5 MeV), use all subsequent hits out to 500 us

Reconstruct the large signal position, and check for the compatibility
Add more variables to purify the sample, efficiency from 30% to 20%
(machine learning applied in the latest SK-IV analyses)

Supernova Relic Neutrino Search with Neutron Tagging at Super-Kamiokande-IV

Astroparticle Physics 60 (2015) 41

Cuts	Bkg Prob. (%)	Efficiency(%)
$N_{10} > 7$	100	30.19 ± 0.04
$N_{10} - N_{cluster} > 5$	25.48 ± 0.04	28.27 ± 0.04
$N_{10} - N_{back} > 6$	21.13 ± 0.04	26.78 ± 0.04
$N_{10} - N_{low} > 4$	4.14 ± 0.02	19.11 ± 0.04
Likelihood ratio > 0.35	1.06 ± 0.01	17.74 ± 0.04

but Super High Energy (~ 7.5 MeV) cuts AmBe and the reactor signal

$\tau = \lambda^{-1} = (209 \pm 3)$ μs

More pure selection:
delayed hits compatible
with the prompt position
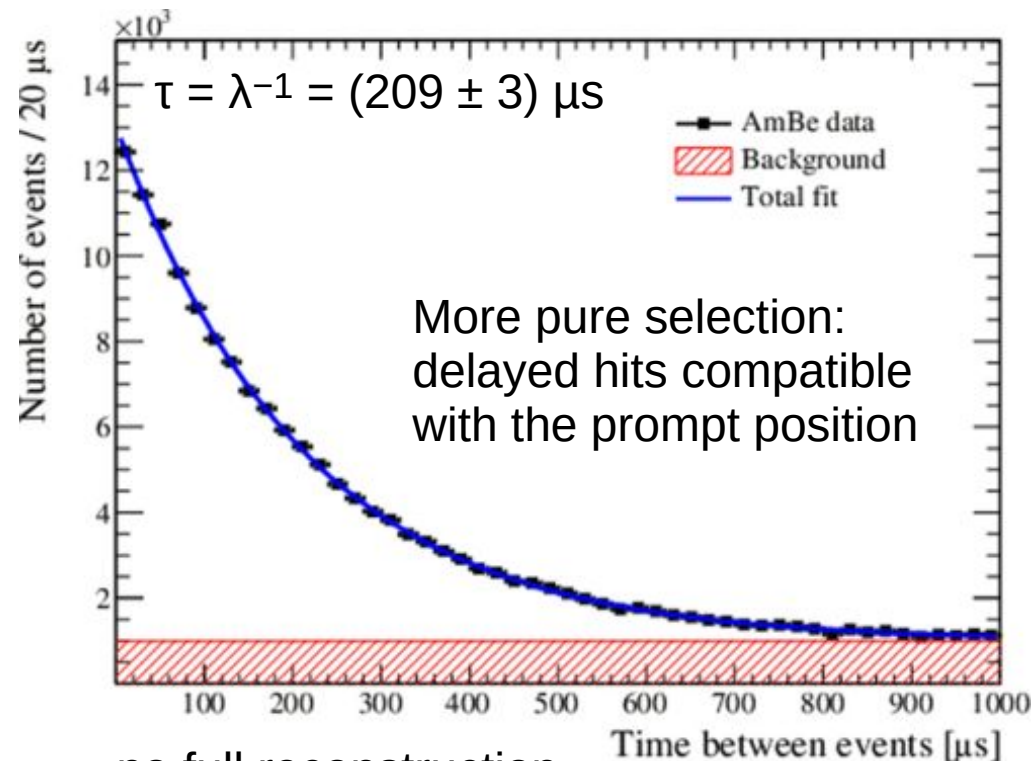
no full reconstruction,
base of SuperKamiokande delayed trigger

the antineutrino search

two statistical methods for very rare signals

keep low energy events only if within 1000 us from well reconstructed prompt with $N_{hits}>15$

Initial selection	Efficiency (%)	IBDs	Accidentals
None	NA	160.4	NA
Trigger	32.9	52.8	NA
Instrumentals [25]	95.7	50.5	NA
Nhits	56.9	28.7	NA
Valid reconstruction	87.2	25.1	NA
Δt	90.7	22.7	6.03e6
FoMs, ITR, β_{14}	88.8	20.2	1.86e6
Fiducial volume	50.0	10.1	5.86e5
E	82.1	8.3	2.61e5
Δr	94.7	7.8	1.11e4
LR selection	44.7	3.5	0.7

→ simulated up to 8.5 m, 160.4 +- 8 (syst)

→ also some positrons below threshold

→ start with 14% IBD for full data analyses

→ cut out the alpha-neutron interactions

→ very similar in the two analyses
need a 10 000 reduction factor

for events that triggered the detector and satisfied the FV, E, and Nhits criteria,
initial IBD selection efficiency was about 60%. Accidentals were 60 / day!

two blind analyses
and independent statistical methods for very rare signals

test accidentals in Δt in 0.5 – 1.0 ms

avoid (α,n) bkg from the AV

avoid atmospheric neutrinos

1. Likelihood Ratio for IBD-like vs random bkg

E vs. β_{14}

||r|| vs u.r

Δt and Δr

	LR		BDT	
	Prompt	Delayed	Prompt	Delayed
Nhits	≥ 15	NA	≥ 15	≤ 25
Δt [μs]	(3, 500)		(3, 500)	
ITR	> 0.5	NA	> 0.5	NA
β_{14}	(-0.6, 1.6)	NA	(-0.6, 1.6)	NA
$\|\mathbf{r}\|$ (internal) [m]	< 5.7	< 5.7	< 5.6	NA
$\|\mathbf{r}\|$ (external) [m]	(6.3, 7.5)	(6.1, 7.6)	(6.4, 7.3)	NA
z (external) [m]	(-5.0, 5.0)		(-5.0, 5.0)	
E [MeV]	(2.5, 9.0)	< 4.0	(2.5, 9.5)	NA
Δr [m]	< 3.0		NA	
$\text{Nhits}_{p,12}$	NA	NA	NA	> 6

	LR	BDT
Reactor IBD	3.5 ± 0.7	4.8 ± 1.4
Accidentals	0.7 ± 0.1	1.4 ± 0.1
(α, n)	0.7 ± 0.7	0.9 ± 0.7
Atm. ν NC	0.4 ± 0.3	<0.6
Sum	5.3 ± 1.0	7.7 ± 1.7
Observation	9	10

2. Boosted Decision Trees

a) a good prompt positron

b) a compatible neutron

Δt and Δr not used directly

E, β_{14}, ||r||, u.r, z +

$N_{p,12}$ and $N_{p,12}/N_{hits}$ +
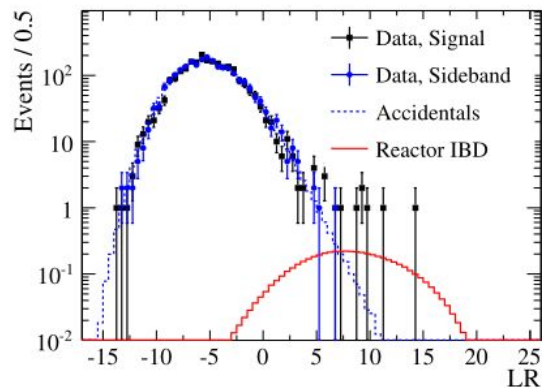
T_{rms} , $N_{cluster}$, ϕ_{rms} , θ_{mean} , θ_{rms}
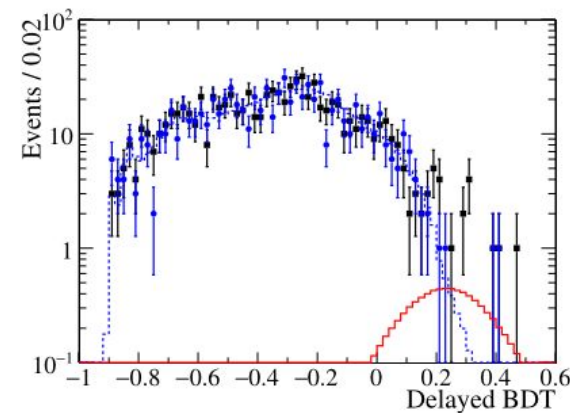
(borrowed from SuperKamiokande)

the 3.5 sigma evidence

and independent statistical methods for very rare signals

	LR	BDT
Reactor IBD	3.5 ± 0.7	4.8 ± 1.4
Accidentals	0.7 ± 0.1	1.4 ± 0.1
(α, n)	0.7 ± 0.7	0.9 ± 0.7
Atm. ν NC	0.4 ± 0.3	<0.6
Sum	5.3 ± 1.0	7.7 ± 1.7
Observation	9	10

Obs-Sum	+3.7 ± 3.2	+2.3 ± 3.5

Exp sensitivity	1.7 σ	2.1 σ
Obs sensitivity	3.0 σ	2.9 σ

Total of 14 events, with only 5 common to both
(47% in common from sim / calib, also for bkg)
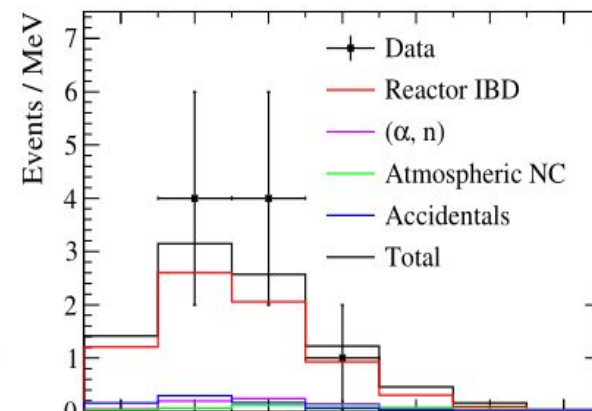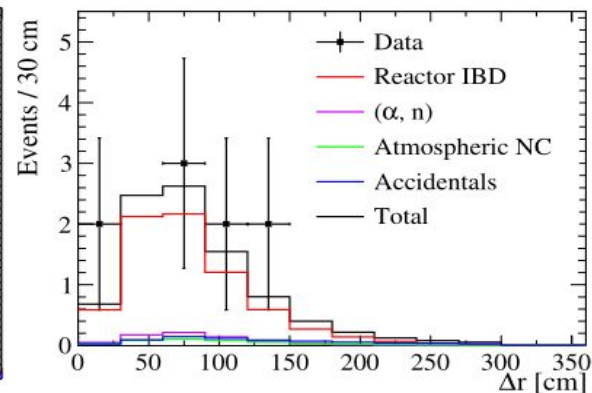expected 3.2 ± 1.0 distinct background events

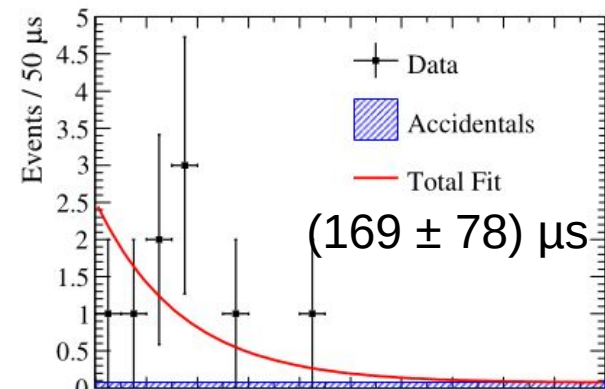Combination gives 3.5 σ from upward fluctuation
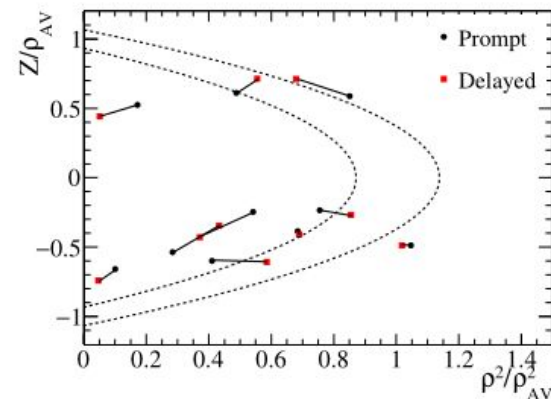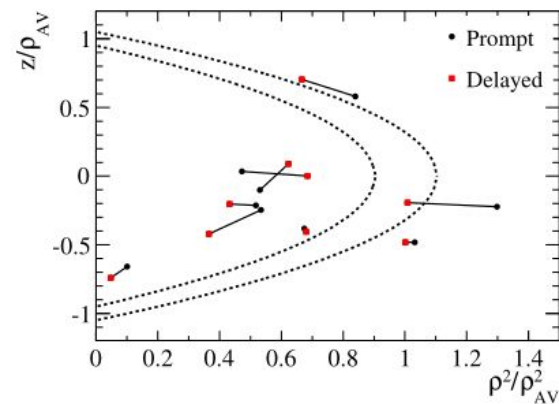
antineutrino candidates
and independent statistical methods for very rare signals
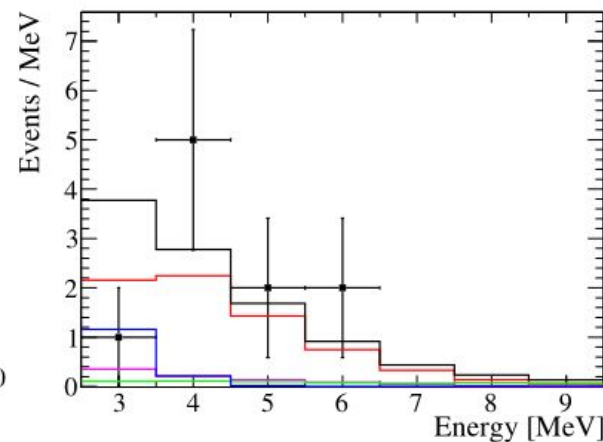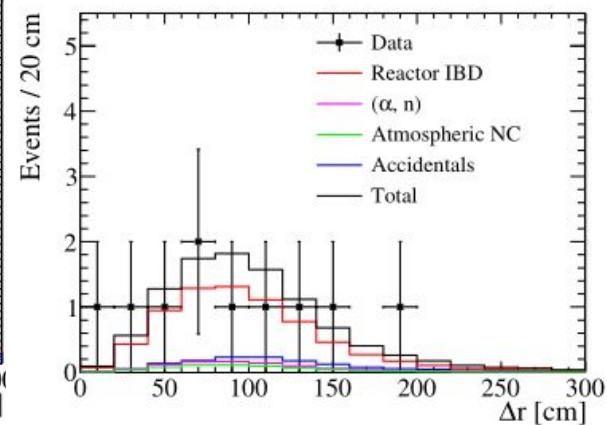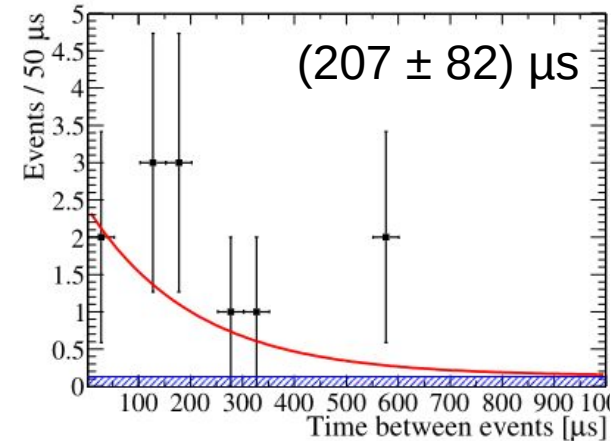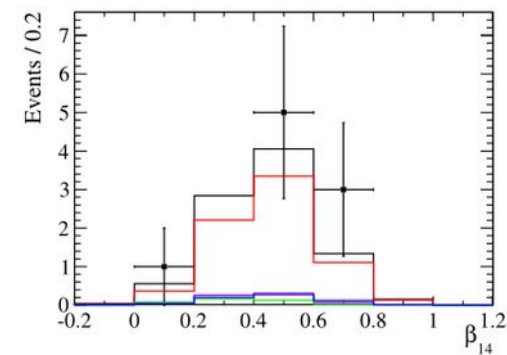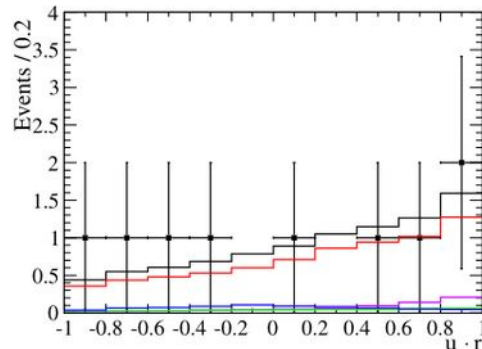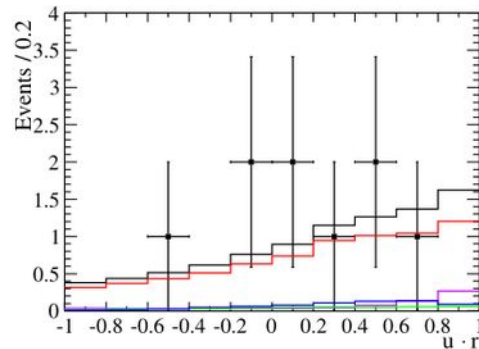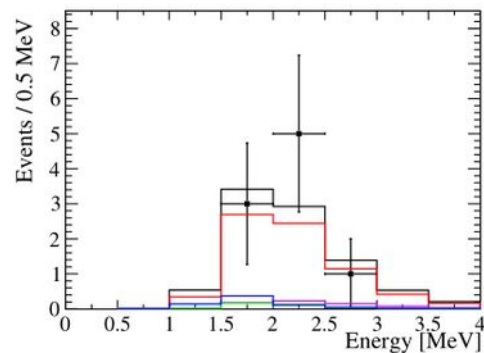

(169 ± 78) µs

(207 ± 82) µs

LR

BDT

antineutrino candidates

and independent statistical methods for very rare signals

two blind analyses
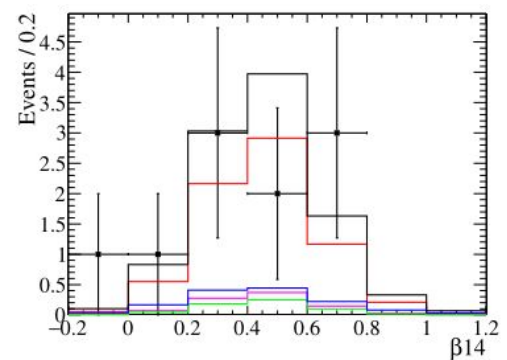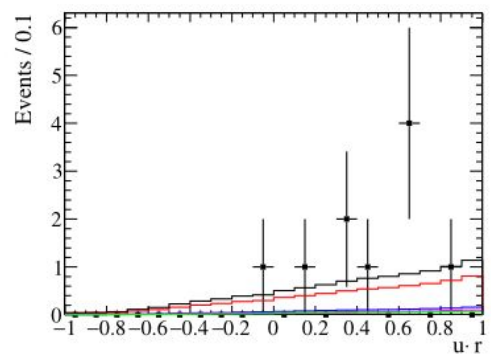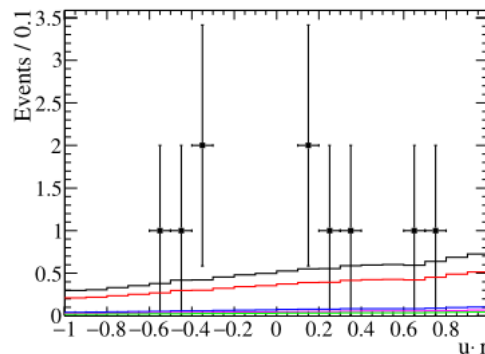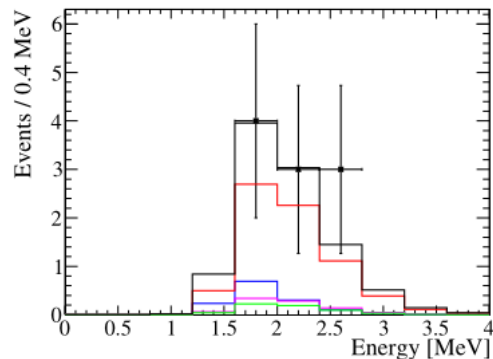
and independent statistical methods for very rare signals

**test accidentals in
Δt sideband to 1 ms**

**avoid (α,n) bkg from the AV
and measure in sideband**

**avoid atmospheric neutrinos
(also tested in sidebands)**

1. Likelihood Ratio for
IBD-like vs random bkg

E vs. β_{14}

$||r||$ vs u.r

Δt and Δr

	LR		BDT	
	Prompt	Delayed	Prompt	Delayed
Nhits	≥ 15	NA	≥ 15	≤ 25
Δt [μs]	(3, 500)		(3, 500)	
ITR	> 0.5	NA	> 0.5	NA
β_{14}	(-0.6, 1.6)	NA	(-0.6, 1.6)	NA
$||\mathbf{r}||$ (internal) [m]	< 5.7	< 5.7	< 5.6	NA
$||\mathbf{r}||$ (external) [m]	(6.3, 7.5)	(6.1, 7.6)	(6.4, 7.3)	NA
z (external) [m]	(-5.0, 5.0)		(-5.0, 5.0)	
E [MeV]	(2.5, 9.0)	< 4.0	(2.5, 9.5)	NA
Δr [m]	< 3.0		NA	
Nhits$_{p,12}$	NA	NA	NA	> 6

	LR	BDT
Reactor IBD	3.5 ± 0.7	4.8 ± 1.4
Accidentals	0.7 ± 0.1	1.4 ± 0.1
(α, n)	0.7 ± 0.7	0.9 ± 0.7
Atm. ν NC	0.4 ± 0.3	< 0.6
Sum	5.3 ± 1.0	7.7 ± 1.7
Observation	9	10

2. Boosted Decision Trees
a) a good prompt positron
b) a compatible neutron

Δt and Δr not used directly

E, β_{14}, $||r||$, u.r, z +

$N_{p,12}$ and $N_{p,12}/N_{hits}$ +

T_{rms} , $N_{cluster}$, ϕ_{rms} , θ_{mean} , θ_{rms}

(borrowed from SuperKamiokande)

the SNO+ trigger model

for efficiency at the lowest energy thresholds
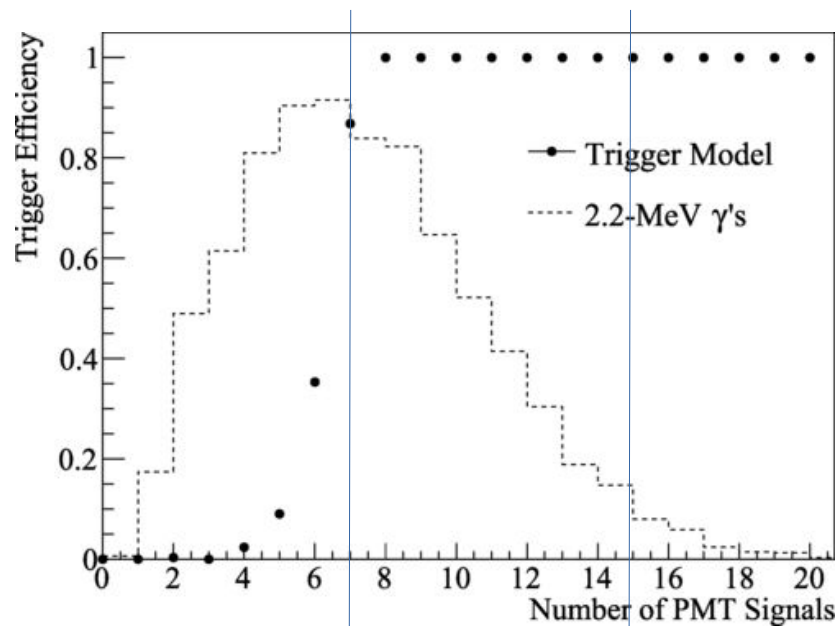
7.0 pulses (89 ns width sum over PMTs)
~ 1.4 MeV electron at the center of the detector

both SNO LETA & SK-IV set triggers at 3.5 MeV,
mostly to avoid large radioactive background rates

One of the main uncertainties in antineutrino search:
simulation efficiency on the full detector volume corrected
by 0.85 ± 0.16 (LR) and 0.89 ± 0.23 (BDT)

the (α,n) background
another first time measurement in water

$^{18}O(\alpha,n)^{21}Ne$ in the water,
$^{21}Ne^*$ (2.8 MeV γ)

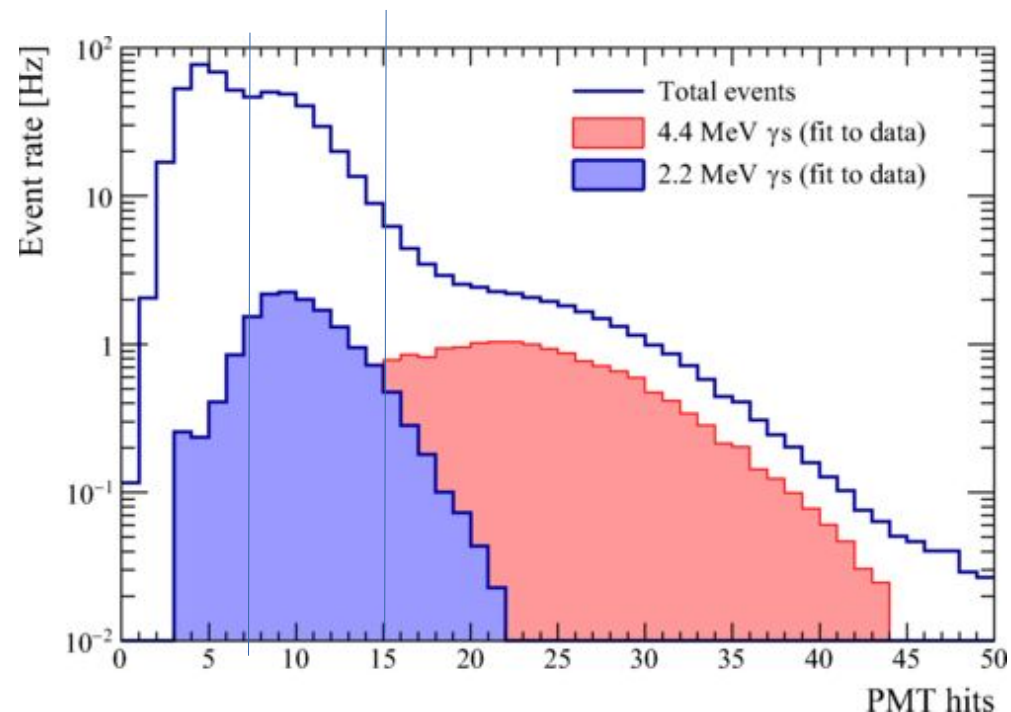$^{13}C(\alpha,n)^{16}O$ in the AV,
$^{16}O^*$ (6.1 MeV γ)

most α from ^{210}Po in the AV
then leaching into the water

expectation from radio-assays
and ex-situ measurements

	LR	BDT
Reactor IBD	3.5 ± 0.7	4.8 ± 1.4
Accidentals	0.7 ± 0.1	1.4 ± 0.1
(α, n)	0.7 ± 0.7	0.9 ± 0.7
Atm. ν NC	0.4 ± 0.3	<0.6
Sum	5.3 ± 1.0	7.7 ± 1.7
Observation	9	10
AV region signal	17	25
background	2.6 +- 0.2	7.1+-0.5

same analyses except for FV
190 days of more pure data +
141 days of less pure data

Higher than predicted: smaller leaching from AV to water?
Scaled the predicted rate from the AV (6.1 MeV γ) by 4,
added a 400% uncertainty for the water (2.5 MeV γ)!

antineutrinos in pure water
how useful can this be?

Nice end-to-end test of SNO+, namely for the trigger model, the (α,n) background, ...

~ 50 % efficiency for triggering neutron capture in water at the center of the detector
~ 33 % efficiency for triggering on reactor antineutrinos in water in the full volume
~ unfortunately also revealed 4 x more (α,n) than expected

SK-IV has similar efficiency but following high energy event (relic SuperNova neutrinos)!

SK-Gd increases the efficiency with 90 % (50 %) with 0.1% (0.01%) concentration of Gd (9 MeV g)
But needed to refurbish the SK tank to avoid Gd leaks to environment
Same would be true with Cd, maybe less with Cl?

Pure water is much easier to use than other materials. Maybe we could have many more neutrino detectors?

A network for reactor antineutrinos, SN and pre-SN antineutrinos, maybe even the very low enegy geo-neutrinos?

antineutrinos in partial fill

45 events for 44.9 expected, 9.4 from reactor and 2.2 geos

$\tau = 253 \pm 52\ \mu s$
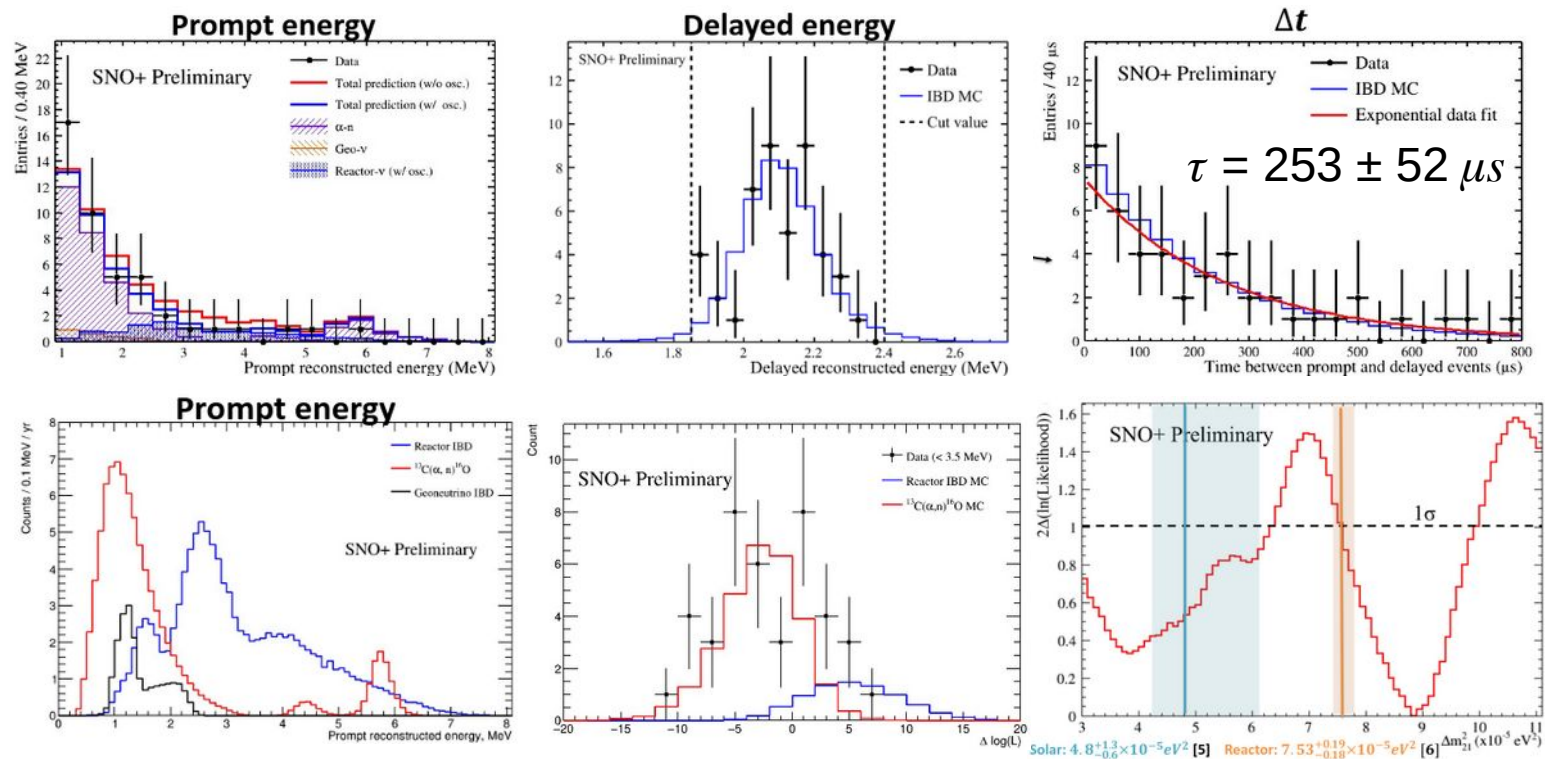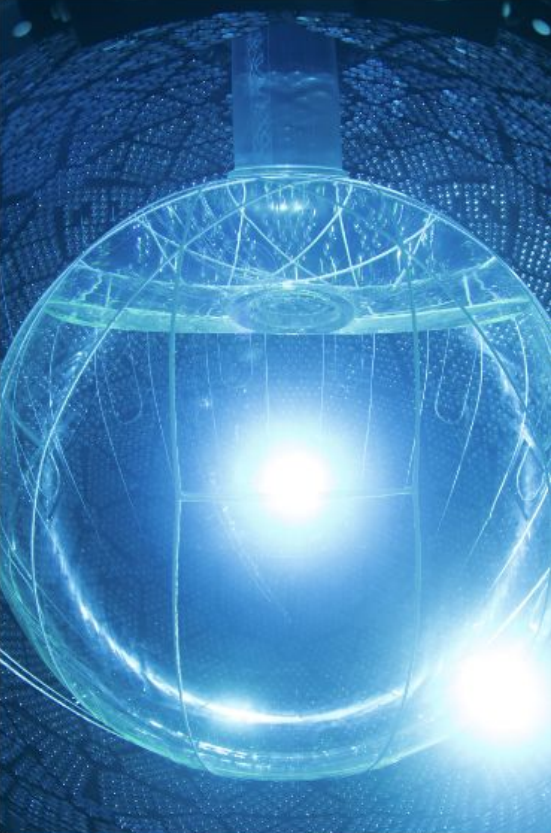
results from
Neutrino 2022

discrimination of (α,n) background   --> measuring oscillations

outlook

SNO+ observed for the first time reactor antineutrinos in water !

An end to end test of the detector for the water phase and beyond

SNO+ is now measuring the reactor anti-neutrino spectrum in scintillator

reactor antineutrinos have high sensitivity to "solar" oscillation parameters
any new measurement of geoneutrinos will help to constrain Earth models

Observation of low energy antineutrinos in a pure water Cherenkov detector
is a technical achievement that may open the way for future projects

SNO+ Collaboration

LIP @ SNO+ supported by
PTDC/FIS-PAR/2679/2021