(α,n) yield in low background experiments
Madrid, 21-22 November 2019

$(\alpha$,n) events in SNO+

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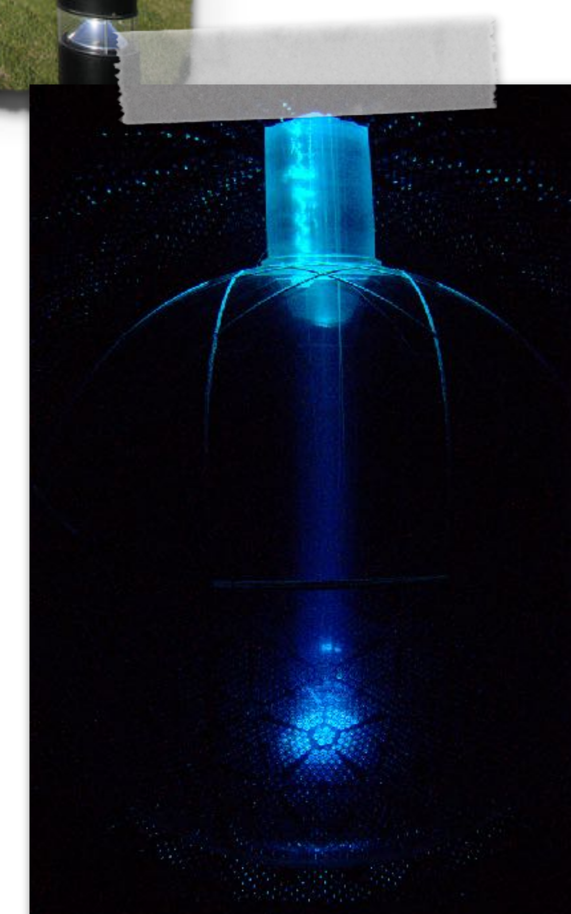
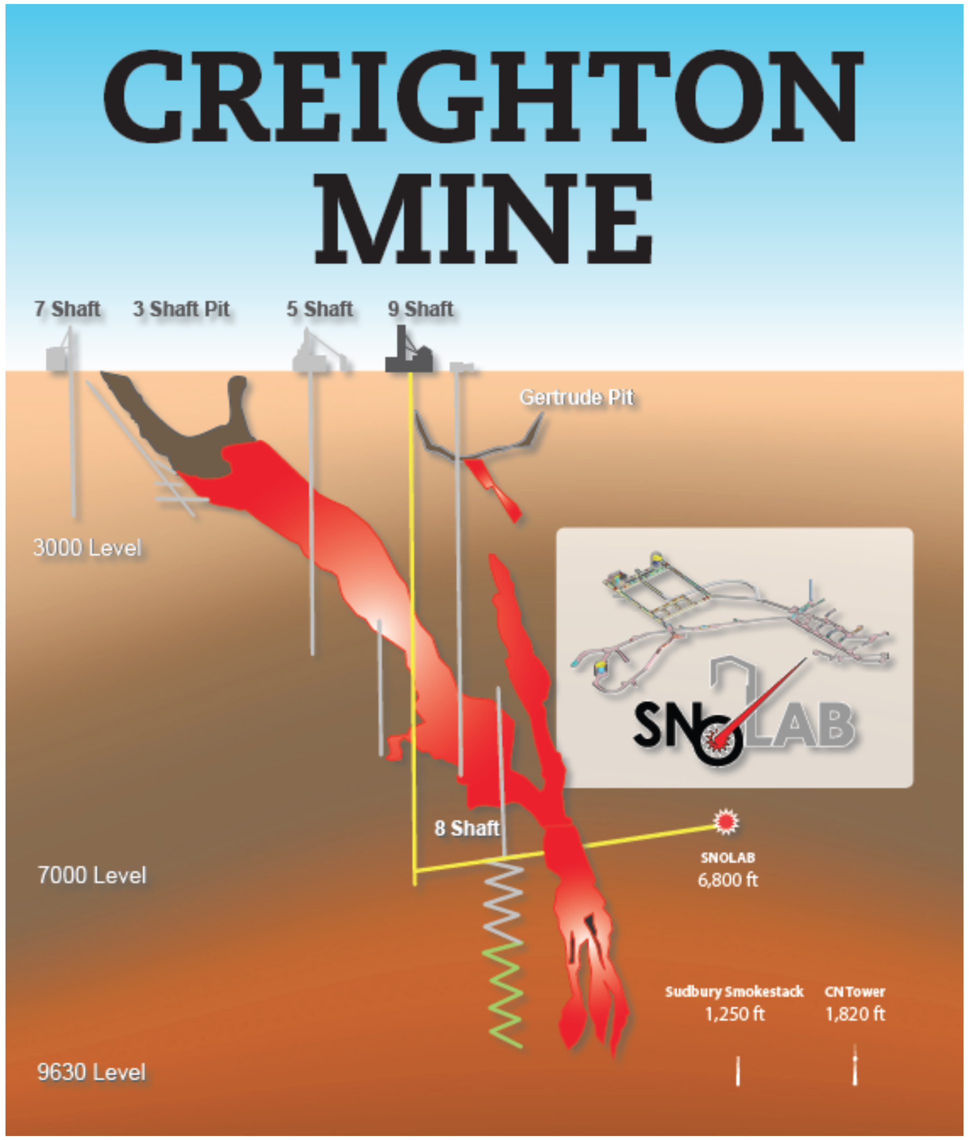
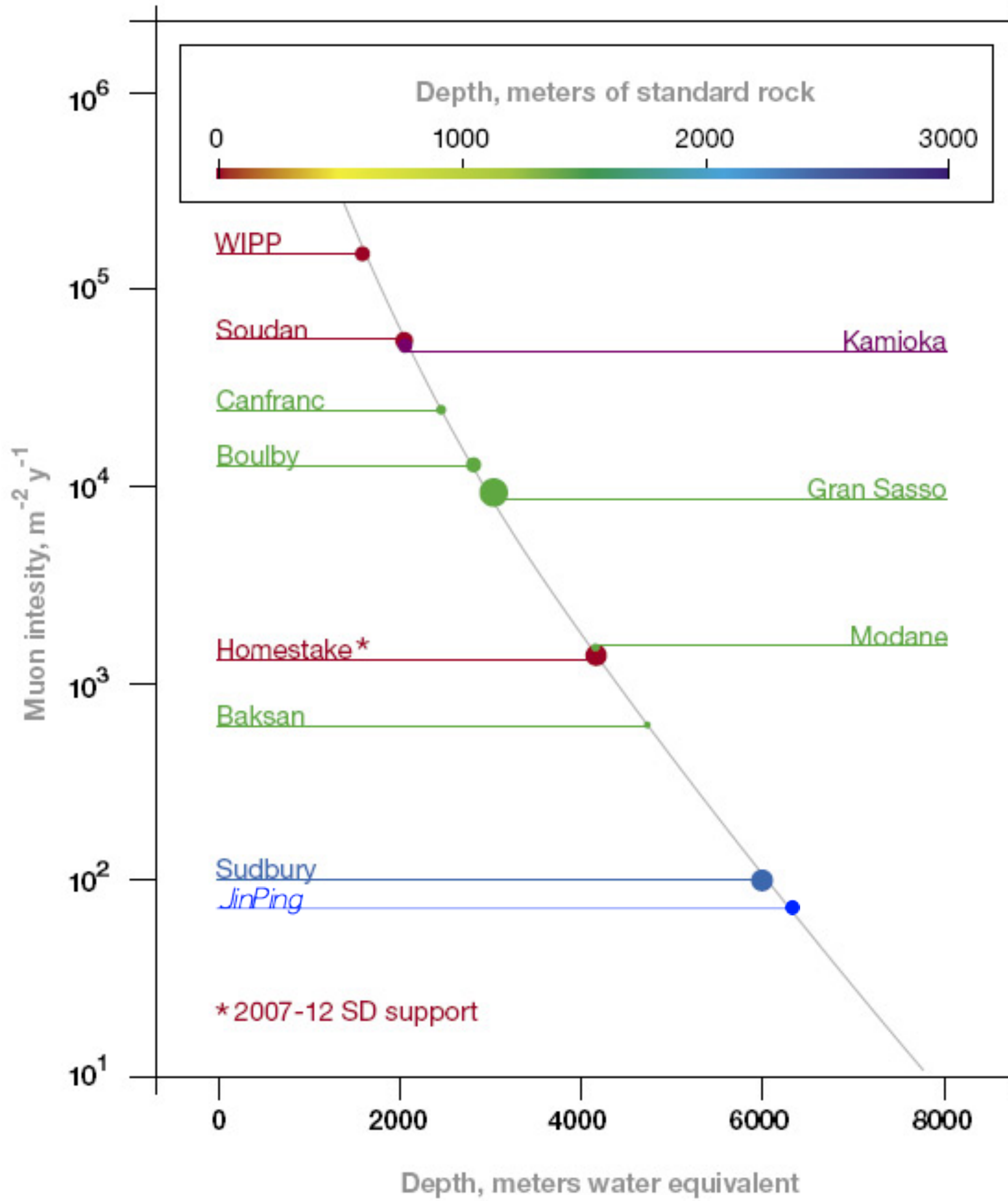
FCT Fundação para a Ciência e a Tecnologia
LIP Lisbon
on behalf of the SNO+ Collaboration

WELCOME TO SUDBURY!

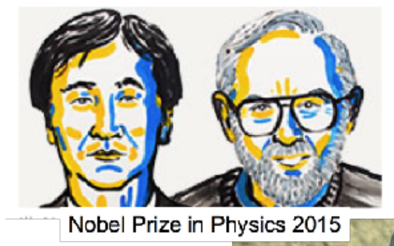


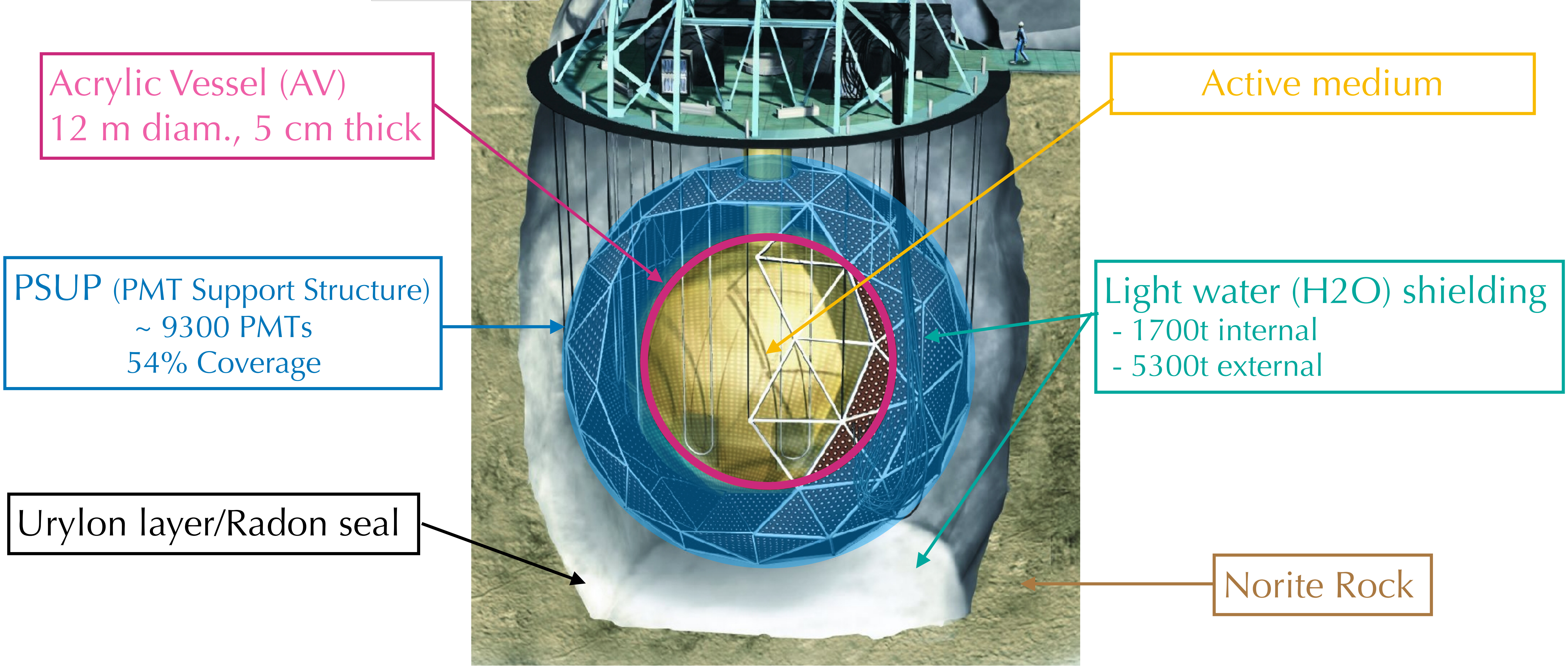


~70 Muons per day



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


Nobel Prize in Physics 2015

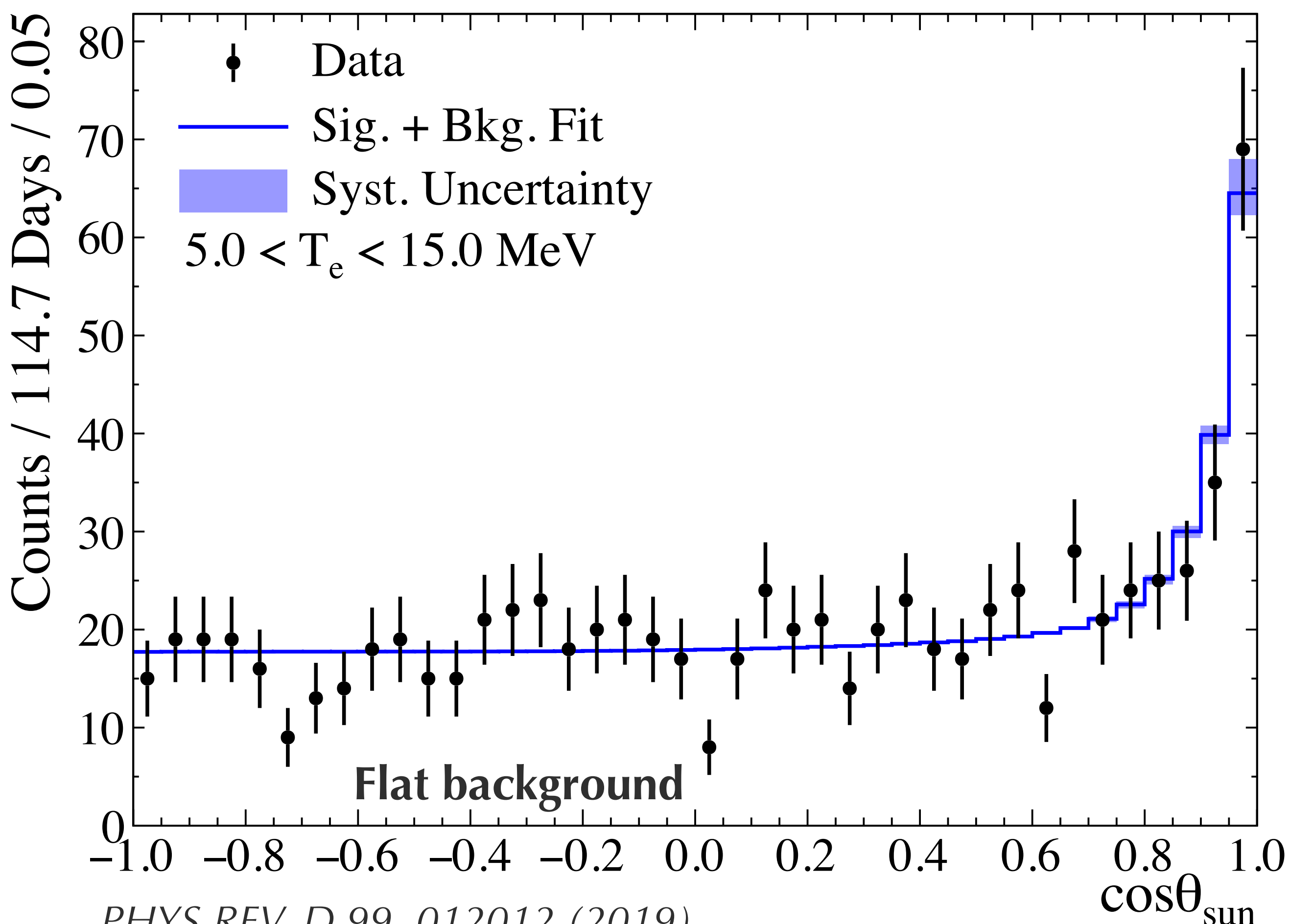

Acrylic Vessel (AV)
12 m diam., 5 cm thick
PSUP (PMT Support Structure)
~ 9300 PMTs
54% Coverage
Urylon layer/Radon seal
Active medium
Light water (H2O) shielding
- 1700t internal
- 5300t external
Norite Rock

SNO+ Phases & Physics

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+ Water Phase Results

^{8}B solar neutrino measurement



PHYS.REV. D 99, 012012 (2019)

SNO+ (2019)

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

SNO

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

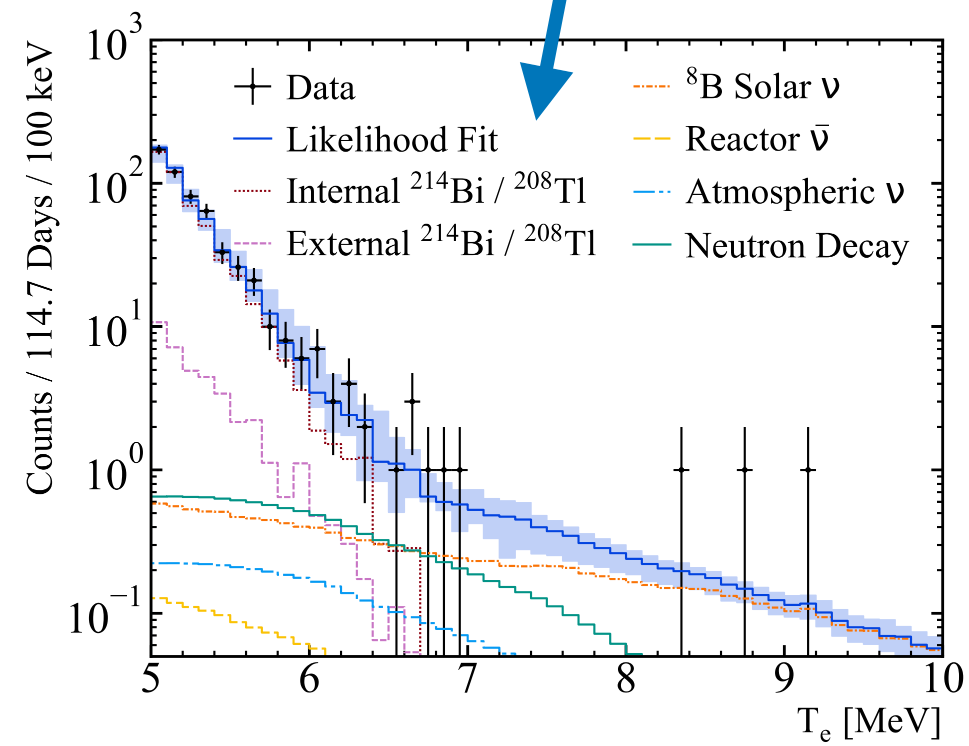
Invisible nucleon decay

Proton decay

$$^{16}\text{O} \rightarrow {}^{15}\text{N}^* + inv$$
$$^{15}\text{N}^* \rightarrow {}^{15}\text{N} + \gamma$$

Neutron decay

$$^{16}\text{O} \rightarrow {}^{15}\text{O}^* + inv$$
$$^{15}\text{O}^* \rightarrow {}^{15}\text{O} + \gamma$$



PHYS.REV. D 99, 032008 (2019)

	Spectral analysis	Counting analysis	Existing limits
n	2.5×10^{29} y	2.6×10^{29} y	5.8×10^{29} y [9]
p	3.6×10^{29} y	3.4×10^{29} y	2.1×10^{29} y [10]
pp	4.7×10^{28} y	4.1×10^{28} y	5.0×10^{25} y [11]
pn	2.6×10^{28} y	2.3×10^{28} y	2.1×10^{25} y [13]
nn	1.3×10^{28} y	0.6×10^{28} y	1.4×10^{30} y [9]

(α,n) Reactions

★ Main targets for the (α,n) reactions:

- ^{13}C in scintillator and acrylic;
- ^{18}O in scintillator, water and acrylic;
- ^{17}O in scintillator, water and acrylic.

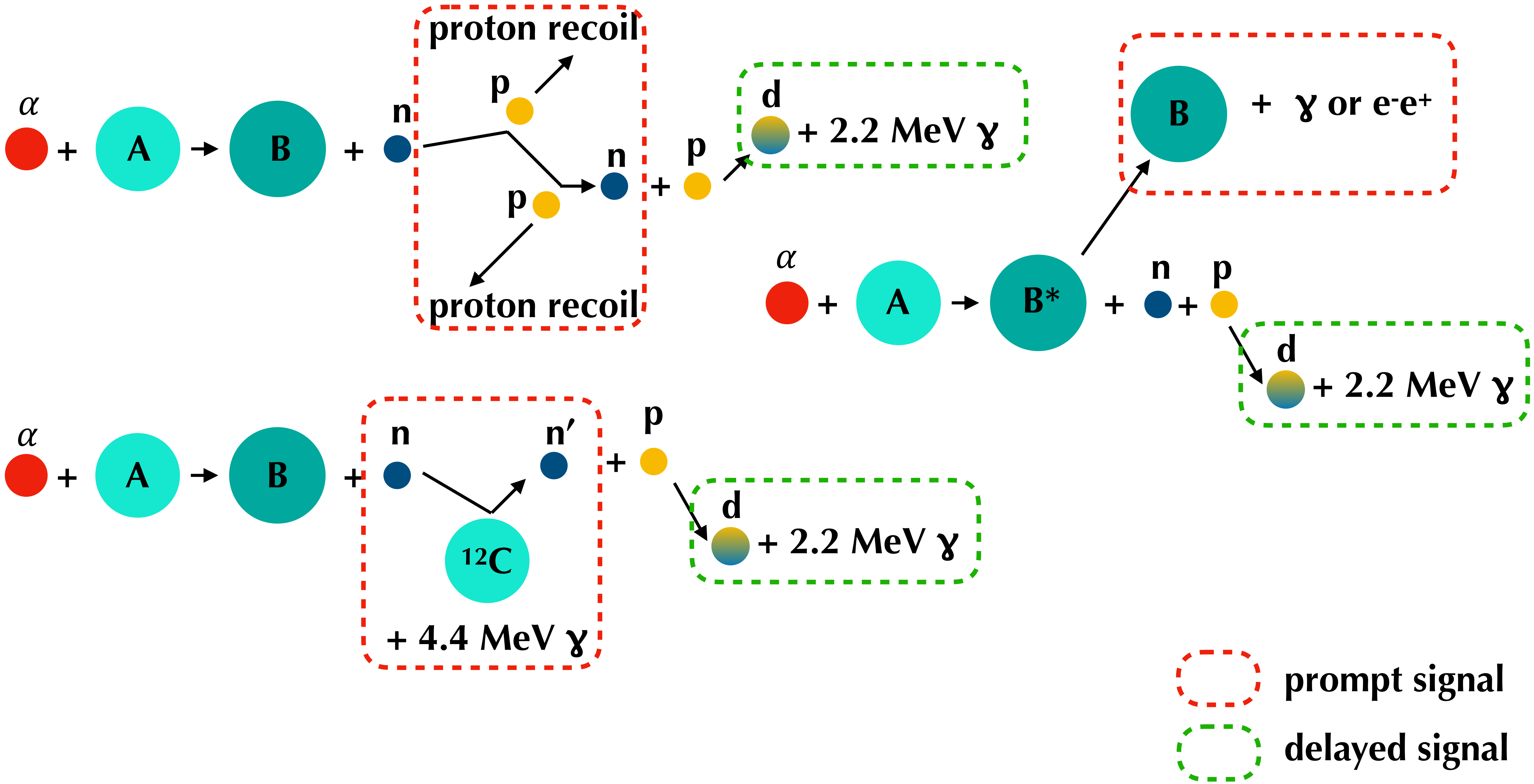
★ Reactions that can happen:

- $^{13}C(\alpha,n)^{16}O$
- $^{18}O(\alpha,n)^{21}Ne$
- $^{17}O(\alpha,n)^{20}Ne$

★ Following events:

- De-excitation of the produced isotope;
- Scattering between neutrons and protons (recoil protons);
- Inelastic scattering with ^{12}C or ^{16}O (gamma emission);
- Neutron capture by protons with gamma emission.

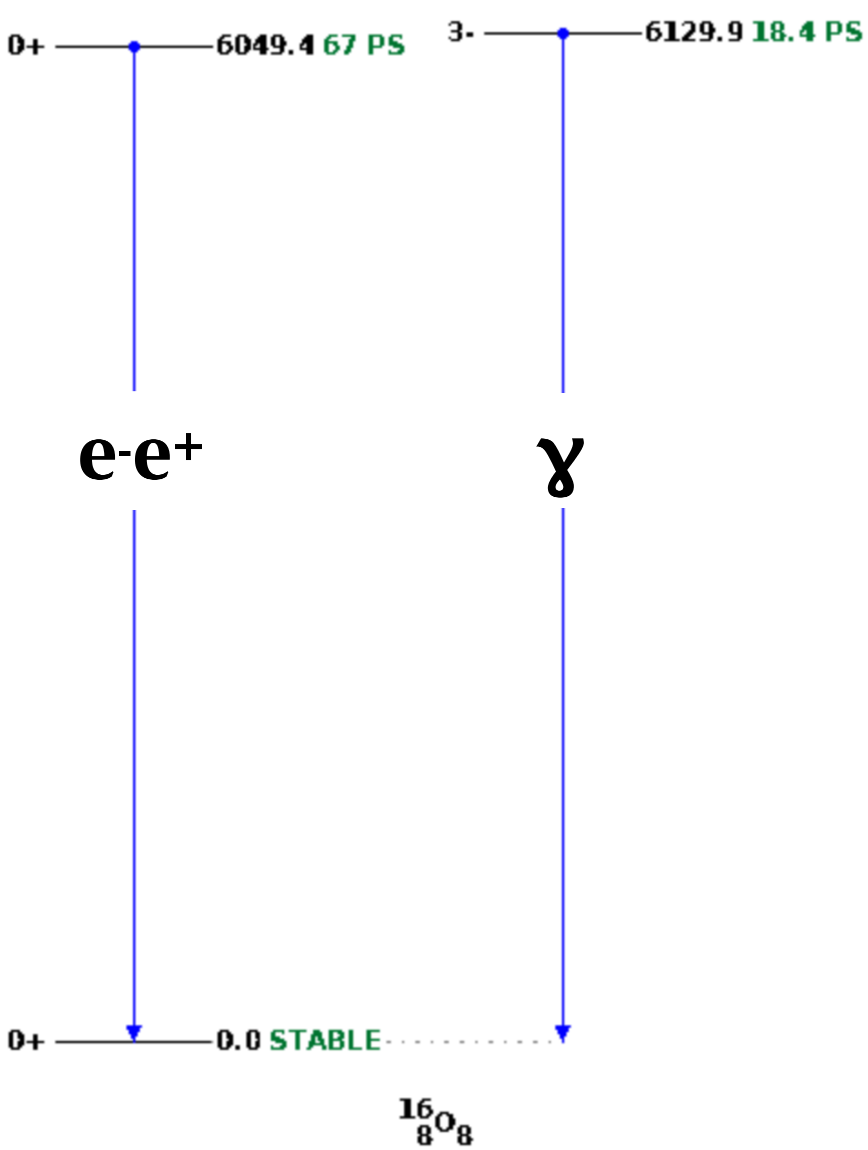
(α,n) Signal



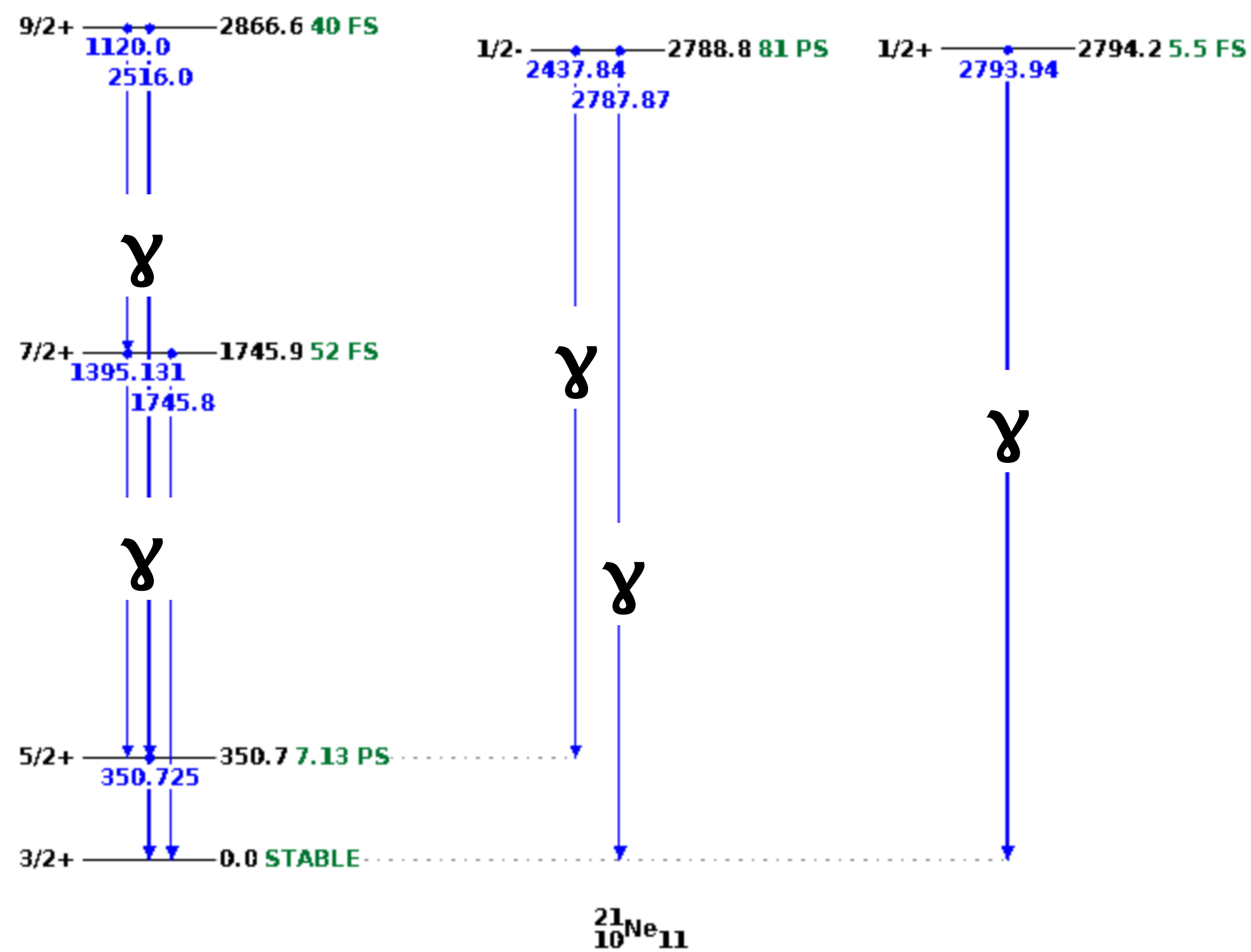
α
A
B
n
proton recoil
p
n
p
proton recoil
p
d
+ 2.2 MeV ɣ
B
+ ɣ or e⁻e⁺
α
A
B*
n
p
d
+ 2.2 MeV ɣ
α
A
B
n
n′
12C
+ 4.4 MeV ɣ
p
d
+ 2.2 MeV ɣ
prompt signal
delayed signal

(α,n) signal

$^{13}C(\alpha,n)^{16}O$



$^{18}O(\alpha,n)^{21}Ne$

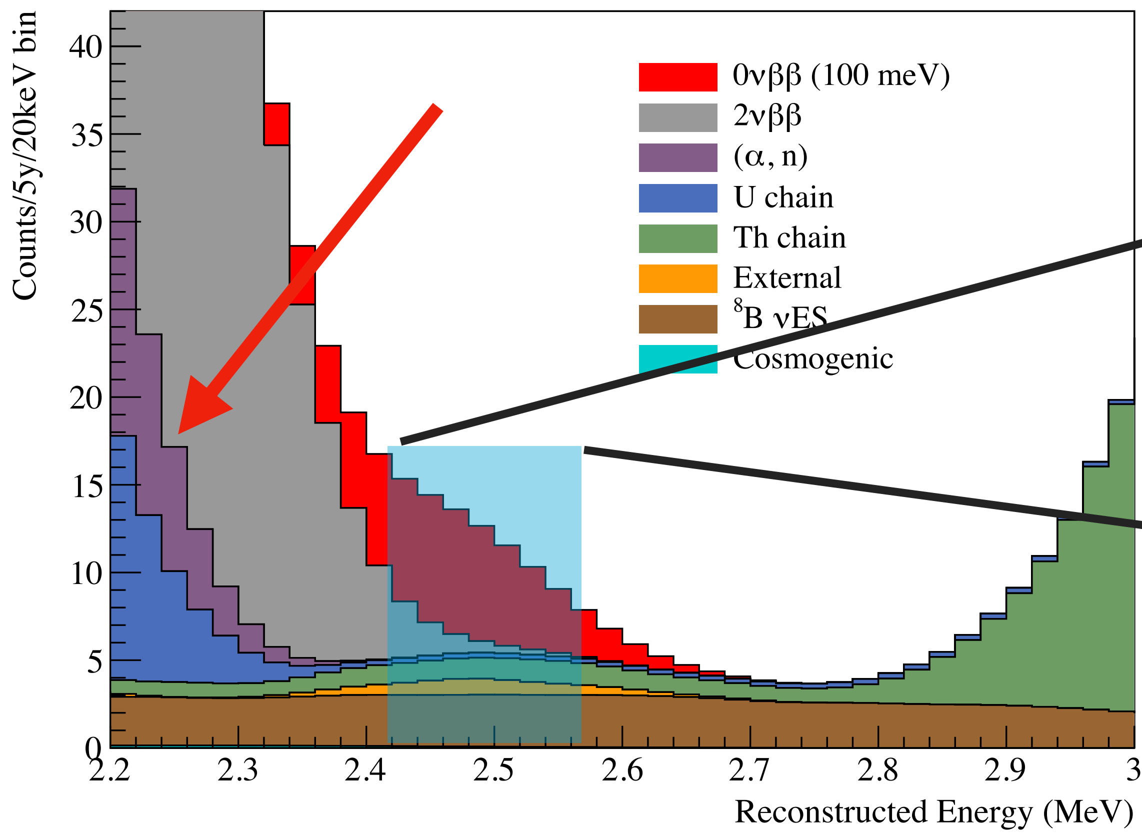


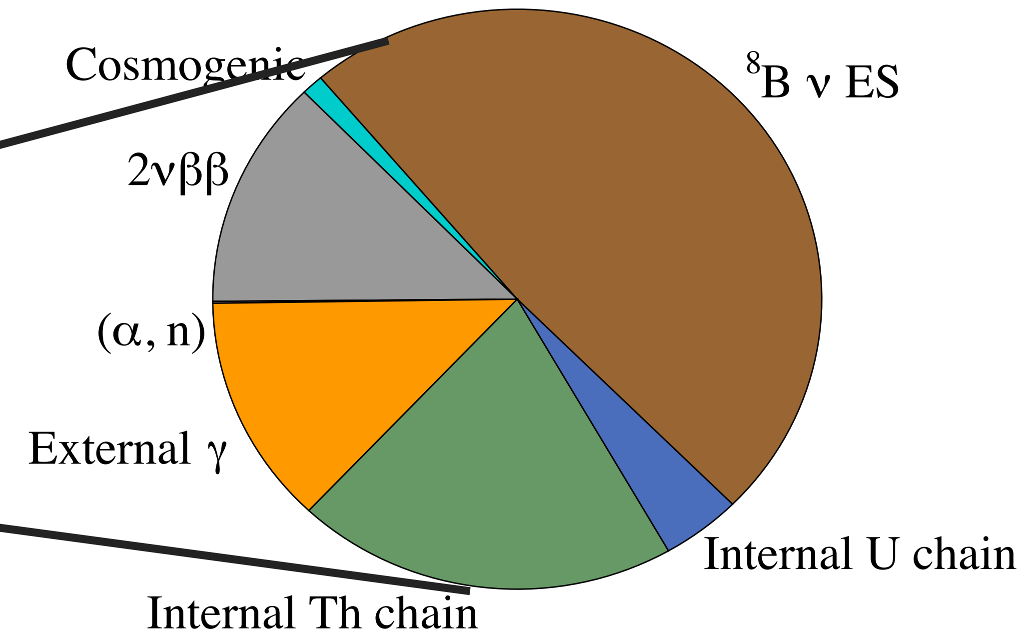
(α,n) Background

★ (α,n) reactions are a background for various SNO+ analysis:

- Analysis of **anti-neutrinos**;
  - The prompt + delay events mimic the Inverse Beta Decay signal;
  - Affect both the water and scintillator phases;
- Analysis of **invisible nucleon decay**;
  - The high energy gammas emitted in the $^{13}C(\alpha,n)^{16}O^*$ reactions on the vessel surface can fall in the Region of Interest for the invisible nucleon decay of $^{15}O^*$ and $^{15}N^*$;
- Analysis of **neutrinoless double-beta decay**;
  - The prompt signal due to protons scattered off by neutrons, and the delayed 2.2 MeV gamma from the neutron capture, can fall in the ROI of the ^{130}Te

(α,n) Background for DBD





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

(α,n):

- alpha-capture on ^{13}C/^{18}O
- production of neutrons
- thermal neutron capture
- delayed coincidence tagging

$(\alpha$,N) Important parameters

★ In order to evaluate the (α,n) background for the various phases and analysis of SNO+ the following parameters are important:

- Sources of alpha particles
  - One of the major sources in scintillator experiments are the ^{210}Po decays, which due to the long $T_{1/2}$ are out-of-equilibrium with the rest of the U-chain

Target	Nat. abund.	(α,n) threshold (MeV)
^{1}H	99.985 %	117.8
^{2}H	0.015 %	12.5
^{3}H	-	11.1
^{12}C	98.9 %	11.3
^{13}C	1.1 %	0
^{14}C	-	2.34
^{14}N	99.634 %	6.09
^{15}N	0.366 %	8.13
^{16}N	-	0
^{16}O	99.762 %	15.2
^{17}O	0.038 %	0
^{18}O	0.2 %	0.85
^{19}O	-	0
^{nat}Te	100%	Min 5.0

★ Potential alpha sources

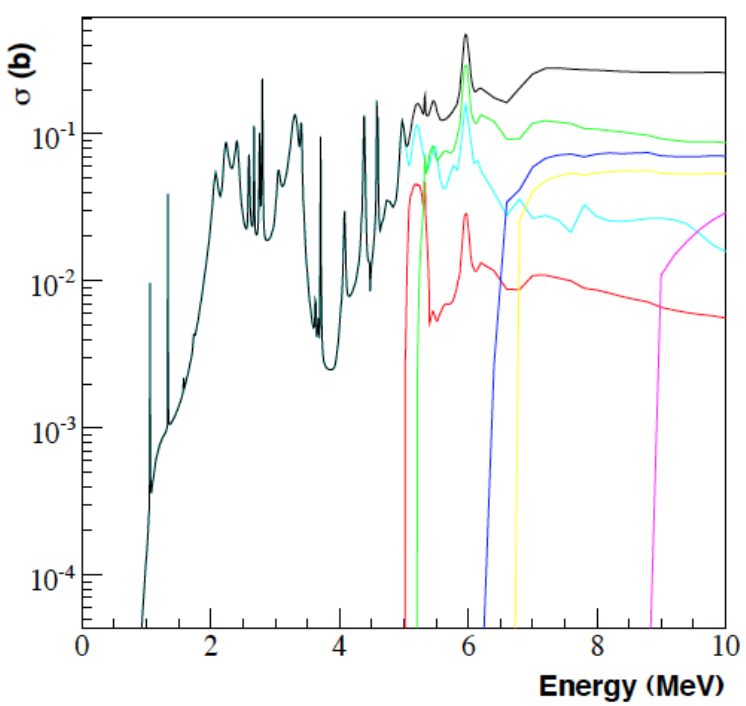
- Rn emanation and Rn ingress
- U & Th chain decays in scintillator/water
- U & Th chain decays in other detector materials (like PMT, acrylic, water)
- ^{210}Po from Rn decay plating onto surfaces (accumulation over time)
  - leach off of ^{210}Po into the target media

- **Conversion of alpha flux into neutron yield**

$$Y_\alpha = \phi_\alpha \cdot n_t \int_0^{E_\alpha} \frac{\sigma(E)}{\epsilon(E)} dE$$

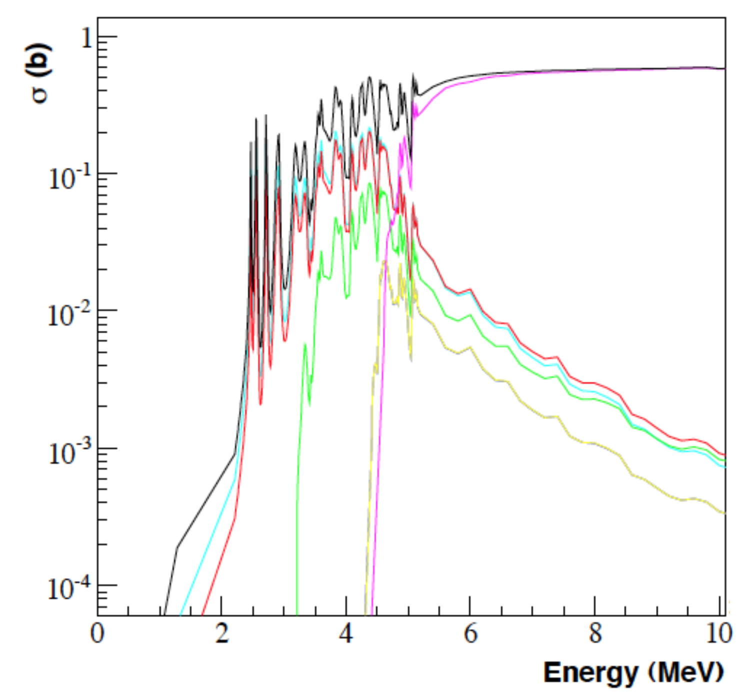
- It depends on the ***material used and slowing down of the alpha particle*** into the material (usually obtained with SRIM);
- It depends on the ***cross section***. Which values are better to use than others (JENDL database, EXFOR data, …)?
  - Larger source of uncertainty;
  - Determines the fraction of events in the excited states vs the ground state.

$^{13}C(\alpha,n)^{16}O$



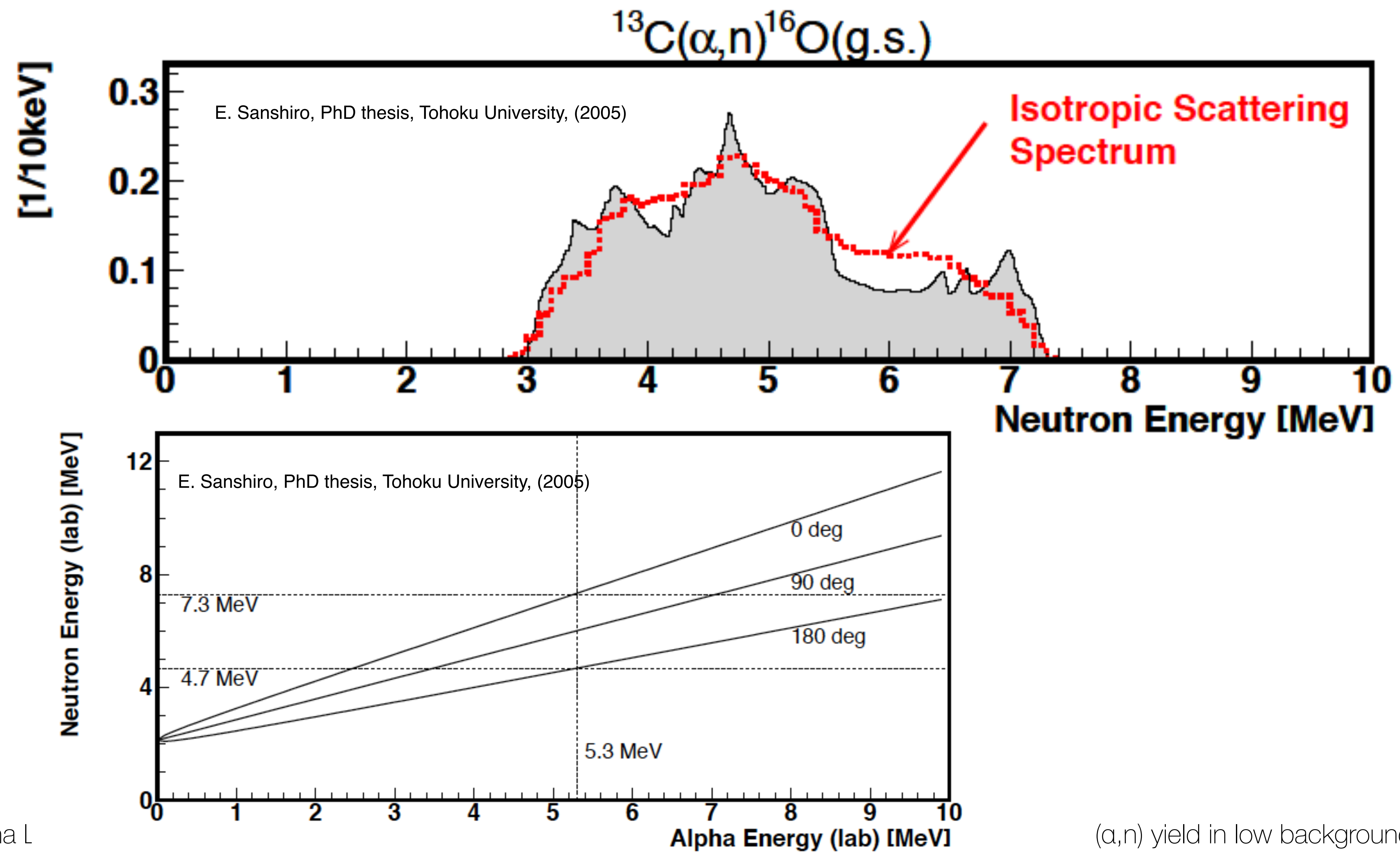
black = total
cyan = ground state
red = first excited state
green = second excited state
blue = third excited state
yellow = forth excited state
….

$^{18}O(\alpha,n)^{21}Ne$



(α,n) Important parameters

- ***Angular dependence*** between the neutron and the alpha
    - For some reactions there are Legendre polynomials to describe the distribution (^{13}C), other are assumed isotropic (^{18}O)



(α,n) in SNO+:
Estimating the number of events

TOOL

- ★ Number of alpha particles & target atoms

\+

- ★ Propagation of alpha particles in the media ← **SRIM**

\+

- ★ Cross sections for the selected reaction ← **JENDL, EXFOR, …**

\+

- ★ Angular distribution ← **THEORETICAL**

SNO+ MC CODE

Neutron flux → **n and α propagation in the scintillator**

Alpha flux → **n and α propagation in the scintillator**

Normalisation

Neutron yield → **# expected events**

SUMMARY

- (α,n) reactions are a background for various SNO+ analysis and phases;
  - Specially critical when searching for rare events
- The input parameters for the SNO+ MC simulation are the neutron flux after the reaction and the alpha energy deposited in the scintillator before the reaction;
- It is important to try to reduce the uncertainty on the cross section, dE/dx of alphas
  - This will affect :
    - the fraction of events in the ground and excited state
    - the calculation of the neutron yield

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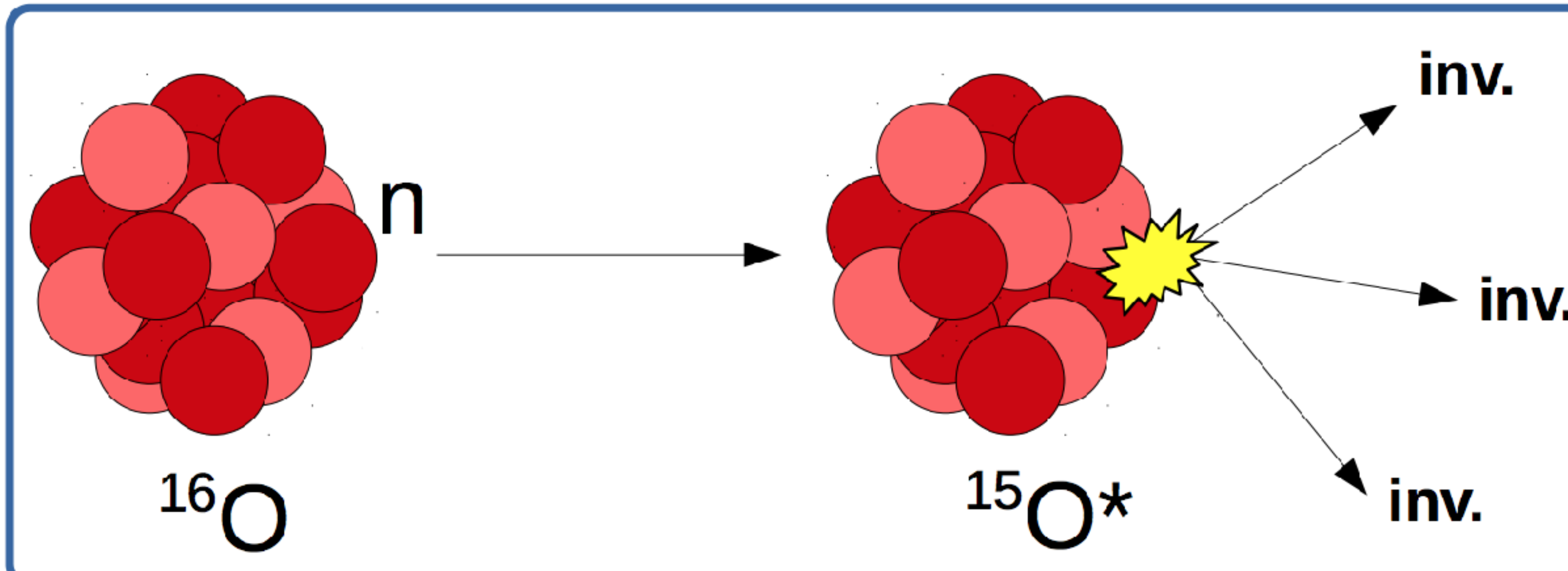
Back-up

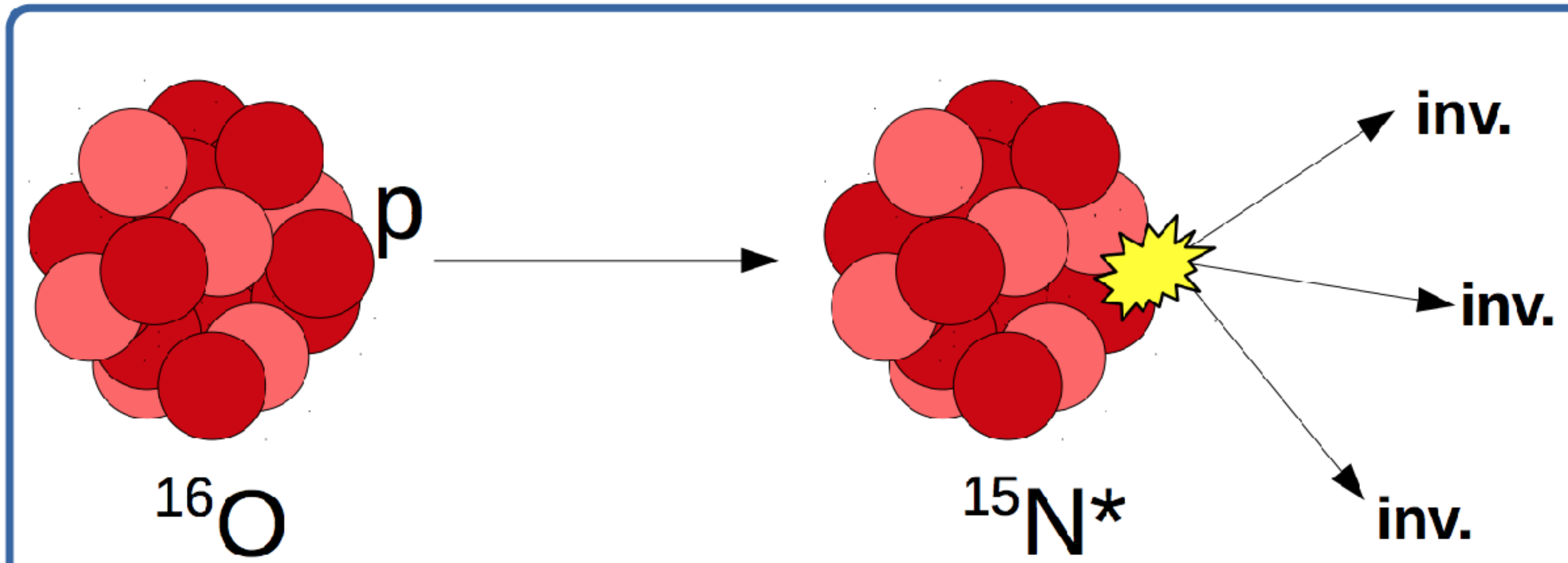
INVISIBLE ND

Phys. Rev. C 48, 1442



neutron → invisible
(e.g. n → 3ν)

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



proton → invisible

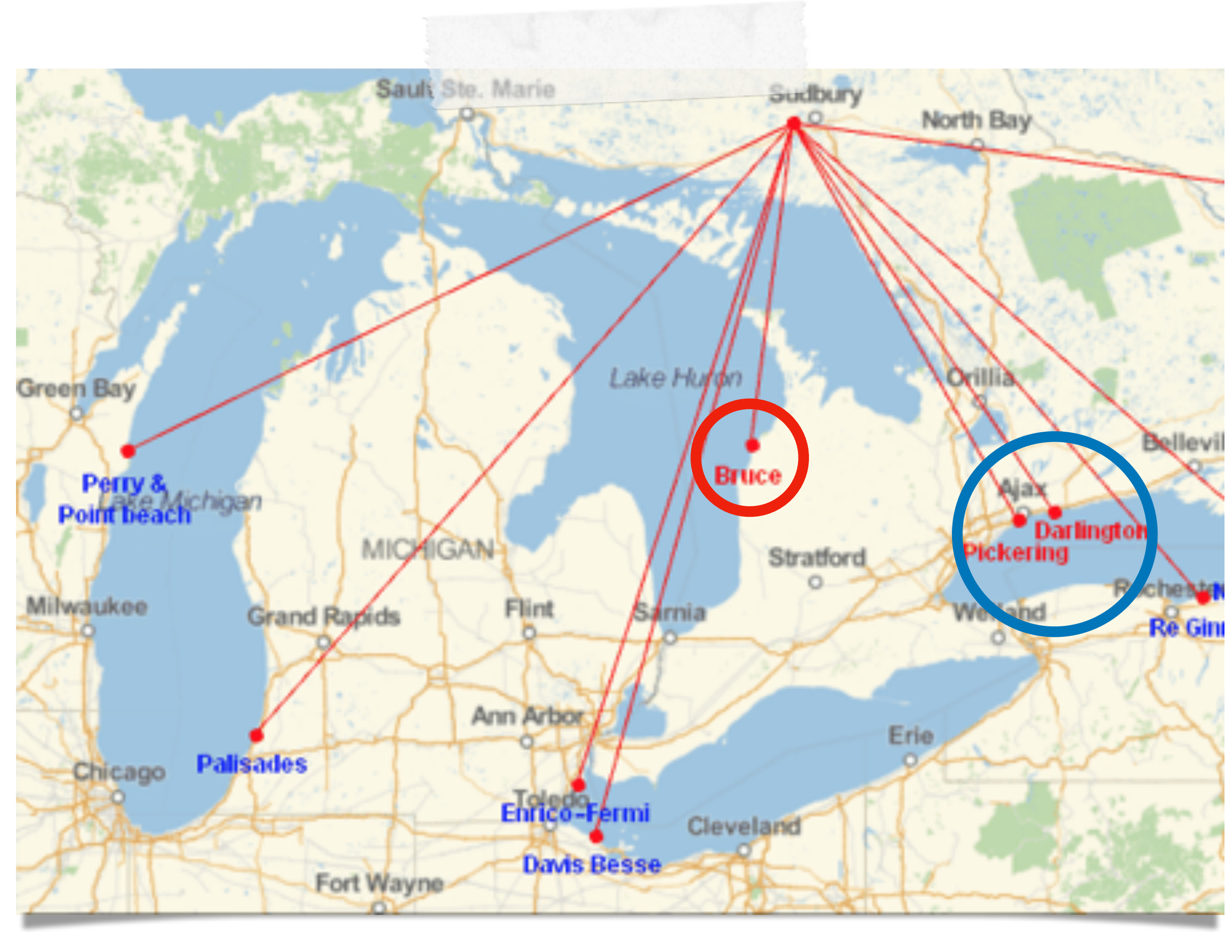
De-excitation gammas:
- 6.18 MeV (44%)
- 7.03 MeV (2%)

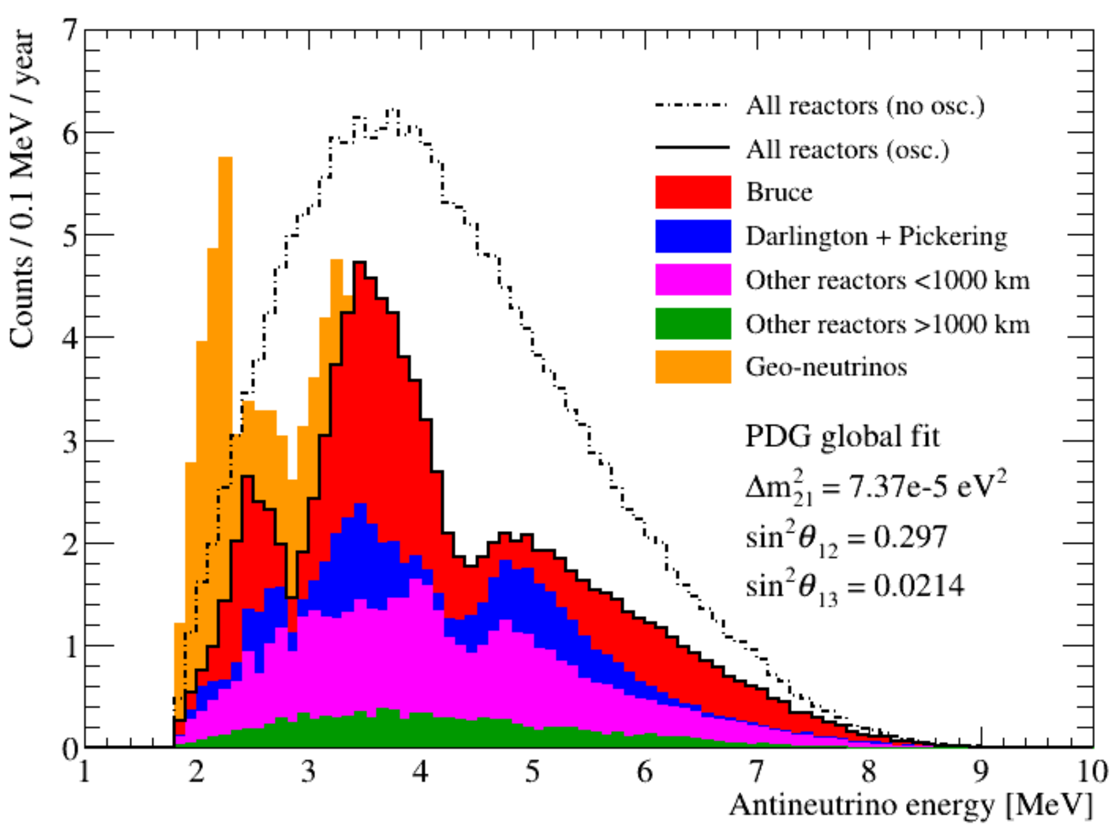
V. Fisher, CIPANP 2018

ANTI-NEUTRINOS DETECTION

Detection mode = Inverse beta decay

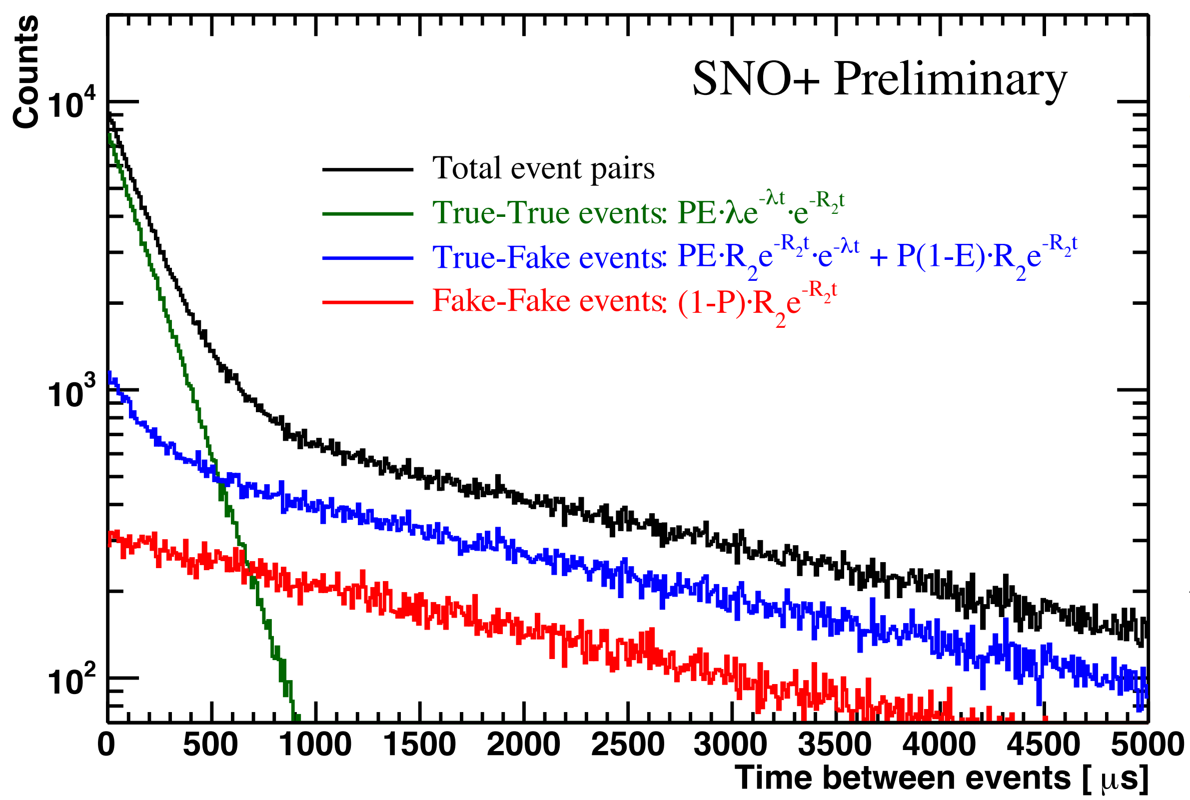
Reactor anti-neutrinos = total flux about 20% of KamLAND, but baseline between reactors and SNO+ gives a unique spectral shape distortion





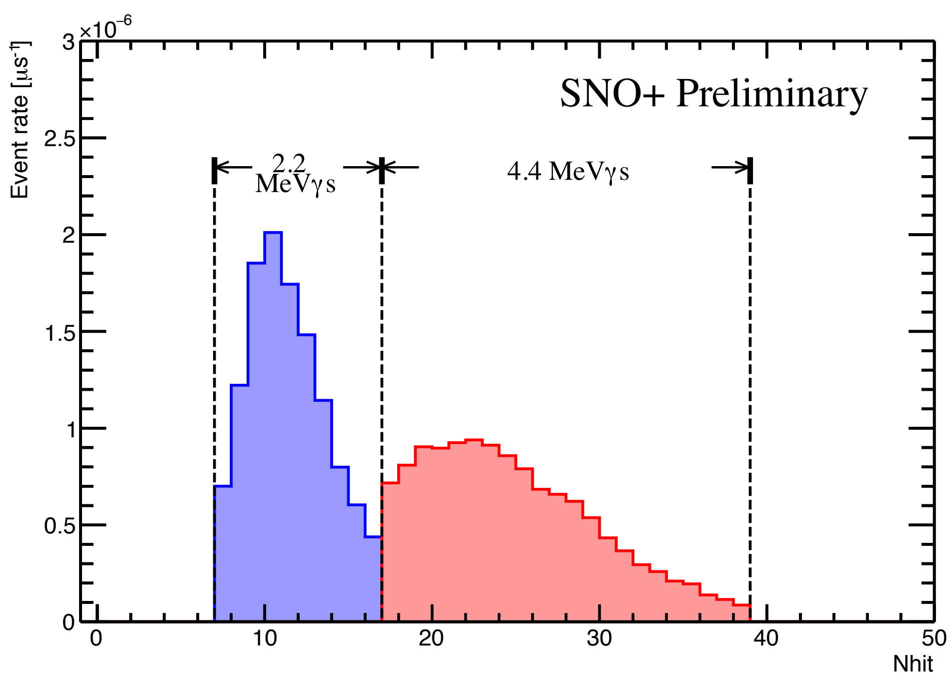
Dashed line: nonoscillated reactor spectrum
Solid line: geoneutrino spectrum
Red: Bruce reactor at 240km
Blue: Darlington & Pickering reactors at 350km
Green+Magenta: Other reactors

Anti-neutrinos Detection



$$F(\mathrm{t}) = NR_1(P \cdot E \cdot (\Lambda + R_2)e^{-(\Lambda+R_2)\mathrm{t}} + (1 - P \cdot E) \cdot R_2 e^{-R_2\mathrm{t}})$$

N = normalisation factor
R_1 = events rate of prompt selection
R_2 = events rate of delayed selection
P = fraction of 4.4 MeV ɣs in prompt window
E = fraction of detected n from all with a 4.4 MeV ɣ
λ = 1/capture time



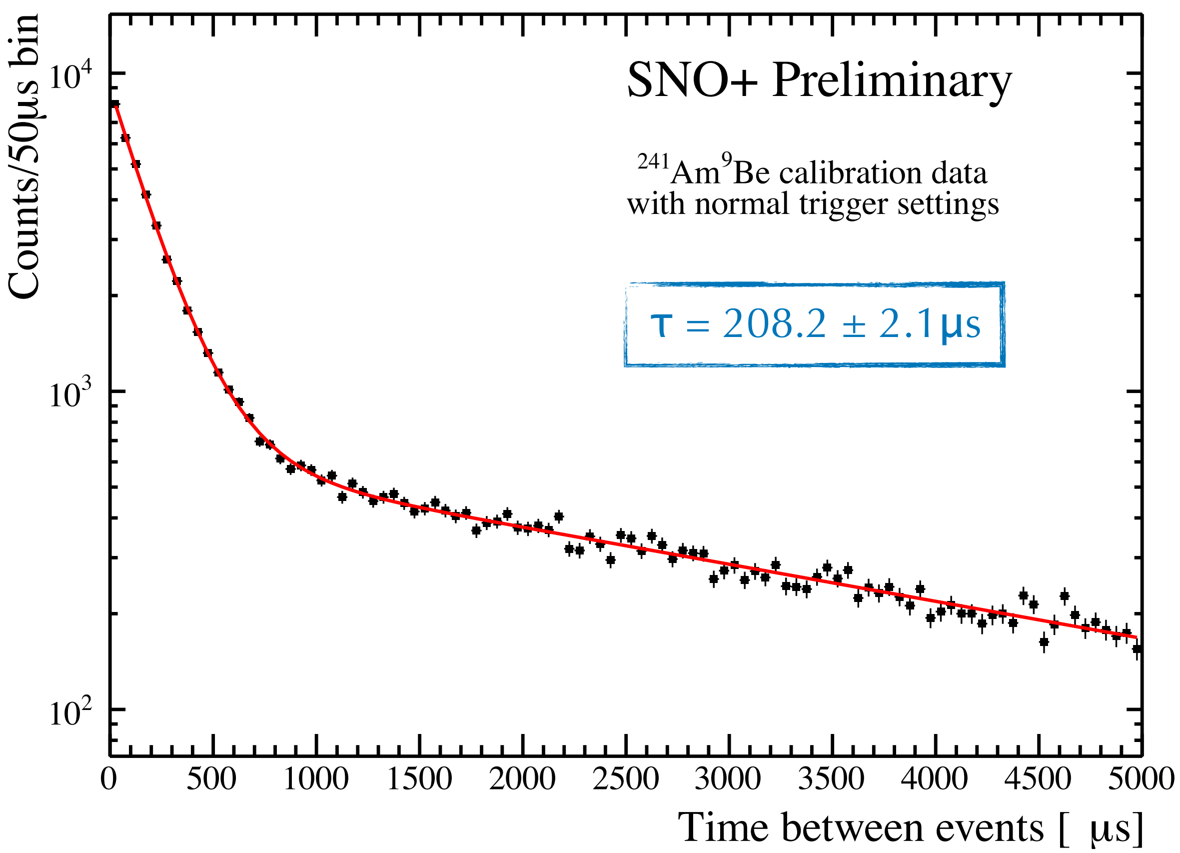
Nhits distribution of the signals extracted from the statistical analysis of coincidences:
Prompt = 4.4 MeV gs
Delayed = 2.2 MeV gs

Neutron Detection

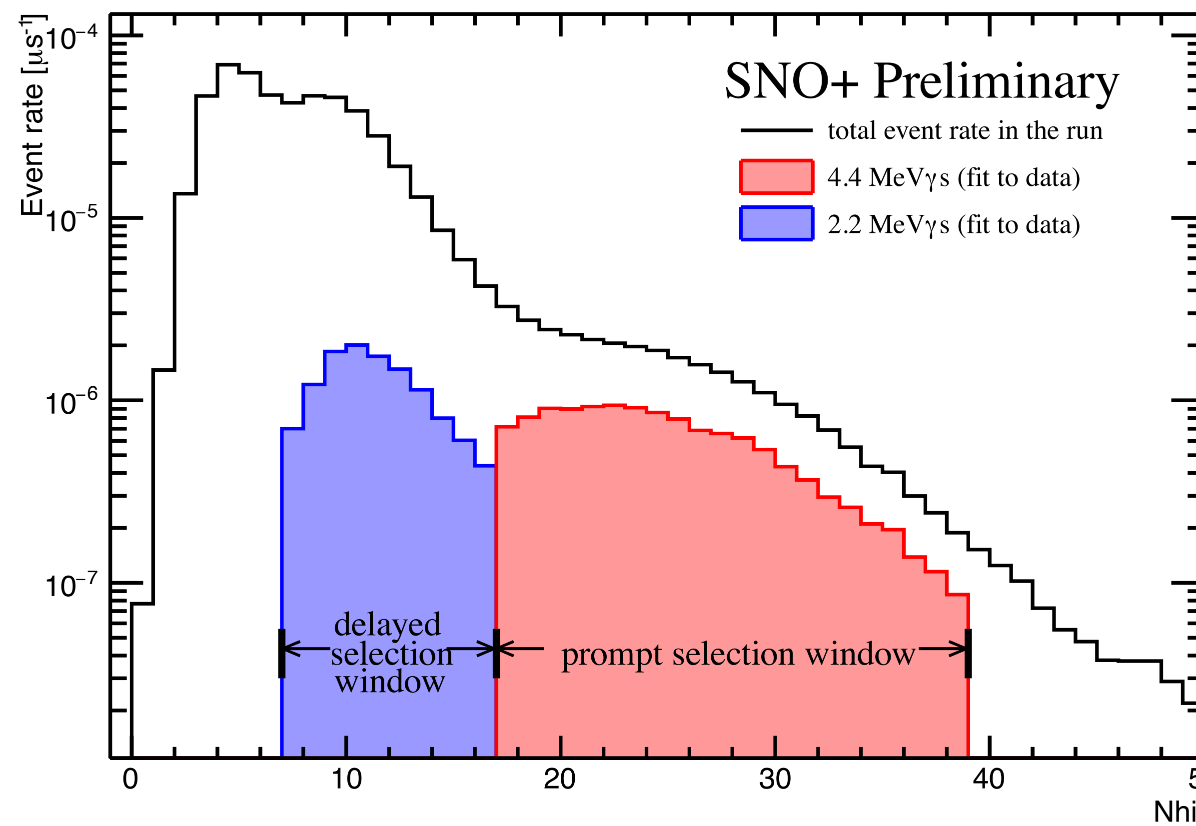
Deployment of AmBe source

- Neutron detection efficiency
- Neutron capture time

Efficiency for triggering on a neutron: 46%



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.