IAEA Technical Meeting on (α,n) nuclear data evaluation and data needs
Online, 8-13 November 2021

(α,n) reactions in low-background neutrino experiments

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$(\alpha$,n) Reactions In Low-Background Neutrino Experiments: Motivation

✓ Low background neutrino physics include experiments that look for:

- **Antineutrinos from reactors**: can help solve the neutrino oscillation tension between reactor and solar
- **Antineutrinos from the Earth**: important to understand the heating mechanism of our planet, search in different locations to disentangle the crust and mantle contributions.
- **Neutrinoless double-beta decay**: shed light on the Majorana nature of the neutrinos, insights to the matter/antimatter asymmetry
- **CP-violation**: Insights to the matter/antimatter symmetry
- **Solar neutrinos**: insight to neutrino oscillations and the interior of the Sun
- **Supernova neutrinos**: information about core collapse and supernova formation
- **Exotics physics**: such as nucleon decay into invisible channels

✓ Advancement of technology allowed the selection of materials with improved purity:

- Large **reduction** of beta and gamma background.
- Backgrounds that were initially negligible became more and more important
- **Neutrons** and **gammas** produced by alpha interactions with detector materials can hide the signal searched for.

(α,n) Reactions In Low-Background Neutrino Experiments: Materials

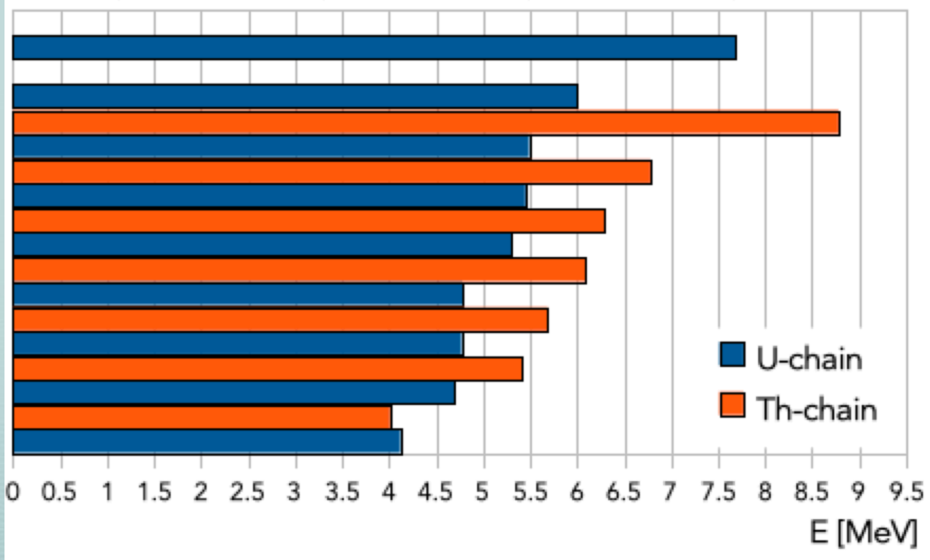
✓ The target of interest for the low background neutrino experiments are:

- **Carbon** (^{13}C): component of liquid scintillators, plastics (such as acrylic, polyethylene, nylon, PTFE) which are often used close to the target volume, rock as many experiments are located in deep underground caverns;
- **Oxygen** (^{17}O and ^{18}O): component of water liquid scintillators, plastics and rock;
- **Nitrogen** (^{14}N): components of platiscs, wavelength shifters, fluors used in liquid scintillators;
- **Fluorine** (^{19}F): component of PTFE that, thanks to the good reflectivity and high resistance is frequently used (enhance light collection, source containers);
- **Aluminum** (^{27}Al): included in aluminum and ceramics
- **Titanium** & **Copper** & **Stainless steel**: used in cryostats, shielding, support structures, purification systems
- **Silicon**: present in quartz, glass, light sensors
- **Beryllium** (^{9}Be) present in wires
- **Argon** and **Xenon**: used in target material
- Isotopes that are **candidates for neutrinoless double-beta decay** studies (Te, Xe, Sn,…).

(α,n) Reactions In Low-Background Neutrino Experiments: Alphas

- Three main processes contribute to the neutron production:
  - Spallation reactions from **muons** in the detector material and rock surrounding it
  - **Spontaneous fission**: mainly from ^{238}U, probability of about $5x10^{-7}$/chain, production of 2 neutrons per reaction. Generally dominates for high Z-materials.
  - **(α, n)** reactions: Generally is dominant source for low Z-materials.
    - Depends on the alpha energy and on the target.
    - The neutrons have a wide spectrum in energy

- Potential alpha sources:
  - **U & Th chain** decays in the target material
  - U & Th chain decays in detector's structure
  - **Rn** emanation and Rn ingress (out of equilibrium)
  - **^{210}Po** from Rn decay plating onto surfaces (accumulation over time, long lived ^{210}Pb)
  - ^{210}Po leach off surfaces into the target media



- Extensive campaigns exist to measure these sources and mitigate the Rn ingress and the ^{210}Po plate out

(α,n) Reactions: Estimating the number of events

Various Codes available
(see talks Westerdale, Cano, Kudryavtsev)

- ★ Number of alpha particles & target atoms

  ➕

- ★ Propagation of alpha particles in the media ← **SRIM, ASTAR(NIST), G4**

  ➕

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

  (➕)

- ★ Angular distribution ← **THEORETICAL**

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

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

Neutron yield → **# expected events**

Normalisation

(α,n) Reactions: Estimating the number of events

Various Codes available
(see talks Westerdale, Cano, Kudryavtsev)

★ Number of alpha particles & target atoms

+

★ Propagation of alpha particles in the media

+

★ Cross sections for the selected reaction

(+)

★ Angular distribution

Few % unc. among models (→ Propagation of alpha particles in the media)

Large uncertainty among models/ experiments (up to 100%) (→ Cross sections for the selected reaction)

Excited states xs not separated

available for few reactions (→ Angular distribution)

Neutron flux → **Large uncertainty in the expected distribution**

Alpha flux → **Large uncertainty in the expected distribution**

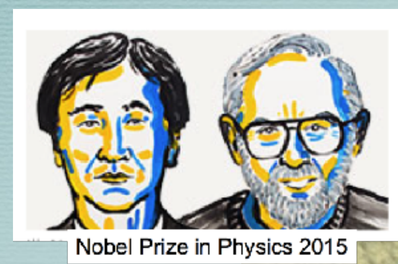
Neutron yield → **# expected events**

Large uncertainty in the number of expected events

(α,n) Reactions in Experiments

- ✓ Three example given
  - ◉ **SNO+**: Water and Liquid scintillator experiment
  - ◉ **DUNE**: Argon TPC
  - ◉ **nEXO**: Xenon TPC

Type of background reactions in Liquid Scintillator based experiments: SNO+

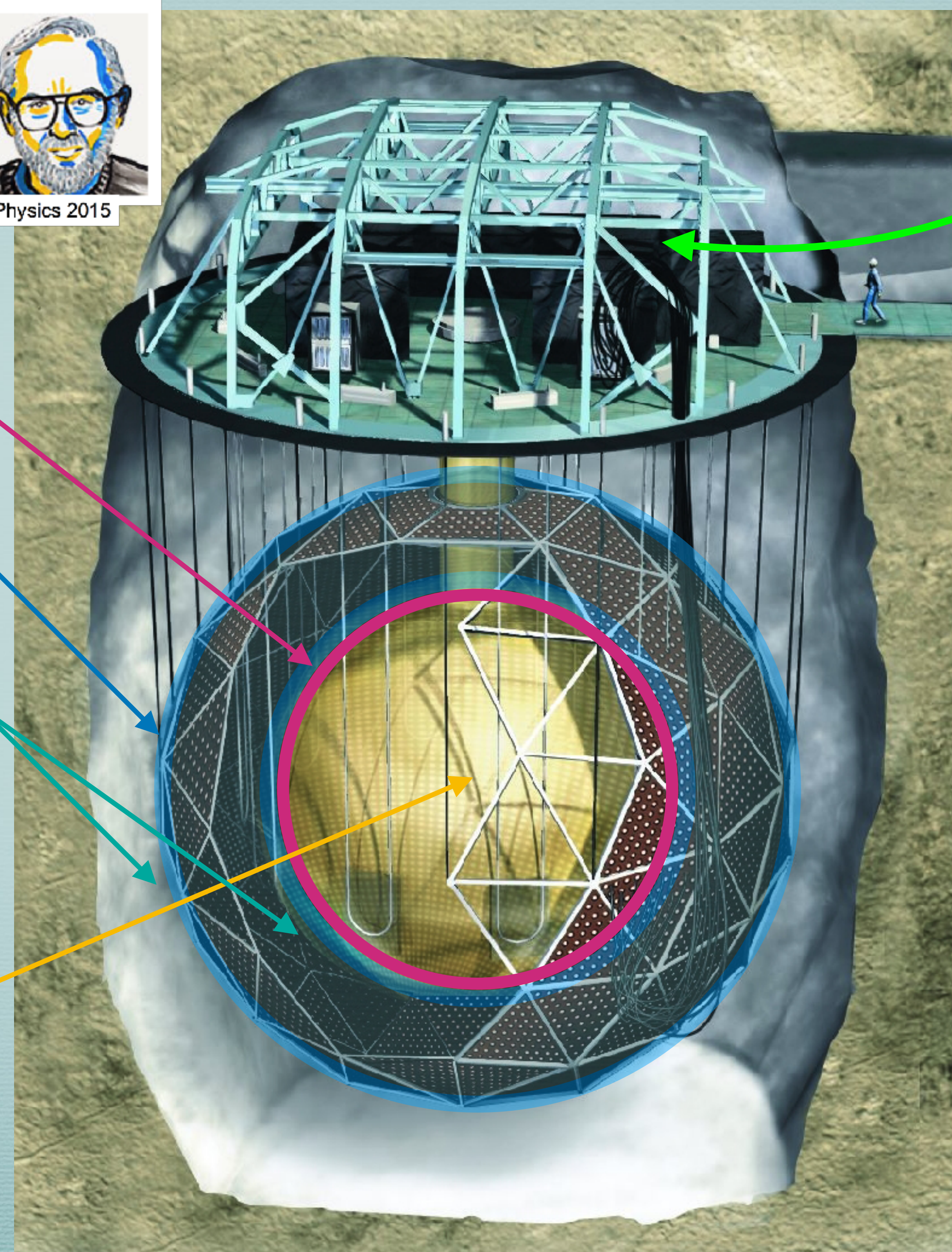


Acrylic Vessel (AV)
12 m diam., 5 cm thick

PSUP (PMT Support Structure)
~ 9300 PMTs
54% Coverage

Light water (H2O) shielding
- 1700t internal
- 5300t external

Active medium:
water,
scintillator,
loaded
scintillator



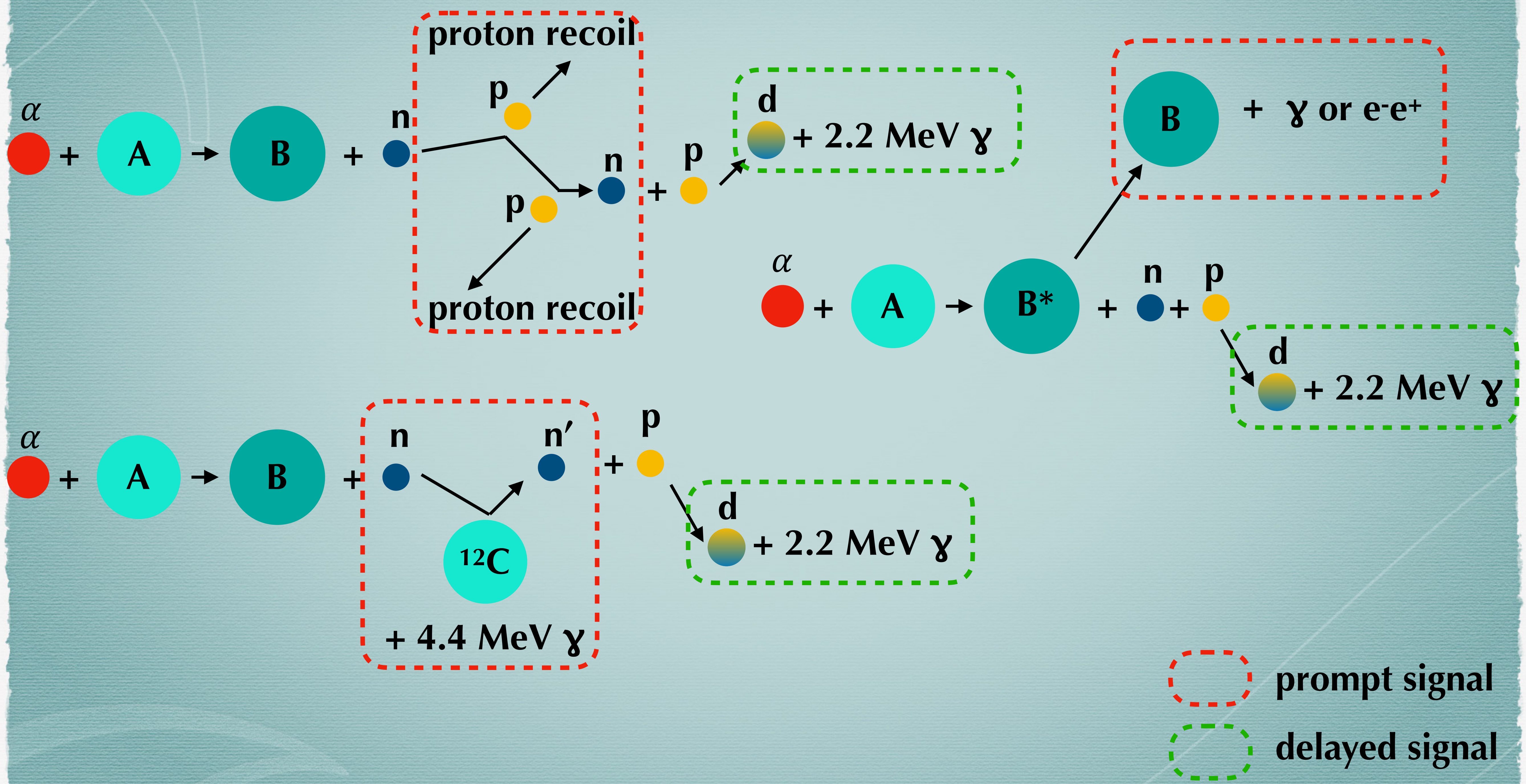
Overburden, 6800 ft,
5890 mwe

✓ Three Phases:
- **Water**: 2017-2019
- **Pure LS**: 2019-now
- **Te-loaded**: late 2022

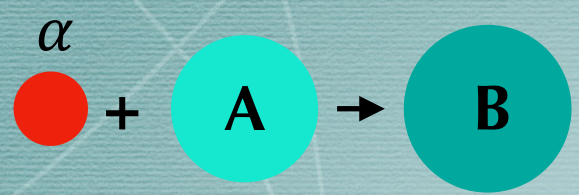
✓ Many Physics possibilities:
- **0νßß-decay** with ^{130}Te
- Solar neutrinos (^{8}B and low energy)
- Supernova neutrinos
- Geo and Reactor antineutrinos
- Exotics physics

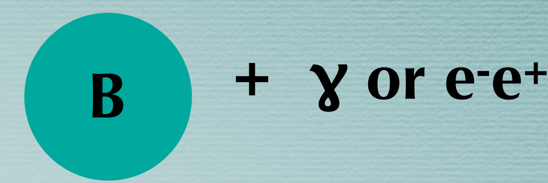
LS-based experiments:
Critical (a,n) reactions

Major source of alphas = ^{210}Po

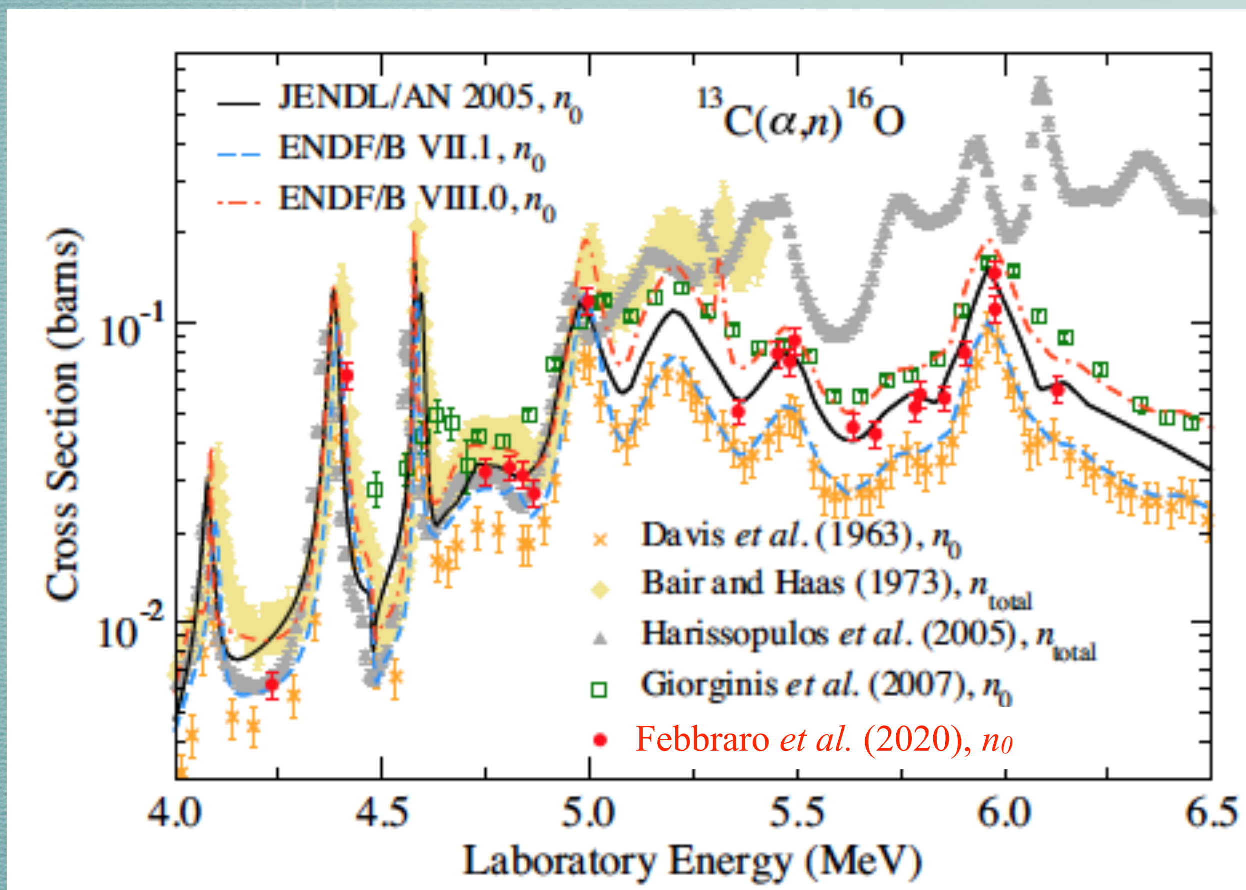


LS-based experiments: Critical (a,n) reactions





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

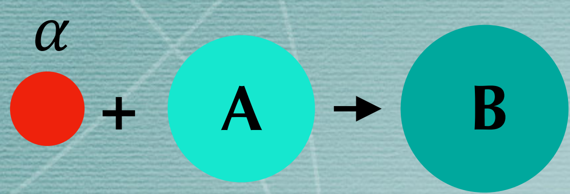


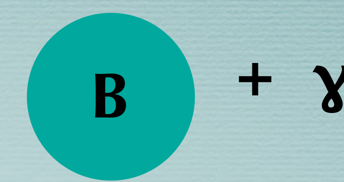
PHYS. REV. LETT. 125, 062501 (2020)

- ✓ Good agreement below 5.0 MeV
- ✓ **High uncertain at larger energy (U/Th-chain alphas up to 9 MeV)**

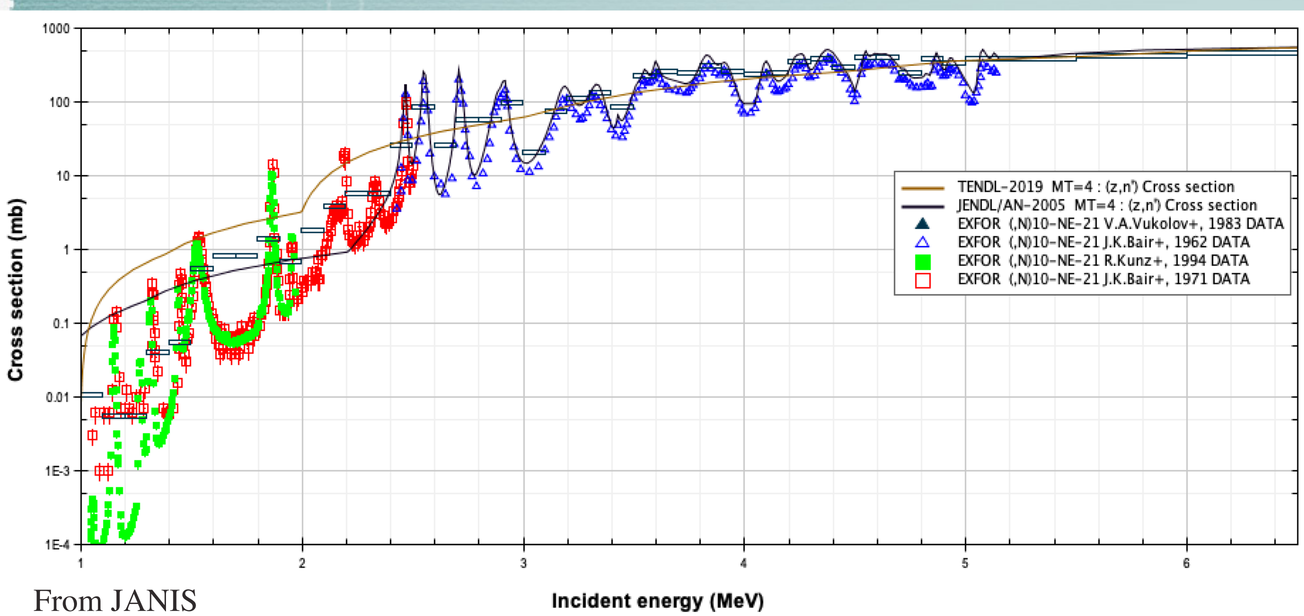
- ✓ The excited states cross section is also very important, high energy gammas fall in the region of interest for some of the analysis
- ✓ For the 1st the excited states (internal pair production) in ^{16}O, the cross section has not been measured.
- ✓ For the 2nd excites state (gamma emission) in ^{16}O, variations of a factor 2 cross section exist

LS-based experiments: Critical (a,n) reactions



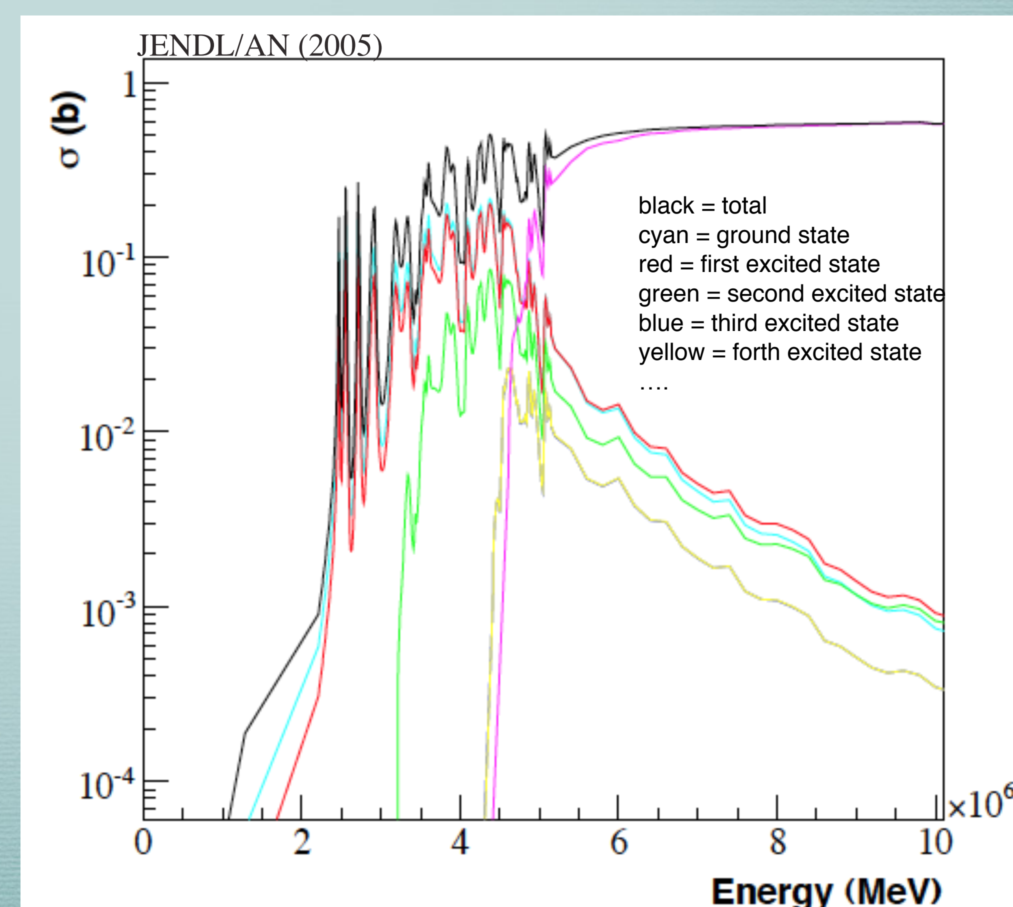


$^{18}O(\alpha,n)^{21}Ne$



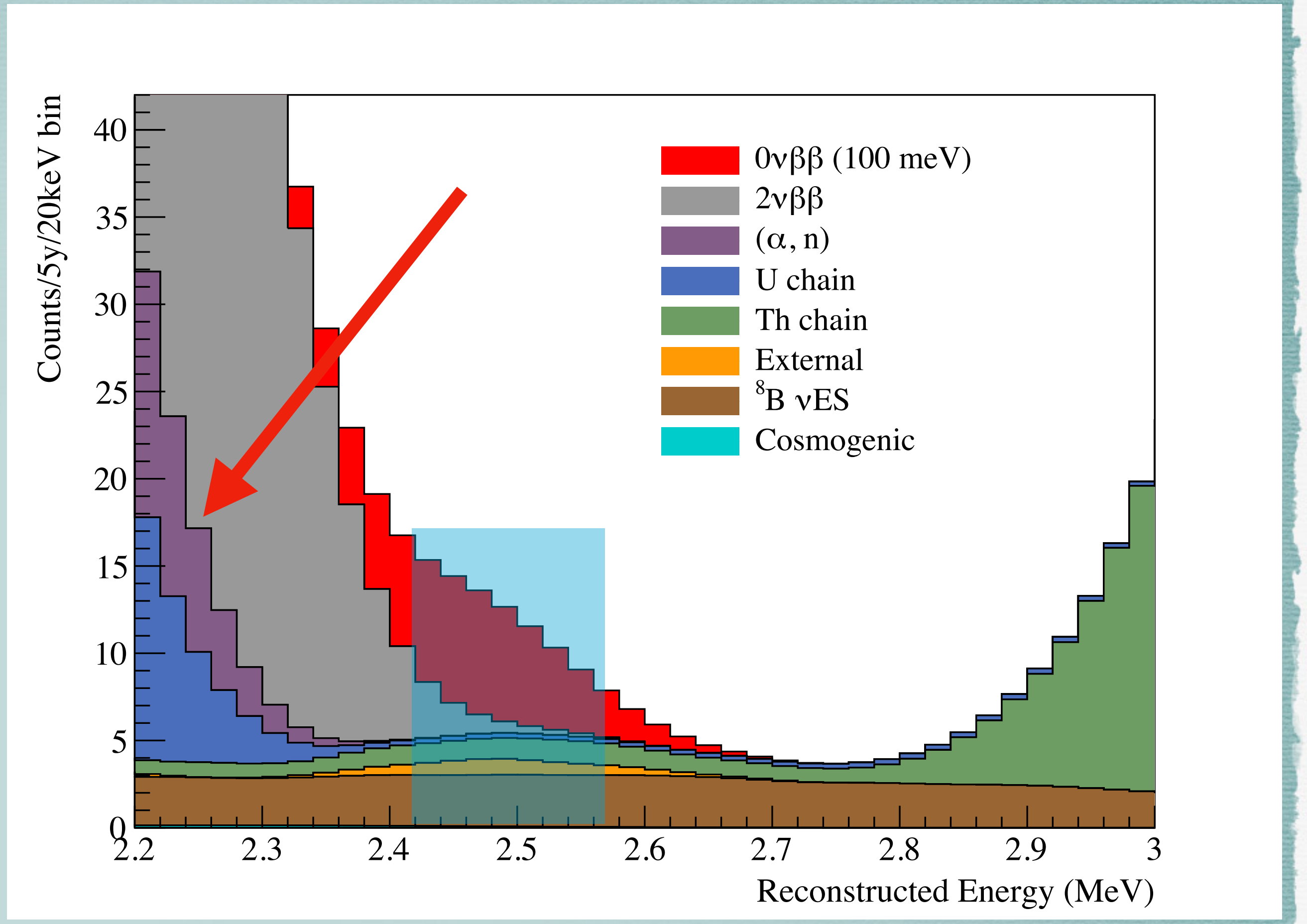
- ✓ **Not so good agreement between data and model**

- ✓ The excited states cross section is also very important, high energy gammas fall in the region of interest for some of the analysis



(a,n) background for SNO+ Physics: Te-loaded

1. Neutrinoless double-beta decay search with ^{130}Te
   - ✓ Q-value of 2.52 MeV
   - ✓ ROI in a 3.3 m radius = [2.42, 2.56]
   - ✓ $^{13}C(\alpha,n)^{16}O$ in scintillator (major)
   - ✓ $^{13}C(\alpha,n)^{16}O$ + $^{18}O(\alpha,n)^{21}Ne$ on the vessel surface (small)
   - ✓ Mitigation strategy:
     - ✓ Delayed coincidence rejection
     - ✓ Fiducialization
     - ✓ Purification of materials



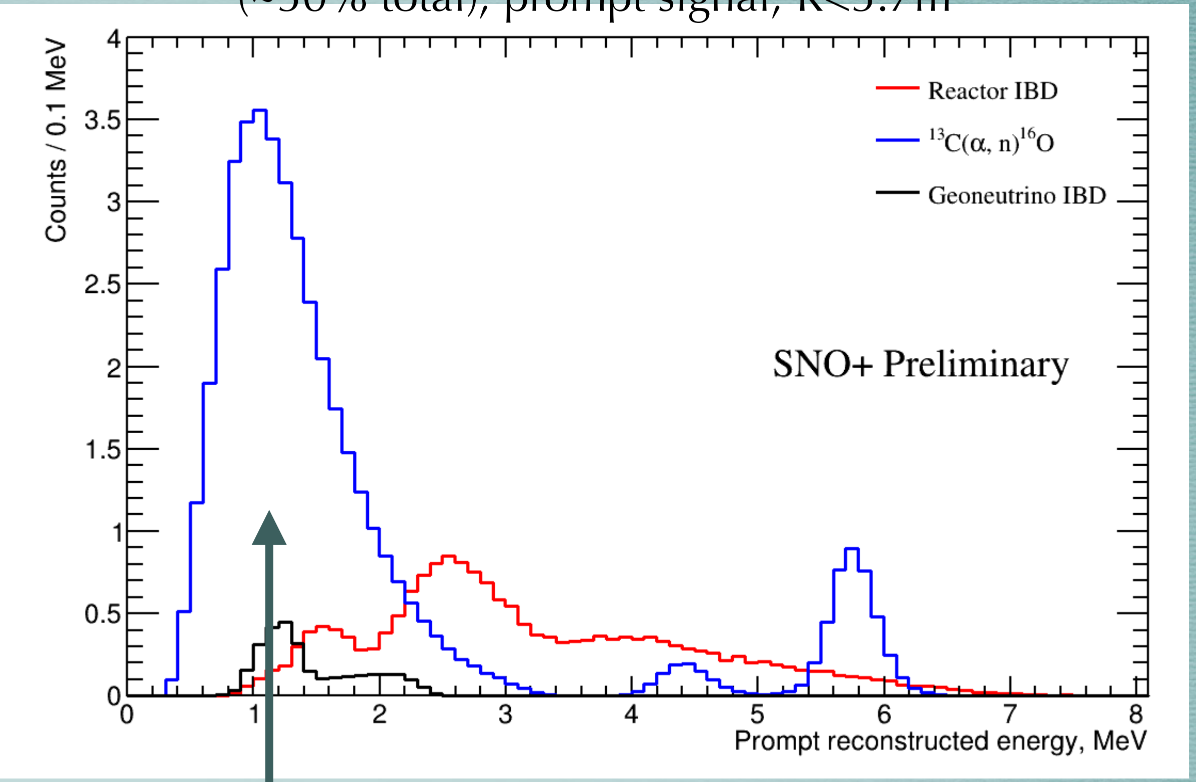
- Prompt signal from proton recoil up to 3 MeV energy
- Delayed signal from neutron capture peaked at 2.2 MeV
- Excited states of ^{21}Ne with energy between 2 and 3 MeV

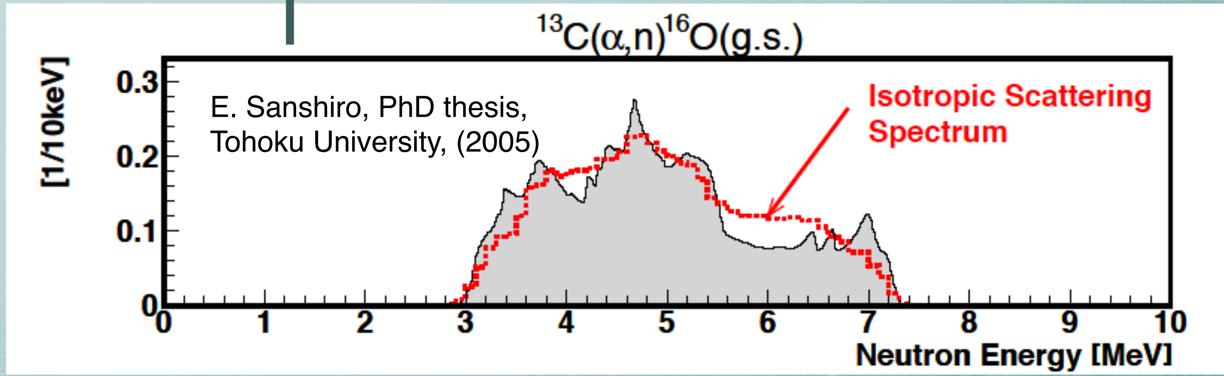
→ Highly reduced by mitigation strategies (subdominat to U and Th)

(a,n) background for SNO+ Physics: scintillator

2. Antineutrino (reactor/geo) measurements via inverse beta decay in scintillator
   - ✓ $^{13}C(\alpha,n)^{16}O$ in scintillator (major)
   - ✓ $^{13}C(\alpha,n)^{16}O$ + $^{18}O(\alpha,n)^{21}Ne$ on the vessel surface (small)
   - ✓ Prompt + Delay events mimic the signal
   - ✓ Mitigation:
     - Distinguishing the signal events from the background events is difficult. Try the development of classifiers
       - alphas, proton and gamma light all contribute to the prompt signal —> **spectral shape is important!**
     - The emission of gammas from the excited states could help to constraint the event's rate at low energy —> **it requires a good knowledge of the ratio GS to Exc**.

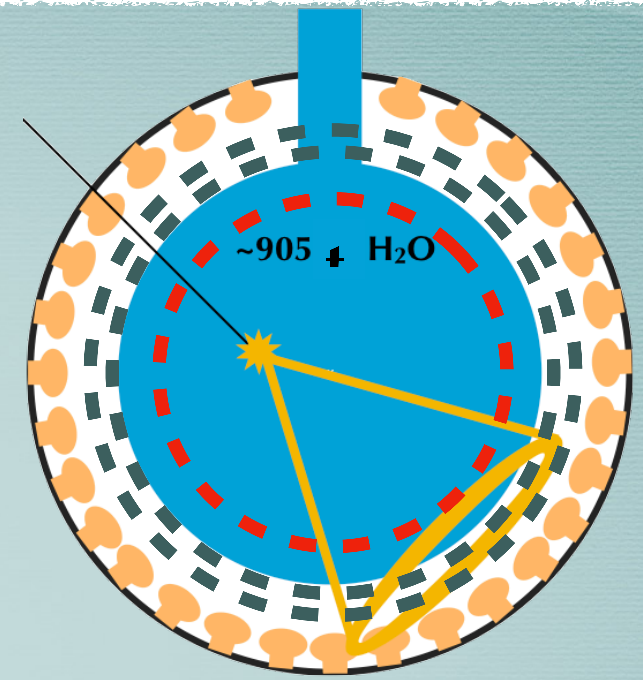
Projection for 6 months of data in 365 t scintillator (~50% total), prompt signal, R<5.7m





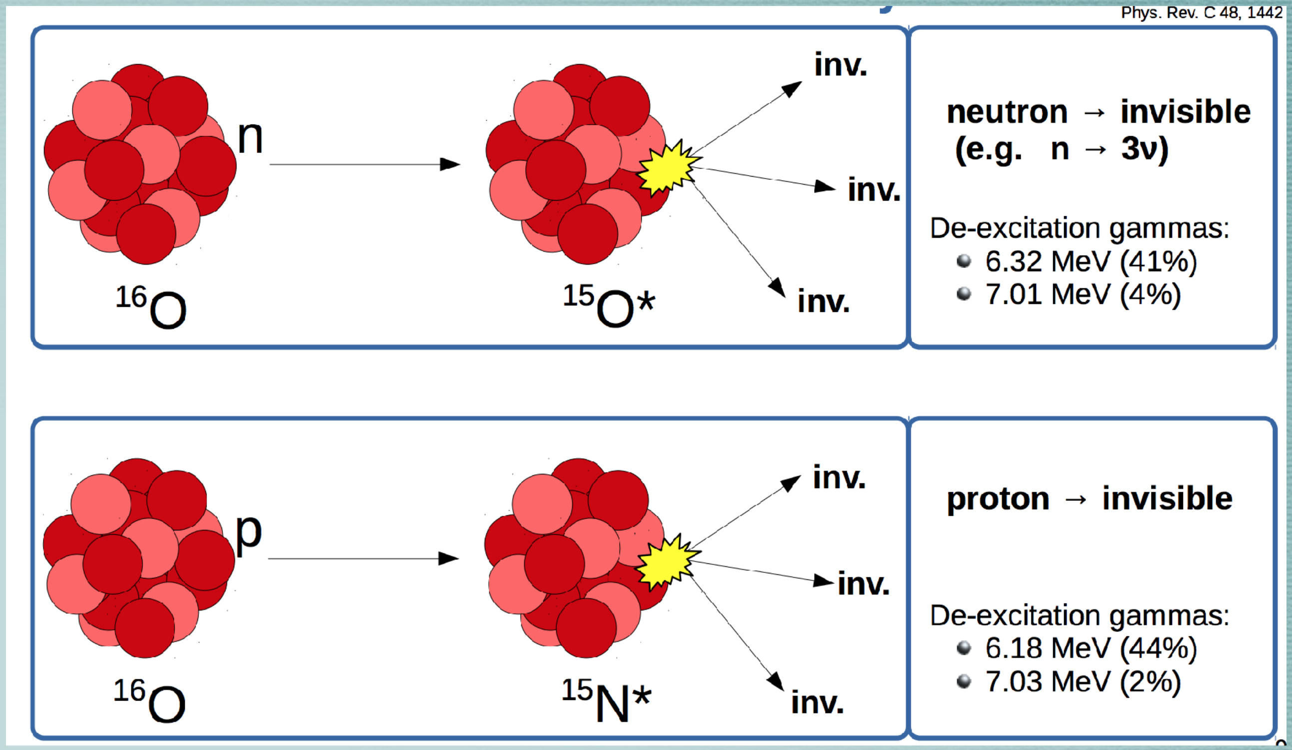
(a,n) background for SNO+ Physics: Water

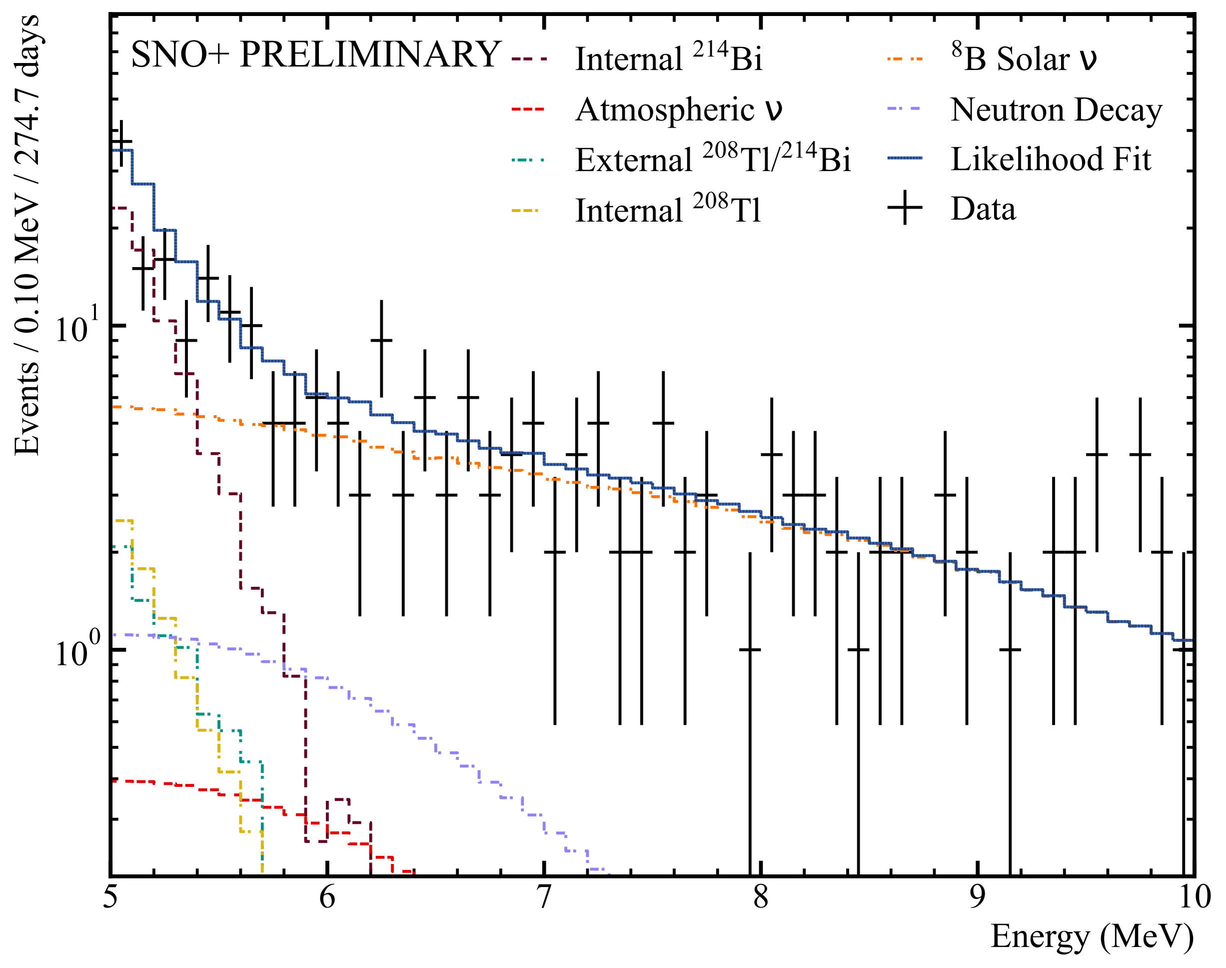
3. Antineutrino (reactor/geo) measurements via inverse beta decay in water
   - ✓ ^{8}O(α,n)^{21}Ne in water
   - ✓ ^{13}C(α,n)^{16}O + ^{18}O(α,n)^{21}Ne on the vessel surface
   - ✓ Prompt signal is from the de-excitation of ^{16}O* and ^{21}Ne*
   - ✓ Delayed signal from the neutron capture
   - ✓ Mitigation:
     - Fiducialization
     - Side band studies near the vessel surface and projection into the fiducial volume —> **large uncertainties on the reaction rates limit the antineutrino search**

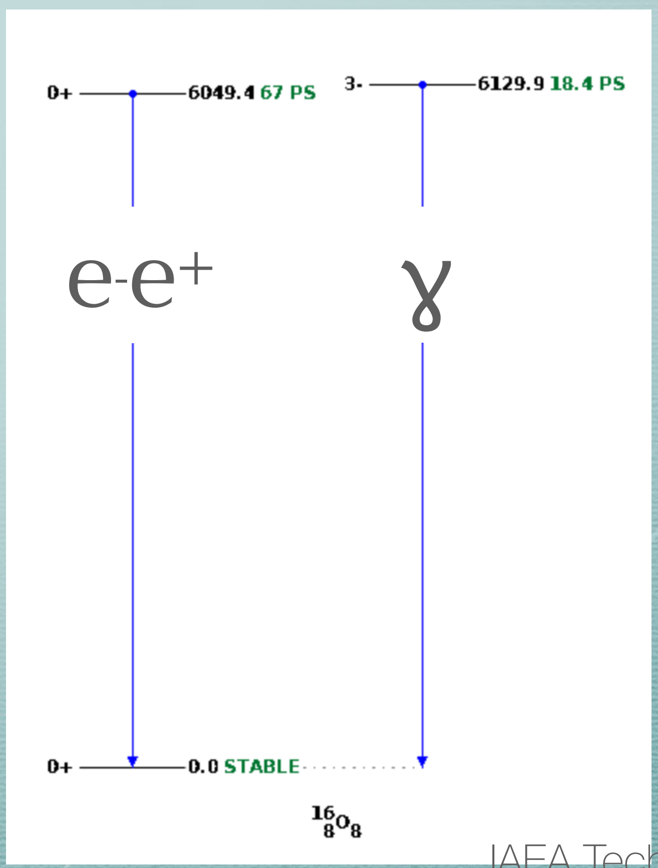


(a,n) background for SNO+ Physics: Water

3. Nucleon decay into invisible channels
   - ✓ $^{8}O(\alpha,n)^{21}Ne$ in water
   - ✓ $^{13}C(\alpha,n)^{16}O$ + $^{18}O(\alpha,n)^{21}Ne$ on the vessel surface
   - ✓ Signal is from the de-excitation of $^{16}O^*$
   - ✓ Mitigation:
     - Fiducialization -> negligible source of background in the ROI of 5 to 10 MeV



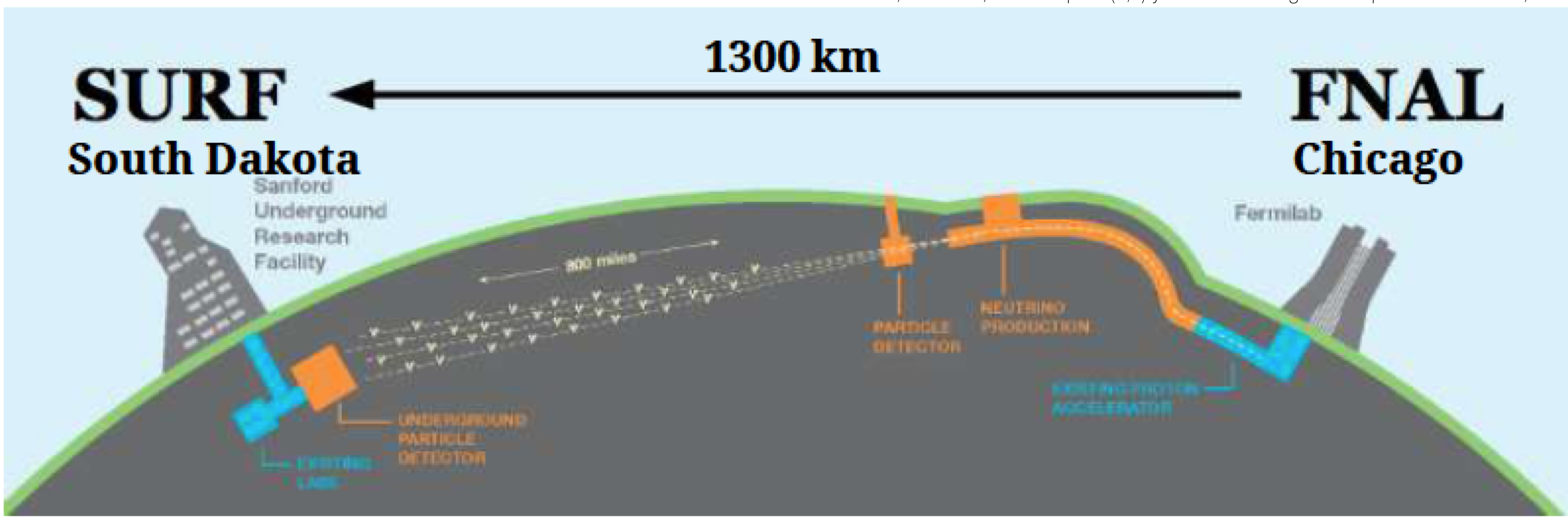




Type of background reactions in Argon-TPC experiments: DUNE

DEEP UNDERGROUND NEUTRINO EXPERIMENT

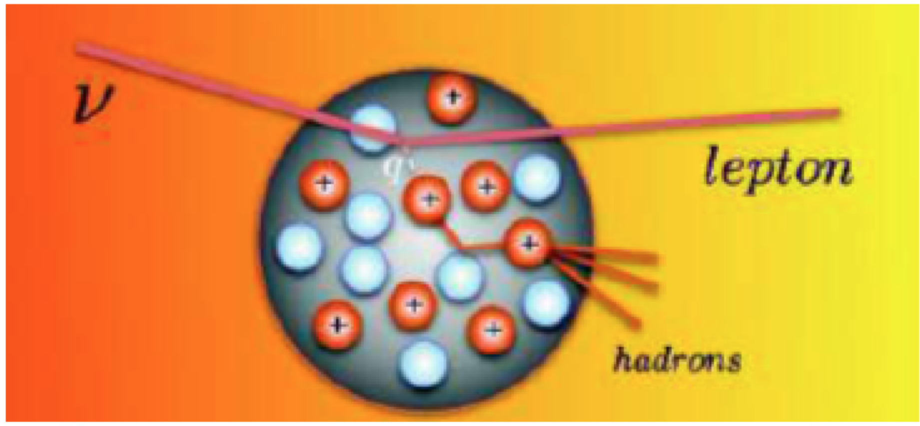
R, Svoboda, Workshop on (α,n) yield in low background experiments CIEMAT, Madrid



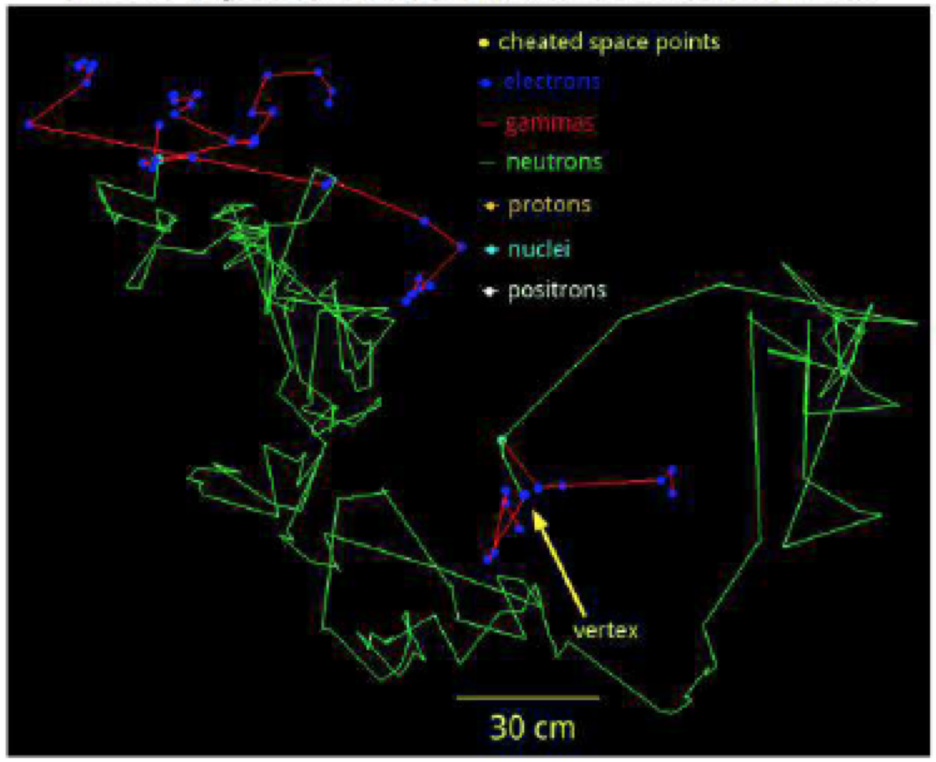
- 1.5 km underground
- On-axis 40 ktonne LAr TPC
- ν_μ disappearance and ν_e appearance to measure MH, CPV, and mixing angles
- Large detector, capable of observing supernova neutrinos, solar neutrinos, nucleon decay and other BSM processes
- New ν_μ beam: 1.2 MW @ 80 GeV protons, upgradable to 2.4 MW
- It can run in neutrino and antineutrino modes by switching the polarity of the magnetic horns.
- Wide band neutrino beam.
- Highly capable near-detector

DUNE: the importance of neutrons

- ✓ Need to understand the neutrino-nucleus complex interactions
  - ✓ Neutrons carry away a large fraction of the energy
  - ✓ Neutron yield is model dependent
  - ✓ Neutrons are hard to detect in LArTPC (“missing” energy) —> requires a good modelling of the neutron capture and transport in LAr
  - ✓ Extremely important for the low energy physics (requires to trigger on very low energy deposition):
    - ✓ **Solar neutrinos**
    - ✓ **SN neutrinos**

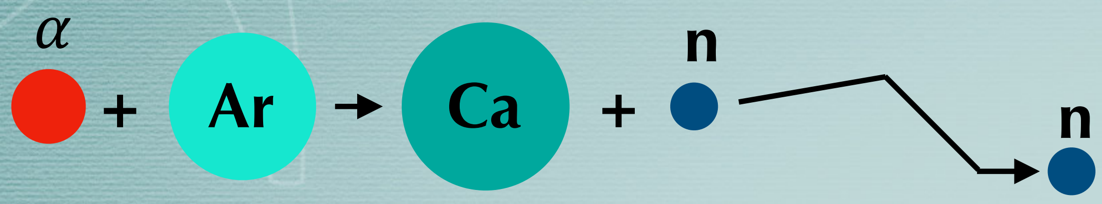


Particle trajectories from a simulated SN event in DUNE

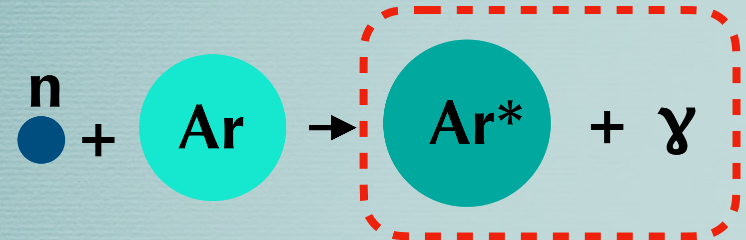


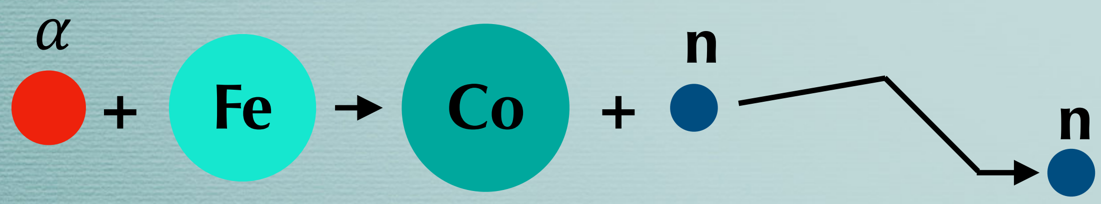
LAr experiments:
Critical (a,n) reactions

Major source of alphas = ^{222}Rn daughters (including ^{210}Po from plate out)

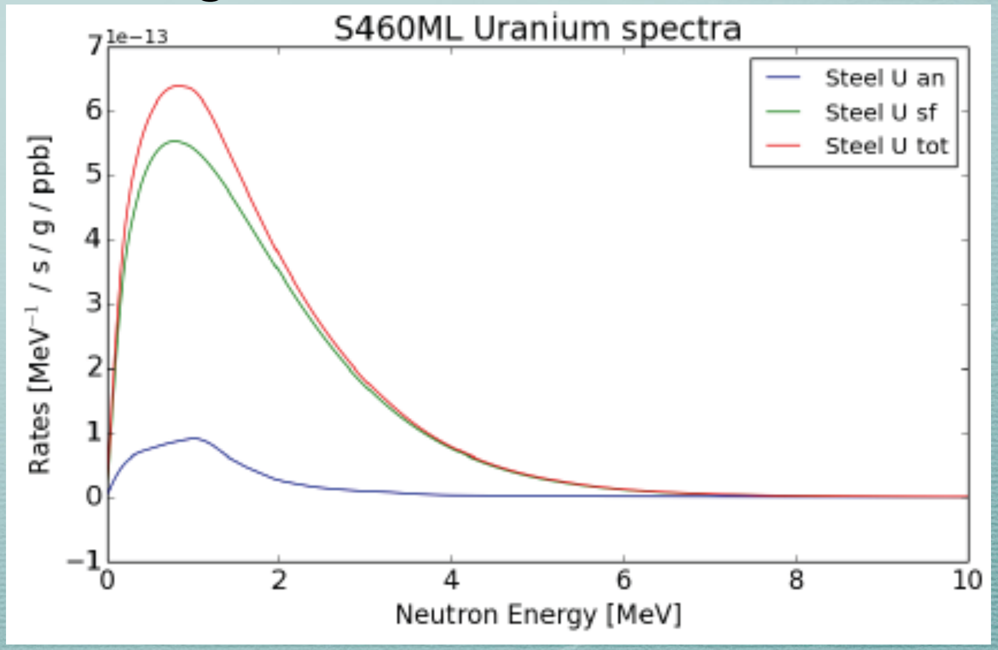


Rn and progeny can give some neutron background if in the liquid (before being removed during circulation) or attached to the walls



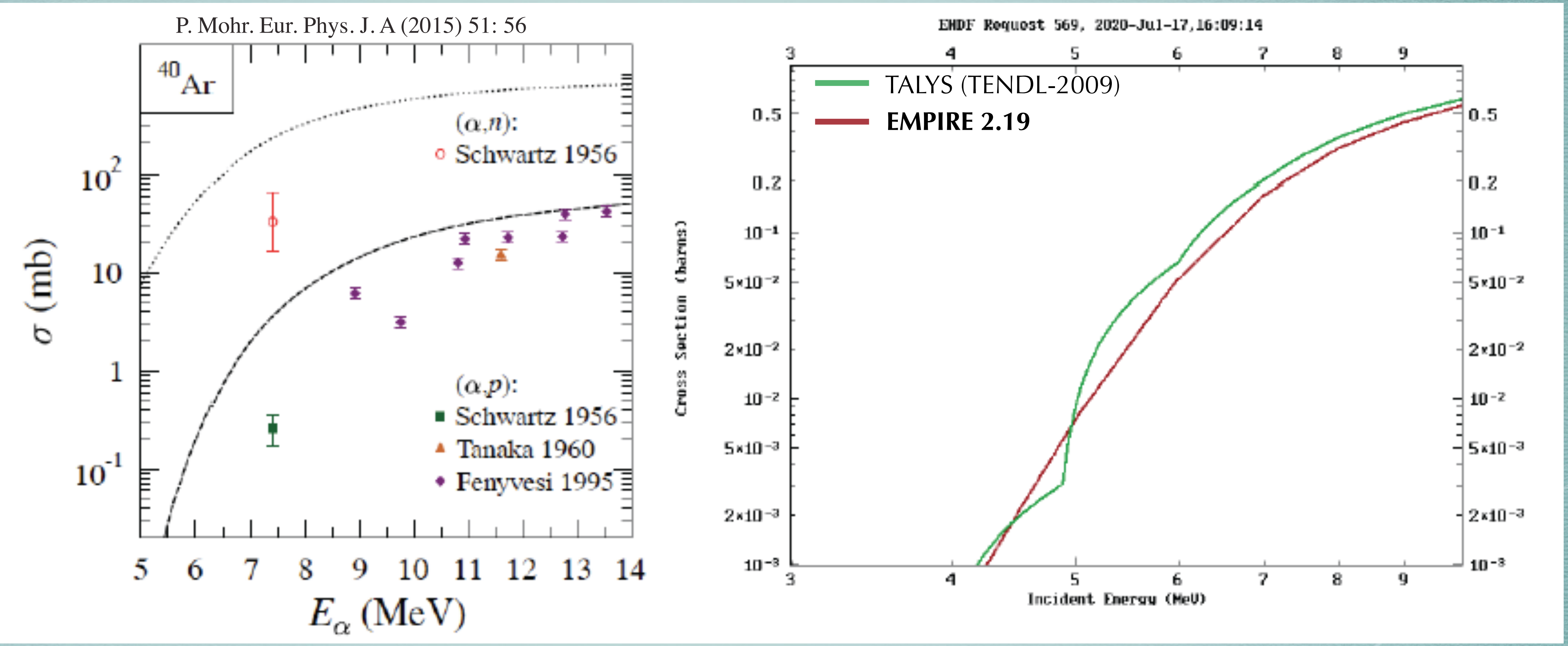


Rn and progeny can give some neutron background in the steel structure.
Subdominant to Spontaneous Fission
Missing model for Fe in JENDL



LAr-based experiments: Critical (a,n) reactions

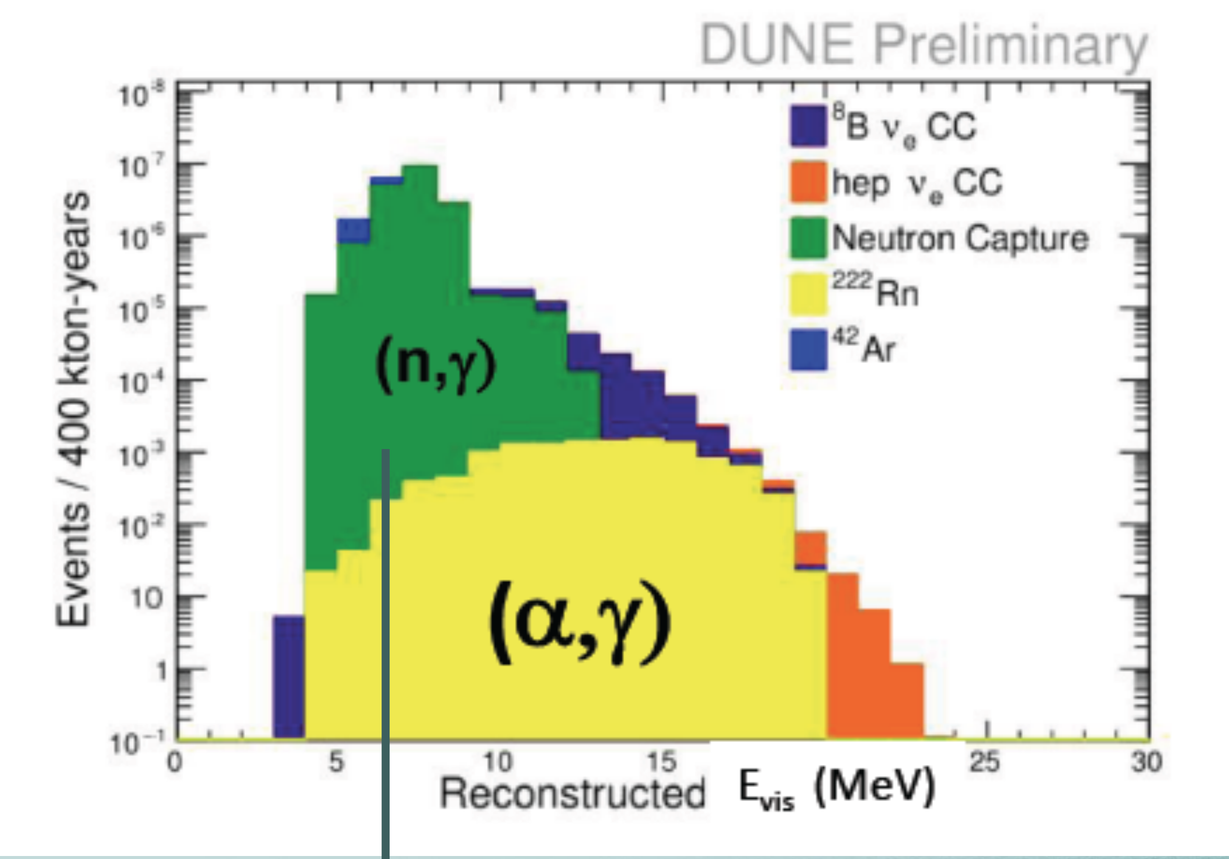
$^{40}Ar(\alpha,n)^{43}Ca$



- ✓ 20% difference for most of the energies
- ✓ Only 1 data point, measurement from 1956 —> Need more data points to validate the model!
- ✓ **Uncertainties are important to set requirements on radon in Argon**

(a,n) background for DUNE: Solar Neutrinos

1. The ability to reject/limit neutrons is crucial for the solar neutrino measurement
   - ✓ Neutron sources include:
     - ✓ External:
       - ✓ (a,n) in Rock and Shotcrete (U/Th)
       - ✓ (a,n) in Support structure (U/Th/Fe)
       - ✓ (a,n) in Cryostat Steel
       - ✓ (a,n) in Be in wires
       - ✓ (a,n) in Insulation
     - ✓ Internal:
       - ✓ (a,n) in Ar from Rn ingress
       - ✓ (a,n) in Ar from dust or leach-off of 210Po from materials
     - ✓ Cosmogenically generated (small)
   - ✓ Mitigation strategy:
     - ✓ Water/Plastic shields for rock and shotcrete (external neutrons)
     - ✓ Quality checks of materials
     - ✓ Background screening
     - ✓ Minimization of exposure to air

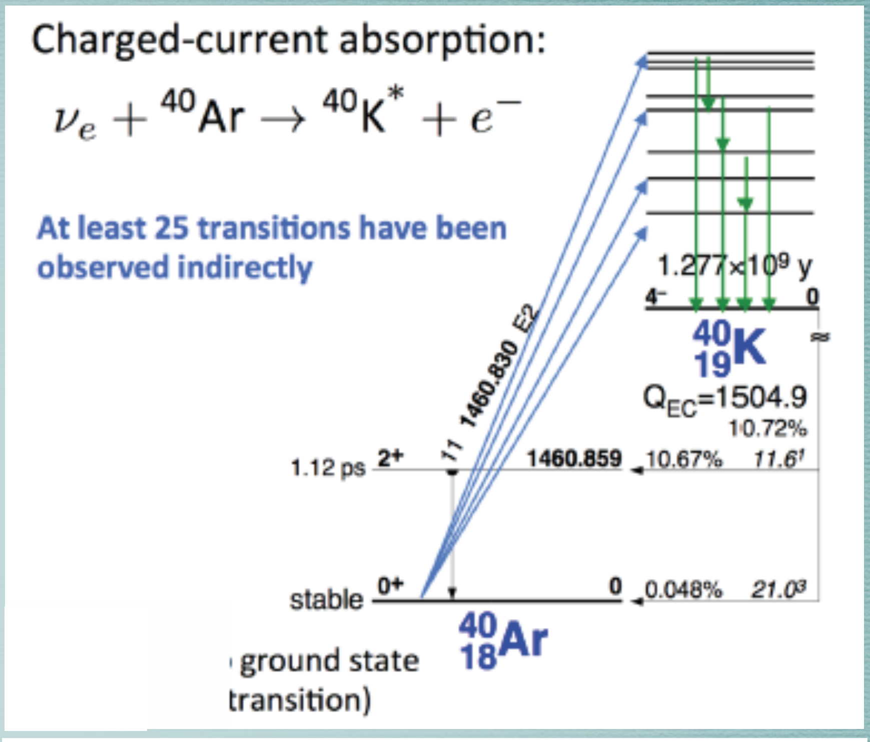


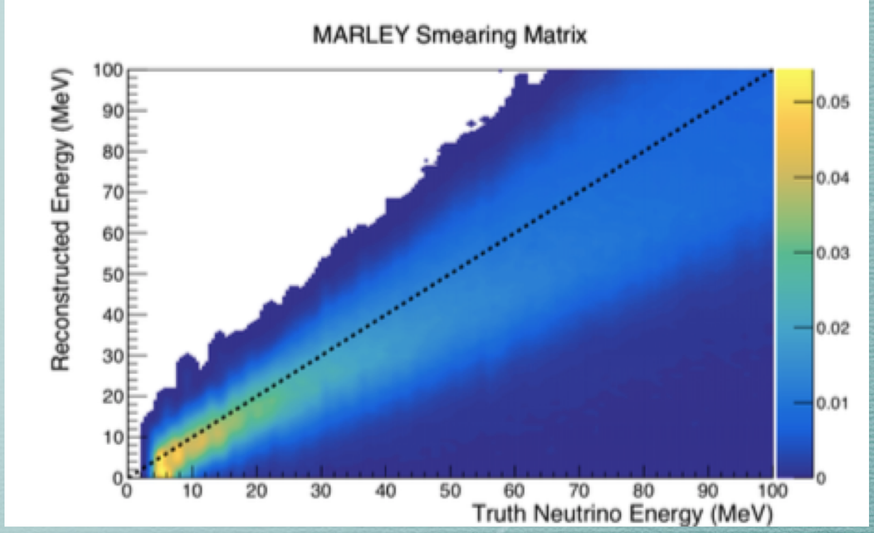
Mitigation will reduce this background BUT if the cross section is much larger than expected it might still be a limiting factor - specially for internal neutrons, i.e. Ar(a,n) -

(a,n) background for DUNE: Supernova Neutrinos

2. Dominant signal from electron-neutrinos
   - ✓ Neutron present two challenges:
     - ✓ The neutrino reconstructed energy is **smeared** by missed neutrons
     - ✓ The rate of neutron backgrounds is expected to be a significant factor in **triggering** DUNE on a SN burst

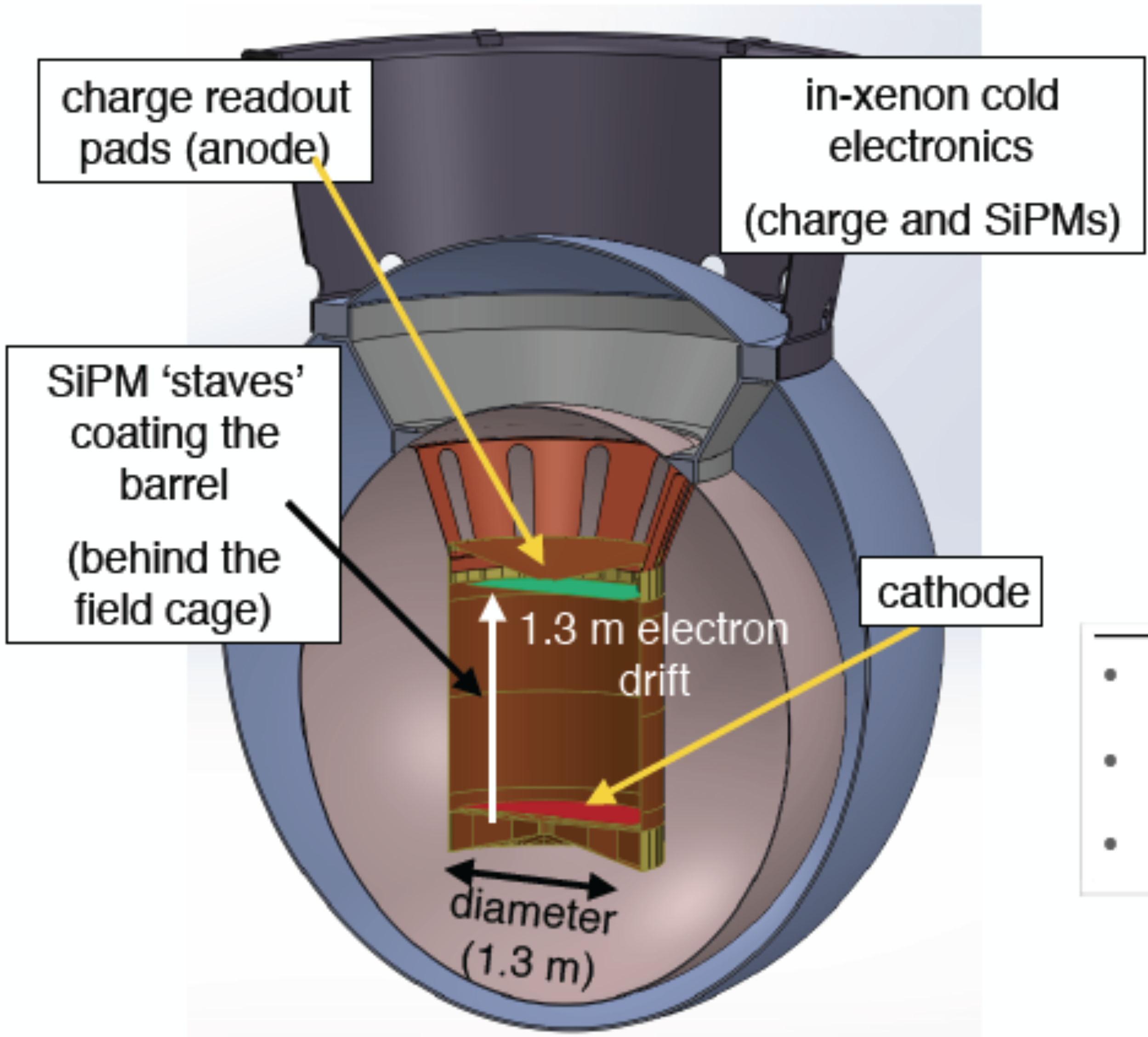
A wrong cross section has a large impact on the triggering





Type of background reactions in LXe experiments: nEXO

A. Pocar, Workshop on (α,n) yield in low background experiments CIEMAT, Madrid



- < 1% energy resolution
- no central cathode
- ≳ 10 ms electron lifetime
- ~500 Rn atoms

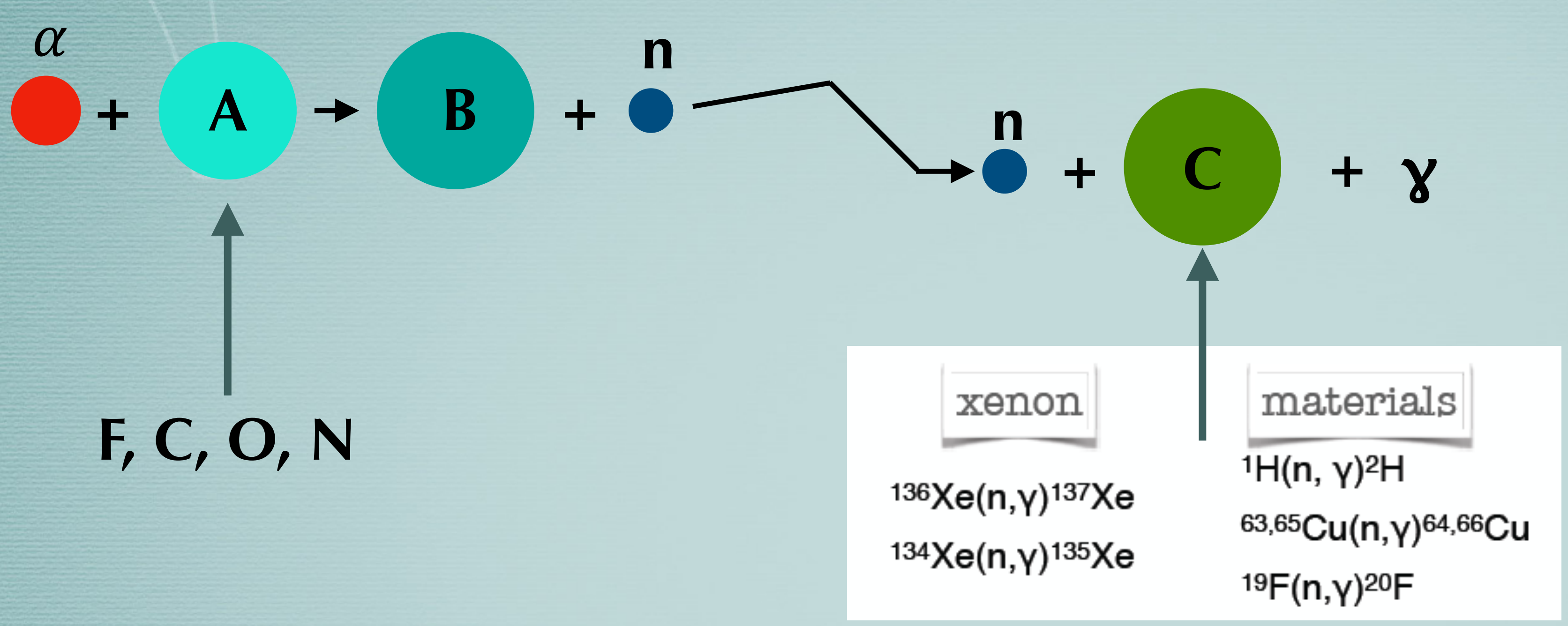
- no plastics, in-Xe cold electronics
- VUV-sensitive SiPMs behind field cage
- charge readout strips

- 25x EXO-200
- enhanced self-shielding
- x100 better $T_{1/2}$ sensitivity

- sensitivity (10 years): 9×10^{27} yr
- energy, topology, standoff & particle ID

LXe-based experiments: Critical (a,n) reactions

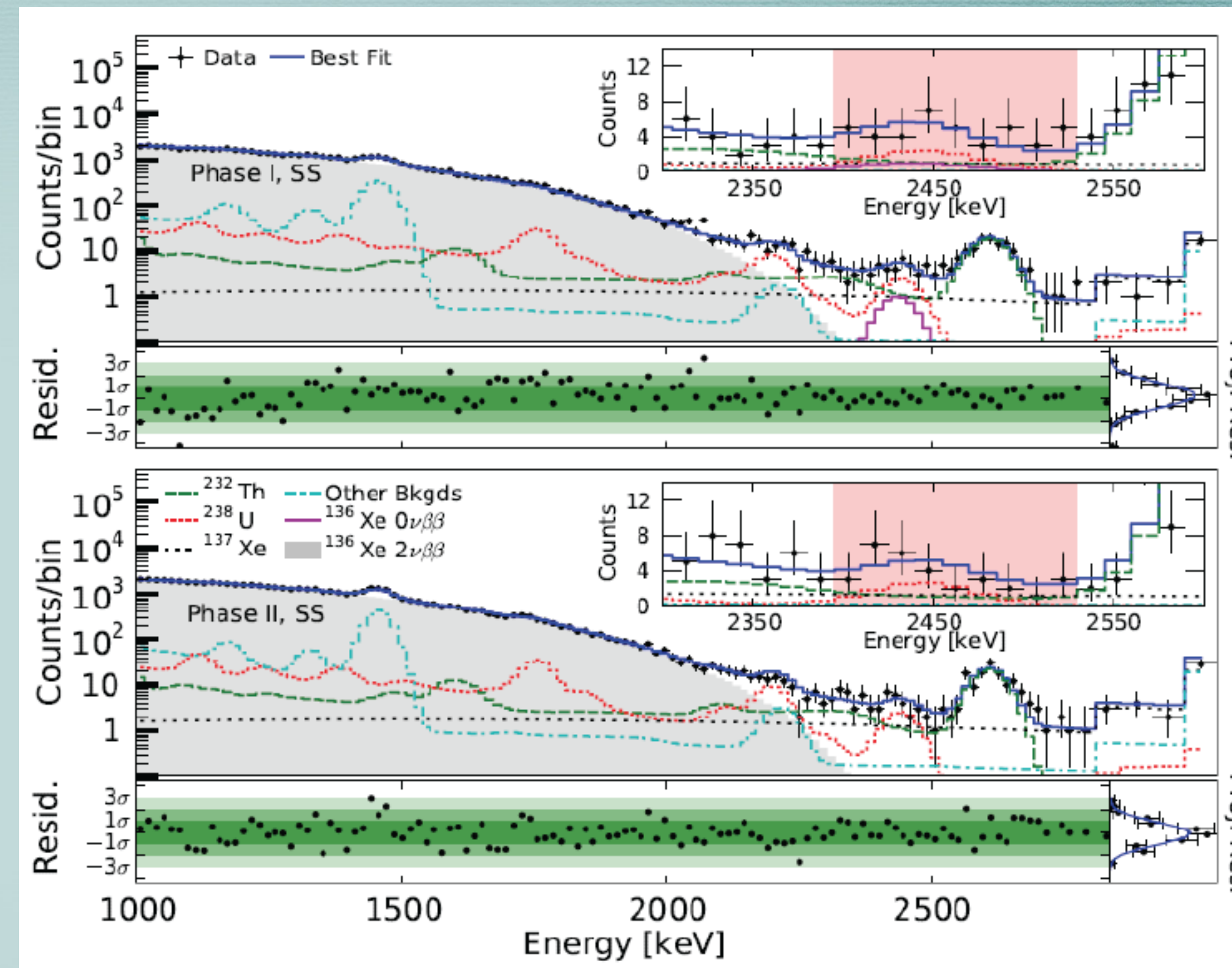
Major source of alphas = ^{210}Po



1. Gammas produced by neutron capture can fall in the region of interest
2. ^{137}Xe is long lived (T1/2 = 3.8 min) and has a high Q-value = 4.2 MeV

(a,n) background for nEXO: ^{137}Xe

1. The beta decay of ^{137}Xe overlaps with the Region of Interest for the neutrino less double-beta decay study:
   - ✓ Neutron sources include:
     - ✓ Muons (major)
     - ✓ ^{210}Po alphas on surfaces and materials in contact with Xe
     - ✓ U/Th alphas in rock
   - ✓ Mitigation strategy:
     - ✓ Coincidence between the muon and gamma emission from 137Xe production
     - ✓ Plastic shield for rock
     - ✓ Background screening
     - ✓ Minimization of exposure to air/dust



Compound	Po Neutron Yield (n/alpha)	Xe capture fraction	Maximal Loading Time (y/m^2)
Sapphire	3.1×10^{-7}	0.071	85.84
Quartz	3.2×10^{-8}	0.066	894.71
HFE	4.3×10^{-6}	0.059	7.47

With mitigation strategy in action the (a,n) background is expected to be negligible compared to the gamma background

Summary

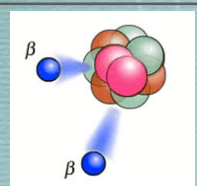
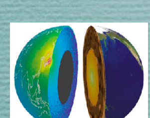
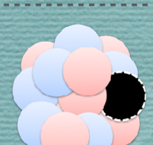
- ✓ (α,n) reactions are a background for various low-background neutrino experiments;
  - ◉ Specially critical when searching for rare events
- ✓ The largest source of uncertainty in the calculation of the expected neutron yield is the discrepancy between models and model and experimental data
  - ◉ Material of interest have few or zero measurements validating the theoretical model
  - ◉ The measurement of the cross section for excited states is most of the time missing
  - ◉ Angular distribution/differential cross sections are also missing for critical materials
- ✓ The future prospectes are:
  - ◉ cross check of the various existing model/databases
  - ◉ list the materials that show the largest tensions
  - ◉ Make a plan of action to reduce the discrepancy

Thank you for your attention

The presenter Valentina Lozza is funded by FCT, Portuguese State grant reference IF/00248/2015/CP1311/CT0001.

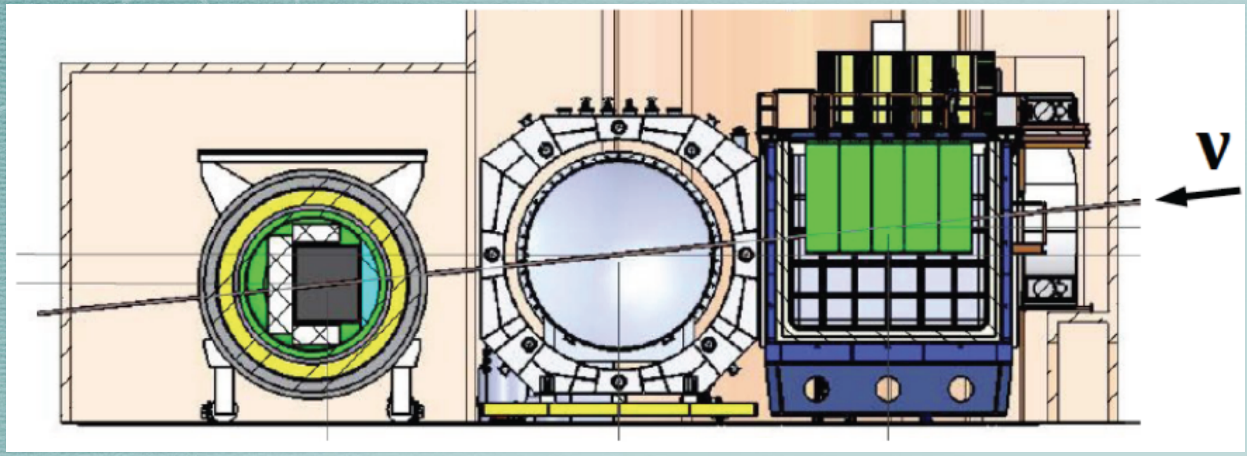
Backup

SNO+ Physics goals and phases

Goal	Water Phase (2017-2019)	Pure LS Phase (Now)	Te-loaded Phase (late 2022)
 0vßß-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

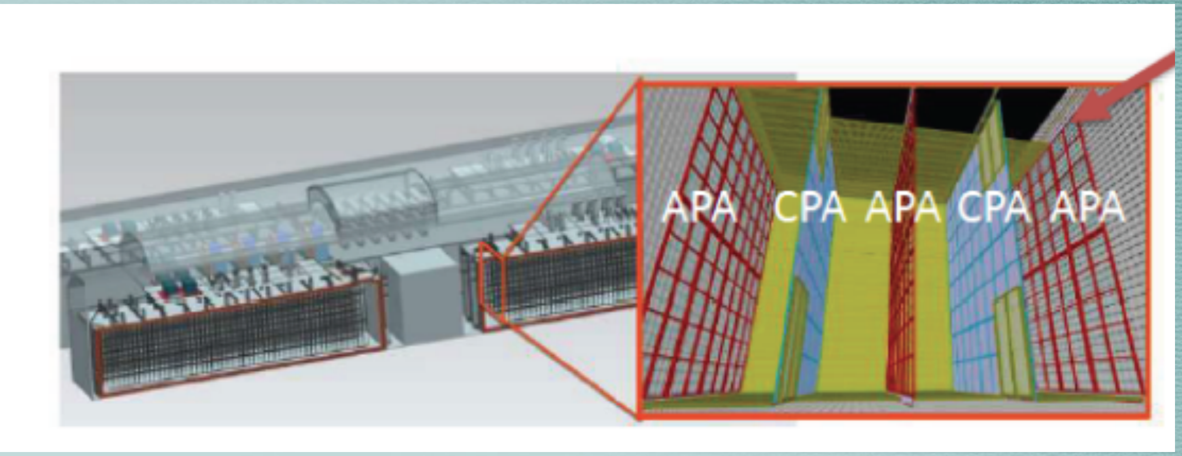
DUNE detector design

Near detector



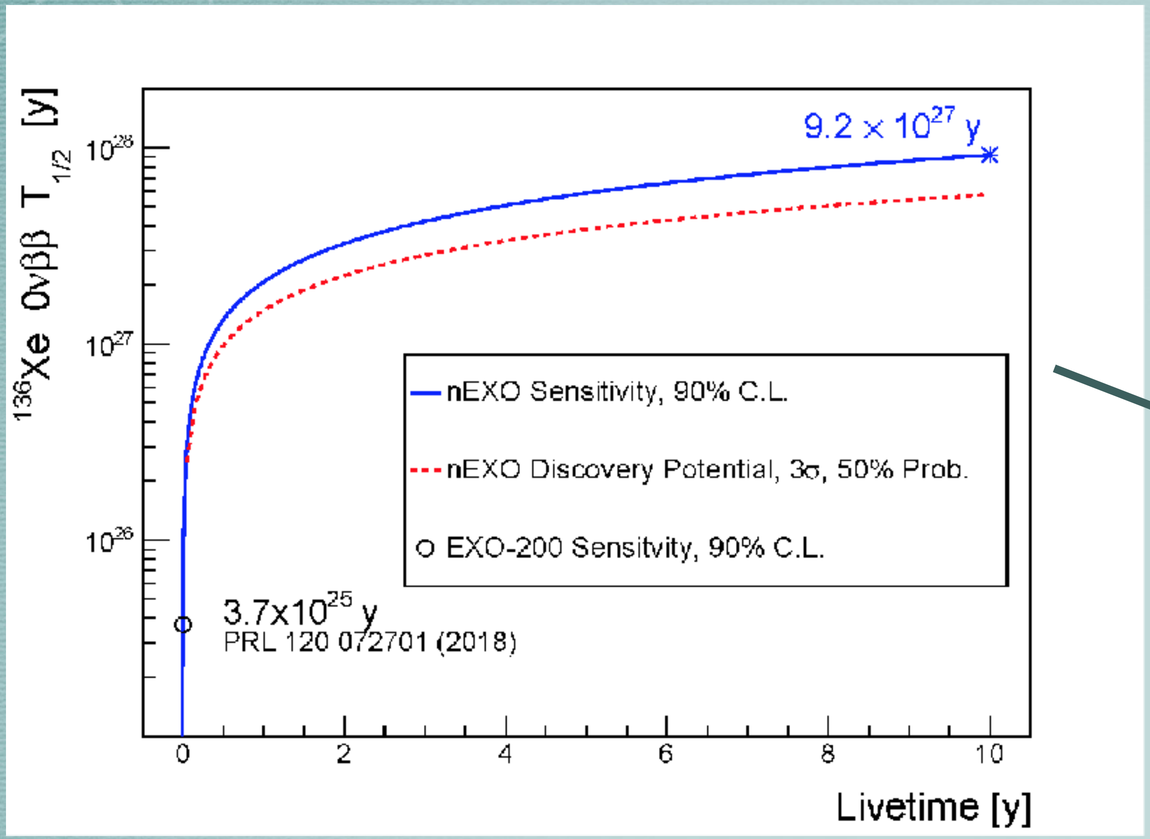
- LAr TPC
- Magnetized, high pressure gaseous Ar TPC
- Magnetized plastic scintillator tracker & on-axis beam monitor

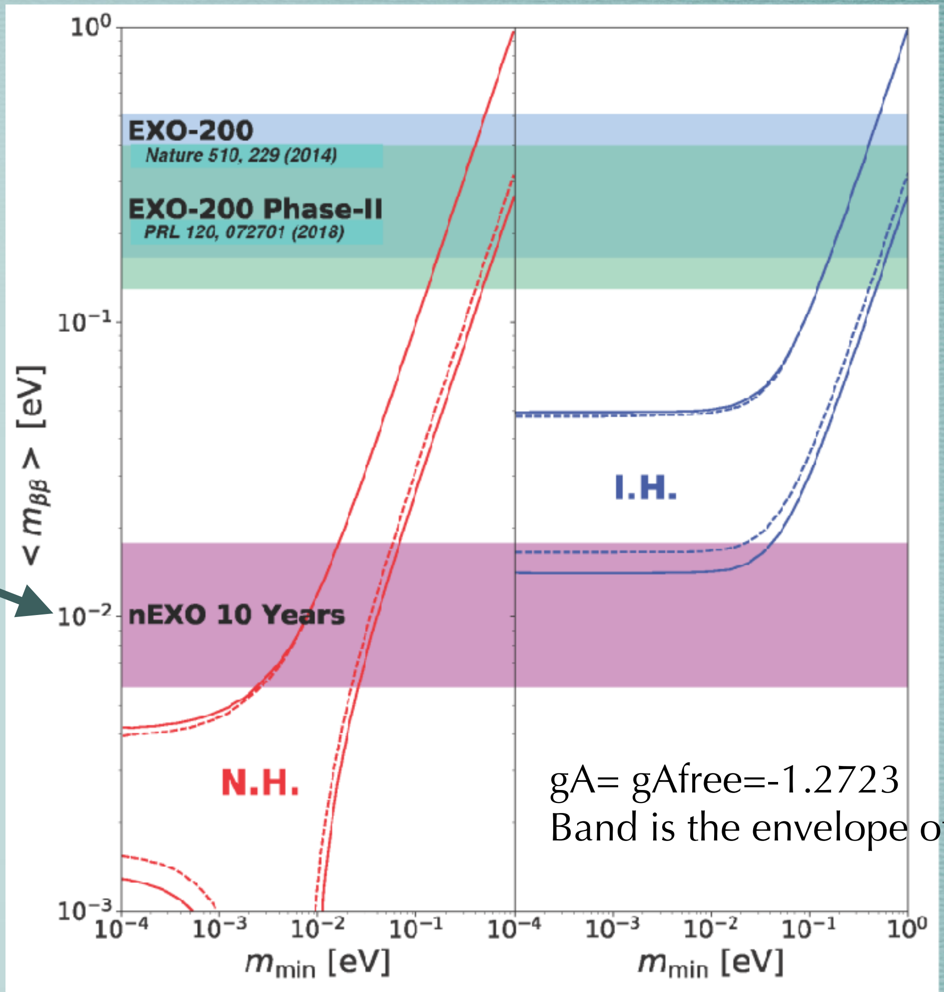
Far detector



- Two designs: Single phase LAr or dual phase (LAr+GAr)
- 4x 10 stone modules deployed in stages
- Suspended Anode and Cathode Plane assembly

nEXO Sensitivity





- ✓ Ultra-low background 'core'
- ✓ Precisely measure background at the periphery
- ✓ Incorporate knowledge of background in sensitivity calculation
- ✓ 'Background index' is fiducial volume dependent