Radiogenic neutron backgrounds in LAr DM detectors

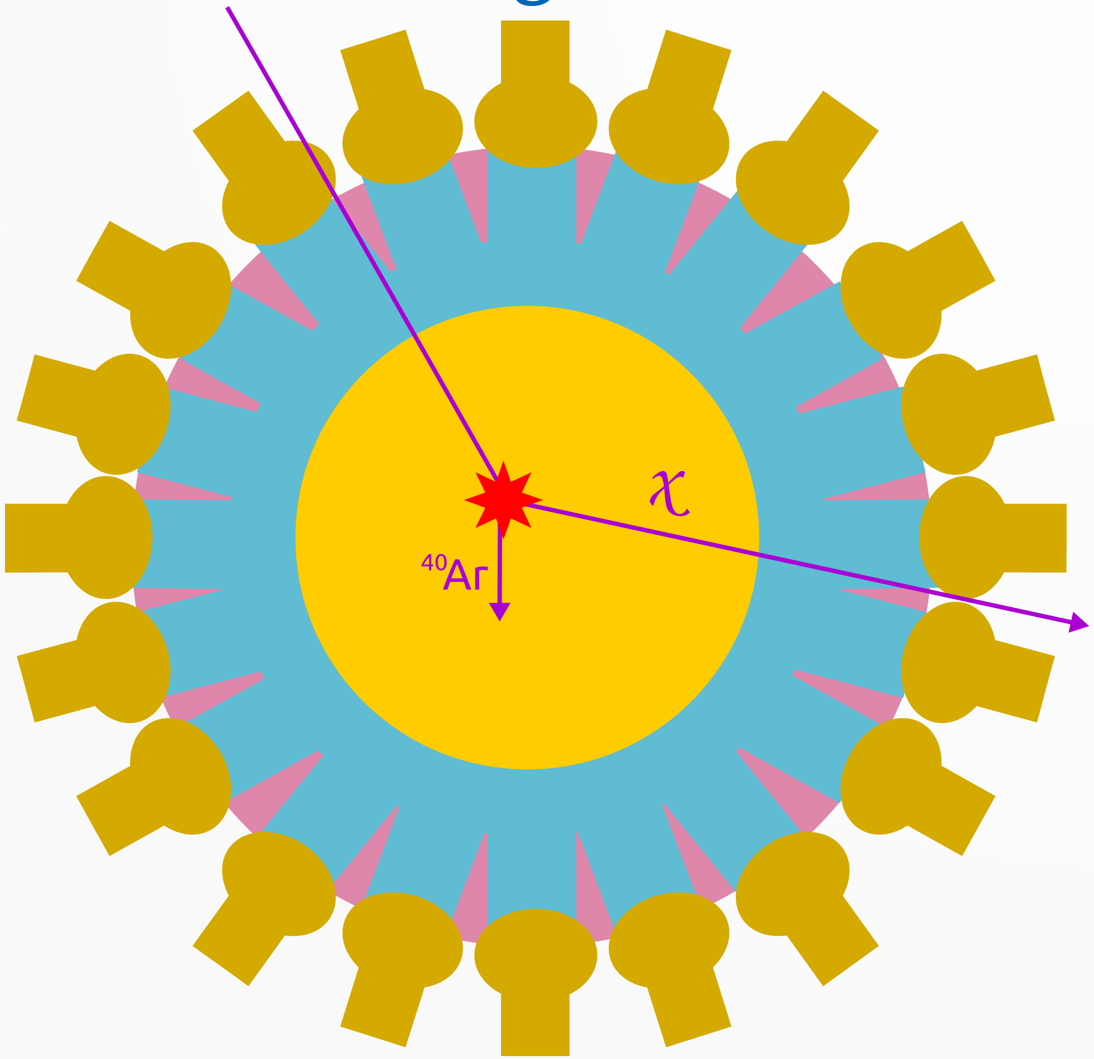
Shawn Westerdale

(α,n) yield in low background experiments

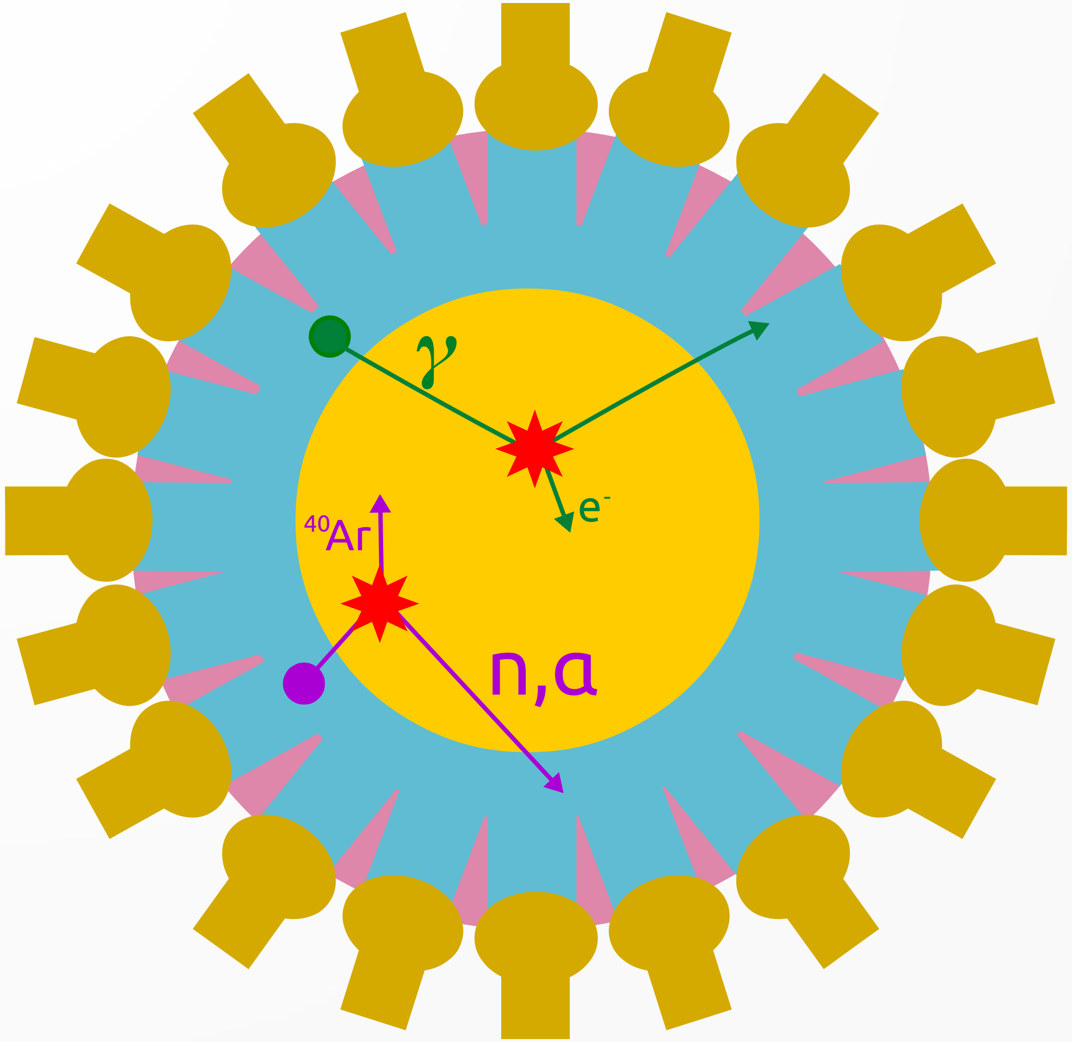
Workshop in CIEMAT, Madrid (2019)

Looking for WIMPs

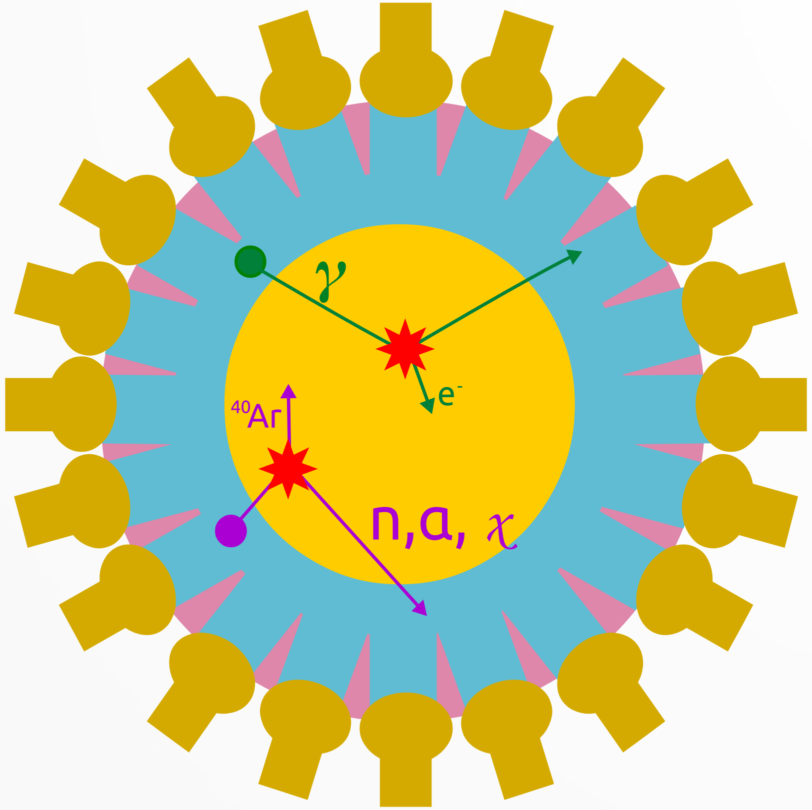
Signal

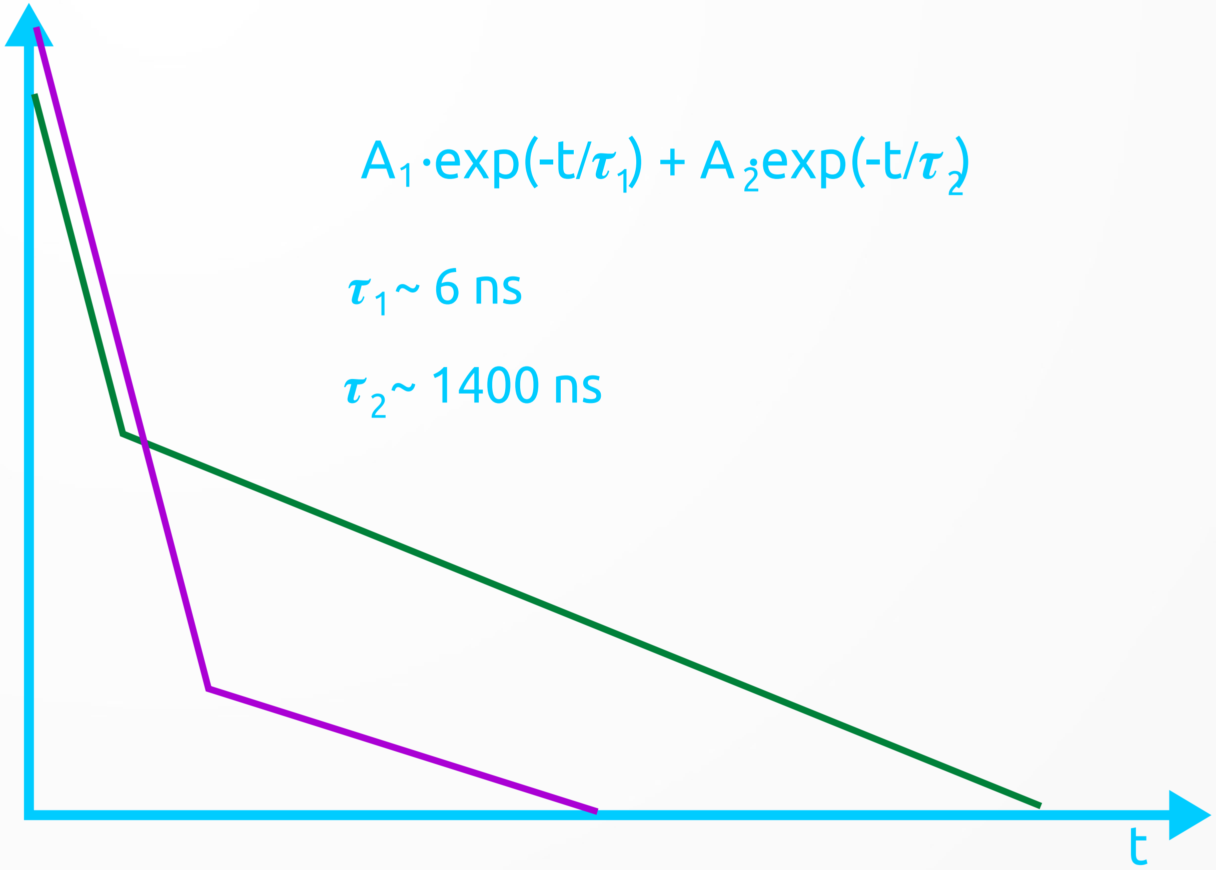


Backgrounds



In LAr detectors, PSD removes ERs





DEAP-3600 reported ~9 orders of magnitude suppression of ERs with 50% WIMP acceptance in lowest 1 keV bin

Note: LXe TPCs also highly suppress ERs by a factor of ~200, by comparing scintillation and ionization channels

NRs may perfectly mimic WIMPs…

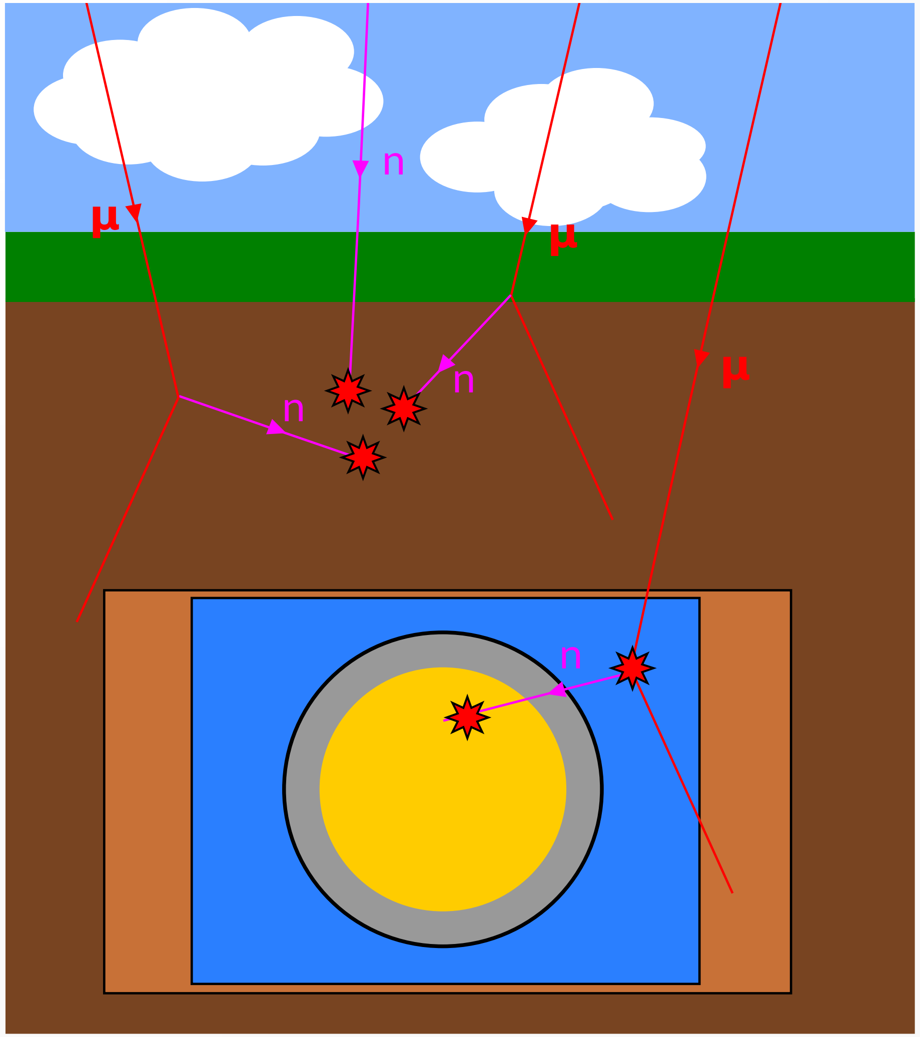
- α-decays on detector surfaces
  - If the event's position can be reconstructed accurately, these can be removed
- Neutrons scattering on target nuclei
  - If they scatter multiple times at different Z-coordinates, TPCs can veto them by detecting the time between the ionization signals at each vertex
  - If they scatter once, they can be exactly WIMP-like
    - Neutron vetoes, like DarkSide-50 used, can mitigate this

Neutron sources: Cosmogenic

Muons can interact with the detector or its environment to produce high energy neutrons that penetrate shielding.

We go deep underground to decrease the flux of these muons.

Water Cherenkov detectors are commonly and successfully used as vetoes to detect passing muons or their associated electromagnetic showers

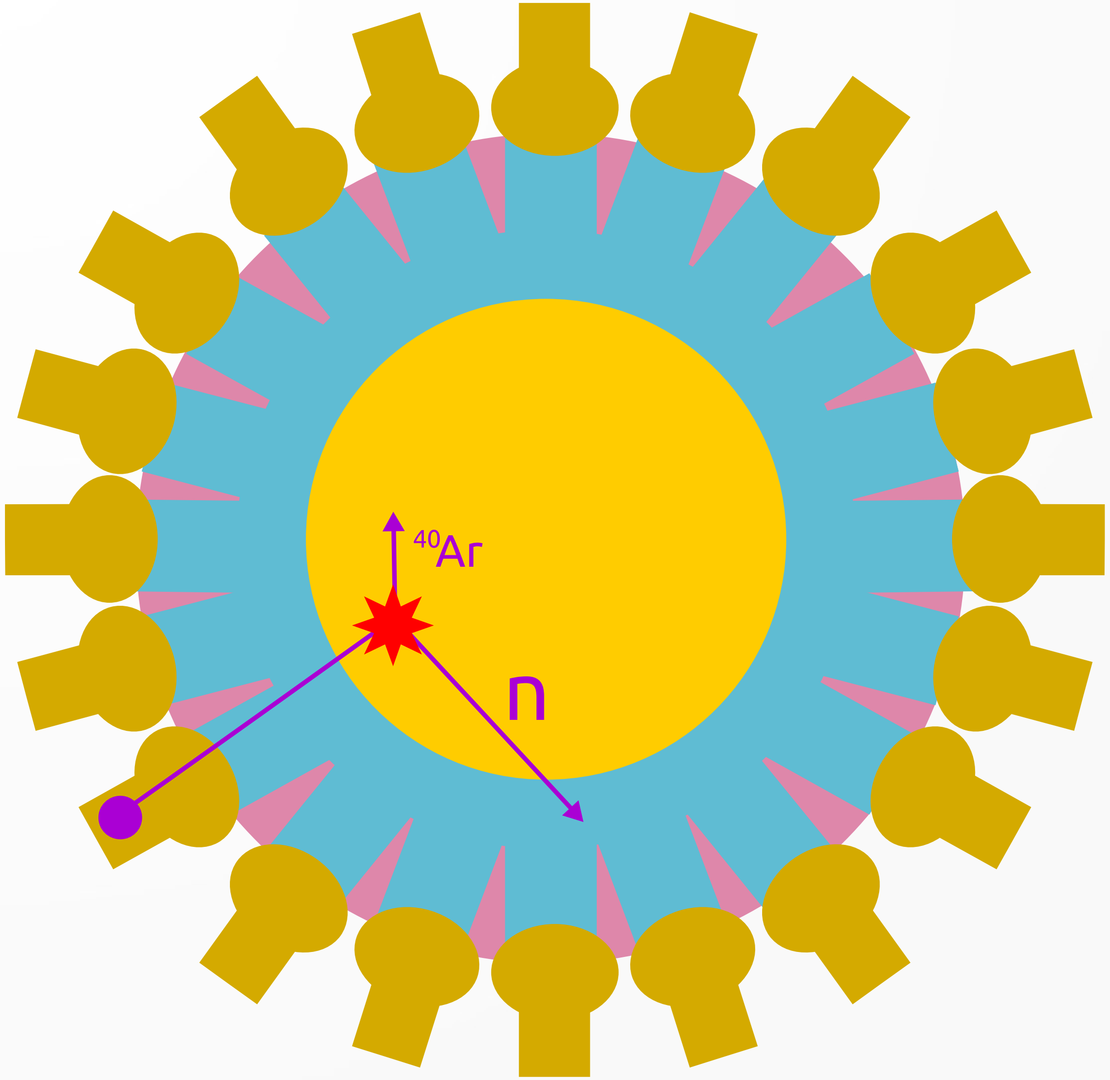


Neutron sources: Radiogenic

May be produced by:

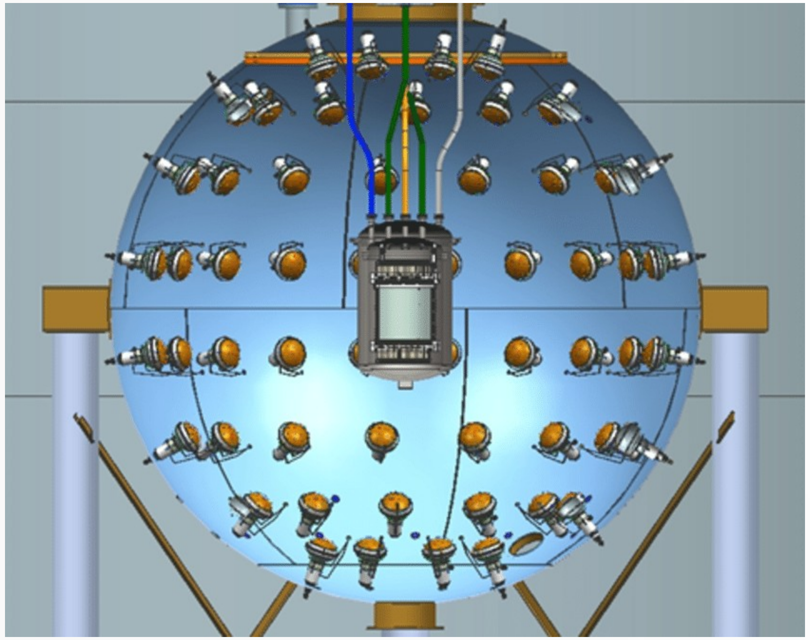
- Spontaneous fission of ^{238}U
- (α,n) reactions
- Other rarer processes:
  - β-delayed emission from ^{210}Tl
  - (γ,n) reactions

This is why we are all here!



A tale of 3 detectors…

DarkSide-50

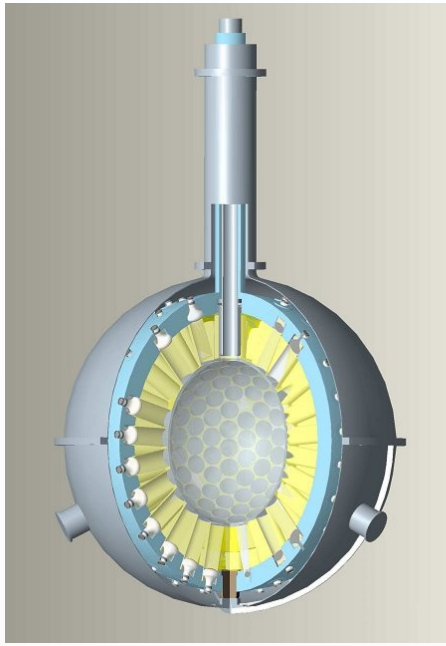


Dual-phase LAr TPC

50 kg LAr in 30 tonne boron-loaded liquid scintillator veto

At LNGS

DEAP-3600

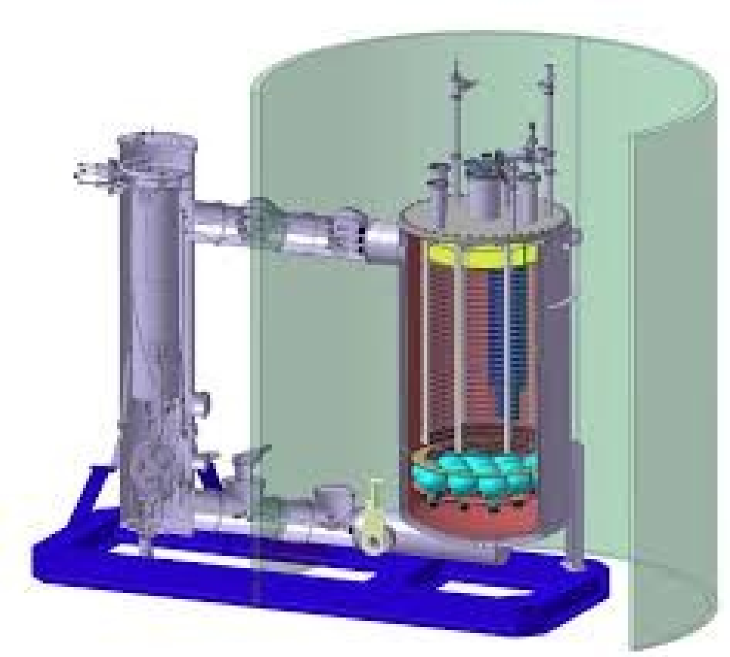


Single-phase LAr detector

3.3 tonnes of LAr in 50 cm of passive acrylic shielding

At SNOLAB

ArDM



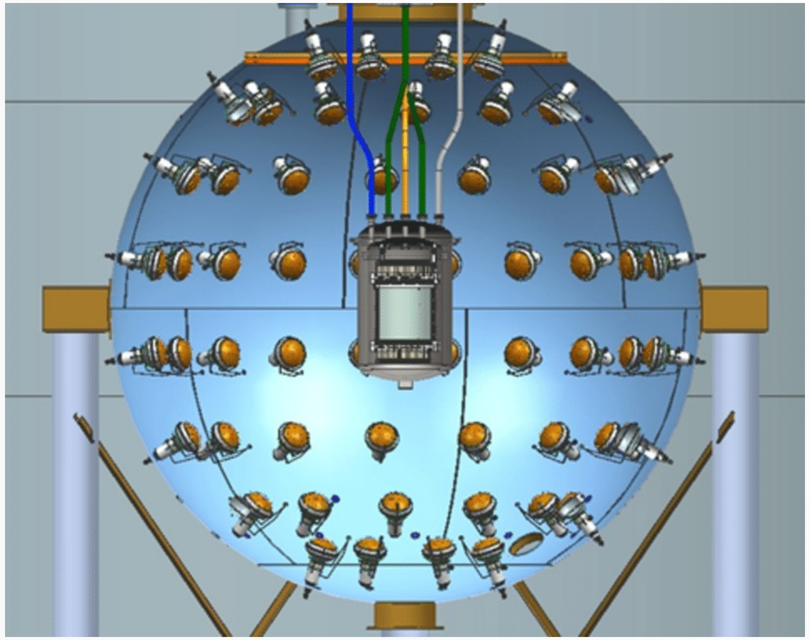
Dual-phase LAr TPC

850 kg of LAr in 50 cm of passive polyethylene shielding

At Canfranc

… with 3 approaches to neutrons

DarkSide-50

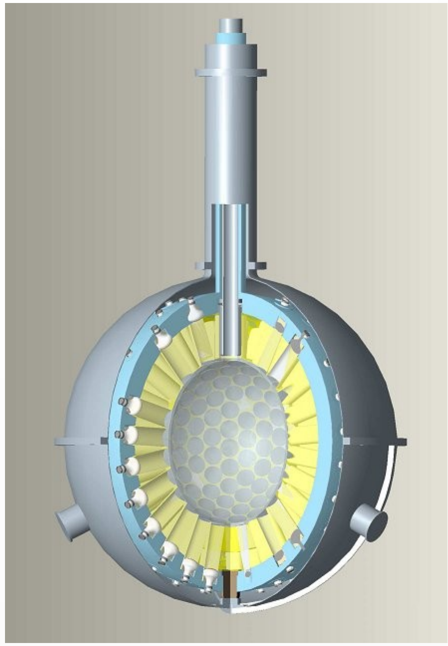


Multiple scatter discrimination

Active boron-loaded veto (also provides *in-situ* measurement)

Minimize material around LAr

DEAP-3600

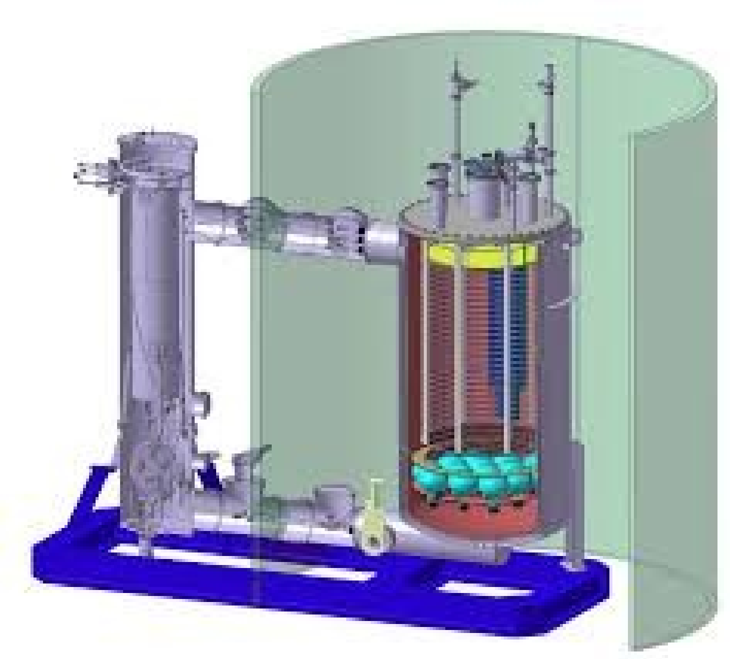


Self-shielding/fiducialization

50 cm passive acrylic shielding (*in situ* measurement via (n,γ))

Maximize material around LAr

ArDM



Multiple scatter discrimination

50 cm passive polyethylene shielding

Maximize material around LAr

DarkSide-50

Neutrons in DarkSide-50

Mitigate neutron events by removing…

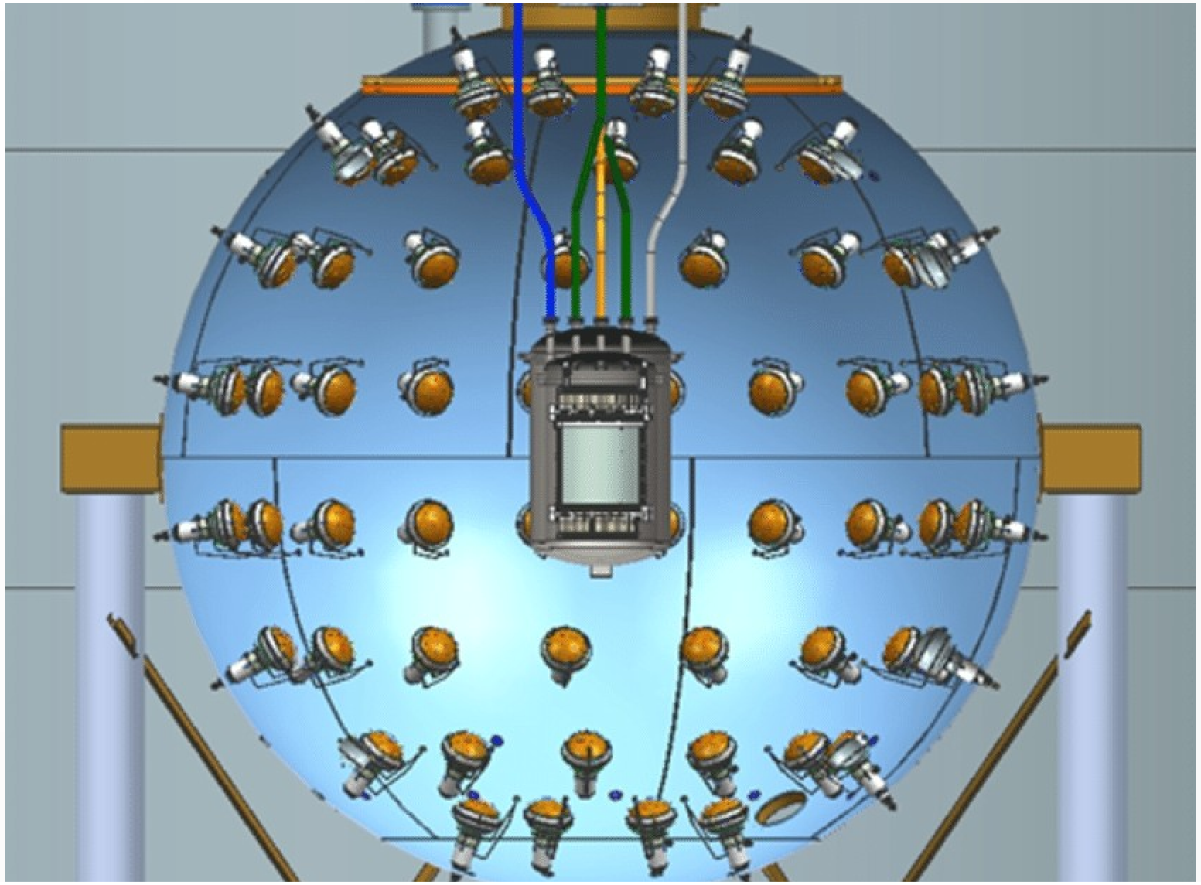
- Multiple scatters in the TPC
- Scatters near the edges of TPC
- Coincidence with neutron veto

S.F. neutrons (^{238}U)

- Average multiplicity: 2.01
- Easy to tag with veto!
- (α,n) are main concern

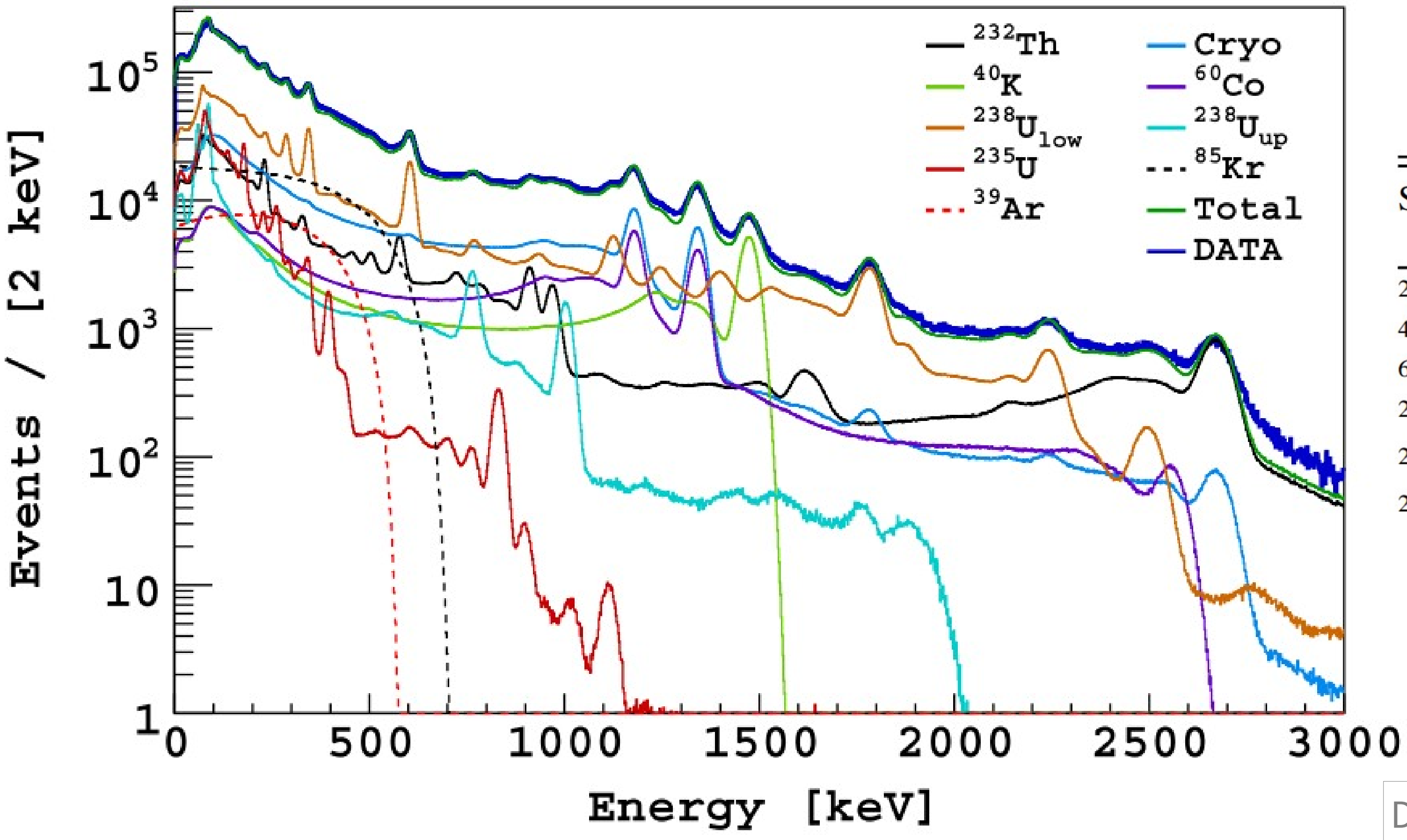
Tag neutrons in veto using

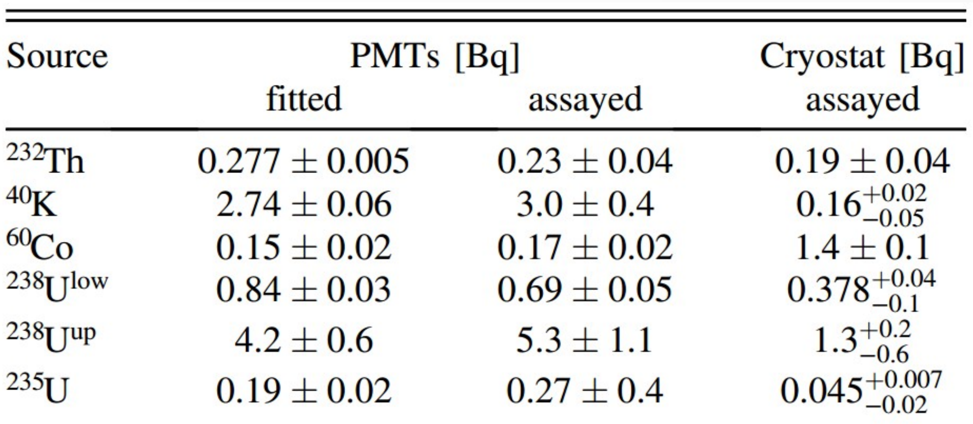
- **Prompt** thermalization signal
- **Delayed** capture signal



95% pseudocumene
5% trimethyl borate
→22 μs thermal neutron capture time, mostly on ^{10}B

DarkSide-50: *In situ* γ band fitting confirms and improves on the assayed activities

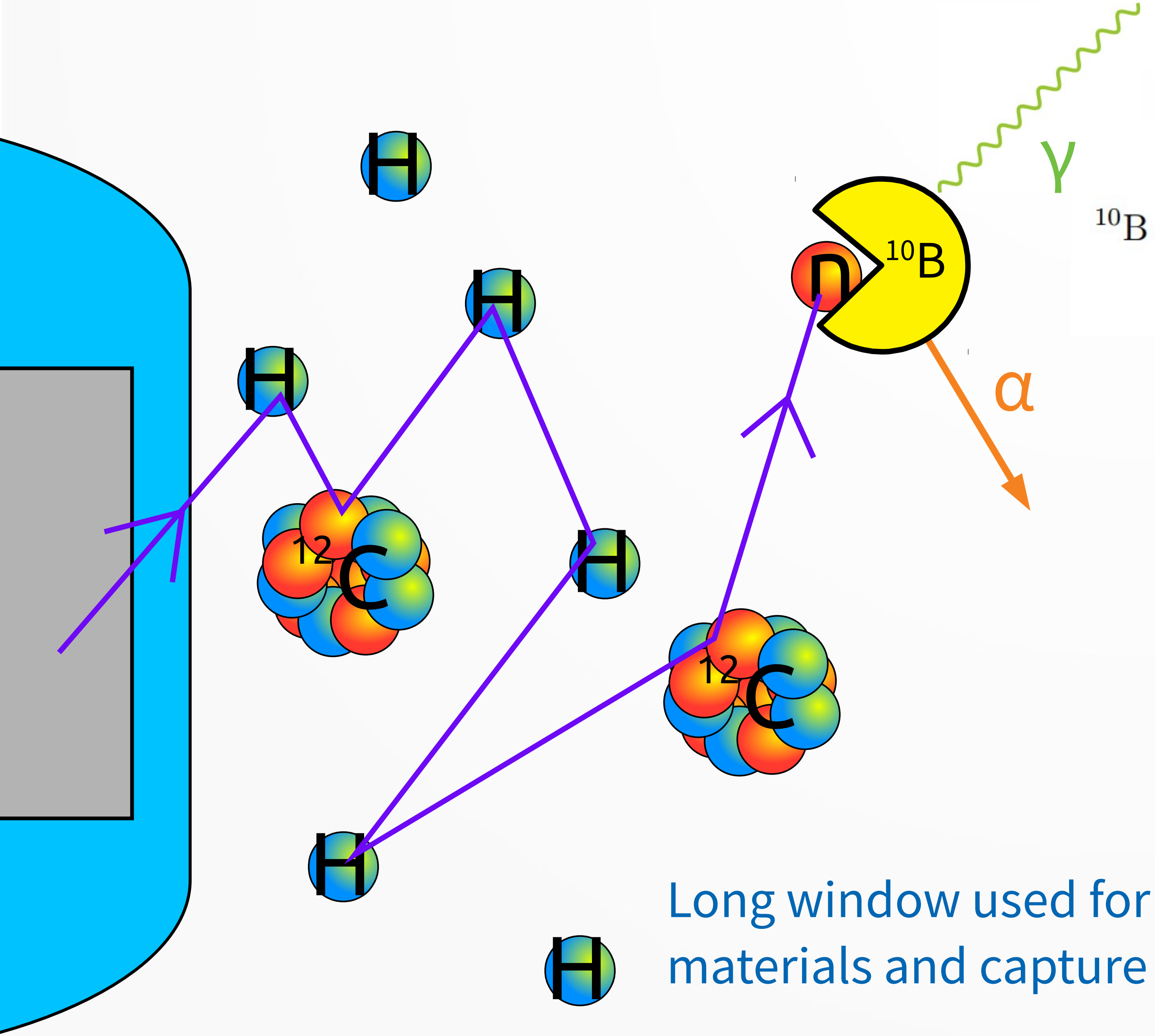




Source	PMTs [Bq] fitted	PMTs [Bq] assayed	Cryostat [Bq] assayed
^{232}Th	0.277 ± 0.005	0.23 ± 0.04	0.19 ± 0.04
^{40}K	2.74 ± 0.06	3.0 ± 0.4	$0.16^{+0.02}_{-0.05}$
^{60}Co	0.15 ± 0.02	0.17 ± 0.02	1.4 ± 0.1
^{238}U$^{\mathrm{low}}$	0.84 ± 0.03	0.69 ± 0.05	$0.378^{+0.04}_{-0.1}$
^{238}U$^{\mathrm{up}}$	4.2 ± 0.6	5.3 ± 1.1	$1.3^{+0.2}_{-0.6}$
^{235}U	0.19 ± 0.02	0.27 ± 0.4	$0.045^{+0.007}_{-0.02}$

DarkSide Collaboration. “DarkSide-50 532-day dark matter search with low-radioactivity argon”. Phys. Rev. D 98, 102006 (Nov 2018)

DarkSide-50: Neutron veto



$$^{10}\text{B} + n \rightarrow {}^{11}\text{B}^* \rightarrow \begin{cases} {}^7\text{Li (1015 keV)} + \alpha \text{ (1775 keV)} & (6.4\%) \\ {}^7\text{Li}^* + \alpha \text{ (1471 keV)}, & (93.6\%) \\ \qquad {}^7\text{Li}^* \rightarrow {}^7\text{Li (839 keV)} + \gamma \text{ (478 keV)} & \end{cases}$$

Thermal neutron capture time: 22 μs

Primary cuts for tagging neutrons:

1) **Prompt cut:** >1 PE in veto in [-50, 250] ns window around TPC signal
2) **Delayed cut**: >6 PE in veto in a 500 ns sliding window covering [0,189.5] μs window after TPC signal

Long window used for neutrons that thermalize in TPC materials and capture more slowly

DarkSide-50: Veto efficiency estimated two ways

- Calibration with AmC neutron source

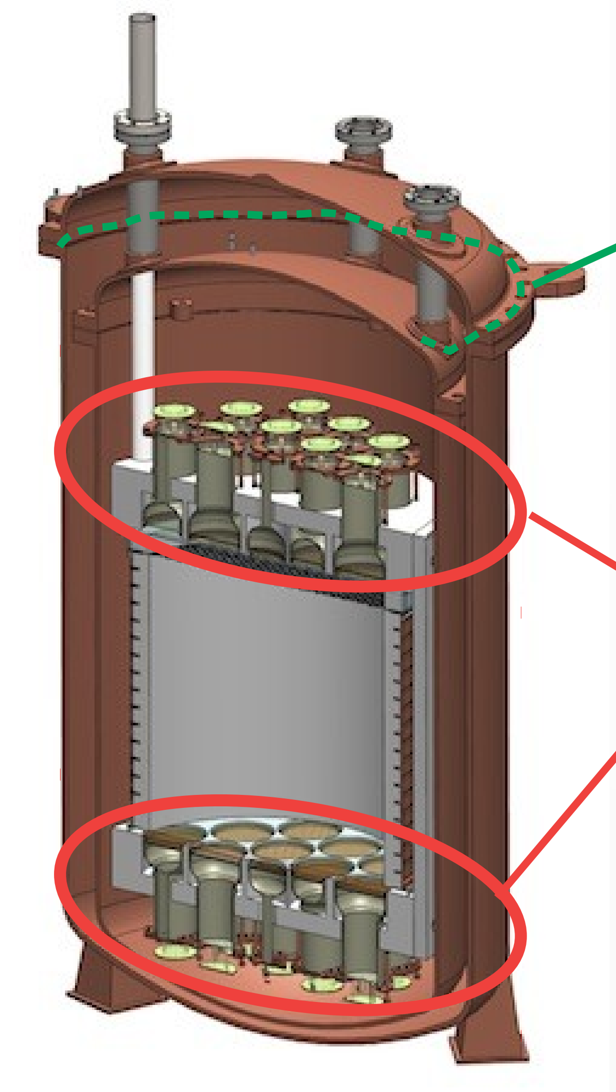
  (no γ’s from source, uncertainties from energy dependence and neutron interactions in veto before reaching TPC)
  - Efficiency from prompt cut only: 99.27±0.05%
  - Efficiency from delayed cut only: 99.58±0.04%
  - Combined efficiency: 99.64±04%
- Monte Carlo simulations

  (Uncertainties in the detector response model and Geant4 neutron & nuclear physics)
  - Efficiency from prompt cut only: ~98.5%
  - Efficiency from delayed cut only: ~99.74%
  - Combined efficiency: ~99.86%

Systematic uncertainties still to be evaluated – some are significant!

“Efficiency” defined to be the fraction of events passing TPC cuts that are removed by veto cuts

DarkSide-50: Dominant neutron sources



Viton o-ring in outer cryostat flange

High neutron flux,
but far from TPC

Ceramic and borosilicate glass in PMTs

These are **the** dominant neutron sources, due to high contamination from upper ^{238}U chain and high (α,n) yield.

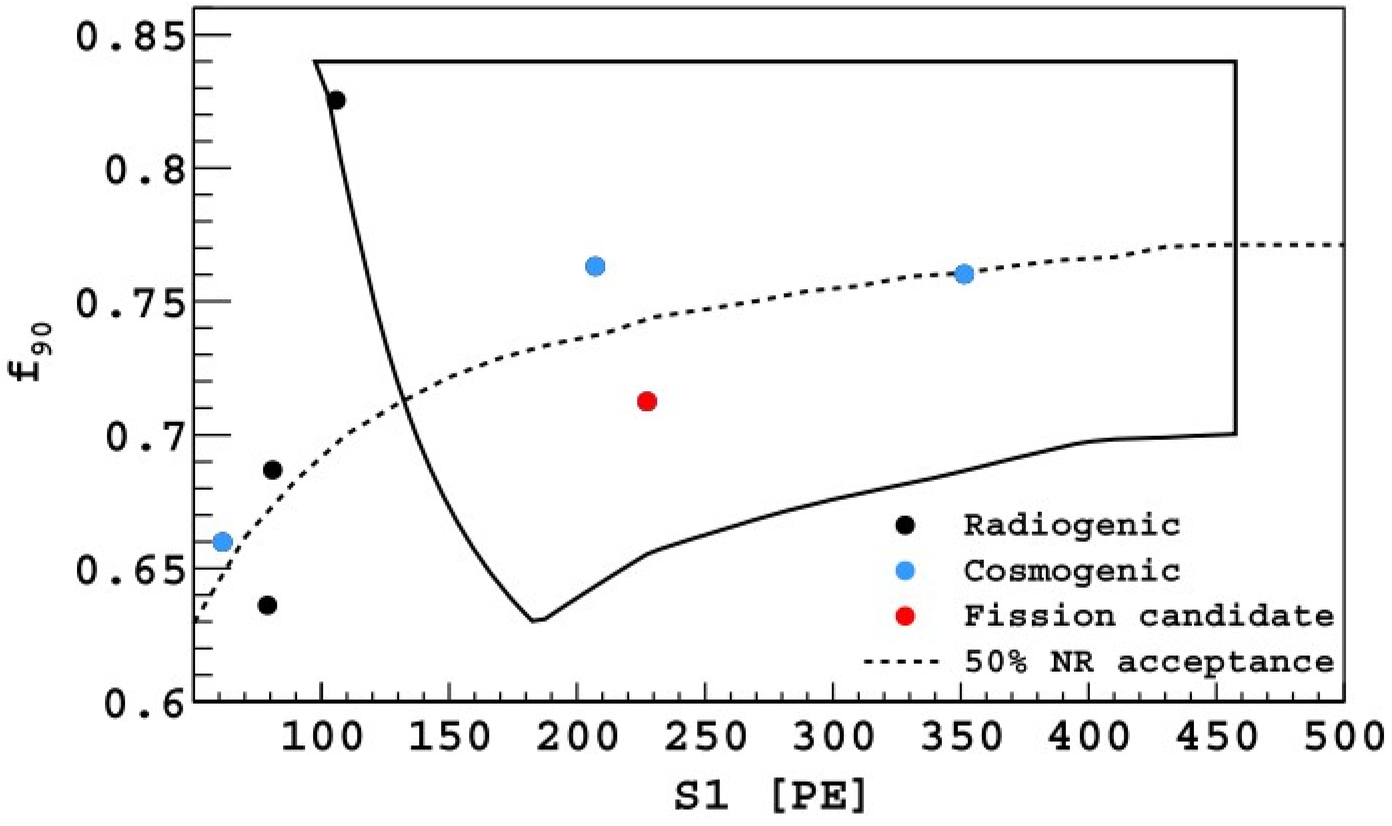
These also constitutes ~90% of radiogenic neutron backgrounds expected, due to proximity to LAr

DarkSide-50: Counting neutrons in 532 days

NeuCBOT and SOURCES-4C both predict more events than are seen, with a bigger excess predicted by NeuCBOT. Systematic uncertainties are still being assessed, and the significance of both excesses falls in an ambiguous area until then.

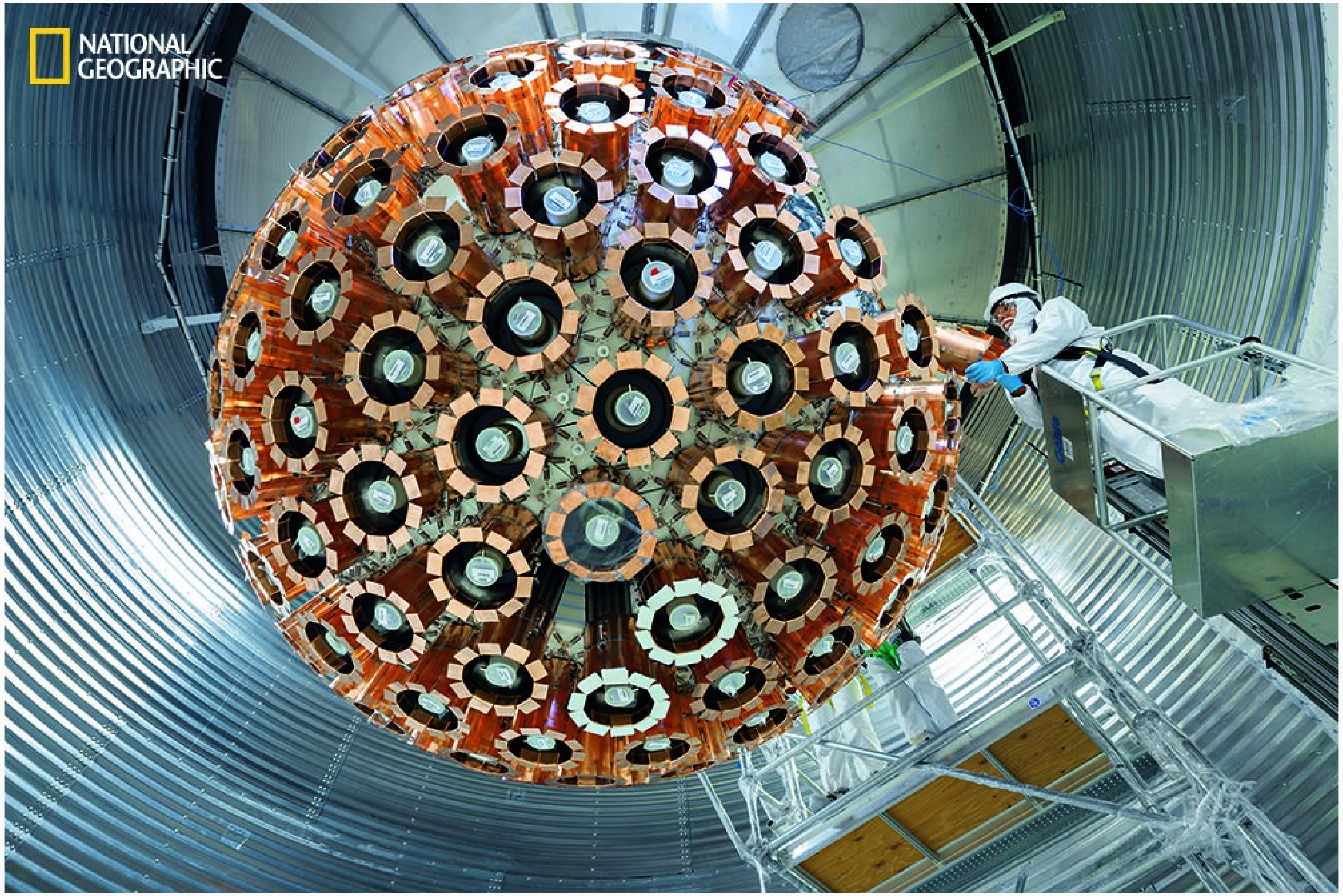
NB: NeuCBOT yields are ~2x higher than yields calculated by SOURCES-4C with JENDL for ^{27}Al. This drives the difference between both predictions, due to the Al in PMT ceramic

Neutron tagging efficiency ~79% with modified cuts



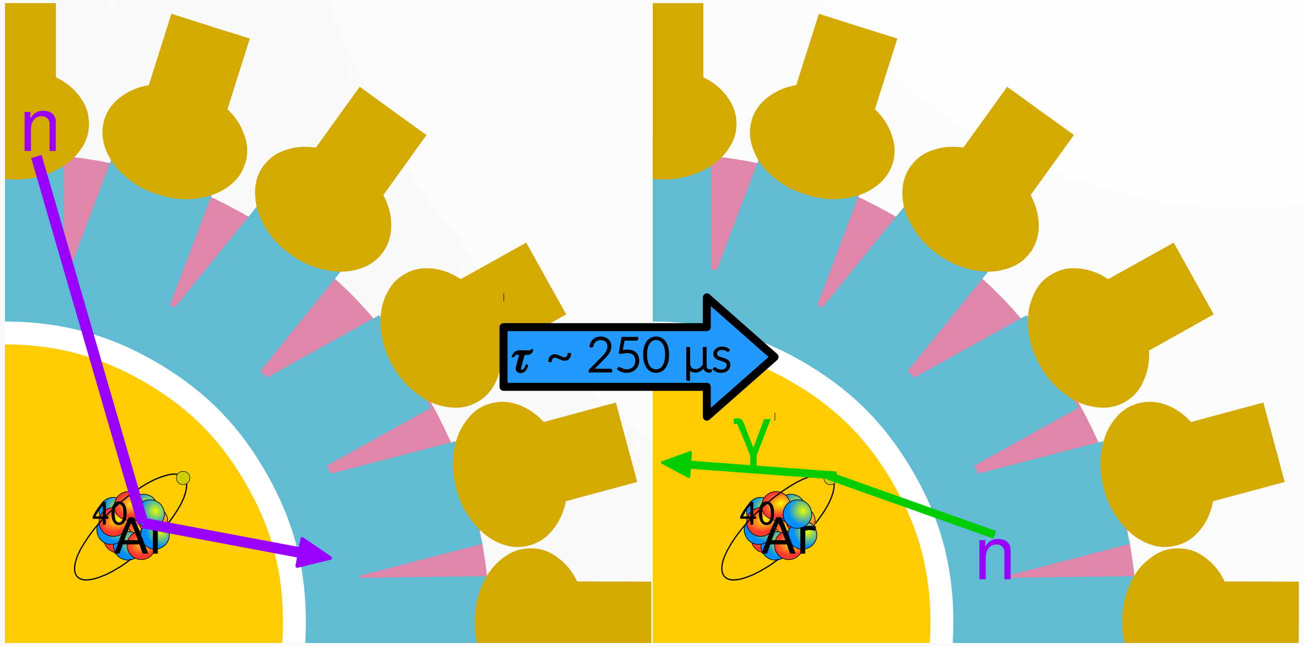
There is also significant uncertainty in boron content of PMT ceramic

DEAP-3600



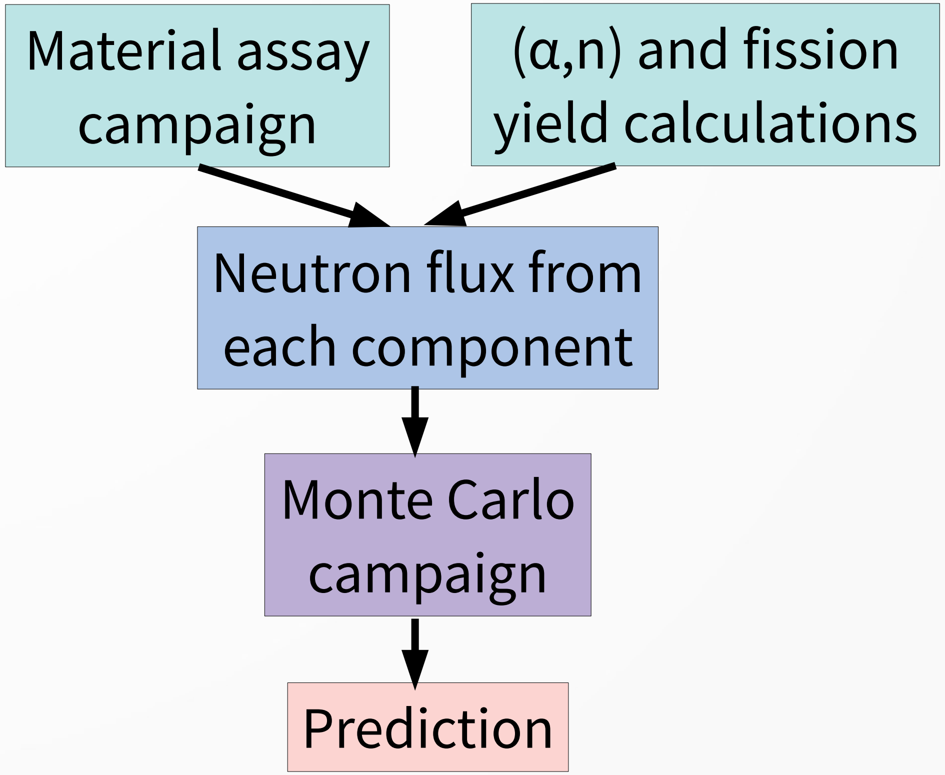
Neutrons in DEAP-3600

In situ data-driven approach



Can test if neutron bkgds match expectations or if there was some unexpected source

Ex situ assay-driven approach



Material assay campaign

(α,n) and fission yield calculations

Neutron flux from each component

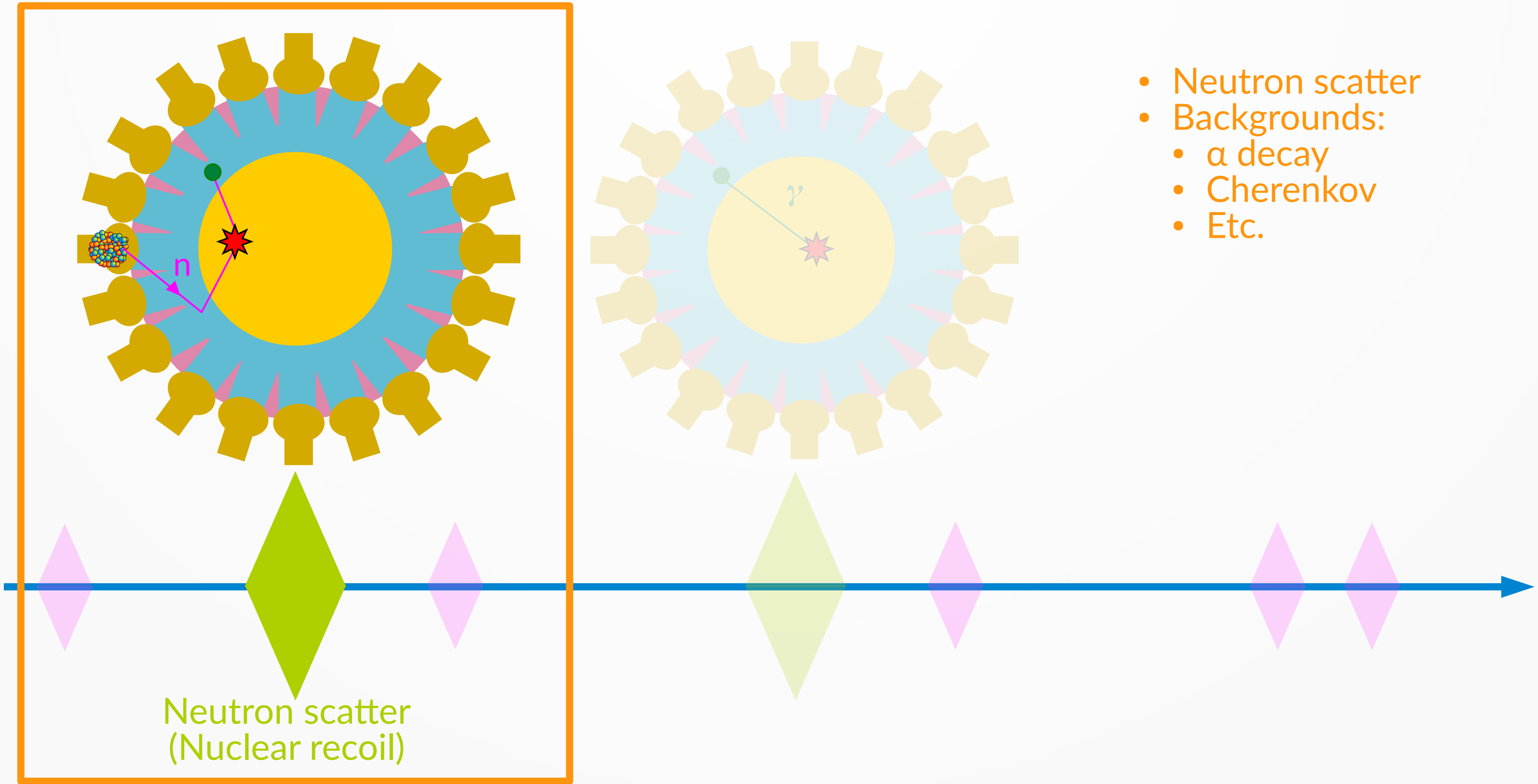
Monte Carlo campaign

Prediction

Can be done before the detector is built, helps with design, sets baseline for what to expect

DEAP-3600: Data-driven approach

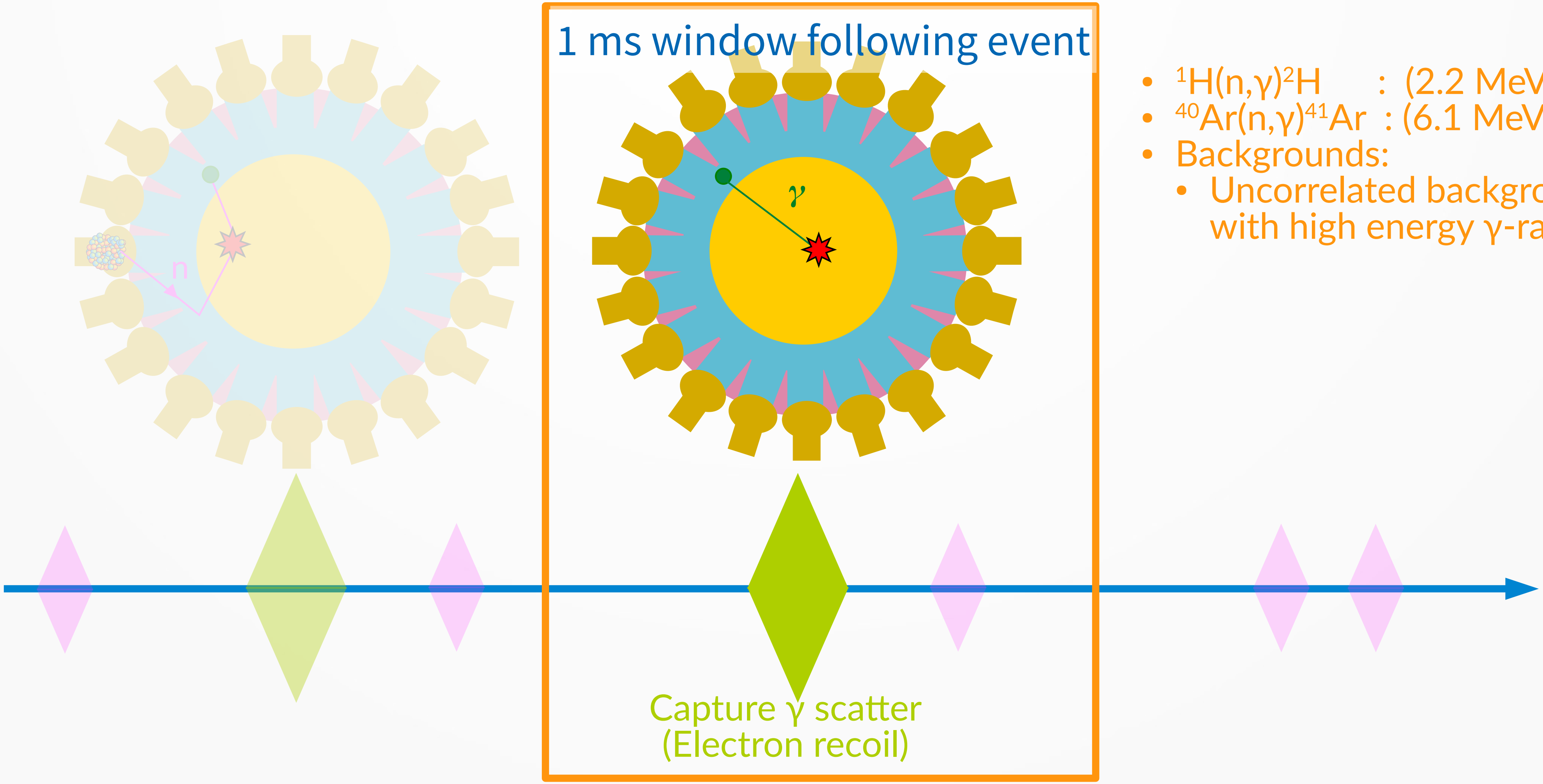
Step 1) Identify neutron scatter candidates with neutron selection cuts



- Neutron scatter
- Backgrounds:
  - α decay
  - Cherenkov
  - Etc.

DEAP-3600: Data-driven approach

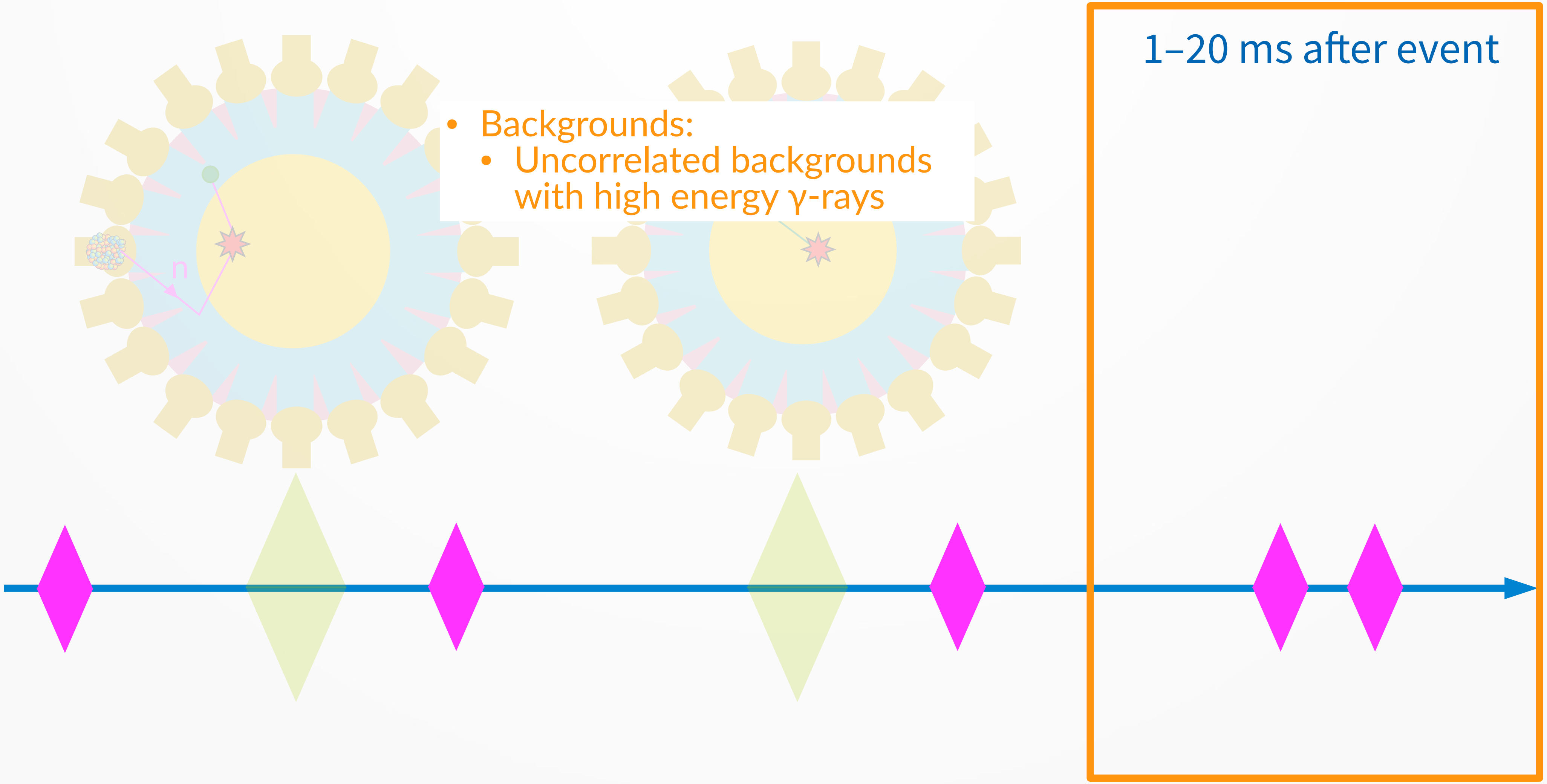
Step 2) Identify neutron capture candidates with γ selection cuts



- $^{1}H(n,\gamma)^{2}H$: (2.2 MeV)
- $^{40}Ar(n,\gamma)^{41}Ar$: (6.1 MeV)
- Backgrounds:
  - Uncorrelated backgrounds with high energy γ-rays

DEAP-3600: Data-driven approach

Step 3) Measure uncorrelated ER rate with γ selection cuts



- Backgrounds:
  - Uncorrelated backgrounds with high energy γ-rays

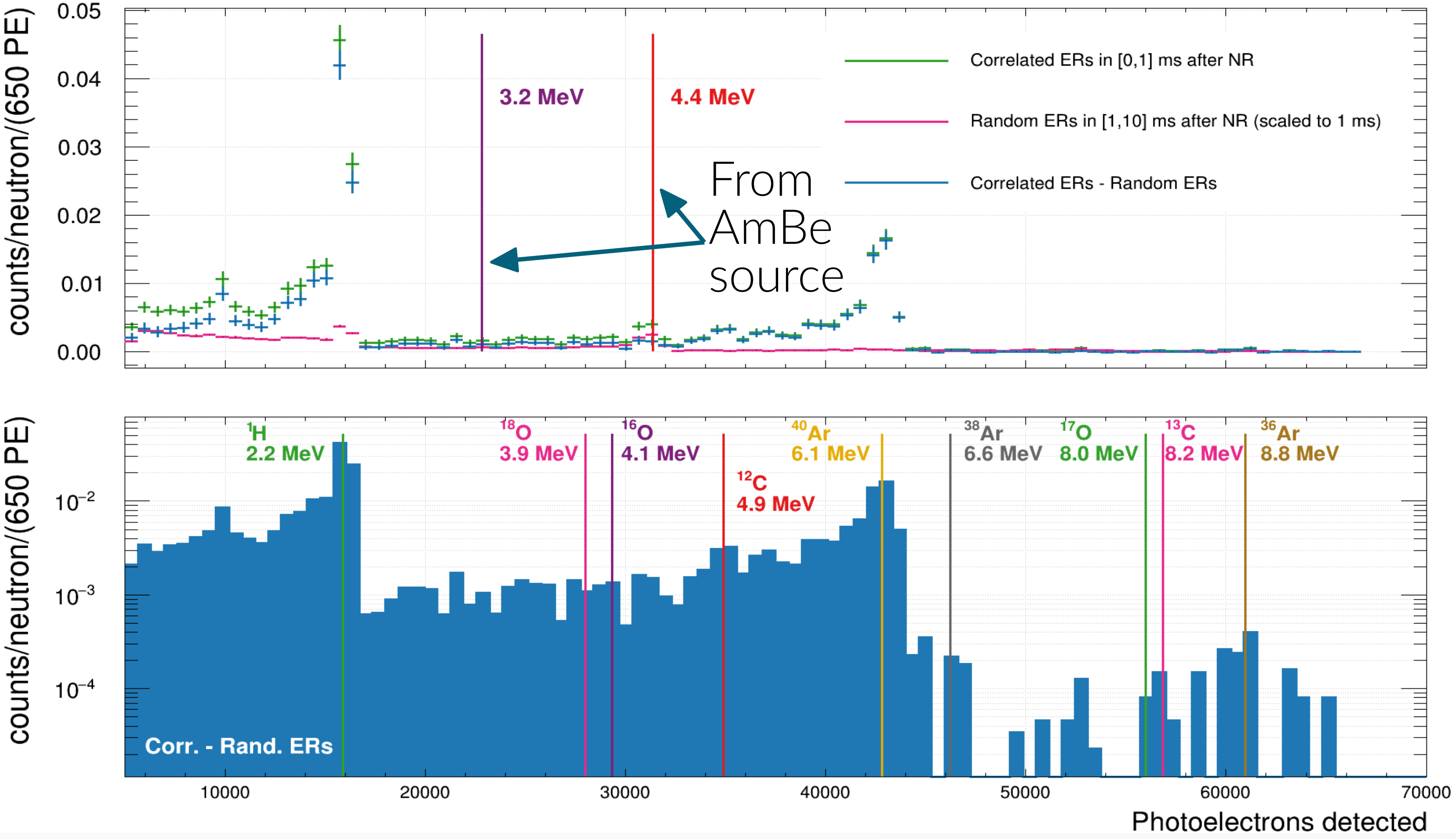
DEAP-3600: Tagging efficiency calibrated with AmBe neutron source – 22.5±0.5% (consistent with simulation)

In 231 days of physics data:

- 7 coincidences tagged
- Expect 1.8±0.3 random coincidences

Correcting for efficiency:

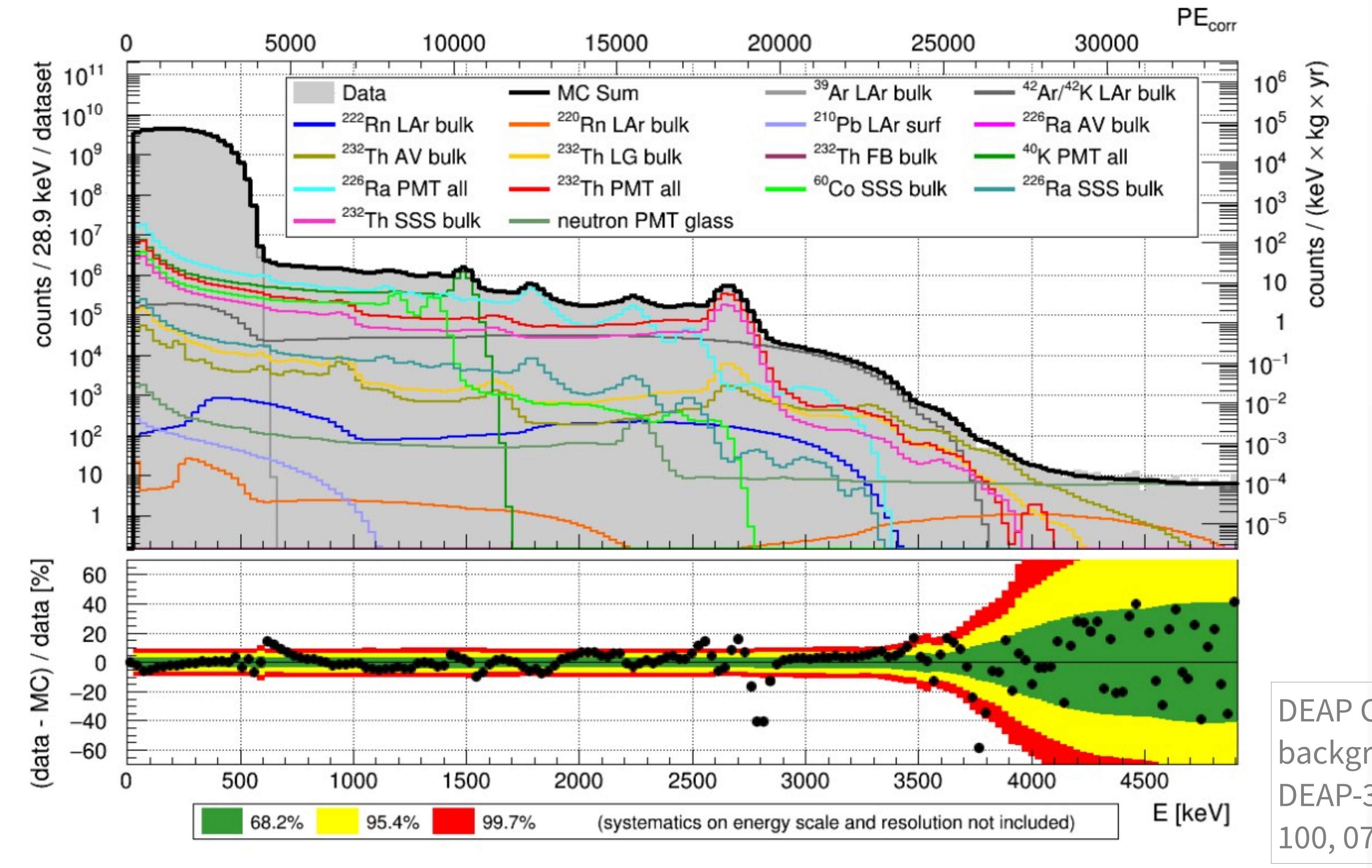
- Events in neutron control region: 23^{+17}_{-14}
- Events in WIMP search ROI, after all cuts: $0.10^{+0.10}_{-0.09}$



DEAP-3600: *Ex situ* assay-driven prediction

- Extensive material assay campaign of every detector component provided measurements (or limits) on ^{238}U, ^{235}U, ^{232}Th contamination levels
- Neutron yield calculations with SOURCES-4C and NeuCBOT
- Extensive preliminary round of simulations identified dominant neutron background sources for more detailed simulation campaign:
  - Borosilicate glass in PMTs (relatively high activity, high (α,n) yield)
  - Ceramic in PMTs (relatively high activity, high (α,n) yield)
  - PVC PMT mounts (relatively high activity, high (α,n) yield)
  - Polyethylene filler blocks (Close to LAr, very large mass makes small activities significant)
  - Polystyrene filler foam (Close to LAr, very large mass makes small activities significant)

DEAP-3600: Validation of assay results in γ spectrum



DEAP Collaboration. "Electromagnetic backgrounds and potassium-42 activity in the DEAP-3600 dark matter detector". Phys. Rev. D. 100, 072009 (Oct 2019)

DEAP-3600: Total predictions agree with both approaches, albeit with large uncertainties

In situ data-driven approach

CR prediction: 23^{+17}_{-14}

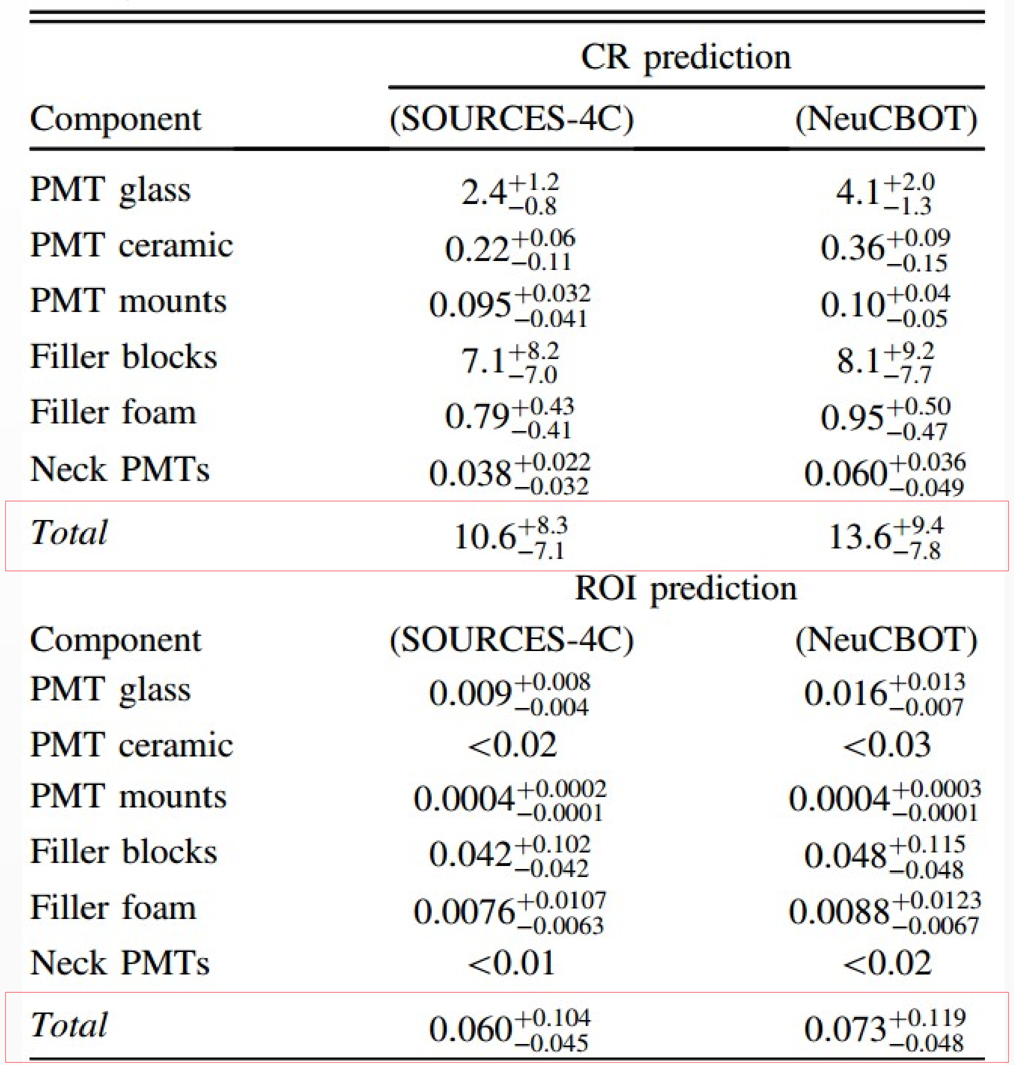
ROI prediction: $0.10^{+0.10}_{-0.09}$

Uncertainties driven by statistics, due to low neutron rate in detector

Uncertainties driven by uncertainties in filler block foam assays

DEAP Collaboration. "Search for dark matter with a 231-day exposure of liquid argon using DEAP-3600 at SNOLAB". Phys. Rev. D. 100, 022004 (July 2019)

Ex situ assay-driven approach

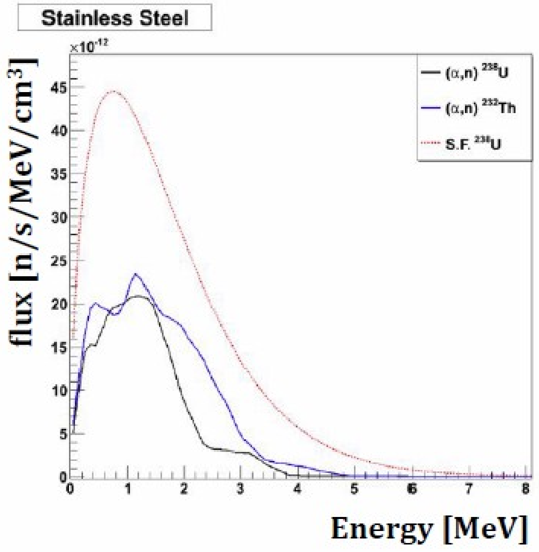


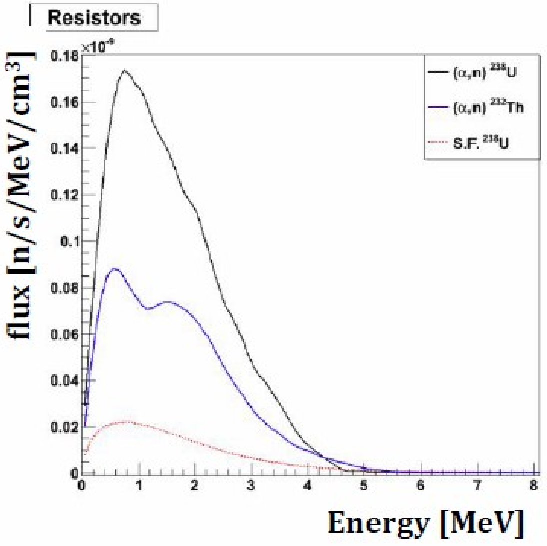
	CR prediction	
Component	(SOURCES-4C)	(NeuCBOT)
PMT glass	$2.4^{+1.2}_{-0.8}$	$4.1^{+2.0}_{-1.3}$
PMT ceramic	$0.22^{+0.06}_{-0.11}$	$0.36^{+0.09}_{-0.15}$
PMT mounts	$0.095^{+0.032}_{-0.041}$	$0.10^{+0.04}_{-0.05}$
Filler blocks	$7.1^{+8.2}_{-7.0}$	$8.1^{+9.2}_{-7.7}$
Filler foam	$0.79^{+0.43}_{-0.41}$	$0.95^{+0.50}_{-0.47}$
Neck PMTs	$0.038^{+0.022}_{-0.032}$	$0.060^{+0.036}_{-0.049}$
Total	$10.6^{+8.3}_{-7.1}$	$13.6^{+9.4}_{-7.8}$
	ROI prediction	
Component	(SOURCES-4C)	(NeuCBOT)
PMT glass	$0.009^{+0.008}_{-0.004}$	$0.016^{+0.013}_{-0.007}$
PMT ceramic	<0.02	<0.03
PMT mounts	$0.0004^{+0.0002}_{-0.0001}$	$0.0004^{+0.0003}_{-0.0001}$
Filler blocks	$0.042^{+0.102}_{-0.042}$	$0.048^{+0.115}_{-0.048}$
Filler foam	$0.0076^{+0.0107}_{-0.0063}$	$0.0088^{+0.0123}_{-0.0067}$
Neck PMTs	<0.01	<0.02
Total	$0.060^{+0.104}_{-0.045}$	$0.073^{+0.119}_{-0.048}$

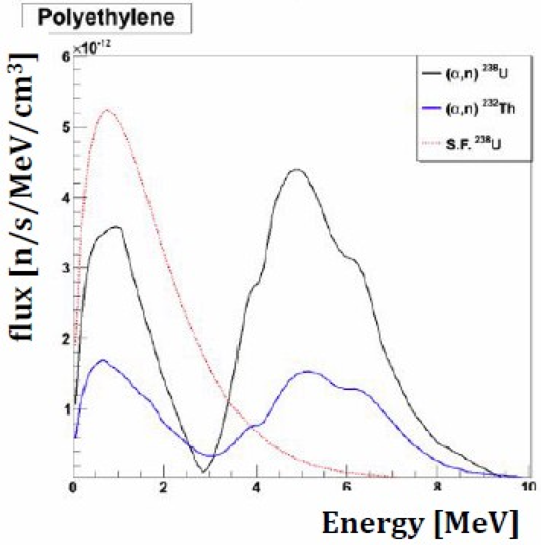
ArDM

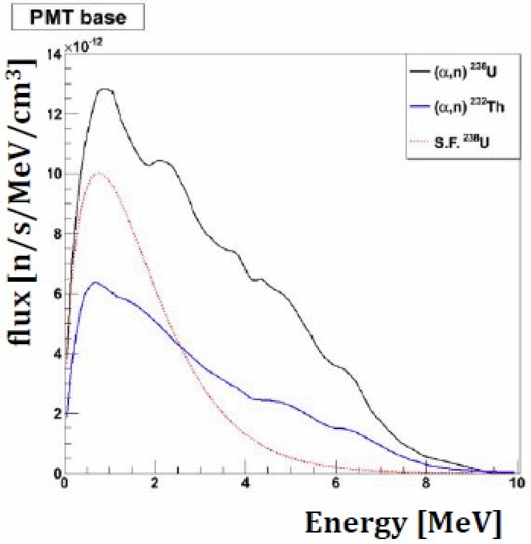
ArDM: Neutron flux calculations

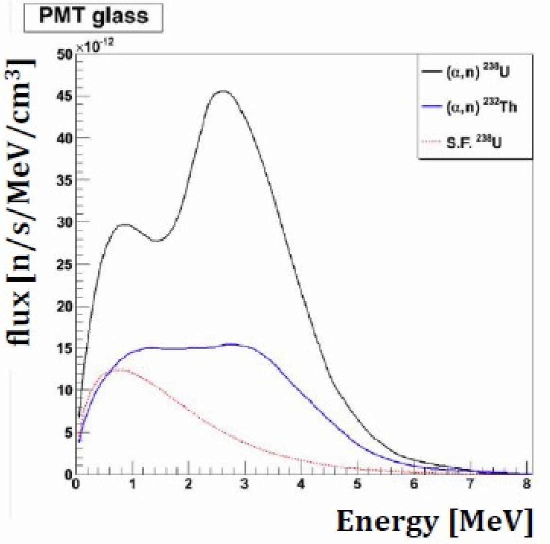
From R. Santorelli









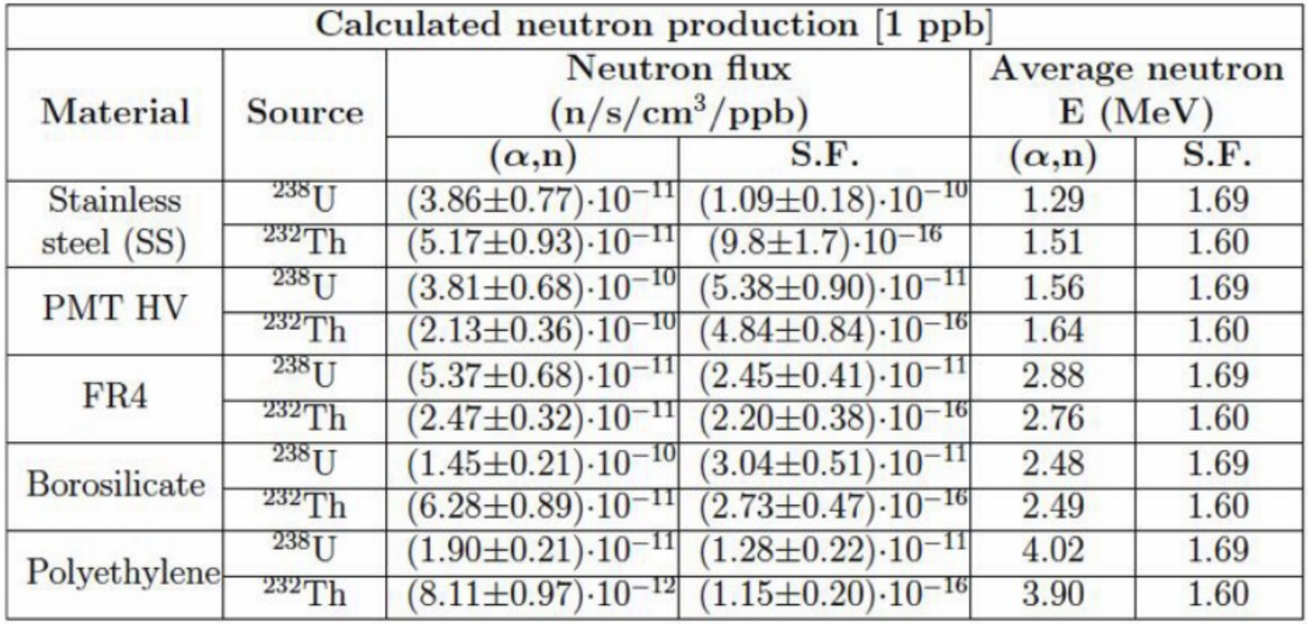


- Considering **1 ppb contamination of ^{238}U and ^{232}Th** in each material, the **neutron energy spectra** was obtained using the **SOURCES** software, taking into account the exact chemical composition of each material.

ArDM: Neutron flux calculations

From R. Santorelli

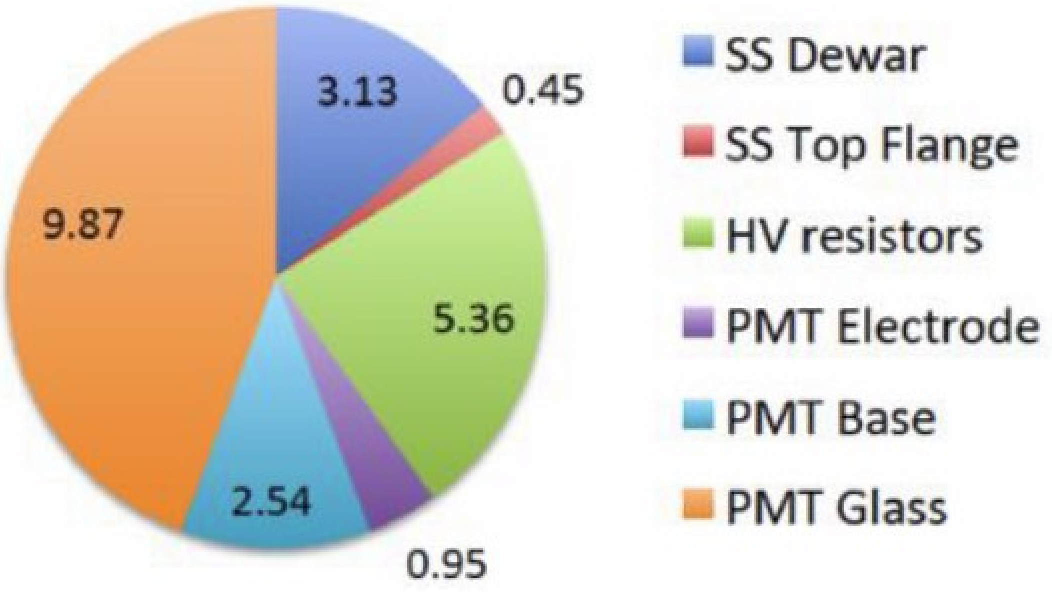
- The **highest flux** is produced by
  - the PMT high voltage resistors.
  - the PMT glass (borosilicate).
- These **results** have to be **combined** with the **activity** measured with the **Ge detector**.



Calculated neutron production [1 ppb]

Material	Source	Neutron flux (n/s/cm³/ppb)		Average neutron E (MeV)	
		(α,n)	S.F.	(α,n)	S.F.
Stainless steel (SS)	^{238}U	$(3.86\pm0.77)\cdot10^{-11}$	$(1.09\pm0.18)\cdot10^{-10}$	1.29	1.69
	^{232}Th	$(5.17\pm0.93)\cdot10^{-11}$	$(9.8\pm1.7)\cdot10^{-16}$	1.51	1.60
PMT HV	^{238}U	$(3.81\pm0.68)\cdot10^{-10}$	$(5.38\pm0.90)\cdot10^{-11}$	1.56	1.69
	^{232}Th	$(2.13\pm0.36)\cdot10^{-10}$	$(4.84\pm0.84)\cdot10^{-16}$	1.64	1.60
FR4	^{238}U	$(5.37\pm0.68)\cdot10^{-11}$	$(2.45\pm0.41)\cdot10^{-11}$	2.88	1.69
	^{232}Th	$(2.47\pm0.32)\cdot10^{-11}$	$(2.20\pm0.38)\cdot10^{-16}$	2.76	1.60
Borosilicate	^{238}U	$(1.45\pm0.21)\cdot10^{-10}$	$(3.04\pm0.51)\cdot10^{-11}$	2.48	1.69
	^{232}Th	$(6.28\pm0.89)\cdot10^{-11}$	$(2.73\pm0.47)\cdot10^{-16}$	2.49	1.60
Polyethylene	^{238}U	$(1.90\pm0.21)\cdot10^{-11}$	$(1.28\pm0.22)\cdot10^{-11}$	4.02	1.69
	^{232}Th	$(8.11\pm0.97)\cdot10^{-12}$	$(1.15\pm0.20)\cdot10^{-16}$	3.90	1.60

Neutrons in 100 live days



Conclusions

- Radiogenic neutron backgrounds form one of the dominant backgrounds for LAr dark matter experiments
- Different experiments take different approaches to handling them
  - *Everyone* has extensive material qualification campaigns to design radiopure materials – Requires knowing how to convert activities to neutron fluxes!
  - Some experiments prioritize vetoing neutrons, while others focus on passively shielding them
- Whatever backgrounds remain after all of this need to be modeled…
  - Need to be able to calculate (α,n) yields!

END