Measuring ^{40}Ar-solar neutrino charged-current interactions in the DEAP-3600 dark matter detector

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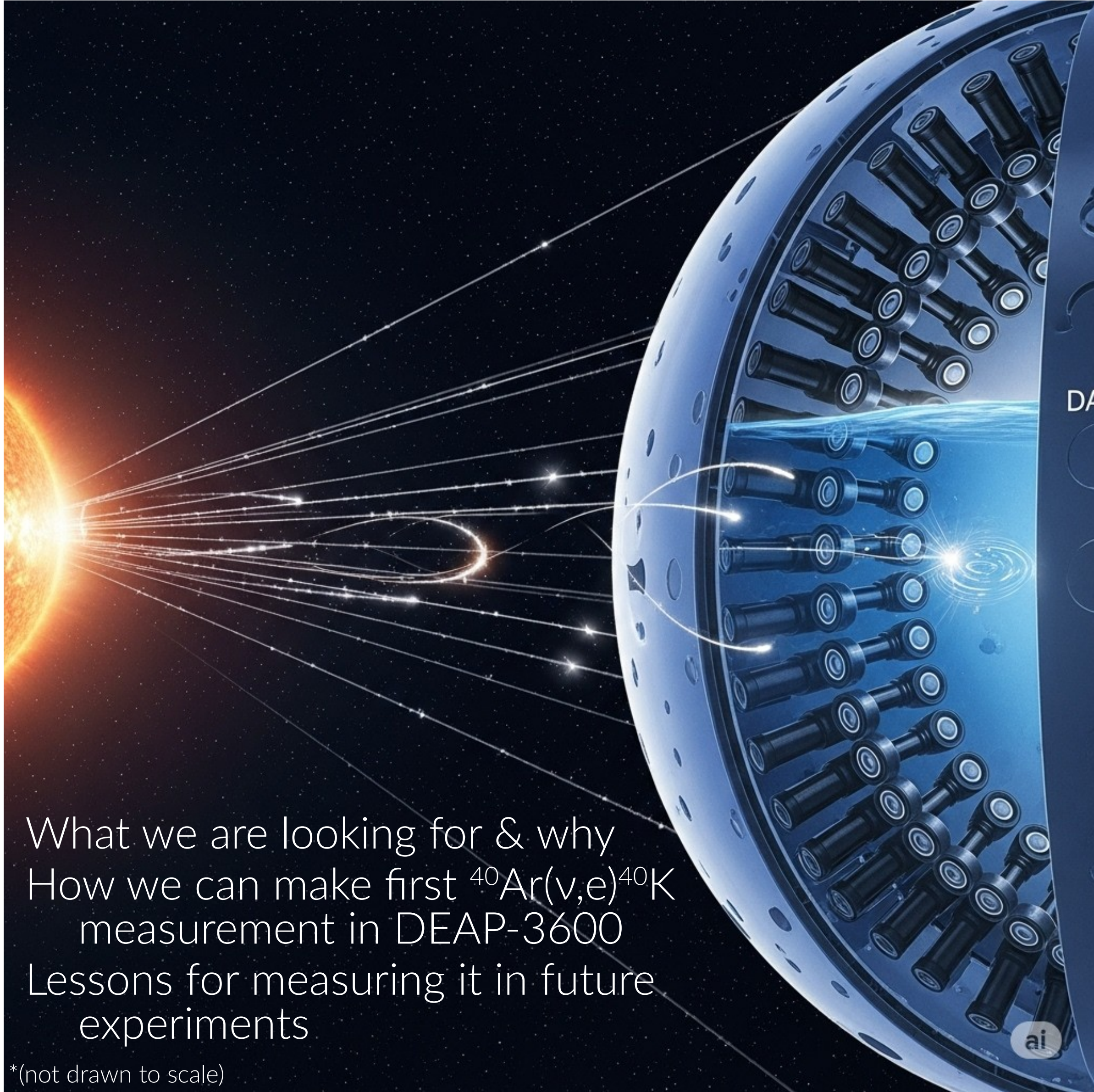
with the DEAP Collaboration

TAUP 2025 – Xichang, China
26 August, 2025

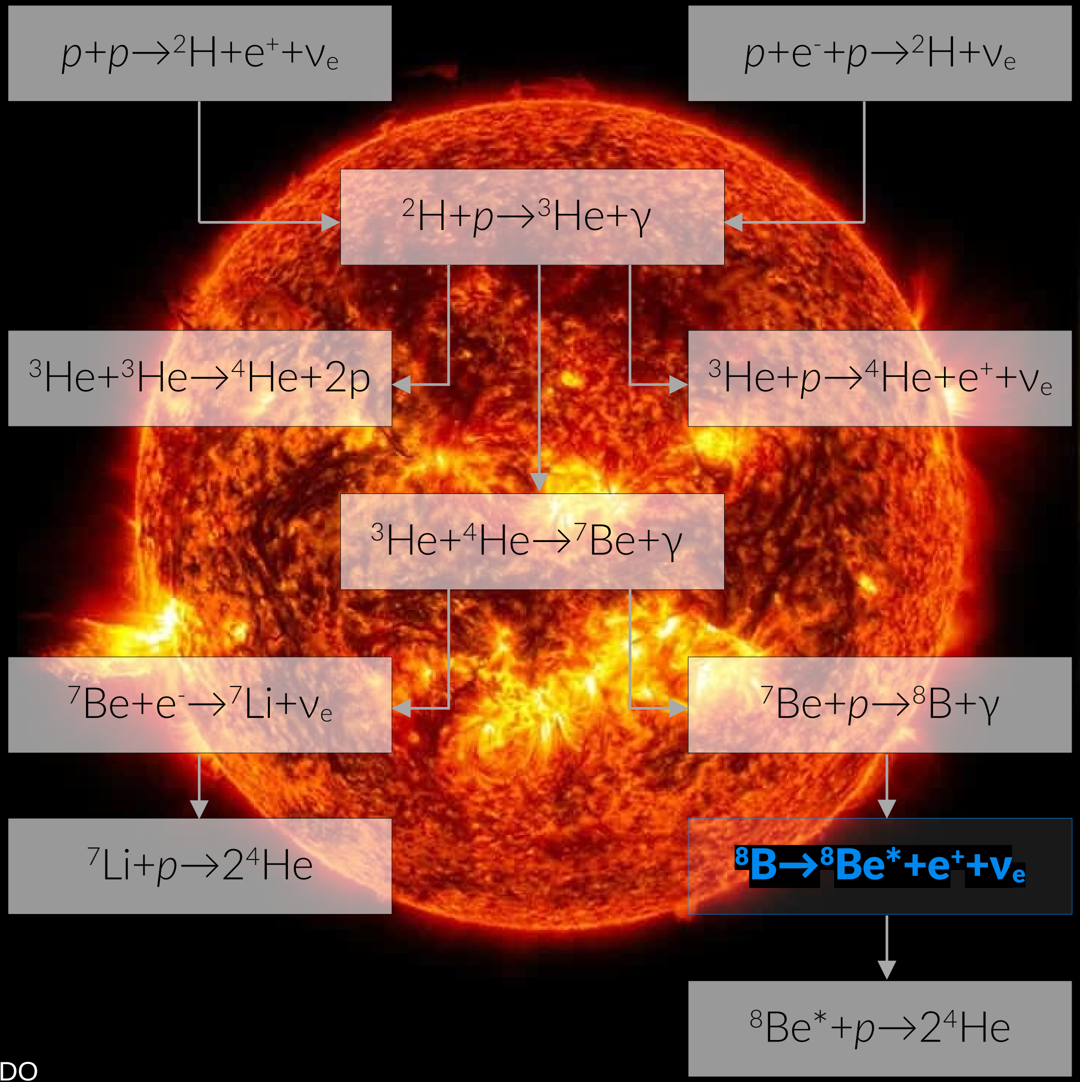
Gemini, draw a picture neutrinos going from the Sun to DEAP-3600

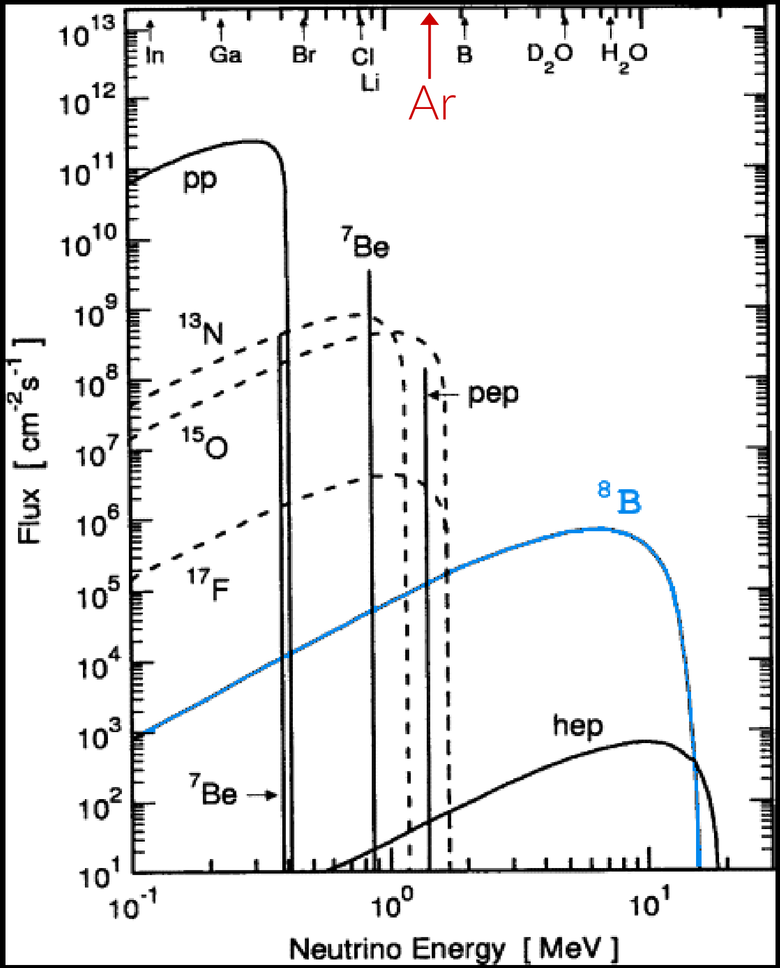


- What we are looking for & why
- How we can make first ^{40}Ar(ν,e)^{40}K measurement in DEAP-3600
- Lessons for measuring it in future experiments

*(not drawn to scale)

pp Chain





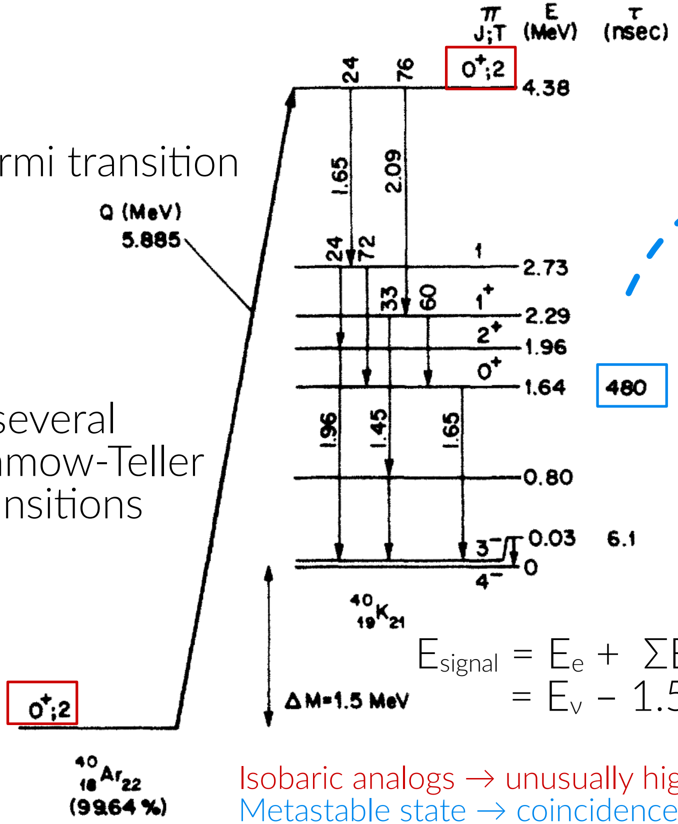
The sun is mass of incandescent gas, a gigantic nuclear furnace
Where hydrogen is built into helium at a temperature of millions of degrees
- They Might Be Giants

NASA/SDO

$^{40}Ar + \nu_e \rightarrow {}^{40}K^* + e^-$

Fermi transition

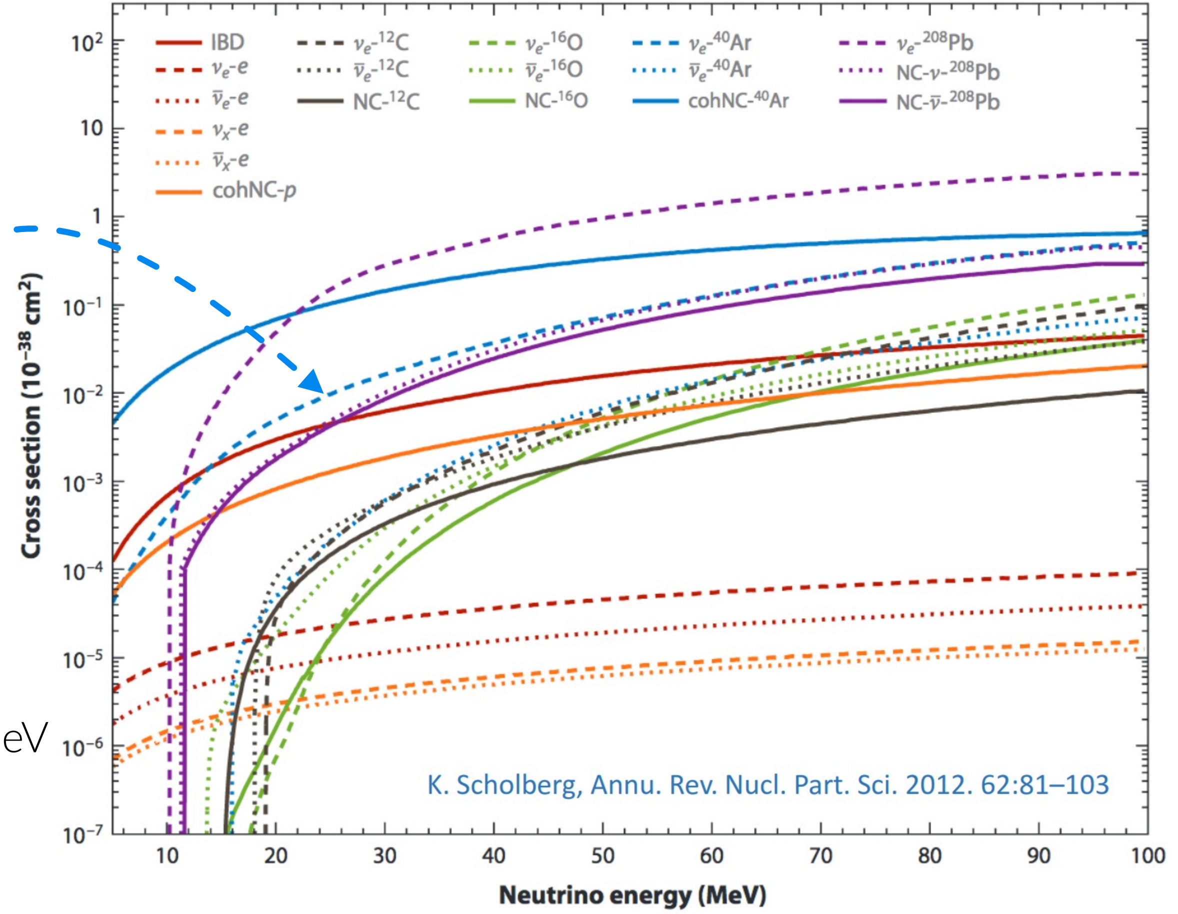
+ several Gamow-Teller transitions



$E_{signal} = E_e + \sum E_\gamma$
$= E_\nu - 1.5$ MeV

Isobaric analogs → unusually high σ
Metastable state → coincidence tag

R.S. Raghavan (1986)



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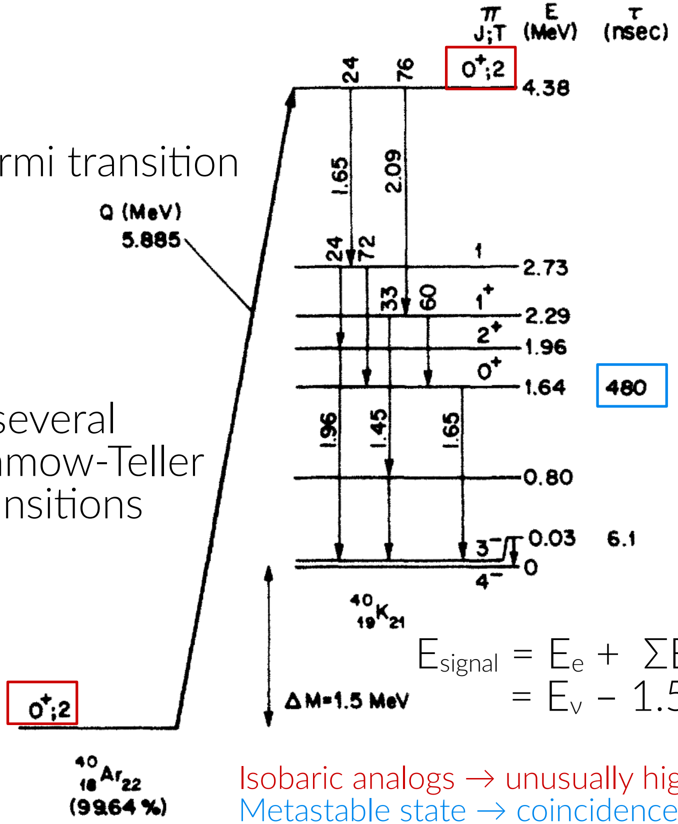

$E_{signal} = E_e + \sum E_\gamma$
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Isobaric analogs → unusually high σ
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Reaction properties:

- High cross section
- Total signal directly reads neutrino energy
- Signals ~10 MeV – higher energy than most abundant bkgds; rarer bkgds dominate
- Meta-stable state can be used to tag above bkgd
- Specifically measures ν_e

Sensitive probe for…

- Solar neutrinos ← this talk!
- Core-collapse supernova neutrinos
- "Low-energy" atmospheric neutrinos (higher E, breakup reactions and others dominate)

$^{40}Ar + \nu_e \rightarrow {}^{40}K^* + e^-$

Fermi tran

+ several
Gamow-Te
transitions

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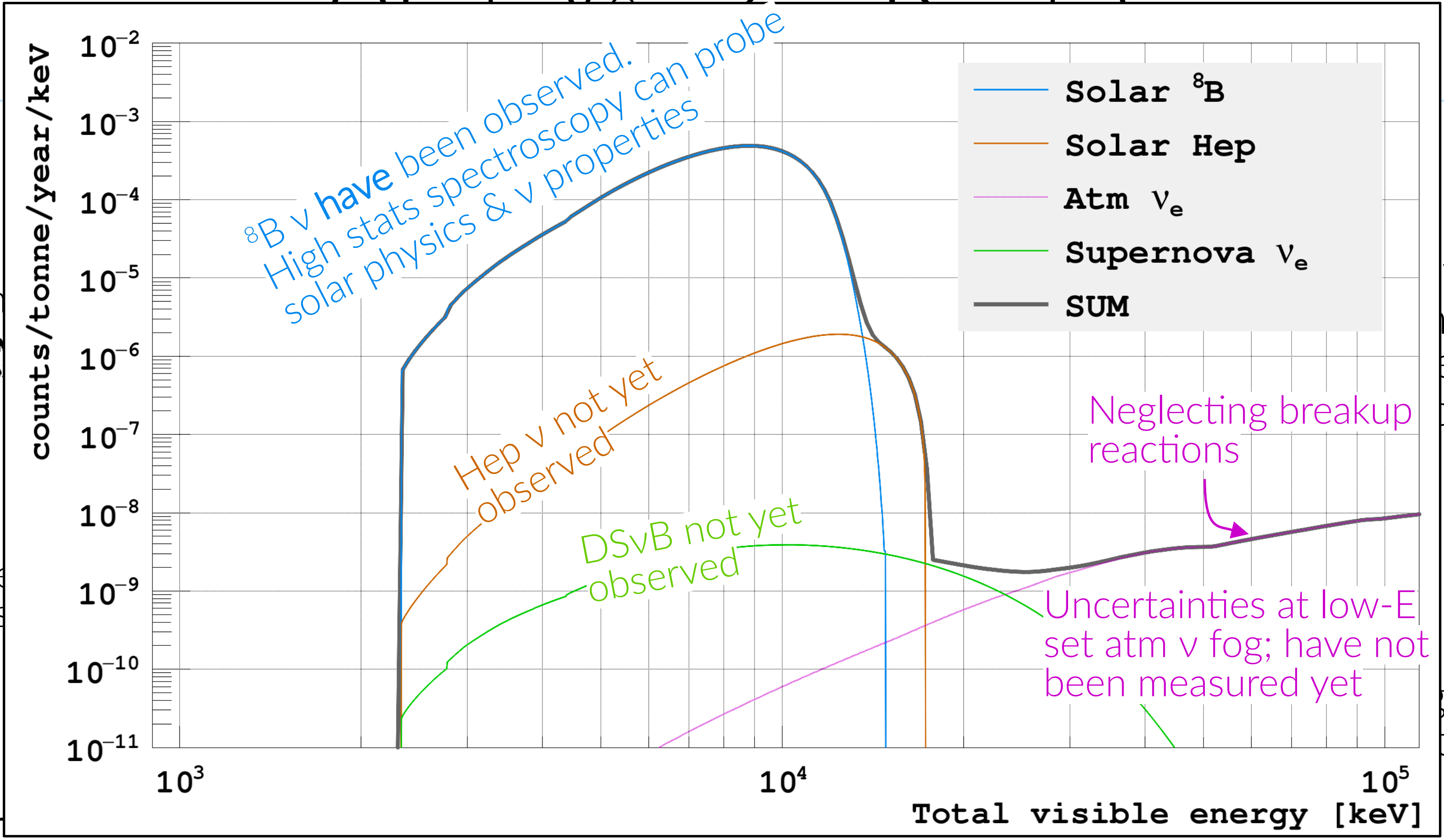
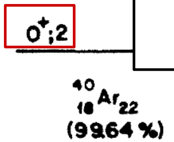


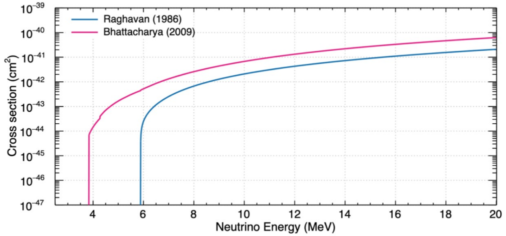


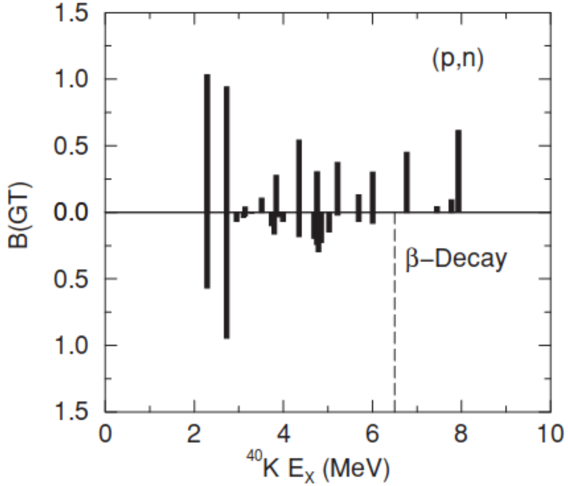
Isobaric analogs → unusually high σ
Metastable state → coincidence tag

R.S. Raghavan (1986)

However…

This reaction has not yet been measured





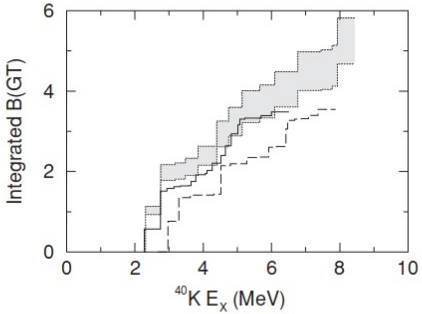
PRC 80, 055501 (2009)

$$\sigma(E_\nu) = \frac{G_F^2 \cos^2\theta_{\rm ud}}{\pi\hbar^4 c^3}\sum_i p_i W_i F(Z, W_i)[B_i({\rm GT}) + B_i(F)].$$

Gamow-Teller & Fermi transition strengths estimated two ways

Bhattacharya (2009): Using $^{40}Ar(p,n)$ forward scattering

Bhattacharya (1998): Using β decay of mirror nucleus ^{40}Ti



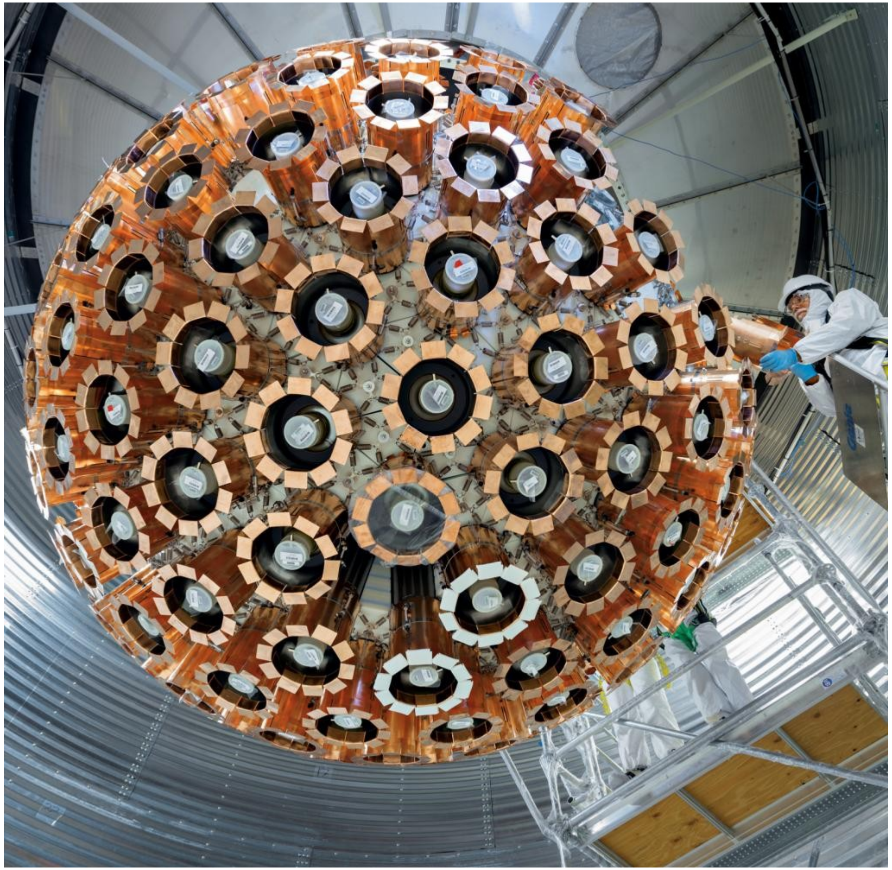
These details are needed to predict signals in future detector, extract physics from ν_e signals, and reconstruct excited ^{40}K state

Need measurements of this reaction!

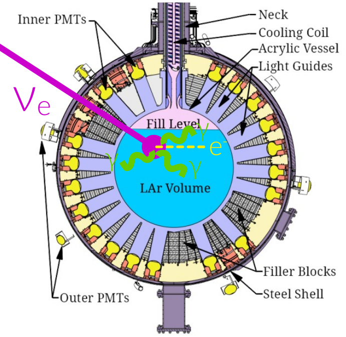
NuDat3 ^{40}K structure >5.6 MeV

E(level) (keV)	XREF	J^π(level)	$T_{1/2}$(level)	E(γ) (keV)	I(γ)	M(γ)	Final Levels	
5681 32	H							
5870 20	J							
5891.90 22	A	(9-)		559.28 22 1016.6 4 1079.1 5 1525.85 27	63 11 48 9 76 14 100 20		5332.91 4875.57 4812.01 4365.77	(9+) 9+ (8+) 8+
6098.22 7	E	(1-,2,3,4-)		1702.35 3 2539.87 7 6067.6 3	100 9 82 9 15.2 15		4395.88 3557.41 29.8299	(2)- (1-,2+,3-,4+) 3-
6118 30	H							
6227.01 25	B	(8,10)-	< 1.4 ps	1351.51 18 1861.3 6 ? 3684?	100 8 <5 <2	E1(+M2)	4875.57 4365.77 2542.79	9+ 8+ 7+
6790 30	H							
≈7000	P							
7033.0 4	A	(9-)		1142.3 5 2219.7 5	59 11 100 18		5891.90 4812.01	(9-) (8+)
7468 37	H							
7472.2 3	AB	(9-,11-)		1245.31 22 1579.3 5	100 19 37 8	D+Q	6227.01 5891.90	(8,10)- (9-)
7748.0 4	A	(9-,10-)		1520.88 30 2872.9 9	30 6 100 18		6227.01 4875.57	(8,10)- 9+
7795 33	H							
7799	E							
7800.70 6	X	(0:3)-						
7802.82 6	X	(0:3)-		?			?	
7808.77 6	X	1+	73 eV 8					
7811.47 6	X							
7811.93 6	X	3-	1.2 eV 2					
7813.56 6	X	(2)-						
7815.18 6	X	2-	1.64 eV 24					
7815.91 6	X	(3-)						
7823.96 7	X							
7824.53 7	X	2+	95 eV 3		?			?
7827.26 7	X							
7830.98 7	X	3-	3 eV					
7832.10 7	X	2-	13 eV 1					
7836.23 8	X	(2-)						
7836.33 8	X	(2-)						
7841.26 7	X	2+	0.54 keV 3					
7843.62 8	X							
7844.45 8	X	2-	42 eV 2	?				?
7850.42 8	X	(2)-					?	
7852.62 8	X							
7852.79 8	X	2-	17 eV 4					
7854.04 8	X							
7855.97 8	X	1+	1.1 keV 1					
7856.94 8	X				?			
7857.99 8	X	1-	83 eV 13					
7860.29 8	X							?
7866.25 9	X	1	1.94 keV 24					
7866.80 9	X							
7873.43 10	X							
7878.23 10	X			?				
7878.74 10	X							
7882.37 10	X						?	
7885.12 11	X	1-	0.47 keV 5		?			
7890.06 11	X							
7890.36 11	X							
7893.94 12	X							

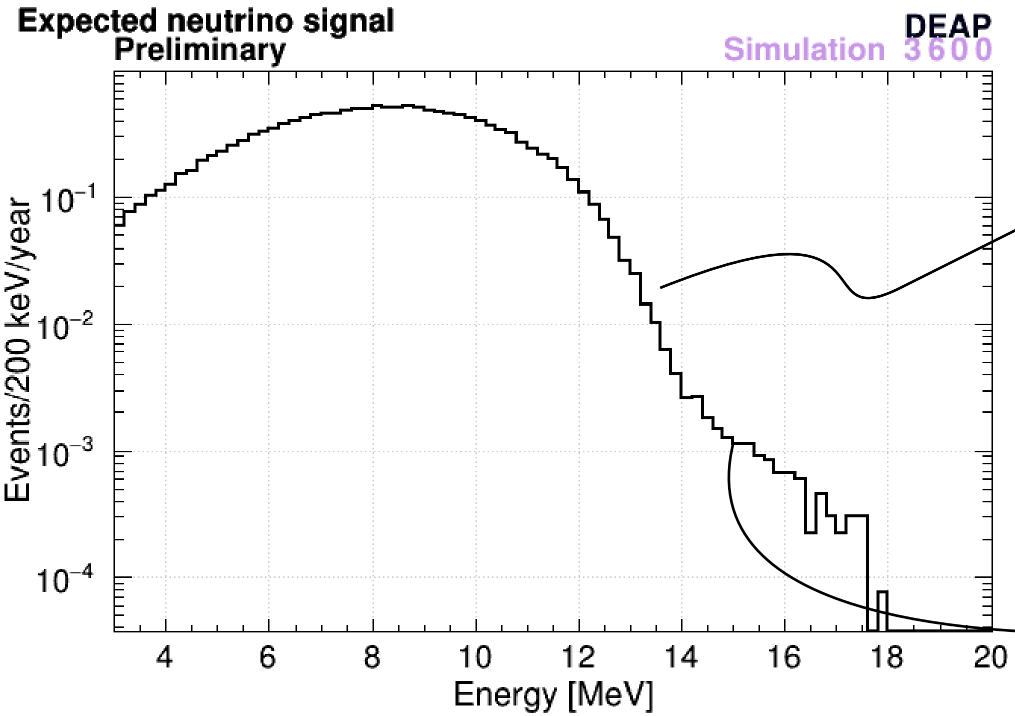
DEAP-3600



- Located 2 km underground in SNOLAB
- 3.3 tonnes of LAr scintillation counter
- Contained in 5 cm-thick acrylic vessel
- Viewed by 255 PMTs via 45 cm acrylic light guides
- Designed to measure ~100 keV nuclear recoils from WIMPs, using pulse shape discrimination to tag and eliminate electron-scattering backgrounds
- Contained in 7.8×7.8 m^2 water Cherenkov muon veto



Signal expectation

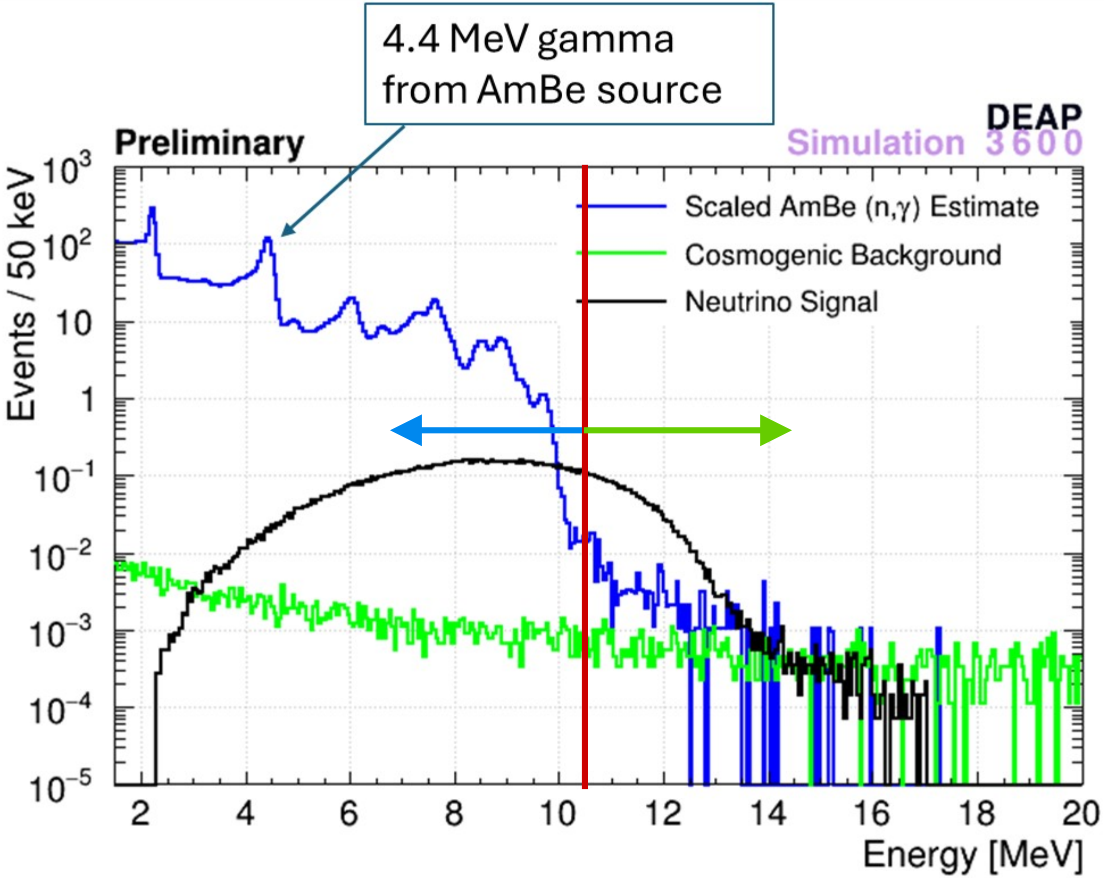


Rate: (2.21 ± 0.21) evts/(tonne-yr)
Exposure: 7.3 tonne-yrs
Expect: 16.1 ± 1.5 evts

Dominant uncertainty:
reaction cross section

Hep neutrinos
(rate too low for DEAP)

Analysis strategy



Low energy region

Dominated by (n,γ) backgrounds

Use delayed coincidence to tag ~50% 1.6 MeV γ-ray delayed by τ~500 ns

High energy region

Above most (n,γ) backgrounds

Main bkgds: (n,γ) tails and cosmogenic muon signals (after muon veto cuts)

Background rates lower than ν rates

Focus for 1st search

ROI: 10.5-13 MeV ← max expected sig.

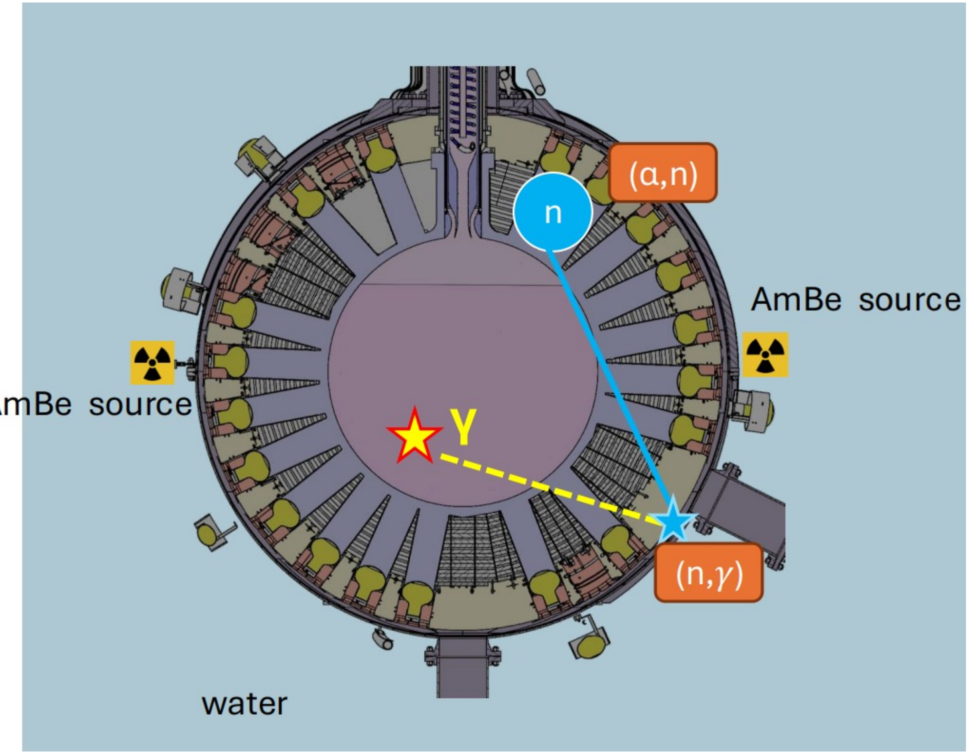
+ sidebands to validate bkgd model

Radiogenic backgrounds

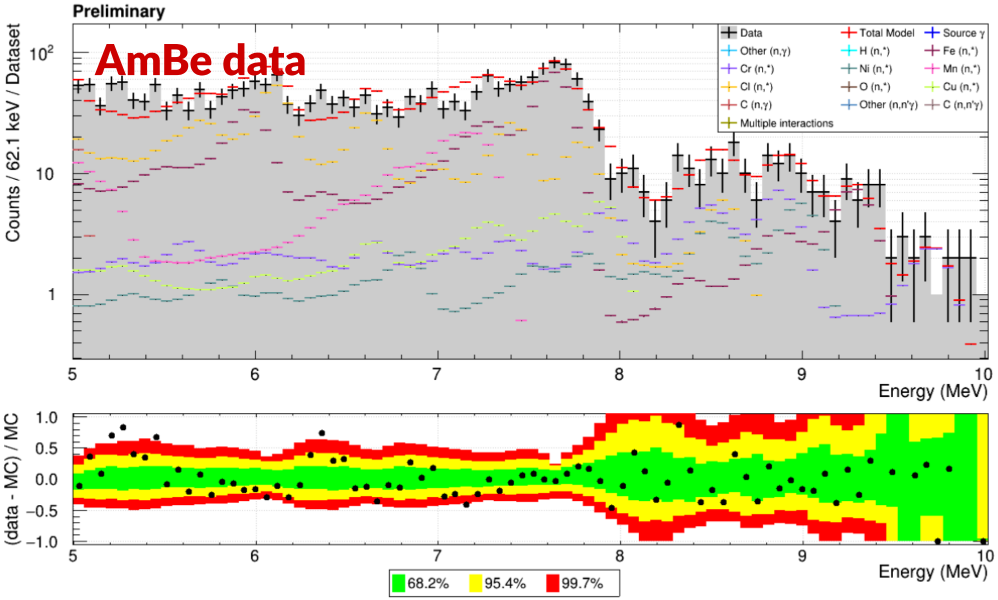
Neutrons are hard (even when they're soft)

Two approaches

Re-scaling AmBe neutrons (w/ corrections)



Fitting simulated neutrons to data



Carl Rethmeier's PhD thesis, Carleton University (2021)

Radiogenic backgrounds

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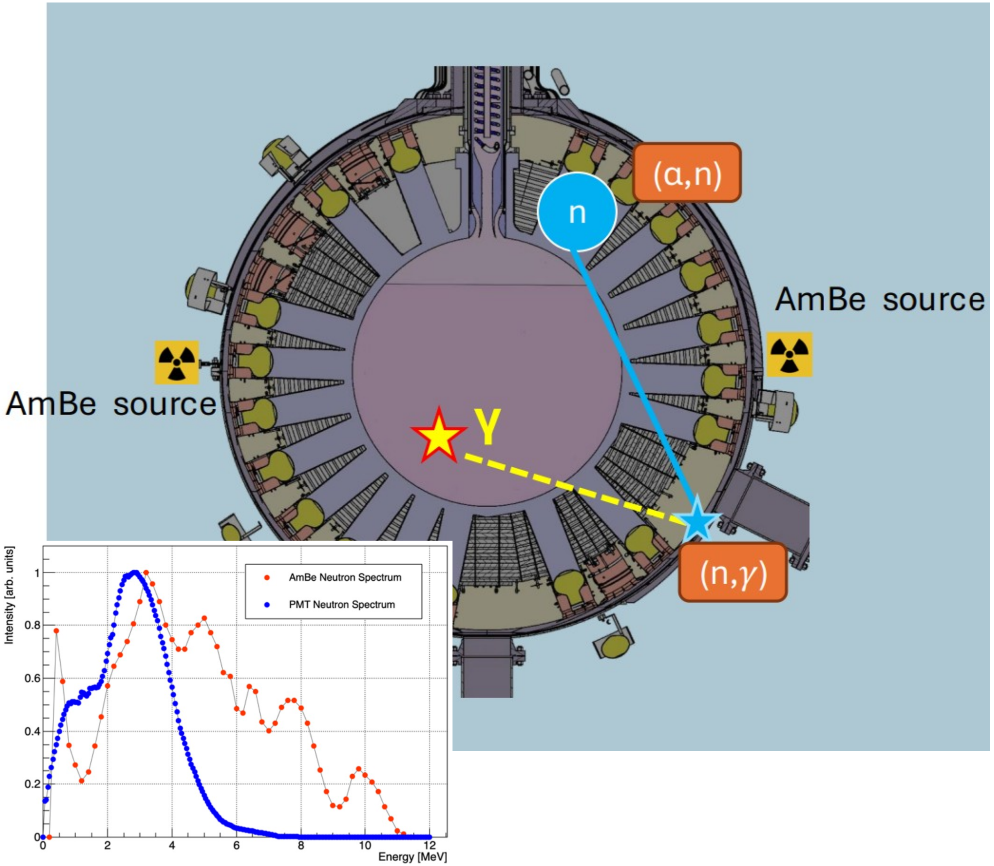
Re-scaling AmBe neutrons (w/ corrections)



Challenges

AmBe spectrum much harder than bkgd neutrons

AmBe neutrons start outside steel vessel; most neutrons start in PMTs, other components

Differences are minor < 10 MeV, important in ROI

Different neutron sources illuminate different materials, hence different targets for (n,γ)

High-energy neutrons are more likely to induce (n,2n) and correlations between (n,γ) and (n,nγ). *Usually O(100 μs) apart*, *but prompt happens!*

Hot AmBe source → high pilup rate

Investigating these using Geant4 simulations, but...
G4 doesn't always get nuclear level structures right! Some non-physical transitions on Ar nuclei

→ **Impedes corrections to AmBe data**

Radiogenic backgrounds

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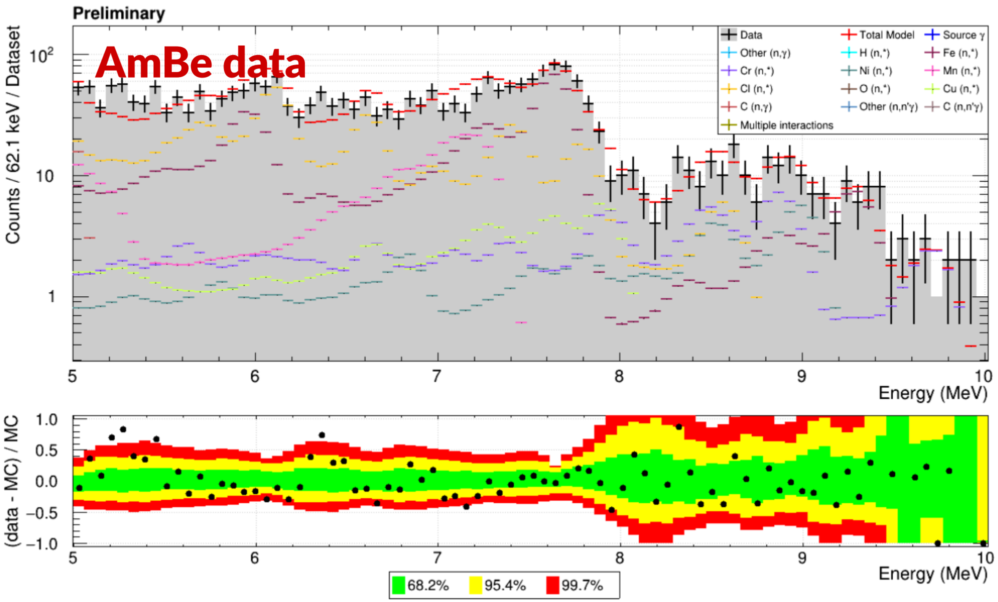
Fitting simulated neutrons to data



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Procedure

Simulate PMT neutrons in Geant4 ← dom. source

Create signal spectra for each element

Let normalization float within 5× of sim. prediction

↰ Accounts for deviations in material illumination, inaccuracies in G4 cross sections, etc.

Fold into Gaussian response function & fit to data

Challenges

Inaccuracies in Geant4 neutron physics

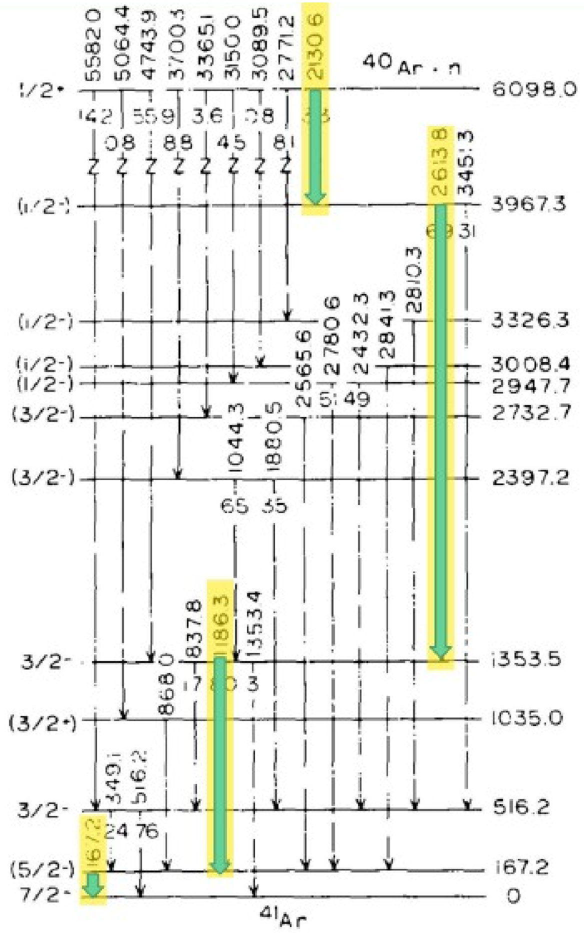
(n,γ) cascade modeled poorly by default G4 models

Detector response depends on event topology; not accounted for in Gaussian response function

Limited calibration above ROI – AmBe (n,γ) below

G4CASCADE

Code for Allowing Simulation of n-Capture and De-excitation with ENSDF

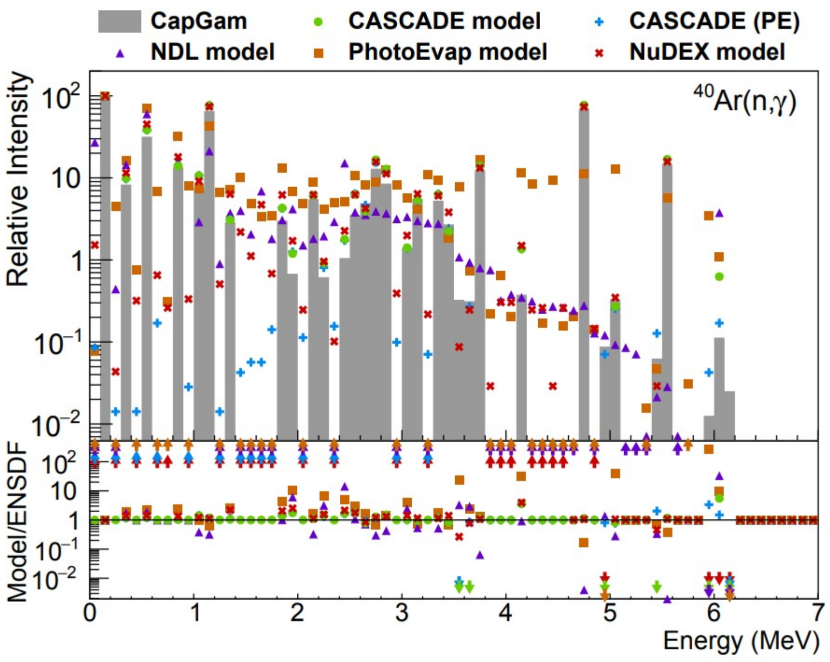


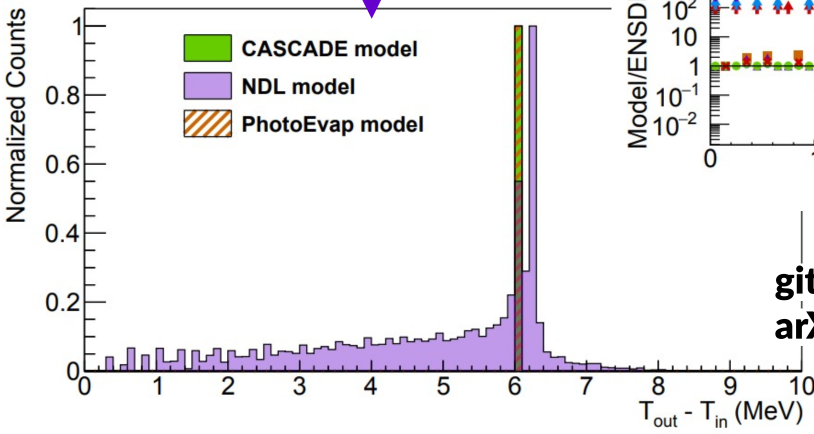
Uses CapGam ENSDF level structure to simulate de-excitation cascade

Reproduces most (n,γ) lines

Correlates γ-rays

→ conserves energy

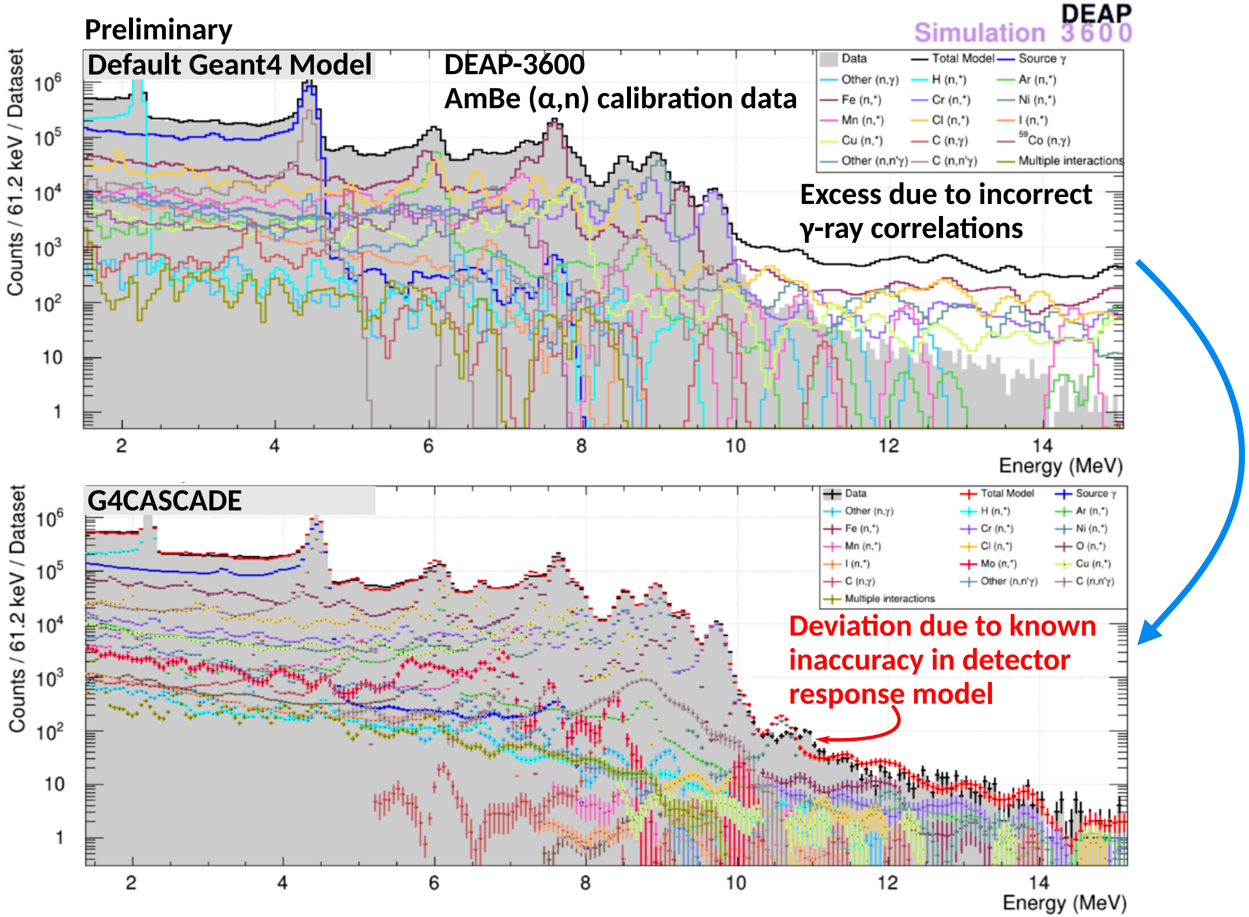




github.com/UCRDarkMatter/CASCADE
arXiv:2408.02774

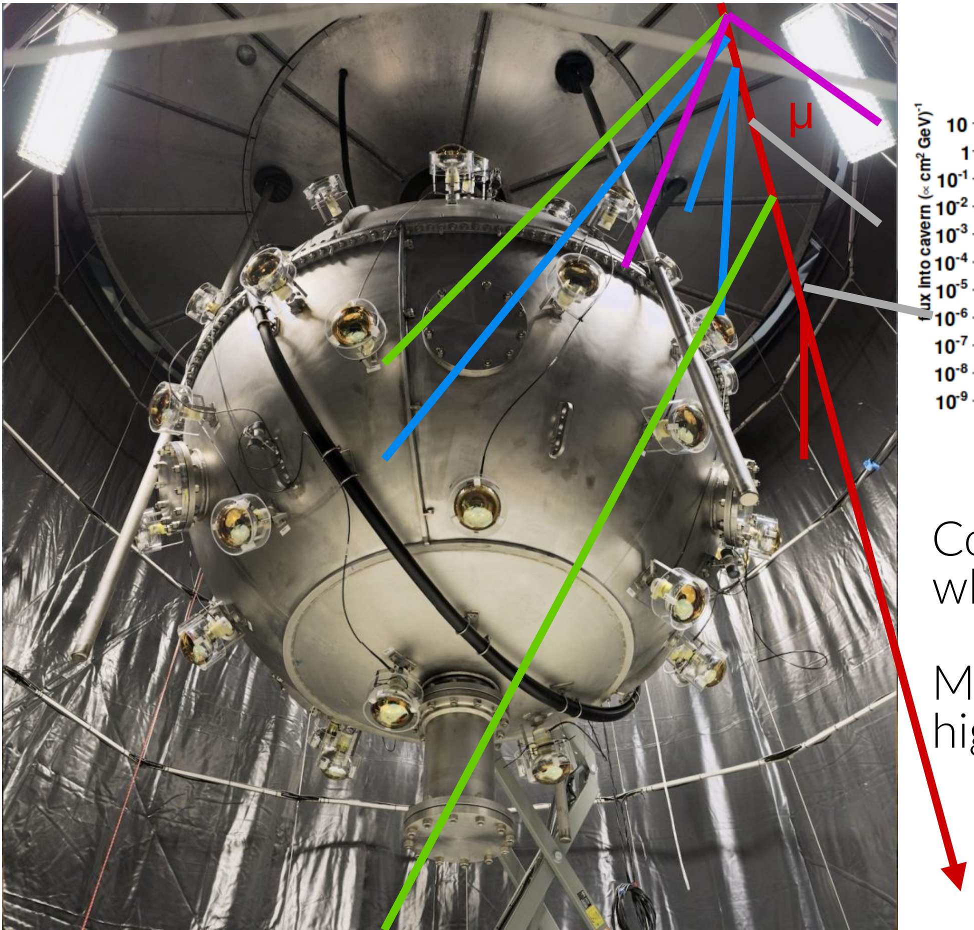
G4CASCADE improves (n,γ) modeling

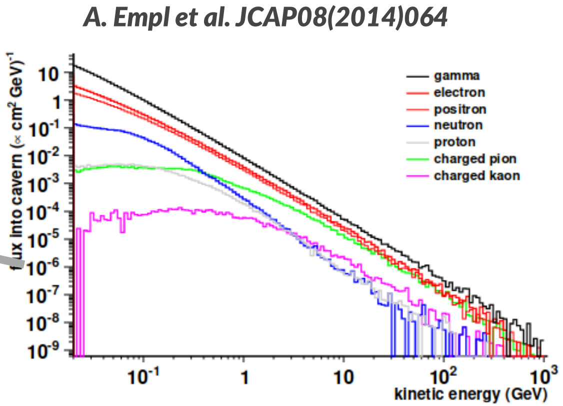
Code for Allowing Simulation of n-Capture and De-excitation with ENSDF

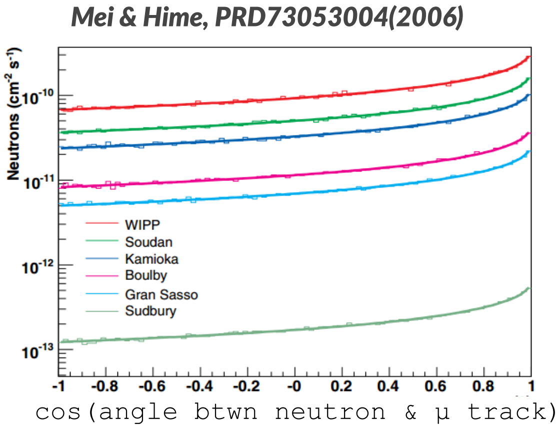


Excesses due to energy non-conservation with G4NDL are fixed with G4CASCADE

Cosmogenic backgrounds: Muons are messy



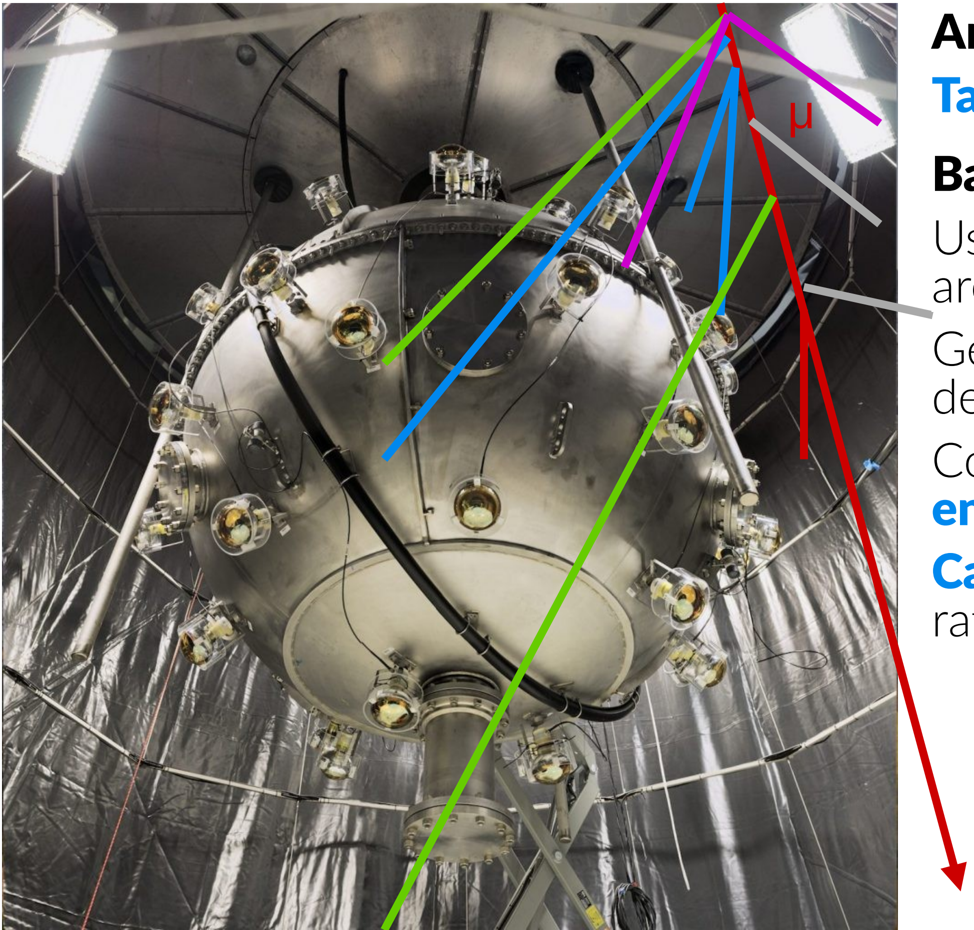




Cosmogenic muons produce large, energetic showers, which can enter the detector **even if the muon misses**

Muons that enter the LAr can activate isotopes with high-energy **decays after muon is long gone**

Cosmogenic backgrounds: Strategy



Analysis strategy

Tag muons in 7.8×7.8 m^2 water Cherenkov muon veto

Background estimation strategy

Use Geant4 and FLUKA to **generate μ showers** in rock around detector. Estimate bkgd rate surviving veto cut

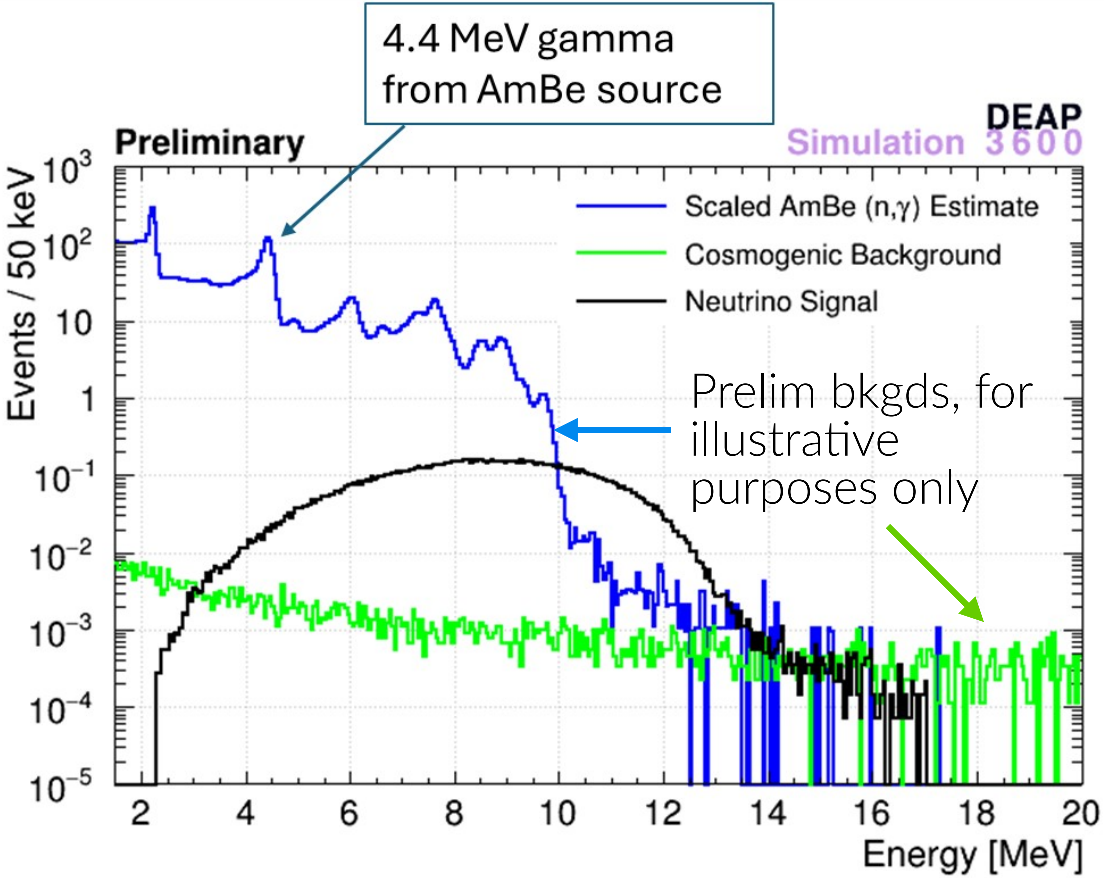
Generate muons in 300×300 m^2 area in rock above detector, **propagate muons and let shower evolve**

Count event rate in ROI and 13–20 MeV sideband vs. **energy deposited/Cherenkov photons in veto**

Calculate bkgd rate after stringent veto cuts, and use rate with veto coincidences and in sideband to validate

Comparable backgrounds from
- **Prompt showers**, where μ misses/glances veto
- **Delayed radioisotope decays**

Status and challenges



Status: ironing out final details

Parallel background estimates are starting to converge, and we are finalizing background model & systematics

Expected background rate is converging well below expected signals in high-energy ROI, though only expect a few ν_e's

Manuscript under preparation

Challenges we tackled for this analysis

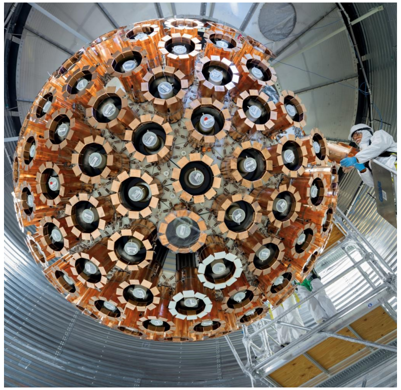
Radiogenic & cosmogenic bkgds are hard to model, many uncertainties. Combining data and simulation approaches helped

Key elements for radiogenic bkgd: Ni, N, Cr, Cl, Si, Fe, B, Ar (incl (n,γ)+(n,nγ) pileup)

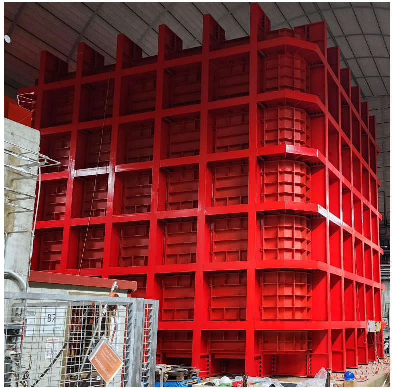
Even with a muon veto, cosmogenic bkgds are significant

You can't spell "solar neutrinos" without "LAr"

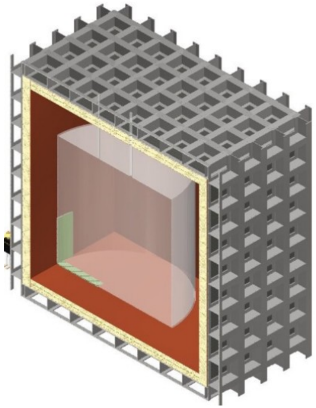
Using ν_e CC – in some cases complemented by CEvNS – future LAr detectors may also be observatories for solar, supernova, and low-energy atmospheric neutrinos



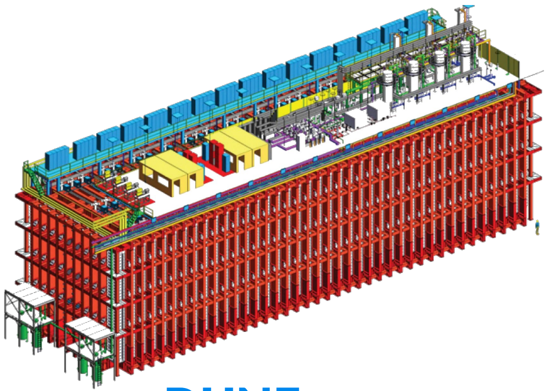
DEAP-3600



DarkSide-20k



Argo



DUNE

DEAP Collaboration:

95 researchers in **Canada**, Germany, Italy, Mexico, Poland, Russia, Spain, UK, USA

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