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Low Background DUNE Module: Expected Requirements and Physics Potential

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Chris Jackson, Eric Church
Richard Saldanha

U.S. DEPARTMENT OF ENERGY BATTELLE

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DUNE Physics Goals

- Comprehensive program of neutrino oscillation measurements
  - Search for CP violation
  - Precision measurements of the phase $\boldsymbol{\delta}$ and mixing angle $\boldsymbol{\theta}_{23}$
  - Determination of the neutrino mass ordering
- Detect and characterize ν_e flux from a core-collapse supernova within our galaxy
- Search for physics beyond the Standard model, including proton decay

- Ancillary goals include:
  - Measurements with atmospheric neutrinos
  - Low-energy astrophysical measurements (solar neutrinos, diffuse supernova neutrino background

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What additional low energy physics reach can we add?

What would it take to turn DUNE into a Dark Matter Detector?

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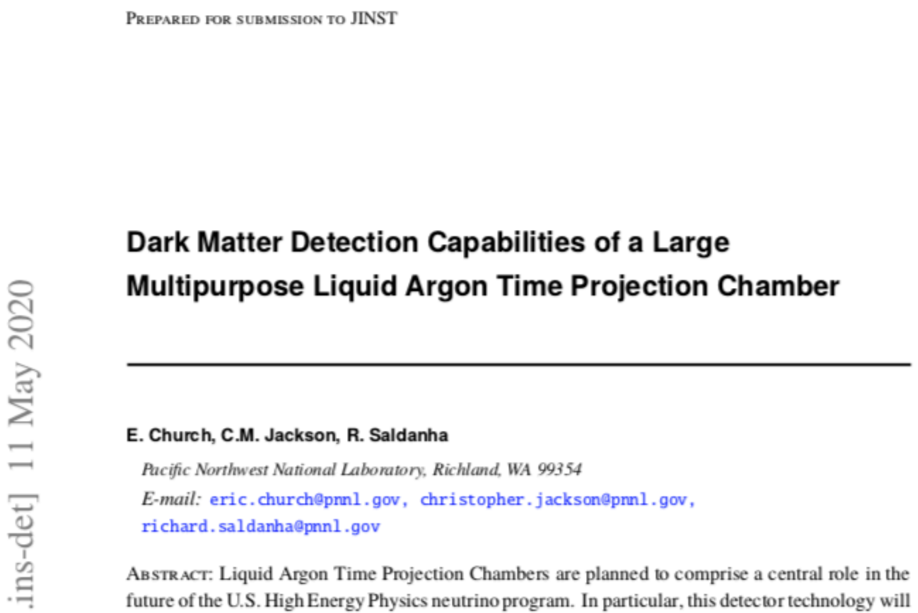
https://www.bnl.gov/dmo2019/index.php

https://arxiv.org/abs/2005.04824
Accepted in J.Inst.



Prepared for submission to JINST

ins-det] 11 May 2020

Dark Matter Detection Capabilities of a Large Multipurpose Liquid Argon Time Projection Chamber

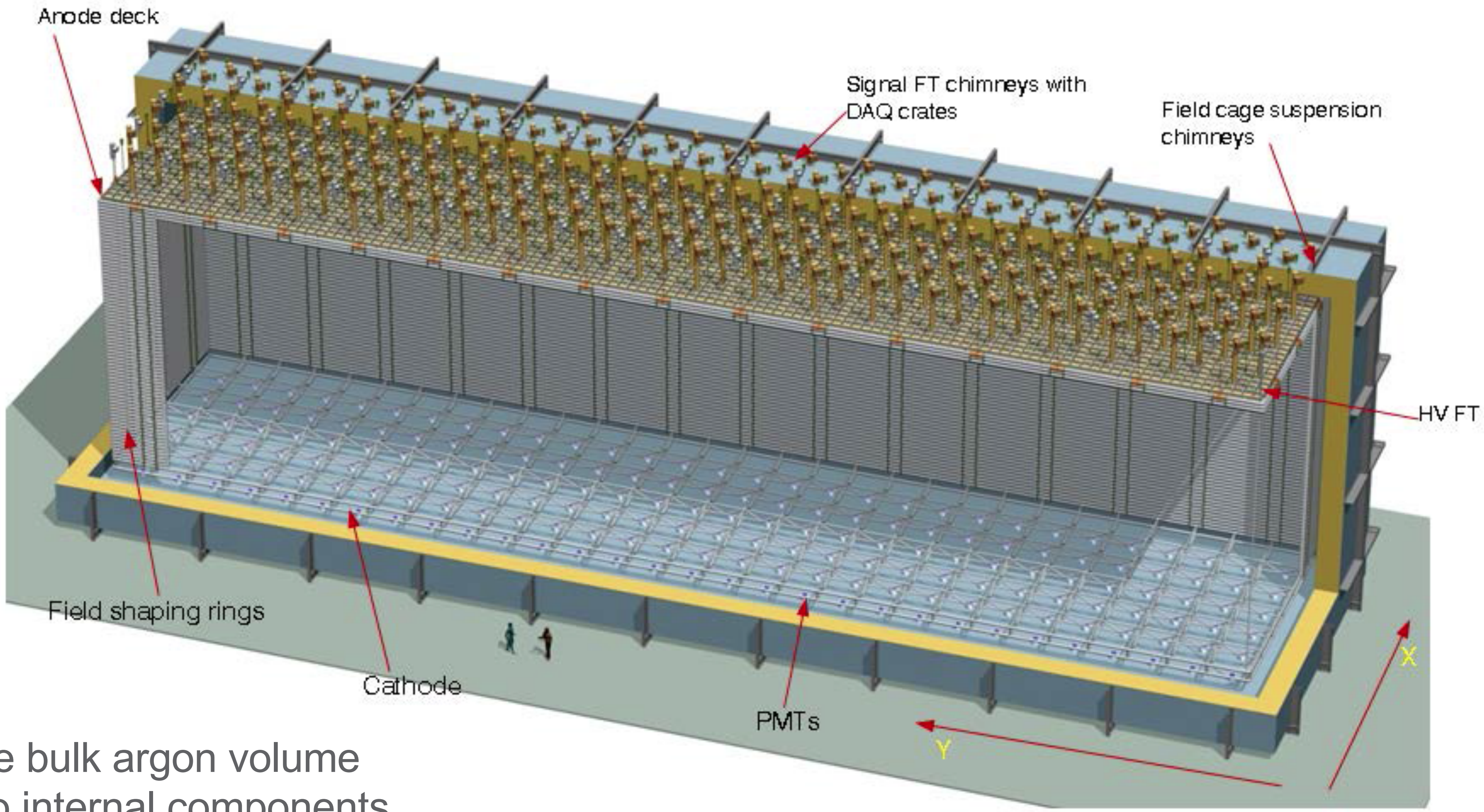
E. Church, C.M. Jackson, R. Saldanha
Pacific Northwest National Laboratory, Richland, WA 99354
E-mail: eric.church@pnnl.gov, christopher.jackson@pnnl.gov, richard.saldanha@pnnl.gov

Abstract: Liquid Argon Time Projection Chambers are planned to comprise a central role in the future of the U.S. High Energy Physics neutrino program. In particular, this detector technology will

What would it take to turn DUNE into a Dark Matter Detector?

- 50-100 keV nuclear recoil threshold
- O(10) background events
- O(100) photons detected per event

Dual Phase Module

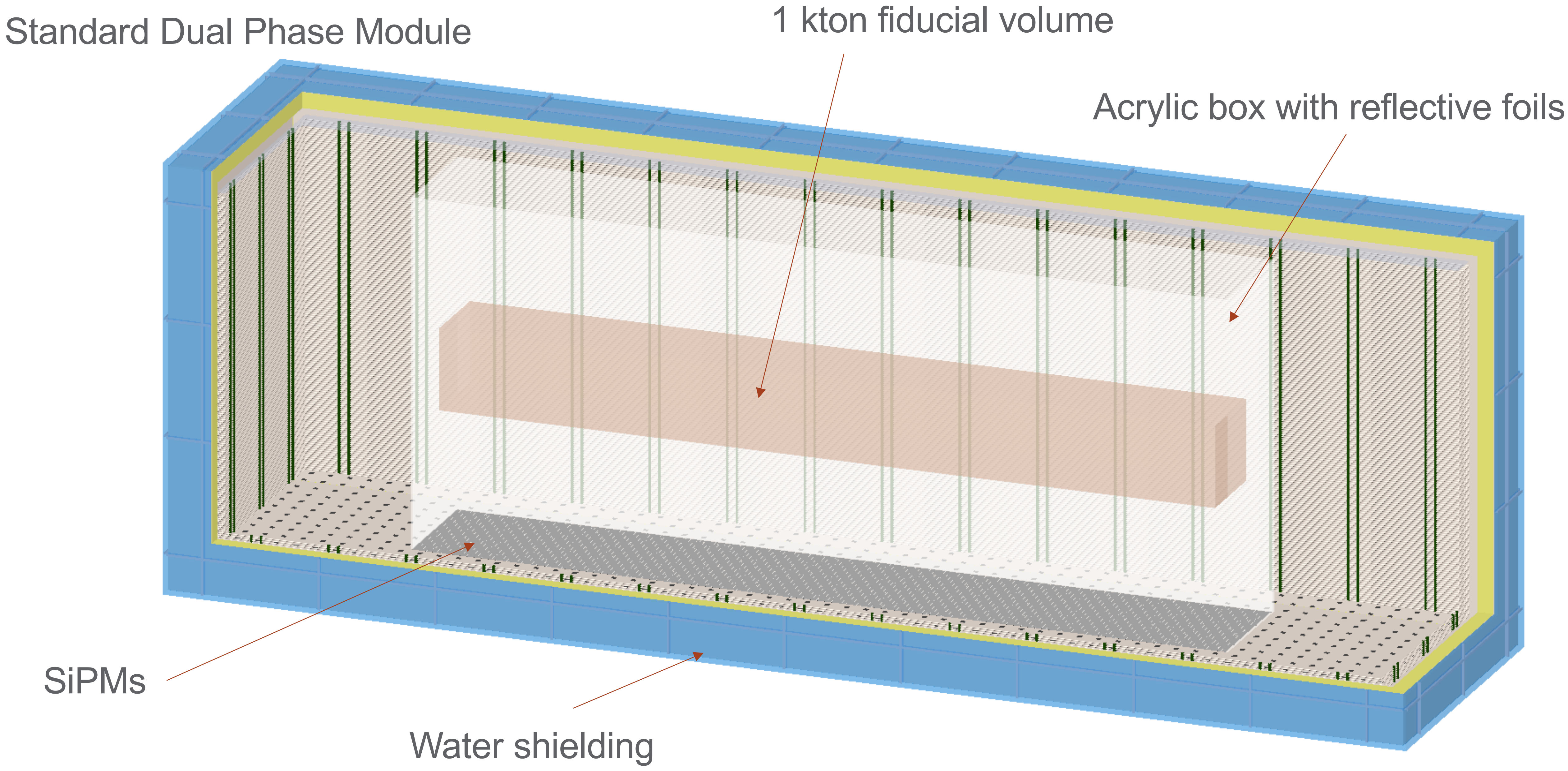


Large bulk argon volume
with no internal components

Low Energy Physics and Dark Matter at DUNE

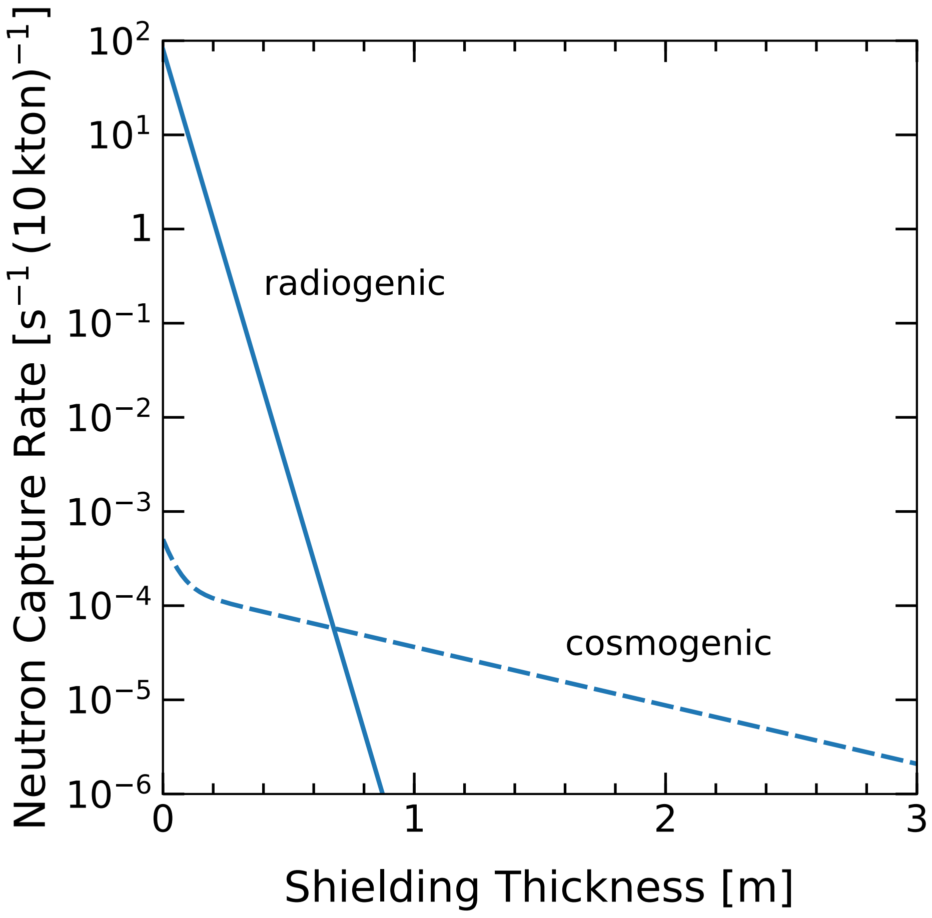
- Dual-phase
  - ✓ bulk argon, without internal components for radiopurity
- Fiducialization
  - ✓ 1 kTonne to remove wall sources
  - ✓ Low radioactivity underground argon
- Additional Neutron shielding
  - ✓ Water and plastic
- High signal/noise from gas-multiplication readout
  - ✓ Use light readout for electroluminescense photons (S2)
  - ✓ SiPMs or ARIADNE cameras
- Enhanced Photon Detection System (PDS)
  - ✓ Reflectors
  - ✓ SiPMs
  - ✓ Increased coverage

The Low Background Module



Neutron Background Reduction

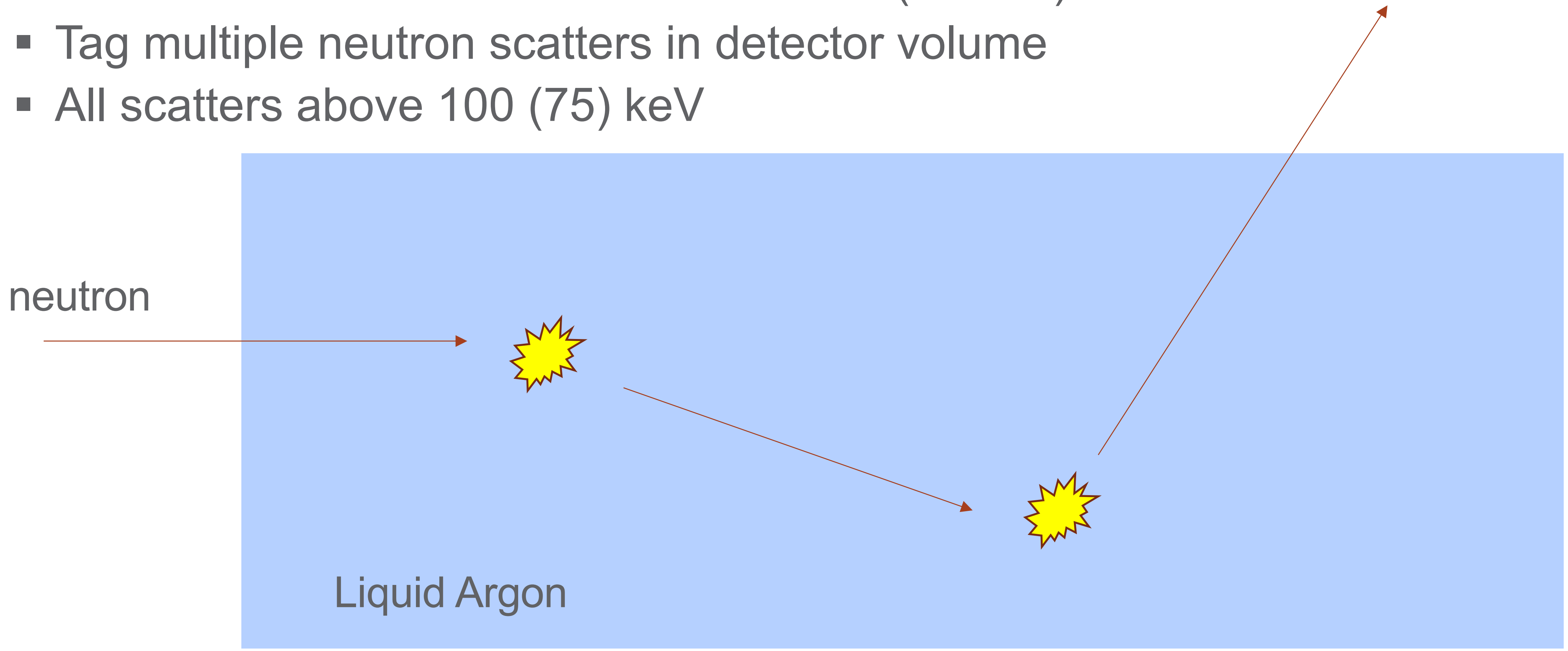
- Shielding
  - 40 cm of water shielding around detector
    - ✓ As proposed in 'Developing the MeV potential of DUNE: Detailed considerations of muon-induced spallation and other backgrounds', Zhu, Li, Beacom, arXiv:1811.07912
    - ✓ ~3 order of magnitude reduction
  - Detailed model of cryostat
    - ✓ 1.2 cm Stainless steel, 1 cm wood, 76cm polyurethane foam, 1.2 cm SS.
  - 5 cm acrylic around fiducial volume, inside argon



arXiv:1811.07912

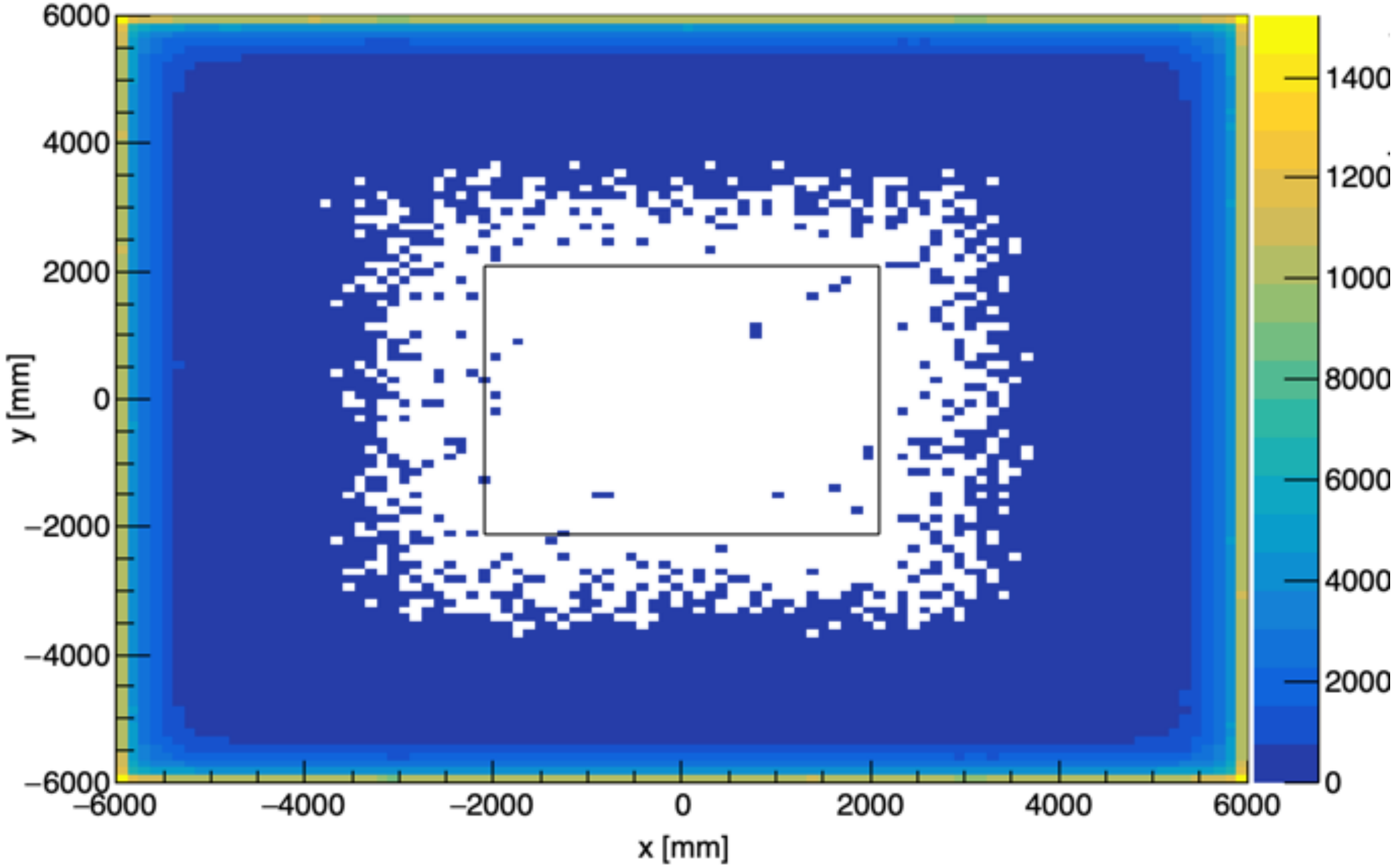
Neutron Background Reduction

- Multi-site rejection
  - TPC has excellent transverse resolution (20 mm)
  - Tag multiple neutron scatters in detector volume
  - All scatters above 100 (75) keV



~30% reduction at 100 keV
~90% reduction at 50 keV

Neutron Background Rejection



Neutron interactions above 100 keV from stainless steel
15 ktyr exposure

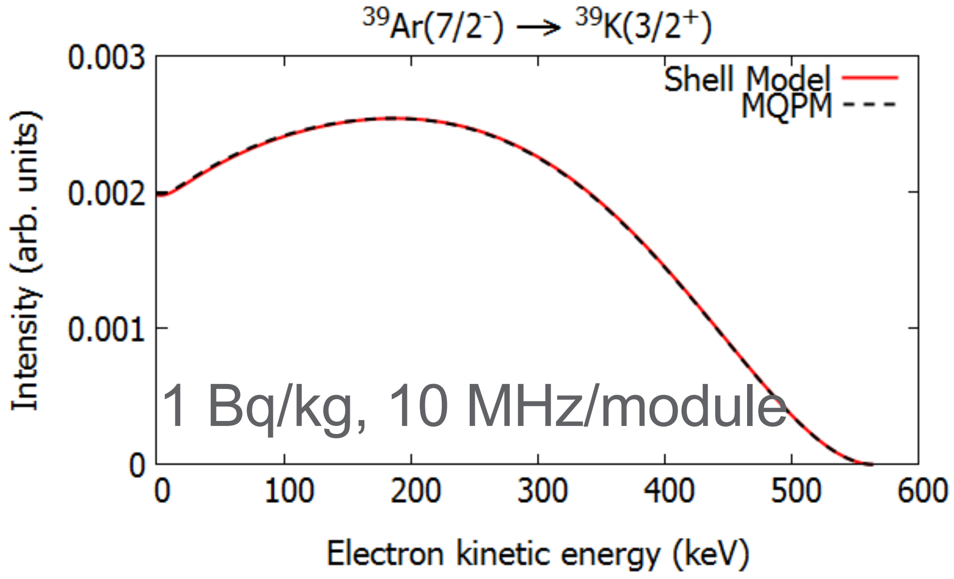
Significant argon self shielding

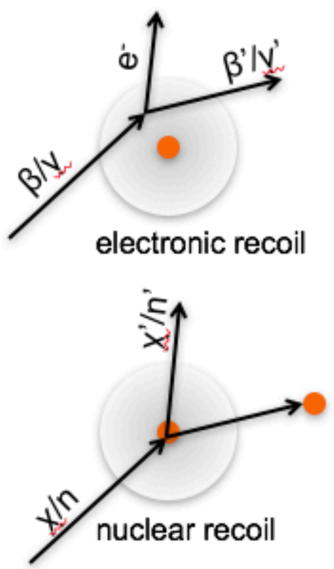
- 1.0 x 10^{-5} n/cm^2/s from rock
- 2.0 * 10^{-9} n/cm^3/s from cryostat steel cold wall
  - (DarkSide: 4.2 x 10^{-11} n/cm^3/s)
  - (LZ: 2.7 x 10^{-11} n/cm^3/s)
- 100 (75) keV threshold
- External neutrons
  - 0.1 (1.6) counts/3 kt.yr
- SS neutrons
  - 1.02 (14.2) counts/3 kt.yr

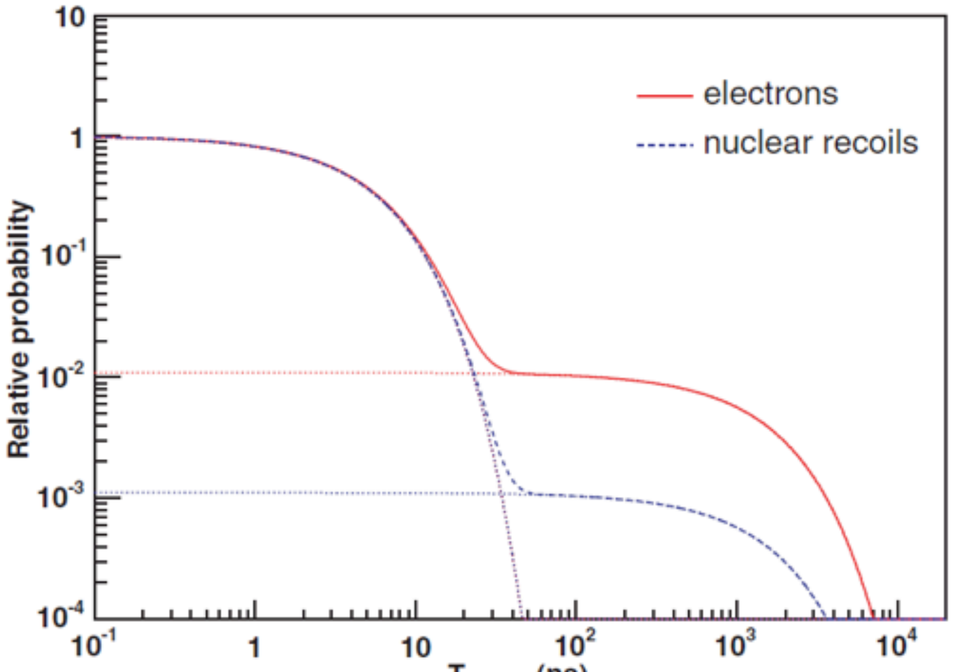
Electron/Gamma Background Reduction

- Direct reduction of Argon-39
  - Low Radioactivity Underground Argon

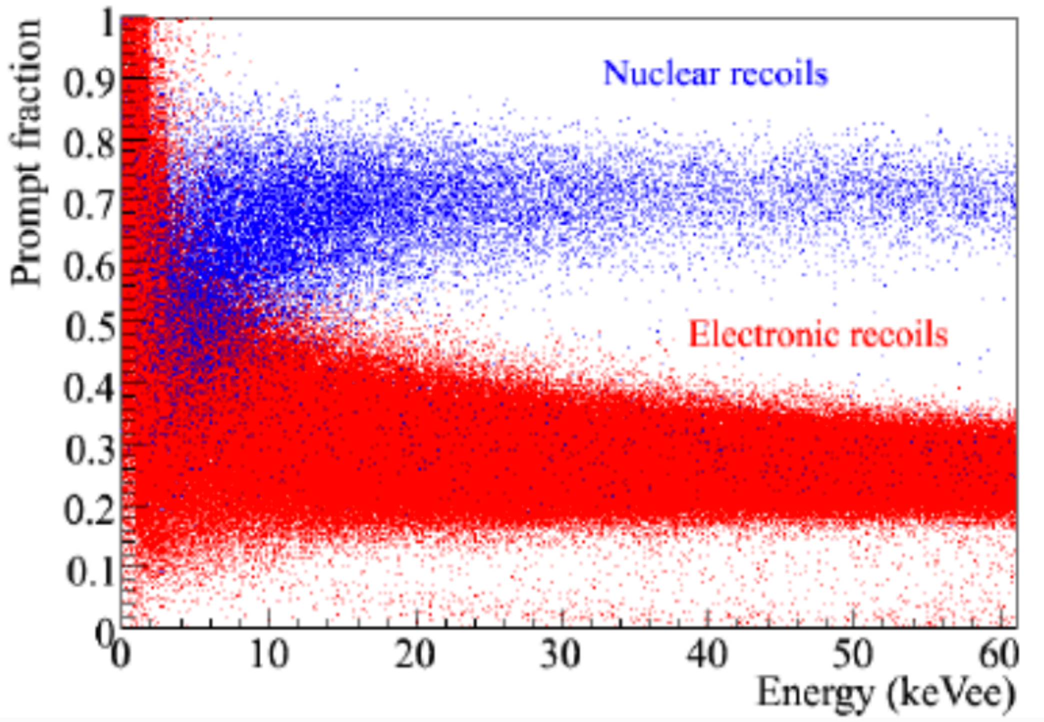
- Pulse Shape Discrimination







Boulay and Hime, Astropart. Phys. 25 (2006) 179

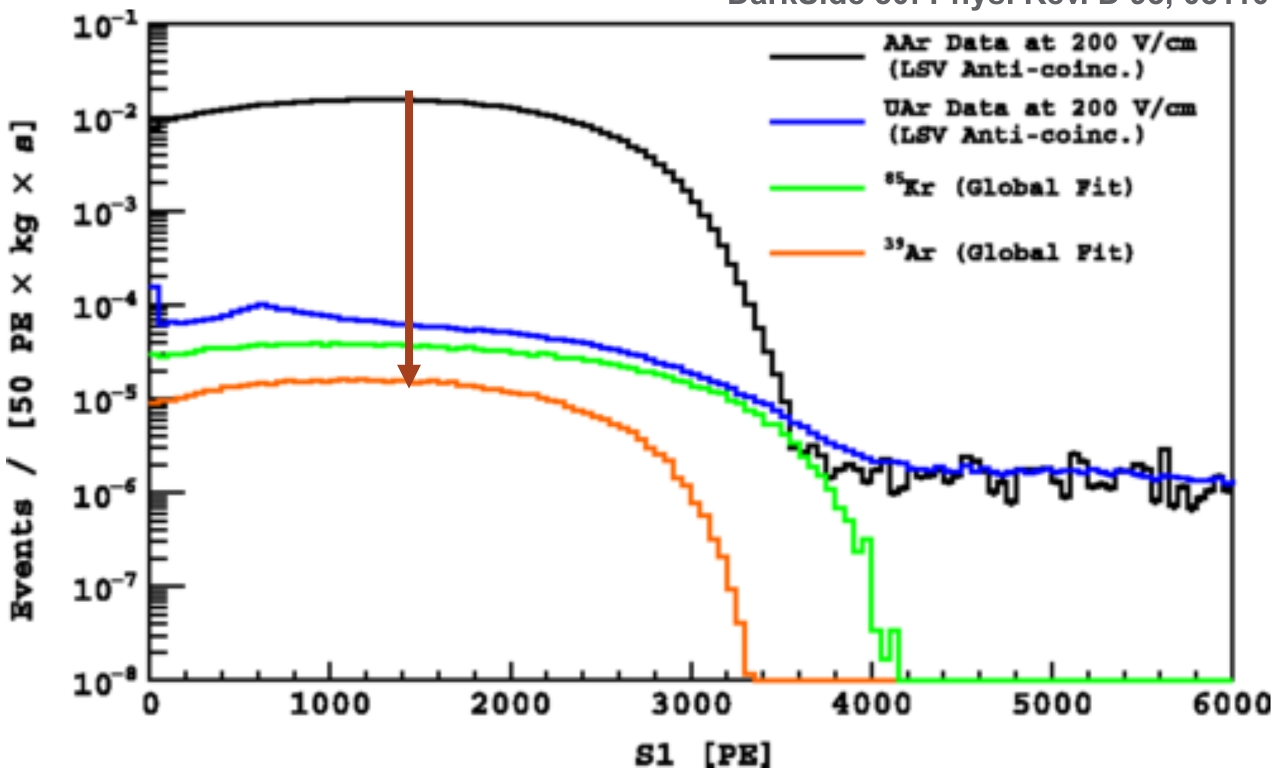


MicroCLEAN Phys. Rev. C78, 035801 (2008)

Low-Radioactivity Underground Argon

- DUNE ^{39}Ar:
  - Atmospheric Ar: 1 Bq/kg, 10 MHz/module
- Underground sources of depleted argon exist
  - Demonstrated in DarkSide-50 (1400x reduction)
  - From $C0_2$ wells in Cortez, CO
  - Planned for DarkSide-20k and GADMC
  - Not large enough for a DUNE module!

DarkSide 50: Phys. Rev. D 93, 081101(R)



1400 lowering in ^{39}Ar rate

Assume DarkSide-50 activities of ^{39}Ar

Low-Radioactivity Underground Argon

- PNNL working to explore large scale underground argon sources
  - **Supplier:** Major U.S. gas producer/supplier *(not disclosed at company request)*
  - **Production rate:** ~5,000 tonnes/year
  - **Ballpark cost:** Could be as low as x3 regular argon

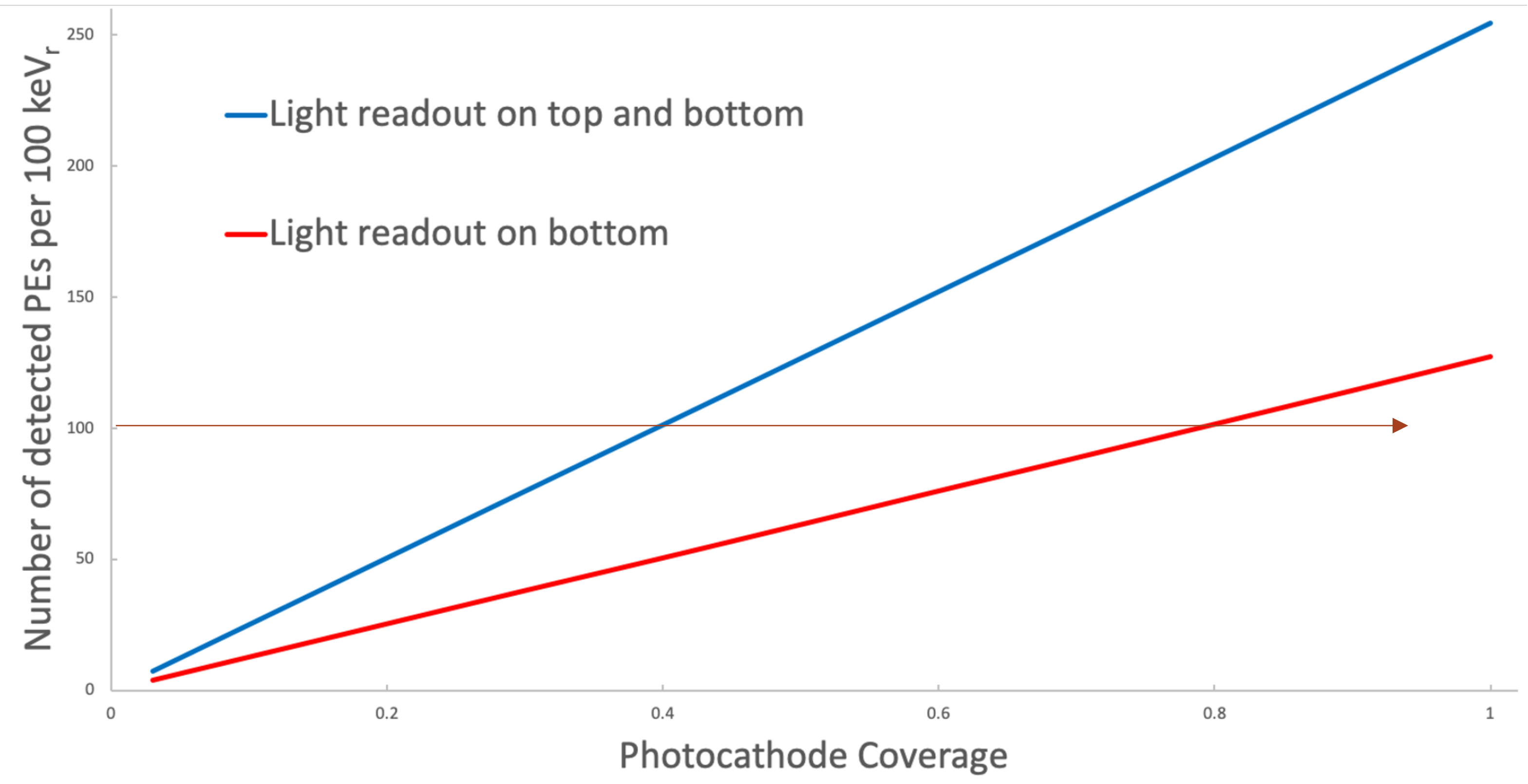
  NOTE: These are very rough estimates.

  Further refinement require expression of true interest from DUNE

- Next steps for physics:
  - Reminder: DarkSide source is the only proven source (i.e., extremely low ^{39}Ar)
  - Measure ^{39}Ar levels from new potential source
  - For ^{42}Ar level, new assay method required – expected to be VERY low

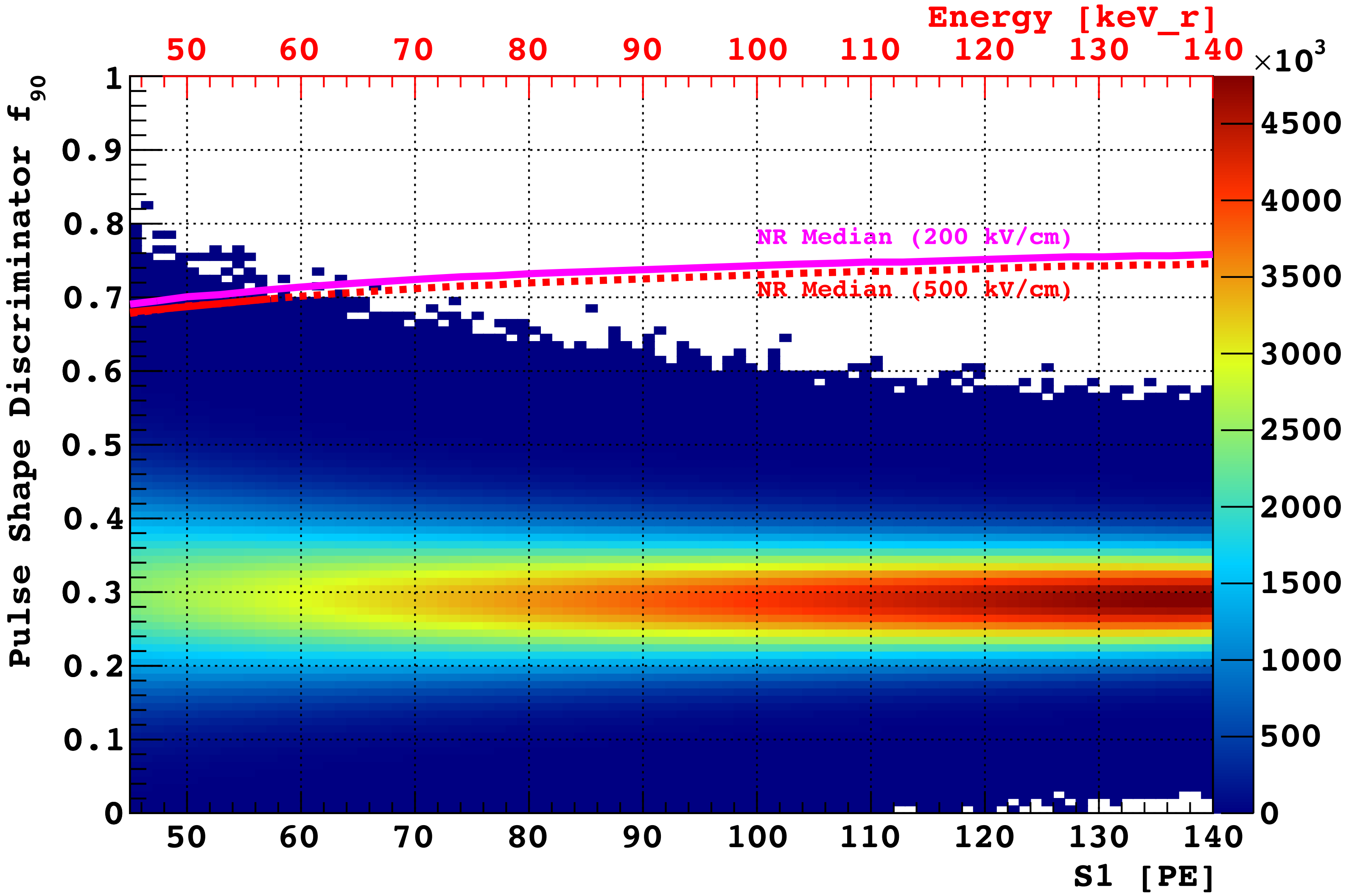
Photon Counting

- Target: 100 photons for PSD
- Extrapolations from SCENE experiment at 500 V/cm:
  - 1250 photoelectrons per 100 keV
- Baseline DP photodetection:
  - 720 PMTs on base
  - 2.5 PE/MeV
- Upgrades to make 100 photons:
  - Reflective foils (97% reflectance)
  - Increased photon detector packing
  - SiPMs (45% QE)
  - ppb levels of impurities



~3600 DarkSide-20k style
12x12 cm SiPM tiles

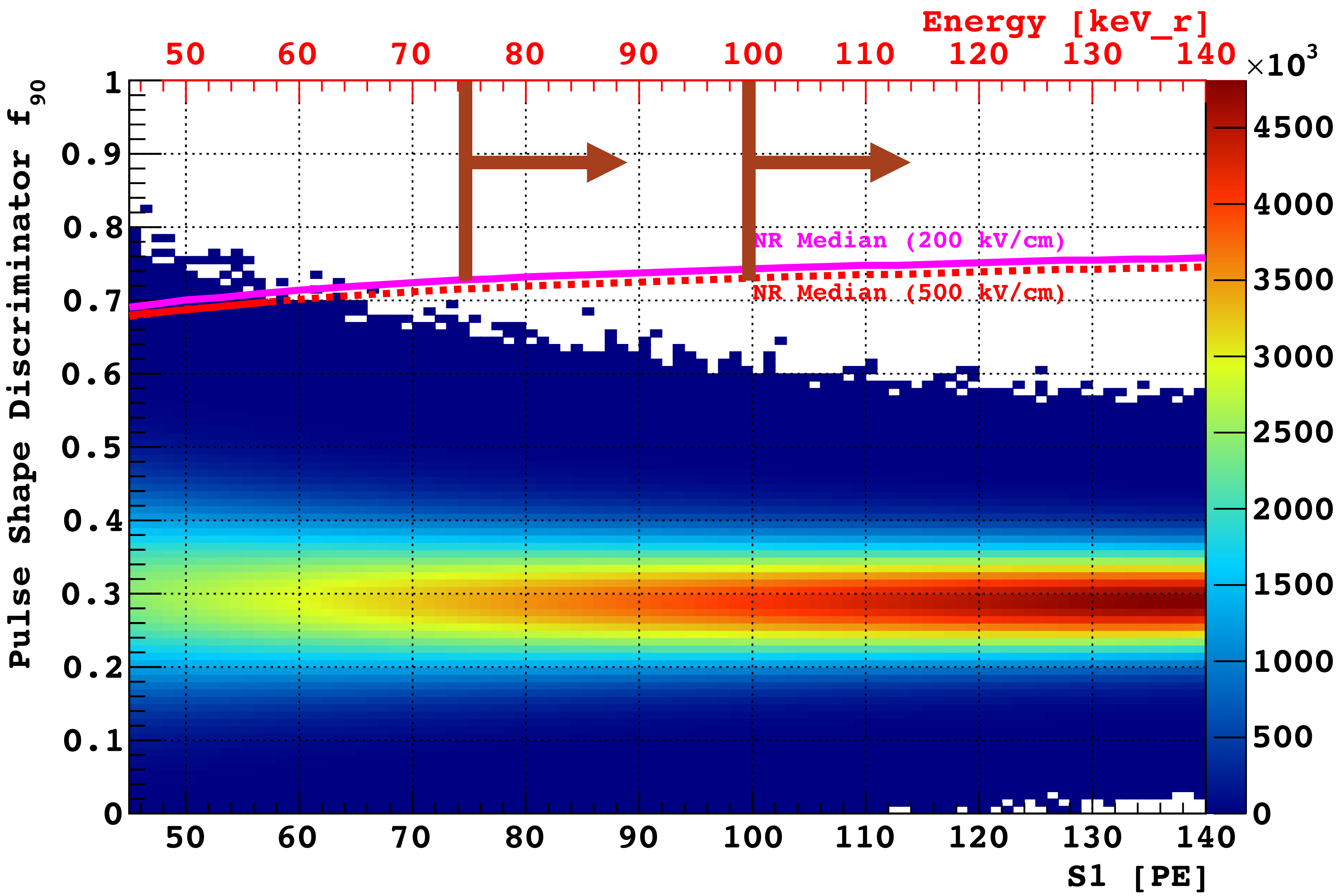
Pulse Shape Discrimination



3 kton.yr simulated exposure, 7.3 x 10^{-4} Bq/kg
100 (75) keV threshold: 0 (1) events

- Pulses shape discrimination variable (F90) vs scintillation light (S1)
- MC simulation code, Poisson distributed photons for prompt (<90 ns) and late (>90 ns)
  - Nuclear recoil scintillation yield quenching and F90 medians from SCENE experiment
  - Electron recoil scintillation yield quenching from SCENE and F90 medians from DarkSide-50

Pulse Shape Discrimination



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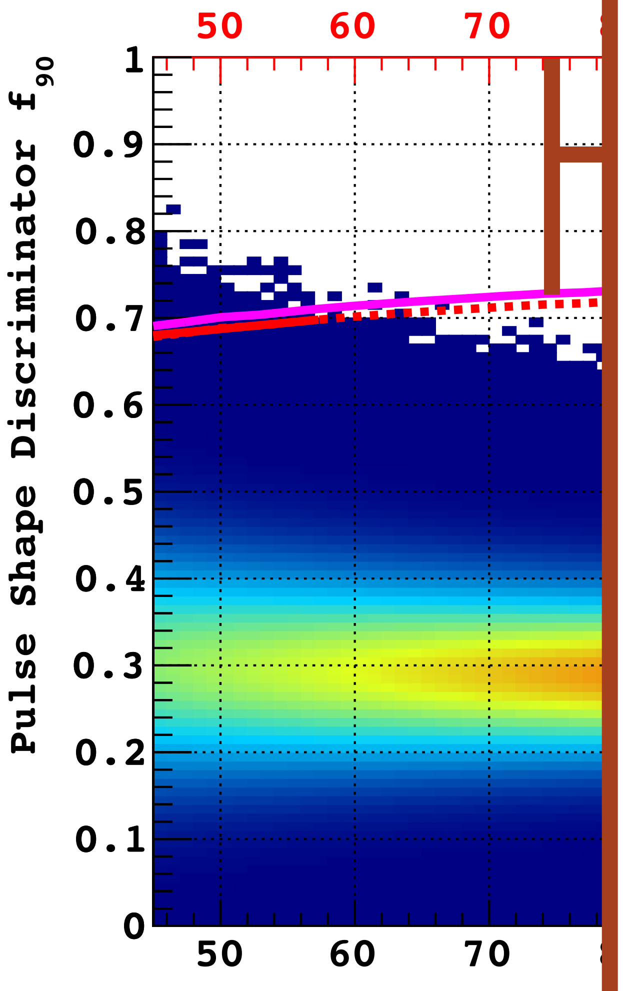
10^{10} PSD Required
~Levels in DEAP-3600

Pulse Shape Discrimination

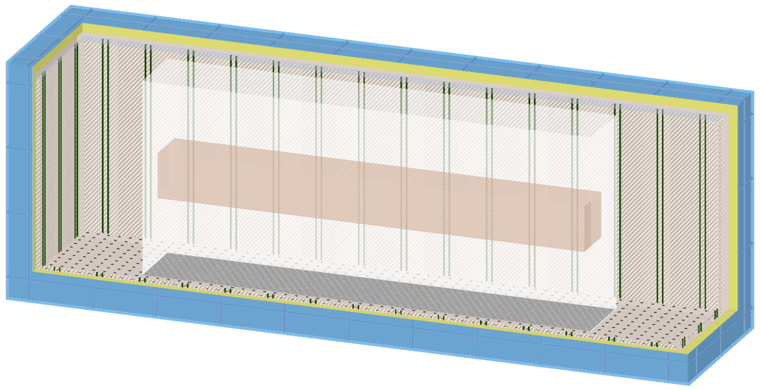


Note on Pileup:

With argon-39 activity of 3.1 kBq within acrylic inner volume -> average of 12 pileup events.

Solution:

- Pattern recognition to associate S1 and S2 light pulses.
- Alternatively, can further segment inner volume into with acrylic/reflector dividers



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Levels in DEAP-3600

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100 (75) keV threshold: 0 (1) events

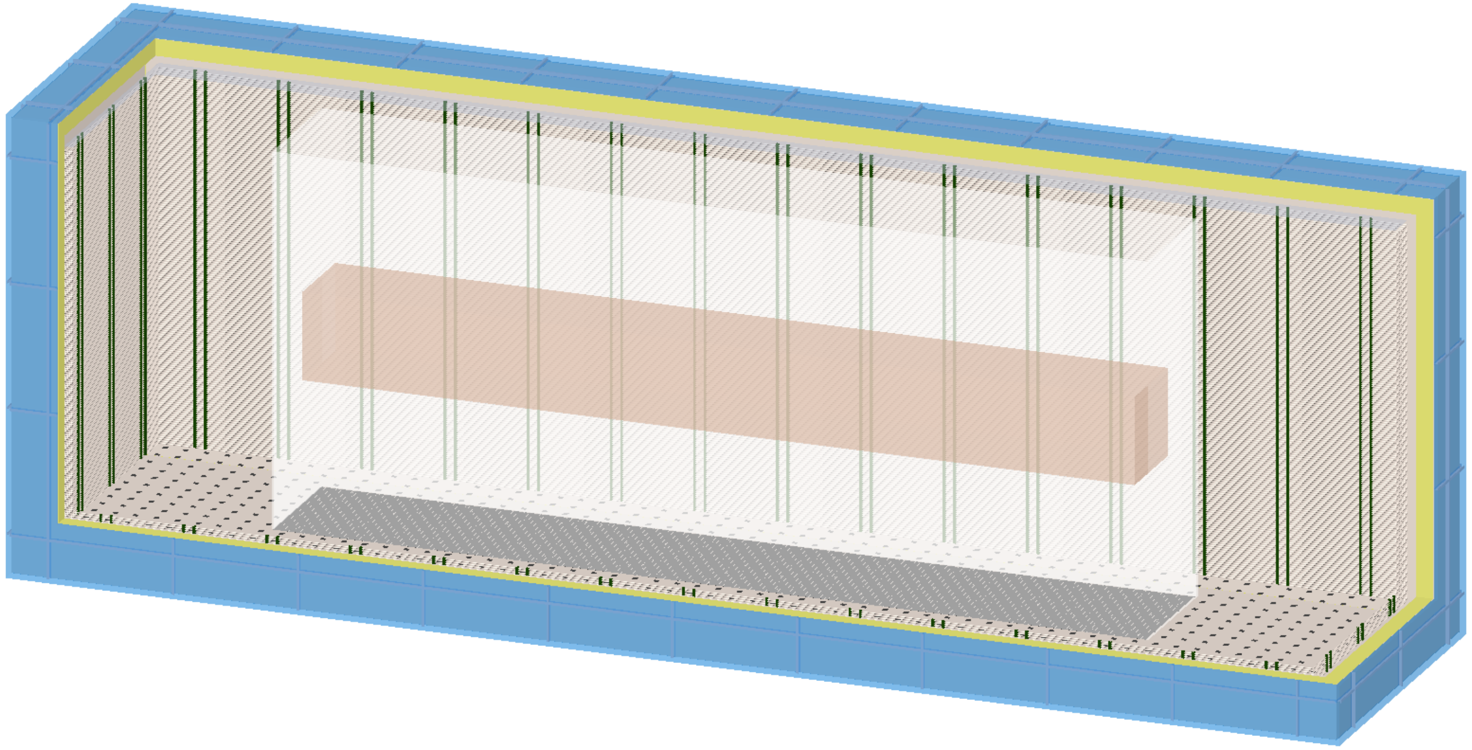
External Gammas

- Manage with:
  - Argon self-shielding
  - Pulse shape discrimination

- Tested with 1.4 MeV and 2.6 MeV gammas from ^{40}K and ^{208}Tl

- 1 Bq/kg ^{40}K and 10 mBq/kg ^{232}Th in G-10 circuit board

- 10 ppt ^{232}Th in acrylic (SNO levels)



Background	Amelioration strategy		Counts/3 kt-yr 100 keV$_r$	75 keV$_r$	50 keV$_r$*
^{40}K gammas from detector top	self-shielding, PSD	bPSD:		< 4.3	
		aPSD:	0	0	0
^{208}Tl gammas from detector top	self-shielding, PSD	bPSD:		< 30	
		aPSD:	0	0	0
^{208}Tl gammas from acrylic	PSD	bPSD:	8.1×10^4	8.5×10^4	8.9×10^4
		aPSD:	0	0	0

Radon Daughters

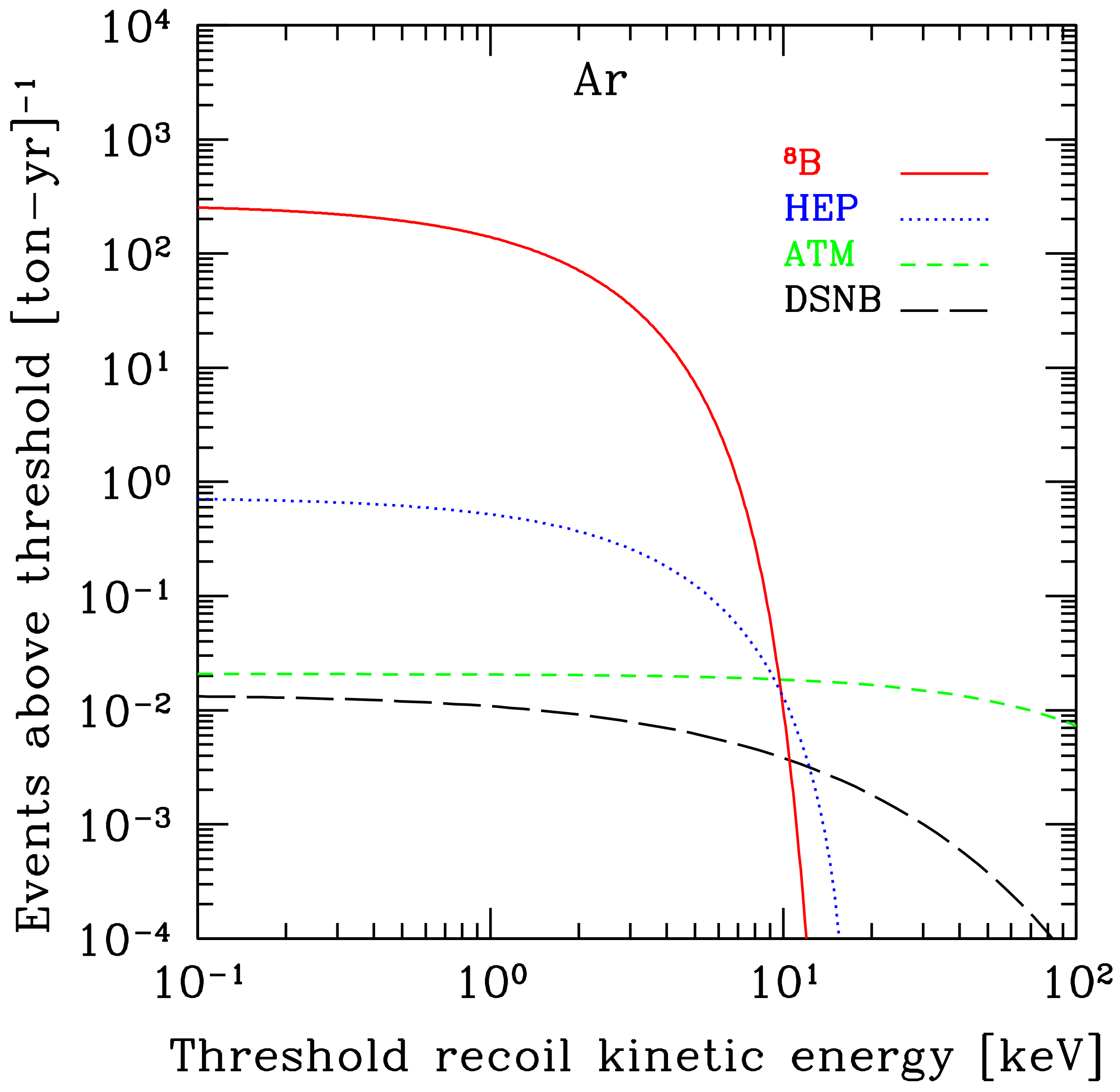
- Assumed: 2 µBq/kg
  - Note: DUNE is targeting 0.1-1 mBq/kg
  - Achieved by DarkSide-50
  - DEAP-3600: 0.2 µBq/kg
  - Will require inline cryogenic radon trap
- Radon Daughter Backgrounds:
  - ^{214}Pb betas (Q=1.024 MeV)
    - ✓ 1.9 x 10^{8} events
    - ✓ <1 % ^{39}Ar, removed by PSD
  - Radon plate-out will be important (e.g. (alpha, n) on ^{13}C in acrylic)
    - ✓ Assumed will be managed during construction
  - ^{40}Ar(alpha,n)
    - ✓ 1.5 x 10^{4} neutrons/17.5 ktons.yr, 3% give single scatters
    - ✓ Tag > 5 MeV alphas directly? Tag ^{43}Ca excited state?
    - ✓ Assumed 0

Neutrino Backgrounds

- This detector will be sensitive to atmospheric neutrinos at the coherent neutrino floor.

- 10 events (100 keV)
- 13 events (75 keV)
- 17 events (50 keV)

- Dominating background



arXiv:0903.3630 [astro-ph.CO], Strigari

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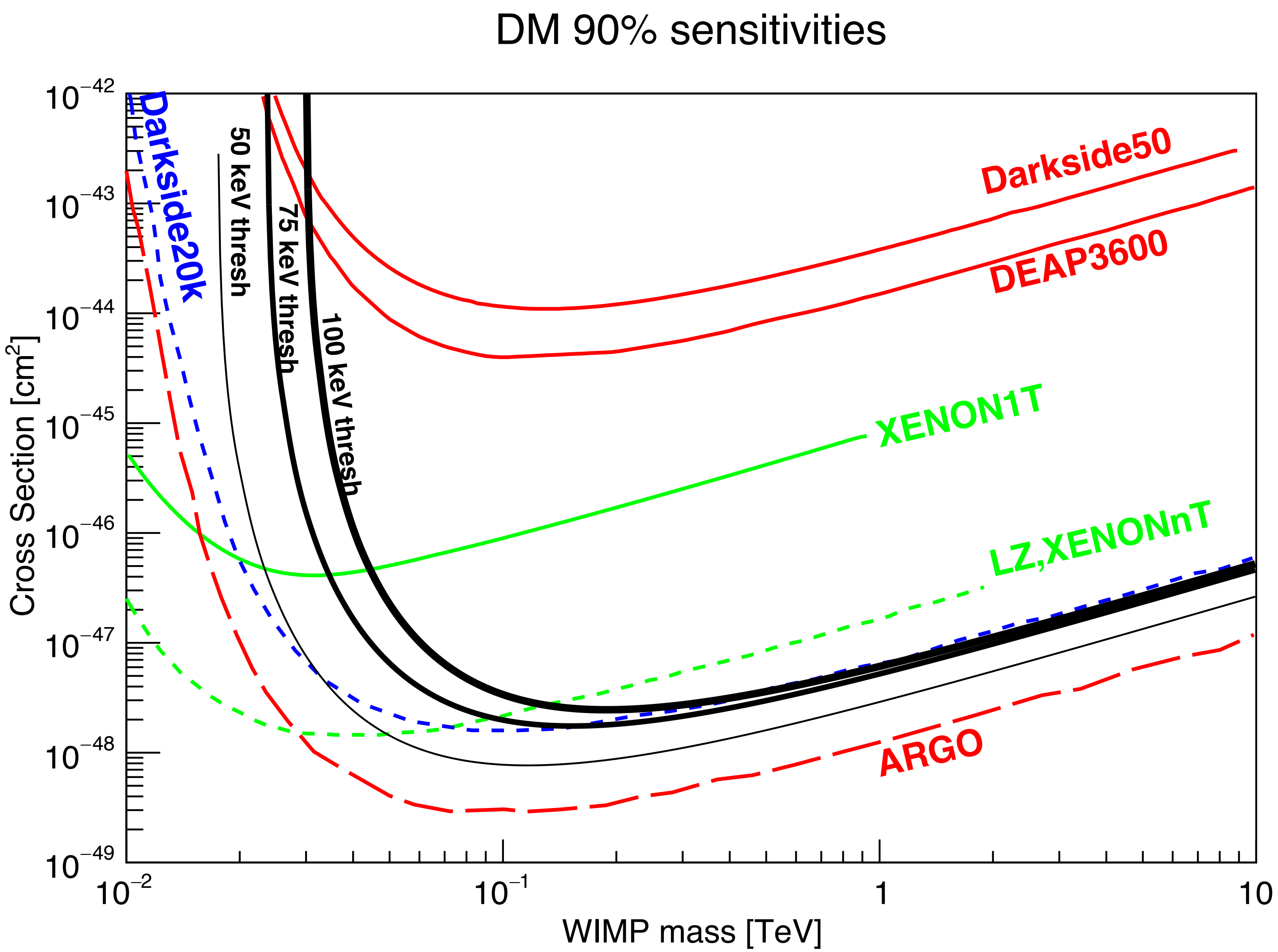
Background Summary

Background	Amelioration strategy		Counts/3 kt-yr		
			100 keV_r	75 keV_r	50 keV_r*
neutrons from external rock	external 40 cm water self-shielding, multi-site rej.		0.1	1.6	13
neutrons from cold cryoskin steel	self-shielding, acrylic, multi-site rej.		1.02	14.2	2
^{40}K gammas	self-shielding, PSD	bPSD:		< 4.3	
from detector top		aPSD:	0	0	0
^{208}Tl gammas	self-shielding, PSD	bPSD:		< 30	
from detector top		aPSD:	0	0	0
^{208}Tl gammas	PSD	bPSD:	8.1×10^4	8.5×10^4	8.9×10^4
from acrylic		aPSD:	0	0	0
^{214}Pb	PSD	bPSD:		$< 1.9\times10^8$	
from radon		aPSD:	0	0	0
^{40}Ar(α, n) from radon	coincident tagging (see Section 3.5)		0	0	0
^{39}Ar betas	UAr, PSD	bPSD:	1.6×10^{10}	1.7×10^{10}	1.8×10^{10}
in argon		aPSD:	0	1	1
atmospheric neutrinos	none		10	13	17
Total			11	30	33

Dark Matter Sensitivity



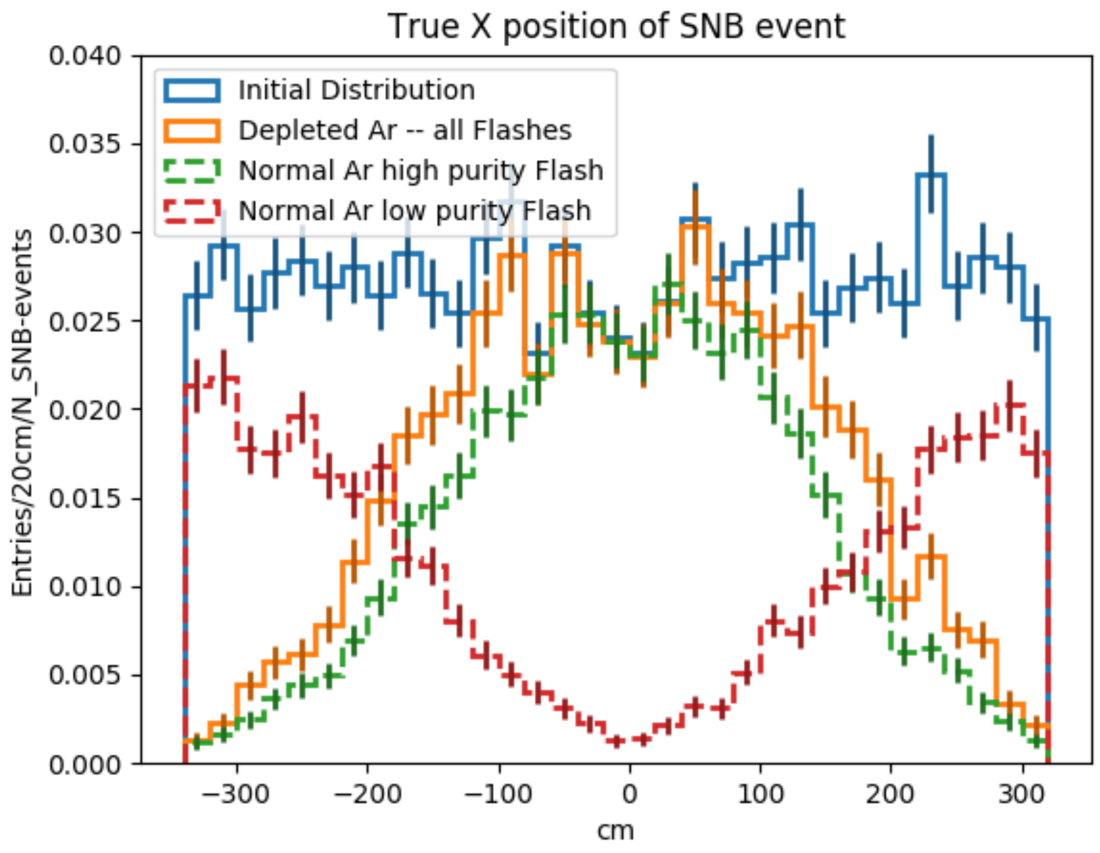
What else can this module do?

- Reduced ^{39}Ar
  - Lower data rates
  - Improved flash finding for T0 in non-beam events
- Reduced neutrons backgrounds
  - Low energy supernova events
  - Diffuse Supernova Neutrino Background
  - Can this module be a supernova trigger?
  - Solar neutrinos – hep detection,
- Improved light collection
  - Coherent neutrino scattering?
  - Beam physics?
  - Rare decays?

Aside: a generic benefit of depleted Ar – flash-track matching is unambiguous

This figure shows that in default design of the single phase detector there are no longer low purity flashes for Supernovae (Marley) events when depleted argon is used. Normally this is a problem at high x.

With depleted Ar one is not faked out by the ^{39}Ar flashes.



Data Rates – Trigger Primitives rate would shrink with depleted Ar

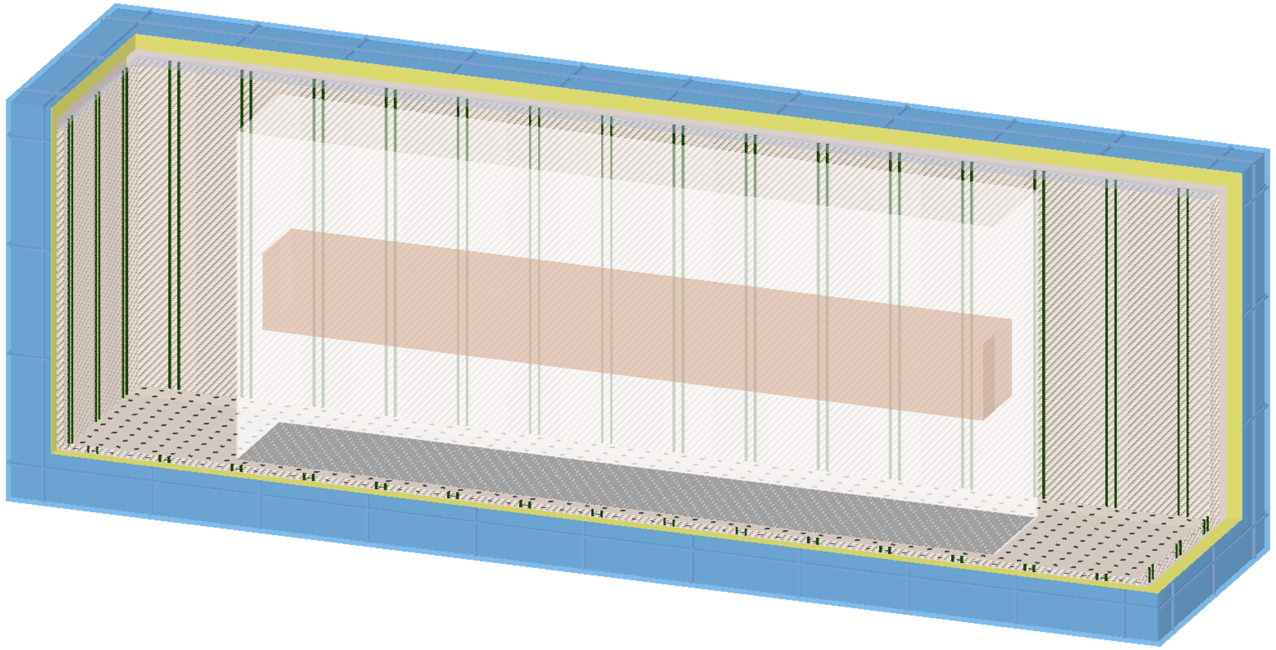
Table 3.1: Anticipated annual, uncompressed data rates for a single SP module (from the SP module IDR volume). The rates for normal (non-SNB triggers) assume a readout window of 5.4 ms. In reality, lossless compression will be applied which is expected to provide as much as a $4\times$ reduction in data volume for each SP module.

Event Type	Data Volume PB/year	Assumptions
Beam interactions	0.03	800 beam and 800 rock muons; 10 MeV threshold in coincidence with beam time; include cosmics
Supernova candidates	0.5	30 seconds full readout, average once per month
Cosmics and atmospherics	10	10 MeV threshold
Radiologicals (^{39}Ar and others.	$\leq$1	fake rate of $\leq$100 per year
Front-end calibration	0.2	Four calibration runs per year, 100 measurements per point
Radioactive source calibration	0.1	source rate $\leq$10 Hz; single fragment readout; lossless readout
Laser calibration	0.2	1×10^6 total laser pulses, lossy readout
Random triggers	0.06	45 per day
Trigger primitives	$\leq$6	all three wire planes; 12 bits per primitive word; 4 primitive quantities; ^{39}Ar-dominated

Would become tens of TB.

Summary

Next steps:
SNOWMASS and Module of Opportunity Concept Papers



- DUNE low background module:
  - Dual phase
  - Increased shielding
  - Fiducialization
  - Low radioactivity underground argon
  - Increased photon detection

- Physics benefits:
  - WIMP Dark Matter detection
  - Supernova and solar neutrinos
  - See talks from this review by Dan, Shirley, Thiago, Gleb that show that every MeV we can drop the current 8-12 MeV trigger requirement quickly buys more physics potential for the DUNE program.

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Thank you