Pacific Northwest
NATIONAL LABORATORY

Building low background kton-scale liquid argon time projection chambers for physics discovery

March 18, 2021

Chris Jackson
PNNL

U.S. DEPARTMENT OF ENERGY BATTELLE

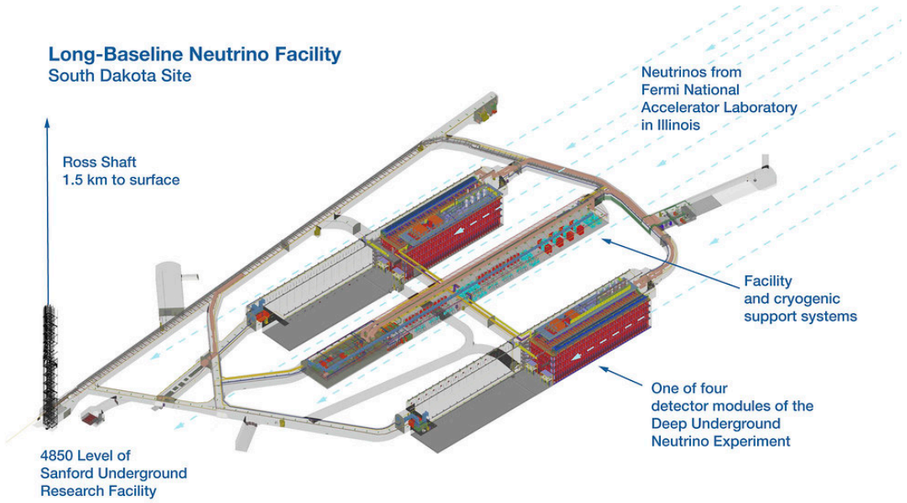
PNNL is operated by Battelle for the U.S. Department of Energy

Introduction

- Value in making experiments multipurpose

- Next-generation neutrino physics LArTPCs have thresholds of ~ 5-10 MeV
- Significant new physics at ~1 MeV or keV scales
  - Neutrino astrophysics, dark matter, coherent elastic neutrino-nucleus scattering,…

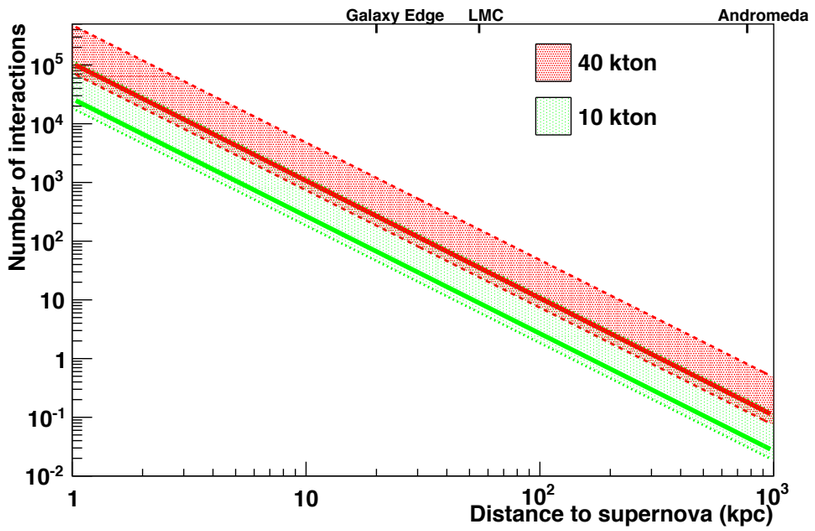
- Potential upgrades to a next-generation (DUNE-like) detector
  - Lower radioactive backgrounds
  - Lower energy thresholds
  - Instrument more densely
  - Do all this without perturbing the main physics goals



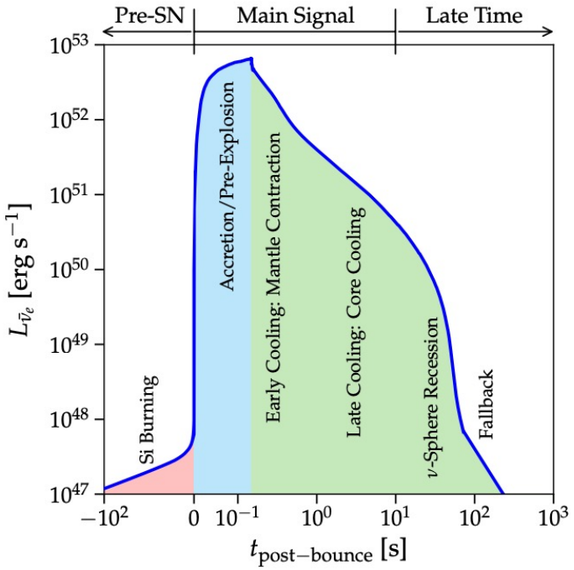
Supernova Burst Neutrinos

- Neutron captures are significant background to low energy neutrino events
  - n + $^{40}Ar \rightarrow {}^{41}Ar^*$ (6.1 MeV de-excitement)
  - n + $^{36}Ar \rightarrow {}^{37}Ar^*$ (8.8 MeV de-excitement)
- Neutron sources include (α,n) from ^{238}U and ^{232}Th in cavern rock, shotcrete, support structure steel, detector components and radon.

Neutrons can mask distant supernovas



Supernova Neutrino Burst Detection with the Deep Underground Neutrino Experiment, Abi et al., arXiv:2008.06647

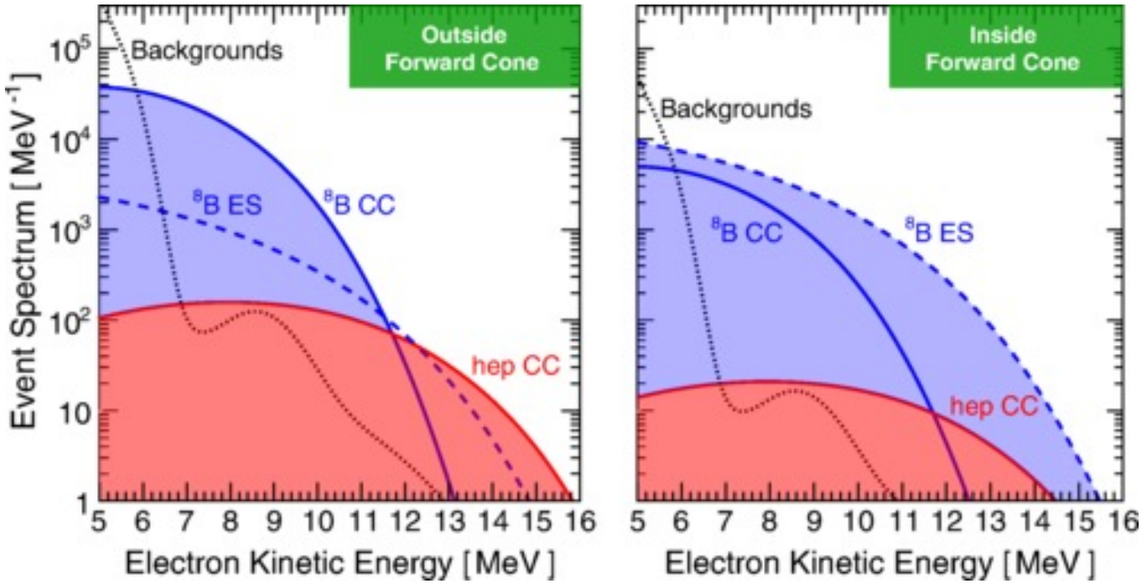


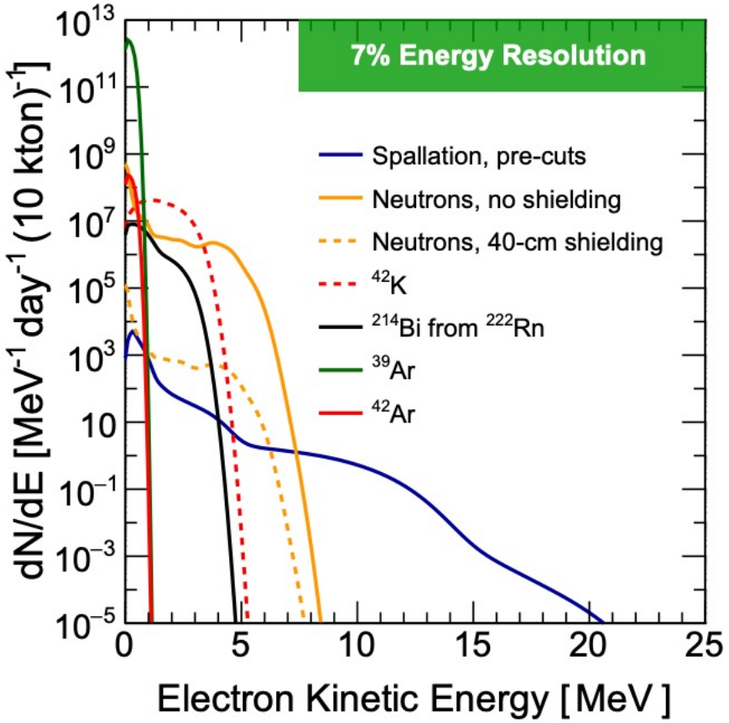
Exciting prospects for detecting late-time neutrinos from core-collapse supernovae, S. Li, L. F. Roberts, and J. F. Beacom, Phys. Rev. D 103, 023016

Neutrons can mask interesting late-time information

Solar Neutrinos

- Neutron captures are significant background to low energy neutrino events
- Beta/gamma events from internal argon backgrounds set threshold
  - ^{42}Ar and ^{42}K
  - ^{39}Ar





DUNE as the Next-Generation Solar Neutrino Experiment, F. Capozzi, S. W. Li, G. Zhu, and J. F. Beacom, Phys. Rev. Lett. **123**, 131803 and supplemental material

What would it take to turn a detector similar to DUNE into a Direct Dark Matter search experiment?

Dark matter detection capabilities of a large multipurpose Liquid Argon Time Projection Chamber, E. Church, C.M. Jackson and R. Saldanha, 2020 *JINST* **15** P09026

What would it take to turn a detector similar to DUNE into a Direct Dark Matter search experiment?

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

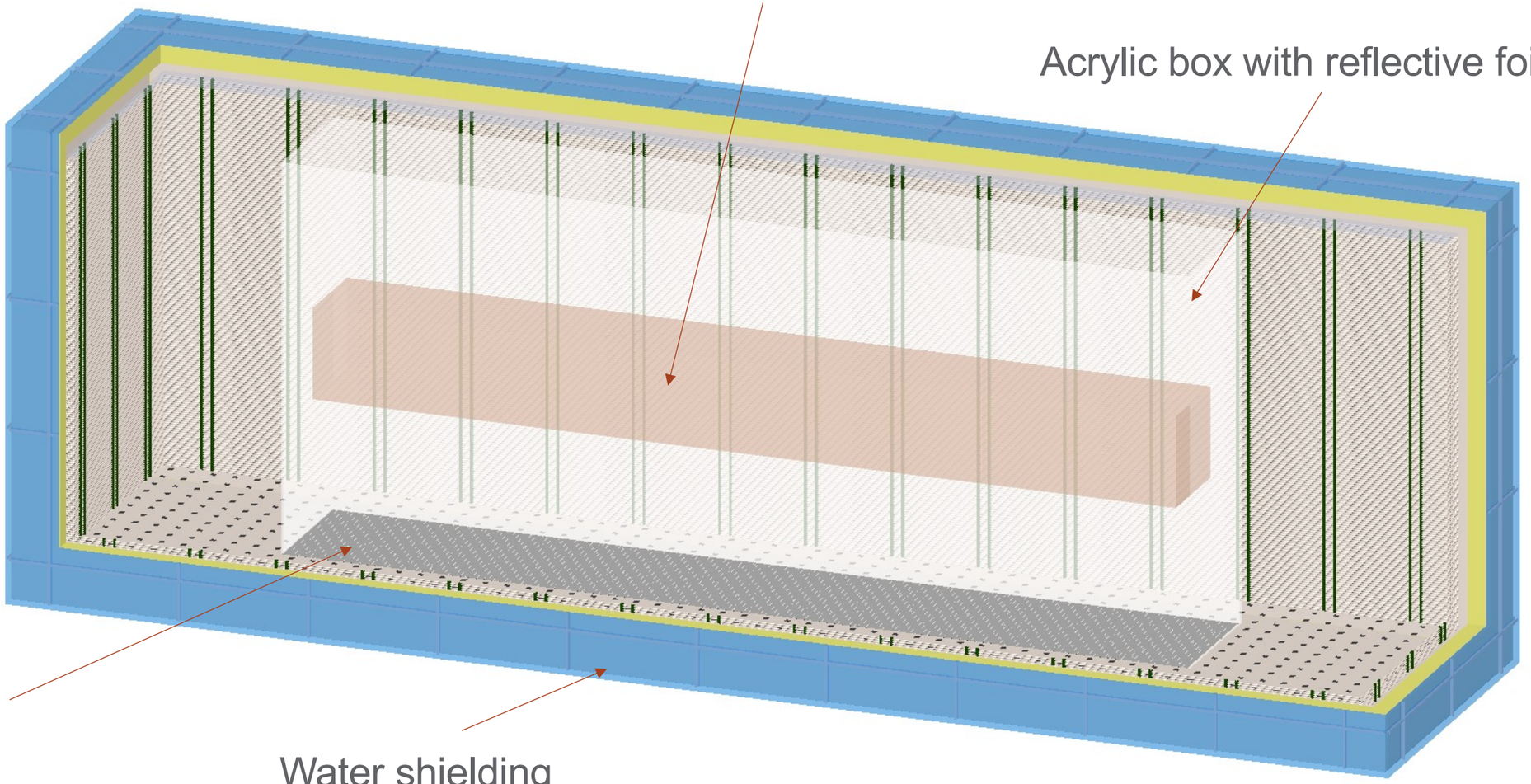
Dark matter detection capabilities of a large multipurpose Liquid Argon Time Projection Chamber, E. Church, C.M. Jackson and R. Saldanha, 2020 *JINST* **15** P09026

Low Background Module

- Large, empty volume such as dual-phase module
  - ✓ bulk argon, without internal components
  - ✓ Radiopurity
- Fiducialization
  - ✓ Inner 1 kTon to remove wall sources
- Additional Neutron shielding
  - ✓ Water and plastic
- High signal/noise from gas-multiplication readout
  - ✓ read small charge signals
- Enhanced Photon Detection System (PDS)
  - ✓ Reflectors
  - ✓ SiPMs
  - ✓ Increased coverage
  - ✓ Increased argon purity

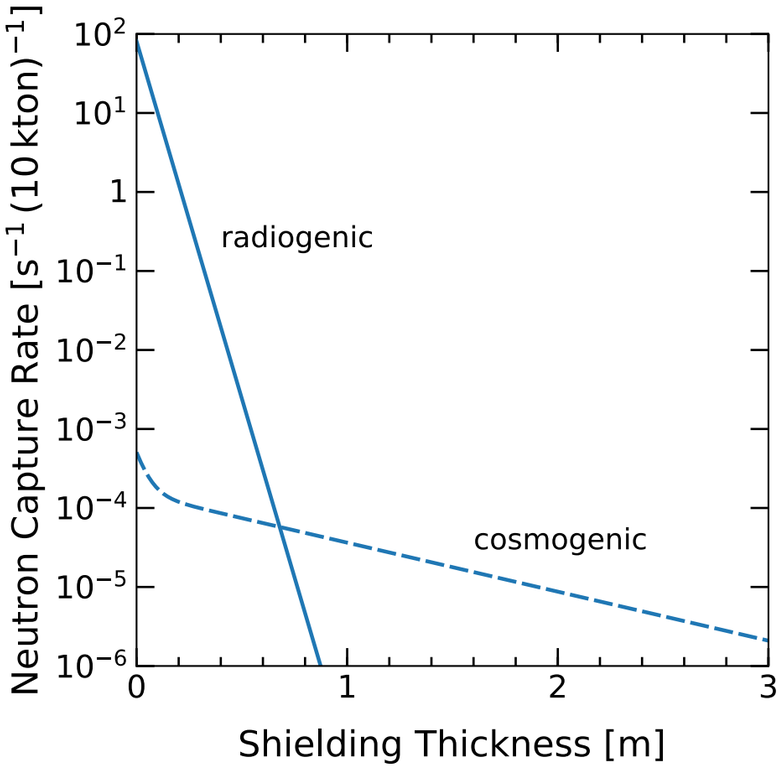
Low Background Module

Standard DUNE-like module



Neutron Backgrounds

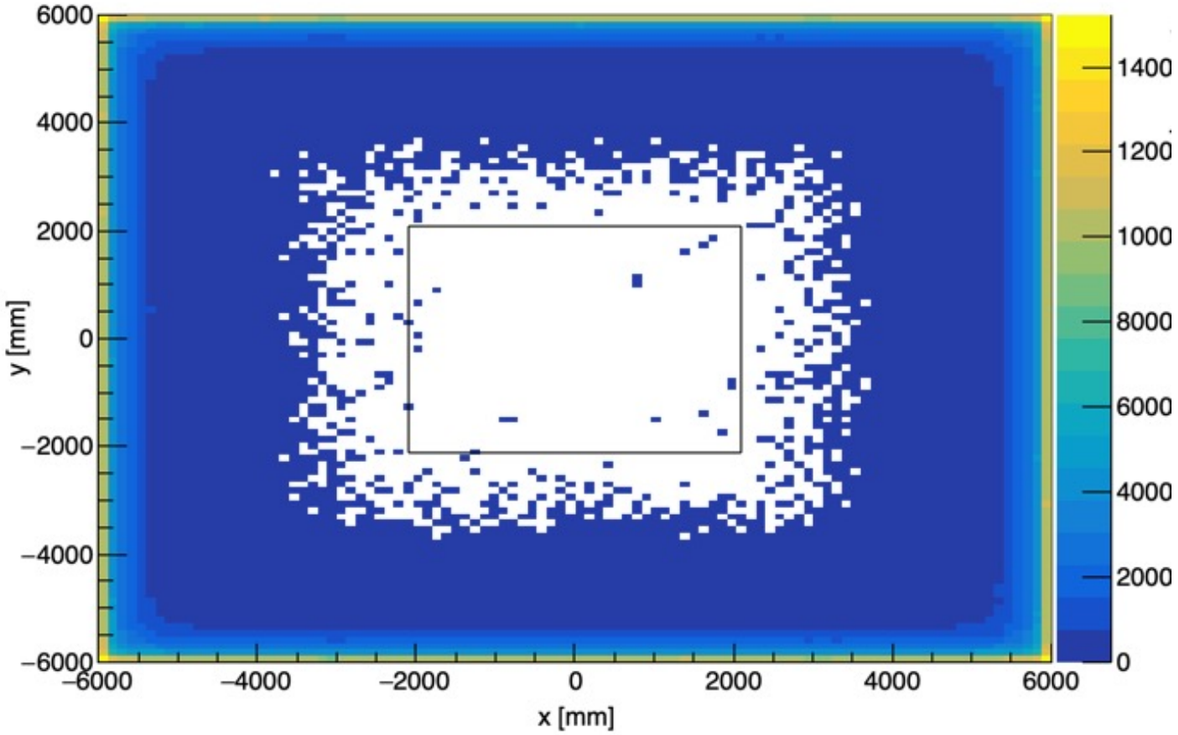
- Shielding
  - 40 cm of water shielding around detector
    - ✓ As proposed by Zhu, Li and Beacom
    - ✓ ~3 order of magnitude reduction
  - Detailed model of cryostat
    - ✓ 1.2 cm Stainless steel, 1 cm wood, 76cm polyurethane foam, 1.2 cm SS
    - ✓ Potential for additional attenuation
  - 5 cm acrylic around fiducial volume, inside argon

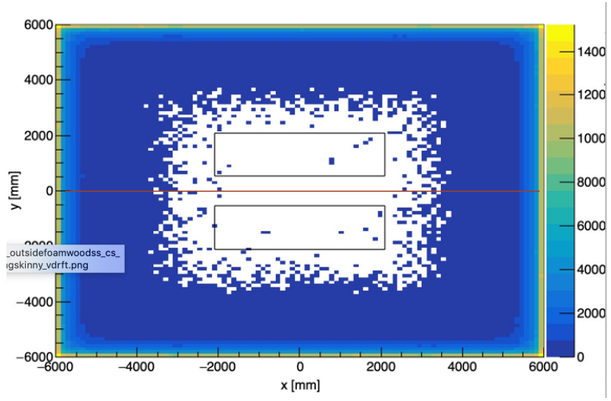


Developing the MeV potential of DUNE: Detailed considerations of muon-induced spallation and other backgrounds, G. Zhu, S. W. Li, and J. F. Beacom, Phys. Rev. C **99**, 055810

Neutron Backgrounds

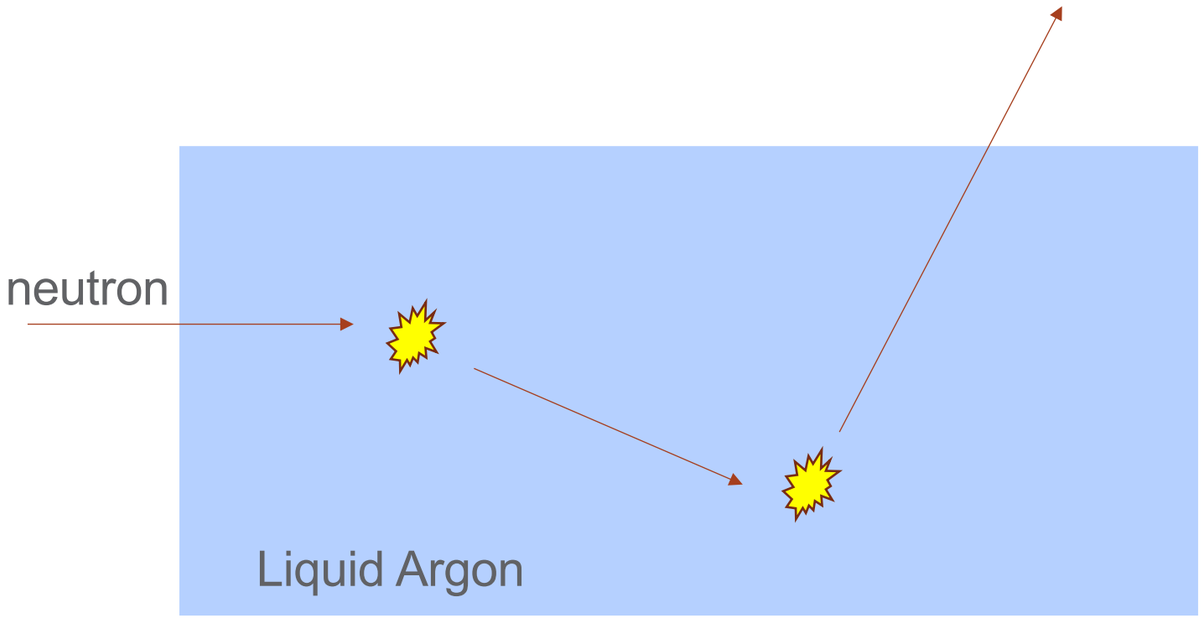
- Shielding
- Fiducialization
  - Significant self-shielding effect from argon
  - Also considering alternate geometries:





Neutron Backgrounds

- Shielding
- Fiducialization
- Analysis Cuts
  - TPC has excellent transverse resolution (20 mm)
  - Tag multiple neutron scatters in detector volume
  - All scatters above 100 (75) keV



Neutron Backgrounds

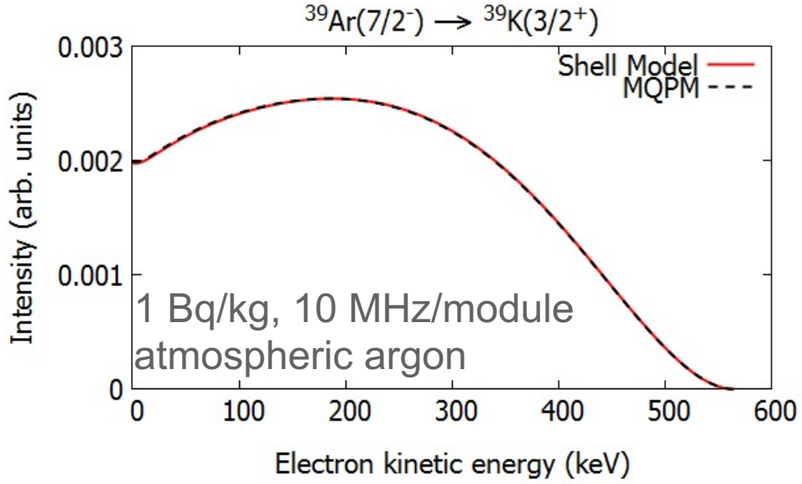
- Shielding
- Fiducialization
- Analysis Cuts
- Radiopurity control

- Internal detector components:
  - For example, stainless steel in cryostat
  - Need **~10^3** more radiopure than planned for default DUNE
  - But LZ/DarkSide expect further 2 orders of magnitude

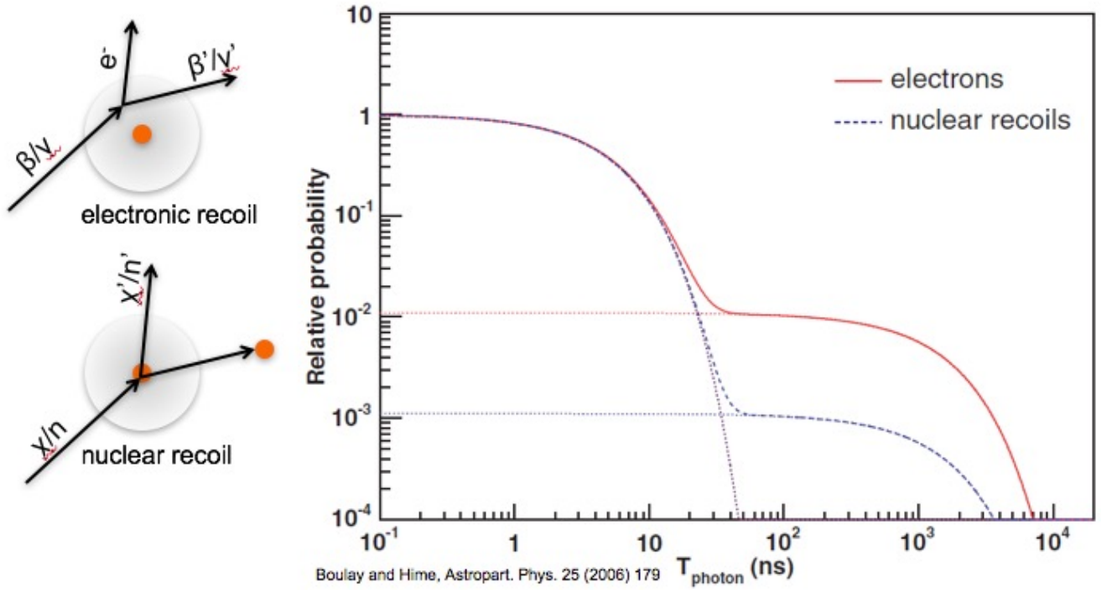
- Radon control
  - Assumed: 2 μBq/kg
  - Need **~10^2-10^3** reduction than planned for default DUNE
  - Achieved by DarkSide-50
  - DEAP-3600: 0.2 μBq/kg
  - Will require inline cryogenic radon trap

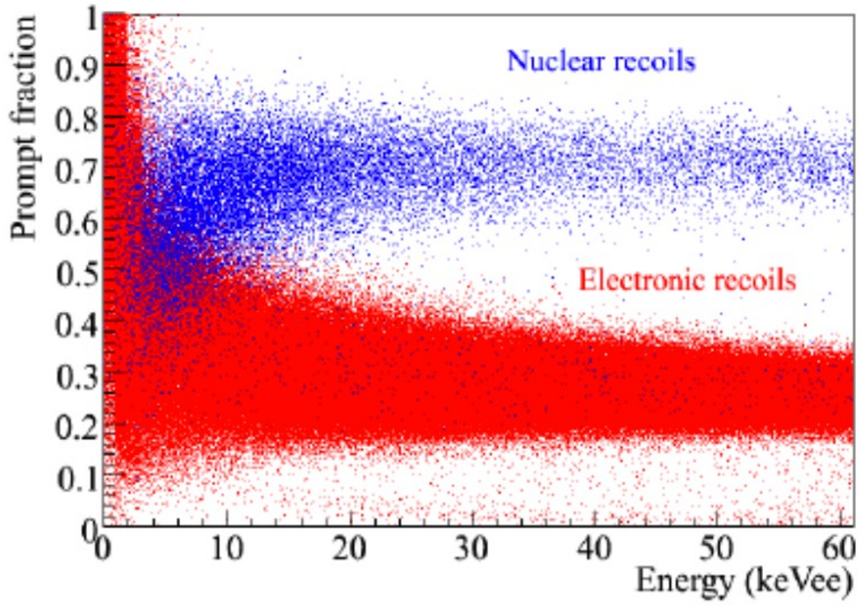
Electron/Gamma Backgrounds

- Direct reduction of Argon-39
  - Low Radioactivity Underground Argon
  - Factor 1400 demonstrated in DarkSide-50



- Pulse Shape Discrimination

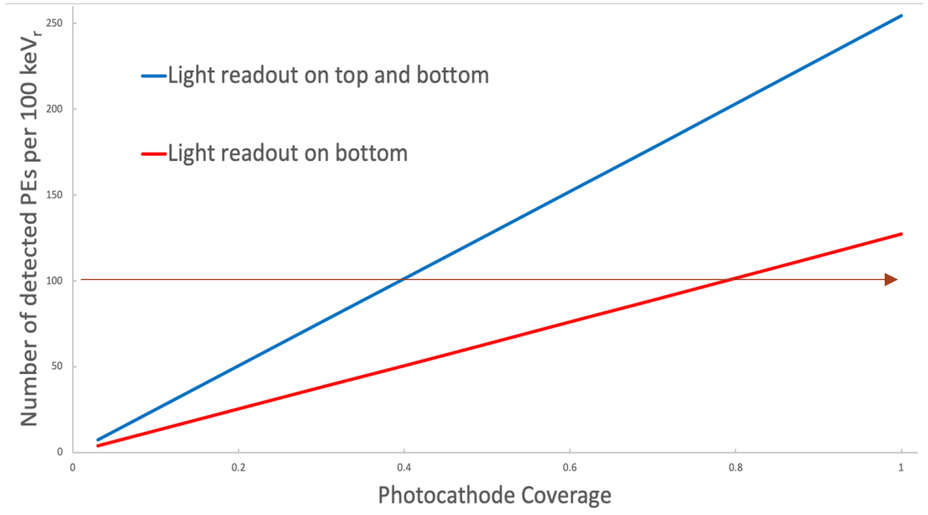


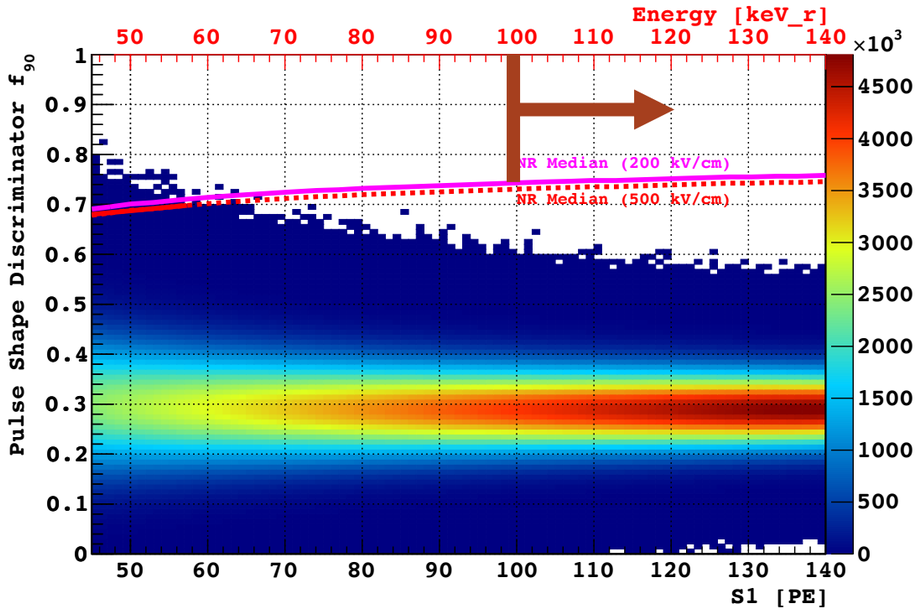


MicroCLEAN Phys. Rev. C78, 035801 (2008)

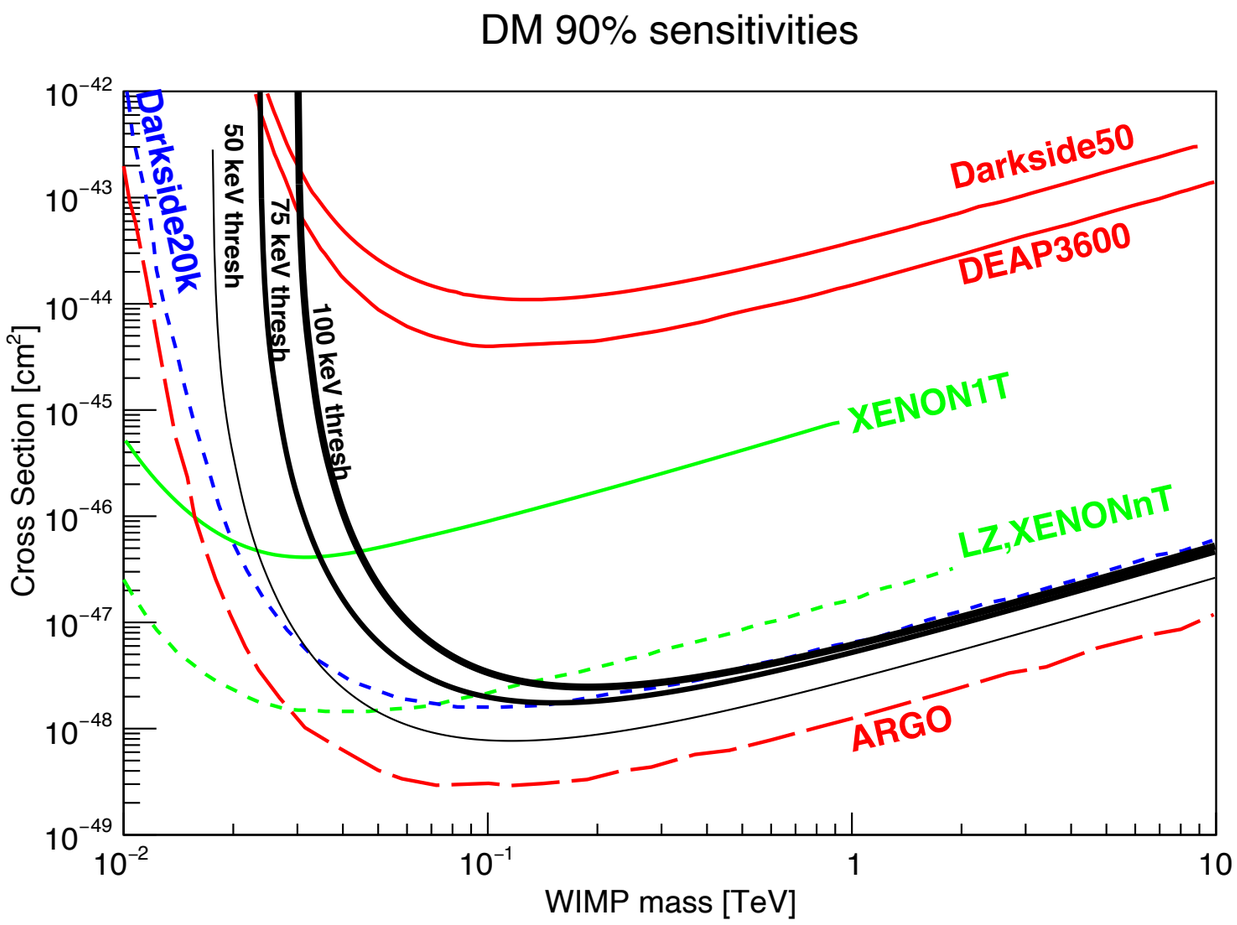
Electron/Gamma Backgrounds

- Target: 100 photons for PSD
- Upgrades to make 100 photons:
  - Reflective foils (97% reflectance)
  - Increased PD packing
  - SiPMs (45% QE)
  - ~3600 DarkSide-20k style 24 cm^2 SiPM tiles
- Pulse shape discrimination:
  - MC simulation code, Poisson distributed photons for prompt (<90 ns) and late (>90 ns)
  - 3 kton.yr simulated exposure, 7.3 x 10^{-4} Bq/kg
  - 10^{10} PSD Required (~levels in DEAP-3600)





Dark Matter Sensitivity



3 kTon-year Low Background Module

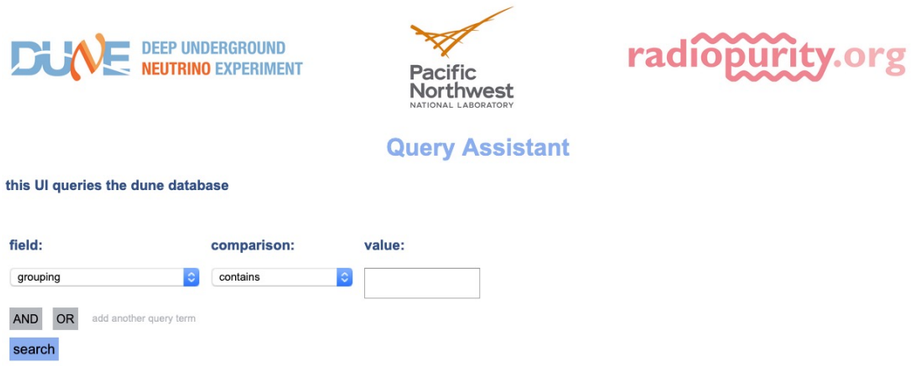
What this module can do…

- ^{39}Ar - data rate, timing resolution, pileup
- Supernova Neutrinos
  - ✓ Trigger (whole 4-module far detector trigger)
  - ✓ Late time supernova neutrinos
  - ✓ CEvNS Glow
  - ✓ Diffuse supernova neutrinos
- Solar neutrinos
  - ✓ Precision measurements
  - ✓ Electron scattering and directionality
- Neutrinoless Double Beta Decay
- CEvNS
- WIMP Dark Matter
- …?

How to build this?

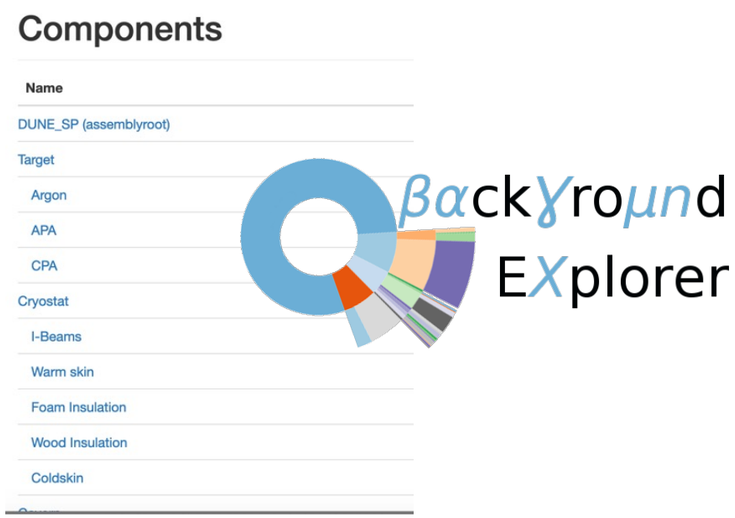
- Radiopurity control on this scale (~20 kTon detector) a huge challenge
- ~10^3 reductions beyond current designs…
- … but this is less than stringent than levels expected in G2 dark matter
- Building framework for QA/QC program

- Assay database
  - Implementation of new version of radiopurity.org database for DUNE
    - ✓ Modern MongoDB backend
    - ✓ New user interface to improve search functionality
    - ✓ Open source code on github: https://github.com/pnnl/Radiopurity-database-assistant
    - ✓ Further development planned:
      - Exploring upgrade of public version at SNOLAB
      - Further development of database contents (spectral information, analysis methods, …)
      - Developing collaboration with SNOLAB and original radiopurity.org authors



How to build this?

- Assay management
  - Radiopurity.org based assay manager
    - ✓ Interface for non-experts to request assays
    - ✓ Guided input of relevant information
    - ✓ Low background experts guide distribution of assay work
    - ✓ Tracks samples and locations
- Assay results and triage
  - Background Explorer
    - ✓ Toolkit for modeling radioactive backgrounds
    - ✓ Rapid evaluation of effect of new assay measurement on background tables
    - ✓ Originally developed for SuperCDMS by Ben Loer
    - ✓ https://github.com/bloer/bgexplorer-demo

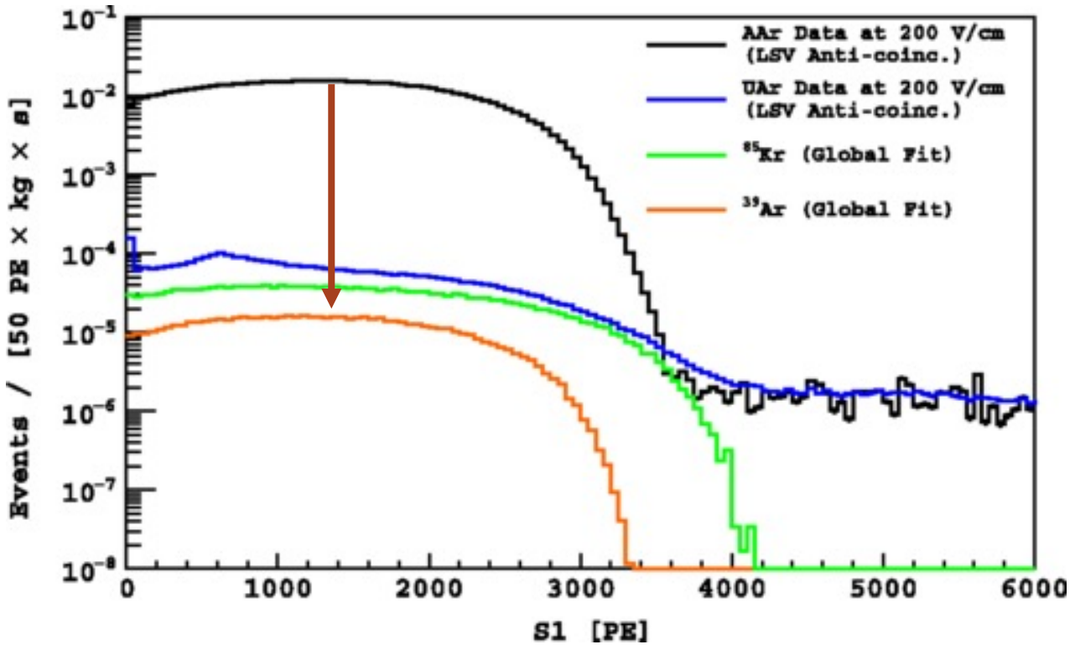


Low-Radioactivity Underground Argon

- 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-like module
- 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.

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

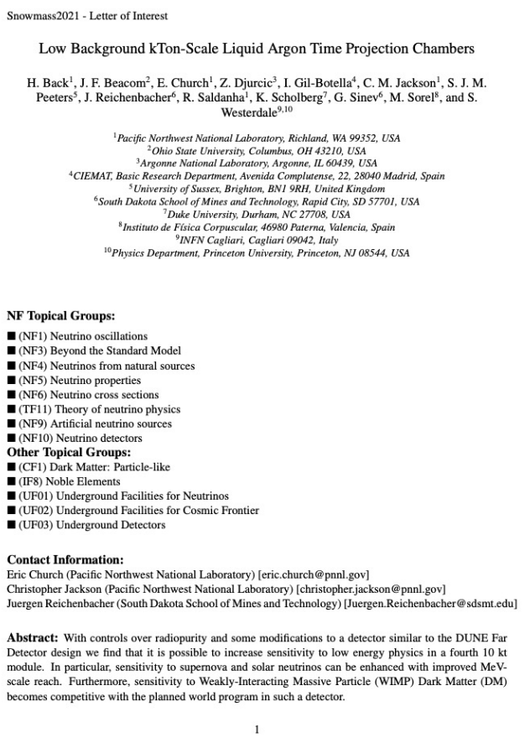


1400 lowering in ^{39}Ar rate

Next Steps

- QA/QC:
  - Designing the sampling program
  - Dust control
  - Radon control

- Low background module:
  - https://www.snowmass21.org/docs/files/summaries/NF/SNOWMASS21-NF10_NF4-CF1_CF0-IF8_IF0-UF1_UF3-137.pdf
  - White paper in preparation
  - Let us know if interested to join…



Snowmass2021 - Letter of Interest

Low Background kTon-Scale Liquid Argon Time Projection Chambers

H. Back[1], J. F. Beacom[2], E. Church[1], Z. Djurcic[3], I. Gil-Botella[4], C. M. Jackson[1], S. J. M. Peeters[5], J. Reichenbacher[6], R. Saldanha[1], K. Scholberg[7], G. Sinev[6], M. Sorel[8], and S. Westerdale[9,10]

[1]*Pacific Northwest National Laboratory, Richland, WA 99352, USA*
[2]*Ohio State University, Columbus, OH 43210, USA*
[3]*Argonne National Laboratory, Argonne, IL 60439, USA*
[4]*CIEMAT, Basic Research Department, Avenida Complutense, 22, 28040 Madrid, Spain*
[5]*University of Sussex, Brighton, BN1 9RH, United Kingdom*
[6]*South Dakota School of Mines and Technology, Rapid City, SD 57701, USA*
[7]*Duke University, Durham, NC 27708, USA*
[8]*Instituto de Física Corpuscular, 46980 Paterna, Valencia, Spain*
[9]*INFN Cagliari, Cagliari 09042, Italy*
[10]*Physics Department, Princeton University, Princeton, NJ 08544, USA*

NF Topical Groups:

- (NF1) Neutrino oscillations
- (NF3) Beyond the Standard Model
- (NF4) Neutrinos from natural sources
- (NF5) Neutrino properties
- (NF6) Neutrino cross sections
- (TF11) Theory of neutrino physics
- (NF9) Artificial neutrino sources
- (NF10) Neutrino detectors

Other Topical Groups:

- (CF1) Dark Matter: Particle-like
- (IF8) Noble Elements
- (UF01) Underground Facilities for Neutrinos
- (UF02) Underground Facilities for Cosmic Frontier
- (UF03) Underground Detectors

Contact Information:
Eric Church (Pacific Northwest National Laboratory) [eric.church@pnnl.gov]
Christopher Jackson (Pacific Northwest National Laboratory) [christopher.jackson@pnnl.gov]
Juergen Reichenbacher (South Dakota School of Mines and Technology) [Juergen.Reichenbacher@sdsmt.edu]

Abstract: With controls over radiopurity and some modifications to a detector similar to the DUNE Far Detector design we find that it is possible to increase sensitivity to low energy physics in a fourth 10 kt module. In particular, sensitivity to supernova and solar neutrinos can be enhanced with improved MeV-scale reach. Furthermore, sensitivity to Weakly-Interacting Massive Particle (WIMP) Dark Matter (DM) becomes competitive with the planned world program in such a detector.

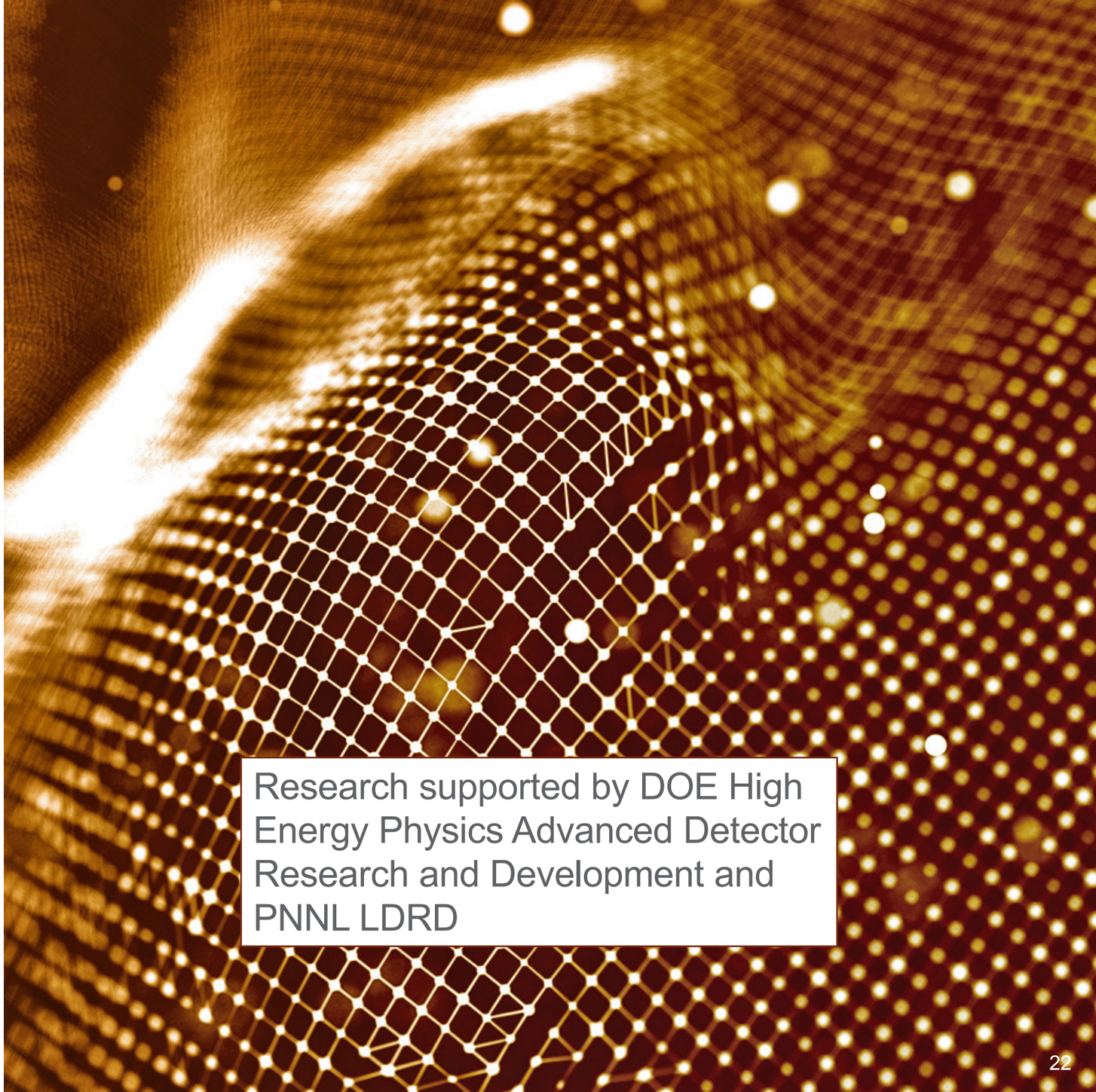
1

Conclusions

- DUNE-like low background module:
  - Bulk argon module
  - Increased shielding
  - Fiducialization
  - Low radioactivity underground argon
  - Increased photon detection
- Physics program includes:
  - Supernova burst, solar neutrinos
  - Direct dark matter
  - …
- Building the framework to support a kTon-scale low background management program

Pacific Northwest
NATIONAL LABORATORY

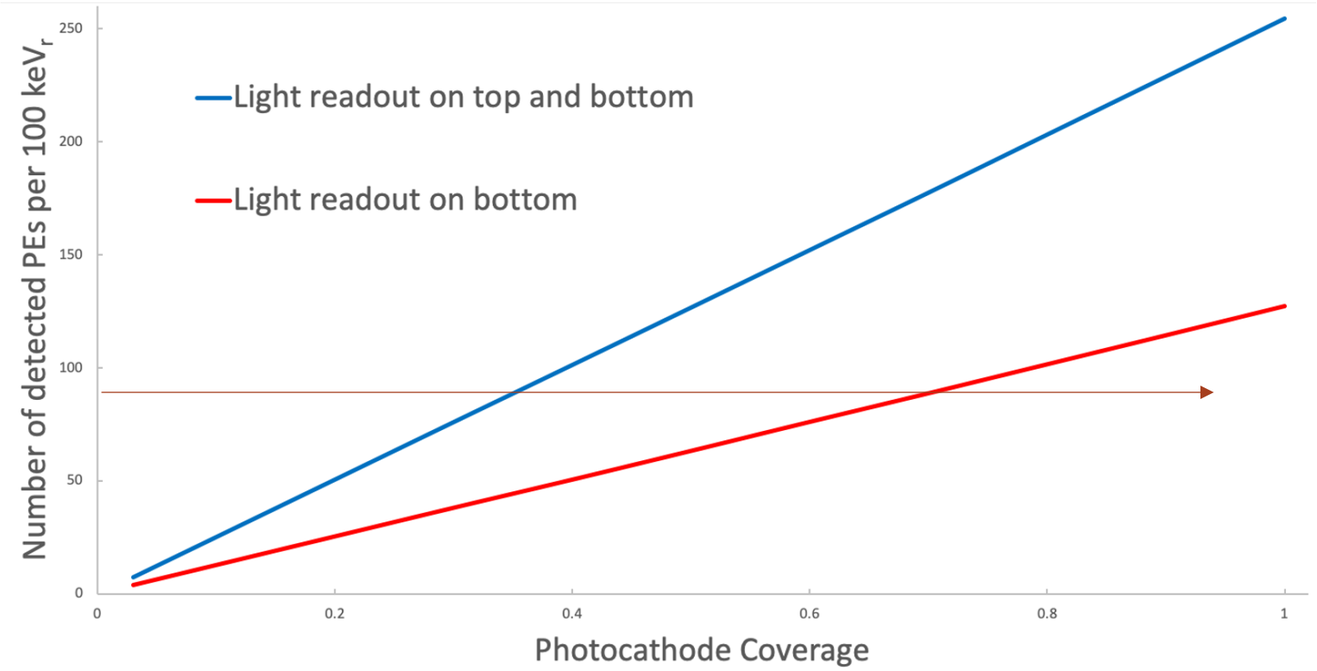
Thank you



Research supported by DOE High Energy Physics Advanced Detector Research and Development and PNNL LDRD

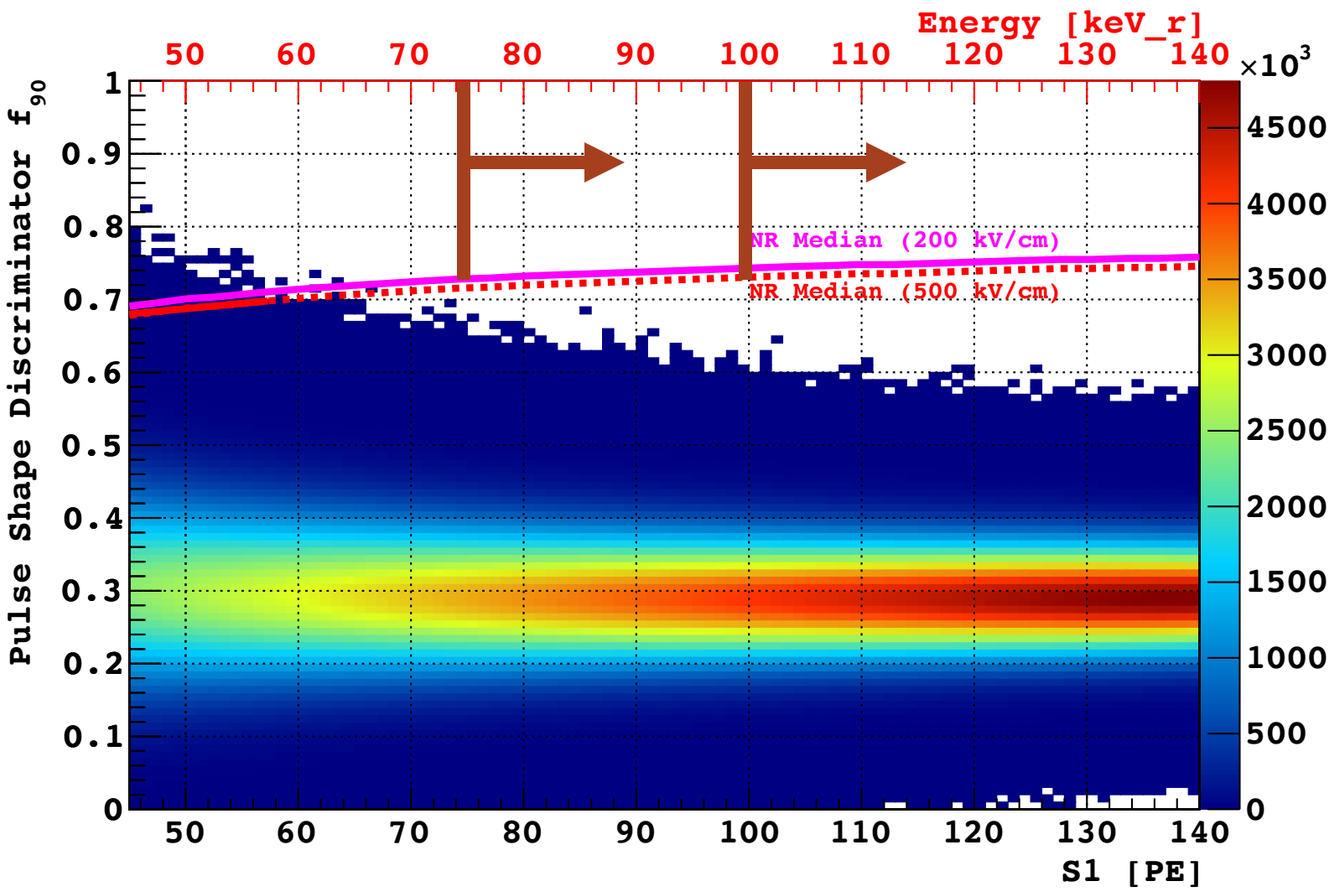
Photon Counting

- 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)



~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

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

Background Table

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 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
^{214}Pb from radon	PSD	bPSD:		$< 1.9\times10^8$	
		aPSD:	0	0	0
^{40}Ar(α, n) from radon	coincident tagging (see Section 3.5)		0	0	0
^{39}Ar betas in argon	UAr, PSD	bPSD:	1.6×10^{10}	1.7×10^{10}	1.8×10^{10}
		aPSD:	0	1	1
atmospheric neutrinos	none		10	13	17
Total			11	30	33