Low Background kTon-Scale Liquid Argon Time Projection Chambers

Snowmass Neutrino Frontier Meeting

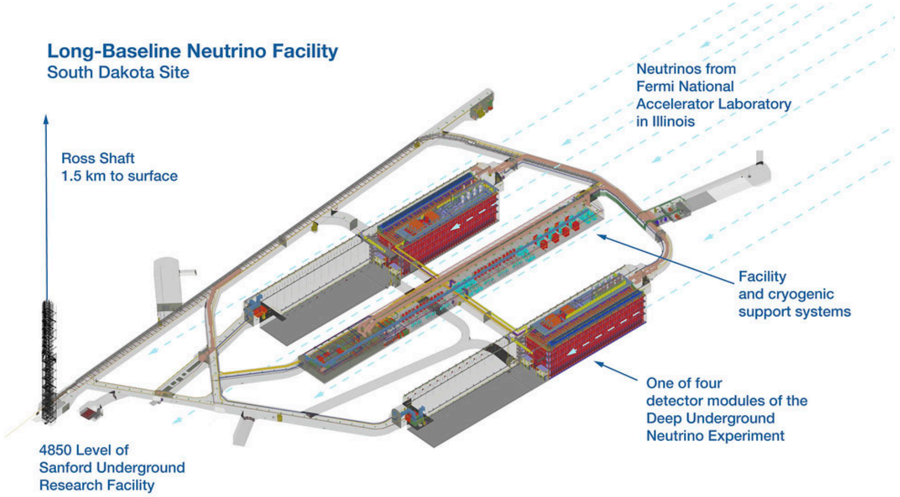
17th December 2021

Low Background kTon-Scale LAr TPCs

- Value in making experiments multipurpose

- Next-generation neutrino physics LArTPCs have thresholds of ~ 5-10 MeV
- Significant new physics at ~1 MeV or 100s keV scales
  - Neutrino astrophysics, neutrinoless double beta decay, dark matter, …

- 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 neutrino oscillation physics goals



Who are we

- Low background module LOI:
  - https://www.snowmass21.org/docs/files/summaries/NF/SNOWMASS21-NF10_NF4-CF1_CF0-IF8_IF0-UF1_UF3-137.pdf
- White paper close to complete

Snowmass2021 - White Paper

Low Background kTon-Scale Liquid Argon Time Projection Chambers

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- We welcome new collaborators/endorsers…

Snowmass2021 - Letter of Interest

Low Background kTon-Scale Liquid Argon Time Projection Chambers

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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

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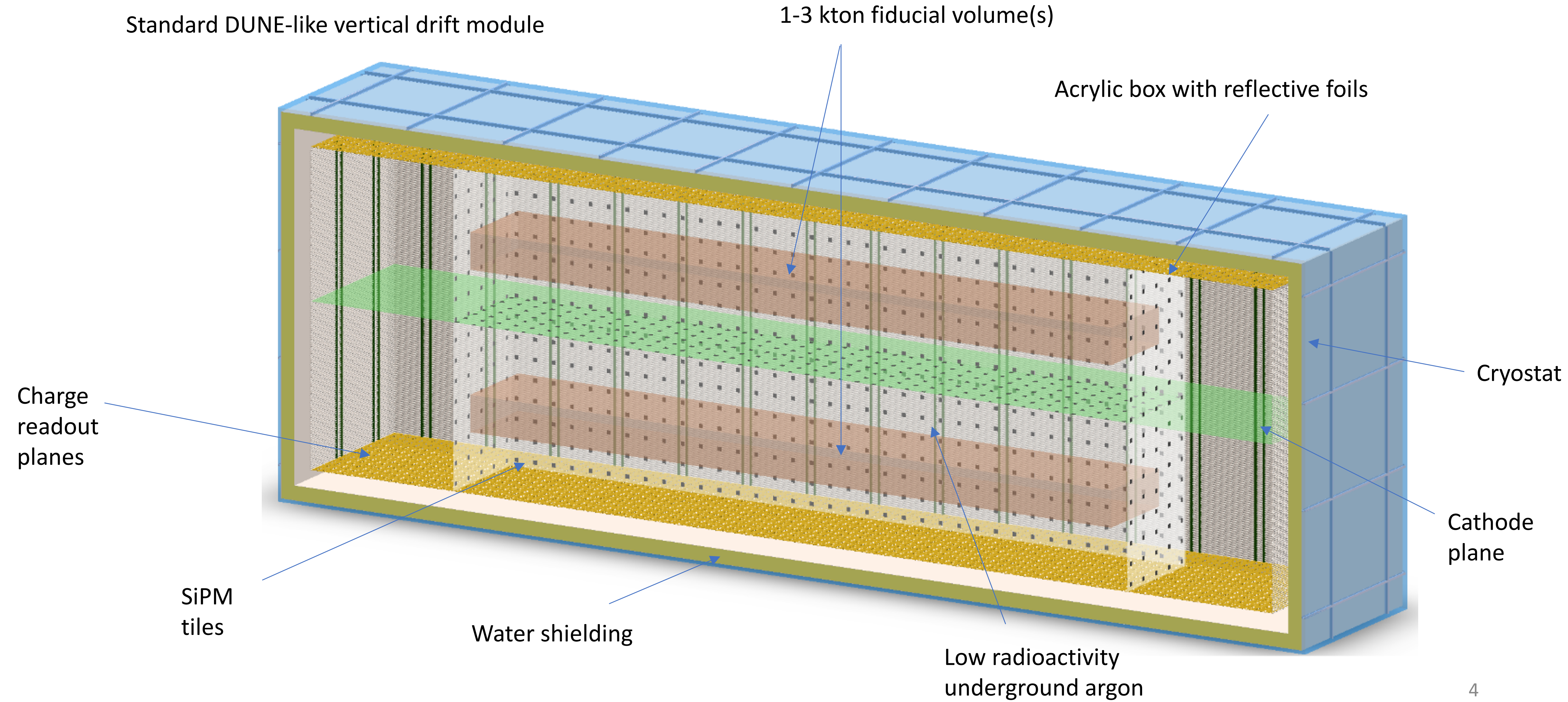
Abstract: With controls over radiopurity and some modifications to a detector similar to the DUNE Far Detector design we find that it is possible to increase sensitivity to low energy physics in a fourth 10 kt module. In particular, sensitivity to supernova and solar neutrinos can be enhanced with improved 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.

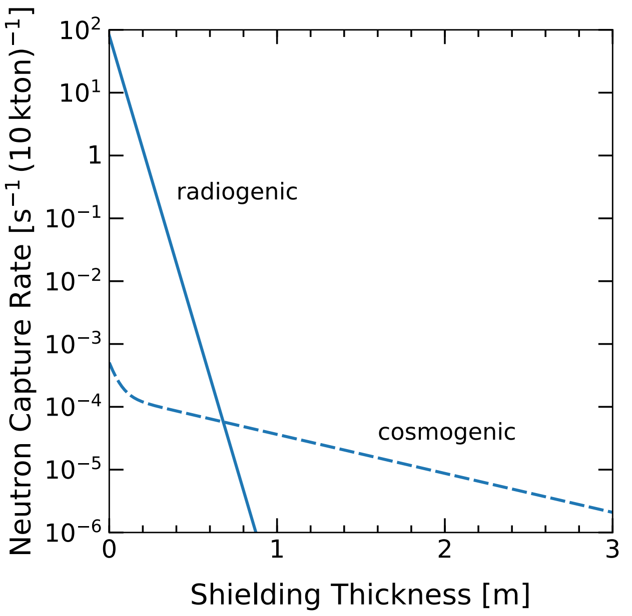
1

Detector Concept

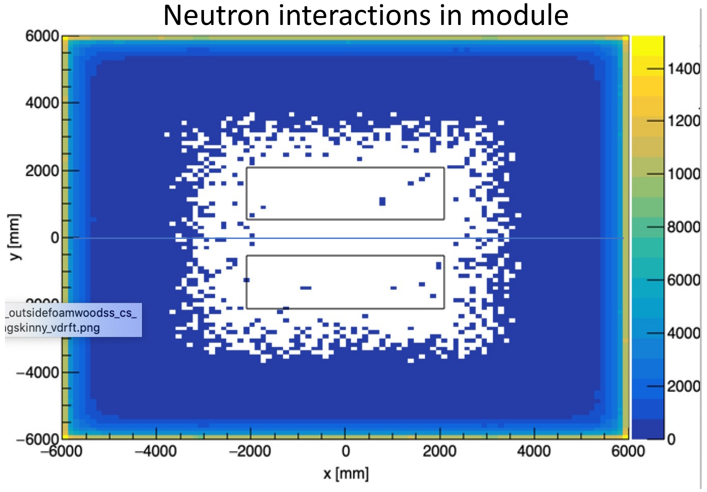


Background Control - Neutrons

- Neutron captures release 6-9 MeV gamma cascades in LAr. Main background to low energy neutrino signals. Neutron induced nuclear recoils main background to WIMP dark matter search
- Cavern rock likely primary source of neutrons (spontaneous fission and (alpha,n))
- Shielding
  - 40 cm of water shielding around detector (proposed by Zhu, Li and Beacom)
    - ~3 order of magnitude reduction
  - Exploring cryostat design options to increase shielding
    - e.g. Boron doped insulation
  - Planes of (doped) acrylic possible as shielding within the LAr
- Fiducialization
  - Significant self-shielding effect from argon from cryostat
- Analysis Cuts
  - TPC has excellent transverse resolution (20 mm). Lower threshold allows to tag multiple neutron scatters in detector volume



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



Background Control – Internal

- Internal detector components:
    - For example, stainless steel in cryostat
    - Need **~10^3** more radiopure than planned for baseline DUNE
    - But LZ/DarkSide expect further 2 orders of magnitude
    - R&D required to develop large QA/QC program. Apply techniques used for dark matter experiments at kton-scale

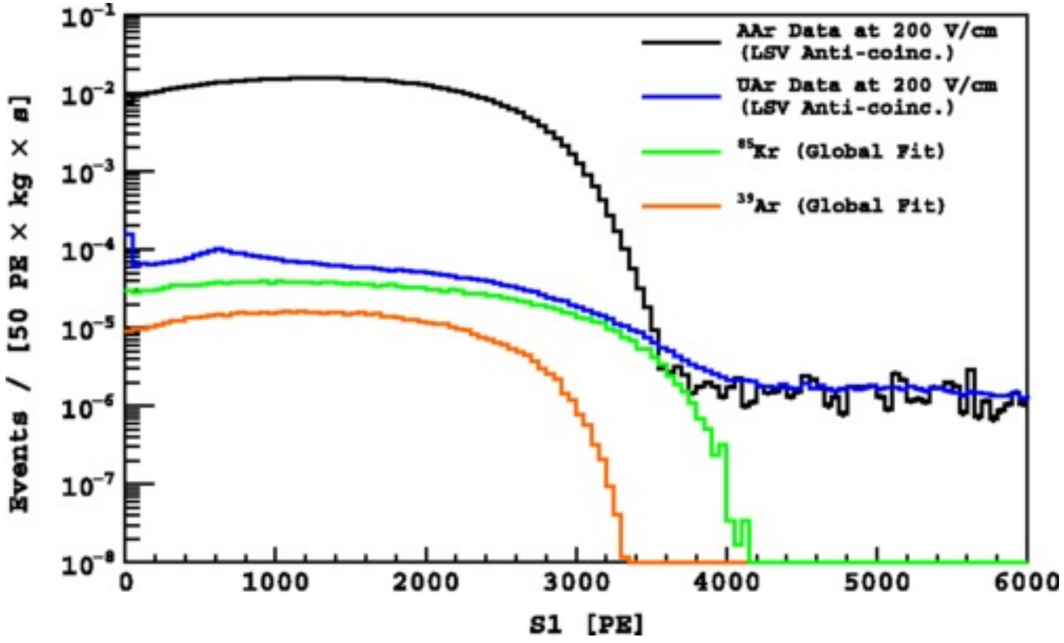
- Radon control
    - Target: 2 µBq/kg
    - Need **~10^2-10^3** reduction beyond baseline DUNE
    - Achieved by DarkSide-50
    - DEAP-3600: 0.2 µBq/kg
    - Large radon emanation control program
    - R&D required to develop kton-scale inline cryogenic radon trap

Background Control – Low Radioactivity Argon

- Atmospheric argon:
  - ^{39}Ar: 1 Bq/kg (10 MHz/module)
  - ^{42}Ar: 0.1 mBq/kg
- Underground sources of depleted argon exist
  - Demonstrated in DarkSide-50
    - 1400x reduction ^{39}Ar
    - Larger reduction of ^{42}Ar likely
  - 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. Preliminary gas analysis indicates mantle origin.
  - **Supplier:** Major U.S. gas producers/suppliers *(not disclosed at company request)*
  - **Production rate:** ~5,000 tonnes/year
  - **Ballpark cost:** Could be as low as x3 regular argon

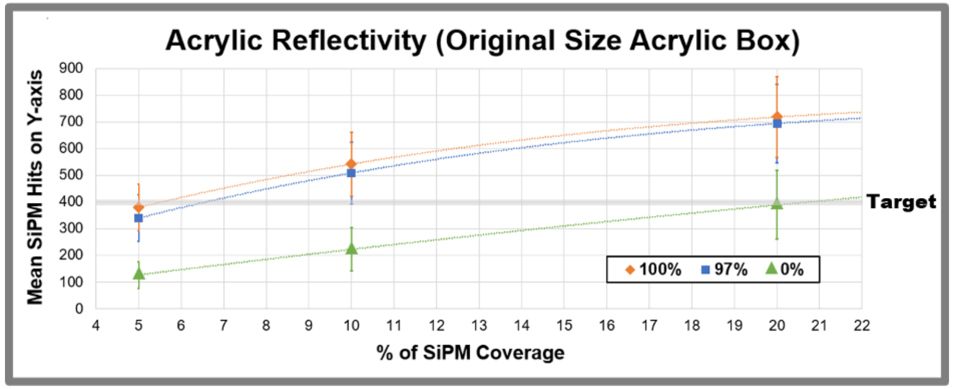
  NOTE: These are very rough estimates.

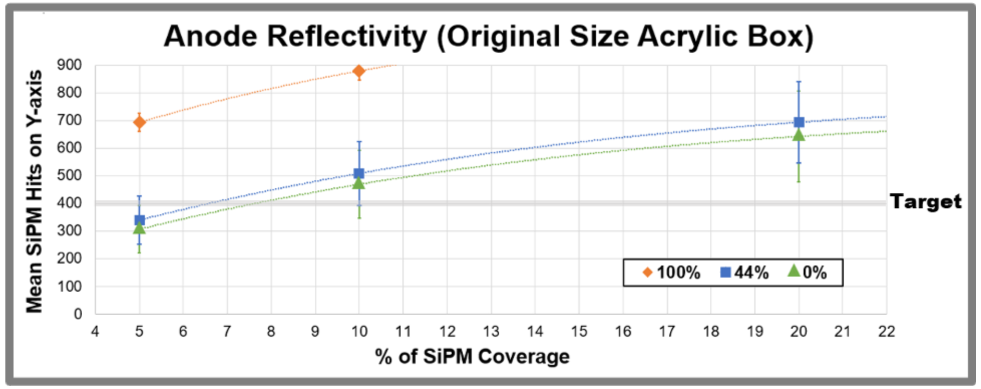
DarkSide 50: Phys. Rev. D 93, 081101(R)



Optical system

- Enhanced Photon Detection System to lower energy threshold
  - Reflectors, SiPM tiles, Increased coverage, Increased argon purity

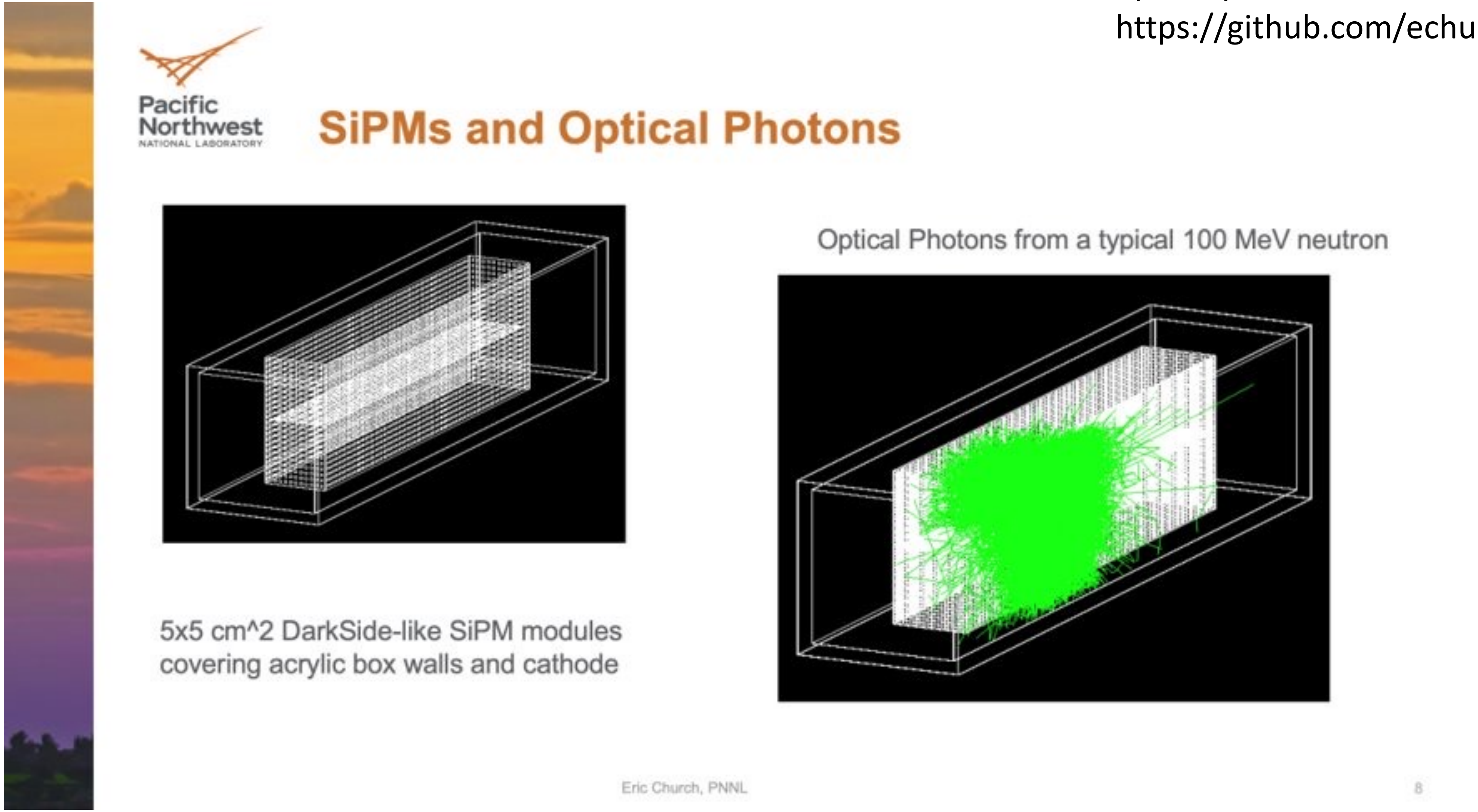




- Studies indicate 10-20% coverage (1500-4000 SiPM tiles) sufficient for pulse shape discrimination for **dark matter search**

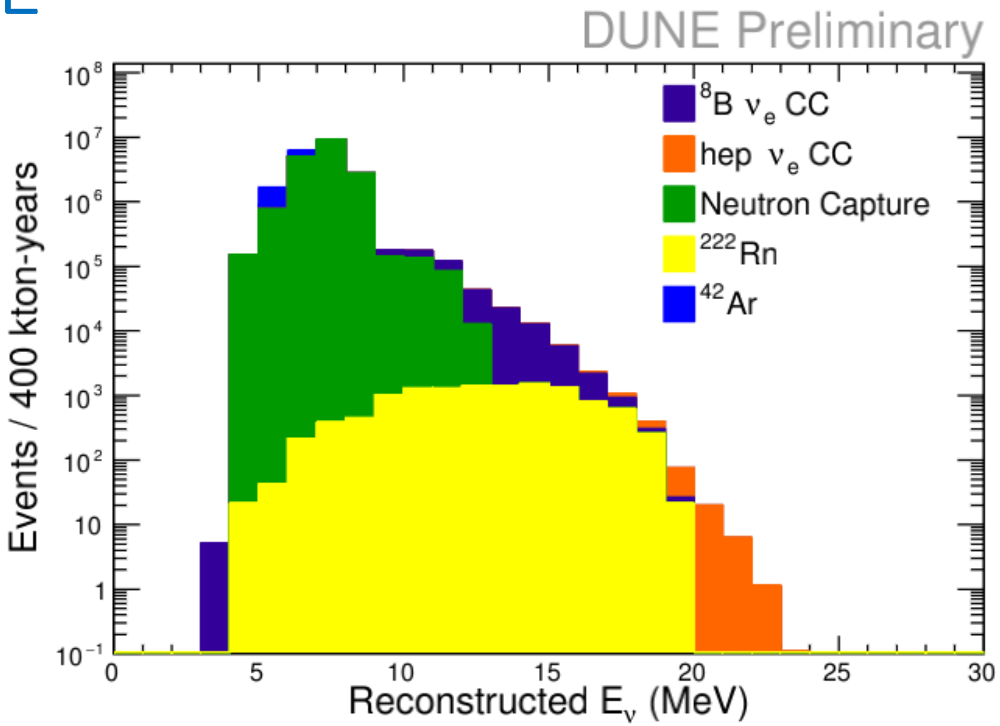
Optical Photons in our Module

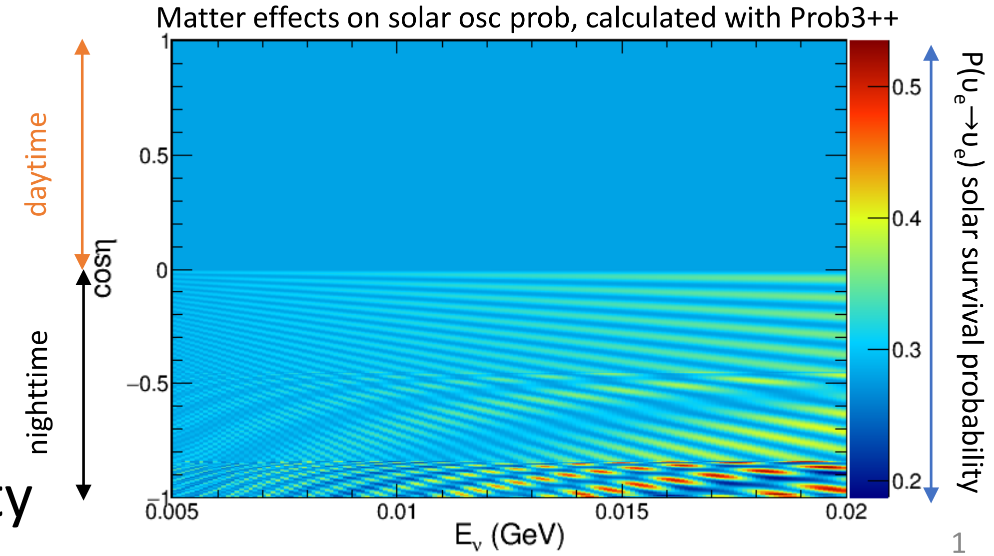
Standalone Geant4 simulation with optical photons: https://github.com/echurch/rdecay02



Solar neutrino opportunities with DUNE

- With 40 kton of fiducial argon, DUNE will collect an enormous sample of solar neutrinos (few 10^6 events)
  - Primarily sensitive to υ_e CC interactions – determination of $\phi(\upsilon_e)$ ideal for oscillations
- Simulation of solar neutrinos and backgrounds has identified a kinematic region where we can study solar neutrinos with the horizontal drift module design
- DUNE has favorable sensitivity to mass splitting parameter, Δm^2_{21}, through day-night effect
  - At night, partial regeneration of $\phi(\upsilon_e)$ increases rate as a function of neutrino energy and nadir angle, η
  - Sensitivity limited by backgrounds and energy resolution which smears ripples in survival probability

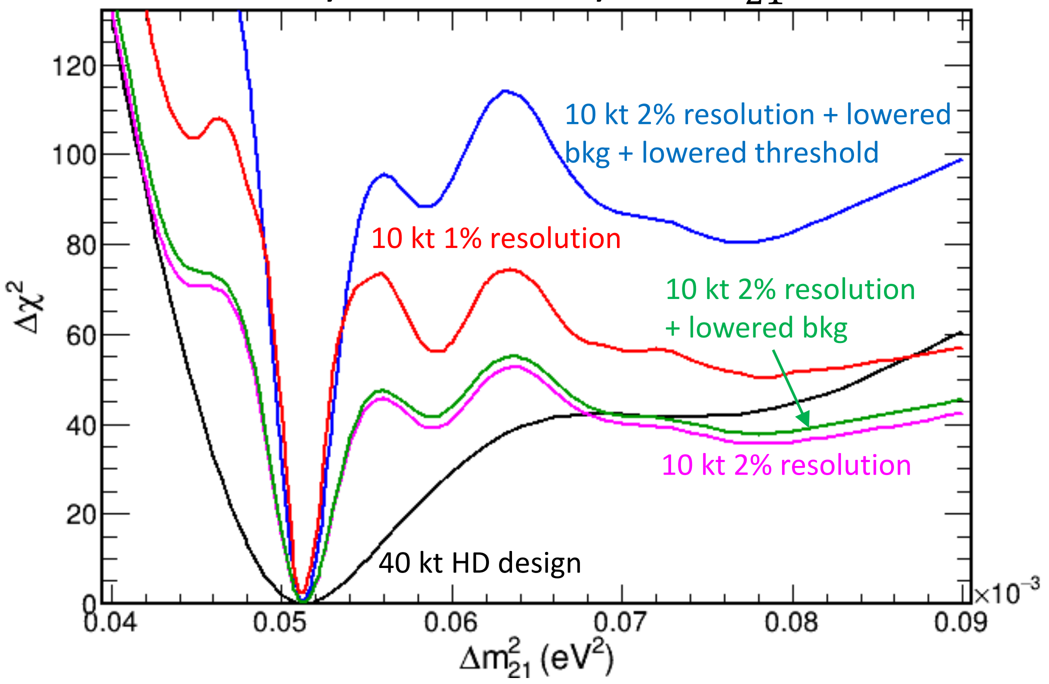




Δm^2_{21} determination with improved energy resolution with VD

- The vertical drift module design offers several opportunities to improve our sensitivity to solar oscillations:
  - Increased PD coverage allows better energy reconstruction and imaging of day/night ripples
  - Potential to significantly reduce neutron capture backgrounds through a portion of fiducial volume
  - Lower energy due to reduced backgrounds
- The Δm^2_{21} measurement using a single VD module would compete with 40 kt of the HD design
- Improved energy resolution also allows searches for exotic oscillation effects and BSM physics (see slides from Gleb Sinev)

10 year sensitivity to Δm^2_{21}

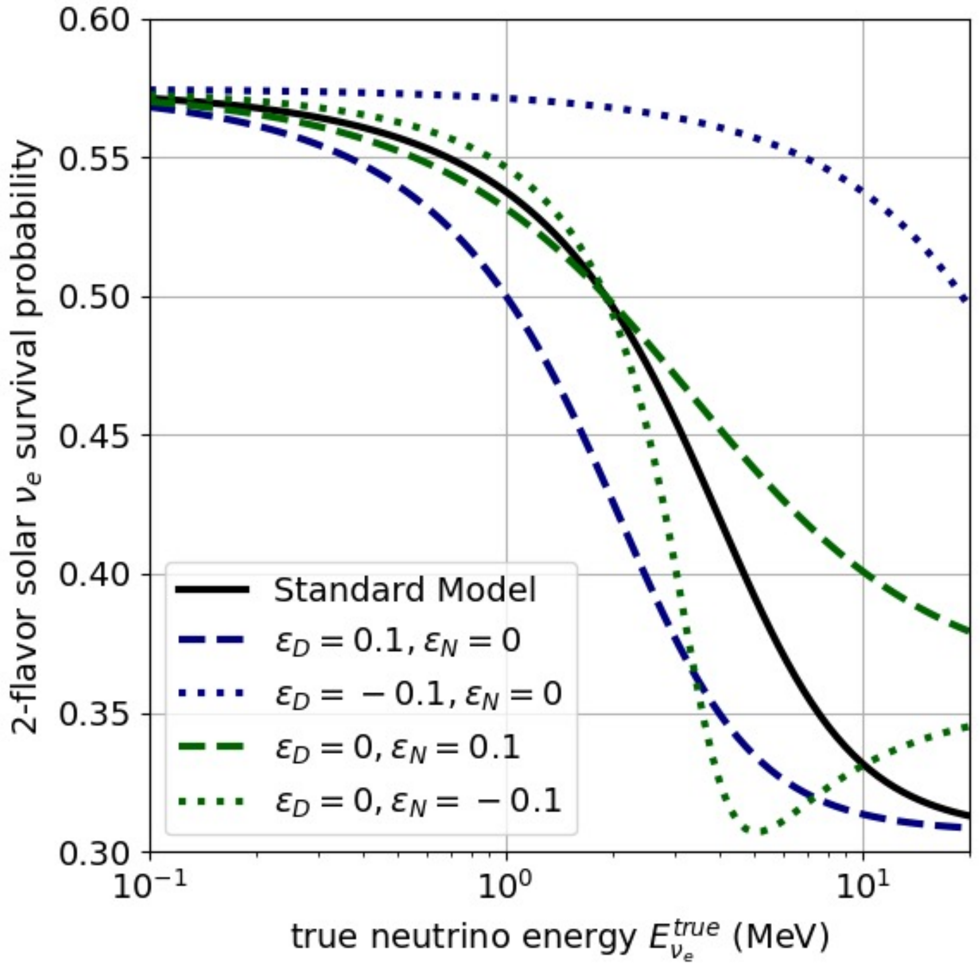


Non-standard neutrino interactions (NSI)

- NSI 2-flavor solar-ν Hamiltonian

$$H_\nu^{NSI} = \sqrt{2} G_F (n_u + n_d) \begin{pmatrix} -\epsilon_D & \epsilon_\mathrm{N} \\ \epsilon_\mathrm{N}^* & \epsilon_D \end{pmatrix}$$

- Solar neutrinos are affected by diagonal and off-diagonal couplings
  - NSI change ν_e survival probability
  - Diagonal coupling can mimic different vacuum Δm^2 values

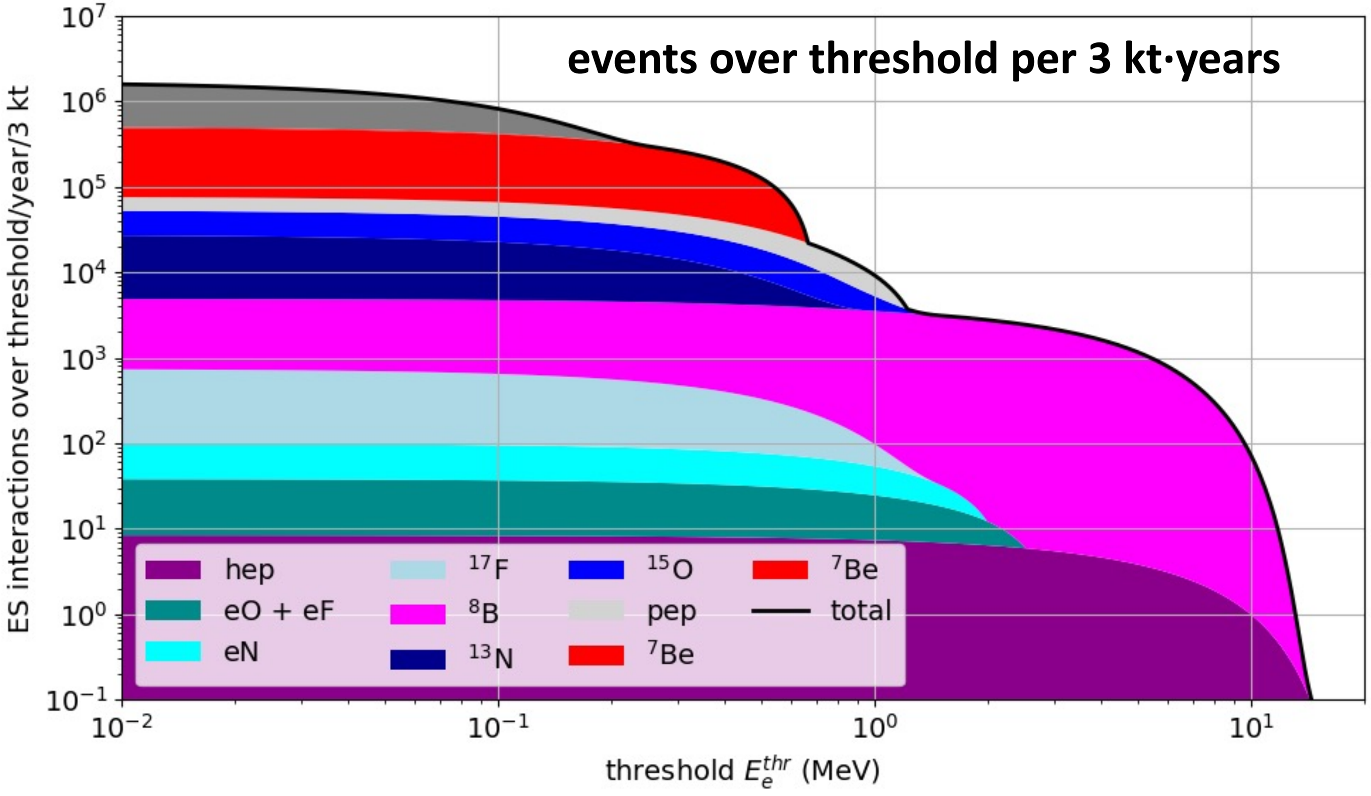


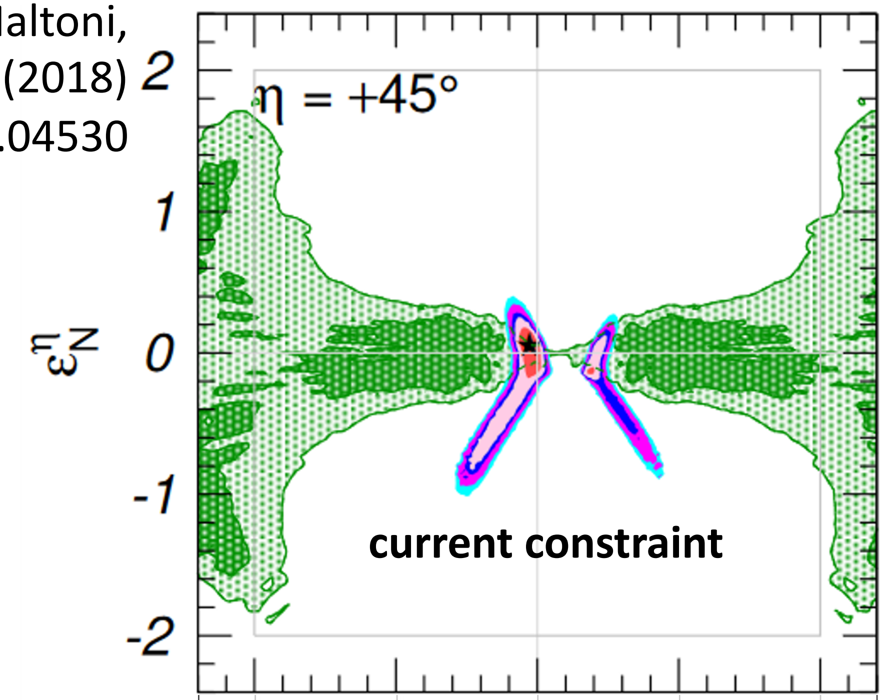
Juergen Reichenbacher and Gleb Sinev, “NSI searches with current and future neutrino and dark-matter experiments”, publication in preparation

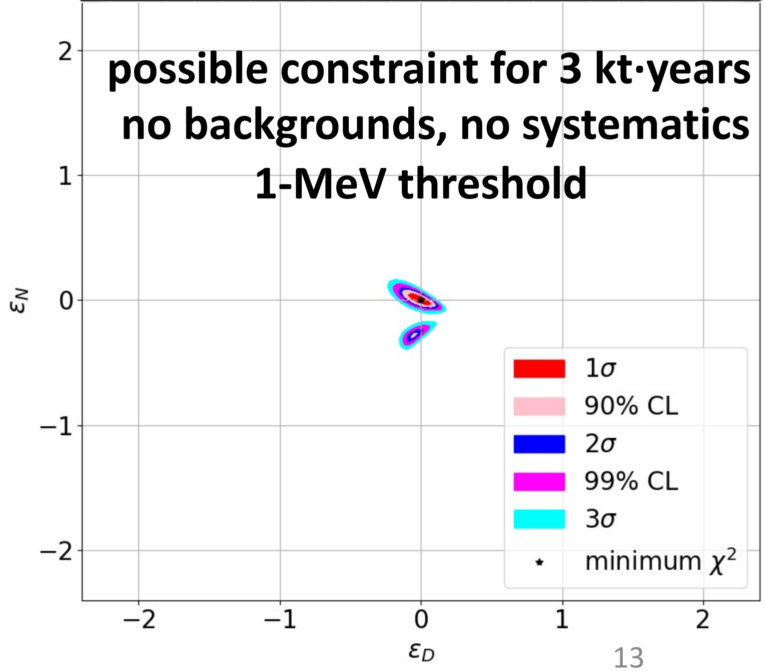
I. Esteban, M.C. Gonzalez-Garcia, M. Maltoni,
I. Martinez-Soler, J. Salvado (2018)
arXiv:1805.04530

Elastic scattering on electrons (ES)

- Can investigate NSI with solar-ν ES in argon
  - Expect many events depending on threshold → good NSI constraint







CNO

- Borexino has made a 3.5 sigma discovery of the existence of CNO solar neutrinos.

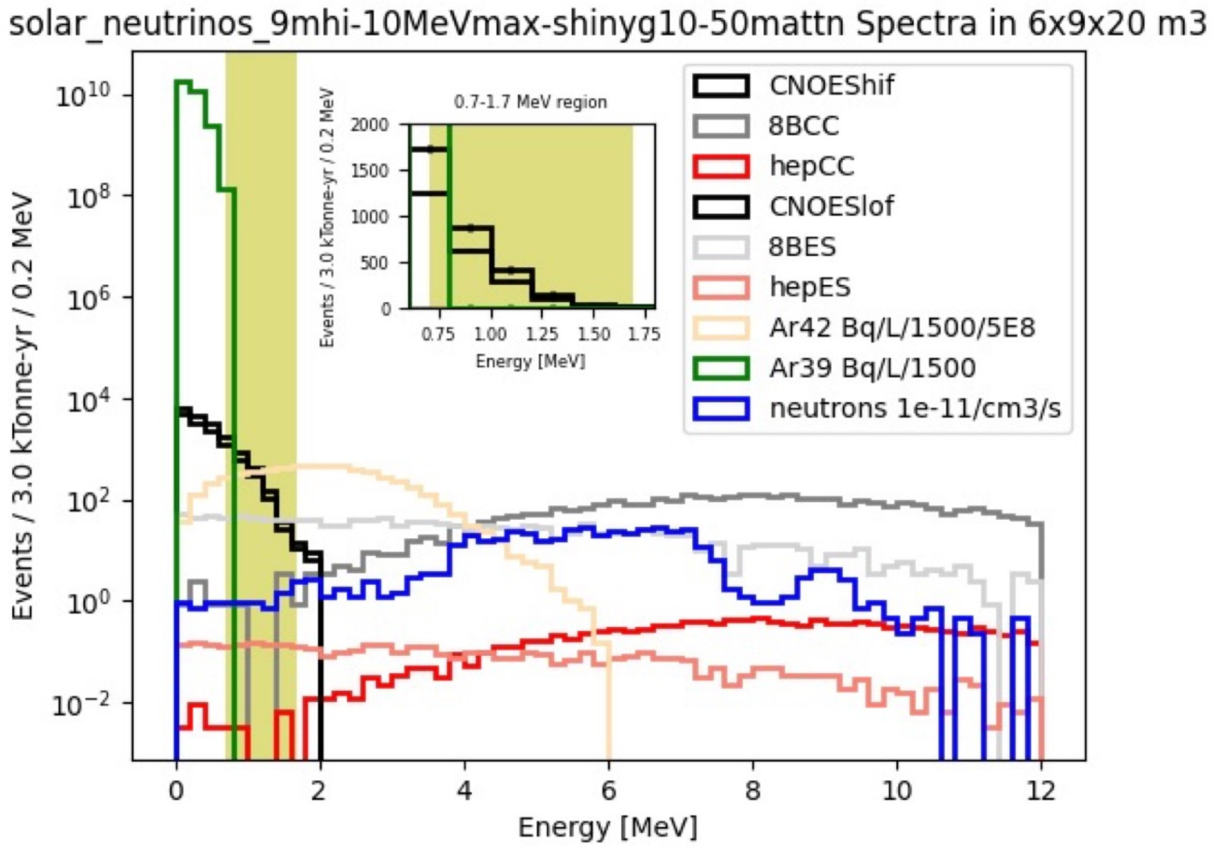
- A module described here can definitively, it appears, select the low or high metallicity solution that prevails in the sun.
- The very low ^{42}Ar that we expect to be present in UAr makes this measurement possible – along with our other radiopurity requirements.
- Following is a simple SiPM hit-calibrated-to-energy plot that shows a region where a definitive CNO measurement is feasible.

CNO Solar

^{42}Ar /= 500 here beyond atmospheric Ar composition.

With UAr we expect very low ^{42}Ar rates. Among other implications, this leads to the ability for detecting CNO solar νs and distinguishing HZ/LZ flux. Neutron rate is low due to requirement on cold cryoskin.

CNO flux from https://iopscience.iop.org/article/10.3847/1538-4357/835/2/202/pdf. *With further x0.5 survival applied.* Only stats errors shown

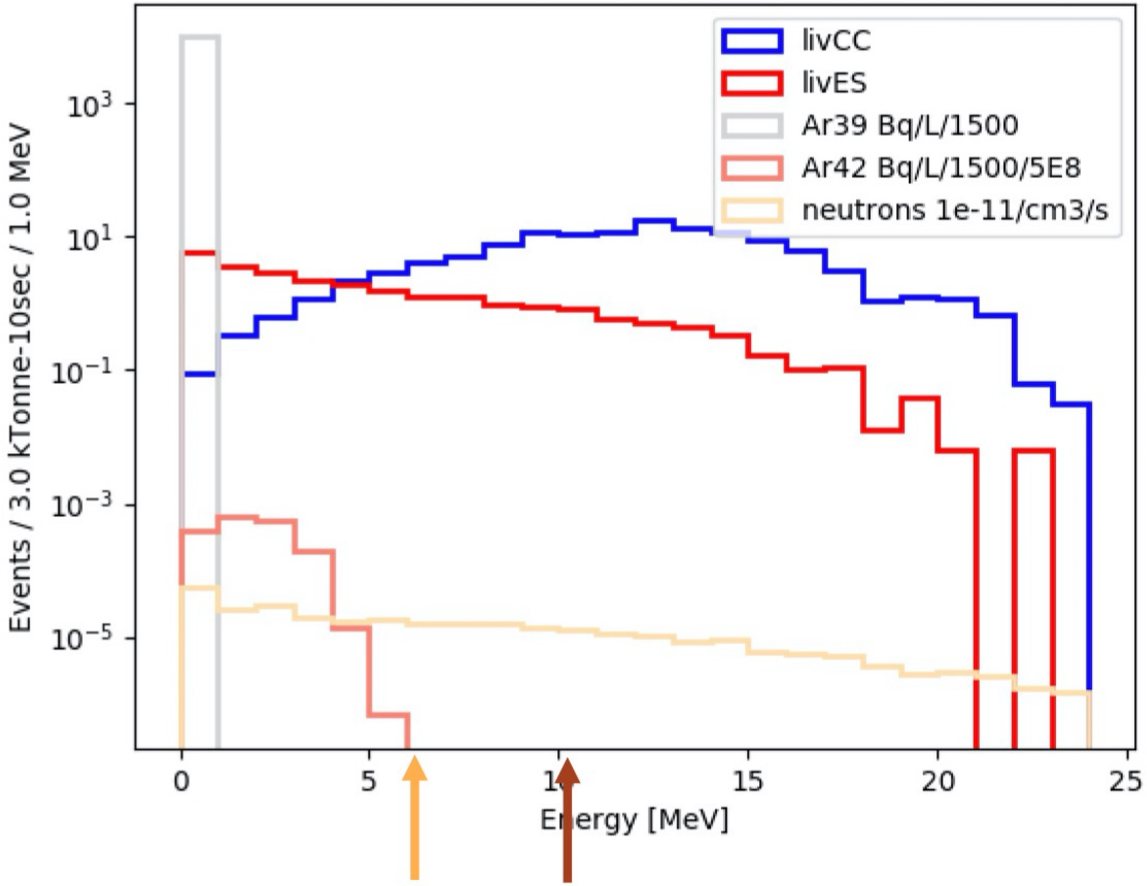


Supernovae at 10kpc

^{42}Ar /= 500 here beyond atmospheric Ar composition.

Clearly a detector of this type allows to see CC/ES spectrum to much lower thresholds.

Radon neglected in this study. Presume will control via material selection, improved detector cleaning, argon recirculation and reconstructions techniques (e.g. alpha tagging)

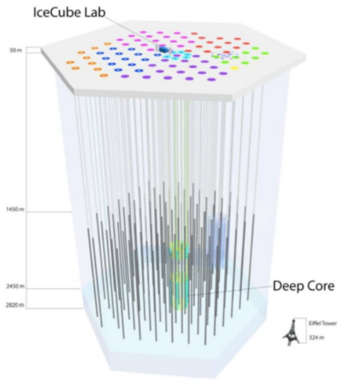


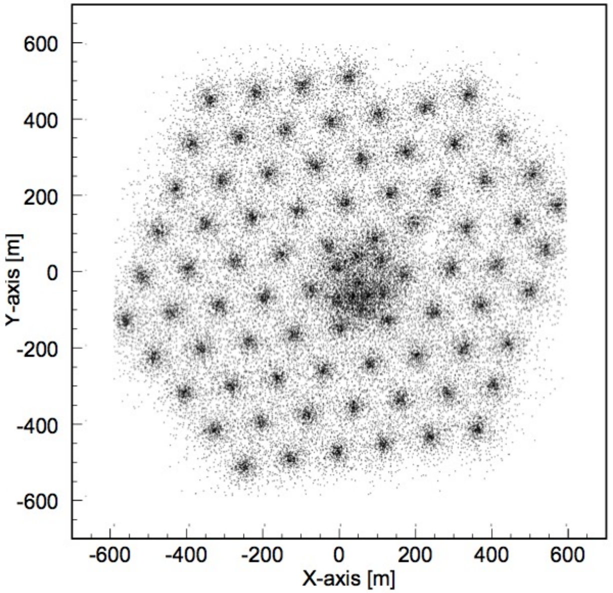
Brown/Orange arrows show rough current DUNE module trigger and data thresholds (due to high n captures)

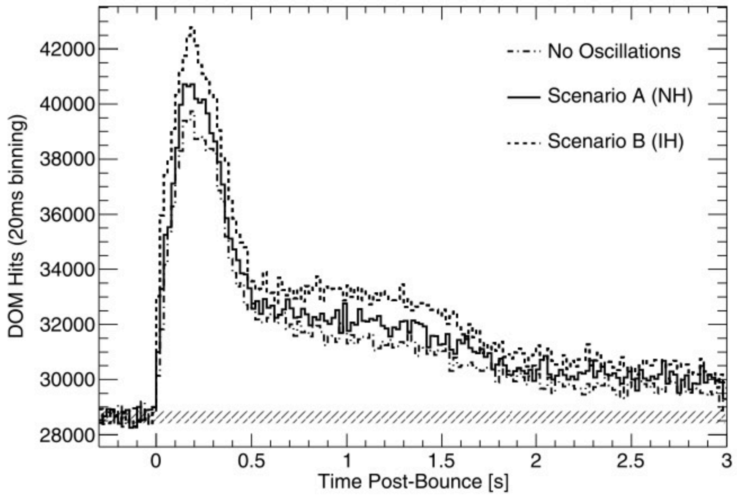
“CEvNS Glow” in large,
high-threshold neutrino detectors

Adryanna Major and Gleb Sinev @ Duke

“IceCube-style” supernova detection:
Cherenkov photons in ice observed as
time-dependent single- (and double-)hit glow over ~10 sec

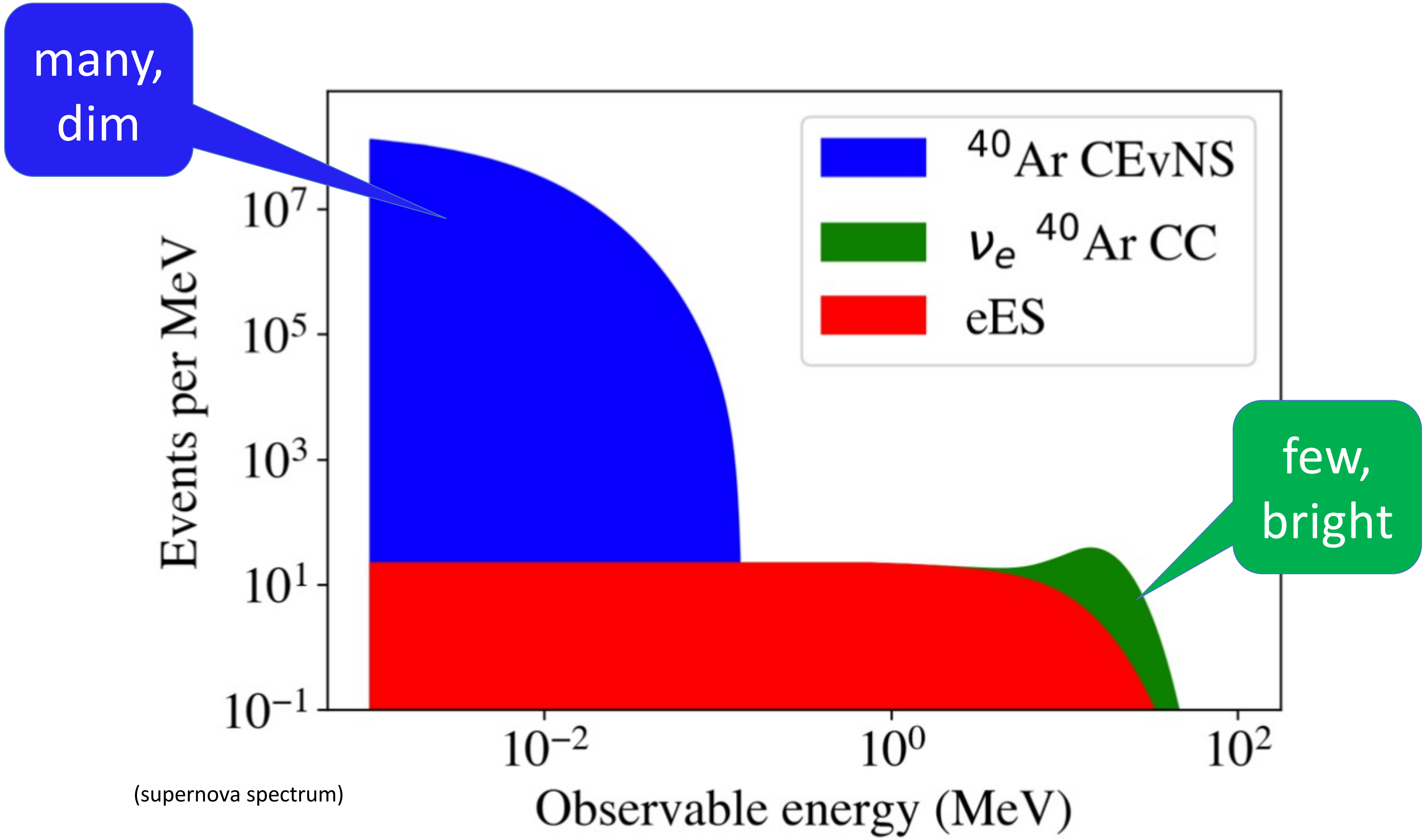






IceCube collaboration, A&A 535, A109 (2011)

Observable energy in argon



(supernova spectrum)

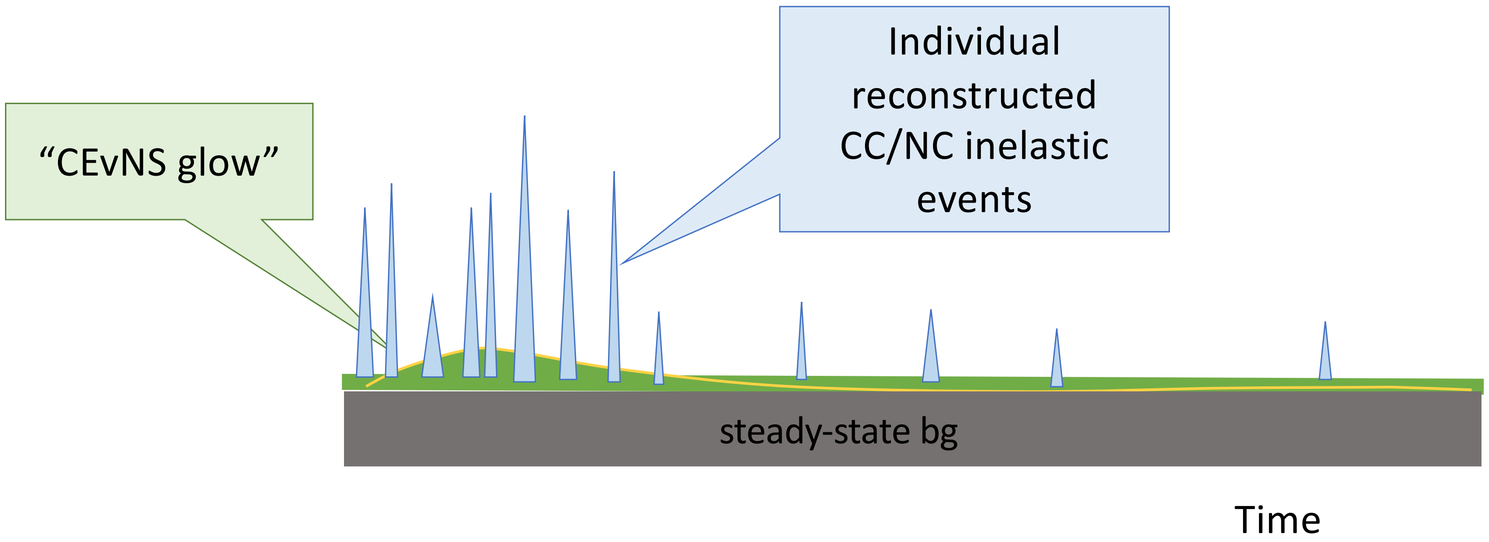
Back-of-the-envelope:

CEvNS signal vs Inelastic (CC/NC) signal:

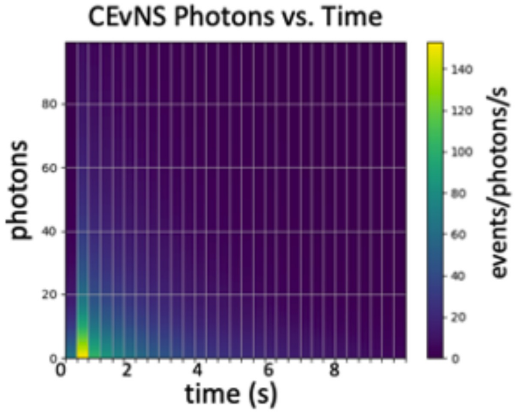
e.g., $\nu_x + A \rightarrow \nu_x + A$ vs $\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$ in argon, or IBD in scint

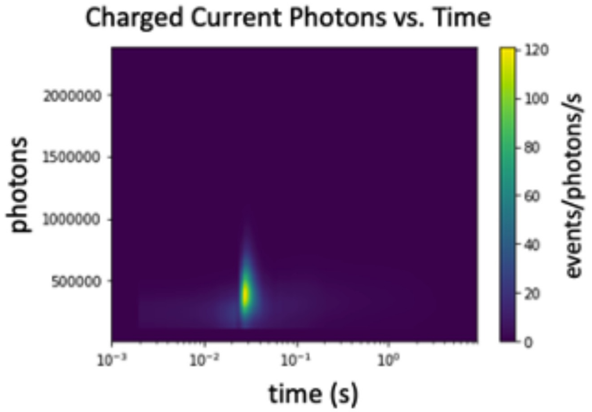
~10^2 more CEvNS events per target wrt CC
~10^{-3} less energy deposited per event for CEvNS wrt CC
~ 6 due to sensitivity to all flavors
~0.001-0.2 quenching factor (photons wrt e/γ energy deposit) for nuclear recoil wrt CC

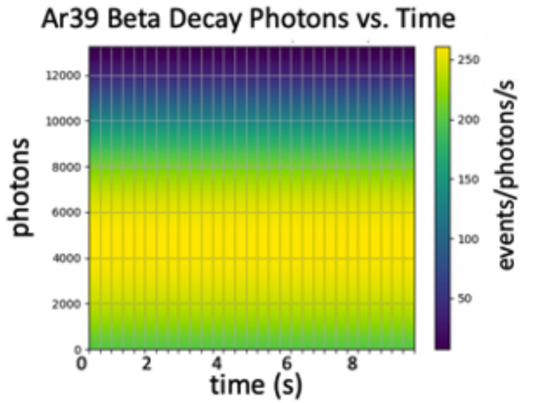
➔Total CEvNS photons are ~few-10% of CC-generated photons,
but, diffused over the burst rather than in individual event spikes
Issue is whether they exceed Sqrt[background]
(and triggering may be challengin!)



CEvNS Glow Photons in LAr: calculation by A. Major, Duke

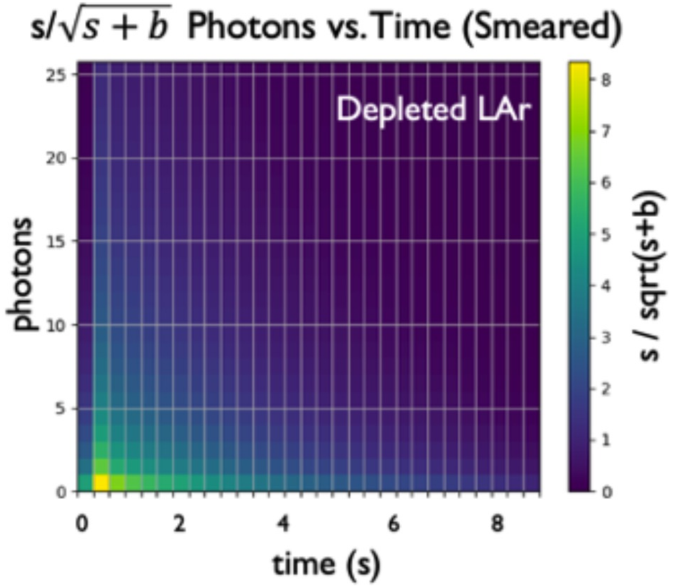






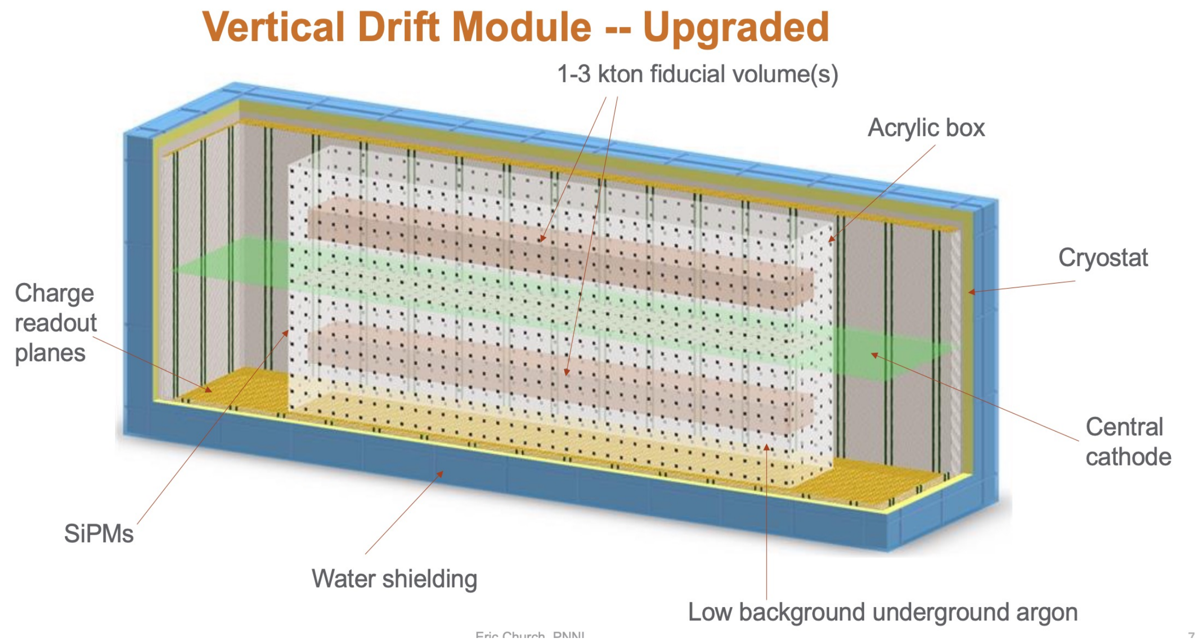
"Garching" supernova model, 10 kt, 10 kpc

Detected photons in simplified detector with ^{39}Ar x 0.001



information
in time,
detected photon
multiplicity
spectrum

Approximate features matched by G4 sim of DUNE low-bg module



E. Church
LIDINE 2021

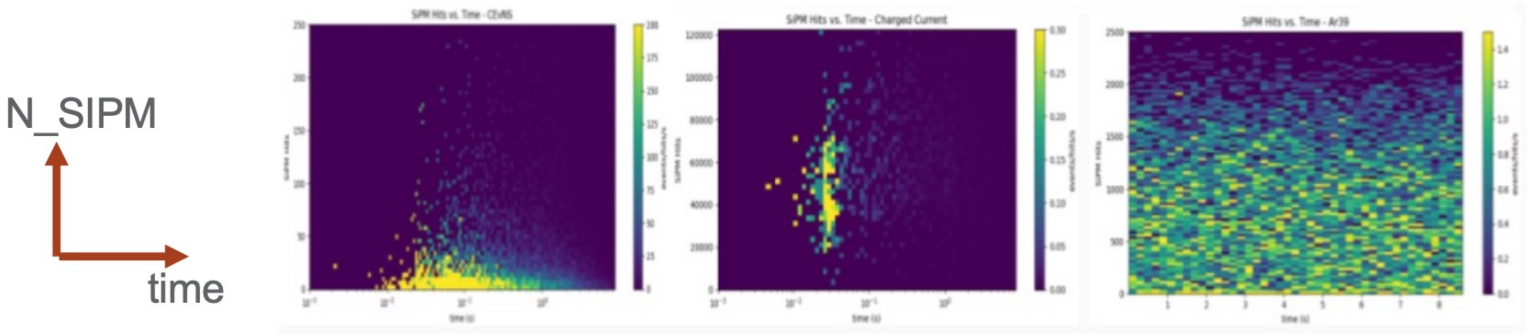


Figure 6: Figures from Carmelo Ortiz, DUNE low energy physics working group meeting,https://indico.fnal.gov/event/50302/

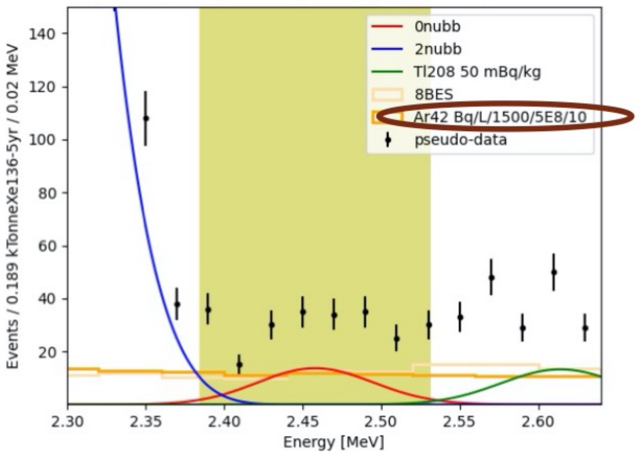
Carmelo Ortiz, Duke

Neutrinoless Double Beta Decay

- We imagine to carve out a one to few year run dedicated to searching for neutrinoless double beta decay by loading at least our inner volume with few% ^{136}Xe
- Such a loading likely spoils our argon PSD and so the Dark Matter WIMP search can not proceed simultaneously
- We require 1-3% energy resolution in order to see the $0\nu\beta\beta$ peak off the end of the $2\nu\beta\beta$ peak.
- Yet to be shown, but such a resolution appears feasible with Q+L calorimetry at ~2.5 MeV.

^{136}Xe $0\nu\beta\beta$

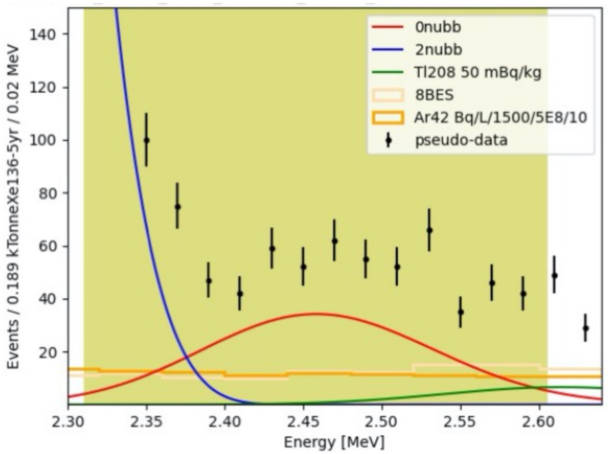
A 3% ^{136}Xe loading over 5 years in a 2 kT LAr box can allow a significant measurement of $0\nu\beta\beta$.



^{42}Ar /= 5000 here beyond atmospheric Ar composition.

σ/Q=1.5%, τ_{hl}=5E28 yrs

These half-lives are at limits and beyond that of nEXO sensitivity



σ/Q=3%, τ_{hl}=1E28 yrs

These plots are unique in that we need good energy resolution.

Curves assume a not-yet-demonstrated charge+light resolution of 1.5% and 3%.

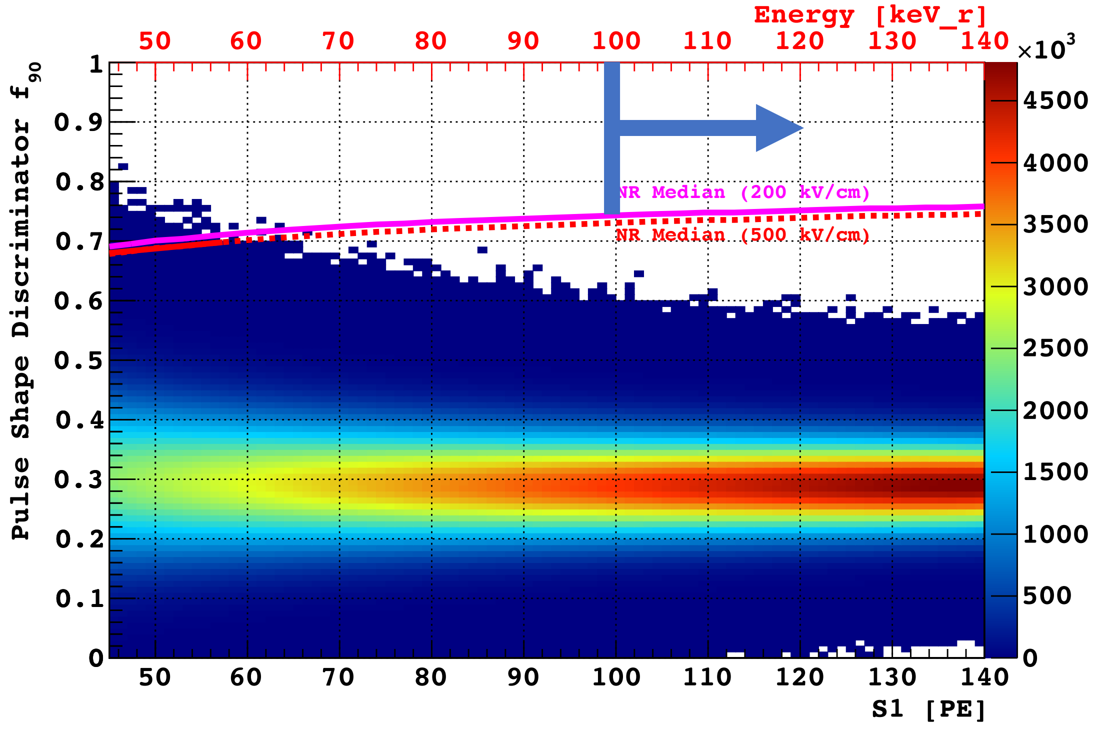
Suggested also by:

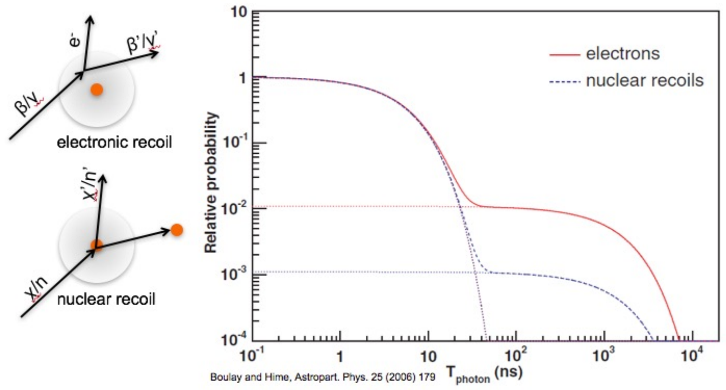
J. Zennamo and F. Psihas and A. Mastbaum, Snowmass 2021 Letter of Interest:https://www.snowmass21.org/docs/files/summaries/NF/SNOWMASS21-NF5_NF10-IF8_IF0_Zennamo-175.pdf

WIMP Dark Matter

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

- Dark matter search requirements:
  - 50-100 keV nuclear recoil threshold
  - O(10) background events
  - O(100) photons detected per event

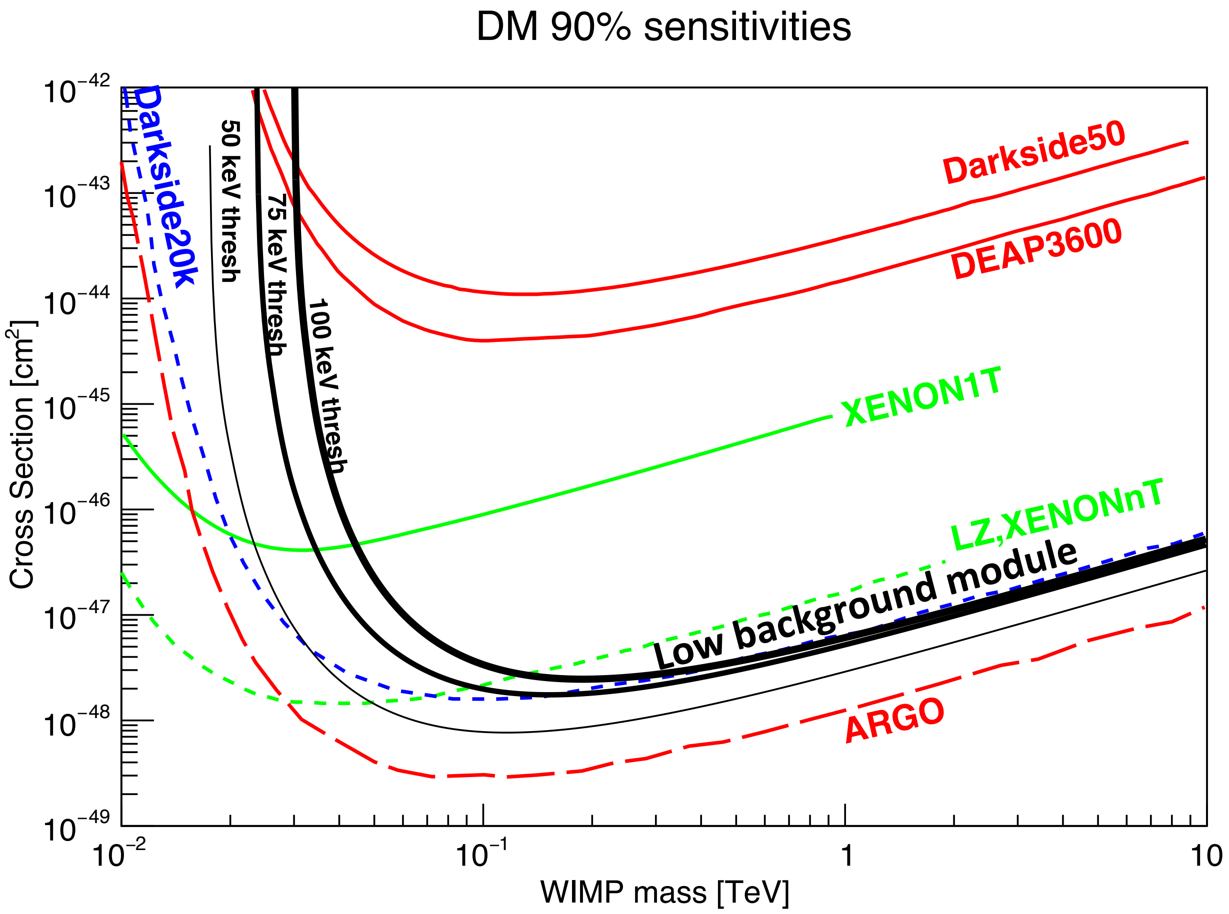




- Pulse shape discrimination:
  - MC simulation code, Poisson distributed photons for prompt (<90 ns) and late (>90 ns)
  - 3 kton.yr simulated exposure, 7.3 x 10^{-4} Bq/kg
  - 10^{10} PSD Required (~levels in DEAP-3600)

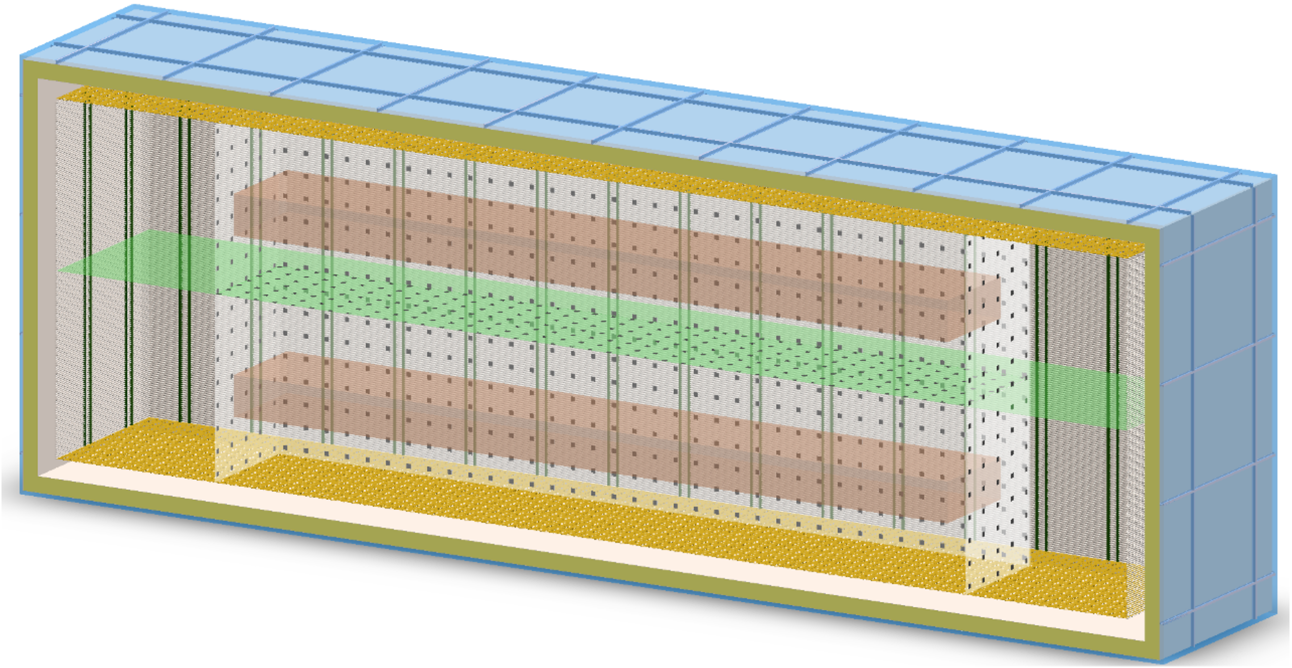
WIMP Dark Matter

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:		< 1.9×10^8	
		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



Summary

- Low background module could enhance program of DUNE-like detector:
  - Solar neutrinos
  - NSI
  - Supernova detection
  - Neutrinoless double beta decay
  - WIMP dark matter
  - …
- Can be achieved with:
  - Shielding
  - Background control
  - Enhanced light detection



Further Details

- Low background module LOI:
  - https://www.snowmass21.org/docs/files/summaries/NF/SNOWMASS21-NF10_NF4-CF1_CF0-IF8_IF0-UF1_UF3-137.pdf
- White paper close to completion

Snowmass2021 - White Paper

Low Background kTon-Scale Liquid Argon Time Projection Chambers

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