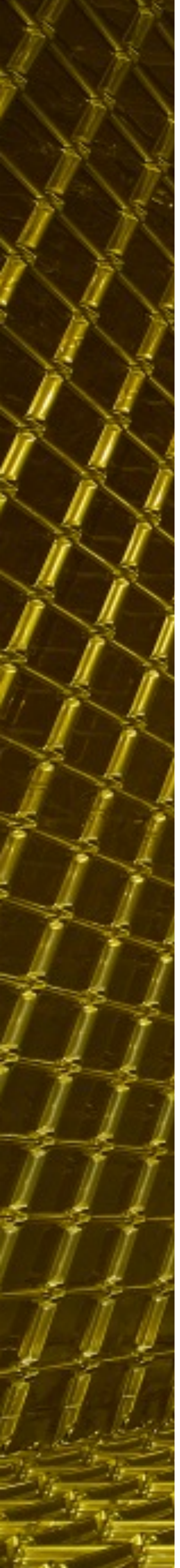

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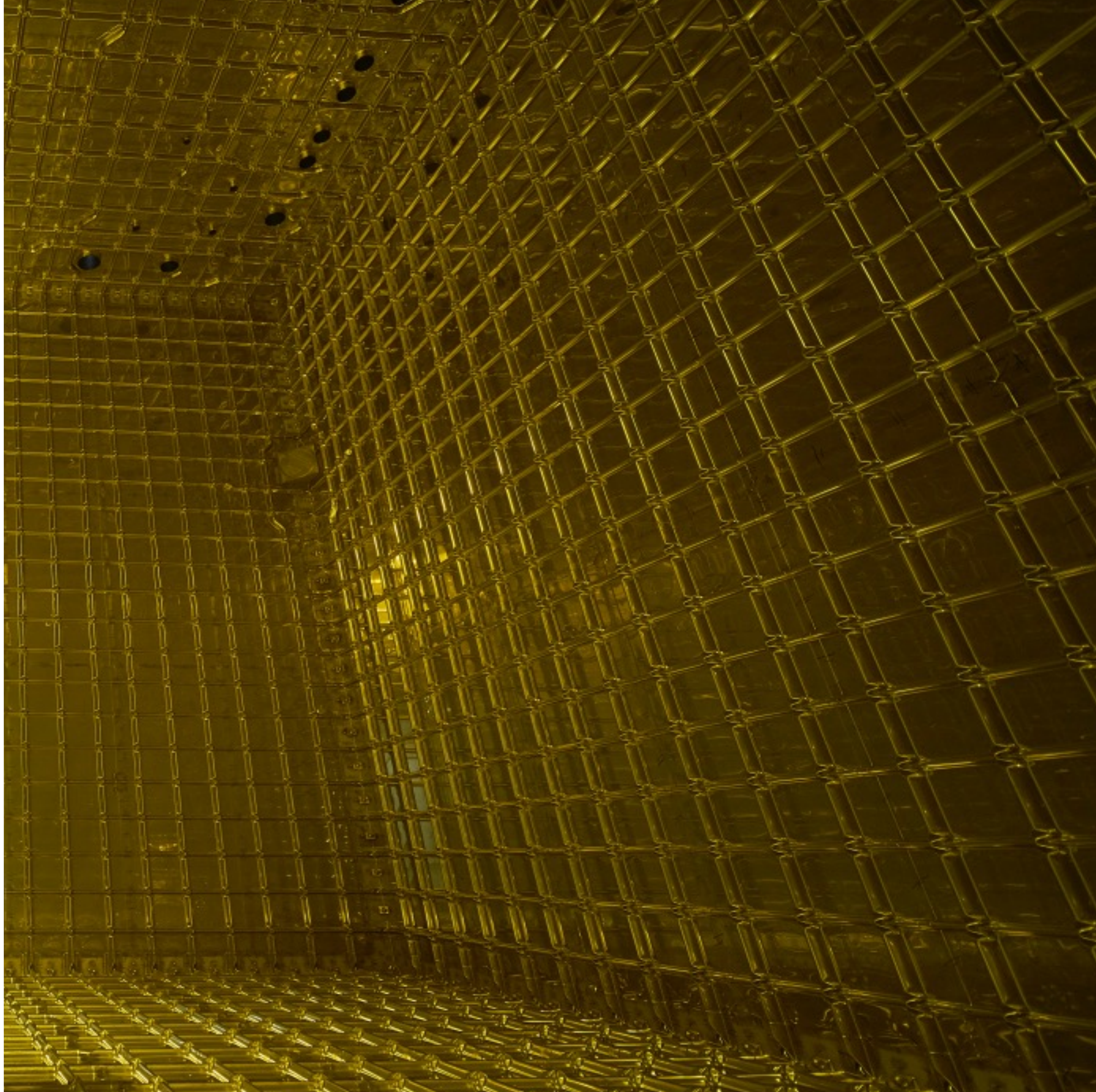
A SURF Low Background Module

Chris Jackson

14th May 2024

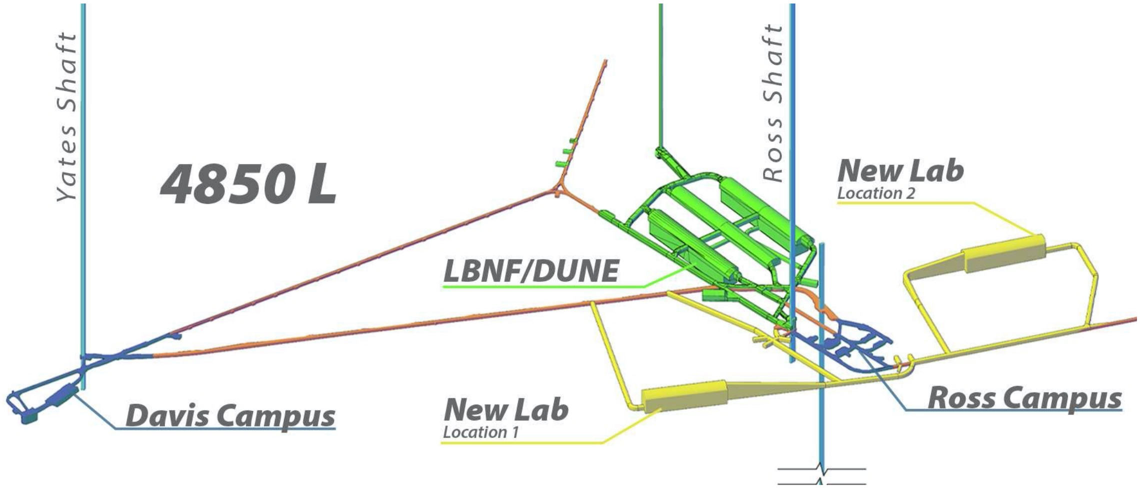


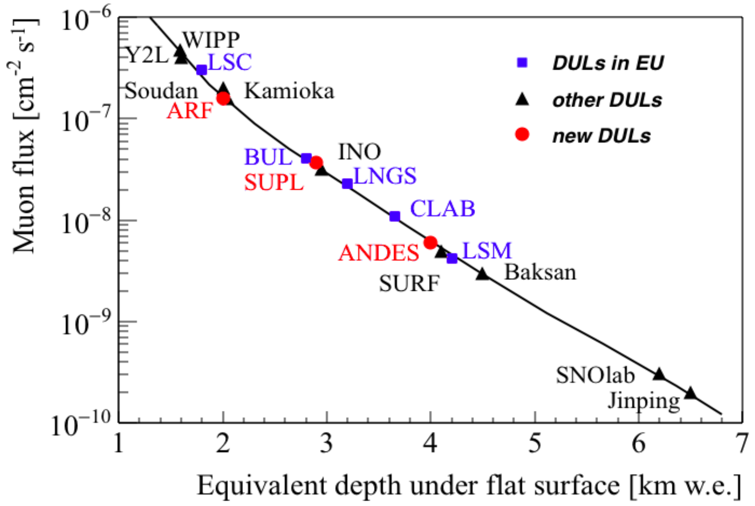
U.S. DEPARTMENT OF ENERGY BATTELLE

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

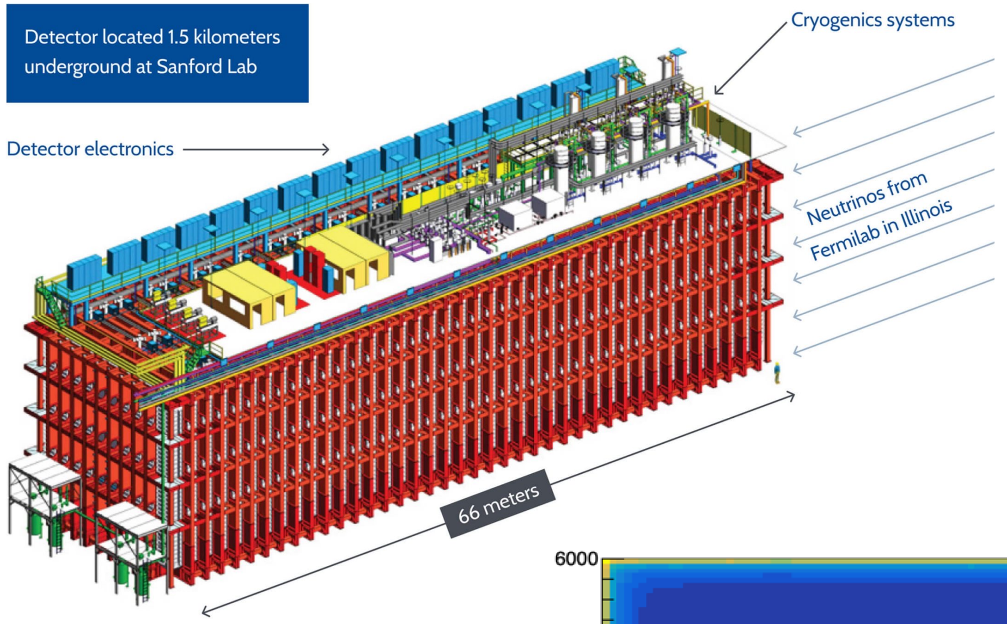
Dune has great low background potential…

… it is deep

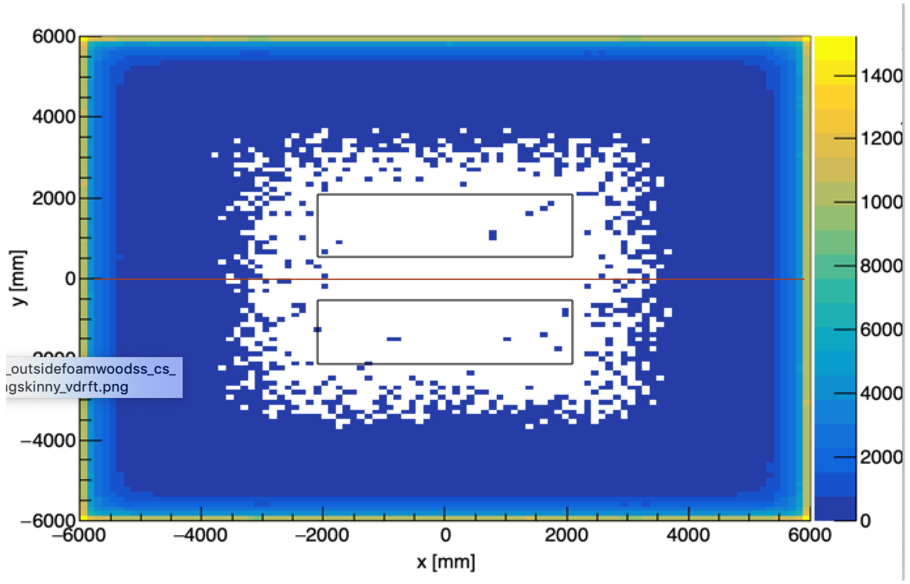




Ianni, TAUP 2017



… it is big

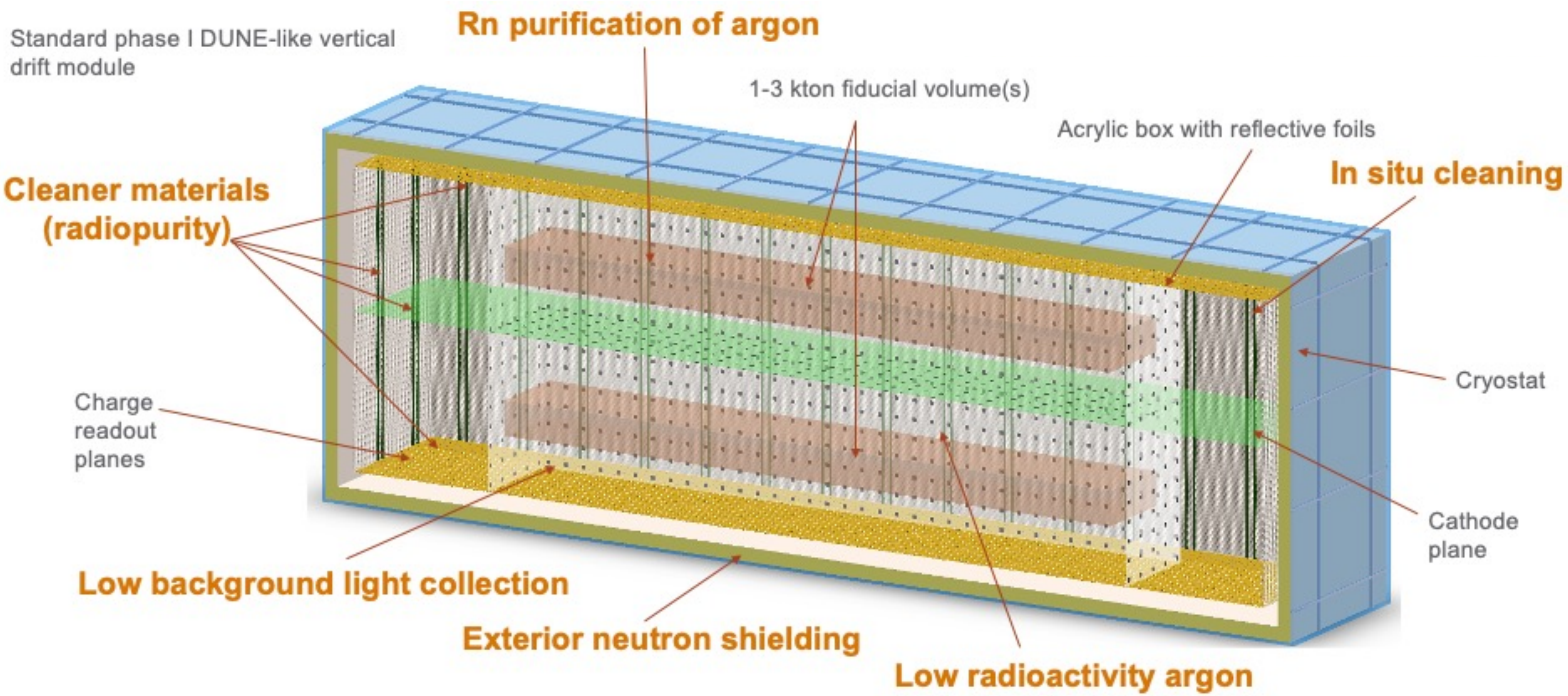


Neutron nuclear recoil events within a single DUNE module

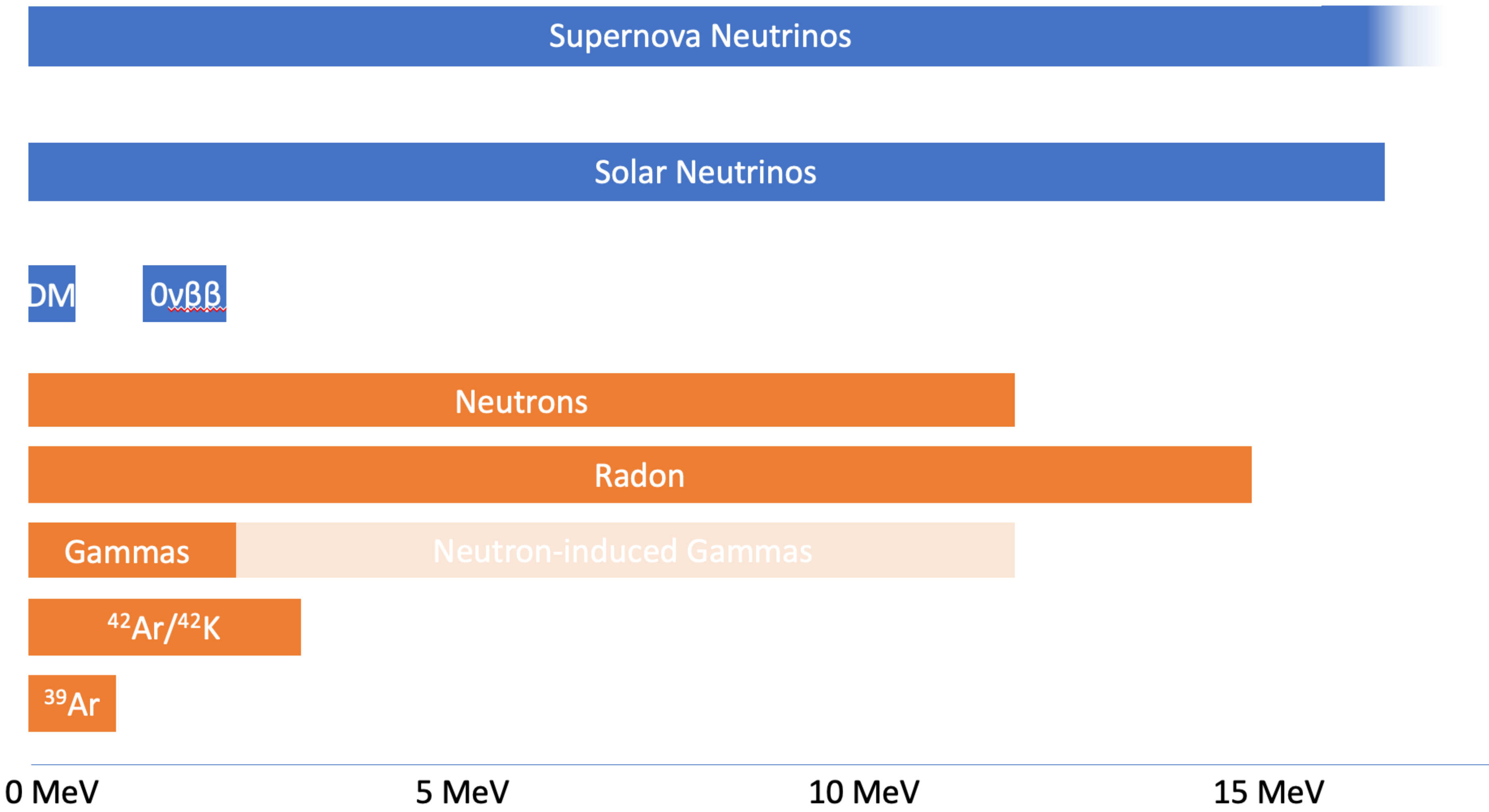
SURF Low Background Module Concept

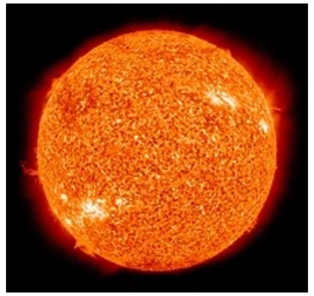
- Build a **low background, low threshold detector** in a DUNE cryostat
  - Enhance sensitivity to low energy physics
  - Do not perturb the neutrino oscillation goals
- Requirements:
  - External shielding
  - Internal background control
  - Enhanced light sensitivity
- Use solutions demonstrated already in low background experiments
  - Main R&D developments required is ‘DUNE-scale’ application
- Will focus on radioactive background control in this talk
  - Applicable to many DUNE Phase 2 concepts

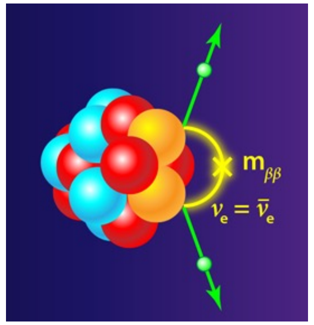
SURF Low Background Module Concept

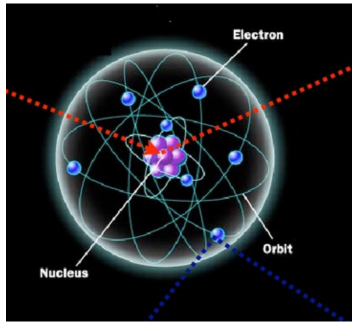


Low Background Physics

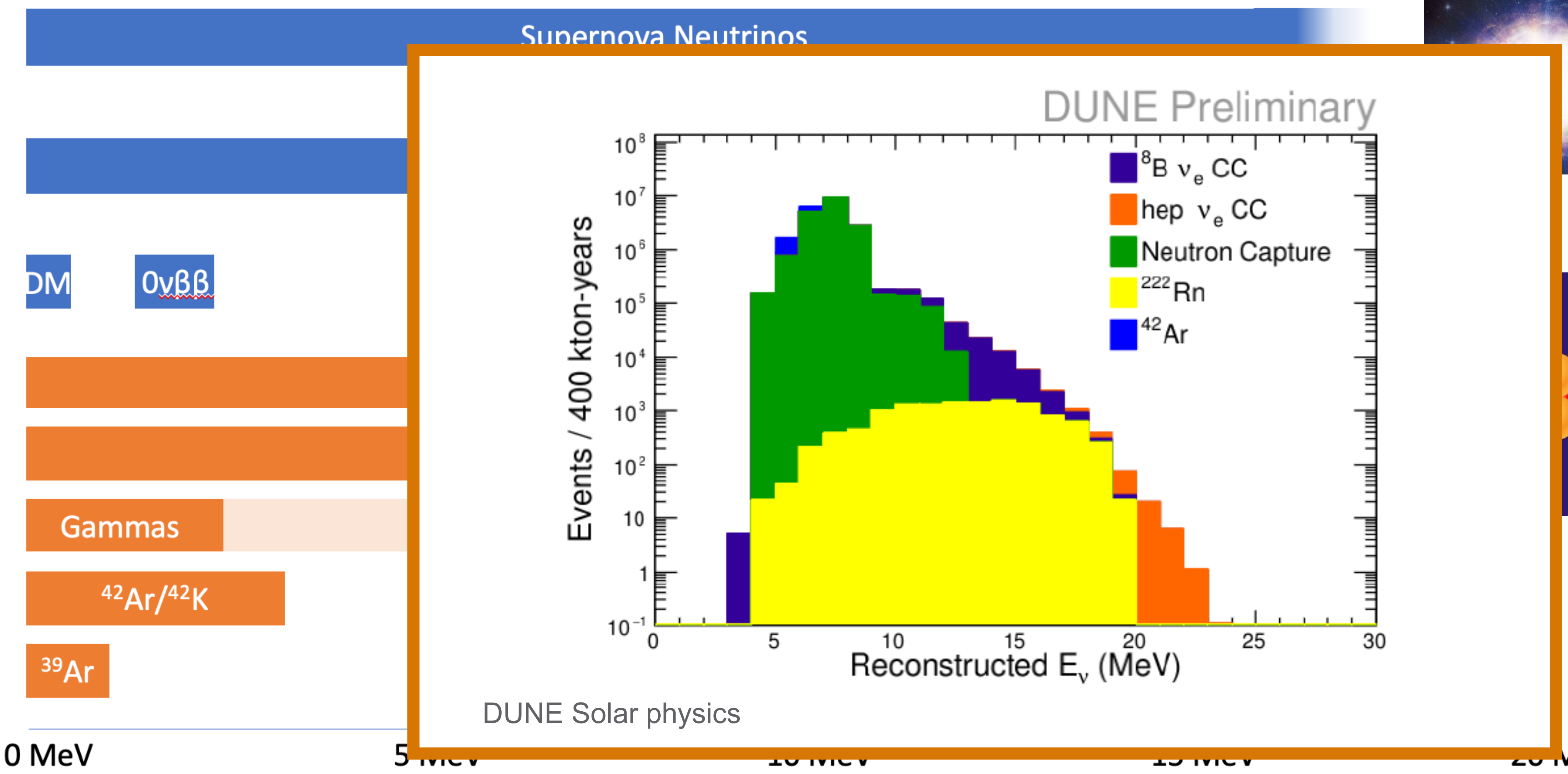


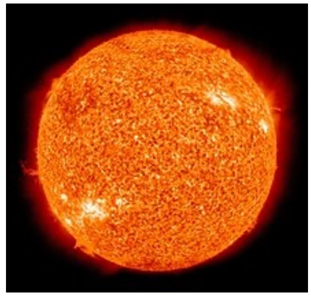


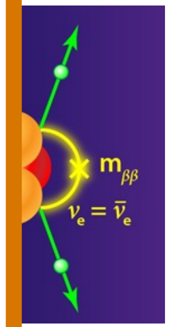


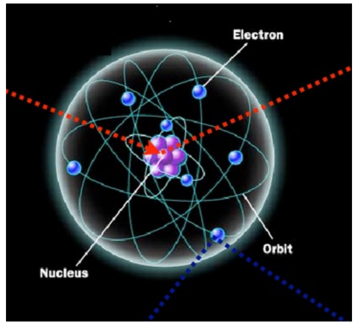


Low Background Physics

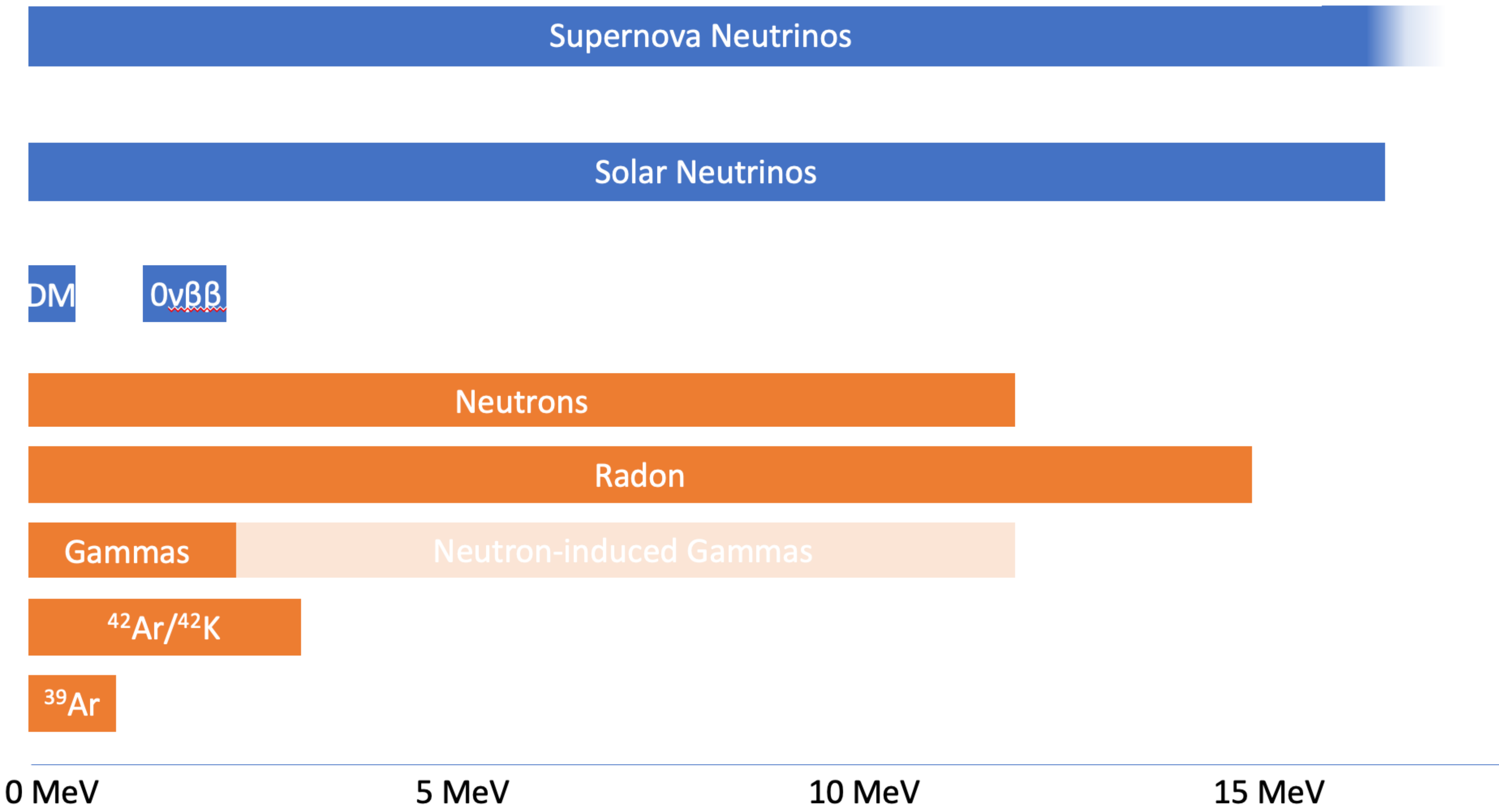


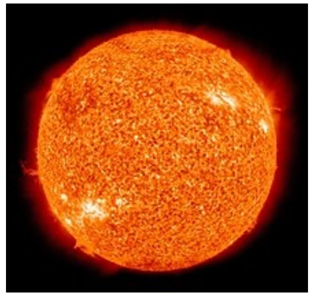


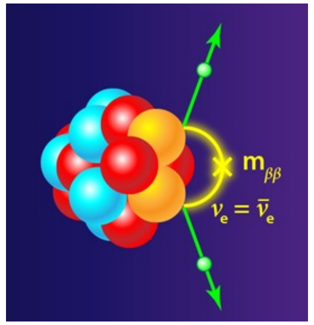


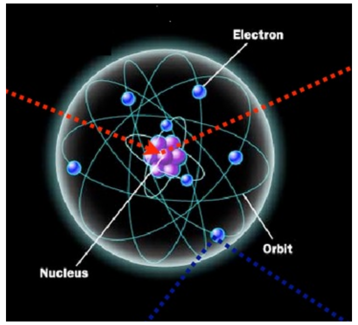


Low Background Physics

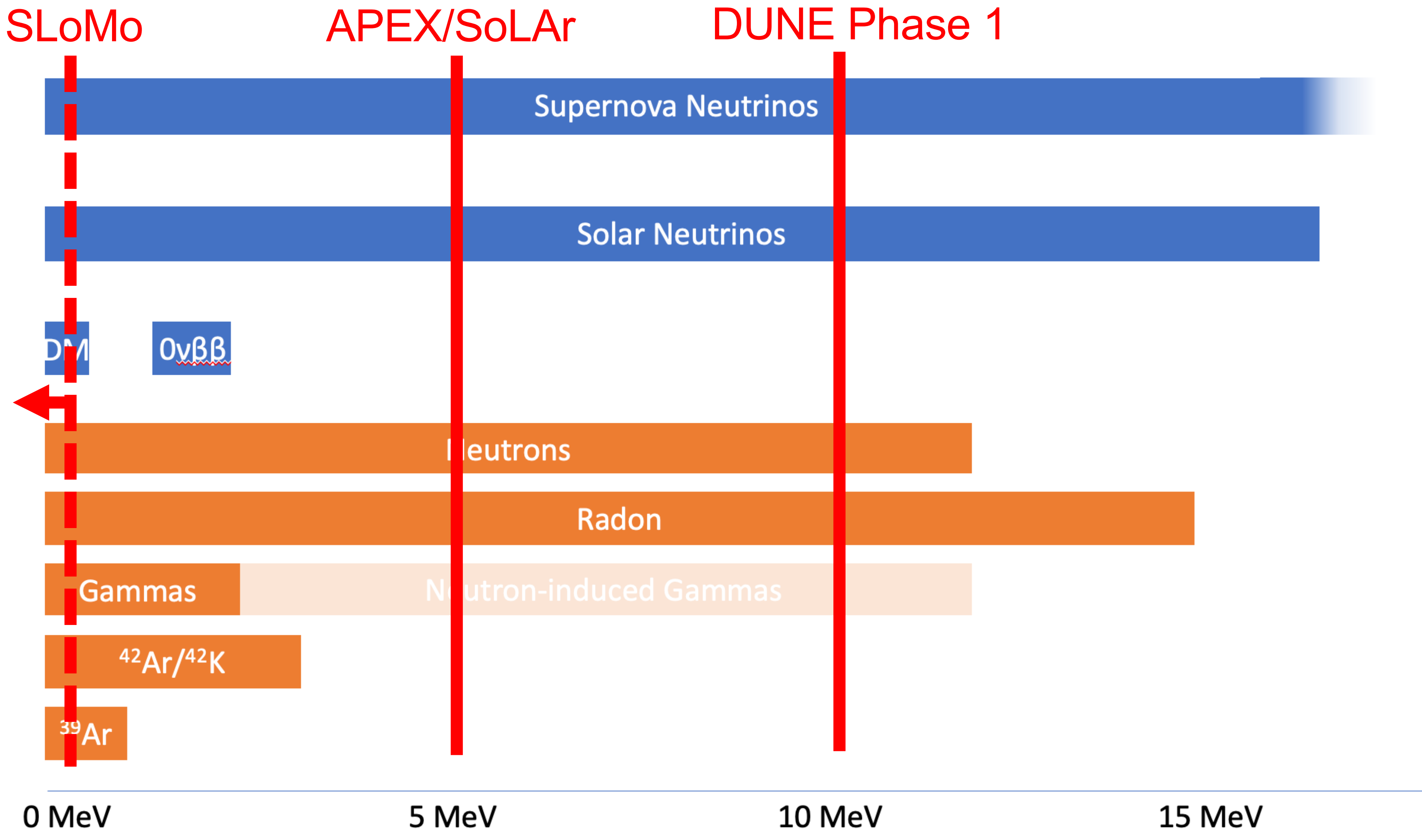


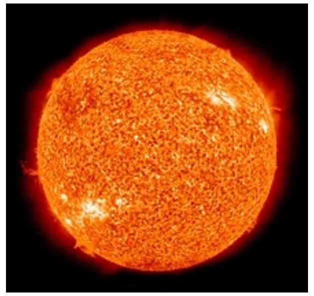


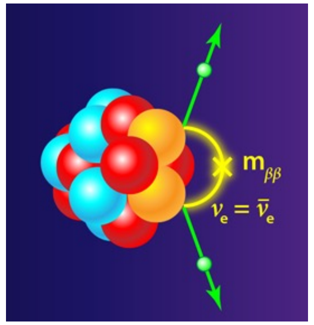


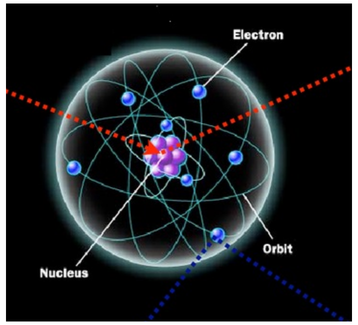


Low Background Physics

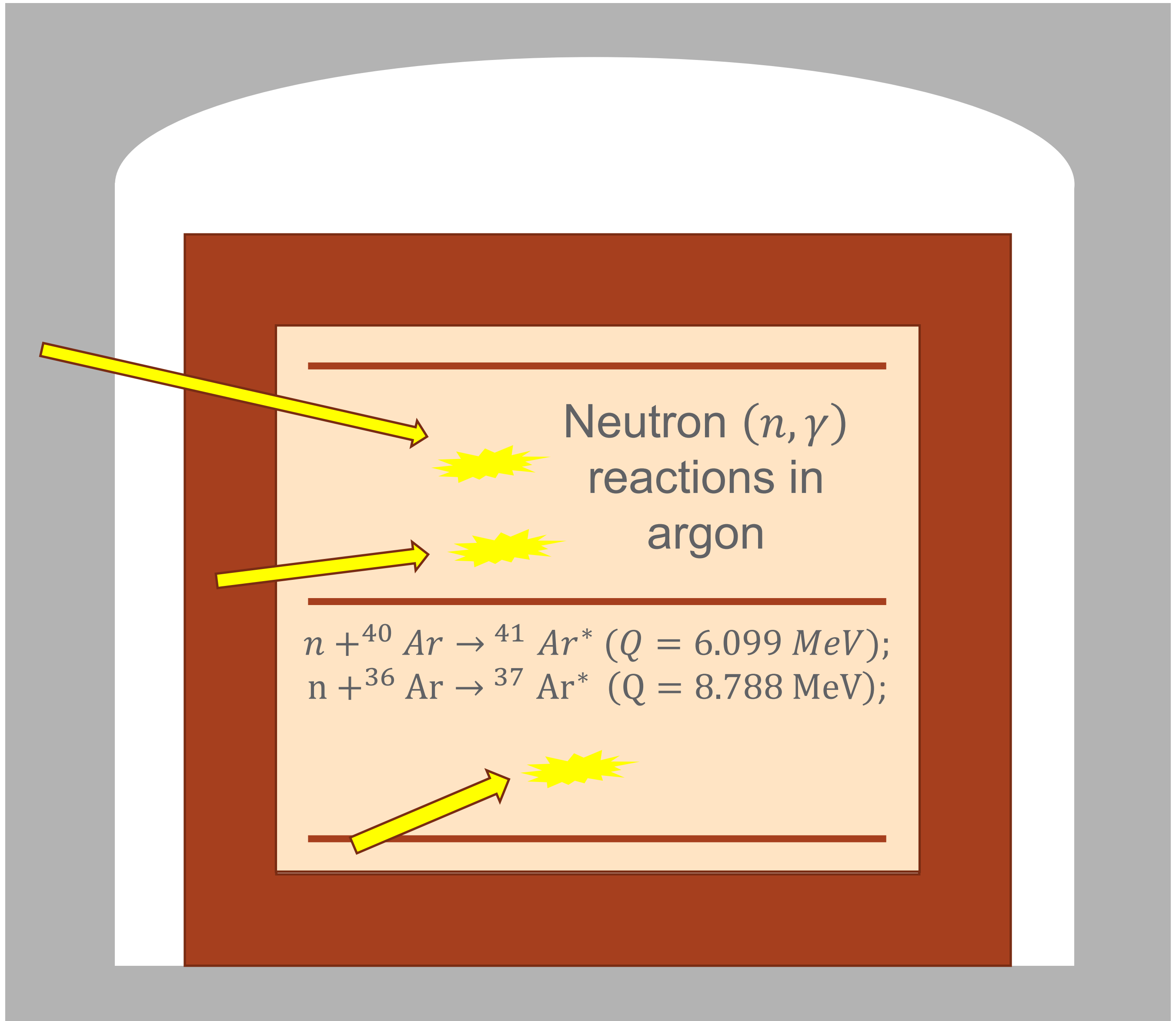




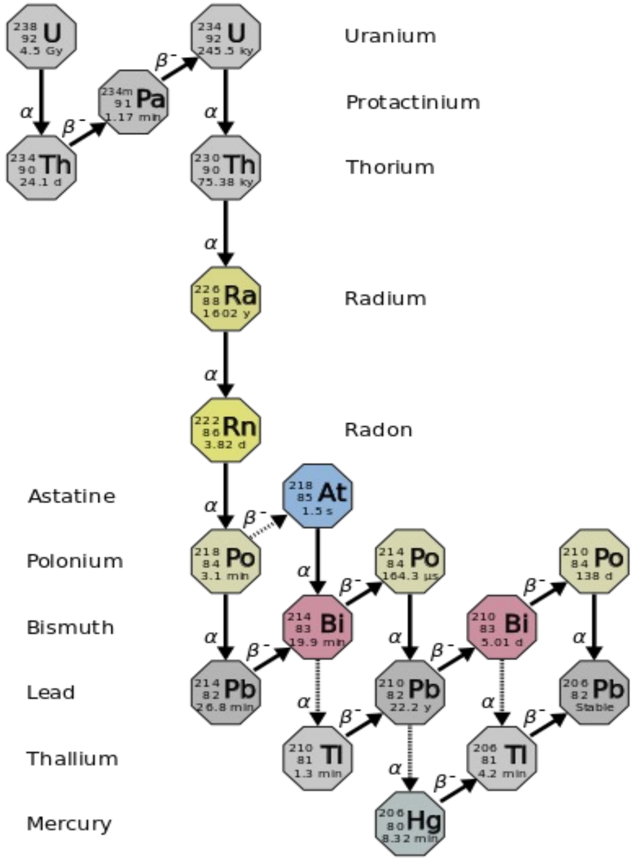


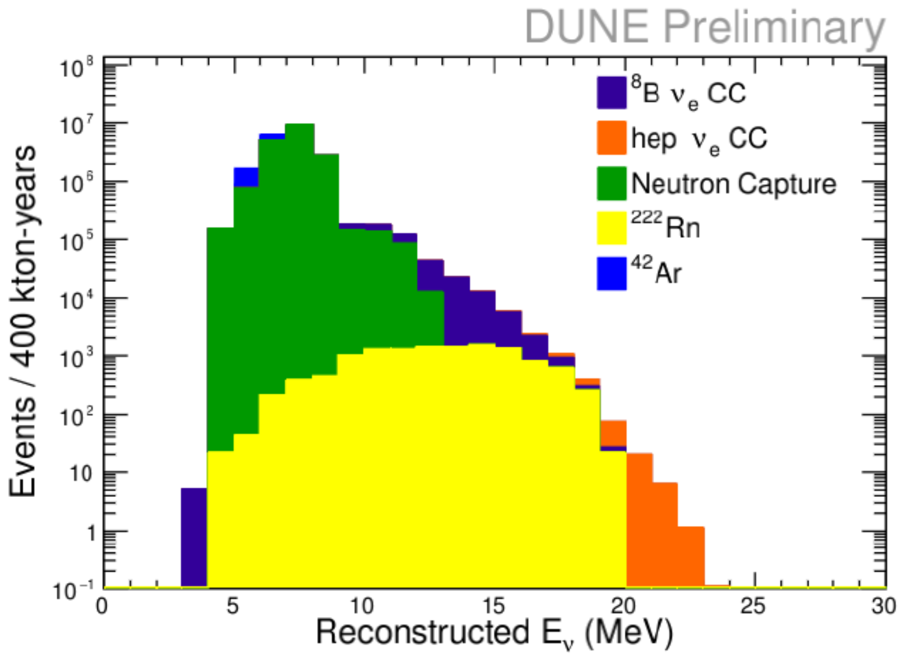


Neutron Backgrounds

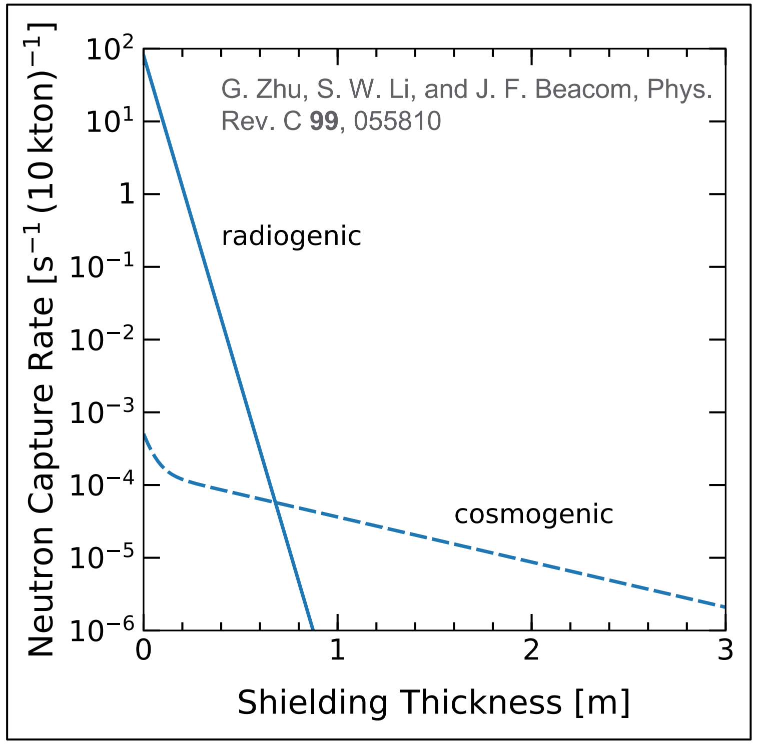


Main sources:Cavern rock/shotcrete/concrete, Cryostat, Detector Components, …





Neutron Shields



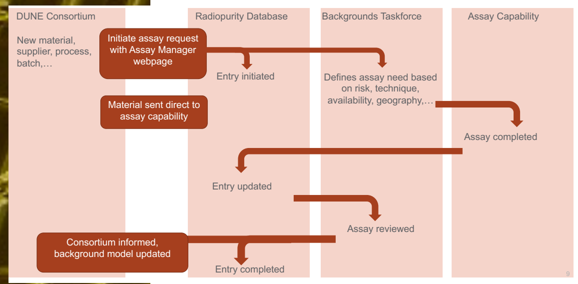
- Neutron shielding
  - No water shield in current DUNE design
  - 40 cm of water shielding around detector (proposed by Capozzi, Li, Zhu and Beacom)
    - ✓ ~3 order of magnitude reduction

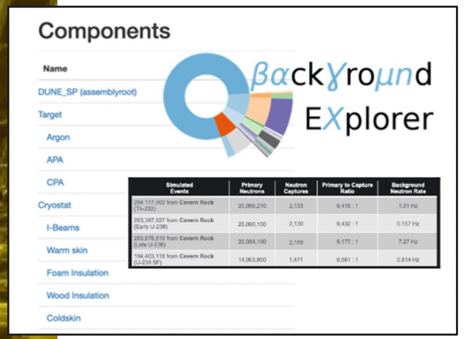
Cryostat design will be important for lower backgrounds

- Internal shielding options
  - Alternate cryostat designs to increase shielding:
    - ✓ High density R-PUF foam
    - ✓ Boron, Lithium or Gadolinium doped layers
    - ✓ ~1 order magnitude reduction
  - Planes of (doped) acrylic possible as shielding within the LAr
    - ✓ DarkSide-20k solution

Internal Detector Background Control

- Must lower unshielded internal neutron sources by same amount as shielded external sources to remain subdominant
- LZ has achieved 10^5 reductions beyond DUNE expected
- Requires careful QA/QC program
  - Less stringent than dark matter experiments…
  - …but at unprecedented scale (e.g. 1 kton stainless steel in cryostat!)





Assays

- HPGe, ICP-MS,…
- Leverage worldwide resources

Radiopurity Database

- Track 1000s of measurements
- Optimize design of assay program

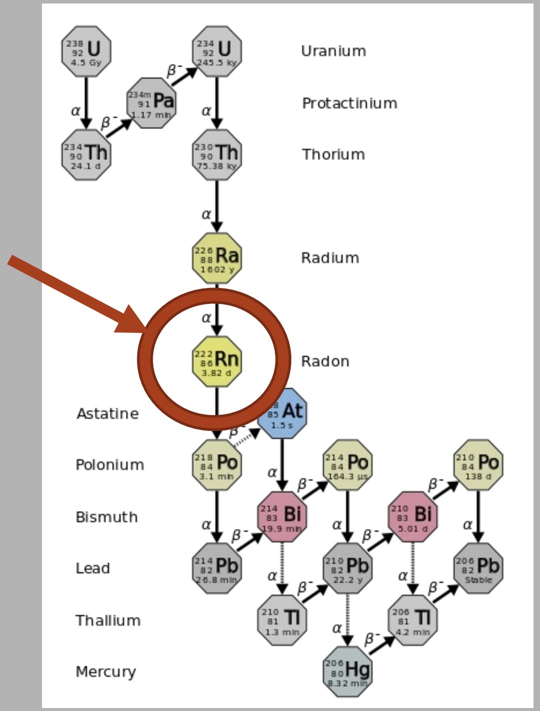
Detector Simulation

- Full detector simulations
- Rapid triage of assay results

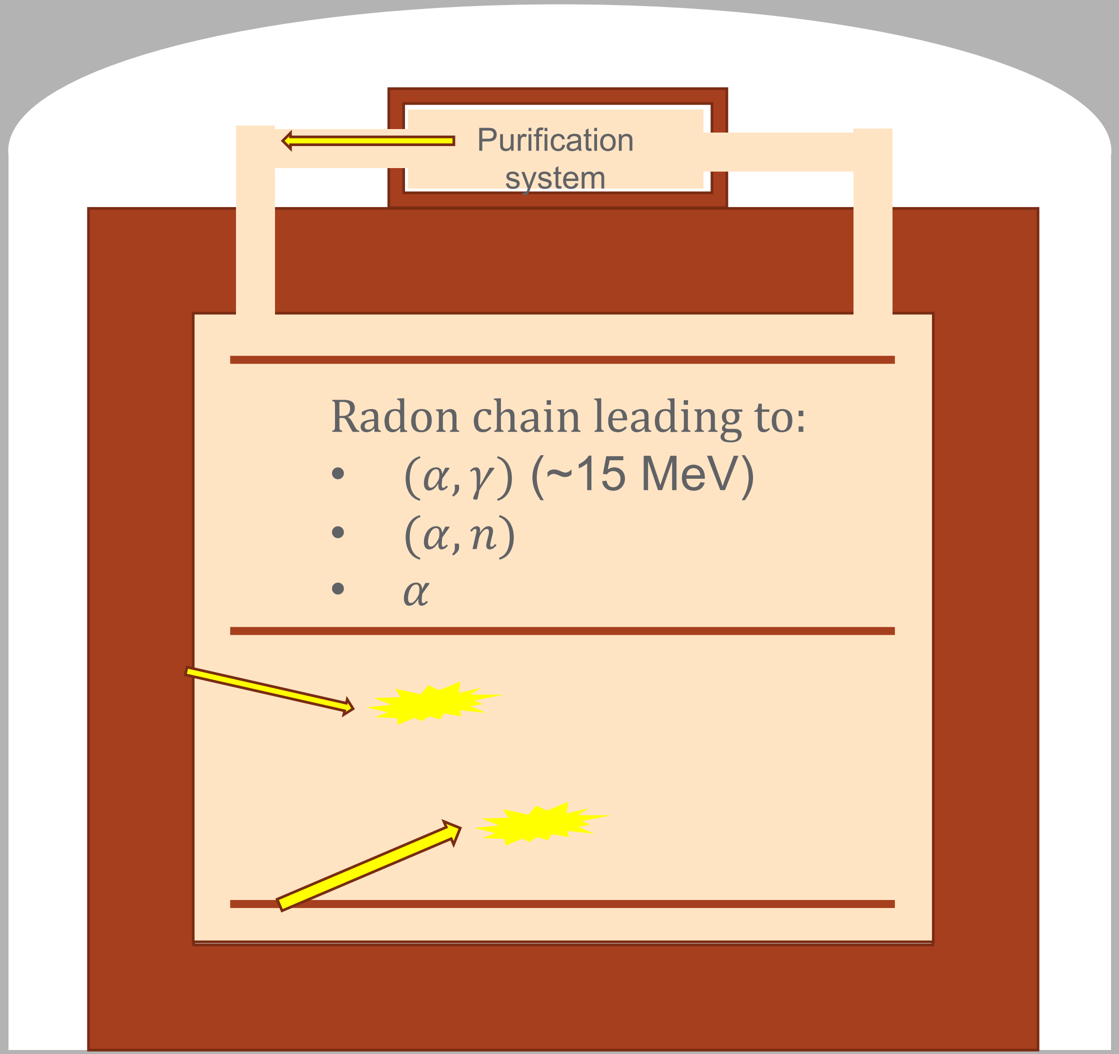
Large-scale assay program

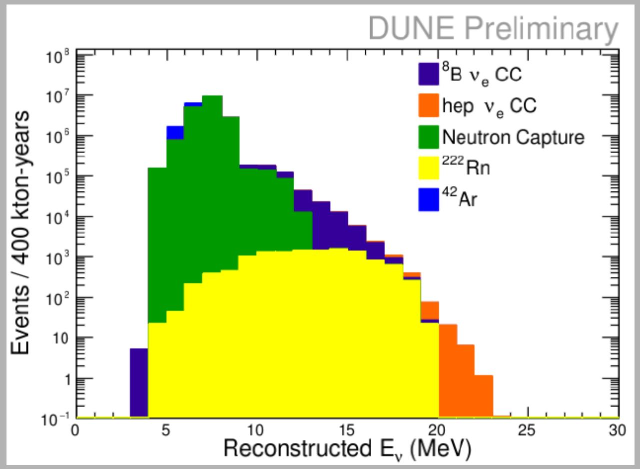
Radiopurity should be specified for detector components. Opportunity to use experience with phase 1

Radon Backgrounds



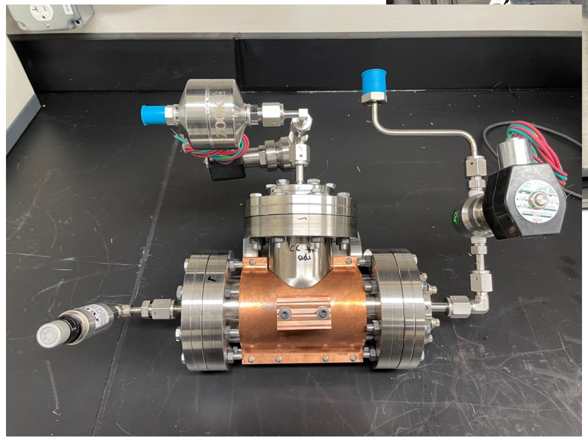
- Radon is highly mobile and can emanate and move within argon
- Main sources:
  - Purification system
  - Cryostat
  - Detector Components
  - …





- DUNE phase 1 targets mBq/kg level
  - Low emanation from purification system measured
  - But many unmeasured components remain
- Target: 10^{-3} radon reduction
- Dark matter experiments have achieved 0.2 µBq/kg

Radon Reduction



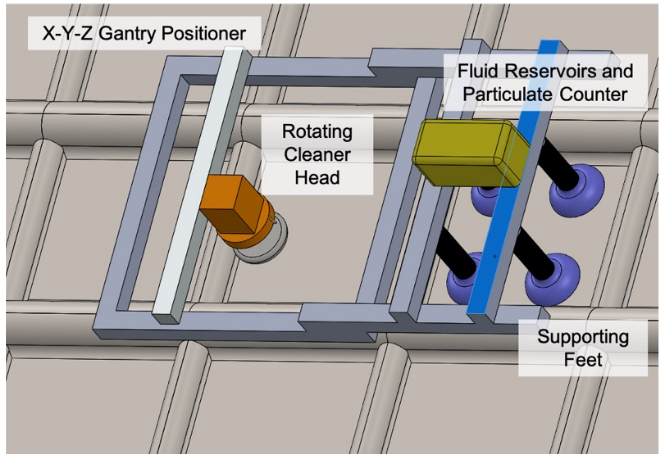
Prototype cryogenic radon emanation bench

Radon removal:

- Argon purification via inline radon trap
  - ✓ MicroBoone filtration system (arXiv:2203.10147 [physics.ins-det])
    - Report copper filter reduction in radon (97 – 99.999%)
      - What is the mechanism?
      - Does it breakdown? Or require cycling?
      - Do we require additional radon purification? (e.g. Radon removal in liquid phase using charcoal - Borexino)

Radon control:

- Emanation measurement materials campaign
  - ✓ Large QA/QC program, new cryogenic systems, high throughput developments
- Surface treatments
  - ✓ Cleaning, passivation, electropolish, electroplate,…
- Dust control
  - ✓ Need reliable, repeatable large-scale cleaning techniques
- Radon reduction system during installation and operation
- Analysis methods (PSD)
  - ✓ Timing is key (doping, reflections)



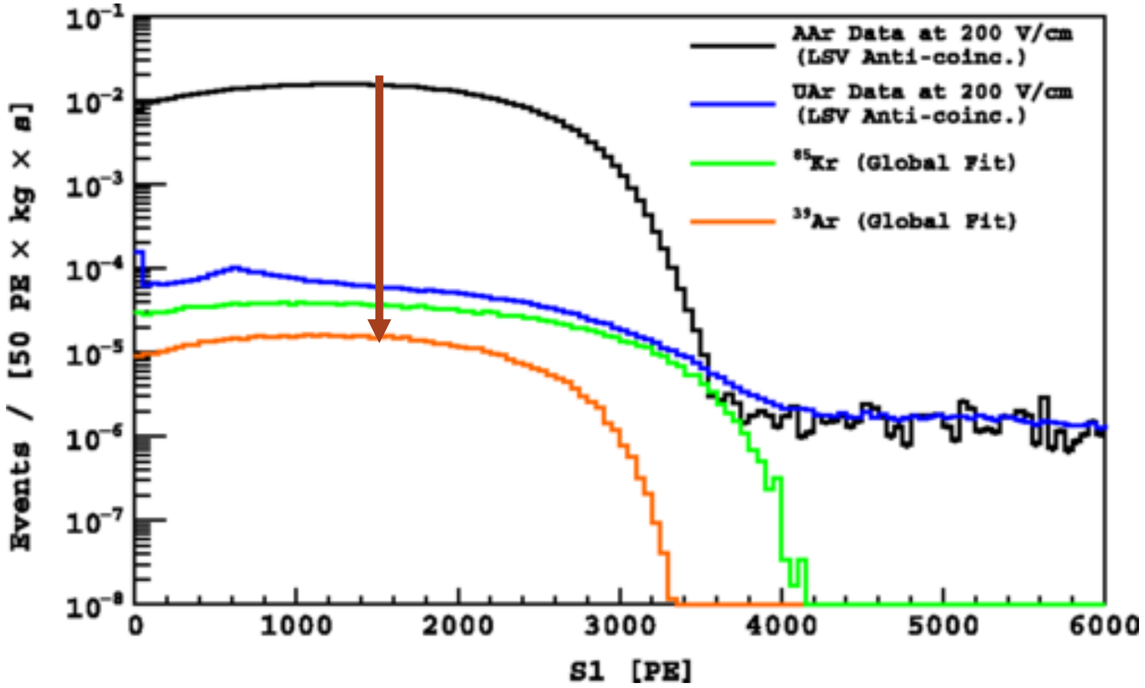
Multiple radon reduction paths to be explored

What is Low-Radioactivity Underground Argon

- Atmospheric argon:
  - ^{39}Ar: 1 Bq/kg (10 MHz/module) – 0.57 MeV endpoint
  - ^{42}Ar: 0.1 mBq/kg – 0.6 MeV endpoint but…
  - Decays to ^{42}K with 3.5 MeV endpoint

- Underground sources of depleted argon exist
  - Demonstrated in DarkSide-50
    - ✓ 1400x reduction ^{39}Ar (air contamination = could be lower)
    - ✓ Larger reduction of ^{42}Ar likely
  - From CO_2 wells in Cortez, CO
  - Planned for DarkSide-20k and GADMC
  - Urania plant production target: 300 kg/day
  - Only vetted source but not large enough for a DUNE-like module

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



^{39}Ar rate: x1400 reduction

Next Generation Production

- Will require large-scale, cost-effective production
- This require:
  - High concentration/chemically enriched underground source
  - Should be parasitic to major underground gas operation
  - Ideally commercial supplier produces argon
    - ✓ Could reuse existing Urania infrastructure

White paper:
A Facility for Low-Radioactivity Underground Argon
arXiv:2203.09734 **[physics.ins-det]**

- PNNL working to explore large scale underground argon sources
  - Preliminary gas analysis indicates mantle origin.
  - **Supplier:** 3 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 for 10 kton+ scales

NOTE: These are very rough estimates.

^{42}Argon Production Underground

^{42}Ca stable 0.647%	^{43}Ca stable 0.135%	^{44}Ca stable 2.086%	^{45}Ca 162.7 d	^{46}Ca stable 0.004%
^{41}K stable 6.7%	^{42}K 12.36 hr	^{43}K 22.3 hr	^{44}K 22.1 m	^{45}K 17.8 m
^{40}Ar stable 99.603%	^{41}Ar 1.83 hr	^{42}Ar 33 yr ?	^{43}Ar 5.4 m	^{44}Ar 11.87 m
^{39}Cl 55.6 m	^{40}Cl 1.38 m	^{41}Cl 34 s	^{42}Cl 6.8 s	^{43}Cl 3.1 s
^{38}S 2.84 hr	^{39}S 11.5 s	^{40}S 9 s	^{41}S 2 s	^{42}S 1 s

Atmospheric Argon:

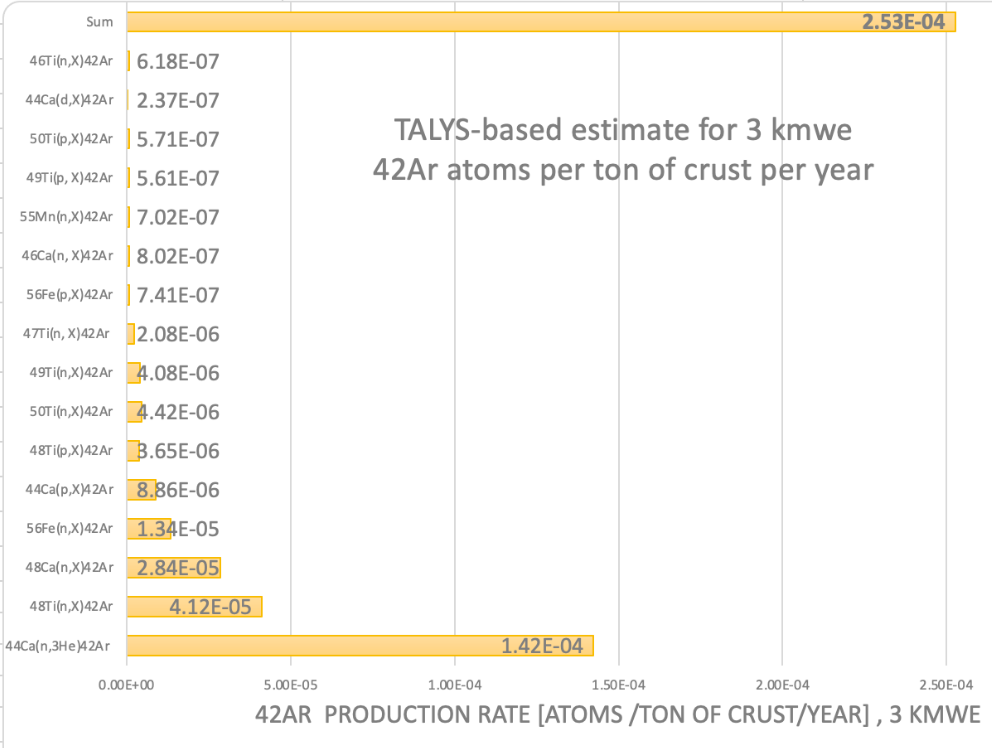
- **^{39}Ar: 1 Bq/kg** (10 MHz/ DUNE module)
- **^{42}Ar: 0.1 mBq/kg**

Radiogenic Production Underground:

- ^{39}K(n,p)^{39}Ar primary ^{39}Ar production underground
  - At least 1500x lower than AAr
- No clear radiometric path for ^{42}Ar

Cosmogenic Production Underground:

- Production calculation: 3 x 10^{-3} ^{42}Ar per ton of crust per year at 3 km w.e.
  - 7 orders of magnitude less than ^{39}Ar at this depth
- But many uncertainties:
  - Crust or mantle origin
  - How much argon diffuses into gas field
- Likely >10^{10} suppression in rate compared to atmosphere



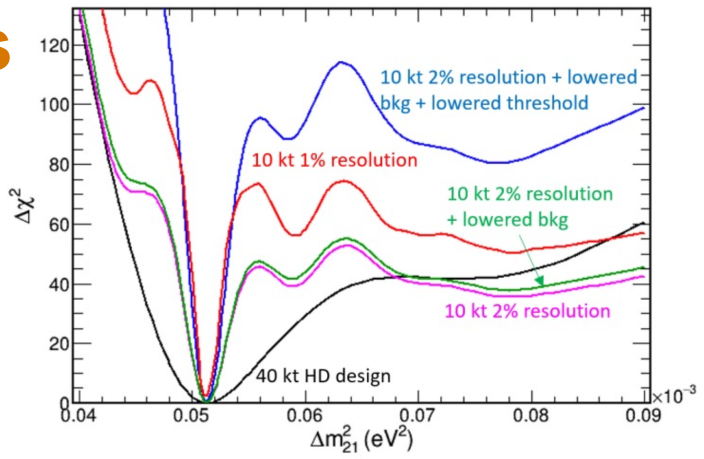
Sharma Poudel, LRT 2022, paper in preparation

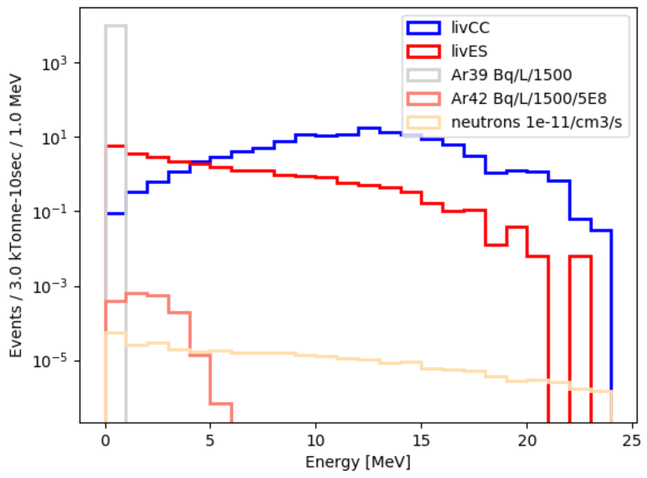
Low Background Module Concept

SLoMo (SURF Low Background Module)

Solar Neutrinos

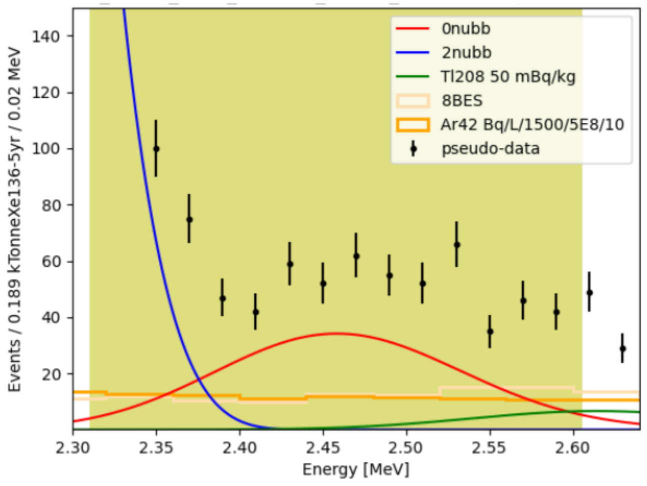
- Precision Δm^2_{21}
- NSI constraints
- Precision CNO, test solar metallicity





Supernova Neutrinos

- Lower threshold, elastic scatters
- Early- and late-time information
- Detection beyond Magellanic Cloud
- CEvNS glow

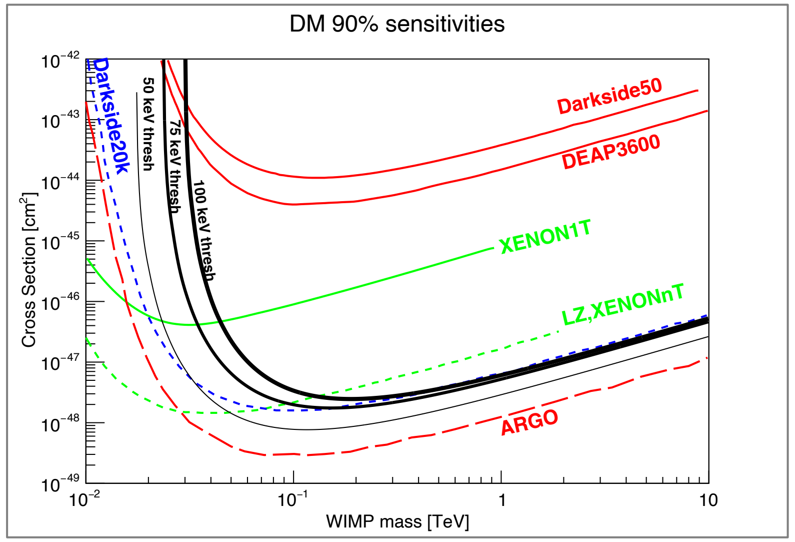


Snowmass White Paper:

Low Background kTon-Scale Liquid Argon Time Projection Chambers

A. Avasthi[1], T. Bezerra[2], A. Borkum[2], E. Church[3], J. Genovesi[4], J. Haiston[4], C. M. Jackson[3], I. Lazanu[5], B. Monreal[1], S. Munson[3], C. Ortiz[6], M. Parvu[5], S. J. M. Peeters[2], D. Pershey[6], S. S. Poudel[3], J. Reichenbacher[4], R. Saldanha[3], K. Scholberg[6], G. Sinev[4], J. Zennamo[7], H. O. Back[3], J. F. Beacom[8], F. Capozzi[9], C. Cuesta[10], Z. Djurcic[11], A. C. Ezeribe[12], I. Gil-Botella[10], S. W. Li[7], M. Mooney[13], M. Sorel[9], and S. Westerdale[14]

Now published: J. Phys. G Nucl. Part. Phys **50** (2023) 060502



Neutrinoless Double Beta Decay

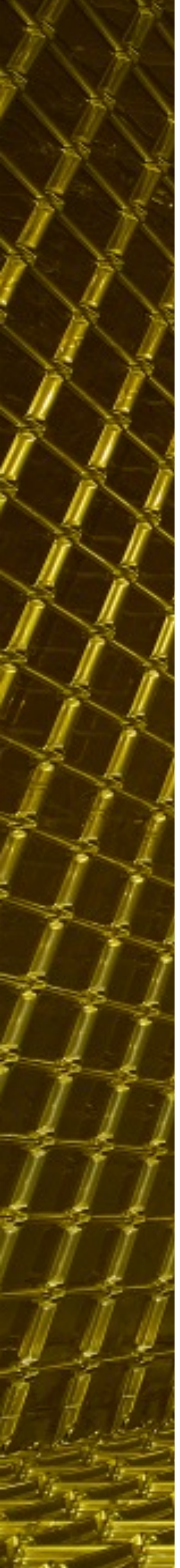
- Confirm ton-scale signal
- Sensitivity beyond inverted hierarchy
- *Requires separate campaign with %-level xenon loading*

WIMP Dark Matter

- Competitive high mass search on fast timescale
- Confirm G2 signal with annual modulation

Conclusions

- Growing interest in lower background and threshold DUNE options:
  - SLoMo, APEX, SoLAr, *LEPLAr, THEIA, …*
- Lower backgrounds possible through multiple, increasingly aggressive, approaches:
  - Materials selection QA/QC
  - Radon reduction
  - Additional shielding
  - Underground argon (*Requires a new source well)
- Expanded physics programs at DUNE possible through these progressively aggressive approaches:
  - Supernova neutrinos
  - Solar neutrinos
  - Potentially neutrinoless double beta decay and WIMP dark matter



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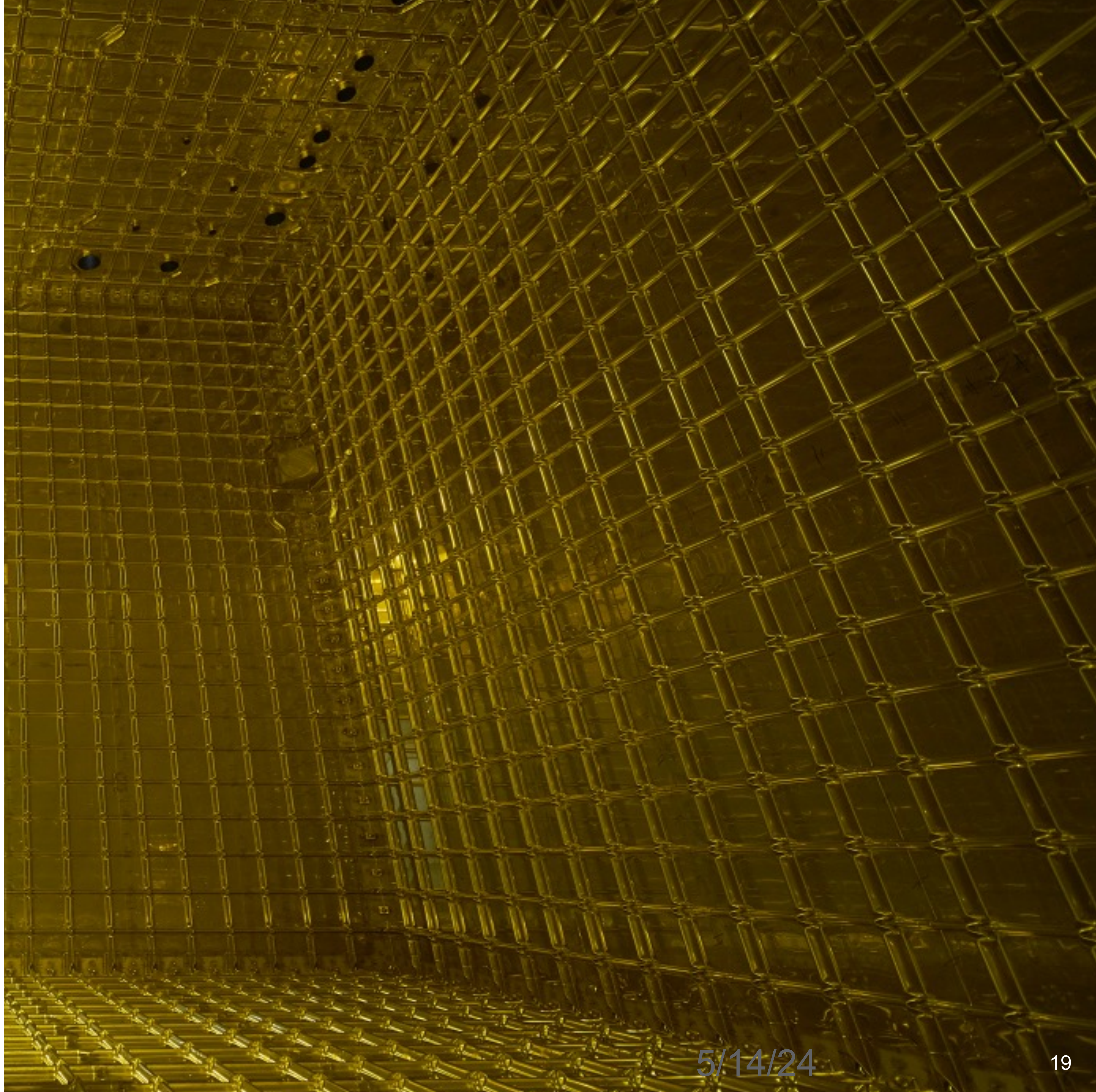
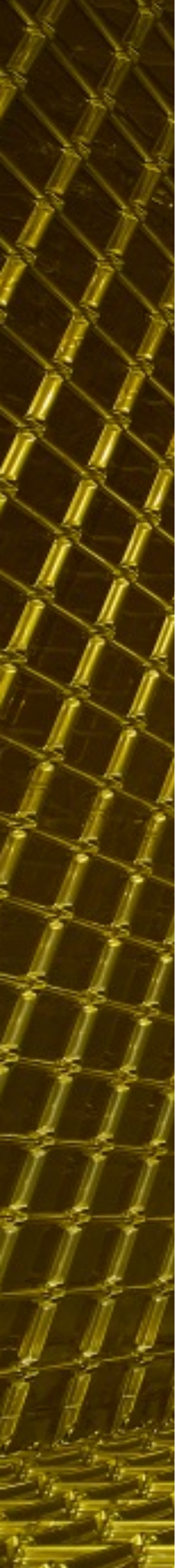
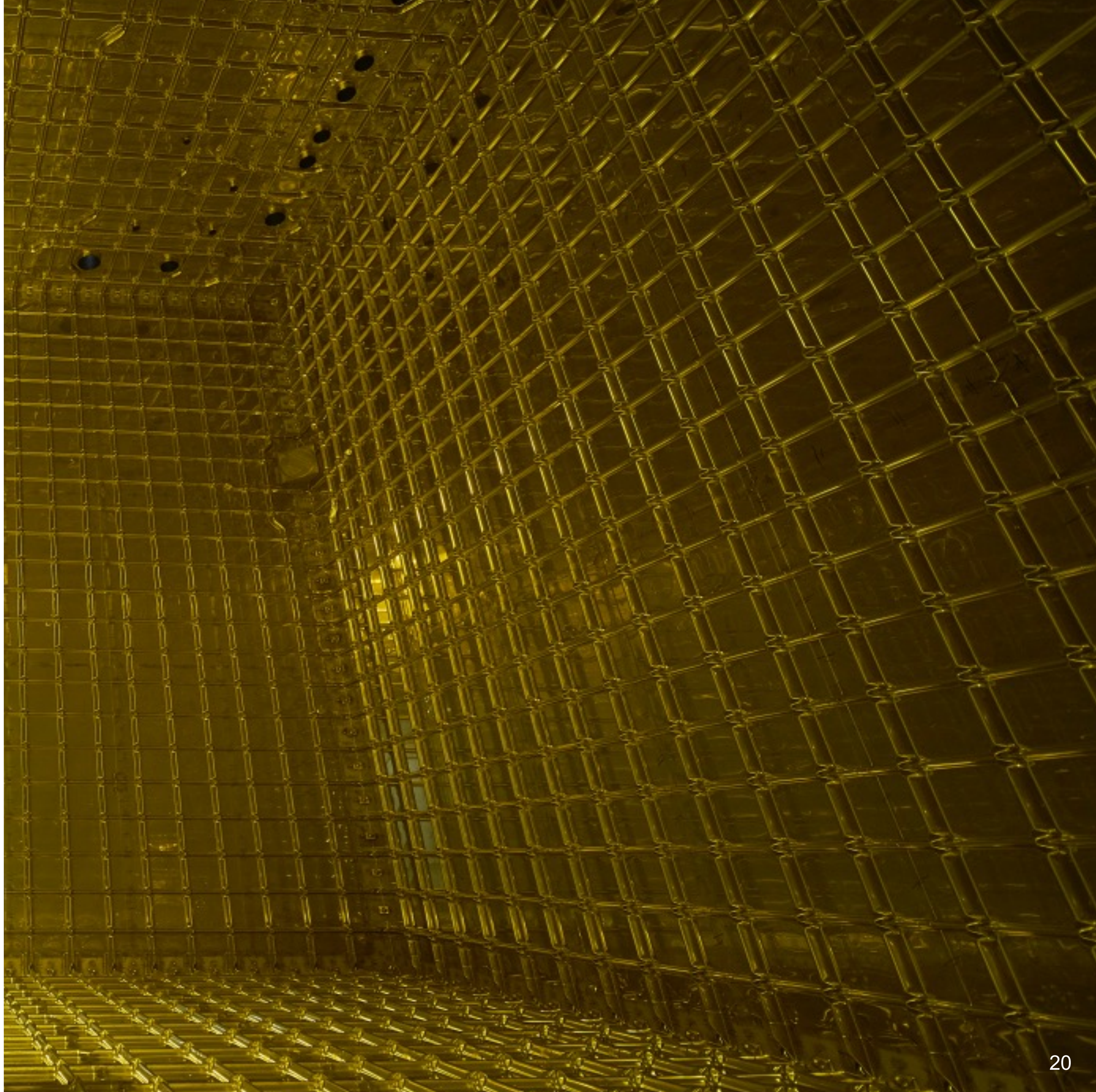
Thank You



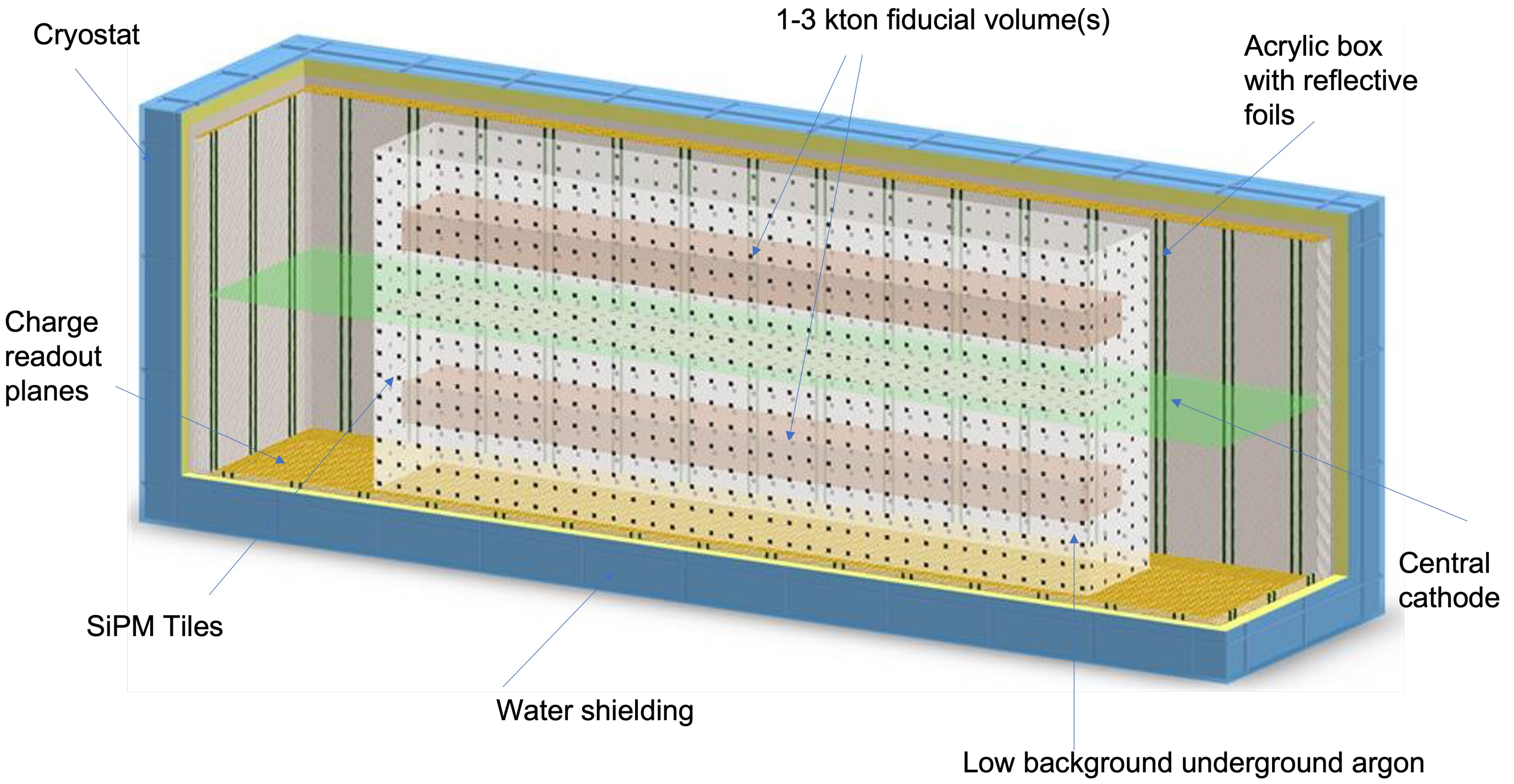


Backup Slides



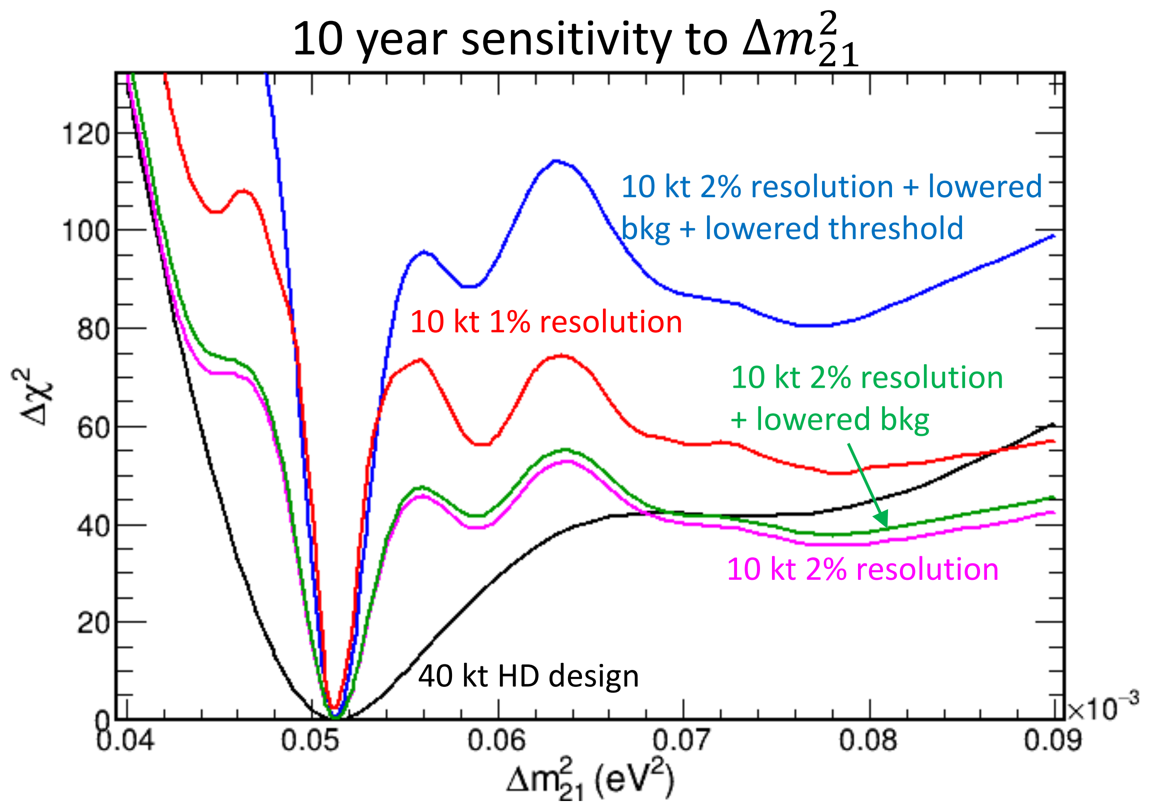
SURF Low Background Module (SLoMo)

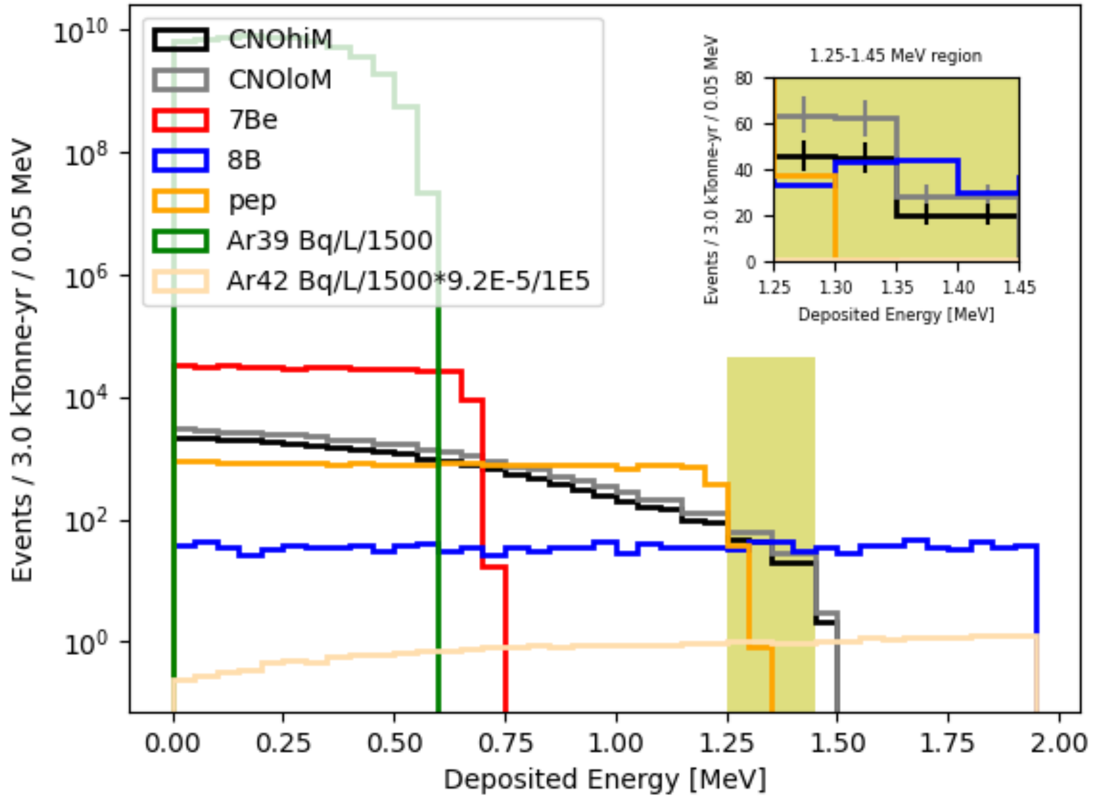
- Development of vertical drift design
- Background Reduction Targets:
  - 10^3 reduction external neutrons
    - ✓ 40 cm water shield outside detector
  - 10^3 reduction internal backgrounds
    - ✓ Largescale materials and assay campaign
    - ✓ Internal shielding in cryostat
  - 10^3 reduction radon
    - ✓ Inline purification system
    - ✓ Emanation control
  - $>10^3$ reduction ^{39}Ar, $>10^8$ reduction ^{42}Ar
    - ✓ Low radioactivity underground argon



- Light Collection Targets:
  - Energy resolution of 2% at 1 MeV (>10% of photons must be collected)
  - Pulse shape discrimination for dark matter search (400 nuclear recoil induced photons at SiPMs surface)
    - ✓ SiPM tiles on acrylic box and cathode plane; reflective coatings on inner walls and anode planes; Argon purity enhanced

Solar Neutrinos





Precision Δm^2_{21} measurements:

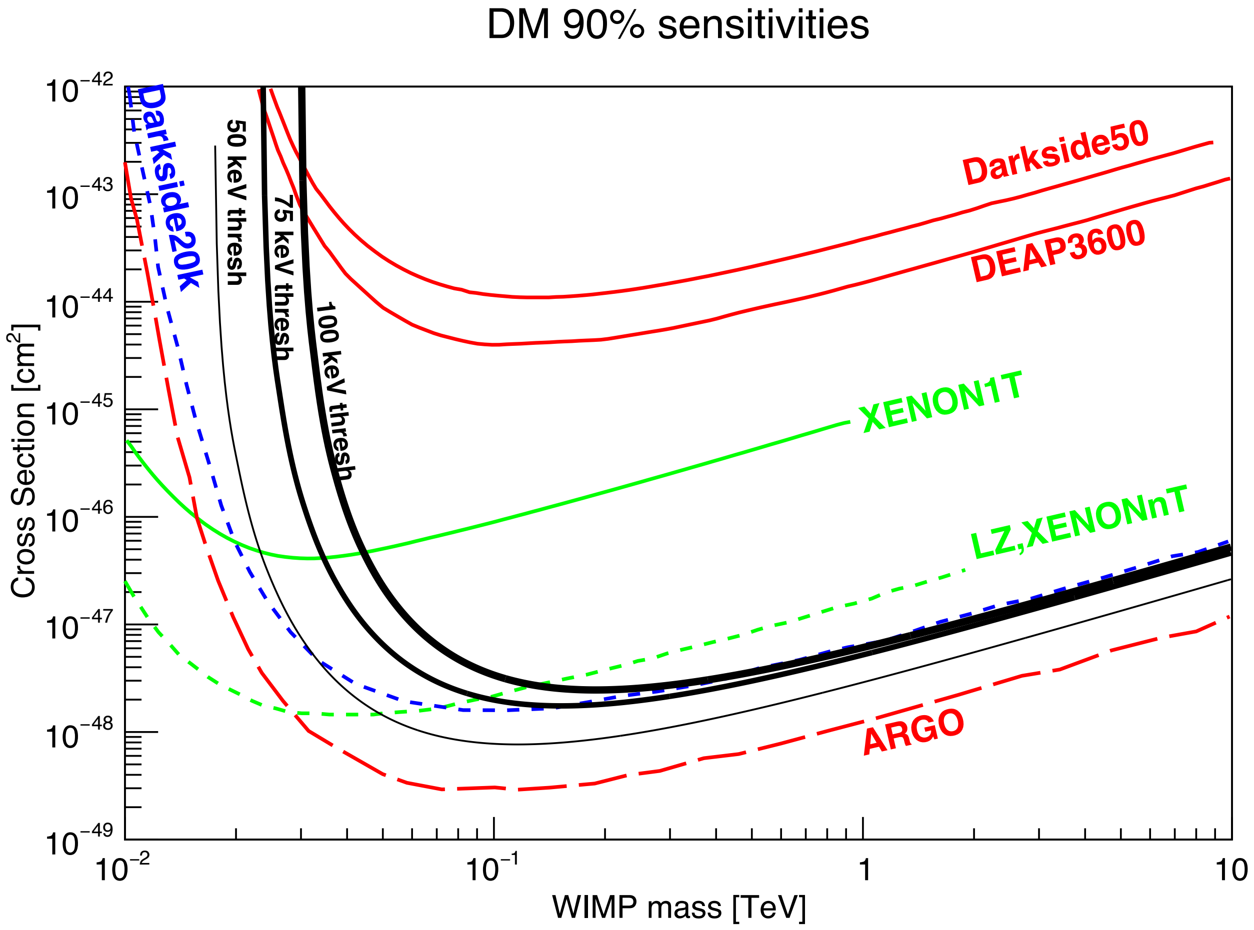
- Test solar/reactor tensions
- NSI constraints

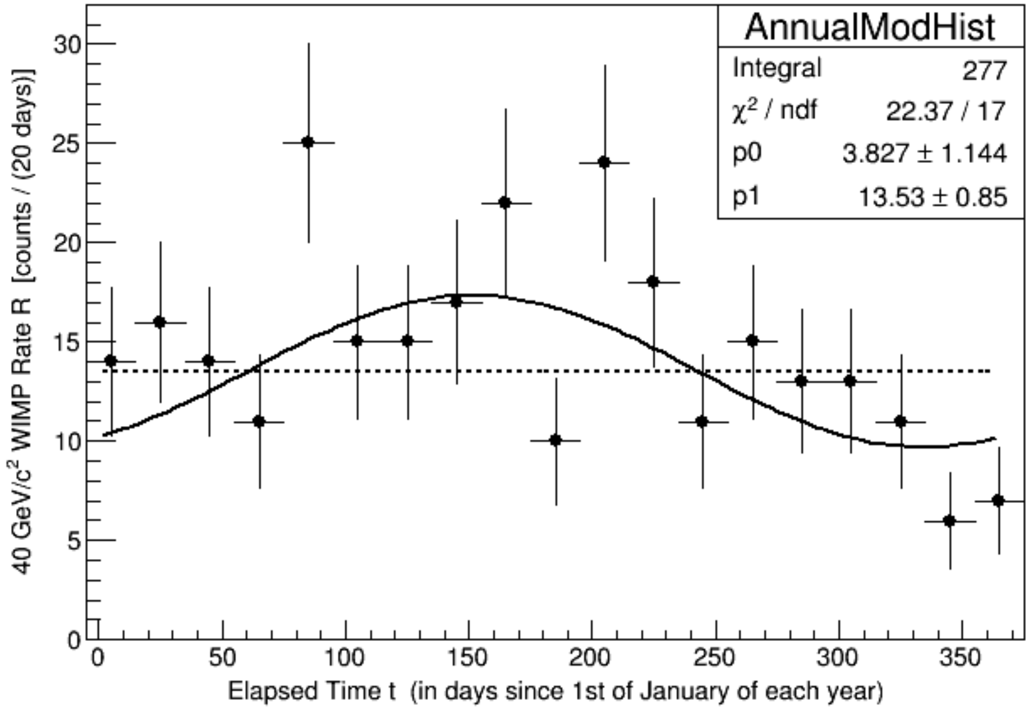
Possible CNO neutrino measurement

- Solar high/low metallicity solution targeted

WIMP Dark Matter

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

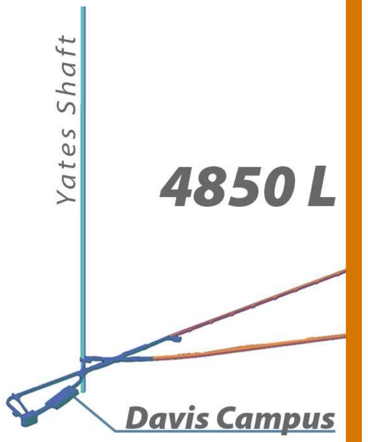


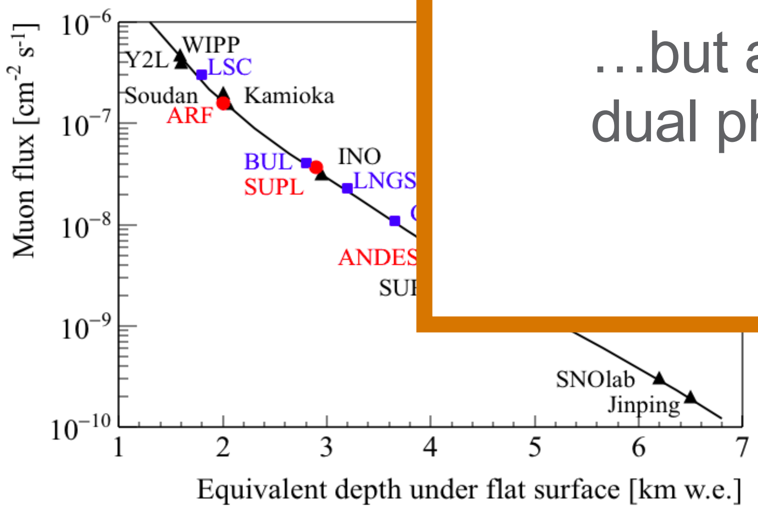


- Sensitive WIMP search in argon on competitive timescale
- Could confirm a signal from G2 experiments using annual modulation

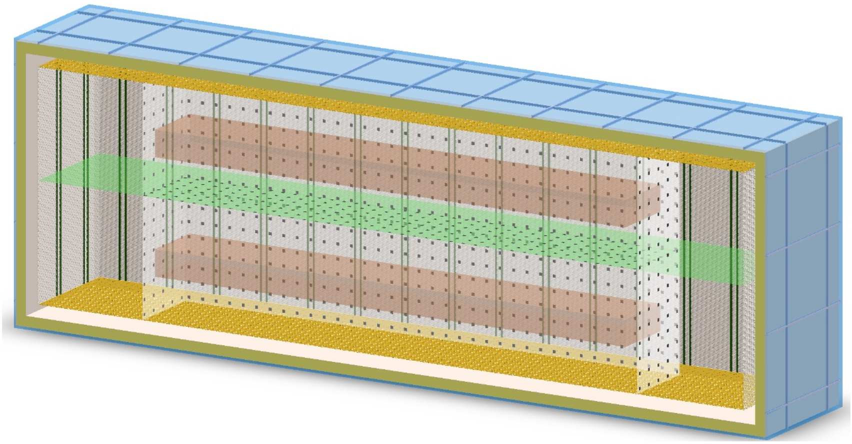
Dune has great low background potential…

… it is deep



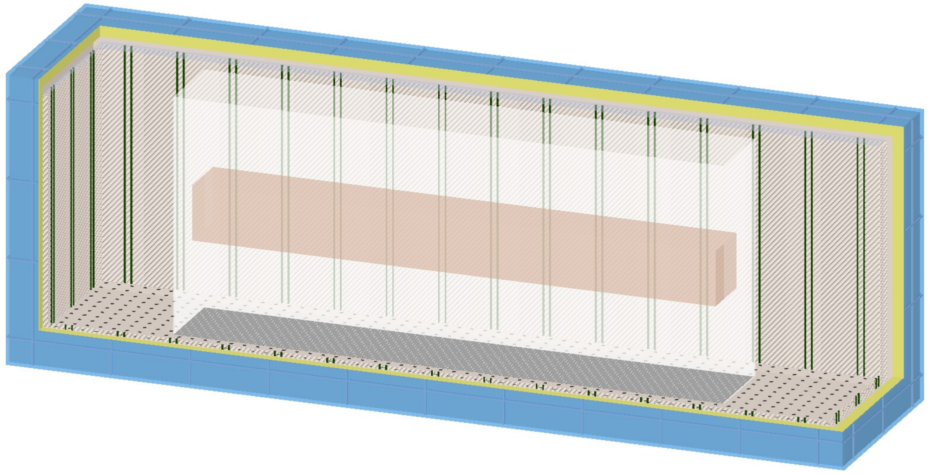


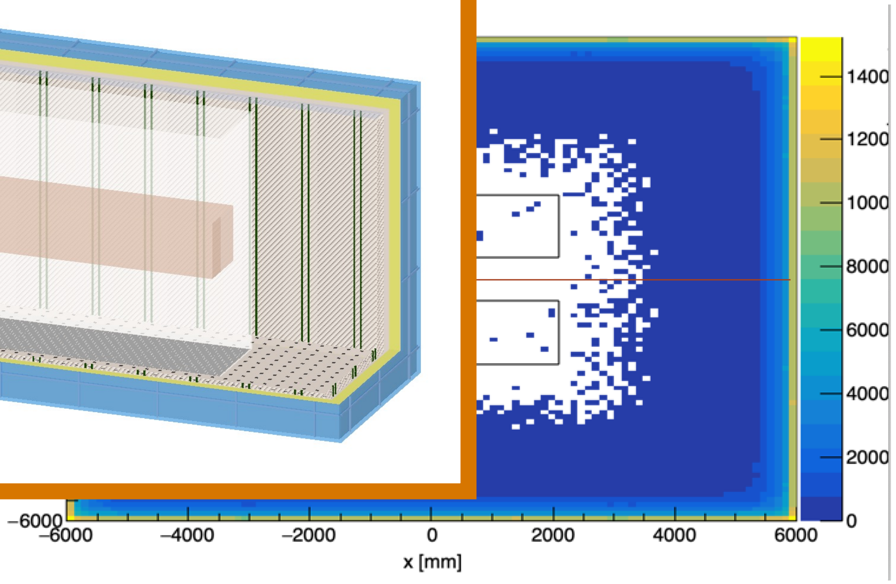
Ianni, TAUP 2017



Fiducialize within a single phase vertical drift…

…but also works well in dual phase options





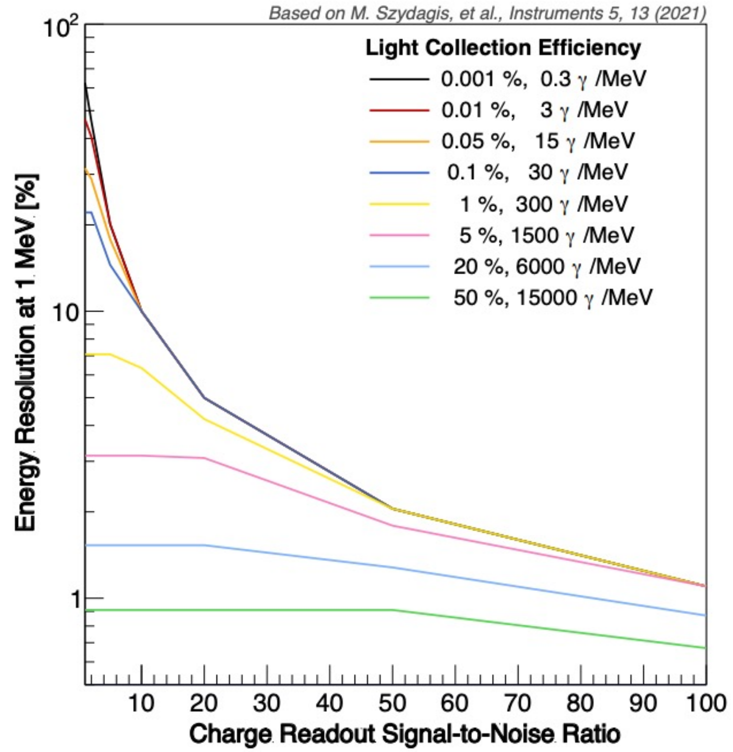
Neutron nuclear recoil events within a single DUNE module

Optical System

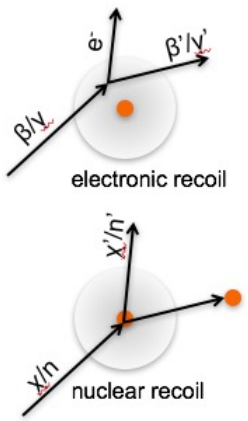
- Enhanced Photon Detection System to lower energy threshold with respect to baseline DUNE design

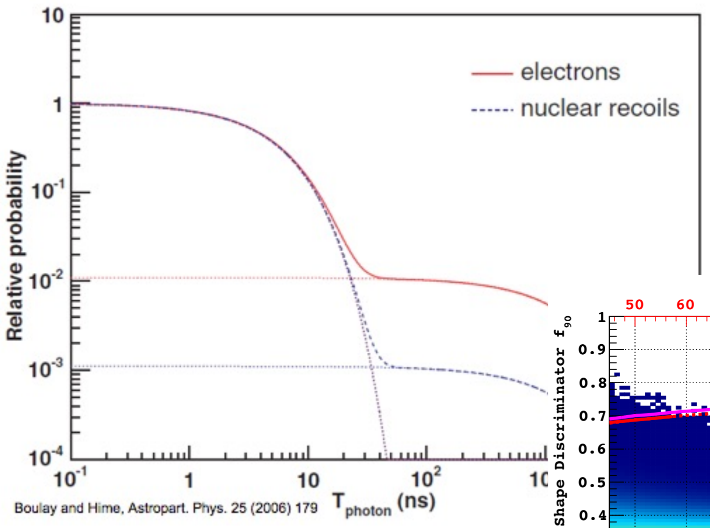
- **Target:** Energy resolution of 2% at 1 MeV (~10% of photons must be collected)
- **Target:** 400 nuclear recoil induced photons at SiPM surface (=100 photons after SiPM efficiency corrections) to allow pulse shape discrimination for dark matter search

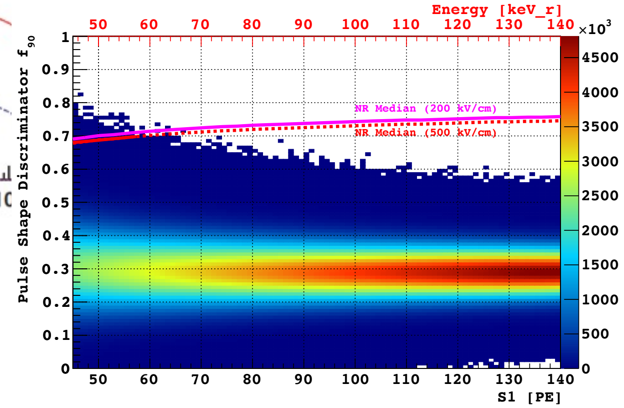
- Studies indicate 10-20% coverage sufficient for pulse shape discrimination for **dark matter search**



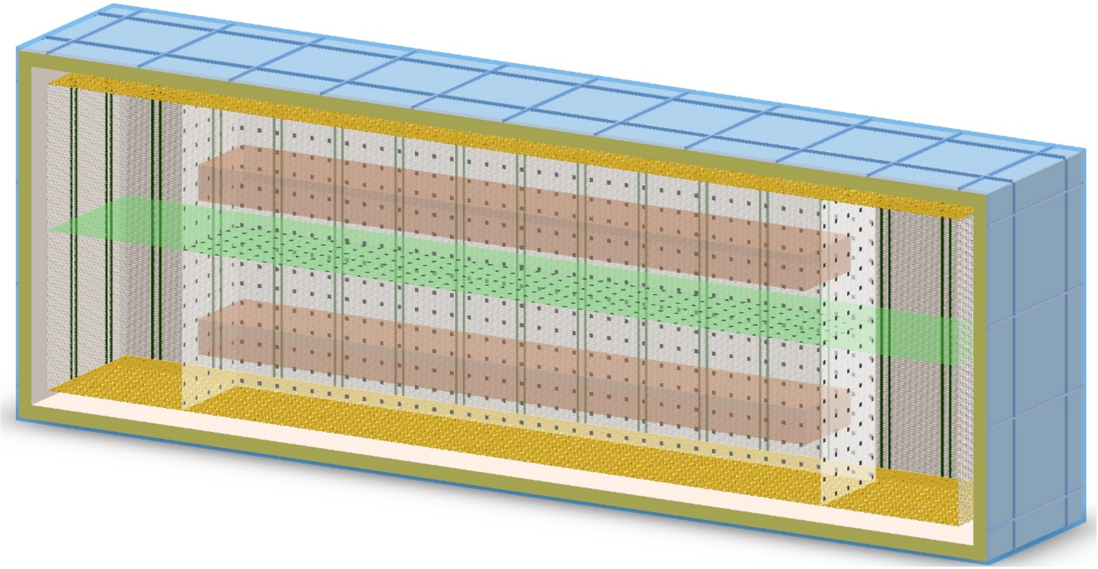
arXiv 2203.14700
NEST, JINST 5(1):13, 2021.



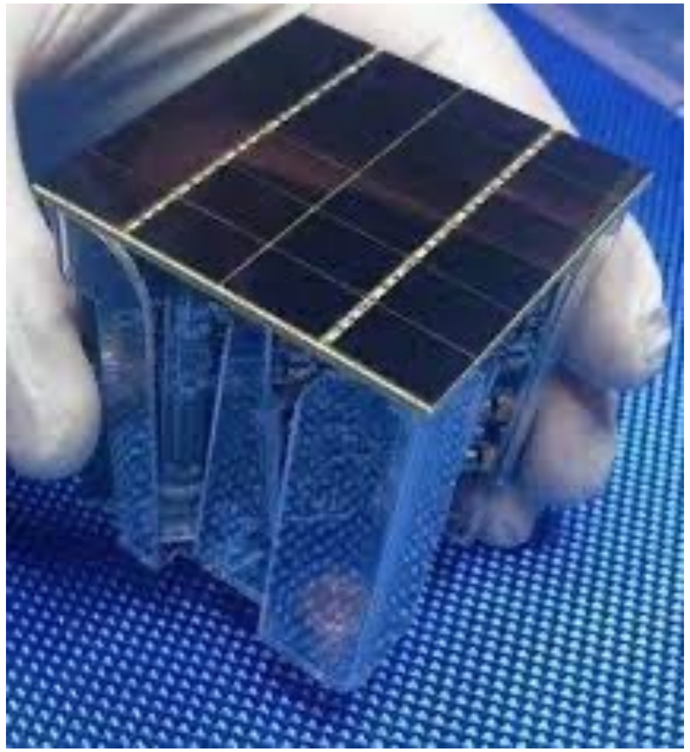




Optical System



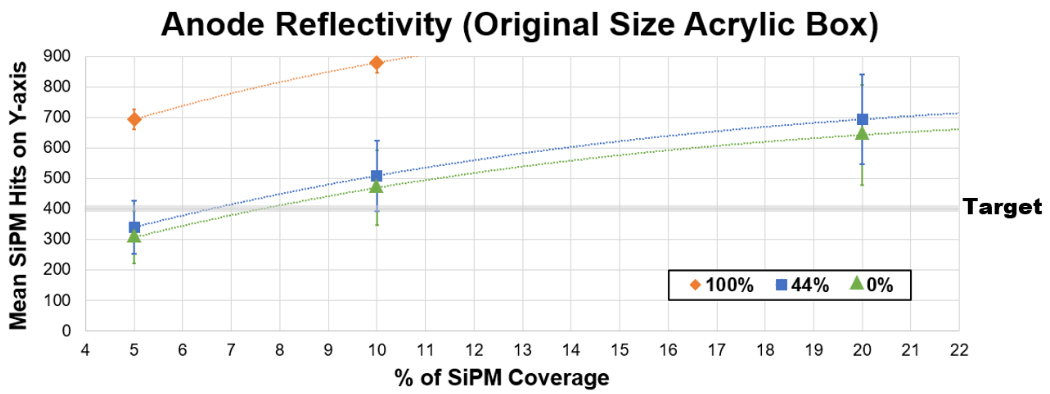
- Enhanced Photon Detection System:
  - SiPM tiles on acrylic box and cathode plane
    - ✓ DarkSide-style tiles
    - ✓ 50% Quantum efficiency (+ plus wavelength shifter efficiencies)
    - ✓ Can operate in high electric field
    - ✓ High volume production capability is being constructed for DarkSide-20k
    - ✓ Require 50,000+ tiles
  - Significant potential overlap with DUNE MoO ideas that enhance light collection:
    - ✓ Light sensitive charge readout, metalenses, dopants,..

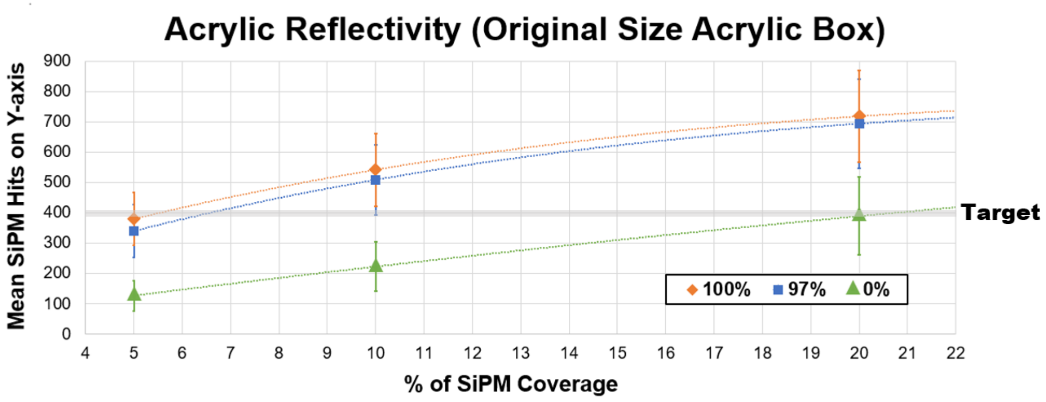


DarkSide SiPM

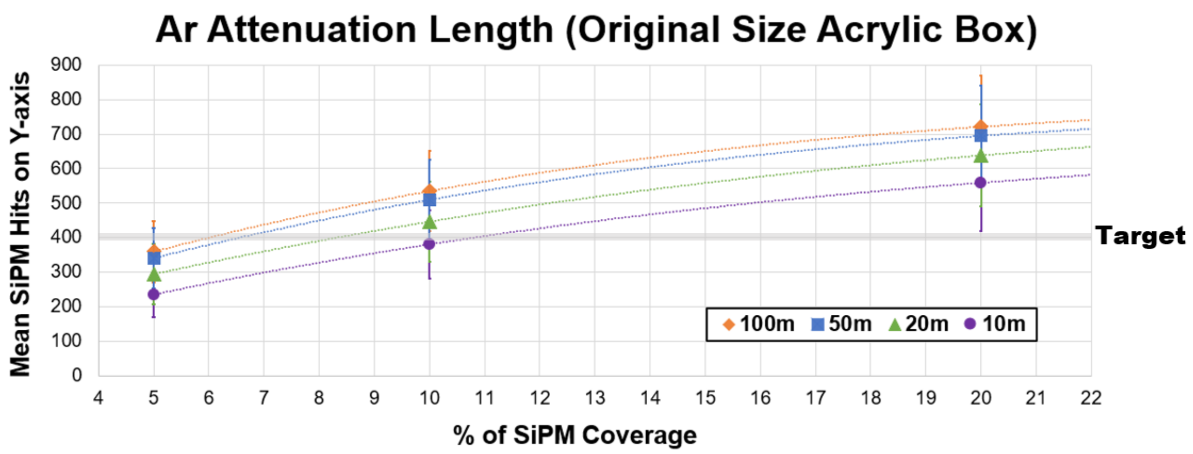
Optical System

- Enhanced Photon Detection System:
  - Reflective coatings on inner walls and anode planes
    - ✓ TPB vs PEN as wavelength shifter
    - ✓ Assume geometric efficiency 50%

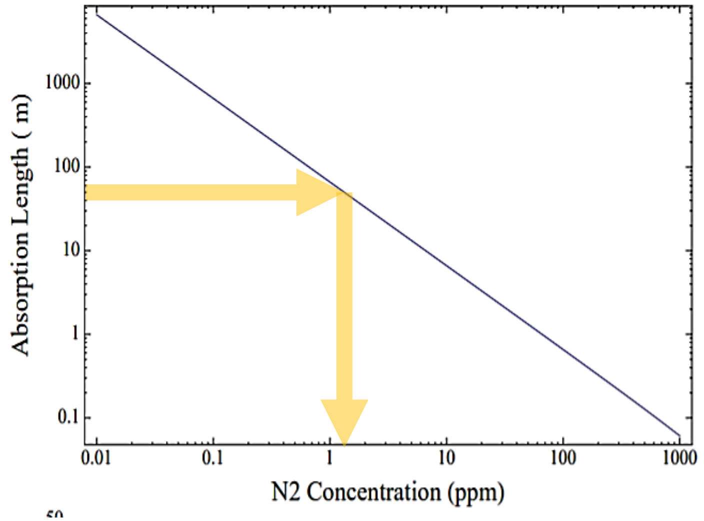




  - Argon purity enhanced to <1.5 ppm nitrogen



Attenuation Length	Minimum SiPM Coverage
100 m	6%
50 m	7%
20 m	9%
10 m	11%



Jones, B. J. P., et al. "A measurement of the absorption of liquid argon scintillation light by dissolved nitrogen at the part-per-million level." Journal of Instrumentation 8.07 (2013): P07011.