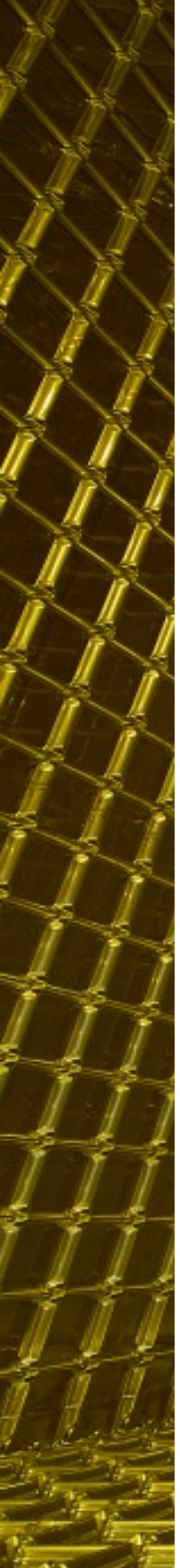

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FD3 Radioactive Backgrounds and Material Selection

June 26th 2023

Chris Jackson

christopher.jackson@pnnl.gov

U.S. DEPARTMENT OF ENERGY BATTELLE

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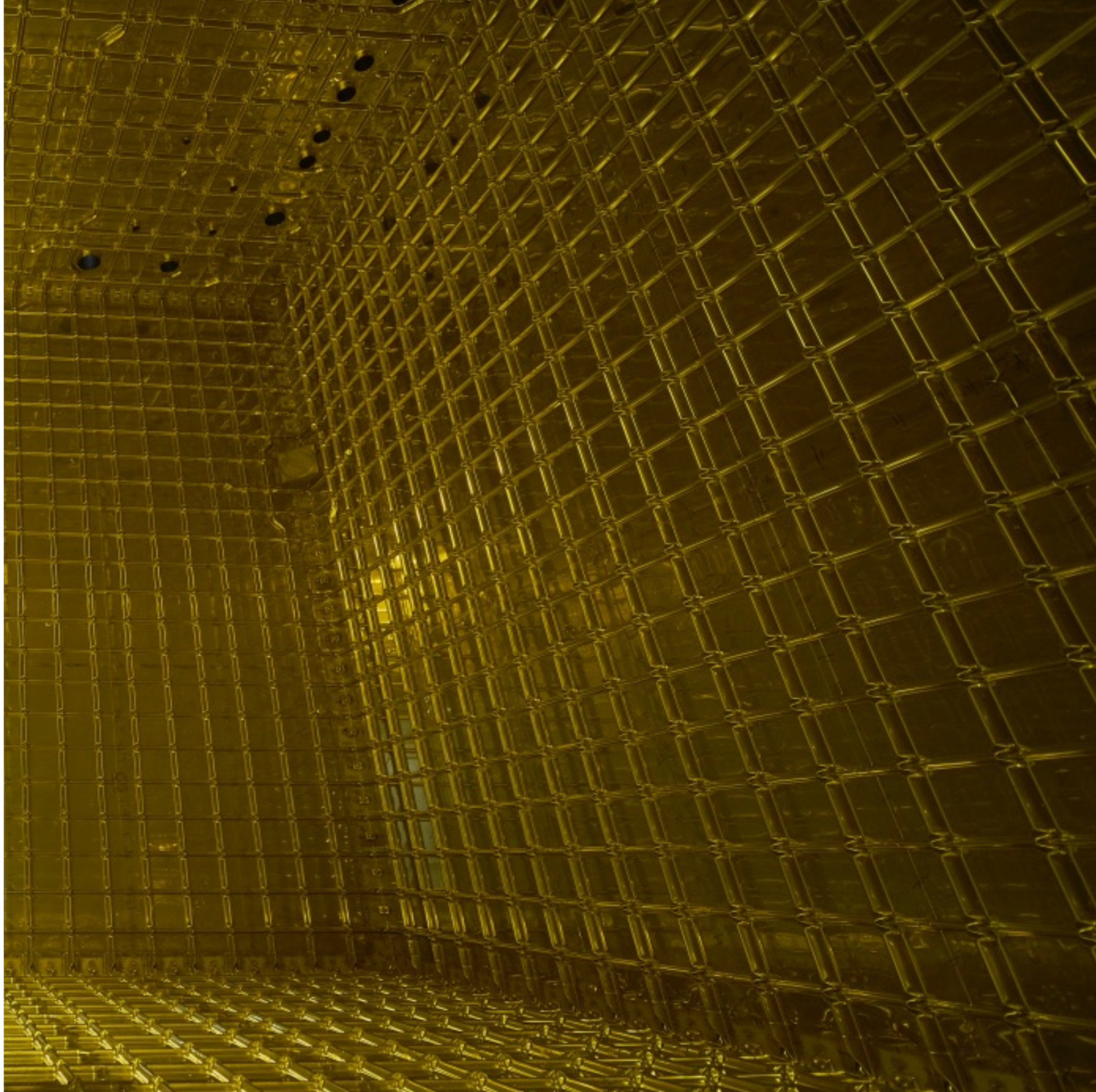
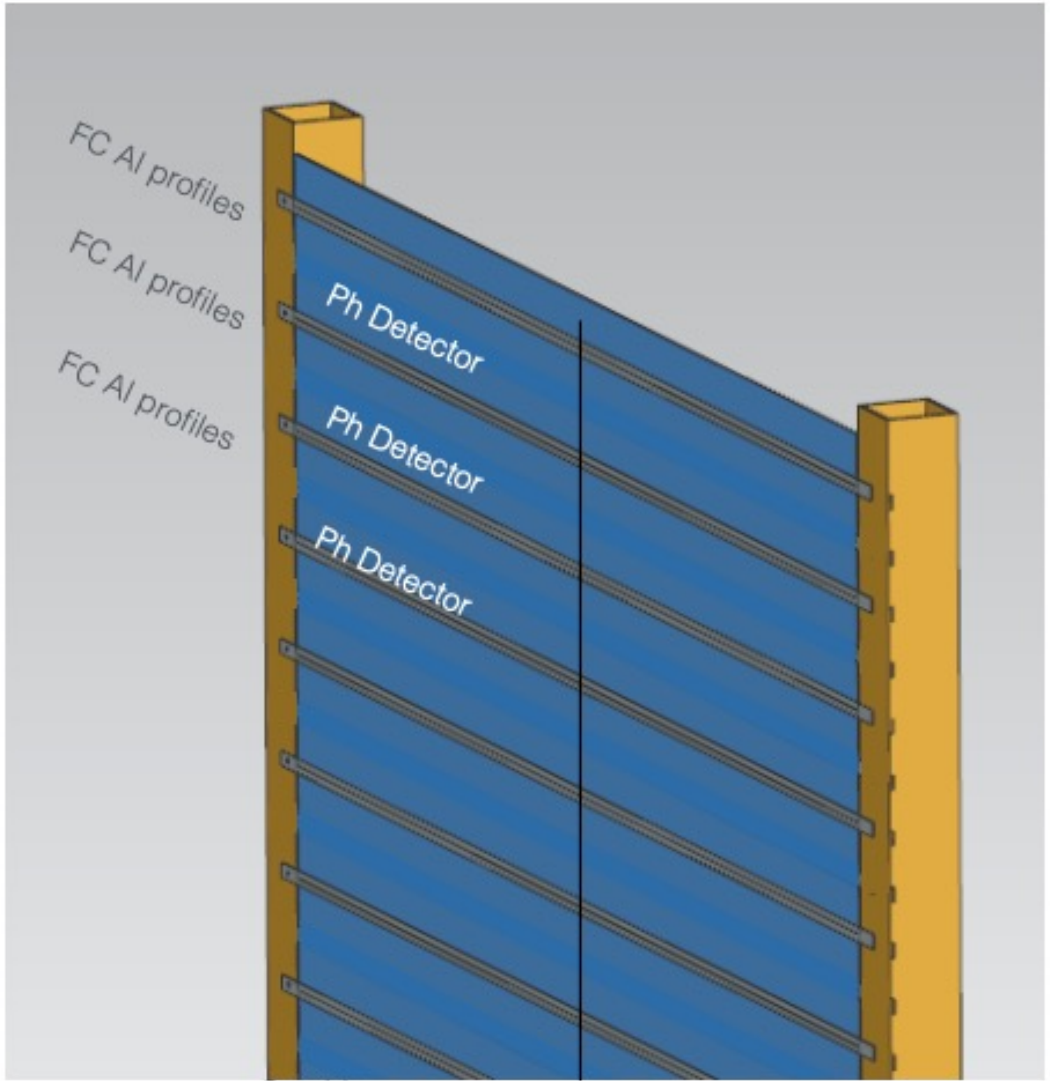
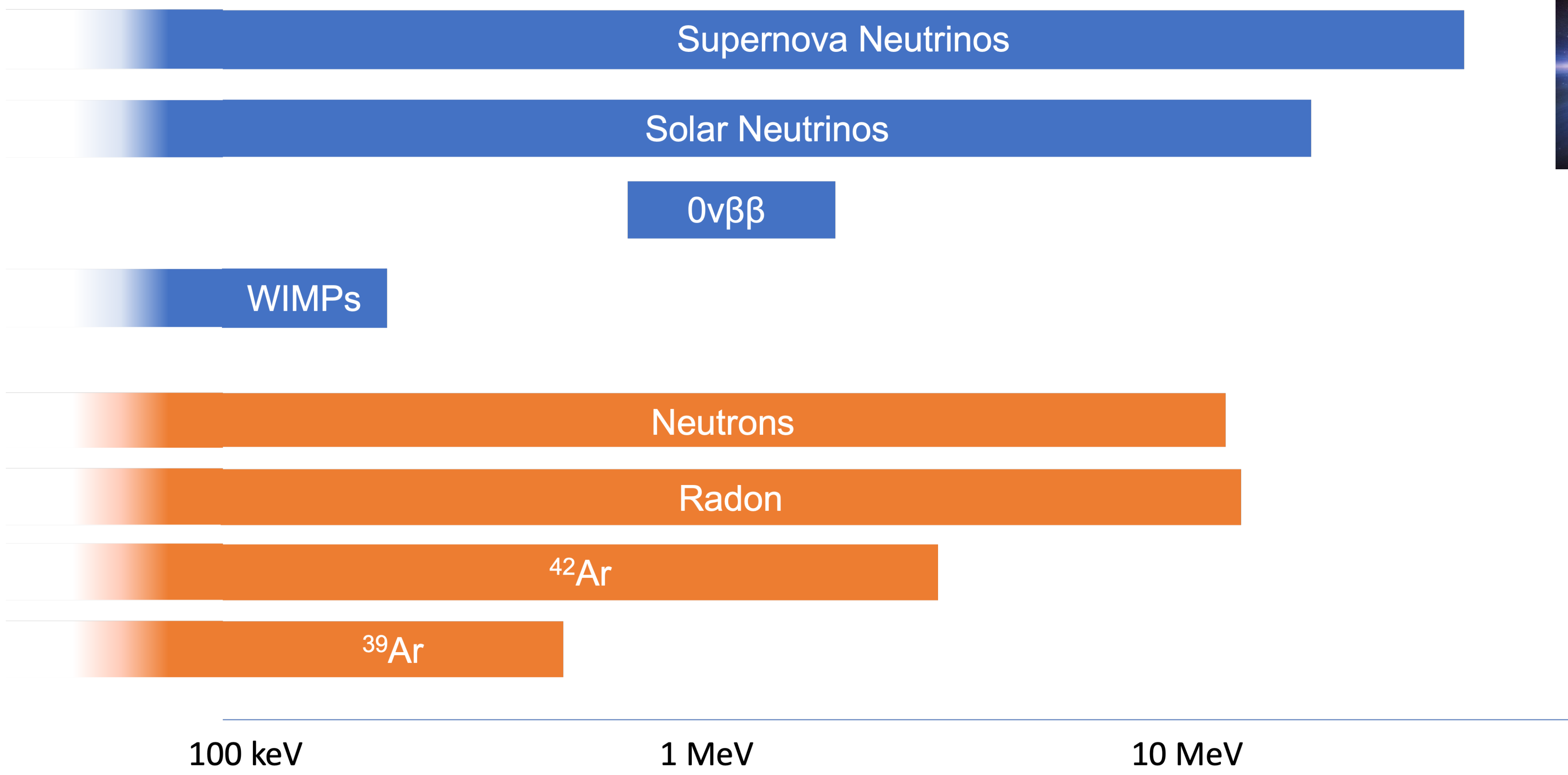


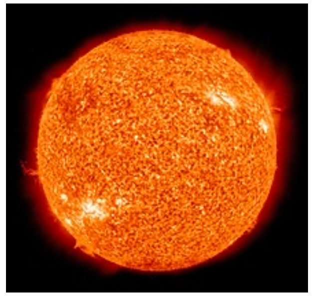
Outline

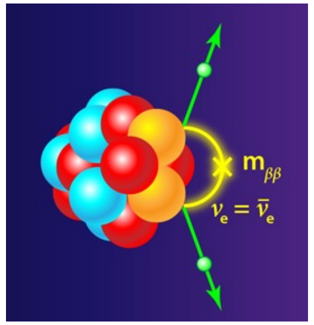
- Low background physics in DUNE
- Neutron background control
- Radon
- APEX thoughts
- Conclusions

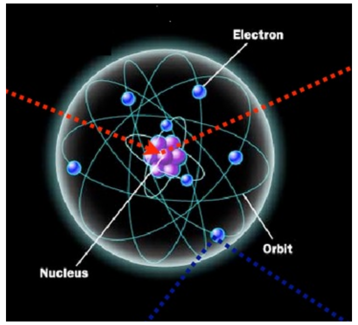


Low Background Physics in DUNE Phase II









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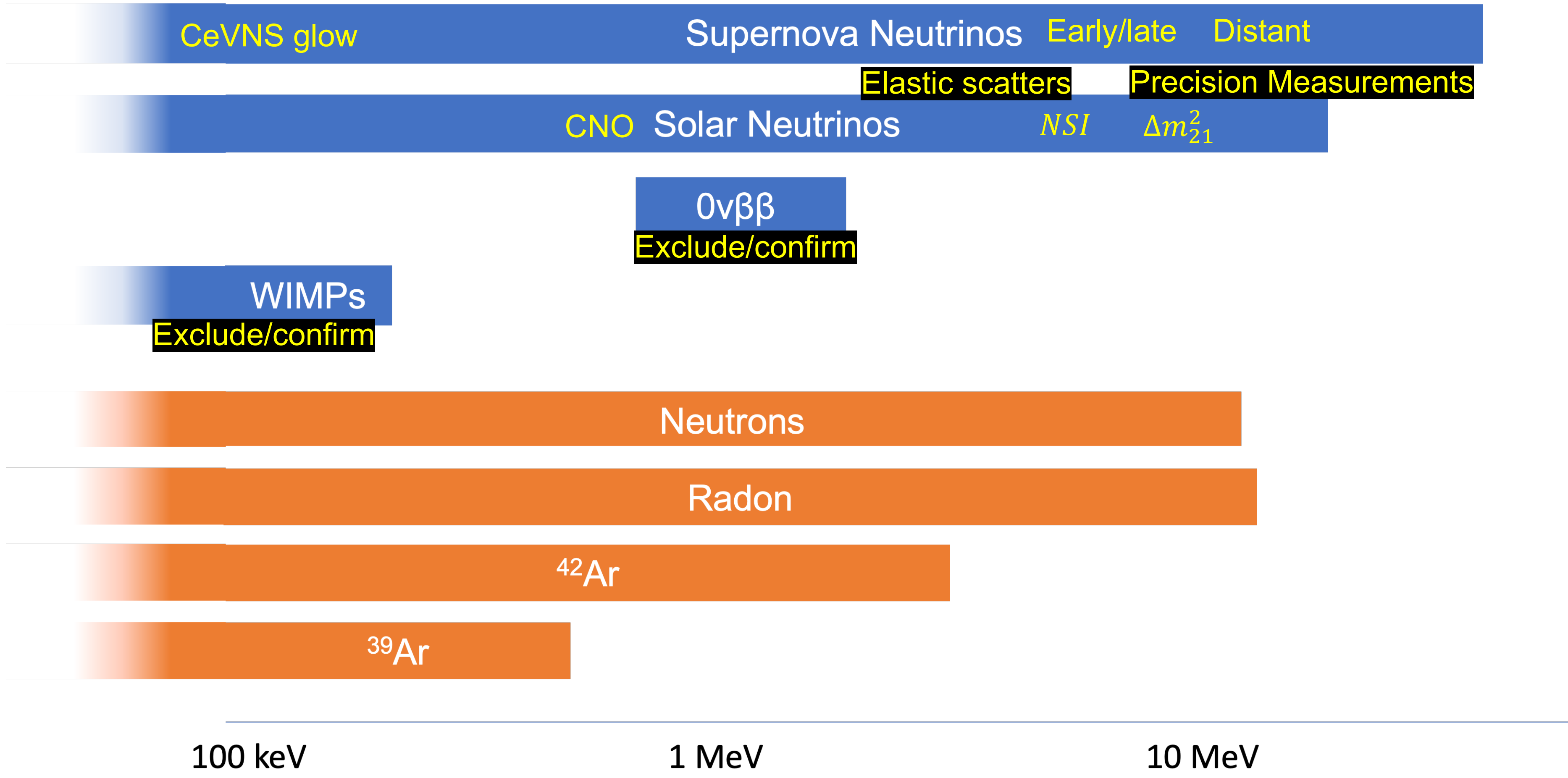

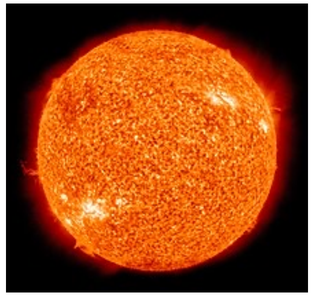

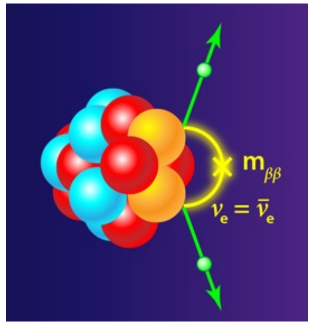

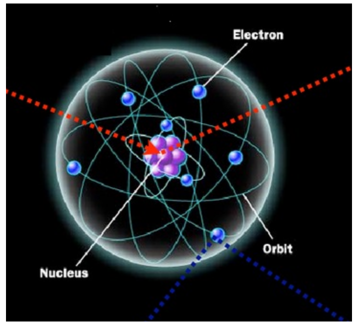

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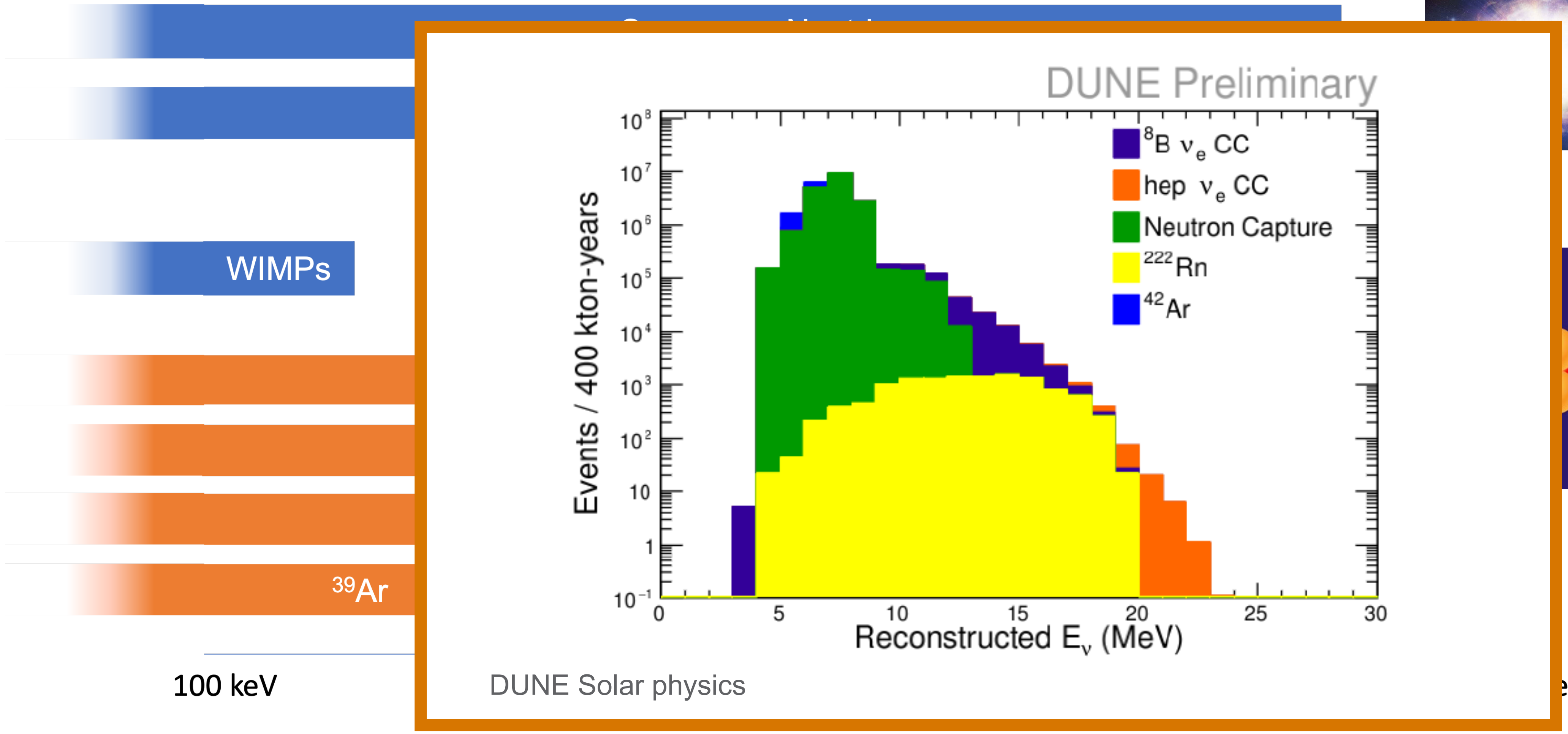
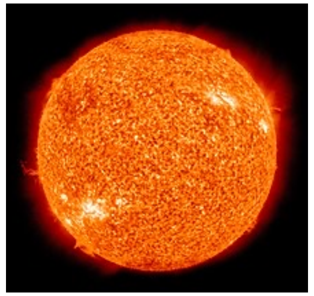
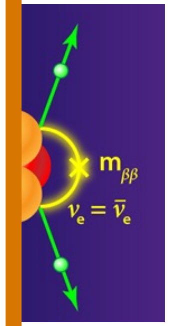
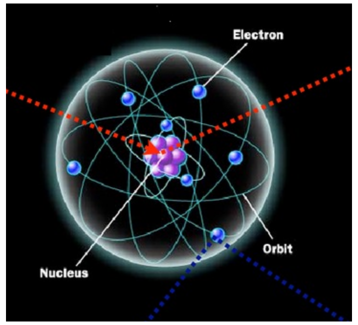
Low Background Physics in DUNE Phase II



DUNE Solar physics







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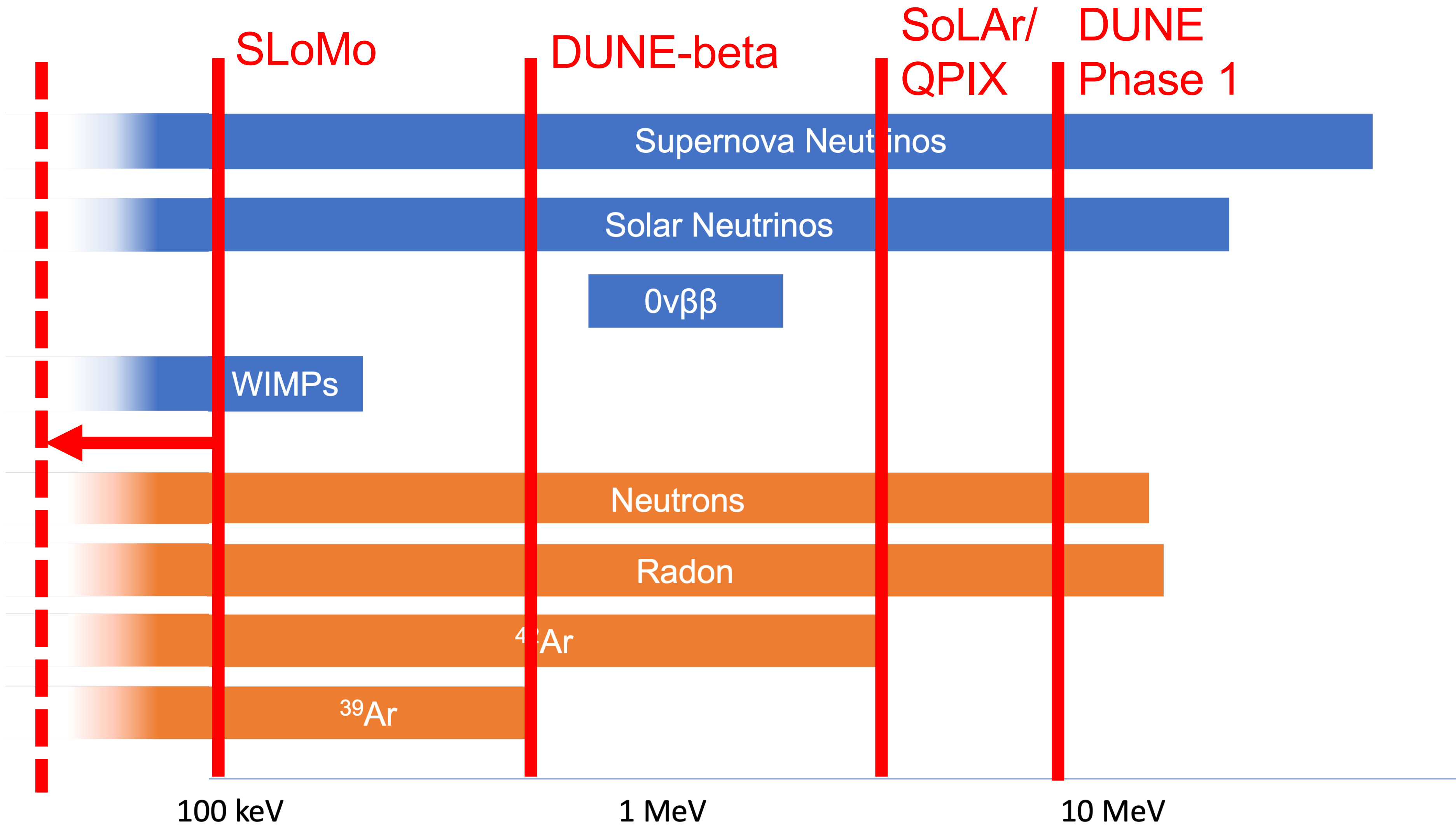
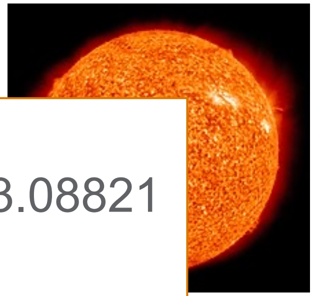
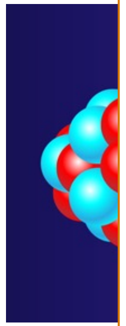


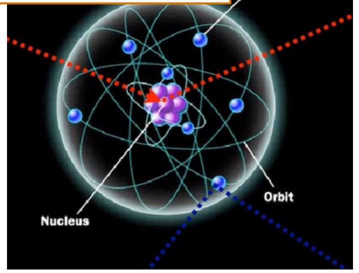




SLoMo:
- arxiv:2203.08821

DUNE-beta:
- arxiv:2203.14700

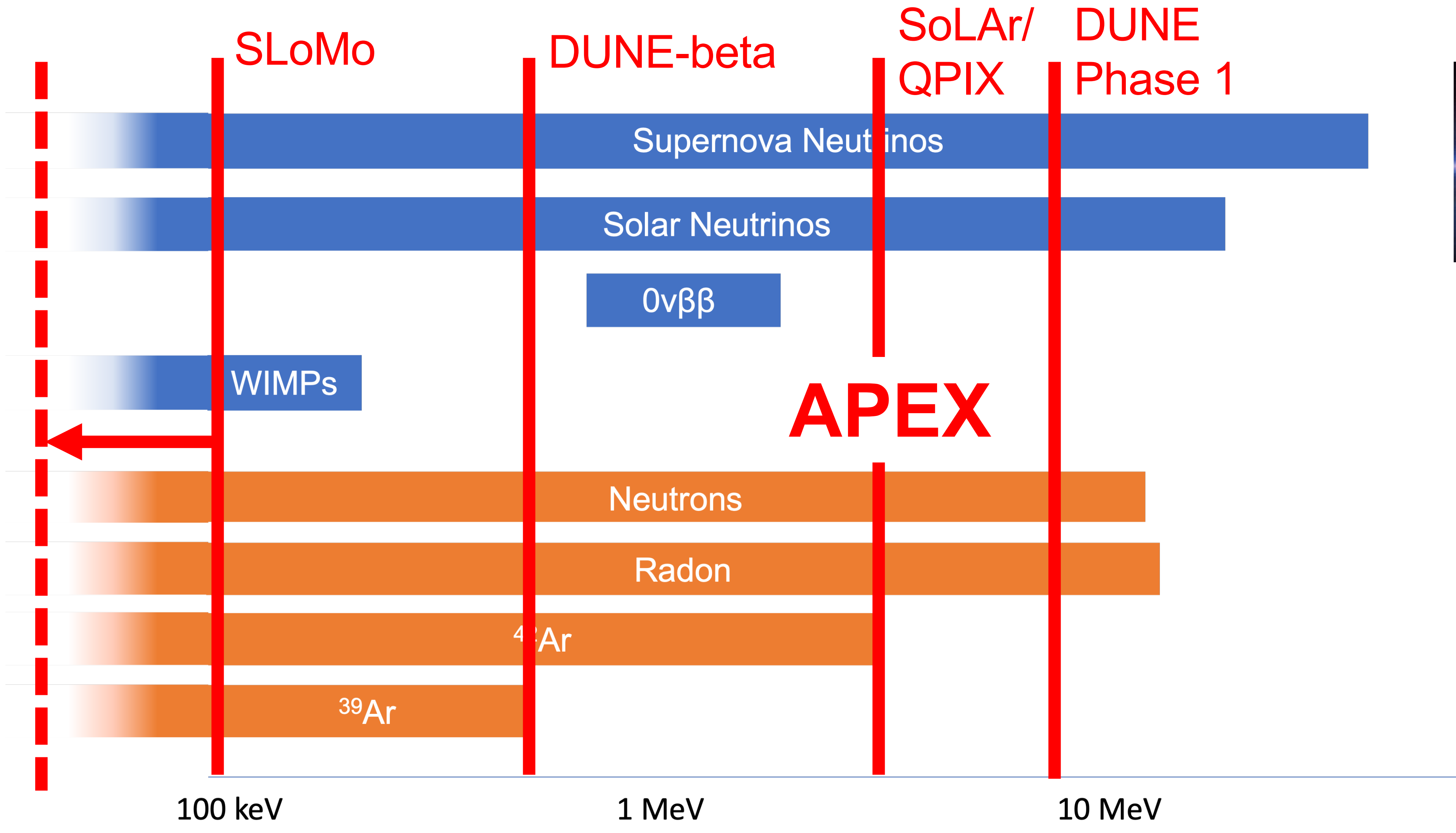
SoLAr:
- arxiv:2203.07501

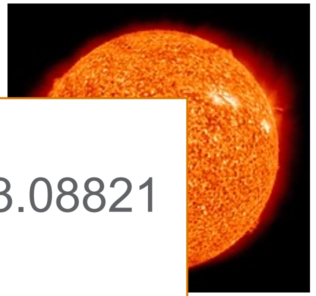


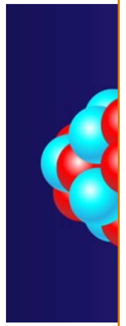
Additional References:

Low-Energy Physics in Neutrino LArTPCs:	arxiv:2203.00740
DUNE as the Next-Generation Solar Neutrino Experiment	Phys. Rev. Lett. 123, 131803 (2019)

Low Background Physics in DUNE Phase II







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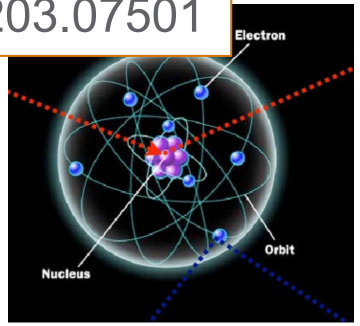

Additional References:

Low-Energy Physics in Neutrino LArTPCs:	arxiv:2203.00740
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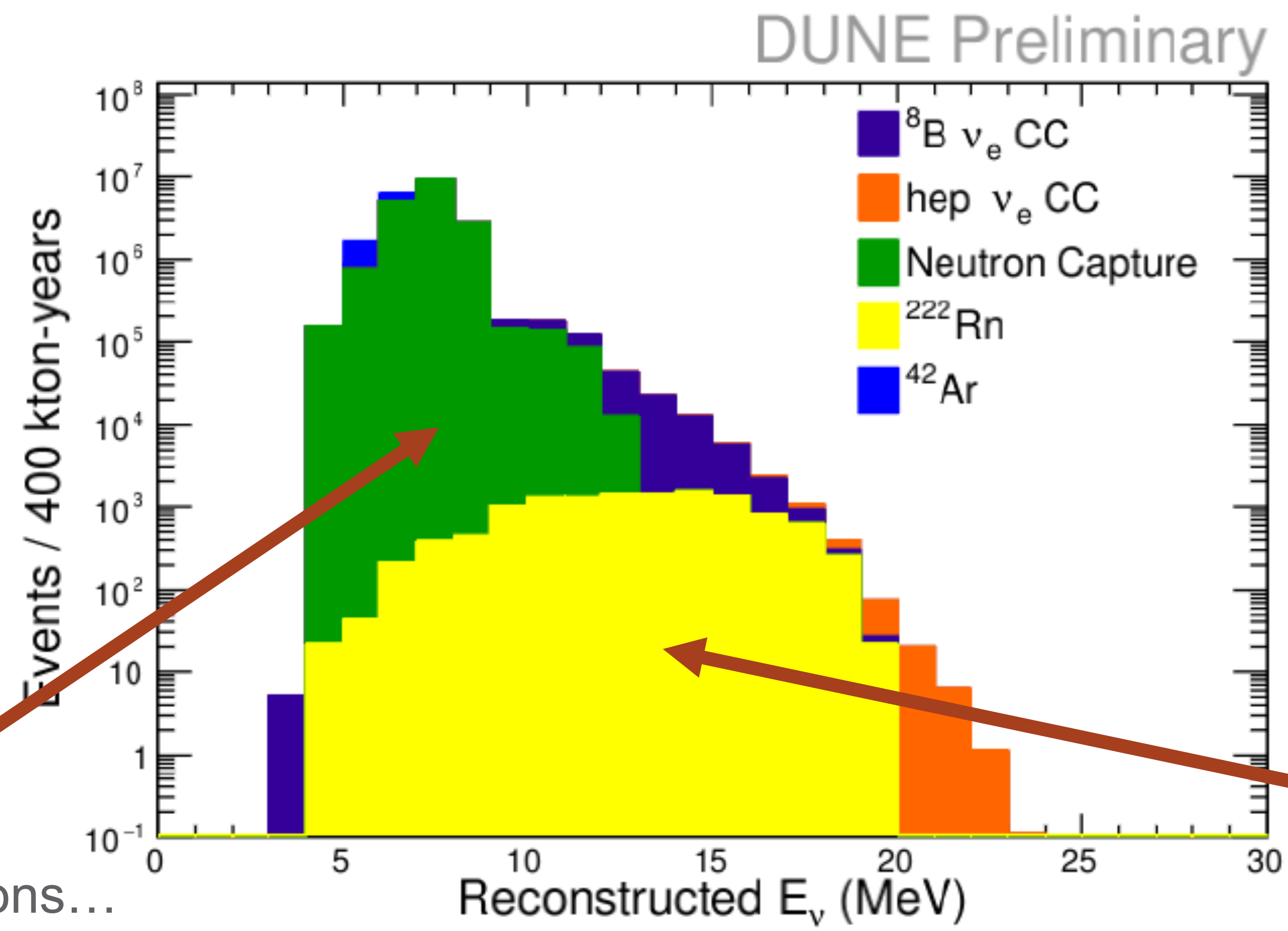
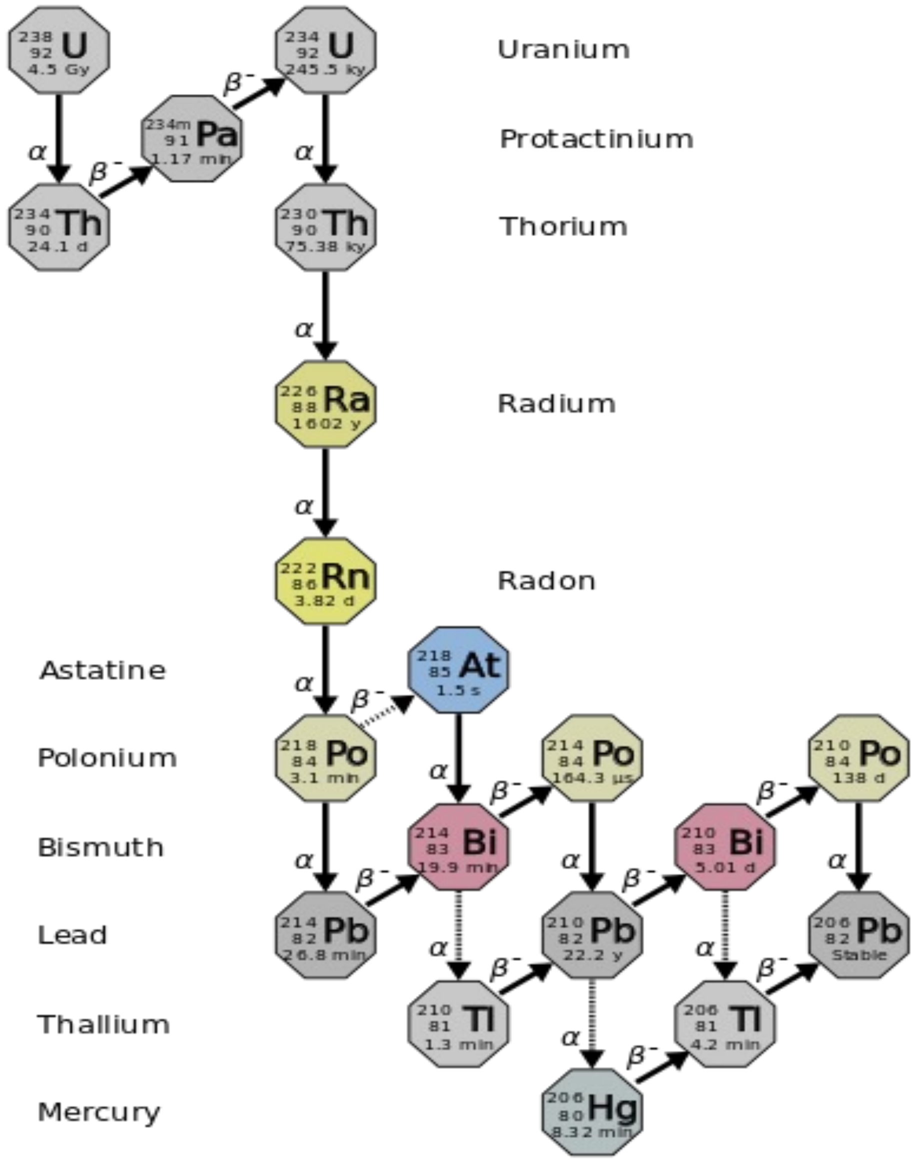
Backgrounds in DUNE

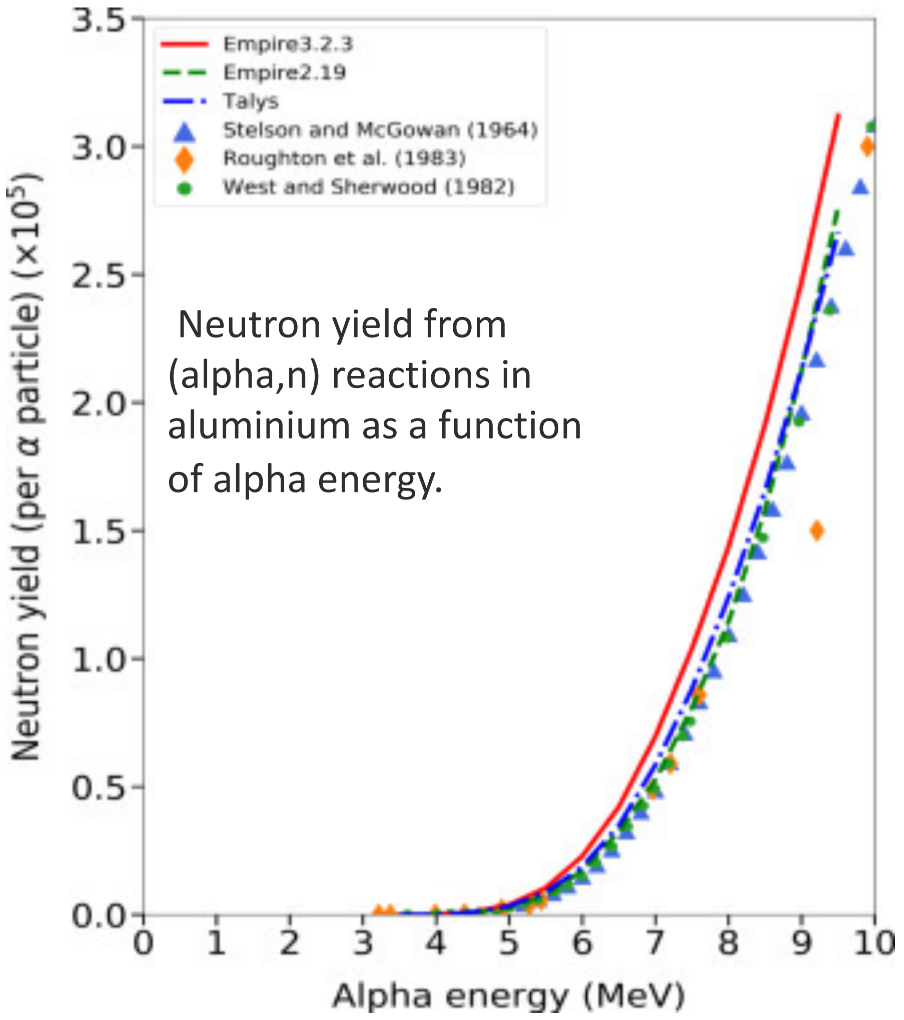


- Dominated by rock neutrons…
- …but we haven't measured the DUNE cavern
- Detector components assumed subdominant…
- … but we are relying on single assays (we have seen 4 order of magnitude variations between batches on other experiments) or estimates from radiopurity.org (which are biased towards 'clean' suppliers)

- Assumed low based on experience with other experiments…
- …but have only assayed filter material so far

Neutron Backgrounds

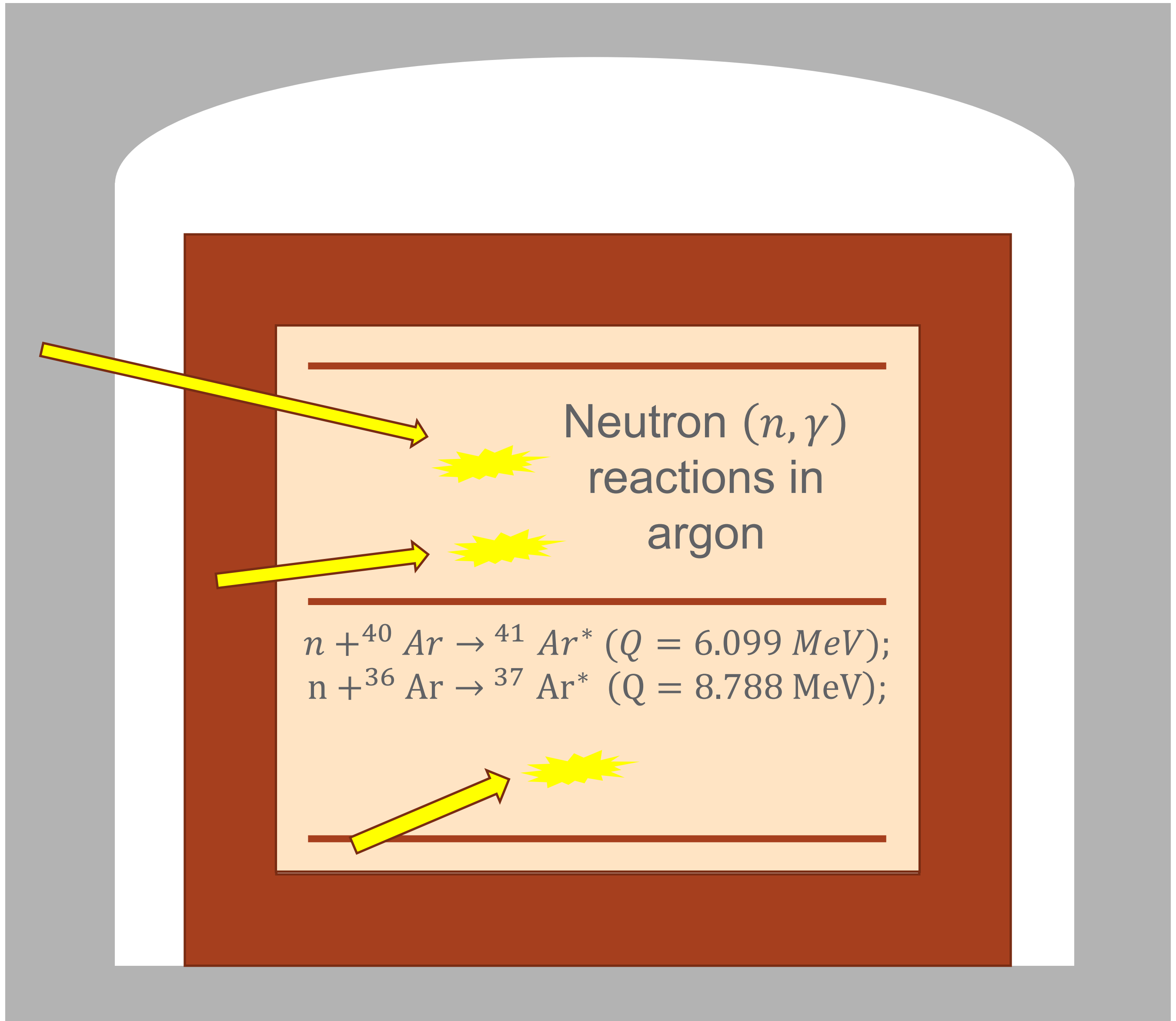




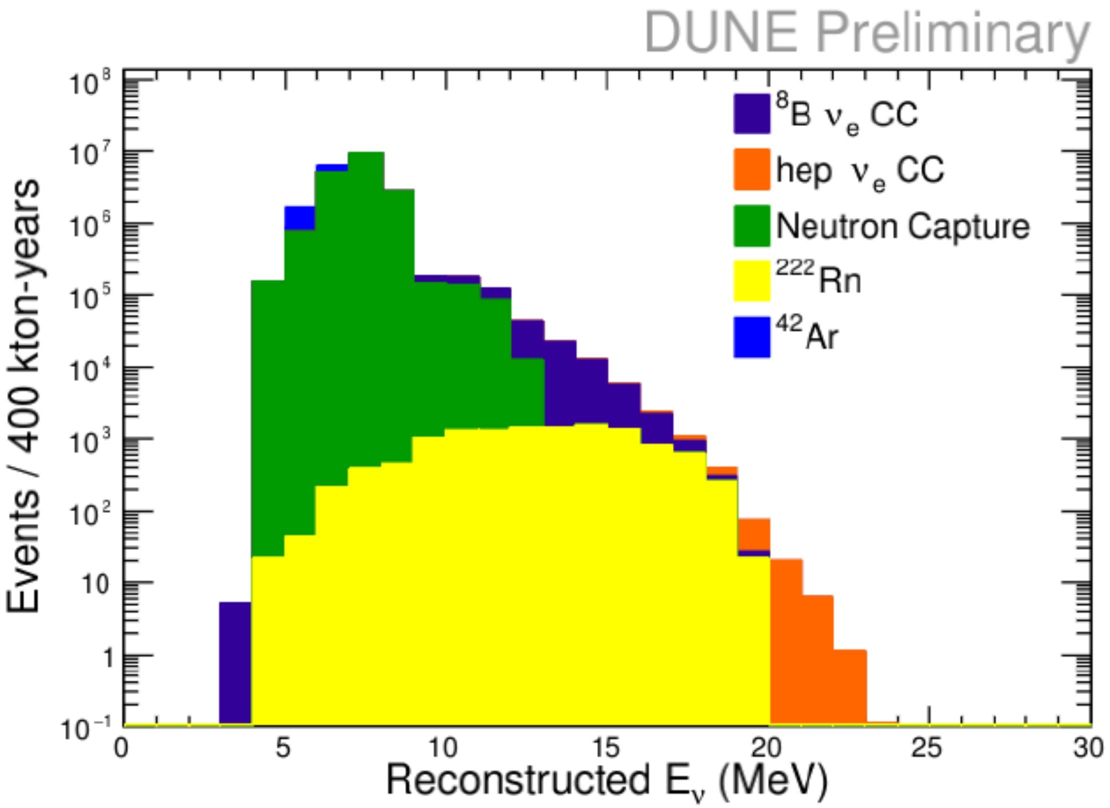
Kudryavtsev, Zakhary, Easeman, NIM Phys Res A, 972 (2020)

- Trace amounts of Uranium/Thorium found in all materials
- Spontaneous fission and (α, n) from U/Th chains

Neutron Backgrounds



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

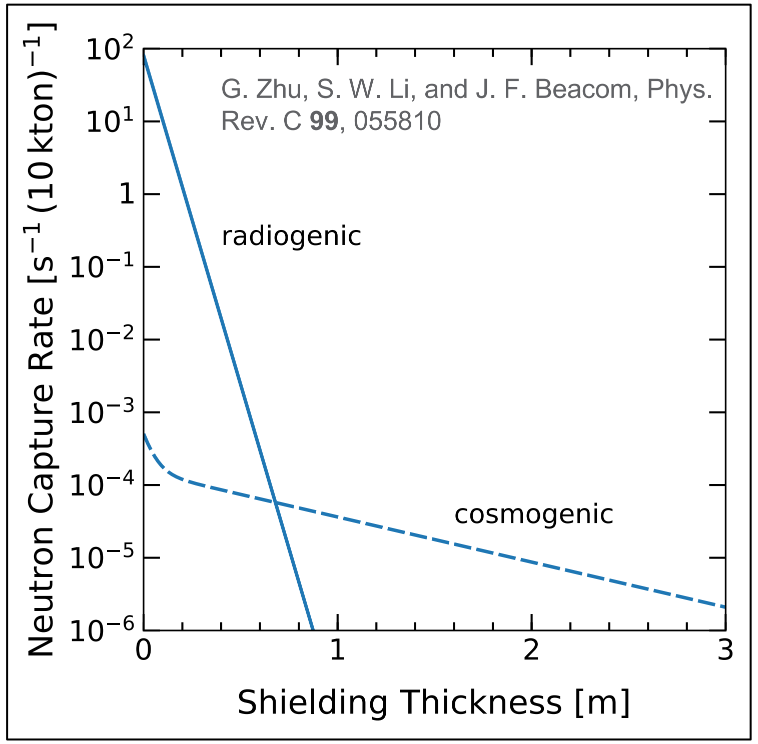


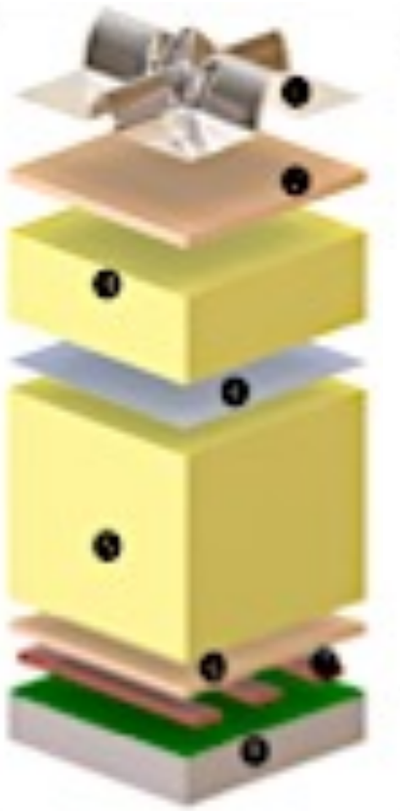
Source	Phase 1Rate [Hz] *
Rock	1.04 +/- 0.13
Concrete	(1.1 +/- 0.05) x 10^{-1}
Shotcrete	1.40 +/- 0.02
I-Beams	(2.13 +/- 0.04) x 10^{-1}
Cold Steel	2.03 +/- 0.05) x 10^{-1}

A. Borkum
docdb -22783

* assays/simulations still ongoing (see e.g. Juergen Reichenbacher talk at collaboration May collaboration meeting)

Neutron Shields





1. Stainless steel primary membrane
2. Plywood board
3. Reinforced polyurethane foam
4. Secondary barrier
5. Reinforced polyurethane foam
6. Plywood board
7. Bearing mastic
8. Steel structure with moisture barrier

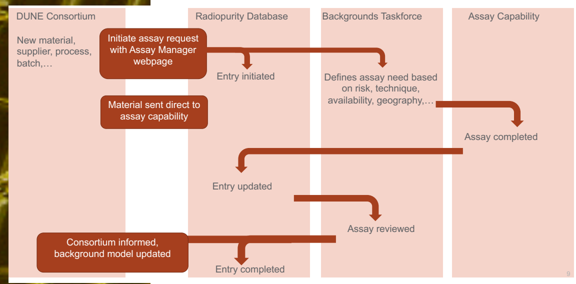
- Neutron shielding
  - No water shield in current DUNE design
  - 40 cm of water shielding around detector (proposed by Capozzi, Li, Zhu and Beacom)
    - ✓ ~3 order of magnitude reduction

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

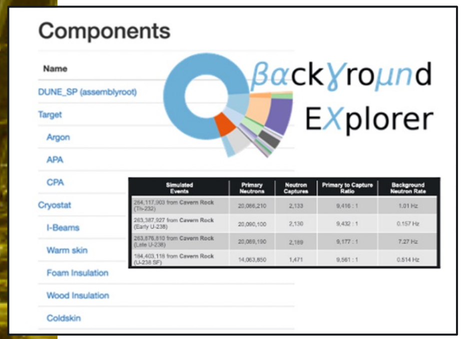
- Must lower unshielded internal neutron sources by same amount as shielded external sources to remain subdominant
- LZ has achieved 10^5 reductions beyond DUNE expected
- Requires careful QA/QC program
  - Less stringent than dark matter experiments…
  - …but at unprecedented scale (e.g. 1 kton stainless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



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

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

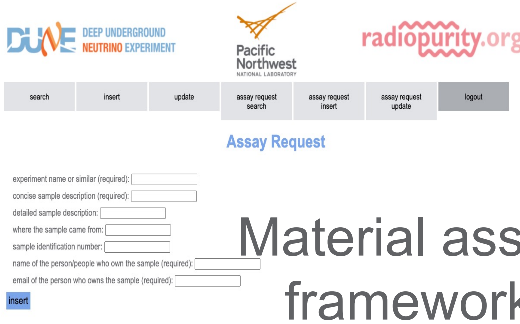
Large-scale assay program



Detector Simulation
- Full detector simulations
- Rapid triage of assay results

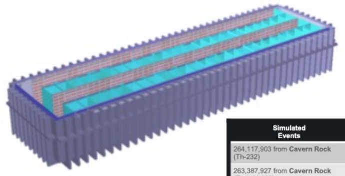
Radiopurity should be specified for detector components. Opportunity to use experience with phase 1

Background Control Strategy

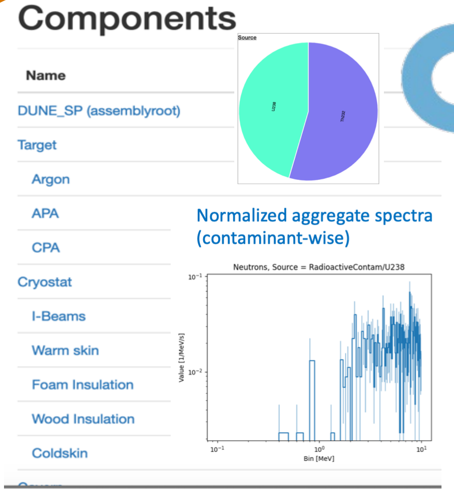


Material assay framework

GEANT4 radioactive background simulations



Simulated Events	Primary Neutrons	Neutron Captures	Primary to Capture Ratio	Background Neutron Rate
264,117,903 from **Cavern Rock** (Th-232)	20,086,210	2,133	9,416 : 1	1.01 Hz
263,387,927 from **Cavern Rock** (Early U-238)	20,090,100	2,130	9,432 : 1	0.157 Hz
263,876,810 from **Cavern Rock** (Late U-238)	20,089,190	2,189	9,177 : 1	7.27 Hz
184,403,118 from **Cavern Rock** (U-238 SF)	14,063,850	1,471	9,561 : 1	0.514 Hz



BackgroundEXplorer

Background triage and assessment

Material selection and physics sensitivities

Background model must be adjusted during production to respond to assays

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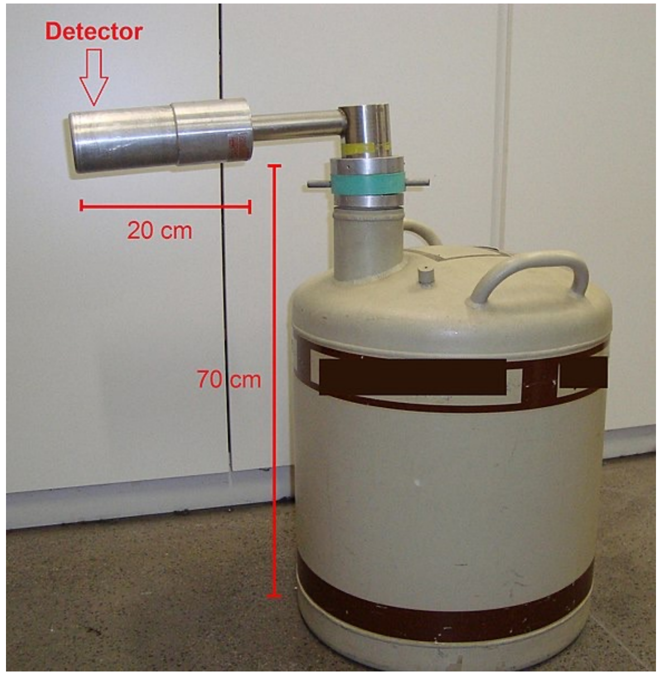
Assay Capabilities for DUNE



High Purity Germanium

Inductively Coupled Plasma Mass Spectrometry

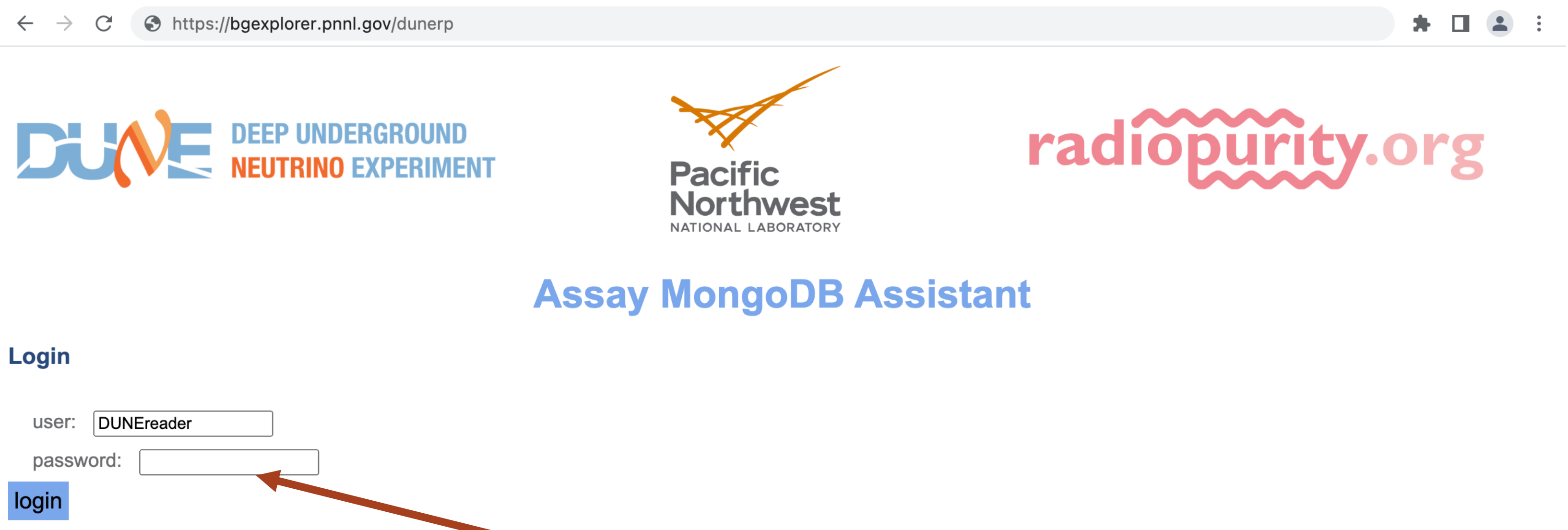
- Continuing to compile assay resources:
  - SDSMT,
  - PNNL,
  - SURF,
  - UCL,
  - Sheffield,
  - Boulby,
  - Marseille

  - Volunteers?

Also:
- Surface alphas spectrometry
- Radon emanation
- …

Radiopurity Database

- DUNE radiopurity database is live
- Write access available on request

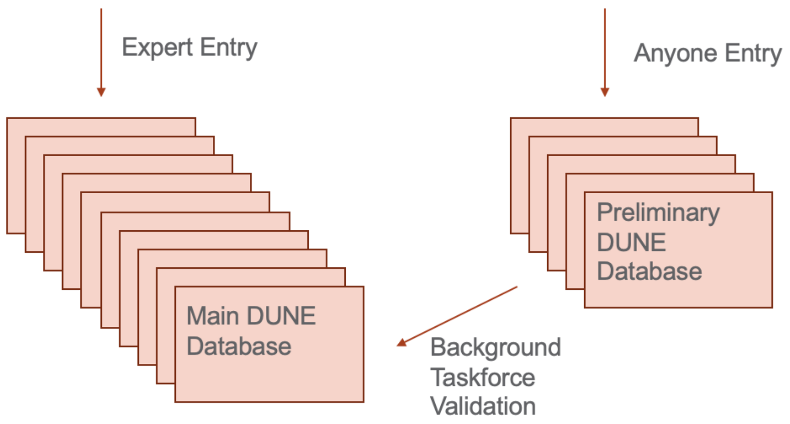


Standard DUNE collaboration password

https://bgexplorer.pnnl.gov/dunerp

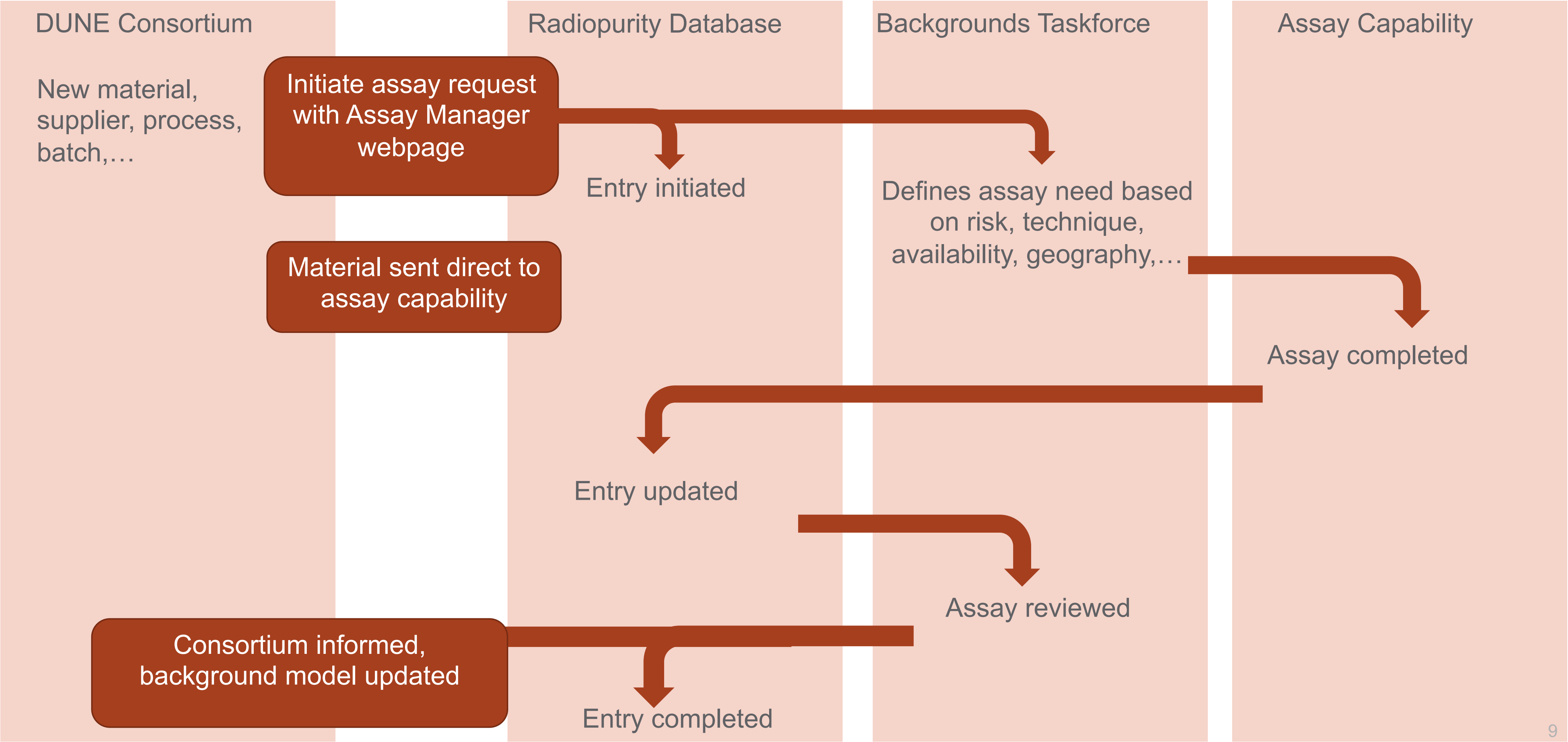
Radiopurity Database

- DUNE radiopurity database is live
- Write access available on request



https://bgexplorer.pnnl.gov/dunerp

Assay Management



Assay program:
- Identify suppliers/ materials
- Study production process
- QA/QC of delivered items

Background Explorer

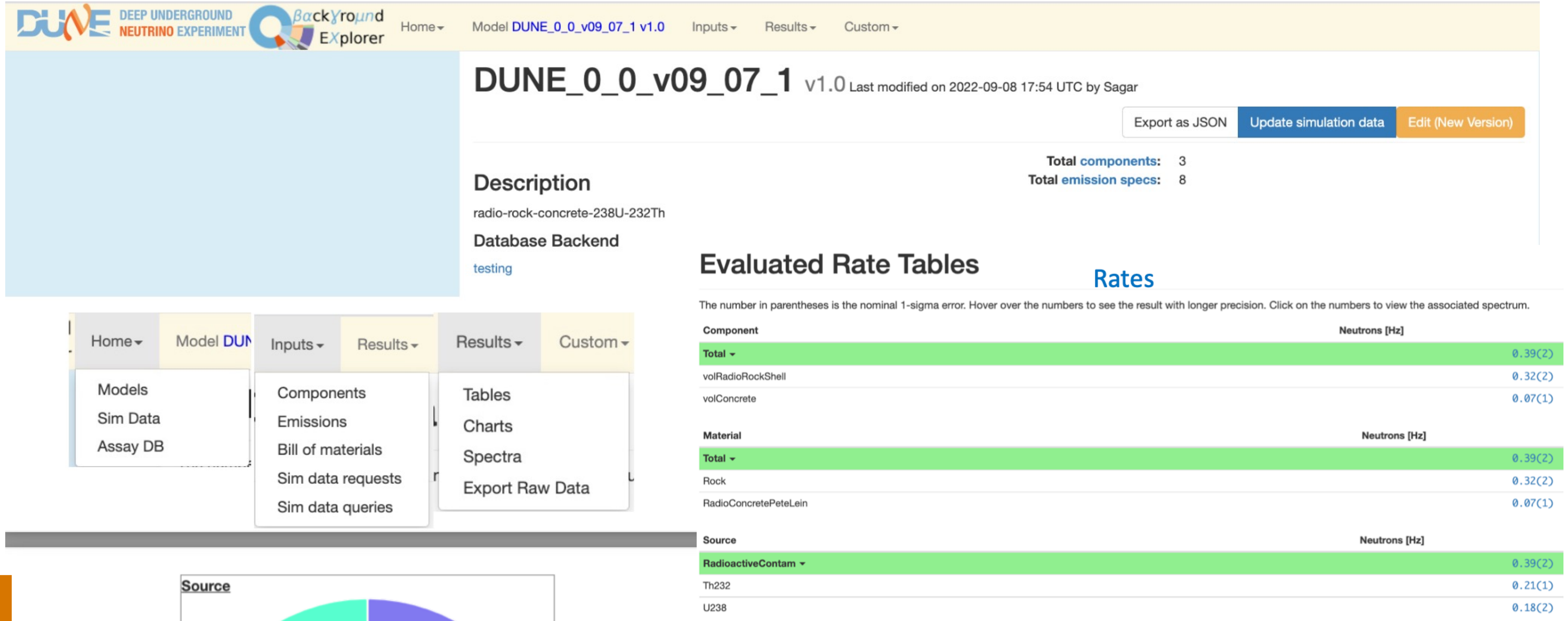
- Toolkit for modeling radioactive backgrounds
- Originally developed for SuperCDMS by Ben Loer

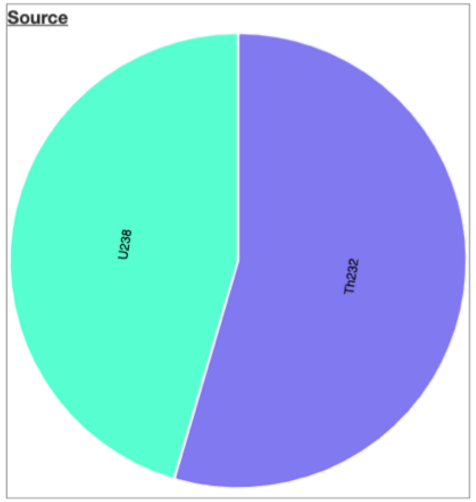
		e.g.:
Bill of Materials	List of all components in assembly with physical properties like material, mass, and surface area	2 kg component
×		×
Component Specifications	Intrinsic radionuclide contamination levels for a given material, total exposure to dust, radon, and cosmic ray activation based on assembly procedures	1 mBq(U238) / kg
×		×
Simulated event fractions	Probability for emission from a particular radionuclide decay at a particular location to generate a background event in the detectors	10^{-3} cts/kg/keV per U238 decay
=		=
Background Model	Spectrum of events predicted during detector exposure	~0.2 dru (cts/kg/keV/day)

https://github.com/bloer/bgexplorer-demo

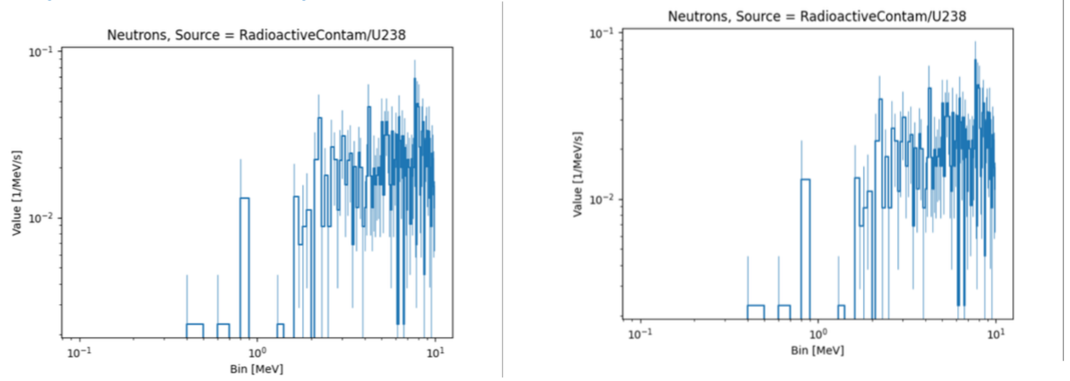
Background Explorer

- DUNE implementation is ready
- Simulations to populate in pipeline (SDSMT +PNNL)

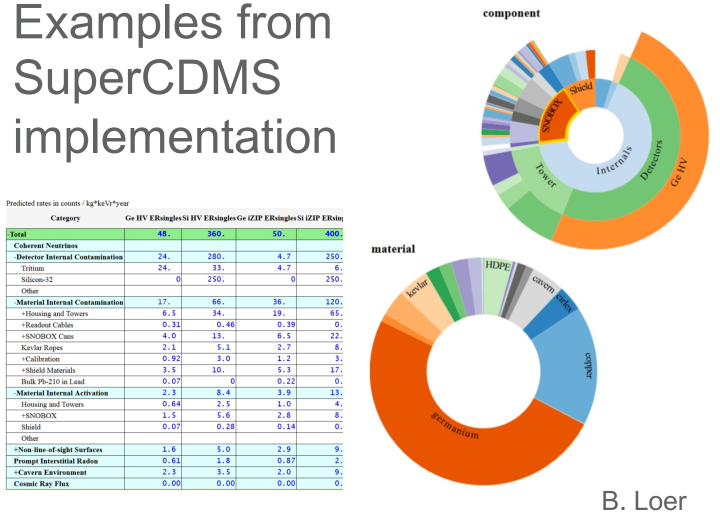




Normalized aggregate spectra (contaminant-wise)

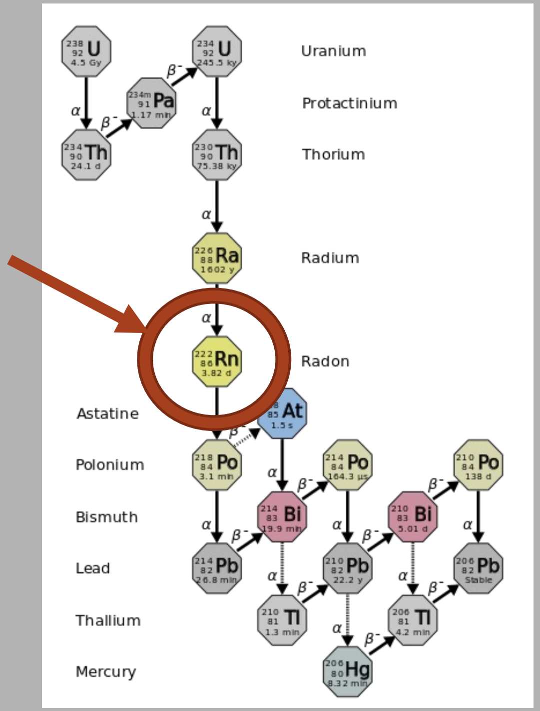


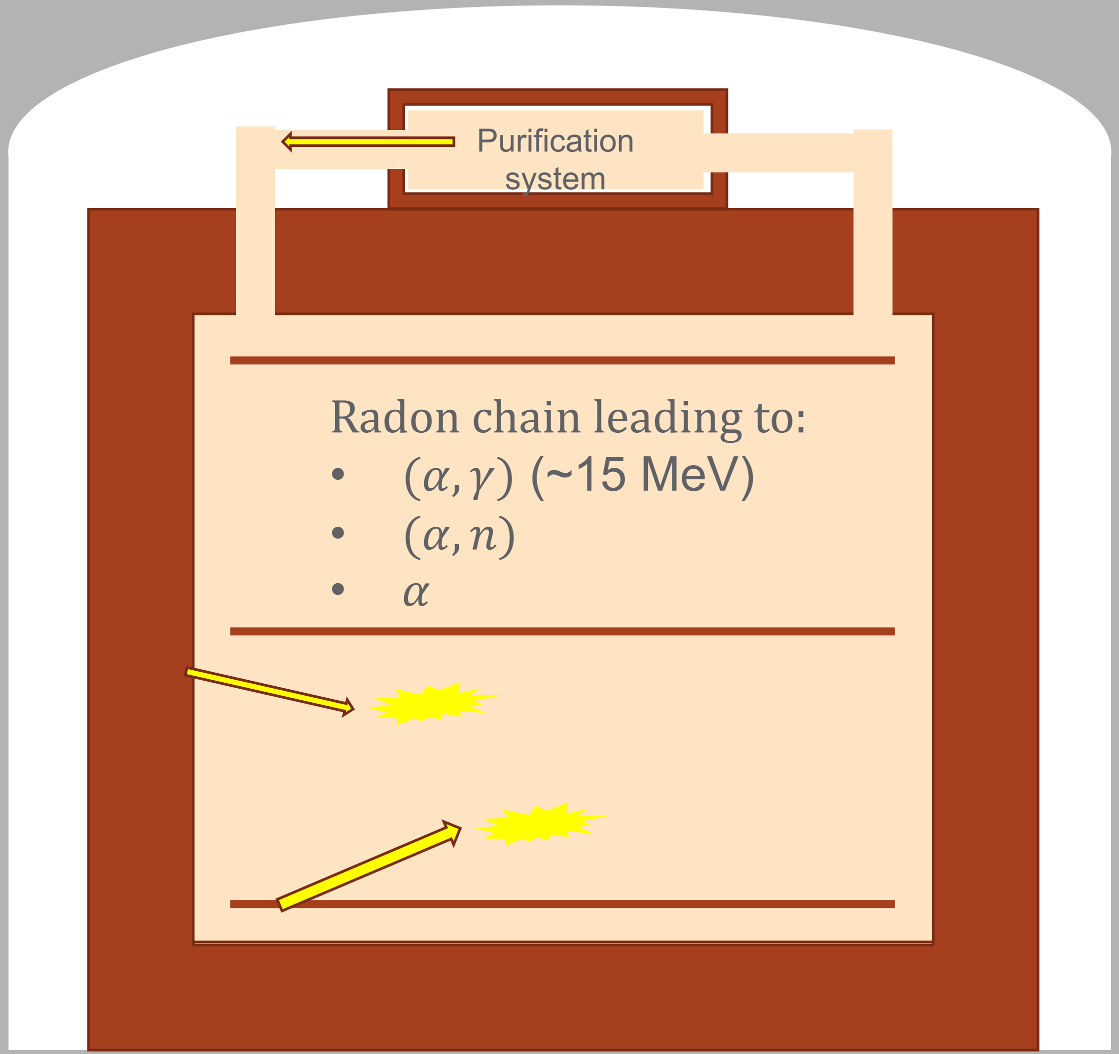
Examples from SuperCDMS implementation

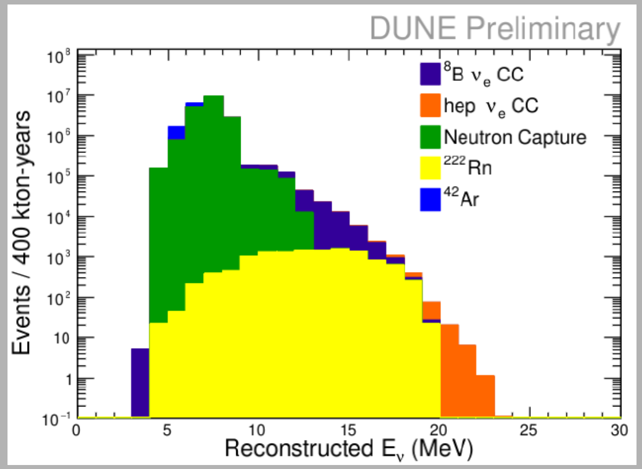


B. Loer

Radon Backgrounds



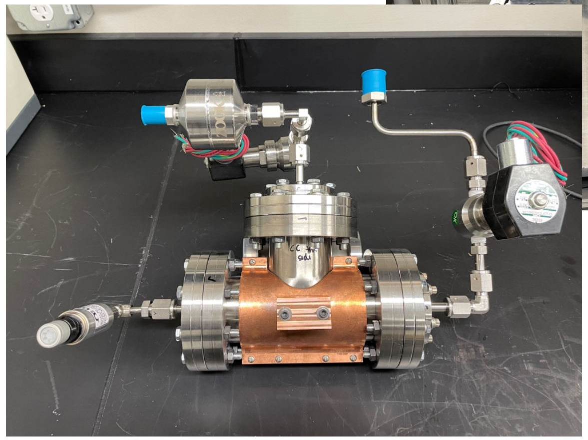




- Radon is highly mobile and can emanate and move within argon
- Main sources:
  - Purification system
  - Cryostat
  - Detector Components
  - …

- DUNE phase 1 targets mBq/kg level
  - Low emanation from purification system measured
  - But many unmeasured components remain
- Dark matter experiments have achieved 0.2 μBq/kg

Radon Reduction



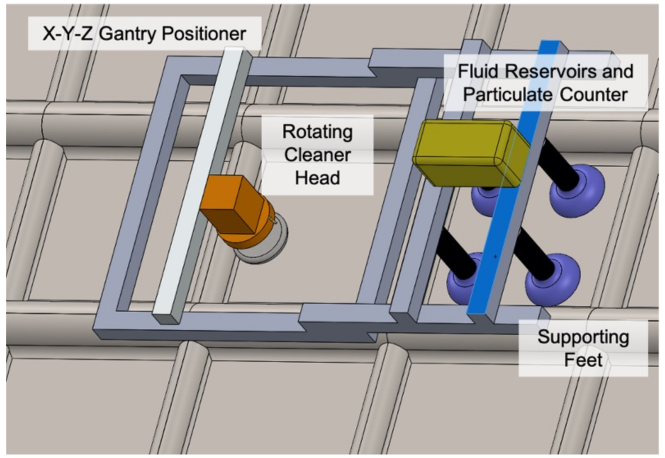
Prototype cryogenic radon emanation bench

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

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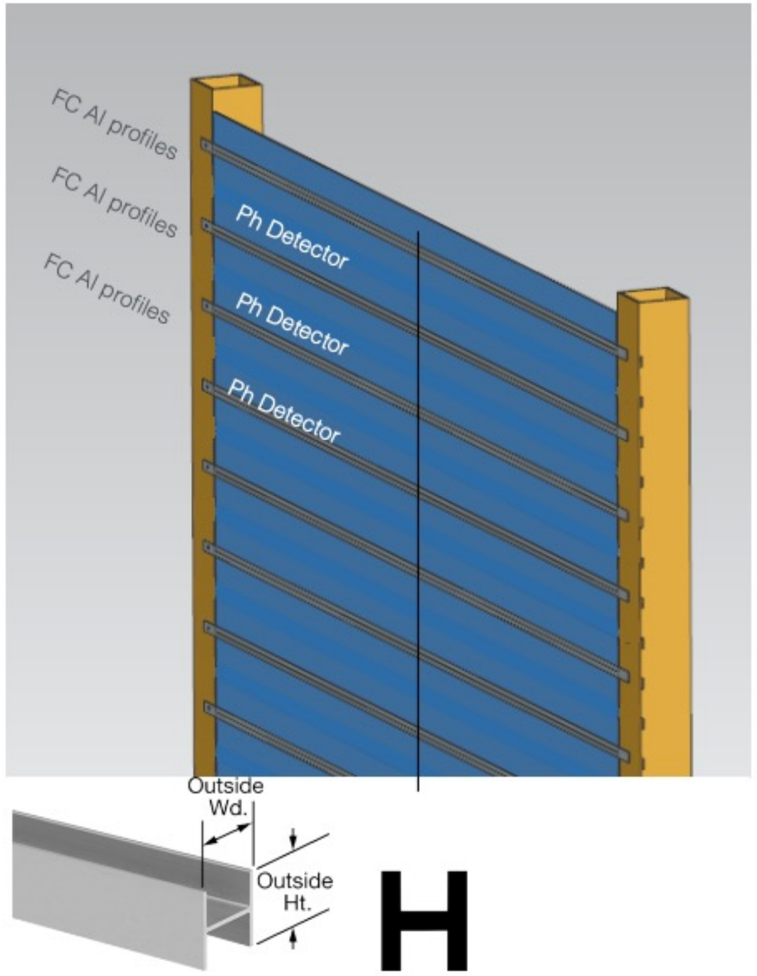
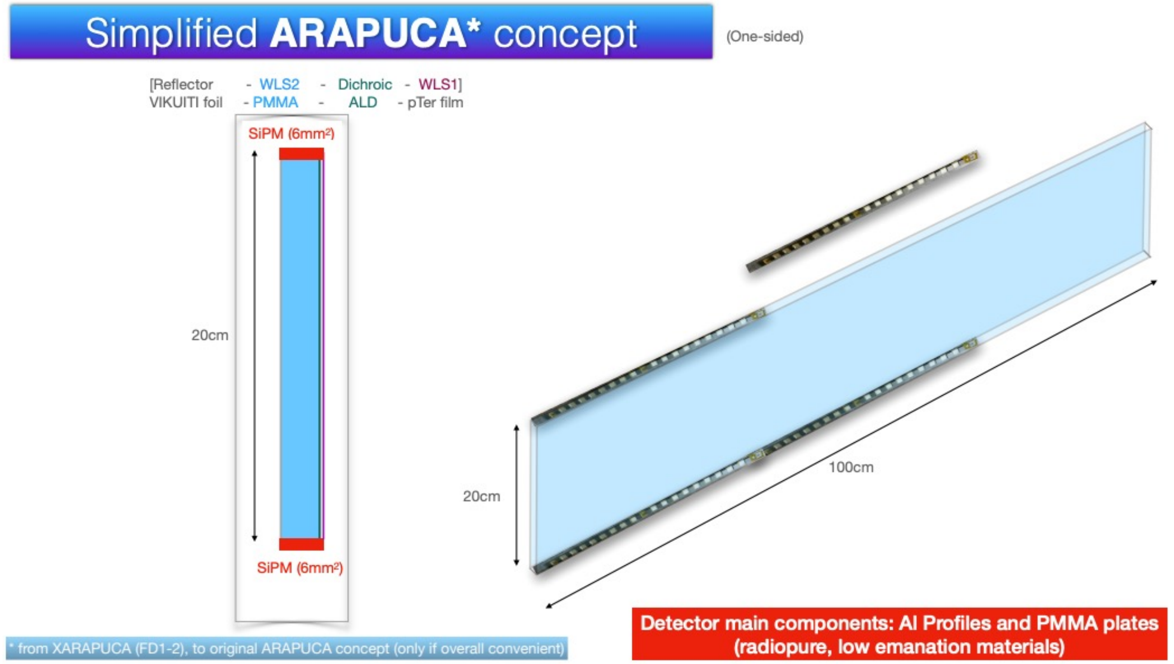
Thoughts on APEX materials

- Aluminum likely could be found radiopure
  - We should be wary of high (alpha,n) cross section
- Existing literature on clean acrylic:
  - E.g DEAP-3600, DarkSide shielding, Xenon,…
  - But significant variation in activities: 4 orders of magnitude
- Reflectors, wavelength shifters, filters have small mass but complicated production increases risk
- DarkSide has clean SiPM production capability
- Cabling/electronics likely radon emanation risk





No DUNE assays of any ARAPUCA system yet!

Other important topics not covered

- Gammas

external background	4pi flux in cavern [cm^-2 s^-1]	reduction factor	attenuation factor	area factor	4pi flux at LAr [cm^-2 s^-1]	rate in full LAr (VD) [Hz]	rate in HD [Hz]	
cavern neutrons	2.94E-06	21.816	10.908	1.3687	2.70E-07	5.34E+00	4.63E+00	predicted and 4.6+/-1.1 Hz in HD from simulation of 1x2x6
n-capture gammas from cryostat	N/A	N/A	N/A	1.3687	1.68E-06	3.32E+01	1.50E+00	predicted rates [Hz] w/ approx. gamma-att. for 1.5 MeV
n-capture gammas from rock/shotcrete	3.75E-06	13.807	6.9035	1.3687	5.44E-07	1.08E+01	4.87E-01	predicted rates [Hz] w/ approx. gamma-att. for 1.5 MeV
cavern gammas from rock/shotcrete	12.60418	23.985	11.9925	1.3687	1.0510	2.08E+07	9.40E+05	predicted rates [Hz] w/ approx. gamma-att. for 1.5 MeV
foam gammas	N/A	N/A	N/A	1.0000	0.0441	8.72E+05	3.95E+04	predicted rates [Hz] w/ approx. gamma-att. for 1.5 MeV

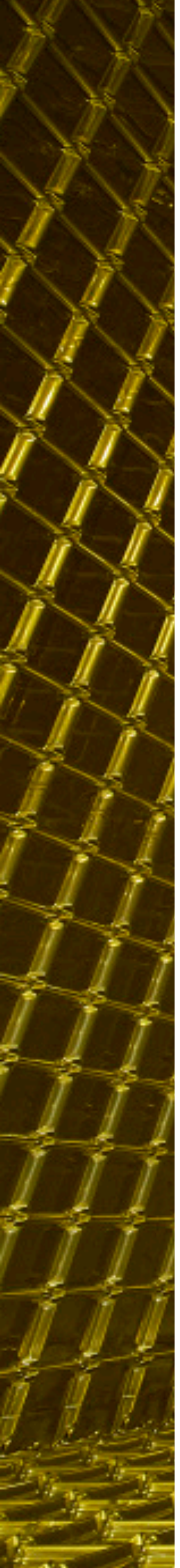
J. Reichenbacher May Collaboration Meeting

- Radon plate out
  - Flashing background directly on light sensors

- Underground argon (argon-42 reduction)
  - Required to lower threshold below ~5 MeV

Conclusions

- Interesting physics available if we lower the energy threshold
  - Supernova neutrinos
  - Solar neutrinos
  - Maybe 0nbb, WIMP dark matter
- All will require lower backgrounds:
  - DUNE Phase 1 backgrounds highly uncertain
    - ✓ **Should specify a background requirement for phase 2 to ensure solar neutrinos**
  - Background model building should start now:
    - ✓ Assay
      - Select suppliers, refine process, QA/QC
    - ✓ Simulations
      - PNNL summer student Carlos Moreno planning to start on this
  - We should be including the cryostat and shielding in this discussion



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End