CoSSURF 2024, in Rapid City, SD:

Radiological Backgrounds in DUNE Far Detectors

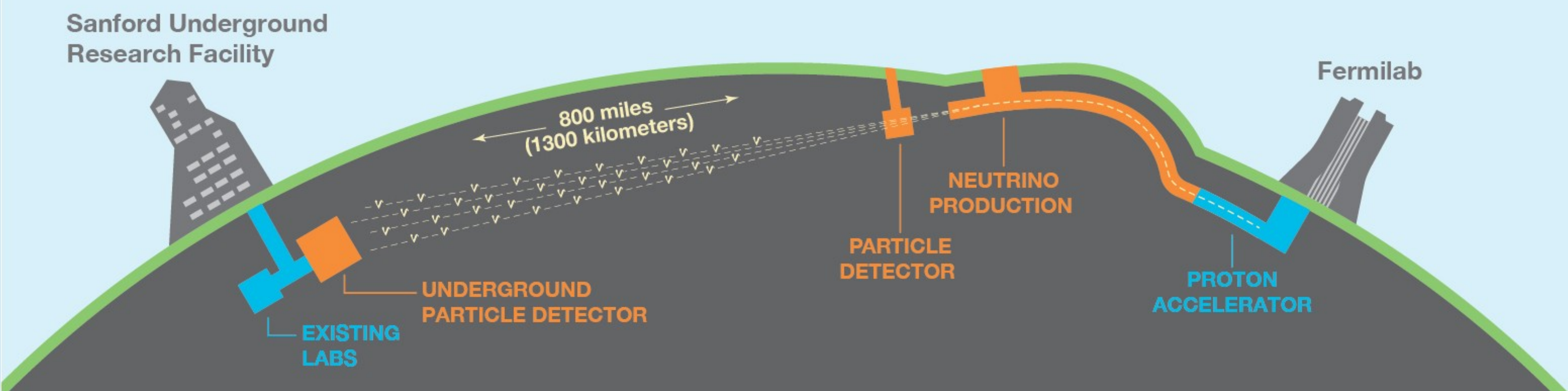
Shawn Westerdale
University of California, Riverside
w/ Juergen Reichenbacher
South Dakota School of Mines & Technology
…for the DUNE Collaboration

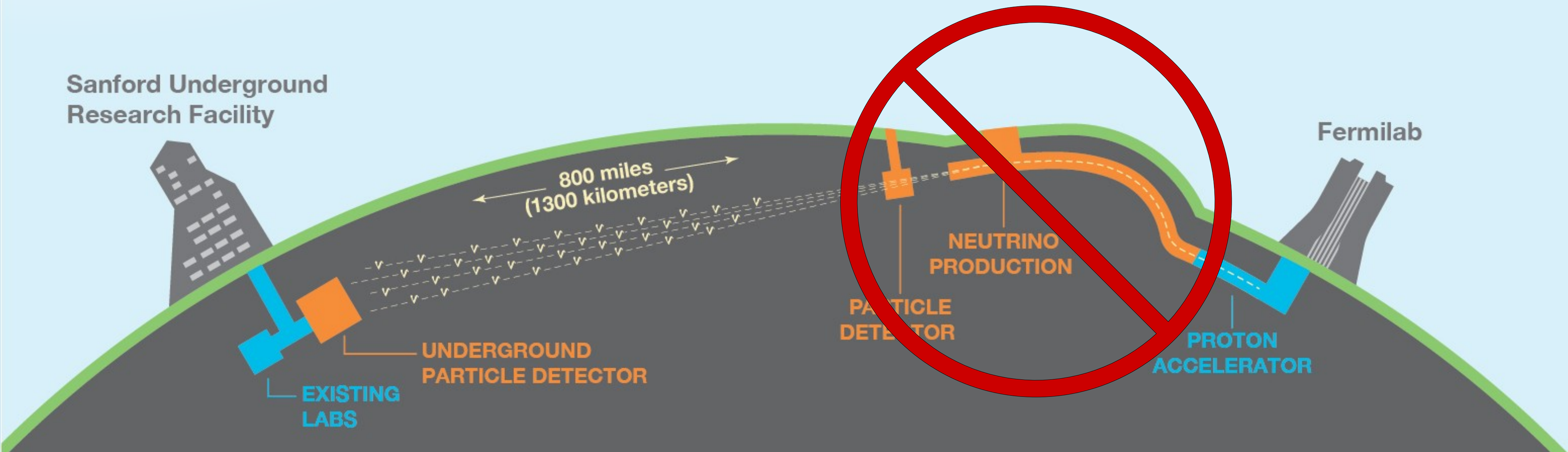
DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

Copilot, draw an illustration of radiological backgrounds in a DUNE far detector

UCR PHYSICS & ASTRONOMY

SOUTH DAKOTA MINES


Sanford Underground Research Facility
Fermilab
800 miles (1300 kilometers)
PARTICLE DETECTOR
NEUTRINO PRODUCTION
UNDERGROUND PARTICLE DETECTOR
EXISTING LABS
PROTON ACCELERATOR



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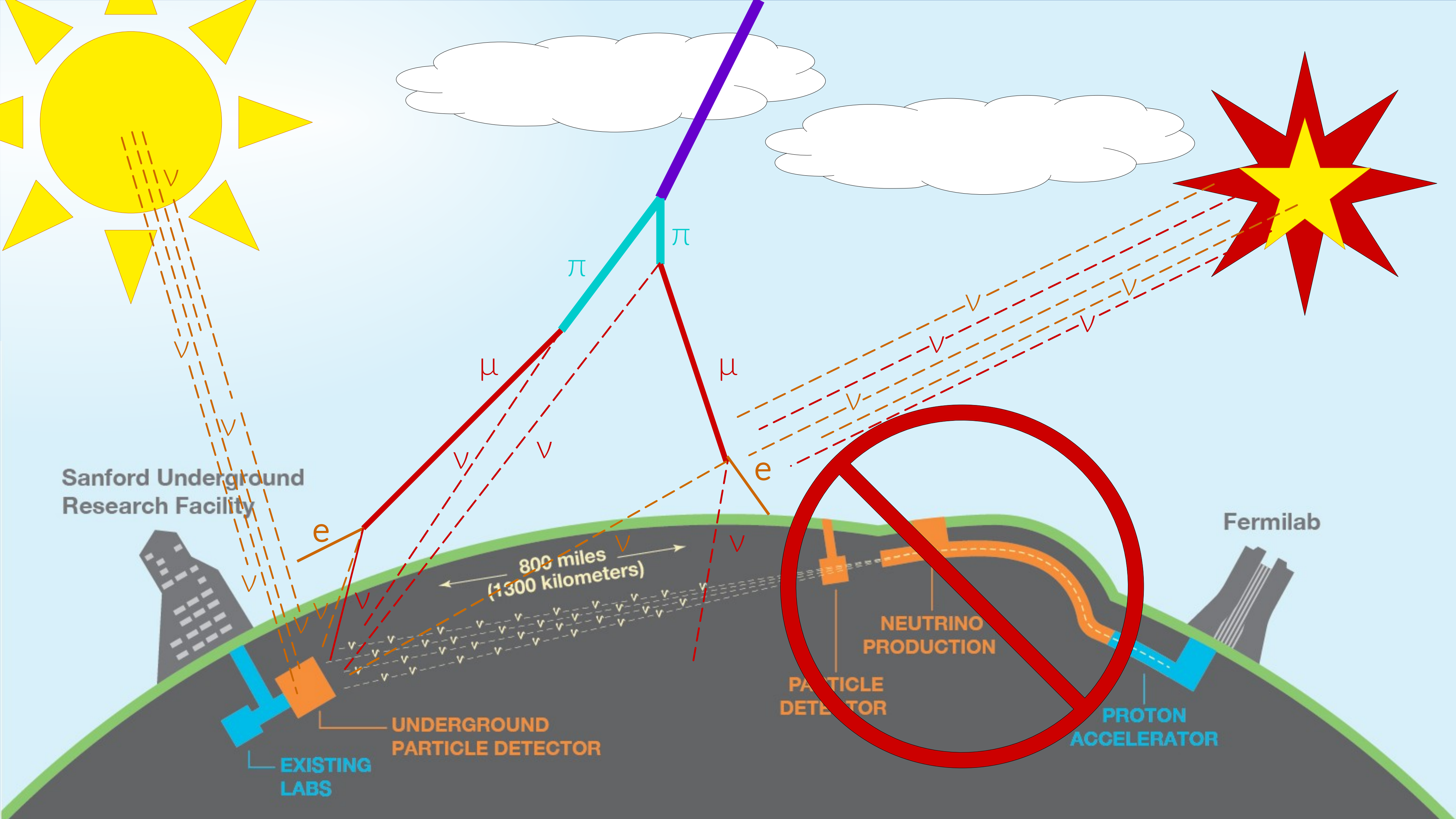

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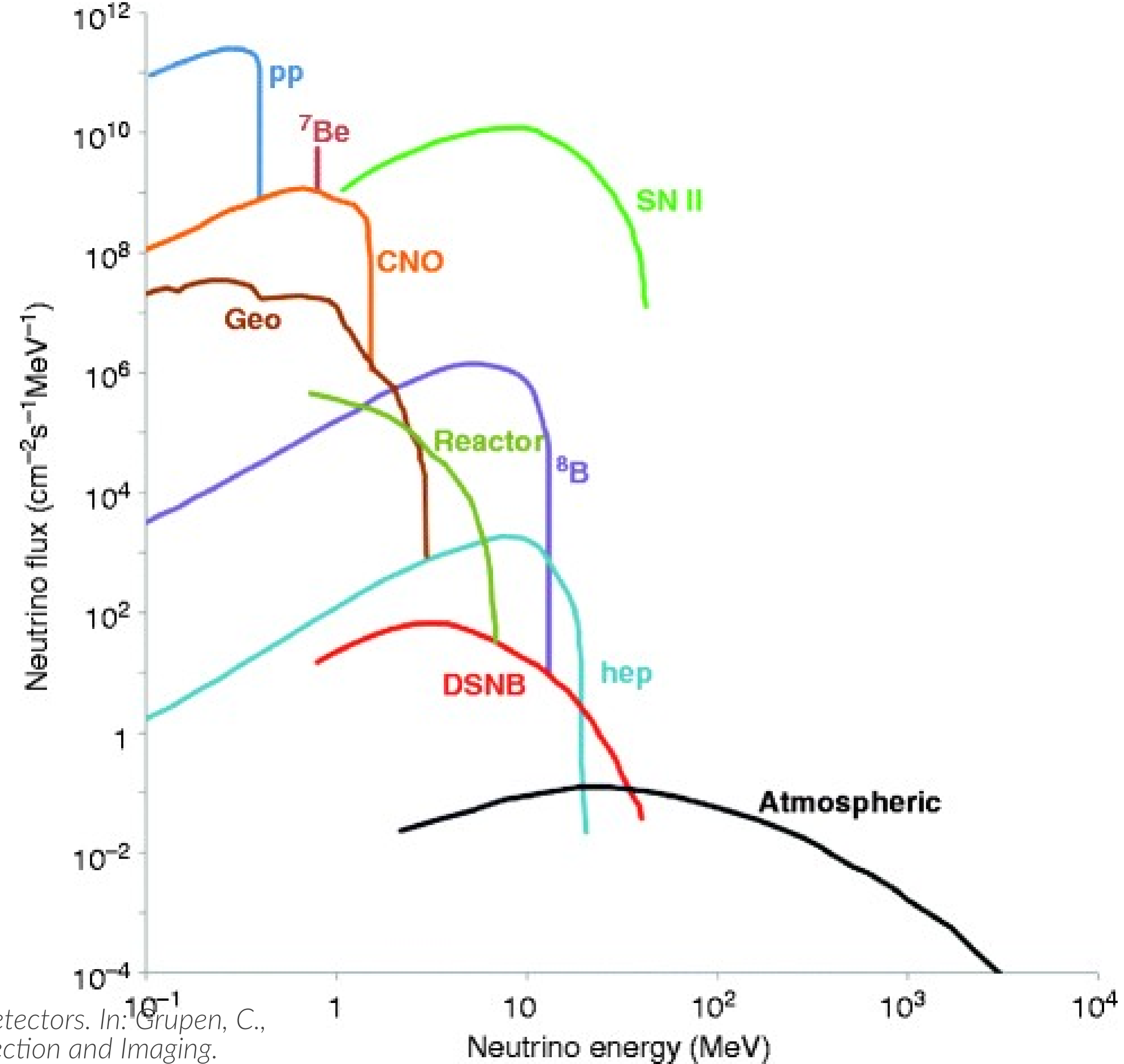
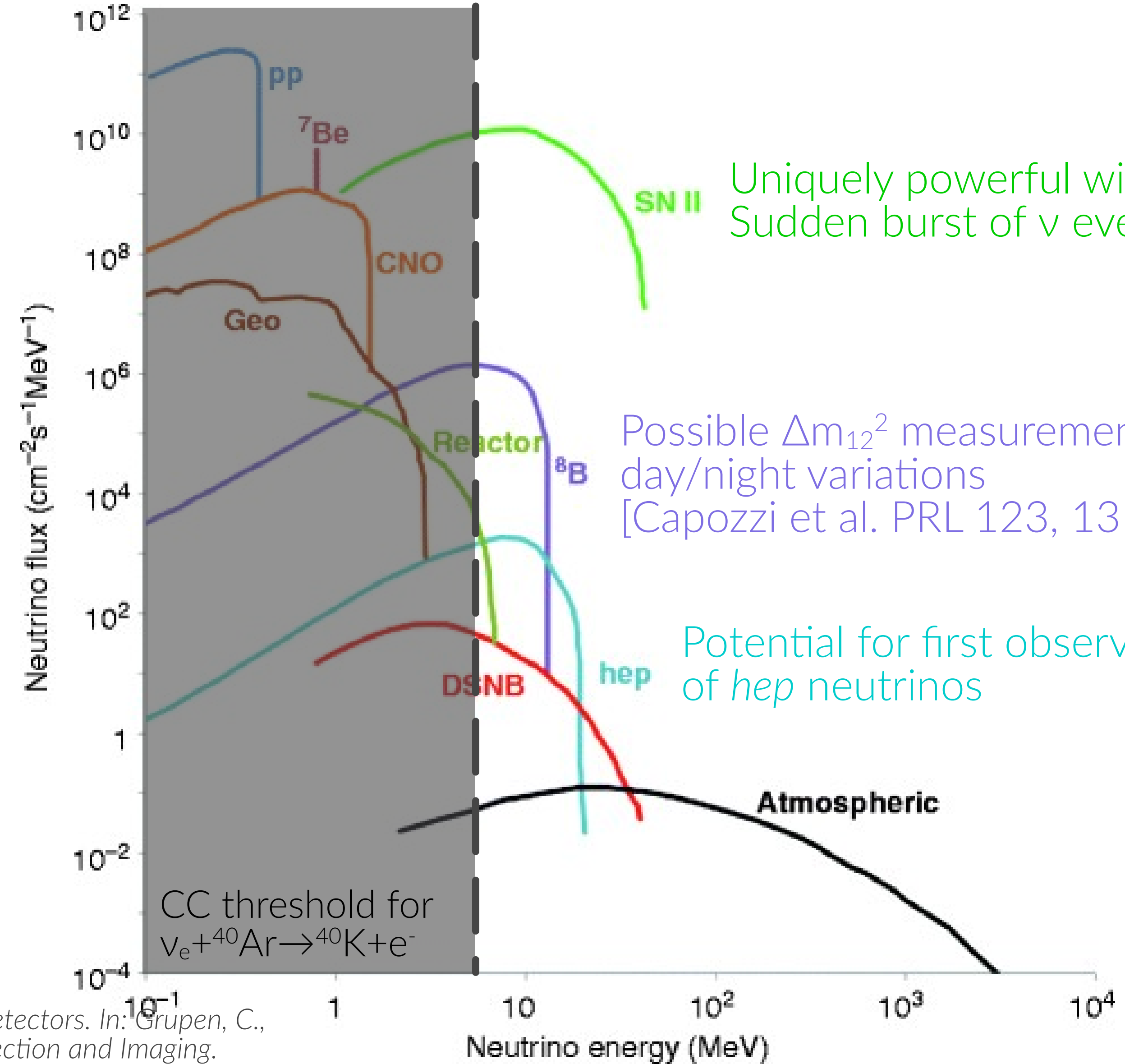


von Feilitzsch, et al. (2012). Neutrino Detectors. In: Grupen, C., Buvat, I. (eds) Handbook of Particle Detection and Imaging.



Uniquely powerful window to ν_e's
Sudden burst of ν events in ~10 s

Possible Δm_{12}^2 measurement using day/night variations
[Capozzi et al. PRL 123, 131803 (2019)]

Potential for first observation of *hep* neutrinos

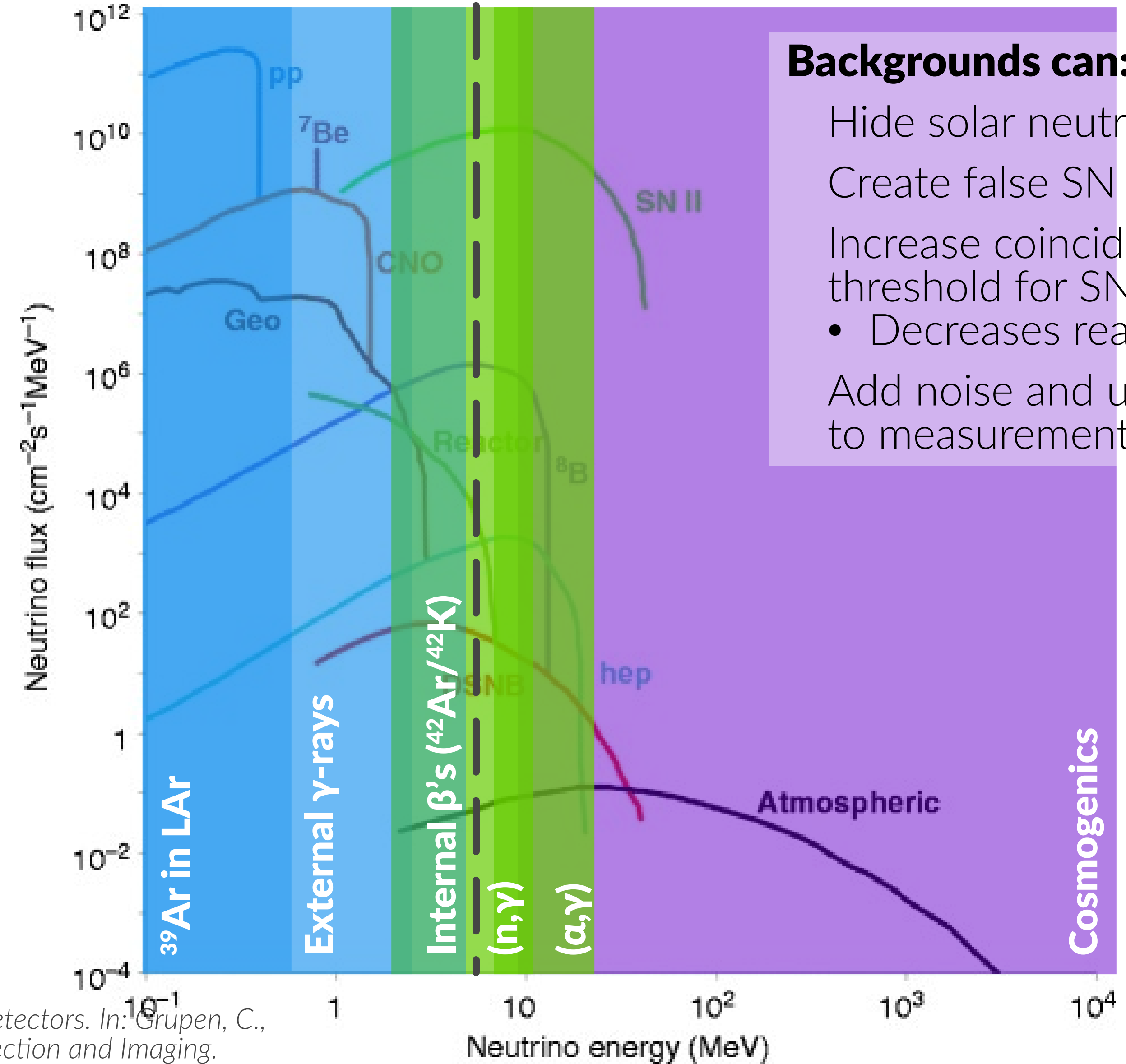
von Feilitzsch, et al. (2012). Neutrino Detectors. In: Grupen, C., Buvat, I. (eds) Handbook of Particle Detection and Imaging.

External radioactivity
$^{238}U/^{235}U$, ^{232}Th, ^{40}K, etc. in detector mat. + rock. Max γ in ^{232}Th chain (^{208}Tl):
E_γ = 2.6 MeV

Internal radioactivity
Dominant: ^{39}Ar (Q_β=565 keV)
2.6–3.5 MeV dominated by $^{42}Ar/^{42}K$ in LAr
Contaminants in LAr (^{222}Rn) can leave α, β, & γ signals
4-9 MeV: α peaks from ^{222}Rn (May be identifiable as nuclear recoils)

Radiative n/α captures
(n,γ) reactions from radiogenic neutrons extend from 2.2–10.5 MeV
(α,γ) in LAr up to ~17 MeV

Cosmogenics
Cosmogenic muon shower products extend to 1 TeV, may stray far from μ track



Backgrounds can:

Hide solar neutrinos

Create false SN alerts

Increase coincidence ν threshold for SNe
- Decreases reach

Add noise and uncertainty to measurements

von Feilitzsch, et al. (2012). Neutrino Detectors. In: Grupen, C., Buvat, I. (eds) Handbook of Particle Detection and Imaging.

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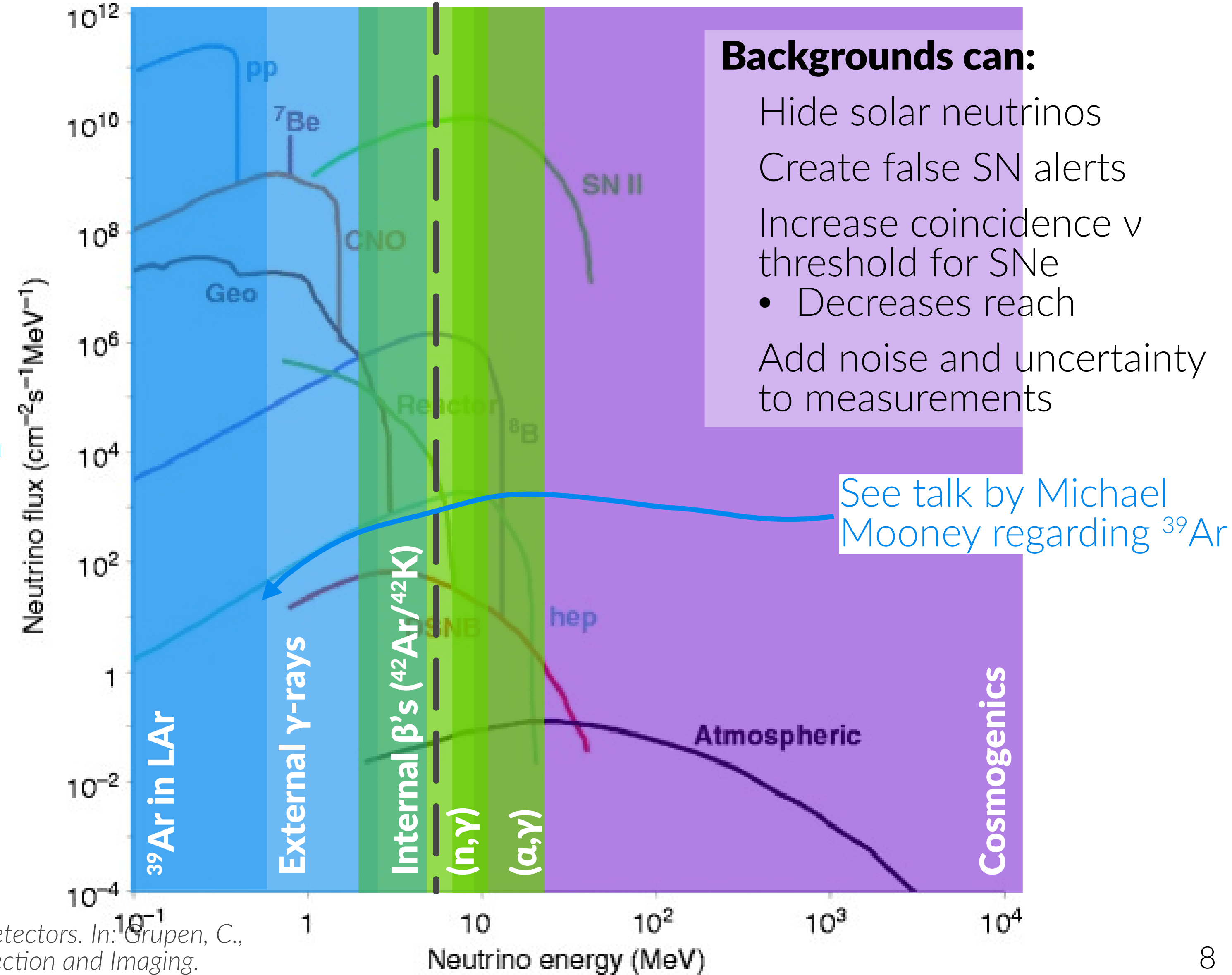

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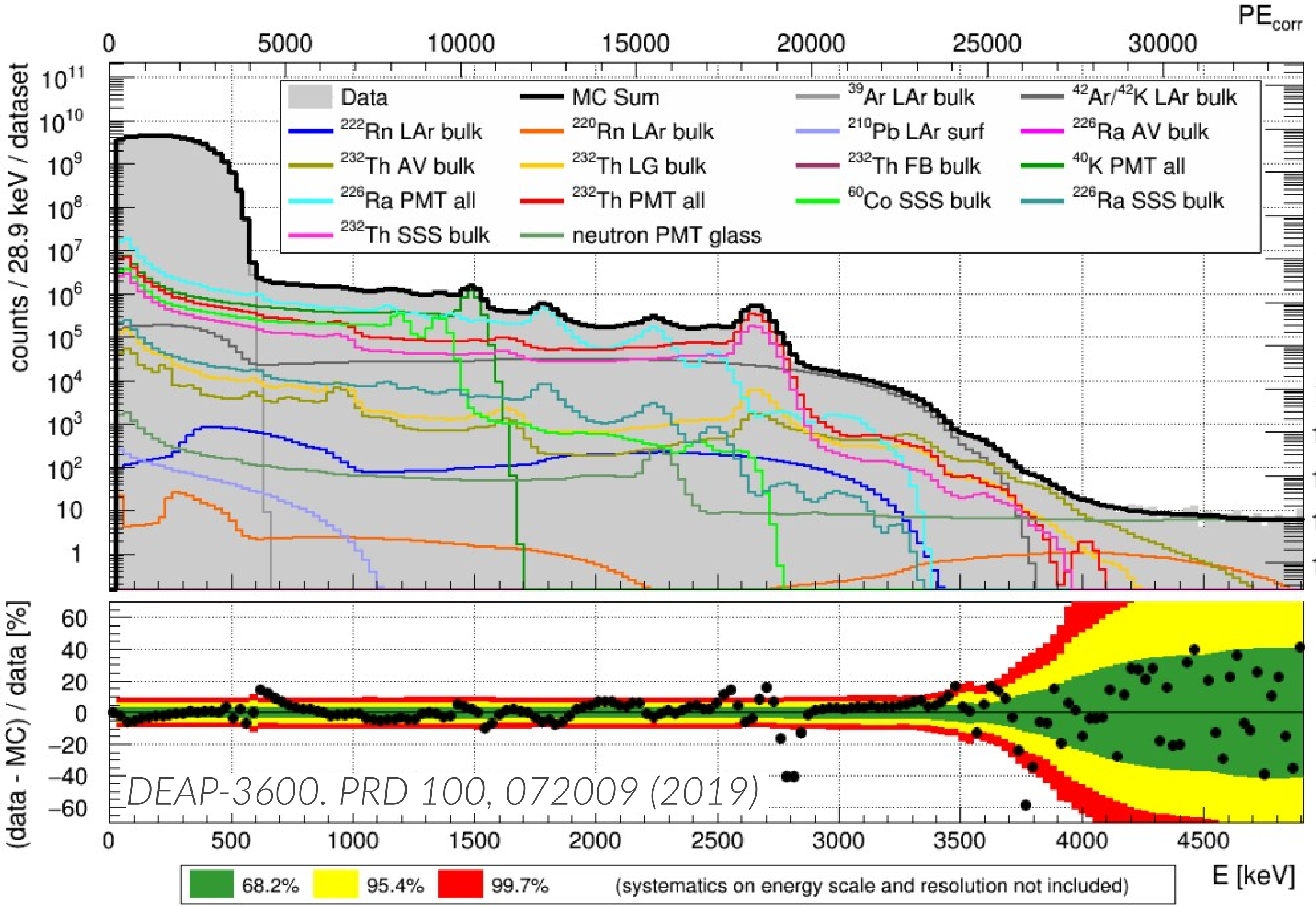
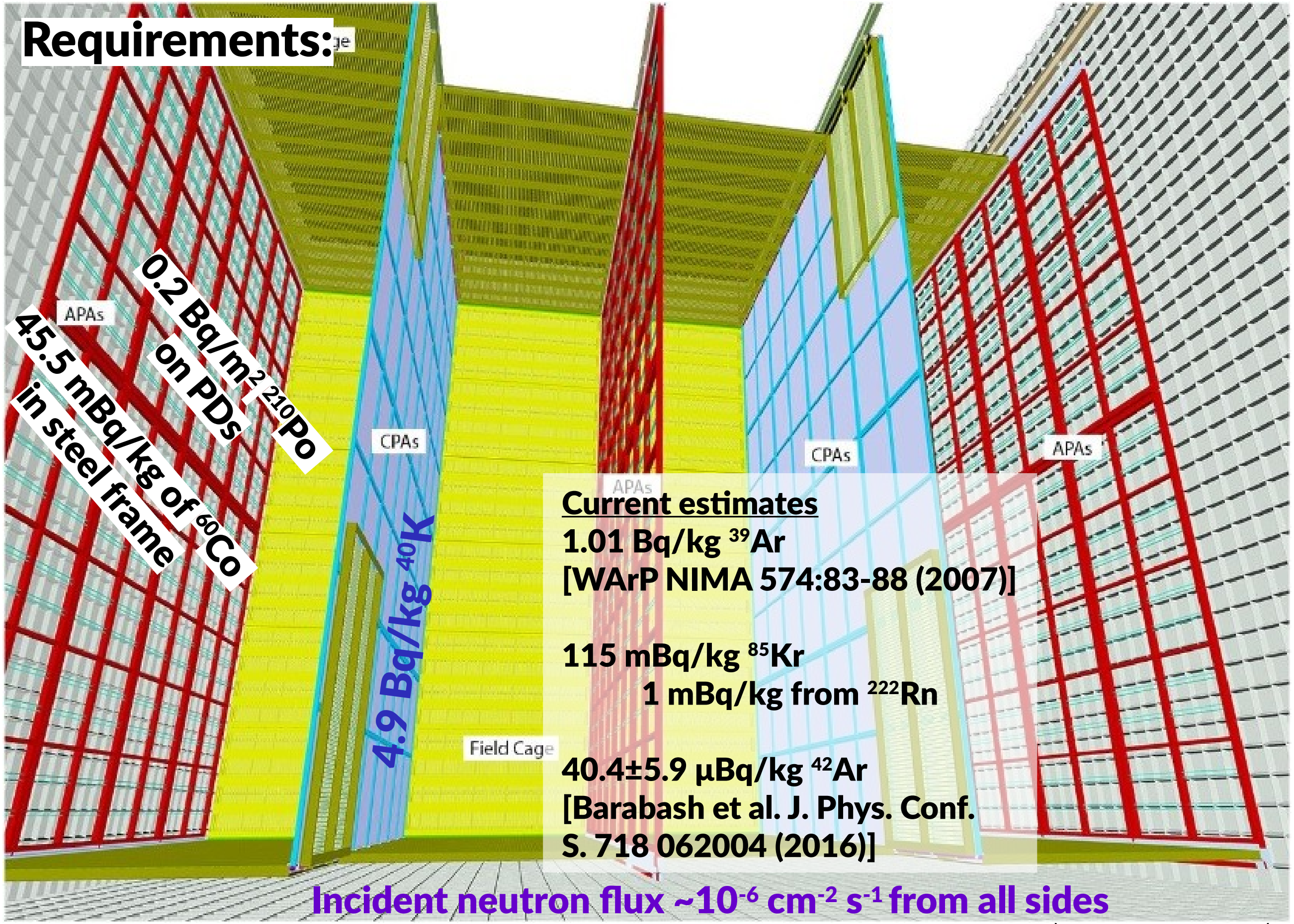
DEAP-3600

3.3 tonne LAr dark matter detector at SNOLAB

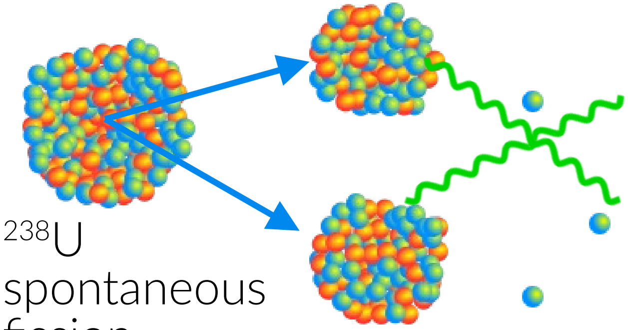


DEAP-3600. PRD 100, 072009 (2019)

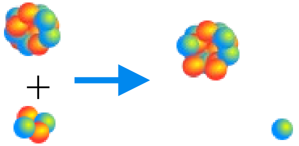
Where does the radioactivity come from?



Neutrons from

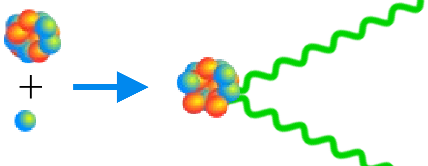


^{238}U spontaneous fission



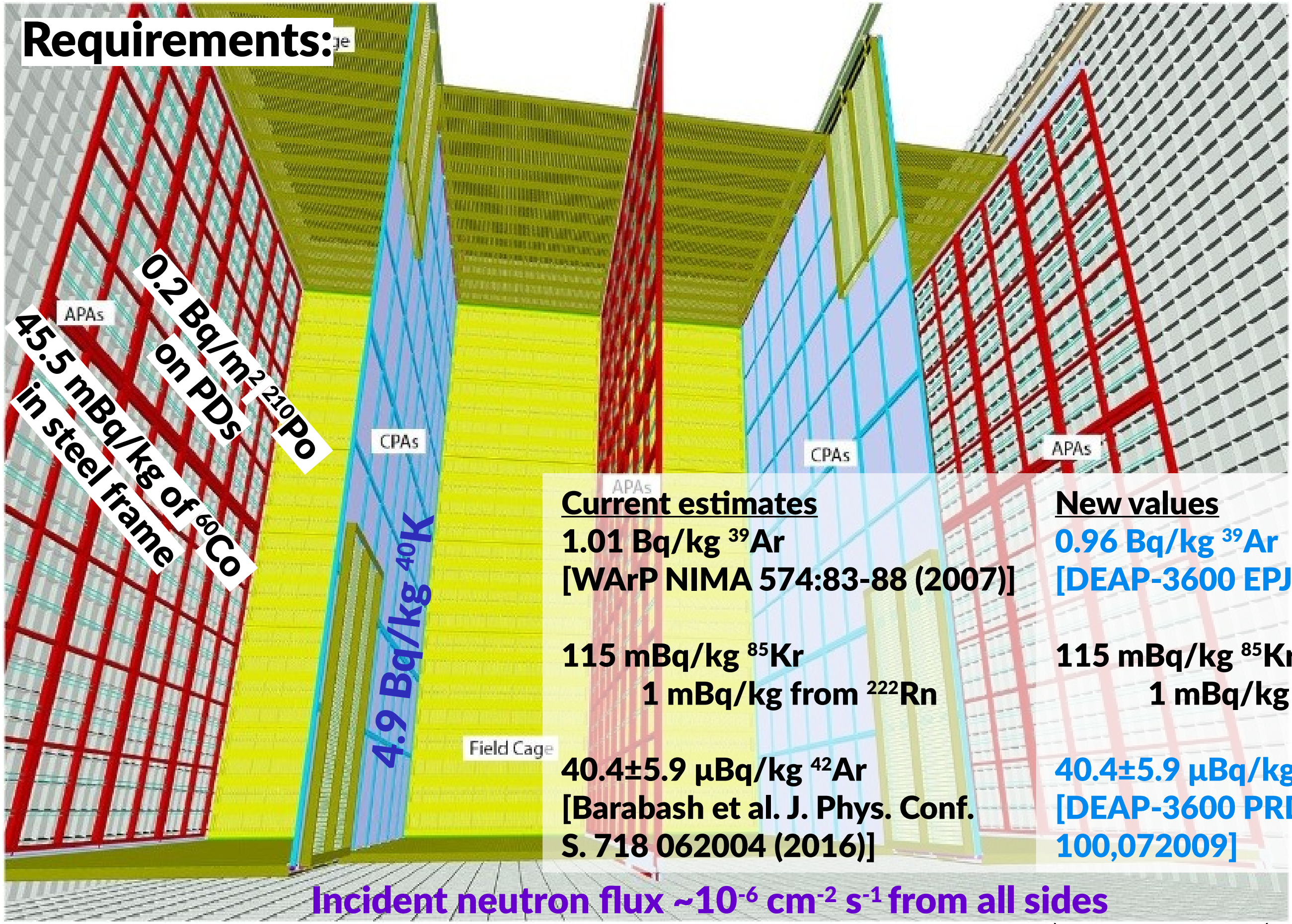
(α,n) reactions from any α-emitter in U/Th chains

(n,γ) de-excitation cascades



Where does the radioactivity come from?

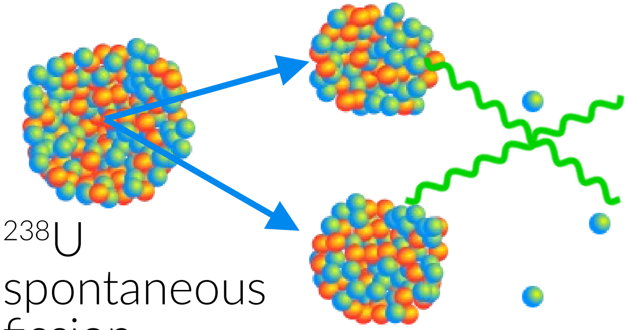
Requirements:



Current estimates	New values
1.01 Bq/kg ^{39}Ar [WArP NIMA 574:83-88 (2007)]	0.96 Bq/kg ^{39}Ar [DEAP-3600 EPJC 83, 642 (2023)]
115 mBq/kg ^{85}Kr 1 mBq/kg from ^{222}Rn	115 mBq/kg ^{85}Kr 1 mBq/kg from ^{222}Rn
40.4±5.9 μBq/kg ^{42}Ar [Barabash et al. J. Phys. Conf. S. 718 062004 (2016)]	40.4±5.9 μBq/kg ^{42}Ar [DEAP-3600 PRD 100,072009]

Incident neutron flux ~10^{-6} cm^{-2} s^{-1} from all sides

Neutrons from



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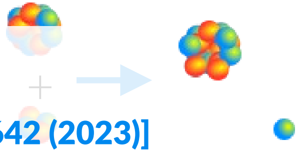

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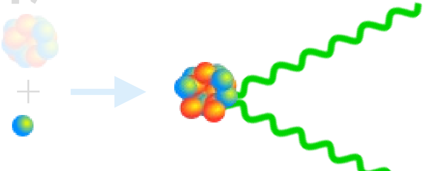
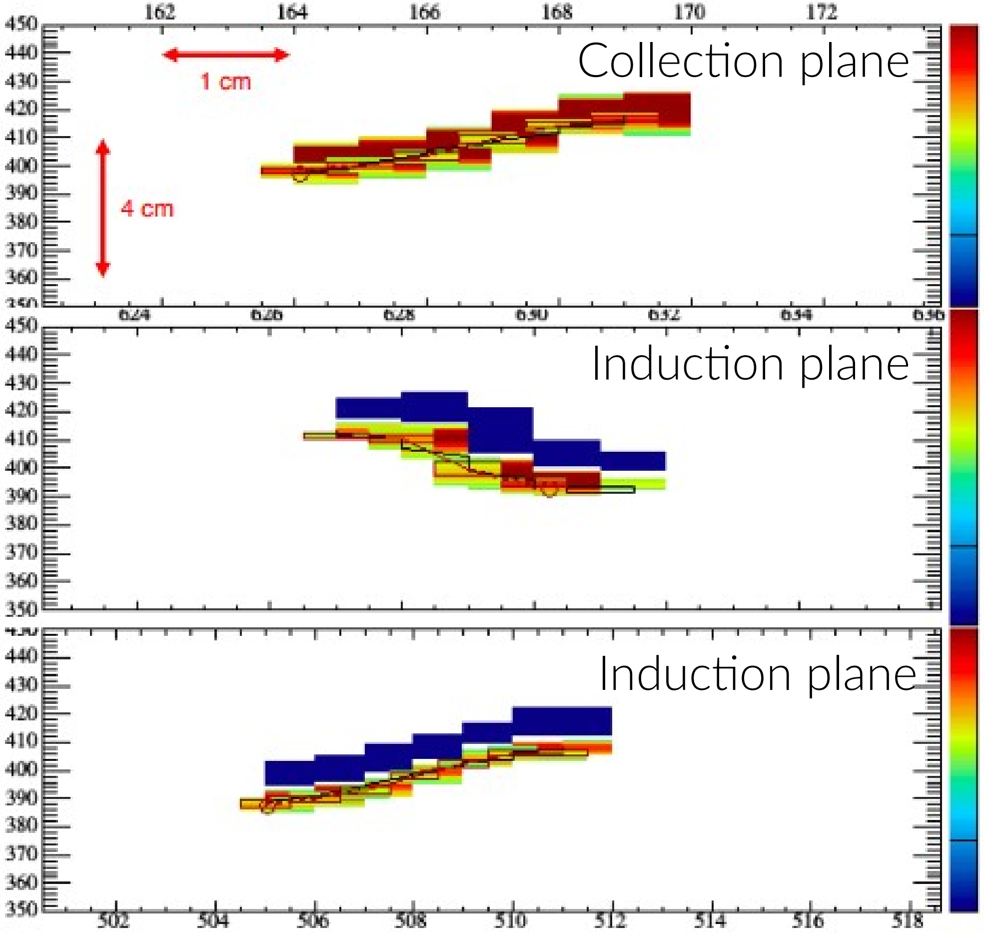
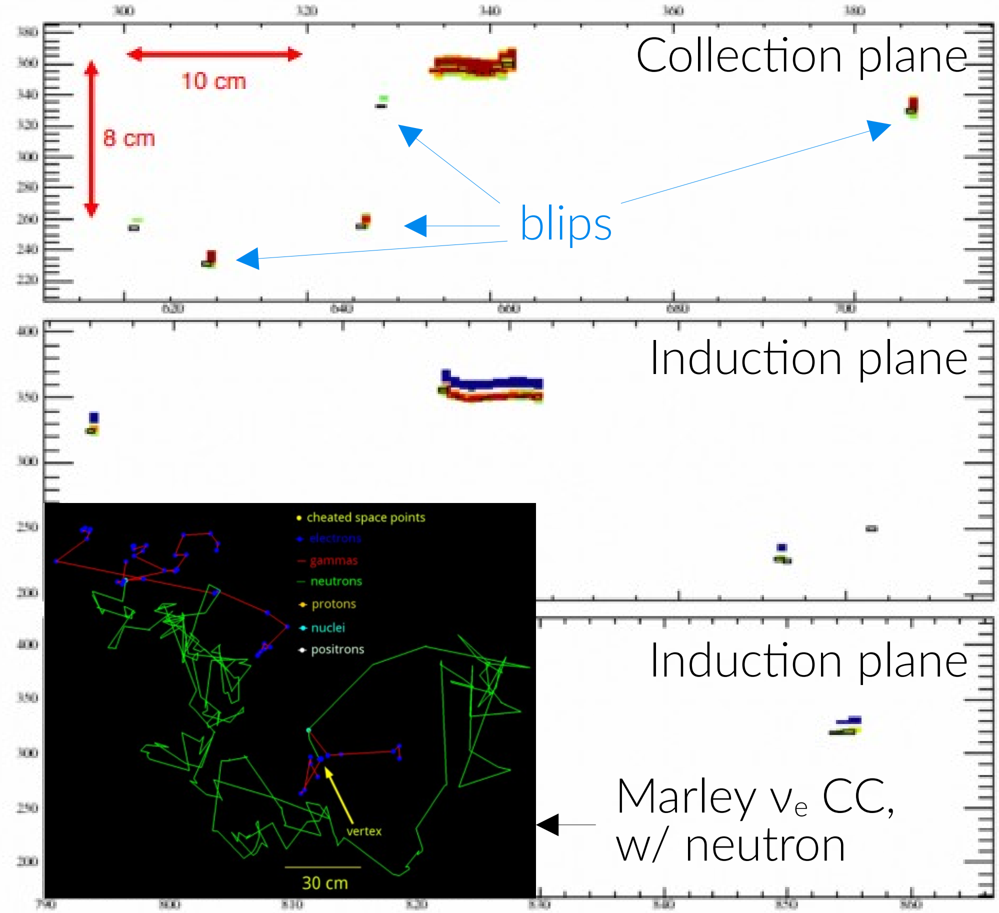


Simulated event displays for supernova neutrino signals (LArSoft)

ν-e^- electron scattering (10.25 MeV e^-)



ν_e CC event (20.25 MeV ν)



time →

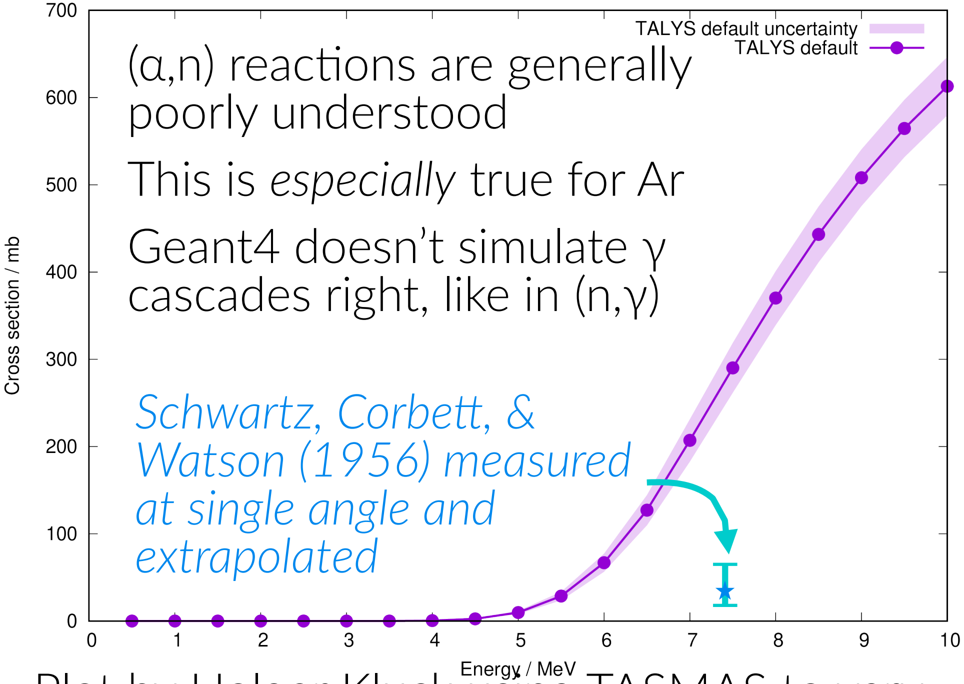
wire number →

DUNE. Eur. Phys. J. C 81 :423 (2021)

Background originating in the LAr cannot be fiducialized away

Rn in LAr → Ar(α,n), Ar(α,γ)
distributed uniformly in fiducial volume
Rn continually emanates into LAr from materials

Neutrons are highly penetrating and can produce (n,γ) in the center of the LAr



(α,n) reactions are generally poorly understood

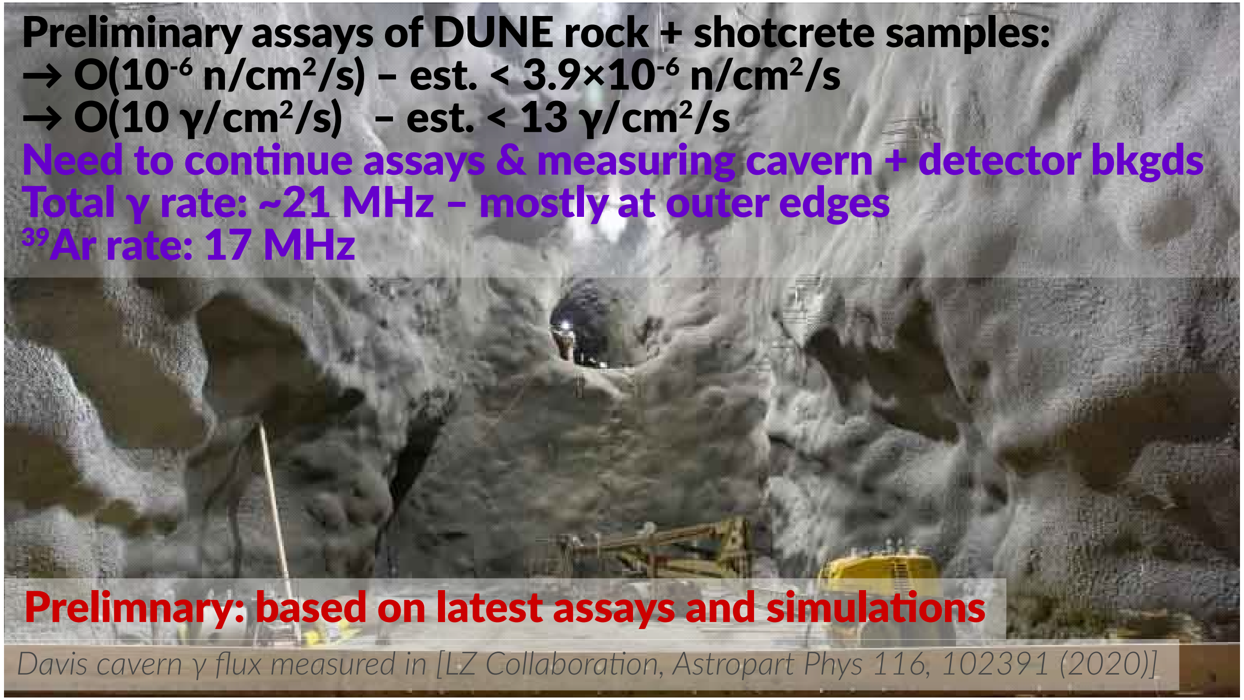
This is *especially* true for Ar

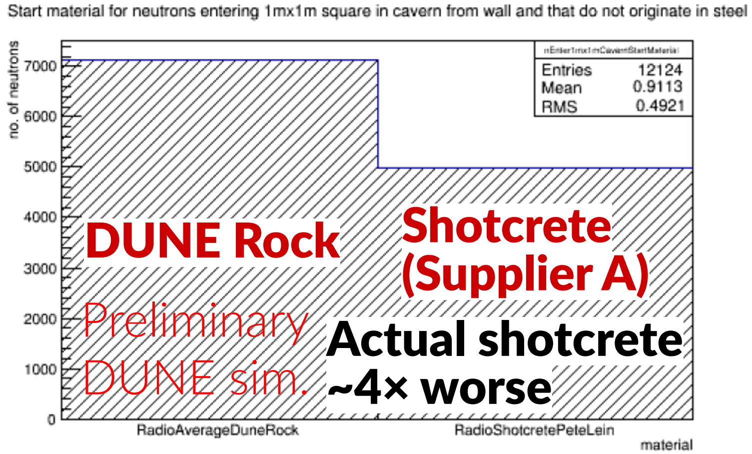
Geant4 doesn't simulate γ cascades right, like in (n,γ)

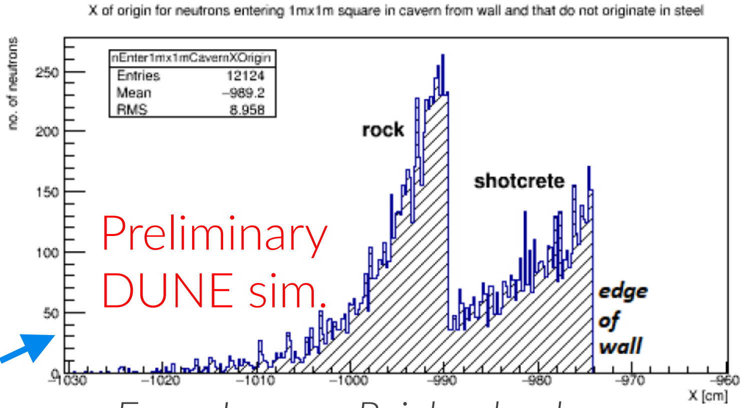
Schwartz, Corbett, & Watson (1956) measured at single angle and extrapolated

Plot by Holger Kluck using TASMAS to vary TALYS "default" uncertainties, defined so that on average, bands cover data/model uncertainties over all reactions

External/Cavern backgrounds







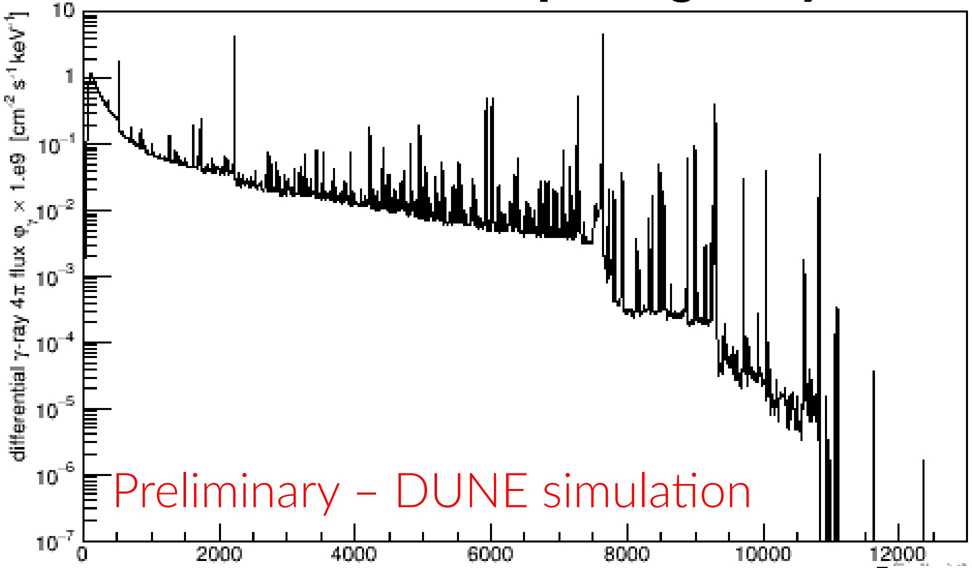
Al in rock/shotcrete makes it a significant neutron source! — High Al(α,n) yield

Simulation w/ LArSoft, Decay0 & new ^{232}Th decay chain implementation

From Juergen Reichenbacher

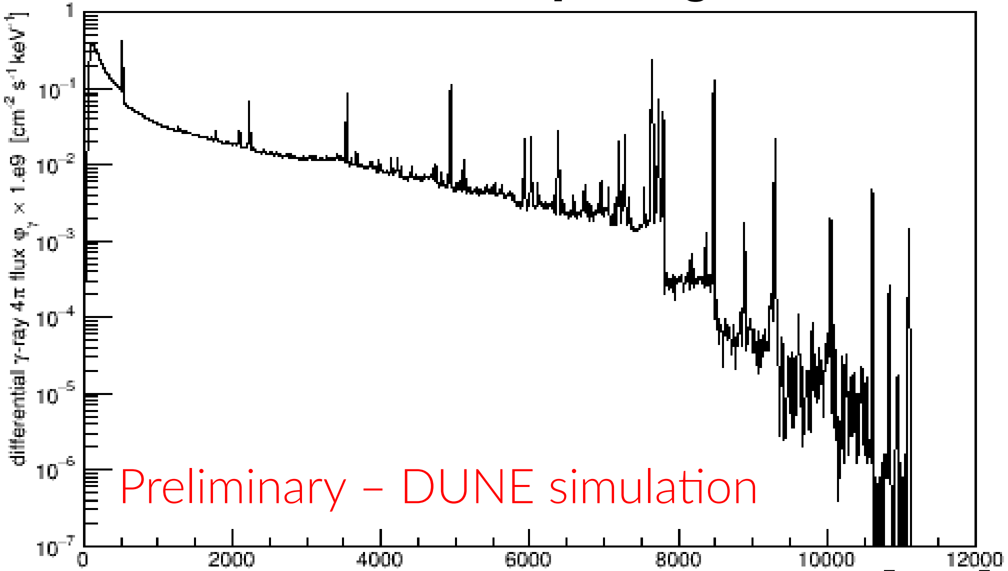
Simulated (n,γ) spectra with native Geant4 models

Cavern neutrons capturing in cryostat



E_γ at LAr interface [keV]

Cavern neutrons capturing in cavern



E_γ at LAr interface [keV]

Neutrons: Tools and needs

(α,n) yields*: SOURCES4A/C, NeuCBOT, SaG4N

Needs extensive radioassays of materials: α- & γ-spectroscopy, ICP-MS, NAA, Rn emanation…

- Also need to know chemical compositions: XRD, XRF, ICP-MS, FT-IR, CHN, …

Significant lack of (α,n) cross section data → large, poorly understood uncertainties

- Need more measurements—Ar and Al are both important isotopes with insufficient data

(n,γ) de-excitation: G4NDL & G4PhotonEvaporation, CASCADE, NUDEX, FIFRELIN

Native Geant4 models G4NDL and G4PhotonEvaporation have issues reproducing γ lines and correlations, don't conserve energy, and don't reproduce summation peaks

CASCADE is an attempt to fix it using ENSDF databases of de-excitation cascades

- https://github.com/UCRDarkMatter/CASCADE - Currently private repository (plan to go public soon): Email shawn.westerdale@ucr.edu for access
- Still holes due to missing data: No data for some isotopes, some isotopes have unplaced γ lines

n and γ fluxes: Need direct measurements of n and γ fluxes in cavern and cryostat

Full simulations may enable ML classifiers to distinguish from ν events

*** New white paper on (α,n) calculations, uncertainties, and data needs – see arXiv:2405.07952**

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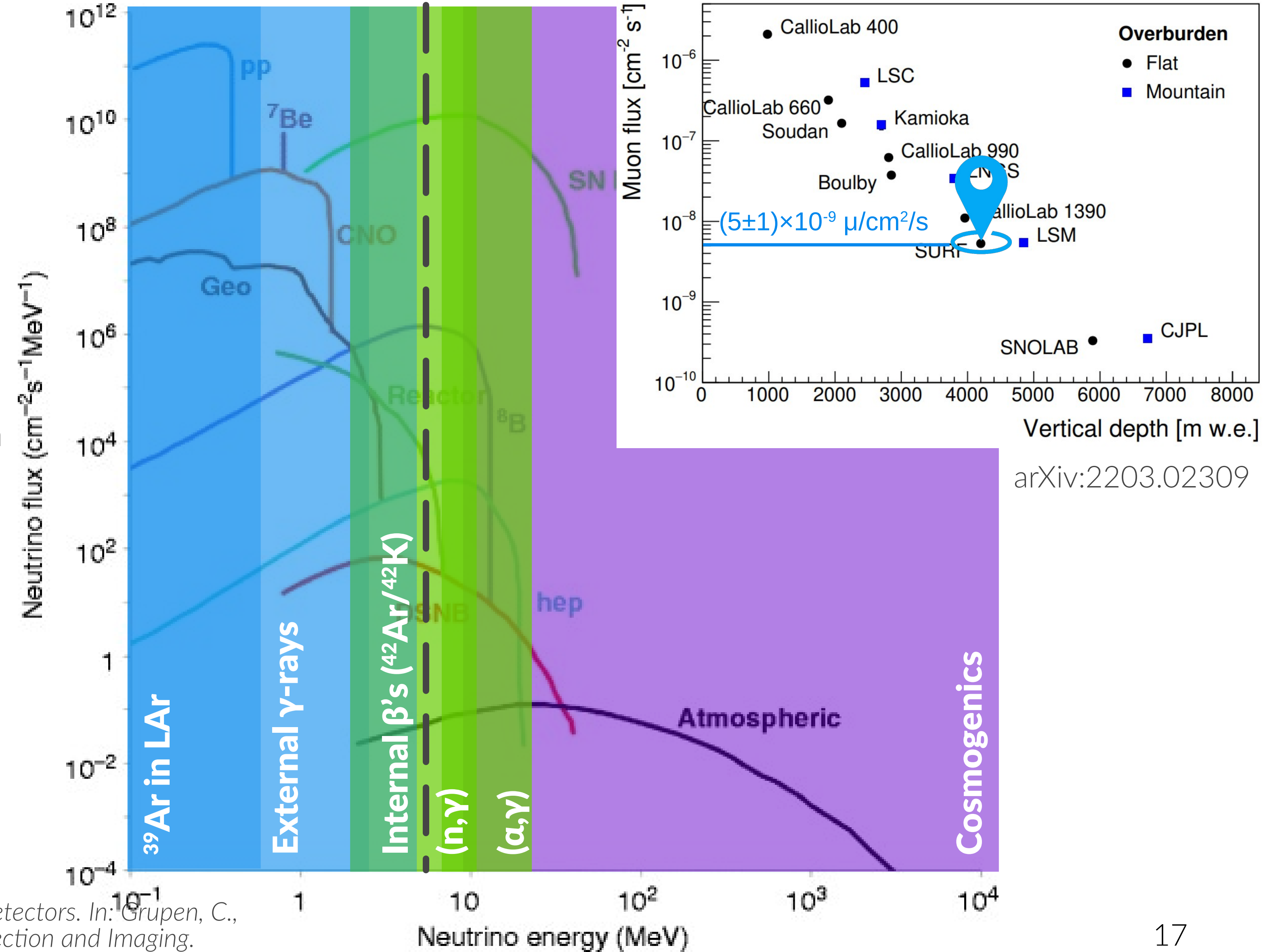
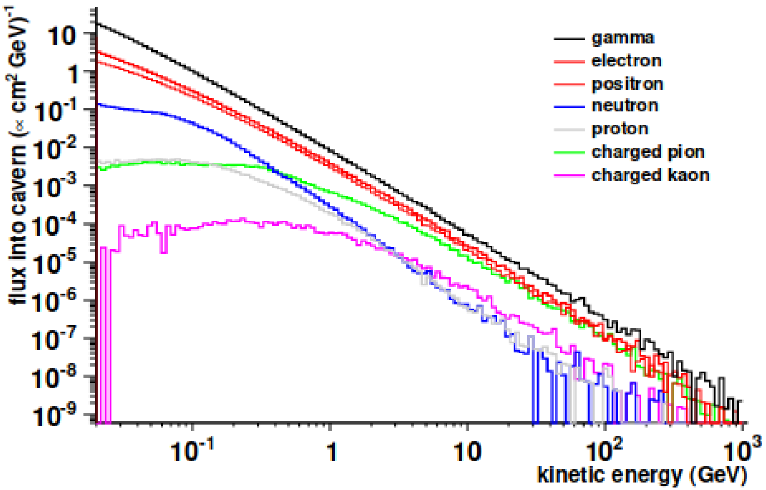


arXiv:2203.02309

von Feilitzsch, et al. (2012). Neutrino Detectors. In: Grupen, C., Buvat, I. (eds) Handbook of Particle Detection and Imaging.

Muon showers underground

FLUKA sims of LNGS for Borexino & DarkSide-50
[A. Empl et al. JCAP08(2014)064]

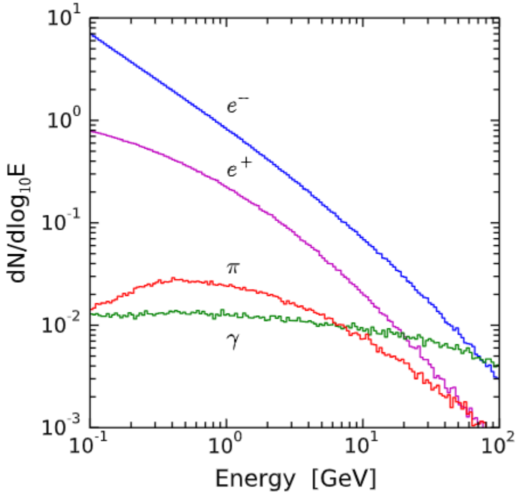


Shower products can make ν-like signals, even if muon does not enter detector

Correlated, energetic (highly-penetrating) neutrons inelastically scatter & capture → mimic neutrino bursts, like supernovae

Muon showers underground

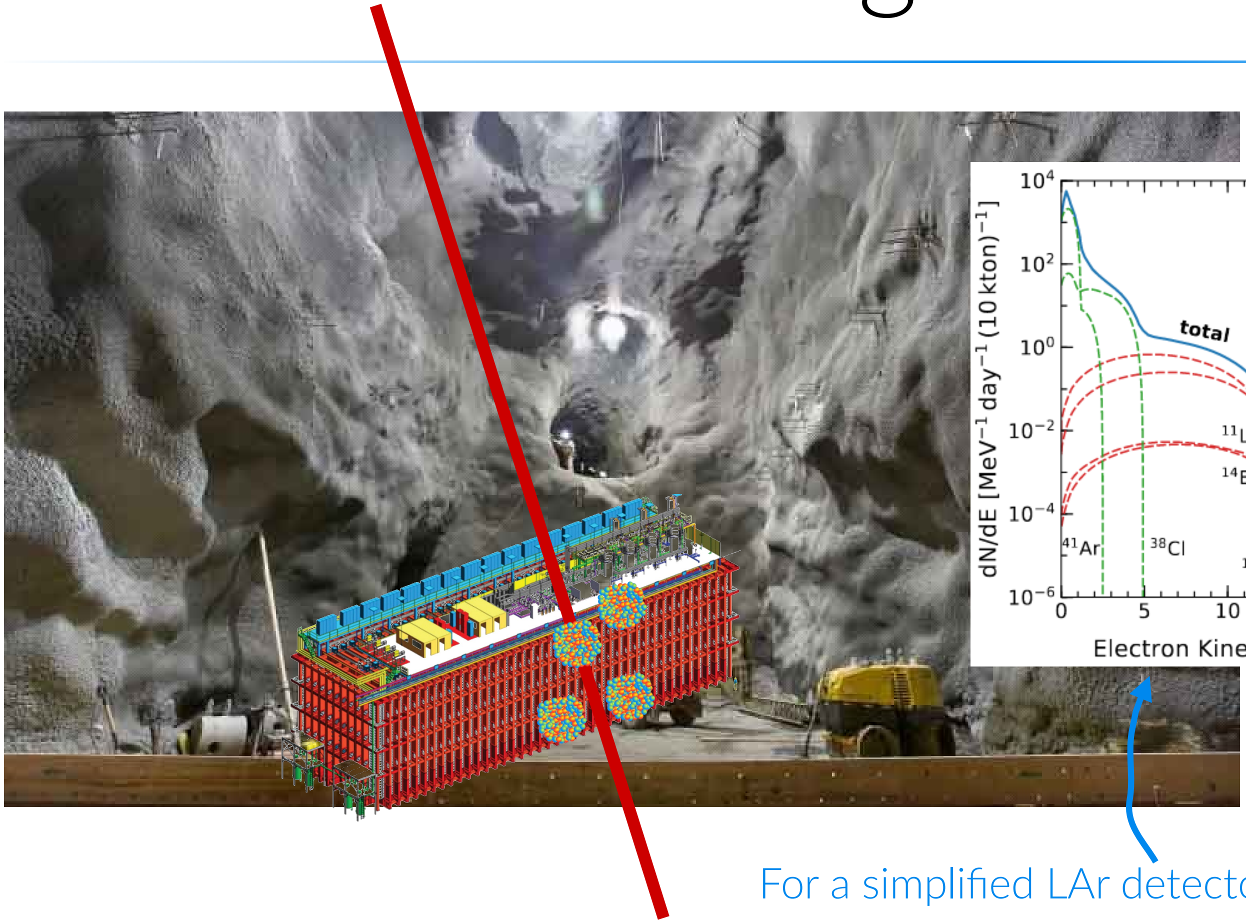
FLUKA sims of Super-Kamiokande
[Li & Beacom, PRD91, 105005 (2015)]



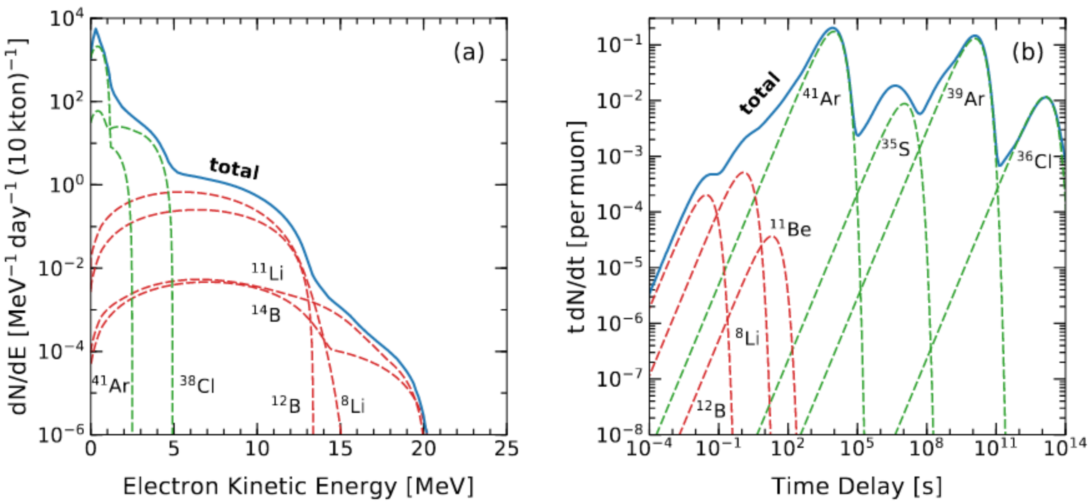
Similar results found for Super-K: π and γ particularly dangerous, as they can penetrate into LAr and make ν-like signals

Hadronic secondaries also primarily responsible for activating target

Short-lived cosmogenic isotope activation



FLUKA simulations of DUNE-like LAr detector [Zhu, Li, & Beacom, PRC99, 055810 (2019)]

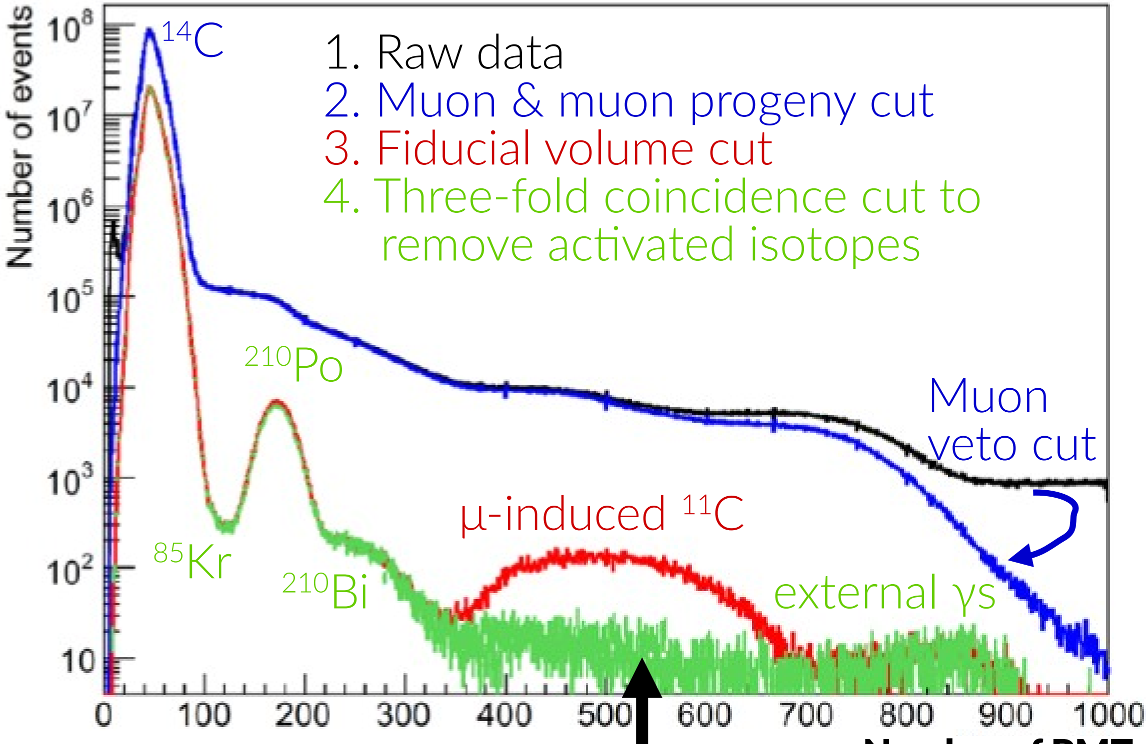


Through-going muons + shower products activate short-lived isotopes → delayed backgrounds at comparable rate to ^{8}B ν's

For a simplified LAr detector – not official DUNE plots

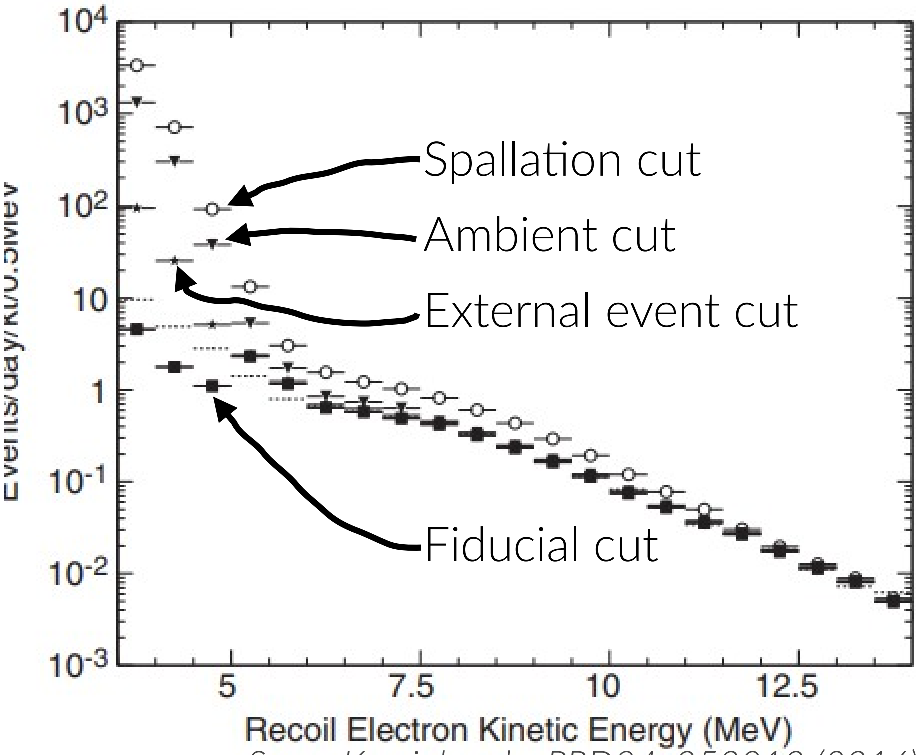
Cosmogenic muons are important bkgds in past solar ν measurements

Borexino



Borexino. PoS(EPS-HEP2019)400

Super-Kamiokande



Super Kamiokande. PRD94, 052010 (2016)

Cosmogenics: Tools and needs

Muon propagation and simulations

Propagation underground: MUSIC/MUSUN, MUTE, Mei& Hime parameterization

Underground muon shower simulations: FLUKA, Geant4

- FLUKA has excellent models of relevant physics, though more data is always needed to improve models, reduce uncertainties—great opportunities for current experiments to perform tests by measuring cosmogenic muon followers, for example, to test activation and neutron production models—μ^{+}/μ^{-} measurements, more IAEA evaluations for exclusive cross sections above 10 MeV [Snowmass2021 CF White Paper on Calibrations & backgrounds for dark matter direct detection arXiv:2203.07623]

Activation: FLUKA

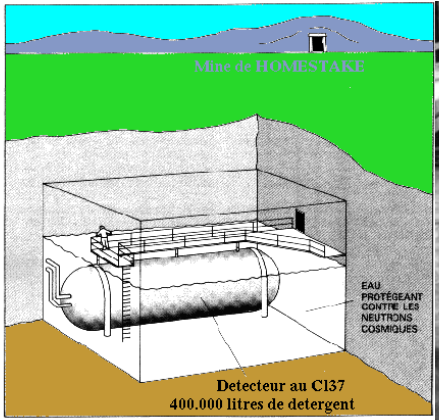
FLUKA is the state of the art for determining the activation of detector materials from cosmogenic muons, though more external data is needed to validate and improve models

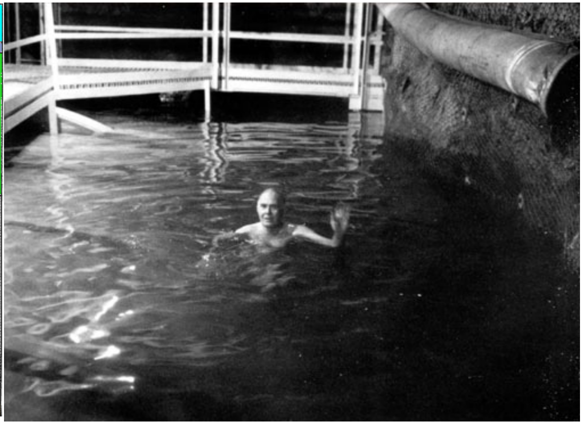
Many experiments use water shields as vetoes

DUNE HD and VD have virtually no passive shielding against rock and cosmogenic backgrounds

Bkgds depend on underground/cavern backgrounds at the Ross campus of SURF

Modules 3 & 4: opportunity for more deliberate bkgd reduction based on what we learn from 1 & 2





Take home messages

Neutron flux from cavern (LArSoft simulations)

Estimated average: O(10^{-6} n/cm^2/s) – <3.9×10^{-6} n/cm^2/s
(n,γ) goes up to ~10.5 MeV

γ-ray flux from cavern (LArSoft simulations)

Estimated: O(10 γ/cm^2/s) – <13 γ/cm^2/s
Go up to ~2.6 MeV; (n,γ) up to ~10.5 MeV

Need to continue assays as we build detector

Also need to understand variations as we excavate & build

Underground muon flux at SURF Ross Campus

$(5\pm1)\times10^{-9}$ μ/cm^2/s at 4200 m.w.e.
Need to better understand muon-induced backgrounds

Underground Rn content at SURF Ross Campus

500 Bq/m^3 of ^{222}Rn on average – can go up to 1 kBq/m^3 depending on ventilation

Radon purity of LAr and detector materials will be very important!

α→5-9 MeV; ^{40}Ar(α,γ)~15 MeV γ's, *ν-like*; ^{40}Ar(α,n) → X(n,γ) up to ~10.5 MeV, *ν-like*

Rn in air & fluid system; Rn progeny plateout on surfaces; Emanation & migration

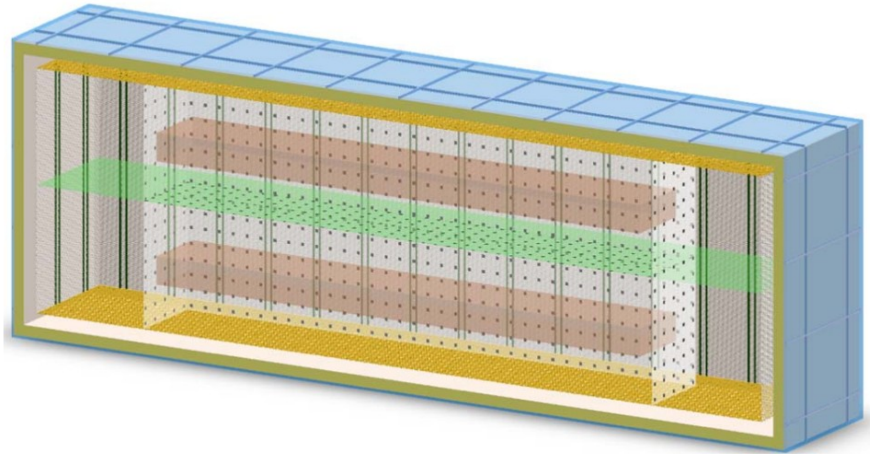
Exciting potential for solar and supernova neutrino physics and beyond if we can understand and mitigate backgrounds—already good progress toward this goal.

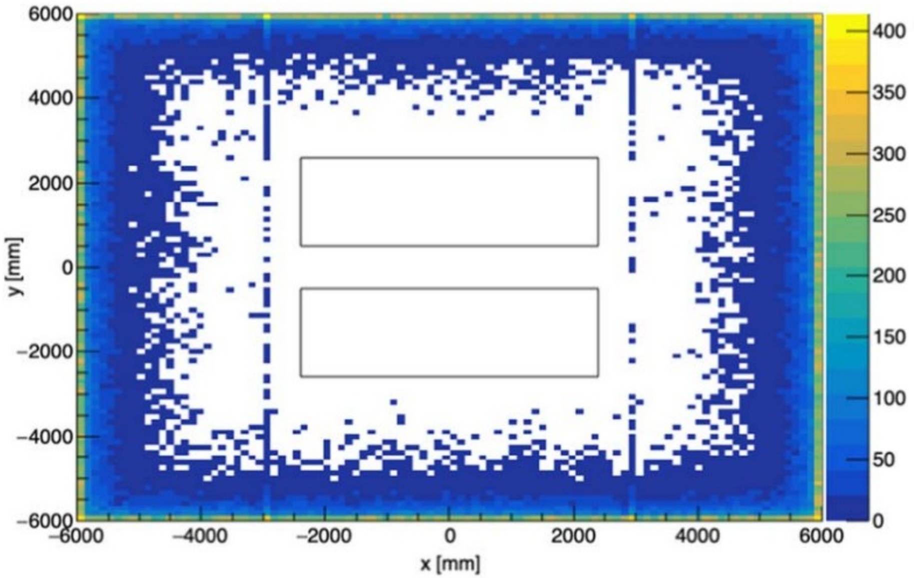
Backgrounds development also improves high energy goals via improved event reconstruction: see arXiv:2203.00740

SLoMo: a potential low-background LArTPC module w/ 3 ktonne UAr

A low-threshold DUNE module would have game-changing physics reach without interfering with main DUNE goals: dark matter detection, more solar ν physics (Δm^2 & NSIs)

Possibility w/ further R&D: 0νββ w/ Xe-doping...





Ultrapure acrylic defining inner UAr vessels (1-3 kt)
Underground argon (UAr) depleted in ^{39}Ar
Self-shielding + 40 cm-thick water shield
Heavy fiducialization + pulse-shape discrimination
Increased photodetector coverage w/ SiPM arrays

Potential to reach thresholds as low as 100 keV
See: arXiv:2203.08821

See Tues talk by Chris Jackson

Similar ideas for SoLAr, QPix, THEIA

END