

CoSSURF 2024, in Rapid City, SD:

# Radiological Backgrounds in DUNE Far Detectors

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South Dakota School of Mines & Technology  
...for the DUNE Collaboration



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



Sanford Underground  
Research Facility

Fermilab

800 miles  
(1300 kilometers)

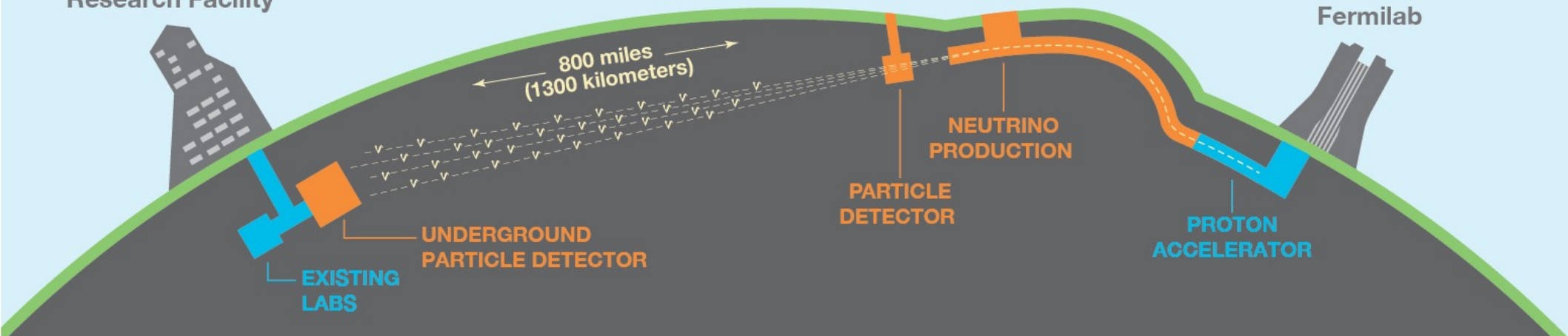
NEUTRINO  
PRODUCTION

PARTICLE  
DETECTOR

PROTON  
ACCELERATOR

UNDERGROUND  
PARTICLE DETECTOR

EXISTING  
LABS



Sanford Underground Research Facility



EXISTING LABS

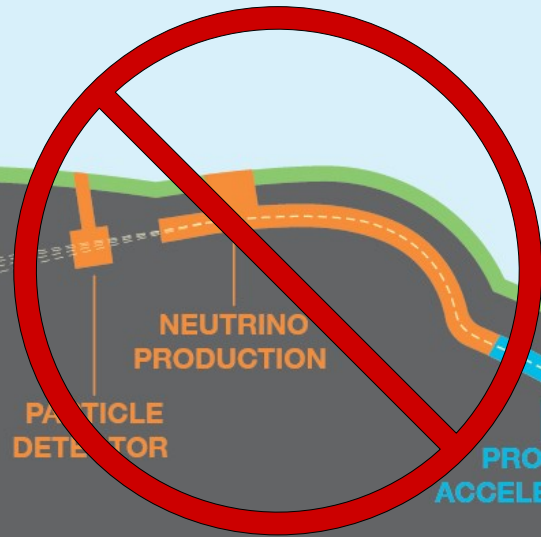
UNDERGROUND PARTICLE DETECTOR

800 miles  
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PARTICLE DETECTOR

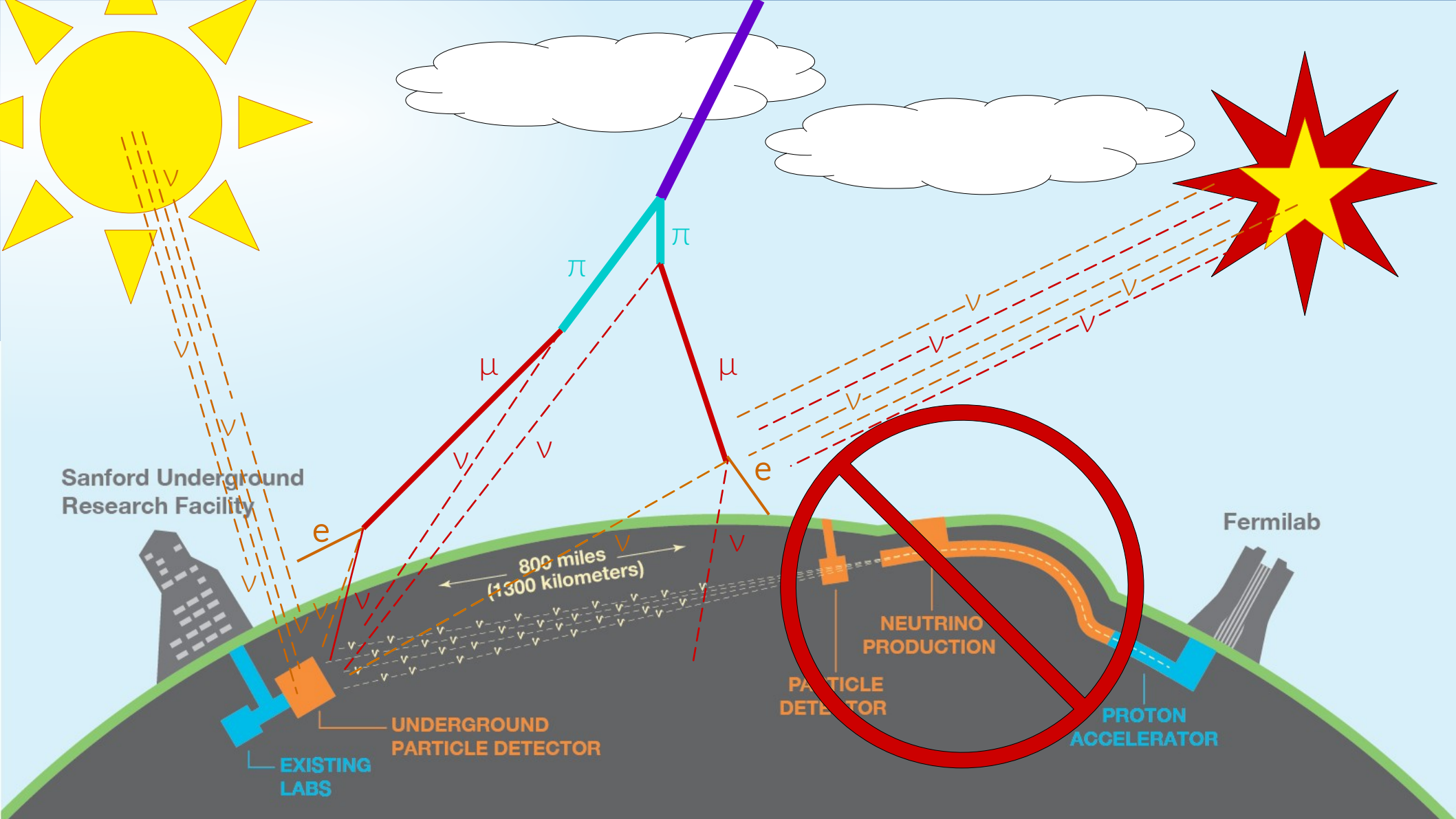
NEUTRINO PRODUCTION

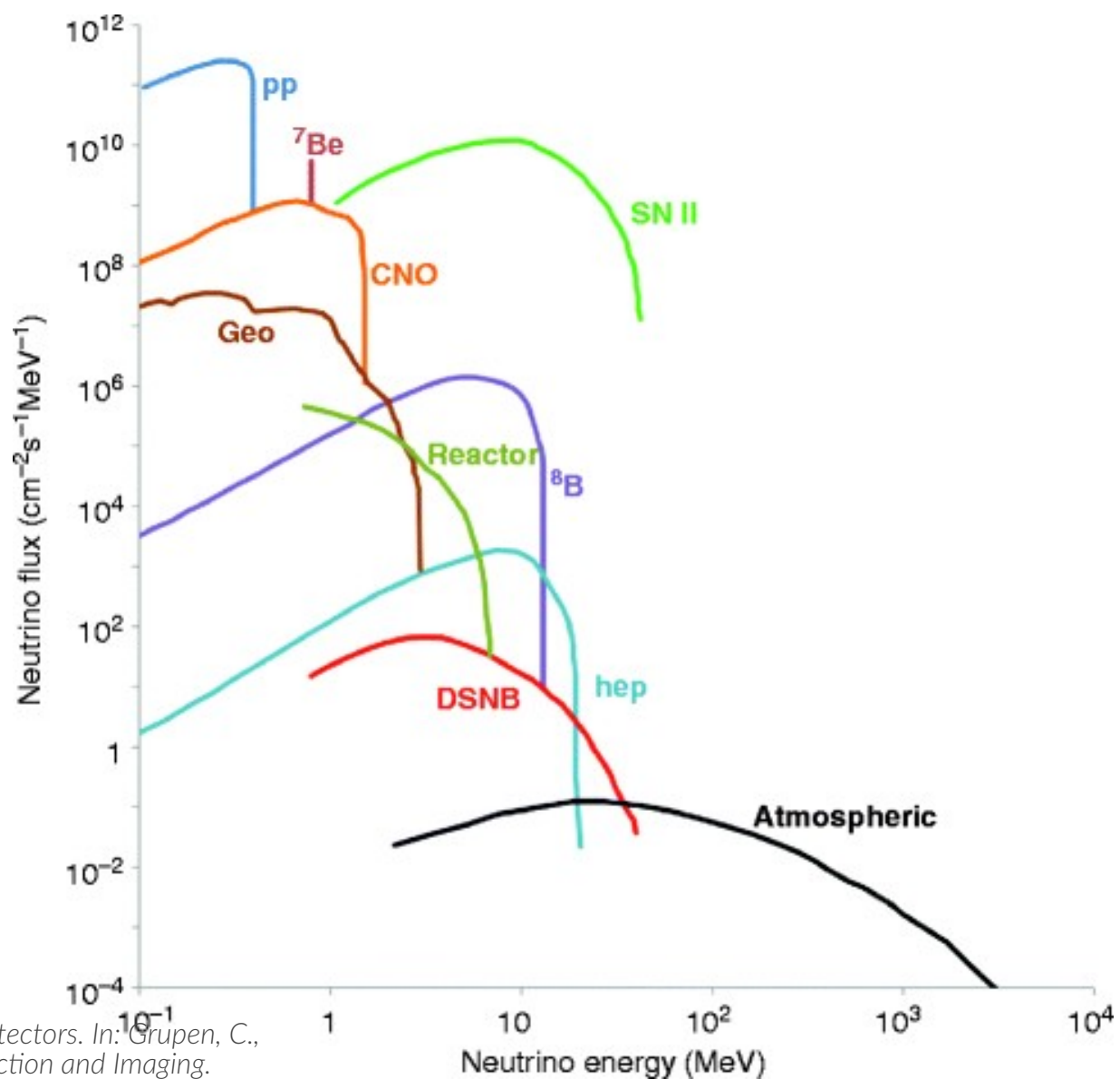


PROTON ACCELERATOR

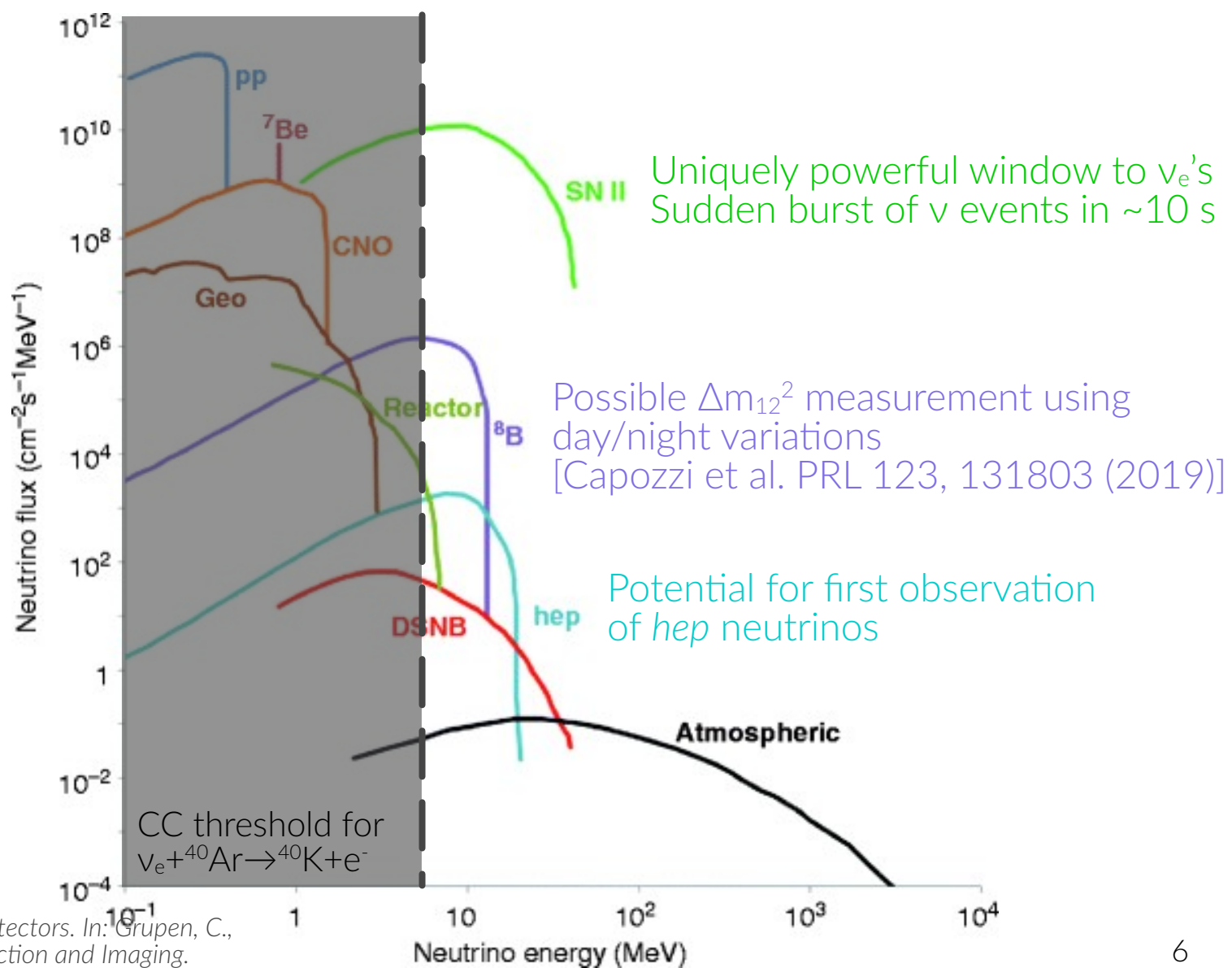
Fermilab











## External radioactivity

$^{238}\text{U}/^{235}\text{U}$ ,  $^{232}\text{Th}$ ,  $^{40}\text{K}$ , etc. in detector mat. + rock. Max  $\gamma$  in  $^{232}\text{Th}$  chain ( $^{208}\text{Tl}$ ):  
 $E_\gamma = 2.6\text{ MeV}$

## Internal radioactivity

Dominant:  $^{39}\text{Ar}$  ( $Q_\beta = 565\text{ keV}$ )  
2.6–3.5 MeV dominated by  $^{42}\text{Ar}/^{42}\text{K}$  in LAr  
Contaminants in LAr ( $^{222}\text{Rn}$ ) can leave  $\alpha$ ,  $\beta$ , &  $\gamma$  signals  
4–9 MeV:  $\alpha$  peaks from  $^{222}\text{Rn}$  (May be identifiable as nuclear recoils)

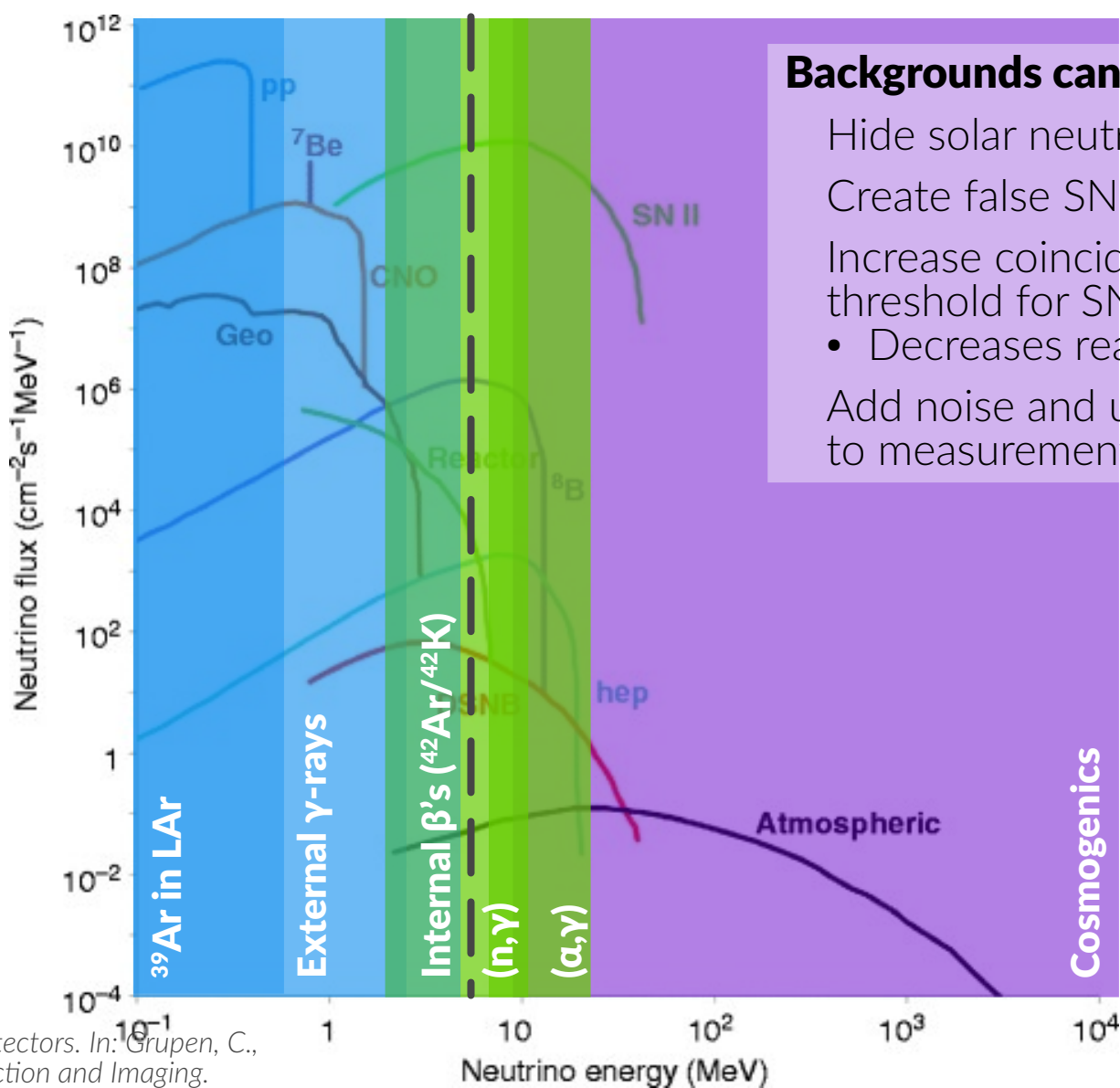
## Radiative n/ $\alpha$ captures

(n, $\gamma$ ) reactions from radiogenic neutrons extend from 2.2–10.5 MeV  
( $\alpha$ , $\gamma$ ) in LAr up to  $\sim 17\text{ MeV}$

## Cosmogenics

Cosmogenic muon shower products extend to 1 TeV, may stray far from  $\mu$  track

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



## Backgrounds can:

- Hide solar neutrinos
- Create false SN alerts
- Increase coincidence v threshold for SNe
  - Decreases reach
- Add noise and uncertainty to measurements

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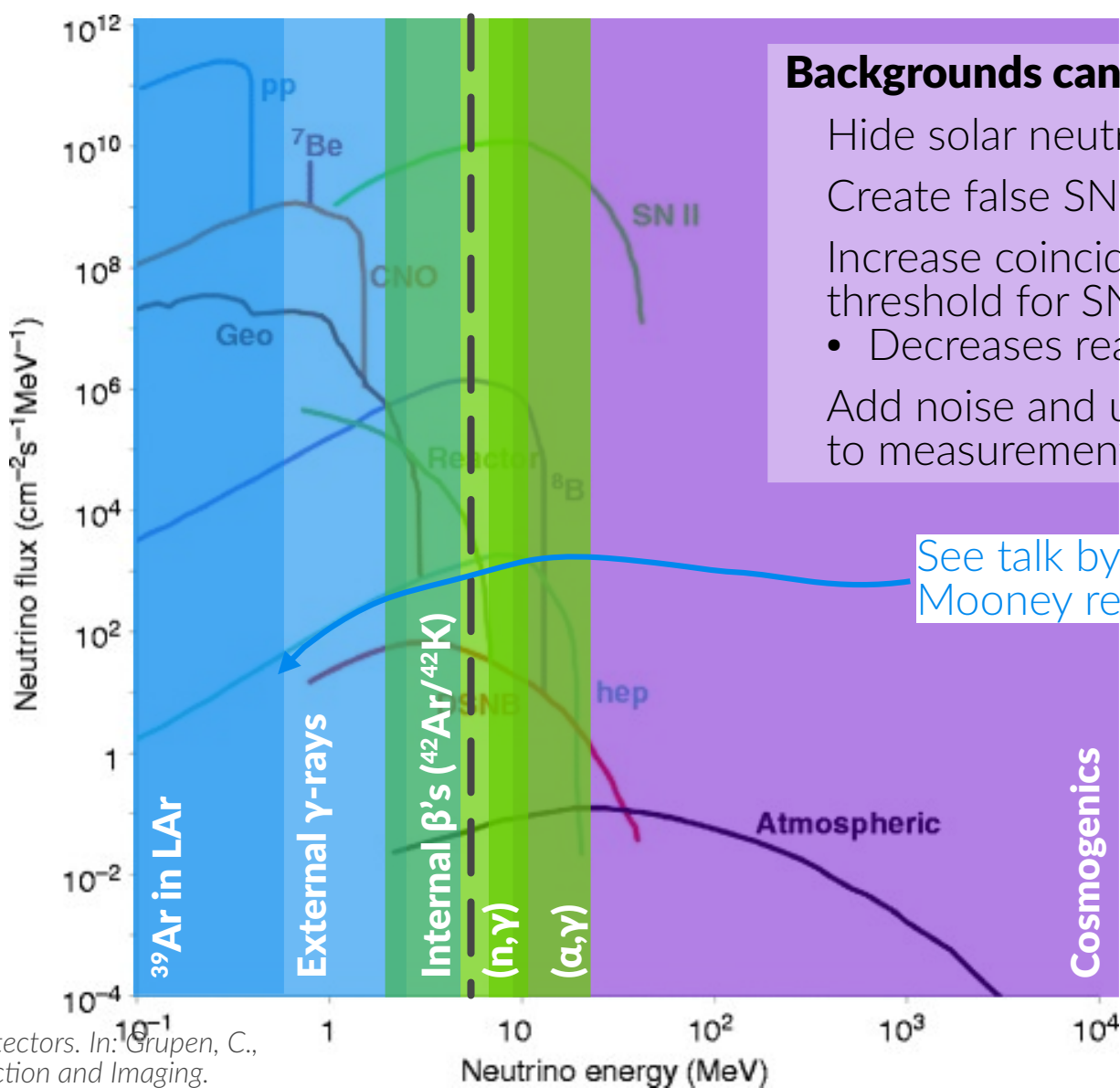
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( $\alpha$ , $\gamma$ ) in LAr up to ~17 MeV

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## Backgrounds can:

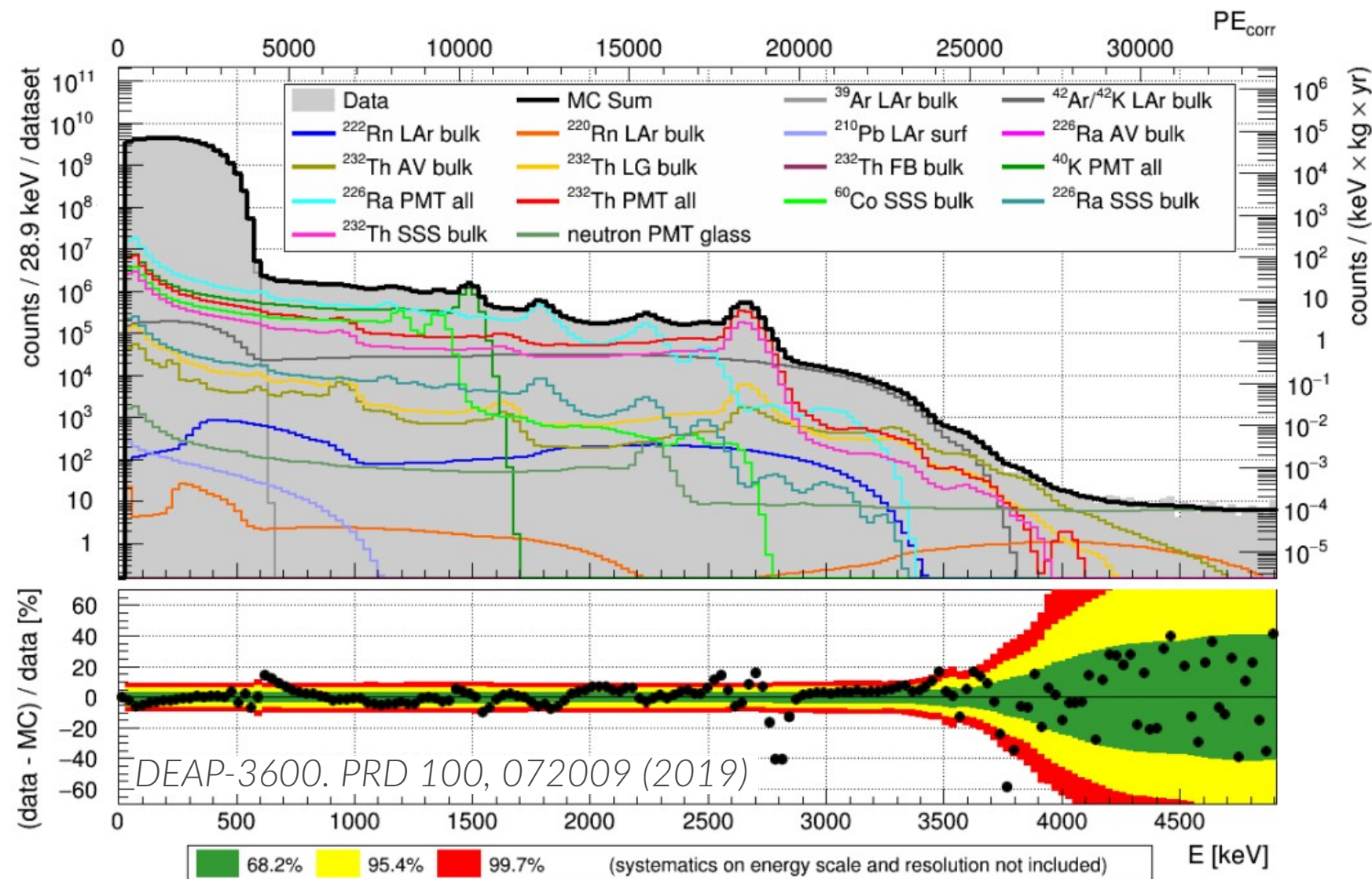
- Hide solar neutrinos
- Create false SN alerts
- Increase coincidence  $v$  threshold for SNe
  - Decreases reach
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See talk by Michael Mooney regarding  $^{39}\text{Ar}$

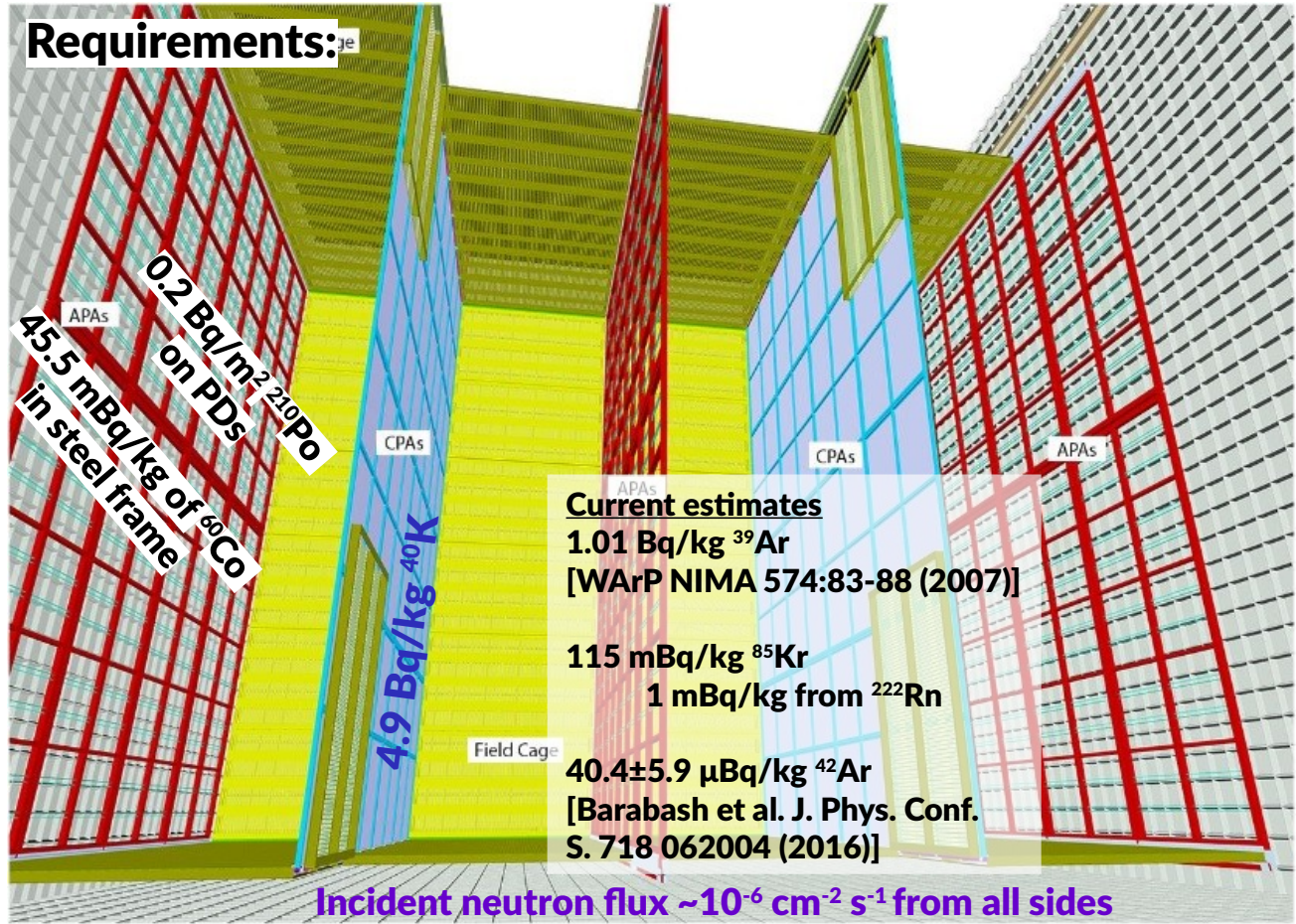


# DEAP-3600

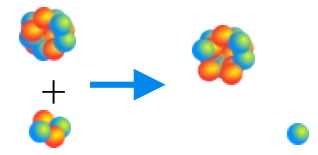
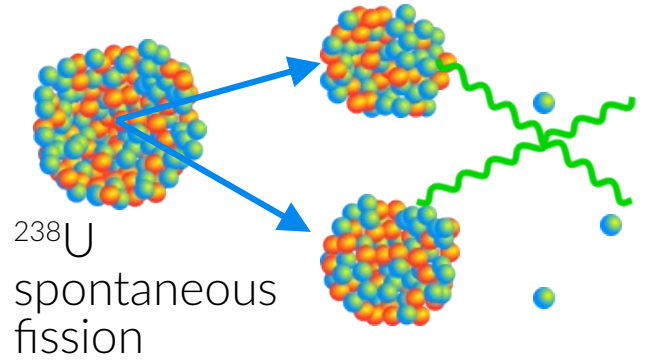
3.3 tonne LAr  
dark matter  
detector at  
SNOLAB



# Where does the radioactivity come from?

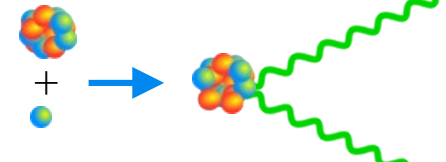


## Neutrons from



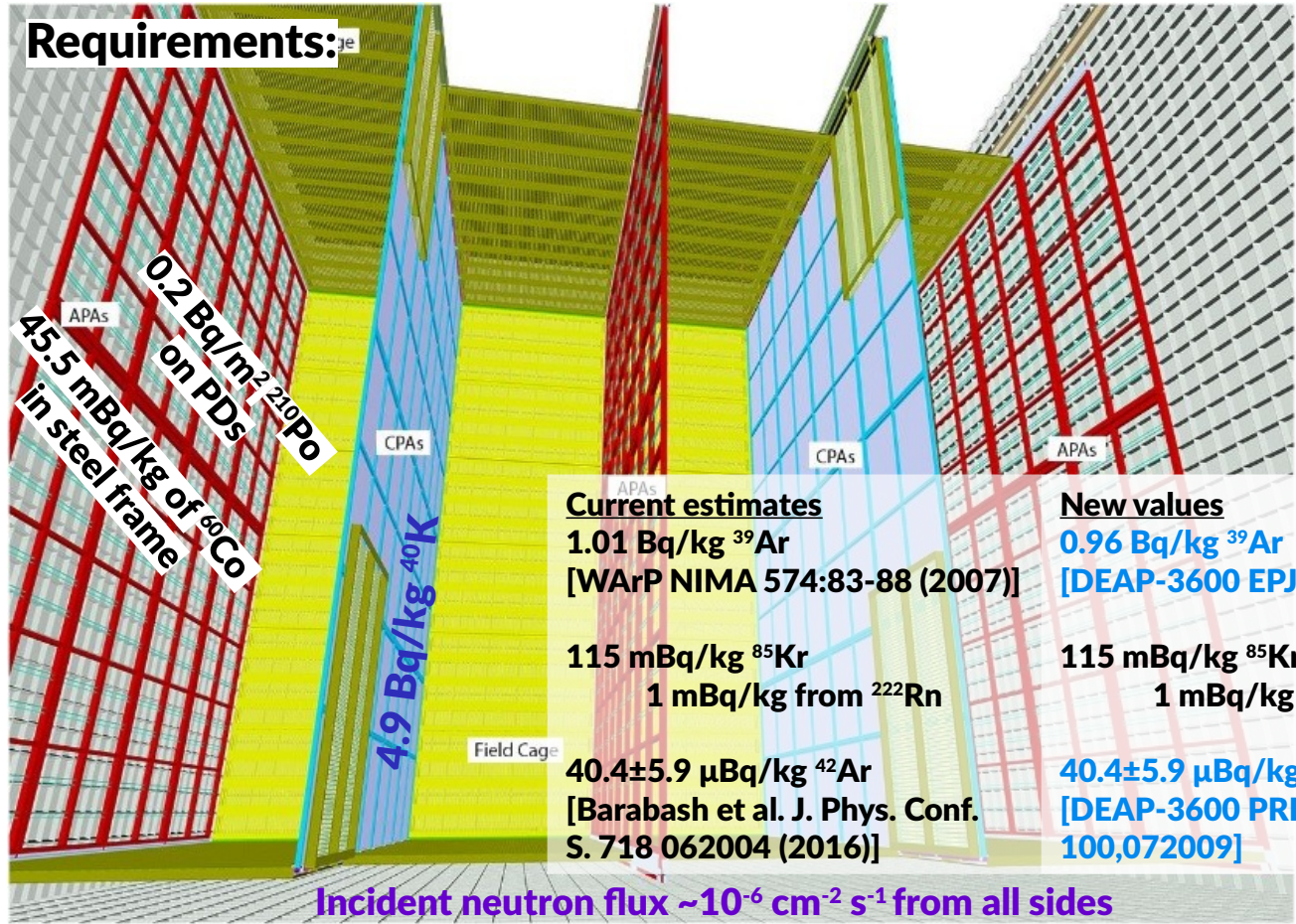
(α,n) reactions from any α-emitter in U/Th chains

## (n,γ) de-excitation cascades

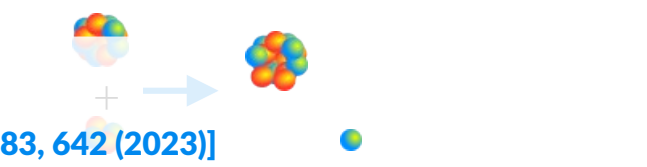
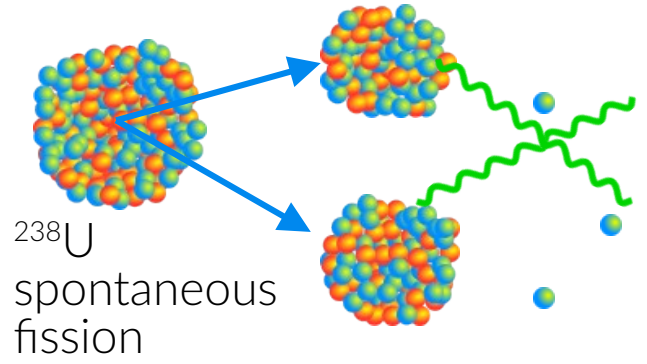




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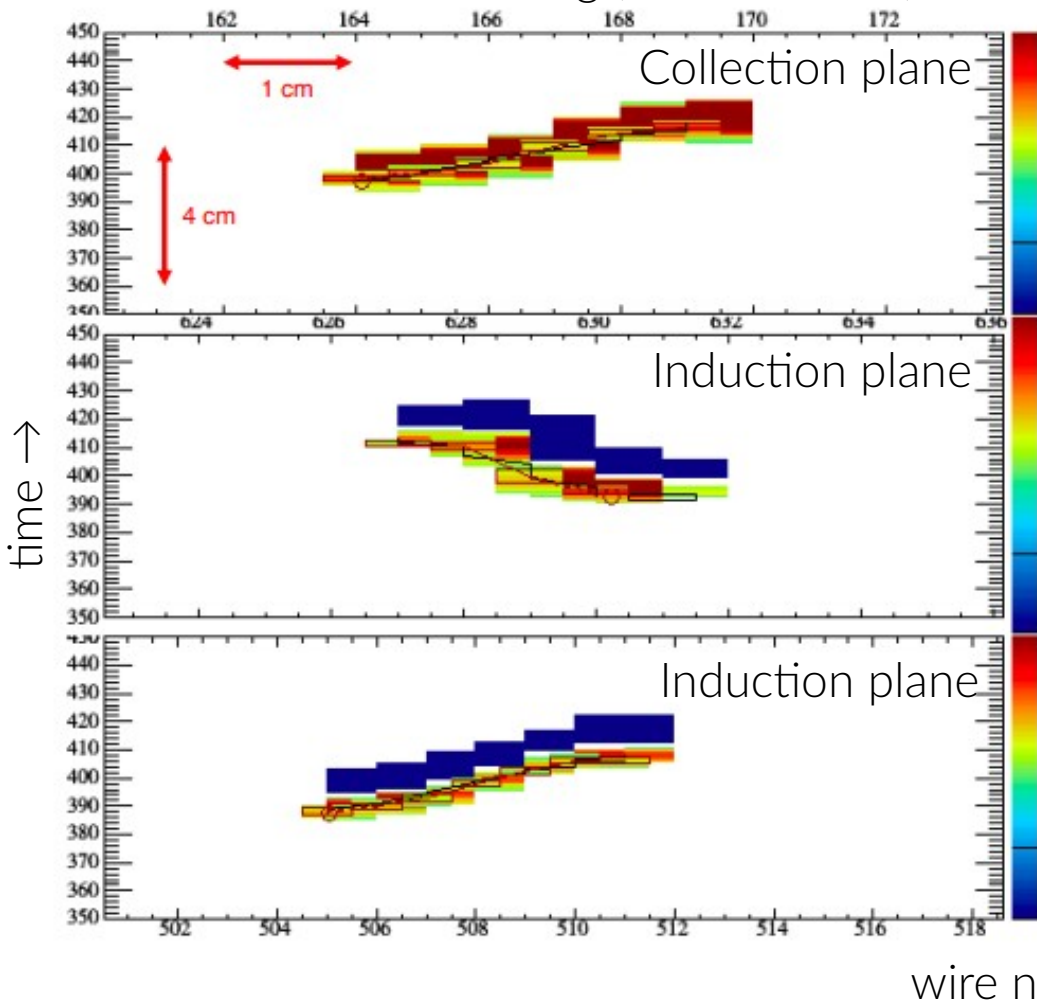


## Neutrons from

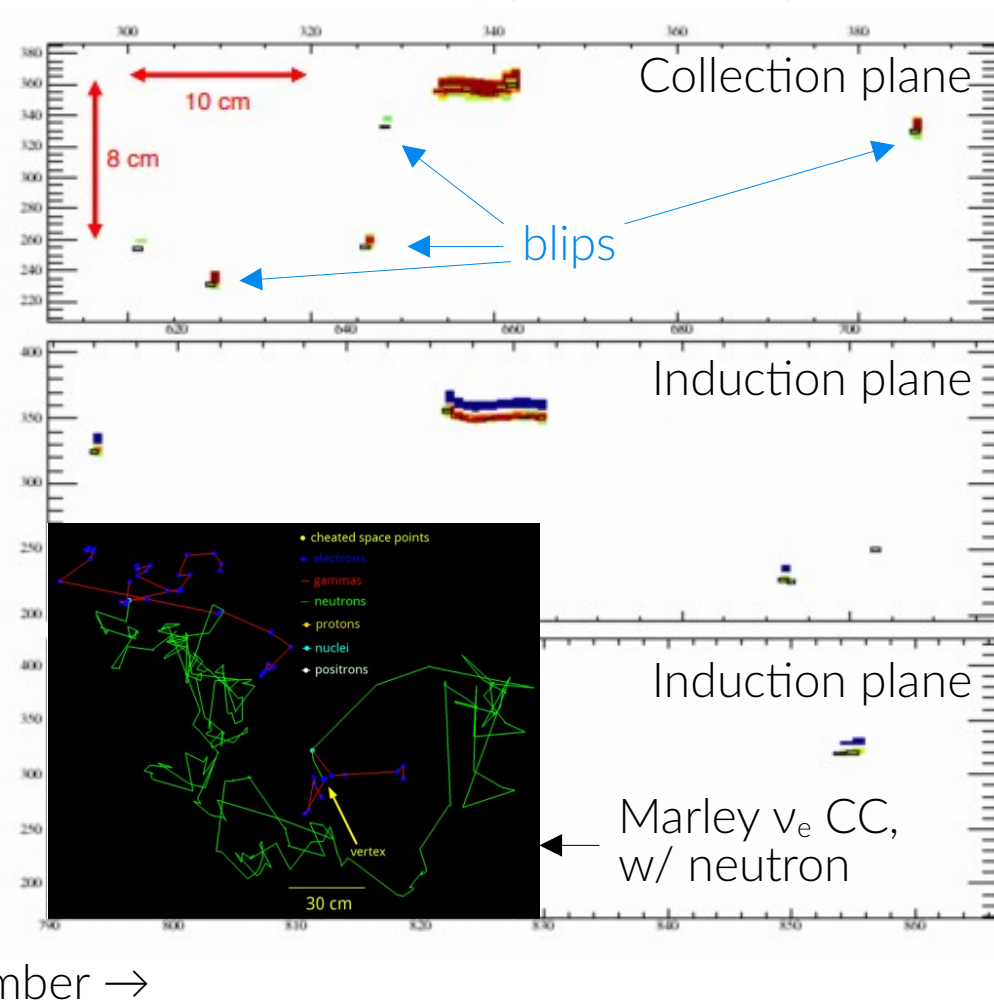


# Simulated event displays for supernova neutrino signals (LArSoft)

$\nu$ - $e^-$  electron scattering (10.25 MeV  $e^-$ )



$\nu_e$  CC event (20.25 MeV  $\nu$ )

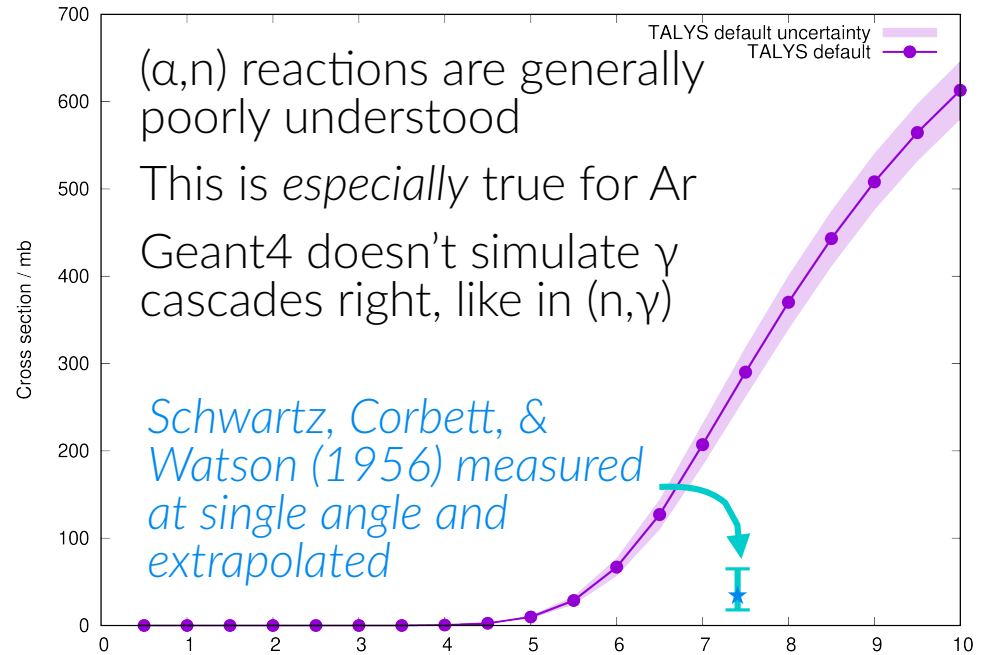


# Background originating in the LAr cannot be fiducialized away



Rn in LAr  $\rightarrow$  Ar( $\alpha$ ,n), Ar( $\alpha$ , $\gamma$ )  
distributed uniformly in fiducial volume  
Rn continually emanates into LAr from materials  
Neutrons are highly penetrating and can produce  
(n, $\gamma$ ) in the center of the LAr

See also: M. Parvu and I. Lazanu JCAP08(2021)042



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

**Preliminary assays of DUNE rock + shotcrete samples:**

→  $O(10^{-6} \text{ n/cm}^2/\text{s})$  – est.  $< 3.9 \times 10^{-6} \text{ n/cm}^2/\text{s}$

→  $O(10 \text{ } \gamma/\text{cm}^2/\text{s})$  – est.  $< 13 \text{ } \gamma/\text{cm}^2/\text{s}$

Need to continue assays & measuring cavern + detector bkgds

Total  $\gamma$  rate:  $\sim 21 \text{ MHz}$  – mostly at outer edges

$^{39}\text{Ar}$  rate:  $17 \text{ MHz}$



**Preliminary: based on latest assays and simulations**

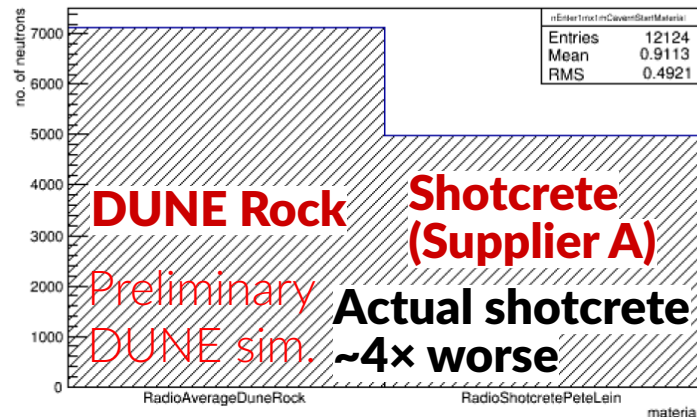
*Davis cavern  $\gamma$  flux measured in [LZ Collaboration, Astropart Phys 116, 102391 (2020)]*

Al in rock/shotcrete makes it a significant neutron source! – High Al( $\alpha, n$ ) yield

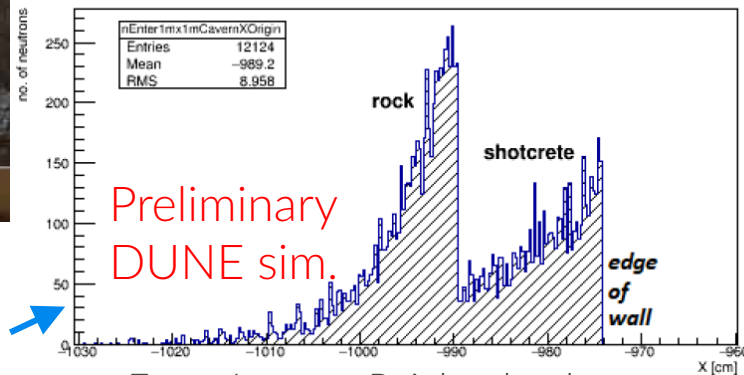
Simulation w/ LArSoft, Decay0 & new  $^{232}\text{Th}$  decay chain implementation

Shawn Westerdale (UC Riverside)

Start material for neutrons entering 1m x 1m square in cavern from wall and that do not originate in steel



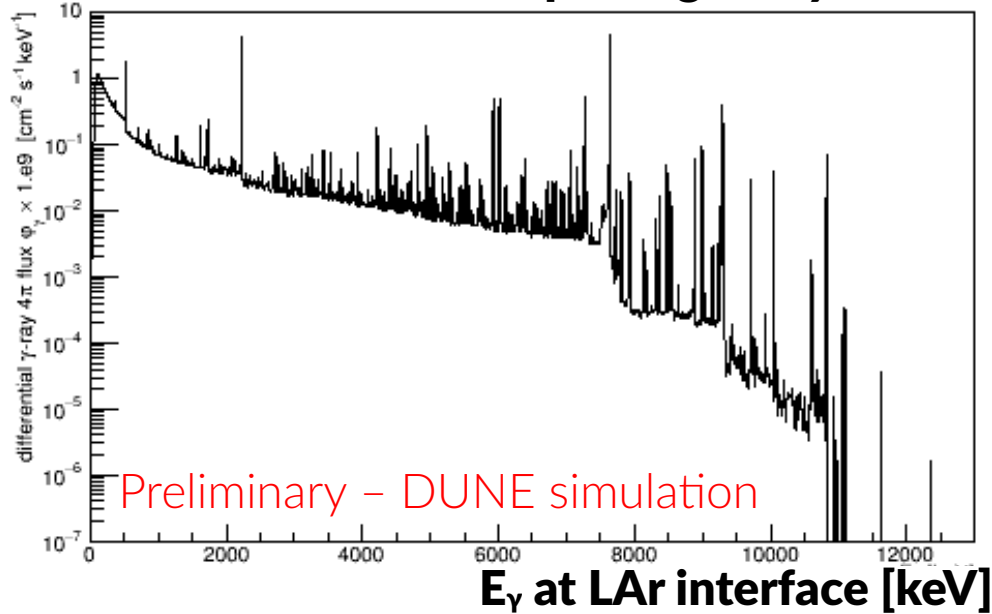
X of origin for neutrons entering 1m x 1m square in cavern from wall and that do not originate in steel



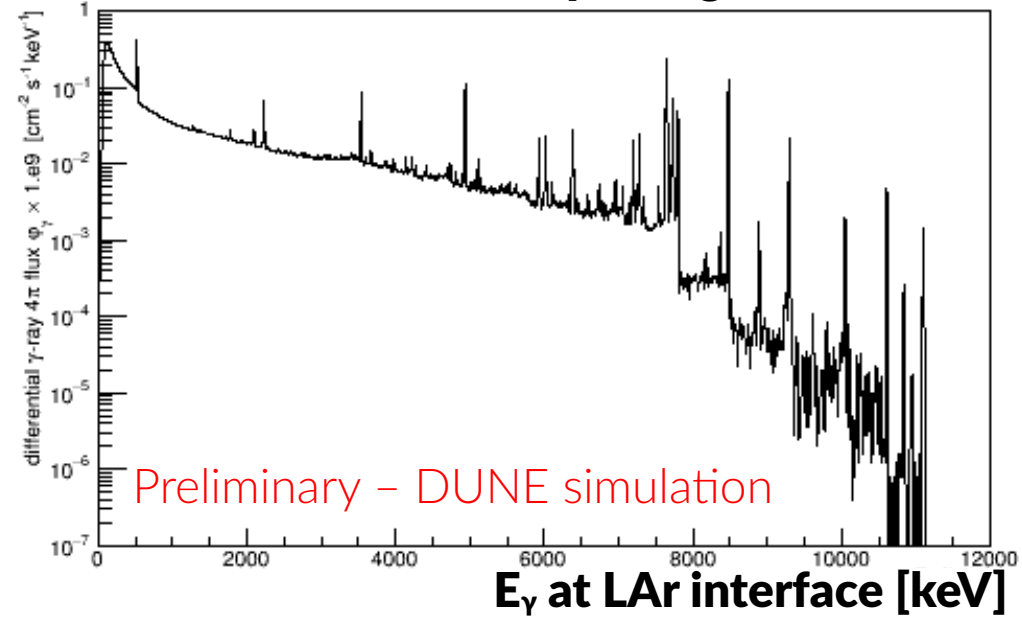
From Juergen Reichenbacher

# Simulated $(n,\gamma)$ spectra with native Geant4 models

## Cavern neutrons capturing in cryostat



## Cavern neutrons capturing in cavern



# Neutrons: Tools and needs

## **( $\alpha$ ,n) yields\***: **SOURCES4A/C, NeuCBOT, SaG4N**

Needs extensive radioassays of materials:  $\alpha$ - &  $\gamma$ -spectroscopy, ICP-MS, NAA, Rn emanation...

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

Significant lack of ( $\alpha$ ,n) cross section data  $\rightarrow$  large, poorly understood uncertainties

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

## **(n, $\gamma$ ) de-excitation**: G4NDL & G4PhotonEvaporation, CASCADE, NUDEX, FIFRELIN

Native Geant4 models G4NDL and G4PhotonEvaporation have issues reproducing  $\gamma$  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](mailto:shawn.westerdale@ucr.edu) for access
- Still holes due to missing data: No data for some isotopes, some isotopes have unplaced  $\gamma$  lines

**n and  $\gamma$  fluxes**: Need direct measurements of n and  $\gamma$  fluxes in cavern and cryostat

**Full simulations may enable ML classifiers to distinguish from  $\nu$  events**

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

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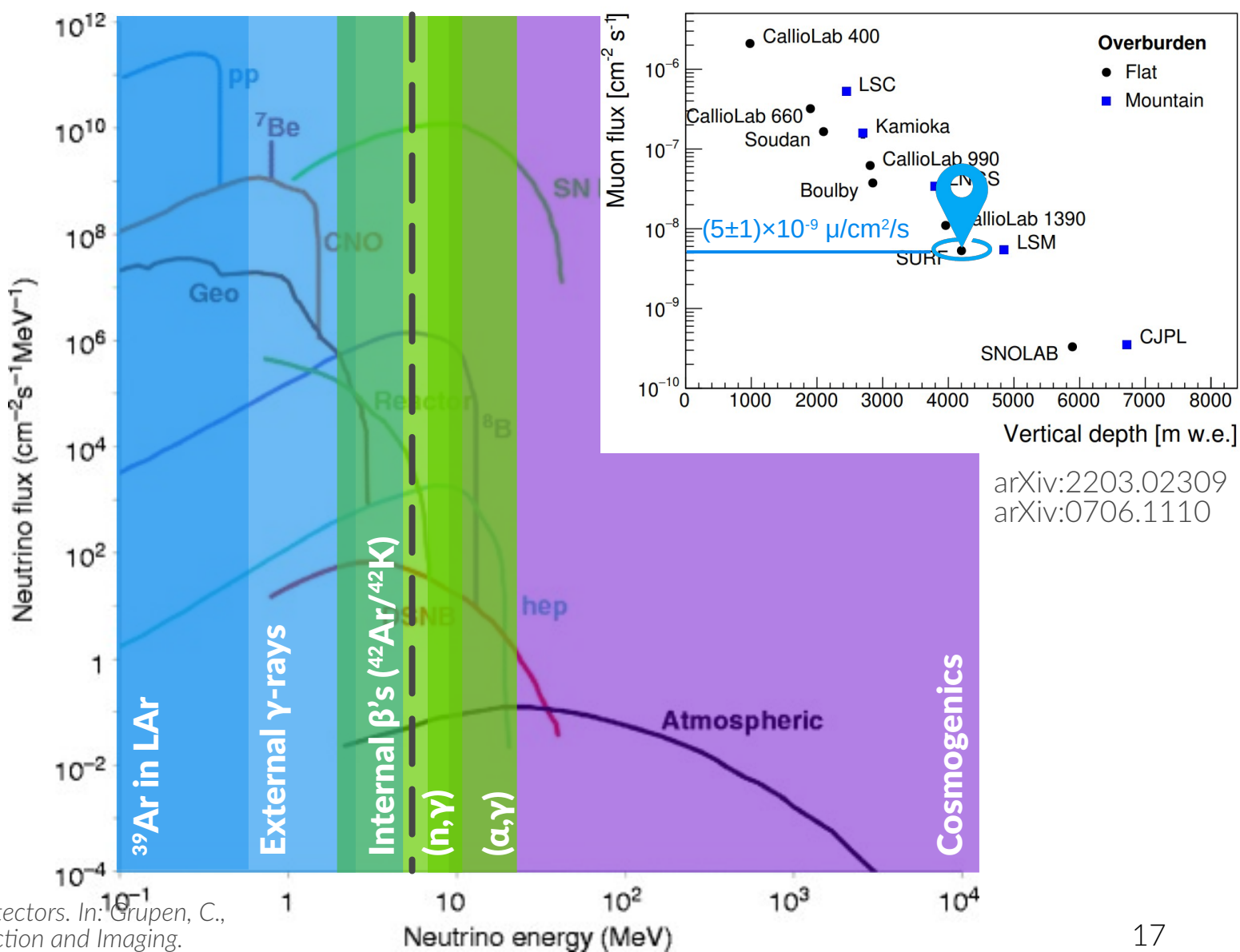
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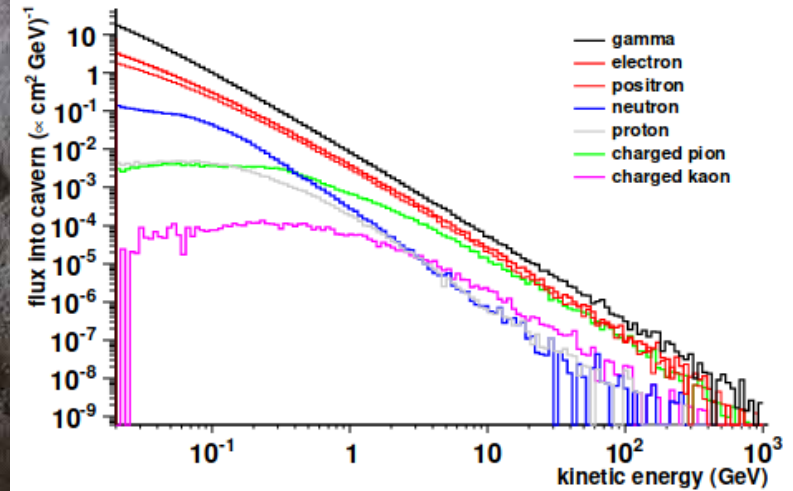




# Muon showers underground



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



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

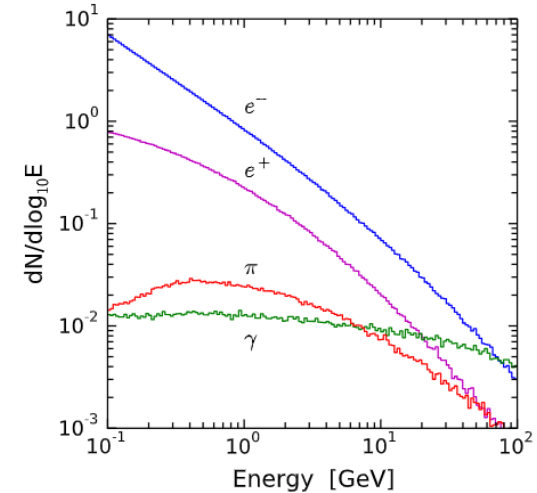
Correlated, energetic (highly-penetrating) neutrons inelastically scatter & capture → mimic neutrino bursts, like supernovae



# Muon showers underground



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



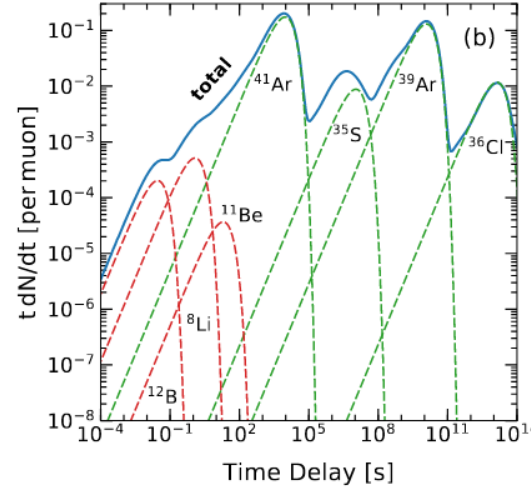
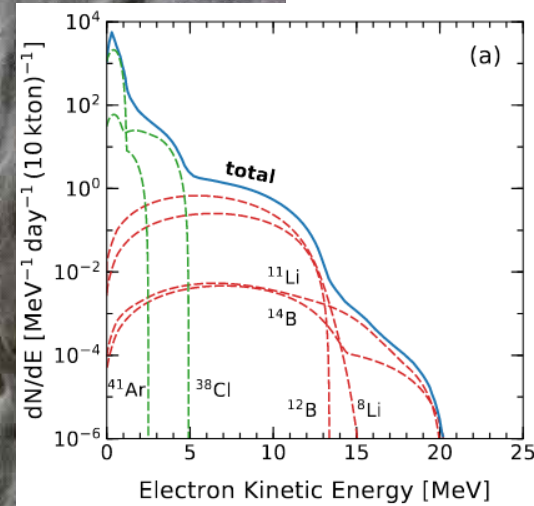
Similar results found for Super-K:  $\pi$  and  $\gamma$  particularly dangerous, as they can penetrate into LAr and make  $\nu$ -like signals

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)]

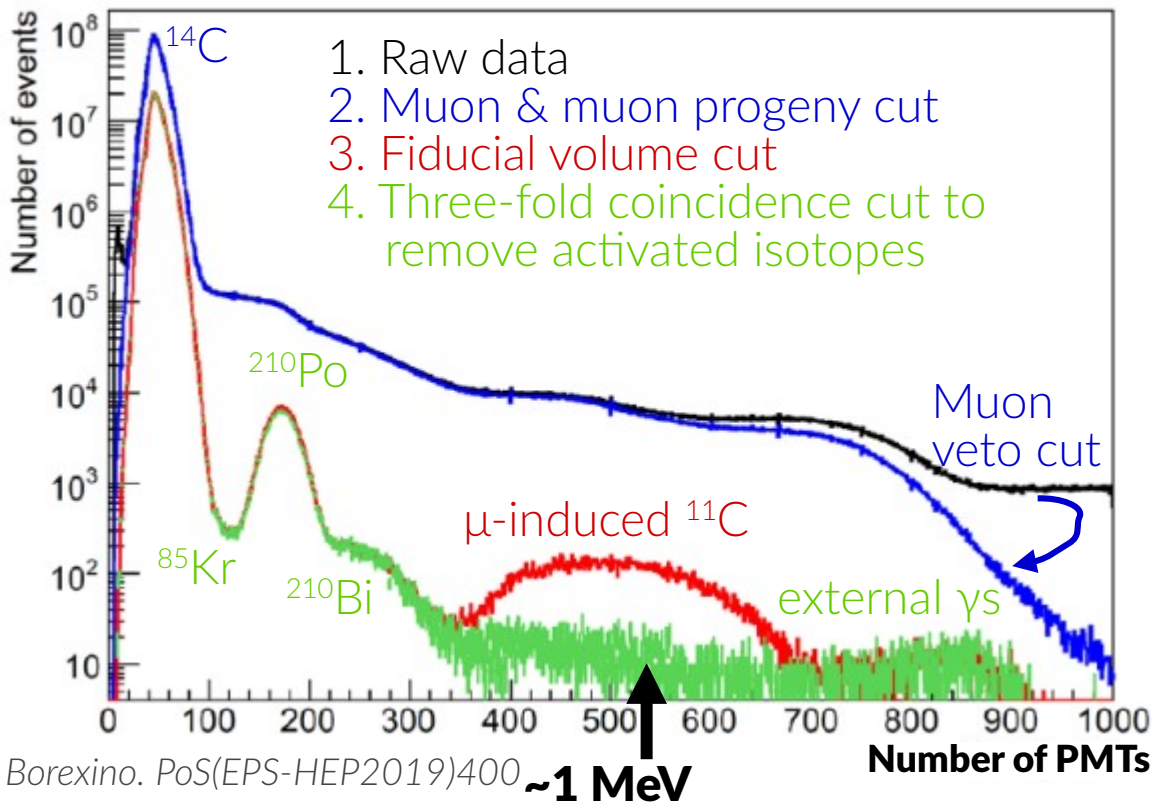


Through-going muons + shower products activate short-lived isotopes → delayed backgrounds at comparable rate to  $^8\text{B}$  v's

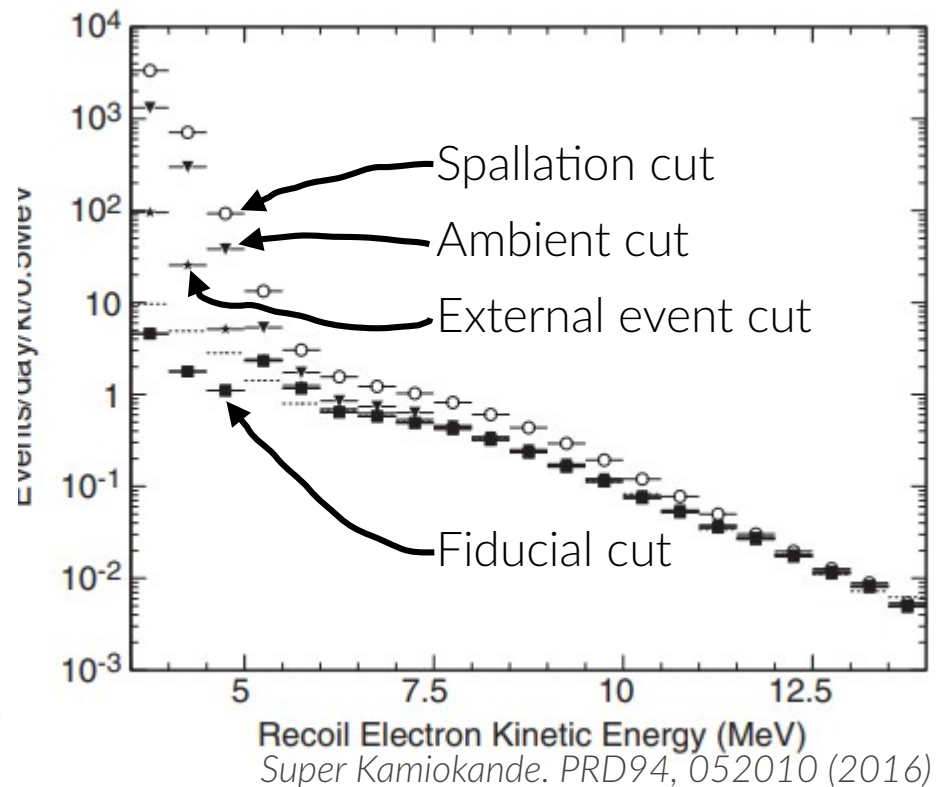
For a simplified LAr detector – not official DUNE plots

# Cosmogenic muons are important bkgds in past solar $\nu$ measurements

## Borexino



## Super-Kamiokande



# 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— $\mu^+/\mu^-$  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](#)

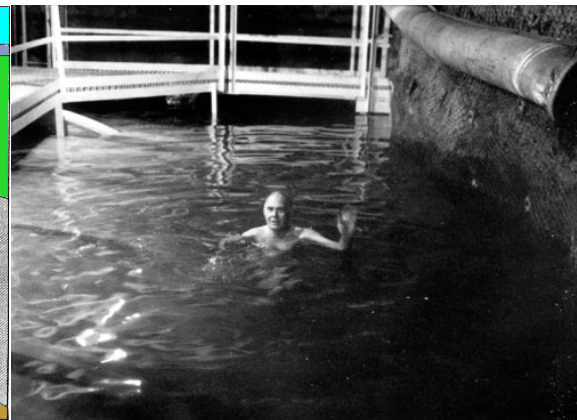
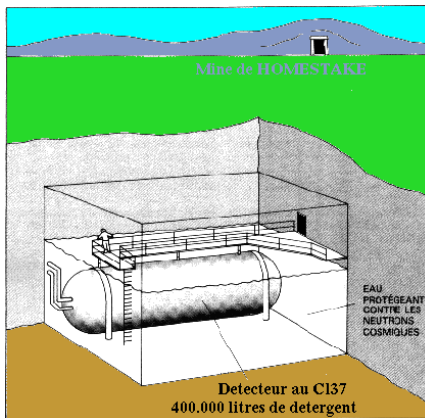
FLUKA is the state of the art for determining the activation of detector materials from cosmogenic muons, though more external data is needed to validate and improve models

## 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:  $O(10^{-6} \text{ n/cm}^2/\text{s})$  –  $<3.9 \times 10^{-6} \text{ n/cm}^2/\text{s}$   
(n, $\gamma$ ) goes up to  $\sim 10.5 \text{ MeV}$

## $\gamma$ -ray flux from cavern (LArSoft simulations)

Estimated:  $O(10 \text{ } \gamma/\text{cm}^2/\text{s})$  –  $<13 \text{ } \gamma/\text{cm}^2/\text{s}$   
Go up to  $\sim 2.6 \text{ MeV}$ ; (n, $\gamma$ ) up to  $\sim 10.5 \text{ MeV}$

## Need to continue assays as we build detector

Also need to understand variations as we excavate & build

## Underground muon flux at SURF Ross Campus

$(5 \pm 1) \times 10^{-9} \text{ } \mu/\text{cm}^2/\text{s}$  at 4200 m.w.e.  
Need to better understand muon-induced backgrounds

## Underground Rn content at SURF Ross Campus

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

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

$\alpha \rightarrow 5\text{-}9 \text{ MeV}$ ;  $^{40}\text{Ar}(\alpha, \gamma) \sim 15 \text{ MeV } \gamma$ 's,  $\nu$ -like;  $^{40}\text{Ar}(\alpha, n) \rightarrow X(n, \gamma)$  up to  $\sim 10.5 \text{ MeV}$ ,  $\nu$ -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.

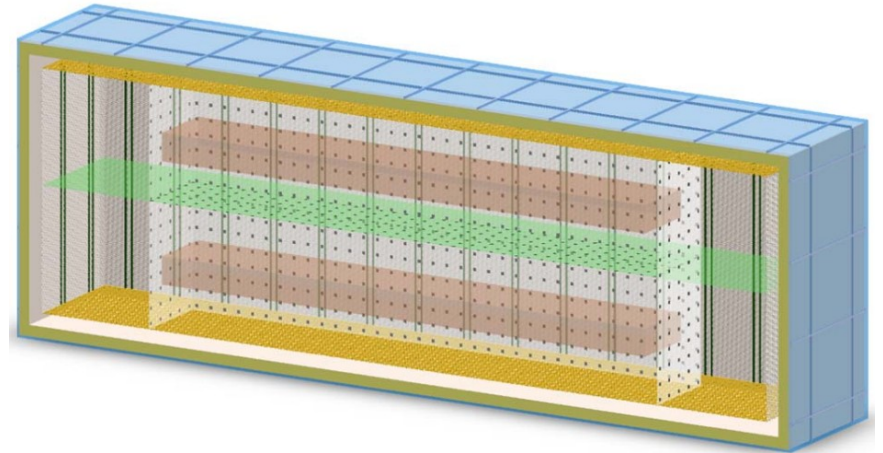
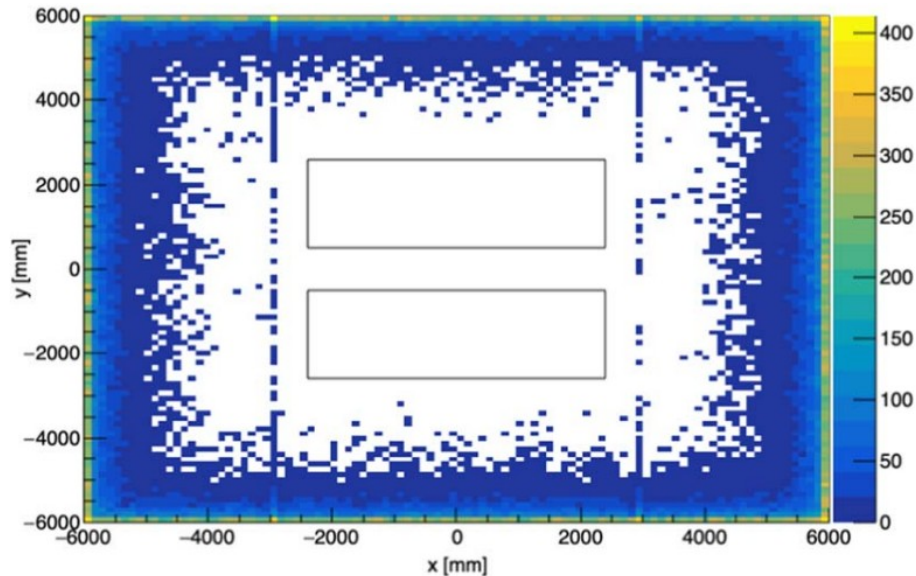
Backgrounds development also improves high energy goals via improved event reconstruction: see [arXiv:2203.00740](https://arxiv.org/abs/2203.00740)



# 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  $\nu$  physics ( $\Delta m^2$  & NSIs)

**Possibility w/ further R&D:**  $0\nu\beta\beta$  w/ Xe-doping...



- Ultrapure acrylic defining inner UAr vessels (1-3 kt)
- Underground argon (UAr) depleted in  $^{39}\text{Ar}$
- 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](https://arxiv.org/abs/2203.08821)

END

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