Backgrounds for Supernova Neutrino Detection with Underground Detectors (Liquid Argon)

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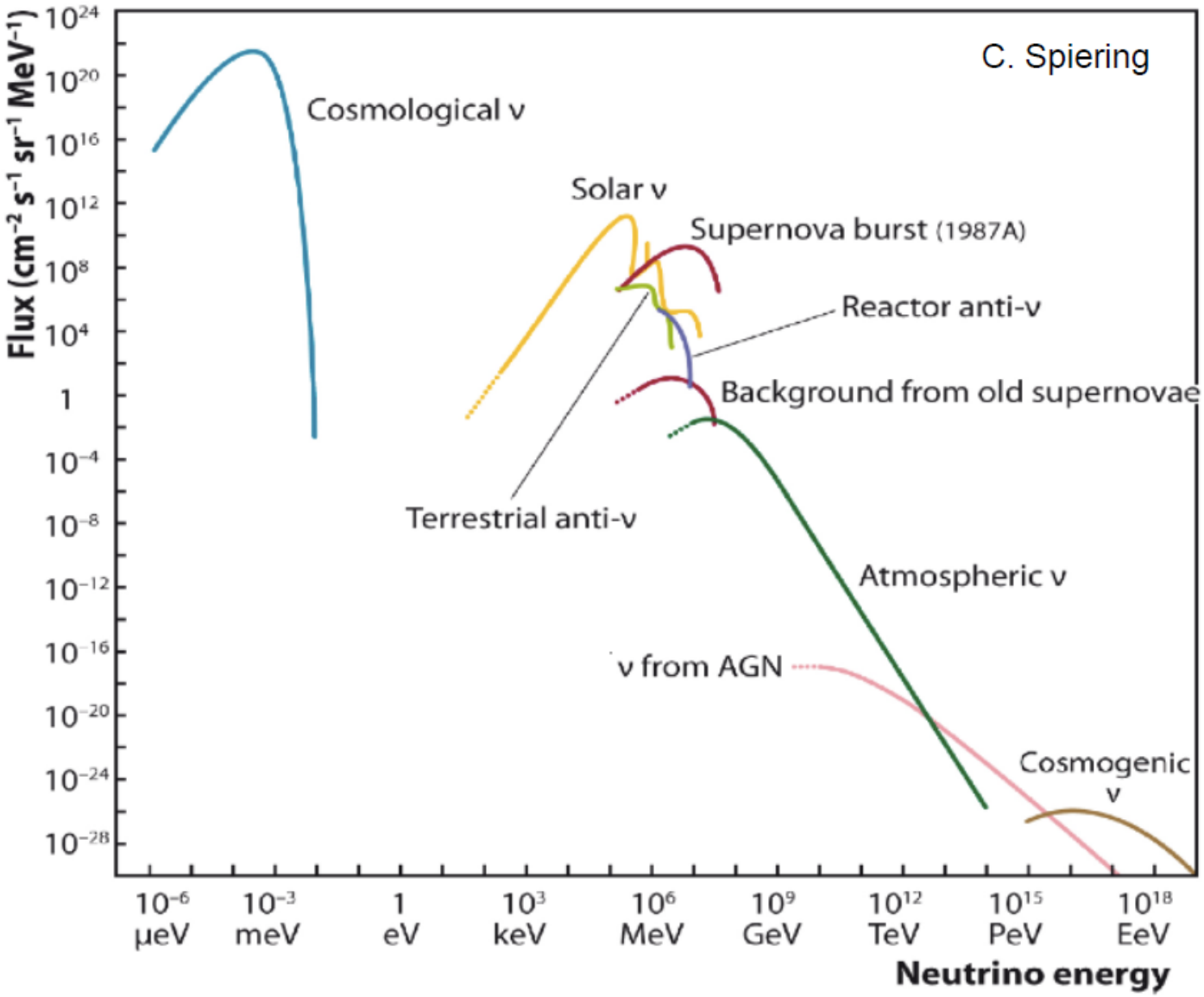
SOUTH DAKOTA MINES

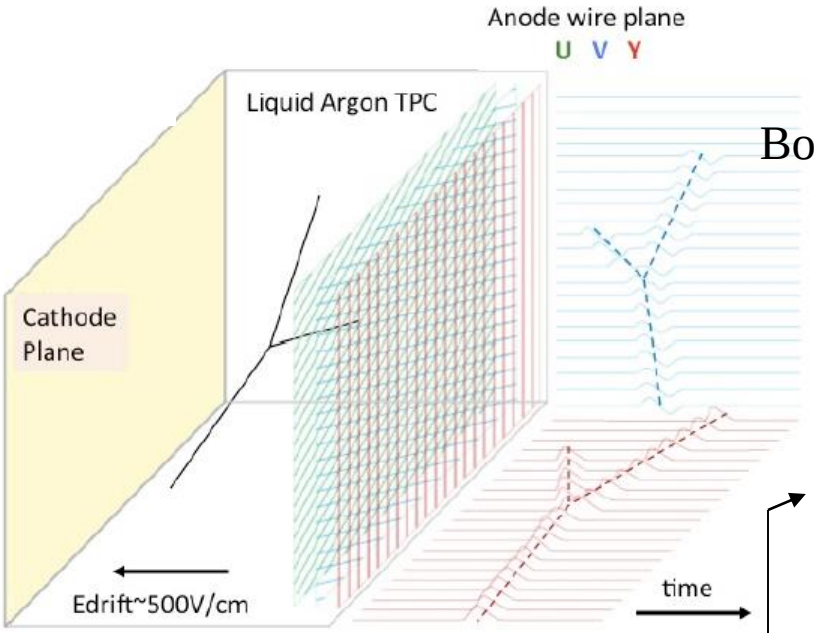
3rd New Physics Opportunities at Neutrino Facilities (NPN)

SLAC (July 12, 2023)

The supernova neutrino signal



Liquid argon time projection chambers



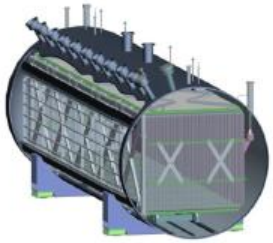
Bo Yu (DUNE)

- fine-grained trackers
- no Cherenkov threshold
- high ν_e cross section

July 21, 2017: groundbreaking @ SURF, as of July 2023 2/3 of excavation done!

ICARUS
(Italy...)
0.6 kton

MicroBooNE
(USA)
0.2 kton



DUNE (USA) 40 kton

SBND (USA), ProtoDUNE-SP/DP (CERN)

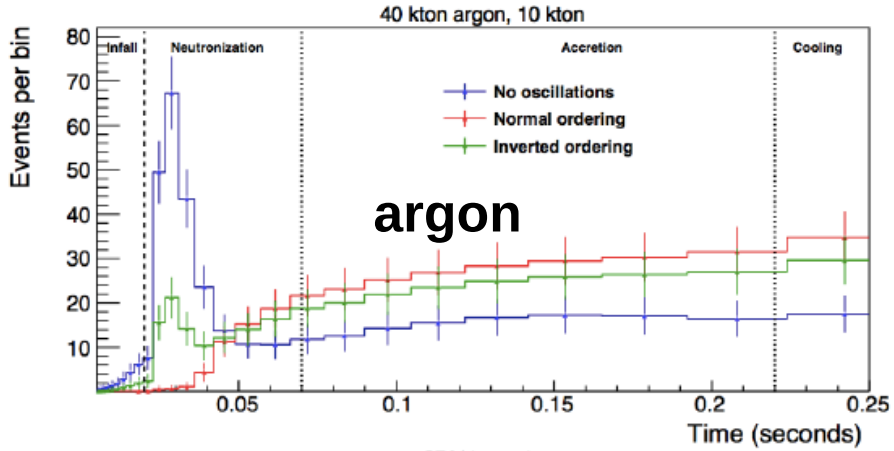
1.) Supernova Neutrinos with Underground Detectors

Kate Scholberg

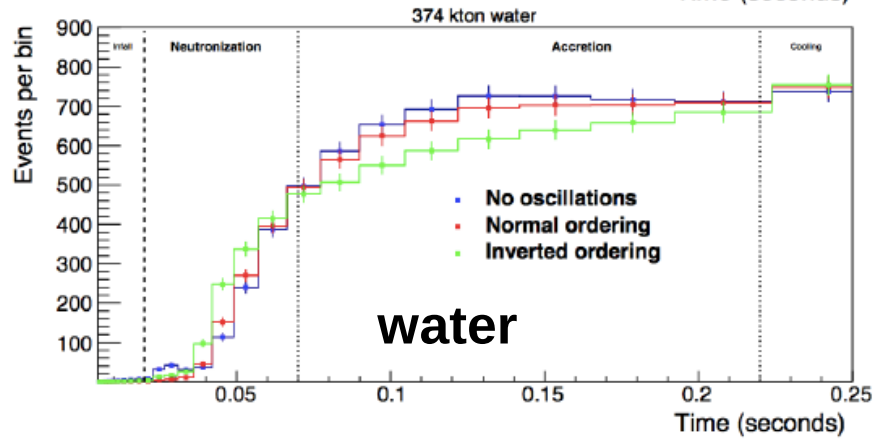
Same supernova model, other future large detectors

- neutronization burst much more visible in LAr
- time profile varies by hierarchy, differently for different detectors

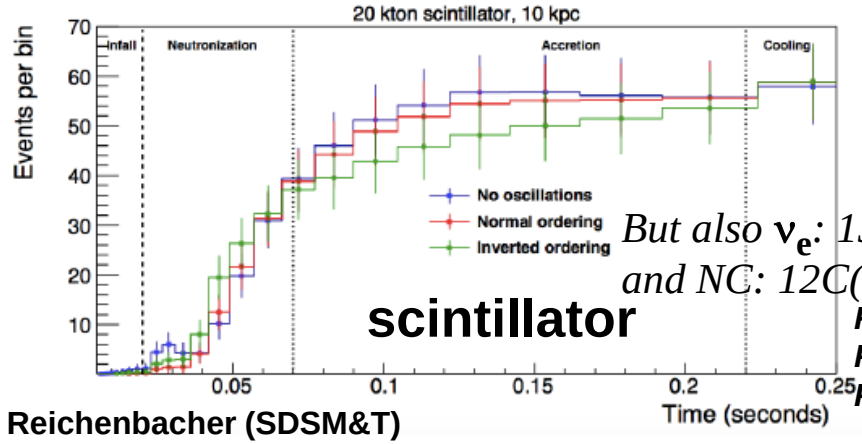
⇒ ***We need LAr SNB detector!***



ν_e



$\bar{\nu}_e$



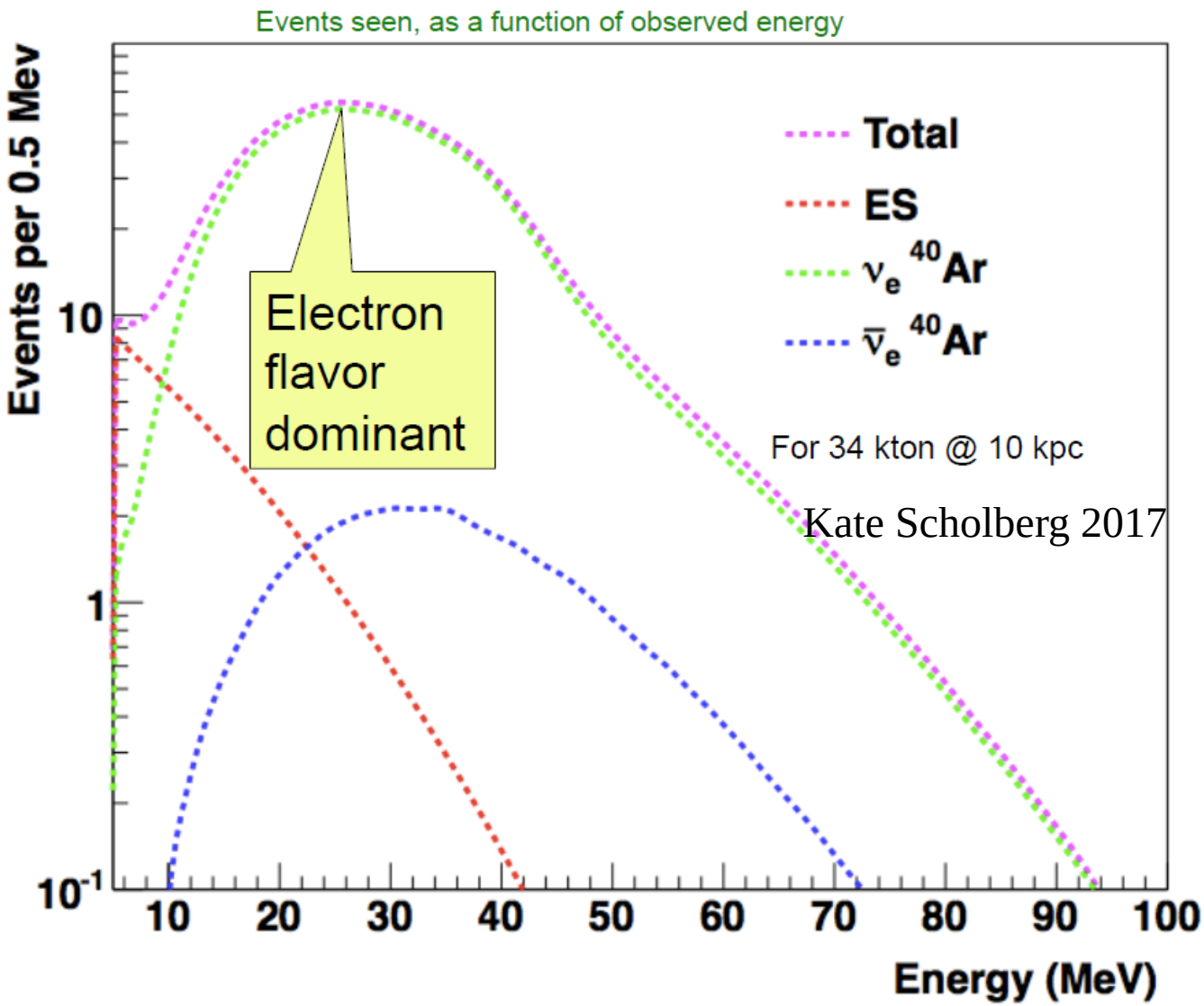
$\bar{\nu}_e$

But also ν_e*:* $^{13}C(\nu_e,e)^{13}N$
and NC: $^{12}C(\nu, 15MeV\gamma)^{12}C^*$

Reichenbacher PhD Thesis, FZKA Report 7093

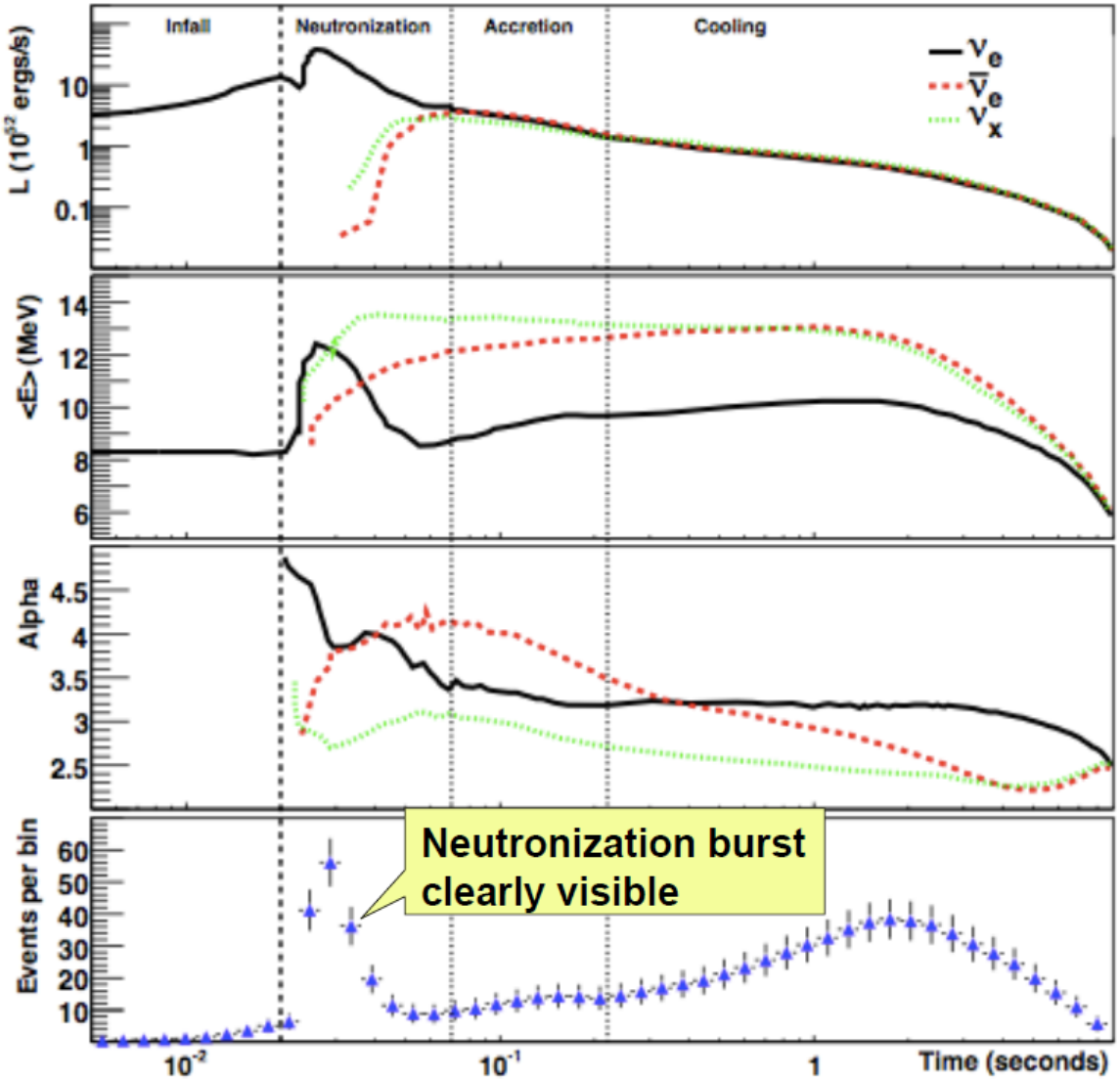
1.) Supernova Neutrinos with Large Underground LArTPC

Supernova signal in a liquid argon detector



1.) Supernova Neutrinos with Large Underground LArTPC

Example of supernova burst signal in 34 kton of LAr



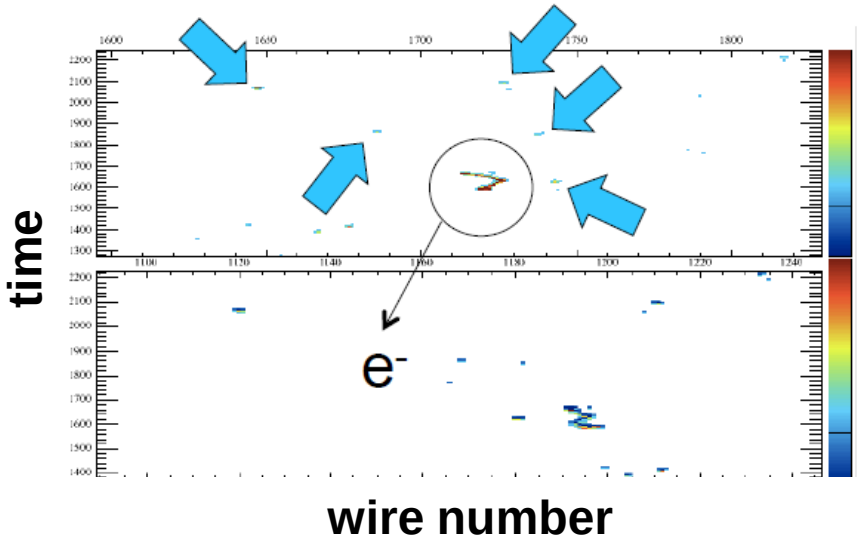
arXiv:1307.7335

Flux from Huedepohl et. al, PRL 104 (2010) 251101 @ 10 kpc

1.) Supernova Neutrinos with Large Underground LArTPC

Can we tag ν_e CC interactions in argon using nuclear deexcitation γ's?

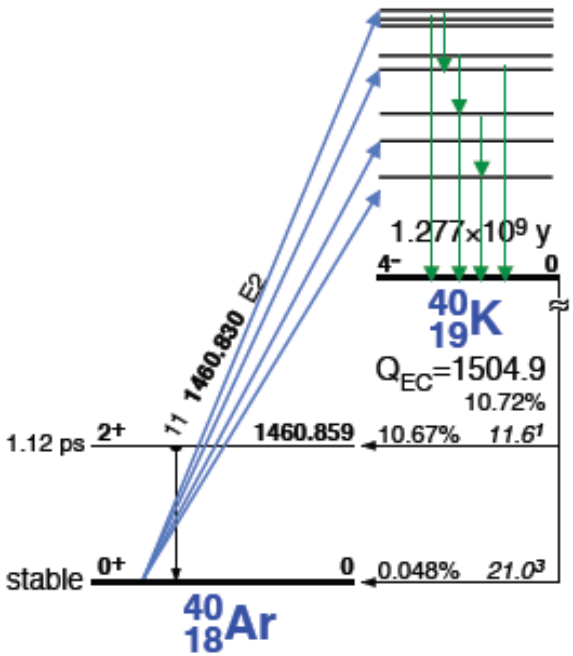
Kate Scholberg



Charged-current absorption:

$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow {}^{40}\mathrm{K}^* + e^-$$

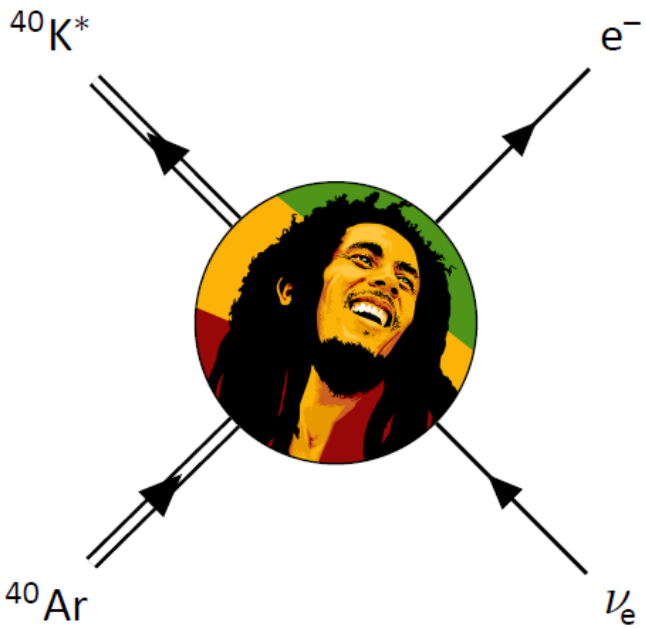
(g.s. to g.s. is 3rd forbidden transition)



20 MeV ν_e, 14.1 MeV e^-, simple model based on R. Raghavan, PRD 34 (1986) 2088
Improved modeling based on ^{40}Ti (^{40}K mirror) β decay measurements in progress
Direct measurements (and theory) needed!

MARLEY: Model of Argon Reaction Low-Energy Yields

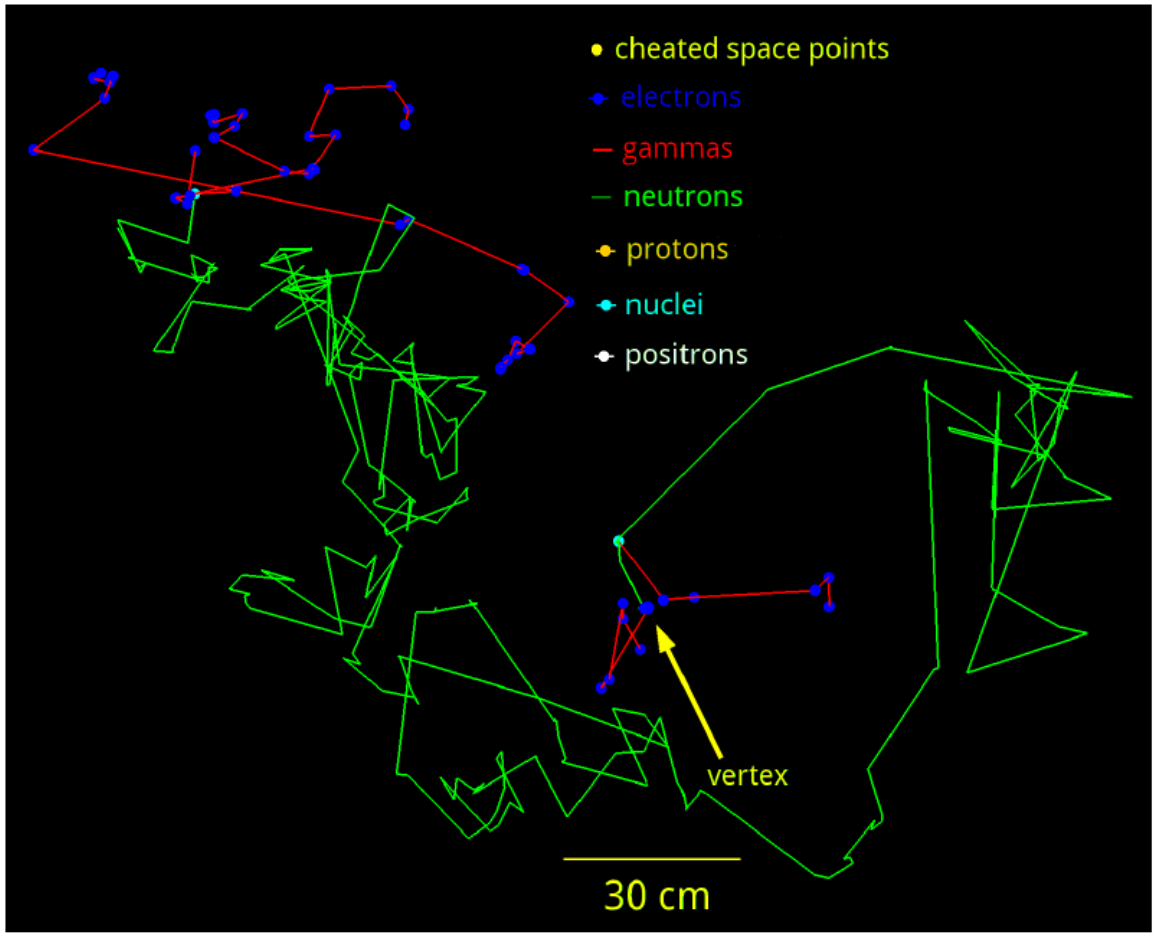
- **Goal:** determine whether "every little thing gonna be all right" for SN neutrino physics in LArTPCs
- Event generator for SN ν on ^{40}Ar
- Current version focuses on generating ν_eArCC events



R. Svoboda,
S. Gardiner,
C. Grant & E. Pantic

Example neutron event (true trajectories)

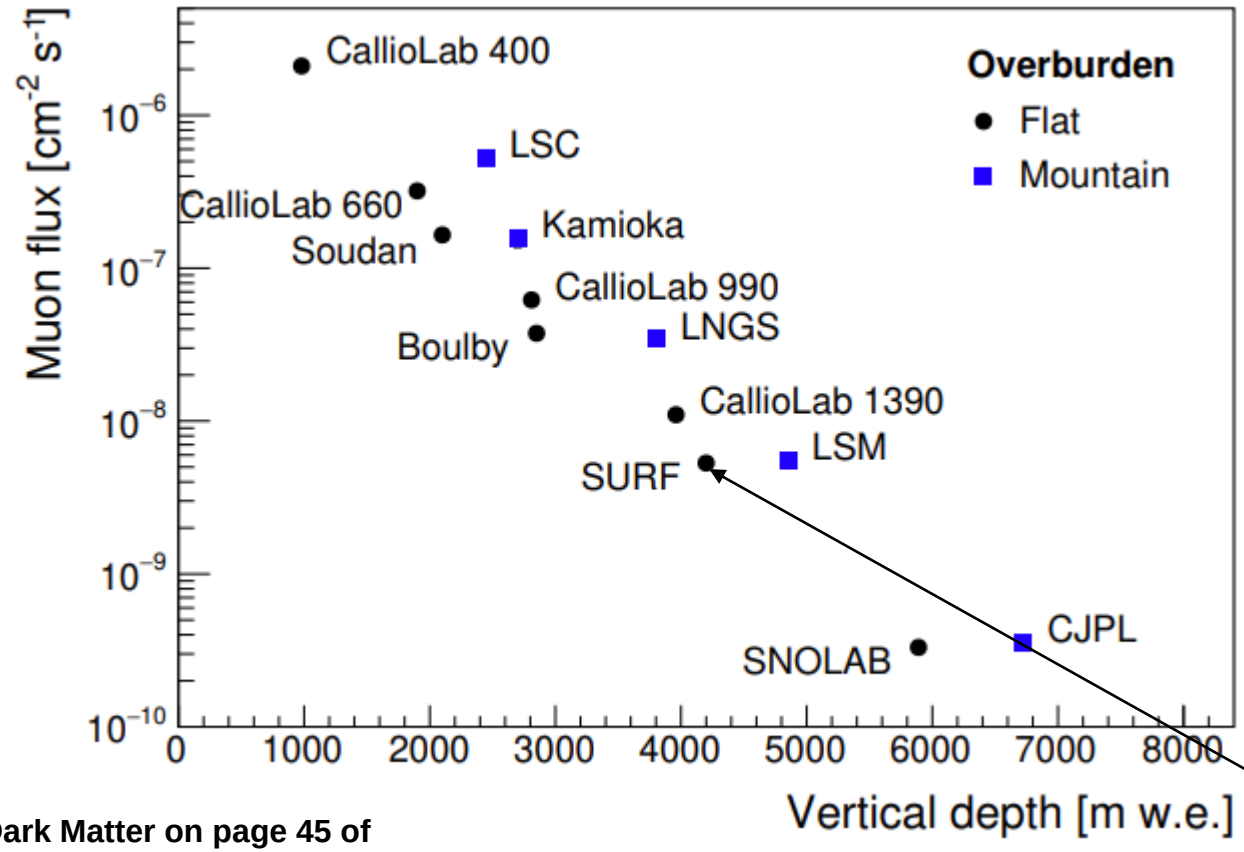
- E_ν = 16.3 MeV
- e^- deposited 4.5 MeV
- No primary γs from vertex
- ^{39}K deposited 68 keV
- n deposited 7.6 MeV (mostly from capture γs)
- Total visible energy: 12.2 MeV
- Visible energy sphere radius: 1.44 m
- Neutrons bounce around for a long time!



-> need to control u/α neutron background!

(see also Nick Carrara's talk)

μ Background at 4850 ft Level at SURF



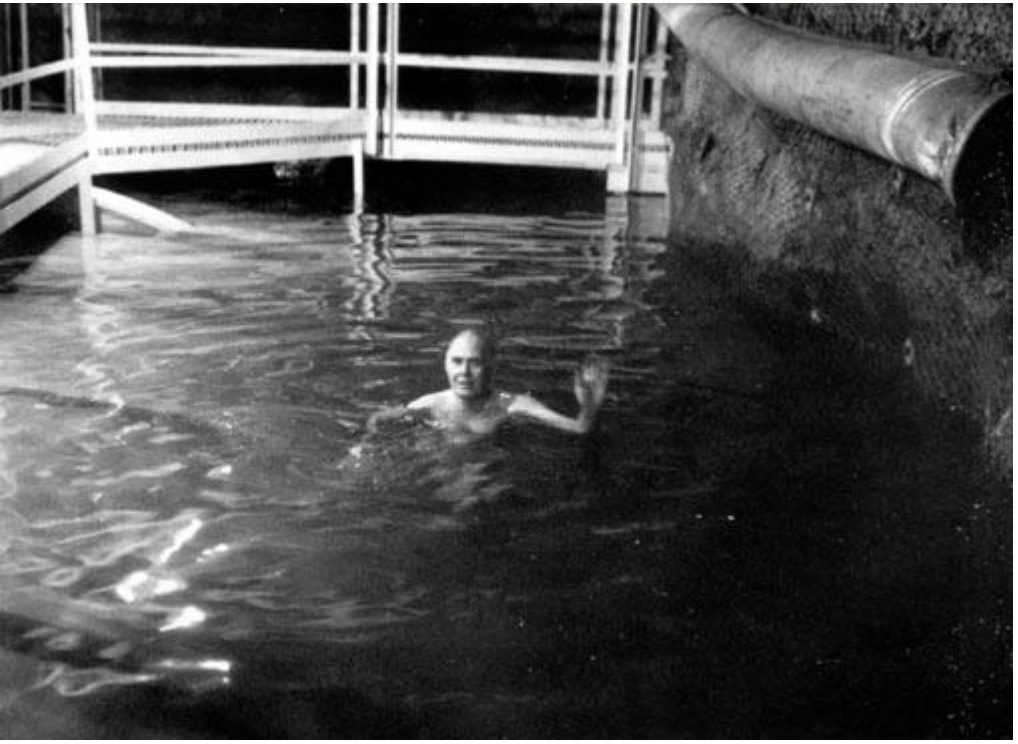
- See LXe G3 Dark Matter on page 45 of
https://arxiv.org/pdf/2203.02309.pdf

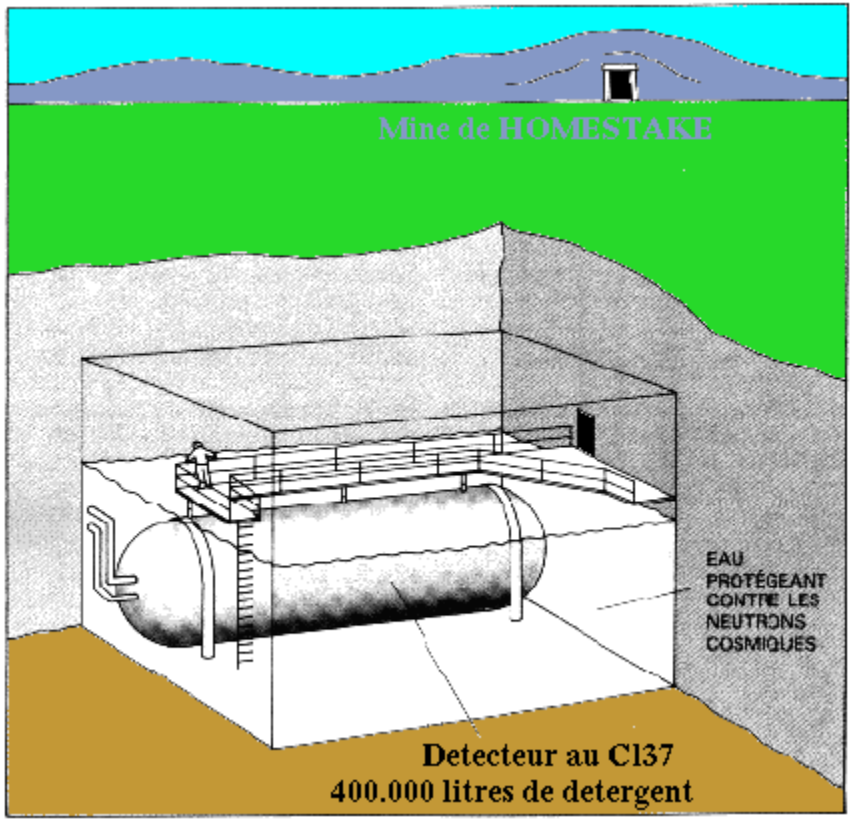
- See ICRC 2007 contribution
https://arxiv.org/pdf/0706.1110.pdf

Underground muon flux at Ross campus (DUNE @ SURF):

(5 ± 1[syst.]) x 10^-9 μ cm−2 s−1 @ 4200 mwe

Ray Davis' Homestake Chlorine Detector had Already a Water Shield





- **DUNE HD & VD have virtually no passive shielding towards rock (and no active veto)**

- **How well DUNE HD, VD, and modules 3 & 4 could do low energy physics depends more or less on the underground cavern background at the Ross campus of Sanford Lab**

External Cavern Backgrounds for Underground Detectors/Cryostats

- Propagated rock&shotcrete neutron spectrum

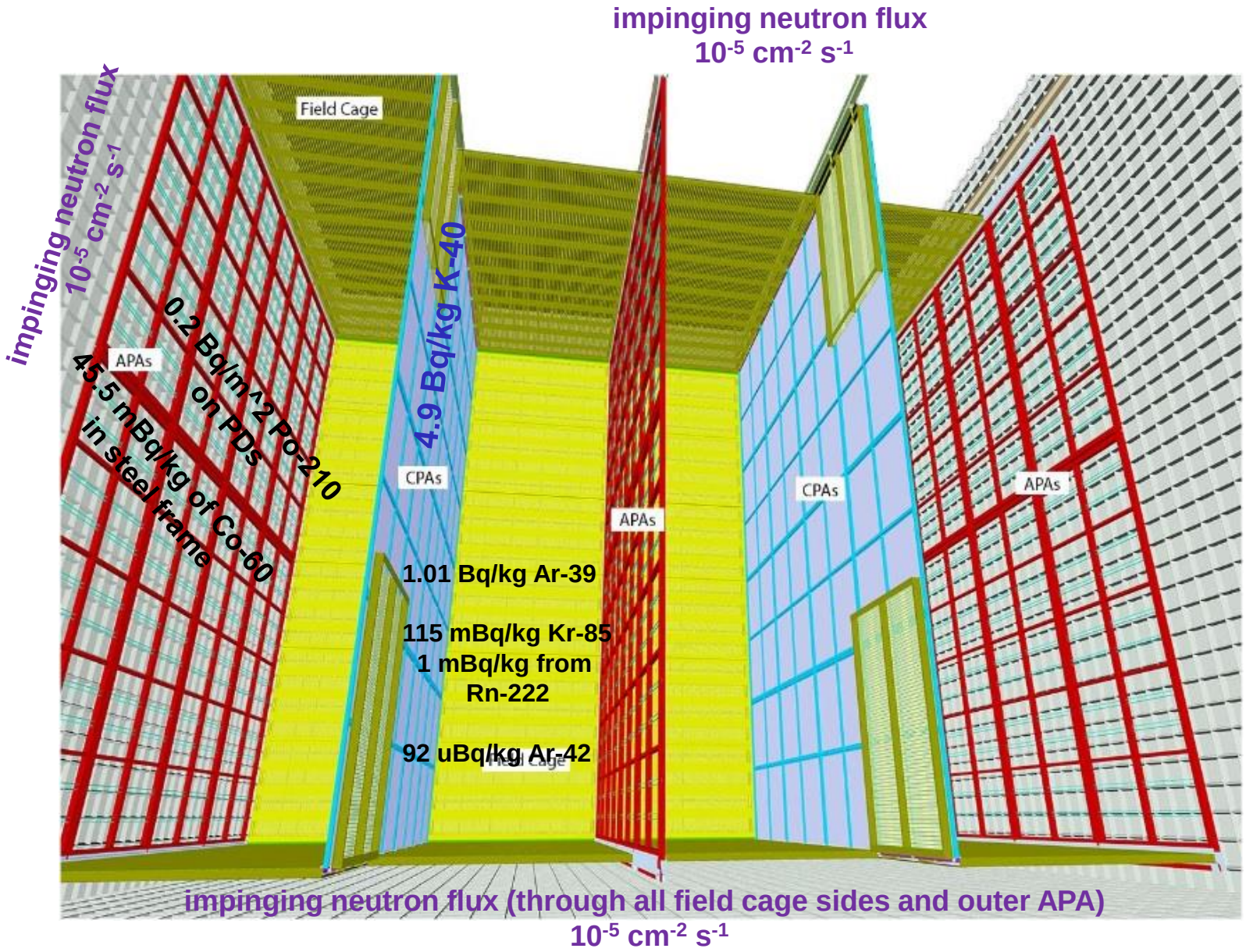
- Propagated gamma-ray spectrum from neutron captures in rock&shotcrete

- Propagated gamma-ray spectrum from neutron captures in cryostat (mostly steel & foam)

- Propagated gamma-ray spectrum from cavern gamma-rays from rock&shotcrete

- Propagated foam gamma-ray spectrum from cryostat insulation

Internal Argon Backgrounds (DUNE HD, TDR)



Cavern Neutrons ARE a Problem for u/g LArTPCs

- neutron captures can look like ν's for DAQ
  (=> rate issue, supernova burst ν trigger efficiency, solar ν's)

- neutrons are difficult to shield
  (=> simulate large geometry w/ detailed chemical composition)

- external radiological neutron flux is important (rock, shotcrete)

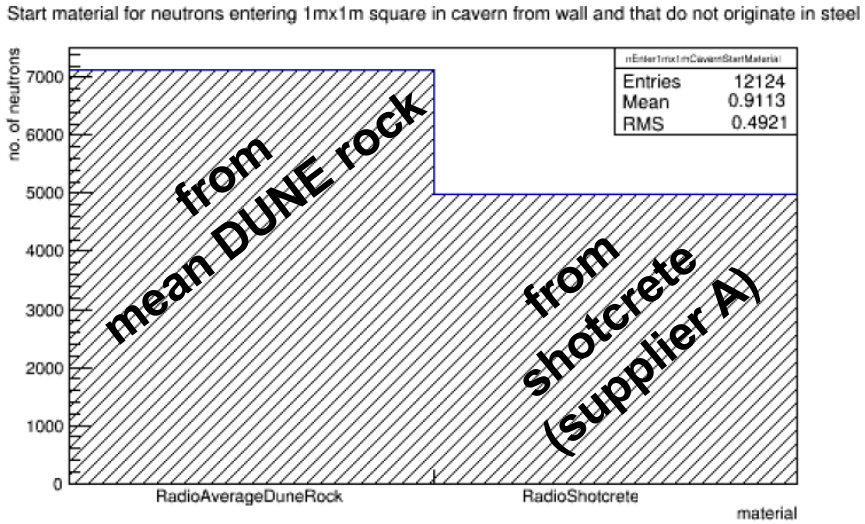
- ^{238}U content of materials for SF

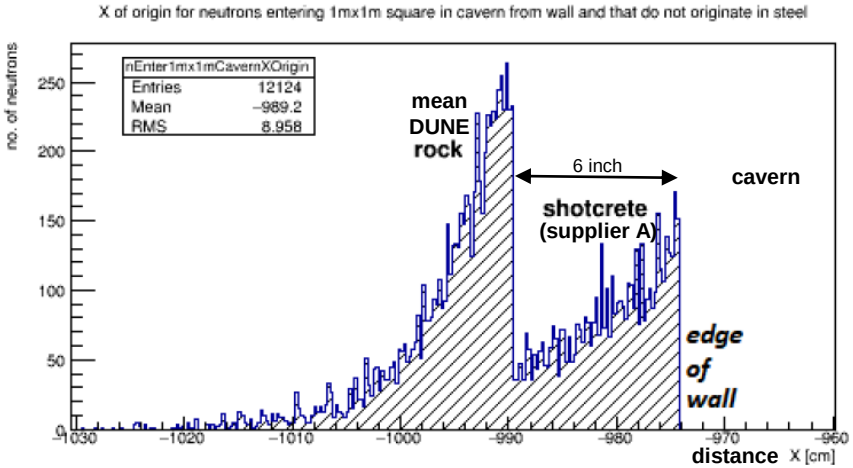
- α emitter content of materials + chemical composition -> (α,n)

- customized (α,n) production yield calculations important!
  (need cross section measurements where uncertainties large)

-> need for entire detector geometry & surrounding environment:
extensive radiological assays + chemical composition assays

Neutron Production from Cavern Walls





work in progress

(simulation w/ LArSoft and Decay0 and new 232Th decay chain implementation)

LArSoft simulated total cavern neutron flux:
(1.08 ± 0.2[syst.]) x 10^-6 neutron cm−2 s−1

with E_{kin} > 0.1 MeV (fast neutron flux in cavern):
(2.24 ± 0.5[syst.]) x 10^-7 neutron cm−2 s−1

Mean DUNE Rock:
66.7 ± 0.3 Bq/kg of 238U
31.8 ± 0.2 Bq/kg of 232Th

Worst rock (2x activity) could cause 60% increase to ≤ 1.7 x 10^-6 neutron cm−2 s−1

Shotcrete Supplier A (15 cm thick):
24.6 ± 0.4 Bq/kg of 238U
6.0 ± 0.2 Bq/kg of 232Th

Worst shotcrete (4x activity) could double rate to ≤ 2.2 x 10^-6 neutron cm−2 s−1

Use worst case as indicated by our latest excavation site assays of shotcrete

Radiological Assay Paradigms for u/g LArTPCs

Radiological assays (γ- and α-spectroscopy, emanation) of materials to quantify background and learn for next u/g LArTPCs (want extensive assay program)!

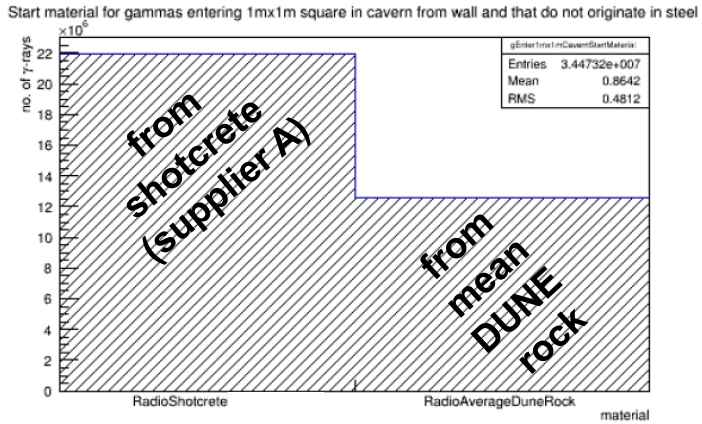
Chemical composition of detector materials very important too (different chemical assay methods like XRD, XRF, ICP-MS, FT-IR, CHN etc. needed for each different type of material!):

- **insulating foam defines neutron attenuation, but also neutron capture time, even in a 10 kt LAr volume (some neutrons can still escape)**
- **critical aluminium content drives (α, n) production rates from rock/shotcrete**
- **cryostat is ~10% of mass of detector (steel's radiopurity?)**

Fast turn-around of assays & simulations can help with sensitivity for next u/g LArTPCs for low energy physics (SNB and solar)

γ-Ray Production from Cavern Walls

(simulation w/ LArSoft and Decay0 and new 232Th decay chain implementation)



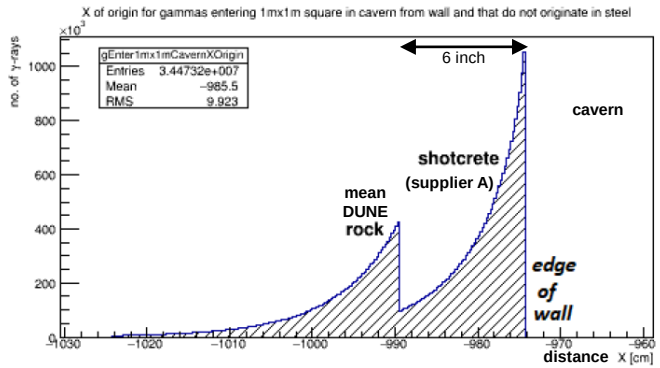
Simulated DUNE cavern γ flux:

3.07 ± 0.2[syst.] γ cm−2 s−1

Mean DUNE Rock:
665.5 ± 1.4 Bq/kg of 40K
66.7 ± 0.3 Bq/kg of 238U
31.8 ± 0.2 Bq/kg of 232Th

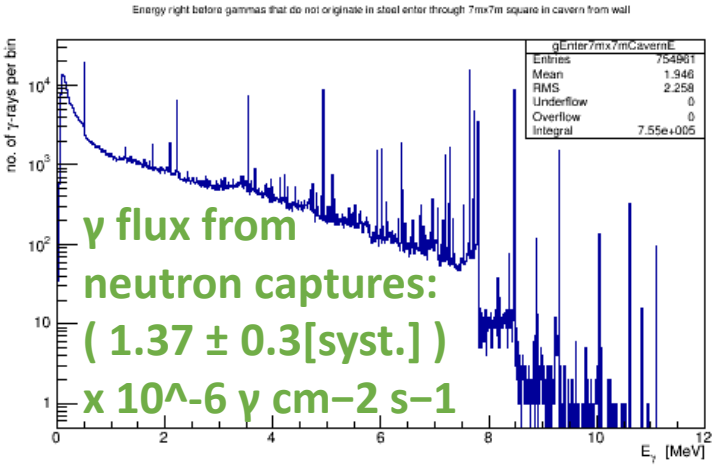
Worst rock (2x activity) could cause 35% increase to ≤ 4.1 γ cm−2 s−1

work in progress



Shotcrete Supplier A (15 cm thick ~2Λ):
105.8 ± 4.5 Bq/kg of 40K
24.6 ± 0.4 Bq/kg of 238U
6.0 ± 0.2 Bq/kg of 232Th

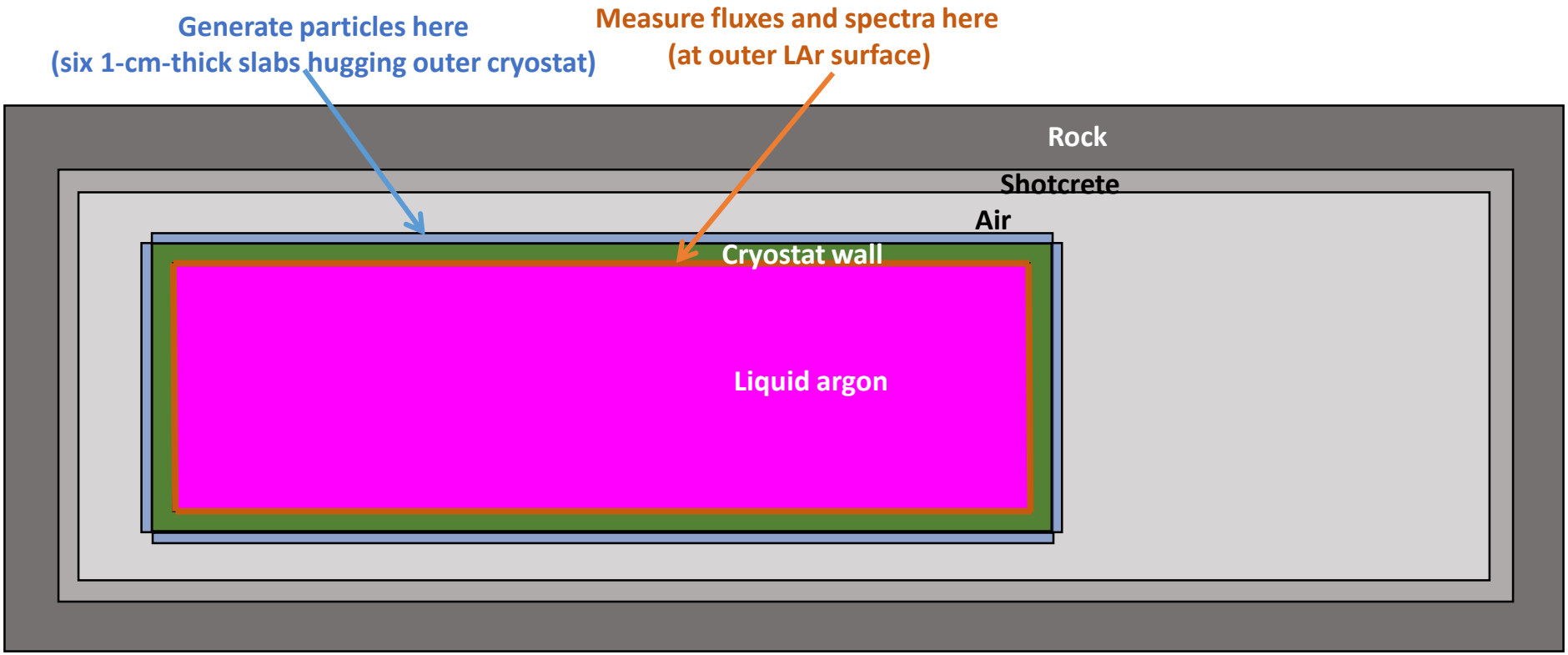
Worst shotcrete (4x activity) could triple γ rate to ≤ 9.2 γ cm−2 s−1



Use worst case as indicated by our latest excavation site assays of shotcrete

LZ Davis campus γ flux measured:
[Astroparticle Physics, Volume 116, Pages 102391 (2020) arXiv 1904.02112] **1.9 ± 0.4 γ cm−2 s−1**

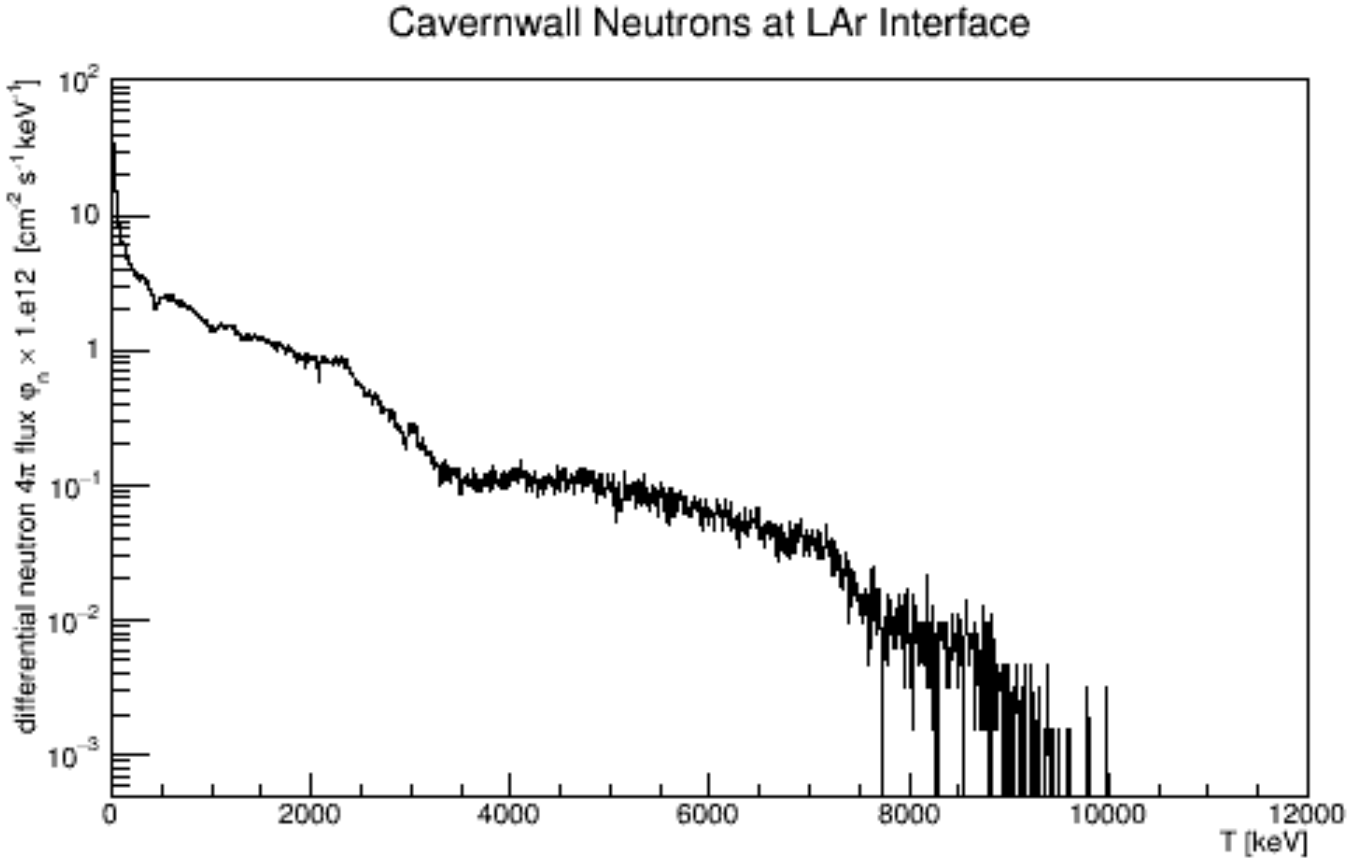
Illustration of cavern view from top (10 kton LArTPC)



Area factor for flux correction at argon interface due to smaller surface area compared to outer cryostat:

$$\mathbf{1.3687} = \frac{\text{cryostat surface [cm^2]}\ \ (1783.6 \times 6583.6 \times 2 \text{ sides}) + (1893.6 \times 6583.6 \times 2 \text{ tops}) + (1893.6 \times 1783.6 \times 2 \text{ faces})}{\text{argon surface [cm^2]}\ \ (1400 \times 6200 \times 2 \text{ sides}) + (1510 \times 6200 \times 2 \text{ tops}) + (1510 \times 1400 \times 2 \text{ faces})}$$

Propagated **cavern neutrons** through cryostat

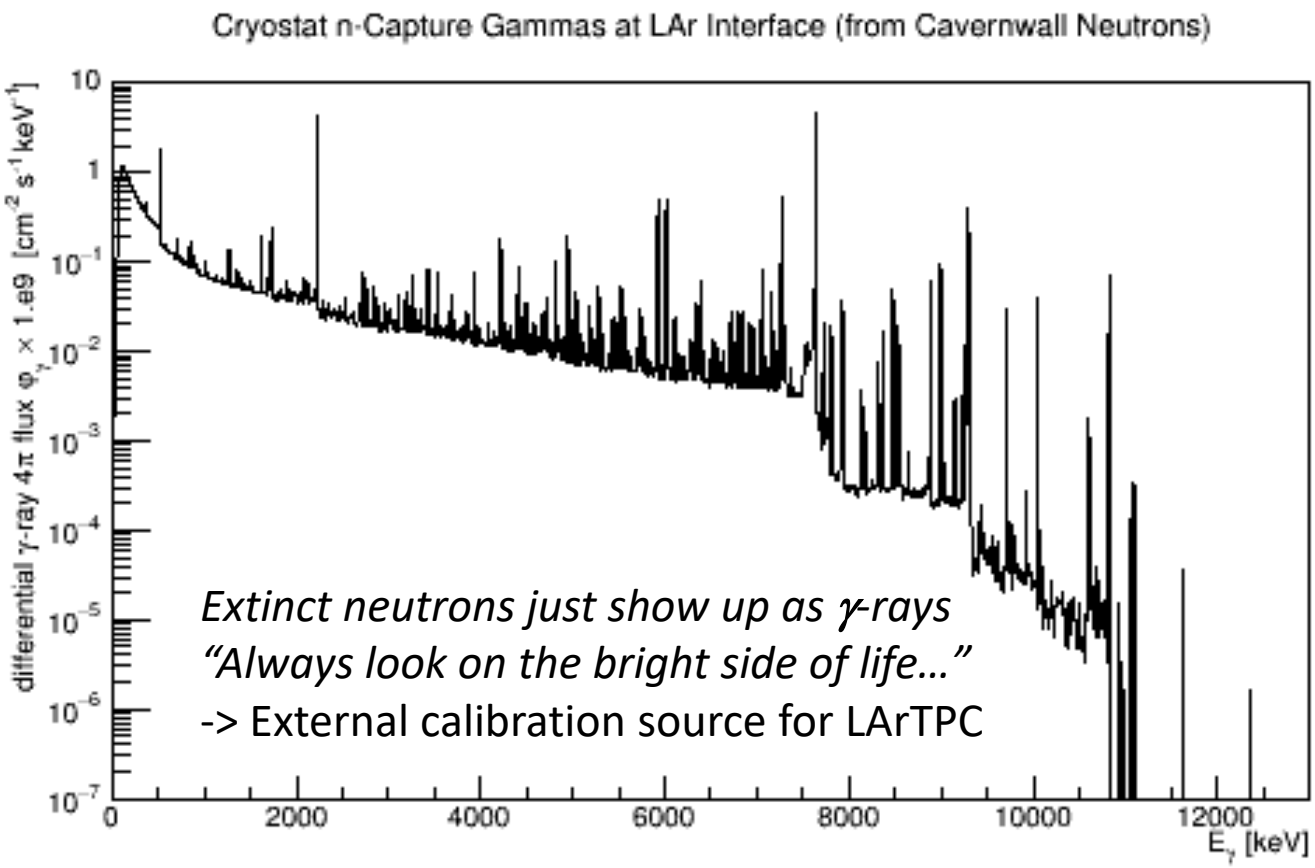


Reduction factor: 21.816 ± 0.009 (stat) ***(for neutrons >0.1 MeV: 90.04 ± 0.17 (stat))***

⇒ **Scale with worst shotcrete (4x activity) <u>double neutron rate</u>**

⇒ **<u>0.26996 ± 0.00036 (stat) 10^{-6} n/(cm^2·s)</u>**

Propagated cavern neutrons: **capture γ-rays from cryostat**

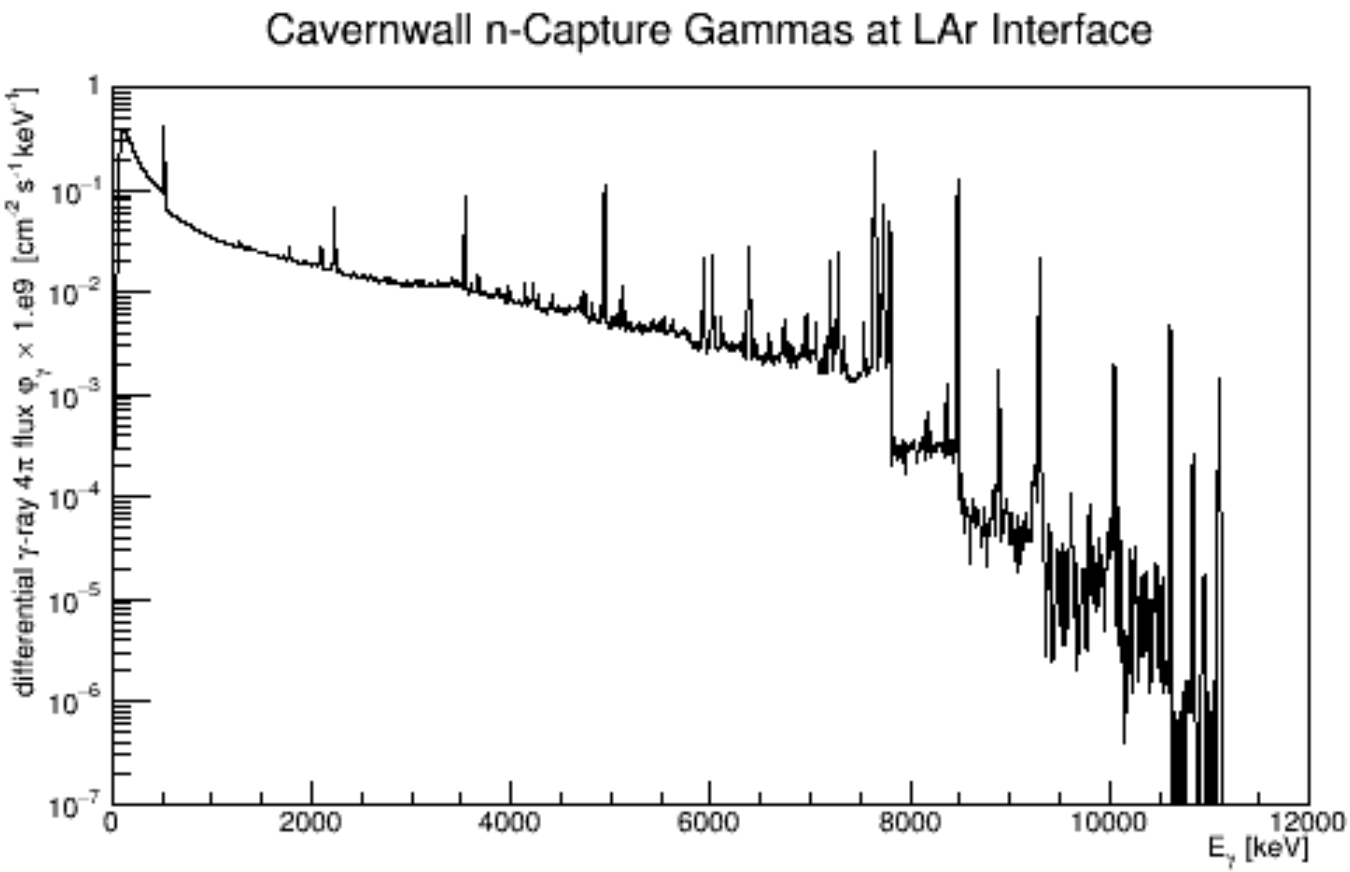


Conversion factor: 0.28515 ± 0.00005 (stat) γ/n

⇒ **Scale with worst shotcrete (4x activity) <u>double neutron rate</u>**

⇒ **<u>1.6793 ± 0.0022 (stat) 10^{-6} γ/(cm²·s)</u>**

Propagated cavern **n-capture γ-rays from rock/shotcrete**

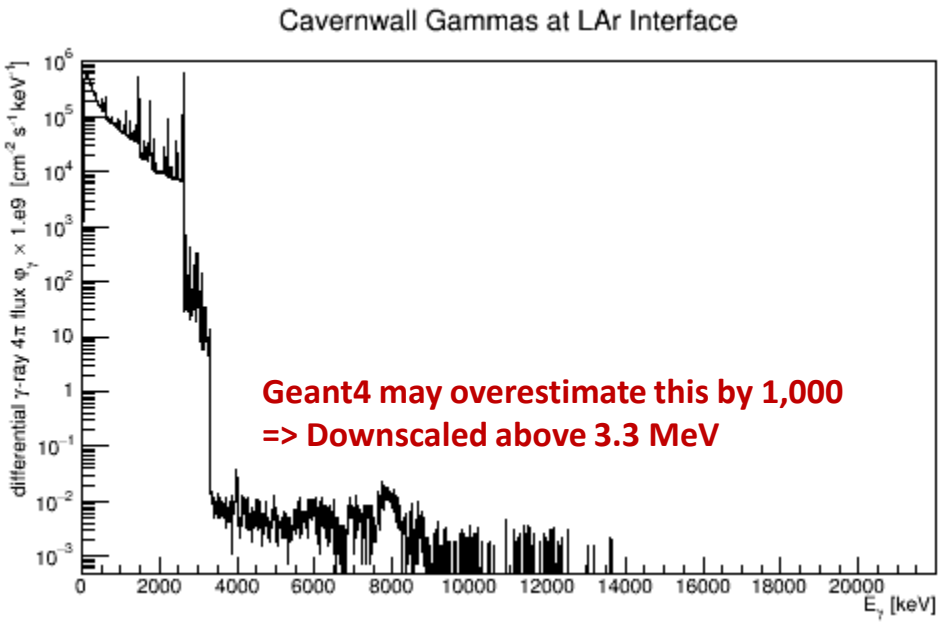


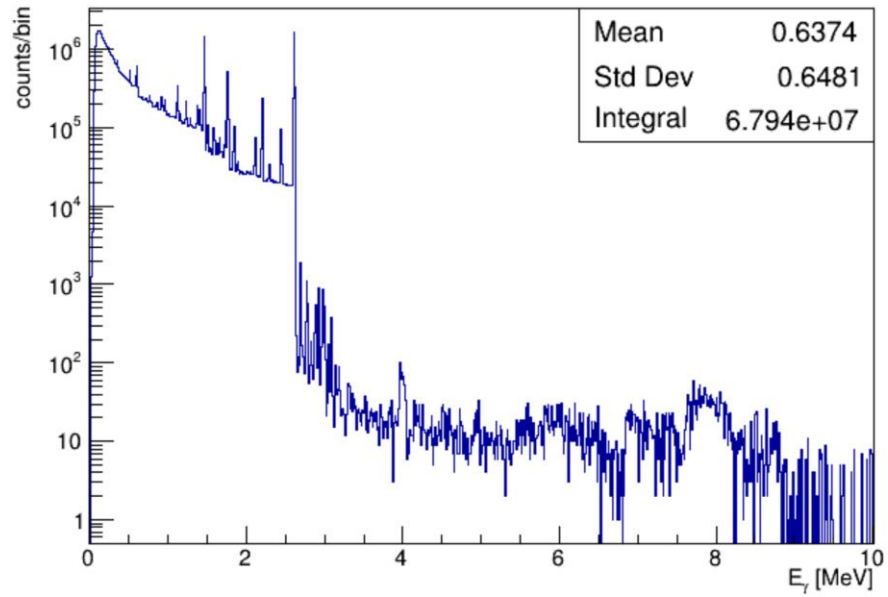
Reduction factor: 13.807 ± 0.002 (stat) *~1/3 of n-capture γ-rays from cryostat!*

⇒ **Scale with worst shotcrete (4x activity) <u>double neutron rate</u>**

⇒ **<u>0.5439 ± 0.0005 (stat) 10^{-6} γ/(cm²·s)</u>**

Propagating **cavern gamma-rays** through cryostat





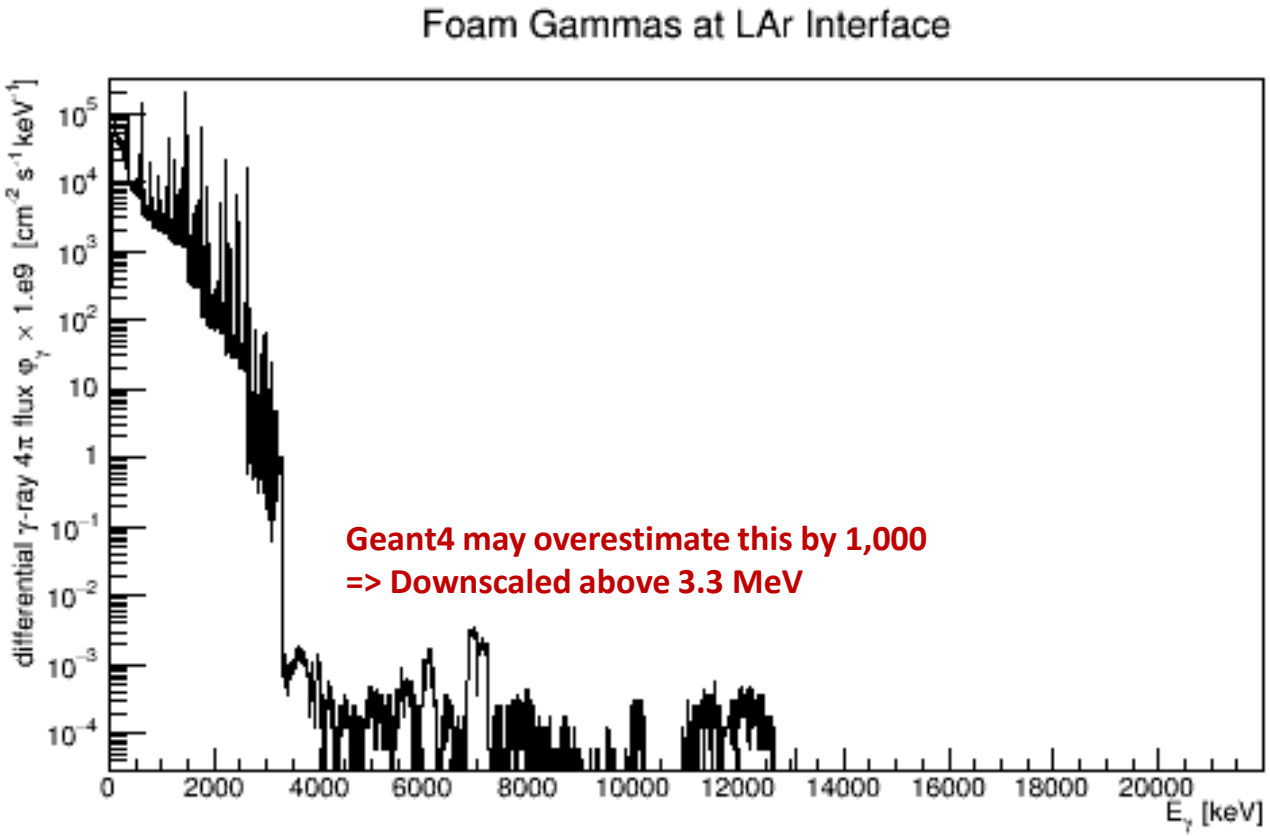
Reduction factor: 23.985 ± 0.003 (stat) ***(for gamma-rays >2.65 MeV: 20.81 ± 0.14 (stat))***

⇒ **Scale with worst shotcrete (4x activity) <u>triple gamma rate</u>**

⇒ **<u>1.05104 ± 0.00021 (stat) γ/(cm²·s)</u>**

-> Want inner passive shielding (e.g. dead outer LAr shell)

Propagating **foam gamma-rays** through cryostat



<u>4π γ-flux at LAr interface</u>: = <u>0.0441274 ± 0.0000073 (stat) γ/(cm²·s)</u>

(full reference argon volume)

=> Subdominant but still simulated

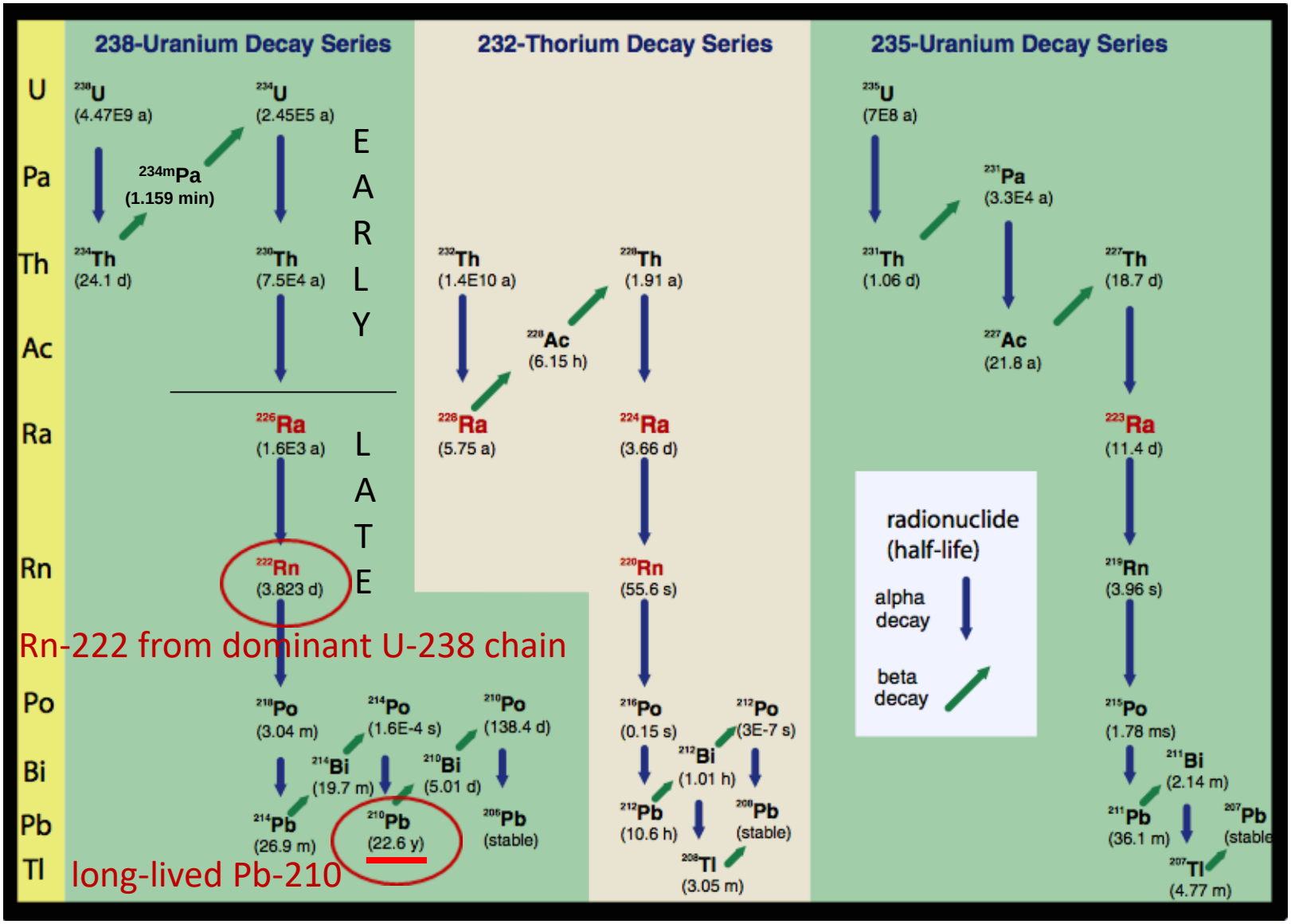
Summary Table of External Backgrounds (Analytical Estimate only, no DUNE Reco Sim)

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

⇒ **rate in full LAr (VD) from cavern gammas from rock/shotcrete is ~21 MHz mostly at outer edges compared to ~17 MHz Ar-39 rate uniformly distributed**

⇒ **neutron capture rates in LAr expected to be below critical SNB trigger rate of 10 Hz**

Early and Late 238U Decay Chain and 232Th Decay Chain



Modified from 'Origin of Radioactivity in Fuel-Cycle Facilities | The National Academies Press'

Light yield for different particles – alphas at ~ 0.8 of `full' yield.

1540 Jpn. J. Appl. Phys. Vol. 41 (2002) Pt. 1, No. 3A

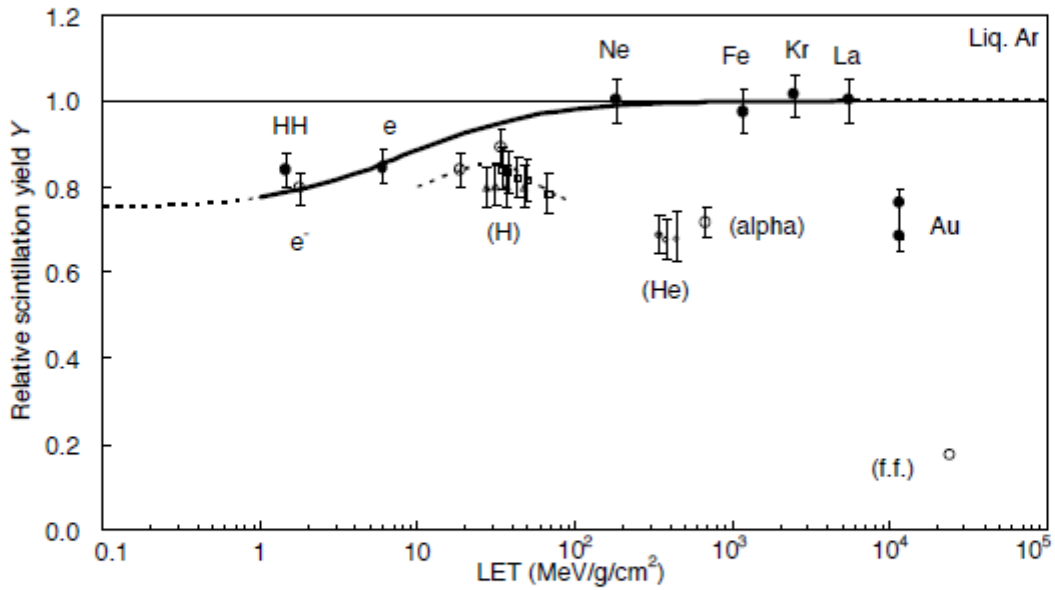


Fig. 2. LET dependence of scintillation yield, Y, in liquid argon. Solid circles show the yields for relativistic particles.[1–3] Non-relativistic particles are represented by open circles.[5–8] Open squares and triangles show the yields for non-relativistic protons[24] whereas small open circles show those for non-relativistic helium ions.[22]

Thanks to Stephen Pordes!

Light and charge yield for electrons and gammas vs Electric Field

[65] S. Kubota *et al.*, *Phys. Rev. B* **17** (1978) 2762;

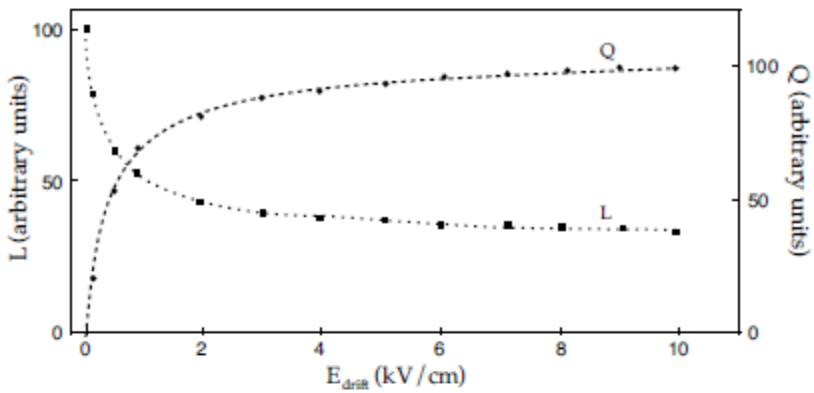


Figure 3.7: The graph shows the behaviour of the luminescence light intensity and of the collected charge as function of the electric field strength. The y axis scales are expressed in arbitrary unit. The left scale refers to luminescence intensity: the value 100 is set for the total light collected at $E_d = 0\ kV/cm$. The right scale refers to wire collected charge and the value 100 is set for the initially produced charge Q_0. About 30% of the light produced at zero field seems to be uninfluenced by the application of the electric field, most likely representing the excitation component of the luminescence [65]. The data refer to 1 MeV primary electrons.

Radon is Potentially a Big Problem for Next Gen Neutrino & DM Experiments (e.g. DUNE)

- **α's have high light yield in LAr (barely quenched)**

- **^{40}Ar(α, γ) -> 15 MeV γ's that look like ν's**

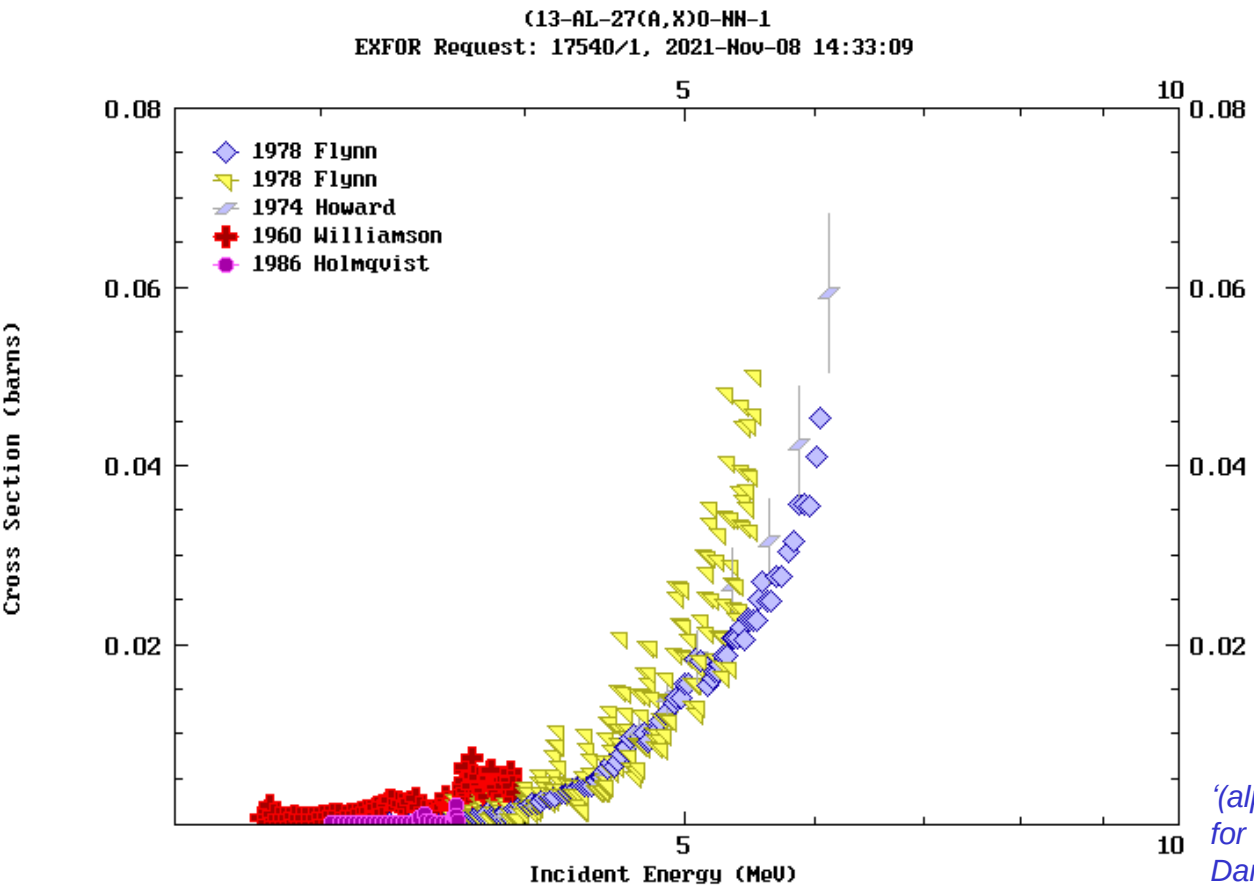
- **^{40}Ar(α,n) -> neutron captures in LAr that look like ν's**

- **α surface contamination from:**
  Construction and installation period:
  - radon daughter plate-out in air (^{210}Pb, $T_{1/2}$=22 y)
  Detector operation period:
  - radon daughter migration in LArTPC (-> cathod)

- **^{222}Rn continuously emanating into LAr from materials**

Precise (alpha, n) Cross Section Data Needed: Aluminium in Rock/Shotcrete and for Argon Target

Aluminium in materials is critical for (alpha, n) production of radiological neutrons (verbal comm. V. Kudryavtsev)



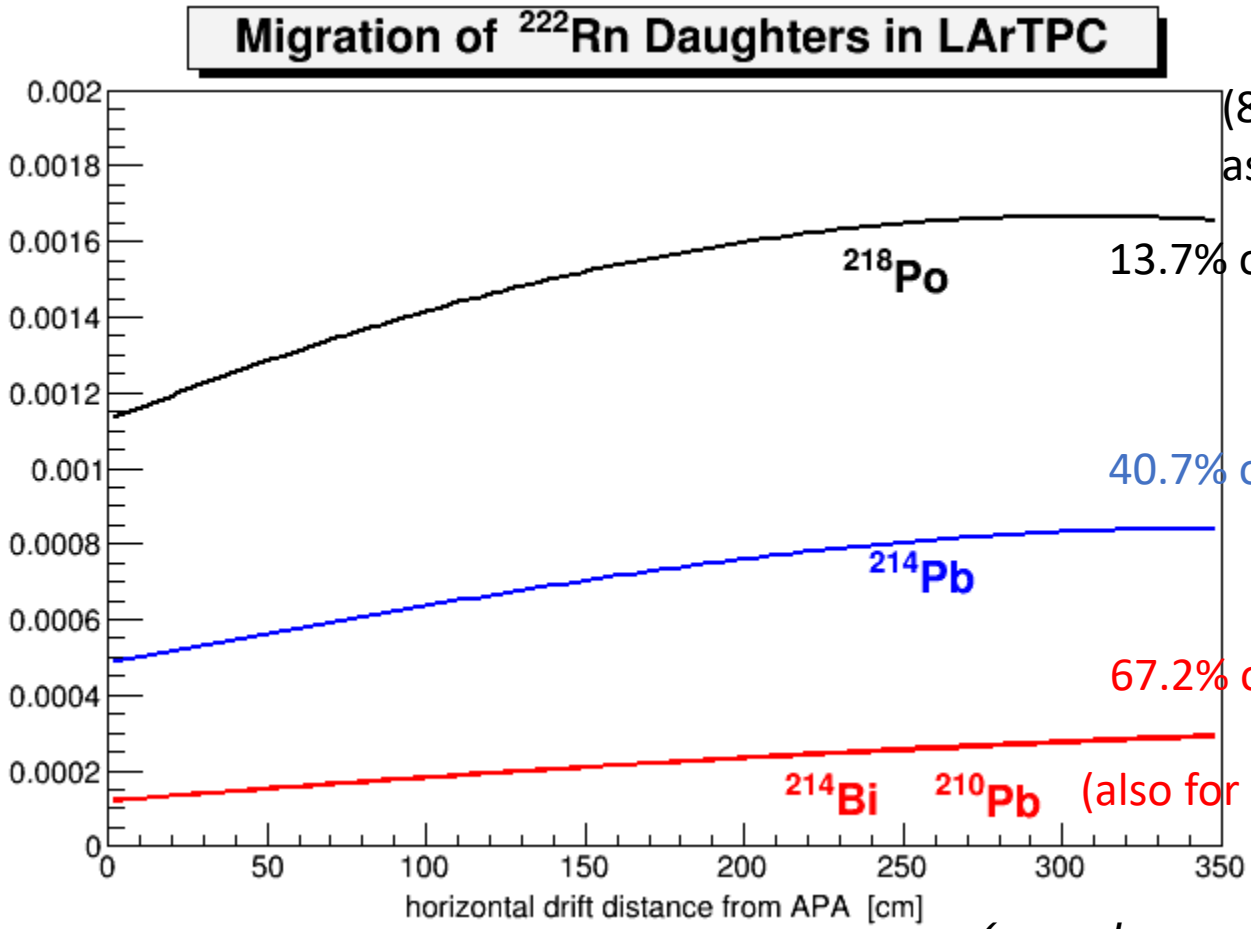
hardly any data at all available for argon!
⇒ More (alpha, n) measurements desirable for critical materials

'(alpha, n) Cross Section Data Improvement Needs for Next Generation Low-Background Neutrino and Dark Matter Experiments'
IAEA Technical Meeting on (alpha,n) nuclear data evaluation and data needs
8th Nov, 2021 Reichenbacher

^{222}Rn DUNE Requirement <1 mBq/kg

(^{220}Rn <1/3 mBq/kg based on filter material radio-assays)

G10/FR4 cathode
measured 4.9 Bq/kg of ^{40}K



(80% of 42K also assumed at cathode)

13.7% on the cathode

40.7% on the cathode

67.2% on the cathode

(also for late ^{220}Rn chain)

(see also Will Foreman's talk)

Summary of External Backgrounds (Ross @ SURF):

LArSoft simulated total cavern neutron flux:
(1.08 ± 0.2[syst.]) x 10^-6 neutron cm−2 s−1

with E_{kin} > 0.1 MeV (fast neutron flux in cavern):
(2.24 ± 0.5[syst.]) x 10^-7 neutron cm−2 s−1

Depending mostly on shotcrete and also rock after excavation:

Worst rock could cause 60% increase of neutron flux to ≤ 1.7 x 10^-6 neutron cm−2 s−1

Worst shotcrete could double total neutron flux in cavern to ≤ 2.2 x 10^-6 neutron cm−2 s−1

Simulated Ross cavern γ flux:

3.07 ± 0.2[syst.] γ cm−2 s−1

γ flux from neutron captures in cavern walls:
(1.37 ± 0.3[syst.]) x 10^-6 γ cm−2 s−1

Depending mostly on shotcrete and also rock after excavation:

Worst rock could cause 35% increase of γ flux to ≤ 4.1 γ cm−2 s−1

Worst shotcrete could triple γ flux in cavern to ≤ 9.2 γ cm−2 s−1

Underground muon flux at Ross campus @ SURF:

(5 ± 1[syst.]) x 10^-9 μ cm−2 s−1 @ 4200 mwe

Underground radon content of cavern air at Ross campus @ SURF:

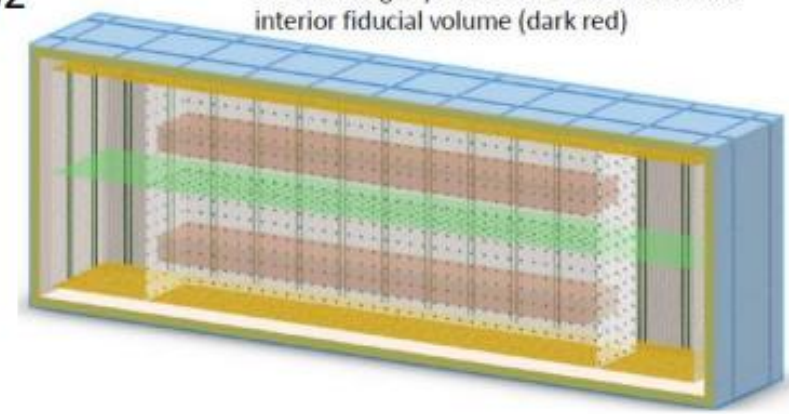
500 Bq/cm^3 of ^{222}Rn on average

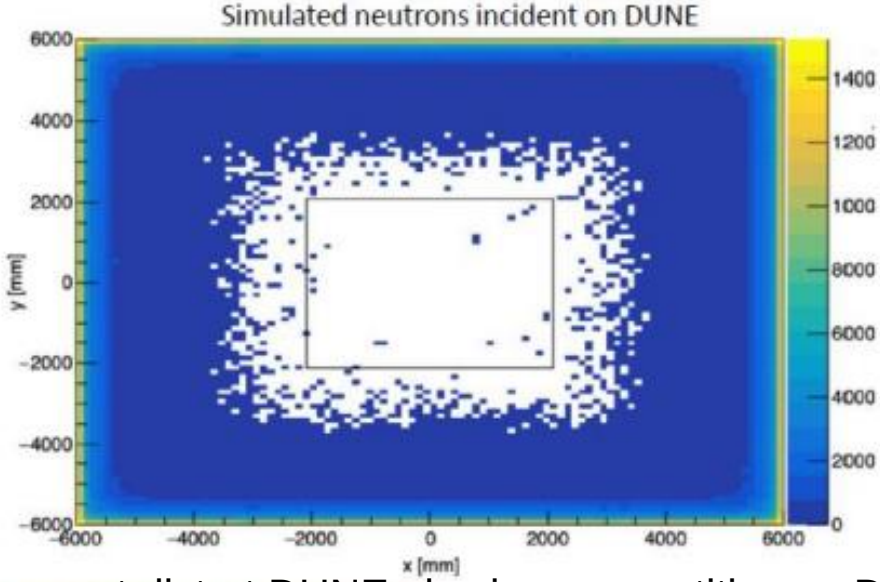
Low Background LArTPC Cryostat ('SloMo' as Potential DUNE Module w/ 3 kton UAr)

- Investment in a DUNE Module of Opportunity would be game-changing for low-energy physics
- Low-background module: *J Phys G* **50** 060502
  - Rate reduced by passive shielding
  - Increased photodetector coverage
  - Heavy fiducialization
  - Argon depleted of ^{39}Ar

(see Dan Pershey's and Gleb Sinev's talks)

DUNE low-background module concept
Increased SiPM (black dots) coverage on interior of acrylic vessel (white) forming volume of increased light yield which contains a 1-3 kt interior fiducial volume (dark red)





Potential for 100-keV thresholds would turn DUNE into a kt-scale powerhouse

All this possible without losing sensitivity to neutrino mixing parameters

⇒ does not distort DUNE physics, competitive on DarkSide timescale, enables more solar neutrino physics (dm^2 & NSI study), 0nubb with xenon doping [***https://arxiv.org/pdf/2203.08821.pdf***]

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