NEUTRINO-LESS DOUBLE BETA DECAY SEARCHES IN ARGON

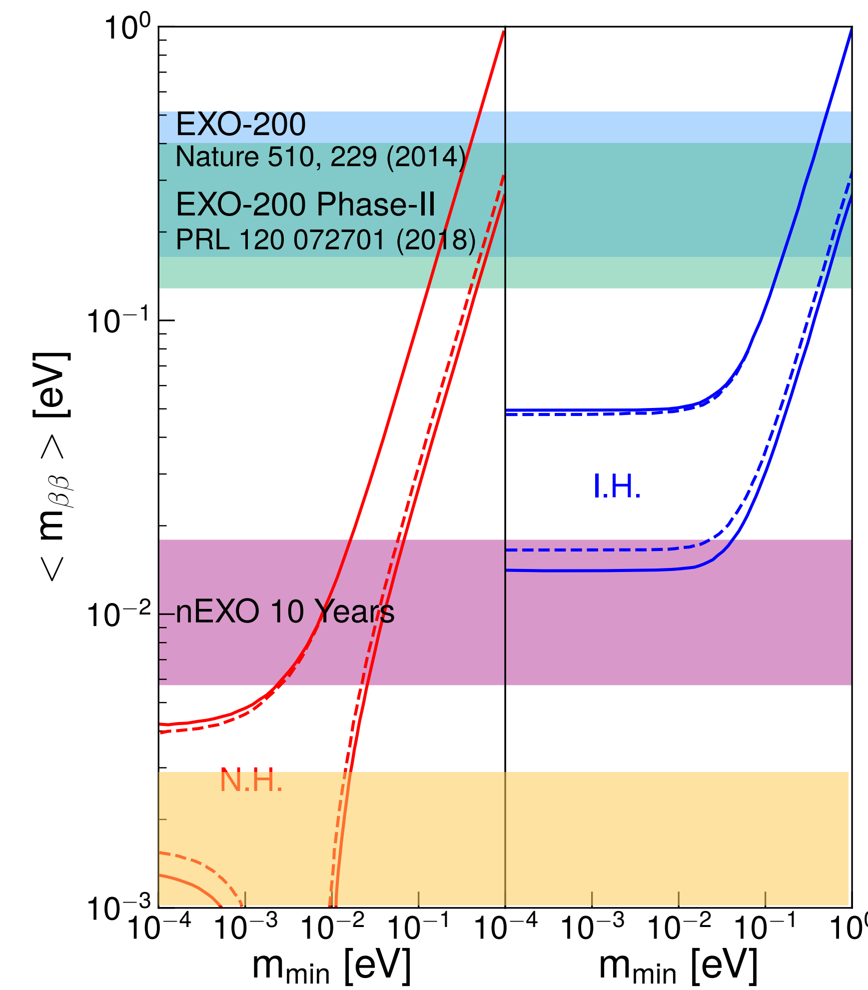
MASAYUKI WADA

INFN Cagliari
Princeton University

30/01/2018 @ ASTROCENT

THE ULTIMATE GOAL IN NEUTRINO-LESS DOUBLE BETA DECAY SEARCHES

- To reach $<m_{\beta\beta}>=1$ meV, depending on matrix element:
  - $T^{0\nu}_{1/2} = (0.4 \div 2.8) \times 10^{30}$ yr
  - $(300 \div 2{,}000)$ tonne×yr of background-free exposure
- What are the fundamental requirements on background?
- Can a LAr-based program help deliver also this fundamental discovery?



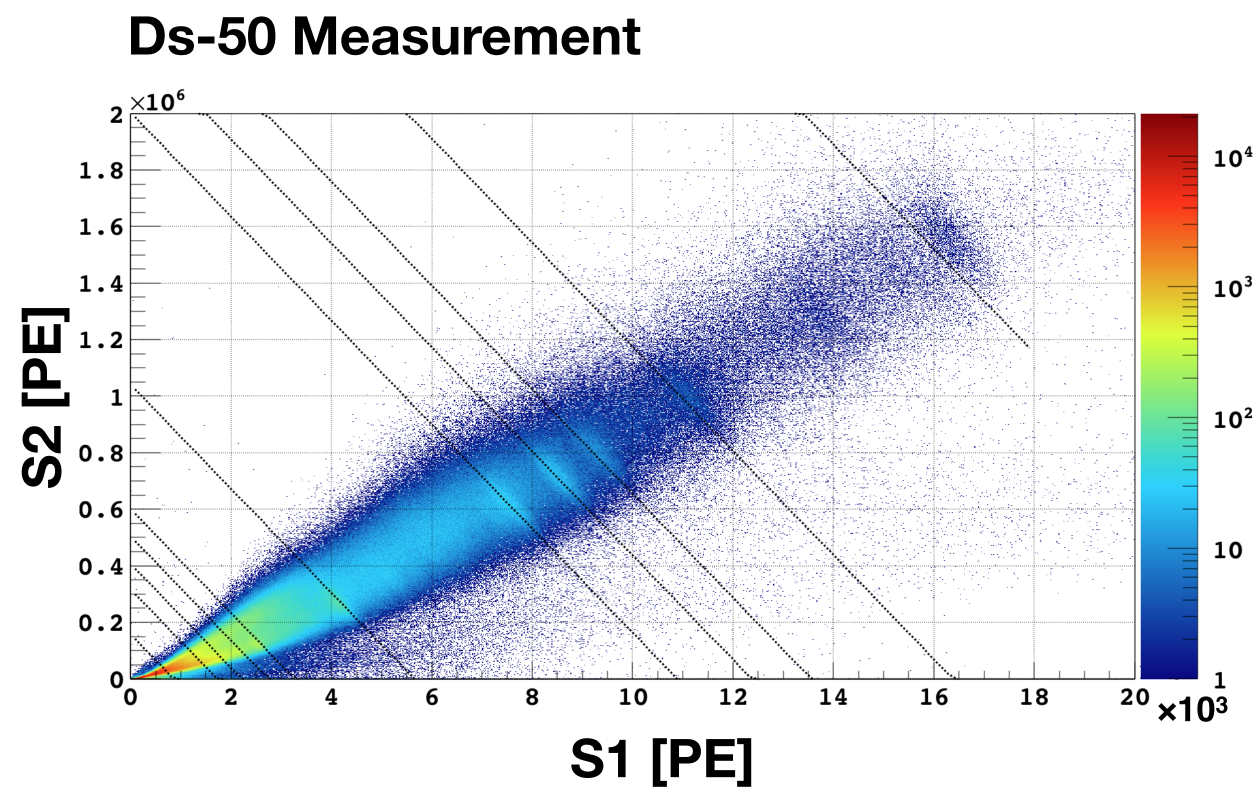
Exclusion sensitivity reach to the effective Majorana neutrino mass [arXiv:1710.05075]

SEARCH FOR NEUTRINO-LESS DOUBLE BETA DECAY IN DARKSIDE/ARGO

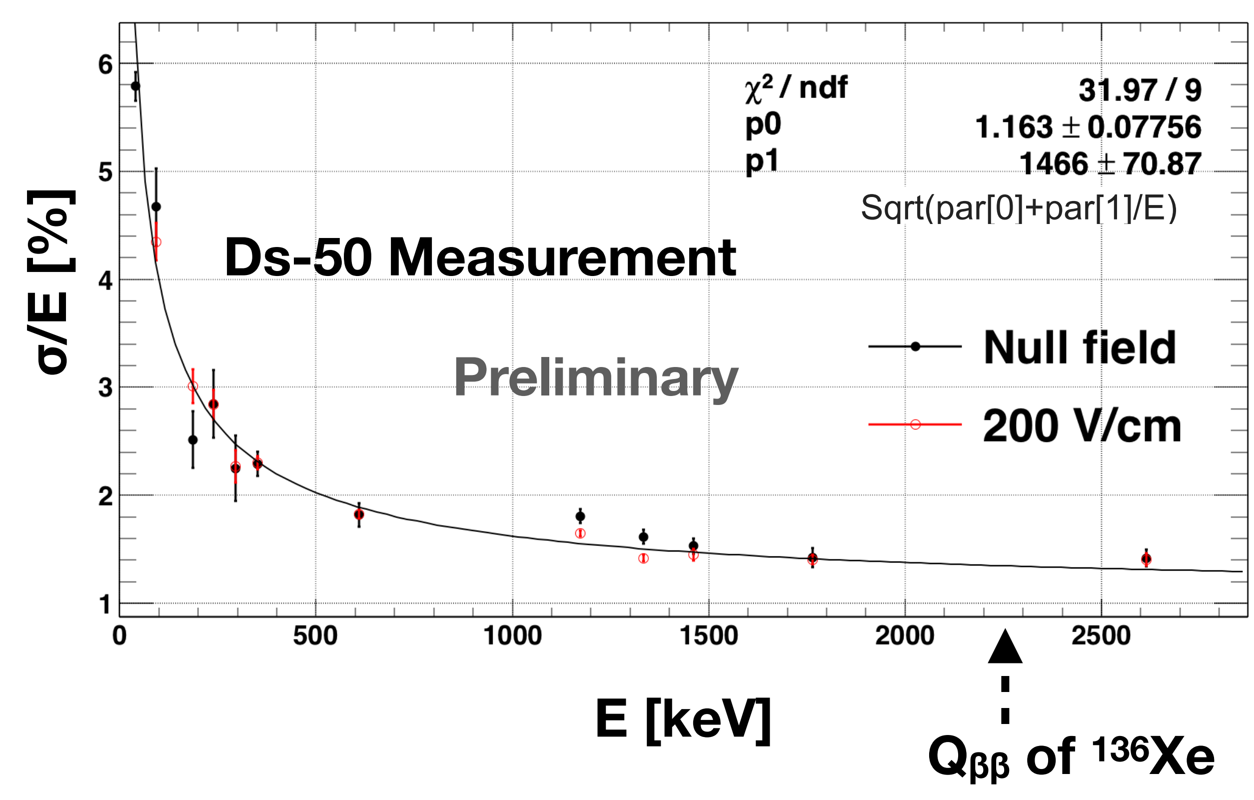
- Dope ^{136}Xe in UAr, use AAr as a veto and thermalizer.
- Energy resolution slightly better than EXO-200:
  - 3.5% FWHM at $Q_{\beta\beta}$ in DS-50 before any attempts at dedicated improvement.
- Much colder temperature colder induces background advantages:
  - Limited radon emanation and enabling of radon-suppression schemes;
  - SiPMs operating with dark current below traditional PMTs levels.
- Lighter target induces greater mean free path strengthening rejection of multi-sited events.
- **Possibility to use the same DarkSide-20k/Argo detector for ^{136}Xe for neutrino-less double beta decay searches after end of dark matter search campaign.**

ENERGY RESOLUTION

- Energy resolution at Q-value of neutrino less double beta decay of ^{136}Xe ($Q_{\beta\beta}$=2457.83 ± 0.37 keV) is important separate $0\nu\beta\beta$ from background.
- EXO-200 reached **σ=1.6%**⁕, **FWHM=3.7%** of energy resolution after long dedicated development.
- DS-50 reached **σ=1.5%**, **FWHM=3.5%** in absence of any fine tuning.
- Expect significant improvements (**FWHM<2%**) in future detectors from:
  - Higher light yield;
  - Greater S2 uniformity;
  - Better position corrections.



The energy is not corrected for nonlinear response of PMTs



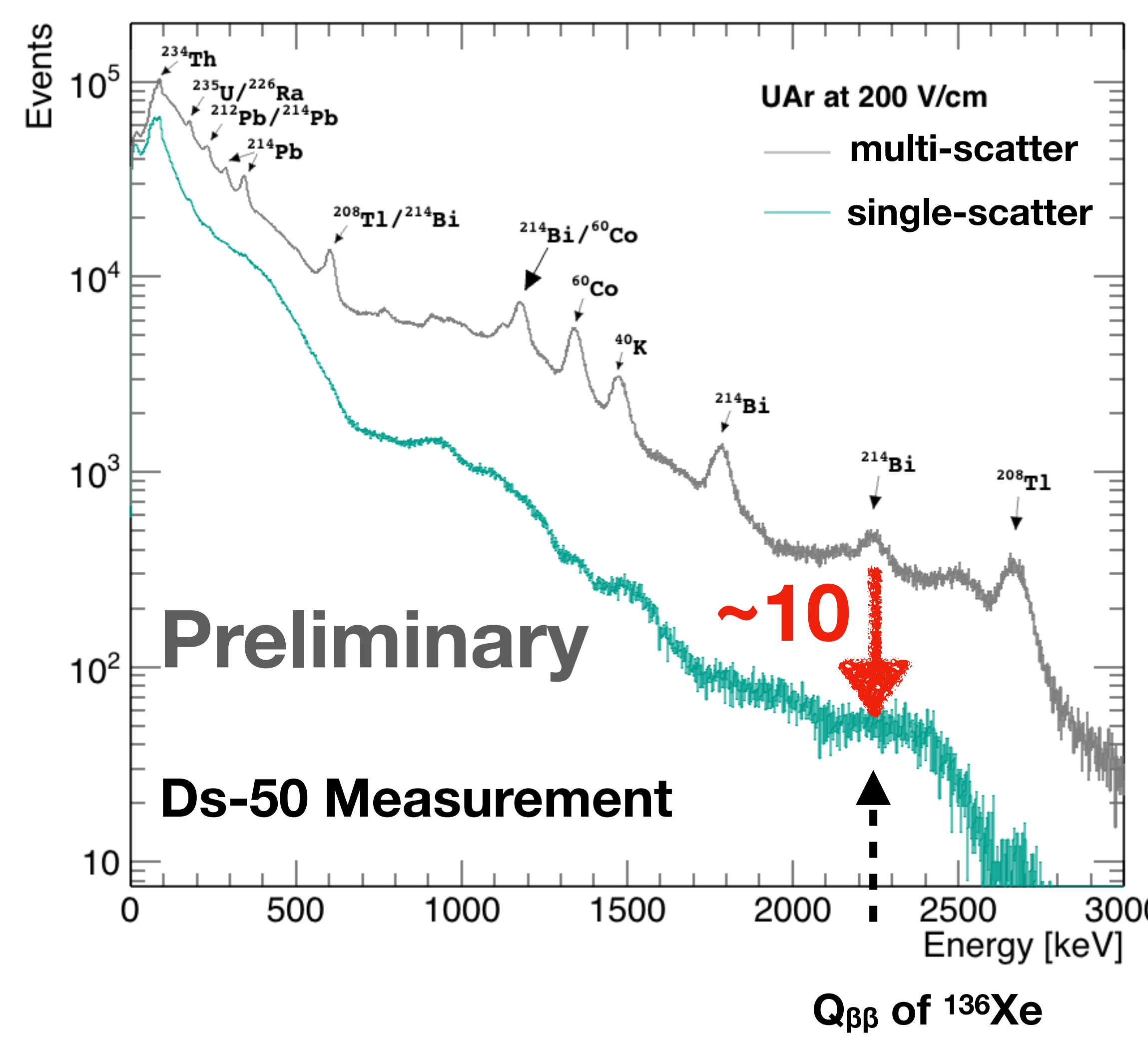
⁕ JINST 11 P07015 (2016)

MULTI SCATTERING

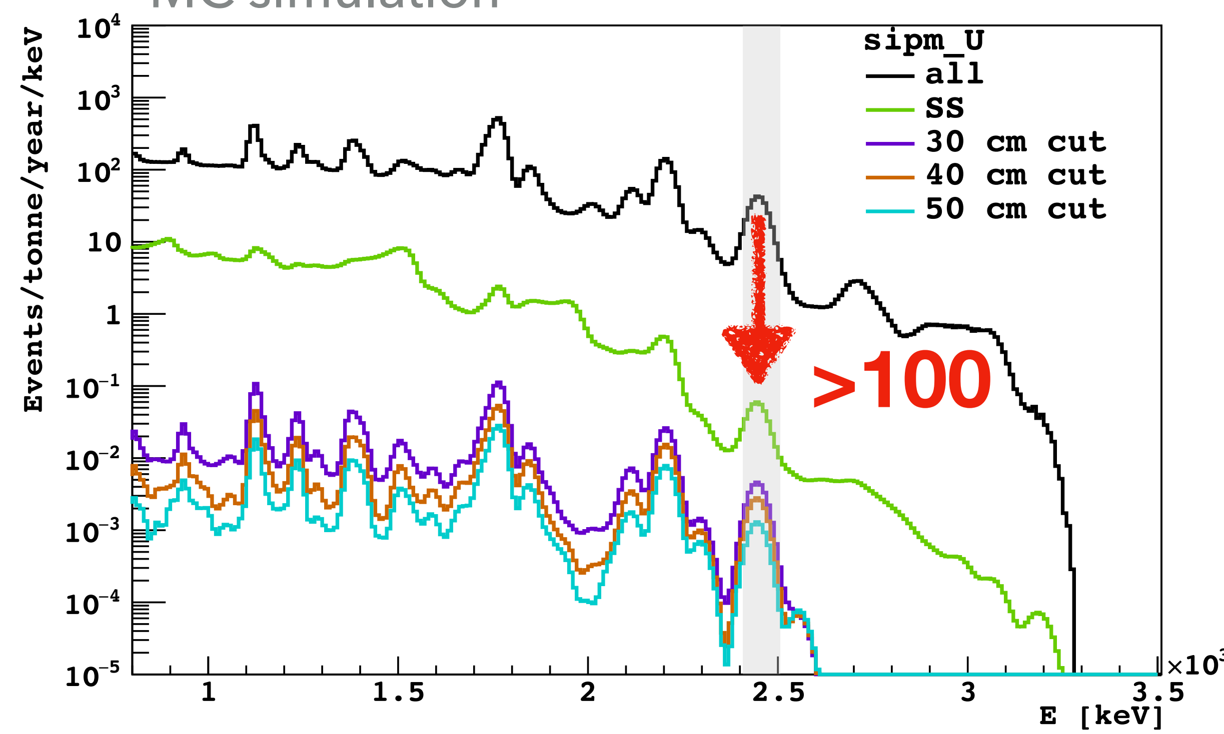
- EXO-200 achieved suppression factor of **2-5*** around $Q_{\beta\beta}$ of ^{136}Xe.
- Suppression factor of **~10** from single-scatter selection measured in DS-50.
- Larger suppression is expected in larger detector due to tighter fiducialization.
- Suppression even larger for key ^{214}Bi contaminant, expected up to **100**.

* Fig. 3 in Nature 510, 229-234 (12 June 2014)

The energy is not corrected for nonlinear response of PMTs



MC simulation



^{222}Rn CONTAMINATION LEVEL

- 2447 keV gamma line from ^{214}Bi (^{222}Rn daughter) is close to the expected 0νββ signal at 2457 keV. This is one of the most important backgrounds.
- Due to lower boiling temperature of argon than xenon, LAr is relatively easier to purify and eliminate Rn contaminations. **One order of magnitude better in LAr.**
- LAr
  - **0.18** μBq/kg in DEAP-3600 [PRL 121, 071801 (2018)]
  - **2.12** μBq/kg in DarkSide-50 [Phys. Rev. D 98 102006 (2018)]
- LXe
  - **6.57** μBq/kg in PandaX-II [Phys. Rev. D 93, 122009 (2016)]
  - **5-12** μBq/kg in XENON1T [Phys. Rev. Lett. 121, 111302 (2018)]
  - **66** μBq/kg in LUX [Phys. Procedia 61, 658 (2015)]
  - **3.65** μBq/kg in EXO-200 [Phys. Rev. C 92 015503 (2015)], and nEXO assumed to have 3 times more total abundance, **0.33** μBq/kg

BACKGROUND

- **Neutrino**
  - Irreducible BG. ν-e scatterings from solar neutrinos. If this rate is too high, this is a disadvantage.
- **2νββ tail**
  - Irreducible BG. Need a good resolution. Could be better than nEXO (~1%), but not compared to LEGEND (~0.1%).
- **Cosmogenic activation of Ar and Xe**
  - Depends on muon flux (the depth of underground lab).
  - If the decay time is short, could be vetoed.
  - A possible disadvantage of LAr-Xe compared to nEXO, which has less mass to be activated.

BACKGROUND

- **Internal**
  - Radon daughters, especially ^{214}Bi
    - Emanation from internal surfaces and gas circulation system.
    - Suppressed by Bi-Po tagging. (^{214}Po half life is 1.63 μs)
    - ^{214}Bi in non-active UAr volume in TPC is dangerous, but suppressed by single scatter and fiducial cuts. Depending on geometry and not included here.
  - ^{42}Ar (daughter ^{42}K is β-emitter with 3.5 MeV endpoint)
    - Expected to be small in UAr. Although in DS-50 we don't observe it, it is not sensitive enough.
- **External** (detector components)
  - Using LAr as a veto.
  - Our advantage thanks to longer mean free path of LAr.

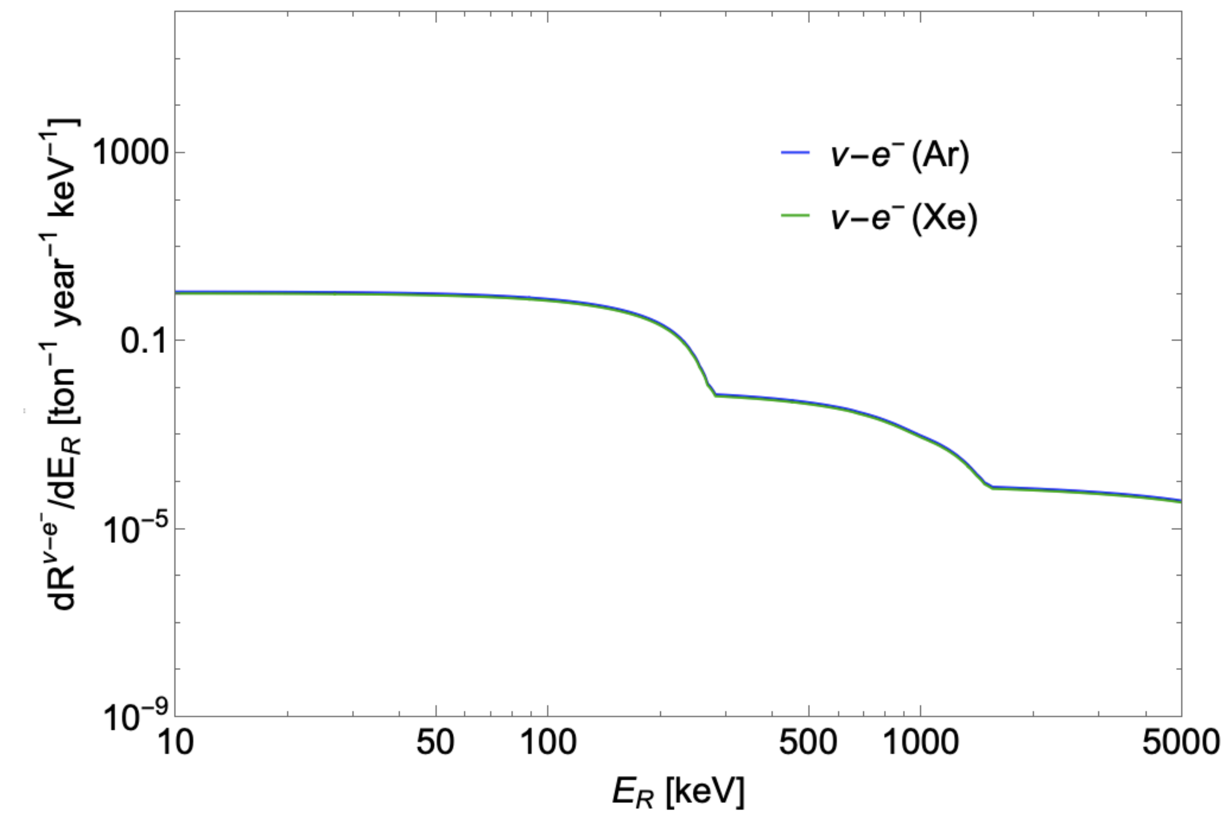
SETUP

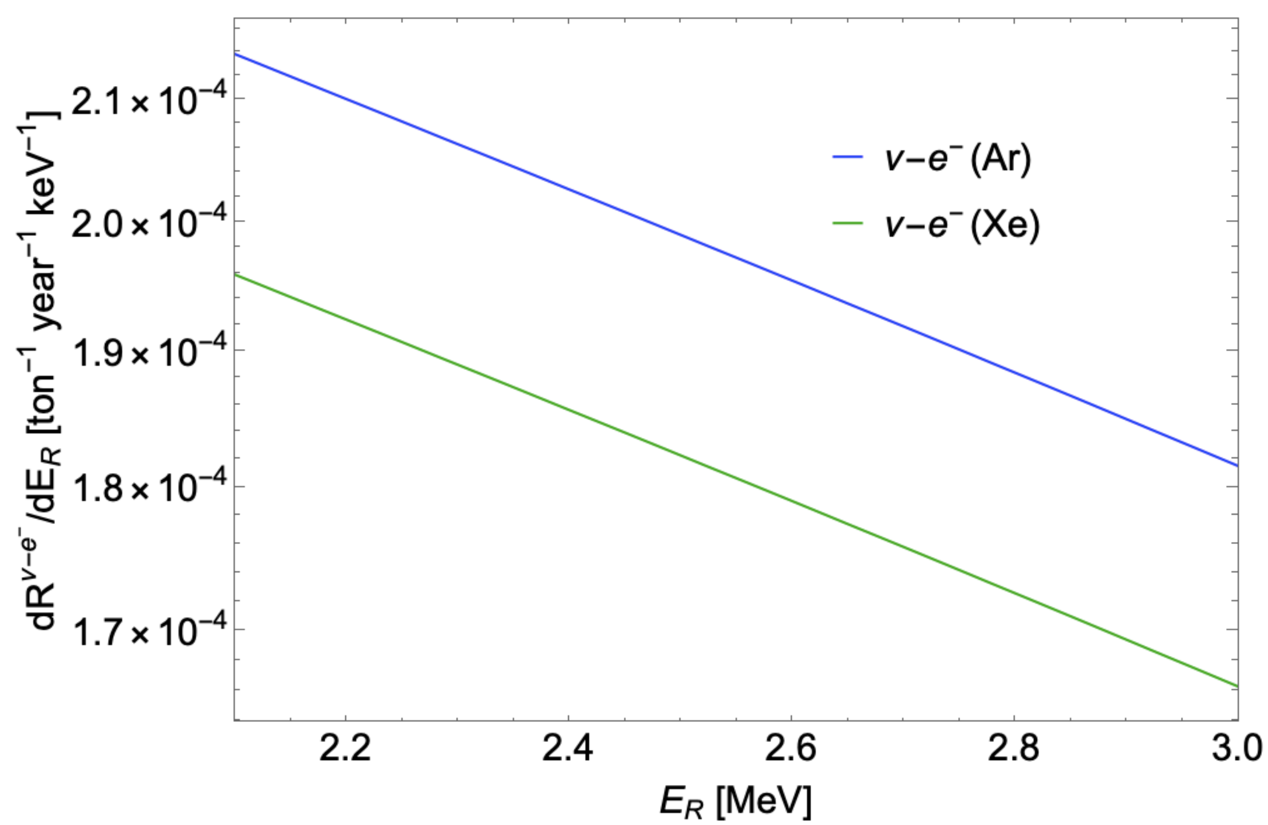
- Run time: 5 years
- ^{136}Xe concentration: 90%
- Xe doping fraction: 3%
- Energy resolution: 1%, ROI is from 2.4 to 2.5 MeV ($\pm 2\sigma$ from $Q_{\beta\beta}$)
- Total mass 377 tonne (10.2 tonne of ^{136}Xe)
- Location is SNOLAB (3.1×10^{-6} μ/m^2/s) instead of LNGS (3×10^{-4} μ/m^2/s)

NEUTRINO

From Matteo C. and Emmanuele P. @ INFN Cagliari

- ν-e scattering
- Main contribution is from solar neutrinos.
- Coherent elastic ν-N scattering is several orders smaller. Ignored
- Ar: 0.020 counts/ton/yr, Xe: 0.018 counts/ton/yr in ROI.
- In ROI, ~**30** events from Ar, **1** events from Xe with 1500 t yr and 50 t yr, respectively.





$2\nu\beta\beta$

- Due to energy resolution, the tail of $2\nu\beta\beta$ spectrum contaminates ROI.
- With 1% energy resolution, the fraction of events in ROI over total is 3.5×10^{-8}.
- Given $T_{1/2}^{2\nu\beta\beta} = 2.165\times10^{21}$ years, 1.34×10-3 event / t yr in ROI.
- With 1500 t yr, it is ~2 events.

NOTE: ^{136}Xe $2\nu\beta\beta$ spectrum was generated with https://github.com/BxCppDev/bxdecay0

COSMOGENIC ACTIVATIONS

- **^{137}Xe in Xe**
  - The activation rate, 2.2×10-3 atoms/kg/yr, is taken from nEXO paper arXiv: 1710.05075 p.8.
  - ^{137}Xe events are simulated and gives 1.38 events (7.33×10^{-4} event / t yr) in ROI.
- **Activation in LAr** at LNGS was studied by D. Franco et. al. in arXiv:1510.04196 *.
  - Activities are scaled down by the muon flux difference between LNGS ($3\text{x}10^{-4}$ μ/m^2/s) and SNOLAB ($3.1\text{x}10^{-6}$ μ/m^2/s).
  - Only selected Isotopes: ^{6}He, ^{28}Al, ^{34}P, ^{37}S, ^{38}Cl, ^{39}Cl, ^{40}Cl, and ^{41}Ar based on activities, are considered.
  - The fraction in ROI is estimated by approximating each beta spectrum with flat spectrum from 0 to its endpoint.
  - Total events are 9 events (4.8×10^{-3} event / t yr) in ROI. Most dominant contribution comes from ^{38}Cl (39%).

* The correction factor of 2 claimed in arXiv:1811.07912 is applied.

INTERNAL BG

- Rn daughters, especially ^{214}Bi has a γ-line at 2448 keV, which is only 10 keV smaller than $Q_{\beta\beta}$=2458 keV.
- It is dangerous, however, could be tagged by Bi-Po. This tagging efficiency is estimated by acquisition window size. Inefficiency is estimated as 1.27×10^{-7}.
- ^{222}Rn contamination level 0.18×10^{-6} Bq/kg from DEAP-3600 is assumed and scaled with surface areas of DEAP and Argo.
- ^{214}Bi decays are simulated uniformly in TPC volume and applied single scatter and fiducial cut.
- With SS + 30 cm fiducial cut, there is about 2.88 event/t yr.
- With Bi-Po tag, it becomes 3.66×10^{-7} event/t yr (5×10^{-4} events).
- Rn daughter decays in dead volume is ignored for now. Need to be studied once the geometry is determined.
- ^{42}Ar (^{42}K) contribution is ignored for now.

EXTERNAL BG

- Detector components: Acrylic vessel and SiPMs are simulated.
- Only ^{214}Bi from ^{238}U chain, ^{208}Tl from ^{232}Th chain, and ^{60}Co are simulated.

Activities	$^{238}U_{low}$	^{232}Th	^{60}Co
Acrylic [µBq/kg]	3.7	5.3	5.3
SiPMs [µBq/PDM]	171.3	139.9	21.7

Events in ROI

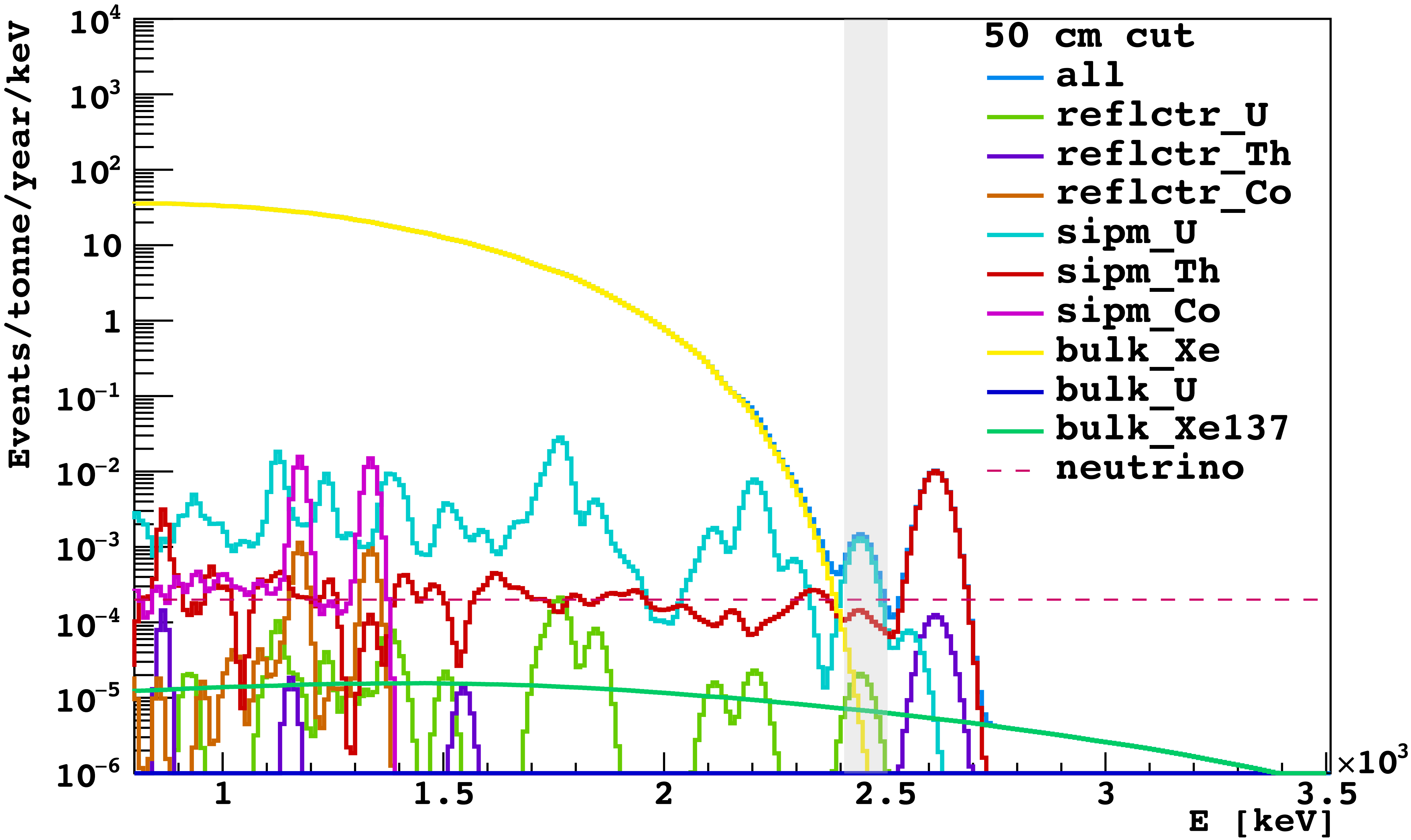
Fiducial cut	30 cm	40 cm	50cm
Acrylic [evt/t/yr]	5.0×10^{-3}	3.2×10^{-3}	1.2×10^{-3}
SiPMs [evt/t/yr]	0.31	0.19	9.0×10^{-2}

Total ~100 events in ROI

DOUBLE BETA DECAY IN ARGO

- At expected 2.3% FWHM, background-free condition would require background index of:
  - 10^{-5} events/(tonne*×year×keV)
- Limiting factors:
  - Uranium, Thorium in SiPMs-based PDMs
    - Still relevant background at current purity levels. Can be suppressed by factor 10÷100 using light guides à la DEAP-3600;
    - I propose that AstroCent play a leading role in developing ultra-clean PDMs for neutrino less double beta discovery.
- ν-e scattering of ^{8}B solar neutrinos
  - Irreducible background at 10^{-4} events/(tonne×year×keV)
  - Constraint can be relaxed by improving energy resolution

* fiducial volume of Xe



Events/tonne/year/keV
10^4
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
1
1.5
2
2.5
3
3.5
$\times 10^3$
E [keV]
50 cm cut
all
reflctr_U
reflctr_Th
reflctr_Co
sipm_U
sipm_Th
sipm_Co
bulk_Xe
bulk_U
bulk_Xe137
neutrino

SUMMARY

- The largest BG contribution is from SiPM. One order higher than the other contributions. Ultra-pure SiPM based module and ways to reduce its contribution are necessary.

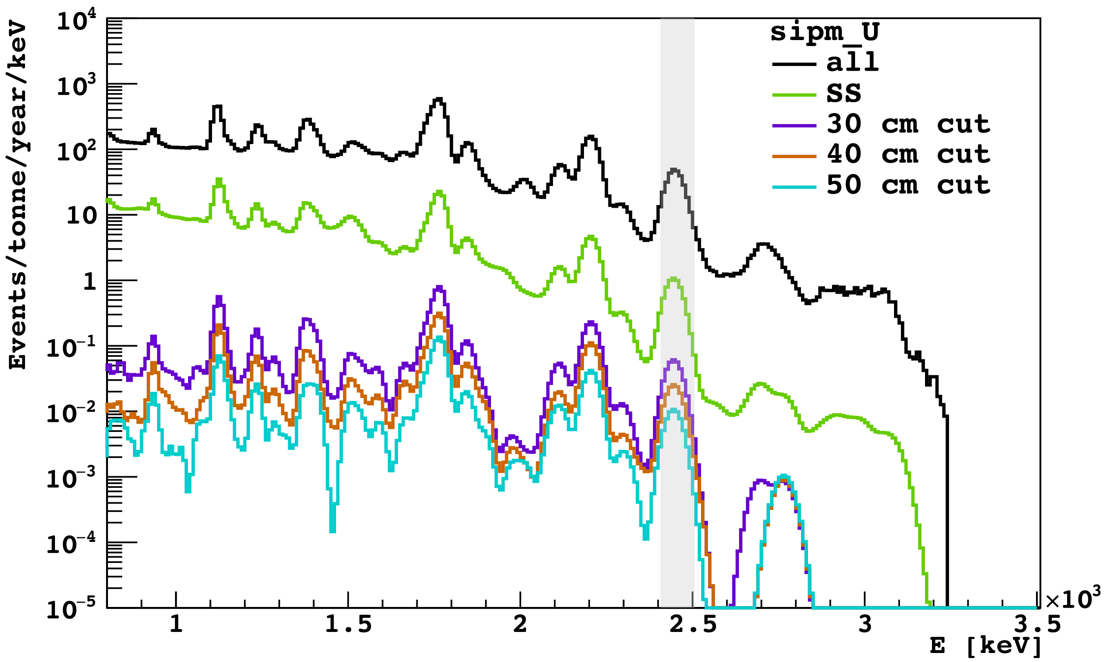
- Solar neutrino is the second largest contribution. LAr fraction need to be reduced.

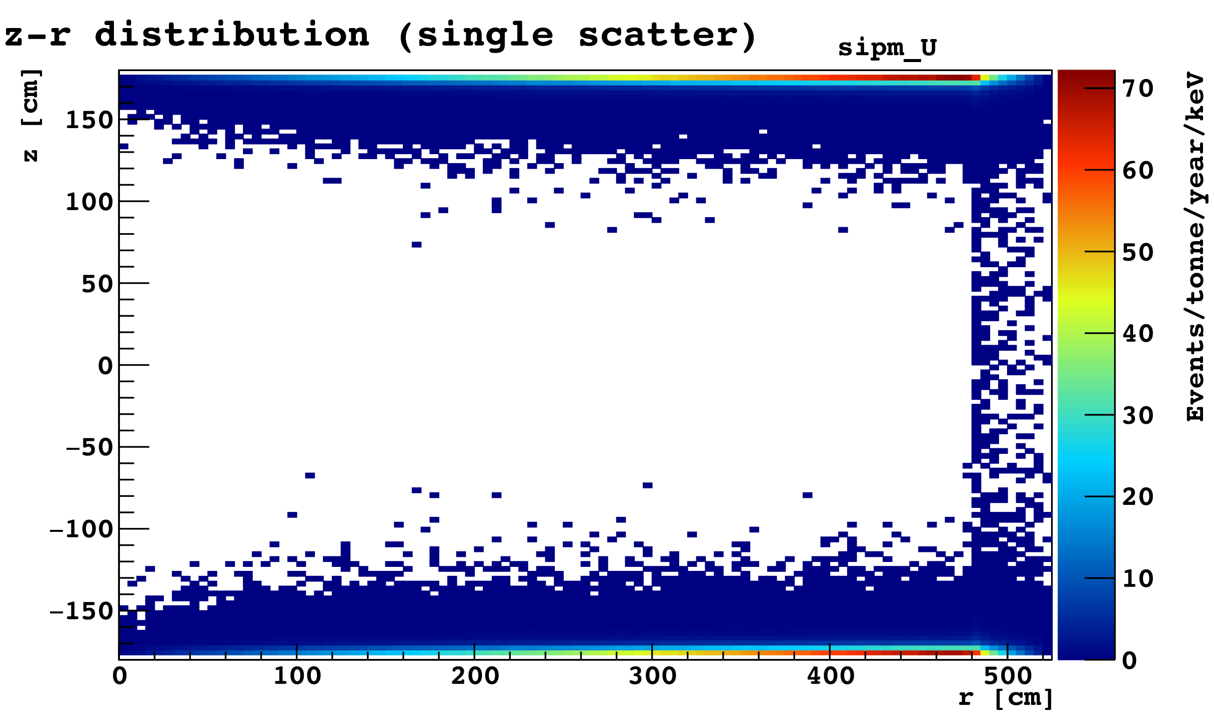
- Currently, the sensitivity is the same order of magnitude as nEXO.

Components \ Fiducial cut	30 cm	40 cm	50cm
Acrylic	5.0E-03	3.2E-03	1.2E-03
SiPMs	0.31	0.19	0.09
$2\nu\beta\beta$	1.3E-03	1.3E-03	1.3E-03
^{222}Rn w/ Bi-Po tag	3.7E-07	3.6E-07	3.6E-07
Cosmogenic (^{137}Xe)	7.4E-04	7.4E-04	7.4E-04
Cosmogenic in LAr	4.8E-03	4.8E-03	4.8E-03
neutrino	0.02	0.02	0.02
Total [evt/t/yr]	**0.34**	**0.22**	**0.119**

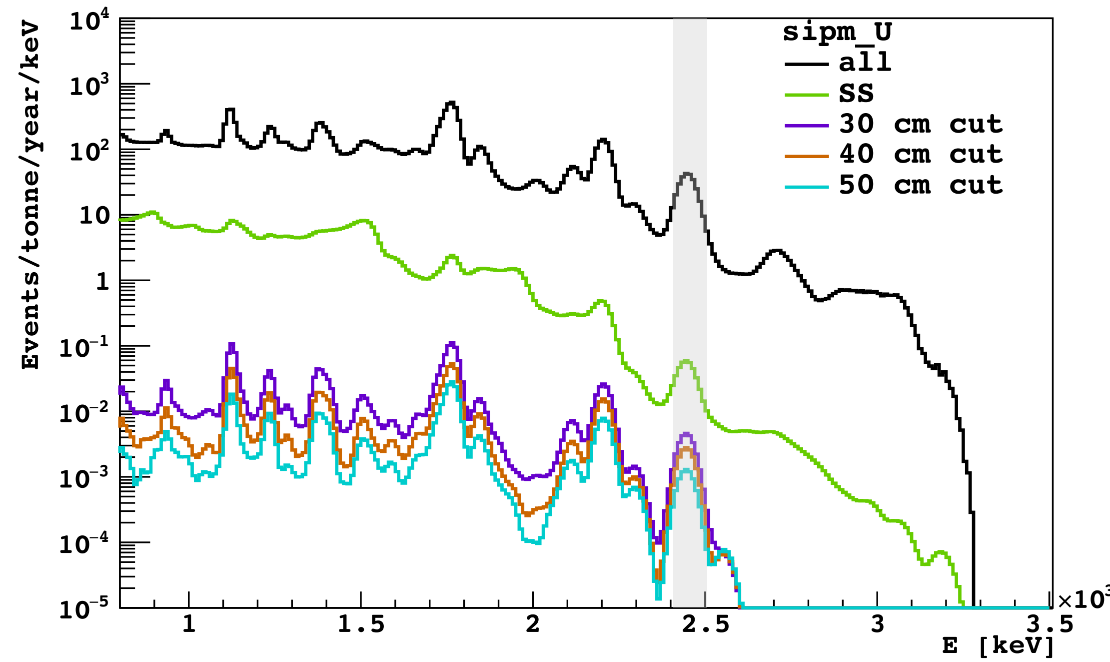
NOTE: The volume is LAr volume

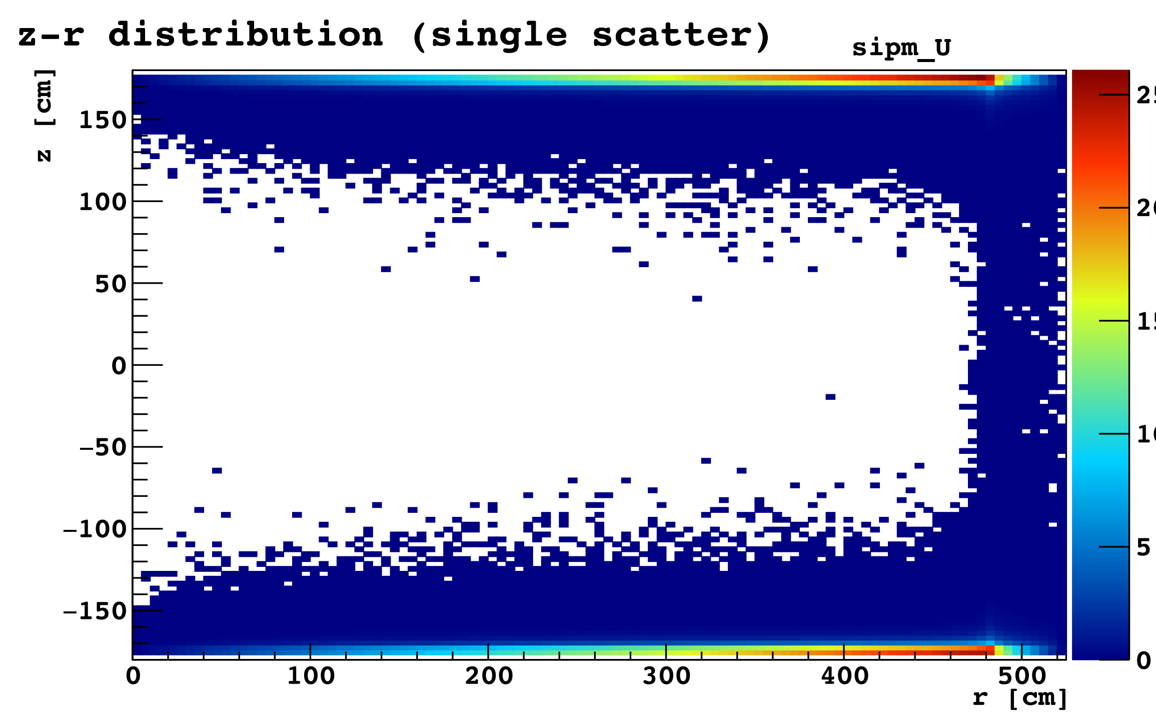
50%–50%





3% Xe





- Higher Xe fraction weaken SS cut efficiency.
- Self-shielding is not strong enough to recover the efficiency loss.