Geant4 based simulations of backgrounds in the CRESST experiment

VIEWS24 | Vienna, Austria | 22.04 – 27.04.2024

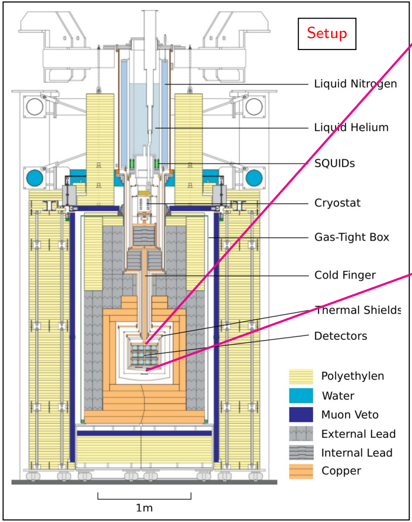
Samir Banik | TU Wien, HEPHY

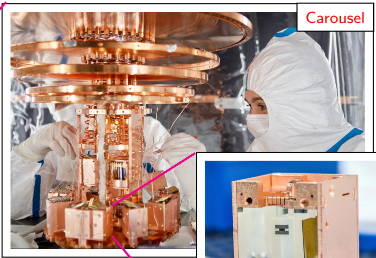
– on behalf of the CRESST collaboration

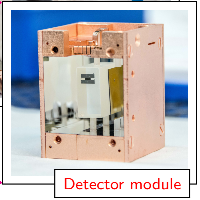
The CRESST experiment

Cryogenic **R**are **E**vent **S**earch with **S**uperconducting **T**hermometers

- Located at LNGS in Italy
- Protected behind layers of passive shielding and an active muon veto

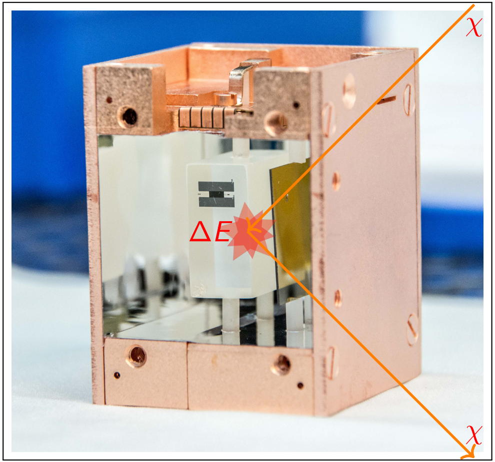






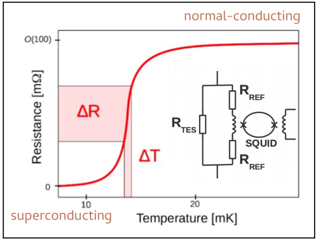
- Detector modules mounted inside "carousel" and cooled down to $\sim$10 mK

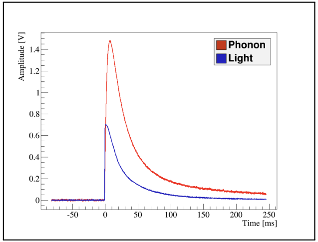
Detection principle

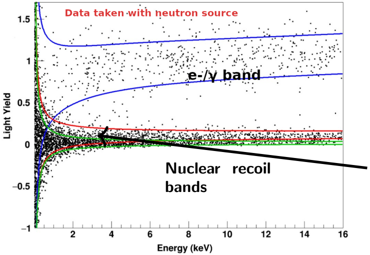


- Main absorber: $CaWO_4$ (traditionally used), Al_2O_3, Si, $LiAlO_2$
- Light detector for background discrimination

$$\Delta E \longrightarrow \Delta T \longrightarrow \Delta R \longrightarrow \Delta V$$



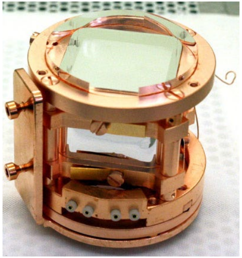




DM expected in the nuclear recoil band

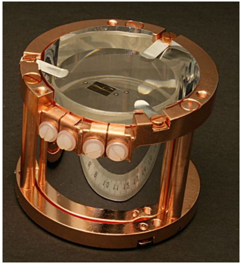
CRESST detectors in different runs

Run 33



TUM40
Mass: 246.2 g
Exposure: 129.9 kg-d
Threshold: 603 eV

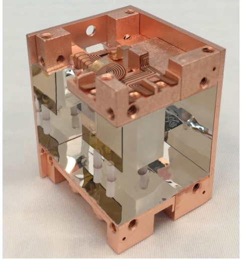
10.1140/epjc/s10052-014-3184-9



Lise
306 g
159 kg-d
306.7 eV

10.1140/epjc/s10052-016-3877-3

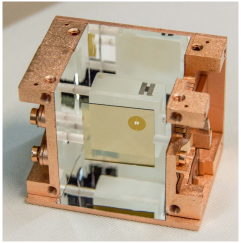
Run 34



Detector A
23.6 g
5.7/2.5/5.5 kg-d
30.1 eV

10.1103/PhysRevD.100.102002, media-tum.ub.tum.de/1393806,10.34726/hss.2021.45935

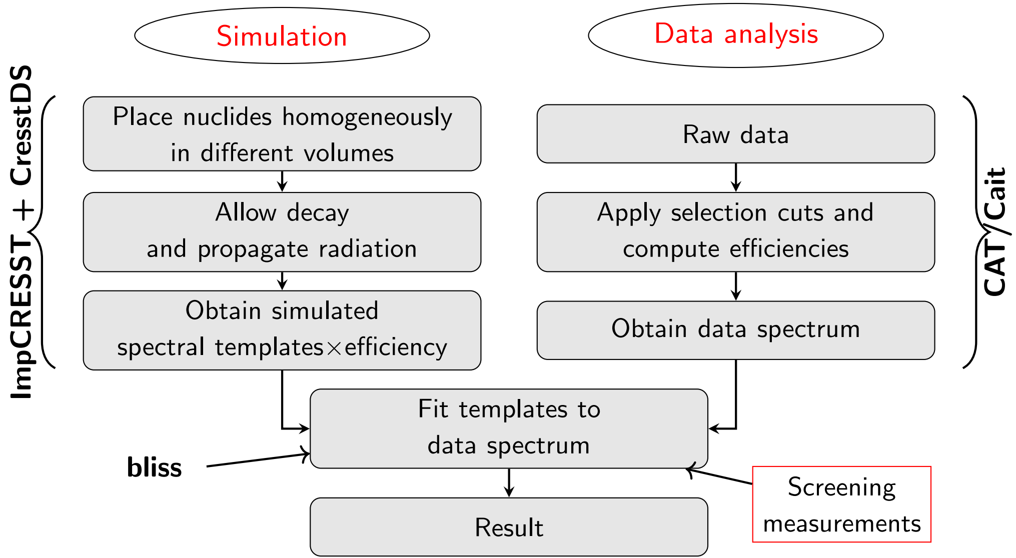
Run36



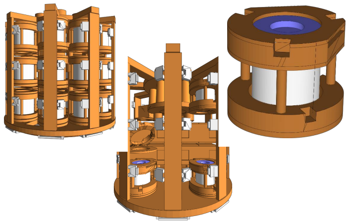
TUM93A
24 g
3.7/8.8 kg-d
54 eV

10.21468/SciPostPhysProc.12.013

How we develop a background model



ImpCRESST and CresstDS for simulation



Eur. Phys. J. C79 (2019) 881.

- We developed "ImpCRESST"- a software based on GEANT4 to model backgrounds, and "CresstDS" to apply energy and time resolution to the simulated data
- Plans to be published in open source
- Some notable features are:
  - Atomic and nuclear physics optimised for accuracy, especially below the MeV-scale
  - A flexible and extendible handling of experimental geometries
  - Recording of data in ROOT files with a structured layout
  - Interface for reading CAD files
  - Interfaces to MUSUN, SOURCES4, and CRY
  - Usable in HPC environments via 'containers' produced with Git CI/CD pipeline

bliss for likelihood fit

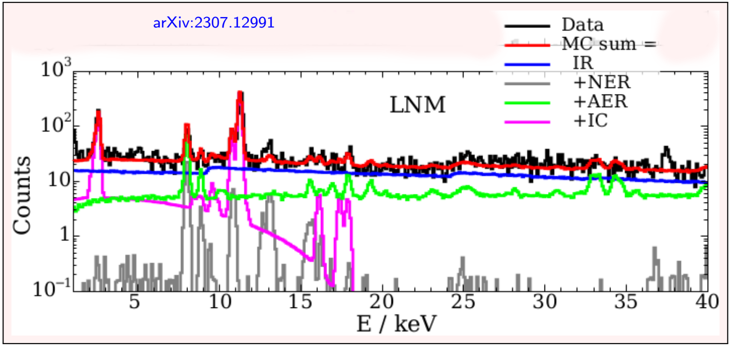
Posterior, Likelihood, Prior, Observations, Parameters (activities)

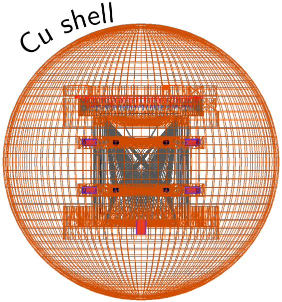
$$p(\boldsymbol{\vartheta}|\boldsymbol{y}) = \frac{\mathcal{L}(\boldsymbol{y}|\boldsymbol{\vartheta}) \cdot \pi(\boldsymbol{\vartheta})}{\int_{\Theta} \mathcal{L}(\boldsymbol{y}|\boldsymbol{\vartheta}') \cdot \pi(\boldsymbol{\vartheta}')\, \mathrm{d}\boldsymbol{\vartheta}'}$$

- **bliss:** Bayesian likelihood normalisation of spectral templates
- Based on the Bayesian Analysis Toolkit, using MCMCs and the Metropolis-Hastings algorithm to determine activities of radioactive contaminants
- Multi-template fit that can handle hundreds of spectral templates and many detectors simultaneously
- Internal handling of efficiencies and optional secular equilibrium
- Easy to use via macro files
- Plans to make 'bliss' public

First CRESST likelihood-fit based background model

TUM40 module with $CaWO_4$ as target crystal of Run 33





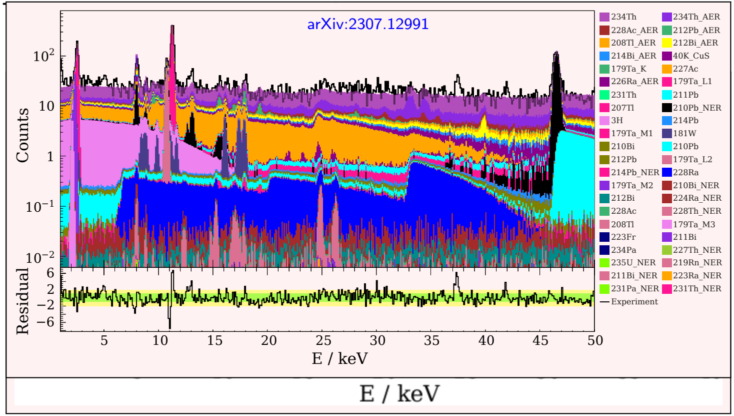
Visualisation of the module as implemented in Geant4

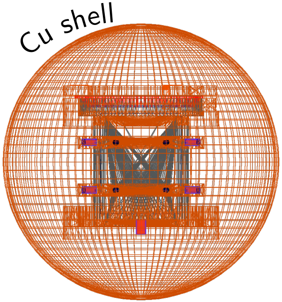
Heaviside step function — Central p-value — Nominal significance level

$$\mathrm{EP} = \frac{\sum_{j=1}^{n_{\mathrm{bin}}} \Theta(p_c(n_j;\,\nu_j) - \alpha)\cdot n_j}{\sum_{j=1}^{n_{\mathrm{bin}}} n_j}$$

- A spherical shell approximation for Cu parts
- Performed a Bayesian extended binned log-likelihood fit of the templates to the data
- We can explain ~83% of the observed background above 1 keV

First CRESST likelihood-fit based background model





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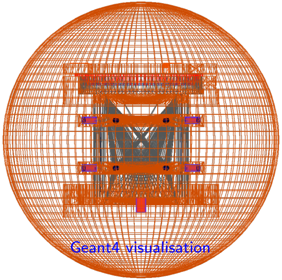
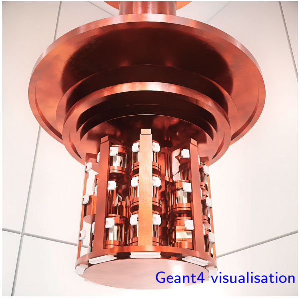
Run 33 extended background model

Simultaneous fit of TUM40 and Lise modules



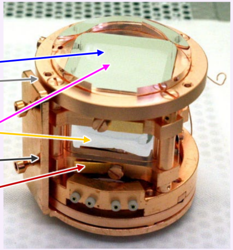
→



- From a single detector module → extended geometry (until cryostat shield)

- 5.6 billion events simulated
- 226 templates per detector

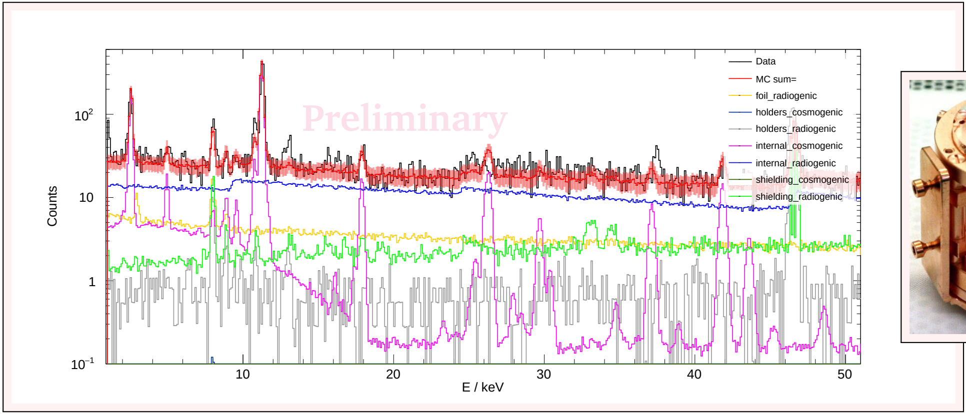
  Bulk contaminations:
  - 46 internal radiogenic (IR)
  - 46 holders radiogenic (HR)
  - 46 shielding radiogenic (SR)
  - 46 foil radiogenic (FR)
  - 27 internal cosmogenic (IC)
  - 7 holders cosmogenic (HC)
  - 7 shielding cosmogenic (SC)
  - 1 bronze cosmogenic (BC)
- 110+ years CPU time

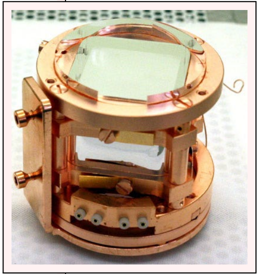


- More radioactive sources: 108 → 226 spectral templates

Run 33 extended background model

TUM40 results

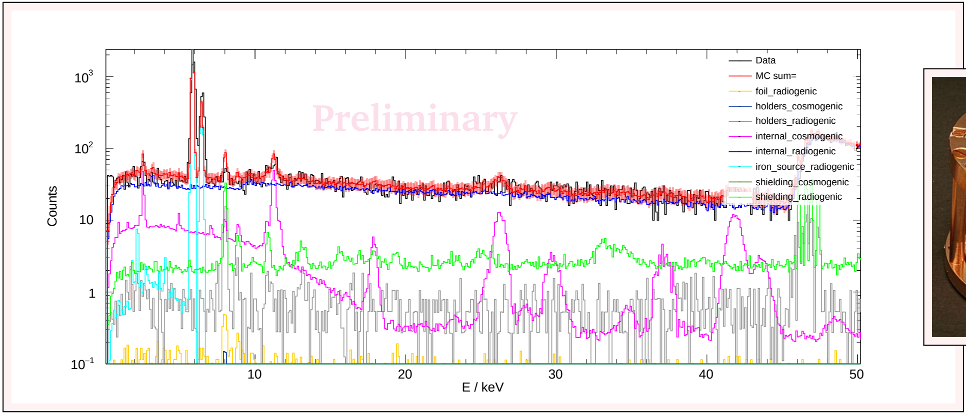


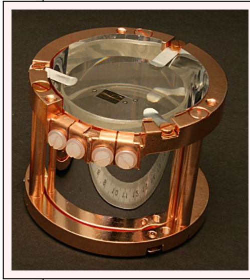


- Majority of background from internal contamination
- Explainable percentage (EP) = 90.5%

Run 33 extended background model

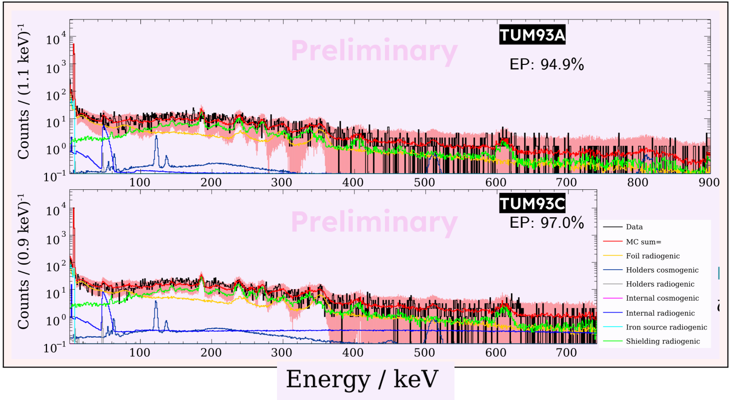
Lise results

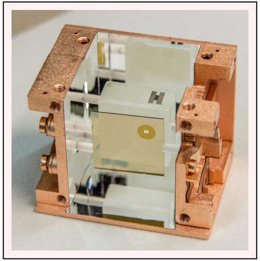




- Explainable percentage (EP) = 86.0%

Run 36 extended background model





- Highly radiopure crystal with limited statistics in the data
- The fitting is challenging due to the limited number of features in the spectrum
- Geant4 is validated for energies above ∼250 eV, necessitating reliable energy loss simulation in the low-energy range

Not only background model!

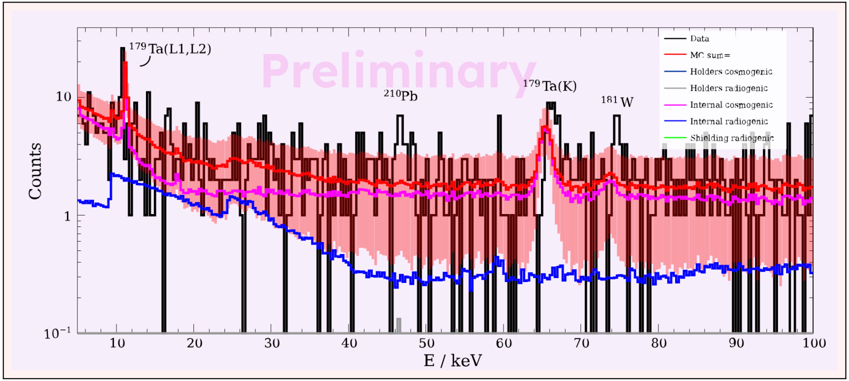
- Surface contamination including different roughness - See talk by **C. Grüner**
- **ELOISE** - Reliable background simulation at sub-keV energies - See talk by **H. Kluck**
- 55Fe source simulation (different runs, different geometries, occurring peaks etc)
- Cosmogenic activation of crystals
- Extended background models (more materials, different targets etc)
- Study new detector modules design for future Runs
- Extensive screening campaign

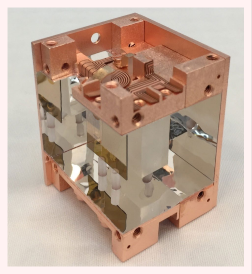
Thank you!


FACULTY OF MATHEMATICS,
PHYSICS AND INFORMATICS
Comenius University
Bratislava
CRESST

Run 34 extended background model

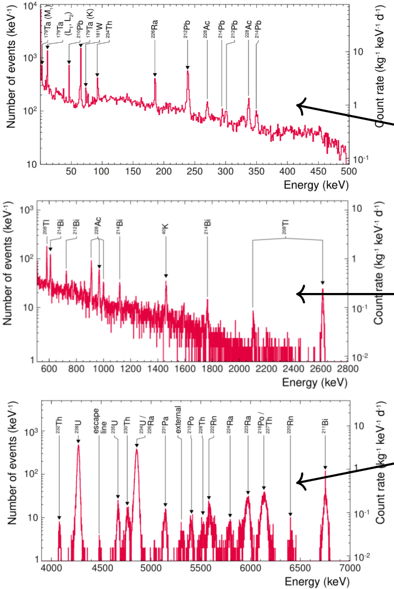
Detector A



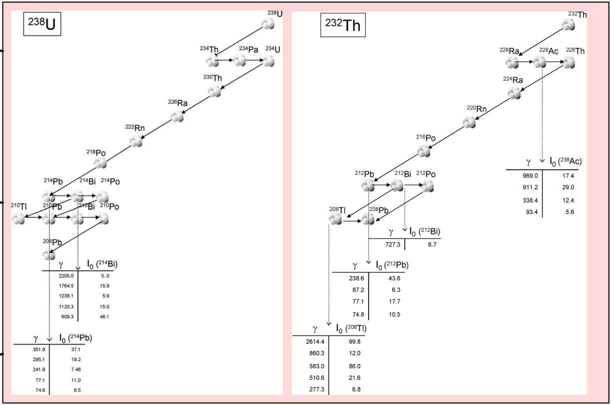


- Limited energy range up to 500 eV; extension of the range in progress with "saturation" fit technique
- Work in progress to include many spectral templates from carousel which are missing in the current fit; high statistics simulations to be done

Internal Radiogenic backgrounds



Naturally occuring decay chains in the crystal produce α and γ peaks in the spectrum.



Internal Cosmogenic backgrounds

$$^{182}\mathrm{W} + \mathrm{p} \longrightarrow {}^{179}\mathrm{Ta} + \alpha$$

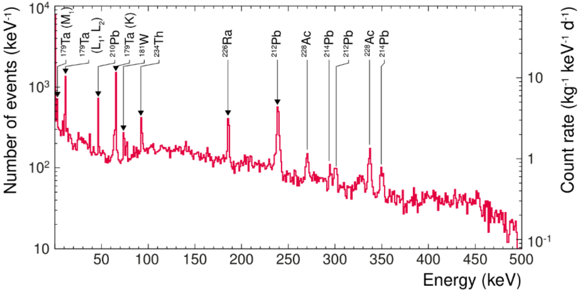
$$\hookrightarrow {}^{179}\mathrm{Ta} + \mathrm{e}^- \longrightarrow {}^{179}\mathrm{Hf}^* + \upsilon_e$$

$$\hookrightarrow {}^{179}\mathrm{Hf} + \text{X-ray}.$$

$$^{183}\mathrm{W} + \mathrm{p} \longrightarrow {}^{181}\mathrm{W} + {}^{3}\mathrm{H}$$

$$\hookrightarrow {}^{181}\mathrm{W} + \mathrm{e}^- \longrightarrow {}^{181}\mathrm{Ta}^* + \upsilon_e$$

$$\hookrightarrow {}^{181}\mathrm{Ta} + \gamma + \text{X-ray}.$$



- The activation of ^{182}W in $CaWO_4$ leads to several peaks in the spectrum
- ^{179}Ta ($T_{1/2}$ =1.82 yr) decay via EC with peaks at
  - 2.60 keV (M1 shell)
  - 10.74 keV (L2 shell)
  - 11.27 keV (L1 shell)
  - 65.35 keV (K shell)
- ^{181}W ($T_{1/2}$ =121.2 d) decay via EC with a peak at
  - 73.6 keV (=67.4 keV X-ray + 6.2 keV γ)
- ^{3}H beta-decay spectrum is also expected

Internal Cosmogenic backgrounds

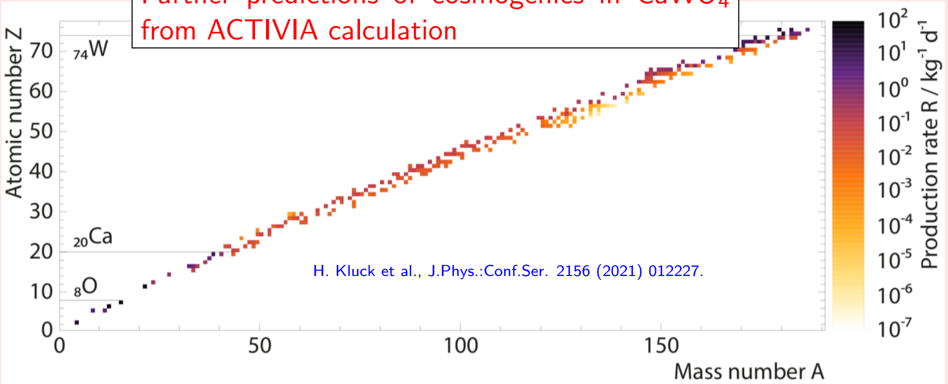
$^{182}W + p \longrightarrow {}^{179}Ta +$

$\hookrightarrow {}^{179}T$

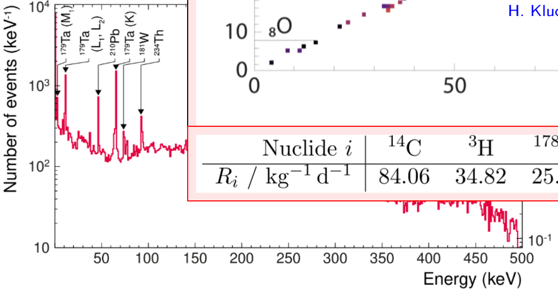
$^{183}W + p \longrightarrow {}^{181}W +$

$\hookrightarrow {}^{181}W$

Further predictions of cosmogenics in $CaWO_4$ from ACTIVIA calculation



Nuclide i	^{14}C	^{3}H	^{178}W	^{179}Ta	^{175}Hf	^{181}W	^{37}Ar	^{173}Lu	^{172}Hf	^{171}Lu
R_i / $kg^{-1}\,d^{-1}$	84.06	34.82	25.91	24.59	16.67	13.74	12.17	11.25	11.12	9.18



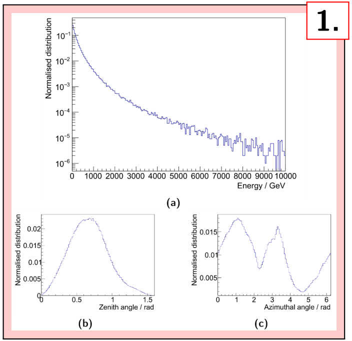
73.6 keV (=67.4 keV X-ray + 6.2 keV γ)

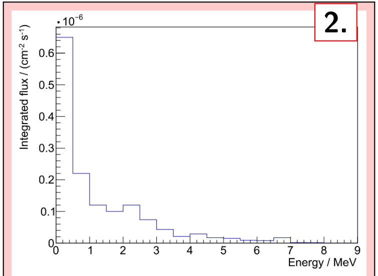
- ^{3}H beta-decay spectrum is also expected

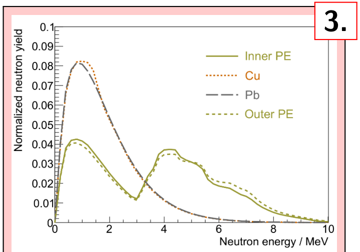
Neutron backgrounds

- Multiple sources

  1. Muon-induced neutrons,
  2. Ambient (α,n) + SF from LNGS rock,
  3. Internal (α,n) + SF neutrons.







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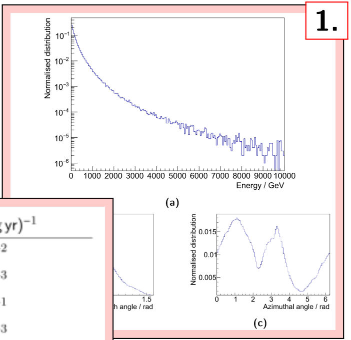

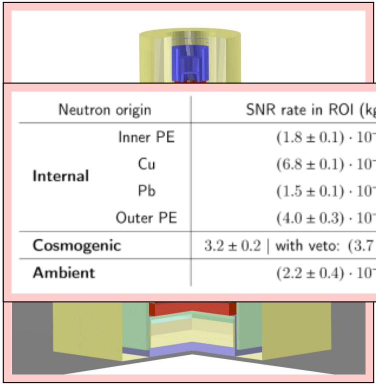

Neutron origin		SNR rate in ROI $(\text{kg yr})^{-1}$
Internal	Inner PE	$(1.8 \pm 0.1) \cdot 10^{-2}$
	Cu	$(6.8 \pm 0.1) \cdot 10^{-3}$
	Pb	$(1.5 \pm 0.1) \cdot 10^{-1}$
	Outer PE	$(4.0 \pm 0.3) \cdot 10^{-3}$
Cosmogenic		3.2 ± 0.2 | with veto: $(3.7 \pm 2.6) \cdot 10^{-2}$
Ambient		$(2.2 \pm 0.4) \cdot 10^{-1}$