

CRESST

Cryogenic Rare Event Search
with Superconducting Thermometers

>Extension of the Geant4 based
Electromagnetic Background Model
of CRESST-II and CRESST-III

Jens Burkhart on behalf of
the CRESST collaboration

>29.08.23, TAUP 2023, Vienna



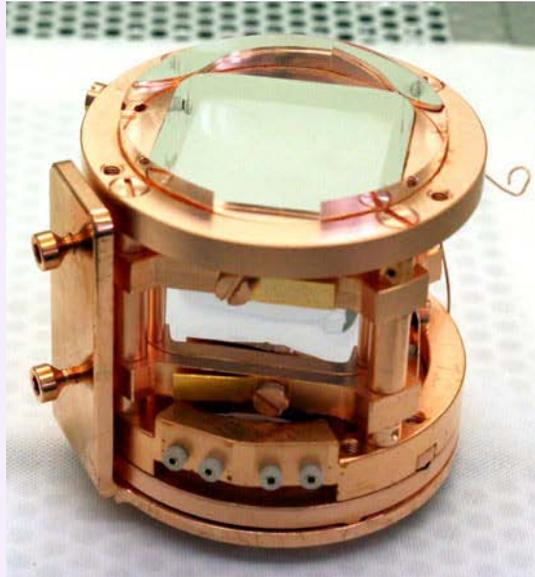
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TÜBINGEN

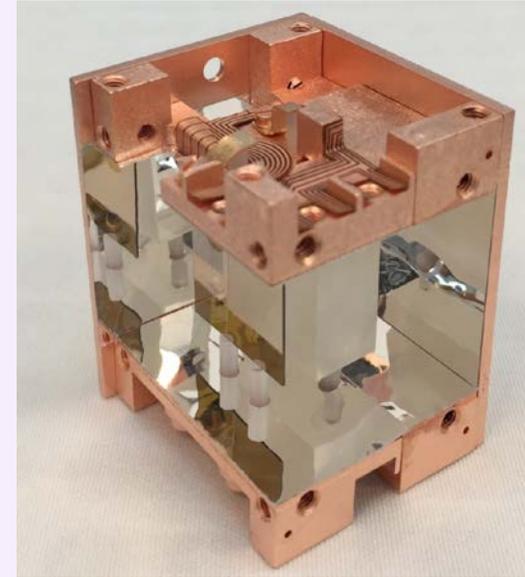


Detector modules

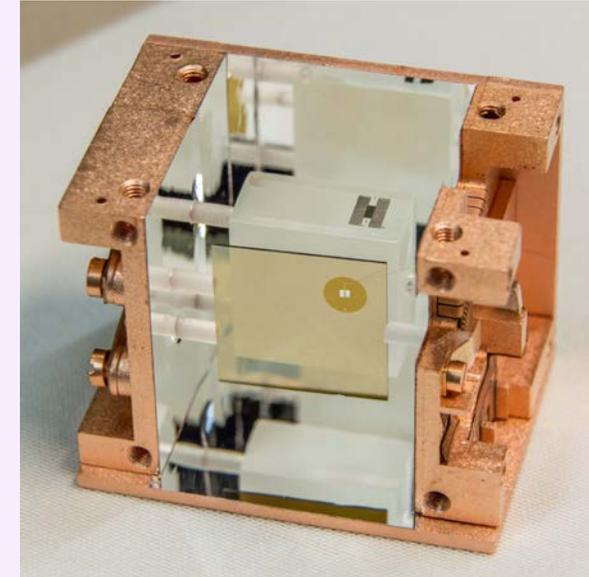
Run33



Run34



Run36
(ongoing)



TUM40

Mass 246.2 g

Exposure(s) 129.9 kg d

Threshold 603 eV

[10.1140/epjc/s10052-014-3184-9](https://arxiv.org/abs/10.1140/epjc/s10052-014-3184-9)

Lise

306 g

159 kg d

306.7 eV

[10.1140/epjc/s10052-016-3877-3](https://arxiv.org/abs/10.1140/epjc/s10052-016-3877-3)

Detector A

23.6 g

5.7/2.5/5.5 kg d

30.1 eV

[10.1103/PhysRevD.100.102002](https://arxiv.org/abs/10.1103/PhysRevD.100.102002),
[mediatum.ub.tum.de/1393806](https://arxiv.org/abs/10.34726/hss.2021.45935),
[10.34726/hss.2021.45935](https://arxiv.org/abs/10.34726/hss.2021.45935)

TUM93A/C

24 g

3.7/8.8 / 4.9/8.2 kg d

54 / 73.6 eV

[10.21468/SciPostPhysProc.1.2.013](https://arxiv.org/abs/10.21468/SciPostPhysProc.1.2.013)

Overview - background model

- Using Bayesian Analysis Toolkit (BAT) to marginalise activities through a spectral template fit via Monte Carlo Markov Chains and the Metropolis-Hastings Algorithm

$$\begin{array}{c}
 \text{Posterior} \\
 \downarrow \\
 p(\boldsymbol{\vartheta}|\mathbf{y}) \\
 \uparrow \\
 \text{Observations}
 \end{array}
 = \frac{\begin{array}{c} \text{Likelihood} \\ \downarrow \\ \mathcal{L}(\mathbf{y}|\boldsymbol{\vartheta}) \end{array} \cdot \begin{array}{c} \text{Prior} \\ \downarrow \\ \pi(\boldsymbol{\vartheta}) \end{array}}{\int_{\Theta} \mathcal{L}(\mathbf{y}|\boldsymbol{\vartheta}') \cdot \pi(\boldsymbol{\vartheta}') d\boldsymbol{\vartheta}'} \leftarrow \begin{array}{l} \text{Parameters} \\ \text{(activities)} \end{array}$$

- Extended binned log-likelihood function:

$$\log \mathcal{L}(\boldsymbol{\vartheta}) = \sum_{j=1}^{n_{\text{bin}}} \underbrace{(n_j \log \nu_j - \nu_j - \log n!)}_{\text{Poisson}}$$

Exp. counts
Sim. counts

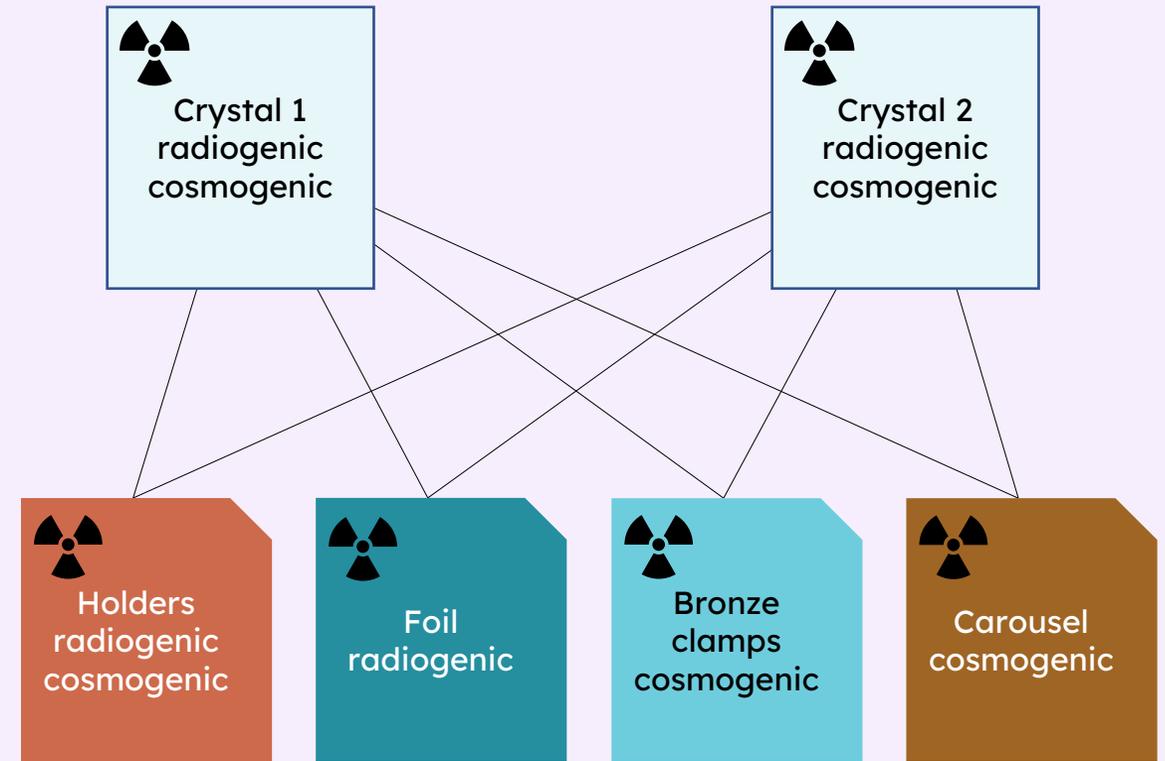
↓
↙

Overview – background components

- Simultaneous fit of multiple detector modules d

$$\log \mathcal{L}(\boldsymbol{\vartheta}) = \sum_d \log \mathcal{L}^d(\boldsymbol{\vartheta})$$

- Contaminations of crystals are assumed to be independent
- Shared** external hardware **components** required to have consistent activities
- Only **bulk** contamination so far
- Currently **excluding** the low energy excess (LEE) (simulation down to ~ 200 eV)



Secular equilibrium (SE) is studied

: Fully broken SE

²³⁸ U
²³⁴ Th
²³⁴ Pa
²³⁴ U
²³⁰ Th
²²⁶ Ra
²²² Rn
²¹⁸ Po
²¹⁴ Pb
²¹⁸ At
²¹⁴ Bi
²¹⁰ Tl
²¹⁴ Po
²¹⁰ Pb
²⁰⁶ Hg
²¹⁰ Bi
²⁰⁶ Tl
²¹⁰ Po

²³⁵ U
²³¹ Th
²³¹ Pa
²²⁷ Ac
²²³ Fr
²²⁷ Th
²²³ Ra
²¹⁹ At
²¹⁵ Bi
²¹⁹ Rn
²¹⁵ Po
²¹¹ Pb
²¹⁵ At
²¹¹ Bi
²⁰⁷ Tl
²¹¹ Po

²³² Th
²²⁸ Ra
²²⁸ Ac
²²⁸ Th
²²⁴ Ra
²²⁰ Rn
²¹⁶ Po
²¹² Pb
²¹² Bi
²⁰⁸ Tl
²¹² Po

: Partial SE

: Semi-broken SE

+ Full potential of simulated data can be explored

- Slowest, most parameters

- **Unphysical**, at least some SE should be retained

Secular equilibrium (SE) is studied

: Fully broken SE

: Partial SE

: Semi-broken SE

^{238}U	^{235}U	^{232}Th
^{234}Th	^{231}Th	^{228}Ra
^{234}Pa	^{231}Pa	^{228}Ac
^{234}U	^{227}Ac	^{228}Th
^{230}Th	^{223}Fr	^{224}Ra
^{226}Ra	^{227}Th	^{220}Rn
^{222}Rn	^{223}Ra	^{216}Po
^{218}Po	^{219}At	^{212}Pb
^{214}Pb	^{215}Bi	^{212}Bi
^{218}At	^{219}Rn	^{208}Tl
^{214}Bi	^{215}Po	^{212}Po
^{210}Tl	^{211}Pb	
^{214}Po	^{215}At	
^{210}Pb	^{211}Bi	
^{206}Hg	^{207}Tl	
^{210}Bi	^{211}Po	
^{206}Tl		
^{210}Po		

+ Faster, less parameters

- Detailed knowledge about chemical cleaning required

- **Too restrictive** for “real” data

Secular equilibrium (SE) is studied

: Fully broken SE

: Partial SE

: Semi-broken SE



- + Still fast, only slightly more parameters
- + Accounts for missing sources with similar spectral shape
- + **Empirical choice** for balance between goodness of fit and parameter restriction

²³⁸ U
²³⁴ Th
²³⁴ Pa
²³⁴ U
²³⁰ Th
²²⁶ Ra
²²² Rn
²¹⁸ Po
²¹⁴ Pb
²¹⁸ At
²¹⁴ Bi
²¹⁰ Tl
²¹⁴ Po
²¹⁰ Pb
²⁰⁶ Hg
²¹⁰ Bi
²⁰⁶ Tl
²¹⁰ Po

²³⁵ U
²³¹ Th
²³¹ Pa
²²⁷ Ac
²²³ Fr
²²⁷ Th
²²³ Ra
²¹⁹ At
²¹⁵ Bi
²¹⁹ Rn
²¹⁵ Po
²¹¹ Pb
²¹⁵ At
²¹¹ Bi
²⁰⁷ Tl
²¹¹ Po

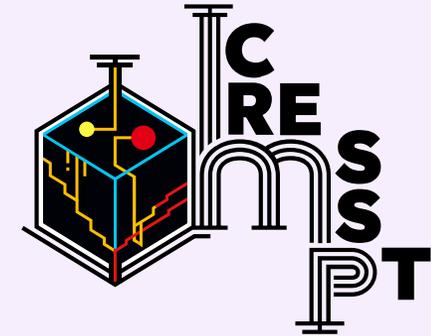
²³² Th
²²⁸ Ra
²²⁸ Ac
²²⁸ Th
²²⁴ Ra
²²⁰ Rn
²¹⁶ Po
²¹² Pb
²¹² Bi
²⁰⁸ Tl
²¹² Po

Not in SE group

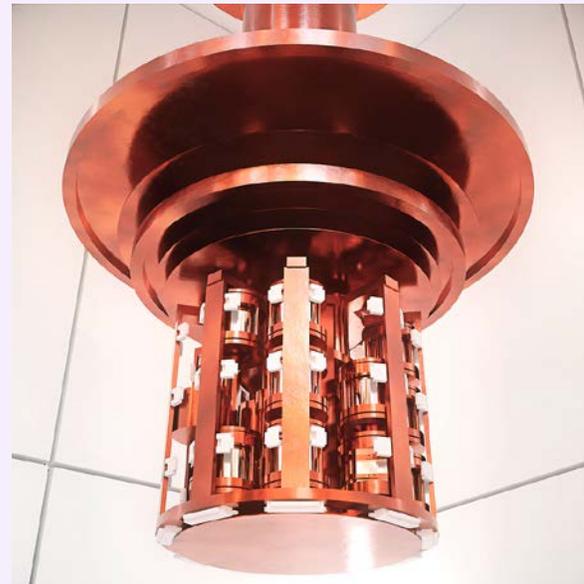
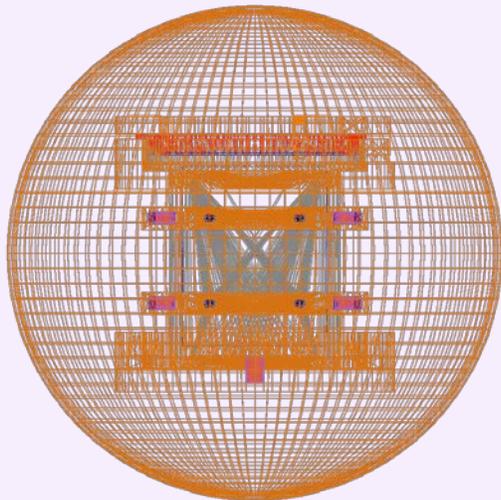
TUM40 & Lise - run33 extended background model

- Major upgrade from 2019 background paper ([10.1140/epjc/s10052-019-7385-0](https://doi.org/10.1140/epjc/s10052-019-7385-0))
- Simultaneous fit of both modules (TUM40 & Lise)
- Degrees of secular equilibrium (SE) studied ([10.1016/j.apradiso.2023.110670](https://doi.org/10.1016/j.apradiso.2023.110670))
- Single detector module \Rightarrow using extended geometry (until cryostat shield)

(TUM40 only)



[10.1140/epjc/s10052-019-7385-0](https://doi.org/10.1140/epjc/s10052-019-7385-0)



Visualisation of open cryostat

[10.34726/hss.2022.104928](https://doi.org/10.34726/hss.2022.104928)

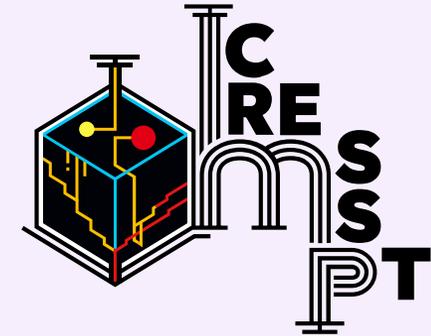
- 5.6 billion events simulated
- 226 templates per detector
 - : 46 internal radiogenic (IR)
 - : 46 holders radiogenic (HR)
 - : 46 shielding radiogenic (SR)
 - : 46 foil radiogenic (FR)
 - : 27 internal cosmogenic (IC)
 - : 7 holders cosmogenic (HC)
 - : 7 shielding cosmogenic (SC)
 - : 1 bronze cosmogenic (BC)
- 110+ years CPU time

Bulk contaminations

TUM40 & Lise - run33 extended background model

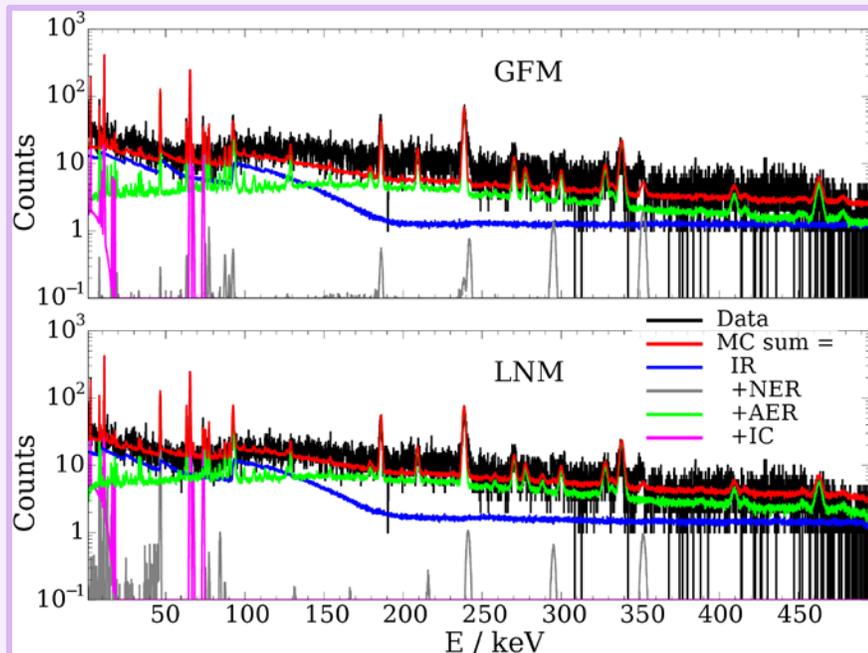
(TUM40 only)

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- Degrees of secular equilibrium (SE) studied ([10.1016/j.apradiso.2023.110670](https://arxiv.org/abs/10.1016/j.apradiso.2023.110670))
- Single detector module \Rightarrow using extended geometry (until cryostat shield)
- More radioactive sources (108 \Rightarrow 226 spectral templates), using ImpCRESST
- Gaussian Normalisation Method (GFM) \Rightarrow Likelihood Normalisation Method (LNM)



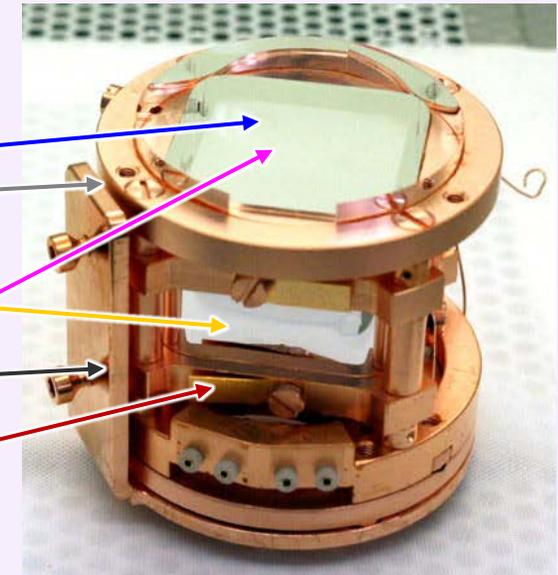
[10.1140/epjc/s10052-019-7385-0](https://arxiv.org/abs/10.1140/epjc/s10052-019-7385-0)

arXiv:2307.12991



Bulk contaminations

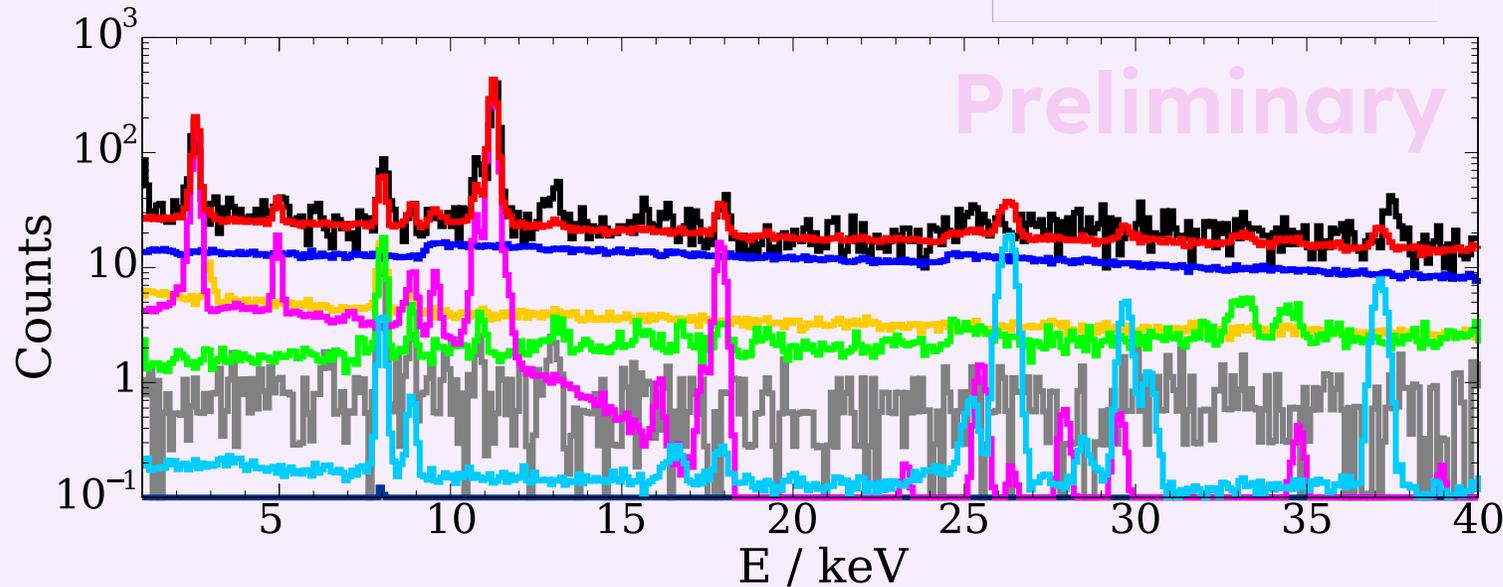
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 - : 7 shielding cosmogenic (SC)
 - : 1 bronze cosmogenic (BC)
- 110+ years CPU time



TUM40 results

- Majority of background from internal contamination
- Some peaks missing, but constant background fits very well

Component	Coverage / %
IR	→ 42.8
IC	→ 19.9
FR	13.2
SR	8.6
HR	2.8
BC	2.2
HC	0.2
Sum	89.5



Explainable percentage (EP) = 78.0%

Coverage ζ = 89.5%

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

Heaviside step function Central p-value Nominal significance level

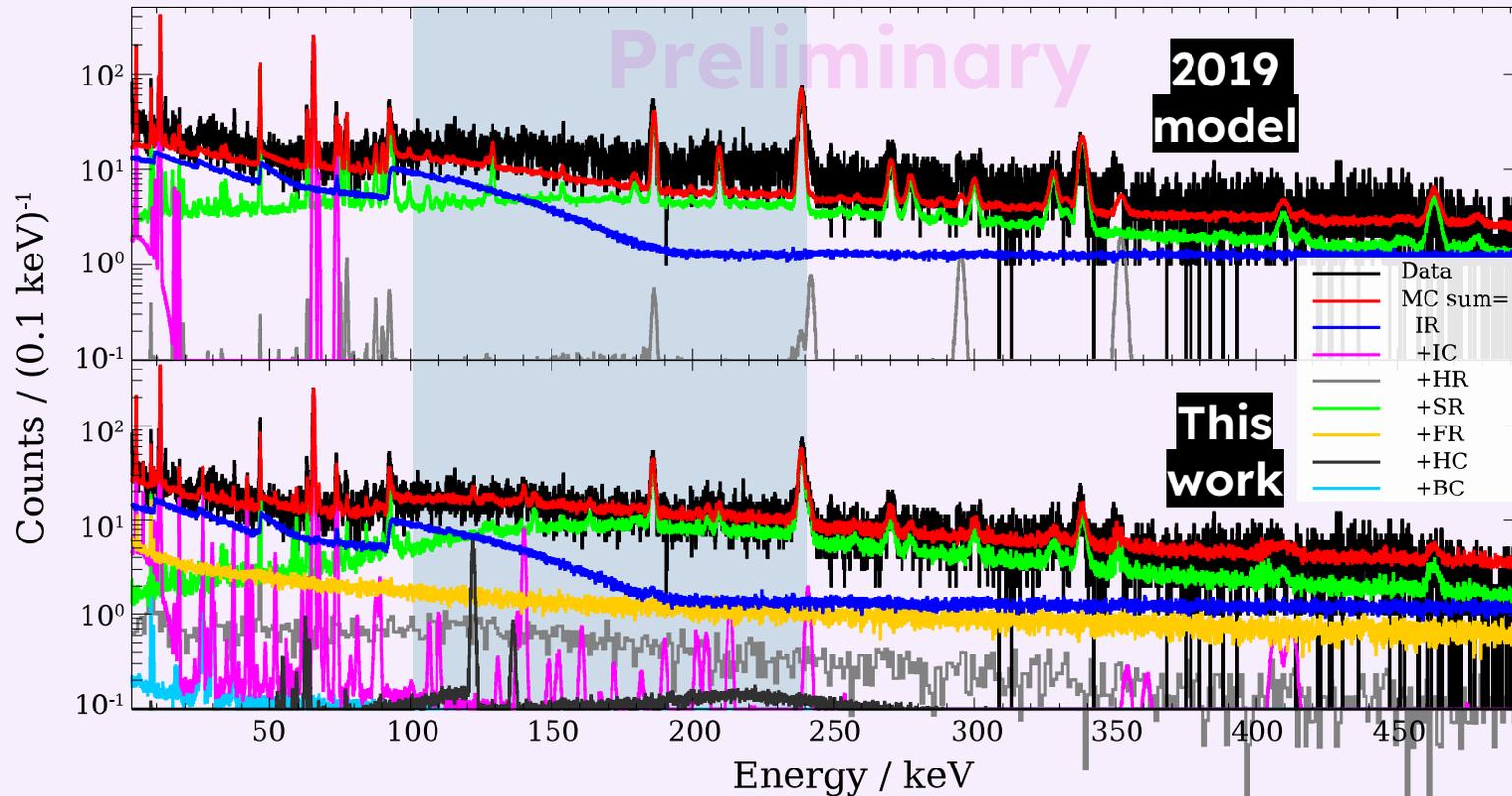
$$\zeta = \frac{\sum_{j=1}^{n_{\text{bin}}} \nu_j \leftarrow \text{Fit}}{\sum_{j=1}^{n_{\text{bin}}} n_j \leftarrow \text{Experiment}}$$



TUM40 results - improvements

EP = 77.2%

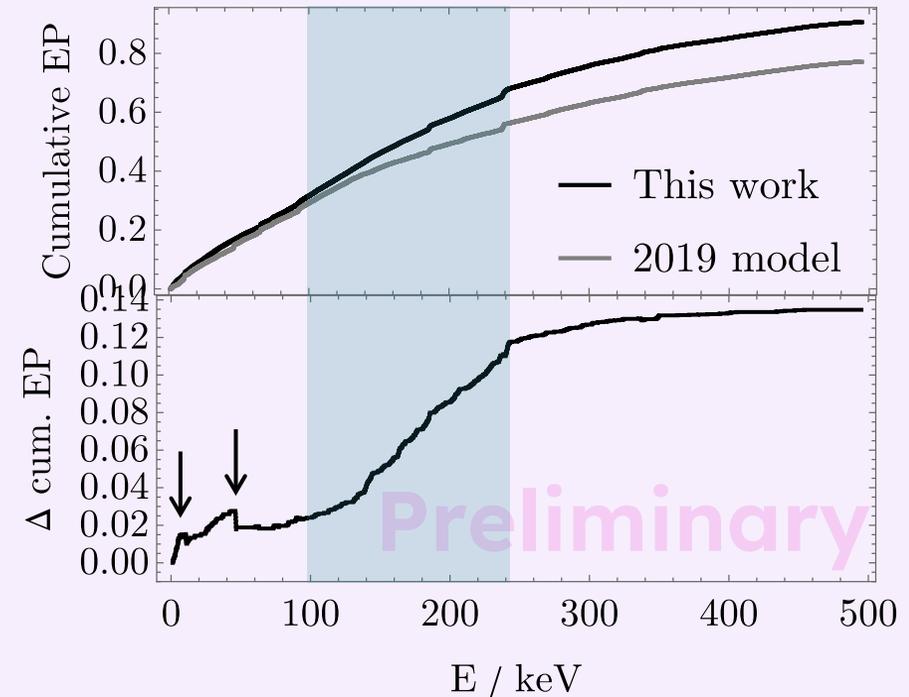
$\zeta = 74.6\%$



EP = 90.7%

$\zeta = 97.7\%$

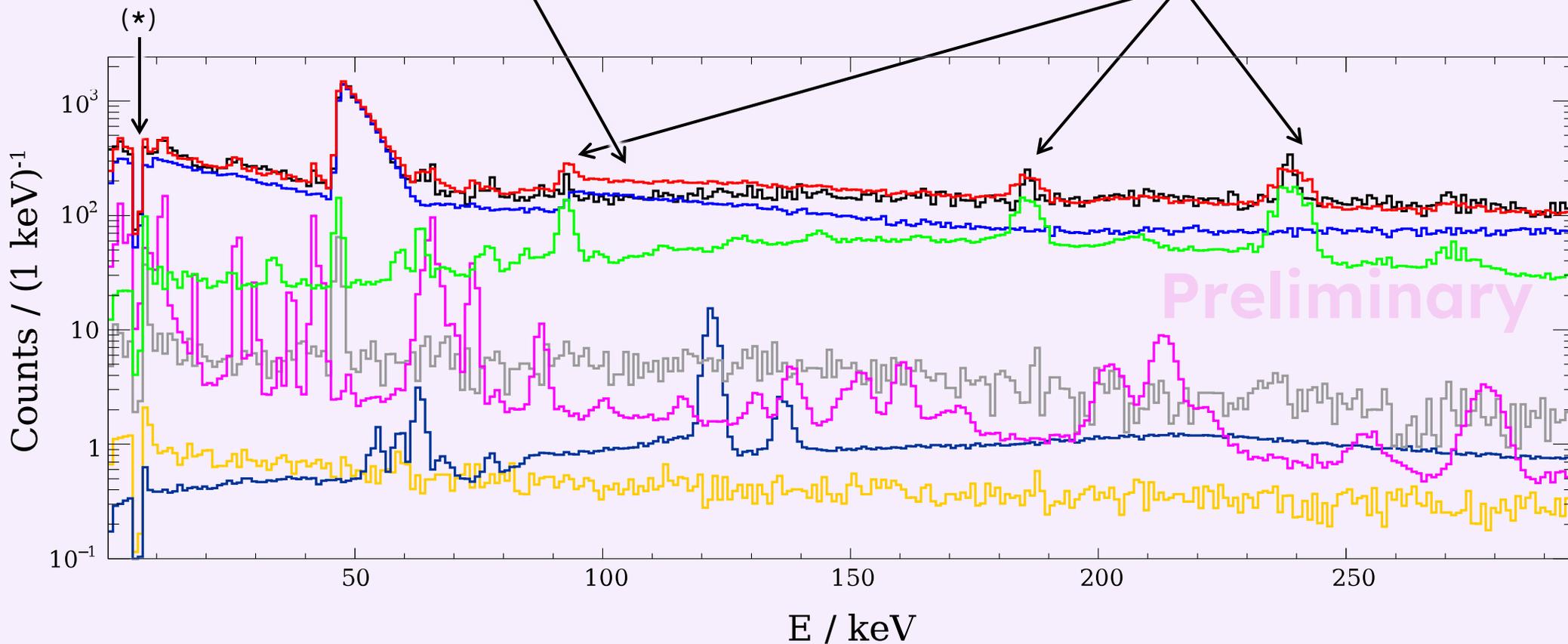
- Improvement mostly in the 100-240 keV range
- Fit only worse for two peaks: IC ¹⁷⁹Ta L1 & L2 and HR/SR ²¹⁰Pb



Lise results

Over-coverage due to IR ^{234}Th

Resolution could still be improved



- Data
- MC sum =
- IR
- +IC
- +HR
- +SR
- +HC
- +FR
- +BC

EP(*): 96.0%

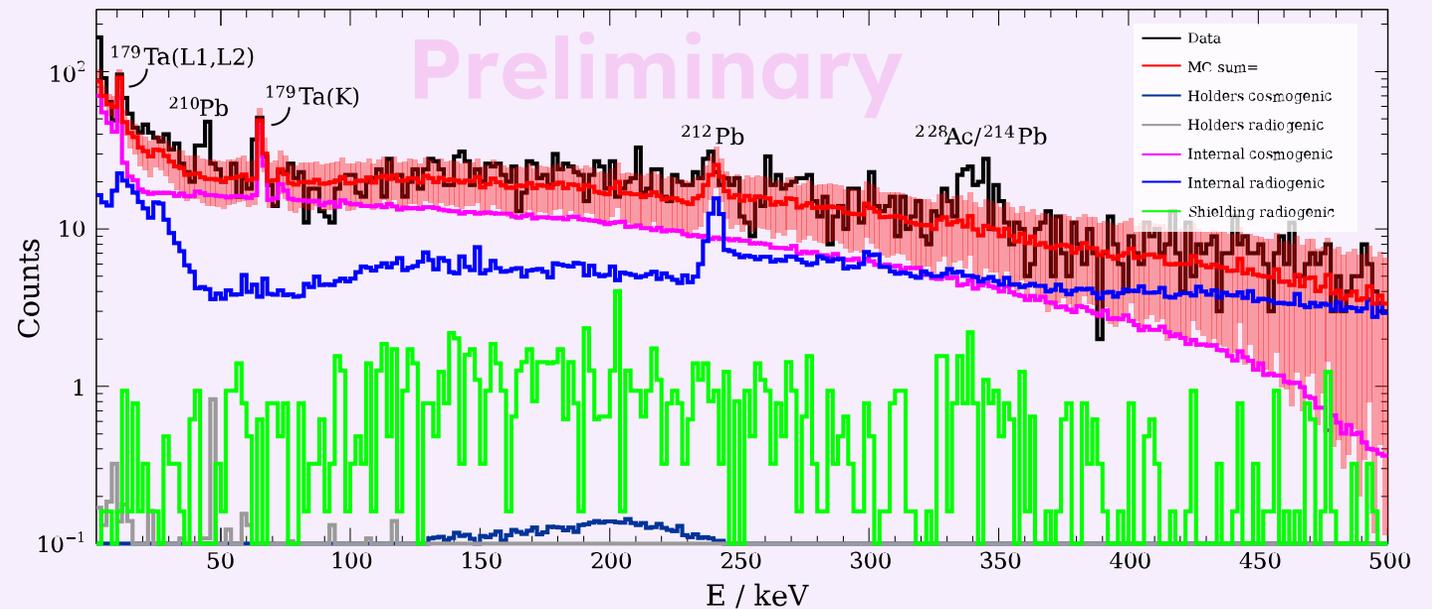
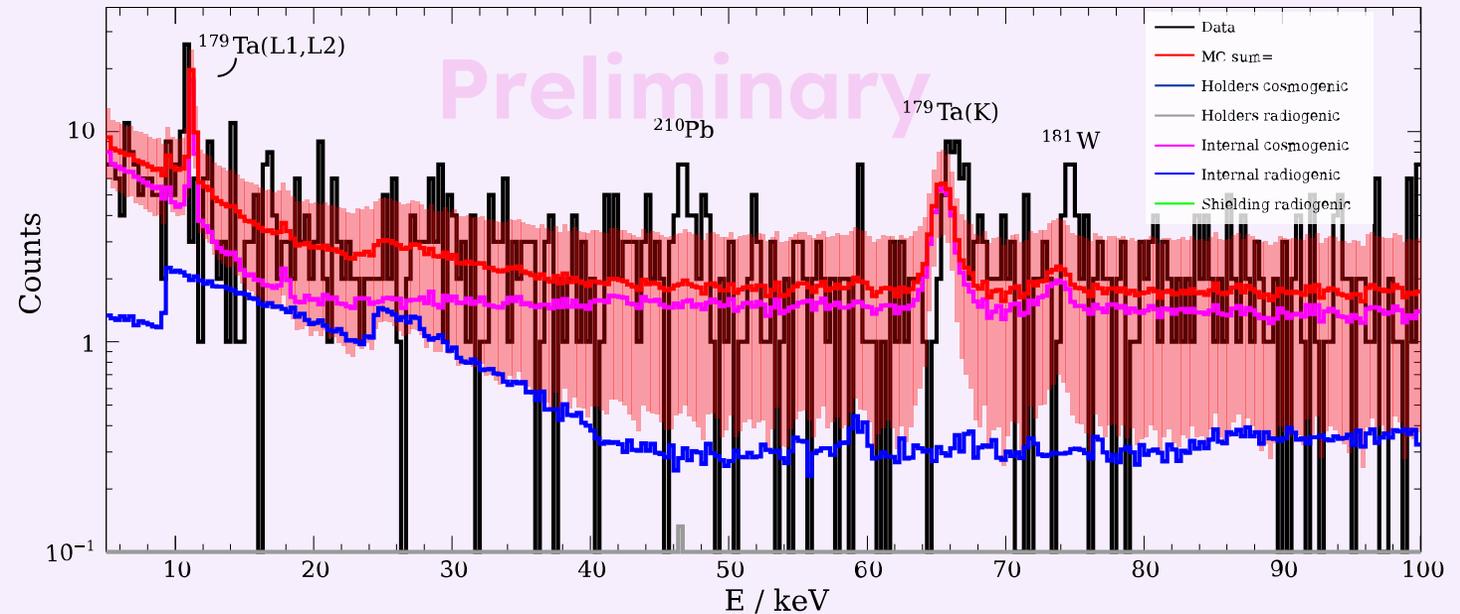
ζ (*): 106.8%

(*) Excluding ^{55}Fe calibration source

↪ **But overall, fit doesn't get any better than this!**

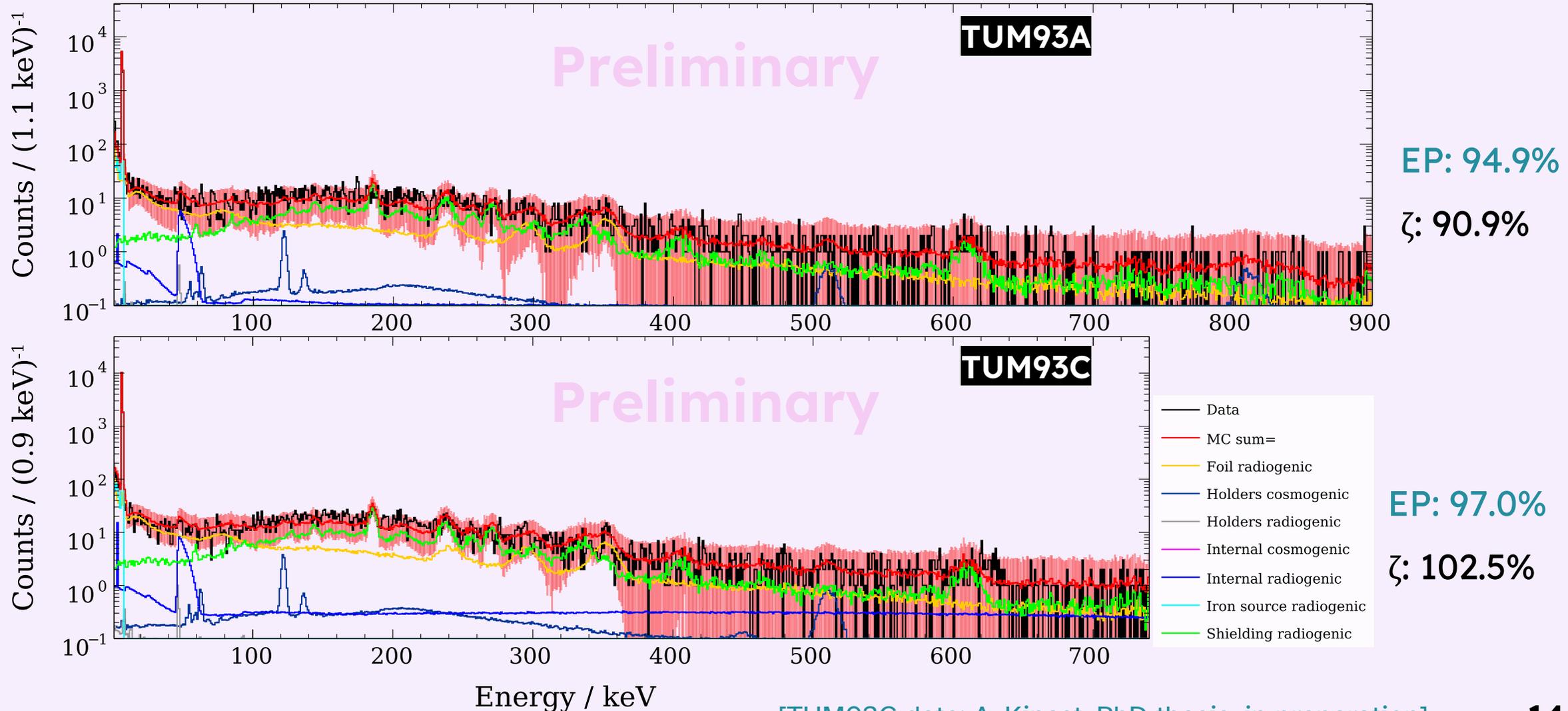
Detector A results, SE

- Limited energy range up to 500 keV \Rightarrow **no alphas**
 \hookrightarrow Extension of energy range with **saturated fit** in progress
- Many spectral templates from carousel still missing, high statistics simulations to be done
- Reconstructed energy needs re-calibration
- Overall coverage: 84.5%

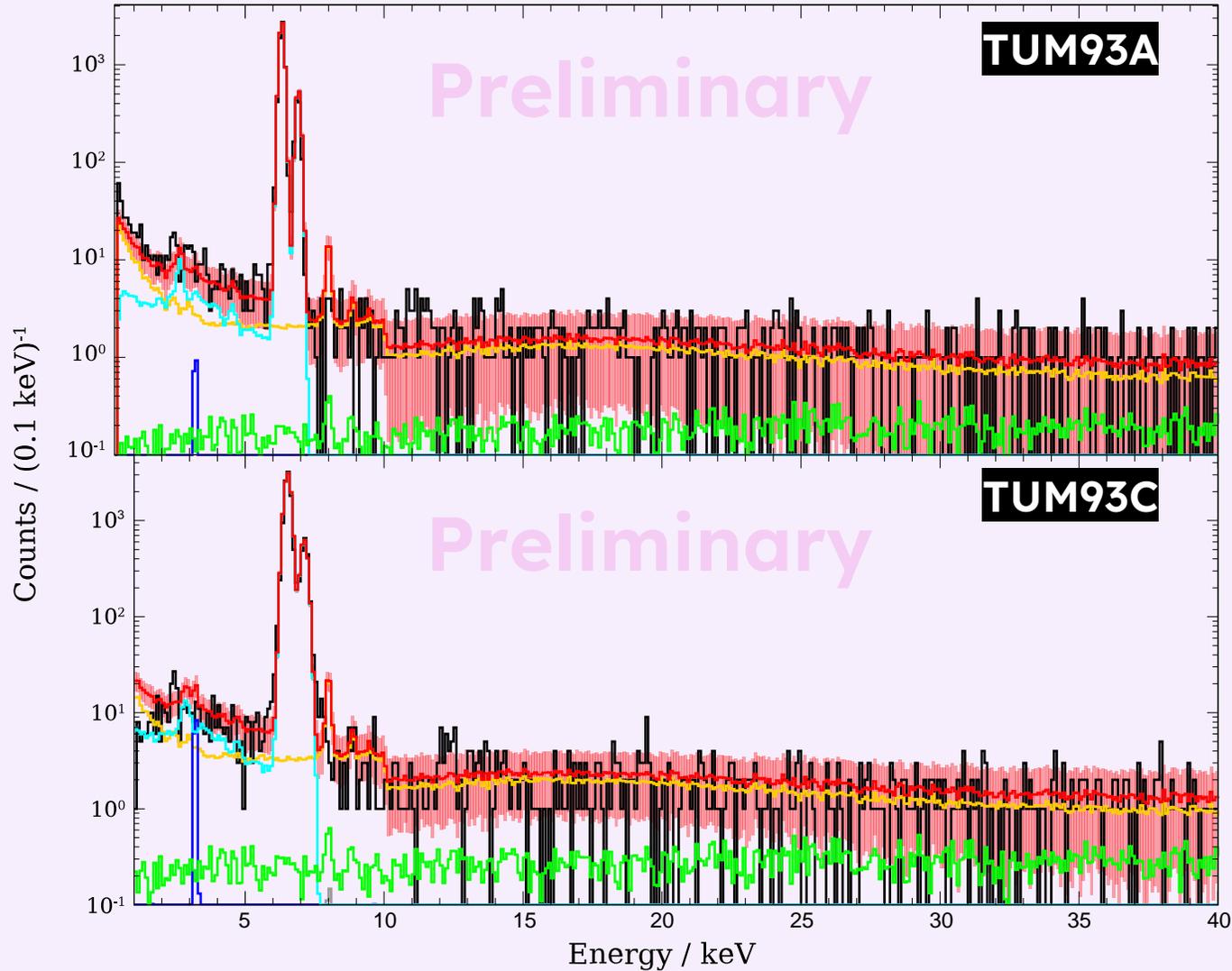


TUM93A/C results, SE, *without* SR & FR limits

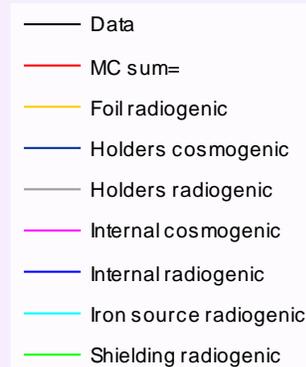
(Simulated templates from DetA used for now)



TUM93A/C results, SE, *without* SR & FR limits



- **Rise** down to 500 eV due to foil-like component in TUM93A
- Tail of ^{55}Fe calibration source has significant contribution below $K\alpha/K\beta$ -peaks
- In the future, neutron recoil peak of $^{182}\text{W}(n,\gamma)^{183}\text{W}$ reaction (112 eV) will be used for low-energy calibration
([10.1103/PhysRevD.108.022005](https://arxiv.org/abs/10.1103/PhysRevD.108.022005))

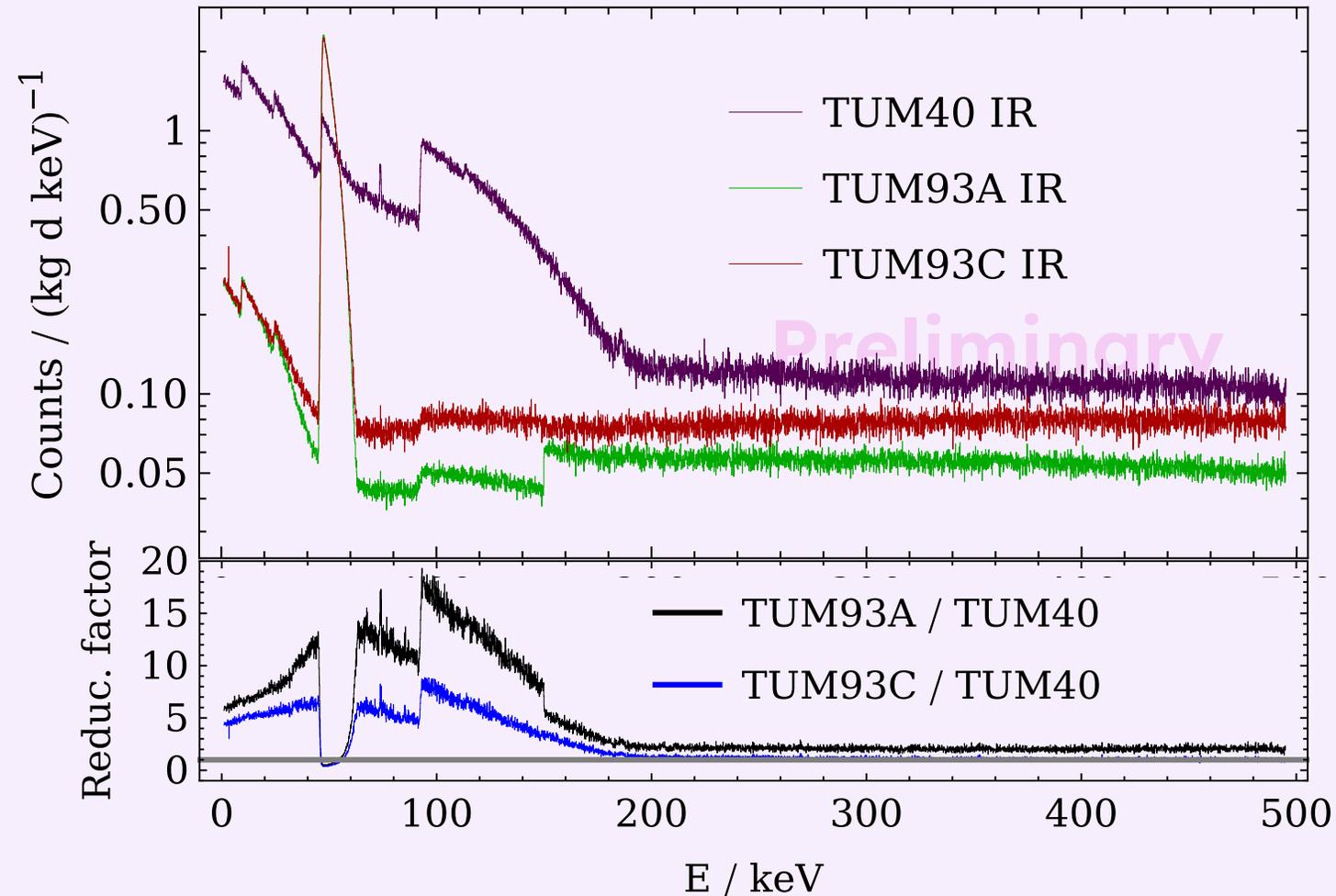


Intrinsic contamination comparison

- Huge improvement of CaWO_4 crystal purity achieved
- Main background contribution **not from intrinsic contamination** (IR & IC) in newer runs

↪ Main background contribution expected from **external contamination** in newer runs

↪ See also [10.21468/SciPostPhysProc.12.031](https://arxiv.org/abs/10.21468/SciPostPhysProc.12.031) for another crystal purity assessment



Intrinsic contamination comparison

- Main background contribution **not from intrinsic contamination** (IR & IC) in newer runs
- Dominant contribution for TUM93A/C not known with confidence because of large tension between screening limits and fit values
- Even then, **crystal purity** can be readily assessed
 - ↳ See [10.1007/s10909-022-02743-7](https://doi.org/10.1007/s10909-022-02743-7) for details about crystal production

Comm-
ercial
↑
TUM-grown

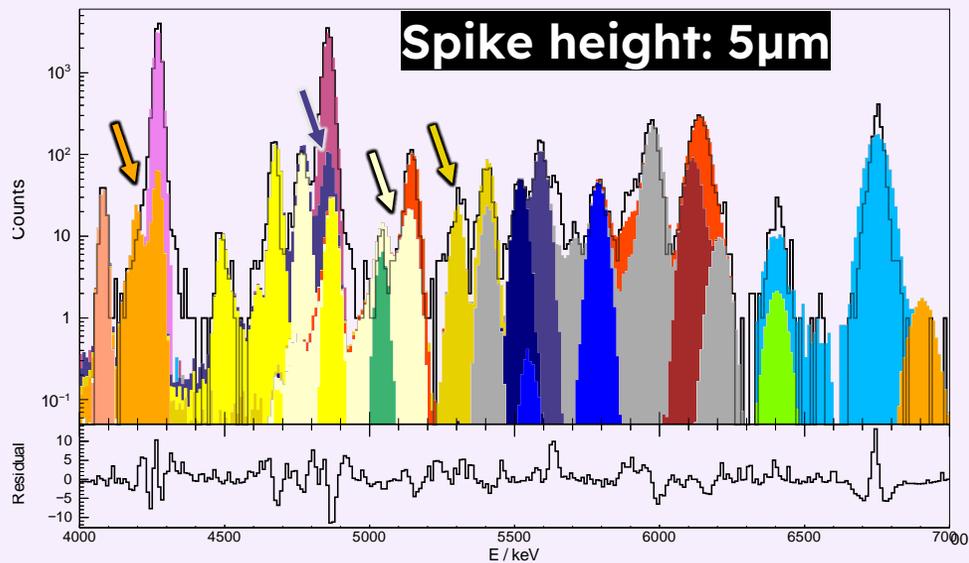
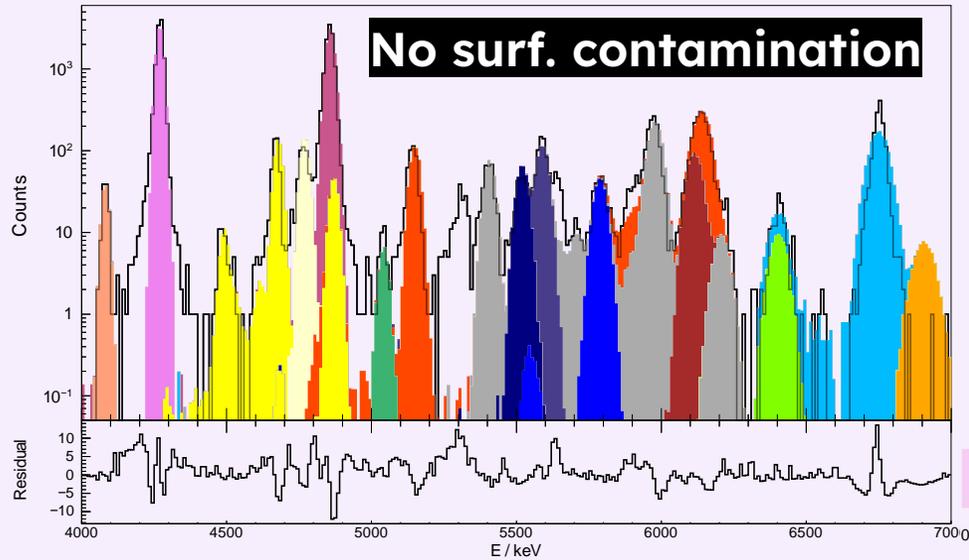
Detector	Activity / $\mu\text{Bq kg}^{-1}$			
	Internal radiogenic		External	
	1*-10 keV	10-40 keV	1*-10 keV	10-40 keV
Lise	171	493	27.2**	77.4
TUM40	109	312	71.4**	171
Detector A***	111	484	1.89**	5.68
TUM93C	52.5	43.5	30.0e3	1250
TUM93A	22.2	37.7	25.6e3	1090

* Slightly different lower limits for each module

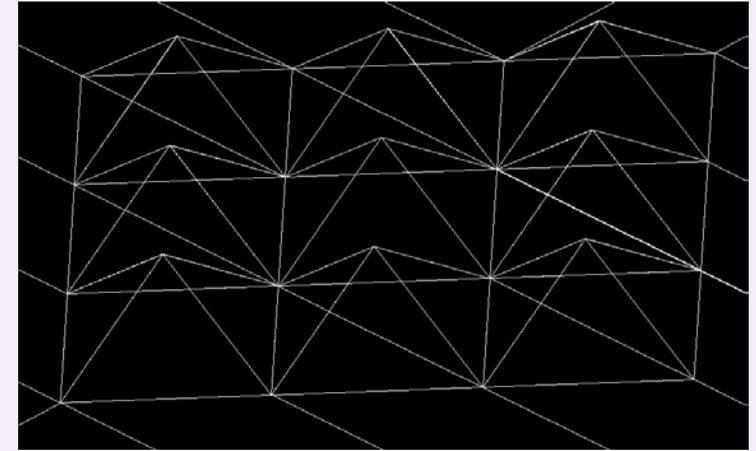
** No iron source present or excluded from comparison

*** SR almost fully neglected because too low statistics

Surface contamination simulation in TUM40



Preliminary

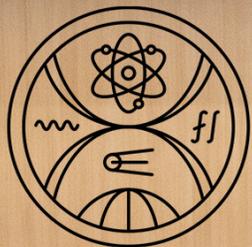


- Surface effects studied by using thousands of **micro-spikes**
- First test with four exemplary alpha-decaying nuclides (^{234}U , ^{238}U , ^{231}Pa , ^{210}Po) is promising
- Implementation by C. Grüner (visit his poster!)

Summary and Outlook

- **Highly detailed** background models of five detector modules
- **Very good reproduction** above the low energy excess
 - ↳ Proves the applicability of our high-dimensional Bayesian likelihood normalisation method (LNM) to a **complex detector inventory**
 - ↳ Profile likelihood **DM exclusion limits** to be calculated
- Models are work in progress, but publication to be expected soon
- See other **CRESST contributions**:
 - : [M. Kaznacheeva, Status of CRESST, Aug 30 4:30PM – Hörsaal 3](#)
 - : [A. Kinast, \$^{17}\text{O}\$ enrichment in \$\text{CaWO}_4\$, poster 605](#)
 - : [L. Meyer, Optimum filter analysis, poster 362](#)
 - : [S. Kuckuk, Likelihood fit of low energy excess, poster 358](#)
 - : [C. Grüner, Geant4 simulation of surface roughness, poster 569](#)
 - : [F. Wagner, Deep reinforcement operated cryogenic calorimeters, poster 392](#)
 - : [A. Bertolini, Low-threshold diamond cryogenic detector, poster 316](#)
 - : [D. R. Fuchs, First single photon observation in CRESST, Aug 28 5:45PM – Hörsaal 3](#)
- See also:
 - : [H. Kluck, Sub-keV electron energy loss in \$\text{CaWO}_4\$ and \$\text{Al}_2\text{O}_3\$, Aug 29 4:45PM – Hörsaal 7](#)

Thanks for your attention!



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CRESST

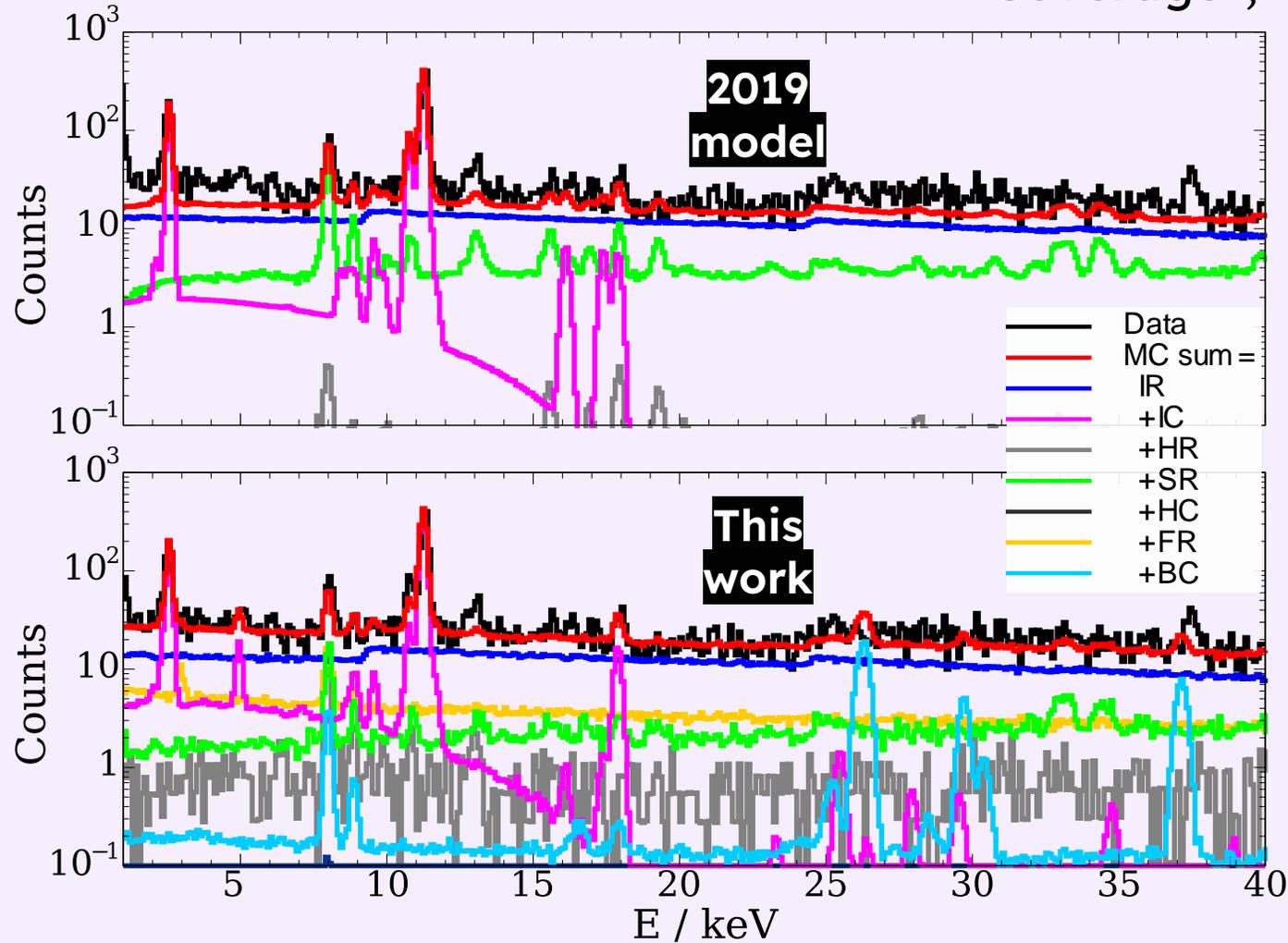


> Backup slides

TUM40 results

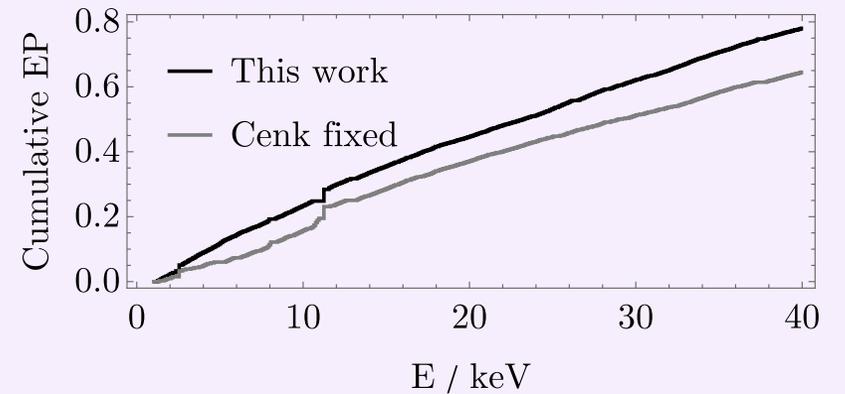
Explainable percentage (EP) = 64.5%

Coverage ζ = 74.6%



Coverage 1-40 keV / %

Component	Cenk fixed	This work
IR	40.7	42.8 ←
IC	17.6	19.9
FR	—	13.2
SR	15.9	8.6
HR	0.2	2.8
BC	—	2.2
HC	—	0.2
Sum	74.6	89.5

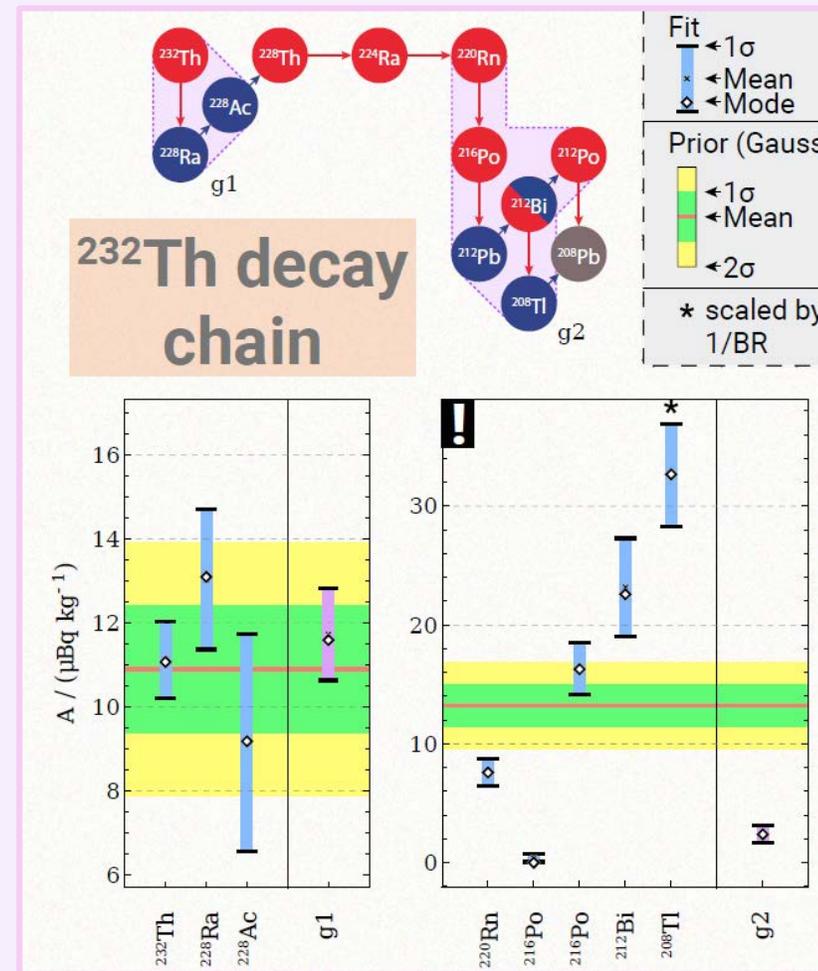
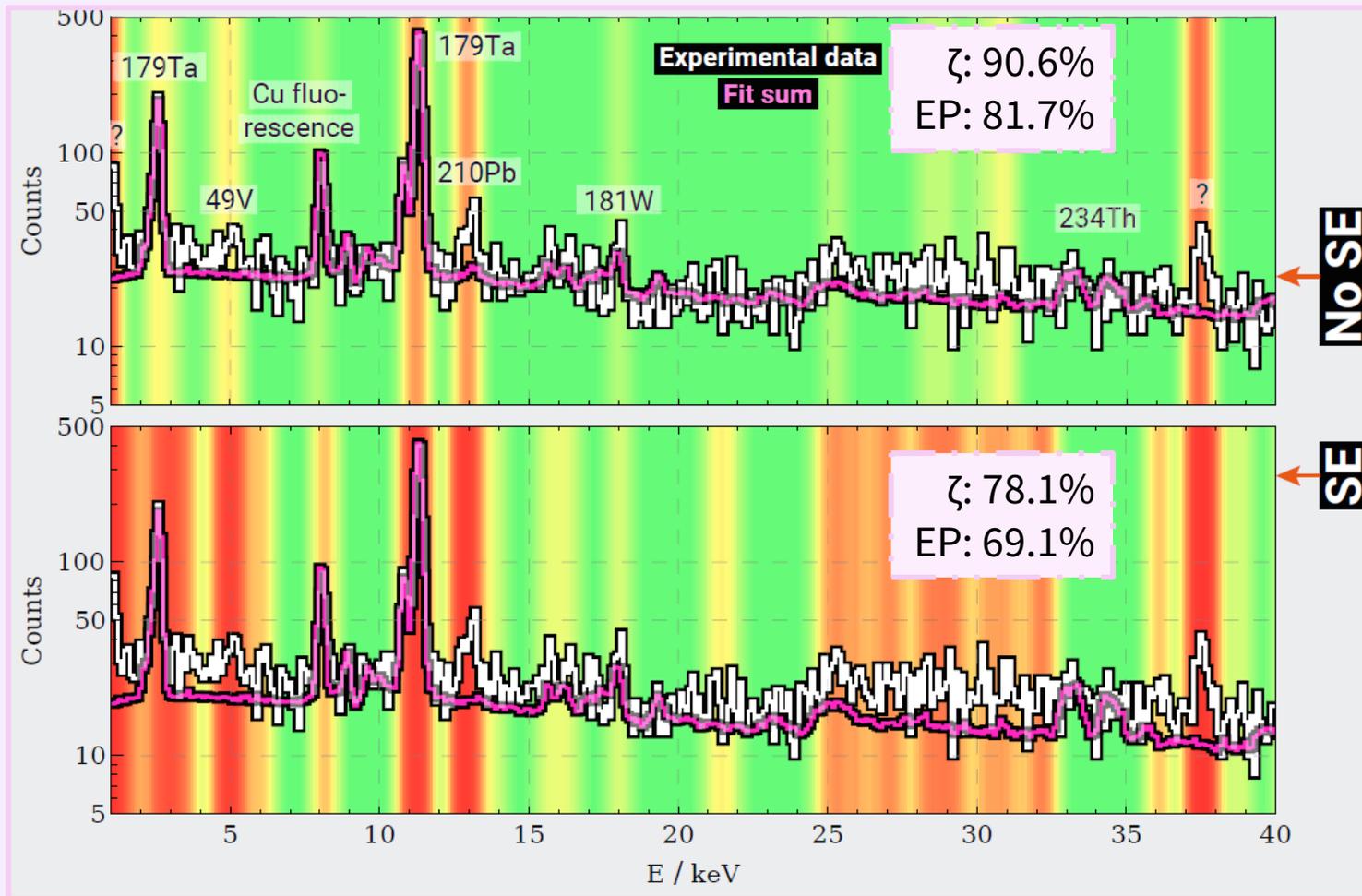


EP = 78.0%

ζ = 89.5%

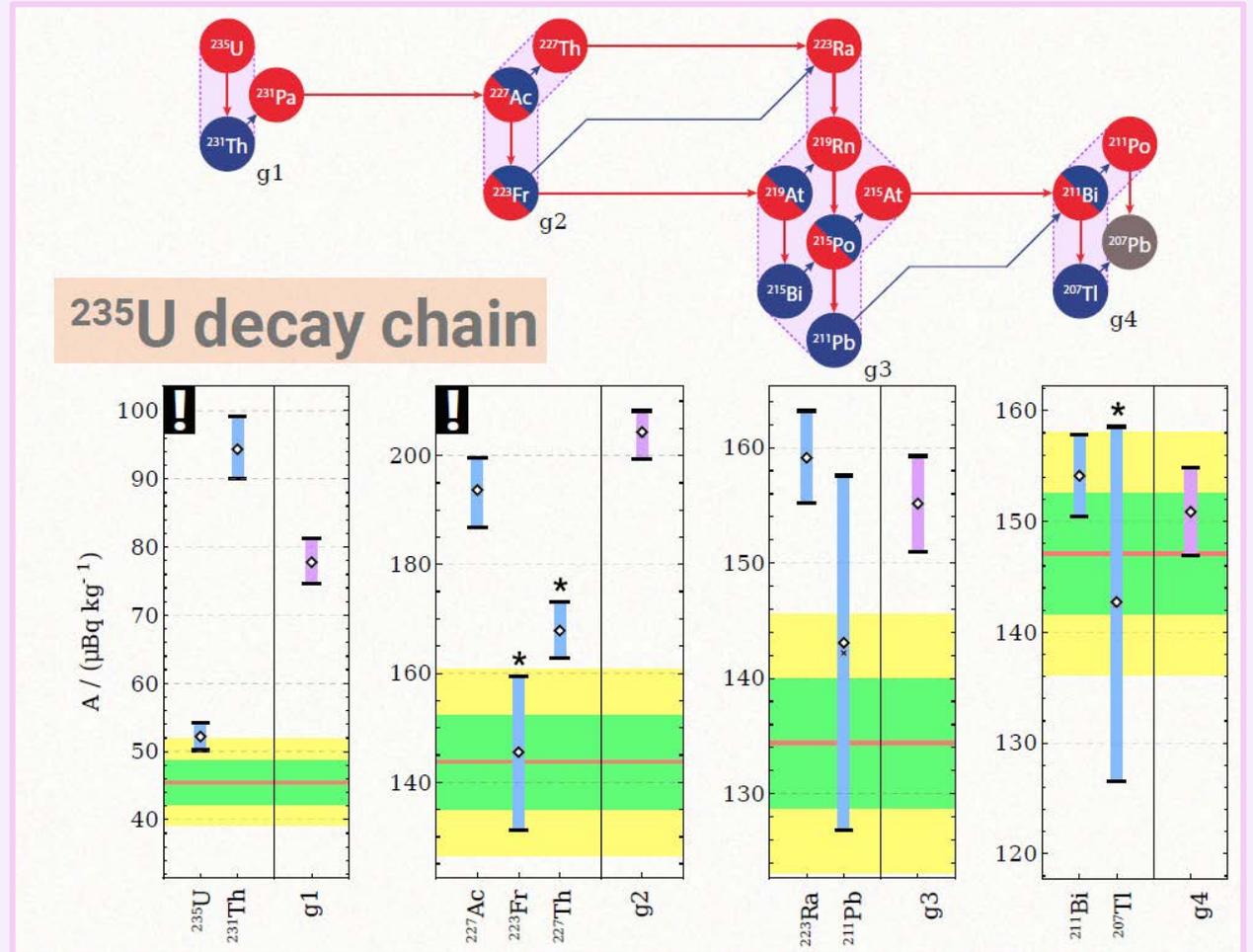
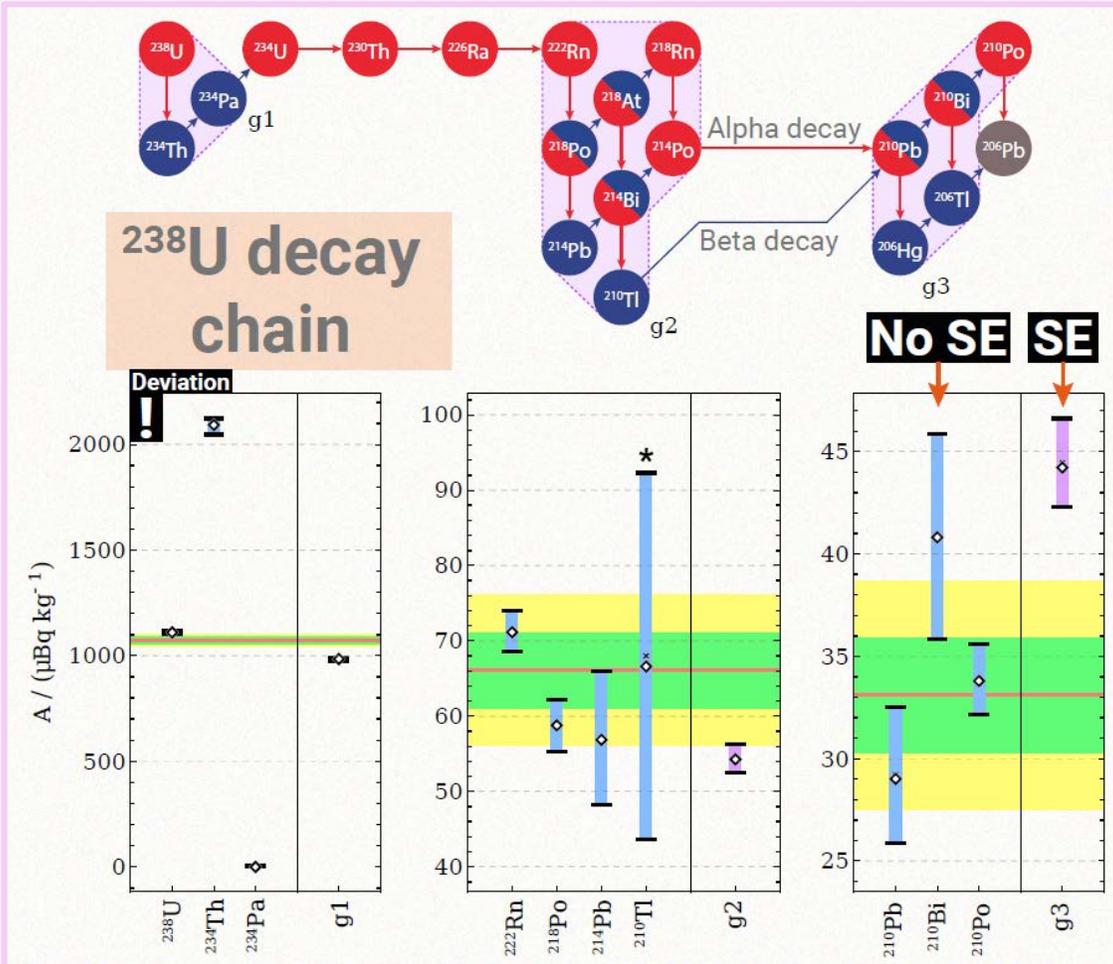
/ICRM-LLRMT conference

SE: secular equilibrium



/ICRM-LLRMT conference

SE: secular equilibrium



Secular equilibrium assumptions

- the initial amount of daughter nuclides must reduce to 10% over the 460 days between the crystal's completion and its arrival at the underground laboratory LNGS, and that
- the relative difference in activities between a parent nuclide and its daughter nuclide, $(A_A - A_B)/A_A$, must be less than 1% over the same time period.

The last condition can be checked using Bateman's analytic solution to the differential equations describing decay chains [69],

$$N_n(t) = N_1(0) \times \prod_{i=1}^{n-1} (\lambda_i) \times \sum_{i=1}^n \frac{e^{-\lambda_i t}}{\prod_{j=1, j \neq i}^n (\lambda_j - \lambda_i)}, \quad (4.1)$$

where

$N_n(t)$... is the number of nuclides of type n after a time t ,

$N_1(0)$... is the number of nuclides at the head of a decay chain at the time $t = 0$, and

λ_i is the decay rate of nuclide i into $i + 1$.

The decay rate is connected to the half-life via

$$\lambda_i = \frac{\ln 2}{t_{1/2, i}}. \quad (4.2)$$

[10.34726/hss.2022.104928](https://hss.2022.104928)

