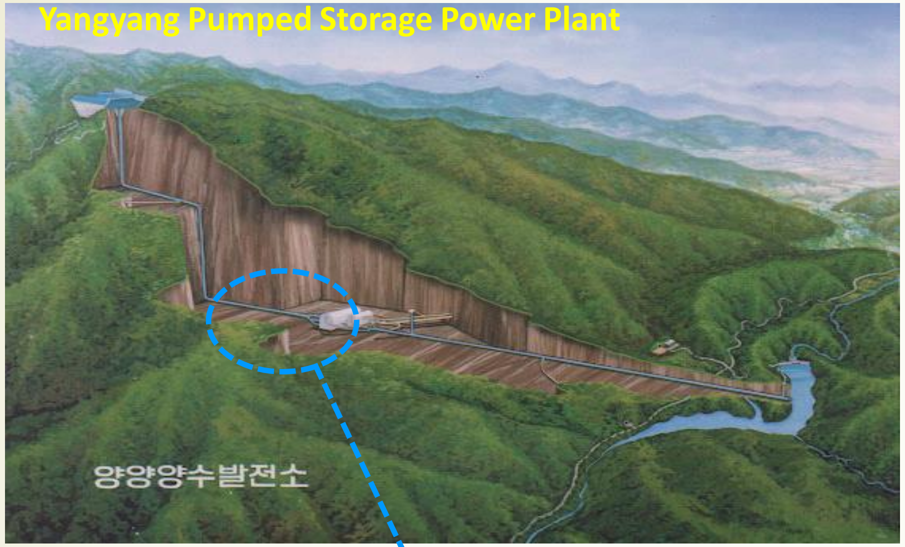
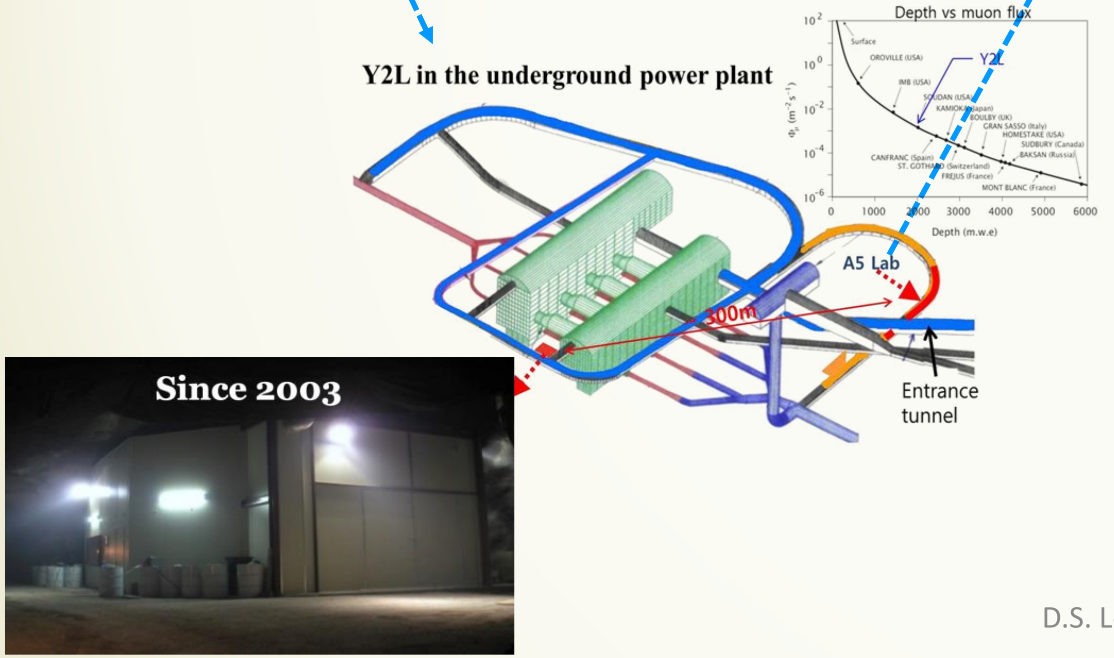
The CAGe germanium array at the Center for Underground Physics

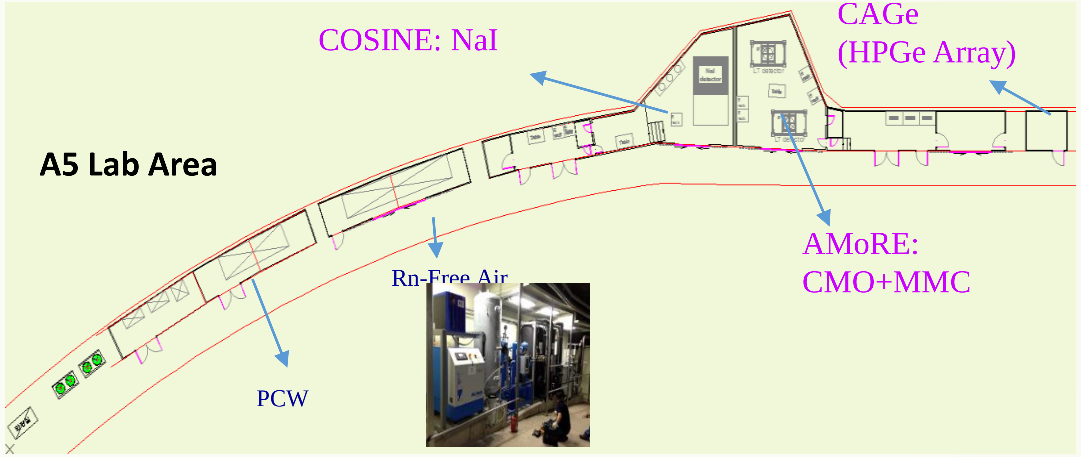
Douglas Leonard

ibs
CENTER FOR UNDERGROUND PHYSICS

Yangyang Underground Laboratory (Y2L)







Minimum vertical depth : 700 m

Drive-in access: around 2 km

A5 lab space (2014 to …) :

AMoRE-pilot/AMoRE-phase I

100Mo DBD experiment.

Cosine NaI dark matter search

14 element HPGe Array

A6 lab space (since 2003):

Home to prior KIMS CsI DM experiment

Houses two 100% HPGe detectors

Other Assay Resources at CUP/Y2L

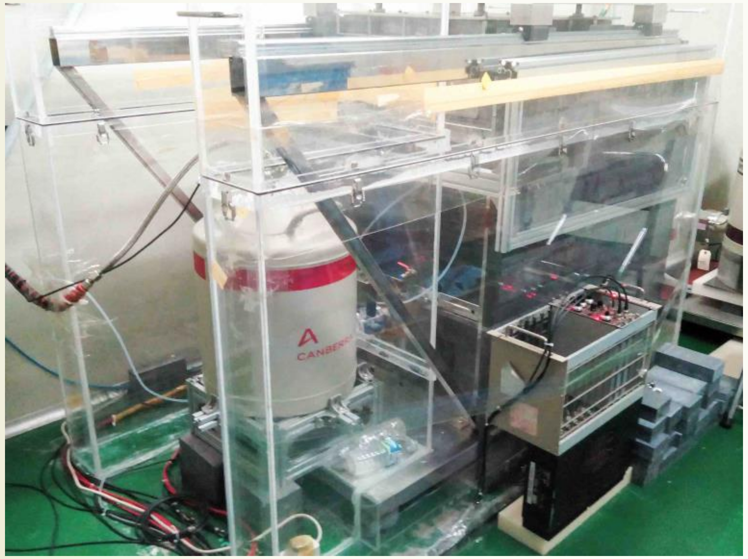
- Two 100% HPGe detectors underground at Y2L A6 site CC1 and CC2, N2 purged for Rn removal. Moved to Yemliab in 2023.
- Both have N2 purge boxes
  - CC1 with lift open access.
  - CC2 with glove-box/ purged airlock access.

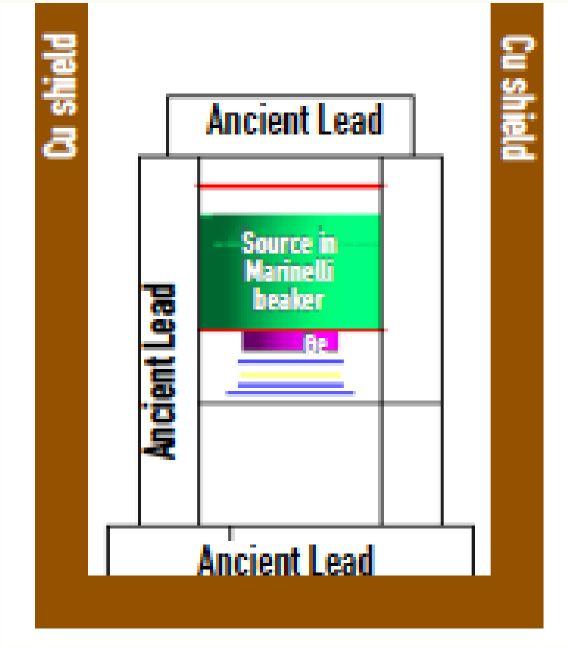
Also

XIA ULtraLo-1800 alpha counter, 1800 cm^2 area. Compliments ICP-MS facilities in Daejeon.

See Poster By Olga Gileva for full Assay and Purification Program.

CC1 at Yangyang:



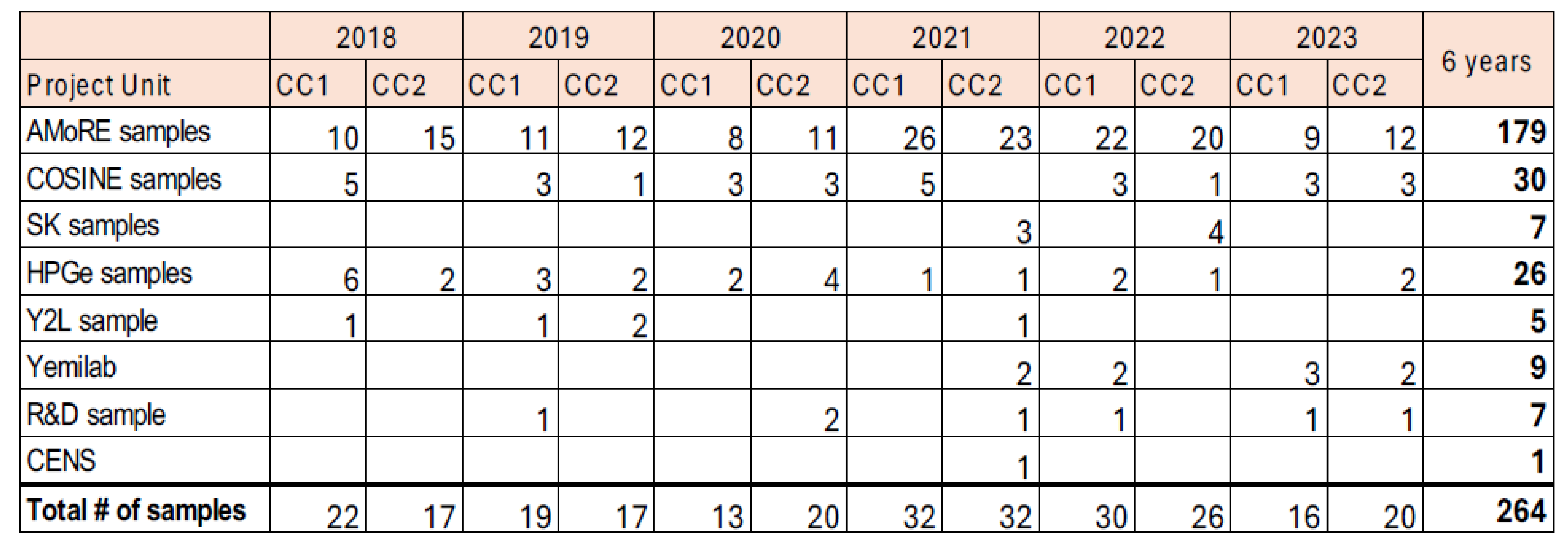


CC2 at Yangyang:

HPGE General Assay Throughput since 2018

- 264 samples! (only counting from 2018)

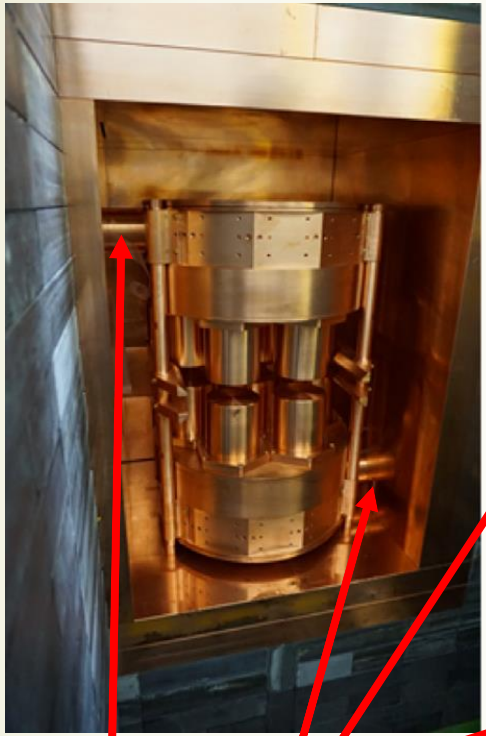
  Almost all by Eunkyung Lee

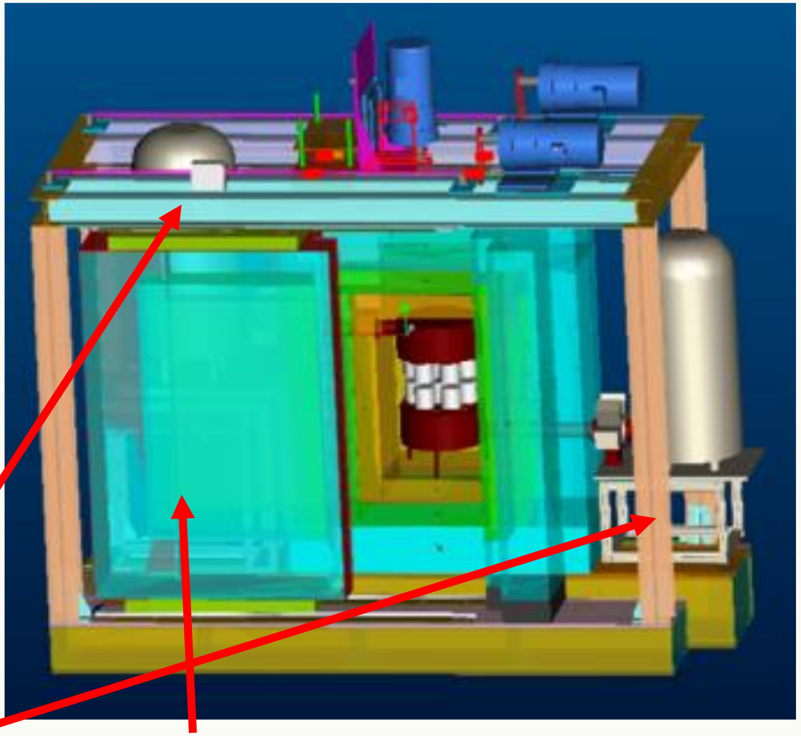


	2018		2019		2020		2021		2022		2023		6 years
Project Unit	CC1	CC2	CC1	CC2	CC1	CC2	CC1	CC2	CC1	CC2	CC1	CC2	
AMoRE samples	10	15	11	12	8	11	26	23	22	20	9	12	**179**
COSINE samples	5		3	1	3	3	5		3	1	3	3	**30**
SK samples								3		4			**7**
HPGe samples	6	2	3	2	2	4	1	1	2	1		2	**26**
Y2L sample	1		1	2				1					**5**
Yemilab								2	2		3	2	**9**
R&D sample			1			2		1	1		1	1	**7**
CENS								1					**1**
Total # of samples	22	17	19	17	13	20	32	32	30	26	16	20	**264**

The CAGe Detector Recap

- See report at LRT 2017 by E. Sala, and poster G.W. Kim



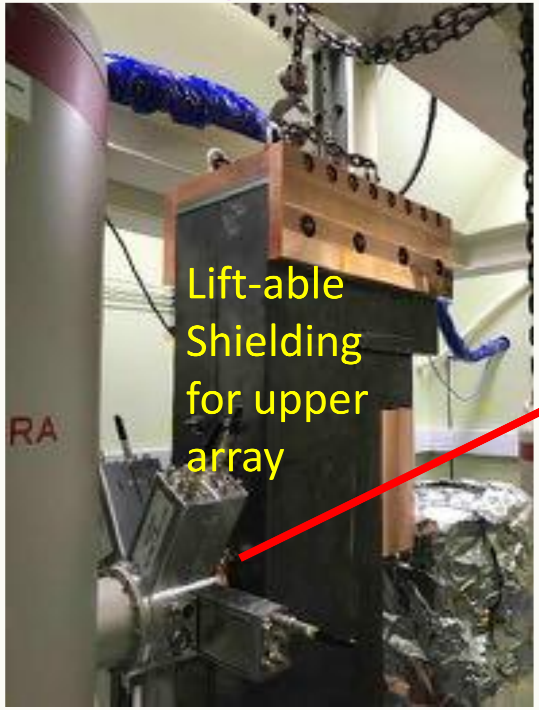


To dewars

Two rolling lead “doors”

Vikuiti foil covers chamber for N2 flushing

During Installation



CAGe still at Y2L Now.

Two arrays, two cryostats.
14 Detectors 70% Rel. Eff. Ea.,
Liftable upper array w/shield
Room supplied with Rn-Free air to 2023

Can’t use 14 MCA’s
So we use NOTICE FADCs,
But still with shaping amps.

Calibration and Summing

- 14 MCA's are silly: We use NOTICE FADCs,

  But still with shaping amps.

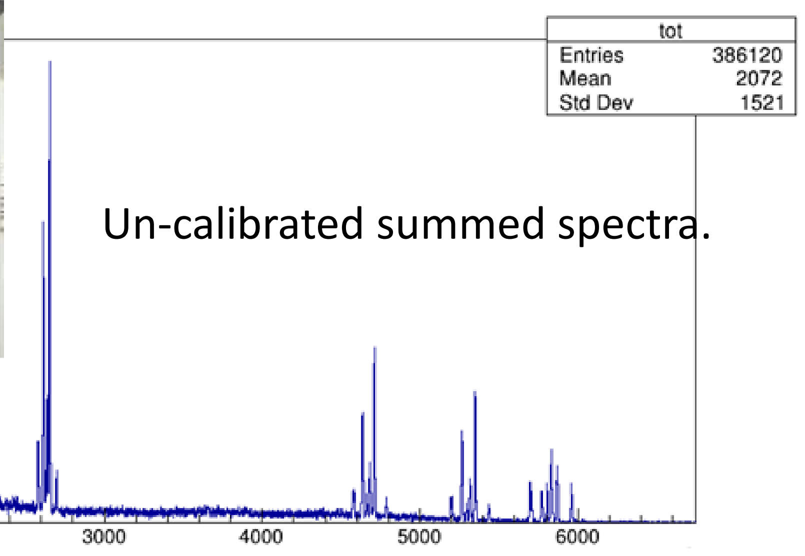
- Multi-detector combined analyses are pretty resource intensive for assay work. -> Solution: Sum.
- For summed gamma energy, or even to combine single-hit analysis (for ease)

  -> we must pre-calibrate, and well.

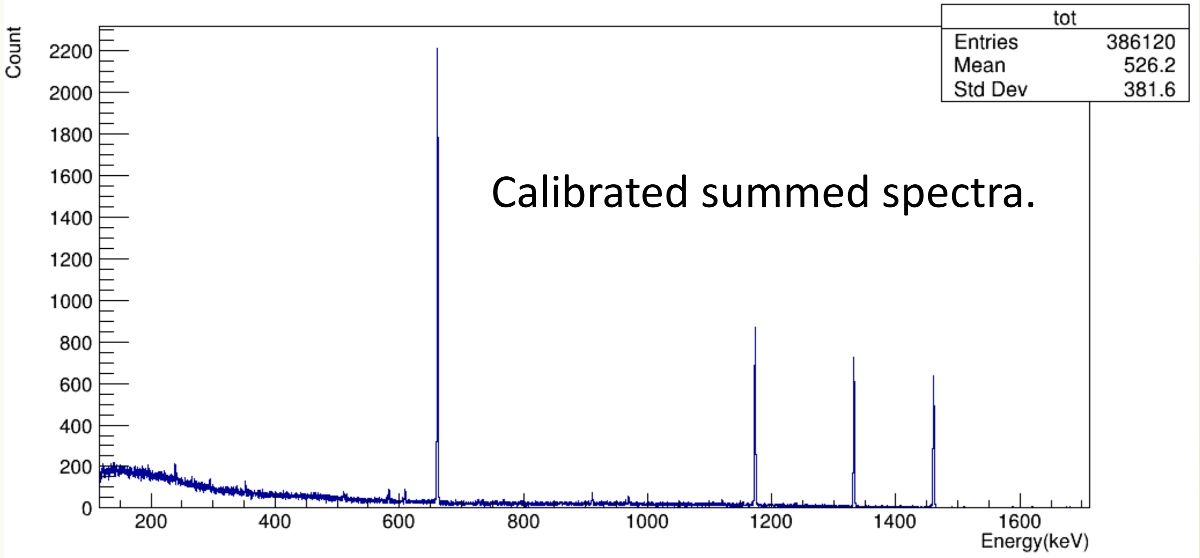
- Shown is multi source, near-point-like calibration source (^{40}K,^{60}Co,^{137}Cs).

- By now we have 3 bad detectors

  (1 off, 2 poor resolution). ☹



Un-calibrated summed spectra.



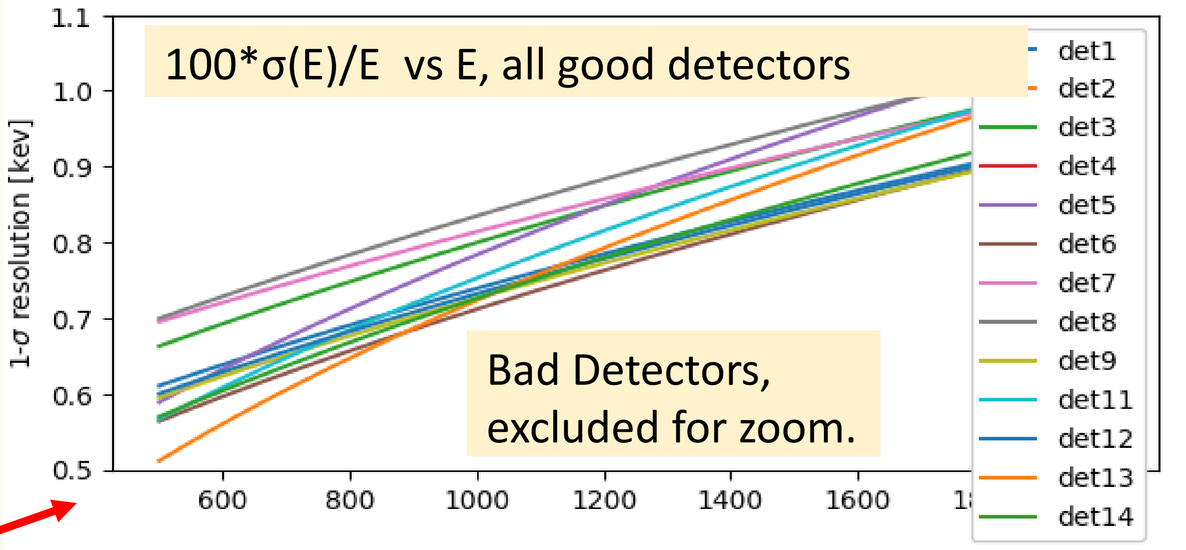
Calibrated summed spectra.

Summed Resolution.

- Multi-source calibration (^{40}K,^{60}Co,^{137}Cs)
- Summing can create non-Gaussian total peak shape and worse resolution, if resolutions or calibrations differ.
- Parameterized fit to resolution for all detectors:

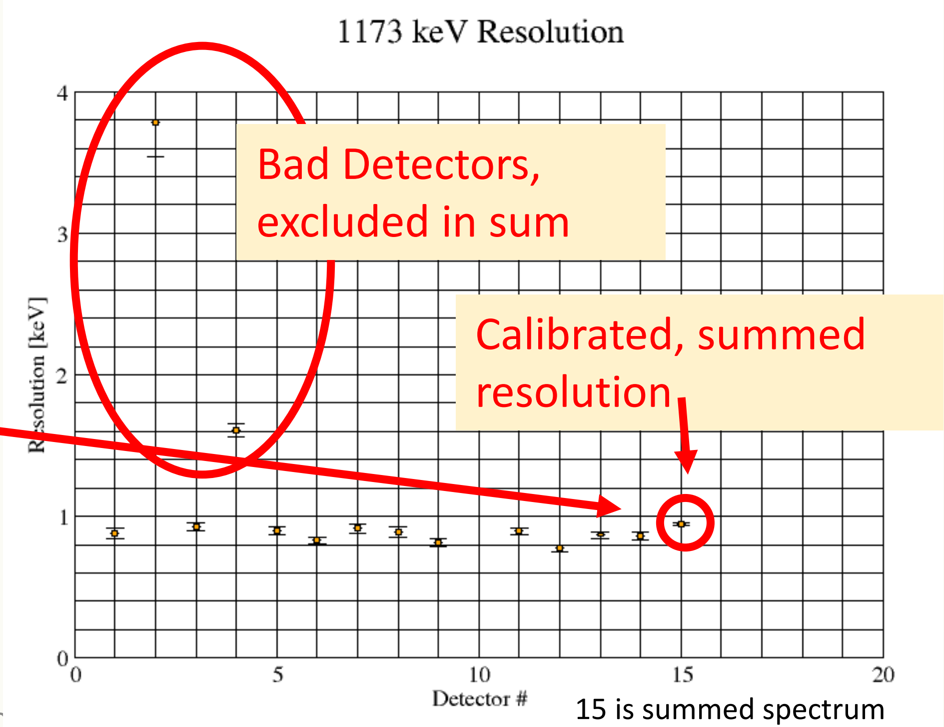
  Good agreement at all energies

- Summed resolution almost indistinguishable from individual detectors.



100*σ(E)/E vs E, all good detectors

Bad Detectors, excluded for zoom.



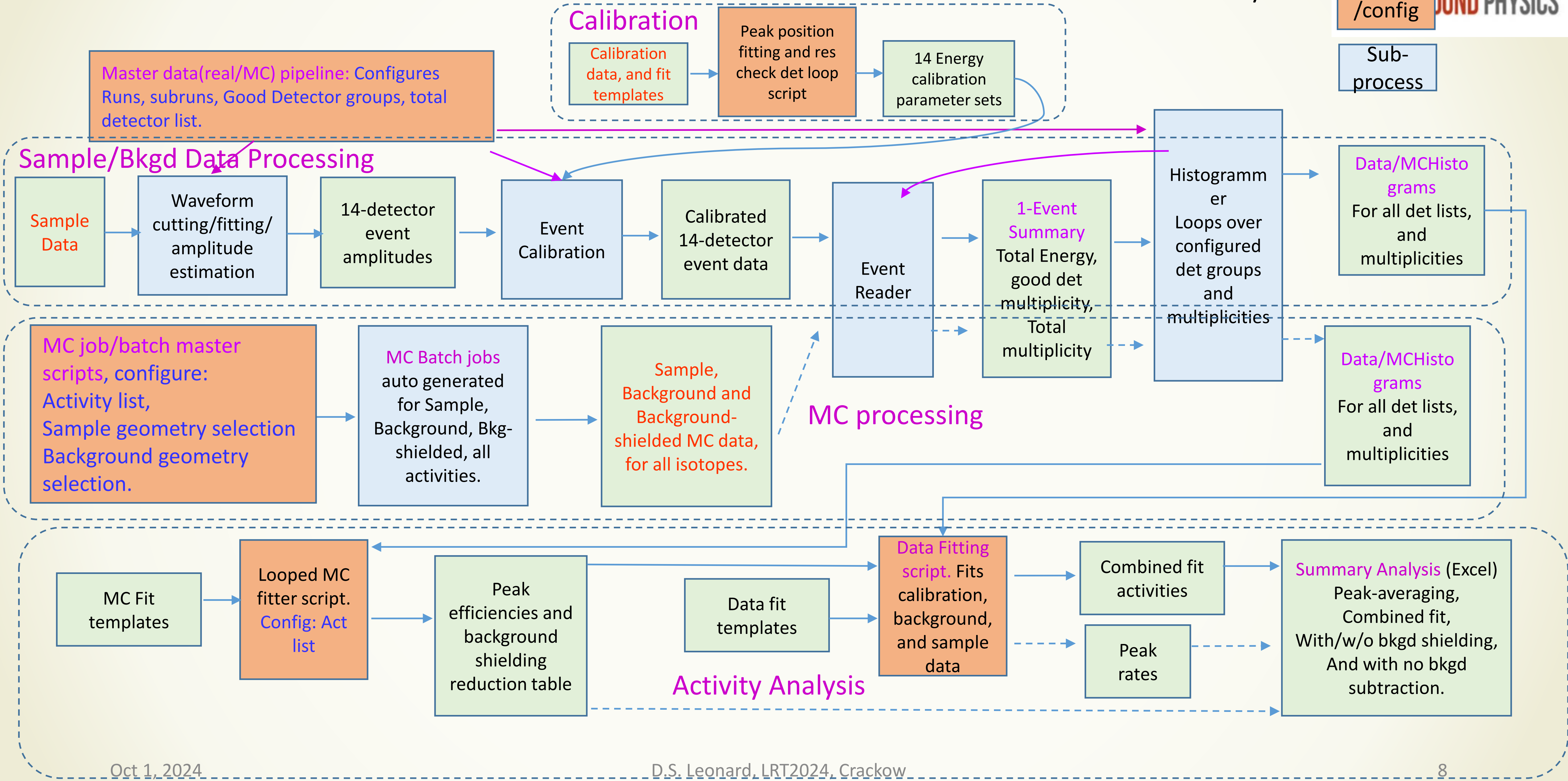
Bad Detectors, excluded in sum

Calibrated, summed resolution

15 is summed spectrum

Rough analysis pipelines/toolchains

Key:
- Process call
- Data I/O
- User process /config
- Data
- Sub-process



Calibration

Calibration data, and fit templates

Peak position fitting and res check det loop script

14 Energy calibration parameter sets

Master data(real/MC) pipeline: Configures Runs, subruns, Good Detector groups, total detector list.

Sample/Bkgd Data Processing

Sample Data

Waveform cutting/fitting/ amplitude estimation

14-detector event amplitudes

Event Calibration

Calibrated 14-detector event data

Event Reader

1-Event Summary Total Energy, good det multiplicity, Total multiplicity

Histogrammer Loops over configured det groups and multiplicities

Data/MCHistograms For all det lists, and multiplicities

MC processing

MC job/batch master scripts, configure:
Activity list,
Sample geometry selection
Background geometry selection.

MC Batch jobs auto generated for Sample, Background, Bkg-shielded, all activities.

Sample, Background and Background-shielded MC data, for all isotopes.

Data/MCHistograms For all det lists, and multiplicities

Activity Analysis

MC Fit templates

Looped MC fitter script. Config: Act list

Peak efficiencies and background shielding reduction table

Data fit templates

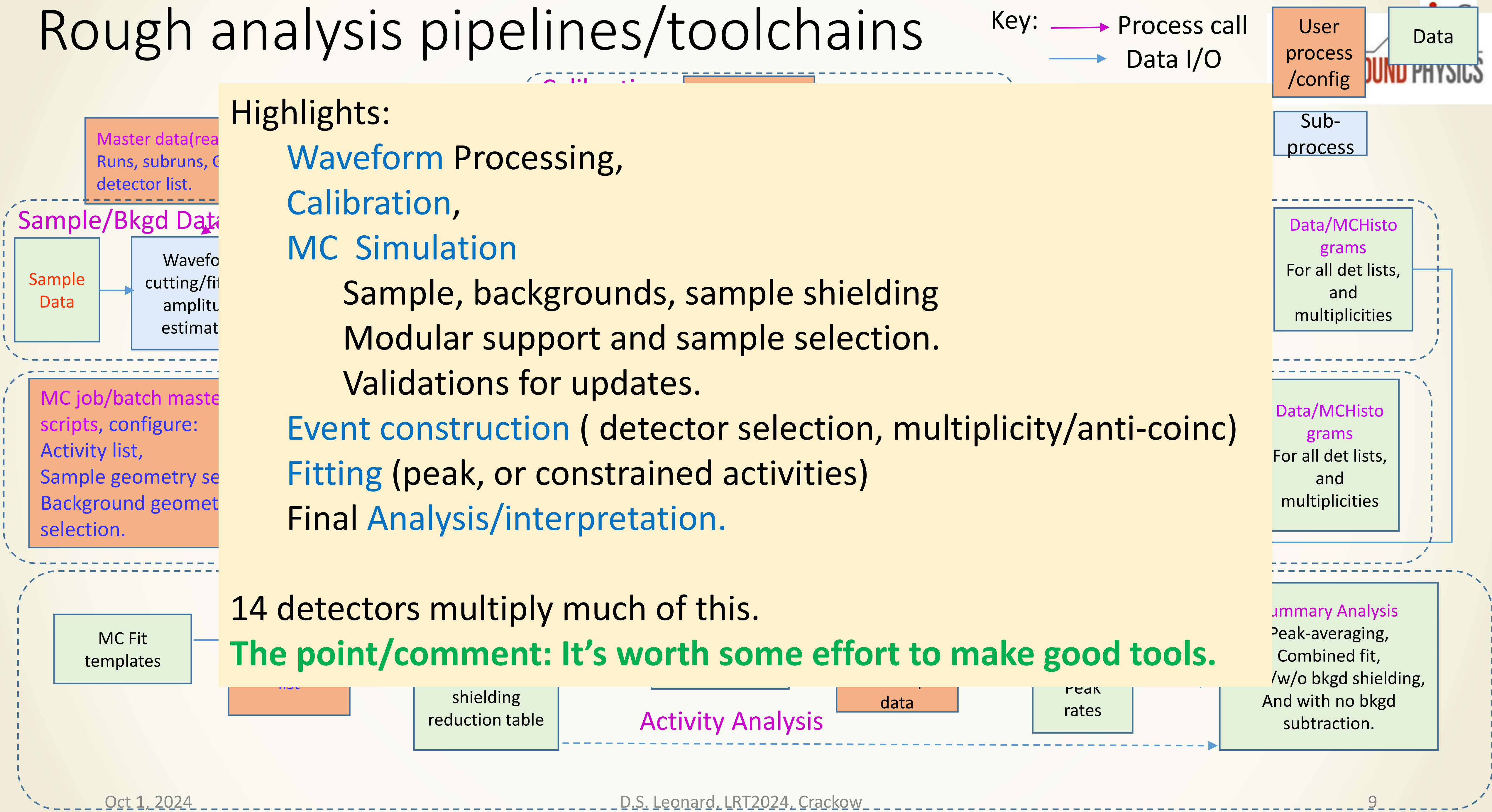
Data Fitting script. Fits calibration, background, and sample data

Combined fit activities

Peak rates

Summary Analysis (Excel) Peak-averaging, Combined fit, With/w/o bkgd shielding, And with no bkgd subtraction.

Rough analysis pipelines/toolchains



Key: Process call

Data I/O

User process /config

Data

Sub-process

Master data(rea
Runs, subruns, G
detector list.

Sample/Bkgd Dat

Sample Data

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scripts, configure:
Activity list,
Sample geometry se
Background geomet
selection.

Data/MCHistograms
For all det lists, and multiplicities

Data/MCHistograms
For all det lists, and multiplicities

Highlights:

- **Waveform** Processing,
- **Calibration**,
- **MC Simulation**
  - Sample, backgrounds, sample shielding
  - Modular support and sample selection.
  - Validations for updates.
- **Event construction** (detector selection, multiplicity/anti-coinc)
- **Fitting** (peak, or constrained activities)
- Final **Analysis/interpretation.**

14 detectors multiply much of this.

The point/comment: It's worth some effort to make good tools.

MC Fit templates

shielding reduction table

Activity Analysis

data

Peak rates

ummary Analysis
Peak-averaging,
Combined fit,
/w/o bkgd shielding,
And with no bkgd subtraction.

Historical and Published Work

MoO_3 Powder measurements

- CAGe used extensively for measurement of MoO_3 powders pre/post purification, for AMoRE crystal growth.
- Results on raw and purified powder published.

[1] S. Y. Park et al NIM A 992, (2021).
[2] O. Gileva et al, Front. Phys., 30 March 2023 Volume 11 - 2023 https://doi.org/10.3389/fphy.2023.1142136

Ref [2] **Unit: uBq/kg:**

	^{228}Ac	^{228}Th	^{226}Ra	^{40}K
Raw $^{100}MoO_3$	260 ± 50	210 ± 50	260 ± 50	8500 ± 1400
Purified $^{100}MoO_3$	<27	<16	110 ± 30	1700 ± 340

Published Work, contd…

- CAGe detector paper, including Rn control, resolution, backgrounds, **o-ring activity survey**, electronics, waveforms etc.

  Leonard, D. S. *et al. NIM A* **989**, (2021). (Detector)

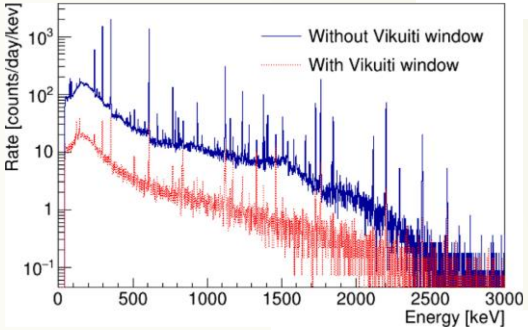
- Efficiency calibration via dead-layer correction

  Park, S. Y. *et al* *App. Radiat.and Isot.* **193**, 110654 (2023). (efficiency)

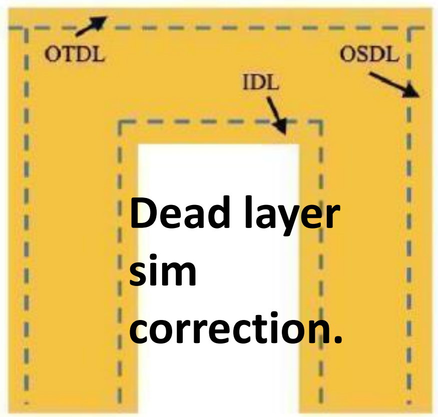
- 180Ta Decay simulation.

  Kim, G.W., *et al. J. Korean Phys. Soc.* 75, 32–39. (180Ta decay)

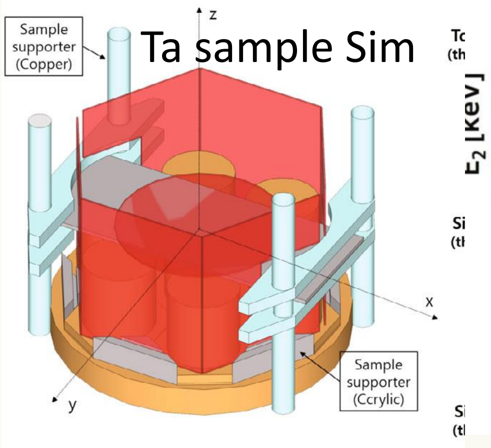
Rn reduction with window and N_2 flush.



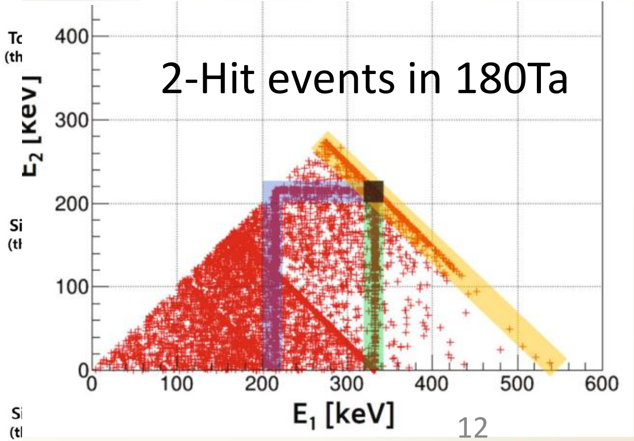

Cal. source



Dead layer sim correction.



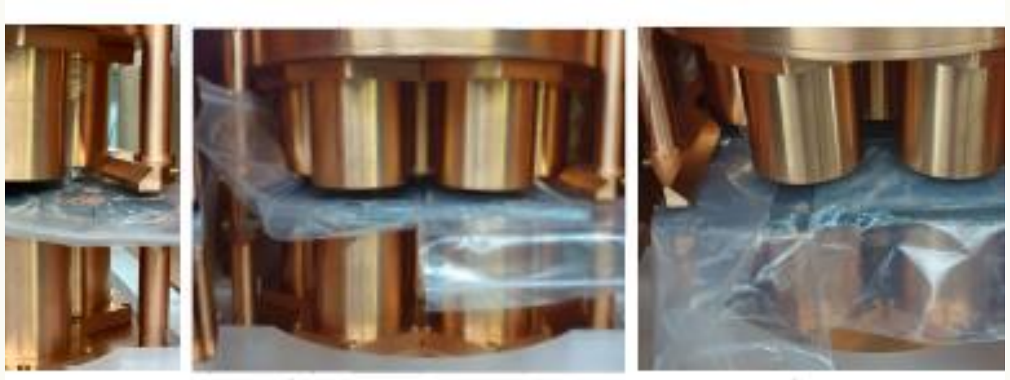
Ta sample Sim



2-Hit events in 180Ta

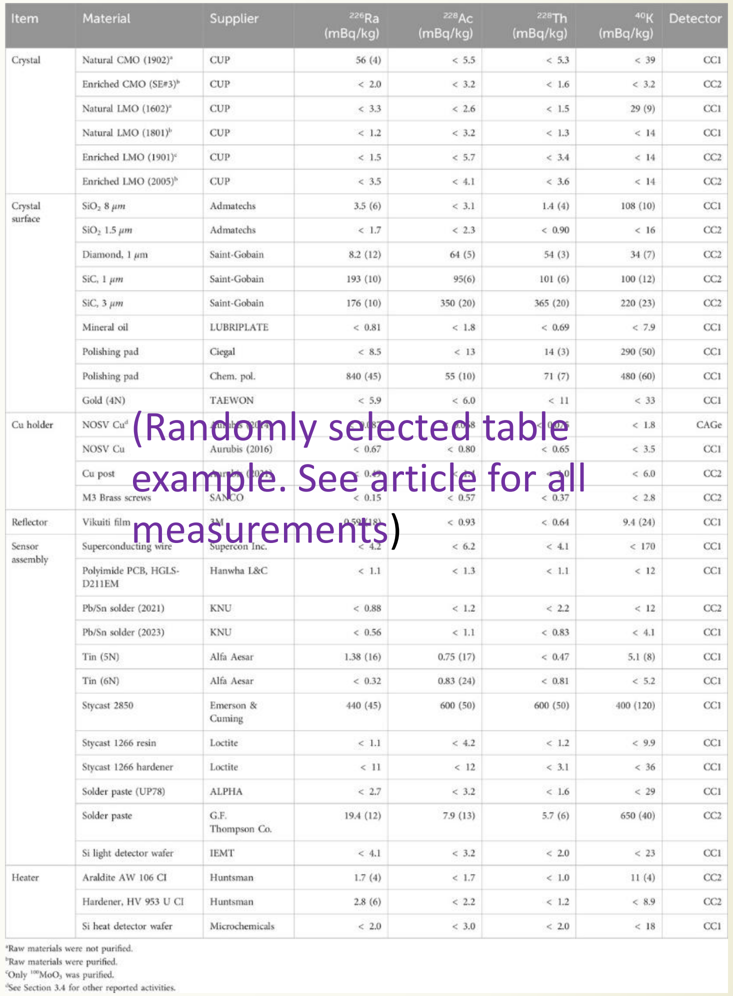
AMoRe-II Radioassay Screening

- Collaboration of all CUP AMoRe assay efforts, especially CC1/CC2 and ICPMS.
- CAGe Highlights:
  - Lead survey measurements.



  - Aurubis NOSV copper, Next slide

Agrawal, A. et al. (AMoRE Collab.) 2024. Front. Phys. 12. https://doi.org/10.3389/fphy.2024.1362209 (AMoRE Assay)



Item	Material	Supplier	^{226}Ra (mBq/kg)	^{228}Ac (mBq/kg)	^{228}Th (mBq/kg)	^{40}K (mBq/kg)	Detector
Crystal	Natural CMO (1902)[a]	CUP	56 (4)	< 5.5	< 5.3	< 39	CC1
	Enriched CMO (SE#3)[b]	CUP	< 2.0	< 3.2	< 1.6	< 3.2	CC2
	Natural LMO (1602)[a]	CUP	< 3.3	< 2.6	< 1.5	29 (9)	CC1
	Natural LMO (1801)[b]	CUP	< 1.2	< 3.2	< 1.3	< 14	CC1
	Enriched LMO (1901)[c]	CUP	< 1.5	< 5.7	< 3.4	< 14	CC2
	Enriched LMO (2005)[b]	CUP	< 3.5	< 4.1	< 3.6	< 14	CC2
Crystal surface	SiO_2 8 μm	Admatechs	3.5 (6)	< 3.1	1.4 (4)	108 (10)	CC1
	SiO_2 1.5 μm	Admatechs	< 1.7	< 2.3	< 0.90	< 16	CC2
	Diamond, 1 μm	Saint-Gobain	8.2 (12)	64 (5)	54 (3)	34 (7)	CC2
	SiC, 1 μm	Saint-Gobain	193 (10)	95(6)	101 (6)	100 (12)	CC2
	SiC, 3 μm	Saint-Gobain	176 (10)	350 (20)	365 (20)	220 (23)	CC2
	Mineral oil	LUBRIPLATE	< 0.81	< 1.8	< 0.69	< 7.9	CC1
	Polishing pad	Ciegal	< 8.5	< 13	14 (3)	290 (50)	CC1
	Polishing pad	Chem. pol.	840 (45)	55 (10)	71 (7)	480 (60)	CC1
	Gold (4N)	TAEWON	< 5.9	< 6.0	< 11	< 33	CC1
Cu holder	NOSV Cu[d]	Aurubis (2014)	< 0.087	[illegible]	[illegible]	< 1.8	CAGe
	NOSV Cu	Aurubis (2016)	< 0.67	< 0.80	< 0.65	< 3.5	CC1
	Cu post	Aurubis (2021)	< 0.49	[illegible]	< 1.0	< 6.0	CC2
	M3 Brass screws	SANCO	< 0.15	< 0.57	< 0.37	< 2.8	CC2
Reflector	Vikuiti film	3M	0.59 (18)	< 0.93	< 0.64	9.4 (24)	CC1
Sensor assembly	Superconducting wire	Supercon Inc.	< 4.2	< 6.2	< 4.1	< 170	CC1
	Polyimide PCB, HGLS-D211EM	Hanwha L&C	< 1.1	< 1.3	< 1.1	< 12	CC1
	Pb/Sn solder (2021)	KNU	< 0.88	< 1.2	< 2.2	< 12	CC2
	Pb/Sn solder (2023)	KNU	< 0.56	< 1.1	< 0.83	< 4.1	CC1
	Tin (5N)	Alfa Aesar	1.38 (16)	0.75 (17)	< 0.47	5.1 (8)	CC1
	Tin (6N)	Alfa Aesar	< 0.32	0.83 (24)	< 0.81	< 5.2	CC1
	Stycast 2850	Emerson & Cuming	440 (45)	600 (50)	600 (50)	400 (120)	CC1
	Stycast 1266 resin	Loctite	< 1.1	< 4.2	< 1.2	< 9.9	CC1
	Stycast 1266 hardener	Loctite	< 11	< 12	< 3.1	< 36	CC1
	Solder paste (UP78)	ALPHA	< 2.7	< 3.2	< 1.6	< 29	CC1
	Solder paste	G.F. Thompson Co.	19.4 (12)	7.9 (13)	5.7 (6)	650 (40)	CC2
	Si light detector wafer	IEMT	< 4.1	< 3.2	< 2.0	< 23	CC1
Heater	Araldite AW 106 CI	Huntsman	1.7 (4)	< 1.7	< 1.0	11 (4)	CC2
	Hardener, HV 953 U CI	Huntsman	2.8 (6)	< 2.2	< 1.2	< 8.9	CC2
	Si heat detector wafer	Microchemicals	< 2.0	< 3.0	< 2.0	< 18	CC1

[a] Raw materials were not purified.
[b] Raw materials were purified.
[c] Only $^{100}MoO_3$ was purified.
[d] See Section 3.4 for other reported activities.

(Randomly selected table example. See article for all measurements)

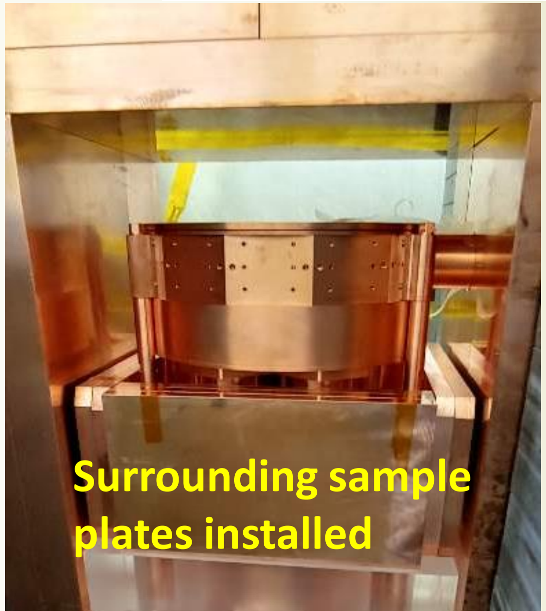
Aurubis NOSV copper

- 145 kg sample from 3 tonne custom-order of Aurubis NOSV copper.
- Machined to central and surrounding plates.
- Data:
  - 82 days good Rn-Free data.
  - 31 days Rn-free background.
  - Systematics limited anyway (next slide.)
- gdfit multi activity-constrained spectral fit needed to ^{231}Pa; helps for ^{227}Ac

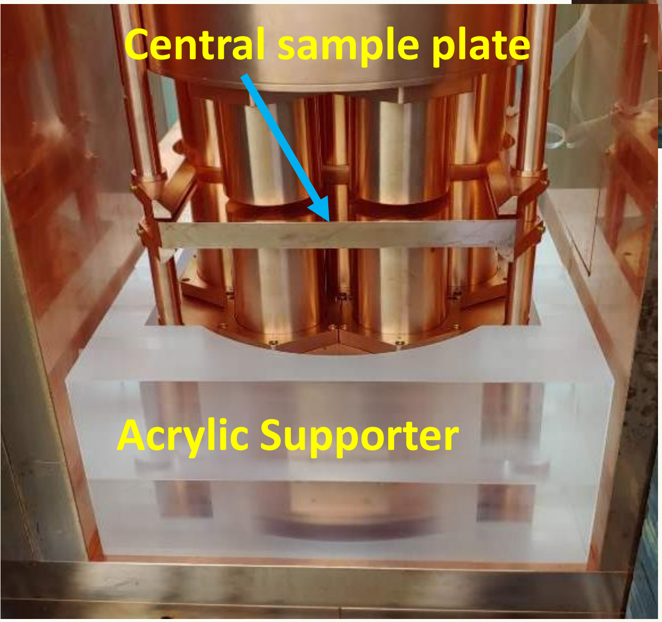
  (Almost every peak has potential interferences, esp. 231 Pa)

See AMoRE assay paper

Chain	Activity uBq/kg
226Ra	<87
228Th	<75
228Ac	<68
40K	<1800
235U	<44
231Pa	<690
227Ac	<32
234Th	<330



Surrounding sample plates installed



Central sample plate

Acrylic Supporter

Sample Background Shielding [1—3]

- First considered for CC1/2 results [1,3]
- MC sims can determine shielding vs E, for known bkgd geometry.

  (Now automated with sample sim)
- Bkgd src isn't known = systematic error.
  - Highest shielding/result: From distributed ie cryostat, air, and perimeter sources (like Rn). Up to 90% shielding for this sample (Rn between window and door).
  - Lowest shielding/result: Detector contact has about 3% bkgd shielding (near 0) due to high eff.
- Observed shielding is very inconsistent with Highest possibility, but could constrain lowest one for other samples.
- For results today, conservatively assume full range.

NOSV Copper Again.

Chain	Activity W/shielding Syst.	uBq/kg Assume No bkgd Shielding	Observed Bkgd reduction
226Ra	<87	<27	~35 +/- 9%
228Th	<75	<21	~20 +/- 10%
228Ac	<68	<28	~26 +/- 17%
40K	<1800	<200	~2 +/- 6 %
235U	<44		
231Pa	<690		
227Ac	<32		
234Th	<330		

Preliminary

[1] Lee E.K, et al. Fall Meeting: Korean Physical Society (2019).
[2] Thiesse M, Scovell P, Thompson L, Appl. Radiat. Isot. (2022) 188:110384.
[3] Agrawal, A. et al. (AMoRE Collab.) 2024. Front. Phys. 12. (AMoRE Assay)

Recent Work

Rn Tent Construction

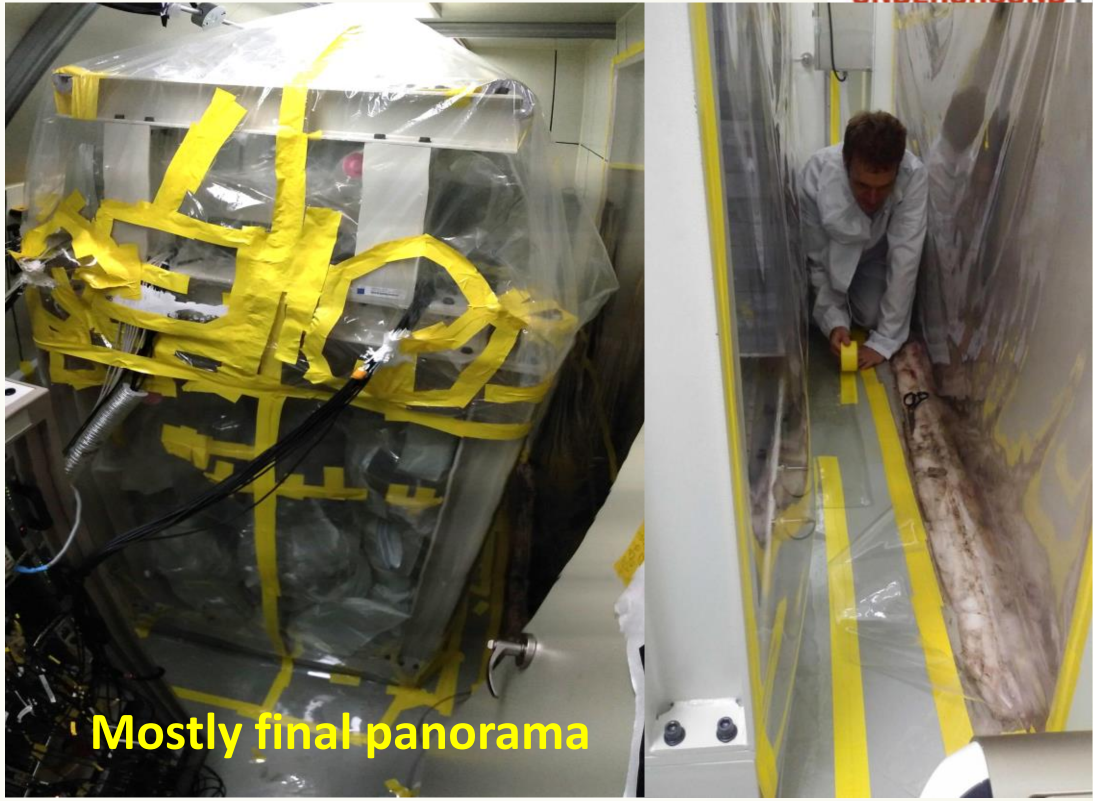
Rn Free air system failed in early 2023. Abandoned mid 2023.

Intsalled vinyl cover over array, secured carefully with tape and glue. (painstaking in tight space)

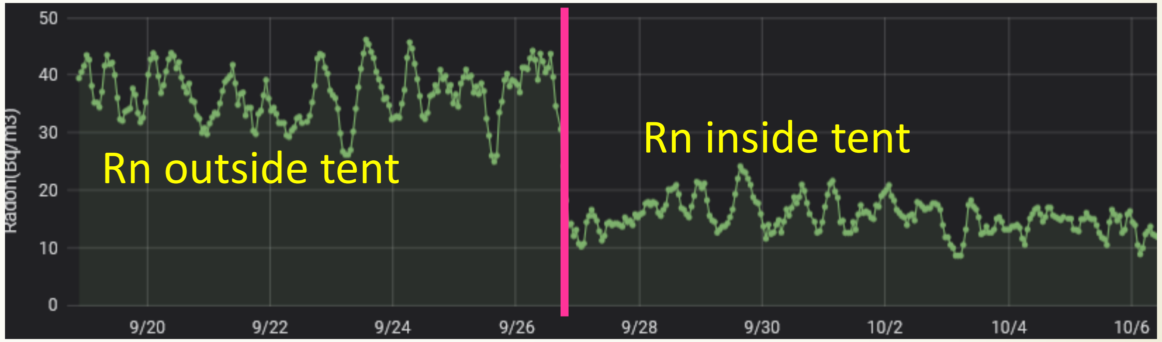
N_2 Flow: ~15 Lpm from chamber flush, avg 20 Lpm from cryo-dewar venting.

Rn outide Pb reduced from ~40 Bq/m^3 to ~15. Not great.
Consistent with poor flush* or Rn emanation.
O2 level ~ 5% (out of ~21% normal) => poor flushing.

609 keV Rate for bkgd lower than Rn-free bgkd rate for Cu study. But, instable.

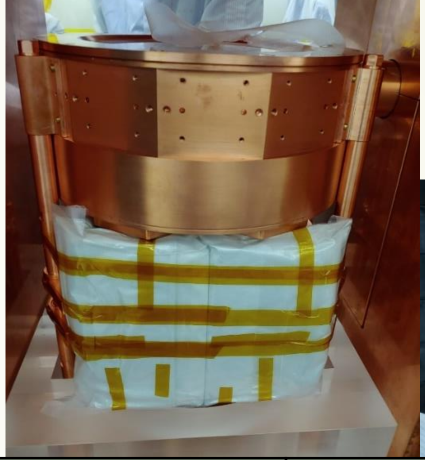


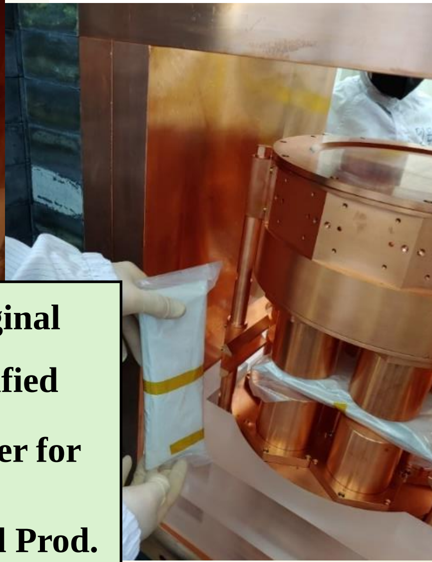
40 Bq/m^3 ->



*Estimates suggest 1--2cm dia. hole enough to harm flushing.

MoO$_3$ Reprocessed from AMoRE LMO Crystal waste (melt).





- Inserted 8.036kg in CAGe.
- Two months Good data started with tent Sept ‘23
- No-sample Rn bkgd is equivalent to ~ 500 uBq/kg of ^{226}Ra signal in sample.

  ex: 10% total bkgd error -> 50 uBq/kg syst.
- Bkgd shielding by sample from

  30 – 80% depending on E.

Chain	**LMOmelt**		**Original Purified Powder for Crystal Prod.**
	Result	**Max bgkd-shielding assump.**	
^{226}Ra	<270	200 ± 40	110 ± 30
^{228}Th	<170	117 ± 27	<16
^{228}Ac	160 ± 60	200 ± 40	<27
^{40}K	4300 ± 1400	5000 ± 900	1700 ± 340
^{235}U	<92		
^{231}Pa	<650		
^{227}Ac	<40		
^{234}Th	<1500		

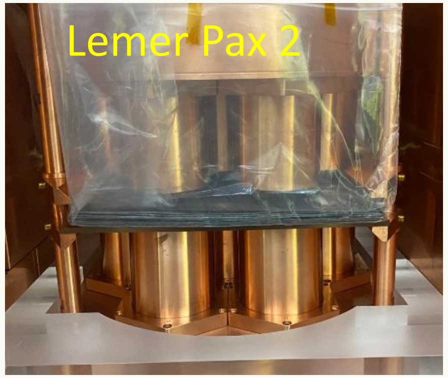
Preliminary

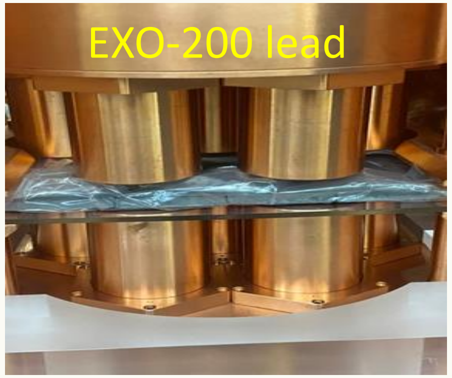
Continued Lead Survey for AMoRE-II

Unit: uBq/kg

- As reported in AMoRE assay paper, lead bkgd is non-trivial.
- More samples measured with tent in 2024.
- ^{226}Ra analysis uses April lead as bkgd for EXO and LP1b. No shielding correction!
- Rn instabilities:
  - Env monitor particle count, O2, Rn, but all were intermittent.
  - Data cuts for low flush rate, stabilized after April.
  - Not all fluctuations fully explained.
  - Lemer Pax 1a and 1b show discrepancy, but not quite identical samples.

See poster by S.Y. Park. AMoRe-rad paper Pb with bkgd shielding update.





Unit: uBq/kg

Chain	Mar. Lemer Pax 1a	Apr. Lemer Pax 2	EXO-200 Pb*	Aug. Lemer Pax 1b
Date (Array DAQ start)	Mar. 6	Apr. 15	Jun. 17	Aug. 26
^{226}Ra	<590	<97	400 ± 90	1030 ± 180
^{228}Th	<170	<120	<190	<140
^{228}Ac	<1500	<3300	<2700	<3000
^{40}K	<260	<160	<120	<200
^{235}U	<600	<400	<1800	<3400
^{231}Pa	<3900	<1900	<5400	<1900
^{227}Ac	<140	90 ± 30	<410	<100
^{234}Th	<3500	<1700	<2500	<2100

Preliminary

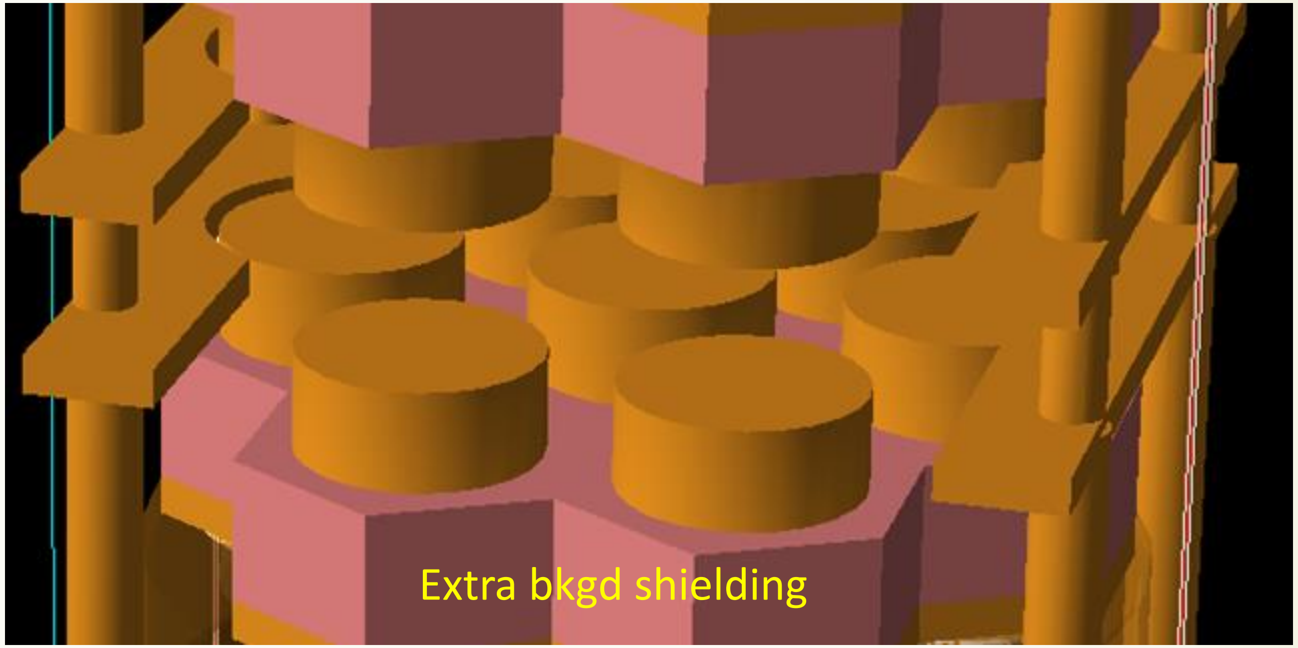
*Thanks to EXO-200/nEXO collaborators A. Piepke and D. Cherniak at U. Alabama

O-ring sim/shields

- Goal study impact of O-rings to backgrounds
- Consider ability to further shield them.
- Added Cu insert (pink) to shield o-rings more.
- Conclusions:
    - O-rings don't contribute much*, Most for ^{40}K ~ 1/3 of total.
    - Shields reduce O-ring bkgd by 30% to 40%.
    - Overall weak improvement.

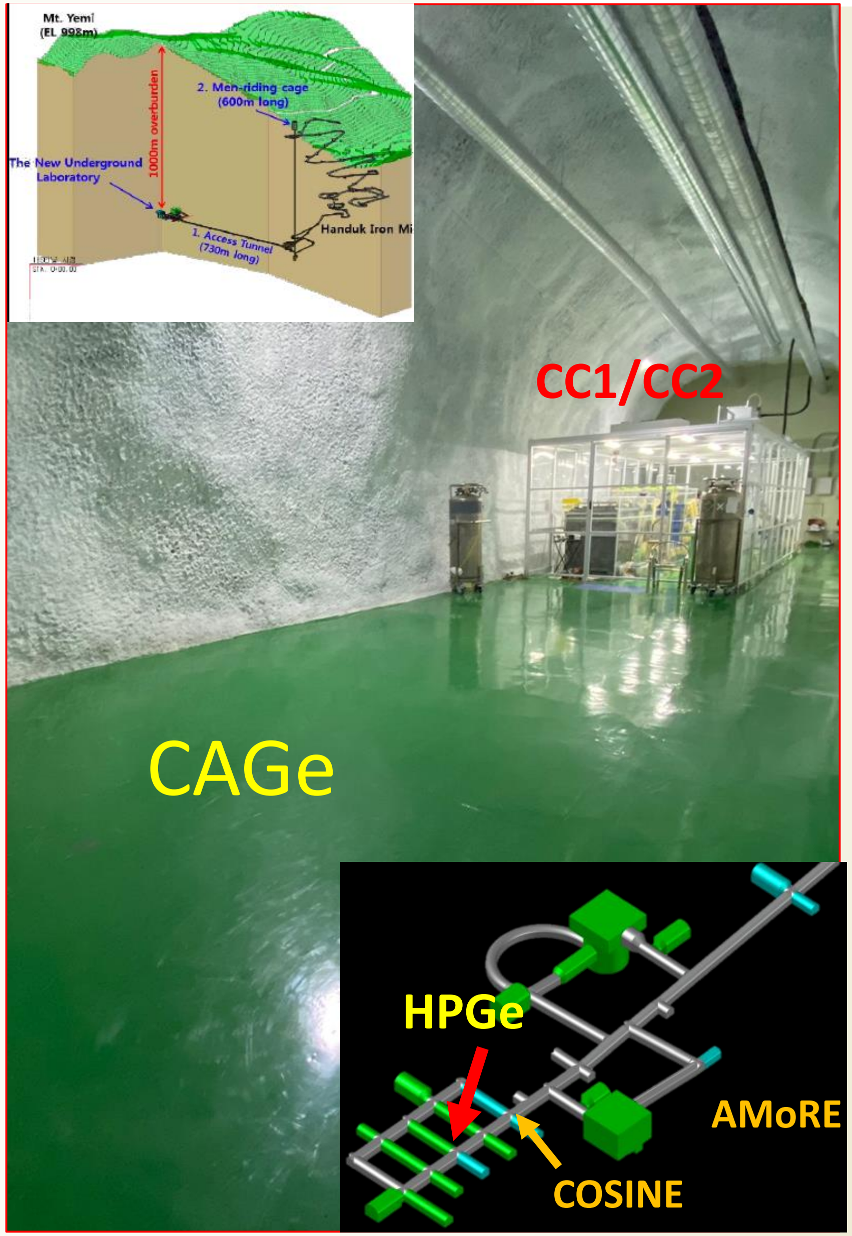
Ex: need 840 mBq/kg 226Ra in O-ring to explain Bkgd, Actual: around 15 to 30mB/kg.

O-ring region redacted



Future at YemiLab (see LRT 2022 talk)

- CAGe is only remaining facility at YangYang.
- Moving to Yemilab 2025 or 2026.
    - Detectors will be thermal cycled and/or reconditioned.
- Will not rely on Rn-Free air systems.
- Planning to upgraded solid (acrylic) N2-flushed enclosure with access accommodations.
    - Rn level cannot be fully stabilized since source is environmental
    - Must be brought to insignificant levels.
    - Requires extremely good sealing and/or higher N2 flow -> Challenging.
- Bkgd shielding is no issue without bkgd.
    - Other backgrounds are already low enough for most measurements (excepting extreme cases like Copper).



Summary

- The CAGe has proven to be a valuable workhorse for high-sensitivity needs.
- Primarily used for AMoRE action-item purposes.
- Room for growth in Yemilab with Rn control upgrades, and future assay and physics searches.

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Purification Team, lead by O. Gileva,
Machining, etc: C.S. Kang,
And full AMoRE Collaboration (crystals, design, sim, etc)
Apologies for any left out.