KDK: First measurement of the ^{40}K ground state electron capture for backgrounds in rare-event searches

Presented By: Matthew Stukel (He/Him), for the KDK collaboration

28th International Conference on Topics in Astroparticle and Underground Physics
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Part 1: KDK

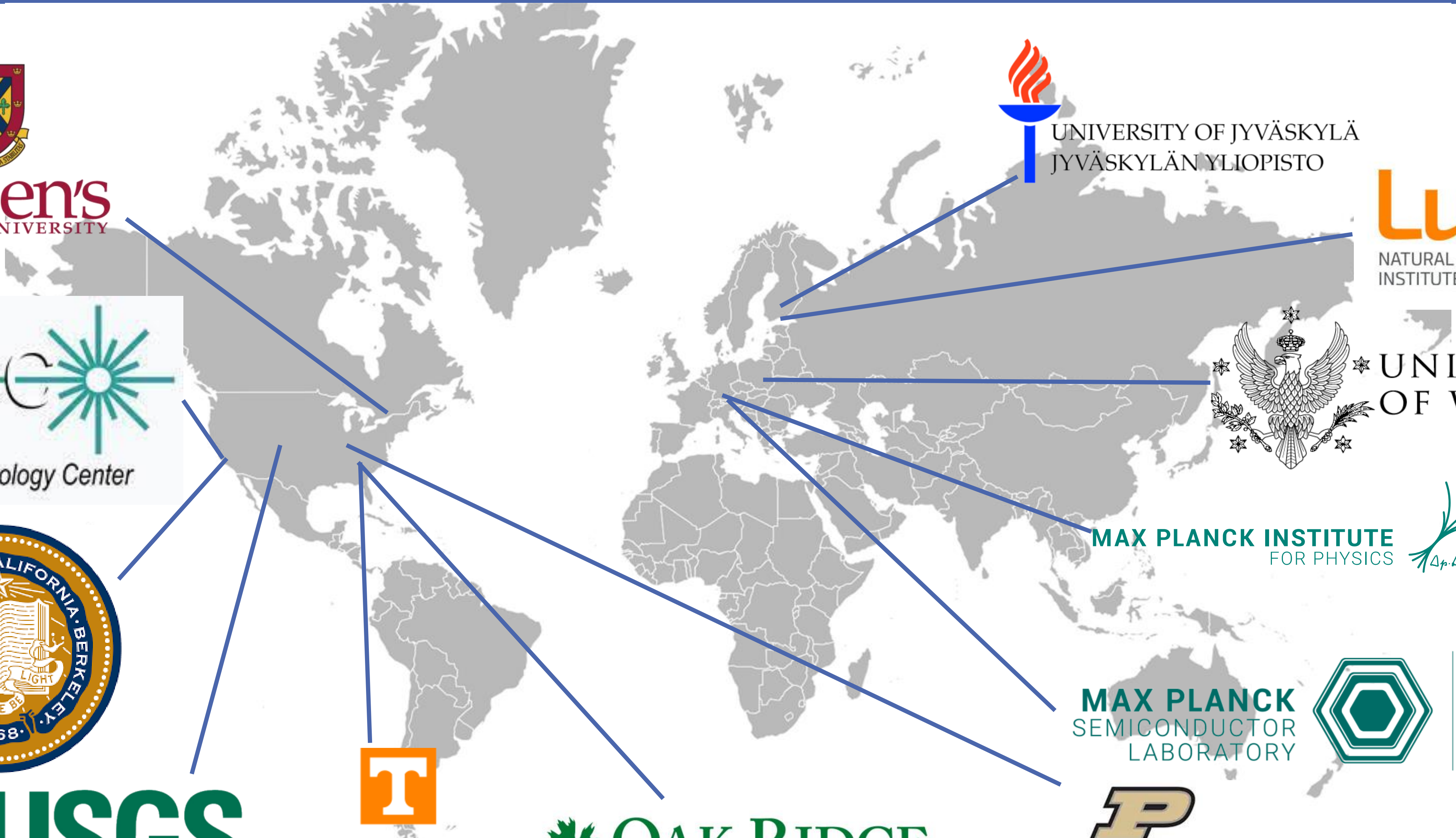
What is KDK?

Potassium

KDK

"Decay"

- KDK is an international collaboration dedicated to the measurement of the ground state electron capture of ^{40}K [1]



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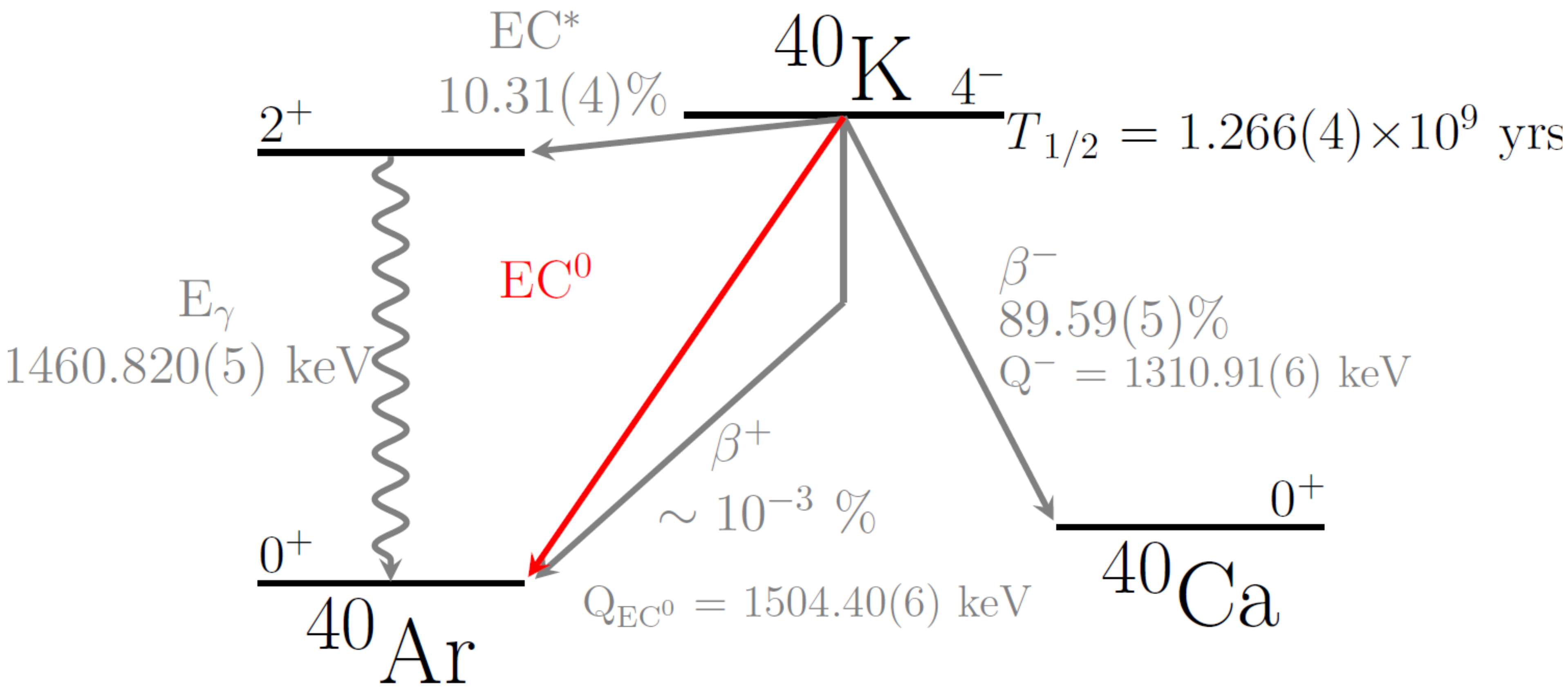
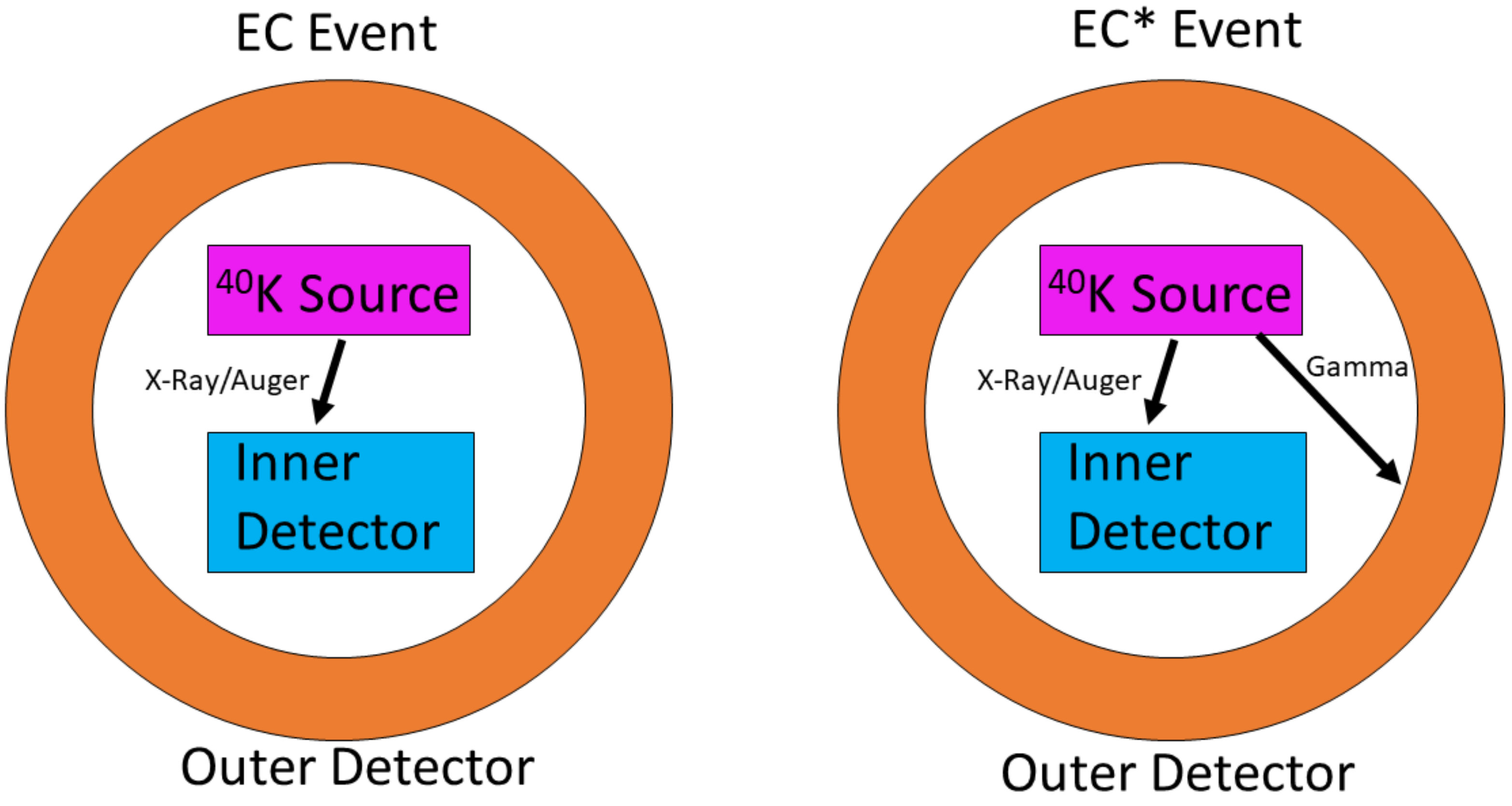
What is ^{40}K?



- **Nuclear Theory:** Rare 3U EC transition, weak-axial vector coupling quenching
- **Particle Physics:** ^{40}K is a background in **rare-event searches:** especially in **NaI based detectors**
  - E.g. DAMA, COSINUS, COSINE-100, ANAIS-112 and PICO-LON
- **Geochronology:** ~10^9 years half-life, excellent for dating

Part 2: Experimental Setup

KDK Experiment

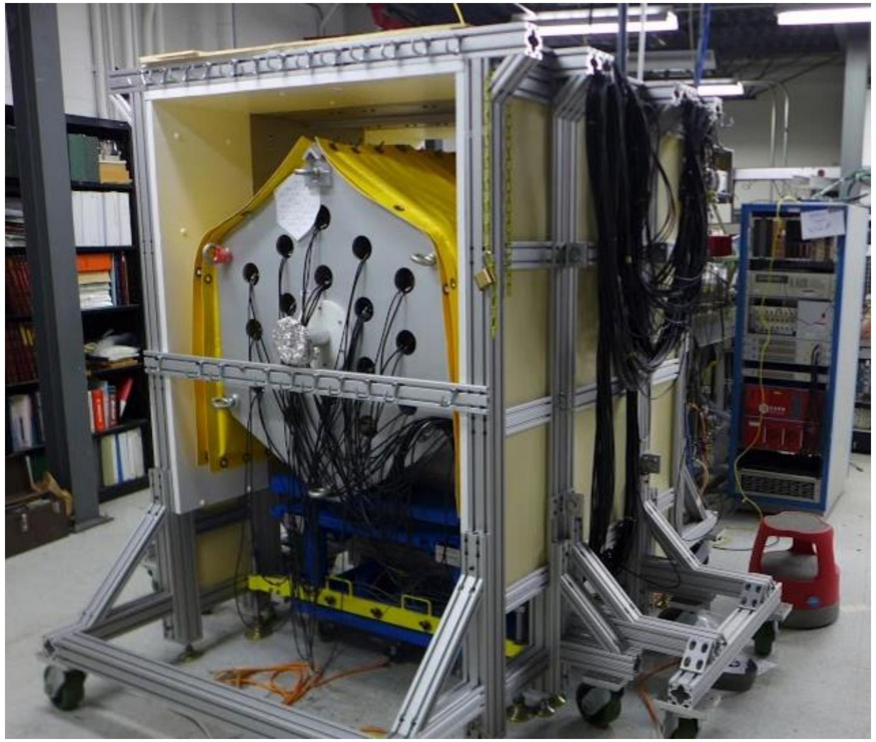


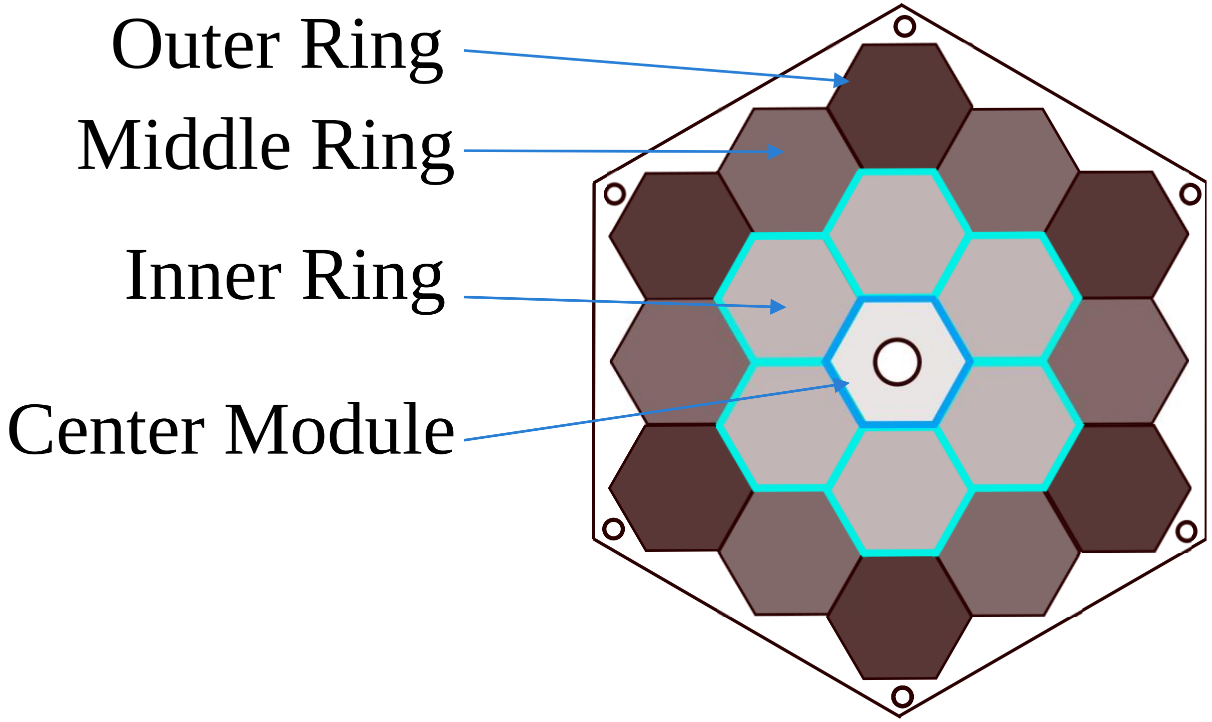
$$\frac{BR_{EC}}{BR_{EC*}} = \rho$$

- Instrumentation paper published in NIM A (2021) [4]

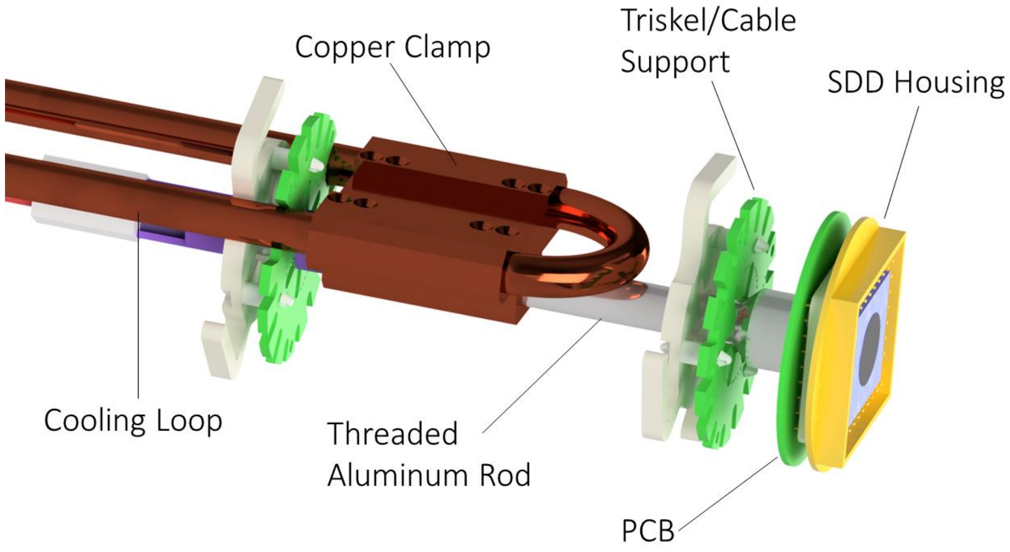
MTAS – External Detector

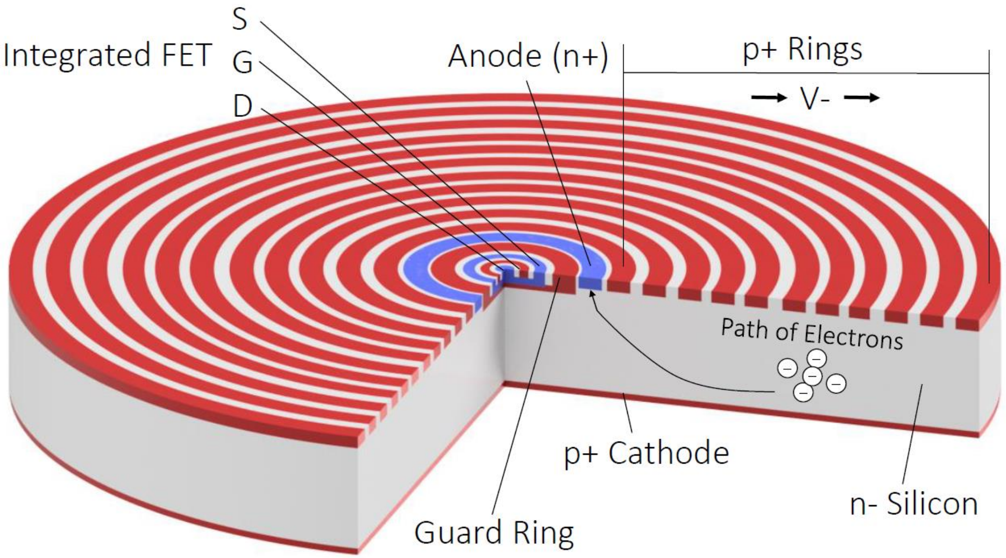
- Modular Total Absorption Spectrometer (MTAS) from Oak Ridge National Lab (ORNL) [5]
- Consists of 19 NaI(Tl) hexagonal shaped detectors (53cm x 20cm) weighing in at ~54 kg each
- MTAS provides ~4π coverage on tagging the 1460 keV gammas





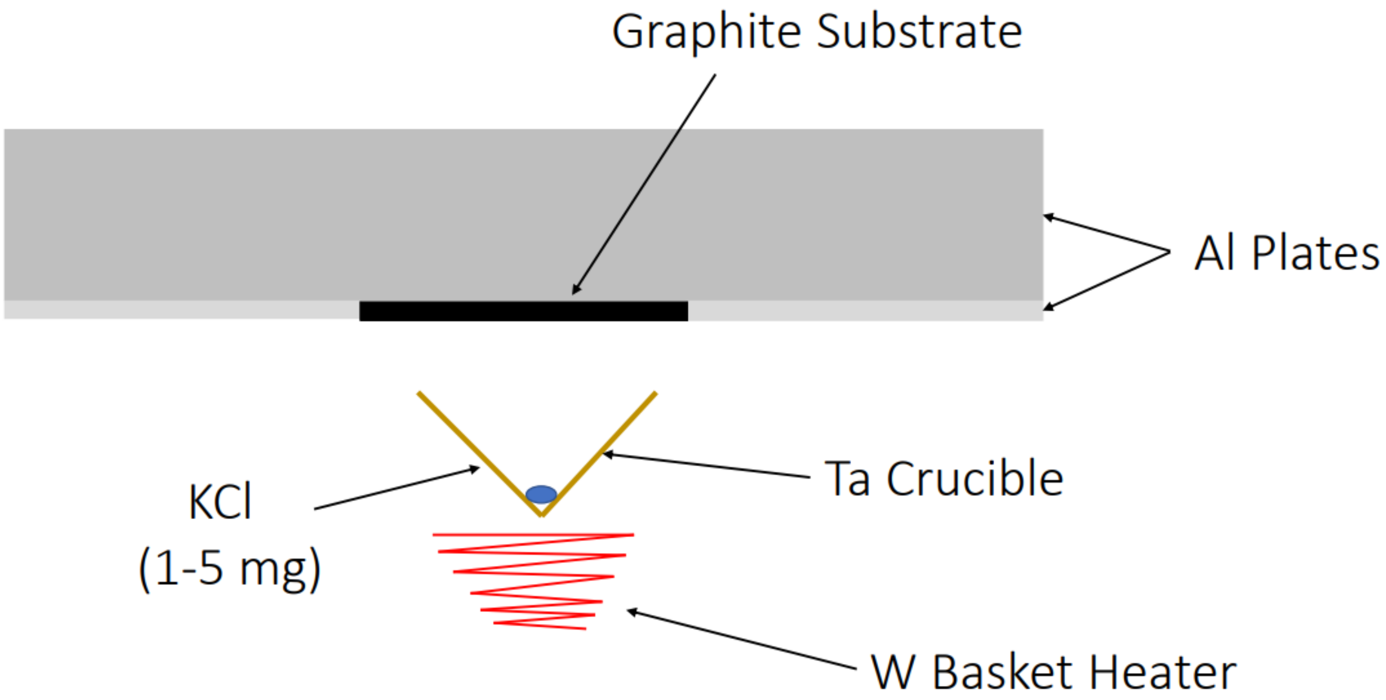
SDD – Silicon Drift Detector

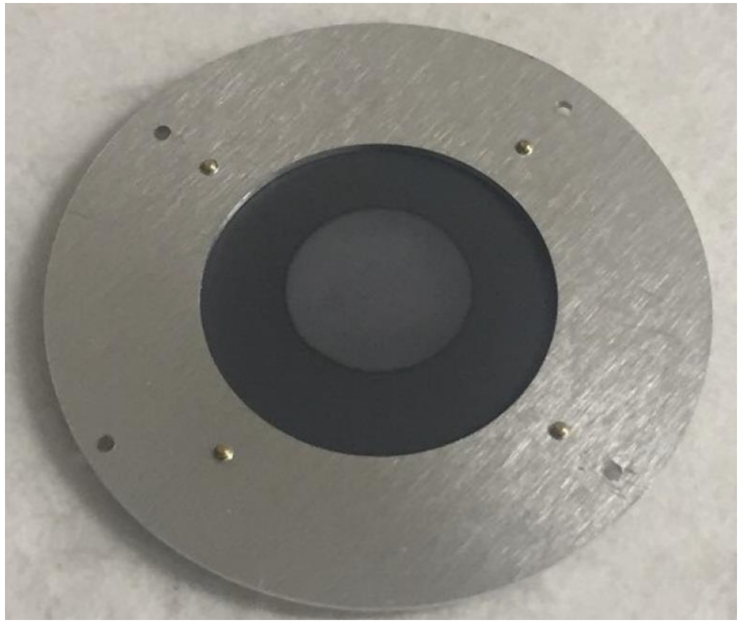


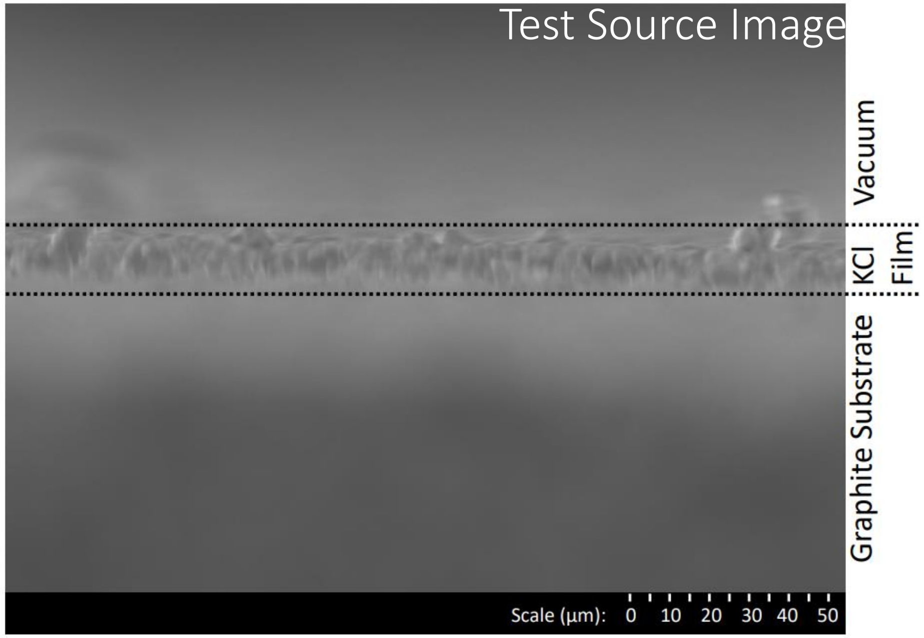


- **Energy Threshold**: ~250 eV
- **Energy Limit:** ~15 keV
- **FWHM:** ~170 eV @ 6keV

^{40}K – Source Development

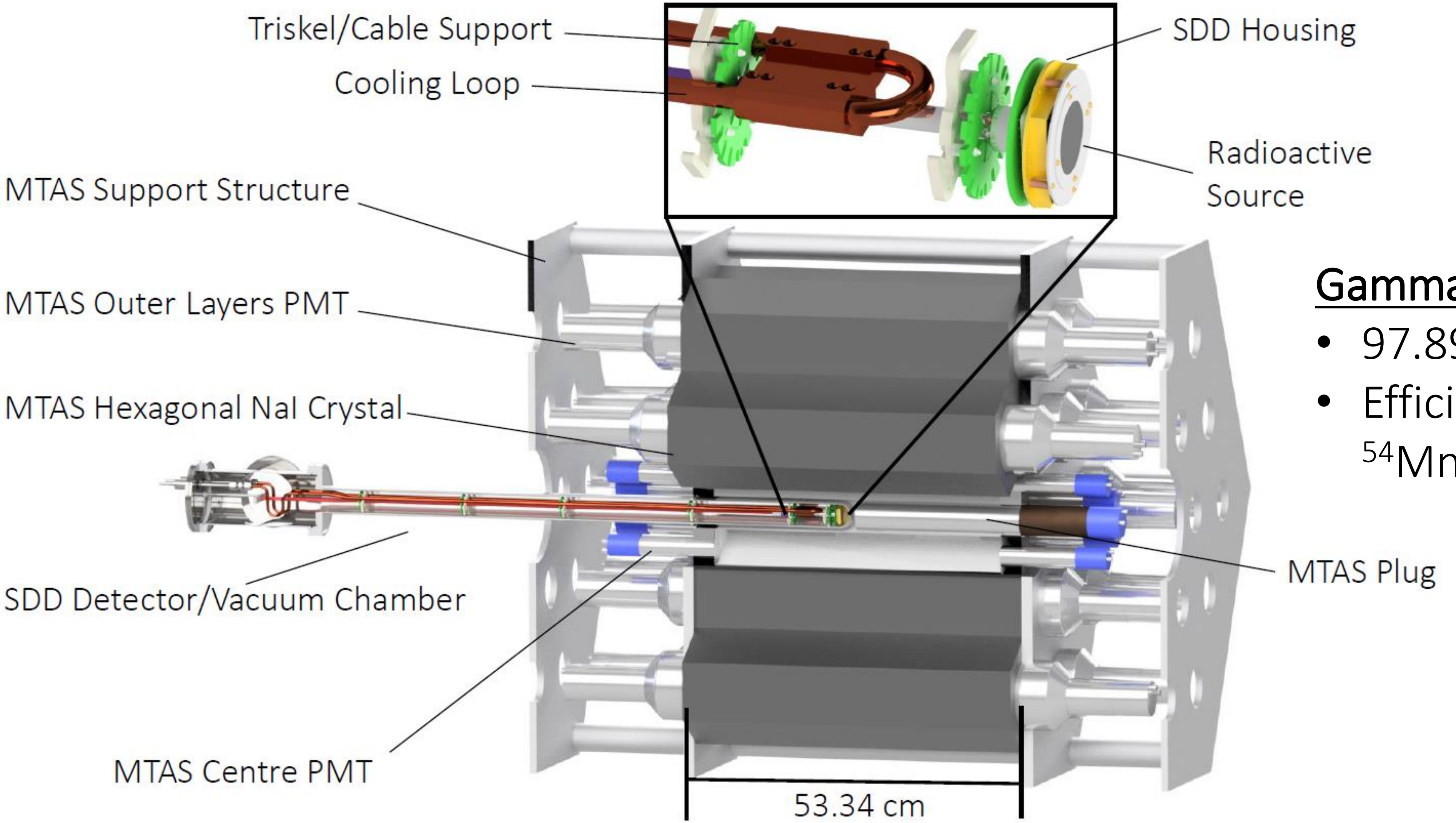






- ELECTRON BEAM DEPOSITION
- 3.0 mg of enriched ($^{40}K/^{Tot}K$: 0.01% -> 16%) KCl
- Source used is 5 µm thick

KDK Experimental Setup

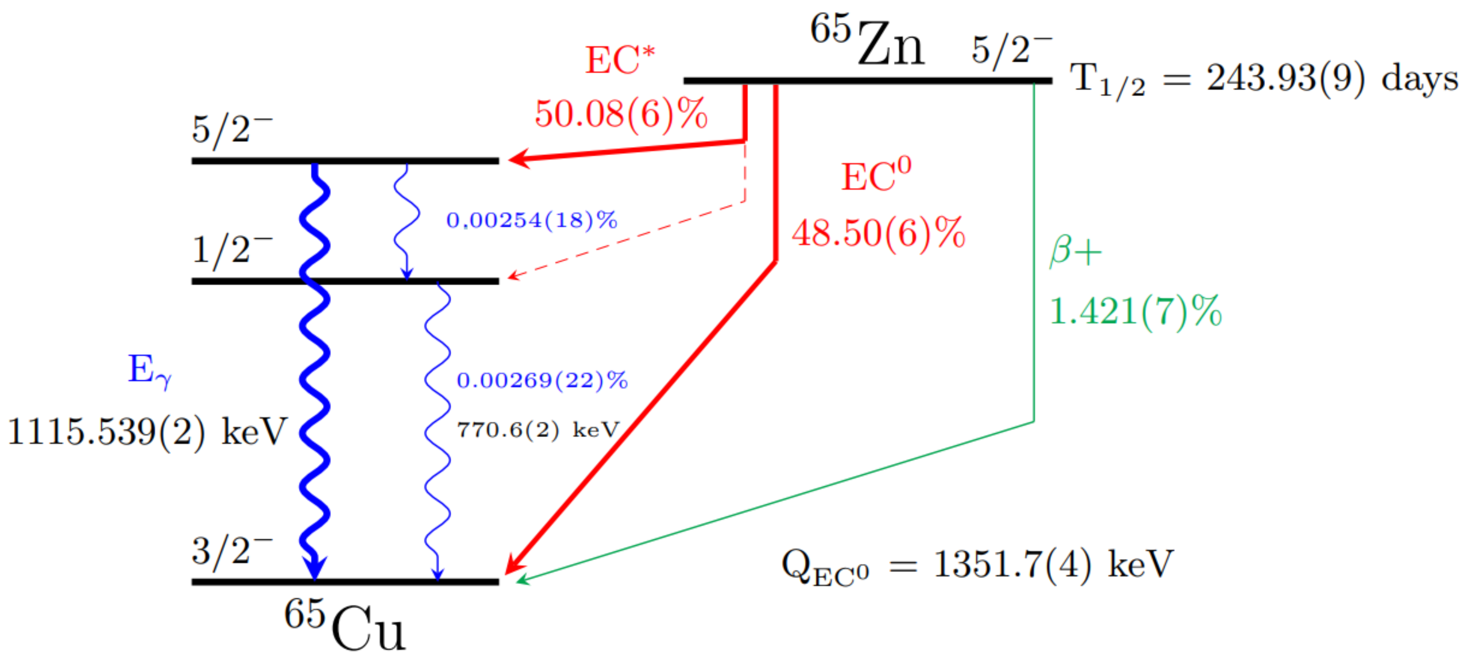


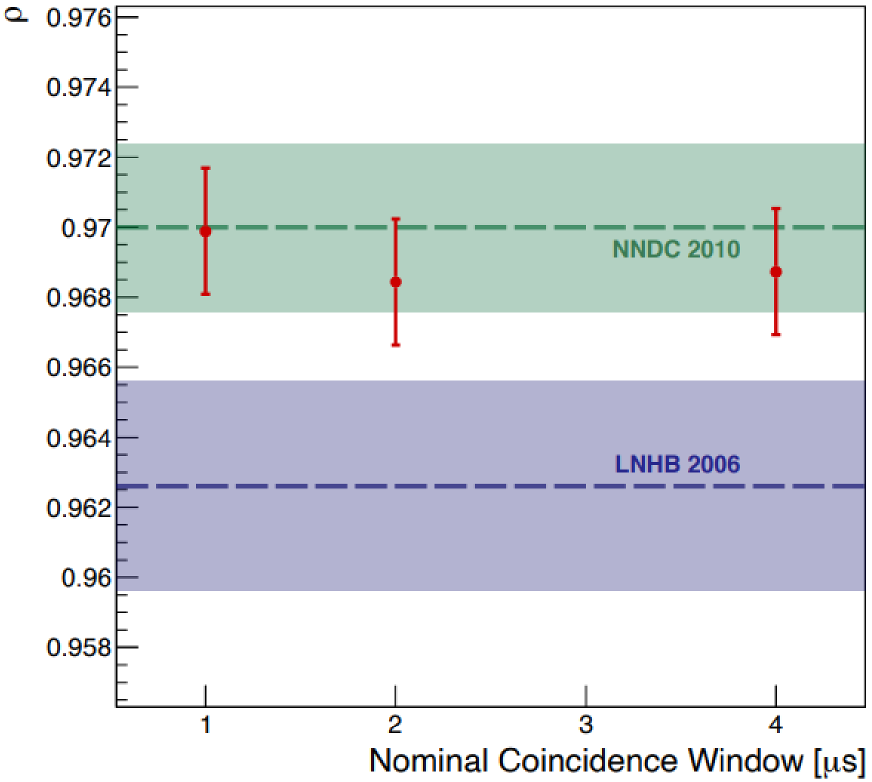
<u>**Gamma Tagging Efficiency:**</u>

- 97.89(6) @1460 keV
- Efficiency calibrated with ^{54}Mn

Part 3: ^{65}Zn

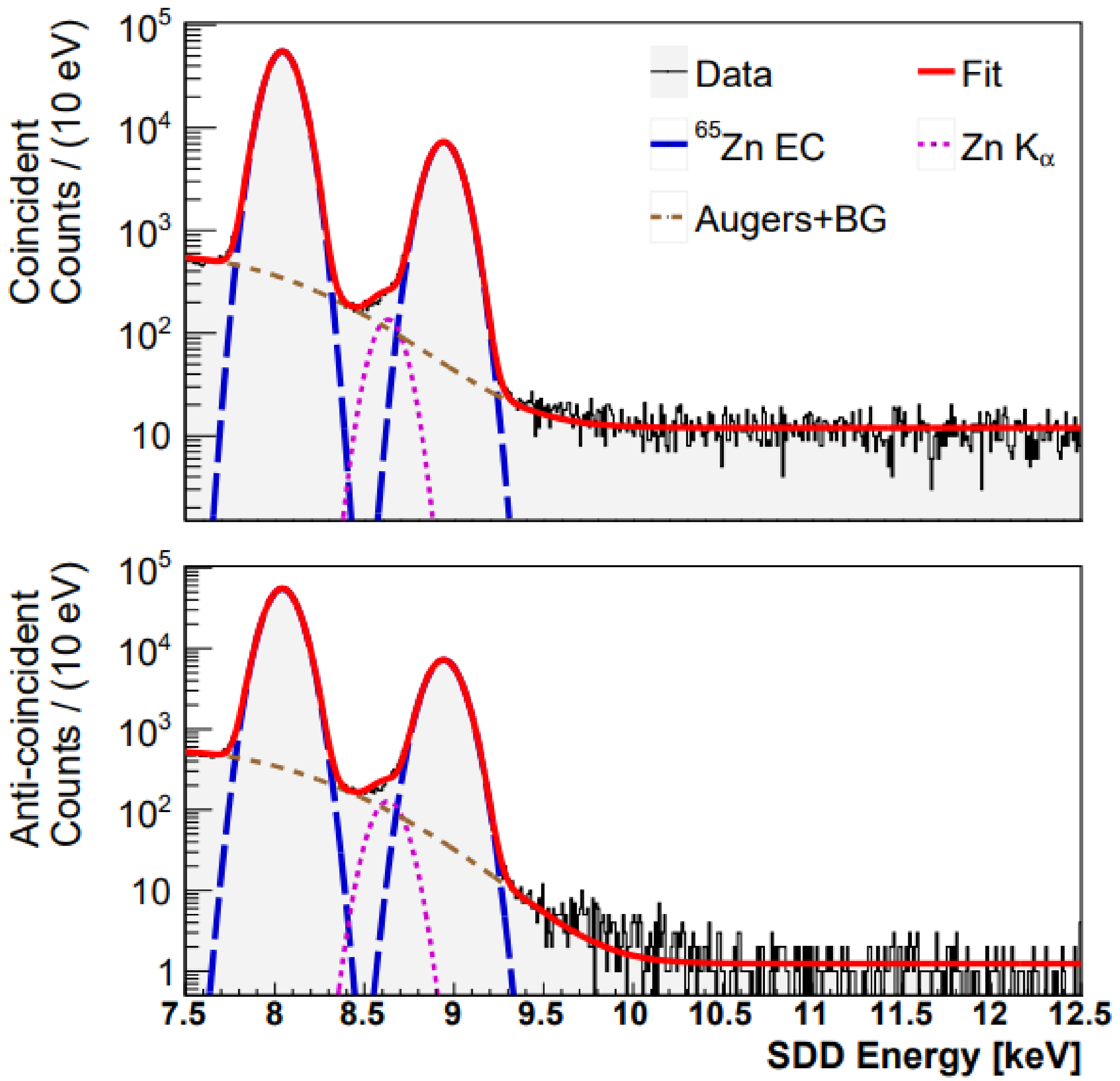
^{65}Zn Measurement

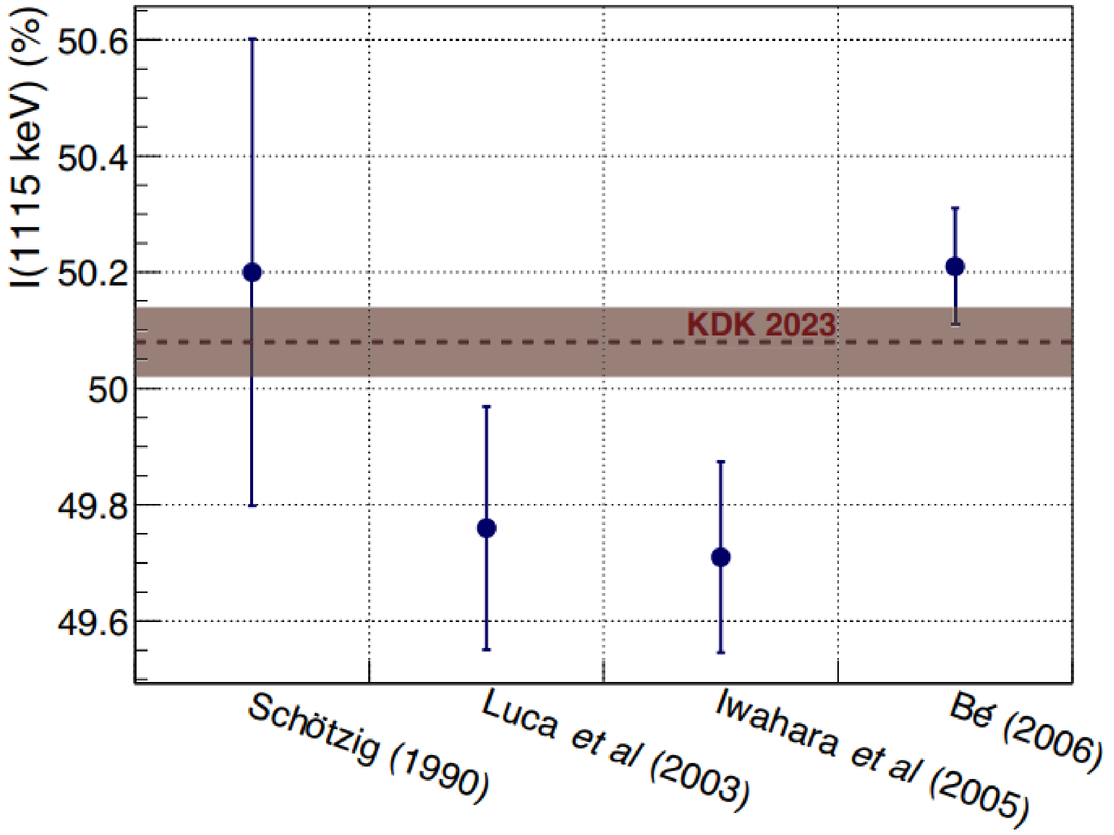




- ^{65}Zn, like ^{40}K, has an excited and ground state decay
  - Excellent testing isotope for the KDK method
- Some disagreement in literature on branching ratio
- Published Results now available [6]

^{65}Zn Measurement II

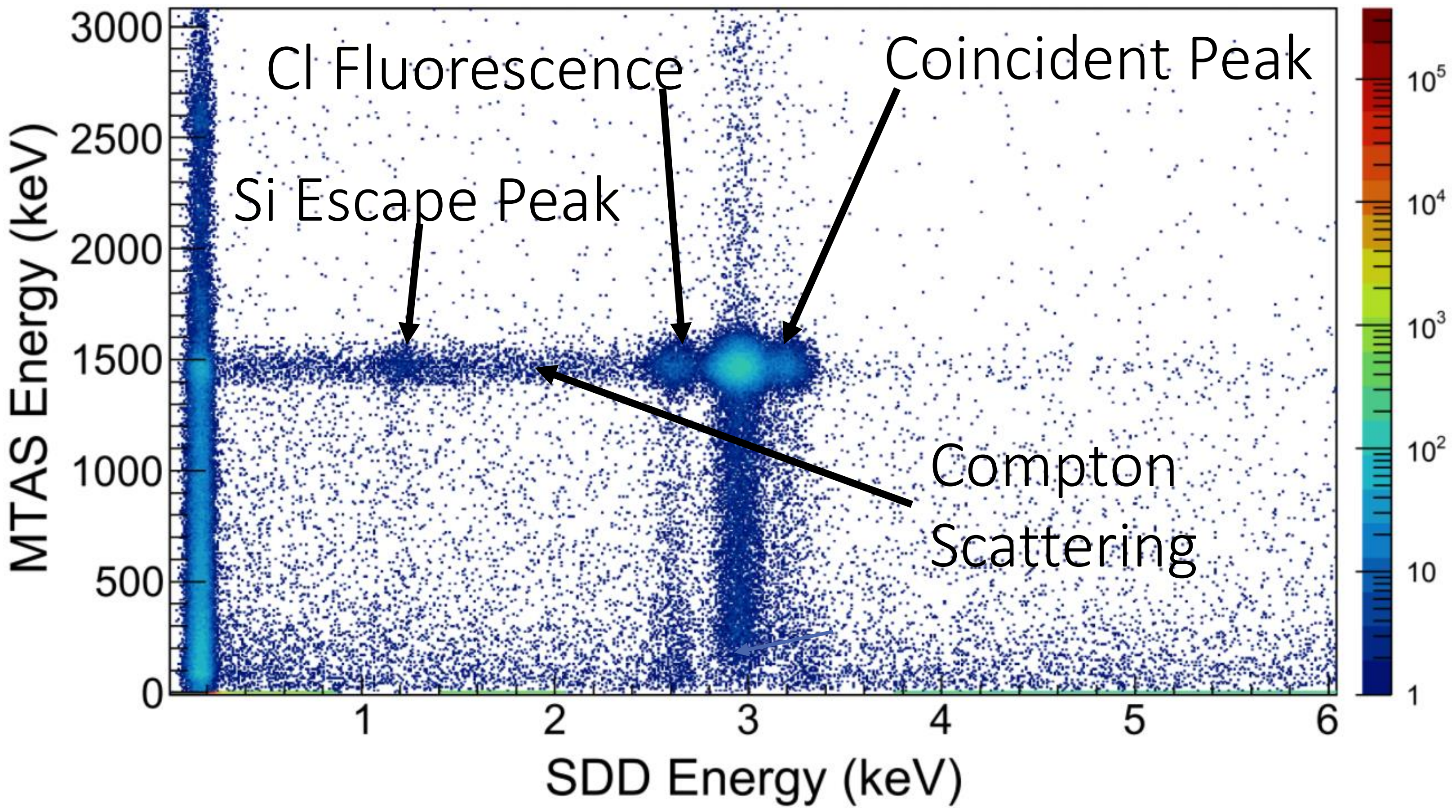




- Result is obtained through a multi-dimensional likelihood fit on the coincidence and anti-coincidence data
- Factor of 2 increase in precision when compared to the leading 2006 results

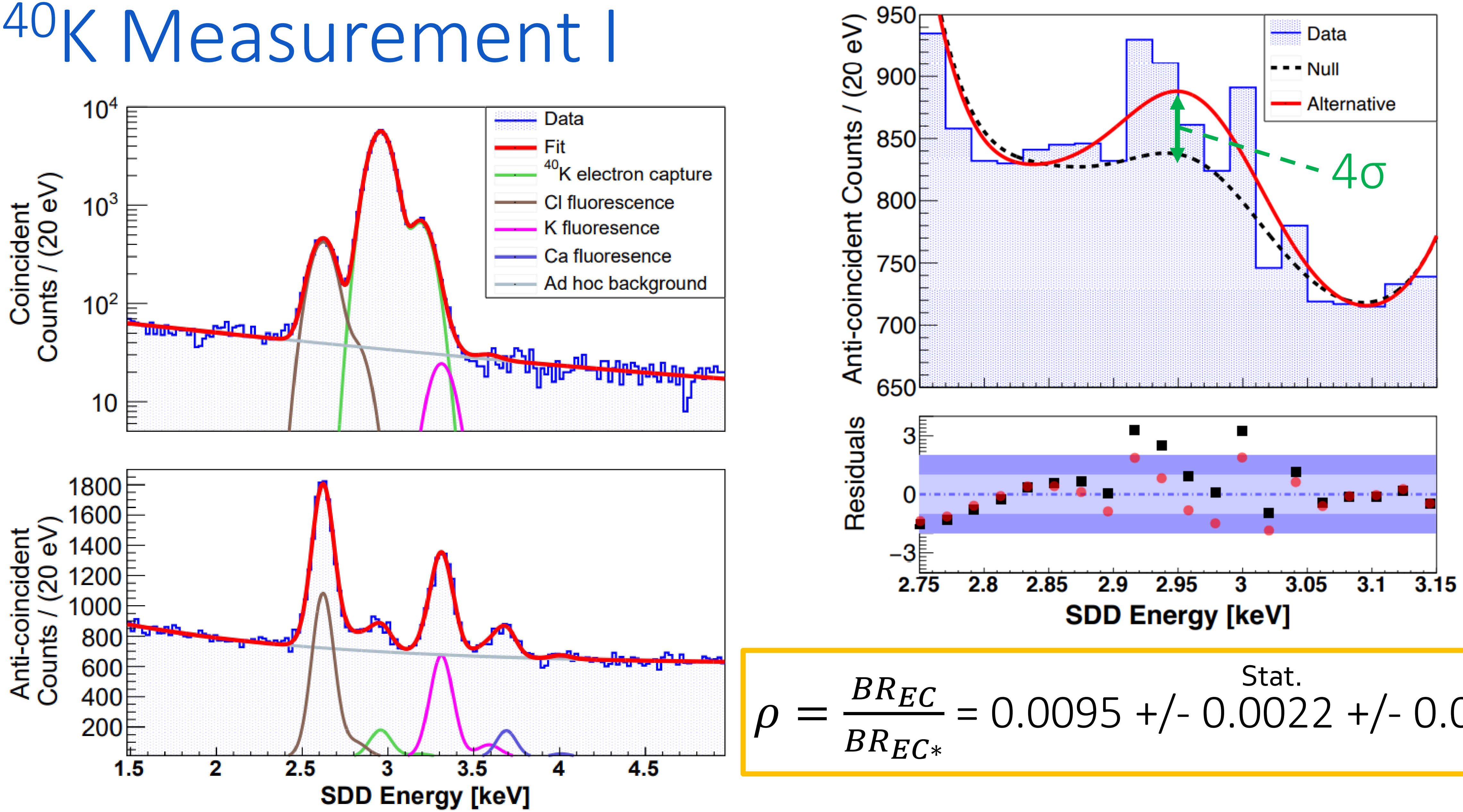
Part 4:Results

^{40}K Blinded BR_{EC} Measurement



- ^{40}K visible in MTAS/SDD
- Total Run Time: 44 days, Total Useable Time: 33 days
- Data was blinded

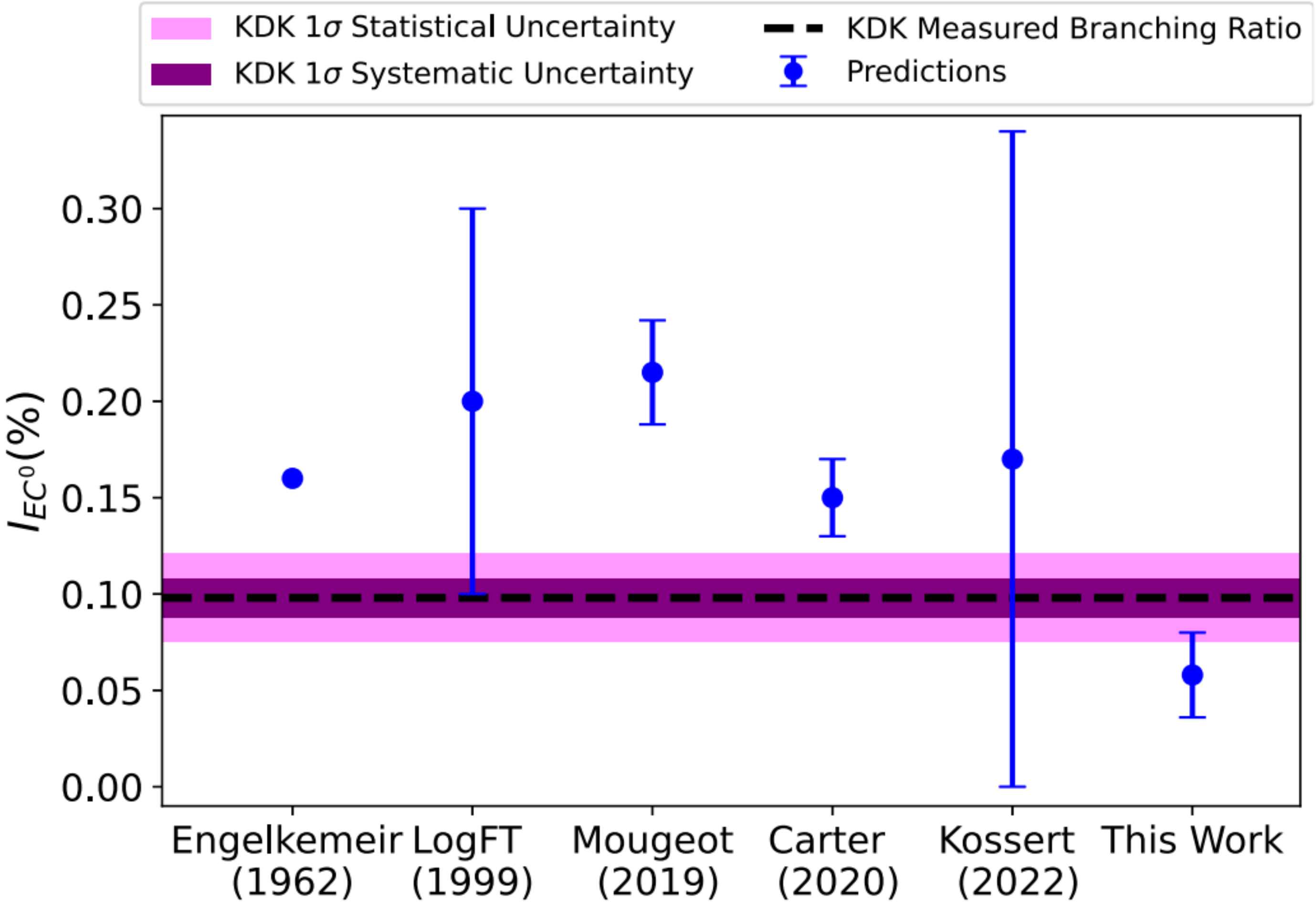
^{40}K Measurement I



$$\rho = \frac{BR_{EC}}{BR_{EC*}} = 0.0095 \pm 0.0022 \text{ (Stat.)} \pm 0.0010 \text{ (Syst.)}$$

^{40}K Measurement II

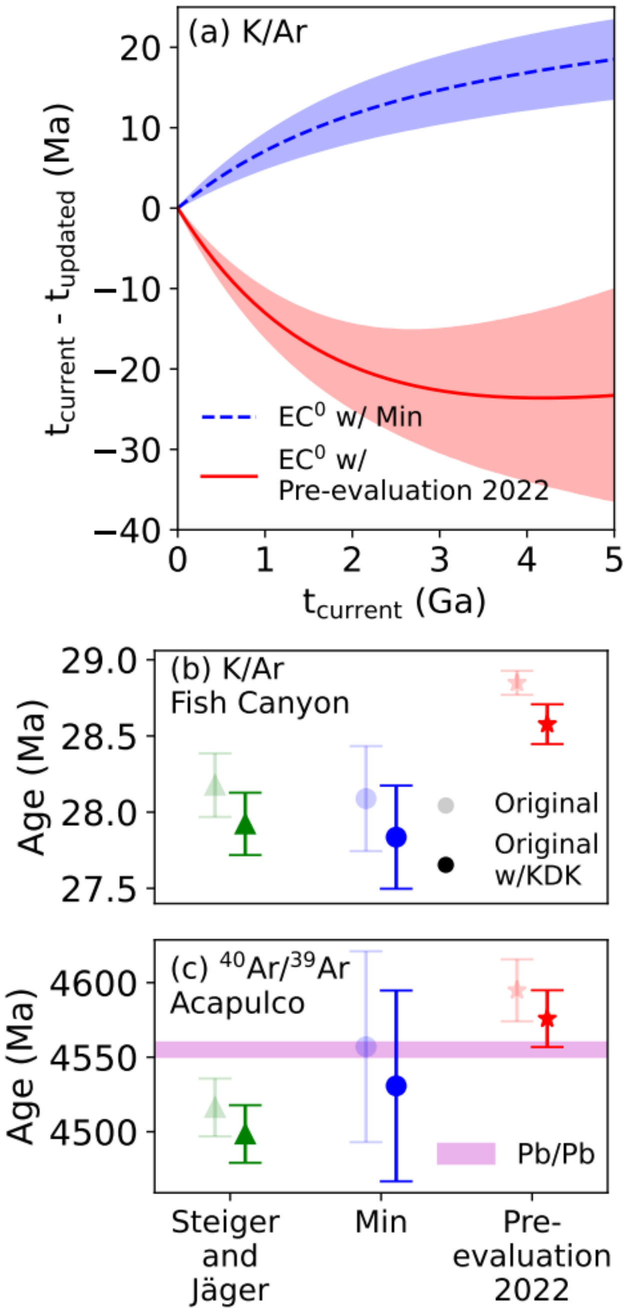
$$I_{EC^0} = (0.098 \pm 0.022)\%$$



- **First measurement of ^{40}K ground state electron capture [7,8]**
  - PRL, PRC
- Comparison of measured value to existing theoretical predictions.
- Measured value is a factor of 2 small then the commonly used 0.2 ± 0.1 % LogFT value
  - Measured uncertainty is a factor of 5 times smaller
- The statistical uncertainty is comparable to the leading theoretical values

KDK Implications

- **Particle Physics:**
  - Quantified a previously unknown low energy background present in many dark matter experiments
  - Because measured BR value was lower then the commonly used value this relaxes the modulation fraction constraint placed on the DAMA/LIBRA experiment
    - Have to wait for great experiments like COSINUS to finish.
- **Nuclear Physics**
  - First measurement of a third-forbidden unique electron capture transition
  - Decay half-lives give access to the weak-axial vector coupling quenching: g_A
  - Improves prediction of $0\nu\beta\beta$ matrix element calculations through better consideration of forbidden contribution, ex. ^{48}Ca
- **Geochronology**
  - Traditional K/Ar ages have been overestimated by not including the ground state decay
    - This is dependent on the decay evaluation chosen
  - Ar-Ar dating is indirectly effected as this method requires the use of K-Ar dated calibration sources



VIEWPOINT

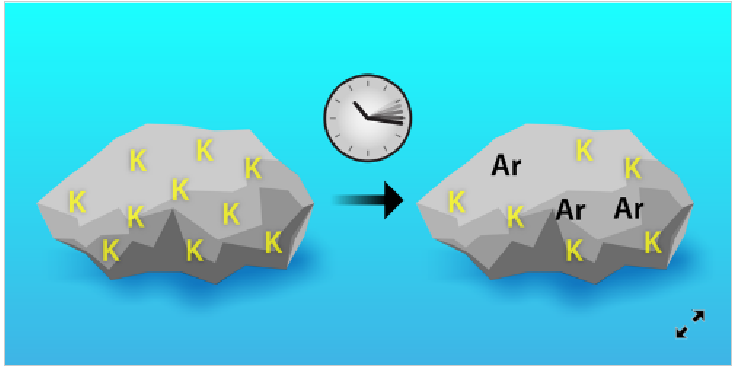
PDF Version

Measuring Decays with Rock Dating Implications

Stephen Ellis Cox
Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY, US

July 31, 2023 • *Physics* 16, 131

Researchers revisit a neglected decay mode with implications for fundamental physics and for dating some of the oldest rocks on Earth and in the Solar System.



APS/Alan Stonebraker

Figure 1: As a rock forms, it traps a set of potassium-40 within the solid. Decays of this isotope produce argon-40. By measuring the amount of argon-40 relative to that of potassium-40, geologists can date the rock.

Rare ^{40}K Decay with Implications for Fundamental Physics and Geochronology
M. Stukel *et al.* (KDK Collaboration)
Phys. Rev. Lett. 131, 052503 (2023)
Published July 31, 2023
Read PDF

Evidence for ground-state electron capture of ^{40}K
L. Hariasz *et al.* (KDK Collaboration)
Phys. Rev. C 108, 014327 (2023)
Published July 31, 2023
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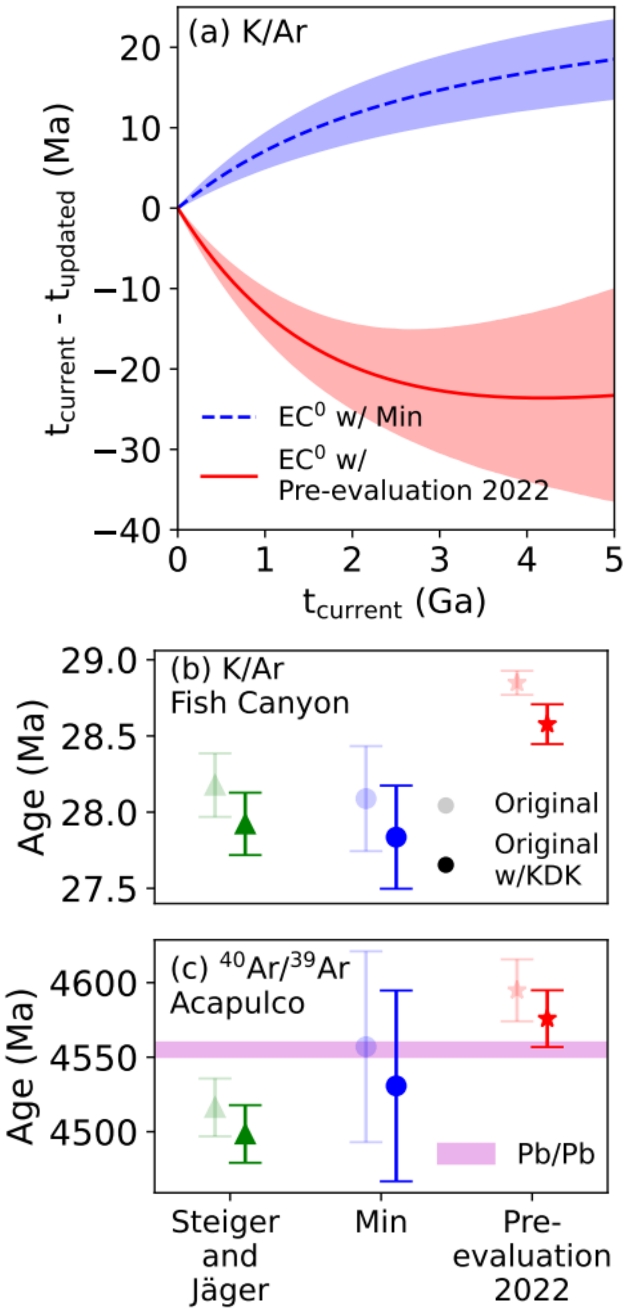
Recent Articles

How Metal Meteorites Magnetize

For a metal meteorite to retain a magnetic field, its parent asteroid may need a cold rubble core to help drive an internal dynamo.



Link: https://physics.aps.org/articles/v16/131

Summary and Future Work

- KDK has performed the first measurement of the ^{40}K ground state electron capture
- Measurement is useful for many different fields: Rare-event searches, Nuclear Physics and Geochronology
- Link to results:
  - Experimental Setup, NIM A
  - ^{65}Zn Results, Nuclear Data Sheets
  - ^{40}K Results, PRL
  - ^{40}K Supplementary Material, PRC
- KDK+ aims to measure the β+ branch

KDK Collaboration

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(Dated: August 16, 2023)

References

1) Di Stefano, P. C. F., et al. "The KDK (potassium decay) experiment." *Journal of Physics: Conference Series*. Vol. 1342. No. 1. IOP Publishing, 2020.

2) Pradler, Josef, Balraj Singh, and Itay Yavin. "On an unverified nuclear decay and its role in the DAMA experiment." *Physics Letters B* 720.4-5 (2013): 399-404.

3) Carter, J., Ickert, R.B., Mark, D.F., Tremblay, M.M., Cresswell, A.J. and Sanderson, D.C., 2020. Percent-level production of 40 Ar by an overlooked mode of 40 K decay. *Geochronology Discussions*, pp.1-21.

4) Stukel, M., et al. "A novel experimental system for the KDK measurement of the 40K decay scheme relevant for rare event searches." *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 1012 (2021): 165593.

5) Karny, Marek, et al. "Modular total absorption spectrometer." *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 836 (2016): 83-90.

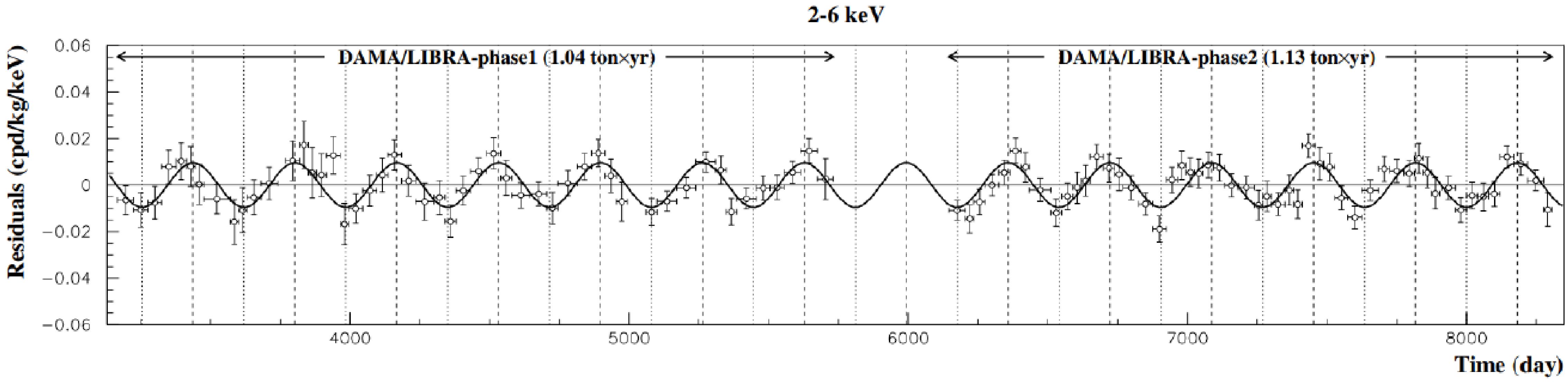
6) Hariasz, L., et al. "Precision measurement of 65Zn electron-capture decays with the KDK coincidence setup." *Nuclear Data Sheets* 189 (2023): 224-234.

7) Stukel, M., et al. “Rare ^{40}K decay with Implications for Fundamental Physics and Geochronology.” *Physics Review Letter 131 (2023)*

8) Hariasz, L., et al. "Evidence for ground-state electron capture of K 40." *Physical Review C* 108.1 (2023): 014327.

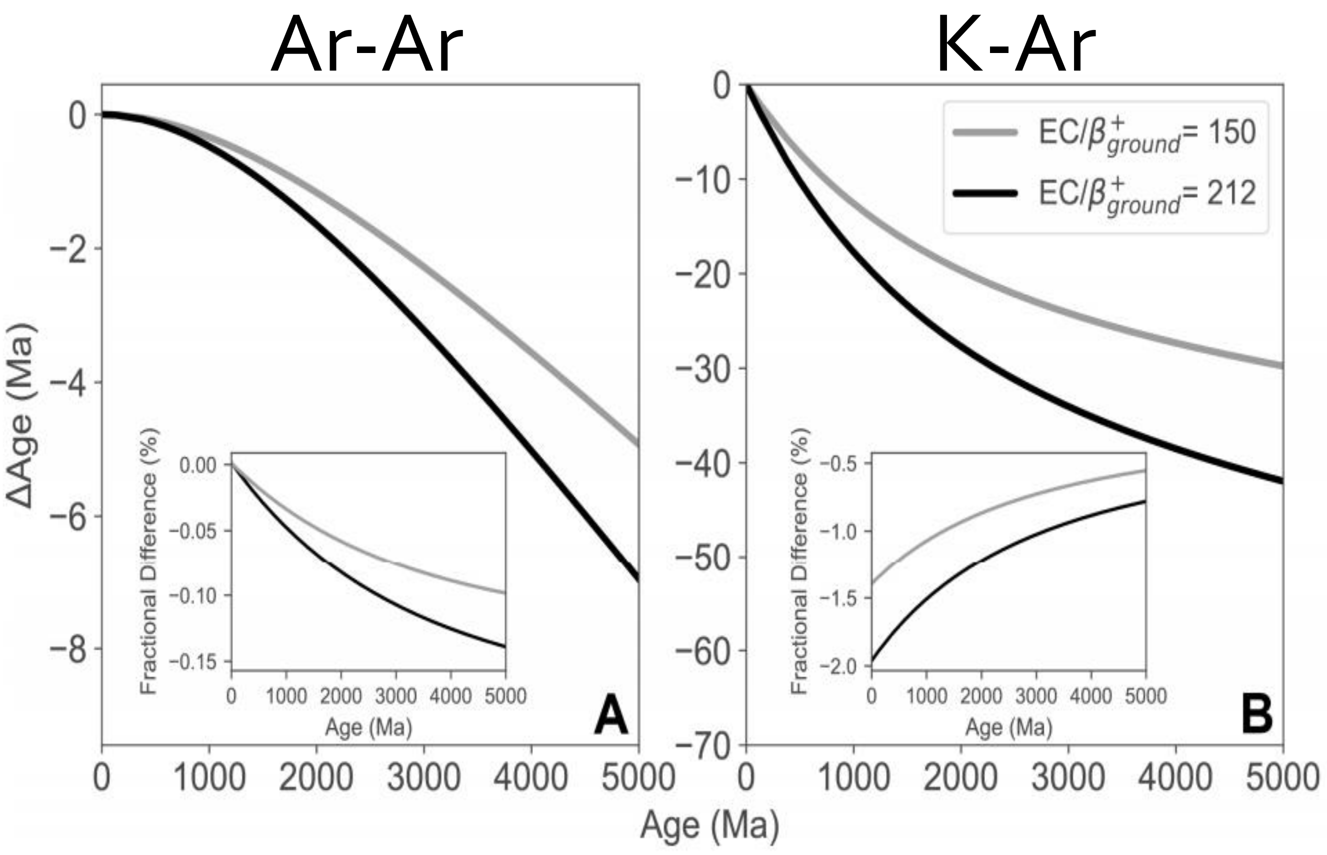
Extra

Why: Effect of ^{40}K on the DAMA Experiment



- DAMA consists of 25 highly radiopure NaI(Tl) crystals.
- Claimed an annual modulation consistent with dark matter since 1997
- Visible in the 1-6 keV energy region, right where ^{40}K electron capture background is
- Pradler, Singh and Yavin showed a measurement of the EC decay can constrain the modulation fraction of DAMA [2]
    - Requires assumption about background and efficiency of DAMA

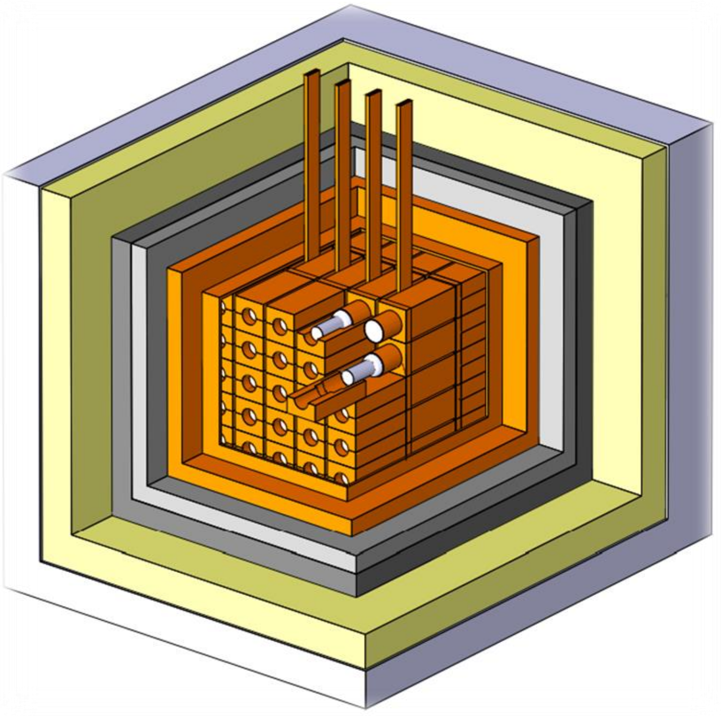
Why: Effect of ^{40}K on Geochronology

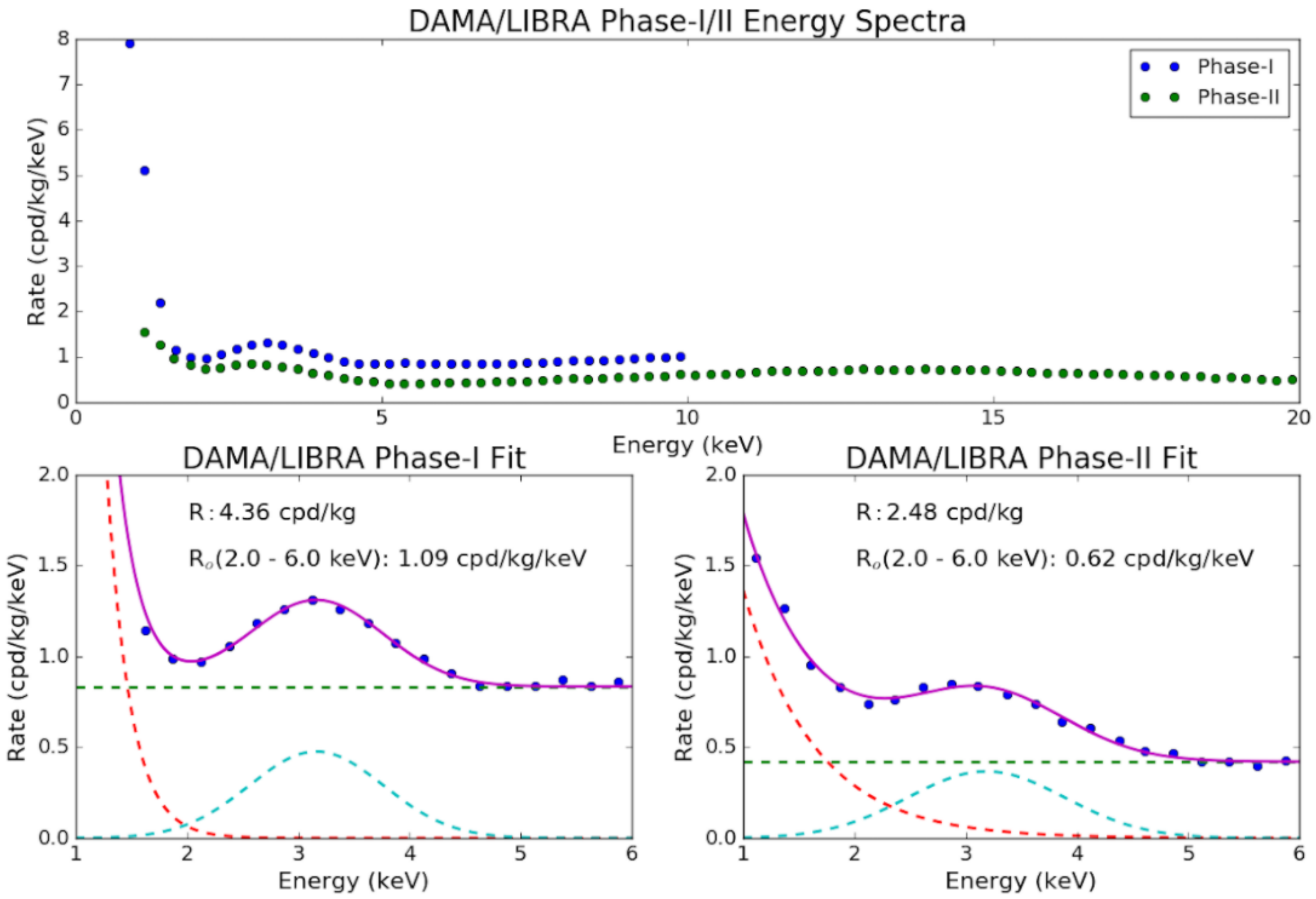


- K-Ar and Ar-Ar dating are widely used to determine the age of rocks and minerals
- Based on the decay constants: λ_T, λ_{Ar}
- Geo. Literature often ignores the existence of the EC decay
- When EC included ages are generally younger [3]
- Shift age by 10 million years
- K-Ar: Used by Mars surface Curiosity Rover
- Ar-Ar: Apollo 11 samples

DAMA/LIBRA Apparatus

https://arxiv.org/pdf/1805.10486.pdf
https://arxiv.org/pdf/0804.2741.pdf





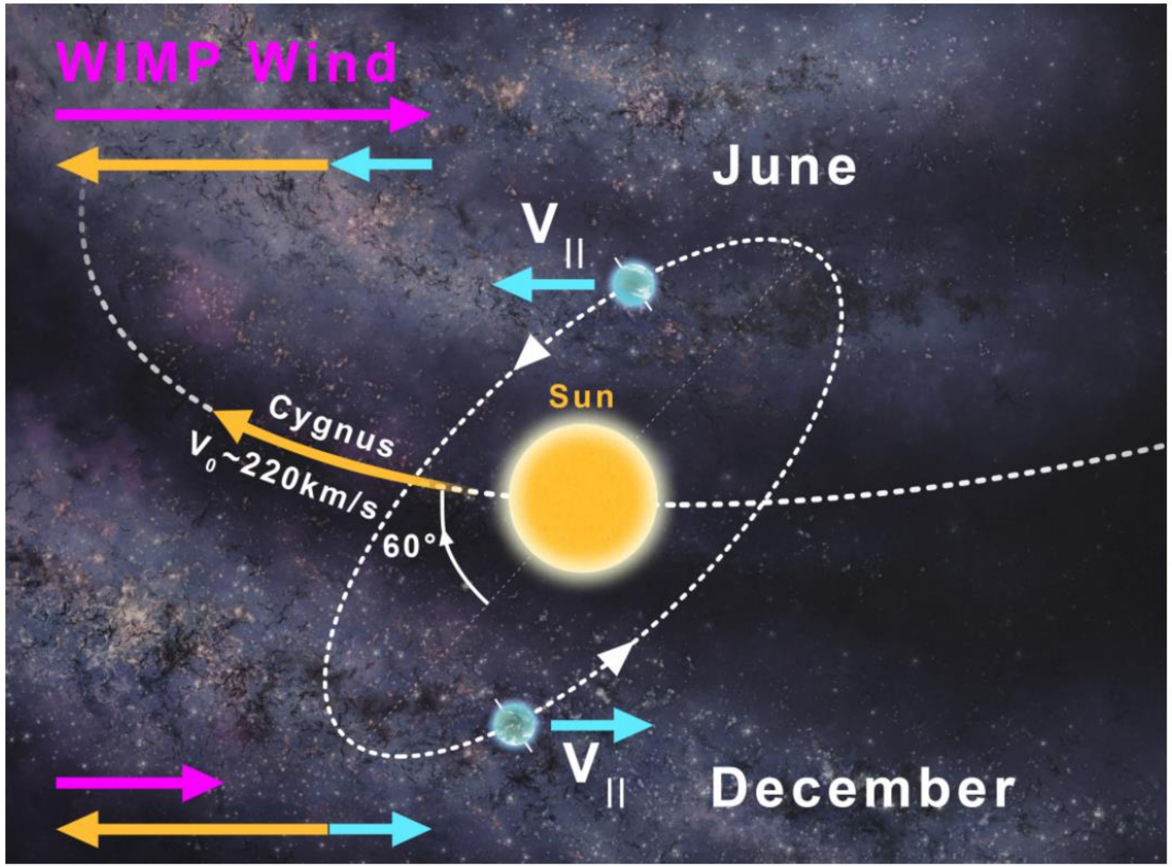
- The DAMA detector consists of 25 highly radiopure NaI(Tl) crystals. (~10 kg each)
- 5x5 matrix with a 10 cm long UV light guide at the end
- The detector is situated in low radioactive copper box. With an additional Cu/Pb/Cd foils/polyethylene/paraffin shield

Direct Detection: Annual Modulation

$$\frac{dR}{dE}(E,t) \approx S_0(E) + S_m(E)cos(w(t-t_0)),$$

$$s_m = \frac{S_m}{S_0},$$

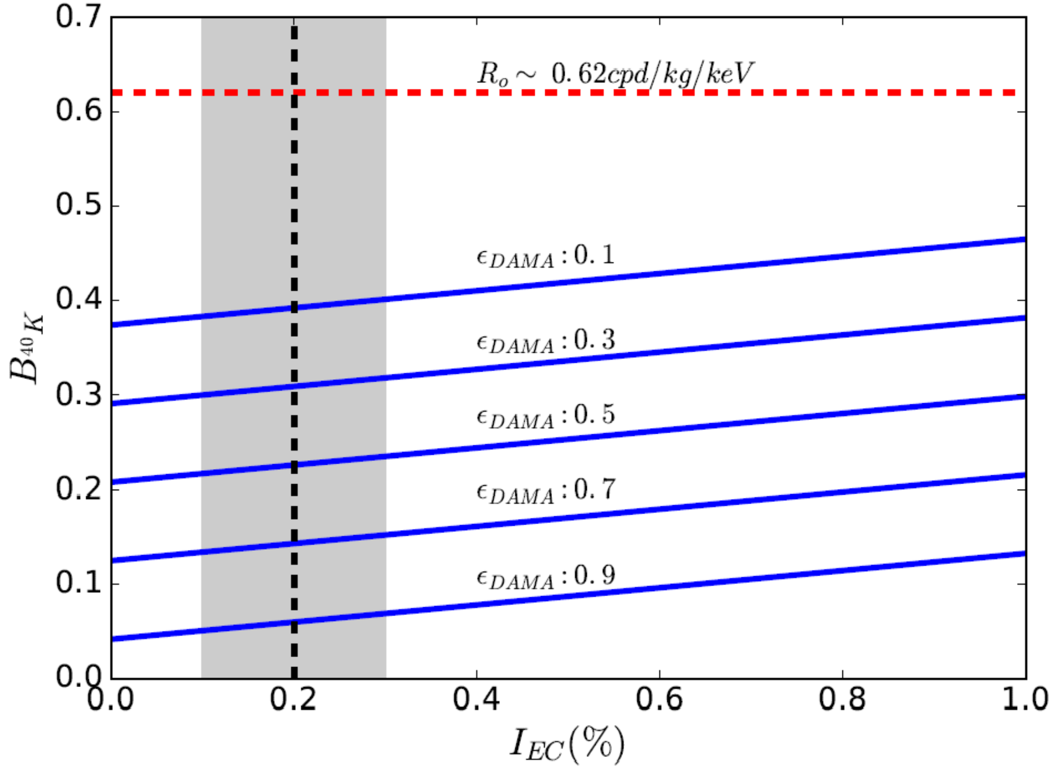
- Motion of the sun and the earth in a "stationary" galactic dark matter halo induces a "WIMP wind"
- In June, the velocity vectors of the Sun and Earth are aligned and the DM flux is at a maximum
- In December, the vectors are opposite and the DM flux is at a minimum
- This change in flux is exploited by certain DM experiments

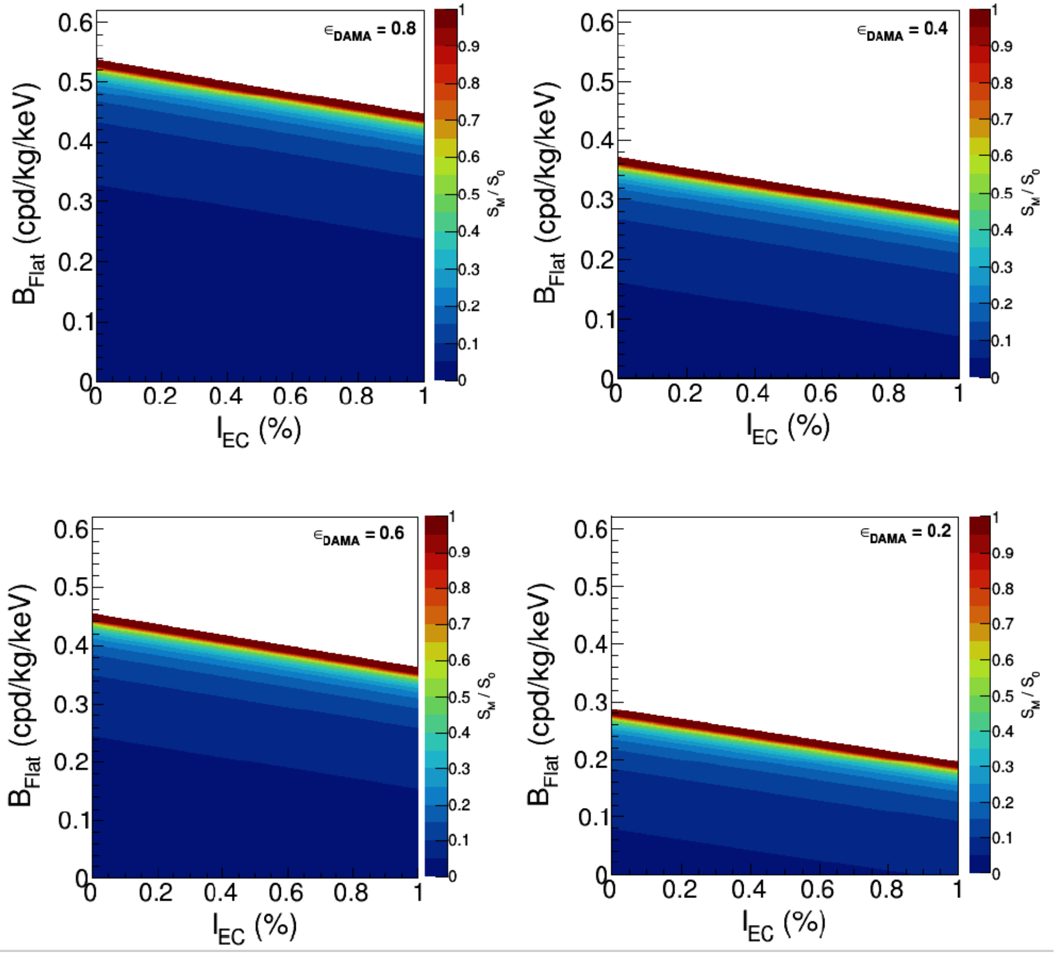


Direct Detection: Annual Modulation 2

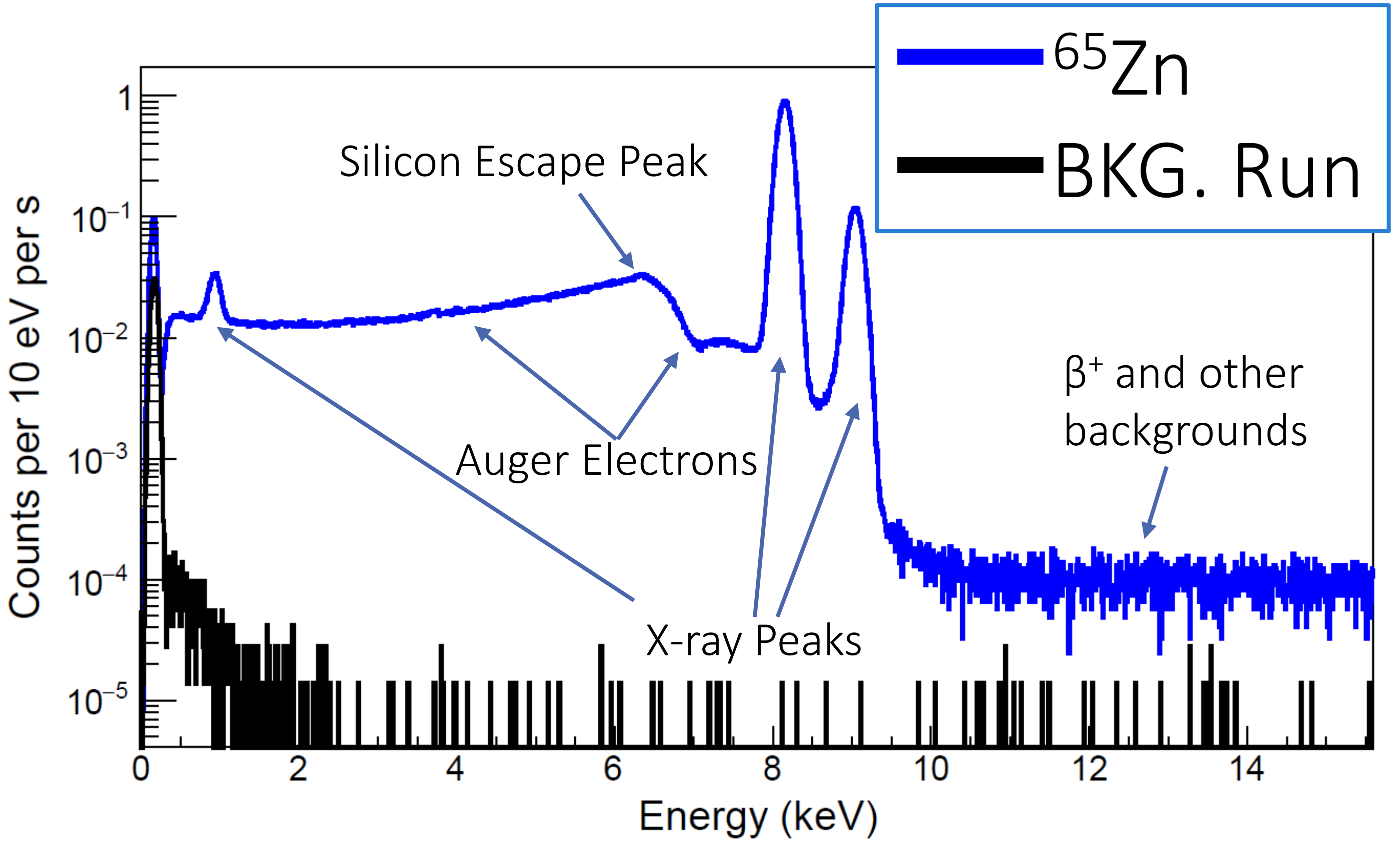
$$s_m = \frac{S_m}{S_o} = \frac{S_m}{R_o - B_o} = \frac{S_m}{R_o - B_{flat} - B_{40K}}.$$

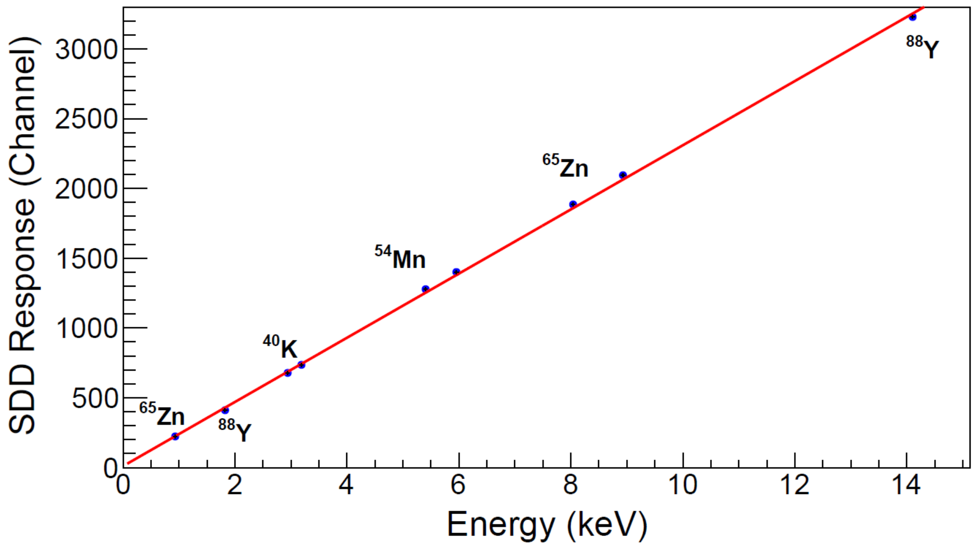
$$B_{^{40}K} = (N_{^{40}K}(\frac{ln(2)}{\tau_{1/2}})(\frac{1}{m_{NaI,kg}})(\frac{1}{4keV})[P_{K^*} I_{EC^*}(1 - \epsilon_{DAMA}) + P_K I_{EC}]).$$





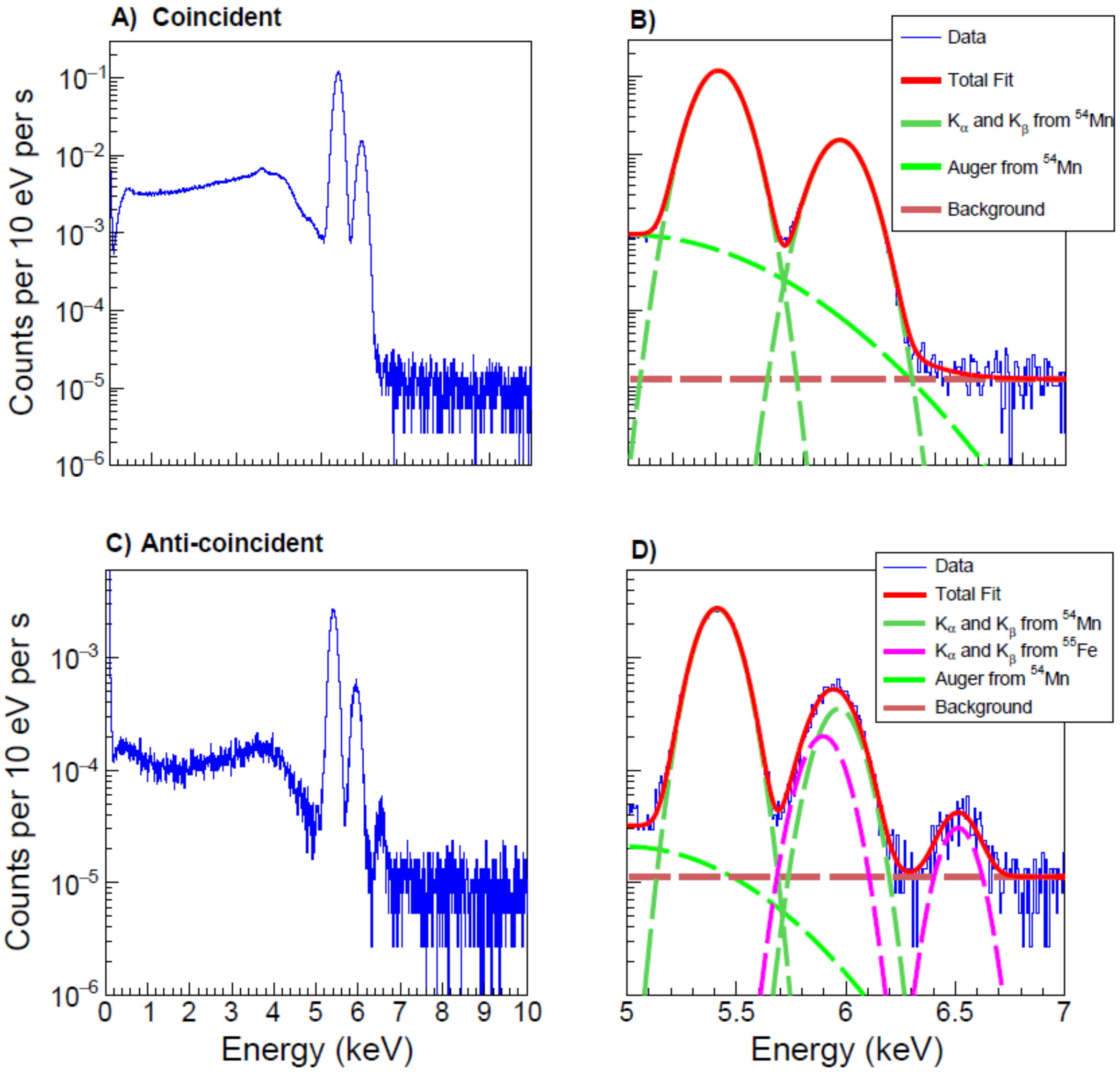
SDD Energy Spectrum and Calibration

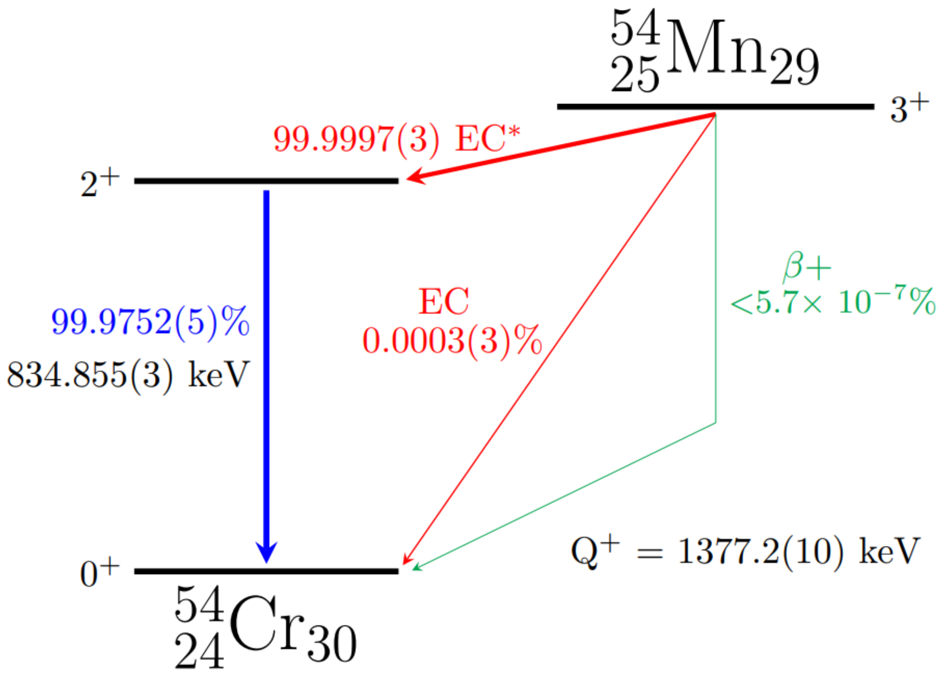




- **Energy Threshold**: ~250 eV
- **Energy Limit:** ~15 keV
- **FWHM:** ~170 eV @ 6keV

Gamma Tagging Efficiency

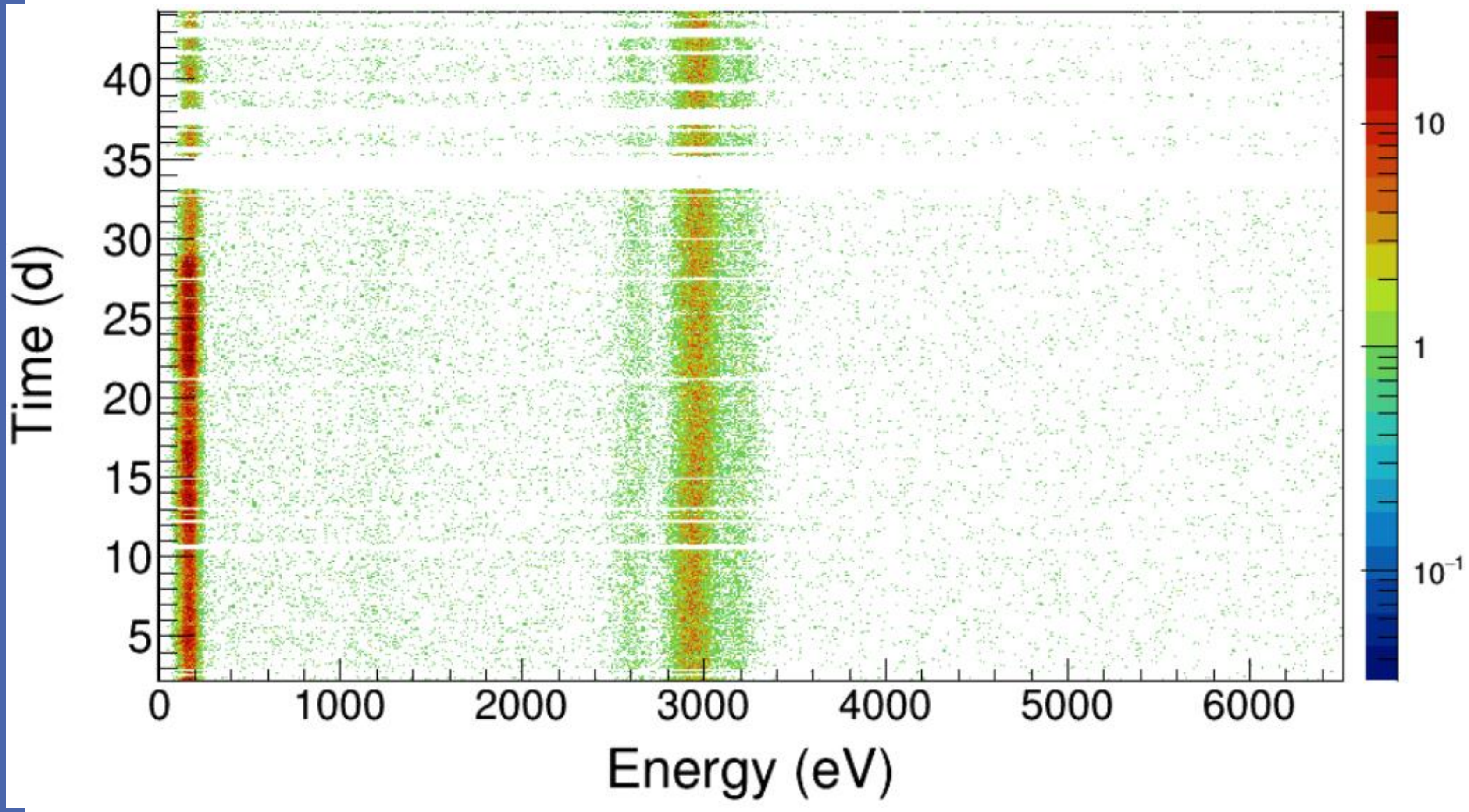




Efficiency

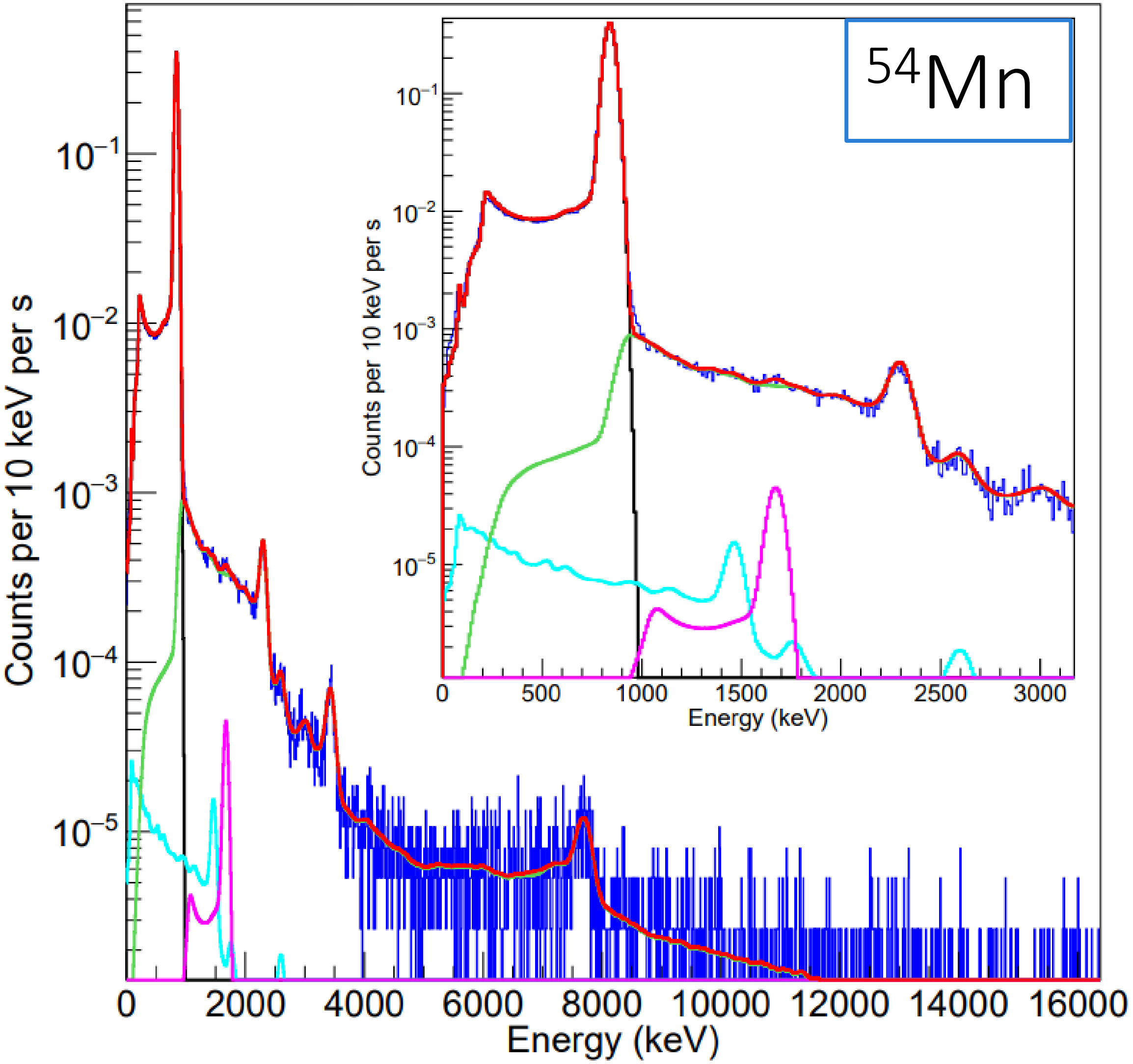
^{54}Mn	Energy & Live Time Correction	^{40}K
97.75(1)%	→	97.89(6) %

^{40}K Blinded BR_{EC} Measurement



- ^{40}K visible in MTAS/SDD setup!
- Total Run Time: 44 days, Total Useable Time: 33 days, Data is blinded

Geant4 MTAS Simulations



- Validated against different physics lists and large increase of materials surrounding the source
- Spectrum of all MTAS events when triggered by the SDD along with Geant 4 fit for a ^{54}Mn source
- Geant modelling allows for the determination of false-negatives

Decay Transition Types

	ΔL	ΔJ	ΔP
Super Allowed	0	0	No
Allowed	0	0, 1	No
First Forbidden	1	0,1,2	Yes
Second Forbidden	2	1,2,3	No
Third Forbidden	3	2,3,4	Yes
Fourth Forbidden	4	3,4,5	No