The KDK and NaI Experiments

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For the 2020 Queen’s University Summer Student Talks
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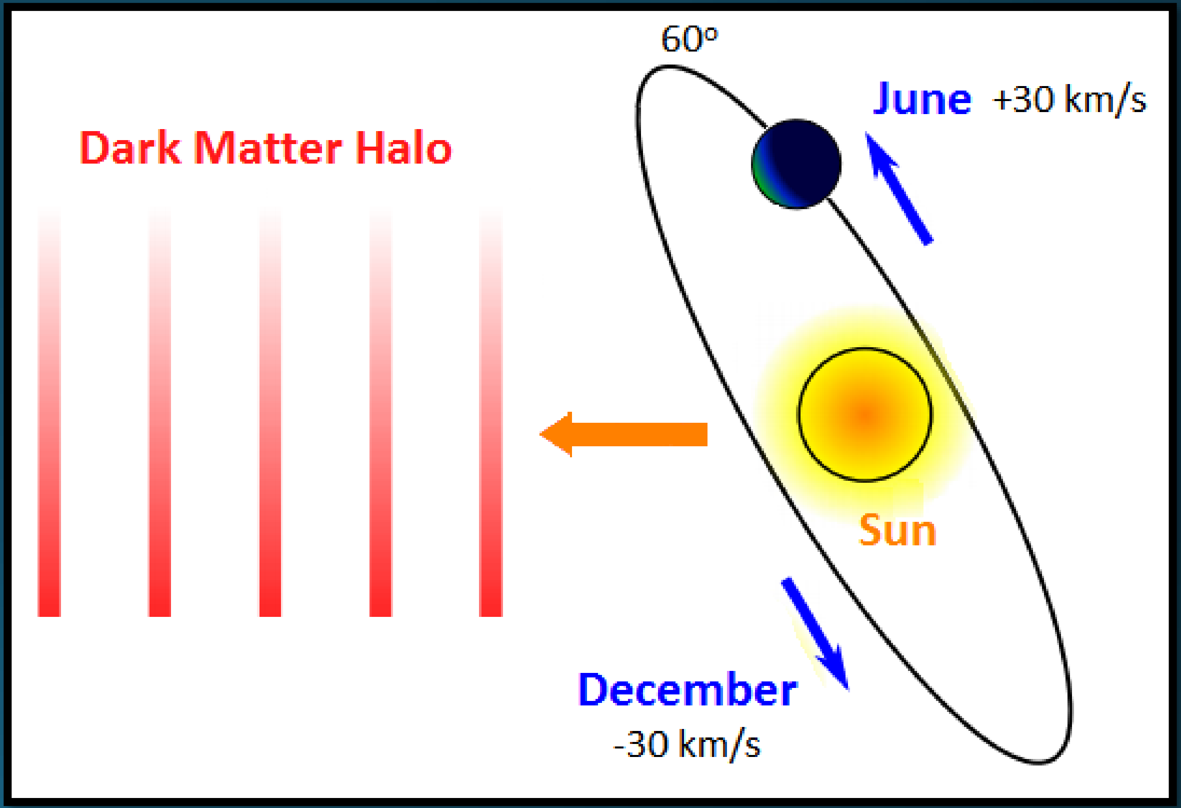
Overview

1. NaI Dark Matter Experiments
2. Nuclear Physics in Dark Matter
3. KDK Experiment

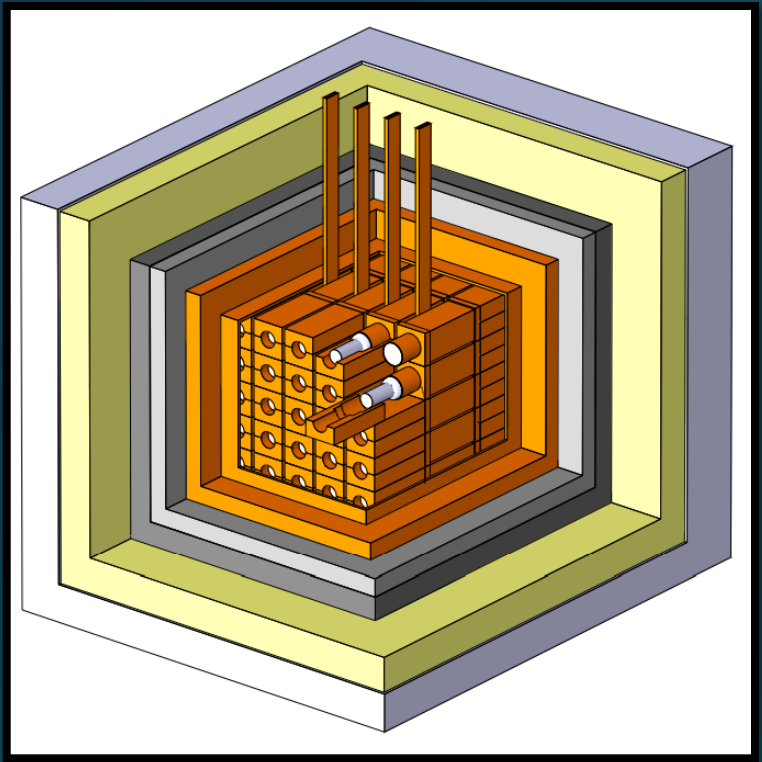
Part 1: NaI Dark Matter Experiments

Annual Modulation

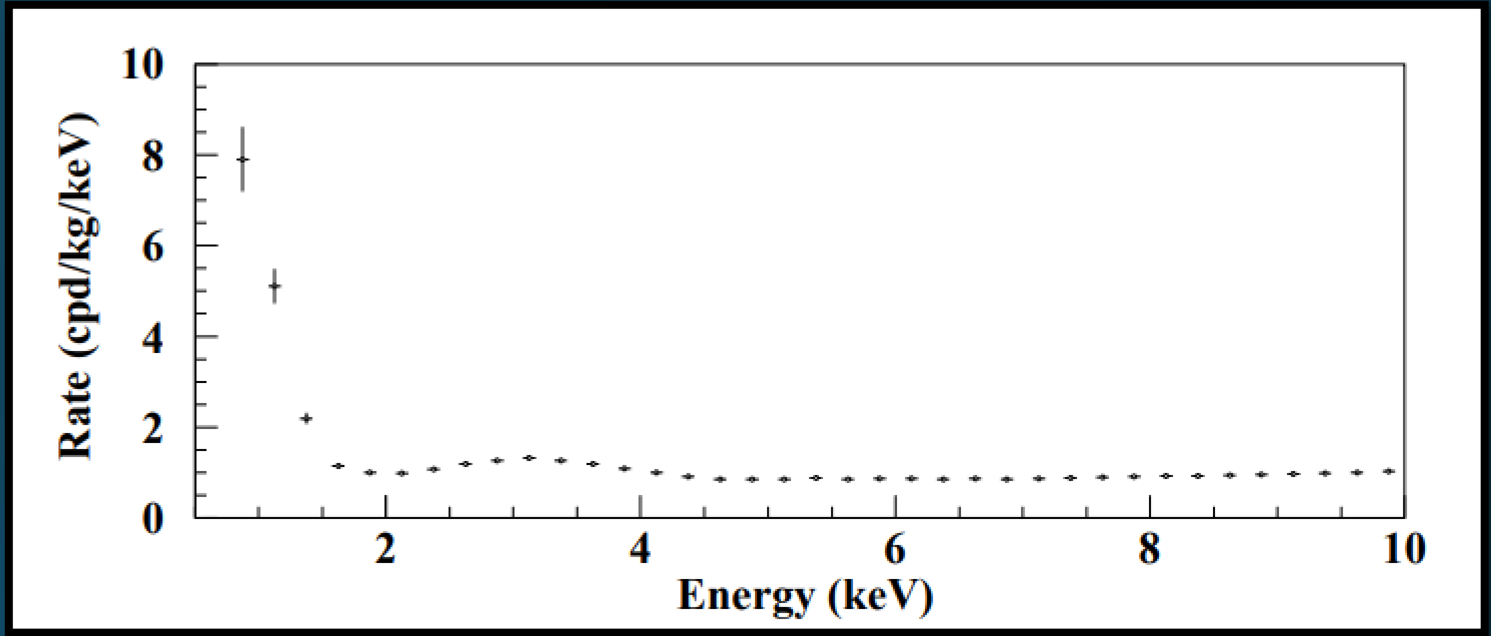
- Throughout the year the Earth will move around the sun with a velocity of 30 km/s^{-1}
- The sun will move through the galaxy which is contained in a uniform dark matter halo, this creates a dark matter (or WIMP) wind
- In June, when the velocity vectors of the Earth and Sun align at a maximum, experiments will see the largest flux of dark matter
- In December, the Earth will be moving against the rotation of the galactic disk giving the smallest flux of dark matter
- The DAMA collaboration attempts to exploit this flux in order to confirm a the presence of a WIMP dark matter signal



DAMA/LIBRA Apparatus



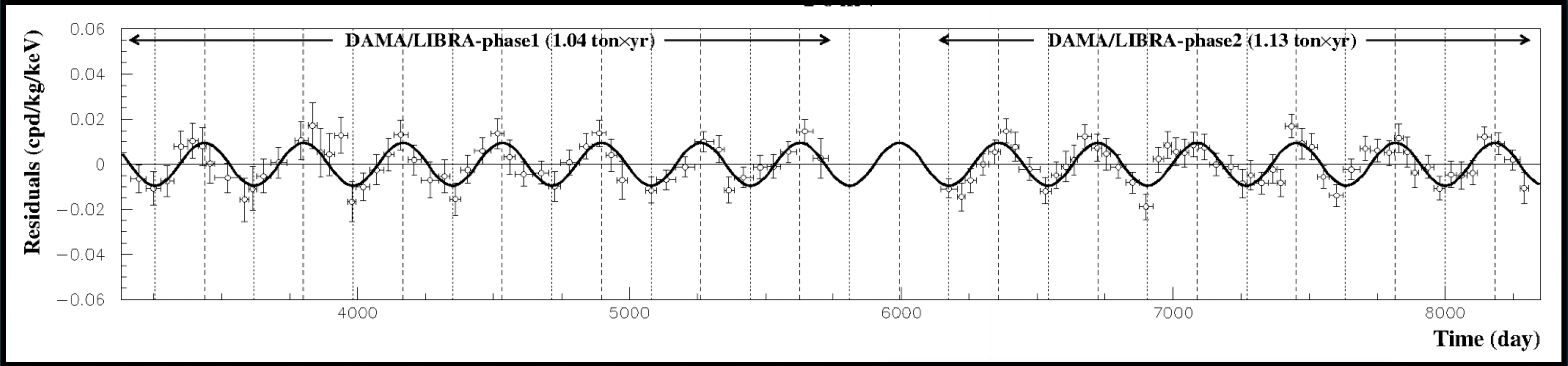
[4] Bernabei, R., et al. "The dama/libra apparatus." *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 592.3 (2008): 297-315.



Bernabei, R., et al. "First results from DAMA/LIBRA and the combined results with DAMA/NaI." *The European Physical Journal C* 56.3 (2008): 333-355.

- 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

DAMA/LIBRA Experiment



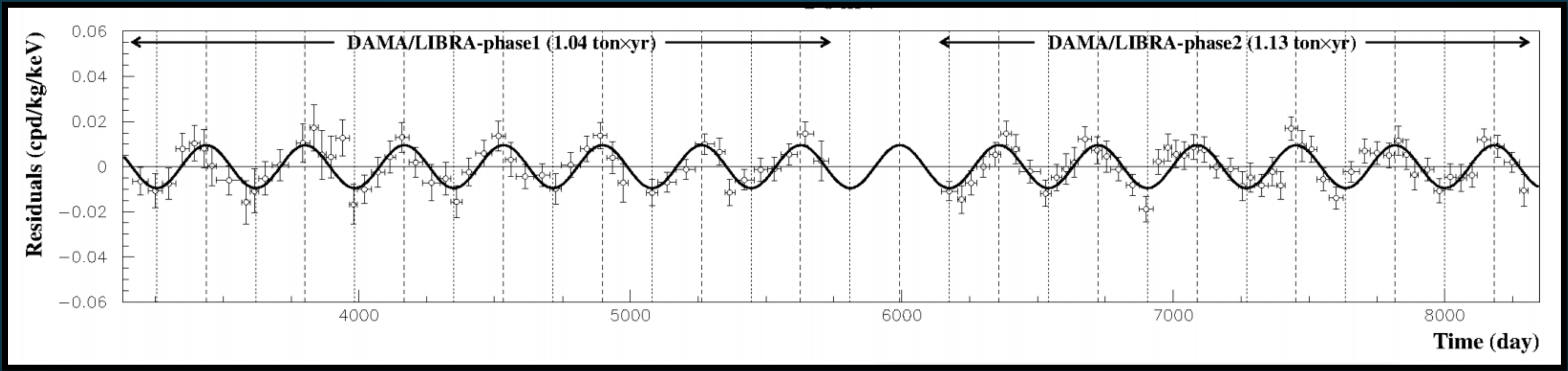
[3]Bernabei, R. et. al.2018. First model independent results from DAMA/LIBRA-phase2. *arXiv preprint arXiv:1805.10486*.

- The DAMA collaboration has claimed a peculiar annual modulation signal since 1997
- Signal is consistent with WIMP dark matter halo predictions
- Signal consists of a time-independent and time-dependent dark matter signal
- S_m : 0.0112 +/- 0.0012 cpd/kg/keV

$$R(t) = B_o + S_o + S_m \cos\big(w(t - t_o)\big)$$

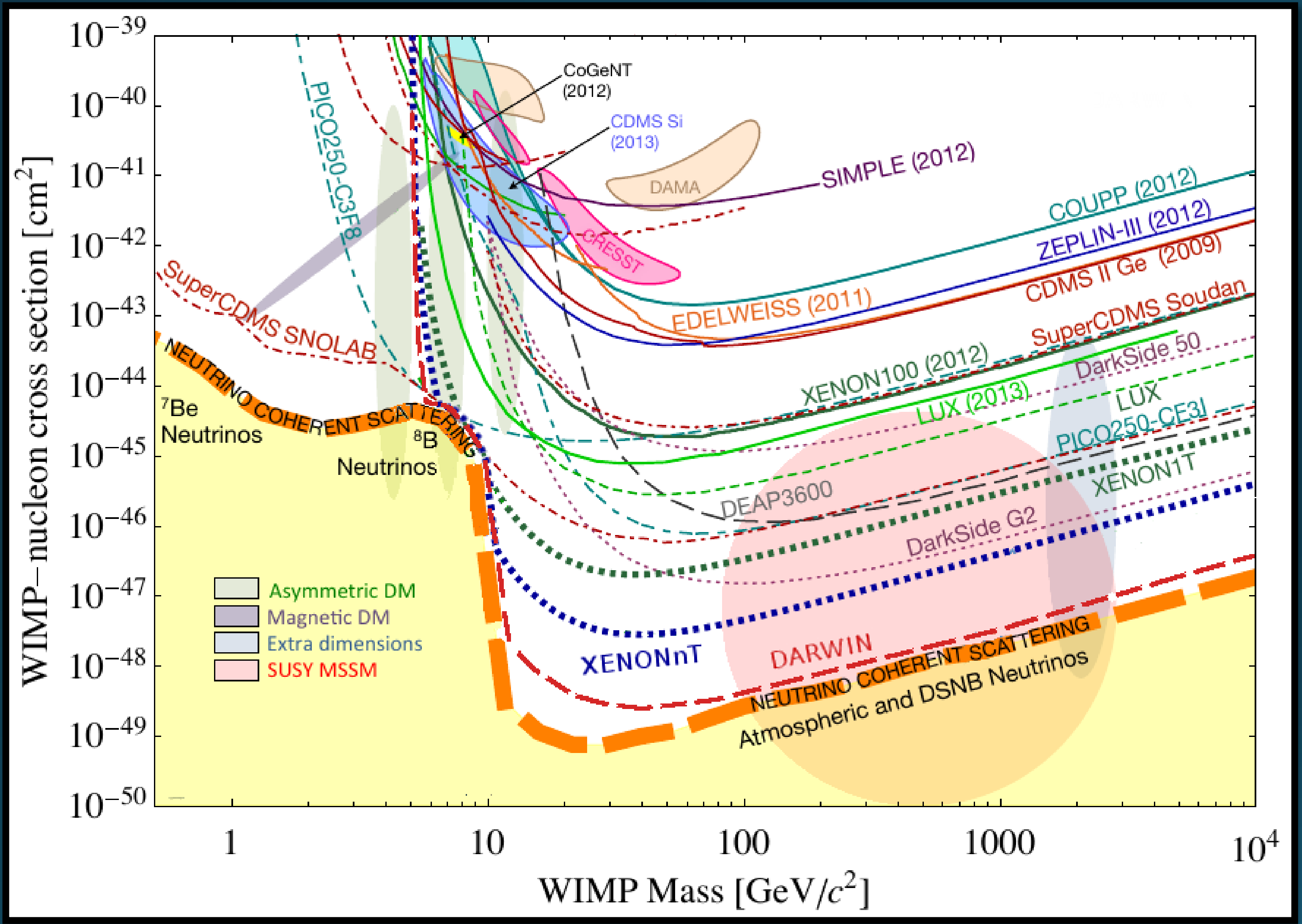
$$s_m^{obs} = \frac{S_m}{\boxed{B_o} + S_o}$$

$$s_m^{max} = \frac{S_m}{S_o}$$



Condition	Specification
1	The rate must contain a component modulated according to a cosine function
2	The period must be approximately one year
3	The phase will peak roughly around June 2nd
4	The modulation will only be present in a well-defined low energy region
5	Dark matter multi-interactions is negligible so all events must be single-hit
6	The ratio of modulation events to unmodulated events should be ~7-30%

Some Issues With DAMA



- Incompatibility with other experiments
- Lack of data transparency
- Unknown/un-modelled background components
  - Especially ^{40}K

Spin-Independent Cross-Section versus WIMP Mass

About interpretation and comparisons

See e.g.: Riv.N.Cim.26 ono.1(2003)1, IJMPD13(2004)2127, EPJC47(2006)263, IJMPA21(2006)1445, EPJC56(2008)333, PRD84(2011)055014, JMPA28(2013)1330022

...models...

- Which particle?
- Which interaction coupling?
- Which EFT operators contribute?
- Which Form Factors for each target-material?
- Which Spin Factor?
- Which nuclear model framework?
- Which scaling law?
- Which halo model, profile and related parameters?
- Streams?
- ...

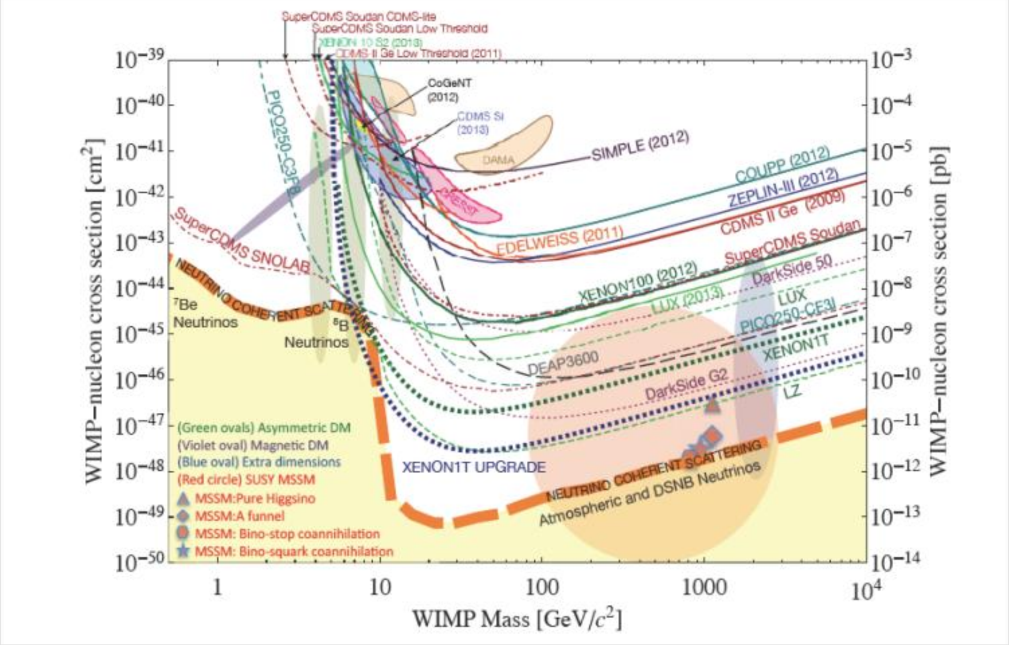
...and experimental aspects...

- Exposures
- Energy threshold
- Detector response (phe/keV)
- Energy scale and energy resolution
- Calibrations
- Stability of all the operating conditions.
- Selections of detectors and of data.
- Subtraction/rejection procedures and stability in time of all the selected windows and related quantities
- Efficiencies
- Definition of fiducial volume and non-uniformity
- Quenching factors, channeling
- ...

Uncertainty in experimental parameters, as well as necessary assumptions on various related astrophysical, nuclear and particle-physics aspects, affect all the results at various extent, both in terms of exclusion plots and in terms of allowed regions/volumes. Thus comparisons with a fixed set of assumptions and parameters' values are intrinsically strongly uncertain.

No experiment can – at least in principle - be directly compared in a model independent way with DAMA so far

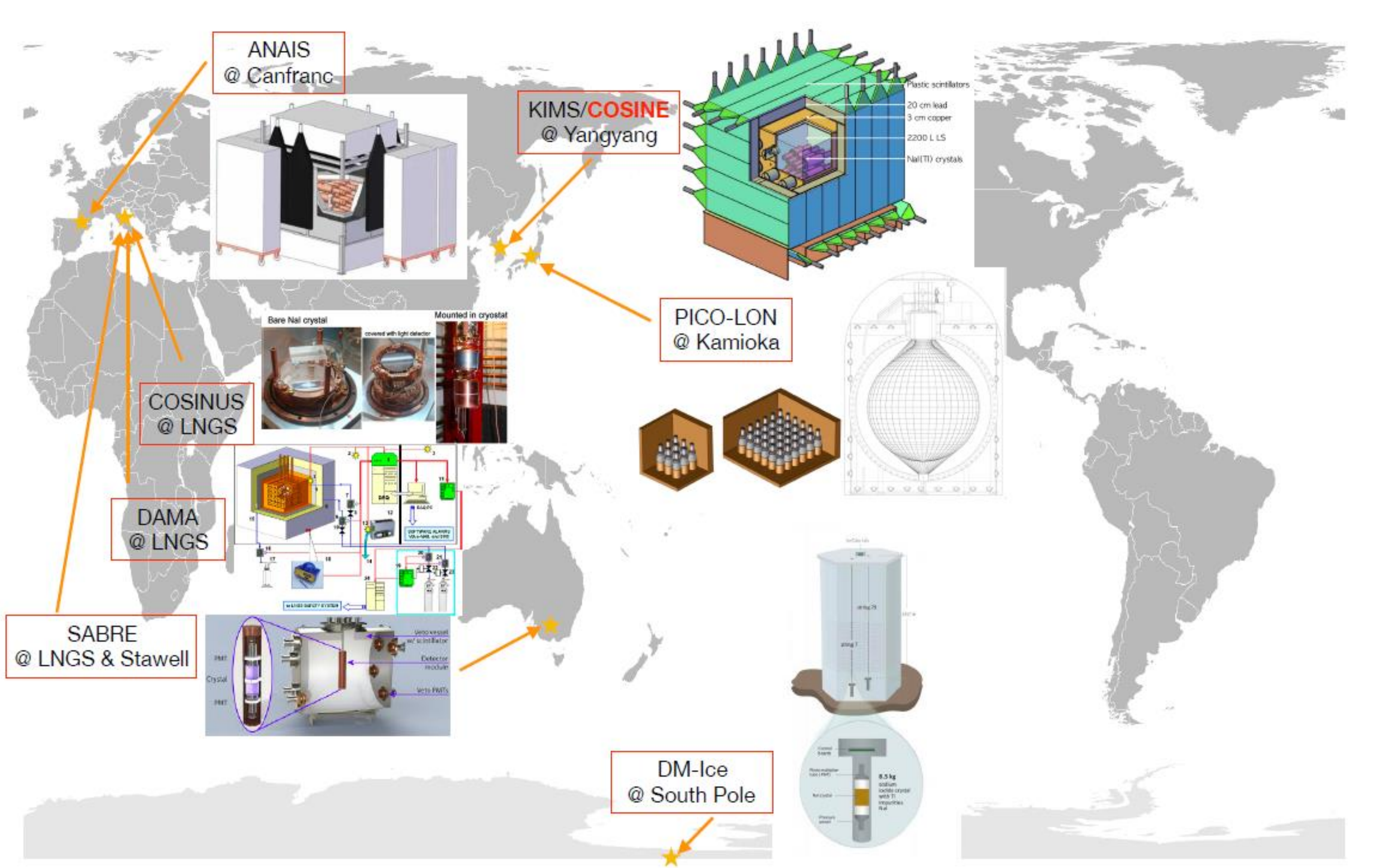
Is it an "universal" and "correct" way to approach the problem of DM and comparisons?



No, it isn't. This is just a largely arbitrary/partial/incorrect exercise

https://agenda.infn.it/getFile.py/access?contribId=34&sessionId=1&resId=0&materialId=slides&confId=15474

Global Efforts using NaI(Tl)



Slides available on each experiment if requested

Part 2: Nuclear Physics in Dark Matter

Lots of Nuclear Physics In Dark Matter

LETTER

https://doi.org/10.1038/s41586-019-1124-4

Observation of two-neutrino double electron capture in ^{124}Xe with XENON1T

XENON Collaboration*

PHYSICAL REVIEW D **100,** 072009 (2019)

Electromagnetic backgrounds and potassium-42 activity in the DEAP-3600 dark matter detector

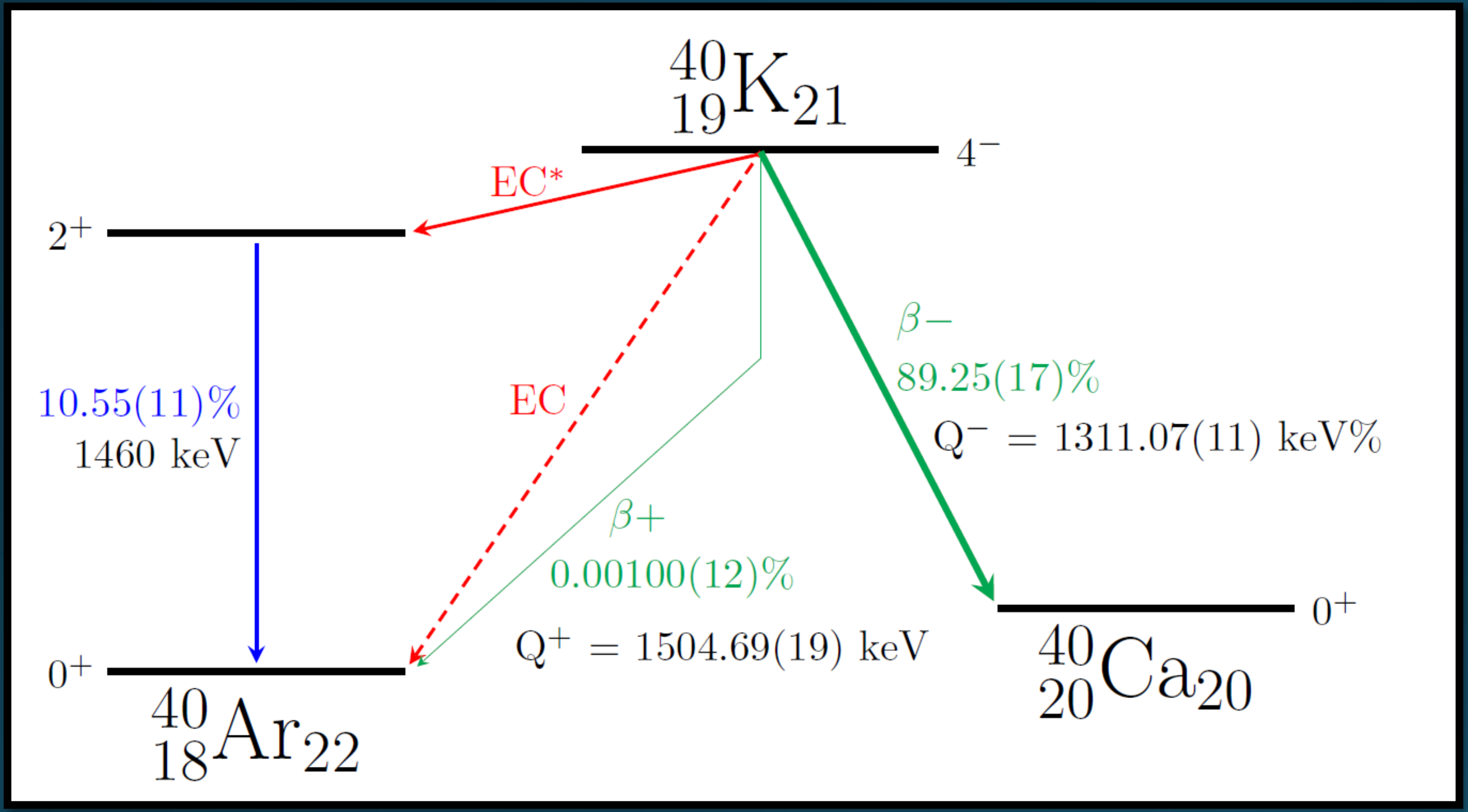
Spectral shapes of forbidden argon β decays as background component for rare-event searches

J. Kostensalo, J. Suhonen and K Zuber

Chinese Physics C Vol. 43, No. 11 (2019) 113001

Searching for neutrino-less double beta decay of ^{136}Xe with PandaX-II liquid xenon detector*

Types of Nuclear Decays



Electron Capture

$${}^{A}_{Z}X_{N} + e^{-} \rightarrow {}_{Z-1}^{A}Y_{N+1} + \upsilon_e$$

β+ Decay

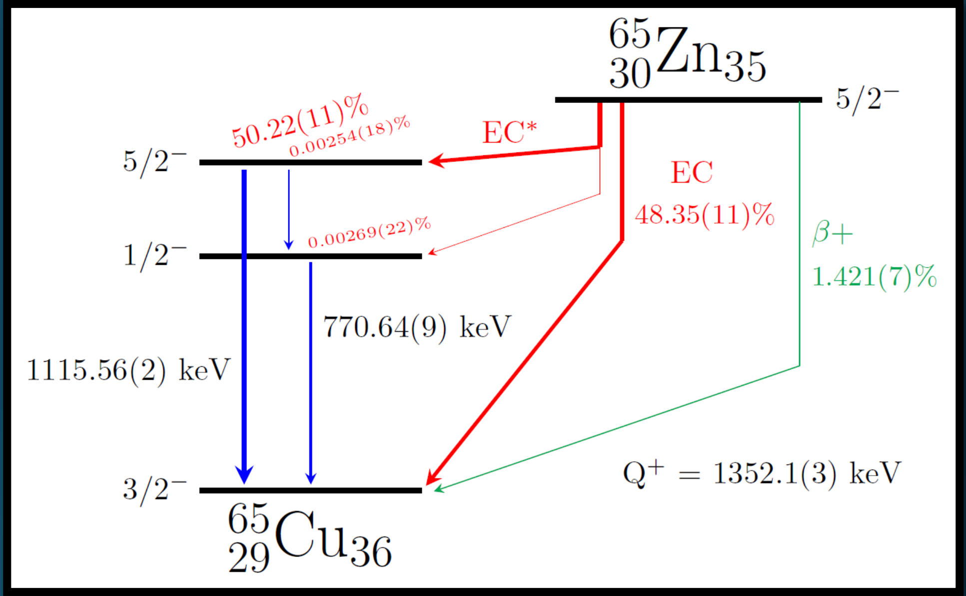
$${}^{A}_{Z}X_{N} \rightarrow {}_{Z-1}^{A}Y_{N+1} + e^{+} + \upsilon_e$$

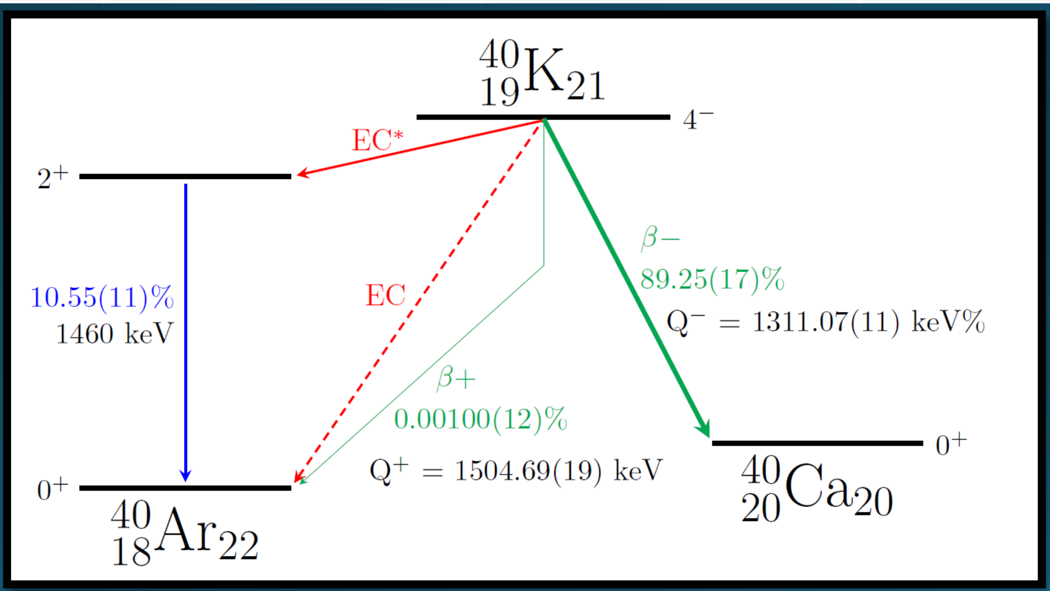
β- Decay

$${}^{A}_{Z}X_{N} \rightarrow {}_{Z+1}^{A}Y_{N-1} + e^{-} + \overline{\upsilon_e}$$

Decay Transition Types

	l	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





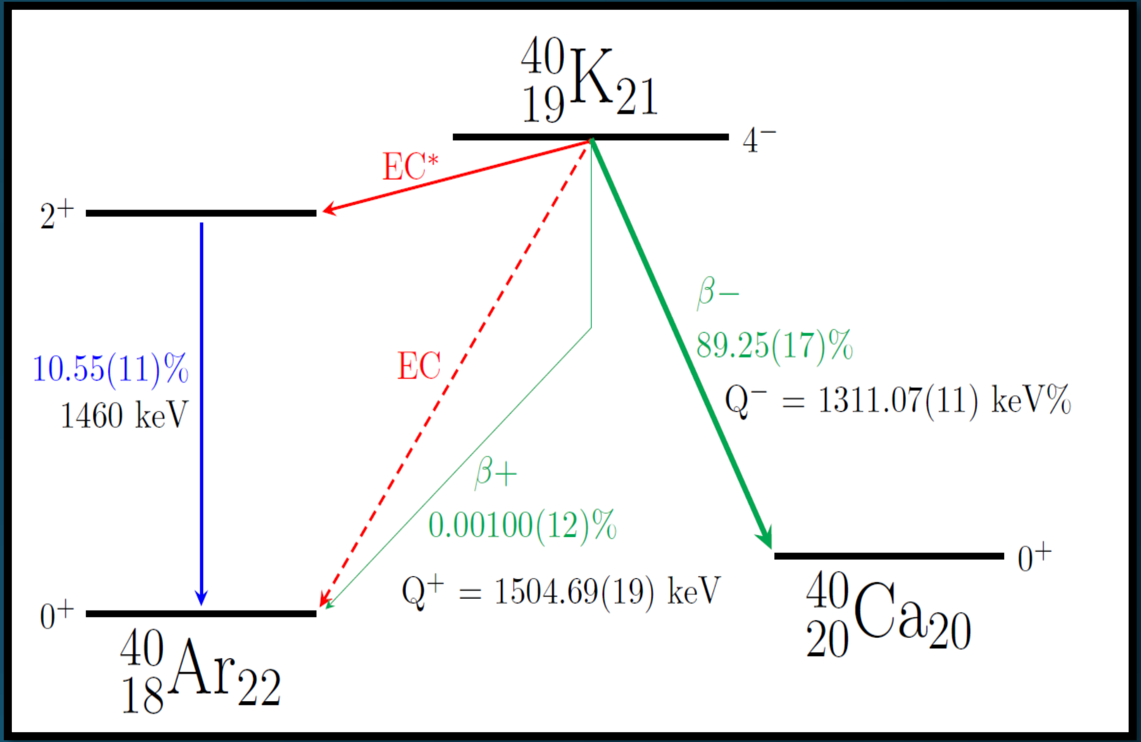
Part 3: What is KDK?

What is KDK?

- Pun for "Potassium Decay"
- KDK is an international collaboration dedicated to the measurement of the **unique-third forbidden** electron capture decay of ^{40}K

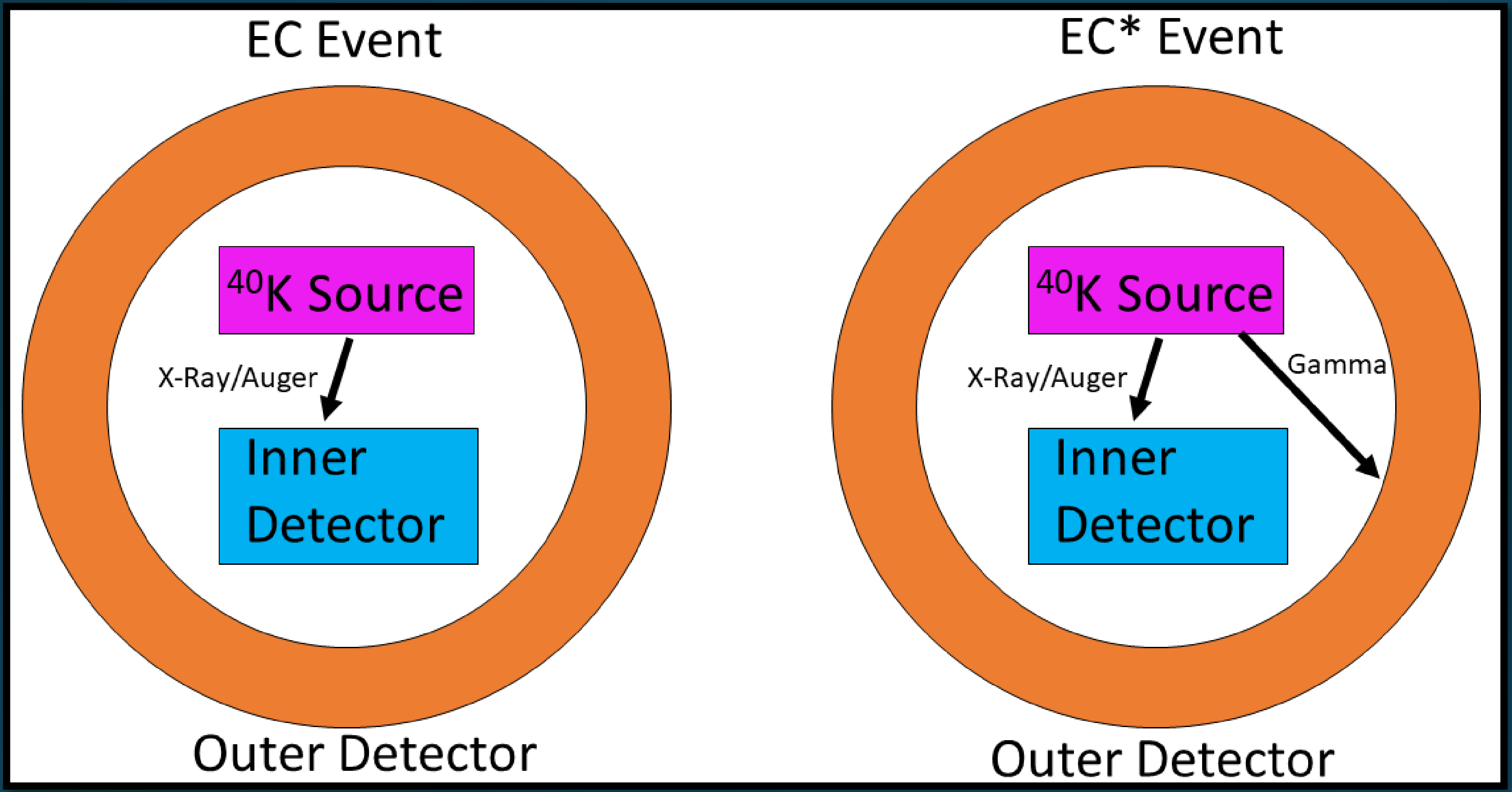
Why ^{40}K?

- Rare example of a unique-third forbidden electron capture decay
- Never been experimentally measured
- ^{40}K (0.0117%) can be found in natural potassium which is a contaminant in NaI
- ^{40}K is a background in many dark matter experiments (DAMA, SABRE, COSINE-100,etc..)
- Increase accuracy in K-Ar (Ar-Ar) dating
- Important Decay Channels:
  - 10.55 % to Ar-40* through electron capture, EC*
  - 0.2 % to Ar-40 through electron capture, EC
  - β- is the dominant decay channel



$$S_m^{obs} = \frac{S_m}{B_o + S_o}$$

KDK Experiment

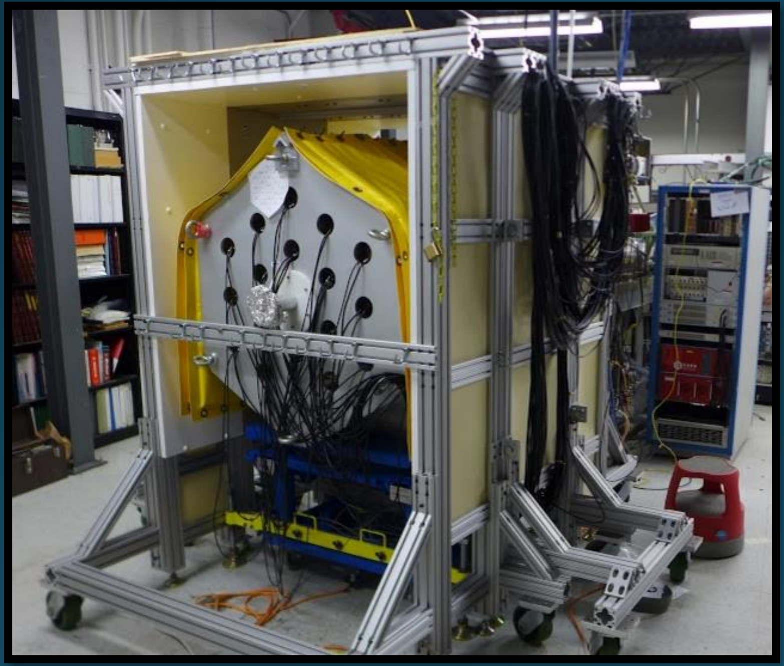


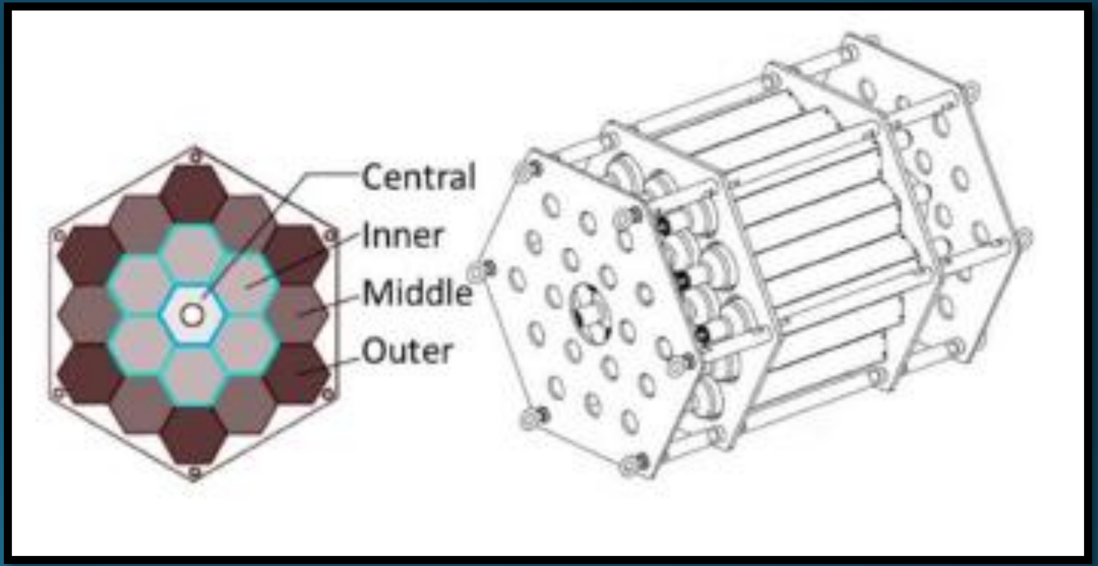
$$\frac{BR_{EC*}}{BR_{EC}} = \kappa$$

- A small, inner detector will trigger on the X-rays from ^{40}K
- The internal detector will be surrounded by an larger detector in order to tag the 1460 keV gammas
- This will allow us to separate the events caused by the EC* decay from the direct EC

MTAS - External Detector

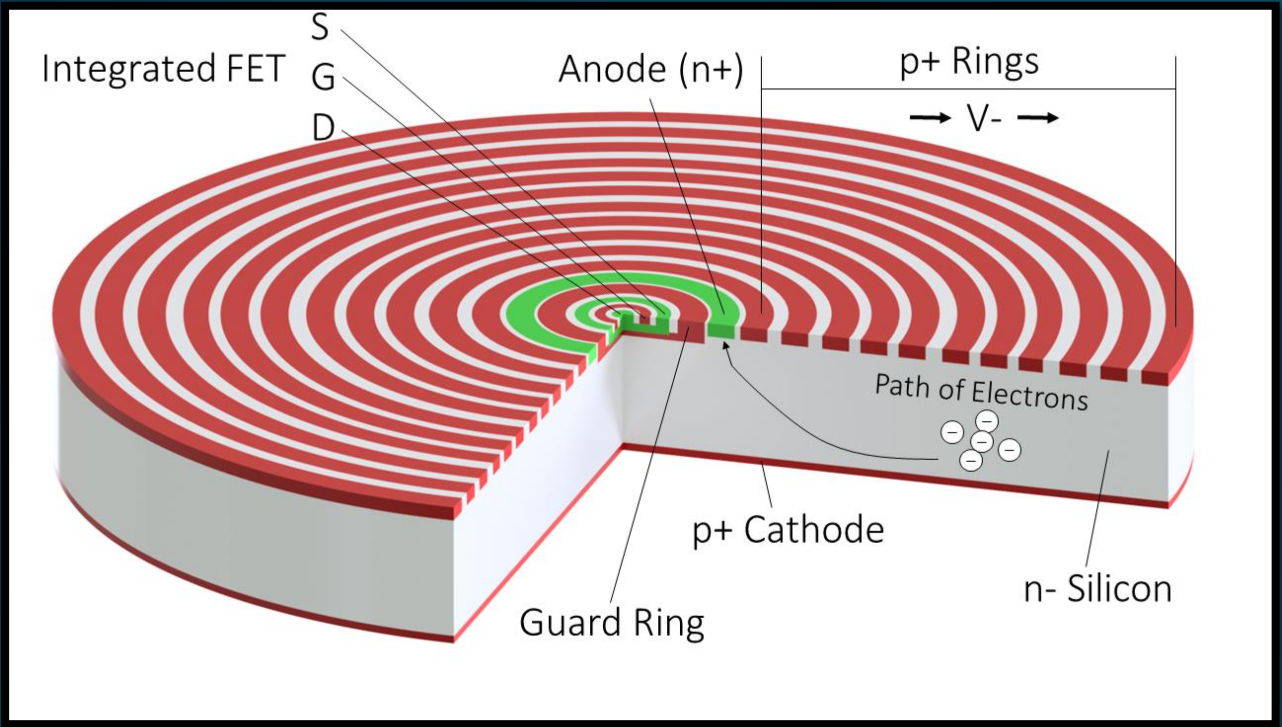
- The proposed external detector is the Modular Total Absorption Spectrometer (MTAS) from Oak Ridge National Lab (ORNL)
- The MTAS detector consists of 19 NaI(Tl) hexagonal shaped detectors (53cm x 20cm) weighing in at ~54 kg each
- MTAS can provide a ~98-99% (SNR=1) efficiency on tagging the 1460 keV gammas and ~4π coverage
- A high efficiency is needed to avoid false positives from the EC* channel and other background sources

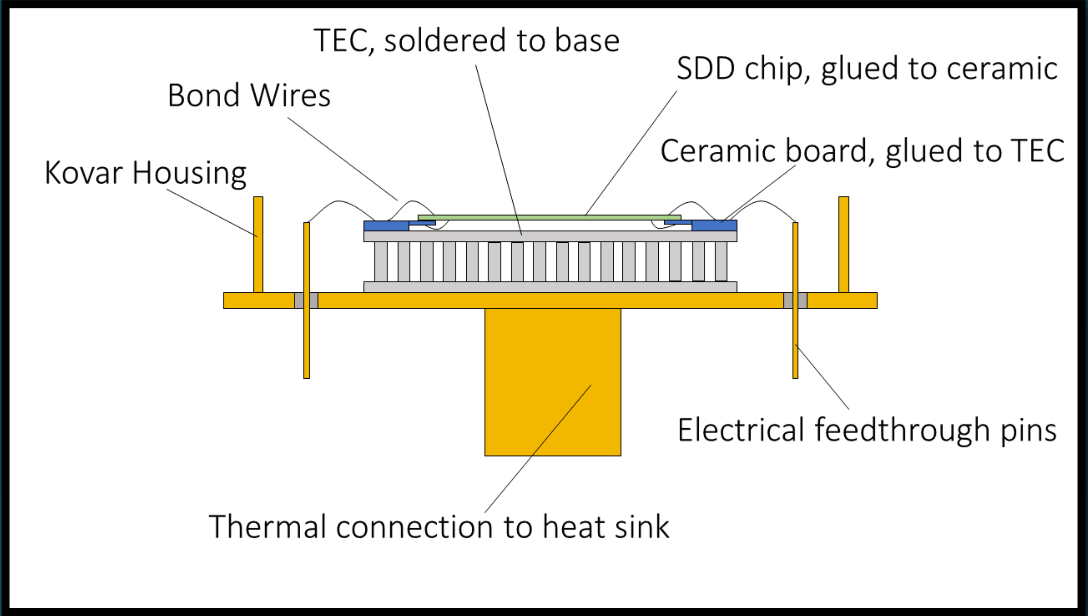


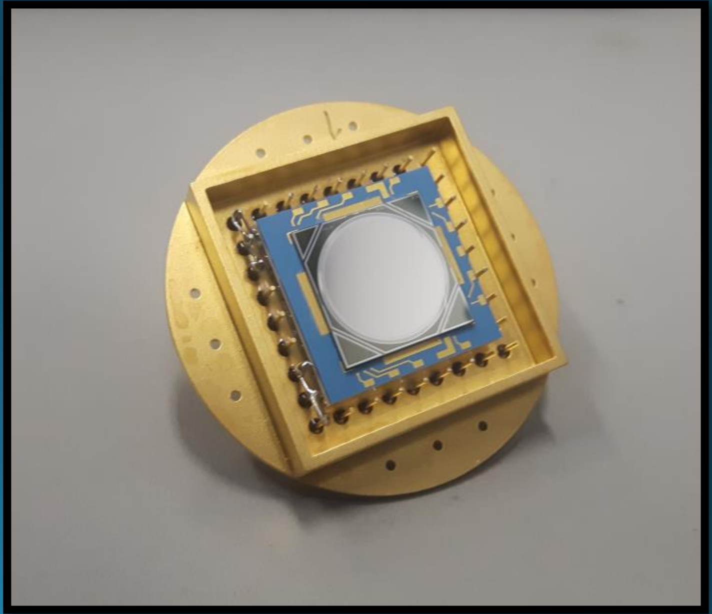


[2] Wolińska-Cichocka, M., et al. "Modular Total Absorption Spectrometer at the HRIBF (ORNL, Oak Ridge)." *Nuclear Data Sheets* 120 (2014): 22-25.

SDD - Internal Detector

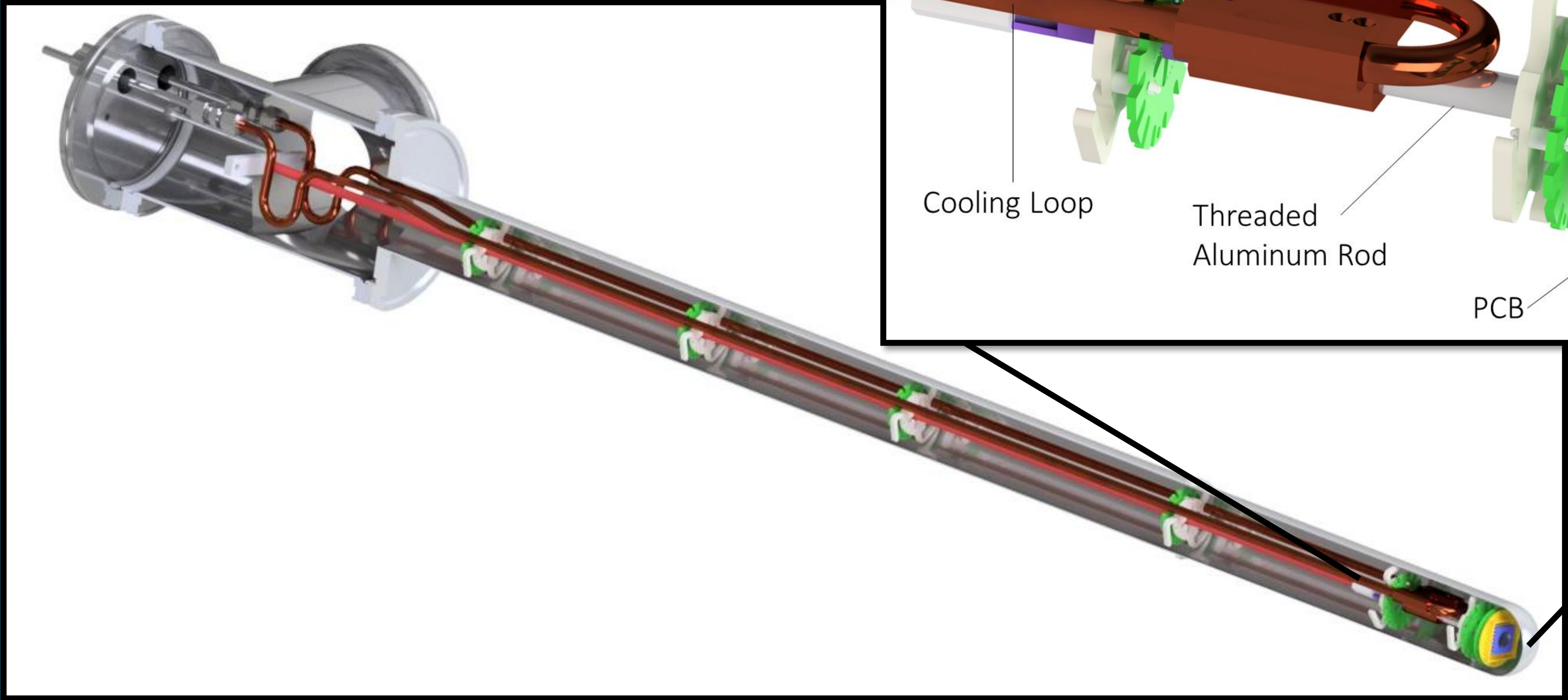


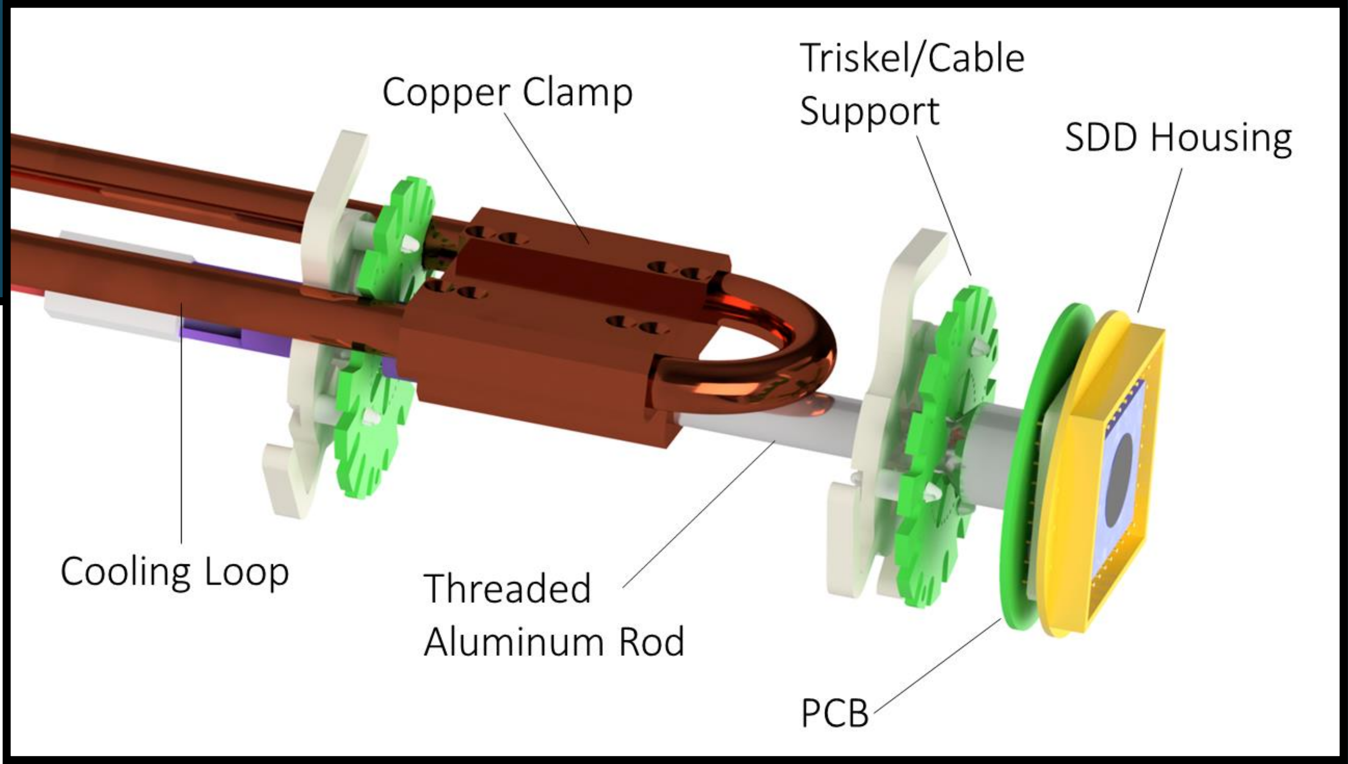




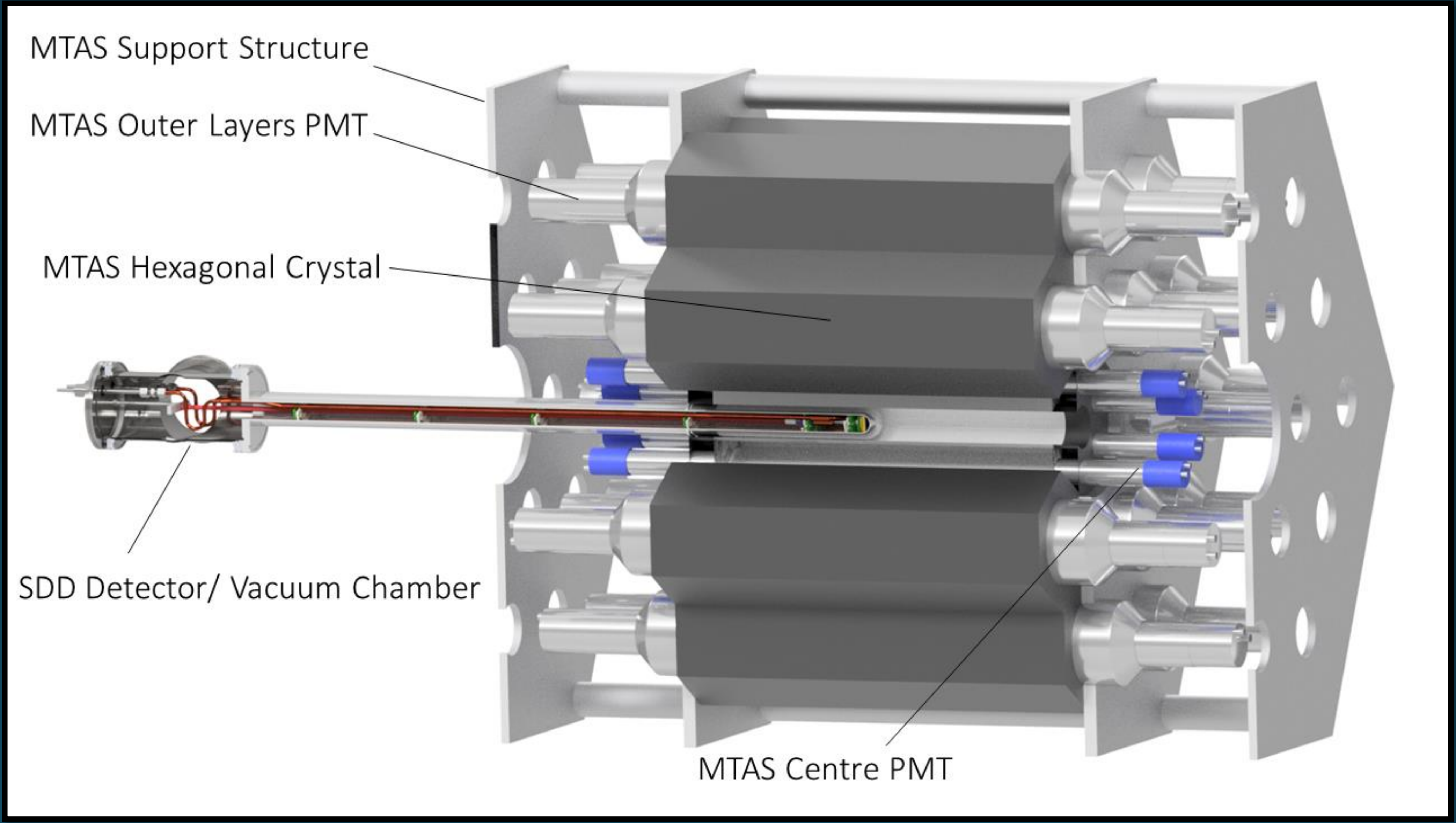
- SDD: Silicon Drift Detector
- Large n-type silicon wafer, small n^+ anode and planar p^+ cathode
- Rings (p^+) surround the anode, creating a potential that guides the electron clouds to the anode
- SDD is cooled to -20°C with a ~100 mm^2 active area
- Advantage is the lower electrical noise than the planar anode counterpart
- Our detector was fabricated by the Halbleiterlabor (German for semiconductor laboratory) of the Max-Planck-Society in Munich, Germany.

SDD - Internal Detector Chamber

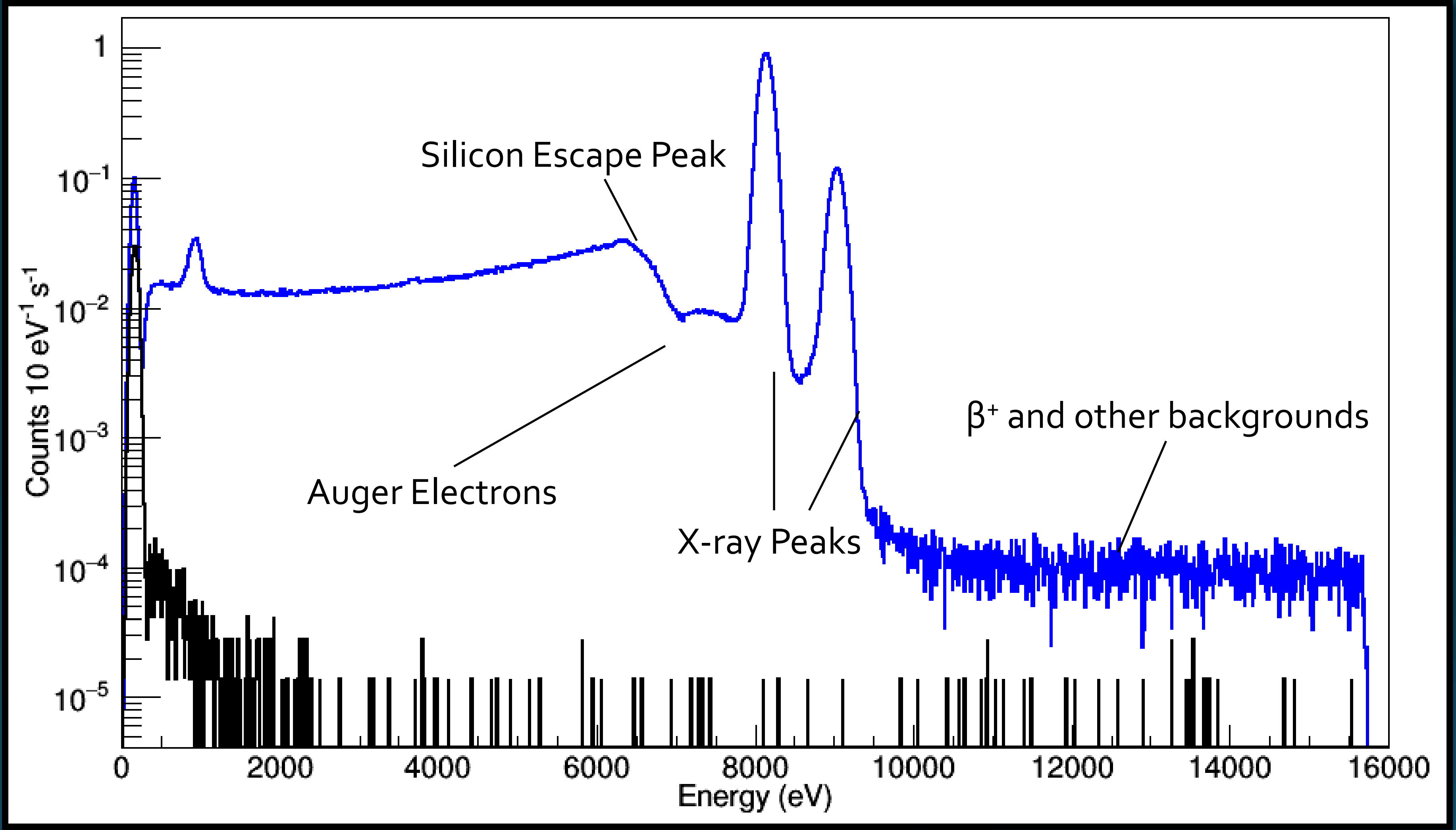


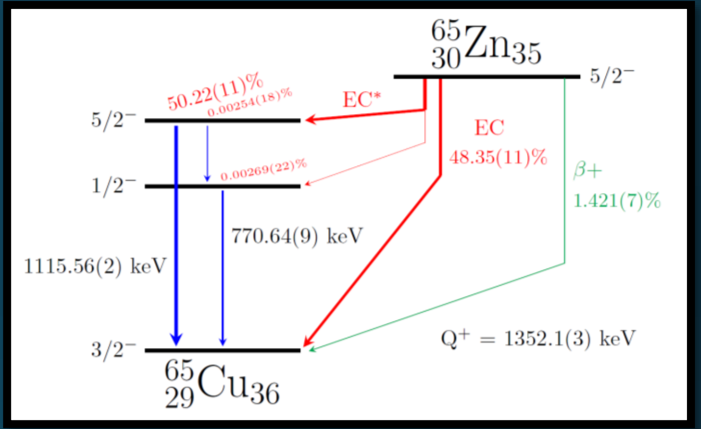


KDK Experimental Setup



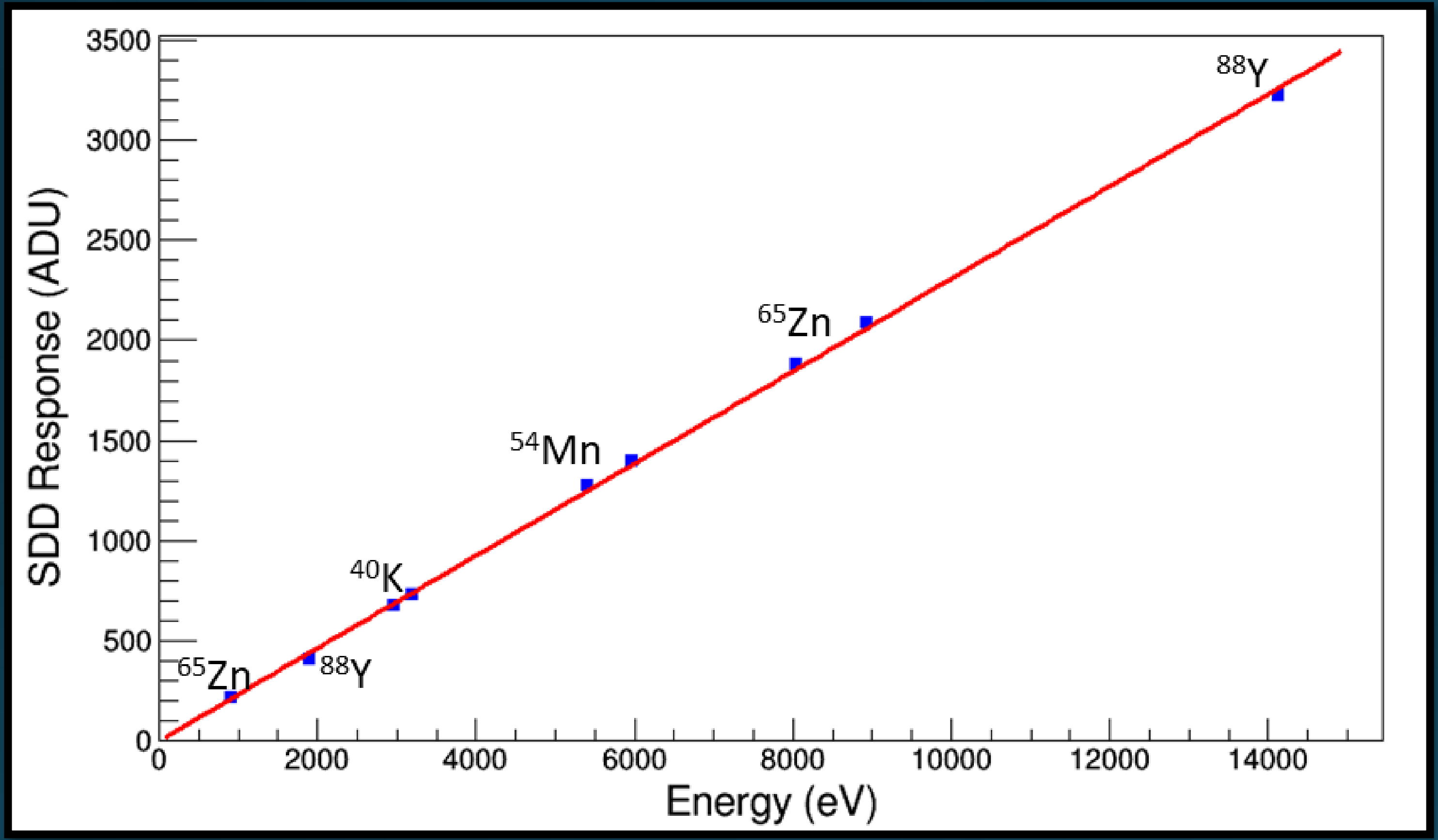
SDD Energy Spectrum Sample





- Energy spectrum of a ^{65}Zn source with background spectrum for SDD
- Visible:
  - X-ray Peaks (K_α, K_β, L)
  - Silicon Escape peak
  - β+ events
  - Auger electrons

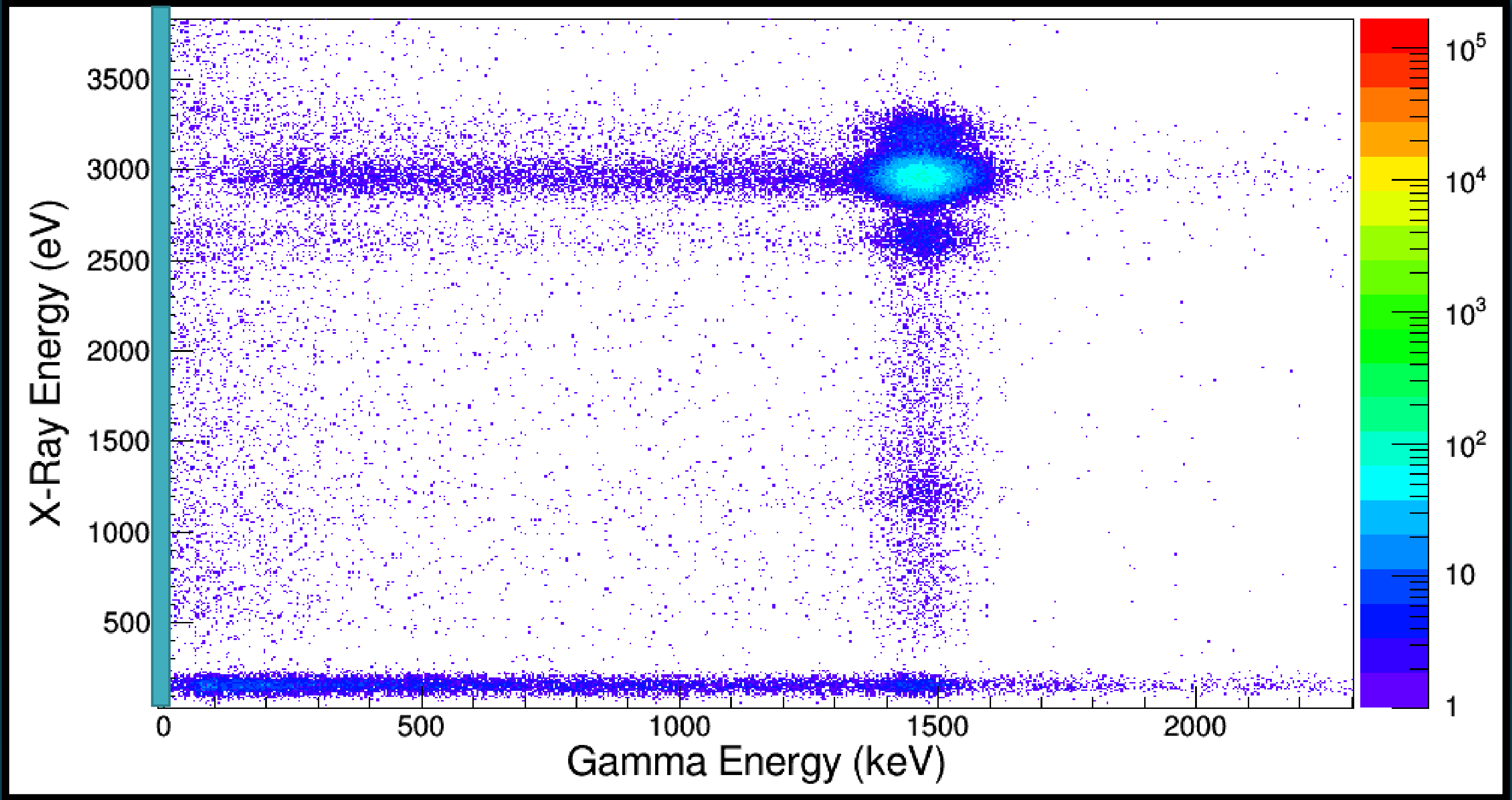
SDD Energy Calibration

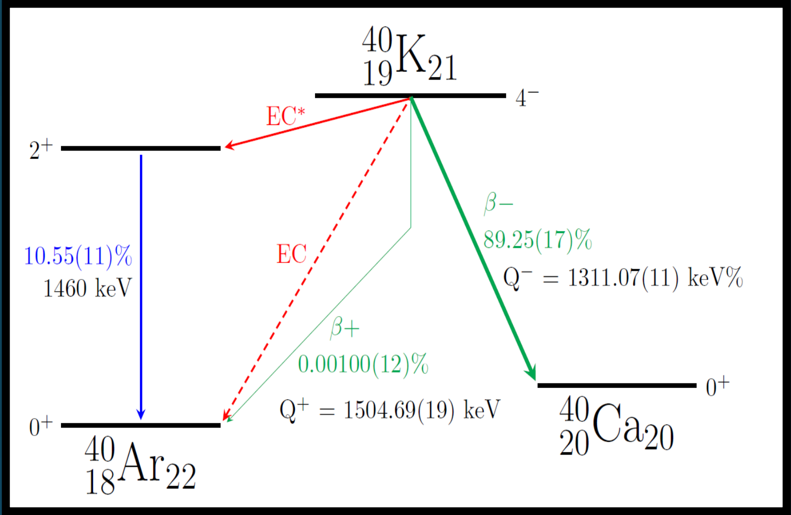


- SDD was calibrated using 4 different sources
  - ^{65}Zn (0.9, 8.0 and 8.9 keV)
  - ^{88}Y (1.8, 14.1 keV)
  - ^{54}Mn (5.4, 5.9 keV)
  - ^{40}K (2.9, 3.2 keV)
- Calibration was very linear
- Energy Threshold: ~250 eV
- Energy Limit: ~15 keV
- FWHM: ~170 eV @ 6keV
- Improvement on performance over an APD (presented at TAUP 2017, see backup slide)

https://indico.cern.ch/event/606690/contributions/2591588/attachments/1497885/2333083/DiStefano_KDK_TAUP_2017.pdf

^{40}K Measurement (Blinded)





- All ^{40}K data was taken during the December 2017 campaign, ^{40}K visible in MTAS/SDD setup!
- Total Run Time: 43 days, Total Useable Time: 33 days, (due to power failure), Data is blinded
- Silicon Escape Peak (~1.2 keV), Cl fluorescence (~2.9 keV)

Summary

- An interesting search for Dark Matter is being performed by NaI detectors across the world
- Nuclear Physics and Dark Matter searches can exist in harmony
- KDK is an experiment dedicated to the measurement of a rare decay of ^{40}K
- Uses a large outer detector MTAS and a small inner detector, SDD

Acknowledgment

KDK Collaboration

N. Brewer[1], P. Di Stefano[2], A. Fijalkowska[1][5][6], Z. Gai[1], C. Goetz[3], R. Grzywacz[3], J. Kostensalo[7], P. Lechner[8], Y. Liu[1], E. Lukosi[3],M. Mancuso[9], D. McKinnon[3], C. Melcher[3], J. Ninkovic[8], F. Petricca[9], C. Rasco[1], K. Rykaczewski[1], D. Stracener[1], J. Suhonen[7], M. Wolińska-Cichocka [1][4][6], Itay Yavin

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[5] University of Warsaw, Warsaw, Poland

[6] Joint Institute for Nuclear Physics and Applications

[7] University of Jyvaskyla, Jyvaskyla, Finland

[8] MPG Semiconductor Laboratory, Munich, Germany

[9] Max Planck Institute for Physics, Munich, Germany

Technical and Electronic Support from M. Constable, F. Retiere (TRIUMF), K. Dering (Queen's University), Paul Davis, University of Alberta

References

1) 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.

2) Wolińska-Cichocka, M., et al. "Modular Total Absorption Spectrometer at the HRIBF (ORNL, Oak Ridge)." *Nuclear Data Sheets* 120 (2014): 22-25.

3) Bernabei, R. et. al. “First model independent results from DAMA/LIBRA-phase2”. *arXiv preprint arXiv:1805.10486*. (2018)

Extra Slides

The different branching ratios of ^{40}K (EC)

LOGFT Value

$$BR_{EC} = 0.2(1)\%$$

[3] Be, M.M., Chiste, V., Dulieu, C., Mougeot, X., Chechev, V., Kondev, F., Nichols, A., Huang, X. and Wang, B., 1999. Table of Radionuclides (Comments on evaluations). *Monographie BIPM-5, 7.*

Indirect Experimental Half-Life Value

$$BR_{EC} = 0.8(8)\%$$

[1] 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.

Recent NNDC Value (2017)

$$BR_{EC} = 0.046(6)\%$$

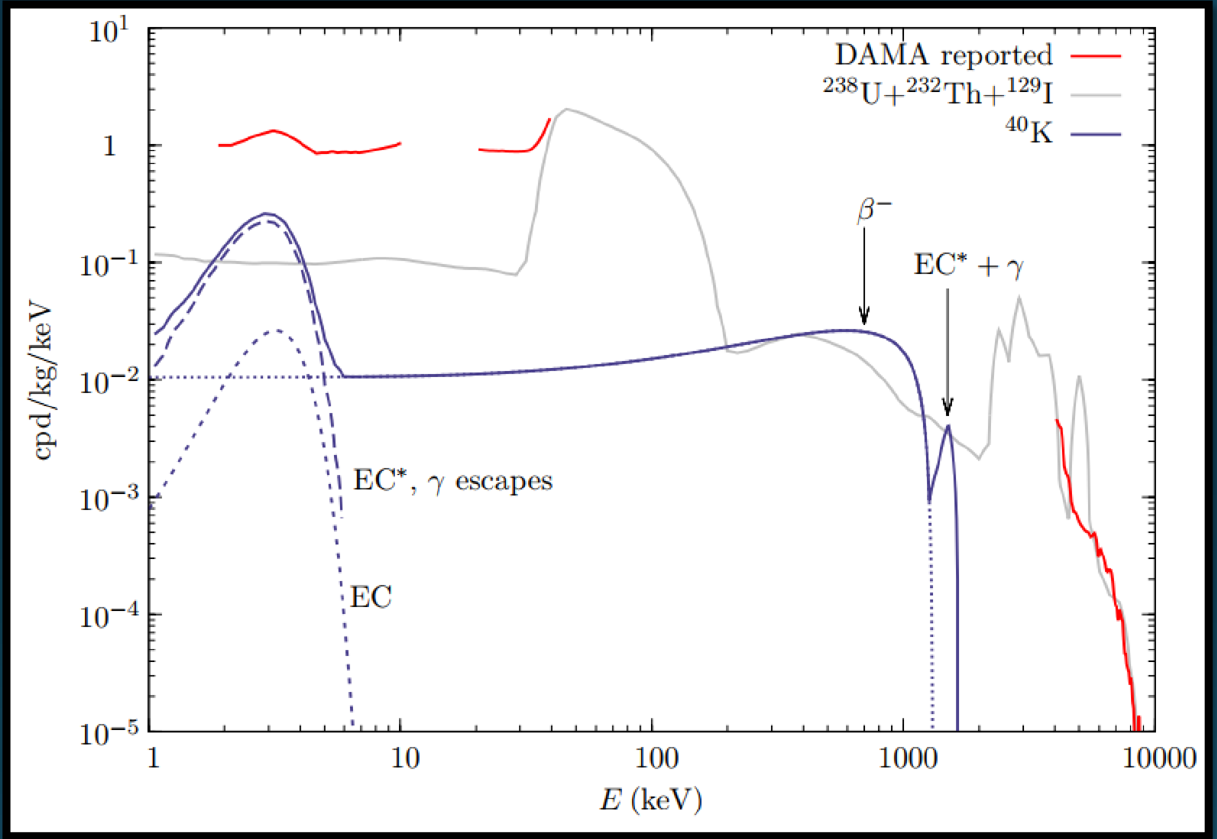
[2] Endt, P.M., 1990. Energy levels of A= 21–44 nuclei (VII). *Nuclear Physics A, 521*, pp.1-400.

KDK Theoretical Value

$$BR_{EC} = 0.064(19)\%$$

From private communication with J. Kostensalo

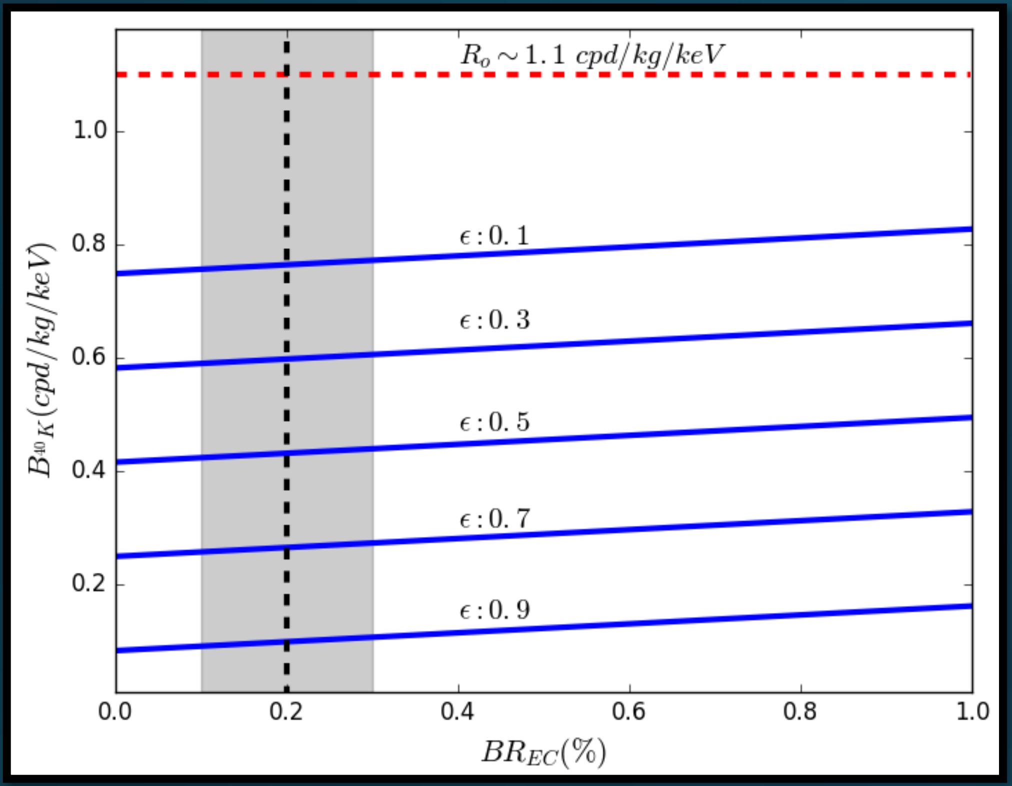
DAMA Single-Hit Event Spectrum



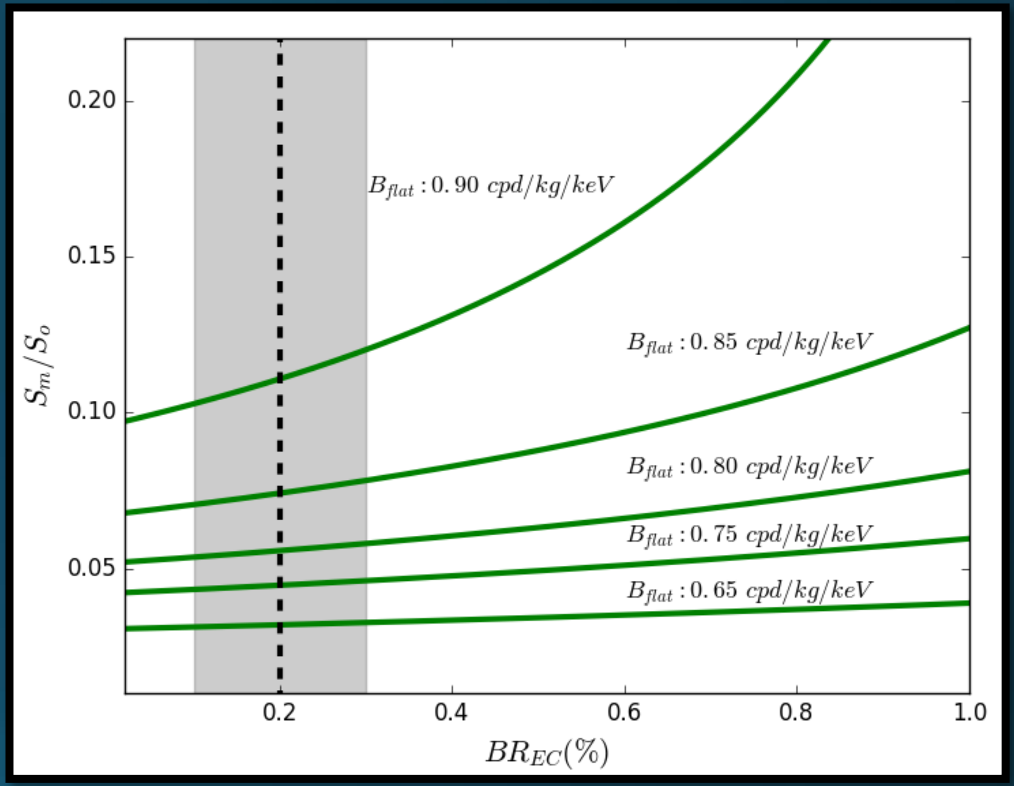
- ^{40}K can contribute to the 2-6 keV, single hit background of the DAMA spectrum in 3 different ways.
  - The β- decay to ^{40}Ca will contribute a flat background
  - The two electron capture channels will contribute to the 2-6 keV energy region: ~3 keV Auger or x-ray contribution
- The grey line is the spectrum from ^{129}I (0.2 ppt), ^{238}U(5 ppt) and ^{232}Th(1.7 ppt)
- Blue line shows the background from ^{40}K.
- Red line is the released data from DAMA
- ^{129}I is naturally produced by spontaneous fission of natural uranium, by cosmic ray spallation of trace levels xenon in the atmosphere and by some cosmic ray muons striking ^{130}Te

[1] 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.

^{40}K Effects On Interpreting DAMA



$$s_m^{max} = \frac{S_m}{S_o}$$



- The uncertainty on BR_{EC} has a large effect on the interpretation of the DAMA signal as a dark matter claim
- A high branching ratio would imply a larger B_o, meaning less room for S_o and thus a higher allowed modulation fraction. (S_m/S_o)
- This could rule out potential dark matter models that explain the DAMA claim