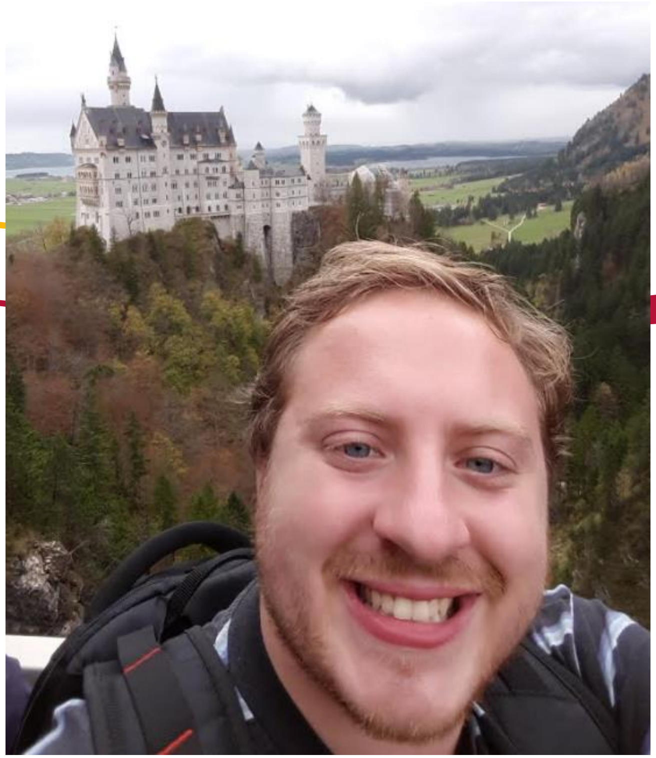
Dark Matter Modulation and The KDK Experiment

Presented By: Matthew Stukel (He/Him),
For the 3rd Annual Summer Particle Physics Workshop
2021/05/12

Who am I?

- Ph.D. student in particle physics at Queen's University
- I work on the KDK project
- Bio:
  - BSc : Applied Physics @ Carleton University
  - Worked 1 year at TRIUMF
  - MSc : Particle Physics @ Queen's University
  - Ph.D.: Particle Physics @ Queen's University
- Big Formula 1 Fan
- Captain of the Queen's Physics Basketball team (Record: 4-56)
- Probably the best Twilight Imperium Player @ Queen's

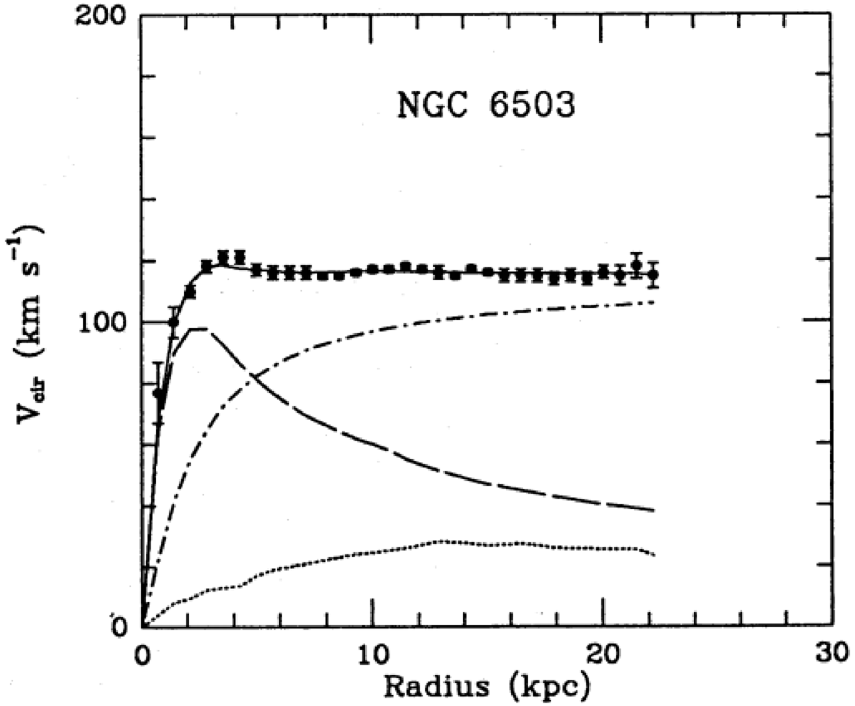


Overview

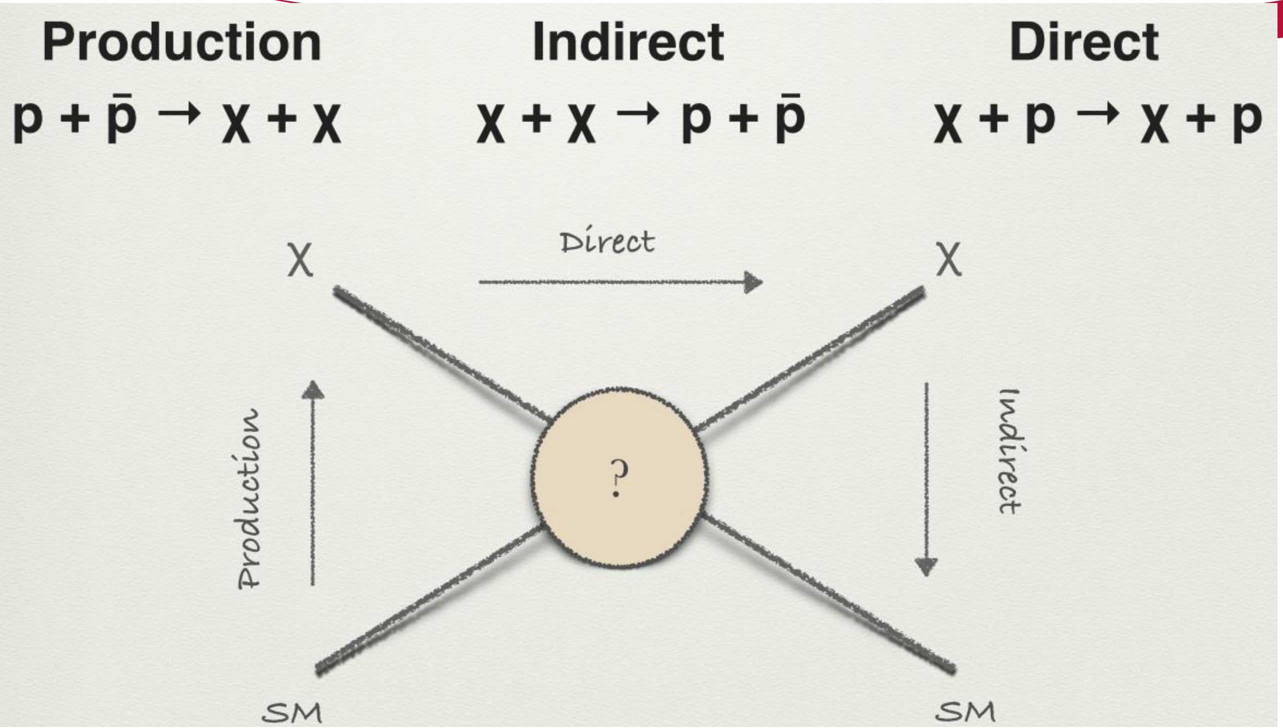
1) Dark Matter and the search for annual modulation
2) Nuclear Physics in Dark Matter
3) KDK Experiment

Part 1: Dark Matter and the search for annual modulation

Dark Matter



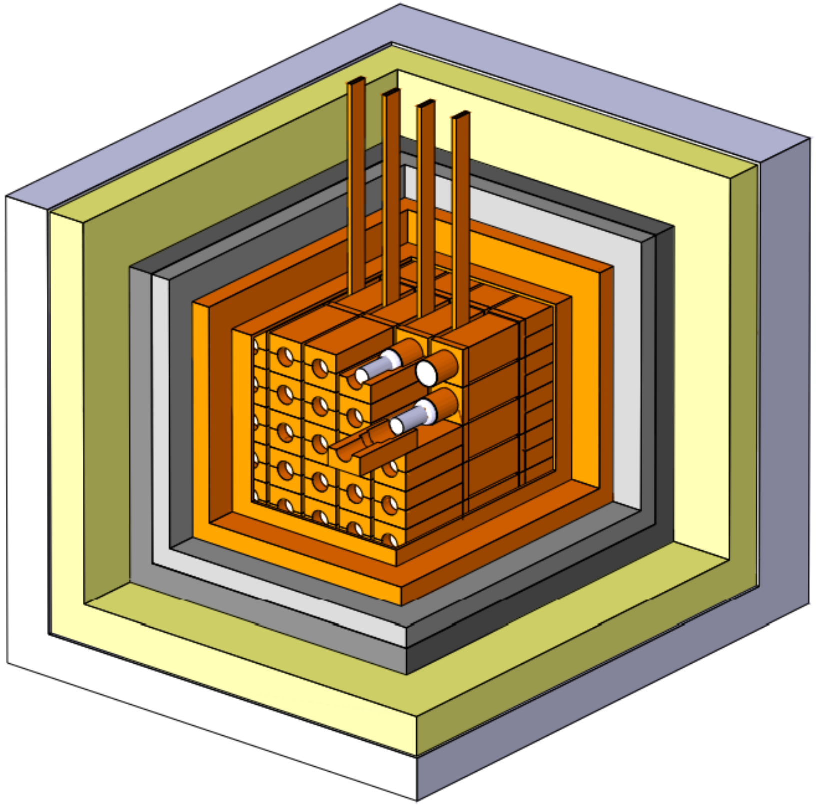
Begeman, K. G et al. "Extended rotation curves of spiral galaxies: Dark haloes and modified dynamics." *Monthly Notices of the Royal Astronomical Society*249.3 (1991): 523-537.



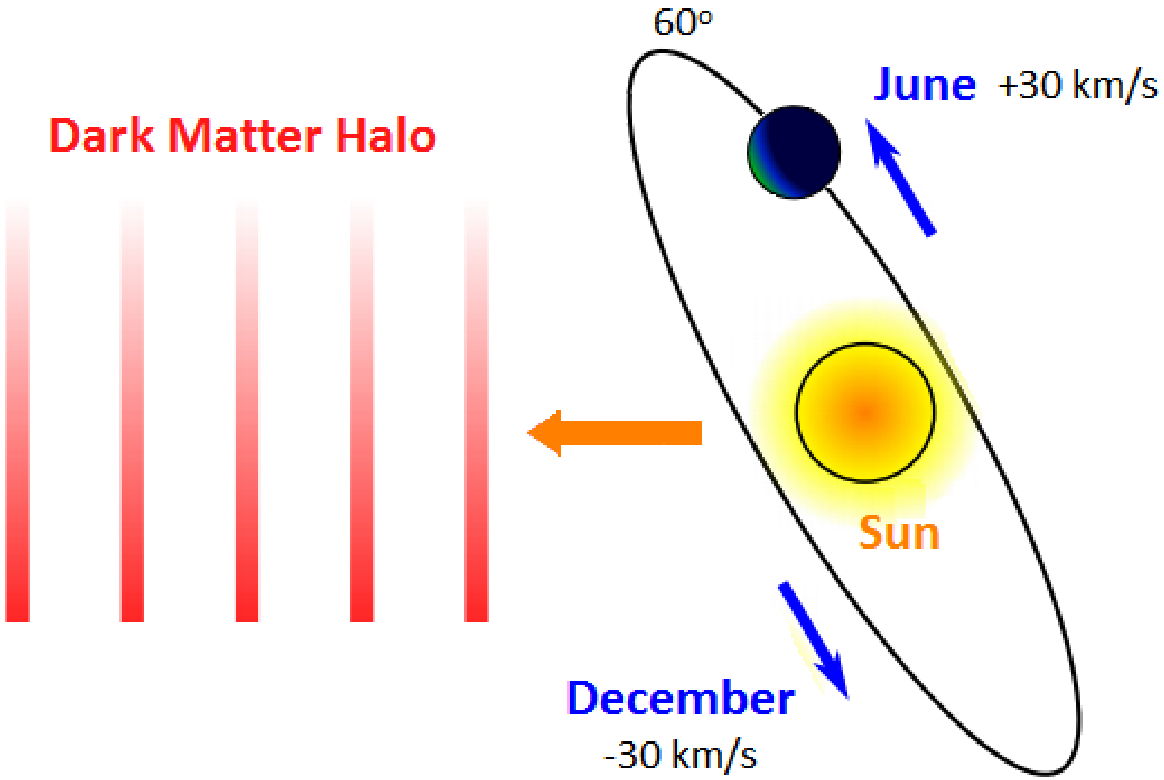
https://www.quantumdiaries.org/2014/10/22/have-we-detected-dark-matter-axions/

- This “dark matter” is expected to make up 26.8% of the mass/energy content of the universe
- Evidence includes: Rotation curves of galaxies, weak gravitational lensing, cosmological modelling
- Many experiments that employ many techniques

Direct Detection: Annual Modulation

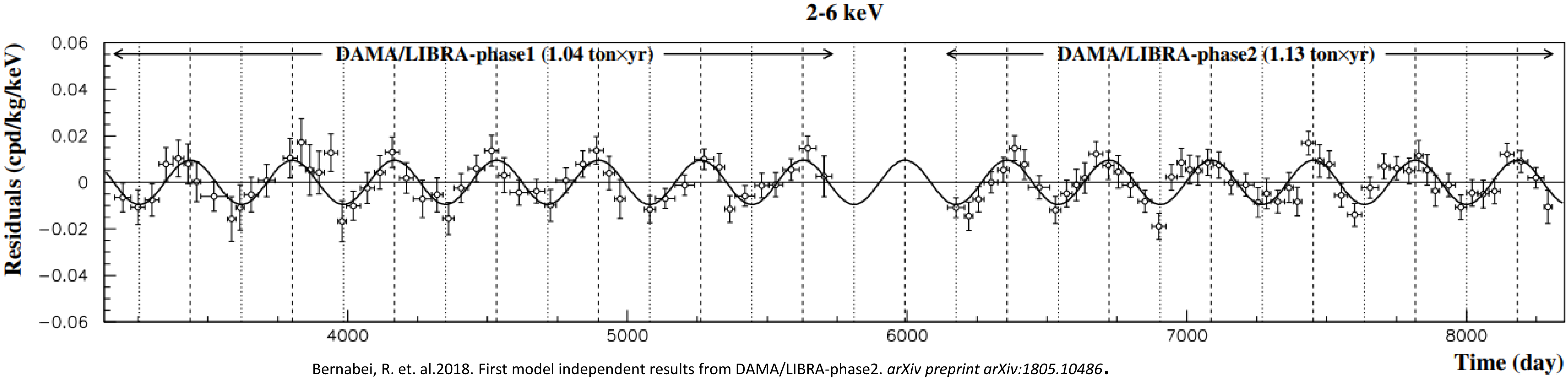


Bernabei, R., et al. "The dama/libra apparatus." *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 592.3 (2008): 297-315.



- The DAMA detector consists of 25 highly radiopure NaI(Tl) crystals. (~10 kg each)
- Search for dark matter **model-independent annual modulation signature**
- The detector is situated in low radioactive copper box in LNGS.

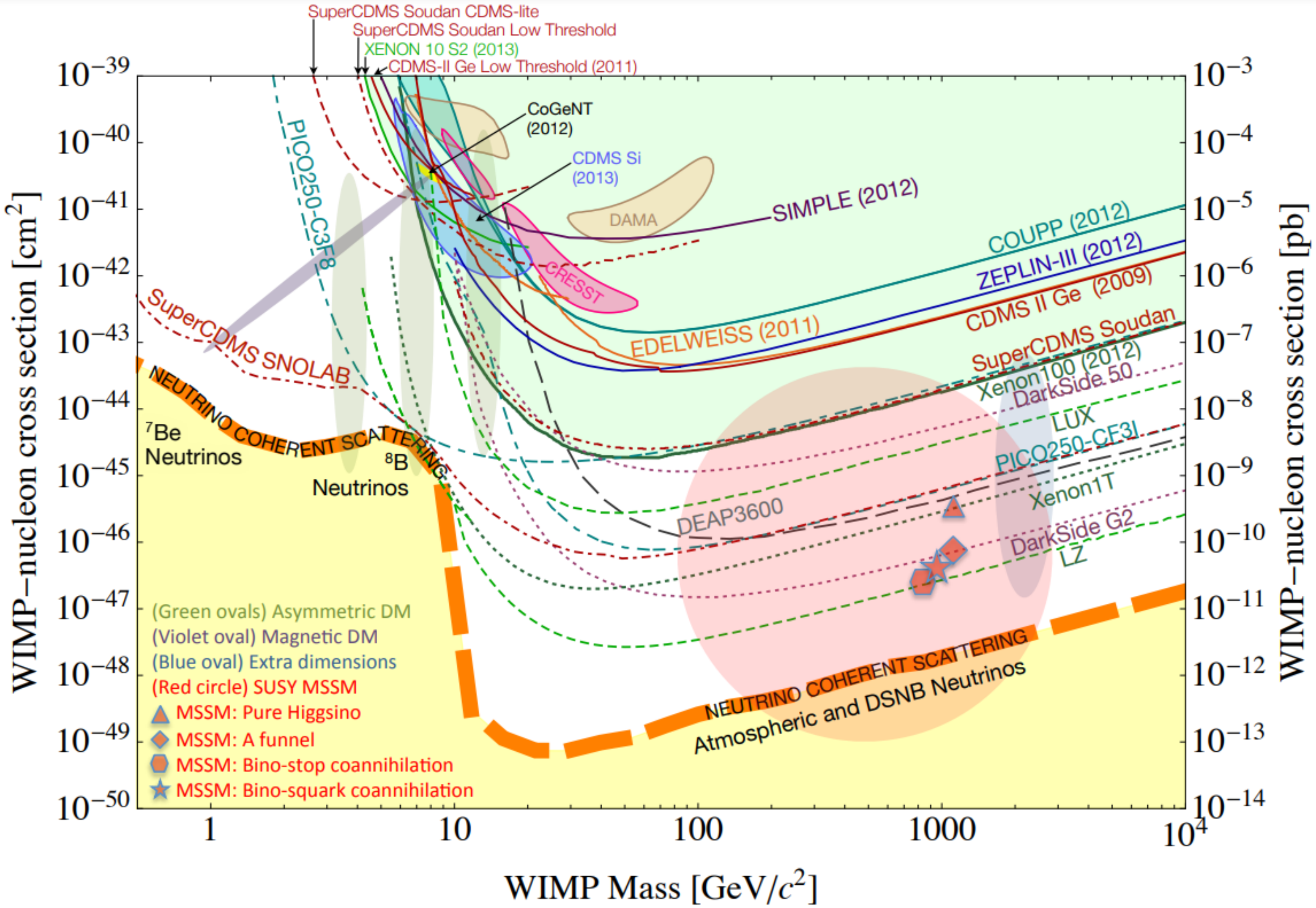
DAMA/LIBRA Experiment



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 (2-6 keV energy region)
- Signal consists of a time-independent and time-dependent dark matter signal
- KDK constrains the time-independent background signal which in turn constrains the time-independent dark matter signal (Itay Yavin)

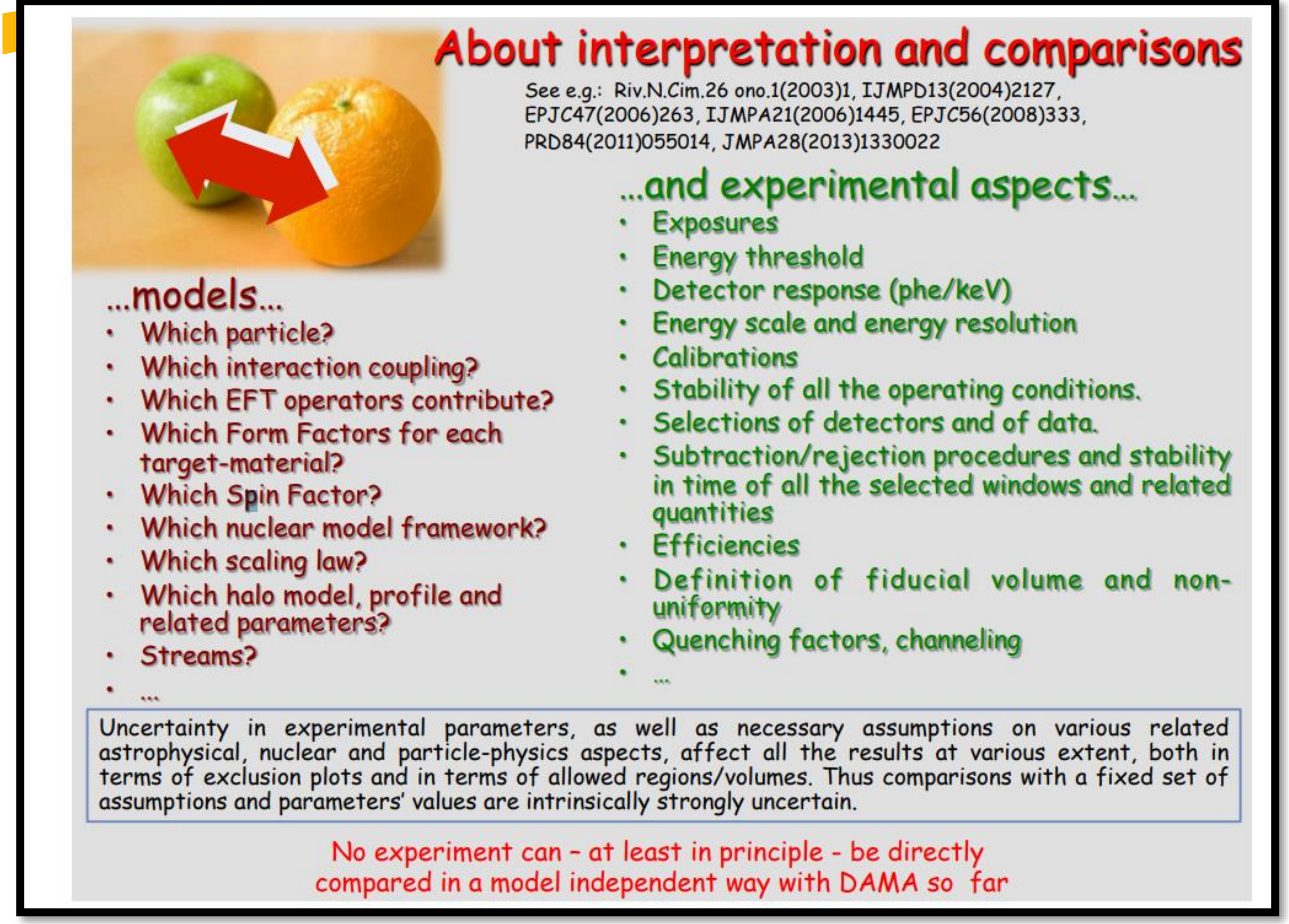
Some issues with DAMA



- Incompatibility with <u>**every other experiments**</u>
- Unknown/un-modelled background components

Cushman, P., et al. "Snowmass CF1 summary: WIMP dark matter direct detection." *arXiv preprint arXiv:1310.8327* (2013).

Some issues with DAMA



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, IJMPA28(2013)1330022

...models...

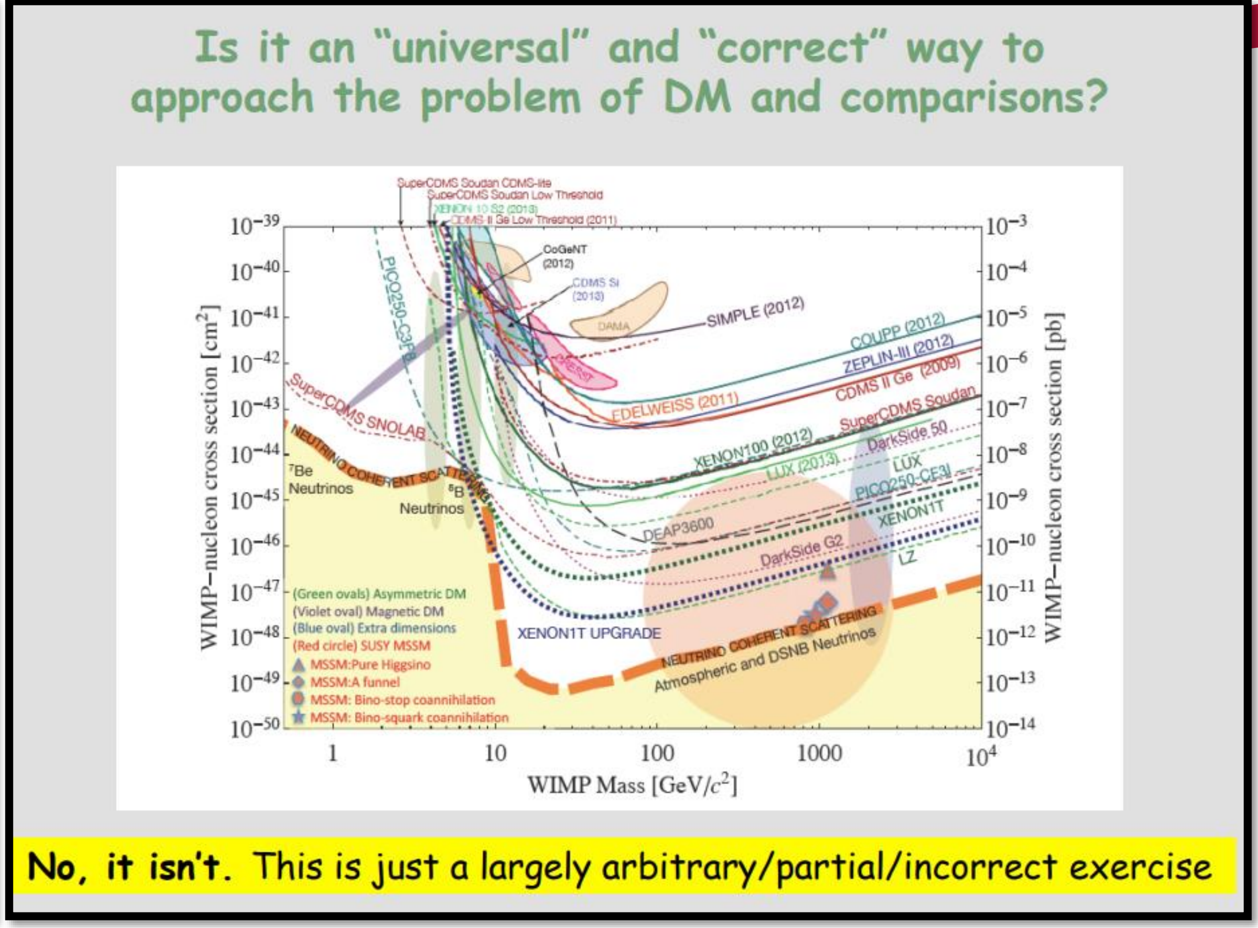
- Which particle?
- Which interaction coupling?
- Which EFT operators contribute?
- Which Form Factors for each target-material?
- Which Spin Factor?
- Which nuclear model framework?
- Which scaling law?
- Which halo model, profile and related parameters?
- Streams?
- ...

...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

DAMA Savior Group

DAMA/LIBRA–phase2 results and implications on several dark matter scenarios

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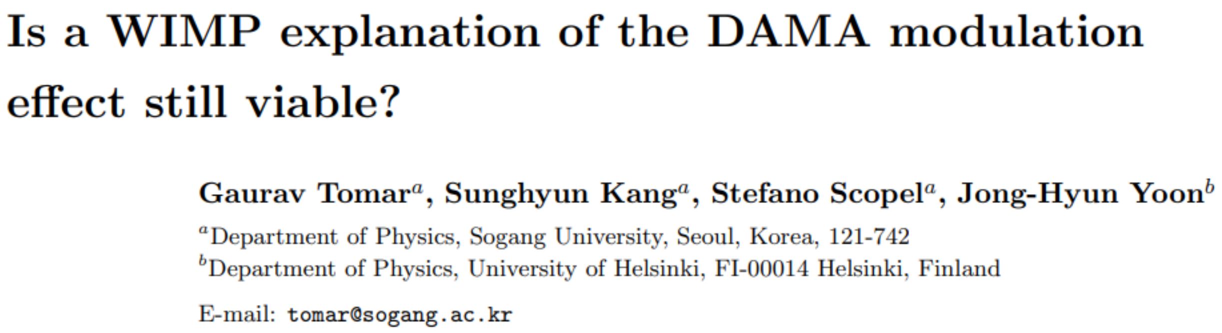

Is a WIMP explanation of the DAMA modulation effect still viable?

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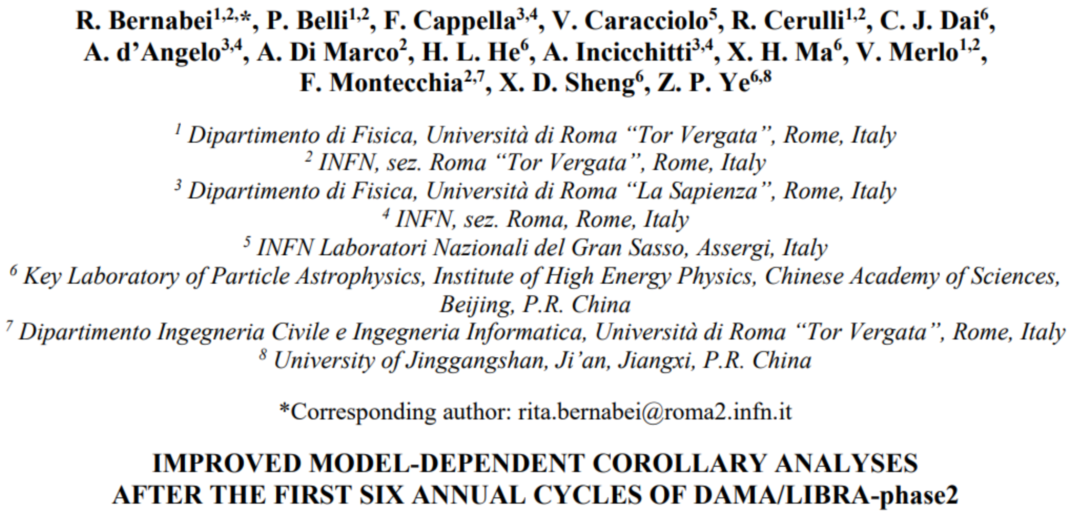
[b]Department of Physics, University of Helsinki, FI-00014 Helsinki, Finland
E-mail: `tomar@sogang.ac.kr`



R. Bernabei[1,2,*], P. Belli[1,2], F. Cappella[3,4], V. Caracciolo[5], R. Cerulli[1,2], C. J. Dai[6], A. d'Angelo[3,4], A. Di Marco[2], H. L. He[6], A. Incicchitti[3,4], X. H. Ma[6], V. Merlo[1,2], F. Montecchia[2,7], X. D. Sheng[6], Z. P. Ye[6,8]

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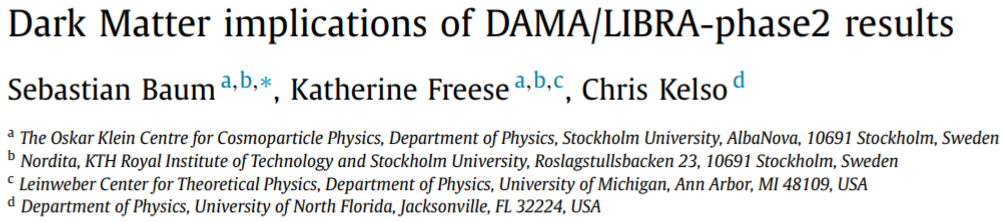
IMPROVED MODEL-DEPENDENT COROLLARY ANALYSES AFTER THE FIRST SIX ANNUAL CYCLES OF DAMA/LIBRA-phase2



Dark Matter implications of DAMA/LIBRA-phase2 results

Sebastian Baum[a,b,*], Katherine Freese[a,b,c], Chris Kelso[d]
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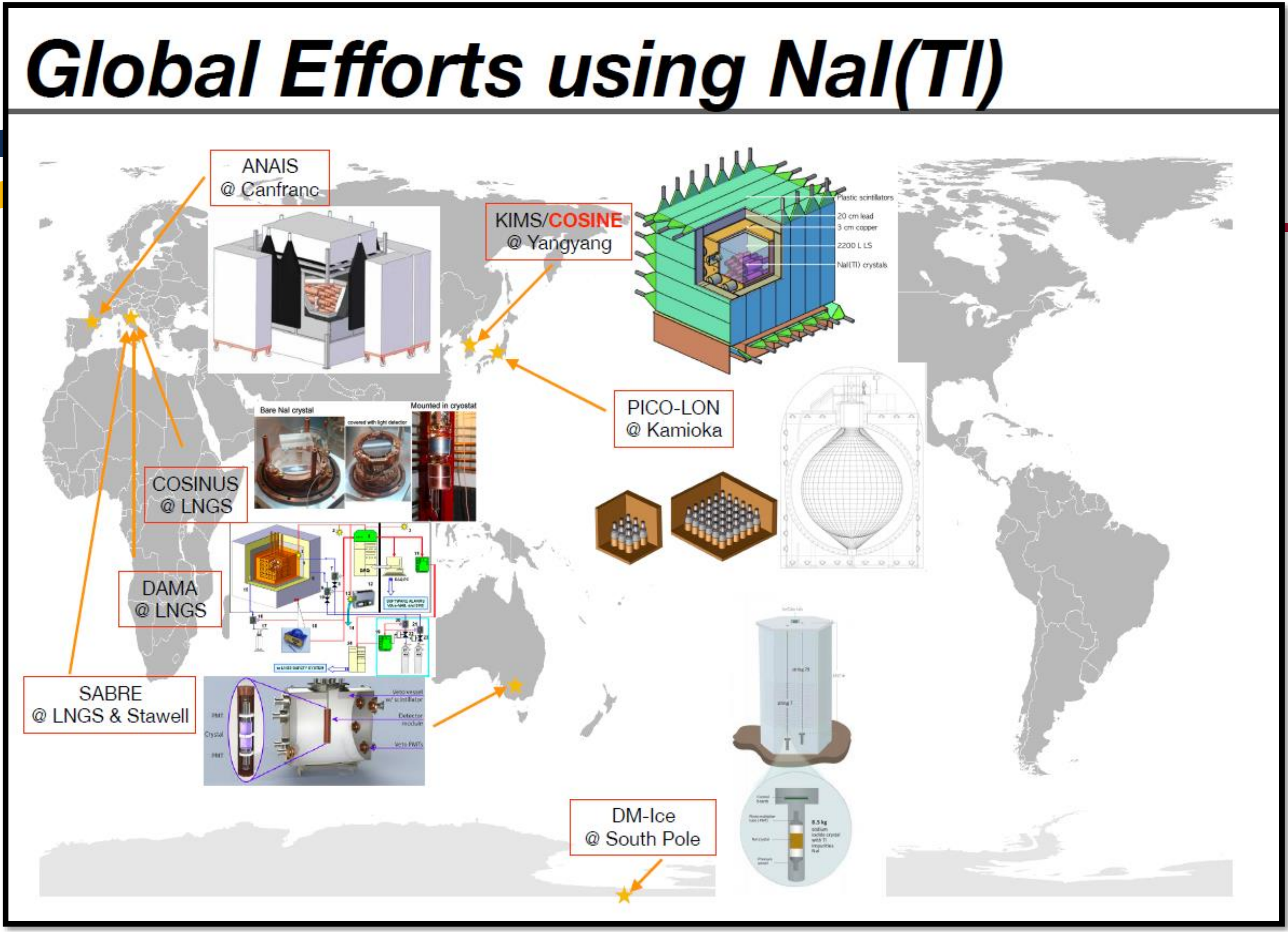
[b] *Nordita, KTH Royal Institute of Technology and Stockholm University, Roslagstullsbacken 23, 10691 Stockholm, Sweden*
[c] *Leinweber Center for Theoretical Physics, Department of Physics, University of Michigan, Ann Arbor, MI 48109, USA*
[d] *Department of Physics, University of North Florida, Jacksonville, FL 32224, USA*



Global Efforts using NaI(TI)

ANAIS
@ Canfranc

KIMS/COSINE
@ Yangyang

PICO-LON
@ Kamioka

COSINUS
@ LNGS

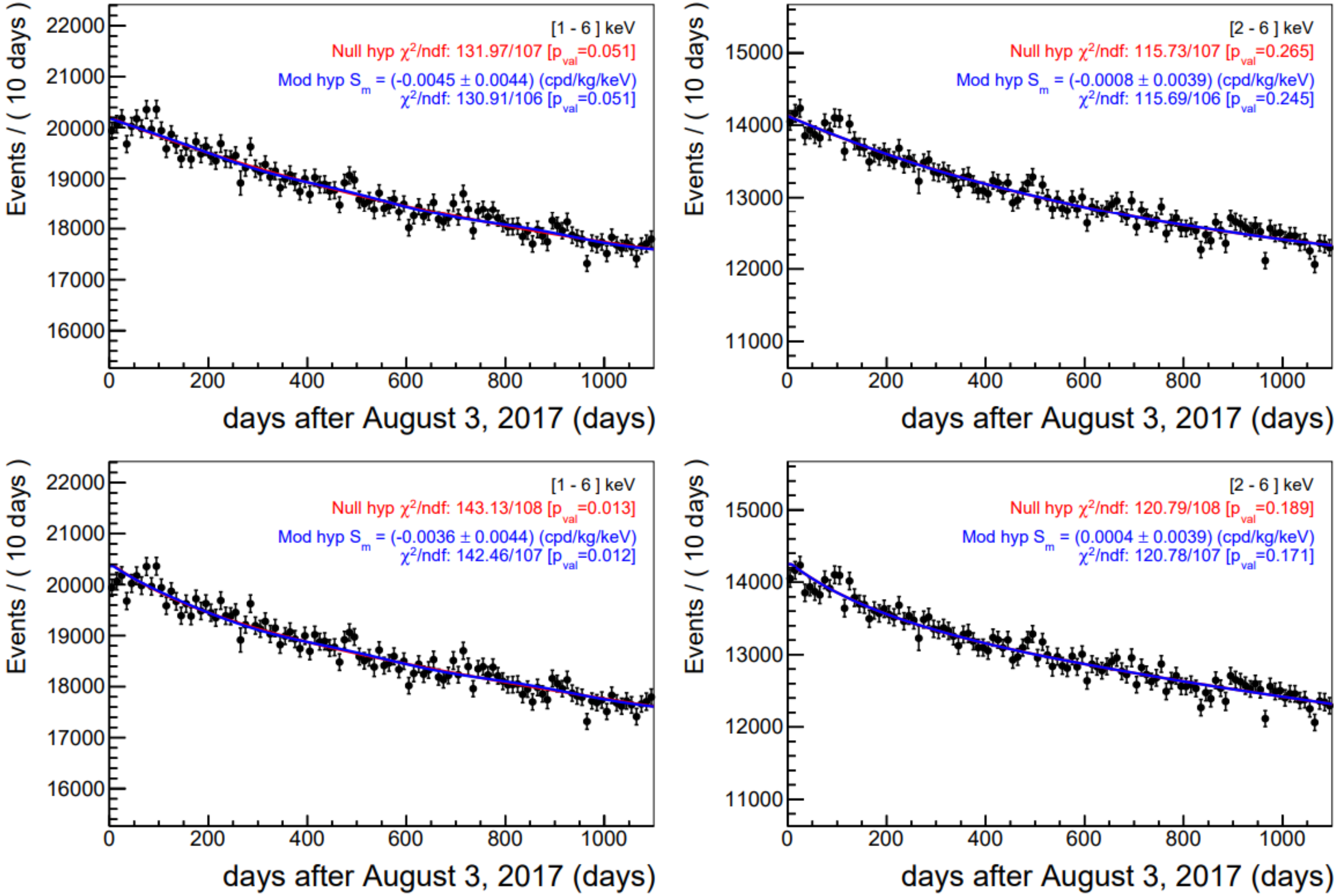
DAMA
@ LNGS

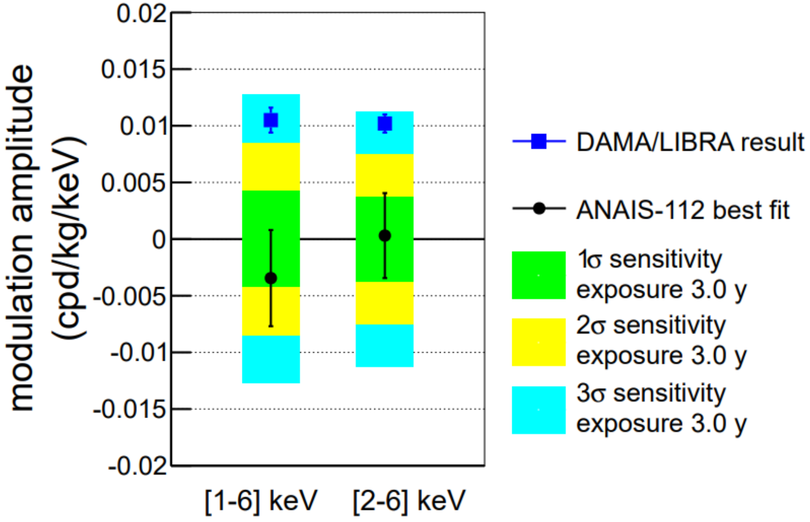
SABRE
@ LNGS & Stawell

DM-Ice
@ South Pole

- Two possible solutions to reconcile the issue
- Direct material comparison
- Study of the DAMA background
    - i.e. KDK

ANAIS-112: 3 Years of Data Taking



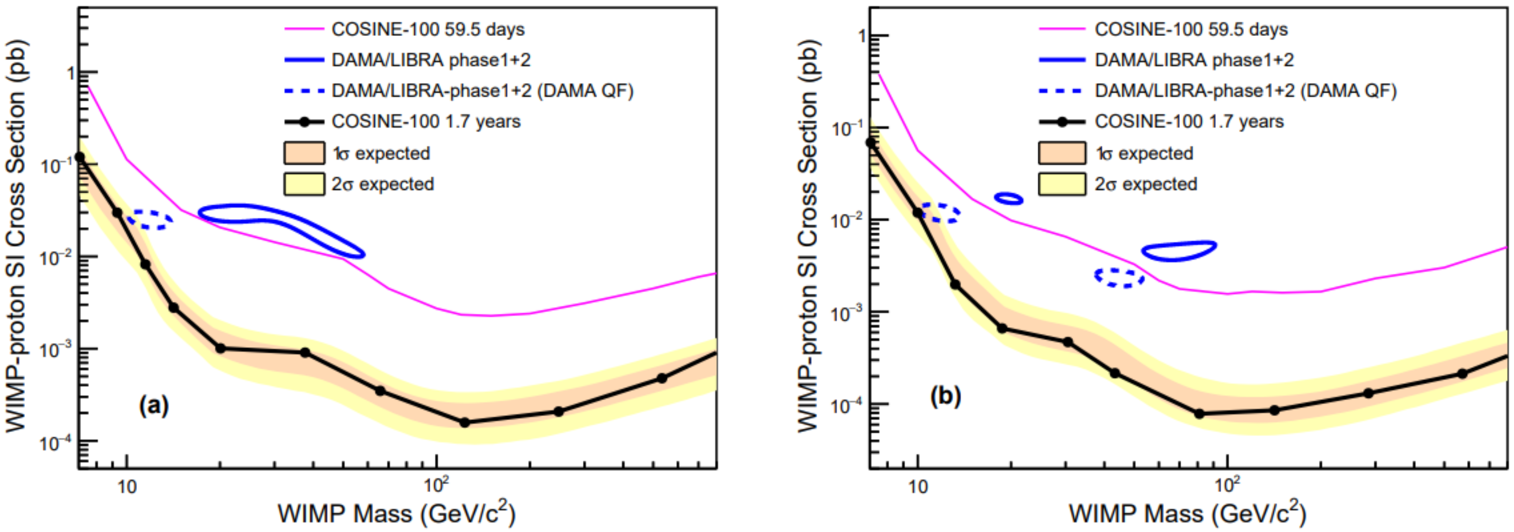


- Incompatible with the DAMA results at 3.3 (2.6)σ , for a sensitivity of 2.5(2.7) σ for [1-6] keV, and [2-6] keV

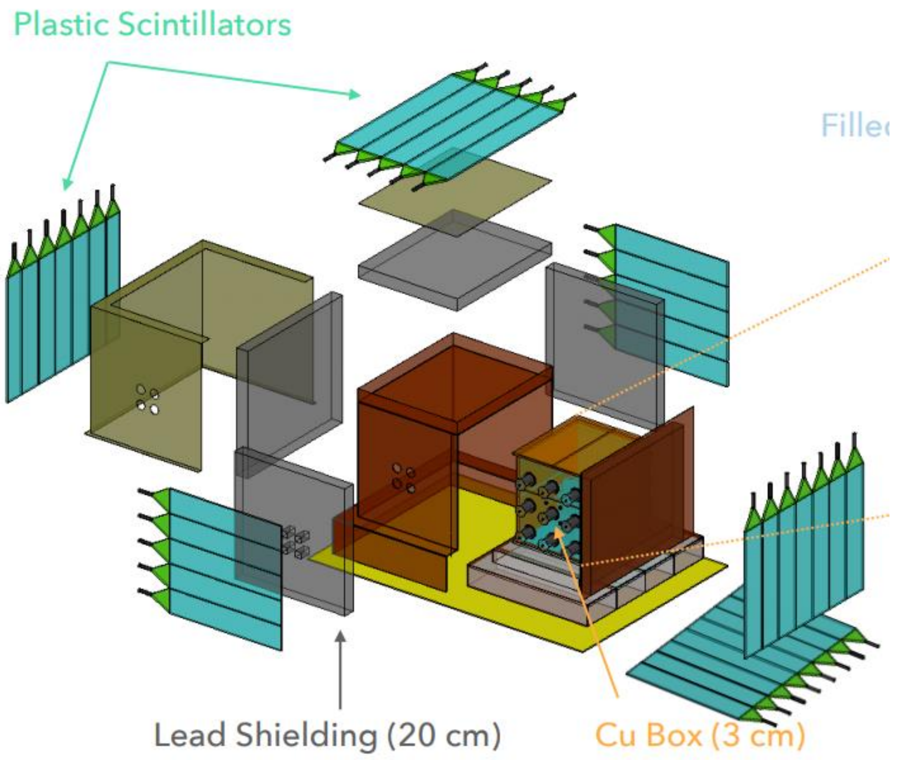
Amare, J., et al. "Annual Modulation Results from Three Years Exposure of ANAIS-112." *arXiv preprint arXiv:2103.01175* (2021).

arXiv:2103.01175

COSINE-100: 1.7 Years of data taking



https://arxiv.org/pdf/2104.03537.pdf



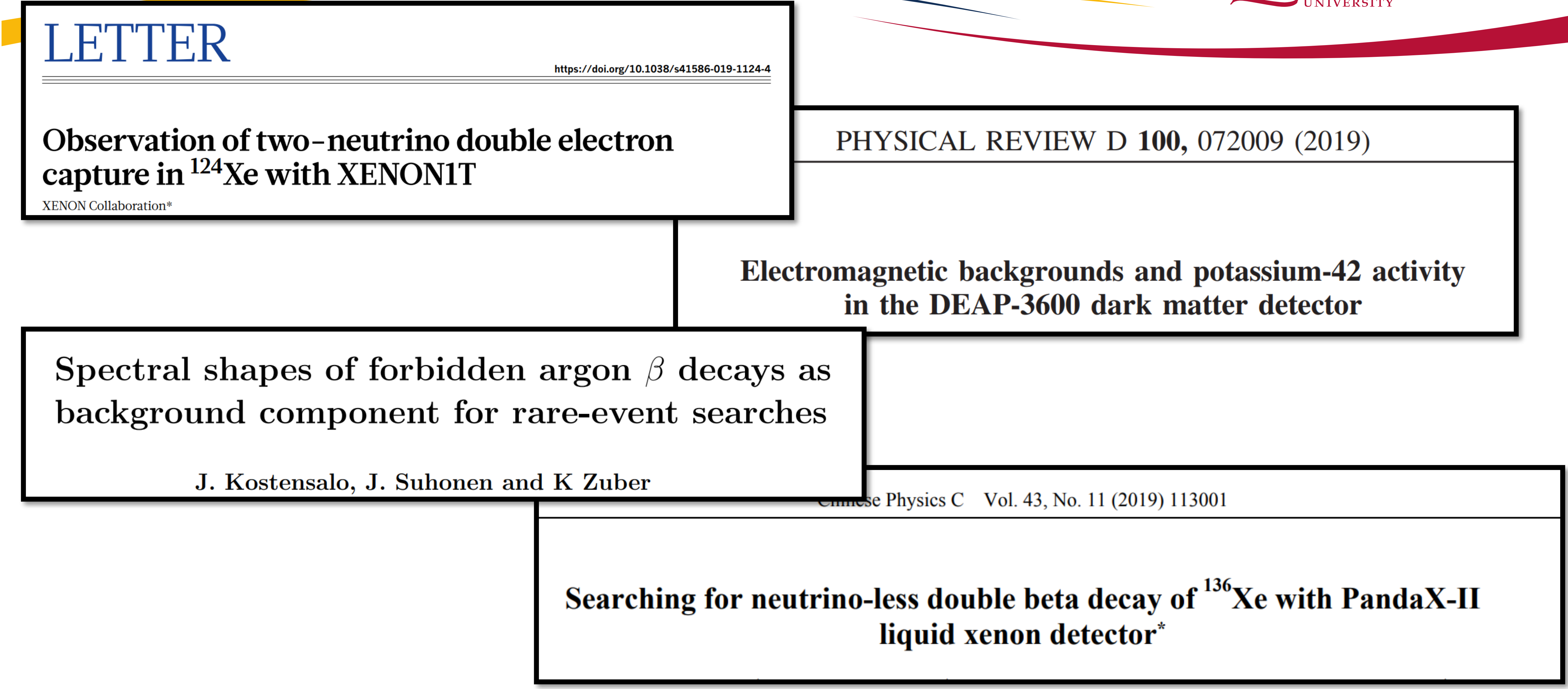
- COSINE-100 strongly constrains the DAMA result as a signal of dark matter origin
- Still need a few years to say for sure

Wall’s Are Closing in

- Walls are closing in on DAMA
- Only time and many more experiments will confirm if this signal is real
- If it’s not dark matter what is it?

Part 2: Nuclear Physics in Dark Matter

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

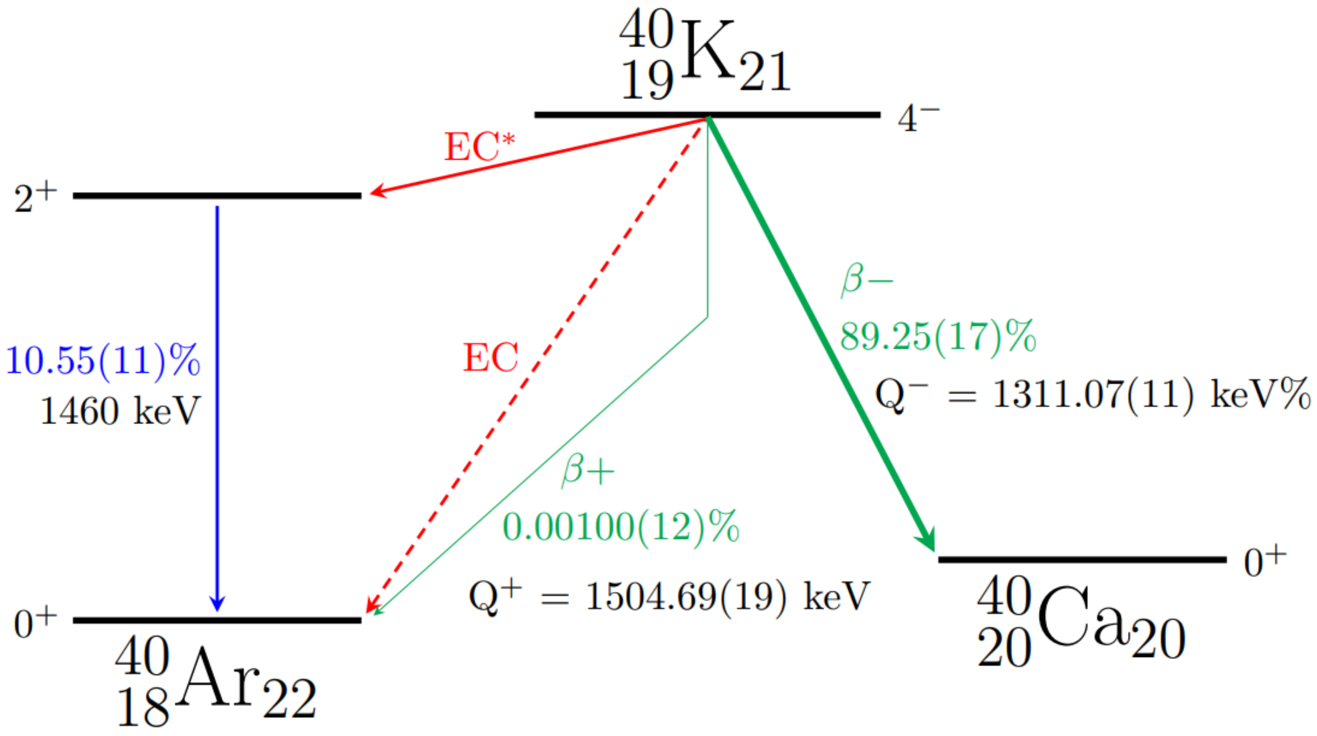
Spectral shapes of forbidden argon β decays as background component for rare-event searches

J. Kostensalo, J. Suhonen and K Zuber

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

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

Nuclear Physics in Dark Matter



Electron Capture

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

β+ Decay

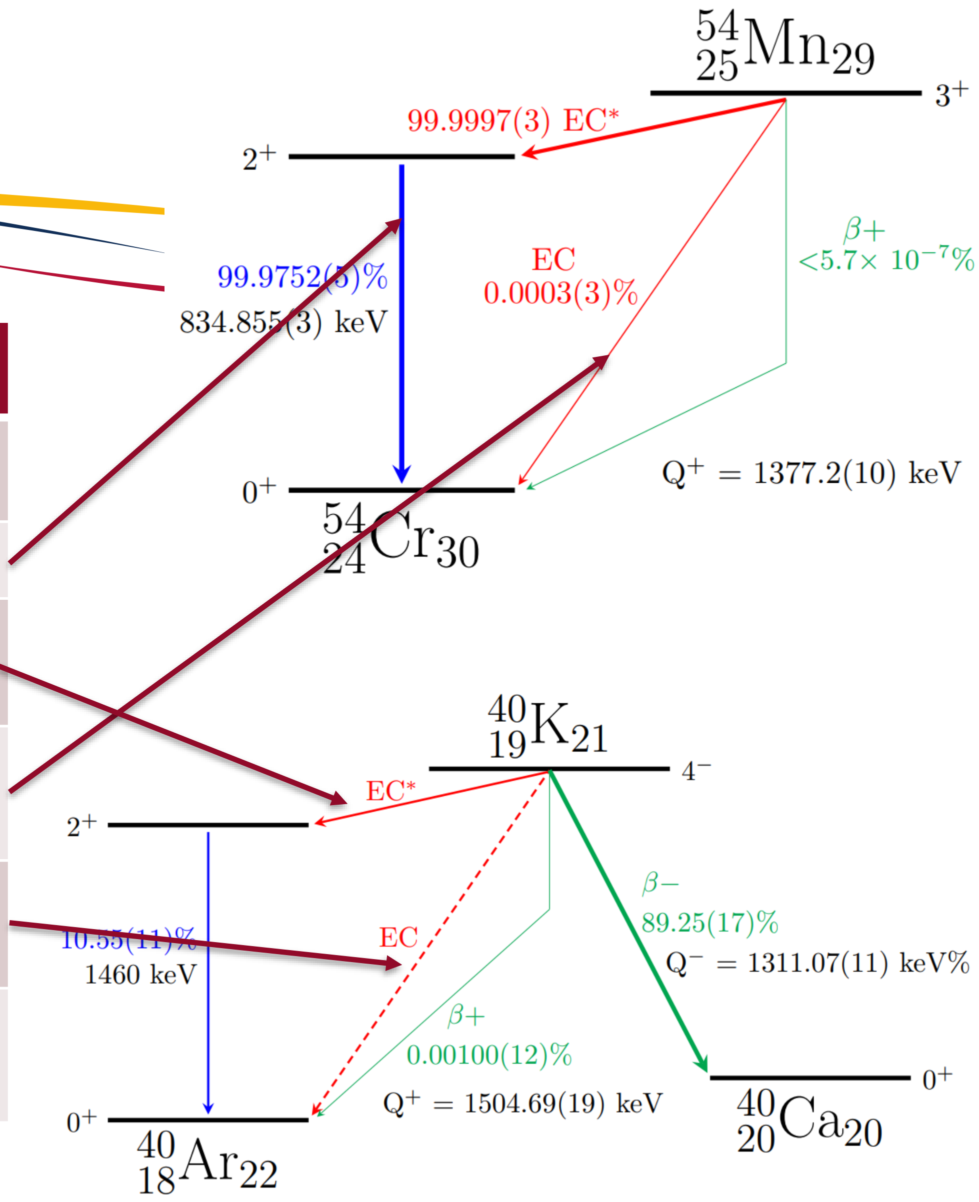
$${}^{A}_{Z}X_N \rightarrow {}_{Z-1}^{\;\;A}Y_{N+1} + e^+ + \upsilon_e$$

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:The KDK Experiment

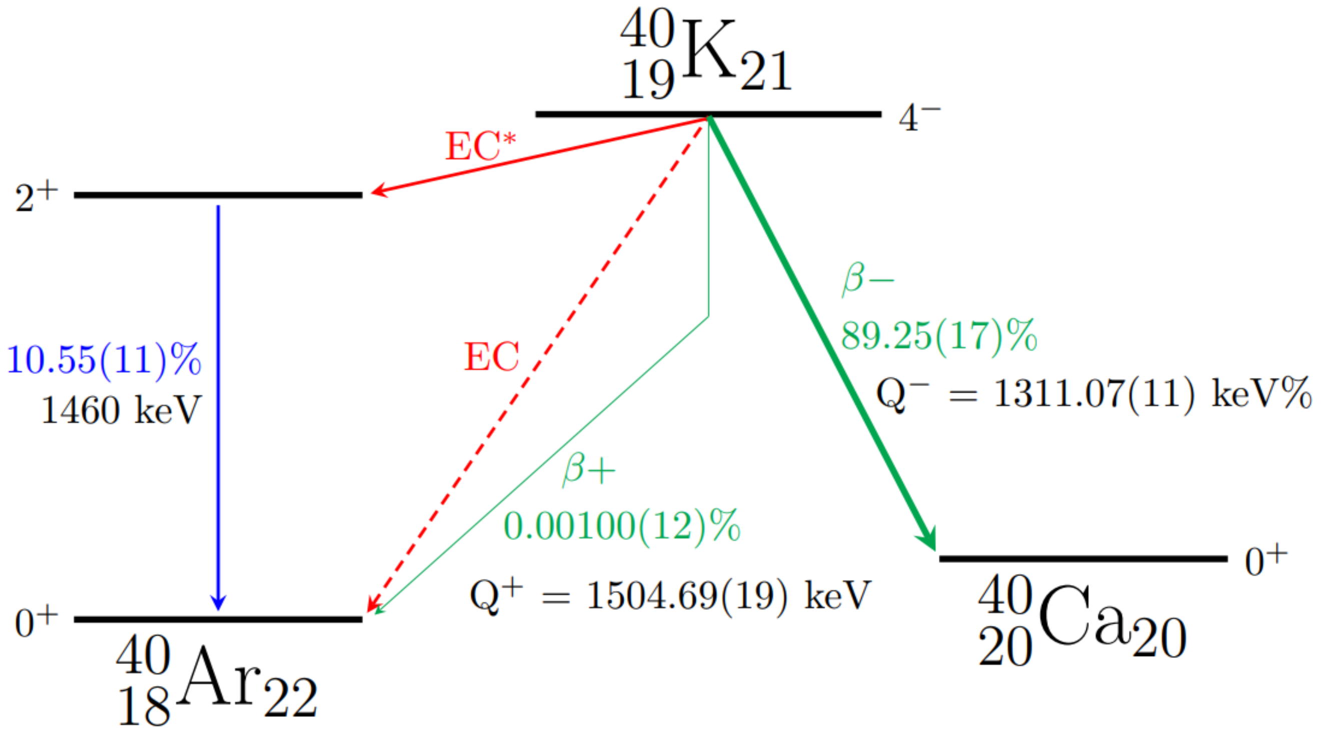
What is KDK?

- Pun for “Potassium Decay”
- KDK is an international collaboration dedicated to the measurement of the ground state electron capture of ^{40}K

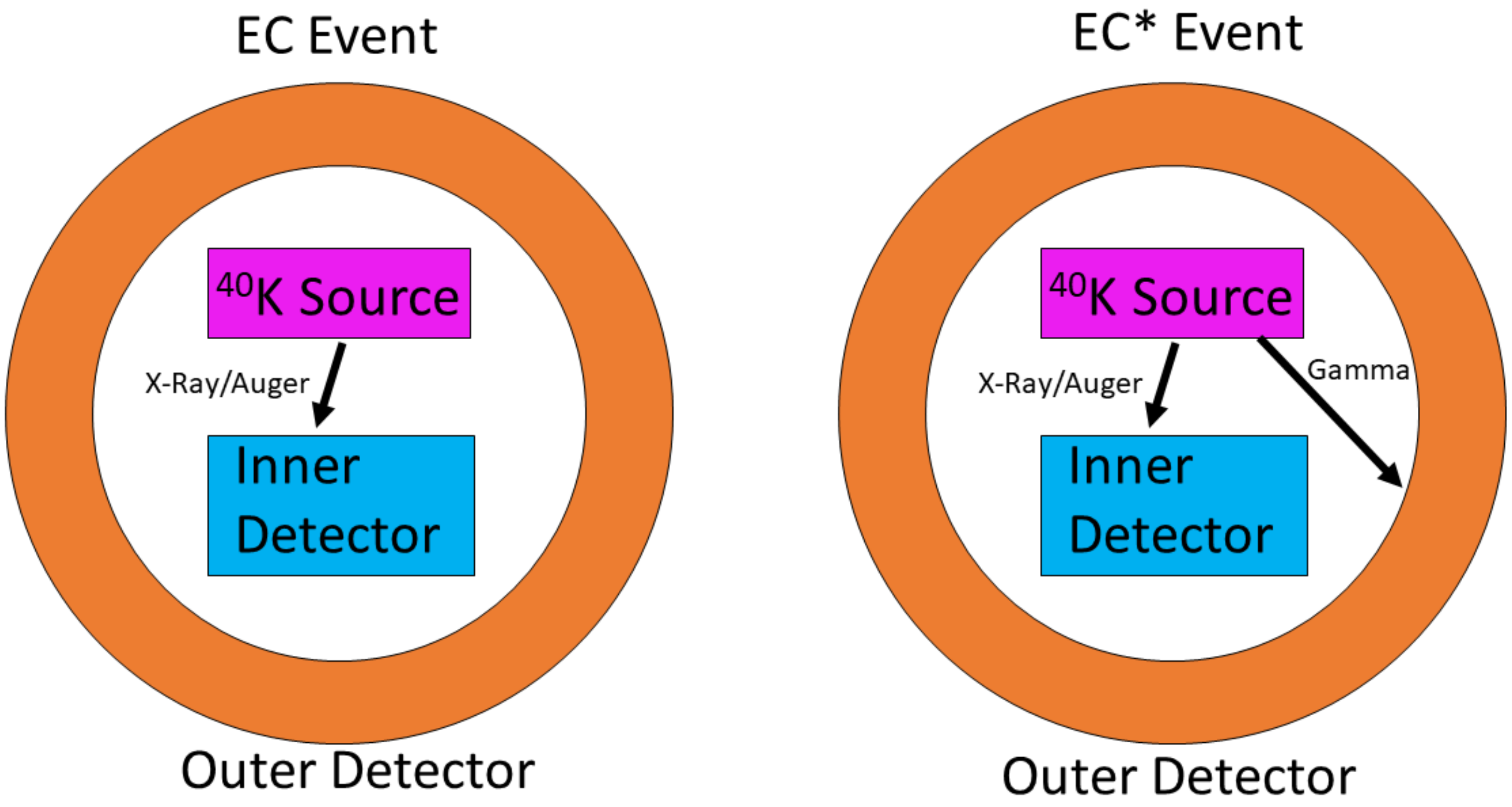
Di Stefano, P. C. F., et al. "The KDK (potassium decay) experiment." *Journal of Physics: Conference Series*. Vol. 1342. No. 1. IOP Publishing, 2020.

Why ^{40}K?

- Rare unique third-forbidden electron capture decay
- Never **measured, only predicted**
- ^{40}K contaminant in NaI a background in many dark matter experiments
- Unable to veto EC to ground state
- Increase accuracy in K-Ar (Ar-Ar) dating: Geochronology
  - Carter, Jack, et al. "Production of 40 Ar by an overlooked mode of 40 K decay with implications for K-Ar geochronology." *Geochronology* 2.2 (2020): 355-365.
- arXiv:2012.15232 (Stukel et al.) submitted to NIM A



KDK Experiment

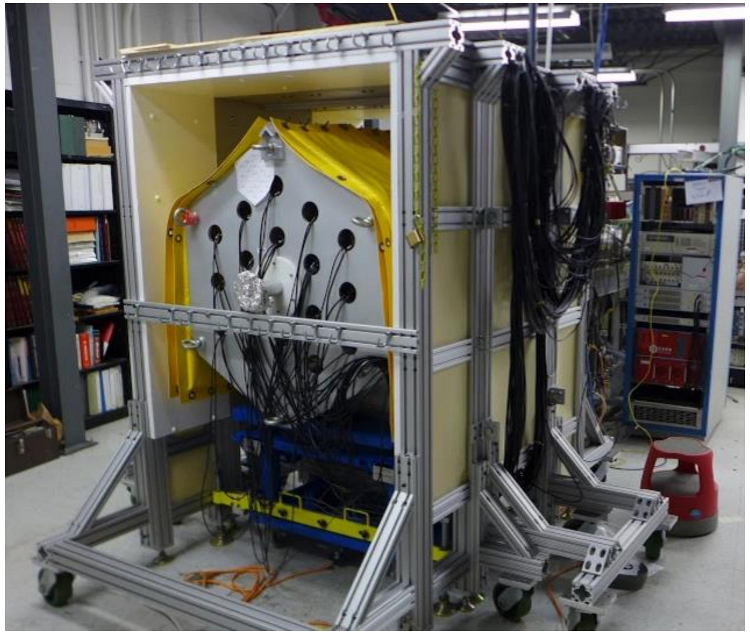


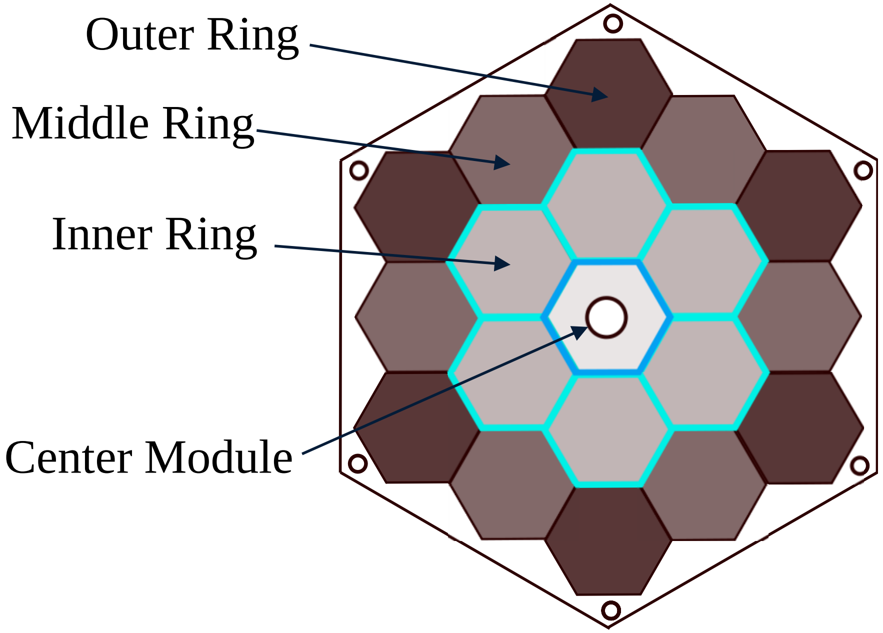
$$\frac{BR_{EC}}{BR_{EC*}} = \rho$$

- Deploy two different inner detector strategies
  - Composite: Separate source and detector (SDD+^{40}K source)
  - Homogeneous: $KSr_2I_5(Eu)$ scintillator

MTAS – External Detector

- The 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 ~4π coverage on tagging the 1460 keV gammas
- A high efficiency is needed to avoid false positives from the EC* channel and other background sources



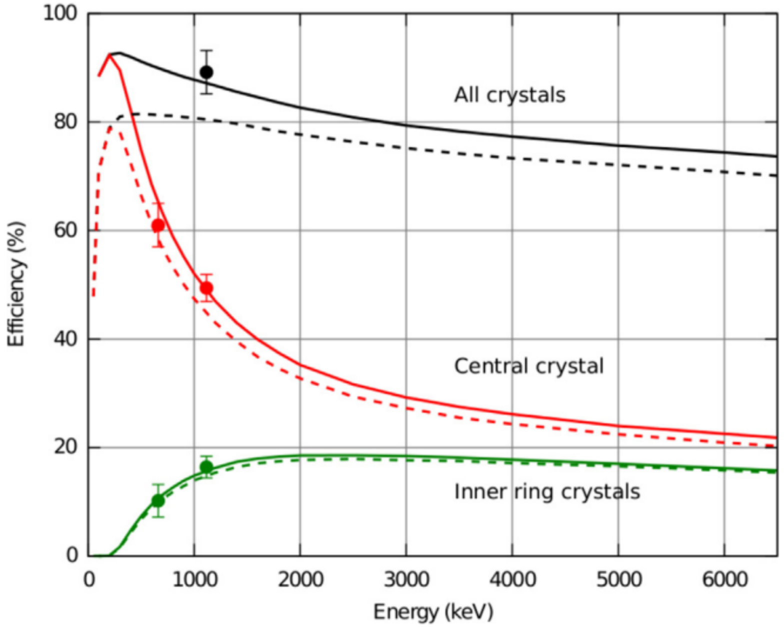


Outer Ring

Middle Ring

Inner Ring

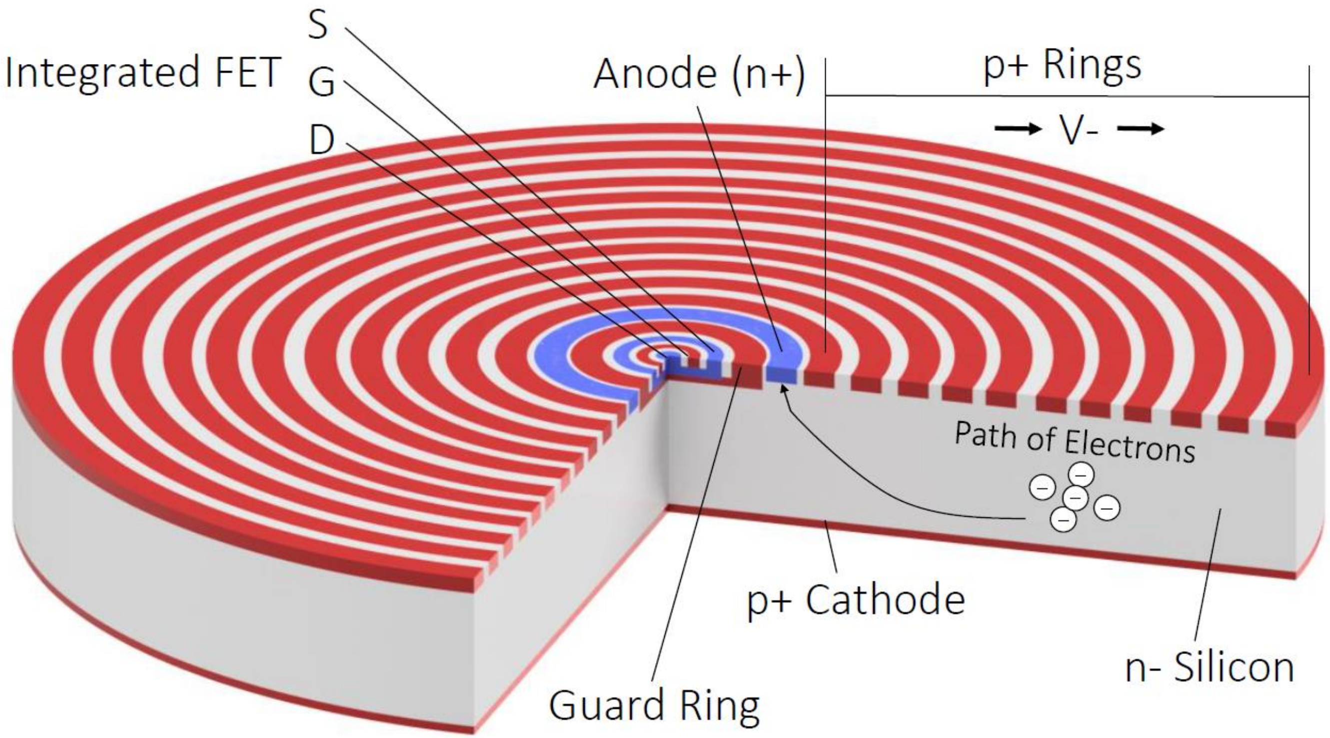
Center Module

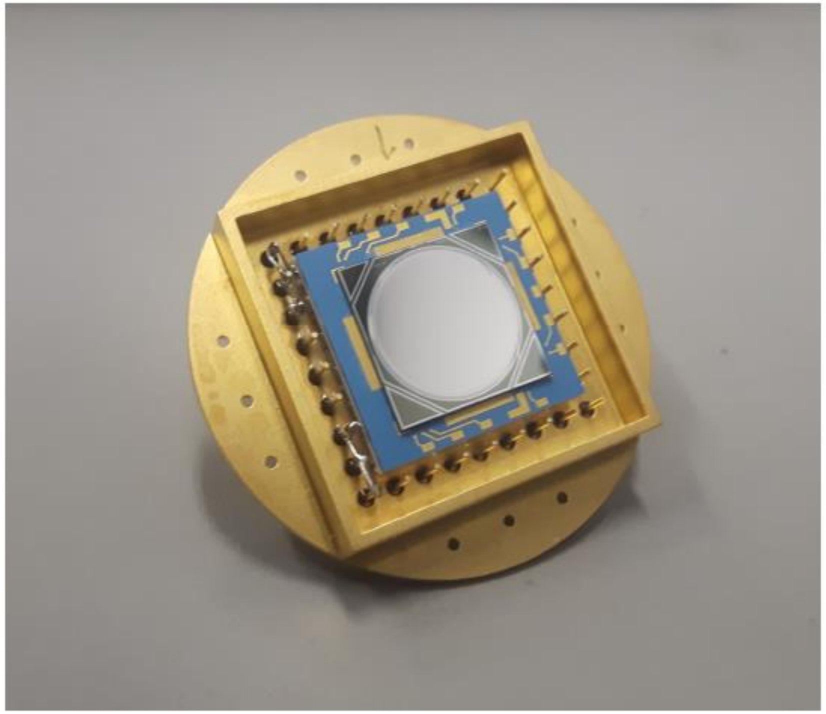


Karny, M., 2016. v. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, *836*, pp.83-90.

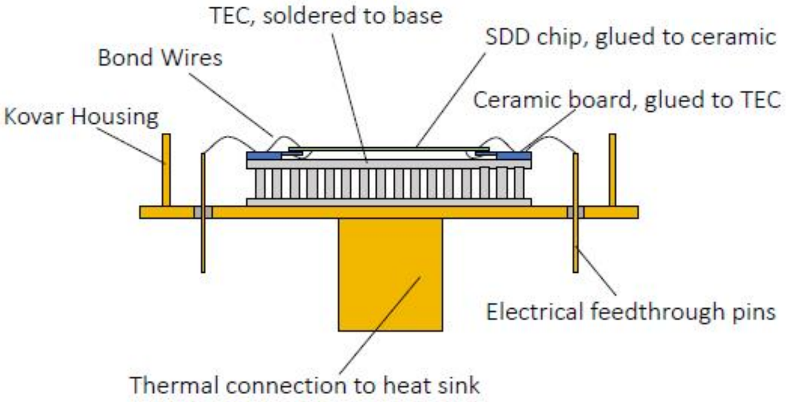
N. Brewer and C. Rasco [4]

SDD Internal Detector



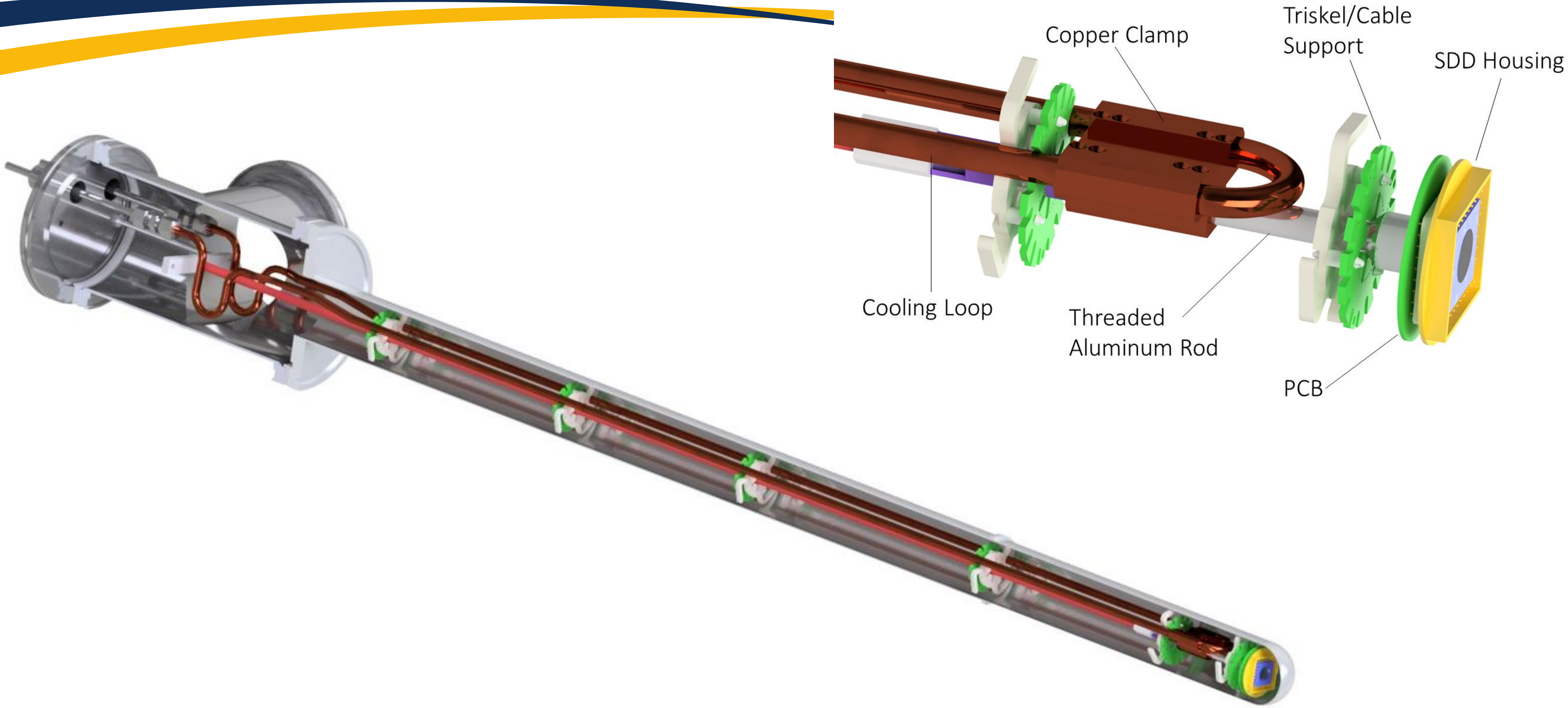


(a)

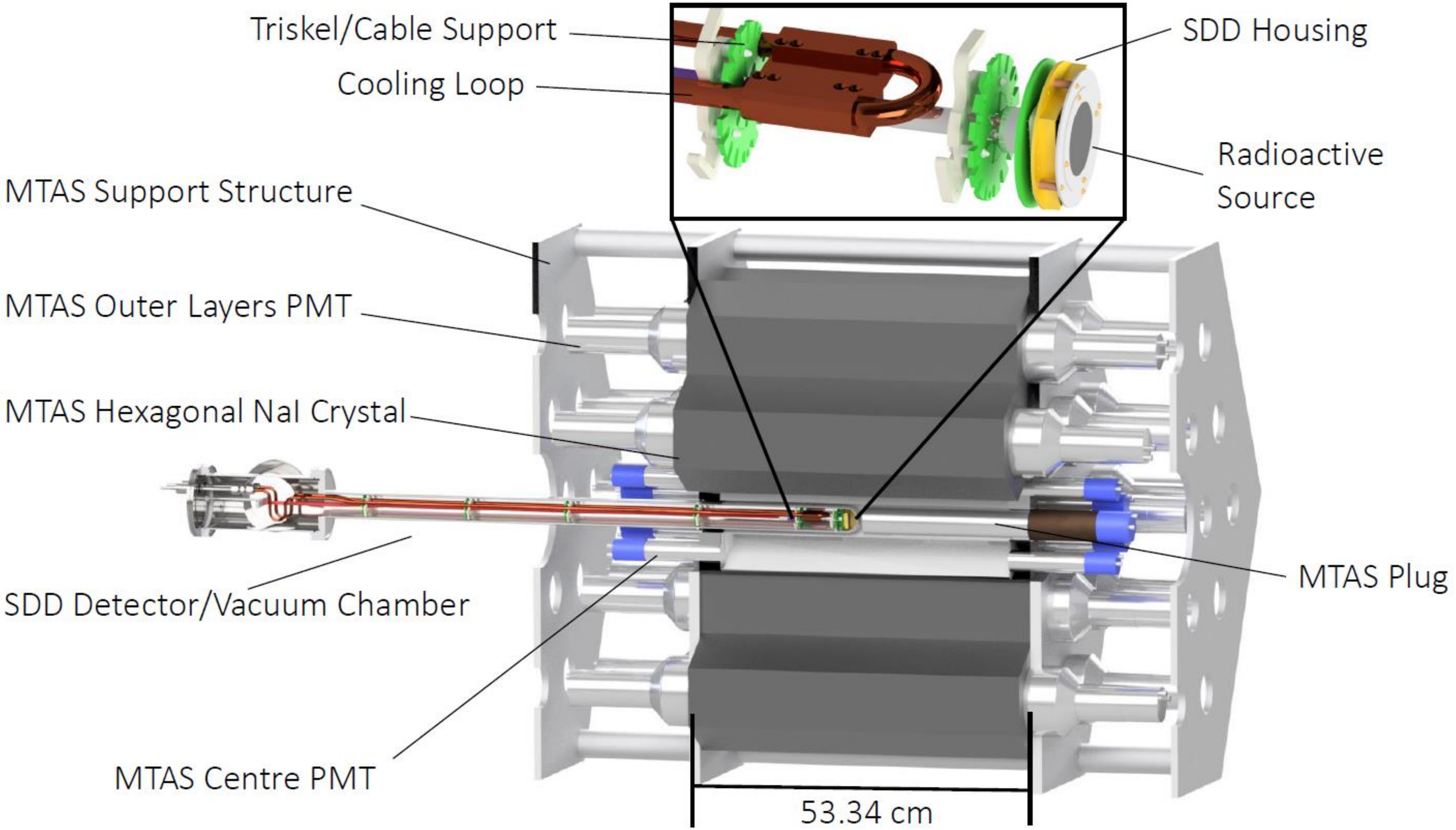


- Large n-type silicon wafer, small n^+ anode and planar p^+ cathode
- Rings (p^+) surround the anode, creating a potential that guides the electron clouds to the anode
- SDD is cooled to -20^{o}C with a ~100 mm^2 active area
- Advantage is the lower electrical noise than the planar anode counterpart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

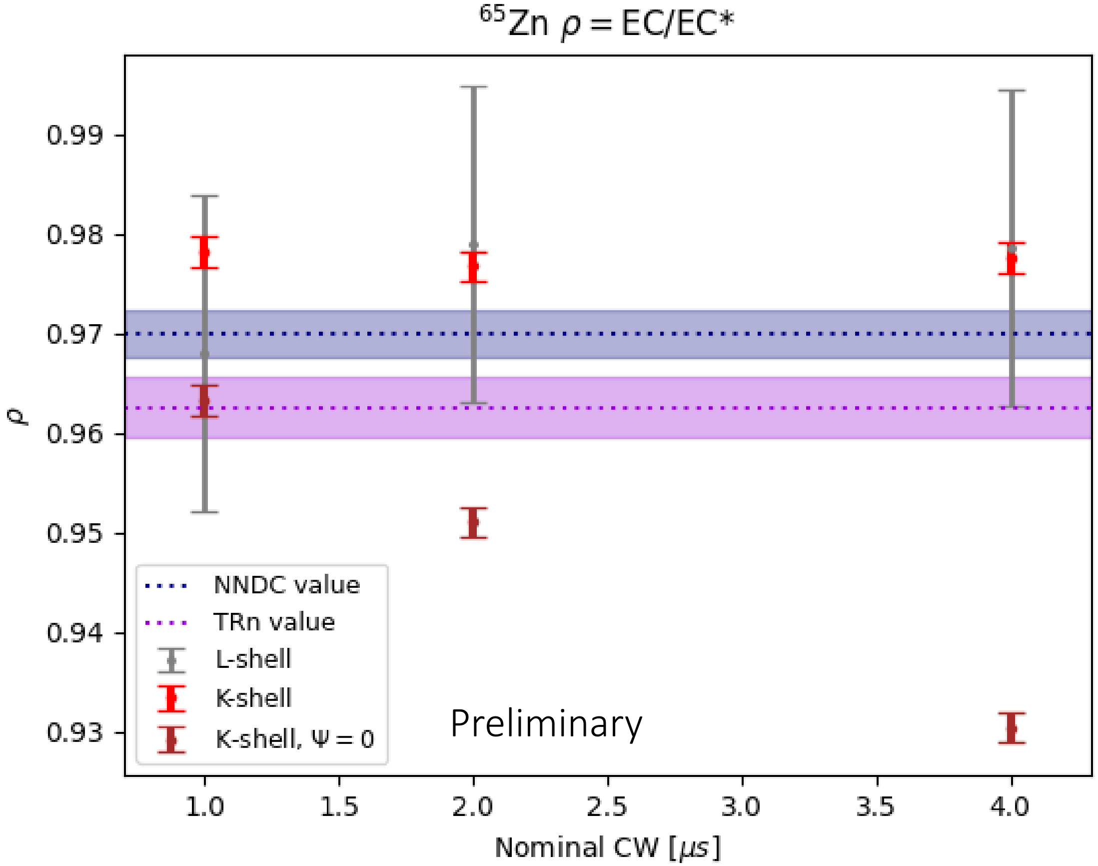
SDD – Internal Detector Chamber



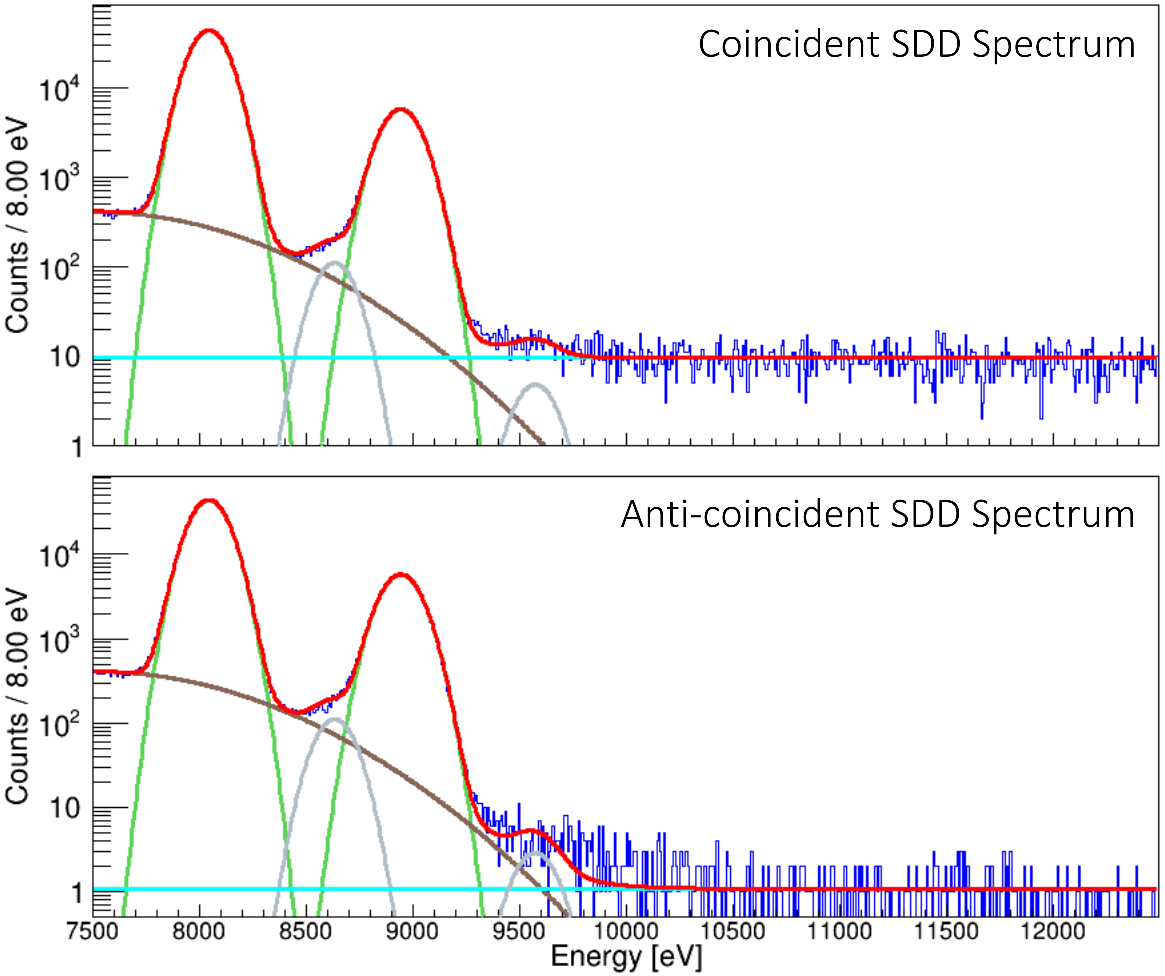
KDK Experimental Setup



Data Analysis: ^{65}Zn BR$_{EC}$ Measurement



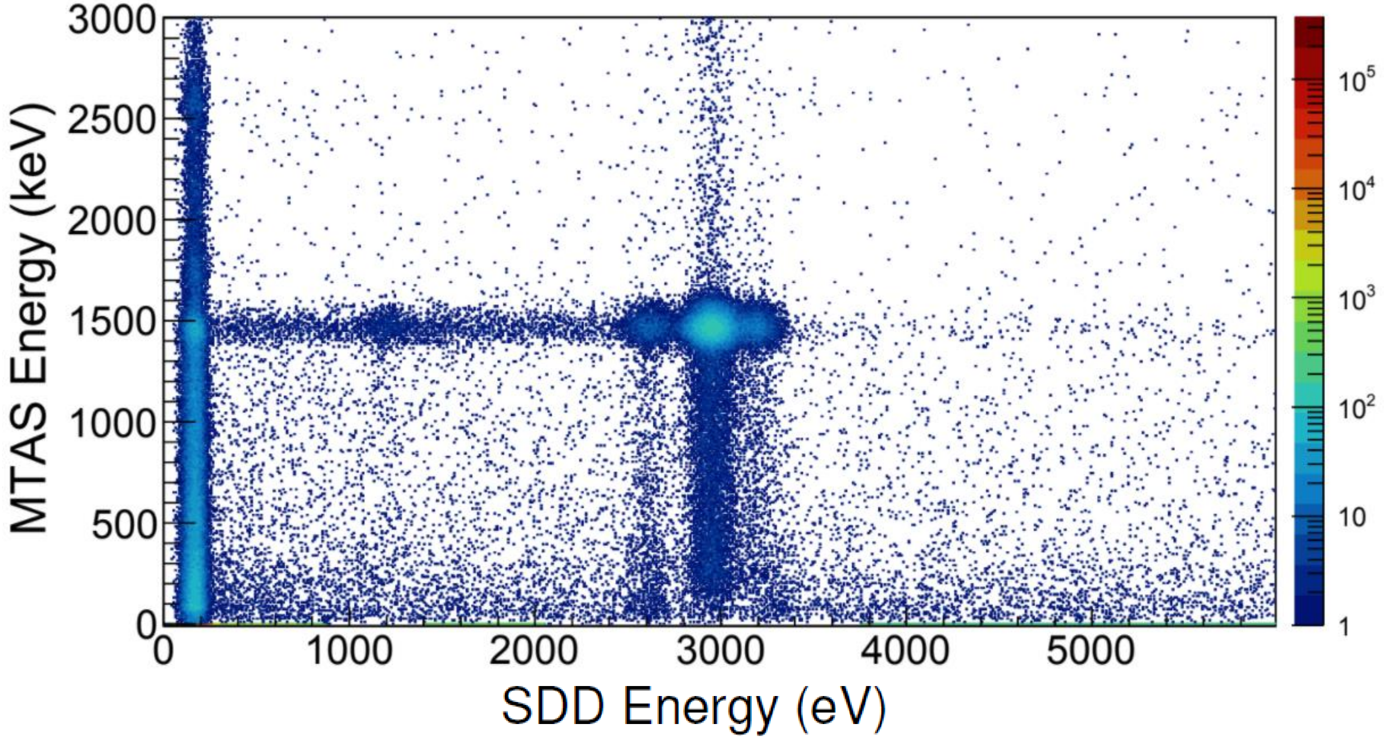
L. Hariasz, for the KDK Collaboration, Publication in preparation

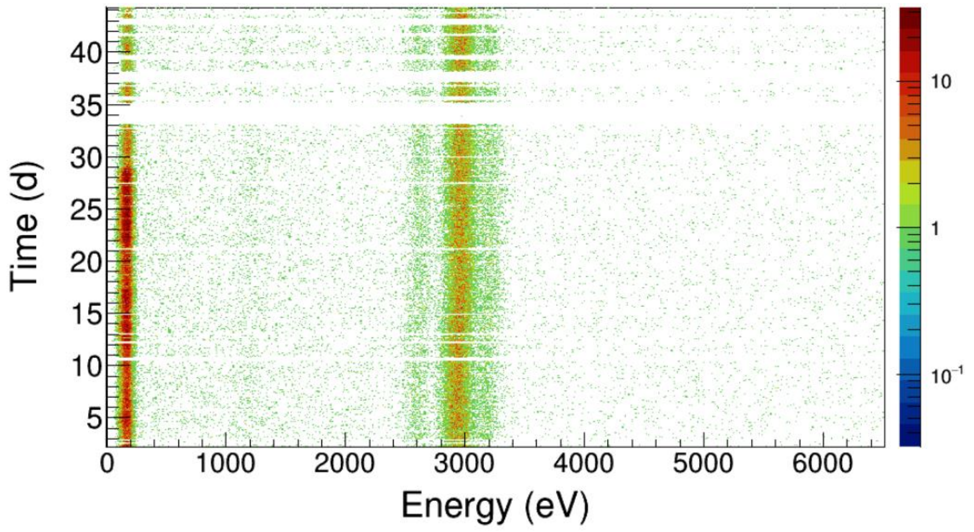


L. Hariasz, for the KDK Collaboration, Publication in preparation

- Common gamma ray calibration source, medical tracer
- Test of the KDK analysis method
- Correcting for false-positives is a must!

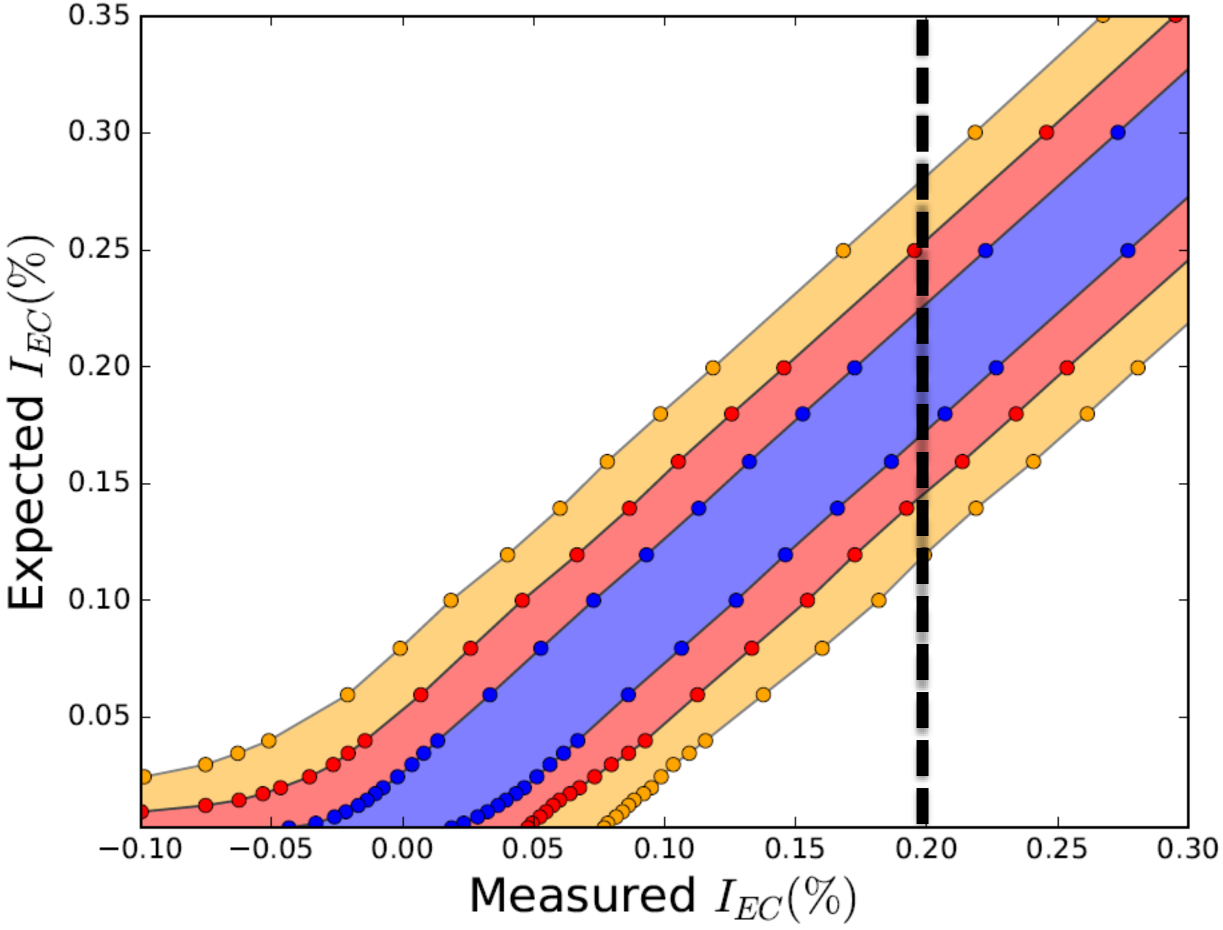
Data Analysis: ^{40}K BR$_{EC}$ Measurement

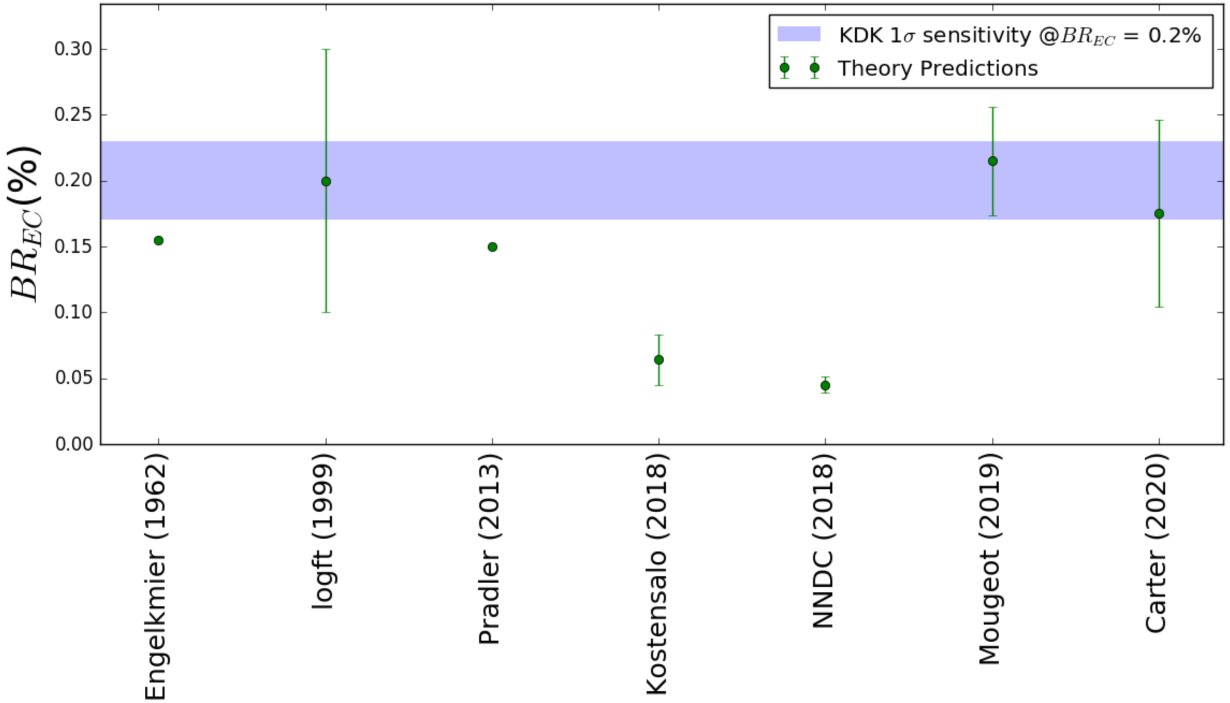




- All ^{40}K data was taken during the December 2017 campaign, ^{40}K visible in MTAS/SDD setup!
- Total Run Time: 44 days, Total Useable Time: 33 days, (due to power unit failure), Data is blinded
- Silicon Escape Peak (~1.2 keV), Cl fluorescence (~2.9 keV)
- Data analysis is ongoing, with results expected soon.

Data Analysis: ^{40}K Sensitivity





- Statistical confidence belt (Feldman and Cousins Ordering Method) for the 44 day ^{40}K KDK experiment
  - Statistics is what will dominate the error for KDK
- The original design goal of the KDK experiment was for a branching ratio of 0.2%.
- Generates a measurement of (0.20 +/- 0.03)% at the 1σ confidence level.
- Able to reject the null hypothesis (I_{EC} = 0.0) with 7σ significance

Summary

- KDK is an experiment dedicated to the measurement of a rare decay of ^{40}K
- Measurement is useful for many different fields: Nuclear Physics, Geochronology and Rare-event searches
- Annual modulation is a useful detection signal for dark matter and going to be of increasing importance over the next decade or so
- Nuclear Physics and dark matter are closely related

KDK Collaboration

KDK Collaboration

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[4] Heavy Ion Laboratory UW, Warsaw, Poland
[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

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