Background rate of X-ray TES micro-calorimeter arrays for elusive particle search experiments

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ABSTRACT

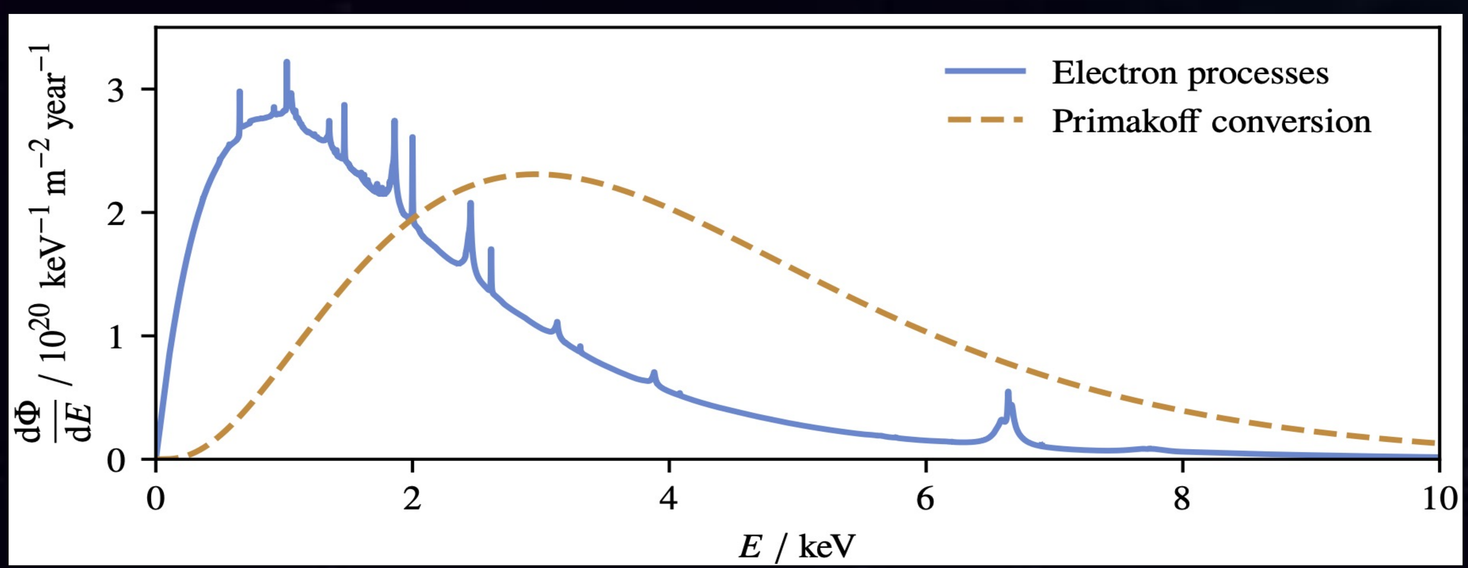
- To achieve the extreme sensitivities necessary to perform elusive particle searches like β-decay spectroscopy for neutrino mass measurement or dark matter detection, future experiments are considering employing large arrays of cryogenic detectors, such as metallic-magnetic calorimeters (MMCs) or transition-edge sensors (TES) *[1]*.
- A TES is a thin film of superconducting material weakly coupled to a thermal bath typically at T < 100 mK, that can be used as a radiation detector by exploiting its very sharp phase transition. We have been developing X-ray TES micro-calorimeters optimized for X-ray astronomy up to energies of 12 keV, as well as a frequency-domain multiplexing (FDM) *[2]* technology to perform their readout. Energies up to ~10 keV are compatible with the expected spectrum of axion-like particles arriving on Earth generated in the Sun by electron processes and Primakoff conversion *[3]*, which will be investigated in the future by axion helioscopes such as IAXO *[4]* and its prototype BabyIAXO. A fundamental instrumental requirement is the background of the X-ray detectors, which should be at a level < 10^{-8} keV^{-1}cm^{-2}s^{-1} (10^{-7} keV^{-1}cm^{-2}s^{-1} for BabyIAXO) *[5]*. TES represent a suitable choice for this science case, given their high energy resolution and quantum efficiency, low intrinsic background and scalability to large (~1000s) arrays.
- In this contribution we present a measurement of X-ray background, using a TES array with 240×240 μm2 absorber area and energy resolution at a level of 2 eV at 5.9 keV with an FDM readout *[6]*.
- We show the data analysis method and prospect possible improvements, such as coupling with a cryogenic anti-coincidence and the introduction of a PTFE and Pb shielding around the sensitive area of the setup, to further reduce the background rate from the measured level with our current TES array, non-optimized for such purpose.

SCIENCE CASE: SOLAR AXIONS

- Axion originally introduced to solve the strong CP problem *[7]*.
- Axions and axion-like particles (ALPs) are attractive candidates for dark matter *[8]* and to explain other astrophysical observations *[9]*.
- Axions are theoretically generated in the Sun via electron processes and Primakoff conversion. The axion flux on Earth is observable via helioscopes, exploiting the axions coupling with a magnetic field B of length L. For light axions (m_a < 10 meV) the conversion probability is *[10]*:

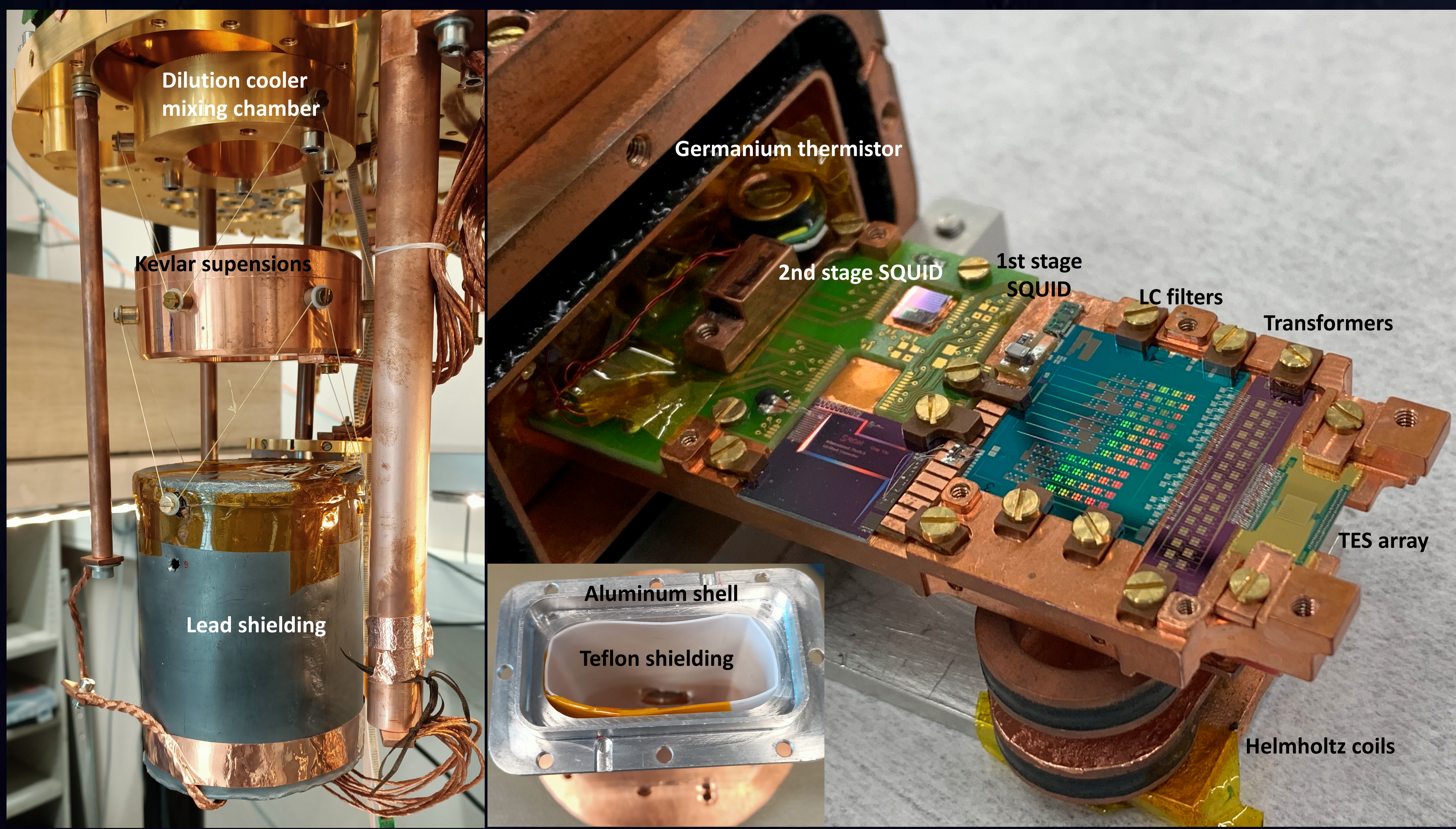
$$P_{a\rightarrow\gamma} = \left(g_{a\gamma}BL/2\right)^2$$

- The energy spectrum of conversion photons has a range of up to approximately 10 keV, with the Primakoff contribution peaked at 3 keV (for $g_{a\gamma} = 10^{-11}$) GeV^{-1}.
- CAST set the best upper limit yet on $g_{a\gamma}$ to 6.6×10^{-11} GeV^{-1} *[11]*. Its successor IAXO will target a sensitivity on $g_{a\gamma}$ of 10^{-12} GeV^{-1}. IAXO's baseline detectors are CAST's Micromegas time-projection chambers *[12]*. For systematics reduction, different detector technologies with similar low background should be employed.



Plot adapted from reference [10]

EXPERIMENTAL SETUP: TES array + FDM readout



DATA ACQUISITION AND ANALYSIS PIPELINE

- TES current from 27 pixels continuosly acquired in 5-minutes chunks (2861 "noise" events, 16384 samples @ 156.25 kHz sampling rate)
- Acquired event processing:
  - ➢ TES baseline subtraction and drift correction
  - ➢ Pulse shape search
  - ➢ Storing of recorded pulse shapes with pixel and timing info for offline analysis
- Photons from ^{55}Fe source + Modulated X-ray Source (MXS) for energy calibration:
  - ➢ Cr-Kα (5.41 keV), Mn-Kα (5.90 keV), Cu-Kα (8.05 keV)
  - ➢ Cr-Kβ (5.95 keV), Mn-Kβ (6.49 keV), Cu-Kβ (8.91 keV)
- Source X-ray spectrum calibrated using optimal filtering in frequency domain *[13]*
- Optimal filter fit positions estimation via Gaussian fitting of spectral lines (A)
- Energy scale calibration using a 3rd order polynomial (B)
- Energy scale cross-calibration between optimal filter and pulse surface
- Event selection:
  - ➢ Energy from pulse surface: exclude baseline drifts/spurious signals
  - ➢ Temporal coincidence: exclude cosmic muons hits
- Energy scale correction in the 0.1 keV to 12 keV range (nominal range for our TES)
- Correction for quantum efficiency for 2.3 µm Au absorber *[14]* (C)
- X-ray background rate estimation from histogram:

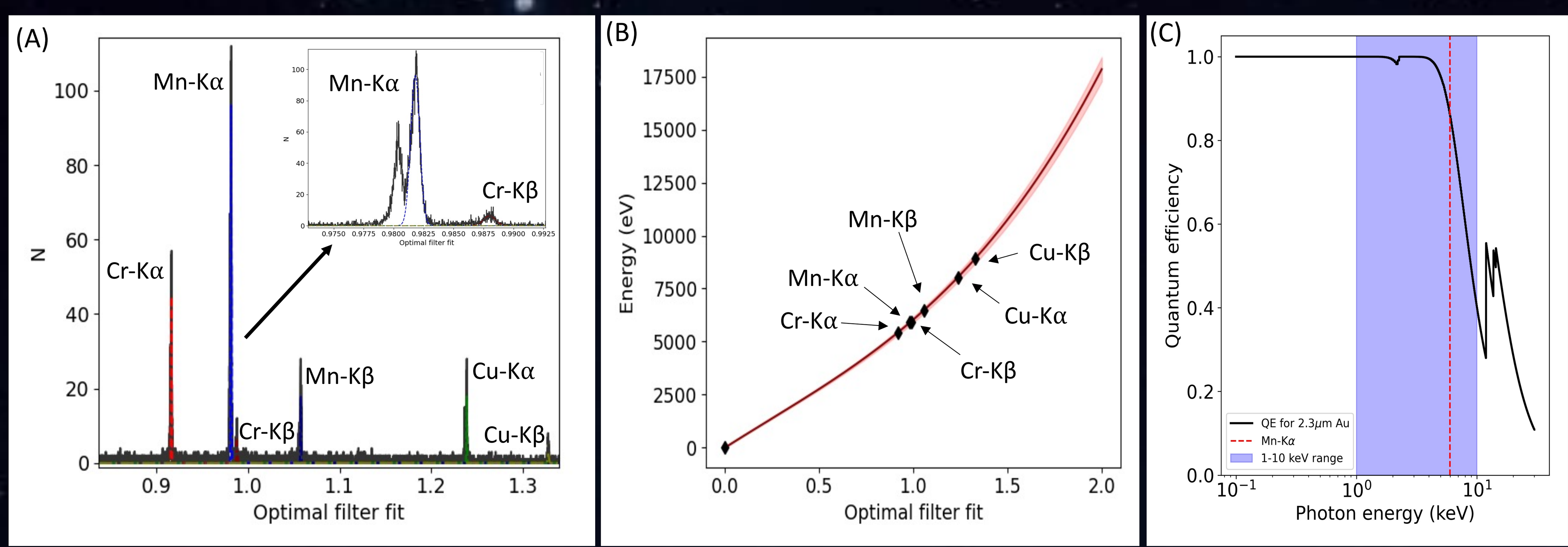
$$\frac{d\Phi}{dE} = \frac{N_{counts}}{\Delta E_{bin} A t}$$

  - ➢ Total active area *A = 27 × (240 µm)² = 0.015552 cm²* (8×0.15 cm² for IAXO *[5]*)
  - ➢ Total acquisition time $t_{noShield}$ *= 41.6 days,* $t_{withShield}$ *= 50.6 days*
  - ➢ Poisson uncertainty per bin σ given by square root of bin counts N_{counts}
  - ➢ Background estimated via Maximum Likelihood estimators (uniform hypothesis):

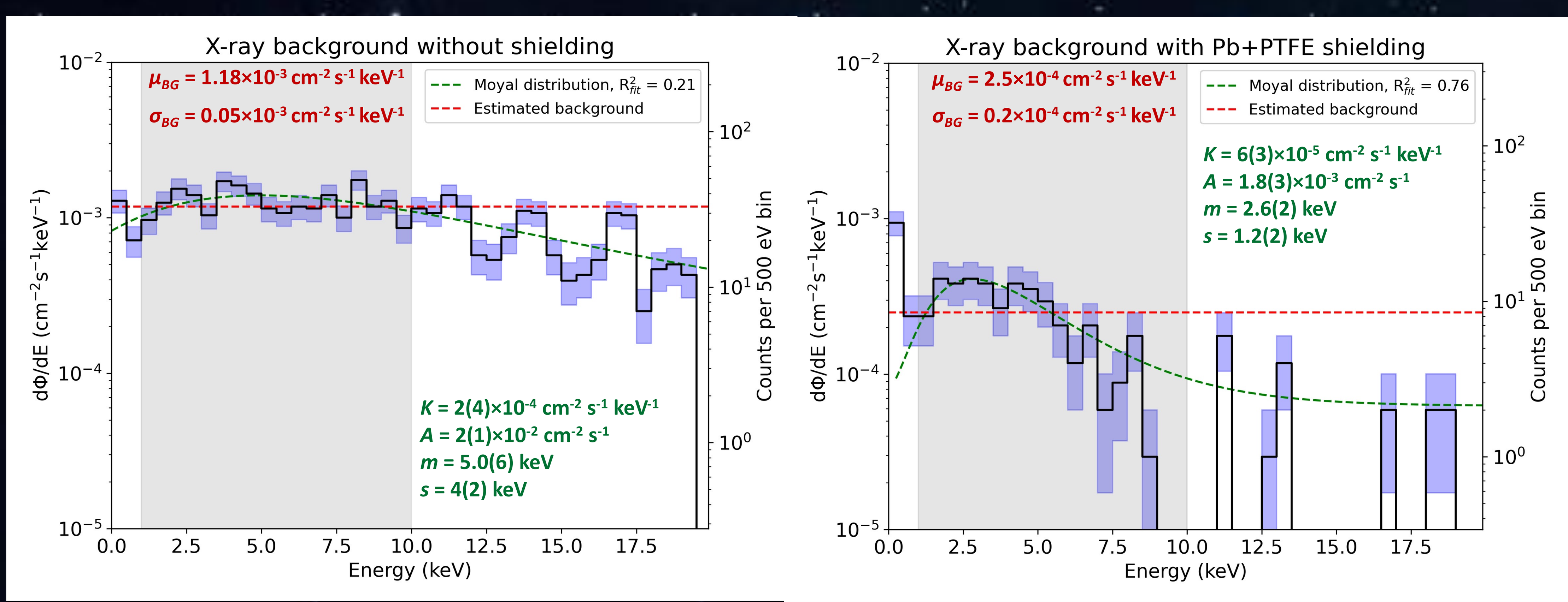
$$\mu_{BG} = \frac{\sum_1^n N_i/\sigma_i^2}{\sum_1^n 1/\sigma_i^2}\ ,\quad \sigma_{BG}^2 = \frac{1}{\sum_1^n 1/\sigma_i^2}$$

  - ➢ Fit of histogram with Moyal distribution to check impact from cosmic muons:

$$K + \frac{A}{s\sqrt{2\pi}} e^{-\frac{\frac{E-m}{s} + e^{-\frac{E-m}{s}}}{2}}$$



RESULTS



CONCLUSIONS AND FUTURE OUTLOOK

- Measured X-ray background without dedicated shielding = $1.18(5)\times10^{-3}$ cm^{-2} s^{-1} keV^{-1}
- Measured X-ray background with Pb+PTFE shielding = $2.4(2)\times10^{-4}$ cm^{-2} s^{-1} keV^{-1}:
  - ✓ comparable level to latest status of R&D for MMCs for BabyIAXO: $1.20(8)\times10^{-4}$ cm^{-2} s^{-1} keV^{-1} *[15]*
  - ✓ statistics hints that background is still dominated by cosmic rays interactions
- Further improvement on the background level can be achieved by:
  - ➢ Integrating an active shielding for cosmic ray rejection, such as Athena X-IFU Cryo-AC (factor 30 improvement expected) *[16]*
  - ➢ Ad-hoc detector array and focal plane design, aided by simulations (xifusim, Geant4)
  - ➢ Employing of materials with higher radio-purity
  - ➢ Operation in dedicated underground facility

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