Frequency Domain Multiplexing readout
for large arrays of transition-edge sensors

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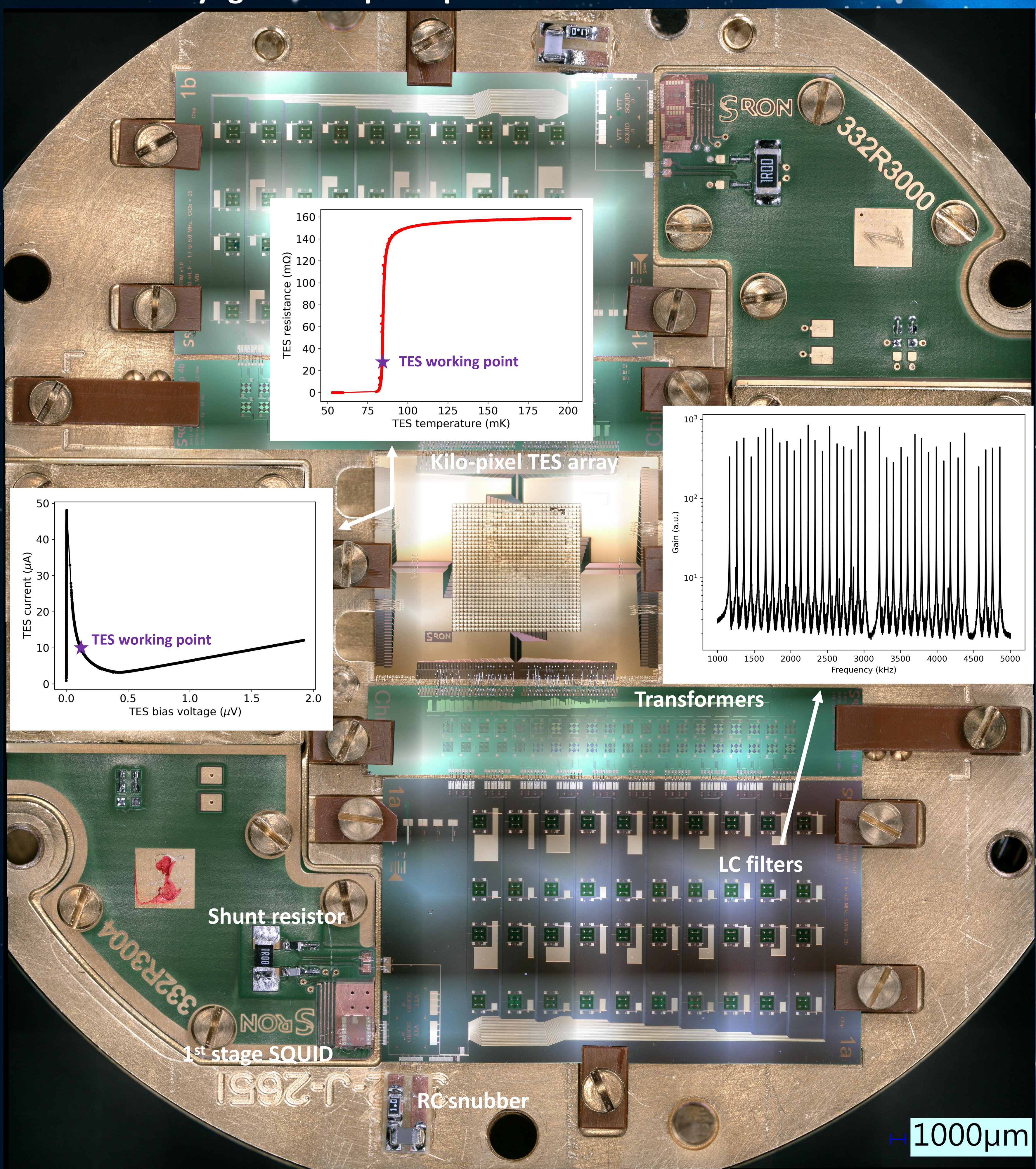
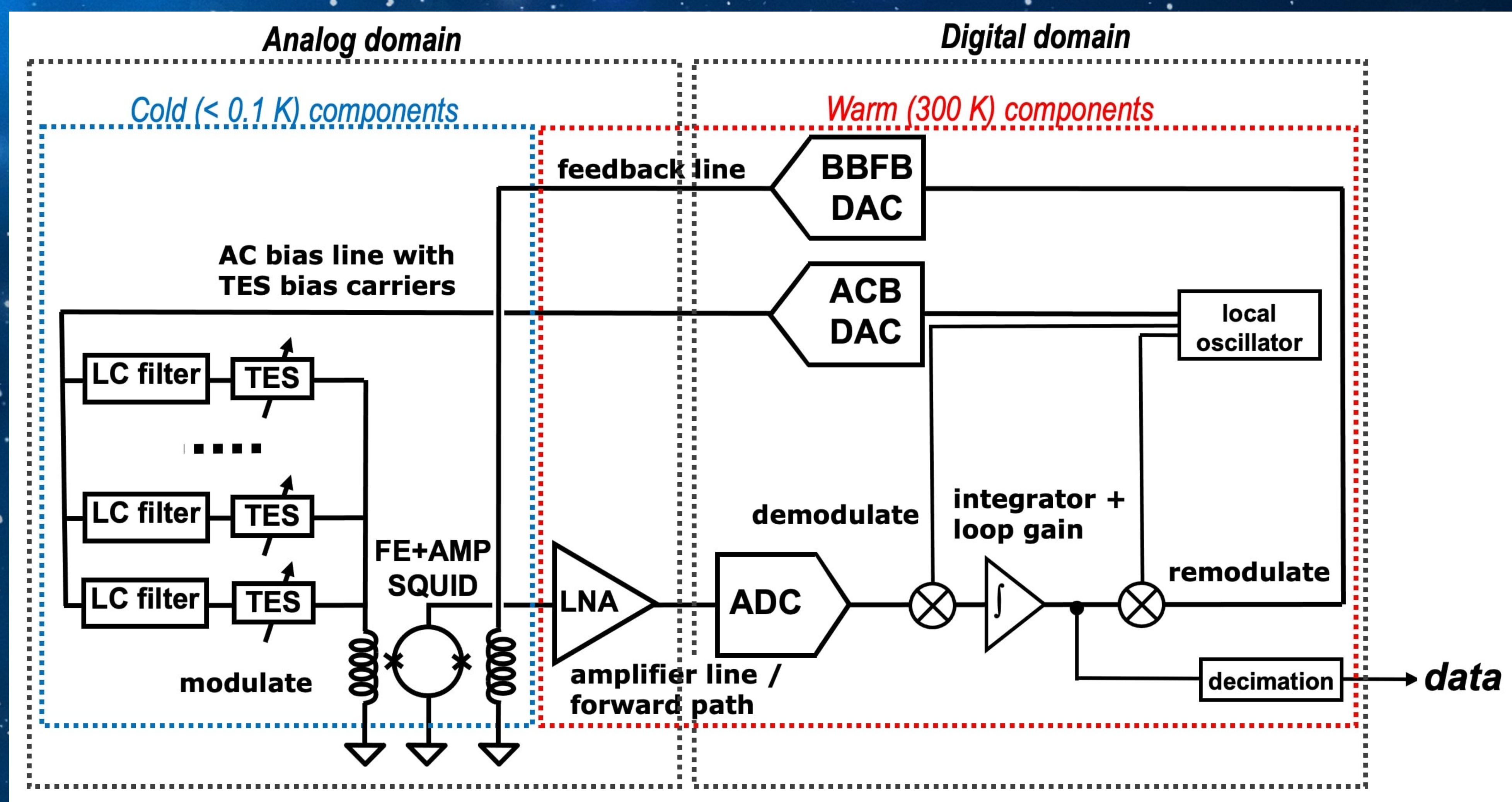
ABSTRACT

- Future experiments pursuing scientific breakthroughs in the fields of astronomy, cosmology or astro-particle physics will take advantage of the extreme sensitivities of cryogenic detectors, such as 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, used as a radiation detector by exploiting its sharp phase transition, providing unprecedented resolving power and imaging capabilities. A TES micro-calorimeter can be used as a non-dispersive spectrometer, with desirable features such as high-dynamic range and large active area. We have been developing TES micro-calorimeters for X-ray spectroscopy as backup option for the Athena X-ray Integral Field Unit (X-IFU) *[2]*, demonstrating under AC bias resolving power capabilities of $E/\Delta E \simeq 3000$.
- Performing the readout of thousands of detectors operating at sub-K temperatures represents an instrumental challenge. To reduce thermal load at cryogenic stage and wiring complexity, a multiplexing scheme is typically used. We have been developing, in the framework of X-IFU, a frequency-domain multiplexing (FDM) technology *[3]*, where each TES is coupled to a superconducting band-pass LC resonator and AC biased at MHz frequencies through a common readout line. The TES signals are summed at the input of a superconducting quantum interference device (SQUID), performing a first amplification at cryogenic stage. A custom analog front-end electronics further amplifies the signals at room temperature. A custom digital board handles the digitization and modulation/demodulation of the TES signals and bias carriers.
- Using Ti/Au TES micro-calorimeters, high-Q LC filters and analog/digital electronics developed at SRON and low-noise two-stage SQUID amplifiers from VTT Finland *[4]*, we demonstrated using two experimental setups the feasibility of our FDM readout technology, with the simultaneous readout of 31 pixels with an energy resolution of 2.14 eV and 37 pixels with an energy resolution of 2.23 eV at an energy of 5.9 keV (*cf.* with standard X-ray detectors such as CCD which have energy resolutions of more than 100 eV).

Cryogenic setup "40 pixel A" for FDM demonstration

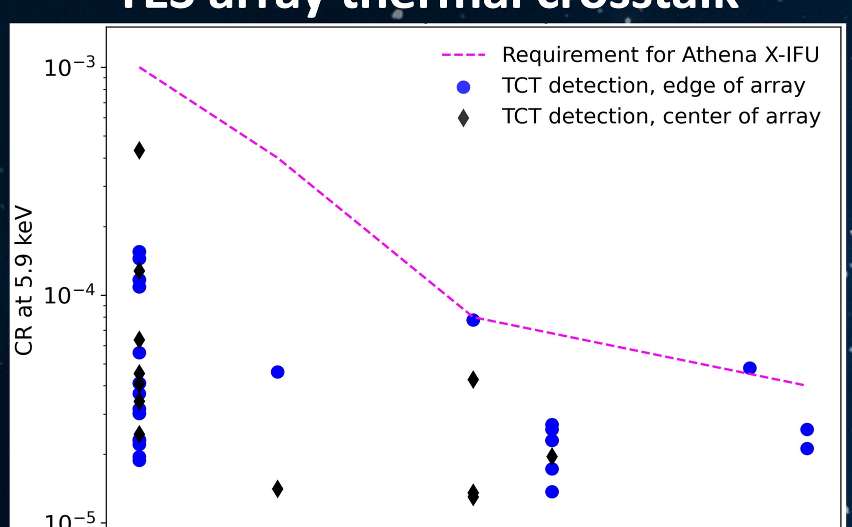


FDM readout scheme

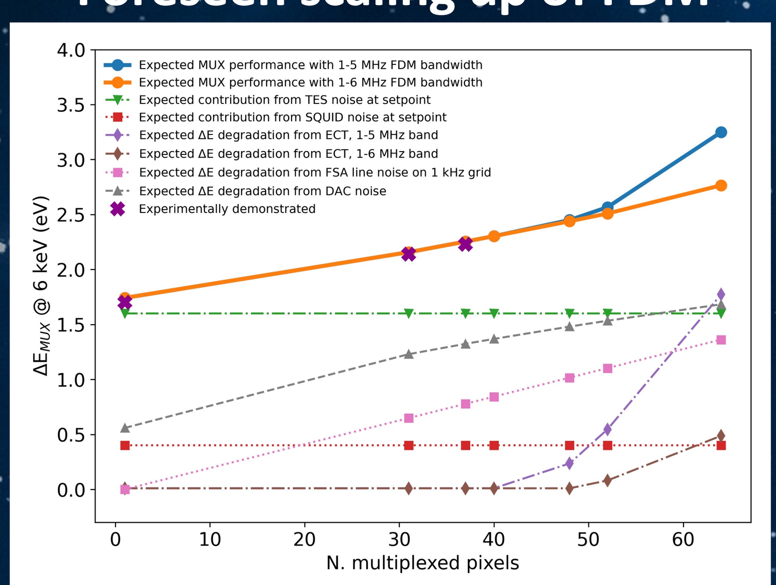


- Setup mounted on the mixing chamber of a Leiden Cryogenics dilution cooler with $T_{bath} \simeq 50$ mK.
- Litographed LC filters with Nb/a-Si:H/Nb parallel plate capacitors and Nb gradiometric spiral inductors *[5]*.
- Superconducting transformer to optimize impedance matching between TES and readout circuit.
- Detectors: 80μm × 13μm, Ti (35nm)/Au (200nm) TES on 500nm SiN membrane coupled to 240μm × 240μm Au absorber, G ≃ 65 pW/K, C ≃ 0.85 pJ/K *[6]*; good thermal crosstalk *[7]*; excellent magnetic field susceptibility *[8]*, high aspect-ratio to mitigate weak link effect *[9]*, slow TES (τ = C/G) to mitigate electrical crosstalk *[10]*.
- VTT SQUIDs, 6 series array @ first stage and 184 × 4 series array @ second stage, typical noise ≃ 4 pA/√Hz
- In-house digital electronics board for system control and readout (DEMUX): AD9726 DACs, Xilinx XC7V585T Virtex 7 FPGA, 20 MSPS sampling and downsampling to 156.25 KSPS via 4-stage digital decimation filter.
- Base-band feedback (BBFB) uses demodulated signal to null the SQUID input to increase dynamic range and linearity of SQUIDs, compensating phase delay via firmware.
- A Frequency Shift Algorithm (FSA) is implemented in the firmware to eliminate performance degradation in multiplexing due to intermodulation distortions *[11,12]*.
- ^{55}Fe source emitting 5.9 keV photons with a 1 count-per-sec rate.
- Pulses energy estimated by using optimal filtering technique *[13]* in frequency space. Energy non-linearity corrected using point information of 0 eV, Mn-Kα (5.9 keV) and Mn-Kβ (6.5 keV). Gain drifts corrected using TES current baseline and pulse height information.
- Spectral performance estimated by fitting the energy spectrum with the Mn-Kα line model from Holzer *[14]* convolved with detector energy resolution, using the Cash statistics *[15]* with the maximum likelihood method.

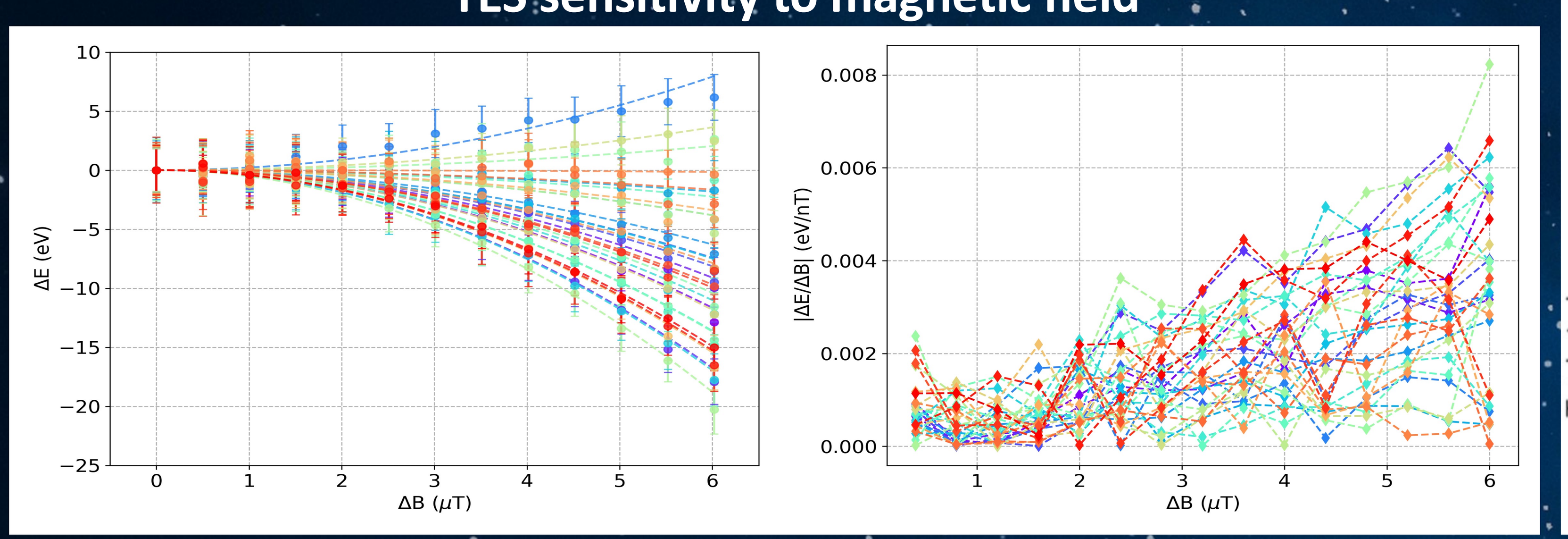
TES array thermal crosstalk



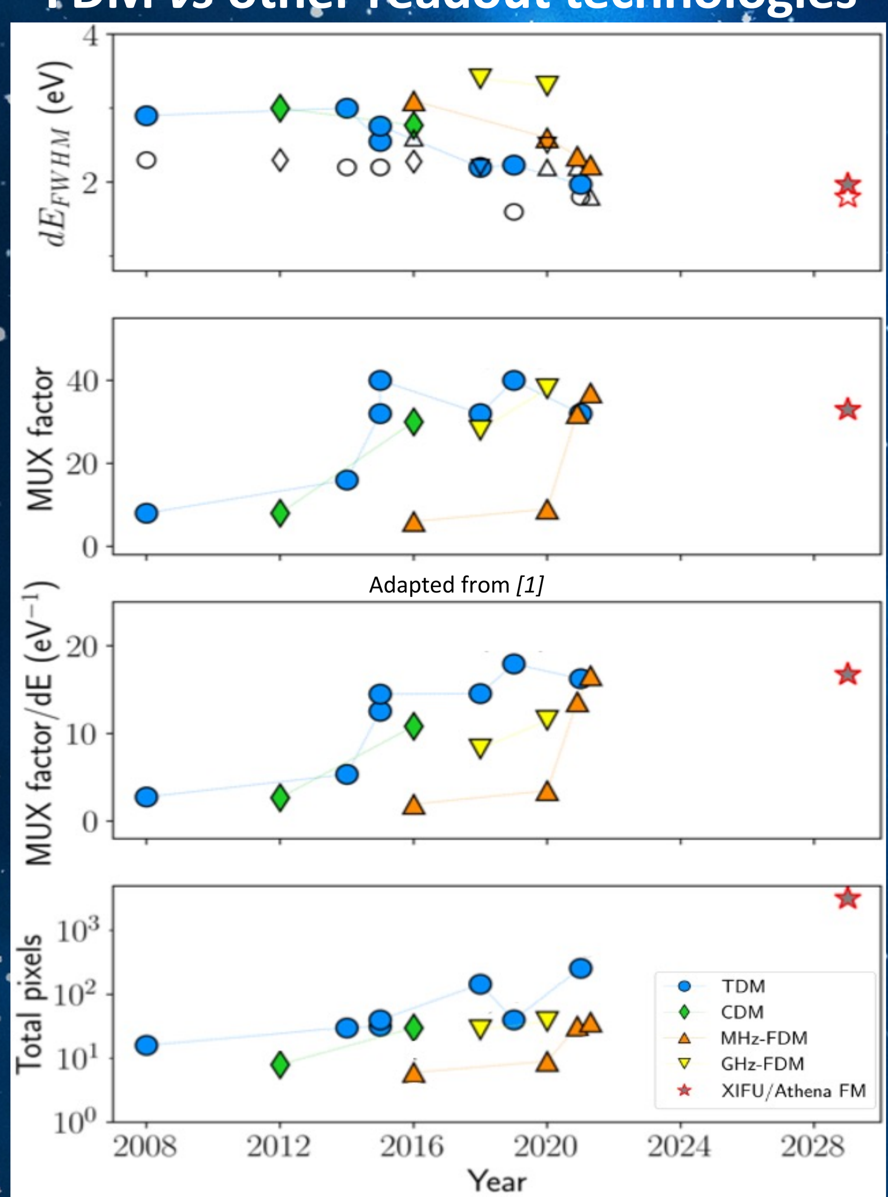
Foreseen scaling up of FDM



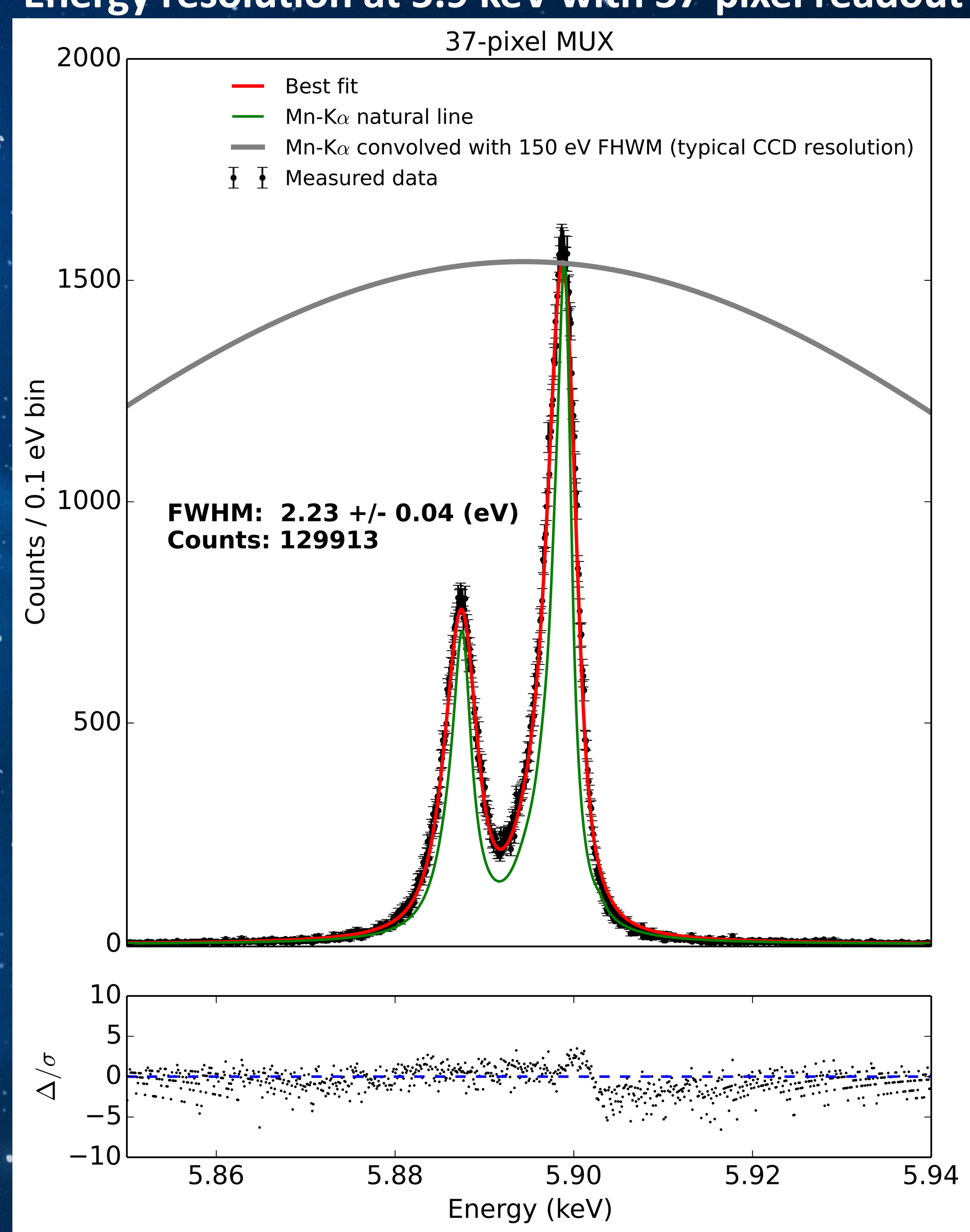
TES sensitivity to magnetic field



FDM *vs* other readout technologies



Energy resolution at 5.9 keV with 37-pixel readout



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