X-ray Microcalorimeters Based on Superconducting Transition Edge Sensors for Astrophysics, Plasma Physics and Particle Physics

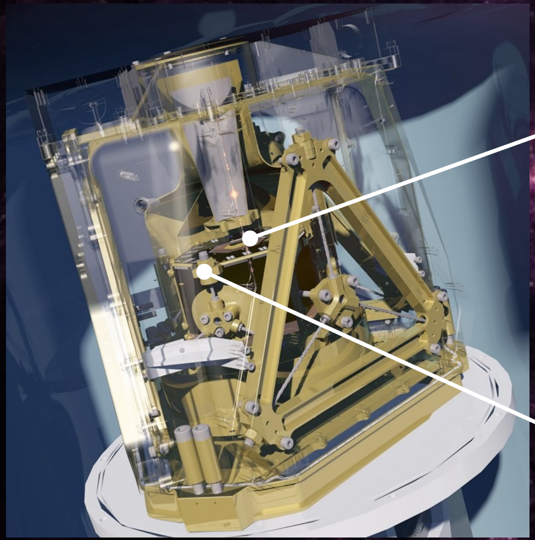
Luciano Gottardi

on behalf of the TES-FDM and ASTRO group at
NWO-I/SRON Netherlands Institute for Space Research

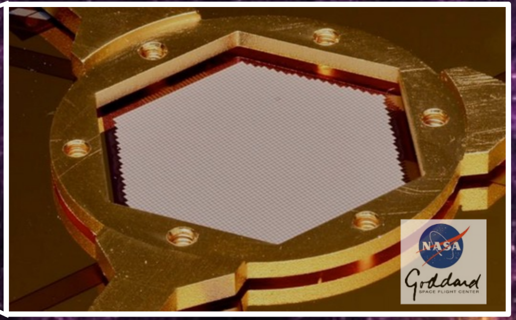
NuMass 2024, Genova, Italy – 1st March 2024

Future X-ray space observatory

- **ATHENA** is a Large ESA mission to study *"The Hot and Energetic Universe"*, launch in late 2030s.
- The **X-IFU** instruments of the payload is a **cryogenic imaging spectrometer:**
  Energy band 0.2 – 12 keV, dE ~ 2.5 eV



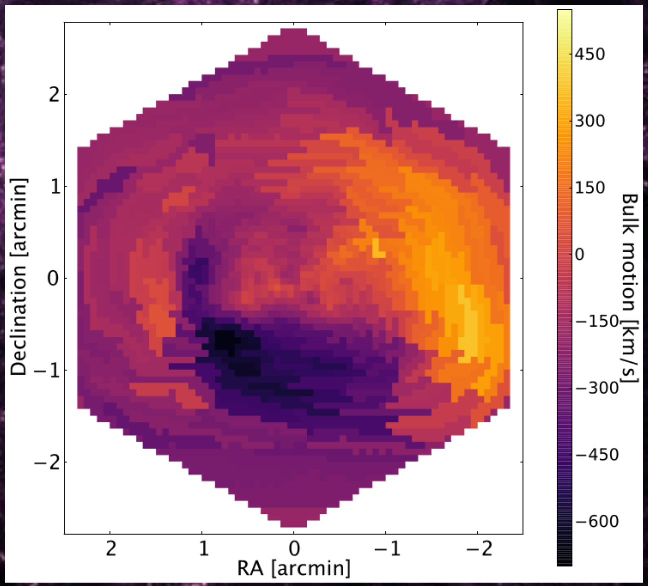
TES array

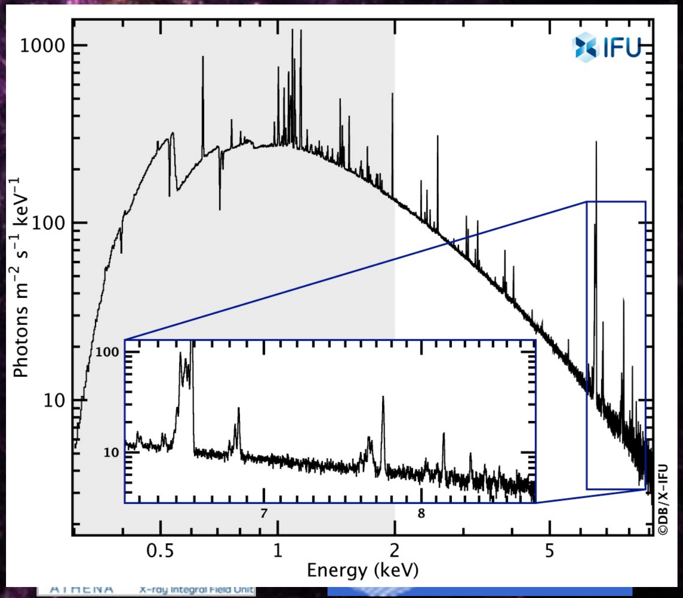


X-ray Integral Field Unit

SRON responsible for the FPA and back-up detector array

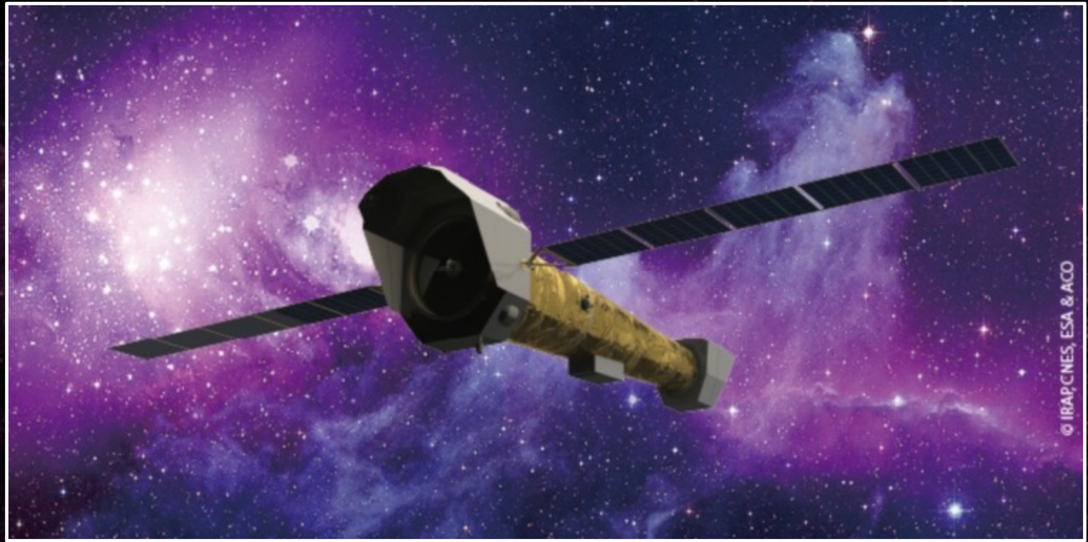
The Hot Universe





Credit: IRAP/CNRS/UT3/CNES/ESA/SRON/NASA-Goddard

Future X-ray space observatory



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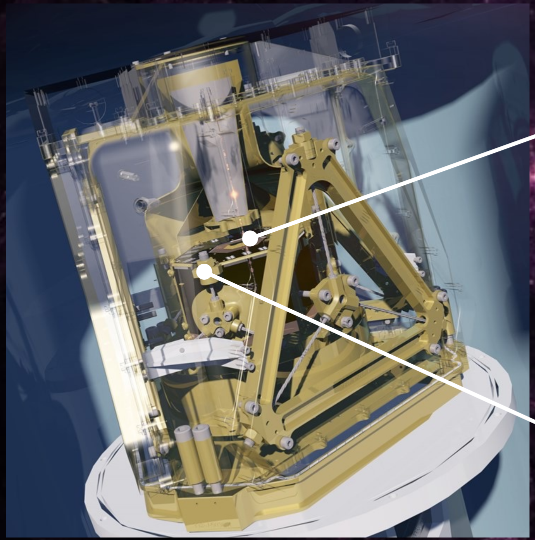
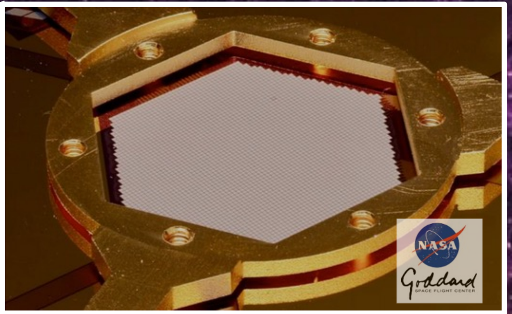
  Energy band 0.2 – 12 keV, dE ~ 2.5 eV

The Energetic Universe

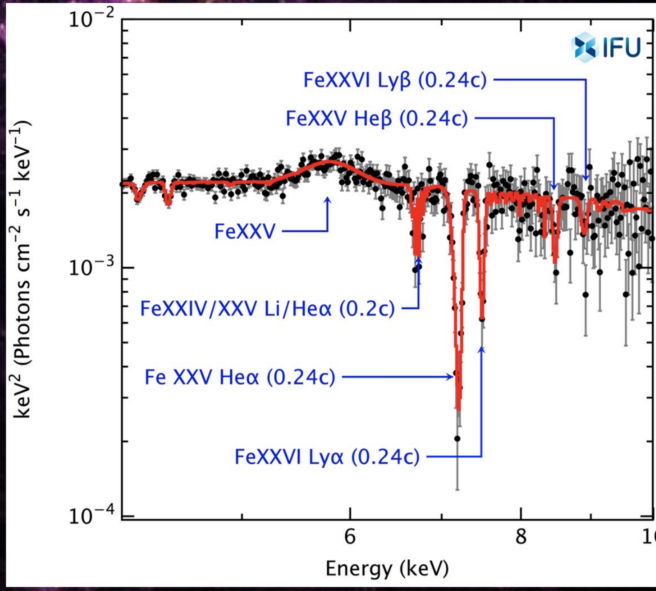


TES array



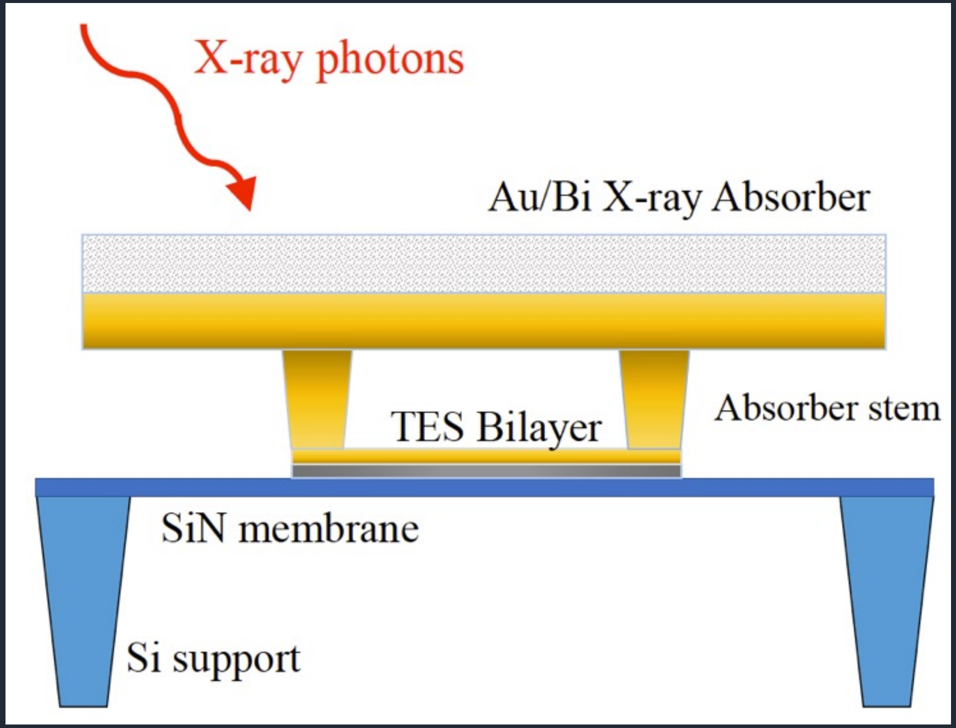
X-ray **I**ntegral **F**ield **U**nit

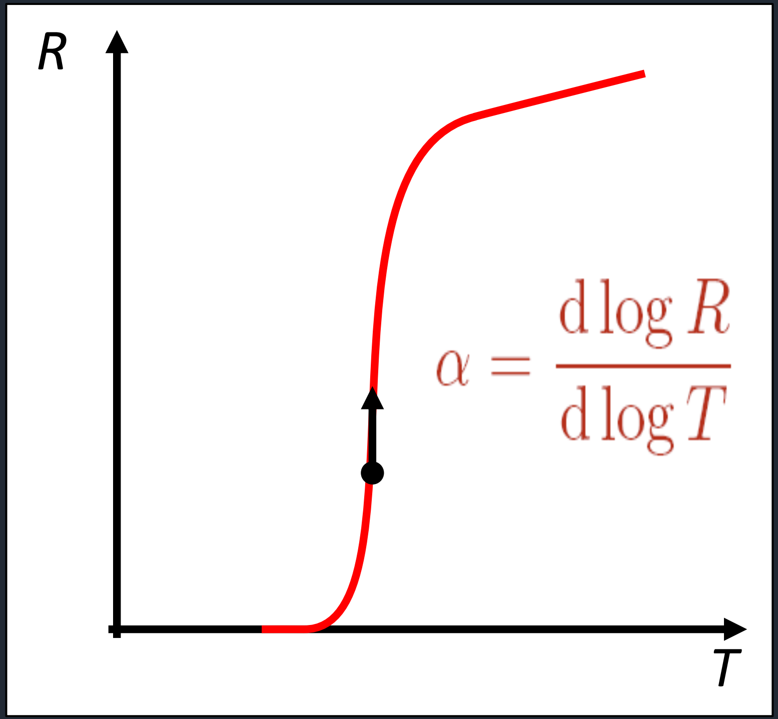
SRON responsible for the FPA and back-up detector array



Credit: IRAP/CNRS/UT3/CNES/ESA/SRON/NASA-Goddard

Superconducting Transition Edge Sensors





- Low temperature detectors T_c~ 90 mK
- Sharp transition α~ 500-1000
- Small absorber (low heat capacity C)
- Limited dynamic range E_{lin}~ C/α

Energy resolution:

$$E_{FWHM} \sim 2.355\sqrt{\frac{4 k_B T_c^2 C}{\alpha}}$$

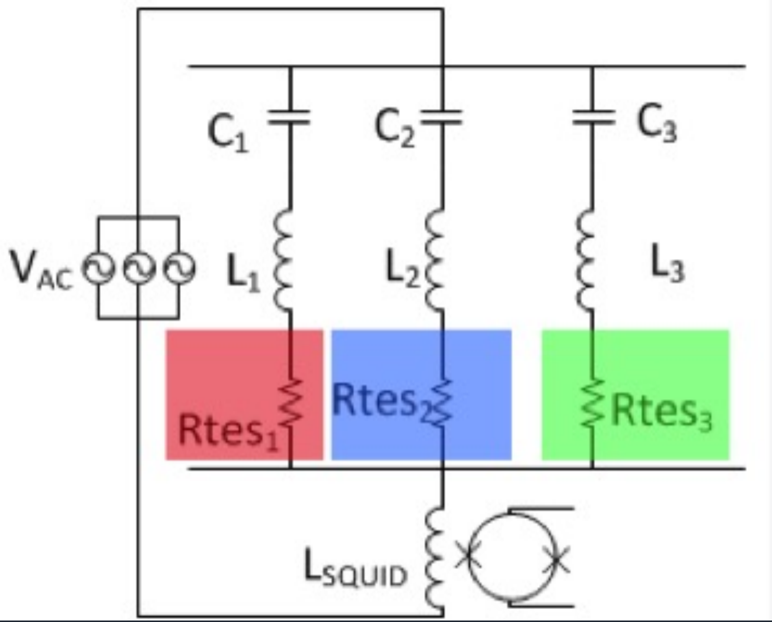
K.Irwin and G. Hilton In Cryogenic Particle Detection; Enss,C. Springer, 2006
J. Ullom and D. Bennett, Superc.Sci.Technol. 28, 084003, 2015
L. Gottardi and K. Nagayashi, Applied Sciences 11 (9),3793, 2021

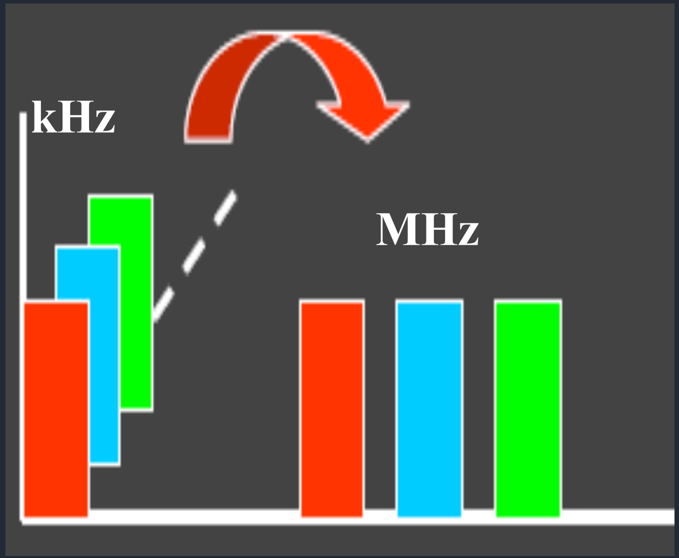
SRON

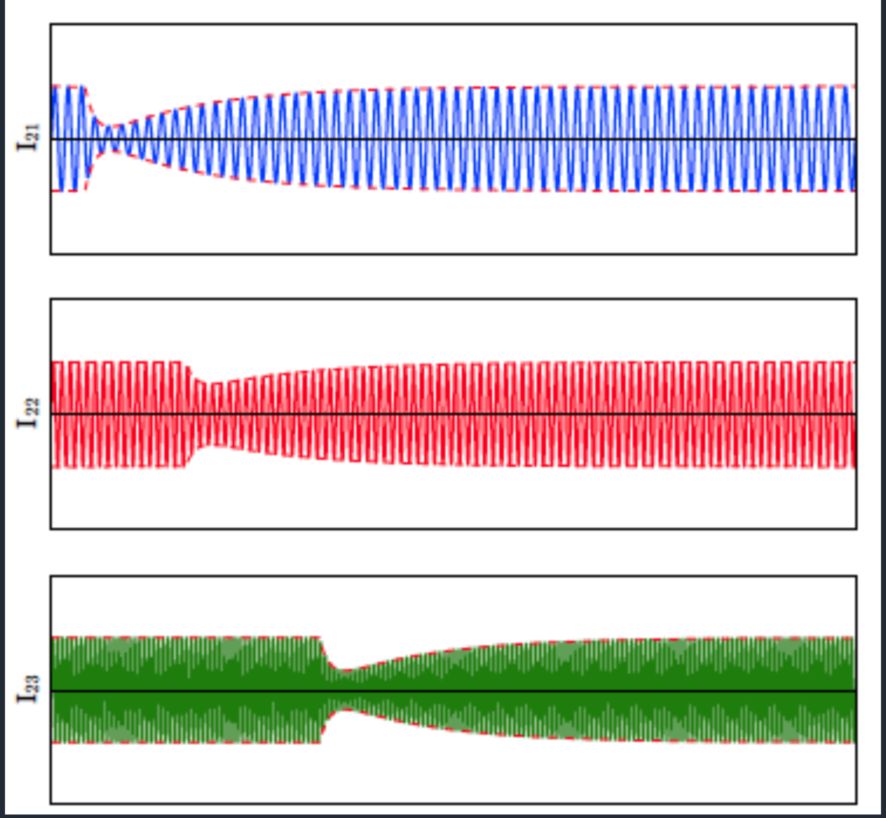
Frequency Division Multiplexing

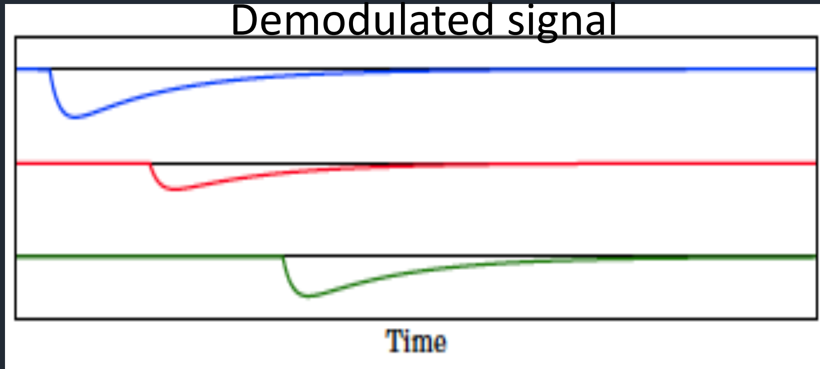
- TES is ac voltage bias and works as AM modulator of the MHz carrier
- High-Q bandpass filters
- Signal is demodulated at room temperature
- Keeps performing with very long harness
- Low sensitivity to parasitic and EMI
- Low electrical cross-talk
- Individual pixels bias addressing

To read out ~ **4000 pixels**
~**100 SQUID channels** are needed
with MUX factor of
40 pixels/channel





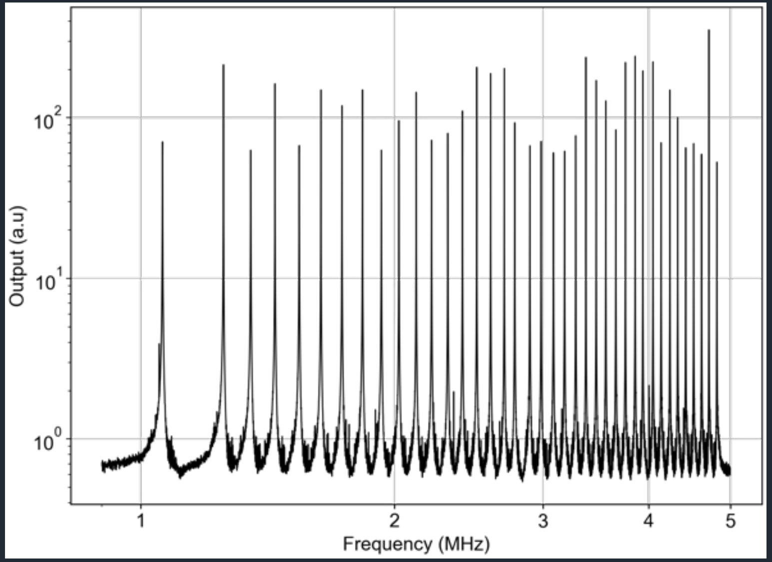


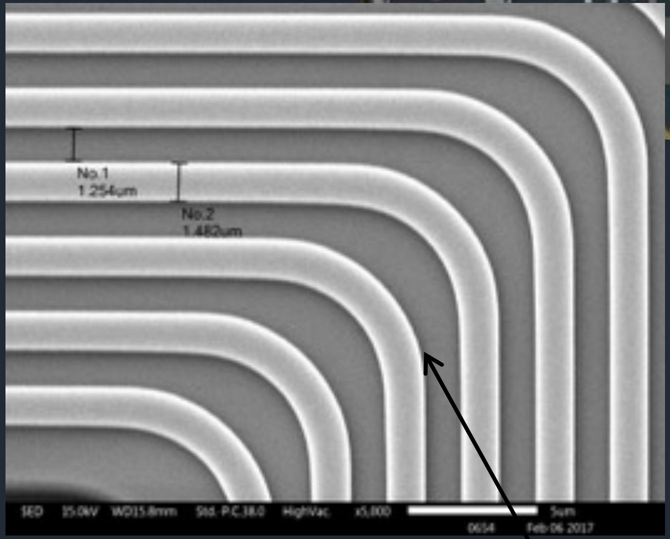


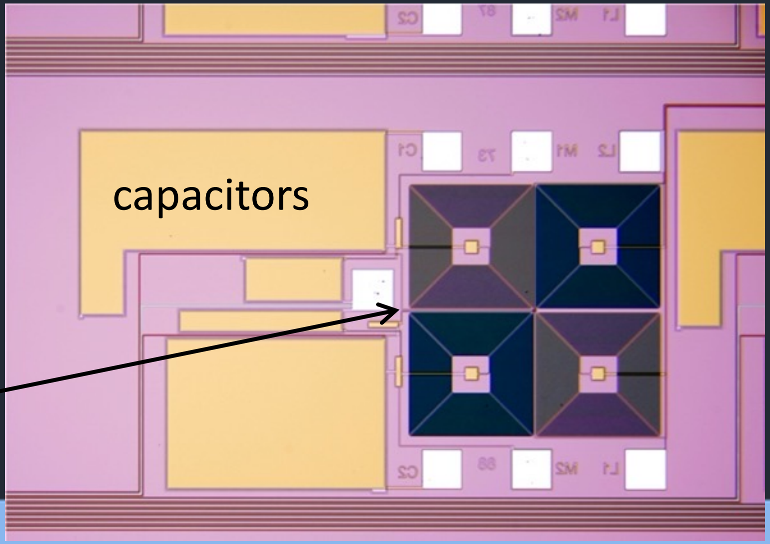
Superconducting high-Q MHz LC filters

M. P. Bruijn, et al., J. of Low Temp. Phys. 167, 695 (2012).

- Thin film Nb superconducting technology
- Coplanar wiring
- Low loss **amorphous silicon** capacitors
- Gradiometric design to minimize pixel crosstalk
- **High yield (> 97%)**



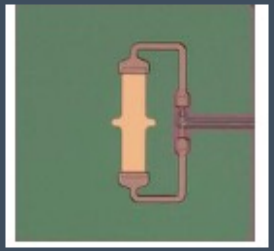


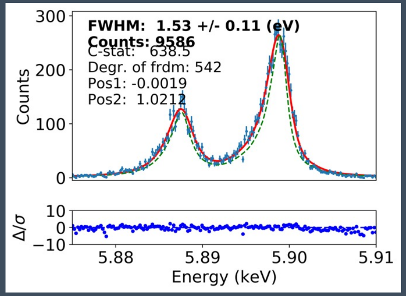


inductors

Latest achievements at SRON

Single Pixel Optimization



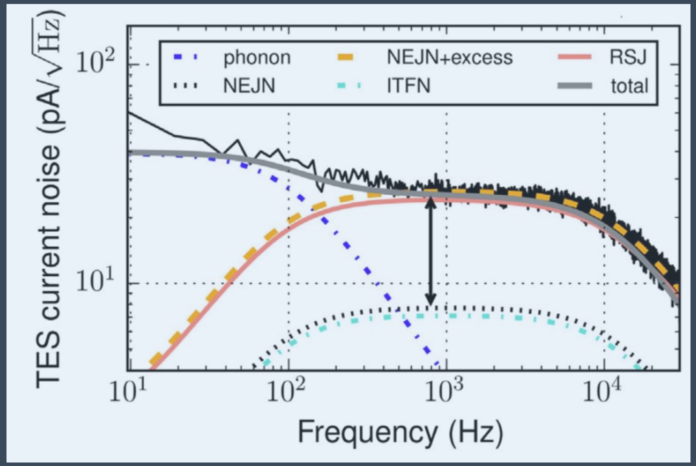


Low aspect ratio, low Rn

High aspect ratio, high Rn

M. de Wit et al., J. Appl. Phys. 128, 224501 (2020),
E. Taralli *et al*. Rev. Sci. Instr.. 92, 023101 (2021)
M. de Wit et al., Phys. Rev. Appl. 16, 04059 (2021)

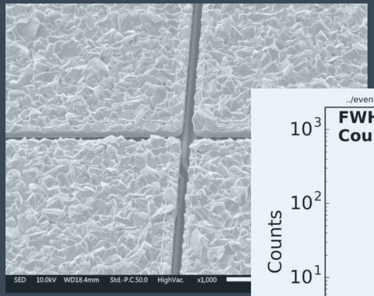
Detector noise well understood

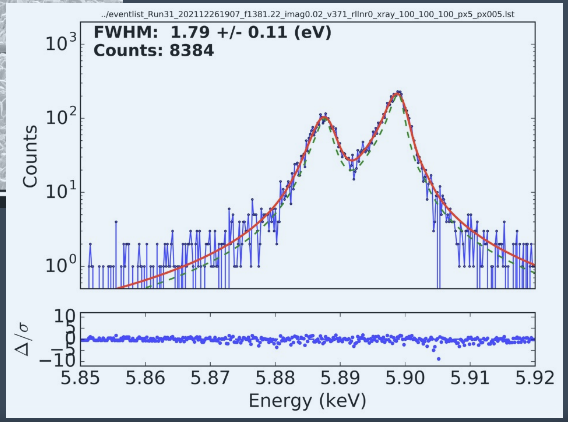


L. Gottardi *et al*., Phys. Rev. Lett. 126, 217001 (2021)

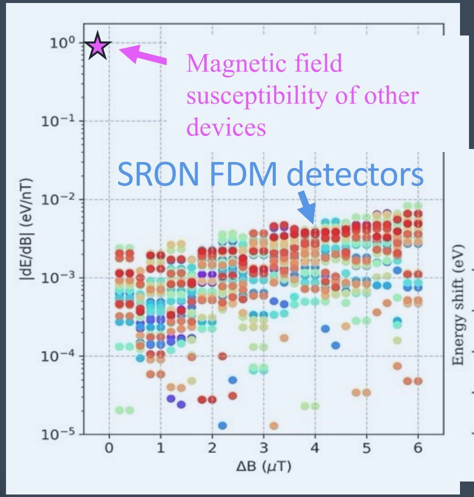
High Quantum Efficiency

Bismuth absorber

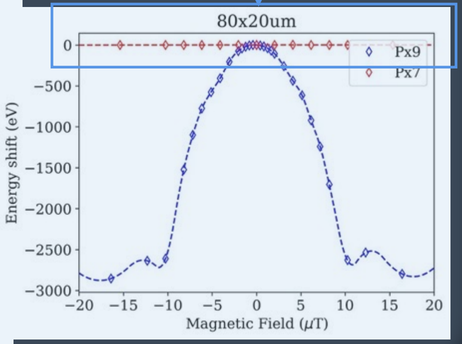




TESs insensitive to external magnetic field

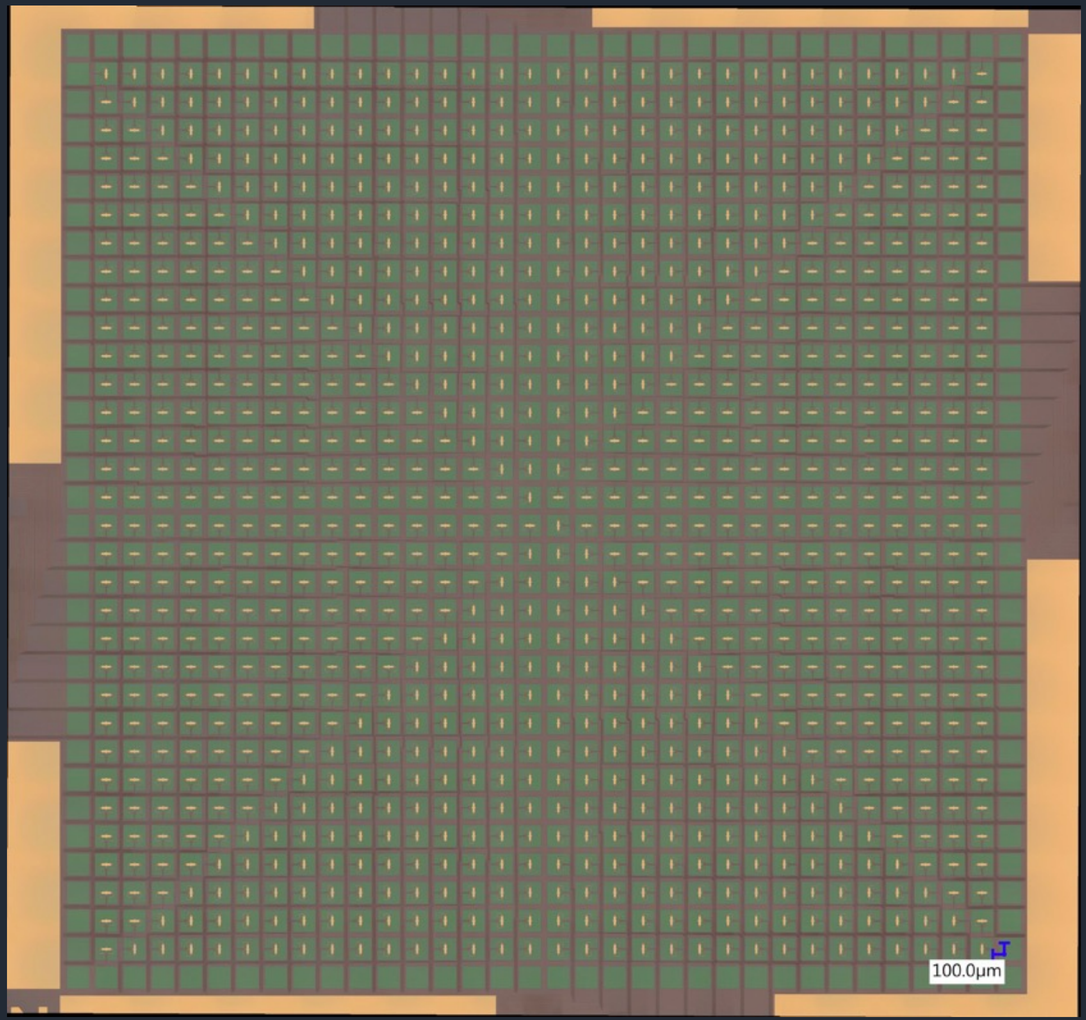


Superconducting ground-plane

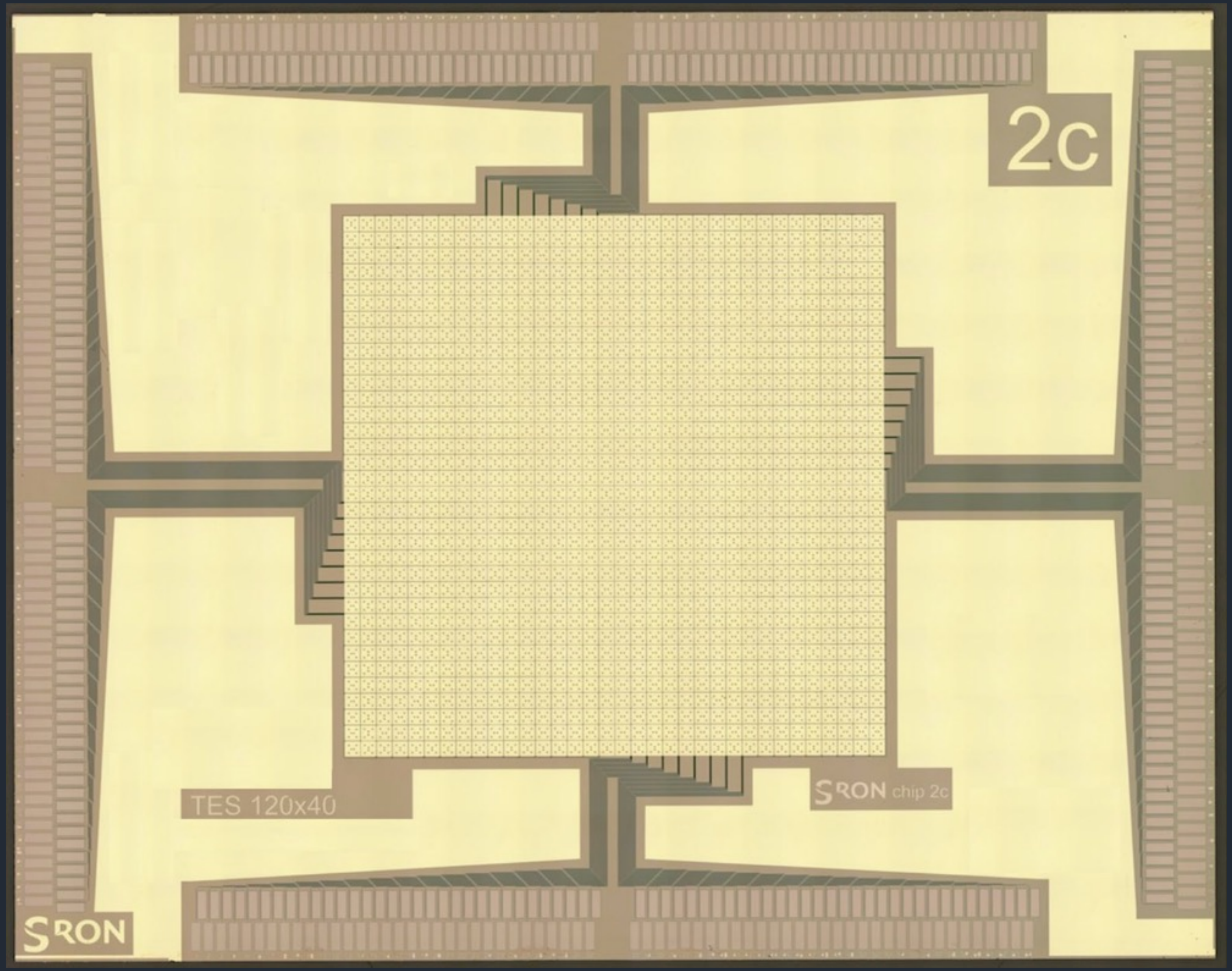


M. de Wit et al., Phys. Rev. Appl. (2022)

X-ray TES microcalorimeters for XIFU



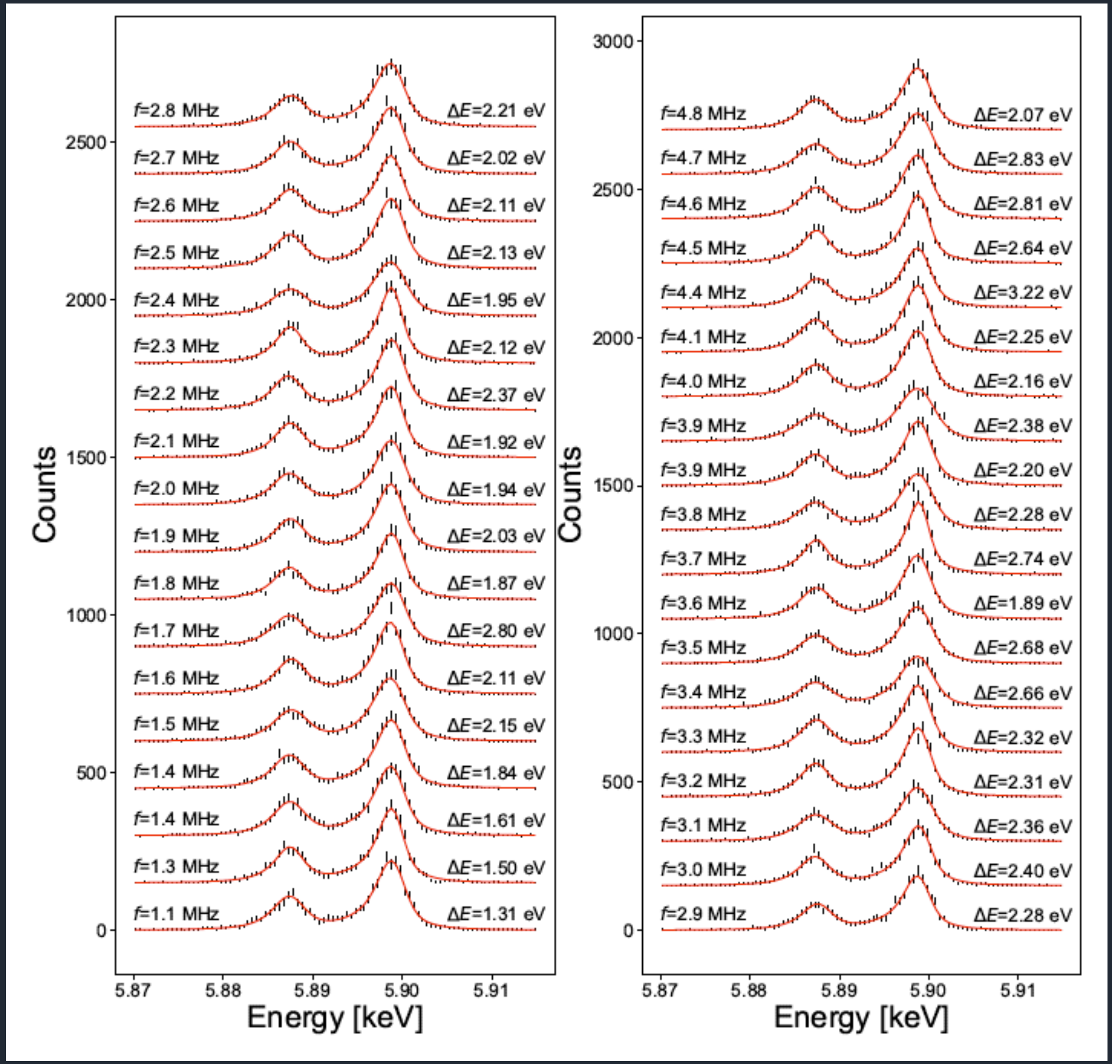
Micrograph SRON 32x32 array before absorber deposition

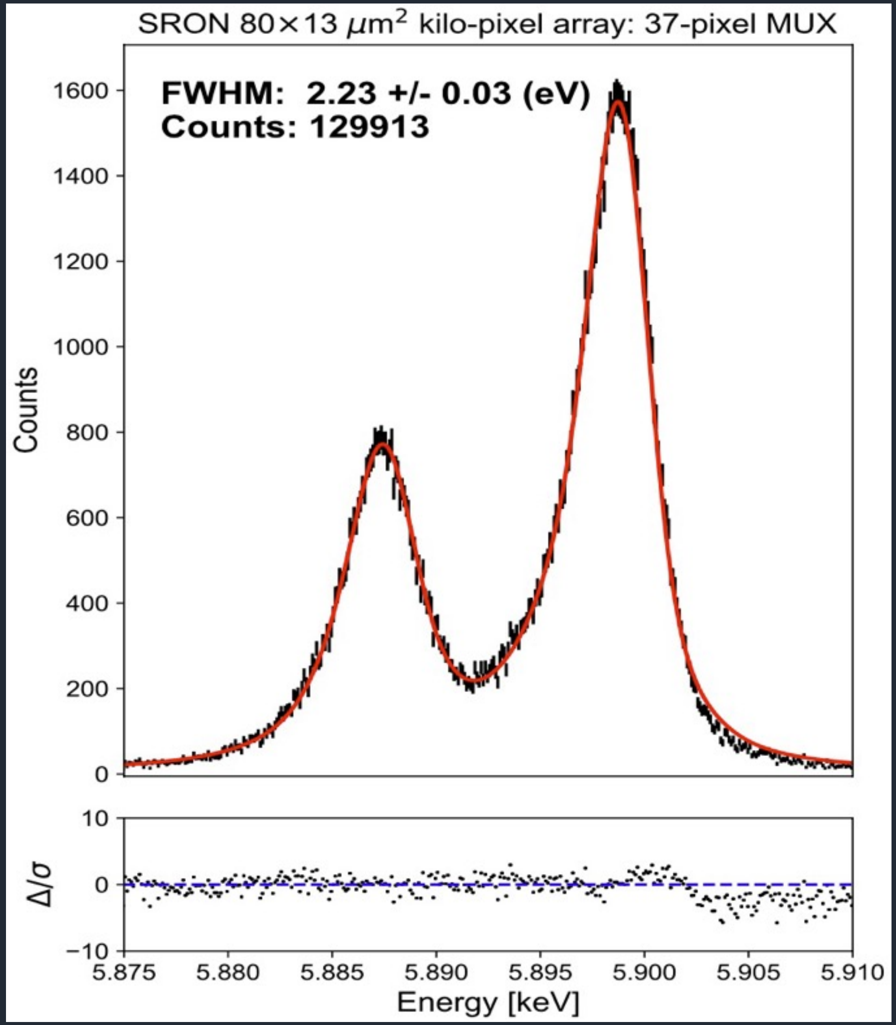


Final chip SRON 32x32 X-ray microcalorimeters

Nagayoshi et al, J. Low Temp. Phys. 199, 2019

Frequency division multiplexing demonstration

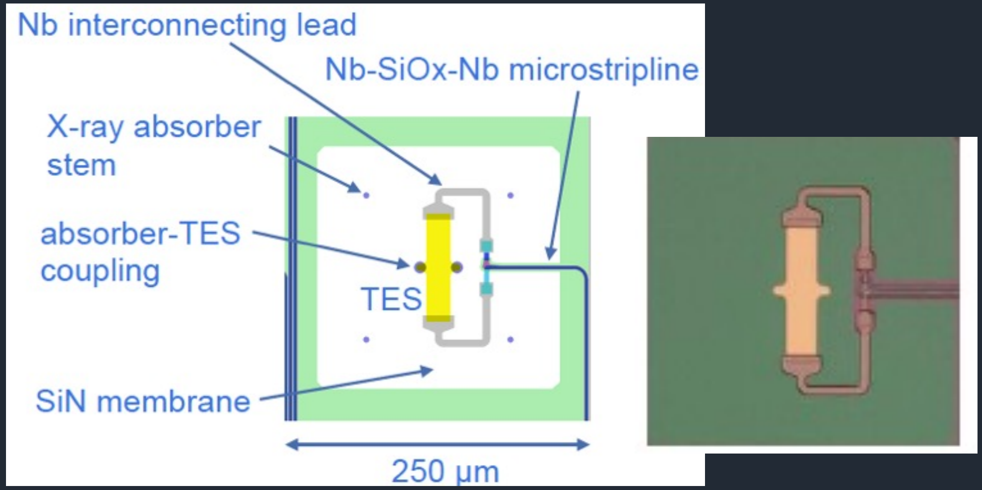




- Energy resolution fulfills XIFU requirements
- SRON technology is ready for scaling up towards a real instrument

Akamatsu et al. JLTP 199, 737 (2020)
Vaccaro, HA et al. RSI 92, 033103 (2021)
van der Hulst, HA et al. RSI 92, 7 (2021)
H. Akamatsu et al. APL 119,18, (2021)

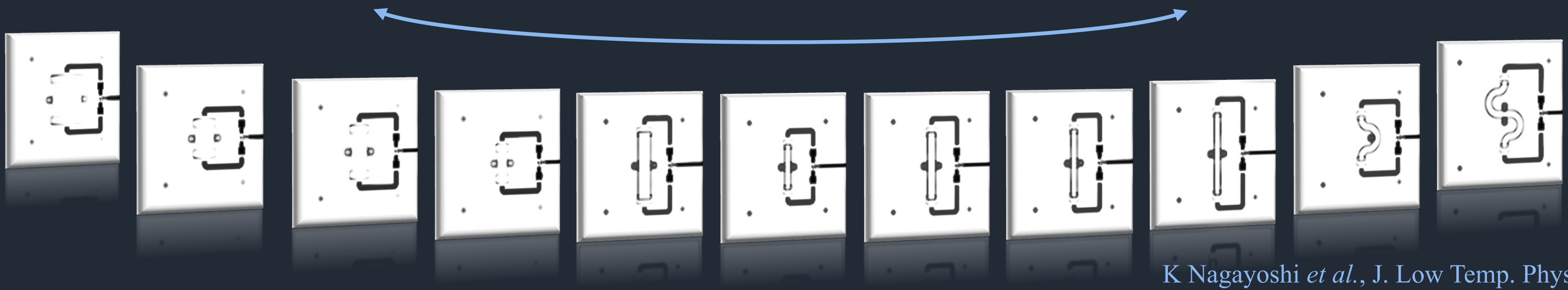
Detector design optimization at SRON



- Deep understanding of the detector physics and noise
- Detector performance improvement from TES geometry optimization
- Successful pixels design optimization on going at SRON

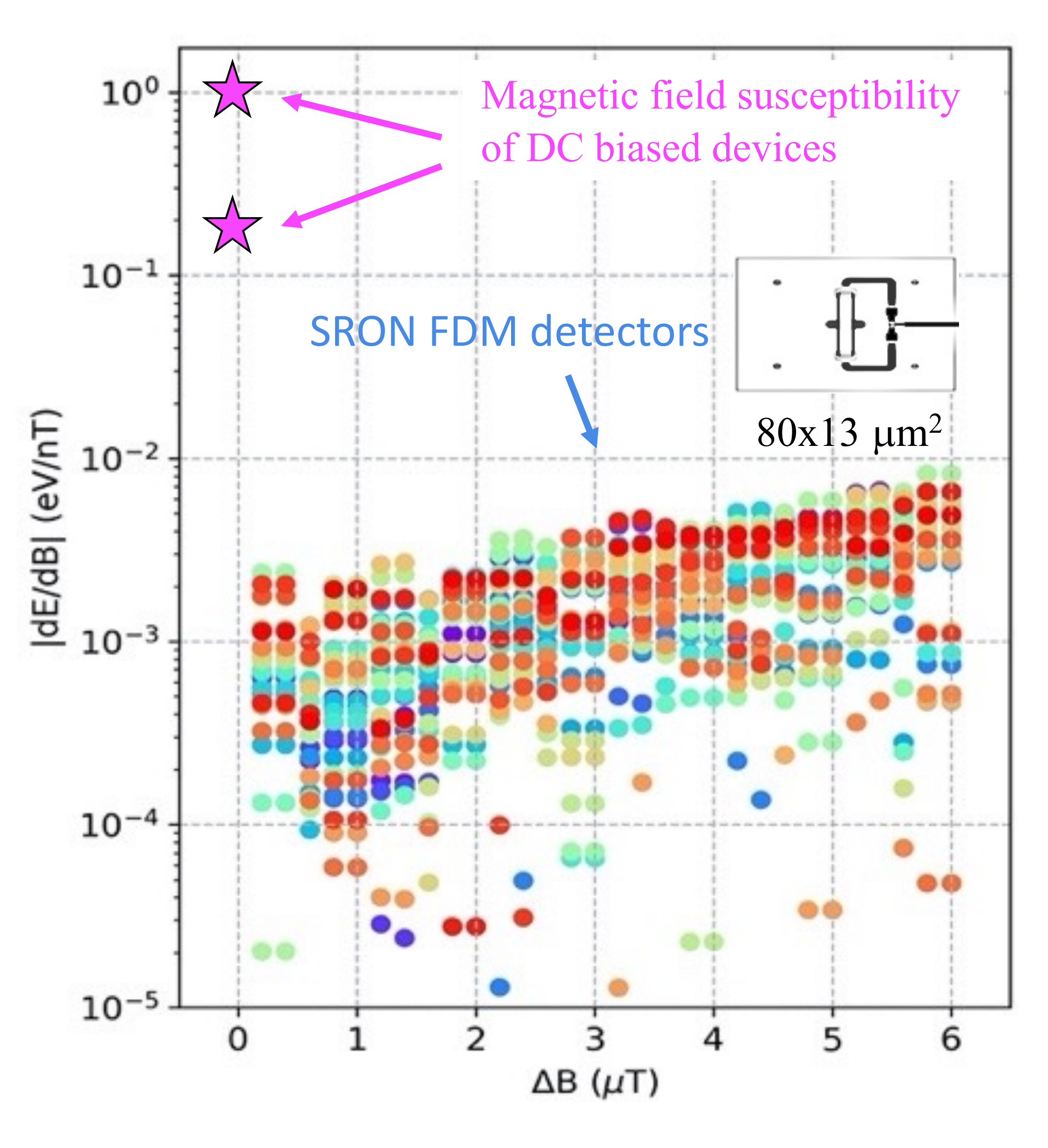
Low aspect ratio, low resistance
Better for TDM/GHz-FDM

High aspect ratio, high resistance
Better for FDM

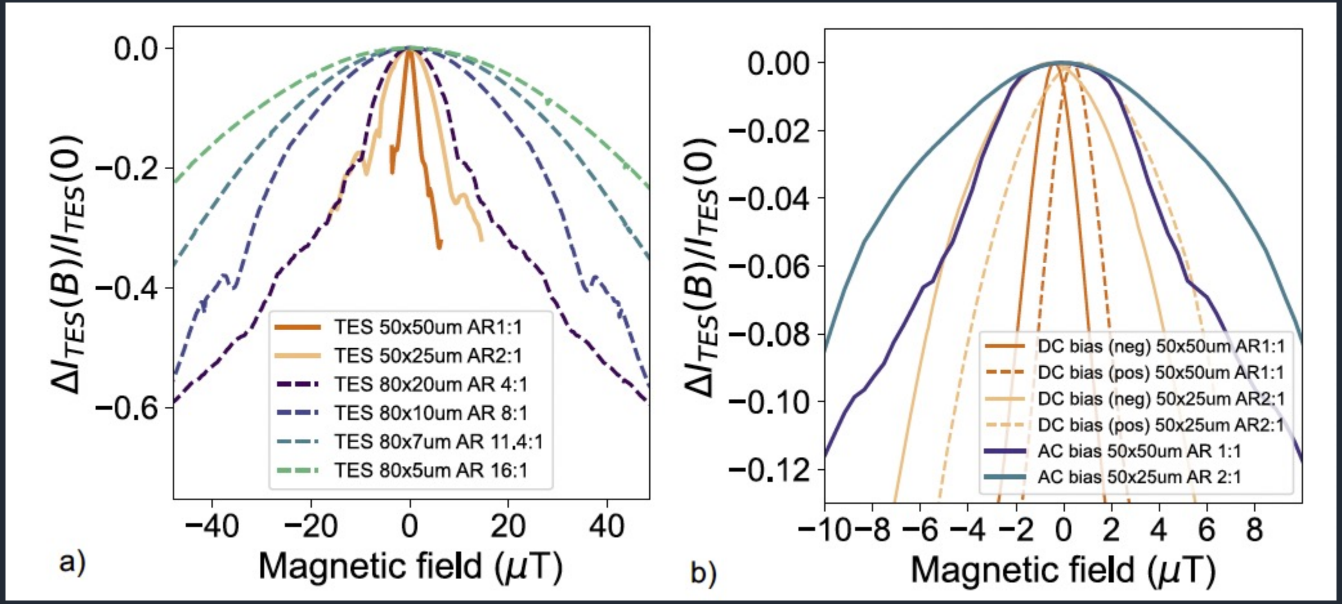


K Nagayoshi *et al.*, J. Low Temp. Phys. **199**, 943-948 (2020)
M. de Wit et al., J. Appl. Phys. 128, 224501 (2020)
L. Gottardi *et al.*, Phys. Rev. Lett. 126, 217001 (2021)
E. Taralli *et al*. Rev. Sci. Instrum. 92, 023101 (2021)

TES magnetic field susceptibility



- DC biased are very sensitive to external magnetic field **dE/dB~ 0.1-1eV/nT** (depending on the geometry)
  - SRON TES-FDM detectors show very low sensitivity to B-field < **5 meV/nT** at **B=0 μT**
- **Requirement** for **X-IFU: 8 eV/nT@ 7 keV,** for **ΔB < 100 nT**
- The FPA design of future TES based instruments for ground-base and space observatory could be greatly simplified when using FDM

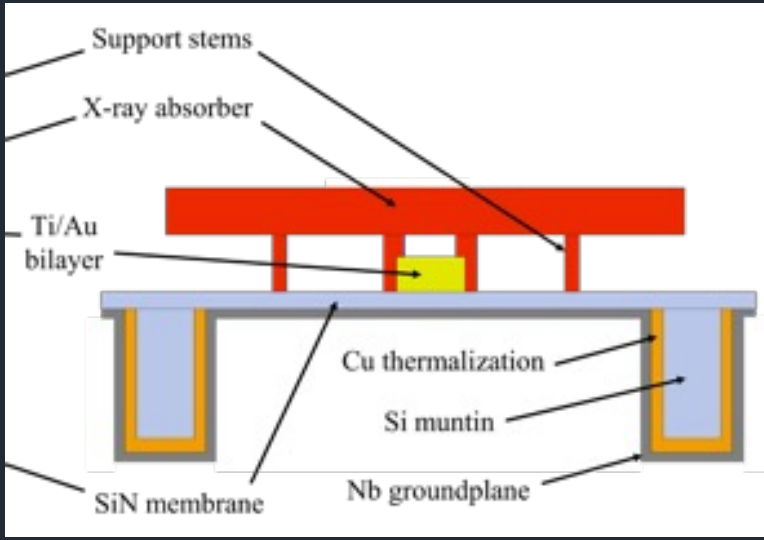


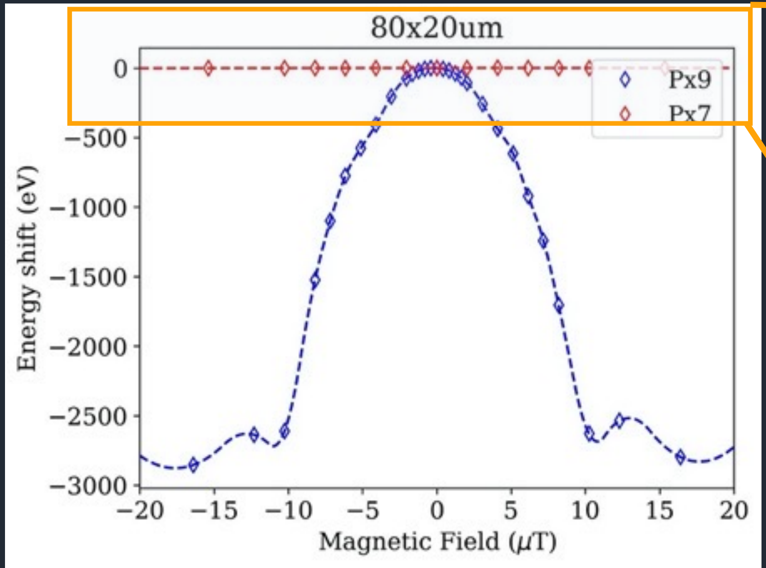
L. Gottardi, S. Smith, pre-print arXiv:2210.06617 (2022)

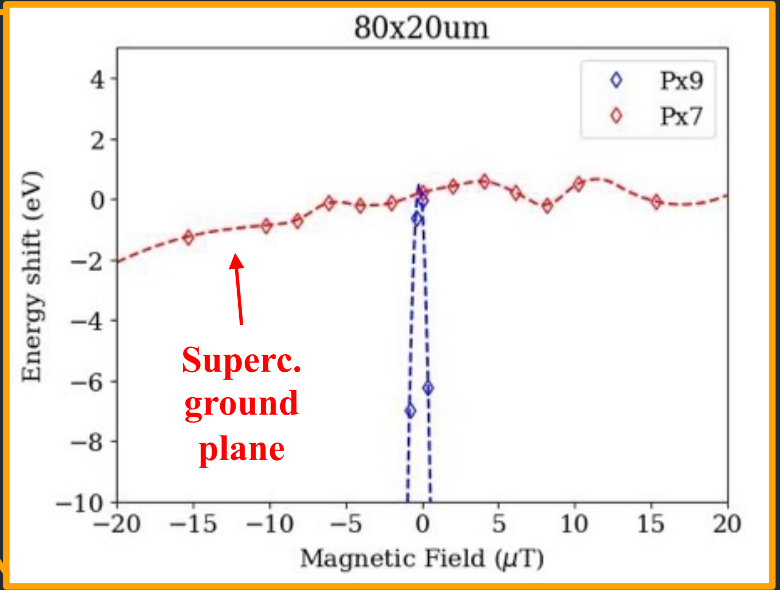
SRON

TES magnetic field susceptibility

New SRON pixel design with
superconducting ground plane
makes the detector
insensitive to magnetic field



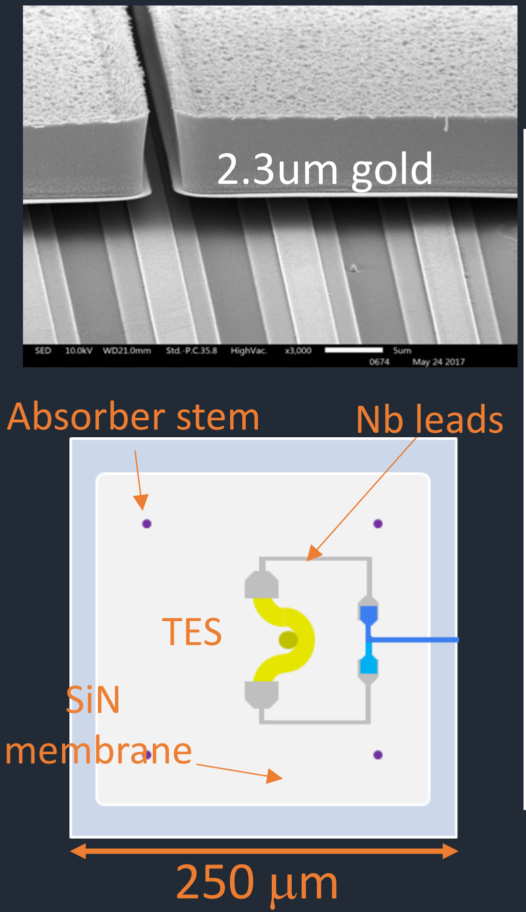


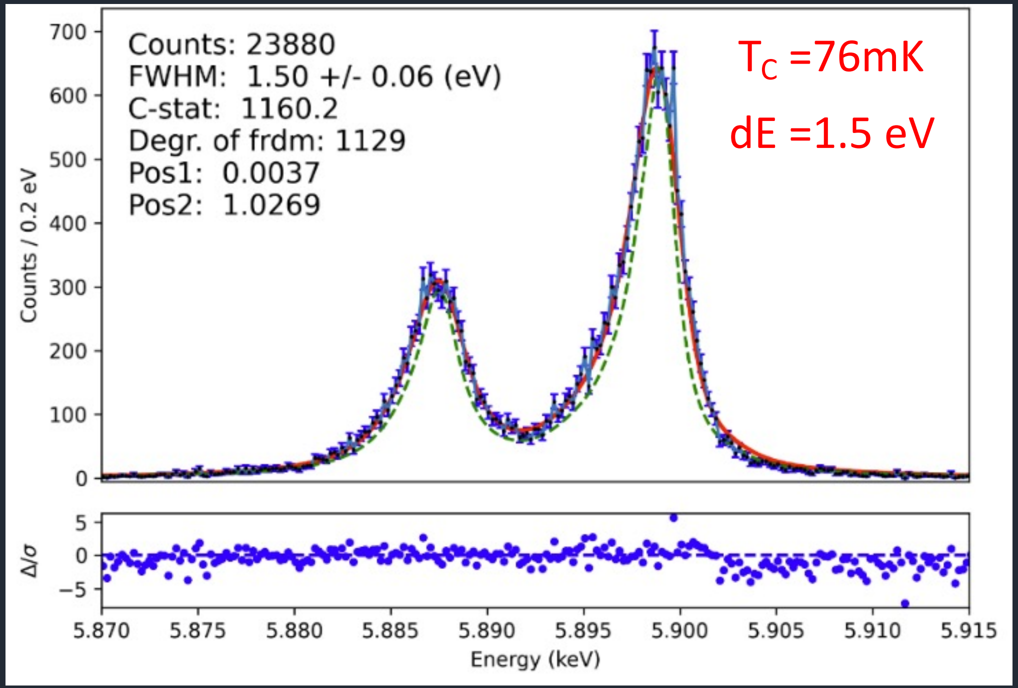


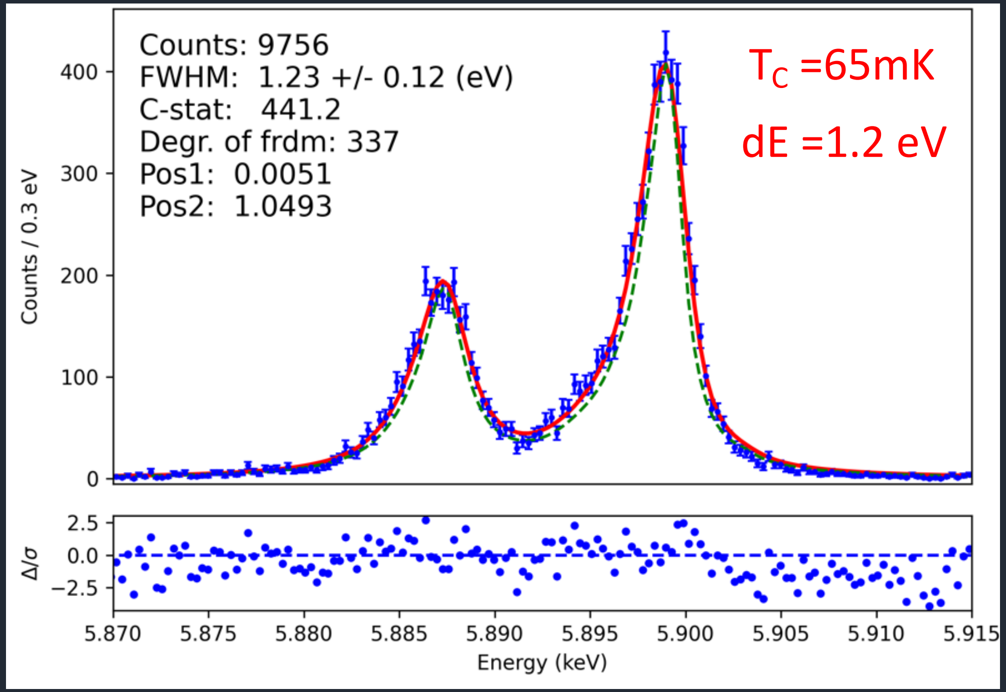
M.deWit et al. Phys. Rev. Appl. 2022

SRON

TES X-ray microcalorimeters for sub eV resolution



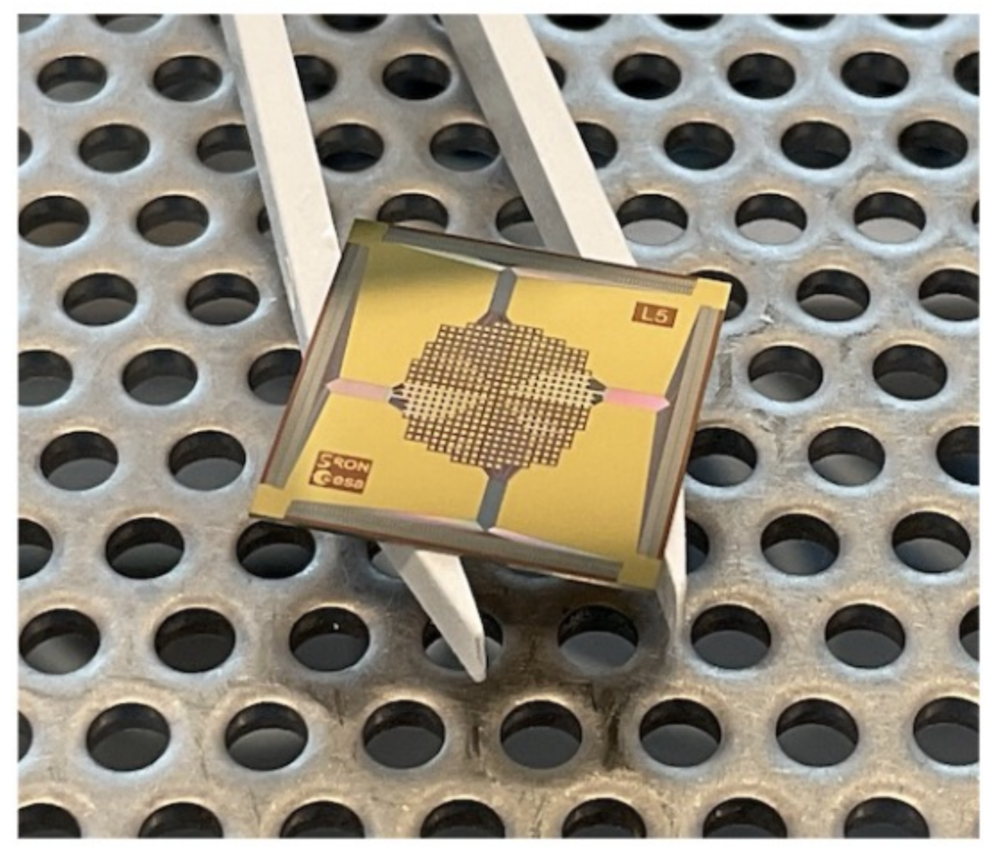


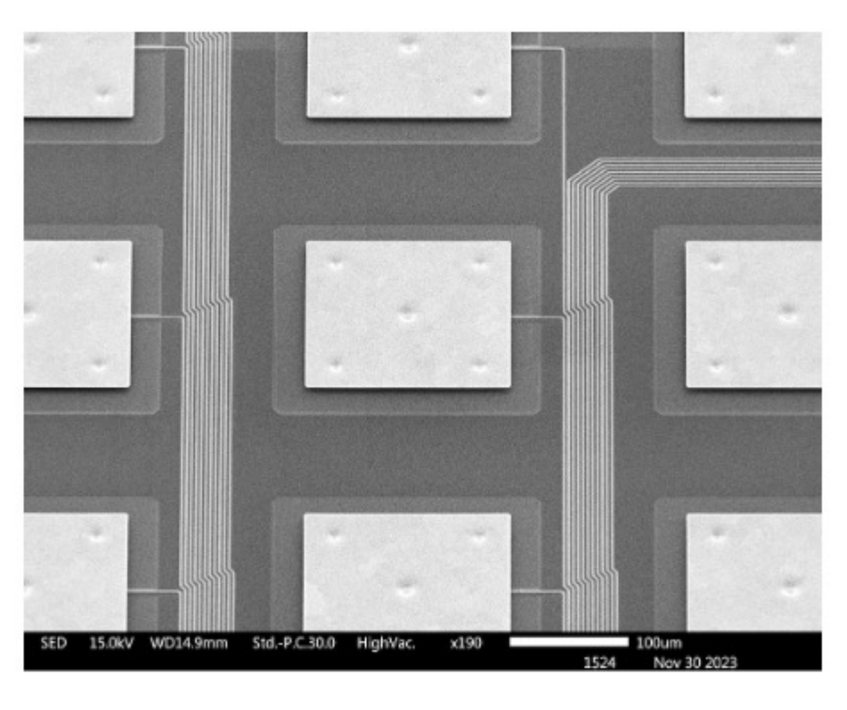


- Existing TES calorimeter optimize for X-IFU like mission have been successfully fabricated in the past year with typical single pixel energy resolution of 1.5 eV @ 6 keV
- By fabricating new TES array with smaller absorbers and lower T_C (~50 mK) we can achieve the requirement for the proposed EBIT experiments. (dE < 1eV @ 1 keV)
- As a proof of principle, we baked one of the existing devices and lower the T_C from 76 mK to 65 mK. We achieved energy resolution of 1.2 eV with a large absorber.

Low heat capacitance, super high-resolution pixels for science at < 2 keV

- Small and thin absorber
- Expected 0.5 eV energy resolution at 1keV in single pixel mode





Ken's presentation

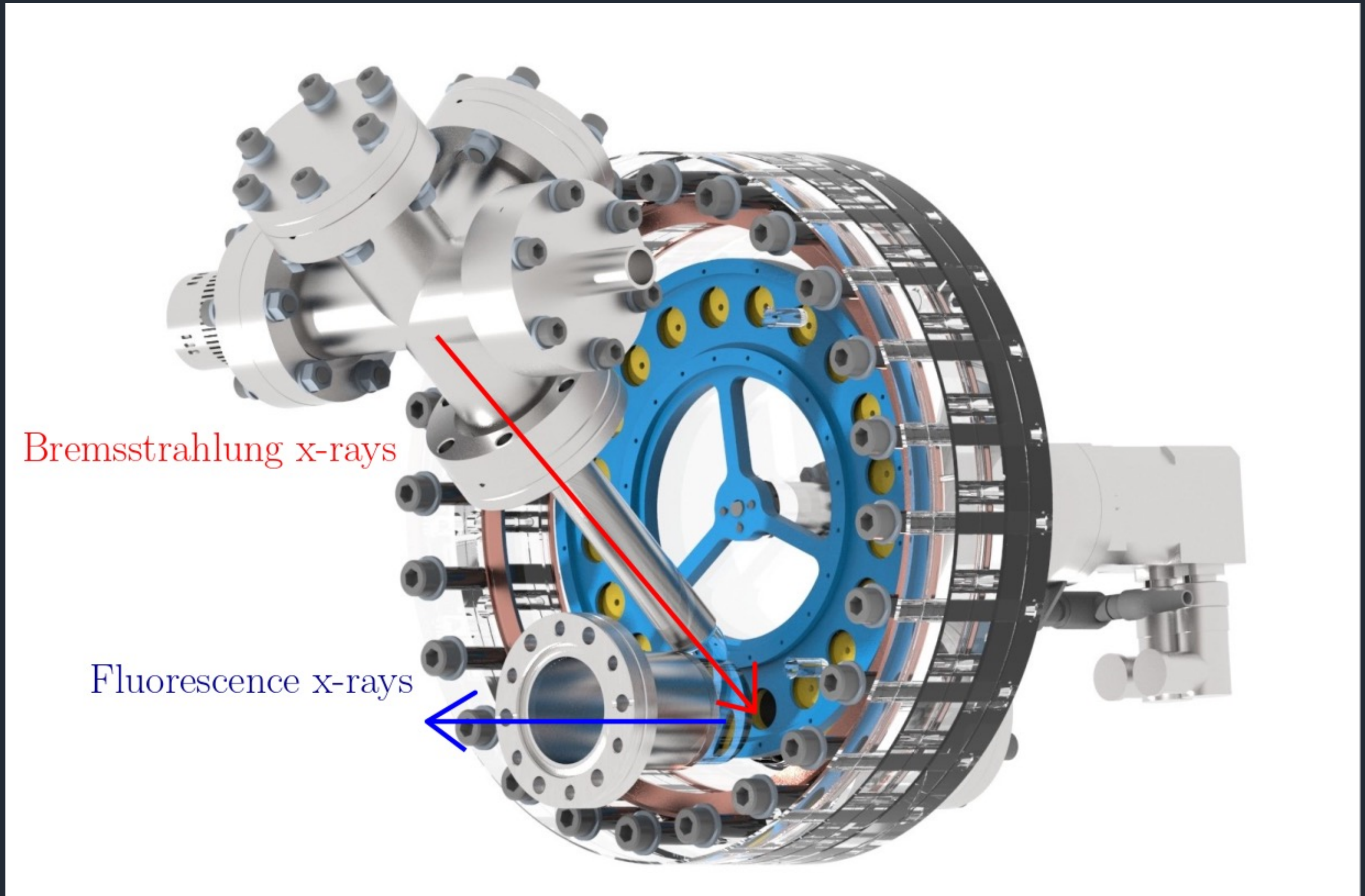
SRON

Ground-based activities at SRON
with TES X-ray calorimeters and FDM read-out

- Calibration campaign of a 2 channels TES-FDM system using fluorescence targets
- Perfomance demonstration of SRON TES FDM system at the MPI-K Electron-Beam Ion Trap facility
- Establishing potential applications of TES X-ray calorimeters in for fusion plasma research and diagnostic, particle physics and material science
- And…*for the fun of it:* low background experiments for solar axion search

SRON

Vacuum Rotating Target Source



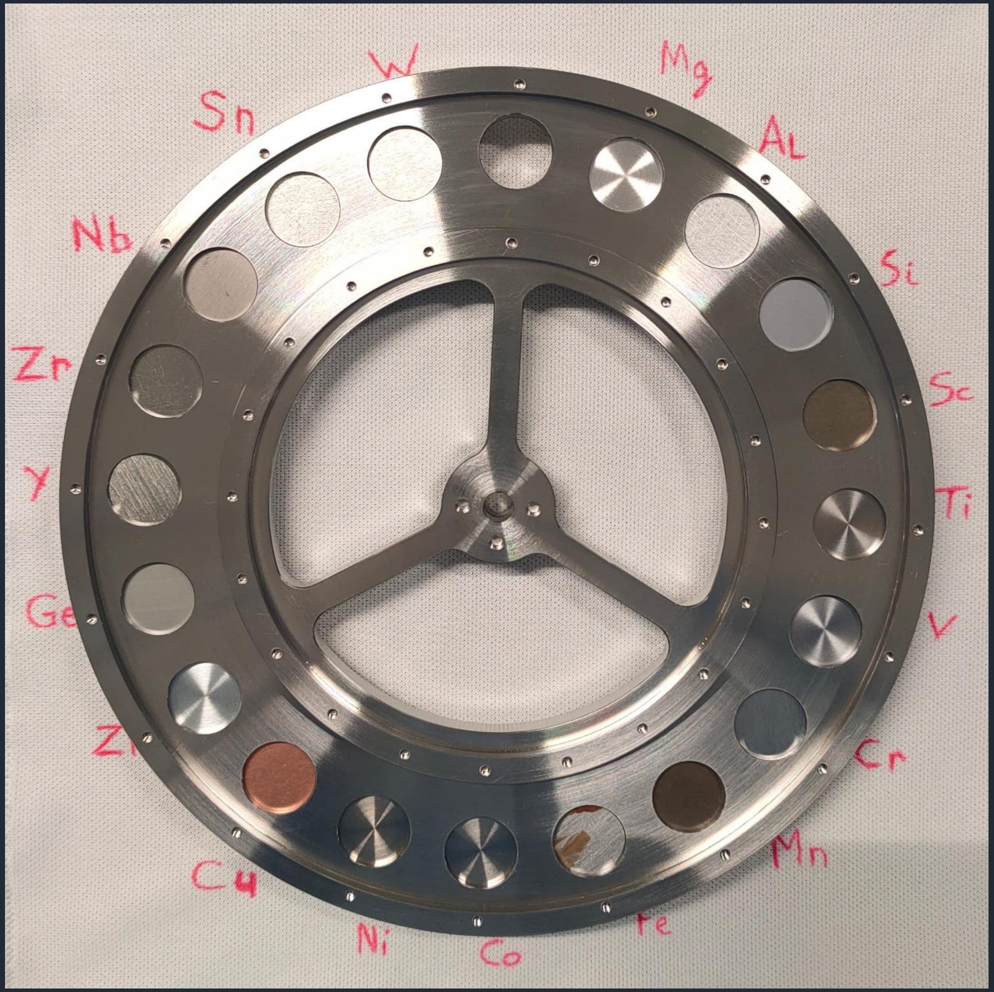
Credit: F. Richters

- The design of the vacuum chamber is based on NASA-GSFC design (with minor modifications). Credits Maurice Leutenegger and Scott Porter NASA/GSFC
- We use a vacuum X-ray tube from McPherson
- Target wheel is motor-driven , controlled via python scripts

Targets wheel

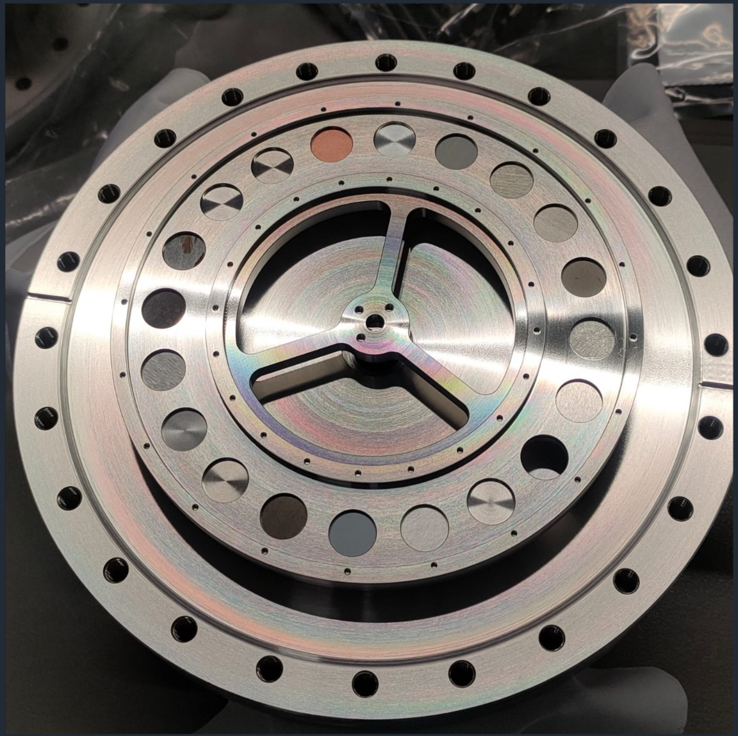
Materials:

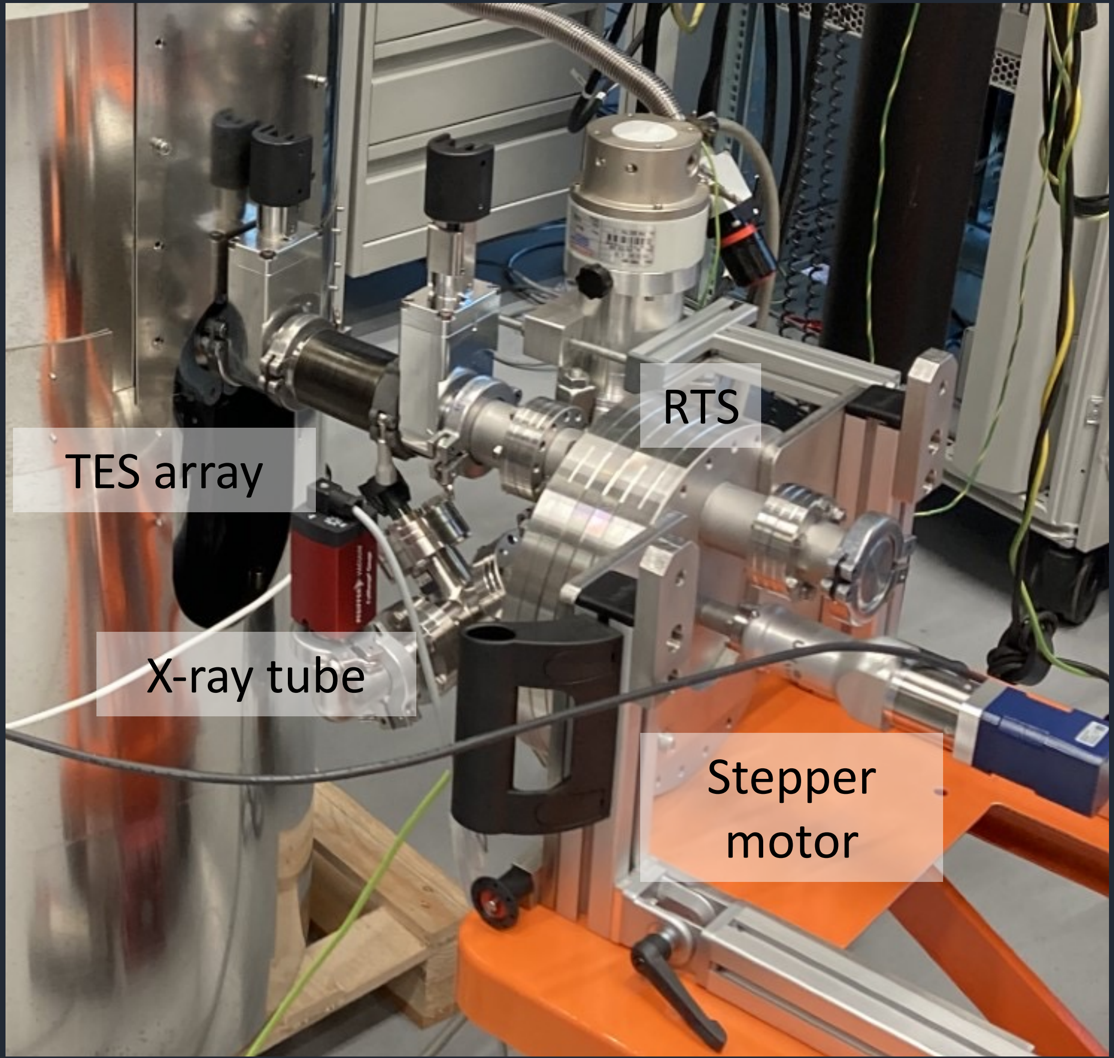
- Mg (magnesium)
- Al (Aluminium)
- Si (Silicon)
- Sc (Scandium)
- Ti (Titanium)
- V (Vanadium)
- Cr (Chromium)
- Mn (Maganese)
- Fe (Iron)
- Co (Cobalt)
- Ni (Nickel)
- Cu (Copper)
- Zn (Zinc)
- Ge (Germanium)
- Y (Yttrium)
- Zr (Zirconium)
- Nb (Niobium)
- Sn (Tin)
- W (Tungsten)



- We have 19 targets of puur materials and one open hole for an external source (MSX/EBITs, Syncrotrons,…)

Pictures



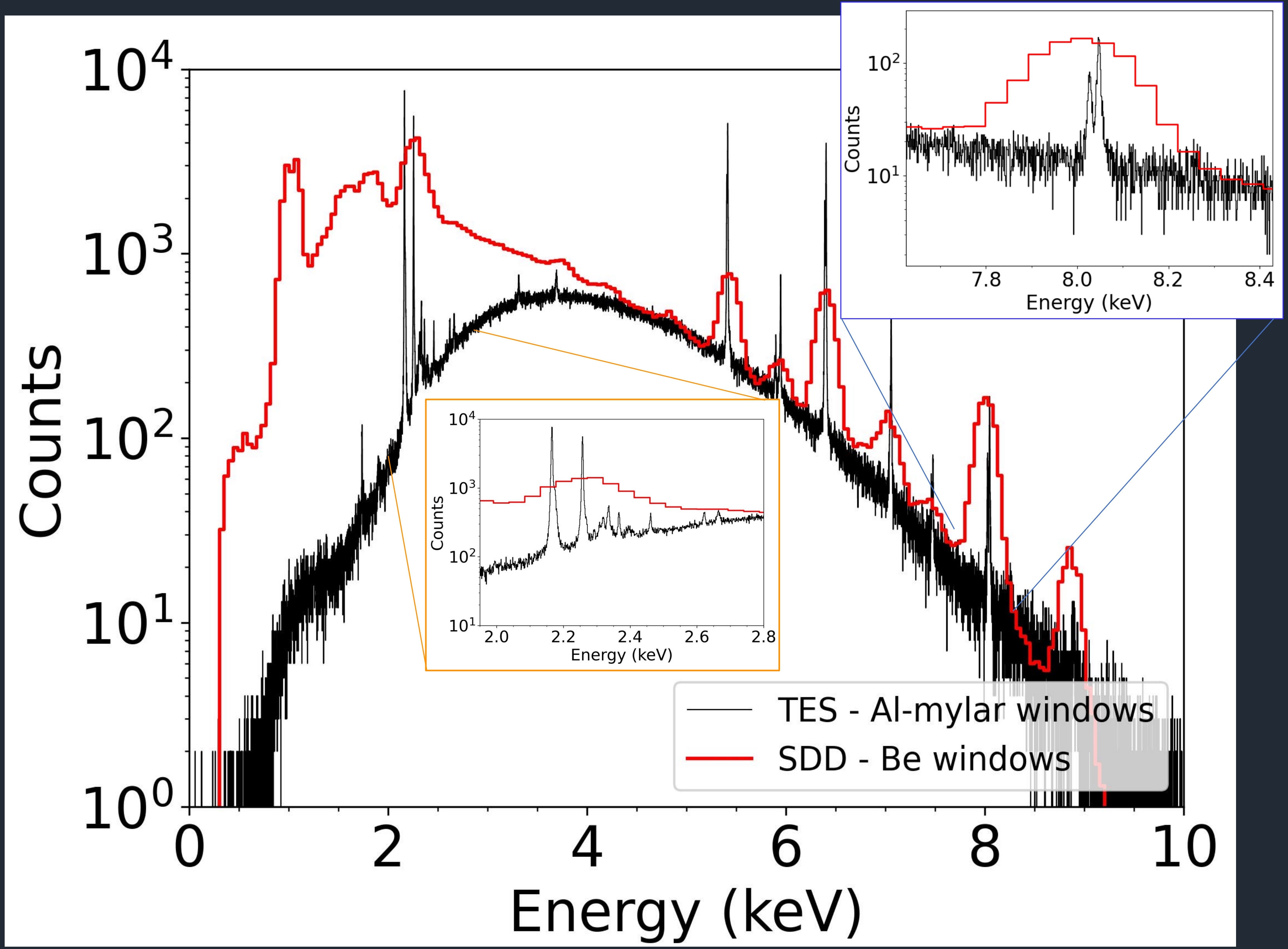


- Many spectral lines are necessary to precisely calibrate TES energy scale
- Athena X-IFU requires energy scale calibration precision < 0.4 eV up to 7 keV
- Rotating Target Source assembled at SRON
- First test activities started + analysis scripts under development

Laboratory high resolution X-ray spectroscopy

- X-ray absorption (XAS),
- X-ray fluorescence (XRF),
- X-ray emission spectroscopy (XES)
- (…)

to measure distribution, chemical state and local structure of elements



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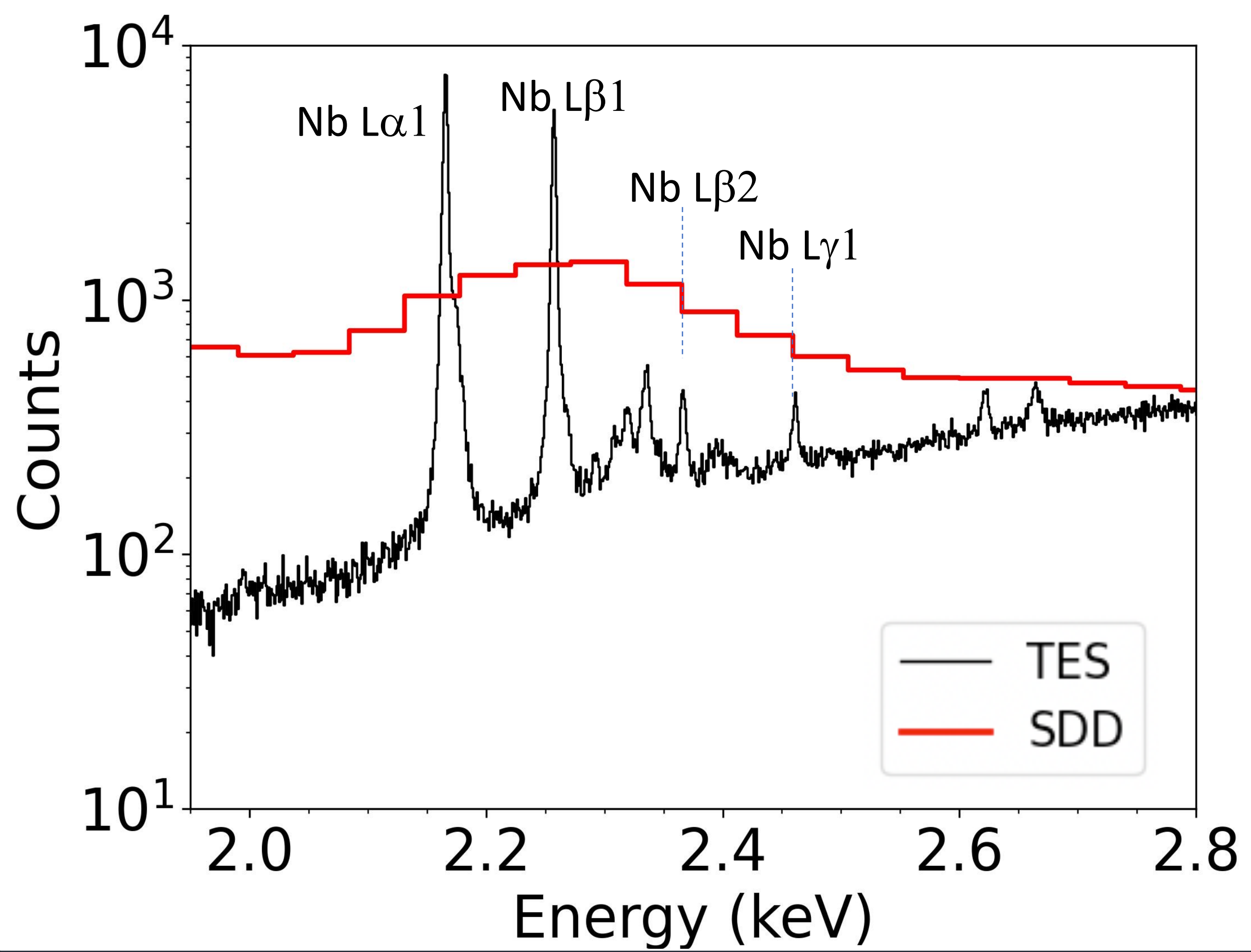
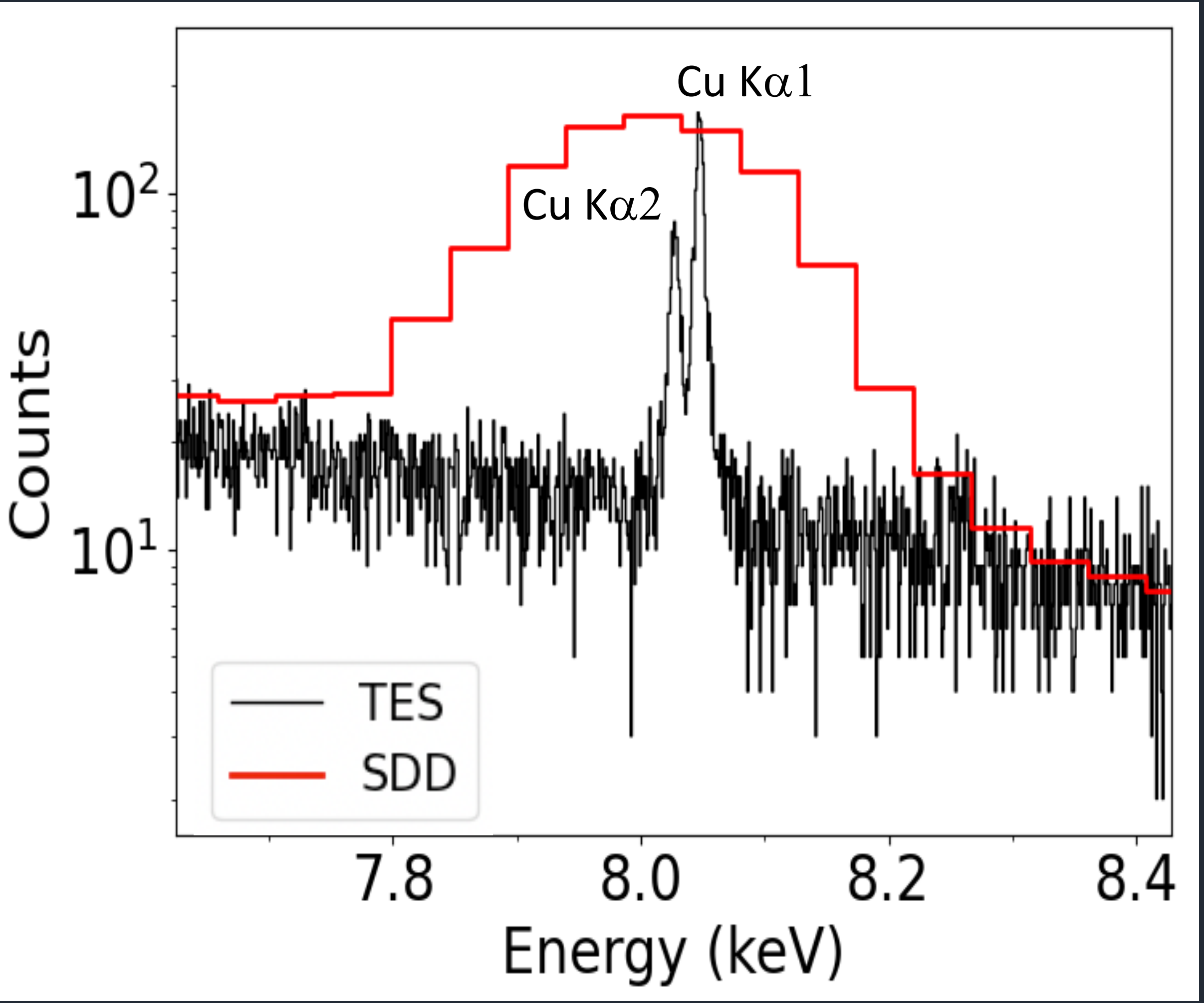
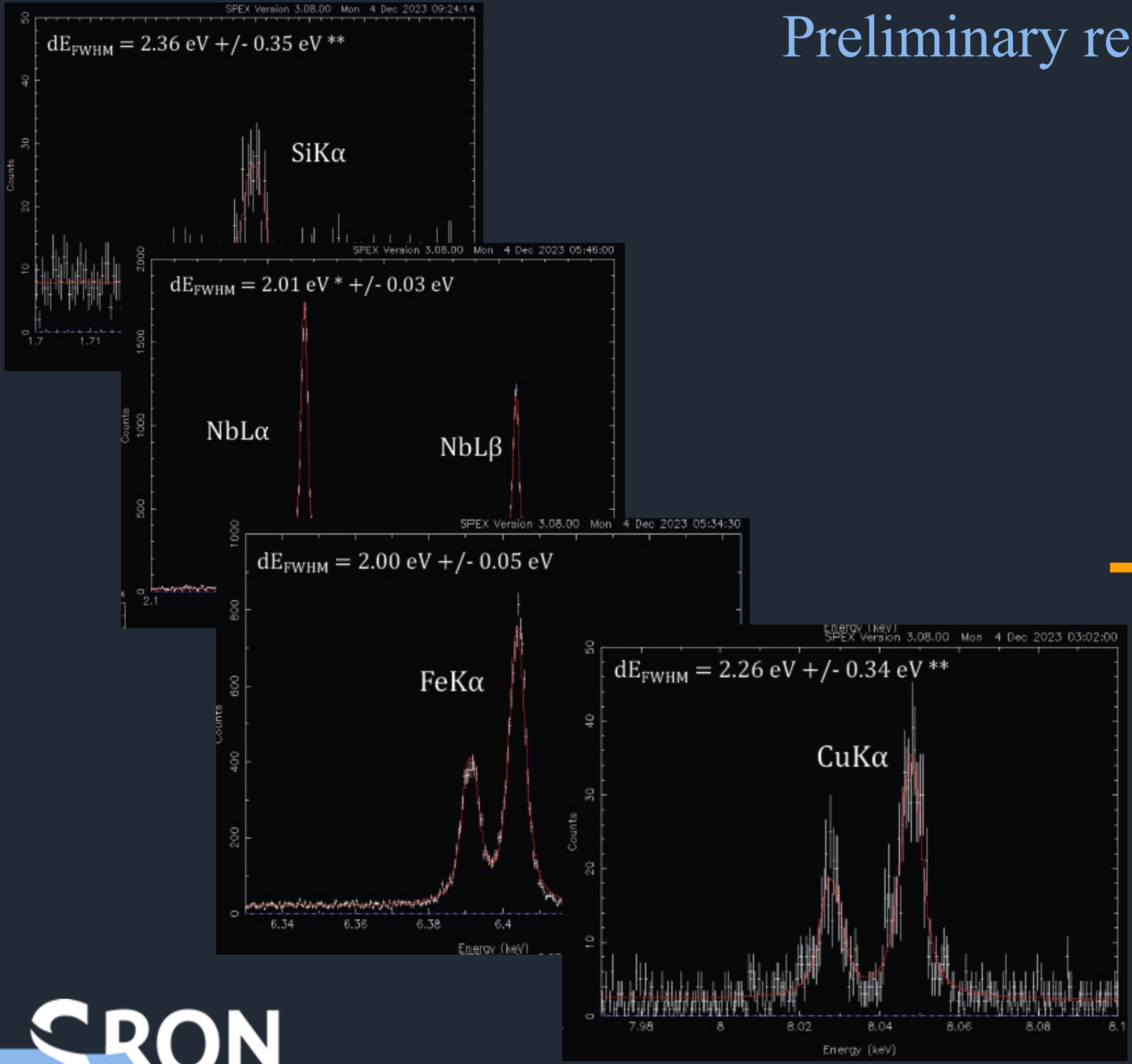
Laboratory high resolution X-ray spectroscopy



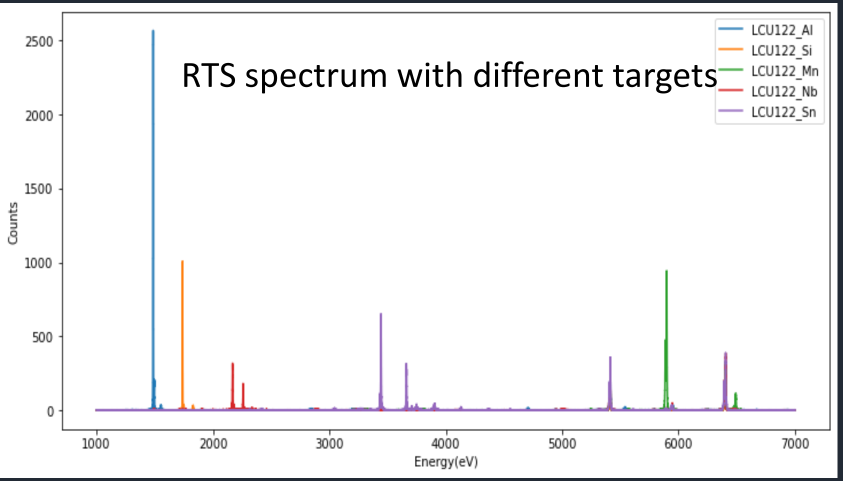


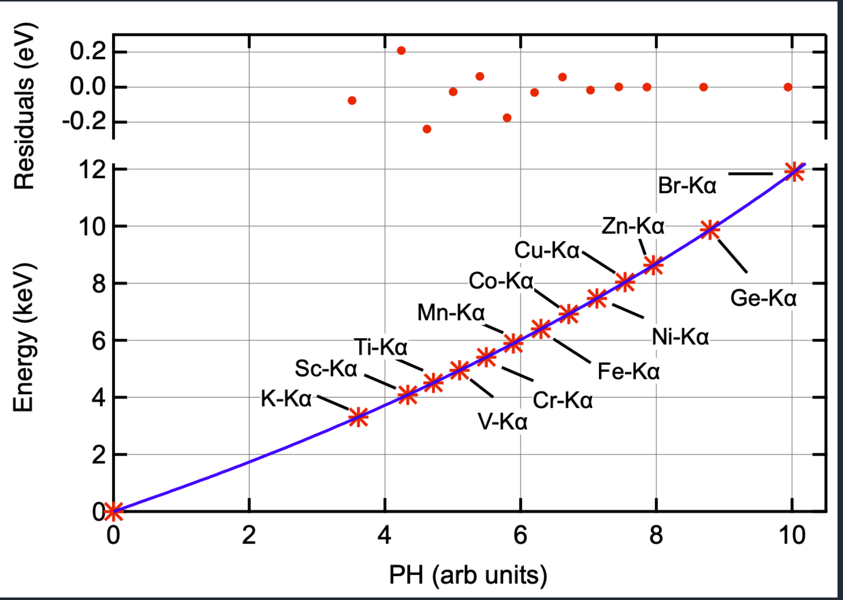
SRON

Preliminary results



Goal

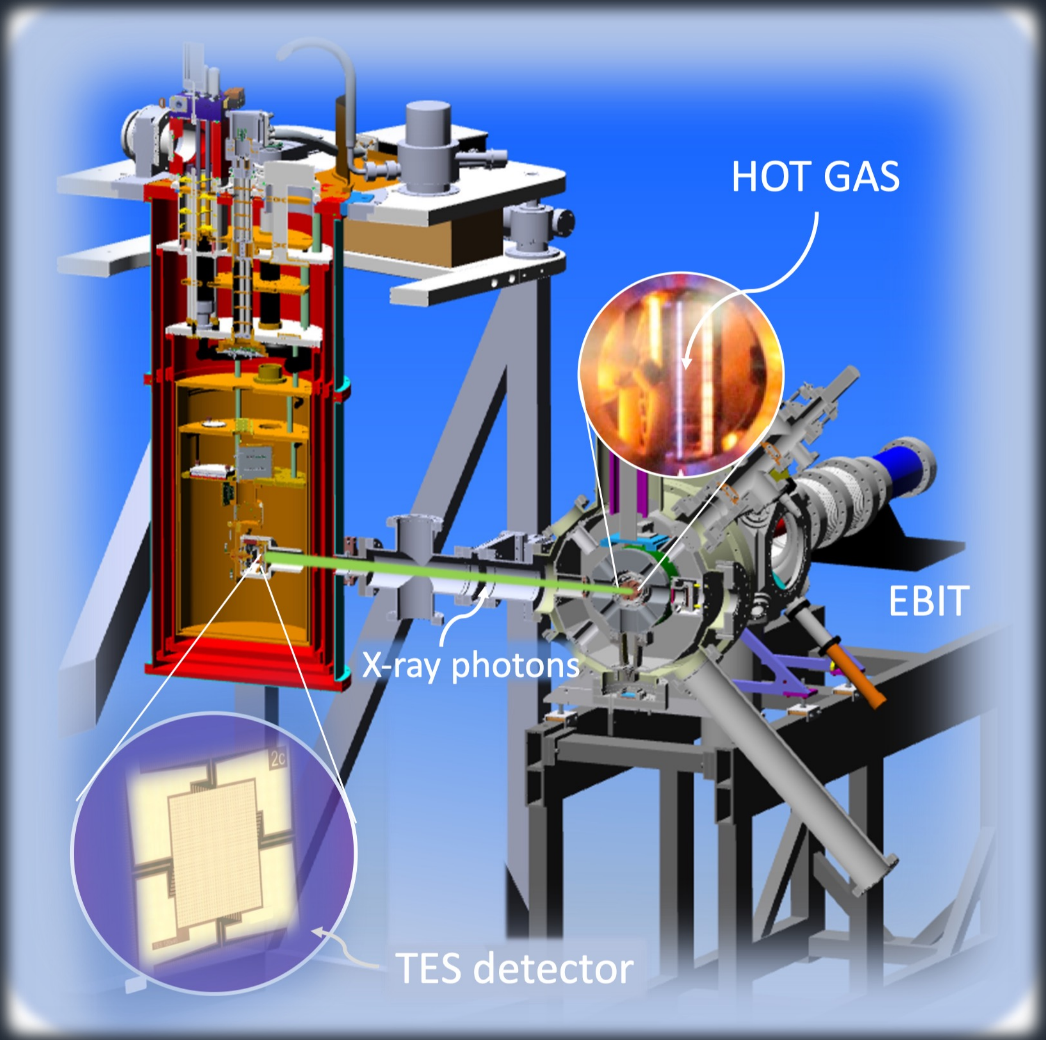




Courtesy: S. Smith, NASA Goddard
L. Gottardi, S. Smith, pre-print arXiv:2210.06617 (2022)

Spectral fits done with SPEX software
https://spex-xray.github.io/spex-help/index.html

SRON TES-FDM system and EBIT



- Temporarily relocate one of the SRON TES systems to the **Electron-Beam Ion Trap** (EBIT) facility at the Max Planck Institute for Nuclear Physics in Heidelberg (Germany) for remote operation during the year 2024
- Obtain atomic knowledge of astronomically relevant atomic species that are difficult to achieve in other facilities
- Tackle issues critical to the XRISM, Athena, LEM science
- Obtain crucial knowledge of calibration issue in X-IFU/Athena and LEM and any other future space missions and ground-based experiments

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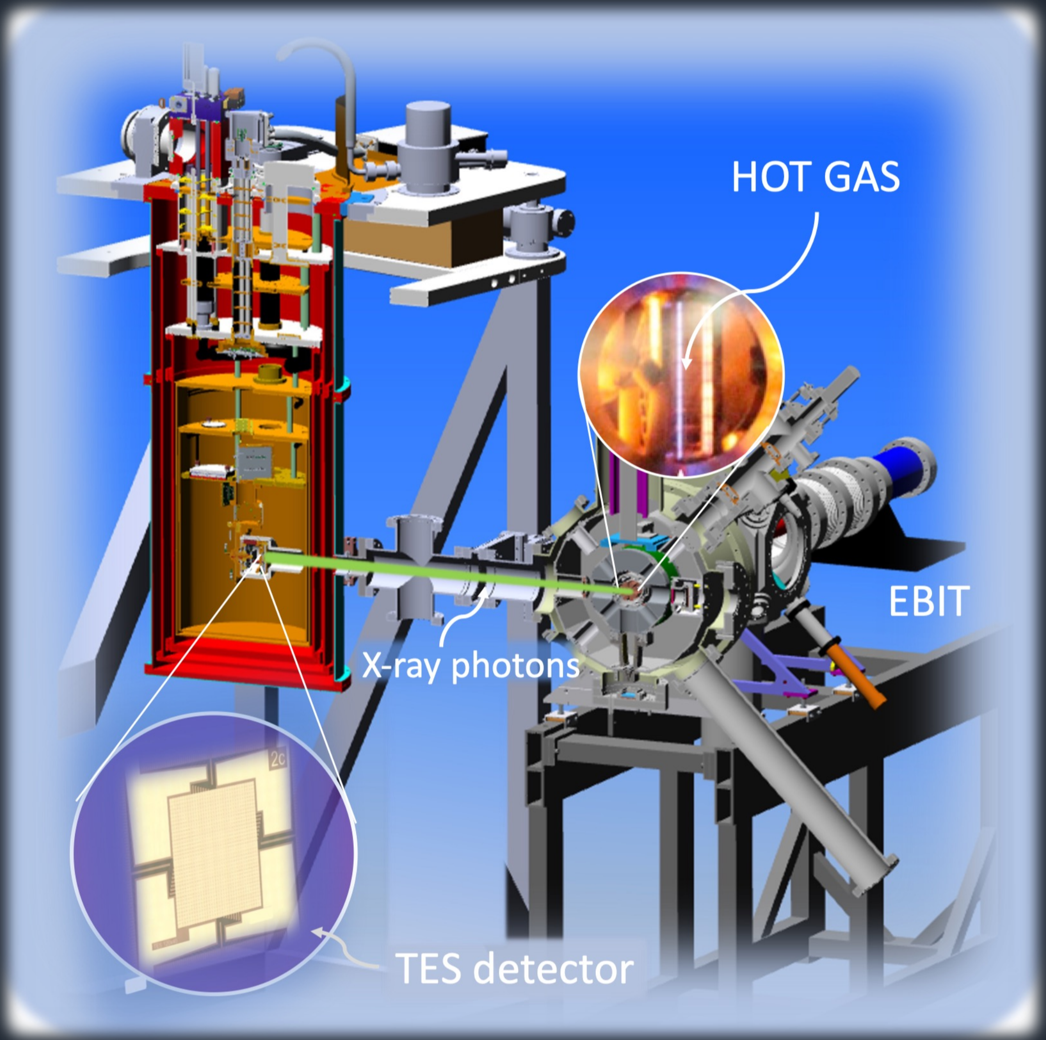
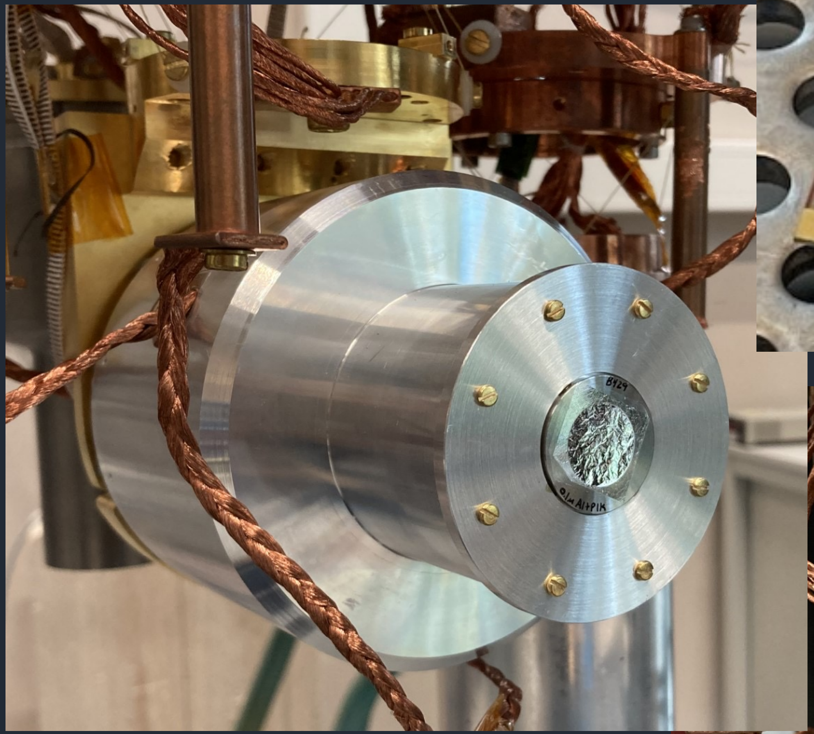
irap astrophysique & planétologie

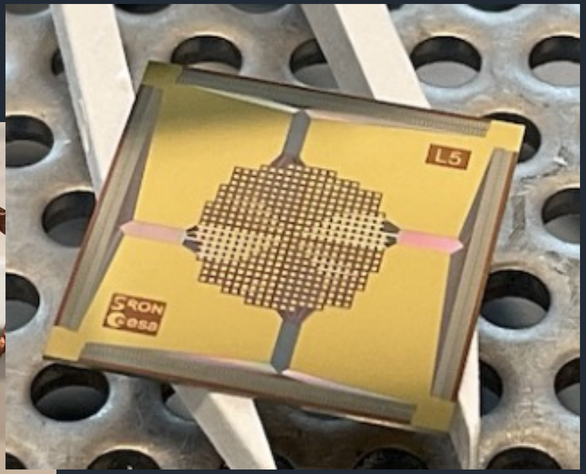
X-IFU ATHENA X-ray Integral Field Unit

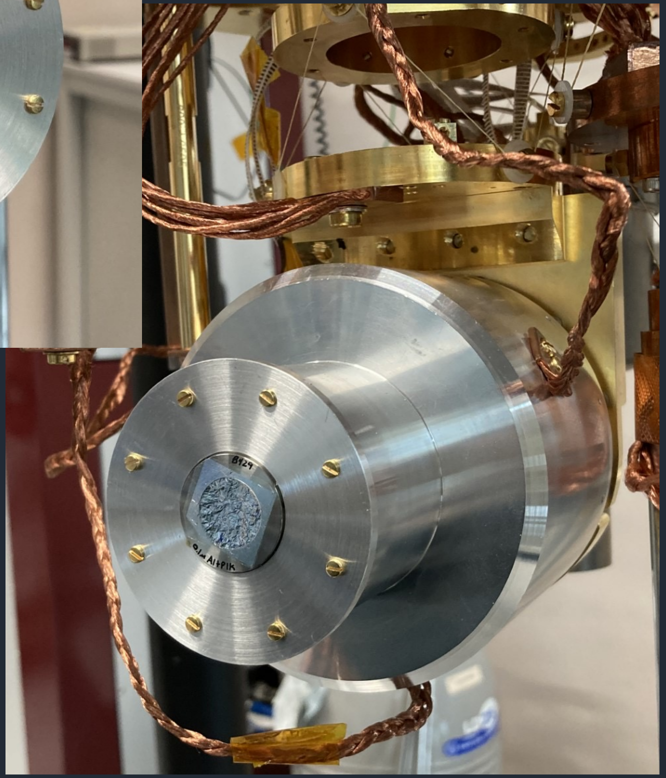
SRON

SRON TES-FDM system and EBIT



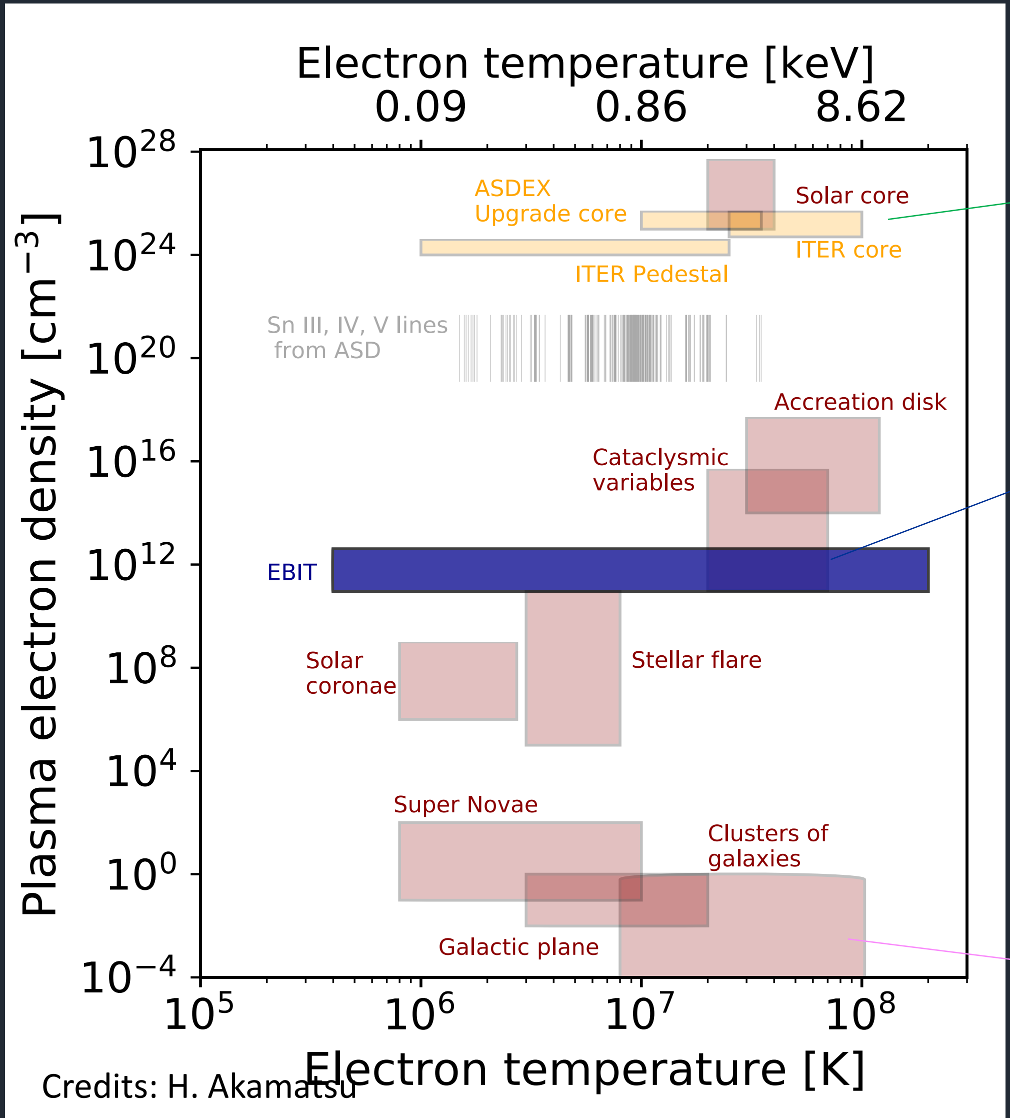


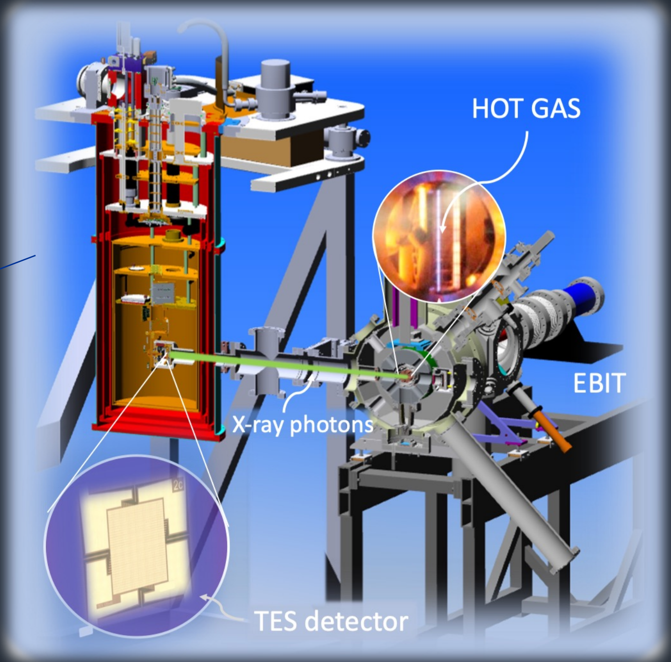




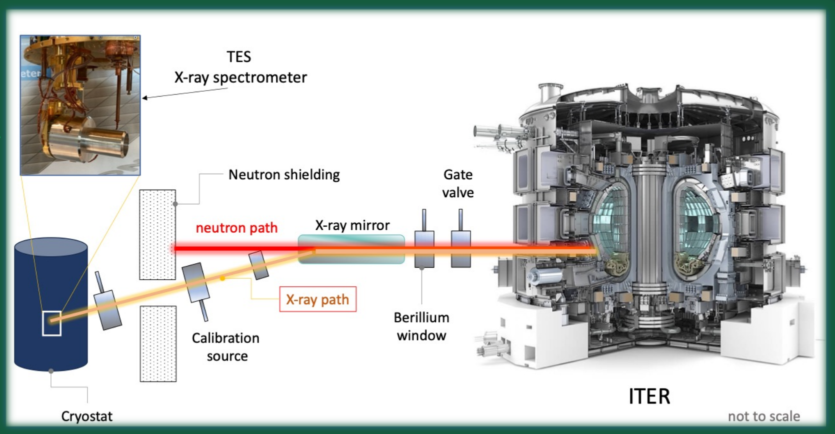
- 2 channels FDM system
- 40 pixels MUX factor
- Total of about 80 pixels
- dE < 1eV resolution at E<2 keV

TES X-ray microcalorimeters + plasma sources



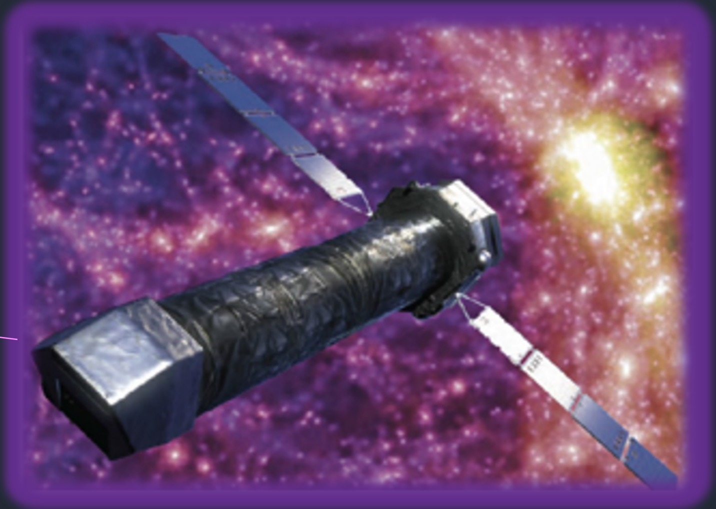


SRON TES+EBIT 2024



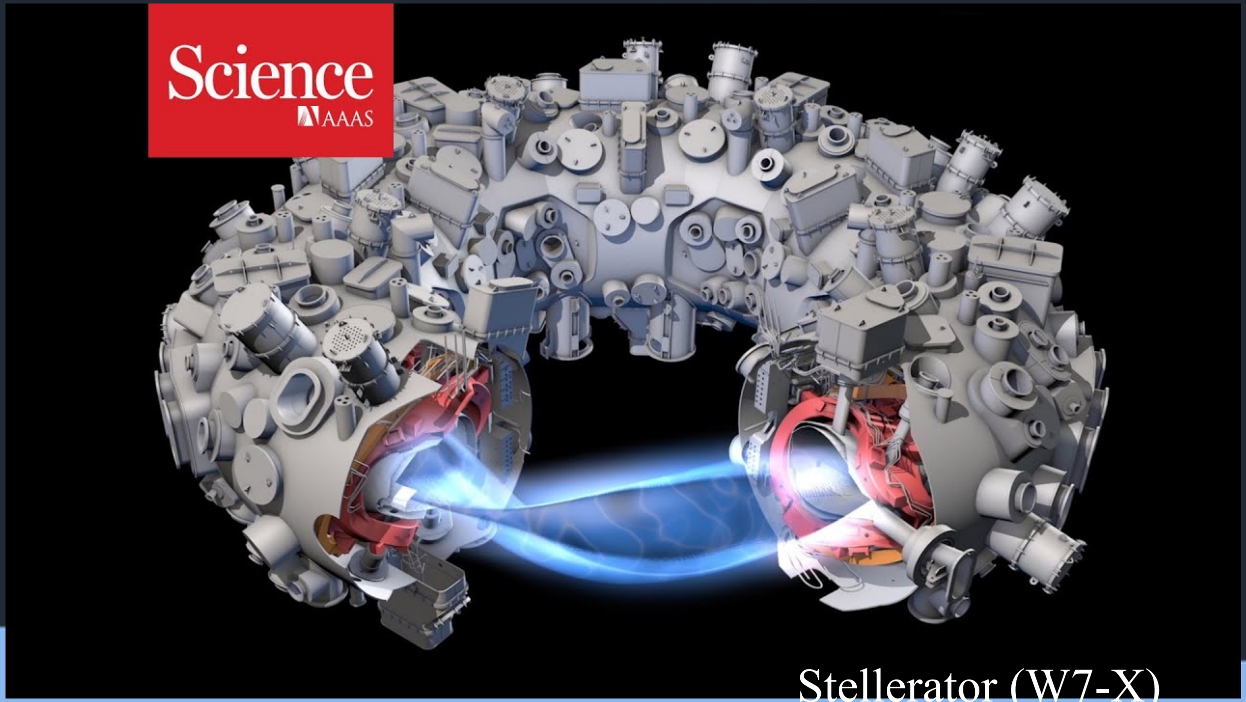
Tokamaks or Stellerator (?)

Athena 2035+

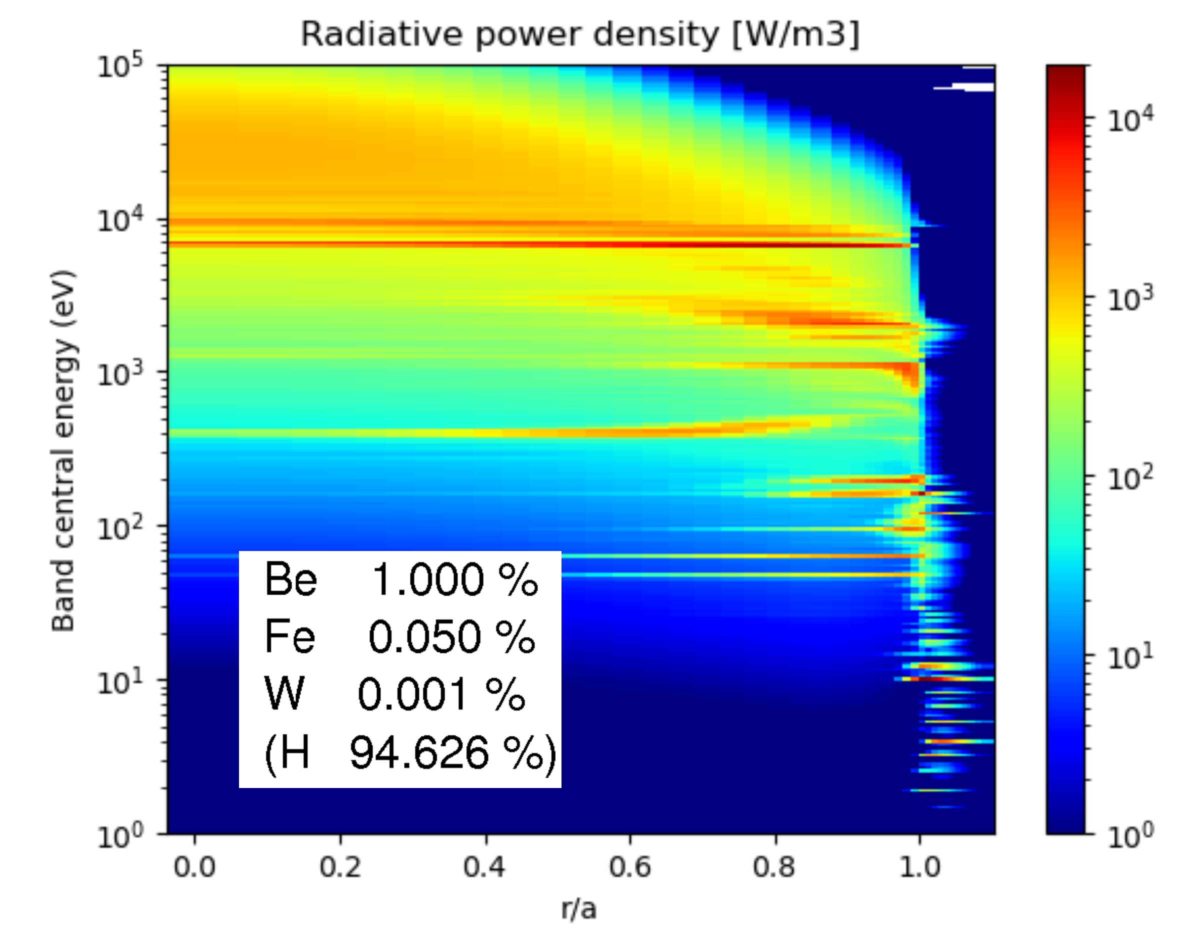


SRON

TES X-ray microcalorimeters for fusion plasma physics

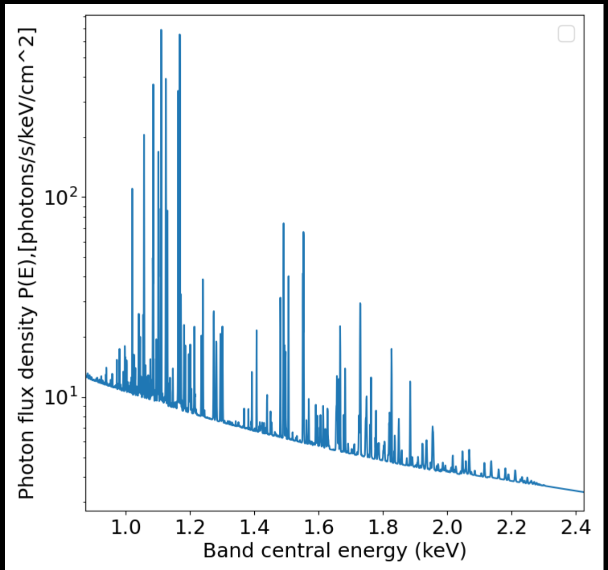


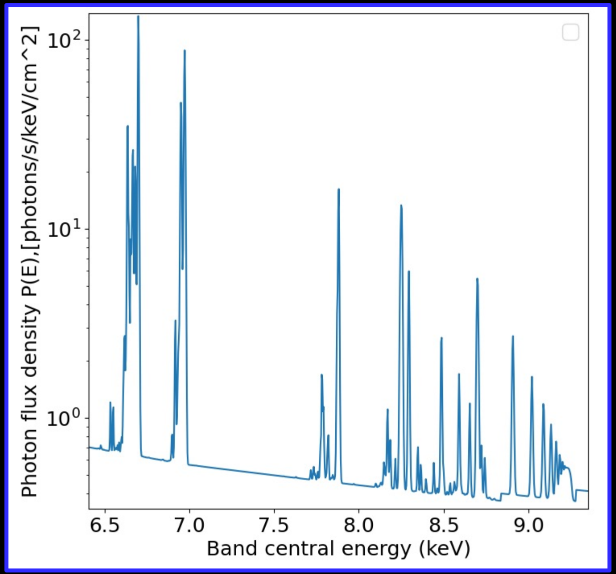
Courtesy: ITER



Beiersdorfer et al. RSI 81,10EE323 (2010)
M. Eckart et al. Rev. Sci. Instrum., 92, 063520 (2021)

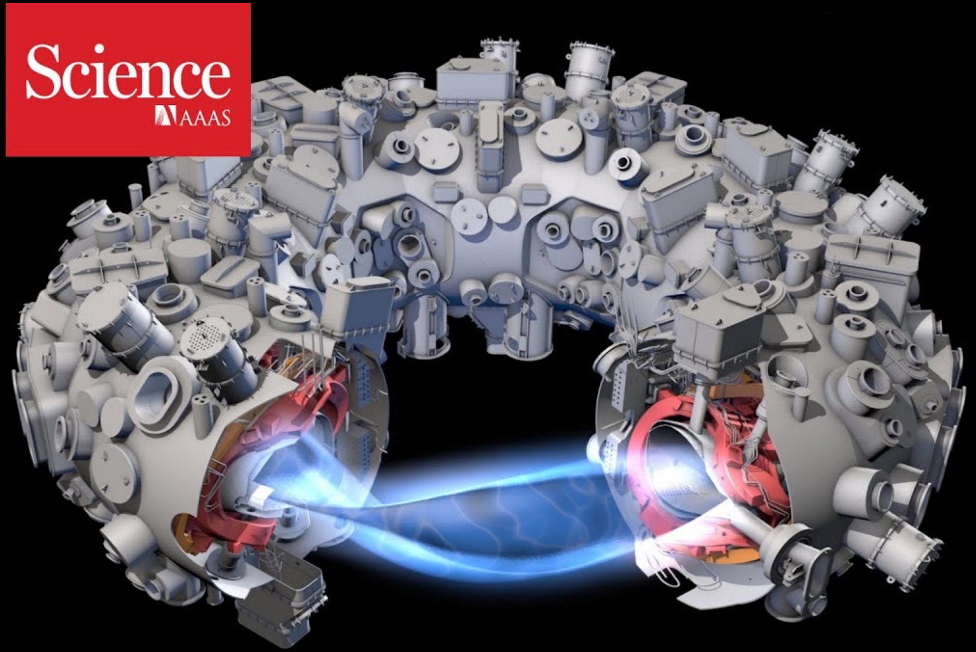
TES X-ray microcalorimeters for fusion plasma physics





- A XIFU-like X-ray spectrometer could be used for diagnostic purpose in fusion plasmas.

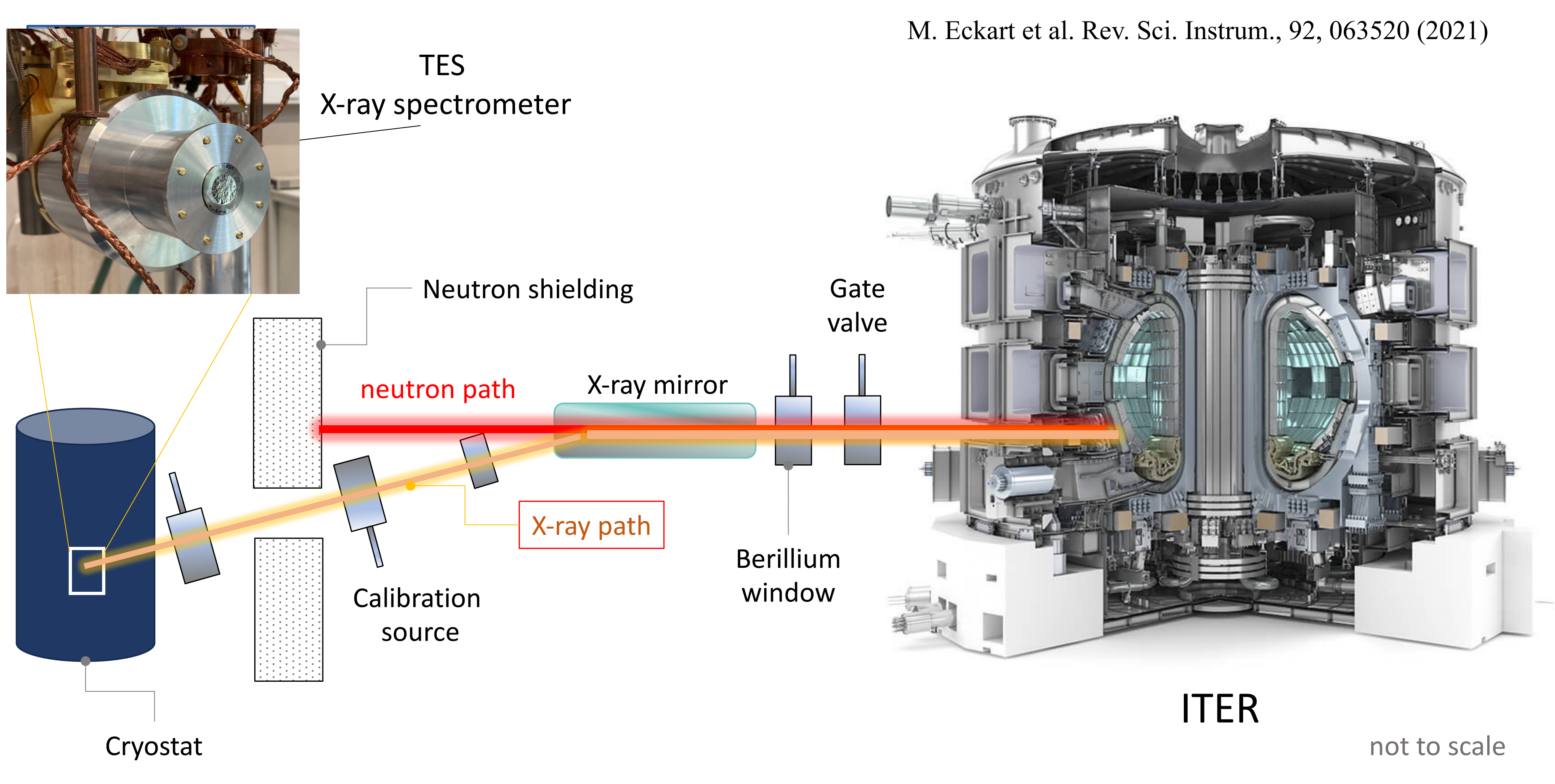
~2000 pixels , dE ~ 3-5 eV,
Count-rate capability ~1Mcts/s



Stellerator (W7-X)

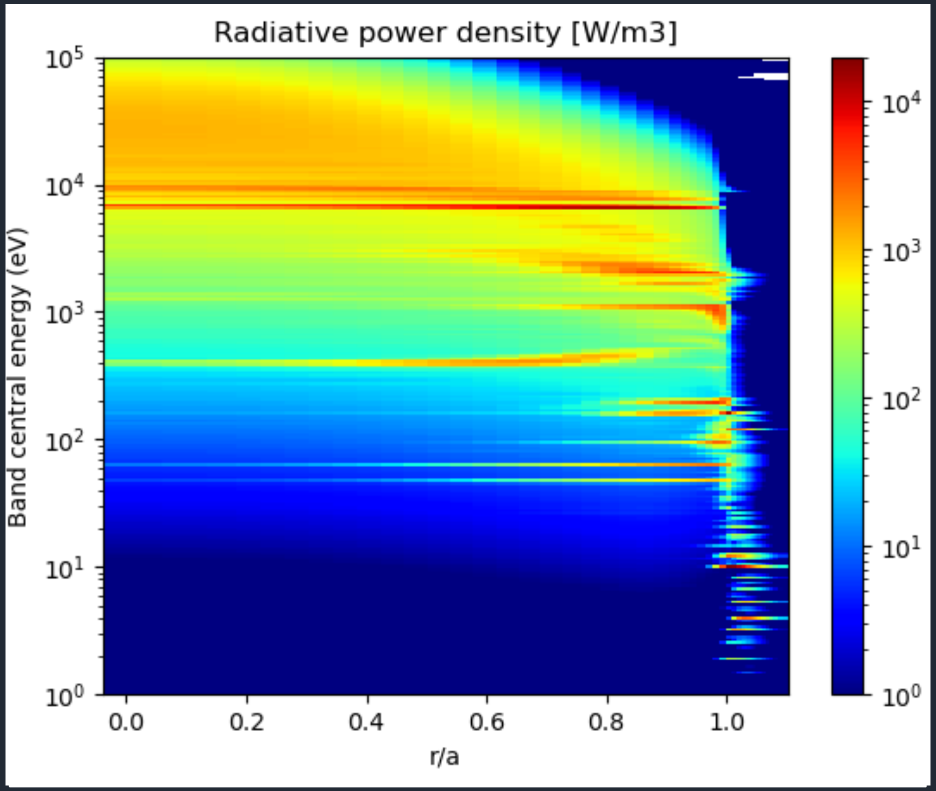
Beiersdorfer et al. RSI 81,10EE323 (2010)
M. Eckart et al. Rev. Sci. Instrum., 92, 063520 (2021)

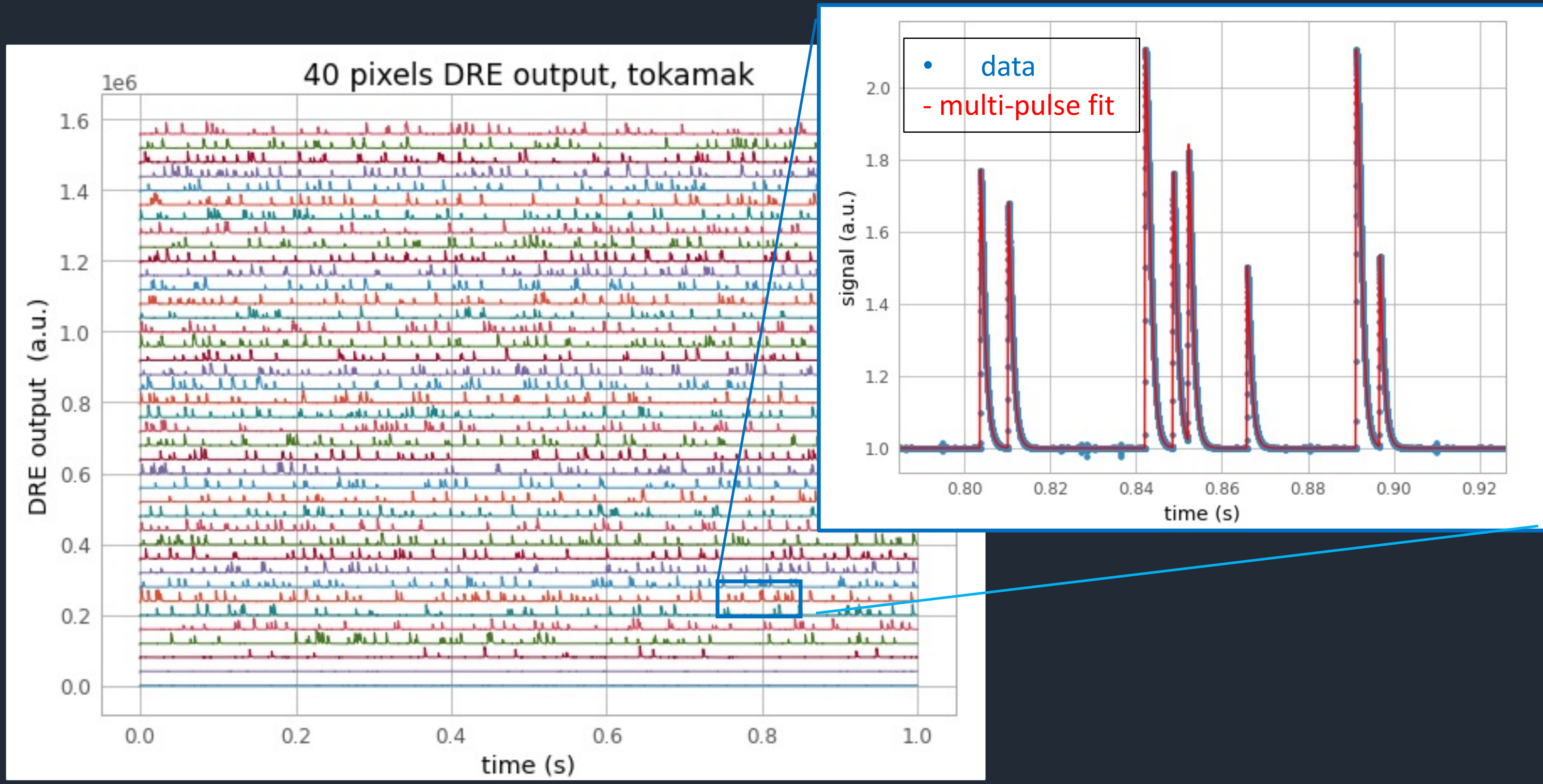
TES X-ray microcalorimeters for fusion plasma physics



- Rising interest in the plasma physics community in TES based X-ray spectrometers
- SRON, DIFFER and TU/e: a feasibility study for the use of TESs at tokamak facilities in Europe
- A XIFU-like X-ray spectrometer could be used for diagnostic purpose at ITER/DEMO.

End-to-end simulation





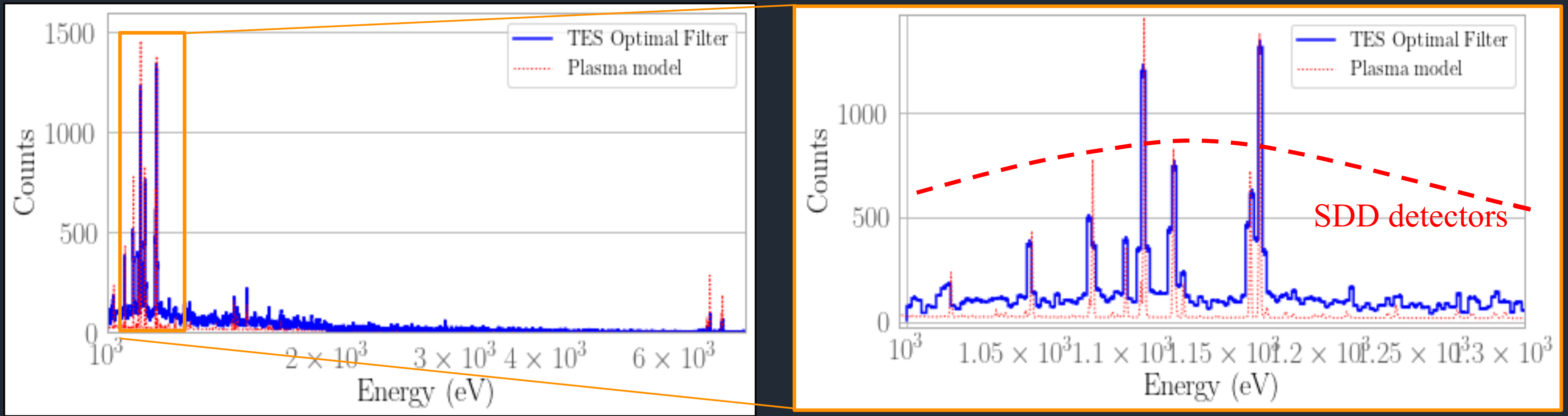
- We use the end-to-end simulator [1] developed for XIFU/Athena to simulate the TES array response to the X-ray radiation expected from the ITER fusion plasma [2]
- **INPUT** : the radiated power profile as a function of energy and plasma radius for the standard ITER scenario without W impurities: Te(0)~25keV, Ne(0)~10^{20}m^{-3}.
- **OUTPUT**: X-ray pulses from a 40 pixels FDM set-up

[1] T. Dauser *et al*., A&A 630, A66 (2019)
[2] Y Gribov. '15MA plasma of inductive scenario at burn (2V2XYR v1.4)' (2010). Available from: https://user.iter.org/?uid=2V2XYR

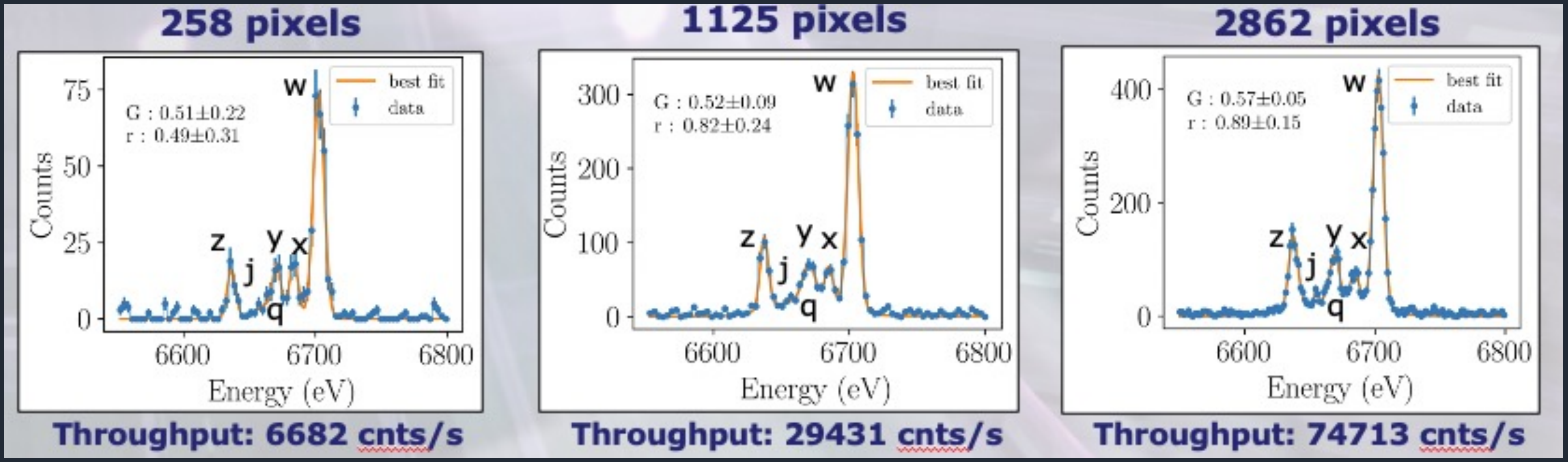
SRON DIFFER

Results from 1 sec data stream

- Broadband high-resolution energy spectrum



- Diagnostic capability using Fe^{+24}



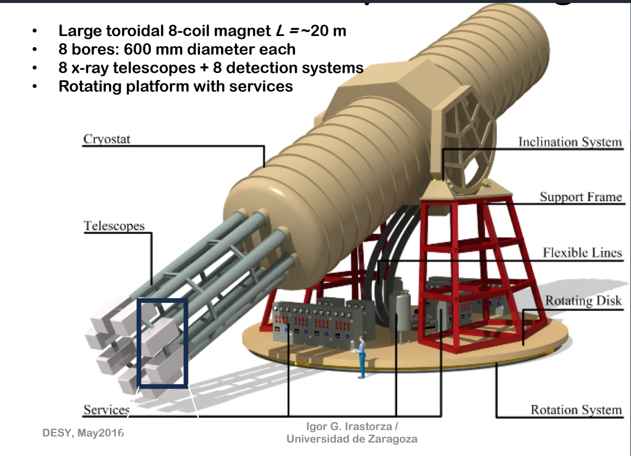
- We used the Fe^{+24} w,z,y,x,q,j lines (6700.4, 6636.6, 6667.57, 6682.33, 6661.94 and 6644.45 eV) to extract plasma density and temperature information as a function of the instrument pixels number

- Other lines at lower energy (Fe-L lines 0.7-0.8 keV) can be used in a similar fashion for the diagnostics

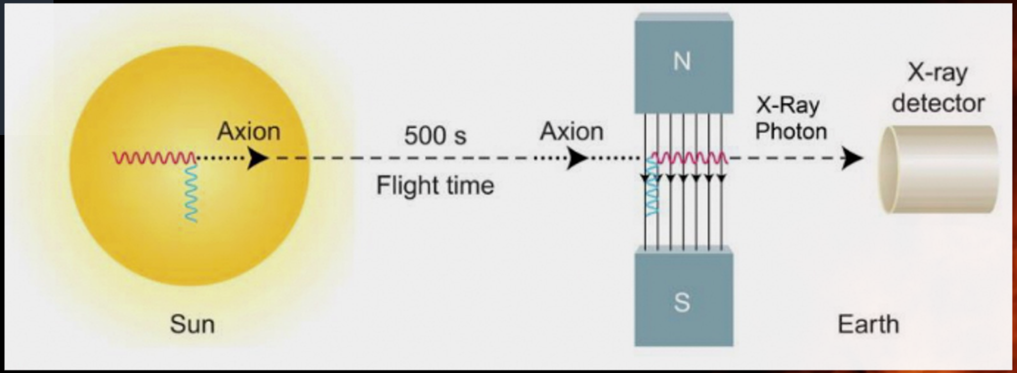
- Simulation performed with XIFU-like pixels at moderate countrate. The detector throughput can be increase of 10 to 20 times with an optimized pixel design

SRON DIFFER

TES X-ray microcalorimeters for solar axion search

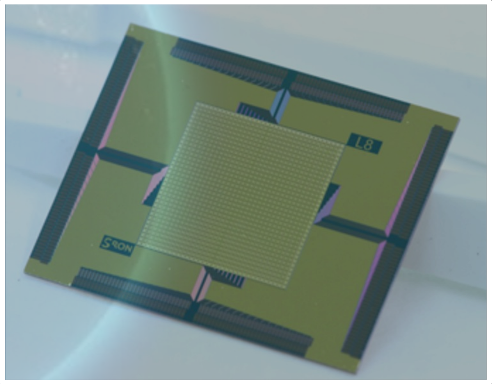


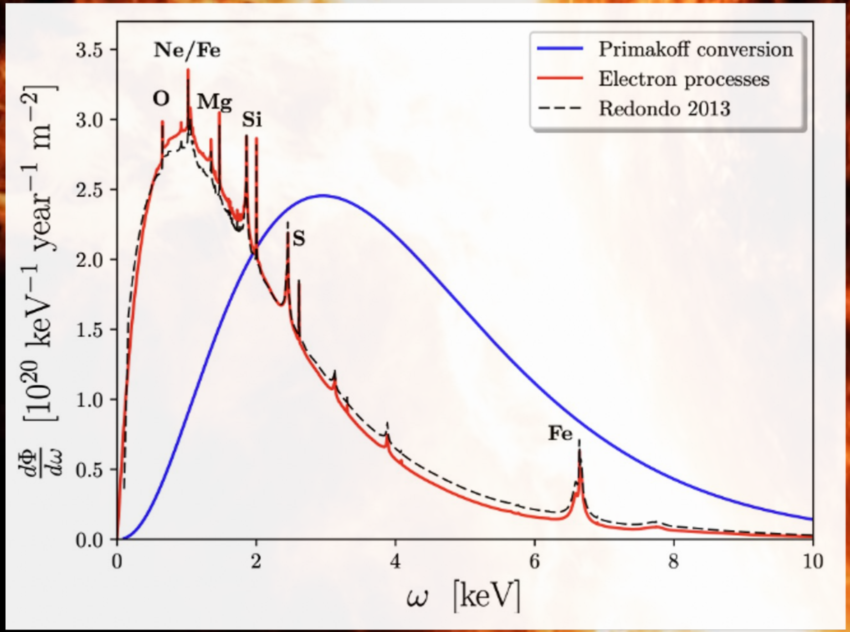
https://iaxo.web.cern.ch



R. Battesti et al., Physics Reports 765-766(15), 2018

axions

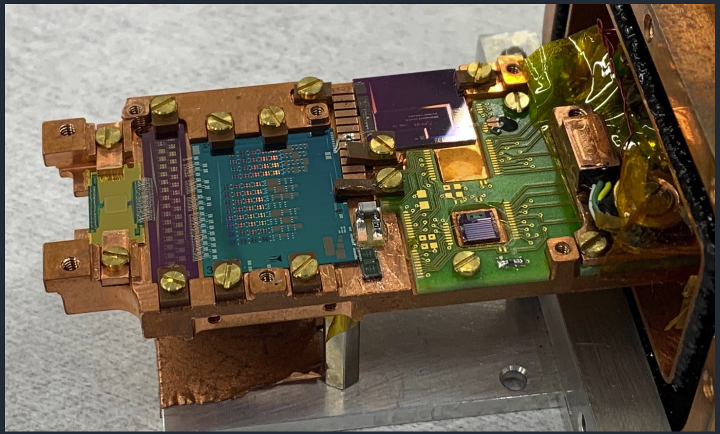




Ultra low background TES X-ray spectrometers

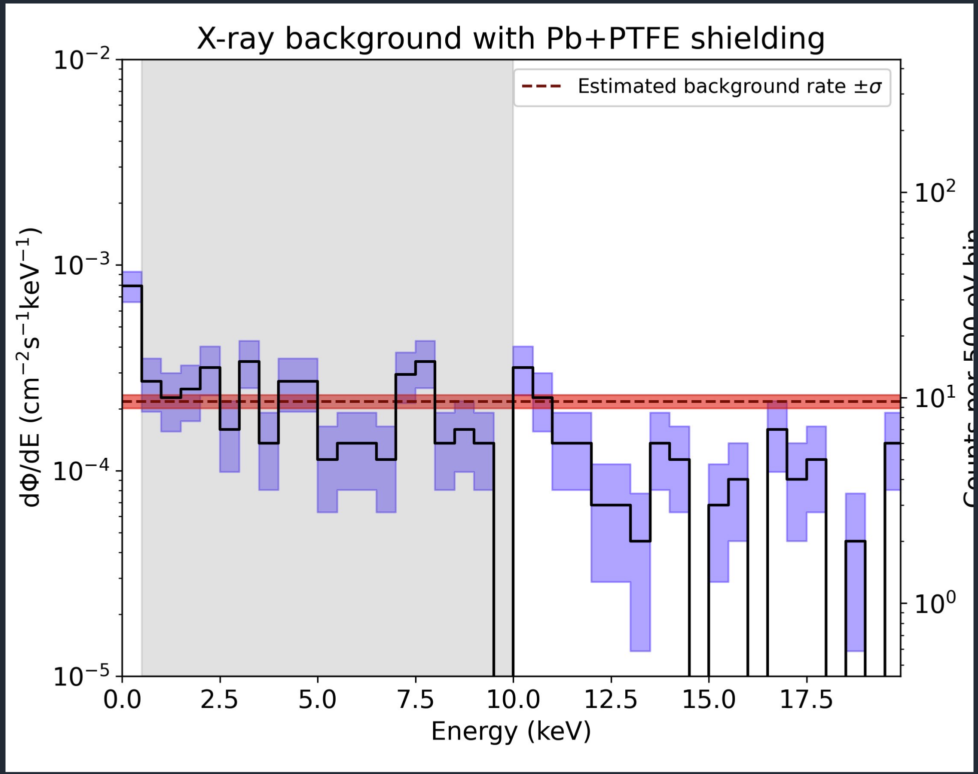
D. Vaccaro et al. RSI,94,4 (2023)

TES X-ray microcalorimeters for solar axion search



Detector technology should have:

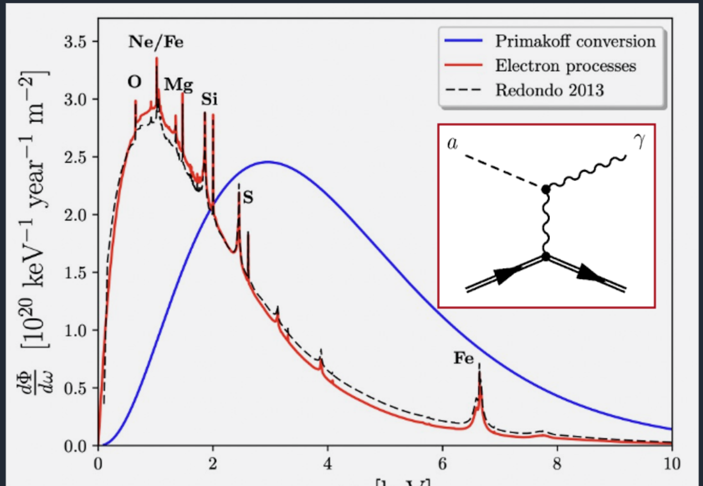
- Large quantum efficiency and effective counting area
- High-resolution spectrometer in 1-10 keV region
- Extremely low background requirement: < 10^{-7} $keV^{-1}cm^{-2}s^{-1}$ (ref. BabyIAXO)
- Proof-of-concept experiment @ SRON w/ sub-optimal setup + makeshift shielding



Summary

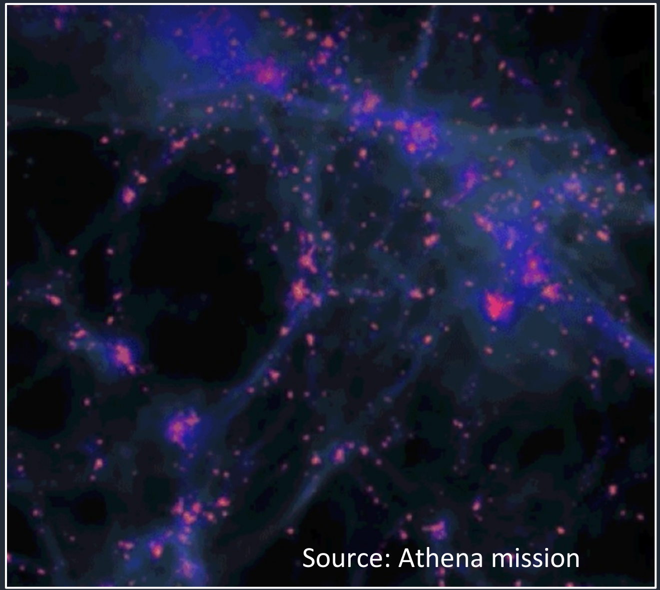
- X-ray imaging spectrometers based on large array of superconducting transition edge sensors perform at very high resolving power in a wide energy range (0 eV - 20keV)
- They have achieved high level of technological maturity to be used on real instruments
- They can be used in a wide variety of space and ground-based applications

Low background experiments
very very few photons



Source: IAXO/DESY

X-ray telescopes
some photons


Source: Athena mission

Fusion plasma
many photons

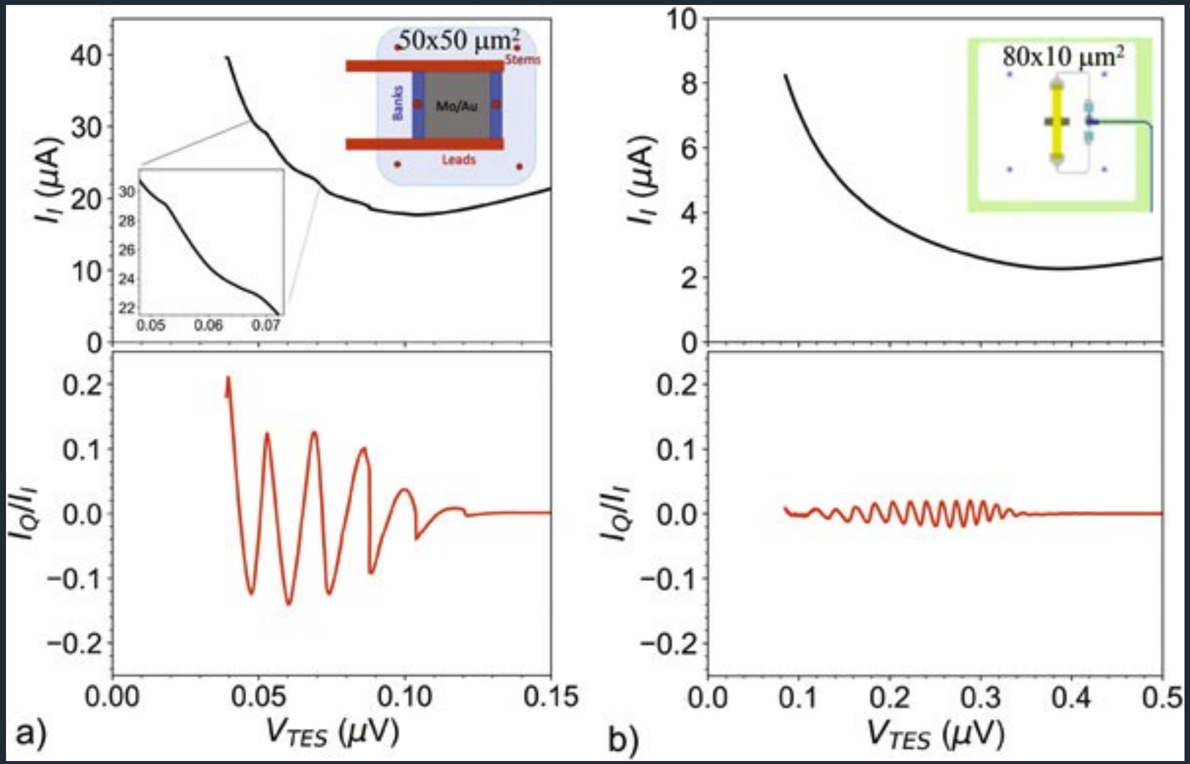

Source: IAEA International Atomic Energy Agency

Detector design optimization for AC or DC biasing

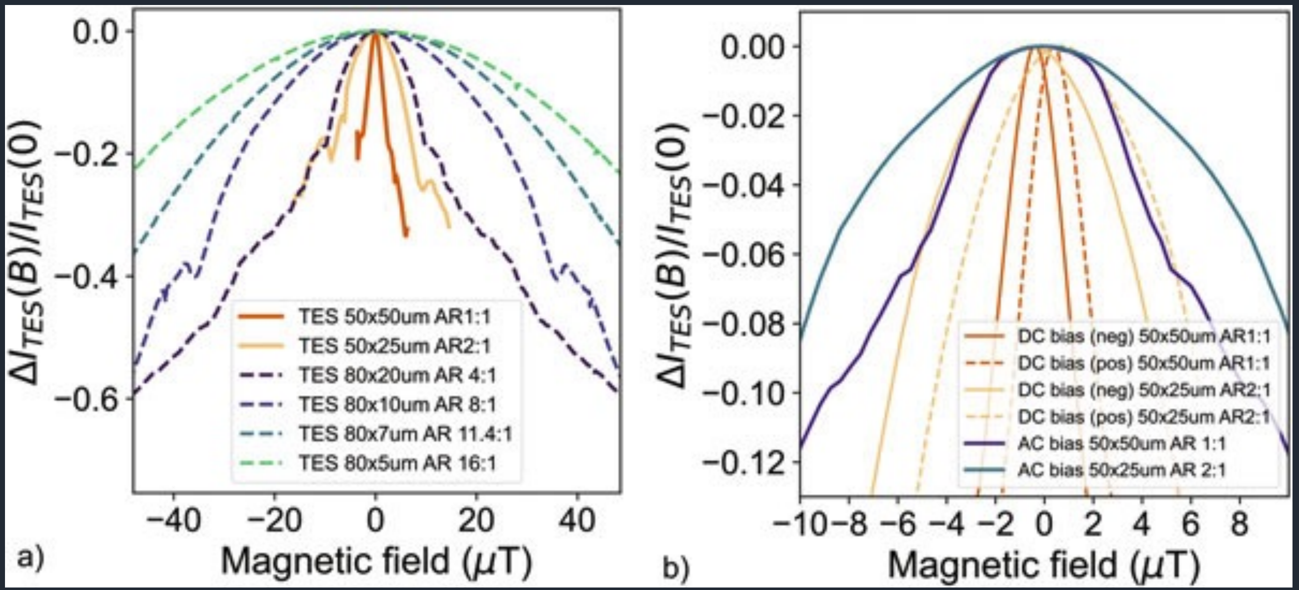
$$J_J(t) = J_c(T)\sin\left[\frac{2eV_{dc}}{\hbar}t + \frac{2eV_{pk}}{\hbar\omega_0}\sin\omega_0 t + 2\pi\frac{A_{\text{eff}}(B_{\perp,DC} + B_{\perp,AC}(t))}{\Phi_0}\right]. \quad (17)$$

$$\varphi \propto \sqrt{P_J R}/f_{\text{bias}}$$

with higher R_N, operating at the same power P_J, the gauge invariant phase difference across the Josephson weak-link is maximized



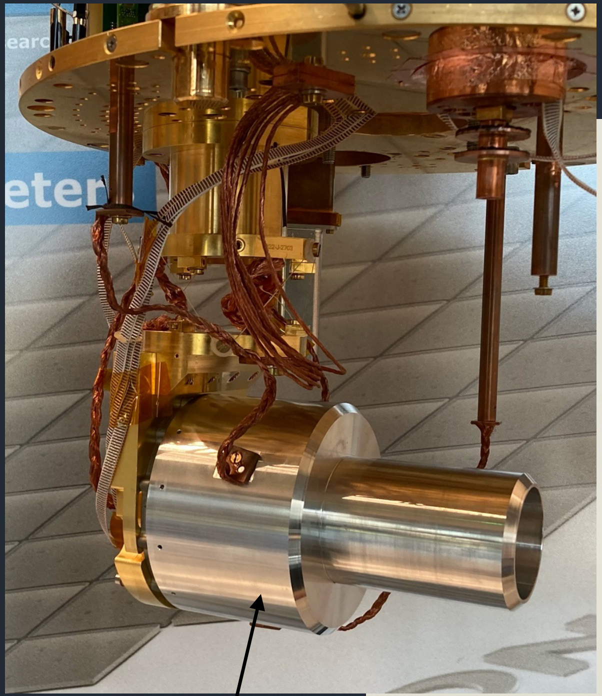
f_{bias}= 4 MHz, P= ~2 pW



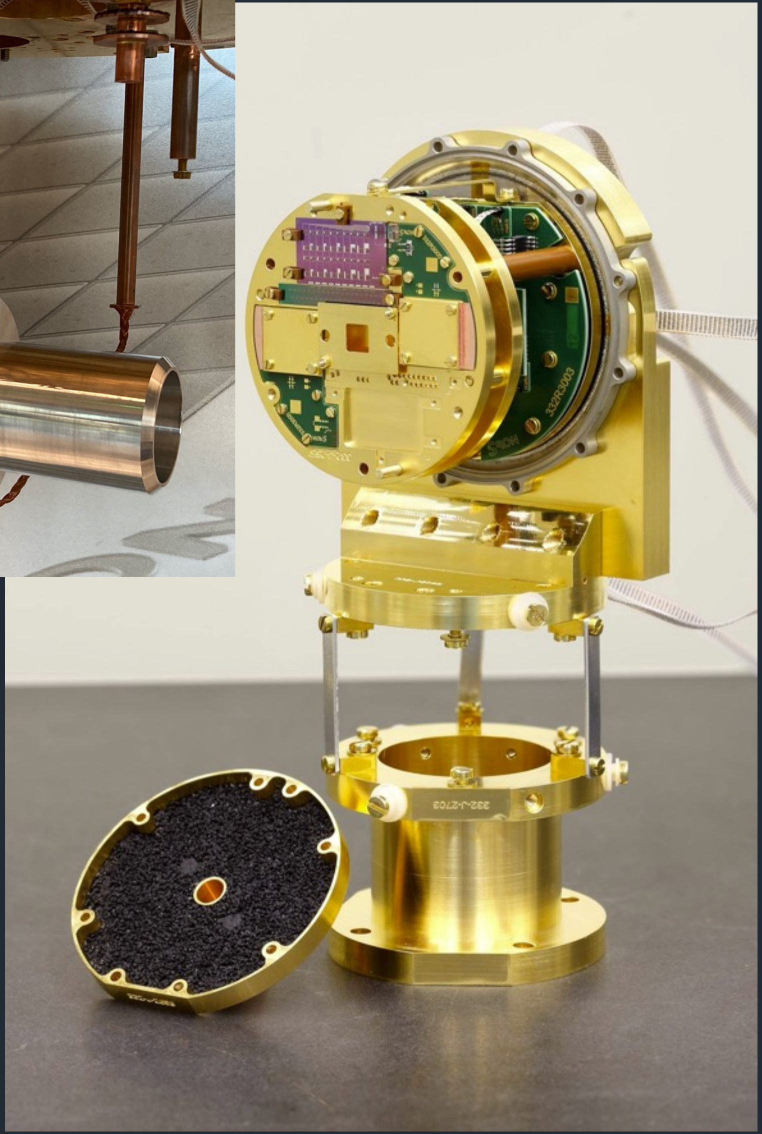
L. Gottardi, S. Smith, pre-print arXiv:2210.06617 (2022)

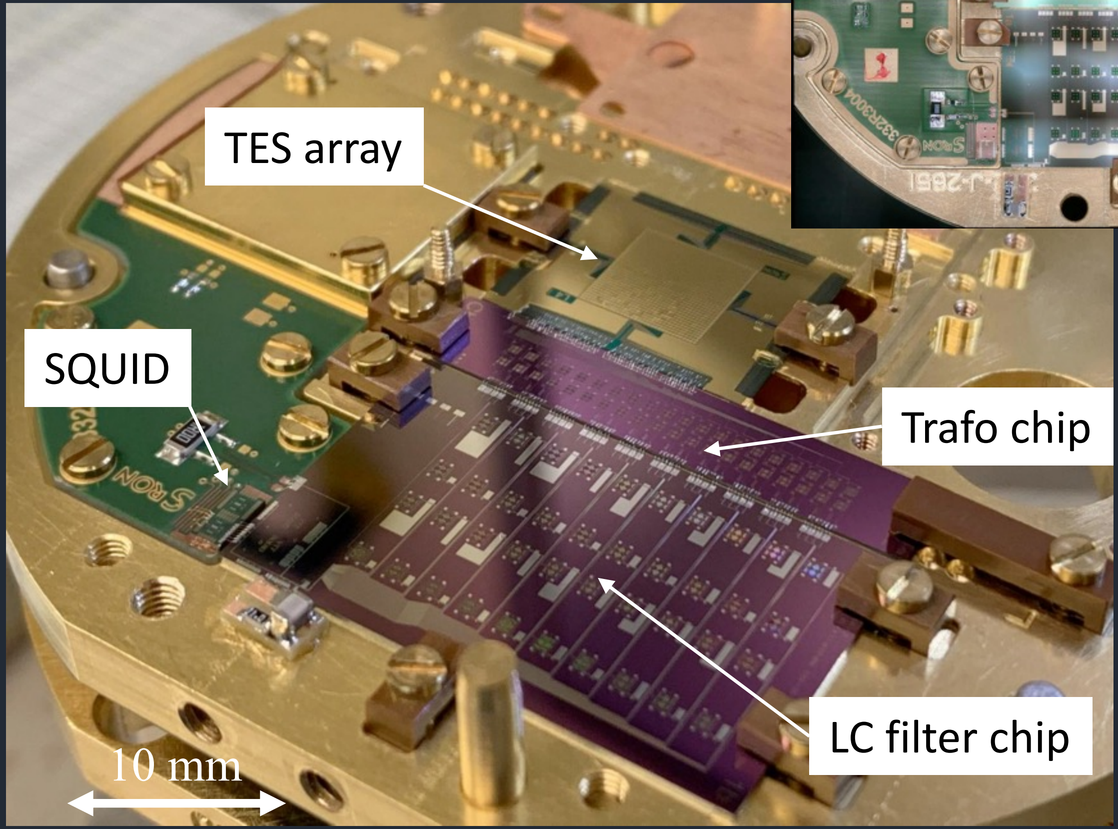
SRON

40 pixels FDM demonstrator

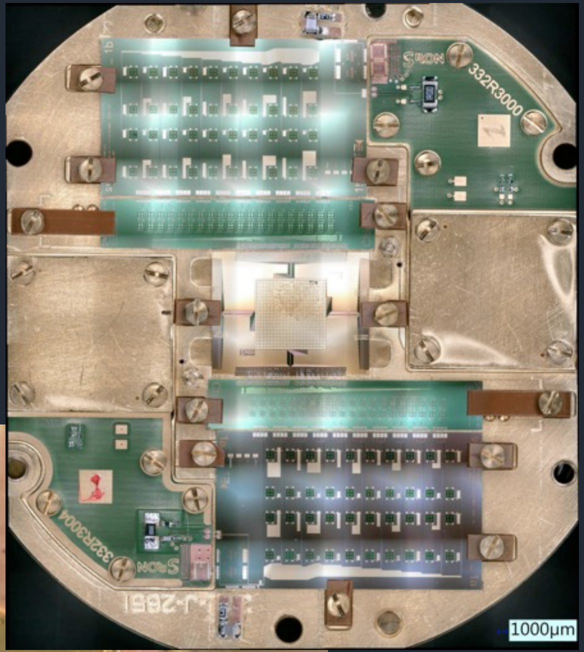


Superconducting shield

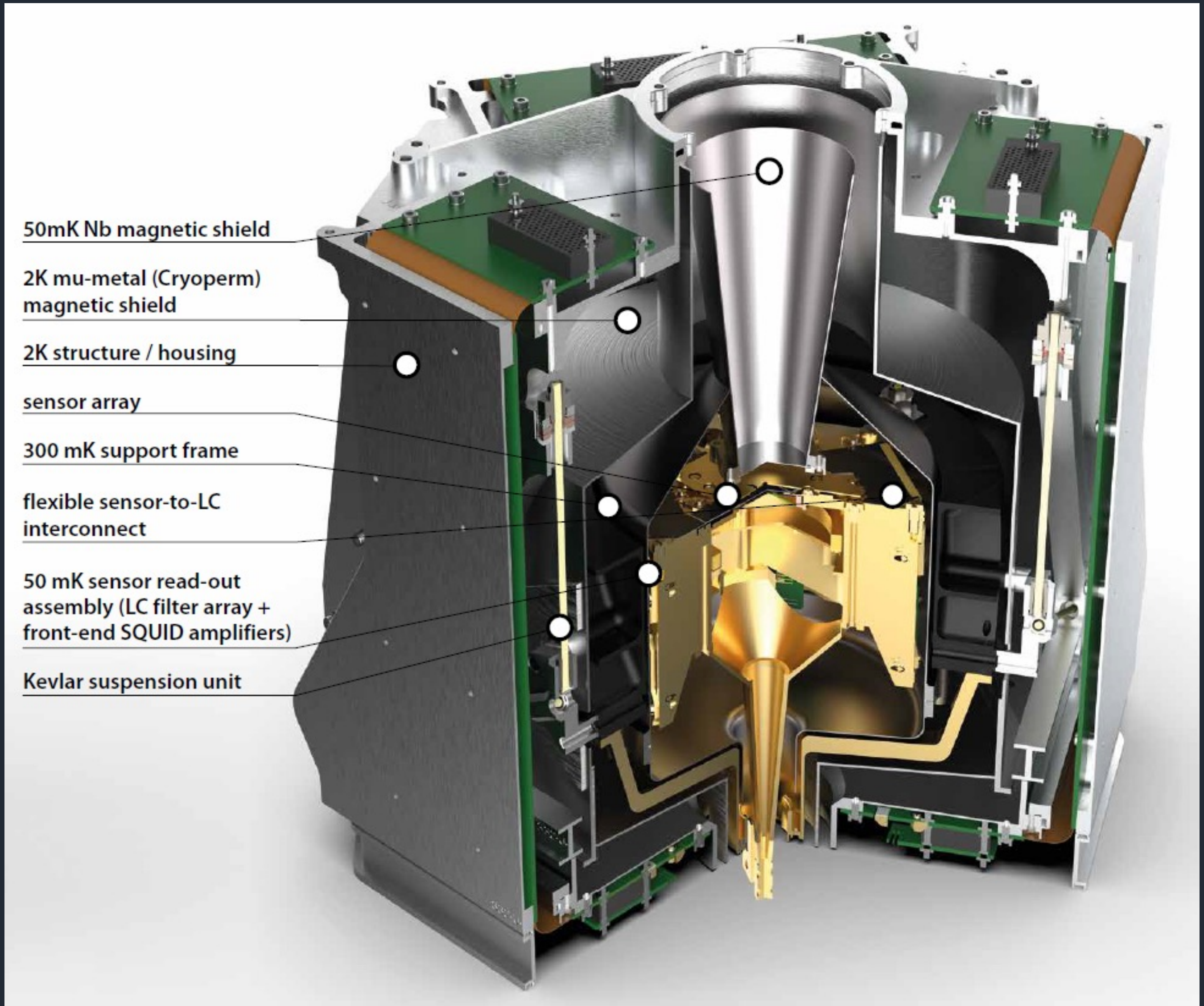


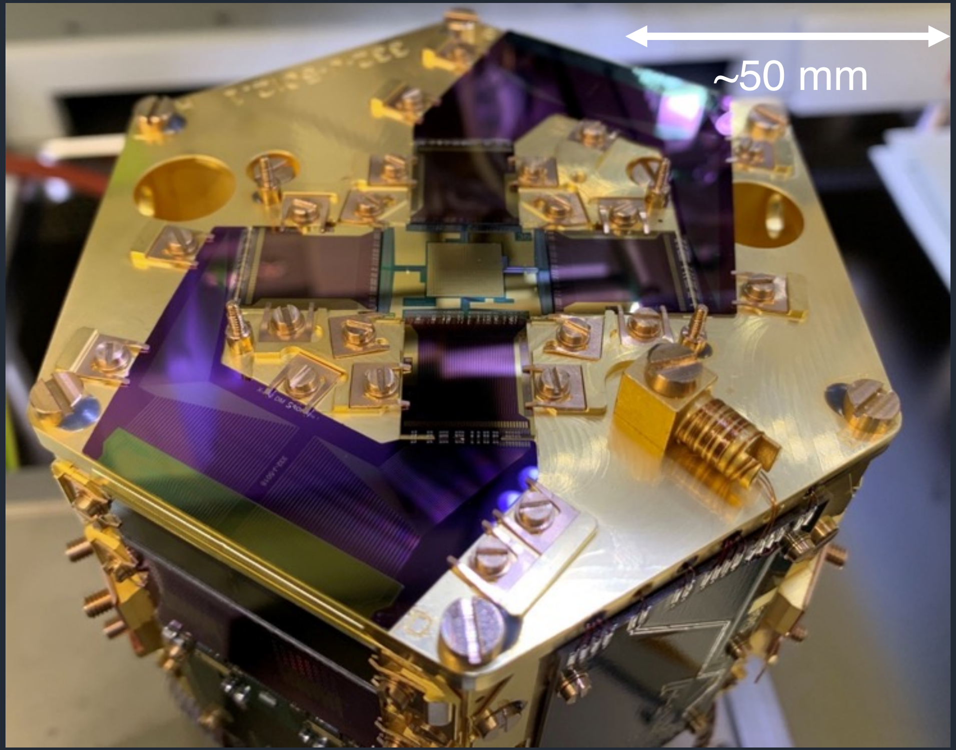


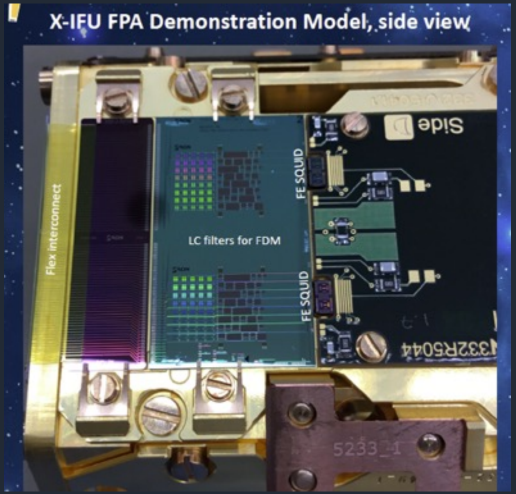
2 channels FDM



FPA-DM for Athena/XIFU





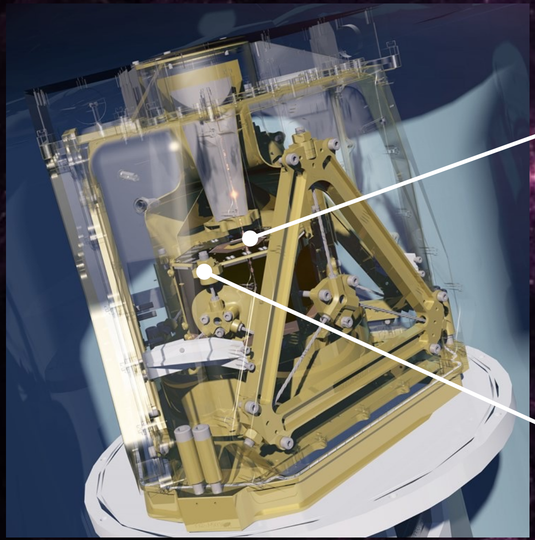


SRON IFU ATHENA X-ray Integral Field Unit

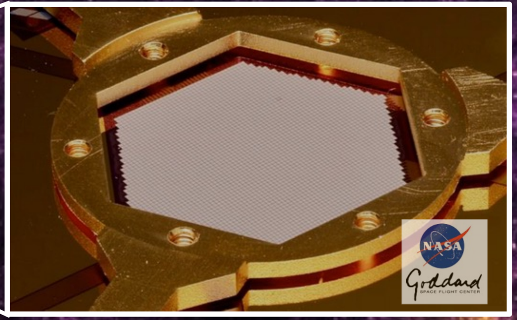
Credits; SRON XIFU/FPA team

Future X-ray space observatory

- **ATHENA** is a Large ESA mission to study *"The Hot and Energetic Universe"*, launch in late 2030s.
- The **X-IFU** instruments of the payload is a **cryogenic imaging spectrometer:**
  Energy band 0.2 – 12 keV, dE ~ 2.5 eV

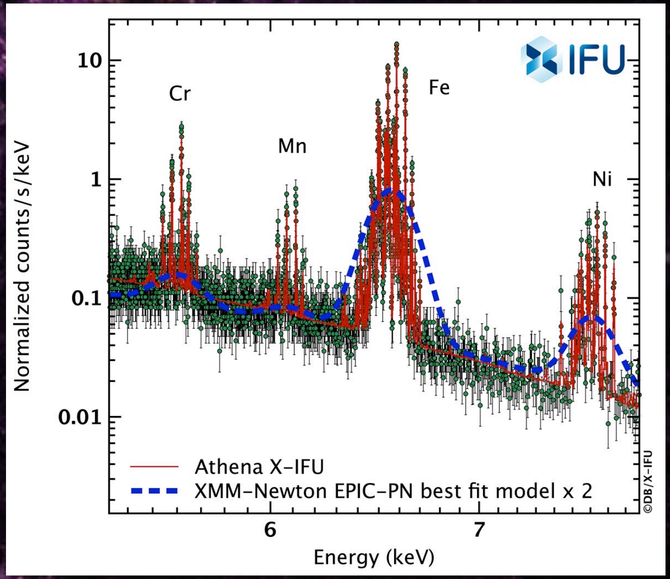


X-ray **I**ntegral **F**ield **U**nit



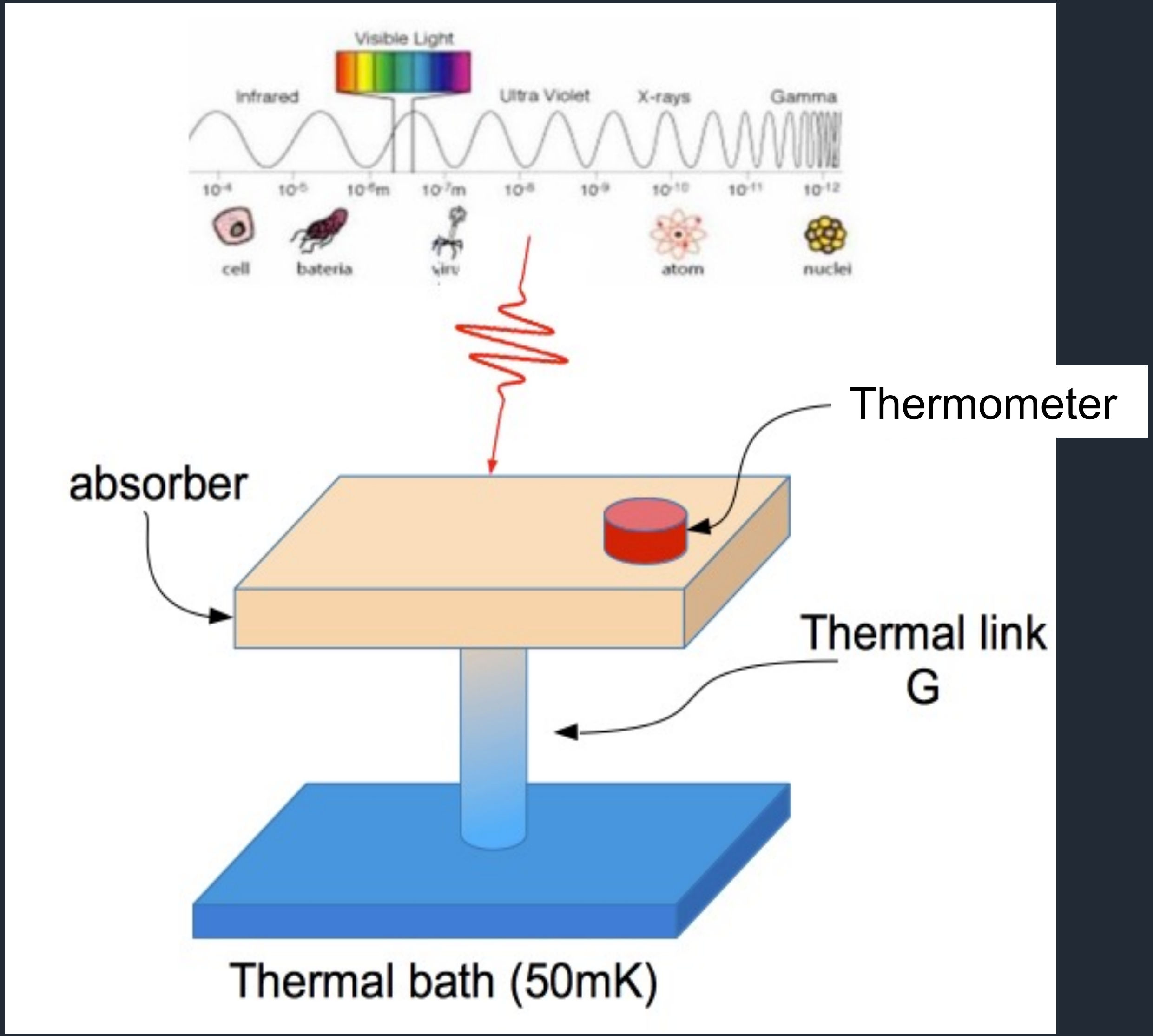
TES array

Observatory Science



Credit: IRAP/CNRS/UT3/CNES/ESA/SRON/NASA-Goddard

Low temperature micro-calorimeters and bolometers



Fundamental elements:
(individually tuneable depending on the applications)

1. Absorber
2. Sensitive thermometer
3. Weak thermal link to bath

K. D. Irwin, Appl. Phys. Lett. 66, 1945 (1995)

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