High resolution imaging X-ray spectrometers based on superconducting transition-edge sensor for astrophysics, fusion science and particle physics

Luciano Gottardi

SRON TES Detector team: M. de Wit, E. Taralli, K. Nagayoshi, M.L. Ridder, K. Ravensberg, S. Visser, M.P. Bruijn, J.-R. Gao

SRON FDM team: H. Akamatsu, D. Vaccaro, J. van der Kuur, M. Kiviranta, C.P. de Vries, B-J van Leeuwen, P. van der Hulst, P. van Winden, A.Y van der Linden, J.W.A. den Herder

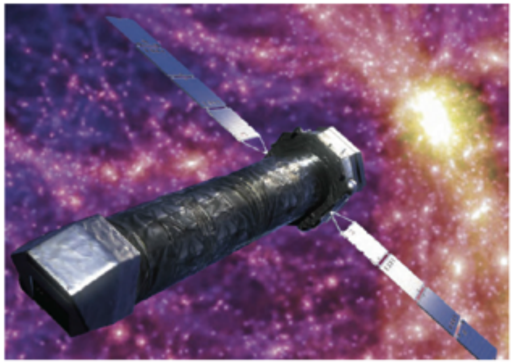
VTT (Finland): Mikko Kiviranta

15th Pisa Meeting on Advanced Detectors – La Biodola - Isola d'Elba, May 22-28, 2022

SRON
Netherlands Institute for Space Research
Netherlands Organisation for Scientific Research (NWO)

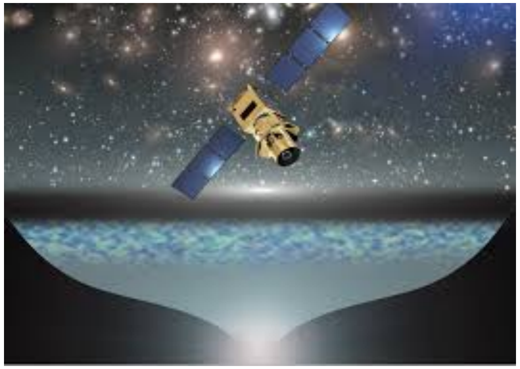
Large array of superconducting detectors for astrophysics

Athena/XIFU (>2034)



ESA large mission to explore The Hot and Energetic Universe

LiteBird (~2028)

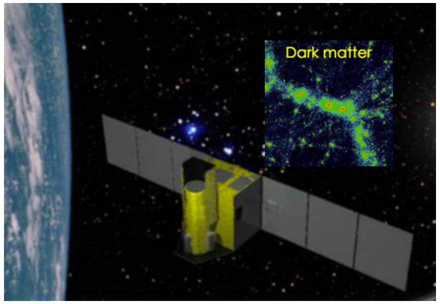


JAXA CMB mission to search for primordial gravitational waves emitted during the cosmic inflation

Hubs

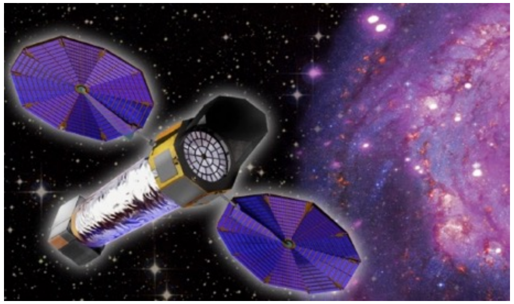
Chinese mission to study 'missing' barions in the universe

SuperDIOS



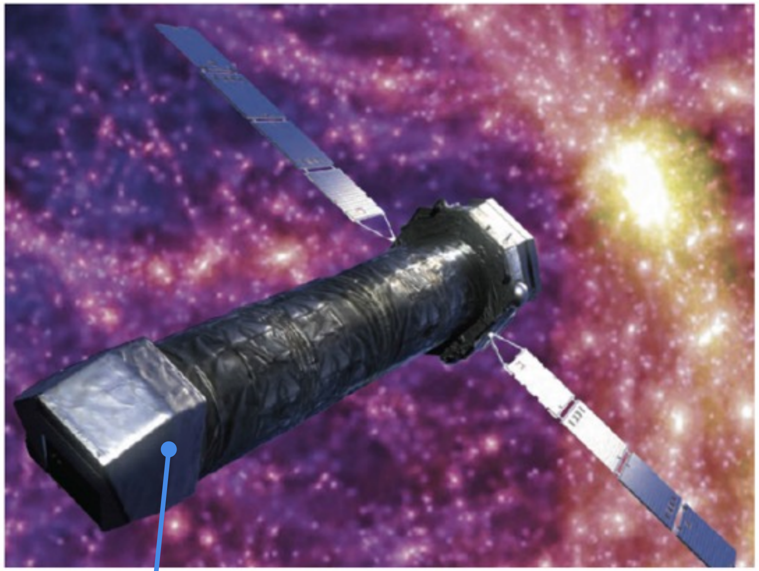
JAXA Diffuse Intergalactic Oxygen Surveyor. An X-ray quantitative exploration of "dark baryon "

Lynx



NASA X-ray Large telescope >100000 pixels

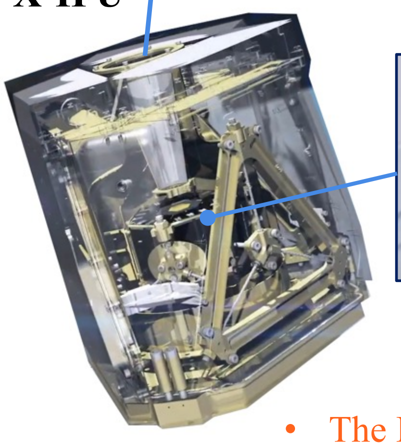
Athena X-IFU



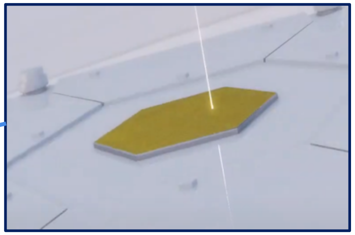
- **ATHENA** is a Large ESA mission to study *"The Hot and Energetic Universe"*, launch in >2034
- The **X-IFU** is one of the two instruments of the payload. It is a **cryogenic spectrometer,** energy band 0.2 – 12 keV

T=**50 mK**

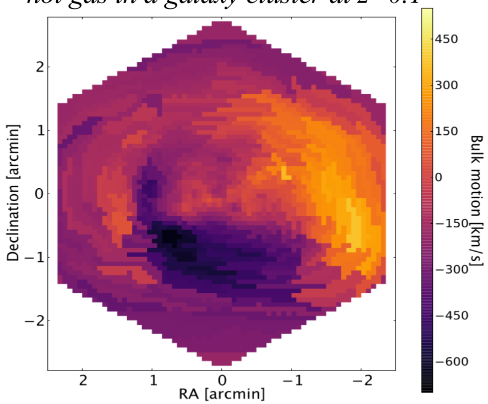
X-IFU



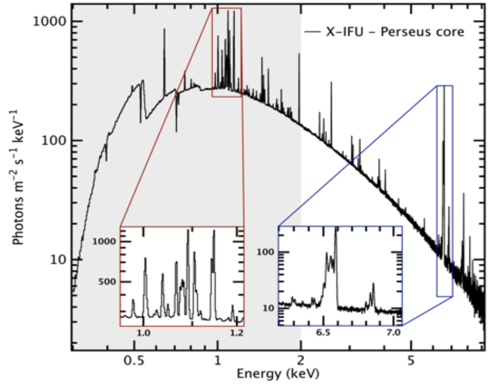
TES-Array detector



Simulated Bulk motion map of the hot gas in a galaxy cluster at z=0.1



Simulated X-IFU spectrum of the core of the Perseus cluster



SRON is developing:

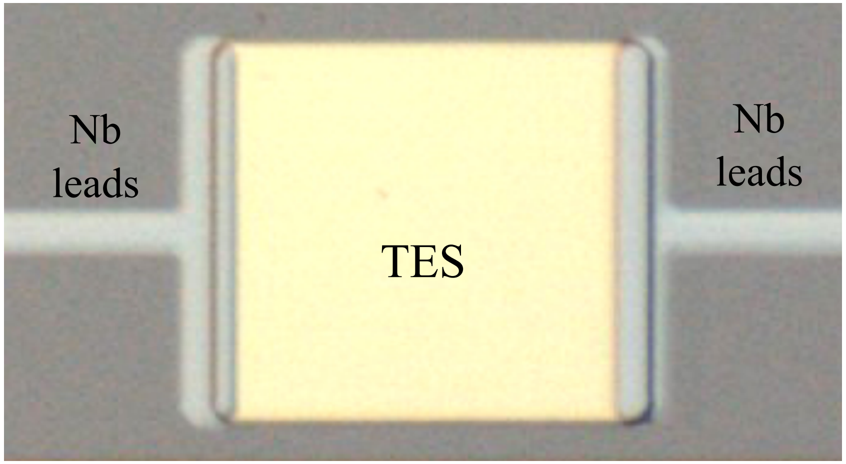
- The FPA (**Focal plane assembly**)
- **The TES pixels array** as backup technology

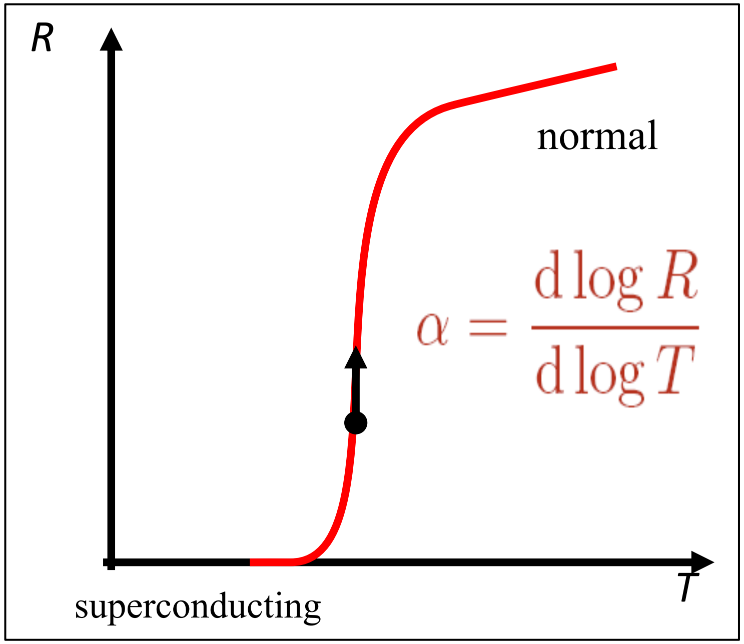
The **X-ray Integral Field Unit**:
Detailed Imaging + High resolution spectroscopy

A **Large and Uniform TES array (~3800 pixels)** with excellent energy resolution:

$\Delta E < 2.5$ eV @ E < 7 keV,
[$\Delta E < 2.0$ eV @ E < 1 keV, $\Delta E < 5.0$ eV @ E = 10 keV]

Superconducting Transition Edge Sensors (TESs): very sensitive low-temperature thermometers





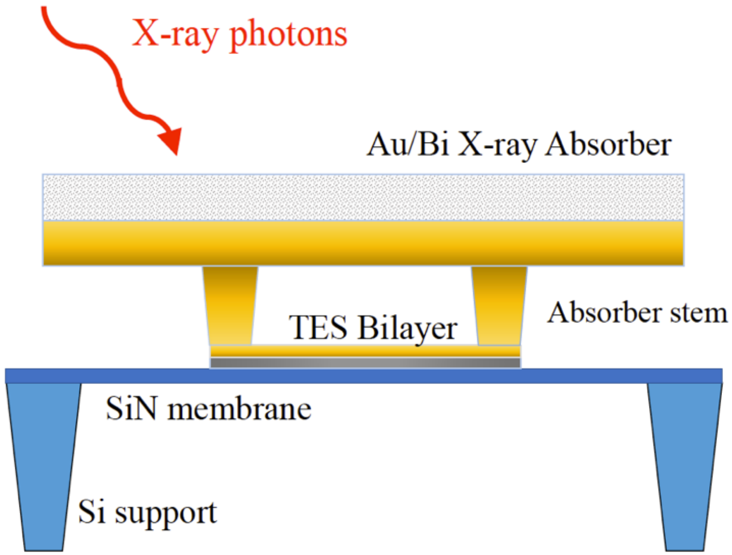
Thin film superconducting bilayer

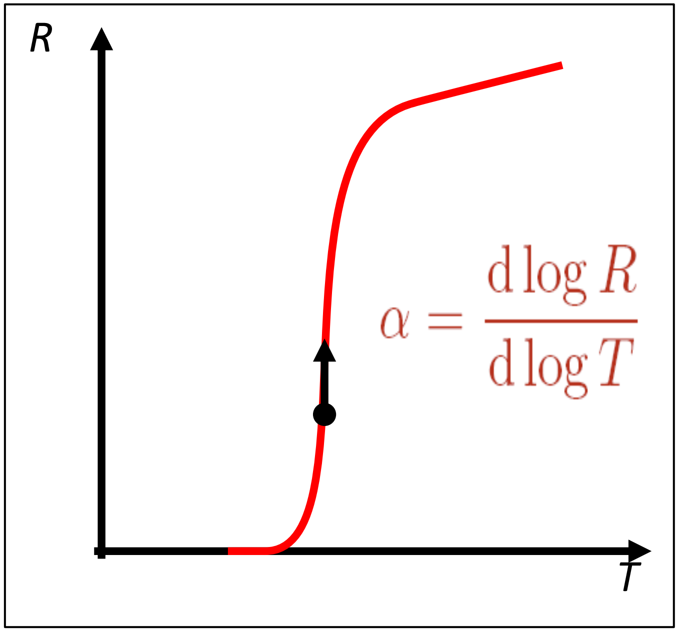
Ti/Au Mo/Au Mo/Cu

$T_C \sim 90$ mK

D. H. Andrews et al., Phys. Rev. 59, 1045 (1941).
K. D. Irwin, Appl. Phys. Lett. 66, 1945 (1995)

TES based microcalorimeters





- 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

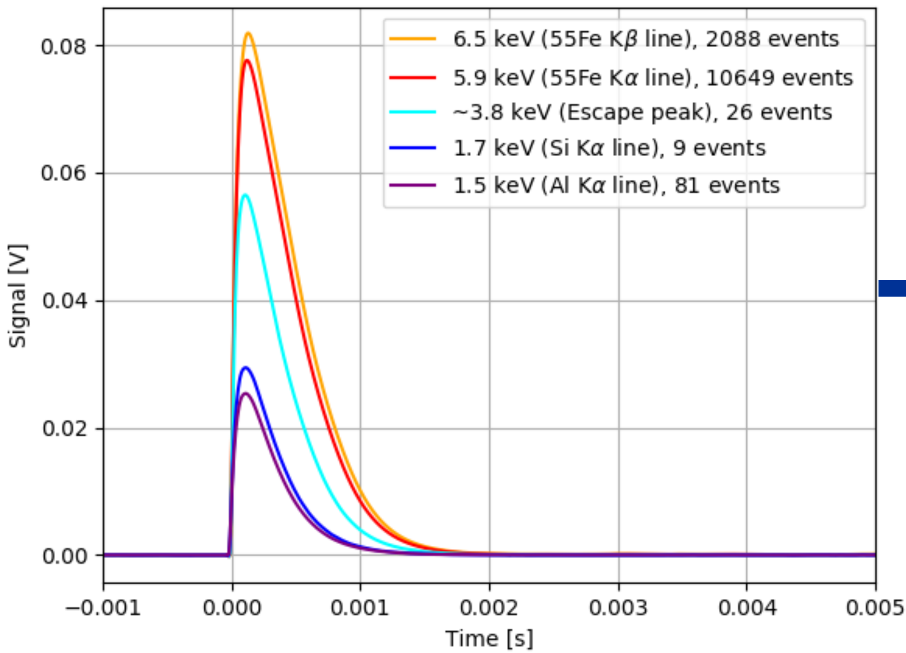
Energy resolution:

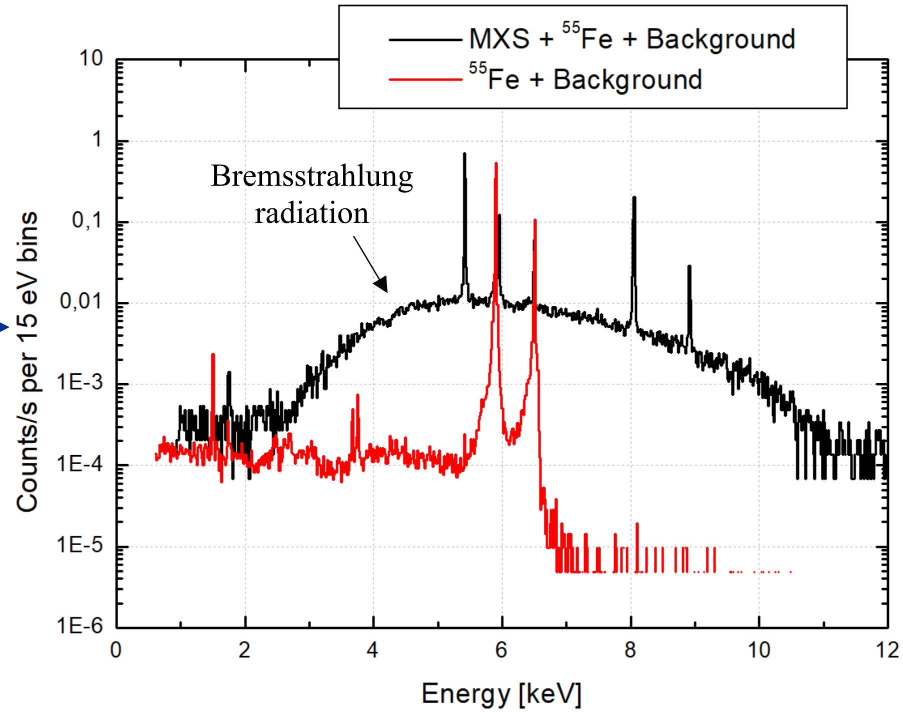
$$E_{FWHM} \sim 2.355\sqrt{\frac{4k_B T_c^2 C}{\alpha}}$$

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

TES microcalorimeters are single photon detectors

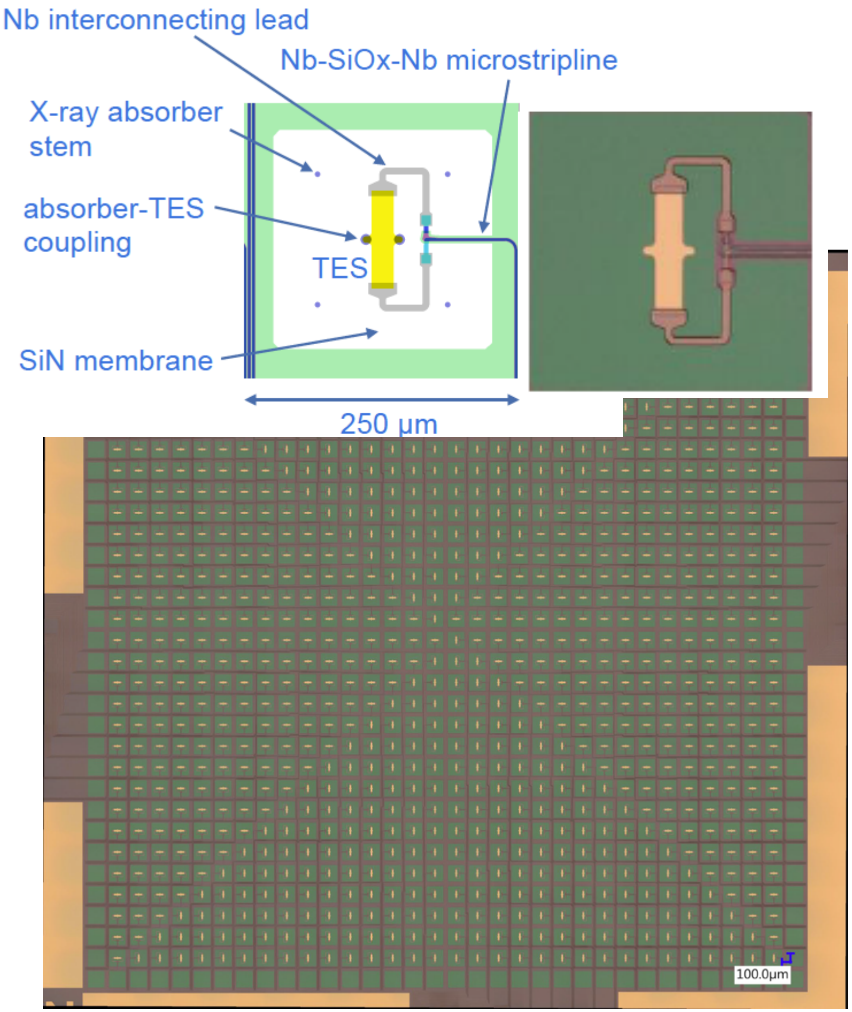




- A TES works as a single photon detector in the optical, Xray or gamma ray spectrum
- The area of each pulse is proportional to the photon energy
- Many photons are collected and a very high resolutions spectrum is obtained
- When done simultaneously with many pixels an image of the source is obtained

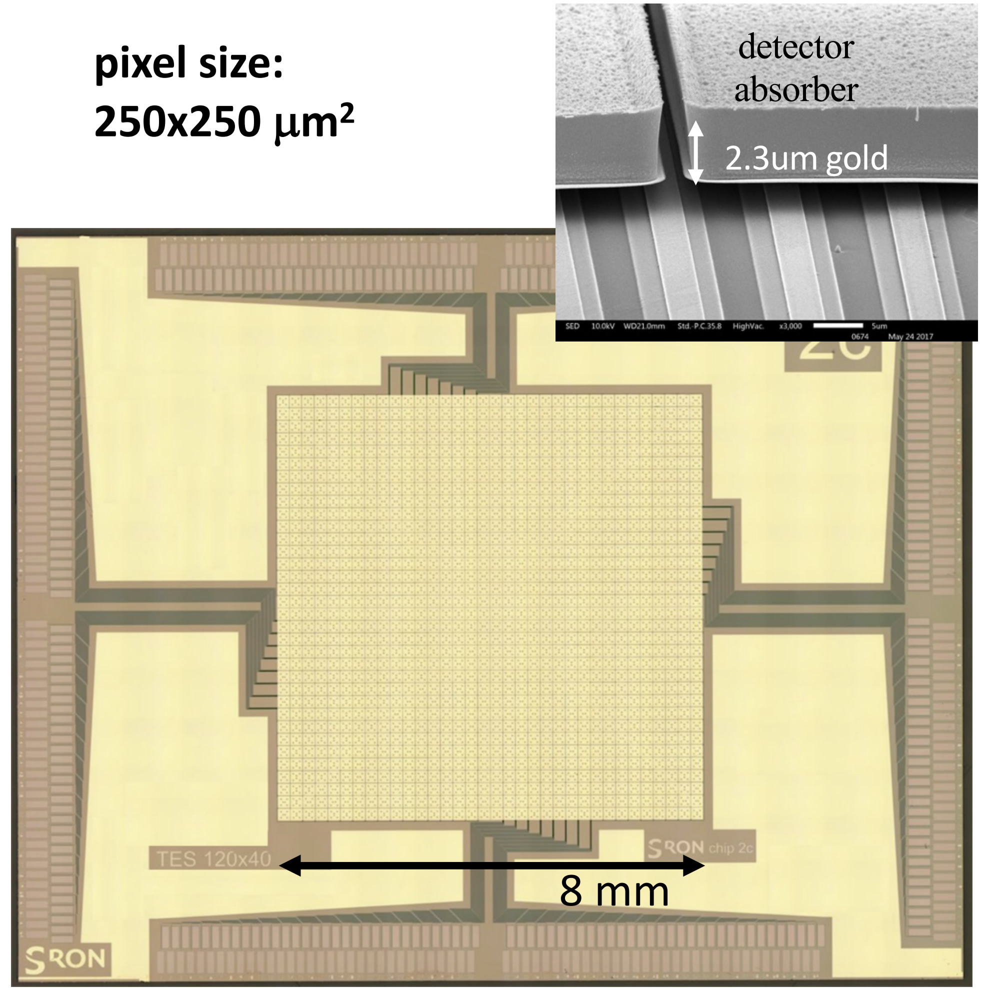
SRON

X-ray TES microcalorimeters for XIFU



Micrograph SRON 32x32 array before absorber deposition

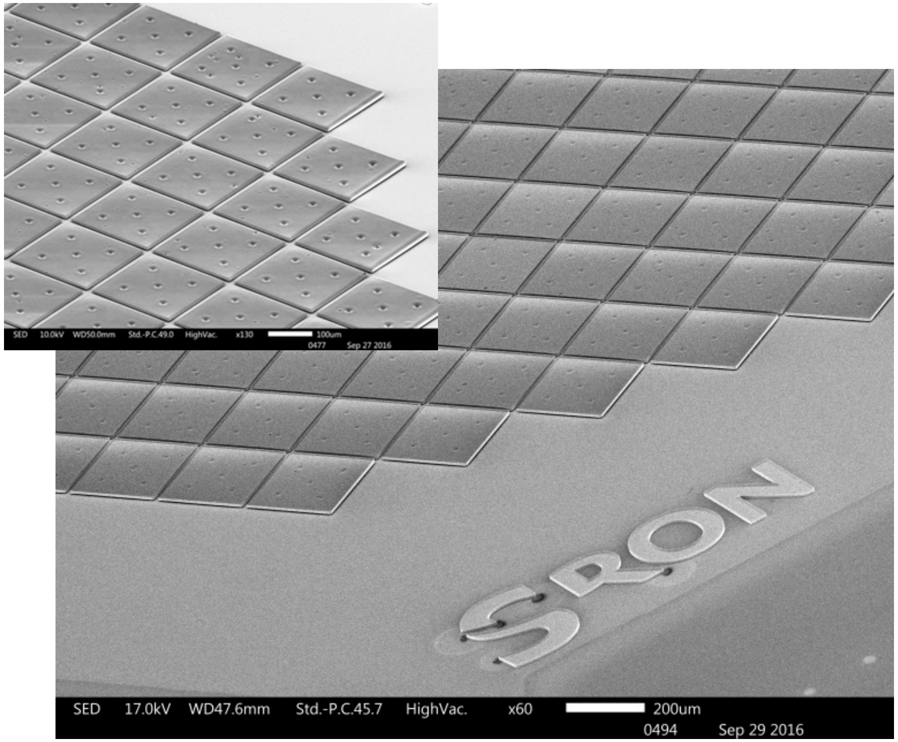
pixel size:
250x250 µm²

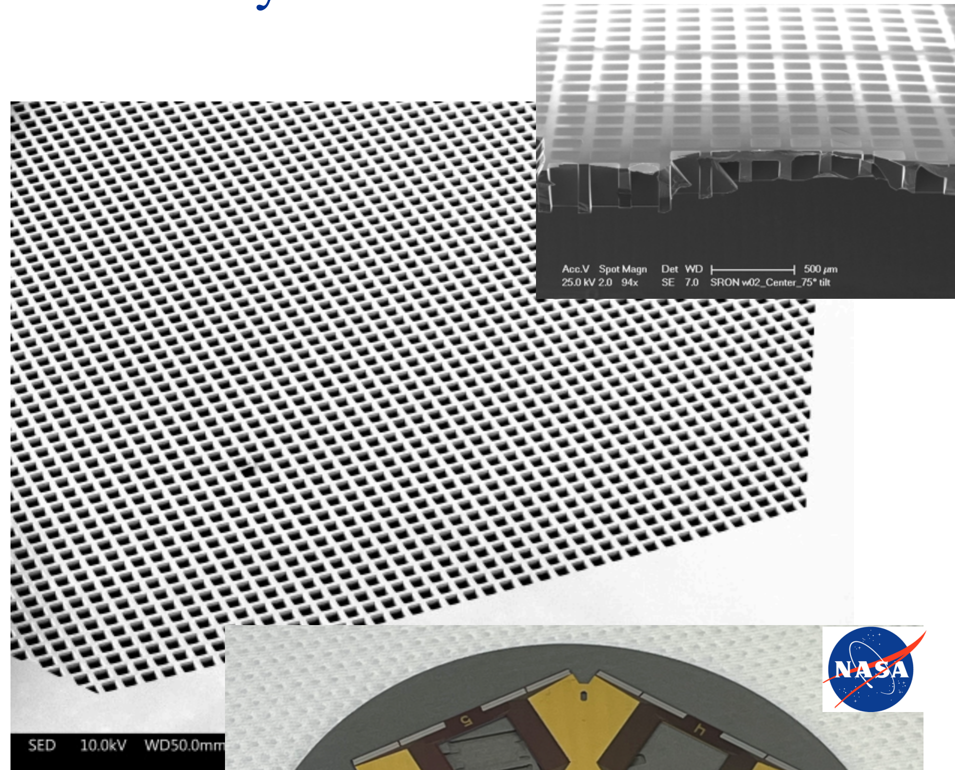


Final chip SRON 32x32 X-ray microcalorimeters

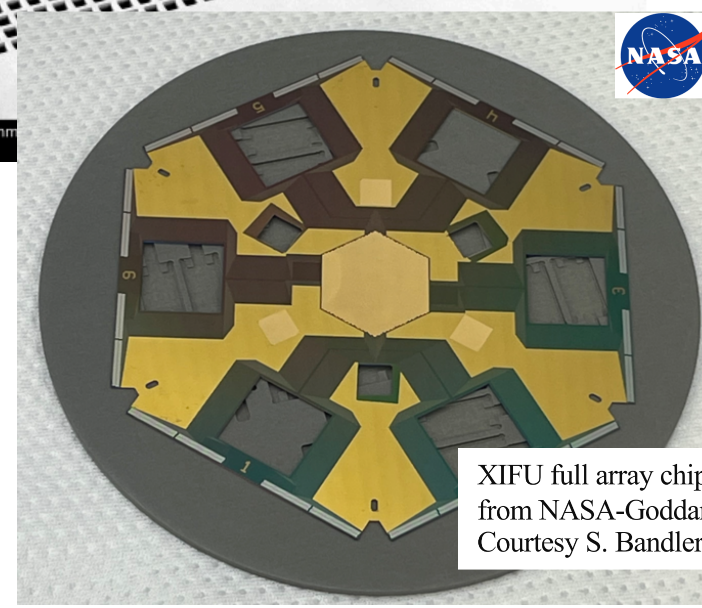
Nagayoshi et al, J. Low Temp. Phys. 199, 2019

X-IFU back-up detectors array at SRON





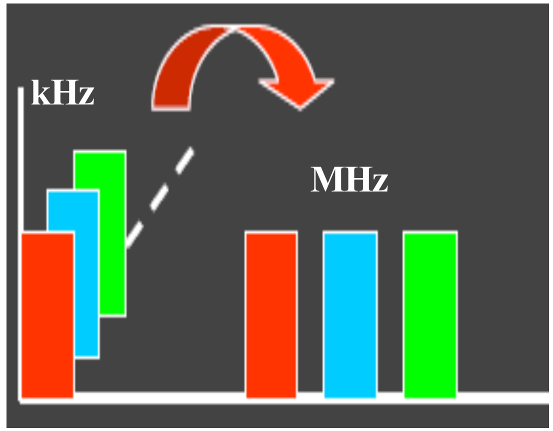
Development foreseen in the next year within ESA contract for the fabrication of a ~3000 pixels fully-functional array as a backup for XIFU

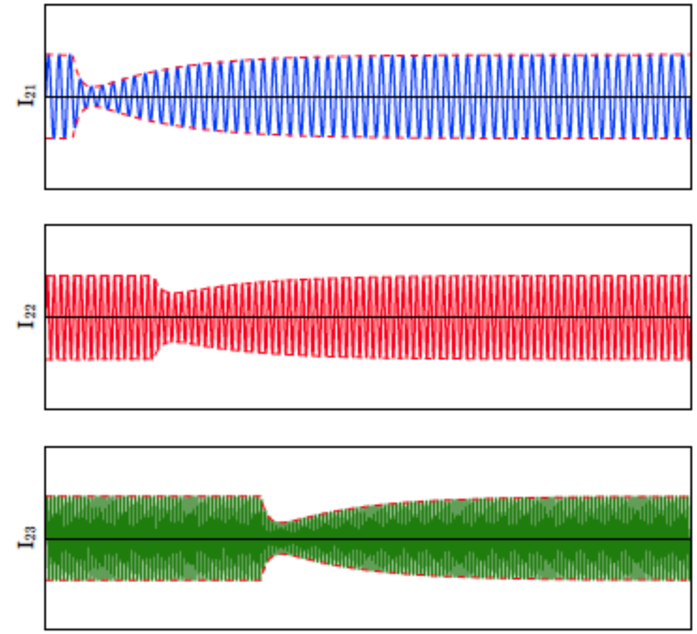


XIFU full array chip from NASA-Goddard Courtesy S. Bandler

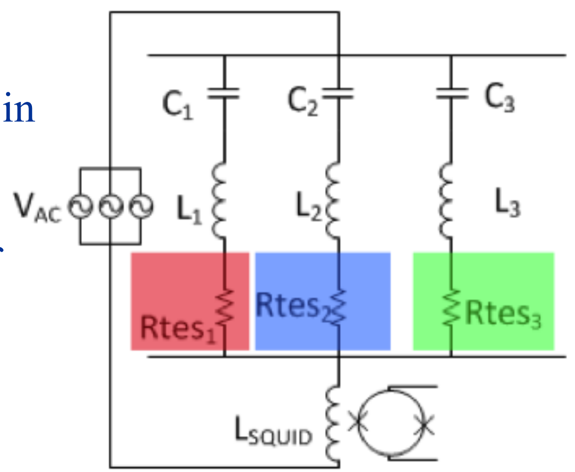
Frequency Division Multiplexing

- TES is ac voltage bias and works as AM modulator of the a MHz carrier
- High-Q bandpass filters
- Signal is demodulated at room temperature

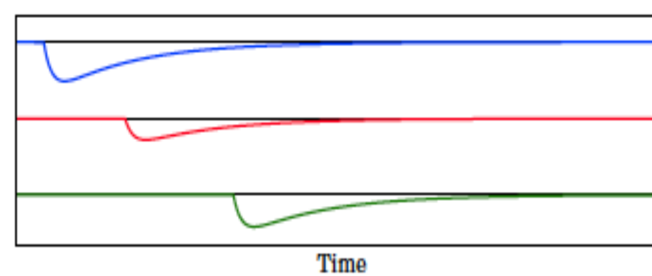




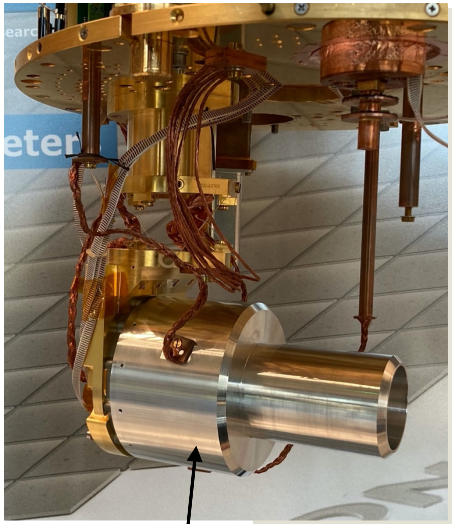
To read out **~3800 pixels** like in XIFU
~100 SQUID channels are needed with MUX factor of
40 pixels/channel

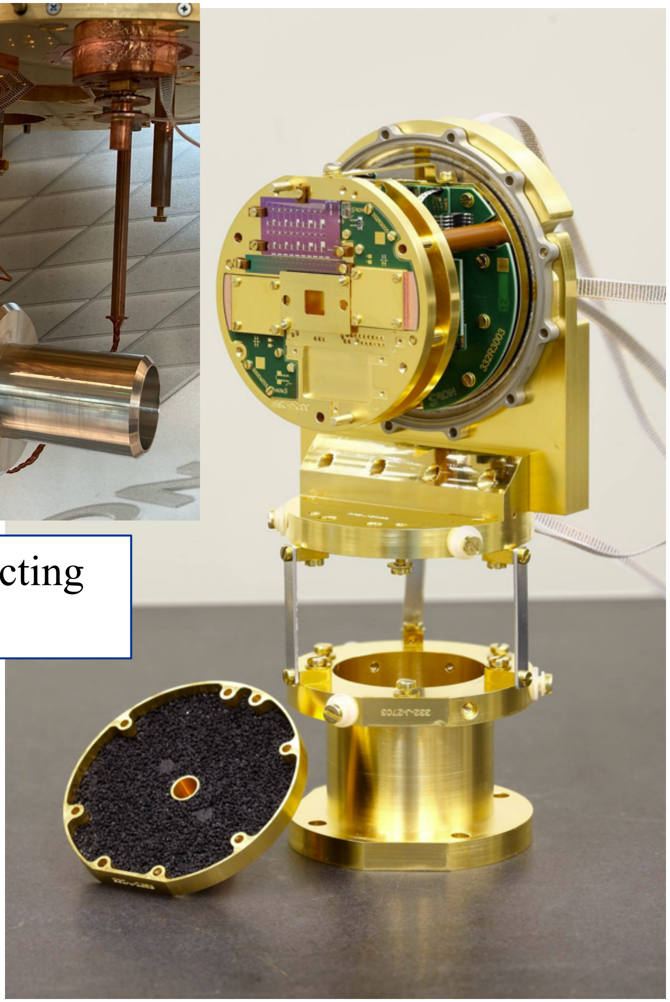


Demodulated signal



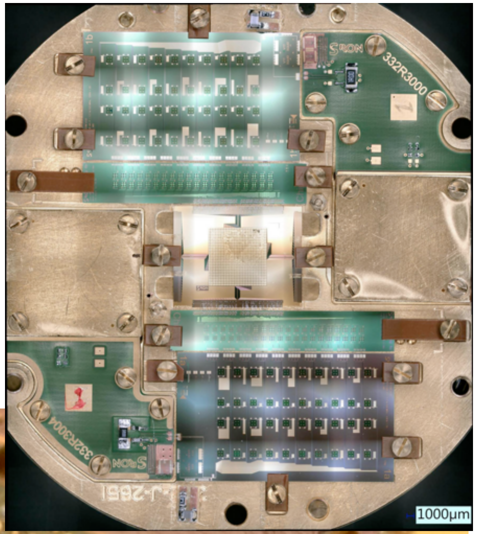
40 pixels FDM demonstrator



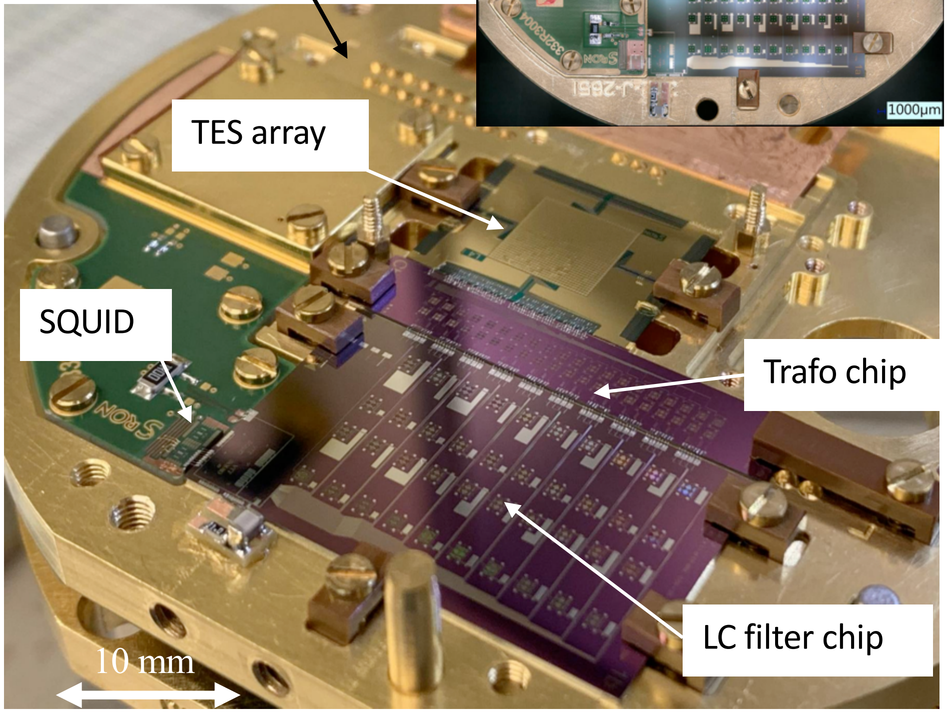


Superconducting shield

2 channels FDM

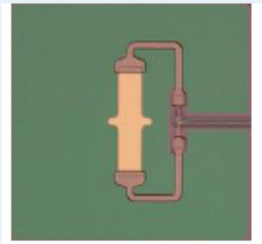


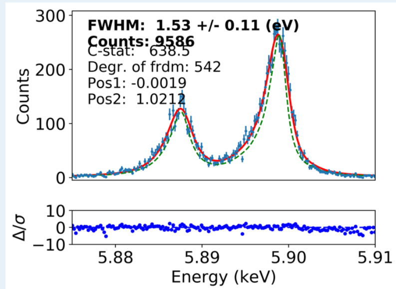
50mK



Latest achievement at SRON

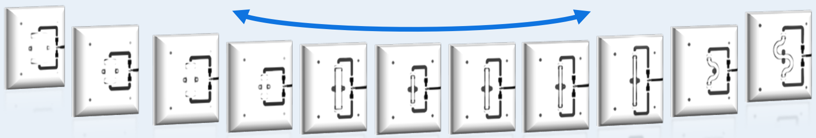
Single Pixel Optimization





Low aspect ratio, low Rn

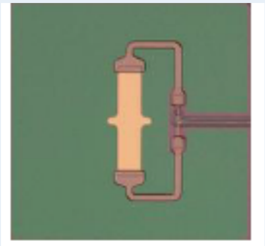
High aspect ratio, high Rn

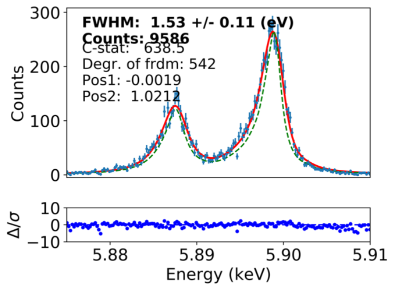


M. de Wit et al., J. Appl. Phys. 128, 224501 (2020),
E. Taralli *et al*. Rev. Sci. Instr.. 92, 023101 (2021)
M. de Wit et al., Phys. Rev. Appl. 16, 04059 (2021)

Latest achievement at SRON

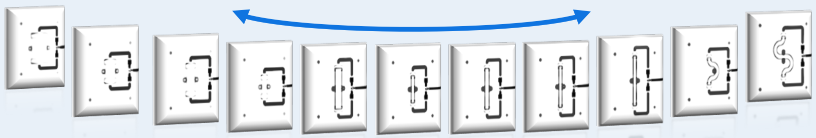
Single Pixel Optimization





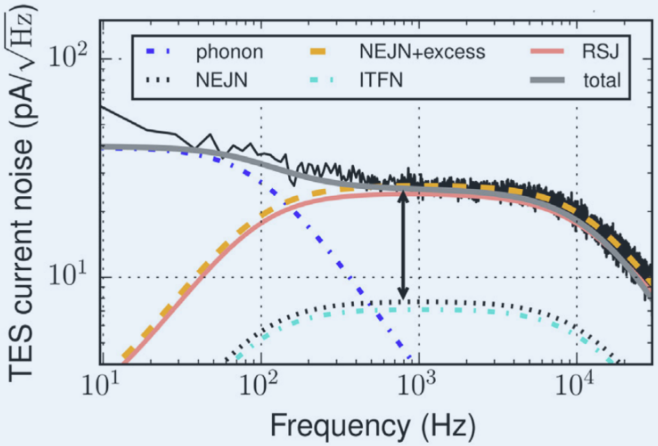
Low aspect ratio, low Rn

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)

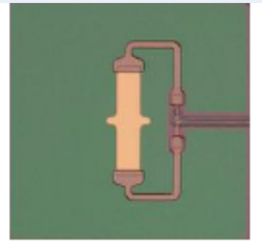
Detector noise well understood

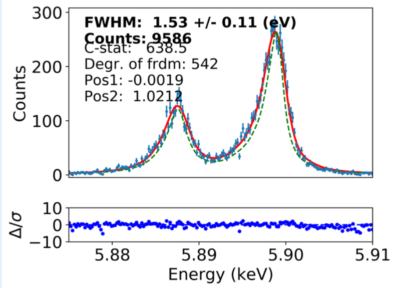


L. Gottardi *et al*., Phys. Rev. Lett. 126, 217001 (2021)

Latest achievement at SRON

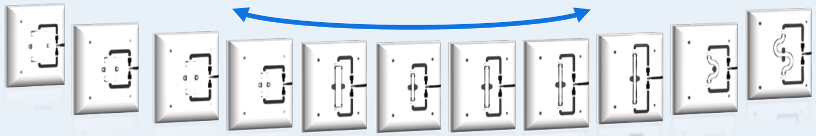
Single Pixel Optimization





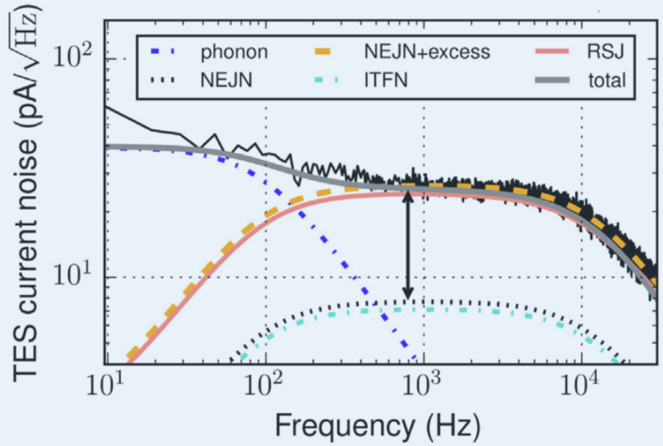
Low aspect ratio, low Rn

High aspect ratio, high Rn



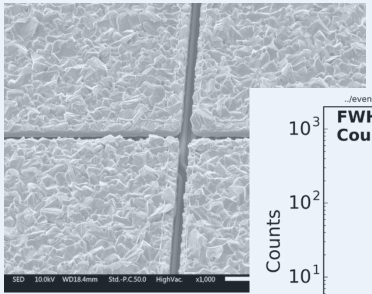
M. de Wit et al., J. Appl. Phys. 128, 224501 (2020),
E. Taralli *et al*. Rev. Sci. Instr.. 92, 023101 (2021)
M. de Wit et al., Phys. Rev. Appl. 16, 04059 (2021)

Detector noise well understood

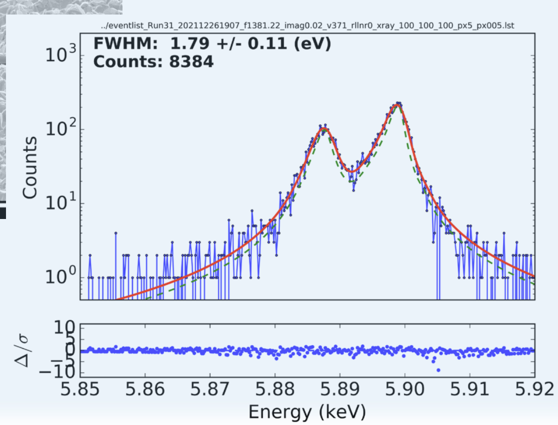


L. Gottardi *et al*., Phys. Rev. Lett. 126, 217001 (2021)

High Quantum Efficiency



Bismuth absorber

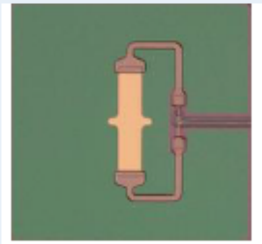


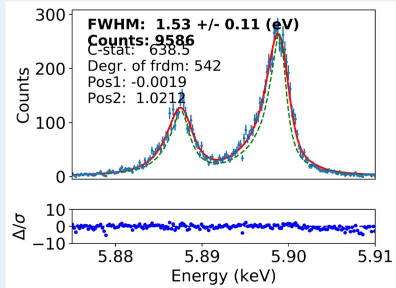
QE 97%

SRON

Latest achievement at SRON

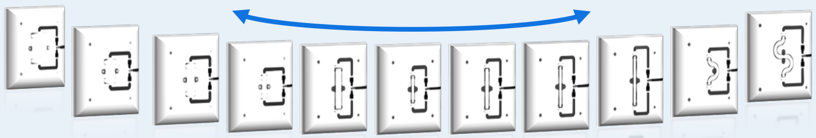
Single Pixel Optimization





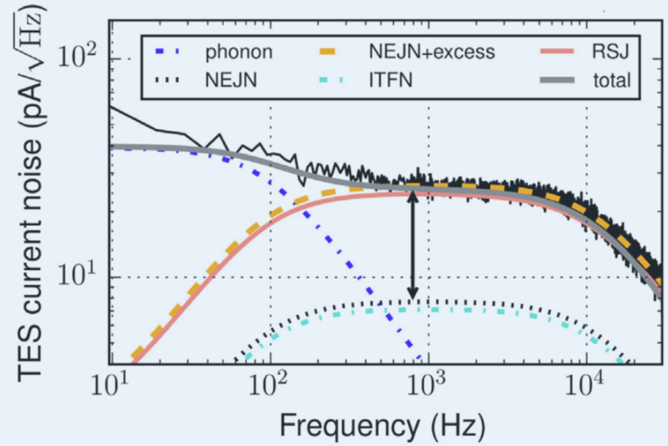
Low aspect ratio, low Rn

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)

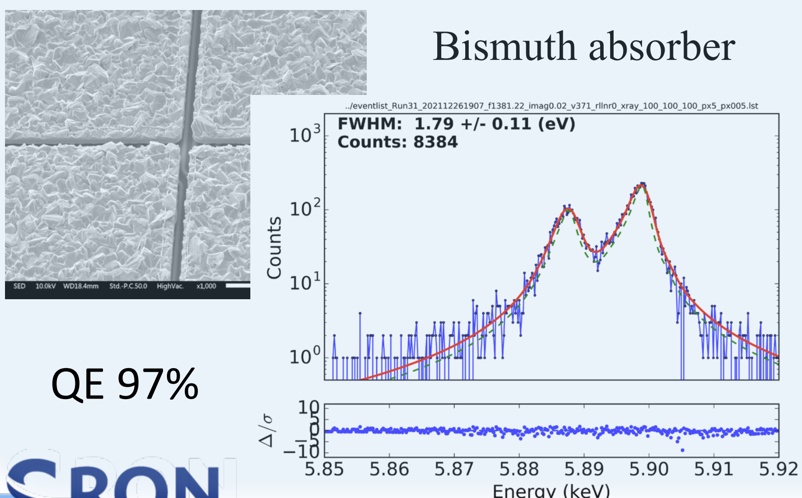
Detector noise well understood



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

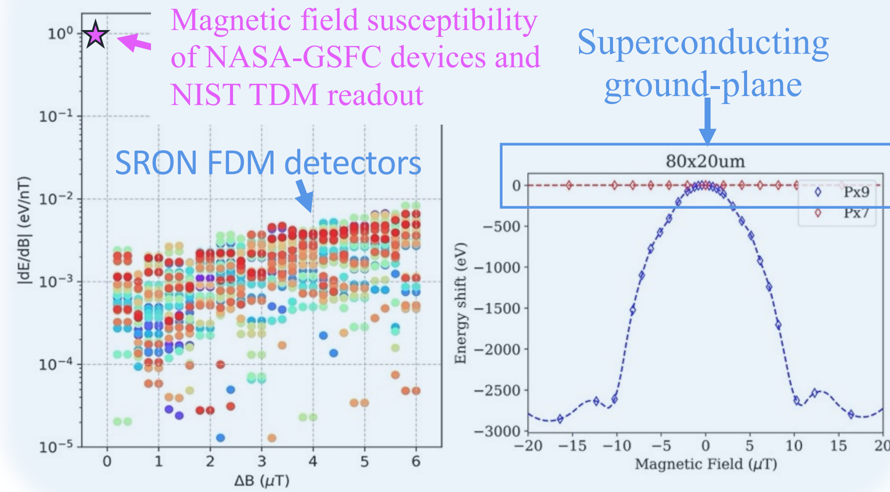
High Quantum Efficiency

Bismuth absorber



QE 97%

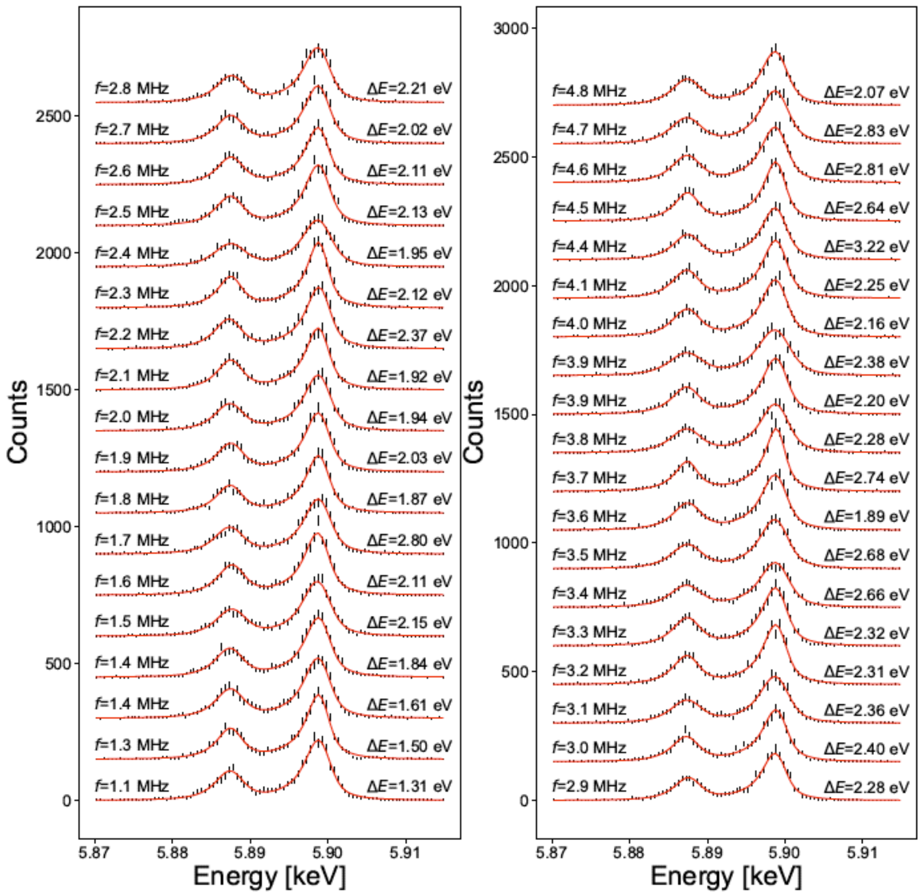
TESs insensitive to external magnetic field

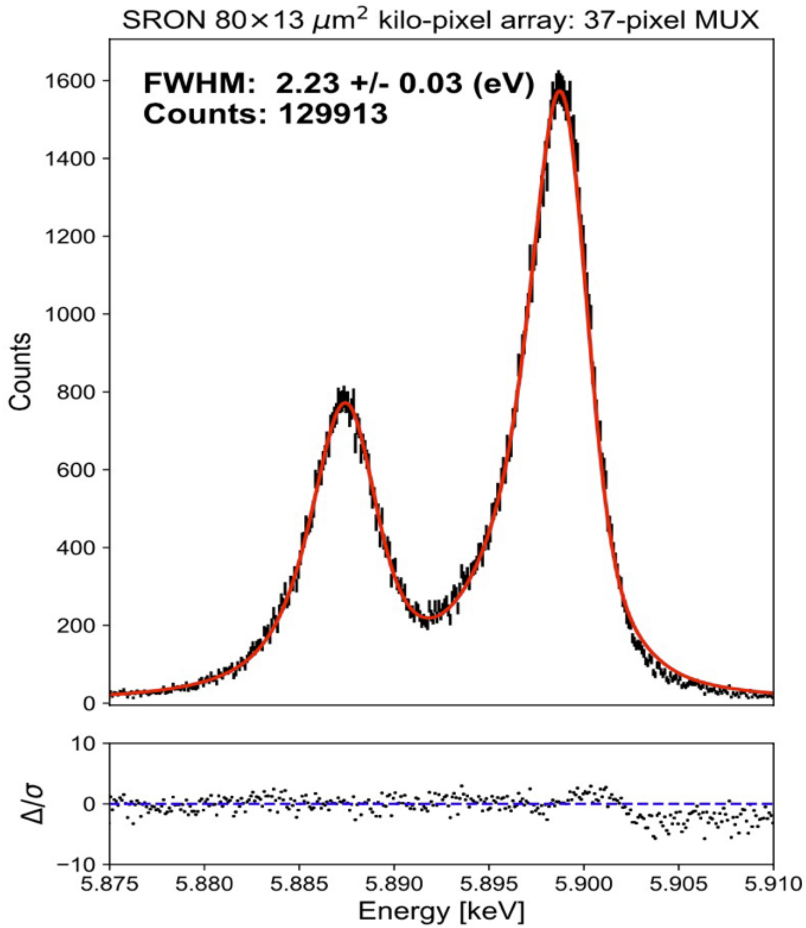


M. de Wit et al., submitted to Phys. Rev. Appl. (2022)

SRON

Frequency division multiplexing demonstration





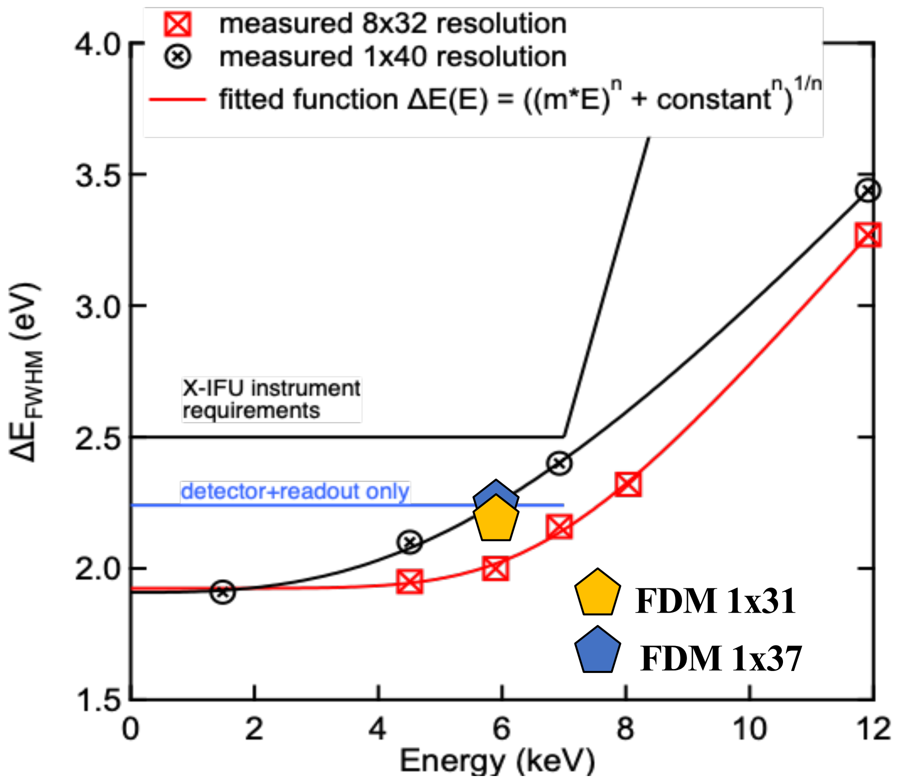
Akamatsu et al. JLTP 199, 737 (2020)
Vaccaro, HA et al. RSI 92, 033103 (2021)
van der Hulst, HA et al. RSI 92, 7 (2021)
H. Akamatsu et al. APL 119,18, (2021)

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

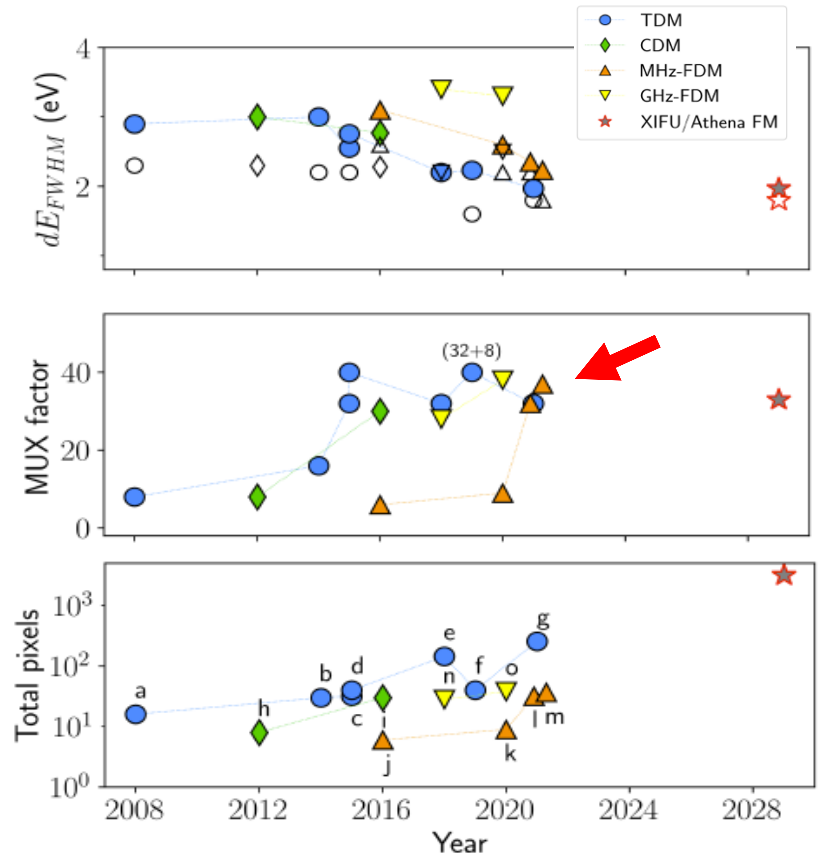
more details in Davide Vaccaro's **POSTER**

Frequency division multiplexing demonstration

Updated from Darkin et al ASC 2020



H. Akamatsu, D. Vaccaro 2021



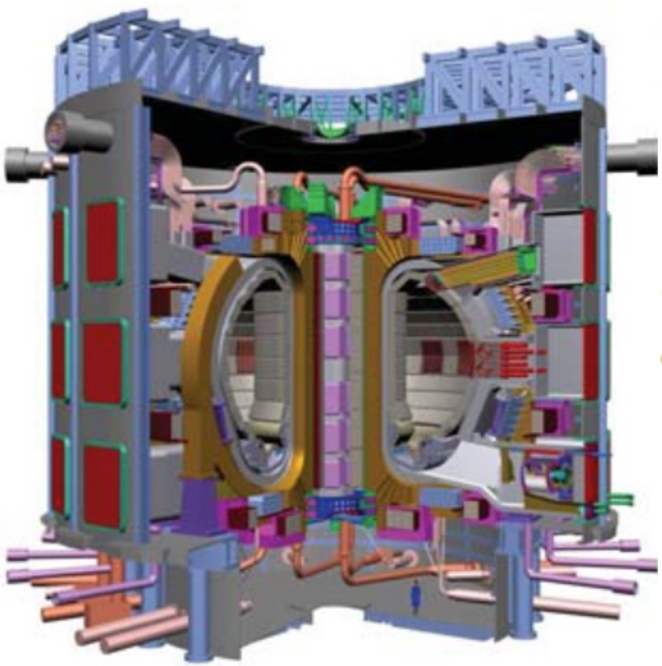
L. Gottardi and K. Nagayashi, Applied Sciences 11 (9),3793, 2021

- FDM performance at 6 keV within X-IFU requirement
- Thermal cross talk level is well below XIFU requirement
- Electrical cross talk between FDM channel is better than 10^{-3} at 6 keV

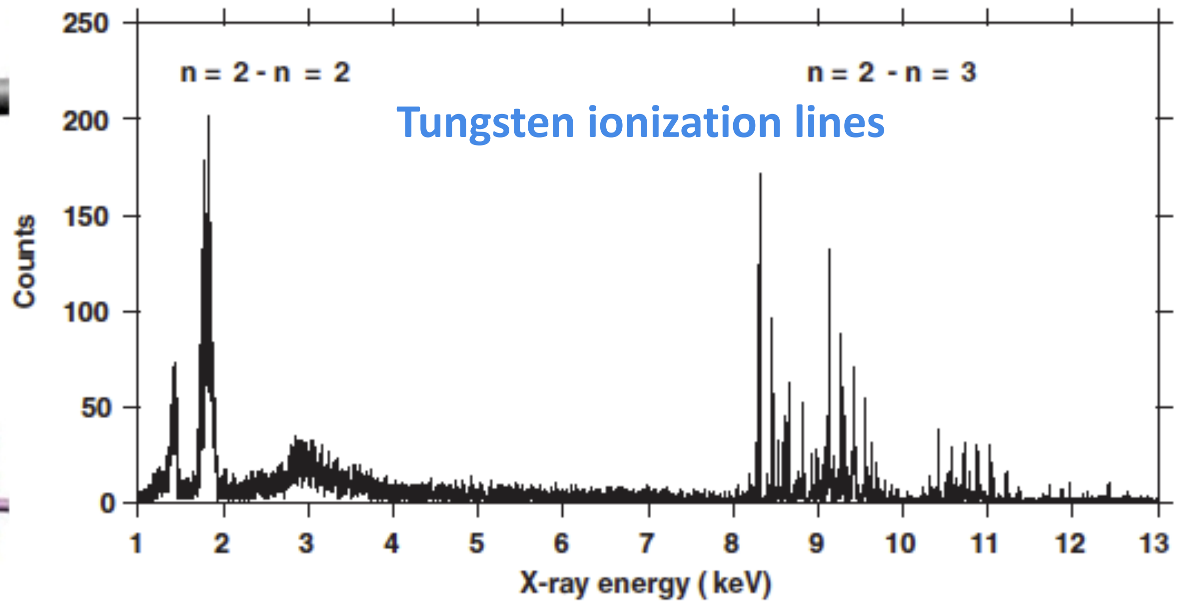
SRON

TES X-ray microcalorimeters for plasma physics

ITER www.iter.org



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



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

~3000 pixels , dE ~ 2.5eV, count-rate capability > 100000 counts/s

TES X-ray microcalorimeters for ITER: the science case

TES arrays → High energy resolution, high quantum efficiency, high count-rate capability,

Energy range from few eV up to > 20 keV

1. **Study of the complex ionization states of High-Z material (Tungsten) and plasma physics**

   - High accurate atomic physics data (such as atomic transition wavelength, intensities, and ionization, excitation and recombination rate) is essential
   - Data from existing tokamak (ASDEX-Upgrade (Germany) , West(France)) or Electron Beam Ions Trap (EBIT)

1. **X-ray diagnostic for future fusion reactors like ITER and DEMO**

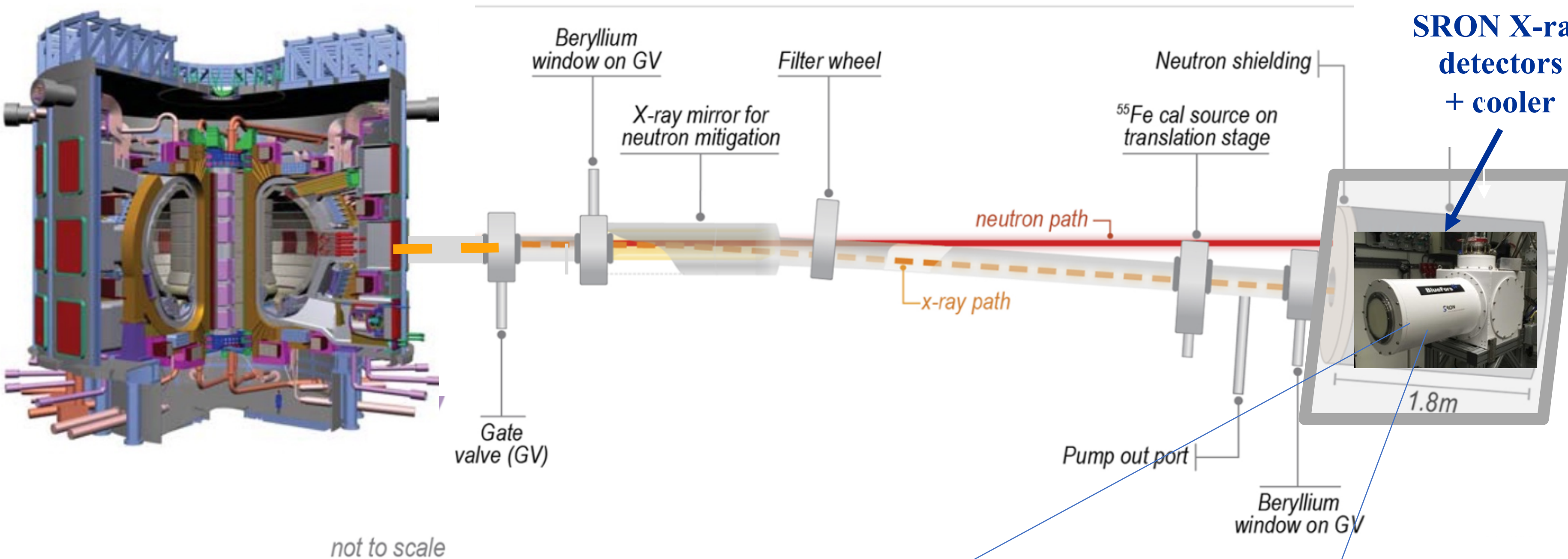
   - Core ion and electron temperature diagnostic
   - High-Z impurities (molybdenum and tungsten) detection
   - Information of the radial profile of the ion temperature
   - Ion flow velocity

R.Neu at al., Handbook for Highly Charged Ion Spectroscopic Research, Chapter 11, 2011
P. Beiersdorfer et al. RSI 81,10EE323 (2010), and AIP Conference, 2017
M. Eckart et al. Rev. Sci. Instrum., 92, 063520 (2021)

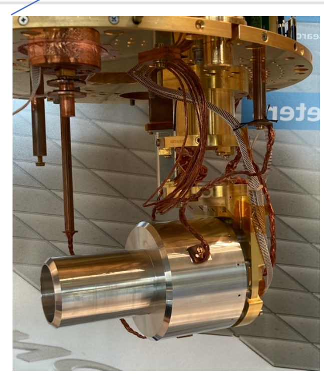
TES X-ray microcalorimeters at nuclear fusion reactors

conceptual design for diagnostic at ITER using TES calorimeters

SRON X-ray detectors + cooler



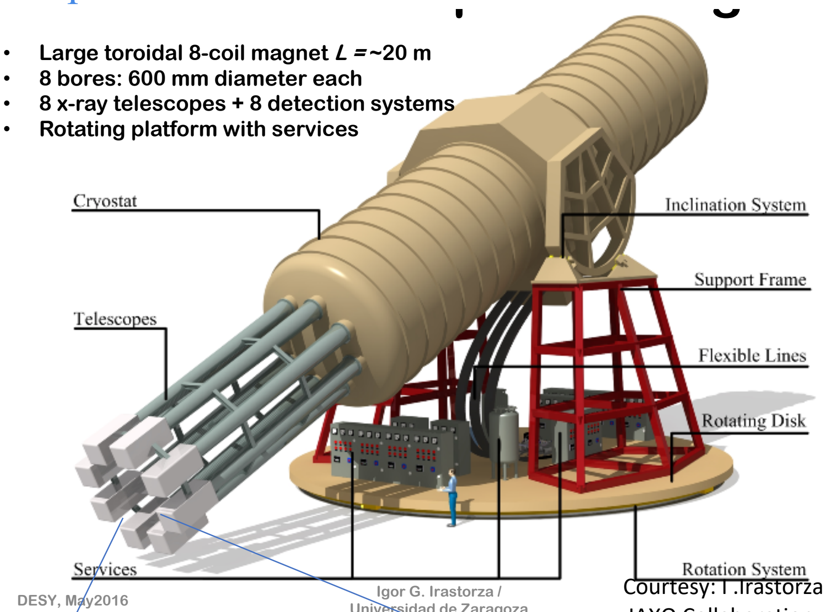
Adapted from
M. Eckart et al. Rev. Sci. Instrum., 92, 063520 (2021)



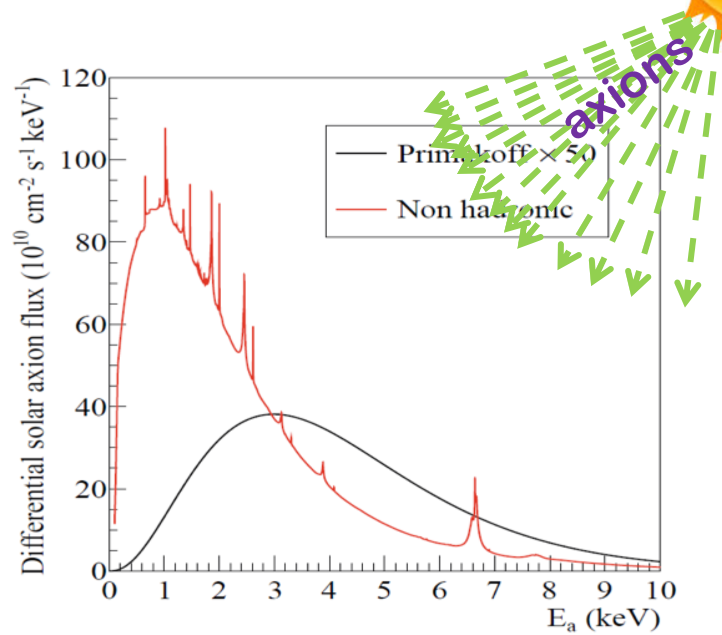
TES X-ray microcalorimeters for solar axion search

IAXO conceptual design
https://iaxo.web.cern.ch

- Large toroidal 8-coil magnet L =~20 m
- 8 bores: 600 mm diameter each
- 8 x-ray telescopes + 8 detection systems
- Rotating platform with services

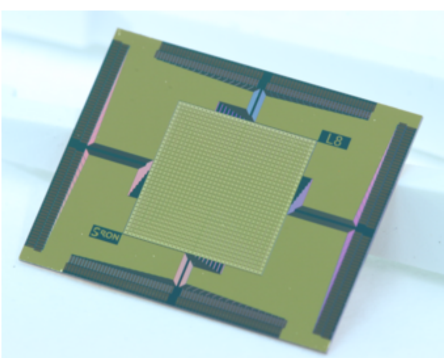


Courtesy: I .Irastorza
IAXO Collaboration

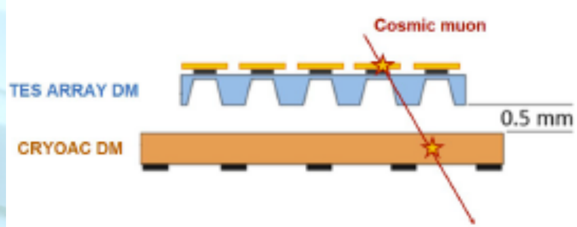


TES-FDM X-ray spectrometer

Potential detector

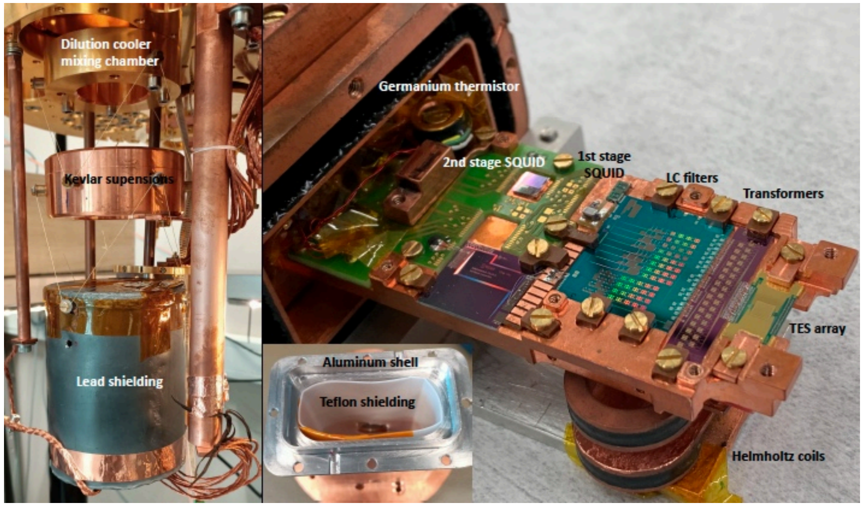


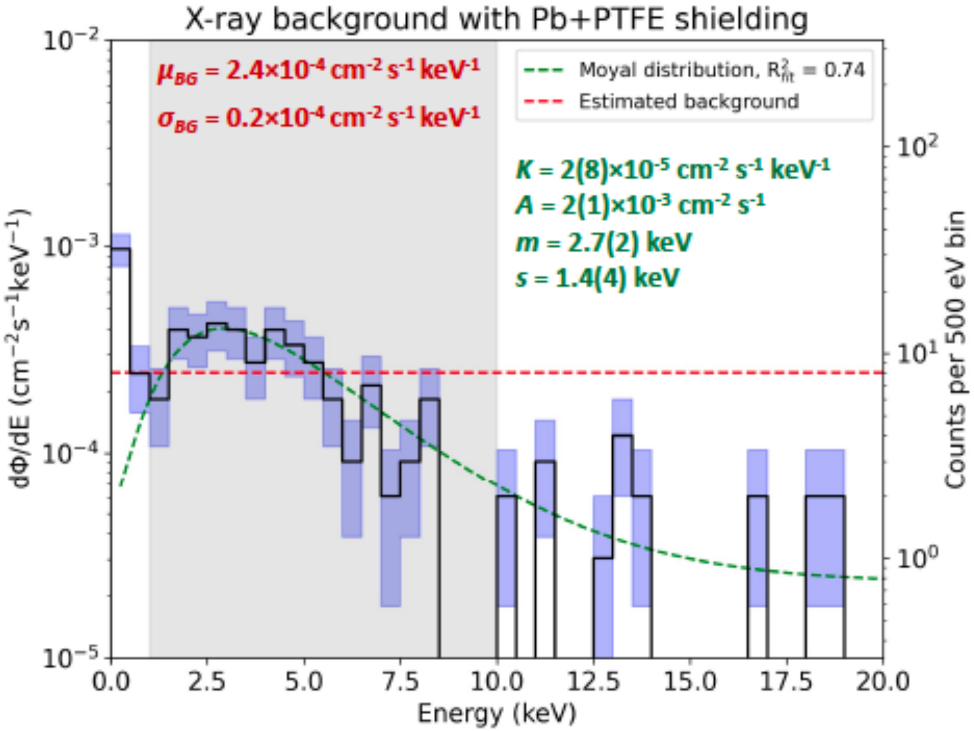
SRON TES array



- large kilo-pixels array
- High X-ray spectral resolution to detect narrow lines and improve detector background
- **Shielding** for secondary electrons and other residual background particle
- Optimized anticoincidence detectors to lower the instrument background to IAXO challenging goal: **10^{-7}cnts/keV/cm^2/s**

TES X-ray microcalorimeters for solar axion search





Background measurement with SRON FDM TES array

See **POSTER** Davide Vaccaro et al. for more details

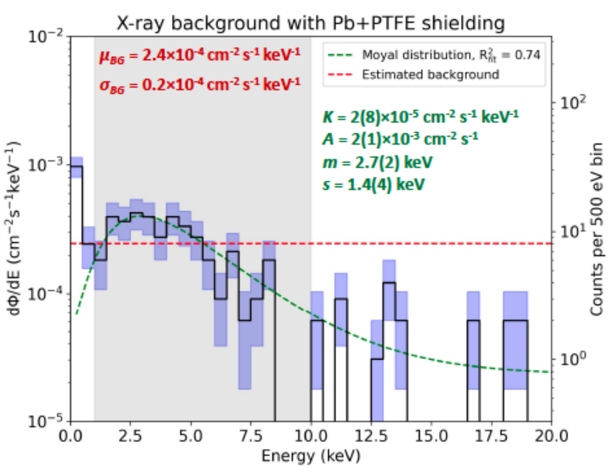
SRON

Summary

- X-ray imaging spectrometers based on large array of superconducting transition edge sensors perform at very high resolving power in a high energy range (100 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

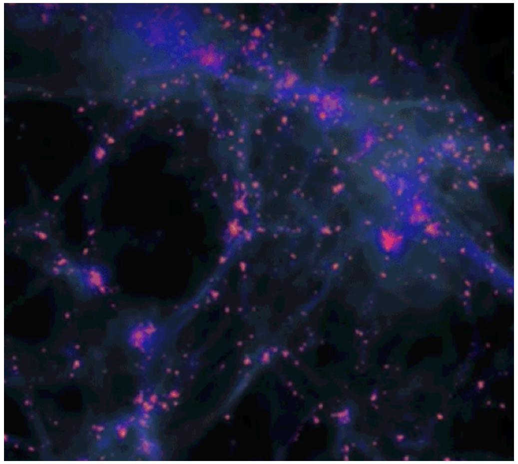
Low background experiments

no photons



X-ray telescopes

some photons



Source: Athena mission

Fusion plasma

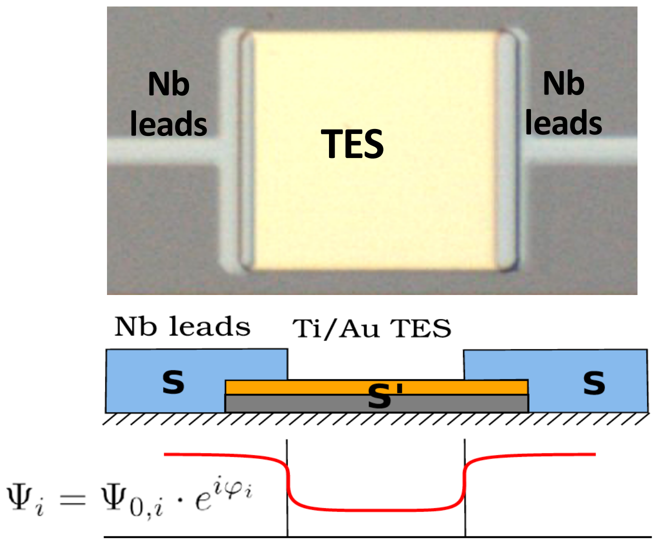
many photons

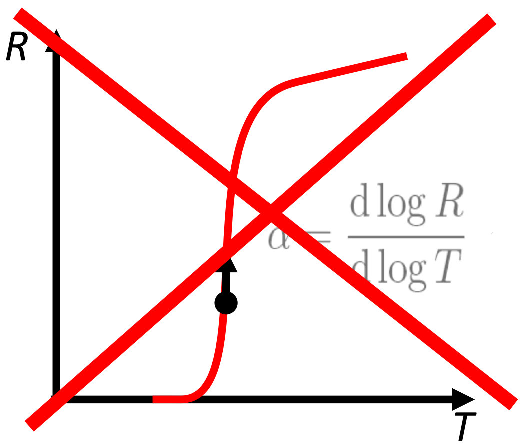
Source: IAEA International Atomic Energy Agency

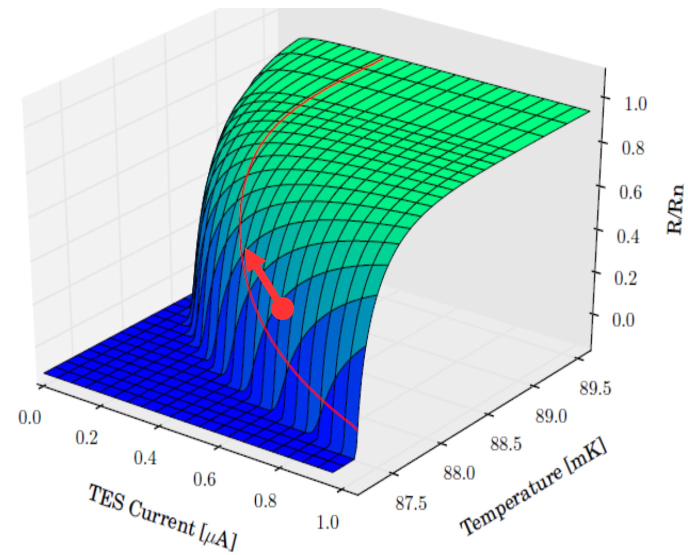
SRON

Transition Edge Sensors Physics: superconducting weak-links

Complex superconducting transition







- Proximity effect from high Tc superconducting leads

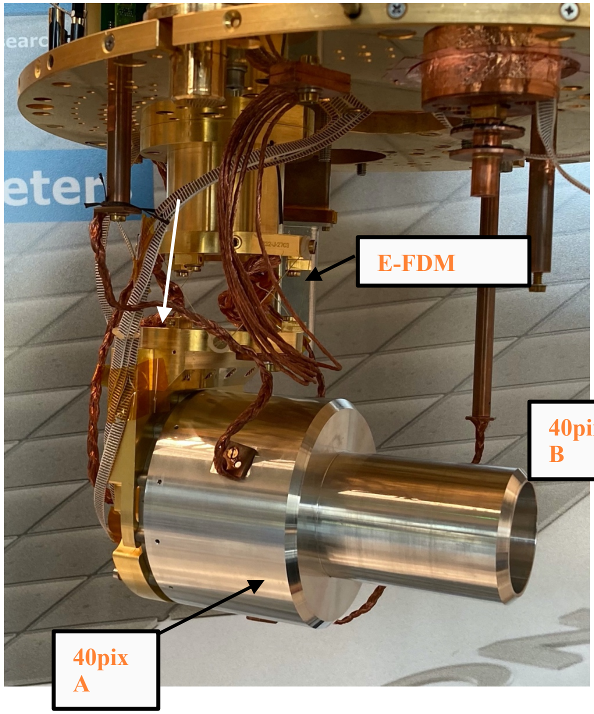
J. Sadleir *et al.* PRL 104, 047003 (2010)
A. Kozorezov *et al.* APL, 99,063503 (2011)
S. Smith *et al.* JAP,114, 074153 (2013)
L. Gottardi *et al.* APL, 105, (2014)
Ullom and Bennet SST, (2015)
R. C. Harwin SST,30,8 (2017)
M.De Wit *et al.* JAP, (2020)
Gottardi *et al.* *PRL* (2021)

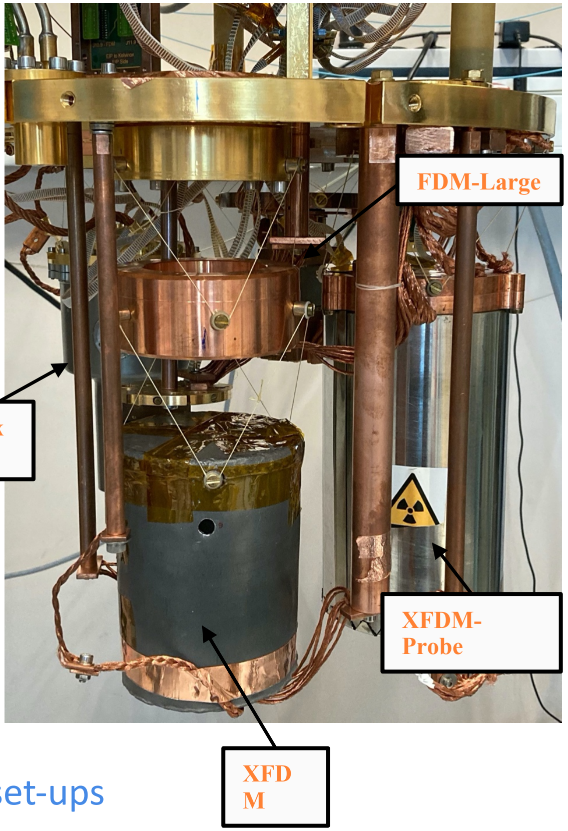
Josephson equations:

$$J = J_c \sin\varphi \qquad \frac{\partial \varphi}{\partial t} = \frac{2e}{\hbar} V_{tes}(t)$$

Transition shape and fluctuations are defined by the phase difference of the superconducting wave functions in the leads

Overview of SRON Leiden lab

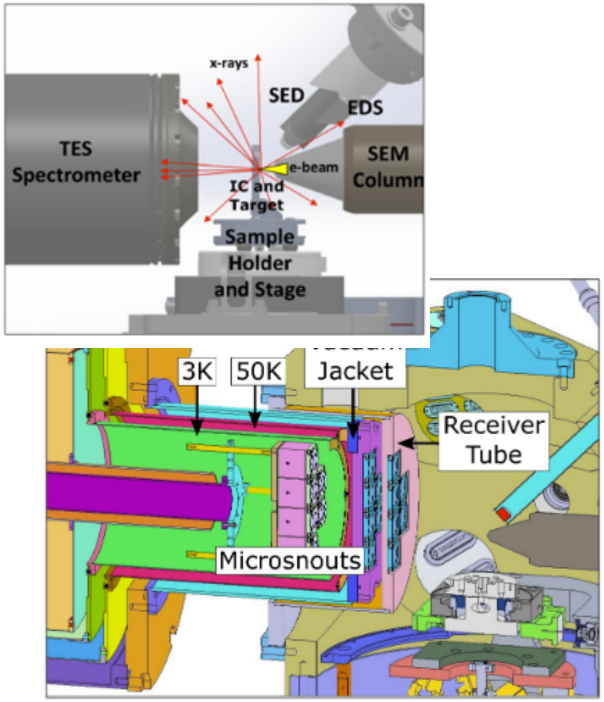




2 Leiden Cryogenics DR with multiple FDM set-ups

SRON

TES X-ray microcalorimeters for material science

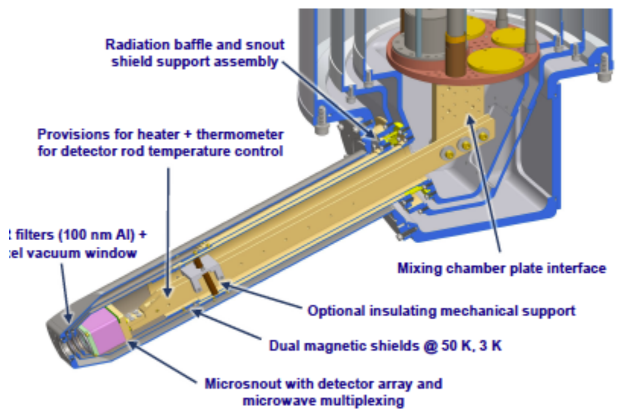


3000 pixels TES spectrometer for Microcircuit tomography

P. Sypryt et al .IEEE TRANS. ON APPL. SUPERC. VOL. 31, NO. 5, (2021)

Hyperspectral X-ray Imaging: Next-Generation TES Microcalorimeters on the SEM

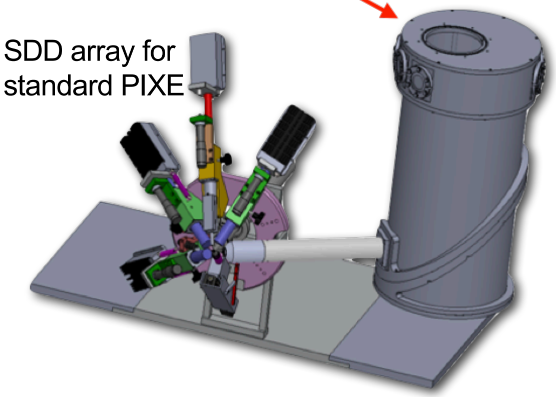
Left: Rendering of HXI instrument attached to the JEOL 7200F SEM in the LANL LTD lab.
Right: BlueFors SD cryostat for the HXI instrument undergoing thermal tests in the LTD lab.



Los Alamos/NIST

High-resolution PIXE spectrometer (TES) *from AHEAD2020 EU H2020 project*

SDD array for standard PIXE



Drawing of the new external beam set-up for atmospehric aerosol analysis at INFN-LABEC, integrating a SDD array with the HR PIXE spectrometer

SRON will deliver chips and electronics

Credits: P. Koshropanah J-W den Helder