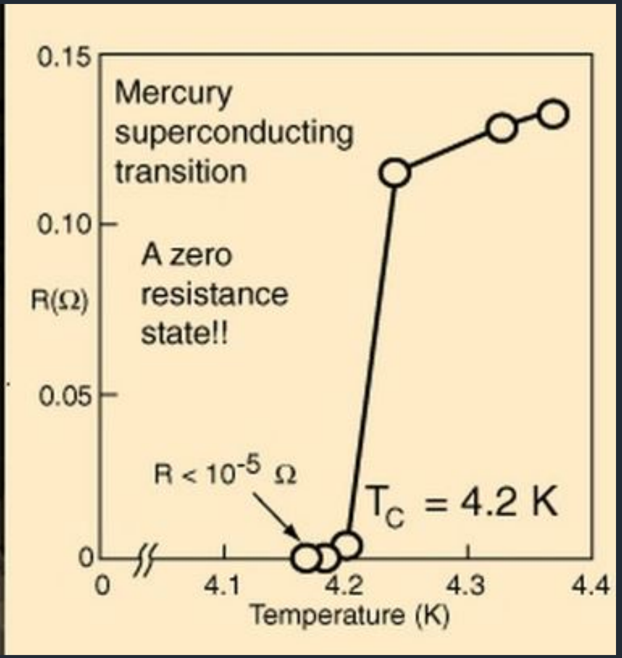
Superconducting high-resolution imaging X-ray spectrometers for space and ground based applications

Luciano Gottardi

Vision, Robotics & Motion, 's-Hertogenbosch, 8 June 2023

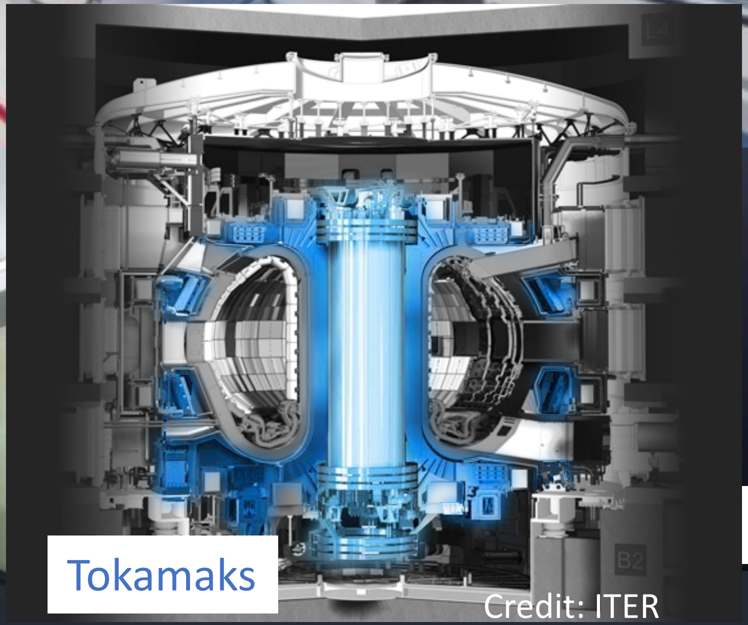
Superconductivity



The superconductivity was discovered in 1911 by Heike Kamerlingh Onnes at the Cryogenic Laboratory at Leiden University.

At 4.2 K (-296°C), he observed a disappearance of resistivity in mercury. His experiments were made possible by the condensation of helium (1908).

Superconductivity is everywhere



Low temperature superconductivity

$$\text{Energy} \propto k_B T$$

$$T \cong 0\ \text{K}$$

Low **Motion**

High **Vision**

SRON

Massive detectors near the absolute zero

The coldest massive objects in the universe

MiniGRAIL (Leiden)
a spherical gravitational waves detector

1.3 Ton CuAl sphere cooled at 65 mK
10^{-19} m displacement sensitivity at 3 kHz

A.De Waard et al., Classical Quantum Gravity 21, S465 (2004)
L. Gottardi et al., Phys. Rev. D. 76, 102005 (2007)

CUORE (GranSasso)
Cryogenic Underground Observatory for Rare Events

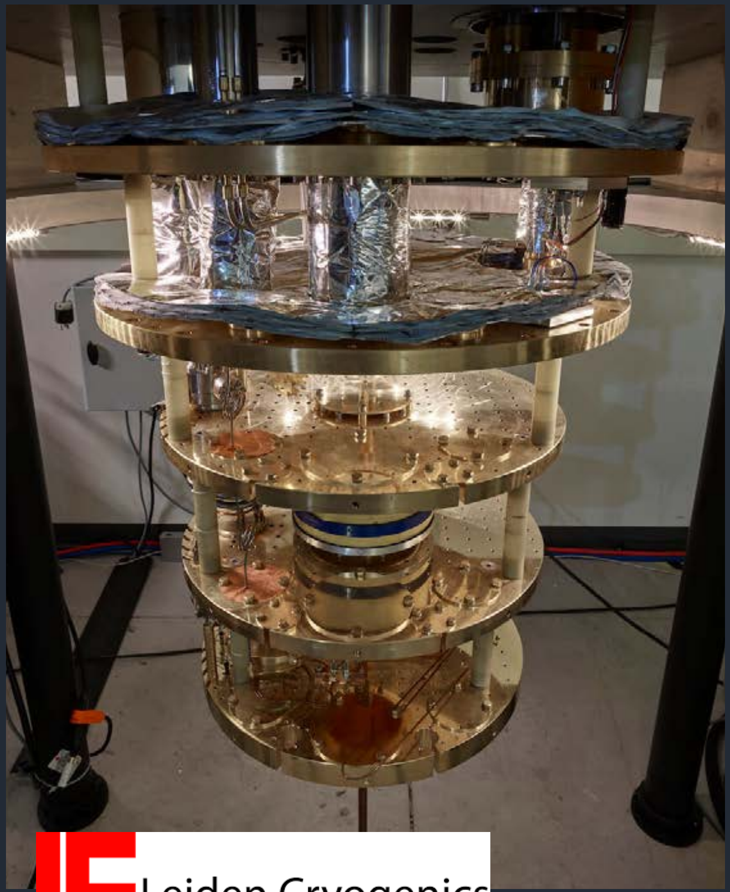
750 Kg TeO_2 crystals + **4 Ton** Cu and lead shields cooled at 10 mK !

The CUORE Collaboration.. Nature 604, 53–58 (2022)

Ultra Low Temperature refrigeration

The Kamerling Onnes' Legacy

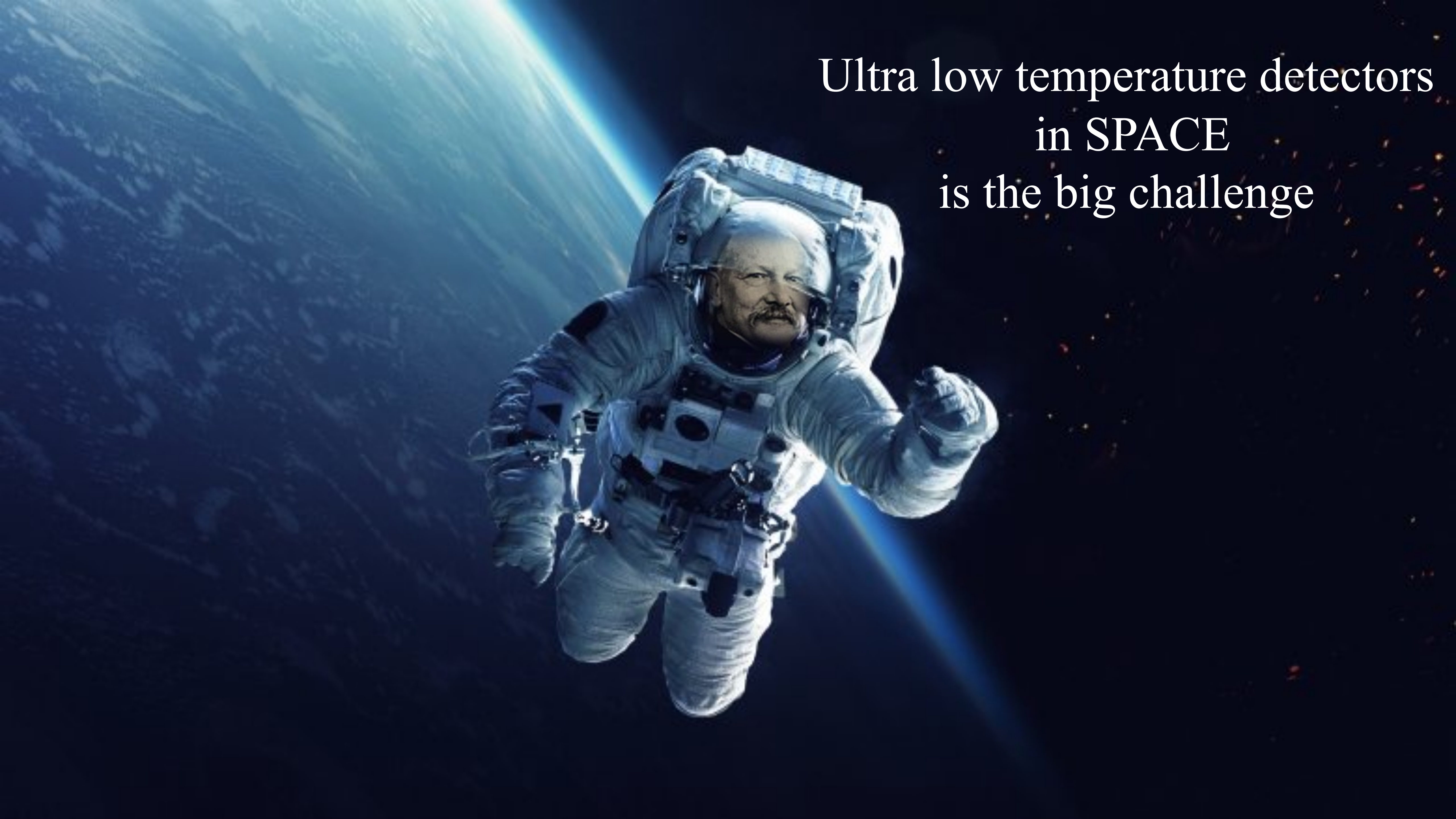
Pioneers and world leaders in ultra low temperature refrigeration



Leiden Cryogenics
Leader in Low Temperature Techniques

BLUEFORS

SRON

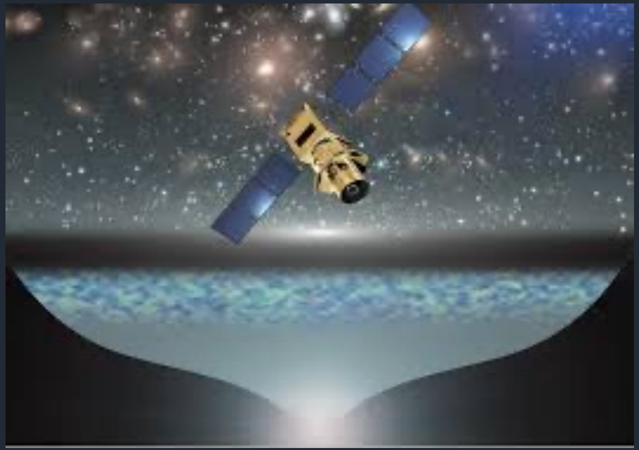

Ultra low temperature detectors
in SPACE
is the big challenge

Large array of superconducting detectors for astrophysics in space

Athena/XIFU (~2035)

ESA large mission to explore The Hot and Energetic Universe

LiteBird (~2028)

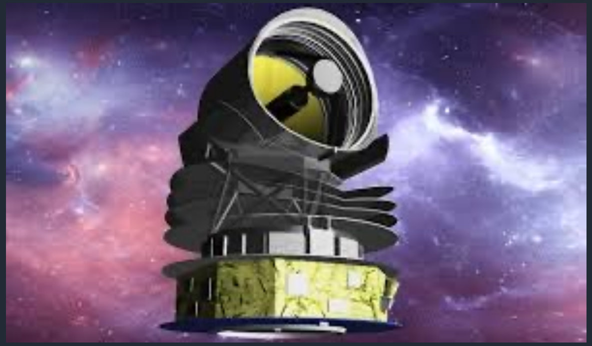


JAXA CMB mission to search for primordial gravitational waves emitted during the cosmic inflation

Hubs

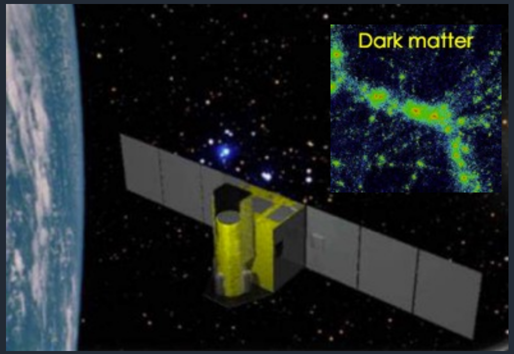
Chinese mission to study ‘missing’ barions in the universe

Spica/SAFARI



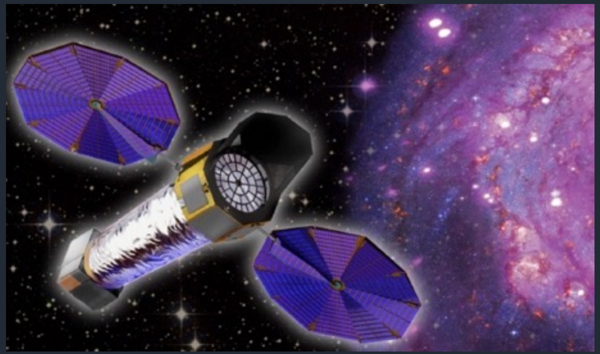
JAXA/ESA infrared space observatories to study formation of stars, planets and galaxies.

SuperDIOS



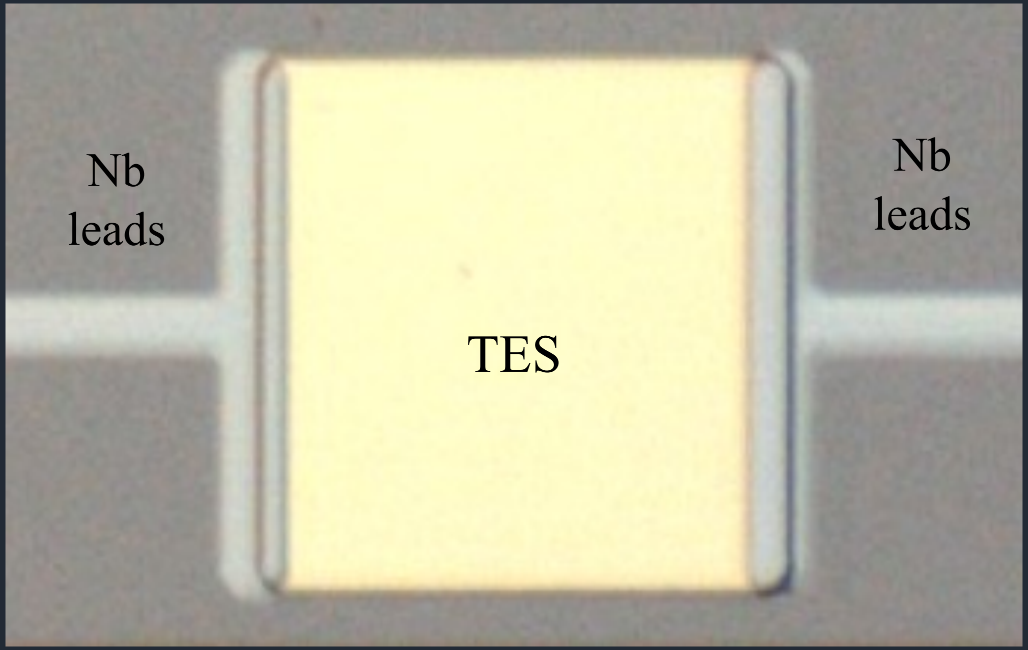
JAXA Diffuse Intergalactic Oxygen Surveyor. An X-ray quantitative exploration of "dark baryon "

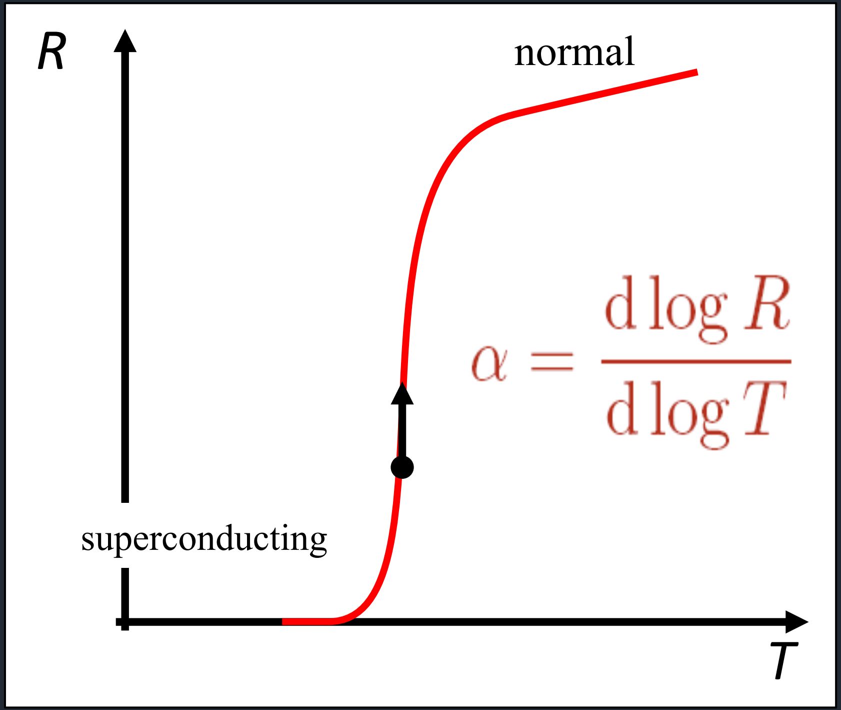
Lynx



NASA X-ray Large telescope
>100000 pixels

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





Thin film superconducting bilayer

Ti/Au, Mo/Au, Mo/Cu

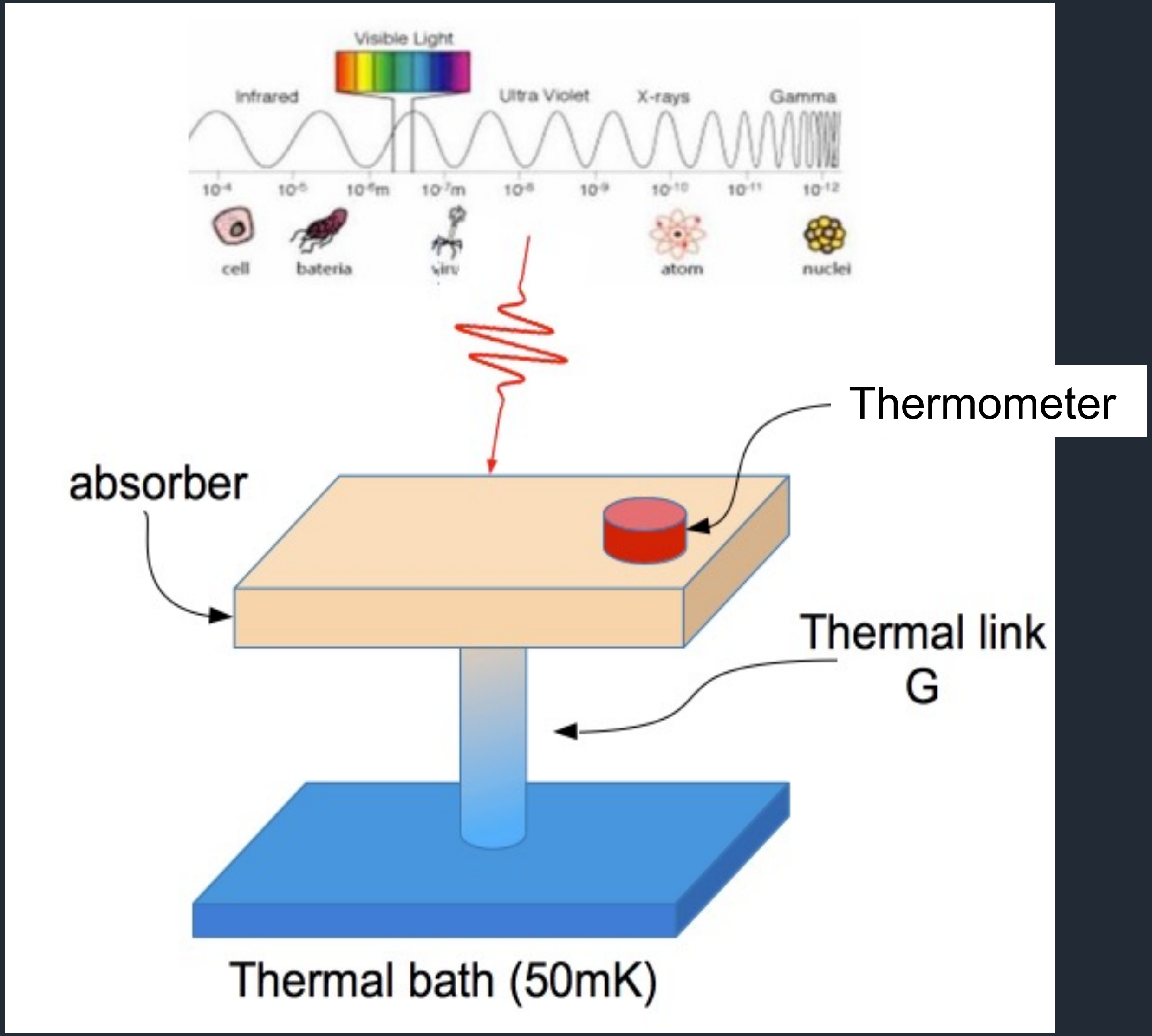
$T_C \sim 90$ mK

D. H. Andrews et al., Phys. Rev. 59, 1045 (1941).

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

SRON

Low temperature micro-calorimeters and bolometers



Fundamental elements:

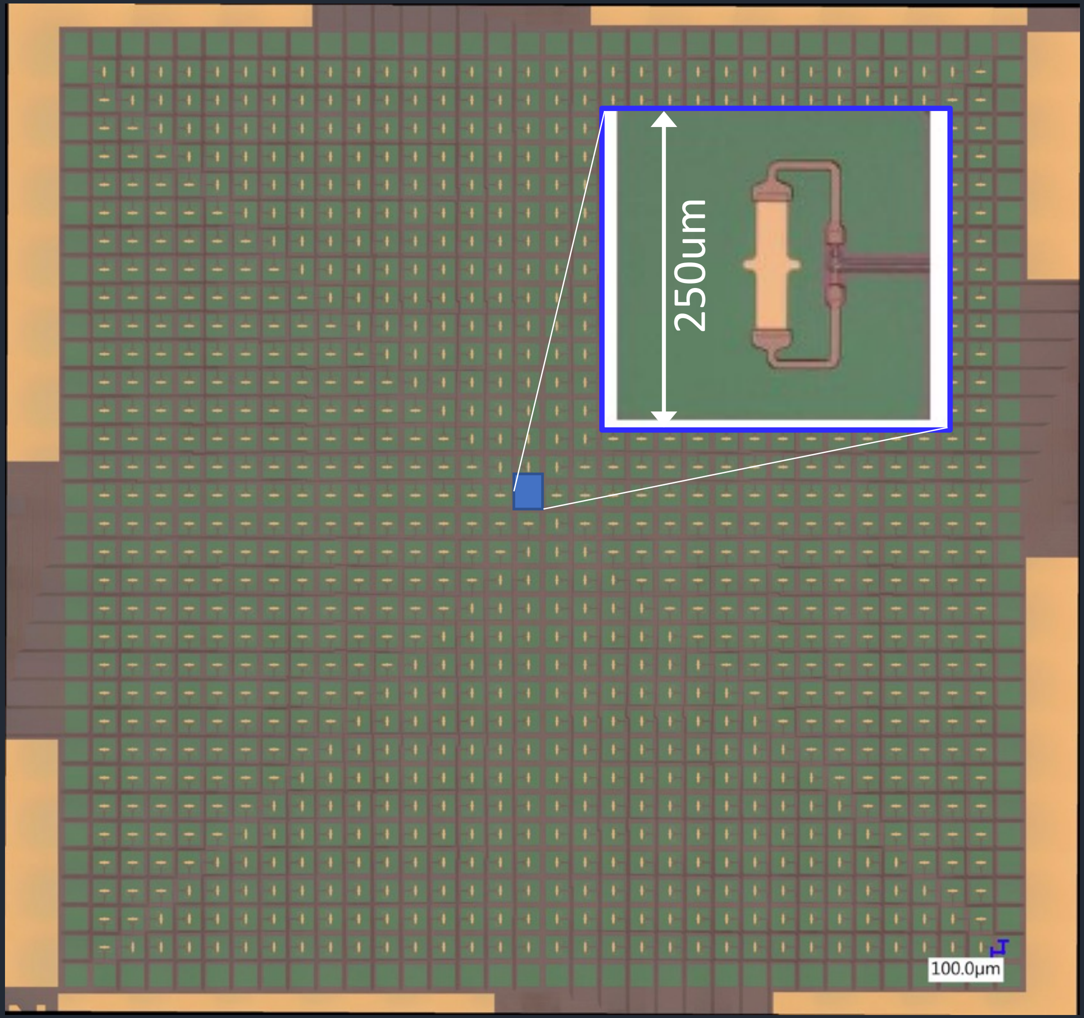
(individually tuneable depending on the applications)

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

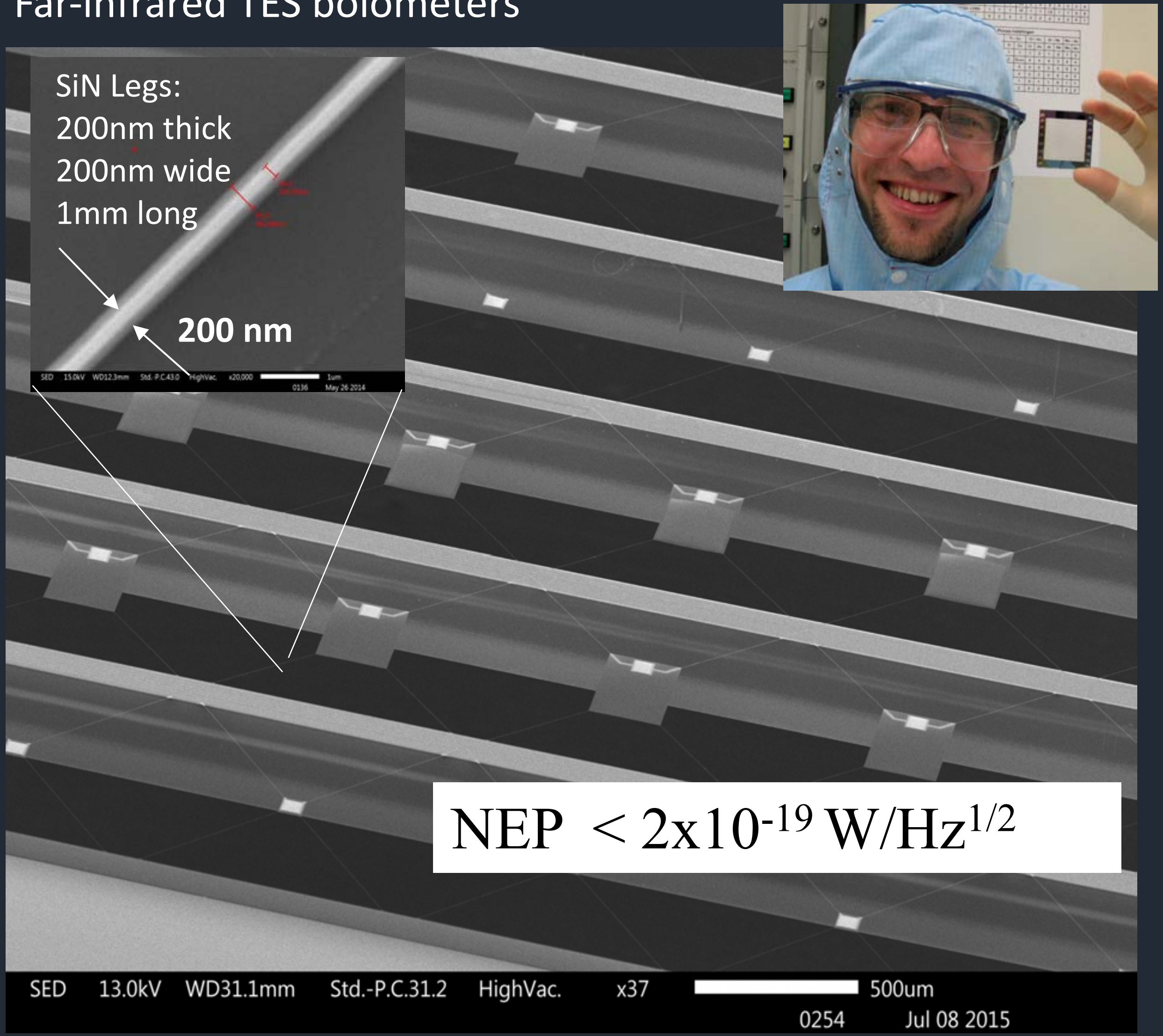
K. D. Irwin, Appl. Phys. Lett. 66, 1945 (1995)

SRON

X-ray TES microcalorimeters



Far-infrared TES bolometers



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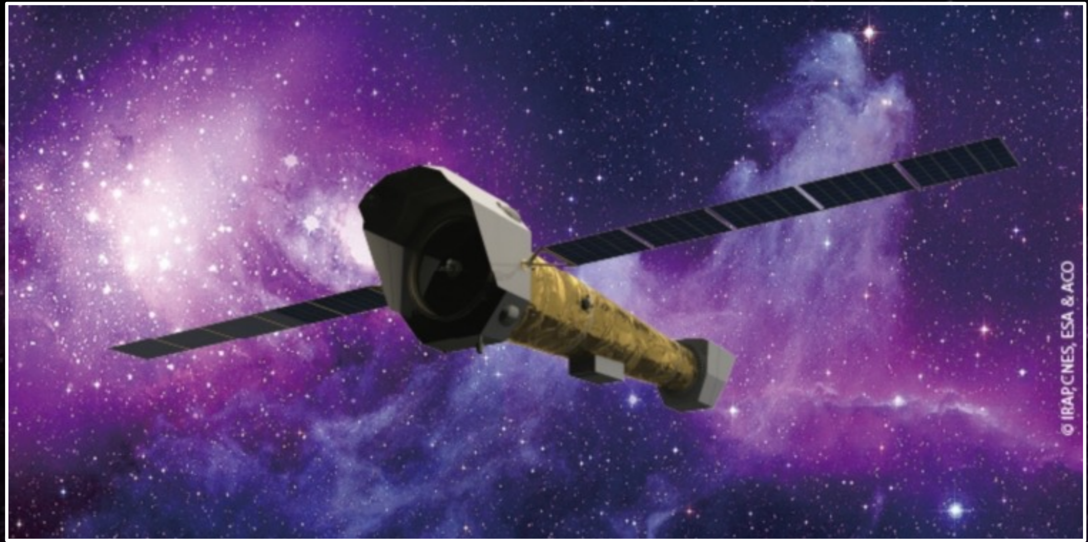
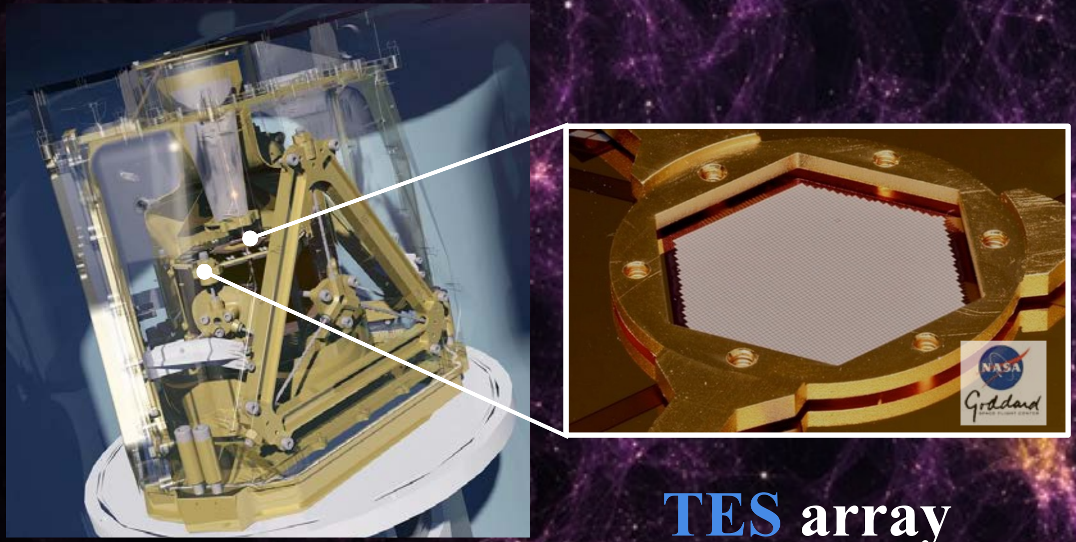
Future X-ray space observatory



- **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

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

Future X-ray space observatory

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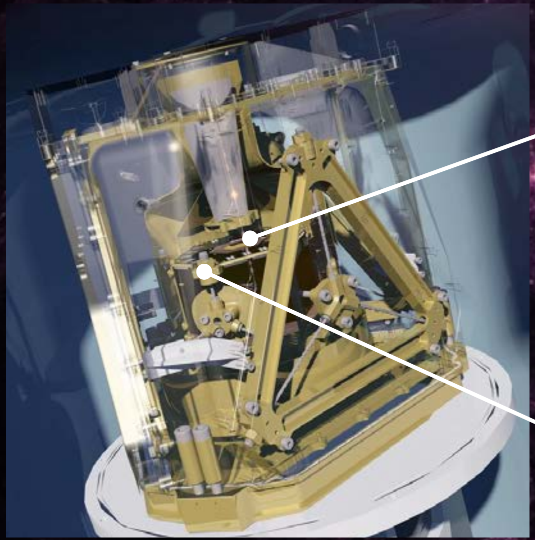
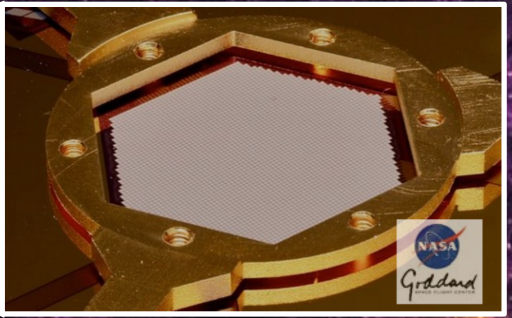
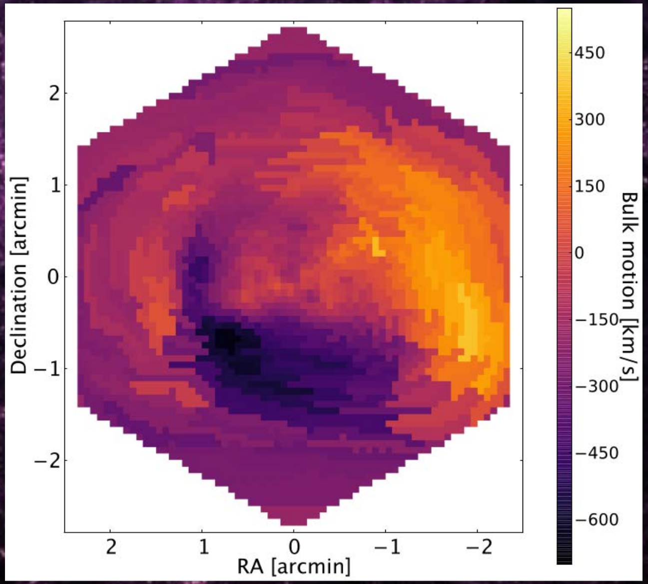
The Hot Universe

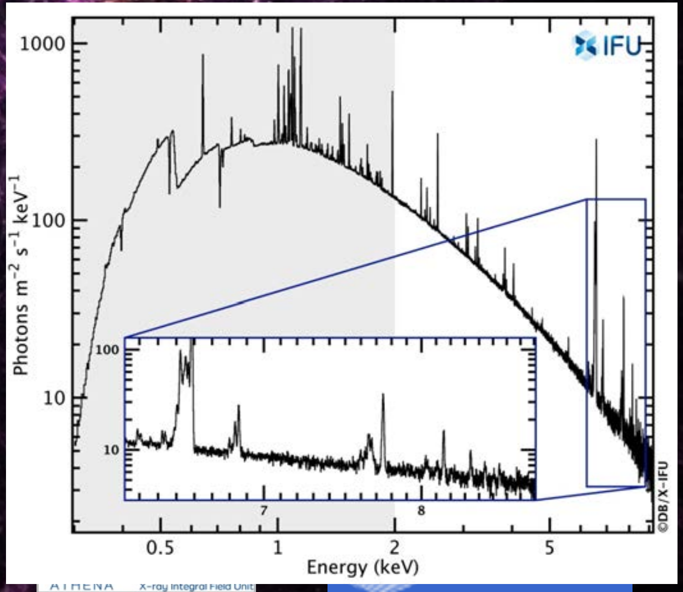




TES array

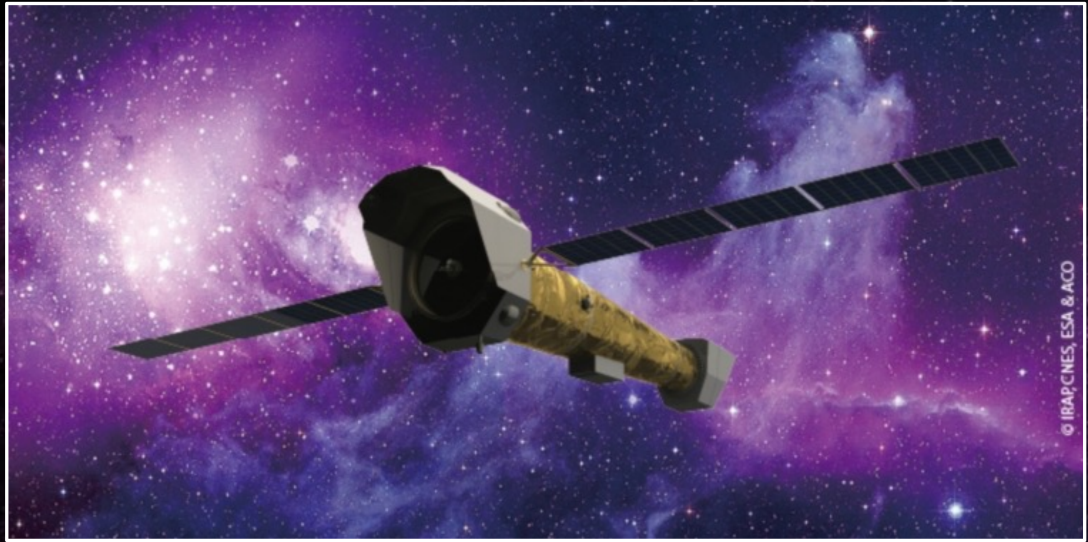
X-ray **I**ntegral **F**ield **U**nit





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

Future X-ray space observatory



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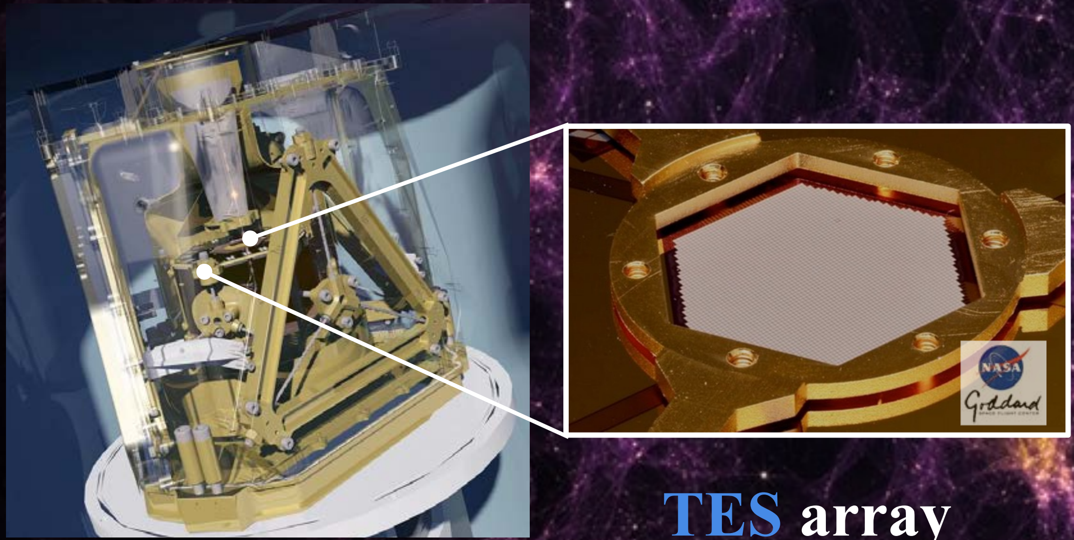
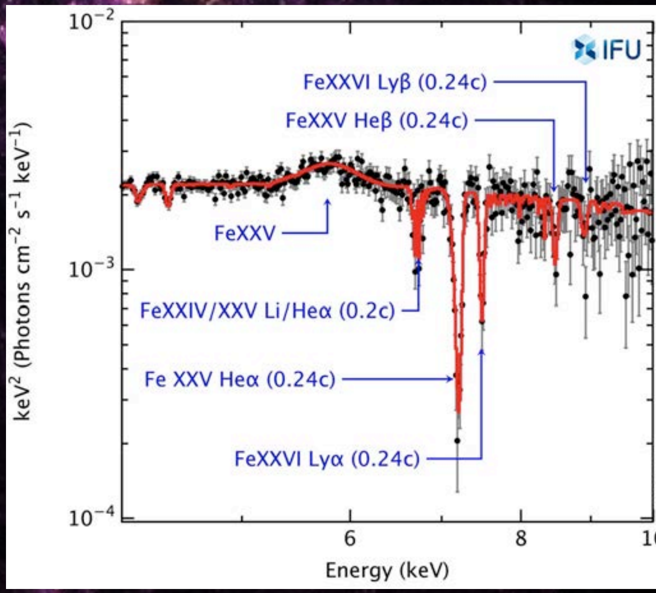
The Energetic Universe



TES array

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



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

Future X-ray space observatory

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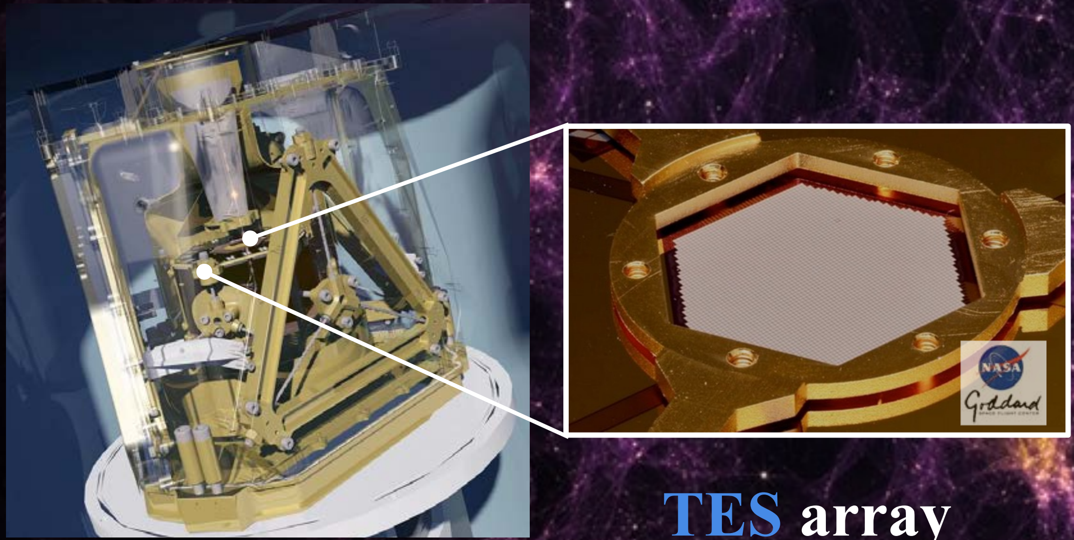
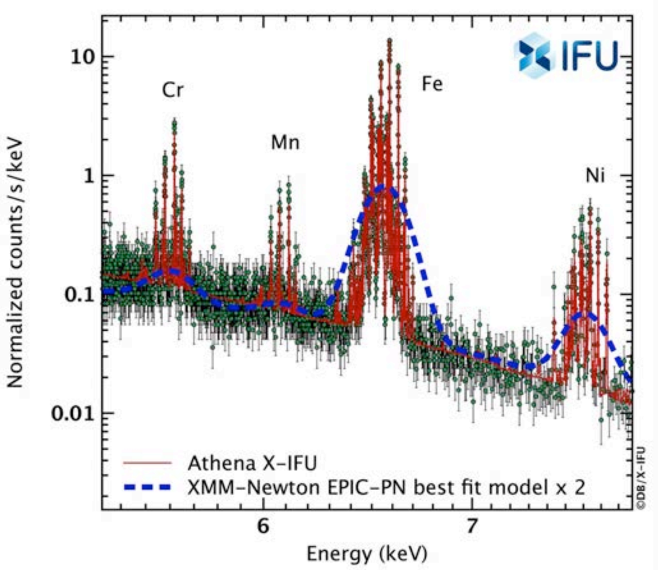


TES array

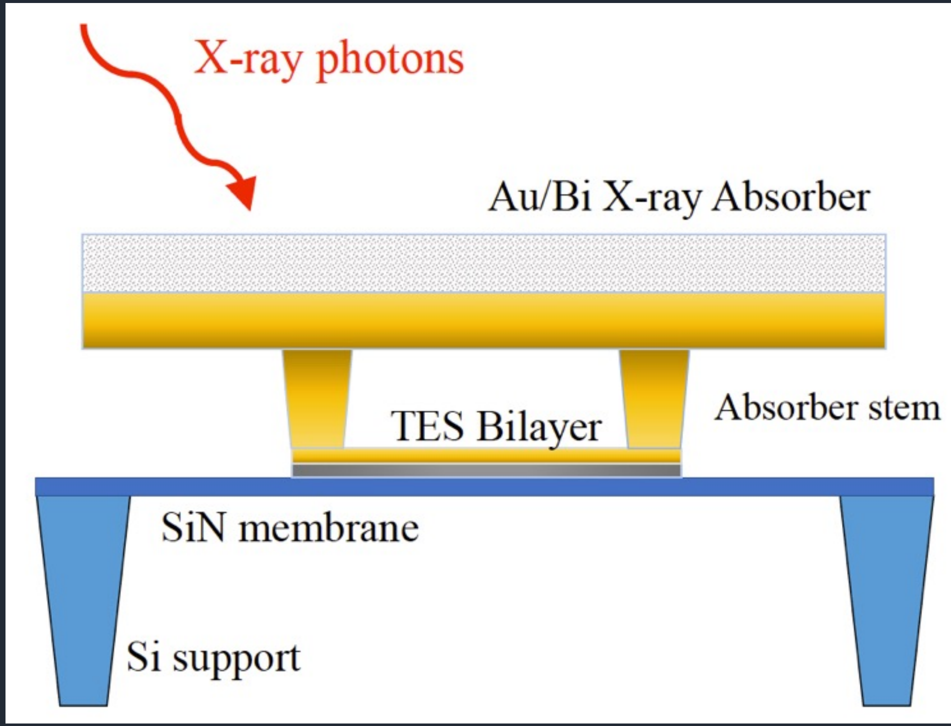
X-ray **I**ntegral **F**ield **U**nit

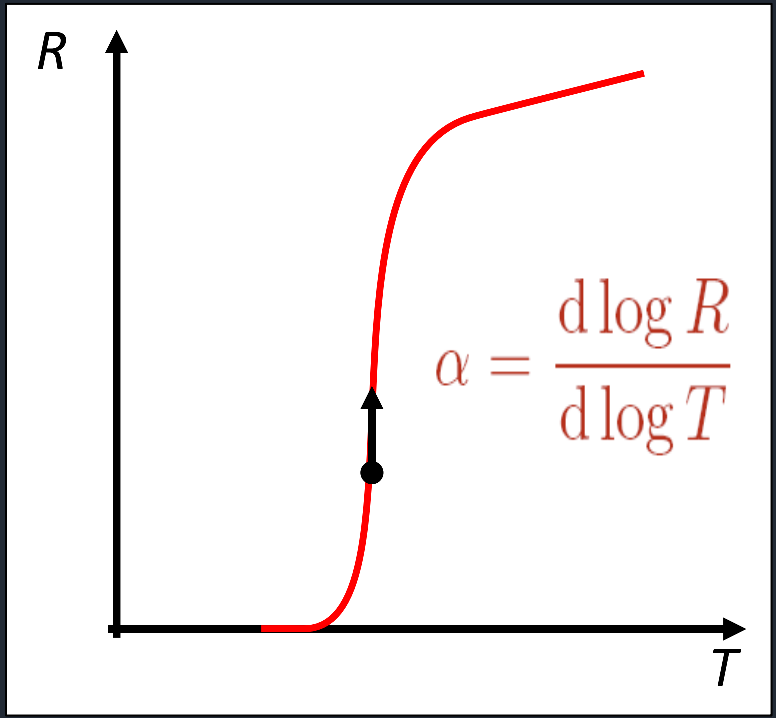
Observatory Science



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

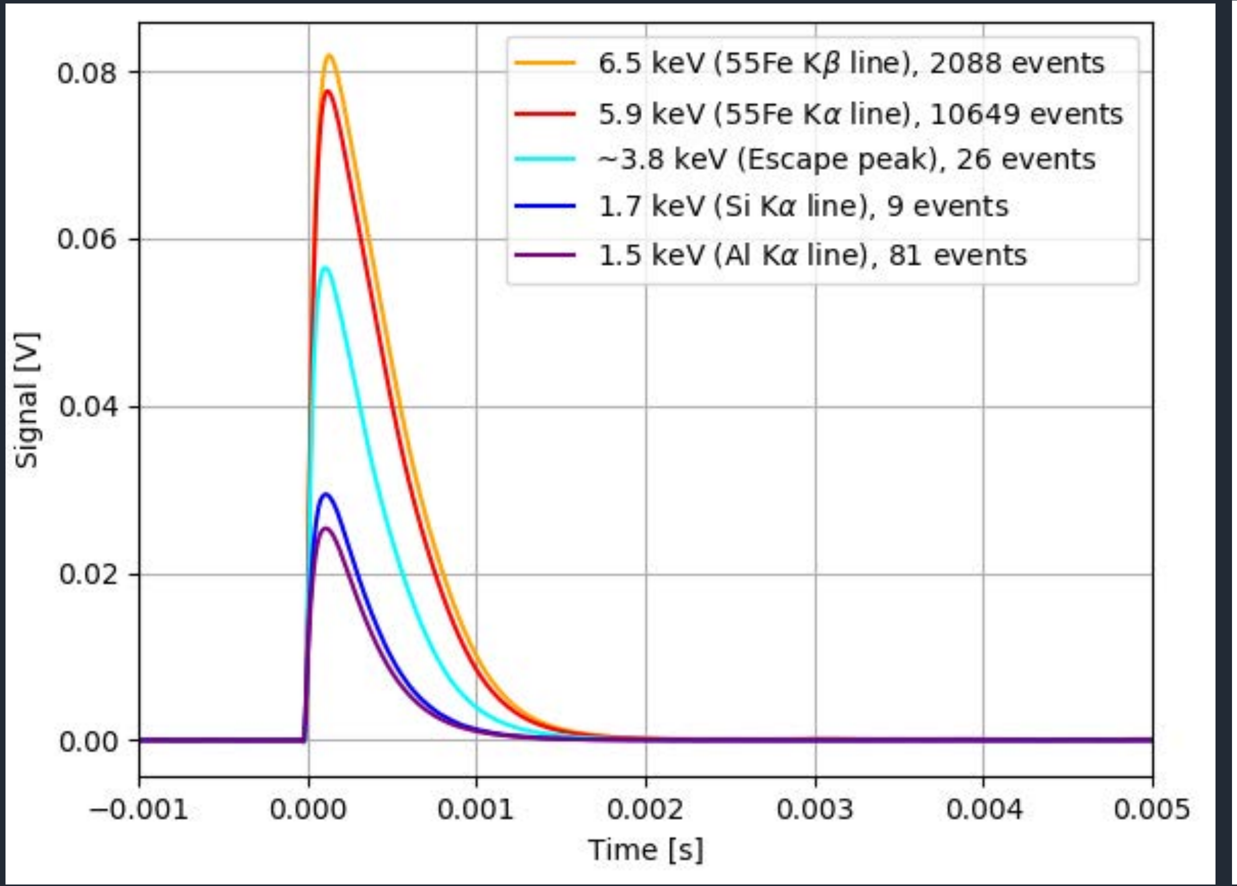
Energy resolution:

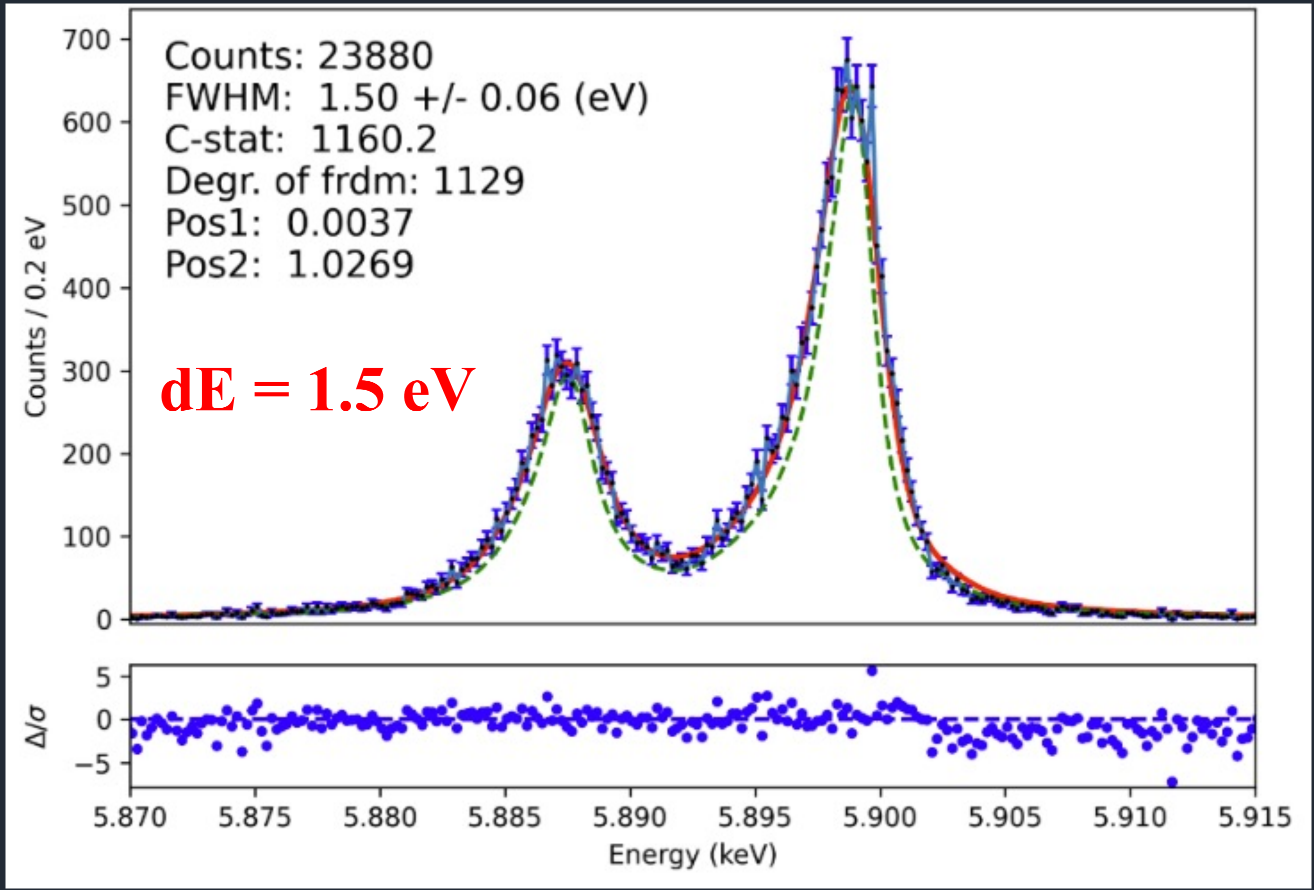
$$E_{FWHM} \sim 2.355\sqrt{\frac{4k_B T_c^2 C}{\alpha}}$$

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 X-ray microcalorimeters





Single photon detectors

High resolving power

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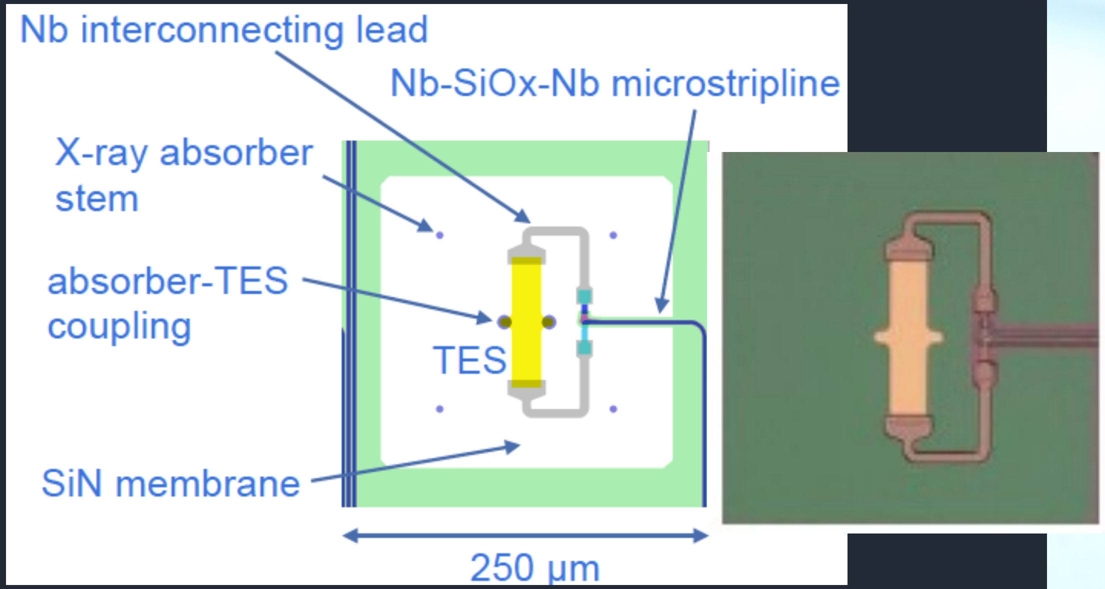
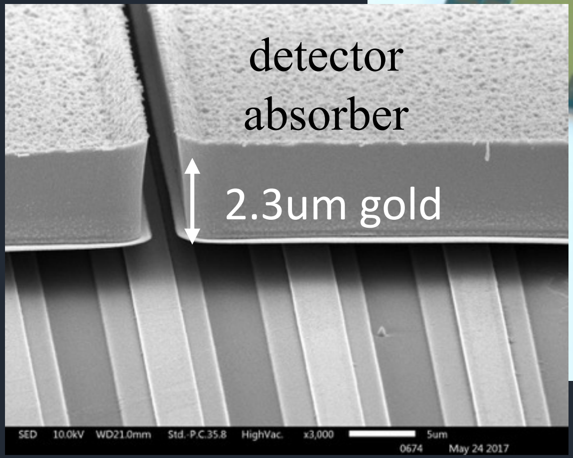
X-ray TES microcalorimeters for XIFU

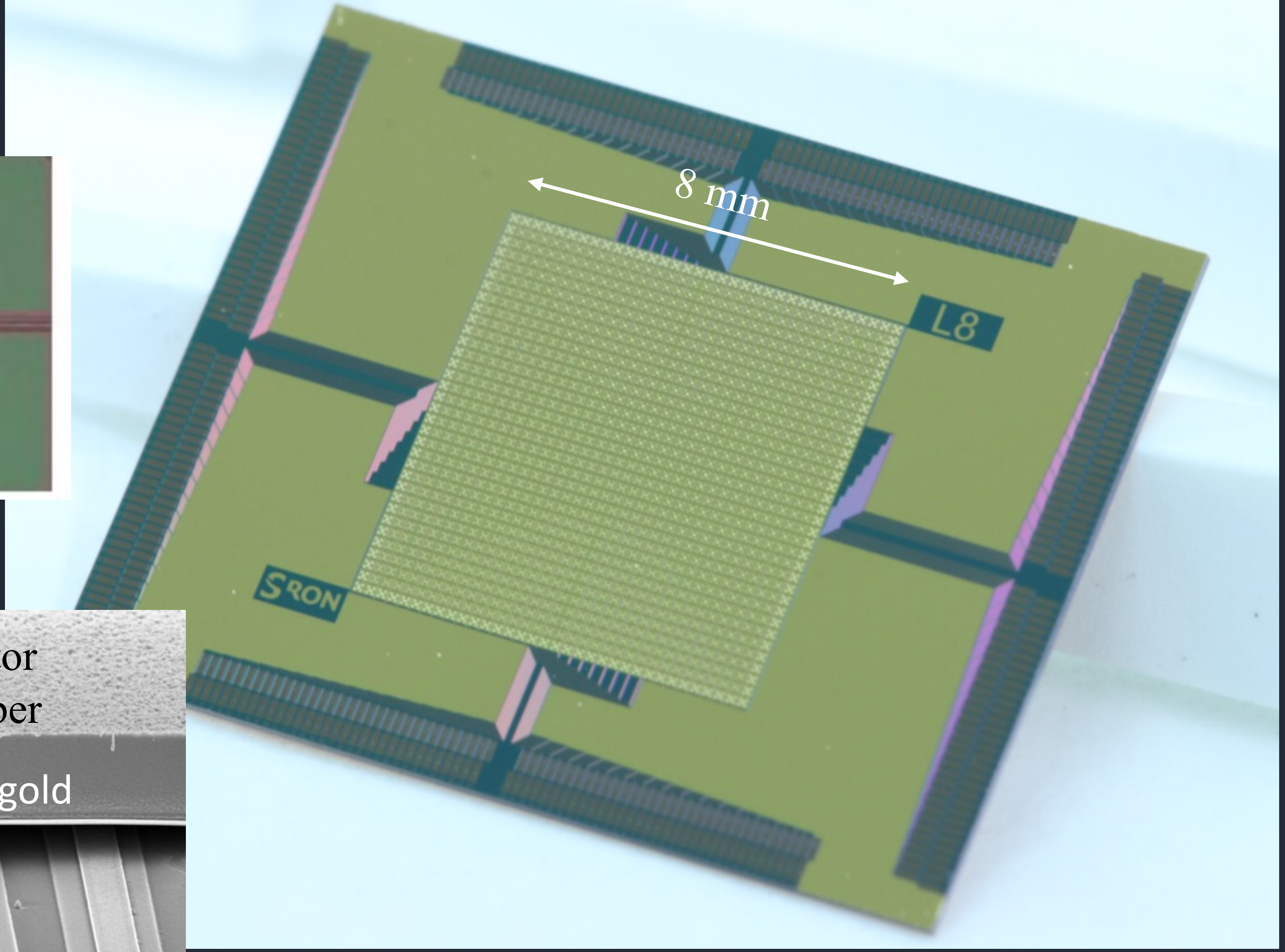


SRON TES:

- Ti(35nm)Au(200nm) bilayer
- Tc~ 90mK
- Normal resistance ~100-300mΩ

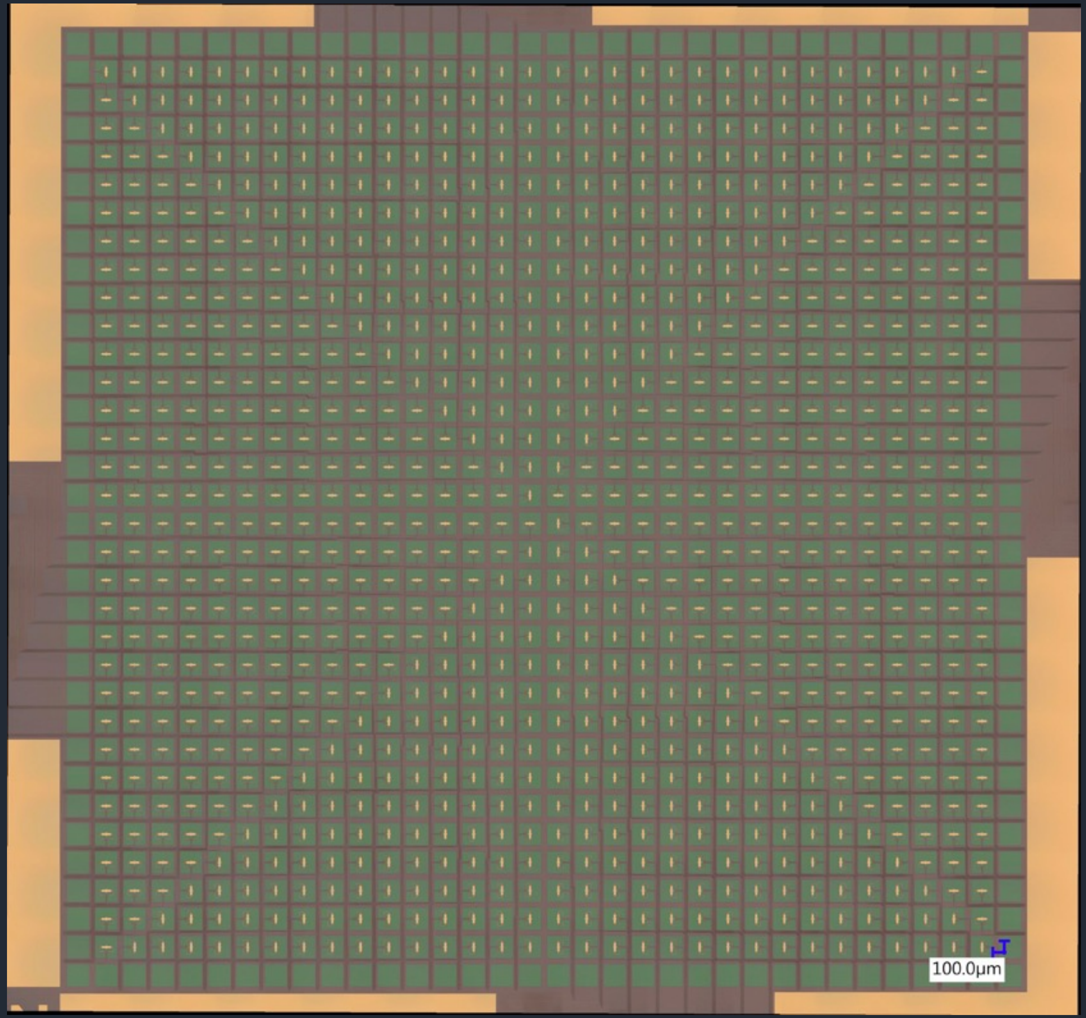


Nagayoshi et al, J. Low Temp. Phys. 199, 2019

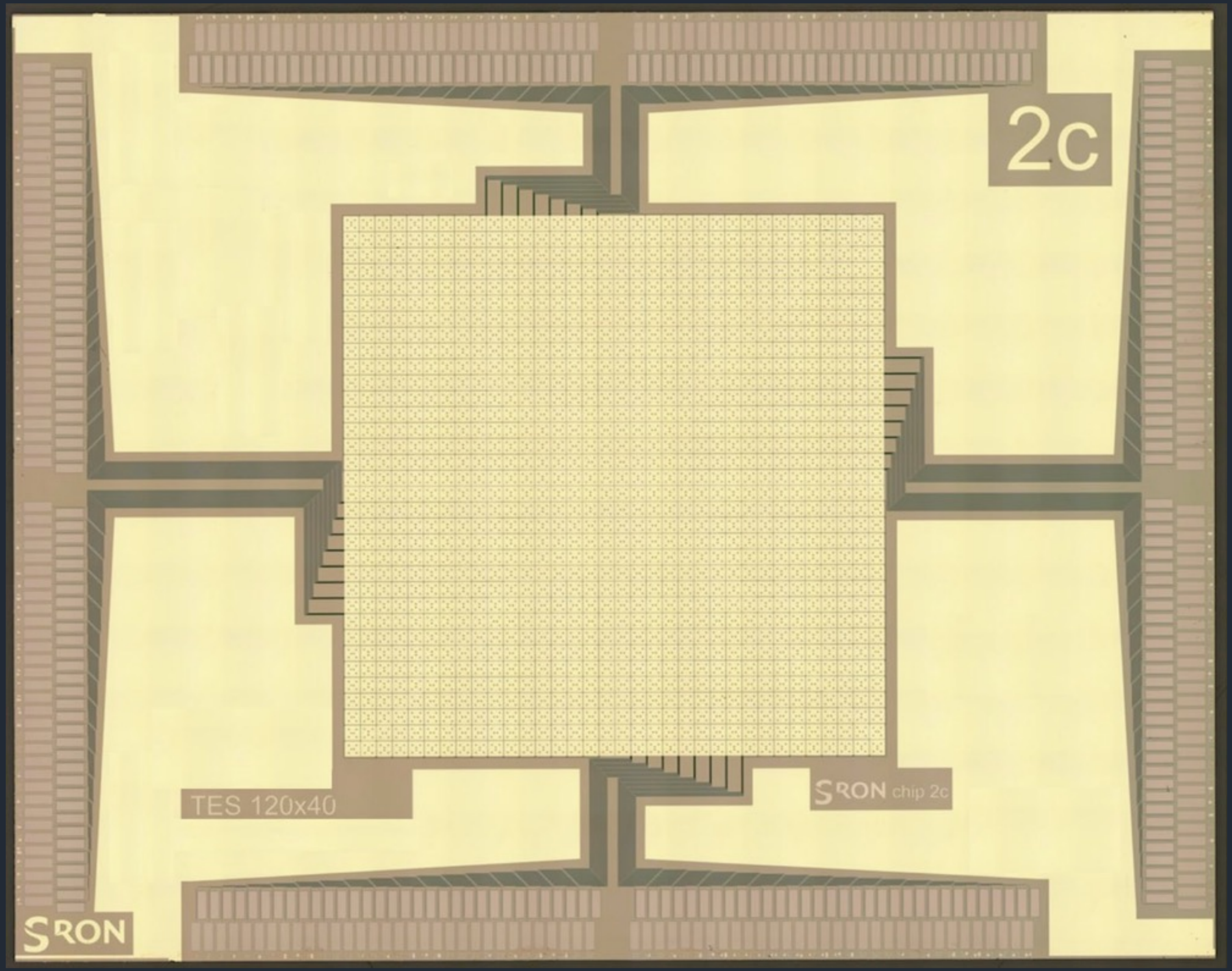


SRON 32x32 TES pixels array with Au absorbers

X-ray TES microcalorimeters for XIFU



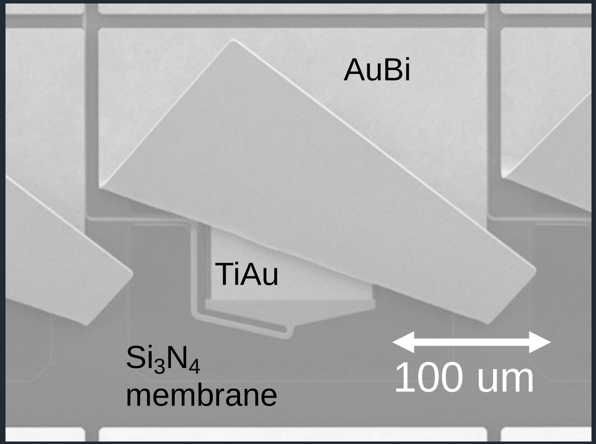
Micrograph SRON 32x32 array before absorber deposition

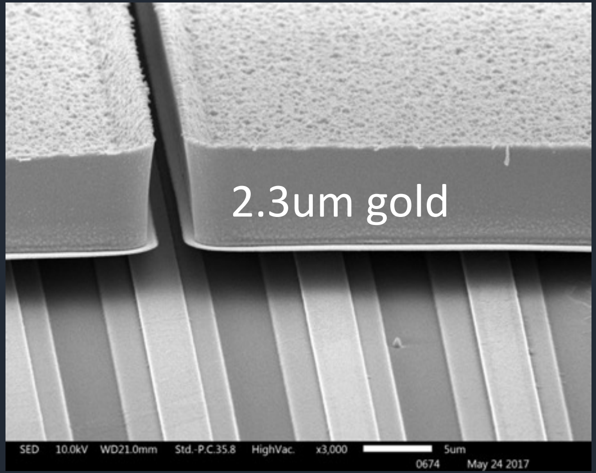


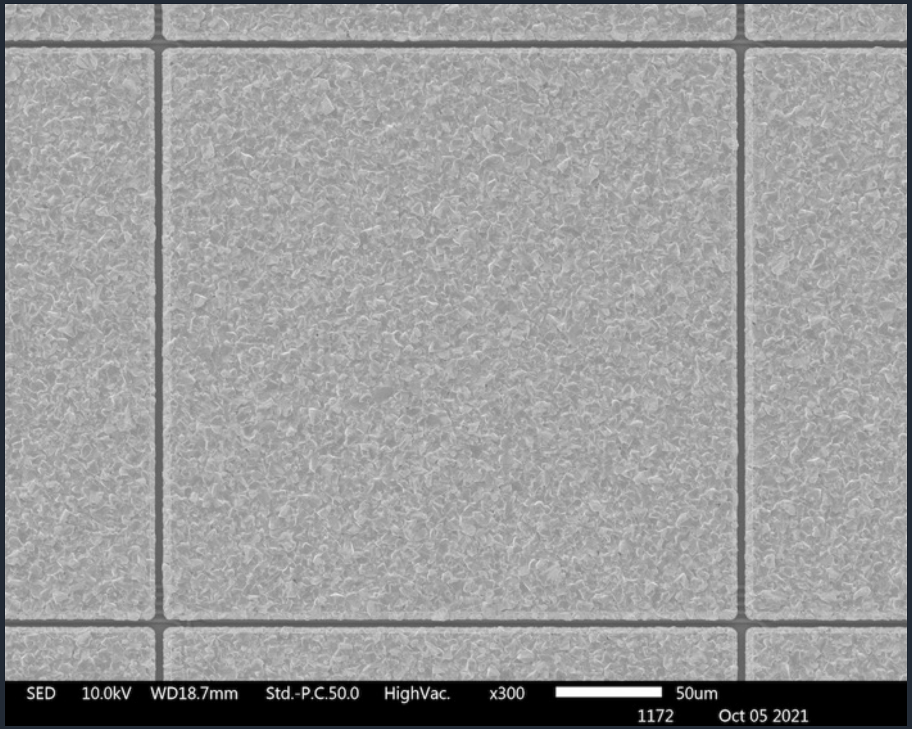
Final chip SRON 32x32 X-ray microcalorimeters

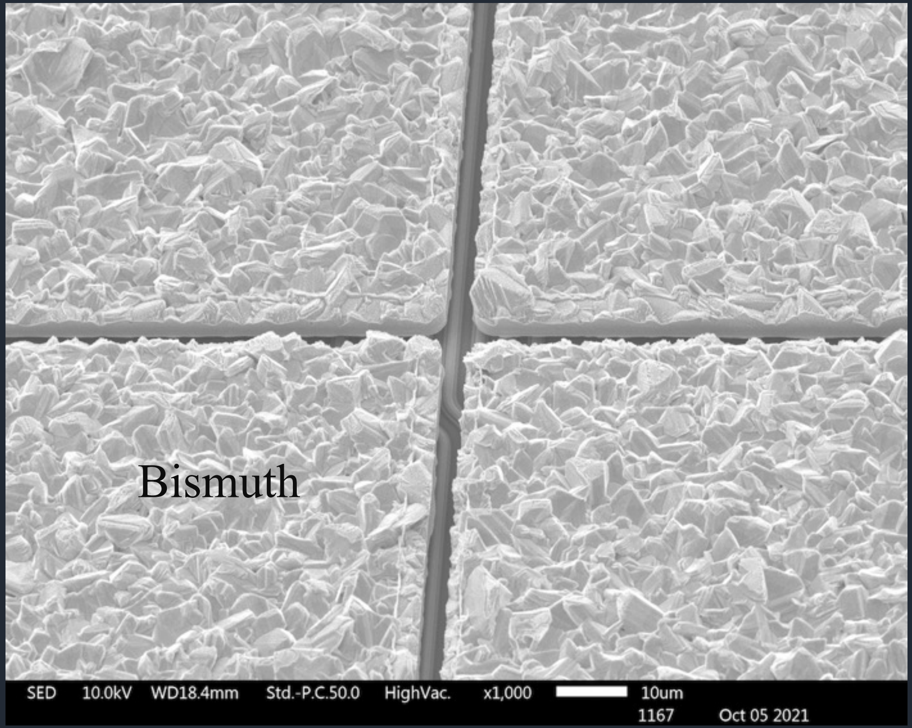
Nagayoshi et al, J. Low Temp. Phys. 199, 2019

High filling factor and high quantum efficiency using Au/Bi







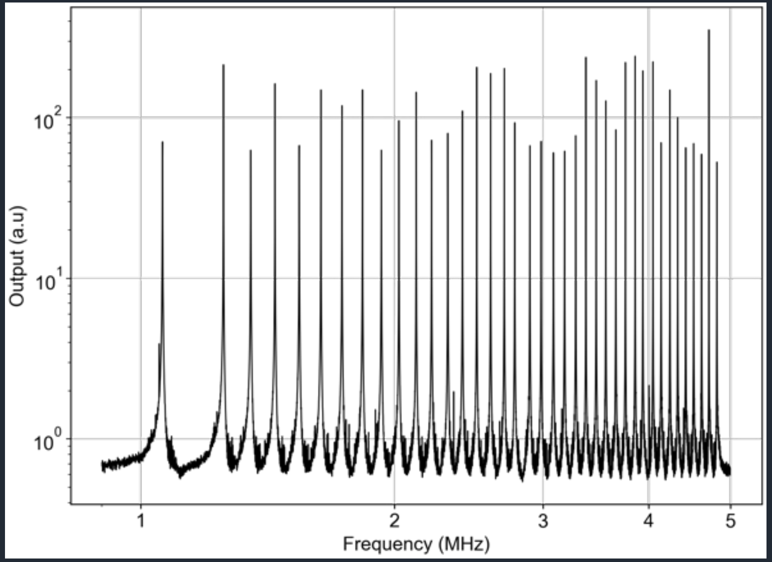


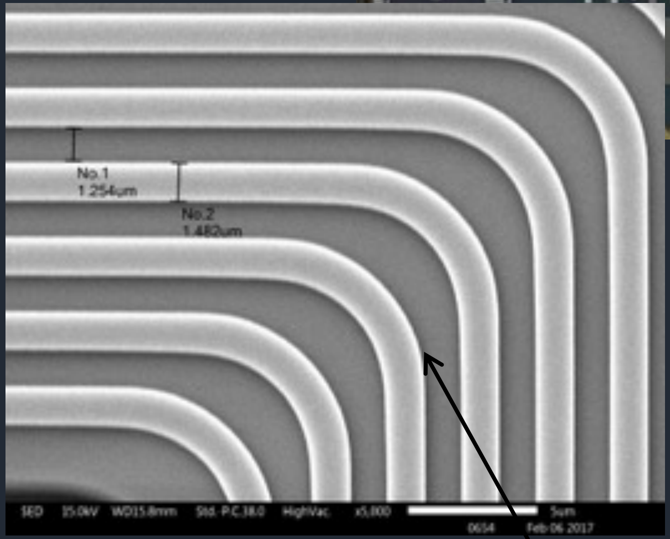
- 2.3 μm electroplated Au absorber QE ~ 83%
- Adding 4 μm electroplated Bi QE → ~ 97%

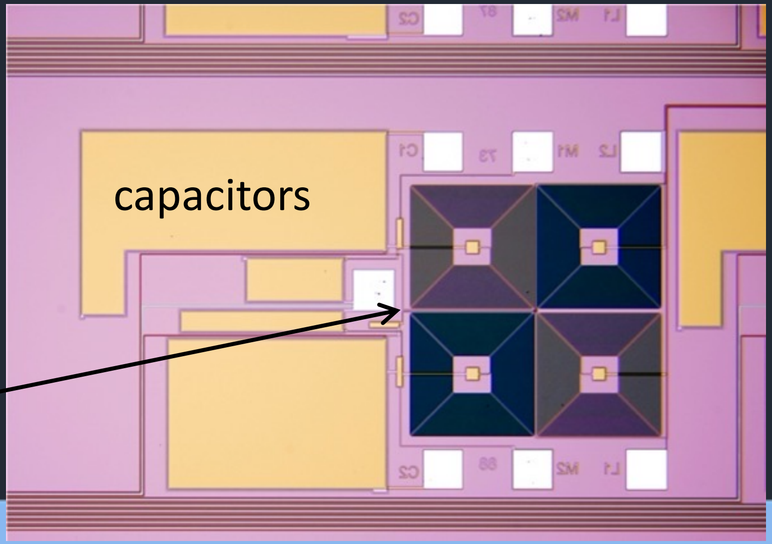
Superconducting high-*Q* MHz LC filters

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

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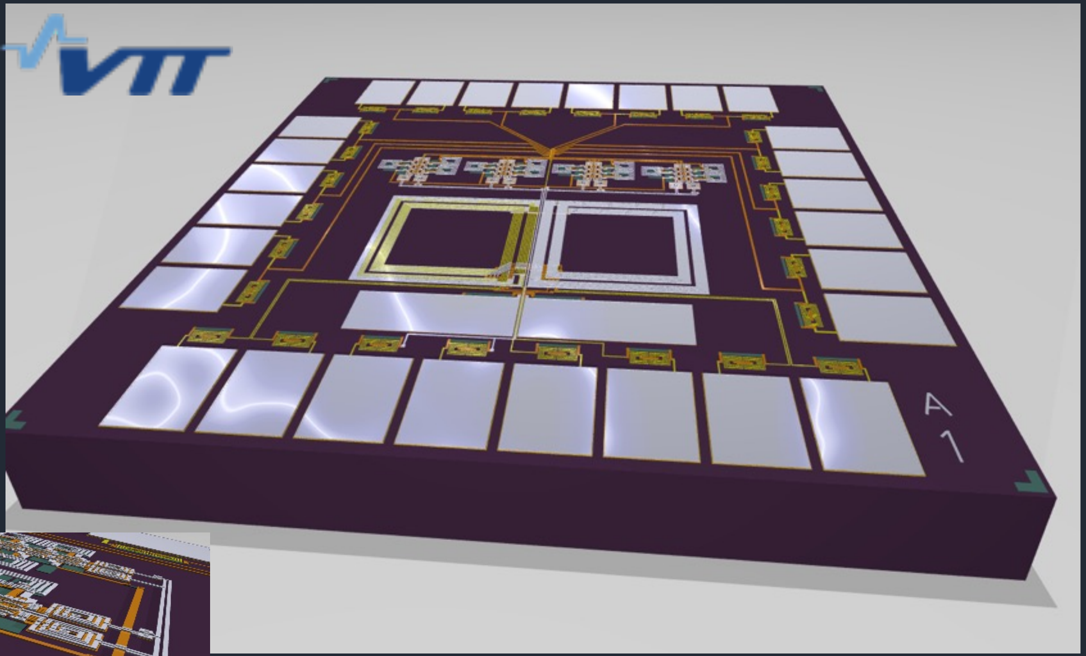
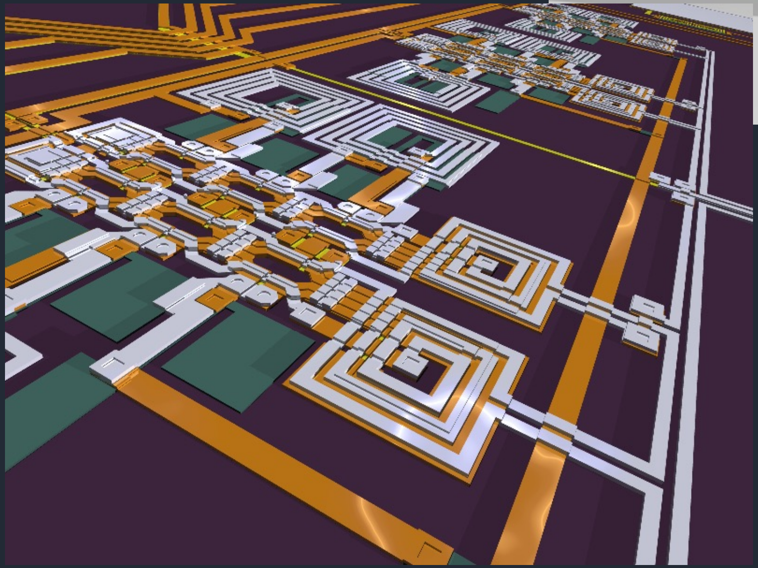
Superconducting QUantum Interference Devices

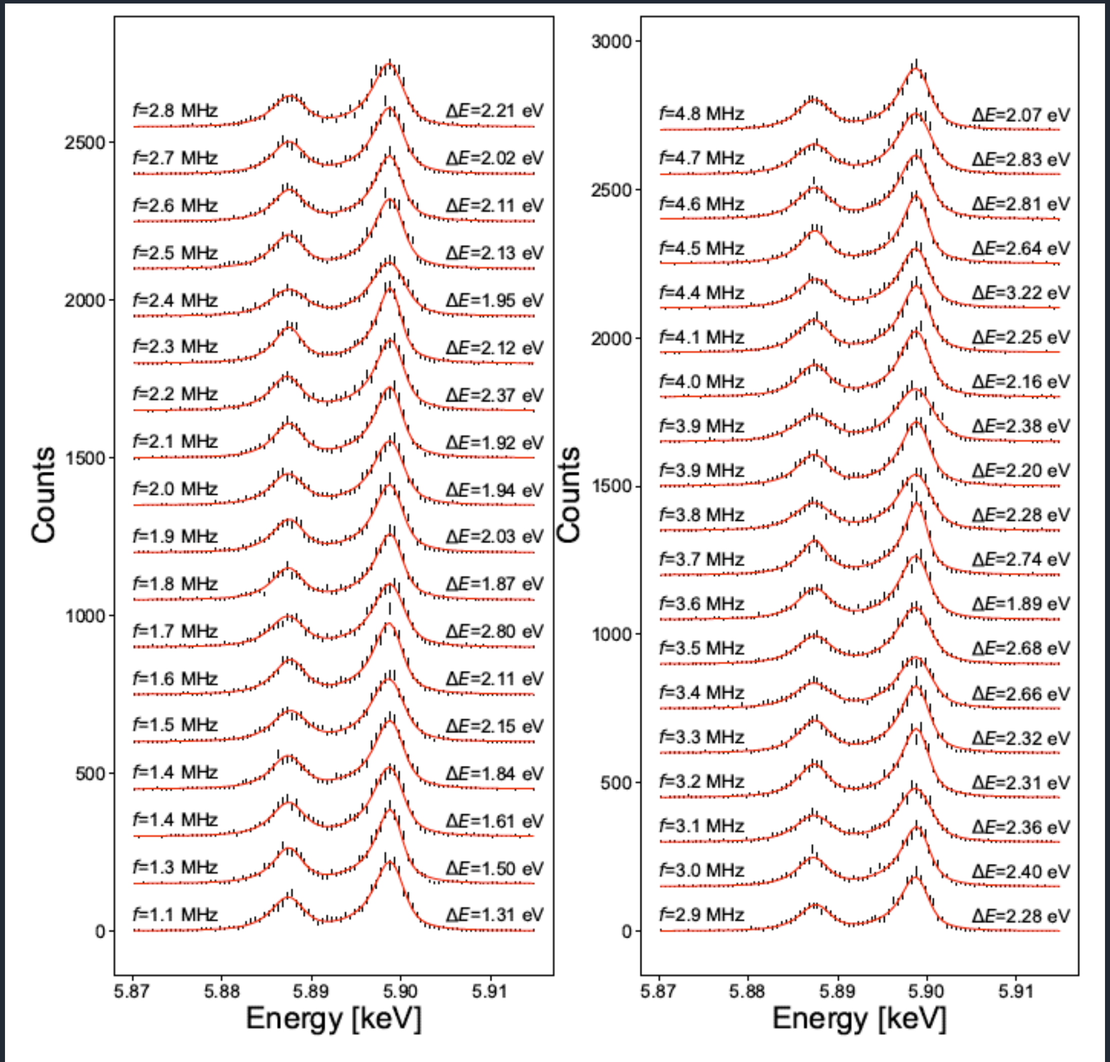
- Nearly Quantum Limited current amplifiers
- Low power dissipation (<1nW) to be used in space
- Gradiometric design
- Low input inductance to minimize signal cross talks

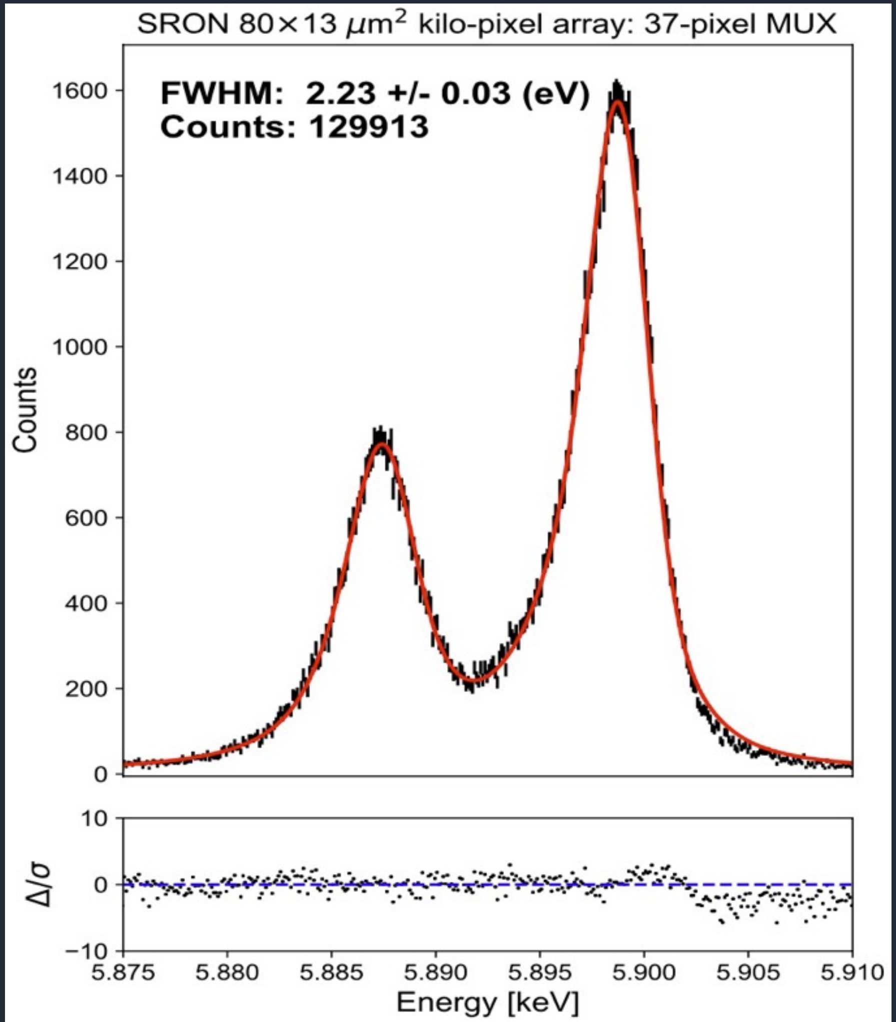




Credits: Mikko Kiviranta, VTT, Finland

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)

SRON

SRON Leiden Cleanroom

E-beam evaporator, cluster tool, LLS

Lithography area

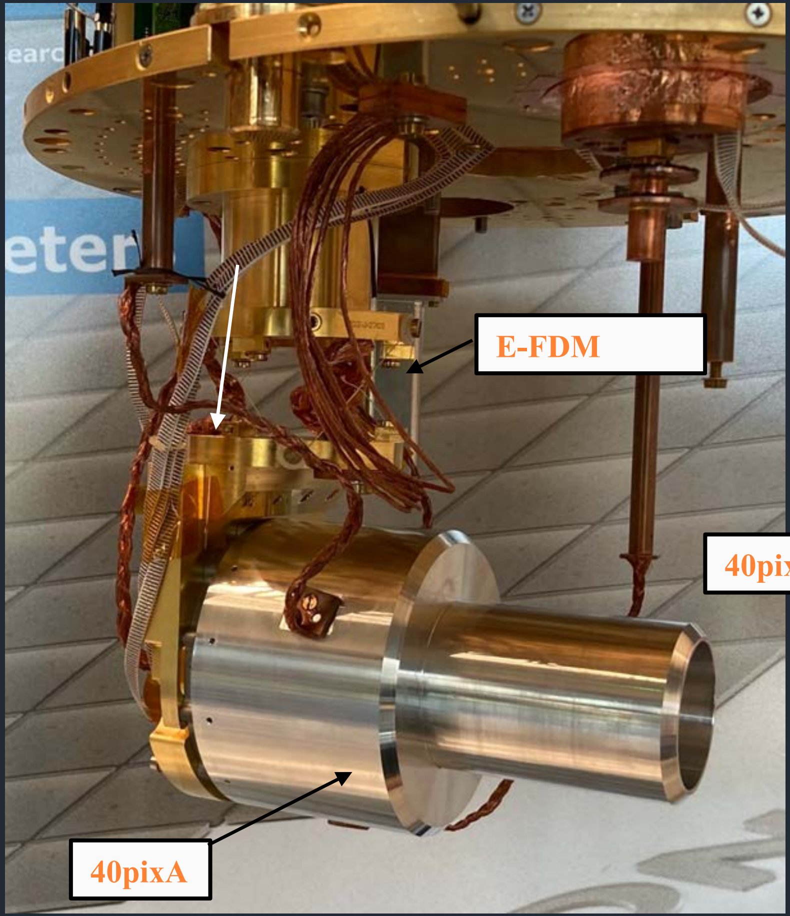
Politeknik: cluster sputter tool

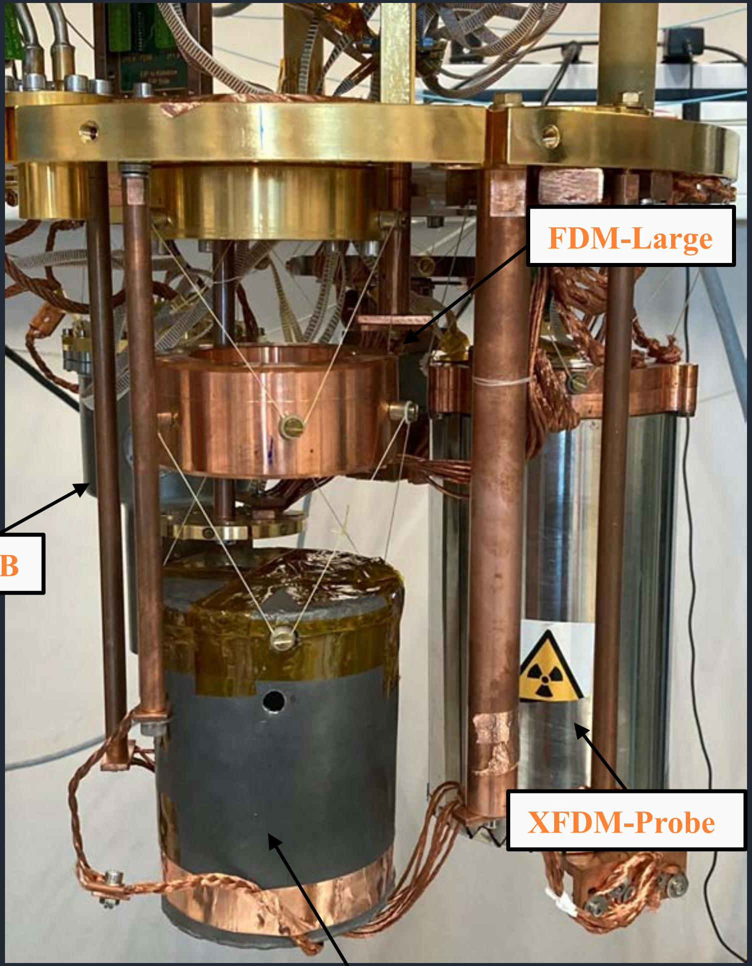
Evatel sputter tool: Nb,Ta,Cu,Al,SiO2,NbTiN,TiN

SRON

Courtesy Marcel Bruijn

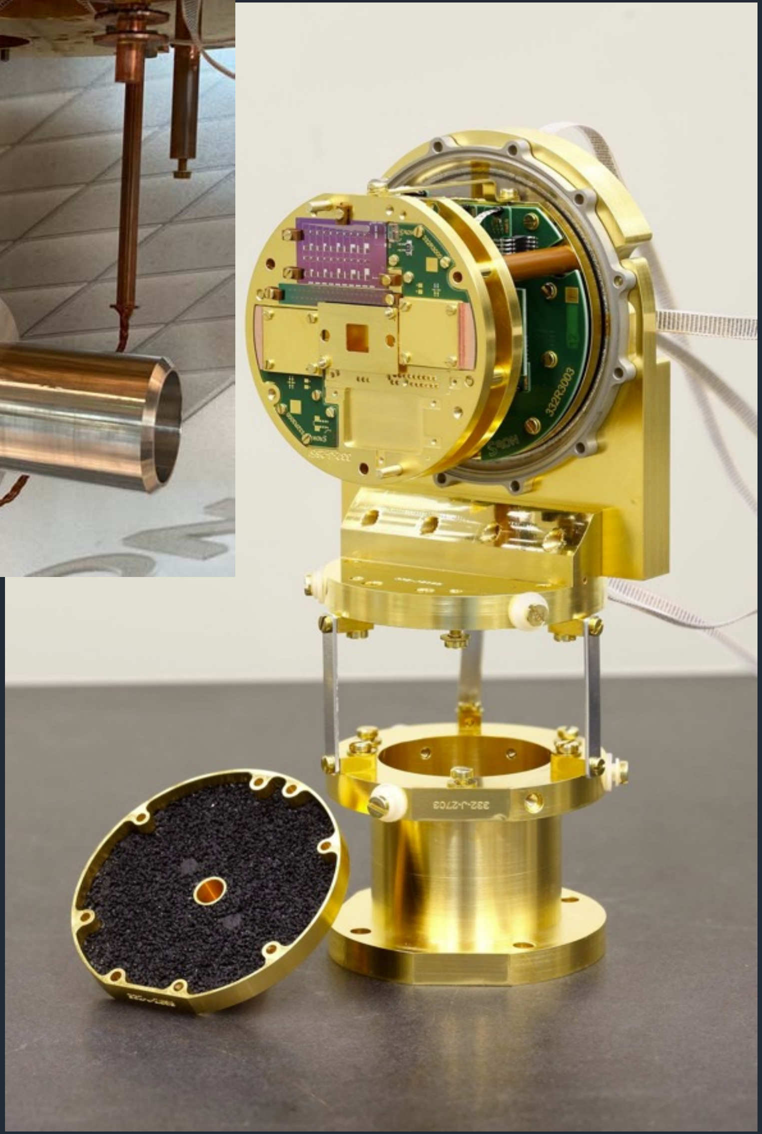
Overview of SRON Leiden lab

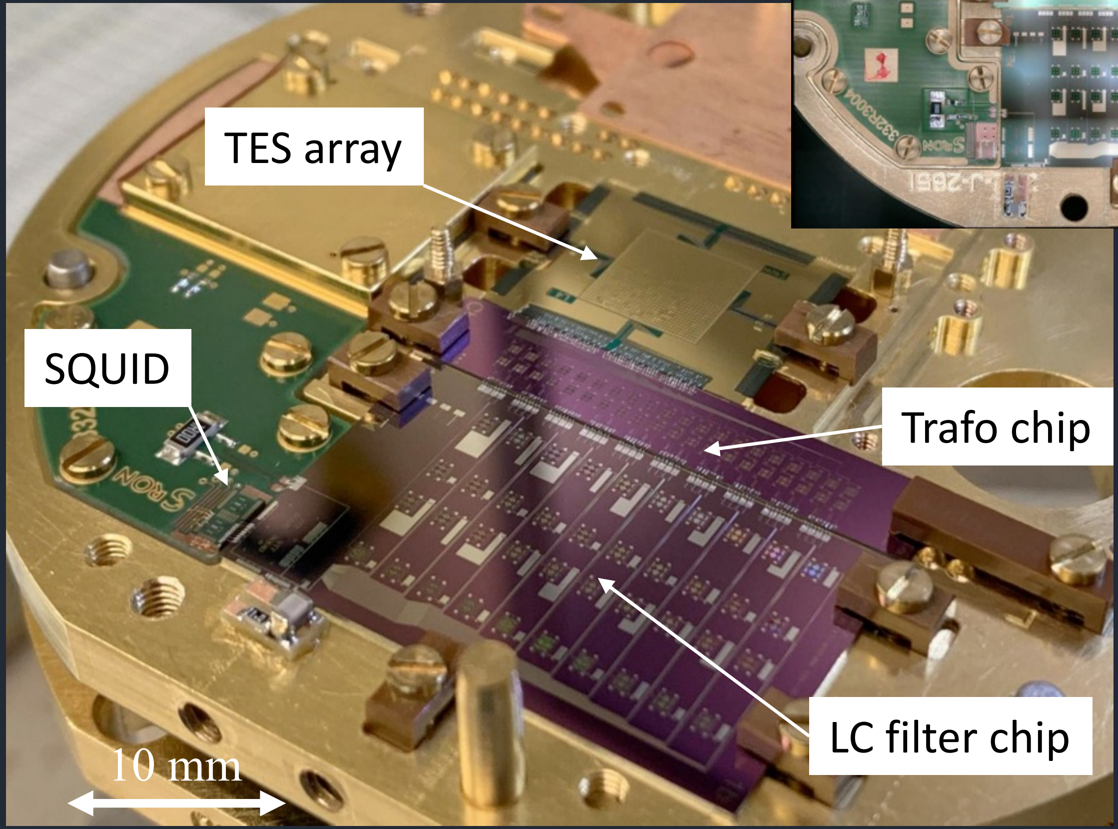




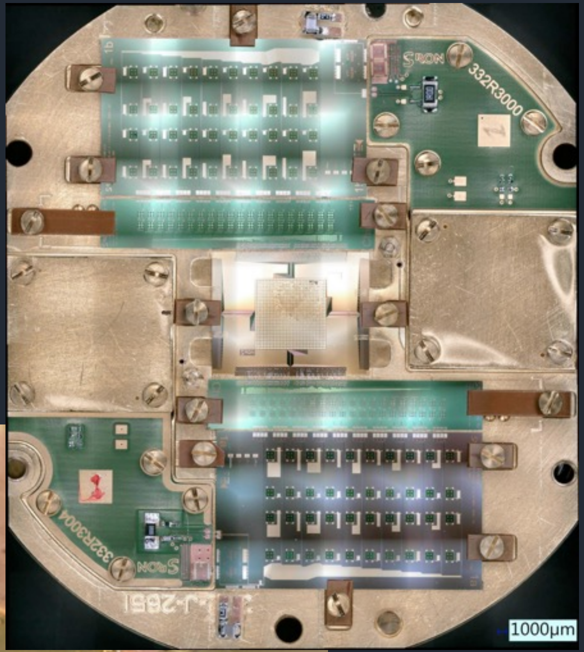
2 Leiden Cryogenics DR with multiple FDM set-ups

40 pixels FDM demonstrator

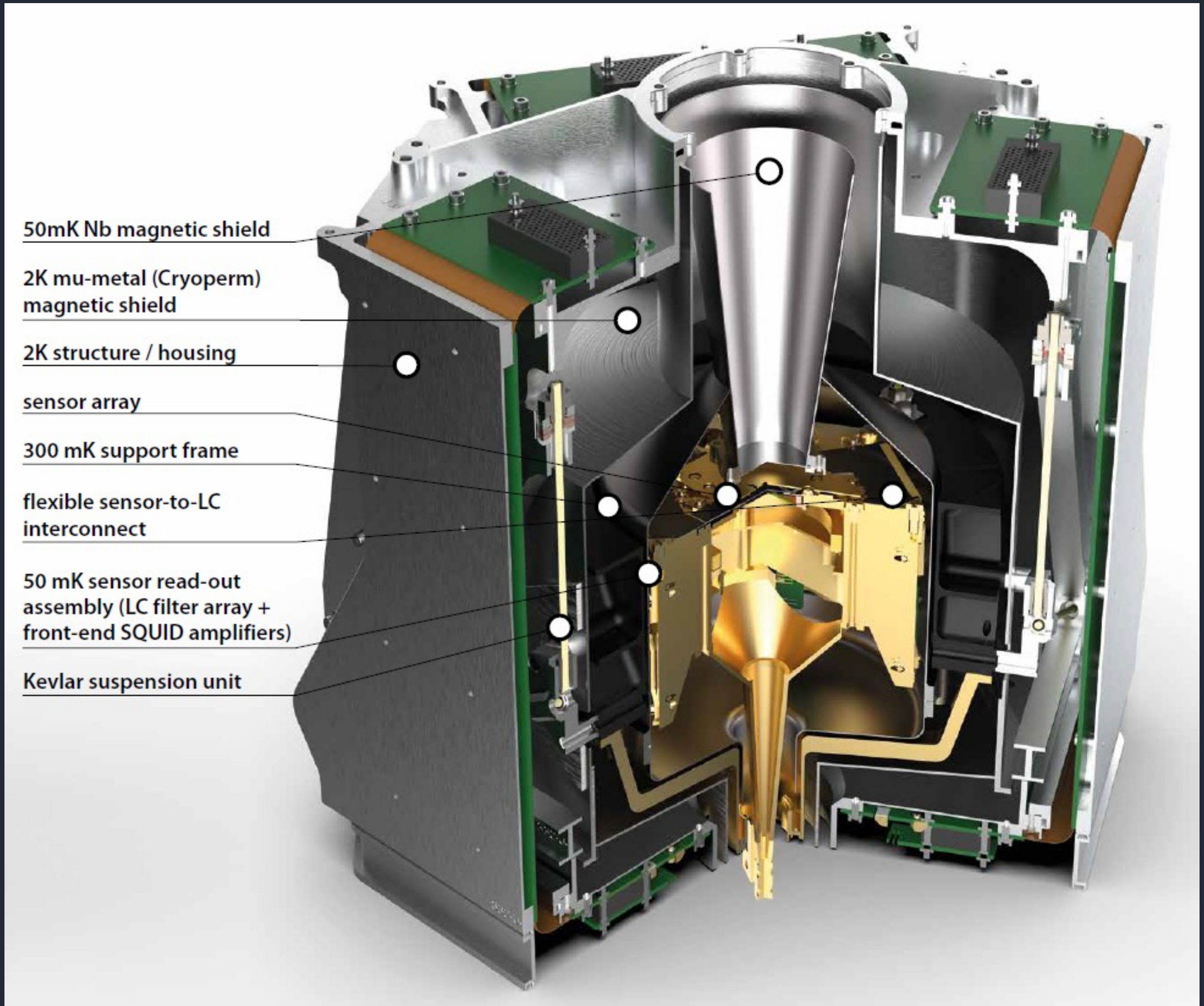


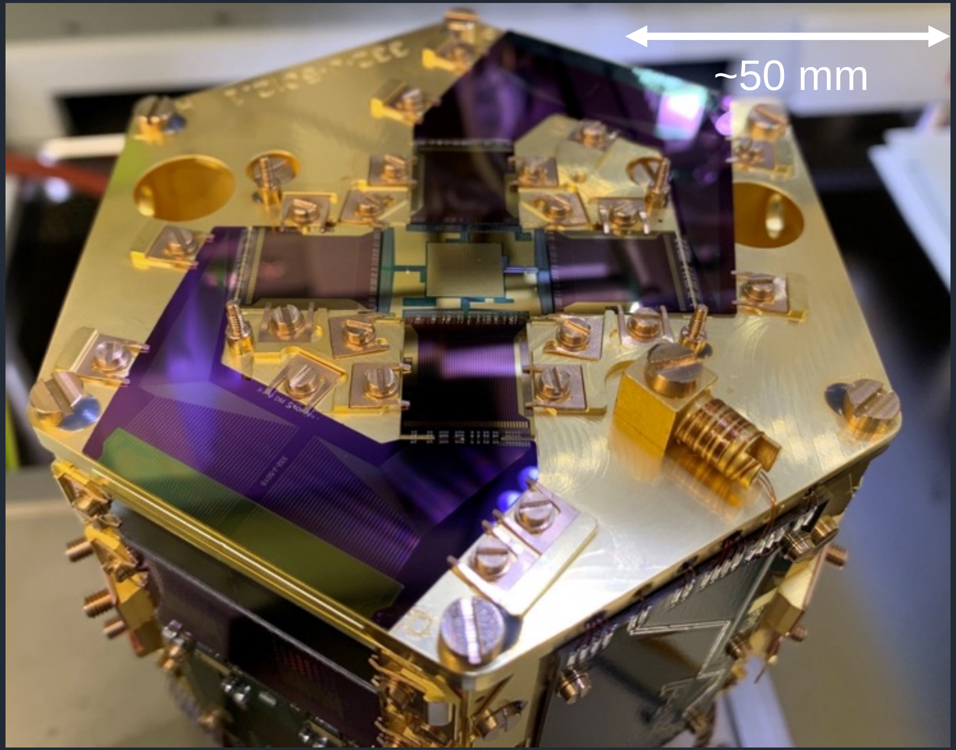


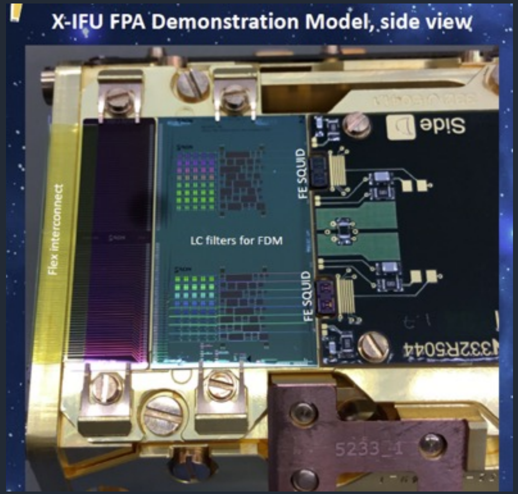
2 channels FDM

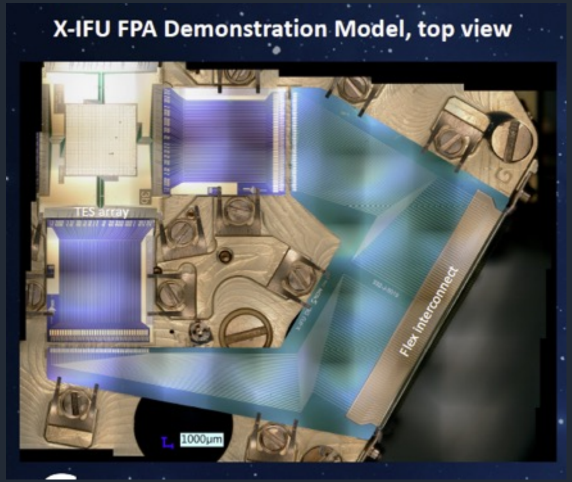


FPA-DM for Athena/XIFU









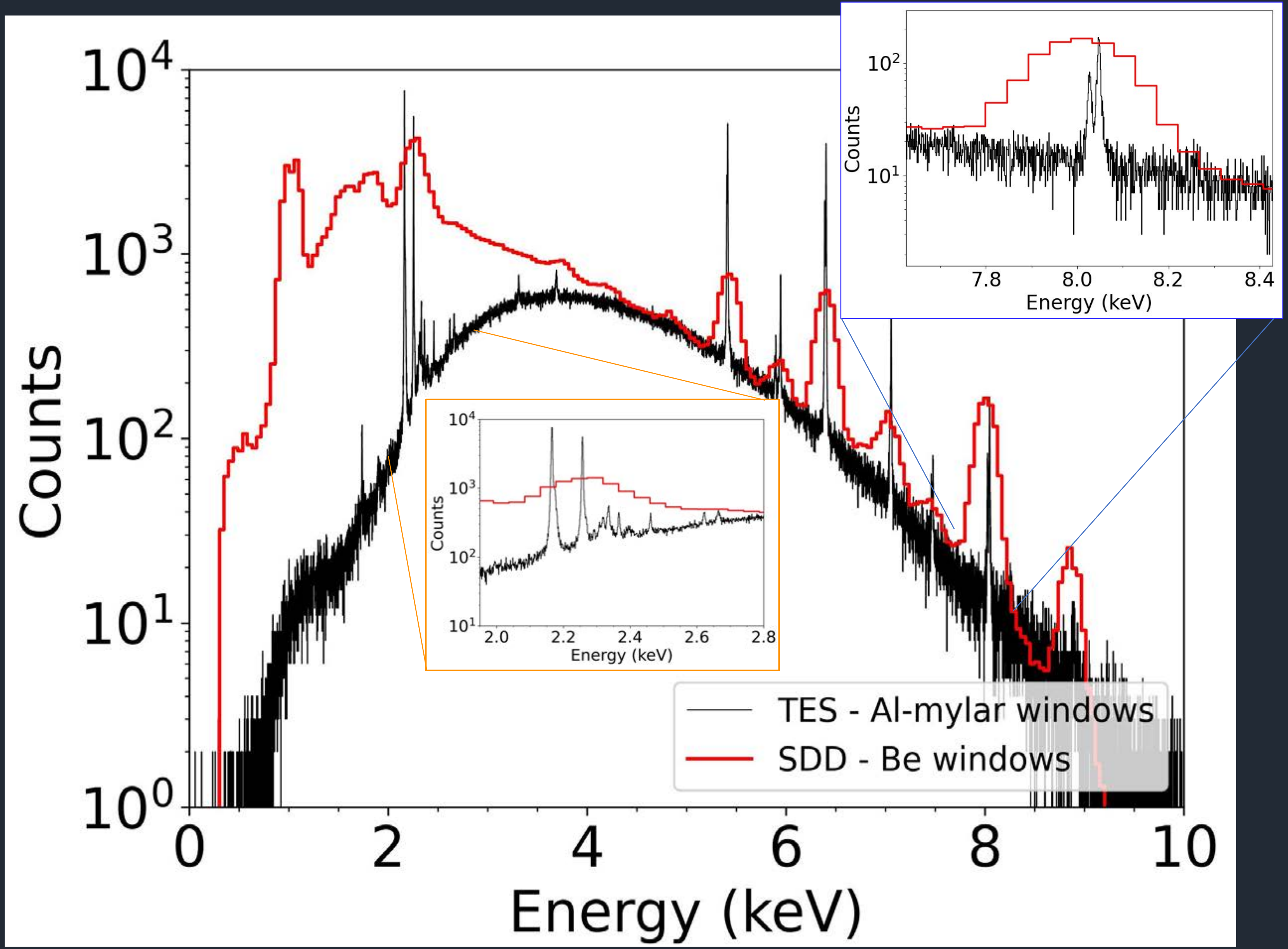
Credits; SRON XIFU/FPA team

TES based high-resolution X-ray spectrometry for ground-based applications

Laboratory high resolution X-ray spectroscopy

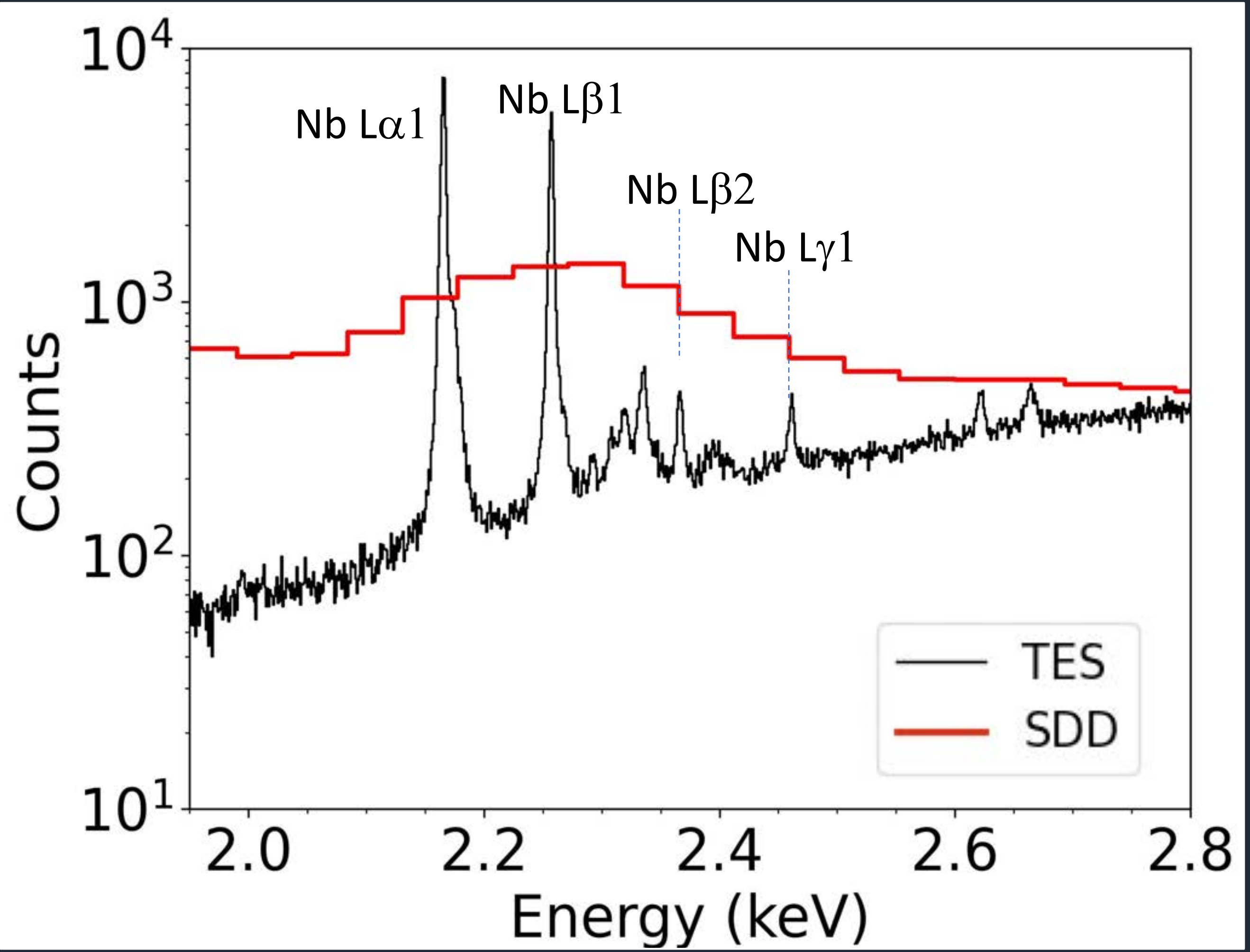
- X-ray absorption (XAS),
- X-ray fluorescence (XRF),
- X-ray emission spectroscopy (XES)
- (…)

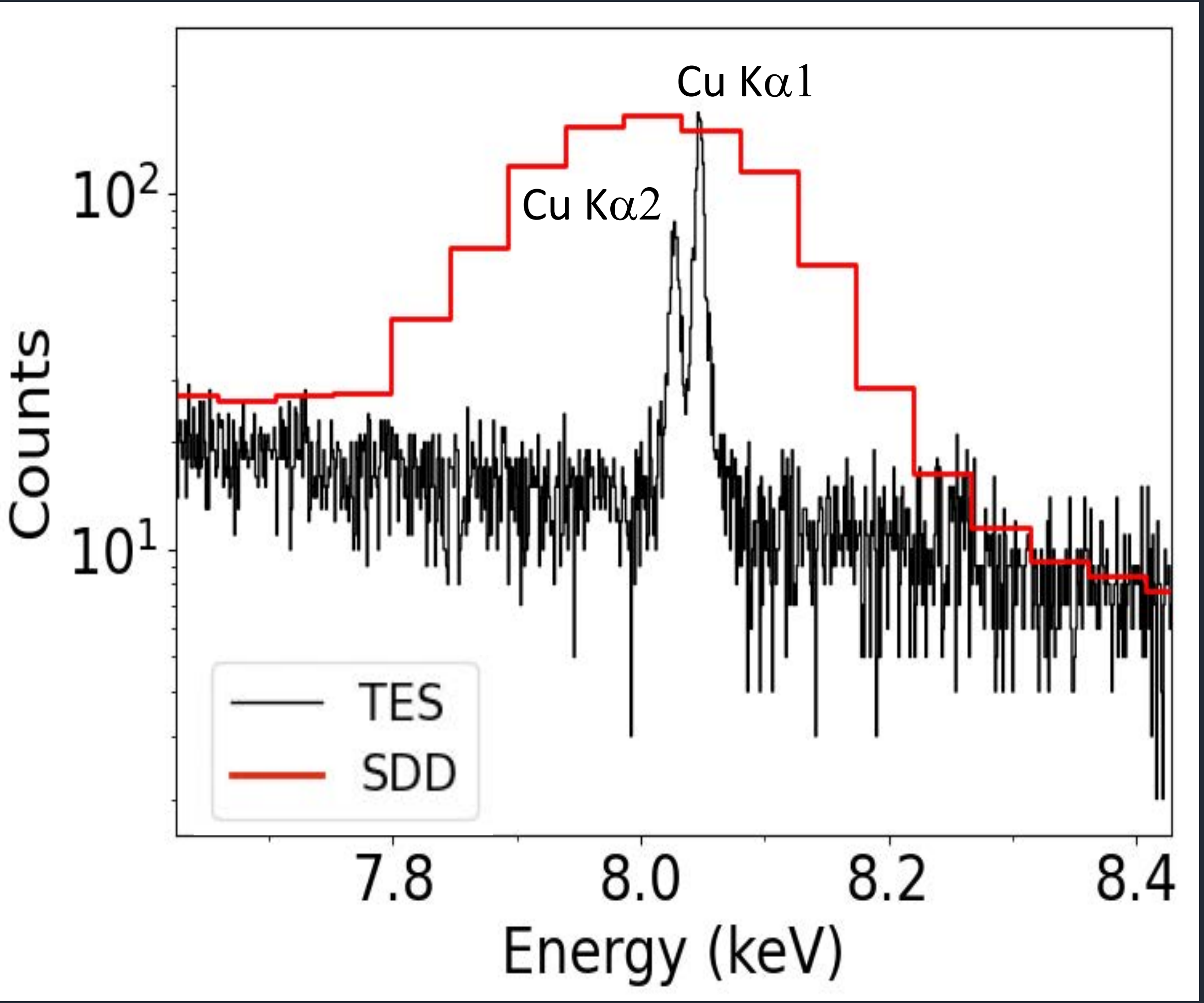
to measure distribution, chemical state and local structure of elements



SRON

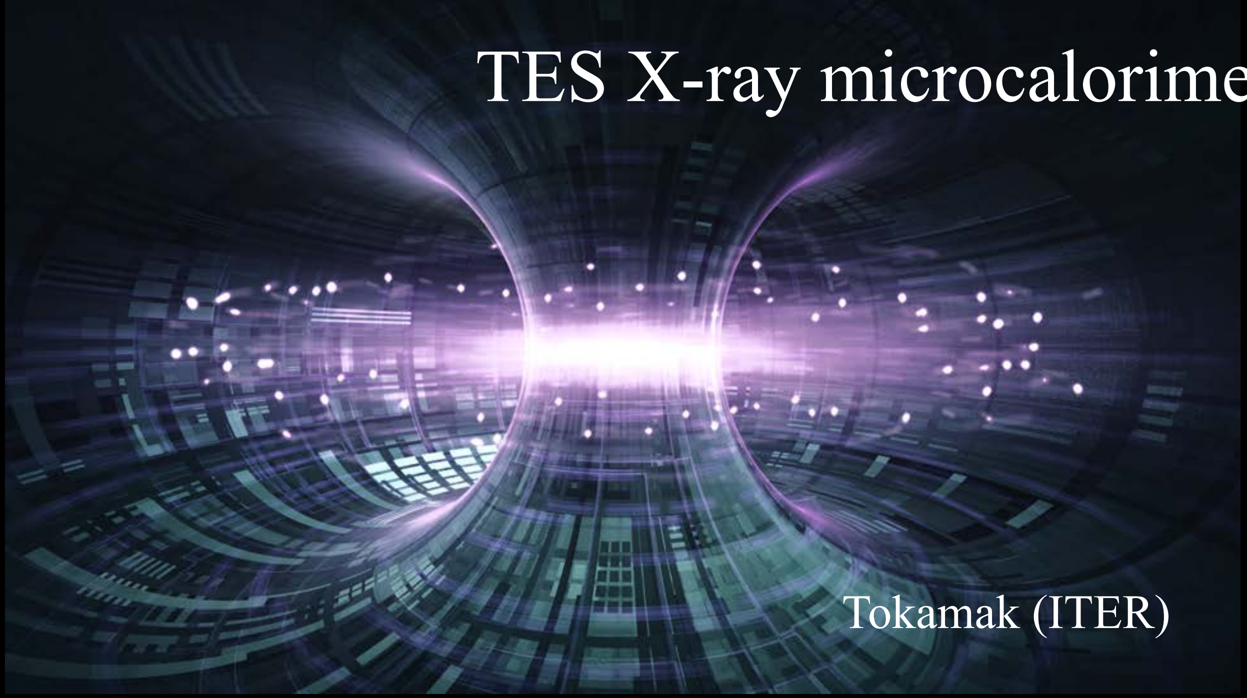
Laboratory high resolution X-ray spectroscopy



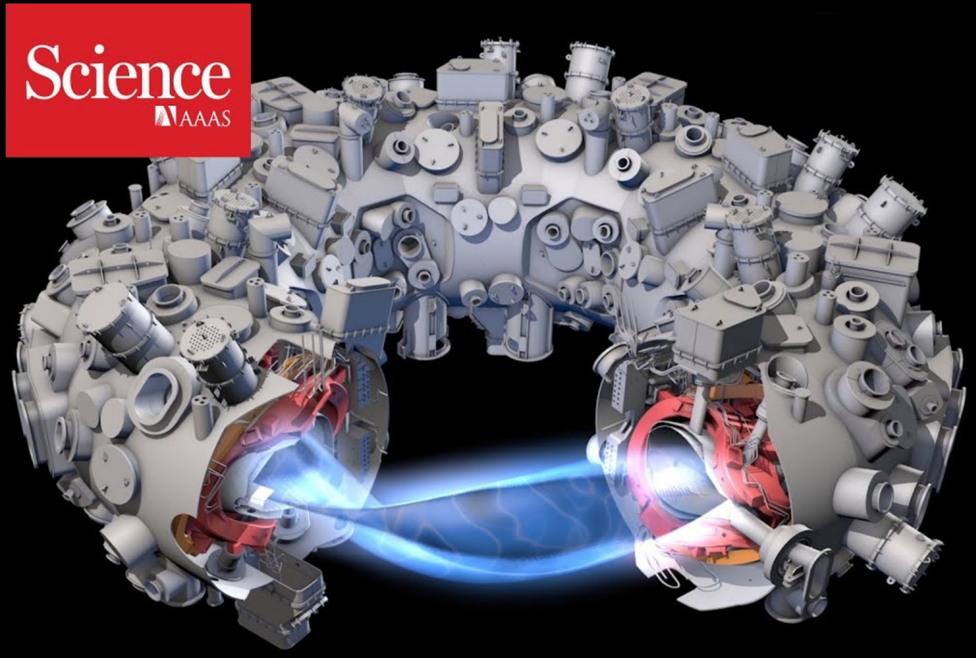


SRON

TES X-ray microcalorimeters for fusion plasma physics

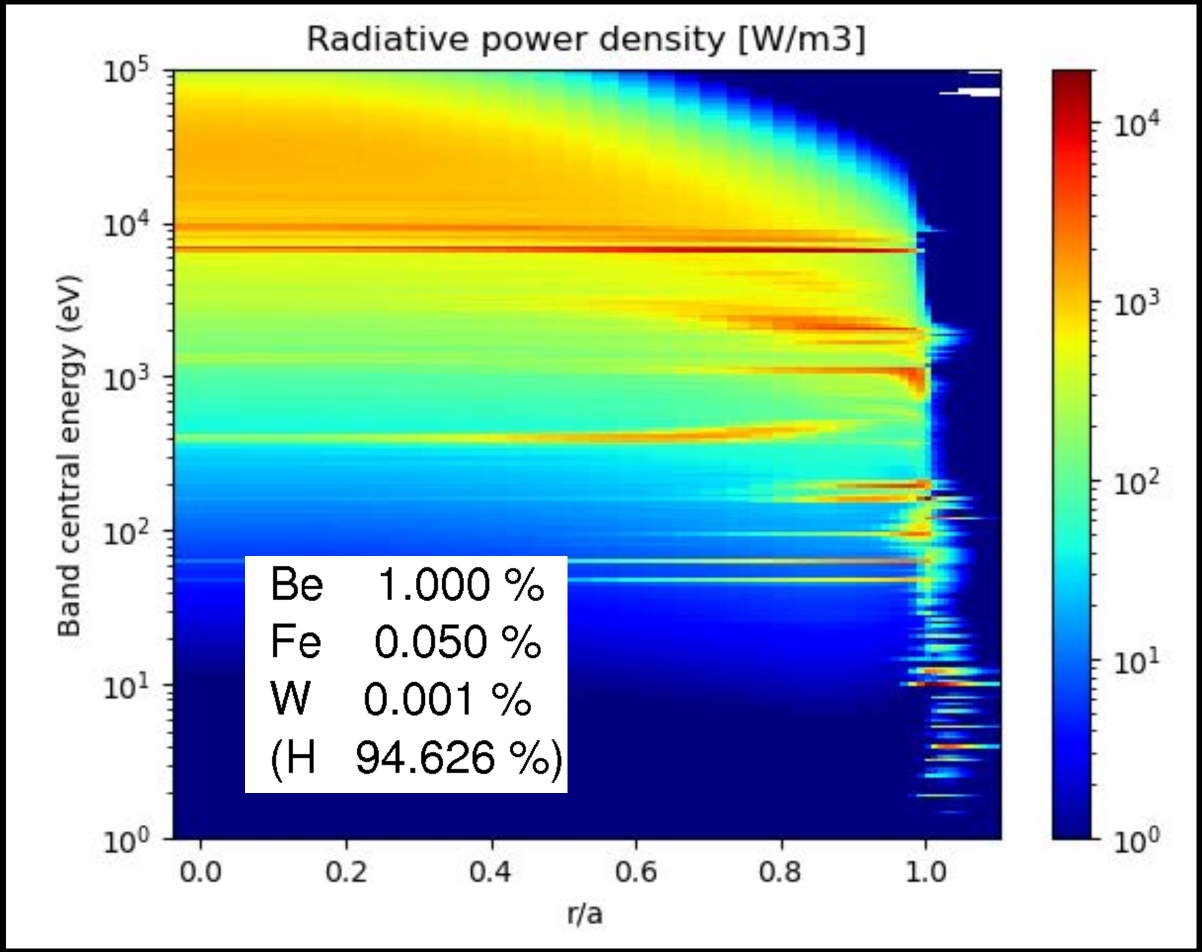


Tokamak (ITER)



Stellerator (W7-X)

Courtesy: ITER



Beiersdorfer et al. RSI 81,10EE323 (2010)

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

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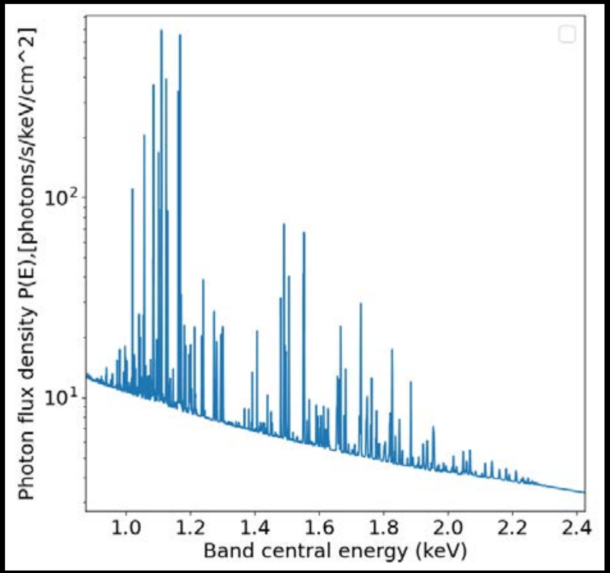
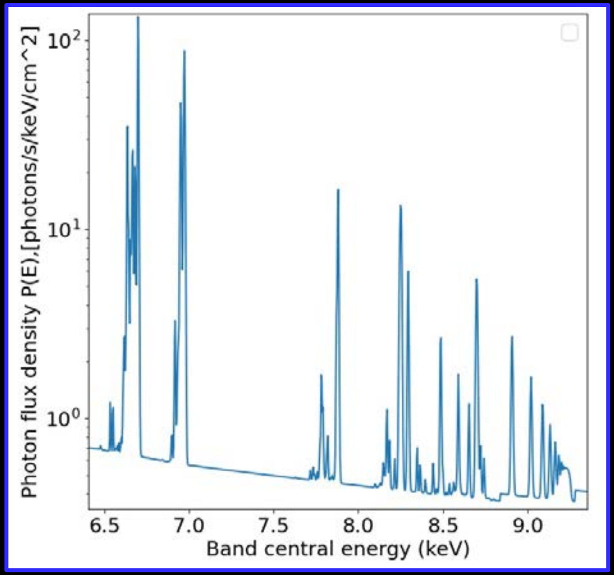
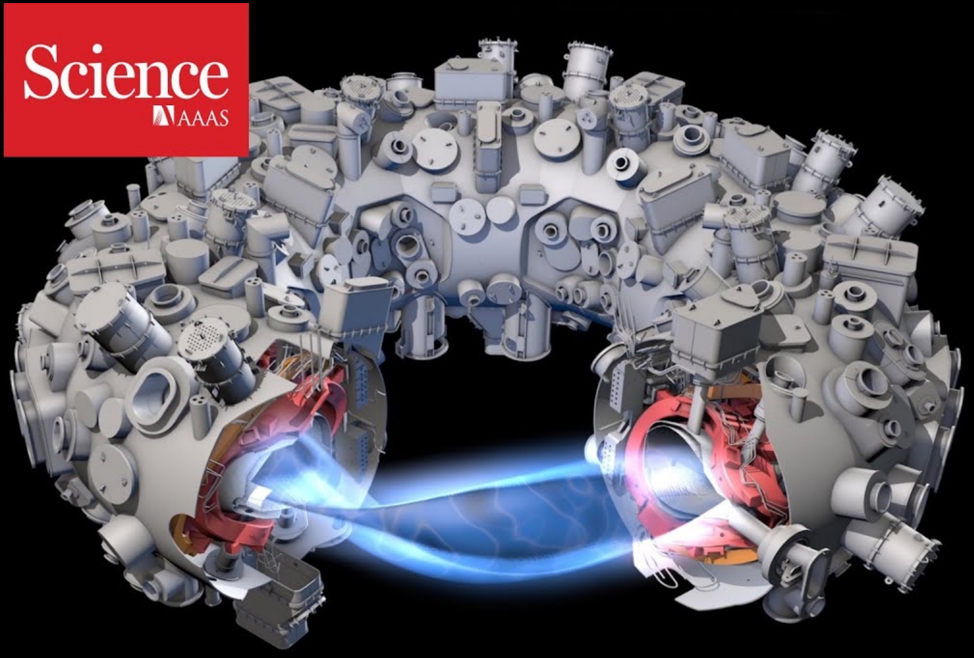






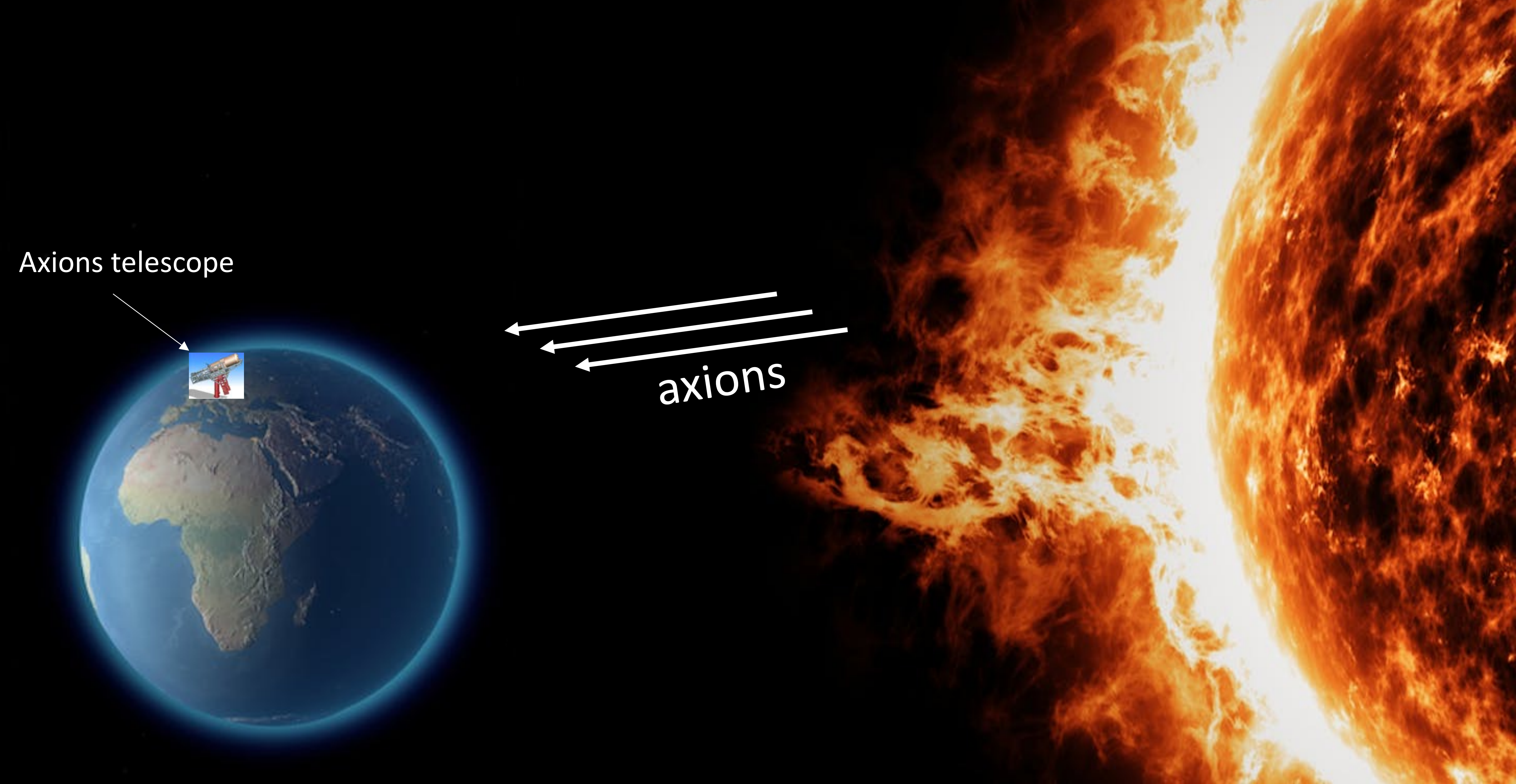
Stellarator (W7-X)

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

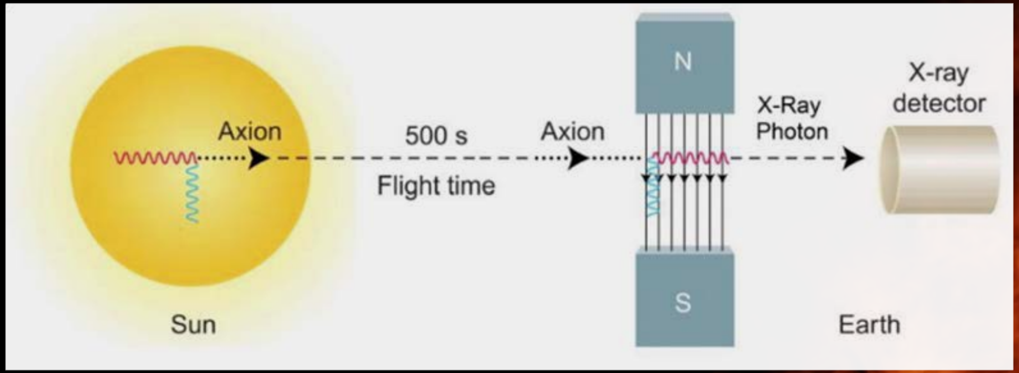
~1600 pixels , dE ~ 3-5 eV,
Count-rate capability ~1Mcts/s

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

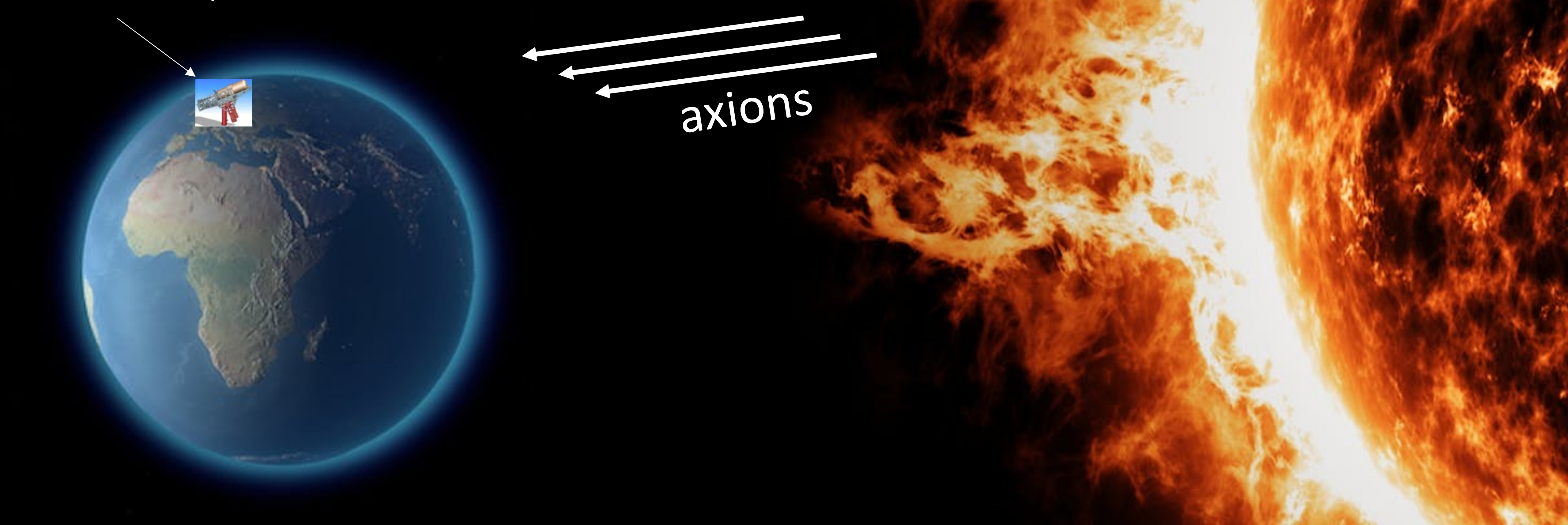
TES X-ray microcalorimeters for solar axion search



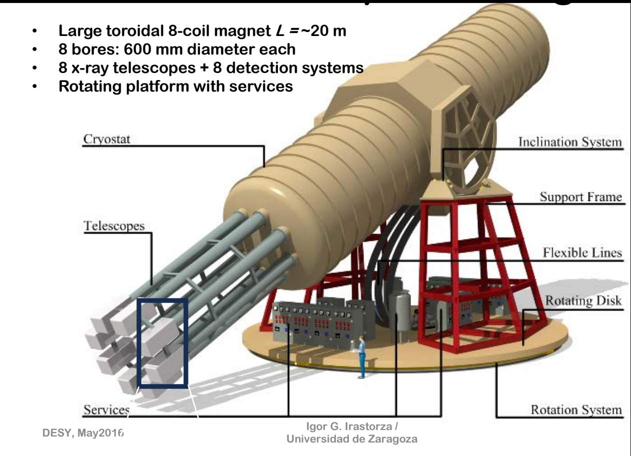
TES X-ray microcalorimeters for solar axion search



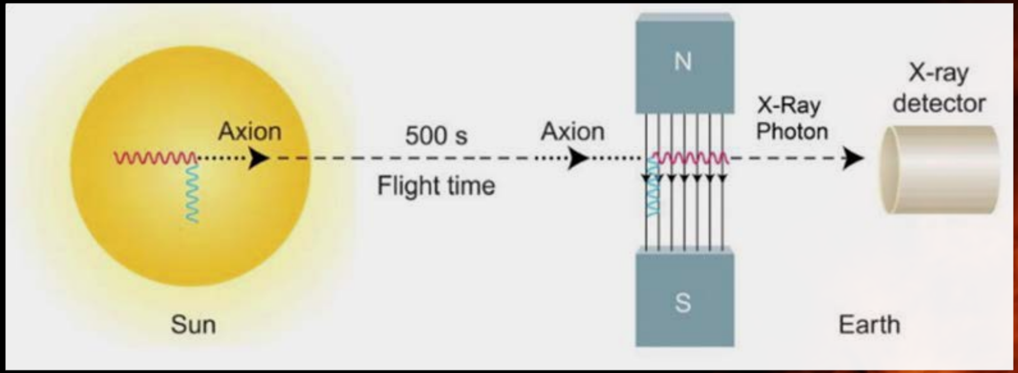
R. Battesti et al., Physics Reports 765-766(15), 2018



TES X-ray microcalorimeters for solar axion search

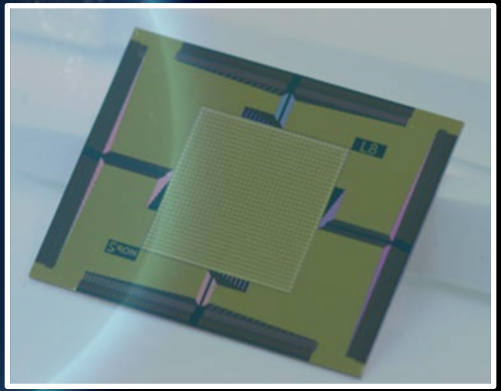


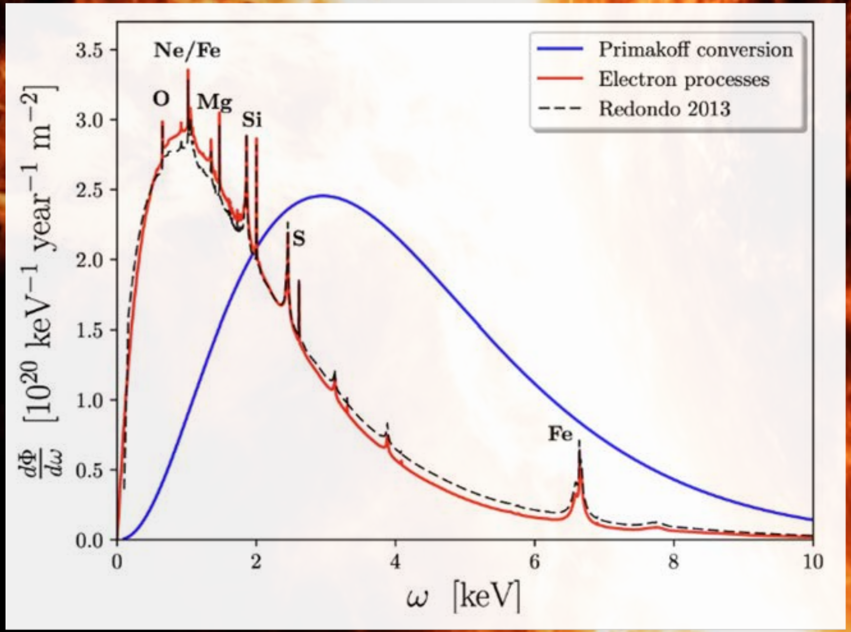
https://iaxo.web.cern.ch



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)

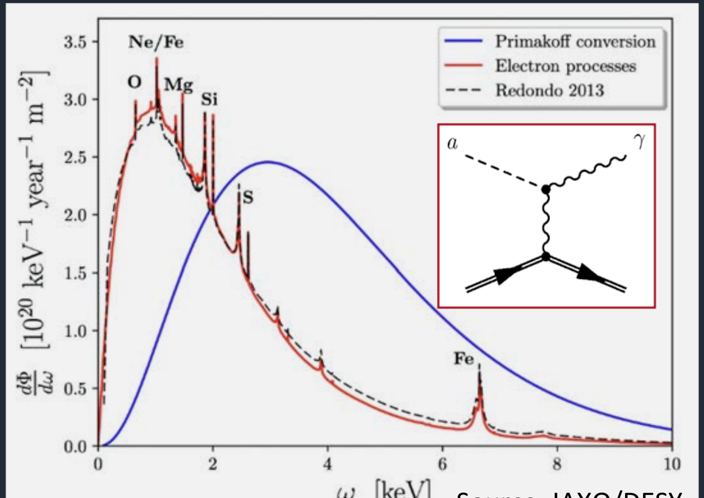
Summary

Superconductivity + Ultra Low Temperature → **High-Vision**

- 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

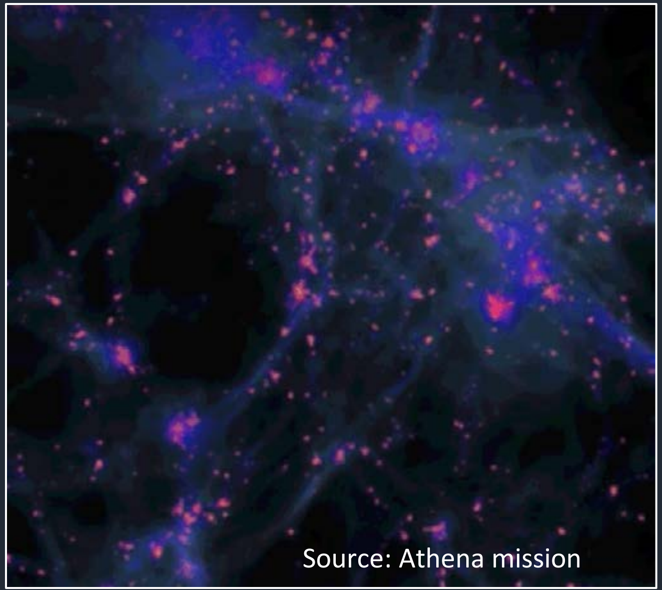
no photons



Source: IAXO/DESY

X-ray telescopes

some photons



Source: Athena mission

Fusion plasma

many photons

Source: IAEA International Atomic Energy Agency