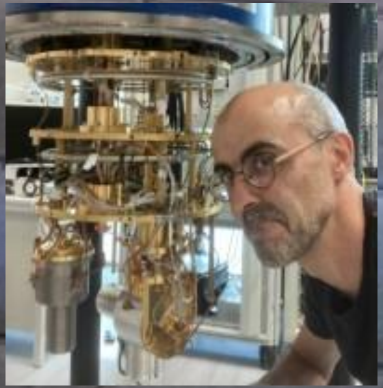
Superconducting Technology for Astrophysics



Luciano Gottardi

NWO-I/SRON Netherlands Institute for Space Research

LGWA meeting 2024, Castel Gandolfo, Italy, 9th October 2024

SRON - The Netherlands Institute for Space Research

ASTROPHYSICS

The Astrophysics programme at SRON is dedicated to unravelling the history of the universe, from the first stars and black holes to large-scale structure

EXOPLANETS

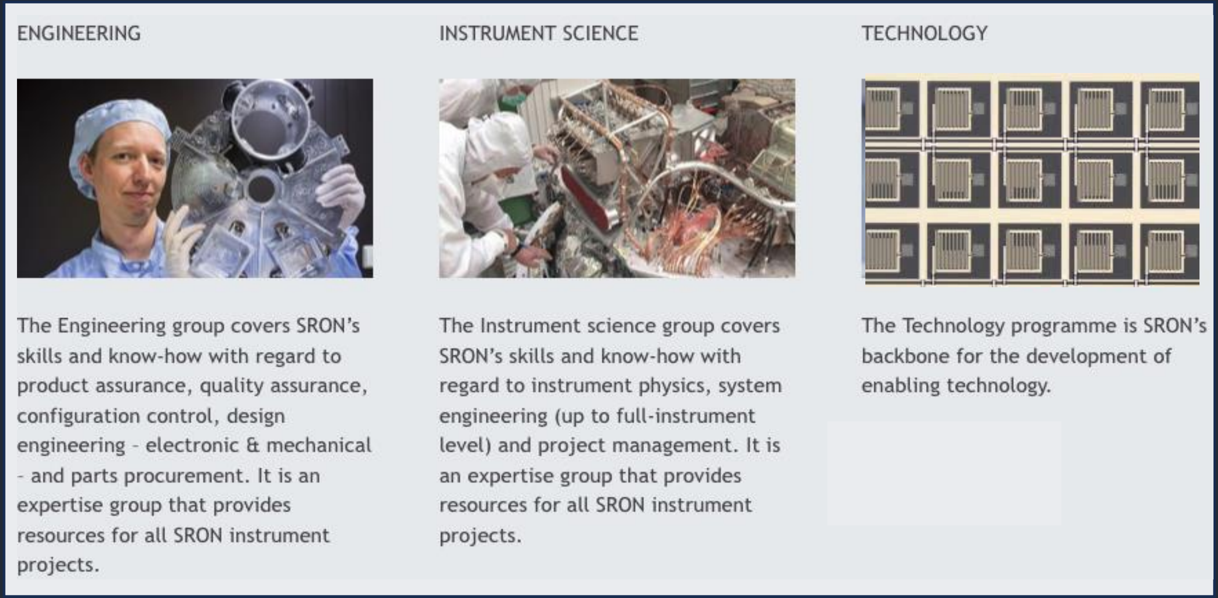
The Exoplanets programme is dedicated to atmospheres of planets beyond our solar system and is an in-between of SRON's Astrophysics and Earth programmes.

EARTH

The Earth programme is aimed at the climate and air quality of planet Earth, with focus on the global carbon cycle and aerosols.

SRON a NWO Institute (like NIKHEF)

SRON's mission is to bring about breakthroughs in international space research. **Our institute develops pioneering technology and advanced space instruments, and uses them to pursue fundamental astrophysical research, Earth science and exoplanetary research**. As national expertise institute SRON gives counsel to the Dutch government and coordinates – from a science standpoint – national contributions to international space missions.



ENGINEERING

The Engineering group covers SRON's skills and know-how with regard to product assurance, quality assurance, configuration control, design engineering - electronic & mechanical - and parts procurement. It is an expertise group that provides resources for all SRON instrument projects.

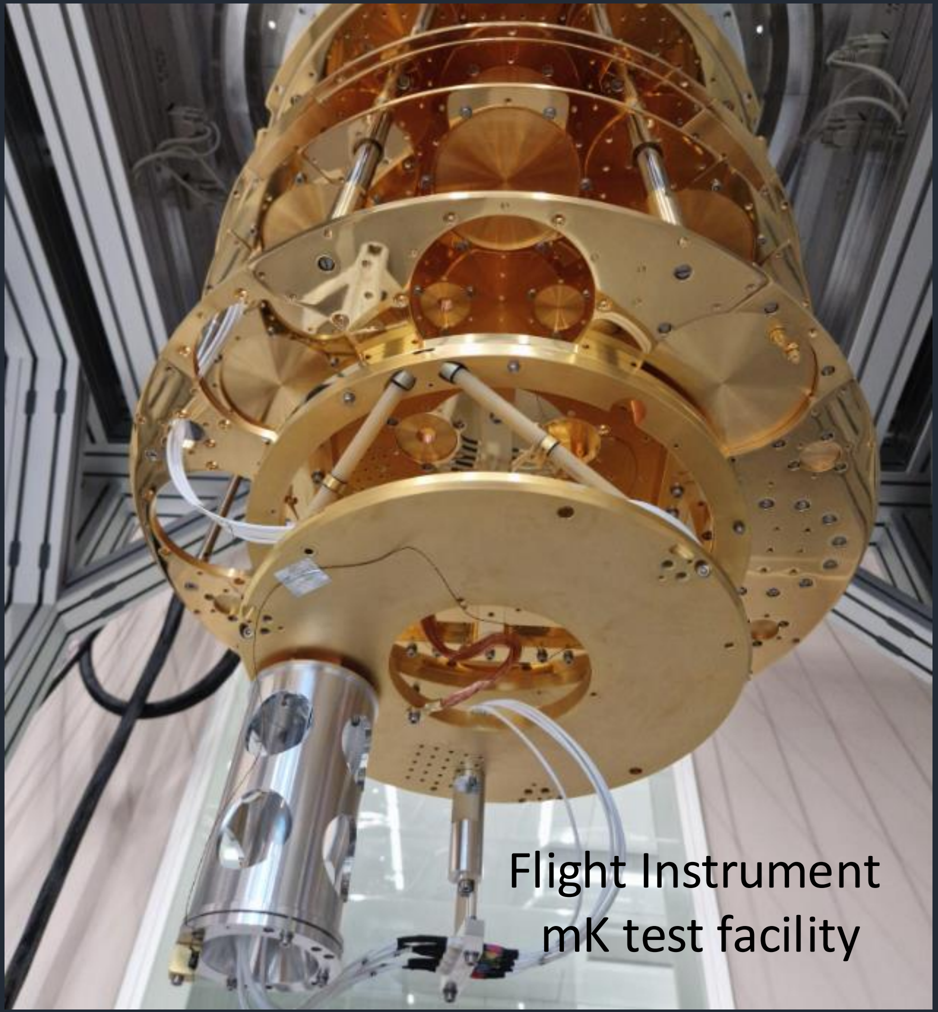
INSTRUMENT SCIENCE

The Instrument science group covers SRON's skills and know-how with regard to instrument physics, system engineering (up to full-instrument level) and project management. It is an expertise group that provides resources for all SRON instrument projects.

TECHNOLOGY

The Technology programme is SRON's backbone for the development of enabling technology.

Overview of SRON Leiden cryogenic lab


Flight Instrument
mK test facility

4 dilution refrigerators and 2 ADRS with multiple cryogenic set-ups for X-ray infrared and optical science

SRON Leiden Cleanroom

E-beam evaporator,cluster tool, LLS

Lithography area

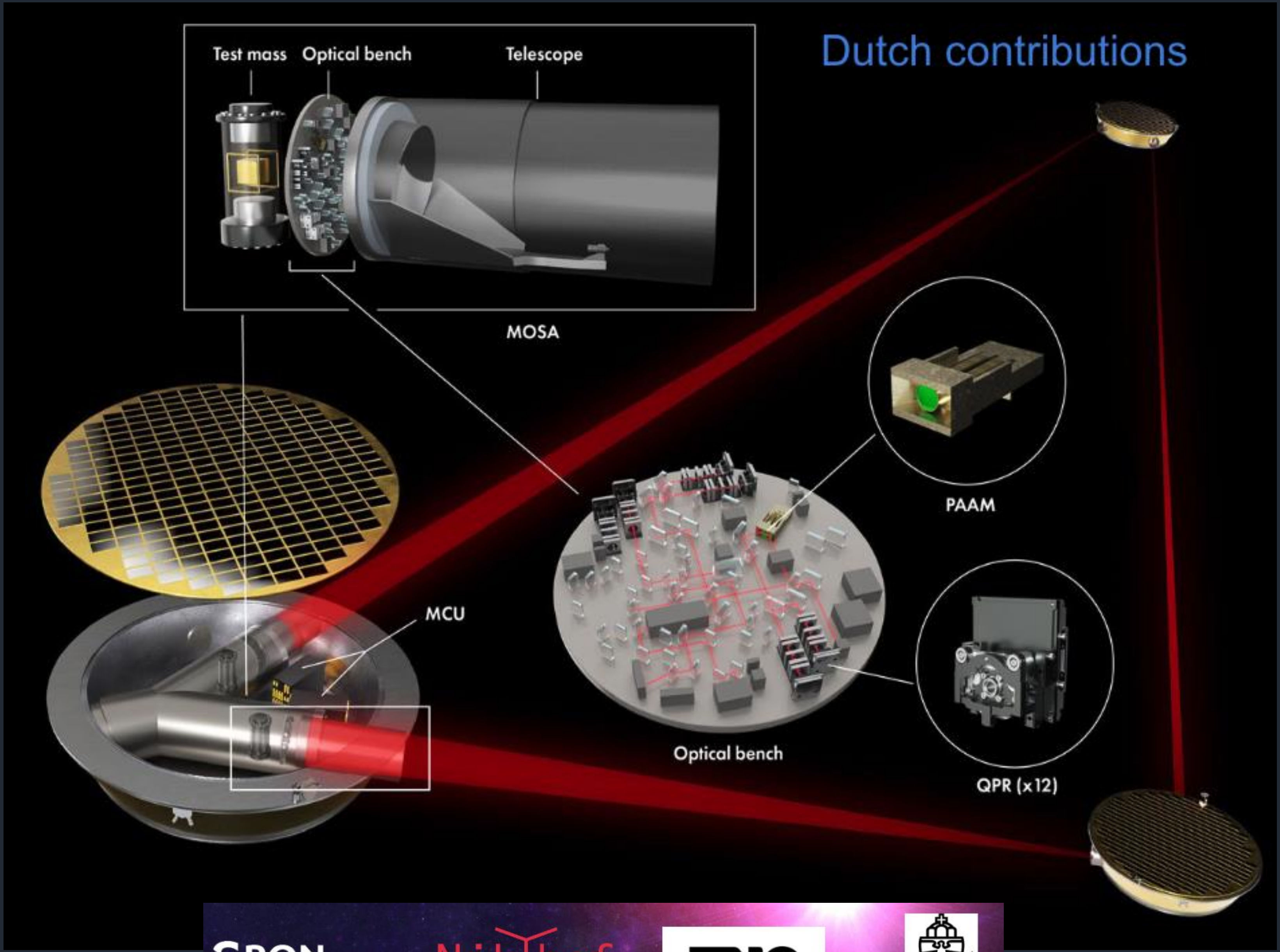
Politeknik: cluster sputter tool

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

Strong collaboration with TU-Delft cleanroom facilities

Courtesy Marcel Bruijn

SRON involvement in LISA



MCU. – Mechanism Control Unit
QPR – Quadrant Photo Diodes
PAAM – Point Ahead Angle Mechanism

SRON Netherlands Institute for Space Research
Nikhef
TNO

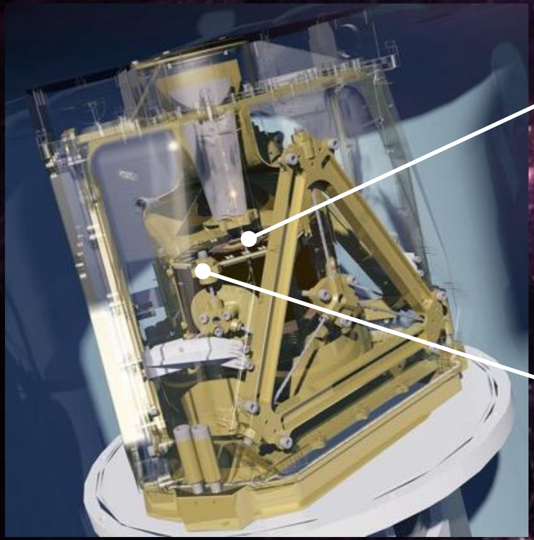
Credit: Peter Dieleman, SRON

Future X-ray space observatory

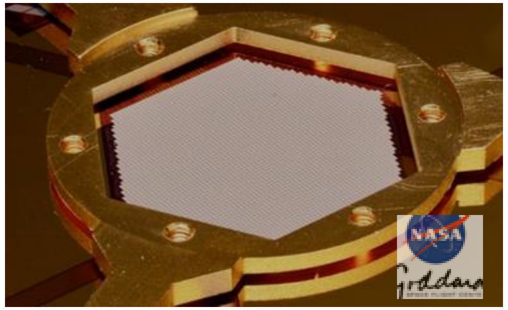
- **ATHENA** is a Large ESA mission to study *"The Hot and Energetic Universe"*, launch in late 2030s.
- The **X-IFU** instruments of the payload is a **cryogenic imaging spectrometer:**

  Energy band 0.2 – 12 keV, dE ~ 2.5 eV

The Hot and Energetic Universe



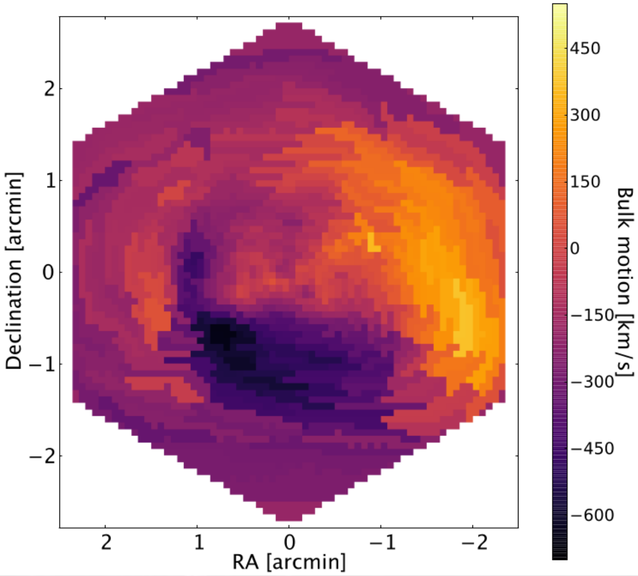
TES array

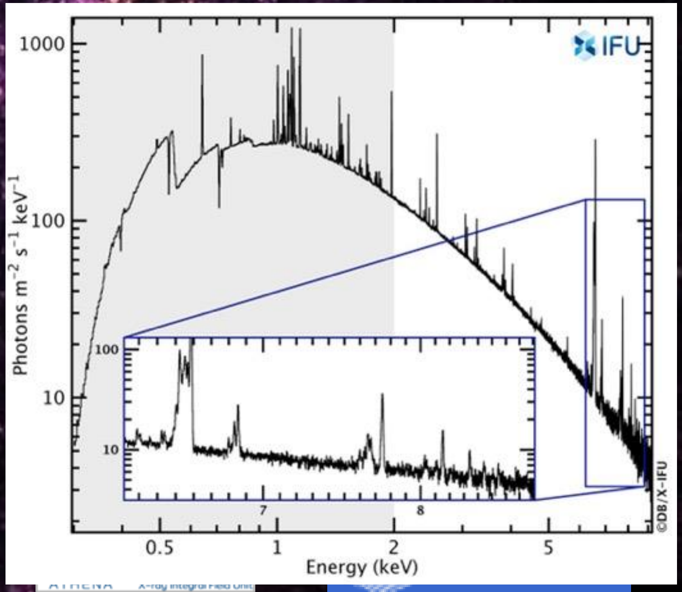


NASA /NIST
detectors and readout

X-ray **I**ntegral
Field **U**nit

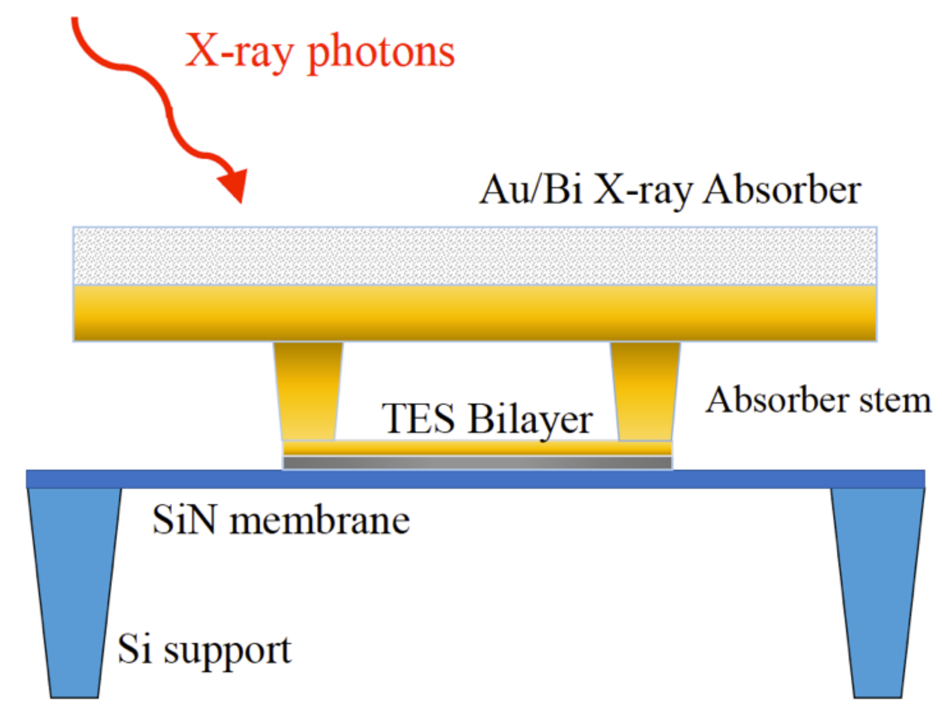
SRON responsible for the FPA
SQUID read-out and back-up
detector array

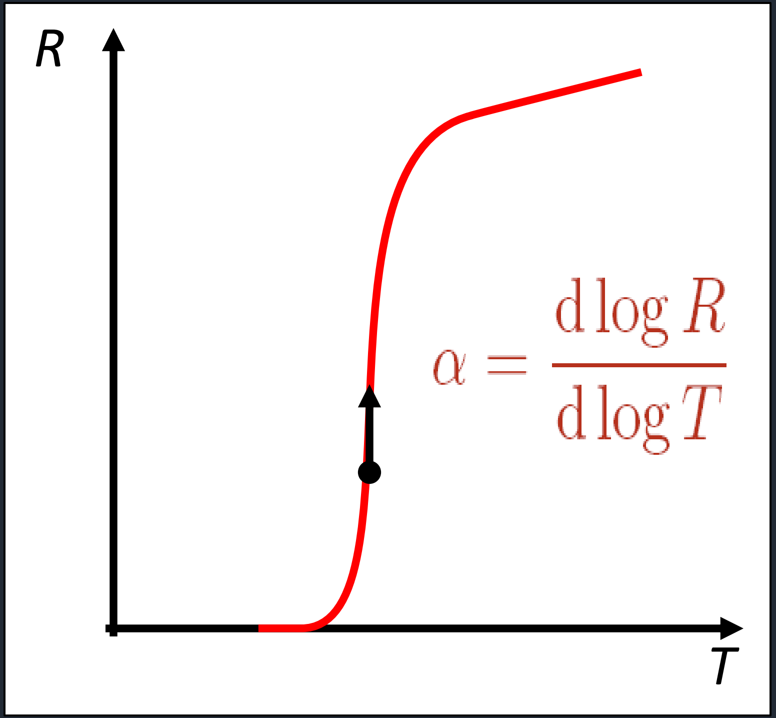




Credit: IRAP/CNRS/UT3/CNES/ESA/SRON/NASA-Goddard

Superconducting Transition Edge Sensors





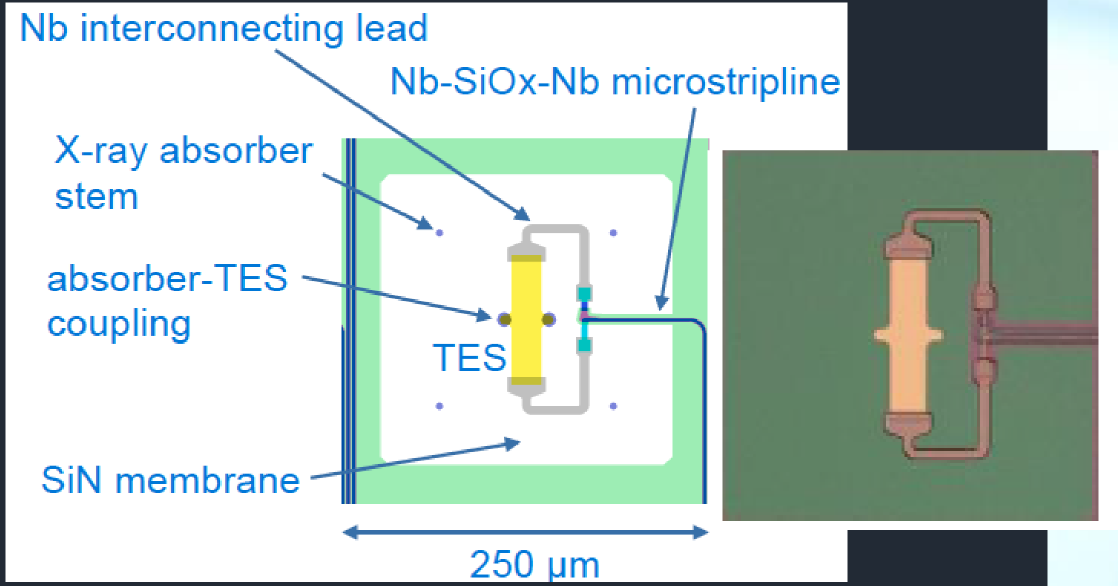
- Low temperature detectors T_c~ 90 mK
- Sharp transition α~ 500-1000
- Small absorber (low heat capacity C)
- Limited dynamic range E_{lin}~ C/α

Energy resolution:

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

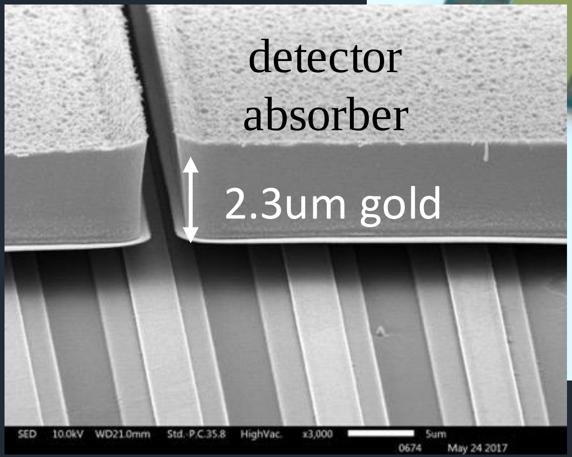
K.Irwin and G. Hilton In Cryogenic Particle Detection; Enss,C. Springer, 2006
J. Ullom and D. Bennett, Superc.Sci.Technol. 28, 084003, 2015
L. Gottardi and K. Nagayashi, Applied Sciences 11 (9),3793, 2021

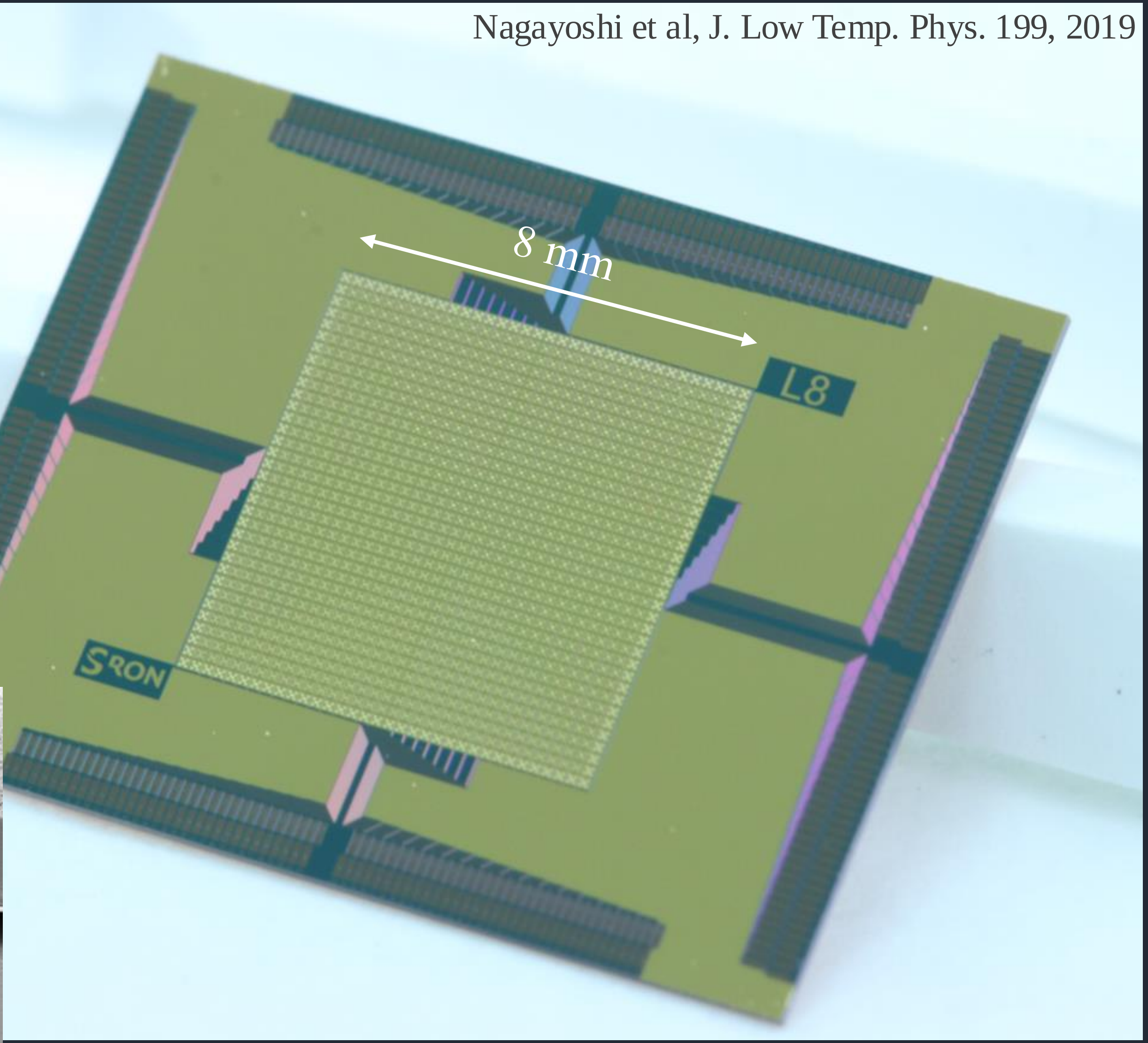
X-ray TES microcalorimeter



SRON TES:

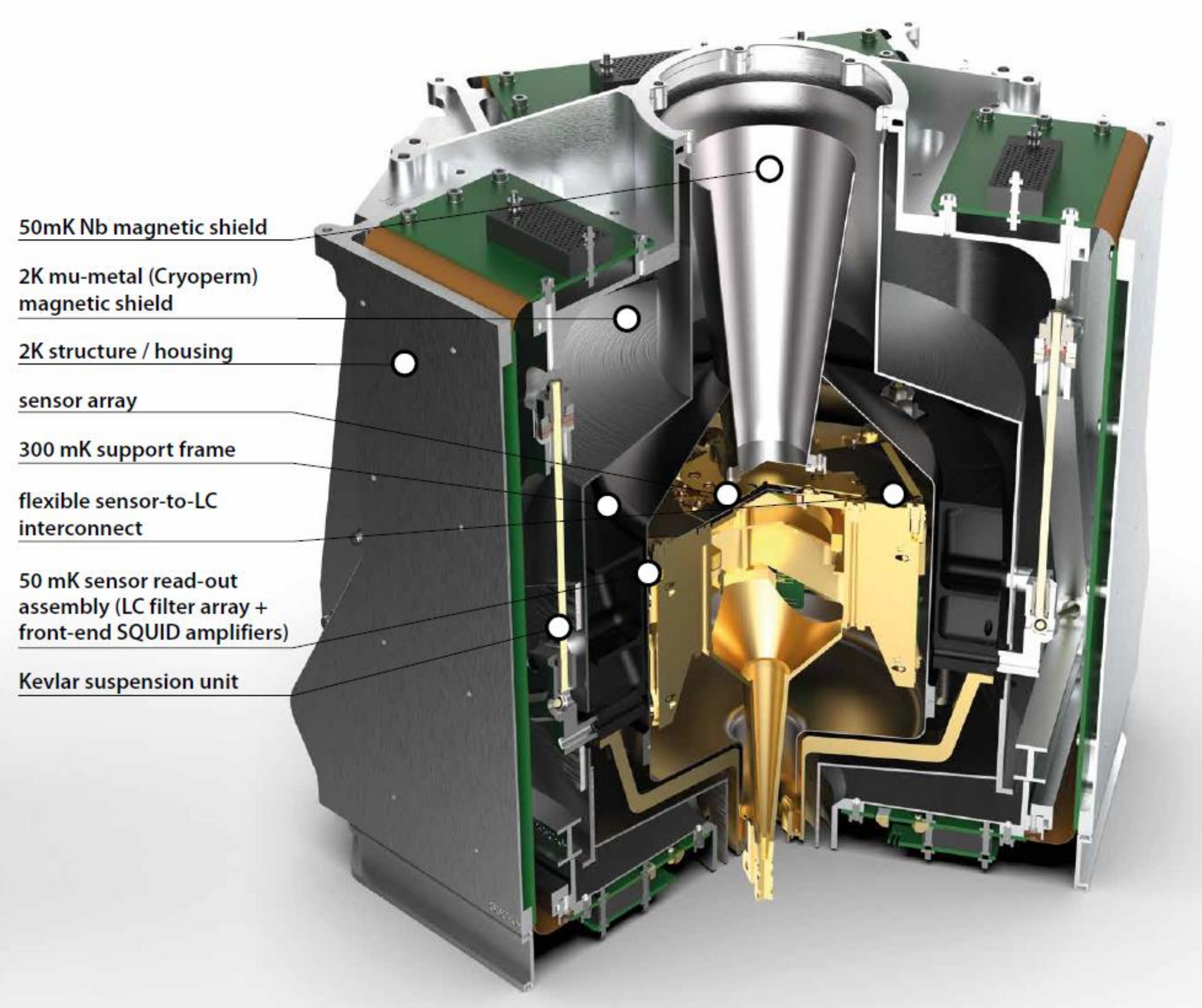
- Ti(35nm)Au(200nm) bilayer
- Tc~ 90mK
- Normal resistance ~100-300mΩ

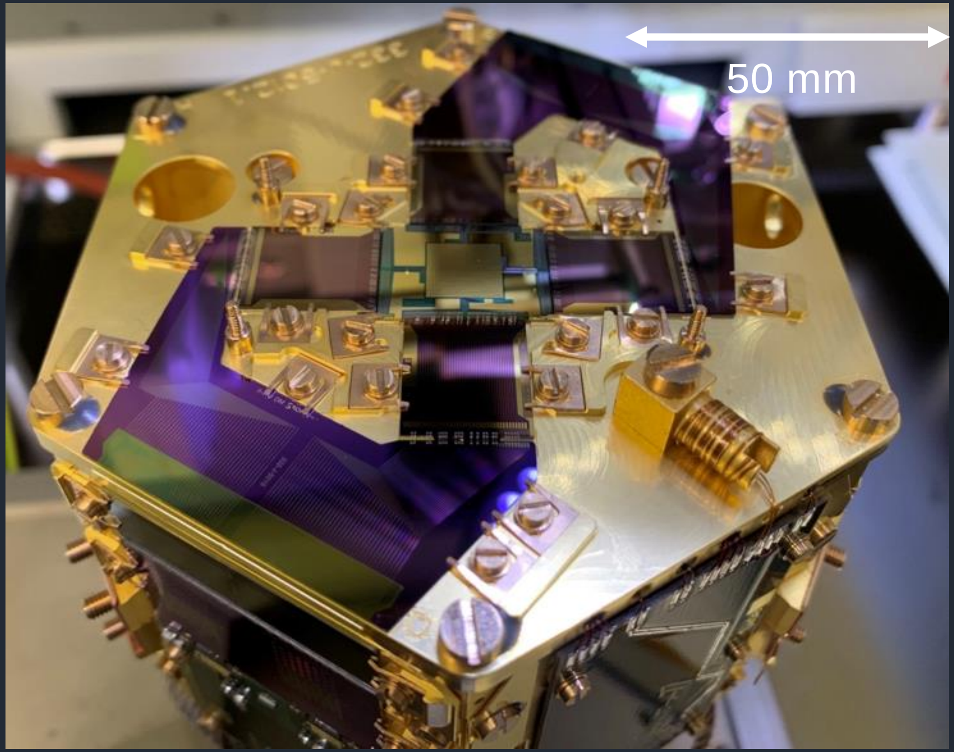


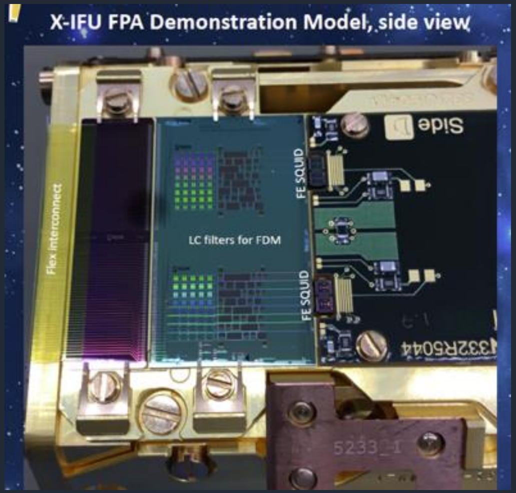

Nagayoshi et al, J. Low Temp. Phys. 199, 2019

SRON 32x32 TES pixels array with Au absorbers

FPA-DM for Athena/XIFU



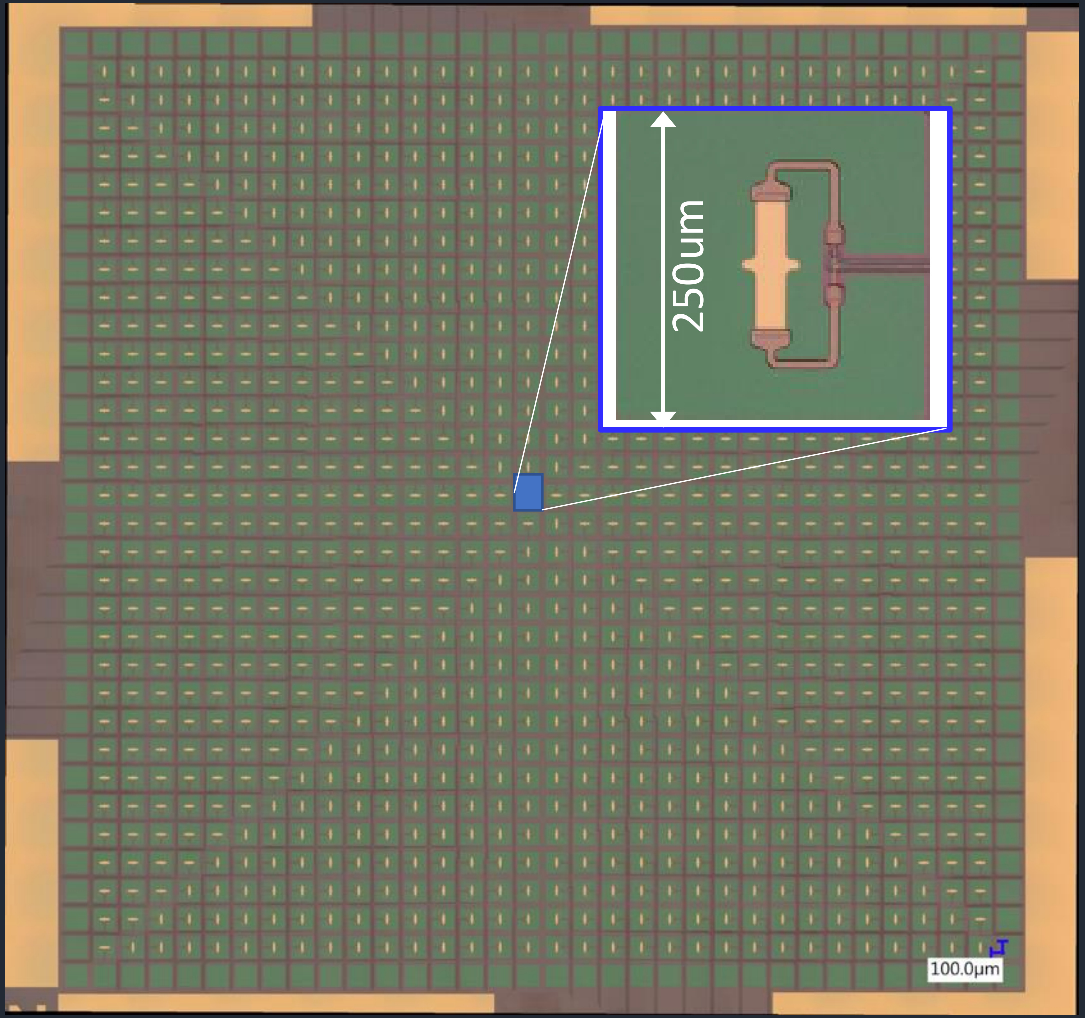



X-IFU FPA Demonstration Model, side view

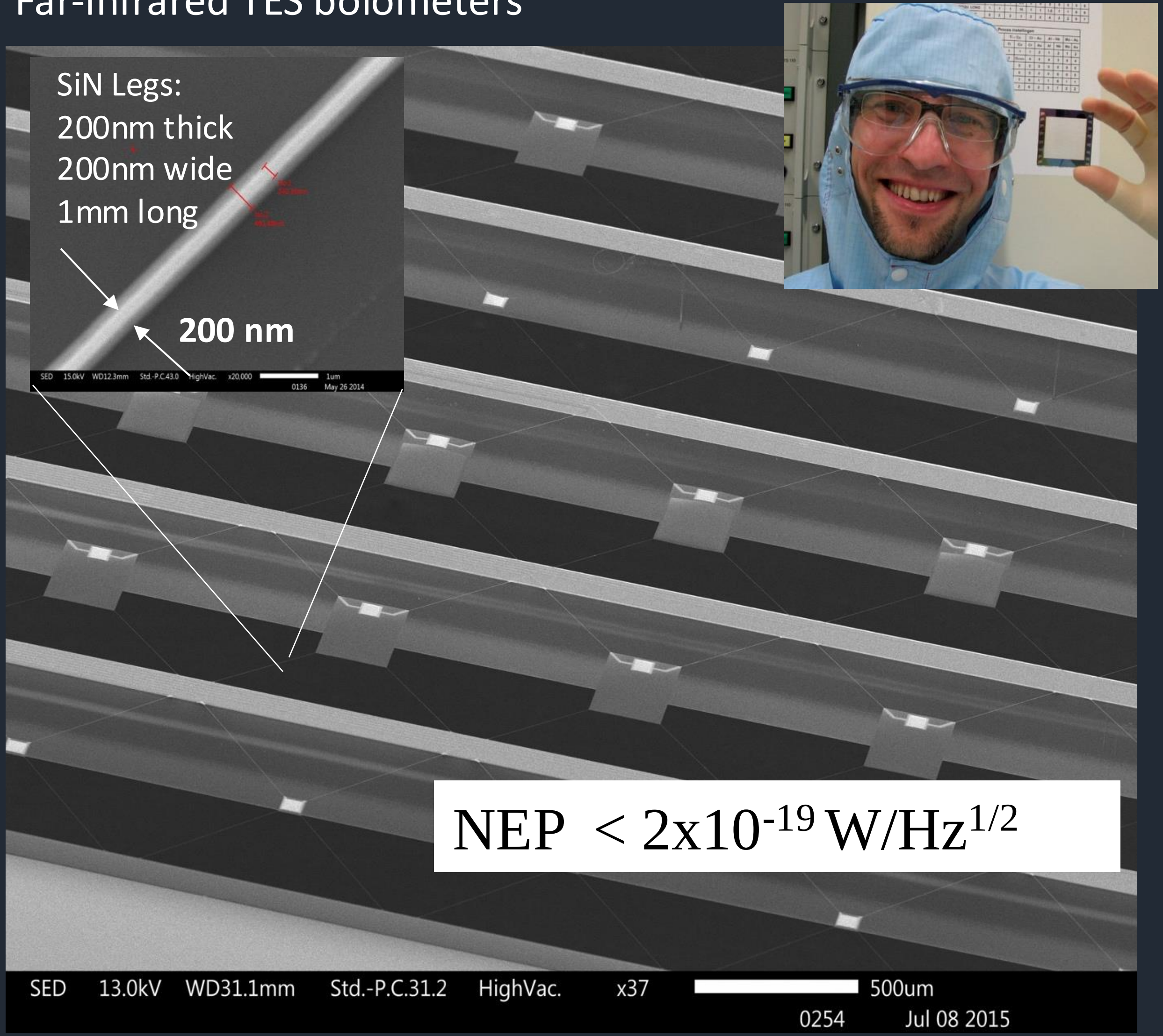

X-IFU FPA Demonstration Model, top view

Credits; SRON XIFU/FPA team

X-ray TES microcalorimeters

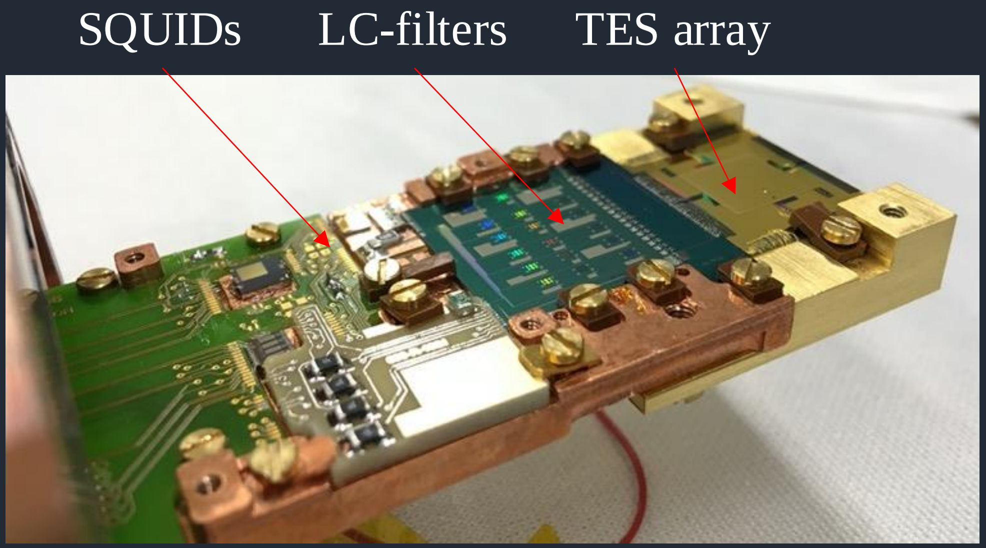


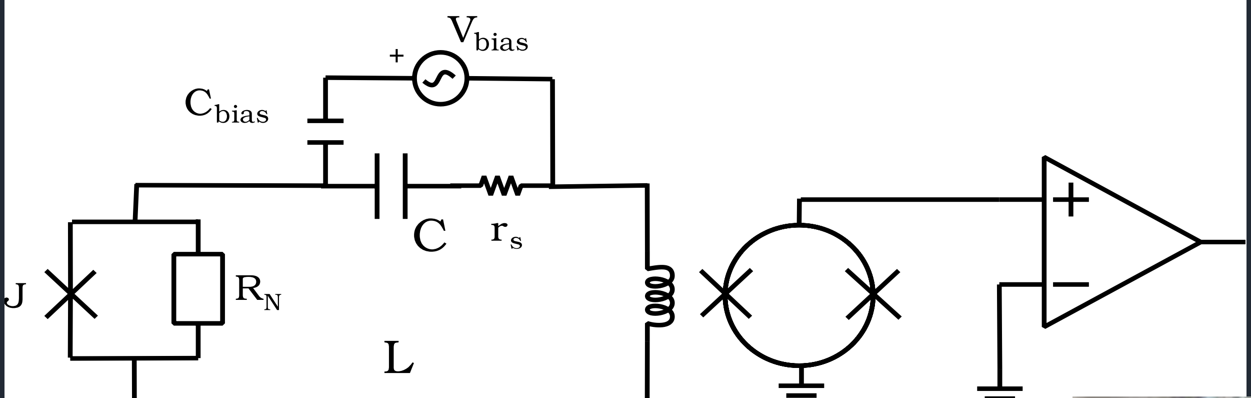
Far-infrared TES bolometers

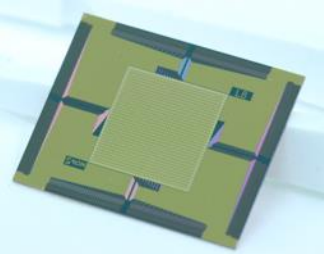


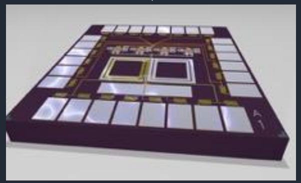
NEP $< 2\mathrm{x}10^{-19}\ \mathrm{W/Hz}^{1/2}$

Frequency Division Multiplexing







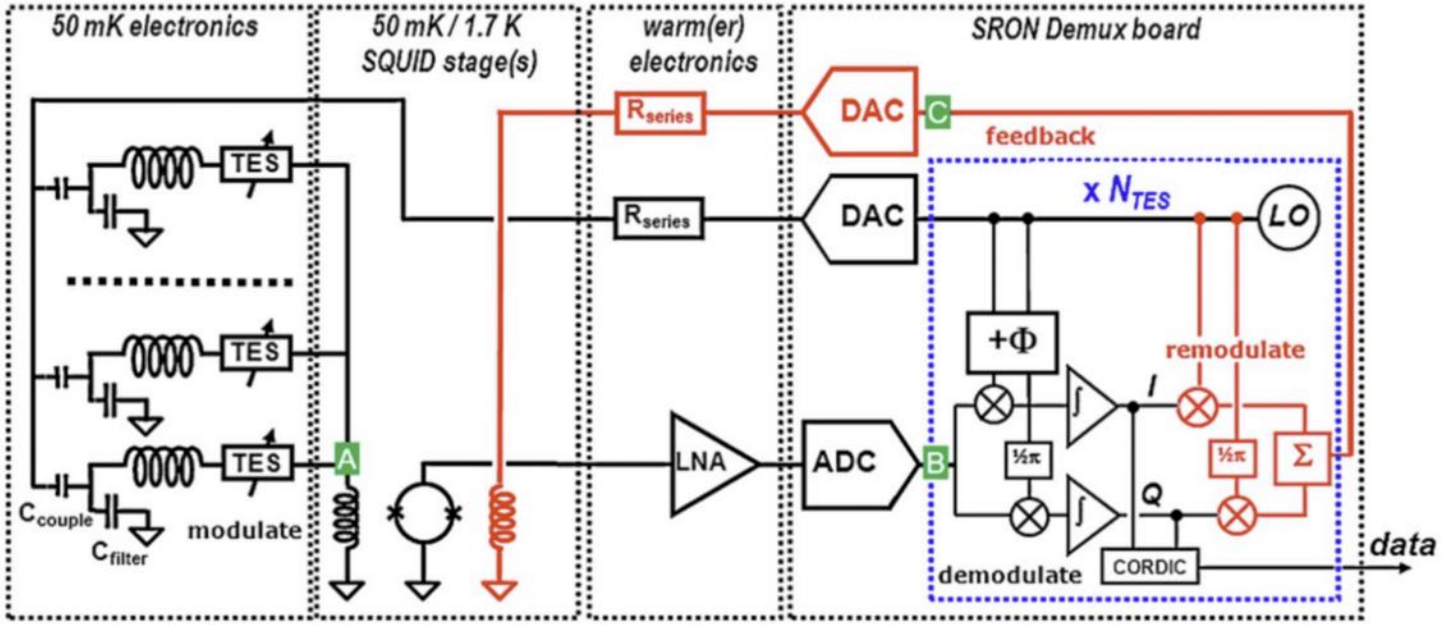


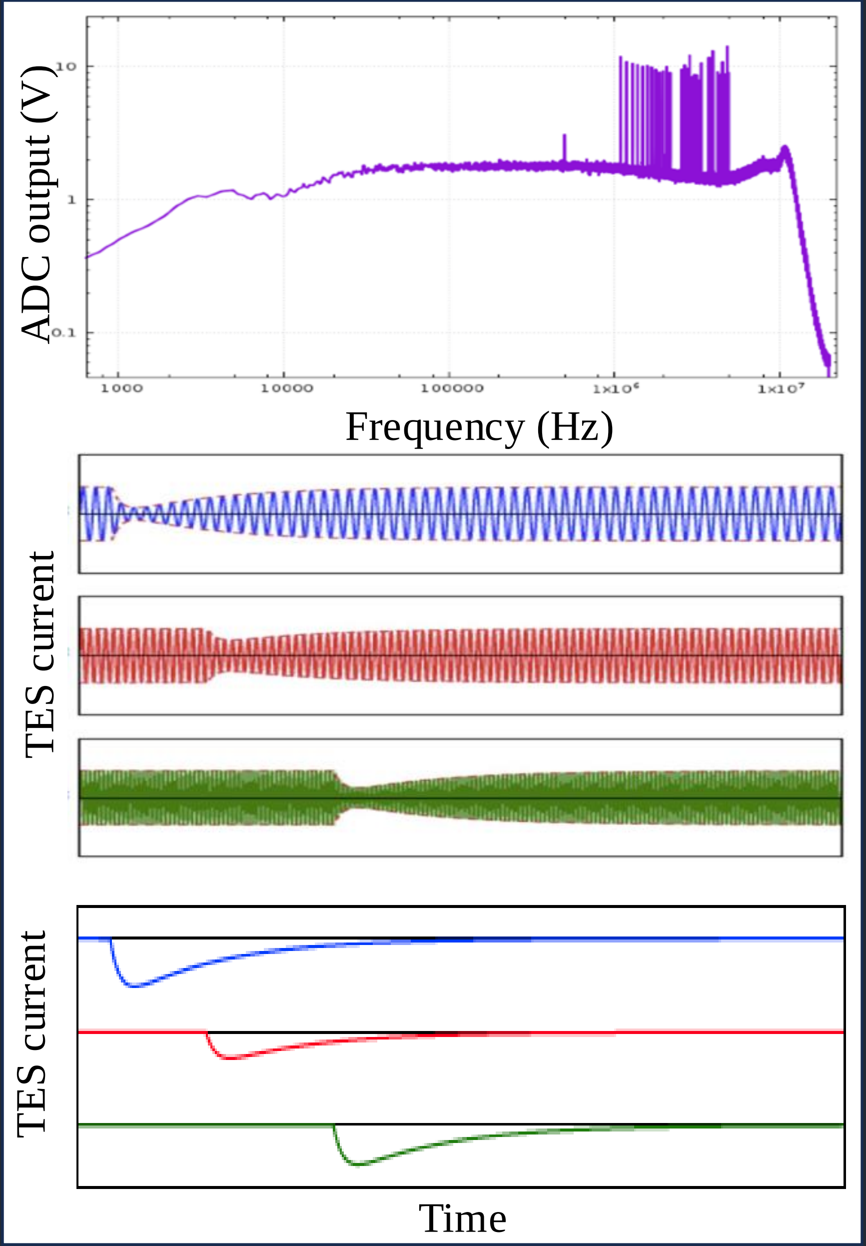
Room temperature
FEE and Demux board

- A TES is **ac voltage biased** between 1 to 5 MHz
- High-*Q* superconducting bandpass filters are used for each pixel (**LC filters**)
- The TES current is measured at 50 mK by very sensitive **SQUID** current amplifiers

Frequency Division Multiplexing

- TES is ac voltage bias and works as AM modulator of the MHz carrier
- High-Q bandpass filters
- Signal summed at SQUID input and   demodulated at room temperature
- Base-band feedback compensates phase delay to increase readout bandwidth
- Performs with very long harness, low sensitivity to parasitic and EMI
- Low electrical cross-talk, Individual pixels bias addressing

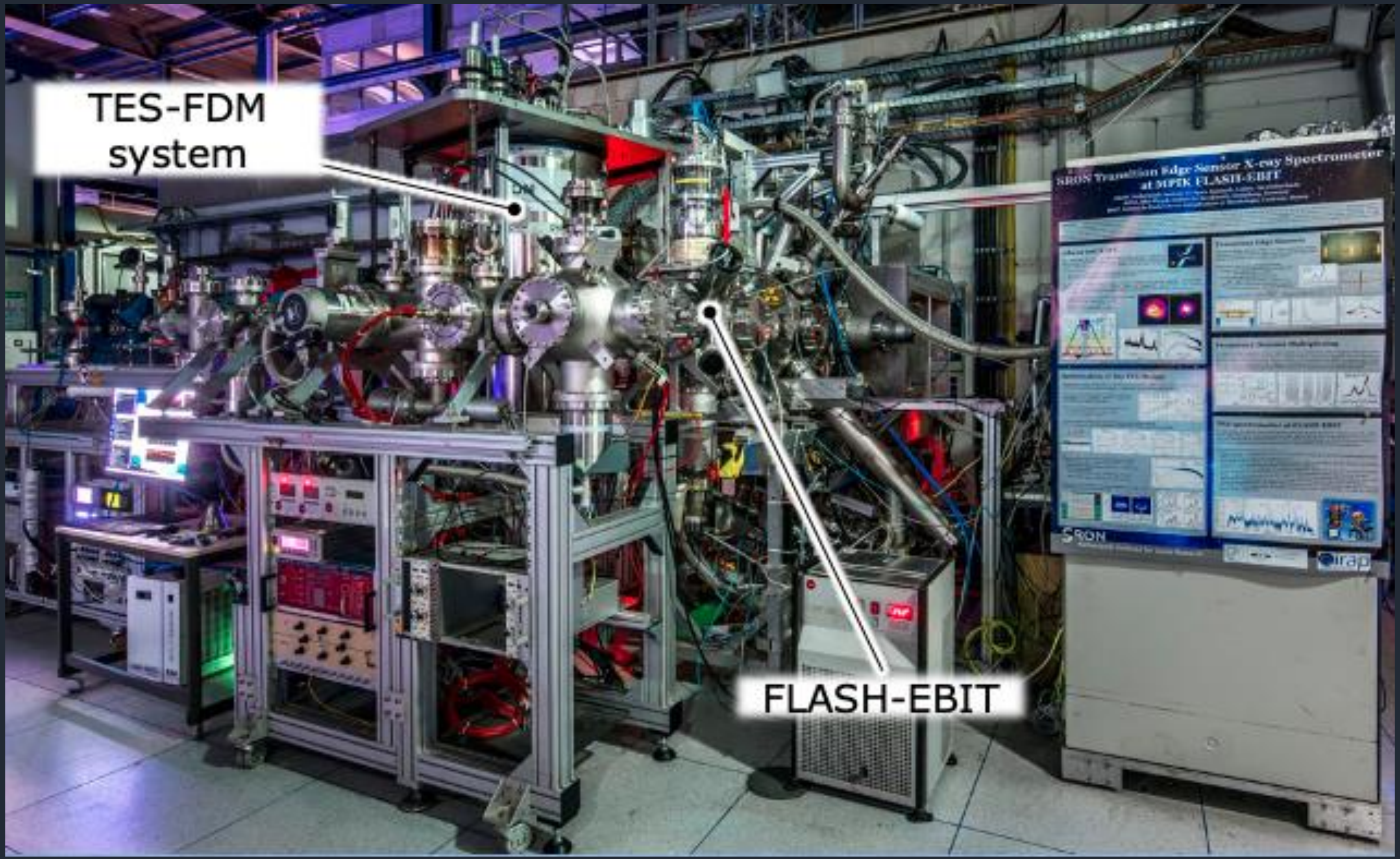


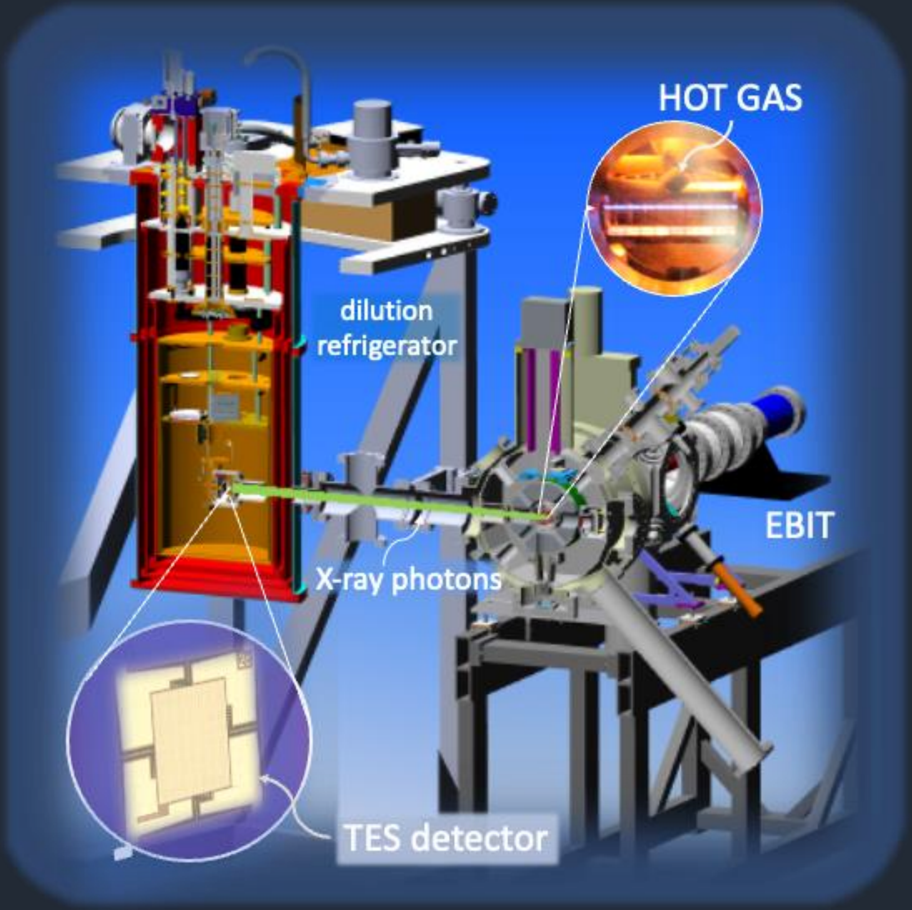


M. Kiviranta, https://arxiv.org/abs/2012.15362 (2020)
J. van der Kuur et al., IEEE Trans. Appl. Sup. 13(2) (2003)
R. den Hartog et al., IEEE Trans. Appl. Sup, 21(3) (2011)

Laboratory Astrophysics

SRON high resolution X-ray spectroscopy of hot plasma at the MPI-K Electron Beam Ion Trap (EBIT) facility





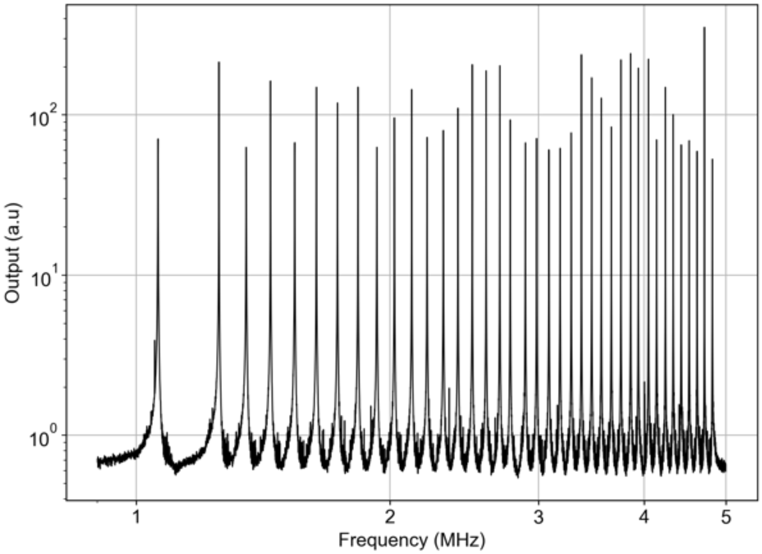
SRON

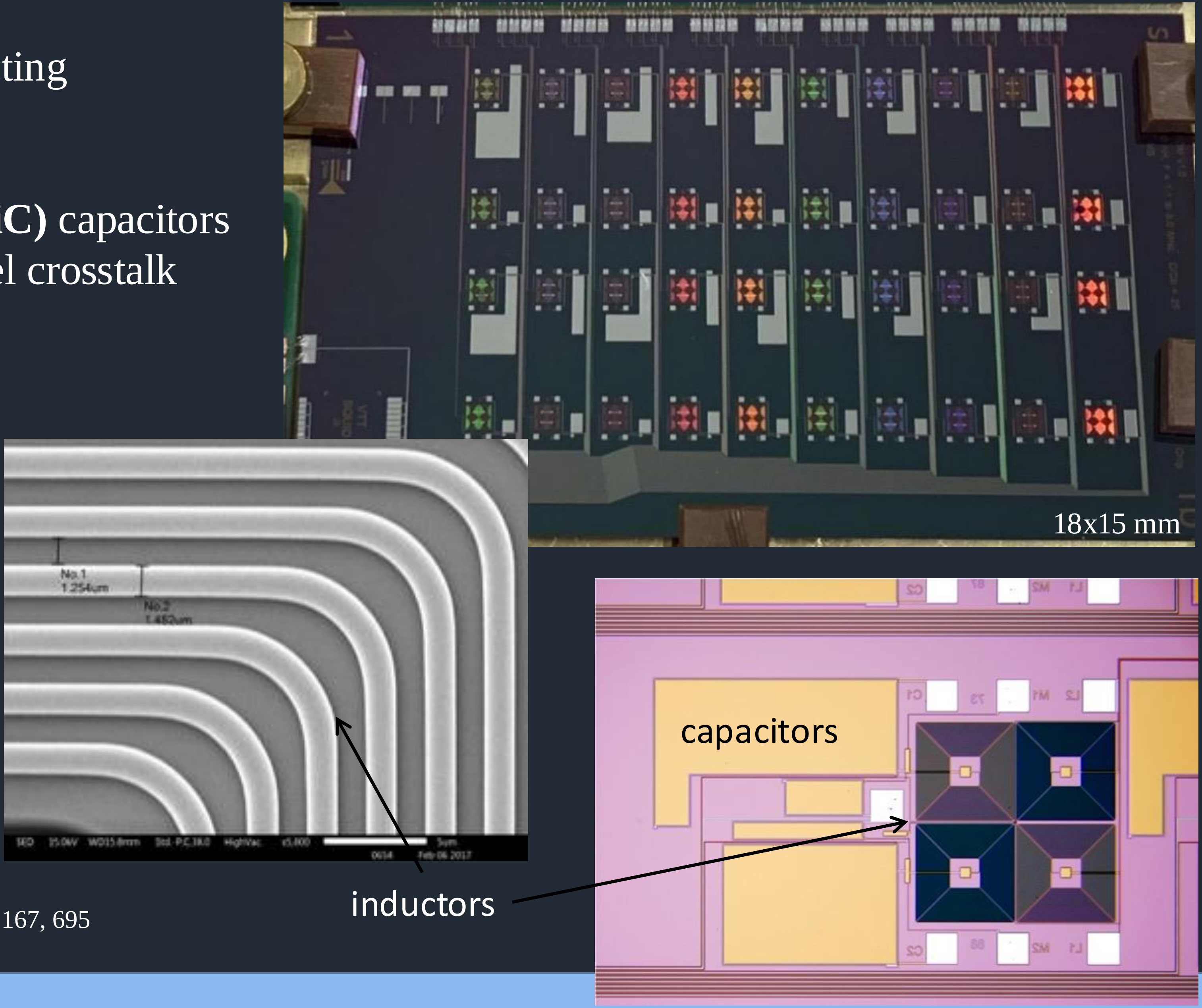
MAX-PLANCK-INSTITUT
FÜR KERNPHYSIK
HEIDELBERG

irap
astrophysique & planétologie

Superconducting high-*Q* MHz LC filters

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

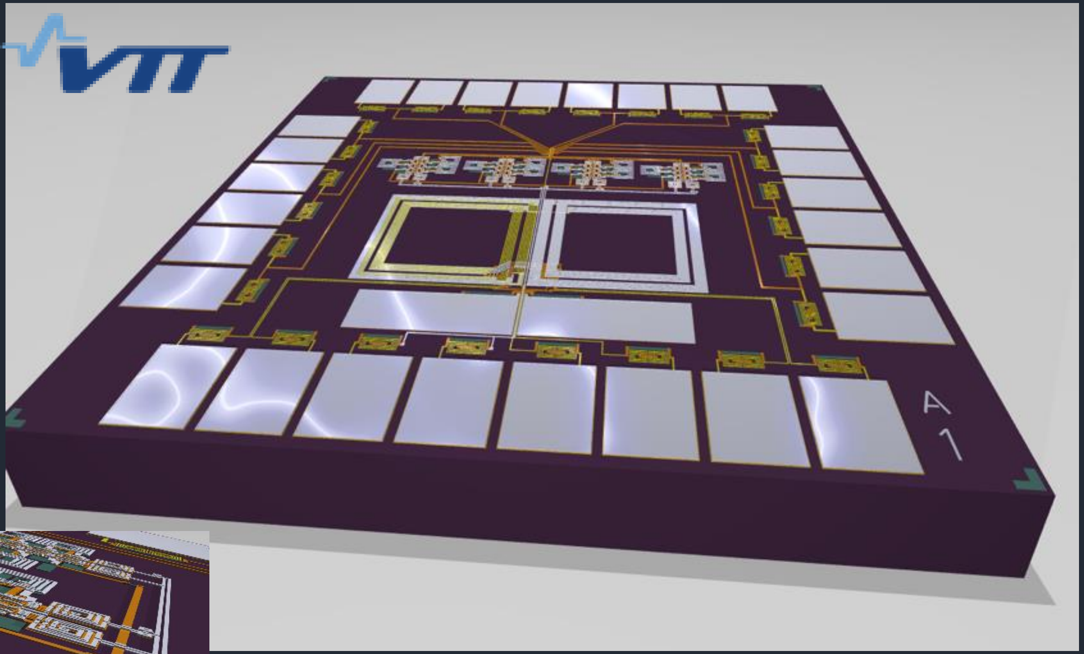


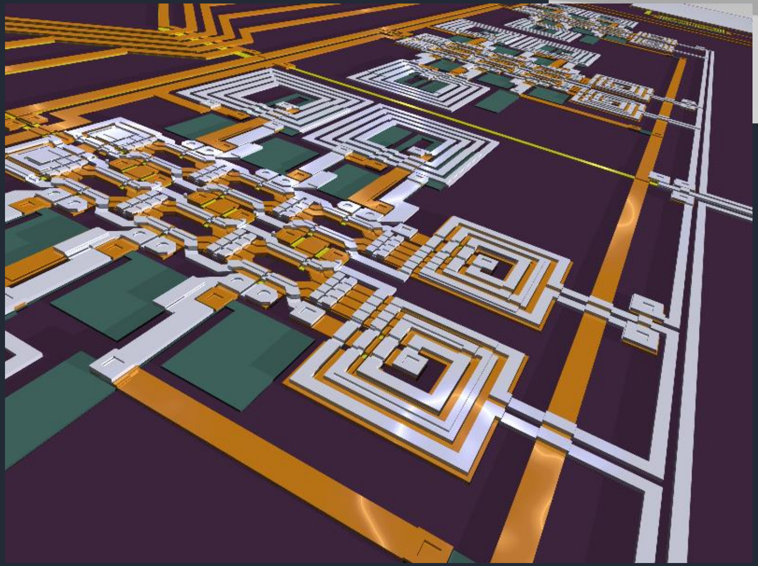


M. P. Bruijn, et al., J. of Low Temp. Phys. 167, 695 (2012).

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

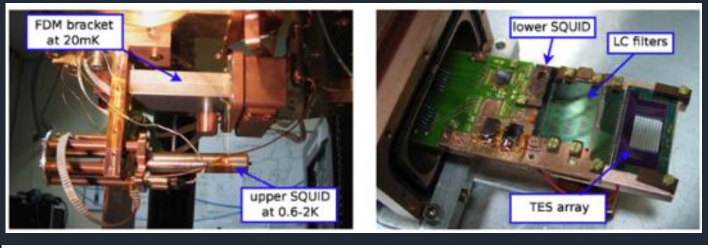


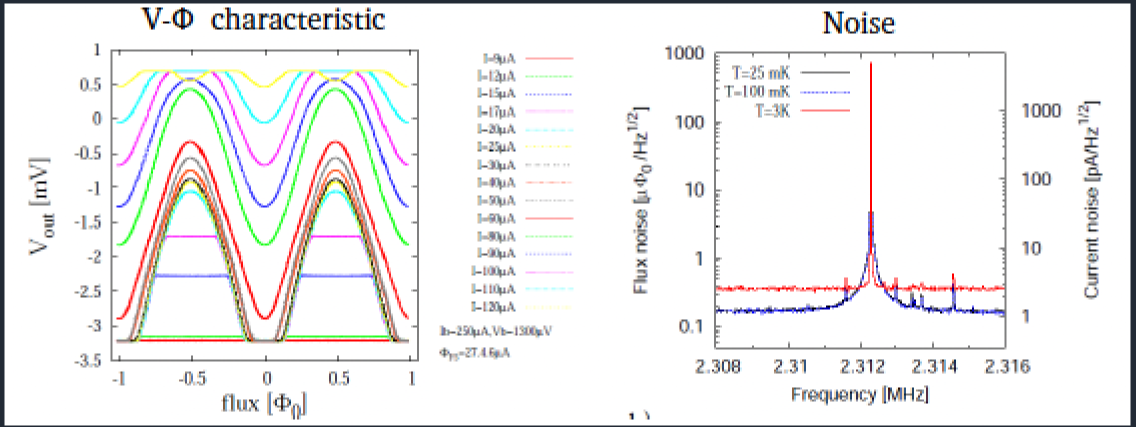


Credits: Mikko Kiviranta, VTT, Finland

SQUIDs and LC resonator performance

Nearly quantum limited two-stage SQUID amplifiers
for the frequency domain multiplexing of
TES based X-ray and infrared detectors





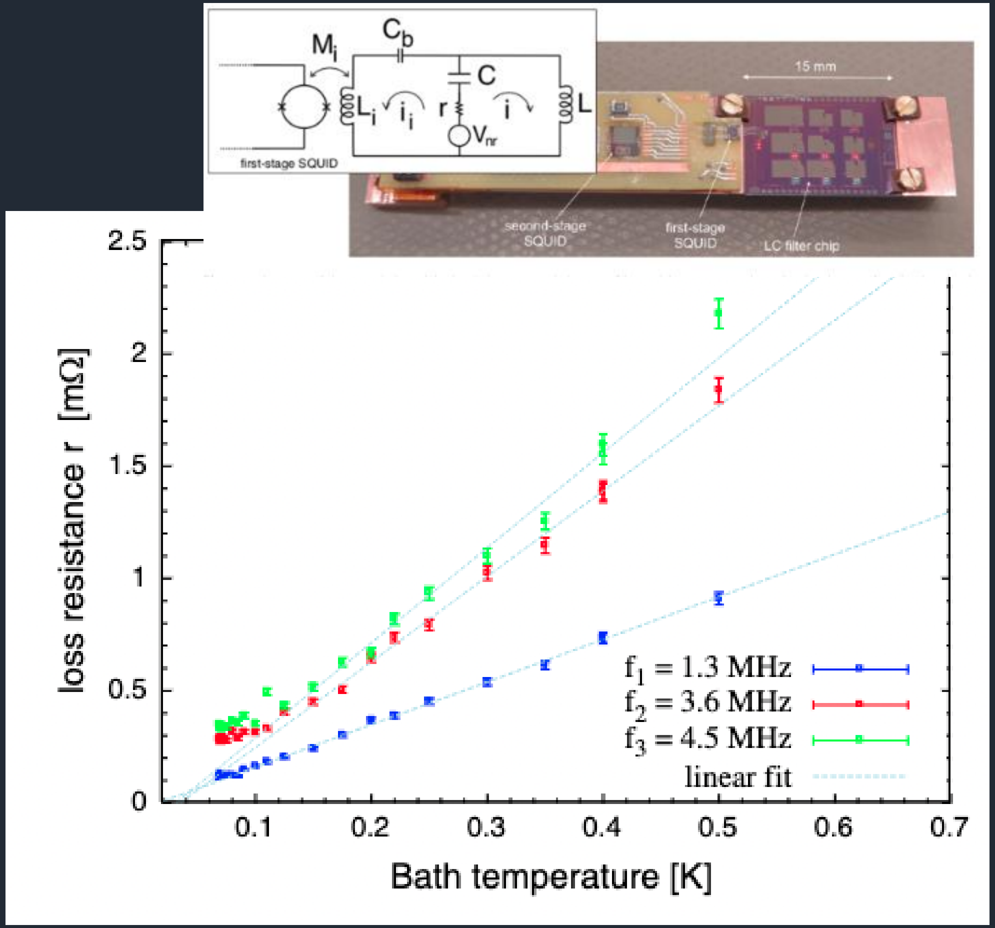
- Best energy resolution:

$$\varepsilon = S_\Phi / 2L_{SQ} \simeq 9\,\hbar \qquad \textit{intrinsic} \quad (L_{SQ}=70\text{ pH})$$

$$\varepsilon_C = 1/2 L_{IN} I^2_{NS} \simeq 15\,\hbar \qquad \textit{coupled} \quad (L_{IN}=3\text{ nH})$$

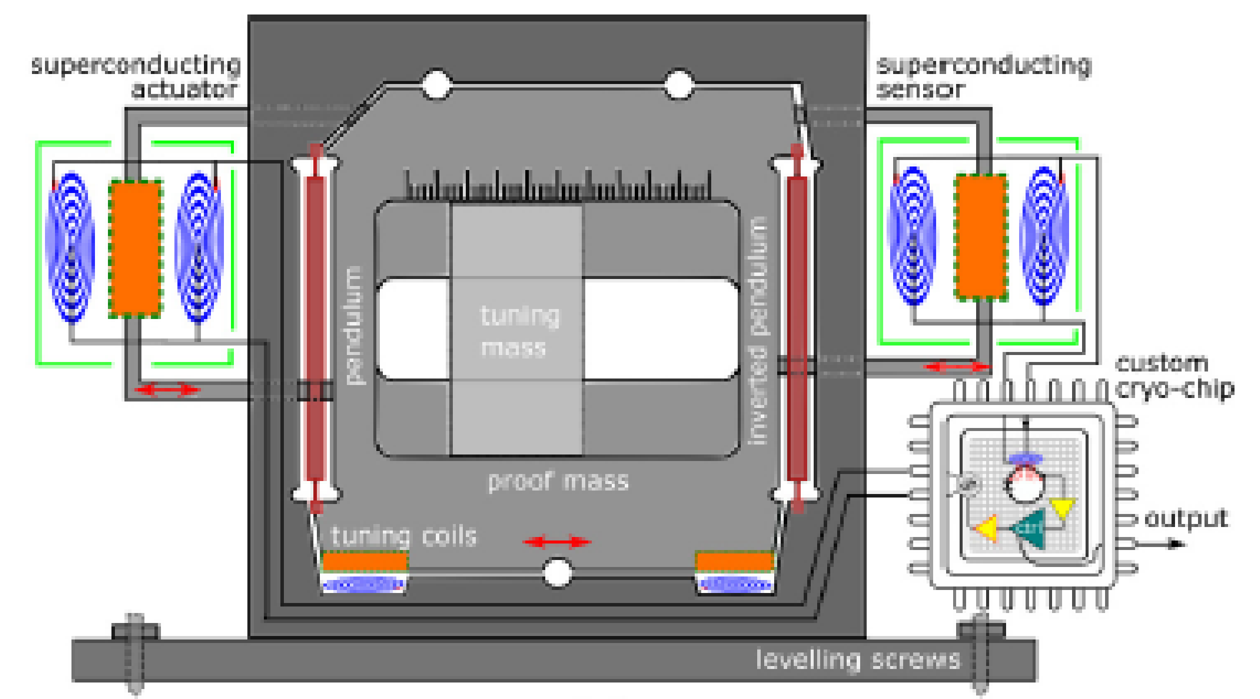
L Gottardi, *et al.*
IEEE Trans. on Appl. Superc. 25 (3), 1-4 (2014)

Intrinsic losses and noise of high-Q lithographic MHz LC resonators
for frequency division multiplexing



L Gottardi, et al. ,
J. of Low Temp. Physics 194, 370-376, 5 (2019)

Superconducting Inertial sensors for the Lunar Gravitational Wave Antenna

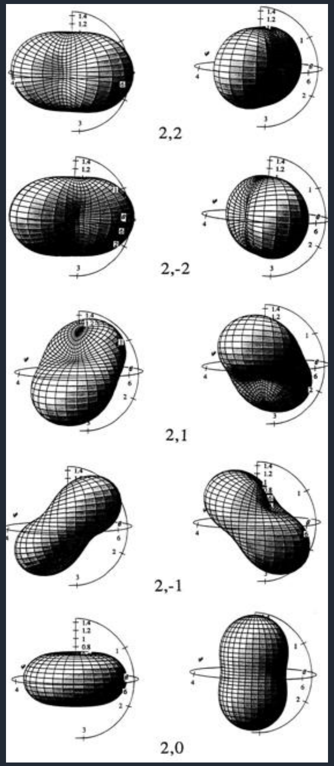


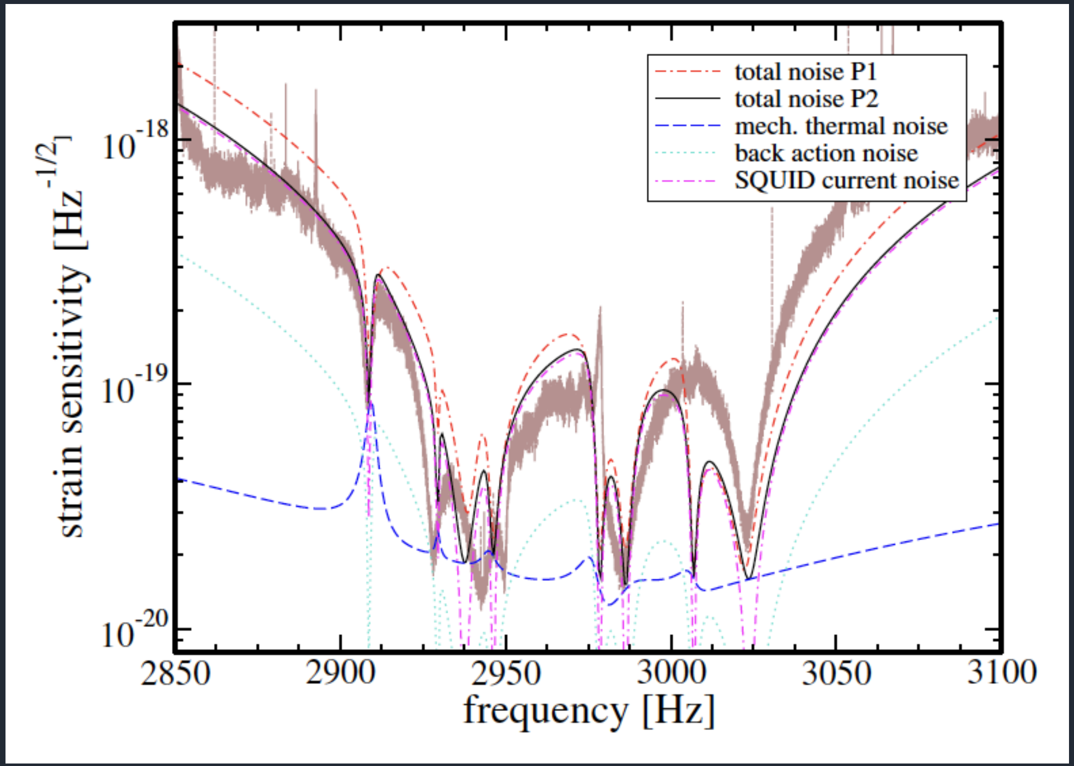
J. V. van Heijningen et al. J. Appl. Phys. 133, 244501 (2023); doi: 10.1063/5.0144687

SRON SQUID and superconducting LC filters technology could be transferred to build a sensitive superconducting inertial sensors and actuators

MiniGRAIL (Leiden)
a spherical gravitational waves detector

A massive detector near the absolute zero





1.3 Ton CuAl sphere cooled at 65 mK

10^{-19} m displacement sensitivity at 3 kHz

$T \sim 5K,\ S_{hh} \sim 10^{-20}\ \mathrm{Hz}^{-1/2}$ → $dx_{sphere} \sim 10^{-18}$ m

Leiden Institute of Physics

E. Coccia, V. Fafone, G. Frossati (1995)
A.De Waard et al., Classical Quantum Gravity 21, S465 (2004)
L. Gottardi et al., Phys. Rev. D. 76, 102005 (2007)

The Moon as a big big spherical gravitational waves detector

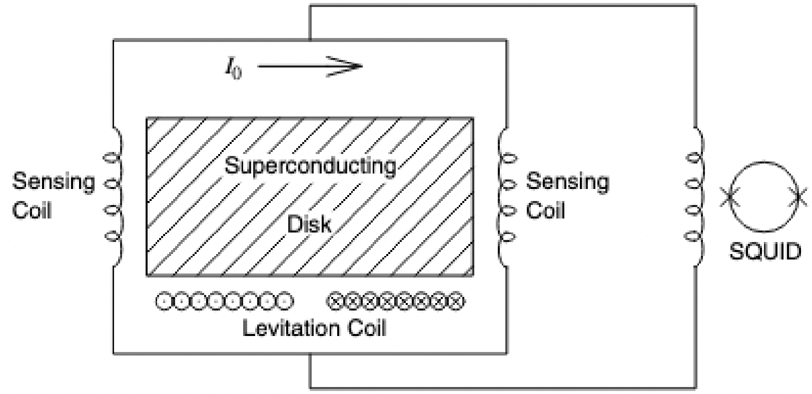
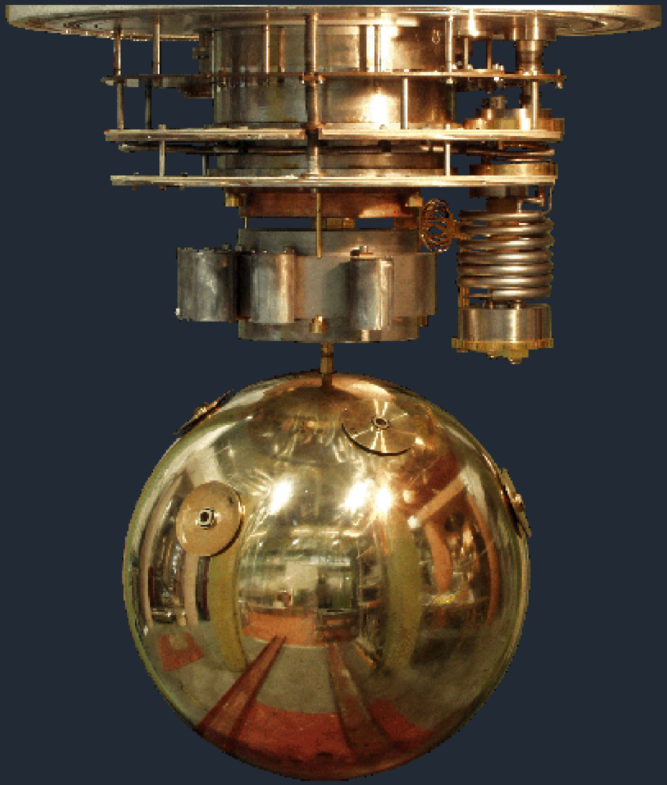


Fig. 2. Schematic of superconducting displacement sensor.

H.J. Paik, K.Y. Venkateswara / Advances in Space Research 43 (2009) 167–170

Johnson, W.W. The Moon as a gravitational wave detector, using seismometers, in: AIP Conference Proceedings 202:1; NASA Work-shop on Physics from a Lunar Base, pp. 183–187, 1989

MiniGRAIL capacitive read-out

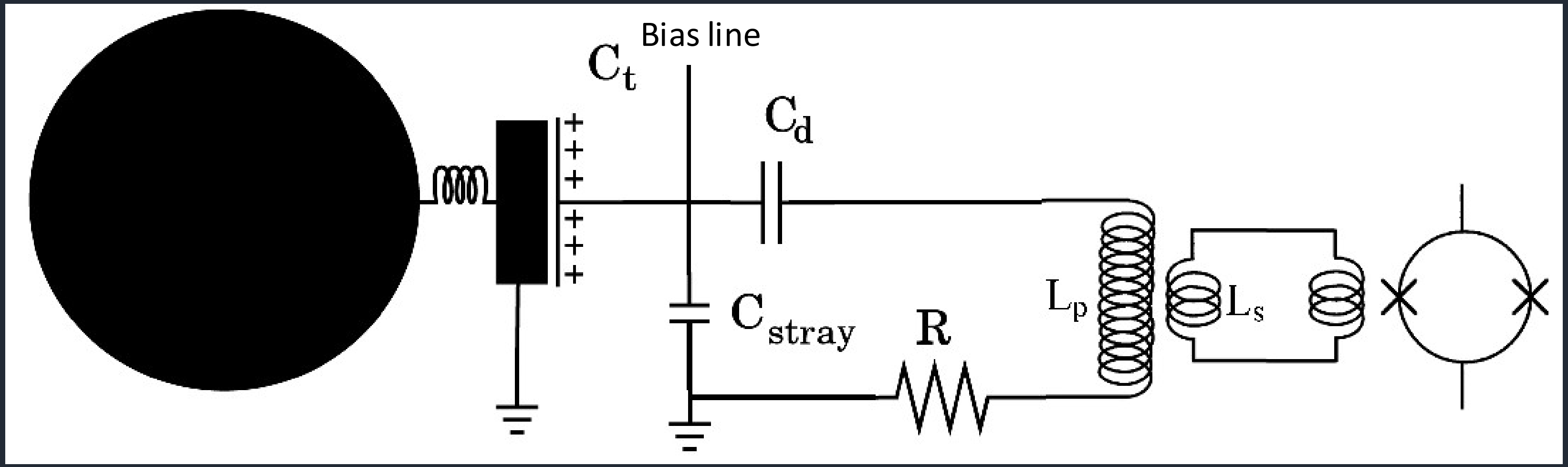


Mechanical amplification

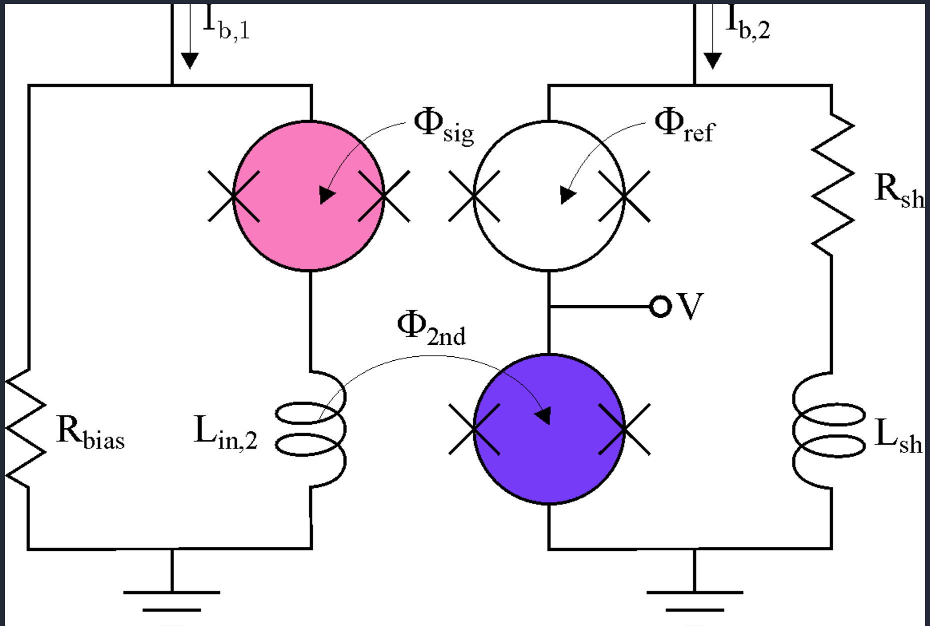
electrical amplification

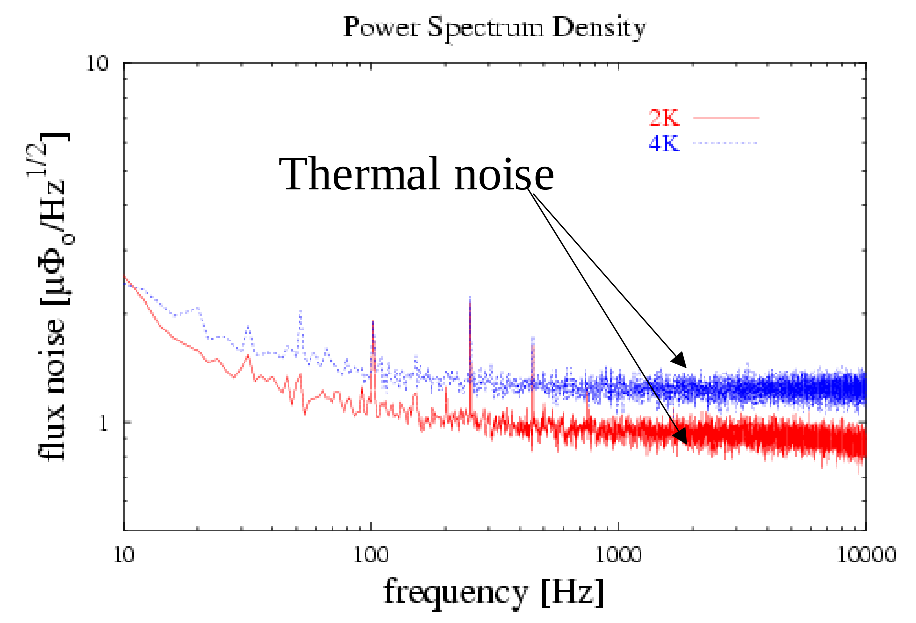
superconducting matching transformer

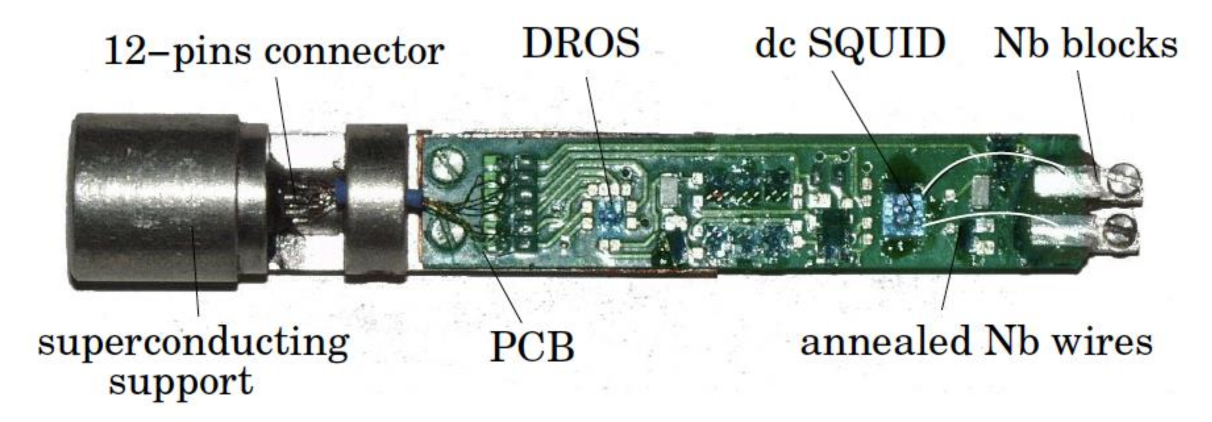
SQUID linear amplifier



Two stage SQUID configuration for MINIGRAIL





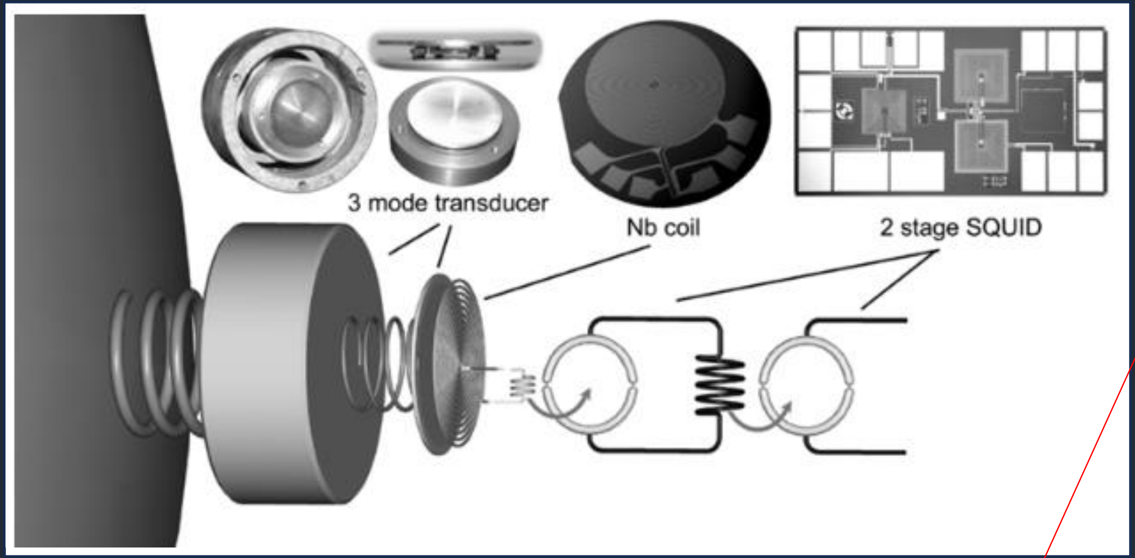


A dc SQUID is used as the sensor and a DROS was used as a cryogenic low-noise preamplifier

In collaboration with Twente University

Luciano Gottardi, PhD Thesis (2004)
M Podt, L Gottardi, A de Waard, G Frossati, J Flokstra IEEE Trans. on Appl. Superc. 15 (2), 785-788,4 (2005)

Two modes inductive transducer for MINIGRAIL



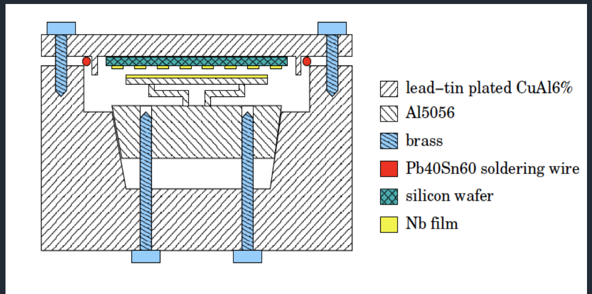
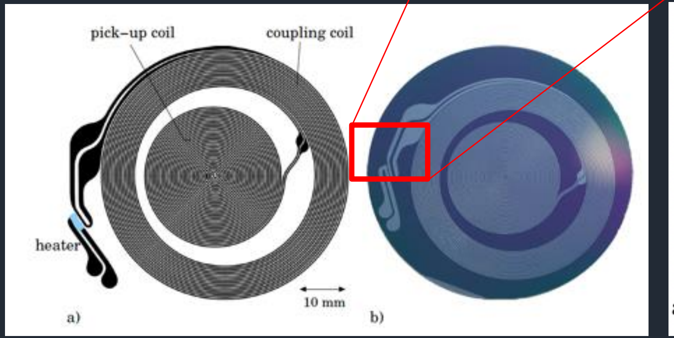
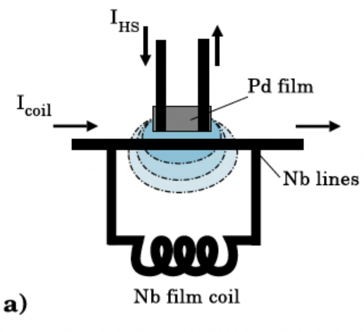


Figure 5.17. Scheme of the resonator-coil assembly.





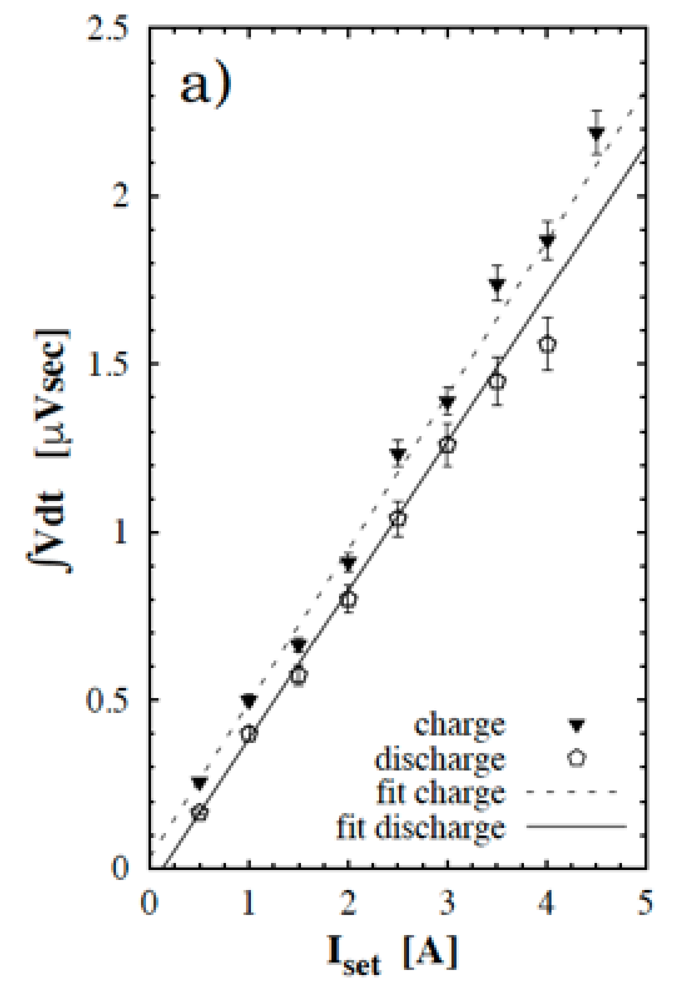
~ 5 cm

800nm thick Nb film

Critical technology

- Mechanical coupling between resonators
- Flat lithographic Nb coil with large current
- Current injection via superconducting heat switch

Succesfully run
persistent current up to ~ 5 A



Leiden Institute of Physics

Luciano Gottardi,, PhD Thesis (2004)

Current activities at SRON related to LGWA + synergies in NL

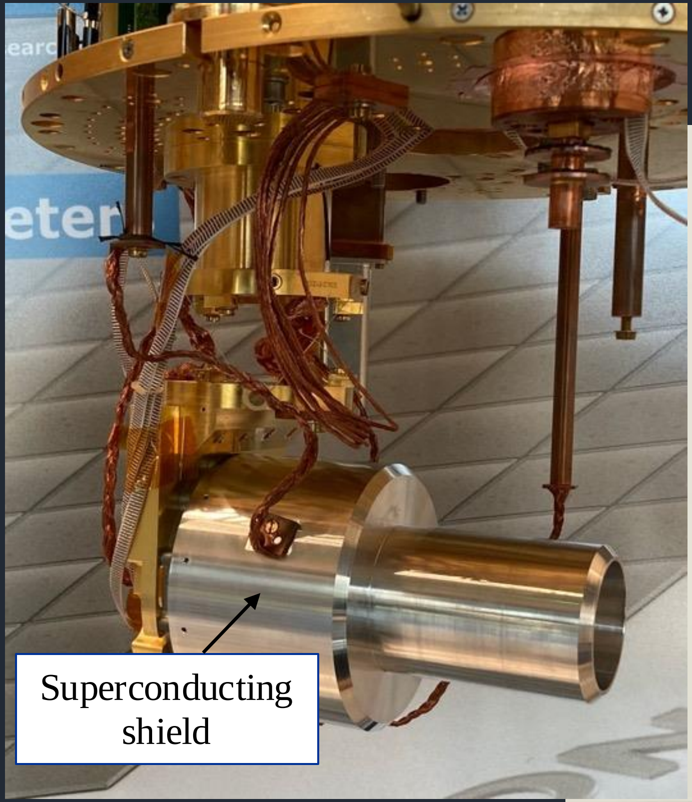
- Space qualification of SQUID and superconducting read-out within Athena/XIFU
  - → Demonstration Model (2025) , Engineering Model (~2028), Flight model (2032)
  - → Increase the TRL level of superconducting technology at mK temperature

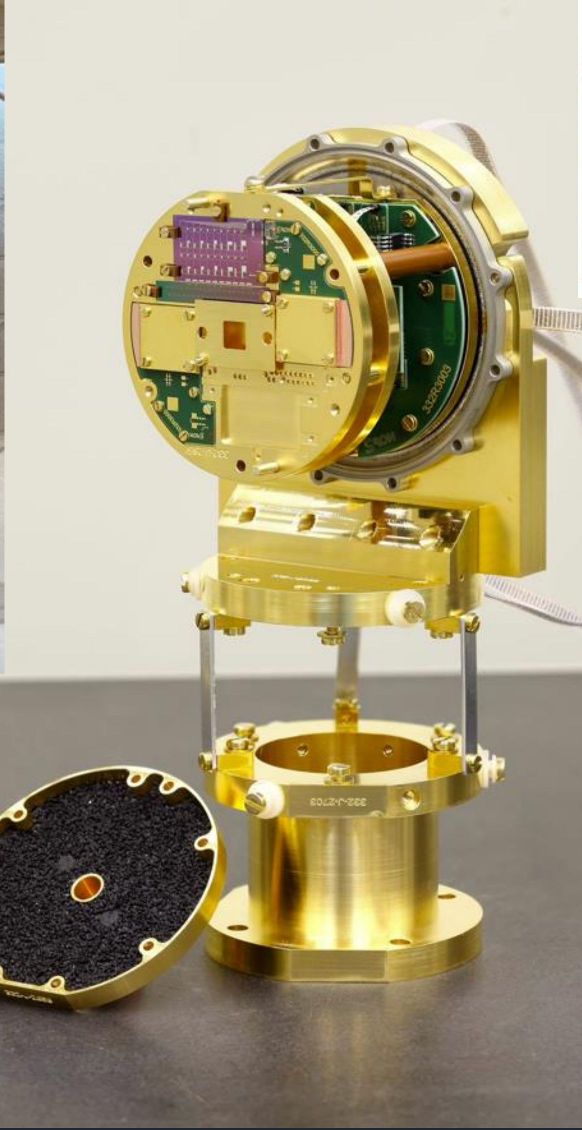
- (Small) contribution to recently financed NL project on "Improved Cold Vibration Isolation for science and industry (ICVI)",
  - collaboration with Leiden University, NIKHEF, and Dutch industries
  - the proposal aims to create value for the Dutch bid on the Einstein Telescope
  - potential for bigger SRON contribution in the future

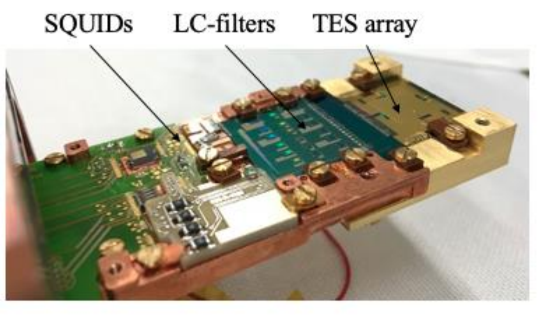
- Concept study to use NbTiN MHz superconducting readout for inertial sensors

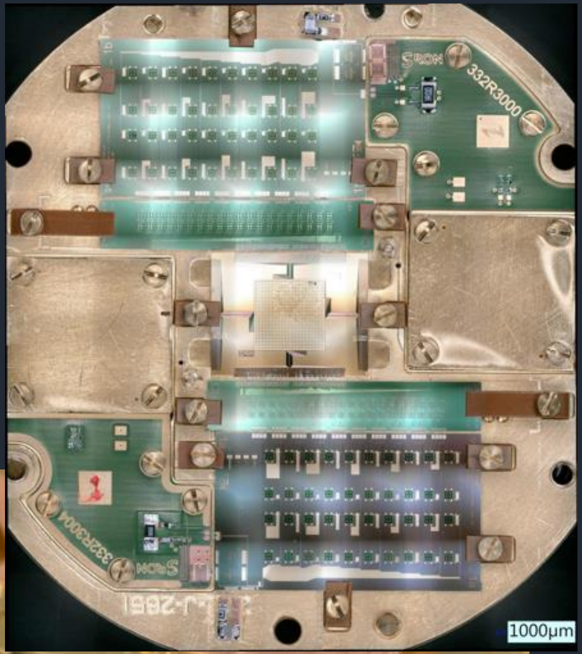
- Low vibration cooler from TU Twente are interesting for TES-based single photon detectors application as well
  - we should team up to create a critical mass in NL

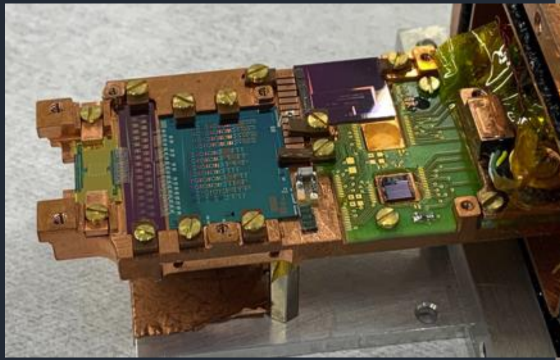
FDM development

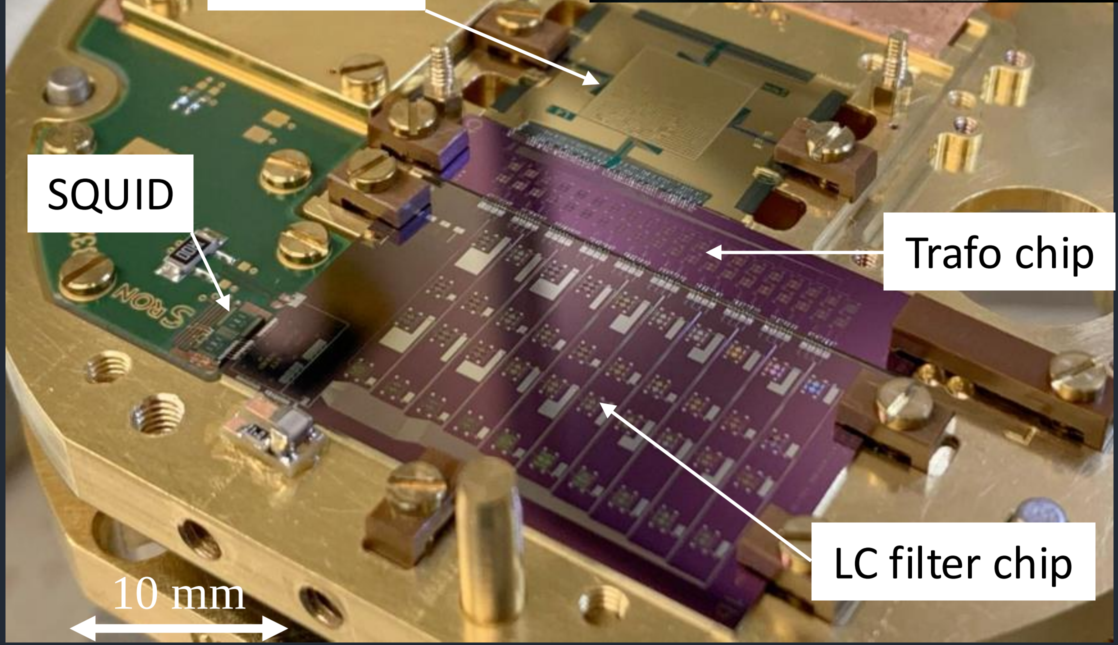








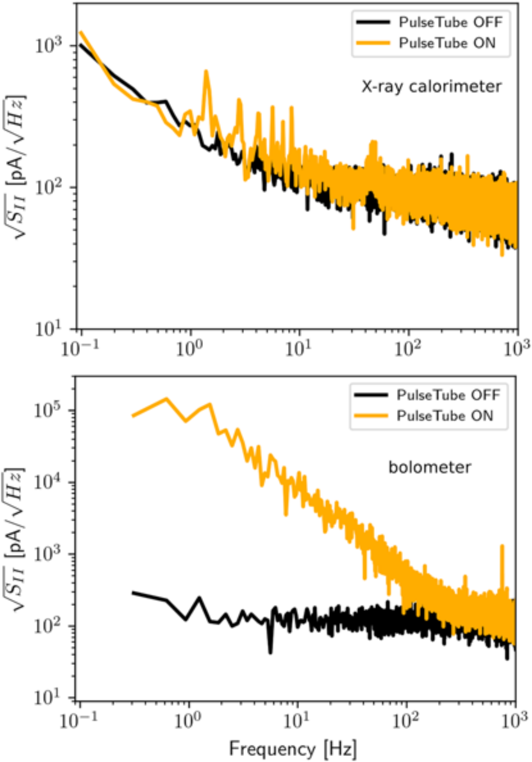


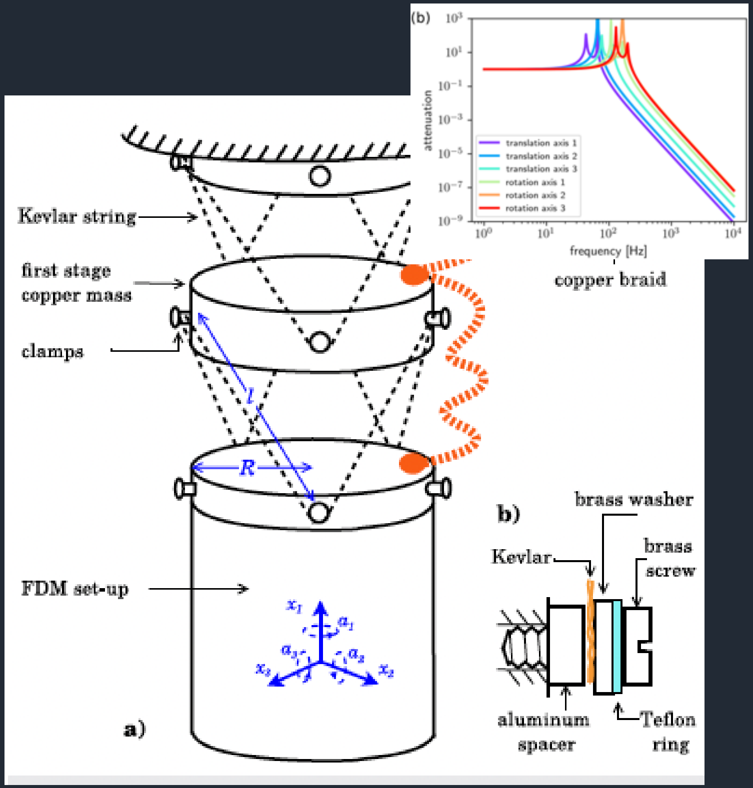


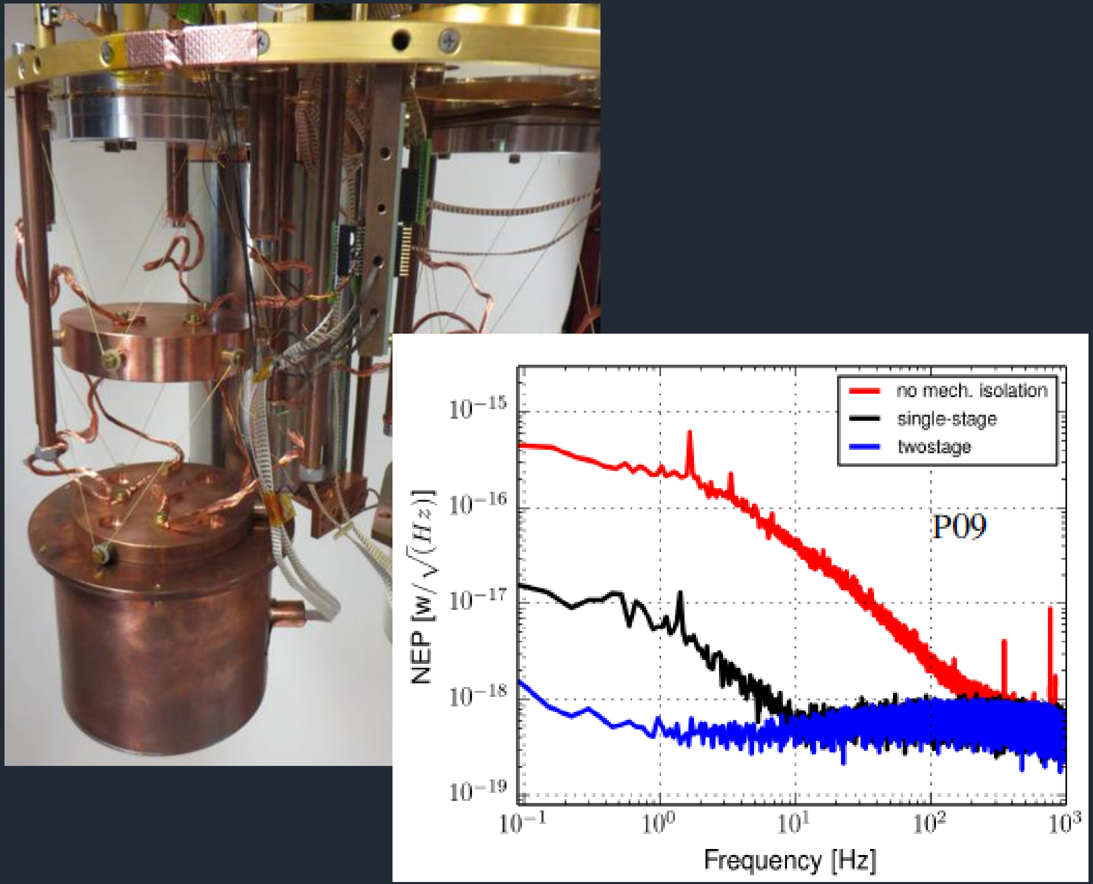
SRON

Damping of micro-vibrations from Pulse Tube Cooler

- High frequency microvibration → up-conversion from PT 1.5 Hz excitation
- Developed a 6 degree-of-freedom vibration isolation system (inspired by GW detectors)

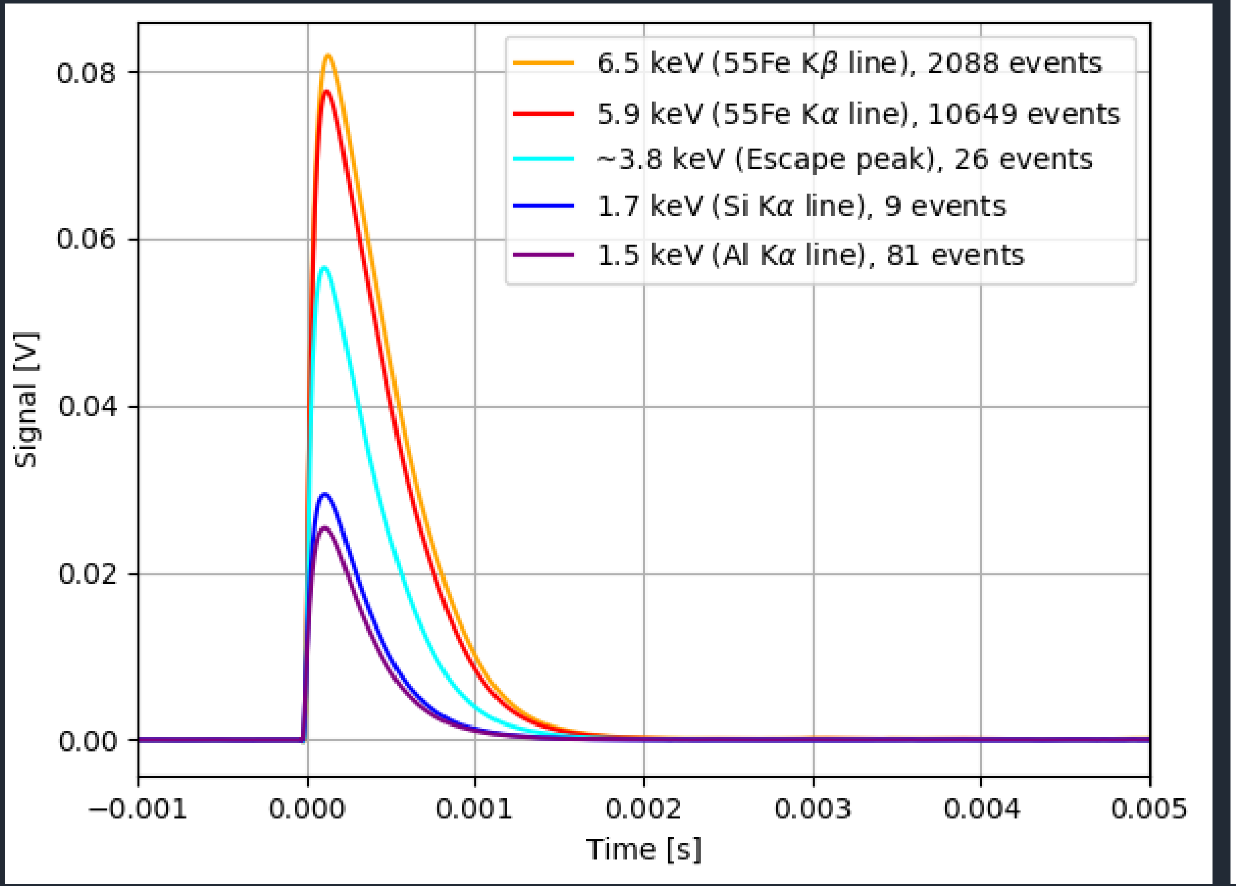


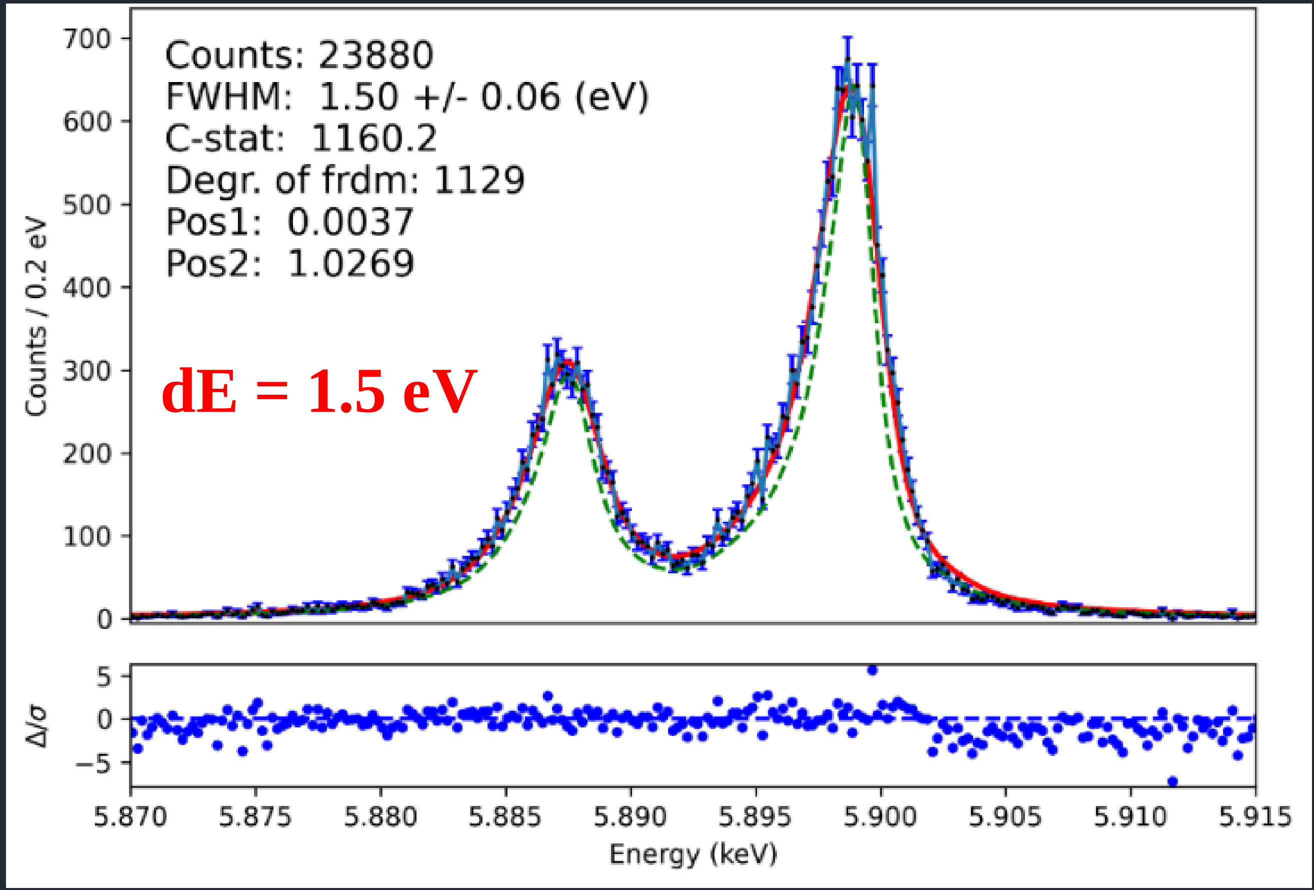




L.Gottardi et al., Rev.Sci.Instrum, 90,055107 (2019)

X-ray TES microcalorimeter

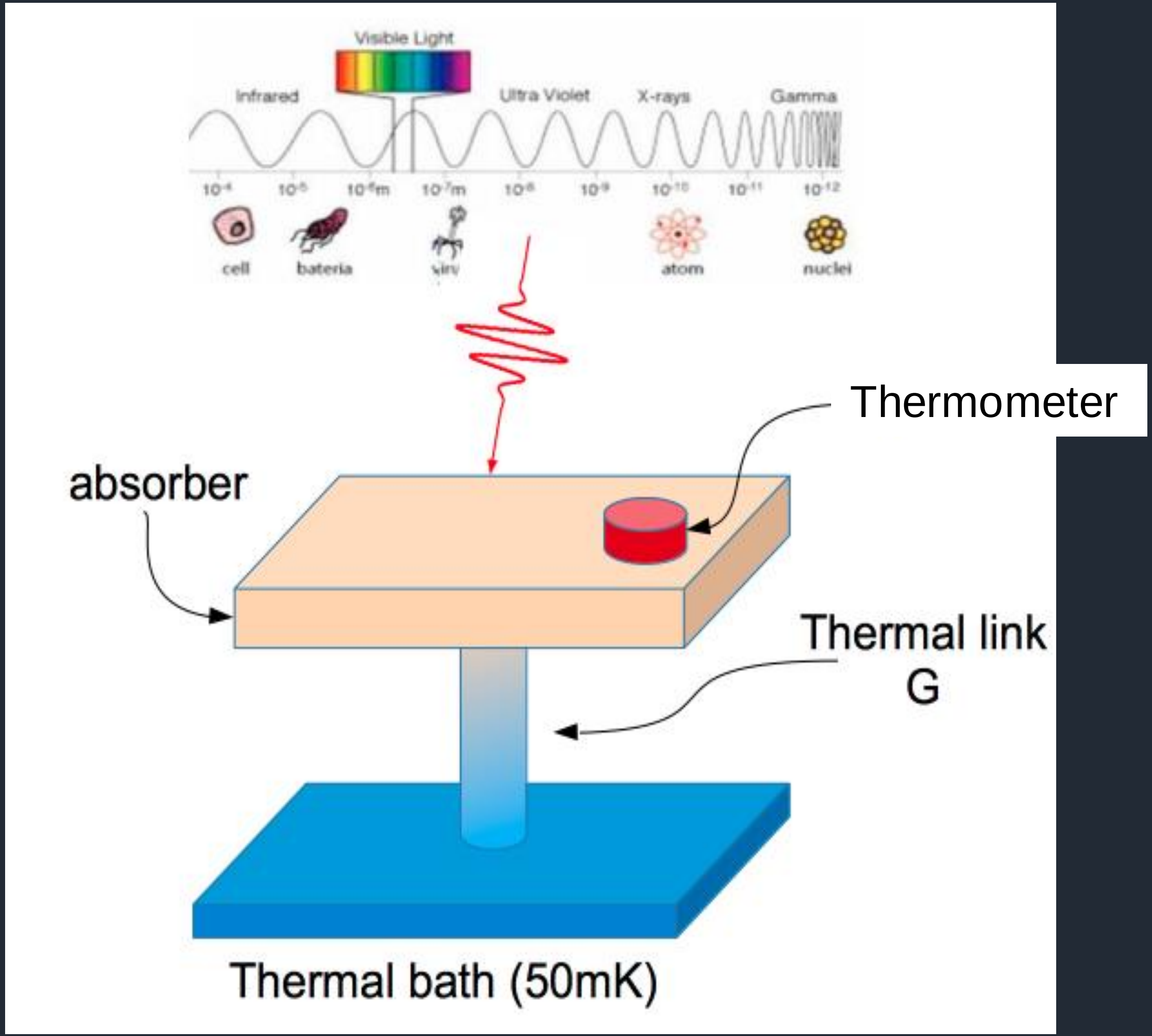




Single photon detectors

High resolving power

Low temperature micro-calorimeters and bolometers



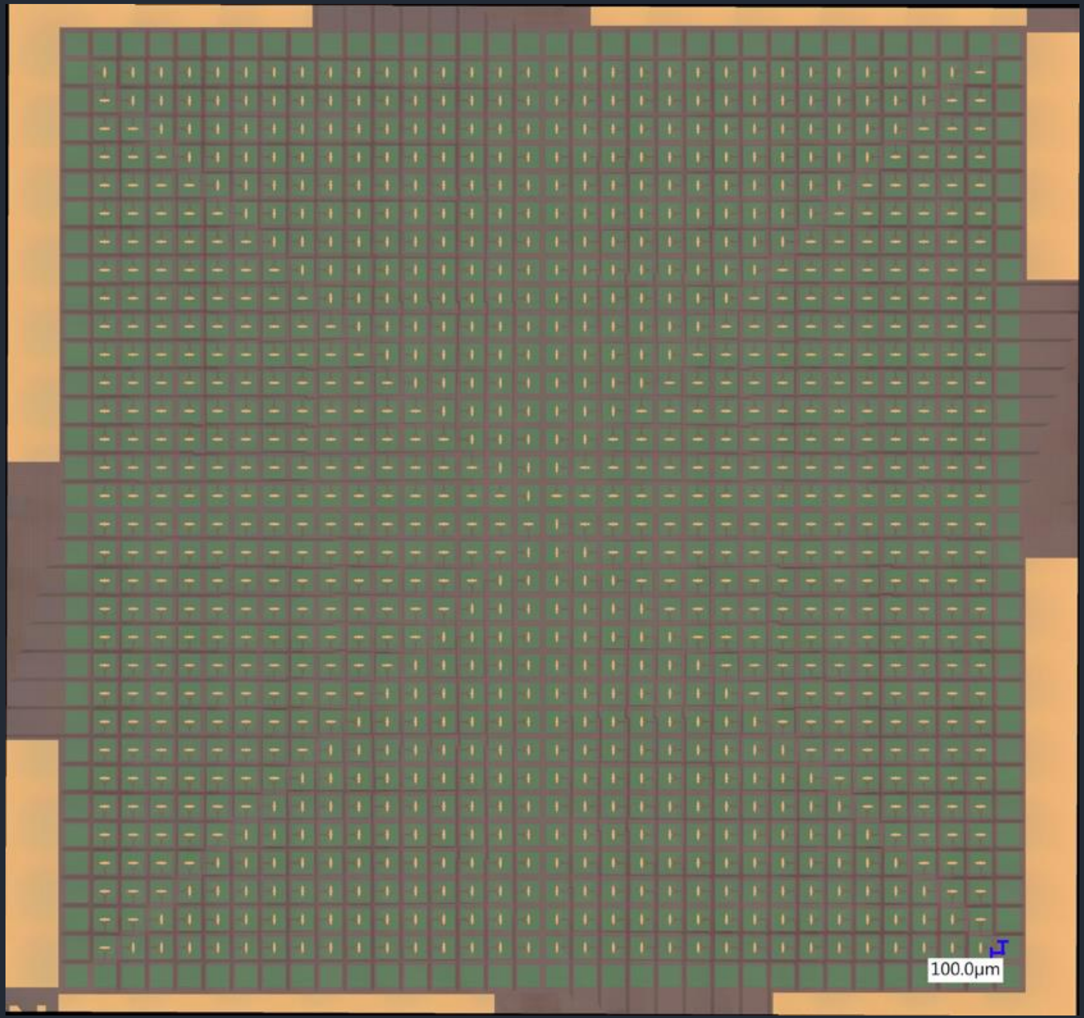
Fundamental elements:

(individually tuneable depending on the applications)

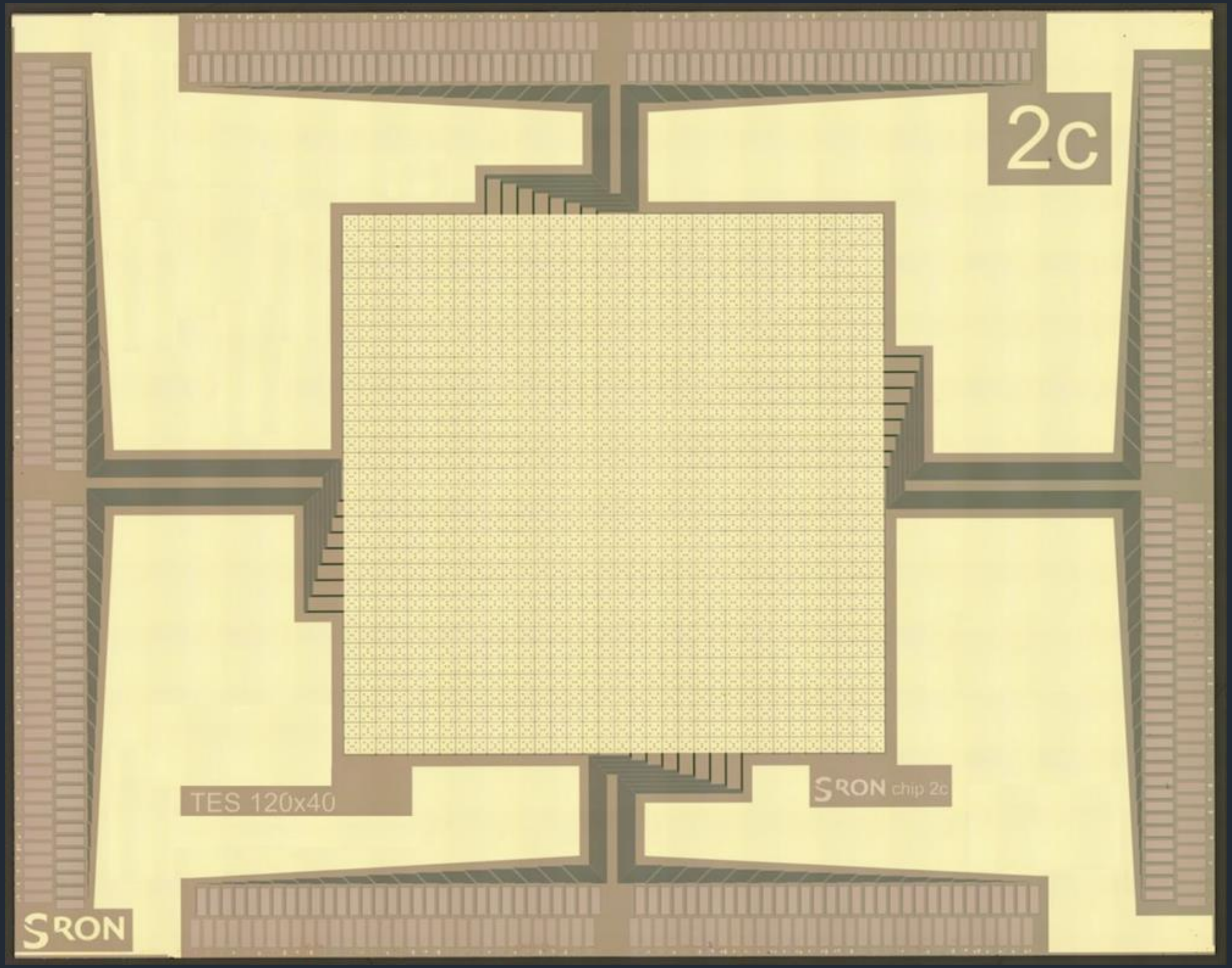
1. Absorber
2. Sensitive thermometer
3. Weak thermal link to bath

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

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