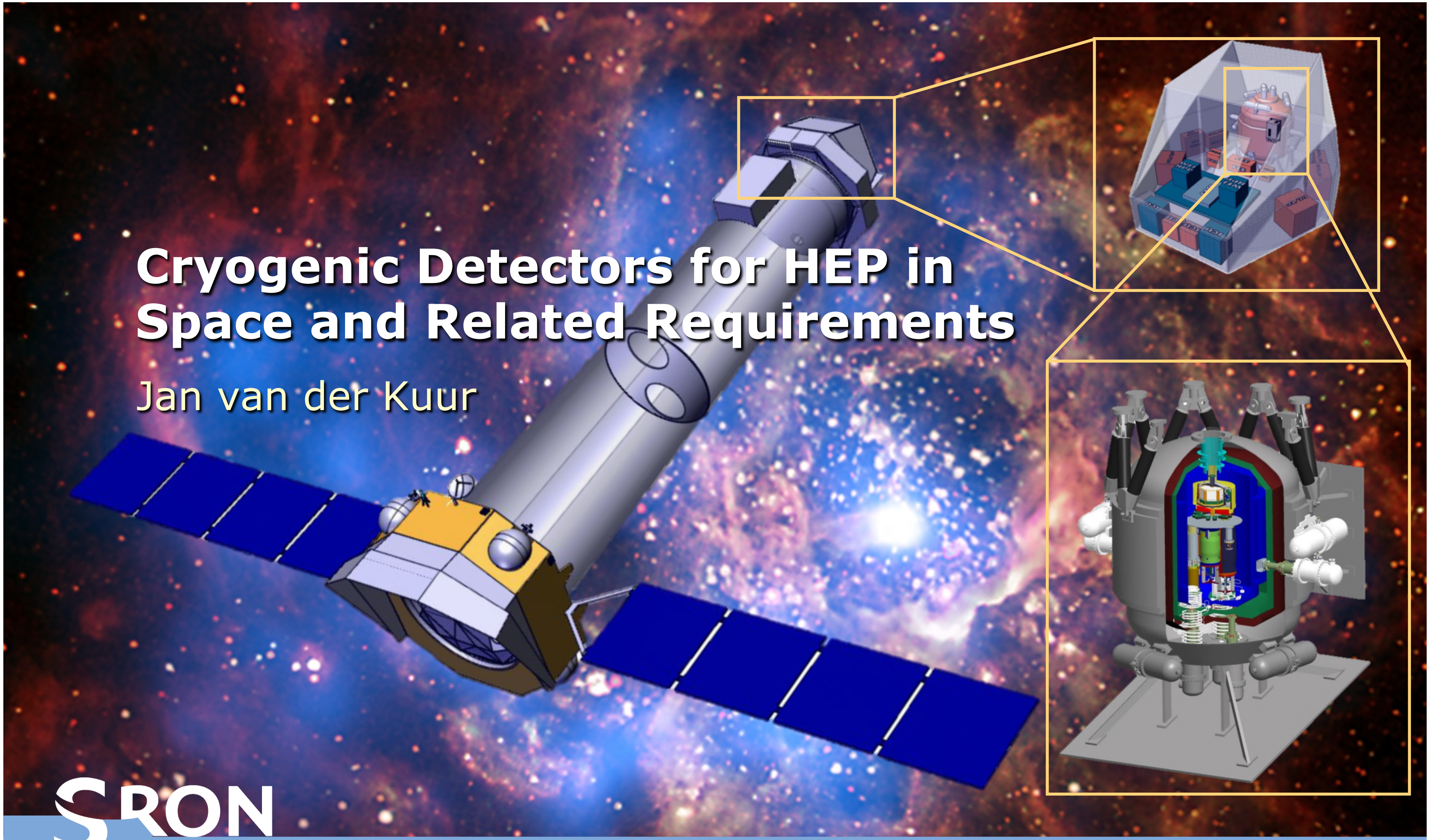
Cryogenic Detectors for HEP in Space and Related Requirements

Jan van der Kuur



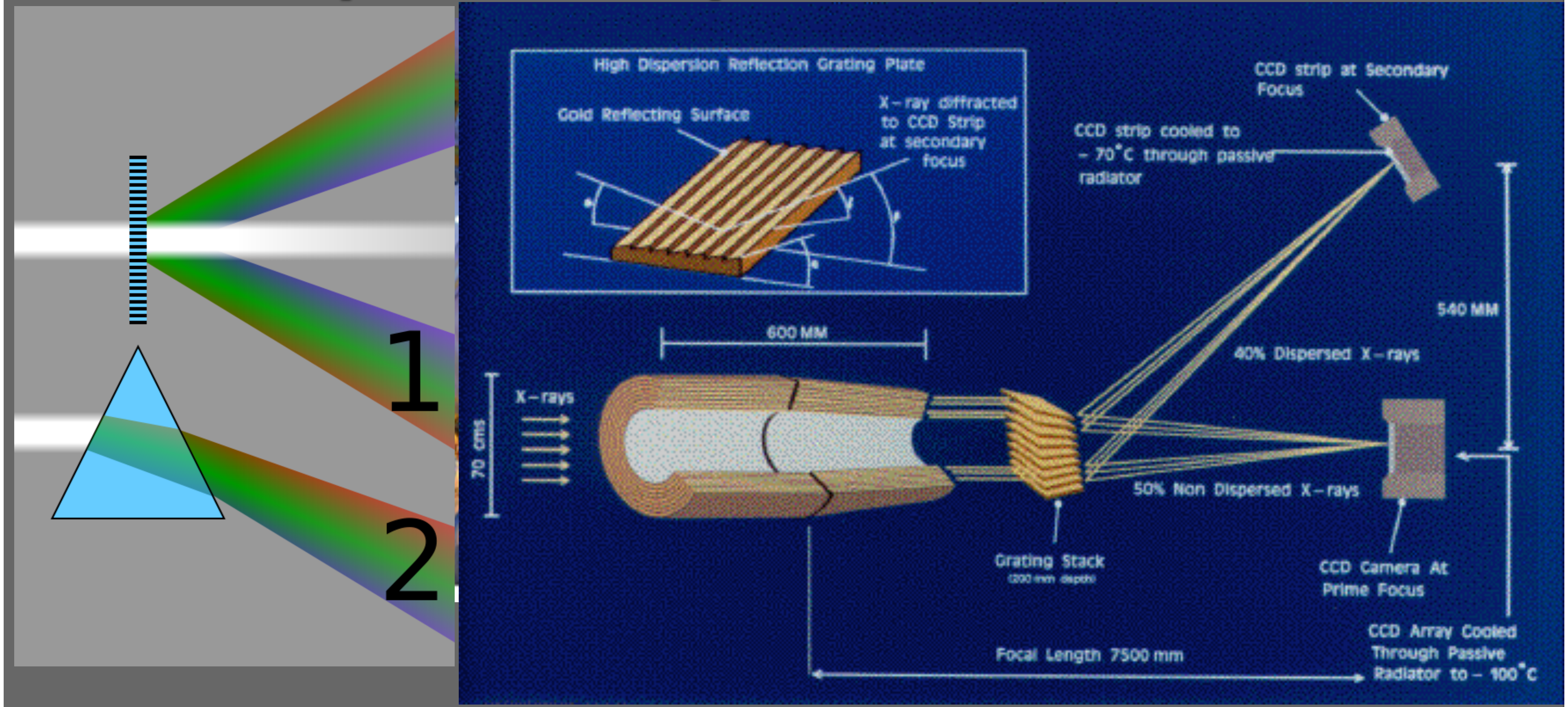
SRON

Netherlands Institute for Space Research

Netherlands Organisation for Scientific Research (NWO)

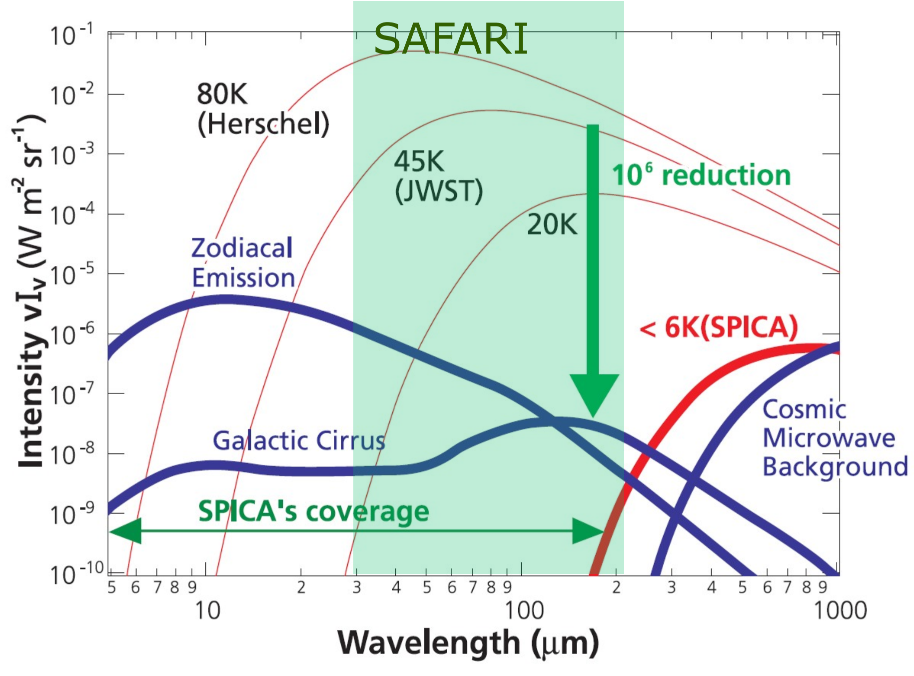
Why do we need cryogenic detectors at mK temperatures for space applications?

XMM X-ray observatory

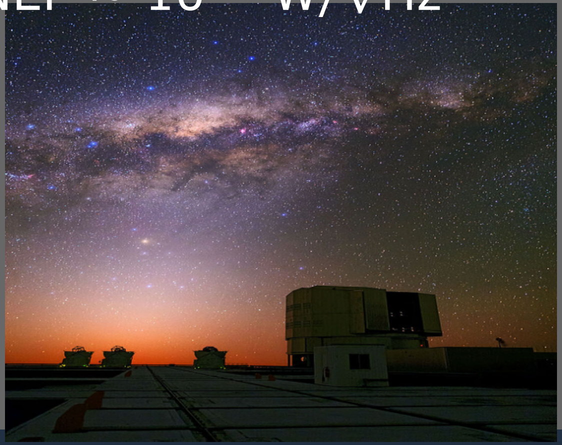


- In orbit since december 1999
- CCD detectors
- Grating spectrometers
- Energy resolution limited at high energies (20eV @ 2.1keV)
- Astronomy requires $\Delta E < 3$eV @ 6keV

Far Infrared astronomy



- Far Infrared sensitivity limited by telescope emission
- Cold mirrors will reduce this telescope background
- Need for imaging sensors with high sensitivity
- SPICA:
  NEP ~ $2*10^{-19}$ W/√Hz
- Ground based, warm optics:
  NEP ~ 10^{-15} W/√Hz



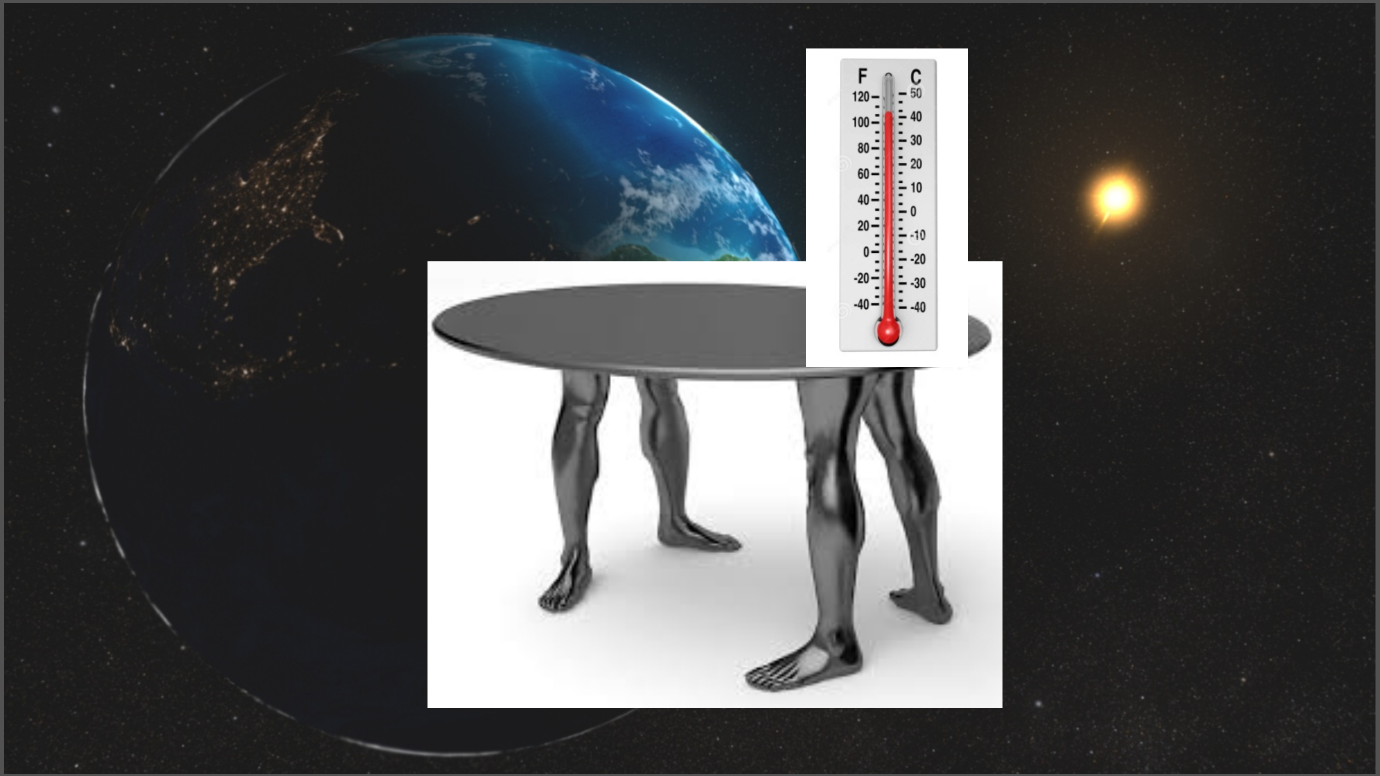
How much is 10^{-19} W?

$1\,\mathrm{m}^2$ telescope @ earth…

…observing a biking light @ the moon…

… provides ~10^{-19} W in its focus

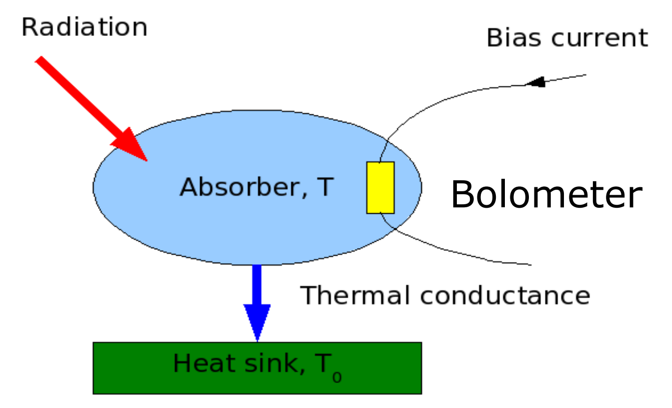
How can 10^{-19} W be detected?



- Cryogenic bolometers can do the job
- 10^{-19} W ⇔ 2µK -> measurable
- Thermal isolation ~50 fW/K needed
- X-ray: 3eV = $5*10^{-19}$ J -> similar values
- Note: Sun provides ~10^{15} K

Equilibrium vs non-equilibrium detectors

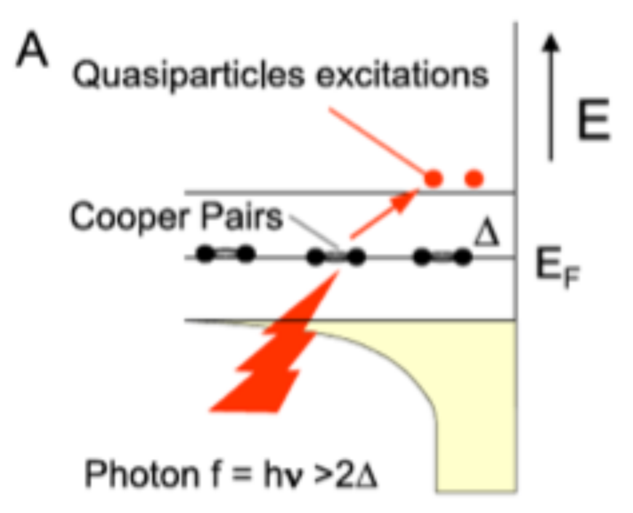
Equilibrium (thermal) detectors



- Radiation heats isolated island
- Temperature change = signal
- ΔR: - semiconductor
  - superconductor (TES)

  ΔH: - SQUID magnetometer
- Noise limit: statistics on number of phonons (shot noise)
- Operates @ ~ 100mK

Non-equilibrium detectors

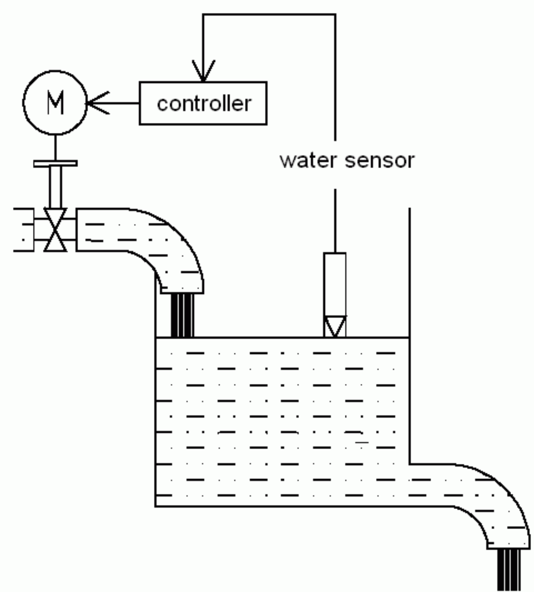


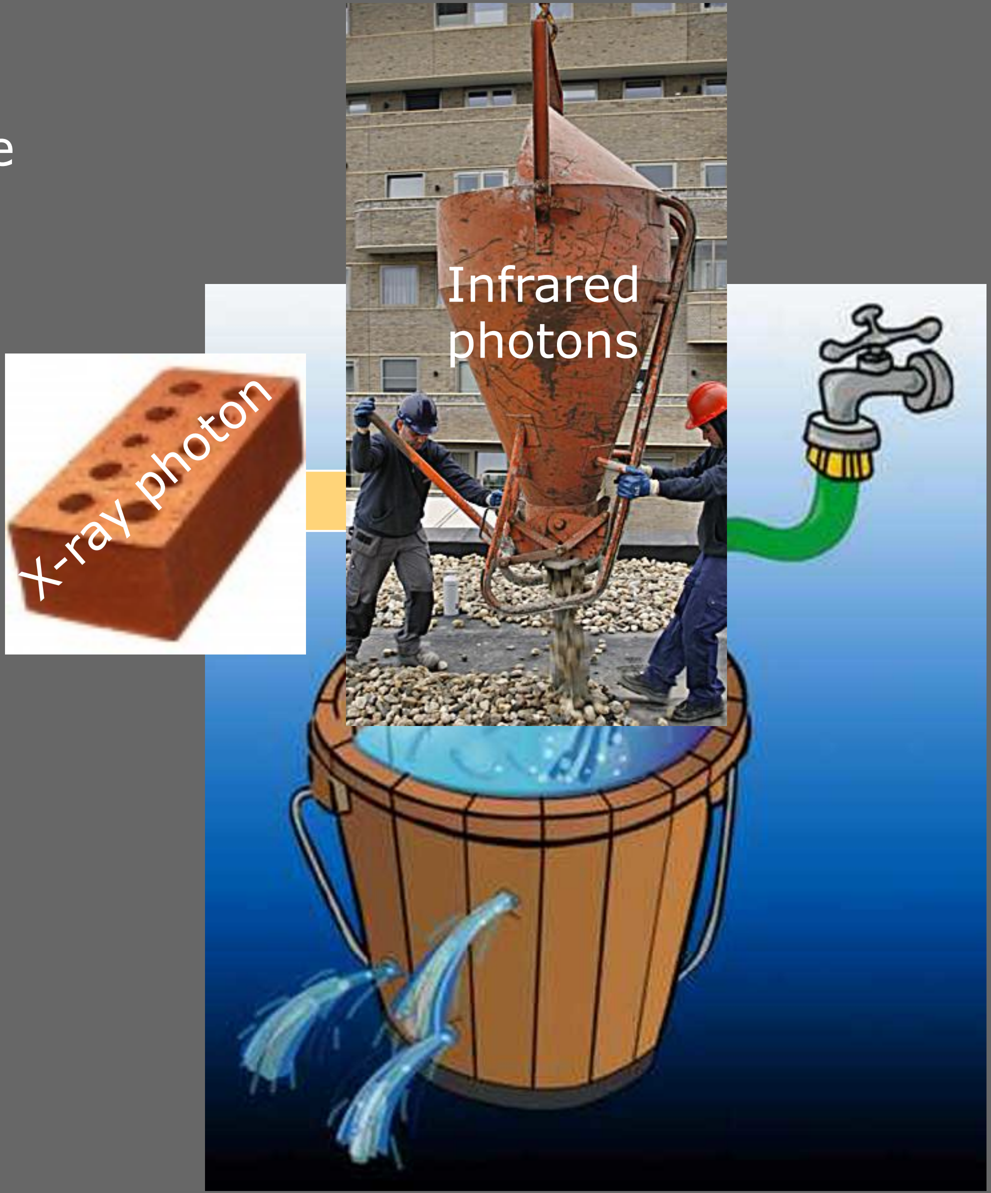
- Radiation breaks pairs
- Broken pairs create signal:
- ΔR: - Semiconductor/STJ
- ΔL: KID (inductance)
- Noise limit: pair creation/ annihilation noise
- Not suitable for X-ray>6eV
- Operates @ ~150mK

Thermal detector operation in practice

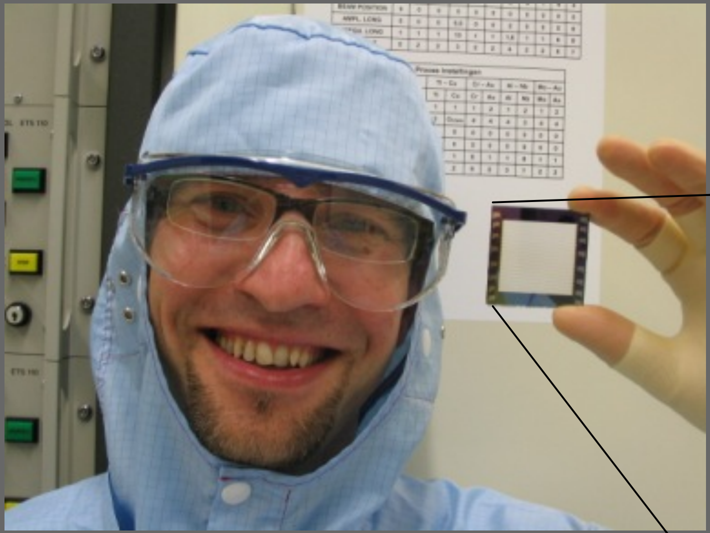
- Water flow = heat flow = signal
- Water volume = temperature
- Volume is regulated by electro-thermal feedback

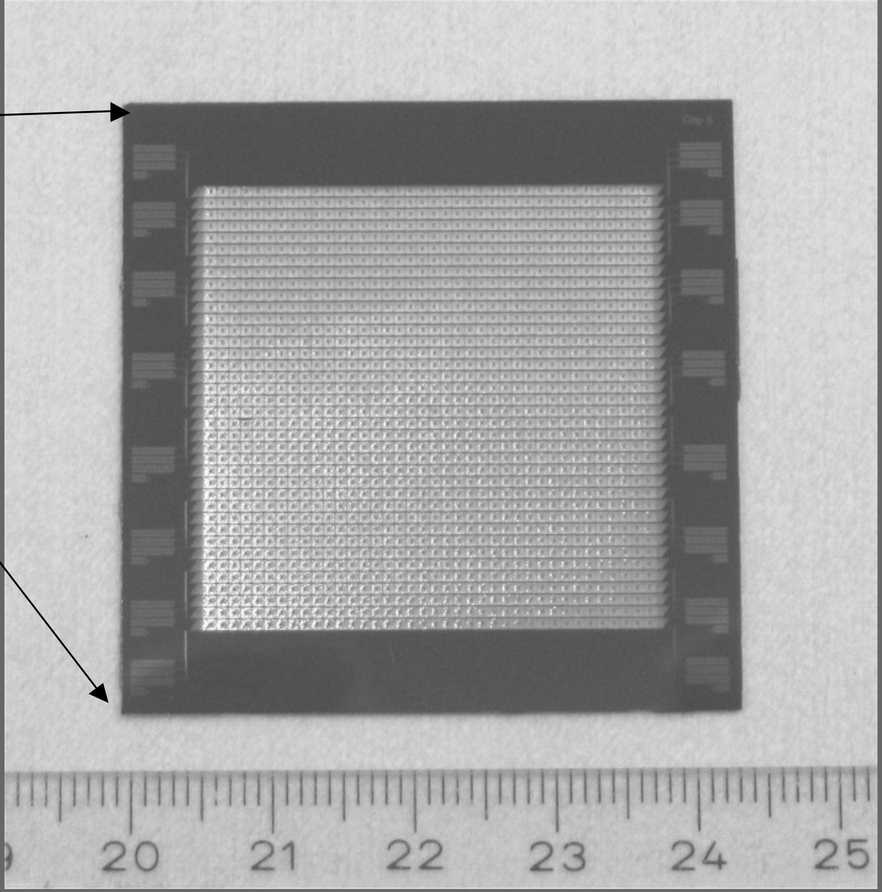
- Calorimeter: energy/photon
- Bolometer: power of many photons

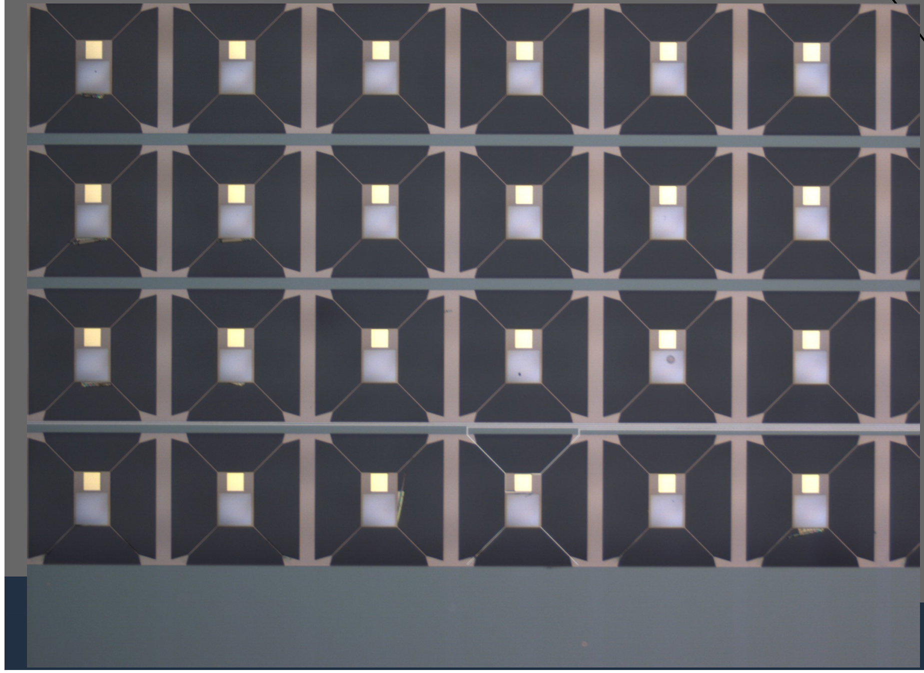




38x38 bolometer array

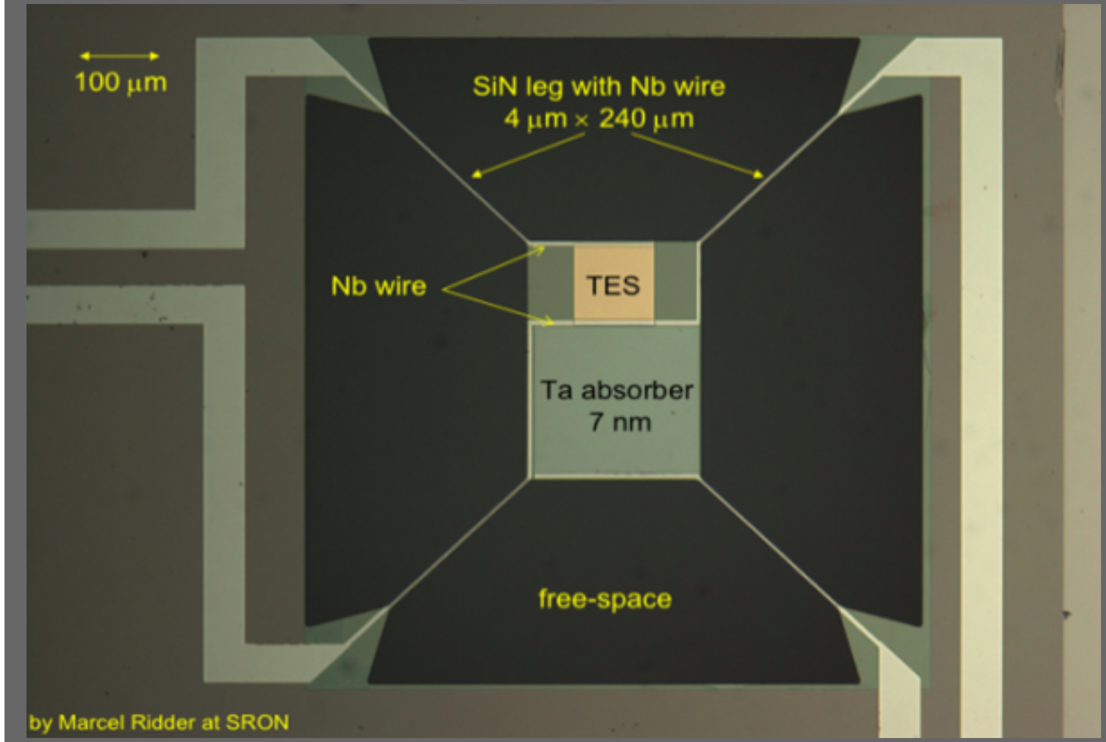




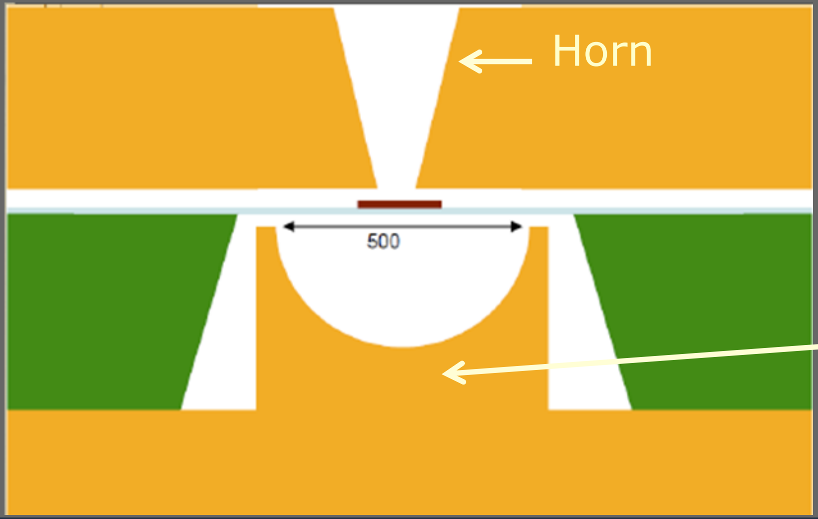


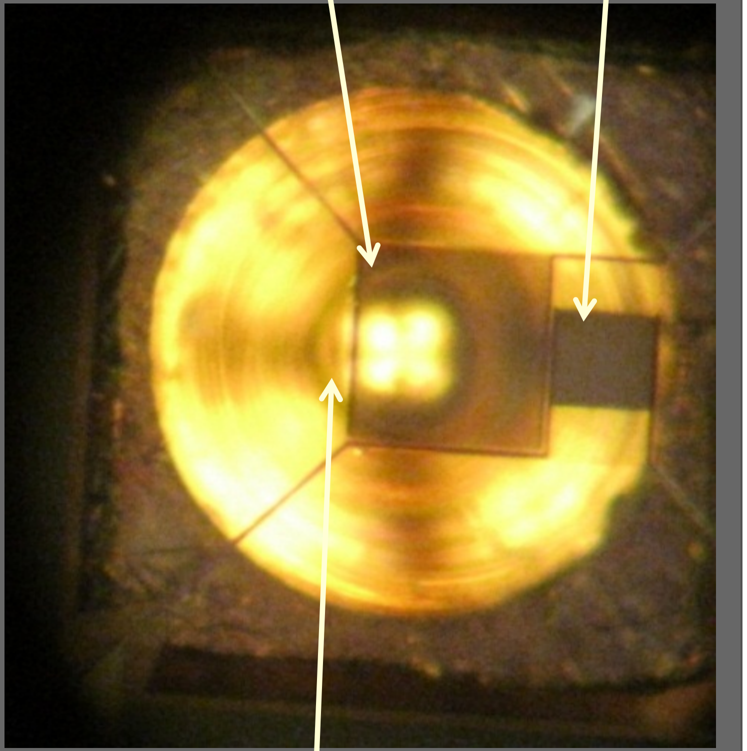
No wiring to test these devices, just a demo

Optical coupling scheme



by Marcel Ridder at SRON





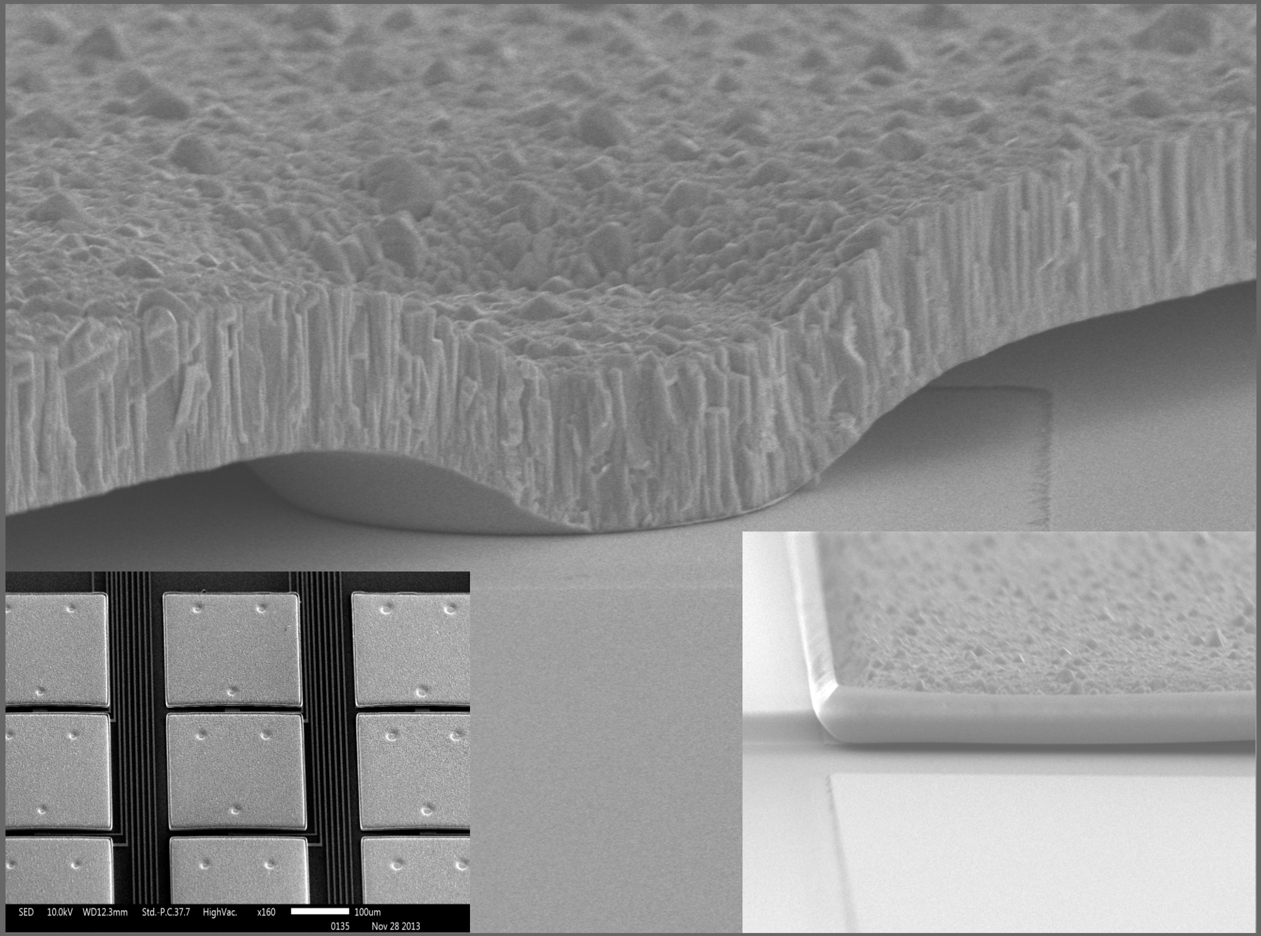
Absorber 200x200 µm

TES

Spherical Backshort

NEP ~ 5 10 $^{-19}$ W/√Hz

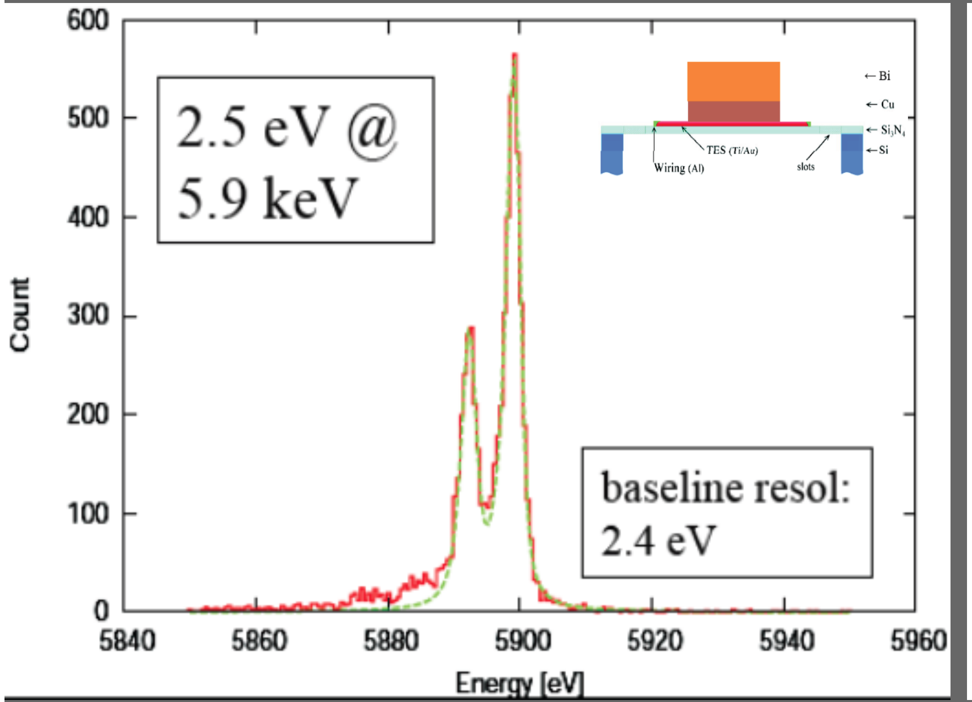
X-ray pixel development



- Development of high-filling factor and high QE pixels array
- 250x250um sputtered Bi on electroplated Au
- TiAu TES with uniform current distribution
- Optimized for the MHz ac-read-out

X-ray pixel performance results

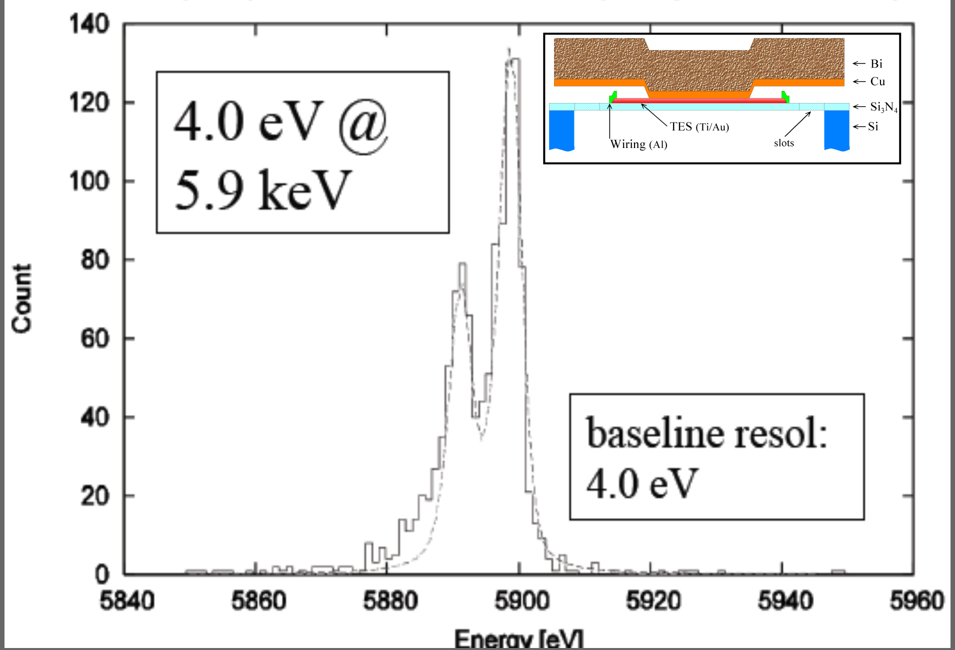
Stopping power 74%,filling factor 20%



TES: TiAuTi
thickness: 20/55/5 nm
size: 150×186 μm^2

absorber: Cu/Bi
thickness: 1/2.64 μm
size: 100×100 μm^2

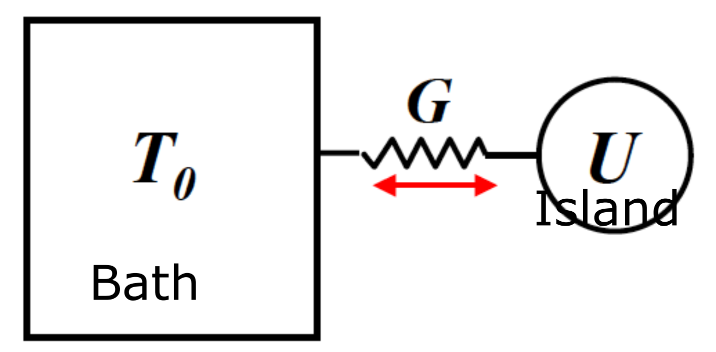
filling factor 92%



TES: TiAuTi
thickness: 20/55/5 nm
size: 146×150 μm^2

absorber: Cu/Bi
thickness: 0.15/3 μm
size: 240×240 μm^2

Energy resolution thermal X-ray detectors



Heat capacity vs T:

$$C \propto T^{\gamma}, \quad \gamma = 1-3$$

Number of phonons: $N \approx \frac{CT}{k_B T}$

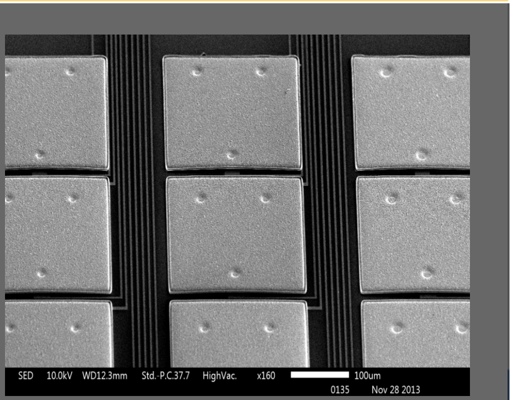
Energy per phonon

$$\Delta U_{rms} = \sqrt{N} \cdot (k_B T) = \sqrt{k_B T^2 C}$$

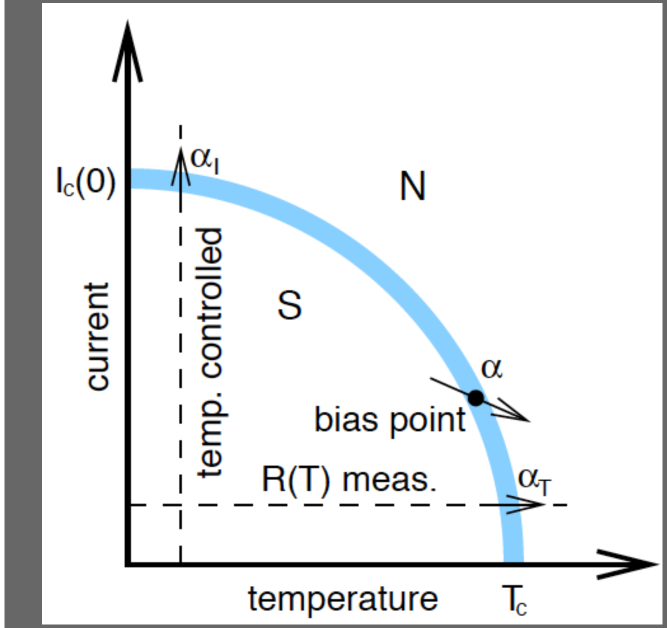
Poisson noise on number of phonons

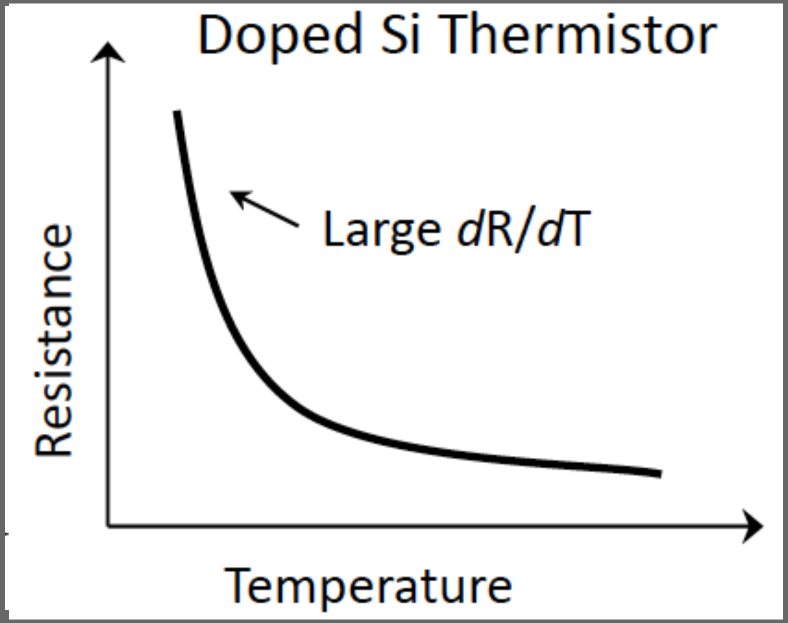
pixel volume set by pixel size/stopping power =>

⇒ Temperature of ~ 100mK required for ΔE < 3eV



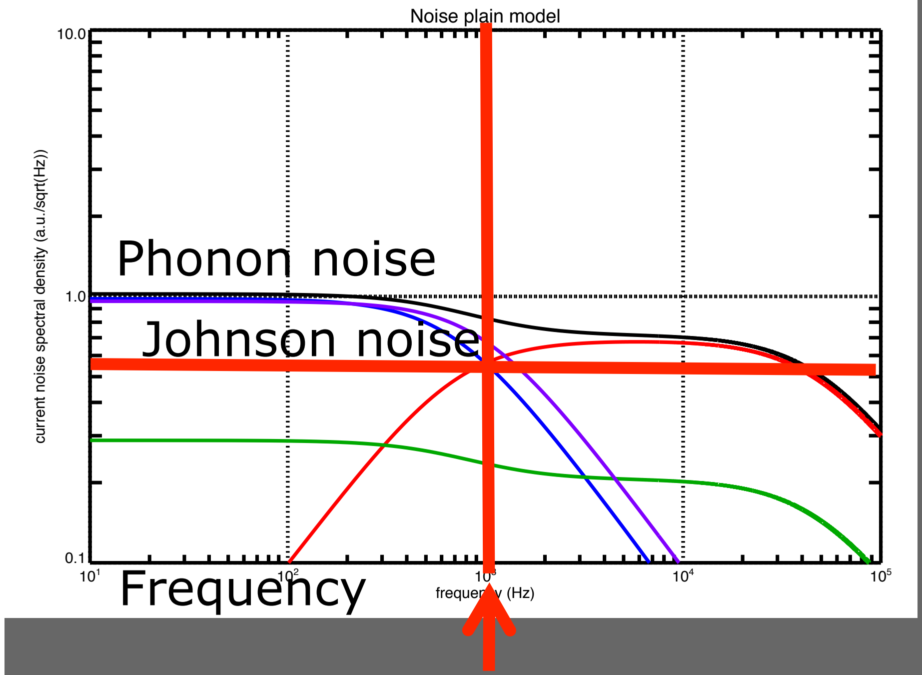
Thermometer sensitivity TES



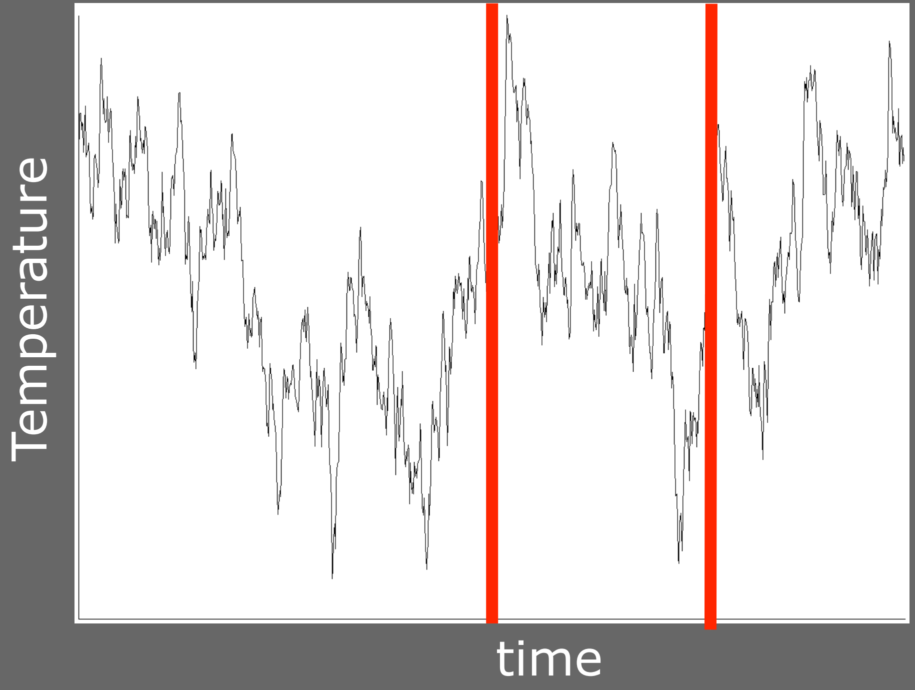


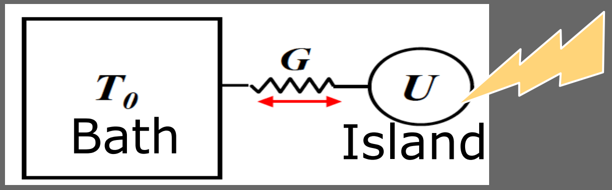
- Superconducting phase transition near Tc
- Strong dependence resistance - temperature
- T_c tuned by proximity effect
- Normalized sensitivity ($\alpha=(dR/R)/(dT/T)$):
  - Si thermistor ~ $\alpha=1\text{-}5$
  - TES ~ $\alpha=100$

Energy resolution vs thermometer steepness (α)

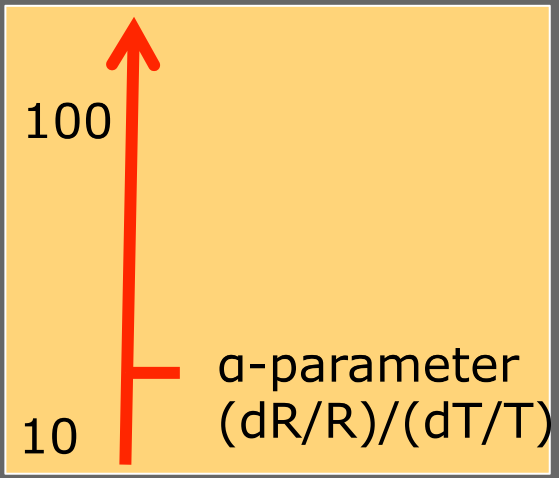


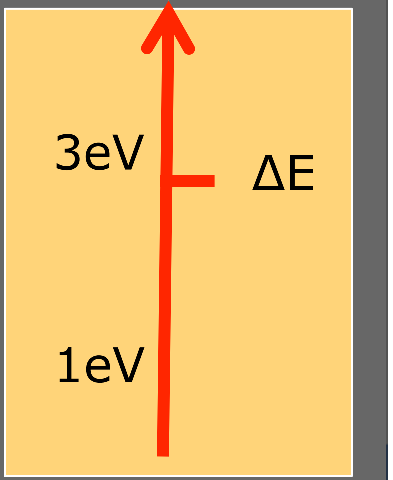
Information bandwidth



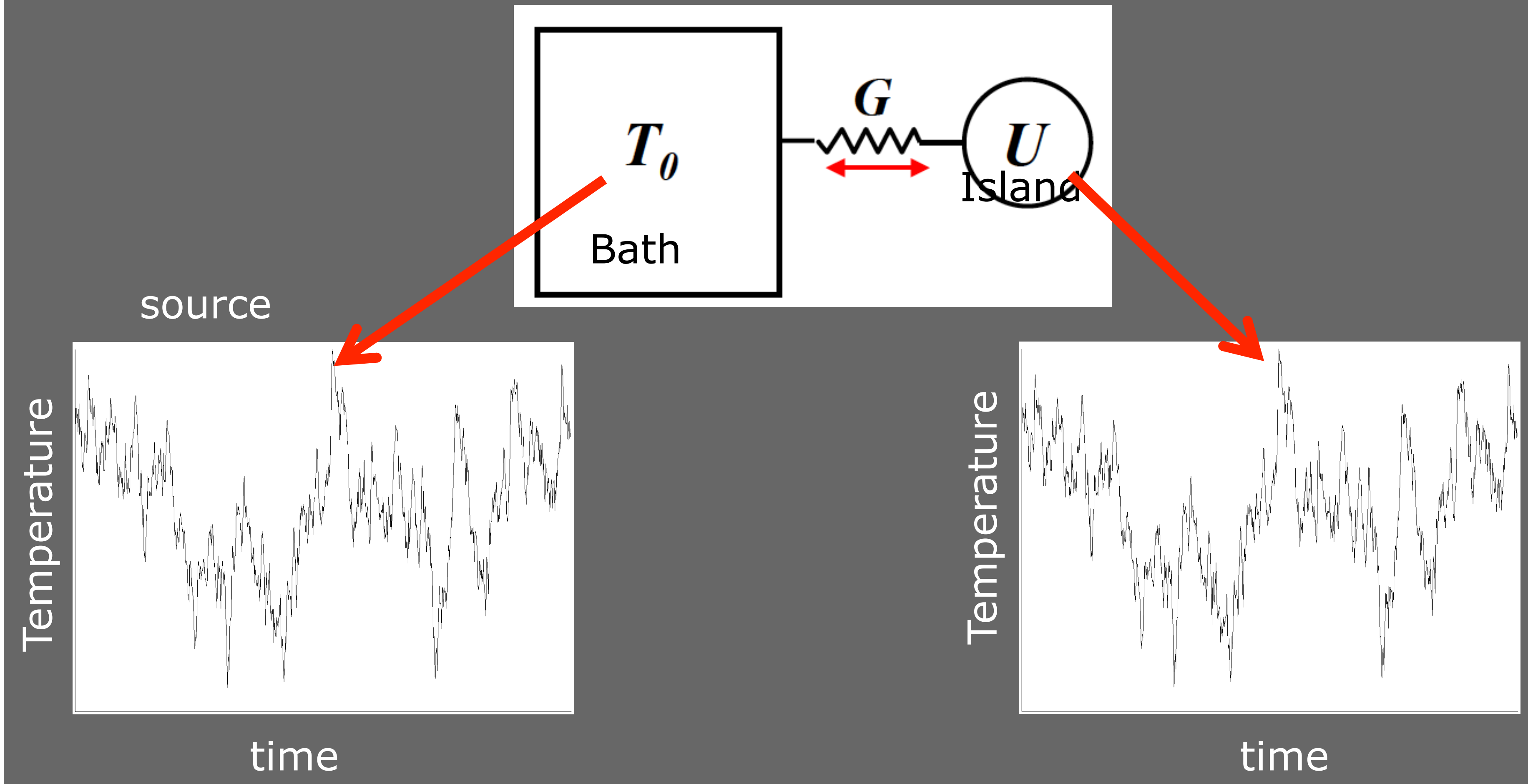


- Thermal inertia prevents fast temperature changes over link
- Photon = δ(t)





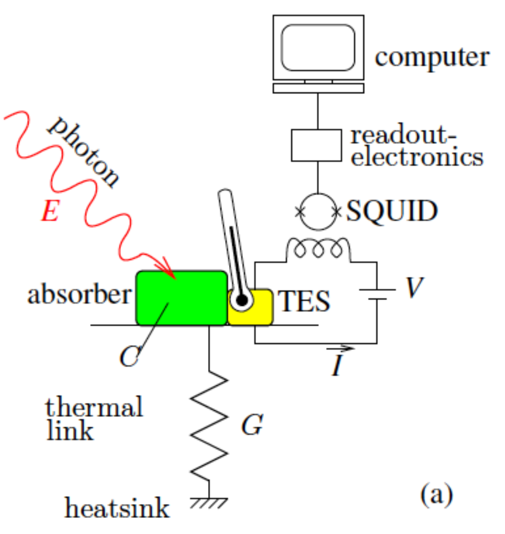
Temperature stability

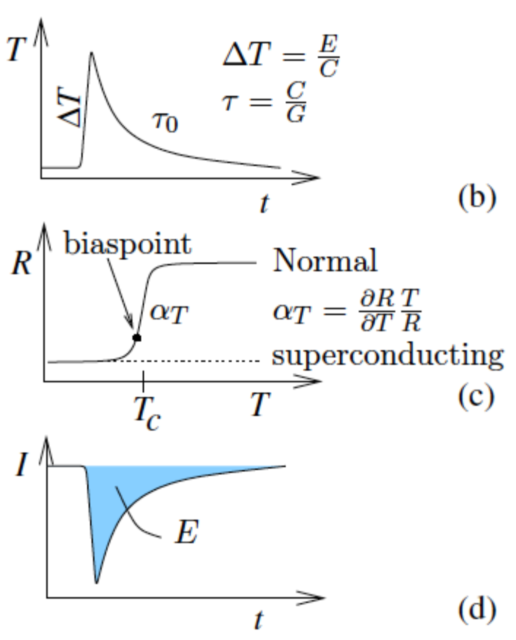


=> Stability bath ~ stability island (0.3 μK rms)

Electrical readout principle

- Voltage biased
- Trans-impedance (current) readout
- SQUIDs as low power amplifiers
- P_{SQUID} ~ 1000*P_{pixel} => multiplexing needed

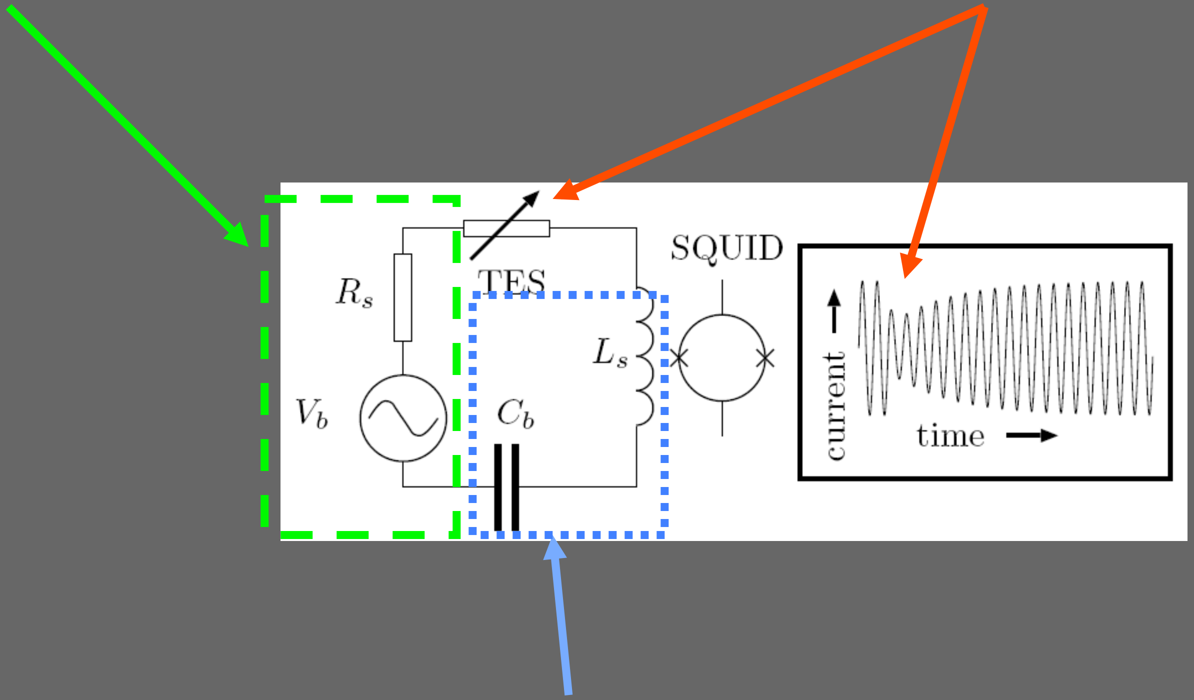




TES as modulator

- AC voltage bias source produces carrier

Thermal signal modulates amplitude of bias current



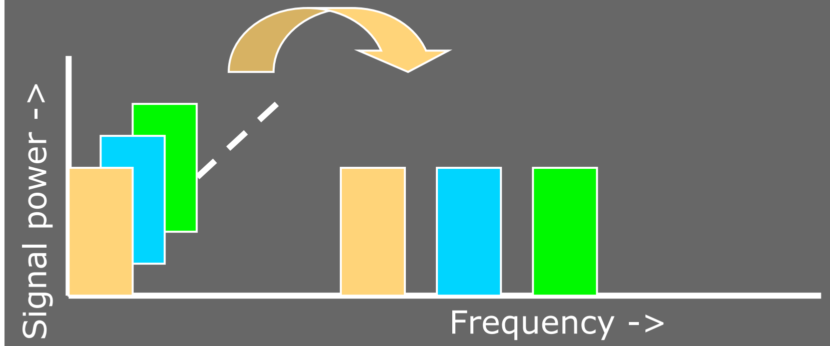
- LC bandpass filter to bandwidth-limit the signal

Multiplexed readout of TESes

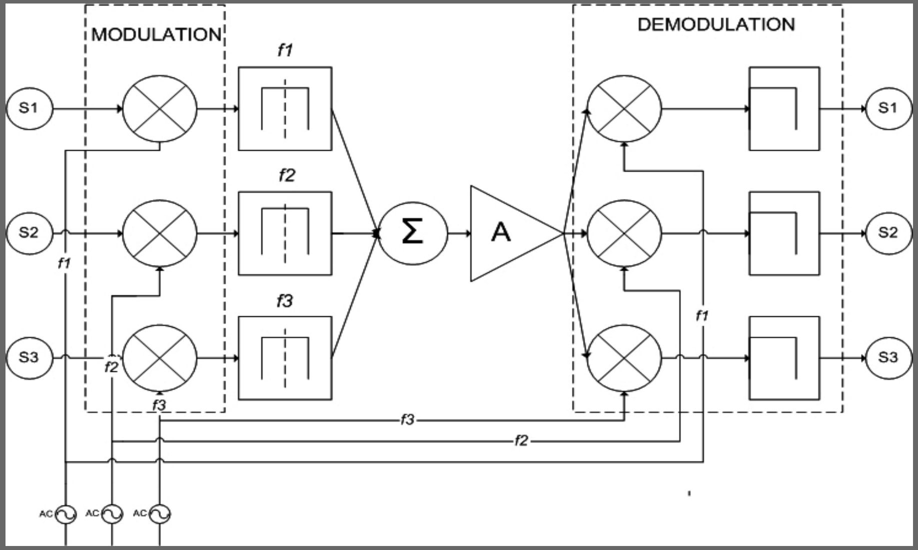
⇒ Use available bandwidth (10MHz) in SQUIDs -> minimization of wires/ dissipation

- No signal loss allowed
- => Use Modulation: shift in frequency space by multiplication with carrier
- => thermal signals become independent
- Voltage source as carrier generator
- TES as amplitude modulator
- LC bandpass filter to separate signals (Q ~ 10^4)
- SQUID in summing point

Modulation: separation in frequency space



“AM radio scheme”

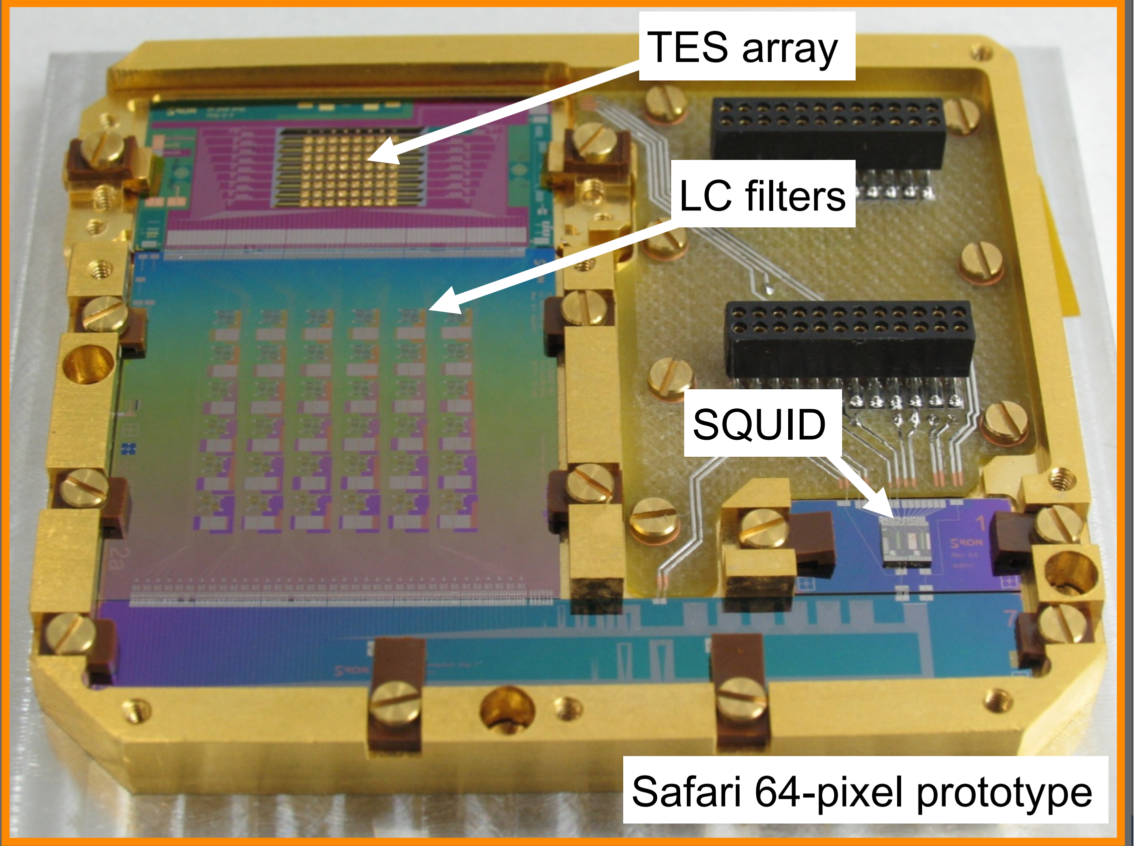


Planar FDM demonstrator

- Light-tight box
- 72 channel LC filter
- Bolometer array
- Digital demodulation

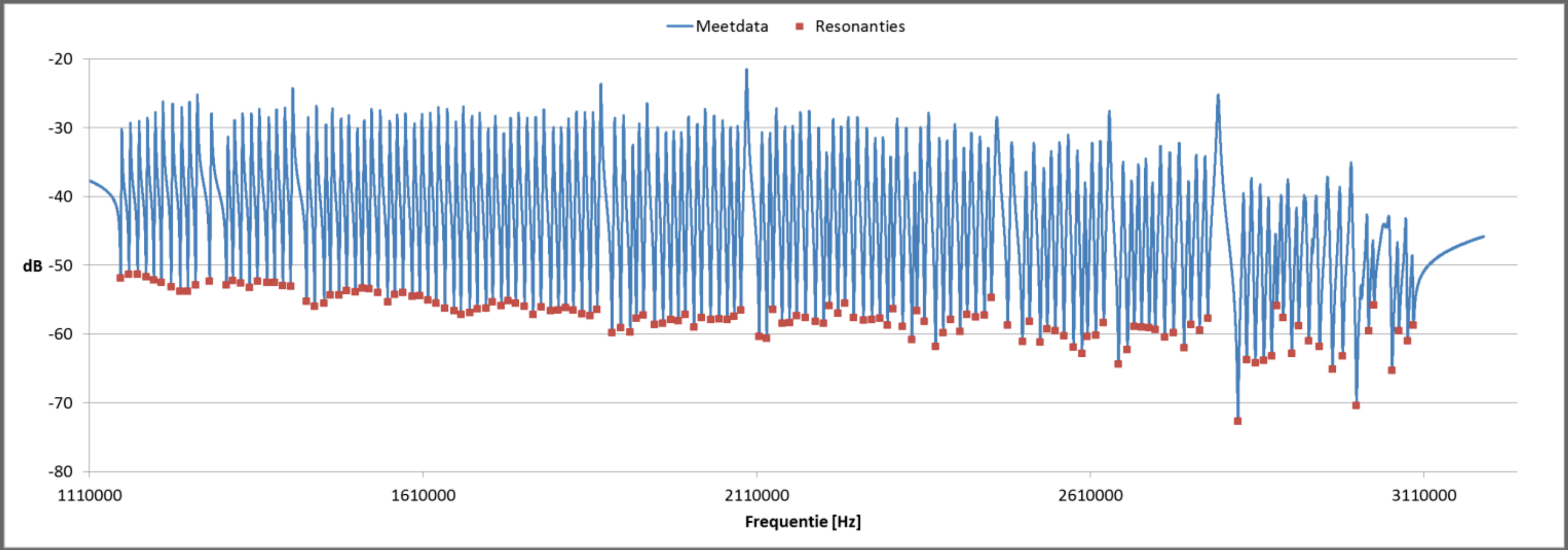
Mux factor:

- 160 pix/channel for infrared
- 40 pixel/channel for Xray



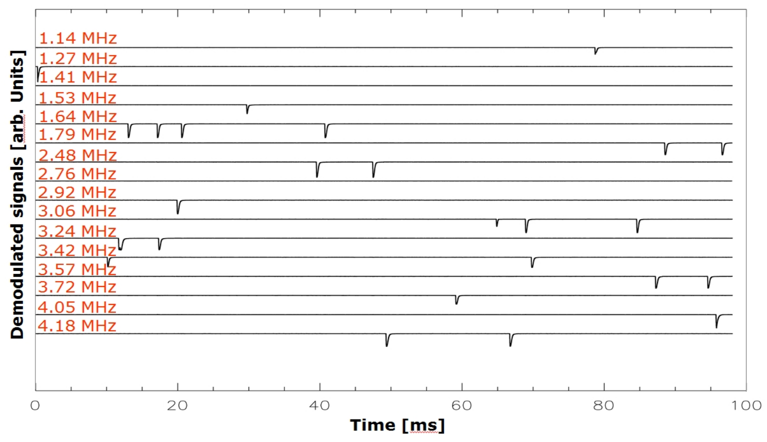
Safari 64-pixel prototype

160 resonators for one channel



- Efficient use of bandwidth
- Low power dissipation

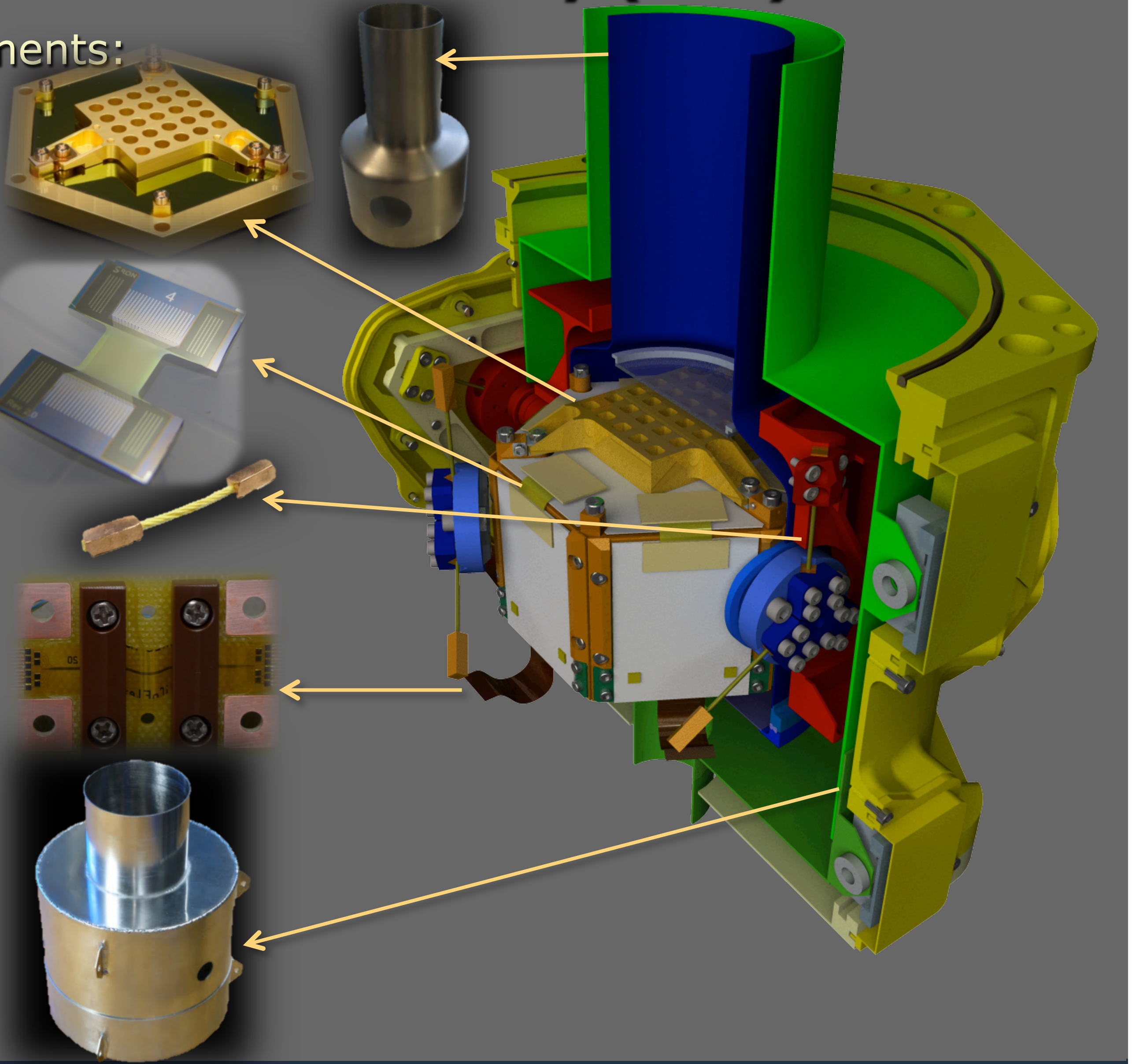
SQUID amplifier: 50 – 100 nW/pixel@4K
(KIDs) 1 muW/pixel @4K

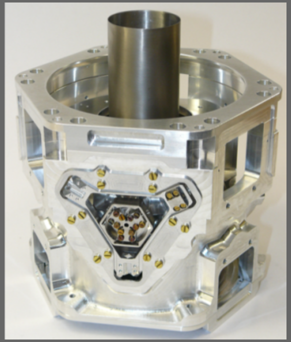


TES detector Focal Plane Assembly (FPA)

FPA technology developments:

- Interconnects
- Detector mounting
- Kevlar thermal insulating suspension
- Magnetic shielding:
  - Niobium (superconducting)
  - Cryoperm 10





Summary

- Next generation space telescopes require very sensitive detectors
- Cryogenic detectors can provide the required performance
- Fundamental thermodynamic laws dictate the use of very low temperatures

Thank you