Microcalorimeters

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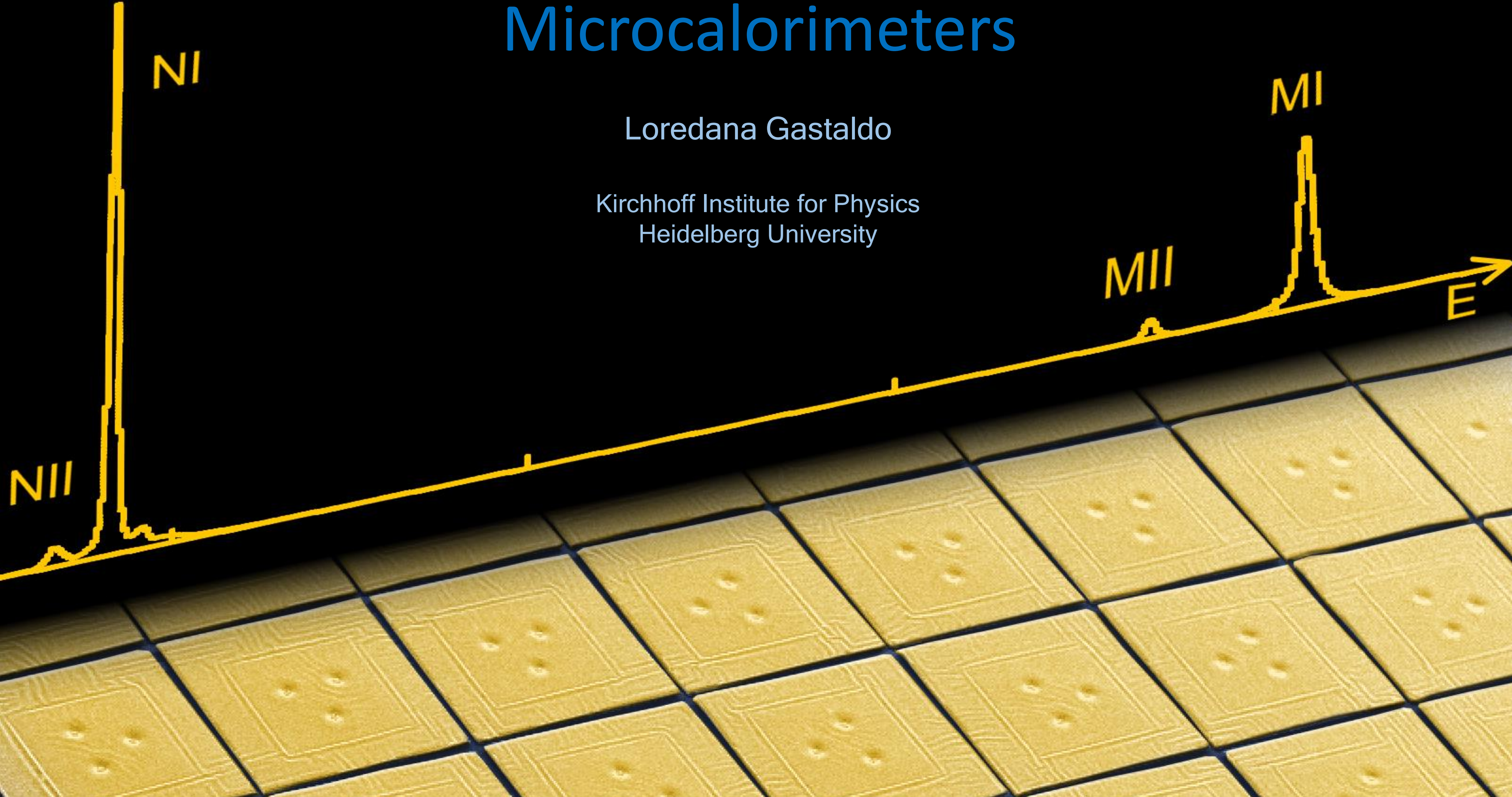
Kirchhoff Institute for Physics
Heidelberg University



Outline

- Basic of low temperature detectors
  - TES
  - MMC
- Overview on some applications
  - Photon detection
  - Neutrino physics
  - Search for Dark Matter interactions

Low temperature microcalorimeters

How do they fit to the quantum sensing school?

Low temperature microcalorimeters

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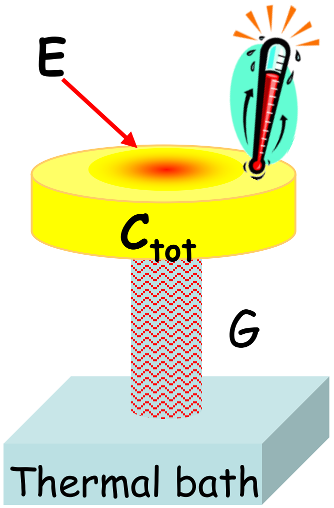
They precisely detect quanta of energy

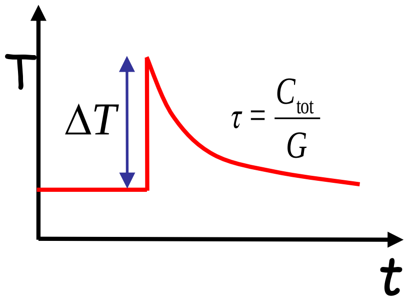
Low temperature microcalorimeters

How do they fit to the quantum sensing school?

They precisely detect quanta of energy … as an increase of temperature



$$\Delta T \cong \frac{E}{C_{tot}}$$



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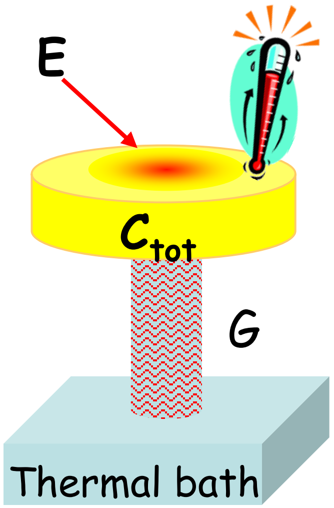

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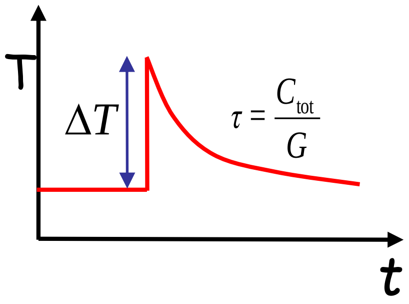
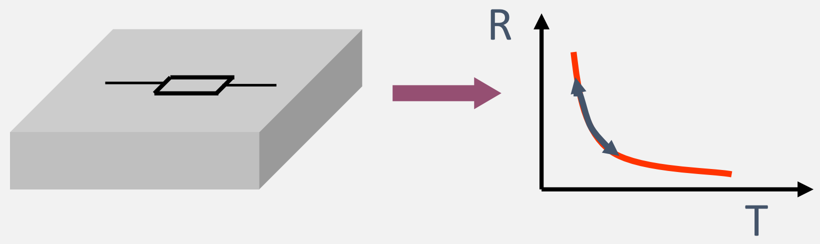


- Very small volume
- Working temperature below 100 mK
  - small specific heat
  - small thermal noise
- **Very sensitive temperature sensors**

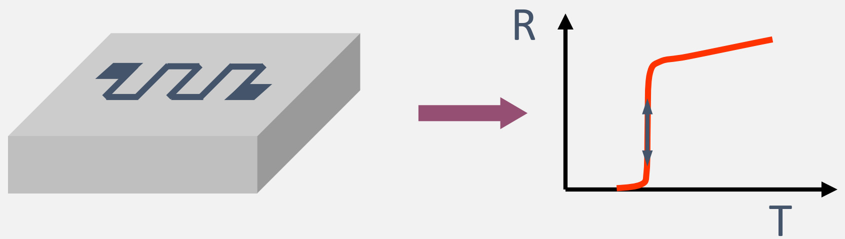
Temperature sensors

Near equilibrium sensors

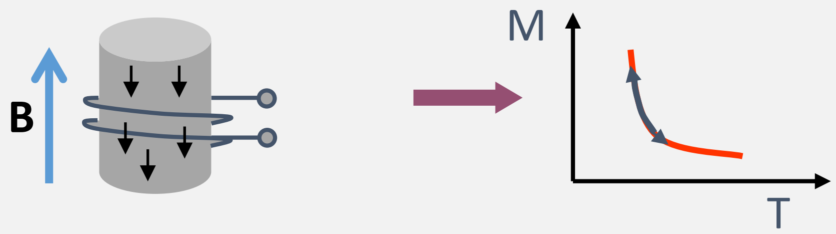
Resistance of highly doped semiconductors



Resistance at superconducting transition,TES



Magnetization of paramagnetic material, MMC



Athermal sensors

Temperature sensors

Near equilibrium sensors

Athermal sensors

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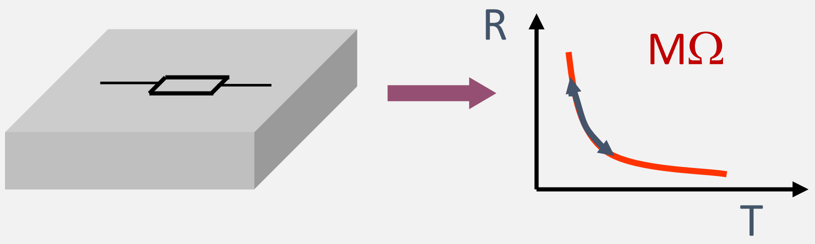

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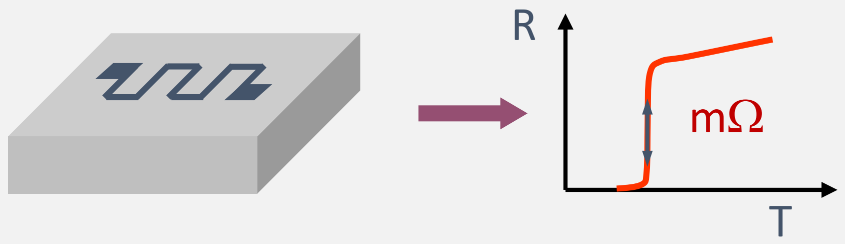

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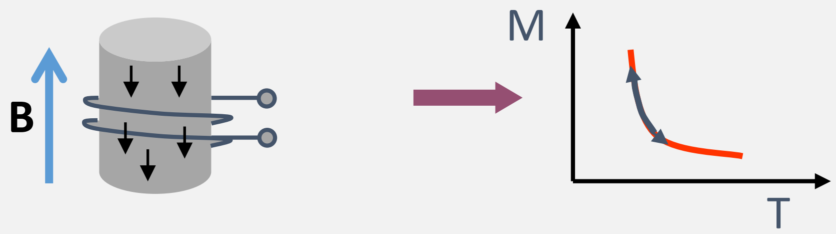

Temperature sensors

Near equilibrium sensors

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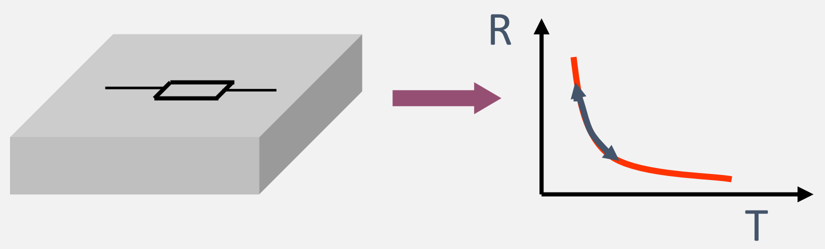

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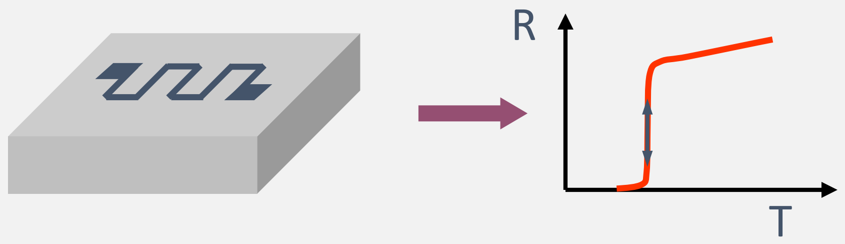

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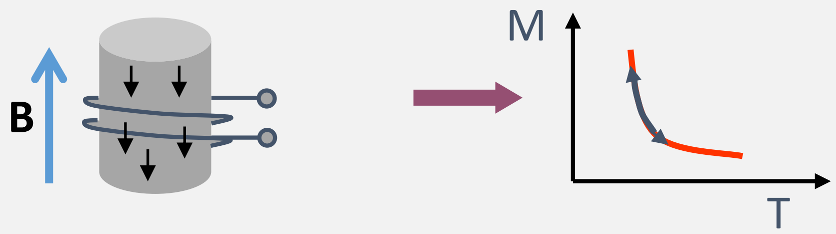
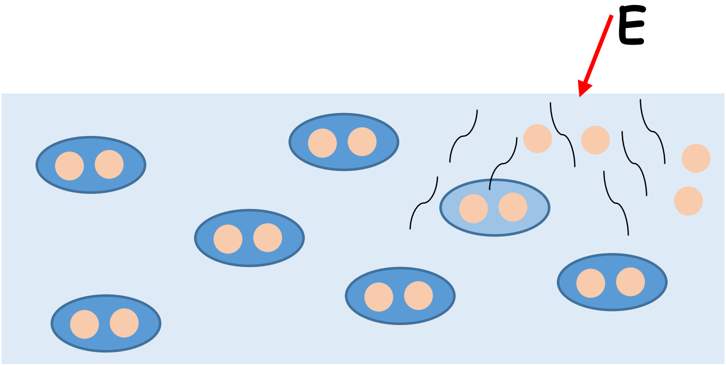


Athermal sensors (based on superconducting films)

Temperature increase induces breaking of Cooper pairs

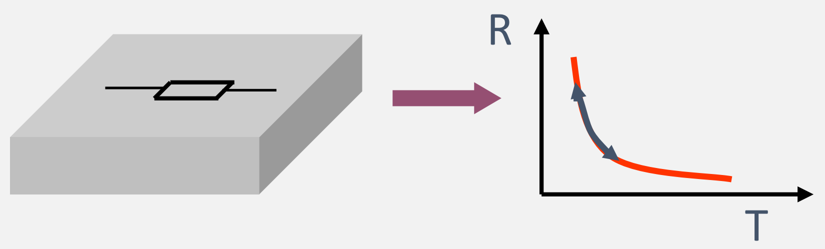


- Very thin superconducting films
- Working at mK
  „no“ quasi-particles @ equilibrium
  long quasi-particle half-life
- **High efficiency of „counting“ quasi-particles**

Temperature sensors

Near equilibrium sensors

Resistance of highly doped semiconductors



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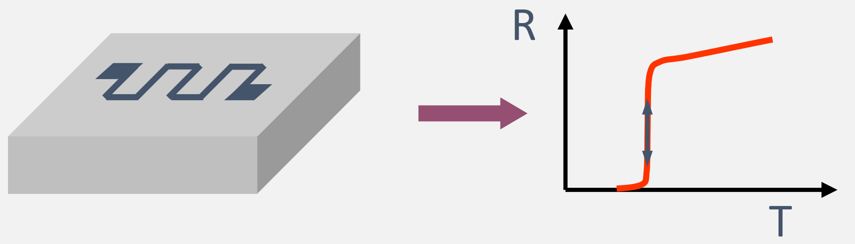

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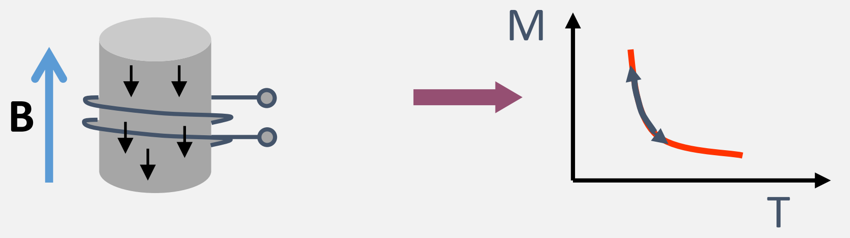

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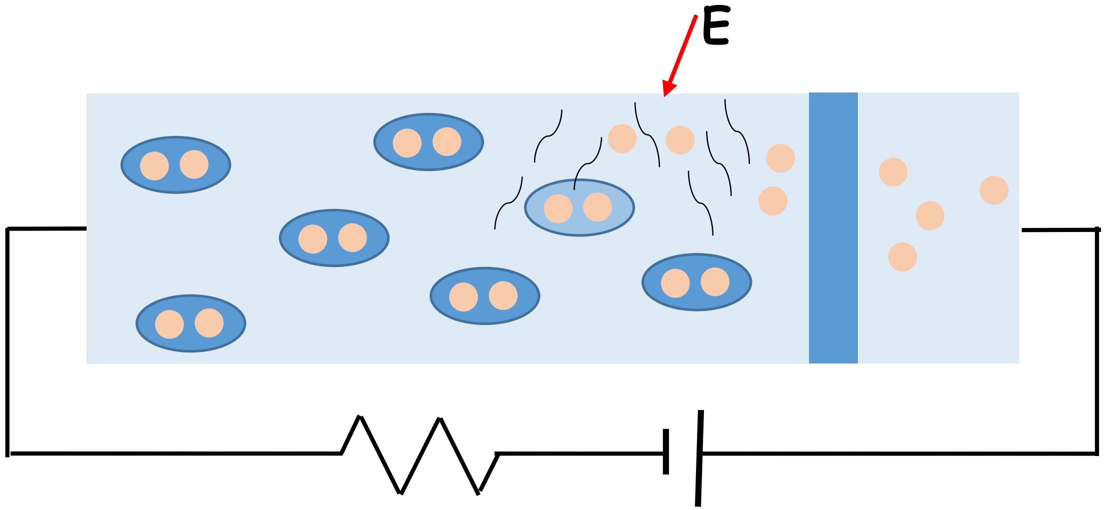


Superconducting Tunnel Junctions - STJ

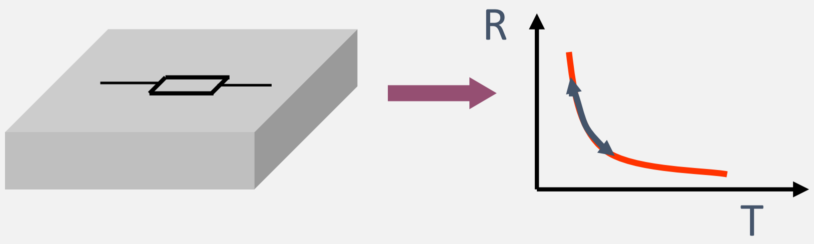
Quasi-particles tunneling through a thin isolating barrier

Measurement of current

Temperature sensors

Near equilibrium sensors

Resistance of highly doped semiconductors



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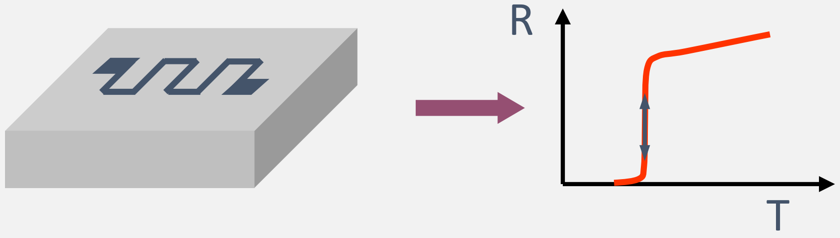

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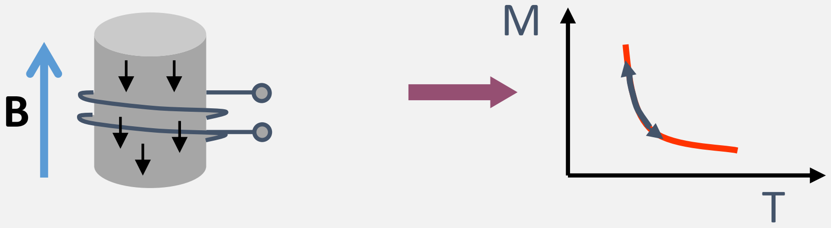

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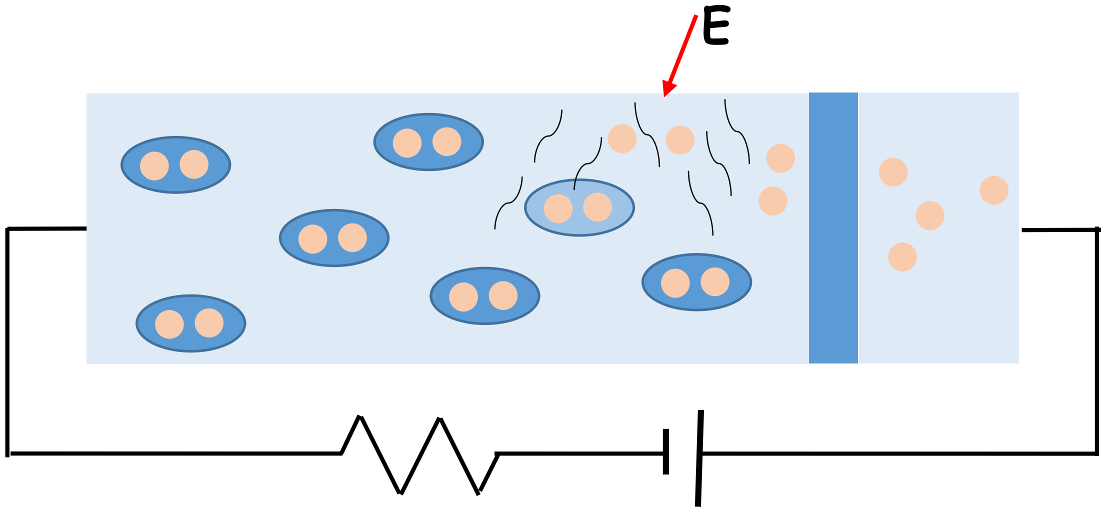

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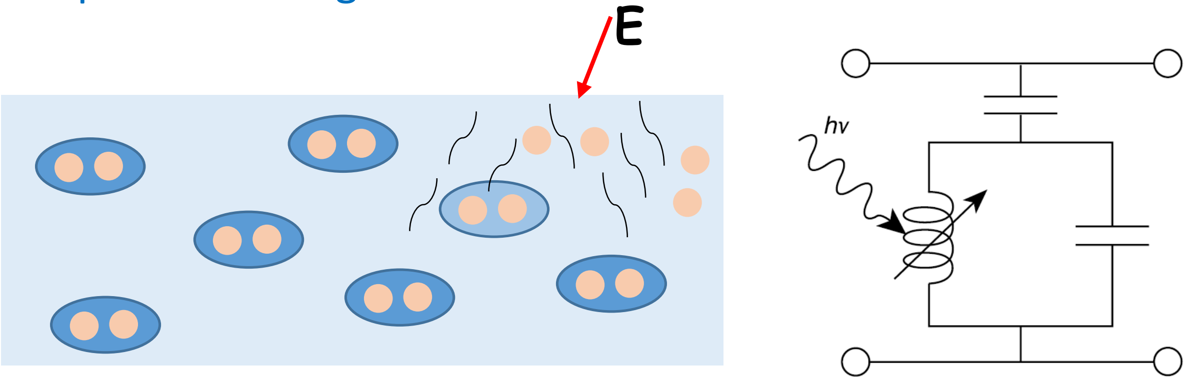
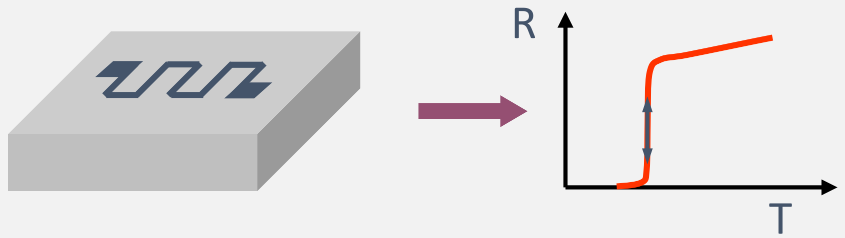


Kinetic Inductance Detectors – KID

Breaking Cooper pairs → change of kinetic inductance

Transition Edge Sensors – superconducting film

Resistance at superconducting transition,TES



Superconducting film operated at the transition temperature

Operating temperature defines:

- heat capacity
- thermal conductance
- thermal noise

In the periodic table only 18 elements with $T_C < 2$ K → only 5 are actually used in TES

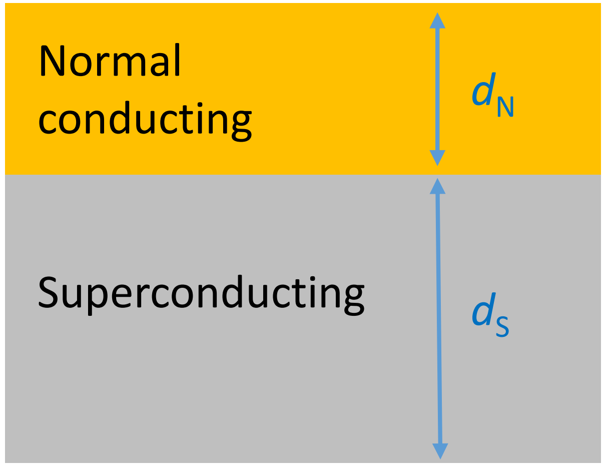
Al	$T_C \sim 1.1$ K	
Ti	$T_C \sim 0.39$ K	
Mo	$T_C \sim 0.92$ K	
W	$T_C \sim 0.012$ K	only elemental superconductor routinely used as TES
Ir	$T_C \sim 0.140$ K	

How to reduce the transition temperature of superconducting films to be ~ 100 mK???

Proximity effect
Magnetic impurities

Transition Edge Sensors – superconducting film

Proximity effect: Lowering the transition temperature of a superconducting film by the presence of a normal metal layer in good electrical contact



If d_N is smaller than the coherence length ξ

→ the bilayer behaves as a homogeneous superconducting film

Superconductors	Normal
Ti	Cu
Mo	Ag
Al	Au
Ir	

Different model have been developed for the description of the physics of bilayer system. As an example Usadel theory:

$$T_C = T_{C0}\left[\frac{d_S}{d_0}\frac{1}{1.13(1+1/\alpha)}\frac{1}{t}\right]^{\alpha}$$

$$\alpha = \frac{d_N n_N}{d_S n_S}$$

$$\frac{1}{d_0} = \frac{\pi}{2} K_B T_{C0} \lambda_F^2 n_S$$

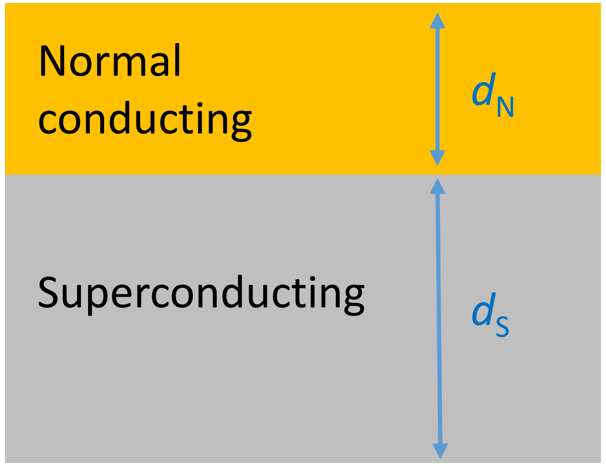
λ_F = Fermi wavelength

n_S, n_N = density of electronic states

t= transmission coefficient

Transition Edge Sensors – superconducting film

Proximity effect: Lowering the transition temperature of a superconducting film by the presence of a normal metal layer in good electrical contact



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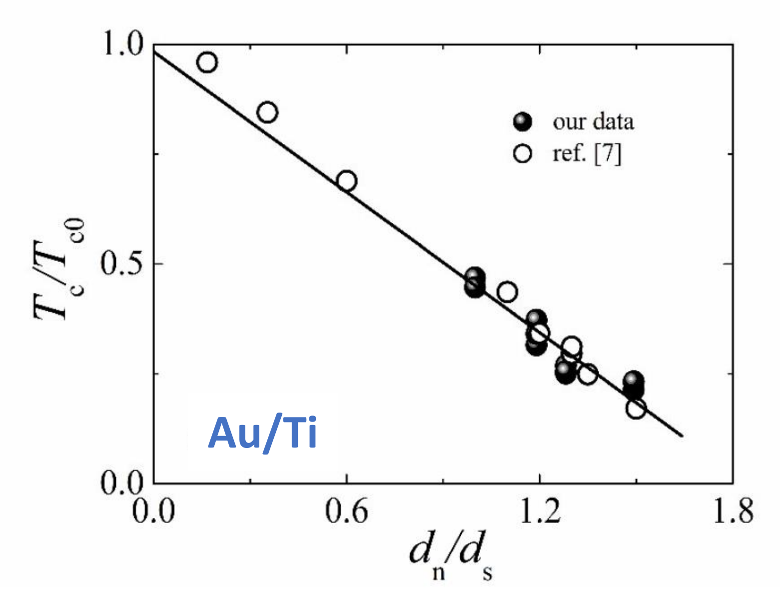
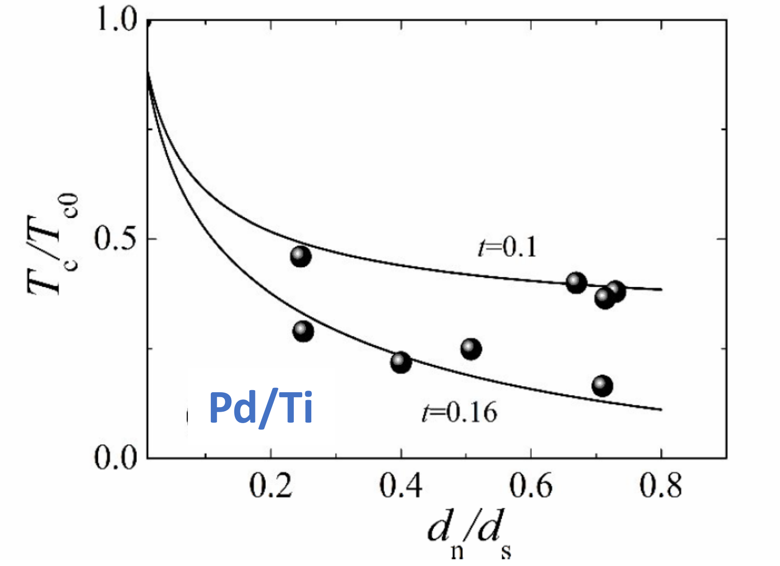
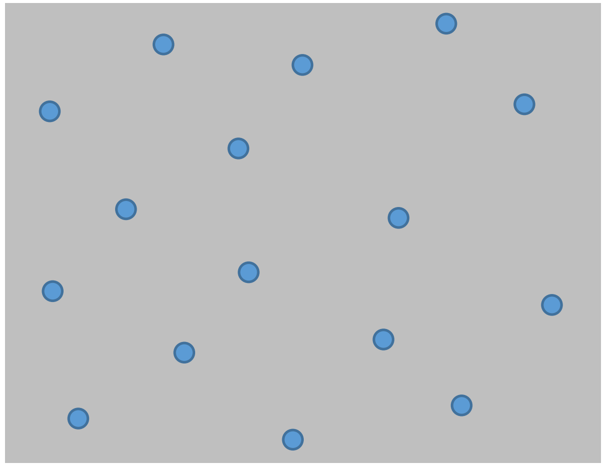




Monticone et al. Journal of Physics: Conference Series **150** (2009) 052168

Transition Edge Sensors – superconducting film

Magnetic impurities: in a superconducting film magnetic impurities induce pair breaking
→ the film thickness is not limited by coherence length



Superconductors	Normal
Al	Mn
Mo	Fe
Ti	

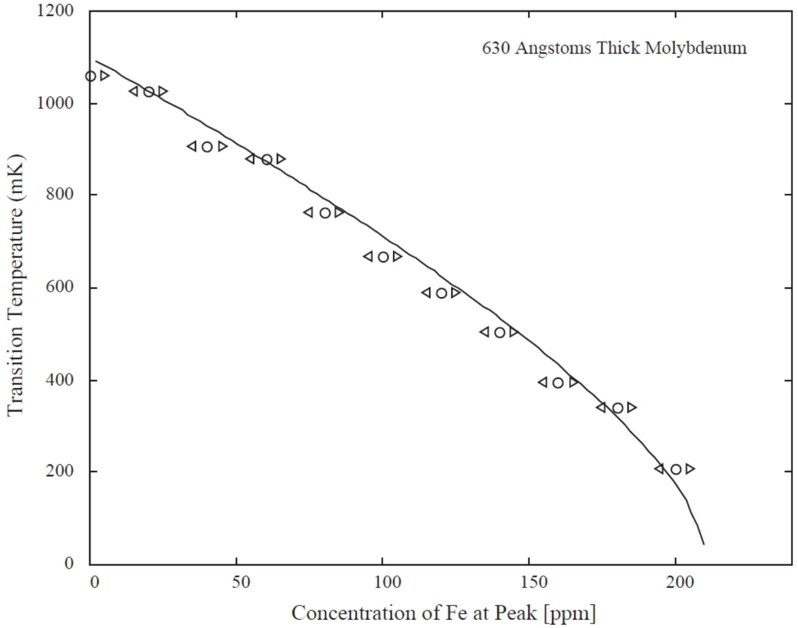


Fig. 2. Reduction of molybdenum film T_c as a function of dopant $^{56}Fe^+$ concentration. The curve shown is a fit to the data using an Abrikosov-Gor'kov model.

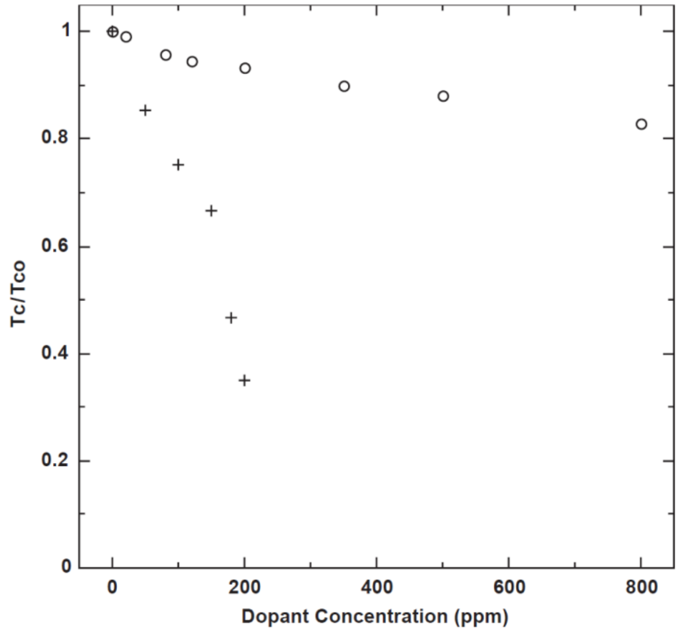


Fig. 3. Titanium film results. Implanting $^{55}Mn^+$ suppressed T_c dramatically (+). $^{56}Fe^+$ had only limited effect (o).

B.A. Young et al., Nuclear Instruments and Methods in Physics Research A 520 (2004) 307–310

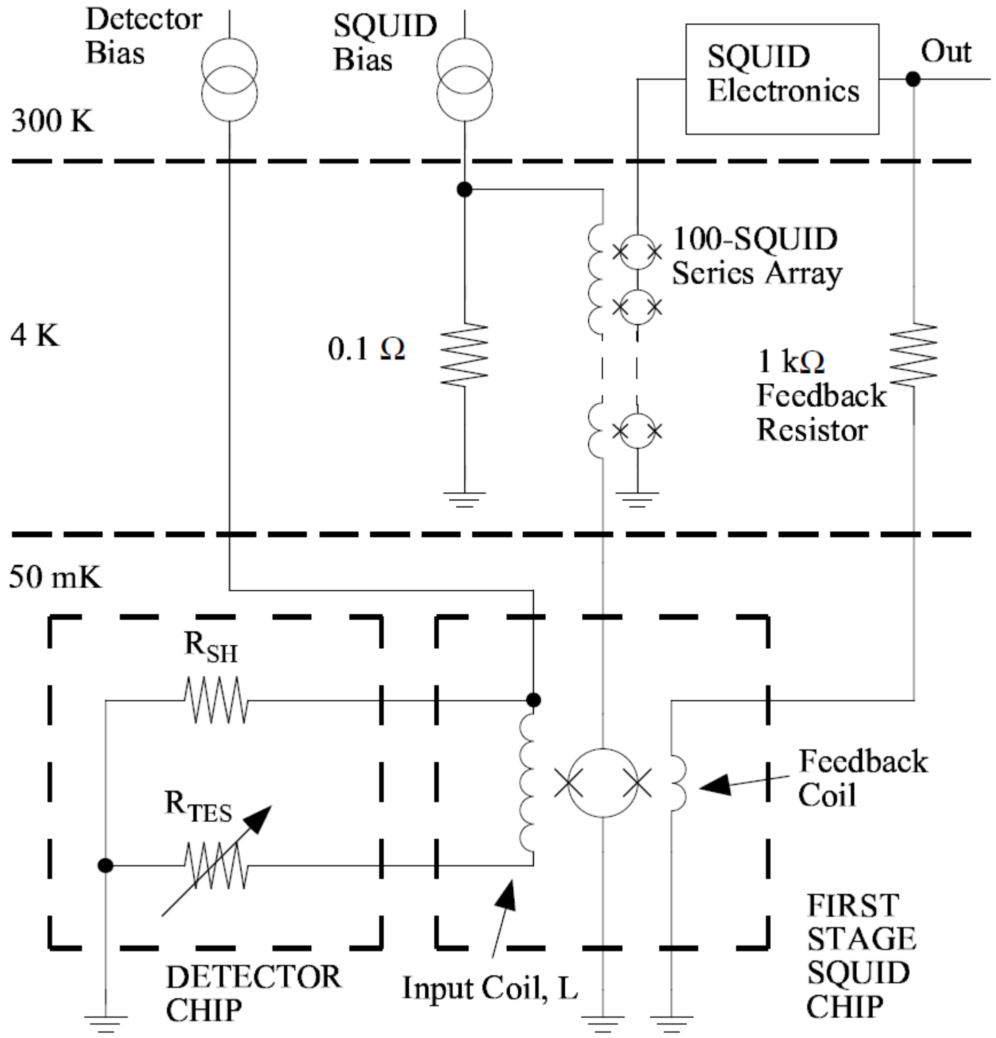
Transition Edge Sensors - signal

$R = R(T,I)$: TES resistance
T: TES temperature

C: Heat capacity TES + absorber
G: thermal conductivity to the bath – $G = nkT^{n-1}$

R_{SH}= shunt resistance $R_{SH} < R$
V = applied constant voltage
I: current through the TES
L: inductance of the input coil of the SQUID

P_{bath}: power flowing to the bath
P_J: Joule power in R
P: signal power



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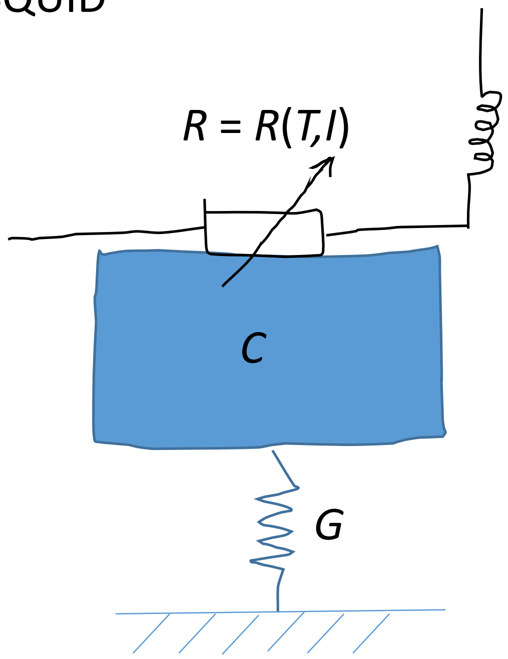
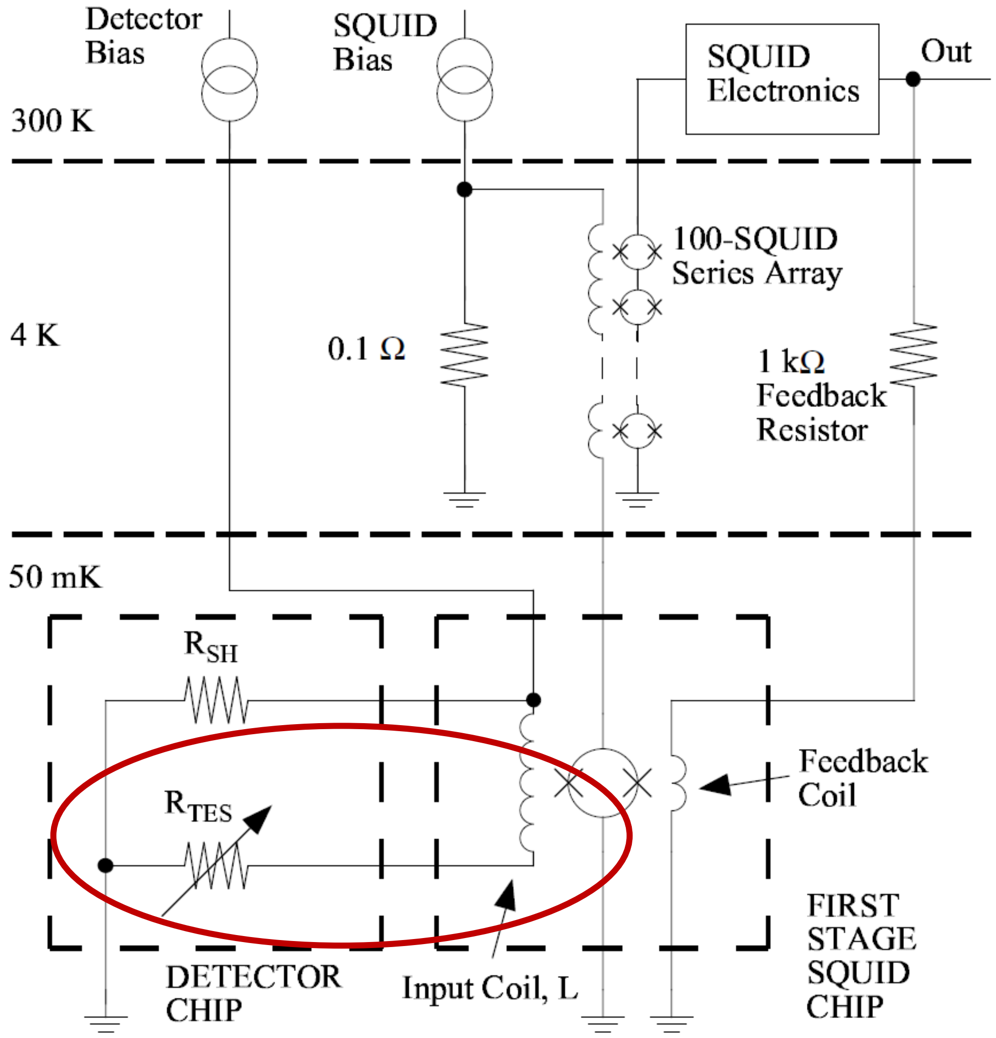




Transition Edge Sensors - signal

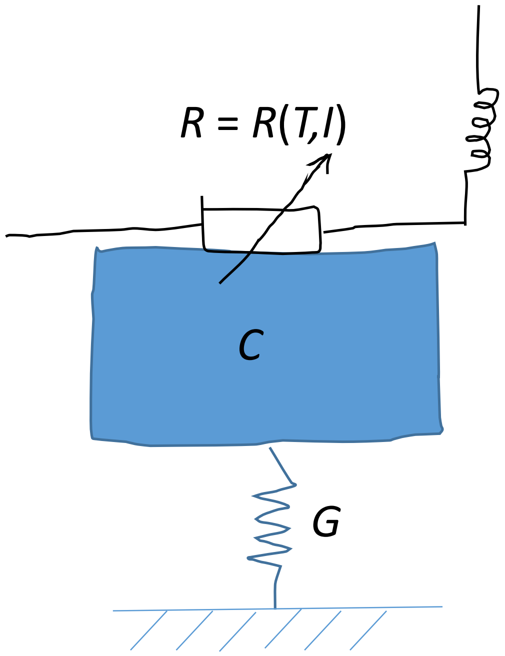
Thermal differential equation:

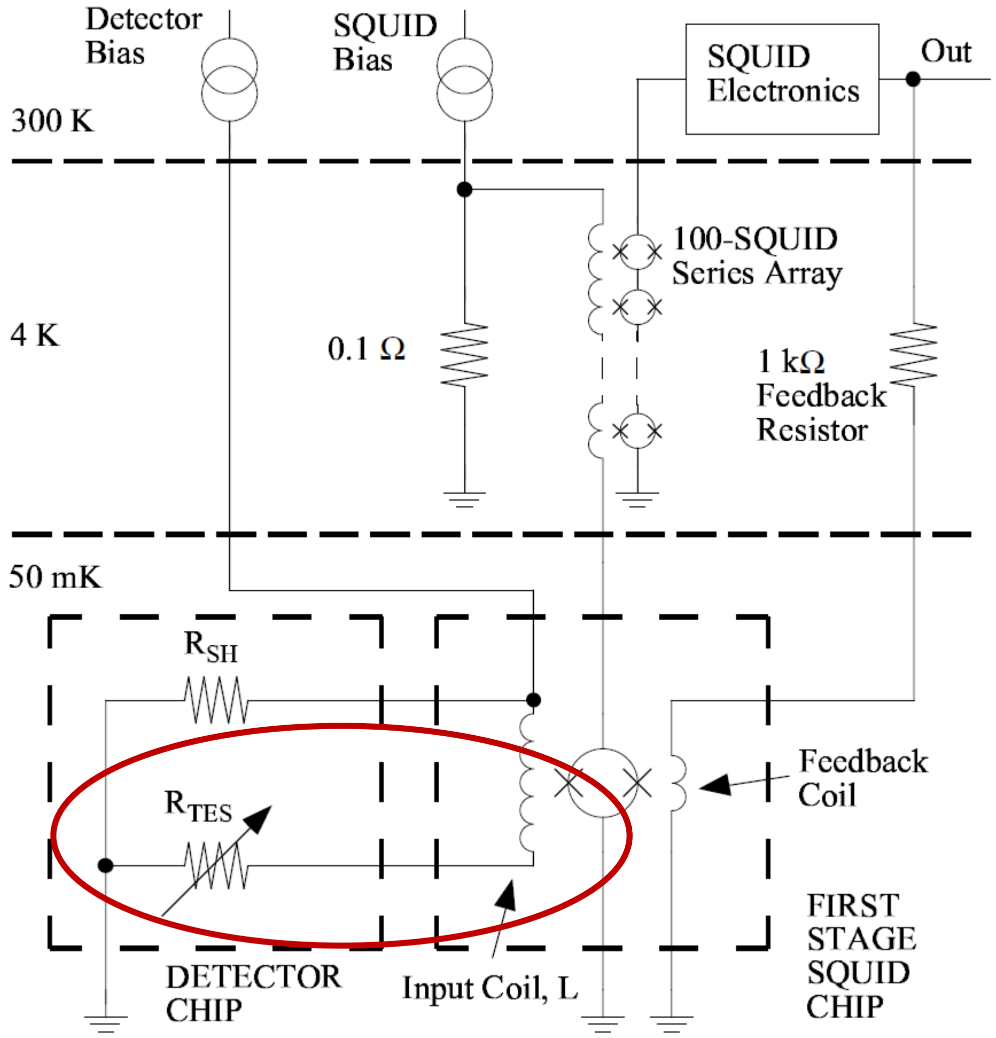
$$C\frac{\mathrm{d}T}{\mathrm{d}t} = -P_{bath} + P_J + P$$

Electrical differential equation:

$$L\frac{\mathrm{d}I}{\mathrm{d}t} = V - IR_{SH} - IR(T,I)$$

Solution in the small signal limit around the values R_0, T_0, I_0 and the temperature dependences of C and G are omitted

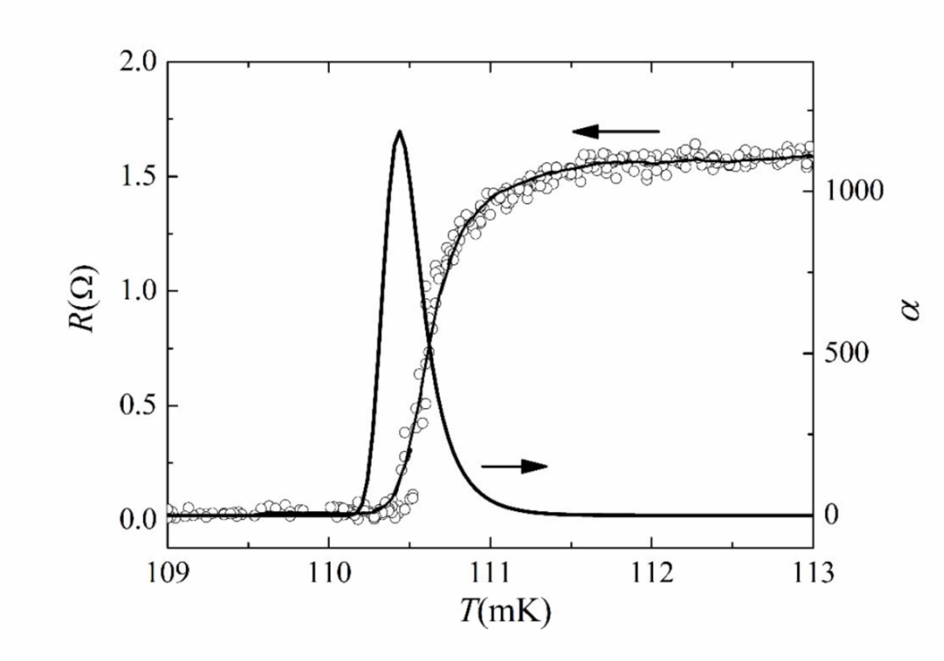




Transition Edge Sensors - signal

$$R(T,I) \approx R_0 + \left.\frac{\partial R}{\partial T}\right|_{I_0} \delta T + \left.\frac{\partial R}{\partial I}\right|_{T_0} \delta I$$

$$\alpha_{\mathrm{I}} = \left.\frac{\partial \log R}{\partial \log T}\right|_{I_0} = \frac{T_0}{R_0} \left.\frac{\partial R}{\partial T}\right|_{I_0}$$



Transition Edge Sensors - signal

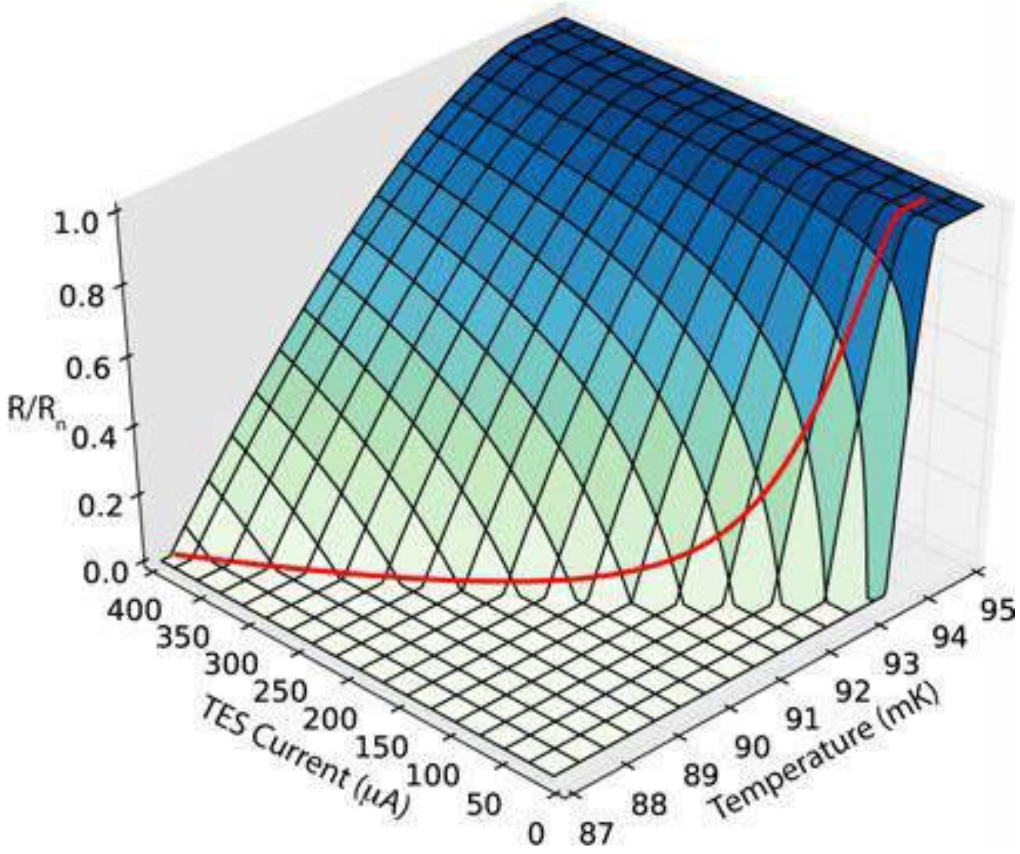
$$R(T,I) \approx R_0 + \left.\frac{\partial R}{\partial T}\right|_{I_0} \delta T + \left.\frac{\partial R}{\partial I}\right|_{T_0} \delta I$$

$$R(T,I) = R_0 + \alpha_{\mathrm{I}} \frac{R_0}{T_0} \delta T + \beta_{\mathrm{I}} \frac{R_0}{I_0} \delta I$$

$$\alpha_{\mathrm{I}} = \left.\frac{\partial \log R}{\partial \log T}\right|_{I_0} = \frac{T_0}{R_0} \left.\frac{\partial R}{\partial T}\right|_{I_0}$$

$$\beta_{\mathrm{I}} = \left.\frac{\partial \log R}{\partial \log I}\right|_{T_0} = \frac{I_0}{R_0} \left.\frac{\partial R}{\partial I}\right|_{T_0}$$

$$R_{\mathrm{dyn}} = \left.\frac{\partial V}{\partial I}\right|_{T_0} = R_0\left(1+\beta_{\mathrm{I}}\right)$$

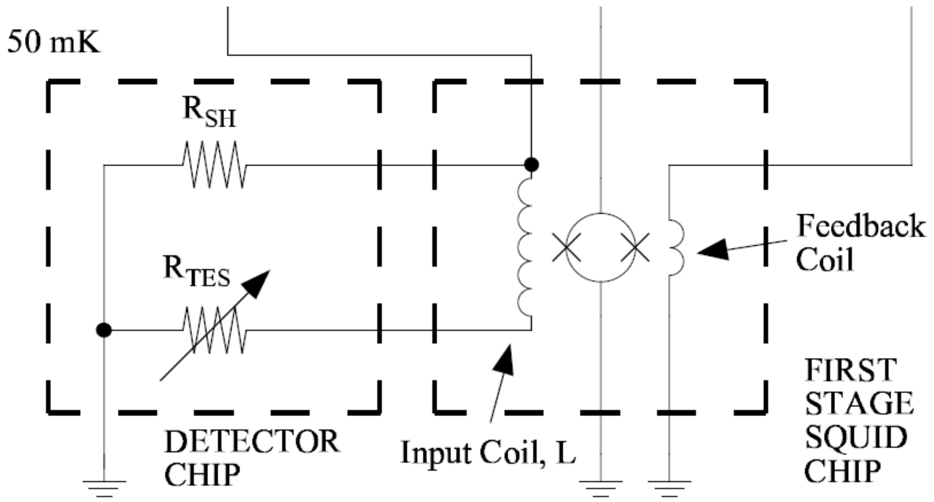


Bennet et al.,LTD16 presentation

Transition Edge Sensors - signal

If $R_{SH} >> R(T,I)$ → I ~constant → $P_J = I^2R$
→ R increases → P_J increases
→ positive feedback

If $R_{SH} << R(T,I)$ → V ~ constant → $P_J = V^2/R$
→ R increases → P_J decreases
→ negative feedback
Negative electro-thermal feedback



The negative electro-thermal feedback makes the working point more stable and decreases the decay time of the current signal with respect to the thermal time constant $\tau_0 = C/G$:

$$\tau_{eff} = \frac{\tau_0}{1 + \alpha/n}$$

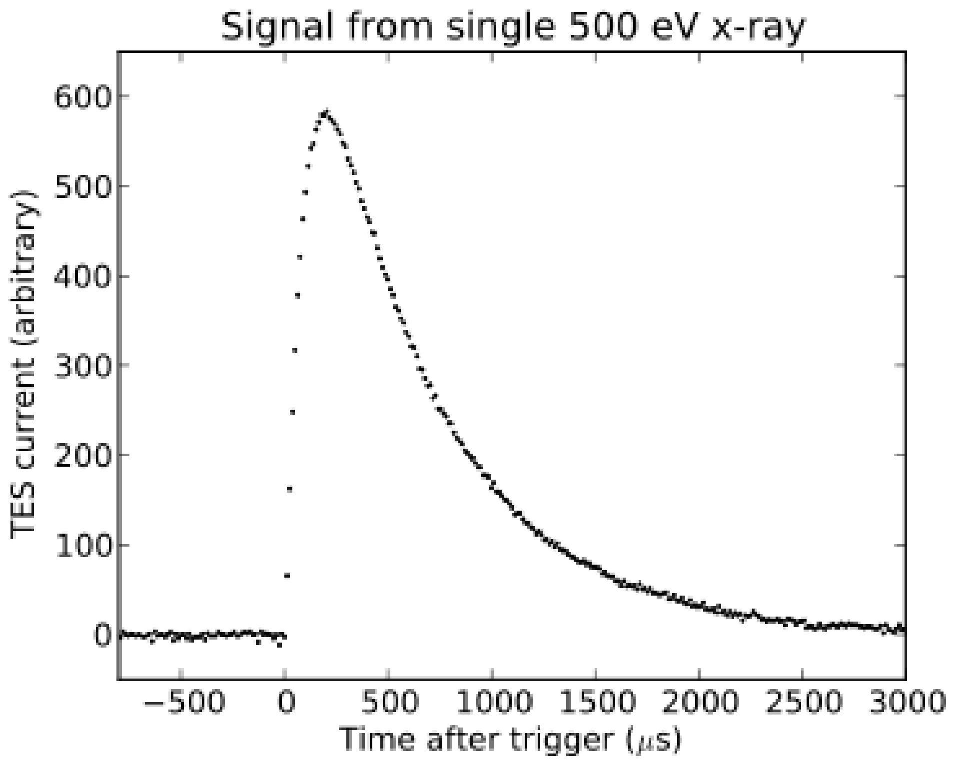
Transition Edge Sensors - signal

Pulse shape:

$$\delta I(t) \propto \left(-e^{-\frac{t}{\tau_+}} + e^{-\frac{t}{\tau_-}}\right)$$

rise time $\tau_+ \sim \tau_{el} = \frac{L}{R_{SH}+R_{dyn}}$

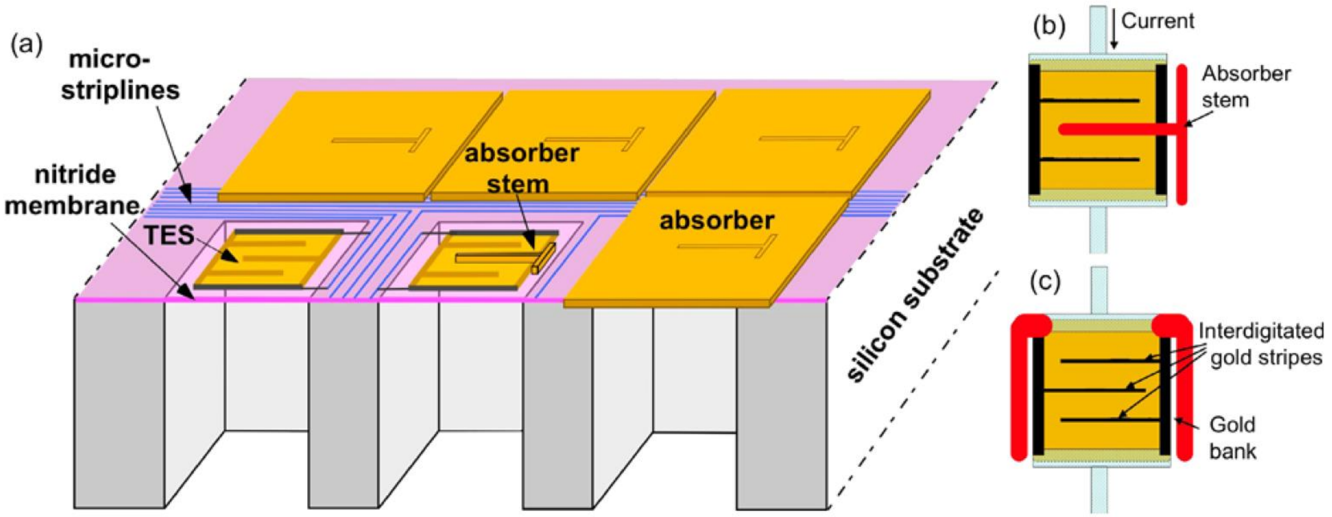
decay time $\tau_- = \tau_{eff} = \frac{\tau_0}{1+\alpha/n}$

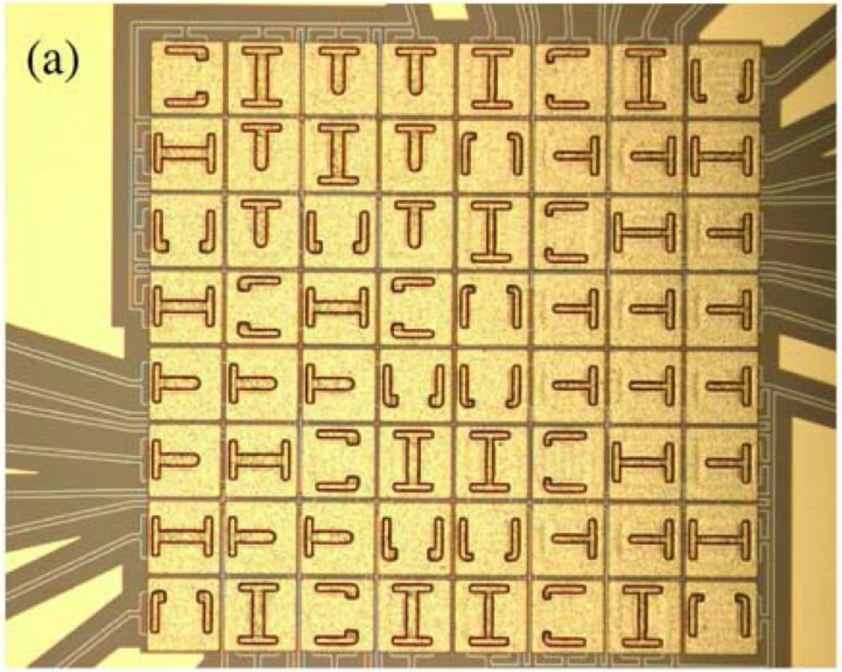


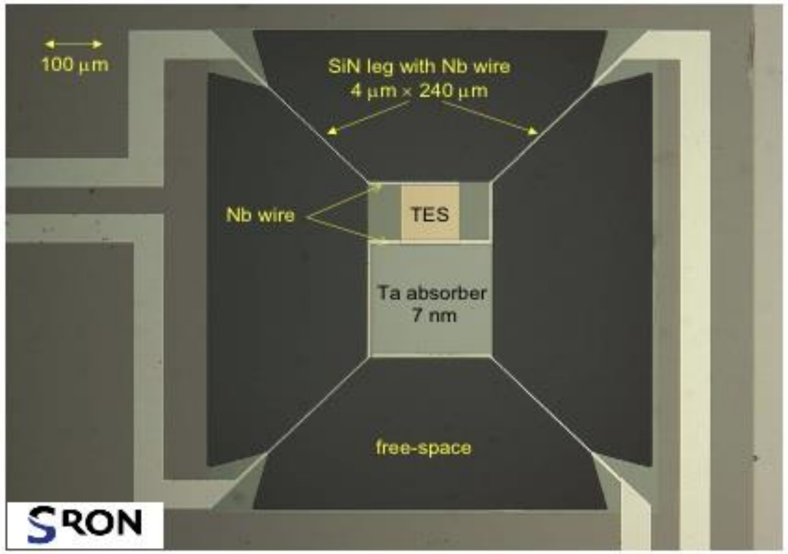
For strong electro-thermal feedback → best energy resolution:

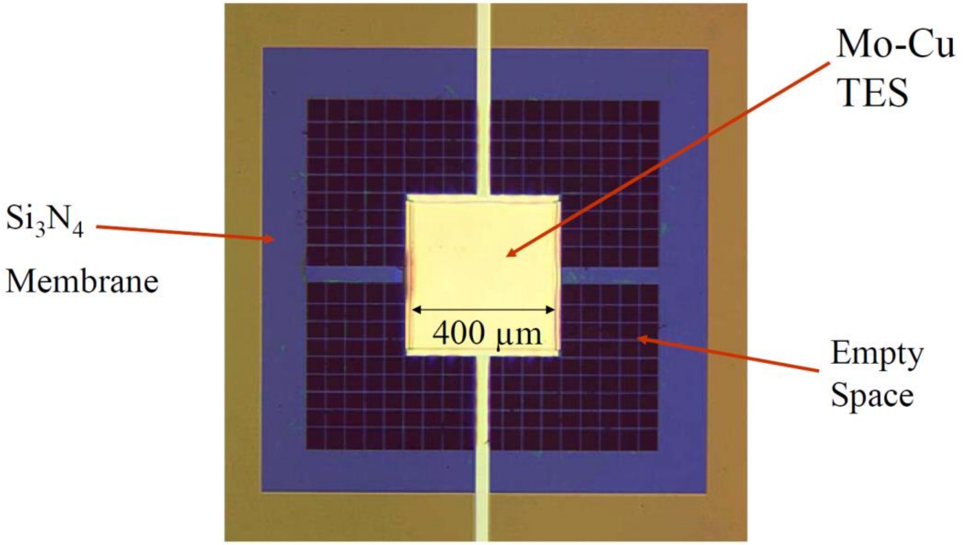
$$\Delta E_{FWHM} = 2\sqrt{2ln2}\sqrt{4k_B T^2 \frac{C}{\alpha}\sqrt{\frac{n}{2}}}$$

Transition Edge Sensors - fabrication

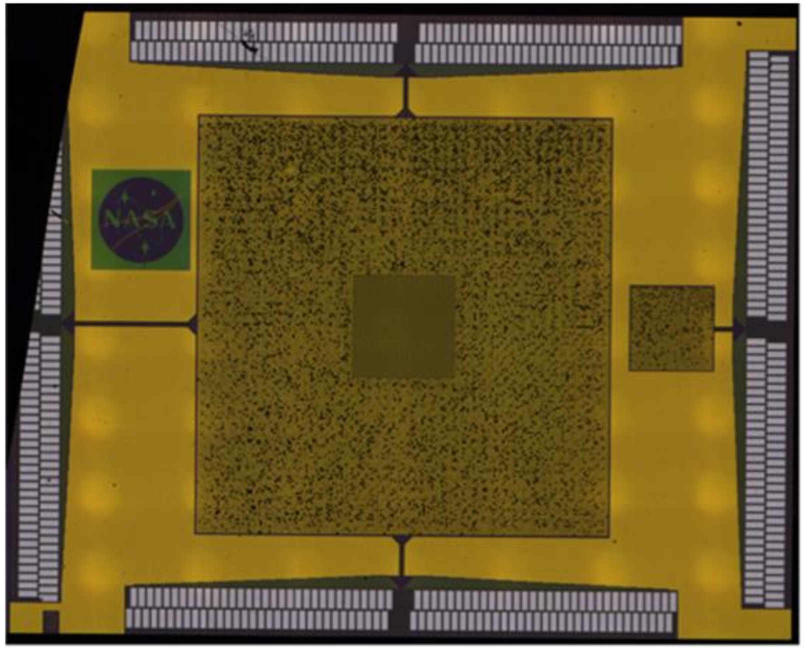


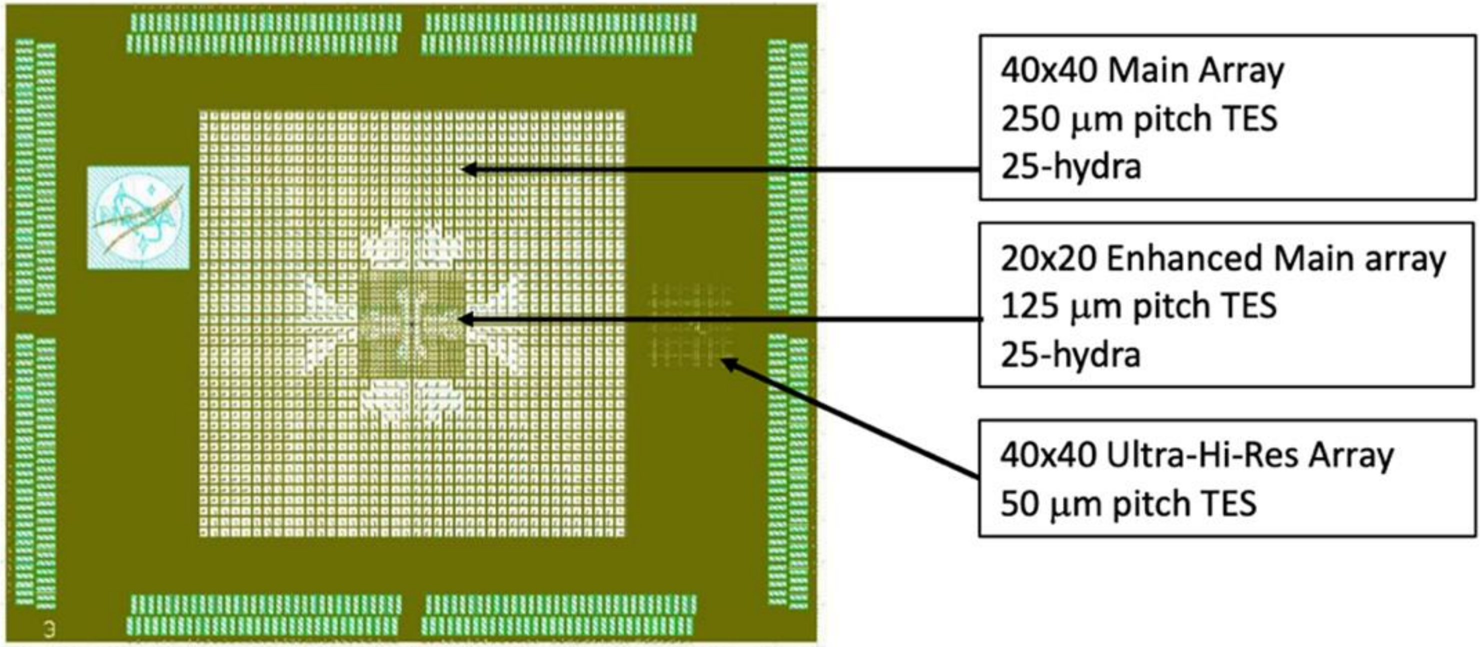






Transition Edge Sensors – Lynx array

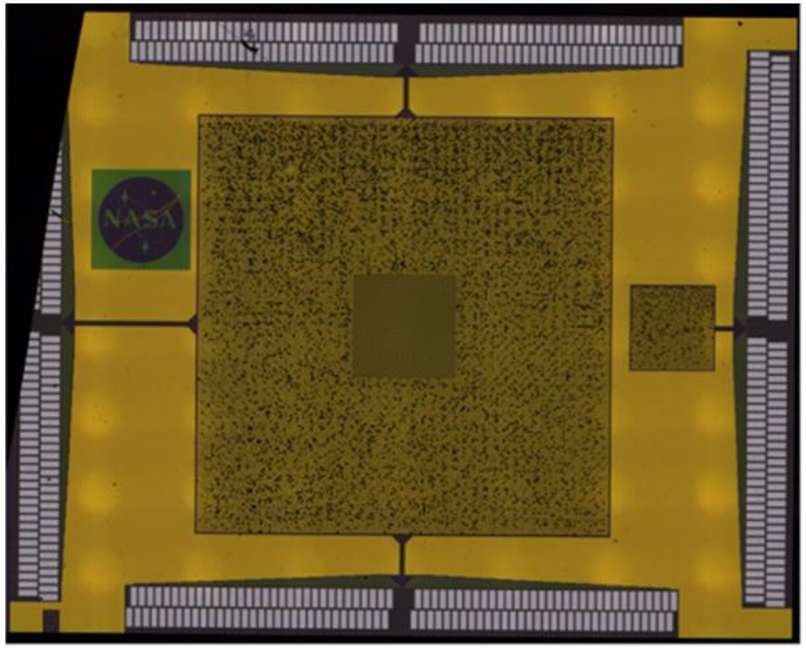


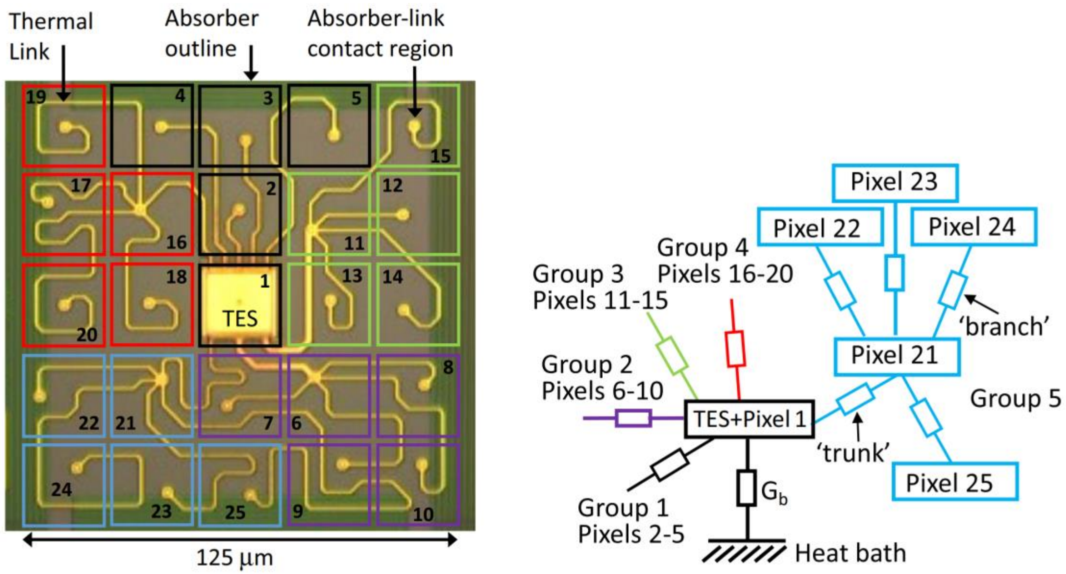


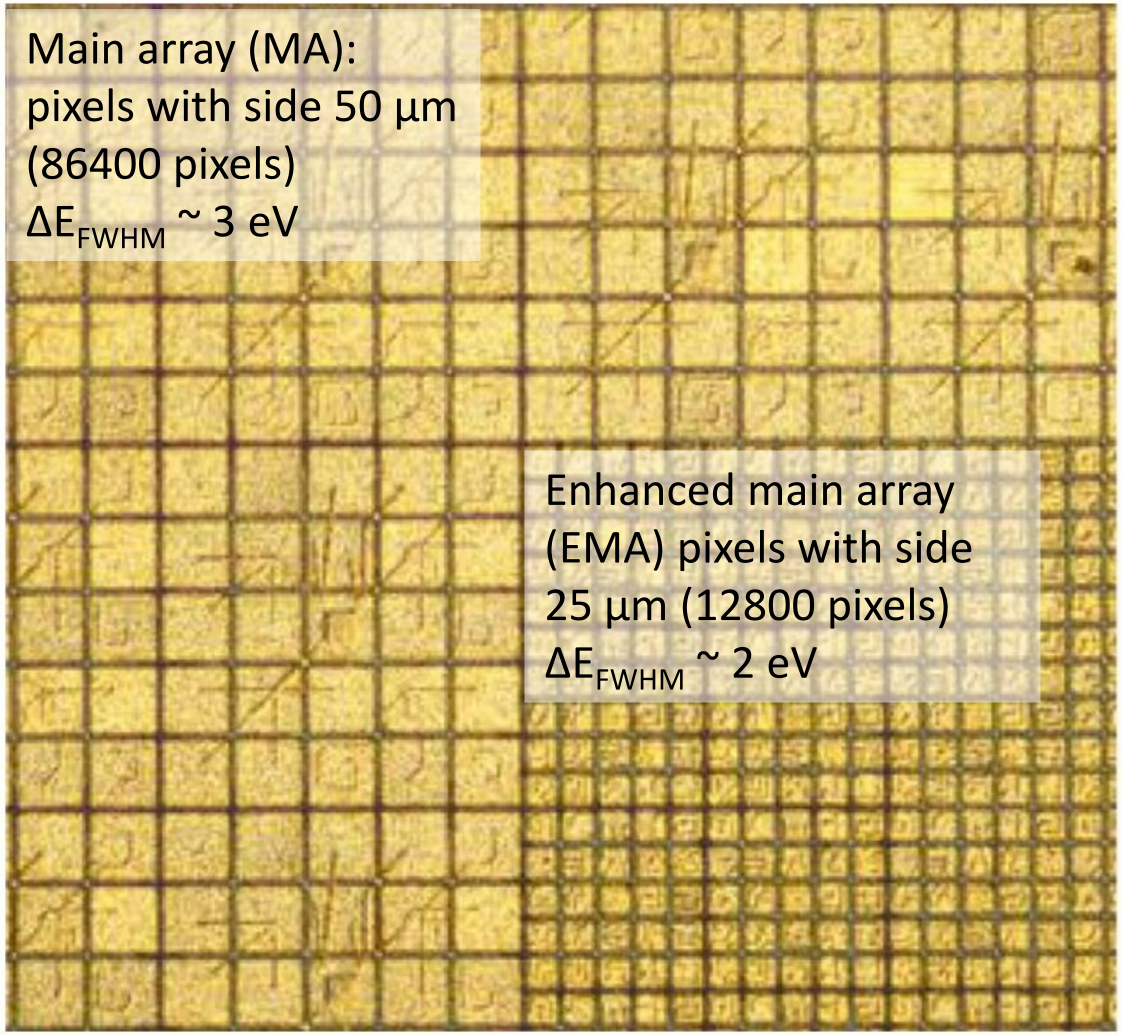
Lynx microcalorimeter array for future NASA mission for soft x-ray astronomy:
< 1″ angular resolution optic
~ 100,000-pixel with energy resolution of ΔE_{FWHM} ~3 eV

S.J. Smith et al., JLTP 199 (2020) 330–338

Transition Edge Sensors – Lynx array





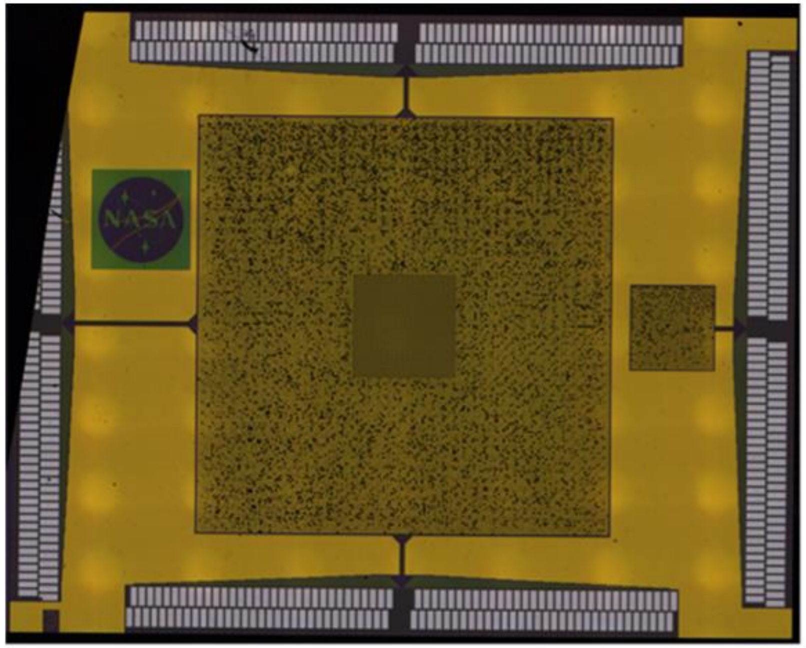


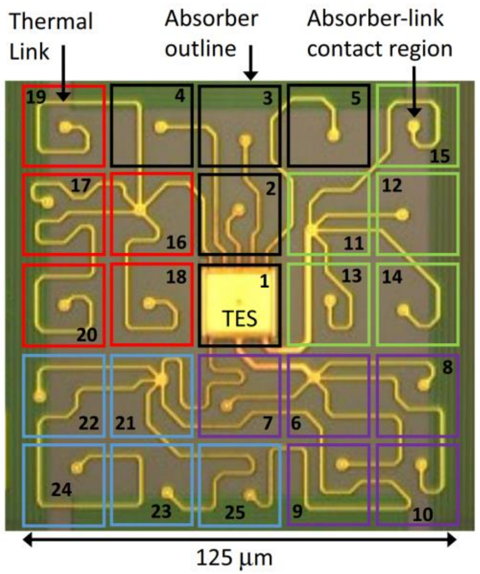
Main array (MA):
pixels with side 50 μm
(86400 pixels)
ΔE_{FWHM} ~ 3 eV

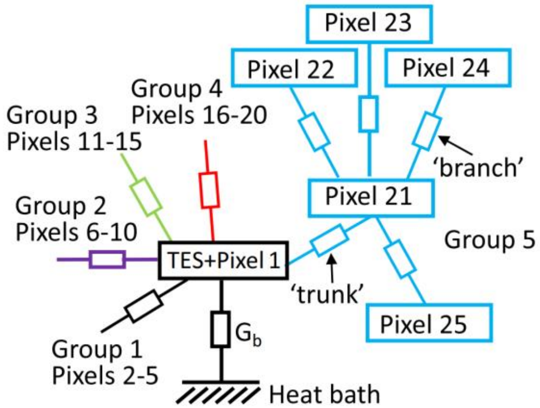
Enhanced main array (EMA) pixels with side 25 μm (12800 pixels)
ΔE_{FWHM} ~ 2 eV

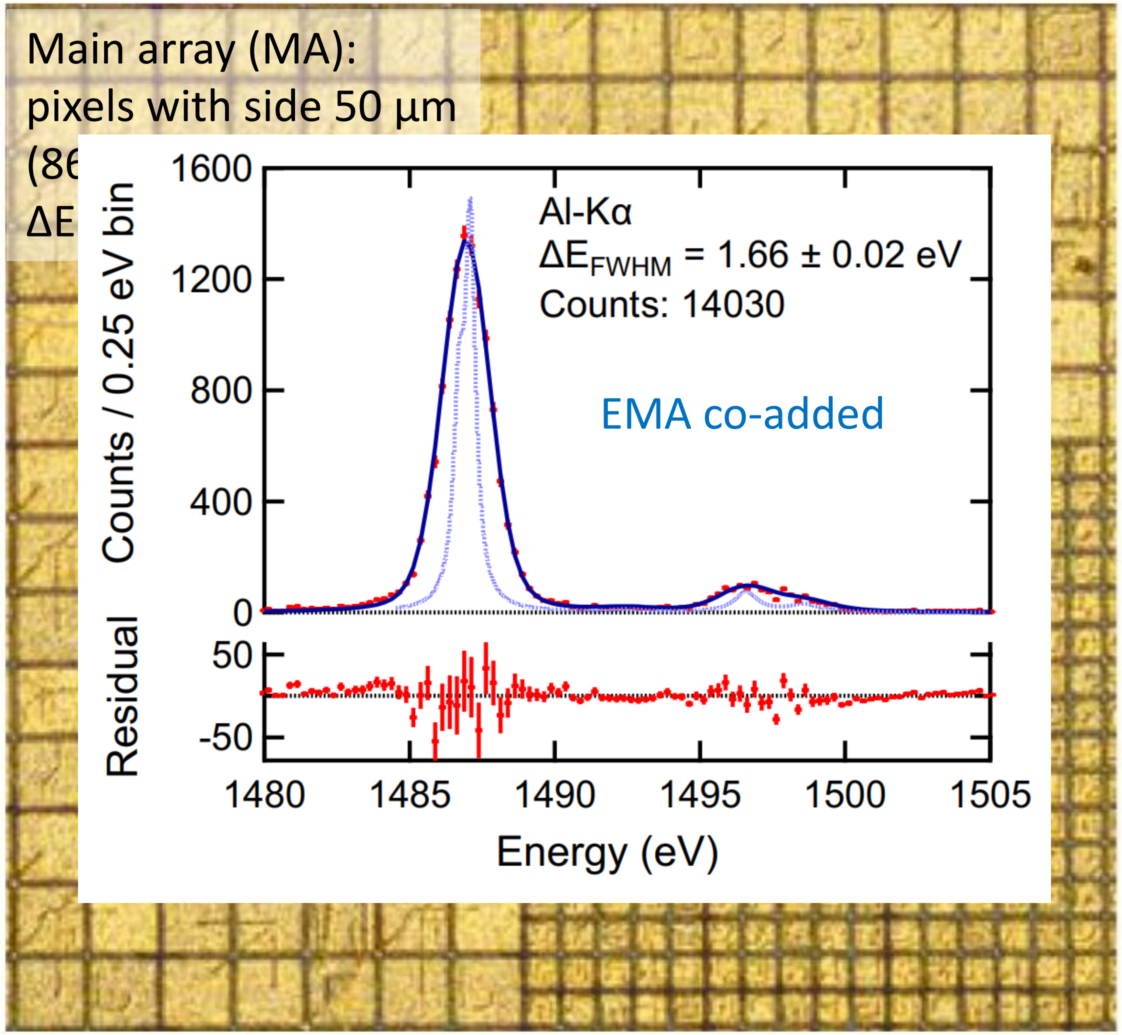
S.J. Smith et al., JLTP 199 (2020) 330–338

Transition Edge Sensors – Lynx array





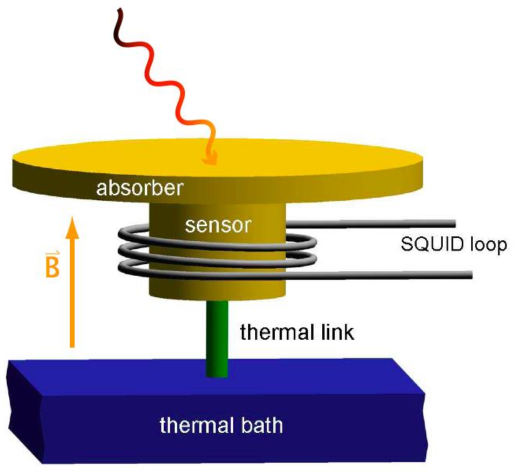




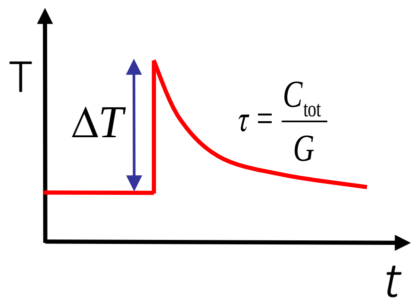
S.J. Smith et al., JLTP 199 (2020) 330–338

Metallic Magnetic Calorimeters

Paramagnetic temperature sensor



$$\Delta T \cong \frac{E}{C_{\mathrm{tot}}} \quad \xrightarrow{\text{MMC}} \quad \Delta\Phi_{\mathrm{S}} \propto \frac{\partial M}{\partial T}\Delta T$$

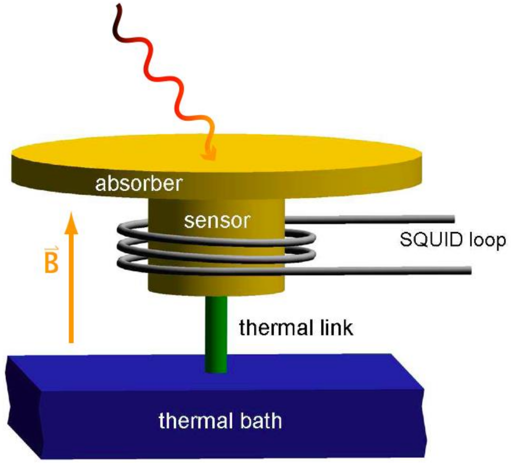


A.Fleischmann, C. Enss and G. M. Seidel,
Topics in Applied Physics **99** (2005) 63

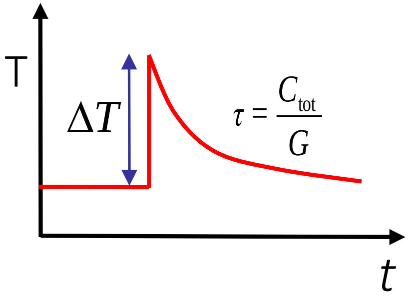
A.Fleischmann et al.,
AIP Conf. Proc. **1185** (2009) 571

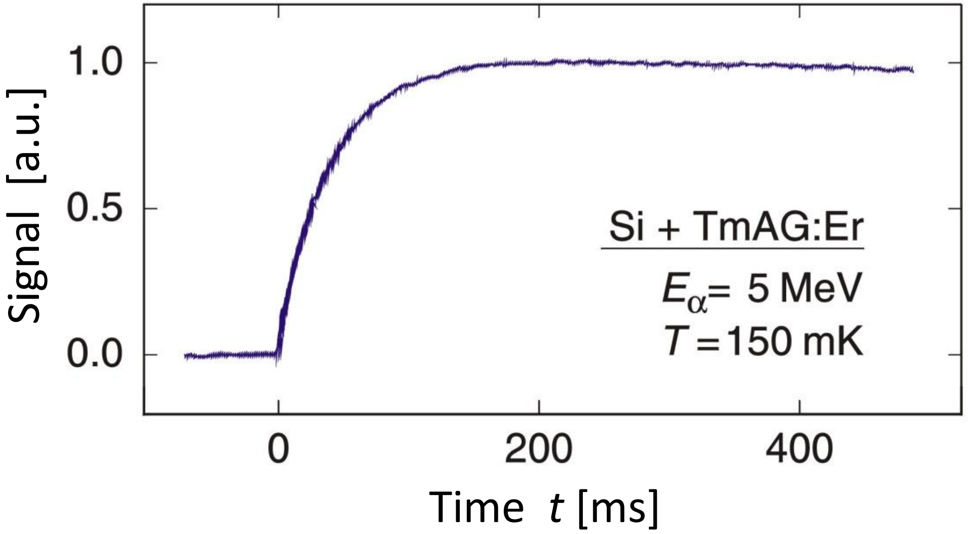
Metallic Magnetic Calorimeters

Paramagnetic temperature sensor



$$\Delta T \cong \frac{E}{C_{tot}} \quad \xrightarrow{\text{MMC}} \quad \Delta\Phi_S \propto \frac{\partial M}{\partial T} \Delta T$$





dielectric sensor:

Bühler & Umlauf '93

phonons — spins

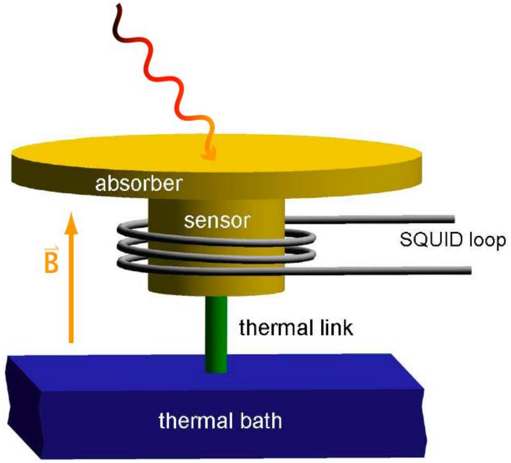
$\tau \cong 50$ ms

A.Fleischmann, C. Enss and G. M. Seidel,
Topics in Applied Physics **99** (2005) 63

A.Fleischmann et al.,
AIP Conf. Proc. **1185** (2009) 571

Metallic Magnetic Calorimeters

Paramagnetic temperature sensor



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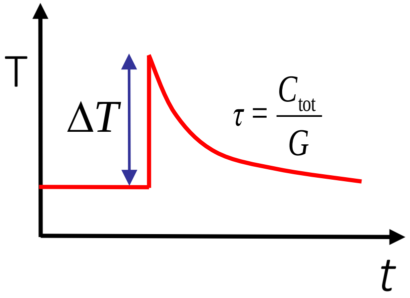
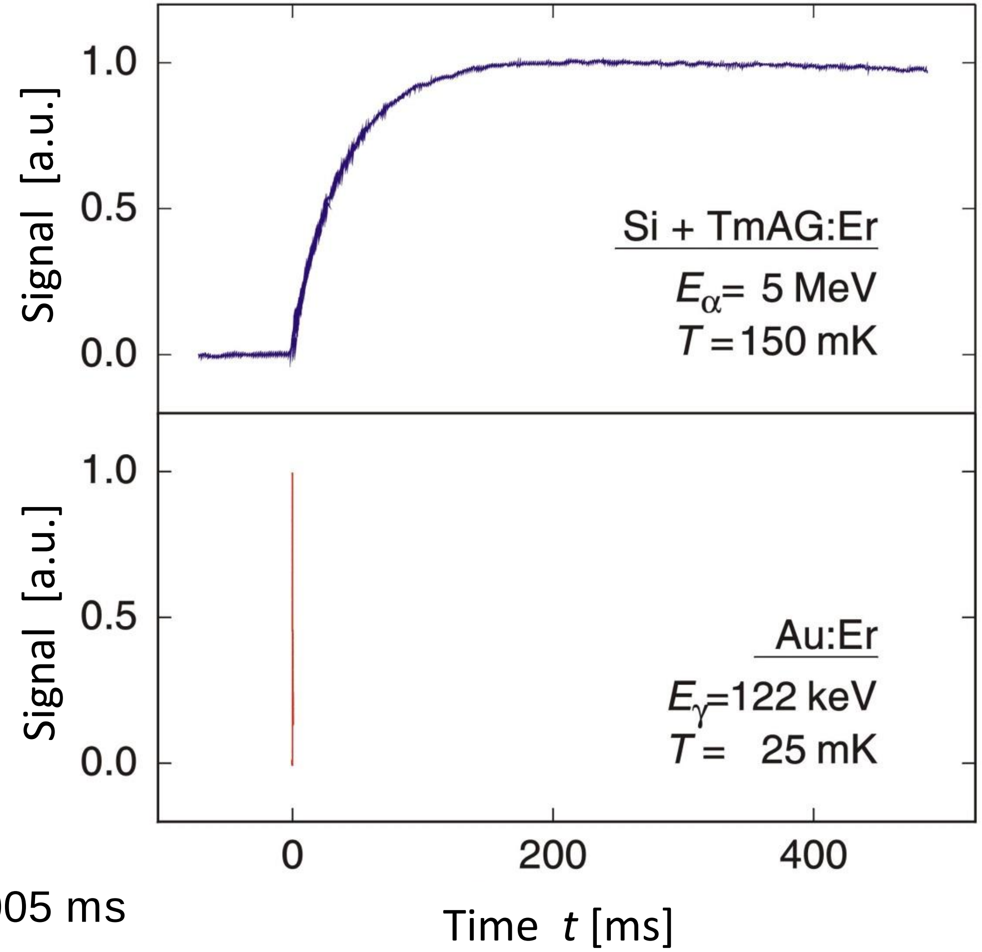




A.Fleischmann, C. Enss and G. M. Seidel, Topics in Applied Physics **99** (2005) 63

A.Fleischmann et al., *AIP Conf. Proc.* **1185** (2009) 571

metallic sensor: Heidelberg '98

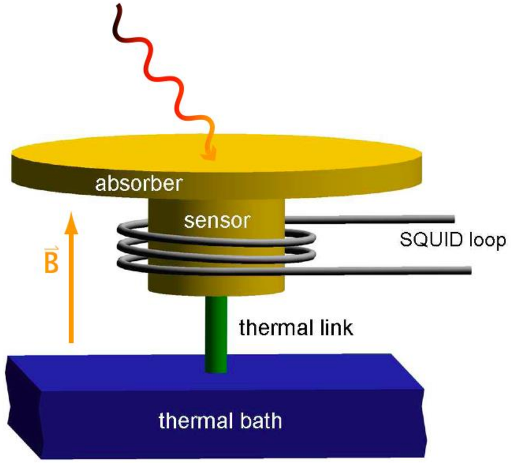
electrons — spins

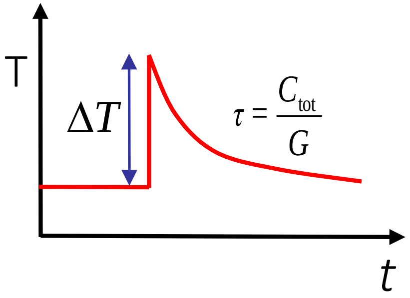
$\tau \cong 0{,}005$ ms

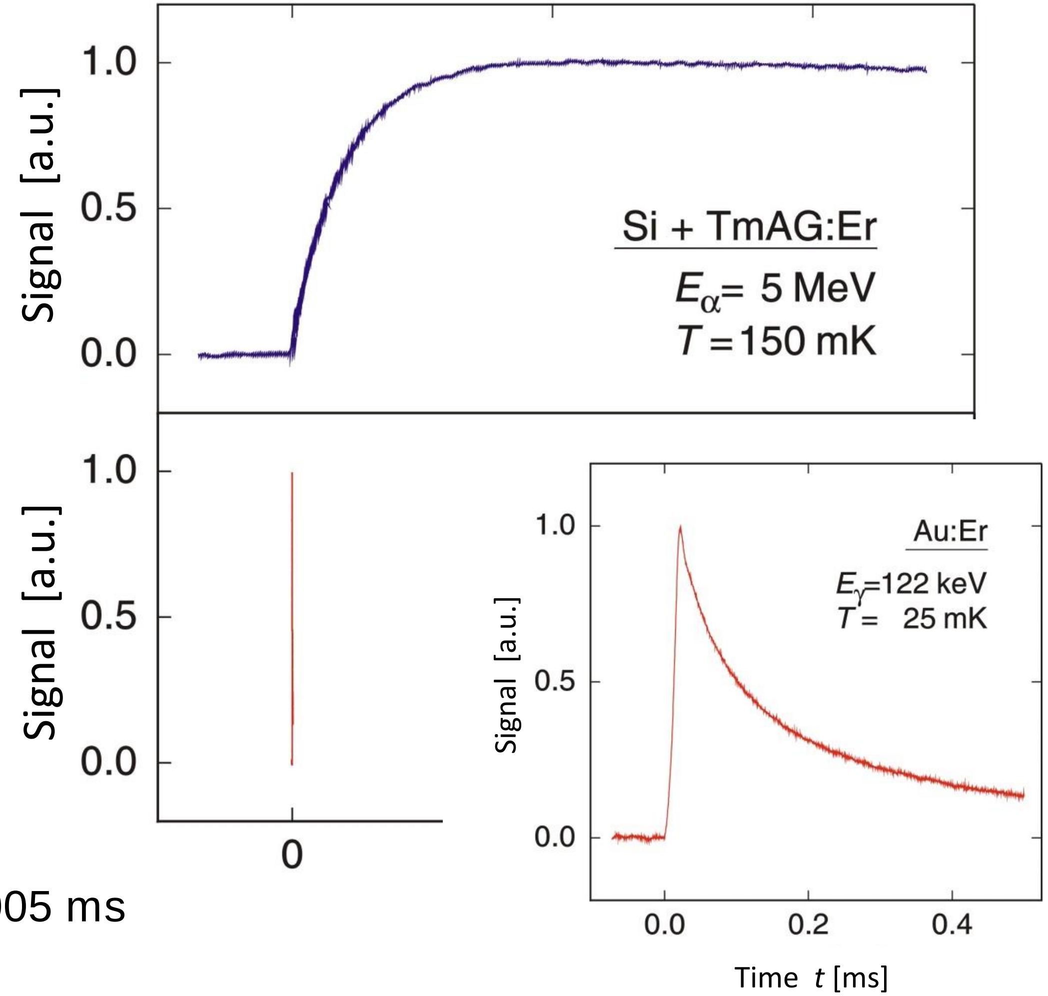
Metallic Magnetic Calorimeters

Paramagnetic temperature sensor

$$\Delta T \cong \frac{E}{C_{tot}} \quad \xrightarrow{\text{MMC}} \quad \Delta\Phi_S \propto \frac{\partial M}{\partial T}\Delta T$$







metallic sensor: Heidelberg '98

electrons — spins

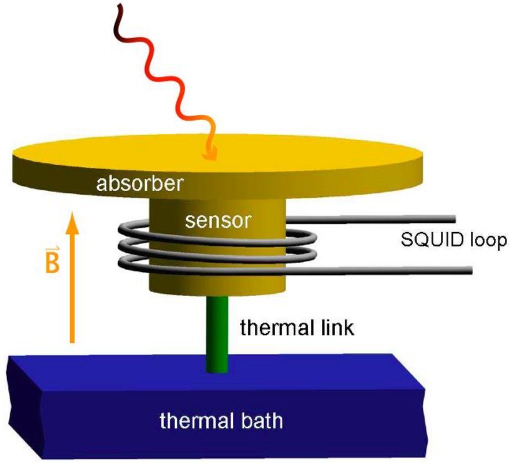
$\tau \cong 0{,}005$ ms

A.Fleischmann, C. Enss and G. M. Seidel, Topics in Applied Physics **99** (2005) 63

A.Fleischmann et al., *AIP Conf. Proc.* **1185** (2009) 571

Metallic Magnetic Calorimeters

Paramagnetic temperature sensor → Dilute alloy Au:Er or Ag:Er (Er concentration: a few hundred ppm)



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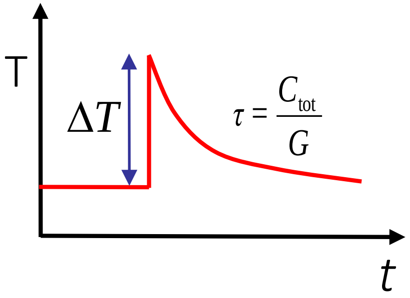
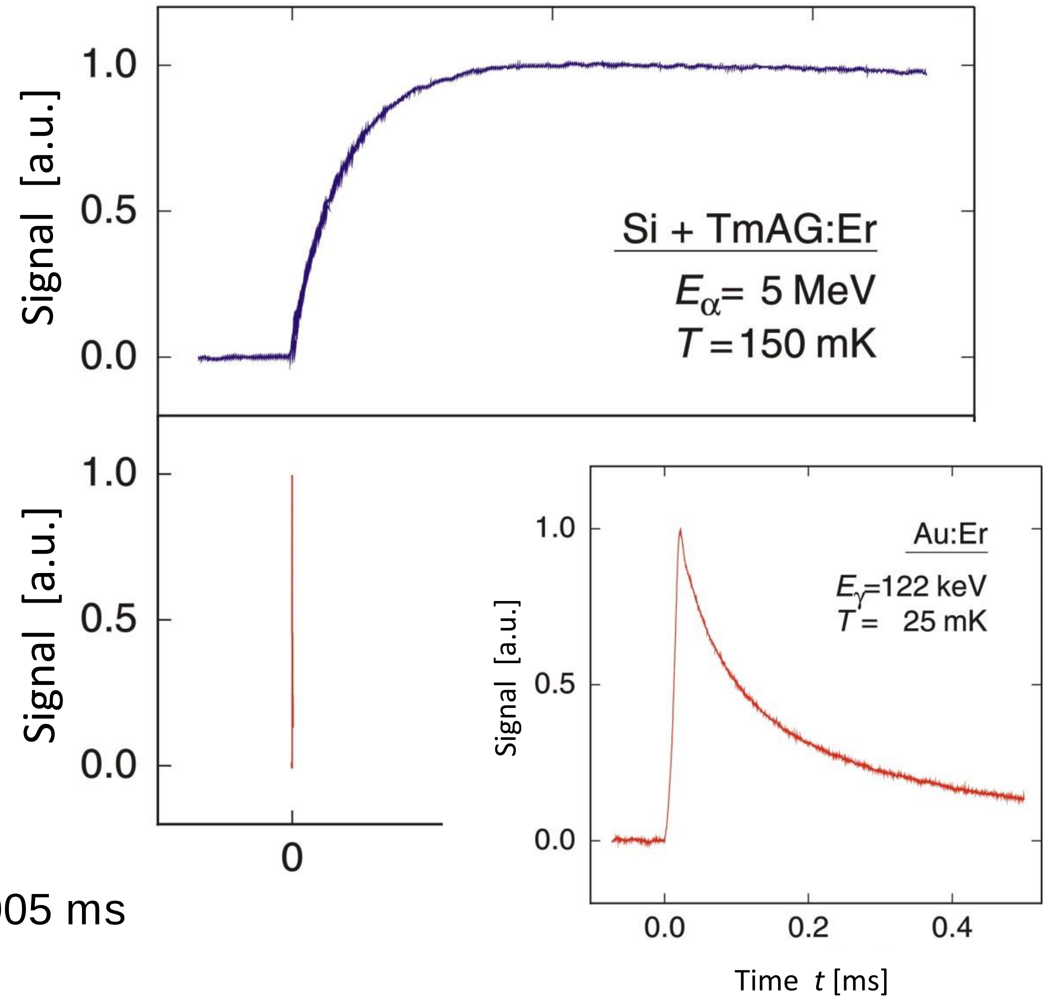




A.Fleischmann, C. Enss and G. M. Seidel, Topics in Applied Physics **99** (2005) 63

A.Fleischmann et al., *AIP Conf. Proc.* **1185** (2009) 571

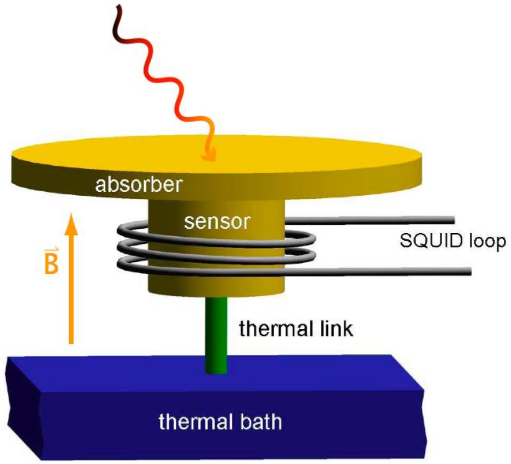
metallic sensor: Heidelberg '98

electrons —— spins

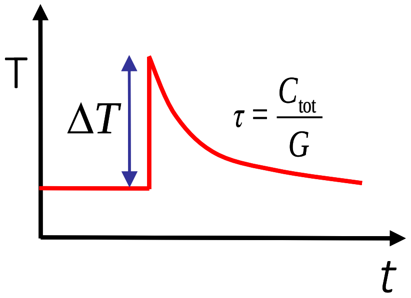
$\tau \cong 0{,}005$ ms

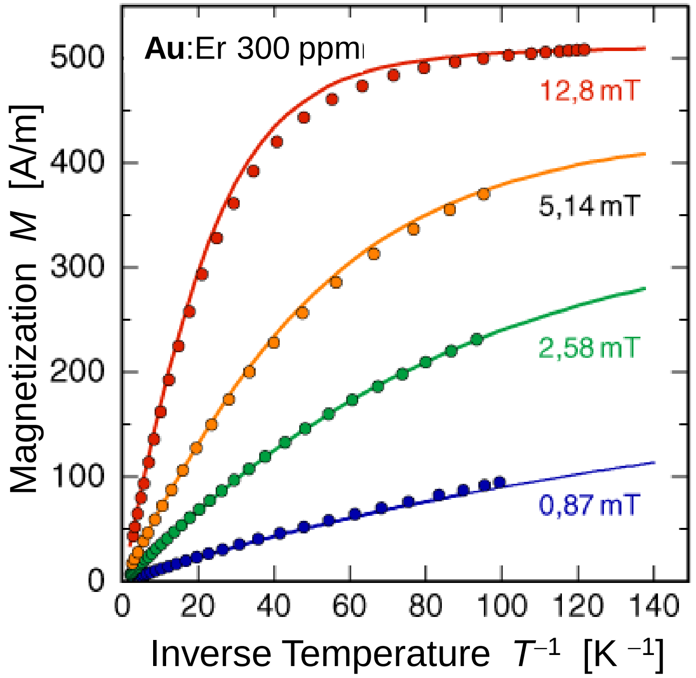
Metallic Magnetic Calorimeters

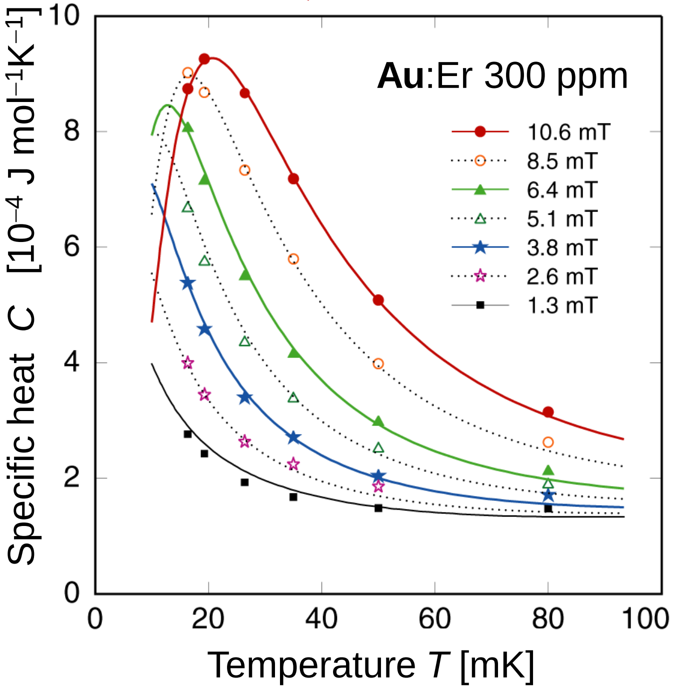
Signal



$$\Delta T \cong \frac{E}{C_{tot}} \xrightarrow{\text{MMC}} \Delta\Phi_S \propto \frac{\partial M}{\partial T}\Delta T \rightarrow \Delta\Phi_S \propto \frac{\partial M}{\partial T}\frac{E}{C_{tot}}$$







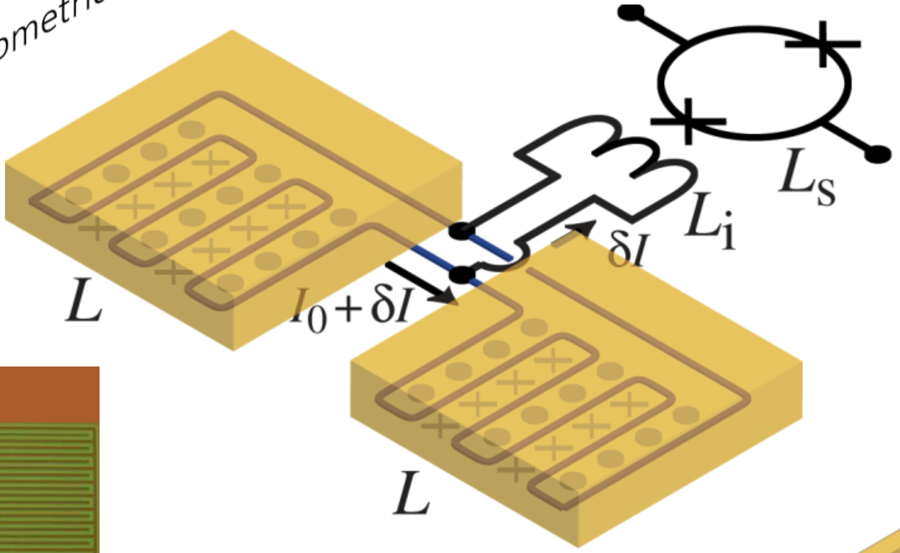
Very good agreement between data and theoretical expectation for interacting spin system

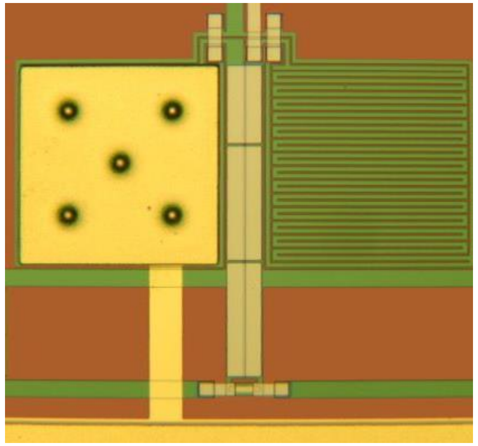
Optimization of detector geometries for different applications

Detector geometries

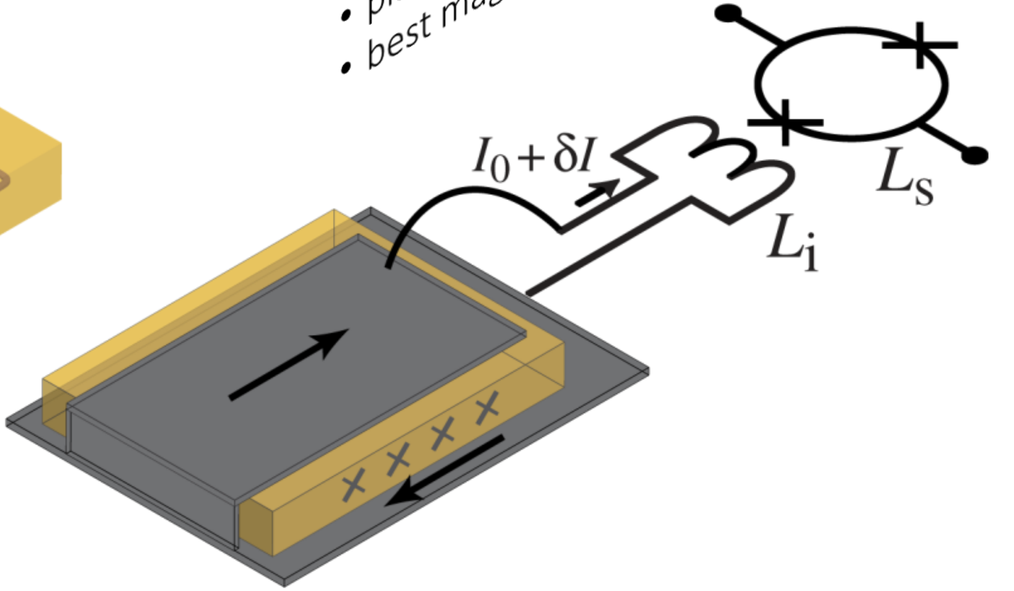
- planar paramagnetic sensor
- superconducting coil
- transformed coupled to a dc SQUID

Well established:
- *superconducting meander shaped pickup loop*
- *planar sensor on top of meander-shaped coil*
- *gradiometric design*

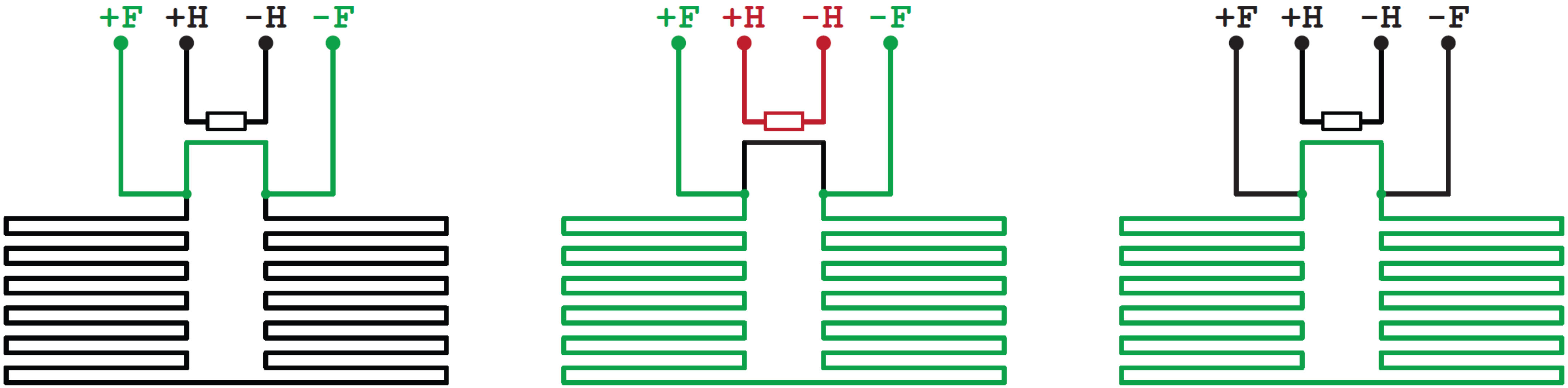




Sandwich geometry:
- *planar sensor sandwiched between stripline*
- *best magnetic flux coupling*

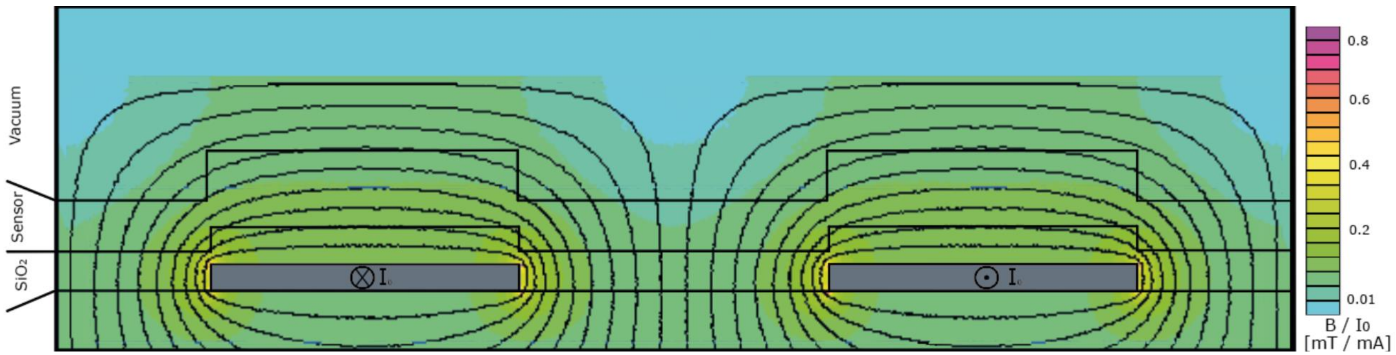


Persistent current



Reliable injection of a persistent current in the superconducting coil:

Achievable critical current density: ~ 10 MA/cm^2

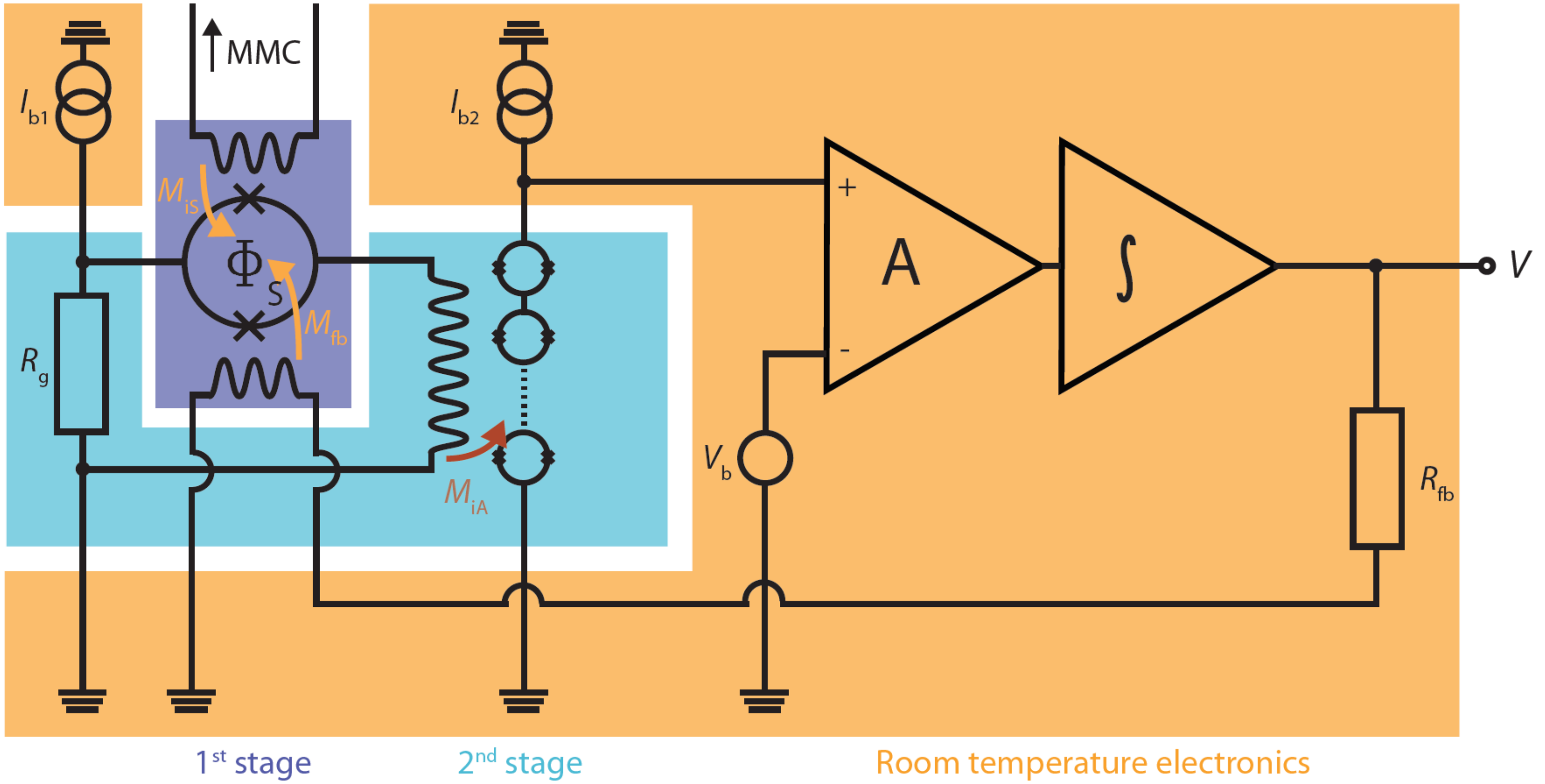


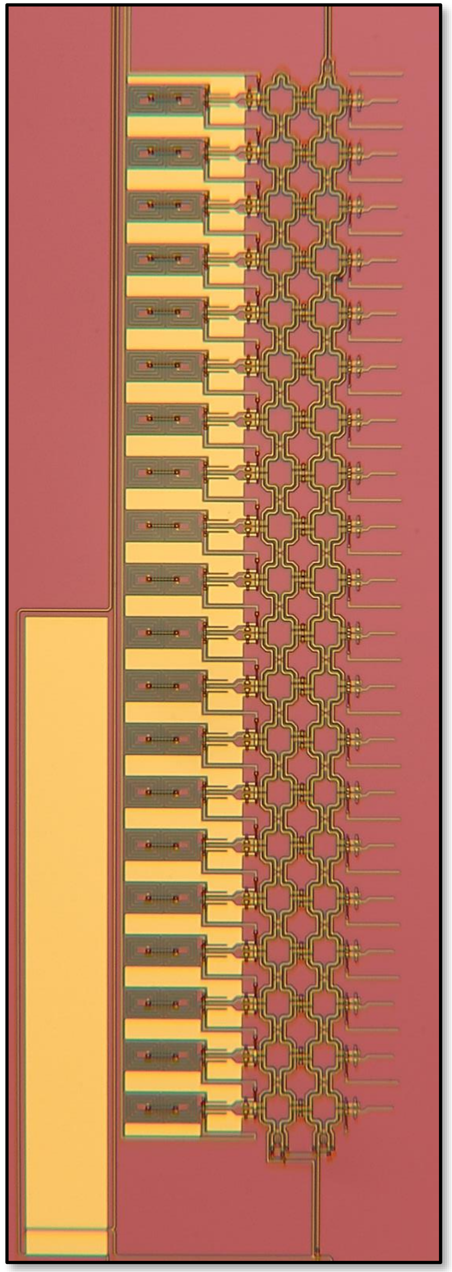
MMC readout

Two-stage dc-SQUID readout with flux-locked loop

low noise

small power dissipation on detector SQUID chip (voltage bias 1st stage)

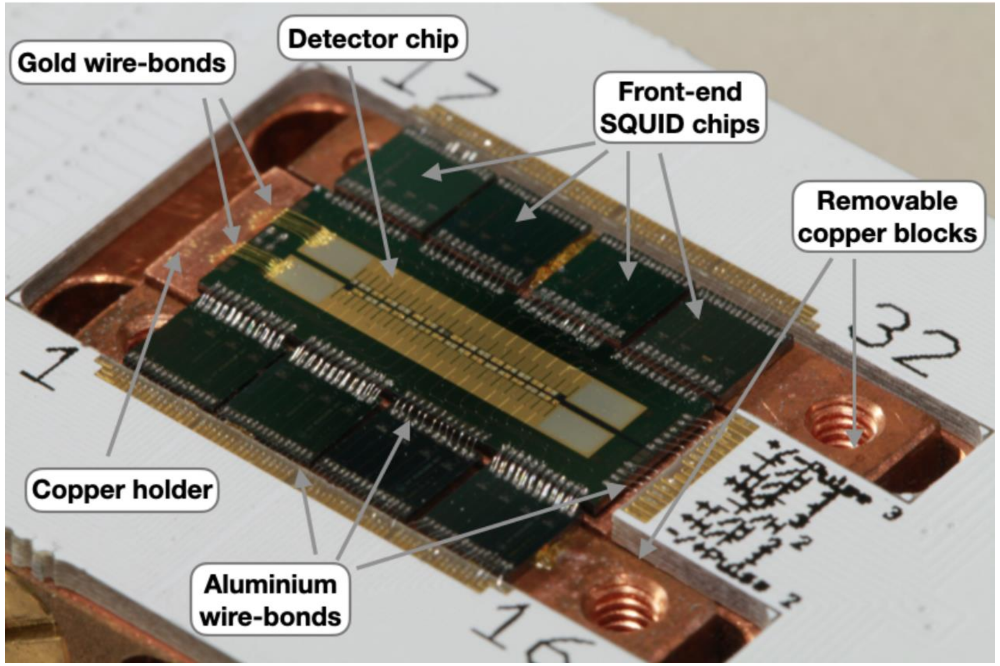




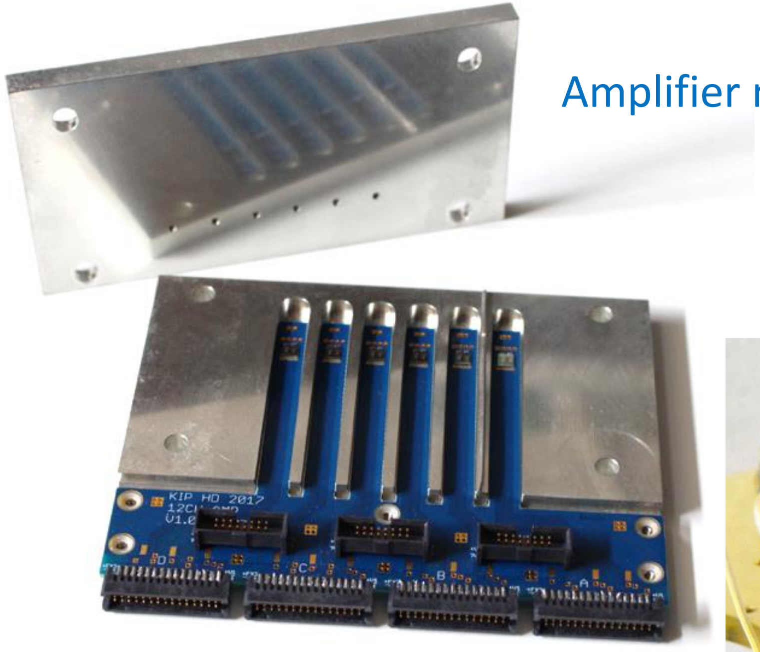
In house produced SQUID array

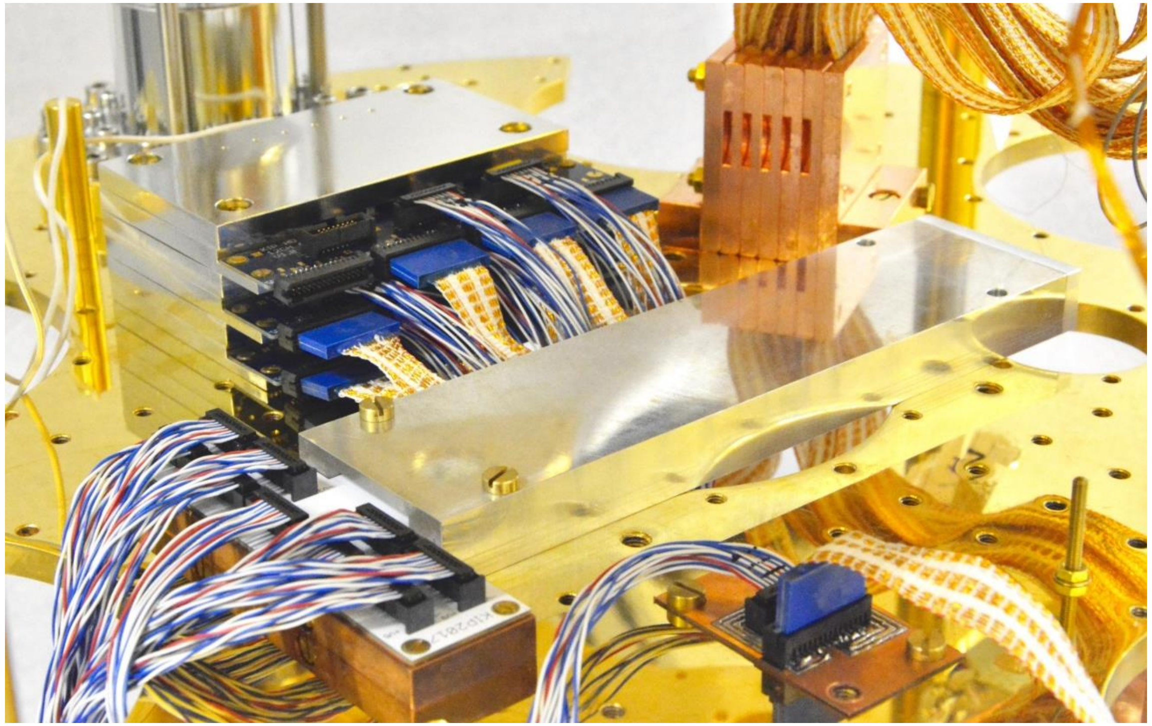
MMC readout

Detector module



Amplifier module

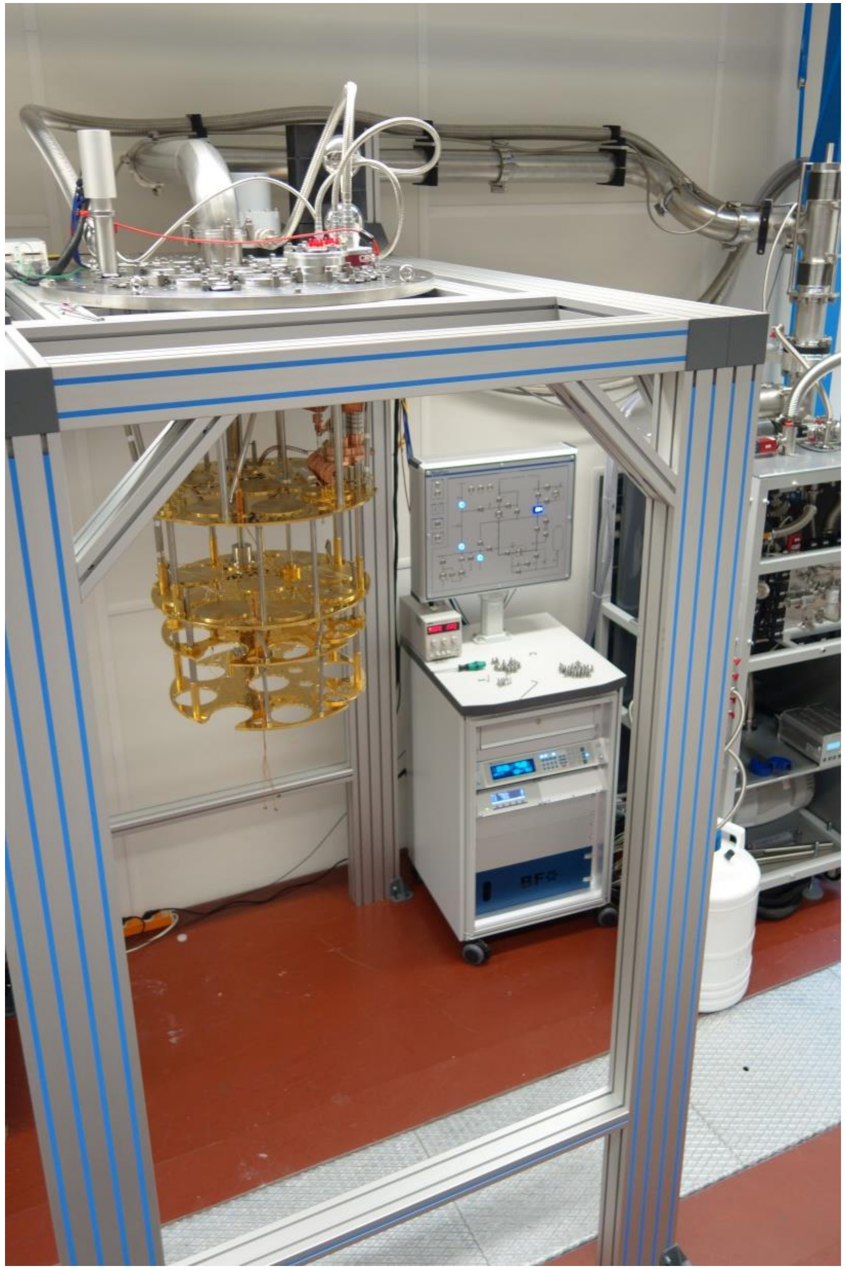


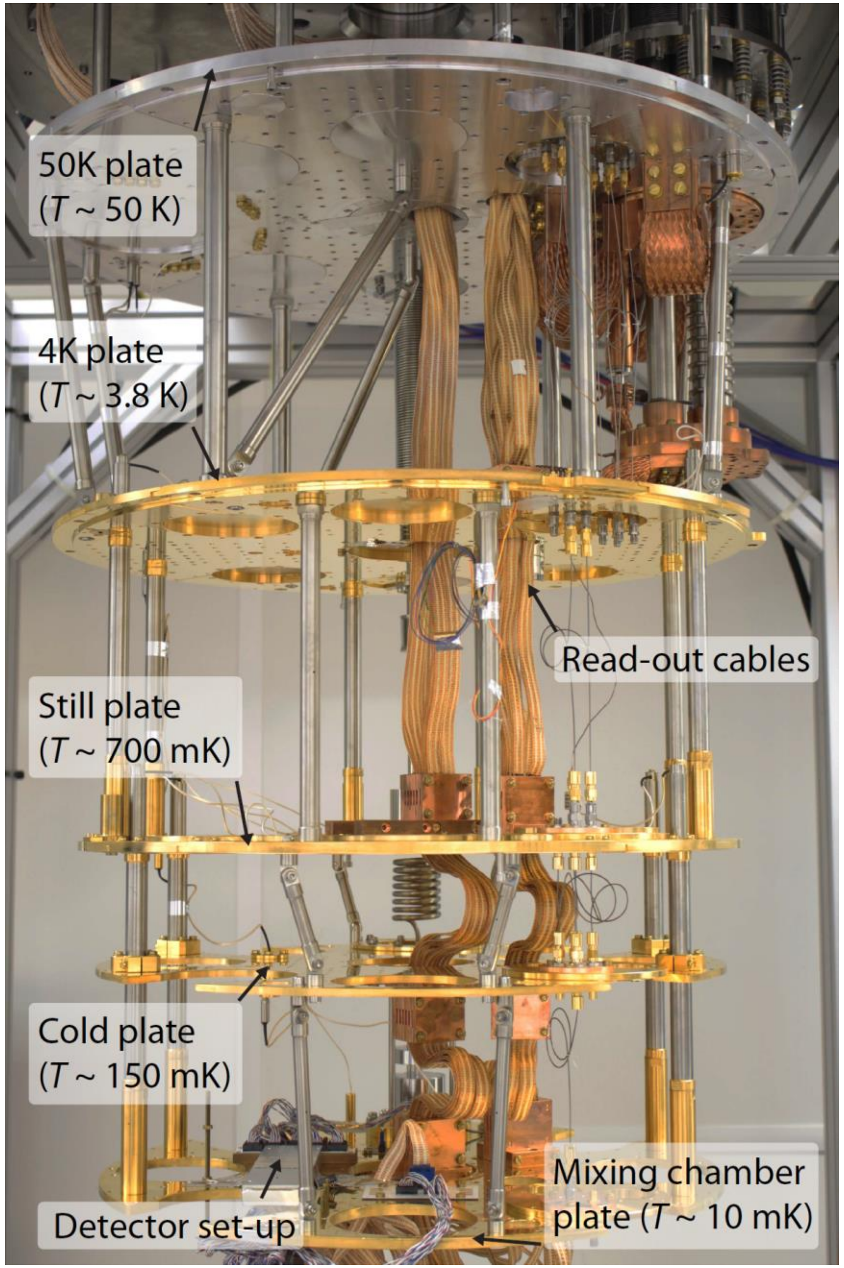


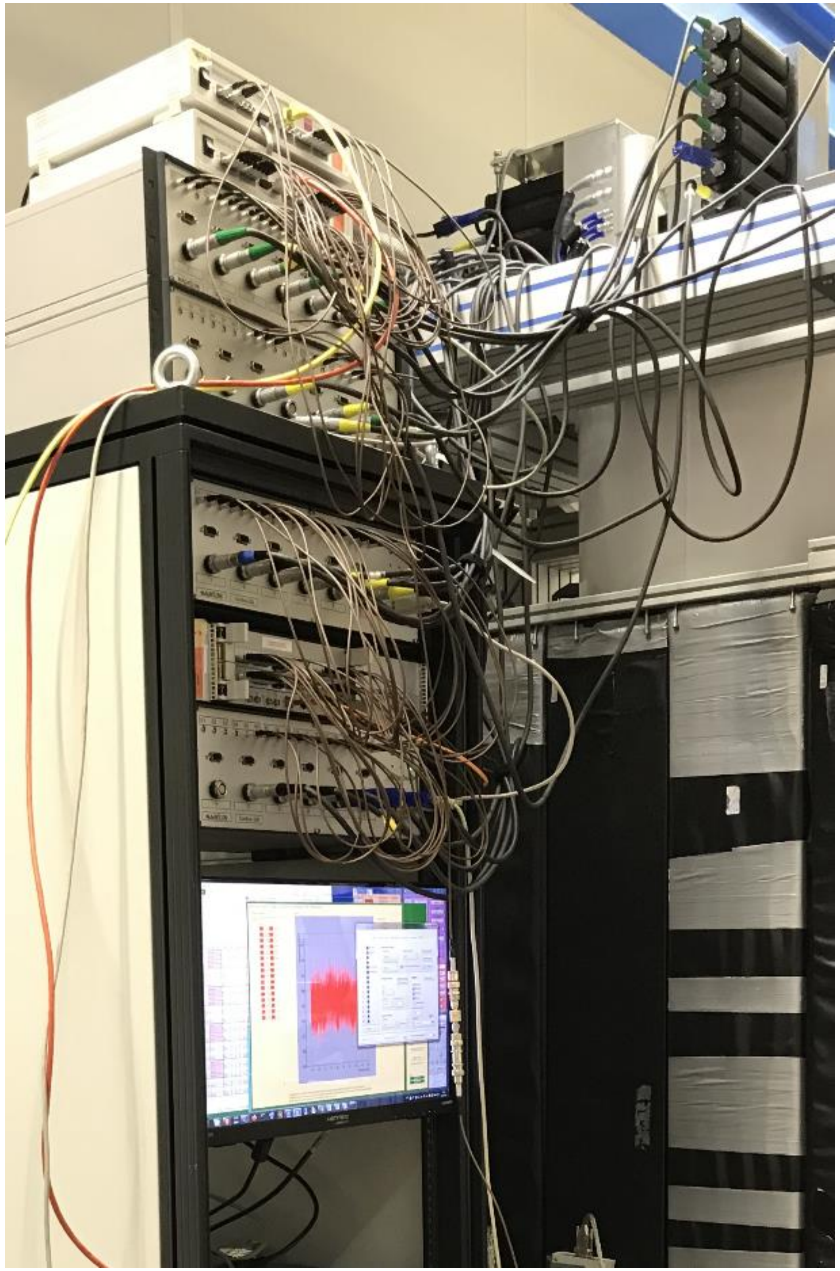
Detector and amplifier module mounted on the mixing chamber plate

F. Mantegazzini et al., *JINST* **16** (2021) P08003, arXiv:2102.11100 [physics.ins-det]

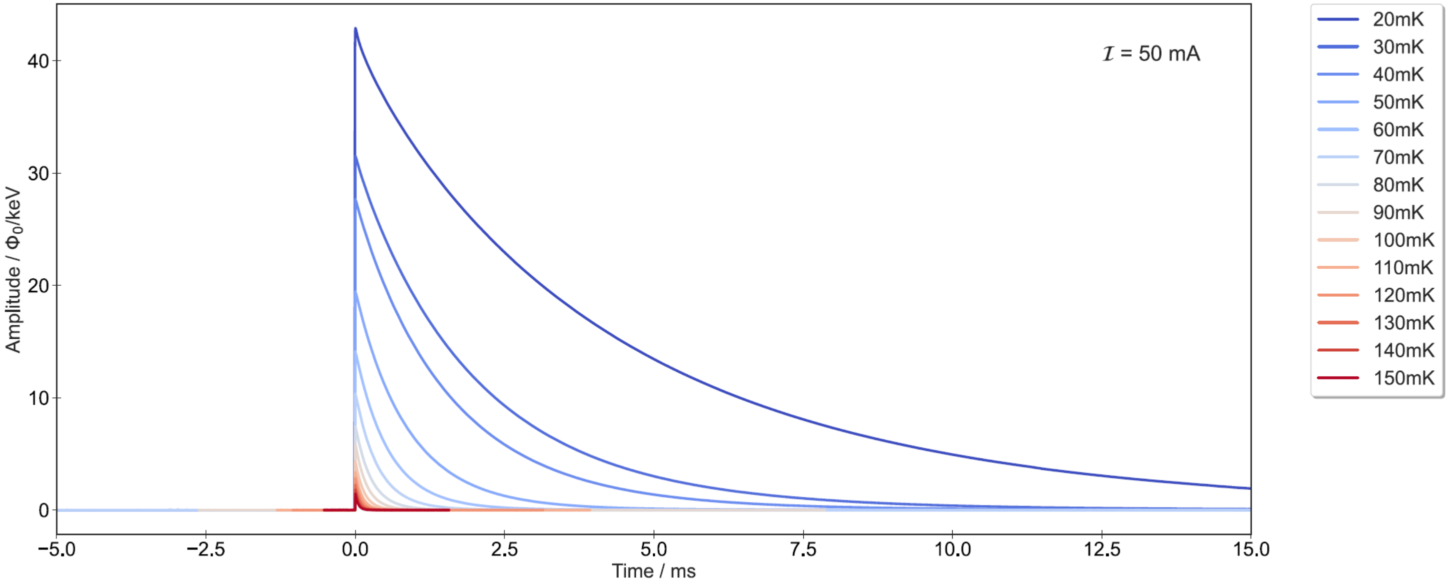
MMC readout




50K plate
(T ~ 50 K)
4K plate
(T ~ 3.8 K)
Still plate
(T ~ 700 mK)
Cold plate
(T ~ 150 mK)
Detector set-up
Read-out cables
Mixing chamber
plate (T ~ 10 mK)



Performance

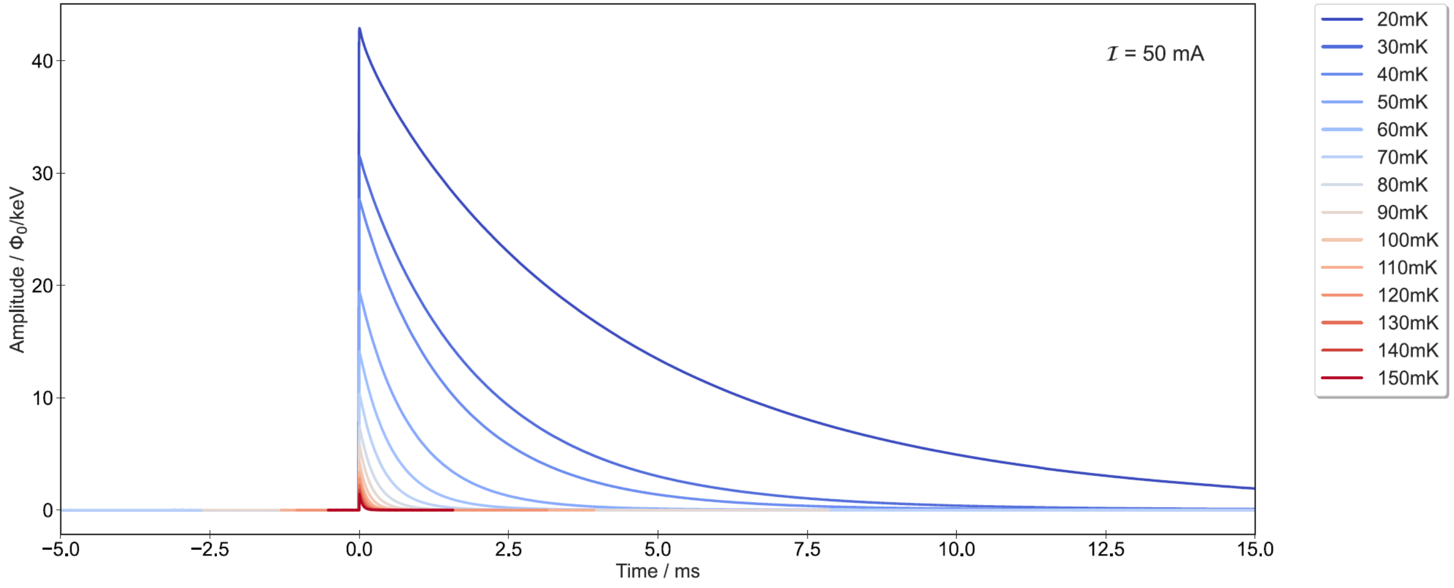


Amplitude proportional to energy

Rise time limited by the electron spin coupling

Decay time given by C/G
→ thermal link optimized for detector heat capacity at operating temperature

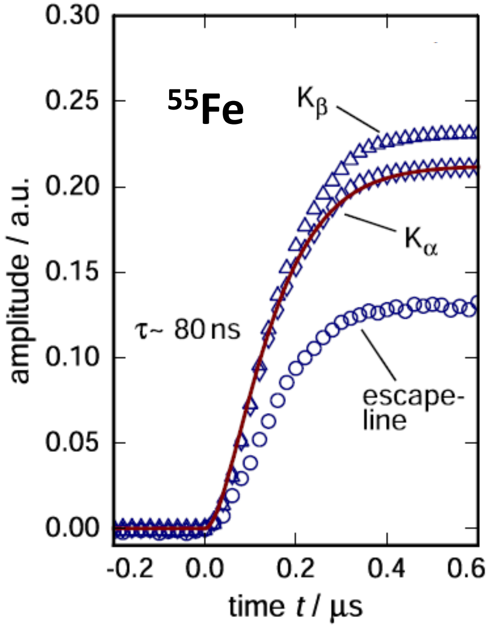
Performance

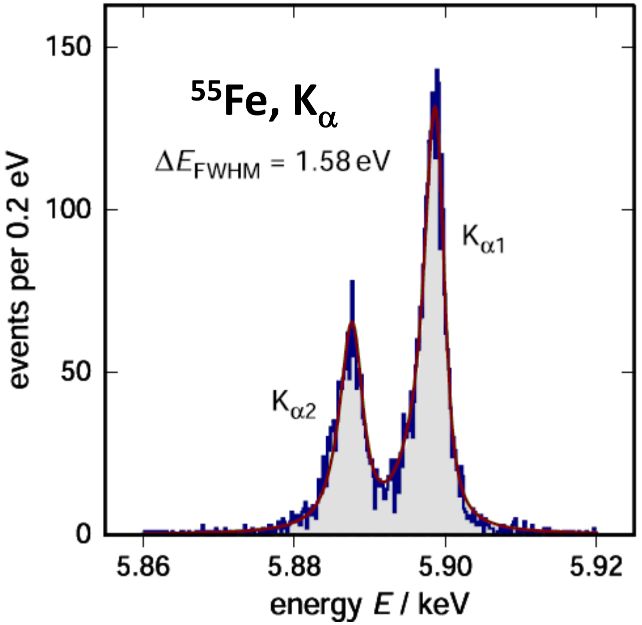


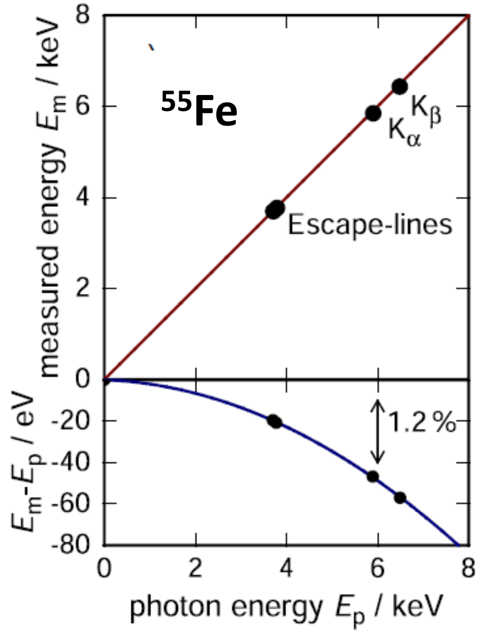
Operation over a large temperature range
→ operation of large arrays

Large dynamic range
→ no saturation of the signal

$$\Delta E_{FWHM} \sim 2.35\sqrt{4k_B T^2 C_e}\left(\frac{1}{\beta(1-\beta)}\frac{\tau_r}{\tau_d}\right)^{1/4}$$







Fast risetime
→ Reduction un-resolved pile-up

Extremely good energy resolution
→ identification of small structures

Excellent linearity
→ precise definition of the energy scale

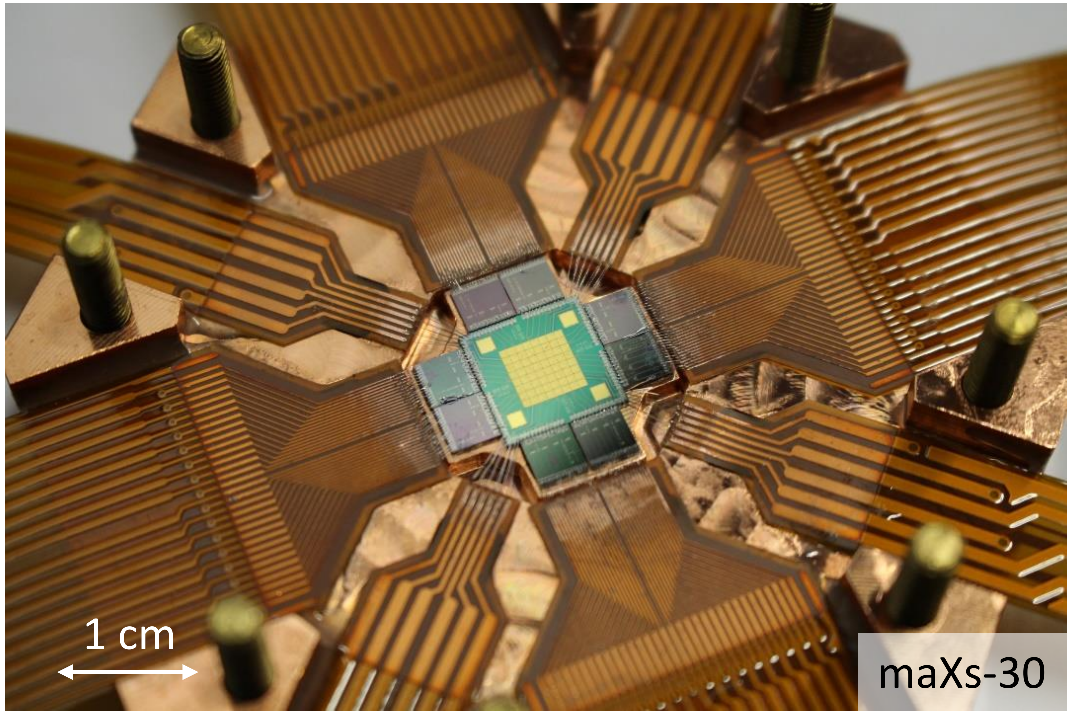
MMC fabrication

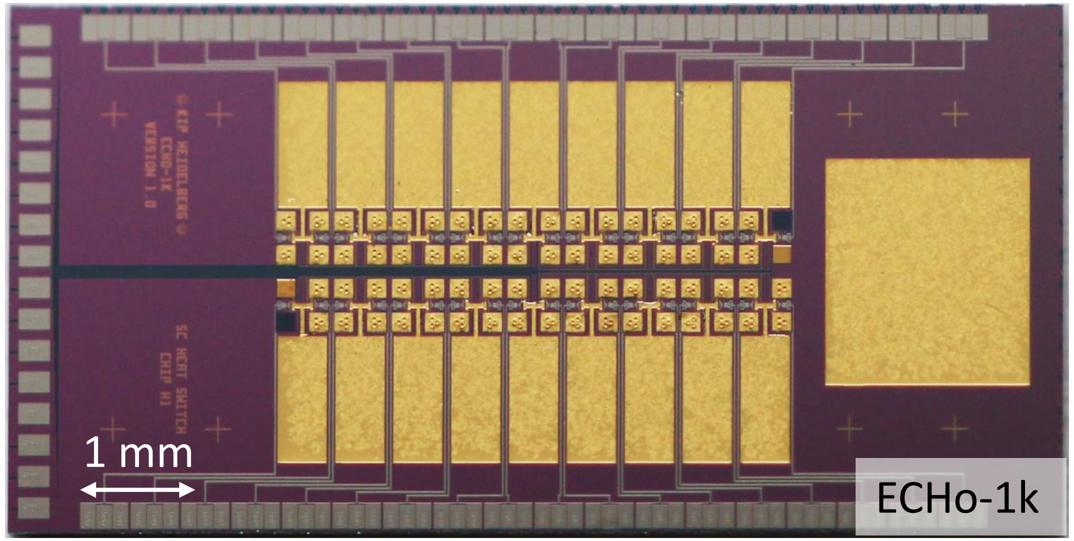
40 m^2 Cleanroom class 100
at Kirchhoff Institute for Physics

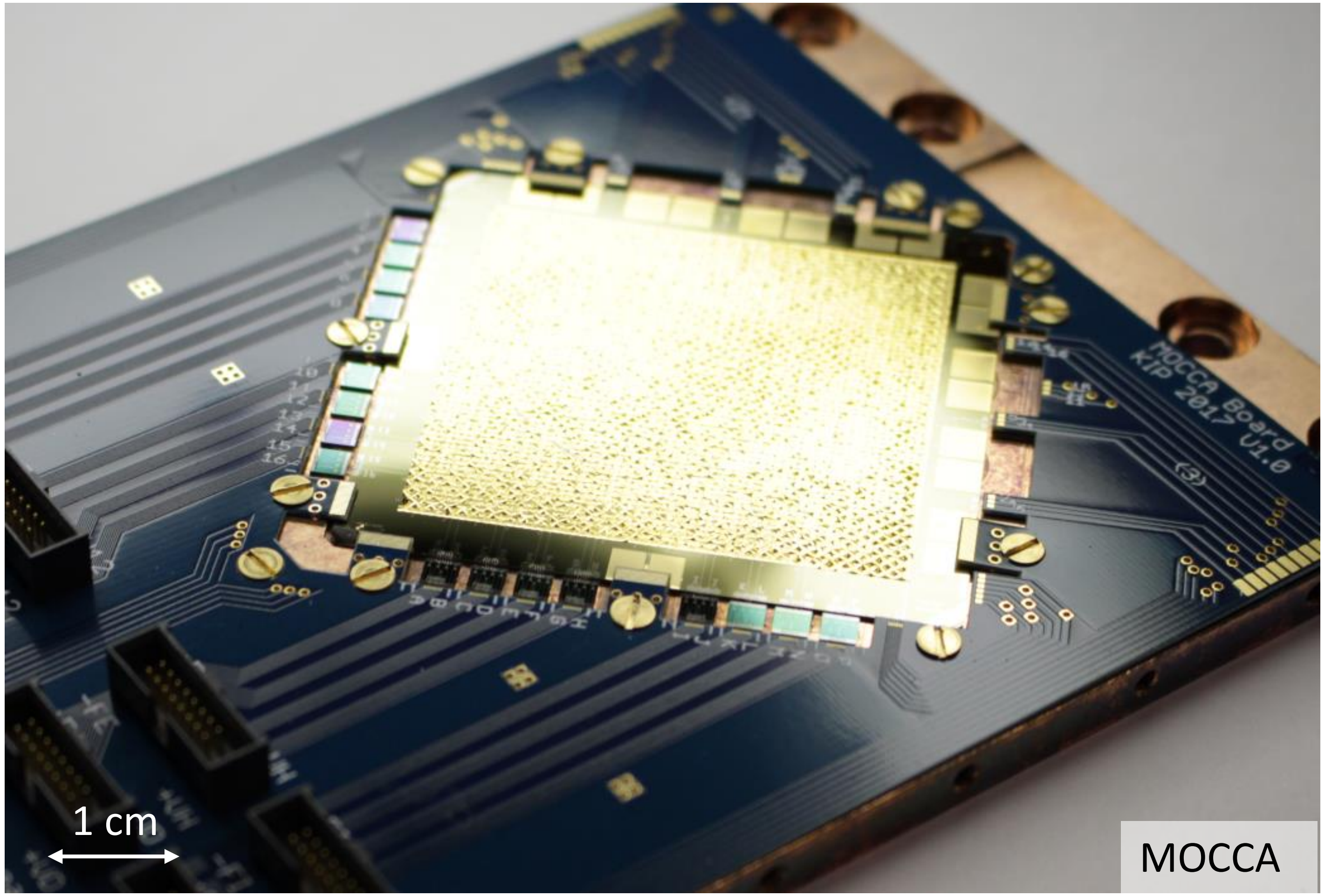
Wet bench
Chemistry bench
Maskless aligner
UHV sputtering system
Dry etching system

- Flexibility in design and fabrication
- Reliable processes for thin films
- Production of MMC array and superconducting electronics

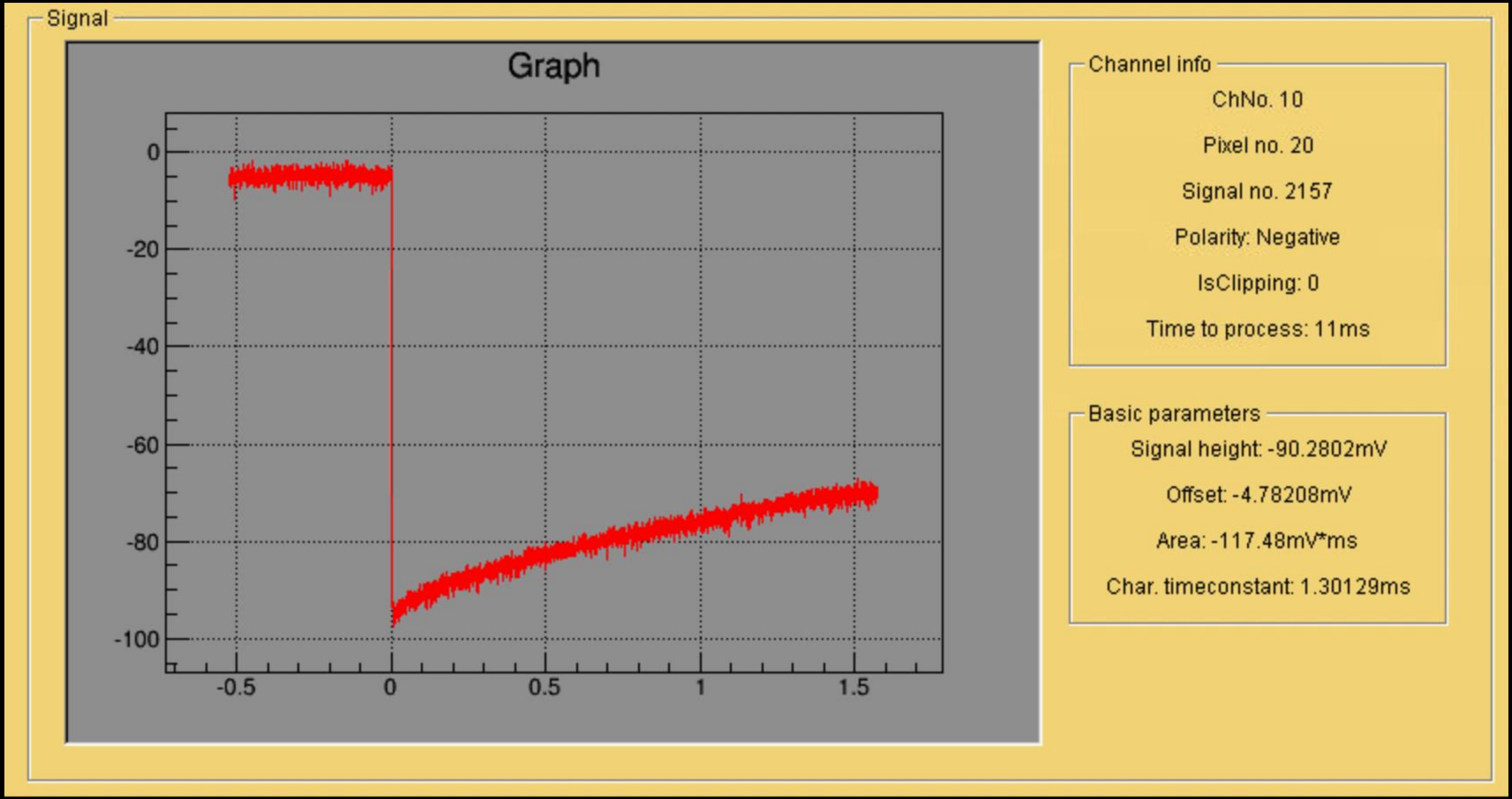
MMC Arrays







ECHo-1k data – Live!



mk temperatures

1/10000

Room Temperature → 30 mK

mk temperatures

1/10000

Room Temperature → 30 mK

Necessary instrumentation

Dilution refrigerators

Adiabatic demagnetization refrigerators

Before ~ 2000 Wet systems

“Complex systems”
Require liquid helium
continuous maintenance

Low temperature detectors mainly for “niche” experiment

mk temperatures

1/10000

Room Temperature → 30 mK

Necessary instrumentation

Dilution refrigerators

Adiabatic demagnetization refrigerators

Before ~ 2000 Wet systems

"Complex systems"
Require liquid helium
continuous maintenance

Low temperature detectors mainly for "niche" experiment

After ~ 2000 Dry system

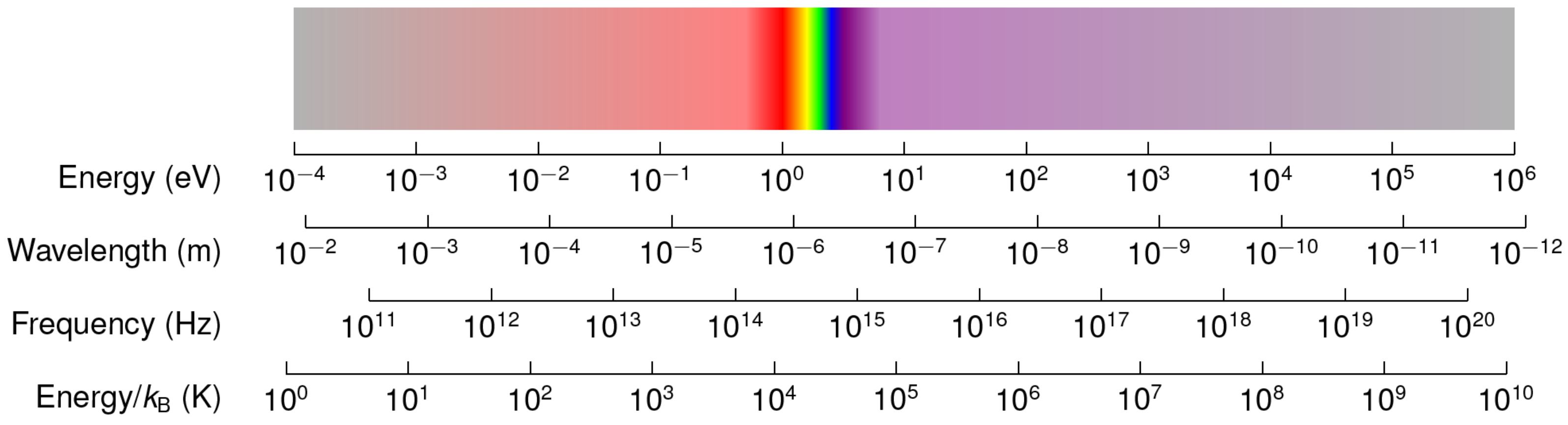
easier handling of operation
no liquid helium is required (even not liquid nitrogen)
possible full remote control – no maintenance

Low temperature detectors in many applications

Outline

- Basic of low temperature detectors
  - TES
  - MMC
- Overview on some applications
  - Photon detection
  - Neutrino physics
  - Search for Dark Matter interactions

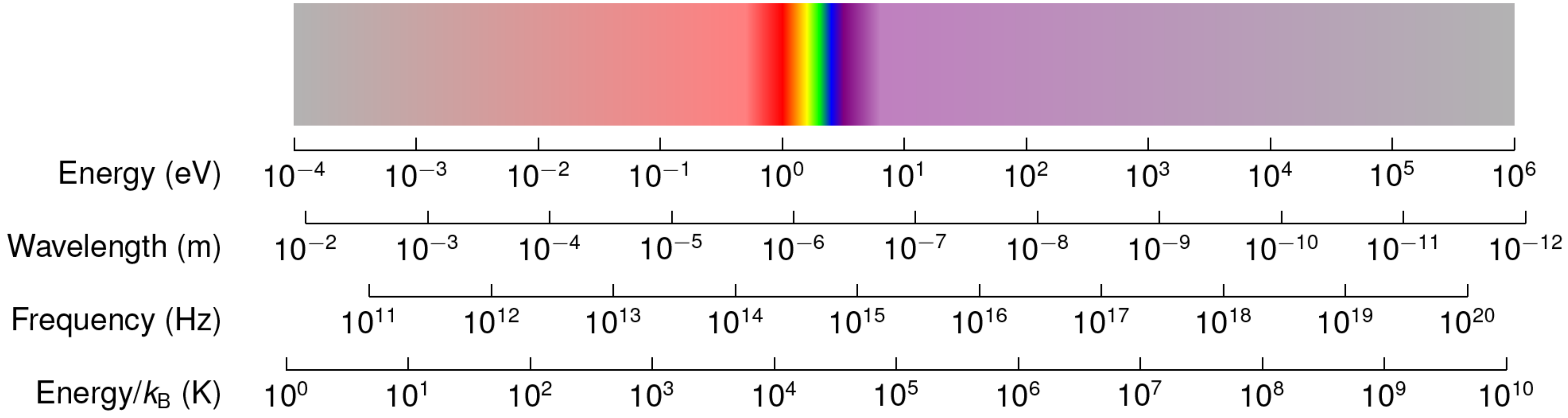
What can LTDs measure - Photons



What can LTDs measure - Photons

TES, mKID, Ge-thermistors, STJ

TES, MMC, Si- Ge- thermistors



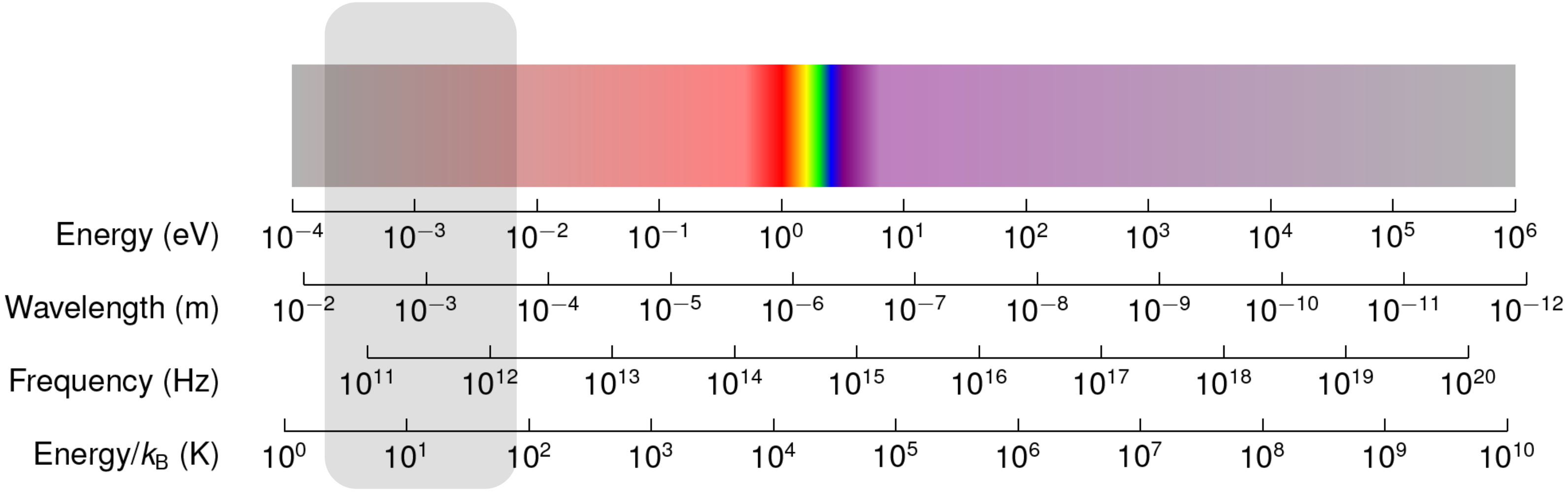
Astronomy
Cosmology

Quantum
information

Astrophysics
QED test
Material analysis
…

Nuclear
forensic

What can LTDs measure - Photons



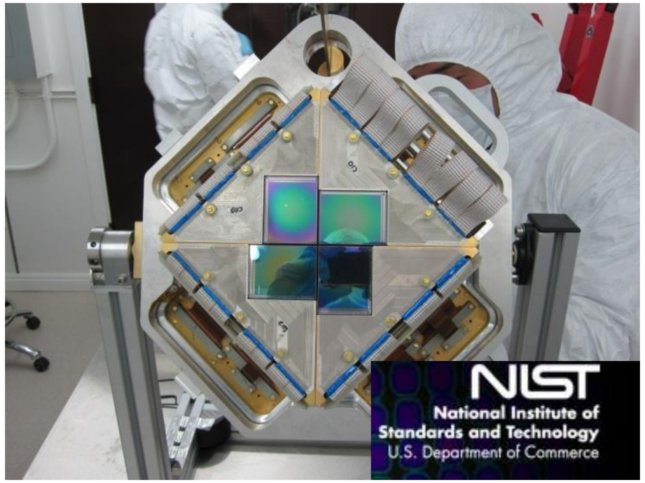
mm and sub-mm cameras

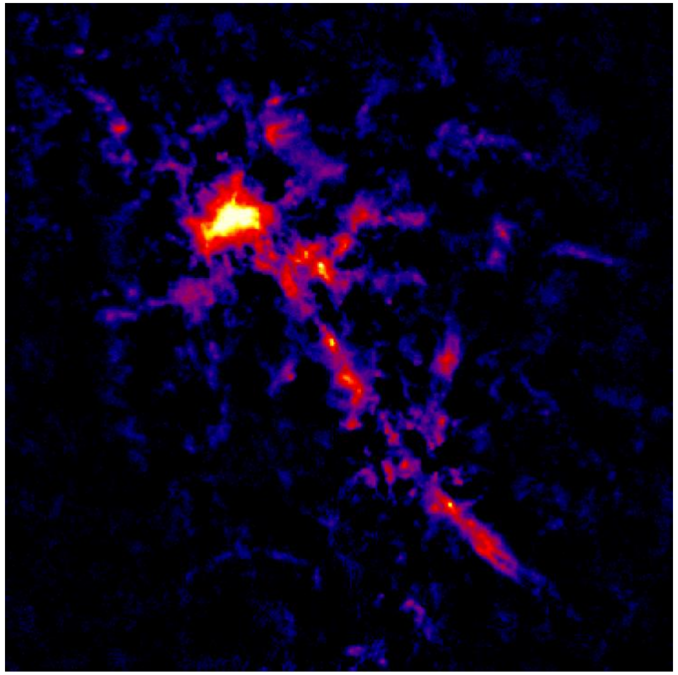
Astrophysics: studying the generation of stars and galaxies from cold gas

Cosmology: study of the Cosmic Microwave Background

SCUBA2 on the James Clerk Maxwell Telescope (JCMT)**:**

- Transition Edge Sensors, 10240 TESs @ T~50 mK
- 0.85 mm (352 GHz) and 0.45 mm (666 GHz)

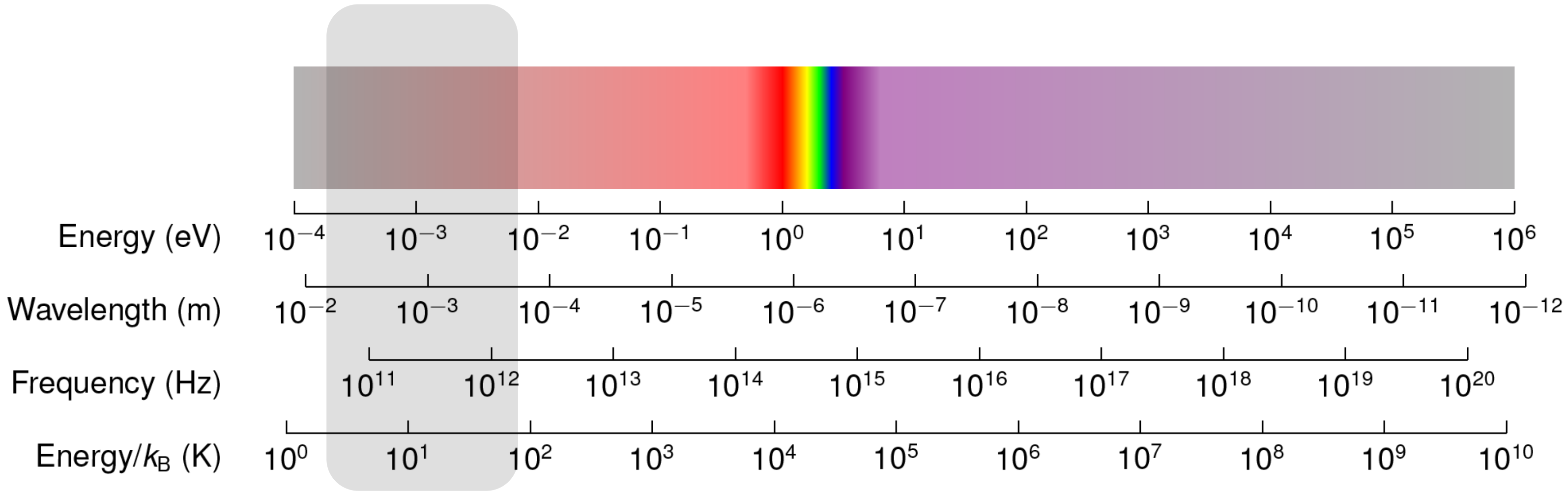




SCUBA2 map of the high-mass star forming region W51 at 850 um

W.S. Holland *Monthly Notices of the Royal Astronomical Society* 430/4 (2013) 2513

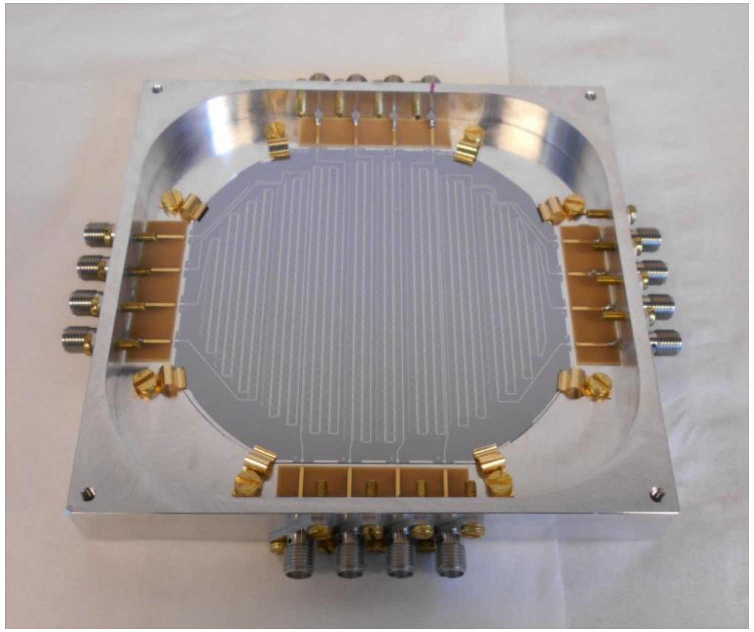
What can LTDs measure - Photons

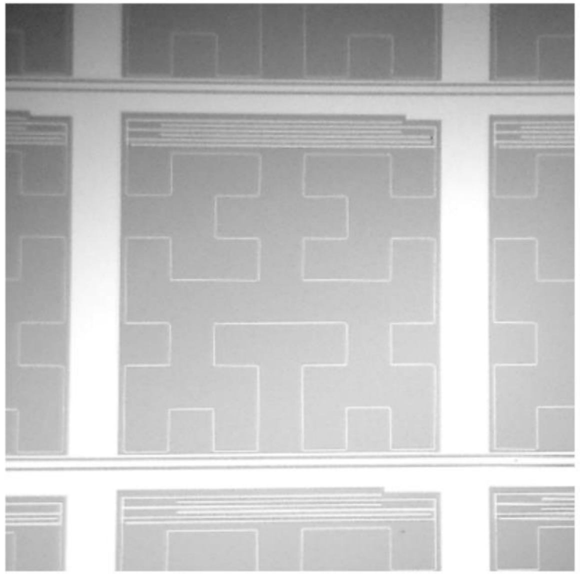


mm and sub-mm cameras

Astrophysics: studying the generation of stars and galaxies from cold gas

Cosmology: study of the Cosmic Microwave Background





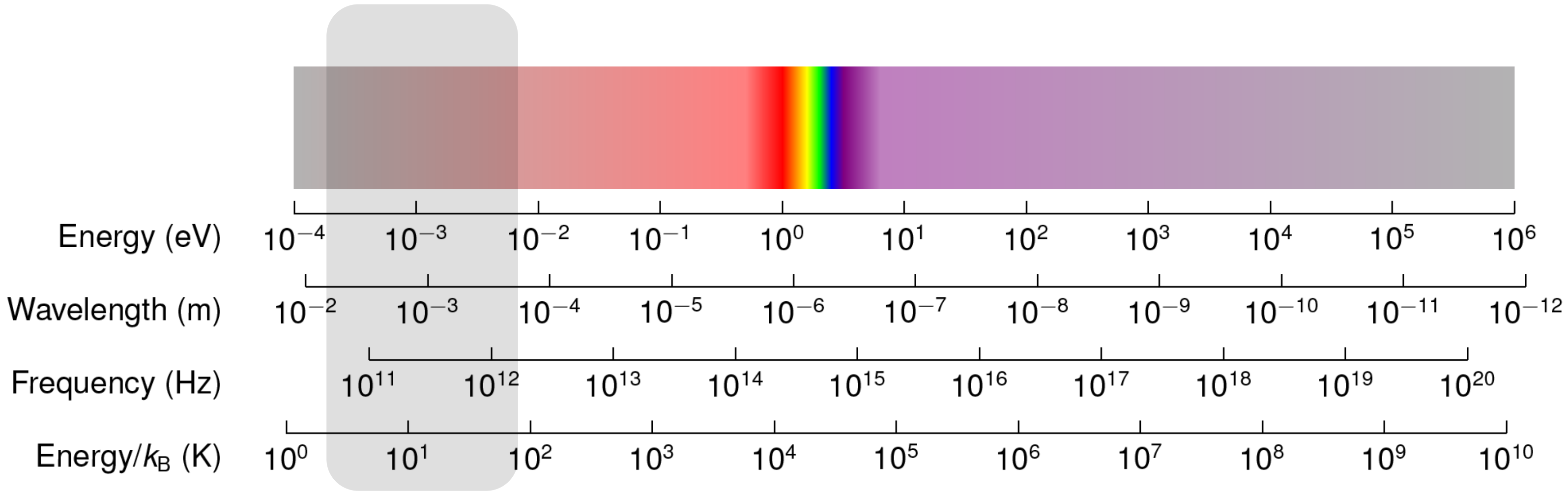
NIKA2 Al Lumped Elements KIDs

- Kinetic Inductance Detector, 2896 KIDs @ T~150 mK
- 2 mm (150 GHz) and 1.15 mm (260 GHz)

Pixel size $2.3 \times 2.3 mm^2$

R. Adam et al., A&A 609, A115 (2018)

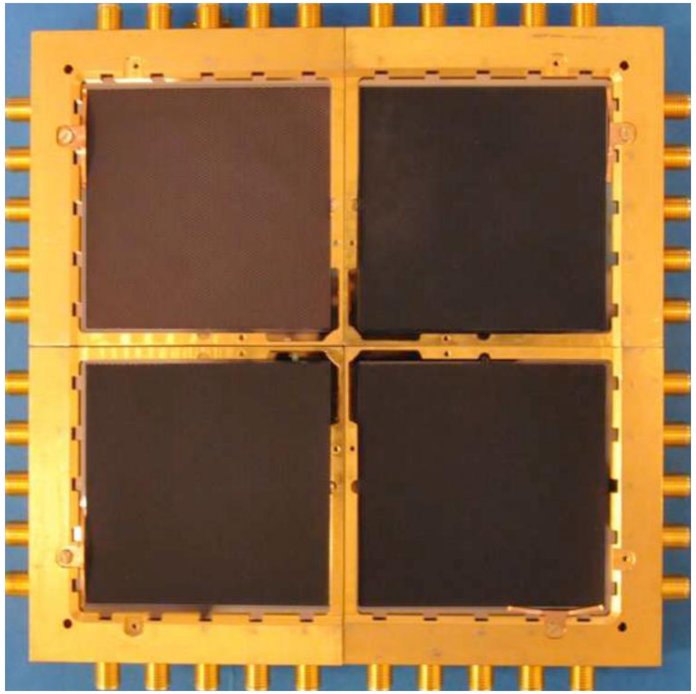
What can LTDs measure - Photons

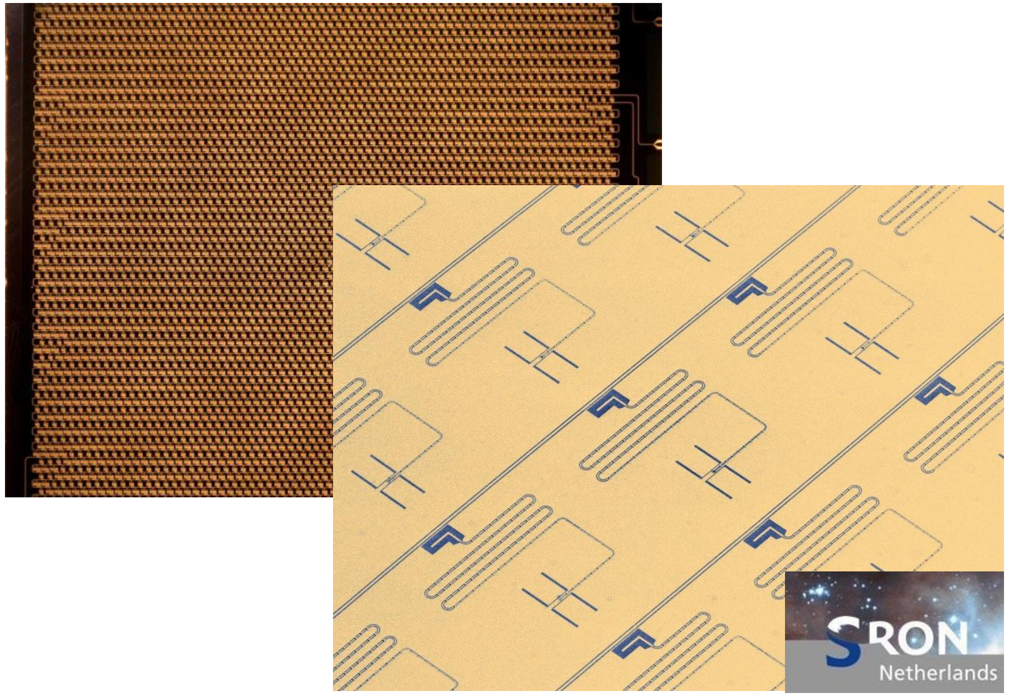


mm and sub-mm cameras

Astrophysics: studying the generation of stars and galaxies from cold gas

Cosmology: study of the Cosmic Microwave Background

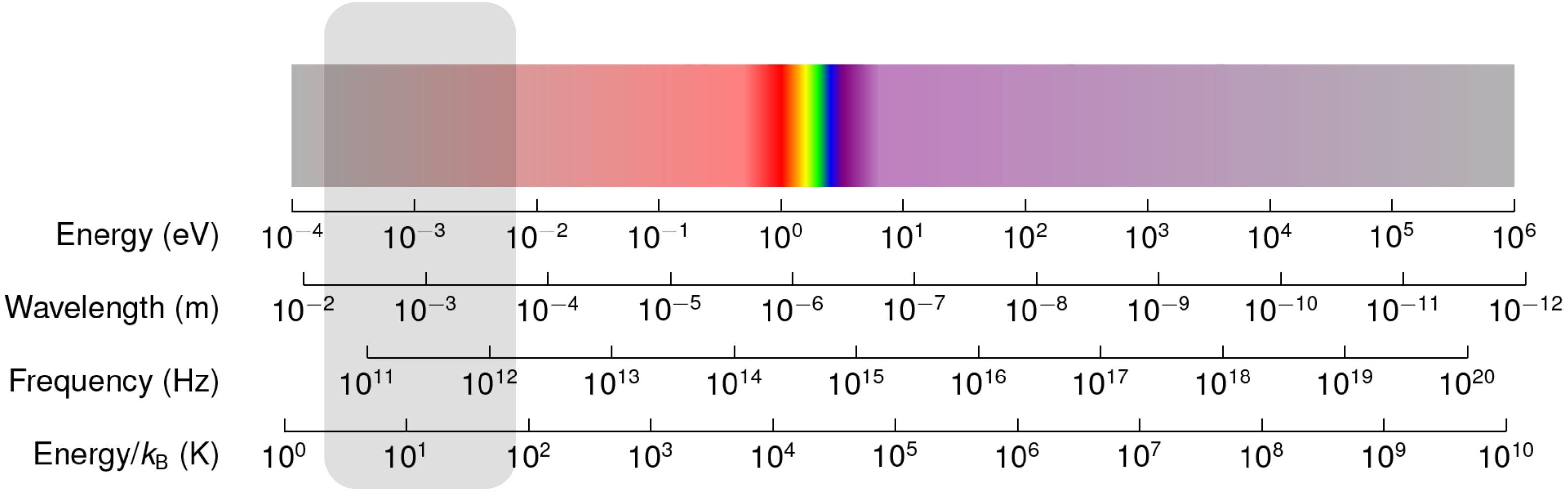




A-MKID (12 m APEX telescope Chile)

Two sub-mm bands (350 and 850 GHz)
Antenna-coupled KID:
- 3,500 pixels @ 0.85mm
- 20,000 pixels @ 0.35mm

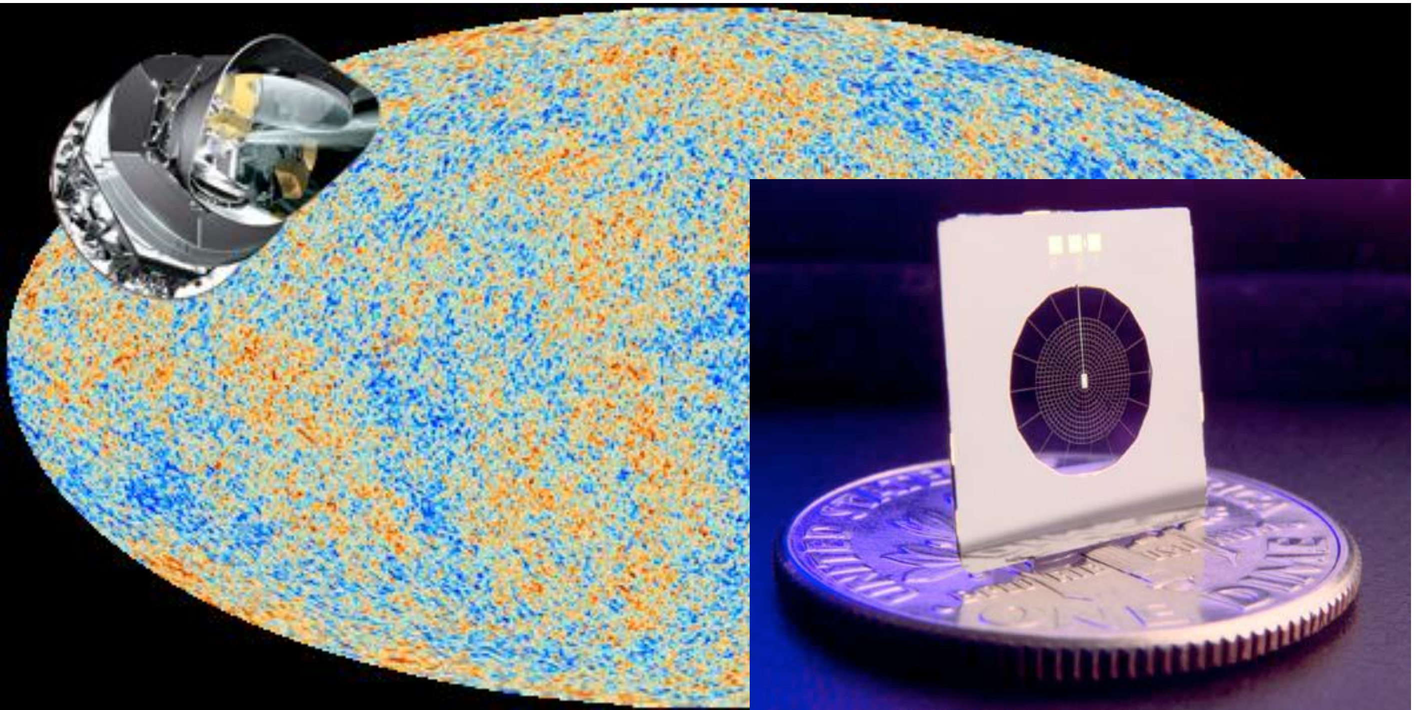
What can LTDs measure - Photons



mm and sub-mm cameras

Astrophysics: studying the generation of stars and galaxies from cold gas

Cosmology: study of the Cosmic Microwave Background

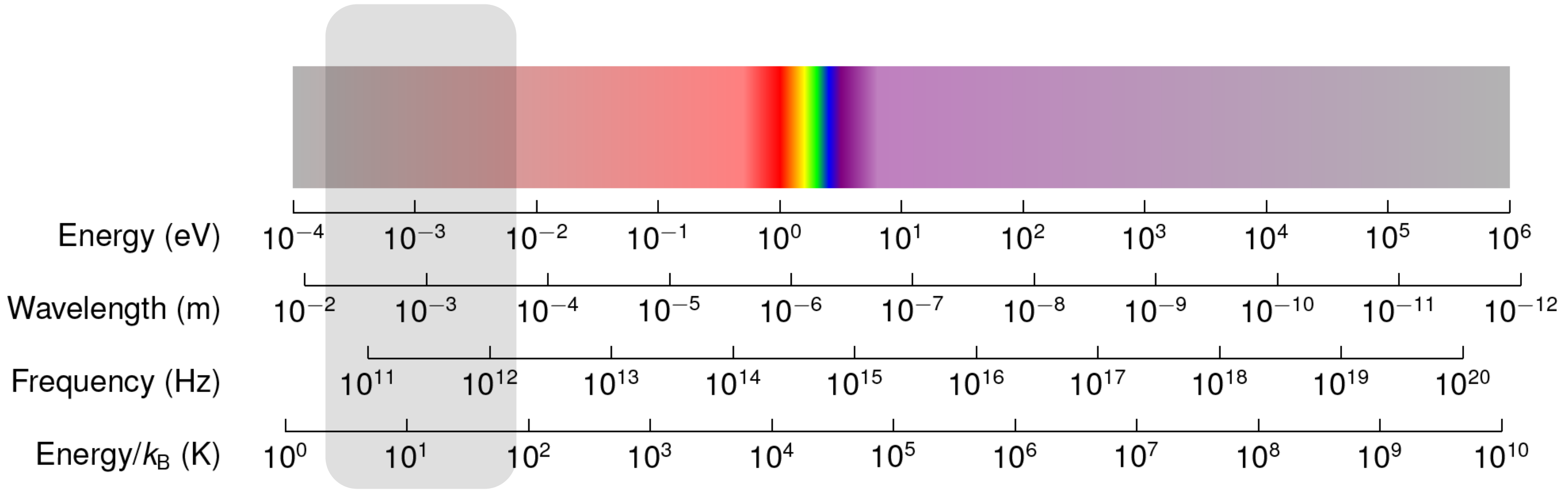


Planck Satellite

High-Frequency Instrument (HFI):
54 Spiderweb absorber coupled to NTD-Ge bolometers (100mK) for the frequency range 100–857 GHz.

Jet Propulsion Laboratory (JPL)

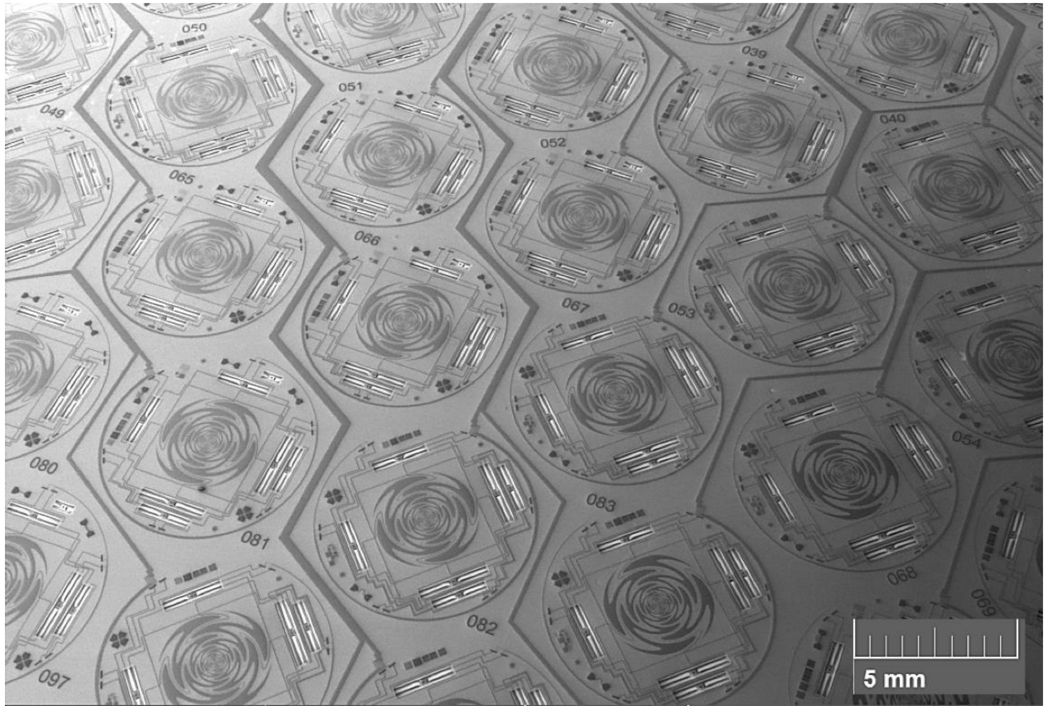
What can LTDs measure - Photons



mm and sub-mm cameras

Astrophysics: studying the generation of stars and galaxies from cold gas

Cosmology: study of the Cosmic Microwave Background



CMB-S4: next-generation ground-based CMB experiment based on antenna coupled TES:

- ~ 500000 detectors (30 - 300 GHz)
- multiple telescopes and sites to map ≳70% of sky

Detector development follows work done in
ACT (Aiola et al. 2020)
BICEP/Keck (BICEP2/Keck Array Collaborations X 2018)
CLASS (Harrington et al. 2016)
POLARBEAR/Simons Array (Suzuki et al. 2016; Hasegawa et al.2018)
SPT (Bender et al. 2018; Sayre et al. 2020)

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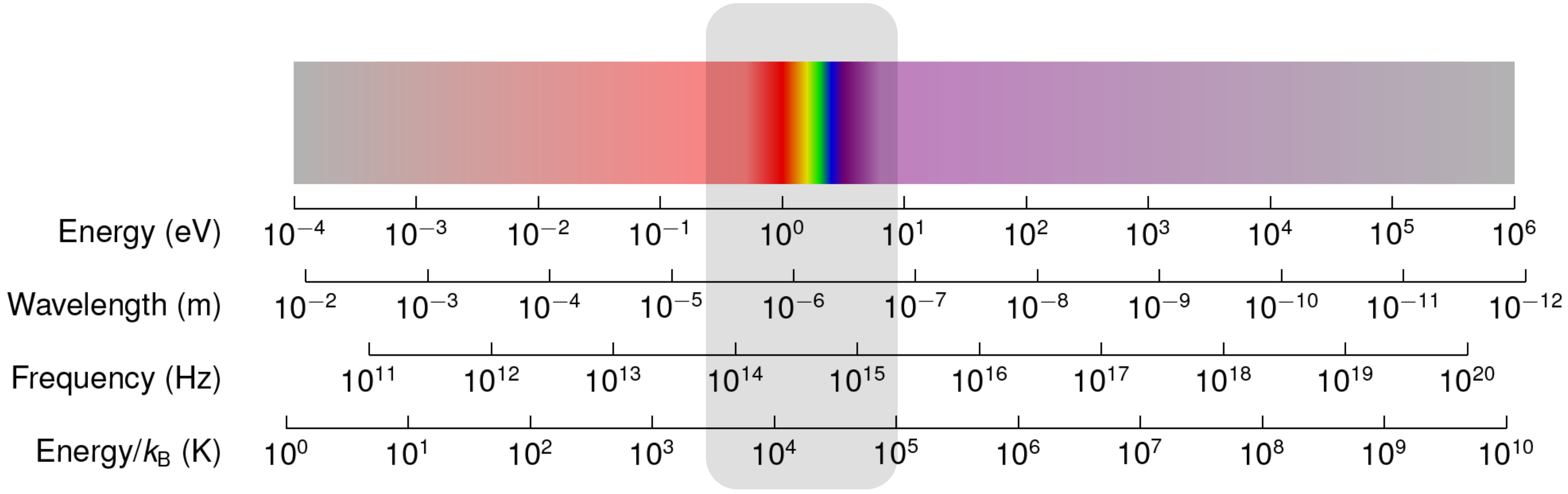
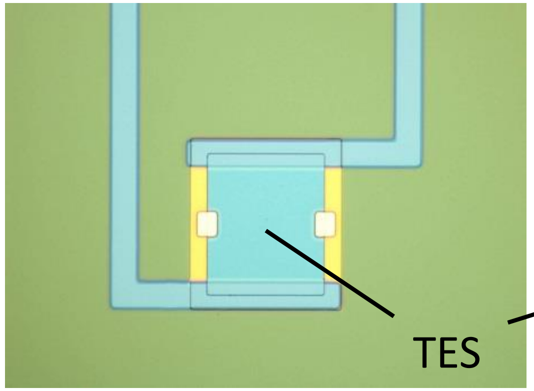


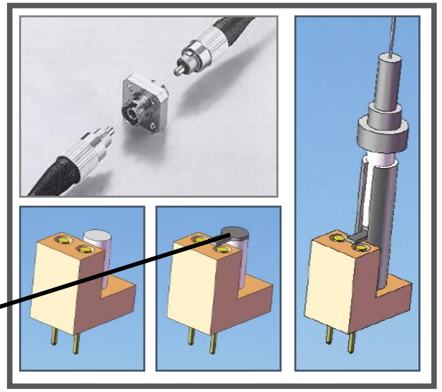
mm and sub-mm cameras

Detection of single NIR and visible photons

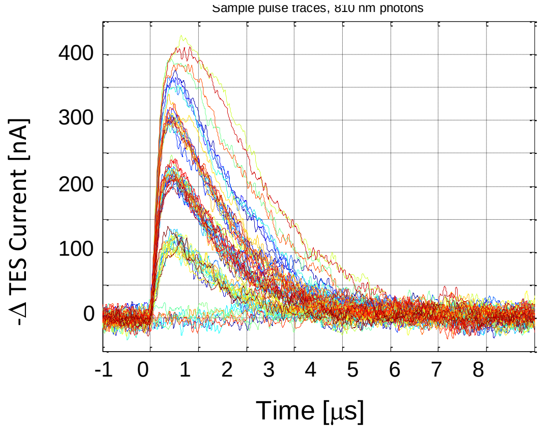
Fibre-coupled TES - quantum cryptography

Detection efficiency close to 100%



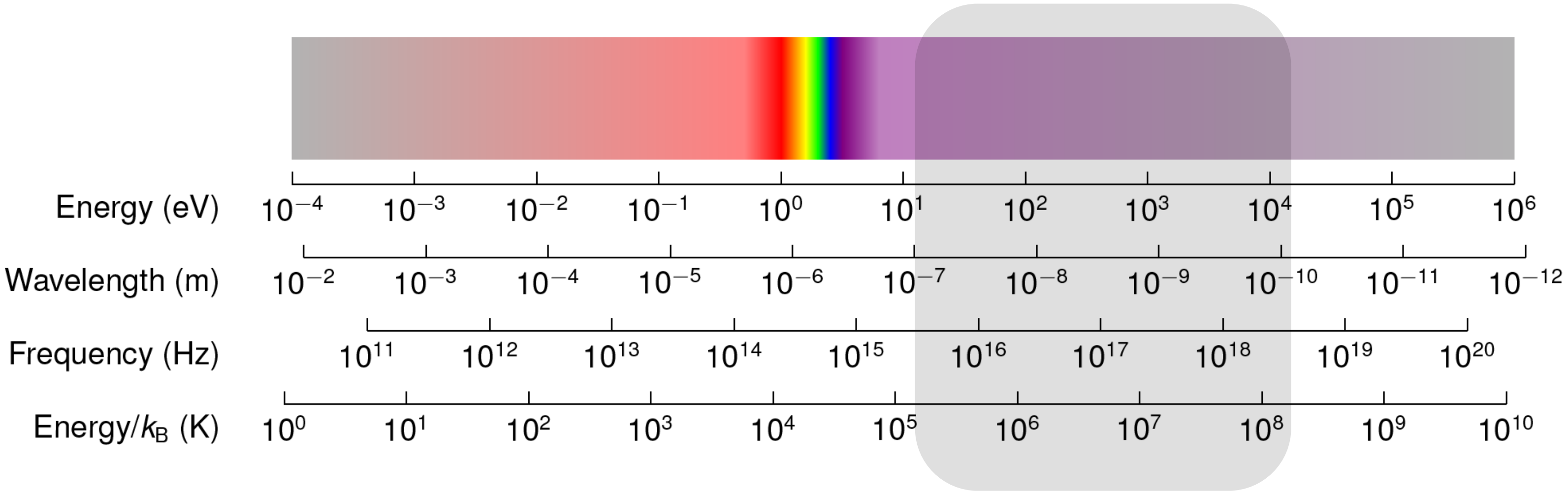


Sample pulse traces, 810 nm photons

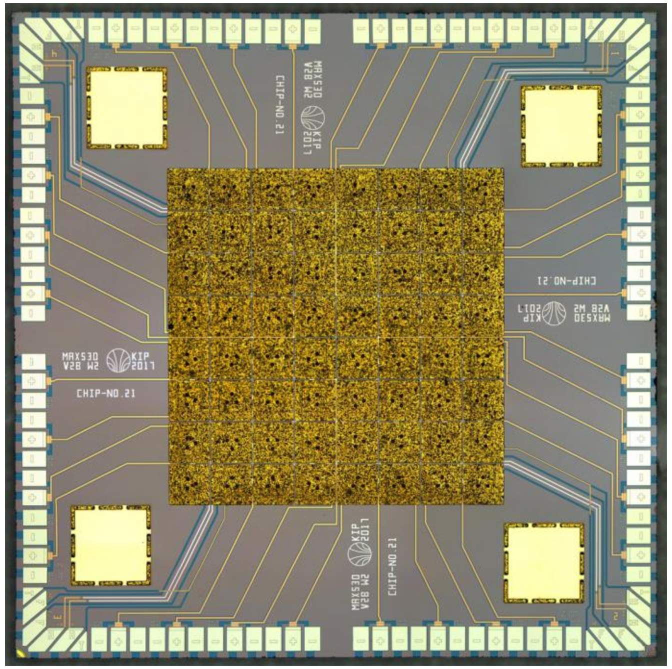


A.E. Lita et al., Optics Express. 16 (5): 3032

What can LTDs measure - Photons

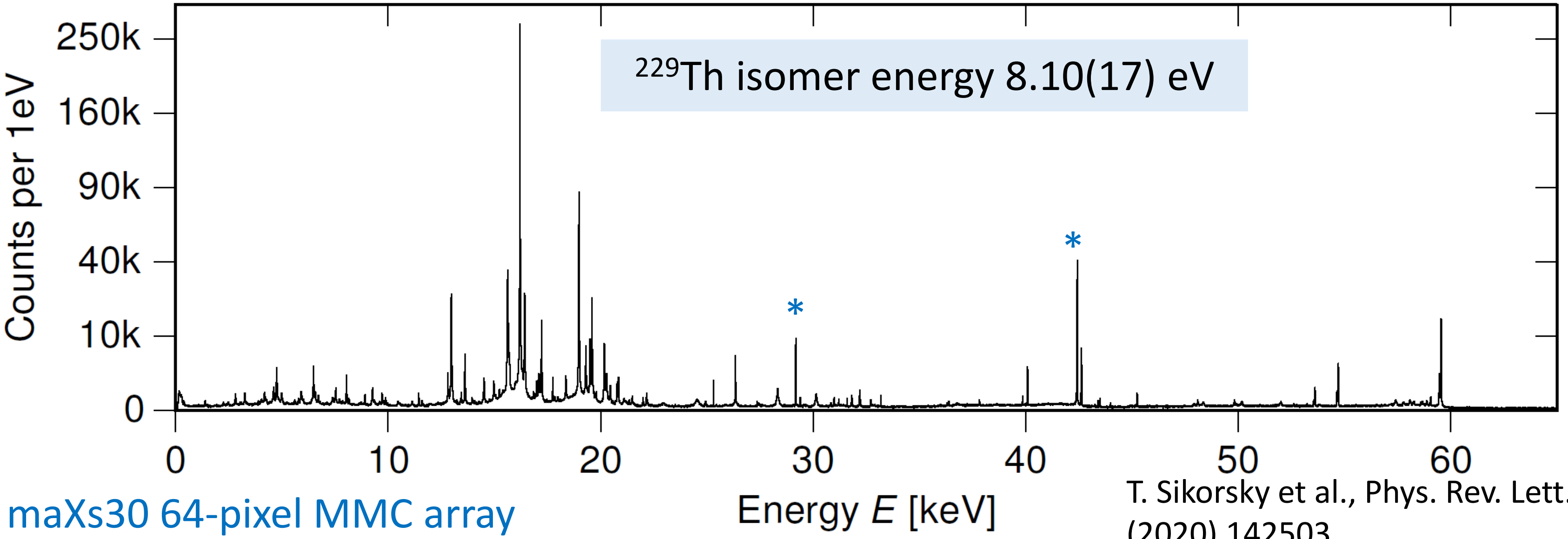


Single x-ray photons
atomic physics, astronomy, material analysis



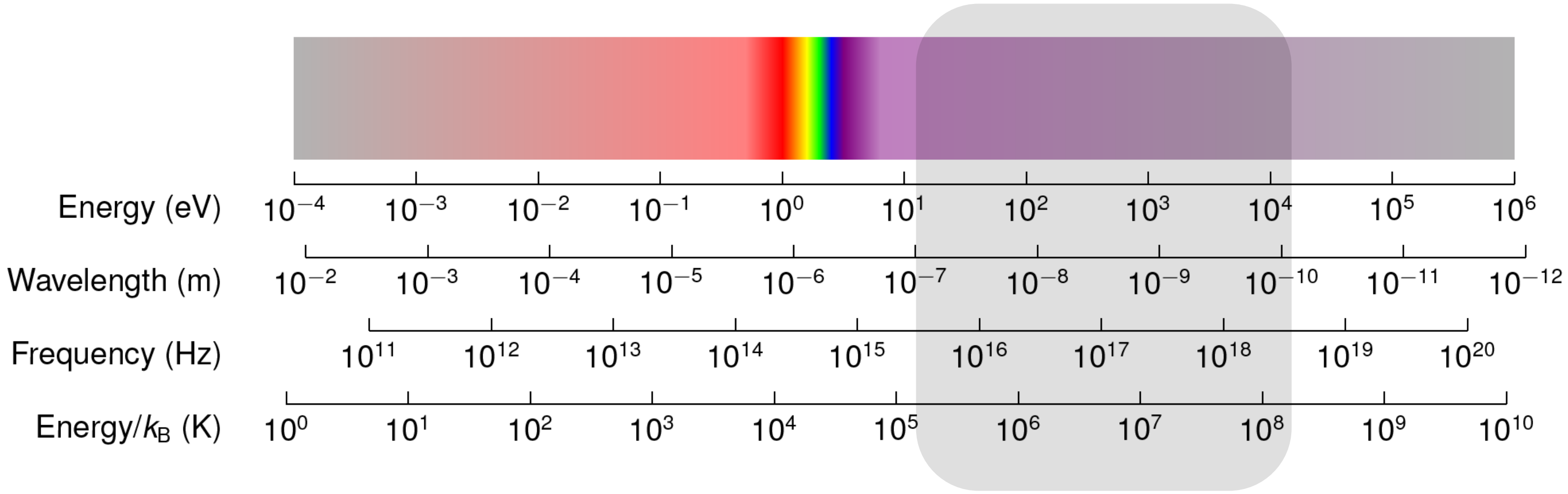
maXs30 64-pixel MMC array

^{233}U + ^{241}Am spectrum



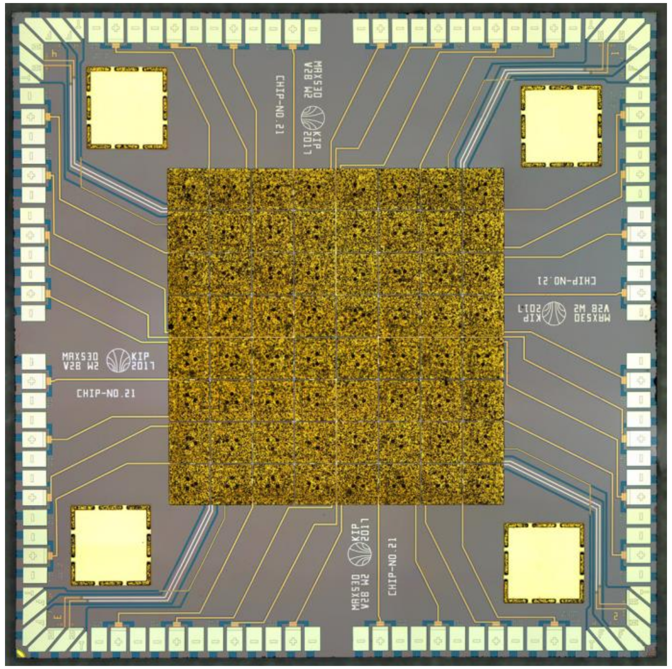
T. Sikorsky et al., Phys. Rev. Lett. 125 (2020) 142503

What can LTDs measure - Photons



Single x-ray photons

atomic physics, astronomy, material analysis



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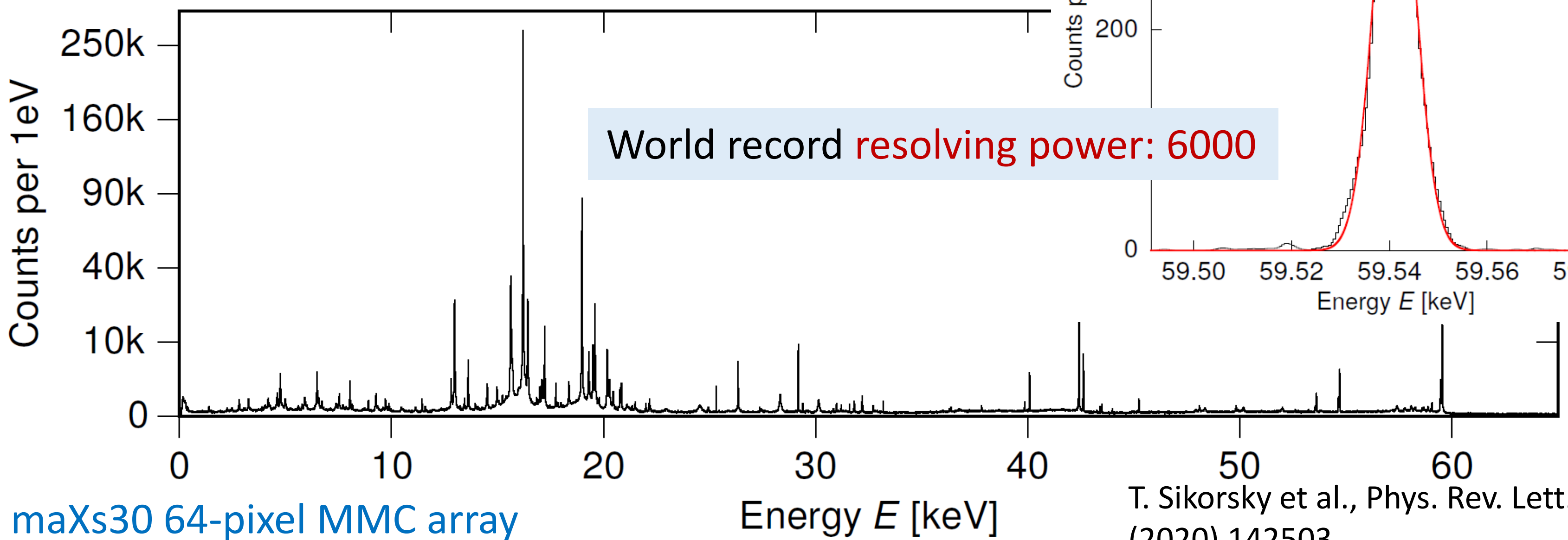
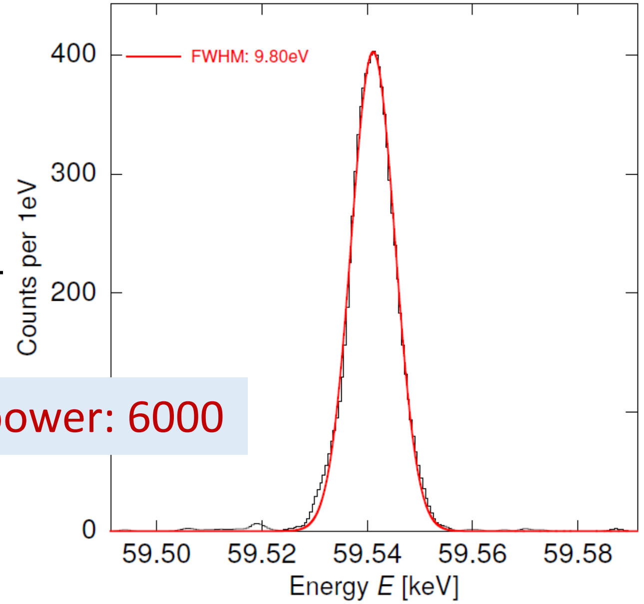
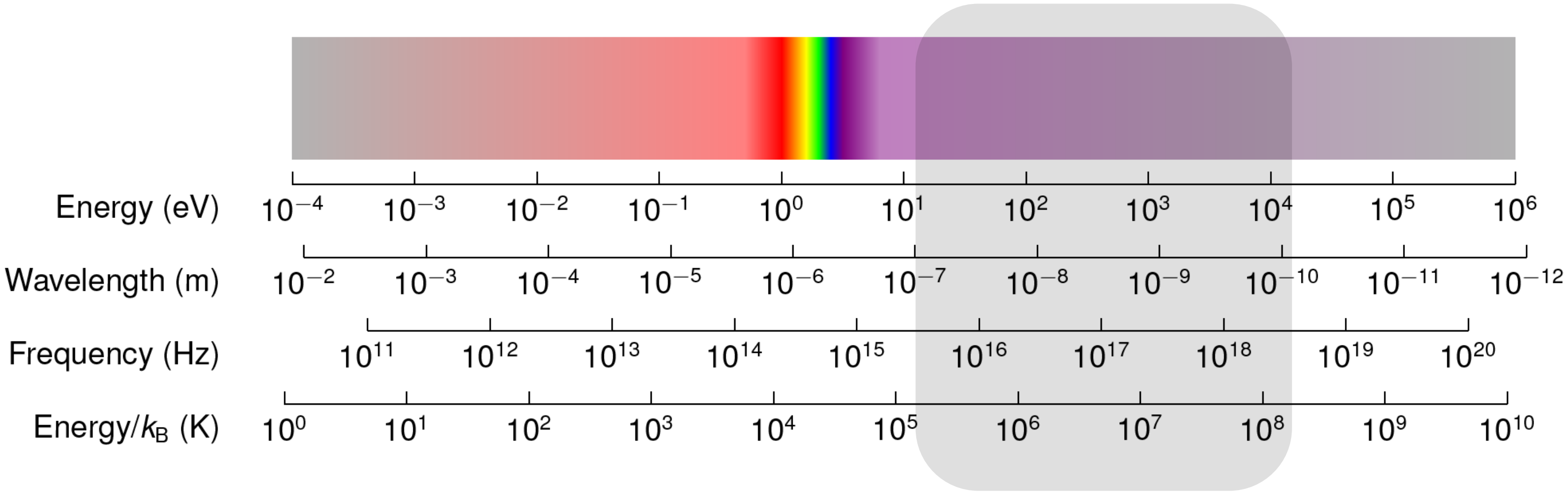




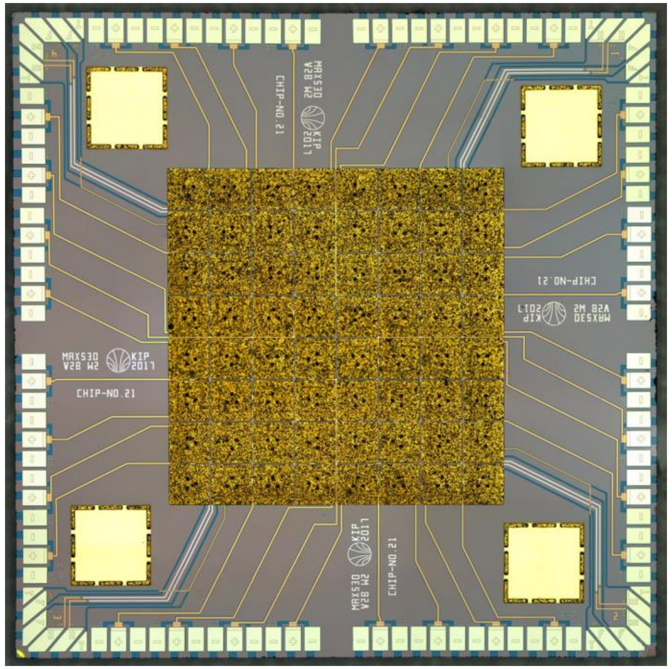
World record resolving power: 6000

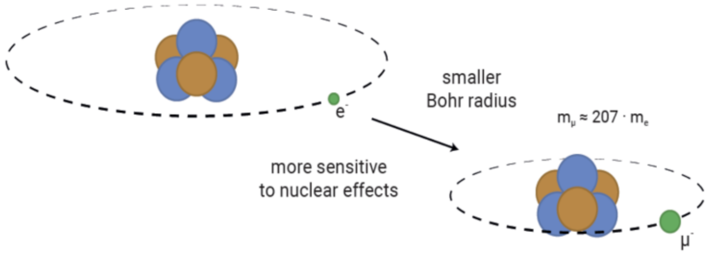
T. Sikorsky et al., Phys. Rev. Lett. 125 (2020) 142503

What can LTDs measure - Photons



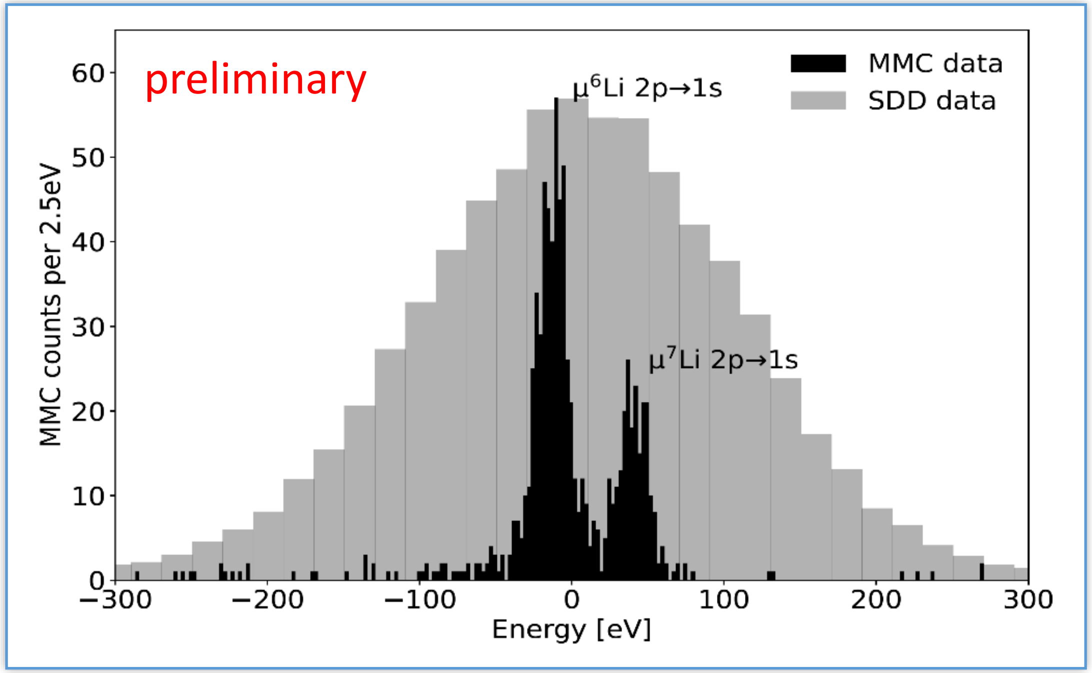
Single x-ray photons
atomic physics, astronomy, material analysis



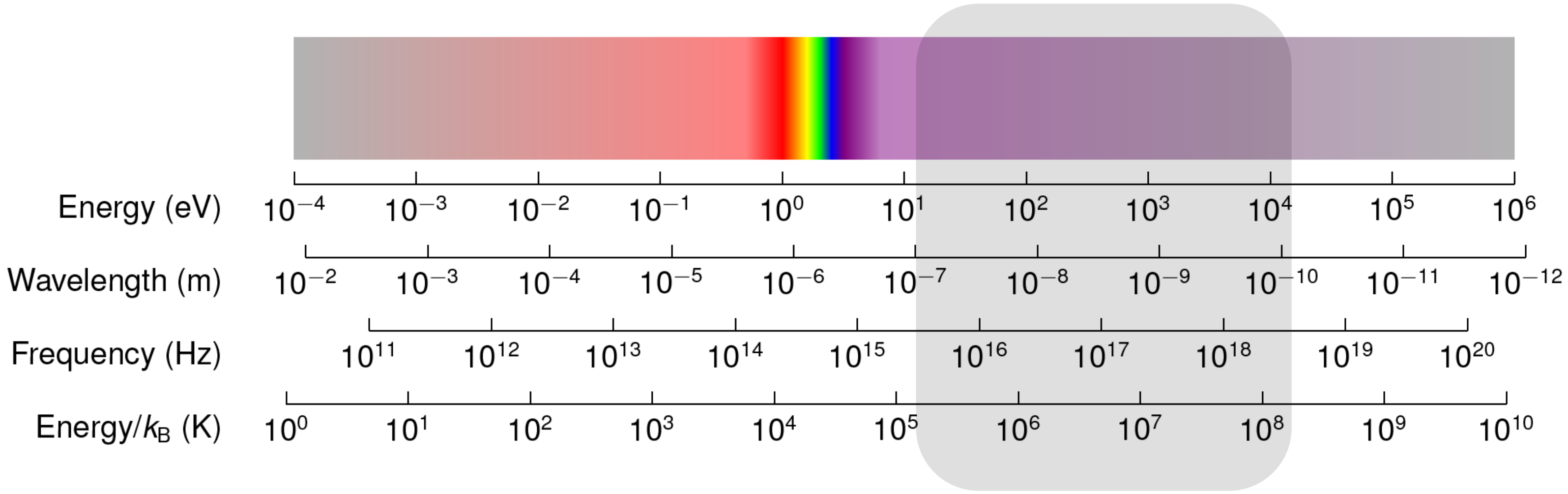


Muonic atoms spectroscopy

maXs30 64-pixel MMC array



What can LTDs measure - Photons



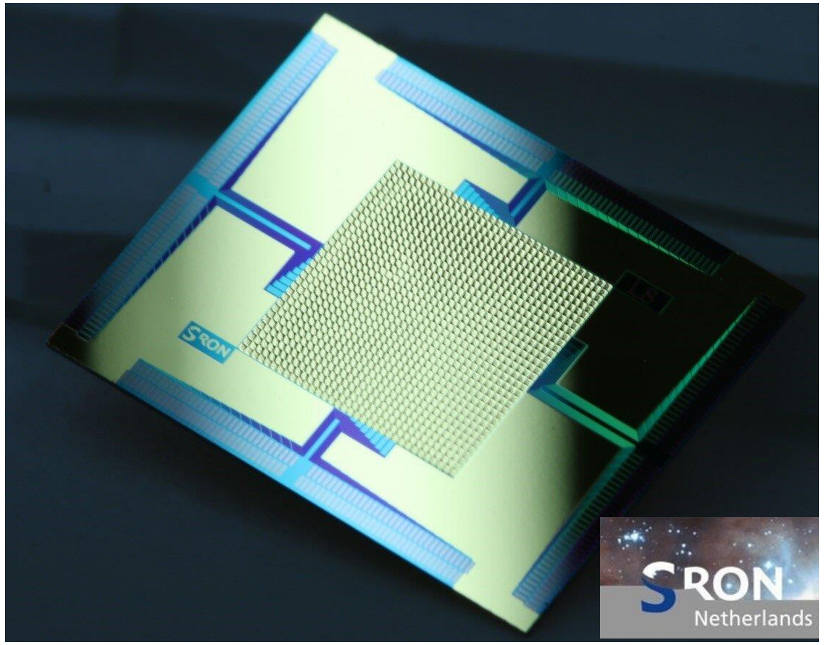
Single x-ray photons

atomic physics, astronomy, material analysis

32×32 pixel x-ray camera for the X-IFU

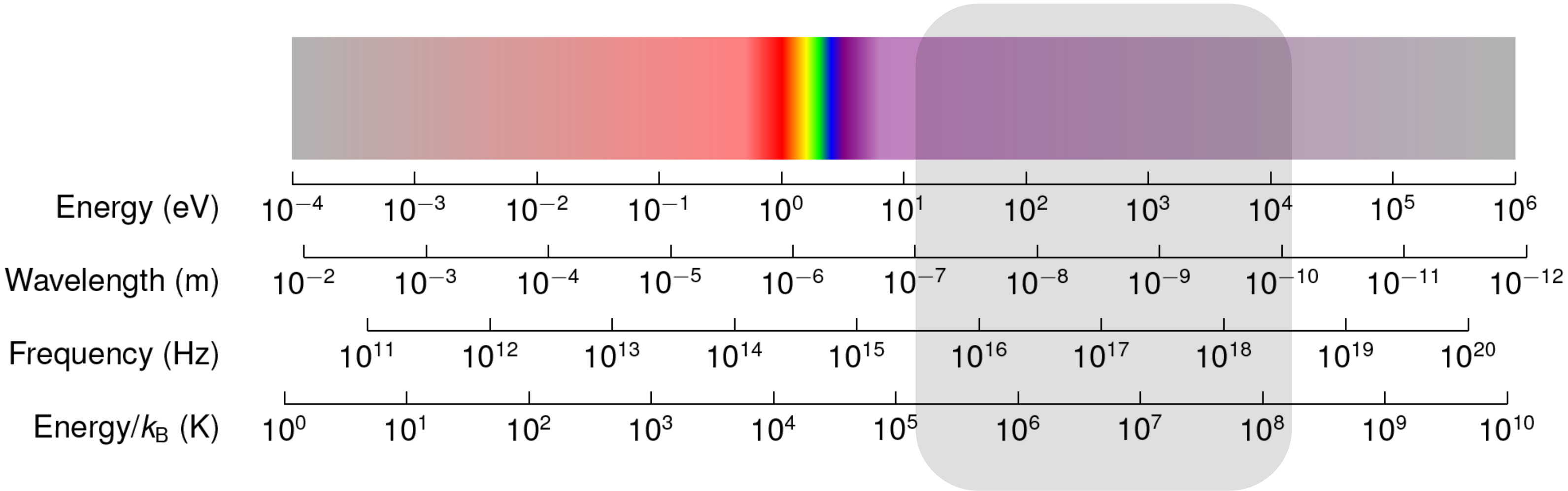
Cryogenic spectrometer, energy band 0.2 – 12 keV

Au absorbers + Ti(35nm)Au(200nm) bilayer → Tc~ 90mK



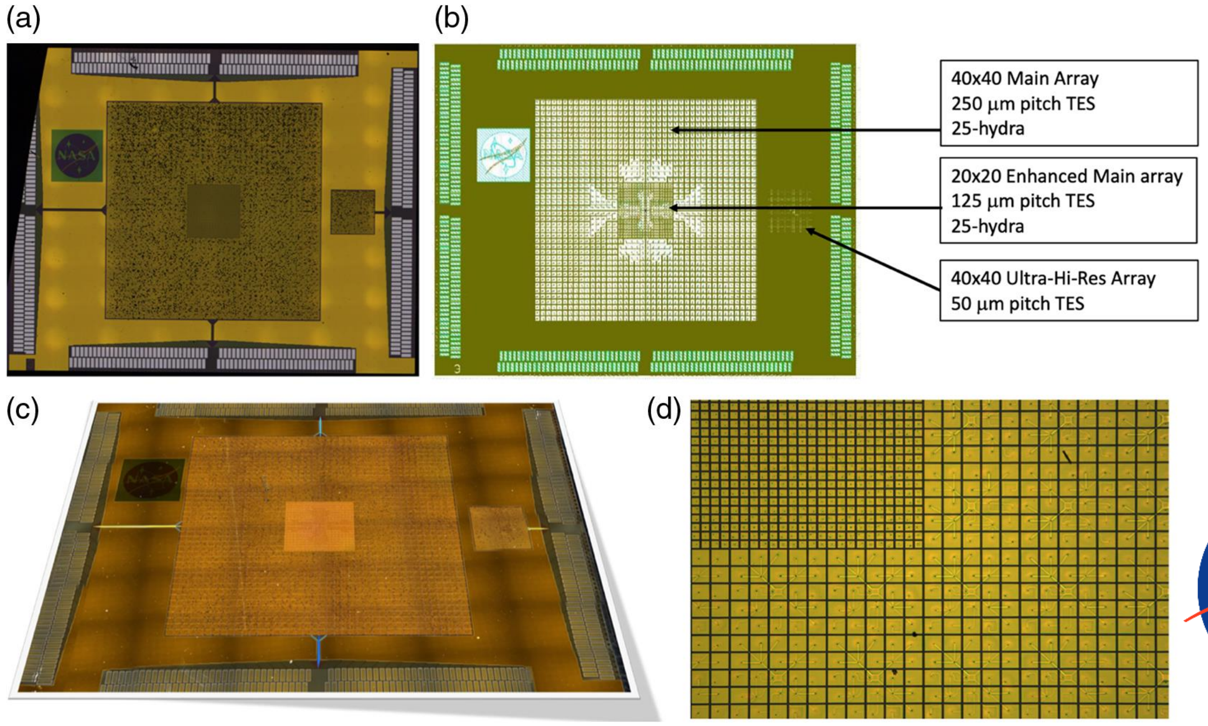
Nagayoshi et al, J. Low Temp. Phys. 199, 2019

What can LTDs measure - Photons



Single x-ray photons

atomic physics, astronomy, material analysis

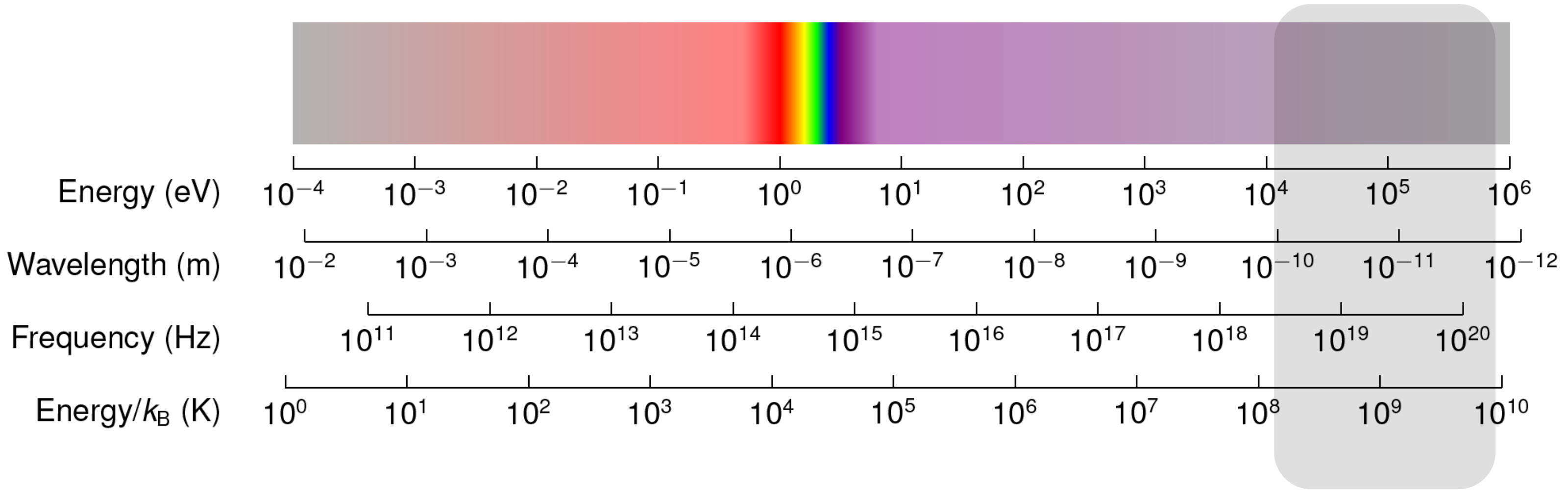


Lynx x-ray microcalorimeter (LXM)

TES (MMC as alternative)

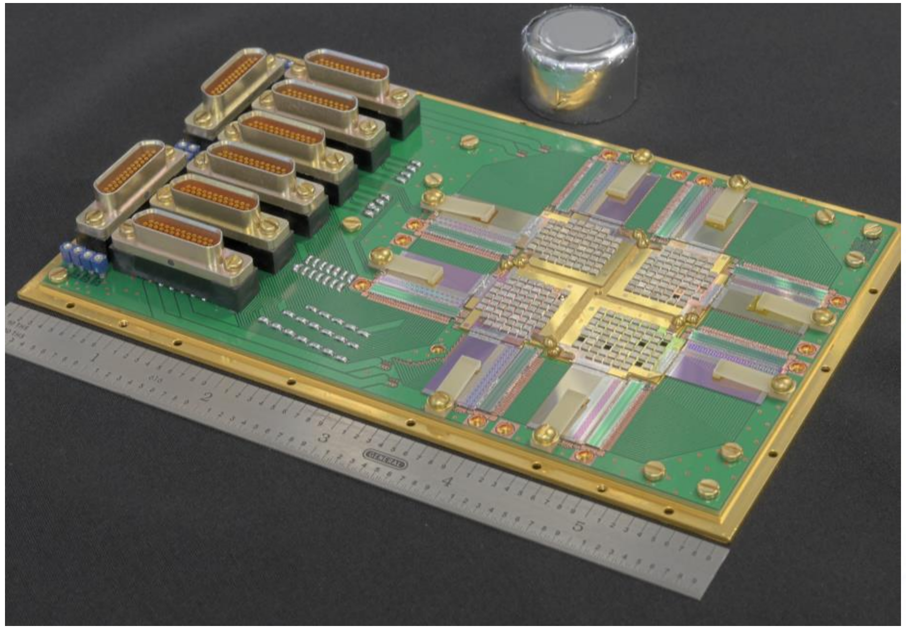
S. R. Bander et al., J. of Astronomical Telescopes, Instruments, and Systems, 5(2), 021017 (2019)

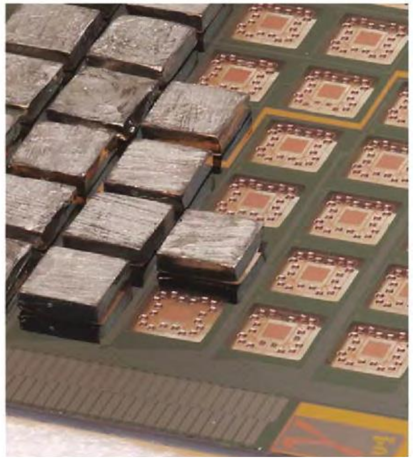
What can LTDs measure - Photons

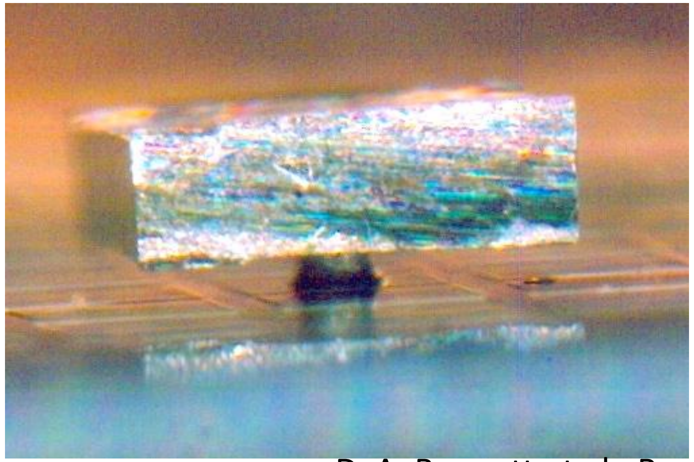


γ- and (α-)detectors

homeland security and nuclear non-proliferation

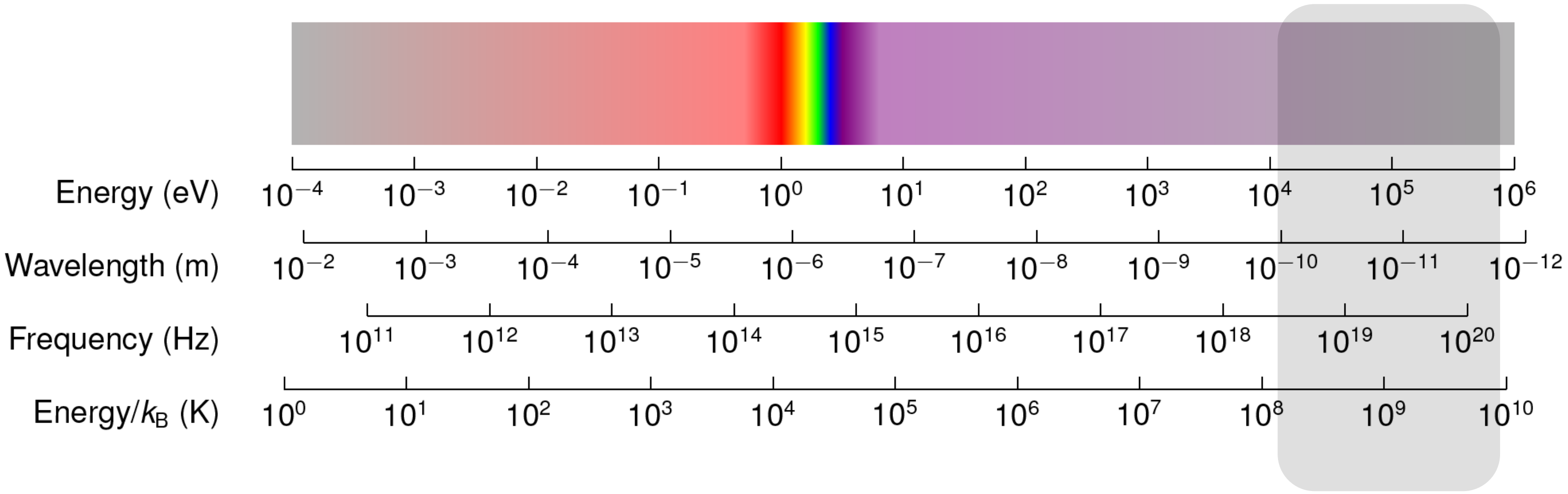






D. A. Bennett et al., Rev. Sci. Instrum. 83 (2012) 093113

What can LTDs measure - Photons



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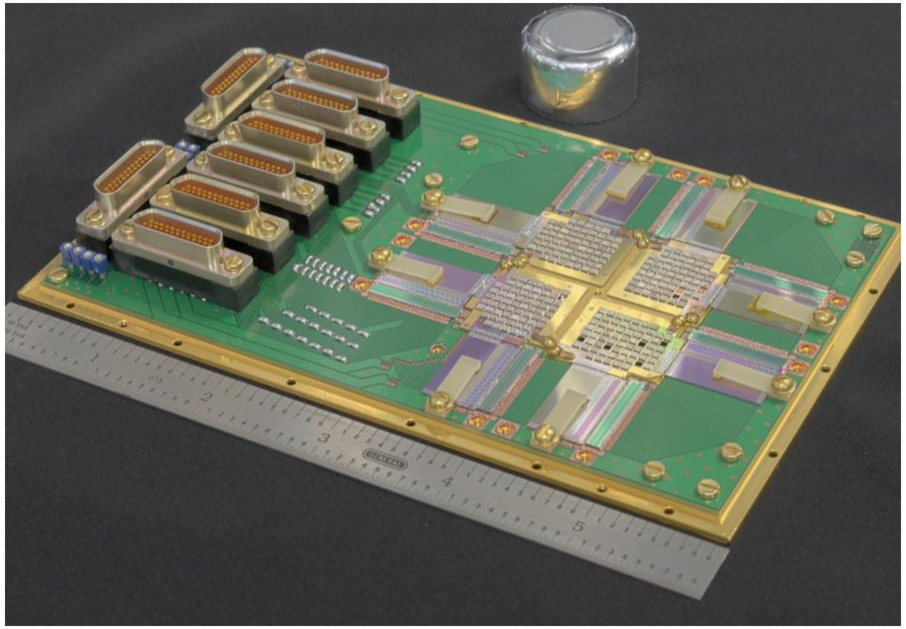
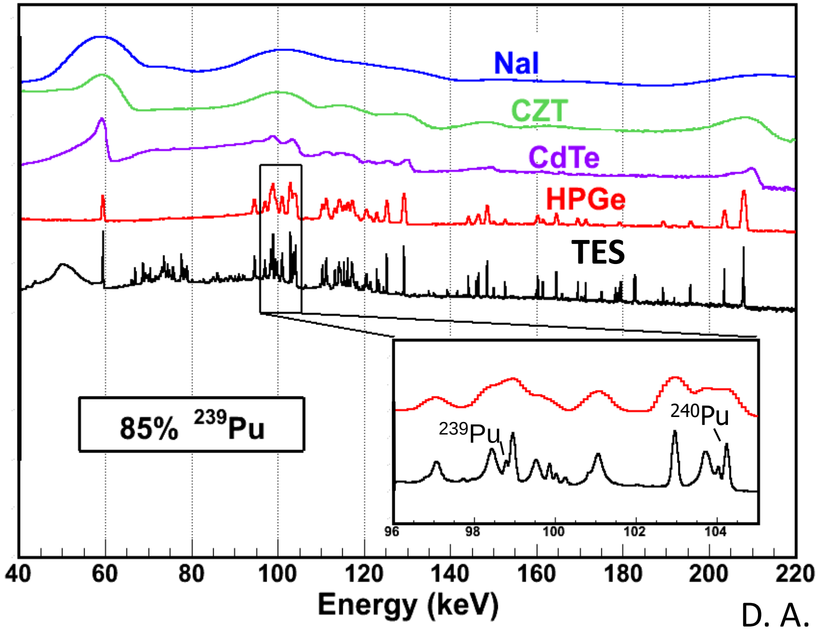




More than a factor 10 better resolving power than typical semiconductor detector

D. A. Bennett et al., Rev. Sci. Instrum. 83 (2012) 093113

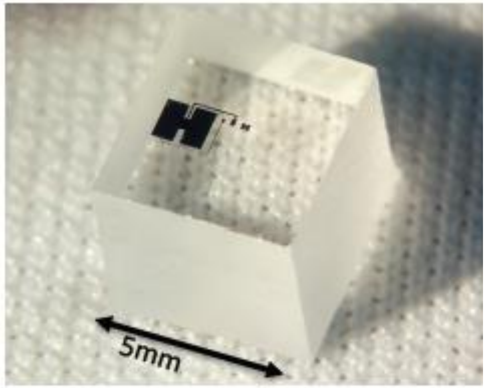
What can LTDs measure – not only photons

Low temperature detector for Neutrino Physics

Neutrinoless double beta decay — CUORE, AMoRE, CUPID

Coherent neutrino nucleus scattering — NuCLEUS (TES), Ricochet (TES), BullKID (mKID)

Neutrino interaction induces a nuclear recoil



R. Strauss et al.,*Eur.Phys.J.C* 79 (2019) 12, 1018

Sterile neutrino searches — BeEST (Ta-based STJ)

nuclear recoil following electron capture in ^{7}Be

Fretwell et al., Phys. Rev. Lett. 125, 032701 (2020)

kink in H-3 beta spectrum with LiF + MMC (Exp. in Korea)

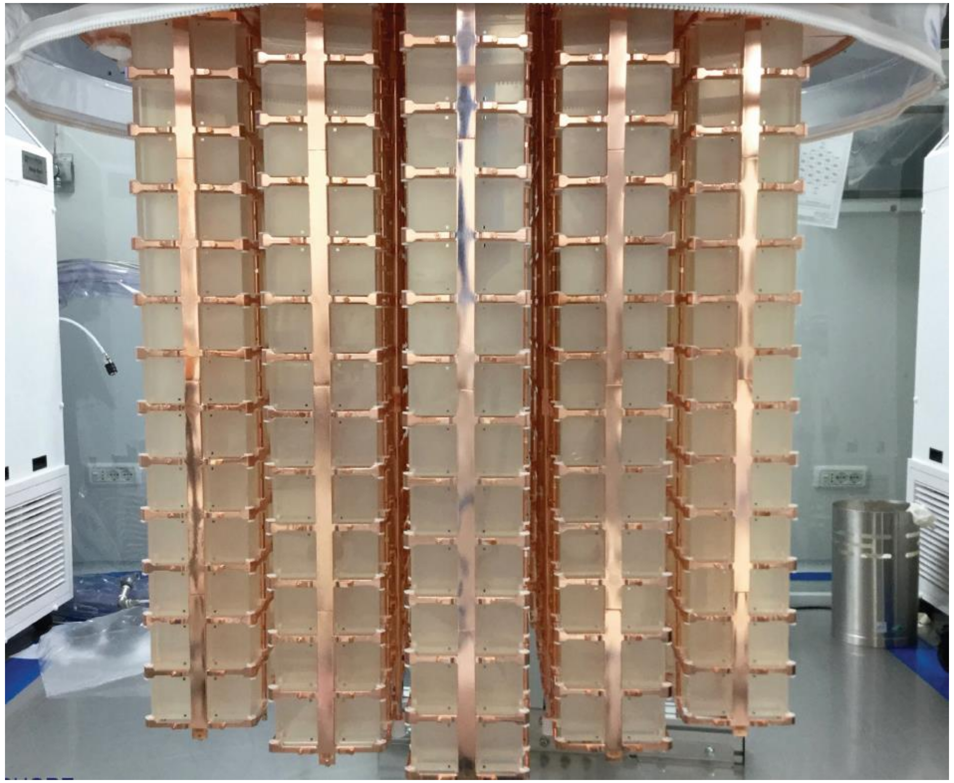
Y.C. Lee et al., *JLTP* **209** (2022) 919

Direct neutrino mass determination — ECHo (MMC), HOLMES (TES)

all the energy released upon electron capture in ^{163}Ho, besides the one taken away by the neutrino

The ECHo Collaboration EPJ-ST 226 8 (2017) 1623

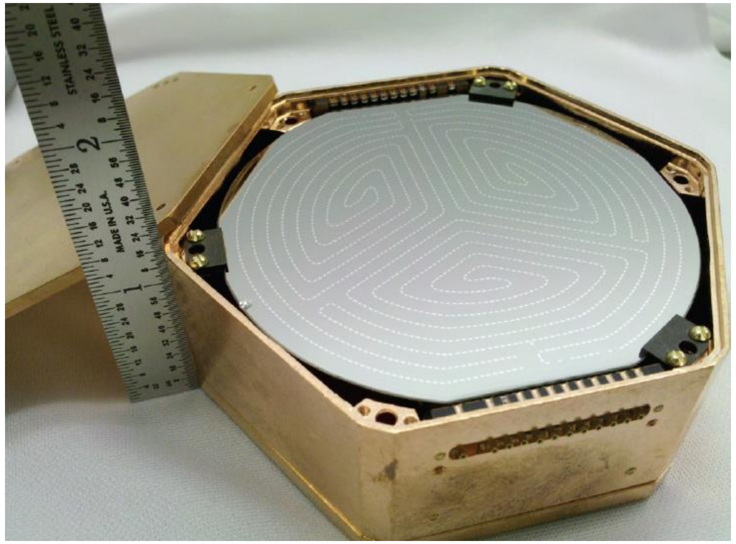
B. Alpert et al, Eur. Phys. J. C 75 (2015) 112



https://www.lngs.infn.it/en/cuore

What can LTDs measure – not only photons

Phys.Rev.Lett. 120 (2018) 6, 061802



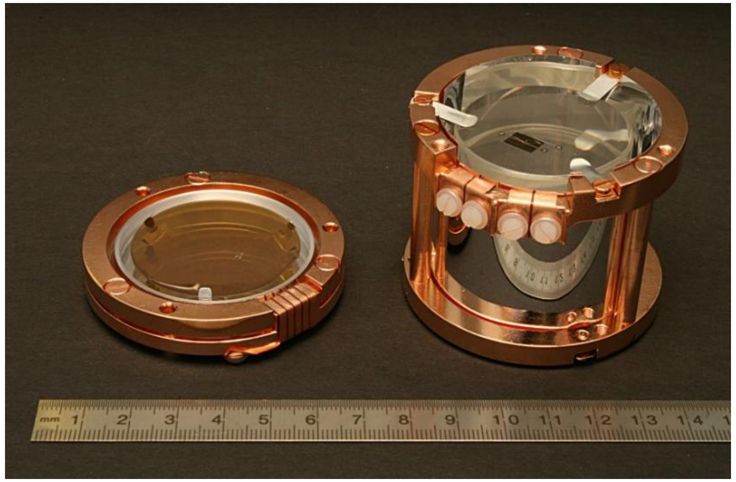
Low temperature detector for Dark Matter sirect searches

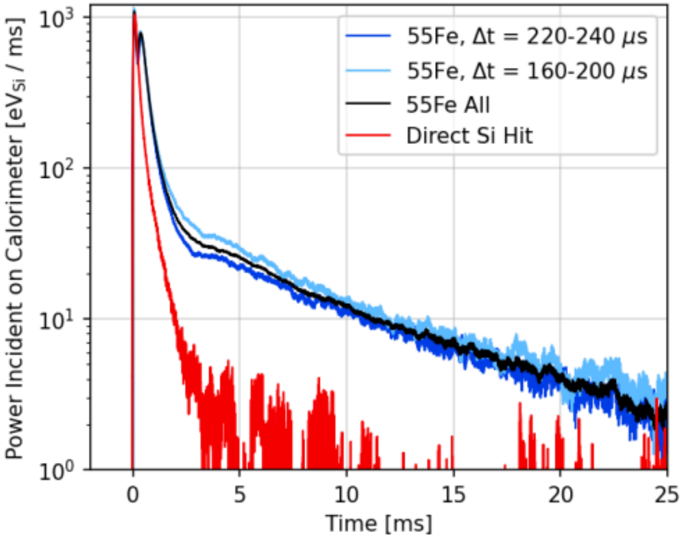
WIMP produces nuclear recoil → temperature rise + charges
Super CDMS (TES)
EDELWEISS NTD-Ge

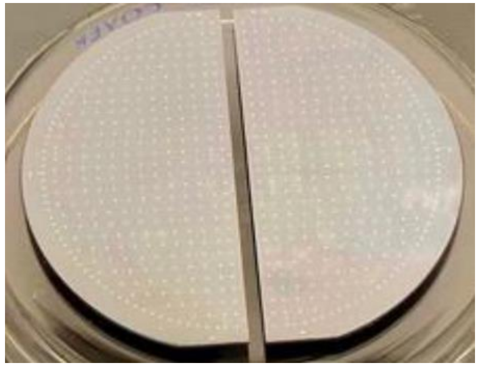
WIMP produces nuclear recoil → temperature rise + light
CRESST (TES)

WIMP produces nuclear recoil on superfluid helium → light + evaporation + de-excitation
HeRALD (TES)
DELight (MMC)

Phys.Rev.D 100 (2019) 10, 102002





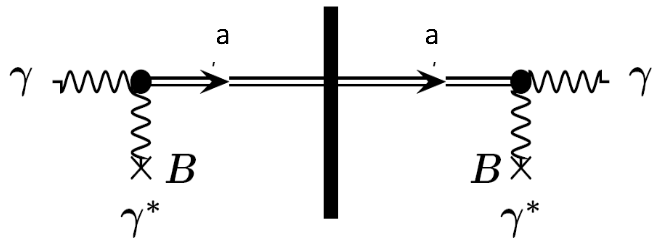


R. Anthony-Petersen et al. (SPICE/HeRALD Collaboration)
Phys. Rev. D 110 (2024) 072006

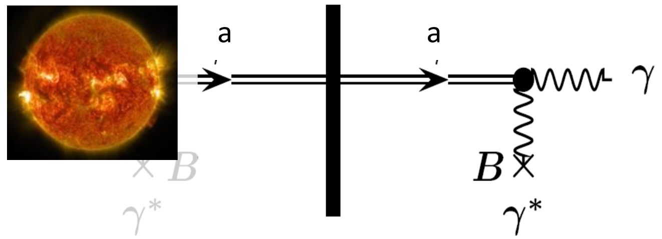
What can LTDs measure – not only photons

Low temperature detector for axion searches

- Purely laboratory experiments
  "light-shining-through-walls",
  optical photons

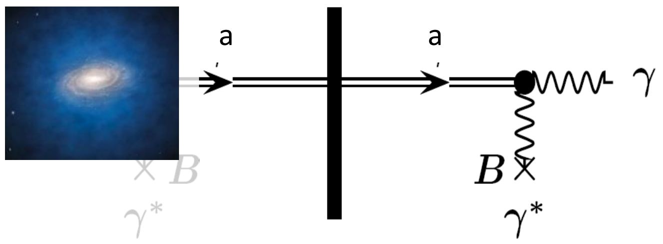


- Helioscopes
  ALPs emitted by the sun,
  X-rays,



-

- Haloscopes
  looking for dark matter constituents,
  microwaves.



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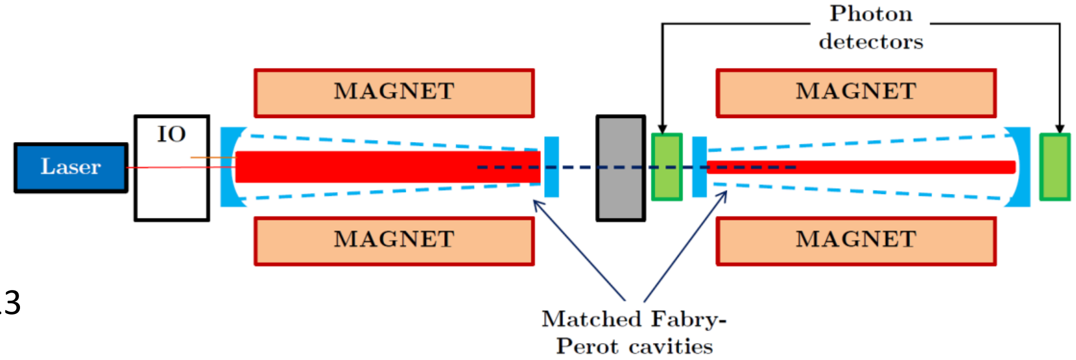
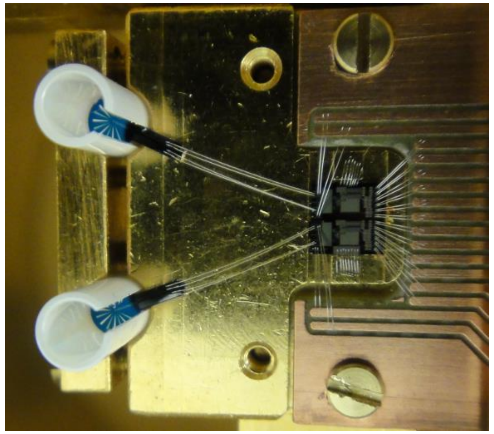
  ALPS experiment

R. Bähre et al., J. Instrum., 8(09):T09001, 2013





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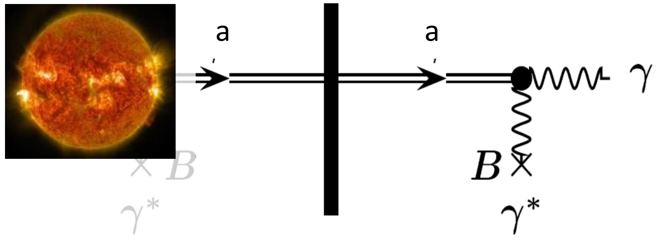

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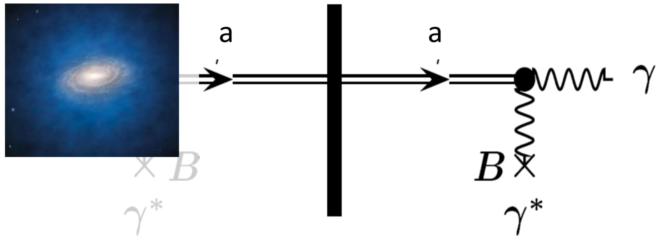

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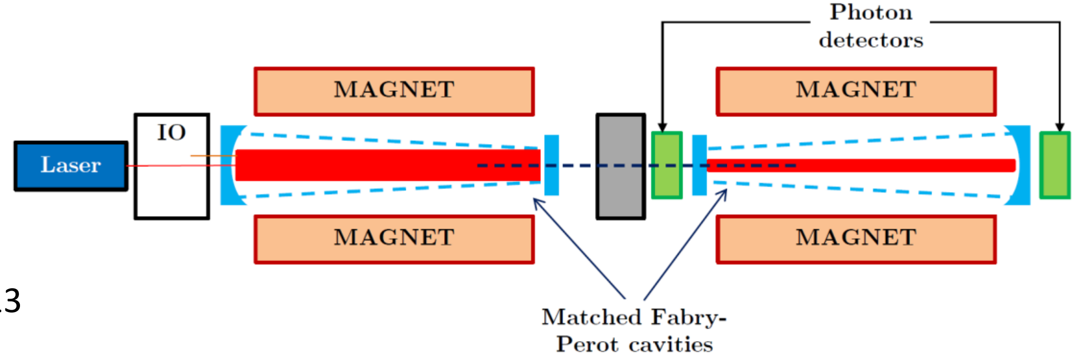
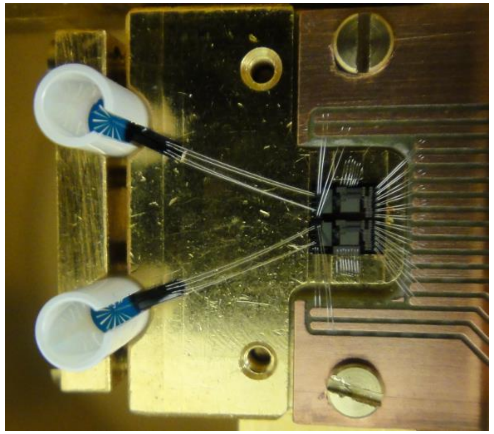
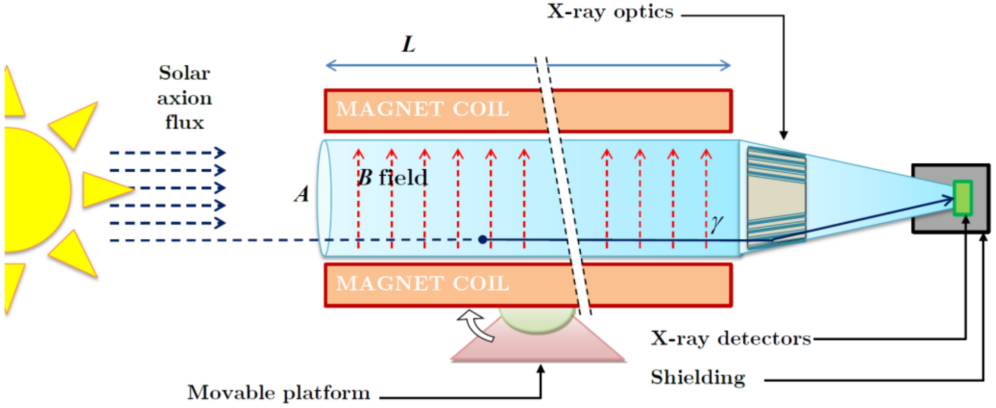
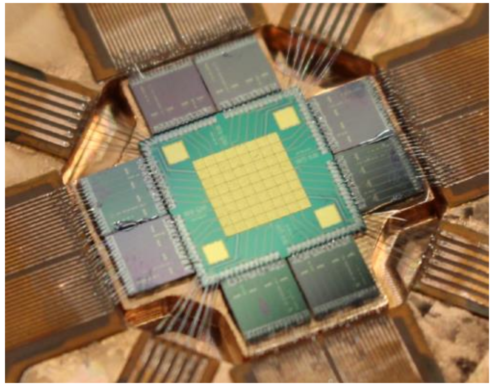




- Helioscopes
  ALPs emitted by the sun,
  X-rays
  (baby)IAXO

  The IAXO Coll., JHEP 2021, (2021) 137





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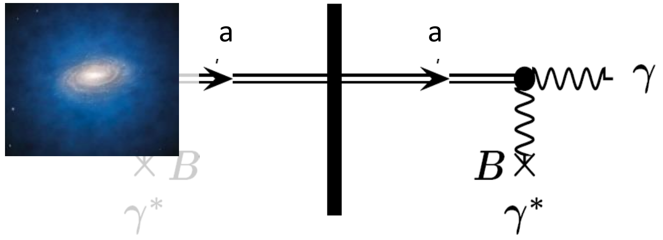
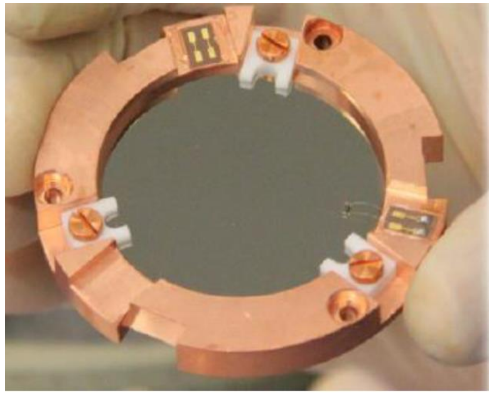
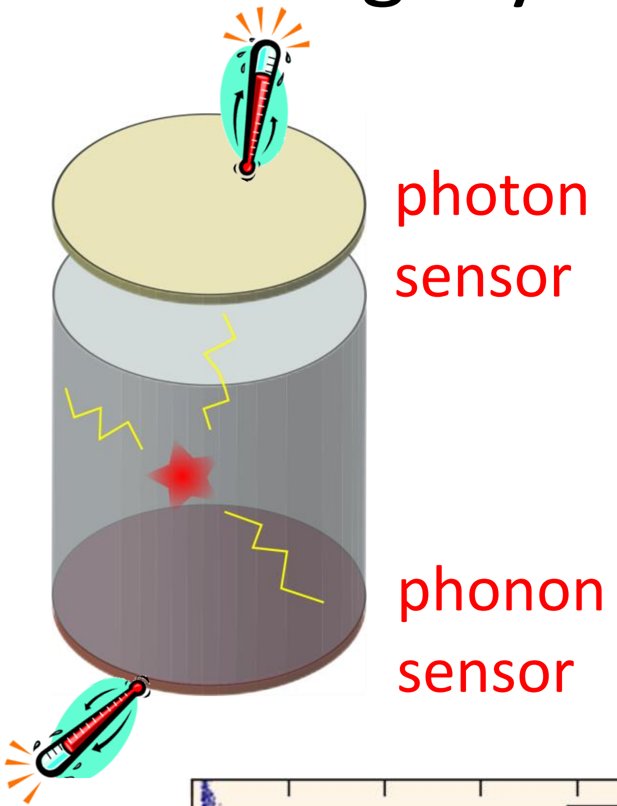
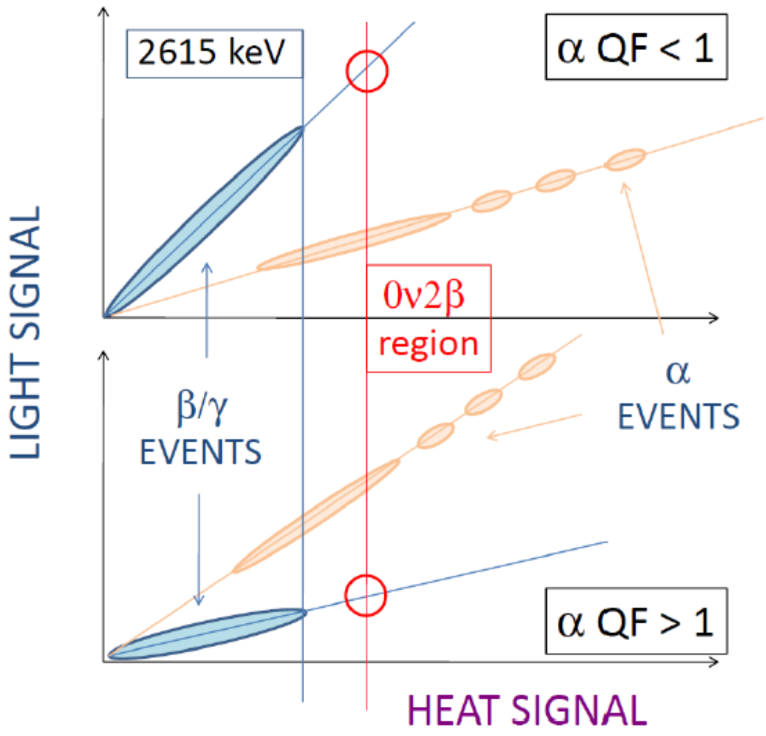
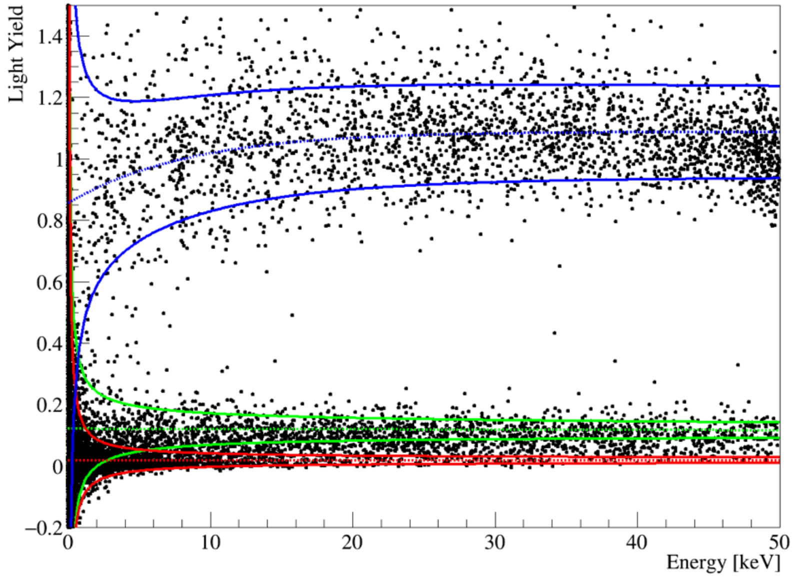


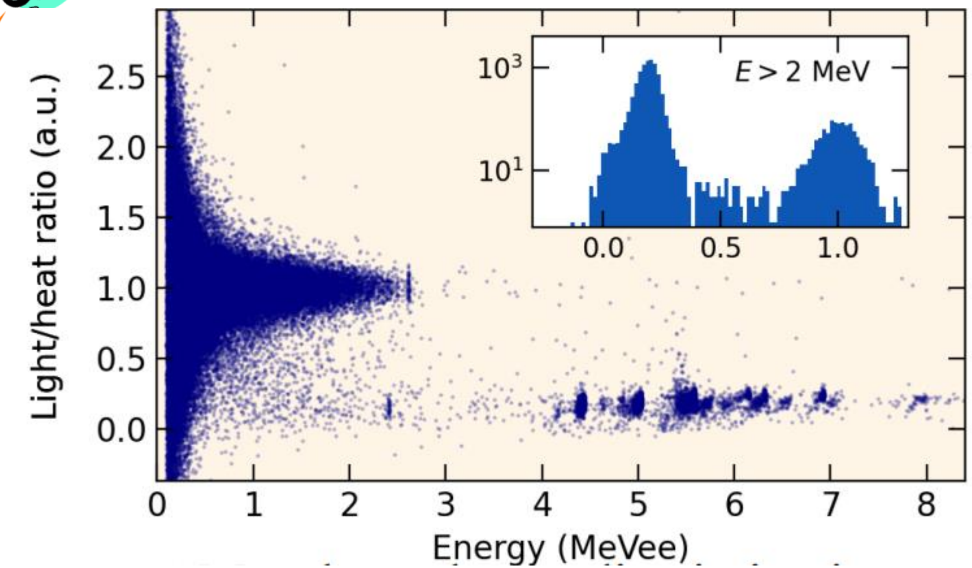


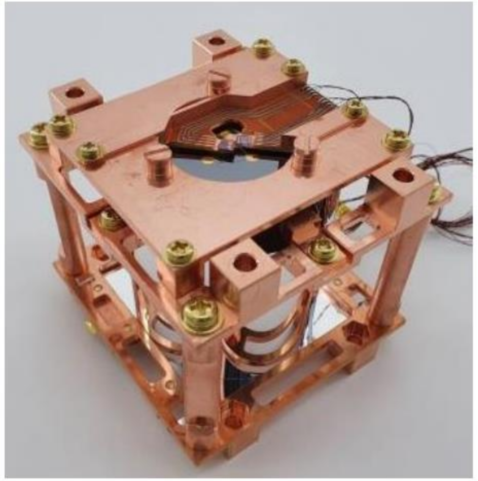
Scintillating crystals



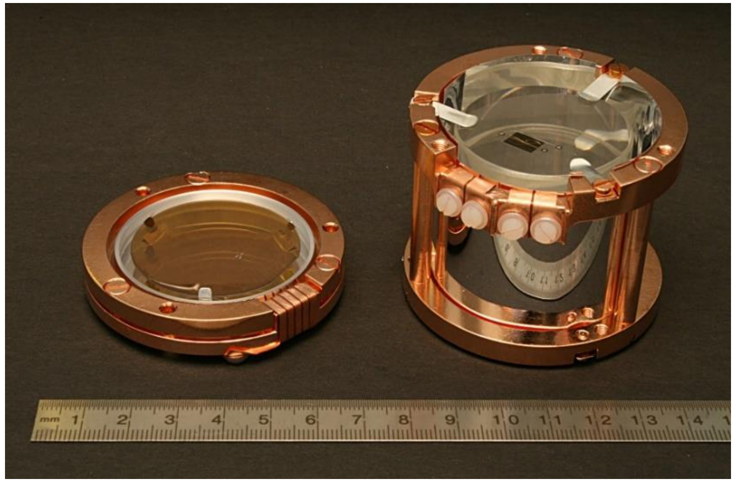






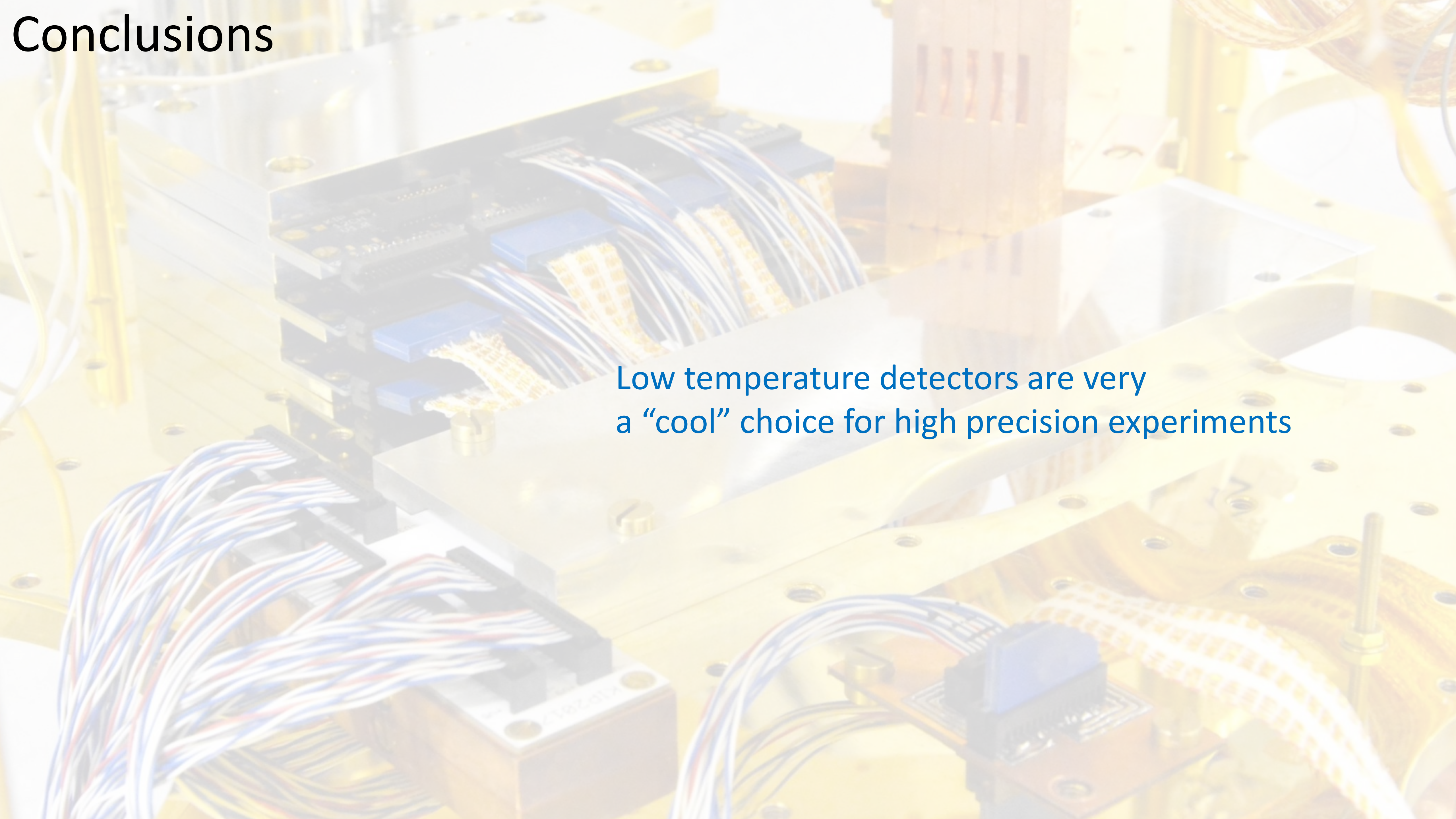


AMoRE Collaboration



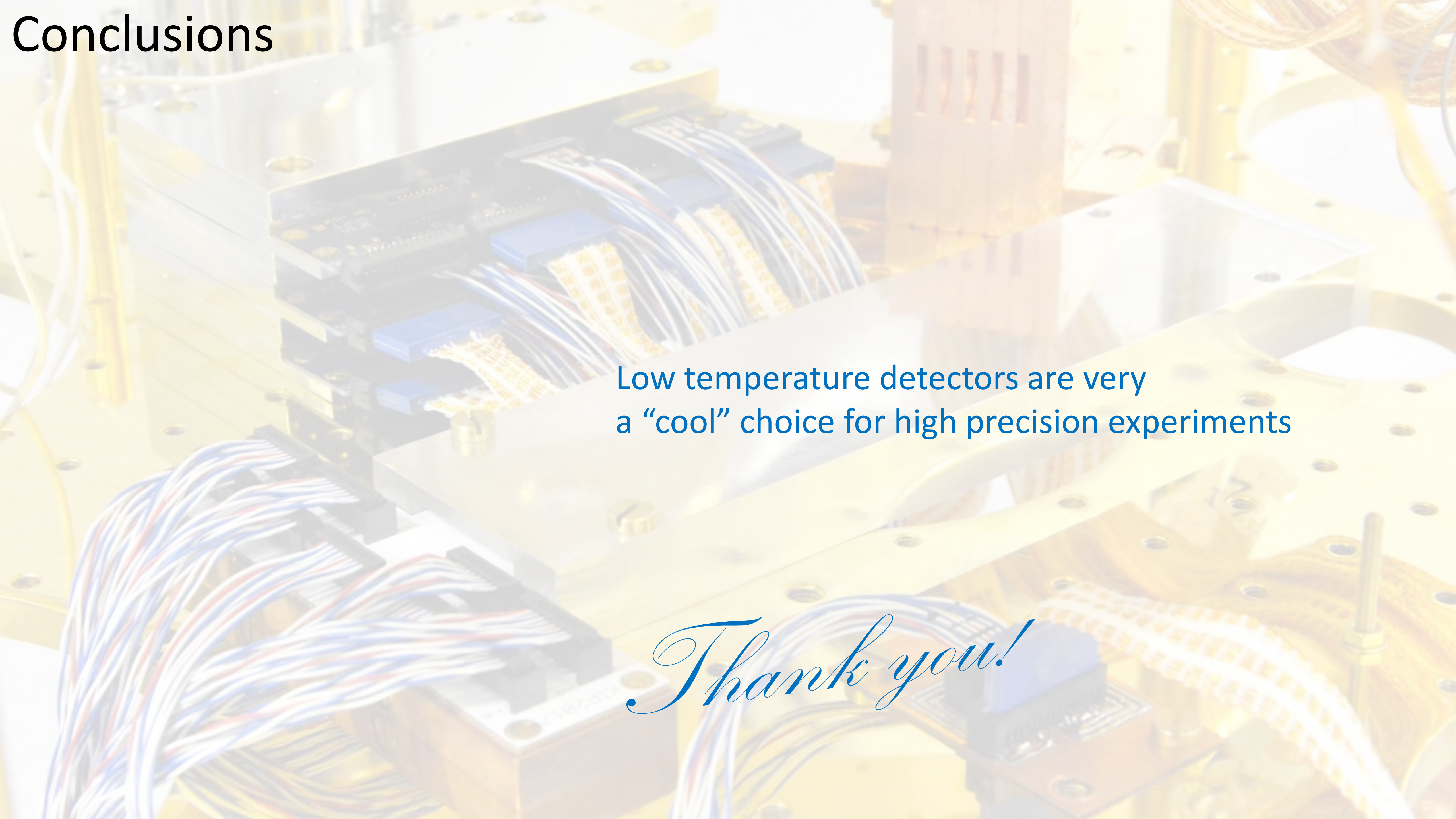
Phys.Rev.D 100 (2019) 10, 102002

Conclusions



Low temperature detectors are very
a "cool" choice for high precision experiments

Conclusions



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Thank you!