Transition Edge Sensors (TES)
technology and application

2nd Workshop on Silicon Sensors for Radiation Detection and Quantum Applications

May, 14 2025

Hotel Schloss Berg
Berg @ Lake Starnberg, Germany

Karoline Schäffner

MPP, Garching, Germany

MAX-PLANCK-INSTITUT
FÜR PHYSIK

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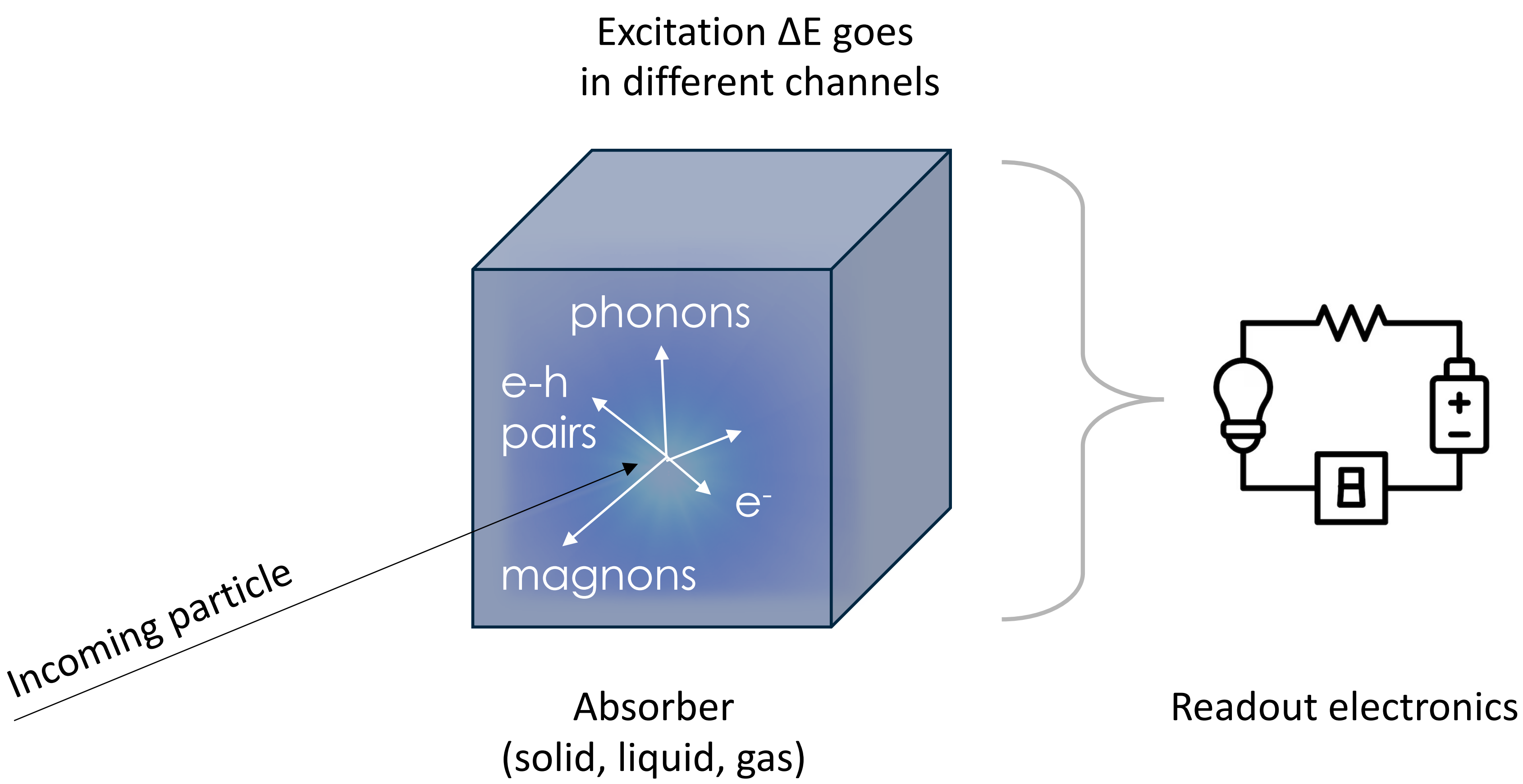
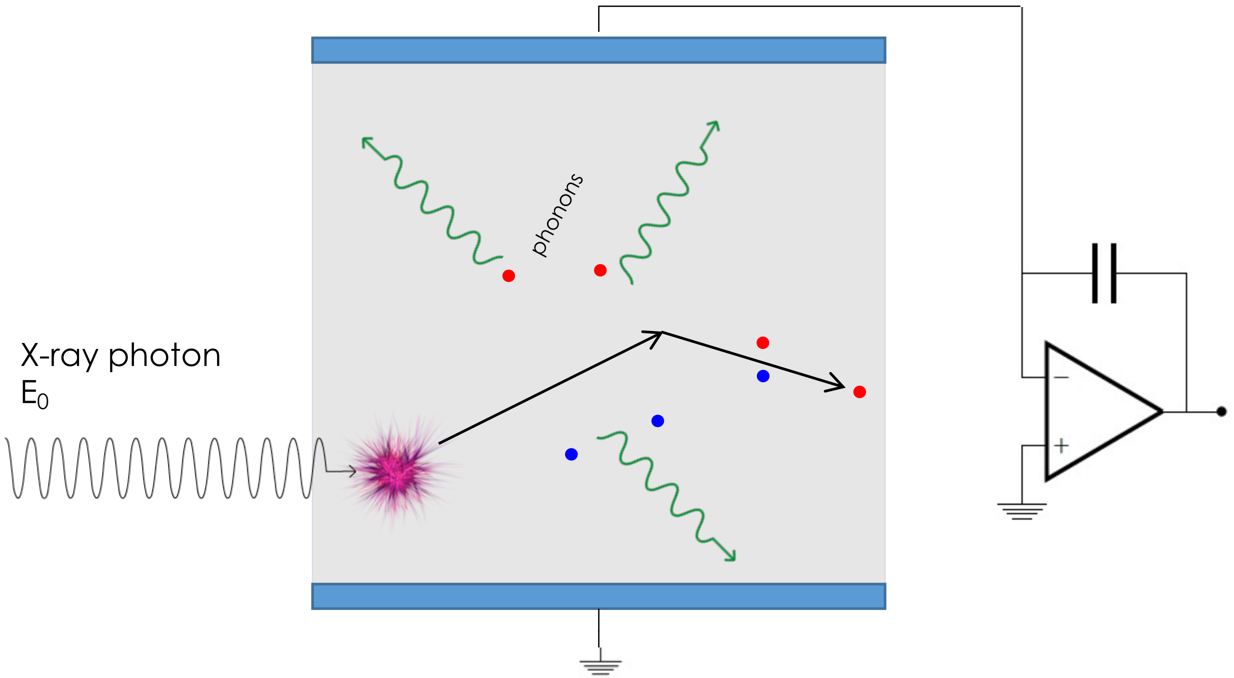
PARTICLE DETECTOR IN A NUTSHELL



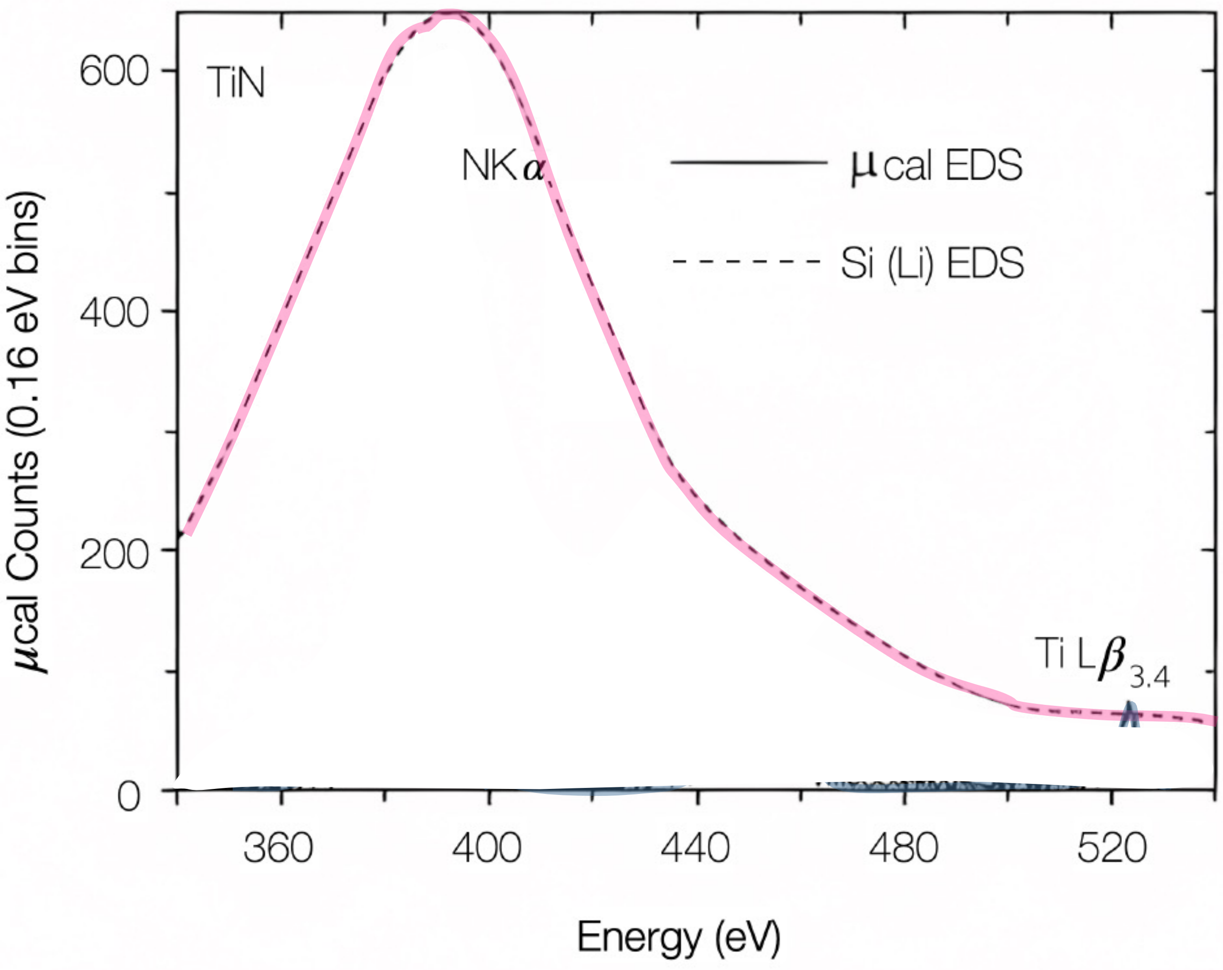
STANDARD IONISATION DETECTOR



- only a fraction of the deposited energy is converted into electron-hole pairs
- Fano factor:
  generation of e-h pairs is not statistically independent, e.g. due to atomic excitations

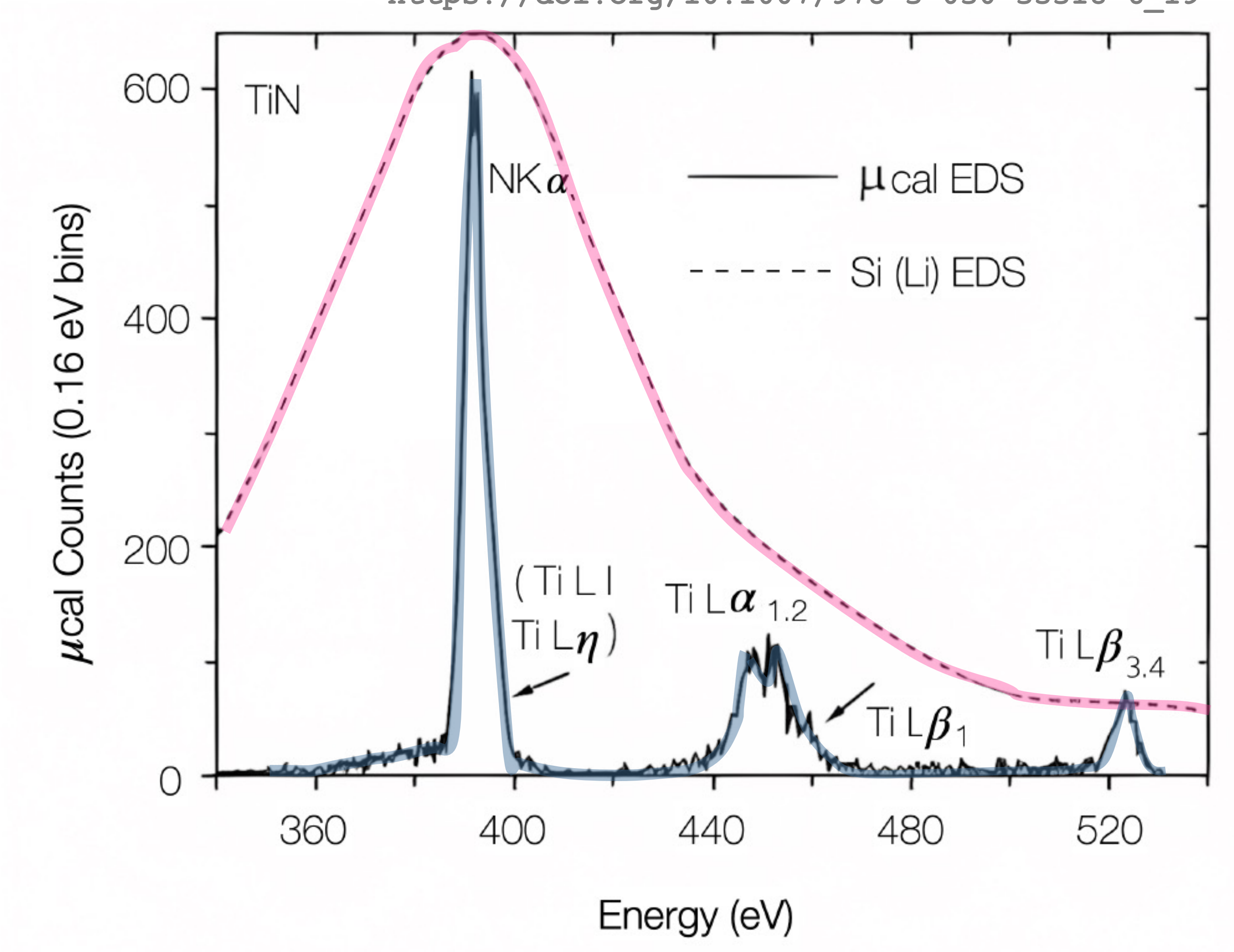
for silicon: $\epsilon(E_0, T) \approx 3.7$ eV / e-h pair

$\delta E = \sqrt{f \epsilon E_0} \approx 120\ eV$ FWHM at 6 keV https://doi.org/10.1007/978-3-030-35318-6_19



Si
Solid-state device

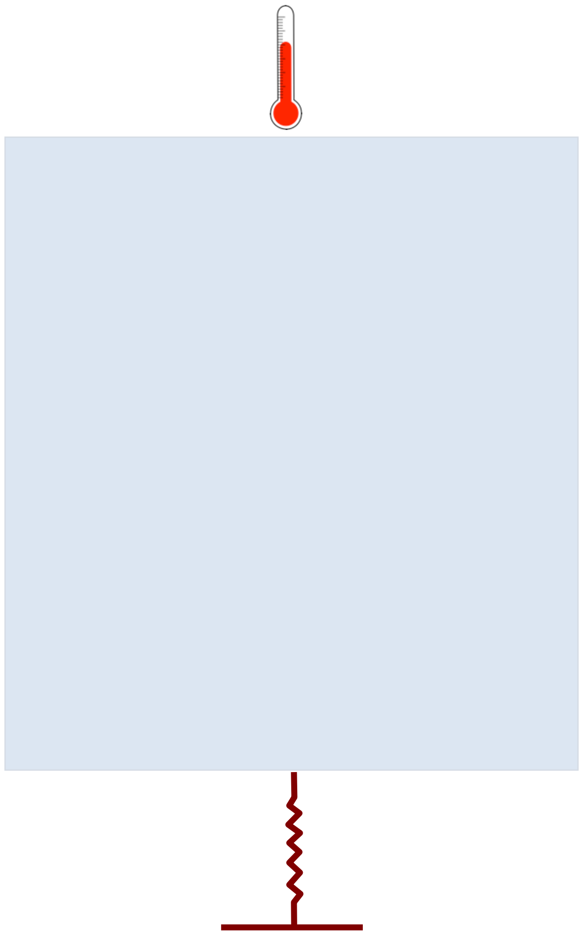
https://doi.org/10.1007/978-3-030-35318-6_19



Si
Solid-state device

Al-Ag bilayer TES
on a Bi absorber

LOW-TEMPERATURE DETECTOR



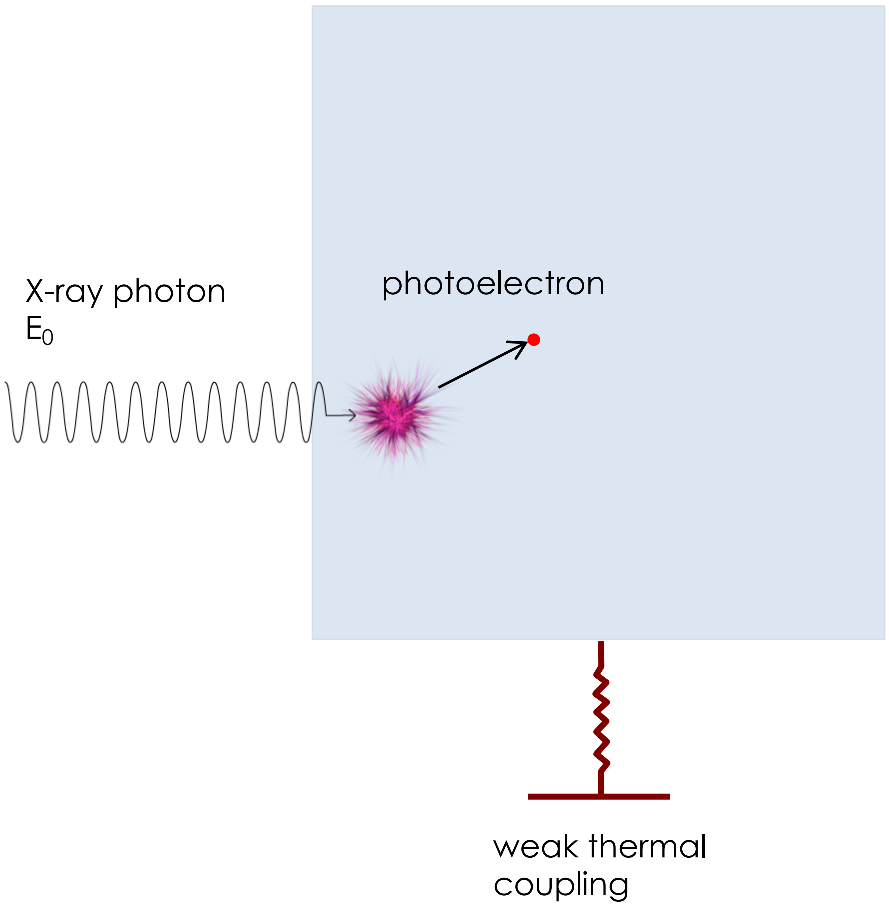
weak thermal
coupling

sensitive thermometer

crystal

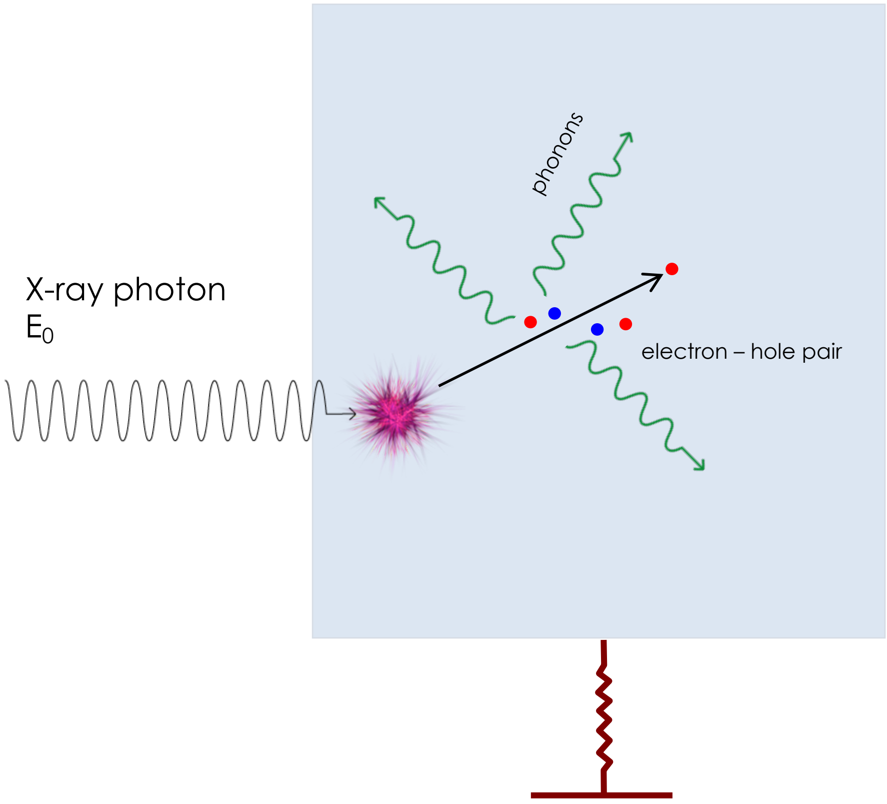
very low temperatures
10 milli-Kelvin

LOW-TEMPERATURE DETECTOR



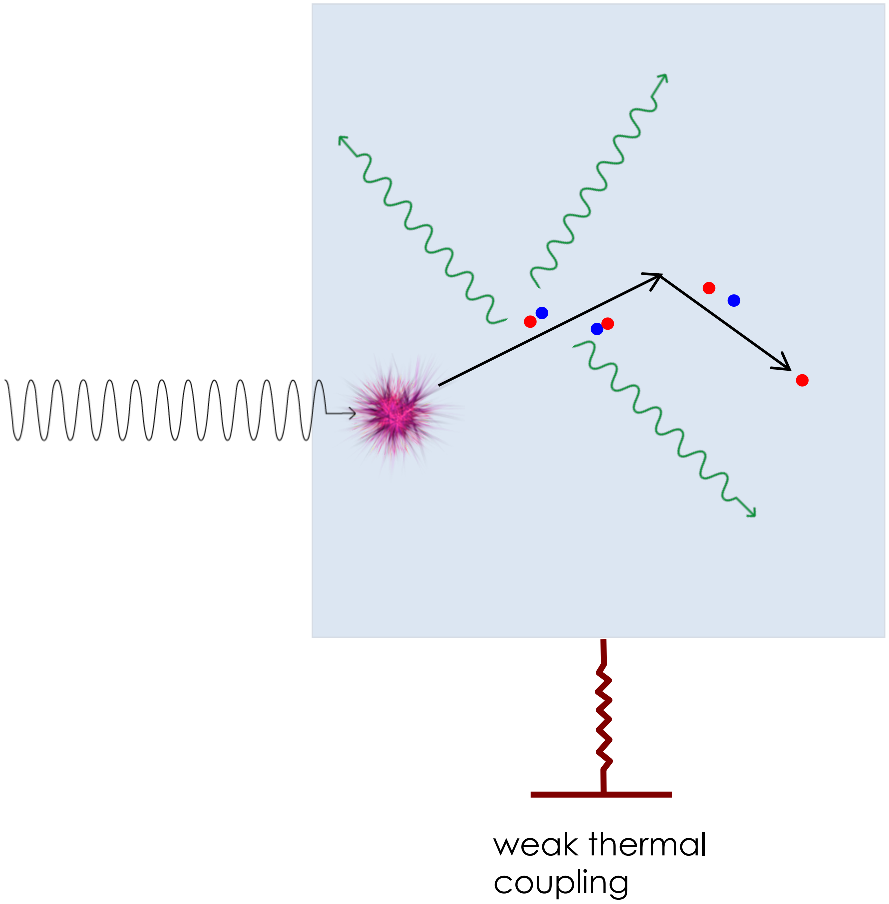
- photon creates photoelectron

LOW-TEMPERATURE DETECTOR



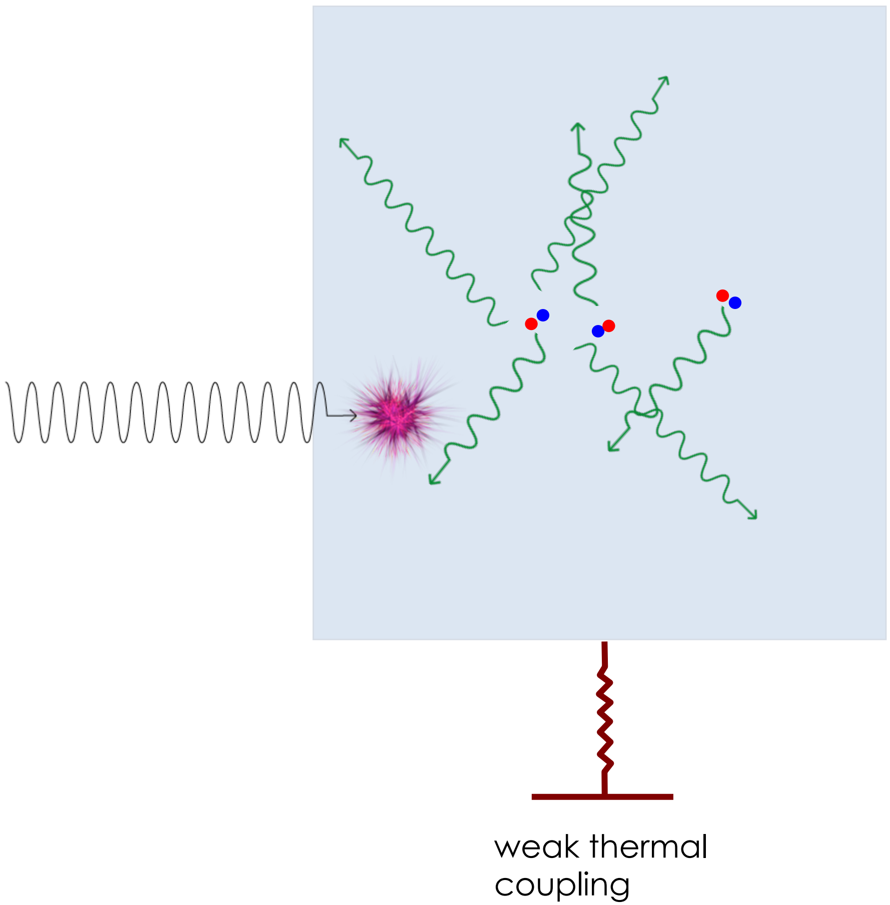
- photon creates photoelectron
- photoelectron goes on creating e-h pairs and high energy phonons

LOW-TEMPERATURE DETECTOR



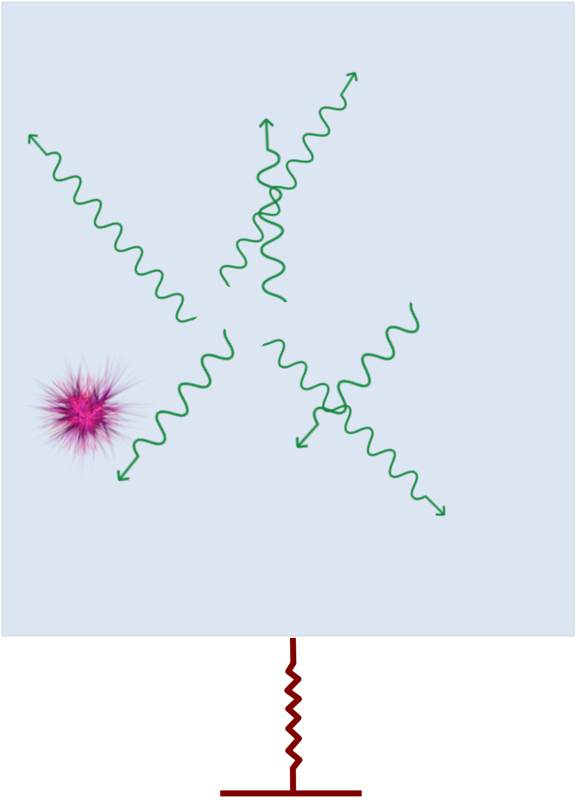
- photon creates photoelectron
- photoelectron goes on creating e-h pairs and high energy phonons
- electron – hole pairs start to recombine while photoelectrons and phonons continue to down-convert

LOW-TEMPERATURE DETECTOR



- photon creates photoelectron
- photoelectron goes on creating e-h pairs and high energy phonons
- electron – hole pairs start to recombine while photoelectrons and phonons continue to down-convert
- electron – hole pairs recombine and emit a phonon

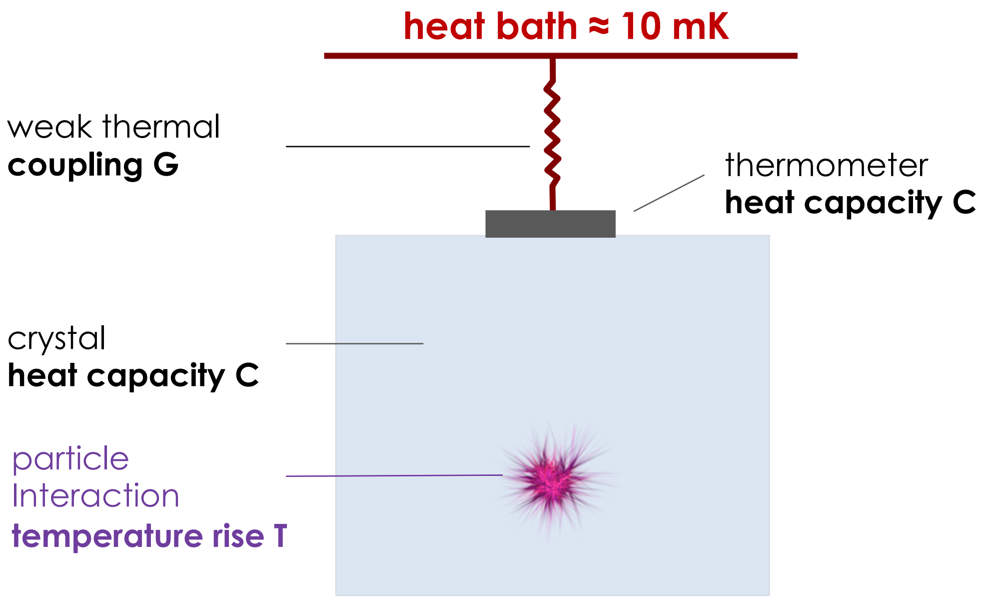
LOW-TEMPERATURE DETECTOR



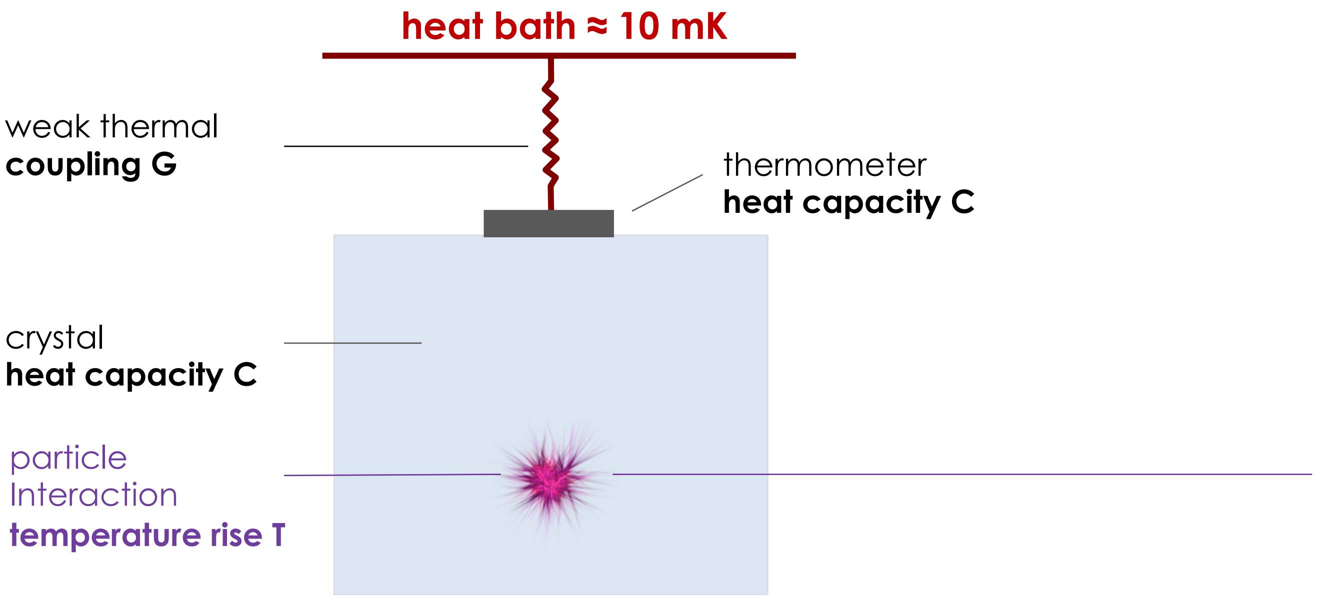
- **IF you have time:**
  (meta-stable states, traps,…)

→ **almost all initial energy will be converted in a thermal signal**

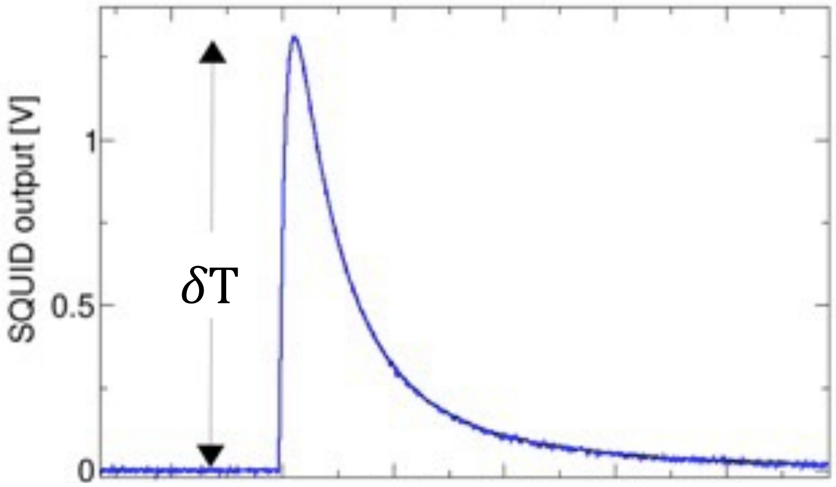
DETECTOR RESPONSE: temperature pulse



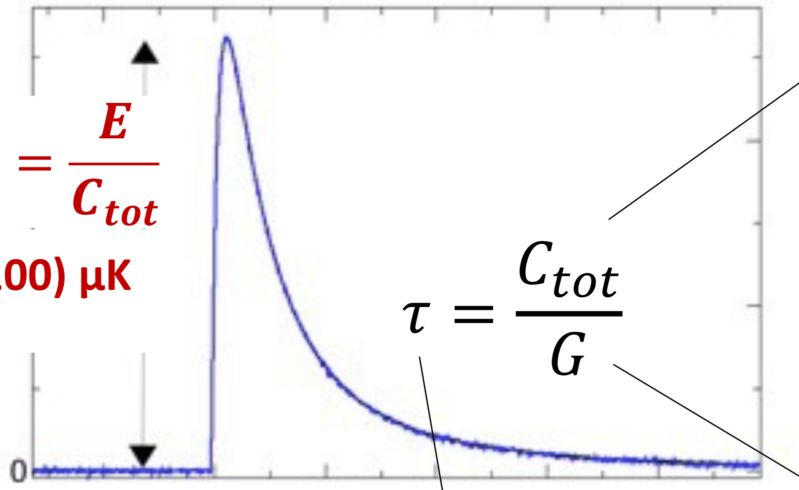
DETECTOR RESPONSE: temperature pulse



Temperature pulse



DETECTOR RESPONSE: temperature pulse



$\delta T = \frac{E}{C_{tot}}$

$\mathcal{O}$ (100) µK

Thermal bath T_{bath} ≈ 10 mK

$\tau = \frac{C_{tot}}{G}$

Relaxation time:
$\mathcal{O}$ (1-100) ms

Total heat capacity

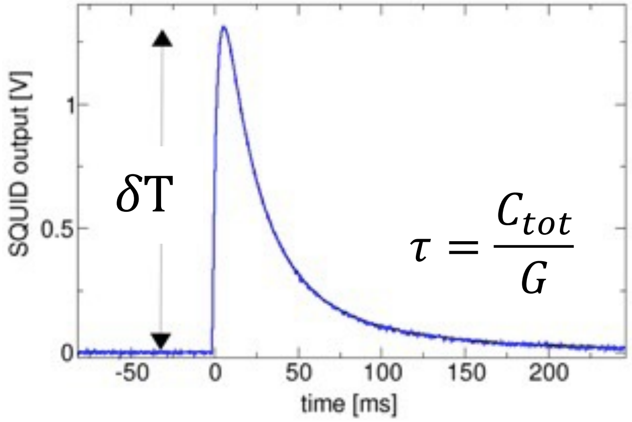
C_{tot}: phonons
electrons
spins
tunneling states
quasi particles

Thermal conductance G

phonons, $C_{ph} \propto T^3$, and electrons, $C_{el} \propto T$,

LIMITATIONS: thermodynamic fluctuations

Temperature pulse



N is the total excitations which have a mean energy **$k_B T$**

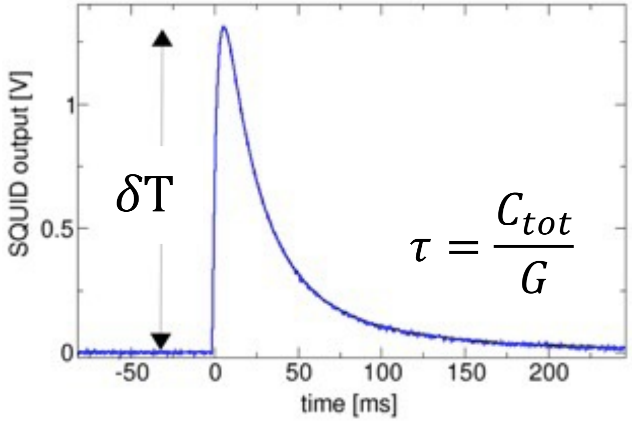
$$N \propto CT / k_B T \quad \text{and} \quad \delta N = \sqrt{N}$$

$$\delta E = \delta N k_B T = \sqrt{k_B T^2 C}$$

noise comes from **irreducible random thermodynamic fluctuations** in energy due to transport across the thermal link

LIMITATIONS: thermodynamic fluctuations

Temperature pulse



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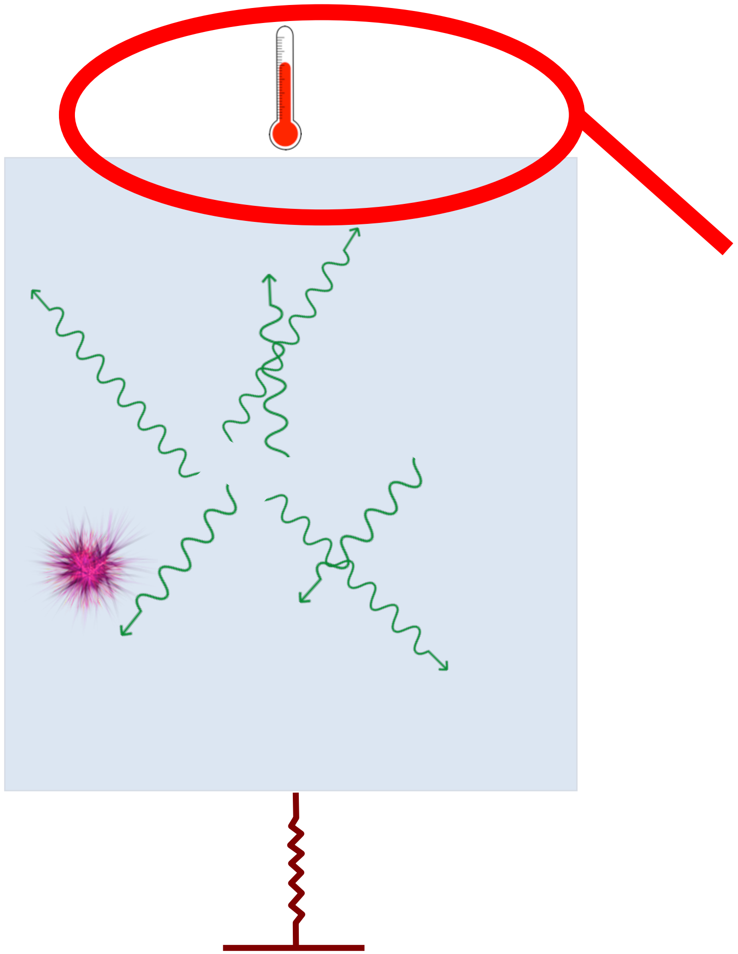
noise comes from **irreducible random thermodynamic fluctuations** in energy due to transport across the thermal link

Intrinsic energy resolution is determined by how well you can measure **T** against thermodynamic fluctuations (in ideal world):

low temperatures → better energy sensitivity

low heat capacity → careful selection of materials with low C

HOW TO MEASURE TEMPERATURE ?

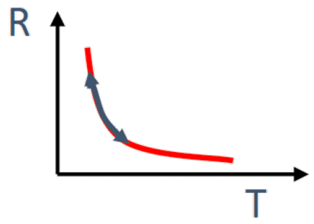


What to use as thermometer?

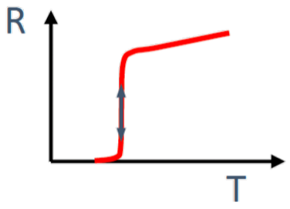
TEMPERATURE SENSORS

THERMAL EXCITATIONS (=EQUILIBRIUM DETECTORS)

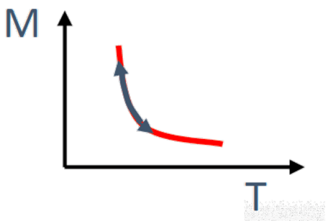
- Doped semiconductor thermistors (NTDs)



- Transition Edge Sensors (TES)



- Metallic Magnetic Calorimeters (MMC)



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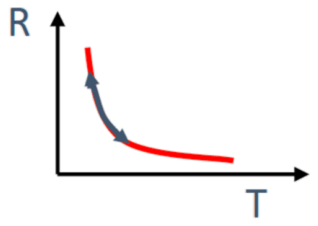

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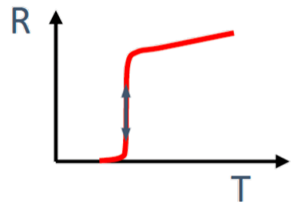

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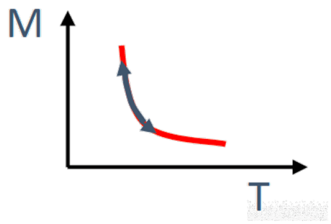

CHARGE-LIKE EXCITATIONS (=NON-EQUILIBRIUM DETECTORS)

- Superconducting Tunnel Junctions (STJ)
- Microwave Kinetic Inductance Detectors (MKID)

TEMPERATURE SENSORS

THERMAL EXCITATIONS (=EQUILIBRIUM DETECTORS)

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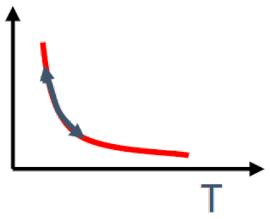

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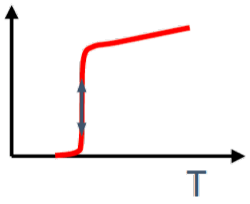

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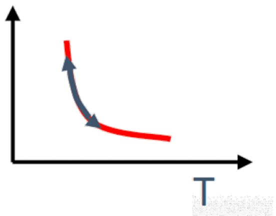
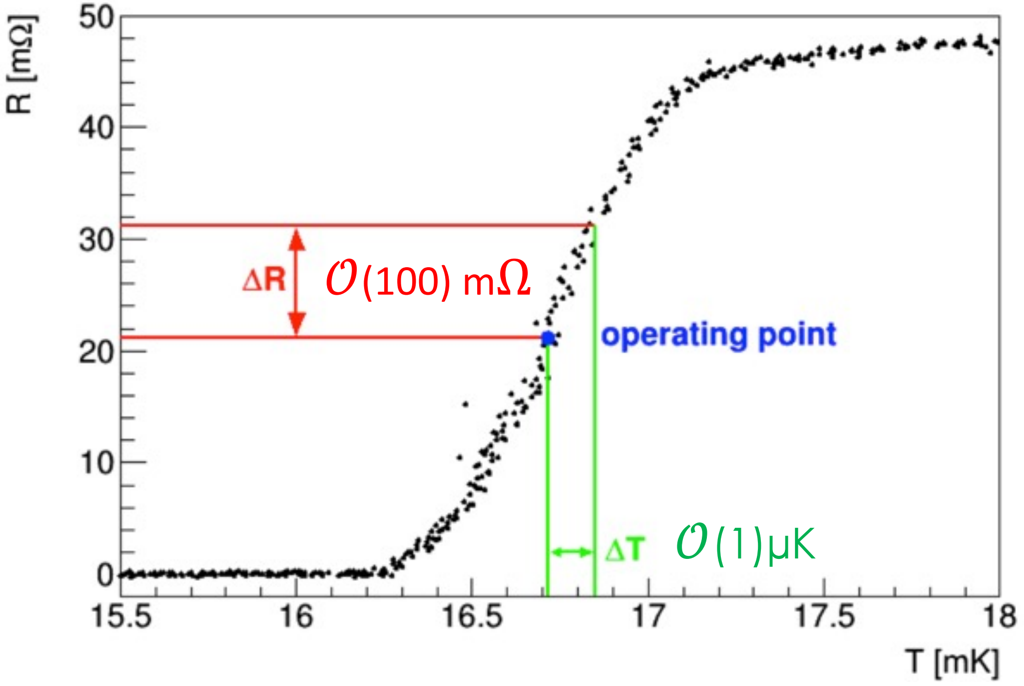


→ *Talk by Sebastian Kempf*

CHARGE-LIKE EXCITATIONS (=NON-EQUILIBRIUM DETECTORS)

- Superconducting Tunnel Junctions (STJ)
- Microwave Kinetic Inductance Detectors (MKID)

TES WORKING PRINCIPLE



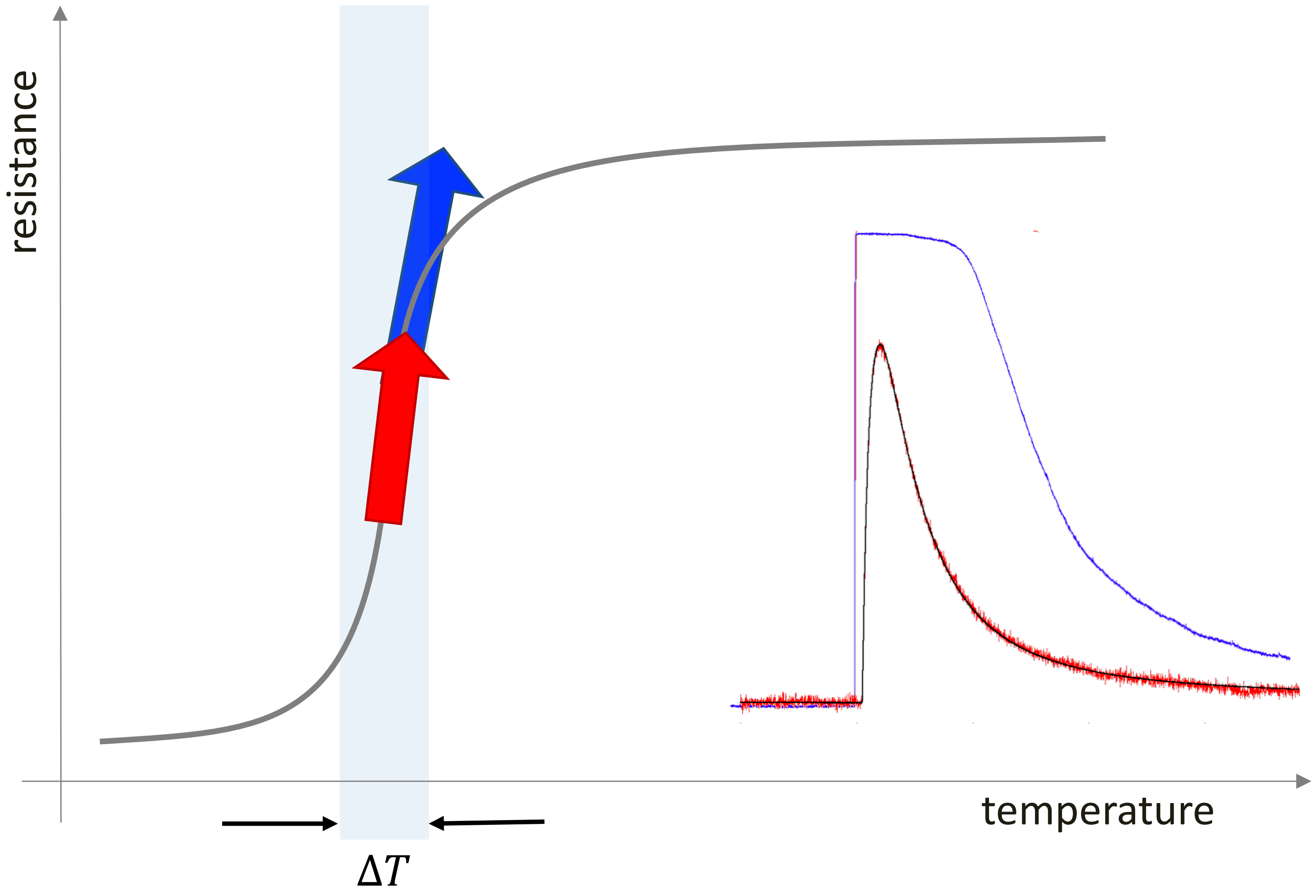
Superconducting film operated in the transition between the normal-conducting and superconducting phase

Operating temperature defines

- heat capacity
- thermal conductance
- thermal noise

→ this sets the sensitivity of the TES

FINITE DYNAMIC RANGE



Once ΔT > transition width

→ dynamic range of TES exceeded

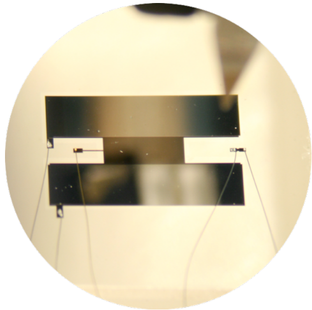
→ resistance does no longer change with temperature

→ BUT: tune TES such that it fits to energy region you are interested in

WHAT SUPERCONDUCTING FILM ?

Elementary superconductors:

Al	$T_C \approx 1.1$ K
Ti	$T_C \approx 0.39$ K
Mo	$T_C \approx 0.92$ K
W	$\mathbf{T_C \approx 0.015}$ **K**
Ir	$T_C \approx 0.140$ K



W – TES

$T_c \approx 15$ mK

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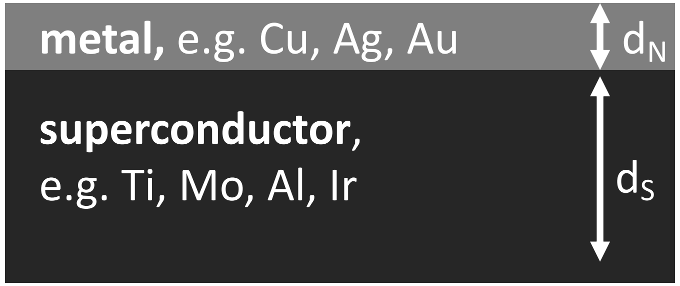
W – TES

$T_c \approx 15$ mK

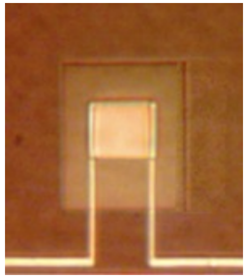
Proximity effect:

Lowering T_c of a superconducting film by the presence of a metal layer in good electrical contact



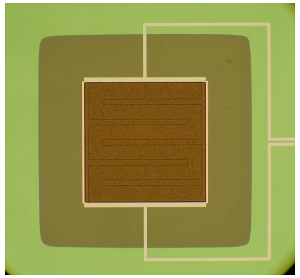
If d_N is smaller than the coherence lengths

→ bilayer behaves as a superconducting film



Ir / Au TES

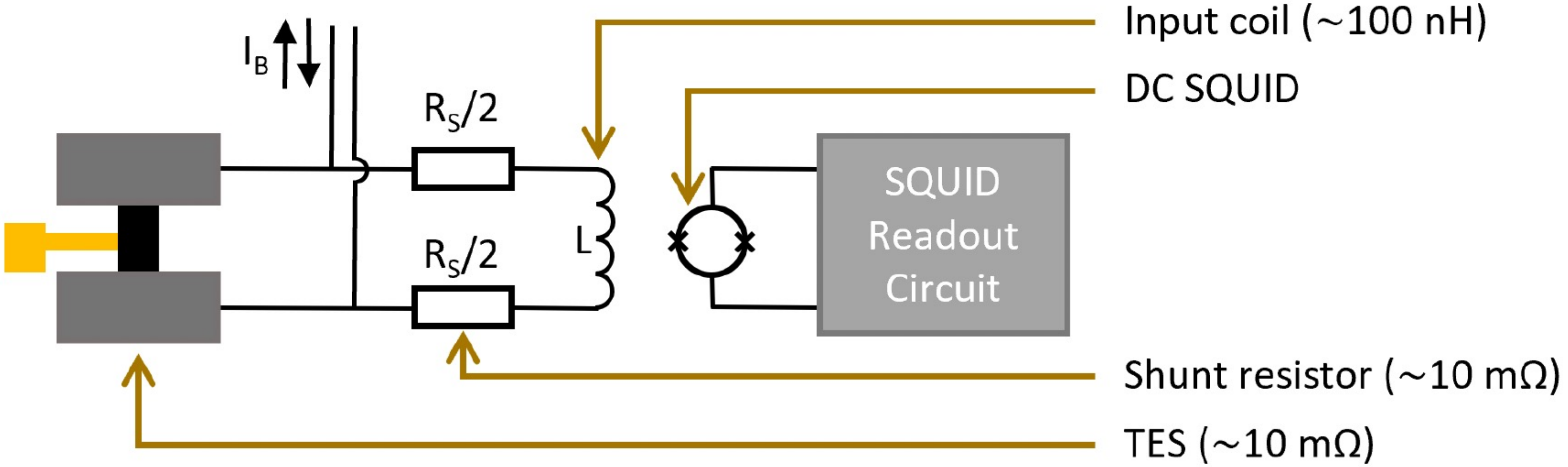
$T_c \approx 70$ mK



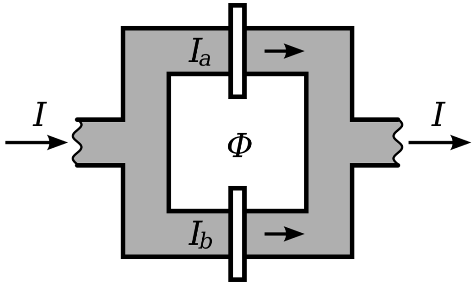
Mo / Cu TES

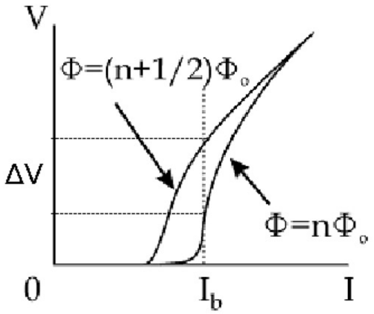
$T_c \approx 100$ mK

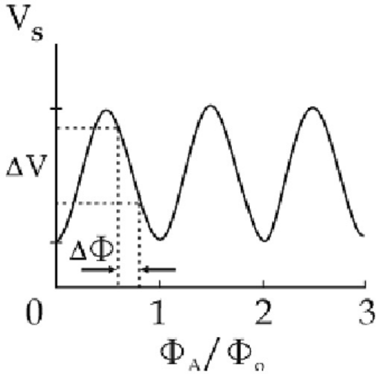
SQUID READOUT Superconducting Quantum Interference Device



dc SQUID:
- sensitive magnetometer
- Josephson junctions
- commercially available

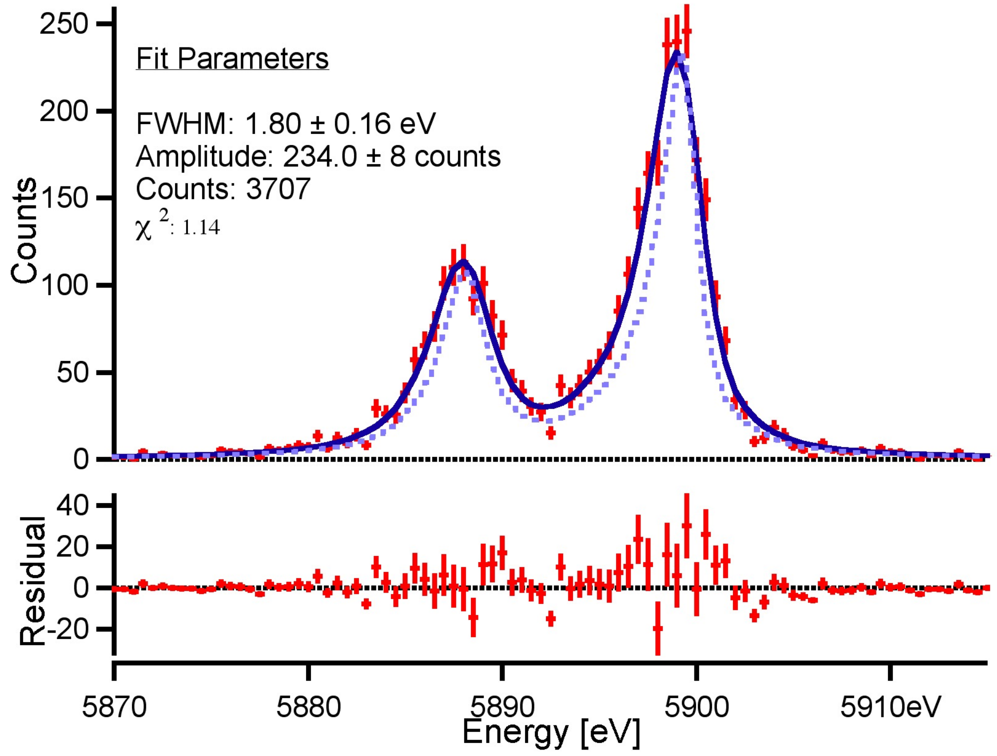






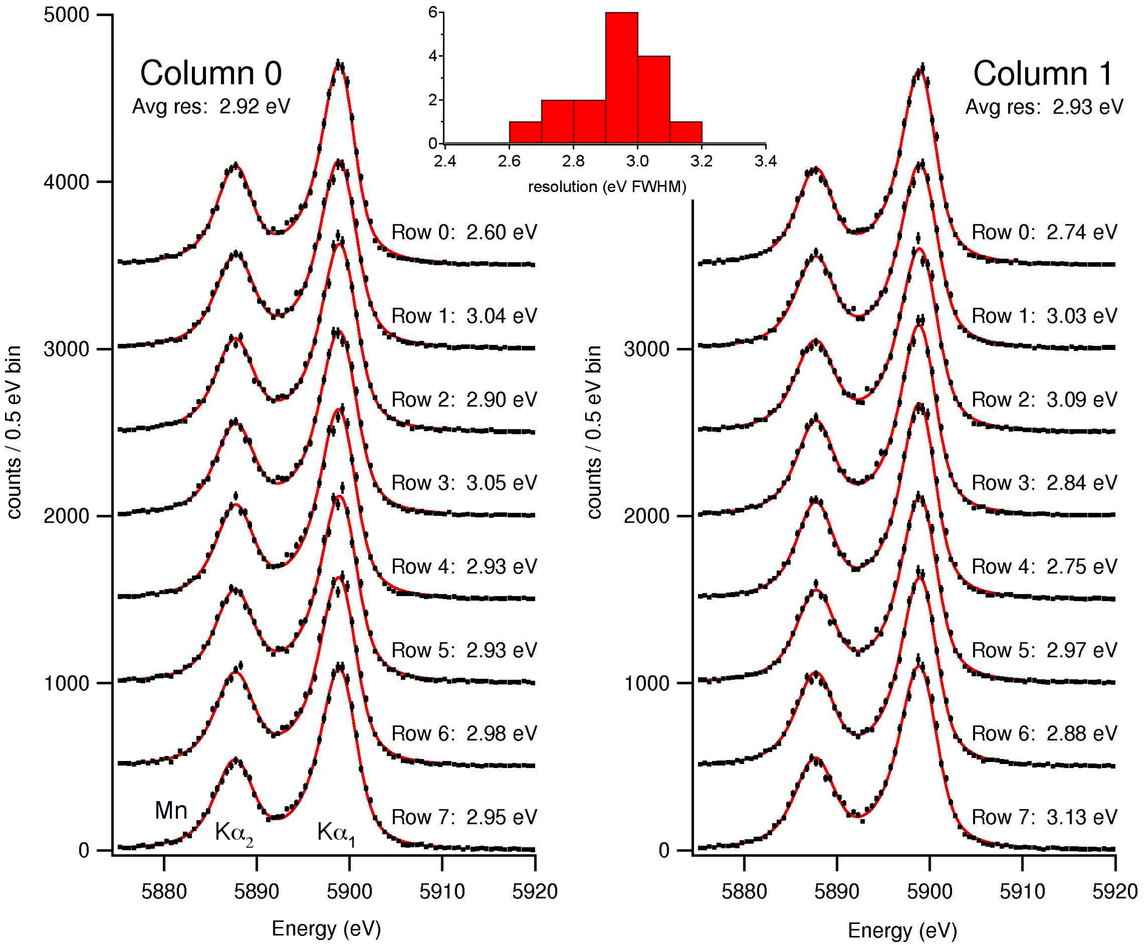
MULTIPLEXING

SINGLE detector



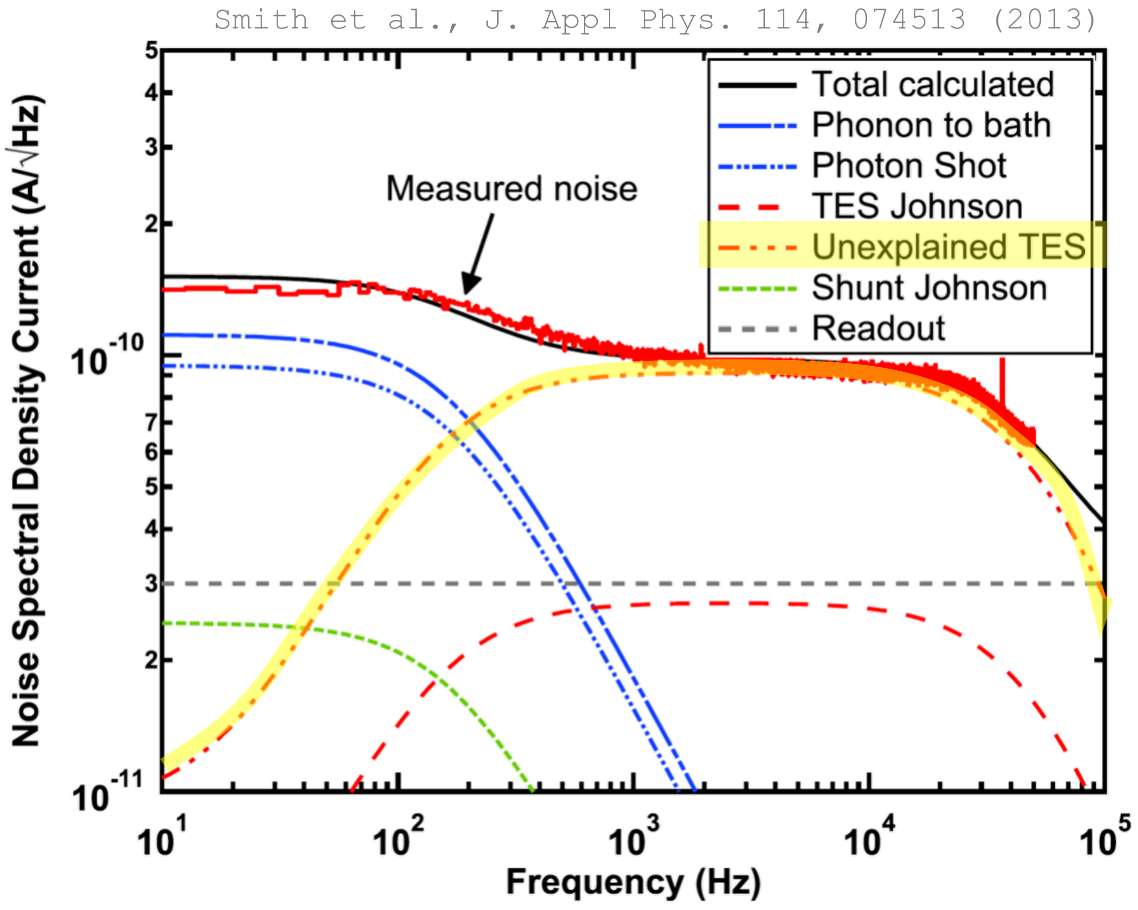
NASA GSFC

MULTIPLEXED ARRAY



NIST/NASA

TES – EXCESS NOISE



TES is a resistor
→ Johnson noise

$$I_{Johnson} \sim \sqrt{\frac{4k_B T_c}{R}}$$

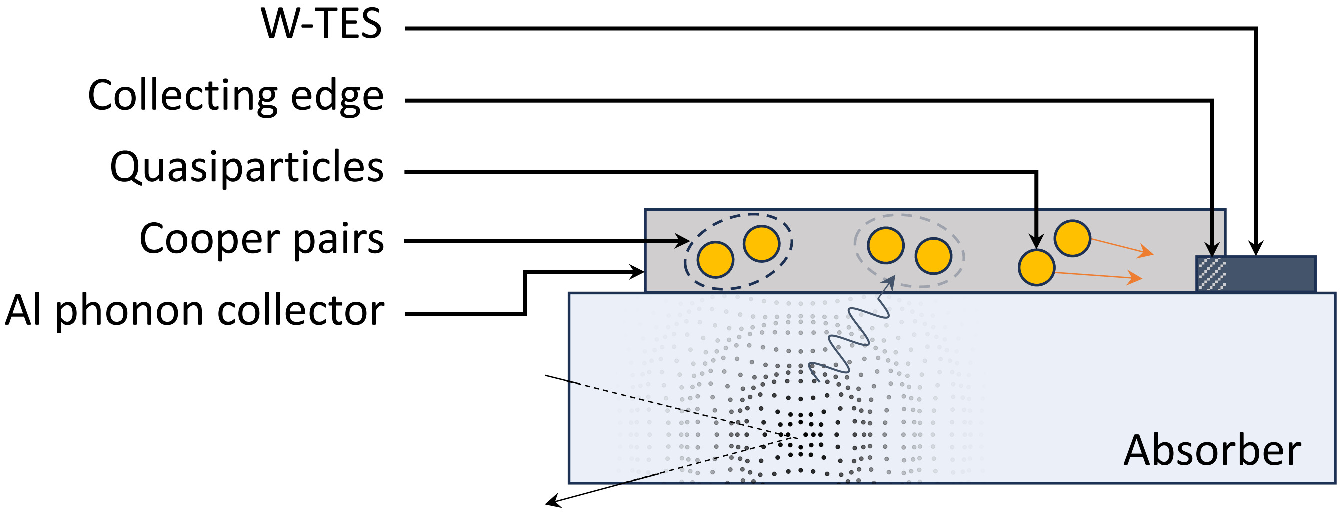
Including both Johnson and the thermodynamic fluctuations noise:

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

→ best ΔE for small T_C and low C

→ $\Delta E_{true} > \Delta E_{FWHM}$

OUR MUNICH TESs



TES used directly fabricated onto absorbers to measure the athermal phonon population created after a particle interaction

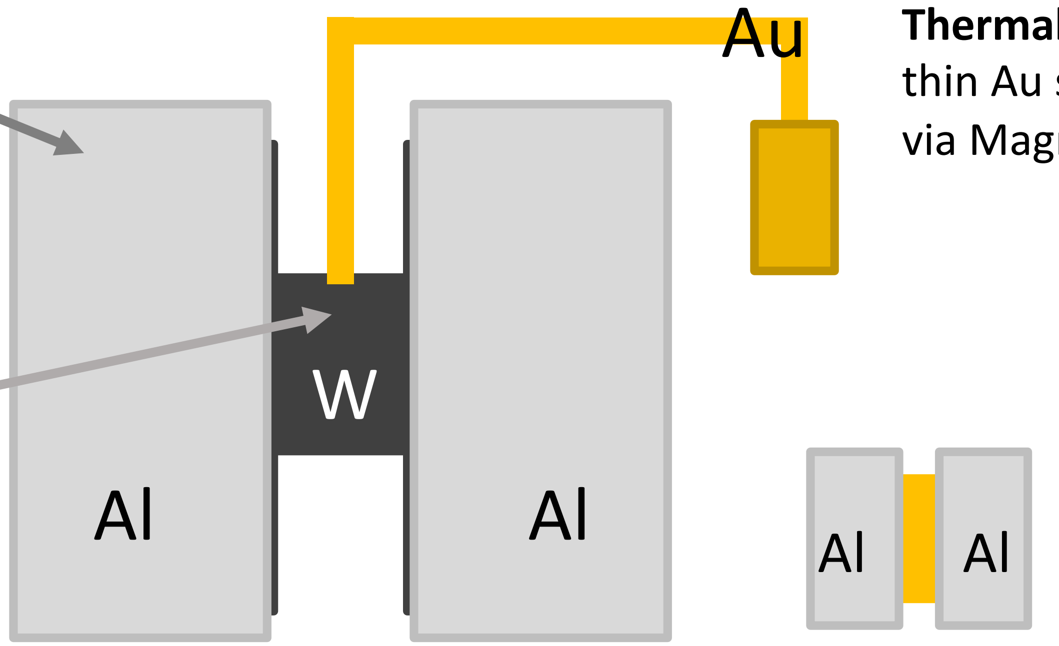
Benefit:
heat capacity of the absorber to first order not relevant
→ use of massive absorbers for e.g. dark matter search is feasible

OUR MUNICH TES IN A NUTSHELL

Phonon collectors
1 µm of Al
via electron-beam evaporation

Tungsten film
150 nm – 250 nm
via electron-beam evaporation

NEW: also W sputtering under investigation



Thermal link
thin Au stripe + thicker bonding pad
via Magnetron sputtering

Ohmic heater to drive TES in operating point
thin Au stripe
1 µm Al bonding pads
via Magnetron sputtering

Note: geometry/size of TES adapted to required sensitivity and use case

Slide borrowed from R. Strauss

History of TES production in Munich

1980

Möẞbauer

Early pioneers at TUM

TUM

Early pioneers at MPP

MAX-PLANCK-INSTITUT
FÜR PHYSIK

Stodolsky, Cooper

1990

v. Feilitzsch

Pröbst

TUM-UGL

2010

NUCLEUS

erc

ORIGINS

RES-NOVA

erc

ORIGINS

Schönert

axions

Petricca

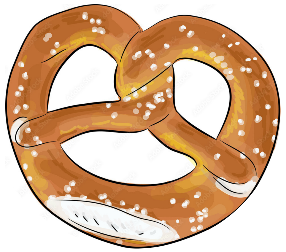
CRESST

COSINUS

CRESST 1
CRESST-II
CRESST-III

Huge expertise built up at MPP

TES FABRICATION



Photolithography

Coating with photo resist
Mask-aligner
Lift-off Process

Wet chemistry

Tungsten etching
Processing

Deposition systems

W	Standard:	E-beam evaporation
	R&D:	Magnetron Sputtering
Al	Standard:	E-beam evaporation
Au	Standard:	Magnetron Sputtering

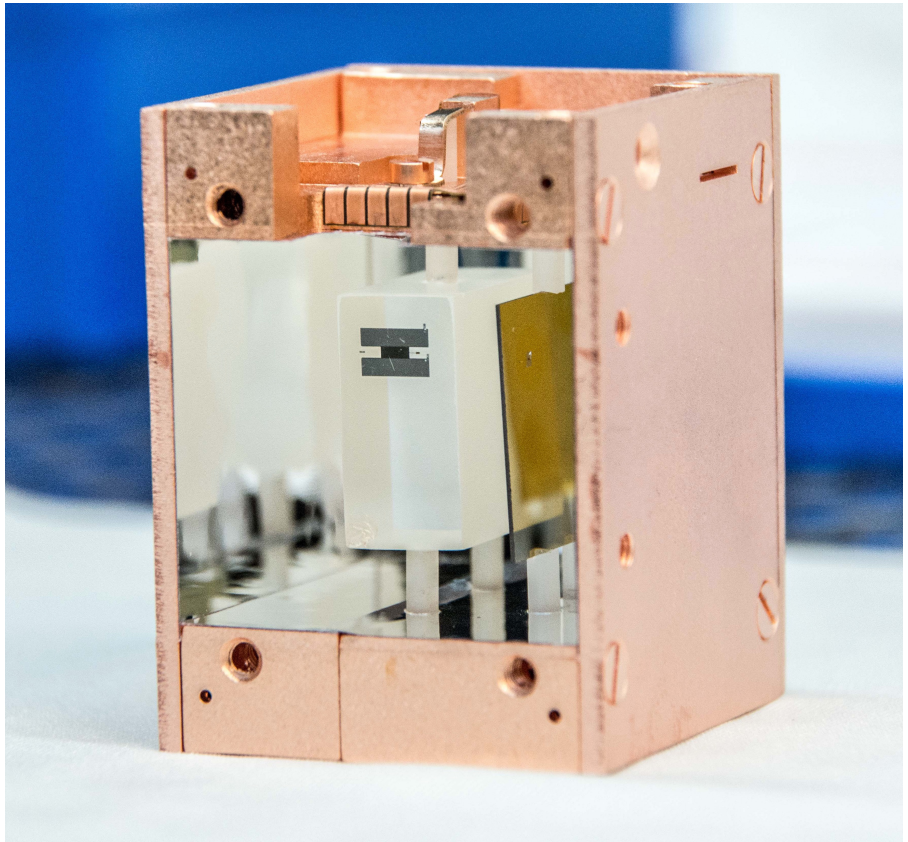
@MPP (F. Petricca group, CRESST)

- functional and fully established production line for W-TES → in commissioning since the move to Garching 02/24
- main focus on W-TES production for CRESST-III; W-TES also for spin-offs COSINUS and NUCLEUS

@TUM (groups S. Schönert & R. Strauss, CRESST, NUCLEUS)

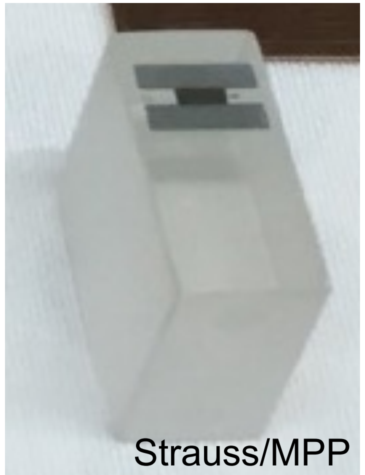
"historic"production line for W-TES, used for R&D purposes, strong focus on W sputtering

CRESST-III DARK MATTER SEARCH



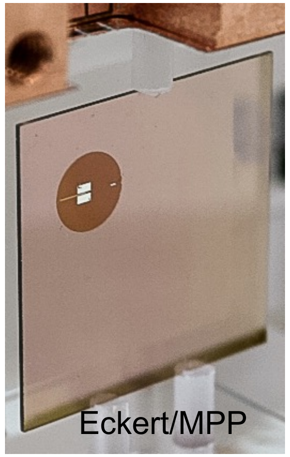
TARGET CRYSTAL

- $CaWO_4$ single crystal
- 20 x 20 x 20 mm^3;   24g

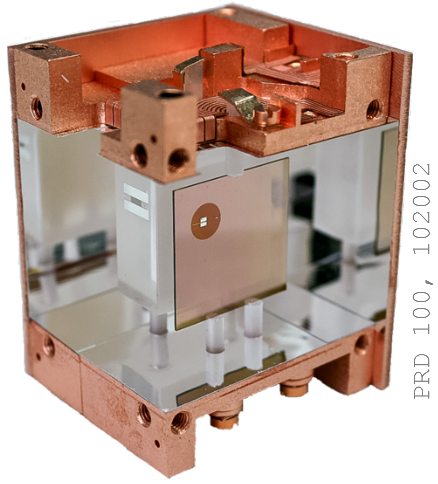


LIGHT DETECTOR

- Silicon on Sapphire (SOS) wafer
- 20 x 20 mm^2 and
  ≈ 0.5mm in thickness
- Baseline resolution: $\boldsymbol{\sigma} \approx 1$ eV

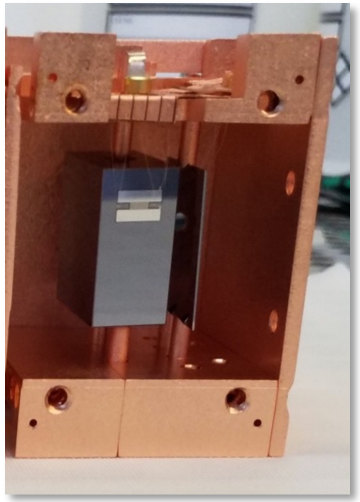


CRESST-III @ LNGS



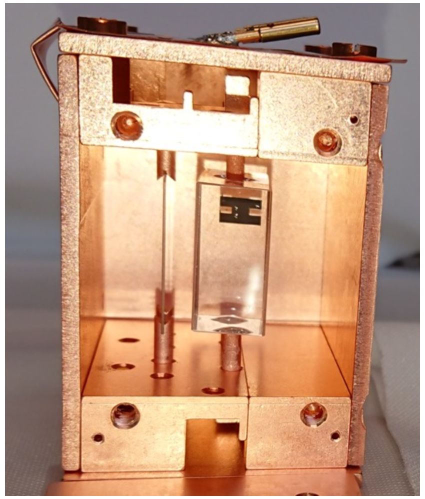
PRD 100, 102002

Detector A - $CaWO_4$:
23.6 g
exposure: 5.698 kgd
E_{th}= 30.1 eV_{NR}



PRD 107, 122003

Si wafer detector:
0.35 g
exposure: 55.06 gd
E_{th}= 10.0 eV_{NR}



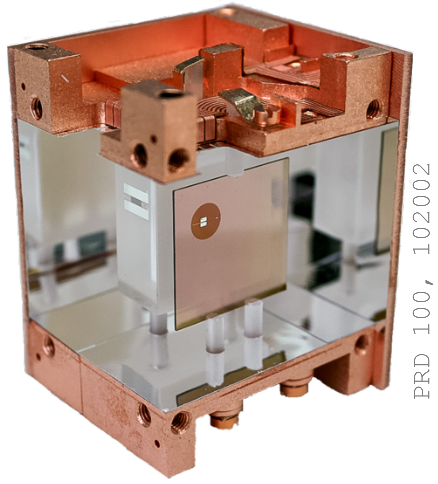
arXiv:2405.06527

Al_2O_3 wafer detector:
0.6 g
exposure: 0.14 kgd
E_{th}= 6.7 eV_{NR}

different target materials in two modi:

- phonons + scintillation (NR/ER discrimination)
- phonons only

CRESST-III @ LNGS



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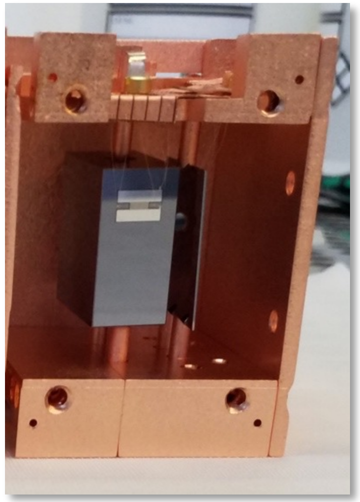
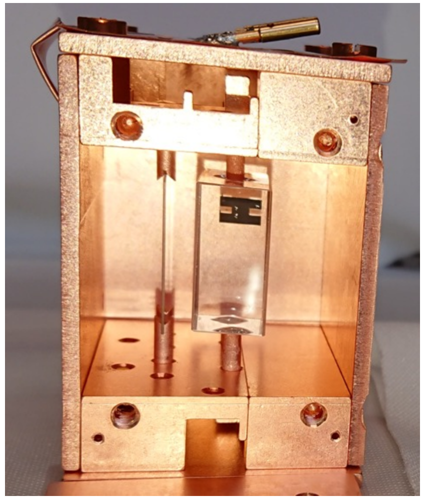
exposure: 5.698 kgd
E_{th}= 30.1 eV_{NR}



Si wafer detector:
0.35 g
exposure: 55.06 gd
E_{th}= 10.0 eV_{NR}

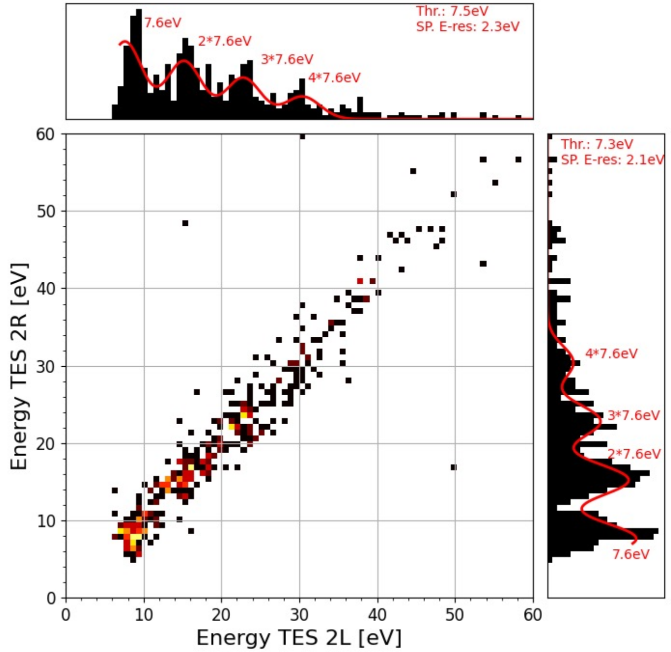


Al_2O_3 wafer detector:
0.6 g
exposure: 0.14 kgd
E_{th}= 6.7 eV_{NR}

different target materials in two modi:

- phonons + scintillation (NR/ER discrimination)
- phonons only

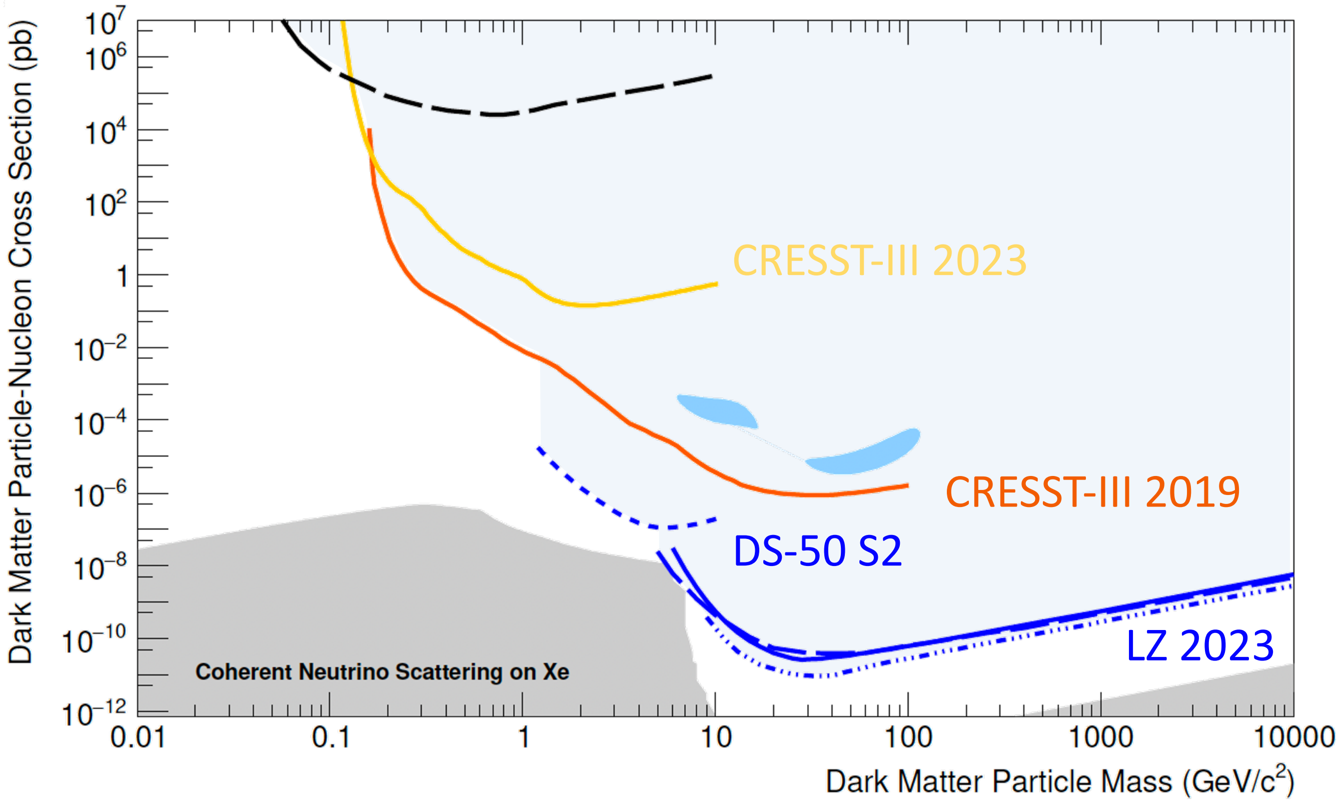
credits: P. Guillaumo, CRESST collaboration



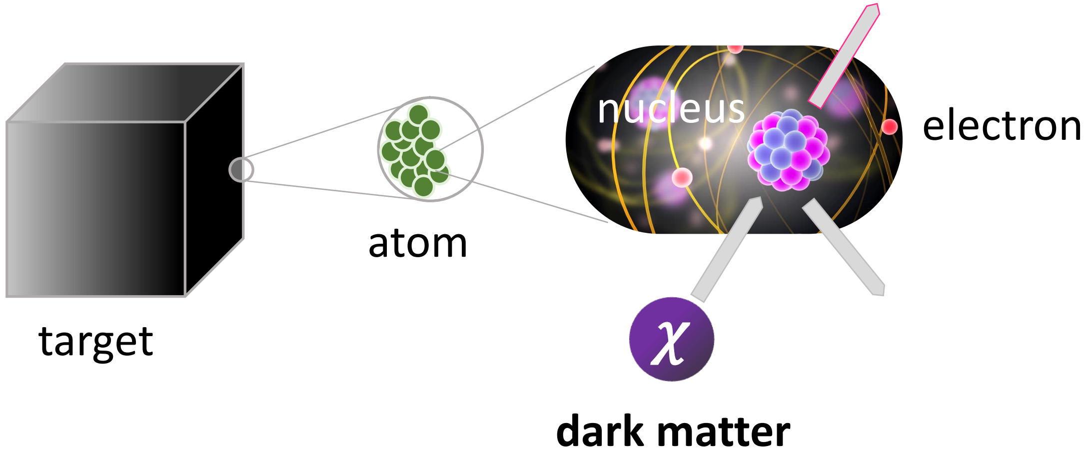
„stack detector" with double TES:

- baseline resolution: ~1 eV
- analysis threshold: ~7.5 eV
- single photon detection

STATUS OF DM DIRECT DETECTION EXPERIMENTS



→ **observable:**
kinetic energy of nuclear recoil

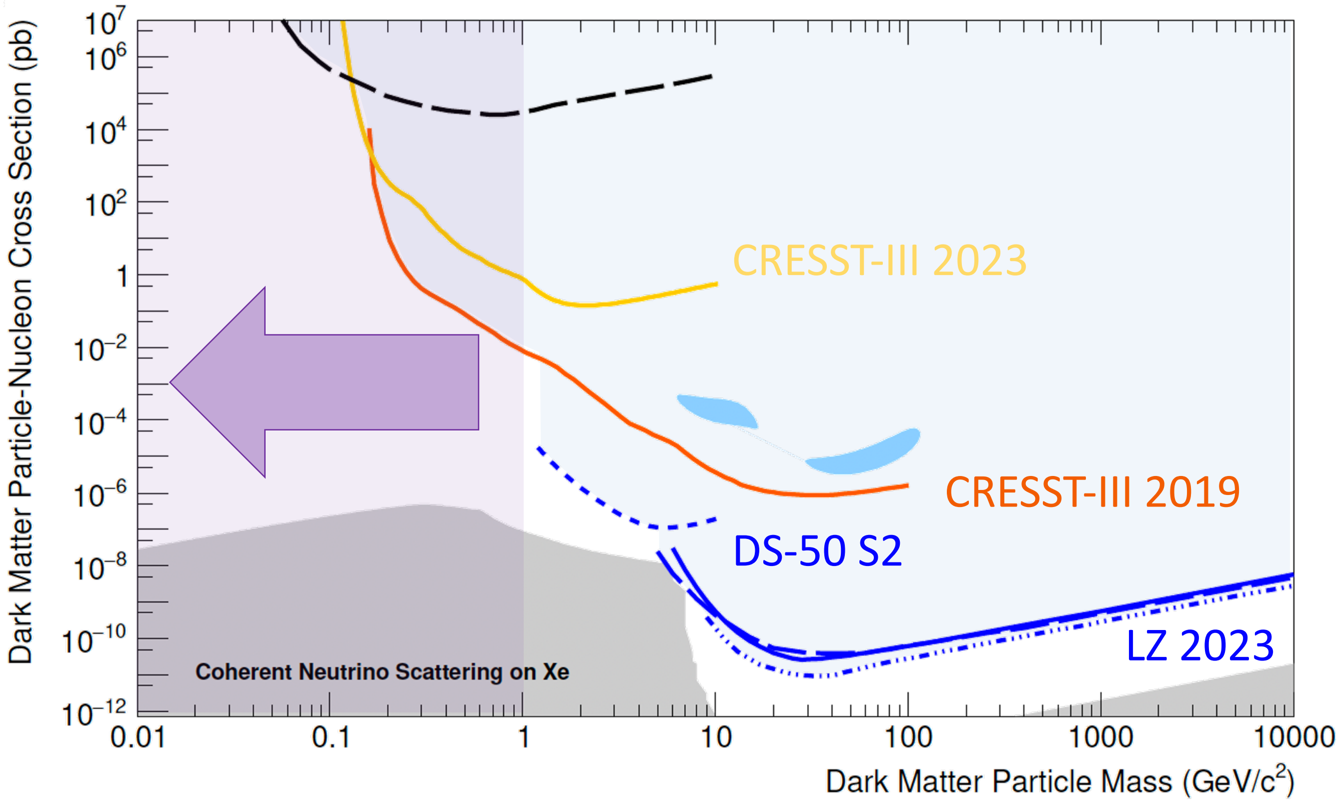


Cryogenic detectors set world leading limits !

CRESST-III:

- resolution of $\mathcal{O}(1)$ eV
- absorber mass $\mathcal{O}(1\text{-}10)$ g
- probed parameter space < 100 MeV/c^2

LOW MASS SECTOR → **discovery potential !!**



Frontier: light particles < 1 GeV/c^2

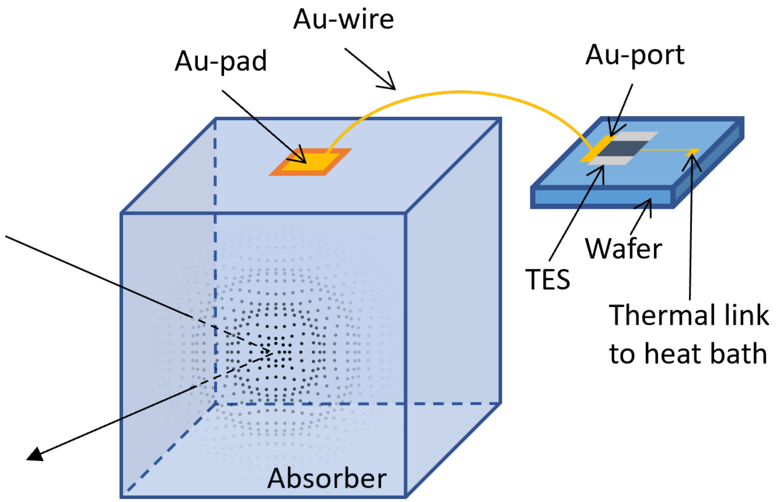
current best limits by cryogenic experiments (CRESST-III, 1.0 eV resolution, TESSERACT has new prototype)

→ detector performance is key

→ vast regions of unexplored space

COSINUS – the "cold" DAMA/LIBRA -check

remoTES readout for NaI NIM A1045 167532



TES on separate wafer

→ absorber excluded from fabrication process

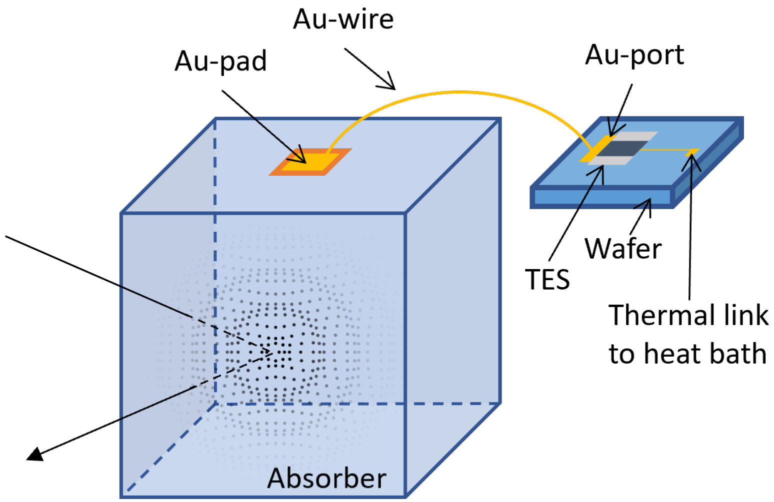
→ **key-technology for NaI**

FUTURE OPPORTUNITIES:

→ open field for novel materials
→ easy-to-fabricate
→ enabling large arrays

COSINUS – the "cold" DAMA/LIBRA -check

remoTES readout for NaI NIM A1045 167532



TES on separate wafer

→ absorber excluded from fabrication process

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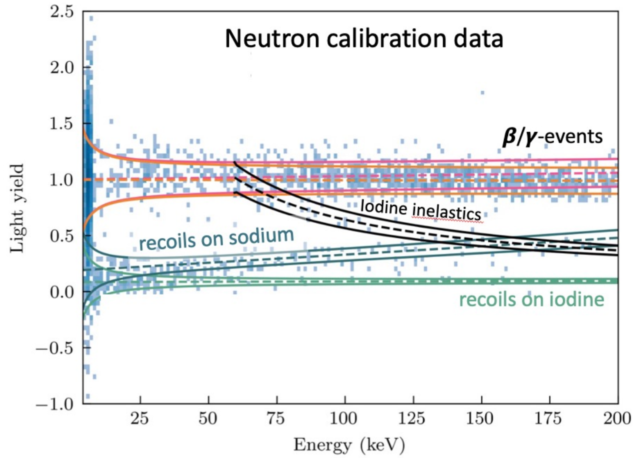
FUTURE OPPORTUNITIES:

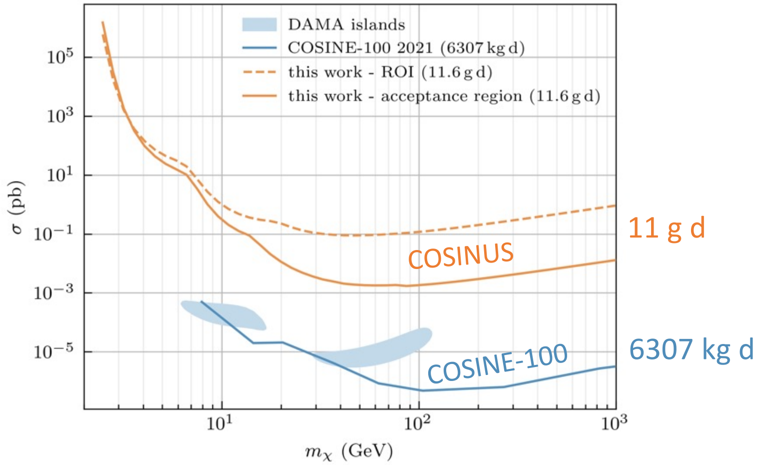
→ open field for novel materials
→ easy-to-fabricate
→ enabling large arrays

first physics results

PRD 110, 043010, 2024

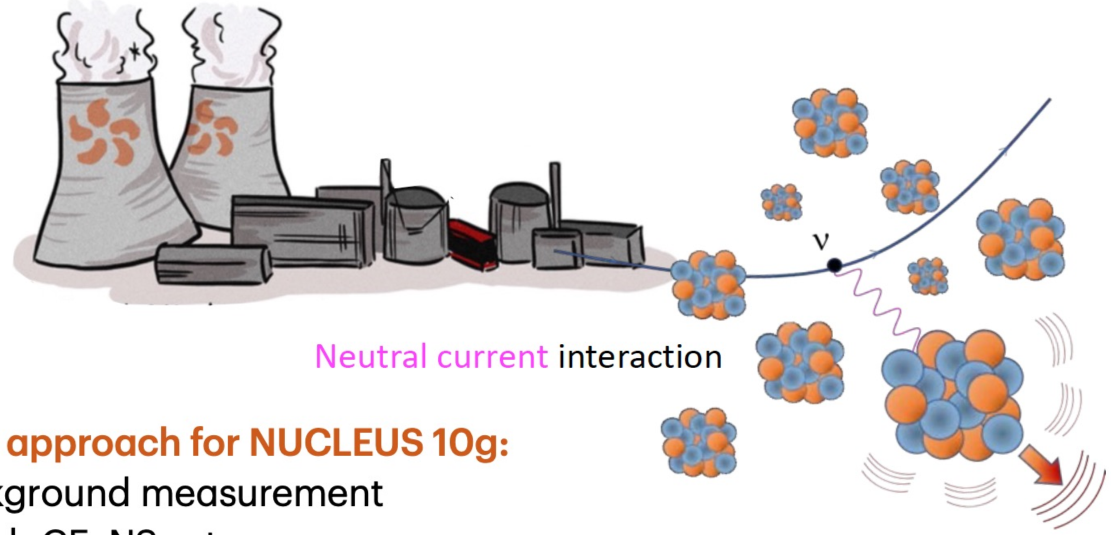


σ(NaI) = (0.441±0.011) keV

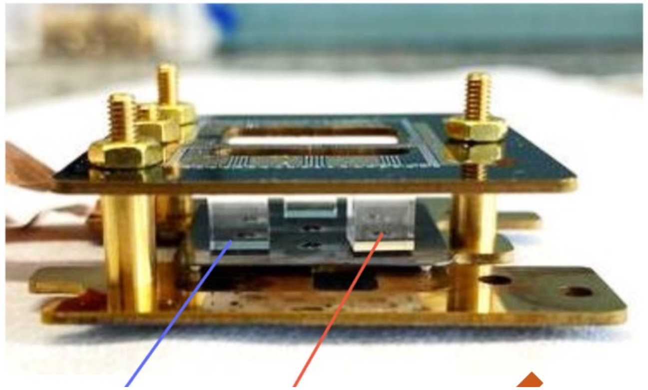


NUCLEUS

Coherent Elastic Neutrino-Nucleus Scattering (CEνNS)

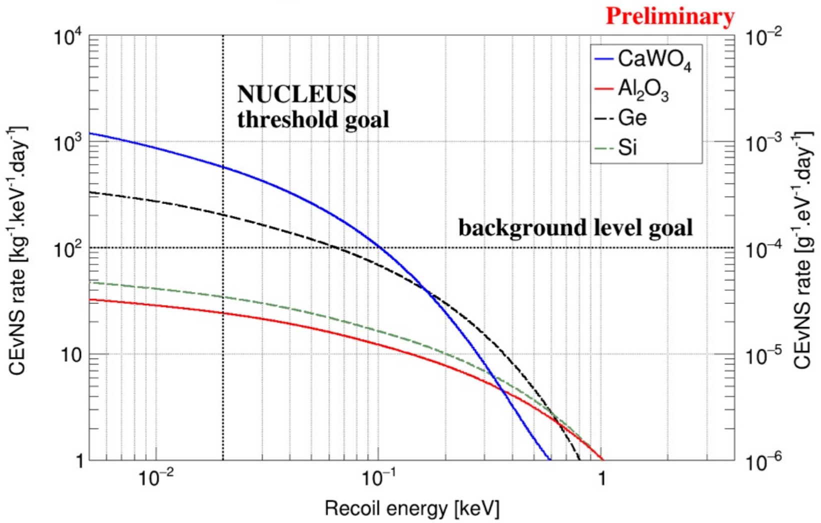


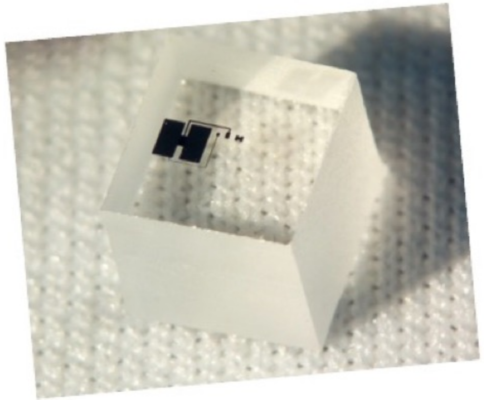
Neutral current interaction



Phys. Rev. D 96, 022009 (2017)

Multi-target approach for NUCLEUS 10g:
- Al_2O_3 background measurement
- $CaWO_4$ high CEvNS rate



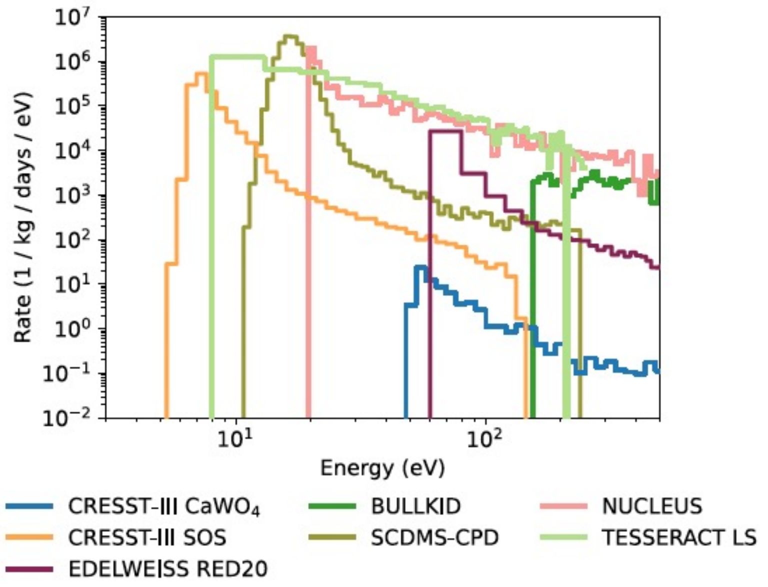


NUCLEUS Al_2O_3 prototype:
- **5x5x5 mm^3**
- **E_{th}= (19.7 +/- 0.8) eV**

PHONON-ONLY LOW ENERGY EXCESS (LEE)

arXiv:2503.08859

SciPost Phys. Proc. 9, 001 (2022)



steeply rising background towards lower energies

→ Low Energy Excesses

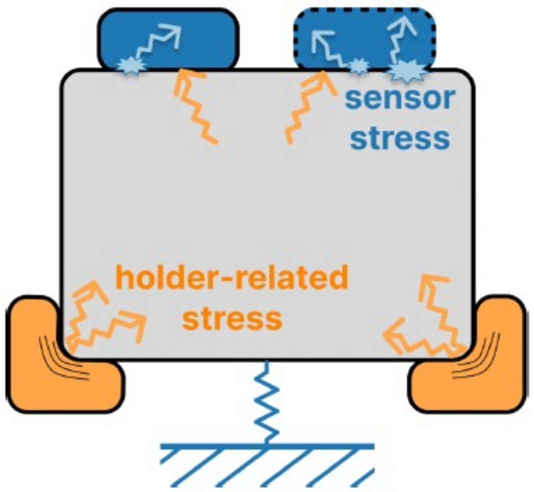
→ LEE has significant impact on dark matter sensitivity

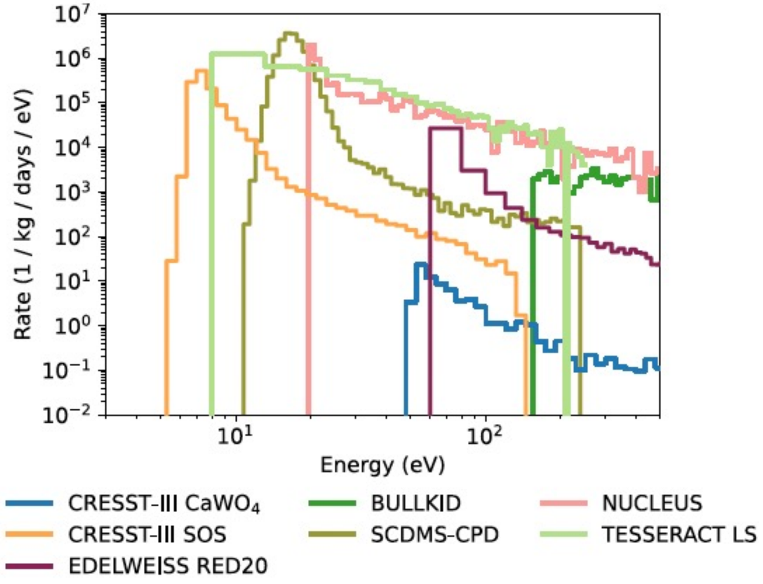
→ active community to solve LEE

PHONON-ONLY LOW ENERGY EXCESS (LEE)

arXiv:2503.08859

SciPost Phys. Proc. 9, 001 (2022)





steeply rising background towards lower energies

→ Low Energy Excesses

→ LEE has significant impact on dark matter sensitivity

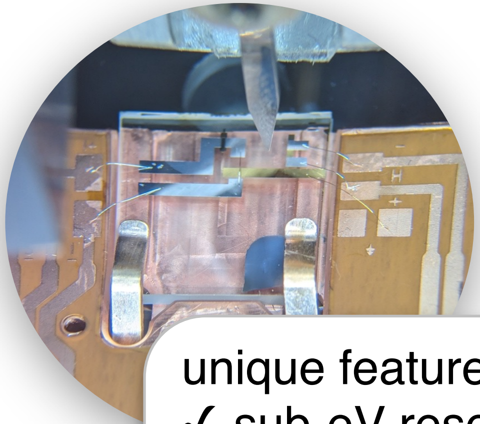
→ active community to solve LEE

Origin(s) still unclear / mitigation strategies under investigation:

- mounting stress / holder related stress
- sensor film relaxation (can be vetoed using more sensors on same target)
- intrinsic to substrate / targets (stress/defects from growth process)
- inconsistencies among different experiments → physics may be different...

(My) future vision for TES-based detectors

develop next-generation TES



unique features:
- ✓ sub-eV resolution
- ✓ reliable fab → T_c at 15 mK
- ✓ scalability $\mathcal{O}(100)$

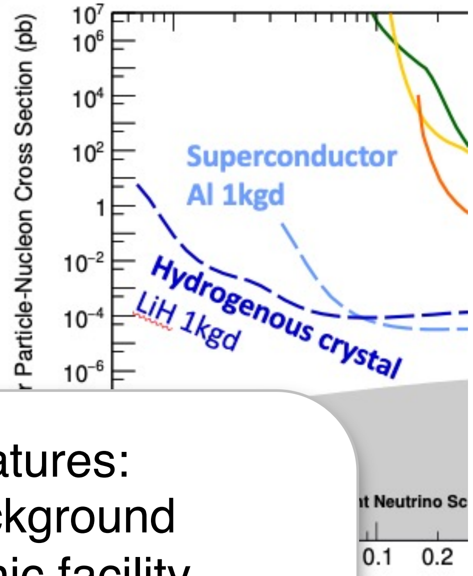
MAX PLANCK
HALBLEITERLABOR

mitigation of the Low Energy Excess (LEE)

strengthen synergies in the framework of the **Cryocluster** for intensive detector R&D

- ✓ collaboration with material scientists and solid state physicists
- ✓ innovative detector designs/layout

large arrays of novel and LEE-free detectors

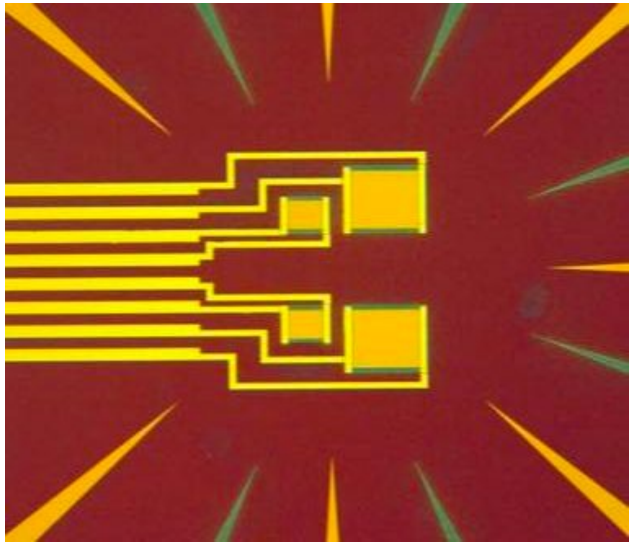


unique features:
- ✓ low-background cryogenic facility
- ✓ multiplexing
- ✓ less complex readout

One more thing…

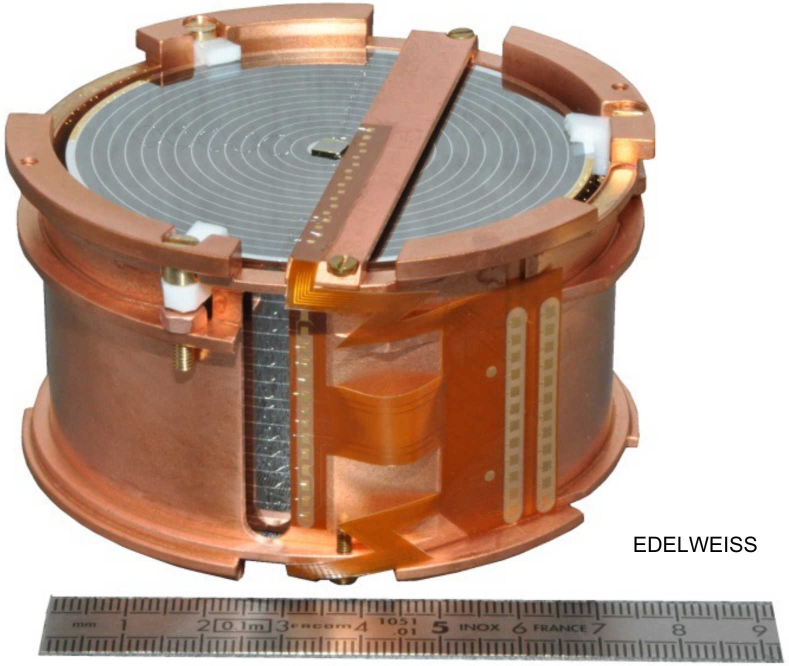
TES-detectors can do more…
LTDs in general, even much more …

LTDs ARE FLEXIBLE – 12th orders of magnitude



SW Nam/AE Lita

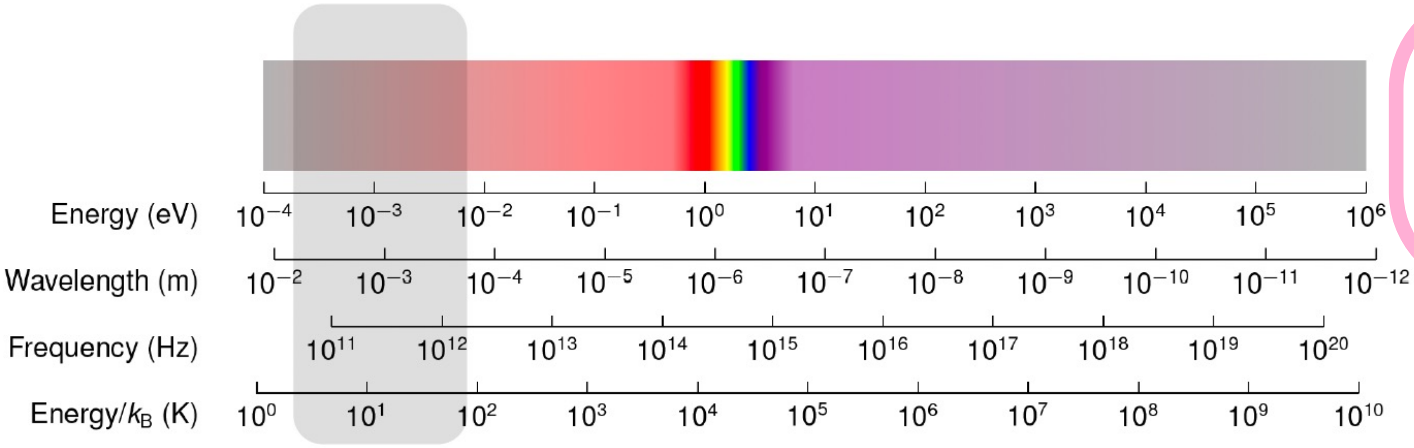
Monolithic W-TES detector
Volume: 2×10^{-16} m^3
Mass: 3 pg



EDELWEISS

Germanium dark matter detector
Volume: 49×10^{-6} m^3
Mass: 870 g

TES TO MEASURE PHOTONS



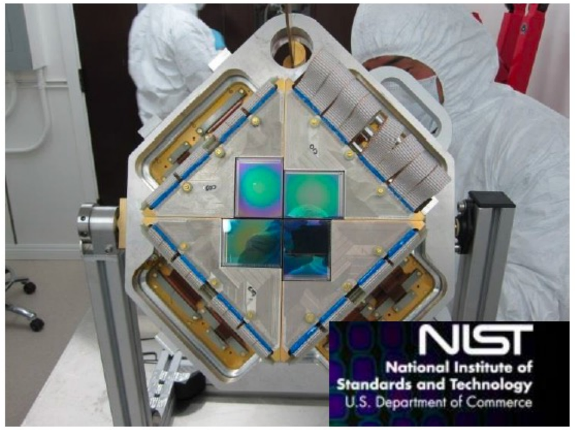
mm and sub-mm cameras

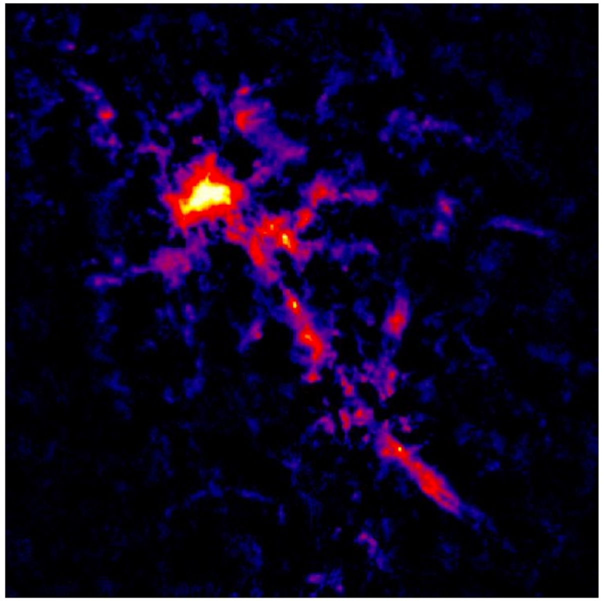
Astrophysics: studying the generation of stars and galaxies from cold gas

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)

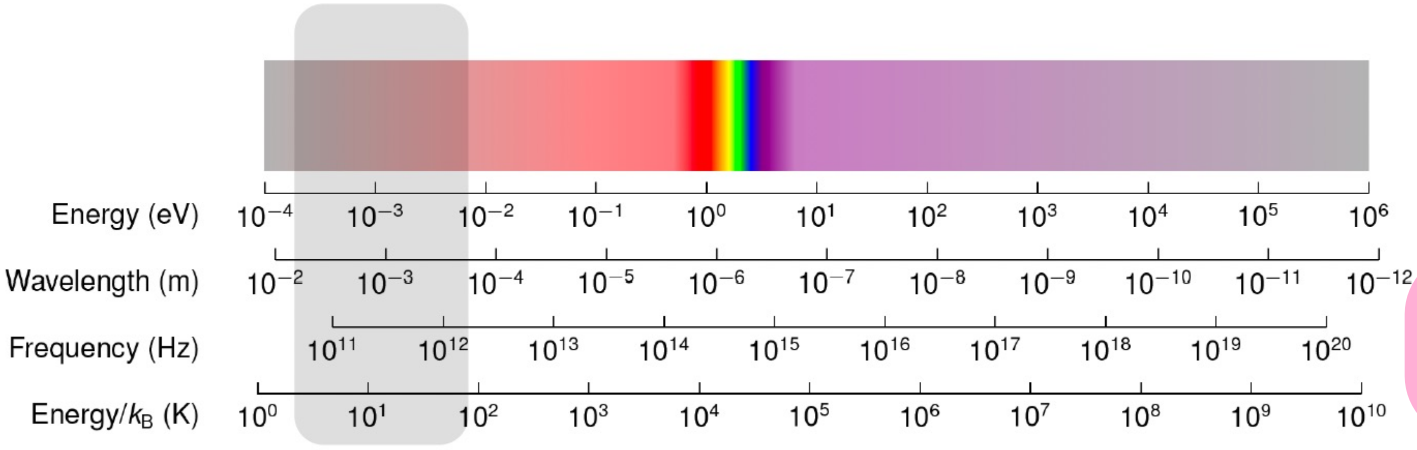




SCUBA2 map of the high-mass star forming region W51 at 850 um

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

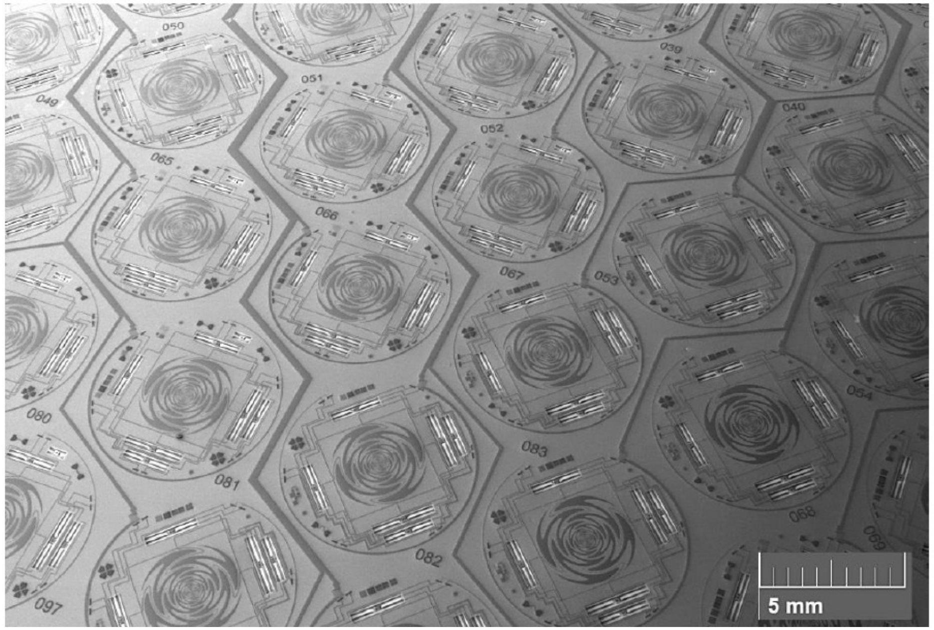
TES TO MEASURE PHOTONS



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)

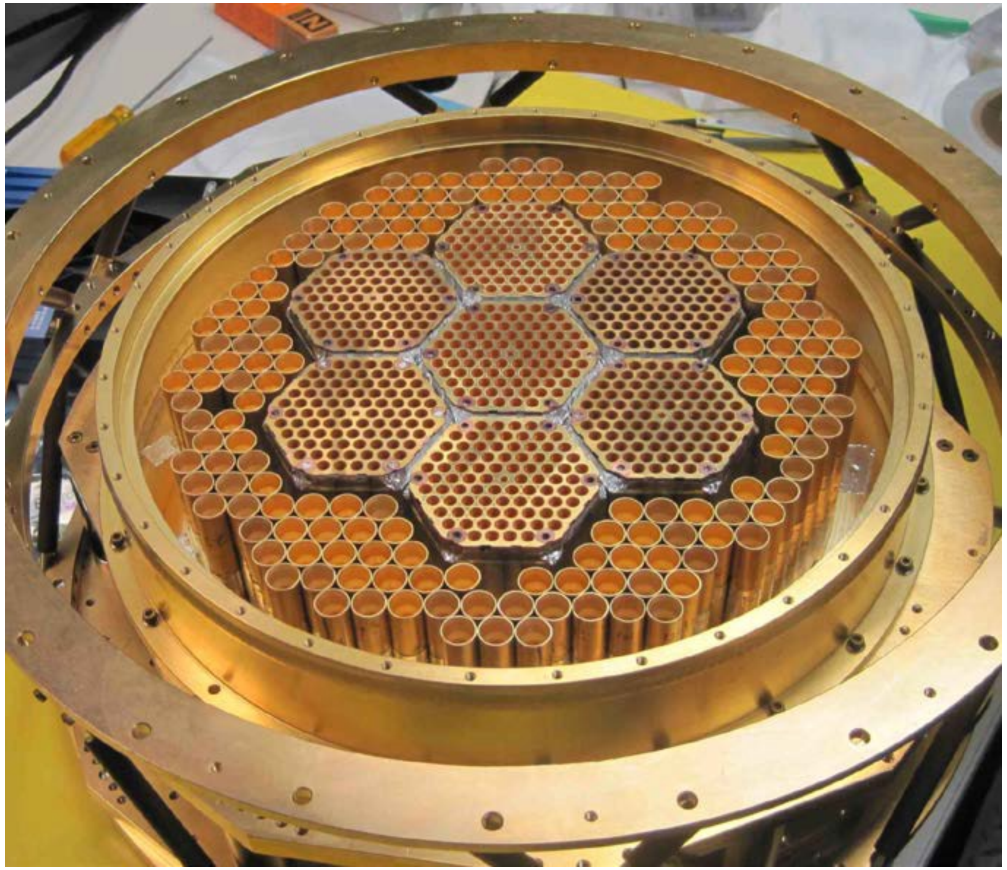
BICEP/Keck (BICEP2/Keck Array Collaborations X 2018)

CLASS (Harrington et al. 2016)

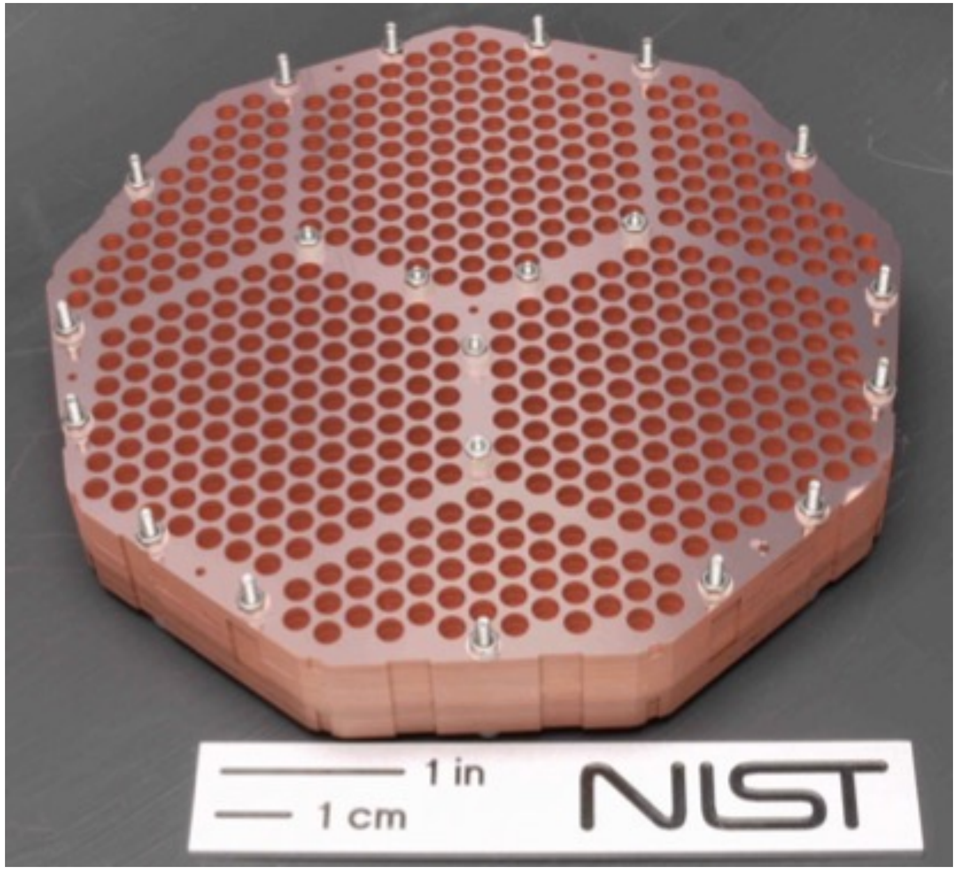
POLARBEAR/Simons Array (Suzuki et al. 2016; Hasegawa et al.2018)

SPT (Bender et al. 2018; Sayre et al. 2020)

COSMIC MICROWAVE BACKGROUND

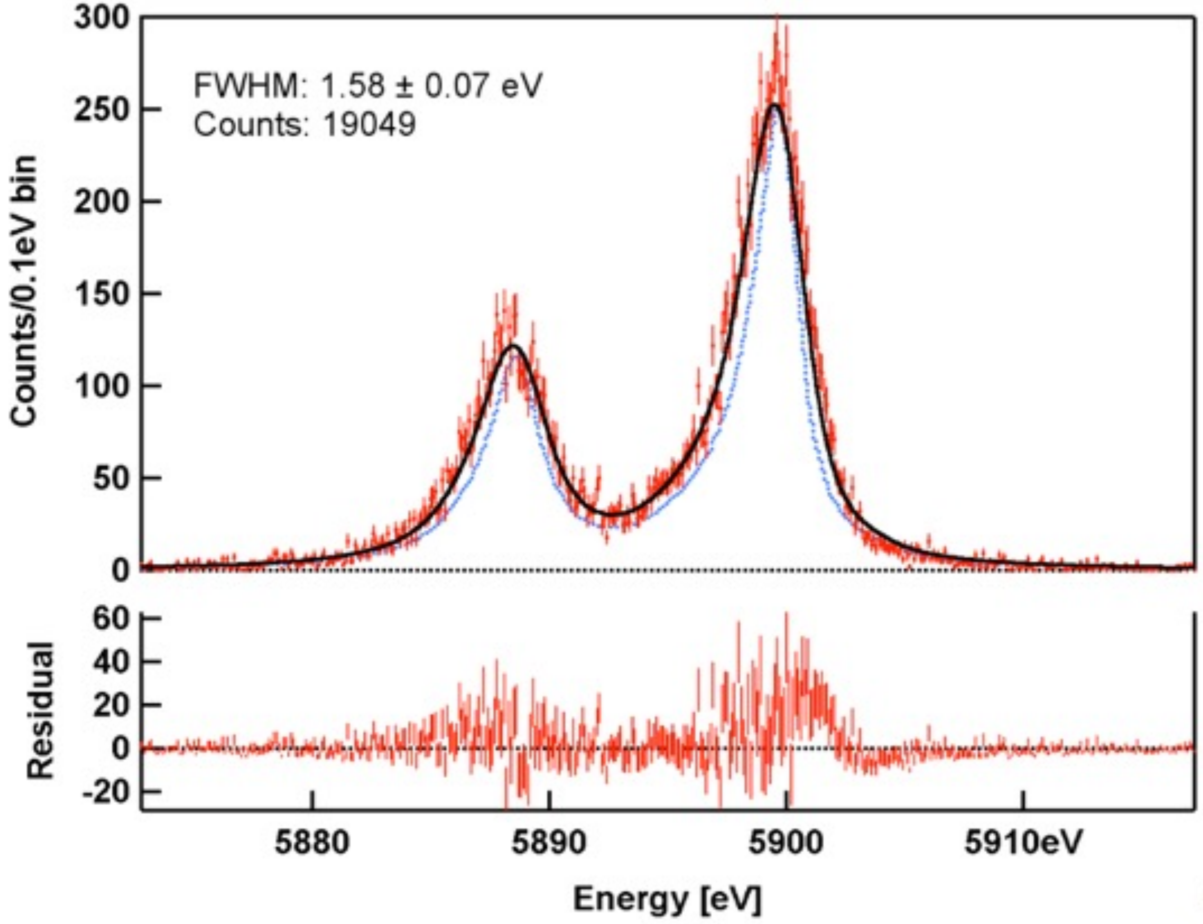


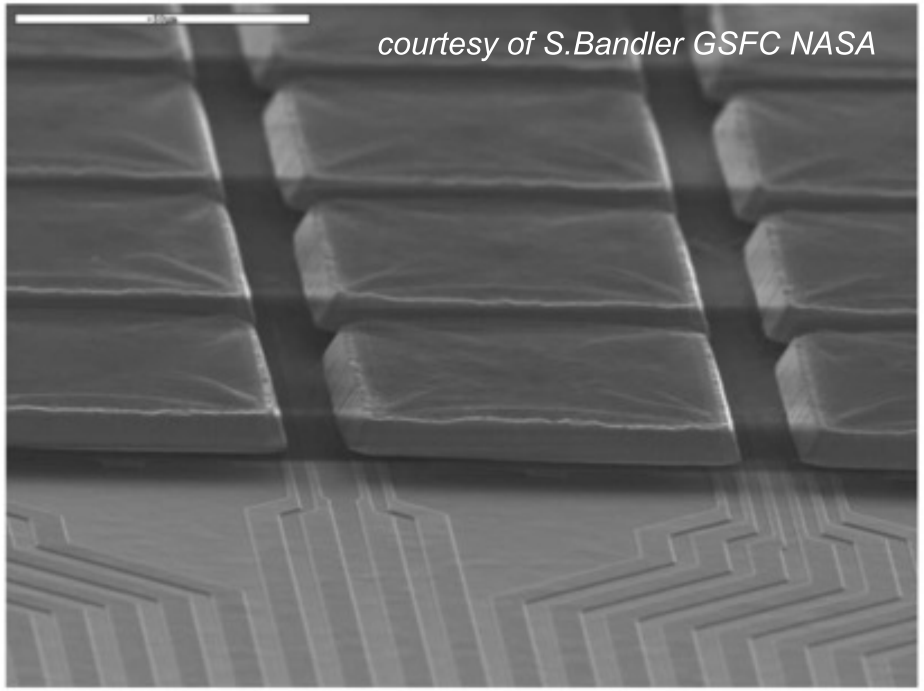
South Pole Telescope
(SPT: 1000 TES pixels)



Atacama Cosmological Telescope
(ACT: 3000 TES pixels)

SOFT X-ray SPECTRUM



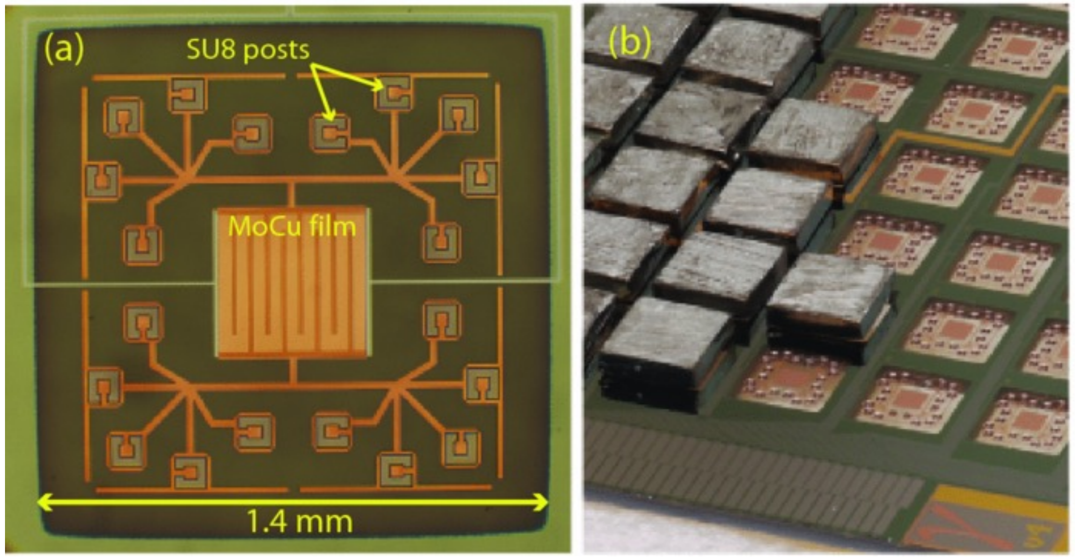


57 μm pixel with 30 μs time constant

thickness of Au absorbers 4.5 μm

1.58 eV FWHM @ 5.9keV

EXTENDING TO ~100 keV



Absorber Sn: 1.45 x 1.45 x 0.38 mm^3

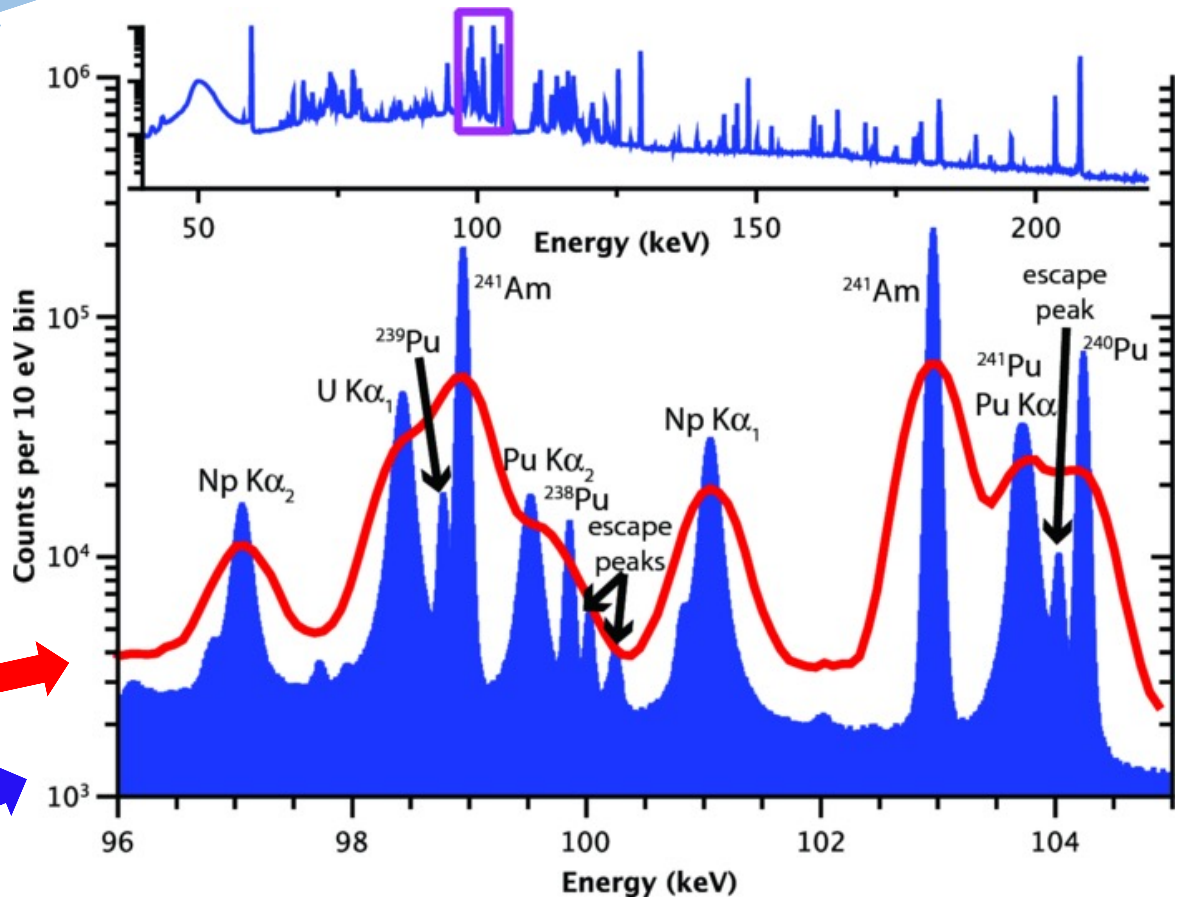
High efficiency for gamma and low C

High purity Germanium detector

$\Delta E = 25$ eV @ 100 keV

TES

SQUID multiplexing



Rev. Sci. Instrum.. 2012;83(9). doi:10.1063/1.4754630

Thank you for your attention!