Transition Edge Sensors:

From First Principles to Applications in Particle Detection and Quantum Technologies

José Alejandro Rubiera Gimeno

Postdoctoral researcher at Helmut-Schmidt-Universität (HSU)

HELMUT SCHMIDT UNIVERSITÄT
Universität der Bundeswehr Hamburg

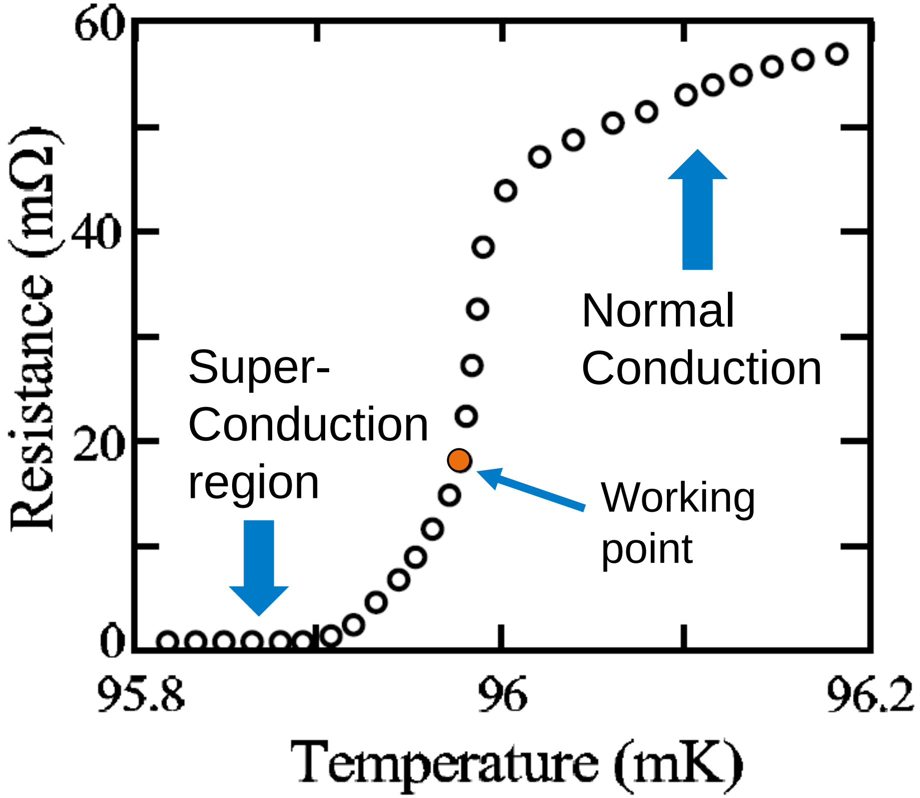
DESY.

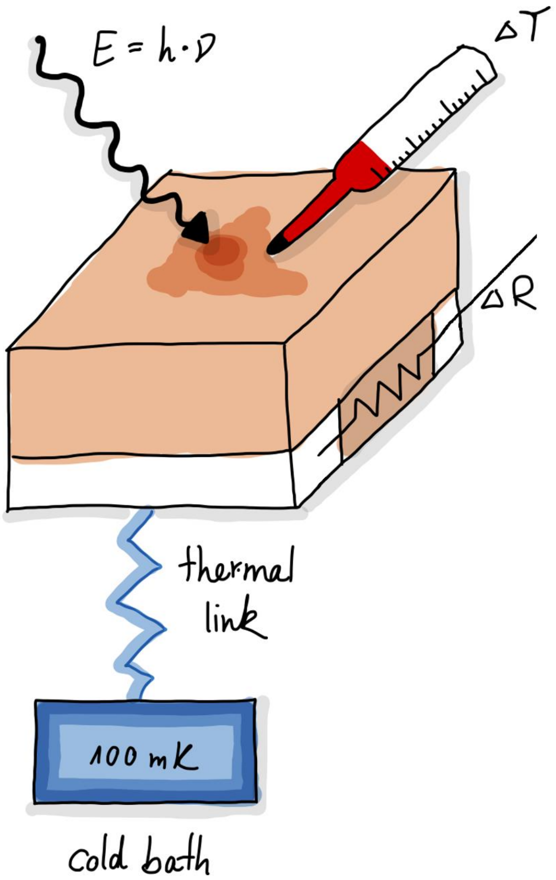
Outline

- Beginning of Transition Edge Sensors (TES)
- TES physics
- High energy photon detection
- Visible to IR photon detection
- Applications in Quantum technologies

*Courtesy of Katharina-Sophie Isleif

Transition Edge Sensor (TES)

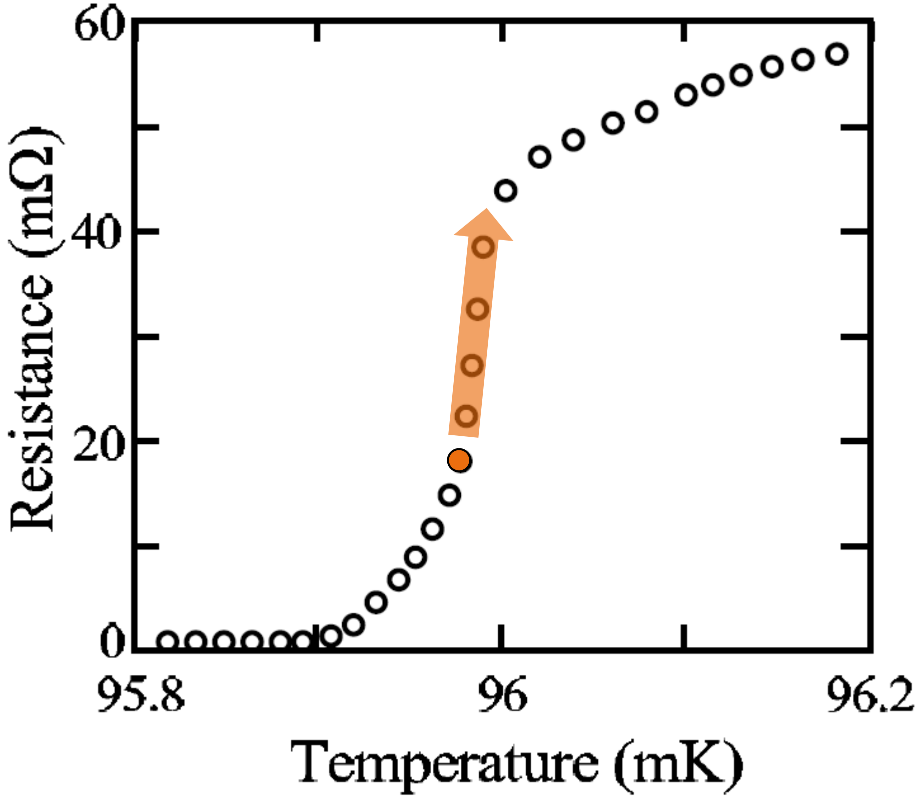


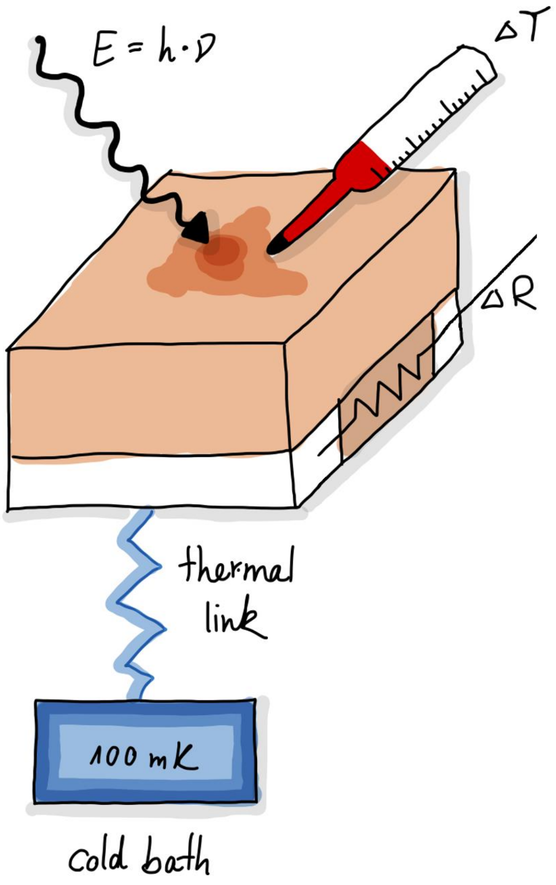


- Cryogenic detector operated at transition region
- Connected to a colder thermal bath
- Possible definition of the point in the transition

K. Irwin, G. Hilton, Transition-edge sensors, in: Cryogenic Particle Detection, Springer Berlin Heidelberg, Berlin, Heidelberg, 2005, pp. 63–150, http://dx.doi.org/10.1007/10933596_3.

Transition Edge Sensor (TES)

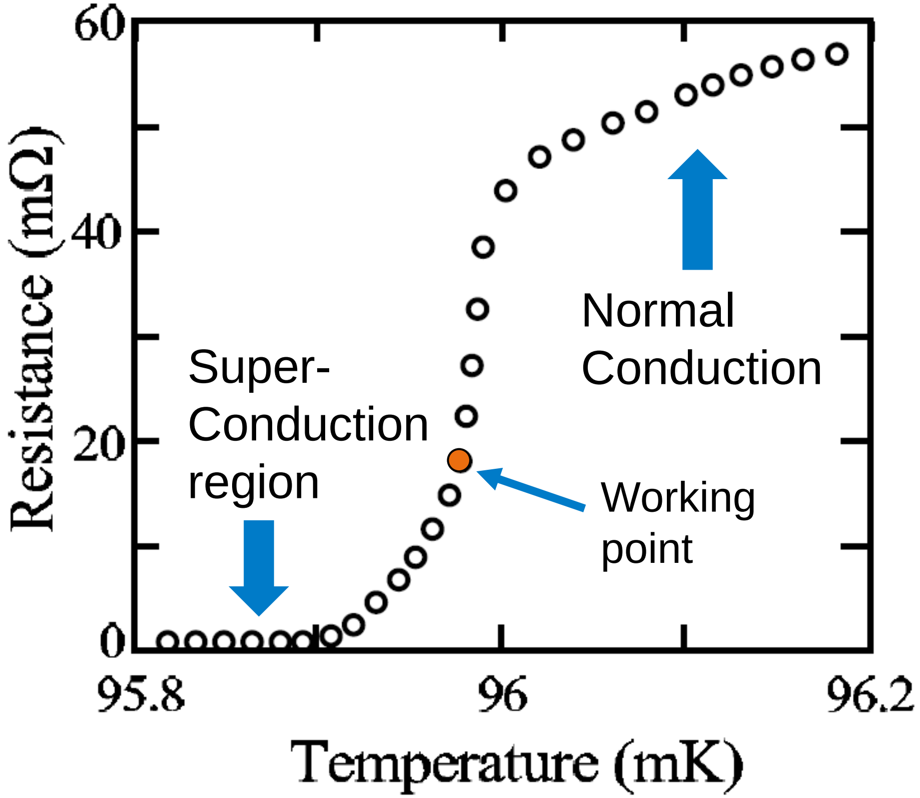


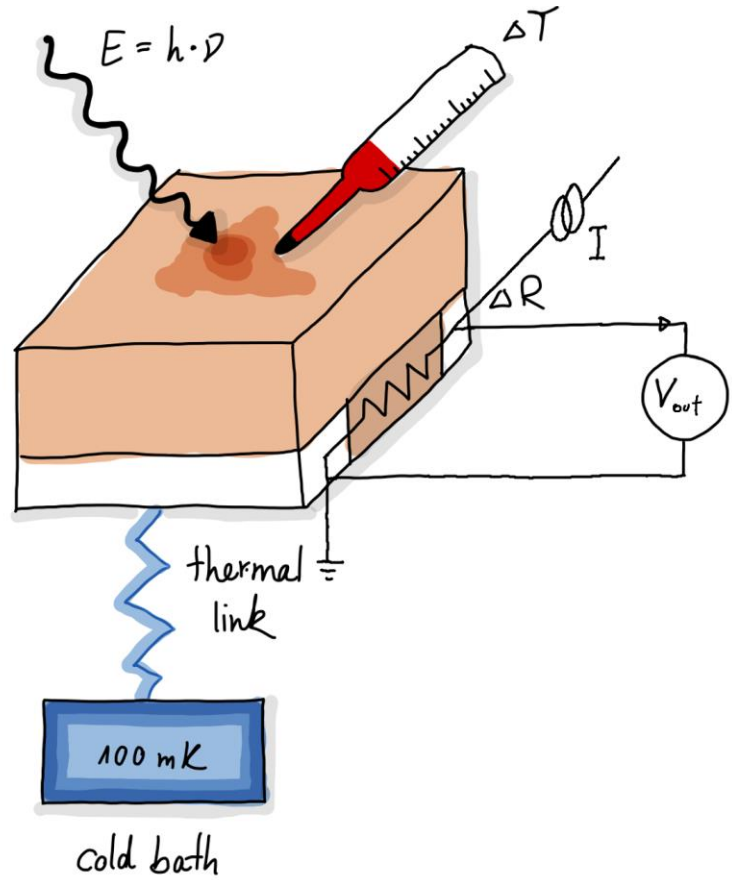


- Cryogenic detector operated at transition region
- Connected to a colder thermal bath
- Possible definition of the point in the transition
- Change in resistance produced by energy deposition
- Very good energy resolution

K. Irwin, G. Hilton, Transition-edge sensors, in: Cryogenic Particle Detection, Springer Berlin Heidelberg, Berlin, Heidelberg, 2005, pp. 63–150, http://dx.doi.org/10.1007/10933596_3.

First TESs (‘40s – ‘90s)

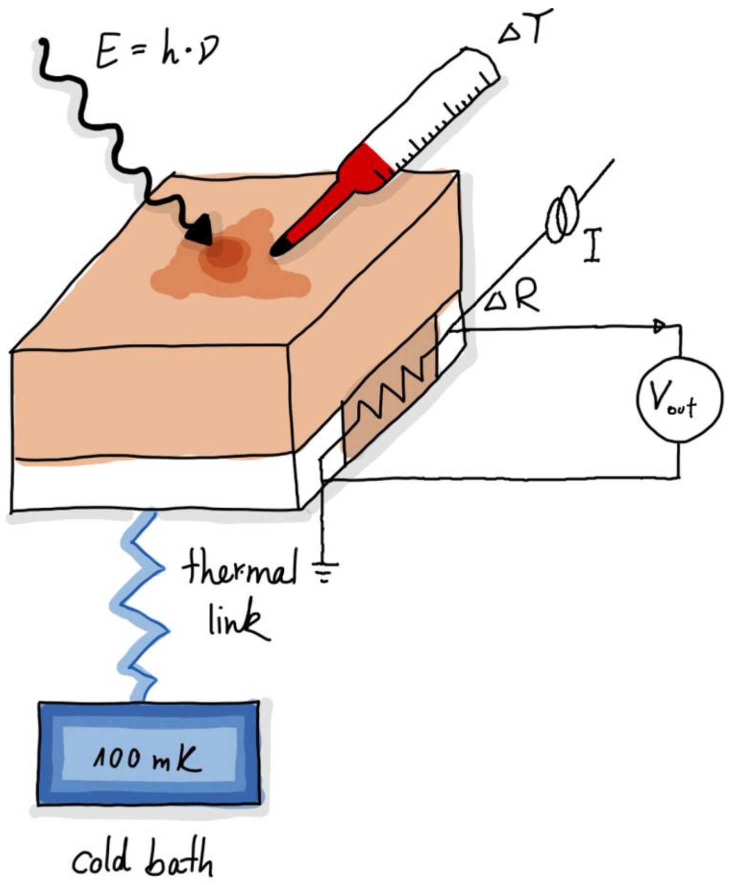




- Cryogenic detector operated at transition region
- Connected to a colder thermal bath
- Possible definition of the point in the transition
    - Controlling bath temperature

K. Irwin, G. Hilton, Transition-edge sensors, in: Cryogenic Particle Detection, Springer Berlin Heidelberg, Berlin, Heidelberg, 2005, pp. 63–150, http://dx.doi.org/10.1007/10933596_3.

First TESs ('40s – '90s)



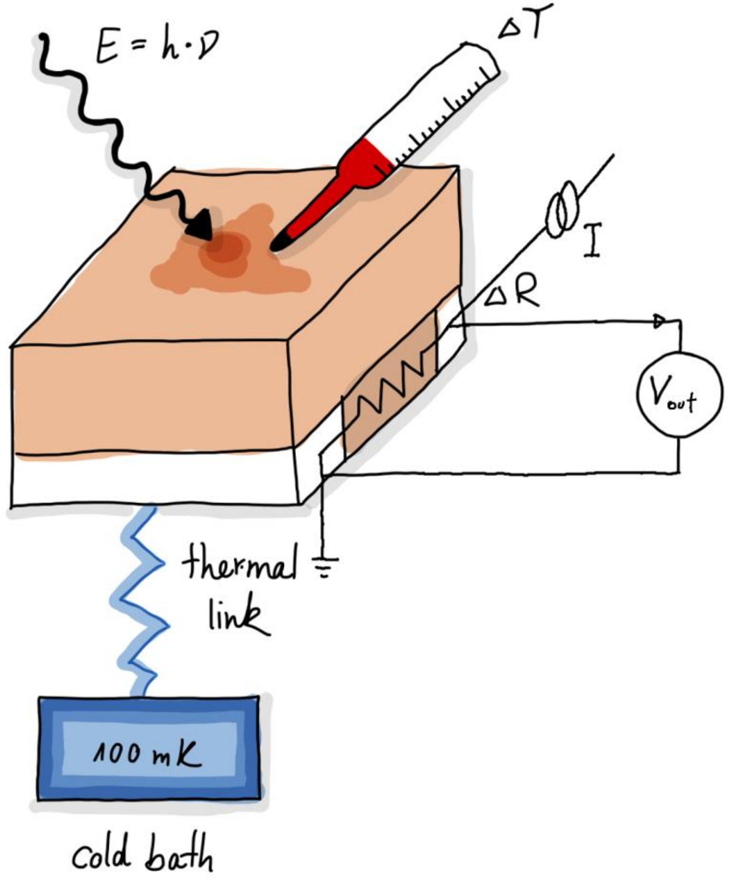
$$C\frac{dT}{dt} = -P_{bath} + P_{ext}$$

$$P_{bath} = K(T^n - T_{bath}^n)$$

Thermal circuit

- Cryogenic detector operated at transition region
- Connected to a colder thermal bath
- Possible definition of the point in the transition
  - Controlling bath temperature

First TESs (‘40s – ‘90s)



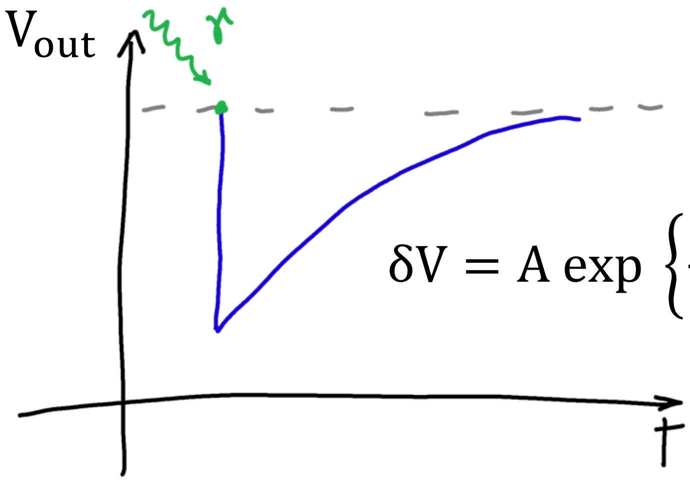
$$C\frac{dT}{dt} = -P_{bath} + P_{ext}$$

$$P_{bath} = K(T^n - T^n_{bath})$$

Thermal circuit

$$IR = V_{out}$$

Electrical circuit

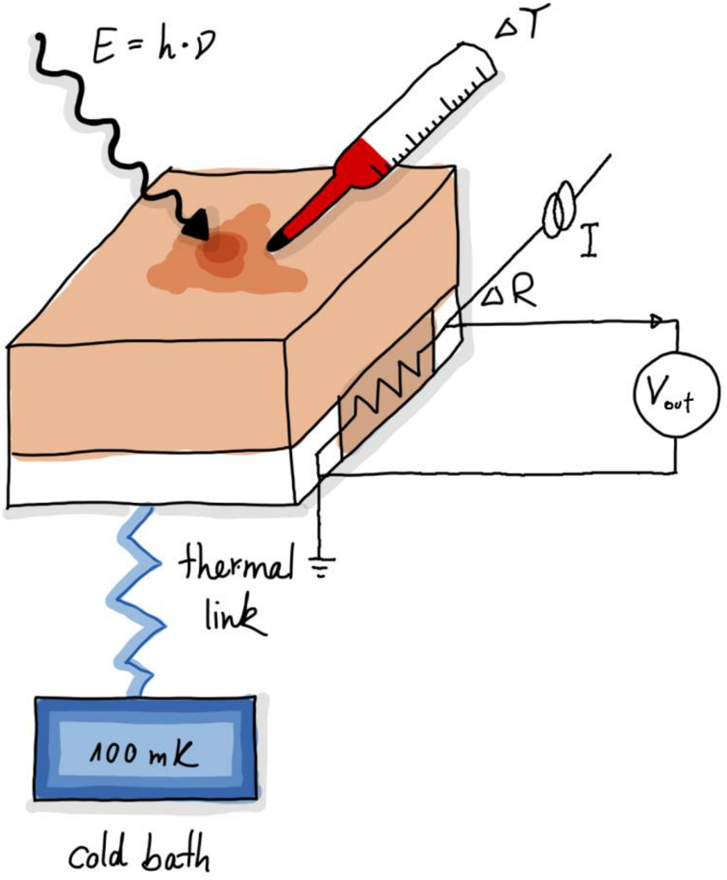


$$\tau = \frac{C}{nKT^{n-1}}$$

$$\delta V = A \exp\left\{-\frac{t}{\tau}\right\}$$

- Cryogenic detector operated at transition region
- Connected to a colder thermal bath
- Possible definition of the point in the transition
  - Controlling bath temperature

First TESs ('40s – '90s)



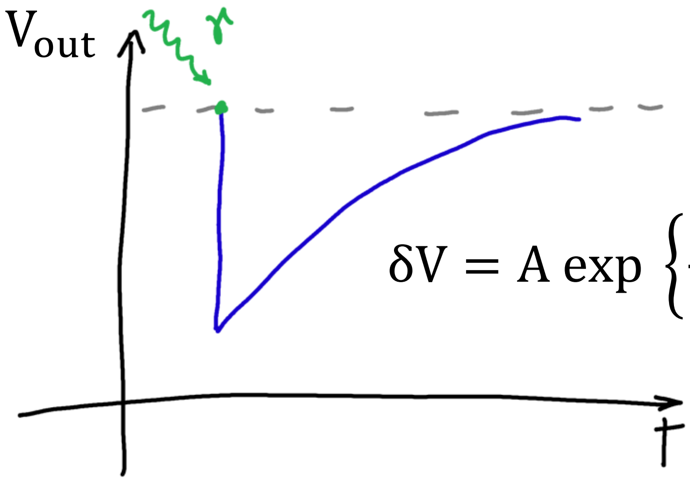
$$C\frac{dT}{dt} = -P_{bath} + P_{ext}$$

$$P_{bath} = K(T^n - T_{bath}^n)$$

Thermal circuit

$$IR = V_{out}$$

Electrical circuit



$$\delta V = A \exp\left\{-\frac{t}{\tau}\right\}$$

$$\tau = \frac{C}{nKT^{n-1}}$$

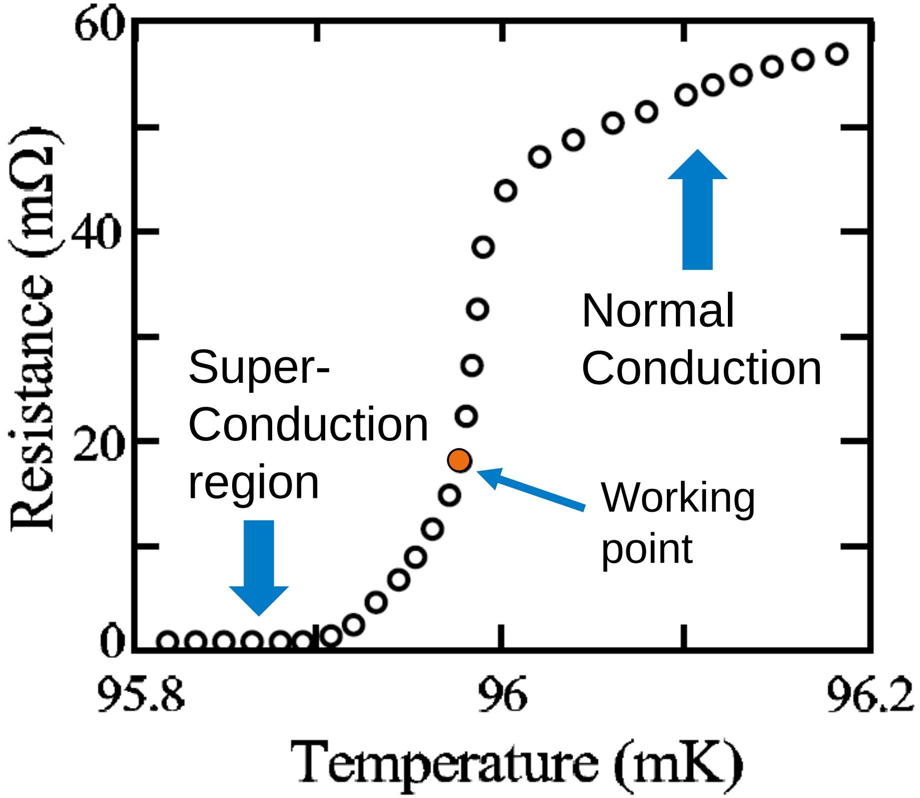
Readout with FET and other solutions

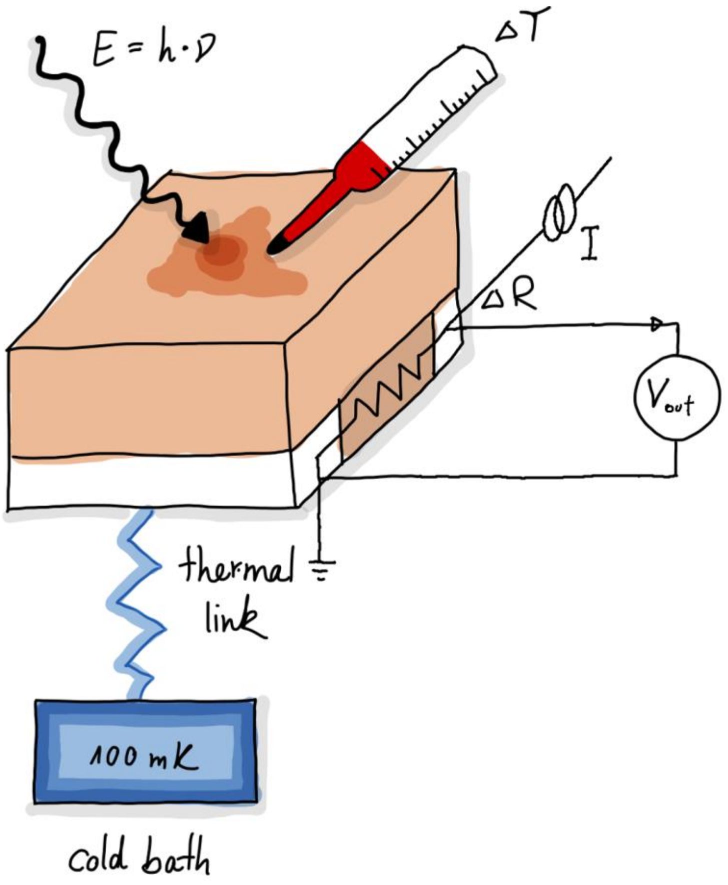
Very noisy ...

- Cryogenic detector operated at transition region
- Connected to a colder thermal bath
- Possible definition of the point in the transition
  - Controlling bath temperature

*Courtesy of Katharina-Sophie Isleif

First TESs ('40s – '90s)



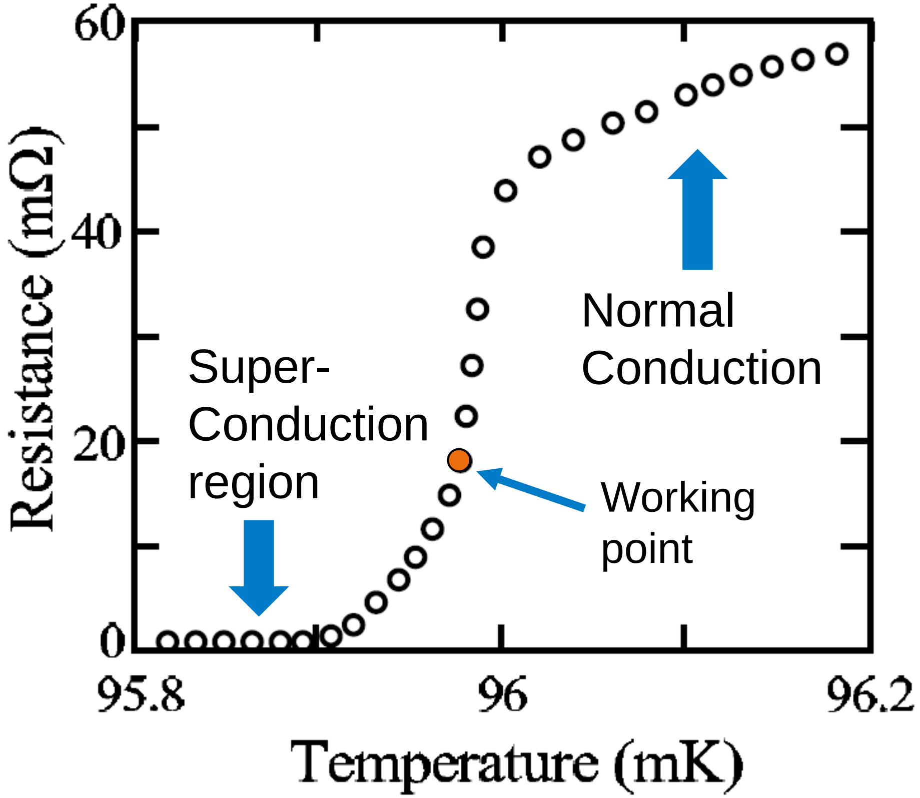


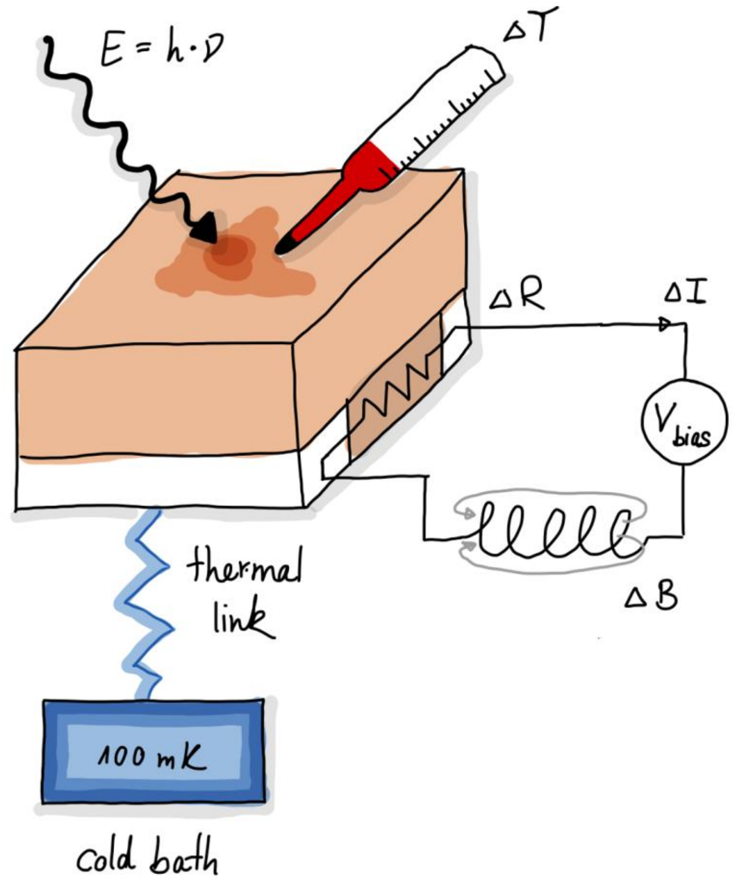
- Cryogenic detector operated at transition region
- Connected to a colder thermal bath
- Possible definition of the point in the transition
  - Controlling bath temperature

K. Irwin, G. Hilton, Transition-edge sensors, in: Cryogenic Particle Detection, Springer Berlin Heidelberg, Berlin, Heidelberg, 2005, pp. 63–150, http://dx.doi.org/10.1007/10933596_3.

*Courtesy of Katharina-Sophie Isleif

Nowadays TES physics



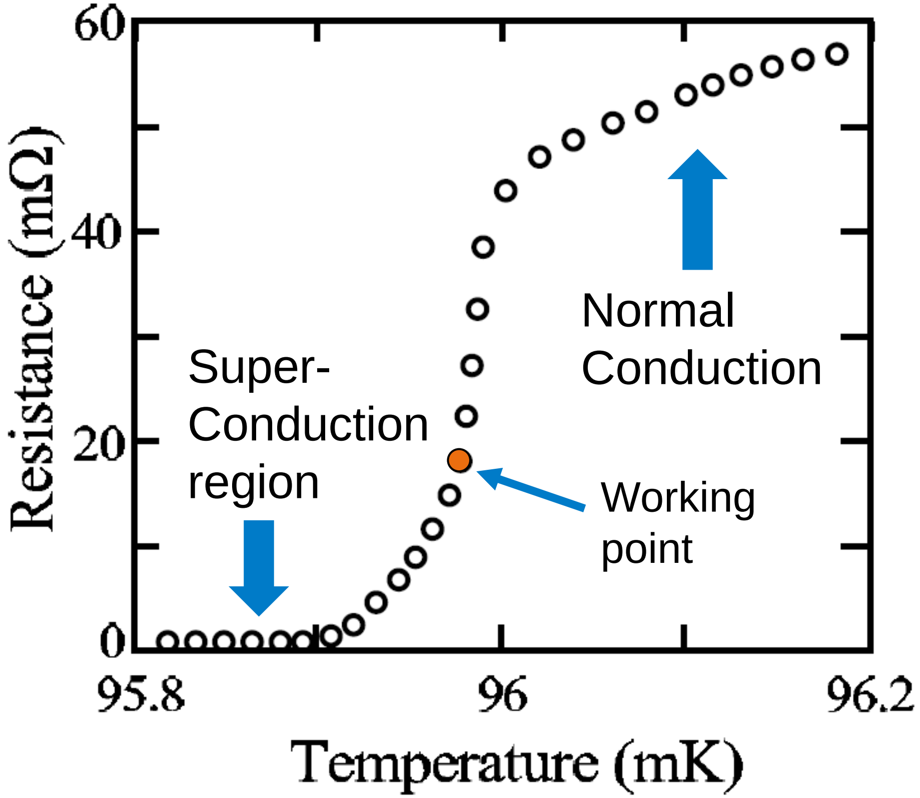


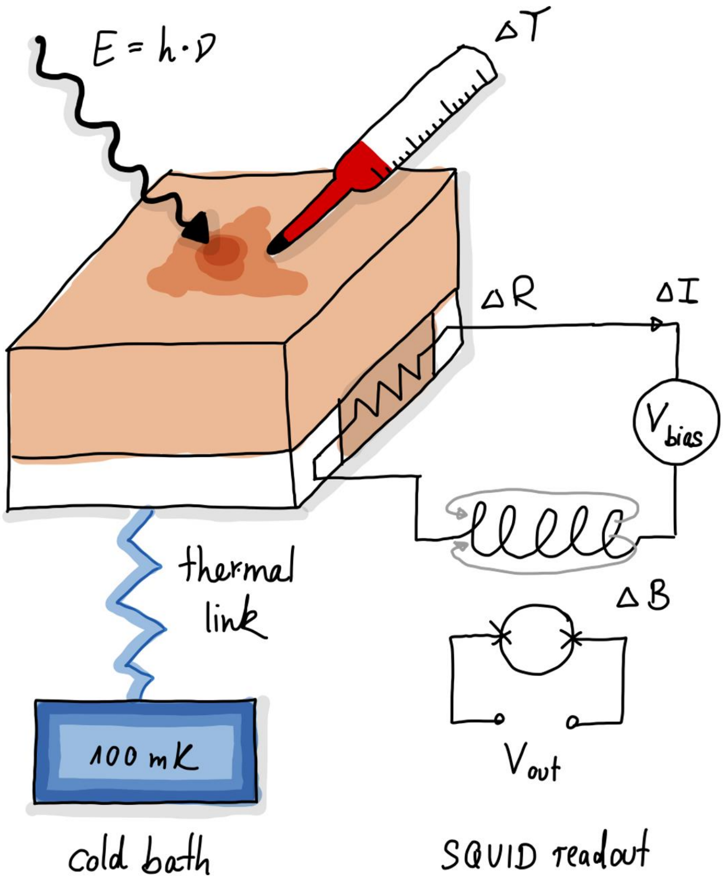
- Cryogenic detector operated at transition region
- Connected to a colder thermal bath
- Possible definition of the point in the transition
  - Voltage-biased TES

K. Irwin, G. Hilton, Transition-edge sensors, in: Cryogenic Particle Detection, Springer Berlin Heidelberg, Berlin, Heidelberg, 2005, pp. 63–150, http://dx.doi.org/10.1007/10933596_3.

*Courtesy of Katharina-Sophie Isleif

Nowadays TES physics

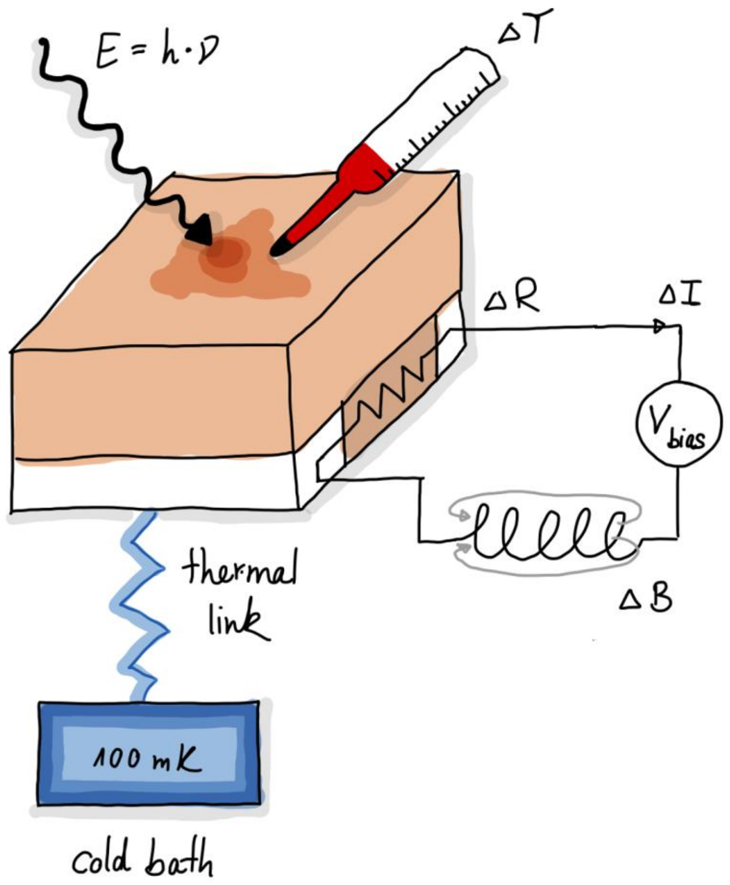




- Cryogenic detector operated at transition region
- Connected to a colder thermal bath
- Possible definition of the point in the transition
  - Voltage-biased TES
- Superconducting Quantum Interference Device (SQUID) readout

K. Irwin, G. Hilton, Transition-edge sensors, in: Cryogenic Particle Detection, Springer Berlin Heidelberg, Berlin, Heidelberg, 2005, pp. 63–150, http://dx.doi.org/10.1007/10933596_3.

Nowadays TES physics



$$C\frac{dT}{dt} = -P_{bath} + V_{bias}^2/R + P_{ext}$$

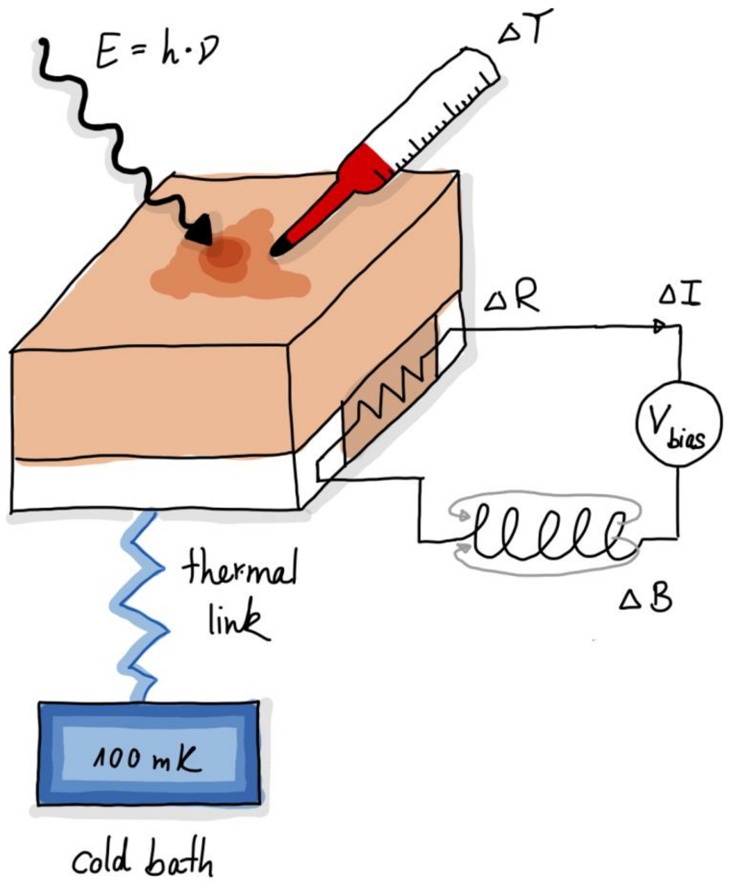
$$P_{bath} = K(T^n - T_{bath}^n)$$

Thermal circuit

TES can be at different temperature than bath

- Cryogenic detector operated at transition region
- Connected to a colder thermal bath
- Possible definition of the point in the transition
    - Voltage-biased TES

Nowadays TES physics



$$C\frac{dT}{dt} = -P_{bath} + V_{bias}^2/R + P_{ext}$$

$$P_{bath} = K(T^n - T_{bath}^n)$$

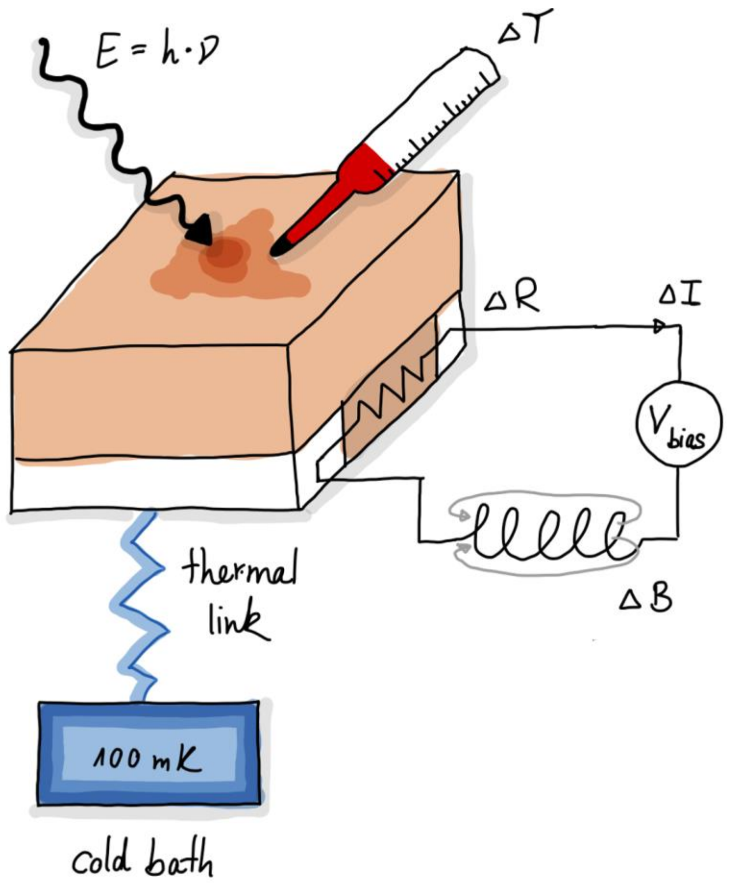
Thermal circuit

$$L\frac{dI}{dt} = V_{bias} - IR$$

Electrical circuit

- Cryogenic detector operated at transition region
- Connected to a colder thermal bath
- Possible definition of the point in the transition
  - Voltage-biased TES

Nowadays TES physics



$$C\frac{dT}{dt} = -P_{bath} + V_{bias}^2/R + P_{ext}$$

$$P_{bath} = K(T^n - T_{bath}^n)$$

Thermal circuit

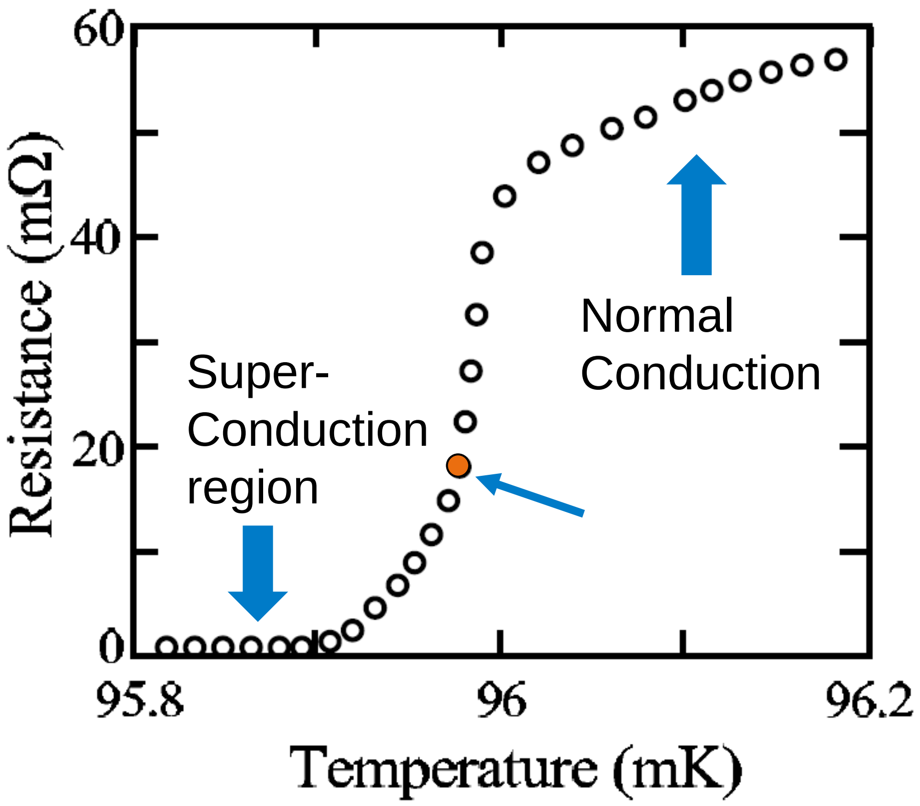
$$L\frac{dI}{dt} = V_{bias} - IR$$

Electrical circuit

Non-linear system

- Cryogenic detector operated at transition region
- Connected to a colder thermal bath
- Possible definition of the point in the transition
  - Voltage-biased TES

TES Small Signal Theory



- Cryogenic detector operated at transition region
- Connected to a colder thermal bath
- Possible definition of the point in the transition
  - Voltage-biased TES

$$\frac{dT}{dt} = -P_{bath} + V_{bias}^2/R + P_{ext}$$

$$P_{bath} = K(T^n - T_{bath}^n)$$

Thermal circuit

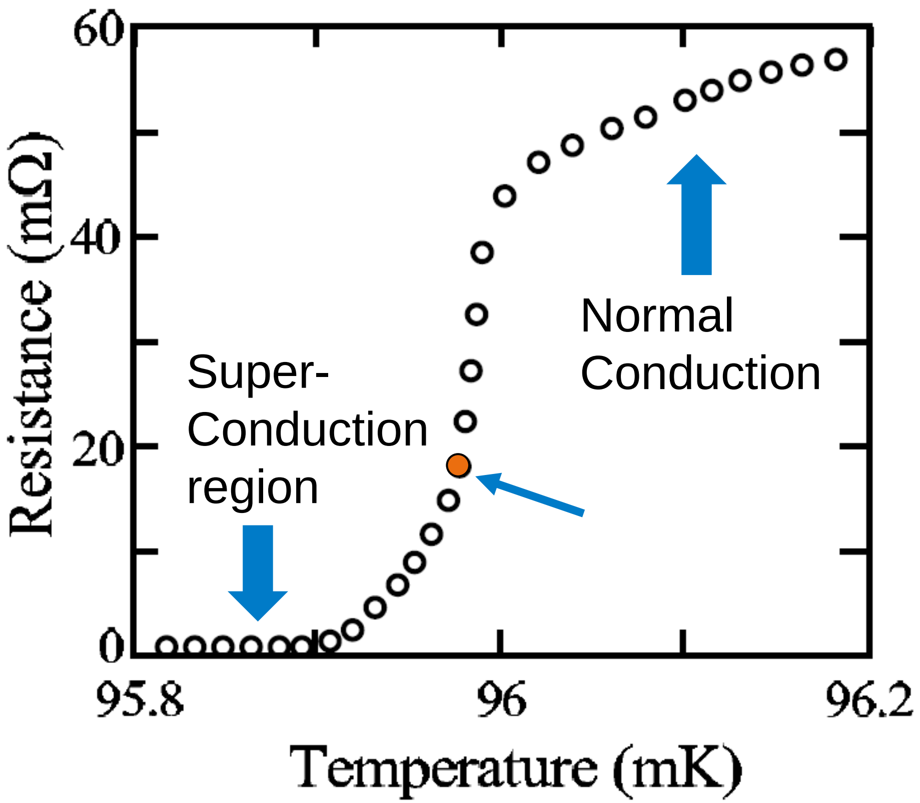
$$L\frac{dI}{dt} = V_{bias} - IR$$

Electrical circuit

Linearize with respect to working point for small variations of T, I and R

$$\alpha = \frac{T_0}{R_0}\frac{\partial R}{\partial T}\bigg|_{I_0} \qquad \beta = \frac{I_0}{R_0}\frac{\partial R}{\partial I}\bigg|_{T_0}$$

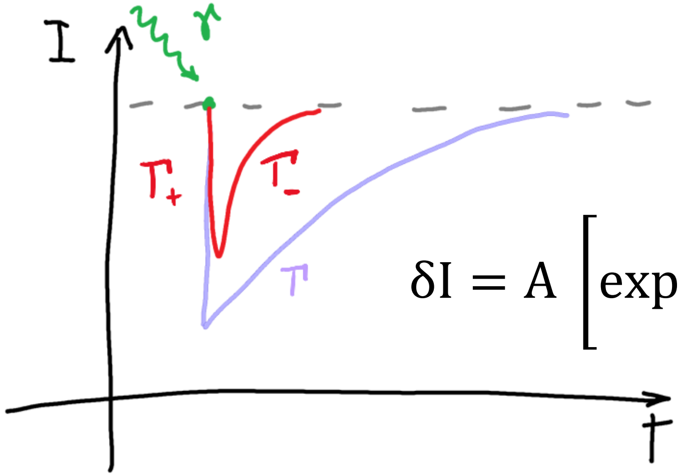
TES Small Signal Theory



$$\alpha = \frac{T_0}{R_0}\frac{\partial R}{\partial T}\bigg|_{I_0} \qquad \beta = \frac{I_0}{R_0}\frac{\partial R}{\partial I}\bigg|_{T_0}$$

If L is small, so $\tau_+ \ll \tau_-$:

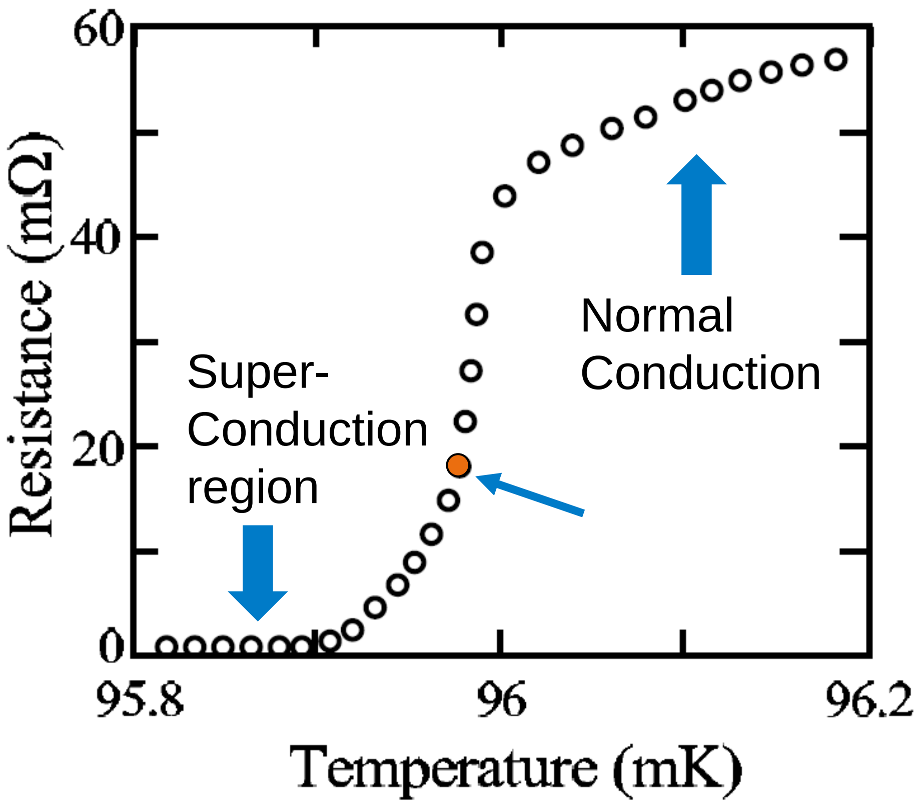
$$\tau_+ = \frac{L}{R_0(1+\beta)} \qquad \tau_- = \frac{\tau}{1+\mathcal{L}/(1+\beta)} \qquad \mathcal{L} = \frac{I_0^2 R_0 \alpha}{G T_0}$$



$$\delta I = A\left[\exp\left\{-\frac{t}{\tau_+}\right\} - \exp\left\{-\frac{t}{\tau_-}\right\}\right]$$

- Cryogenic detector operated at transition region
- Connected to a colder thermal bath
- Possible definition of the point in the transition
  - Voltage-biased TES

TES Small Signal Theory



$$\alpha = \frac{T_0}{R_0}\frac{\partial R}{\partial T}\bigg|_{I_0} \qquad \beta = \frac{I_0}{R_0}\frac{\partial R}{\partial I}\bigg|_{T_0}$$

If L is small, so $\tau_+ \ll \tau_-$:

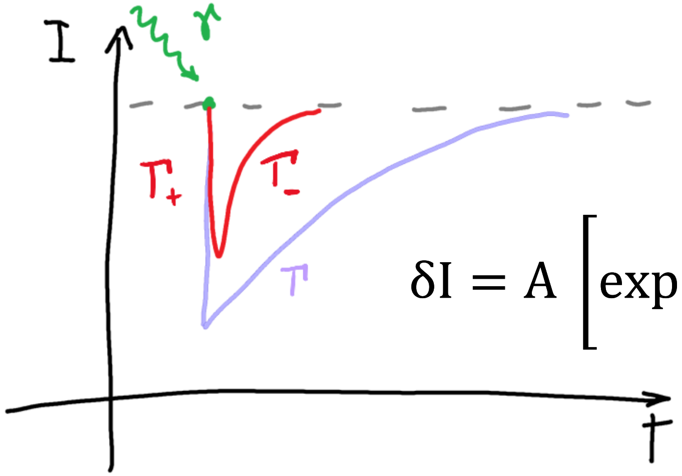
$$\tau_+ = \frac{L}{R_0(1+\beta)}$$

Slower rise time

$$\tau_- = \frac{\tau}{1+\mathcal{L}/(1+\beta)}$$

Faster decay time

$$\mathcal{L} = \frac{I_0^2 R_0 \alpha}{G T_0}$$



$$\delta I = A\left[\exp\left\{-\frac{t}{\tau_+}\right\} - \exp\left\{-\frac{t}{\tau_-}\right\}\right]$$

- Cryogenic detector operated at transition region
- Connected to a colder thermal bath
- Possible definition of the point in the transition
  - Voltage-biased TES

TES Strong ETF

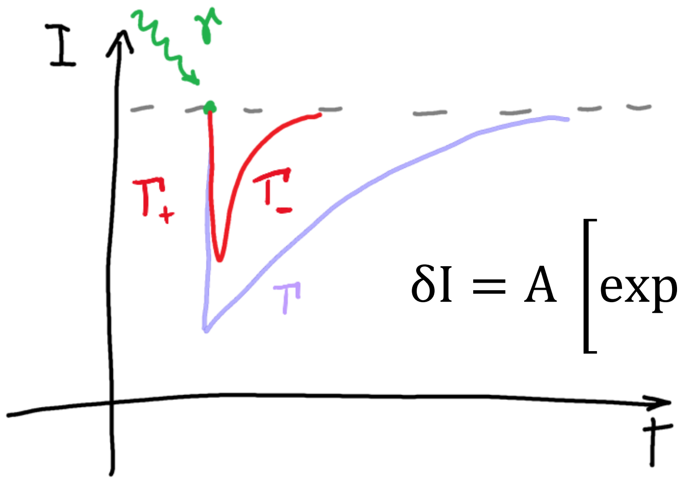
$$\alpha = \frac{T_0}{R_0}\frac{\partial R}{\partial T}\bigg|_{I_0} \qquad \beta = \frac{I_0}{R_0}\frac{\partial R}{\partial I}\bigg|_{T_0}$$

If L is small, so $\tau_+ \ll \tau_-$:

$$\tau_+ = \frac{L}{R_0(1+\beta)} \qquad \tau_- = \frac{\tau}{1+\mathcal{L}/(1+\beta)} \qquad \mathcal{L} = \frac{I_0^2 R_0 \alpha}{G T_0}$$

Strong electrothermal feedback (ETF) if $\mathcal{L} \gg 1$

$$\tau_- = \frac{\tau}{1+\alpha/n}$$



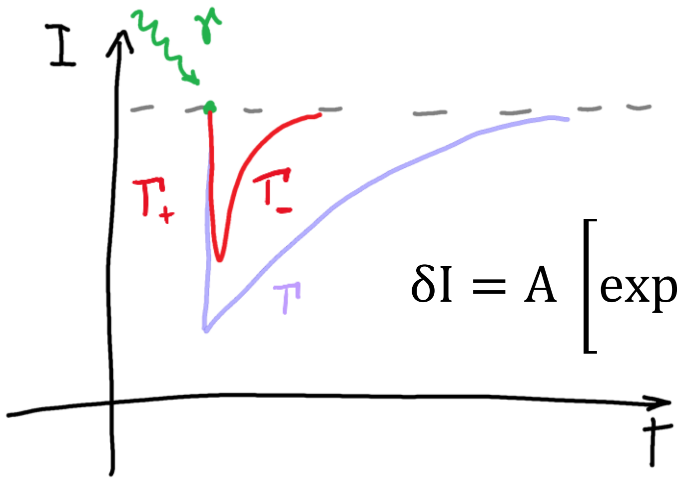
$$\delta I = A\left[\exp\left\{-\frac{t}{\tau_+}\right\} - \exp\left\{-\frac{t}{\tau_-}\right\}\right]$$

TES Strong ETF

$$\alpha = \frac{T_0}{R_0}\frac{\partial R}{\partial T}\bigg|_{I_0} \qquad \beta = \frac{I_0}{R_0}\frac{\partial R}{\partial I}\bigg|_{T_0}$$

If L is small, so $\tau_+ \ll \tau_-$:

$$\tau_+ = \frac{L}{R_0(1+\beta)} \qquad \tau_- = \frac{\tau}{1+\mathcal{L}/(1+\beta)} \qquad \mathcal{L} = \frac{I_0^2 R_0 \alpha}{G T_0}$$



$$\delta I = A\left[\exp\left\{-\frac{t}{\tau_+}\right\} - \exp\left\{-\frac{t}{\tau_-}\right\}\right]$$

Strong electrothermal feedback (ETF) if $\mathcal{L} \gg 1$

$$\tau_- = \frac{\tau}{1+\alpha/n}$$

TES as bolometer:

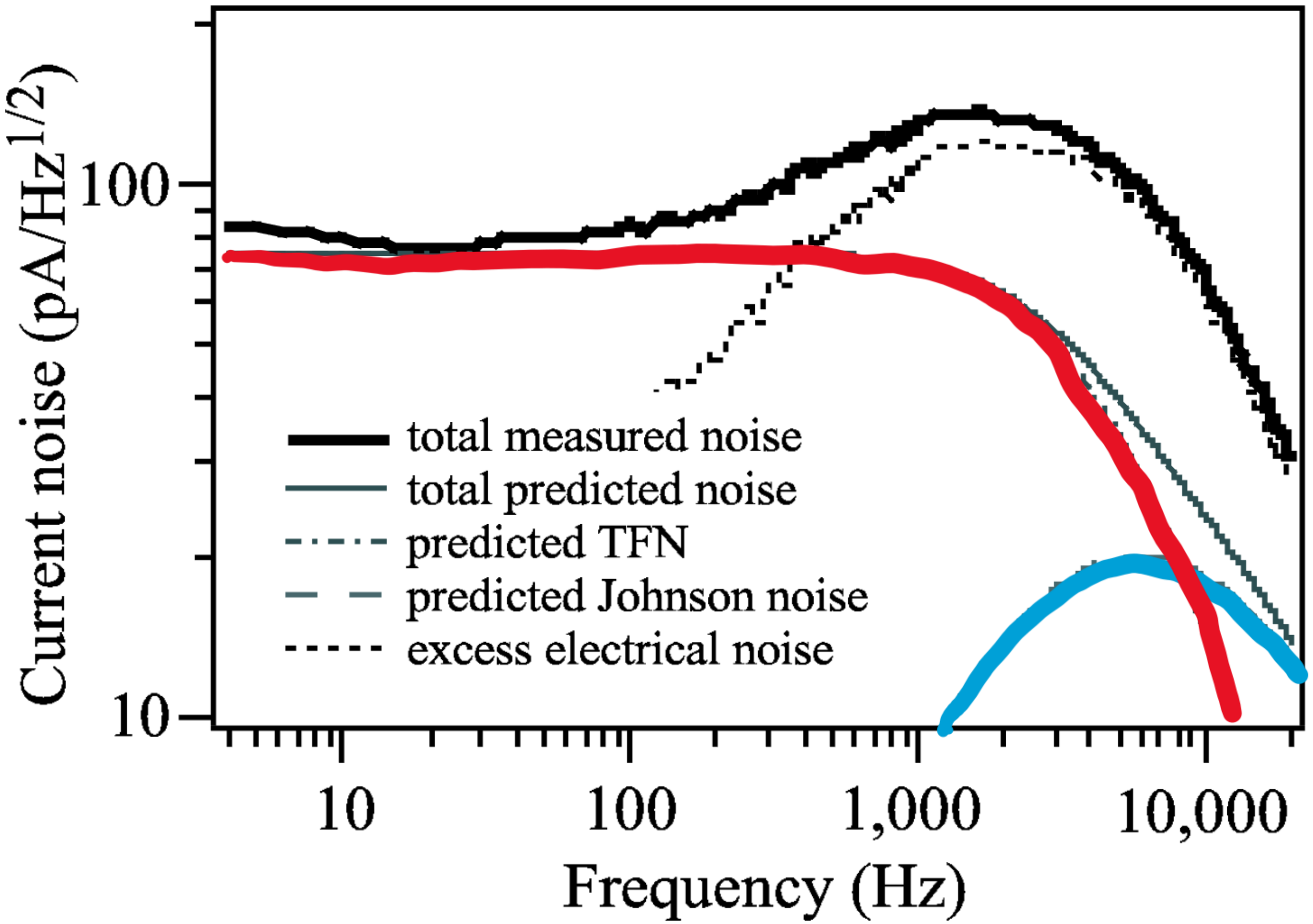
$$P = -I_0 R_0 \delta I$$

TES as calorimeter:

$$E = -I_0 R_0 \int_0^\infty \delta I(t)\,dt$$

K. Irwin, G. Hilton, Transition-edge sensors, in: Cryogenic Particle Detection, Springer Berlin Heidelberg, Berlin, Heidelberg, 2005, pp. 63–150, http://dx.doi.org/10.1007/10933596_3.

TES noise and energy resolution



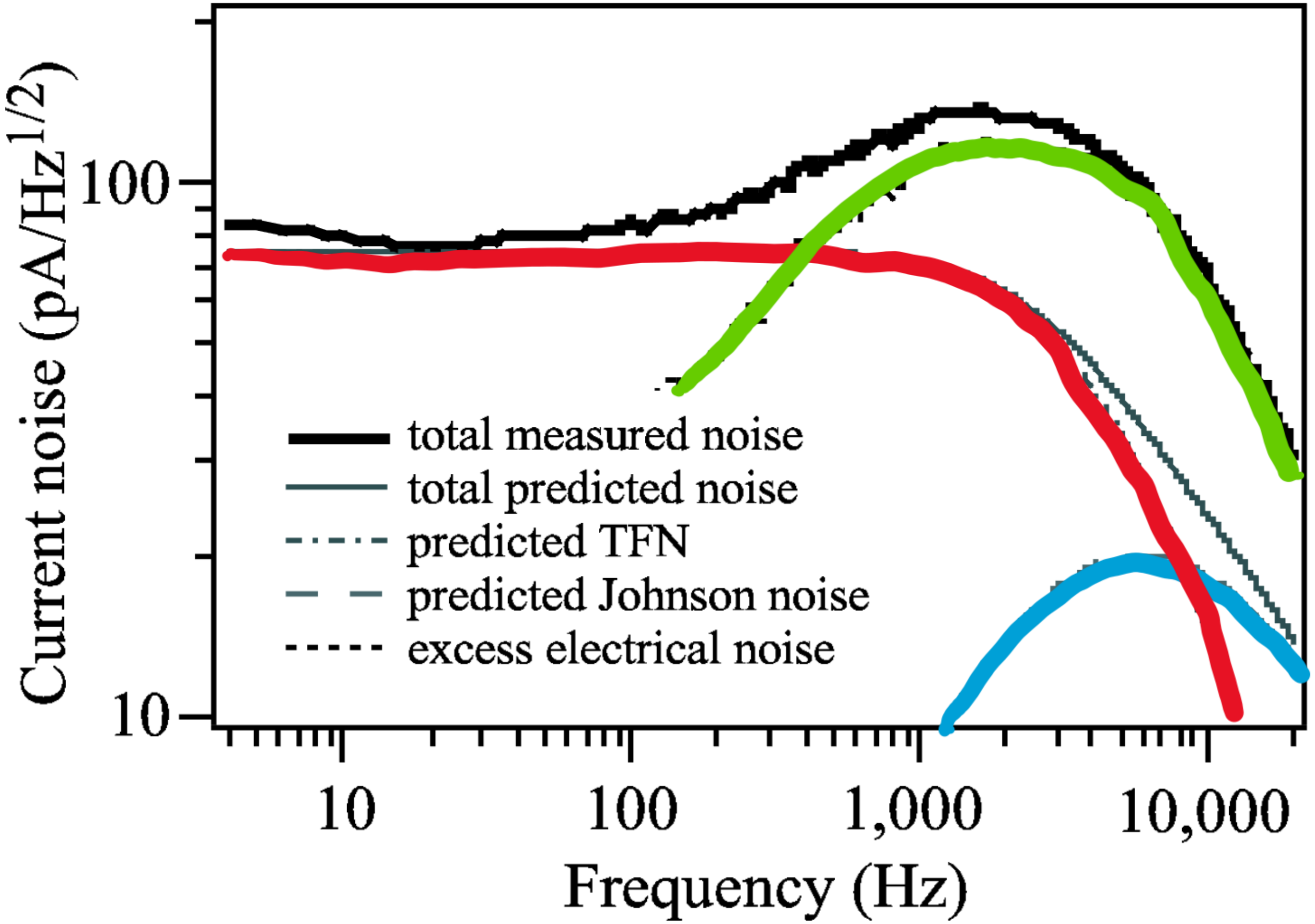
Thermal fluctuation noise (TFN) } Thermal noise

Johnson or Nyquist noise } Electronic noise

$$\Delta E_{FWHM} = 2\sqrt{2\ln 2}\ \sqrt{4k_B T_0^2 \frac{C}{\alpha}\sqrt{\frac{n}{2}}}$$

K. Irwin, G. Hilton, Transition-edge sensors, in: Cryogenic Particle Detection, Springer Berlin Heidelberg, Berlin, Heidelberg, 2005, pp. 63–150, http://dx.doi.org/10.1007/10933596_3.

TES noise and energy resolution



Thermal fluctuation noise (TFN) } Thermal noise

Johnson or Nyquist noise } Electronic noise

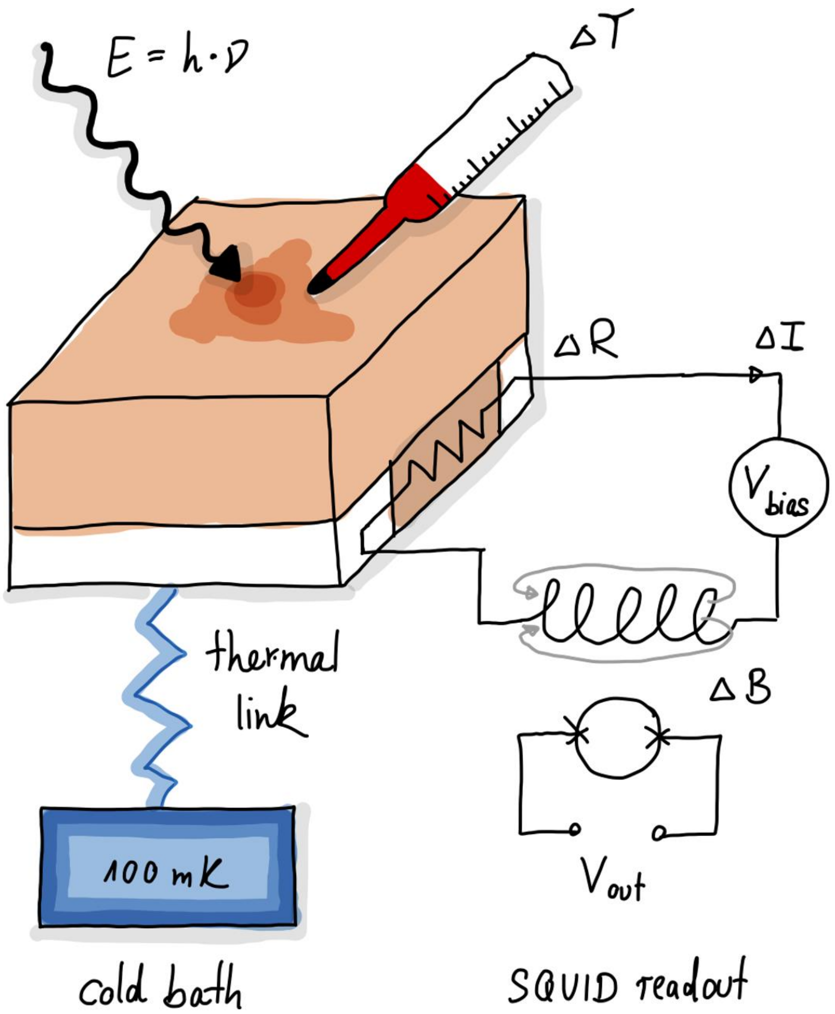
Excess noise

$$\Delta E_{FWHM} = 2\sqrt{2\ln 2}\sqrt{4k_B T_0^2 \frac{C}{\alpha}\sqrt{\frac{n}{2}}}$$

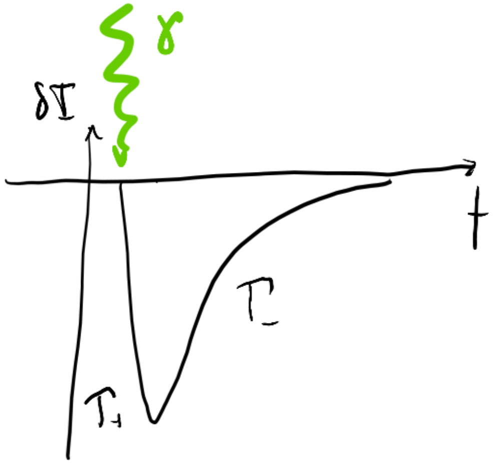
$$\Delta E_{true} > \Delta E_{FWHM}$$

K. Irwin, G. Hilton, Transition-edge sensors, in: Cryogenic Particle Detection, Springer Berlin Heidelberg, Berlin, Heidelberg, 2005, pp. 63–150, http://dx.doi.org/10.1007/10933596_3.

TES physics summary



TES in strong ETF



Rise time $\tau_+ = \frac{L}{R_0(1+\beta)}$

Decay time $\tau_- = \frac{C/G}{1+\alpha/n}$

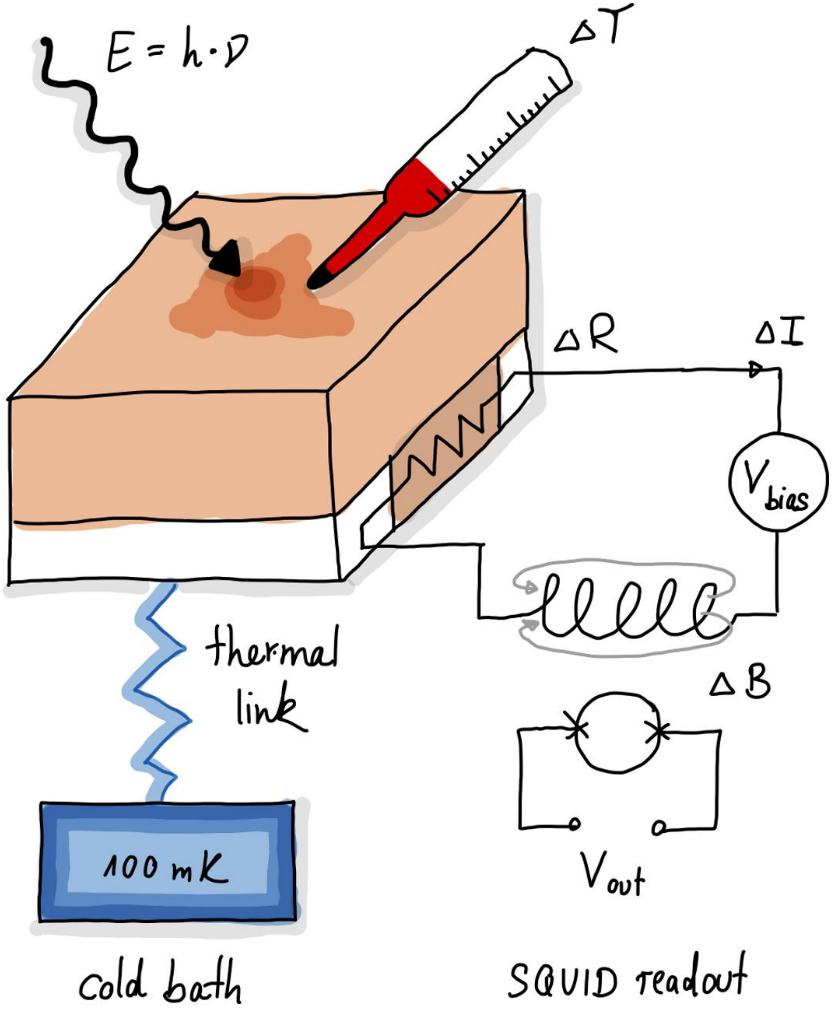
Measured power with TES as bolometer $P = -I_0 R_0 \delta I$

Measured energy of photon with TES as calorimeter $E = -I_0 R_0 \int_0^\infty \delta I(t) dt$

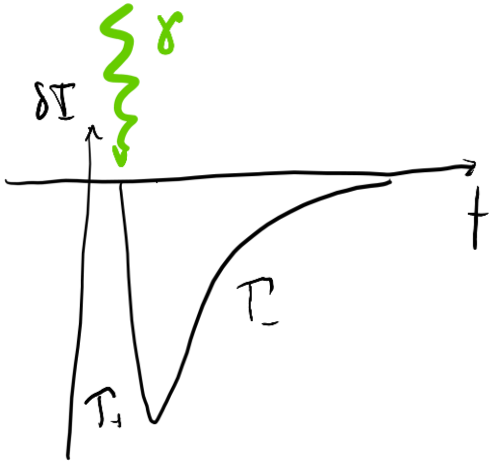
Theoretical limit for TES energy resolution $\Delta E_{FWHM} = 2\sqrt{2\ln 2}\sqrt{4k_B T_0^2 \frac{C}{\alpha}\sqrt{\frac{n}{2}}}$

*Courtesy of Katharina-Sophie Isleif

TES physics summary



TES in strong ETF



Rise time $\tau_+ = \frac{L}{R_0(1+\beta)}$

Decay time $\tau_- = \frac{C/G}{1+\alpha/n}$

Measured power with TES as bolometer $P = -I_0 R_0 \delta I$

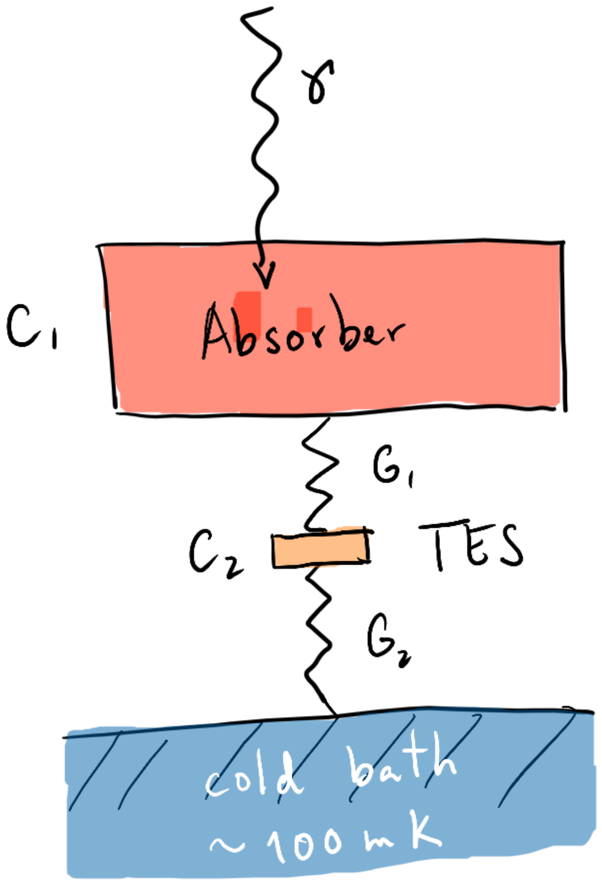
Measured energy of photon with TES as calorimeter $E = -I_0 R_0 \int_0^\infty \delta I(t) dt$

Theoretical limit for TES energy resolution $\Delta E_{FWHM} = 2\sqrt{2\ln 2}\sqrt{4 k_B T_0^2 \frac{C}{\alpha}\sqrt{\frac{n}{2}}}$

*Courtesy of Katharina-Sophie Isleif

High energy photon detection

X-ray and gamma TES detectors



Absorber big enough to increase probability of X-ray and gamma interaction

Decay time $$\tau_- = \frac{C/G}{1 + \alpha/n}$$

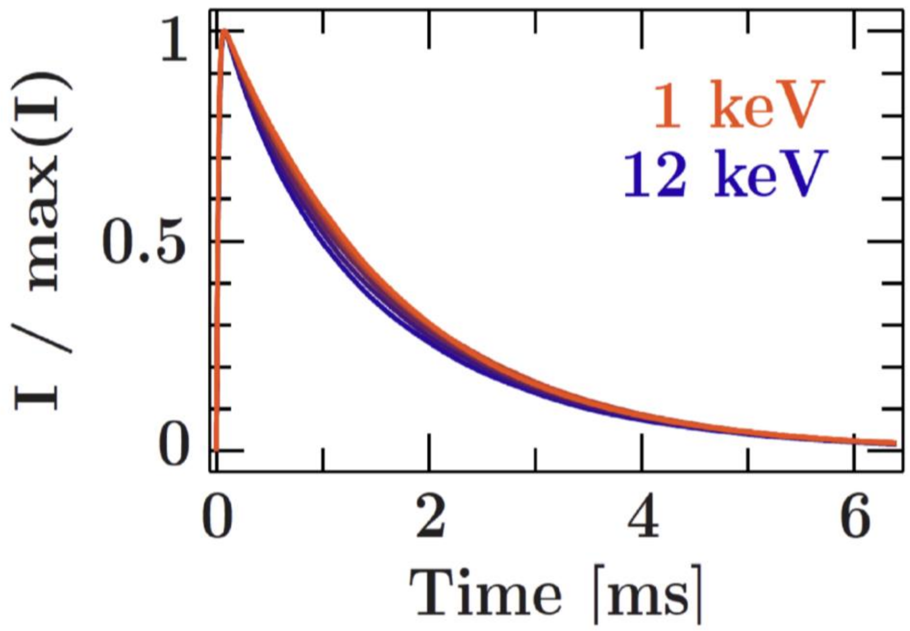
Theoretical limit for TES energy resolution $$\Delta E_{FWHM} = 2\sqrt{2\ln 2}\sqrt{4 k_B T_0^2 \frac{C}{\alpha}\sqrt{\frac{n}{2}}}$$

C increases due to the absorber

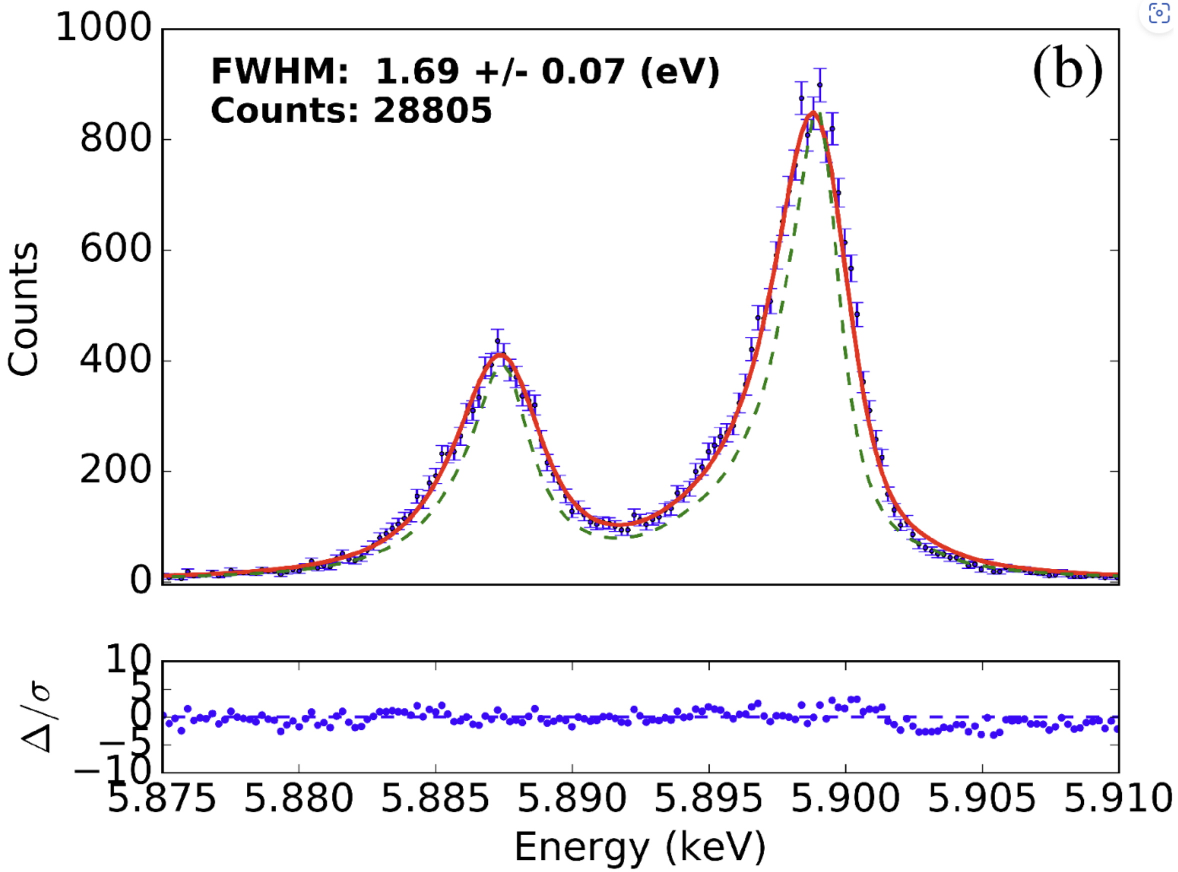
ΔE worsens and τ_- increases

X-ray and gamma TES detectors

C increases due to the absorber
ΔE worsens and τ_{-} increases

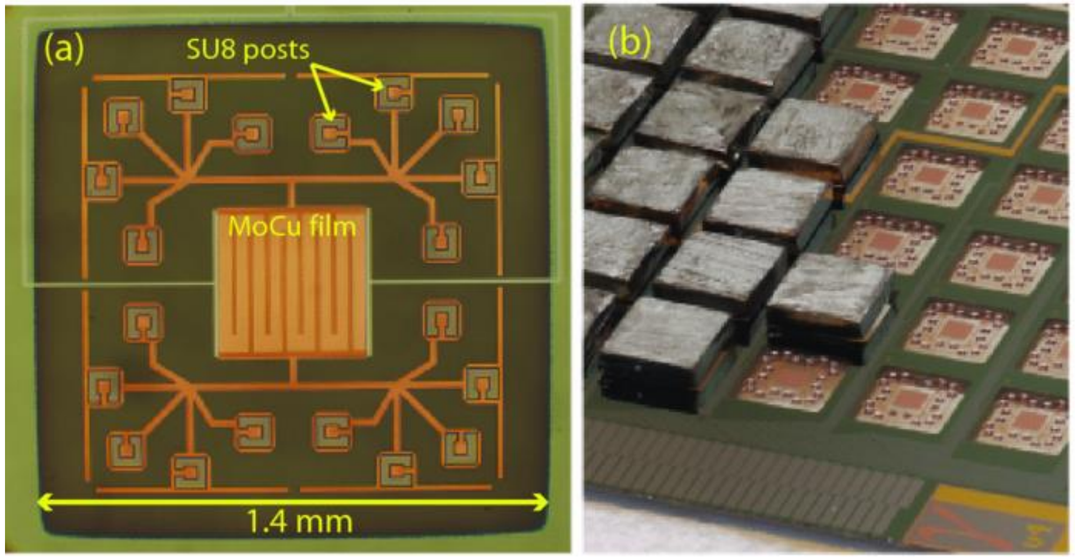


Very high S-to-N ratio
Excellent energy resolution of ~0.01%



A Review of X-ray Microcalorimeters Based on Superconducting Transition Edge Sensors for Astrophysics and Particle Physics. *Applied Sciences*, *11*(9), 3793. https://doi.org/10.3390/app11093793

Extending the range to ~100 keV



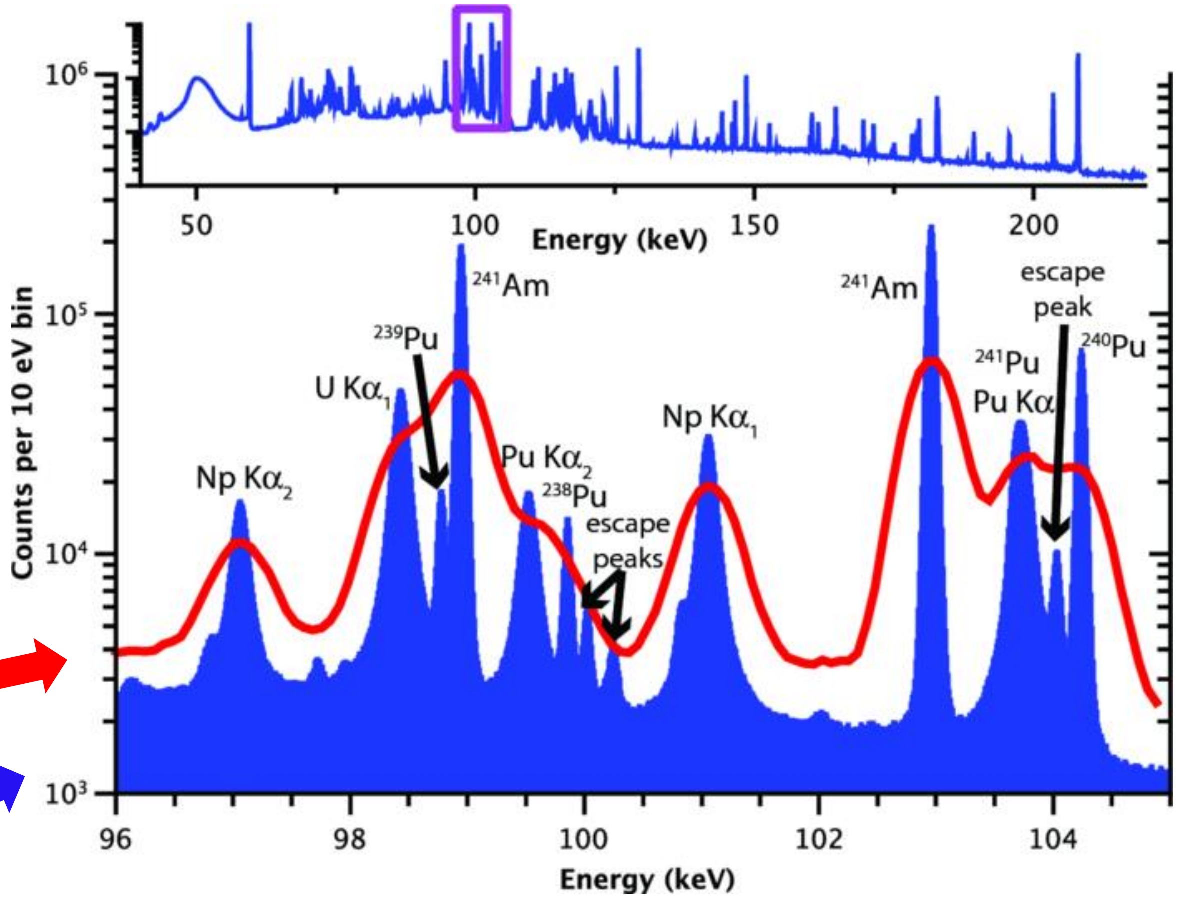
Absorber Sn: 1.45 x 1.45 x 0.38 mm^3

High efficiency for gamma and low C

High purity
Germanium detector

$\Delta E = 25$ eV @ 100 keV

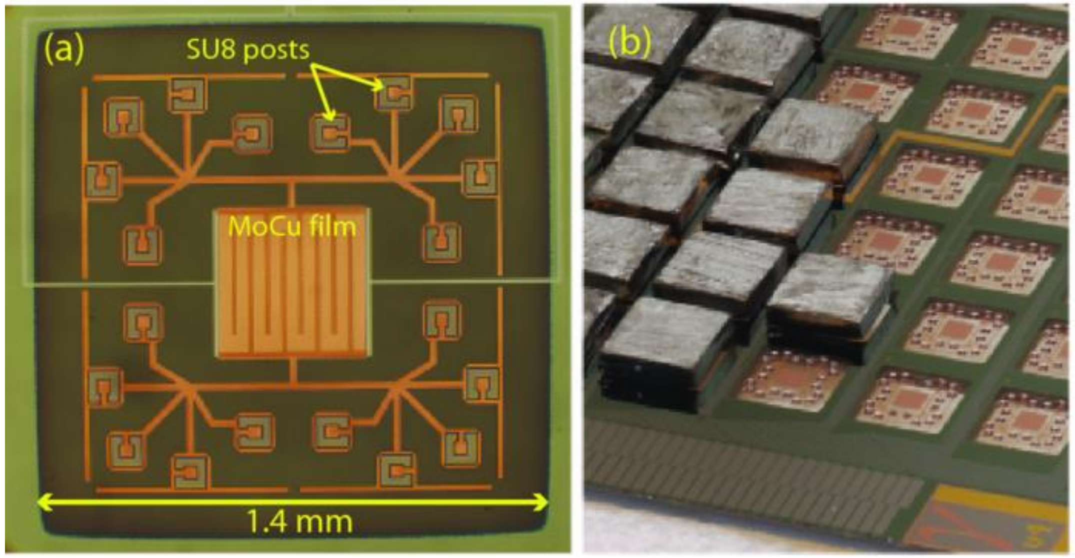
TES



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

Extending the range to ~100 keV

SQUID multiplexing



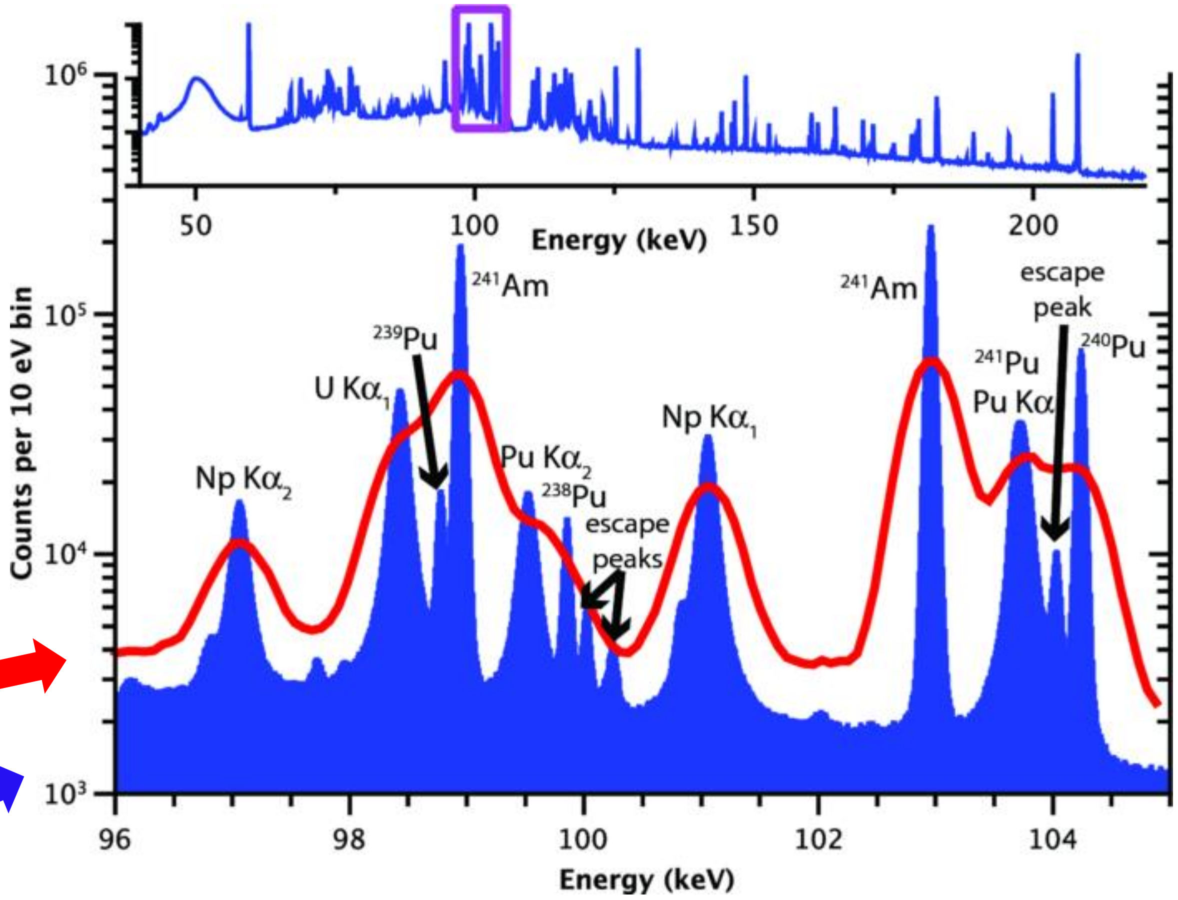
Absorber Sn: 1.45 x 1.45 x 0.38 mm^3

High efficiency for gamma and low C

High purity
Germanium detector

$\Delta E = 25 \text{ eV} @ 100 \text{ keV}$

TES



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

X-ray astrophysics

- X-rays emitted by ionized atoms and energetic electrons near active objects
- Energies of discrete X-ray lines reveal elements
- Doppler shift of lines indicate dynamic conditions of elements
- Presence of several ionization lines

⬇

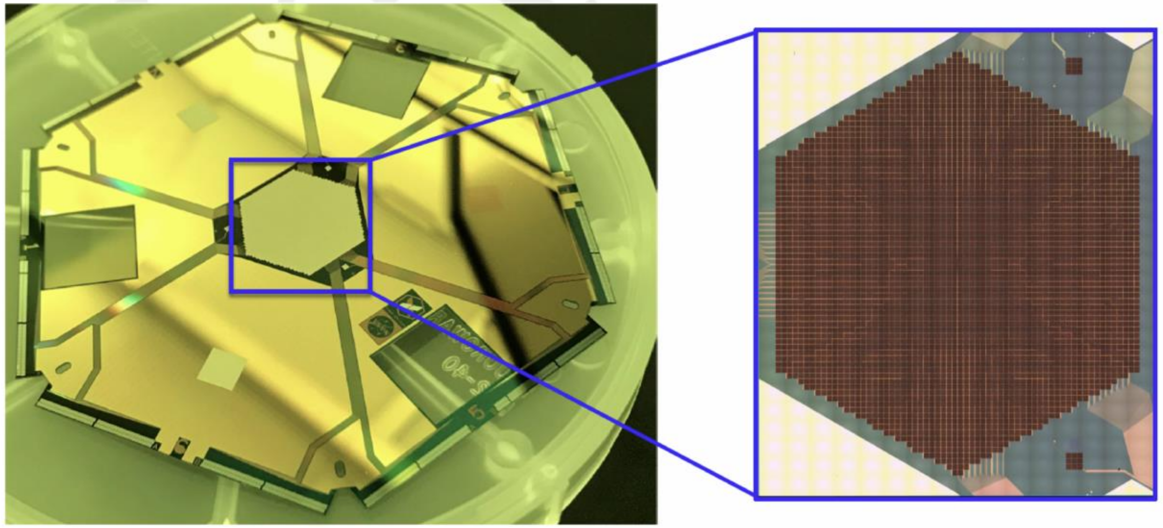
Requires excellent energy resolution

X-ray astrophysics

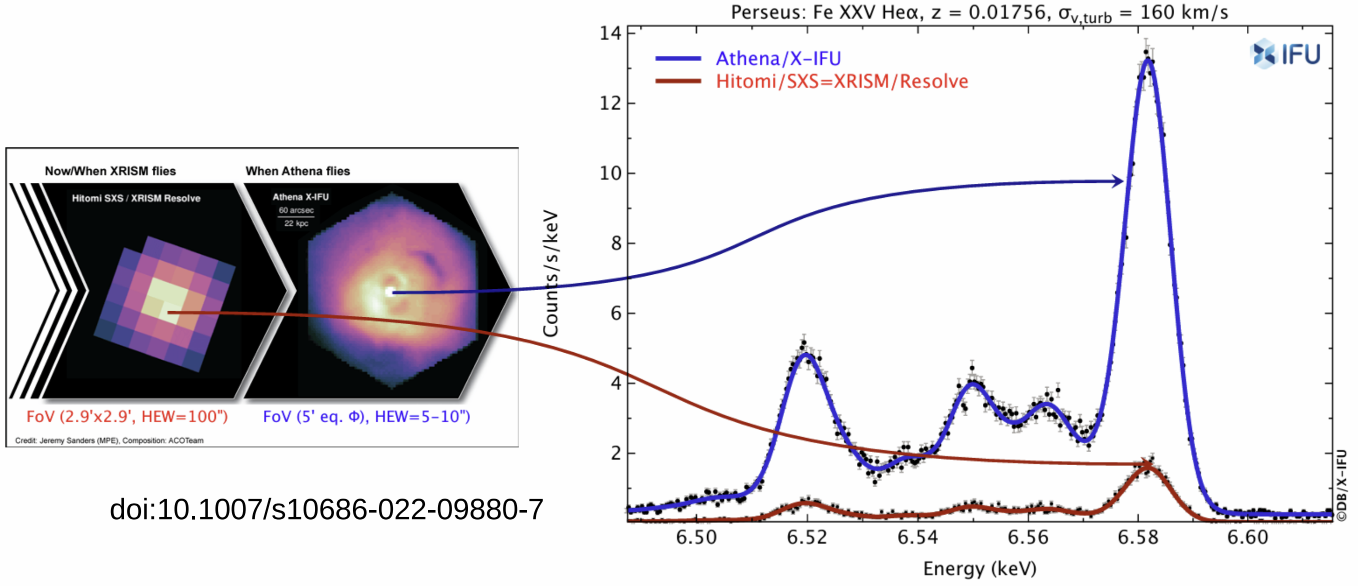
- X-rays emitted by ionized atoms and energetic electrons near active objects
- Energies of discrete X-ray lines reveal elements
- Doppler shift of lines indicate dynamic conditions of elements
- Presence of several ionization lines

↓

Requires excellent energy resolution



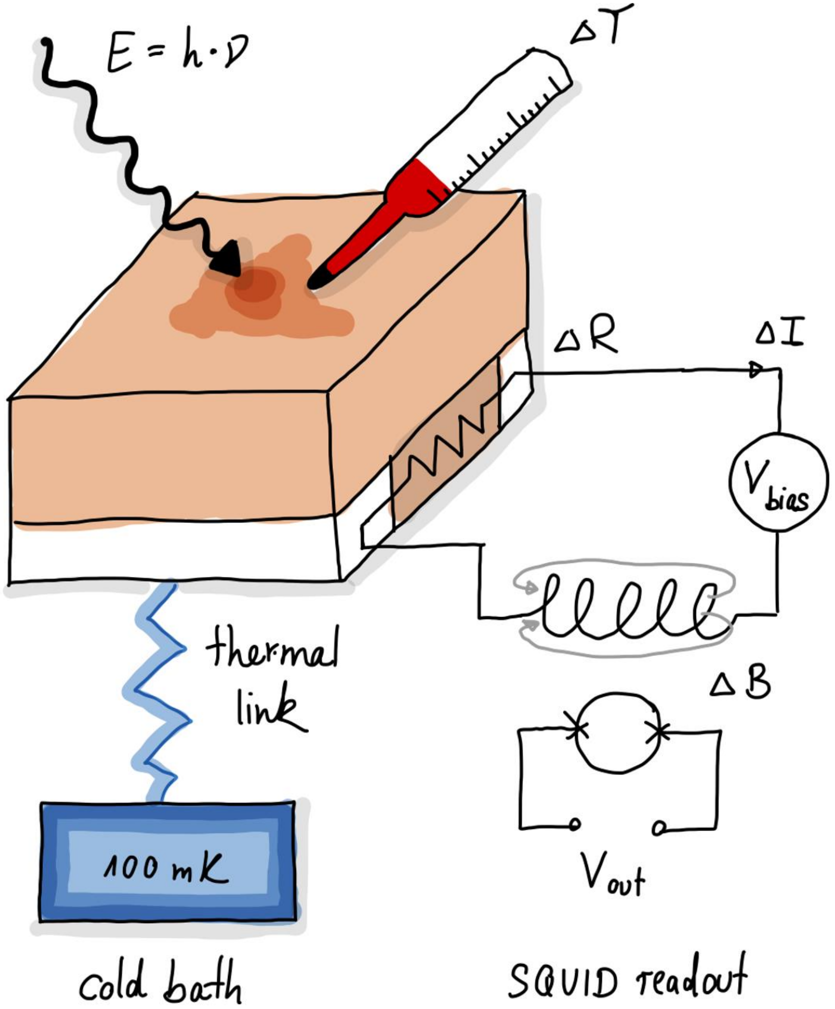
Athena/X-IFU to be launched with more than 3000 pixels



doi:10.1007/s10686-022-09880-7

Visible to IR
photon detection

Visible to IR photon TES detectors



The TES is the absorber → C lower
ΔE is lower and τ_{-} also lower

Decay time $$\tau_{-} = \frac{C/G}{1 + \alpha/n}$$

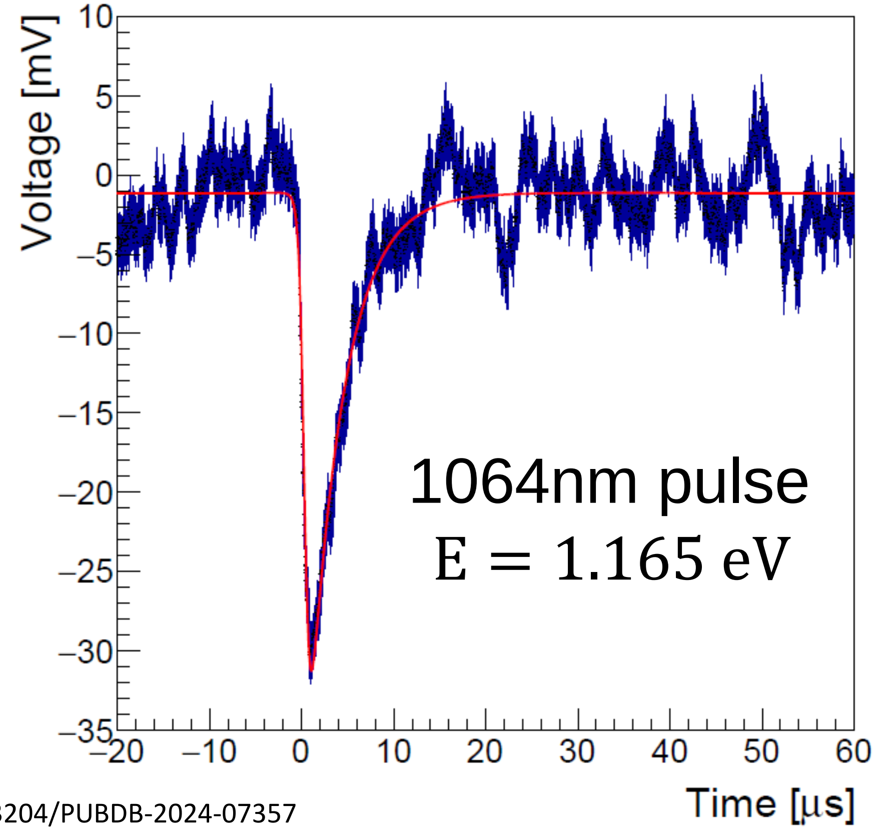
Theoretical limit for
TES energy resolution

$$\Delta E_{FWHM} = 2\sqrt{2\ln 2}\sqrt{4k_B T_0^2 \frac{C}{\alpha}\sqrt{\frac{n}{2}}}$$

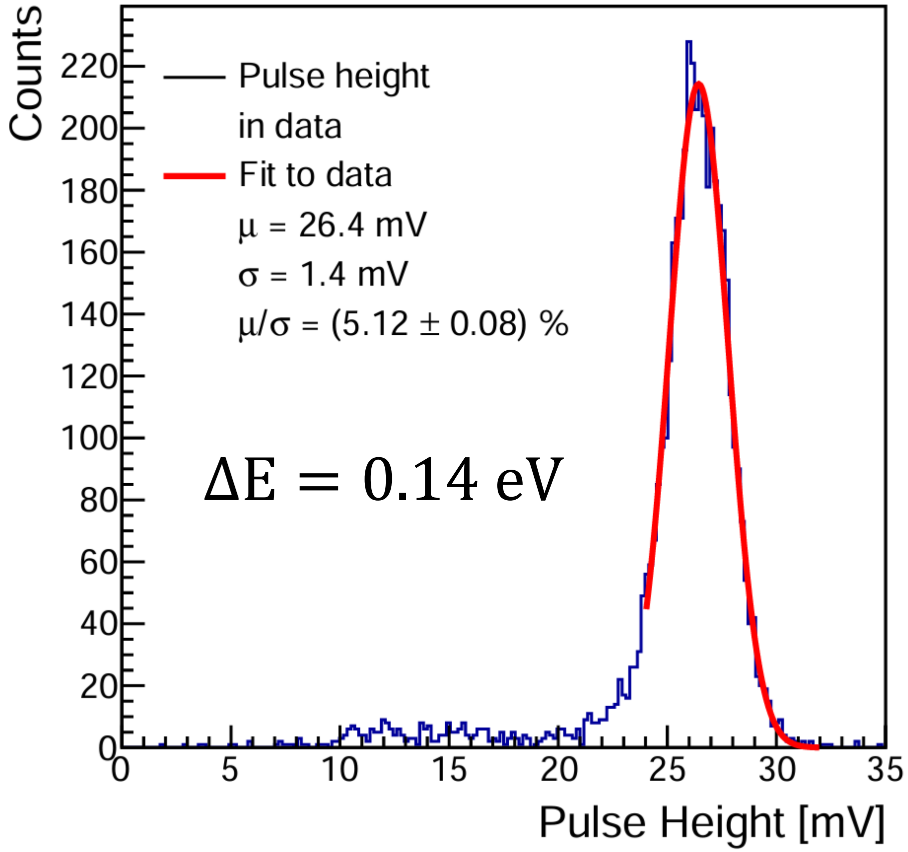
Visible to IR photon TES detectors

The TES is the absorber → C lower

ΔE is lower and τ_{-} also lower

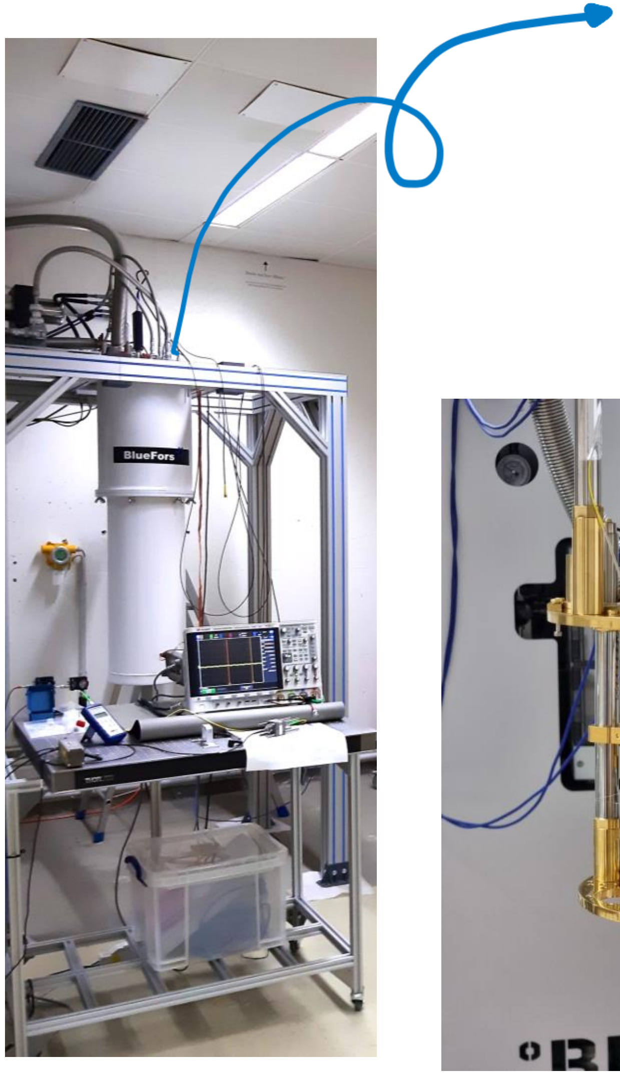


doi:10.3204/PUBDB-2024-07357



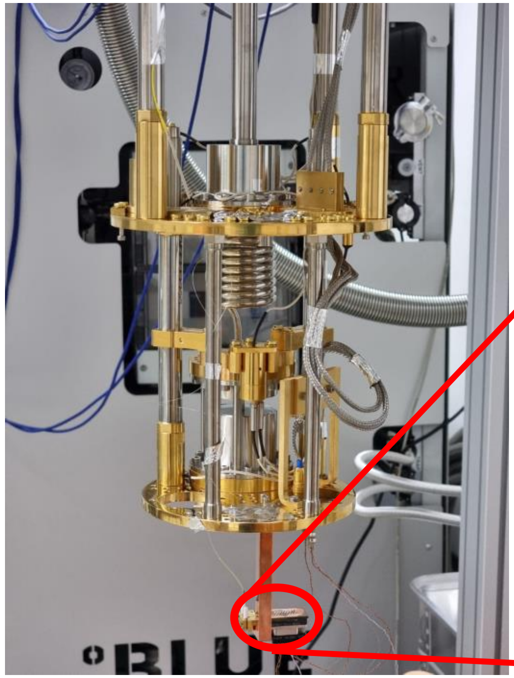
$\Delta E \sim 0.1$ eV and much faster $\tau_{-} \sim 1\ \mu s$

Propagating photons to the detector

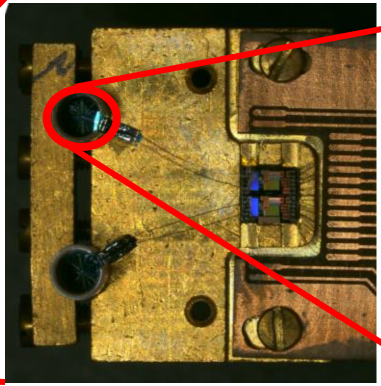


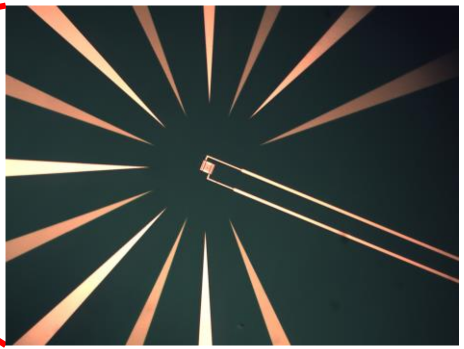
Use of an optical fiber to transmit photons to the TES

* TES setup at DESY



A tungsten microchip ($25\ \mu\text{m} \times 25\ \mu\text{m} \times 20\ \text{nm}$) provided by NIST and SQUID and packaging PTB stabilized in the transition region (~ 140 mK)



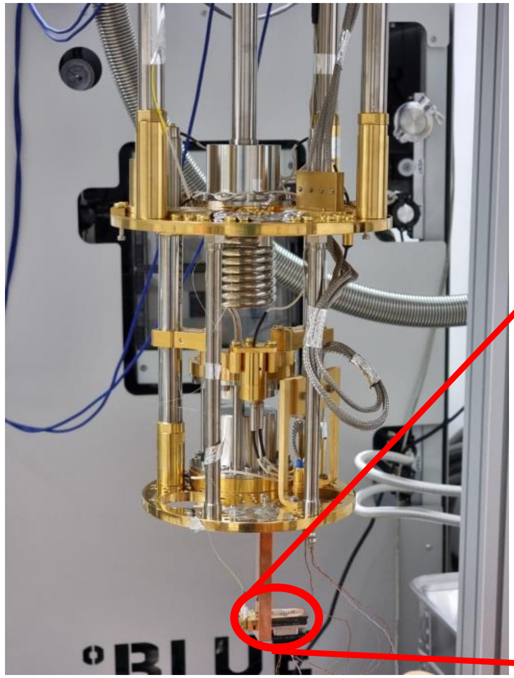


Optimized for $1064\ \text{nm}$ photon $\mathrm{E} \approx 1.2\ \text{eV}$ with an optical stack

Propagating photons to the detector

Use of an optical fiber to transmit photons to the TES

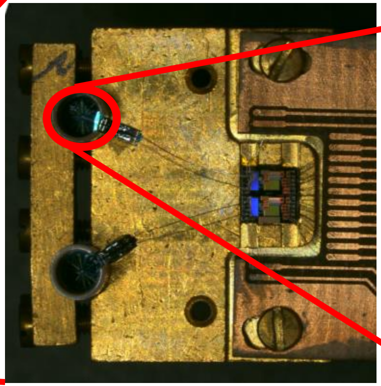
* TES setup at DESY

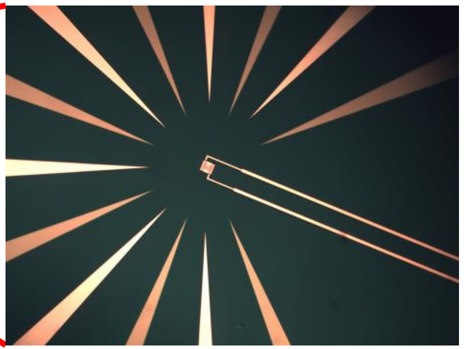


TES at DESY for the ALPS II experiment

doi:10.22323/1.449.0567

A tungsten microchip ($25\ \mu\text{m} \times 25\ \mu\text{m} \times 20\ \text{nm}$) provided by NIST and SQUID and packaging PTB stabilized in the transition region (~ 140 mK)





Optimized for $1064\ \text{nm}$ photon $\text{E} \approx 1.2\ \text{eV}$ with an optical stack

Background in the TES

[1] doi:10.22323/1.398.0801
[2] doi:10.3204/PUBDB-2024-07357

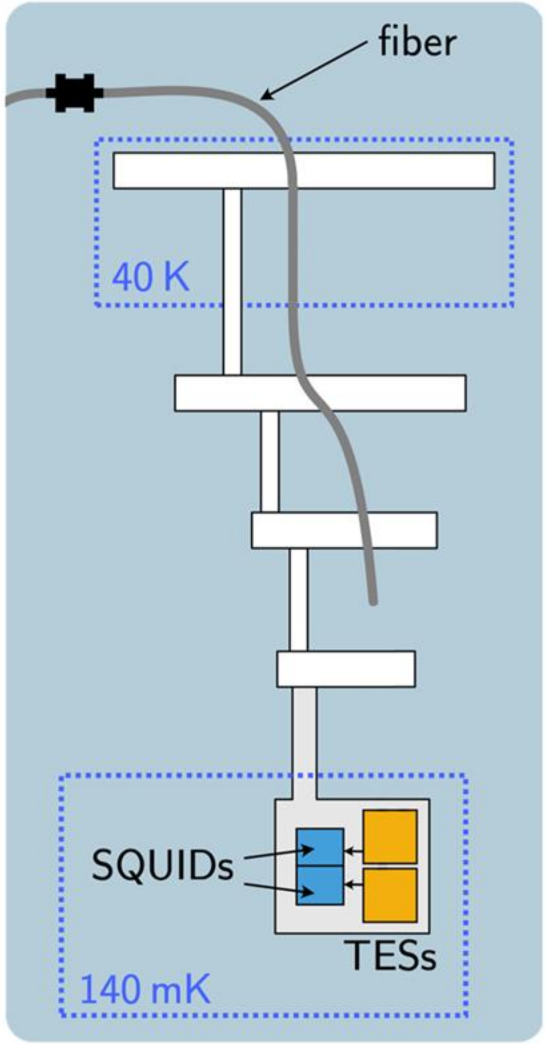
Fiber disconnected from the TES.

The recorded rate of events in the order is usually below 10^{-1} cps (depends on the trigger)

Origin associated to radioactivity and cosmic rays.

TES response different than photon pulses. Allows pulse shape discrimination and machine learning

e.g. [1]
$< 10^{-5}$ cps @ 1064nm



Schematic adapted from Katharina-Sophie Isleif.

[1] doi:10.22323/1.398.0801
[2] doi:10.3204/PUBDB-2024-07357

Background in the TES

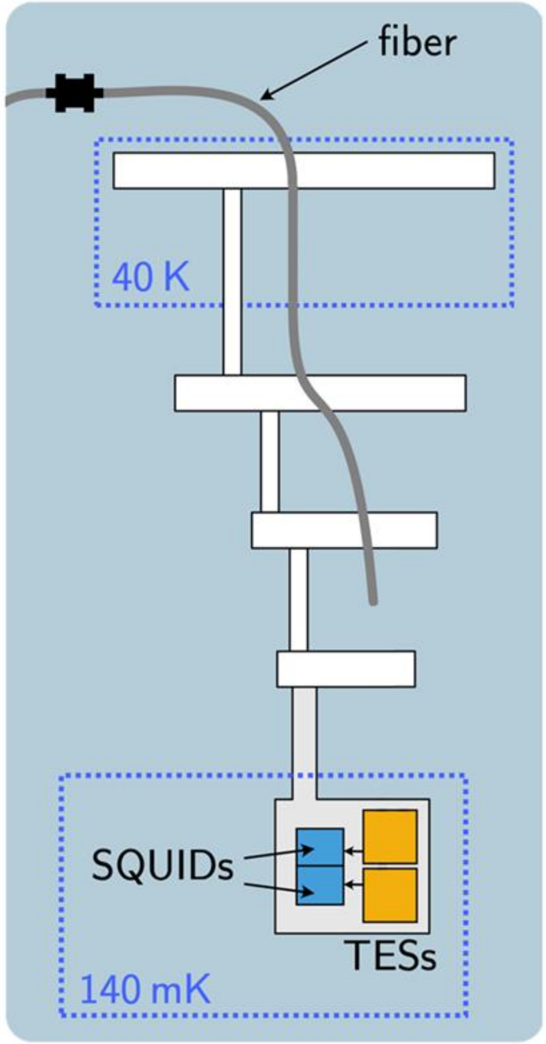
Fiber disconnected from the TES.

The recorded rate of events in the order is usually below 10^{-1} cps (depends on the trigger)

Origin associated to radioactivity and cosmic rays.

TES response different than photon pulses. Allows pulse shape discrimination and machine learning

e.g. [1]
$< 10^{-5}$ cps @ 1064nm



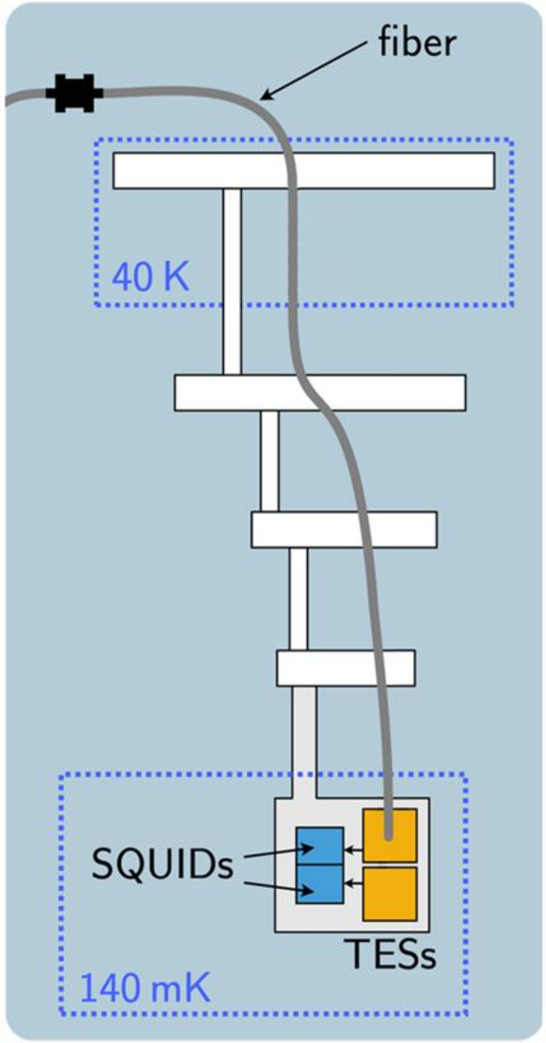
Fiber connected from the TES and other end in the dark.

The recorded rate of events in the order can be up to 10^{1} cps (depends on the trigger)

Mainly Black Body Radiation coupling to the optical fiber.

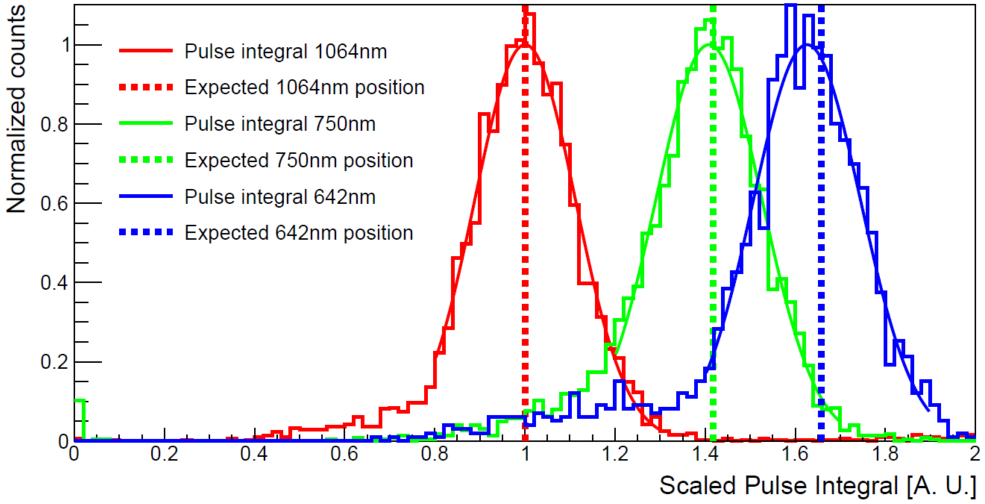
TES energy resolution allows background discrimination [2]
$< 10^{-4}$ cps @ 1064nm

Very low background requires other strategies.

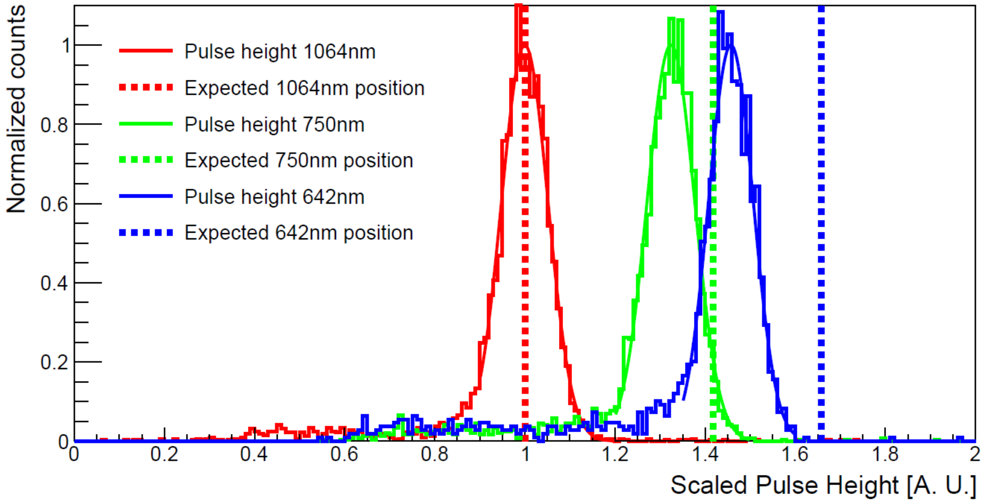


Schematic adapted from Katharina-Sophie Isleif.

Multicolor measurement with TES



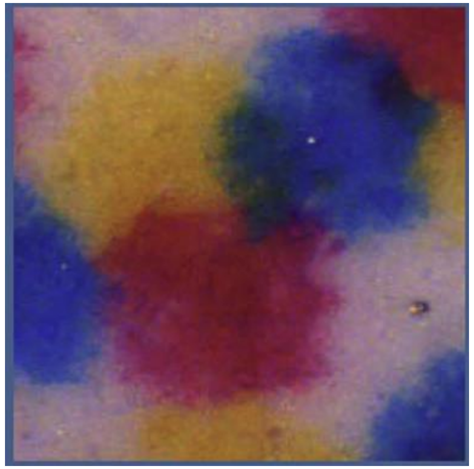
(a)



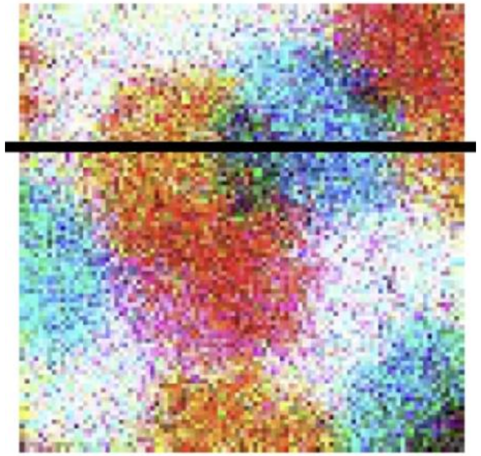
doi:10.3204/PUBDB-2024-07357

- Use in energy dispersive spectroscopy for bioanalysis research and industry.
- Sensitive to different wavelengths

CMOS



TES



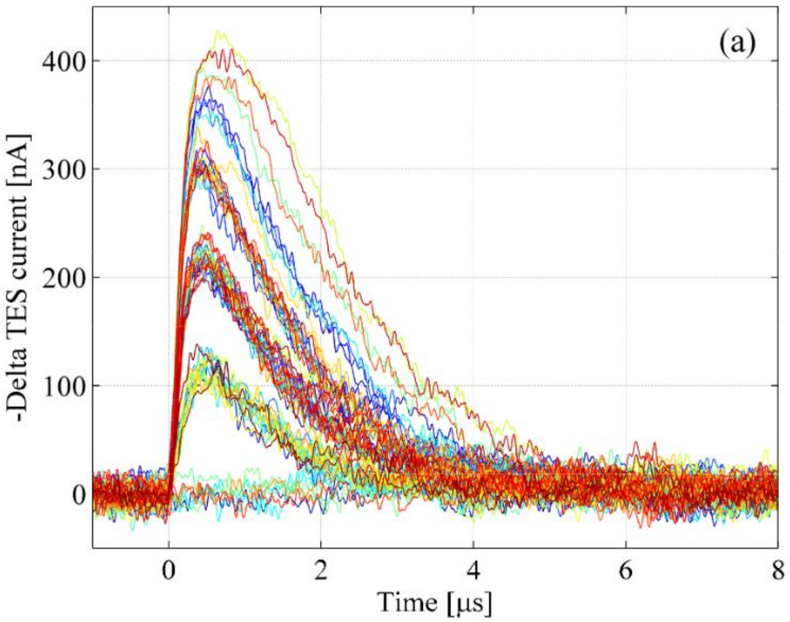
Conditions:
100x brightness
10x exposure

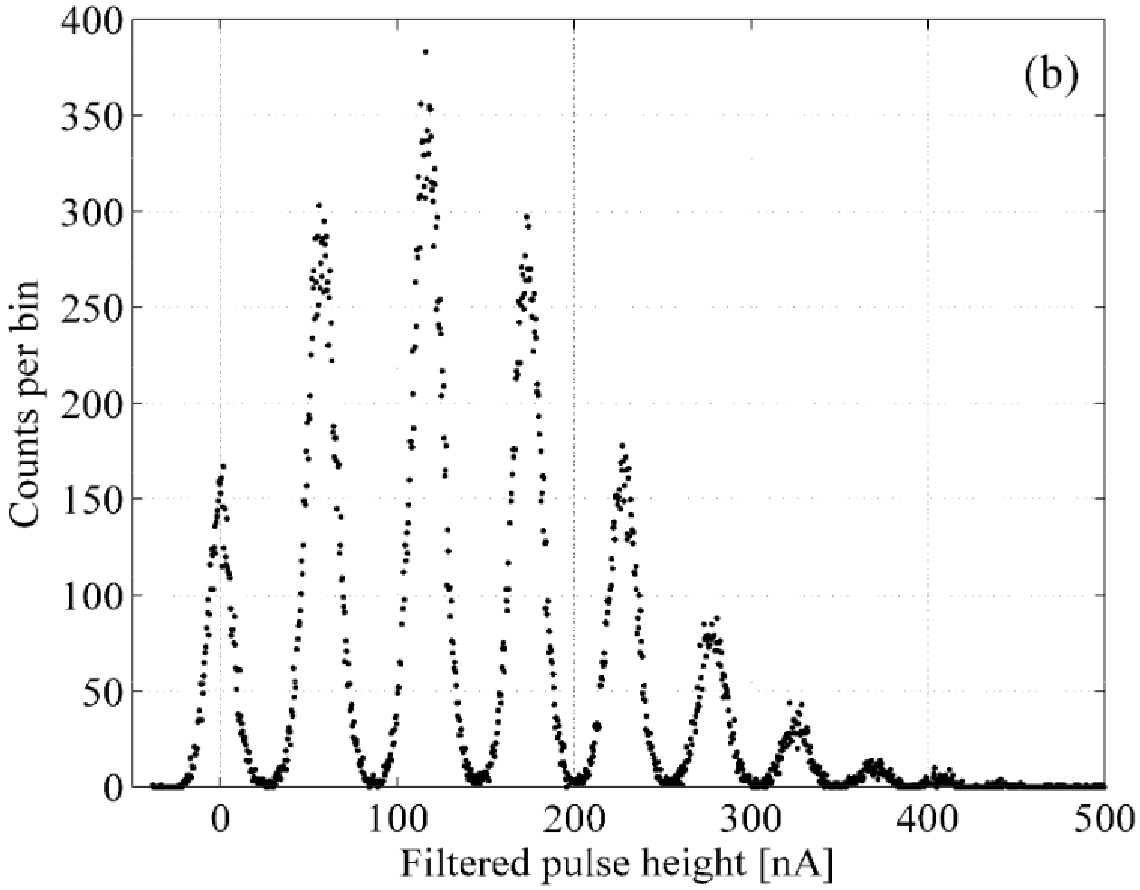
Exposure 8 min

doi:10.1038/srep45660

Photon Number resolution

- Near unity quantum efficiency
- Very good photon number resolution
  - Number of photons of same wavelength arriving at a given time.
- Maximum repetition rate depending on decay time of TES pulses

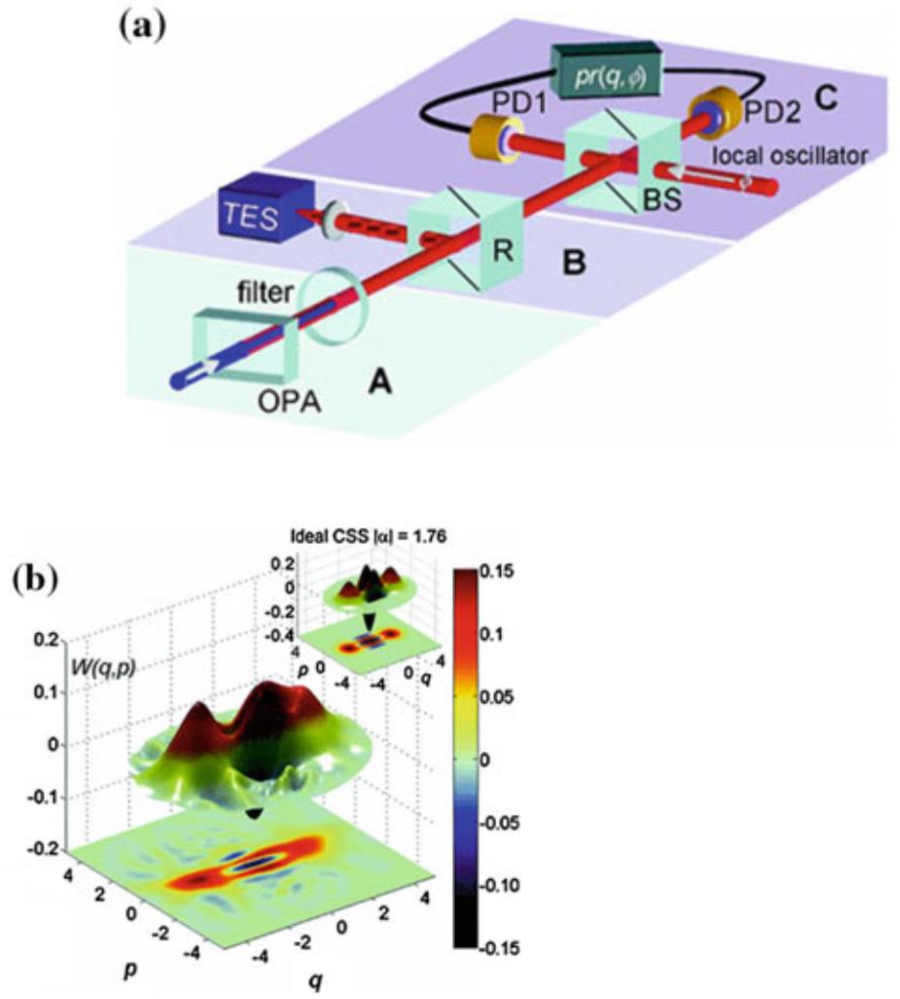




doi:10.1117/12.852221

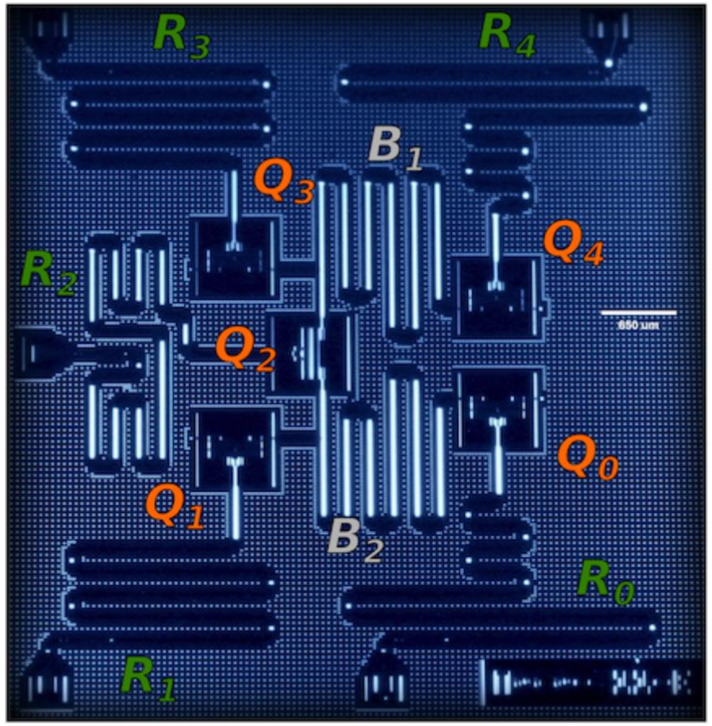
Quantum Metrology with TESs

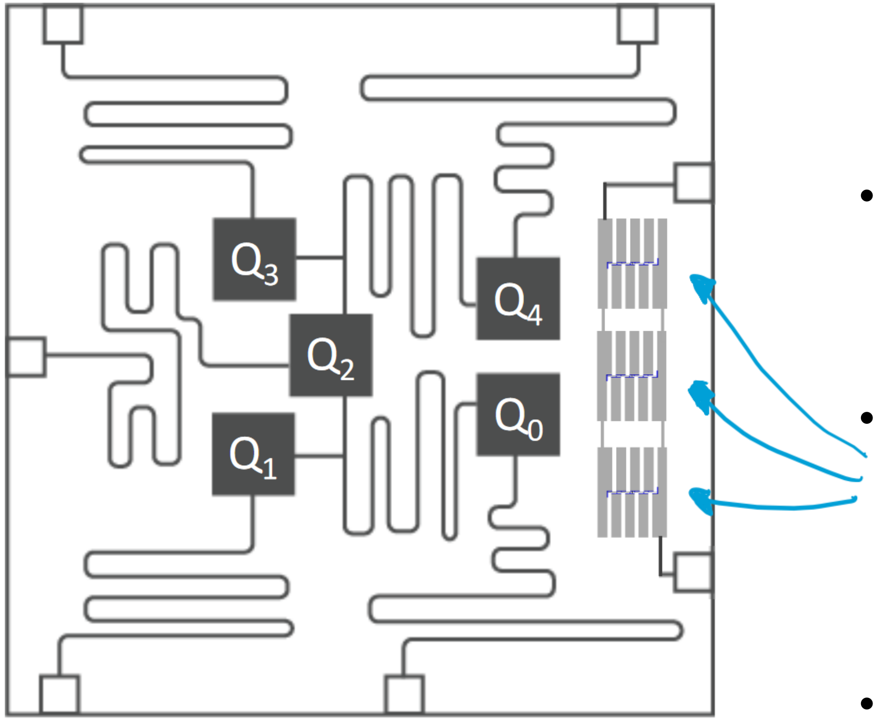
- TES allow direct access to photon statistics from light sources.
- Possibility to study entangled and squeezed states.
- Analysis and exploration of solid-state-based quantum light sources for applications in quantum information, quantum-enhanced sensing and quantum metrology



doi:10.1103/PhysRevA.82.031802

TES in quantum computing





doi:10.1103/PhysRevApplied.16.024025

- Combining TES with a superconducting qubit on a shared silicon substrate.
- Idea of detecting correlated disturbances induced by the radiation.
- TES as a veto to reject the calculations that could be potentially incorrect due to an environmental disturbance.
- Monitoring with a TES has been demonstrated.

doi:10.1117/12.852221

Towards future TESs

- High detection efficiency > 95%, up to 99.8% @ 1550nm
- Faster TESs
- Better energy resolution
- Improve in readout complexity
- Lower background level

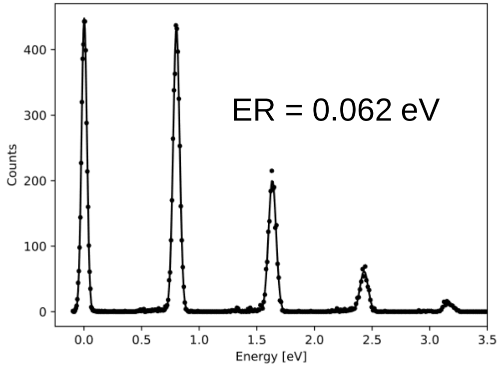
doi:10.1117/12.852221

Towards future TESs

- High detection efficiency > 95%
- Faster TESs
- Better energy resolution
- Improve in readout complexity
- Lower background level

An optical transition-edge sensor with high energy resolution

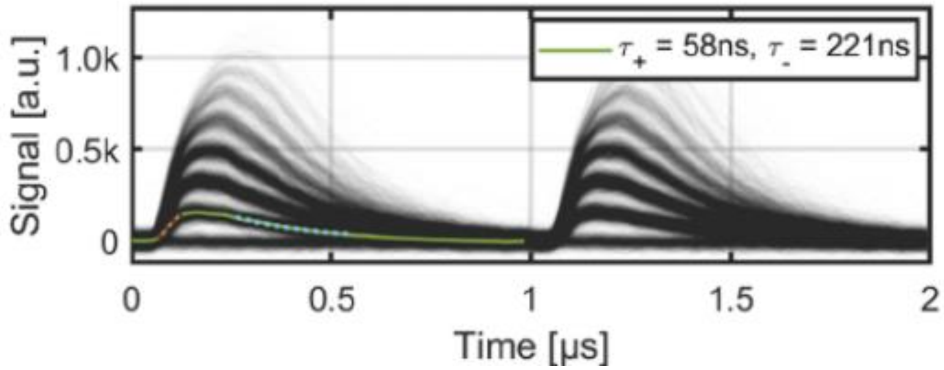
K. Hattori[a,b,c] & T. Konno[a] & Y. Miura[a] & S. Takasu[a] & D. Fukuda[a,c]



Fast transition-edge sensors suitable for photonic quantum computing

Cite as: J. Appl. Phys. 133, 234502 (2023); doi: 10.1063/5.0149478
Submitted: 17 April 2023 · Accepted: 25 May 2023 ·
Published Online: 16 June 2023
View Online Export Citation CrossMark

Ruslan Hummatov,[1,2,a)] Adriana E. Lita,[2] Tannaz Farrahi,[1,2] Negar Otrooshi,[1,2] Samuel Fayer,[3] Matthew J. Collins,[3] Malcolm Durkin,[1,2] Douglas Bennett,[2] Joel Ullom,[2] Richard P. Mirin,[2] and Sae Woo Nam[2]

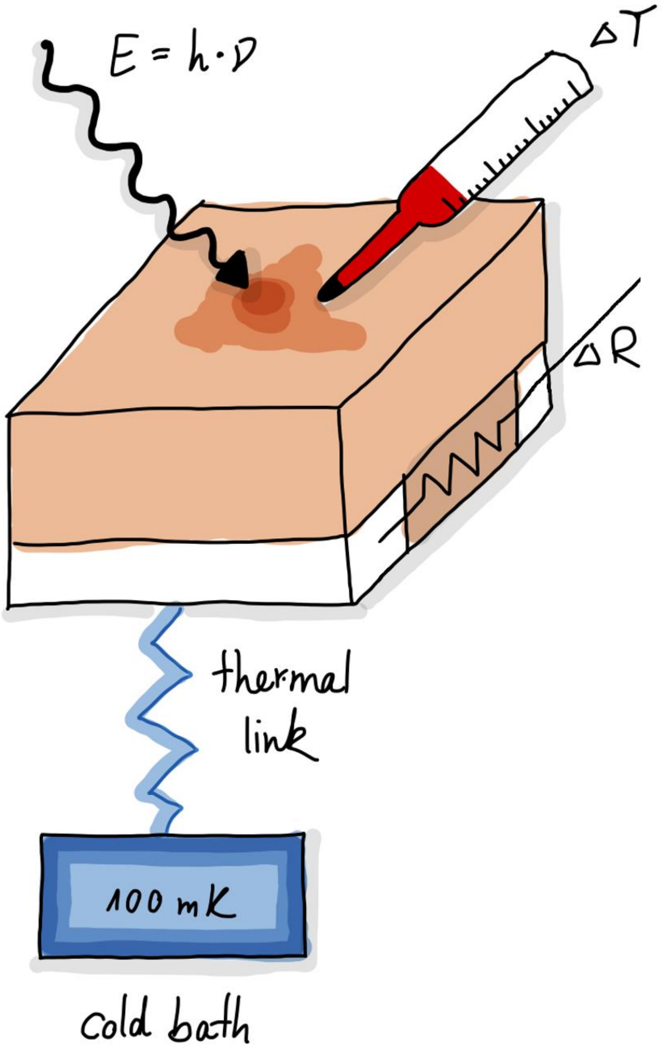


https://doi.org/10.1038/s44172-024-00308-y

Kinetic inductance current sensor for visible to near-infrared wavelength transition-edge sensor readout

Paul Szypryt[1,2], Douglas A. Bennett[2], Ian Fogarty Florang[1,2], Joseph W. Fowler[1,2], Andrea Giachero[1,2,3], Ruslan Hummatov[1,2,4], Adriana E. Lita[2], John A. B. Mates[2], Sae Woo Nam[2], Galen C. O'Neil[2], Daniel S. Swetz[2], Joel N. Ullom[1,2], Michael R. Vissers[2], Jordan Wheeler[2] & Jiansong Gao[2,5]

Thank you!

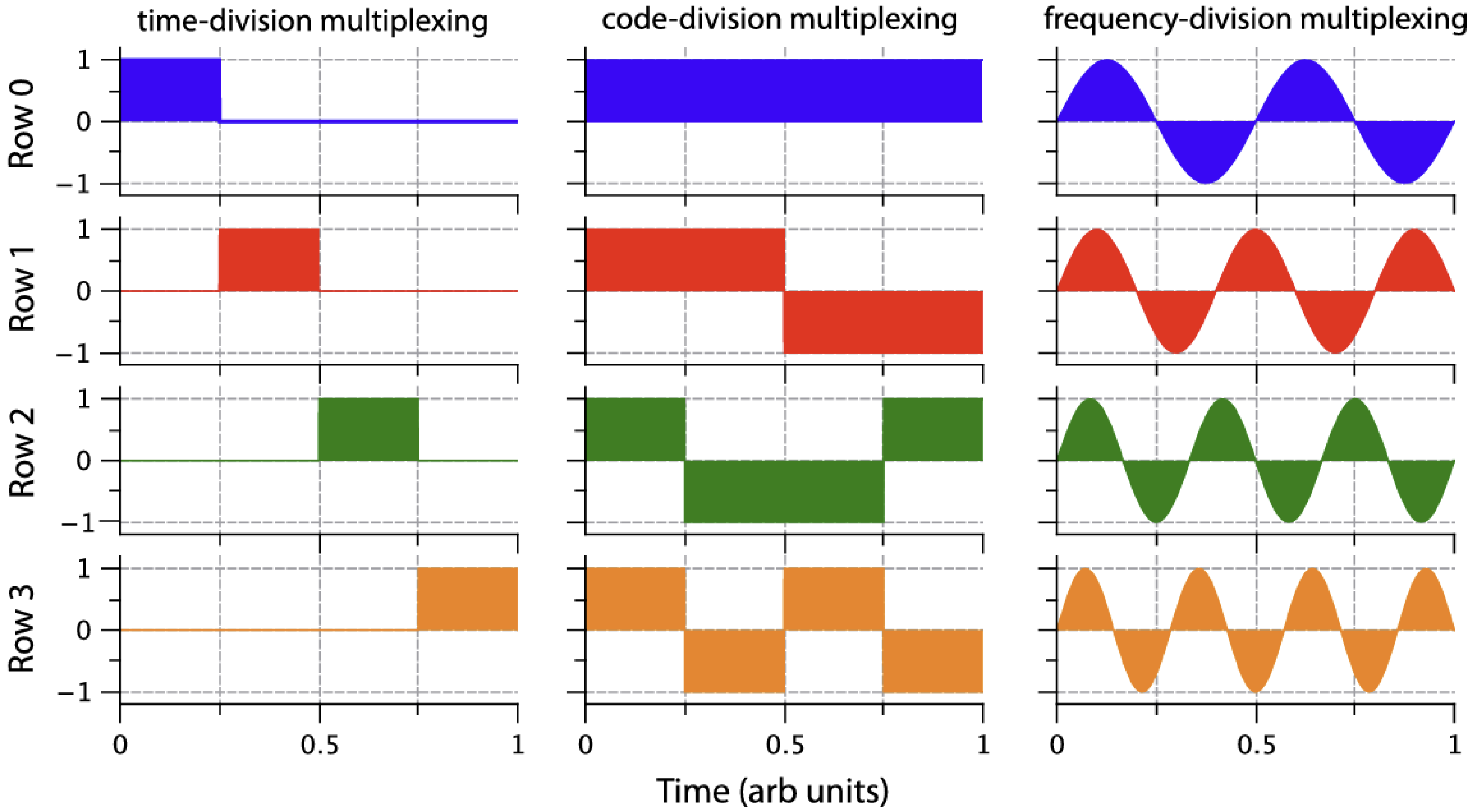


References

- Transition-edge sensors, in: Cryogenic Particle Detection. http://dx.doi.org/10.1007/10933596_3
- A Review of X-ray Microcalorimeters Based on Superconducting Transition Edge Sensors for Astrophysics and Particle Physics. https://doi.org/10.3390/app11093793
- A high-resolution gamma-ray spectrometer based on superconducting microcalorimeters. https://doi.org/10.1063/1.4754630
- The Athena X-ray Integral Field Unit: a consolidated design for the system requirement review of the preliminary definition phase. https://doi.org/10.1007/s10686-022-09880-7
- Optimizing a Transition Edge Sensor detector system for low flux infrared photon measurements at the ALPS II experiment. https://doi.org/10.3204/PUBDB-2024-07357
- A TES system for ALPS II - Status and Prospects. https://doi.org/10.22323/1.449.0567
- Superconducting transition-edge sensors optimized for high-efficiency photon-number resolving detectors. https://doi.org/10.1117/12.852221
- Generation of optical coherent-state superpositions by number-resolved photon subtraction from the squeezed vacuum. https://doi.org/10.1103/PhysRevA.82.031802
- Sensor-Assisted Fault Mitigation in Quantum Computation. https://doi.org/10.1103/PhysRevApplied.16.024025
- Fast transition-edge sensors suitable for photonic quantum computing. https://doi.org/10.1063/5.0149478
- An optical transition-edge sensor with high energy resolution. https://doi.org/10.1088/1361-6668/ac7e7b
- Kinetic inductance current sensor for visible to near-infrared wavelength transition-edge sensor readout. https://doi.org/10.1038/s44172-024-00308-y

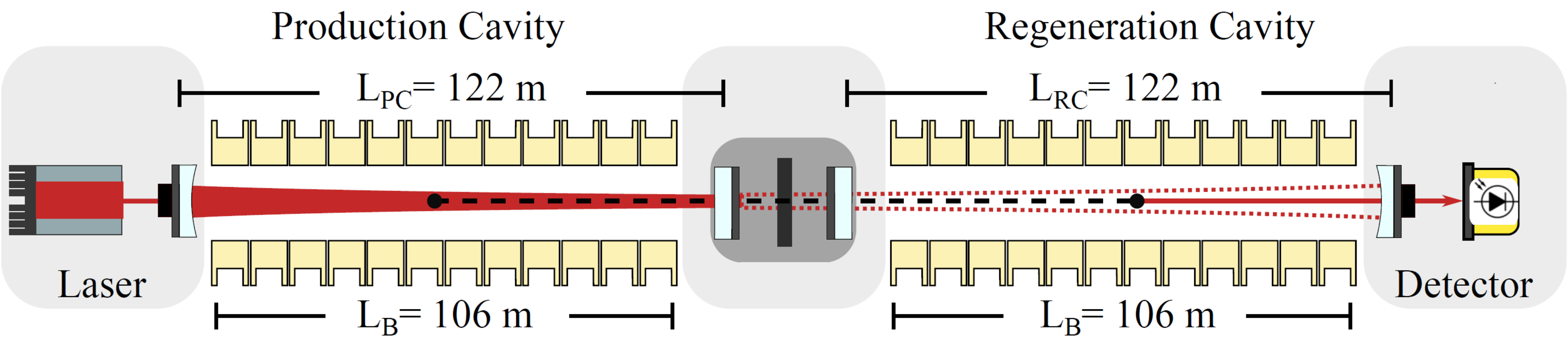
Backup

SQUID multiplexing



Also, microwave KID
And microwave SQUID

Any Light Particle Search II (ALPS II)



$$p_{\gamma\to a\to\gamma} = 8\cdot 10^{-26}\,\frac{\beta_{PC}}{5000}\,\frac{\beta_{RC}}{16000}\left(\frac{g_{a\gamma\gamma}}{0.2\cdot 10^{-10}\ \mathrm{GeV}^{-1}}\,\frac{B}{5.3\ \mathrm{T}}\,\frac{L_B}{106\ \mathrm{m}}\right)^4$$

Enhancement by optical cavities

Motivated by astrophysics

Schematic adapted from Todd Kozlowski

Transition Edge Sensor in ALPS II

Requirements for ALPS II:

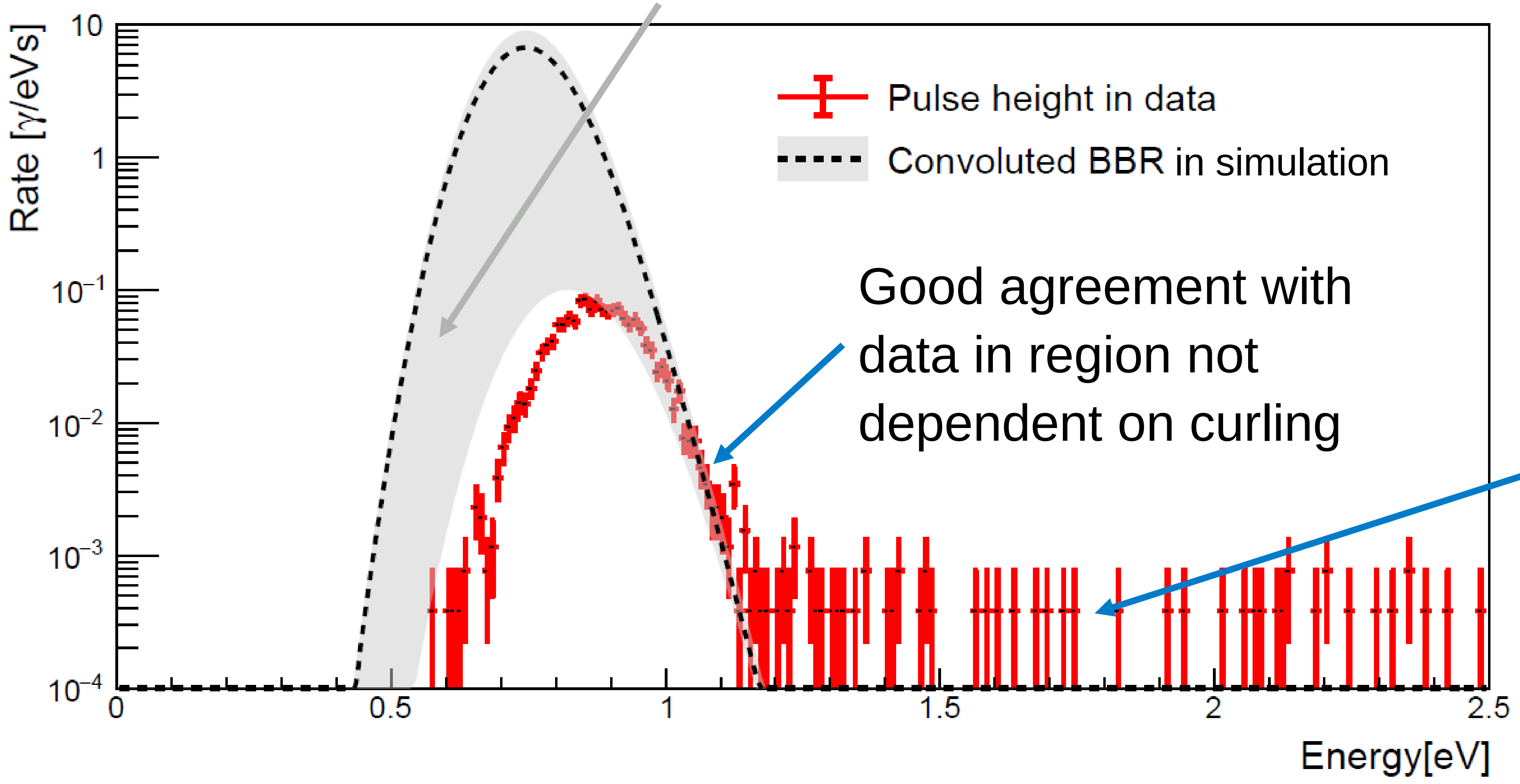
- Sensitivity to very low rates (1-2 photons a day)
- Low energy photon detection (1064nm equivalent to 1.16eV)
- Long term stability (~ 20 days)
- High system detection efficiency [1]
- Low background rate: $< 7.7 \cdot 10^{-6}\mathrm{cps} \sim$ 1 photon (1064nm−like) every 2 days
  - Intrinsics [2]
  - Extrinsics
  - Good energy resolution (for background rejection) [1]

[1] J. A. Rubiera Gimeno, F. Januschek, K.-S. Isleif, A. Lindner, M. Meyer, G. Othman, C. Schwemmbauer, R. Shah, "A TES system for ALPS II - Status and Prospects", PoS EPS-HEP2023 (2023) 567. https://doi.org/10.22323/1.449.0567
[2] Rikhav Shah, Katharina-Sophie Isleif, Friederike Januschek, Axel Lindner and Matthias Schott, "TES Detector for ALPS II", Proceedings of The European Physical Society Conference on High Energy Physics, Volume 398, Page 801, (2022); https://doi.org/10.22323/1.398.0801

doi:10.3204/PUBDB-2024-07357

Extrinsics background

Additional curling uncertainty



Good agreement with data in region not dependent on curling

Remnant intrinsic background