JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

NSC
Nanoscience Center

Superconducting thermoelectric detector

Tero T. Heikkilä
Nanoscience Center/Department of Physics,
University of Jyväskylä, Finland

Ozaeta, Virtanen, Bergeret, TTH, PRL 2014
TTH, Ojajärvi, Maasilta, Strambini, Giazotto, Bergeret, Phys. Rev. Applied (in press) arXiv:1709.08856
Chakraborty, TTH, J. Appl. Phys. (in press) arXiv:1804.08319
Bergeret, Silaev, Virtanen, TTH, Rev. Mod. Phys. (in press) arXiv:1706.08245

Funding by
ACADEMY OF FINLAND
RESEARCH FUNDING AND EXPERTISE
FUNDING OPPORTUNITIES
FUTURE & EMERGING TECHNOLOGIES

International Summer School in Nanophysics

Local organizers at HUT

C. G. Aminoff
T. Heikkilä
O. Ikkala

M. Kaivola
T. Pohjola
M. M. Salomaa

Materials Physics Laboratory

Advisory organizing and program committee

K. Kaski, HUT
P. Kuivalainen, HUT
H. Lipsanen, HUT
R. Nieminen, HUT

M. Paalanen, HUT
J. Tulkki, HUT
T. Tuomi, HUT

J. Pekola, Jyväskylä
G. Schön, Karlsruhe
H. Stubb, Turku
J. Turunen, Joensuu

Nanoelectronics 11. - 14. 8. 1998

Franz Himpsel, Madison
Magnetic Quantum Wells; Nanowires

Olli Ikkala, HUT
Polymeric Self-Assembled Nanostructures

Mats Jonson, Chalmers
Bio-Magnetic Composites and Nanocomponents

Leo Kouwenhoven, Delft
Semiconductor Quantum Dots

Colin Lambert, Lancaster
Transport in Superconducting Nanostructures

Jukka Pekola, Jyväskylä
Tunnel Junctions and Fabrication Techniques

Dan Ralph, Cornell
Nanostructures in Study of Interacting Electrons

Gerd Schön, Karlsruhe
Single-Electron Tunneling

Nano-optics 17. - 20.8. 1998

Jochen Feldmann, München
Optical Experiments on Semiconductor Nanostructures

Ari Friberg, Stockholm
Optical Near-Field Theory

Frank Jahnke, Marburg
Excitons and Nonequilibrium Effects in Microcavities

Kenichi Nishi, NEC
Characteristics of Self-Assembled Quantum Dots

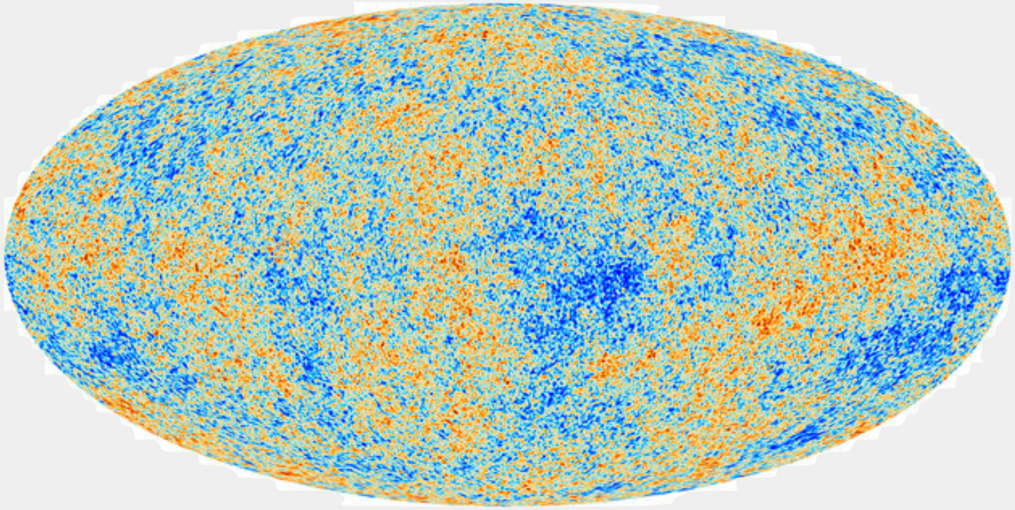
Vahid Sandoghdar, Konstanz
Interaction of Light and Matter in the Optical Near Field

Jari Turunen, Joensuu
Diffractive Optics: Electromagnetic Theory

Frank Wyrowski, Jena
Realizing Optical Functions by Microstructured Surfaces

Helsinki University of Technology, Otaniemi, Finland http://focus.hut.fi/nanoschool/

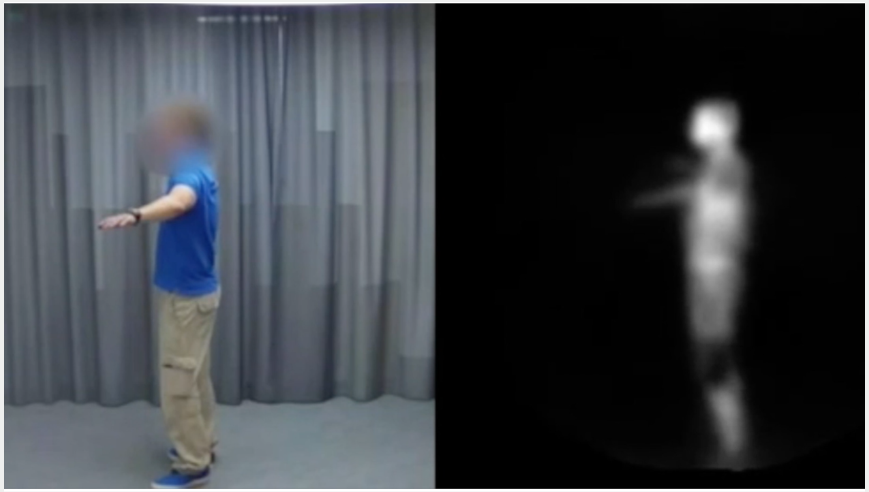
Superconducting detectors

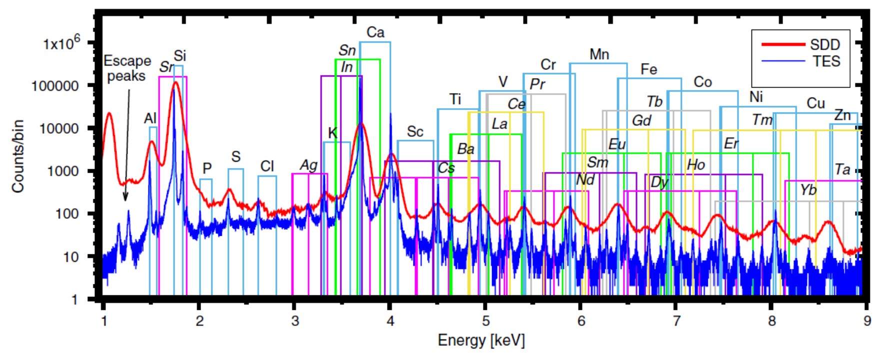


Cosmic microwave background CMB: Map of the temperature fluctuations (power) measured by the ESA Planck satellite

Security imaging (A. Luukanen)
(see asqella.com/videos)

ASQELLA

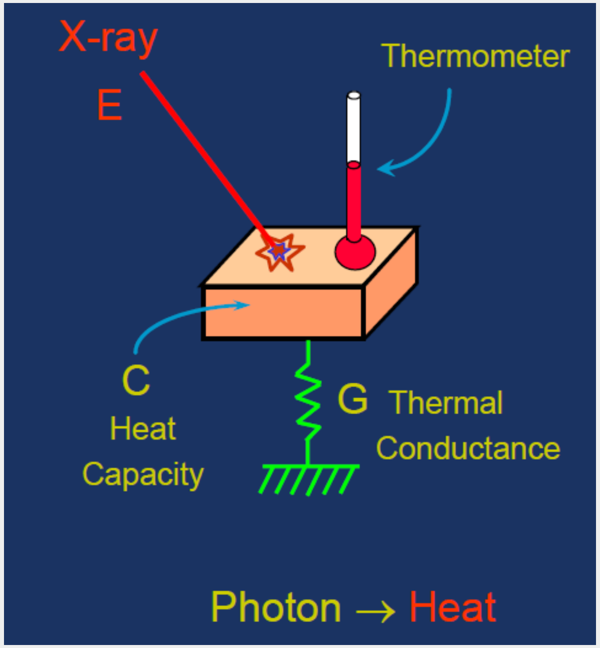




X-ray materials analysis (I. Maasilta, et al., JYU)

TES and KID

Presently: two generic types of superconducting detectors



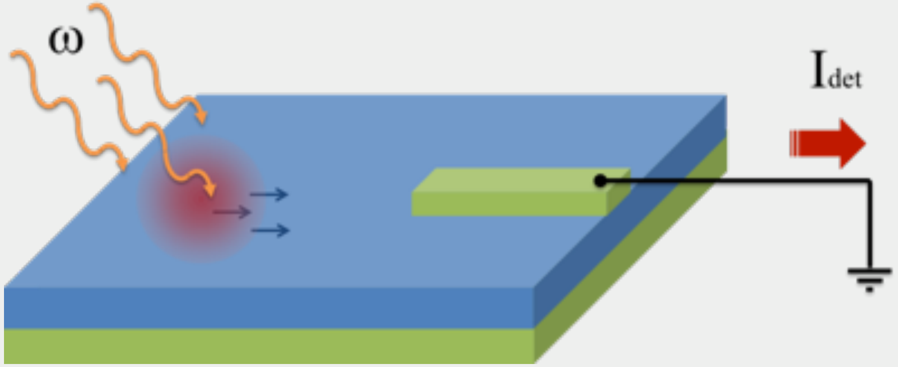
Transition edge sensor TES: thermometer= resistance at the superconducting transition

Kinetic inductance detector KID: thermometer = *T*-dependent inductance in a superconductor

In both cases, an external read-out signal is needed!

More: Giazotto, TTH, Luukanen, Savin, Pekola, RMP 2006

Thermoelectric detector TED



Jones, J. Opt. Soc. Am. (1947)
van Vechten, *et al.* (1999)
L. Kuzmin (2010)
Varpula, *et al.* APL (2017)
… and a few others

Low T: low noise!

$$I_{\rm det} = \alpha \Delta T / T \propto P_\gamma$$

Advantage: self-powered by measured radiation

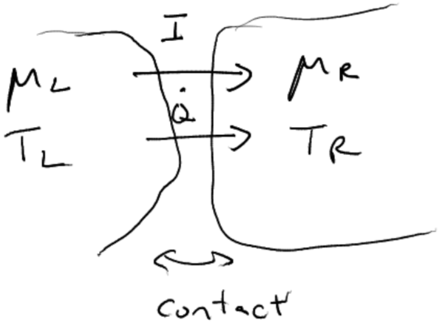
Independent of overall temperature fluctuations

BIG disadvantage: usually $\alpha \neq 0$ only above room temperature

Thermoelectric effects

Linear response charge and heat currents across an interface:

$$\begin{pmatrix} I \\ \dot{Q} \end{pmatrix} = \begin{pmatrix} G & \alpha \\ \alpha & G_{\mathrm{th}}^{\mathrm{tot}} T \end{pmatrix} \begin{pmatrix} V \\ -\Delta T/T \end{pmatrix}$$



$eV = \mu_L - \mu_R$

$\Delta T = T_L - T_R$

$$G_{\mathrm{th}}^{\mathrm{tot}} = G_{\mathrm{th}} + G_{\mathrm{th,spurious}}$$

Junction

Phonons, other baths

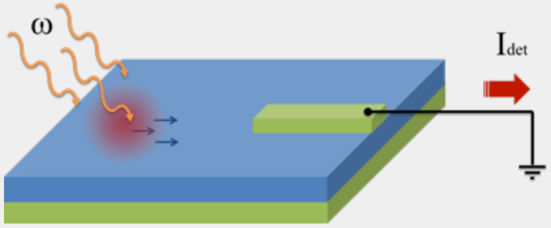
“True” figure of merit

$$ZT = \frac{\alpha^2}{G_{\mathrm{th}}^{\mathrm{tot}} G T - \alpha^2}$$

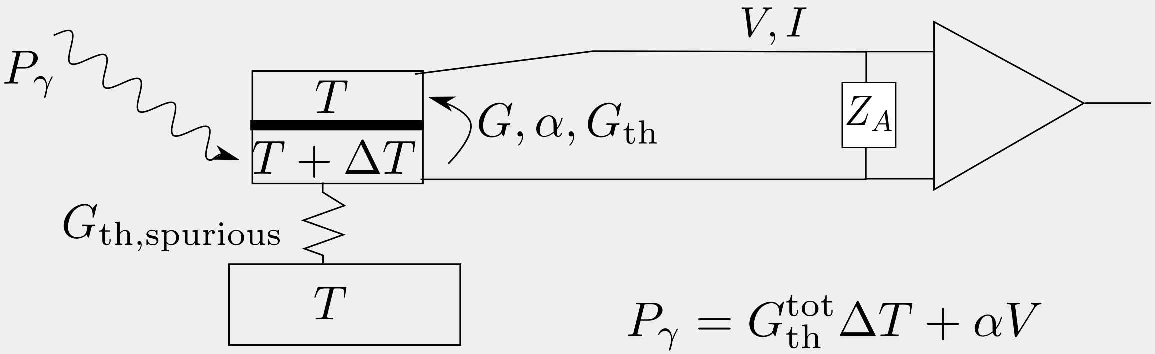
“Intrinsic” figure of merit

$$ZT_i = \frac{\alpha^2}{G_{\mathrm{th}} G T - \alpha^2} > ZT$$

Thermoelectric detection



(Bolometric detection)



$$P_\gamma = G_{\rm th}^{\rm tot} \Delta T + \alpha V$$

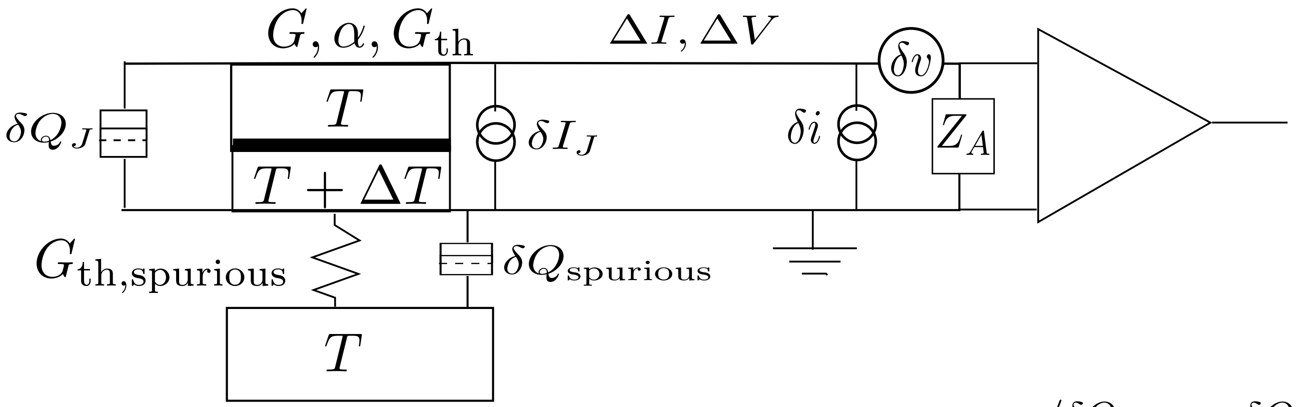
Generic Z_A: coupled thermal balance and current conservation equations

$Z_A \to \infty$: voltage detection $$\lambda_V = \frac{V}{P_\gamma} = \frac{\alpha}{G_{\rm th}^{\rm tot} G T - \alpha^2} = \frac{ZT}{\alpha}$$

$Z_A \to 0$: current detection $$\lambda_I = \frac{I}{P_\gamma} = \frac{\alpha}{G_{\rm th}^{\rm tot} T}$$

Duality?

Noise analysis



$$\langle \delta I^2 \rangle = 4 k_B T G$$

$$\langle \delta \dot{Q}_J^2 \rangle = 4 k_B T^2 G_{\rm th}$$

$$\boxed{\langle \delta I \delta \dot{Q}_J \rangle = -4 k_B T \alpha}$$

$$\langle \delta Q_{\rm spurious} \delta Q_{\rm spurious} \rangle = 4 k_B T G_{\rm th,spurious}$$

$$NEP^2 = \frac{\langle \Delta V^2 \rangle}{\lambda_V} = \frac{\langle \Delta I^2 \rangle}{\lambda_I} = \frac{4 k_B T^2 G_{\rm th}^{\rm tot}}{ZT}$$

Noise equivalent power

Optimize by choosing $G_{\rm th} = \sqrt{1 + ZT_i}\, G_{\rm th,spurious}$, with $ZT_i = \alpha^2/(G_{\rm th} G T - \alpha^2)$

$$\Rightarrow \quad NEP^2_{\rm opt} = \frac{4 G_{\rm th,spurious} k_B T^2 (1 + \sqrt{1 + ZT_i})^2}{ZT_i} \xrightarrow{ZT_i \to \infty} 4 G_{\rm th,spurious} k_B T^2$$

(TES TFN)

Thermoelectricity

Density of states

Diffusion constant

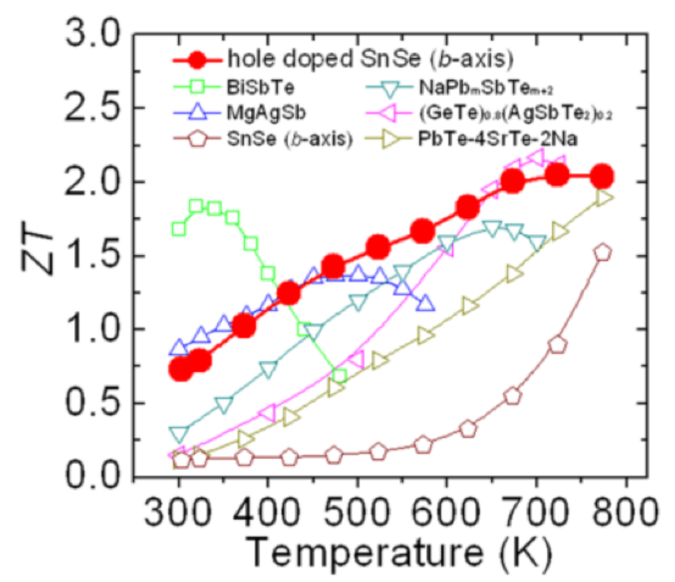
Boltzmann theory: $\alpha \propto \int dE \, \frac{E\nu(E)D(E)}{4k_BT\cosh^2\left(\frac{E}{2k_BT}\right)}$

Electron-hole asymmetry needed!

Metals: $\alpha \sim o\left(\frac{k_BT}{E_F}\right)$ Small!

Semiconductor devices: large ZT, but only around room temperature!

Zhao, et al., Science **351**, 141 (2015)



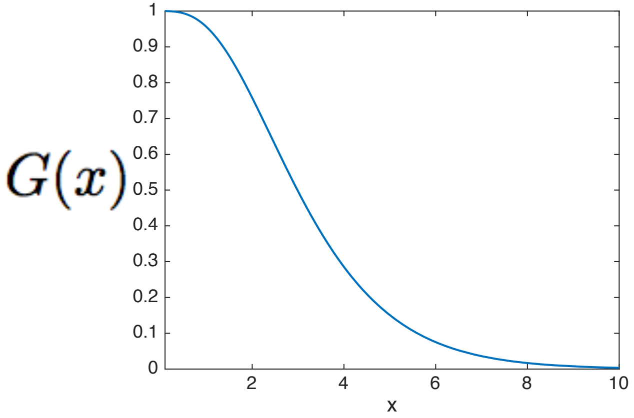
Main message: no known strong thermoelectric at low T!

Thermoelectricity in superconductors

Many textbooks: no thermoelectric effects because they are cancelled by supercurrent (Meissner 1927).
Ginzburg (1944): possible to see in multiply connected structures, but very small

The size of thermoelectric coefficient in bulk superconductors:

$$\alpha = \underset{\overset{\uparrow}{\text{Small}}}{\alpha_N}\,\underset{\overset{\uparrow}{\text{Small}}}{G}(\Delta/T)$$

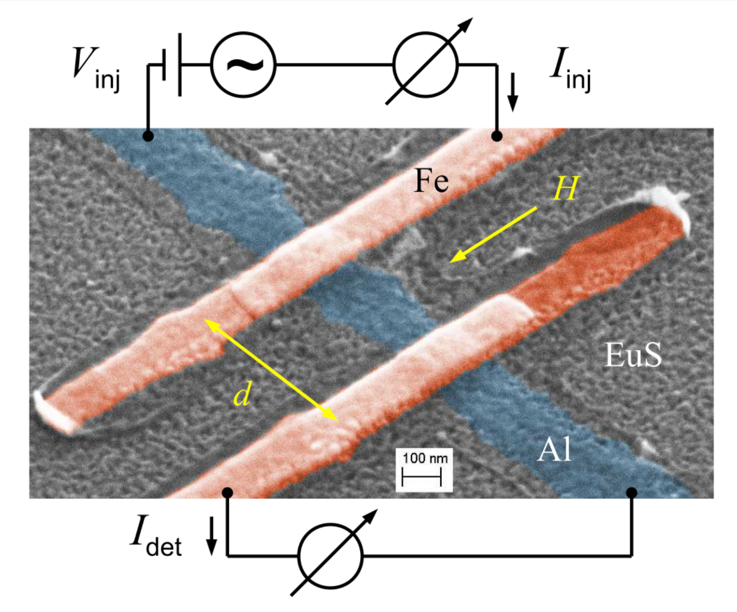


$$\alpha_N = \frac{\pi^2 G k_B}{6e}\frac{k_B T}{E_F}$$

Gal'perin, Gurevich & Kozub Sov. Phys. JETP (1974)

Main message (before 2014): superconductors are extremely poor thermoelectrics!

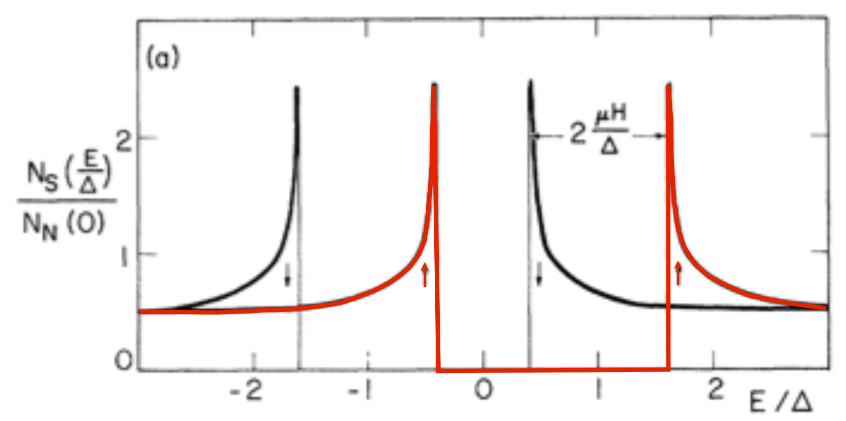
Super/ferro hybrids



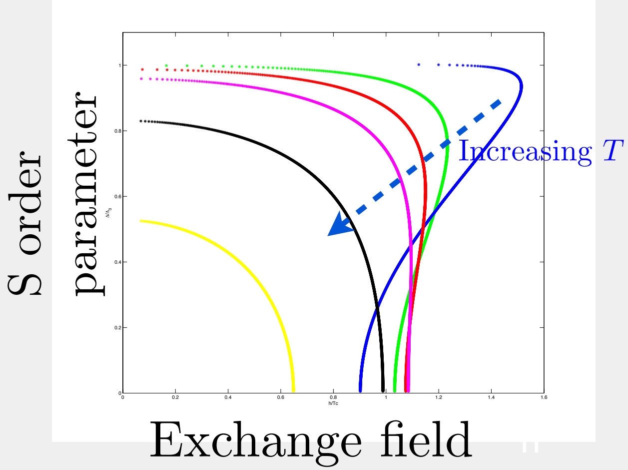
Wolf, Sürgers, Fischer & Beckmann, PRB **90**, 144509 (2014)

Fe: ferromagnetic metal
Al: superconductor (below 1 K)
EuS: ferromagnetic insulator

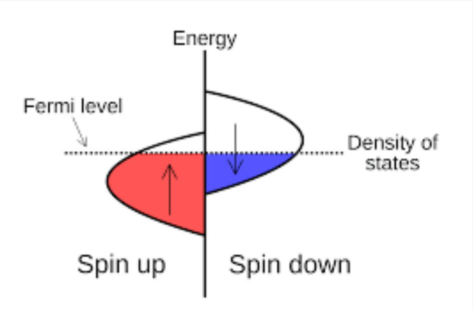
Magnetic proximity effect into S: exchange field "leaks" into S: spin-split density of states



Exp: Meservey, Tedrow (1971)
Moodera, *et al.* (1990, 2013)
and many others

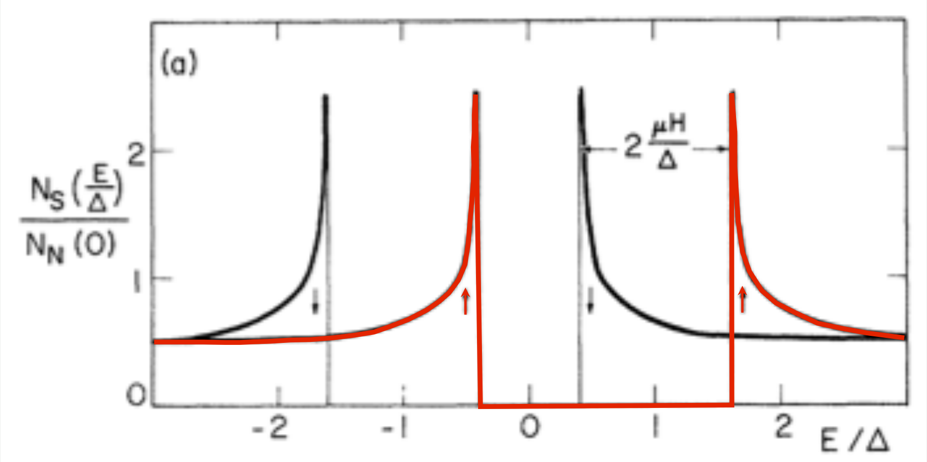


Super-ferro: ingredients



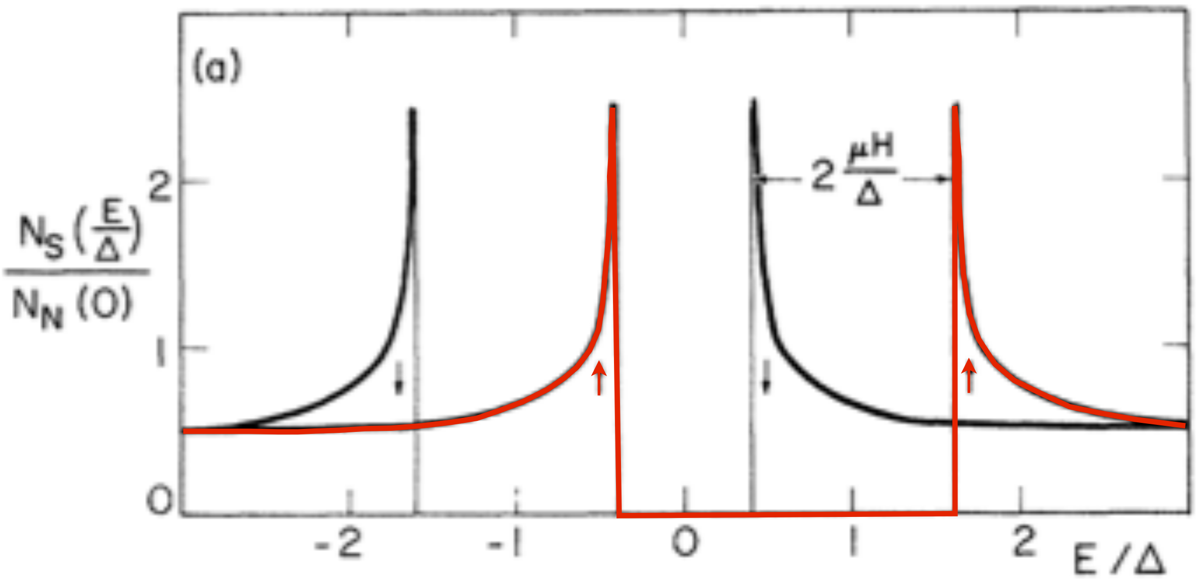
Ferromagnet: spin-dependent Fermi level $\longrightarrow$ spin-dependent contact resistance

Polarization: $P = \frac{R_\uparrow - R_\downarrow}{R_\uparrow + R_\downarrow} \in [-1, 1$



superconductor with spin splitting h

Large thermoelectric effect:



1. Large e-h asymmetry *per spin*
2. For $P \neq 0$, different spin contributions weighed differently

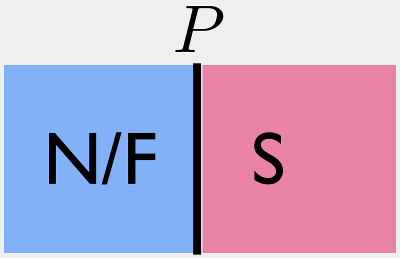
Ozaeta, Virtanen, Bergeret, TTH, PRL 2014

Spin-splitting field + polarization

Linear response: $\begin{pmatrix} I \\ \dot{Q} \end{pmatrix} = \begin{pmatrix} G & P\alpha \\ P\alpha & G_{\rm th}T \end{pmatrix} \begin{pmatrix} V \\ -\Delta T/T \end{pmatrix}$

Polarization!

$$\alpha = \frac{1}{2eR_T} \int_{-\infty}^{\infty} dE \, \frac{E[N_\uparrow(E) - N_\downarrow(E)]}{4k_BT\cosh^2\left(\frac{E}{2k_BT}\right)}$$



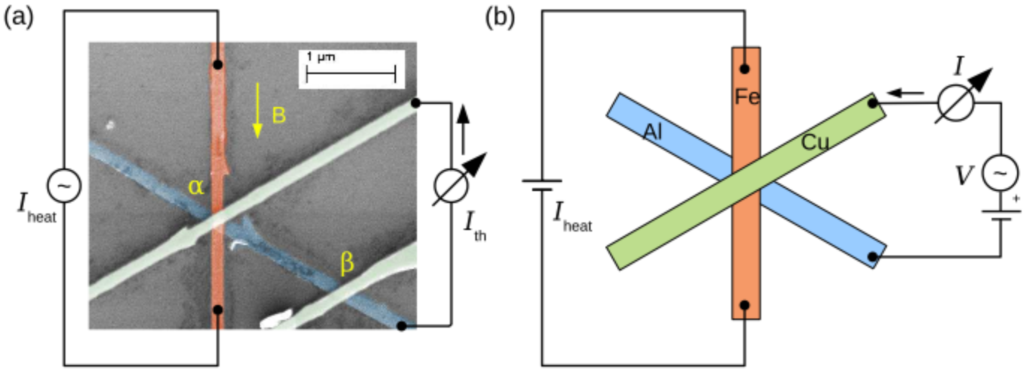
$$G \approx G_T\sqrt{2\pi\tilde{\Delta}}\cosh(\tilde{h})e^{-\tilde{\Delta}}\,,$$
$$G_{\rm th} \approx \frac{k_BG_T\Delta}{e^2}\sqrt{\frac{\pi}{2\tilde{\Delta}}}e^{-\tilde{\Delta}}\left[e^{\tilde{h}}(\tilde{\Delta}-\tilde{h})^2 + e^{-\tilde{h}}(\tilde{\Delta}+\tilde{h})^2\right]\,,$$
$$\alpha \approx \frac{G_T}{e}\sqrt{2\pi\tilde{\Delta}}e^{-\tilde{\Delta}}\left[\Delta\sinh(\tilde{h}) - h\cosh(\tilde{h})\right]$$

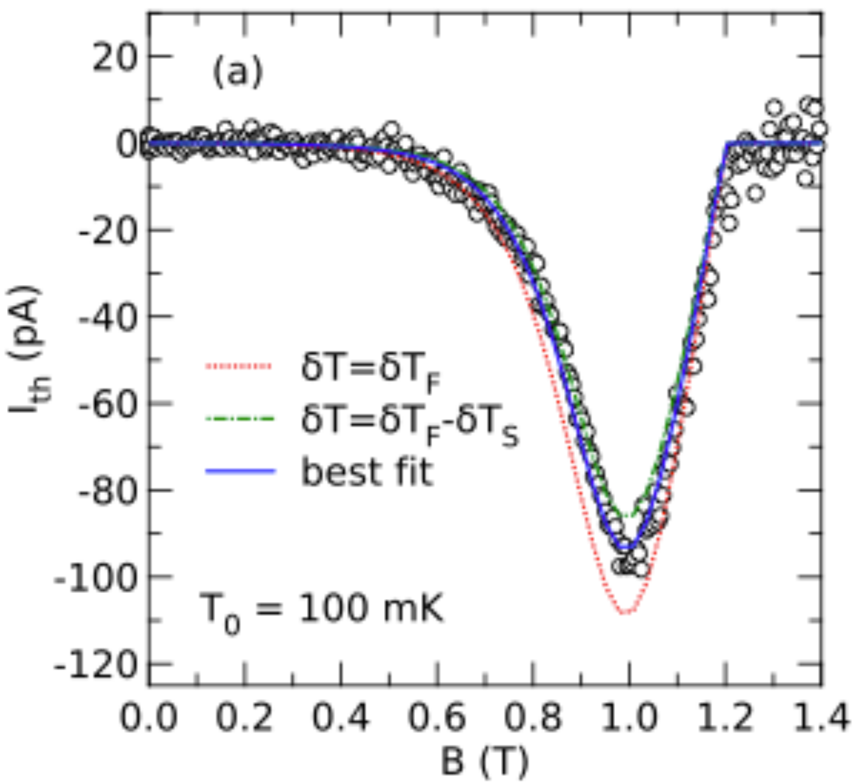
Ozaeta, Virtanen, Bergeret, TTH, PRL 2014

PRL **116,** 097001 (2016) PHYSICAL REVIEW LETTERS week ending
4 MARCH 2016

Observation of Thermoelectric Currents in High-Field Superconductor-Ferromagnet Tunnel Junctions

S. Kolenda, M. J. Wolf,[*] and D. Beckmann[†]
Institute of Nanotechnology, Karlsruhe Institute of Technology, Karlsruhe, Germany



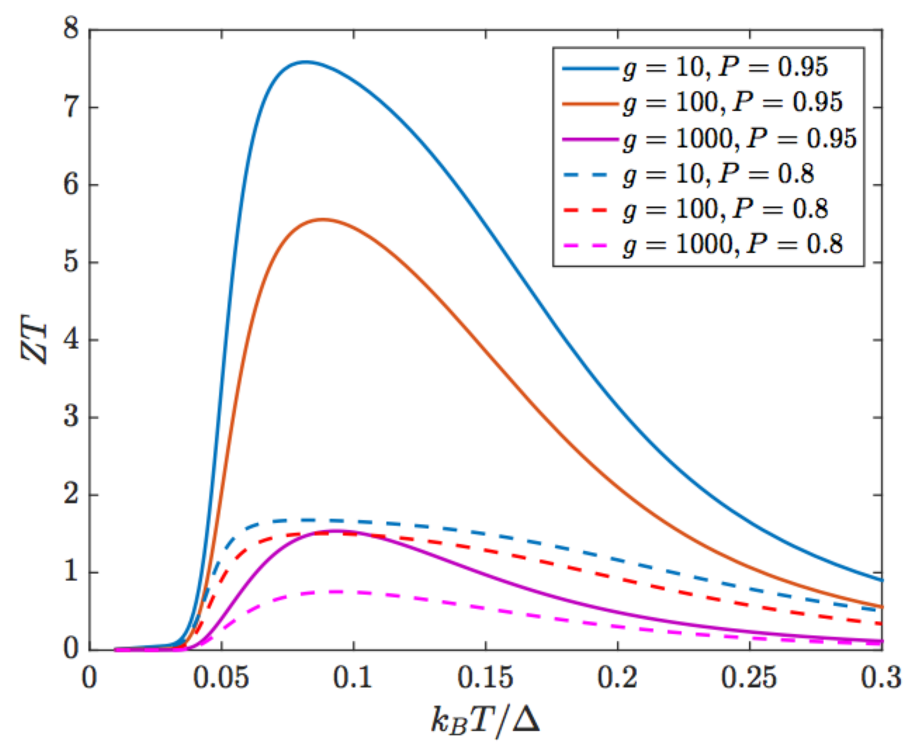


Only fit parameter: exact temperature difference

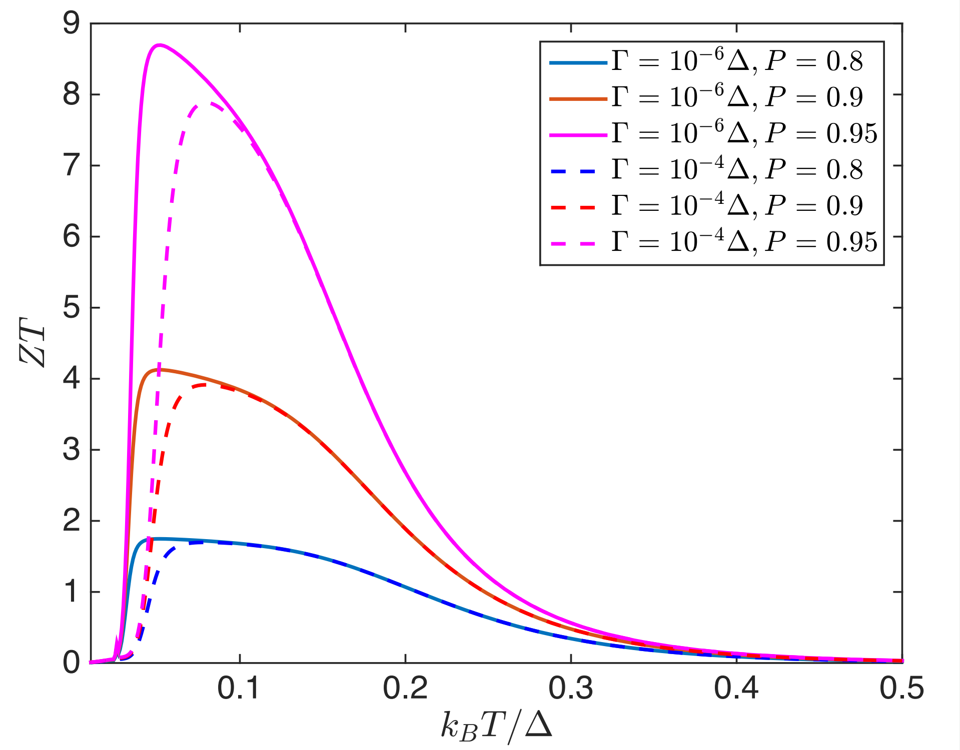
S-F heat engine: “real” *ZT*

$h = 0.5\Delta$

FNF island (antiparallel magnetizations)



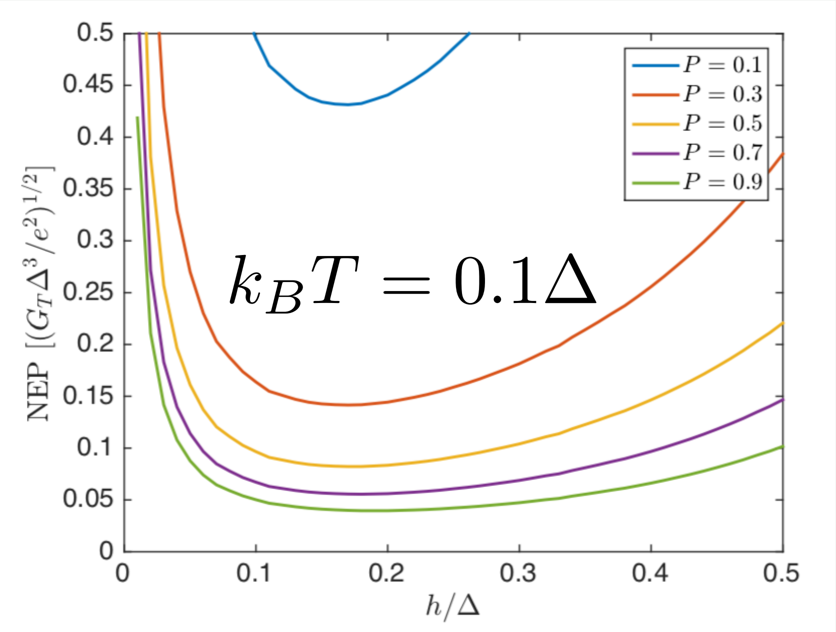
S island (F electrodes)

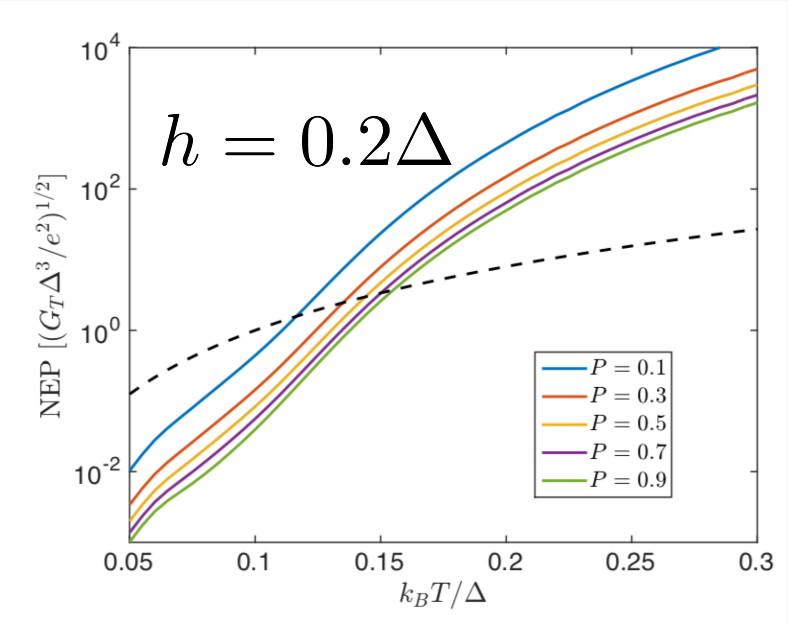


$g \sim$ relative strength of spurious heat conduction

$\Gamma \sim$ ”Dynes” parameter, quality of the BCS gap

NEP and energy resolution





Unit scale $\sim 10^{-18}\ \mathrm{W}/\sqrt{\mathrm{Hz}}$

(roughly TES TFN at the same T)

In the S state!

In the N state! (dashed line)

$$NEP^2_{\mathrm{TED}} = \frac{4G_{\mathrm{th,spurious}}k_BT^2(1+\sqrt{1+ZT_i})^2}{ZT_i} \xrightarrow{ZT_i\to\infty} NEP^2_{\mathrm{TES}} = 4G_{\mathrm{th,spurious}}k_BT^2$$

Example: $\Omega = 10^{-19}\ \mathrm{m}^3,\ G_T^{-1} = 400\ \mathrm{k}\Omega\ (\mu\mathrm{m})^2$, Aluminum

Current or voltage measurement?

Add amplifier noise power spectral density (voltage noise S_V^A or current noise S_I^A):

Voltage noise: $NEP_{\rm A,V}^2 = \frac{S_V^A G T G_{\rm th}^{\rm tot}}{zT(1+zT)}$ $r_V \equiv \frac{NEP_{\rm A,V}^2}{NEP^2} = \frac{S_V^A}{4k_BT}\frac{G}{(1+zT)}$

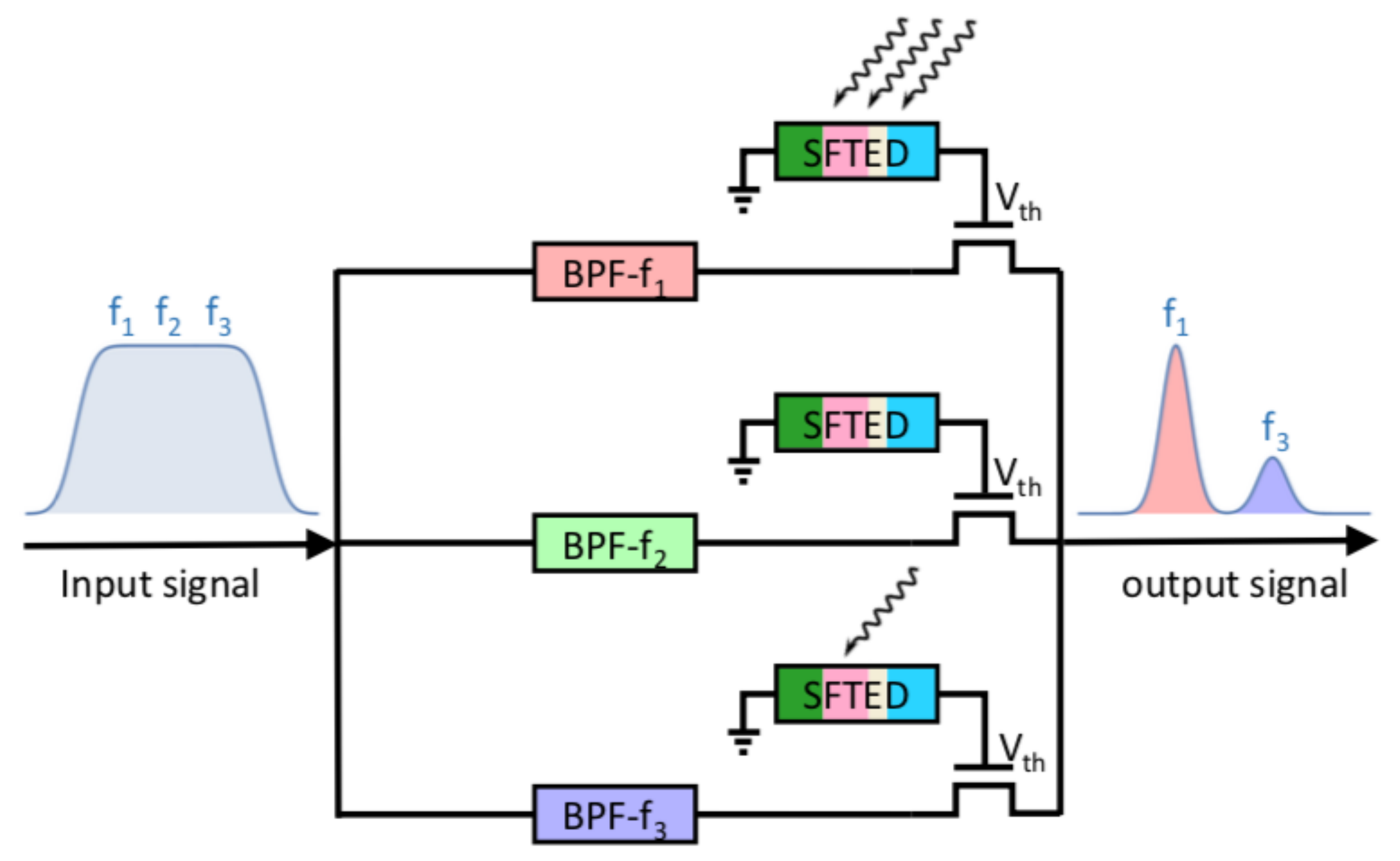
Current noise: $NEP_{\rm A,I}^2 = \frac{S_I^A(1+zT)G_{\rm th}^{\rm tot}T}{GzT}$ $r_I \equiv \frac{NEP_{\rm A,I}^2}{NEP^2} = \frac{S_I^A}{4k_BT}\frac{(1+zT)}{G}$

Using $\sqrt{S_V} = 0.3$ nV/$\sqrt{\rm Hz}$ yields
$r_V \approx G\Delta/(G_T k_B T)(1+ZT)^{-1} \ll 1$ whenever $k_BT \ll \Delta$

Using $\sqrt{S_I} = 0.5$ fA/$\sqrt{\rm Hz}$ yields
$r_I \approx 10^{-4}\Delta G_T(1+ZT)/(Gk_BT)$, exceeds unity for $k_BT \lesssim \Delta$

Voltage measurement is preferred due to the high dynamic resistance of the junction!
However, at low *T*, the bandwidth may become quite low.

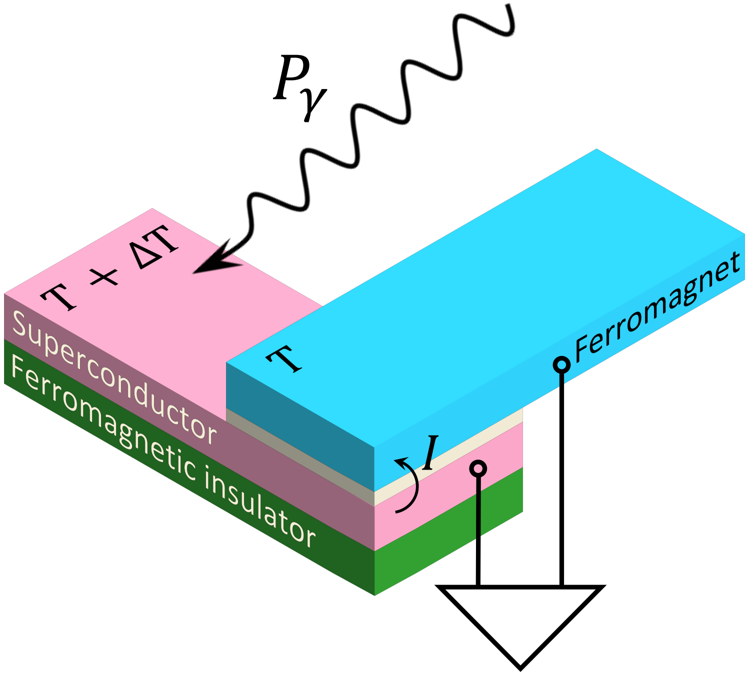
Multiplexing…



SUPERTED

New type of an ultrasensitive thermoelectric radiation sensor

Sept. 2018-Aug 2022



$$I \propto \Delta T \propto P_\gamma$$

FUNDING OPPORTUNITIES
FUTURE & EMERGING TECHNOLOGIES

Open postdoc position!

Collaborators

Sebastian Bergeret
San Sebastian

Mikhail Silaev
Jyväskylä

Pauli Virtanen
Pisa

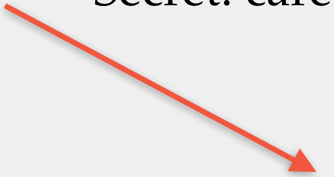
Francesco Giazotto
Pisa

Ilari Maasilta
Jyväskylä

Elia Strambini
Pisa

Risto Ojajärvi
Jyväskylä

Subrata Chakraborty
Jyväskylä



Secret: career in physics?

Happy birthday, Jukka!