UNIVERSITA' DEGLI STUDI DI MILANO BICOCCA

INFN Istituto Nazionale di Fisica Nucleare

Direct neutrino mass measurement with Transition Edge Sensors and Kinetic Inductance Microwave Detectors

The International Workshop on Prospects of Particle Physics:
"Neutrino Physics and Astrophysics"

HOLMES

fondazione cariplo

erc European Research Council

Neutrino mass

Already known

- Neutrinos have mass
- Interaction eigenstates $|\nu_l\rangle$ can be espressed

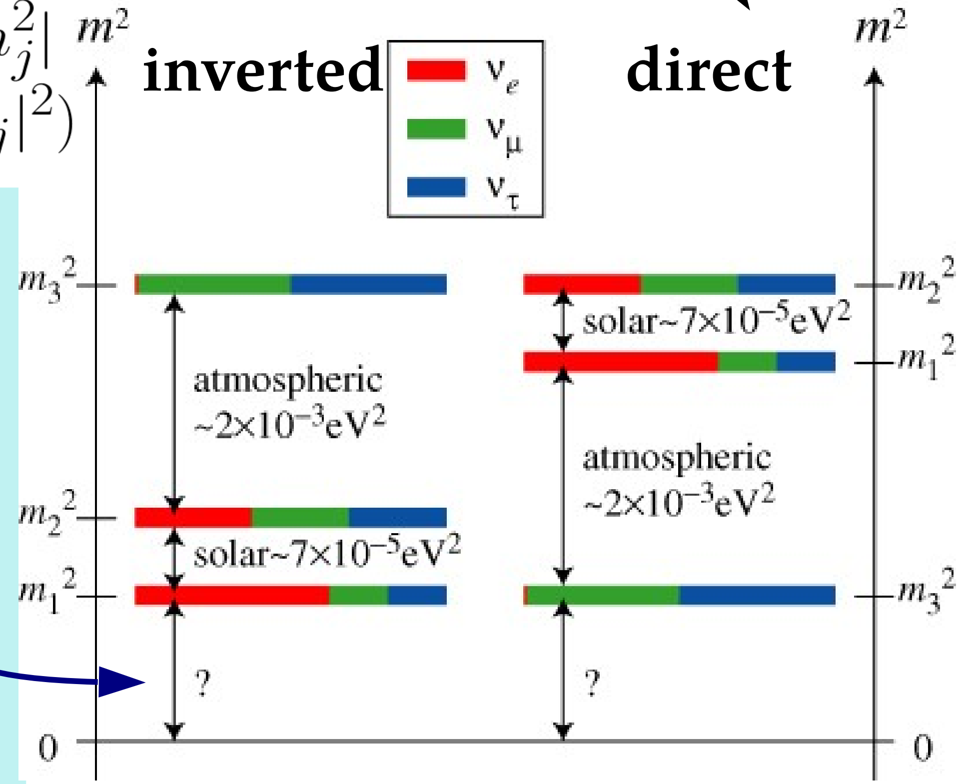
in term of mass eigenstates $|\nu_\alpha\rangle$

$$|\nu_l\rangle = \sum_\alpha U_{\alpha l}|\nu_\alpha\rangle$$

Neutrino oscillation give a piece of informations

$$\Delta m_{ij}^2 = |m_i^2 - m_j^2|$$

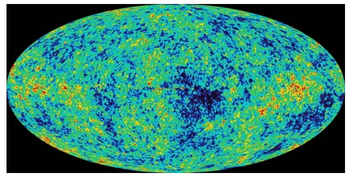
$$sin^2(2\theta_{ij}) = f(|U_{ij}|^2)$$

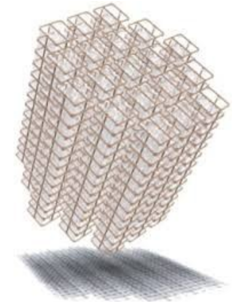


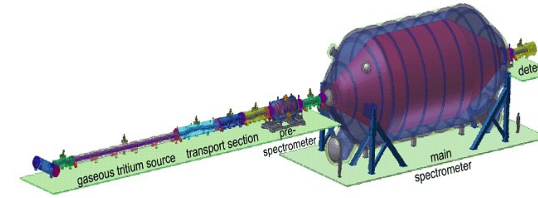
Unanswered questions

- hierarchy
  - Degenerate $m_1 \approx m_2 \approx m_3$
  - Inverted $m_1 < m_2 << m_3$
  - Direct $m_3 << m_1 < m_2$
- Absolute mass scale
- Dirac or Majorana particle
- ?

Mass measurements







Method	Cosmology	0νββ decay	β spectrum endpoint
Observable	$m_\Sigma = \Sigma_i m_{\nu i}$	$m_{\beta\beta} = \left\lvert \Sigma_i m_{\nu i} U_{ei}^2 \right\rvert$	$m_\beta = \left(\Sigma_i m_{\nu}{}_i^2 U_{ei}^2 \right)^{1/2}$
Status quo	~0.1 eV	~0.1 eV	2 eV
Next generation	0.01 eV	0.01 eV	0.2 eV
Systematics	large	good	large
Model	dependent	dependent	independent

- m_Σ is strongly dependent on cosmological assumptions

The evaluation of nuclear matrix elements involved in 0νββ decay is a major challenge (IMB, QRPA)

- Direct measurement of beta or Electron Capture (EC) spectrum is not model dependent

spectrometers: external β source
calorimeters: β o EC embedded in the detector

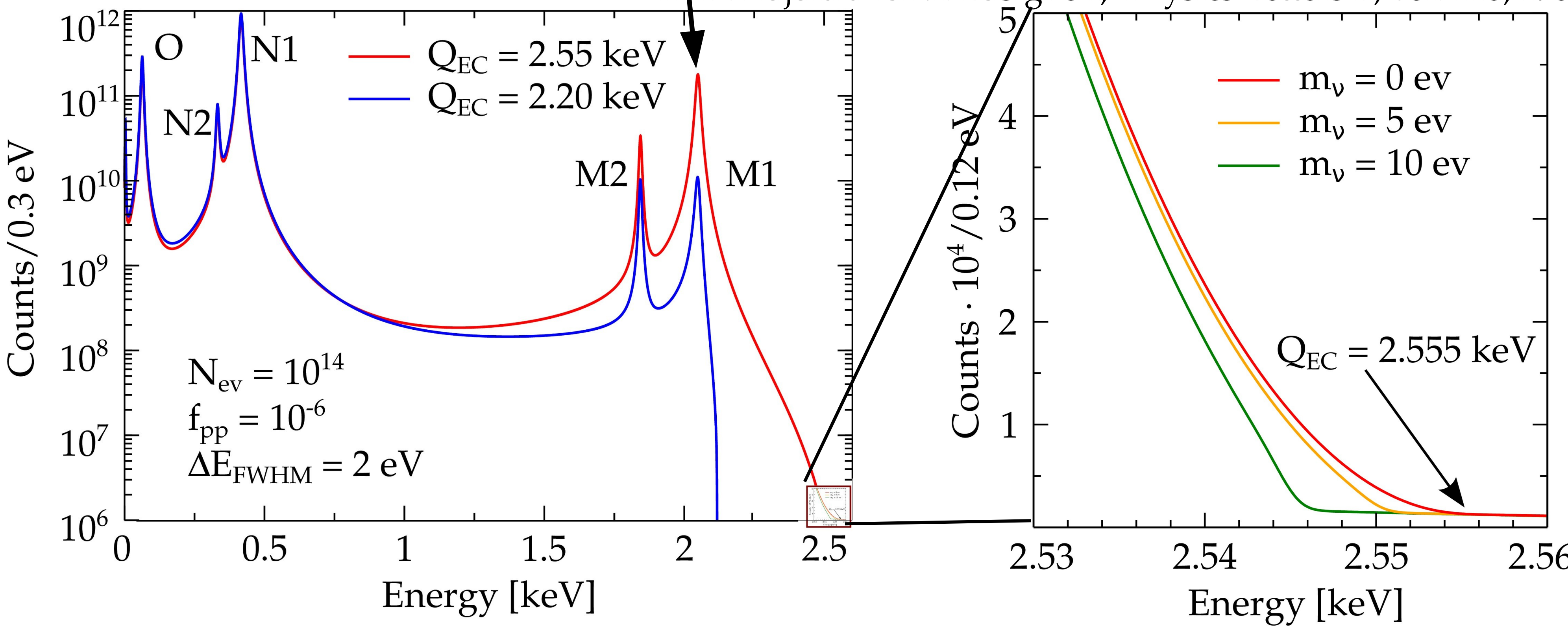
Electron capture of ^{163}Ho

A promising isotope for a direct neutrino mass measurement is ^{163}Ho

$$^{163}\mathrm{Ho} + \mathrm{e}^- \rightarrow ^{163}\mathrm{Dy}^* + \nu_e$$
$$^{163}\mathrm{Dy}^* \rightarrow ^{163}\mathrm{Dy} + \mathrm{E_C}$$

Electron capture from shell > M1

A. D. Rujula and M. Lusignoli, Physics Letters B, vol. 118, 1982.

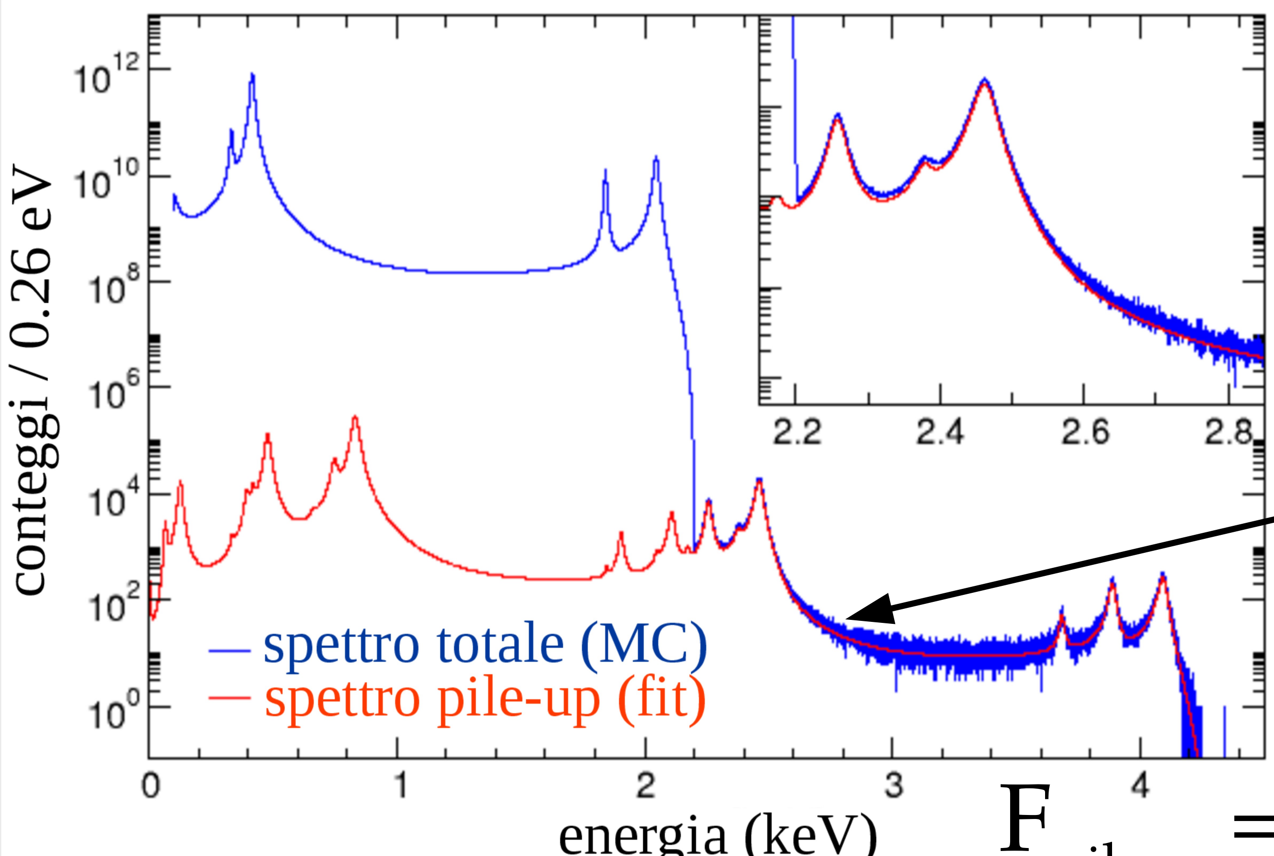


Event rate at the end point $\propto \sqrt{(\mathrm{Q} - \mathrm{E_c})^2 - \mathrm{m}_\nu^2}$

End point

The ability to measure m_ν or to set a limit depends on the number of decays close to the end point, which is strongly dependent on the relative position of the Q-value with respect to the M1 resonance

- Measured QEC (2.2 ÷ 2.8 keV) suggested 2.555 keV
- $T_{1/2}$ =4750 y → good sensitivity with 6.5*10^{16} nuclei (300 decay/s per detector)



Pile up (hence pile up resolving ability) is a crucial factor for the sensitivity of m_ν

$$f_{pile\text{-}up}=\tau_R A_\beta$$

$$F_{pile\text{-}up}= 1\ \mu s * 300\ Hz \sim 10^{-4}$$

HOLMES (ERC-Advanced Grant n. 340321)

goal

- neutrino mass measurement: m_ν statistical sensitivity as low as 0.4 eV
- prove technique potential and scalability:
  - assess EC Q-value
  - assess systematic errors

baseline

- Transition Edge Sensors (TES) with ^{163}Ho implanted Au absorbers
  - $6.5\text{x}10^{13}$ nuclei per detector $\rightarrow$ 300 dec/sec
  - $\Delta E \approx 1$eV and $\tau_R \approx 1\mu$s
- 1000 channel array
  - $6.5\text{x}10^{16}$ ^{163}Ho nuclei $\rightarrow$ $\approx 18\mu$g
  - $3\text{x}10^{13}$ events in 3 years

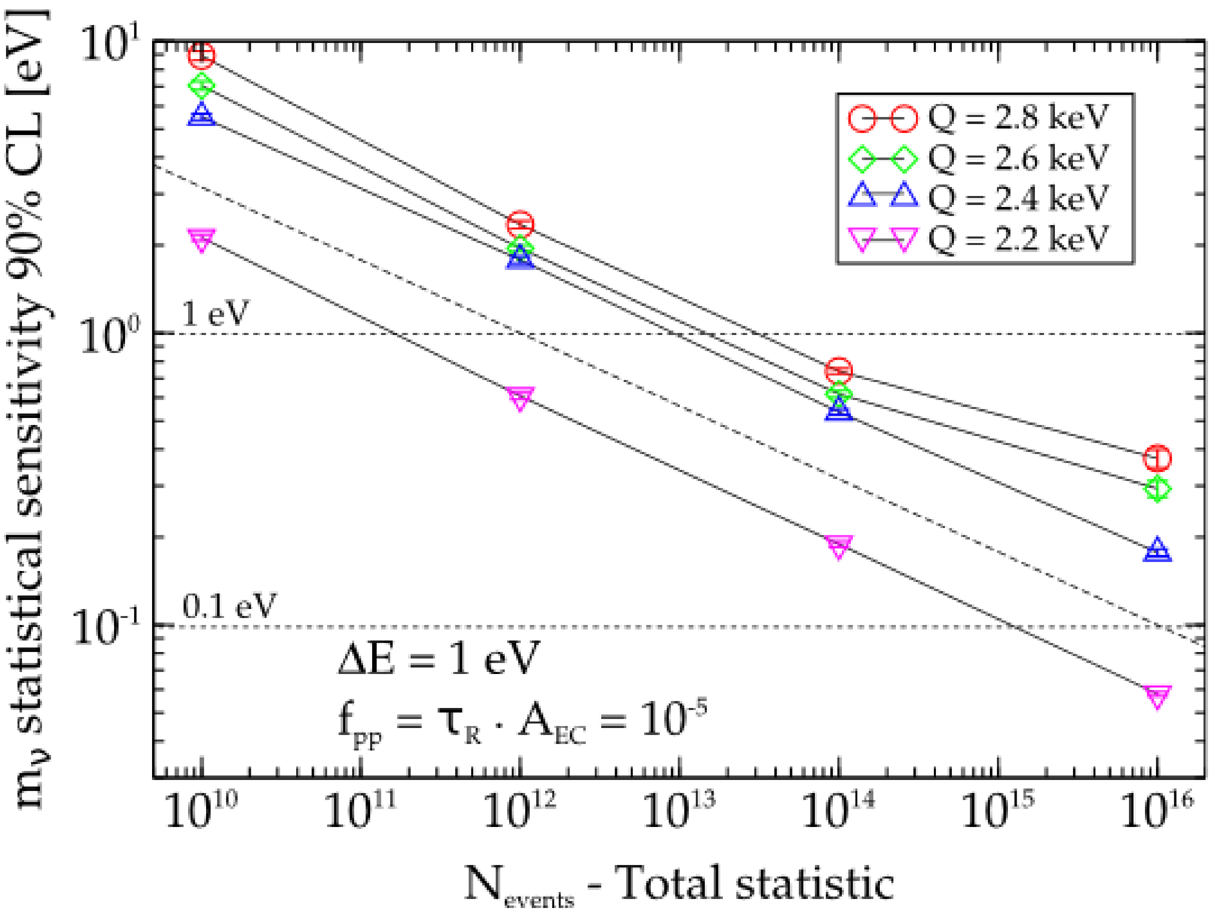
European Research Council

→ Project Start: 1 Feb 2014

B. Alpert et al, accepted in EPJ-C, arXiv:1412.5060

http://artico.mib.infn.it/nucriomib/experiments/holmes

Sensitivity on m_ν



Experimental requirements to gather high statistics

10^{13} events in 3 years time

Detectors:

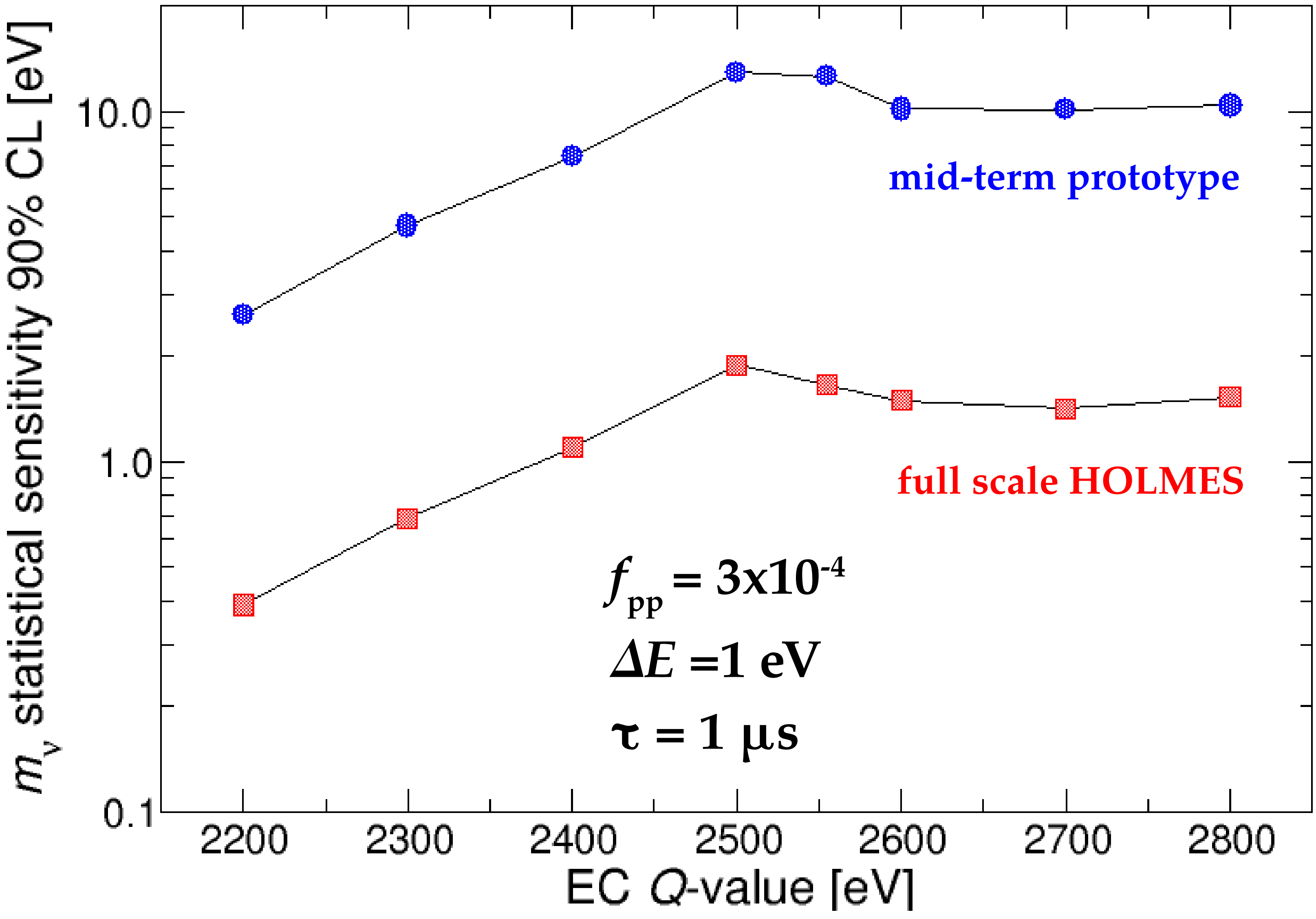
- Energy resolution 1 eV @ 2 keV
- Time resolution 1 μs
- Very large detector array (1000 detectors)

Best choice: LOW TEMPERATURE DETECTORS

Calorimeters coupled to Transition Edge Sensors with RF multiplexed readout

Microwave Kinetic Inductance Detectors (MKIDs) with implanted Holmium

HOLMES baseline



16 channels

t_M=1 month

A=300Hz/ch

$\rightarrow 10^{10}$ decays

1000 channels

t_M=3 years

A=300Hz/ch

$\rightarrow 3x10^{13}$ decays

Requirements for 0.2 eV sensitivity

A_β [Hz]	j_R [^{c}s]	ΔE [eV]	N_{ev} [counts]	exposure [det×year]
1	1	1	2.8×10^{13}	9.0×10^{5}
1	0.1	1	1.3×10^{13}	4.3×10^{5}
100	0.1	1	4.6×10^{13}	1.5×10^{4}
10	0.1	1	2.8×10^{13}	9.0×10^{4}

Q_{EC} = 2200 eV
bkg = 0

5000 pixels/array
3 arrays
1 year
~2*10^{17} ^{163}Ho nuclei

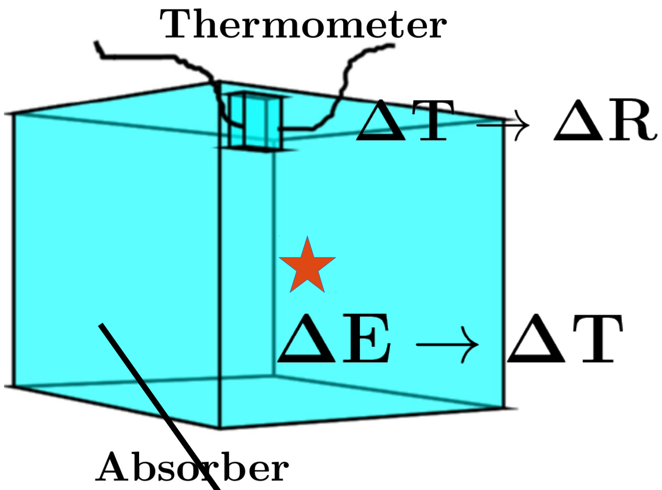
A_β [Hz]	j_R [^{c}s]	ΔE [eV]	N_{ev} [counts]	exposure [det×year]
1	1	1	3.8×10^{15}	1.2×10^{8}
1	0.1	1	1.6×10^{15}	5.3×10^{7}
100	0.1	1	9.8×10^{15}	3.1×10^{6}
10	0.1	1	3.8×10^{15}	1.2×10^{7}
10	1	1	9.8×10^{15}	3.1×10^{7}

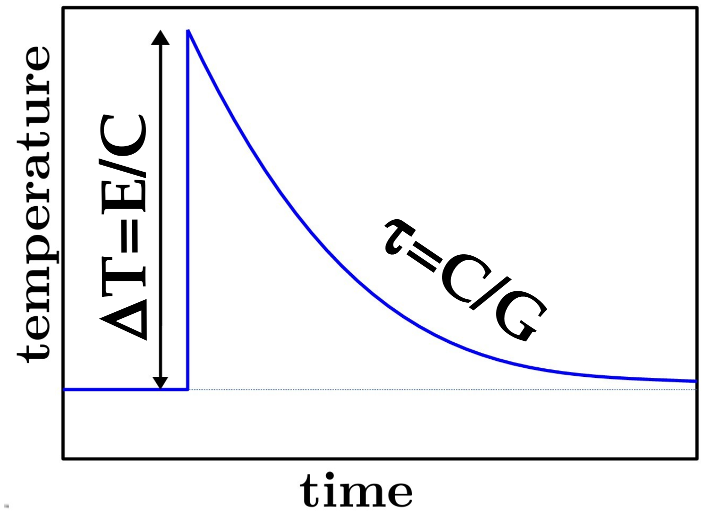
Q_{EC} = 2800 eV
bkg = 0

60000 pixels/array
5 arrays
5 year
~4*10^{18} ^{163}Ho nuclei

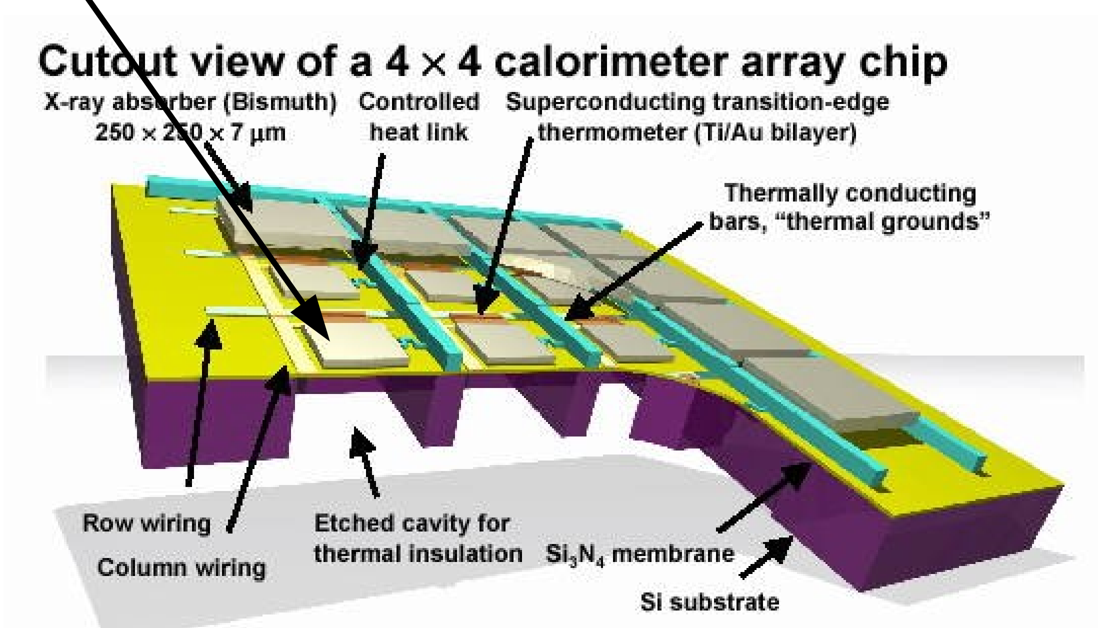
A. Nucciotti, accepted in EPJ-C, arXiv:1405.5060

Low temperature calorimeters

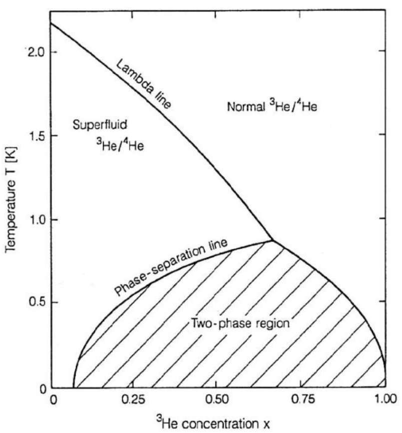


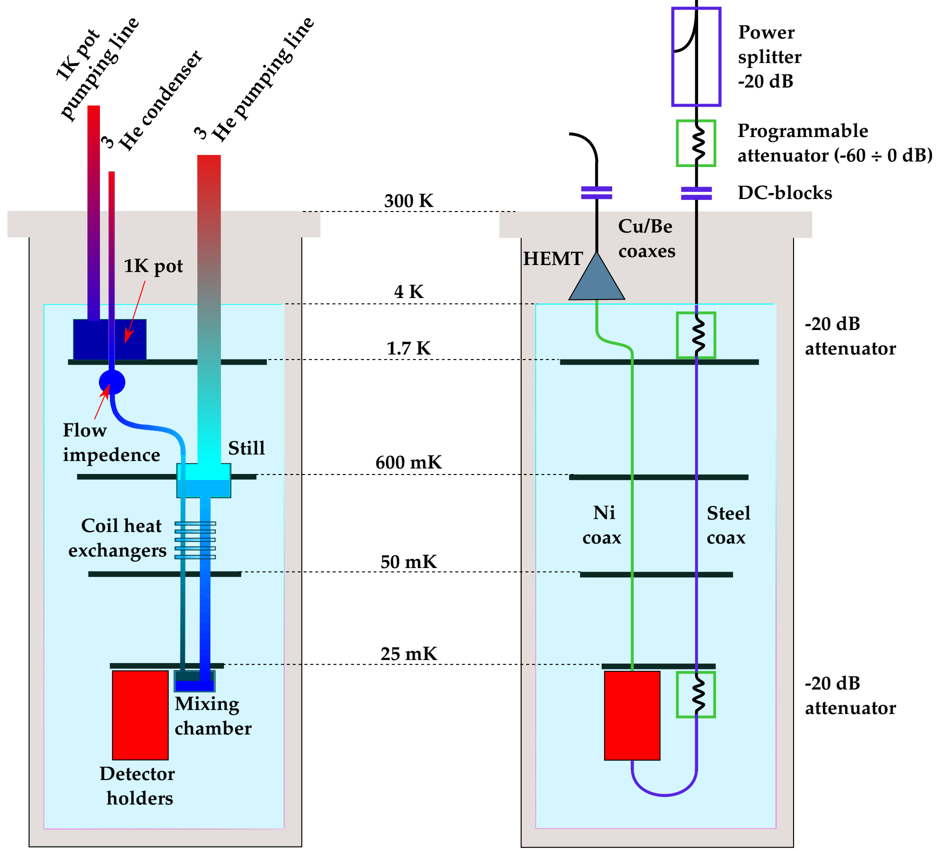


C-> thermal capacity of the absorber
G-> thermal link detector-cryostat



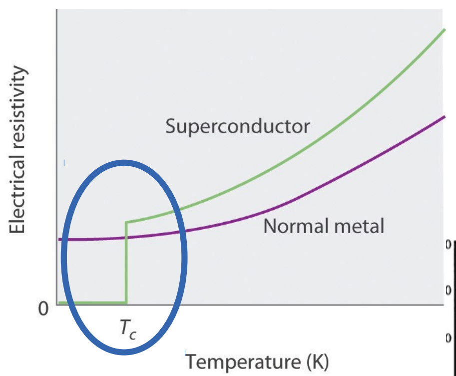
Dilution refrigerator

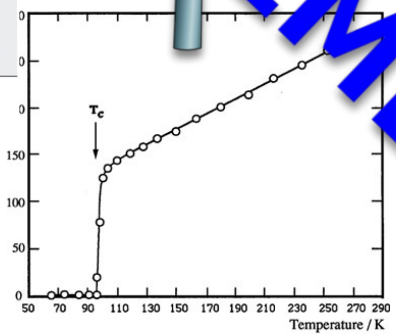




How to measure

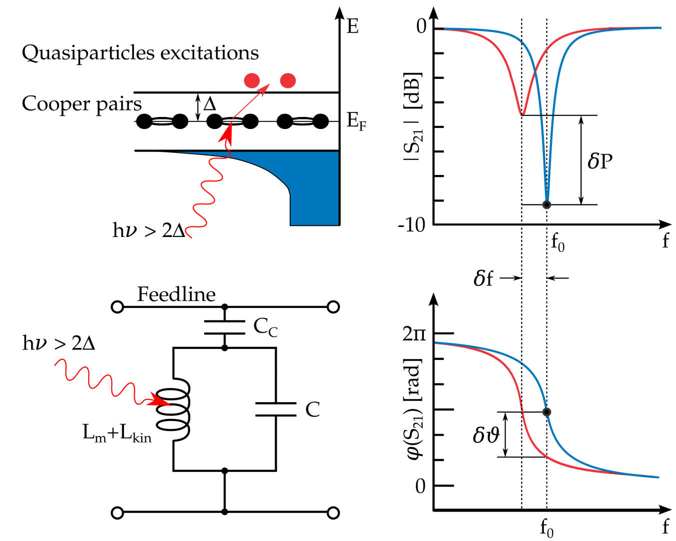
Transition Edge Sensors





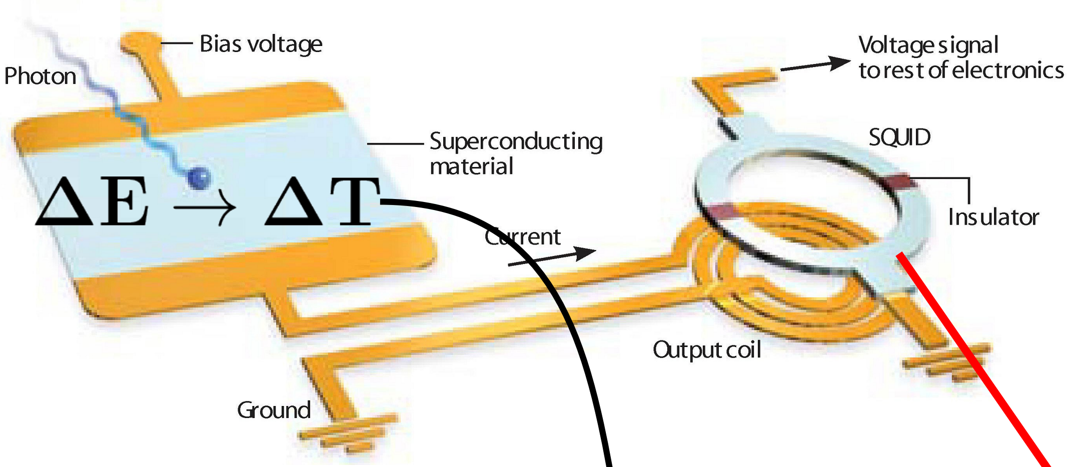
- Superconductor kept at the bottom of the transition region
- Incoming radiation ($E_\gamma > 2\Delta$) breaks cooper pairs in the superconductor
- Pair braking causes resistivity increase in the TES circuit
- A coupled DC-SQUID is used to measure current variation
- For multiplexing, a RF-SQUID can be coupled to a resonant circuit which is continuously excited with a microwave signal

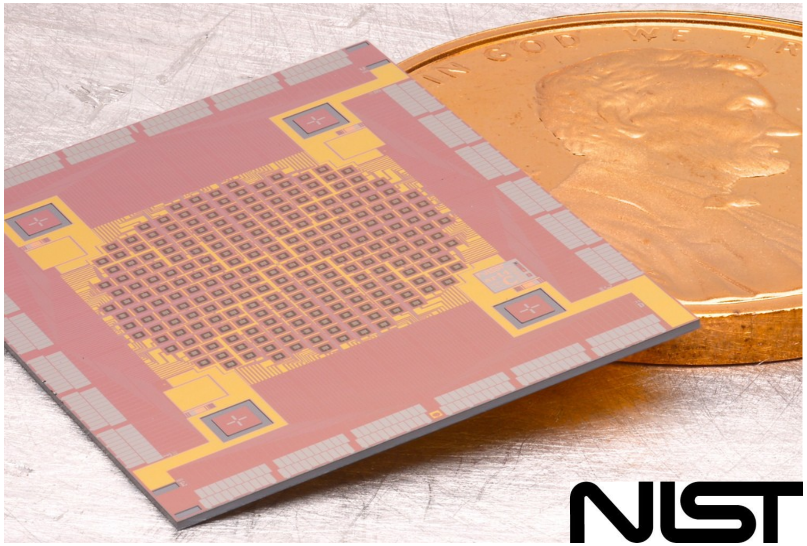
Microwave Kinetic Inductance Detector



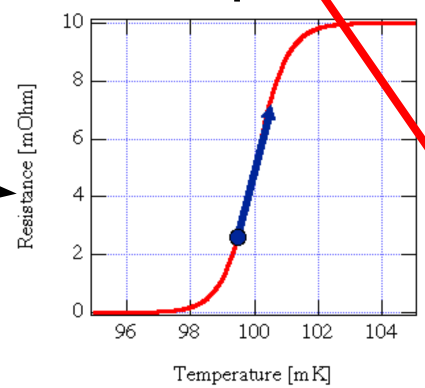
- Pair breaking radiation ($E_\gamma > 2\Delta$) creates quasi particle density (n_{qp})
- New quasi-particles change the surface impedance
- A resonant RLC circuit litographed in a thin film is used to sens L_S and R_S
  - $Z_S = R_S(n_{qp}) + j\omega L_S(n_{qp})$
  - L_S: kinetic inductance
  - R_S: dissipation
- To monitor the resonant circuit, it is continuously excited with a microwave signal

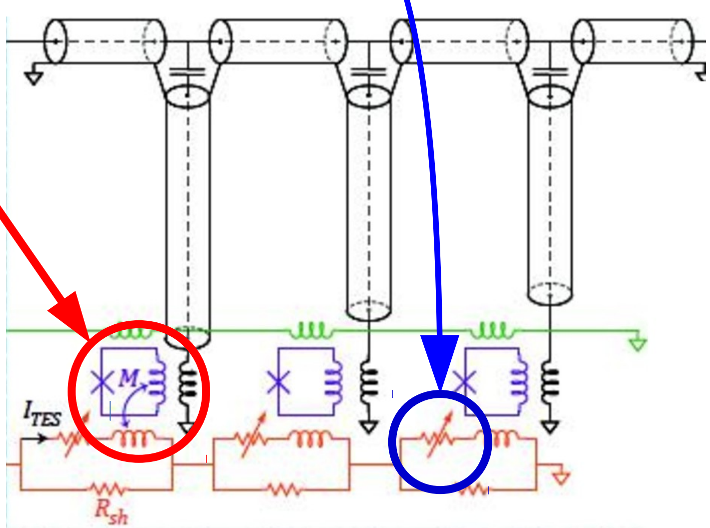
TES operation





$\Delta T \rightarrow \Delta R$

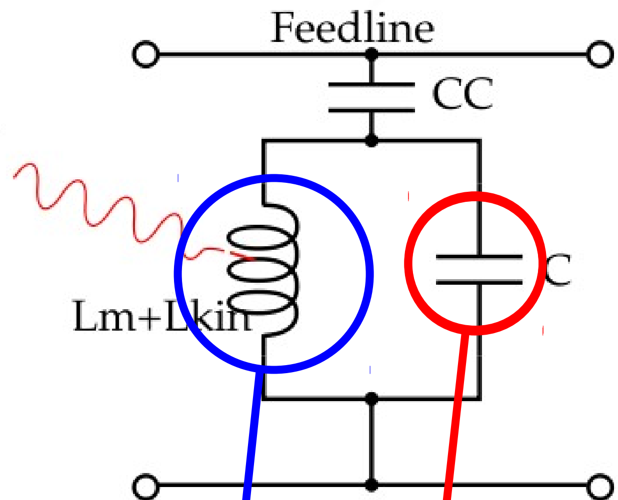


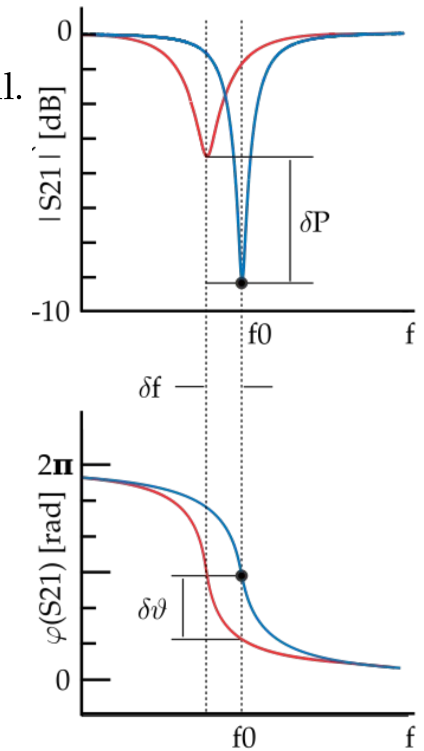


- Gold&Bismuth absorber coupled to a Transition Edge Sensor (TES)
- ^{163}Ho implanted in Au, covered with Bi for better thermal performance
- MoAu or MoCu TES, $T_c \approx 100$ mK
- Detectors suspended on SiN_x to reduce thermal conductance towards bath
- Rf-SQUID readout

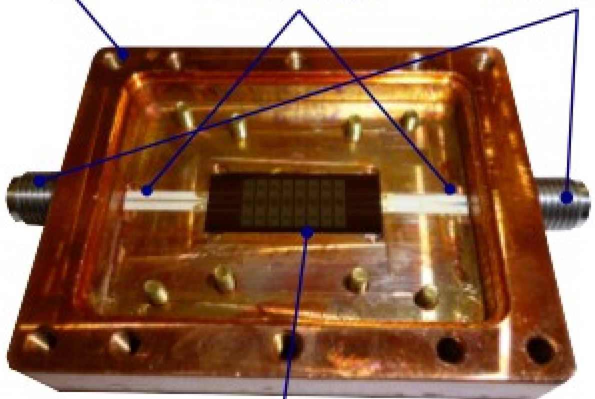
MKIDs operation

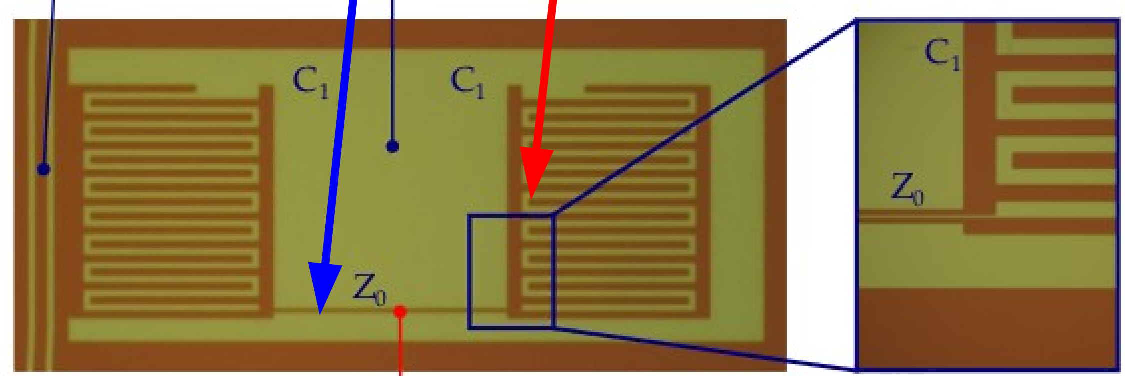
Incident photons change the surface impedance of a superconductor through the Kinetic Inductance Effect. Proposed for the first time in in 2003, P. K. Day et al. Nature 425 (2003) 817 .



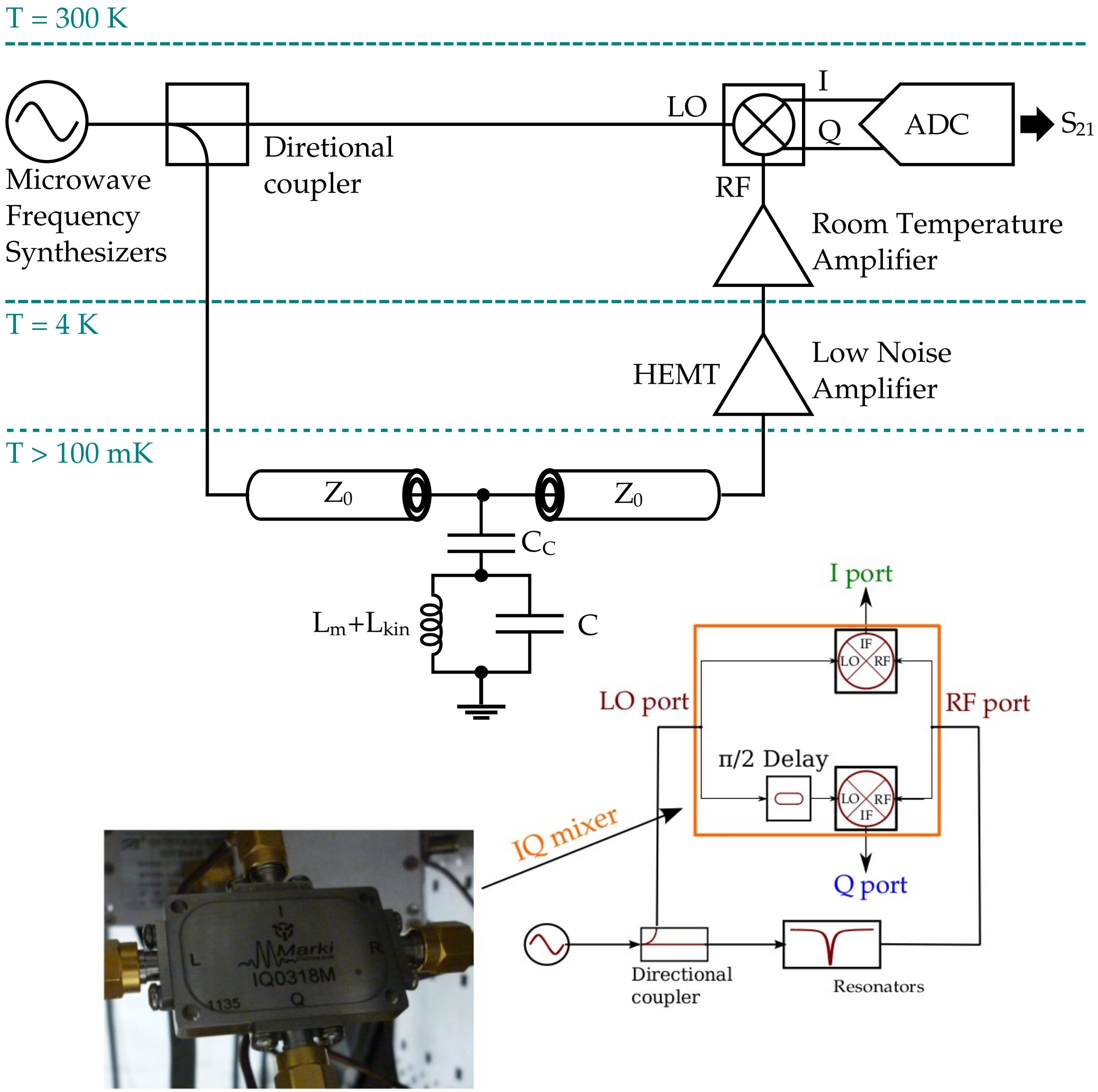


Devices designed to operate in non-equilibrium mode and tested with low energy X-ray sources collimated in an area of 300 μm around the center of the inductor by a collimator





Readout: homodyne detection

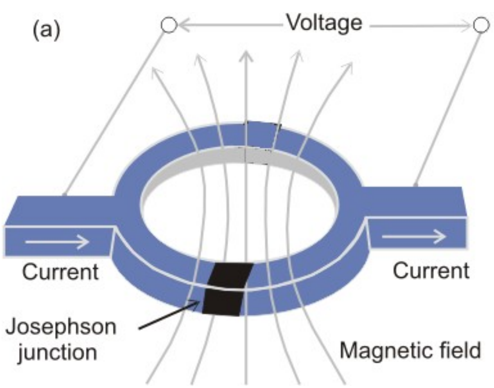


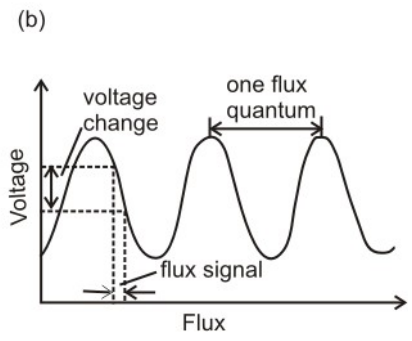
Either detector types rely on a resonant circuit that is sensible to inductive variation

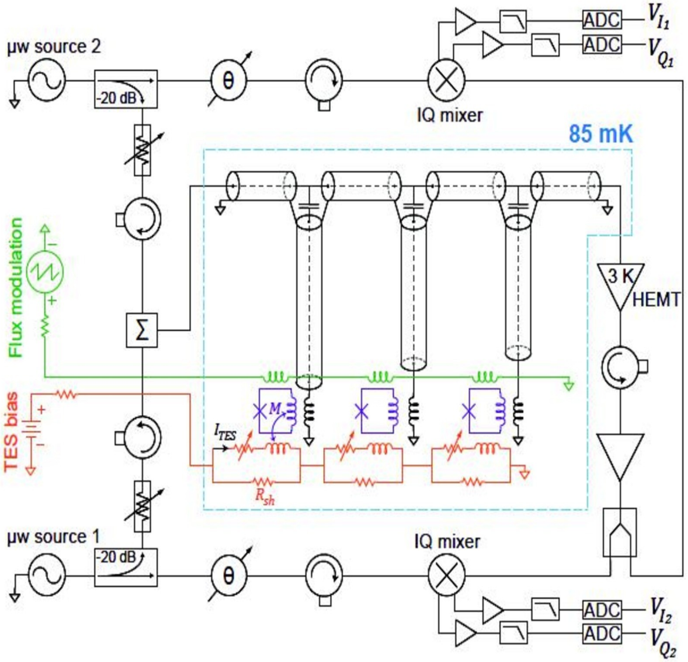
- A microwave signal is generated by a synthesizer and then split in two;
- One copy is sent into the cryostat and onto the transmission line of a microresonator chip, through a HEMT (High Electron Mobility Transistor) amplifier, and back out of the cryostat to an IQ mixer (RF);
- The outputs I and Q represent the real and imaginary parts of the transmitted signal S 21 (forward transmission coefficient), and are easily converted to describe the phase and amplitude of the signal transmitted past the resonator.

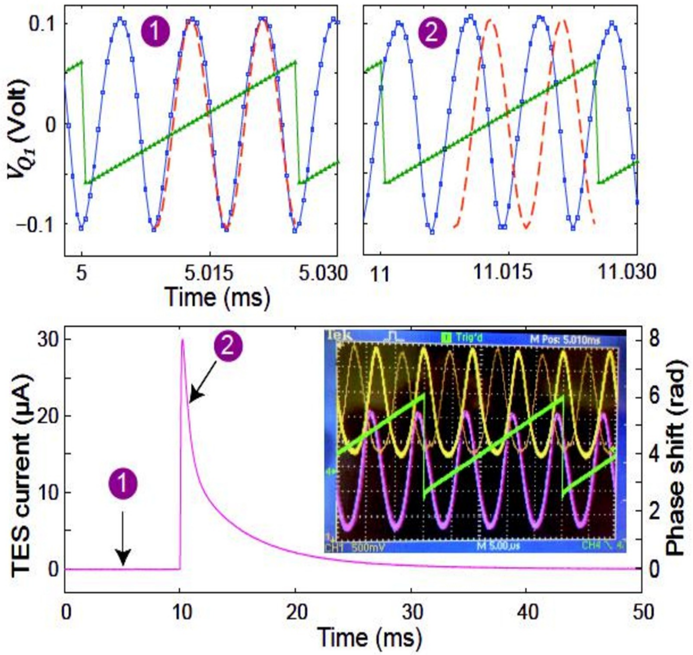
RF-SQUID readout for TES

- The SQUID traduces changes in input current to changes in phase of a microwave signal.
- A SQUID shows a periodic response function to flux variation
- We use flux-ramp modulation to linearize the response; The amplitude of the ramp is tuned such that it provides ~ $3\Phi_0$ of flux per ramp period

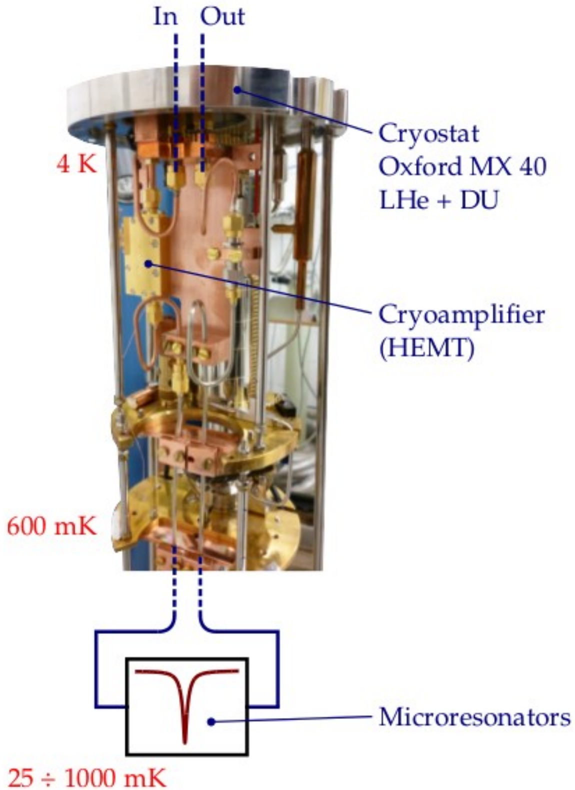


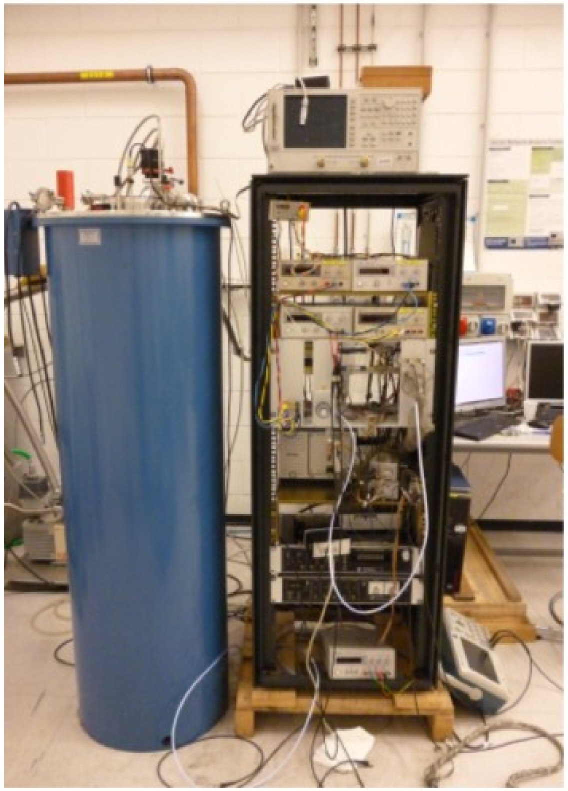


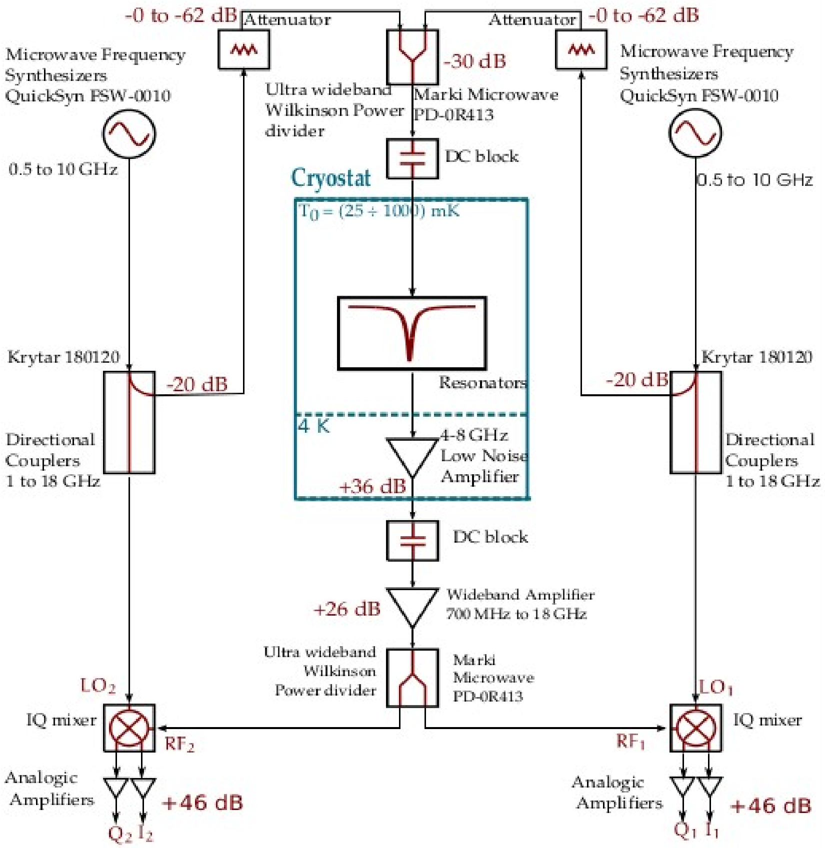


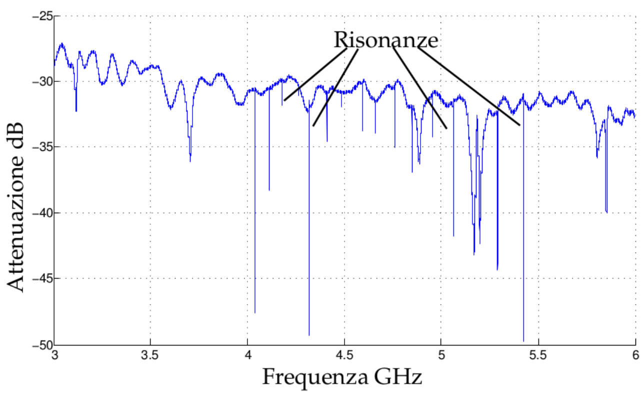


Multiplexing





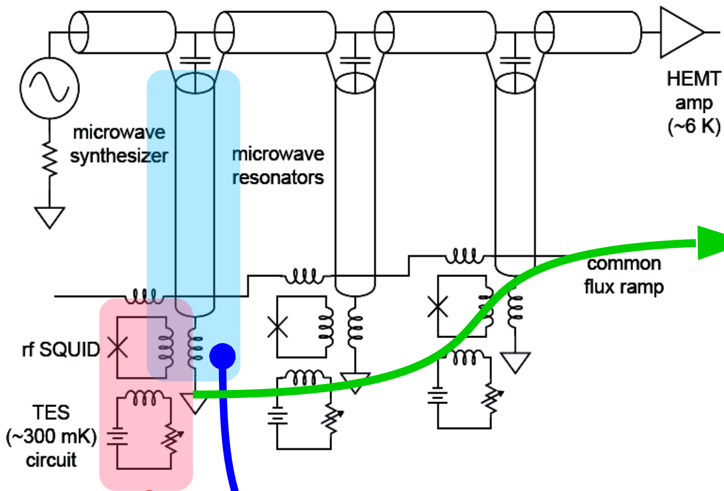


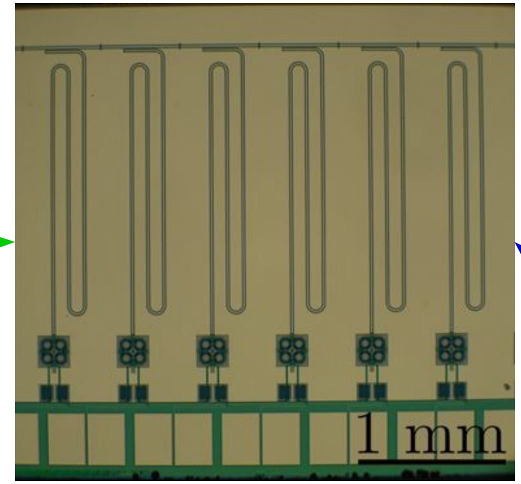


A two channel *brute force* multiplexed system is used to read two different resonators using only one coax line through all the cryogenic system.

- MKIDs are directly excited by the incoming microwave
- A SQUID coupled to a resonator is used in case of TES employment

Multiplexing/2

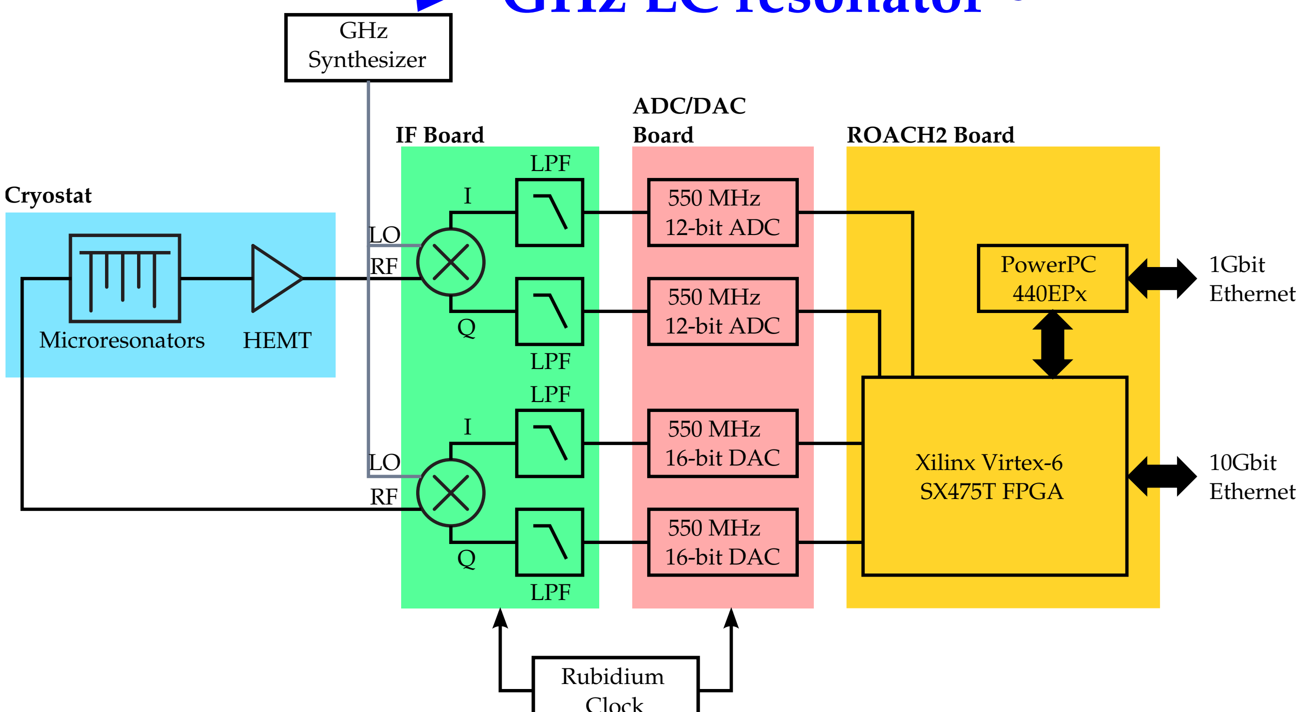


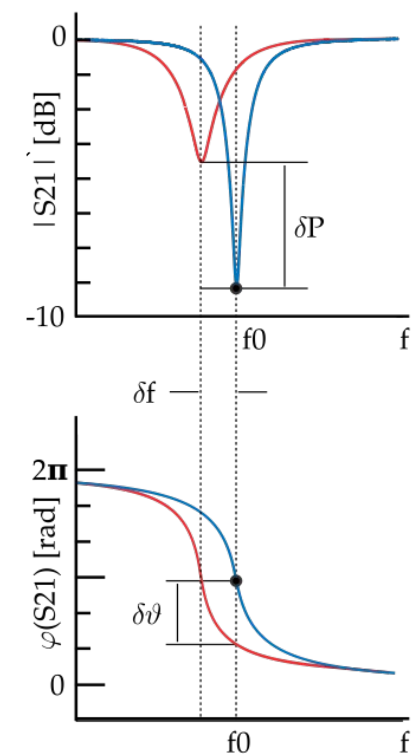


MHz flux ramp modulation

GHz LC resonator

LC resonator transmission

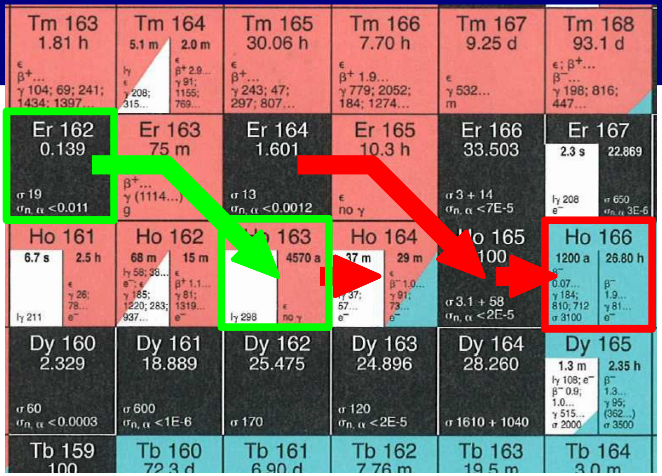




Holmium production

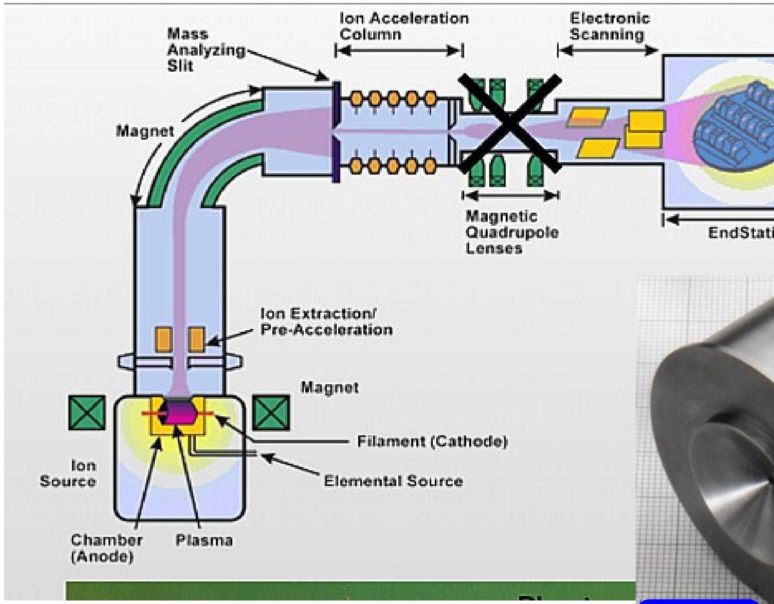
- ^{163}Ho production by nuclear reaction
  - high yield
  - low by-products contaminations (in particular ^{166m}Ho, β $\tau_{1/2}$=1200y)
- ^{163}Ho separation from Dy, Er, ...
  - radiochemistry (before and/or after irradiation)
  - magnetic mass separation
- ^{163}Ho embedding in detector
  - implantation +magnetic separation
  - Au film deposition for full containment

HOLMES baseline



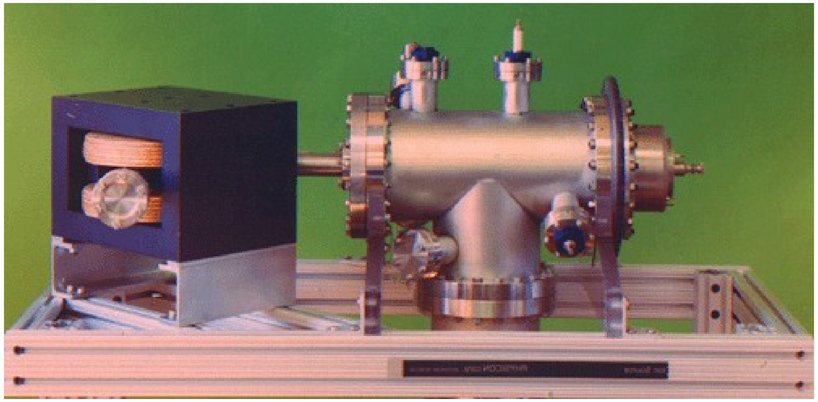
$$^{162}\mathrm{Er}\ (n,\gamma)\ ^{163}\mathrm{Er} \qquad \sigma_{thermal} \approx 20\mathrm{b}$$

$$^{163}\mathrm{Er} \rightarrow\ ^{163}\mathrm{Ho} + \nu_e \qquad \tau_{1/2}^{EC} \approx 75\mathrm{min}$$



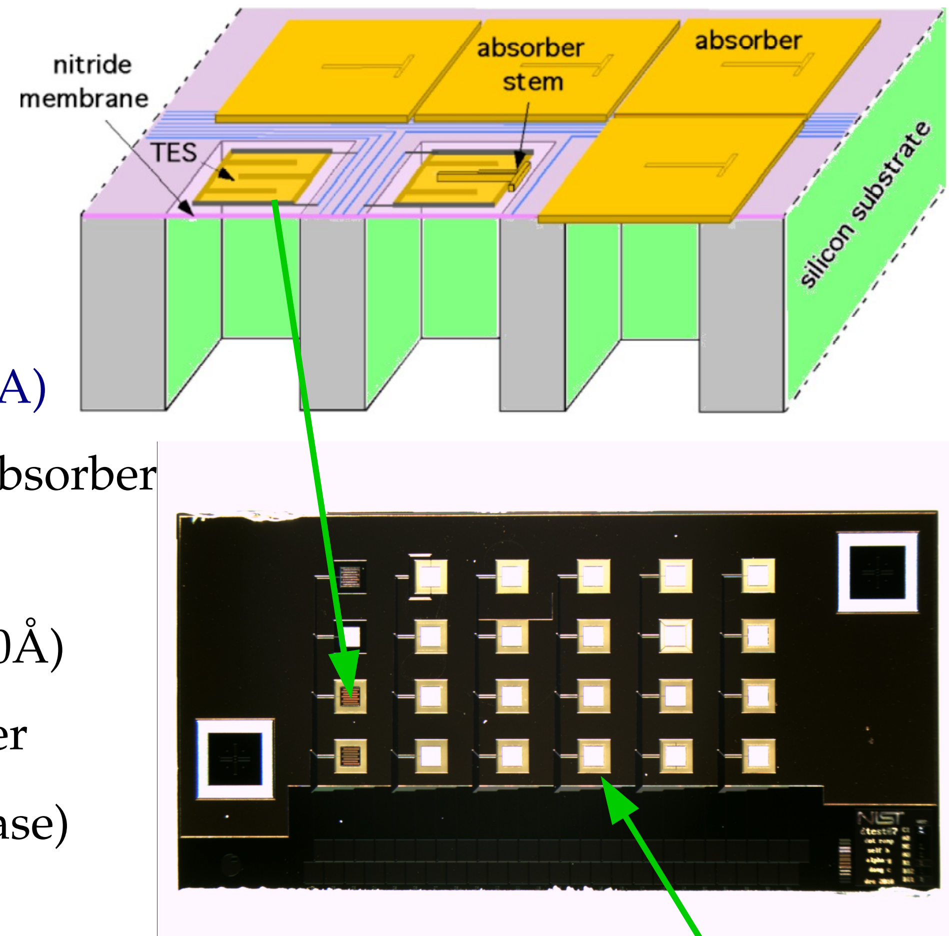
Metallic ^{163}Ho/Er/Au cathode

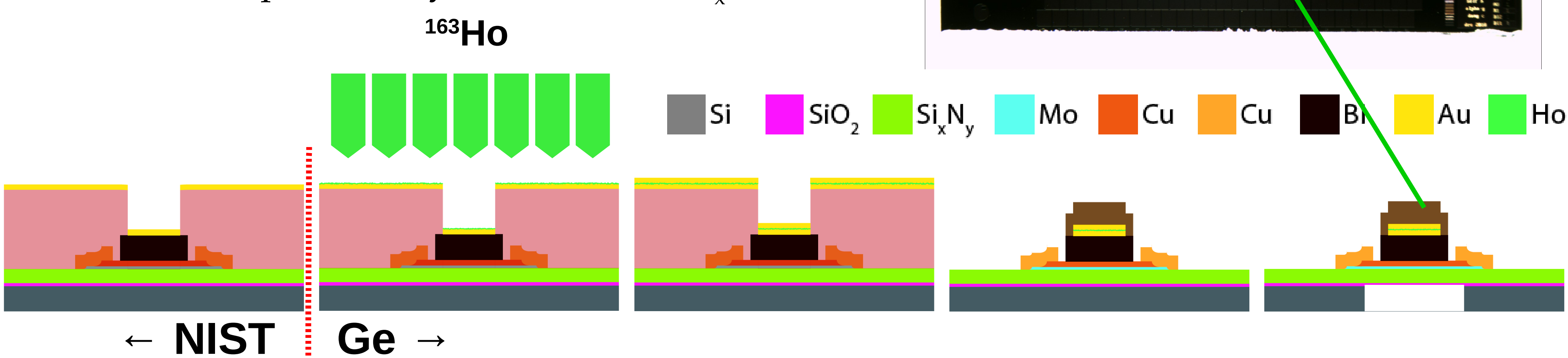
penning sputter source



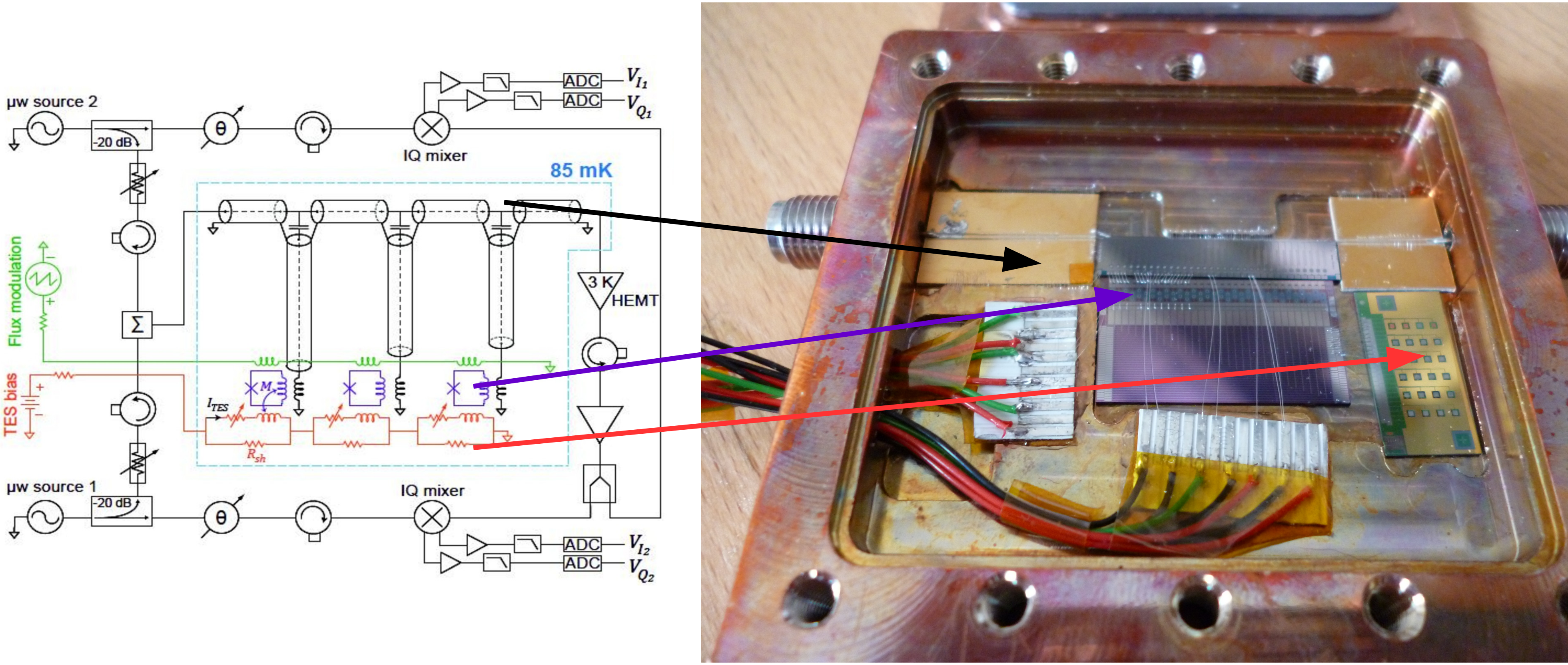
TES production

- single pixel development @Genova
  - ▷ optimize design for speed and resolution
  - ▷ define process for ^{163}Ho implantation
- array design @Genova
- subcontract array fabrication (NIST, Boulder, USA)
  - ▷ subcontractor fabricates array with 1 μm Au absorber
- Genova completes array fabrication
  - ▷ Genova implants ^{163}Ho at shallow depth (≈100Å)
  - ▷ Genova covers implant with 1 μm Au absorber
  - ▷ Genova completes array fabrication (SiN_x release)





TES for HOLMES R&D



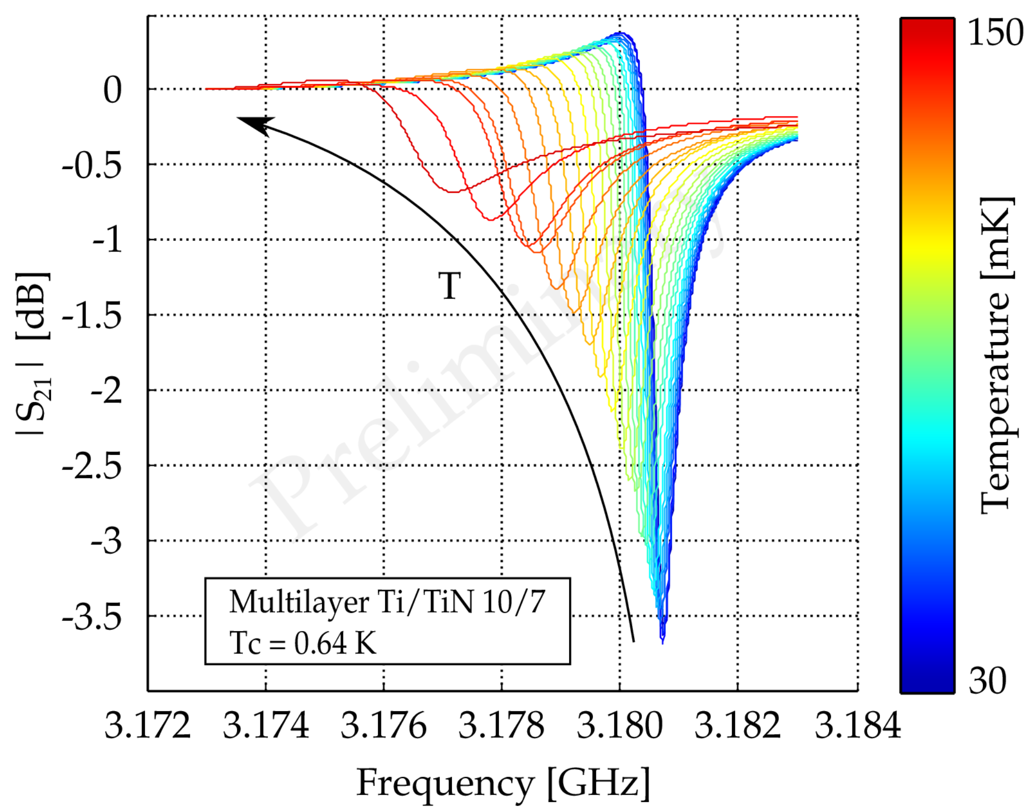
- First test on ramp and resonant circuit in run0 (Sep 2014)
  Cryogenic system (Oxford Instruments TL-400 dilution refrigerator) prepared with new RF line and multiplexing readout
- TES test due to be done in run1 (Feb 2015)

Ramp test → OK

Readout RF circuit resonances checked → OK

Thermal mode MKIDs

- A temperature change can produce an identical increase of quasiparticle population of an external pair-breaking, J. Gao et al. J. Low Temp. Phys. 151 (2008) 557
- The effect of a small variation in temperature leads to a change in the surface impedance due to a change in kinetic inductance L_S.
- The amplitude and phase shifts of S 21 depends on the increase in equilibrium thermal quasiparticle population due to the bath temperature variation.



Very sensible detectors if:

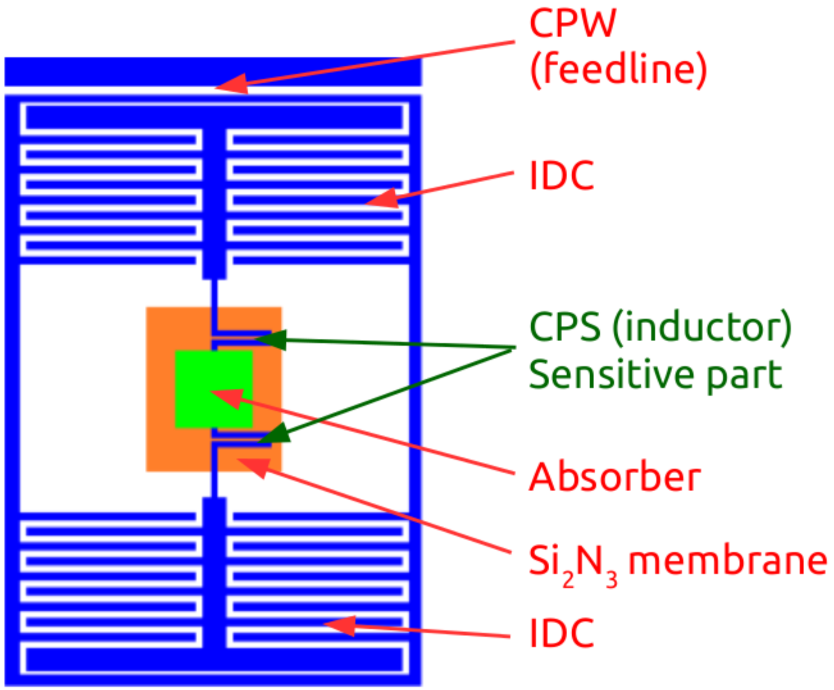
- devices with critical temperature low enough ($T_c < 500$ mK);
  - the sensitivity improves as the T_C is lowered ($\delta f \propto 1/T_C^2$);
  - low energy gap Δ;
  - slower recombination time τ_{qp} (i.e. low G-R noise) ;
- operating at very low temperature to minimize the absorber thermal capacity ($T < T_c/4$);

MKIDs with absorber

- Energy resolution for a metal absorber (i.e. Gold) 200 μm × 200 μm × 2 μm working at T = 50 mK, it is possible to have resolution around 1 eV
- Time resolution: for resonator frequencies = (1 ÷ 6) GHz range, rise time around 1μs or less is achievable.

Metal Absorber: thermally coupled with the inductive part and suspended Si_2N_3 membrane:

- Absorbers with a very high stopping power are needed in order to avoid loss of energy and to keep the thermal capacity as low as possible.
- A thickness of 5 μm of Gold provides a stopping power close to 100% radiation of energies up to 6 keV and 45% at 20 keV;



Possible geometry design

Thank you for your attention